The Scientific Landscape in the 2040's

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Current Key scientific questions

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 cosmic microwave background, 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 and chemical 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, such as Mars or 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 to fund the computational and theoretical efforts that go

But see also e.g. the 2020 Decadal Survey on Astronomy and Astrophysics.

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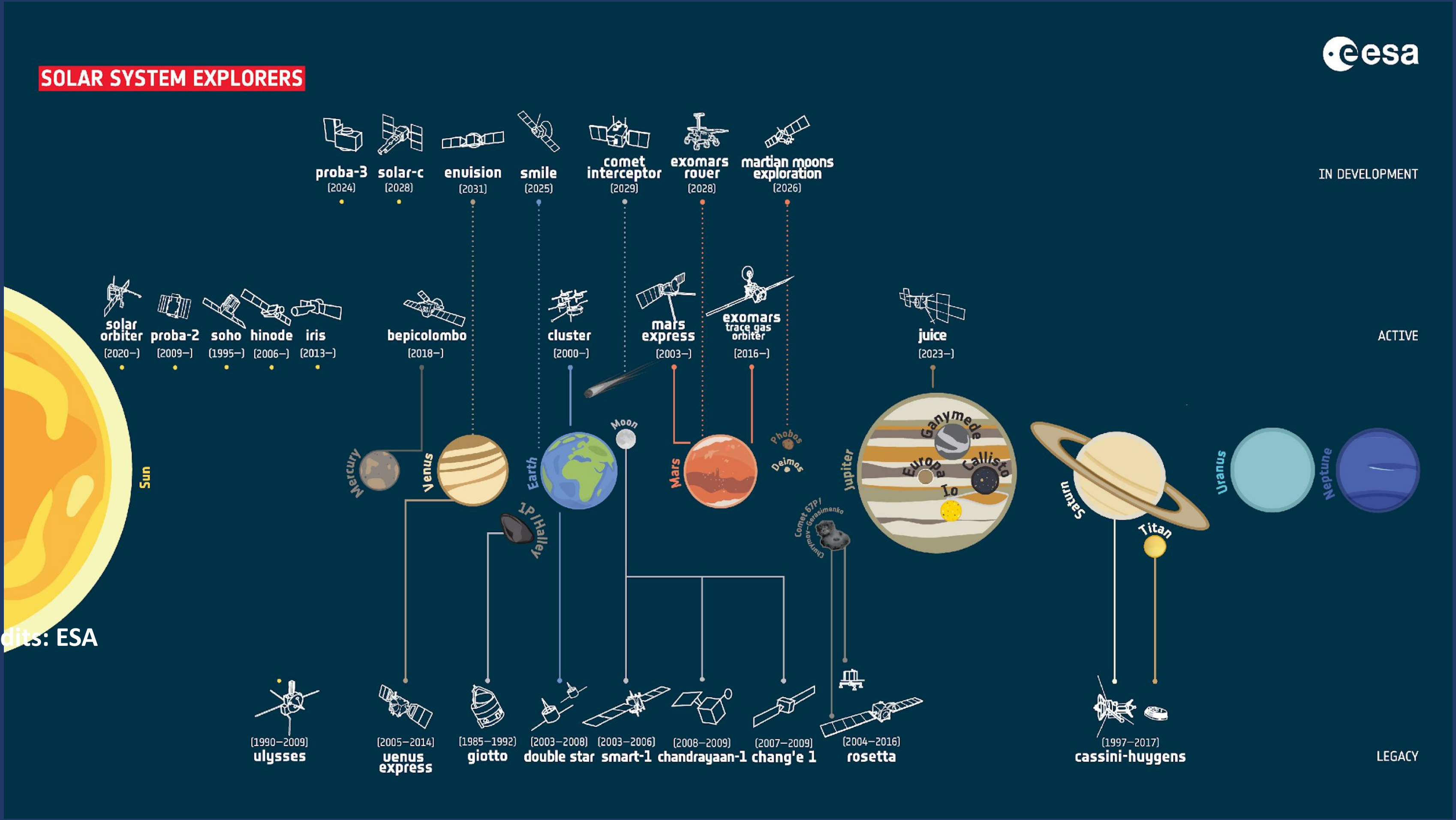
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IN DEVELOPMENT
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ACTIVE
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Sun
Mercury
Venus
Earth
Moon
Mars
Phobos
Deimos
1P/Halley
Comet 67P/Churyumov-Gerasimenko
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[1990–2009] ulysses
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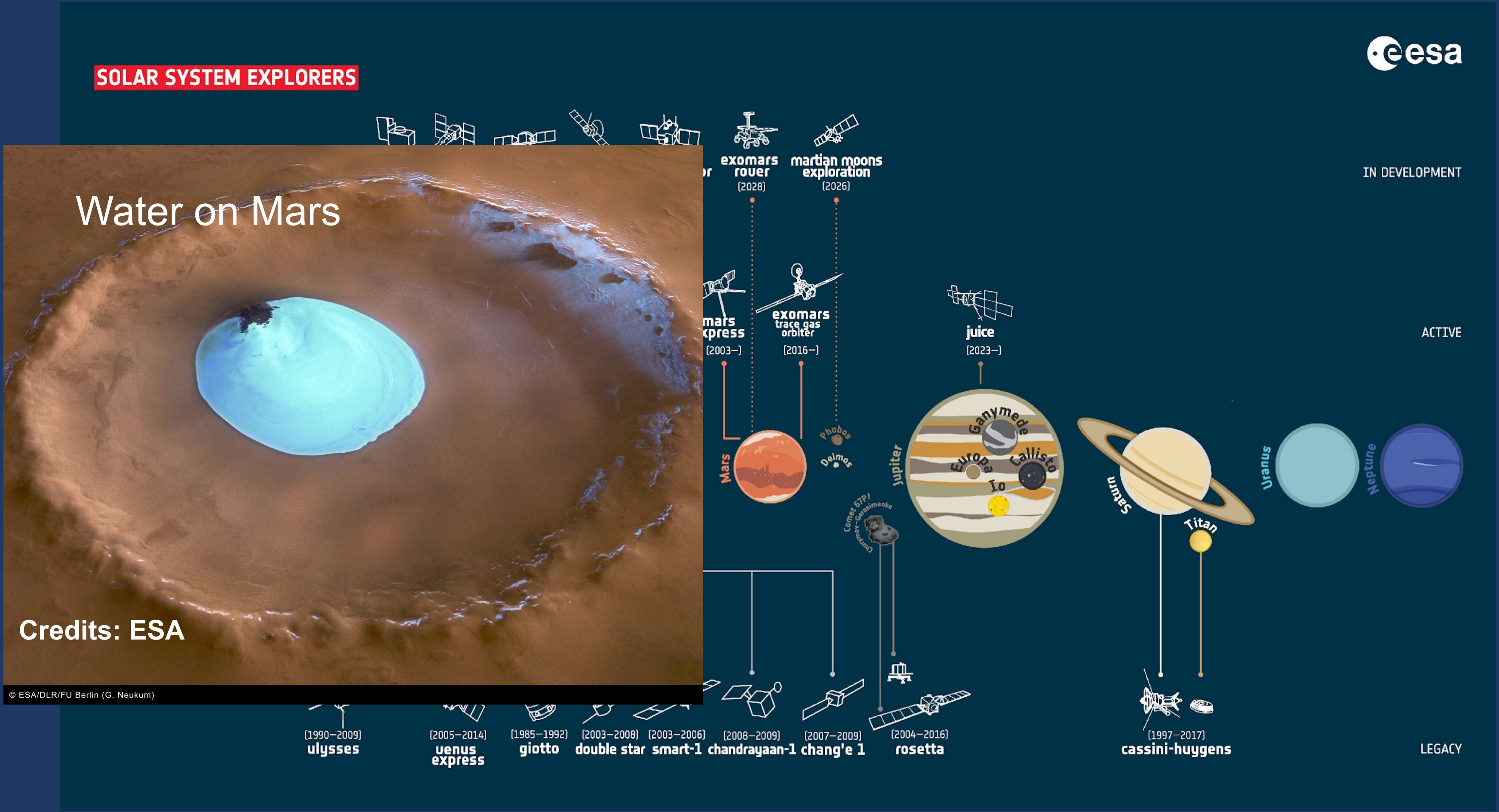
[1997–2017] cassini-huygens

