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L'attività di ricerca del RSN4 nel contesto internazionale. Il punto di vista del Consiglio Scientifico

Consiglio Scientifico - INAF

Science Vision & Infrastructure Roadmap 2020-2030

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ASTRONET
www.astronet-eu.org

An Integrated Roadmap For European Astronomy

Roadmap preliminary Executive summary

SCIENTIFIC PRIORITIES

The strategic Roadmap for the next decade of European Astronomy is based on the scientific aspirations of the community to answer fundamental questions about our Universe, the most pressing being:

- What is the nature of dark matter and dark energy?
- Are there deviations from the standard theories and models (general relativity, cosmological model, standard model of particle physics)?
- What are the properties of the first stars, galaxies and black holes in the Universe?
- How do galaxies form and evolve, and how does the Milky Way fit in this context?
- What are the progenitors of astronomical transients?
- What physical processes control stellar evolution at all stages, from formation to death, and how?
- What are the necessary conditions for life to emerge and thrive? Are we alone?
- How do planets and planetary systems form and evolve?
- What is the impact of the Sun on the heliosphere and on planetary environments?
- What are/were the characteristics and habitability of various sites in the solar system (Mars, Jupiter's icy moons, ...)
- What is the origin of cosmic rays of all energies?
- How can extreme astrophysical objects and processes probe new fundamental physics?

A general theme of the roadmap is the need for an **integrated approach to decision-making** if we are to achieve our scientific goals. This includes, for example, the necessity of planning for rapid response, small-scale facilities to complement large flagship observatories, to consider requirements for data processing, storage and dissemination at the stage of mission/facility planning, and to fund the computational and theoretical efforts that go hand-in-hand with breaking new observational grounds. While the strategic roadmap is shaped by science goals, its implementation must also respect the increasing desire of the European community to ensure Astronomy research is conducted in a sustainable and equitable manner that also fulfils our roles as educators and responsible citizens.

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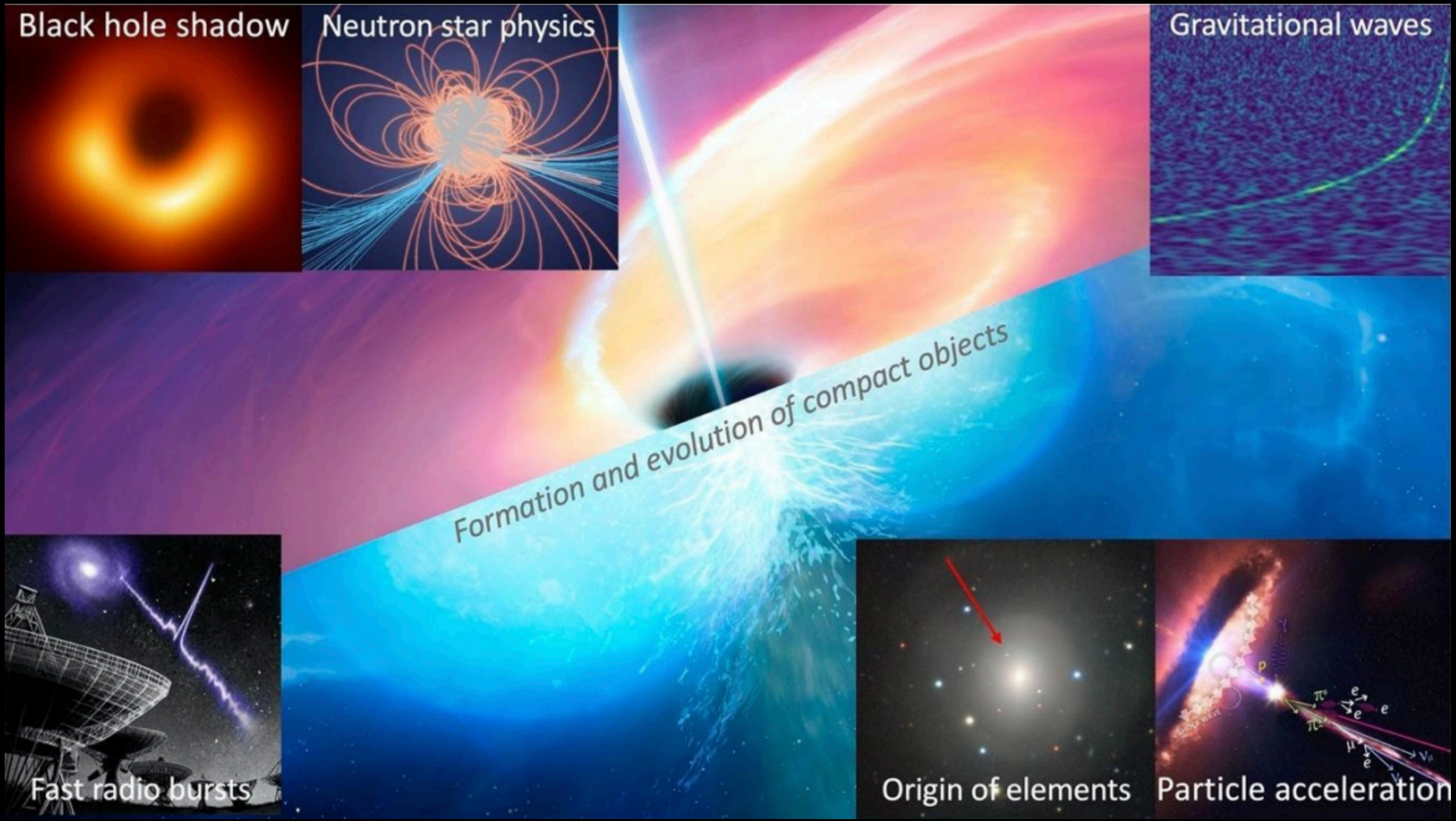
Extreme Astrophysics and Fundamental Physics



1) What is the nature of matter at nuclear densities?

2) Where are the heavy elements made?

3) How do compact objects produce energy and accelerate particles at all scales?

4) What is the origin of cosmic rays of all energies?:

5) How do compact objects form and evolve?

6) To what precision can general relativity describe gravity?

7) What new fundamental physics can be probed with extreme astrophysical objects?

Astroparticle physics is the fascinating field of research at the intersection of astronomy, particle physics and cosmology. It simultaneously addresses challenging questions relating to the micro-cosmos (the world of elementary particles and their fundamental interactions) and the macro-cosmos (the world of celestial objects and their evolution) and, as a result, is well-placed to advance our understanding of the Universe beyond the *Standard Model of particle physics* and the *Big Bang Model of cosmology*.

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Introduction

Astroparticle physics is the rapidly evolving field of research that lies at the point where astronomy, particle physics and cosmology meet. Experimentally, it combines the advanced instrumentation harnessed by particle physicists with the highest standard of imaging of the cosmos undertaken by astronomers. Theoretically, it connects the Big Bang Model of cosmologists to the Standard Model of particle physicists; the former gives a detailed description of the evolution of the macro-cosmos while the latter describes the micro-cosmos with stunning precision. Scientifically, it aims to gain insights into long-standing enigmas at the heart of our understanding of the Universe – for example:

- **The Extreme Universe:** *What can we learn about the cataclysmic events in our Universe by combining all of the messengers – high-energy gamma rays, neutrinos, cosmic rays and gravitational waves – that we have at our disposal?*
- **The Dark Universe:** *What is the nature of Dark Matter and Dark Energy?*
- **Mysterious neutrinos:** What are their intricate properties and what can they tell us?
- **The Early Universe:** *What else can we learn about the Big Bang – for instance, from the cosmic microwave background (CMB)?*

Large-scale multi-messenger infrastructures

To improve understanding of our Universe, APPEC identified as a very high priority those research infrastructures that exploit all confirmed high-energy 'messengers' (cosmic particles that can provide vital insights into the Universe and how it functions). These messengers include gamma rays, neutrinos, cosmic rays and gravitational waves. European coordination is essential to ensuring timely implementation of such infrastructures and enabling Europe to retain its scientific leadership in this field.

1. High-energy gamma rays

Through the use of ground-based gamma-ray telescopes (e.g. HESS and MAGIC) and key participation in satellite missions such as Fermi, Europe has played a leading and pioneering role in establishing high-energy gamma rays as an ideal messenger to enable exploration of the extreme Universe – as demonstrated by the astonishing number of gamma-ray sources discovered in recent years. The next-generation European-led, ESFRI-listed global project will be the Cherenkov Telescope Array (CTA), which has excellent discovery potential ranging from astrophysics to fundamental physics. The CTA is expected to start full operation as an observatory in 2023.

APPEC fully supports the CTA collaboration in order to secure the funding for its timely, cost-effective realisation and the subsequent long-term operation of this observatory covering both northern and southern hemispheres.

2. High-energy neutrinos

IceCube's first observation of PeV-scale cosmic neutrinos in 2013 has opened an entirely new window onto our Universe: neutrino astronomy. As well as presenting the opportunity to resolve neutrinos' mass hierarchy by studying atmospheric neutrinos, this led ESFRI to include KM3NeT 2.0 in its 2016 roadmap, with operation anticipated to commence in 2020. Within the Global Neutrino Network (GNN), the IceCube, KM3NeT and Baikal-GVD collaborations already join forces to provide a network of large-volume detectors viewing both northern and southern hemispheres and to exploit efficiently the full discovery potential inherent in neutrino astronomy.

For the northern hemisphere (including Baikal GVD), APPEC strongly endorses the KM3NeT collaboration's ambitions to realise, by 2020: (i) a large-volume telescope with optimal angular resolution for high-energy neutrino astronomy; and (ii) a dedicated detector optimised for low-energy neutrinos, primarily aiming to resolve the neutrino mass hierarchy. For the southern hemisphere, APPEC looks forward to a positive decision in the US regarding IceCube-Gen2.

