INAF Strategic Vision

Introduction

Astronomy is arguably the oldest of the natural sciences.
Over the course of human civilization, the sky has provided the means to measure time and the succession of the seasons, to guide the traveler, to understand our place in the Universe.
Astronomical knowledge was remarkably advanced in Babylon, Egypt and China thousands of years ago and developed through the centuries with Aristarcos and Tolomeus in Greece and Copernicus, Kepler and Galileo in Europe. It was in Italy with Galileo Galilei at the beginning of the 17th century that Astronomy and Physics were united, deriving mathematical predictions of celestial motions from assumed physical causes.
Astronomy led the scientific revolution, which continues to this day and has revealed that the sky visible to the naked eye is really just a hint of a vast and complex cosmos, within which our home planet is but a pale blue dot.
Our current knowledge of the Universe extends from a state of extremely high density and temperature, the so-called *Big Bang*, 13.7 billion years ago, to the present state of accelerated expansion, pushed by an obscure force called *dark energy*. We know that the majority of matter in the Universe is "dark" and not made of baryons (proton and neutrons) which compose the ordinary matter.
We have explored the cosmos, not just by observing through the tiny visible window used by our eyes, but also by exploiting four independent channel of information: the electromagnetic spectrum, from radio waves with wavelengths larger than tens of meters to gamma rays with wavelengths 1,000 times smaller than a proton, cosmic rays, neutrinos and gravitational waves. Information about the constituents of the ambient interstellar and interplanetary medium has been gained by collecting and chemically analyzing interstellar dust grains that penetrate into the Solar System and samples returned to Earth from asteroids and meteorites.
Dramatic discoveries came about through the application of modern technology and human ingenuity to the ancient craft of observing the sky. In the coming decade, major challenges loom that require the development of fundamental new theories. Observations and computer simulations are necessary components, but to complete the path from discovery to understanding, theorists will need to freely exercise their imaginations.
To optimize the exploitation of the limited resources available it is imperative that the Italian community develops a unified vision of Astrophysics, identifies its likely evolution and sets priorities.
To this purpose, the Istituto Nazionale di Astrofisica (INAF), which has the duty to promote and coordinate the astrophysical research activities in collaboration with the Universities and other national and international Institutes, has elaborated its Strategic Vision (SV) for the next decade 2020-2029. The preparation of this plan has been assigned to the INAF Scientific Council (CS), which drafted the SV between May 2016 and May 2019, based on an extensive and intensive interaction with the Italian astronomical community, mediated by the Scientific Macro-Areas (MA, Macroaree Scientifiche).

Executive Summary

The Istituto Nazionale di Astrofisica (INAF) has the duty to promote and coordinate the astrophysical research activities in collaboration with the Universities and other national and international Institutes. In this Strategic Vision Document, the INAF Scientific Council, in close collaboration with the whole Italian astronomical community through the Scientific "Macro-Areas" Committees, has identified the most promising scientific and technological fields in which INAF has and/or should have a leading position during the next decade 2020-2029.

This has been done by first identifying the major current "key questions" in Astrophysics, as well as the best methods to tackle them. Questions and methods have then been rearranged as a function of the existing and future projects, summarized in Appendix 1.1, providing a non-exhaustive list of the activities, including the enabling technologies, in which INAF is or should be involved. From the analysis of this material a few high priority undertakings and some major recommendations which are considered particularly important for the future development of the Italian Astrophysics have been derived.

These are not intended as the only goals that INAF should pursue in the future, but as goals that are of special relevance and should not be missed, together with other important activities, small-scale extremely innovative high-risk high-gain projects and the unceasing unforeseen breakthroughs that make Science a surprising and exciting discipline.

Top priority undertakings

Participation to the large international facilities of the future

A number of major international facilities of the future that have already a significant Italian participation are considered as top priorities for the scientific and technological investment by INAF. They are: SKA, ELT, Euclid, Athena and CTA.

In order to ensure an adequate scientific return, it is mandatory to support and enlarge the involved communities in all the relevant aspects, from technological development, to data analysis/archiving and theoretical interpretation (including computer simulations).

This requires a strong participation to "precursor" programs/facilities, with the specific and focused aim of developing the skills and gathering the ancillary data necessary to maximise the scientific return of the top priority facilities.

In particular, for what concerns the ELT, it is necessary to strongly support and expand the role of INAF in ESO, aiming at a leadership role comparable to other major European nations, with a special focus for the development of advanced instrumentation.

The exploration of the Solar System

The last years have seen an incredible leap in our knowledge of the bodies forming our system and of the interaction between these bodies, the Sun and the interplanetary space, and the next decades list of the targets to be explored (Uranus, Neptune, …) will probably be completed. In a nearer future instead we will see an in-deep exploration of bodies like Mercury, Mars, Jupiter satellites and the Sun, performed by the missions BepiColombo, Exomars,, Juice and Solar Orbiter. Many of the Italian researchers involved in these missions, often with key and leadership roles, belong to INAF. INAF should encourage and support these researchers in their efforts to assume a leadership role both in the pre-launch phases and in the post-launch phases, providing adequate resources to the laboratory and theoretical activities necessary for an optimal exploitation of the data.

Life beyond our Solar System

Exoplanetary astrophysics is today a key priority at the center of the scientific agendas (and roadmapping exercises) of all the leading institutions in astronomy as well as space agencies, with a broad, multi-technique portfolio of ground- and space-based programs across a wide range of wavelengths.

INAF only recently has become an important player in the exoplanet arena, thanks to a strategic choice of investments, training of early-career researchers, and scientific and technological involvement in major ground-based and space-borne programs.

The frontier of the field over the next 10-15 years will center on the complete characterization (occurrence rates, internal and atmospheric composition) of exoplanets in the solar neighborhood, with the ultimate goal of identifying biomarkers in the atmospheres of temperate Earth-type planets around stars similar to the Sun.

It is of the highest priority for INAF to not only consolidate its participation to, but produce increasing efforts (at all levels) to secure key, leadership roles in the projects at the forefront in exoplanetary science aimed at reaching objectives with profound scientific, intellectual, and cultural relevance.

Multimessenger Astrophysics

Thanks to the heritage of the Italian community working on GRBs and on high energy missions, INAF is playing a major role in this field that will become more and more important in the next decade. Keeping a high profile international role in multi-messenger astrophysics is a top priority that requires an increasing level of effort and resources.

This must be done, in particular, by supporting the aspects that are more relevant for the experience of the INAF scientists (e.g. electromagnetic follow-up, theoretical astrophysics, development of new facilities/satellites for e.m. observations) in close collaboration with other major players at national (INFN, ASI, University groups) and international level (ESA, ESO). Adequate resources must be devoted to support the technological, observational and theoretical activities of the most promising groups in order to maintain a relevant presence in such a competitive field.

Fundamental (Astro)physics

It is expected that decisive progress will be made in the next decade towards solving problems of Dark Matter and Dark Energy. Astrophysics is in the unique position to gather information with many types of cosmological probes over a wide range of scales and cosmic time, which is mandatory in order to separate cleanly the true properties of the Universe from imperfections in our observations. The challenge now is to turn our knowledge in precision measurements, for example determining “equation of state” for Dark Energy and its variation with time to a precision better than few percent.

Astrophysical observations will provide fundamental clues about possible extensions beyond the Standard Model (e.g. the properties of neutrinos, any violation of the laws and symmetries of fundamental physics, the variation of the physical constants, the energy scale of the fundamental interactions). These studies, strictly interdisciplinary, have a deep synergy with the direct search of the dark matter and other particles carried out in ground-based laboratories, and need adequate resources and large partnerships (see also below: the fourth General Recommendation).

General Recommendations

Support to Theoretical Astrophysics
The role of theorists is fundamental to extract the ultimate knowledge from the most advanced facilities, to plan new ones, and to interconnect different fields. Theorists have become more and more engaged with current datasets, planning new facilities, missions and in computational approaches to simulate astrophysical phenomena. Every participation to a new project or facility should involve a commensurate number of theorists and interpretative astrophysicists to ensure an adequate scientific return for the Italian community.
INAF should set up a specific program to support Theoretical Astrophysics.

Encourage coordination and creation of large groups
INAF should promote the coordination of individual researchers and communities working in similar/homogeneous fields where our community plays an already well established role at international level in order to optimize resources and form groups with ``critical mass''.
Considering the very long development/construction times, adequate ''roadmaps'' should be defined in order to maintain the scientific expertise of the already well-established groups at international level over such long periods and to train/form the scientists that will design, build and exploit the big facilities/missions of the future. This requires an adequate and carefully tuned balance between long- and short-term projects.

Support "Basic Research" projects
Besides the large projects described above, it is fundamental to support scientific and technological projects small in size but with important scientific return, as well as curiosity driven research. This must be done with regular (i.e. with a well-defined and known timeline, as well as consolidated rules) emission of competitive calls for scientific and technological research projects.

Foster interdisciplinary partnerships
Several major activities (such as, e.g., Solar System research and the astrophysics of planetary systems) have an extraordinary potential to propel interdisciplinary activities within the Institute and to foster interdependence across astronomy and other disciplines, such as chemistry, geology, biology, and computer science.
It is important to promote and develop joint efforts aimed at enhancing interdisciplinary, convergent research in astronomy and astrophysics both within INAF (i.e. across the different National Research Groups) and with colleagues in other organizations and laboratories.

Improve the cooperation with ASI
Space missions are a fundamental component of modern research in Astrophysics, and many INAF researchers are involved at various levels in most of the space missions of astrophysics interest. INAF researchers would benefit from a more strict cooperation between INAF and the Italian Space Agency, based on the respective specificities/complementarities and following clear and transparent rules. INAF should be involved in all phases of the participation of its researchers to a space mission and take part in the approval process of a proposal for the scientific participation to a mission team and/or the building of an instrument, and then contribute with ASI in giving support to the involved team.

Give an effective role to the "National Scientific Committees"

In order to reach the above-mentioned goals the action of the new "National Scientific Committees" will be instrumental and has to be supported by all possible means, fostering a high-level scientific and technological debate and investing them with real programming and monitoring powers, taking advantage of the best practices of other institutions such as INFN, with the aim of further developing the astrophysical cultural level in the Italian community.

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Acronyms

AGN: Active Galactic Nucleus
ALMA: Atacama Large Millimeter Array
ARIEL: Atmospheric Remote-sensing Infrared Exoplanet Large-survey
BAO: Baryonic Acoustic Oscillations
BH: Black Hole
CHEOPS: CHaracterising ExOPlanet Satellite
CMB: Cosmic Microwave Background
CTA: Cherenkov Telescope Array
DE: Dark Energy
DM: Dark Matter
ELT: Extremely Large Telescope
EoR: Epoch of Reionization
ESPRESSO: Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations
EST: European Solar Telescope
EVLA: Expanded Very Large Array
GIARPS: GIANO-B + HARPS-N
GR: General Relativity
HARPS-N: High Accuracy Radial velocity Planet Searcher - North
HPC: High-Performance Computing
HST: Hubble Space Telescope
HUDF: Hubble Ultra-Deep Field
ICM: Inter-Cluster Medium
IGM: Inter-Galactic Medium
ISM: Interstellar Medium
IRAM: Institut de RAdioastronomie Millimétrique
JUICE: JUpiter ICy moons Explorer
JWST: James Webb Space Telescope
LOFAR: Low-Frequency Array
LSS: Large-Scale Structure
LSST: Large Synoptic Survey Telescope
NIR: Near Infrared
NOEMA: Northern Extended Millimeter Array
NS: Neutron Star
NTD: Neutron Transmutation Doped
PdBI: Plateau de Bure Interferometer
PLATO: PLAnetary Transits and Oscillations of stars
R&D: Research and Development
RSD: Redshift-Space Distortion
SFR: Star Formation Rate
SDD: Silicon Drift Detectors
SiPM: Silicon PhotoMultiplier
SKA: Square Kilometer Array
SMBH: Super-Massive Black Hole
SN: SuperNovae
SPAD: Single Photon Avalanche Diode

SPICA: Space Infrared Telescope for Cosmology and Astrophysics
SQUID: Superconducting QUantum Interference Device
SZ: Sunyaev-Zeldovich
TES: Transition Edge Sensor
TESS: Transiting Exoplanet Survey Satellite
TNO: Trans-Neptunian Object
UVCS: Ultraviolet Coronagraph Spectrometer
VISTA: Visible and Infrared Survey Telescope for Astronomy
VLA: Jansky Very Large Array
VLT: Very Large Telescope
VST: VLT Survey Telescope
WFIRST: Wide Field Infrared Survey Telescope
WIMP: Weakly Interacting Massive Particle

Major challenges in Astrophysics over the next decade

1. Solar, interplanetary and magnetospheric physics

Keywords: Sun, solar structure, heliosphere, magnetospheres and planetary environments, cosmic rays, interaction of magnetic field and plasma.

Key questions:

1. ***How does the Sun give origin to the heliosphere and control its evolution? How does the Solar System evolve in relation with the parent star and interplanetary medium?***
- *How is the solar magnetic field produced? What is the role of turbulent magneto-convection in the mechanisms giving origin to the solar dynamics and variability?*
- *What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?*
- *Which processes are active today in the interaction between the interplanetary medium and the bodies surface and environment, and/or played a role in the early history of the Solar System?*

2. ***Which is the influence of the Sun and the radiation environments on the human activities and on life?***
- *Which are the particle radiation and electromagnetic fields dynamics in the planetary environment (with focus on the Earth)? And how are they driven by external agents (space weather)?*
- *How can the space weather be monitored and forecasted?*

The magnetic field generated inside the Sun threads through the solar atmosphere, the heliosphere and the planets magnetospheres; on the other hand, the entire Sun, the solar wind, the heliosphere, and the outer atmospheres of several planets are in plasma state.
The studies relevant to solar and interplanetary medium interactions with the magnetospheres, the upper atmospheres and the surface of the bodies in the solar system are fundamental for the understanding of the Solar System evolution, and also as paradigm for extrasolar planetary systems.
The studies relevant to solar, interplanetary and magnetospheric physics provide unique insight on basic physics of, for instance, magnetized plasma, turbulence and collisionless shock-waves particle acceleration. Plasmas are ubiquitous in the Universe and their dynamics is at the base for several processes occurring in stellar and planetary environments. Investigating solar and heliospheric plasma dynamics and its relationships with heating and acceleration processes, as well as the interaction with the planetary environments, are therefore central issues to unveil the physical mechanisms which are responsible for many emission processes in astrophysical objects.

1.1 Generation of magnetic fields and role in the solar atmosphere

Understanding the processes of generation of magnetic fields and of their emergence, evolution and periodic variability in the stellar atmosphere is still a major challenge for solar physics. The solar dynamo operates in the depths of the convection zone, where an oscillating magnetic field is maintained by plasma motions. Structure and dynamics of the polar convection zone have not been probed yet via helio-seismology. To answer the questions “How is the magnetic

flux transported to and reprocessed at high solar latitude?, Why does magnetic activity change with time?", it is important to detect the most important flows at and below the solar surface, in particular at high latitudes. They are: differential rotation, meridional circulation, torsional oscillations. Note that a two-level meridional circulation has been recently detected by the space instrument HMI on board the Solar Dynamics Observatory. All this requires going out of the ecliptic to observe solar polar flows and fields. A polar mission, flying above the poles of the Sun, could be actually suitable for this purpose.
Heating of the outer solar atmosphere is still one of the major enigmas of solar and (stellar) physics and of basic plasma physics: we miss an overall picture of the mechanism(s) at work. Most of the proposed scenarios are based on dynamic magnetic field rooted in the lower atmosphere, continuously shacked, shuffled and concentrated by photospheric plasma motion and organized in bundles of sub-arcsec transverse spatial scales. Heating is therefore generated by the turbulent dissipation of twisted magnetic fields and is an evident manifestation of the magnetic coupling occurring all over the solar atmosphere. EUV and UV spectroscopic observations of the solar disc have shown that a highly dynamic and complex system of magnetic structures forms the base of the corona. It is through these structures that the energy created in the interior of the Sun must be transported and dissipated to heat the corona and accelerate the solar wind. They are also likely channels for transporting mass to the upper atmosphere. Thus, in order to unravel the mystery of coronal heating one has to understand (in the optical and infrared bands) the properties of magnetic fields in the lower solar atmosphere and its interaction with plasma motion plus, at the same time, to study the processes of energy dissipation in the solar corona through UV, EUV and X-ray observations. The complementary support of MHD modeling with high performance computing is a crucial ingredient for a significant progress in the understanding of coronal dynamics and heating.

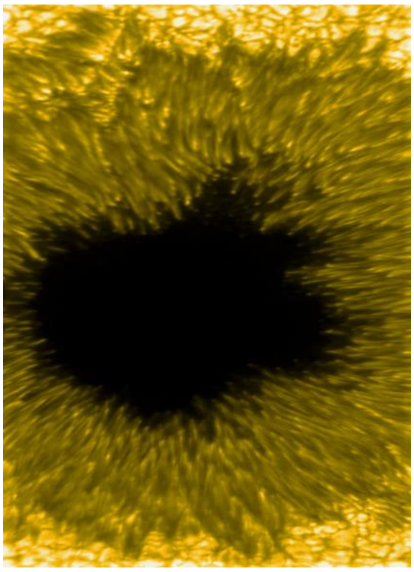


Fig.1.1 Image of the solar photosphere obtained by IBIS in the continuum of the line Fe I at 617.3 nm.

The problem of coronal(-like) heating is also fundamental in many other astrophysical objects and understanding the heating of the apparently stable solar coronal magnetic arches is important for fusion plasma studies, along with the problem of hot plasma confinement in stable configurations.
Flare and flare-like events heat large amounts of the solar plasma explosively up to 10^7 K, Coronal Mass Ejections (CMEs) hurl up 10^{16} g of solar plasma in interplanetary space. These are the most energetic and explosive solar events, due to the sudden release of energy stored in

magnetic fields, delivering up to 10^{32} erg in a few minutes. Flares and CMEs are somehow related, and often occur together. They manifest themselves over the entire electromagnetic spectrum; they also eject plasma and high-speed particles, which blast through the entire solar system. One of the best candidates for the plasma mechanisms at work is the magnetic field lines rearrangement and “reconnection”. These phenomena provide a clue to more energetic phenomena occurring in stellar atmospheres and other astrophysical magnetized plasmas. Key problems in this field are the understanding of the mechanisms through which energy is gradually stored in the magnetic field, the instabilities which trigger the phenomena onset, and the various plasma phenomena which convert the energy into heat, motion of accelerated particles and much more.

Despite its importance, we still have very few measurements of the intensity of coronal magnetic fields. Typically our knowledge is based on the extrapolation to the corona, by means of Maxwell equations, of photospheric magnetic fields obtained through magnetographs. Direct measurements of the coronal magnetic fields are possible by means of coronographic spectro-polarimetric techniques in optical/IR and in the ultraviolet (thus from space), because resonance polarization of spectral lines is modified by the magnetic field (the Hanle effect). This effect has been recently applied in astrophysics to the determination of the vector magnetic field in solar prominences and in other astrophysical objects.

1.2 The expanding solar wind and interplanetary medium

The Earth and the whole Solar System are immersed in the solar heliosphere, the extension of the solar atmosphere flowing as a wind into the interplanetary and interstellar space. Studies of the solar wind, of its chemical composition (known to be different from the photospheric one), of its structures in the ecliptic plane and outside of it, its changes with the phases of the solar cycle, its evolution in the outer heliosphere, the physics of the solar wind acceleration, are important scientific problems. The solar wind rapidly becomes collisionless away from the Sun and shows peculiar phenomena; for instance, it is a unique lab where to study turbulence phenomena. Observations from space-born instruments are of vital importance in this context, and in-situ measurements provide unique diagnostics of the plasma characteristics, composition and distribution functions.

The extremely successful SOHO mission with its high sensitivity visible light coronagraphs (LASCO C1, C2 and C3) covering uninterruptedly the outer corona/inner heliosphere at wide angle has allowed us to fully understand the importance of the coronal mass ejections in influencing the heliospheric and Earth-magnetospheric system. With the first ultraviolet coronagraph spectrometer (UVCS), flown on SOHO, we have been able to identify and investigate the solar wind at coronal level, via Doppler dimming techniques. The fast (800 km/s) and the slow (a few 100 km/s) solar winds originate from different parts (respectively open magnetic field regions and coronal streamers) of the solar corona and most likely undergo different acceleration mechanisms. The fast wind is quite accelerated by outgoing waves which preferentially “push heavy ions” as SOHO/UVCS observations suggest; the slow wind is less understood.

Understanding the solar winds, their acceleration and their relationship to the originating solar regions and magnetic structure may help us to understand the generation of other astrophysical plasma flows. For instance, since stars lose their angular momentum through winds, the solar wind would bring insight into the problem of angular momentum loss of stars.

In spite of the numerous and continuous improvements in our understanding of the mechanisms governing the solar corona and its dynamics, none of the previous missions have been able to fully explore the interface region where the solar wind originates and heliospheric structures

are formed with sufficient observational capabilities to link solar wind structures back to their source regions at the Sun.
To answer the question: "How does the Sun and its magnetic field create and control the heliosphere?" it is essential to perform in-situ measurements of the solar wind plasma, fields, waves, and energetic particles close enough to the Sun to prevent any modification of the observed properties due to subsequent transport and propagation processes. Simultaneous high-resolution imaging and spectroscopic observations of the Sun and inner corona in and out of the ecliptic plane will allow to relate in-situ measurements back to their source regions and structures on the Sun, and to characterize the dynamics and composition of the major plasma components in the corona and solar wind acceleration sites. The proximity to the Sun will also give the advantage of flying with an angular velocity significantly closer to that of Sun's rotation than the angular velocity of the Earth at 1 AU. This allows observations of both the on-disc and inner corona for a significantly longer temporal interval than as seen from 1 AU, which can be used to disentangle the evolution of coronal structures and solar rotational effect on medium-term time scales. For example, a continuous coverage of the pre-eruption, eruption and reconfiguration of the solar corona in response of a CME is allowed, with a significantly reduced effect of solar rotation.
The astrophysical plasmas have been widely documented to be in a turbulent state since the early interplanetary space missions of the late 60s. Dissipation of turbulent fluctuations is also recognized to play a relevant role in plasma energization in galaxies, stellar environments, interplanetary and interstellar media, shock waves, planetary magnetospheres and cosmic rays propagation. In this framework, the heliosphere and the planetary magnetospheres are unique places where these processes can be studied and investigated, being possible in these regions to directly measure several physical quantities via in-situ missions. Regarding *in-situ* studies of heliospheric and magnetospheric plasmas Europe is leader in the worldwide scenario, having funded missions as ESA-Ulysses and ESA-Cluster (*Cornerstone Mission ESA*) in the last 20 years. These space missions have allowed to investigate the features of heliospheric plasmas in regions, not previously explored, and to make studies of the plasma dynamics in three dimensions. In particular, ESA-Cluster mission allowed making great advancements in the understanding of plasma energization during magnetic reconnection, as well as, plasma turbulence features in the near-Earth regions and in the solar wind, allowing for the first time to get multipoint measurements of plasma parameters and magnetic fields.

1.3 Space weather science

The dynamics of the Sun is the driver of a wide number of processes that take place in the heliosphere and that affect the planetary bodies and their environments. In fact, the solar dynamics is responsible for the occurrence of magnetospheric storms and substorms, as well as for the Earth's and planetary climate. The study of such processes and how the expansion of the solar atmosphere, which is the driver of the solar wind, interacts with the planetary magnetospheres, ionospheres and atmospheres, has become one of the main scientific topics all over the world, which is generally addressed with the term "Space Weather". Anyway, thanks to the recent observations, this term acquired a more wide meaning, being, indeed, related to the physical and phenomenological state of the ensemble of natural space environments throughout the Solar System, as well as any other planetary system. The associated discipline aims at monitoring, analysing and modelling the interactions of the solar wind with the near-planetary space, at understanding and predicting the state of the Sun, the interplanetary and planetary environments, and the solar/non-solar driven perturbations that affect them. Clearly, all these analyses are also finalized to forecast and now-cast the possible impacts on biological and technological and man-made systems. Although focused on the Sun as the main driver for the related phenomena, also other agents, (as magnetospheric plasma, cosmic rays, space dusts…) may act as drivers of space weather. In the space science community, Space Weather has become a central topic and it is formerly included in the decadal programs of space agencies, such as, for instance, the NASA and the ESA.

On the side of scientific studies related to the Space Weather, one of the most crucial phenomena is the magnetic reconnection, which is at the base for the transfer of energy, mass and momentum from the solar wind to the planetary and terrestrial magnetospheres. The understanding of the energy transfer at Earth's magnetopause, via magnetic reconnection process and/or flux transfer events, is, indeed, the central issue to develop numerical codes for the forecasting tools. Great advances have been done by means of the ESA-Cluster mission, which allowed for the first time to study the energy and plasma transfer at the Earth's magnetopause and the role that magnetic reconnection processes play on a 3-dimensional side, down to the ion-inertial length scales. Other main issues are related to the understanding of the internal magnetospheric processes responsible for the development of magnetic storms and substorms. In the last five years, some space missions (see e.g. NASA-THEMIS mission) were devoted to study the physical mechanisms acting in the Earth's geomagnetic tail regions, which cause magnetospheric substorms and storms. Furthermore, the role and the impact on planetary and terrestrial environment of solar energetic particle (SEP) events (defined as those events that, at energies >10 MeV, exceed the flux threshold of 10 pr $cm^{-2}s^{-1}sr^{-1}$) and galactic cosmic rays are other central topics of space weather related studies. For instance, SEPs and galactic cosmic rays induce effects in the terrestrial atmosphere, such as particle precipitations, radio disturbances, radiation threat to astronauts and aircraft crew and passengers, atmospheric ozone depletion and minor components variability, cloud formation, climate changes. Hence, the understanding and the capability to forecast SEP events and the study of the galactic cosmic ray variability are of a crucial importance for the large impact that these phenomena have on the natural and anthropogenic systems. INAF has a long tradition in solar, heliospheric, magnetospheric and geospheric observations through a series of instruments, most of which have collected data of the solar-terrestrial environment for decades. In this framework, at the beginning of 2019, INAF has started the setup of a national Space Weather Service Network (INAF NSWSN) that is based on the observing and simulation resources located at several INAF research observatories and institutes. Each research structure covers one or more aspects of operational Solar, Interplanetary, Magnetospheric, and Ionospheric Weather by detecting extragalactic, galactic, and solar photon and particle emission, interplanetary, magnetospheric and ionospheric perturbations, mostly by dedicated instrumentation apart from the large single-dish radio telescopes, whose use is in sharing with other scientific tasks. Meanwhile, new instruments have been acquired like, e.g., the large antenna radio telescopes, dedicated radio monitors, HF radars in Antarctica, etc., and is participating in LOFAR whose applications for Space Weather are under study and will be implemented in the forthcoming years. The richness of INAF assets and expertise are unique and allows a comprehensive coverage for nowcasting and forecasting purposes.

In the frame of other solar system bodies, Mercury is one of the most interesting planets from the Space Weather point of view, having a weak internal magnetic field in a region very close to the parent-star. Extreme conditions of solar wind, UV flux and surface temperature, in combination with high reconnection rate, result in a dynamic exosphere configuration, surface currents and induction effects. Even after the MESSENGER mission, many old and new questions remain unsolved, as the current system closure given the absence of a ionosphere, or the role of plasma impacting on the surface in the Mercury's evolution.. Moreover, the Mars and Venus interaction with the solar wind shows the case of unmagnetized bodies that produce induced magnetosphere. Past missions (MEX and VEX) provided important information, but lacking of magnetometer, the details of the interaction are still unknown. The Moon interaction with the solar wind, especially in the near-by on the magnetic anomalies, represents another interesting example of plasma interaction with a mini-magnetosphere, also of particular interest in view of possible human colonization. Solar events such as CMEs and/or SEP events activate macroscopic Planetary Space Weather phenomena, especially in these inner planetary environments. In the past decade, our understanding of the space weather at the Saturnian and Jovian magnetosphere and the interaction processes with their icy moons has been essentially improved (thanks to the NASA/ESA/ASI Cassini mission and the modeling efforts). The Juno observations allowed the imaging of both the Jupiter's Northern and Southern aurorae with unprecedented spatial and time resolution greatly improving our knowledge of the Jupiter's interaction with the solar wind and the Jupiter's magnetosphere dynamics. Other unique environments of particular interest for the magnetospheric interaction are the Uranus' and Neptune's peculiar magnetospheres at unusual shear angle with the interplanetary magnetic field which should determine specific reconnection features and plasma dynamics during different seasons and periods of solar activity. Finally, the understanding of the space weathering of the minor bodies, like asteroids and comets, the milestones of our Solar System, is crucial for depicting their evolution.

1.4 Science activities for the next decade

In the next future Europe will continue to support the studies on solar, heliospheric, magnetospheric and planetary plasmas by the next missions ESA/JAXA-Bepi Colombo (*ESA Cornerstone Mission*), ESA-Solar Orbiter and ESA-JUICE. These missions, which are part of the *ESA-Cosmic Vision 2015-2025,* will allow investigating the physical mechanisms responsible for the emergence of magnetic fields, the acceleration and heating of the solar wind, as well as for the acceleration of CMEs and SEPs, and their interaction with the Hermean magnetosphere and environment.

The role that turbulence plays in the acceleration, energization and dissipation of collisionless plasmas will be a central topic in the next decade. In particular, the investigation of the kinetic scales, will be the crucial to unveil the aforementioned mechanisms. These studies are of a universal importance in astrophysics, being, indeed, astrophysical plasmas non-collisional. In this framework, the heliosphere and the near-Earth environment can be considered as a privileged laboratory where direct *in-situ* measurements of the physical quantities down to the kinetic scales could be exploited. In this regard the participation of the INAF scientists to the future missions of the *ESA Cosmic Vision 2015-2025* program will be extremely relevant.

In addition, the first light of two revolutionary 4-meter-aperture telescopes designed to investigate our active Sun at unprecedented resolution from near ultraviolet to near infrared wavelengths, the American DKIST and the European EST, is planned in the next decade. Equipped with state-of-the art instrumentation, these telescopes will help scientists to understand in more detail the magnetic coupling of the solar atmosphere. INAF scientists will participate to the activities and observations of both telescopes.

The studies of the physical processes responsible for the Sun-Earth and the Sun-planets interactions will be of a key importance to understand either the complex dynamics of the terrestrial and planetary environments either the influence of Sun and the radiation environments on human activities on Earth and on the space exploration in the next decades.

Other studies of interest in the next decade focus on a large ensemble of cross-disciplinary topics, including:

1. the variability of solar irradiance and its effects in the heliosphere and on the Earth's environment;
2. the emergence and/or propagation of solar coronal ejecta in the heliosphere;
3. the role of turbulence in several processes, e.g., the magnetic reconnection, cosmic ray and SEPs propagation, interplanetary shocks.
4. the variability of terrestrial and planetary magnetospheric regions under different solar wind plasma conditions;
5. the modulation of galactic cosmic rays (on short-, medium- and long-term basis);
6. the interaction of solar wind and/or magnetospheric plasmas with planetary/satellite surfaces, as well as with (thick or tenuous) atmospheres and ionospheres;
7. the processes at the base for the inter-hemispheric asymmetries in the magnetospheric-ionospheric coupling processes;
8. exosphere generation processes;
9. the interactions of Earth's and planet's radiation belts with atmospheres, satellites and rings;
10. the impact of SEP and/or cosmic rays on circum-terrestrial and circum-planetary space;
11. space weathering (alteration that occurs to objects exposed to the harsh environment of outer space);
12. planetary or lunar surface charging at bodies possessing tenuous atmospheres;
13. effects of SEP, GCR, radiation and charge deposition on spacecraft and space instrumentations, on telecommunications and terrestrial applications.

The above arguments will represent some of the fundamental targets of the future researches in which the research scientists of INAF will be directly involved. The method of investigation will comprise

- in situ observation of electromagnetic fields and charged and neutral particles nearby the Sun, in the planetary environments as well as in the interplanetary space;
- remote sensing observations from space and from Earth ground in different wavelength from radio, IR, visible up to UV, EUV and X-ray of the Sun and the auroral emissions;
- ground based observations of high energy particles and plasma circulation;
- MHD modelling of magnetic structures and radiative hydrodynamics simulations;
- Monte Carlo modeling of the planetary environment, its interaction with energetic particles and solar wind, plasma circulation and exospheric generation processes;
- laboratory experiments on ionospheric conditions for plasma interaction with planetary analogues.

Key Question	Method(s)	Project(s)
1. **How does the Sun give origin to the heliosphere and control its evolution? How does the Solar System evolve in relation with the parent star and the interplanetary medium?**		
1a. How is the solar magnetic field produced? What is the role of turbulent magneto-convection in the mechanisms giving origin to the solar dynamics and variability?	Study the magnetic field at high spatial resolution and more sensitive spectro-polarimetric capabilities over a wide range of atmospheric heights, including coronal regions (coronagraphy). New observations of solar polar flows and fields out of the ecliptic. MHD modelling of magnetic structures and radiative hydrodynamics simulations with high performance computing	Existing: DST/IBIS, SST, GREGOR, HINODE, SDO, IRIS Future: DKIST Solar Orbiter EST
1b. What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Optical and IR observations of the lower solar atmosphere. Observation of the solar corona through UV, EUV and X-ray. Perform in-situ measurements of the solar wind plasma, fields, waves, and energetic particles at different distances from the Sun for investigating the turbulence role in the acceleration, energization and dissipation Simultaneous high-resolution imaging and spectroscopic observations of the Sun and inner corona in and out of the ecliptic plane. MHD modelling of coronal structures	Existing: DST/IBIS, SST, GREGOR, HINODE, SDO, STEREO, IRIS, CLUSTER, SVIRCO Future: DKIST Solar Orbiter Parker Solar Probe BepiColombo EST Proba-3
1c. Which processes are active today in the interaction between the interplanetary medium and the bodies surface and environment, and/or played a	In situ observation of electromagnetic fields and charged and neutral particles in the bodies' environments and interplanetary medium at energies ranging from thermal to MeVs	Existing: MEX JUNO CLUSTER SVIRCO SUPERDARN

role in the early history of the Solar System?	Remote sensing observations from space of the Auroral emissions (IR, visible and UV), of the plasma interaction with exosphere and surface (Energetic Neutral Atoms), of the exospheres (UV) and simultaneous observation of the Sun (radio, visible, UV and X-ray).	ITACA THEMIS solar telescope Future: BepiColombo Solar Orbiter JUICE Proba-3
	Ground-based observations of aurorae and exospheric emissions from planets and moons (visible). Ground based observations of high-energy particles.	
	MHD modelling of magnetic structures. Monte Carlo modeling of the planetary environment, plasma circulation and exospheric generation processes.	
	Laboratory experiments on ionospheric conditions and plasma interaction with planetary analogue	
2. What is the influence of the Sun and the radiation environments on the human activities and on life?		
2a. What are the particle radiation and electromagnetic fields dynamics in the planetary environment (with focus on the Earth)? And how is it driven by external agents (space weather)?	Simultaneous in situ observation of electromagnetic fields and charged and neutral particles in the bodies environments and interplanetary medium at energies ranging from thermal to MeVs	Existing: DST/IBIS, SST, GREGOR, HINODE, SDO, STEREO, IRIS, CLUSTER SVIRCO SUPERDARN ITACA Future: BepiColombo JUICE Solar Orbiter Parker Solar Probe EST Proba-3
	Remote sensing observations from space of the auroral emissions (IR, visible and UV), of the plasma interaction with exosphere and surface (Energetic Neutral Atoms, ENA), and simultaneous observation of the Sun (visible, UV and X-ray) and ground based observations of high-energy particles.	
	Coordinated ground-based observations and space measurements of aurorae and	

	exospheric emissions from planets and moons (visible). Global numerical models of plasma ejection from the Sun, plasma transport and circulation and exospheric generation processes.	
2b. How can the space weather be monitored and forecasted?	Monitoring of the Sun activity Monitoring the CGR and SEP Monitoring the solar wind at different distances from the Sun Monitoring the geomagnetic or magnetospheric activity of other planets via magnetic field, aurorae, plasma, and ENA observations Developing forecasting tools	Existing: SUPERDARN SVIRCO ITACA SWENET DST/IBIS SST GREGOR HINODE SDO STEREO IRIS SRT LOFAR Future: Solar Orbiter EST SWEATERS

2. The Solar System

Keywords: planets, satellites, small bodies, Solar System formation, astrobiology

We study the Solar System because we want to understand the processes that led to its formation and subsequent evolution, as well as the major mechanisms that still control the appearance, behavior and properties of the Sun and of all the bodies orbiting around it.
Another reason is that we know today that planetary systems are a common phenomenon in the galaxy, and we observe an astonishing variety of possible outcomes of the processes responsible for the formation of these systems. The study of our own Solar System is crucially important to understand the role played by the physical processes that may have been responsible also for the formation of so large a variety of extrasolar systems. At the same time, the study of extrasolar systems, observed in different phases of their evolution, is useful to understand many aspects of the possible history of our own system, especially during the early phases of its formation.
Our knowledge of the Solar System has been enormously growing in the last decade thanks to greatly successful space missions and ground-based observation activities that have provided new information, often with an unprecedented detail, about planets and satellite systems, as well as many of the small bodies that orbit the Sun at different heliocentric distances. This wealth of new data has stimulated many new ideas and experimental work, leading to the development of new theories to explain the extreme complexity and diversity of the phenomena that we observe. We are, anyway, still exploring our system, as even the best known bodies, such as Mars and the Moon, still keep unexplained phenomena and features, and classes of bodies exist not yet visited by a spacecraft or poorly observed with a telescope: the trans-Neptunian Objects (TNO), for example, the elusive main belt comets and the dynamically new comets, whose surface has never been observed. The gathering of more information, to be accomplished by space missions and ground-based observation, is fundamental in order to develop better theories and answer the key questions:

- ***Which processes determined the formation and evolution of the Solar System?***
- ***Which are the processes determining the appearance and properties of the bodies of the Solar System?***
- ***Which are the evolutionary processes giving origin to the emergence of life?***

2.1 The formation and evolution of the Solar System

A major step forward in the study of the formation of the Solar System in recent years has been the transition from the study of the formation of individual bodies, and of specific families of bodies, to that of the evolution of the Solar System as a global entity. This transformation has been triggered by the study of exoplanets, which revealed that planetary migration is a quite common process outside the boundaries of the Solar System, especially when it comes to giant planets.
We have always known that the current system is the result of the complex interaction of physical, chemical, geological, and dynamical processes that have shaped the planets and the other bodies. What we have realized in the last years, based on increasing evidence coming from observations and theoretical models, is instead the crucial role played by early migrations of Jupiter and Saturn in shaping the young Solar System. This early phase of complex planetary migrations gave rise to a major episode of mutual collisions and collisions with planets, during the so-called Late Heavy Bombardment epoch that occurred about 3.8-3.9 Gyrs ago. This chaotic phase may also have been responsible for the delivery of water to our planet.

Among the main open problems these global studies are confronting with we can list:

- *identify the mechanism responsible for the formation of the planetesimals, and the timescale on which it acts;*
- *identify the formation regions of the giant planets in the Solar System and the mechanism(s) responsible for the migration event(s) that modified their orbits;*
- *understand the origin of the water in the inner Solar System and the mechanism(s) and timescale of its delivery;*
- *understand why super-Earths did not form in the Solar System, given that they are the class of planetary bodies currently estimated as the most abundant among exoplanets;*
- *understand whether the Solar System is a "typical" planetary system, or if represents instead an uncommon outcome of the formation process.*

In this context, the gathering of new data from space and from ground allows us to use the bodies of the Solar System as natural laboratories to study the working of the different physical process relevant to planetary formation. An outstanding example has been recently supplied by the discoveries made by the NASA mission Dawn during its exploration of the asteroid Vesta. Since over the last 30 years Vesta represented one of the main observational constraints for the study of the dynamical and collisional evolution of the inner Solar System, these discoveries put into question several of our pre-Dawn ideas and the theoretical models based on them.

In parallel to this change in our approach to the study of the formation of the Solar System, also the study of planetary formation as a whole underwent an important transformation. Until a few years ago, in fact, the study of exoplanets, of circumstellar discs and of the Solar System proceeded more or less independently from each other, and each field of study possessed its own individual nature. With the increase in the complexity of the theoretical models and the need for observational parameters on which to test them, however, these fields of study became more and more interdisciplinary entwined. While the Solar System remains an unparalleled natural laboratory, the dynamical and statistical study of exoplanets allowed for filling major gaps in our understanding of planetary formation and of its possible outcomes (e.g. the diffuse evidence of planetary migration and the discovery of super-Earths and sub-Neptunian planets, classes of planetary bodies not represented in our system). The study of circumstellar discs allowed, on one hand, the characterization of the environment within which planets form and, therefore, the gathering of indirect information on the now-dispersed circumsolar disc. On the other hand, the ever-increasing detail of astronomical observations is now allowing for directly observing the first phases of the birth of giant planets in circumstellar discs, thus providing an observational validation to processes that the Solar System allowed to reconstruct only at a theoretical level.

2.2 Study of the gravity field of planetary bodies

The study of the internal structure of a planet or a moon (but also of a minor body) requires an ensemble of dedicated experiments, usually known as Radio-Science experiments, in which an essential role is fulfilled (besides the tracking) by the precision orbit determination and by the measurements of accelerometers/gradiometers. In case of orbit determination, a special and relevant duty is accomplished by accelerometers. These instruments have as main objective the measurement of the non-gravitational accelerations diverting the trajectory of a spacecraft from its motion along a geodetics, i.e. from the motion of an ideal test particle. This information, combined with tracking data and other measures, allows to retrieve important information on the coefficients of the gravitational field of the planet or the moon, from which we can derive the moment of inertia and the structure of the interiors. Actually, mapping the gravitational field of a celestial body allows to gather important information about its internal structure and local mass distribution. All these data are fundamental to help in understanding the geophysical and geological processes on the planetary body and, at last, on the overall planet dynamics and evolution. Moreover, gradiometry allows to produce a direct measure of the components of the gravity tensor and hence of the gravitational field, through the differential measure of acceleration between two relatively close points, overcoming some of the disadvantages of the current measurements methods. Such a measure can be performed by means of a gradiometer or by the difference between two measures with accelerometers.

2.3 Mercury, Venus, Mars and the Moon

The inner planets provide a unique opportunity to study the processes leading to habitable worlds. Venus, Mercury, Mars and the Moon hold clues to different aspects of the origin of the planets and habitable environments in the inner solar system. They have undergone a substantial processing of their surfaces after their formation, due to endogenous processes for those that are geologically active, and anyway to the continuous bombardment of asteroids and comets in planet crossing orbits. The Moon and Mercury preserve records of past events whose traces have been largely erased on Earth and Venus. In many ways, Venus is Earth's twin in the Solar System, and provides a natural laboratory for understanding the evolution of Earth-like planets and their atmospheres, including how Earth's atmosphere might change in the future.

Exploration of the inner Solar System is vital to understand how Earth-like planets form and evolve and how habitable planets may arise throughout the galaxy. *Understanding processes on a planetary scale — volcanism, tectonics, impact bombardment, evolution of atmosphere and magnetosphere, and development and evolution of life — requires a comparative study of the planets closest to Earth in order to know the effects associated with size and distance from the Sun, composition, and type of dissipation of internal energy over time*. A comparison of the inner planets shows the importance of a large moon in making the Earth unique and perhaps uniquely suitable for life. One of the great advances of geosciences has been to recognize that the present-day Earth represents just one step in a progression of changes driven by a complex set of interrelated planetary factors. Coupled with this recognition is the revelation that Earth's atmosphere and biosphere are fragile entities, easily perturbed by planetary-scale processes.

MESSENGER in four years of orbit around **Mercury** discovered several new characteristics of the planet but raised many more questions, from the internal structure to the environment and the surface. Before the NASA mission we have thought Mercury a planet dead since hundreds of millions of years, but the new observations showed us a planet still alive, or at least alive up to few tens of millions of years ago. Several pyroclastic events have been mapped witnessing a quite recent activity, and new mystery features, called hollows, have been discovered, in many sites on the surface, most likely associated to volatiles. But MESSENGER has not been able to provide information on the surface composition; moreover, water ice seems to be present in the shadowed crater walls on the poles, as is the case of the Moon. *Only the ESA-JAXA mission BepiColombo, launched in 2018, will be able to answer these important questions, as others related to the internal structure and the exosphere.* These key questions are fundamental to better understand the origin and evolution of the terrestrial planets, considering that Mercury is the end-member of our Solar System.

Despite the many probes entered into the atmosphere and landed on the **Venus**' surface, there is still a lot of work to do in order to shed light in the largely unexplored part of the planet underneath the thick clouds layers. Venus is a sort of extreme natural laboratory where modelling and data live in perfect symbiosis. Venus Express observations show Venus is an active planet. *Monitoring of the surface to verify the existence of recent and active volcanism on the planet will be necessary to identify possible lava flows, and hence to map the signs of the recent activity. The understanding of the climatology of Venus is essential also to constraint the state of the art modelling of our Earth,* important for the prediction of the global warming mechanisms in long term. Moreover, Venus is commonly considered as the most probable terrestrial planet-like to be found as exoplanet, so that the validation of the modelling can benefit from the support of a much more studied case in our Solar System. Beyond the interest in science, *Venus is also an excellent opportunity to design and develop robotics systems in an extremely hostile environment*, as that found in the deep atmosphere down to the surface of the planet.

The spectroscopic and compositional properties of the lunar crust rocks are of interest because they will contribute to the scientific background for global models of lunar crust formation and evolution. Current models of the **Moon** crust composition are in fact based on the integration of the rock compositions from the crater central peaks with the geophysical models of crust thickness. Although the spectral reflectance characteristics of lunar rocks and their component minerals are well studied, some problems remain open relative to the spectroscopic identification and quantitative determination of the mineral phases welded into compact rocks. The objective of on-going and planned activities is to develop spectral libraries of rock component minerals that are assembled in making rocks. Multiscale (laboratory, in-situ, from remote) and multi-temperature measurements simulating the lunar surface conditions will contribute to both in-situ and remote exploration of the Moon.

Another important aspect is *the study of the deformations related to impact cratering, basin modification processes and impact crater degradation of the Moon.* Accurate 3D topography from stereo reconstructions will allow the detection and characterization of structures related to impact craters, multi-ring basins, wrinkle ridges, lobate scarps and grabens. Statistical and morphometric analysis of lunar simple impact craters will provide new methods for dating planetary surfaces.

The *presence of water on the lunar surface* is a scientific topic that has gathered a renovated interest, thanks to the indirect observation done by Clementine and Lunar Prospector missions and by renewed analysis of Apollo lunar samples. Two are the most probable mechanisms that could explain the presence of water in the craters of polar caps: cometary or asteroidal impacts and solar-wind proton implantation. *Of particular interest will be to investigate the effects of the coupling between ice and the regolith surface and bulk properties on the sublimation process compared with pure water ice and regolith simulants.*

The lunar exploration is becoming more and more important, involving several space agencies and institutes, and is not focused only on scientific purposes. International collaborations have already started to discuss specific projects, as the Deep Space Gateway with the involvement of ESA and the European community. There is also a specific interaction between ESA and the Chinese Space Agency (CNSA) on the Lunar exploration on the data exploitation of Chang'e' 4 and future collaboration for the next Chinese missions.

Being the closest body to the Earth, its investigation allows thinking to its surface as a possible reservoir of material to be returned to Earth for laboratory analysis. The PROSPECT package, proposed to ESA for Lunar Exploration, will be flown to the lunar South polar region on the Russian Luna-27 mission in 2020. PROSPECT will measure the composition, abundance and isotopes of volatiles at the lunar surface and demonstrate water extraction for resource utilisation.

Mars, between the terrestrial planets the one similar in some sense to the Earth, deserves a special place. Mars shows evidence of a past in which water was flowing on its surface, with

enormous implications on the possibility of lifeforms, and of substantial climate change, which could reflect processes that influenced all of the inner planets.
With mounting evidence of a wet and warm past on Mars, the Agencies programs are shifting the focus from a strategy generally known as "Follow the Water" to a strategy aimed at answering the next logical question, "Did life ever arise on Mars?". The successes of recent missions have led to conclude that Mars could have supported microbial life. Therefore, the space programs are evolving to focus on determining whether Mars was ever been habitable and, through a strategy of "Seeking Signs of Life," if evidence of extinct or extant life can be identified: the primary goals of the ExoMars program is looking for traces of gases and life.
In the future, *it will be important to analyse the surface, searching for methane sources and using 3D images, to study minor gases and dust distributions, to investigate on the existence of biomarkers on the surface of Mars, through the triboelectricity effect on dust and sand in the Martian environment*. Moreover, the *atmospheric models for Mars* have not been well validated due to a lack of sufficient observational data, and thus confidence in them is limited. *Density, pressure, temperature, and wind data are essential measurements to be done by future instrumentation.*
Although constrained budgets do not support a sample return mission in the foreseeable future, *the collection and return of samples from Mars remains one of the highest priorities in the next decade*.

2.4 The outer planets and their satellites
The detailed mechanisms of formation of the planets in the outer Solar System are still not well understood, as several different hypotheses are being evaluated and analyzed. *Comparative study of their atmospheres is a key tool to gain insights on the most intimate nature of these complex systems*, where effects of non-linear phenomena (such as turbulence) become often dominant. In particular, the role of different modes of transport for energy and momentum can be assessed only comparing different planets where these factors have different relative importance. In actual terms, *the validation of Global Circulation Models (GCM) against data from different planets becomes feasible only when extensive datasets on main atmospheric fields (wind speeds, temperature, composition) become available at different spatial and temporal scales*. Similarly, magnetospheric physics also finds formidable challenges in describing the outer planet systems: extreme field strengths, strong interactions with moons and rings, variety of ion sources, substantial non-dipolar components are unique opportunities to detect faults and improve our current models.
The outer Solar System hosts a significant amount of water and volatiles. Beyond the "snow line" or "frost line" located at roughly 2.7 AU from the Sun, where radiation equilibrium temperature drops below ~150 K, water ice is stable over geologic timescales on the surface of airless bodies. At larger heliocentric distances, water ice is the major constituent of the surface and interior of the satellites revolving around the outer planets. *Close exploration of the icy satellites of the giant planets deserves a very high priority*. While some satellites are known or expected to host large subsurface reservoirs of liquid water, the chemistry of the regular satellites of the giant planets can be directly related to a physical process similar to the one that, at a larger scale, led to the formation of the planets themselves.

The complexity of the **Jupiter system**, which includes more than 60 moons and a well developed magnetic environment, makes it a *paradigm of a planetary system, and as such a good example to investigate the conditions for planetary formation and emergence of life.* Recently we had a better insight in the Jupiter environment (atmospheric composition,

magnetosphere, aurorae) thanks to the Juno mission (arrived to Jupiter on 4 July 2016). In this respect, the community is actively involved with the Jupiter Infrared Auroral Mapper (JIRAM) instrument that allowed to acquire insight on the North and South aurorae, as well as cloud composition.
Jupiter and its major moons are traditionally thought of as a miniature Solar System. The results obtained by the NASA Galileo mission clarified that liquid water layers of varying thickness affect the interiors of Europa, Ganymede and Callisto. This water is stable over geologic timescales and is mixed with other non-ice materials, including salt minerals and possibly organics, which could make these environments habitable. This finding, together with direct observation of water vapor plumes that rise from the icy crust of Europa, has in fact paved the way for a new season of space exploration of these icy moons. The first two large-class missions explicitly devoted to the study of **Europa** and **Ganymede** will be NASA Europa Clipper and ESA JUpiter ICy moons Explorer (JUICE), due to arrive at Jupiter by 2028 and 2030, respectively. It should be noted that JUICE and Europa Clipper will greatly contribute to the study of the other two Galilean moons Callisto and Io, less important with respect to astrobiology but no less interesting in terms of geophysical properties and origins.