Credits: ESA



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LEGACY
Water on Mars
Credits: ESA
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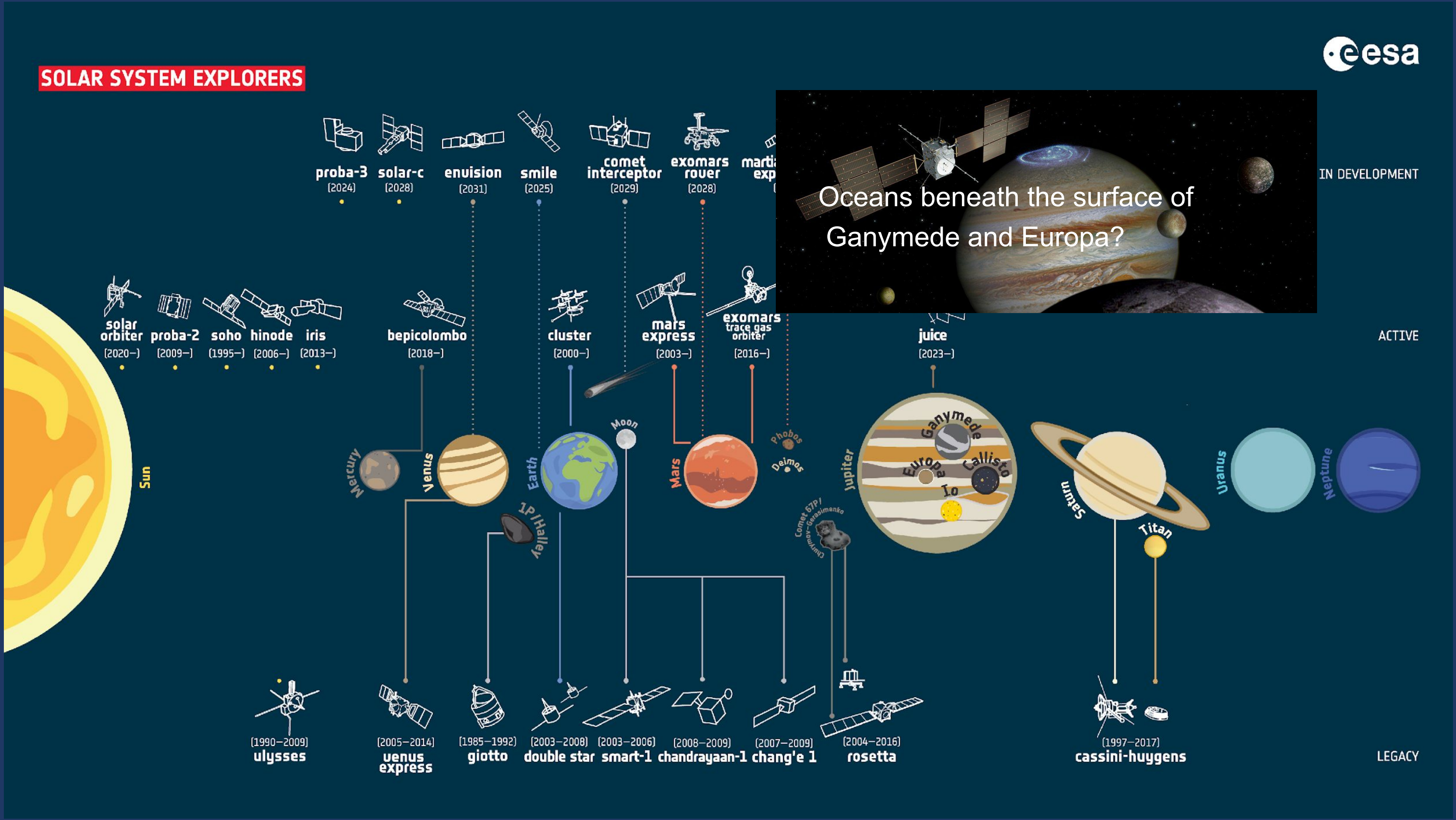
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LEGACY
Oceans beneath the surface of
Ganymede and Europa?

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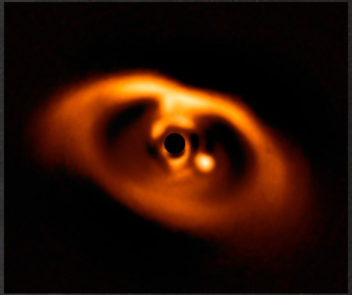
How do planets form and evolve?