3. High-energy cosmic rays

The Pierre Auger Observatory is the world's largest, most sensitive ground-based air-shower detector. Understanding the evident flux suppression observed at the highest energies requires good mass resolution of primary cosmic rays: are they predominantly light nuclei (protons) or heavy nuclei (like iron)? This is the missing key to deciding whether the observed cut-off is due to particles being limited in energy because of interactions with the CMB, or to cosmic accelerators 'running out of steam' to accelerate particles. The Auger collaboration will install additional particle detectors (AugerPrime) to measure simultaneously the electron and muon content of air showers, in order to help determine the mass of primary cosmic rays. This upgrade will also deepen understanding of hadronic showers and interactions at centre-of-mass energies above those accessible at the LHC.

APPEC strongly supports the Auger collaboration's installation of AugerPrime by 2019. At the same time, APPEC urges the community to continue R&D on alternative technologies that are cost-effective and provide a 100% (day and night) duty cycle so that, ultimately, the full sky can be observed using very large observatories.

4. Gravitational waves

The first direct observations of gravitational waves by the LIGO-Virgo consortium have revealed a scientific treasure trove. Multi-solar-mass black holes coalescing within seconds into one larger black hole and simultaneously radiating the equivalent of a few solar masses of energy as gravitational waves are now an established fact; they also provide unprecedented tests of General Relativity. Another new, revolutionary window onto our Universe has therefore now opened: gravitational-wave astronomy. In this field, the laboratories that host gravitational-wave antennas play a crucial role by developing new technologies to increase detection efficiencies further. The incredibly high precision in monitoring free-falling objects in space recently achieved by ESA's LISA Pathfinder mission is an important step towards complementary (low-frequency) space-based gravitational-wave astronomy.

With its global partners and in consultation with the Gravitational Wave International Committee (GWIC), APPEC will define timelines for upgrades of existing as well as next-generation ground-based interferometers. APPEC strongly supports further actions strengthening the collaboration between gravitational-wave laboratories. It also strongly supports Europe's next-generation ground-based interferometer, the Einstein Telescope (ET) project, in developing the required technology and acquiring ESFRI status. In the field of space-based interferometry, APPEC strongly supports the European LISA proposal.

Medium-scale Dark Matter and neutrino experiments

APPEC considers as its core assets the diverse, often ultra-precise and invariably ingenious suite of medium-scale laboratory experiments targeted at the discovery of extremely rare processes. These include experiments to detect the scattering of Dark Matter particles and neutrinoless double-beta decay, and direct measurement of neutrino mass using single-beta decay. Collectively, these searches must be pursued to the level of discovery, unless prevented by an irreducible background or an unrealistically high demand for capital investment.

5. Dark Matter

Elucidating the nature of Dark Matter is a key priority at the leading tip of astroparticle physics. Among the plethora of subatomic particles proposed to explain the Dark Matter content of our Universe, one category stands out: the Weakly Interacting Massive Particle (WIMP). WIMPs arise naturally, for instance, in supersymmetric extensions of the Standard Model of particle physics. Many experiments located in deep-underground laboratories are searching for WIMP interactions. For masses in excess of a few GeV, the best sensitivity to WIMPs is reached with detectors that use ultra-pure liquid noble-gas targets; such detectors include XENON1T (using 3.5 tons of xenon) and DEAP (using 3.6 tons of argon), which both started operating in 2016. Their sensitivity can be further enhanced by increasing the target mass. A suite of smaller-scale experiments is exploring, in particular, low-mass WIMPs and other Dark Matter hypotheses such as those based on dark photons and axions.

APPEC encourages the continuation of a diverse and vibrant programme (including experiments as well as detector R&D) searching for WIMPs and non-WIMP Dark Matter. With its global partners, APPEC aims to converge around 2019 on a strategy aimed at realising worldwide at least one 'ultimate' Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.

6. Neutrino mass and nature

Despite all previous efforts, some of the neutrino's very fundamental characteristics remain unknown. Notably, these include neutrino mass and whether the neutrino is its own anti-particle or not (in other words, whether it is a Majorana-type particle or a Dirac-type particle). Both of these issues can be explored by studying the beta decay of selected isotopes. Single-beta decay allows direct kinematical inference of neutrino mass; first results from the world-leading KATRIN experiment in Germany are eagerly awaited. The double-beta decay of, for instance, germanium, tellurium or xenon, meanwhile, is used to probe physics beyond the Standard Model in a unique way by searching for decays without neutrinos. This process is only allowed if neutrinos are Majorana-type particles and its observation would not only reveal the neutrino's nature and pinpoint its mass but also demonstrate violation of lepton number. Among the various experiments worldwide searching for neutrinoless double-beta decay, European experiments such as GERDA (focusing on germanium), CUORE (tellurium) and NEXT (xenon) are some of the most competitive.

APPEC strongly supports the present range of direct neutrino-mass measurements and searches for neutrinoless double-beta decay. Guided by the results of experiments currently in operation and in consultation with its global partners, APPEC intends to converge on a roadmap for the next generation of experiments into neutrino mass and nature by 2020.

Synergies with astronomy, particle physics and cosmology

To shed light on neutrino mixing and the neutrino mass hierarchy, APPEC is a long-term proponent of experiments using natural neutrinos from the Sun and from Earth's atmosphere as well as neutrinos from nuclear reactors and accelerators. Recognising the increasingly interdisciplinary reach of astroparticle physics, APPEC has broadened the scope of its roadmap to include explicitly two topics referred to in its 2008 science vison: the CMB and Dark Energy. These are flourishing fields of research, as demonstrated by Nobel Prizes awarded in 2006 and 2011. They not only complement core astroparticle physics topics but also yield stringent constraints on neutrino masses and on the role of neutrinos in the early Universe. So far in these recommendations, the focus has been on projects primarily funded by European astroparticle physics agencies. By contrast, for the three topics addressed in this subsection, the main funding is likely to come from US and Asian agencies or from the European particle physics and astronomy communities.

7. Neutrino mixing and mass hierarchy

Neutrino oscillation – implying neutrino mixing and thus the existence of non-zero neutrino masses – was discovered by experiments with solar and atmospheric neutrinos and rewarded with Nobel Prizes in 2002 and 2015. For precise determination of the intricacies of neutrino mixing – including the much-anticipated violation of matter/anti-matter symmetry in the neutrino sector, and the neutrino mass hierarchy – dedicated accelerator neutrino beams and neutrinos from nuclear reactors are ideal. With the Double Chooz concept, the Borexino liquid scintillator and the ICARUS liquid-argon time-projection-chamber technologies, Europe was a pioneer in this field and large-scale facilities are now envisaged in the US (the DUNE long-baseline neutrino experiment) and Asia (the JUNO reactor neutrino experiment); DUNE emerged after the first of a series of global neutrino physics strategy meetings co-initiated by APPEC in 2014. Together with the Hyper-Kamiokande proposal

ASTRONOMY & ASTROPARTICLE PHYSICS

Astronomy & Astroparticle Physics seek to understand the Universe and its components: from its still mysterious beginnings to its growing complexity, with the formation and evolution of galaxies, stars and planetary systems, until the emergence of life. The main science questions addressed by the RIs can be summarized as follows:

- understand the origin of the Universe and its main constituents;
- understand the extreme conditions the Universe hosts;
- understand the formation of galaxies and their evolution;
- understand the formation of stars and planets;
- search for planetary systems in our galaxy, study the Solar System and extrasolar planets, search for life and understand the conditions enabling life.

ASTRONOMY & ASTROPARTICLE PHYSICS

The domain relies on a combined approach of observations, theoretical work and modelling, and more and more on laboratory experiments. The level of precision necessary to constrain models requires high-performing space, ground-based and underground observatories, mostly built and managed through international collaboration, and exploited in synergy. Observations of our Universe extend beyond the historical optical domain, to the whole electromagnetic spectrum from radio waves to gamma-rays, and new messengers such as gravitational waves and neutrinos. Multi-messenger astronomy, with its multi-wavelength, multi-instrument approach, is the new frontier to study the phenomena of the Universe and their evolution. Underground physics laboratories investigate the rarest phenomena to discover dark matter and the nature of neutrino mass.

….the potency of international and interdisciplinary collaboration….

	VISION	GAPS & CHALLENGES	ESFRI RIs
ASTRONOMY & ASTROPARTICLE PHYSICS	Understand the Universe and its constituents, their origin and evolution	Integration of multi-messenger information	CTA
		Temporal domain	ET
		Search for life	ELT
		High angular resolution/adaptive optics	EST
			KM3NeT 2.0
			SKAO

Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020)

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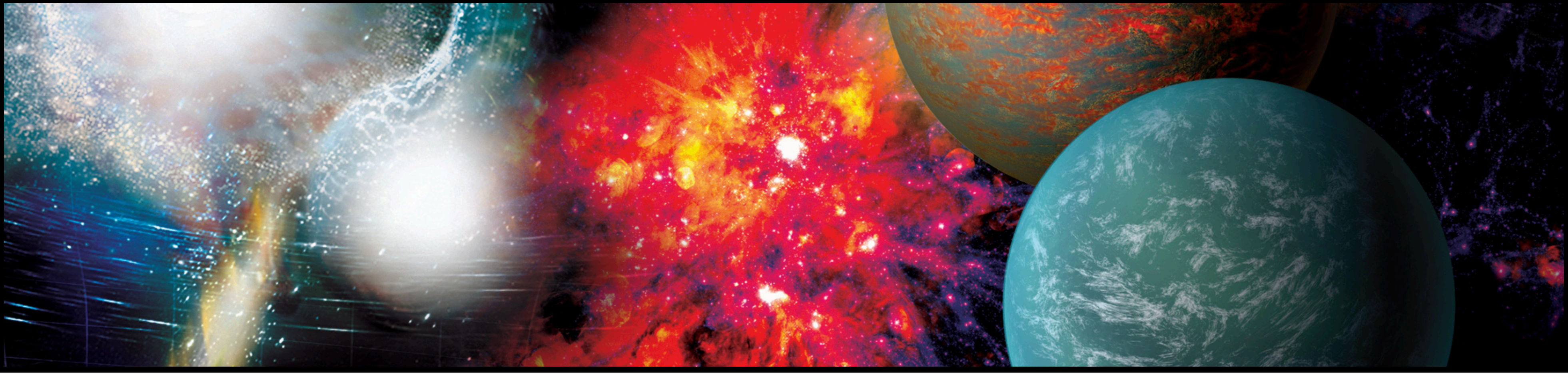

Scientific Priorities

The report identifies three priority scientific areas that motivate recommended investments over the next decade:

- **Pathways to habitable worlds** – Identify and characterize Earth-like planets outside this solar system, with the ultimate goal of obtaining imaging of potentially habitable worlds.
- **New windows on the dynamic universe** – Probe the nature of black holes and neutron stars — and the explosive events that gave rise to them — and understand what happened in the earliest moments in the birth of the universe.
- **Drivers of galaxy growth** – Revolutionize understanding of the origins and evolution of galaxies, from the webs of gas that feed them to the formation of stars.