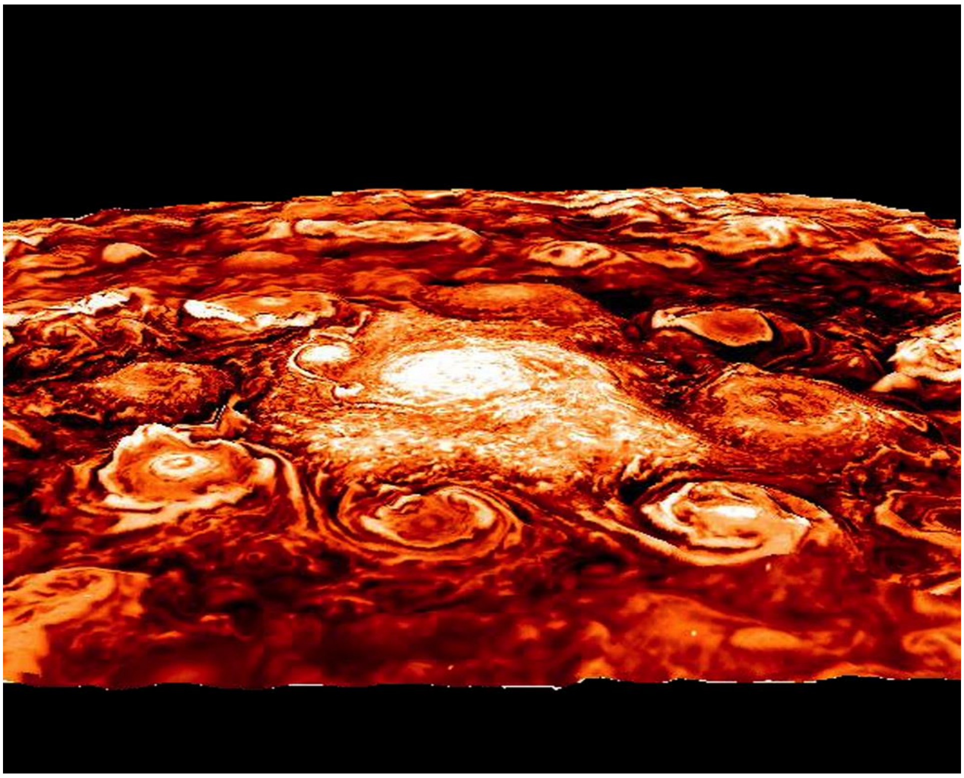


Fig. 2.1 An infrared 3-D image of Jupiter's North Pole, derived from data collected by the Jovian Infrared Auroral Mapper(JIRAM) instrument aboard NASA's Juno spacecraft.

The **Saturn system** is fascinating for its complexity and the presence of some of the most interesting satellites from the point of view of astrobiology. Important studies to perform on Saturn through space and ground-based observations are the *atmospheric structure investigation, the analysis of ring properties and the methane distribution investigation*.
Over a decade of flybys and seven flythroughs of the plume, Cassini has determined that **Enceladus** has a global ocean of salt water, organics, and a possible hydrothermal system or systems at the ocean's base. This makes Enceladus a *key target for future exploration*, as one

of the best bodies to search for extant life. The first step of flying again through its jets with more advanced instruments, to do either in situ measurements or collect a sample for return to Earth, may be accomplished in the near-term with a medium-class mission.
The dense and thick atmosphere of **Titan**, the largest moon of Saturn, hides an incredible world made up of seas and lakes of liquid methane and ethane, hydrocarbons-rich sand dunes, and possible cryovolcanic features. Its interior is likely to host a subsurface ocean, where liquid water could be mixed with ammonia. Results obtained on Titan by Cassini have already shaped future mission proposals with a set of investigations meant to cover specific gaps left behind. *Key goals are, among others: unveil and map the surface composition (inventory of organic constituents and presence/absence of ammonia), which provide clues for the origin of life; shed light on the methane cycle and the methane reservoirs; assess whether cryovolcanism and tectonism are actively ongoing or are relics of a more active past; clarify the existence of a magnetic field and of a sub-surface ocean; and shed light on the chemistry that occurs in the upper atmosphere at 400-900 km, which remains poorly explored after Cassini. In addition, seasonal changes of the atmosphere at all levels, and the long-term escape of constituents to space, so far are only marginally understood.*
The ice giants **Uranus and Neptune** represent a fundamental stepping stone in our quest to understand the formation and the history of the outer Solar System. The importance of understanding Uranus and Neptune, moreover, extends beyond our Solar System, as ice giants appear to be much more common than gas giants among exoplanets. In the framework of future missions being defined for the exploration of Uranus and Neptune, *the study of the atmospheres of these 'icy giants' (that present substantial seizable amounts of C, N, and O in their gaseous envelopes) is the primary investigation task for these systems*, since they present in several aspects unique phenomenologies. Furthermore, investigation of bulk compositions will provide key constraint for planet formation scenarios on these remote regions. Unique are also the *opportunities to investigate the mechanisms of planetary space weather*: strong non-dipolar components of the magnetic fields, unique geometrical configuration of rotation and magnetic axes, complex auroral systems already detected from ground observers points to Uranus as a key test to validate our current view on magnetosphere physics. *Joint spectroscopic and geologic measurements of their major icy moons will be key instead in providing important clues about those processes that, at various spatial scales, shaped their current aspect, with particular emphasis on the identification and mapping of endogenous vs. exogenous processes on the main Uranian moons and ongoing cryovolcanic activity on Triton.*

2.5 Primitive bodies: comets, asteroids, TNOs and meteoroids

The so-called minor bodies are crucially important targets for investigations based on both remote sensing and in situ exploration. Although partly reprocessed by interaction with the solar radiation, impacts and fragmentation throughout the Solar System history, and by gravitational and non-gravitational mechanisms causing in many cases a complex orbital evolution, the small bodies are the most direct residuals of the original planetesimals that accreted into the major planets. Moreover, small bodies include in some cases organic materials, which are the elementary bricks in the construction of life.
Among the major discoveries that in the last decade changed and reshaped our views, we can list:

- ✓ The improvements in solar system dynamical studies, that revealed a complex history of mixing between bodies formed in different regions of the solar system.
- ✓ The improvements in our knowledge of the physical properties of active and non-active primitive bodies orbiting at different heliocentric distances.

- ✓ The discovery of water ice on asteroids such as 16 Psyche and 24 Themis, and of a new class of objects, the Main Belt comets.
- ✓ The discoveries of the Dawn mission on 4 Vesta and Ceres, that shed more light on the formation processes of the asteroids and of the Solar System in general.
- ✓ The discoveries of Rosetta, that reshaped our views on the formation of comets and changed many concepts on their activity and composition.

The last years saw also important changes in the way we collect information on the minor bodies, with the *increasing importance of geomorphologic and geologic studies of the surfaces made possible by incredibly detailed images*. *A further major improvement is now awaited from sample-return missions.*

Detailed studies are being devoted to primitive small bodies belonging to **the Near Earth Object, asteroid, Centaur and Trans-Neptunian populations**. The "primitive" small bodies have formed in the water- and organic-rich outer regions of the protoplanetary disk, and are thought to include the most probable source of terrestrial prebiotic material. Moreover, current exobiological scenarios for the origin of life invoke the exogenous delivery of organic matter to the early Earth. The planets of the inner Solar System experienced an intense inflow of organic-rich material for several hundred million years after they formed, and the earliest evidence for life on Earth coincides with the decline of this bombardment.

The analysis of Gaia data will be a major step forward in asteroid science. Even after the end of the mission, the Gaia catalogue of stellar positions and asteroid orbits will make it possible to extend enormously the use of the technique of *stellar occultations for the accurate determination of asteroids sizes and shapes.* This will be a major research activity in asteroid science for the years to come, starting from the first intermediate data releases of Gaia, and it is important to plan since now the necessary activities, which might be also an excellent way to make good use of several small telescopes that are currently idle, or close to dismissing. Note that star occultation events give the best results when the same event is observed from different observers along the shadow track, because this leads to a direct reconstruction of the profile of the occulting body. *A good coordination of the observers, including also possibly active groups of amateurs, is then highly desirable.*

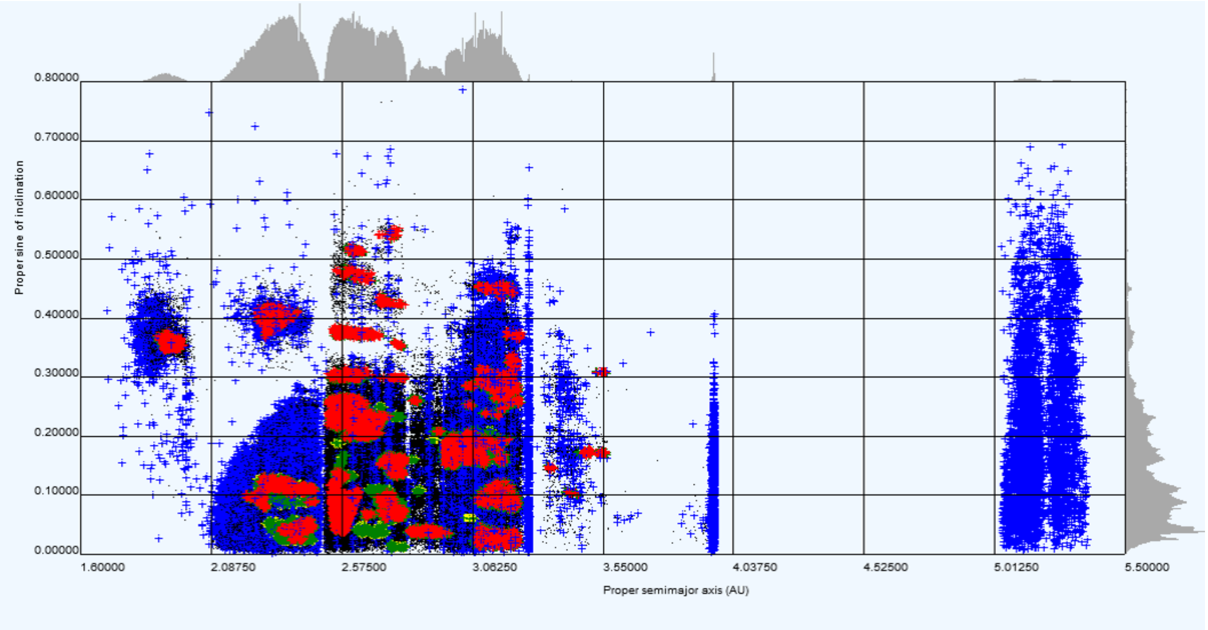


Fig.2.2 Plot of sin (proper orbital inclination) versus proper orbital semimajor axis for main belt asteroids and Jupiter Trojan asteroids. Red and green points indicate members of dynamical families identified using classical methods of Hierarchical Clustering (Milani et al., 2014).

It has been known for decades that most of the planetesimals originally accreted in the region occupied by the current asteroid Main Belt have been removed and lost forever during the early chaotic phases of evolution of our planetary system. Very recently, however, the discovery of a rare class of objects exhibiting unusual polarimetric and spectroscopic properties (the so-called "**Barbarian" asteroids**) suggests that these objects could be the rare survivors of the very first generation of planetesimals accreted in the inner Solar System. In particular, *we need further evidence to confirm that Barbarians are extremely old and primitive*. If this is found to be true, these rare asteroids will be the ideal targets for space missions aimed at recovering samples of the most primitive materials accreted at the dawn of the Solar System.
Other interesting targets for an in-situ exploration would be *classes of asteroids that have never been explored before, such as the so-called metallic asteroids of which 16 Psyche is a good example, and the increasing number of asteroids on which traces of water ice have been found, such as 24 Themis.* To this list we have to add the dwarf planet **Ceres**, recently explored by Dawn, that would deserve a much more complete analysis.
Rosetta gave an incredible amount of new data with unprecedented details on the nucleus and the coma of a **comet**; it will take years to the community to fully exploit all the new information. Already the data on the structure and composition of the nucleus of 67P/Churyumov-Gerasimenko have changed our views on the formation and evolution processes of the comets. At the same time we are aware that there could be wide differences between the not yet explored dynamically new comets (DNC), never entered before in the inner Solar System, and comets belonging to the other dynamical classes. Major *further improvements in the knowledge of comets are expected to come, besides from exploration missions to other cometary nuclei, from sample-return missions and, as far as regards the formation processes, from the study of dust formation processes that could be performed for example with ALMA or SKA.*

The traditional distinction of the small bodies between asteroids and comets has been becoming much less sharp in recent years. Apart from the well-known fact that extinct comets can be present in the population of near-Earth asteroids, an important discovery has been that of the existence of the so-called **Main Belt comets**, small bodies having asteroidal orbits, which have found to exhibit episodes of cometary activity. *It is necessary to get more data about these objects, and to study how the observed cometary activity can be triggered by a variety of possible mechanisms, in particular by the heliocentric distance and by the possible occurrence of small impacts removing some surface material.*

The study of bright **meteors**, or “fireballs”, is rapidly developing in Europe, due to the availability of a new generation of all-sky cameras and to the active role played by the French community. Italy has represented for a long time a gap in the coverage of the European sky for what concerns professional networks of meteor observers. *Fireball events are not important only in a statistical sense*, namely to assess the inventory and size distribution of small planetary bodies beyond the limit of detection for telescopic observations. *They can also be associated to the actual fall of* ***meteorites*****,** whose study is of outstanding importance for our understanding of the history of the Solar System. A synergy with INFN researchers is also developing, to use detectors aboard the ISS to observe in the UV both events of ultra-energetic cosmic rays, and meteors of different brightness.

2.6 Astrobiology: the Solar System as a laboratory to study the conditions giving origin to the emergence of life

Astrobiology is the study of origin, evolution and distribution of life in space. *Astrobiology is a research discipline that ranges in wide areas of the scientific fields and needs a high level of multidisciplinary know-how, including astrophysics, biology, chemistry, biophysics, and geology, and requires a joint effort of theory, observations, computer simulations and laboratory experiments.* Life is the result of the growth of molecular complexity and evolution strictly linked to planetary environments. The number of organic molecules that have been discovered in space is continuously increasing. They are formed in cold molecular clouds and in the early phases of star formation. Our understanding of the evolution of organic molecules and their journey from molecular clouds to the early Solar System and Earth provides important constraints on the emergence of life on Earth and possibly elsewhere. Minerals have a relevant role in driving the prebiotic evolution of complex chemical systems, mediating the effects of electromagnetic radiation, influencing the photostability of organic molecules, catalyzing important chemical reactions, and/or protecting molecules against degradation. *It is thus necessary to study in laboratory the photostability of biomolecules (e.g. nucleobases, amino acids, carboxylic acids, fatty acids, etc.) under space conditions in the presence of mineral matrices* in order to investigate both the prebiotic processes that might have had a role in the development of the first living entities on Earth and the physical and chemical processes occurring in extraterrestrial environments.

The Solar System can be considered as a laboratory to study habitability, and the conditions and evolutionary processes that can give origin to the emergence of life. The increasing knowledge of the evolution of our Solar System and the discovery of extrasolar systems have opened a number of questions on the origin of life and on conditions that may allow its evolution. The determination of the habitability conditions, for instance the presence of liquid water and energy sources able to sustain life, that are not necessarily associated with a single specific environment, will be important to identify potentially habitable planets in other systems. Solar System itself may present such conditions in sites other than Earth, and mechanisms of evolution of habitable environments through the solar systems have to be

studied. *In order to answer the fundamental question on the origin of life is crucial to understand in which conditions life may be originated, controlled and sustained, and in particular how this occurs if prebiotic material is brought in from elsewhere.* The influence of small bodies on early planetary environment, and the high energy radiation from the parent young star may be essential for the onset and survival of life. *The study of molecular evolution of abiotic organics present in solar system objects, including the early Earth, under the combined role of physical agents such as thermal variations, high energy particles, photons and solar wind irradiation is a task that will be pursued in the next decade.*
At the same time the feedback on chemistry of planetary atmospheres is an important issue that will expand our understanding of the general principles of habitability.

2.7 Science activities for the next decade

In the next years, our community will be busy working on the operations and the data from operative (Gaia, Juno, BepiColombo) and future operative missions (JUICE); a big effort will be devoted to interpret the enormous amount of information obtained by these missions as well as by those recently concluded (Cassini, Rosetta, Dawn). This will contribute to elaborate and refine theories advanced to explain the formation and evolution of these planets and satellites in the general context of planetary systems science.

Due to the involvement of the Italian community with still operative and future missions (Mars Express, Mars Reconnaissance Orbiter, ExoMars), Mars exploration, with the study of its evolution and past habitability, and the search for traces of life, will continue to be an important activity. An optimal data exploitation will greatly benefit from high-quality laboratory work.

· The exploration of our Solar System has just begun: there still are several planetary bodies, such as the ice giants Uranus and Neptune, large icy satellites, Main Belt and dynamically new comets, peculiar classes of Main Belt and near-Earth asteroids which are still poorly known or even not yet closely explored by a spacecraft. Efforts will be devoted to conceive and design missions and instruments for these new targets, as well as to perform dedicated campaigns of ancillary observations from ground-based and space-based facilities.

· In the next years the Italian scientific community will be certainly receiving samples of asteroids (from the missions OSIRIS-REx and Hayabusa 2) and, according to the plans of different space agencies, also of comets, of our Moon and of Mars. In this context, our community will actively participate in the international efforts for the preparation and development of analysis facilities, and for developing the necessary skills.

Key Question	Method	Project
Processes that determined the formation and evolution of the Solar System	Detailed information on primitive bodies, planets and satellites	BepiColombo, JUICE, ExoMars
	Remote observations of primitive bodies, exoplanetary systems (dust aggregation processes, formation processes)	SKA, ALMA, JWST, other ground-based and space telescopes
	Numerical simulations (dynamical evolution, formation processes, thermophysical evolution and differentiation…)	HPC
	Laboratory experiments (dust aggregation, …)	
Processes determining the appearance and properties of the bodies of the Solar System	Detailed information on all the bodies of the Solar System (surfaces and atmospheres)	BepiColombo, JUICE, ExoMars, Gaia
	Remote observations of all the bodies of the Solar System	ALMA, SKA, JWST, other telescopes
	Numerical simulations (thermophysical codes, simulation of atmospheres, …)	HPC
	Laboratory experiments (spectroscopic measurements, …) Study of analog terrains and sites	
Evolutionary processes giving origin to the emergence of life	Detailed information on bodies that could harbor, or have harbored, life forms Detailed information on bodies that could have, or have had, liquid water Detailed information on organic material and ices in the Solar System	ExoMars, JUICE
	Remote observation of primitive bodies (organic material and ices)	ALMA, SKA, other telescopes
	Numerical simulations	HPC
	Laboratory experiments Study of analog terrains and sites	

1. Extrasolar Planetary Systems

Keywords: planetary systems, host stars, stellar environment

The properties of extrasolar planets, such as orbit characteristics, mass, radius, structural and atmospheric compositions, and multiplicity rates constitute the fundamental observational fossil evidence of complex planetary formation processes in circumstellar discs with different physical and morphological properties. The determination of the architectural, structural, and atmospheric characteristics of exoplanets combined with the variety of gravitational interactions (e.g., resonant, secular) in multiple systems (with Super Earths and mixes of terrestrial and gas giant planets) observed at the present time also allow us to reconstruct the history of migration and dynamical evolution of exoplanetary systems during and post-formation. The proper understanding of the mechanisms of formation, physical and dynamical evolution of planetary systems is also directly linked to the properties of the parent stars (mass, chemical composition, age) and the stellar environment. Finally, the definition of planetary habitability and the identification of habitable environments are key steps towards the detection of life beyond Earth. The key questions (all of equally high priority) are thus identified and discussed below in detail.

The key questions: 1) what are the architectures and dynamics of planetary systems as a function of mass, radius, and orbital separation?; 2) what are the chemistry and dynamics of exoplanetary atmospheres?; 3) how do planetary architectures, interior structures and atmospheres depend on the host stars' characteristics and their environment?; 4) what are the evolutionary processes giving origin to the emergence of life?

3.1 **Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation**

The discovery of thousands of exoplanetary systems thanks primarily to high-precision radial-velocity surveys and transit programs both from the ground and in space (see Fig. 1) has revealed an extraordinary diversity of their architectures: highlights include compact systems of planets of small size / mass around solar-type stars; other systems containing isolated Earths and Super Earths with short orbital periods, or individual hot Jupiters; multiple systems of gas giants at distances of a few tens of AU. This diversity represents a constant stimulus for theoretical research on the formation and evolution of extrasolar planets and our solar system. The next decade forefront research in the field will tackle many of the still open questions:

- *How common is the solar system? Why does it not contain super Earths or hot Jupiters?*
- *What is the influence of gas giant planets and the interactions between them on the formation and survival of (possibly habitable) rocky planets?*
- *To what extent the architecture and physical properties of a planetary system and the possible existence of habitable planets in it depend on the characteristics of the protoplanetary disk (mass, chemical composition, morphology) as opposed to stochastic processes related to planetary interactions?*

- What is the origin of the observed diversity in planet densities, and thus inferred internal composition, particularly for mini-Neptunes and Super Earths?
- Do water worlds, i.e. small planets composed for ~50% of water (above an iron core and silicate mantle), really exist?
- What is the role of dynamical interactions in planetary migration processes for systems with massive Jovian planets as opposed to compact super Earth and mini-Neptune systems?

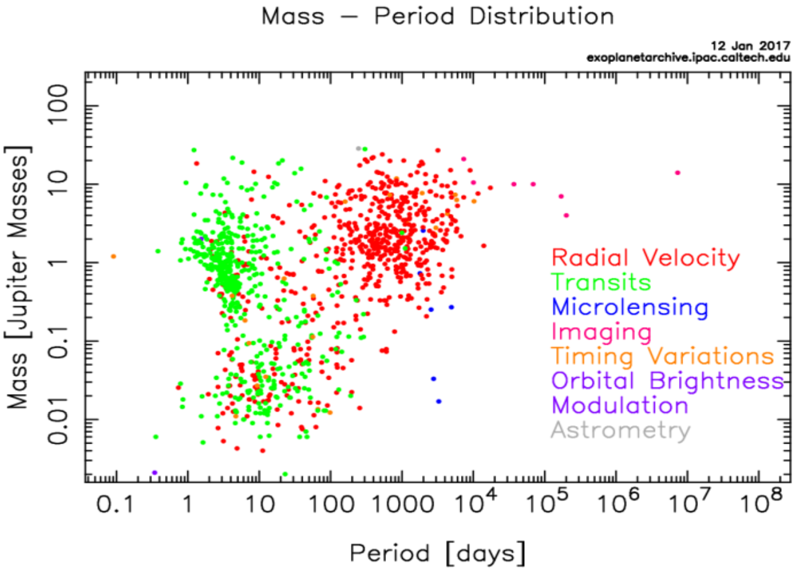


Fig.3.1 - Exoplanet mass - period diagram (as of Jan 2017).

Answers to these fundamental questions in the study of exoplanetary systems certainly require further efforts from both the theoretical point of view and observation. Discoveries of new exoplanets and increasingly detailed characterizations of already known systems will allow a greater exploration of the parameter space (planetary and stellar) and allow performing increasingly accurate individual and statistical analyses. These will provide a crucial testing ground for planetary formation and evolution models, for example to compare the observations with synthetic planetary populations.
Doppler and photometric transit techniques have today reached a high degree of maturity, and they will still contribute critically to the advancement of the field in the next decade, particularly when applied in combination to the class of transiting exoplanet systems. INAF has recently become a major player in the field. *The Global Architecture of Planetary Systems (GAPS) long-term programme with HARPS-N/TNG has coagulated the Italian exoplanet community.* GAPS has allowed INAF researchers to begin impacting the field with a manifold, competitive project aimed at describing the architectural properties of planetary systems across a wide range in mass and orbital separation as a function of stellar properties and environment. *INAF also lead the recently concluded EU-funded ETAEARTH project that uses HARPS-N GTO spectroscopy, Kepler+K2 photometry and Gaia astrometry for the accurate determination of the structural properties of transiting terrestrial planetary systems.* Over 50% of the objects in the mass-radius diagram with

accurate mass determinations shown in Fig. 3.2 have been measured by HARPS-N within the context of the ETAEARTH project.

HARPS-N will remain highly competitive for several years to come, playing a major role (with direct INAF involvement) in the accurate mass determination of small, close-in transiting planets in transit around bright stars revealed by future exoplanet transit missions (that see a strategic INAF involvement). Detailed structural characterization of these systems will allow searching for significant correlations between planet interior composition and stellar elemental abundances as well deriving accurate mass-radius

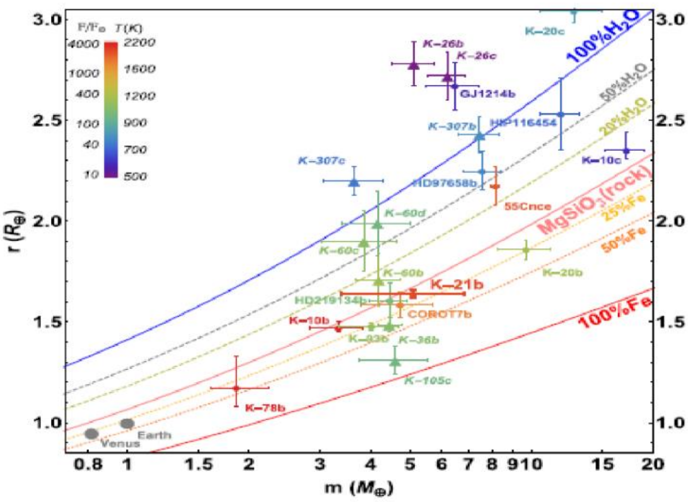


Fig. 3.2 - Mass-radius diagram for transiting planets with masses to 30% accuracy below 20 Earth masses Exoplanet mass - period diagram (as of Jan 2017).

relations to establish the transition between rocky and volatile-shrouded planets as a function of irradiated flux. Some of the systems will also be prime targets for subsequent atmospheric characterization with e.g. JWST. *The simultaneous visible and NIR wavelength coverage provided by the combined observing mode of GIANO+HARPS-N (GIARPS) made available by INAF at the TNG will offer a novel opportunity to INAF researchers.* GIARPS will be exploited for high-precision Doppler monitoring and close-in planet (hot Jupiter) detection around very young stars, providing crucial information on the time scales of planet migration, the mechanisms that cause it and the impact of star-planet tidal interactions. *On similar time scales, the ESPRESSO/VLT ultra-high-precision visible spectrograph (in which INAF plays a relevant role with direct access to the GTO program) will have the capability to detect low-mass planets in the habitable zone of stars similar to the Sun, using very high cadence observing strategies on a limited number of stars for several years.*

High-precision astrometry with *Gaia is expected to deliver tens of thousands of new detections of intermediate-separation* (up to several AUs) giant planets, thus revolutionizing our understanding of the frequencies and architecture of planetary systems up to the mass transition region between gas giants and brown dwarfs, as a function of varied stellar host properties (mass, age, chemical composition, and environment).

High-contrast imaging near-infrared observations with present and upcoming instruments (with strong INAF participation and direct INAF PI-ship) for determination of the physical properties of wide-separation (tens of AUs) young giant planets will allow to obtain decisive inferences on the formation mechanisms (core accretion, disk instability, disk fragmentation) and orbital evolution mechanisms in a regime of separations entirely *complementary to astrometry, RVs, and transit photometry.* These observations will also provide deep insights on the variety of possible interactions between planets and the circumstellar disks that are deemed to be responsible for the plethora of different observed disk morphologies. In the longer term, it would be strategic for INAF to become involved in WFIRST that is set to achieve a visible-wavelength contrast level of 10^{-9} and an inner working angle of less than 0.2 arcsec in its coronagraphic mode, and will observe known nearby exoplanets and perform a survey of the nearest stars to search for exoplanets with sensitivity to mature Neptunes and Super Earths.

3.2 **Chemistry and dynamics of exoplanetary atmospheres**

The measurement of the mean density and the identification of molecules in the atmospheres of transiting terrestrial-type as well as giant extrasolar planets are crucial to understanding the processes of planetary formation and evolution, giving rise to an extraordinary variety of internal composition, chemistry and atmospheric dynamics (including the cloud formation), with interaction mechanisms (especially for rocky planets) between structural and atmospheric properties, and with crucial repercussions on potential prospects for habitability. Currently, data from space-borne and ground-based instruments (gathered primarily through broad-band photometry and low-resolution spectroscopy) are already leading to nominal inferences of various atmospheric properties of exoplanets. Highlights from the analysis of exoplanetary spectra include the detection of atomic and molecular spectral features; observation of day-night temperature gradients; and constraints on vertical atmospheric structure. These results in turn allow placing early constraints on a myriad of atmospheric processes.

Future progress in atmospheric observations and theory will advance exoplanetary characterization in three distinct directions (see Fig. 3). Firstly, robust inferences of chemical and thermal properties will enhance our understanding of the various physical and chemical processes in giant exoplanetary atmosphere. Secondly, better constraints on the elemental abundance ratios in such atmospheres will begin to inform us about their formation environments. Finally, high precision observations will help determine the atmospheric compositions of super-Earths, which, in turn, will constrain their interior compositions and evolutionary history from the time of formation. Ground-based, high-dispersion spectroscopy (HDS) in the near infrared (NIR) has recently become a very effective tool for studying exoplanet atmospheres. At high spectral resolution molecules are resolved into individual lines, so that species can be robustly identified by line matching with planetary model templates. HDS in the NIR allows to detect molecular species and attenuations by hazes/clouds, but also to estimate abundances (e.g. C/O and O/H), and to uncover the presence of winds flowing from the hot dayside to the cooler night hemisphere. Contrary to low- and –medium resolution observations, it critically provides access to emission spectroscopy studies for close-in non-transiting systems.

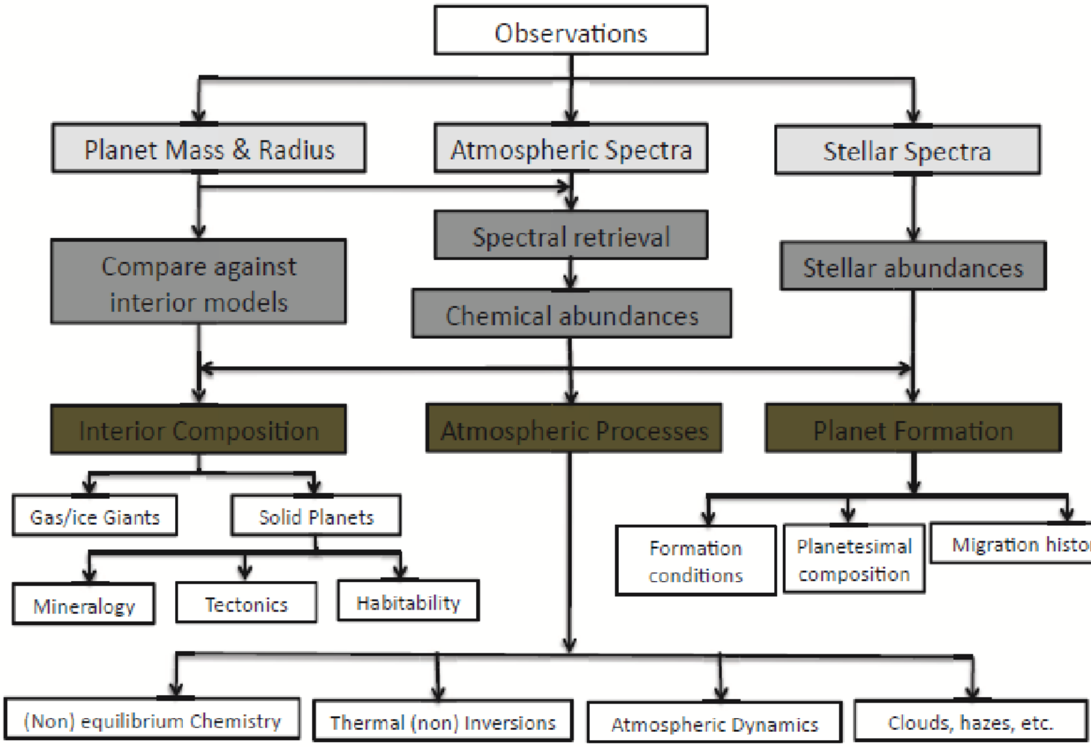


Fig.3.3 - Schematic diagram of the pathway to exoplanet characterization (from Madhusudhan et al. 2014, PPVI, UoA Press).

The INAF community is expected to get deeply involved in the study of exoplanetary atmospheres, in particular with the access to the unprecedented, simultaneous visible and NIR wavelength coverage provided by the combined observing mode of GIARPS made available by INAF at the TNG. Especially in the NIR, GIARPS will allow studying the atmospheres of transiting (but also non-transiting) hot Jupiters and possibly Neptune-sized planets orbiting relatively bright stars (K < 8-9).
The exploitation of the potential of GIARPS for exoplanet atmospheres' characterization will pave the way, over the next decade, to new opportunities for INAF to become a leader in the field of planet atmospheric studies via HDS in the visible and NIR, with instruments designed for larger-aperture telescopes. *Spectacular successes for ground-based transmission spectroscopy and phase variation studies at high spectral resolution in the visible and NIR are expected with upcoming instrumentation in which INAF has roles of responsibility or actual PI-ship (e.g., HIRES/ELT).* Such facilities could also make it feasible to characterize the atmospheres of terrestrial-size exoplanets. In space, the James Webb Space Telescope (JWST) currently offers the best future prospects for detailed studies of exoplanetary atmospheres. Given its large aperture and spectral coverage, JWST will be capable of obtaining very high S/N, low and medium resolution spectra of selected numbers of transiting hot giants planets, warm Neptunes, and temperate super Earths around low-mass stars, thereby rigorously constraining their chemical and thermal properties. In particular, the spectroscopic capabilities of instruments aboard JWST will provide a wide wavelength coverage including spectral features of all the prominent

molecules in gas giant atmospheres. *On the other hand, dedicated space survey missions for atmospheric characterization of exoplanets such as ARIEL (selected by ESA as the M4 mission, with INAF coPI-ship) observe a large number (~1000) of transiting planets for statistical understanding, including hot and warm gas giants, Neptunes, and hot super Earths, therefore providing a representative picture of the chemical nature of the exoplanets and relating this directly to the type and chemical environment of the host star.*
New specialized instruments for high-contrast imaging (HCI) presently or soon to become available at ground-based telescopes behind newly designed adaptive optics systems will provide NIR fluxes and high-SNR low-resolution spectra for young Jovian planets on wide orbits (tens of AUs). *In the southern hemisphere INAF has strategic involvement in SPHERE/VLT, while in the north the Institute leads the construction of SHARK/LBT.* The prospects for atmosphere characterization are excellent with access to so large an amount of spectral data. Even at low resolution, broad molecular features from H_2O and CH_4 should be measurable. If clouds are present, the spectra will be noticeably smoother and redder. Having access to Y and J bands will greatly aid in narrowing in on the preferred range of cloud particle sizes and thicknesses. H and K-band spectra will provide independent estimates of surface gravity. Furthermore, having spectra for many planets with different ages, masses, and luminosities will quickly lead to improvements in theory and help disentangling model degeneracies such as those between effective temperature and surface gravity. The ELTs and new instrumentation in space promise to greatly increase the number of directly imaged planetary systems, with greater contrasts and down to lower masses and/or to older ages. JWST, with IR and mid-IR capabilities, will provide much needed longer wavelength capability for direct spectroscopy of sub-Jovian planets. *Finally, the combination of HDS and HCI will allow systematic investigations of the atmospheric composition of potentially habitable terrestrial planets around the nearest solar-type stars with the aim of detecting possible biogenic gases (H_2O, O_2, CH_4, and CO_2).*

3.3 **Dependence on host stars and stellar environment properties**

A key step will be to accurately gauge the role of stellar mass and chemical composition (used as proxies for those of circumstellar disks) in the efficiency of formation of systems across a range of masses, radii, and orbital architecture. The evolution of the orbital, structural, and atmospheric properties of exoplanets can only be studied effectively by connecting the observations of 'mature systems' with the determination of the spectrum of initial conditions in the protoplanetary disks around young stars. Finally, it should be understood in detail the impact of 'environmental' effects such as binarity and variable stellar density (clusters) on the frequencies and physical and dynamical characteristics of exoplanetary systems. These fundamental questions are closely linked to other issues, such as the understanding of a) how the activity and stellar evolution affect planetary systems, b) how star formation might influence the spectrum of initial conditions and c) how specific concepts related to mature planetary systems, in particular habitability (and the possibility of development of complex biology), are affected by the various levels of interaction between the above processes.

The INAF exoplanet community through the GAPS programme with HARPS-N at TNG is leading fundamental experiments aimed at quantifying the connections between planet occurrence rates over wide ranges in mass and orbital separation and stellar properties and *environment, with focused RV searches for Neptunes and Super Earths around low-mass stars and metal-poor dwarfs as well as investigations of the abundance of Jovian planets around stars in open clusters.* The high-quality HARPS-N data have also allowed the GAPS team to undertake systematic analyses of the effects of star-planet tidal interactions on the orbital architecture of close-in transiting giant planets, as well as studies of the extent of magnetic star–planet interaction (SPI) and its detectable effects in systems with close-in massive planets.

The challenge to better our understanding of the connection between exoplanets and their host stars during the next decade will be faced through very large stellar samples monitored with cutting-edge instrumentation, both from the ground and in space. *High-precision measurements with Gaia (in which INAF is strongly involved) of millions of stars of all ages, spectral type, and chemical composition, with sufficient astrometric sensitivity to giant planetary companions on intermediate separations, will allow unveiling the fine structure of the behavior of planet occurrence rates with host star mass, metallicity, and evolutionary status. In combination with results from transit surveys and RV work, astrometric data will also shed light on the architectures and frequencies of S-type and P-type (i.e. circumbinary) planetary systems.* The dependence of exoplanet systems' frequencies, physical properties, architectures, and evolution on stellar age and density will be accurately tested by the combination of ground- and space-based multi-technique data of large samples of young stars gathered with visible and NIR instrumentation (astrometry, direct imaging, and RV) sensitive to different regimes of orbital separation and planetary mass.

Finally, the availability of high-sensitivity, multi-technique data across a range of wavelengths will allow to refine existing and develop novel methods to carefully gauge, mitigate, and correct the effects of stellar activity in the measurements (often seen as the limiting factor for low-mass, small-radius planet detection). On the other hand, it will improve our comprehension of the details of the complex SPI effects, that are not only relevant for hot Jupiters, but likely affect the evolution of habitability conditions on rocky planets, particularly those orbiting low-mass stars, but also those around young, active solar-type stars.

Key Question	Method	Project
Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation	Mass, radius, and orbital parameters determination with high-precision radial-velocities, photometry, astrometry, and direct imaging	HARPS-N, GIARPS, ESPRESSO, TESS, CHEOPS, PLATO, Gaia, SPHERE, SHARK, PCS/ELT, WFIRST
Chemistry and dynamics of exoplanetary atmospheres	Observations of large samples of exoplanet atmospheres with medium and high-resolution transmission and emission spectroscopy in the visible and NIR both from the ground and in space, ground-based high-contrast imaging	GIARPS, CRIRES+, ESPRESSO, ELT (HIRES & METIS), JWST (NIRSpec & MIRI), ARIEL, SPICA, SPHERE, SHARK, PCS/ELT
Dependence on the properties of the host stars and stellar environment	Planet properties as function of stellar characteristics (mass, chemical composition, age, binarity) and environment (disks, clusters) with high-precision radial-velocities, photometry, astrometry, and imaging	HARPS-N, GIARPS, ESPRESSO, TESS, CHEOPS, PLATO, Gaia, SPHERE, SHARK, PCS/ELT

3.4 Astrobiology: conditions and evolutionary processes giving origin to the emergence of life

Astrobiology is a wide research discipline that ranges in wide areas of the scientific fields and needs a high level of multidisciplinary know-how, including astrophysics, biology, chemistry, biophysics, and geology, and requires a joint effort of theory, observations, computer simulations and laboratory experiments. Astrobiology is thus the study of origin, evolution and distribution of life in space. Life is the result of the growth of molecular complexity and evolution strictly linked to planetary environments. The number of organic molecules that have been discovered in space is continuously increasing. They are formed in cold molecular clouds and in the early phases of star formation. Our understanding of the evolution of organic molecules and their journey from molecular clouds to the early solar system and Earth provides important constraints on the emergence of life on Earth and possibly elsewhere. Minerals have a relevant role in driving the prebiotic evolution of complex chemical systems, mediating the effects of electromagnetic radiation, influencing the photostability of organic molecules, catalyzing important chemical reactions, and/or protecting molecules against degradation. *It is thus necessary to study in laboratory the photostability of biomolecules (e.g. nucleobases, amino acids, carboxylic acids, fatty acids, etc.) under space conditions in the presence of mineral matrices* in order to investigate both the prebiotic processes that might have had a role in the development of the first living entities on Earth and the physical and chemical processes occurring in extraterrestrial environments.

The increasing knowledge of the evolution of our solar system and the discovery of extrasolar systems have opened a number of questions on the origin of life and on conditions that may allow its evolution. The determination of the habitability conditions, for instance the presence of liquid water and energy sources able to sustain life, that are not necessarily associated with a single specific environment, will be important to identify potential habitable planets in the Solar and in other systems. Solar system itself may present such conditions in sites other than Earth, and mechanisms of evolution of habitable environments through the Solar systems have to be studied. *In order to answer the fundamental question on the origin of life is crucial to understand in which conditions life may be originated, controlled and sustained, and in particular how this occurs if prebiotic material is brought in from elsewhere.* The influence of small objects on early planetary environment, including the high energy radiation from the parent young star may be essential for the onset and survival of life. *The study of molecular evolution of abiotic organics present in Solar System objects, including the early Earth, under the combined role of physical agents such as thermal variations, high energy particles, photons and solar wind irradiation is a task that will be pursued in the next decade.*

At the same time *the feedback on chemistry of planetary atmospheres is an important issue that will expand our understanding of the general principles of habitability.*

The definition of habitability, the identification of habitable environments, and the detection of life beyond Earth are centerpiece in the geoscience, planetary science, and astrobiology literature. Over the next decade the disciplines of astronomy and astrophysics have the potential to contribute dramatically to these aspects, ultimately bringing us ever closer to answering the age-old question: “Are we alone?” The ability to achieve ground-breaking results will be crucially enhanced by the establishment of a systematic and multidisciplinary approach that will tackle the issues from a three-fold perspective:

i) Theoretical investigations of habitability conditions, as independent of the actual emergence of life in a given planet, will have to be pursued vigorously. A paradigm shift

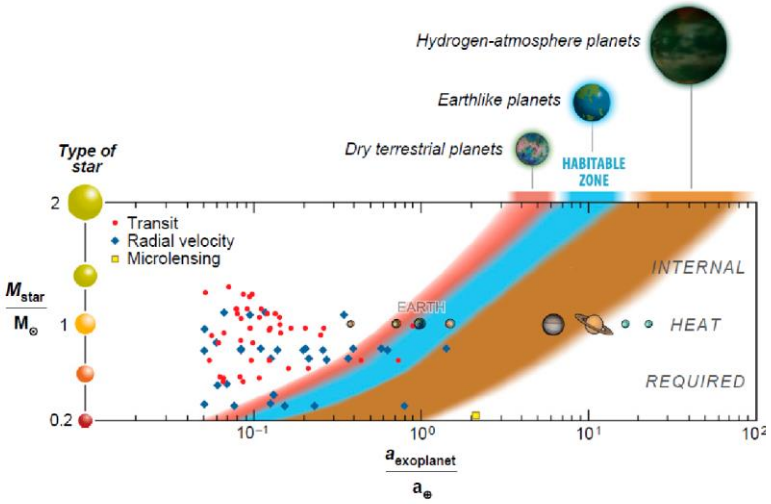


Fig. 3.4 - The extended Habitable Zone (from Seager 2014, PNAS).

is now occurring, in which the star-specific concept of Habitable Zone is being revised by a planet-specific concept of habitability (see Fig. 4), to explain the huge diversity of planetary systems in terms of masses, orbits, and star types and the variety of possible planetary atmospheres based on the stochastic nature of planet formation and evolution. In this respect, increased sophistication in planetary climate models is highly desirable, exploring the possibility to shy away from the Earth-centric liquid water criterion.

Dynamical and radiative transfer modelling can also support or constrain the identification of new observables for present or future investigations.

ii) Laboratory support, essential to investigate the extreme environment found and expected in most of the exoplanetary systems, as well as to fill critical gaps in our ability to model exoplanet atmospheric processes. These investigations include molecular opacity line lists for different broadening gases, extended databases for collision-induced absorption, dimer opacities and chemical reaction rates, laboratory studies of haze and condensate formation and optical properties, measurements of gas photo absorption cross sections at high temperatures, and new approaches in the study of biosignature gases.

iii) Next decade observing programs to detect biosignatures gases in potentially habitable rocky worlds. It will be necessary to gather observational data for the largest possible sample of potentially habitable exoplanets, to gain a probabilistic assessment of the commonality of biosignatures gases by mitigating the inevitability of false positives. ***In space, the fast track to the detection of atmospheric gases that might be potential signs of life will be provided by JWST that will investigate the atmospheres of habitable rocky Super Earths around low-mass stars discovered in transit by upcoming transit missions. Later on, the combination of HDS and HCI with HIRES/ELT (with INAF PIship) and PCS/ELT (with strong INAF involvement) will open up the door to the atmospheric characterization of rocky planets in the habitable zone of our nearest stellar neighbors.***

Key Question	Method	Project
Evolutionary processes giving origin to the emergence of life	Detailed information on bodies that could harbor, or have harbored, life forms Detailed information on bodies that could have, or have had, liquid water Detailed information on organic material and ices in the Solar System	ExoMars, Juice
	Observation of primitive bodies (organic material and ices)	ALMA, SKA, other telescopes
	Numerical simulations	HPC
	Laboratory experiments Study of analog terrains and sites	
Evolutionary processes giving origin to the emergence of life	Atmospheres of terrestrial planets in the habitable zone with medium and high-resolution transmission and emission spectroscopy in the visible and NIR both from the ground and in space. Ground-based High-contrast imaging.	Evolutionary processes giving origin to the emergence of life

4. Star Formation (local and global)

Keywords: star formation, magnetic field, turbulence, protoplanetary disks, jets, accretion, cosmic rays.

The Milky Way Galaxy, our home, is a complex ecosystem where a cyclical transformation process brings diffuse baryonic matter into dense unstable condensations to form stars, that produce radiant energy for billions of years before releasing chemically enriched material back into the Interstellar Medium (ISM) in their final stages of evolution. Star Formation (SF) is the trigger of this process, eventually driving the evolution of ordinary matter in the Universe from its primordial composition to the present-day chemical diversity necessary for the birth of life. Stars are known to form in molecular clouds, but the early phases of the process, i.e. the collapse of an otherwise stable clump of gas and dust into a self-gravitating proto-star, are still far from being understood. To collapse, a cloud must be able to efficiently cool away the heat produced, shed away the primordial angular momentum which would otherwise lead the proto-star to rotate at breakup speed. The collapse has also to win against ambient magnetic field and cloud turbulence.

The accretion disc, generated by the conservation of angular momentum during the collapse of the parent cloud toward the formation of the star, is where the planets have their origin. Therefore it is crucial to define the properties and evolution of the disc, to establish the correct initial setup for the formation of the planets, and shed light on processes such as the aggregation of solids up to the formation of planetesimals, the chemical evolution of the molecular content toward the formation of pre-biotic species, the dynamical evolution of the disc material leading to the different planetary architectures.

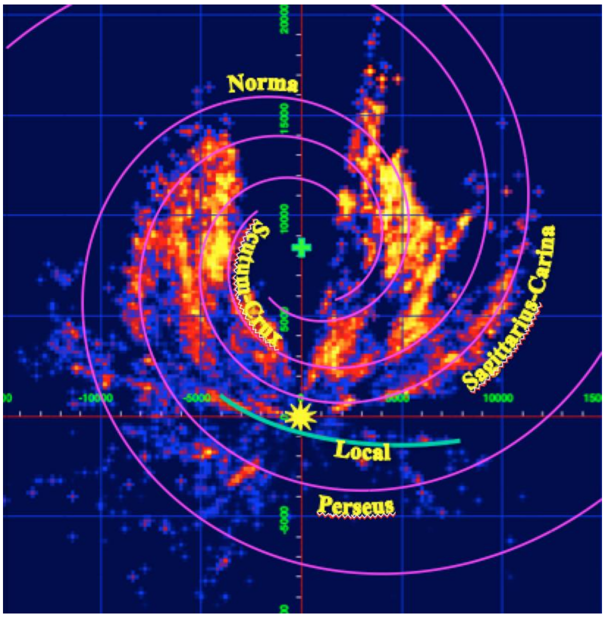
The key questions to tackle:

- **Global star formation properties in the Milky Way Galaxy**
- **Physics of individual star formation events**
- **Proto-planetary discs: initial conditions for the formation of planets**

4.1 Global star formation properties in the Milky Way

The latest generations of continuum and spectroscopic surveys of the Galactic Plane with SPITZER and HERSCHEL satellites as well as with major single dish radio facilities, have transformed the picture of the Milky Way Galaxy as a star formation engine. In a traditional ”slow formation” picture, diffuse ISM is accumulated by large-scale perturbations such as the passage of a spiral arm. Shielding by dust and surface reactions on grains promotes the HI→H2 transition, which in turn allows the formation of other molecules that cool the cloud. Gravity, mediated by the magnetic fields leads to unstable dense clumps, that can further differentiate into a multiplicity of cores. Typically each core harbors a forming Young Stellar Object (YSOs) eventually leading to a single star or a close binary. Alternative more dynamical scenarios posit that molecular clouds are transient, short-lived structures created in the post-shock regions of converging large-scale flows or in turbulence driven compression that produce layers and filaments where column density builds up, shielding material from the interstellar radiation. Cooling and gravitational instabilities will naturally arise, fragmenting the filaments under the effect of self-gravity into chains of dense supercritical turbulent clumps that harbor massive protostars and protoclusters. Indeed, one of the most important and unexpected discoveries of the Herschel Satellite is the Galaxy-wide ubiquity of the filamentary nature of the cold, dense

and potentially star-forming phase of the ISM.. On larger scales, cloud and star formation rates are enhanced close to spiral patterns but it is still unclear if spiral density waves actively build up dense clouds and induce SF or simply assemble star-forming regions.
INAF is at the forefront in this field, with leading roles in HERSCHEL and SPITZER Galactic Plane surveys like Hi-GAL and MIPSGAL, as well as with important participations in ESO-APEX surveys ATLASGAL and SEDIGISM. INAF is also leading the EU-funded VIALACTEA project assembling all Galactic Plane surveys into a coherent knowledge-base, as a framework for an integrated Galaxy-scale study of global star formation. The figure shows the first resolved map of the Galactic SF rate (SFR) obtained by the VIALACTEA project.
The final aim is to relate the end-products of star formation measured by the SFR and Star Formation Efficiency (SFE, stellar mass produced per unit mass of available dense gas), to the physical mechanism responsible for the onset of star formation. Doing this in very different places of the Galaxy and with significant statistics is the necessary step to put star formation in the global context and be a reference for extragalactic studies to create a proxy for star formation in nearby galaxies, as well as star formation history from a cosmological viewpoint. *The creation of a 'fundamental theory' or, rather, of a galaxy-scale predictive model for star formation in the Milky Way that can serve as a "z=0 template" for external galaxies, is the key challenge that will be faced in the next decade.*



Ground-based single dish millimetric/centimetric facilities like IRAM, APEX, SRT, GBT, ARO, etc., will spectroscopically follow-up tens of thousands of star-forming sites catalogued by HERSCHEL to trace the evolutionary footprint on the chemistry, physics and dynamics of the dense clumps that are the progenitors of stellar clusters. At the same time, these facilities are ideally suited to map the physical conditions of their host filamentary structures, to follow the complex filament-clump interplay and determine the role of filaments at all spatial scales from several tens of parsecs of giant filaments to the smaller and kinematically coeherent "fibers" out of which low-mass "cores" originate. Determining if the filament to clump fragmentation process happens in isolation or with continuous feed from the surrounding ISM is crucial to discriminate the dominant mechanisms that determine the products of star formation. *Polarization measurements with single-dish facilities, together with Faraday tomography with LOFAR, EVLA, ASKAP e SKA will allow us to dramatically improve our understanding of the role of magnetic fields during the collapse of the various phases of the interstellar medium and at all Galactic spatial scales.* It is mandatory to carry out these studies with large and statistically significant samples that trace the variety of conditions found in a typical spiral galaxy like the Milky Way.

