

GdL ASI - Exoplanets, Stars, the Milky Way, and the Local Group

A. Sozzetti, F. Borsa, M. P. Di Mauro

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ASI Roadmapping Exercises

Ten-year thematic roadmaps on the state of the art and frontier challenges of solar system science and astrophysics to guide the space community's activities. WGs set up to analyze scientific and technological areas of development, producing final reports.

Solar System WG:

- Solar Physics
- Inner Solar System
- Outer Solar System
- Small Bodies

Astrophysics WG, ASI Coordinator Immacolata Donnarumma:

- Origin and Evolution of the Universe
- Extreme Universe
- Galaxy, Stellar and Planetary Formation and Evolution

Members of Astrophysics WG invited in late 2022, WG activities started in 2023.

Results of Astrophysics WG presented at the community at ASI HQ in April 2025:
Workshop "**Verso una roadmap italiana per la scienza nel settore dell'astrofisica spaziale**"

Galaxy, stellar and planetary formation

ASI co-chairs

Manuele Gangi¹, Elisabetta Tommasi¹

co-chair

Alessandro Sozzetti²

members

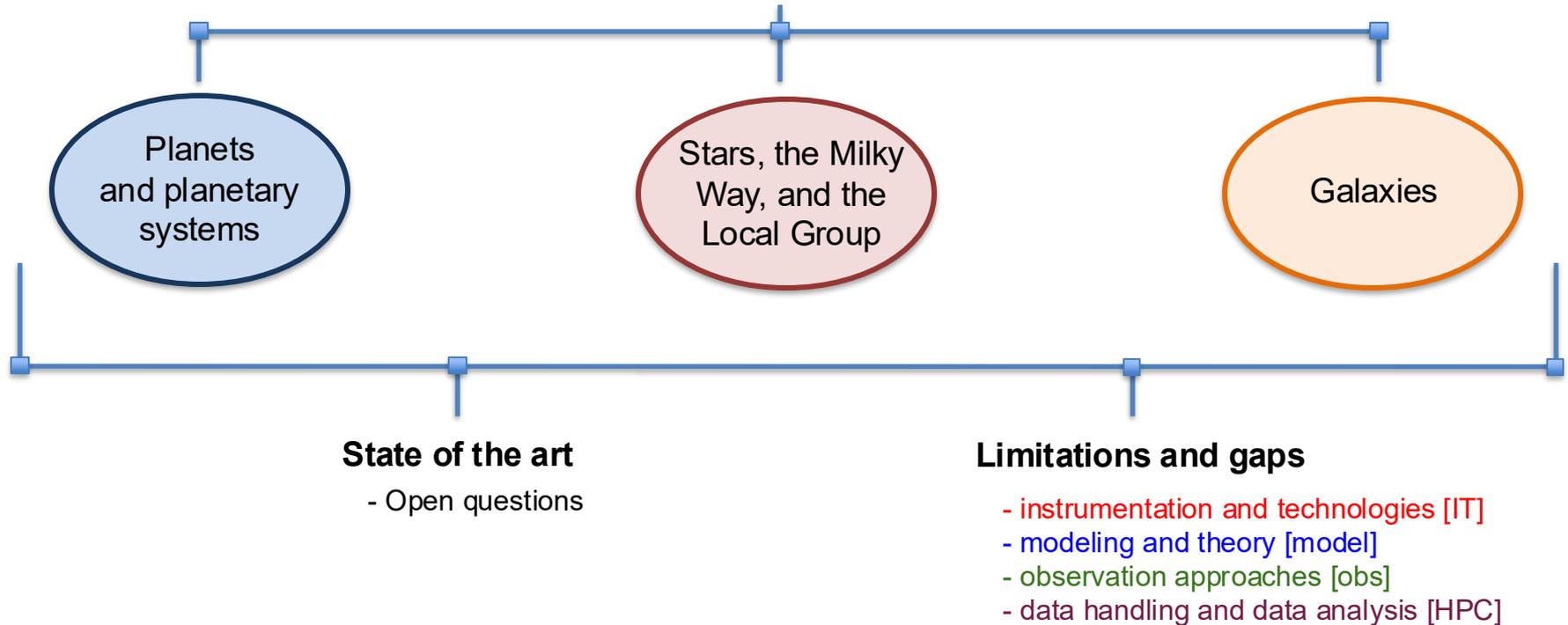
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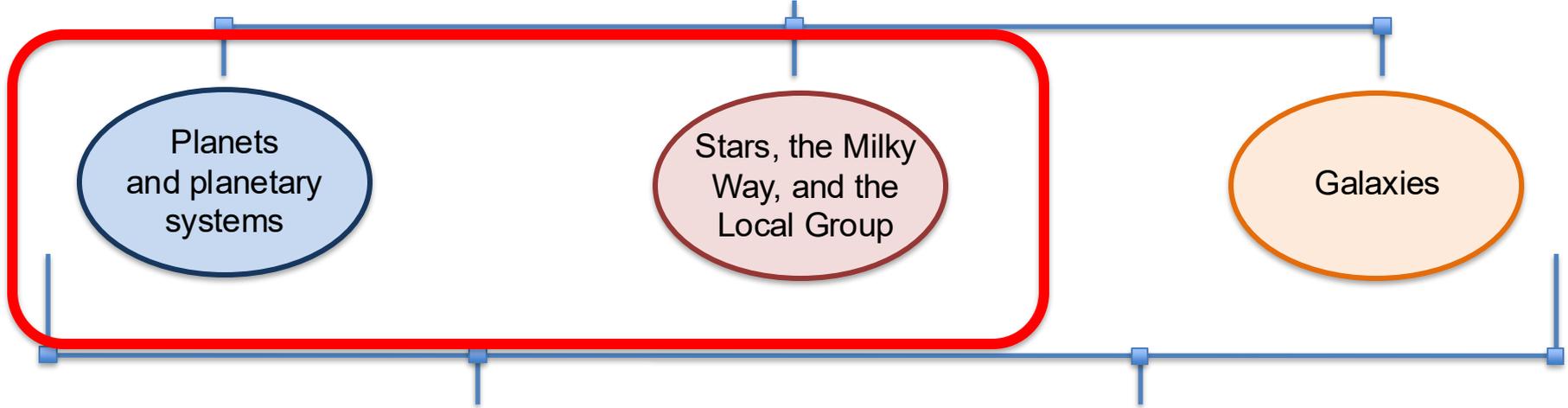
NB: not the first time this happens.