Pathways to Discovery in Astronomy and Astrophysics for the 2020s

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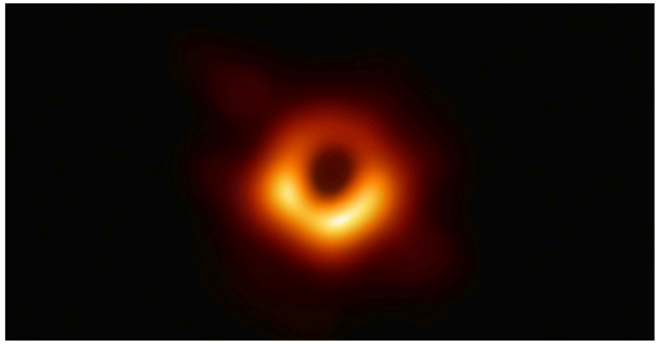
Key Scientific Challenges for the Next Decade

Worlds and Suns in Context

Priority Area: Pathways to Habitable Worlds



New Messengers and New Physics

Priority Area: New Windows on the Dynamic Universe

Cosmic Ecosystems

Priority Area: Unveiling the Drivers of Galaxy Growth

Over the next decade, a range of complementary observations—from radio to gamma rays, gravitational waves, neutrinos, and high-energy particles—will enable investigations into the most energetic processes in the universe and address larger questions about the nature of dark matter, dark energy, and cosmological inflation. These growing capabilities will enable closer study of neutron stars, white dwarfs, black hole collisions, stellar explosions, and the birth of our universe.

Voyage 2050

Final recommendations from the Voyage 2050 Senior Committee

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Recommendations for Large Mission Scientific Themes

- Moons of the Giant Planets: (1) Habitability of ocean worlds; (2) search for biosignatures; (3) Connection of interior and near-surface environments
- From Temperate Exoplanets to the Milky Way: (1) Characterization of the Atmosphere of Temperate Exoplanets; (2) Galactic Ecosystem with Astrometry in the Near-Infrared
- New Physical Probes of the Early Universe: (1) New Opportunities for Exploring the Early Universe; (2) Precision Spectroscopy of the Fireball Universe; (3) Adding Colour and Depth to the Gravitational Wave Sky

Potential Scientific Themes for Medium Missions (among the others):

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- Probing the Violent and Explosive Universe at High Energies: Accretion by Compact Objects and Astroparticle Physics

Space-based X-ray and gamma-ray detectors, with improved capabilities with respect to the current generation, such as high-sensitivity, large field-of-view detectors, and/or sensitive keV–MeV spectropolarimetry based on new technologies, will allow us to detect and investigate the most extreme and violent physical phenomena in the Universe and provide a powerful and fundamental synergy with gravitational wave astronomy.

Unresolved questions related to explosive nucleosynthesis in stellar explosions, the origin of cosmic rays, accretion and ejection mechanisms in stellar and supermassive black holes and neutron stars, could be solved with missions with these capabilities, as well as boosting the discovery rate of known and unknown rare classes of transient sources throughout the Universe.

Potential Scientific Themes for Medium Missions (among the ohters):

- Space (Radio) Interferometry with Ground-based Telescopes for Probing the Physics of Black Holes

The first images of the close environments of a black hole obtained in recent years with the Event Horizon Telescope's observations of the nucleus of M87 offered the first glimpse of the power of long baseline, high frequency radio interferometry to deliver remarkable images close to the event horizon.

…..

Space radio interferometry would increase the length of available baselines significantly, allowing image quality improvements of factors of at least several over what is currently possible

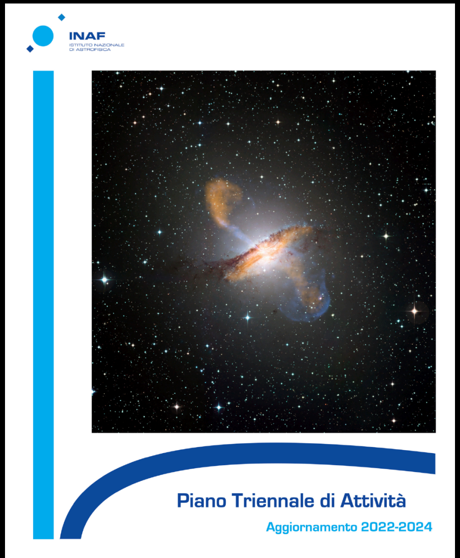
- Quantum Mechanics and General Relativity

Despite extensive testing of the fundamental theories of quantum mechanics and general relativity, no violations have yet been observed of their predictions in experimental situations.

The following topics were discussed by the Topical Team as representing possible experiments in this area of fundamental physics: tests of quantum mechanical wave function collapse for different mass test particles, tests of the Equivalence Principle. tests of quantum coherence over large distances. tests of gravitational redshift, improved measurements of the PPN parameters.

From PTA: RSN4 main research lines

- Galactic and extragalactic compact objects
- Cosmic explosion
- Multi-messenger astronomy
- Fundamenntal phyisics experiments



Tight activity links with RSN1 (cosmology and dark matter), RSN2 (stellar evolution), RSN5 (science programs for space missions and ground-based telescope development)

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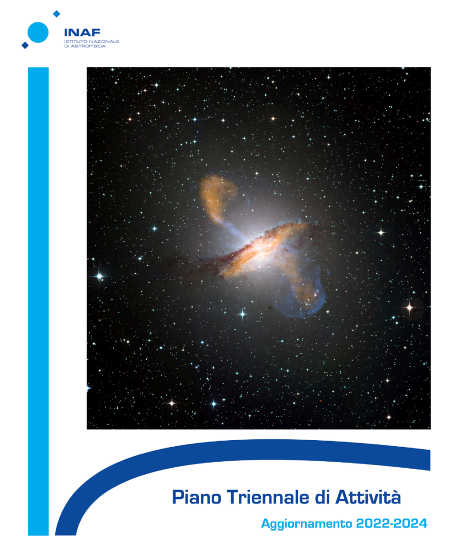
RSN4 aims at studying and understanding:

1) matter under extreme conditions
2) fundamental physics and possible new physics
3) the mechanisms of acceleration and transport of cosmic rays (their impact on star formation and galactic evolution)
4) explosive processes and their progenitor systems (understanding the final stages of stellar evolution)
5) the evolution of the structures of the Universe



This is pursued through the OBSERVATION and THEORETICAL INTERPRETATION of emission electromagnetics from compact objects at all scales (white dwarfs, neutron stars, holes black holes of stellar or supermassive mass at the center of galaxies)

Primary observations: high-energy radiation (X-rays and gamma rays, VHE), crucial multiband campaigns (e.g., in radio, infrared and visible bands) and multi-messenger astronomy (gravitational wavess, cosmic rays and neutrinos)

Conclusions. I

- All the most relevant scientific topics according to the current international roadmaps are covered by RSN4 in an almost balanced way

Research Lines Distribution: Schede

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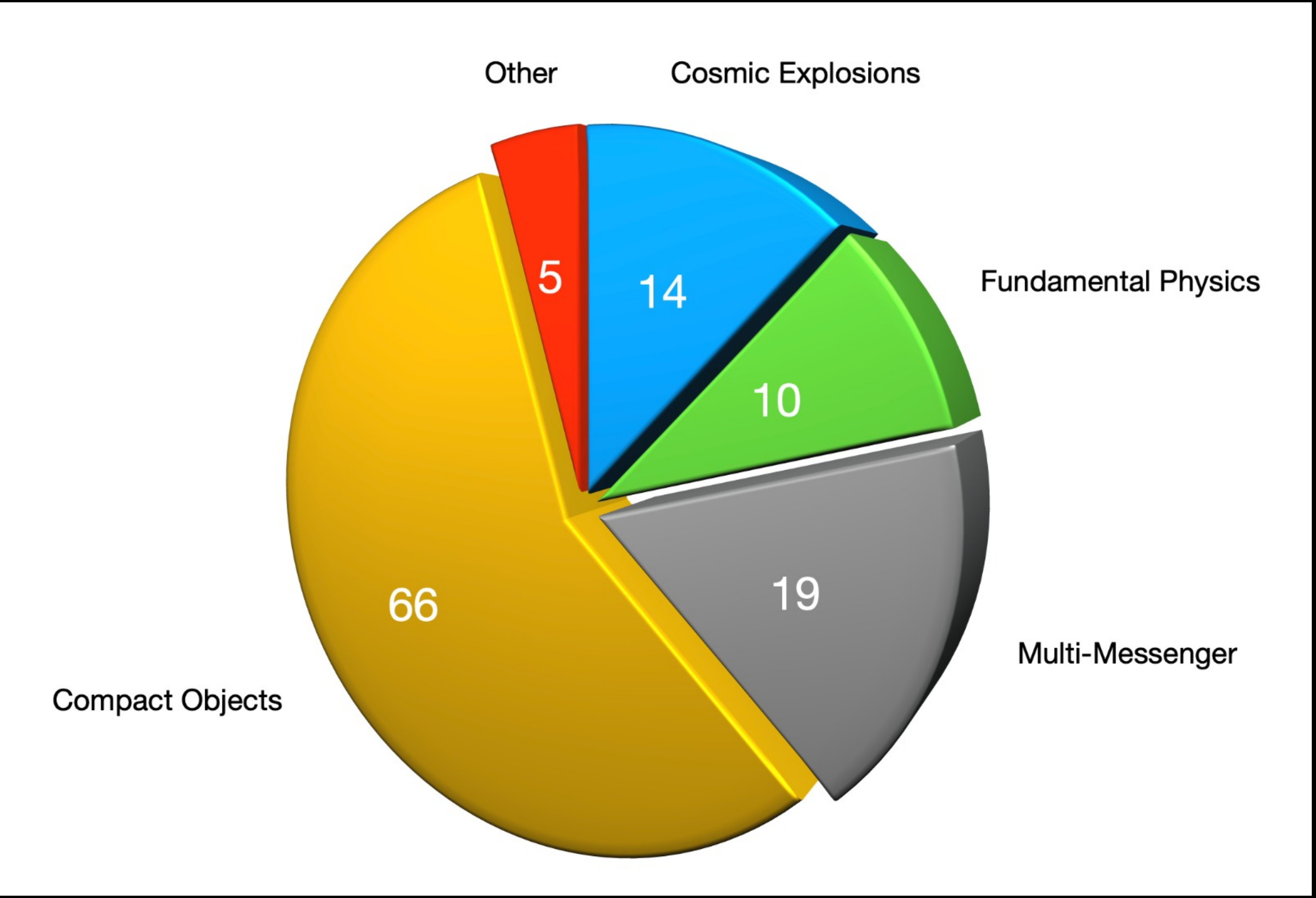