An even more important role in the field will be played by very high-spatial resolution observations from the infrared to the millimeter and radio. ALMA+ACA, together with facilities like NOEMA and SMA, will allow surveys of several thousands of star-forming as well as prestellar clumps in a variety of Galactic environments to follow with unprecedented detail and sensitivity the physics, chemistry and dynamics of the fragmentation and initial accretion of the stellar cluster precursors. *JWST will be crucial to trace the timescales of the emergence of new stellar generations; the shape of the 1-20μm continuum with NIRCam and MIRI is a key observable to trace the approach of forming YSOs toward the ZAMS, while spectroscopy with MIRSpec and MIRI will allow us to monitor the resolved properties of the emerging radiation field and the wind/shock conditions in the clumps.* At the long wavelength side of the electromagnetic spectrum, clump surveys with ASKAP, MeerKAT and SKA will be able to record the first sign of emission from radio jets or thermal free-free that generally mark the arrival of each forming YSO on the ZAMS. *INAF researchers participate to Galactic Plane Surveys projects with ASKAP and MeerKAT.*

With the distance determination toward millions of stellar objects, folded with the distribution of dust from ISM and molecular clouds, Gaia will build an unprecedented 3D tomography of the Galactic ISM. *The photometric properties of YSOs imaged by Gaia as a function of the position with respect to spiral arms will allow us to trace evolutive gradients and the role of spiral arms as active "triggers" of SF, or relegate them to a more marginal role of ISM "collectors".*

It will be critical to make decisive progress in the fields of new data-mining and machine-learning technologies. The scientific analysis of an extensive and extremely complex and inhomogeneous body of knowledge (photometry and spectroscopy, compact as well as extended structures) will require automated and supervised analysis workflows with decision-making capabilities to carry out the evolutionary classification and determination of SFR and SFE for tens-of-thousands of star forming sites in the Galaxy.

4.2 Physics of individual star formation events

Physical and chemical properties go hand in hand, so the study, over the entire mass spectrum, of the chemical evolution in star forming regions is of paramount importance for the understanding of their evolution. Particularly relevant for theoretical models are the initial conditions, derived from pre-stellar and massive cores in infrared-dark clouds in the low-mass and high-mass regime, respectively. Sub-mm observations of key molecules like those rich in Deuterium, both at low and high angular resolution, are essential for the study of the very first phases of star formation since they allow determining the spatial distribution of the different molecular species. INAF investigators are in first place in this type of research and will continue such kind of studies by performing surveys in the sub-mm regime using the ESO-ALMA and IRAM facilities. *These facilities, ESO-ALMA in particular, will play a crucial role also in the study of later phases of gravitational collapse, when the infalling matter starts to accumulate in a circumstellar disk around the forming protostar.*

Analytical calculations and numerical simulations have shown the catastrophic impact on the formation of protostellar discs that a Galactic magnetic field frozen during the collapse phase may have. Theoretical studies have been focused on the dissipative processes leading to the gas/magnetic field decoupling, but both the mechanisms (e.g. ambipolar diffusion, macroscopic instabilities and turbulence, disalignment between magnetic field and angular momentum of the cloud, etc.) and the spatial and temporal scales of decoupling are still debated. The different scenarios can be distinguished by the kinematics of the ionized and neutral gas, and by polarimetric measurements of the thermal emission from the dust grains.

The ALMA interferometer is crucial for that. In addition to theoretical models, INAF researchers have developed numerical tools to produce synthetic maps of polarized emission convolved with the interferometric response that will allow a direct comparison of the models with the observations.

Young protostars are still immersed in their gas and dust envelope, hence the main tools to study them are observations in the millimeter and radio domains. However, an important role on cooling and mass transfer in outflows/jets is played by the hot gas, which emits in the mid and far infrared, mainly in lines of neutral atoms and simple molecules (e.g. [OI]63μm, H2, CO, H2O). The Herschel satellite represents a break-through, because it revealed these species, pinpointing the *shock waves*, generated in the violent expulsion of matter during the first phase of active accretion onto the protostar, as the main source of their emission. *In the next years, the JWST (MIRI in particular), thanks to its higher spatial resolution will allow conducting detailed studies of the morphology and excitation conditions of this gas and its role in the star formation process.*

Collimated jets are the main mechanism by which accreting protostars lose angular momentum. Jets are launched and collimated via a magneto-centrifugal process which has the capability to remove the excess angular momentum. The magnetic braking is so efficient when the field and the spin axis are aligned that Keplerian discs may be initially suppressed beyond 10 AU, while larger Keplerian discs might result from misaligned B-Ω configurations. However, studying the interface between jet and disc, with its small angular scale, has been so far not achievable. It is still not clear from which disc portion jets originate, in any case less than 10 AU, and how much angular momentum is transported away by the jet. Studies in the Near Ultraviolet with HST or with forthcoming UV facilities allow to probe the core of the jet, that carries the most reliable signature of the launch mechanism. In addition (Sub-)mm molecular lines are used to probe the base of the jet still embedded in the parental envelope. To test the MHD models and the magnetic field structure it is also essential to map the continuum polarization produced by magnetic alignment of dust grains. However, the available resolution (~0.2" at most) does not allow us to constrain the jet ejection size. *A break-through will be obtained by reaching in the (sub-)mm domain a typical spatial resolutions of 1 AU, i.e. 15 mas in Taurus. This will provide long-awaited critical observational constraints to models of jet launching, disk, and planet formation. This will happen with the ESO-ALMA, and IRAM-NOEMA facilities.* The INAF star and planet formation group is a numerous and dynamic community leading high impact research in this field, such as the study of jets/disk using ALMA through A-rated projects and a number of IRAM NOEMA large programs (e.g. CALYPSO, SOLIS) dedicated to the pristine jet/disk systems (see Figure 2).

To globally understand the role of jets in the process of protostellar evolution, it is of crucial importance to determine the frequency at which jets manifest and how their properties depend on those of the central source. This is now possible thanks to the large spectroscopic surveys of young stellar objects, such as those conducted with VLT/X-Shooter, allowing the analysis of the physical properties of the gas in the jet in a statistically significant fashion. INAF researchers are particularly active in this field, within the framework of the collaboration JEDI (Jets and Disks @ INAF) and in synergy with ongoing ALMA surveys. These observations are fundamental for the comprehension of the disc dispersion mechanisms and evolution, and their dependence on the rate of mass accretion and mass loss. Such studies will be extended to a wider range of mass and age of the central sources. *The X-Shooter-ALMA synergy will allow* *building a unified and robust picture of the evolution of the star-disc system, and measure the intertwined effects of planet formation, disc structure, viscous evolution, disc wind, and photo-evaporation. Together with near future observations with GIANO/GIARPS and CRIRES+, this represent preparatory activity for the exploitation of future instrumentation at ELT, in particular HIRES.*

High contrast and spatial resolution observations in the optical and near infrared acquired with adaptive optics make possible the investigation of the inner disc and jet regions (10-20 AU from the star). Observations by the INAF teams are currently being conducted with VLT/SPHERE and LBT LUCI and LBTI, and will be strategic for future observations with SHARK-NIR and V-SHARK at the LBT. In perspective, VLT/ERIS and ELT/HIRES, investigating the atomic emission lines in the VIS/NIR domain, will give a great wealth of diagnostics on the physical parameters and on the kinematics of the flows.

In the near future this kind of studies will also be conducted in the mid infrared with JWST, extending to much younger sources than done so far. *The MIRI instrument, in particular, is fundamental for investigating the properties of the hot gas in the disc/jet of protostars and identifying biologically important molecules like water and hydrocarbons around forming stars. INAF teams are actively participating to combined HST / JWST projects within the Early Science Research and Open Time JWST frameworks. In the long term, the SPICA satellite will allow conducting spectroscopy in the far infrared.*

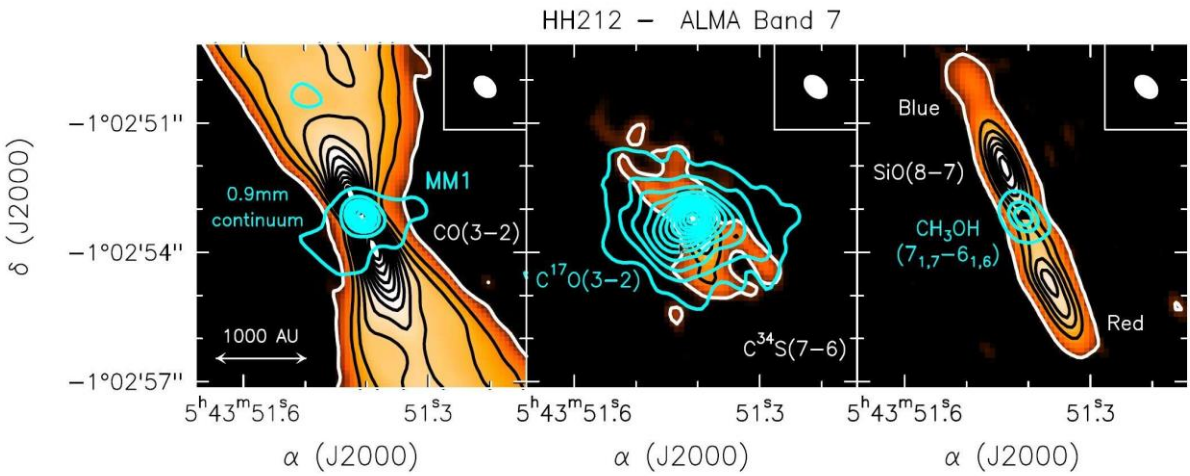


Fig.4.2 - The HH212 protostellar system as observed with ALMA–Band 7. Continuum and molecule emissions are labelled and indicated by different colours in the three panels.

4.3 Proto-planetary discs: initial conditions for the formation of planets

From the observational standpoint, our understanding of the disc dynamics and chemistry, as initial conditions for the formation of planetary systems, will require a) the robust determination of the dust to gas mass ratio in disc, b) the search for possible mechanisms to counteract the fragmentation and the migration toward the star of the mm/cm-sized dust grains (dust traps), c) the measurement of the fraction of discs actively accreting matter on the star, d) the identification of the mechanisms generating the rich disc structures observed (gaps, rings, spirals, etc.), and their relation with the presence of newly formed planets. Such issues will have to be investigated as functions of the central star properties (mass and age), and will require achieving a statistically significant census of structured discs, at different masses and ages, of the central star. On the theoretical side important studies will have to be conducted on the interaction between diffuse gas and dust in the disc and already formed bodies, which can explain the observed pattern and be predictive on the presence of unseen planets in young systems. The role of cosmic rays, from the interstellar medium and locally accelerated in proto-stars, will also have to be studied. In fact, they regulate the coupling between the gas and the magnetic field, they have an impact on the size of the region where the magneto-rotational instability is active, and the cosmic-ray ionisation rate is a fundamental parameter to interpreting the observed abundances. Besides cosmic rays induce stochastic heating on dust grains and they may be responsible for the desorption of complex organic molecules.

So far, the direct detection of the proto-planetary candidates leading to the observed disc structures has been possible only in a small number of specific cases. To carry out a statistically significant survey on this topic one has to use high spatial resolution instruments in the Infrared and in the (sub)-millimeter domains. This is a field in which INAF has a strong potential, thanks to the involvement in AO-assisted instrumentation like VLT/SPHERE, LBT/LBTI and LUCI and, in perspective, LBT/SHARK, ERIS/VLT (first light expected for 2021) and in a more distant future the ELT instruments assisted by the MAORY AO module, commissioned to INAF. In principle NIR interferometry with the VLTI allows the best spatial resolution for the observation of the innermost part of discs. *INAF followed the development of the VLTI beam combiner AMBER, and will collaborate with the groups involved in the second-generation combiners, like GRAVITY and MATISSE, that will overcome the past sensitivity limitations. In space, JWST will work at diffraction limited resolution in the NIR/MIR.* INAF did not participate in the development of the space observatory, but the telescope will be used by INAF to explore selected cold, embedded systems in all their possible facets. Finally, INAF groups are international leaders in this field also thanks to strong commitments in observational programs that are tackling the above issues using high-spatial resolution at (sub)-mm wavelengths with e.g. IRAM and ALMA.

The investigation on the emergence of life occupies a crucial position in the INAF strategic plan. What are the basic chemical mechanisms that led atoms to molecules and then to life? *With HERSCHEL and ALMA we could finally start the study of astrochemistry, and it is now clear that molecular complexity advances at every evolutionary stage of the system, from the simplest molecules in the ISM to the Complex Organic Molecules (COMs) detected in the protostellar environment.* INAF is actively involved at the forefront in this field, as, e.g. in the study of the distribution in space of water and organic molecules, such a CH_3CN, important for the synthesis of amino acids and related to the transport of organic material from comets to planets, and CH_3OH, which arises on ice-covered grains, and is the first step for the formation of COMs.
The abundances and formation patterns of COMs (in particular amino acids such as Glycine, glycolaldehyde, phospholipids and phosphates, pluri-carbonated, branched, and chiral molecules) are the key to understanding the formation of pre-biotic material in the disc and its subsequent delivery onto the planets. Another important aspect to be explored is the fractionation of isotopes in space that will also lead to big advances in the understanding of the occurrence of the chemical chains that led to life.

Along this line of research, the main goal for INAF is the detection of the amino acids in the diffuse gas. The typical sizes of the regions associated with COMs' emission are less than about 1 arcsec (hot-cores, jets). The spatial resolution offered by the new generation of interferometers is fundamental to resolve the emitting region. The way forward is to collect high resolution unbiased spectra covering the largest possible frequency range, in order to have the most complete census of the present species. Future developments of ALMA, with a single receiver covering the range from 67 GHz to 116 GHz (a project on which INAF plays an important role), will be instrumental. SKA will offer a unique combination between high-sensitivity and high-angular resolutions (1-10 mas, depending on frequency), particularly if optimized also for frequencies up to 10-15 GHz, to produce a complete inventory of interstellar species accessible in the cm-range. In the Northern hemisphere IRAM-NOEMA will provide 12 antennas in 2018 observing in the 0.8-3 mm range with a final spectral resolution < 100 mas. INAF should definitely invest resources in joining the IRAM-NOEMA international consortium. In this respect, **the** strong INAF participation to the program IRAM/NOEMA "SOLIS: Seeds Of Life In Space" is already producing impacting science. Thanks to SOLIS, formamide (a crucial molecule that leads to the synthesis of metabolic and genetic macromolecules capable of reproducing themselves using external energy) has been spatially resolved for the first time around a proto-Sun analog, and modeled through quantum chemistry calculations. Moreover, the SOLIS observations have also shown that the growth of long carbon chains (that may have been an important carbon reservoir in the origin and development of life on Earth) are promoted by the irradiation of energetic particles experienced by the young Solar system.

On a different but complementary ground, a strategic investigation on the disc structure will be the determination of the magnetic configuration, which is crucial for many different reasons (e.g., driving the transport / extraction of the angular momentum out of the disk, which in turn allows for the observed accretion onto the central star). ALMA will allow us to derive the distribution of the magnetic field via the polarization of the dust continuum emission from the disc, and in a near future, via the line polarized emission at the base of jets. This will finally allow testing the scale-free jet launch models, including those developed in INAF, applicable to magnetized discs around compact objects of any mass, from brown dwarfs to active galactic nuclei.

In parallel with the magnetic configuration, the inner disc and the jet acceleration region will be extensively investigated with high spatial resolution observations in the VIS/NIR domain with LBT, HST and, in perspective, with VLT/ERIS and ELT/HIRES. In-depth studies of the jet-disc feedback will allow unveiling: a) its impact on the chemistry of the surface layers; b) its effects on the photoevaporation of the disc material, thus setting stringent limits to the disc lifetime, to the mass content left to build the giant gaseous planets, and to their ability to migrate; c) the dynamical influence of jet asymmetries, that can generate large scale motions within the disc layers in the region where planets originate; and d) the screening effect to UV stellar radiation caused by the dust grains of smaller size transported within the outflows.

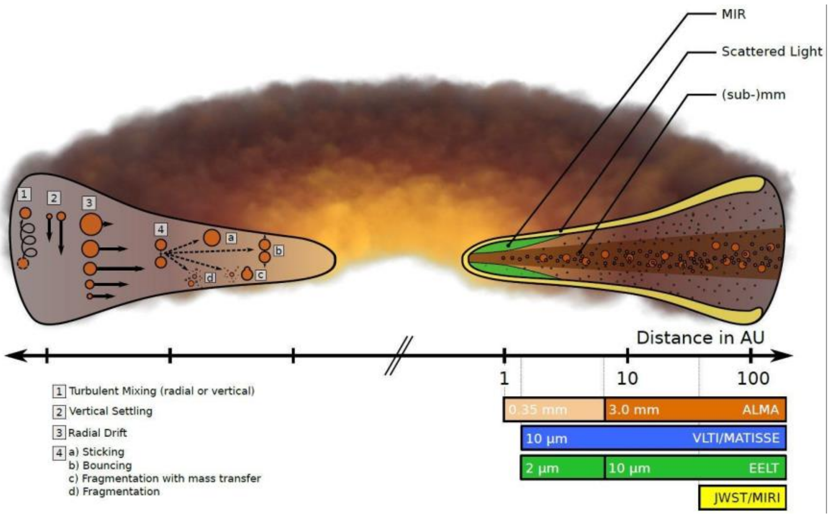


Fig.4.3 - Illustration of the structure and evolution processes of dust, and observational constraints for a typical proto-planetary disk (Testi et al., 2014, PPVI, UoA Press p. 339-361).

Key Question	Method	Project
Global star formation properties in the MilkyWay Galaxy : Molecular clouds & dense gas.	Star formation rate, star formation efficiency. Physical mechanism responsible for the onset of star formation in very different places of the Galaxy. Creation of a 'fundamental theory' of a galaxy-scale predictive model for star formation that can serve as a "z=0 template" for external galaxies.	IRAM, APEX, SRT, GBT, ARO, LOFAR, EVLA, ASKAP SKA, ALMA + ACA, NOEMA, SMA, JWST, MeerKAT
Physics of individual star formation events and stellar clusters.	Fragmentation of dense clumps and evolution to dense cores. Monolithic collapse vs dynamic competitive accretion and potential mergers. Core migration in clumps. Origin of the IMF, also in low metallicity environments, and of the stellar binary fraction. From the core to the protostar and formation of the circumstellar disk. Theory of dissipative processes tested with polarimetric studies of dust thermal emission. Morphology and excitation conditions in the disk gas phase and its role in protostellar evolution. Modelling of the jet launching mechanisms and link with the angular momentum evolution. Feedback of jets and outflows on the properties of the disk. Chemistry of the disk material and formation of complex molecules. Determine IMF in low-metallicity environments.	ALMA, IRAM, GIANO, GIARPS , CRIRES+, HIRES, HST, JWST, SPHERE, LUCI, LBTI, Gaia, GES SHARK-NIR, V-SHARK, MICADO, MAORY
Proto-planetary discs: initial conditions for the formation of planets	Robust determination of dust-to-gas mass ratio in disks. The mechanisms to counteract the fragmentation and the migration toward the star of mm/cm-sized dust grains. The measurement of the fraction of discs actively accreting matter on the star. The identification of the mechanisms generating the rich disc structures observed (gaps, rings, spirals, etc.), and their relation with the presence of newly formed planets. Mass accretion and ejection as a function of stellar parameters, in solar and low-metallicity environments.	IRAM, ALMA, SPHERE, LBTI, LUCI GIANO, GIARPS, CRIRES+, SHARK, ERIS, AMBER, GRAVITY, MATISSE, JWST, MAORY, HIGHRES,

5. Stellar Evolution

Keywords: stellar physics, convection, rotation, magnetic field, explosion, ejecta, remnant, age, asteroseismology, stellar models, space missions

Stars constitute the building blocks of much of the visible Universe, therefore the understanding of their evolution and nucleosynthesis is a key astrophysical goal for the future. In particular, the knowledge of the structure and evolution of stars, both as single objects and as part of stellar aggregates, is crucial for our understanding of resolved stellar populations in Galactic and extragalactic environments, for the definition of standard candles to be used in the cosmic distance ladder, for robustly measuring ages, for dating the oldest stellar systems and in turn the universe itself.
The Italian community has a leading role in the field of stellar evolution with competitive teams investigating different ranges of stellar parameters and dealing with open problems in stellar astrophysics, also focusing on the implications of their studies in a wider astrophysical context.

The stellar evolutionary framework built by the Italian community has been demonstrated to be highly accurate in the prediction of observed stellar properties in various Galactic and extragalactic environments. In this field, the Italian teams working on stellar evolution have a worldwide recognized expertise with important reference stellar model databases that have been made available to the whole scientific community, and a huge number of milestone papers on all the relevant evolutionary phases. This leadership should not absolutely be lost in the next decade, but-actually it should be made stronger. In fact, there are several critical scientific issues that have to be fully exploited.

The key question:

5.1 Taking stellar models to the next power

Although the development of evolutionary codes, and the canonical physical framework have reached a satisfactory level of accuracy and reliability, there still are several physical mechanisms such as rotation and related rotational induced mixings, magnetic fields, thermohaline mixings, internal gravity waves, and mass loss that are still poorly known.
These physical processes have been – so far - poorly investigated, or in most cases even ignored, in almost all the stellar evolutionary computations due to both the huge complexity of their inclusion in a stellar evolutionary code, and the fact that their efficiency, and –hence - their impact on stellar models, is sometimes controlled by a number of free parameters usually poorly constrained by observations.
However, since the last decade, thanks to the "asteroseismology revolution", stellar astrophysics is entering in a new era. Starting with the CoRoT mission, although the largest contribution is coming from the Kepler satellite, asteroseismology of Sun-like stars and more evolved objects such as Red Giants and Red Clump stars is actually providing a tool for studying the intimate secrets of stars, thus offering an unprecedented approach for investigating the real efficiency of physical processes usually ignored in stellar model computations. Just to mention an important issue, seismic analysis is actually showing that present generation of stellar models underestimate the capability of stars to extract angular momentum from the inner regions, i.e. the level of torque between the inner core and the outer envelope. This is clearly a proof that, together with rotational mixings, some other processes such as internal gravity

waves and/or magnetic field have to contribute to the angular momentum transport. This issue has been only marginaly investigated so far.

In this context an important step forward would be also represented by the development of 3D stellar models. This is a very ambitious project and there are only a few international teams that are already working in this direction. *The Italian community should definitely avoid to miss this chance, by favouring the growth of a competitive Italian team including new young astronomers but relying on the experience of current stellar evolution leaders.* The results based on 3D simulations can also be used as guidelines to update the treatment of non-canonical physical processes in traditional 1D codes.

New ground-based and space facilities are in progress and planned for the coming decade. These will allow us to obtain excellent accuracy observations of stellar oscillations for a variety of stars in different evolutionary stages, and in turn a unique benchmark for testing and improving stellar evolution models. Indeed asteroseismology is one of the most powerful techniques to investigate the stellar inner structure and to constrain the physical properties.
On the other hand, stellar evolution can provide a fundamental support to asteroseismologic surveys, in particular in the context of "Galactic archeology" (see Section 7). In fact, the most basic stellar parameters provided by asteroseismology are the present stellar mass – usually different from the initial mass as a consequence of mass loss processes - the radius and the distance for thousands of single stars within some tens of kpc. However, asteroseismology by itself cannot provide stellar ages: this result can be achieved only by combining seismic data with the astrometric information provided by the Gaia mission and with the predictions of extended, homogeneous and updated sets of stellar models. This combination is able to provide estimates of field star ages with errors lower than the ones obtained with other methods.
As mentioned before, asteroseismology provides an estimate of the actual mass of the star, whereas the evolutionary lifetimes – i.e. the age of the star in a specific evolutionary stage – are fully determined by its initial mass. This implies that a better understanding of the efficiency of mass loss and of the physical mechanisms triggering this process, is mandatory in order to improve both the accuracy of stellar models and their predictive capability when used in combination with seismic measurements.
The accuracy of age determination can be increased by orders of magnitude, when relying not only on the basic stellar parameters provided by asteroseismology – that are obtained by still debated approximated scaling laws – but on the comparison of the full empiric seismic spectrum with the corresponding model predictions. However, in order to accomplish this effort, one needs an extended dataset of stellar structure models to be used as input files in both radial and non-radial pulsation codes. Needless to say, this is an extremely demanding effort both in terms of computing time and storage capabilities. The Italian stellar evolution and pulsation community is strongly collaborating with international research teams on these important topics.
By relying on the experience developed with the asteroseismological results of the CoRoT and Kepler satellites, the Italian community working on stellar evolution is also deeply involved in the preparatory phase of the new missions TESS and PLATO, that will revolutionize our views of stars and stellar systems. In particolar, the NASA mission TESS will be launched in 2017 and will scan the whole sky to discover thousands of planets around bright stars (cool dwarfs of spectral type K and M), but will be blind to earth-like size planets. On the other hand, the ESA mission PLATO 2.0 will detect and characterize planets around bright solar-like stars and provide accurate seismology for 85000 stars, and in turn, stellar radii and masses at a ~2%

level of precision and – when supported by detailed stellar evolutionary predicitions - ages at ~10%. These results will be crucial also for the synergy with Gaia parallaxes. Moreover, SKA will allow us to investigate the strenght and properties of stellar magnetic fields with high accuracy. The involvement in these observational projects makes extremely timing the need for the Italian stellar evolution community to have the opportunities and facilities for investigating the above mentioned scientific issues.

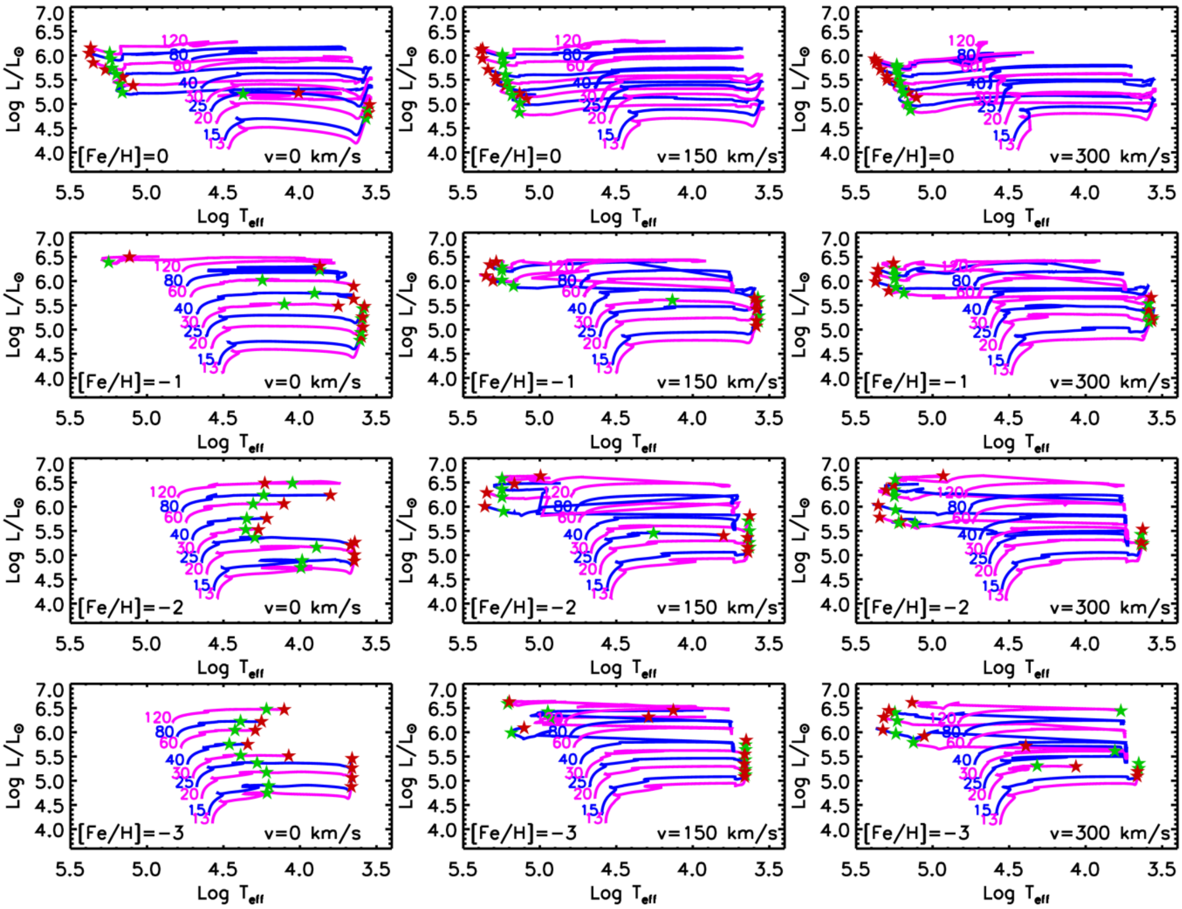


Fig. 5.1 - Theoretical presupernova evolutionary tracks in the HR diagram of a set of massive star models in the range 13-120 M⊙. The green stars mark the core He depletion while the red stars refer to the presupernova stage. The left, center and right panels refer to models with initial rotation velocity v = 0, 150, and 300 km/s, respectively. The models with metallicities [Fe/H]=0, -1, -2 and -3 are shown from the top to the bottom.

It goes without saying that the knowledge of the internal structure of the stars and an accurate determination of the mass loss history enable us to deduce their evolution and the final fate. In the following we discuss different final evolutionary scenarios depending on the initial stellar mass range.

a) Massive stars, i.e., those evolving through all the stable nuclear burning stages and eventually exploding as core collapse supernovae, play a fundamental role in the evolution of the Universe. Among other things, they synthesize most of the elements during their hydrostatic and explosive burning stages, especially those necessary to life, and therefore contribute significantly to the chemical enrichment of the Universe. After the explosion, they leave compact remnants, neutron stars or black holes, that can be identified through observations. In this context, massive stars became recently very interesting in the framework of multimessenger astronomy. The first (and to date only) two direct detections of gravitational waves (GW150914 and GW151226) have been associated with the merger of two black holes, presumably of stellar origin, with masses ~36-29 $M_{\odot}$ and ~14-7 $M_{\odot}$, respectively. *Which is the evolutionary path leading to the formation of black holes in a similar mass range? How does this evolutionary path depend on the initial stellar parameters, i.e., mass, metallicity, rotation velocity? Which is the expected frequency of black hole binaries and with which mass ratio? Aswering these questions will mean a key step forward for a better–understanding of the gravitational wave sources, for a correct interpretation of the next detections we expect from the ground based instruments (Advanced-LIGO, Advanced-VIRGO) as well as from the next generation of space detectors that will be fully operating in the coming 30 years (eLISA).*

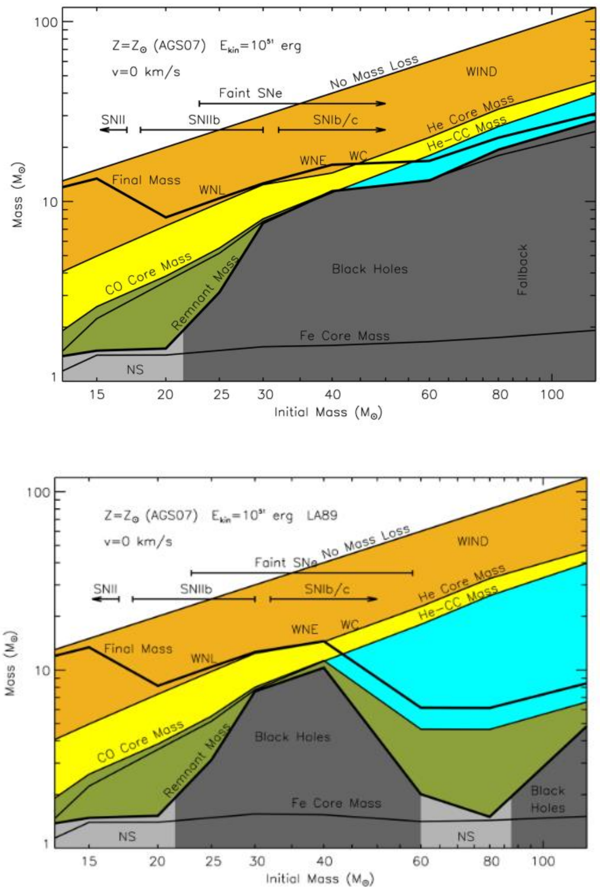


Fig.5.2 - Effect of mass loss during the Wolf-Rayet (WR) phase on the final remnant mass. Left panel: final masses and remnant masses (thick-solid lines) as a function of the initial mass after the explosion for models computed with the mass loss prescription for the WR phase provided by Nugis and Lamers (2000). Right panel: same as left panel but for models computed with the mass loss for the WR phase provided by Langer (1989). Also shown in the figures are the maximum He core, He convective core and CO core masses, the minimum masses that enter the various WR stages, the limiting mass between stars exploding as SNII and SNIb/c, the limiting mass between stars forming neutron stars and black holes after explosion.

In general the remnant mass of a core collapse supernova depends on both the presupernova evolution and the dynamics of the explosion. At present there is no self-consistent, well established model for the core collapse supernovae that is able to obtain the explosion with the typical observed properties, even with the most updated hydrodynamical models and microphysics ingredients. Work is underway by all the theoretical groups to better understand the problem and we may expect progresses in the next future. The presupernova evolution is still largely affected by the well known, longstanding uncertainties of stellar evolution, i.e., all those physical phenomena that require a multidimensional treatment like, e.g., convection and rotation (Figure 1). *A key step forward to an improvement of the predictive power of massive star models will be achieved only when full 3D evolutionary models will be available (see above).* Another ingredient in the stellar models that plays a pivotal role in determining the final remnant mass is the mass loss history (Figure 2). This can be inferred from the study of the interaction between the ejecta released in the stellar explosions and the pre-existing circumstellar material (CSM). During the shell-shell interactions hard radiation (X and UV, detected with instruments on-board of satellites like Swift, XMM, Chandra) is emitted, as well as soft radiation (such radio emission will be detectable up to high redshift once SKA will be operative). *In this framework, it will be of paramount importance to carry out a census and a close monitoring of the final phases of massive stars, the so called hyper-giants which populate the brightest part of the HR diagram.* Most of the massive stars evolve during the so called Luminous Blue Variable (LBV) phase, where they experience strong episodes of dynamical mass ejection. Given the transient nature of this phenomenon, as well as its sporadic occurrence, a continuous monitoring of the sky would certainly greatly push forward our understanding of this mysterious phase. *In this context, we expect that the multiband high performance monitoring capabilities of LSST will allow us to significantly increase the number of confirmed LBV stars. In this way we will have more accurate determinations of the length of the LBV phase, the properties (mainly the location in the HR diagram) of the stars during this unstable stages and the total amount of mass lost, either in total and per eruption. These data will greatly improve our understanding of this phase as well as its impact on the determination of the initial mass-remnant mass relation for massive stars.*

b) The 2-4m class telescope will play a key role in spectrophotometric studies of the new transients in the Local Universe. *In this framework, the new foreseen spectrographs having a medium resolution over a wide spectral range (from UV up to NIR), e.g. SOXS and NTE will provide a relevant contribution.* Such observations, for the brightest events (Galactic or belonging to the Local Group), will also be carried out with the 1.5m class telescopes. Moreover, the study of LBV historical light curves, could be boosted by using archive photographic plates. *It would then be very important the digital scanning of all plates available in the archives of the Italian telescopes, even the smaller ones, and put the digital data on-line and to make available an incremental public database, which collects the light curves and spectra of these extreme stars.* In such a way, we will be able to either keep trace of the evolution with time of these objects, and to create a database to be efficiently used to ingest the data coming from future instrumentations. *Further information could be gathered from the study of circumstellar envelopes around massive stars of the Milky Way and Local Group and, for this aspect, the high spatial resolution of the next generation instruments in the optical (ELT) and in the radio (SKA) will be crucial.*

c) For the low to intermediate mass stars the mass loss also plays a key role for the determination of their final fate. Notably, for stars having at birth M<10 M, most of the H-rich envelope is expelled during the asymptotic branch (AGB), with a mass loss rate ranging from 10^{-7} to 10^{-4} Msun/yr. However, for stars with M<1.5 Msun a relevant part of the H-rich envelope is also lost during the first rise towards the giant branch (RGB). In any case , the final fate of these stars is the formation of a cool white dwarf, usually made of a mixture of C and O (for stars with initial mass M<8M) or a mixture of O and Ne (for stars with initial mass

8<M/Mo<10). It goes without saying that an accurate determination of the mass loss history in during the RGB and AGB phases is crucial in order to obtain a reliable estimate of the initial to final mass relation.

In particular, the Asymptotic Giant Branch (AGB) phase is characterized by the highest rates of mass loss that the low-intermediate mass stars experiment during their life, with consequent chemical enrichment of the interstellar medium in terms of dust and gas. AGB stars play a vital role in many astrophysical environments, ranging from the Universe Local up to the most remote regions of the Universe and study of physical and chemical properties of these stars is fundamental to track the chemical evolution of the Milky Way, to correctly determine the relationship between the initial mass and the final mass of the stars of intermediate mass, for the understanding of the formation mechanisms of the multiple populations in Galactic globular clusters, to analyze the processes of formation of planetary nebulae and pursue their spectroscopic characterization.

The envelope of AGB stars is lost by cold and dense winds, suitable for condensation of gas molecules into dust. Radiation pressure on dust grains triggers the acceleration of the wind, favoring the mass loss in these structures. *However the description of the mechanisms of formation of dust in the winds of AGB stars is critical for the interpretation of the infrared observations of the evolved populations, for example in the Magellanic Clouds and the dwarf galaxies of the Local Group, and for the study of extinction properties of galaxies.*

In INAF there is a long tradition in the modeling of the thermal pulse phase of AGB stars allowing significant progress in the field of theoretical astrophysics research in the international context. Furthermore recent observations at high spatial resolution and high signal-to-noise ratio, obtained using tools such as ALMA and Hershel, have stimulated within INAF a new research aimed at the investigation of the dust formation process in the stellar wind, with the first modeling of this process as based on a self-consistent description of the AGB phase. *This new release of AGB + dust models was tested against the infrared data, taken with the Spitzer Space Telescope, of the evolved stellar populations of the Magellanic Clouds, finding an excellent agreement between theoretical modelling and observations, which allowed a full characterization of the AGB stars in these galaxies. Such a fruitful approach, not only represents a major step in the understanding of the gas and dust pollution from AGB stars, but also demonstrates that these models can be used to characterise evolved stellar populations in different environments.*

These findings are timely with the upcoming instruments such as NIRCam and MIRI on board of the James Webb Space Telescope and the Multi-Adaptive Optics Imaging Camera for Deep Observations for the European Extremely Large Telescope, which will enormously increase the number of galaxies where AGB stars will be resolved and studied. Furthermore, LSST will open important possibilities on still poorly known aspects of the AGB evolution: the pulsation and its impact on the dust formation process.

Key Question	Method	Project
Taking stellar models to the next power	Comparison with astrometric information, and accurate asteroseismic data; Developing of suitable numerical algorithms to implement multidimensional physical phenomena in 1D stellar evolutionary codes based on 3D simulations; Developing of 3D stellar models; Refining dust formation codes through the comparison with observations at high spatial resolution and high signal-to-noise ratio or via observational tools that will enormously increase the numbers of galaxies where AGB stars will be resolved. Developing of hydro-dynamical codes for investigating the impact/efficiency of non-canonical mixing processes; Comparison with updated magnetic fields measurements.	Kepler, Gaia, TESS, PLATO, JWST, ALMA.Hershel, LBT,VLT, SKA, LSST, ELT

6. Relativistic astrophysics and astroparticles

Keywords: *Relativistic compact stars (white dwarfs, neutron stars, quark stars, etc..) - Black holes at all mass scales – GRBs, Fast Radio Bursts, SN explosions, Novae, and other transient phenomena – Cosmic Rays and astroparticles – Gravitational Waves*

Key questions:

- Reveal and study the effects of GR in the strong field limit

- Measure the properties of BHs (mass, spin) and understand how energy is extracted from them

- Physics of accretion and ejection onto/from compact objects

- Study the particle acceleration processes at all different scales

- Search for electromagnetic counterparts of gravitational waves and of neutrino sources

- Use the compact objects and high-energy observations to constrain fundamental laws of nature (e.g. Lorentz Invariance Violation, axion-like particles, dark matter)

6.1 Probing Black holes and compact objects

Black holes (BH) are fully characterized by only three parameters: mass, angular momentum per unit mass (a=J/M) and electric charge. All additional information is lost inside the event horizon, and is therefore not accessible to external observers. Astrophysical BHs are even simpler, since their charge is expected to be zero in all situations of astrophysical interest. Despite much progress in the search for BHs over the last three decades, it is mainly through the mass argument (i.e. a mass larger than the maximum possible NS mass) that sources have been until recently identified as BHs. With the first detection of gravitational waves (GWs) in September 2015 and the identification of their source as a merger of two ~30 Msun black holes, stellar-mass BH existence has been finally proved. Although this unavoidably implies that also event horizons must exist, direct evidence of the latter is still missing. However, direct observations of effects related to the presence of the horizon are expected to be possible in the near future, though limited to the super-massive black hole (SMBH) at the centre of the Milky Way, through mm VLBI observations of the BH shadow (Event Horizon Telescope). The most precise observations performed up to now resolve regions of the size of the Earth orbit at the Galactic centre. An improvement by a factor of ~10 is needed to truly resolve the SMBH horizon. Currently, a few methods to identify the presence of a black hole in a system have been proposed. One of these methods addresses directly the absence of a surface of the compact object. If the accretion flow is radiatively inefficient, as is observed at low accretion rates, in the absence of a surface, energy can be lost inside the horizon, while in case of a neutron star the same energy would be radiated at the surface. This results in a difference in X-ray luminosity at low rates between NS and BH systems, which is observed but difficult to quantify, and in a difference in energy spectrum, hampered by the lack of statistics. Future high sensitivity high-energy observations can be used discriminate between radiatively inefficient flows on BHs and neutron stars. Other methods rely on effects of General Relativity (GR) in the strong-field regime. In particular, the presence of an innermost stable circular orbit around a compact object, whose value depends on the parameters of the object (such as spin and mass) is expected to effectively terminate the radiative accretion flow. This inner radius can be measured in different ways. Detailed modeling of the energy spectrum of an accretion disk, when present, can lead to the determination of its luminosity and therefore of its size. This has been applied to BH binaries, but requires high-sensitivity observations and broad-band

coverage to determine the broad-band spectrum. The analysis of the relativistic deformation of the fluorescent iron Ka line is another way to determine how close to the compact object the accretion flow goes. Detailed observations of red-shifted, broadened and skewed iron line profiles allow one to measure the angular momentum per unit mass, since the inner stable orbit has a radius which depends on a=J/M. For a maximally rotating BH this radius is about six times smaller than for a non-rotating BH. This means that line profiles emitted by matter around a rotating BH are more relativistically distorted because matter feels a stronger field. Furthermore, if the line emission is produced within a relatively small `hot spot' on the accretion disc, then the mass can be estimated, assuming Keplerian disc rotation, by determining the orbital period and the spot location from the line amplitude and energy. Finally, modeling of fast timing features such as quasi-periodic oscillations (QPO), originating in the inner accretion flow, can be connected to GR parameters and yield spin and mass measurements. A few measurements are available, but instruments with a much larger effective area are required to confirm the applicability of the models.
X-ray polarimetry can also be used to probe strong-field GR effects. In AGNs, a rotation with time of the polarization angle of the Compton reflection component (produced with the iron line) is in fact expected and, more generally, a time-dependent polarization angle would be a clear signature of the presence of strong field GR effects. Analogously, a rotation with energy of the polarization angle of the thermal disc component is expected in BH X-ray binaries.

6.2 Binary compact objects

Double Neutron Star Binaries are excellent laboratories for Gravitational Physics. The discovery of PSR1913+16 in 1975 provided the first indirect evidence of gravitational radiation. PSR0737-3039, the first double pulsar, discovered in 2004, is an even better laboratory for high density matter and GR, allowing the determination of all the geometrical parameters of the system and the measurement of five Post Keplerian parameters (parameters that quantify the deviation from Kepler Laws). These results have yielded more extensive tests of GR than those derived in 30 years of observation of PSRJ1913+16. Further improvements of these tests, as well as the measurement of new parameters, have been recently achieved. Continuing to monitor the system will allow us to constantly increase the precision of our measurements and, in particular, to determine the moment of inertia of a NS.
While Double NS binaries are the best tests beds for GR, white dwarf-pulsar binaries in close orbits are the most promising targets for constraining alternative theories of Gravity. PSRJ1738+0333, for instance, currently places the strongest bound on the linear coupling constant $\alpha 02 < 0.5\times10{-}6$ in the strong quadrature coupling regime ($\beta 0 >> 0$), 10 times more constraining than the measurements of the Cassini spacecraft. At smaller values of $\beta 0$, its current limit is only a factor of $\approx$1.7 less constraining than the Cassini limit, and it can improve and surpass the laser Solar System tests in the upcoming years.
The new planned radio surveys will also have the capability of unveiling a putative pulsar orbiting a BH: such a system may probe relativistic gravity with a discriminating power surpassing all other methodologies.

6.3 Gravitational waves from binary compact objects

BH binaries are the ideal laboratory to probe GR in strong, relativistic conditions. By tracking the phase and amplitude of GWs during spiral-in, merging, and ring-down, one can extract extremely precise information about the stress-energy tensor. Binary waveforms depend, on the most general case, on 17 parameters, and high signal-to-noise ratio GW detections can provide measurements with unprecedented accuracy. As an example, binary mass, chirp mass, and reduced mass can be measured to a few parts in 10^5 with space interferometers. Compact binaries (NS-NS, NS-BH and BH-BH), and massive black hole binaries (MBHBs) produce signals in two different GW frequency domains, 1-1000 Hz and mHz, respectively, where space-based and, limited to the former range, ground-based interferometers are sensitive. Coalescing NS-NS, NS-BH and BH-BH binaries are primary sources of high frequency gravitational radiation for ground based interferometers. The cosmic rates at which such events take place are uncertain.

While electromagnetic counterparts of coalescing stellar-size black holes are covered by similar uncertainty (theory envisages possible multi-wavelength transients associated with the relativistic outflows produced after the merger), double neutron star mergers are associated with detectable electromagnetic sources. The GW event of 17 August 2017 was a watershed for multi-messenger astrophysics: the gravitational event, recognized as a merger of compact stars of which at least one is a NS, had a gamma-ray counterpart detected by the Fermi GBM and INTEGRAL and unambiguously identified as a short GRB, an X-ray aftermath that is consistent with radiation from the interaction of the blast wave with the circumstellar medium, and an early optical/infrared counterpart ("kilonova") that bears the spectroscopic signature of r-process nucleosynthesis, i.e. the formation of neutron-rich radioactively unstable atoms. Double compact star mergers were thus proven to be privileged sites of production of 50% of the elements heavier than iron.

Owing to their demonstrated association with compact star mergers, short GRBs offer a way to measure the rate of GWs, alternative to that inferred from relativistic binary pulsars in our Galaxy. However, also in this case significant uncertainties are involved, due for example to the unknown collimation angles, luminosity function and fraction of compact binaries producing a short GRB. The possibility that deformed fast spinning NSs produce long lasting high frequency GW signals detectable with present or next generation ground based interferometers has received a great deal of attention. The two main scenarios involve old NSs in low mass X-ray binaries, which are spun up to millisecond spin periods by accretion torques, and newborn fast spinning magnetars.

If SMBH were common in the past as they are today, and if galaxies merge as implied by hierarchical clustering models of structure formation, then MBHBs must have been formed in large numbers during the cosmic history. GWs from MBHBs in the mass range 10^5-10^7 Msun are among the best targets for space-borne interferometers, while high precision timing over a sample of some tens of millisecond radio pulsars (the so-called Pulsar Timing Array) can make a direct detection of the GW background at nano-Hz frequencies, most likely generated by SMBH in galaxy cores.

Detection of GW from MBHBs is interesting for two reasons: first, it will probe in situ strong gravity in the non-linear relativistic regime; second, GWs can complement electromagnetic observations to investigate the cosmic evolution of structures, such as galaxy interactions and mergers, and the demography of SMBH.

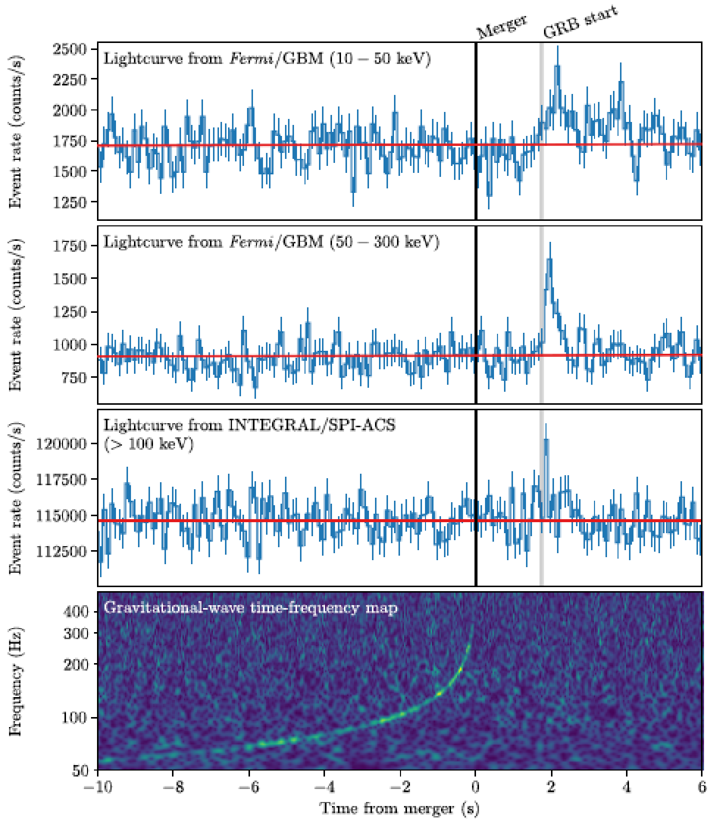


Fig. 6.1 - GW signal from GW170817 and the associated short GRB observed with Fermi/GBM and INTEGRAL. Credits: Abbot et al. 2017, ApJ 848, L13.

Theoretical predictions for the mechanisms of angular momentum loss, driving the evolution of low-mass close binaries (CBs) containing compact objects include magnetic braking, gravitational radiation and, for CVs also mass loss due to Nova explosions. The current observational evidence of their efficiency relies on the measured orbital period distribution only. The detection of GW from CBs with one or two WDs will provide observational support to the theory and will allow the identification of a large and hidden population of degenerate ultra-short period binaries, including WD systems which are thought to be the link to SNIa supernova progenitors.

6.4 Matter under extreme conditions

Neutron stars (NSs) are ideal laboratories to study matter in extreme conditions (density, magnetic field), not reachable in ground-based laboratories. Crucial insights on the equation of state and other properties of matter at nuclear densities can be derived from the following measurements.

If the highest frequency Quasi-Periodic Oscillations (QPOs) in the X-ray flux of accreting NSs corresponds to the frequency of motion of matter close to the star surface, then an upper limit on the NS radius can be inferred, therefore constraining the equation of state. This technique has already been applied to QPO data obtained with RXTE, but its full potential can only be exploited through higher throughput (large collecting area and band extended to higher energies) studies addressing the signal shape, its energy dependence and harmonic content in much greater detail.