E.g., back in 2007 ASI Astrophysics WG with G. Micela (Chair), L. Amati, S. Mereghetti, M. Turatto, A. Celotti

Galaxy, stellar and planetary formation



Galaxy, stellar and planetary formation



State of the art

- Open questions

Limitations and gaps

- instrumentation and technologies [IT]
- modeling and theory [model]
- observation approaches [obs]
- data handling and data analysis [HPC]

QUESTIONS	OBSERVABLES	ONGOING MISSIONS	PLANNED MISSIONS	LIMITATIONS AND GAPS L: limitation, G: gap instrumentation and technologies [IT] modeling and theory [model] observation approaches [obs] data handling and data analysis [HPC]
Q2: Demographics and new discoveries: What is the global architecture of planetary systems? How does it depend on the parent stars' properties?	Astrometry (global and narrow-angle) <ul style="list-style-type: none"> true masses 	Space <ul style="list-style-type: none"> Hipparcos HST Gaia Ground <ul style="list-style-type: none"> VLT (FORST) VLT (GRAVITY+) 		L: centroid accuracy, calibrations [IT] G: ultra-high-precision (< 1 μ as) differential astrometry, high-precision (10 μ as-level) NIR astrometry [obs], [IT] L: computing resources/techniques [HPC], modeling [model]
	Transit photometry <ul style="list-style-type: none"> radii statistics 	Space <ul style="list-style-type: none"> Kepler/K2 TESS CHEOPS Ground <ul style="list-style-type: none"> SuperWASP HATNet HATSouth 	Space <ul style="list-style-type: none"> PLATO 	L: length of uninterrupted time-series [obs] L: computing resources/techniques [HPC], modeling [models]
	Radial velocities VIS <ul style="list-style-type: none"> minimum masses statistics 	Ground <ul style="list-style-type: none"> 3.6m (HARPS) TNG (HARPS-N) HIRES VLT (ESPRESSO) EXPRES 	Ground <ul style="list-style-type: none"> HARPS3 KPF ELT (ANDES) 	L: stellar activity [HPC], long-term instrumental stability [IT], computing resources/techniques [HPC], modeling [model]
	Radial velocities NIR <ul style="list-style-type: none"> minimum masses statistics 	Ground <ul style="list-style-type: none"> CARMENES Spirou 3.6m (NIRPS) CRIRES+ 		L: stellar activity [HPC], long-term instrumental stability [IT], telluric correction, computing resources/techniques [HPC], modeling [model]