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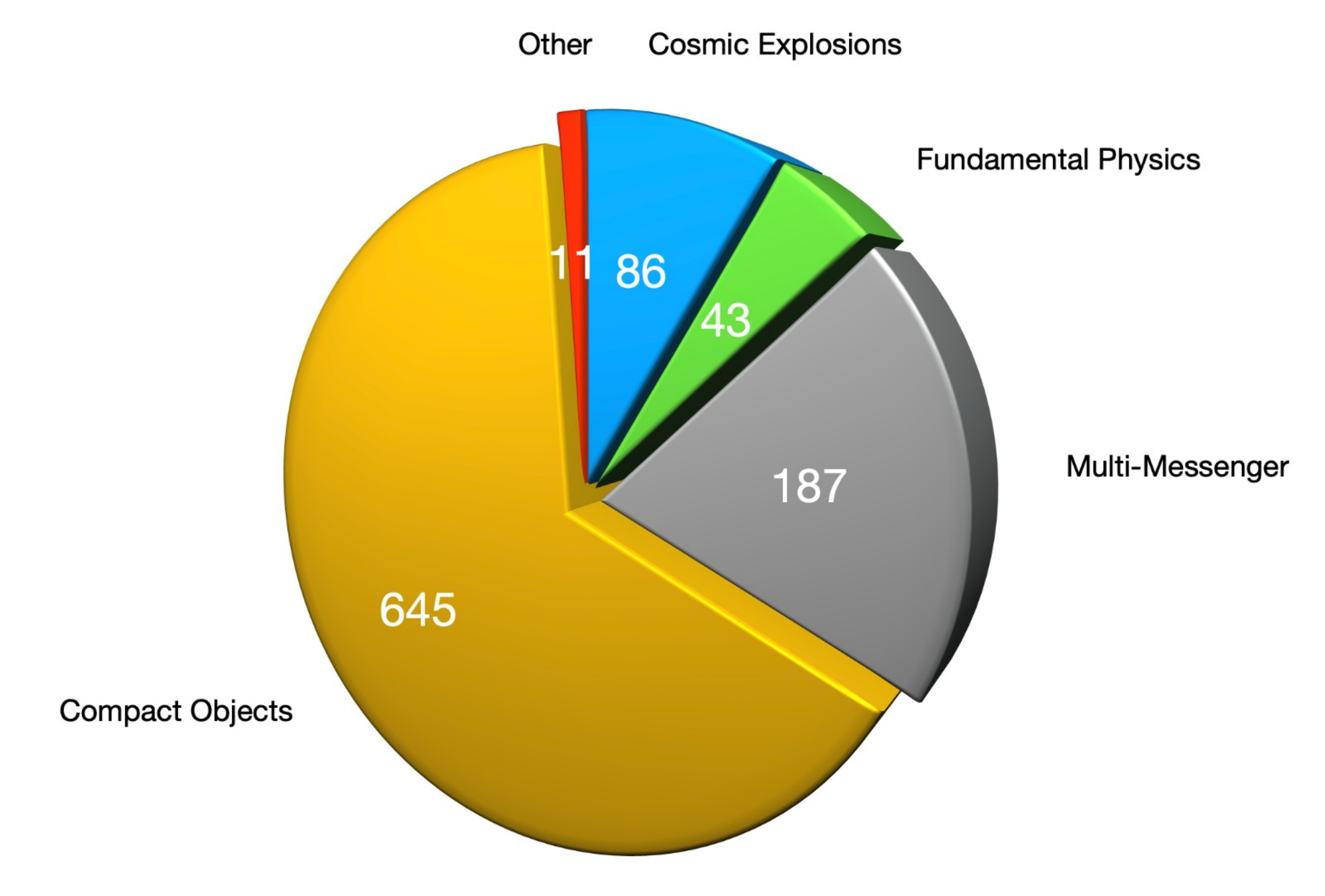

Overview of The Most Relevant International Observing Facilities According to the International Roadmaps of interest for RSN4

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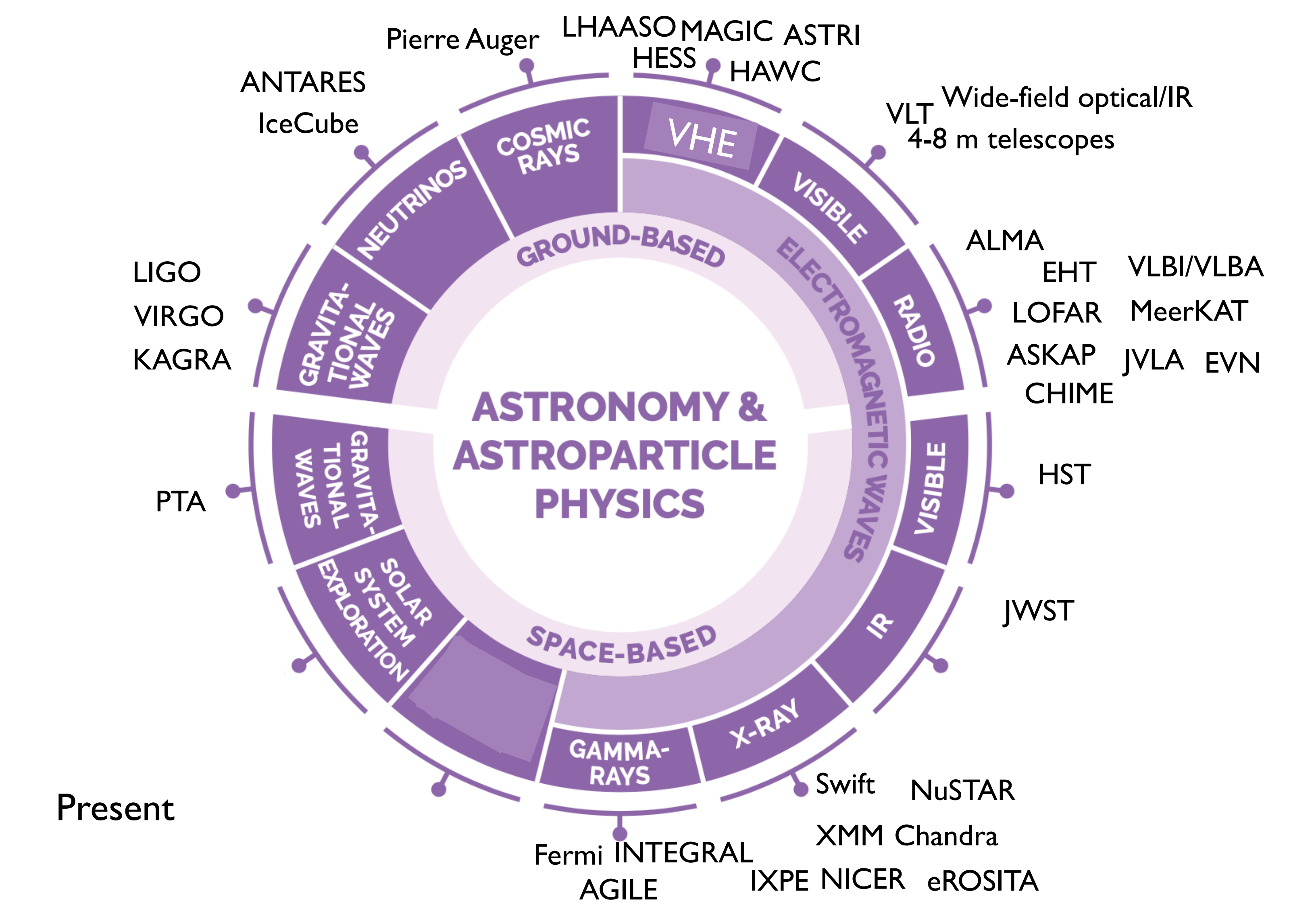

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RSN4 Projects Involving Existing International Observing Facilities