- What are the conditions for the formation of planets and the emergency of life

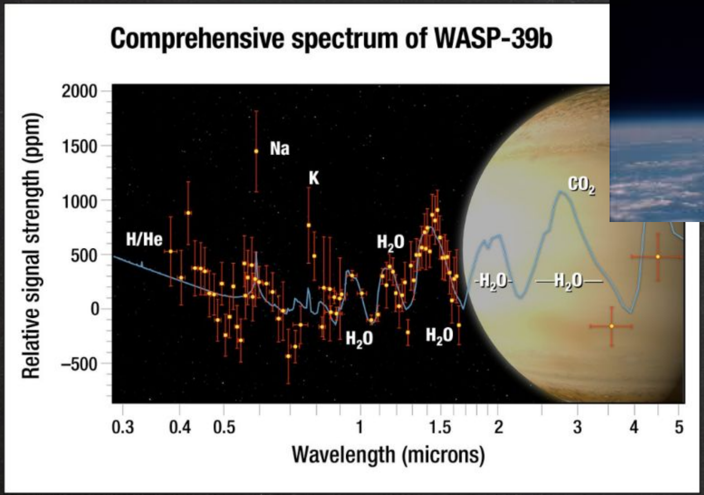


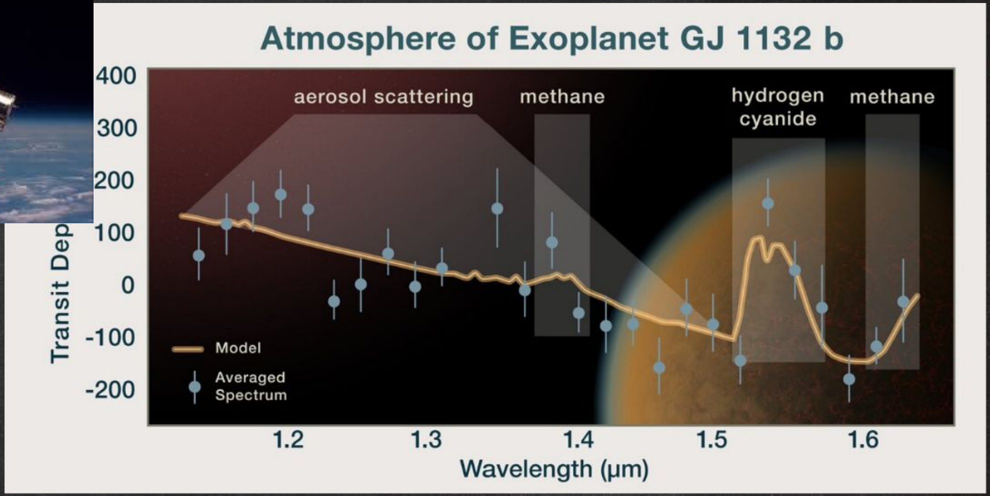
We deal with an extraordinary **diversity of planetary systems architectures**

→ synergy among different instruments and approaches for studying planetary system architectures at various distances from the host star

- High-resolution spectroscopy (e.g. HARPS, HARPS-N, GIANO, ESPRESSO)
- photometry (e.g. ground-based, Kepler, Cheops, TESS, PLATO)
- astrometry (e.g. Gaia)
- modeling

Is there life out there?

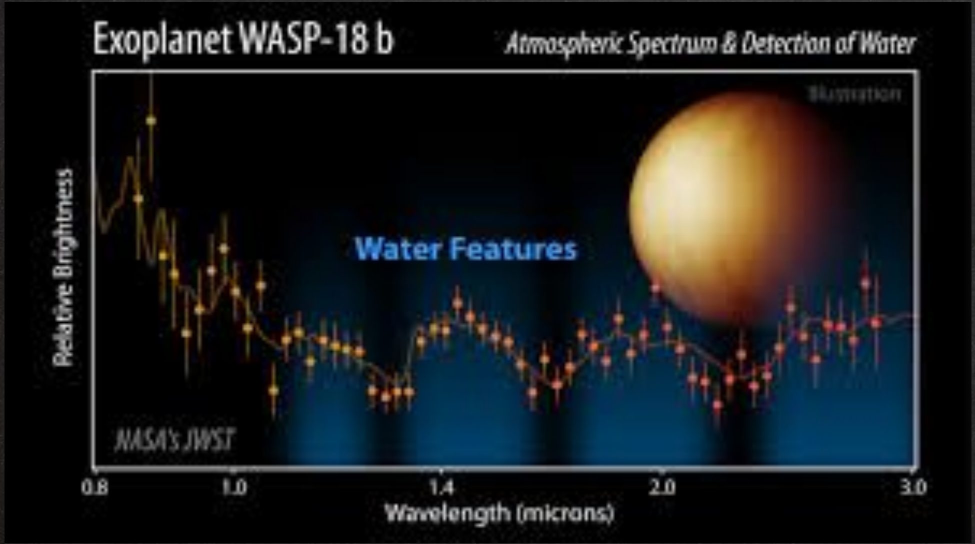




Changeat 2024, Wakeford 2018, Angelos 2019

Is there life out there?

NIRISS instrument on Webb maps an ultra-hot Jupiter-like exoplanet's atmosphere (Coulombe et al. Nature 2023)



3D structure of the atmosphere and Titanium chemistry of WASP-121 b with ESPRESSO in 4-UT mode (Seidel et al. Nature 2025; Prinoth et al. A&A 2025)

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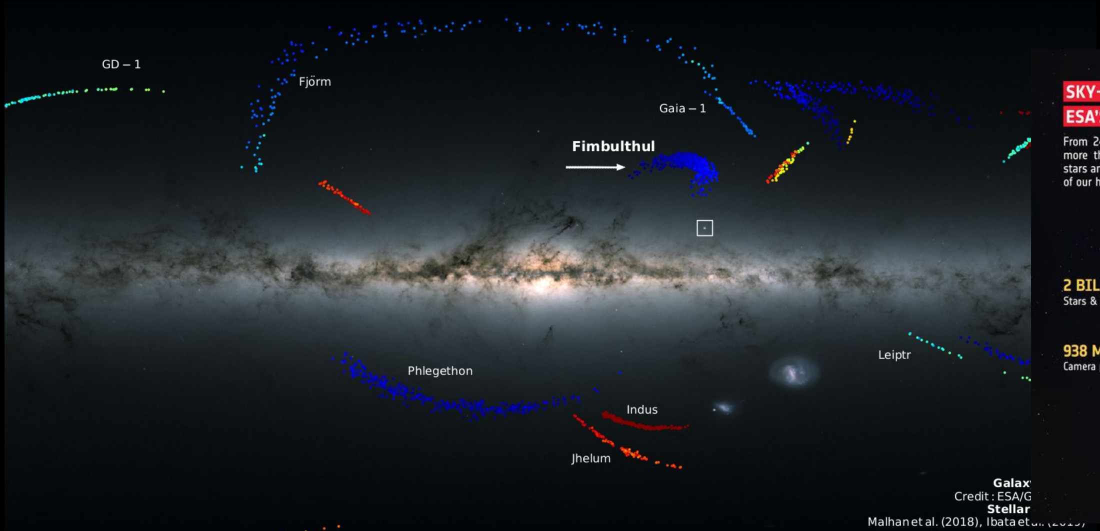
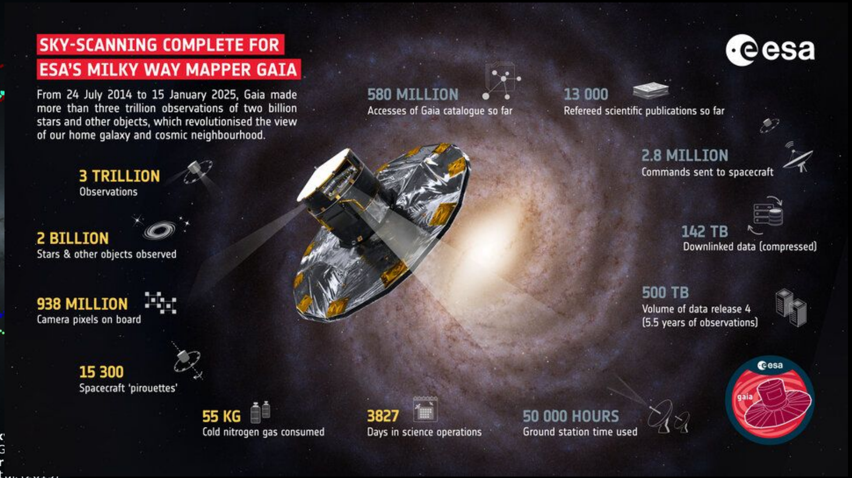
The formation and evolution of the Milky Way and its satellites

The formation history of our Galaxy, of its structure and evolution can be investigated in terms of hierarchical models of galaxy formation.





In the last decade, this research is experiencing unprecedented progress thanks to innovative observational projects both from Earth and from Space (e.g. ESA Gaia complemented by ongoing spectroscopic surveys).