State of the art

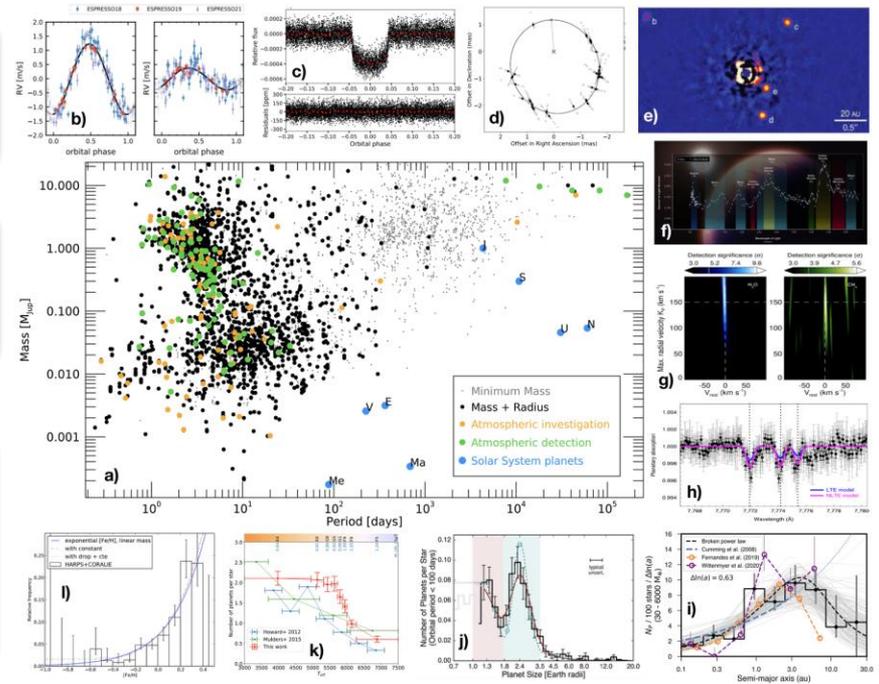
Planets and Planetary systems

Q1: Planet formation, evolution, death: How do planetary systems form and evolve? How is this evolution going to end?

Q2: Demographics and new discoveries: What is the global architecture of planetary systems? How does it depend on the parent stars' properties?

Q3: Interior and Atmospheric Characterization: How much can we tell about exoplanets' interior composition? Do we understand atmospheric environment and processes? Are we able to search for evidence of biomarkers?

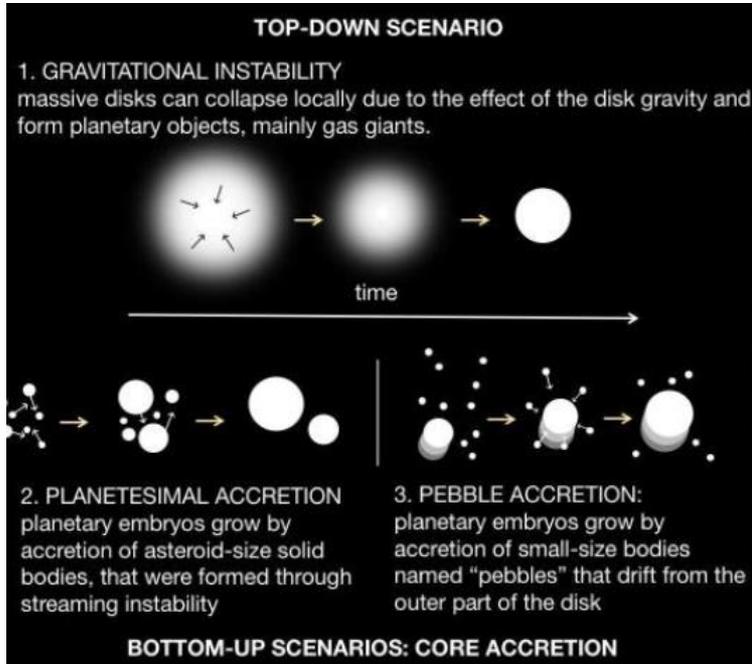
b) Faria+22; c) Valdes+23; d) Holl+23; e) Marois+10; i) Fulton+21; j) Fulton+17; k) Yang+20; l) Mortier+13; f) NASA/ESA; g) Giacobbe+21; h) Borsa+22



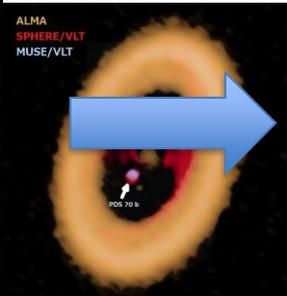
State of the art

Planets and Planetary systems

Q1: Planet formation, evolution, death: How do planetary systems form and evolve? How is this evolution going to end?