Direct information on the redshift at the NS surface can be obtained from faint ion spectral lines originated on the surface itself. Detections of such lines (in particular Fe XXVI, Fe XXV and O VIII) have been reported in the past but again a systematic study awaits a much higher throughput X-ray observatory. Combined with the NS spin period inferred from pulsations and/or burst oscillations, the lines' profile obtained in this way would yield measurements of

the NS mass and radius.
High precision pulsar timing is already providing us with the most precise determinations of the masses of neutron stars. As mentioned above, long term timing of the double pulsar system J0737-3039 will enable a precise measurement of its moment of inertia, and hence of the radius with enough accuracy for ruling out 90% of the proposed equations of state for nuclear matter.
Magnetars are (isolated) NSs which are powered mainly by magnetic energy (they include soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs)). Most of them are transients, implying a total population in the Galaxy much larger than the currently known sample (about 30, including candidates). There are by now different lines of evidence supporting the view that SGRs and AXPs host neutron stars with magnetic field strengths of at least 10e14-10e15 Gauss, including the detection of proton cyclotron lines in the phase-resolved X-ray spectra of these sources. Another evidence would come from phase and energy resolved polarimetry of SGRs that would show both proton cyclotron resonances and vacuum polarization resonances. The extension of the investigation of their very hard X-ray component to higher energies could shed some light on the phenomenology of the magnetosphere in such extreme fields. High throughput instrumentation with good spectral resolution would be ideally suited to reach this goal. SGRs sporadically emit giant flares during which enormous amounts of energy (up to 10e47 ergs) are emitted in the initial sub-second spike. These events likely arise from sudden large-scale rearrangements of the extremely intense magnetic fields of these magnetars, possibly triggered by a major fracturing of the NS crust. An intense giant flare (such as that from SGR 1806-20 in 2004) occurring in a galaxy at tens of Mpc would appear as a short GRB. Therefore giant flares from SGRs might constitute a subclass of short GRB.
The study of isolated NSs (not powered by accretion and therefore offering in principle a much ‘’cleaner’’ environment) is also useful to probe the properties of matter in extreme conditions. The main tool in this respect is provided by X-ray observations of the thermal emission from the star’s surface, which is affected by the internal structure and evolution, as well as by the composition and magnetization of the star’s atmosphere. High resolution, time-resolved spectroscopy over a broad energy range is essential to properly identify lines and other spectral features (that can thus provide a gravitational redshift) and to derive the neutron star radius and surface temperature distribution, while spectrum and phase resolved polarimetry could test vacuum birefringence predicted by Quantum Electrodynamics.
Quantum Chromodynamics predicts that matter in extreme conditions could be in the form of a Quark-Gluon Plasma. It has been speculated that, due to accretion, a NS could temporarily be in this state before collapsing to a BH. The time spent by the star in this state depends on the properties of the Quark-Gluon Plasma. If this transition to Quark-Gluon Plasma occurs, then there should be in Nature NS more compact than could be expected on the basis of any equation of state for ordinary matter. Quark stars of this type would provide an unprecedented test bench for fundamental physics.

6.5 Physics of accretion and ejection

Accretion plays a fundamental role in powering the emission from compact objects at different scales, but the details of the processes through which gravitational energy is converted into radiation are still poorly known. The still widely adopted optically thick and geometrically thin α-disc (“standard Shakura & Sunyaev” model) is likely too simple to describe the complex observed phenomenology, especially at high and very low accretion rates. Much attention is being devoted to the investigation of the transport of angular momentum in accretion discs through magnetic turbulence and magneto-rotational instability. Although analytical studies can still provide invaluable progress, numerical simulations are necessary to quantify the importance of the physical effects generated in the non-linear evolution of these astrophysical scenarios. Near BHs, GR effects are also important. With the numerical tools currently available, it is now possible to move beyond the simple search for stationary or quasi-stationary solutions, while putting some of the original ideas of the pioneering works (such as Shakura-Sunyaev model) on a more quantitative level.

There is wide consensus that the observed hard X-ray emission is due to Comptonization of soft (optical-UV for AGN, soft X-ray for binaries) seed photons by a population of hot (10^9 K) electrons. Modeling the X-ray spectra with a proper Comptonization model provides key information on the system geometry and physical status of the accretion flow (the thermal or non-thermal nature of the population of electrons). In galactic binaries, there is evidence that different processes are at work in different source states and hybrid thermal/non-thermal spectra have been observed. To make a significant advance in this field, a combination of theoretical and observational efforts is needed. More sensitive X-ray measurements, extending up to the energies where the spectra show a cutoff (tens or hundreds of keV), are needed, together with optical/UV and X-ray simultaneous monitoring. On the theoretical side, we stress the need to understand why systems with a stellar mass BH show noticeable differences compared to their bigger counterparts, despite the similarity in the physics of accretion that should be the same for both classes of objects.

The study of accretion onto neutron stars and white dwarfs provides a wealth of information on phenomena related to the presence of a "hard" stellar surface and of a magnetosphere. Such phenomena require an understanding of boundary layer physics, accretion torques, magnetospheric and column accretion, radiative transfer and resonant cyclotron scattering in strong magnetic fields, and unstable thermonuclear burning of freshly accreted material in the star's surface layer. A complete comparison between properties of BH, NS and WD accretion is essential for the understanding of all classes of systems.

An important problem that remains currently unsolved is the observation that, although all galaxies host a SMBH in their central region, most of them do not appear to be currently active. The most striking case is that of our own Galaxy, whose BH at the Galactic Center has luminosity about ten orders of magnitude lower than the Eddington limit for a BH of its mass (i.e. 2.6x10e6 solar masses). Its X-ray emission exhibits two different states. In the quiescent state, weak emission appears to originate in an extended area around the BH, giving evidence for hot accreting gas in the environment of Sgr A*. Sgr A* itself displays X-ray flares which occur about once per day, during which the emission rises by factors up to 100 for several tens of minutes. The short rise-and-decay times of the flares suggests that the radiation must originate in a region within 10 Schwarzschild radii from the BH. Both the quiescent and the flaring states have been modeled in terms of radiatively inefficient accretion predicting a very hard spectrum, peaking around 100 keV. High sensitivity hard X-rays instruments in the 10-100 keV band are required to confirm this hypothesis. There is evidence that the Galactic center BH was much more active a few hundred years ago, based on the X-ray pure reflection spectrum of Sgr B2, a molecular cloud at a projected distance from Sgr A* of about 100 pc. It is then possible that Sgr B2 is echoing a past activity of Sgr A*. A polarimetric measurement would definitely confirm that the illumination is coming from Sgr A* (from the polarization angle), and help estimating the true distance of Sgr B2 (from the degree of polarization) and the epoch when the BH was active.

A common feature of stellar size and supermassive BHs is the ejection of both winds and jets moving at relativistic speed. The presence of jets might be a key element to understand how the central engine works. While magneto-hydrodynamic processes are widely recognized to be involved in the collimation and acceleration of jets, the specific mechanisms of launching and

fueling them are not known in detail. Moreover, we still do not know whether the jets are mainly made of leptons, or by Poynting flux. Advances in the understanding of these phenomena rely on multi-wavelength and polarization observations. The measure of the jet diameter can provide information on the size of the region where the jet is formed and initially accelerated. According to current models, the twisted magnetic field lines are anchored in the inner part of the rotating accretion disk. The last stable orbit then determines the minimum jet width. Present mm-VLBI provides a resolution of 15 gravitational radii, but in the near future the resolution can be significantly improved, thus allowing a direct test of whether BH rotation plays a role in jet formation.
In stellar size BHs, episodes of ejection are clearly associated with particular source states as defined by spectral and time-variability properties; in particular, sharp state transitions, involving marked spectral changes and the appearance of particular features in the fast time variability appear to be correlated with the presence of jets. Therefore, broadband sensitive instrumentation as well as efficient continuous monitoring of the sources are needed. Reaching a full understanding of the accretion/ejection properties in stellar-mass systems will directly connect to the models for AGN, since large-scale correlations have been found linking the two classes of systems, indicating that many properties of accretion and ejection are largely mass-independent.
For accreting NS in binary systems the connection between disk and jet is still very poorly understood. Observations of NS binaries at different luminosities in X-rays and near-IR/radio regimes will be crucial to determine the frequency of the jet break and its evolution.
A few msec pulsar binaries found to transit from disc-state (LMXB state) to rotational powered state (radio state) are now challenging our understanding of accretion/ejection mechanism at the magnetospheric boundary. Particularly intriguing is the recent detection of X-ray msec pulsations interpreted as accretion and optical msec pulsations which cannot be due to accretion. The forthcoming years will see the advent of fast-timing coordinated observations in the X-rays, optical/NIR, radio and gamma-ray regimes that will be crucial to understand the interplay of accretion and ejection processes in moderate magnetic field environments. Observations of low-luminosity accreting msec pulsar binaries, along with their long-term luminosity variability would greatly help in shedding light on the accretion geometry and interaction with the NS magnetic field as well as on the link with the – heretofore few - identified transitional systems. These aspects will benefit from coordinated X-ray, optical/nIR and radio observations with current (XMM-Newton, Parkes, SRT, ALMA, VLT, TNG) and future (eXTP, ATHENA, Meerkat, LSST, SKA, ELT, CTA) facilities.
The recent Fermi-LAT discovery of novae during outburst indicates that novae are a newly discovered class of gamma-ray emitting galactic objects. The ejection of matter during nova explosions and the physics of colliding shocks in both symbiotic and classical novae has still to be understood. Observations since the early phases of nova outburst over a wide energy range including, gamma-rays, X-rays, optical to the radio regime will be crucial to understand particle acceleration processes and the link to mass outflow.

According to unified schemes, the different classes of AGNs can be explained in terms of different viewing angles. Blazars, in which the jet is seen nearly face on, are extremely interesting because they possess a prominent high energy emission: ~60% of all gamma ray sources detected by Fermi/LAT belong to the Blazar class and ~70 Blazars have been detected at TeV energies by Cherenkov telescopes, constituting about 1/3 of all known TeV sources. This clearly indicates that particle acceleration must be taking place in these sources. Details of the spectral and temporal variability depend on the jet composition. As different energy

bands in these variable systems test different emission components and jet scales, simultaneous observations across the whole electromagnetic spectrum (from radio waves to gamma-rays) are of paramount importance and should be pushed toward achieving higher sensitivity and spatial resolution across the spectrum.
Radio Galaxies (RGs) with the jet pointed away from the observer are considered the parent population of blazars. They are much fainter and difficult to detect at high energies because their non-thermal emission is not significantly Doppler-boosted. Indeed the number of observed RGs at high energies is small, about twenty in the 0.1-100 GeV and only five in the TeV band.
Nonetheless, Radio Galaxies are the most suitable class of extragalactic objects to explore the connection between jet and accretion flow. As jets in RGs are less biased by relativistic effects, the observer can have a direct view of the accretion processes. A sudden decrease in the X-ray flux shortly followed by the appearance of a superluminal radio emitting feature and a gamma-ray flare has been observed in at least two radio galaxies. This seems to relate instabilities in the accretion disk to the ejection of matter down the jet.
Finally, the jet misalignment in RGs favors the study of extended regions (lobes), usually overwhelmed by the jet emission in blazars, up to GeV energies, improving our comprehension of the acceleration processes occurring even at kpc distances from the black hole.

Massive outflows at non-relativistic or trans-relativistic speeds are also common. The mass ejection from the most extreme AGNs can be prominent, close to the Eddington accretion rate. The velocities could be as high as 10-30% of the speed of light. These outflows are usually highly ionized and are investigated through both high ionization UV and X-ray lines. The mechanism for the launching of the outflow is largely an open issue, and presumably will require an intensive theoretical effort and some innovative ideas. On the observational side, the most relevant information is still missing: the geometric, kinematics and ionization structure of the flow, needed to determine the rate at which matter is ejected and the associated kinetic energy, cannot be probed in sufficient detail with present instruments. High spectral resolution, high sensitivity instruments are necessary to exploit the diagnostic capabilities of the iron absorption lines in the X-ray band.
AGN winds and jets can propagate in the ISM, ICM and IGM. Because of their large total energy, relativistic jets might play a crucial role in the energy balance of the media through which they propagate. The interaction of these large-scale ejections with the surrounding medium is of crucial importance for groups and clusters of galaxies. In these large, approximately virialized structures, phenomena of strong interactions between radio-galaxy jets and the ICM are clearly observed in the form of bubbles and cavities, as well as in the form of particle acceleration to supra-thermal energies and related emissions.

The powerful natural gamma-ray beam of blazars can be used to measure the intervening astrophysical and cosmological radiation fields (the Extragalactic Background Light, EBL) and even probe the existence of the predicted tiny intergalactic magnetic field. Blazars have been also examined in view of the search for possible sources of ultra-high energy cosmic rays. In a possible scenario, the peculiar hard gamma-ray spectrum of some blazars could flag the re-processing of ultra-high energy photons emitted by UHECR interacting with the background radiation while propagating from the blazar to the Earth. In this case, the detection of photons of energies around 10-20 TeV from sources at $z>0.1$ or even 1 TeV for $z>1$ is expected, enormously enlarging the cosmological "gamma-ray horizon". The same photomeson reactions involved in the production of photons result in the emission of high-energy neutrinos.

Neutrinos could also be produced within the jet. Both FSRQ and BL Lacs have been considered as sources for the recent IceCube detection.
The use of the blazar beams to uncover the spectral footprints of the interaction of high-energy photons with axion-like particles (very light particles predicted in several extensions of the Standard Model) is an exciting possibility actively discussed in the community. Similar effects are expected from the hypothesized breaking of the Lorentz invariance at high-energy, which would allow high-energy photons to acquire an “effective mass”, leading to the suppression of the photon-photon scattering and thus to the free propagation from large cosmological distances.
The forthcoming new generation of Imaging Atmospheric Cherenkov Telescope arrays, like CTA, will have not only the capabilities to expand in sensitivity, redshift, and photon energy the Fermi all-sky investigation, but even perform for the first time an unbiased sky survey over 3 decades higher in energy than was performed by Fermi, hence looking for new unexpected sources and phenomena.

6.6 Fast Radio Bursts

Fast Radio Bursts (FRBs) are enigmatic, short-duration (milliseconds) flashes of radio emission. The dispersion of their signal points towards an extragalactic origin and implies radio luminosities orders of magnitude larger than those of all other known short radio transients. Only very recently one such signal, FRB 121102, the only FRB for which multiple pulses were detected, has been firmly localized in a dwarf galaxy at redshift z=0.2. Another one, FRB 150418, has been tentatively associated with an elliptical galaxy at z =0.5, hosting a faint AGN. FRBs hence appear to be not only extragalactic, but cosmological and, as such, have the potential to be used as probes of the distant Universe. What powers FRBs radio emission remains, however, still undetermined. It is also unclear whether the repeating FRB 121102 is the same sort of signal as the other ones, for which, despite extensive follow-up observations, a single pulse only has been detected. FRBs could very well be the manifestation of different phenomena, as in the case of GRBs.

6.7 Gamma Ray Bursts and luminous supernovae

Gamma Ray Bursts (GRBs) are short (0.1-100 s) bursts of gamma-rays produced during the collapse of a very massive star or during the merger of two collapsed objects. Their cosmological origin could be inferred only after the observations with BeppoSAX in 1997, some 30 years after the discovery of GRBs. If isotropic, the energy emitted in the prompt gamma-ray phase corresponds to a luminosity ~10e54 erg/s, making GRBs the biggest cosmic explosions after the Big Bang.
GRBs are the most extreme special relativistic macroscopic objects in the universe, producing expanding shells of material moving with bulk Lorentz factors of order 100-1000. The related complex phenomenology can be explained in terms of creation of a fireball, due to the enormous initial energetic input and a transformation of the internal energy of this fireball into kinetic energy of expanding plasma. Part of this kinetic energy is later converted into accelerated particles, through mechanisms that are subject of active investigation, and then into radiation, the so-called GRB.
The scenario described above branches into several of the hottest problems of 21st century astrophysics:

- Understanding the GRB itself implies that we understand: the formation of a hot fireball, special and general relativity, particle acceleration processes, relativistic collisionless shocks, jet formation and collimation, particle acceleration, accretion processes, radiation mechanisms.

- GRBs emerge from regions of active star formation in galaxies. GRB being associated with massive stars can be used to investigate the star formation rate, and the initial stellar mass function as a function of redshift. Furthermore, they can be used as “lighthouses” to investigate the ISM of their host galaxies (metal abundances, dynamics, gas ionization, dust content).
- The reionization epoch. Because GRBs are so bright, they are a suitable tool to probe the so-called Dark Age of the Universe.
- The fate of the baryons. GRB can be used as lighthouses to light up the so called “oxygen forest”, thereby allowing us to map the web of dark matter induced filamentary structure of the Universe and possibly find the X-ray signal corresponding to the presence of a warm medium of ordinary matter, that is believed to hide the so-called missing baryons.
- Fundamental physics. GRBs can be used to constrain exotic effects of violation of fundamental symmetries such as the Lorentz invariance, possible consequence of some theories of quantum gravity.

Swift has detected 15 GRBs at z>5, i.e. 1% of all Swift GRBs, with the farthest being at z = 9.2. These can be used to trace star formation, re-ionization and metal enrichment in high redshift galaxies. Furthermore, Swift has dramatically increased the sample of long-duration GRBs that are used to investigate the correlations between observables, which open the possibility to turn GRBs into standard candles employable for precision cosmology.

The energy involved in GRB explosions is huge and it is released in a small region. Therefore, a quasi-thermal equilibrium (at relativistic temperatures) between matter and radiation is reached, with the formation of electron-positron pairs accelerated to relativistic speeds by the high internal pressure. This is a fireball. The presence of even a small amount of baryons makes the fireball opaque to Thomson scattering, so that the internal energy of the plasma is gradually transformed into kinetic energy of the fireball, which therefore accelerates until it reaches a coasting phase. At some point the fireball eventually becomes transparent. If the central engine works intermittently, the expanding fireball can contain inhomogeneities induced by shells moving with slightly different Lorentz factors. The occasional interaction between faster and slower shells is responsible for the formation of internal shocks and is expected to give rise to the observed temporal variability of the GRB emission. The whole fireball also interacts with the surrounding interstellar medium in the host galaxy, thereby snowplowing material and forming the external shock. Particle acceleration at these shocks and the following related radiative processes are seen to be responsible for the GRB and its afterglow emission. Though the general picture is rather well defined, there are numerous aspects of the processes of acceleration and radiation that are considered as hot topics for the theoretical research in the field.
One of the greatest unknowns in GRB science is the nature of the progenitor, though fortunately the general guidelines illustrated above can be discussed without specific assumptions on the nature of the progenitor.
Long GRBs follow the likely highly anisotropic collapse of the stripped core of a star more massive than ~20 Msun and may derive from a relativistic jet/outflow launched either by a rapidly accreting black hole (collapsar) or formed via “magnetic tower” mechanism by a highly magnetized rapidly spinning proto-NS (magnetar). In both cases, the energy budget is dominated by the kinetic energy of the core-collapse supernova (1-5 x 10e52 erg), which is an order of magnitude larger than the collimation-corrected total energy of the GRB (10e51 erg). Short GRB are produced after two compact stellar objects merge into a single BH surrounded by an accreting torus. In all progenitor scenarios, the central engine is a fast spinning compact

star surrounded by a very dense torus. The energy should then be made available in the form of neutrinos, accretion of the material in the torus onto the compact object, rotation of both the torus and compact star and magneto-hydrodynamical processes. Observations of the GRB light curves, spectra and close environments confirm the association of the phenomenon with massive stars. In particular, nearly all low redshift GRB have an unambiguously detected accompanying stripped-envelope supernova, whose explosion epoch is compatible with being simultaneous with the GRB start time. However, the connection between the supernova explosion or compact star merger and the formation of the central engine and development of the GBR fireball remains subject of investigation.

Estimates of the amount of material close to the GRB site and its composition (metals) would shed light on the history of the pre-ejected material and thus on the evolution of the progenitor massive star. Short-lived absorption features and variable column densities would flag the presence of a nearby absorber affected by the burst prompt emission and early afterglow.

Emission features yield information on the kinematics of the ejection, abundances, and location of the reprocessing medium. High resolution, low energy spectra of X-ray afterglows are necessary to extract the relevant information from these features.

One crucial piece of information is the total energy budget of a GRB. Taking into account the collimation angle of the jet, it appears that the energy content of different bursts is universal, ~10e51 erg, so that the efficiency in converting the total energy into high-energy radiation, as well as the fireball baryon loading, should also be universal. In the collapsar scenario, where the fireball has to propagate through the stellar interior, this is unlikely to happen. On the other hand, if the fireball is magnetically dominated, rather than matter dominated, a high degree of polarization of the GRB radiation might arise and polarization measurements at early times could be of crucial importance.

In the internal shock scenario the colliding shells are both relativistic, and after the collision, the merged shell is still relativistic. The liberated energy is a small fraction of the initial one. The efficiency of transformation of bulk kinetic energy into radiation is therefore small. On the other hand, efficient external shocks should produce the afterglow. Thus the afterglow should be more energetic than the prompt emission, contrary to what is currently observed. This paradox has not yet been solved.

Synchrotron radiation appears to be the most likely mechanism powering the afterglow at radio, optical and X-ray frequencies. However, the hardness of the spectrum seems to disagree with the predicted synchrotron-limiting slope. For GRBs at low to moderate redshifts, an extension of the measured afterglow spectra up to 50-100 keV (where the Compton component should dominate) would be crucial to test emission mechanisms. Observations of the early afterglow, expected to be bright at the high energies, have been carried out with Swift, that detected bright early (t<10e4 s) flares, presumably due to prolonged engine activity, and by Fermi-LAT in the MeV-GeV band where only ~5% of GRBs are detected. The MeV-GeV radiation exhibits a monotonic decay, in line with multi-wavelength behavior, and its nature is compatible with synchrotron in an external shock. The present observational frontier is represented by TeV afterglow emission, never so far detected and possibly within the reach of the CTA experiment, at least for GRBs at z <~ 1.

A variety of GRBs with softer spectrum, so called X-ray flashes, first discovered by BeppoSAX, have been studied by Swift that detected numerous members of this class. In two cases at particularly low redshift, accompanying supernovae were detected in the optical, similar in type to those connected with classical GRBs (i.e. stripped-envelope), but of lower energy and luminosity.

Noteworthy, stripped-envelope (i.e. hydrogen and helium poor) core-collapse supernovae with energies significantly larger than the canonical 10e51 erg, although not as energetic as those accompanying GRBs, are now regularly detected by deep, high cadence, wide field optical surveys. They represent ~5% of all stripped-envelope supernovae and are the probable result of an asymmetric collapse; they often emit copiously at X-ray and radio frequencies and are good candidates both for TeV detection with CTA and, if very nearby, GW and MeV neutrino detection. Their observation will give fundamental information on the pre-supernova mass loss and its connection with the initial mass of the progenitor, core-collapse physics, and compact remnant formation. A further important result of the on-going un-targeted surveys is the big number of exotic transients discovered (ranging from the ultra-faint up to the super-luminous ones, including the recently detected superluminous supernovae), whose observed properties are not yet fully studied and theoretical interpretation almost completely missing. The theory runs from electron capture SNe to stellar mergers, for the fainter transients, up to pair instability, shell-shell collisions, magnetars for the SLSNe.

6.8 The origin of Cosmic Rays

During the pioneering experiments of 19th century on electrostatic phenomena, scientists noticed the puzzling phenomenon of discharge of the gold leaves of electroscopes in the absence of external action. This indicated that there was some sort of ionization taking place in the air inside the electroscope, eventually leading to the electric discharge of the system. In 1912, V. Hess performed his pioneering first balloon flights that showed that this ionizing radiation, initially thought to be coming from the Earth surface, was in fact coming from outer space. This mysterious radiation was given the name of Cosmic Rays. Experiments aimed at unveiling the origin of Cosmic Rays proliferated and, while their technical potential improved, people realized that this radiation was in fact made of charged particles (east-west effect), with energies that were higher and higher when measured with better and better experimental setups. It took much time and many experiments before we reached our most recent understanding of this phenomenon: cosmic rays are extremely energetic charged particles, with energy that ranges between 10^6 eV and more than 10^20 eV. At the lowest energies their origin is related to and/or affected by phenomena taking place in the Earth-Sun surroundings. At energies of a hundred billion eV, cosmic rays start being generated in distant sources inside our Galaxy. At these energies their flux at the Earth exceeds ~1 particle per square meter per second. At larger energies, their number decreases rapidly, and at the highest probed energies, ~10^20 eV, the flux corresponds to roughly one particle per square km per century!

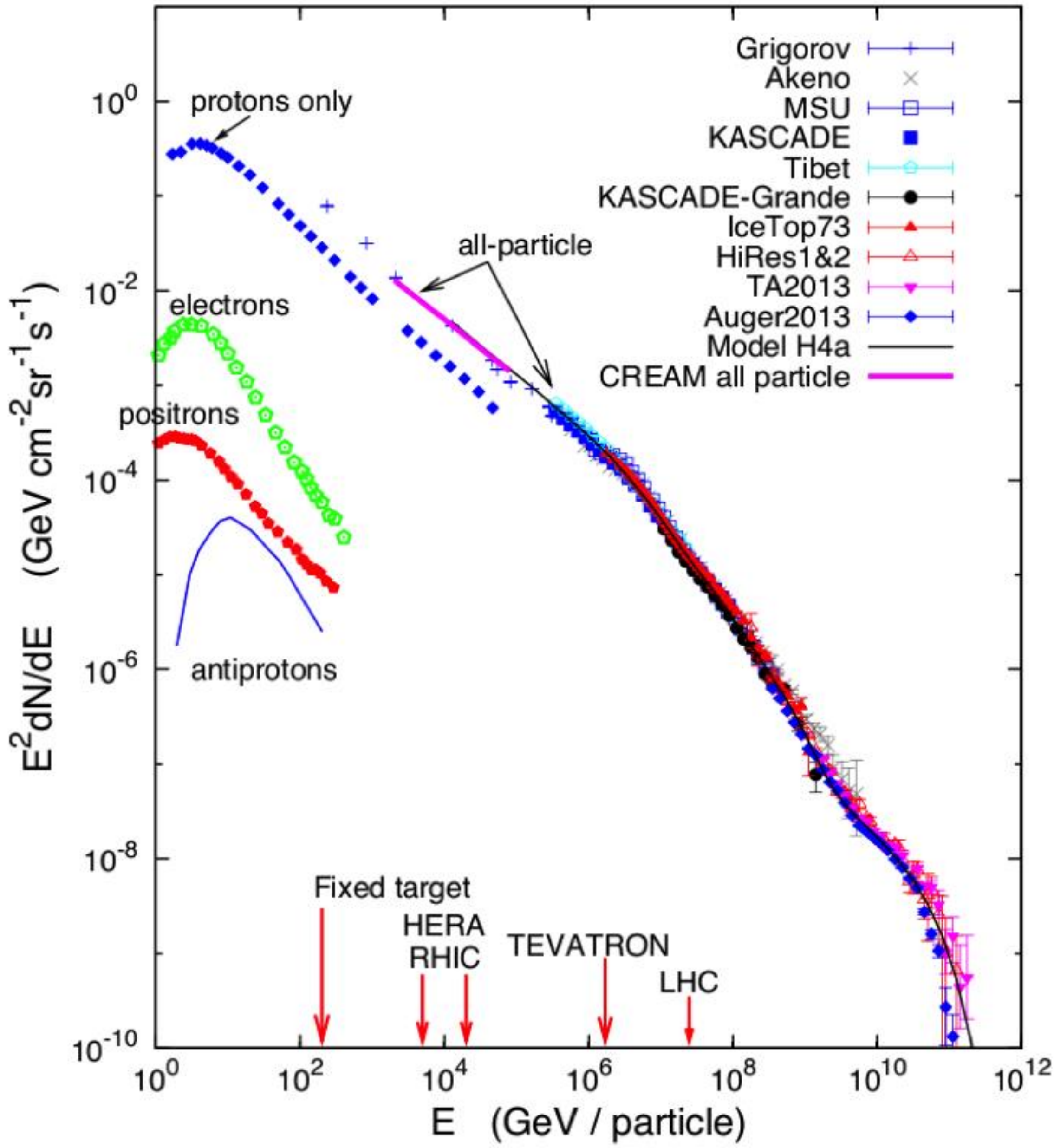


Fig. 6.2 - Energy spectrum of cosmic rays (credits Blasi 2013, A&ARev 21,70).

Such energy is only a few orders of magnitude below that corresponding to the so-called Grand Unification of Forces, where scientists expect that all fundamental forces but gravity unify in a single type of interaction.

The existence of cosmic rays forces us to envision new, quite violent places in the Universe in which Nature manages to transform other forms of energy to extremely energetic sub-nuclear particles, far from being in thermal balance with their surroundings. The investigation of the processes of particle acceleration in astrophysical environments has been mentioned many times in this document, to stress the fact that it is absolutely central to a variety of non-thermal phenomena, from GRBs to AGNs, from clusters of galaxies to supernovae.

As far as the origin of Cosmic Rays is concerned, the association of the bulk of Cosmic Rays with Supernova (SN) Explosions occurring in our Galaxy has been around for a very long time and become a paradigm. These cosmic explosions eject several solar masses of material into the interstellar medium, enriching it with heavy elements, such as iron. The ejected material expands outward from the explosion site at supersonic speeds, forming a shock wave that heats up the gas and, at the same time, energizes a small fraction of particles to large supra-thermal energies: these will eventually become Cosmic Rays. The high-speed material ejected during the SN explosion leads to the development of shell-like nebulae called Supernova Remnants (SNRs), where, on top of thermal material, seen through line-emission, radio, X-ray and gamma-ray observations show the presence of non-thermal particles, that have been accelerated up to multi-TeV energies. The shock wave generated by the SN explosion is thought to be responsible of such acceleration. Determining the physical conditions in its environment is essential to understand particle acceleration in the Galaxy, and is a subject of very active investigation, pursued by all means, from observations in all wavebands to theoretical modeling, both analytical and numerical. Needless to say that these sources will be the primary targets for the upcoming Cherenkov Telescope Array.

The acceleration process that is thought to be at work in SNRs and the main responsible for CR acceleration is called diffusive shock acceleration and consists of repeated crossings of the SNR shock surface. At each crossing the particle gains a small amount of energy and at the same time has a finite probability of escaping the system downstream of the shock. While the basic formulation of this shock acceleration mechanism has been in place since the ‘70s, important progress has come during the last decade from investigation of the dynamical reaction that accelerated particles exert on their accelerator: this reaction reflects in a change of the shock dynamics and thermodynamics and in the amplification of the ambient magnetic field. These phenomena affect in turn the properties of the system as an accelerator, with crucial implications for the particle spectra and the maximum energy that can be achieved. This entire theoretical framework, known as “non-linear theory of particle acceleration at shock fronts”, has provided a powerful tool to interpret the wealth of information that high-energy observations of SNRs have brought about, and has allowed us to readily transform it into improved understanding. The synchrotron X-rays detected by Chandra and XMM from young and nearby SNRs have shown that these objects accelerate electrons up to energies of 1-10 TeV and host magnetic fields as high as a few hundreds of μG. Such high magnetic fields in turn are interpreted as produced by the instabilities induced by accelerated particles. The estimate of the acceleration efficiency that follows is about 10-20%, exactly what is needed for SNRs to be the primary contributors to the Cosmic Ray flux measured at Earth. At the same time such intense magnetic fields, being self-generated by the particles, would be tangled exactly on the appropriate scales to ensure efficient particle scattering, and as a consequence speed up the acceleration process so that very high energy can be reached, up to few PeV for protons and about 30 times higher for iron nuclei.

Of course, the particles that are seen emitting in SNRs in most wavebands are electrons, rather than protons or nuclei, and their maximum energy is limited by radiation losses, which force it to be always much lower than 1 PeV. The best direct diagnostics for protons, which are the main constituents of CRs detected at Earth, comes instead from gamma-rays and neutrinos, the primary outputs of the interaction of energetic hadrons with the interstellar medium. The long sought evidence of gamma-rays from SNRs has finally come thanks to the gamma-ray space telescopes AGILE and Fermi and to the ground based Cherenkov arrays, HESS, MAGIC and VERITAS. Even after gamma-rays are seen, however, the issue of assessing whether they are of hadronic origin or rather the result of Inverse Compton scattering of the synchrotron emitting leptons is not trivial at all. In the case of gamma-rays from SNRs, however, the contemporary operation of all the above mentioned instruments, and the existence of a well-established theoretical framework has been crucial for quick scientific progress, allowing to discriminate the origin of the emission in the different cases. We have found that what looked as the best candidate for hadronic emission at the time of the previous version of this document, RXJ1713-3946, is most likely dominated by leptons in gamma-rays; at the same time, we have indirect but strong evidence that in Tycho protons are being accelerated up to 500 TeV at least; finally, we are fully confident that the gamma-ray emission from the SNRs W44 and IC443 is of hadronic origin. The last two sources are middle aged SNRs interacting with molecular clouds, which provide the ideal target for relativistic protons to produce gamma-rays through neutral pion decay. The main question then becomes whether one is seeing emission from freshly accelerated hadrons or rather by cosmic rays from the galactic pool that are caught by the slow radiative shocks of these remnants and there compressed and reaccelerated. The answer to this question, which is in a way even more subtle than that concerning the leptonic or hadronic origin of the gamma-ray emission, has come, in the case of W44 at least, from a combination of broad band and multi-messenger observations and theory: while most of the gamma-ray emission detected from this remnant by AGILE and Fermi can be explained as due to reaccelerated particles, a fraction of freshly accelerated protons is likely required.

Needless to say that the advent of CTA, together with upcoming and existing neutrino telescopes such as IceCube, ANTARES and Km3Net, is promising to boost considerably our ability at detecting the emission of hadronic CRs directly from their accelerators. At the same time, recent theoretical achievements have finally provided us with a physically correct description of cosmic ray modified shocks propagating in a partially ionized medium, opening up new possibilities of investigating the acceleration of CRs through optical studies: 1) The width of the broad and narrow components of the Balmer line bears information on the energy density in the form of CRs at a supernova shock; 2) The spectrum of CRs accelerated at the shock is sensibly affected by the presence of neutral hydrogen near the shock. Comparison between theory and observations of SNR blast waves, carried out with sufficiently high spatial and spectral resolution, can provide a direct estimate of the shock acceleration efficiency. Such observations can be presently carried out e.g. with the GHaFaS spectrometer, mounted on the William Herschel Telescope in La Palma, or with MUSE on VLT, and will in the future benefit by the GMT (Giant Magellan Telescope) and ELT (Extremely Large Telescope).

On their way from the sources to the Earth, CRs interact with the gas and magnetic field in the interstellar medium, providing a glow of diffuse radio emission, X-ray radiation and gamma rays that we observe from the Earth. The observation of these radiations allows us to achieve a better understanding of the processes involved in the acceleration of CRs and the random wandering that takes CRs from their sources to Earth through diffusion in the magnetic field. During their journey, CRs also ionize part of the medium that they cross, thereby allowing the regulation of the rate of formation of stars in the Galaxy. The ionization of neutral media affects the interplay of gas and magnetic fields, in particular in dense molecular clouds, where most stars form. The gravitational collapse that leads to the formation of stars happens with a rate that is regulated by the strength and structure of magnetic fields and by the gas itself that will end up in the star. CRs are the thermostat of all these complex phenomena. In a way, they contribute to form those stars that will in turn return their energy to CRs after their death. The death of these stars also returns to outer space those heavy elements and in particular those iron

and carbon nuclei that are so fundamental for the development of life.
The interactions of these high-energy bullets hitting the interstellar medium induce spallation of heavy nuclei. This very important process pollutes the Galaxy with light elements such as boron and lithium that are very poor in the primordial soup that emerged from the Big Bang and that can be found in the Galaxy mainly as a result of the presence of CRs and their interactions with the Galaxy. The measurements of the abundances of these elements, referred to as “secondaries” in the following, as well as of the positrons which are by-products of the same interactions, are precious to understand the processes responsible for diffusion in the Galaxy.

Extraordinary progress in this respect has come in the last decade from direct CR detection experiments. The Voyager spacecraft has finally provided us with the spectrum of CRs outside the Sun termination shock, where particles are unaffected by the solar wind and their spectrum is hopefully representative of the galactic average. At the same time, PAMELA and AMS-02 have highlighted unexpected anomalies in the CR spectrum below the ‘knee’ that appeared so far featureless: there are breaks in the spectra of the most abundant species, protons and He nuclei, that are likely to be telling us that non-linear effects are not only important for CR acceleration but also to correctly describe their propagation. A fascinating possibility is that up to few hundred GeV the transport of CRs through the Galaxy is mostly determined by the turbulence they self-induce.
At larger energies, where CRs are too few to efficiently excite waves and simply propagate in the large-scale field that pervades the Galaxy, measurements of the ratio between the flux of secondaries and that of primary CRs (namely nuclei that are directly accelerated in the sources) has an energy dependence that is directly related to the turbulence spectrum. AMS-02 is extending the measurement of this ratio to high energy and with sufficiently high precision so as to allow us to use it as the best available diagnostics of the underlying turbulence. In a similar way, the accurate AMS-02 measurement of the flux of antiprotons and the ratio of their flux to that of protons is being intensively studied to reveal possible discrepancies within the standard view of CR propagation in the Galaxy.

Finally, direct detection experiments (PAMELA, AMS-02, Fermi-LAT) discovered the so called “rise in the positron fraction”, which attracted an enormous interest in the community: the ratio between CR positrons and electrons increases with energy above a few tens of GeV. Such a behavior might be due to some subtleties in CR propagation that we are still missing or to the contribution of some source of positrons in the Galaxy that has been so far neglected. The initial suggestion of a dark matter related origin of the excess positrons has progressively yielded to the idea that the “excess” positrons come from more standard astrophysical sources, pulsars, that are well known factories of leptonic antimatter. Pulsars are highly magnetized fast spinning neutron stars that release most of their rotational energy in the form of a magnetized relativistic wind mostly made of electron-positron pairs, thanks to very effective pair production in the star magnetosphere. The interaction between such a wind and the surrounding medium, either the parent SNR or the ISM, produces a non-thermal nebula, called Pulsar Wind Nebula (PWN).

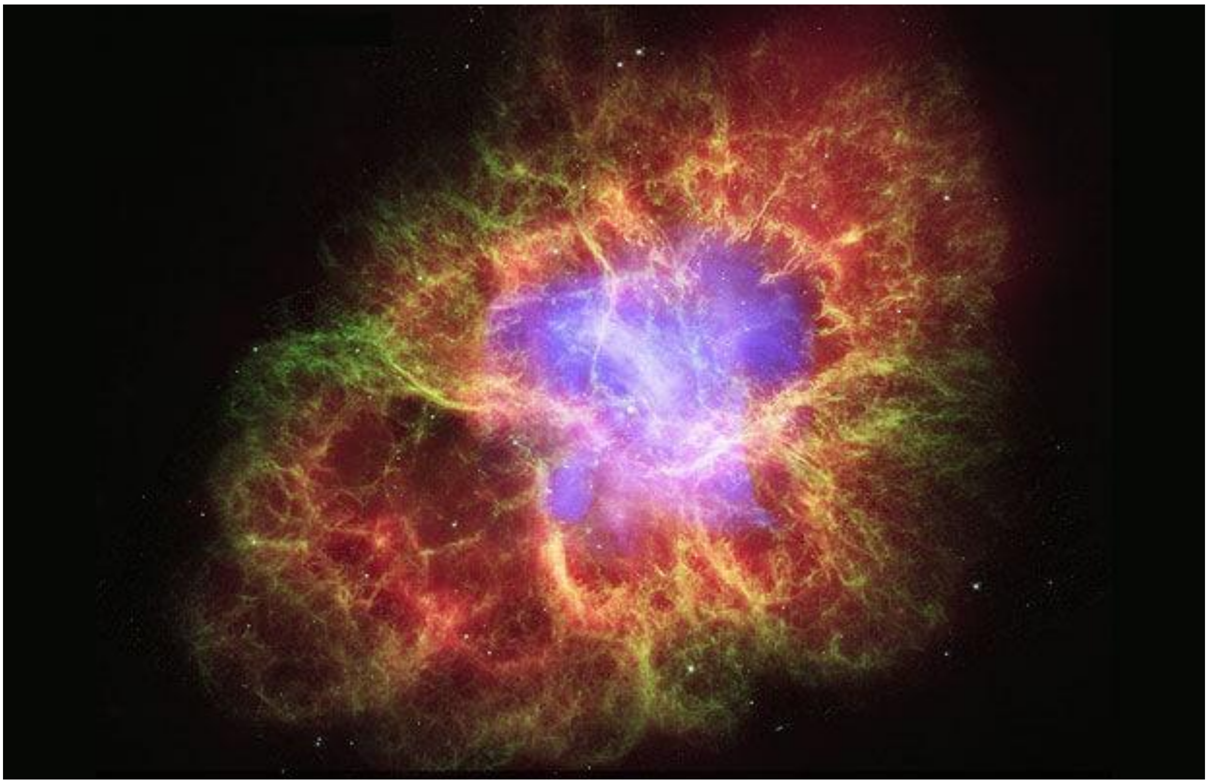


Figure 6.3 - Composite image of the Crab Nebula. X-rays from Chandra in light blue, optical from HST in green and dark blue, infrared from Spitzer Space Telescope in red. Credits: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/ESA/ASU/J.Hester & A.Loll; Infrared: NASA/JPL-Caltech/Univ. Minn./R.Gehrz.

PWNe are sources of central interest for High Energy Astrophysics studies: they host the most relativistic outflows in Nature, with Lorentz factors estimated in the range 10^4-10^8 and are the most efficient particle accelerators known: the class prototype, the Crab Nebula, shows an acceleration efficiency approaching 30% and is the only source from which we have direct evidence of PeV particles, though leptons, rather than hadrons. How such efficient acceleration is achieved is a deep mystery, and a question that is attracting increasing attention from the moment the positron excess was detected with confidence and PWNe entered the realm of CR sources. Understanding the processes of particle acceleration and escape from these sources is a challenging task, which requires coupling of the CR dynamics to the evolution of the PWN-SNR system in the framework of relativistic MHD. Such an effort is however strongly encouraged also by the fact that assessing the pulsar contribution in terms of CR positrons is essential to properly evaluate the possible contribution from Dark Matter related processes.

At energies of roughly 3×10^{15} eV the observed spectrum of CRs shows a feature, known as the knee. The mystery of this feature has been haunting scientists for decades but experiments such as KASCADE (and previous observations carried out with EAS-TOP) have shown that the mass composition appears to change across the knee, becoming heavier at higher energies. This picture is consistent with lighter elements being accelerated to lower energies than heavier elements, namely all elements would be accelerated to the same maximum rigidity (ratio of momentum p to the charge q, R=p/q). On the other hand, recently, other experiments, such as ARGO-YBJ and Tibet Array, have shown that the knee in the light component (protons and helium nuclei) is rather at ~700 TeV, quite below the all-particle knee, thereby raising an issue on what is exactly going on.

This uncertainty also affects our understanding of the so-called transition region between Galactic CRs and extragalactic CRs, also referred to as ultra high energy cosmic rays (UHECRs). In the standard scenario, consistent with KASCADE data and further strengthened by KASCADE-Grande data, Galactic CRs end at energies around a few times 10^{17} eV with a predominantly heavy composition, yielding to UHECRs that enter the game at energies around 10^{18} eV, where the mass composition starts becoming light again, a result confirmed by the two largest CR detectors operating at such high energies, Telescope Array (TA) and the Pierre Auger Observatory. The latter has, so far, collected the highest statistics of UHECR events.

The propagation of UHECRs over cosmological distances opens new questions of unprecedented interest: for protons with sufficiently high energy, the scattering with the photons in the cosmic microwave background gives rise to photopion production (pions appear in the final state). In 1966 two Russian scientists, Zatsepin and Kuzmin and an American scientist, Greisen, predicted independently that this particle physics interaction would cause the appearance of a feature in the spectrum of cosmic rays (the GZK feature), a flux suppression, which became thereafter the Holy Grail of CR physics. For nuclei, the relevant interaction process is photodisintegration: a nucleus of mass A, colliding with photons in the background light (comprised of the fossil radiation of the Big Bang, the CMB, and the light produced by stars and reprocessed by dust) turns into a lighter element. For an iron nucleus the photodisintegration process results in a spectral feature similar to, but not identical, to the GZK. The Auger measurements of the spectrum and mass composition of UHECRs have completely changed our way of looking at this field: these data have shown that a feature resembling the GZK does exist, but at the same time that the mass composition is mixed at energies >10^18 eV. While the mass composition is mainly light at 10^18 eV, it becomes increasingly heavier at higher energies. Theoretical investigation of this surprising situation has led to further surprise in that it has been showed that the injection spectra (at the sources) necessary to reproduce the data are extremely hard, quite unlike the ones typically observed in astrophysical sources, with the possible exception of rapidly rotating pulsars and perhaps a handful of other possibilities. The future of the investigation in this field is bound to be filled with better and possibly complementary measurements of the mass composition and with compelling explanations of the wealth of observations that will become available.
In addition, the results of CR research indicate the importance of magnetic fields on several Mpc scales in galaxy clusters and cosmic filaments. Their evolution is an open problem, and the subject of multi-wavelength investigation (EVLA, ALMA, SKA precursors, Planck, Fermi, LBT and eROSITA).

Key Question	Method	Project
Physics of accretion and ejection onto/from compact objects	Efficient/inefficient accretion modes. Winds and jets. Numerical simulations.	Chandra, XMM, Swift, Nustar, radio and mm telescopes. SKA, Athena, CTA, Ligo-Virgo
Reveal and study the effects of GR in the strong field limit	X-ray timing and spectroscopy	Chandra, XMM, Swift, Nustar Athena
Measure the properties of BHs (mass, spin) and understand how energy is extracted from them	Broad Iron lines. Feedback: Interplay between galaxy and BH	Chandra, XMM, Swift, Nustar Athena
Study the particle acceleration processes at all different scales	Jet structures on sub-parsec-pc scales. Hot spots and radio lobes. Radio relics in clusters. Supernovae remnants. Pulsars, Gamma-ray burst	Chandra, XMM, HST, radio and mm telescopes. SKA, Athena, CTA, IXPE
Search for electromagnetic counterparts of gravitational waves and of neutrino sources	Electromagnetic counterparts of gravitational waves. Gamma-ray bursts. Blazars-Radio galaxies as possible sources of neutrinos.	Ligo-Virgo and all the available telescopes/satellites CTA
Use the compact objects and high-energy observations to constrain fundamental laws of nature (e.g. Lorentz Invariance Violation, axion-like particles, dark matter)	Blazar spectra at TeV energies WIMPs	CTA Athena

7 The Milky Way and the Local Group

Keywords: Stellar Populations - Stellar Clusters - The Interstellar Medium - Formation and Chemical evolution of the Milky Way - Star formation history and chemical evolution of local galaxies – Heavy elements nucleosynthesis - The extragalactic distance ladder

The study of galactic substructures is on the one hand a fundamental task to explore regions of the Universe closer to us and on the other hand a key ingredient to study the formation and evolution of galaxies. In particular, the investigation of the MW implies a complete understanding of the formation and chemo-dynamical evolution of its component populations, including star clusters. While the MW remains our benchmark for the study of the formation and evolution of galaxies, differences might exist among different morphological types of galaxies and one should test to what extent the assumption of the MW as a Rosetta stone is eventually a valid one. An important challenge for next decade astrophysics is the determination of extremely precise stellar distances and the characterization of several physical properties of stars and galaxies; this can be addressed by studying both unresolved and resolved stellar populations, in particular pulsating stars.

The Italian community has a leading role both in the observations and interpretation and modeling. It is essential to maintain and reinforce this leadership in the next decade, by addressing several critical scientific issues that have to be fully resolved.

The key question we need to address is the formation and evolution of the Milky Way (as a Rosetta stone for all galaxies).
This requires studying and understanding:
1) the formation of the sub-galactic structures, in the Milky Way and in the Local Volume
2) the chemo-dynamical evolution of stellar clusters
3) the star formation history in the MW, the Local Group and beyond
4) the resolved and unresolved stellar populations by means of well-behaved tracers.
5) the production of heavy elements via the s-process (traced by massive as well as AGB stars) and the r-process (traced by supernovae and/or neutron star mergers).

7.1 The formation and evolution of sub-galactic structures in the Milky Way and the Local Volume.

Despite the recent advances, there are still many general open questions, such as: Do galaxies form from the merging of primordial building blocks and/or from systems in which star formation was already in place? What is the nature of the different galactic components? What is the relation between disc and bulge/bar? Is the history of star formation a relatively smooth process, or highly episodic in time and clustered in space? How is the metal content spatially distributed in disc galaxies and how does it evolve with time? How does the combination of nucleosynthetic yields, star formation history, stellar mass function, and gas in/outflows result in the complex metallicity and abundance patterns that vary with age and orbit within the Galaxy and its satellites? What is the nature and amount of Dark Matter (DM) in the various Galactic components?
These topics can be addressed with different approaches, one of which is the detailed study of nearby galaxies, starting from our own Galaxy, the Milky Way (MW), that can be used as a "Rosetta stone". The wealth of data that have become available in the recent past have opened a new view on our Galaxy adding more complexity to the overall picture. It is now clear that it

is unlikely that one component of the MW can be separated from another; migration affects thin/ thick disc formation; disc instability might be responsible for the bar formation; bar/bulge/inner halo seem to be connected. In this context, it is important to have a global view of the kinematics, dynamics and chemical evolution of the Galaxy as a whole. This is the goal of the Galactic Archeology.

Reconstructing the complex evolution of galaxy populations implies deriving the 3D spatial distribution and structure, as well as the distributions of kinematics, metallicity/abundances, and ages, i.e., f(Vr, [X/H], t), for large, possibly unbiased samples of stars and clusters belonging to the various sub-galactic structures. For the Galactic populations, thanks to the many astrometric, photometric, and spectroscopic surveys carried out in the last years, those distributions are now much better defined. Astero-seismological data (such as those by the CoRoT and Kepler satellites) contributed to the definition of one of the main property of the stellar components, the age.

In the discs, the availability of elemental abundances for large samples of stars in the MW field and in open clusters has provided a significant contribution to the accurate measurement of both the radial and vertical metallicity and abundance gradients. Also, chemo-kinematics correlations, such as the rotation velocity vs. [Fe/H] or [α/Fe], have clearly showed opposite slopes for the thin disc stars and the more ancient thick disc stars. These findings, combined with the apparent bimodal distribution of the Galactic disc stars in the [α /Fe]-[Fe/H] plane, seem to suggest that the definition of the thick and thin disc stars should rely more on the chemical abundances in place of the former division based on spatial and kinematic properties. Although the observations of the metallicity and abundance trends of different stellar populations are well consistent with an inside-out formation scenario, the actual processes that have determined the star formation history and chemo-dynamical evolution of the Galactic disc is still matter of debate. For instance, the role of the secular effects, such as the radial migration due to non-axisymmetric components (i.e. spiral arms and central bar) with respect to the external perturbations triggered by merging events of satellites is still unclear. This is the reason why, after more than thirty years from the discovery of the Galactic "thick" disc, we still cannot say if this component resulted from a top-down accretion process or from a bottom-up heating mechanism. Furthermore, very recently it has been shown that young clusters located in the inner parts of the disc are significantly more metal-poor than older counterparts, implying a complex combination of star formation, accretion history and inflows, radial gas flow, supernova feedback, etc.

As for the Galactic halo, several authors have shown the presence of a number of stellar over-densities in the outer regions, thus supporting current theories of hierarchical structure formation in a cold dark matter cosmological scenario. The investigation of stellar streams and planar alignments in the Galactic halo is a hot topic, as these substructures are currently interpreted as the signatures of satellite disruption and merging with the Milky Way. However, it is still unclear to which extent the halo was formed by accretion or in situ, and up to now the number of detected streams its at odds with model predictions. A number of INAF researchers are involved in the reconstruction of the original birth groups of stars in the halo in order to gain insight in their formation, using kinematics and chemical tagging. It is crucial to disentangle the components accreted from those formed in-situ in the Halo, to trace back the stars originated in (partially or completely) disrupted globular clusters and accreted satellites, thus estimating their contribution to build up the Halo itself and providing crucial constraints

on the poorly understood issue of the formation of these systems and the challenging evidence of multiple stellar populations in globular clusters.
Similar advancements will be fundamental in our understanding of the formation of the Bulge, its chemical evolution and its substructures (if any). Bulges have long been expected to form either during the initial monolithic collapse of the Galaxy (classical bulge), or through merging of disc clumps at high redshift. This picture has recently undergone a dramatic change. It is now widely believed that our Galaxy hosts a boxy peanut-shaped pseudo-bulge of a secular origin, implying that the formation of the bulge occurred later and most likely out of disc material. However, hints have been advanced that the inner Galaxy is indeed a very complex structure, possibly including several stellar components with different properties, maybe also both a boxy-peanut pseudo-bulge and a classical bulge. All these components have different morphological, kinematical, and chemical properties and might not be obvious to disentangle, but they are fundamental to understand the dynamical processes governing the MW formation and evolution.