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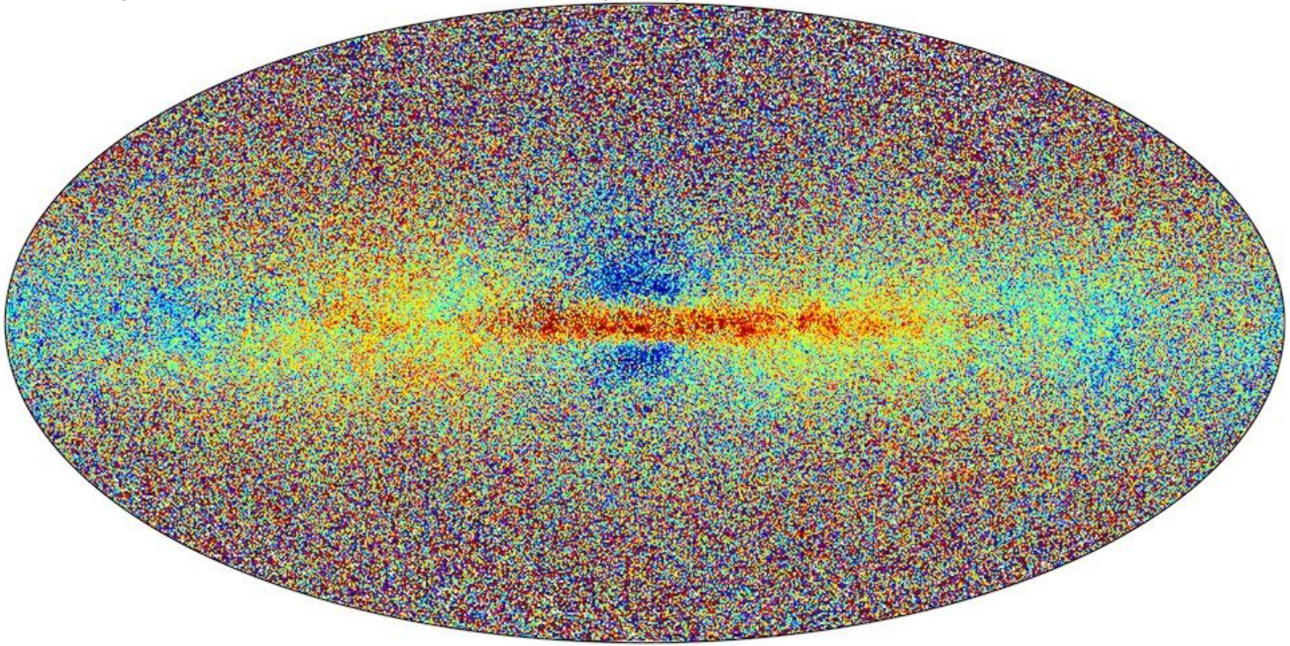
How chemical elements are created?

→ understanding the chemical evolution of the Galaxy and the formation of chemical elements both within stars and in the catastrophic phenomena that lead to stellar explosions.

This all-sky view shows a sample of the Milky Way stars in Gaia’s data release 3.



ESA-Gaia

The colour indicates the stellar metallicity. Redder stars are richer in metals.

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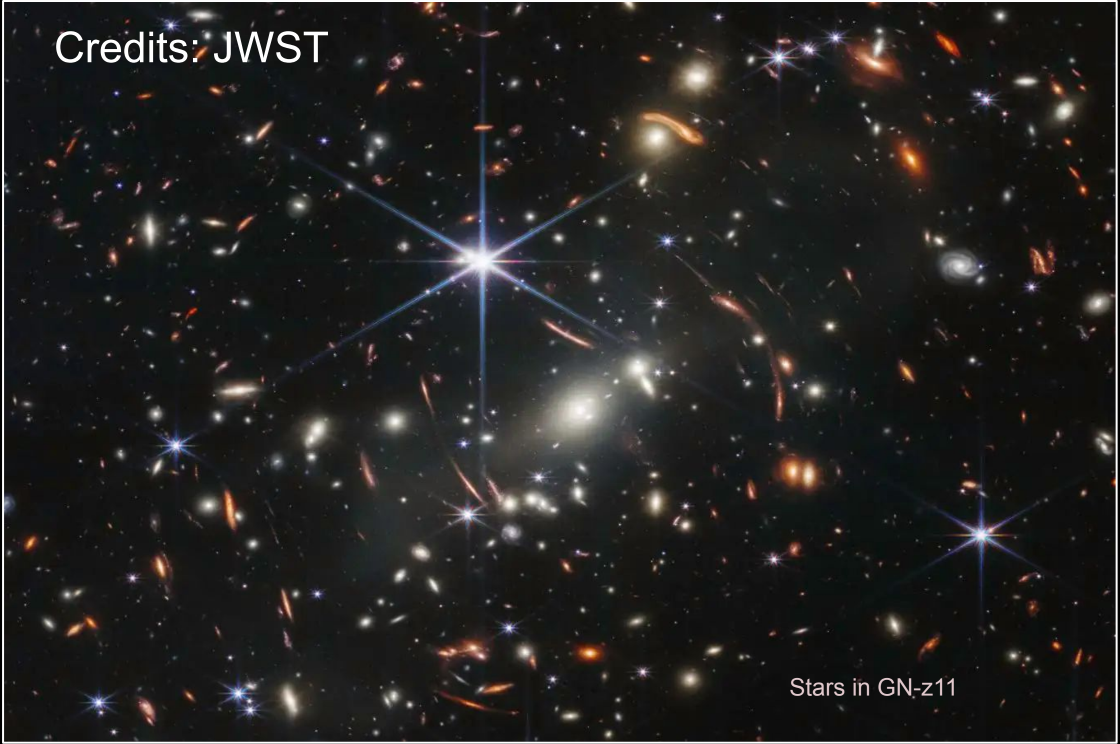
1.280 × 853

The first stars in the Universe



→ investigating individual stars in more distant galaxies and trace their history back to the very early Universe.

The ELT will be used to investigate individual stars in other galaxies, including their kinematics and chemical abundances.

Among other facilities, ANDES will also explore the most primitive stars and measure their chemical make-up.

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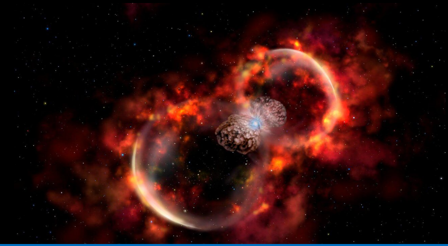
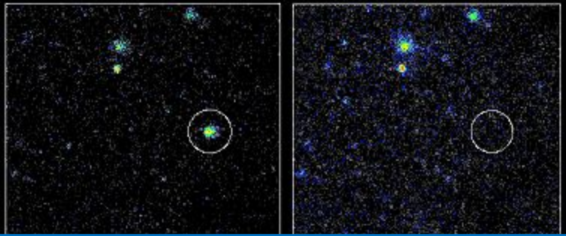
What are the pathways leading to the formation of various stellar endpoints?

More accurate characterization of:

- **initial to final mass** relation
- **yields from stars** in the full range of mass
- **Census of variable phenomena** to constrain stellar progenitors of cosmic explosions.
- discovering **new classes of transients**





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How the most extreme physical conditions govern transient events?