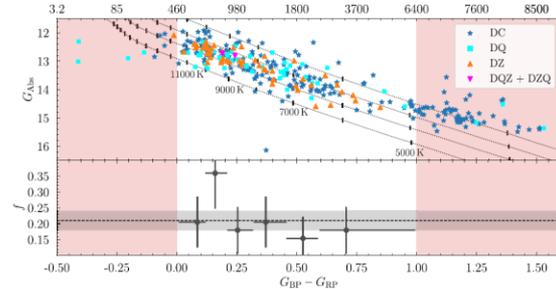


- Core-dominated accretion more common formation mode
- Protoplanetary disk substructures (rings, gaps) carved by forming planets (?)
- Disks' molecular content (CO, hydrocarbons) linked to atmospheric properties



Processes

Evolution



Isella+ 2019

Manser+ 2023

- Many processes (photoevaporation, stellar encounters, migration, scattering, tidal and long-term dynamical interactions) drive evolution
- Planetary systems' fate ultimately tied to the evolution of the primaries off the main sequence

Limitations and gaps

Planets and Planetary systems

Q1: Formation and evolution

L High Spatial Resolution VIS-IR-RADIO imaging

- au-scale disk substructures
- disk size distributions
- radial extent of gas and dust

L UV Medium-Res Spectroscopy

- post-MS exoplanet chemistry

L Low- to Medium-Resolution VIS-IR-RADIO spectroscopy

- dynamics of disk substructures
- disks' dust composition
- disks' compositional gradients

KEY OPEN QUESTIONS

- Protoplanetary disks: mass distribution
- Protoplanetary disks: water budget
- Protoplanetary disks: gas/dust microphysics
- Protoplanetary disks: 3D modeling
- Forming Planets: demographics
- Post-MS systems: chemistry of planetary debris
- Post-MS systems: mineralogy of gas/dust disks

G Low, Medium, High-Resolution Infrared Spectroscopy

- *Effective disk mass tracers (HD)*
- *Large samples of disk masses*
- *Detailed water (gas and ice) budget*

RV, Transits, Astrometry, HCI, GW

- Detection of forming giant planets
- Detection of post-MS planets **L**

L Modeling

- 3D MHD modeling of gas-dust-solid interactions
- hybrid pebble/planetesimal accretion

G Lab Experiments

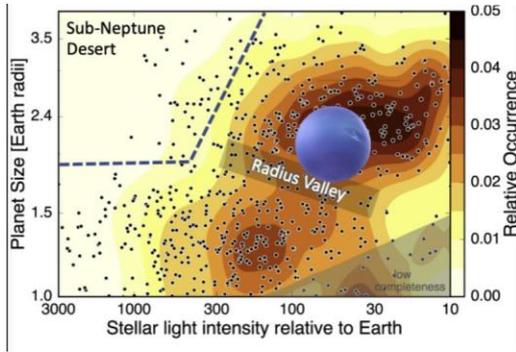
- *particle sticking mechanisms*
- *gas and dust phase chemistry*
- *dust-ice mixtures properties/behaviour*

State of the art

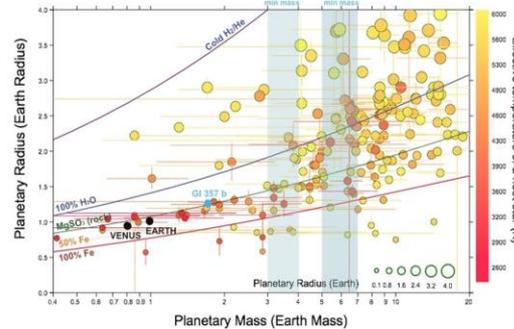
Planets and Planetary systems

Q2: Demographics and new discoveries: What is the global architecture of planetary systems? How does it depend on the parent stars' properties?

Fulton+ 2017



Kaltenegger+ 2019

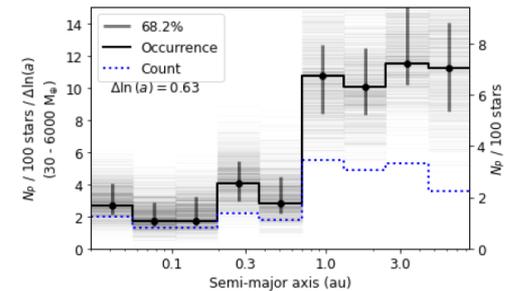


TECHNIQUES/OBSERVABLES

- Radial velocities (VIS/NIR)
- Transit photometry
- Astrometry (global/relative)
- High-contrast imaging
- Microlensing