Whilst the past years have already witnessed significant progress, the next decade will lead to transformational changes in this area of research thanks to the Gaia space mission, with a significant involvement of the INAF community, and to the growing number of associated ground-based surveys. The combination of astrometry, photometry and precise information from high resolution spectroscopy will allow a full chemical and kinematical characterization of huge samples of MW field and cluster populations. In particular, multi-object spectroscopy is critical to complement and fully exploit the exquisite Gaia dataset, possibly with a telescope dedicated to massive multiplex spectroscopy, a MOS facility on ELT in the more distant future This, by comparison with updated stellar models and in synergy with astero-seismology, will permit to crucially constrain their ages. Precise 6D characterization and properties plus abundances and ages will then be available for millions of stars, down to faint magnitudes and for the entire volume of the MW, providing detailed constraints on chemo-dynamical models of clusters and MW populations. For the exploitation of these extremely accurate data, we also need to develop suitable methodology and to redefine the current Newtonian galactic models in a fully consistent relativistic dynamical context. Due to the unprecedented quality of the Gaia data we expect to use relativistic kinematics and dynamics and define new astrometric parameters, to test non-linear relativistic effects due to our local weak-field sources; this can then be extended to the analysis of extrasolar systems and clusters. The first issue is the understanding of the correct gravity to implement in the new branch of relativistic/gravitational astrometric modeling, developing innovative numerical and analytical tools (see, e.g., the Gaia mission) to properly applying General Relativity to both observational and theoretical astronomy. This goes far beyond the Gaia mission itself and will have important implications also for future space projects. Finally, modeling of stellar structure, stellar atmospheres, and the chemo-dynamical and hydro-dynamical modeling of stellar systems formation and evolution, will certainly profit from the upcoming computational resources and the supporting infrastructure that are being supported presently (ASDC, Trieste, Cineca) in Italy. In all these scientific areas and technology, and in ground and space missions, the INAF contribution is strong and qualified.

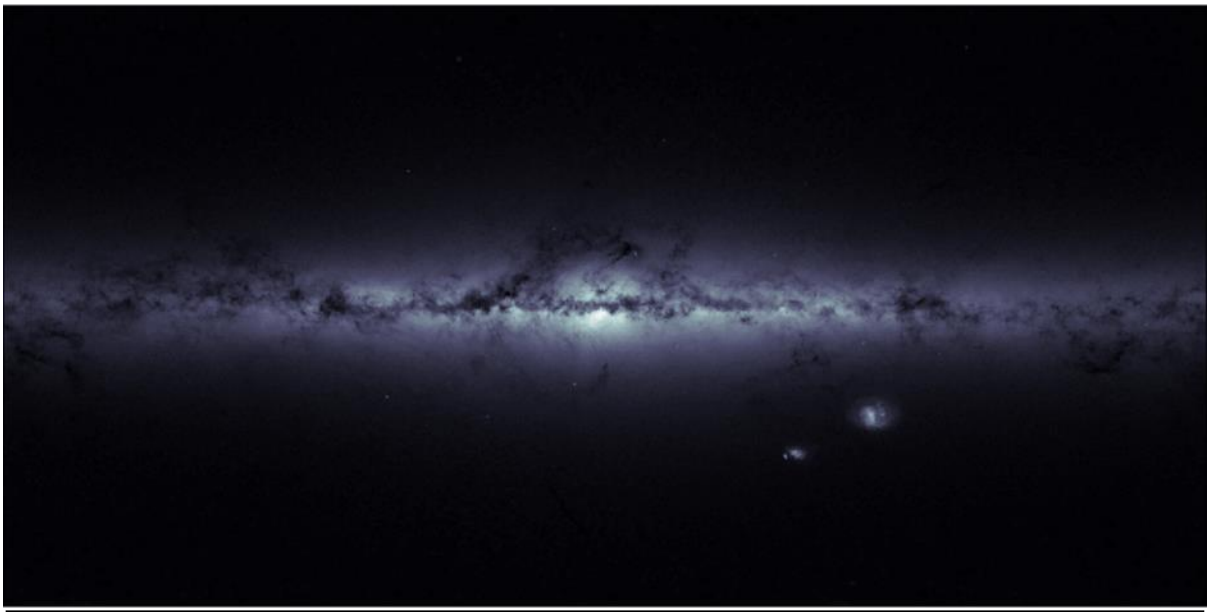


Figure 7.1 - The first map of the sky produced by Gaia (Credits: ESA/Gaia-CC BY-SA 3.0 IGO).

7.2 The chemo-dynamical evolution of star clusters in galaxies.

The physical processes leading to the formation and dissolution of open clusters are crucial elements to understand disc formation and evolution, since the most critical parameters to model the Galaxy formation and evolution, i.e., the initial mass function and the star formation rate are regulated by these processes. Understanding globular clusters formation and chemo-dynamical evolution has strong impact on our understanding of structure formation and early evolution, but also on star and planet formation (see Sect.3), since, the properties of star and planetary systems depend on the star formation environment (see Sect.4).

Open Clusters

Recent developments obtained thanks to the surveys mentioned above have evidenced complex kinematic substructures in young regions and possible age dispersions, which challenge cluster formation models. Indeed, despite their relevance in Galactic and stellar astronomy, several issues of the current paradigm describing formation and subsequent dispersion of the open clusters are still open. We know that clusters form from the gravitational collapse and fragmentation of molecular clouds. However, the role of important physical processes, such as the turbulence, the magnetic field and the stellar feedback is far from clear and much debated. Furthermore, it is not clear if the cluster dissolution is driven by the stellar feedback and regulated by the star formation efficiency or rather dominated by stellar two-body interactions. Gaia exquisite astrometry and photometry are expected to substantially improve our knowledge.

Crucially, towards the end of the next decade open star clusters will also become one of the main tools to link the star formation process and chemo-dynamical evolution in our own Galaxy with those in other galaxies in the Local Group (LG). In particular, the deep photometric and astrometric data from the LSST, coupled with spectroscopy from the ELT, will allow performing detailed studies of young star clusters in nearby galaxies. Thanks to the new instrumentation, it will be possible to reach not only the emission-line populations, but also to perform detailed abundance studies of star clusters ranging a wider interval in ages in galaxies located up to distances of 20 Mpc. This will open new horizons in the study of the radial metallicity distribution, allowing us to extend our view to a larger number of galaxies with a variety of morphology and environment.

Globular clusters

The study of Galactic and extragalactic globular clusters (GCs) has undergone a revolution in the last 20-30 years, due in part by new observational technologies, and guided by INAF researchers. Multiple stellar populations with different chemical composition and photometric properties are now ubiquitous in all properly studied GCs. The chemical species involved are mostly light elements (C, N, O, Mg, Al, Na). The vastly different chemical composition has an impact on the photometric properties of GC stars, that form multiple sequences in color-magnitude diagrams. These discoveries required a deep rethinking of GC formation and evolution, and of their role as simple stellar populations. The understanding of how stellar clusters form and evolve remains a complicated task and new scenarios for their formation were devised, that need to be explored and that open up the question on the impact that clusters (or their progenitors) had in the formation and evolution of the Galaxy halo, or more in general of the Milky Way. The production sites of the chemical abundance variations were identified in the CNO hydrogen burning that takes place either in the cores of massive stars or the shells in AGB stars; however, we still cannot build a self-consistent model describing how the CNO products can be transferred and re-used from one population to the other within the GCs. For example, according to current scenarios, it is necessary to assume that GCs were extremely more massive initially, and then lost most of their mass, preferentially of the first generation stars, i.e., those with a composition similar to that of the Galactic halo. This hypothesis seems to clash with the size ratio of GC and halo populations in dwarf galaxies like Fornax. Ultimately, the fact that GCs show chemical variations while neither open clusters (which are younger and more metal-rich) nor dwarf galaxies (which are more massive and complex) show any trace of them, puts our comprehension of how stellar systems form in doubt, and in turn this puts in doubt our comprehension of how galaxies form and evolve. It is necessary to assume that the initial conditions in which GCs formed were significantly different from those that we observe today, a not unrealistic assumption, and keep in mind that those environments could be the primordial building blocks that gave origin to the halo of the MW and the other galaxies that we observe today.

Also in this case the answer to these questions can only come from the large projects that are currently underway from the ground and from space. Gaia will help in deriving accurate orbits (and therefore the GC provenance) and the internal kinematics (and therefore the characterization of multiple populations) of GCs in the Milky Way and in the Local Group. The ongoing ground-based spectroscopic projects of INAF researchers, the large scale surveys like Gaia-ESO, WEAVE and MOONS, the photometric studies using abundance variation-sensitive filters (e.g. the ultraviolet) will provide a complete chemical and astrophysical characterization of the multiple populations, with samples 10 or 100 times larger than the ones available now, and more precise and accurate measurements. All this will help in pinning down the GC properties that allow for the presence of multiple populations.

7.3 The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond.

The LG and nearby group galaxies offer the possibility to investigate the composition of populations of different ages in galaxies other than the MW.

There are a number of open issues that make the study of the SFH and properties of different galaxies a challenging topic. In particular: - Is there a low luminosity threshold for galaxy

formation? Is there any evidence of accretion/interactions of resolved star forming (dwarf) galaxies? Is the census of small satellites consistent with CDM predictions on galactic scales? Is the spatial distribution of dSphs (planar vs spherical) consistent with CDM? Can we test different DM models with 3D resolved velocities? Do sub-Gyr age measurements reveal any cosmologically-driven synchronization in the SFHs?
To face these open issues large surveys of Galactic and extragalactic resolved stellar populations are mandatory. For the first time in history, ongoing and planned photometric and spectroscopic surveys using existing or upcoming facilities and space missions are - and will be - allowing us to collect a large enough amount of data of sufficient quality to lead to a statistically significant mapping of composition, kinematics and SFH of large number of stars in all Galactic components and in the LG and beyond. This unprecedented flow of optical, ultraviolet and infra-red spectro-photometric data, made of proprietary data and planned public archives, combined with the latest generation of detailed chemo-dynamical models will allow us to shed light on the formation of the LG galaxies, including the spiral galaxy Andromeda, dwarfs spheroidals and dwarf irregulars, and the newly discovered ultra-faint dwarf galaxies, that have been hypothesized to represent the building blocks of the Galactic and M31 halo. Ellipticals and blue compact dwarfs (i.e. the most and the least evolved ones) are not present in the LG and we need to extend the study well beyond it. These studies require accurate photometry over a long wavelength baseline. In this respect the synergy between ELT, HST, JWST will be very important: the exceptional resolution will open to the exploration of the very crowded inaccessible portions of galaxies, enabling detailed studies of the SFH in those regions where most of the action takes place. In the next decade a large aperture, optical near-IR space telescope, with a large field of view and spectroscopic and photometric capabilities, appears as the key capability for ambitious Galactic and LG surveys. Such an instrument would provide precision velocities and abundances for millions of targets beyond reach of present-day telescopes and/or distributed over very large areas, allowing us a complete overview of the SFH and chemo-dynamical evolution of the Galactic populations and the MW nearest satellites.

7.4 The role of pulsating stars and Surface Brightness Fluctuations as tracers of resolved and unresolved stellar populations.

An important challenge for next decade astrophysics is the determination of distances with a precision better than 5% from the Local Group to about 200 Mpc as the crucial ingredient not only to constrain the Universe geometry (see Sect. 9) but also to characterize several physical properties of stars and galaxies (including dynamical time scales, masses, ages, linear sizes etc…).
As well know, in the Milky Way (MW) and in photometrically resolved galaxies, the study of the different types of hosted pulsating stars (in different evolutionary phases) allows us to trace the intrinsic properties (age and chemical composition) and, through individual distance estimates, the spatial distribution of the associated stellar populations. This approach also permits to point out the possible presence of radial trends, haloes and/or streams, and in turn to reconstruct the star formation history of the investigated galaxy and to obtain information on galactic formation and evolution mechanisms.
In this context the Gaia mission, with a significant participation of INAF researchers, will be a milestone. Through a multi-epoch monitoring of the full sky, Gaia will get the position, the parallax, the proper motion and the time series photometry of thousands of pulsating stars in the MW and its surroundings, down to a faint magnitude limit of G $\sim$ 20.7 mag. In particular, Gaia's complete census of the Galactic Cepheids and RR Lyrae will allow a breakthrough in our understanding of the MW structure by tracing variable stars of various ages in the Galactic

bulge, disc, halo, likely revealing new streams and faint satellites as the signatures of the MW hierarchical build-up. The picture of the MW provided by Gaia will represent an unprecedented benchmark for testing current theories of galactic formation and evolution.
The INAF researchers that have already a leading role in the fields of stellar evolution and pulsation theories will be able to compare their model predictions with Gaia measurements, thus allowing a crucial step forward in our knowledge of stellar physics. An increasing involvement of the INAF scientific community is foreseen with the aim of optimizing the scientific exploitation of Gaia data.
In the next future the participation of a number of INAF researchers to the LSST mission will extend the same level of accuracy reached in the Milky Way with Gaia to Local Group (LG) galaxies and beyond. Indeed, the distance measurements provided by LSST (that extend Gaia capabilities to a five magnitudes fainter) for Cepheids and RR Lyrae, will allow us: i) to constrain to an unprecedented level of accuracy the relations that make these stars primary distance indicators; ii) to derive the 3D structure of the investigated systems; iii) to constrain the physical and numerical assumptions of pulsation models.
Finally, using JWST and subsequently ELT (with spatial resolution similar to the one of the Hubble Space Telescope) it will be possible to extend Classical Cepheid observations up to the crowded fields of the Coma cluster and RR Lyrae observations in elliptical and giant spiral galaxies up to 6 Mpc.
The study of extra-galactic non resolved stellar populations can largely benefit from the use of the SBF method, especially in view of the forthcoming wide and deep optical and near-IR imaging surveys.
The study of extra-galactic stellar populations, based on integrated colors and magnitudes, is hampered by the well-known age-metallicity degeneracy, namely: a change in age for a factor of three can mimic a metallicity change for a factor of two. Hence spectroscopy is essential for providing robust constraints to the physical properties of unresolved stellar systems.
However, the analysis of SBF gradients, and SBF colors, has shown that accurate constraints to the luminosity-weighted dominant stellar population can be provided for early-type galaxies. The great advance of the proposed tool, with respect to, for example, spectroscopic studies, is that the data needed for the analysis of SBF colors and SBF gradients will come "for free" from the planned, or ongoing, imaging surveys, without the need of any extra observing time than the time already allocated in the survey. Hence, at least for morphologically nearly-undisturbed, early-type galaxy, very accurate local and global stellar population properties, with an accuracy of ~0.2 dex in [Fe/H], will be at the reach for galaxies with high enough signal to noise ratio for SBF measurement to be possible.

7.5 The nucleosynthesis of heavy elements in the Milky Way

The kilonova SSS17a observed after a few days since the gravitational waves detection of GW170817 has been connected to the decay of a few 10-3 MSUN of heavy radioactive nuclei produced by the rapid neutron capture process (the r-process) taking place within the ejecta of the previous binary neutron star merger. This fact renewed and magnified the interest of the scientific community in the nucleosynthesis of the heavy elements.
It is well known that the vast majority of isotopes heavier than iron are produced through neutron captures. Half of the heavy elements are produced by the slow neutron capture process (s-process), which takes place in the He-rich mantle of Asymptotic Giant Branch (AGB) stars undergoing recursive thermal pulses and during the core He-burning and C-shell burning phases of massive stars evolution. The other half comes from the r-process, for which a growing amount of evidences indicates as most probable site the merging of small compact objects,

such as two binary neutron stars or a neutron star and a black hole, without ignoring the possible (important) contribution from Supernovae explosions. While the s-process is characterized by rather low neutron densities and proceeds along the so-called β-stability valley, the r-process is at work in a more extreme environment, with a sudden (Δt<1 sec) release of an enormous amount of neutrons (larger than 1023 cm-3). As a consequence, the fingerprints from those processes are easily identified in the stellar abundances, thanks to the ratio between elements mostly produced by one process or another (e.g. barium for the s-process and europium for the r-process). In the past years, INAF staff largely contributed on this subject from both an observational and theoretical point of view.

For instance, the Gaia-ESO high-resolution spectra obtained with UVES allowed the determination of abundances of a large variety of elements including many neutron-capture elements: five s-process dominated elements (Y, Zr, Ba, La, Ce), one r-process dominated element (Eu), and three elements with significant contributions from both processes (Mo, Pr and Nd). Taking advantage of the large and homogeneous sample of stellar parameters and elemental abundances of Gaia-ESO, it is thus possible to study the evolution of the abundances of the neutron-capture elements in different Galactic component.

Large ongoing spectroscopic surveys such as APOGEE and GALAH will at their completion deliver the abundances for several elements, among which neutron capture ones, for up to 1 million starts. An even more detailed chemical characterization, including n-capture elements, for a sample of 2.5M stars in the Galactic halo and disk(s) will be delivered by WEAVE, a planned survey (starting in Fall 2019) in which INAF is a founding partner. INAF staff have already studied the neutron capture enrichment in the galactic halo, but these models have to be coupled with powerful statistical tools in order to answer key questions on the production of neutron capture elements and r-process events. In particular, it has to be established whether the NSMs are the sole responsible of the chemical enrichment in our Nearby Universe (or other actors are playing a role). Moreover, the rate and timescale of r-process event(s) necessary to explain the enrichment in the Galactic halo have to be constrained.

From the stellar modelling point of view, the contribution from INAF people to the s-process nucleosynthesis is worldwide recognized, as testified by the many papers on the subject and by the FRUITY web repository, currently the only database in the world entirely dedicated to the nucleosynthesis of AGB stars. Moreover, the contribution from massive stars to the weak component of the s-process has also been carefully determined by INAF researchers. The detailed understanding of s-process nucleosynthesis is fundamental to derive the r-process contribution to the solar inventory, since our current theoretical knowledge of the r-process is far from being complete (as a matter of fact the r percentage is calculated as r=1-s). Therefore, any study related to the s-process is of interest for the r-process nucleosynthesis. Notwithstanding, a detailed understanding of the r-process is mandatory. In the future, INAF could make strides in the theory of the r-process taking advantage of the scientific profiles already structured in its staff as well as developing synergies with other research institutes (in particular with the INFN, not only on the gravitational wave side, but also on neutron capture and nuclear fission measurements, which strongly shape the resulting heavy elements distributions).

7.6 What do we need?

In the last years INAF researchers have had key roles and impact results in this research field. INAF strength originates from the scientific expertise of the researchers, as well as from the development, participation, and scientific exploitation of ambitious observational programs. In particular, the involvement of the INAF community in the Gaia mission is significant, as is the participation in the Gaia-ESO Survey, currently the largest stellar survey performed on a 8m class telescope, and in WEAVE and MOONS (and Euclid, PLATO, THEIA) preparation and science case definition.

In order to maintain those key roles and scientific excellence, it is necessary to:
• form, in synergy with Universities, a new generation of researchers with expertise in stellar spectroscopy, astrometry, chemo-dynamical modeling, astero-seismology, analysis of large databases and data mining;
• strengthen and fund INAF participation in big projects/surveys and international collaborations, and open new ones;
• support the involvement (both technological and scientific) in activities dedicated to the development of new instrumentation for [massive] multiplex spectroscopy ;
• dedicate support and funds to the development of theoretical tools, data mining and, in general methods and tools for the scientific exploitation of the wealth of information from ongoing and future instrumentation/surveys;
• foster collaborations and synergies both within MA2 (e.g., with the star formation community) and with MA1 (and MA5). In this regard, it is desirable, within each of the INAF MAs, the birth of working groups on multi-disciplinary / cross-cutting themes for establishing synergies wherever possible.

Key Question	Method	Project
Formation and evolution of sub-galactic structures in the Milky Way and the Local Volume	Detailed study of our Galaxy and nearby galaxies, mapping 3D spatial distribution and structure, kinematics, metallicity, abundances, and ages. Theoretical modelling. General relativity.	Gaia, Gaia-ESO, APOGEE1/2, GALAH WEAVE, MOONS 4MOST, ELT, Pan-STARRS, LSST, Kepler, Euclid, THEIA, HST, JWST, WFIRST, HPC
The chemo-dynamical evolution of star clusters in galaxies	Large, unbiased samples of clusters (open, globular) and of their population studied with accurate, precise photometry, astrometry, spectroscopy. Models of cluster formation, evolution, dissolution.	Gaia, Gaia-ESO, WEAVE, MOONS, 4MOST, GIARPS, CRIRES+, ESPRESSO, ELT (HIRES & MOS), HPC, Pan-STARRS, LSST
The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond.	Use large scale galactic and extragalactic surveys (photometric, astrometric, spectroscopic) to map structure, composition, kinematics and star formation history in MW and LG galaxies. Test galaxy formation mechanisms in CDM models.	OGLE, J-PAS, Pan-STARRS, Gaia, WEAVE, LBT, VISTA, VST, ALMA, LSST, Euclid, HST, JWST, DESI, WFIRST, Euclid, ELT
The production of heavy elements via the s-process and the r-process	Multi-epoch, all-sky monitoring of resolved variables (MW different components, external galaxies) to derive 3d structure and constrain pulsation models. Study unresolved populations using photometric surveys.	Gaia, LSST, JWST, MICADO@ELT, Euclid
The role of pulsating stars and Surface Brightness Fluctuations as tracers of resolved and unresolved stellar populations	Multi-epoch, all-sky monitoring of resolved variables (MW different components, external galaxies) to derive 3d structure and constrain pulsation models. Study unresolved populations using photometric surveys.	Gaia, LSST, JWST, MICADO@ELT, Euclid

8. Formation and Evolution of Galaxies and Cosmic Structures

Keywords: Galaxies and AGN, Clusters of Galaxies, IGM and reionization

Key Question:

What are the physical processes driving the assembly and the evolution of structures on scales of galaxies up to clusters of galaxies?

- **Properties of first galaxies and black holes. Sources responsible for the reionization(s)**
- **Origin and fate of galaxies, the galaxy stellar mass function and morphological differentiation.**
- **Feedback processes among the different components of galaxies (stars, gas, dust) and AGN. Role of DM halos.**
- **External and internal mechanisms (environment and relationship with the Cosmic Web) regulating the efficiency of star formation and the structural parameters of galaxies.**
- **Census and distribution of mass/energy in large-scale structures (hot baryons, AGN-ICM connection, turbulence, non-thermal phenomena and their relationship with the thermal phenomena mapped in X-ray and with the Sunyaev-Zeldovich effect).**

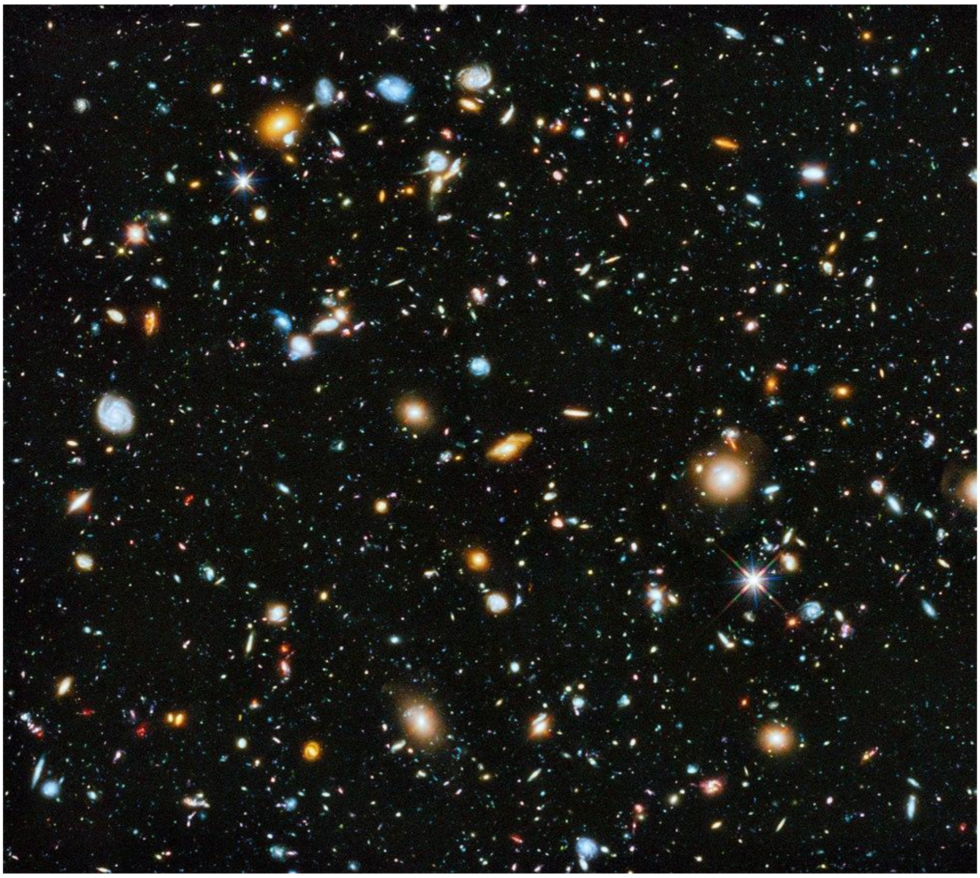


Fig.8.1 – The Ultra-Deep Field (HUDF) imaged by the Hubble Space Telescope records the light (from the ultraviolet to near-infrared) of distant galaxies down to the faintest limits reached by an optical telescope.

Dark energy, dark matter, and baryons are the basic components of the currently accepted cosmological scenario (see Chap. 9). The structures populating the Universe are the result of the growth of fluctuations of the primordial density distribution: while the backbone of the large scale structure of the Universe is determined by its cosmological parameters and by the gravitational interaction of the dominant dark matter, **the assembly and the evolution of structures on scales of galaxies and up to cluster of galaxies** are mainly **driven and strongly affected by the complex physics of baryons**. The challenge of the next decade will be **understanding these processes through the comparison of multi-wavelength observations with theoretical models and simulations**.

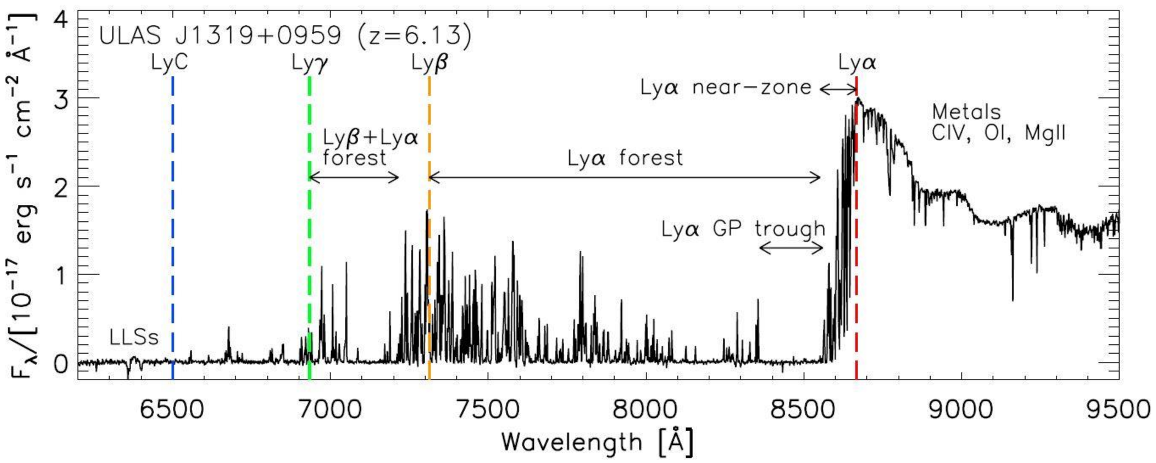


Fig.8.2 - A high signal-to-noise spectrum of the quasar ULAS J1319+0959 at z = 6.13 obtained with the X-Shooter spectrograph on the Very Large Telescope (VLT). The Lyα forest traces diffuse hydrogen in the IGM, which becomes almost completely opaque by z ~ 6. Metal absorption lines, which trace the chemically enriched gas around galaxies, can be seen redward of the Lyα emission peak.

8.1 The Epoch of Reionization

The epoch of reionization (EoR) represents a crucial turning point in cosmic history: in less than a billion year after the big bang the radiation produced by the first luminous objects ionized nearly every hydrogen atom in the diffuse intergalactic medium. Understanding reionization still lies at the very frontier of our current cosmological observations and represents one of the major goals of the next decade for several reasons: it is the last major global phase transition in the Universe and determining when it occurred, as well as the physical processes involved and the nature of the sources of ionizing radiation, gives unique insight into the formation of the first galaxies and black holes, many of which are too faint to observe directly. Besides, understanding reionization is instrumental for fully exploiting the CMB and the IGM as cosmological probes.

When and how did reionization occur? CMB measurements of the optical depth for Thomson scattering locate the EoR at an approximate redshift z~7.5, while Ly-α emitter surveys and absorption spectra of z≥6 quasars, providing information about the opacity/neutral fraction of the IGM, quickly increasing with redshift, and its thermal history, show that the reionization was substantially completed by z~6. Constraints on the timing remain broad and it is not yet clear that the constraints are mutually consistent. A convenient probe to study the EoR has been identified in the redshifted 21cm signal due to the interaction between the CMB and the diffuse neutral hydrogen, detected with radio interferometers. The next decade will be crucial for the development of this field of research: the first statistical measurements will be obtained, paving the way for the 21cm tomography enabled by the next generation radio interferometers [SKA]. Independent and complementary constraints on the amount of neutral hydrogen present at EoR will be obtained with: (i) surveys of z>6 Ly-α emitters: sub-mm observations (e.g. of the [CII]λ158μm line, ALMA) allow us to determine redshifts (in the absence of Ly-α), dust, SFR and ionization properties simultaneously; space and ground-based NIR observations will provide the ability to confirm increasingly fainter star forming galaxies, by accessing alternative redshift indicators such as the nebular emission lines ([CIII], HeII, etc.) [JWST, ELT]; (ii) spectroscopic observations of quasars at z≥6: several dedicated surveys are going on or planned to discover bright quasars at z≥6 [Euclid, WFIRST]; VIS-NIR spectroscopic observations will put constraints on the amount of neutral hydrogen and, at the same time, detect the imprint of the chemical elements formed by the first objects. The current studies now constrain the timing of reionization with precision comparable to Planck, providing a fully independent check on the CMB results; they are however limited by the small number of high-redshift QSOs that can be studied at high resolution (R ≥40.000). A high-resolution optical-NIR spectrograph on an ELT would give access to hundreds of QSOs delivering robust constraints.

Which sources caused reionization? Although it is widely accepted that the production of ionizing radiation is likely due to star formation and/or nuclear activity, the global contribution of each of these objects to the ionizing background is still largely debated. While the census of star-forming galaxies at z>6 and up to redshift 11 represents the current frontier, the search for the sources that reionized the universe requires deep characterization of: (i) the nature of the stellar populations (and/or nuclear activity) and the gas and dust content of the first objects; (ii) the physical mechanisms that allow the ionizing radiation to escape the natal galaxies and reach the intergalactic medium: this is related to feedback processes, eventually connected to the metal pollution of the intergalactic space; (iii) low-luminosity/mass domains within the first Gyr, at the level of star-cluster formation, to probe the first episodes of star-formation. These three issues will be addressed in the next years by peering near and mid-infrared wavelengths (1-30μm) with spectrographs and imagers [JWST, Euclid, WFIRST, ELT, VLT].

How, when and where did the first SMBHs form? The existence of luminous QSOs at z>7, i.e. when the Universe was less than 1 Gyr old, represents a persistent challenge for extragalactic astrophysics. What is the origin of the seeds that later became SMBHs? How accretion could be that efficient? What were the environmental conditions that made their growth possible? What is the nature of the faint AGNs that are still unobserved? The best way to tackle these key questions in the forthcoming decade will be i) exploiting deep X-ray observations [Chandra and XMM] of high-z QSOs to reveal the physics of accretion of early SMBHs and whether their fueling occurs in dense environments populated by other, smaller and possibly obscured, companion BHs and ii) carrying out wide and deep surveys in the IR (complemented at other wavelengths) and deep X-ray blank sky fields to discover the typical population of accreting BHs at z>7 iii) The expertise accumulated with these efforts will be the key to exploit at best the wide-and-deep X-ray surveys that will be performed and will bring a major breakthrough in this area [Athena].

8.2 The origin and evolution of galaxies

The origin and evolution of galaxies is one of the most intriguing and complex chapters in the formation of cosmic structures. Understanding galaxy evolution requires knowledge about how galaxy properties depend on environment and cosmic time. Many physical processes may shape galaxies: The (atomic and molecular) gas, being the raw fuel for the formation of stars, plays a dominant role in the growth of galaxies and, at the same time, is enriched by stellar products redistributed in the galactic halo by feedback mechanisms. AGN activity is partly regulating, and partly being regulated by star formation. Stellar mass and environment, and possibly other factors, govern the processes that lead to the quenching of star formation and to the emergence of the passively evolving sequence. Moreover, galaxy assembly is certainly connected to dark matter growth. In short, galaxies are complex systems living in dynamical environments.

In this context, the basic key question is: **which physical processes drive the transformation of galaxy properties?** Astronomers can hint at the answer(s) by observing the properties of nearby galaxies in great details, and at the same time looking at the distant Universe to examine the properties of galaxies at different epochs in the past. To ultimately understand the physics of galaxy formation and evolution, a continuous comparison and feedback between the empirical picture derived from observations and theoretical models is needed.

The basic question mentioned above can be broken up in different, but interconnected, sub-topics:

- How different were primordial galaxies from their more recent analogs? Which is the IMF of the very low metallicity stellar populations at high-z? What is the dust content of high-z primordial galaxies?
- How does the baryon cycle between gas/metals in galaxies and gas/metal 'outside' (in the inter or circum-galactic medium) work? How much gas/metals are recycled and can we distinguish between gas that is infalling for the first time with respect to gas that has been already in a "galactic wind"? What is the chemical enrichment history of galaxies?
- What is the relative role of AGN and stellar feedback in determining the star formation history? What are the physical mechanisms driving these different modes of feedback? How does energy couple with the surrounding interstellar medium? Are black holes and galaxies co-evolving? i.e. are nuclear activity and star formation in causal or incidental relation?
- Has it been established beyond a reasonable doubt that the cosmic star formation history is driven by gas accretion and "external" processes are important only for low-mass galaxies?
- What physical processes shape and transform the structural parameters of galaxies? What drives the size evolution of massive early-type galaxies? What is the origin of the connection between the properties of galaxy central regions (<1 kpc) and the main mechanisms of mass and size growth?
- What is the role of hierarchical assembly in determining the physical properties of galaxies in different environments (field, clusters etc.)? How does this change as a function of cosmic time, being the environment evolving in a hierarchical universe, and how does this scale with mass? What is the relative contribution of the environmental-quenching processes, like ram-pressure and/or tidal stripping, harassment, group-cluster collisions and starvation, at different redshifts? What is the link between the properties of galaxies and DM halos in which they reside? To what extent is galaxy evolution driven/modulated by the assembly of dark matter haloes?

Some of these key questions will be tackled in the forthcoming decade(s) in different ways:

- A detailed picture of the stellar and (multi-phase) gas kinematics, gas inflows and outflows in both high-z and mid-z star-forming galaxies and its connection with the circum-galactic and inter-galactic medium is becoming accessible thanks to spatially resolved (optical/IR/radio) spectroscopy [COS@HST, ELT, ALMA, MUSE@VLT, WEAVE, SKA and its precursors].

- Molecular gas reservoirs typical of galaxies with normal star formation rates and masses can be measured up to z~2 and beyond as well as the dust content up to z~6, providing key on the baryon cycle and re-cycle [ALMA, VLA, IRAM PdBI & NOEMA]. In this respect it will be fundamental an accurate calibration of the conversion factors between molecular species (e.g. CO and H2) as a function of redshift.
- Statistical studies of the HI content of galaxies and its evolution with cosmic time will finally become feasible through next-generation surveys of the 21cm line [SKA and its precursors, see also the ALFALFA survey at z~0].
- The physical processes at work in the ISM will be investigated through the whole cosmic history of the Universe by measuring all the key elements of the galactic baryon cycle with sensitive mid- and far-Infrared spectroscopy, since most of the energy emitted by stars and accreting super-massive black holes is absorbed and re-emitted by dust [JWST]. Other relevant facilities will be designed in the next decade, although they will not be operational in the next decade [e.g. SPICA].
- Next-generation radio surveys will have the sensitivity to provide a complete census of star formation and AGN processes up to high redshift and irrespective of obscuration [SKA and its precursors].
- Central regions of massive early type galaxies at z>0.8 and beyond will become observable thanks to the improvements in resolution, probing the connection between them and the size/mass growth of galaxies [JWST, ELT].
- Structural parameters and galaxy morphology (including the effect of merging) over large sky areas and in a variety of environments in the last 10 Gyr of the Universe history will be sampled by future large surveys from space and from ground, allowing to link the galaxy evolution markers (size, mass, shape of galaxies, presence of disk instabilities) with the driving mechanisms of the galaxy growth and transformation. [Euclid, LSST, VST, VISTA].
- Statistical studies (e.g. luminosity, stellar mass and star formation functions) at different epochs from deep multi-wavelength and large area surveys can probe the assembly history of different types of galaxies in different environments reaching a stellar mass regime where model predictions are already in tension with the present, limited data [Euclid, LSST]
- (Proto)clusters at the peak of the cosmic star formation rate (z~2) start to be detected in sizeable numbers and are being observed with sufficient level of detail to study their member galaxies at a critical phase of the cluster assembly [VISTA, Euclid]. It is essential to understand if and how they are connected to the virialized structures observed at lower redshift.
- The dark matter content of various systems is becoming accessible with the multi-object spectroscopic follow-ups, strong and weak lensing and X-ray observations, making possible to reconstruct the stellar and dark mass assembly of these systems and to study the evolution of the link between the observed baryons and the dark matter halo [VLT, WEAVE, 4MOST, MOONS].

8.3 Census and distribution of mass/energy in large-scale structures

How do baryons in groups and clusters accrete and dynamically evolve in massive DM haloes? What drives the chemical and thermo-dynamical evolution of these structures? How and when the first collapsed groups form? What is the interplay between galaxies and supermassive black *holes, and how does it evolve in galaxy groups and clusters? Where are the missing baryons at low redshift and what is their physical state?*

Clusters of galaxies are the largest gravitationally-bound structures of the universe and – in a hierarchical formation scenario – the most recent forming in the cosmic history.
X-ray observations will play a major role to answer these questions considering that hot, X-ray emitting plasma dominates the baryonic content. Key observables include the gas temperature and density, its metal abundance and velocity, all of which are provided via observations of the X-ray spectral continuum and emission lines. The thermal pressure along the line of sight can also be probed at mm wavelengths through the Sunyaev-Zeldovich effect due to the inverse Compton scattering of CMB photons by the electrons in the intra-cluster medium (ICM). These observables allow us to investigate how the gravitational energy shapes cluster assembly, and how, and in which fraction, it is converted into thermal and non-thermal components, producing turbulence and kpc-scale bulk motions. The latter processes leave footprints in the radio band that are extremely powerful tools to study the details of the formation of large scale structure. Radio halos and relics (Mpc-size synchrotron radio sources associated with the ICM in a number of galaxy clusters), as well as newly discovered very steep spectrum sources in clusters and groups, are the results of the injection of turbulence and shocks in the ICM as consequence of merger and accretion events. The observational properties of diffuse cluster radio sources are extreme, and a challenge for the present radio interferometers, to the extent that only the most extreme mergers in the most massive systems can be traced and studied in the radio band, and major questions remain unanswered, such as: What are the details of the accretion of smaller systems? How far in redshift can we detect radio halos and relics? How far in redshift can we detect mini-halos (diffuse cluster sources found in the cores of relaxed systems)? [LOFAR, SKA]
On smaller scales, the interplay of the ICM with the cluster member galaxies is observed to modify the expectations from pure gravitational collapse by, e.g., adding energy and metals through supernova winds and establishing an energetic feedback with a central supermassive black hole. The details of these processes (What regulates the feedback process from the central galaxies in clusters (mostly cool core)? How can we develop a comprehensive model to describe the full baryon cycle in cool cores?), in particular in its energetic balance, are still not known and require X-ray observations with high throughput at arcsec spatial resolution.
On larger scales, theory predicts that most of the baryons in the local Universe reside in vast non-virialized filamentary structures that connect galaxy groups and clusters in a warm-hot phase (10^5 - 10^7 K). Although it will be extremely hard to constrain the thermal continuum emission from this WHIM, the discrete transitions of highly ionized metals residing there already at redshift ~4, will provide a good proxy to detect and characterize this gas with X-ray instruments, whereas radio emission associated to it can provide some limits to the magnetic field in such environments. [Athena, SKA]

To make progress in this research field it is necessary to couple results from observations with predictions of numerical simulations and semi-analytical models, in particular to interpret future data and to define new observational strategies. High-resolution hydrodynamical simulations probing physical processes effects on small scales, and semi-analytic models probing cosmological volumes are needed, both of them including realistic modelling of first stars and black holes, metal enrichment, UV photoionization background, stellar and AGN feedback, radiative transfer and of some complex physical processes that are now modelled subgrid or in post-processing (e.g. star formation and feedback). High performance computing

will significantly develop in the coming years in terms of hardware resources, software and algorithms, implying in particular an increase in the dynamical range covered.
Since answering those question usually requires analyses involving datasets of considerable size, showing non trivial variety/structure, and involves bootstrap, data mining techniques, advanced machine learning methods, Markov-Chain Monte Carlo sampling of the parameter space, addressing these questions is interlinked to the emerging astro-statistics and astro-emittersinformatics disciplines.

Key Question	Method	Project
Properties of first galaxies and BH. Epoch of Reionization Sources of reionization.	21 cm tomography	SKA
	Surveys of primordial objects in the IR and submm. Multi-wavelength studies of individual objects. Studies of low-redshifts analogous of primordial sources. Evolution of the opacity of the IGM QSO Ly-α absorption damping wings Statistics of Ly-α emitters	ALMA, JWST, Euclid, VLT, ELT, WFIRST, SPICA
	High-resolution optical-NIR spectroscopy: thermal history of the IGM	ELT
	Deep fields of X-ray sources	Chandra, XMM, Athena
	Numerical simulations. Inclusion of physical processes presently modeled as subgrid or in post processing (radiative transfer, star formation, feedback)	HPC
Origin and fate of galaxies the galaxy stellar mass function and morphological differentiation. Feedback processes among the different components of galaxies (stars, gas, dust) and AGN. Role of DM halos. External and internal mechanisms (environment and relationship with the Cosmic Web) regulating the efficiency of star formation and the structural parameters of galaxies	Detailed observations of gas kinematics, outflows, inflows. Connection with CGM and IGM. High-resolution optical-NIR spectroscopy: observations of heavy elements at high-redshift	SKA, ASKAP, MeerKAT, ALMA VLT, ELT WEAVE HST, SPICA
	Observations of molecular gas Census of star formation and AGN processes	ALMA VLA IRAM NOEMA
	HI content of galaxies	SKA
	ISM in the MIR and FIR	JWST SPICA
	Connection between the central region and the growth of galaxies at high redshift	JWST ELT
	Link the galaxy evolution markers (size, mass, shape of galaxies, presence of disk	Euclid LSST

	instabilities) with the driving mechanisms of the galaxy growth and transformation. Statistical studies (e.g. luminosity, stellar mass and star formation functions) at different epochs from deep multi-wavelength and large area surveys.	VST VISTA SPICA
	(Proto)cluster assembly at z>2	VISTA Euclid
	High resolution hydrodynamical simulations probing physical processes effects on small scales, and semi-analytic models probing cosmological volumes, both of them including realistic modelling of metal enrichment, UV photoionization background, stellar and AGN feedback, radiative transfer. Analysis of large datasets involving data mining techniques, advanced machine learning methods, Markov-Chain Monte Carlo sampling.	HPC astro-statistics astro-informatics
Census and distribution of mass/energy in large-scale structures	X-ray observations, S-Z effect Radio halos, relics WHIM emission	Athena LOFAR SKA

9 Cosmology and Fundamental Physics

Keywords: Geometry of the Universe, Cosmological parameters, Dark Matter, Dark Energy, Fundamental Physics.

Key questions:

- **The nature of Dark Matter**
- **The nature of Dark Energy**
- **Understanding gravity on large cosmological scales**
- **Initial conditions of Cosmology**
- **Fundamental interactions and constants of Physics**
- **The cosmic distance ladder and the Hubble constant debate**

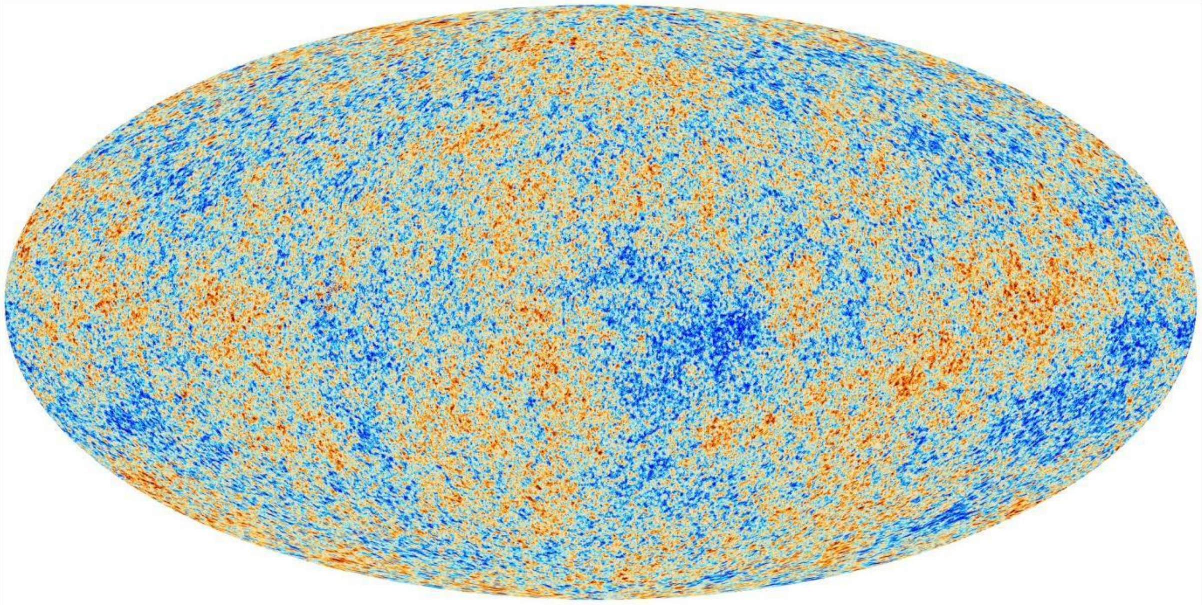


Fig.9.1 - The anisotropies of the Cosmic microwave background (CMB) as observed by the Planck satellite. The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380.000 years old. It shows tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of future structure formation. Credit: ESA.

Modern cosmology covers a large number of key issues concerning the early Universe, its global geometry and its evolution, the nature and properties of its constituents, i.e. of both the known and the still unknown elementary particles, in a remarkably close connection with fundamental physics. The Universe is a laboratory that offers access to regimes not available on Earth and continues to be a testing and discovery ground for the basic laws of nature: observations of orbiting planets provided verifications of Newton's and Einstein's theories of gravity; in more recent years, observations of radio pulsars and solar system objects have shown with exquisite sensitivity that general relativity is, indeed, correct, at least when gravity is weak; the recent direct observation of gravitational waves from the merging of black holes is a breakthrough of enormous momentum.

The cosmological knowledge is closely linked to the astrophysical phenomena described in the previous paragraphs that give origin to the formation of cosmic objects in various ages and at various scales: from the first stars and the first black holes that determine the cosmological reionization, to the formation of galaxies, of the clusters galaxies and the general large-scale structure of the Universe.

The precise determination of the cosmological parameters, in standard and non-standard scenarios, provide fundamental information to answer the key questions. The past fifteen years have seen the confirmation from measurements of the truly remarkable discovery that the expansion of the Universe is accelerating. In modern language, this acceleration is attributed to the effect of a mysterious substance called dark energy that accounts for 68% of the mass-energy of the Universe today causing galaxies to separate at ever faster speeds. The remainder of the mass-energy is 5% regular matter and 27% a new type of matter, dubbed dark matter, that is believed to comprise new types of elementary particles not yet found in terrestrial laboratories.

9.1 The nature of Dark Matter

The evidence for the existence of a large, obscure component of the Universe (**Dark Matter**, DM) is nowadays supported by a set of astronomical observations, like the rotation curves for a large number of spiral galaxies, the mass of galaxy clusters as determined from X-ray observations and gravitational lensing, the peculiar velocity field of galaxies, CMB anisotropies, the observed growth of large scale structures.

This finding has arisen many fundamental questions. **What is the nature of DM?** Is it of particle nature or not? Despite the fact that most solutions to the DM conundrum involve new particles, the possibility that the DM puzzle is solved by other type of new physics, e.g. **modification of gravity at large distances**, is still alive.

Recent measurements carried out on merging clusters of galaxies have posed strong constraints on these scenarios: there are observations showing a clear spatial separation between the light-emitting baryons and the centers of concentrations of (dark) matter, identified through combined use of X-ray imaging and optical maps of gravitational lensing. If matter is not where baryons are, modifications of gravity have a somewhat hard time to explain observations. Not excluded is the possibility that DM is (at least partly) composed of a population of primordial black holes from the Big Bang not taking part in the primordial nucleosynthesis.

If DM is made of particles, which new particle is it and what are its characteristics (mass, interactions, etc.)?

The observations of cosmic structures can reveal fundamental properties of the nature of DM (self-interacting, pressure, annihilation, decay etc.) and possible candidates (WIMPs, axions, sterile neutrinos, gravitinos...), in particular by studying the free streaming scale and effects on the expansion of the Universe:

a) Observations on relatively small scales (<1 Mpc) of the dynamics of dwarf galaxies, of groups and clusters and strong lensing.

b) Observations on medium to large scales (10-100 Mpc): clustering of galaxies and weak lensing and tomography of the intergalactic medium.

c) Observations at high energy (gamma, X-ray, TeV) can reveal the continuum or/and the line emission resulting from the decay or annihilation of DM particles.

9.2 The nature of Dark Energy

In 1998, observations of Type Ia supernovae provided evidence for an acceleration of the cosmic expansion, believed to be caused by a new "dark energy" (DE) component.
The understanding of the physics of DE has to explain why the cosmological constant takes on a vastly smaller than the expected value with reference to the Planck scale. The most direct approach is the study of parametric forms of the equation of state of the DE by:
a) the expansion of the Universe traced e.g. with the SN Ia or with the Sandage Test.
b) the measurement of baryonic acoustic oscillations (BAO), and
c) the growth of perturbations by the study of redshift-space-distortions (RSD), clusters of galaxies, cosmic shear (weak gravitational lensing) and Lyman-α forest.

9.3 Understanding gravity on large cosmological scales

The impact of DM and DE on the large-scale structure (LSS) and the cosmic microwave background (CMB) is essential to investigate their physical properties, their interactions, their evolution over cosmic time, and for the **understanding of gravity on large cosmological scales**. In this context, the study of the CMB and LSS must be considered, conceptually and programmatically, as a unique experiment, from which it is possible to obtain basic information about the constituents of the Universe and the fundamental laws that determine its evolution.