The main drivers are:

- the study of **Galactic and extragalactic compact objects** and **cosmic explosions**
- **multi-messenger astronomy**
- fundamental physics experiments and the **search for new physics**.



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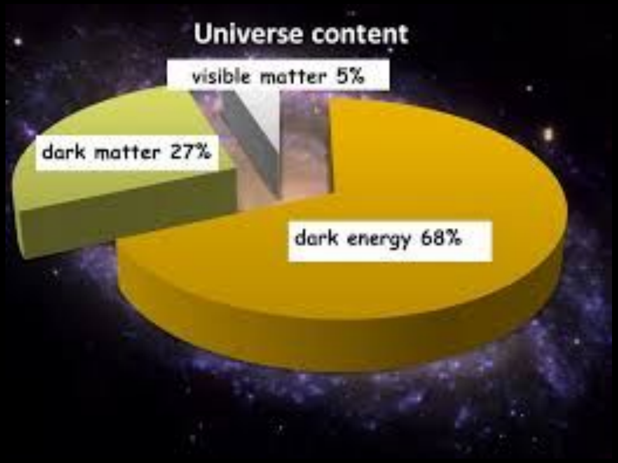
What is the nature of dark matter and dark energy?

How does gravity behave on cosmological scales?



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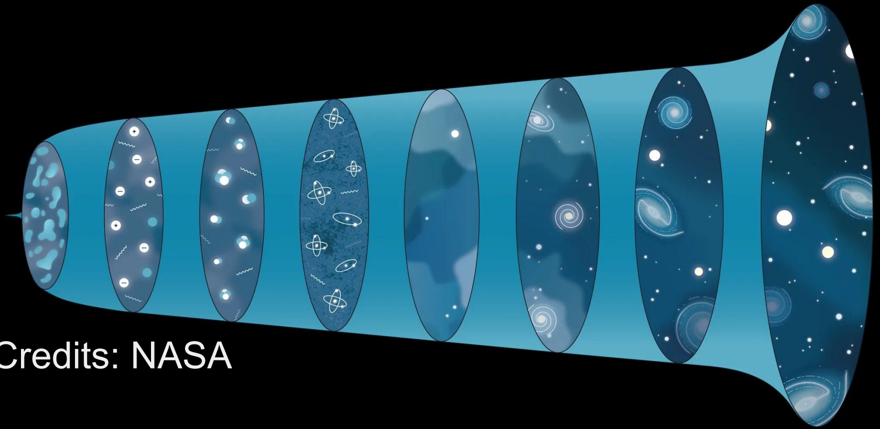
Galaxies and cosmology

Understanding the evolution of the Universe from the Big Bang to the present era is one of the fundamental challenges of modern astrophysics.



Credits: NASA

→ to understand the physical processes that regulate the formation and evolution of large-scale components of the Universe, such as galaxies and supermassive black holes in their nuclei, groups and clusters of galaxies, and their distribution in the cosmic-web.

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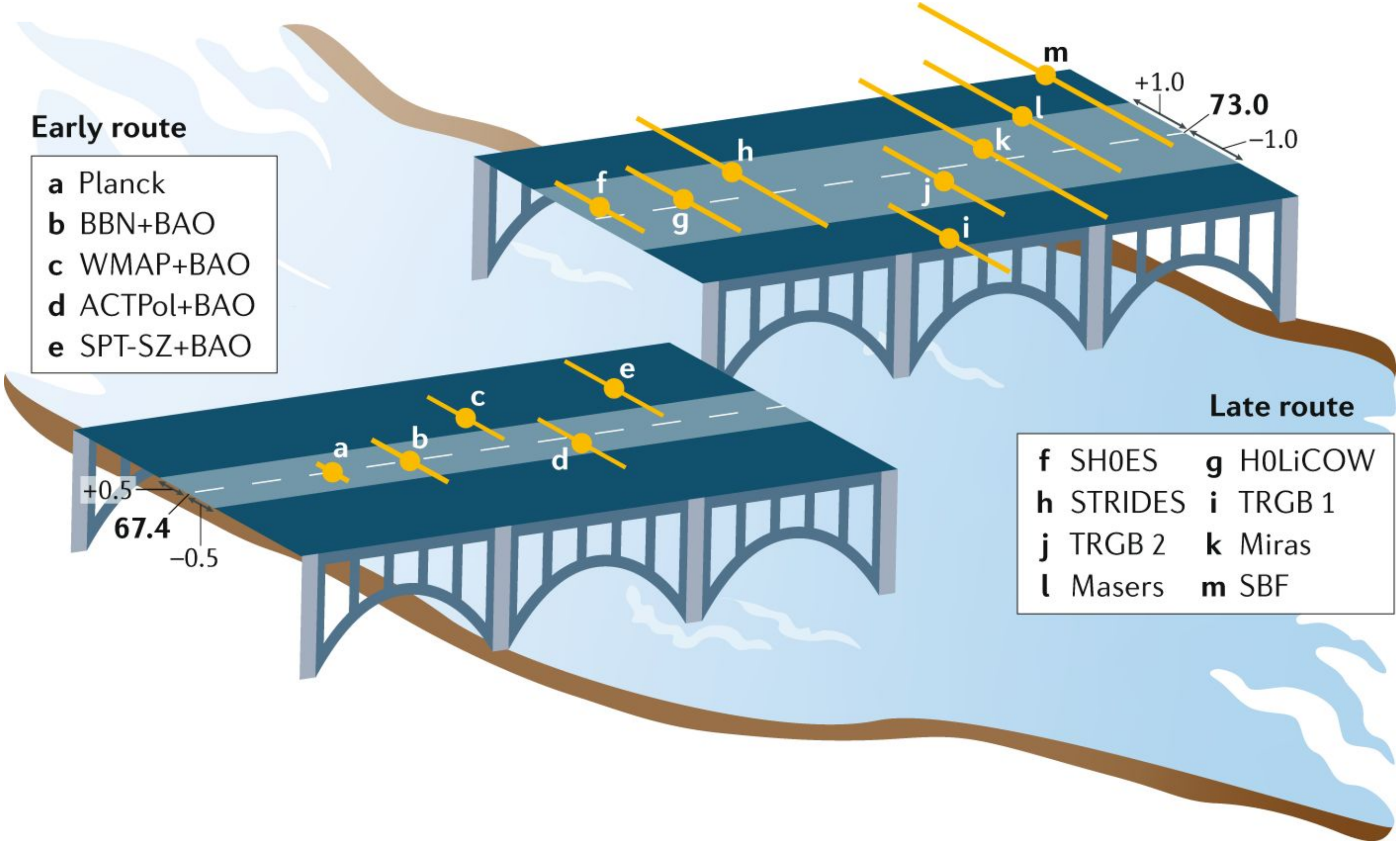
The Hubble constant tension

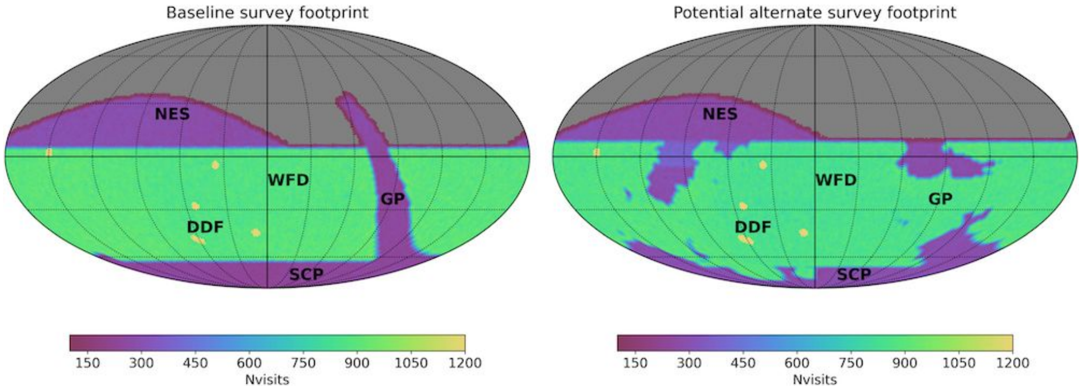


To try to answer these questions many facilities are ongoing or upcoming, that will modify the astrophysical landscape.