- most abundant close-in planets: super-Earths and sub-Neptunes;
- their size distribution is bimodal;
- they can be rocky, water-worlds, or have gas envelopes;
- there is a hot-Neptune desert, but gas giants are found out to 100s au;
- giant planet frequency correlates with both stellar mass and metallicity;
- the frequency of true Jupiter analogs is around 10%;
- all low-mass stars likely host one super-Earth;
- one in four solar-type stars host an Earth-like planet;
- dynamically packed configurations of close-in, small planets are common

Lagrange+ 2023



Limitations and gaps

Planets and Planetary systems

Q2: Detections and demographics

KEY OPEN QUESTIONS

- Detections: true Earth analogs
- Detections: terrestrial planets at or beyond the snow line
- Detections: the unexpected! E.g., co-orbitals
- Demographics: diversity of architectures
- Demographics: occurrence of Earth analogs
- Demographics: occurrence of Solar System analogs
- Demographics: mass vs mass ratio
- Demographics: M_p , R_p distributions vs a_p , M_s
- Demographics: architectures vs host properties and environment

L/G

Modeling/Theory

- High-performance calculus
- *Combined demographics techniques*
- *Physical processes in global formation models*

L Radial Velocities (VIS, NIR)

- Stellar activity (rotation, cycles) correction
- Telluric lines correction
- Long-term instrumental stability

L Transit Photometry

- Length of uninterrupted time-series

G Astrometry

- *Narrow-field: sub- μ s precision*
- *Instrumental stability*
- *Centroiding accuracy, calibrations*

L/G Direct Imaging (VIR, IR)

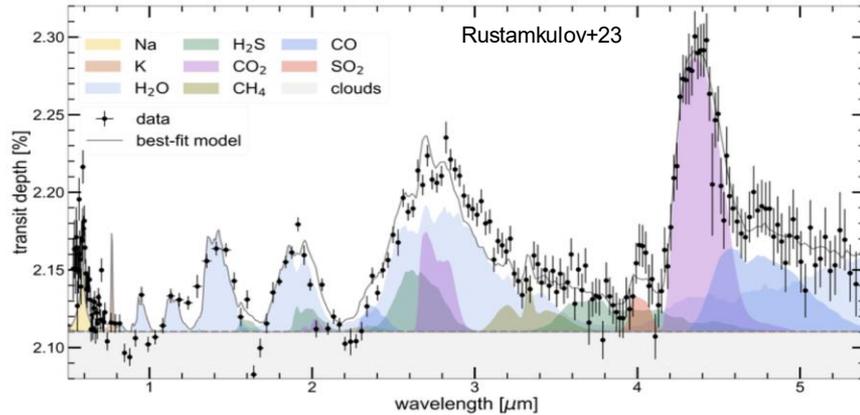
- *Starlight suppression (contrast) technologies*
- *Stability (orbital, thermal)*

L Microlensing

- Lens mass / distance degeneracy breaking

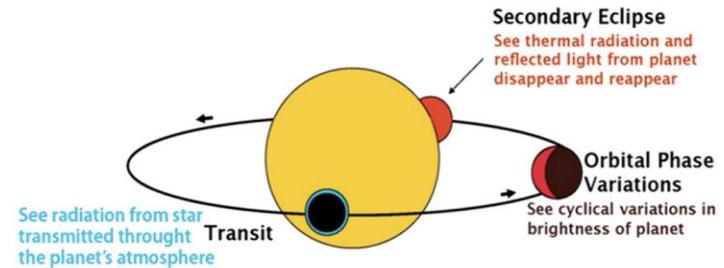
State of the art

Planets and Planetary systems



- Composition of atmospheres can trace the planet's formation and evolution;
- Observations in transmission, emission, reflection;
- Atmospheric evaporation and mass loss related to radiation environment;
- Ultra-hot gas giants: traces of iron and other metals;
- Hot gas giants: dominated by molecular species (H₂O, CH₄, CO);
- Winds, non-equilibrium chemistry, atmospheric circulation/temperature patterns and gradients, 3D structure;
- For colder/smaller close-in planets, thick clouds/hazes or no atmosphere?

Q3: Interior and Atmospheric Characterization:
How much can we tell about exoplanets' interior composition? Do we understand atmospheric environment and processes? Are we able to search for evidence of biomarkers?



Beichman et al. 2014

TECHNIQUES/OBSERVABLES

- HR spectroscopy (VIS/NIR)
- LR spectroscopy (VIS/NIR)
- Phase curve photometry
- High-contrast imaging

Limitations and gaps

Planets and Planetary systems

Q3: Atmospheric characterization

KEY OPEN QUESTIONS

- How to relate high to low atmosphere?
- What is the overall atmospheric scenario?
- Is variability of hot gas giants related to stellar activity?
- Do hot rocky worlds have atmospheres?
- Can we detect Earth-like planets atmospheres?
- Are we able to search for biomarkers in other planets?