9.4 Initial conditions of Cosmology

Recent observations of the microwave background are consistent with the theory that the Universe underwent an exponential expansion (the so-called **inflation**) in the first 10^{-32} s from the big bang and the scale of the Universe that we see today grew from its infinitesimally small beginnings to a few centimeters.
Inflation is commonly regarded as a brilliant avenue to solve some of the problems of the basic Big Bang scenario: the postulated early exponential expansion brings distant regions of the Universe (much larger than the current size of the horizon) in causal contact at such early times. This simple idea leads to two crucial predictions:
1) the Universe is expected to be surprisingly close to flat;
2) the Universe should appear extremely homogeneous and isotropic, even in regions that in the present Universe should never have been in causal contact.
The most crucial consequence of the inflationary paradigm is in the implication that the primordial perturbations, as observed in the CMB and later amplified to turn non-linear and seed the formation of structures, originate from quantum fluctuations in the very early Universe. At a later stage in the development of the inflationary paradigm it was realized that such inflation-amplified quantum fluctuations offer a simple way to explain the characteristic shape of the primordial (Harrison-Zeldovich) power spectrum, which undoubtedly should be considered a success of the theory.
The flatness, isotropy and shape of the power-spectrum appear to be both confirmed by measurements of the CMB on all scales and to a different extent they are both corroborated by observations of the large scale structure of the Universe. Although all this does not confirm directly the inflationary scenario, it certainly provides strong arguments in its favor. In these first moments in time, physics has to be pushed to the extreme and possibly beyond our current understanding of it, which makes cosmological studies of the highest importance.
Observations foreseen in the next decade have the potential to verify specific predictions of Inflation and discriminate between different versions of the theory. It should be possible to test the energy scale of inflation, the amount of primordial gravitational waves generated during

inflation, and their induced B mode polarization, and, at the same time, the spectrum of initial perturbations, both of scalar and tensor type.
Observations of the CMB have a unique potential in investigating inflation: the major long-term goal is the direct detection of the B-mode spectrum that is associated with primordial tensor perturbations in the early Universe and will provide decisive confirmation of inflation.
Such deep polarization maps may give indications on the inflationary energy scale and probe ultra-high energy physics to levels beyond what can be obtained with any conceivable terrestrial particle accelerator. The ultimate aim of this investigation is testing inflationary models by checking a sort of consistency between scalar and tensor perturbations, by measuring deviations from Gaussian statistics and by achieving an even better determination of the spectrum of the primordial fluctuations.
The amplitude of the B-modes induced by gravitational waves is very difficult to predict in the context of any theory, but it is typically expected to be <1% of temperature anisotropy. This imposes new challenging requirements on instruments and observational techniques. A high signal-to-noise, full-sky imaging required to reach this goal is beyond the foreseeable future, but it is important to move some intermediate steps that can lead to the necessary technology. Advances in both bolometer and coherent receiver technology appear promising, particularly for large focal plane arrays.

9.5 Fundamental interactions and constants of Physics

The Universe is an extremely promising laboratory to investigate fundamental physics, and more specifically extensions of physics to very high energies or very small spatial scales, such as the properties of neutrinos, any violation of the laws and symmetries of **fundamental physics**, **the variation of the physical constants**, the energy scale of the fundamental interactions, etc.
These studies, strictly interdisciplinary, have a deep synergy with the direct search of the DM and other particles carried out in our ground-based laboratories and in high-energy astrophysics. Furthermore, the multifrequency approach to these cosmological studies, possible thanks to the variety of observational infrastructure, allows us to increase significantly the control of systematic and, therefore, to achieve high reliability in answers to the above mentioned fundamental questions.
Cosmology involves large distances, which allow us to investigate tiny effects that may become detectable when integrated over such long times, offering a unique opportunity.

The determination of many physical characteristics of structures in the Universe (luminosity, mass, dynamical timescales, star-formation rate, physical size etc.) relies on the previous knowledge of a distance. Several cosmological quantities, like the Hubble constant and its related parameters (e.g. the neutrino mass), are also strongly tied to distances. Distances are also a key ingredient for understanding large-scale galaxy flows, hence large scale mass distributions.

9.6 The cosmic distance ladder and the Hubble constant debate

Determining accurate distances for a large sample of galaxies within the ~200 Mpc limit is then a key for understanding the properties of the dark components in the Universe, for creating a solid anchor for the extragalactic distance scale, for the precise determination of cosmological parameters, and studies of galaxy flows and ultimately the detailed 3D distribution of galaxies as testing particles of the cosmological Large Scale Structure.

The next decade will certainly be a critical one for this topic. The results expected from Gaia for the local distance scale, the surveys of type Ia supernovae (SNeIa) for the cosmological scale, and the improvements on intermediate scale distance indicators bridging the gap between the local and cosmological regimes, will allow a quantum leap in the field, likely reaching the long desired 1% accuracy on large scales in ten years from now.

The local distances that are being fixed by the Gaia mission will be fundamental to constrain the distance scales of currently adopted primary and secondary distance indicators that are used to reach cosmologically interesting distances and in turn to constrain the Hubble constant.
Among primary distance indicators, classical Cepheids and RR Lyrae are the most important standard candles in the Local Group, associated to pop I and pop II stellar systems, respectively, adopted to calibrate several secondary distance indicators. Thanks to their Period-Luminosity (PL) relation and to their intrinsic high luminosity, classical Cepheids allow us to determine the distance of far-away resolved stellar systems with recent star formation episodes. On the other hand, the distance determination of old stellar systems can be obtained from RR Lyrae stars by using their Cepheid-like PL relation in the near and mid infrared bands, as well as their Luminosity-Metallicity relation.
The most used secondary indicators (e.g. Tully-Fisher, Type Ia Supernovae, Surface brightness fluctuations, Novae, the Globular Cluster Luminosity Function) are calibrated using Classical Cepheids and/or RR Lyrae. Based on these indicators, the estimated value of the Hubble constant is H0~73 km/sec/Mpc, in contrast with the recent value of 66 km/sec/Mpc obtained from the analysis of Planck data, based on the cosmic microwave background. In this context, it is fundamental to try to reconcile the inconsistency between the values of H0 through more accurate calibrations of the different steps of the cosmic distance ladder, and/or by using distance indicators directly able to reach cosmologically significant distances (e.g. the recently discovered Ultra Long Period Cepheids, potentially allowing us to go farther than 100 Mpc, whose reliability as standard candles is under study). These studies will be combined with the development of a theoretical scenario for pulsating stars, based on non-linear hydrodynamical models including a non local time dependent treatment of convection for different masses, luminosities and chemical compositions. These models will allow us to reproduce the observed properties and to derive information on both the intrinsic stellar parameters and the individual and mean distances. On this basis, a theoretically supported calibration of the extragalactic distance scale will be provided.

As for secondary distance indicators, Supernovae (SNe) are key tools to probe the nature of Dark Energy and will be the main targets of future experiments like, for example, DES, Euclid, LSST, WFIRST. These experiments will dramatically beat down both the statistical (enormously increasing the number of discovered events) and systematic errors connected to the photometric calibration.
On the other hand, in order to define the absolute calibration of the Cosmic distance ladder and to check and to keep under control the possible cosmic evolution of the SN properties, we need to observe in great details a large number of SNe in the local Universe. The big differences among the SNe seen in the observed data demand to revise and improve the classification scheme. To this end, the spectrophotometric observations are crucial to characterise the physical parameters of the explosions and the physical properties of the progenitors.
Meanwhile, it is mandatory to verify the possible calibration the super-luminous SNe in order to extend the Cosmic distance ladder up to redshift z~3-8.

All the above studies require a high temporal frequency, a wide wavelength range, and a good spectral resolution. The ESO public survey (PESSTO), for example, taught that a rapid access to specialised instruments like X-Shooter at VLT, SOXS at ESO-NTT and NTE at NOT is mandatory.

The acquired data will be used to answer to several open questions, among which the most urgent are: understanding the physical nature of the SNIa progenitors (single-degenerate, double degenerate, or both; to constrain the channels leading to the super- or sub-Chandrasekhar mass explosions); define the energy source of the super-luminous SNe (pair instability, shell-shell collision, magnetar…); and much more.
In spite of the unquestionable power of these super-luminous events, SNe have the drawback of taking place in unforeseeable galaxies and in unpredictable location in galaxies. Hence, one or more extra-galactic distance indicators are needed to match the distance scale of the local Universe, mapped with Gaia, to the high-z regime where SNe are more efficient. One of the most promising techniques for such interval is the Surface Brightness Fluctuations (SBF) method.

To date, the typical overall uncertainty on SBF distances is <~0.10 mag (<~5% on linear distances). A large fraction of the total error comes from the zero-point calibration (~0.08 mag), based on Cepheid distances. It is expected that the results by Gaia will reduce such component of the error budget to a negligible factor (<0.02 mag).
Hence, in the forthcoming decade, the study of extra-galactic distances with SBF, by coupling the small statistical and systematic errors of the method, with a) the wide range of distances at the reach with SBF, and b) the large sample of targets available thanks to the ongoing (with VST or CFHT) and/or programmed optical/near-IR surveys (with LSST, or Euclid), will allow us to find answers to many of the open questions related to the need of accurate, i.e. ~1% precise, distances. On even larger scales and space-time distances, Baryonic Acoustic Oscillations offer another important tool for measuring angular-size distances. The method is based on the imprints left on the redshift-dependent power spectrum and correlation functions of galaxies and IGM transmission by acoustic perturbations of the plasma at recombination. This method will be systematically exploited by all-sky surveys (LSST, Euclid).

Key Question	Method	Project
The nature of Dark Matter	Dynamics of galaxies and clusters of galaxies	VLT LBT ELT Euclid LSST JWST
	Growth of structure Surveys of galaxies	SKA Euclid VLT VST LSST
	Density fluctuations of the IGM	VLT, ELT

	Emission from annihilating DM	FERMI, XMM CTA Athena
The nature of Dark Energy	Gravitational lensing	Euclid LSST
	Growth of structure Surveys of galaxies	SKA Euclid VLT VST LSST
Understanding gravity on large cosmological scales	Large Scale Structure Sandage test	Euclid ELT SKA
Initial conditions of Cosmology	CMB polarization and spectral distortions Strong and weak lensing, cosmic shear Surveys of Galaxies Dynamics of Clusters	Euclid LSST VST VISTA
Fundamental constants and principles of physics	Variation of fundamental constants	VLT, ELT
	High energy interactions Anomalous photon propagation	CTA
The cosmic distance ladder and the Hubble constant debate	Parallaxes Standard candles/sticks SNIa, BAO	Gaia Euclid TNG HST VLT JWST ELT

10 Enabling Technologies

Nowadays we entered the era of the extremely large projects (e.g. ELTs, SKA, CTA, Euclid, PLATO, ATHENA, JUICE, LISA, etc.) in Astronomy, involving basically the whole international community. INAF community must play a central role in this framework, both scientifically, by accessing and exploiting such advanced instrumentations, and technologically, by participating with major roles to the design, development and construction thanks to the proper state-of-art capabilities.
In order to achieve these ambitious results, the technological developments and activities should be encouraged, supported and adequately funded by the institute itself. Support should be not limited to well-established activities in already selected projects but it should include R&D activities aimed at leading and/or maintaining INAF at the top level in the international context. For this reason, support should be mostly focused on the fields where INAF has demonstrated a high degree of excellence.
Even if the process is not straightforward, R&D activities may result on transfer of technology to industries and, in the end, to the Society potentially bringing a wide spread benefit. Such activities have potentially the capability of attracting additional funding from external sources and/or to improve ministerial funds when important results are claimed.

10.1 Opto-mechanical system for VIS/NIR Astronomy

Since the opto-mechanical systems are the basis of every new instrumentation and telescope, the ongoing study and construction of Extremely Large Telescopes (and of their solar analogues, EST and ATST) and of the new space missions require new challenges to be fronted in this field, with a very wide range of different instruments to be exploited and a huge number of science cases to be possibly fulfilled.

10.1.1 Spectrometers and high efficiency dispersers

Spectroscopy in the optical and near-IR is a fundamental and unique tool to study the key issues of modern Astrophysics, from e.g. the chemical analysis of the atmospheres of extra-solar planets to the physical characterization of the first objects at high redshifts. The new instruments foreseen in the roadmap for large (VLT-class) and giant (ELT-class) telescopes includes mainly **optical and near infrared spectrometers**. Moreover, a large number of present and future surveys, both ground and space based, needs to be accompanied by spectroscopic follow-up observations.
INAF has contributed - and is actively participating – to the design and construction of many spectrometers (e.g. the ESO instruments VIMOS, X-SHOOTER, ESPRESSO, MOONS, SOXS). These contributions fostered research and development activities – in collaboration with specialized Italian Industries - on the most crucial sub-systems and technologies related to the spectrometers design and integration, and in particular:
new technologies for high efficiency dispersers
optimization of cryogenic sub-system
high-precision opto-mechanical design and alignment technologies

Dispersing elements play a fundamental role in the astronomical spectrographs for defining the resolution, dispersion capability and the overall efficiency of the instrument. In the recent past years, an interdisciplinary study on **silicon grisms** has been done, involving INAF and CNR. Silicon is a material with a large wavelength transmission band (from 1 to 100+ µm) and is the most suitable material to make transmission dispersant devices at high efficiency in the infrared, both for ground and space applications. Due to the crystalline nature of silicon, only nanotechnologies can be used and a good experience has been done in this field, which eventually produced a silicon grism working in the H band, currently installed in the NICS camera at TNG. Few other groups and laboratories (Penn State University, Univ. of Texas at Austin) in the world can provide experience and technology to build such devices. Low and medium resolution spectrographs have benefited in the last 15 years from the evolution of **volume phase holographic gratings** (VPHG) that show efficiencies higher than 90%, easy customization and good stability. More recently, new technologies are entering in this field, such as the **lithographic gratings**. Such kind of technology allows in principle to enhance the efficiency and, at the same time, to reduce the overall instrumentation size with respect to the classic grating, opening the scenario to new design concept of spectrograph. INAF is nowadays acknowledged as International leader in this technology field as demonstrated by the participation to MOONS, WEAVE, SOXS and ESPRESSO.

INAF boasts two decades experience in the design and construction of **cryogenic spectrometers** working at infrared wavelengths. Currently, INAF is a world leader in the field of high resolution infrared spectroscopy, thanks to GIANO instrument within the Galileo National Telescope. The design and construction of this spectrometer has been enabled by a deep and continuous collaboration with highly specialized Italian Industries in the cryogenics and optics fields. This collaboration exploited also the testing of new technologies related to micro-optics for fiber-IR and related cryogenic interfaces. Future targets should be the development of ultra-stable cryostats (temperature variation of less than 0.001 K/day) and coatings with very high efficiency (less than 0.3% losses per surface over the whole infrared band) for large cryogenic optics. All these activities shall be focused to the optimization of the performance of spectrometers aimed to instrumentation for Extremely Large Class Telescopes where INAF is going to assume European Leadership in the next decade thanks to HIRES.

The INAF collaborations in many European spectrometers, (e.g. the ESO instruments VIMOS, X-SHOOTER, ESPRESSO, MOONS, SOXS) granted the expansion of knowhow and heritage in the design, integration and testing activities. New instruments are facing bigger telescopes and more demanding technical requirements (e.g. stability, dimensions, light-weighting). INAF is currently playing a leading role in the deploying of innovative techniques both in the design and in the Alignment, Integration and Verification (AIV) fields.

New design and system engineering techniques oriented to the integrated multidisciplinary design coupled to early stage end to end parametric models have been adopted for past instruments (X-Shooter and ESPRESSO @ VLT) and are evolving towards new class ones (HIRES @ EELT). New **alignment techniques** have been developed starting from previous investment that enabled the acquisition of cutting-edge metrology. New parameters in terms of time, efficiency, repeatability and stability are defined in the opto-mechanical integration field. In detail opto-mechanical alignment based onto **mechanical fine metrology** can reduce the working time even of large instrumentation. The coupling of the mechanical metrology technologies with the optical direct measurement enables a further step in the precise characterization of the mechanical interfaces with respect of the optical ones. Large instrumentation (e.g. HIRES, MAORY) would greatly benefit from the use of these techniques as it significantly simplifies integration phases.

10.1.2 Wide-Field opto-mechanical systems

Galactic and extra-galactic science often require field of views noticeably larger than the ones available in conventional instruments. There are a few 8-m class telescopes nowadays equipped with very wide field instruments, such as LBT (equipped with the Large Binocular camera, 23’x25’ FoV), the Magellan Telescope (Megacam, 25’x25’ FoV) and the Subaru Telescope (Hyper Suprime Cam, 34’x27’ FoV). Additionally, several astronomical sites have 2-3m class telescopes equipped with wide field imagers, such as the 2.2m MPG/ESO at la Silla (WFI, 34’x33’ FoV), the VST 2.6m telescope (1°x1° FoV) and the VISTA 4.1m telescope (1.5°x1.5° FoV), being the last two located at Paranal and dedicated to wide field imaging in the Visible and the Near Infrared respectively. General consensus is that, in the era of the extremely large telescopes, there will be even more 8-10m class telescopes dedicated to Large Field, and this fact poses several opto-mechanical technological challenges. Such wide field instruments normally require correctors characterized by very **large and fast optics** (sometimes with **aspheric sag**), at the edge of the current technological feasibility and very challenging from the opto-mechanical design point of view. This set of problems has to be faced also in space instrumentation as in the case of PLATO. INAF has been involved in the past years in a few wide field projects, designing both telescopes and instruments dedicated to this purpose. The VST at Paranal is a large field telescope entirely dedicated to wide field surveys, and it has been entirely designed and built in Italy. The LBC at LBT is a double camera instrument, with the two channels optimized to work one in the red and the other in the blue wavelengths of the visible band.

10.1.3 Freeform and off-axis aspheric optics manufacturing and testing

In the era of Extremely Large Telescope, the size of the optics of both the telescope and the instrumentation has been significantly increased. In addition to that, the improved manufacturing of **freeform and off-axis aspheric optics** enables optical design much more performant on one side but more complex on the other side. The possibility to realize such complex optics is directly related to the capability of measure their surfaces with the proper accuracy. Thanks to several national grants and international grants, INAF deployed an integrated R&D activity oriented to join and optimize optical manufacturing techniques with several testing approaches. The researching activity on new and/or optimized polishing techniques is oriented on the combination between bonnet and fluid polishing with Ion Beam Figuring that allows optimizing the surface errors from hundreds of microns peak to valley down to few dozens of nanometer. This optimization of manufacturing techniques triggers the development of the related metrology; the test and calibration of meter-class optics with high-accuracy is a complex task, since they are intrinsically difficult to measure due to the size of the reference beam from the interferometer and eventually the reference optics. Several approaches have been implemented to be able to capture all the optical characteristics starting from the low (spatial) orders up to the high (and very high) ones. The critical point is the reference to be used for the measurement. Different solutions has been adopted and deployed: in addition to the traditional lens based nulling system, the one based on a computer-generated hologram is able to combine both accurate reference surface and self-alignment tools, overcoming the size problem of the null optic.

10.1.4 Development and optimization of coronagraphic systems

Exo-planets search has become very popular in the last years, both because it is a science field very attractive and popular not only between the astronomers and because technology is improving very quickly, making possibly doable, in the very next future, direct imaging of rocky Earth-like planets. Even if the very high resolution required for the observations will be provided by the next generation of ELT, the excellent performance of the last generation AO systems and a number of new very efficient coronagraphic techniques pushed several 8-10m class telescopes to implement instruments dedicated to planet finding. SPHERE@VLT, GPI@GEMINI and SCExAO@SUBARU are routinely operating surveys to detect and characterize exo-planets, also performing the follow-up of space missions (such as Kepler) which are creating catalogues of planets candidates. These instruments are also strategic as pathfinders for the ELTs, where the increased resolution will allow searching for planets closer to the hosting star, increasing in this way the possibility to observe rocky planets. INAF is designing and building SHARK, an instrument for LBT mostly dedicate to planet finding, that will perform **coronagraphic imaging** and low resolution spectroscopy both in the optical and near-IR bands. Since the time scale of the ELTs first light is about 10-15 years from now, all the results obtained in this field in the next years will be particularly valuable to be possibly retrofit in the ELTs planet finders' opto-mechanical design and development. There are several challenges, concerning the opto-mechanical development, inherent to coronagraphic instruments. The extreme resolution needed requires a delivered optical quality that has to be extremely good, impacting on:

- the optical design, which has to deliver an intrinsic optical quality nearly perfect
- the mechanical design, which has to ensure very low flexures and very good thermal stability not to deteriorate the image quality
- the very tight manufacturing tolerances for the optics, which also require excellent flatness and state of the art micro-roughness to minimize scattered light
- the challenging AIV procedure, that has to maintain the final delivered optical quality to extremely high values

For the manufacturing of the opto-mechanical components, the co-operation with the industries is mandatory for the production of state of the art elements and to possibly push some of the optics characteristics (i.e. micro-roughness) to values never achieved in the past.

10.1.5 Heat rejection technologies

The upcoming 4m class solar telescopes present new technological problems to tackle. One of the most vexing is the dissipation of the extremely large amount of heat collected by the primary mirrors without affecting the local seeing. The solution adopted calls for the realization of a **heat rejecter**, which builds on the know-how of nuclear reactor technology to efficiently exchange heat among the coolant and the heated surface. Since 2009, the Italian community involved in the EST design study is working in close connection with the industrial partners to the realization of such an heat rejecter. This study has been financed through an UE-FP7 grant and in 2013 has been further financed through a UE-H2020 grant to produce a scaled working prototype to be installed at the prime focus of the GREGOR telescope. The heat-rejecter is a critical part of the solar telescope EST, and both the technological case and the innovative solutions adopted make this a unique case in the world, with the Italian scientific and technological community at the very forefront of innovation.

10.1.6 Spectro-polarimeters

Polarimetry is a powerful diagnostic tool to study astrophysical sources. Radiation mechanisms that produce similar radiation output can be disentangled by means of their polarization signatures. Also, polarization provides unique insights into the geometry of unresolved sources, even at cosmological distances, which remains hidden in the integrated light. In an observational science such as astronomy, this carries even higher weight because polarimetry goes directly to the heart of the problem, i.e. the underlying physical process.INAF has a large expertise in the construction of polarimetric units, e.g. SARG, PAOLO, CAOS and HARPS-North, and to the Phase-A study of high resolution spectropolarimeter for ELT with the aim to implement a polarimetric unit.

The availability of efficient adaptive optics systems at major **solar telescopes** has made possible the routine use of high throughput instruments based on multiple **Fabry-Perot interferometers**, performing integral field (imaging) spectroscopy and polarimetry. In stable seeing conditions provided by the AO, these instruments can overcome the limitations of slit-spectrographs (very limited spatial coverage) or broad-band filters (little spectral discrimination). Imaging spectrometers have proven to be very efficient in obtaining fast and reliable spectral and polarimetric information over extended field of views. These latter observational characteristics are of paramount importance to account both for large-scale convective motions, and for the magnetic connectivity of widely separated regions, of particular relevance in the chromosphere. At present, only four Fabry-Perot interferometer based imaging spectro-polarimeters are available for solar observations. Among those, IBIS Italian Interferometric BIdimensional Spectrometer (IBIS) is a double Fabry-Perot system developed at INAF with contributions from the Universities of Florence and Tor Vergata. Given the excellent performances, it is now understood that imaging spectro-polarimeters will represent the "work-horses" of the future 4m class solar telescopes. Both DKIST (Daniel K. Inosouke Telescope) and EST (European Solar Telescope) plan to have several such instruments working in parallel in different spectral ranges. No other operating instrument of this kind, nor planned for the next few years, possess the same diagnostic power and versatility as IBIS. Investing on the development of this technology will allow the Italian scientists to maintain a prominent role within the solar community interested in ground-based observations. Indeed, the experience gained in the past years in the design, assembly and upgrade of IBIS is an important asset for the Italian participation to the solar telescopes of the future. Consequently, Italian scientists already have an active role in international working groups charged to study the design and operation of different sub-systems, including similar spectro-polarimeter imagers, for these future large solar telescopes.

10.1.7 Space weather opto-mechanics systems

There is increasing need for synoptic imagers of the Sun, capable of delivering high cadence magnetograms and dopplergrams for several scientific purposes: gravity waves search on the solar surface, fast transients from active regions studies, the detailed analysis of the evolution of the photospheric magnetic field during and before flares and CMEs as well as space weather uses. Today, Italy has a recognized leadership in the design and development of opto-mechanics system based on Magneto Optical Filters to acquire full disk spectro-polarimetric images. Due to their characteristics (absolute spectral stability, imaging and measure of both magnetic field and LoS velocity associated to different height of the solar atmosphere) these instruments are most suited to acquire dataset for the scientific task list above. In particular, they are of extreme interest for the space weather application, since they can be used both for the computation of proxy of the solar activity and for the possible forecasting of flare events. Italy has a strategic role at international level, which is testified by the several ongoing collaborations (e.g. Hawaii University, JPL) and financed projects (e.g. MAP, ASI). Italy has the only laboratory suited for the testing and calibration of the MOF cells and the know-how to design and realize both the opto-mechanics of the entire acquisition system and the instrument management and data calibration software. Among the possible future developments, there already ongoing collaborations for a balloon-borne implementation, for the realization of a prototype with high TRL for space environment (for the next space weather missions) and also for a use in tandem with a Fabry-Perot interferometer for high cadence studies of MHD waves in the solar atmosphere.

10.2 Active and Adaptive Optics

Active and Adaptive Optics in Astronomy have been historically an European affair, with a parallel and mostly inapplicable progress carried out overseas in the context of military and strategic application at the time of the Ronald Reagan Strategic Defense Initiative. With the TNG and LBT development, however, the Italian footprint on the field became more and more relevant giving a unique flavour to the Italian astronomical community involved in such a field, along with the French school, that is the only other one that is significant in this area. While Active Optics pioneering is born within ESO (although in connection with the Italian industry, so that in the development of the TNG there has been a privileged path to acquire and master the related technology in Italy) and the first European Adaptive Optics System spoke French, a large fraction of the innovations, both in terms of components, concepts and realizations, are marked with a distinguished Italian flag. Large thin, force actuated, deformable mirrors (commonly referred to as "secondary adaptive mirrors") are not only developed and today basically produced exclusively through the INAF development and a network of Italian industries, essentially in a monopoly regime, but the most appreciated wavefront sensing techniques (with the pyramid sensor being the most prominent in a long list) with a number of approaches, in large part already demonstrated on the sky, comes again from INAF. A key role has been played by INAF in the development of Multi-Conjugate Adaptive Optics, a technique for extending the corrected field of view, which is based on the use of multiple adaptive mirrors and multiple reference sources: in particular, INAF was involved with ESO in the VLT/MAD experiment for the first on-sky demonstration of Multi-Conjugate Adaptive Optics. Such leadership is obviously challenged, mostly by other European groups, with the focus on non-conventional approaches in Adaptive Optics, like implementation of Multi Object Adaptive Optics, an area where France, Netherland and UK have spent some significant time, especially in view of multiplexing instruments, an area where recently little has been pursued from the Italian side. The connection with industry at level of components made the Italian offer a unique one, while at level of Prime Contractor there is not yet evidence of industries heavily involved in such a field.

10.2.1 Active Optics

The **active optics**, invented at ESO and first applied to the NTT (whose design was used also for the Italian TNG) enabled an historic improvement in the image quality of optical telescopes, which can now deliver seeing limited images even in the best astronomical sites or, in collaboration with the adaptive optics system companions, go down to the diffraction limit. The active optics has become a basic component of any modern telescope with mirror diameters of 2 m or more and, in the long term future, definitely it will still be one of the basic systems of any top class optical (and not only) telescope. In the forthcoming extremely large telescopes, part of the wavefront control will be under the responsibility of the low frequency (active) correction system that will aim at removing most of the physical system errors, leaving to the high frequency (adaptive) system the remaining corrections. Although the active optics might be considered a mature technology, the number of existing systems is still rather small, limited to the 2 to 10-m telescopes built after the nineties. Actually, the implementation always claims for a custom design, where the Italian combination of INAF + industry has had a leading role in projects like TNG, LBT, VST. Interesting perspectives for new developments are in the emerging class of wide-field telescopes (e.g., VST, VISTA, the future LSST), where there are tighter requirements for the alignment and hence for the active optics systems, setting new challenges and enlarging the paradigm. In such class of telescopes, information about the telescope aberrations may be obtained by analysing the variations of ellipticities of the stars across the field in the scientific image, potentially removing the necessity of a “physical” wavefront sensor. Such technique, originated within the VST framework, is an example of the Italian innovation potential in the active optics field. The combination of INAF expertise and several Italian SMEs has been successful in several projects, where the design was partially or totally (as in the most recent VST case) done in Italy. Thanks also to a long collaboration with the ESO inventors of active optics, INAF has developed a huge know-how and now masters this technology. This expertise is attractive also for the Italian industry that needs (and sometimes looks for) the INAF collaboration for its placement in the worldwide market of telescope systems design.

10.2.2 The MAORY Adaptive Optics system

MAORY (Multi conjugate Adaptive Optics RelaY) is one of the four first-light ELT instruments approved for construction: it is an adaptive optics module, designed to enable high-angular resolution observations in the near infrared with the ELT, offering two adaptive optics modes: Multi-Conjugate and Single-Conjugate Adaptive Optics. Its wavefront sensing system is based on the use of both mesospheric Laser Guide Stars and natural stars. Wavefront compensation is performed by the telescope’s adaptive and tip-tilt mirrors M4 and M5 and by additional adaptive mirrors inside the optical train of the instrument. Key design drivers for the Multi-Conjugate Adaptive Optics mode are uniformity of compensation over the field of view, stability of the performance with changing external conditions and sky coverage, i.e. the capability to achieve the nominal performance over a large fraction of the observable sky. MAORY is a large-size instrument: according to the current design, it occupies a cubic volume of about 8 meters on a side. The instrument design is based on forefront technologies in different fields such as adaptive optics, adaptive mirrors, fast low-noise optical and infrared cameras, real-time computing, 1-meter class off-axis aspherical optical components and precision mechanics. The development of such a complex instrument requires advanced project management, system engineering and product assurance approaches, similar to what is required for a space project. INAF is the lead institute of the MAORY project: it is responsible for the instrument design, construction, integration and commissioning. The timely and successful development of this instrument represents a major endeavour for INAF and also an opportunity to consolidate the institute’s expertise and its capability to manage large instrumental projects. Guaranteed Time Observations on the ELT will be granted to INAF for the construction of the instrument. A close synergy throughout the project duration between INAF scientists and the technical team that is designing and building the instrument is the gateway to ensure the effective scientific exploitation of the ELT and of its instrumentation.

10.2.3 Optical turbulence characterization and forecast

The **forecast of the Optical Turbulence** (OT) can be very critical and challenging to support the Service/Queue Mode observations that all top-class telescopes and ELTs are planning to implement to optimize the use of different instrumentation, particularly those supported by AO and/or interferometry. The scientific impact of new facilities/AO techniques will be strongly dependent on the observations efficiency. The worst enemy to beat is the turbulence. The most important science drivers are the identification of temporal windows with excellence turbulence conditions to carry on the most challenging scientific programs and the optimal

management of observations. INAF reached a leading international role on researches in the optical turbulence (OT) forecast for applications to the ground-based astronomy. INAF already implemented a completely automatic and operational system (ALTA Center) for the nightly forecast of OT and atmospheric parameters relevant for ground-based observations as integral part of the Service Mode system of LBTO. A similar system is under discussion with ESO for VLT (Cerro Paranal) and ELT (Cerro Armazones). Interest from other top-class telescopes/sites in the world (Cerro Pachon-Gemini, Roque de Los Muchachos-GTC/TMT, Las Campanas-GMT) has been expressed.
A couple of interesting achievements are worth of mention here:

- Development of algorithms for the OT parameterization in numerical non-hydrostatical mesoscale models in stable and strongly stable regimes to improve the model performances. These regimes are those characterizing the night time and corresponds to the most difficult conditions in terms of theory.
- OT ensemble forecasts, i.e. to provide information on the OT forecast in terms of probability. It should represent an important change of paradigm of the OT forecast and we expect a much higher impact on the application of the Queue Mode.

Model validation in day-time conditions is important for applications to solar AO systems but it can have important applications in different contexts other than astronomy that requires model predictions on the whole 24h time scale. Among these, we remember optical communication from low Earth orbit (LEO) or geostationary Earth orbit (GEO) satellites (a contract with ONERA/CNES is under discussion); global climate change (a crucial social issue) strictly related to models ability in well reconstructing the atmospheric flow hydrodynamic in stable regimes; sustainable energies and civil aviation because of the clear-air turbulence. At present different instruments conceived for the OT measurements exist but important uncertainties between different instrumentation is still not negligible. The main challenging problems strictly related to the instrumentation development in the next decade are summarized here. INAF is directly involved in all these research activities. A set of Main Goals can be identified:

- Quantification of the absolute measurement of the optical turbulence.
- Development of vertical profilers (monitors) with more or less high vertical resolution.
- OT measurements provided by AO systems.
- Effects of the Outer scale.
- Effects of the Scintillation.

10.2.4 Active Optics for Radio Antennae

Active optics concept takes place also in modern **large radio antennae**. Thermo-mechanical deformations, induced by gravity and insulation, may prevent the observations at a given frequency because of wavefront distortion. As in the case of optical telescope, the shaping of the reflector shall reach an accuracy of about λ/10 of the observing frequency. As an example, for observing a 100 GHz, a shaping of the reflector at 0.15 mm accuracy has to be reached (taking into account the back travel from the main reflector). For tens-meter-class radio telescopes an active shaping of the reflector is mandatory to reach the diffraction limit. That is done by using up to hundreds actuators along the dish area. While for visible telescopes, controlling systems of the induced deformation (close-loop control) has been developed (amongst others Shack-Hartmann and pyramid sensors), the counterpart in radio frequency is not yet developed: actually an active optics radio-antenna operates in open-loop regime. INAF own the second greater active radio telescope in the world (the Sardinia Radio Telescope, SRT, with a main dish of 64 meter, while the greater one is the Green Bank Telescope, a 100 meter dish sited in WV - USA). The Italian astronomical community is then directly involved in finding solutions for this very challenging problem and we recommend to put strong effort in solving this question.

10.2.5 Polarization-free AO systems

Over the last ten years solar AO has become a reliable technology, routinely used for high-resolution spectro-polarimetric observations of the solar atmosphere. This allowed to study the complex interplay between plasma and magnetic field, necessary for understanding the mechanisms that lead to the onset of impulsive space weather events. These events, having a direct impact on critical infrastructures, such as for instance satellite operations, power grids, communications, aviation, and global positioning systems like GPS and GALILEO, can result in important economic aftermaths. For these reasons, very recently, the forthcoming 4-metre class European Solar Telescope (EST), whose construction phase is expected to start in 2019 and first light expected in 2026, was included in the ESFRI 2016 roadmap. EST will provide very high spatial (20-30 km on the photosphere), spectral ($R > 300000$) and temporal resolution (a few seconds) observations of the solar atmosphere, with an unprecedented high polarimetric accuracy (10^-6) and sensitivity. To this aim, EST will be equipped with a complex **MCAO system**, integrated into the optical design, which must **minimize the instrumental polarization**. This represents a major challenge, considering the high polarimetric accuracy needed. However, this is not the only challenge to face. Indeed, the development of large format etalons for high precision polarimetry, high cadence large format broadband imagers, infrastructure control and the identification of suitable strategies for the handling and storage of the large volume of data expected from the telescope, are other important tasks in which the Italian community has contributed since the beginning of the EST design phase in 2008. Indeed the development of such technologies is a major breakthrough not only in solar physics but also in other astrophysical areas. INAF is involved in the study and development of the EST AO system, by leading the assessment of the performances of polarization-free AO configurations and their polarimetric calibration. INAF is also contributing to activities aimed at developing large format cameras for high precision polarimetry and wavefront sensing, in cooperation with all major European research institutions involved in the EST project. Over the coming years, the outcome of these technological tasks is expected to have a significant impact also in other astrophysical research areas where high precision polarimetry is becoming an important tool (e.g. exoplanet detection, star formation, etc.). The target for the next coming years is the successful operation and exploitation of such a complex polarization-free AO systems, and related technologies, at major 4-meter class solar facilities.

10.2.6 Space applications

Nowadays, the interest in the international community for application of **active and adaptive optical elements** onboard the space mission instrument is largely increasing, stimulated by next generation concepts for 4m class optical/UV **space telescopes**, envisaged substituting HST. INAF is focusing on the possibility to use the adaptive “secondary mirror” technology applied to large primary mirrors or petals of deployable primary mirror. The mirror in this case will be driven at low frequency correcting thermo-elastic deformations effects along the orbit and/or possible misalignment after launch. Currently a first prototype has been tested in INAF in collaboration with the Italian Space Agency and Italian Industry reaching a TRL between 4 and 5.

In the next decade the aim is to push existing Adaptive Optics technology in order to overcome the principal historical shortcoming of this technique, allowing to use it in almost every area of astrophysical research. The expected main developments are:

Wide Field Adaptive Optics, an area where INAF mastered, together with ESO, the very first Multi Conjugated system at the VLT, and where Italy is involved in the LBT (with the realization of the first Raileigh beacons based Ground Layer System), in the ELT (with the realization of MAORY, the ELT first-light Multi-Conjugate Adaptive Optics module), and possibly with a further step toward shorter wavelength at the VLT. In addition to the development of forefront instrumentation, still a number of concepts and of dedicated wavefront sensors can still make a great leap in this area. Mesospheric or Rayleigh generated artificial references are still today scrutinized with variations of conventional Wavefront Sensor while it has been shown by several studies from INAF that dedicated approach could lead to a significant advantage.

Adaptive Optics toward the shorter wavelengths, and especially in the visible, as still today most Adaptive Optics system are de facto confined to the Near Infrared region, making the applicability to the most recent and large format systems less immediate. Pushing toward the visible poses a number of challenges, primarily because of the small equivalent collecting area per sub-aperture, requiring the conception of much more innovative and efficient wavefront sensing, and secondarily to the development of large format compensators and the implementation of huge control systems. Large apertures combined with artificially generated beacons make an interesting cross fertilization between this and the previous areas, where it is likely to happen that each would benefit from the finding of the other. Achieving routinely in the bluer portion of the spectrum what today is achieved in near Infrared is an accessible goal within the coming decade, although it still likely requires a few small leaps in several areas, with a large inter-disciplinarily in order to be effective. We detail in passing that INAF AO groups actively and successfully pursued visible AO with the SHARK-VIS instrument for LBT and the well-received proposal of a MCAO system for visible wavelength in the context of the new generation AO supported VLT instruments.

Control Strategy for ELT AO system. Larger and more accurate Adaptive Optics systems will make little and subtle effects (differential chromatism, second order effects into distortions, cophasing of large number of segments or of large segmented deformable mirrors, to cite a few examples of relevance in the next decade) become the main residual enemy to fight, making development in control strategy an area where INAF should spend some significant resource also in view of leading large programs involving Adaptive Optics. Further to MAORY areas of interest involve other large facilities like EST in the Solar science, the GMT 25m telescope, and other future applications on ELTs.

Space telescopes Adaptive Optics. Another emerging field is the application of AO techniques to the development of space telescopes where the goal performances are no longer met by passive components. This is the case for phasing and overall control strategy that directly bring into play the already achieved ground based AO results, and additionally design of suitable deformable mirrors and other kind of components that are now moving in the direction already identified for ground based telescopes.

Non astronomical application of AO techniques. The optics and photonics field is growing in importance at a very high rate in the last few years. Sophisticated techniques like Adaptive Optics originally developed for ultimate performance of ground based telescope find nowadays applications in several field of Photonics like optical metrology, biomedical measurements of human eye, microscopy, space debris, laser power concentration. Environmental control to mention only a few. We believe that INAF (channelling possibly through existing national facilities) should dedicate some resources to the exploitation of technology transfer enabled by its leading experience in AO.

10.3 UV, X, gamma, TeV opto-mechanical system

The development and realization of grazing incidence Wolter-like optics for X-ray astronomy carried out in the past two decades represents a great success for the Italian community. This technological area became a strategic sector thanks to extensive and consolidated collaboration between ASI and INAF, with the important involvement of industrial partners.
In particular in the past years it was set-up in Italy the Ni electroforming technology. This approach foresees the development of superpolished pseudo-cylindrical mandrels made of Aluminum with electro-less plating in Kanigen, that are precisely figured in order to assume the negative shape of the grazing incidence mirrors to be realized. The mirror shells are then fabricated via replication, after having firstly deposited the reflecting layer of Au on the mandrel surface and the electroformed the Ni walls on the gold-coated mandrels. Many confocal shells are then nested together in order to form a complete mirror module. It should be noted that the technology has been developed in collaboration with the Media Lario. This company has been committed, not only by INAF and ASI, but also through contracts with other international Space Agencies and Institutes, to realize the optics for several X-ray missions using the Ni technology (Beppo-SAX, Spectrum X/Gamma/Swift, XMM-Newton, Simbol-x/NHXM, e-Rosita/Spectrum, Einstein Probe, eXTP). Apart from the well consolidated Ni technology, there are future X-ray astronomy missions in which the Italian community will be involved that require alternative manufacturing processes, in order to obtain an better performance in terms of effective area, angular resolution and weight. In particular INAF, with the support of ASI and ESA, and co-working also with other International Institutes and agencies like NASA, JAXA and MPE, is engaged the technological efforts for the development of:

- X-ray optics based on thin glass segments
- X-ray optics based on Si substrates
- X-ray optics based on thin monolithic shells

10.3.1 Glass segments technology

In the past few years INAF led an extended development activity funded by ESA aiming at the realization of optics based on thin (a fraction of mm) thickness. The initial target project was IXO (International X-ray Observatory) that just recently evolved in the ATHENA mission. INAF has then set-up innovative proprietary methods, together with Labs and facilities, for the **hot forming of the glass segments** and their integration into stacks of parabola-hyperbola confocal mirrors. The new hot slumping process (different from the approach that was been developed in USA by NASA/GSFC) foresees the application of pressure during the thermal slumping process, in order to increase the contact of the glass segments with the replication mold and, at the time, avoid any sticking of the two surfaces and increase of the micro-roughness. The integration is then carried out in a semi-automatic way, using a special integration machine. The proper figure imparted by reference mandrels is frozen by means of reinforcing ribs connecting each segment to the next one. Using this approach, large size prototypes with a large number of parabola-hyperbola mirrors were developed and X-ray tested, achieving very good angular resolution results (HEW < 20 arcsec). The method is now evolved in the **"cold" replication** approach of very thin glass sheets (0.2-0.4 mm). This solution is particularly interesting because it can deliver highly performance mirrors in terms of angular resolution and weight but with a great reduction of the production costs and time, since the hot forming part is no not anymore needed. After having elastically bent thin flat glass foils using a mandrel, their shapes are then maintained by stacking the segments using ribs, starting from a solid support structure. The target mission for the use of this technology is FORCE (Focusing On Relativistic Universe and Cosmic Evolution), being studied by the Japanese JAXA Agency and the Universities of Miyazaki, Osaka and Nagoya. FORCE will be an X-ray observatory with an operational energy band up to 80 keV, with an angular resolution of 15 arcsec. The mission represents de facto a follow-up of the NASA mission NUSTAR (characterized by a much worse angular resolution, about 1 arcmin). The collaboration with the Japanese colleagues has already been established. It is planned within the next couple of years to realization, in collaboration with the colleagues in Japan, of an X-ray optics prototype bases on cold slumped glass segments and with a multi-layer reflective coatings.

10.3.2 Technologies based on Silicon segments

The next large X-ray missions under study by ESA and NASA, ATHENA and LYNX, are based on large size optics (baseline of 3 m diameter) made of many **Silicon segments** assembled together. It should be noted that Silicon is a very attractive material for space implementations, because of the excellent thermo-mechanical parameters, including a very good thermal conductivity. In particular, Athena is being realized under ESA's coordination using the so-called Silicon Pore Optics (SPO) technology. Si substrates are elastically bent to assume parabolic or hyperbolic shapes (as needed for making Wolter I optics) and then stacked together in many layers by means of ribs and aligned to form the so-called X-Ray Units. The technology is promising but, at present, it didn't yet fully demonstrate the accomplishment of 5 arcsec HEW resolution required by the project. INAF is involved in the consolidation of the process by means of design and simulation activities and developing new methods and facilities for the testing and calibration of the optics elements (including the Beatrix facility. One very promising solution under study in USA by NASA/GSFC for the implementation of the LYNX mission is the direct optical polishing and figuring of Silicon - previously grinded - segments. Stacks of mirrors are therefore obtained connecting the segments to each other using a kinematic mount system. The final goal is to achieve an angular resolution better than 1 arcsec. In this context INAF is collaborating with NASA/GSFC with the final ion-figuring correction to the Si segments. The results so far obtained are very promising and the collaboration between INAF and NASA/GSFC will continue during the next couple of years with the goal of developing representative prototypes. The construction of the **BEaTriX** (Beam Expander Testing X-ray) facility is ongoing at INAF, with the direct support of ESA and of the European community with the AHEAD program. The facility will generate a broad (170 x 60 mm2), uniform and low-divergent (1.5 arcsec HEW) X-ray beam within a small lab (7 x 14 m2), using an X-ray microfocus source, a parabolic mirror, a crystal monochromation system and an asymmetrically-cut diffracting crystal. Once completed, BEaTriX will be the reference facility to test the Silicon Pore Optics modules of the ATHENA X-ray observatory, in full illumination, without being affected by the finite distance of the X-ray source. The facility is designed to operate at 1.5 keV and 4.5 keV, by implementing two switchable monochromation stages and asymmetrically-cut crystals. Owing to the quite short range required to obtain a parallel beam with this setup, a low vacuum level (10-2 mbar) is required to avoid noticeable beam extinction. In addition to a modular vacuum approach, the low vacuum will allow reducing the time required to evacuate the tank, in turn enabling a test rate that will match the ATHENA SPO production. The facility will be completed by 2019 and then operated in close cooperation with ESA.

10.3.3 Thin monolithic shell

The implementation on of an X-ray mission with high imaging capabilities, similar to those achieved with Chandra (< 1 arc second Half Energy Width, HEW), but with a much larger throughput (2.5 m2 effective area @1 keV), represents a compelling request by the scientific community. To this end, as already mentioned, LYNX/XRS mission is being studied in USA, with the participation of international partners. In order to figure out the challenging technological task of the mirror fabrication, different approaches are considered, based on monolithic and segmented shells. Starting from the experience done on the glass prototypal shell realized in recent past years, the direct polishing of thin (2mm thick) fused silica monolithic shells is being investigated at INAF as a possible solution, working with the ASI support and in close cooperation with NASA/MSFC. It should be noted that in this case the mirror shells are about a factor 10 thinner than Chandra. In order to make feasible process, a temporary stiffening structure is used to support the shell during the figuring and polishing operations and to manage the handling up to its integration in the telescope structure. After the grinding and the polishing phases (performed by INAF in cooperation also with external industries), in order to achieve the required surface accuracy, a final ion beam figuring correction is foreseen. A prototype is being developed, to be tested by 2018 at NASA/Marshall.

10.3.4 Spin-off of the ongoing X-ray optics developments in other scientific and technological applications

The X-ray optics technologies under development can have important applications in other areas of science and for civil use. In this respect, it is e.g. interesting for INAF the realization of ground-based helioscopic systems for the observation of axion and axion-like particles (that could constitute an important component of dark matter in our Universe). Axions could be produced within our Sun via Primakov effect, due to the solar magnetic field. In this respect, the IAXO (International Axion Observatory) project is currently being studied, with a possible significant Italian participation mainly related to the realization of the X-ray optics based on cold glass slumping. Other interesting applications concern the use of grazing incidence optics for muons focusing in the context of particle physics experiments like e.g. FAMU (Physics with MUI Atoms - RAL R512, Italian contribution led by INFN Trieste), related to the measurement of the proton charge radius and the persistence of discrepancy called "proton radius puzzle". As far as civil society is concerned, the introduction of X-ray imaging and focusing techniques for biomedical applications (in particular, for the mammographic screening to be performed with quasi-monochromatic and collimated conventional X sources) and for the identification of contaminants in the food industries represent possible interesting spin-offs. Specific activities are being carried out in INAF to explore this kind developments and technology transfer. In this respect, it should be noted that in the past the Ni electroforming approach developed for X-ray optics has been successfully transferred to other fields, such as the realization of collector optics in nano-lithography EUV beamlines and optics for space for free space communications and LIDAR systems.

10.3.5 Broad Band Laue Lenses for hard X and soft gamma rays

In the band between a few tens (~50) and several hundreds (~700) of keV, one of the most promising solutions for the realization of narrow-field telescopes is represented by broadband **Laue lenses**. These focussing optics would allow the attainment of a sensitivity of the order of 100 times with respect to current telescopes, and angular resolutions of at least one order of magnitude better (~20 "). These features would enable us to solve many of the problems still open in this energy range, and, for the first time, to add the measurement of polarization as an observational "standard mode" for the hard X-/soft g-rays sky when used in conjunction with innovative focal plane detectors. One of the great advantages of a Laue lens telescope is that it can extend the bandwidth up to at least 600 keV with a focal length of about 20 m, which is still implementable in a single satellite mission. In Italy the interest was the development of broadband Laue lenses for the observations of source continuum emission and lines (even broad) in the energy band between several tens to several hundreds of keV. A decade ago ESA itself made a study on the use of Laue lens based telescopes for satellite missions. This type of development is currently an Italian prerogative, as at the European and global level we are the only ones who have made substantial investments, funded primarily by the ASI, in this direction and have still an intense activity going on. In recent years, the activities oriented towards the development of a reliable technology for the realization of broadband Laue lenses has allowed to obtain several important results both on the assembly of a Laue lens system and on the development of crystals to optimize the PSF of the lens itself. This development was coordinated by the University of Ferrara and sees the collaboration of INAF, the IMEM/CNR of Parma, and some specialized industrial companies (DTM-Modena and Thales-Alenia). Currently the collaboration, using the purpose-built X-ray facility in the LARIX laboratory at the Ferrara, is building a prototype module of a Laue Lens, operating between 90 and 300 keV and with a focal length of 20 meters. The construction will implement an advanced technology with a total error of less than 10 arcsec using crystals of GaAs (220) and Ge (111) bent with innovative techniques developed within the same collaboration. With this technic, it is possible to drastically improve the performance of the lens in terms of focussing and reflectivity, i.e. a sensitivity improvement of at least a factor of 100 better than existing instruments. Within these activities, the role of INAF research groups has been of fundamental importance for the realization of the X-ray system for the assembly and testing of the lens prototypes. Currently, the INAF group is heavily contributing to the definition of upcoming activities involving different developments including new curved supports for the crystals with high stiffness and thermal stability, and the development and realization of an active system to control the orientation of the base modules from which a lens petal is constructed. To date, the technological development has led to the laboratory testing of various subsystems and components (e.g. adhesives, crystals, and supports) necessary for the realization of a Laue lens, and it can be said that TRL ranges from 3 to 4. The development of this technology offers different perspectives to Italian industry in mechanical engineering, precision metrology and activities related to its space qualification. Prospects for the application of this technology are related to the development of satellites for astronomy in the hard X-/ soft g-rays (10-10000 keV). With the achievable high sensitivity and angular resolution, several of the scientific objectives (see ESA and NASA vision documents) identified as a priority for the observation and study of space in the coming decades can be met. Furthermore, the use of broadband Laue lenses coupled with focal planes with high spectroscopic and 3D spatial resolution, represent a challenging opportunity to implement polarimetry as a standard observational method also in this energy range, with obvious major benefits for the understanding of the active mechanisms in cosmic sources of hard X-/soft g-rays. The current level of development of broadband Laue lenses still requires the solution of various technological problems largely related to the space qualification of the various components and subsystems. The development of Laue lenses for space may represent an important opportunity for INAF to keep the already established role of leader in the field of X ray optics and thus ensure to the national community a leading role in the definition and implementation of the next (10 -20 years) missions dedicated to X- and g-ray astronomy.