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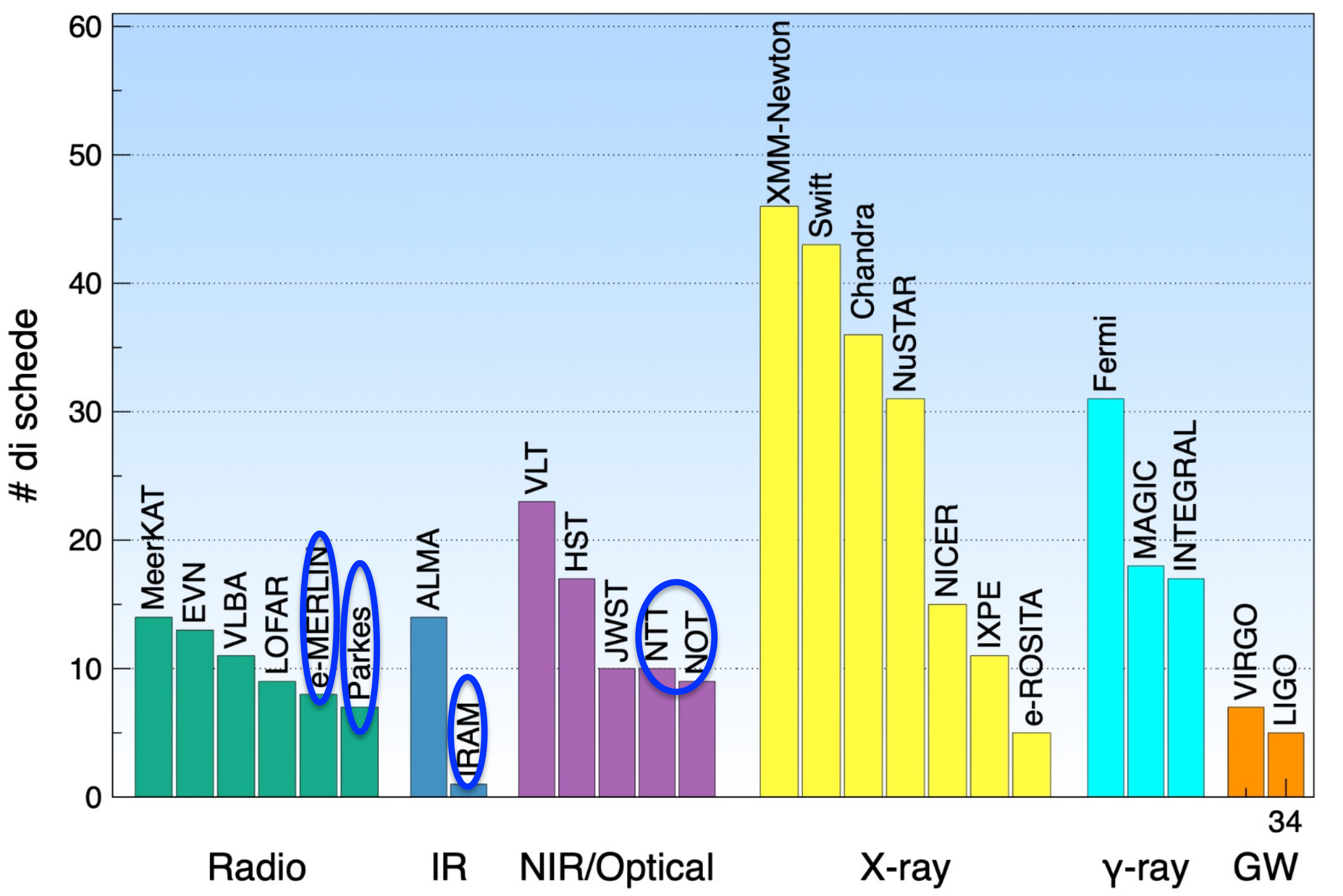

Overview of The Most Relevant International Observing Facilities According to the International Roadmaps of interest for RSN4

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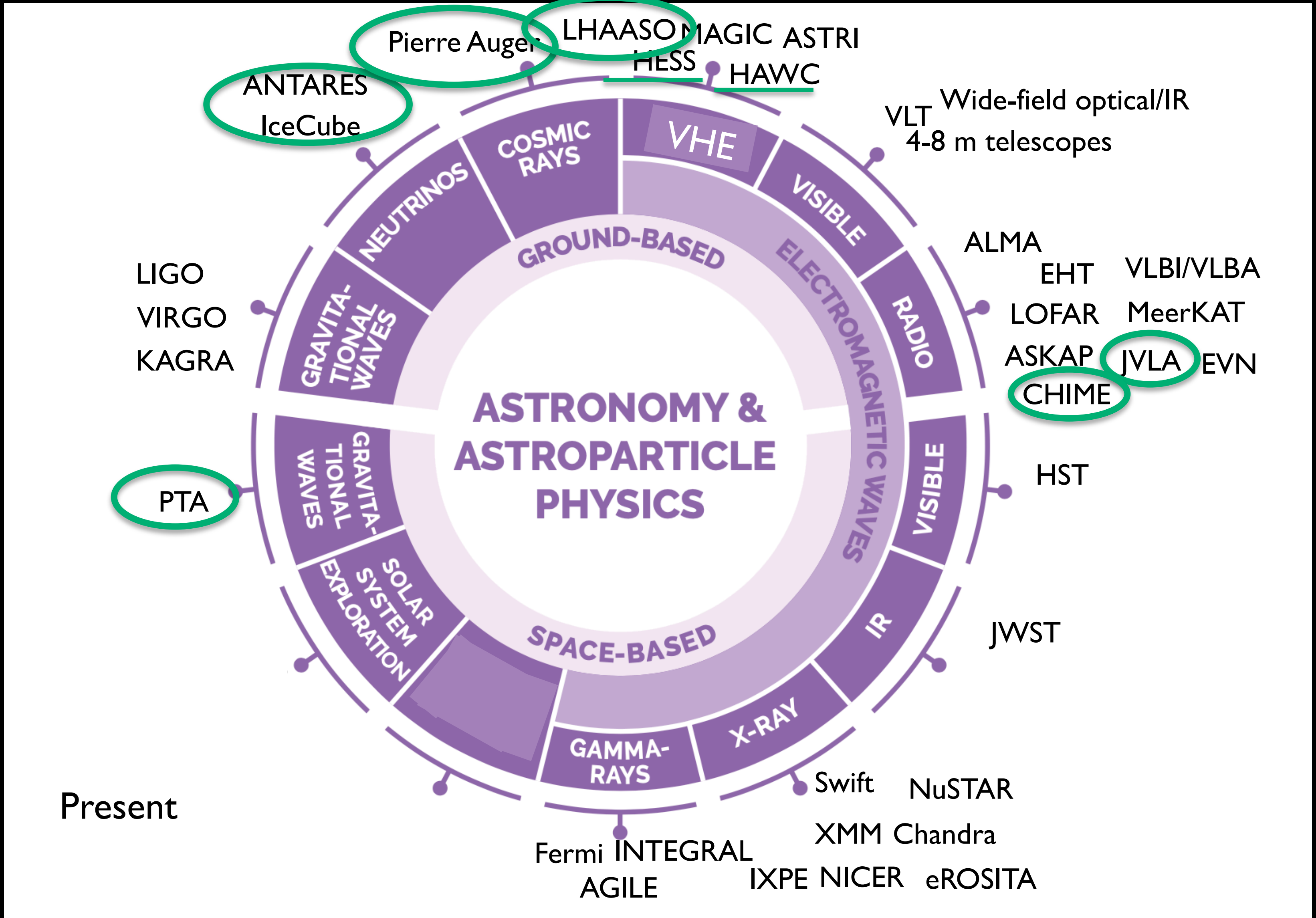

From:

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- GWIC

Conclusions. II

- All the most relevant scientific topics according to the current international roadmaps are covered by RSN4 in an almost balanced way

- RSN4 is interested in the most relevant international observing facilities at work

RSN4 Projects Involving Existing "National" Observing Facilities

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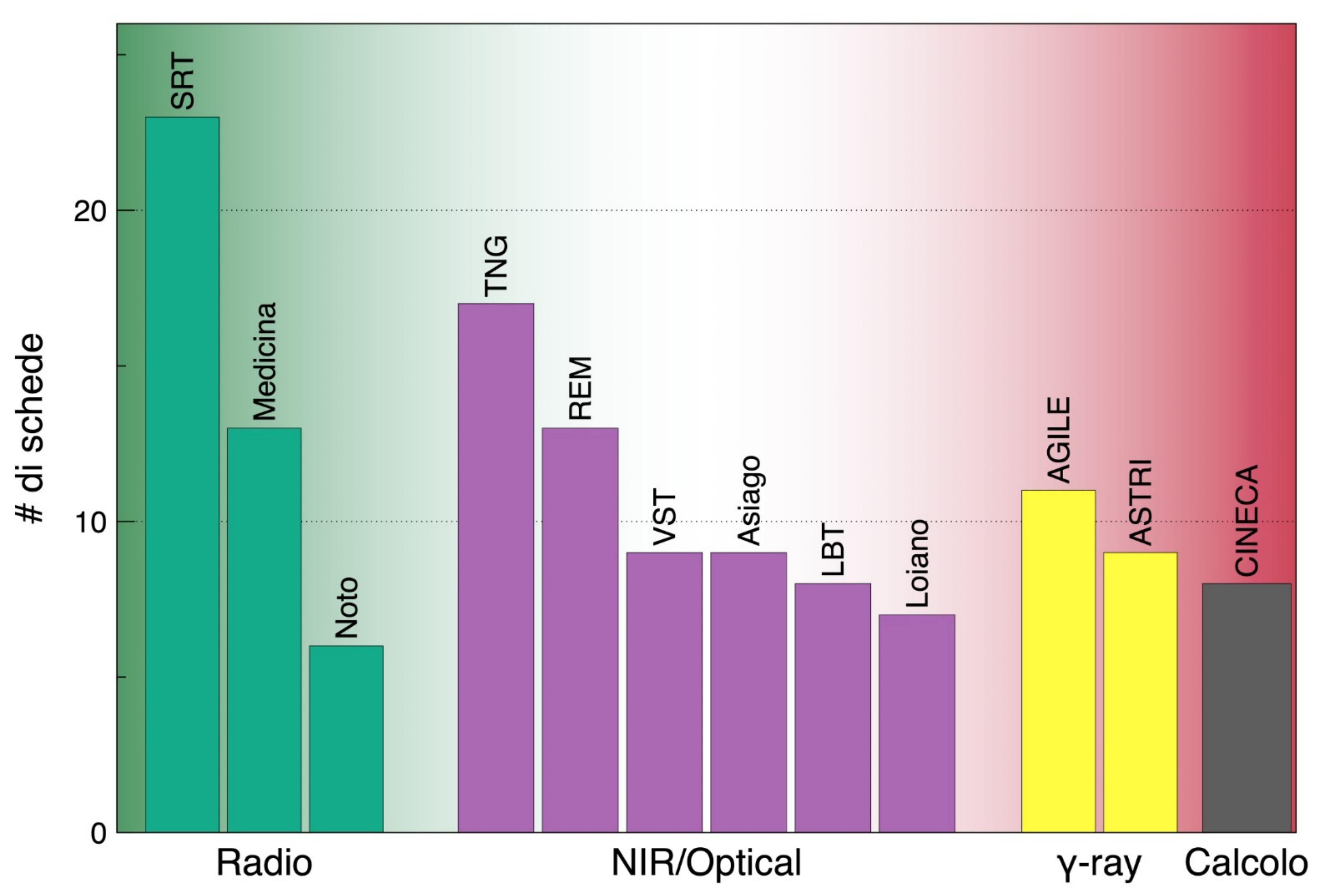

