Large Astronomical Facilities: Their Fundamental Importance for Swiss Astronomers

(or, why is today's progress in this field only possible via participation in large scale international/European Facilities/Programs)

The full memberships of Switzerland in the two inter-governmental organizations related to astronomy, which are the European Space Agency (ESA) and the European Southern Observatory (ESO), represent two essential contributing factors to the very high quality of the research in astronomy and cosmology in Switzerland: astronomers in Switzerland have a direct access to all ESO telescopes and to the fleet of ESA satellites

Major Milestones in the last two decades

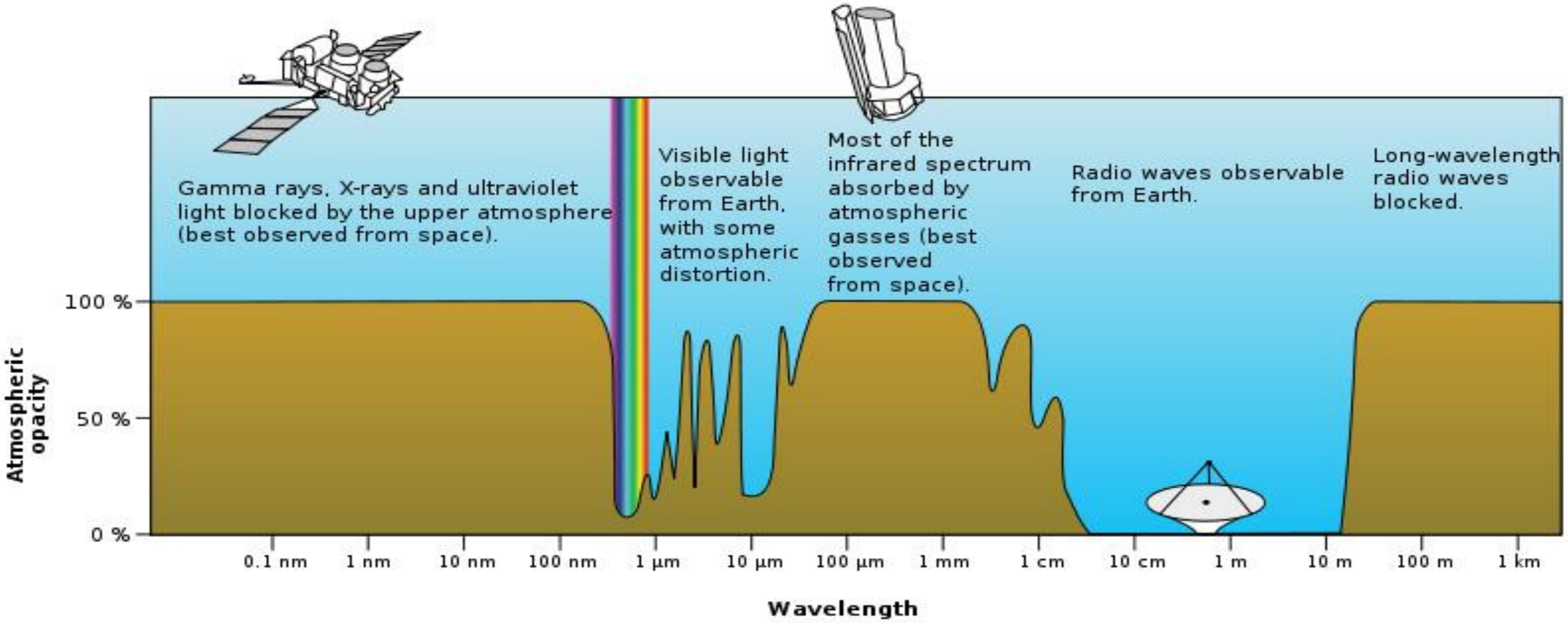
- **The Universe**: Observation of the Cosmic Microwave Background (CMB) with the satellites COBE (1989-1993, NASA), WMAP (2001-2006, NASA) and Planck (2009-2013, ESA) ➡ 2.725 K, spatial variations by 10^{-5} (Nobel Prize 2006)
- **Planets**: First discovery of an exo-solar planet in 1995 by Swiss Astronomers Mayor & Queloz (Balzan, Shaw, Kyoto .. Prizes)

in between

- **Stars and Stellar Deaths**: Understanding the sun via neutrino oscillations (Nobel Prize 2015), utilizing supernovae to understand expansion of the Universe ➡ dark energy (Nobel Prize 2011)
- **Observation/Evolution of Galaxies**: In order to understand the gravitational fields in galaxies (rotation curves etc.) we need dark matter (postulated already in 1933 by Swiss/US astronomer Fritz Zwicky)