Lab, Modeling and Theory

- Accurate HR molecular linelists
- 3D modeling of planets and stars
- Unambiguously identify a gas as a biomarker
- Framework to relate high to low atmosphere

Data analysis

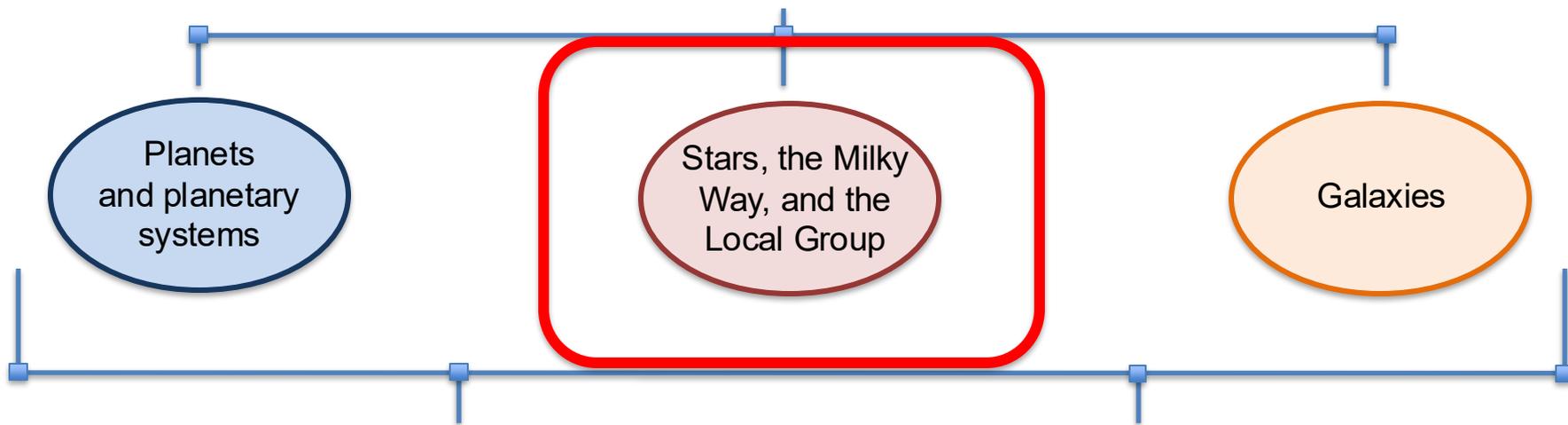
- New modeling/computing strategies to deal with 3D modeling and the increasing amount of data

Observational approaches

- Radiation environment: missing EUV flux
- Telluric correction: problem for characterization of planets in the Habitable Zone

Instrumentation and techniques

- Joint use of high-contrast imaging and high-resolution spectroscopy



State of the art

- Open questions

Limitations and gaps

- instrumentation and technologies [IT]
- modeling and theory [model]
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State of the art

Stars

Q1: How do stars form? What are the relevant mechanisms and typical conditions? Global star formation properties in the Milky way

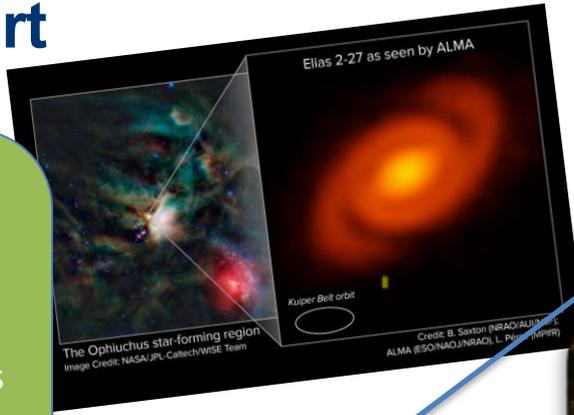
Q2: How do stars evolve and how do they die? What is the role of turbulence and mixing? What is the role of magnetic activity along the evolution? What is the impact of stellar multiplicity?

Q3: How were stellar populations in the Galaxy and the Local Group assembled? How did they evolve chemo-dynamically across time? How did they interact and influence each other?



State of the art

Stars



Q1: How do stars form?

What are the relevant mechanisms and typical conditions?