10.3.6 Thin large area filters for X-ray detectors in Space

Large area thin filters are used to protect X-ray detectors from out of band radiation or low energy charged particles, to define pass-bands, and to protect the sensitive detector area from contamination. Thin filters are also used to thermally isolate telescopes. In order to fully exploit the capabilities of high performance X-ray Observatories, filters must be accurately designed, built, and tested. Large size plastic films with sub-micron thickness coated with a metal have been traditionally used in Space to protect X-ray detectors. In particular, in the last years, Polyimide has been largely used as plastic foil and Aluminum as metal coating being highly reflective from the visible to the IR. Such filter material has been used on Chandra, XMM-Newton, as well as on solar experiments such as Hinode demonstrating reliability and long-term stability. Aluminum coated thin polyimide foils have been also investigated for the LAD experiment on board LOFT and are currently the baseline for the X-Ray Integral Field Unit (X-IFU) and Wide Field Imager (WFI) detectors on board the future ESA large mission ATHENA. The research group at INAF-OAPA and UNIPA-DIFC has been largely involved with key responsibility in the design and calibration of filters for some of the instruments on-board the major X-ray observatories such as the HRC on board Chandra, the EPIC camera on board Newton XMM, the X-Ray Telescope on board Hinode, the LAD detector on LOFT, and is currently responsible for the design and development of the focal plane filters of the X-Ray Integral Field Unit (X-IFU) and Wide Field Imager (WFI) detectors on-board ATHENA. For the X-IFU, the use of X-ray micro-calorimeters with Transition Edge Sensor technology and SQUID-based front-end electronics puts an additional requirement on filters to shield RF EMI from the spacecraft operation and telemetry. The thin Aluminum coating is not effective in attenuating the RF and fine pitch metal meshes with small blocking factors need to be used. Research activities related to the development of thin large area filters for high energy space application include:

- mechanical and optical design;
- modelling and simulation (Ray tracing, X-ray transmission, UV/VIS/IR transmission, RF attenuation of metal meshes, structural analysis, estimates of BKG contributions, etc.);
- laboratory testing performed within the institutes or in external facilities (Scanning Electron Microscopy, X-Ray Photoelectron Spectroscopy, Atomic Force Microscopy, X-Ray Absorption Spectroscopy, UV/VIS/IR spectroscopy, X-ray imaging, thermo-vacuum, vibration and acoustic tests, etc.).

The research activity involves different groups within INAF and the University (UNIPA, UNIGE) as well as a wide international collaboration. The research group led by UNIPA and INAF is responsible for the design and development of the focal plane filters of the two X-ray detectors on-board the next ESA large mission for High Energy Astrophysics named ATHENA and is currently involved in the Phase-A study activities as a member of the two instrument consortia. While the technology of thin polyimide coated with Aluminum is quite consolidated in space for detectors operating at room temperature, the need to operate at low temperatures, the very large size of the filters and the requirement to also provide RF attenuation put new challenges on the development of the filters for ATHENA. Beside the technology based on Polyimide and Aluminum, another technology based on Silicon Nitrade membranes will be investigated in collaboration with a Finnish company supported by ESA. Metal meshes with small blocking factors need also to be studied to provide mechanical support and RF attenuation. Design and test activity on thin filters are currently ongoing on the Sino-European mission eXTP, on the Large Area Detector inherited by the LOFT design, and on the HERMES cubesat project. For both these experiments filters are being developed in cooperation with the IHEP institute of the Chinese Academy of Sciences.

10.4 IR/VIS/UV/X/gamma/TeV detectors and readout electronics

The development of innovative sensors for radiation of all wavelengths is crucial for the development of innovative astronomical instrumentation. The new sensors (with the associated read-out electronics, in some cases establishing a new state-of-the-art) are often the enabling technologies of new observational techniques, enabling the INAF community to propose new and ground-breaking instruments or missions and/or to gain leading roles in the international collaborations.

10.4.1 Silicon Photomultiplier (SiPM)

During the last decade the **Silicon PhotoMultiplier (SiPM)** became a valid alternative to PMTs in almost all astronomy applications. The SiPM is a light sensitive sensor originally developed in Russia at the end of ’90, which consists of a high density matrix of Single Photon Avalanche Diode (SPAD) with a common output load. Each diode is operated in a limited Geiger mode, in order to achieve a gain at the level of 10E6. Incident photons are detected by individual microcells that avalanche and release a fixed quantity of charge whilst a quenching resistor stems the avalanche and resets the microcell: the output is the sum of all of the microcells. SiPMs, now commercially available, show very attractive performances for astronomical instrumentation: excellent single photon resolution, excellent timing (hundreds of picoseconds), high photon detection efficiency, low bias voltage, no damage when exposed to ambient light, insensitive to magnetic field. SiPM have also drawbacks: very high dark counts, after-pulses, optical crosstalk, gain strongly dependent on temperature and sensitivity to red light, where most of the night sky background is concentrated. Recently, the manufacturers reduced dark counts and optical cross-talk. The use of high purity crystals reduced the after-pulses, as well as the bias voltage. The SiPM were first studied in INAF in 2011, as focal plane sensors of the Imaging Atmospheric Cherenkov Telescope (IACT). ASTRI SST-2M is a Cherenkov telescope prototype proposed by INAF as Small Sized Telescope (SST) for the Cherenkov Telescope Array (CTA) observatory. Characterization tests at INAF laboratories of SiPM from various manufacturers led Hamamatsu to greatly improve their devices. Two Italian industries also offer state-of-the-art SiPM: AdvanSiD and ST Microelectronics. Future improvements of SiPM performance are expected: reduction of the sensitivity in the infrared range (important whenIR dominates the background) and the gain vs. temperature dependence.

10.4.2 Silicon Carbide Photo Multiplier (SiCPM) for UV solar blind application

Interest in UV light sensitive and visible blind detectors for medical, military, industrial and environmental applications have stimulated the research community to improvements in device design and processing. Among all the UV light sensitive semiconductor materials, **4H-SiC based photodiodes** represent the most suitable choice for UV astronomy owing to their high intrinsic visible blindness, good quantum efficiency, very low dark current, ruggedness and mature process technology. Recently, the CNR-IMM Catania has developed vertical Schottky 4H-SiC UV detectors with continuous thin metal film Ni2Si front electrode, demonstrating good morphological repeatability and uniformity on wafer of the electro-optical detectors performance with high wafer yield. The optical characterization demonstrates a maximum responsivity of 0.11 A/W at 280 nm, corresponding to a quantum efficiency of ~50%. The responsivity measured on these new junction photodiodes is comparable or higher than that measured on similar design technologies proposed in the past and obtained by ion implantation. The dark current is remarkably lower than on relatively large area detectors (1 mm^2). These detectors are thus at the state of the art in UV light detection field and can represent the first step towards the development of high signal-to-noise ratio 4H-SiC detectors working in avalanche mode (either APDs or SPADs) for extremely low light intensity detection. The roadmap foreseen at the CNR-IMM Catania, in collaboration INAF and with ST Microelectronics, is similar to that which has led to a SiPM starting from an APD. This collaboration succeeded in obtaining SiC-APD. The next step will be the realization of a SiC-SPAD (technology that allows to operate a SiC-APD in Giger mode) using quenching resistors and finally assembling many SiC-SPAD in parallel to obtain **SiCPMs**.

10.4.3 Optical detectors

In the present day all the ground telescopes and several space missions use **CCD** or **CMOS** detectors. These detectors are continuously improving in term of size, readout noise and performance. The limitations of CMOS with respect to CCD in terms of area, possibility to do large mosaics and fill factor have been solved. The current state of the art offers the possibility of large mosaics of CCD and CMOS detectors (e.g., with abuttable 9232 X 9216 CCDs or 1920 x 4608 CMOS). The new CMOS detectors reach a fill factor close to 100% and high QE. The main differences between CCD and CMOS are in the extended range of high QE (400-800 nm) and low dark noise (4e-/pix/hour) of the CCD compared with the limited range of the QE, high dark noise (1800 e-/pix/hour) and fast readout time of the CMOS detectors. These characteristics make CCD the most suitable detector for long time exposures with high QE extended in a wide range (spectroscopy, imaging) and the CMOS optimal for short-time exposure applications (fast imaging, adaptive optics, space applications). The technological aspects related to the CCD and CMOS ranges from the front end electronics to the FPGA/ASIC development to laboratory test and detectors characterization. While the detectors are made by the industry, the development of the front-end electronics, the detector controller, the test and the characterization are carried out in the INAF institutes. The heritage of INAF in terms of know-how in electronic development and test is valuable and require resources. In particular two major topics should be addressed in the future: FPGA and ASIC technology in CCD/CMOS electronics development and the laboratory facilities for the characterization and test of optical detectors.

10.4.4 IR detectors

The **near IR and medium IR** (from 0.8 to 28 μm) is important for both space and ground astronomy. Technologies for large area, pixelated detectors are all based on high cost and low-moderate yield hybrid manufactured in separated steps. The sensitive layer, where junctions are produced, is separately grown and hybridized via patented technologies on a silicon readout chip capable of random or sequential addressing and signal extraction from each sensitive junction. Some lower-cost and lower performance technologies do the complete grow of the detecting layer starting from the silicon readout multiplexer. Key parameters for this detector class are: dark current and readout noise specifically for space-based observations; pixel saturation charge and readout speed for ground observations below 2-2.5 μm; Quantum Efficiency uniformity and absolute level; Persistence charge accumulation and realize modalities.

The sensitive layers with already available detectors from 1k x 1k to 4k x 4k pixels are:

- **HgCdTe** 0.8–10 µm with the advantage of lower cutoff tunability at construction phase. Detector of this class are at the base of the focal planes for JWST, Euclid and WFIRST for space for the ESO VISTA ground telescope.
- **SiAs** Impurity Band Conduction 3–28 µm. This is a switchable gain high readout rate for next generation VLTI instruments and for METIS, on ELT.
- **InGaAs** 1–1.7 lower cost technology compared to hybrid MeCdTe proposed for SNAP dark-energy mission but replaced by HgCdTe.

The national industry (Leonardo, DRS) on these technologies lags behind US off the shelf products, which offer limited choices. ESA has been recently trying and push the European industry through industrial tenders. The involvement of the astronomical community is and will be based on laboratory performance evaluation, optimization and adapting to different applications. For the electronics directly interfaced to NIR/IR detectors only one US provider is available for ASIC-based electronics, able to cope with the required performance: this is becoming a tight bottleneck, being impossible to handle 4kx4k class detectors in space. ESA is also here pushing the European industry and Italy is quite active (OHB in Euclid, Sitael) on the FPGA and ASICs. A key aspect, as for other enabling technologies, is the preservation and generation-transfer of the know-how available in the institutes.

10.4.5 Large area Silicon Drift Detectors (SDD)

The **Silicon Drift Detectors (SDD)** were invented at Polytechnic of Milan and later developed in Italy by INFN for particle physics experiments. SDD are suitable for several applications in astronomy, reaching performance near to the physical limit in spectroscopy mode. They can operate both as direct X-ray detectors or, in gamma ray instruments, as photodiodes for the read-out of scintillating crystals. SDD are semiconductor detectors that can be designed in different sizes and geometries, in single pixel, large area or arrays or matrices of small pixels. Due to the small capacitance of the charge-collecting anodes, large sizes of the active area cause a limited increase of the detector noise, as the leakage current component can be reduced by proper technological processes and/or via moderate cooling.

A collaboration with INAF brought SDDs into space astronomy as enabling technology for large-area spectral-timing experiments. A large collaboration between INAF, INFN, Universities (PoliMi, Uni-Pv and UniBo) and FBK (Fondazione Bruno Kessler, Trento) supported by INFN, ASI and INAF has developed over the past 10 year several geometries, ranging from the largest SDD ever produced (77 cm^2) to small detectors (few mm^2) to array of sub-mm^2 pixel. As the full exploitation of SDD performance can be achieved only through very low-noise read-out electronics, the design of several circuits (ASIC) has been developed by the same consortium, Actually, both the technology for the SDD production developed in Italy by FBK and the low-power, low-noise read-out electronics (designed at PoliMi) have reached world-record noise levels at room temperature (close to the Fano limit). The SDD technology is continuously improving by addressing topics like thinning the input window or reducing its inactive area. The consortium involving INAF, INFN, FBK and Universities is unique, in being able to design, produce, integrate and implement in experiments state-of-the-art SDDs and read-out electronics. In fact, the consortium was able to successfully propose the LOFT mission concept to ESA (involving for the first time the deployment of 10 m^2 of SDDs) and it is now studying and proposing other mission concepts - eXTP with China, STROBE-X with NASA, THESEUS and eASTROGAM with ESA and HERMES with ASI – based on the Italian SDD technology. INAF is one of the main actors in the development of the HERMES project, aimed at the deployment of a constellation of nano-satellites equipped with innovative X-ray and gamma-ray detectors for observations and localization of GRB and other high energy transients like the electromagnetic counterparts of gravitational wave events. HERMES will contribute to the objectives of Space 4.0, by identifying and standardizing innovative approaches for manufacturing, assembling and testing miniaturized components. Space 4.0 wants to change the market mechanism in the space sector, opening the possibility of carrying out even complex and ambitious space applications to a wide audience of key players, such as Universities, research institutes and SMEs.

10.4.6 Single Photon Avalanche Diode (SPAD)

Detectors with sub-nanosecond time resolution are required for several astronomical applications. As examples, in space gamma-ray astronomy in the GeV range EGRET, AGILE and Fermi could not implement time-of-flight capabilities for charged particle rejection, due to the lack of very fast detectors; on the ground, with the rise of 40-m class telescopes, observations of single optical photons with timing resolutions lower than a nanosecond may open the new frontier of quantum astronomy. This will allow to fully exploit the quantum properties of the radiation (e.g. in the correlations between the arrival times of each detected photon) as an independent diagnostic. For this, timing resolution around 50 ps and a front-end electronics able to acquire billions of events per second are required. The **SPAD** devices described in the previous sections feature high photon detection efficiency around 490nm, a remarkable timing accuracy as good as 40 ps, although with no spectroscopic capabilities. Italy has expertise for custom designs and manufacture: SPAD are developed at Politecnico di Milano and manufactured at IMM-CNR. Their application in astronomy have been studied within INAF and ASI funded technological projects were SPADs from 50 µm and up to 500 µm diameter have been realized, characterized and coupled to fast plastic scintillators for particle detection.

10.4.7 3D CZT/CdTe spectro-imager detectors

Two possible approaches for the observations X and Gamma ray (50-1000 keV), are available: wide field instruments for transient sources and sky surveys (coded mask instruments and advanced Compton telescope) and narrow field telescopes with high sensitivity (Laue lenses and concentrators) for individual sources. They require very different characteristics for the detectors: large area detectors with moderate spatial and spectral resolution and with fast timing vs compact detectors with high spatial and energy resolution and good timing properties. For the latter, the main development is in semiconductor devices (**CdTe and CZT**) for **3D spectro-imaging** in which the INAF research groups were among the first promoters at the European level, long collaborating with groups at DTU-Space, CEA/Saclay and LIP-Coimbra. INAF researchers also proposed these detectors for scattering polarimetry at the focal plane of broadband Laue lens telescopes and/or high-energy concentrators. Their sensitivity will allow high-energy polarimetry to become a standard method of observation for X and gamma-ray sources, in addition to spectroscopy, imaging and timing. At present INAF works closely with IMEM/CNR, DIFC (Palermo University), Pavia University and INFN. INAF groups contribute design configuration and optimization and 3D basic sensors, in addition to the characterization and performance evaluation of both single sensors and detection systems. In collaboration with DTU-Space INAF has tested single spectroscopic sensors with 3D capability. To achieve complete focal plane systems several technological issues remain open: integration of single sensors with the front-end electronics, packaging in replicable modules and development of dedicated ASICs. CZT/CdTe 3D spectroscopic imager has application also in other fields such as nuclear medicine, environmental monitoring and security checking.

10.4.8 NTD Germanium X-Ray microcalorimeters

Cryogenic semiconductor **micro-calorimeters based on NTD (Neutron Transmutation Doped) germanium** have been largely used since the late '80s, proving themselves to be robust, reliable, with a low sensitivity to static magnetic fields, easily usable in a wide range of temperature and with a wide dynamic energy range. They are able to provide a very high energy resolution, with a read-out electronics based on low noise, low cost, commercially available components. Single, micro-machined micro-calorimeters with NTD Germanium thermistors have widely and successfully been adopted from infrared to soft-gamma rays. However, an all-planar technology to build scalable arrays has never been developed. The aim at INAF is to develop a planar process to build scalable arrays, optimizing the performance for X-ray detection, and to increase the count rate. Only a few research groups are currently working on the NTD Ge microcalorimeters. INAF, in collaboration with the University of Palermo, has a long experience on single-sensor NTD Ge microcalorimeters. In particular, it recently developed some of the key processes enabling the planar fabrication of sensor arrays. Several international collaborations are involved, most noticeable the Harvard-Smithsonian Center for Astrophysics, Cambridge (Boston, MA) and the Alternative Energies and Atomic Energy Commission (CEA), Paris.

10.4.9 TES Microcalorimeter detectors and Cryogenics

The technology related to the **TES** (Transition Edge Sensor) detectors is divided as follows: **Microcalorimeter detectors** and its readout electronics (cold based on SQUID, and warm) and **Cryogenics**. The main scientific driver is related to the ATHENA ESA mission. An INAF-INFN collaboration started 15 years ago to master the TES technology for X-ray astrophysics, and have been among the founders of an international consortium (with SRON, NASA/GSFC and ISAS/Tokyo University). This consortium has now the responsibility to build the TES-based X-IFU instrument on board ATHENA, in which INAF has the responsibility of the design (scientific requirements and detector specification) and test of the Cryogenic Anti-Coincidence detector (CryoAC) of X-IFU, aimed at reducing the particle background, including the cryogenic and warm readout electronics. For the CryoAC INAF proposed a novel application of the TES technology that exploits thin, large area TES-pixelated absorber and a fast/high count rate detector. The cryogenics plays a fundamental role: design, development and test of items enabling the above technologies to be cooled and to work at 0.1K, dealing with normal-metal, semiconductors and superconductors. Skill on cryogenics is needed (from the scientific to the technological point of view), as well as facilities based on Pulse Tubes, dilution refrigerators or ADRs (Adiabatic Demagnetization Refrigerators) and vacuum technologies. The basic concept of CryoAC for X-ray missions was adapted in Italy from dark matter detectors. The spin-off towards the Italian industries is quite robust. TAS-I has been involved in this technology (electronics) since the beginning. More recently, the project has involved in the electronics and structural issues CGS/FBK. The CryoAC will be fully developed in Italy, offering a leading position in the context of the TES cryogenic particle anticoincidence detectors. A long-term goal is to build a complete low background TES-based detector for high resolution X-ray spectroscopy including the CryoAC, a small TES-array, and the cryogenic electronics.

10.4.10 Gas Pixel Detectors and Compton Polarimetry

The **Gas Pixel Detector (GPD)** is a gas proportional counter for X-rays and is capable to produce images of the tracks of photoelectrons emitted after the absorption of a photon. The GPD was invented and developed by a collaboration between INAF and INFN as a detector to

measure the polarisation of X-rays for astrophysics application. The current version of the GPD is sensitive from ~2 keV to ~10 keV (due to the quantum efficiency of the gas mixture, currently He – DME). “Heavier” mixtures (e.g., based on Ar) and minor design modifications can allow to raise the upper energy bound up to ~35 keV. Beside the primary driver as polarimeter, the GPD has an additional application as imager, with a spatial resolution of ~30 μm. An array of GPDs can be used e.g. as focal plane detector for Lobster Eye Optics or as position sensitive detector for energetic neutral atoms, that would require replacing the Be entrance window with a less opaque material (still able to sustain the pressure), e.g. a thin layer of SiN. In the international context, the GPD is one of the two instruments developed to measure the polarisation of X-rays via photoelectric effect. The GPD technology enabled the successful proposal of the XIPE mission to ESA and is now the focal plane instrument of the Imaging X-ray Polarimeter Explorer (IXPE) mission selected by NASA and for the Polarimetry Focusing Array onboard the eXTP Sino-European mission.
Above 20-30 keV the polarisation of X-rays can be measured by exploiting the anisotropy of the Compton Effect. The detector is composed of a low-Z scattering element (where the Compton scattering occurs) and a high-Z absorber (which detects the scattered photon via photoelectric effect). A design under study at INAF is composed of an array of low-Z and high-Z scintillators read out by SiPMs, operated in coincidence to reduce the background. The SiPMs are lighter, smaller and more compact than PMTs and do not require high voltage, allowing to design detectors with larger area, composed of a pattern of an array of the basic unit (scintillator with SiPM), suitable to detect astrophysical transient in hard X-rays, like Gamma Ray Bursts. The **Compton polarimeter** is developed at INAF. In the current effort, the SiPMs are purchased from Hamamatsu.

10.4.11 Readout Electronics

The philosophy that drives the development of instrumentation and **support electronics** is to design and/or develop special electronics inside INAF laboratories, a task that can hardly be accomplished by external companies for highly specific scientific instrument. This is particularly true for electronics that involve Application Specific Integrated Circuits (ASIC) or programmable logic, like Field Programmable Gate Array (FPGA). As an example, for the latter the scientists drive the development of the FPGA firmware in order to satisfy the scientific requirements. During the prototyping activity, the development requires flexibility to changes in the logic, easily (and cost-effectively) done only at institute level. The industry enters mainly at the engineering phase, for satellites or ground telescopes. The development of specific electronics thus requires that the expertise is maintained in the INAF laboratories, working in synergy with industries.

10.5 Optics, receivers and back end electronics for radio and microwaves instrumentations

Forthcoming radio astronomy experiments will require instruments with large field of views, high sensitivity and high resolution in time and spectral domain. Some examples of these scientific goals are the mapping of bright Galactic Extended Radio Sources, large survey of diffuse emissions, the search of B-Mode of the CMB polarization, and fast radio burst (FRB) search. A new generation of instruments which are going to be developed are aperture arrays, phased array feed, cryogenic focal plane arrays. These instruments will need cutting-edge technologies like Antenna systems and beam-forming technologies, multi-beam and multi-frequency systems, RF and Power Analog signals transport over optical fibers, acquisition Electronics and signal processing back end.

10.5.1 Pre-SKA and SKA activities

In the framework of **SKA**, INAF is member of the the AADC (Aperture Array Design and Construction) Consortium, working on the Low Frequency Aperture Array (LFAA) work package. In particular, INAF in collaboration with University of Bologna leads the design and the development of the analog receivers system, participates to the development of the signal processing system for a pre-treatment of the data and to the calibration and characterization of antennas and the array of each station. Also, INAF is the work-package leader in the receiver task. Arrays like MAD (Medicina Array Demonstrator) and SAD (Sardinia Array Demostrator) developed by INAF will allow to study acquisition systems and algorithms for latest generation back-ends, testing the technologies for LFAA.
By the time SKA will be operating, single-dish antennas will play a key role to observe large fields on the sky. This class of telescope will have great advantage by **PAF (Phased Array Feeds)**, which will allow better focal plane sampling and larger field of view, with respect traditional single-beam and multi-beam coherent receivers. INAF has been involved in PAF development with PHAROS, contributing to the cryostat and vacuum window design, construction and test, to the LNAs, VGA MMIC and to the phase shifters and controlled attenuators. However, in the framework of the SKA Advanced Instrumentation Program (AIP) INAF is also involved in the upgrade of the PHAROS PAF to a new instrument, named PHAROS2, that will reuse most part of the existing PHAROS hardware. In addition to contribute to the field tests of PHAROS and PHAROS2 and to define the system architecture and the detailed specifications of the PHAROS2 sub-assemblies, the INAF contribution aims at developing the following PHAROS2 hardware: the Local Oscillator (LO) distribution; the warm RF/IF section; the Radio Frequency (RF) over Fiber (RFoF) section; the digital beam-forming, correlator and post correlation beamforming (PCB) section with iTPMs and Pcs/GPUs.
SKA pre-construction activities in INAF have been well resourced and have played a significant role in a number of pre-construction consortia. Italian efforts have involved partnerships between research agencies, universities, and industry in design and prototyping activities. Several industrial partners have been involved during AADC works. Particular mention to the contract Leonardo Finmeccanica provision of an engineering and industrialization study of the **Front End optical transmitter and optical receiver** sub-assemblies in the LFAA RX chain. The study includes also design improvements, mass-manufacturability and testing, reliability and maintenance. There are also collaborations with Optel, Lightech and MWF for developing RF over fiber technologies and with SANITAS EG for the design of the acquisition systems. Italy is exploring the possibility to host the SKA Integration and Test Facility (ITF) in Medicina. The Italian team has designed and prototyped the control over two main elements of the SKA-low signal path, the front end (FE after the LNA to optical transmission of RF over fibre), and the signal conditioning before the analog to digital conversion. Both of these elements have been the result of Italian design, prototyping, and industry involvement and represent excellent opportunities for an Italian in-kind contribution to the SKA-low budget. Other plausible areas for Italy to invest in SKA-low are hybrid cables and subrack assemblies.

10.5.2 CMB instrument oriented technologies

Major US funding agencies and Institutions recognize the important scientific priority of CMB studies and related technology developments. Specifically, the US Department of Energy (DOE), and the National Science Foundation (NSF) request that the Astronomy and Astrophysics Advisory Committee (AAAC) establish a Cosmic Microwave Background Stage 4 Concept Definition Task force (CMB-S4 CDT) as a subcommittee in order to develop a concept for a **CMB-S4 experiment**, i.e. the next generation of CMB experiments. The expected low level of the polarized signal requires a technology development that is at the edge of the current capabilities. Moreover, the polarized signal is dominated by foregrounds emissions as demonstrated by the false detection of B-modes by BICEP. Up to now the state-of-the-art is represented by telescopes with about 1000 detectors. The target of the CMB-S4 is to build half million polarized detectors arrays mounted on dedicated CMB telescopes. This huge number of detectors is necessary to obtain the required sensitivity for B-mode polarization measurements but several questions arise: How well the optical response in terms of beam symmetry, cross-polarization, and side-lobe rejection can be maintained with planar antennas? What is the optimal set of observation frequencies to disentangle the CMB signal from foregrounds? What is the best trade-off between detector stability, sensitivity and cryogenic environment? What is the optimal calibration strategy to characterize hundred thousands of detectors in term of noise, stability and full optical response? Moreover at frequencies lower than 100 GHz, where the minimum of foregrounds is, due to high diffraction effects, the ‘traditional’ microwave techniques (feed horn + OMT + Radiometer) are still preferable. It is the case of the INAF project **LSPE/STRIP** constituted by an international collaboration aimed to build in two years scale a CMB/Foreground telescope in Tenerife together with LSPE/SWIPE balloon experiment.

Thanks to the worldwide recognised experience on ESA Planck satellite hardware development and recent involvement on ALMA upgrades studies, INAF is leader at international level on the development of **space, balloon-borne, and on-ground radiometric instruments for CMB**. The in-house capabilities cover the optical design and development thanks to the unique expertise in designing and simulating telescopes for CMB; the Radio frequency (RF) and passive components development (corrugated horns, OMTs, waveguide components) thanks also to the recent design, fabrication and testing of 50% bandwidth corrugated feeds and Orthomode Transducer (OMT) for ALMA band 2+3 (67-116 GHz) cartridge prototype; the high performance microwave and mm-wave calibrators development for ground and space applications; the radiometer testing and calibration; the thermal engineering and Cryogenics, that, in this field, is not a support but is fully part of the instrument development process since directly determines the final performances. For activities in this cutting edge technology field, a System Engineering and AIV approaches, even during early stages of developments, are mandatory. Although different Italian institutions and universities works on CMB-driven technologies, INAF is the only Italian Institute in which System Engineering (including system Thermal and RF Engineering) and AIV are applied for the development of CMB experiments.

In a long term perspective, the development strategy could include:

- Antenna systems and beam-forming technologies;
- Acquisition Electronics and signal processing back end;
- Multi-beam and multi-frequency systems;
- RF and Power Analog signals transport over optical fibers;
- Cryogenics and thermal engineering.

10.5.3 Antenna systems and beam-forming technologies.

Several technologies have been developed in the LFAA framework. **Analogue fibre optical RF** may be applied to the short/long distance wide-band transportation, distribution of clock signals and sync ground instrumentation. The Power over Fibre technique allows to power remote electronics without using copper cables. Developed acquisition boards can be useful for a large amount of instrumentations that require compactness, on board high speed computation and high speed throughput data rate. INAF developed a **Unmanned Air Vehicle** (UAV) system which provides useful information in commissioning and characterizing antennas, complementary to those given by other approaches like astronomical calibration or anechoic chamber tests. The **PAF** is a very interesting and promising receiver for improving the radio telescope performances in terms of better sampling of the focal plane and to increase and adapt its field of view by steering the synthesized beams. The scientific advantages are mainly related to the possibility of increasing the speed of surveys and to improve the antenna resolution. All the most important radio-astronomical research centers in the world are investing in this new technology.

10.5.4 Acquisition Electronics and signal processing back end

The activities related to the design and production of **digital back-end** for radio and microwave astronomy, are concentrated within the INAF Institutes involved in projects as SKA, ALMA, VLBI and single dish. All they have robust and well established partnerships with institutes all over the world, not only relative to major projects environment, but also in the field of single dish equipment that is in SRT a fertile field of use. They are mainly focused in the following fields:

- Digital electronics design and hardware production (FPGA, ASICS, boarding, housing and cooling);
- Firmware Design and engineering, in particular for FPGA-based systems;
- Software Development and engineering

These activities had a big impact on Italian industry. The collaboration with INAF has projected the partners companies to the forefront of international views, together with opportunities of contracts and future collaboration focusing the development of innovative instrumentation. Medium and small size companies are able to develop digital back-end solutions and equipment, from design to engineering, and compete as part of consortia with international standard, creating innovative and performing solutions. The cooperation in the industrial sector is fundamental for an institute as INAF, which has the vocation to share in and drive major projects in which the management of the design, construction and engineering of prototypes involves an increasingly large number of parts, requiring mass production.

The development of back-end systems for radio and microwave astronomy is supported by scientific requirements and consequent technological specifications and sometimes concurrent with each other:

- covering all the sky frequencies up to and beyond 100 GHz requires to have instantaneous bandwidths capable of increasing the sensitivity in continuous, and to perform a broadband spectral analysis;
- increasing number of sensors distributed on the focal plane implies the development of algorithms and numerical synthesis devices for which it is not suitable a post-processing after the storage phase, as an immediate data reduction, mainly due to the amount of data that must be processed and the needs of calibration and tuning of the instruments.

- developing instrumentation whose control systems tends to integrate at the data production mechanism, along with the continuous increase in performance in terms of computing power and the reduction in size, implies the development of devices closest to the real-time processing, capable of increasing the observational duty cycle and efficiency.

These factors contribute today to move to a new type of back-end 'on-field' oriented, with intermediate performance in terms of calculation, low-power and high programmability, located in the immediate vicinity of the front end. Furthermore, it will require the use of instrumentation 'big data' oriented, where high performance is the decisive factor. Also, the development of new generation back-end (both two described types) is related to the improvement of device performances, in terms of calculation density, re-configurability, programming, speed grade and power consumption:

- ADC (Analog/Digital converter) , expected to run more than 100 GSample at milliwatts of power consumption;
- FPGA , this technology is already mature (now at about 20 nm) and would be upgraded at the limit of the Moore Law in few years, as sub-nanometric;
- GPU , towards 100 thousand cores, 10 Ghz memory clock, etc,
- 3D Board design solutions able to optimize higher frequency performances (more than 20 Ghz for clock frequency).

The performance of these devices are sufficient, for the next 10 years, to ensure the construction of computing tools and back-end able to meet the observational requirements described in the previous sections. In parallel in order to improve the performances of the components, the market for digital processing is evolving towards integration philosophy, creating hybrid board that can divide tasks among different components (computing accelerator, reading and data storage, digital I/O, etc.) and apply a parallel computing approach. At the same time, software solutions should improve performances by using tools that share development environment able to program different devices as one (as for example the OpenCL solution) and provide quite the same performance reached by a hardware programming. Although for the next 10 years, the same technology used today could ensure performances required by new radio-astronomy tools, we must prepare the ground to implement the next revolution for computing systems, both at hardware and algorithmic, which will take place in the next few years and that is called ‘quantum computing’.

10.5.5 Multi-beam and multi-frequency systems

Cluster of detectors represents the future for instrumentations both for CMB and Radio Astronomy survey and imaging. Even though the science needs are different (high sensitivity for CMB studies, wide-field mapping for single dish and interferometers), the technology development areas are in common. These areas include the end-to-end study and characterization of the antenna response with array of detectors, development of compact **multif-requency feeds and Orthomode Transducers** using cutting-edge and fabrication technologies. The areas in which INAF owns the capabilities to contribute at the development of technologies are mainly the followings:

- Compact wide-band passive components development (corrugated feed horn, OMTs, waveguide systems as polarizer, filters, WG routing).
- Cryogenic calibrators for microwave and mm-wavelengths arrays.
- System Engineering activity applied to the development of complex arrays.
- AIV technique to integrate, test and calibrate complex arrays (from hundreds to thousands of RF detector chains)

- Array / Telescope coupling design, optimization and full RF verification with state-of-the-art EM software (like GRASP).

All these areas are addressed by the activities within INAF Institutes related to ongoing projects like LSPE/STRIP, ALMA band 2+3 development, SRT upgrades.

10.5.6 RF and Power Analog signals transport over optical fibers

In recent years, **RFoF** has revolutionised the mobile telecommunications industry, especially for giving mobile users full coverage, even in radio shadow areas, such as road tunnels, underground stations or large buildings. These links are deployed for millions mobile networks in developing countries such as China as a cost effective way to expand the coverage of base stations. As a result of such mass production and improved production facilities, RFoF links employing high performance lasers and detectors have reduced dramatically in cost and the whole industry sector has become established. Perspective for the future will be the increasing of the total link-length up to 40Km without losing performances and decreasing costs of the RFoF modules. RFoF is an attractive technology for implementation in the SKA.

10.5.7 Cryogenics and thermal engineering

Cryogenics and microwaves are tightly related since the microwave instrumentation needs to be cooled down at cryogenics temperature to reach sensitivities that are requested by the ambitious scientific goals. The thermal environments should be designed and developed to guarantee the necessary thermal stability and duration to exploit the instrument performances at the best. This requires accurate choice of materials and instrumentation, and accurate thermal design with advanced software. Cryogenics and thermal aspects are fundamentals also in the design and development of dedicated test environment for accurate characterization and calibration of instruments. In recent years, the demand of cryogenic working temperature environment is involving more and more detector technologies covering a wide range of observation frequency (from radio to gamma-ray).

To face the needs in integrating and test cryogenic radiometers the Cryowaves Lab in INAF-IASF integrates cryogenic and microwave facilities and competences, Thanks also to the sharing of the instrumentation with INAF/IRA the laboratory is equipped to perform W-band measurements at cryogenic temperature down to 2.5Kelvin. The two cryo-facilities permit to test materials and instrumentation up to about 1-meter in size. At the moment is used to integrate and test the 67-116 GHz Band 2+3 ALMA cartridge prototype and will be host the LSPE/STRIP instrument for system level tests. The INAF/OAA RF laboratory is equipped by a 4-ports VNA up to 116 GHz and permit to accurately test and develop passive components and horn antenna pattern in anechoic chamber.

10.6 Specific technologies for Planetology, Space Weather and Gravitation oriented instrumentations

Among the enabling technologies, special attention needs to be paid on a transversal development line which cannot be framed in the previous ones, since collects interdisciplinary technological know-how and applies to different scientific fields. Actually, this domain ranges from the investigation and monitoring from space of planets (Earth included) at different levels (atmosphere, surface, gravity) to the simulation of planetary environments and instruments test carried out on-ground in ad-hoc-enabled special facilities.

10.6.1 Labs and test instrumentations, characterization, planetary environment emulator

Laboratory activity in INAF has a well-established and long experience. Activity in the lab spans from the characterisation of planetary analogues (meteorites, minerals representative of the surface of asteroids, comets, Mercury, Mars, etc.) to simulation of chemical-physical conditions characteristics of different planetary environment, in particular the terrestrial ionosphere and magnetic field, atmospheres of planets as Venus, Jupiter or exoplanets. Along with the development of new future space missions dedicated to the exploration of the outer solar system and to the sample return, new laboratory activities are going to be implemented and built up. New setups allowing to characterise the optical performance of materials, plasma and fields detectors, optical fibers and subsystems at different temperatures and exposed to harsh radiation environment are becoming a need to base a solid instrument development in house or in collaboration with industries. Radiative transfer modelling requires sometime the state of the art characterisation at extreme conditions, especially for exotic worlds found in extrasolar systems at present time. This essential support to the data interpretation and modelling from the lab requires technological development and expertise in different fields with the aim to build up spectroscopic databases in support of future space missions and ground based observations. The study of a planet' habitability, one of the breaking through concept of the new fields of science investigation, requires new setup concepts to trace the evolution of micro-organisms in controlled atmosphere, to monitor how they can affect the gaseous environment and what can be observable remotely. A long and fruitful experience has been reached thanks to the development of **spectrometers in the VIS-IR range**, in particular imaging spectrometers, a technology in which Italy is extremely competitive and with a solid reference for future investments. Just to cite some past and present examples: VENUS-Express, Cassini-Huygens, Rosetta, Dawn, Juno, etc. For the future, missions planned as BepiColombo, ExoMars and JUICE represent an important path for the future generation. Beyond ESA, the long experience of Italy and INAF team has consolidated very good partnerships with NASA, JAXA, CNSA and other space agencies. The work in collaboration with high level technological industries has established also an important asset for the Italian system in terms of R&D and social impact. Large steps forward can be imagined in the next years, particularly in the field of the **miniaturisation**, as it has been done for MicroMIMA, of the robotic exploration as for example MAMISS and of the instrumentations dedicated to the collection and return of samples from the Moon as for example PROSPECT. The highest priority in the next decades will be the development of new enabling technologies for hostile environments as those encountered in the magnetic field of Jupiter and its satellites and for the exploration of the external solar system, in particular Uranus and Neptune. A lot of interest and involvement is dedicated to in situ probes such as landers, balloons, drones and gliders with the objectives to study active volcanism, composition and dynamics of the atmospheres.

10.6.2 Contamination measurement system and Micro balances

Planetary protections are regulated through legal aspects agreed by all space agencies that guide the design of space mission to protect solar system bodies from **contamination** by Earth life forms, and protecting Earth from possible life forms that may be returned from other solar system bodies. Planetary protection is essential to preserve our ability to study interesting planets, moons and small objects of our Solar System from astrobiology point of view. The contamination of celestial bodies by Earth organisms and organics needs to be avoided because it could lead to false-positive results. The second aspect of planetary protection aims to protect the Earth's biosphere from extra-terrestrial agents, which might be harmful if released into the

Earth environment. Contamination prevention must maintain the samples returned from space missions in their pristine status for long-term storage. Contamination prevention affects hardware of spacecraft, instruments and electronics avoiding any kind of release of contaminants during the visit of mission target. Thus, any transfer of chemicals, liquids or particulates of terrestrial origin (environmental, human, processing, facility, equipment and working activity) to the target has to be minimised. **INAF astrobiology laboratory** is equipped with cleanrooms with airlock and clothing-change area where contamination prevention and control for space hardware is performed. At INAF laboratory, known contaminants on surfaces and air are monitored periodically both by passive witness plates mounted in different places of the cleanroom and by active monitoring instruments (FTIR, HPLC, LCMS). Concerning unknown contaminants, tests and analyses are also performed periodically. The results of these tests and analyses are used to calculate expected contamination levels and their subsequent effects on space hardware and if other relevant parameters are known, providing input for engineering control to remove or minimise contaminants. INAF is involved in planetary protection activities of ExoMars 2016 and 2020 missions to Mars, is responsible for planetary protection activities for the design of international curation facility for sample returned from space and is responsible for planetary protection policy and requirements for missions to icy moons (Europa, Enceladus, Titan, etc.).

The project CAM (**Contamination Assessment Microbalance**), funded by ESA, is aimed to the development of an engineering model of a sensor, based on Quartz Crystal Microbalance (QCM) technology, able to monitor contamination processes in space due to outgassing by spacecraft components. CAM is the first sensor completely developed in Europe. Among the QCM based sensor, CAM presents innovative features:

- Crystals' temperature can be directly measured thanks to the resistors directly integrated on the crystals themselves, increasing the measurements precision
- Large dynamical range of measured contaminants masses.
- Large operative temperature range and temperature stabilization capability.
- State of the art frequency resolution.

The CAM consortium is leaded by INAF and includes IAA-CNR and PoliMI. The same consortium has already collaborated to the VISTA (Volatile In-Situ Thermo-gravimeter Analyzer) project, aimed to the in-situ measurement of volatile materials on planetary surfaces and to the development of the instrument MOVIDA (MOon Volatile, Ice and Dust Analyzer) for a future possible Moon lander. QCM is suitable as technological transfer in the framework of gas and particulate emission monitoring in civil motorized vehicles, industrial process and volcanos. The next step for the CAM project is the development of a flight model aimed to the outgassing and outdoor contamination monitoring by sensitive elements suche as solar panels and optical elements.

10.6.3 Neutral atoms detection systems

The investigation of the interaction of bodies in the Solar System with the environments via detection of **Energetic Neutral Atoms** (ENA) is a relatively recent technique with extensive technological development after the first dedicated mission in 2000 (IMAGE-NASA mission) devoted to Earth environment. The neutral atoms do not interact with electromagnetic fields. Hence, they have the property to maintain their characteristics (energy, distribution and direction) unchanged since the generation time, if their energies are high enough to consider the gravitational effects negligible. So we have a good way to obtain the information about the generation process through ENA detection, similarly of imaging performed with photons. We know three main generation mechanisms of atoms at energies well above the gravitational effects: charge-exchange, back scattering and ion sputtering processes from atmospheres and surfaces. The energy range spans from tenths of eV up to hundreds of keV. The power of this technique has been demonstrated by the results obtained by many ENA imagers flown in space missions, and is proven by the inclusion of ENA imagers in many of the future Solar System missions. The required sensor designs and technologies are different depending on the energy range. In particular the choice and development of particle detectors (i.e. Micro Channel Plate, CEM) is a crucial point in the instrument design, together with the used devices for noise rejection, like ion deflectors and UV filters. INAF was involved in the design and realization of many ENA sensors since the early development of this technique (ISENA instrument on SAC-B mission in 1996, ASPERA-3 and ASPERA -4 of the MEX and VEX missions in 2003, SERENA-ELENA sensor for BepiColombo mission expected in 2018. In particular, INAF acquired a prominent position in the international context in the low ENA detection. The ELENA sensor design is innovative since, given the efficient and innovative technologies developed for ion and UV rejection, it can detect the neutral particles without ionization, so that ELENA can be considered a kind of particle pin–hole camera. Thanks to this new sensor design, an unprecedented angular resolution of low – ENA detection has been achieved, thus a real imaging of the backscattering from planetary surfaces trough ENA will be possible. The tests of the instrument are performed in the vacuum chamber in INAF where an ion beam source is available. Future technological development includes new prospective for detectors under investigation (i.e. Gas detector and APD for energetic neutral atoms detection, shuttering system for Time of Flight, dedicated coatings for MCP efficiency enhancement, etc.) together with the optimization of the sensor subunits (ion deflectors, UV filters, Time of Flight solution).

10.6.4 Stereo-cameras

The 3D mapping of a planetary surface has become almost mandatory in planetary space missions and enabled the morphological analysis of any feature, providing a fundamental step forward for planetary geology. Moreover, the 3D information is required by many instruments on board the planetary missions in order to accurately register their measurements. INAF realised the first **stereo camera**, on satellite, based on the stereo acquisition of the push-frame and with the two channels converging on the same detector. This novel stereo approach makes easier the matching between more images of the same region and, at the same time, makes more compact the instrument design. INAF is PI of SIMBIO-SYS, on board the ESA mission BepiColombo, including the new stereo camera. Then the same stereo camera concept has been implemented on CaSSIS on board Exomars TGO, where INAF is CoPI. The projects involving stereo cameras have been realised in collaboration with the major European institutes involved in planetary missions, as the IAS (France), the dept. of Physics in Bern, the DLR in Berlin. Moreover, there is collaboration with Chinese institutes within the MoonMapping project of ASI involving also 3D mapping of the Moon and the implementation of a stereo camera for future Chinese exploration of the terrestrial planets. The stereo cameras mentioned have been realised from the Leonardo s.p.a. that acquired a unique expertise in this field, at European level with possible extension to the USA. An important evolution of STC, introducing also the hyperspectral information, brought to the deposit of a patent, on September 2016, for an HYPerspectra Stereo Observing System, (HYPSOS) together with the EIE Group.

10.6.5 Coronagraphs

In the last two decades, the observation of the solar corona from space has let to breakthrough advancement in the understanding of the acceleration and heating mechanism of the solar wind and of the highly energetic transient events of the solar atmosphere (e.g., coronal mass ejections, solar energetic particles). INAF, together with the Italian space industry, has played a key role in developing, testing and operating space-based, solar coronagraphs that adopt innovative designs and technologies. Based upon the heritage of the UVCS coronagraph for the SOHO missions (launch 1994) and on that of the SCORE coronagraph for the NASA sub-orbital mission HERSCHEL (first launch 2009), INAF is the PI institution, and Thales-Alenia Space, Italy, is the prime-contractor, of the Metis coronagraph for the ESA Solar Orbiter mission. The innovative Metis design of the telescope apodization scheme includes novel optical technologies such as multi-wavelength optical coating, space-qualified liquid-crystal polarimeter. INAF is Lead-CoI for the Italian contribution to the ASPIICS coronagraph for PROBA-3. This is the first formation-flying space mission. INAF is responsible for the development of the formation flying sensors and algorithms, as well as the ultra-narrow bandpass filters developed with Optec (MI).

10.6.6 Technologies and instrumentations for experimental gravitation

In the last years, the investigation of planets **gravitational field** carried out by planetary missions has become an objective more and more chased by the scientific community. This is due to its invaluable capability of providing an understanding of the interiors of planets, a link between the interiors and the surface features, a view of the overall planet dynamics and evolution. In the classic radio-science experiments a high accuracy tracking by ground stations of a spacecraft orbiting a planet, following its free-fall in the gravity of the central body, allows to reconstruct the gravity field once the non-gravitational forces acting on it are carefully monitored and evaluated through high sensitivity **accelerometers**. Technologies involved behind these high sensitivity sensors intertwine remarkably interdisciplinary know-how and expertise: measurement of very tiny displacements and forces, active and passive thermal control systems, environmental noise reduction, testing of new sensing materials, ad-hoc interface and control electronics, mechanical design and manufacturing. **Gravity gradiometry**, enabling the reconstruction of the gravity field from measurements of gravity gradients, represents an innovative and promising method to push the investigation of planets to higher spatial resolutions. Such a sensing technology would enable the capability of identifying smaller and smaller surface and subsurface features, fundamental to understand the geophysical and geological processes of planets. The common technology behind these two types of sensors enables the capability to arrange and to carry out fundamental physics experiments focused on the verification of General Relativity and its connections to quantum gravity as well as verifications of the Einstein Equivalence Principle in the Weak Equivalence Principle formulation and the measurement of the Newtonian gravitational constant. INAF developed a well-established know-how and expertise with the first high sensitivity accelerometer ISA to be launched in 2018 through the ESA BepiColombo mission. INAF sensing technology employs mechanical-suspended sensors which feature the capability to be used for on-ground applications as well, such as networks of seismometers on the surface of planets, in addition to Earth (or Moon) as well, or as instruments for monitoring low frequency vibrations (induced on the frame of a telescope for instance). INAF, PI of ISA accelerometer on-board BepiColombo, is involved in the definition of experiments, the development of prototypes, the sensors calibration and the data analysis methodologies. A joint collaboration was established with the Radio Science Laboratory at "La Sapienza" University, Thales Alenia Space and ASI. INAF is involved in LARASE as well, a project (INFN funded) devoted to study laser ranging data of geodetic satellites such as LAGEOS, LAGEOS II and LARES in order to test important general relativistic predictions in the field of the Earth, at the same time placing constraints to alternative theories of gravitation. Very promising perspectives of INAF technology application are foreseen for next radio-science experiments which aim at sending spacecrafts to Jupiter and its icy moons, in addition to advanced studies for Venus and Uranus/Neptune. A first step towards the planetary seismology is starting with the NASA InSight mission to Mars. In general, significant progresses on the study of planets interiors would come from synergic investigations from space and from ground.

10.6.7 Plasma Chamber SIM.PL.EX

The **plasma chamber** developed at INAF is a European unique facility capable to reproduce a large volume ionospheric environment, which is particularly suitable to perform studies on a variety of plasma physics subjects that can be summarises as follows:

- Calibration of ground and space borne plasma diagnostic sensors (Langmuir probes, Retarding Potential Analyser, etc.);
- Functional tests of experiments envisaged to operate in a ionospheric environment (sensors exposed to space plasma);
- Characterisation and compatibility tests of components for space applications (materials, satellite paints, photo-voltaic cells, etc.);
- Basic plasma physics experiments (interaction of charged bodies with plasma, two plasma interaction processes, propulsion and power generation in space through electrodynamic tethers);
- Tests on active experiments which use cathodes and/or plasma sources (ion thruster, ion beam neutralizers, hollow cathodes, field effect emitters, plasma contactors).

The facility consists of a large volume vacuum chamber (a cylinder of length 4.5 m and diameter 1.7 m) equipped with a plasma source of Kaufman type. This source produces Argon plasma with parameters (i.e. electron density and temperature) very close to the values encountered in the daytime ionosphere at F layer altitudes. A variation of plasma density in the experimental region downstream the source, could be obtained by varying the source current discharge and neutral gas flow rate. The plasma generated by the source is accelerated into the chamber at a velocity that can be tuned to simulate the relative motion between an object orbiting in space and the ionosphere ($\cong$ 8 km/s). This feature, in particular, allows laboratory simulations of compression and depletion phenomena typical of the ram and wake regions around ionospheric satellites (e.g. ISS). In addition, a new plasma source able to simulate the interplanetary solar wind is currently under development. Moreover, the facility is equipped with a two-axis magnetic coil system capable to control the ambient magnetic field. The field vector components within the chamber can be independently controlled along axial and vertical directions. In this way, the plasma beam and the magnetic field pattern can be set to reproduce the conditions encountered by satellites in both equatorial and polar orbits. The magnitude of the field can be varied between 0 and 10-4 T. In particular, experiments in absence of the field can be performed by annulling the Earth's magnetic field. In fact the terrestrial field can be compensated down to a residual value of 2.5×10-6 T in a volume of about 1 m3 located close to the coil center. Such a residual field is sufficient to consider the plasma non magnetised, being the electron gyroradius (with Te $\cong$ 2000 K) of the same order of the chamber dimensions (i.e. the electron motion is not dominated by the field but rather by collisions with the chamber wall). At present time, the Plasma Chamber Research group is involved in the calibration tests of Electric Field Detector (EFD), Langmuir probes, Ion Drift Meter, Ion Capture Meter, and Retarding Potential Analyser of CSES satellite (China) and in the development of the Italian EFDs. In addition, an experiment for a new Magnetic/Plasma propulsion is in progress.

10.6.8 Facilities (cryogenics, calibration and test, metrology)

One of the key strengths of INAF is the possibility to use, in collaboration with the industry, several **facilities** to test space components and/or instruments which are part of a payload. Such facilities allow to assembly, to characterise, to test and to calibrate instruments in different environmental conditions for space and ground applications.

10.7 Software, Computing and Data Management

Progress in astrophysics is, and in the near future will be, strictly driven by instrumentation of ever growing complexity, and by a new generation of telescopes and larger observatories. These facilities allow performing observations at higher spatial, temporal and spectral resolution, on wider fields and/or at increased depth. Coping with such an increase in complexity and size is possible by advances in several technological fields, including optics, materials, detectors and high-performance software for instrument control, data processing and data analysis. In particular, the **embedded real time SW** (for both instrument control and data processing) should be indeed considered an important component of any astronomical instrument. A common trait of future observing facilities is the need to accurately control in (close to) real-time many of its elements in order to achieve the required performance and, ultimately, the desired science results. As a matter of fact, once the instrument HW is finalised, the only component that can be still modified to solve problems and to optimize the instrument performances is the on-board control and pre-processing SW. With respect to the **high performance data analysis SW**, the data volumes and rates produced by the new facilities are growing exponentially, greatly accelerating our understanding of the physical universe, but posing severe constraints on the required computational efficiency, archival research and data processing and understanding. Furthermore, **numerical simulations** are increasingly becoming the dominant or even the only way in which various complex phenomena (e.g., star formation, lensing or galaxy formation) can be modelled and understood. A typical modern sky survey may produce hundreds of petabytes of re-usable images, and may detect between 10^8 and 10^9 sources, with an associated parameter space of about 10^2 up to 10^3 attributes for each source. Astrophysics therefore may well be considered as an integral part of the **Big Data** phenomenon. This creates new possibilities to carry out research and to share knowledge within the community, to cross-fertilise with other disciplines and to re-use information for education and outreach, as we move rapidly towards Open Science. But both the scientific opportunities and the technological challenges are conditioned and dependent by data modelling, data processing, data mining and fusion, across different wavelengths, temporal, or spatial scales. As a consequence, a coordinated and efficient **e-infrastructure**, and the related know-how in SW development, is necessary to allow Big Data to be exploited to their full potential.