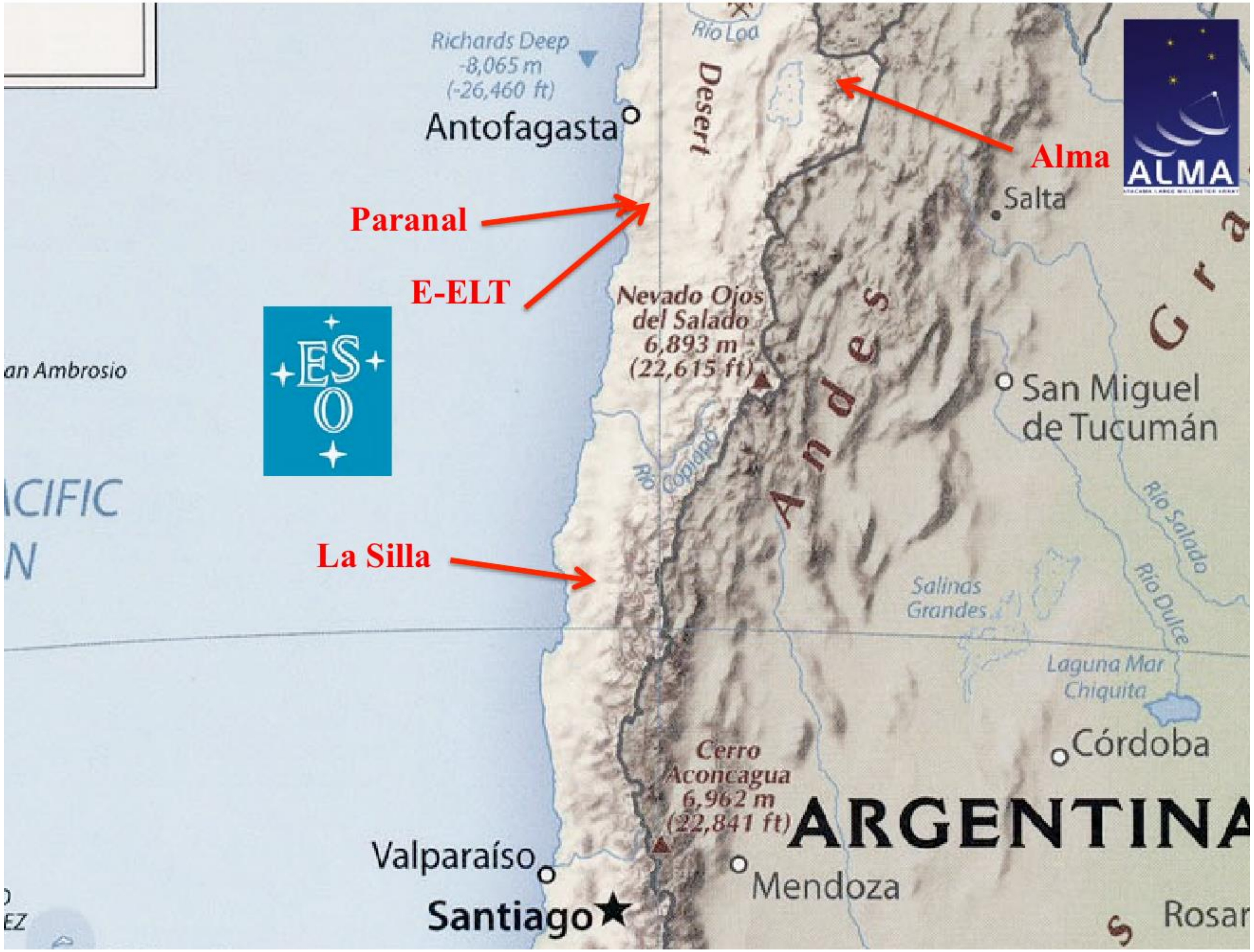
the total mass/energy of the universe contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy

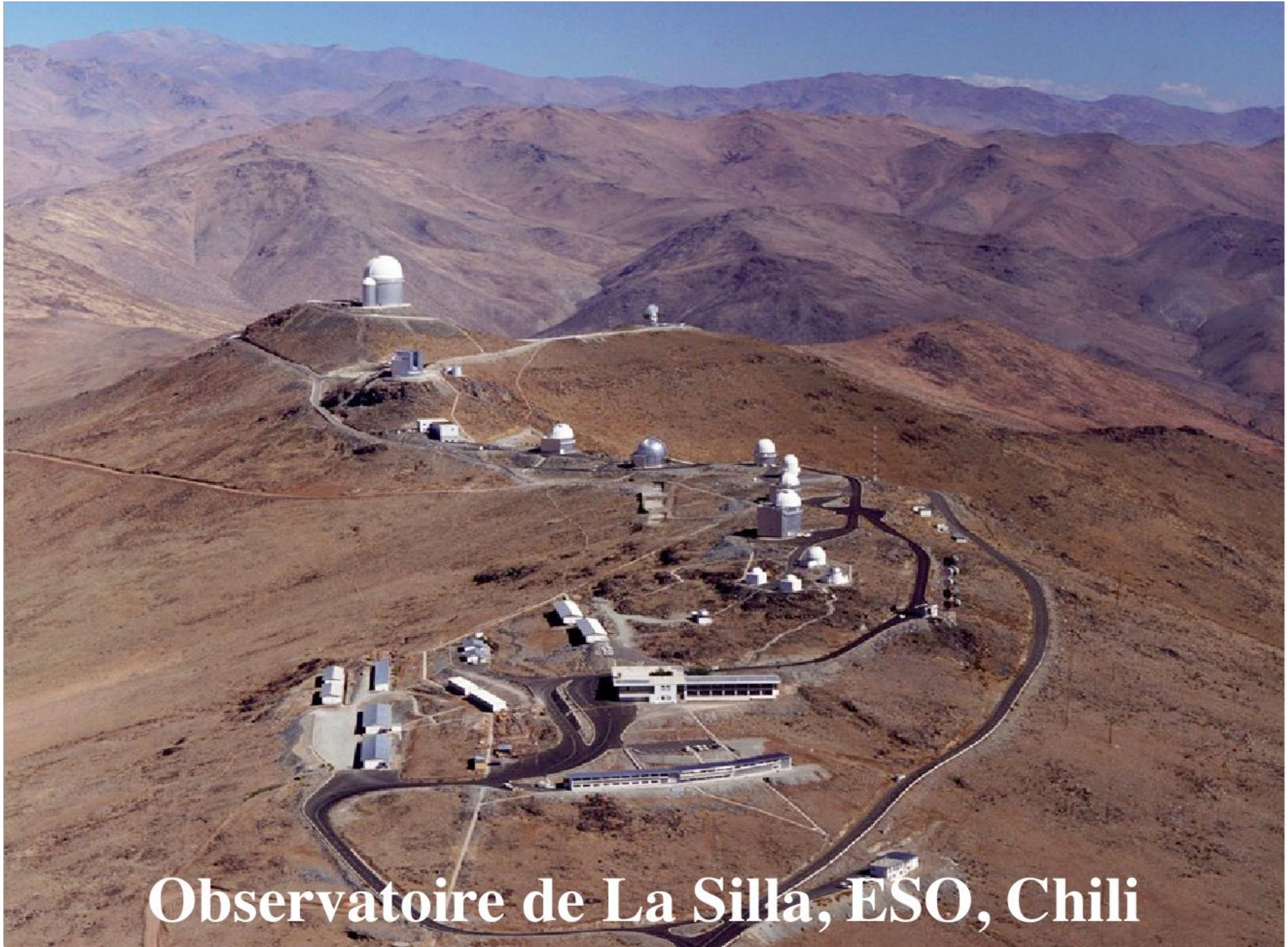
How to observe radiation of astrophysical objects?