To imagine the scientific landscape in the 2040s
→ look at astrophysics in the 2030s

Astrophysics in the 2030s

- **Southern optical sky sampled to 27 mag** and **millions of transients** with hourly to yearly variability observed by **Rubin/LSST**



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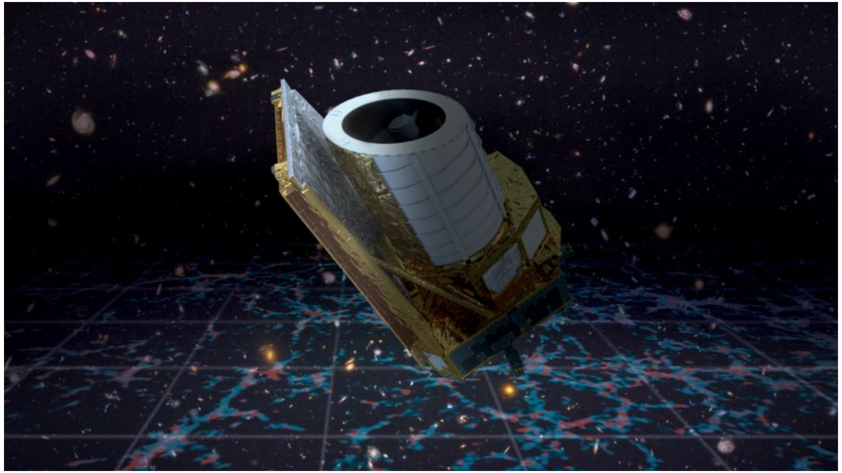

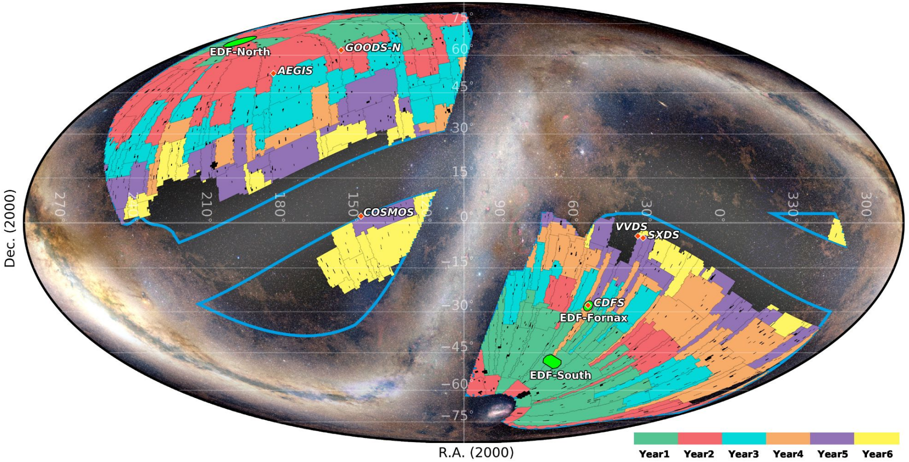

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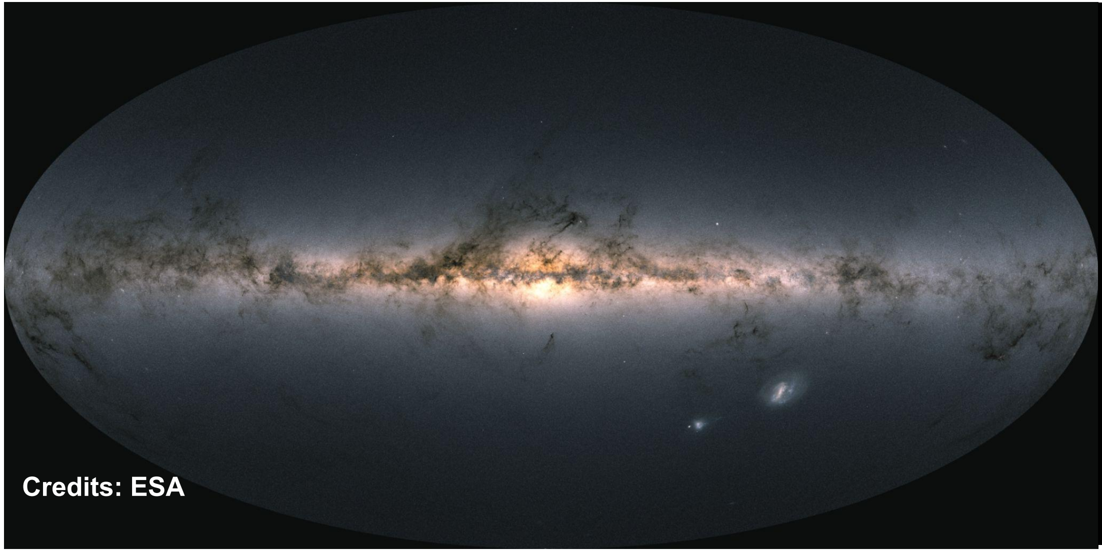

Data Release 4 → mid 2026

Data Release 5 → end of 2030

→ an extraordinarily precise three-dimensional map of more than 2 billions stars throughout our Milky Way galaxy and beyond, mapping their motions, luminosity, temperature and composition.

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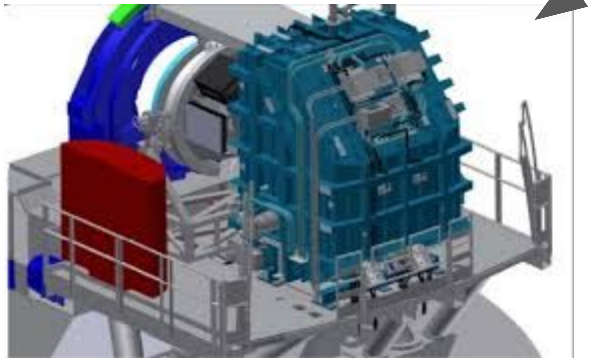
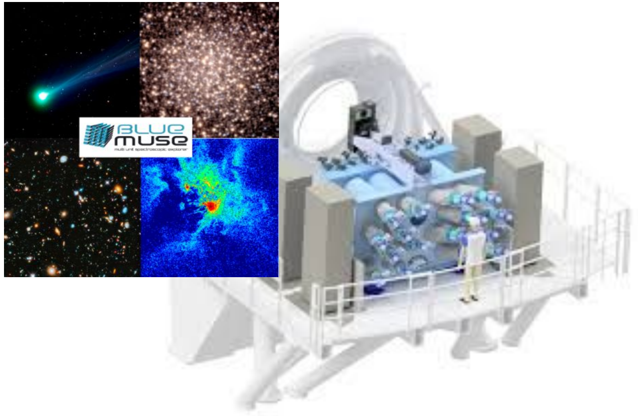
Moons, CUBES and **BlueMuse** operational