RSN4 Projects Involving Existing International and "National" Observing Facilities

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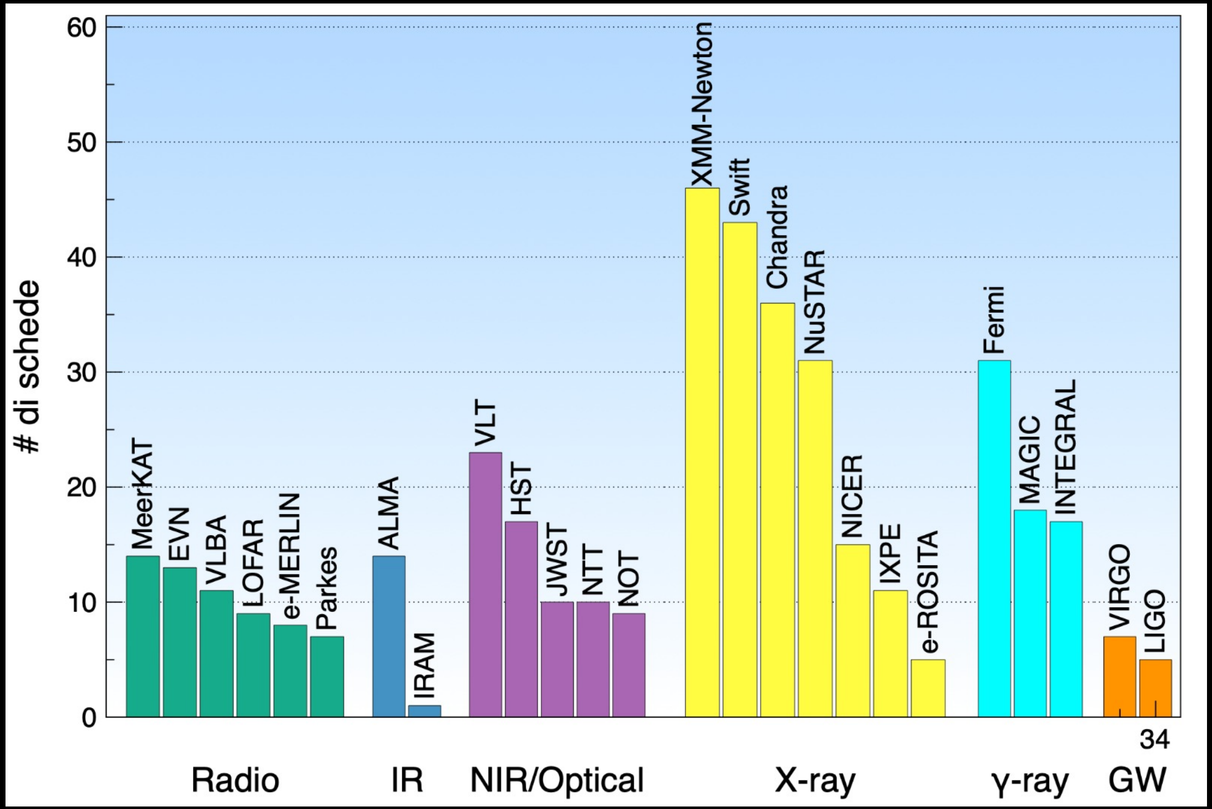

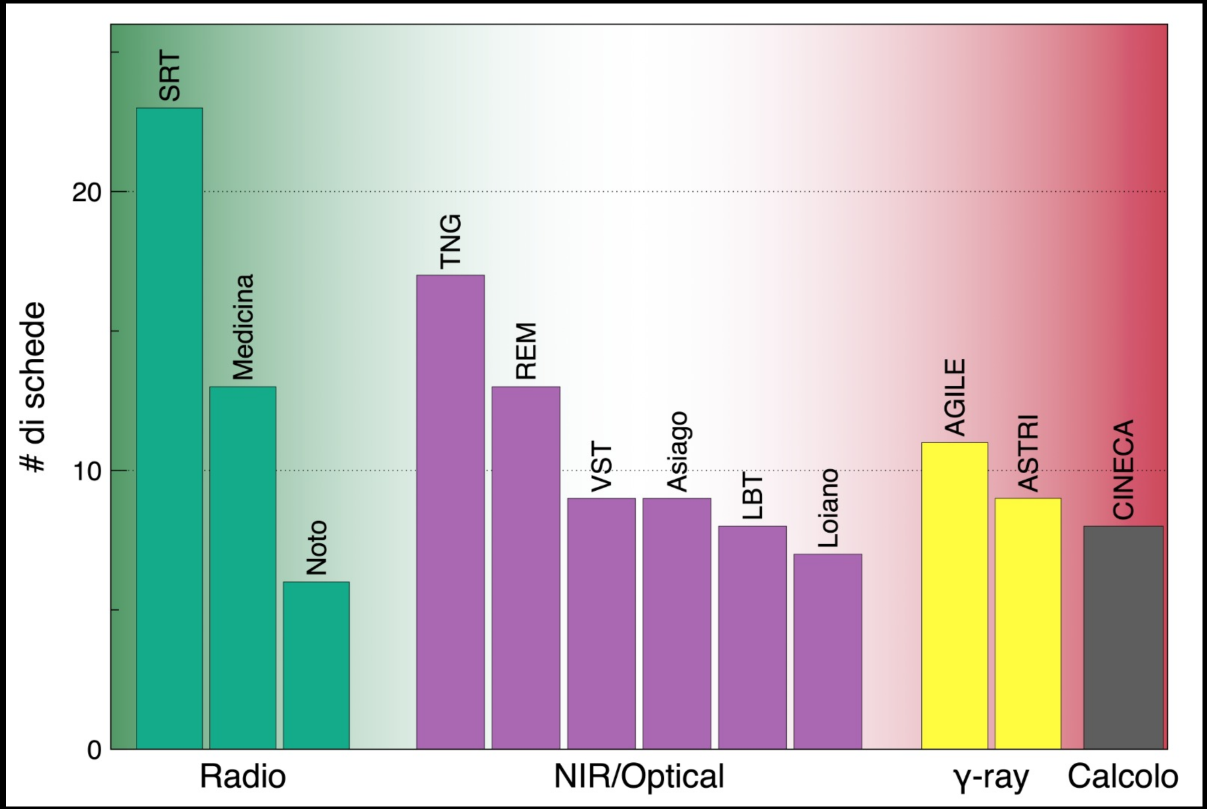

Conclusions. III

- All the most relevant scientific topics according to the current international roadmaps are covered by RSN4
- RSN4 is interested in the most relevant international observing facilities at work
- National observing facilities represent equally efficient complementary tools
- Presence of theoretical community interested in numerical simulations ready to exploit the future national and international facilities

Overview of The Most Relevant International Future Facilities According to the International Roadmaps of interest for RSN4