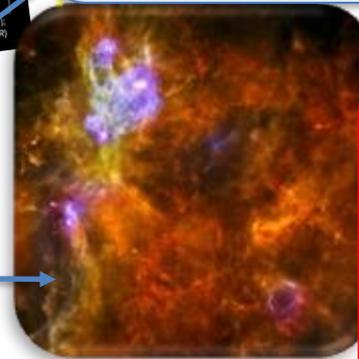
Global star formation properties in the Milky way

Formation occurs in interstellar molecular clouds of very cold gas and dust and can be studied only on infrared, radio, and UVX-ray light able to penetrate the surrounding dust

Radio telescope campaigns, interferometry

- star formation rate
- continuum emission
- radio free-free emission from O stars in the Galactic disk
- fragmentation and disk formation of high mass stars
- circumstellar disks
- gas envelopes

Radio telescope Polarimetry-magnetic fields



IR, MIR, Far Infrared spectroscopy

- gas tracers
- star formation rate
- radial velocity
- jets and gas outflows

MIR and FIR High resolution high contrast imaging (direct imaging)

- jets and gas outflows
- identification of Young Stellar Objects
- continuum emission from shock-heated gas

Near and Mid infrared interferometry

- stellar surface imaging
- circumstellar disk and dust clouds
- chemical and physical processes in cold regions

XUV spectroscopy

- Dust extinction
- star formation rate
- Temperature
- Abundances
- Emissions

Limitation and gaps

Stars

Q1: How do stars form?

- detect very cold matter (<140 K)
- FarIR observations can detect protostars long before they "turn on" visibly
- High-spectral resolution observations to infer the most important gas transitions lines and transitions for molecular gas (H₂O, CO) inaccessible from the ground

Radio telescope, interferometry

- Space-based interferometry
- ultra-high angular resolution (100 micron arc-sec) to remove the ground-based limitations of atmospheric absorption.

Ex: a small number of spacecrafts or 20-30 microsats formation-flying with a beam combining hub.
100 μ arcs resolution (1000x Chandra)



Space based Far- IR spectroscopy (25-350 μ m)

- High spectral resolution ($R > 100000$)
- large aperture (> 3,5m, larger than Hershel mission),
- perhaps single dish on the Moon [IT]
- Special Cooling facility able to last longer



- **Modeling** → atomic and molecular transitions
- **Treatment of Data** → Big Data, Artificial Intelligence, Machine Learning, Neural network techniques

State of the art

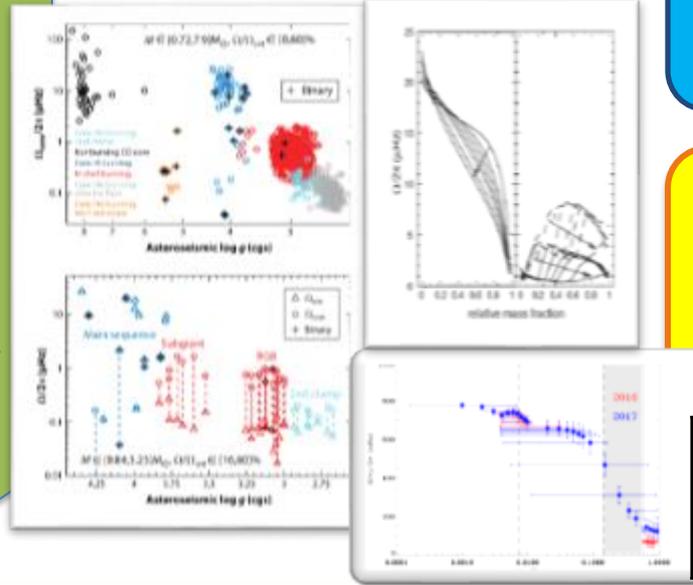
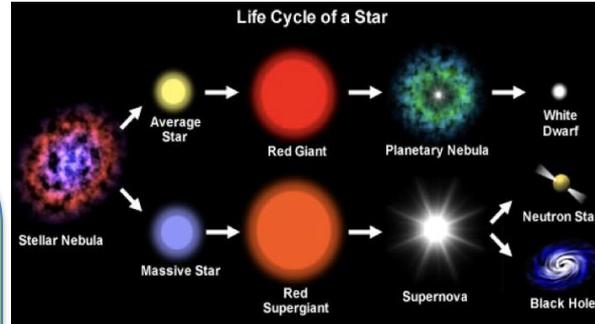
Stars

Q2: How do stars evolve and how do they die?

What is the role of turbulence and mixing?

What is the role of magnetic activity along the evolution?

What is the impact of stellar multiplicity?