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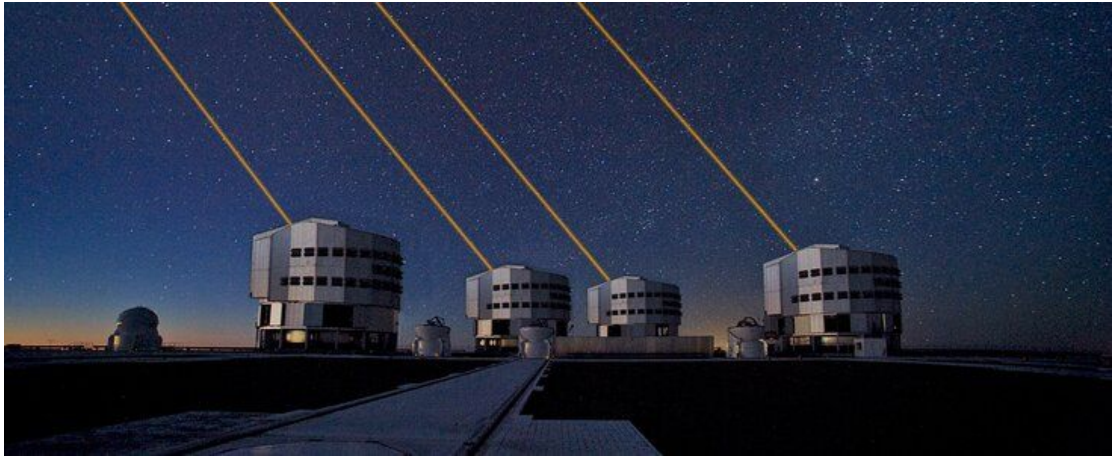

GRAVITY+ upgrade to VLTI and its GRAVITY instrument.

→ imaging of fainter and more remote astronomical objects than previously possible.

→ improving the high contrast precision on bright objects.

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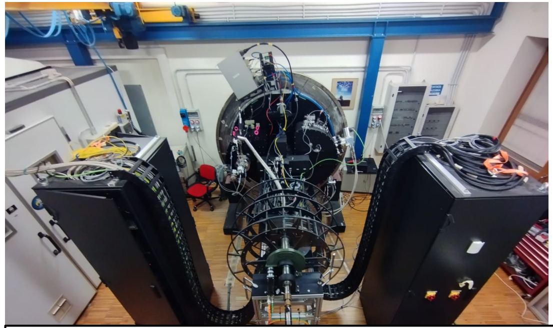
- **4MOST**, **SOXS**, **NIRPS** operated for more than 5 years

→ more than 20 million spectra.

NIRPS (Near InfraRed Planet Searcher) → Earth-like rocky planets that could potentially be habitable.



SOXS → Follow up of transient and variable events observed by ongoing and upcoming surveys

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  observed
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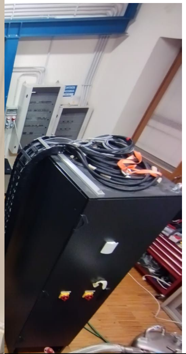
- VLT in its ... (WSU)
  complete
- 4MOST,



→ more thar ... f transient

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- Surveys such as **DESI**, **WEAVE** and **PFS** completed → **Galactic and extragalactic goals, dark Universe**

The **Dark Energy Spectroscopic Instrument** → five-year survey to create the largest 3D map of the Universe ever
→ an unprecedented look at the **nature of dark energy and its effect on the large-scale structure**.

WEAVE (WHT Enhanced Area Velocity Explorer) is a new multi-object survey spectrograph for the William Herschel Telescope
→ **Galactic and extragalactic astronomy**.

The **Subaru Primary Focus Survey**
→ wide range of wavelengths ranging *from the near-ultraviolet, through the visible, and up to the near-infrared regime*

→ dark matter and dark energy.
history of galaxies

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- DESI, and WEAVE surveys completed → Galactic and extragalactic scientific goals, dark Universe
- The ELT, CTAO, SKAO, ngVLA operational → A revolution for astrophysics

Astrophysics in the 2030s

- ***The Extremely Large Telescope operational***

The ELT will tackle the biggest scientific challenges of our time

→ **tracking down Earth-like planets** around other stars in the **habitable zones** where life could exist.

→ probing the **nature of dark matter** and **dark energy**.

→ studying **stars in our Galaxy and beyond, black holes, evolution of distant galaxies**, up to the very first galaxies in the **earliest epochs of the Universe**.

But…..**new and unforeseeable questions** will surely arise, given the capabilities of the ELT.

Astrophysics in the 2030s

• *The CTAO operational*

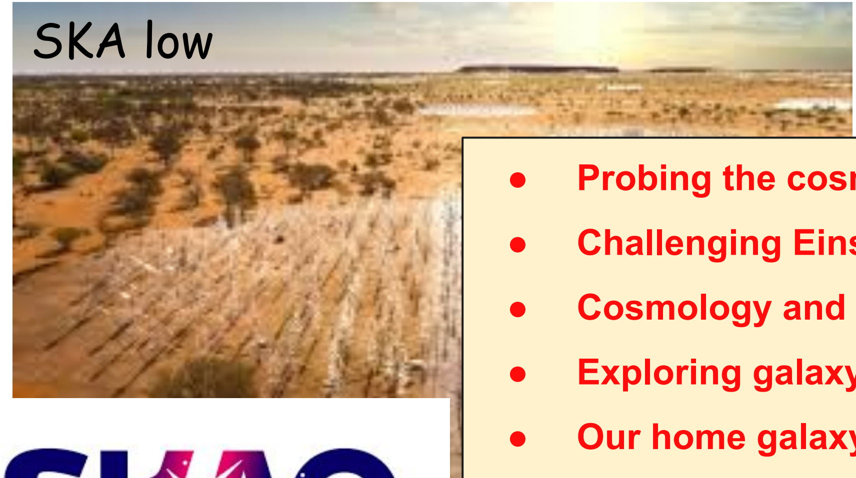
→will transform our understanding of the high-energy Universe, addressing the key questions:

1. **Understanding the Origin and Role of Relativistic Cosmic Particles**
2. **Probing Extreme Environments**
3. **Exploring Frontiers in Physics**

Astrophysics in the 2030s

• SKAO operational

The SKAO is a next-generation radio astronomy-driven Big Data facility that will revolutionise our understanding of the Universe and the laws of fundamental physics.



- Probing the cosmic dawn.
- Challenging Einstein.
- Cosmology and dark energy.
- Exploring galaxy evolution.
- Our home galaxy.
- Seeking the origins of life.
- Studying our nearest star.
- Understanding cosmic magnetism.