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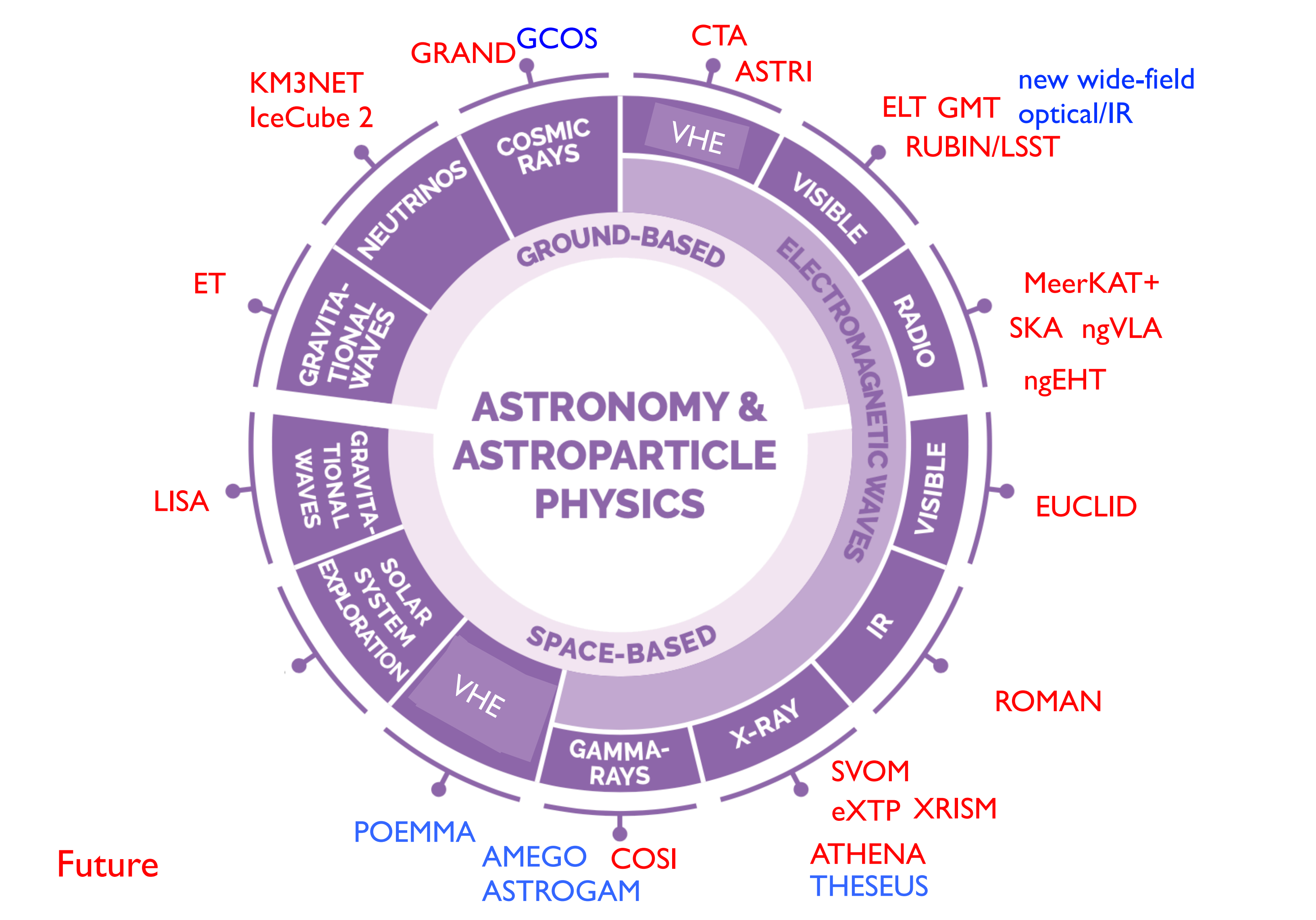

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RSN4 Projects Involving Future International Observing Facilities

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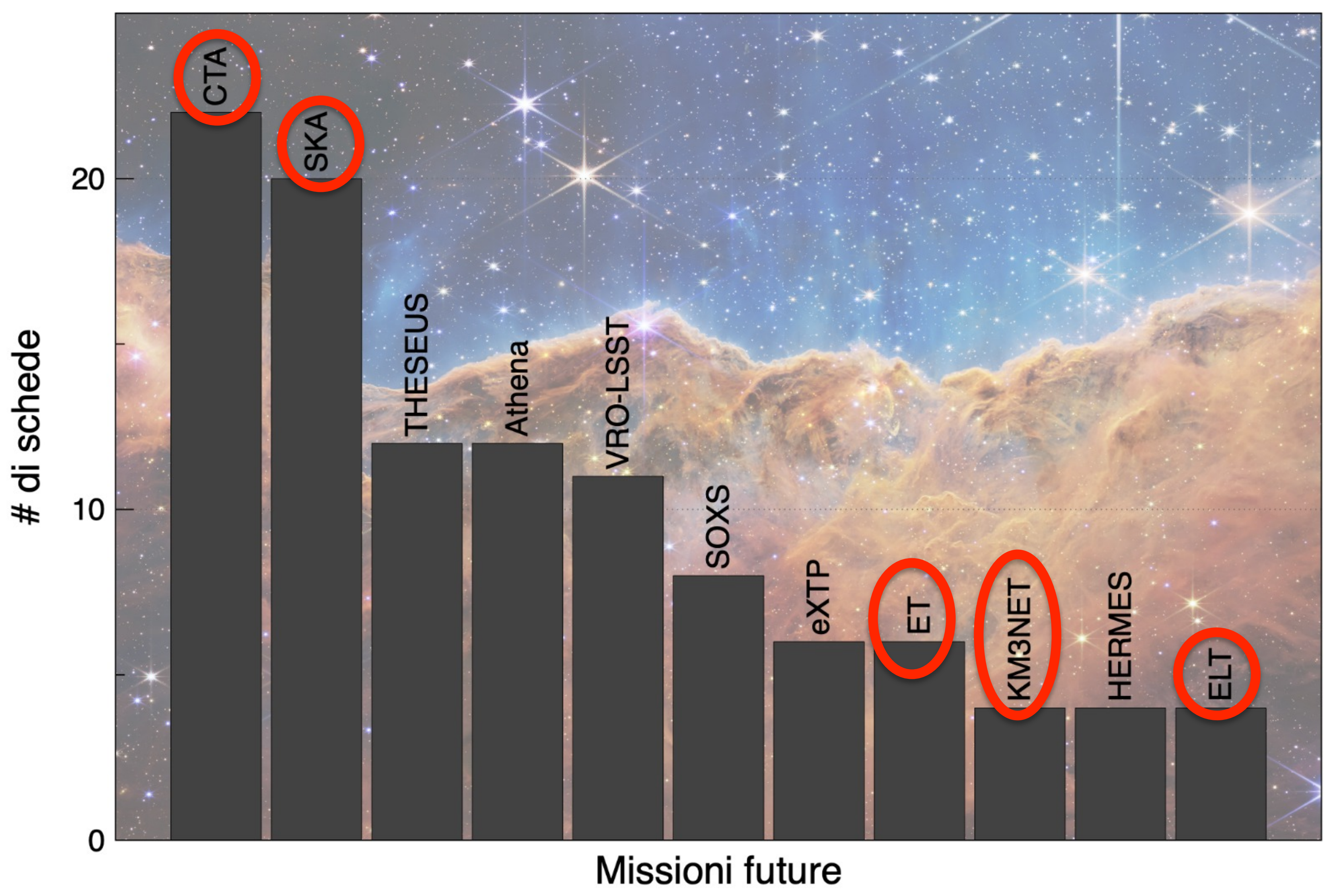

ESFRI

Overview of The Most Relevant International Future Facilities According to the International Roadmaps of interest for RSN4

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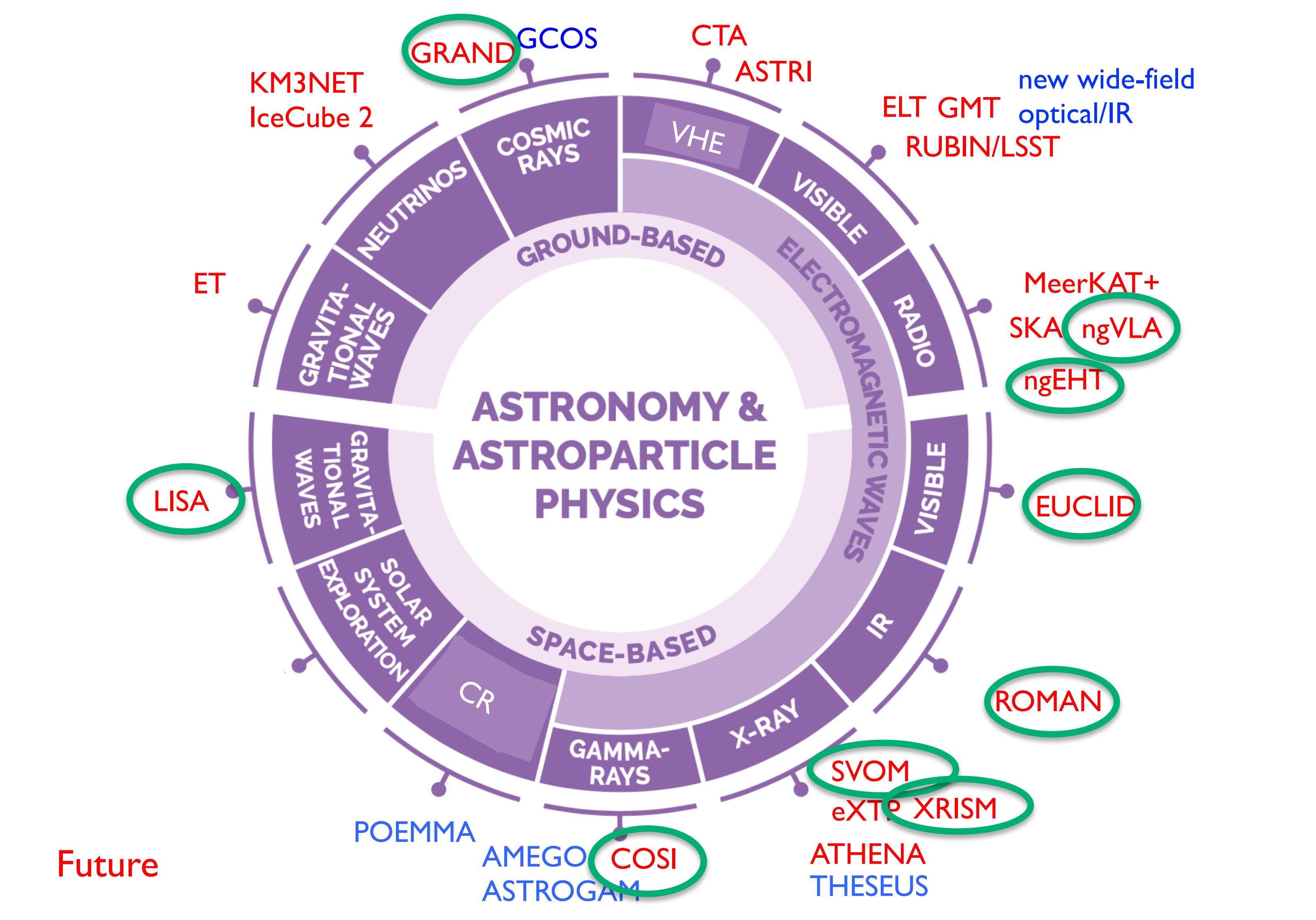