High resolution multiwavelength spectroscopy

- stellar surface parameters
- dynamical characteristics



Astrometry

- Positions
- kinematics
- distance



Photometry, Asteroseismology

- color index, flux, luminosity
- stellar mass, radius, age
- internal structure and rotation

Spectropolarimetry

- Magnetic fields

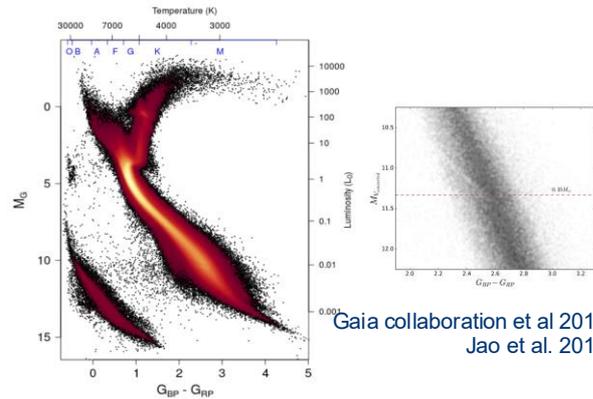
State of the art

Stars

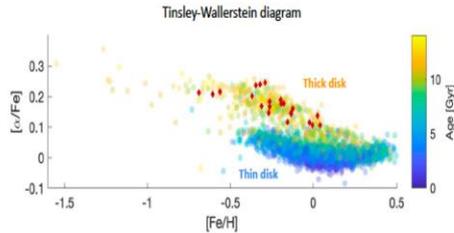
Q3: How were stellar populations in the Galaxy and the Local Group assembled?

How did they evolve chemodynamically across time?

How did they interact and influence each other?



Enormous progress has been made in the last decades in this field, thanks to the data from large surveys and space missions



Adapted from Miglio et al. (2021)

Astrometry

- proper motion
- parallax
- radial velocity
- bulk motions of clusters

Spectroscopic wide field survey

- surface parameters
- dynamical parameters

Interferometry

- stellar radius
- stellar mass

Photometry, Asteroseismology

- color index, brightness
- stellar mass, radius, age
- internal structure
- internal rotation

Limitation and gaps

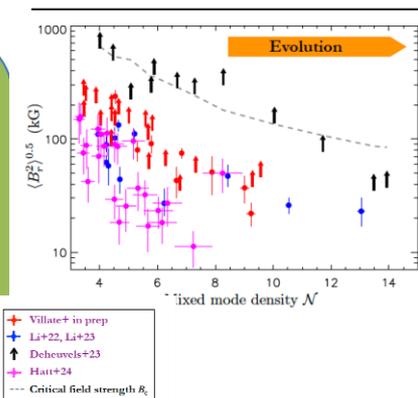
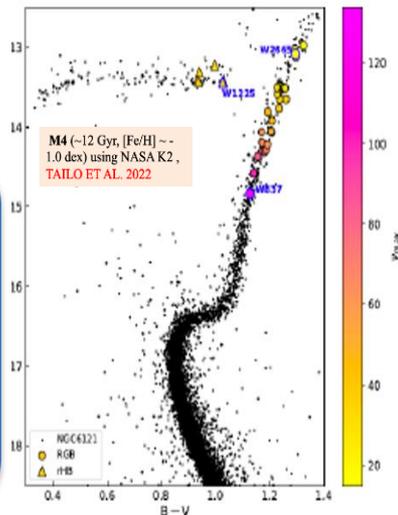
Stars

Q2: How do stars evolve and how do they die?

- Angular momentum transport
- Mass-loss efficiency along evolution
- Internal and surface magnetic fields
- Modelling convective instability
- calibrating efficiency of mixing

Q3: How were stellar populations in the Galaxy and the Local Group assembled?

- Crowded regions: cores of clusters
- Galactic bulge and disk
- Chemical evolution



Asteroseismology

High precision Optical Photometry

- short-cadence (<10s),
- long temporal time series >4 months

High resolution (R=110000) spectroscopy

- High precision radial velocity (< 1.5 m/s)
- long temporal series >1year ,high S/N

High precision Astrometry

- angular resolution (<1 μ arc-sec)
- Long monitoring >1000hr

High resolution spectroscopy

- Space/ground (R=60000-100000)
- at least 4 windows in a wide spectral range ($\lambda=380-850$ nm)
- multimode fibers, high stability

"Verso una roadmap italiana per la scienza nel settore dell'astrofisica spaziale"

*"This document represents the **first result** of the two-year activities carried out by the working group and is presented to the community with the aim of achieving maximum dissemination and to receive feedback to be incorporated for future updates"*

Publication of the complete report (all sub-WGs) on the ASI website after the workshop

Last update: possible roadmap presentation by ASI chairs at CTS ASI and then report publication