Astrophysics in the 2030s

- **The ngVLA becoming fully operational**

Early Science start date in 2028, with full array operations beginning in 2034

(1) Unveiling the Formation of Solar System Analogues;

(2) Probing the Initial Conditions for Planetary Systems

(3) Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion

(4) Science at the Extremes: Pulsars as Laboratories for Fundamental Physics;

(5) Understanding the Formation and Evolution of Stellar and Supermassive Black Holes

Astrophysics in the 2030s

- Southern optical sky sampled to 27 mag and millions of transients with hourly to yearly variability observed by Rubin/LSST
- Extragalactic near-infrared sky sampled to 25 mag by EUCLID → large-scale structure, dark Universe
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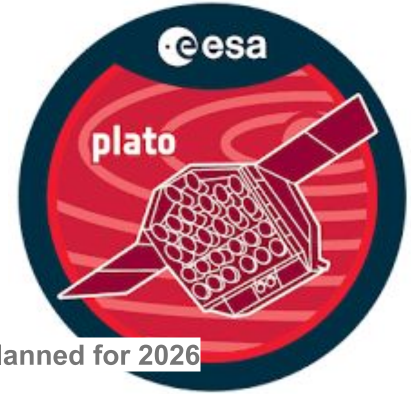
Astrophysics in the 2030s

- **ESA's PLATO and ARIEL missions operational**



Launch: **planned for 2026**

ESA's mission **Plato, PLAnetary Transits and Oscillations of stars** will:

- **study terrestrial exoplanets** in orbits up to the habitable zone of Sun-like stars;
- **measure the sizes of exoplanets**;
- discover **exomoons and rings** around them;
- characterise **planets' host stars** by studying tiny light variations in the starlight it receives.

ESA's mission **Ariel, Atmospheric Remote-sensing Infrared Exoplanet Large-survey** will:

- inspect the **atmospheres of a thousand planets** in our galaxy orbiting stars other than the Sun;
- reveal the **ingredients of these atmospheres** and the presence of clouds, and **monitor how weather conditions change over time**

Launch: **planned for 2029**

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Astrophysics in the 2030s

WST

• ATHENA about to be launched

Advanced Telescope for High Energy Astrophysics

NewAthena has been conceived as a powerful X-ray observatory with an unprecedented combination of collecting area, survey capabilities and energy resolution.

The main scientific goals will be:

- to investigate **some of the hottest and most energetic astrophysical phenomena;**
- to explain **how and why ordinary matter assembles into the structures** we see today;
- to unveil **how *black holes grow and shape their environment***, *as well as the* ***cosmological evolution of the galaxies*** *hosting them.*

Launch date around 2037

Astrophysics in the 2030s

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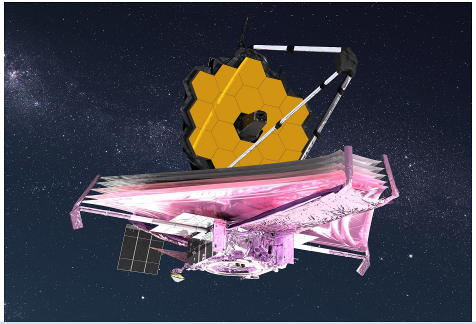
Astrophysics in the 2030s

- **NASA's JWST finishing its first decade**



Mission Goals

- **Early Universe** : Search for the first galaxies or luminous objects formed after the Big Bang
- **Galaxies Over Time**: Determine how galaxies evolved from their formation until now
- **Star Lifecycle**: Observe the formation of stars from their initial stages to the formation of planetary systems.
- **Other Worlds** : Measure the physical and chemical properties of planetary systems, including our own Solar System, and investigate the potential for life in those systems

Astrophysics in the 2030s

- **Nancy Roman Telescope Operational**

The Nancy Grace Roman Space Telescope will look at billions of cosmic objects to explore how planets, stars, and galaxies form and develop over time.

→ designed to settle essential questions in the areas of

- **dark energy**
- **exoplanets**
- **infrared astrophysics**

Then, in the 2040s…

All these facilities thanks to their fantastic multi-band imaging capabilities will have detected and classified a huge number of objects.

Astrometric, spectroscopic (and multimessenger) capabilities will have allowed us to characterize significant samples of targets.

Will have we answered to these Key questions?

- What is the impact of the Sun on the heliosphere and planetary environments?
- Can we find biotic conditions on other bodies of the Solar System?
- How do extrasolar planets form and evolve? Can we find life out there?
- How did the Milky Way and its satellites form and evolve?
- What is the origin of chemical elements that trace galactic evolution?
- What is the link between the endpoints of stellar evolution and progenitors?
- How the most extreme physical conditions govern transient events?
- What is the nature of Dark Matter and Dark Energy (or modified GR)?
- What are the progenitors and the electromagnetic counterparts of GW?
- How GW events relate with heavy element production and cosmology?
- What is the large scale structure of the Universe?
- What is the cause of the Hubble constant tension and of other cosmological ones?

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Not completely but new insights will have been provided !

But new questions will be opened!!

and … new knowledges call for new expertises!

For example for solar system and exoplanets

Astrochemistry

Astrobiology

For example for solar system and exoplanets

Astrochemistry

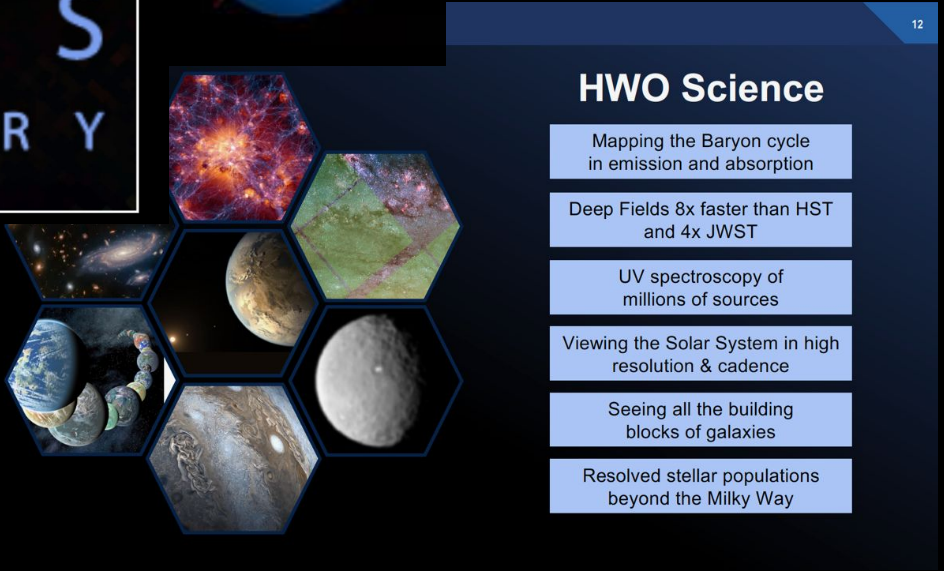
Astrobiology

Because the big question is:

Can these worlds host life?

Next challenge for NASA

HABITABLE WORLDS OBSERVATORY



The NASA Habitable Worlds Observatory is a large infrared/optical/ultraviolet space telescope, the first telescope designed specifically to search for signs of life on planets orbiting other stars.

What is next challenge for ESO?

The ESO Expanding Horizon Exercise

Transforming Astronomy in the 2040s

http://next.eso.org

ESO's Next Programme


Thanks!