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Conclusions.VI

- All the most relevant scientific topics according to the current international roadmaps are covered by RSN4

- RSN4 is interested in the most relevant international observing facilities at work

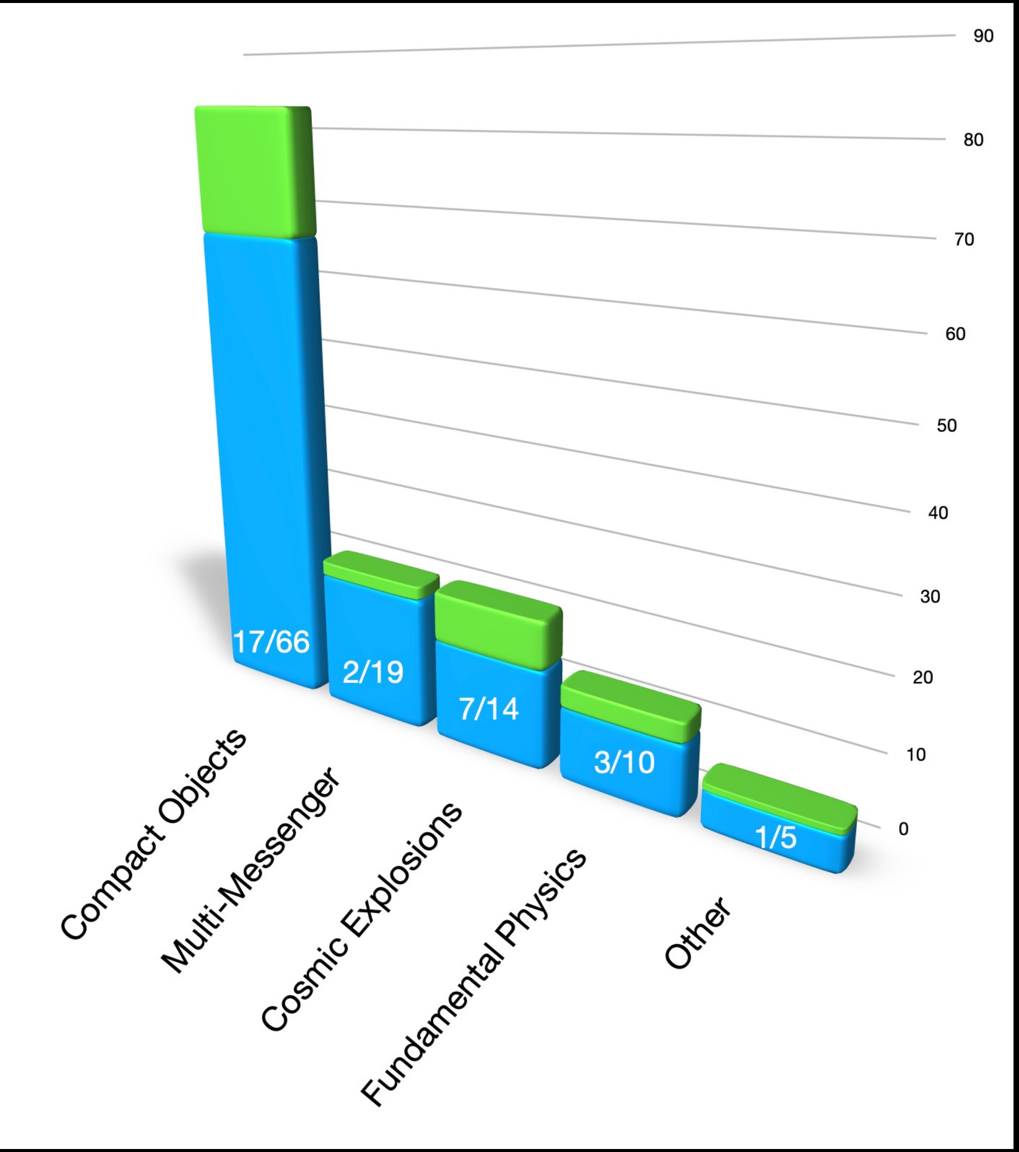
- National observing facilities represent equally efficient complementary tools

- Presence of a non negligible theoretical community interested in numerical simulations ready to exploit the future national and international facilities

- Among the ESFRI Landmark Projects in which RSN4 is mostly involved, CTA and SKA are considered significantly, ELT, ET, KM3NETstill marginal

- Among the most relevant international future facilities identified by the roadmaps little interest in LISA, Euclid, ngEHT and ngVLA

Scientific Topics Distribution: Funding



Schede
Progetti Finanziati

Scientific Topics Distribution: Funding

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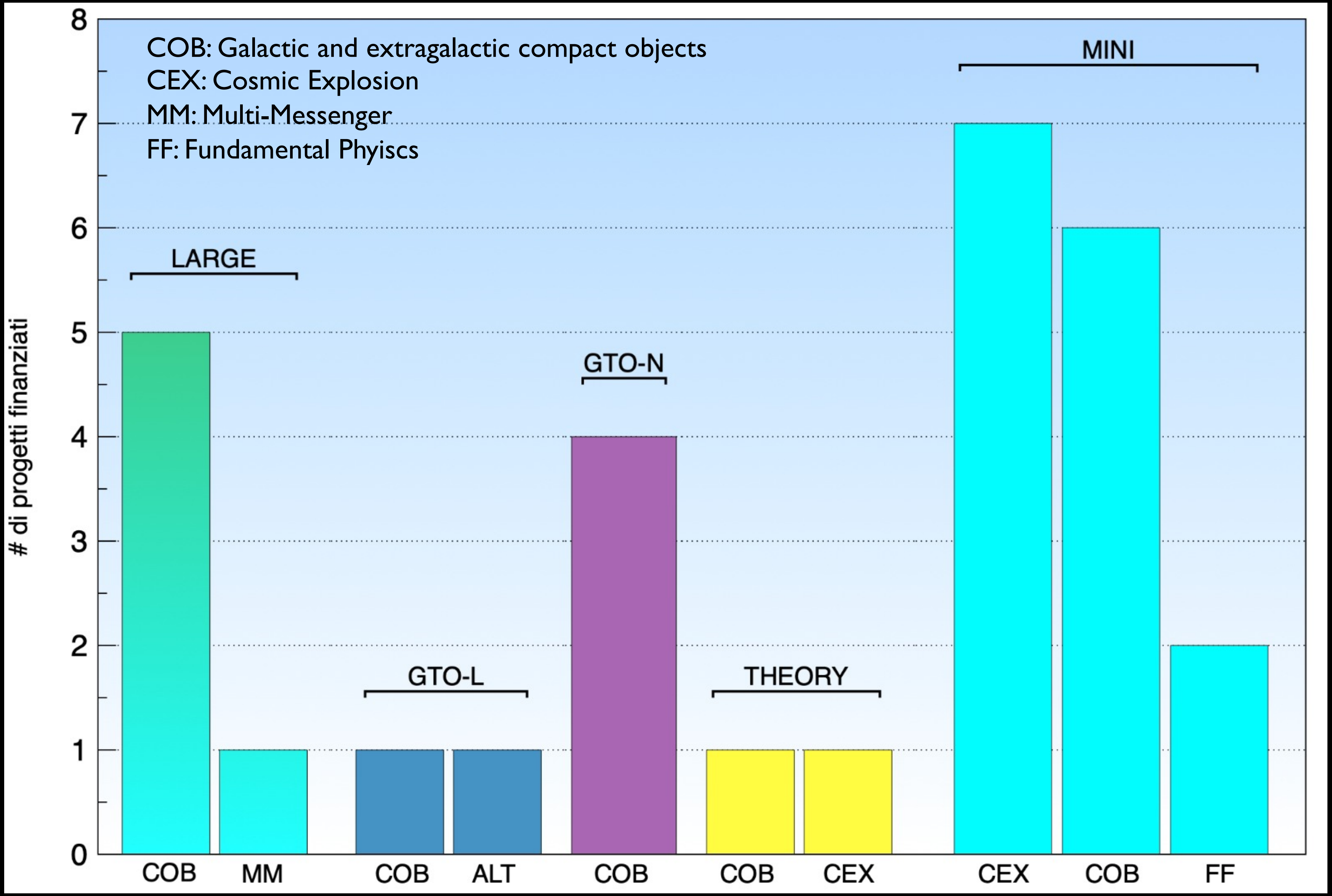

Summary and Conclusions

- All the most relevant scientific topics according to the current international roadmaps are covered by RSN4
- RSN4 is interested in the most relevant international observing facilities at work that will be continuously supported in the future
- National observing facilities represent equally efficient complementary tools
- Presence of a non negligible theoretical community interested in numerical simulations ready to exploit the future national and international facilities
- Among the ESFRI Landmark Projects in which RSN4 is mostly involved, CTA and SKA are considered significantly, ET, ELT, KM3NET still marginal
- Among the most relevant international future facilities identified by the roadmaps little interest in LISA, Euclid, ngEHT and ngVLA
- COB supported by almost all the financial channels, CE theory and mini, MM only large, FF only mini
- Effective in obtaining financing for Large Grants (6 Large Grants out of 16)

Possible Arguments of Discussion

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- Reading the "*schede*" emerges graininess, overlapping projects: healthy competitions or collaborations/coordinations?
- Stimulate interest in all those facilities in which INAF is mostly involved (ELT, ET, KM3NET)
- Stimulate interest in facilities such as LHAASO, EHT, LISA
- Future after Fermi, XMM, Swift? ..after Fabrizio's ESA view..(THESEUS, Athena, GRINTA, ASTROGAM, HERMES, eXTP, COSI, Star-X, AXIS)
  Other band (ULTRASAT, UVEX)?
- Astronomy+astroparticle+fundamental physics. How to enhance synergies? (see European calls, Germany example..)
- High-redshift??
- Enhance collaboration with other RSNs?