The European Commission plans to create a new European Open Science Cloud (EOSC) by interconnecting the existing research infrastructure, with the goal of offering to European researchers and science and technology professionals a virtual environment to store, share and reuse data across disciplines and borders. The Commission is therefore investing directly, overall, 2 billion of Horizon 2020 funding in the European Cloud initiative for a period of 5 years, out of an estimated total of 6.7 billion to fully cover the initiative, which includes additional public and private investment. The initial part of this H2020 funding has already been allocated to a number of e-infrastructure projects: EGI, EUDAT, IndigoDataCloud, and EOSCpilot. Two important projects for our community funded by H2020, ASTERICS (which focuses on the e-infrastructure needed by the ESFRI and other world-class projects in astrophysics and astro-particles) and AENEAS (concentrating on the future needs for SKA)

have no definite links with the above-mentioned generalist e-infrastructure projects. What the astrophysical community is thus lacking is a connection between the capabilities of managing data and of performing processing on them within the same interoperable environment, such as the Cloud expects to be. The European Commission has also recognized the need for an EU-level policy in HPC to optimise national and European investments addressing the entire HPC ecosystem, and adopted its HPC Strategy on February 2012. The Commission underlines that it is strategic to develop the next generation of HPC technologies, applications and systems to reach exascale capacity: this will engage an European-wide effort to develop autonomous technology to build exascale systems and novel applications within ~10 years. The new generation of **HPC technology** will cover the whole spectrum from processors and system architectures to high-level software and tools, to delivering prototype exascale systems and associated applications (H2020 - FET program). Moreover, we must consider that HPC, mainly used in the last few years for large simulations (e.g. cosmological simulations), now starts to be a fundamental infrastructure for the data analysis processes of new experiments (e.g. Gaia mission, Euclid preparatory phase/simulations, etc.). Data processing pipelines being designed or built for new ground- based and spaceborne observing facilities are in the process of adapting to this new trend. But it is now recognised that data management also needs to modify its approach: to allow Big Data to be properly exploited, they are expected to be compliant to the FAIR principles (Findable, Accessible, Interoperable, Reusable). The astronomical community is at the forefront of the FAIR adoption, due to the widespread use of the **Virtual Observatory** standards defined by the IVOA (International VO Alliance). In recent years multidisciplinary activities have started within the Research Data Alliance (RDA), aiming at achieving FAIR management of data in the different domains and across them; IVOA participates in the RDA.
A confluence of two factors pushed astronomy to the forefront of data-intensive science. First, astronomy has embraced **ICT and data mining** as powerful means for dealing with the data and as an evolutionary process to satisfy the most demanding scientific challenges. Second, the advent of large digital sky surveys pushed the astronomical community towards the solutions proposed by the Virtual Observatory and Knowledge Discovery in Databases initiatives. One of the main consequences is the recent emergence of **Astroinformatics & Astrostatistics**, a discipline bridging astrophysics on one side, and ICT and data mining on the other. Nowadays there is an exponential proliferation of free data mining services and infrastructures, several of them already scientifically validated in astrophysics (e.g. Knime, Orange, Rapid Miner, Weka, VoStat and DAMEWARE). Moreover, Astroinformatics carried a rising up of several international initiatives, such as the ASAIP (Astrostatistics and Astroinformatics Portal), dedicated symposia and the first European professorship of Astroinformatics, appointed to INAF staff. The importance of these activities for astrophysics has been recognised also by the IAU, through the creation of specific Commissions: B1 (Computational Astrophysics), B2 (Data and Documentation) and B3 (Astroinformatics and Astrostatistics).
With respect to the problem of **controlling** with an adequate precision all the elements of a complex astronomical instrumentation, it should be noted that it has been treated differently depending on the domain (e.g. optical/radio) or the constraints (e.g. space or ground environment). A wide range of computing technologies have been adopted (CPU, PLC, FPGA, DSP), sometimes privileging performance, other times constrained by existing standards. As a result, the reference context for this type of activity is on one side characterized by the effort made at space agencies' level for standardizing on-board software applications and algorithms and on the other side by the effort made by some European Scientific Institutions in the definition of a common framework for the development of all the future real-time applications for the monitoring and control of the astronomical instrumentation. In the first case, both ESA

and NASA in the past years supported R&D activities mainly devoted to the construction of coherent frameworks for the development of Control Software at satellite level, like, e.g. the NASA Core Flight Software System. In the second case, an ongoing effort in facing the problems due to the HW obsolescence issues and in building efficient distributed architectures, has led to the development of open source middleware solutions embedded into more general multi-purpose frameworks (e.g. the TANGO control system) and to an effort in the exploration of the possibility to adopt COTS industrial standard solutions (e.g. OPC UA).

The national scientific community has been involved in the development of the European **e-infrastructure** since its very beginning. INFN has been among the leading developers of the distributed computing Grid infrastructure (EGEE) in the last decade, and is currently leading the IndigoDataCloud e-infrastructure project funded by the EU H2020 programme. CINECA has been involved since the beginning in the development of the European HPC network (DEISA, PRACE). A few INAF researchers have been involved in the development and especially in the use of these e-infrastructures; there are recent minor participations in IndigoDataCloud, EGI-Engage and EOSCpilot.

The **ICT Unit** of the Scientific Directorate has carried out surveys and consulted several times the community of INAF scientists involved in different research aspects such as theoretical astrophysics, data analysis, modelling etc. On the basis of the results of such surveys, INAF has recently signed a formal agreement with CINECA to provide computational resources on infrastructures of the class of Tier-0 and Tier-1 for the needs of the community: the agreement has a 3 years breadth, is renewable every year and provides also specific support for the development and porting of key applications on innovative HPC systems based on accelerators. This infrastructure is also fundamental to start to develop the prototype SW infrastructure for the analysis of large/big data that are expected from the most important experiments as mentioned above. But experiences, and the results of the above-mentioned surveys, have also shown that the Grid and HPC mechanisms have proven to be only partially useful to solve the variety of different computing challenges that the INAF community is facing. In particular, the INAF scientists have evidenced the lack of a Tier2-class system capable of covering HTC and small-HPC computing activities. A pilot project (CHIPP) started in March 2017, and uses existing infrastructure (at OATs and OACt) aiming at verifying if systems internal to the Institute can cover a missing part of the community needs, and if there are enough scientists wishing to use this type of facilities. INAF, through the H2020-funded ExaNeSt e EuroExa, is also playing a central role in the European context for what concerns the FETHPC projects, in particular for the prototyping of HW and SW and for the development of a new generation of astrophysical codes able to benefit of exascale computing capabilities. As a consequence, we are actively working to have a new generation of researchers with high specialization to join with specific research groups that require fundamental contribution for innovative computational infrastructure and for complex data analysis with very large datasets.

Concerning activities related to **Astroinformatics & Astrostatistics**, progress in this arena is already active within INAF. It is based on activities of individual research groups in collaboration with large survey projects, promoting data mining R&D, decision support and computing solutions to approach “data driven” problems in a wide spectrum of astrophysical contexts, especially when traditional approaches may result less efficient.

As for data management, INAF staff has been working for the past 12 years on the definition of VO standards, and now leads IVOA WGs and Interest Groups. Therefore the INAF **data archives** installed at IA2 and in other structures, including those stored at ASDC, are compliant with VO standards, and this is an excellent stepping-stone for the development of FAIR archives within future projects. Furthermore, the INAF group is the only one in the world-wide

astrophysics domain having worked on the interoperability between data management and processing, and on bringing processing to the data within a coherent environment.
With respect to the activity of (near) **real time SW** development, the Italian Astronomical community has since a long time a strong involvement in many projects for the construction of observing facilities and instruments, both space borne and ground-based, and across all domains of the electromagnetic spectrum. In particular, the past experiences in the development of **control software and data processing pipelines** for VLT, LBT, VST, TNG, WHT, SRT, etc. and in instruments like FLAMES, X-SHOOTER, SPHERE, GIANO, LBC, VIMOS, ESPRESSO, have allowed INAF to gain the expertise needed to become a competitive actor in this field at European and world level. The strategic decision to become a member of the TANGO collaboration provides also the necessary baseline for future developments of object oriented control applications. Analogously, for space borne instrumentation, Italy has played leading roles in designing and implementing **control systems** and the **science ground segment** for some of the most successful ESA space missions, , e.g. for LFI/Planck, SPIRE, PACS and HIFI for Herschel, Gaia, VIRTIS/Rosetta, etc. The gained know-how in real-time SW space applications, together with the acquired knowledge of the very stringent and rigorous standards for the development of space qualified SW, can be considered as the key for similar collaborations in the future space mission of interest for the INAF science. There is also a strong and solid know-how on data handling of the space missions related to high energy astrophysics (e.g. BeppoSAX, Swift, INTEGRAL, NuSTAR, AGILE, Fermi, etc.). Starting from the BeppoSAX experience INAF scientists and engineers have developed the data analysis software for the X-ray telescope on board Swift, for the X-ray telescope on board NuSTAR but also for gamma ray instruments on board the AGILE mission. Now, starting with the participation in the MAGIC experiment, also data analysis software for Cherenkov telescopes is developed within the ASTRI and CTA projects. The Gaia data have led astronomical community in the Big Data Era and INAF is contributing on both data reduction and analysis of Gaia data with ALTEC and large databases management at ASDC. Also for the next decade, INAF and the Italian Astronomical community have already put in place strong involvements in many projects that are currently in the design or construction phase. Among them we can mention the ground-based CTA, ELT, SKA, the space missions like Euclid, Plato, Athena, plus possibly ARIEL, SPICA and NASA/OST. For many of these projects Italy is contributing key parts of the **control systems** (either for the observing facilities themselves or for the instrumentation), as well as **data analysis infrastructures** (e.g. science ground segments, or data processing pipelines). These collaborations, focused on SW aspects, will provide the INAF community with a guaranteed scientific return, thus confirming the strategic importance of the SW development expertise within INAF. At the same time, the use of data from new-generation large surveys, such as the ground based Large Synoptic Survey Telescope (LSST), might shed light on the nature of dark energy and dark matter and possibly revolutionize modern physics.
As described above, the **control software** is one of the key elements of an observing facility. A proper connection between the science requirements and the design and implementation of the control software is fundamental to reach the science goals. This is more easily achieved if the relevant skills and competencies are present within the Institute and work side by side with the science community. This is even more important if we consider that custom solutions are expensive both to implement and to maintain (especially in the long term) and the possibility to share either already implemented applications or already acquired expertise provides a mean for keeping the costs under control and increasing the overall efficiency. Proper coordination

of the existing competencies would allow INAF to become a reference institution at European level for this kind of activities.

The **data processing and computing** challenges, plus the preparation for the large projects mentioned above, involving in the medium term the INAF community basically constitute a continuum requiring a variety of computing, storage and transmission power. It is therefore reasonable to state that there is not, nor is likely to appear soon, a catch-all solution. In a 7-10 years perspective the needs of the community are likely to be satisfied by a whole set of different e-infrastructures, such as individual laptops, local clusters, cloud (EOSC, commercial) distributed computing, dedicated computing, HPC. Such systems shall include the capability of using hardware accelerators (currently GPUs, FPGA, and other non-conventional mechanisms). Efforts are necessary to ease the transition from one system to the other, ideally building an integrated, or at least interoperable ecosystem. INAF needs to invest on the e-infrastructures it can afford, i.e. personal and local computing, plus INAF-wide "Tier2" computing, making sure that its scientists are allowed and trained to use the global domain-agnostic facilities (the EOSC Cloud, the HPC network). Actually, in a view of optimisation of resources, it is important for INAF to take advantage of infrastructures supported by the European Commission. On the other hand, it is strategic for INAF to develop the next generation of HPC applications towards exascale capacity, joining the European-wide effort to develop autonomous technology to build exascale systems and novel applications within ~10 years.

Large archives are instead something that the astronomical community needs to develop on its own, due to the peculiarity of data, metadata and access techniques. The main priorities in this field are investments on new technology for efficient access to online data and fast data preservation systems. The FAIR principles for huge data need always to be guaranteed to ensure the highest degree of exploitation: this means that there is a need for extension and generalisation of the IVOA standards, both to allow covering new sets of data currently unsupported, and to take advantage of domain-agnostic e-infrastructure developed in the framework of EU support to science. Key in this view is to work on interoperability and federation between data and computing, thus extending the current VO vision.

The real job of science, data analysis and understanding and knowledge discovery, starts after data processing and delivery through the archives. The profound, universal change in the ways we do data-driven science has been recognized for over a decade now, and is sometimes described as e-Science. The e-Science expressly tailored on Astrophysics is **Astroinformatics**. Born as a typical multi-disciplinary framework, this discipline has a nature and a vocation completely horizontal with respect to astrophysical research topics: it is therefore the most suitable mechanism to profit of the current wealth of data. Many good statistical and data mining methods exist, gradually permeating the astronomical community, although their uptake has been slower than what may be hoped for. Effective, scalable software and a methodology needed for knowledge discovery in modern, large and complex data sets typically do not exist yet, at least in the public domain. The key to further progress in the Big Data scenario is to promote and sustain R&D in data mining and exploration tools able to operate on the tera-scale data sets and beyond.

11 The Project-Question-Method Matrix

In the previous sections it has been developed a detailed analysis of the most challenging scientific questions for the next decade, of the enabling technologies required to answer them and of plausible/possible INAF contribution to the major projects in the international scenario. It is now possible to rearrange the previous tables in one table grouping questions and methods as a function of the projects (see Appendix 1.1 and 1.2).

This list is intended to include all the projects that can give a substantial contribution to solve the "key questions". It should not be intended as exhaustive of all the projects in which INAF is or should be involved, nor of those that are being discussed within the astrophysical community, for at least two reasons. On the one hand besides the large projects listed here, it is important to support the small-scale, extremely innovative, high-risk high-gain projects, on which a scientific community thrives. On the other hand in scientific research the investigation or even the solution of a problem continuously generates more complex and fascinating questions. Obviously in the next decade new and unforeseen concepts and projects will be proposed and will have to be evaluated and eventually inserted in the strategic context laid out by this plan and its future updates.

Appendix 1.1 Projects with a significant future technological involvement of INAF

Project	Key Question	Method	Future INAF technological contribution
SKA	Processes that determined the formation and evolution of the Solar System	Observations of primitive bodies, exoplanetary systems (dust aggregation processes, formation processes)	Antenna systems Heat rejecter Phased Array Feeds Front end optical transmitter and receiver Analogue fiber optical RF/ RFoF UAV Digital back-end Readout Electronics Real time SW Control SW Big Data Data analysis infrastructures
	Proto-planetary discs: initial conditions for the formation of planets	Formation and evolution of disks: solids from dust to planets, gas content, dissipation, chemical evolution of complex organic molecules, wind properties from thermal free-free and radio lines. Magnetic field orientation and amplitude around jet/disks. Disk-star-planet interaction	
	Evolutionary processes giving origin to the emergence of life	Observation of primitive bodies (organic material and ices)	
	Taking stellar models to the next power	Comparison of magnetic fields measurements with model predictions	
	Physics of accretion and ejection onto/from compact objects	Observations of galactic and extragalactic compact objects	
	Equation of state of nuclear matter and “strange” stars; Pulsars; compact binary systems	Measurements of periods and period derivatives, moments of inertia of compact stars	

	Global star formation properties	Faraday tomography, thermal free-free, HI and RRL. Complete inventory of interstellar species accessible in the cm-range	
	Origin and evolution of galaxies	HI content of galaxies Detailed observations of gas kinematics, outflows, inflows. Connection with CGM and IGM	
	Properties of first galaxies and BHs Sources of reionization	21 cm tomography.	
	Cosmology with LSS of the Universe: nature of the DM and DE, Physics of the initial conditions (non-gaussianity)	Intensity mapping	
LOFAR	Global star formation properties in the MW: molecular clouds & dense gas Formation and evolution of galaxies The lifecycle of radio AGN	SFR, star formation efficiency, Physical mechanism responsible for the onset of star formation in very different places of the Galaxy. Creation of a ’fundamental theory’ of a galaxy-scale predictive model for star formation that can serve as a "z=0 template" for external galaxies. Radio-continuum observations of synchrotron emission from galaxies and AGNs	
	How can the space weather be monitored and forecasted?	Monitoring of the Sun activity Developing forecasting tools	

SRT	Global star formation properties in the MW: molecular clouds & dense gas Particle acceleration processes at all different scales Physics of accretion and ejection onto/from compact objects	SFR, star formation efficiency, Physical mechanism responsible for the onset of star formation in very different places of the Galaxy. Creation of a 'fundamental theory' of a galaxy-scale predictive model for star formation that can serve as a "z=0 template" for external galaxies. Role magnetic fields in during the collapse of the various phases of the interstellar medium and at all Galactic spatial scales Jet structures on sub-parsec-pc scales. Hot spots and radio lobes. Radio relics in clusters. Supernovae remnants. Pulsars, Gamma-ray burst. Efficient/inefficient accretion modes. Winds and jets.	Active optics Phased Array Feeds Front end optical transmitter and receiver Analogue fiber optical RF/ RFoF Digital back-end Readout Electronics Real Time SW Control SW Big Data Data analysis infrastructure
	How can the space weather be monitored and forecasted?	Monitoring of the Sun activity Developing forecasting tools	
ALMA	Origin and evolution of galaxies		Heat rejecter Digital back-end Readout Electronics Multi beam and multi frequency systems Cryogenics and Thermal Engineering Data analysis infrastructures
	Global star formation properties	Surveys of several thousands of star-forming as well as pre-stellar clumps in a variety of Galactic environments	
	Physics of individual star formation events	Surveys of cores, protostars, and circumstellar disks. Astrochemistry of early phases, formation of complex molecules.	

	Proto-planetary discs: initial conditions for the formation of planets.	Robust determination of dust-to-gas mass ratio in disks. Dust evolution, disk dissipation. Distribution of the magnetic field around young stars. Spectro-imaging of molecular jets and outflows. Studies on angular momentum evolution. Identification of the mechanisms generating disk structures (gaps, rings, spirals, etc.), and their relation with the presence of newly formed planets.	
	Processes that determined the formation and evolution of the Solar System	Observations of primitive bodies, exoplanetary systems (dust aggregation processes, formation processes)	
	Evolutionary processes giving origin to the emergence of life	Observation of primitive bodies (organic material and ices)	
	Jet production and ejection in accreting systems	Observation of multi-wavelength spectra and fast time variability	
SPICA	Origin and evolution of galaxies	ISM in the MIR and FIR	Control SW Real Time SW Data analysis infrastructures
	Star formation vs. gravitational accretion in high-redshift sources	Spectroscopy in the far infrared	
	Physics of individual star formation events	Spectropolarimetry in the FIR	
ARIEL	Chemistry and dynamics of exoplanetary atmospheres	Very high S/N, low and medium resolution NIR/MIR transmission and emission	Free-form/aspheric optics Cryogenics and Thermal Engineering Readout Electronics

		spectroscopy (down to the Super Earth regime).	Onboard Electronics Real Time SW Control SW Ground segment Data analysis infrastructures
Gaia	Formation and evolution of sub-galactic structures in the Milky Way and the Local Volume	Astrometric results also combined with spectroscopic complementary data	Data analysis infrastructures
	The chemo-dynamical evolution of star clusters in the MW and in other galaxies	Astrometric results also combined with spectroscopic complementary data	
	The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond	Astrometric results also combined with spectroscopic complementary data	
	The role of pulsating stars and Surface Brightness Fluctuations as tracers of resolved and unresolved stellar populations	Astrometric results also combined with spectroscopic complementary data	
	Taking stellar models to the next power	Comparison with astrometric information , complemented by spectroscopy and asteroseimology	
	Global star formation properties in the Milky Way	3D tomography of the Galactic ISM. 3D of pre-MS objects compared with prestellar and protostellar clumps to trace SFH across Galactic spiral arms.	
	Physics of individual star formation events and stellar clusters.	Astrometric information, complemented with spectroscopy.	

		Origin of the IMF, also in low metallicity environments, and of the stellar binary fraction.	
	Proto-planetary discs: initial conditions for the formation of planets.	Astrometric measurements complemented with spectroscopy: star and disk parameters	
	Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation	Astrometry: unbiased census of mass and orbital properties of giant planets at intermediate separations	
	Dependence on host stars and stellar environment properties.	Astrometry: planet properties as function of stellar characteristics (mass, chemical composition, age, binarity) and environment (disks, clusters)	
VLT	The Nature of Dark Matter	Dynamics of galaxies and clusters of galaxies Growth of structure Surveys of galaxies Fluctuations in the intergalactic medium	High efficiency dispersers Spectrometers NIR/VIS Optimization of cryogenic subsystem High-precision opto-mechanical design and alignment technologies Free-form/aspheric optics Coronagraphic system Active Optics Optical Turbulence characterization and forecast Wide-Field AO Visible band AO Optical detectors IR Detectors
	The Nature of Dark Energy		
	Understanding gravity on large scales		
	Initial conditions in Cosmology		
	Properties of first galaxies and BH. Sources of reionization.	Surveys of Ly-α emitters and primordial objects.	

	Origin and evolution of galaxies.	Detailed observations of gas kinematics, outflows, inflows. Connection with CGM and IGM.	Readout Electronics Real time SW Control SW Data analysis infrastructures
	Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation.	Mass and orbital parameters with ultra-high-precision spectroscopy down to habitable-zone terrestrial planets	
	Chemistry and dynamics of exoplanetary atmospheres.	High-contrast imaging, medium and high-resolution transmission and emission spectroscopy (from Super Earths to gas giants).	
	Physics of individual star formation events	Large spectroscopic surveys for mass accretion/ejection properties as a function of stellar parameters. Spectro-imaging of star formation regions. Feedback of outflows on parent clouds.	
	Proto-planetary discs: initial conditions for the formation of planets	High contrast and high spatial/spectral resolution observations of the inner disk and jet launch region. Photoevaporated and neutral winds. Dynamics of atomic jets, feedback on disk properties. Mechanisms generating the rich disc structures (gaps, rings, spirals, etc.), and their relation with the presence of newly formed planets.	
	Taking stellar models to the next power.	Comparison of accurate data with stellar models	

	Formation and evolution of sub-galactic structures in the Milky Way and the Local Volume	High resolution spectroscopy, including the Gaia ESO survey, complemented by astrometry and photometry	
	The chemo-dynamical evolution of star clusters in galaxies.	High resolution spectroscopy including the Gaia ESO survey, complemented by astrometry and photometry	
NTT-SoXS	Distance Ladder EM counterparts of GW events	early follow-up of transient events	High efficiency dispersers Spectrometers NIR/VIS Optimization of cryogenic subsystem High-precision opto-mechanical design and alignment technologies Optical detectors IR Detectors Readout Electronics Control SW Data analysis infrastructures
VST	Origin and evolution of galaxies	Link the galaxy evolution markers (size, mass, shape of galaxies, presence of disk instabilities) with the driving mechanisms of the galaxy growth and transformation	Wide-Field opto-mechanical system Active Optics Optical detectors Readout Electronics Control SW Data analysis infrastructures
	The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond.	Accurate wide field photometry of stellar populations.	
	Electromagnetic counterparts of GW	Large FOV optical search of GW error boxes	

TNG	Chemistry and dynamics of exoplanetary atmospheres	High-resolution transmission and emission spectroscopy in the visible and NIR	High efficiency dispersers Spectrometers NIR/VIS Optimization of cryogenic subsystem Wide-Field opto-mechanical system Spectro-polarimeters Active Optics Optical detectors IR Detectors Readout Electronics Control SW
	Proto-planetary discs: initial conditions for the formation of planets	Spectroscopy with HARPS-N, GIANO (and GIARPS): mass accretion and ejection as a function of stellar parameters. Neutral and atomic winds, frequency of jets and outflows. Photoevaporation signatures.	
	The chemo-dynamical evolution of star clusters in the MW and in other galaxies	Spectroscopic observations	
	Formation and evolution of sub-galactic structures in the Milky Way and the Local Volume	Spectroscopy with HARPS-N, GIANO (and GIARPS	
	Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation	Spectroscopy with HARPS-N, GIANO (and GIARPS)	
	Dependence on the properties of the host stars and stellar environment	Spectroscopy with HARPS- N and GIARPS	
	Imaging and spectroscopic follow-up of high energy transients	Optical and NIR imaging, spectroscopy and polarimetry	
	Processes that determined the formation and evolution of the Solar System	Spectroscopic observations of primitive bodies	

LBT	The Nature of Dark Matter	Dynamics of galaxies and clusters of galaxies Growth of structure Surveys of galaxies Fluctuations in the intergalactic medium	High efficiency dispersers Optimization of cryogenic subsystem High-precision opto-mechanical design and alignment technologies Wide-Field opto-mechanical system Coronagraphic system Active Optics Optical Turbulence characterization and forecast Wide-Field AO Visible band AO Optical detectors IR Detectors Readout Electronics Real Time SW Control SW
	The Nature of Dark Energy		
	Taking stellar models to the next power	Comparison of accurate photometric data with stellar models.	
	The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond.	Photometric surveys	
	Physics of individual star formation events	Testing the models of the jet launching mechanisms and link with the angular momentum evolution. Jet properties at high angular resolution as shock structure, mass and momentum outflow rate.	
	Proto-planetary discs: initial conditions for the formation of planets	Statistically significant surveys of protoplanetary disk properties. High contrast and high spatial resolution observations of disc structure, identification of planetary bodies in evolved disks. Jet properties at their base.	
	High energy transient late, faint phases, close environments and host galaxies	Late deep imaging and spectroscopy	

ELT	The Nature of Dark Matter	Dynamics of galaxies and clusters of galaxies Growth of structure Surveys of galaxies Fluctuations in the intergalactic medium	High efficiency dispersers Optimization of cryogenic subsystem High-precision opto-mechanical design and alignment technologies Wide-Field opto-mechanical system Free-form/aspheric optics Coronagraphic system Spectrometers NIR/VIS Spectro-polarimeters Active Optics MAORY-like technologies Optical Turbulence characterization and forecast Wide-Field AO Control Strategy for ELT AO system Optical detectors IR Detectors Readout Electronics Real time SW Control SW Data analysis infrastructures
	The Nature of Dark Energy		
	Understanding gravity on large scales		
	Initial conditions in Cosmology		
	Properties of first galaxies and BH. Sources of reionization.	Surveys of Ly-α emitters and primordial objects	
	Origin and evolution of galaxies	Detailed observations of gas kinematics, outflows, inflows. Connection with CGM and IGM	
	Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation	High-contrast imaging and astrometry for mass and orbital parameters determination	
	Chemistry and dynamics of exoplanetary atmospheres.	High-dispersion spectroscopy and direct imaging of transiting and wide-separations planets	
	Dependence on the properties of the host stars and stellar environment.	High-dispersion spectroscopy and direct imaging of transiting and wide-separations planets	
	Evolutionary processes giving origin to the emergence of life.	High-dispersion spectroscopy and direct imaging of terrestrial planets in the habitable zone.	

	Physics of individual star formation events.	High resolution spectroscopy. Dynamics of YSOs in fragmenting clumps and comparison to submillimeter cores. Origin of the IMF, also in low metallicity environments, and of the stellar binary fraction.	
	Proto-planetary discs: initial conditions for the formation of planets.	High spatial resolution imaging of disks, structure and disk-planet interaction. High resolution spectroscopy: mass accretion and ejection as a function of stellar parameters, in solar and low-metallicity environments. High spectral and spatial resolution studies of jet kinematics and dynamics : physical properties, angular momentum transport. Photoevaporated winds, disk dissipation. Star-disk-jet connection, magnetospheres.	
	Taking stellar models to the next power.	Comparison of accurate photometric and spectroscopic data with stellar models.	
	Formation and evolution of sub-galactic structures in the Milky Way and the Local Volume.	Massive multiplex spectroscopy.	
	The chemo-dynamical evolution of star clusters in galaxies.	High resolution multiplex spectroscopy.	
	The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond.	High spatial resolution data.	

	The role of pulsating stars and Surface Brightness Fluctuations as tracers of resolved and unresolved stellar populations.	High spatial resolution data. High resolution spectroscopy.	
	High energy transients in very crowded fields or at high/very high redshift; nebular phases of supernovae and distant super-luminous supernovae	AO-assisted imaging and spectroscopy	
LSST	Origin and evolution of galaxies	Link the galaxy evolution markers (size, mass, shape of galaxies, presence of disk instabilities) with the driving mechanisms of the galaxy growth and transformation	Data analysis infrastructures
	Taking stellar models to the next power	Accurate distance determinations. Test of physical and numerical assumptions in stellar models.	
	The chemodynamical evolution of star clusters in galaxies	Deep photometric and astrometric data.	
	The role of pulsating stars and Surface Brightness Fluctuations as tracers of resolved and unresolved stellar populations.	Accurate astrometric data, distance determinations.	
	Proto-planetary discs: initial conditions for the formation of planets.	Survey and identification of transient young stellar objects: mass accretion and ejection as a function of stellar parameters, and link with disc evolution.	
	Formation and evolution of	Deep photometric and astrometric data.	

	sub-galactic structures in the Milky Way and the Local Volume		
	Transient sky	Intensive monitoring, search for SN and tidal disruption events, GRBs, afterglows	
CHEOPS	Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation	Photometry: follow-up of transiting and non-transiting extrasolar planetary systems for improved and new radius and period determination.	High-precision opto-mechanical design and alignment technologies Free-form/aspheric optics Large/Fast Optics Data analysis infrastructures
	Dependence on the properties of the host stars and stellar environment	Photometry: follow-up of transiting and non-transiting extrasolar planetary systems	
Euclid	Nature of dark energy		Readout Electronics IR detectors Real Time SW Control SW Data analysis infrastructures
	Nature of DM		
	Origin and evolution of galaxies	Link the galaxy evolution markers (size, mass, shape of galaxies, presence of disk instabilities) with the driving mechanisms of the galaxy growth and transformation	
	Formation and evolution of sub-galactic structures in the Milky Way and the Local Volume The production of heavy elements via the s-process and the r-process	Multi-epoch, all-sky monitoring of resolved variables (MW different components, external galaxies) to derive 3d structure and constrain pulsation models. Study unresolved populations using photometric surveys.	
	The role of pulsating stars and Surface Brightness Fluctuations as	Multiepoch, all-sky monitoring	

	tracers of resolved and unresolved stellar populations		
	The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond.	Use large scale galactic and extragalactic surveys (photometric, astrometric, spectroscopic) to map structure, composition, kinematics and star formation history in MW and LG galaxies. Test galaxy formation mechanisms in CDM models.	
Athena	Physics of accretion and ejection onto/from compact objects	Time-resolved spectroscopy	Glass segments technology Testing/calibration facility for large segmented optics Thin large area filters for X-ray detectors TES Microcalorimeter detectors and Cryogenics Data analysis infrastructures
	Non-thermal emission from high energy transients; thermal supernova radiation	Intensive monitoring, especially at medium/late epochs; accurate spectroscopy	
	Dark matter	continuum or/and line emission resulting from the decay or annihilation of DM particles.	
	Census, distribution and properties of cosmic hot gas	Thermo- and chemo-dynamics of hot and warm diffuse baryons (ICM, WHIM)	
CTA	Origin of Cosmic Rays, particle acceleration, propagation and impact on the environment	Observation of SN remnants and candidate sources of acceleration up to 100 Tev	Glass segments and replication technology SiPM detectors Readout Electronics Real Time SW Control SW Data analysis SW

	Probing Extreme Environments: processes close to neutron stars, black holes, relativistic jets, winds and explosions; non-thermal emission of highly and ultra-relativistic sources	monitoring and spectroscopy of blazars, pulsars, Galactic transients, SN remnants; search of GRB TeV emission	
	Constrain fundamental laws of nature (e.g. Lorentz Invariance Violation, axion-like particles, dark matter)	Search of time correlations between TeV and lower energy light curves; observation of spectral anomalies and anomalous cosmic absorption	
	TeV counterparts of GWs and UHE neutrino sources	Search and follow-up imaging and spectroscopy	
THESEUS		Wide-field monitoring with arcmin location accuracy Wide-band spectral measurements of Gamma Ray Bursts Real-time localization and autonomous IR repointing of GRB sources	Silicon Drift Detectors (coupled with scintillator detectors) Readout Electronics Testing/calibration facility
IXPE	Non-thermal phenomena in relativistic source, massive stars, supernova remnants	Imaging X-ray polarimetry; simultaneous spectral, spatial, and temporal measurements	Gas Pixel Detectors Readout Electronics Testing/calibration facility
	Determining the geometry and the emission mechanism of Active Galactic Nuclei and microquasars		
	Finding the magnetic field configuration in magnetars and		

	determining the magnitude of the field		
	Finding the mechanism for X ray production in pulsars (both isolated and accreting) and the geometry		
HERMES	Accurate location of medium-bright GRBs and their exploitation for multi-messenger astrophysics and fundamental physics (e.g., testing Lorentz invariance)	Network of cubesats carrying GRB detectors with large energy band (few keV – several MeVs) and timing resolution of ~100ns	Silicon Drift Detectors (coupled with scintillator detectors) Readout Electronics Testing/calibration facility
eXTP	Matter under extreme conditions of density (equation of state in neutron stars, QCD), gravity (accretion in strong field gravity, GR) and magnetism (magnetars and pulsars, QED). Accurate localization of GRBs and X-ray transients.	Unprecedented combination of timing, spectral and polarimetric sensitivities in the 0.5-30 keV energy range. 4 m^2 effective area through X-ray telescopes and collimators. >900 cm^2 effective area X-ray polarimeters at 2 keV. Wide field monitor with 4sr simultaneous field of view, in 2-50 keV.	Large-area Silicon Drift Detectors Gas Pixel Detector Nickel replica X-ray optics
IBIS	How is the solar magnetic field produced? What is the role of turbulent magneto-convection in the mechanisms giving origin to the solar dynmics and variability?	Study the magnetic field at high spatial resolution and more sensitive spectro-polarimetric capabilities.	Spectro-polarimeters
	What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Optical and IR observations of the lower solar atmosphere.	

	What are the particle radiation and electromagnetic fields dynamics in the planetary environment (with focus on the Earth)? And how is it driven by external agents (space weather)?	MHD modelling of magnetic structures and radiative hydrodynamics simulations with high performance computing.	
DKIST	How is the solar magnetic field produced? What is the role of turbulent magneto-convection in the mechanisms giving origin to the solar dynmics and variability?	Study the magnetic field at high spatial resolution and more sensitive spectro-polarimetric capabilities over a wide range of atmospheric heights, including coronal regions (coronagraphy).	
	What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Optical and IR observations of the solar atmosphere, from the photopshere to the corona.	
EST (European Solar Telescope)	How is the solar magnetic field produced? What is the role of turbulent magneto-convection in the mechanisms giving origin to the solar dynamics and variability?	Study the magnetic field at high spatial resolution and more sensitive spectro-polarimetric capabilities.	Heat rejecter Spectro-polarimeters Space weather system Polarization-free AO system Control Strategy for EST AO system Real Time SW Control SW Optical Turbulence characterization and forecast Active Optics Wide-Field AO Data analysis infrastructures Large archives
	Physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles	Optical and IR observations of the lower solar atmosphere.	
	What are the particle radiation and electromagnetic fields dynamics in the planetary environment (with focus on the Earth)? And how is it	Coordinated ground-based observations and space measurements. Global numerical models of plasma ejection from the Sun, plasma transport and circulation.	

	driven by external agents (space weather)?		
Solar Orbiter	How is the solar magnetic field produced? What is the role of turbulent magneto-convection in the mechanisms giving origin to the solar dynmics and variability?	Study the magnetic field at high spatial resolution and more sensitive spectro-polarimetric capabilities over a wide range of atmospheric heights, including coronal regions (coronagraphy)	Coronagraphic system Real Time SW Control SW Readout Electronics
		New observations of solar polar flows and fields out of the ecliptic.	
	What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Observations of the solar chromosphere and corona through VL, UV, EUV and X-ray.	
		Simultaneous high-resolution imaging and spectroscopic observations of the Sun and inner corona in and out of the ecliptic plane.	
		Perform in-situ measurements of the solar wind plasma, fields, waves, and energetic particles at different distances from the Sun for investigating the turbulence role in the acceleration, energization and dissipation.	
		MHD modelling of coronal structures.	
	What are the particle radiation and electromagnetic fields dynamics in the planetary environment (with	Remote-sensing observation (VL, UV, EUV and X-ray) from space of the solar corona and inner heliosphere.	

	focus on the Earth)? And how is it driven by external agents (space weather)?		
		Coordinated ground-based observations and space measurements. Global numerical models of plasma ejection from the Sun, plasma transport and circulation.	
BepiColombo	Processes that determined the formation and evolution of the Solar System Formation and evolution of Mercury Link of Mercury with its environment	Characterization of Mercury, its exosphere and magnetosphere	Stereo-cameras high resolution camera Spectrometers NIR/VIS Accelerometers Neutral particles detection system Real Time SW Control SW Readout Electronics
ExoMars	Processes that determined the formation and evolution of the Solar System Evolutionary processes giving origin to the emergence of life	Study of Mars (soil and atmosphere)	Spectrometers NIR/VIS stereocamera Real Time SW Control SW Readout Electronics
JUICE	Processes that determined the formation and evolution of the Solar System Formation and evolution of Jupiter icy satellites and the emergence of habitable environments	Remote sensing analysis of Ganymede, Europa, Callisto and Jupiter	High-precision opto-mechanical design and alignment technologies Free-form/aspheric optics Large/Fast Optics Spectrometers NIR/VIS Real Time SW

	Giant planets atmosphere processes		Control SW Readout Electronics high-resolution cameras data fusion and integrated data bases Data analysis infrastructures
PLATO	Taking stellar models to the next power	Comparison with accurate asteroseismic data	High-precision opto-mechanical design and alignment technologies Wide-Field opto-mechanical system Free-form/aspheric optics Readout Electronics Real Time SW Data analysis infrastructures
	Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation	Photometry: Statistical study of transiting extrasolar planetary systems, with emphasis on the properties of terrestrial planets in the habitable zone of solar-like stars.	
	Dependence on the properties of the host stars and stellar environment	Photometry: Statistical study of transiting extrasolar planetary systems and central star characterization through seismology	
CHIPP Cloud Computing HPC - HPT	Processes that determined the formation and evolution of the Solar System	Observations of primitive bodies, exoplanetary systems (dust aggregation processes, formation processes)	HPC Real Time SW Data analysis infrastructures High performance data analysis
	Processes determining the appearance and properties of the bodies of the Solar System	Observations of all the bodies of the Solar System	
	Evolutionary processes giving origin to the emergence of life	Observation of primitive bodies (organic material and ices)	

	Taking stellar models to the next power	Computation of models	
	Global star formation properties	Radiative transfer models of star forming regions. Workflow-oriented Data Mining/Machine Learning applications for evolutionary classification of star formation regions combining data and knowledge from the optical to the radio.	
	The chemodynamical evolution of star clusters in galaxies	Chemodynamical modelling, formation and disruption modelling	
	Formation and evolution of sub-galactic structures in the Milky Way and the Local Volume	Structure and pattern recognition	
	Origin and evolution of galaxies	Link the galaxy evolution markers (size, mass, shape of galaxies, presence of disk instabilities) with the driving mechanisms of the galaxy growth and transformation	
	Cosmological parameters Nature of gravity	LSS of the Universe within standard and non-standard cosmological models	
SCORE	Where does origin the slow solar wind from? What is the variation of helium abundance in coronal structures? (a) departures from primordial composition; (b) fractionation region for helium in the solar atmosphere	Establish relative roles of gravitational settling and coulomb friction in slow solar wind acceleration regions (e.g. streamers, coronal hole boundaries, fine structures)	Coronagraph system VL Detector Real Time SW Control SW Readout Electronics Testing/calibration facility

	Facilitate future investigation of CMEs, kinematics, and solar cycle evolution of the electron, proton, and helium corona	Measure helium abundance profile in the extended corona (heliocentric distances 1.25 - 3.5 solar radii) Establish flight heritage via suborbital investigation of remote sensing techniques for the ESA/NASA Solar Orbiter coronagraph: Metis	
PROBA-3/ ASPIICS	What is the nature of the solar corona on different scales? What processes contribute to the, heating of the corona? What processes contribute to the solar wind acceleration?	Full FOV observations of the corona Determination of electron density with polarized light observations and of temperature with narrow band filters in different temperature regimes High cadence observations of small scale features Observing coronal structures at highest possible time cadence and spatial resolution in white light (electron density) and different temperature regimes. Coronal Seismology Measure proper motion velocity and acceleration profiles of solar structures ("blobs") at highest possible temporal and spatial resolution in white light (electron density) and different temperature regimes to map the outflow of the slow solar wind Investigations of small & scale dynamic structures in the solar wind source region in	Testing/calibration facility

		particular at the interface between fast and slow streams	
AntarctiCor	How does the topology and time evolution of the magnetic field of the inner solar corona (i.e., heliocentric heights: 1.15-2.0 solar radii) determine the origin of the slow and fast solar wind? What is the nature of the solar corona on different scales? Facilitate future investigation of coronal magnetic field diagnostics. Proof-of-concept of ground-based and balloon-borne instrumentation network for continuous space weather monitoring	Measure the plane-of-the-sky components of the coronal magnetic field vectors with narrow bandpass polarimetric observations of field-sensitive linear polarization in emission-lines from ionized-iron. Observing coronal structures at highest possible time cadence and spatial resolution in visible-light (electron density) with the long duration ground observations made possible by the Antarctic summer Validate via ground tests in extreme environment the remote sensing techniques for the ESA PROBA-3 ASPIICS coronagraph, and HEMERA balloon payloads	Coronagraphic system Control SW Testing/calibration facility

Appendix 1.2 Projects without a significant future technological involvement of INAF

Project	Key Question	Method
VLA, ASKAP, MeerKAT	Origin and evolution of galaxies	Observations of molecular gas Non thermal processes in cosmic structures
	Global star formation properties	Non thermal processes, emission from radio jets, thermal free-free, HI and Radio Recombination Lines
IRAM PdBI & NOEMA	Origin and evolution of galaxies	Observations of molecular gas
	Global star formation properties	Surveys of several thousands of star-forming as well as pre-stellar clumps in a variety of Galactic environments
	Physics of individual star formation events	Formation of the circumstellar disk and generation of outflows. Surveys of discs/jets/outflows around low-mass protostars. Astrochemistry of inner (10au scale) protostellar and protoplanetary disks. Complex organic molecules as prebiotic bricks.

APEX	Global star formation properties in the MilkyWay Galaxy: Molecular clouds & dense gas.	Ground-based single dish millimetric/centimetric observations
JWST and HST	Properties of first galaxies and BH. Sources of reionization.	Surveys of Ly-α emitters and primordial objects
	Origin and evolution of galaxies	
	Chemistry and dynamics of exoplanetary atmospheres	Very high S/N, medium resolution NIR/MIR transmission and emission spectroscopy (down to the Super Earth regime).
	Evolutionary processes giving origin to the emergence of life	Atmospheres of habitable rocky Super Earths around low-mass stars
	Global star formation properties	Shape of the 1-20μm continuum with NIRCam and MIRI Imaging spectroscopy of ices and molecular species with MIRSpec and MIRI. Dynamical and radiative feedback in fragmenting massive clumps
	Physics of individual star formation events.	Morphology and excitation conditions of the gas (MIRI) and its role in the star formation process. Identification of biologically important molecules around forming stars. Measurement of the fraction of disks actively accreting matter on the star. Properties of jets derived from NIR and MIR emission

		lines. High angular resolution spectro-imaging of the inner disk and jet launch region. Feedback of jets and outflows on the properties of the disk.
	The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond.	Exploration of very crowded inaccessible portions of galaxies.
	Proto-planetary discs: initial conditions for the formation of planets.	Diffraction limited imaging and spectroscopy in the NIR/MIR.
	The role of pulsating stars and Surface Brightness Fluctuations as tracers of resolved and unresolved stellar populations.	MIR PL and PW relations and extension of the Cepheid distance calibration.
	Processes that determined the formation and evolution of the Solar System	Observations of primitive bodies, exoplanetary systems (dust aggregation processes, formation processes)
	Processes determining the appearance and properties of the bodies of the Solar System	Observations of all the bodies of the Solar System
	Evolutionary processes giving origin to the emergence of life	Observation of primitive bodies (organic material and ices)
	Remnants and close environments of high energy explosions: supernovae and GRBs at high redshift; binary mergers and kilonovae	Deep imaging in UV, optical, NIR

WFIRST	Properties of first galaxies and BH. Sources of reionization.	Surveys of Ly-α emitters and primordial objects.
	Chemistry and dynamics of exoplanetary atmospheres	Observations of exoplanet atmospheres with high-contrast imaging
	Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation.	Astrometry: survey of the nearest stars with sensitivity to Neptunes and Super Earths.
	Formation and evolution of sub-galactic structures in the Milky Way and the Local Volume.	Detailed study of our Galaxy and nearby galaxies. Kinematics of Stellar Streams in Our Local Group of Galaxies.
	The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond.	Detailed study of our Galaxy and nearby galaxies. Kinematics of Stellar Streams in Our Local Group of Galaxies.
VISTA	Origin and evolution of galaxies	Link the galaxy evolution markers (size, mass, shape of galaxies, presence of disk instabilities) with the driving mechanisms of the galaxy growth and transformation
	The star formation history (SFH) in the Milky Way, in the Local Group galaxies and beyond.	Wide field photometry of stellar populations and time-series observations of pulsating stars.
	Electromagnetic counterparts of GW	Large FOV optical search of GW error boxes

XMM-Newton	Physics of accretion and ejection onto/from compact objects	Time-resolved photometry and spectroscopy
	Non-thermal emission from high energy transients; thermal supernova radiation	Intensive monitoring, especially at medium/late epochs; accurate spectroscopy
	Non-thermal continuum of highly relativistic sources	GRID monitoring and spectroscopy of blazars, pulsars, Galactic transients, SN remnants
Chandra	Physics of accretion and ejection onto/from compact objects	deep imaging and spectroscopy of faint sources
	X-ray emission from PWNe and supernova remnants, high energy transients and supernovae	High-resolution imaging and spectroscopy, especially at late epochs
Swift	Physics of accretion and ejection onto/from compact objects	Monitoring of bright galactic sources and AGNs
	Non-thermal emission from high energy transients and explosive phenomena; thermal supernova radiation	Early epoch observations of GRBs and supernovae; intensive monitoring of galactic transients
NuStar	Physics of accretion and ejection onto/from compact objects	Deep imaging and accurate spectroscopy of hard X-ray continuum emitters (Galactic sources, AGNs)

	Non-thermal continuum emission from high-energy transients	Spectroscopy of GRBs, supernovae, Galactic transients at early/medium phases
	Nucleosynthesis	Hard X-ray line spectroscopy of novae, supernovae
INTEGRAL	Physics of accretion and ejection onto/from compact object	Spectroscopy of Galactic sources and bright AGNs
	Search and follow-up of electromagnetic counterparts of gravitational waves and of neutrino sources	Time analysis of ACS signals; large FOV imaging; spectroscopy of high energy counterparts
	Nucleosynthesis	MeV ray line spectroscopy of novae, supernovae
	Search and follow-up of GRBs and other explosive phenomena	Rapid turnaround imaging and spectroscopy
Fermi	Search and follow-up of GRBs and GW sources	Early imaging and spectroscopy
	Non-thermal continuum of highly relativistic sources	GBM detection, localization and spectroscopy of GRBs; LAT monitoring and spectroscopy of blazars, pulsars, Galactic transients, SN remnants

AGILE	Search for electromagnetic counterparts of GW and neutrino sources	Imaging of GW error boxes, imaging and spectroscopic follow-up
	Non-thermal continuum of highly relativistic sources	GRID monitoring and spectroscopy of blazars, pulsars, Galactic transients, SN remnants
HXMT	Physics of accretion and ejection onto/from compact objects; Non-thermal continuum emission from hard X_ray sources; observe X-ray binaries to study the dynamics and emission mechanism in strong gravitational or magnetic fields	Pointed observations of celestial X-ray sources with a set of collimated instruments covering the energy band from ~1 to ~300 keV, with unprecedently large area (5100 cm2) in 20 – 300 keV
	Monitoring the Galaxy in hard X-rays, discovery and characterization of new hard X-ray transients, unprecedented census of hard X-ray sources in the Galaxy	Survey of the hard X-ray sky with unprecedented sensitivity by exploiting the direct demodulation technique
	Physics of GRB prompt emission; use of GRB prompt emission spectral properties for cosmology; detection and characterization of counterparts to GW sourcees (e.g., short GRBs).	Operation of the HE instrument in GRB mode, thus providing an unprecedented effective area of more than 200 cm2 in the 300 keV – 3 MeV energy band
SST	How is the solar magnetic field produced? What is the role of turbulent magneto-convection in the mechanisms giving origin to the solar dynmics and variability?	Study the magnetic field at high spatial resolution and more sensitive spectro-polarimetric capabilities.
	What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Optical and IR observations of the lower solar atmosphere.

	What are the particle radiation and electromagnetic fields dynamics in the planetary environment (with focus on the Earth)? And how is it driven by external agents (space weather)?	MHD modelling of magnetic structures and radiative hydrodynamics simulations with high performance computing.
HINODE	What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Observations of the solar chromosphere and corona through VL, UV, EUV and X-ray.
	What are the particle radiation and electromagnetic fields dynamics in the planetary environment (with focus on the Earth)? And how is it driven by external agents (space weather)?	MHD modelling of coronal structures.
STEREO	What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Observations of the solar corona through VL, UV, EUV and X-ray.
	What are the particle radiation and electromagnetic fields dynamics in the planetary environment (with focus on the Earth)? And how is it driven by external agents (space weather)?	Perform in-situ measurements of the solar wind plasma, fields, waves, and energetic particles at different distances from the Sun.
SDO	What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Observations of the solar chromosphere and corona through VL, UV, EUV and X-ray.
		MHD modelling of coronal structures.
IRIS	What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Observations of the solar chromosphere and corona through UVand EUV.

		MHD modelling of coronal structures.
Parker Solar Probe	What are the physical mechanisms regulating the heating of astrophysical plasmas and acceleration of high-energy particles?	Remote-sensing VL observations of the corona and inner heliosphere.
	What are the particle radiation and electromagnetic fields dynamics in the planetary environment (with focus on the Earth)? And how is it driven by external agents (space weather)?	Perform in-situ measurements of the solar wind plasma, fields, waves, and energetic particles at different distances from the Sun for investigating the turbulence role in the acceleration, energization and dissipation.
TESS	Properties of first galaxies and BH. Sources of reionization.	Deep fields of X-ray sources.
	Architecture and dynamics of planetary systems as a function of mass, radius and orbital separation	Photometry: Statistical study of transiting extrasolar planetary systems, with emphasis on the properties of terrestrial planets in the habitable zone of low-mass stars.
	Dependence on the properties of the host stars and stellar environment	Photometry: Statistical study of transiting extrasolar planetary systems
	Taking stellar models to the next power	Comparison with accurate asteroseismic data
CINECA PRACE HPC and HTC facilities	Origin and evolution of galaxies	Link the galaxy evolution markers (size, mass, shape of galaxies, presence of disk instabilities) with the driving mechanisms of the galaxy growth and transformation

	Formation and evolution of sub-galactic structures in the Milky Way and the Local Volume	Structure and pattern recognition
	The chemodynamical evolution of star clusters in galaxies	Chemodynamical modelling, formation and disruption modelling
	Processes that determined the formation, evolution appearance and properties of the Solar System Evolutionary processes giving origin to the emergence of life Taking stellar models to the next power	Computation of models
	Global star formation properties	Radiative transfer models of star forming regions. Workflow-oriented Data Mining/Machine Learning applications for evolutionary classification of star formation regions combining data and knowledge from the optical to the radio.