Certain wavelengths of light (i.e. electromagnetic waves) *— in fact, most of them — never reach the ground: they are absorbed by our atmosphere. Space telescopes placed above our atmosphere can observe these wavelengths. Visible and most radio wavelengths do reach the ground (the "optical window", i.e., the visible light, and the "radio window") and can be observed by ground-based telescopes. A limited amount of infrared (IR) and ultraviolet (UV) light also reaches the ground. Other wavelengths have to be observed from space telescopes. SOURCE: commons/Wikimedia.*
Other forms of observations (i.e. ***gravitational waves****) require different detection methods.*

ESO Telescopes in Chile

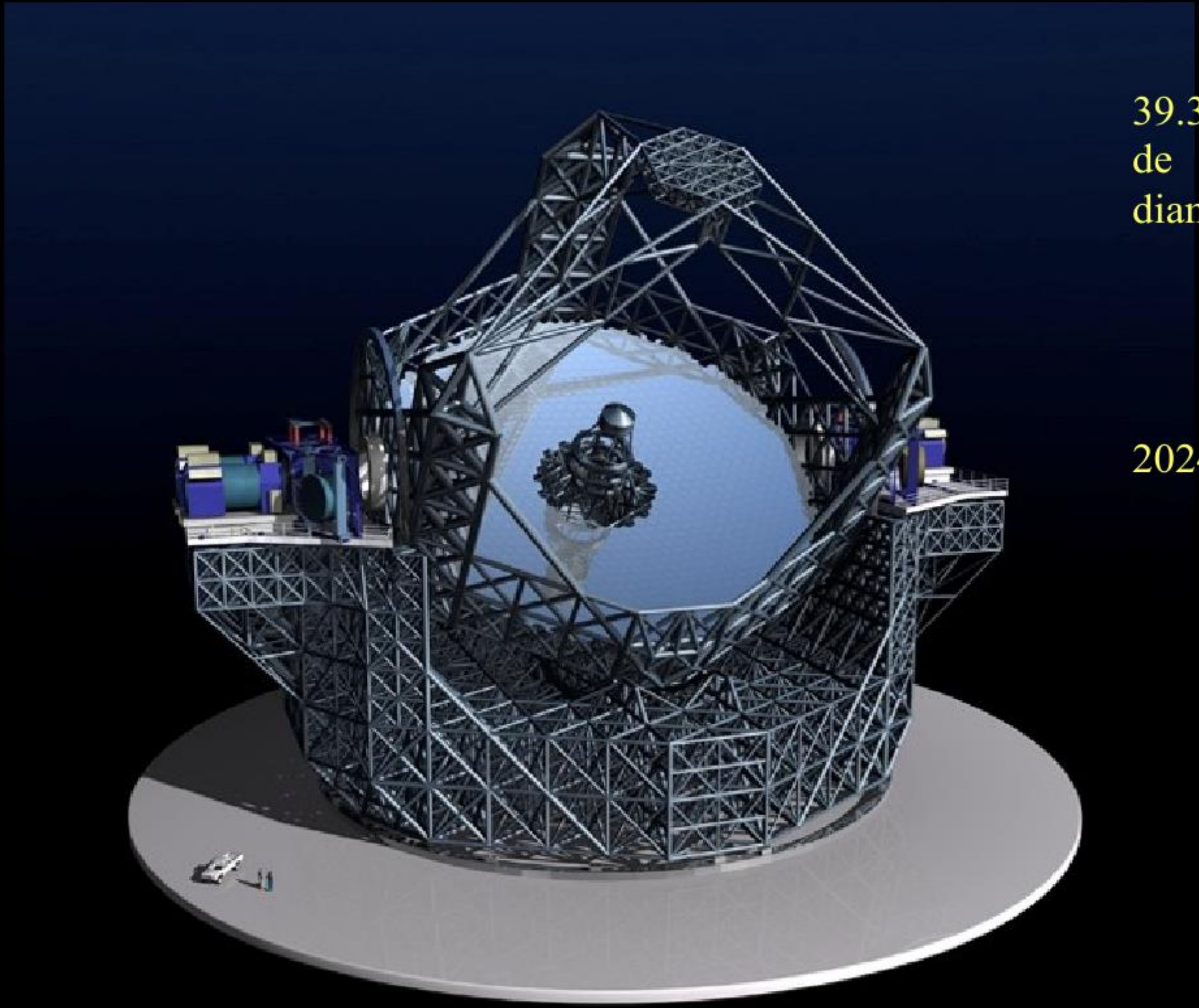



Observatoire de La Silla, ESO, Chili


European Southern Observatory
VLTI - VST - VISTA

ALMA Atacama Large Millimeter Array   ESO - USA - Japan   Inauguration March 14, 2013

E-ELT European Extremely Large Telescope ESO



39.3 m
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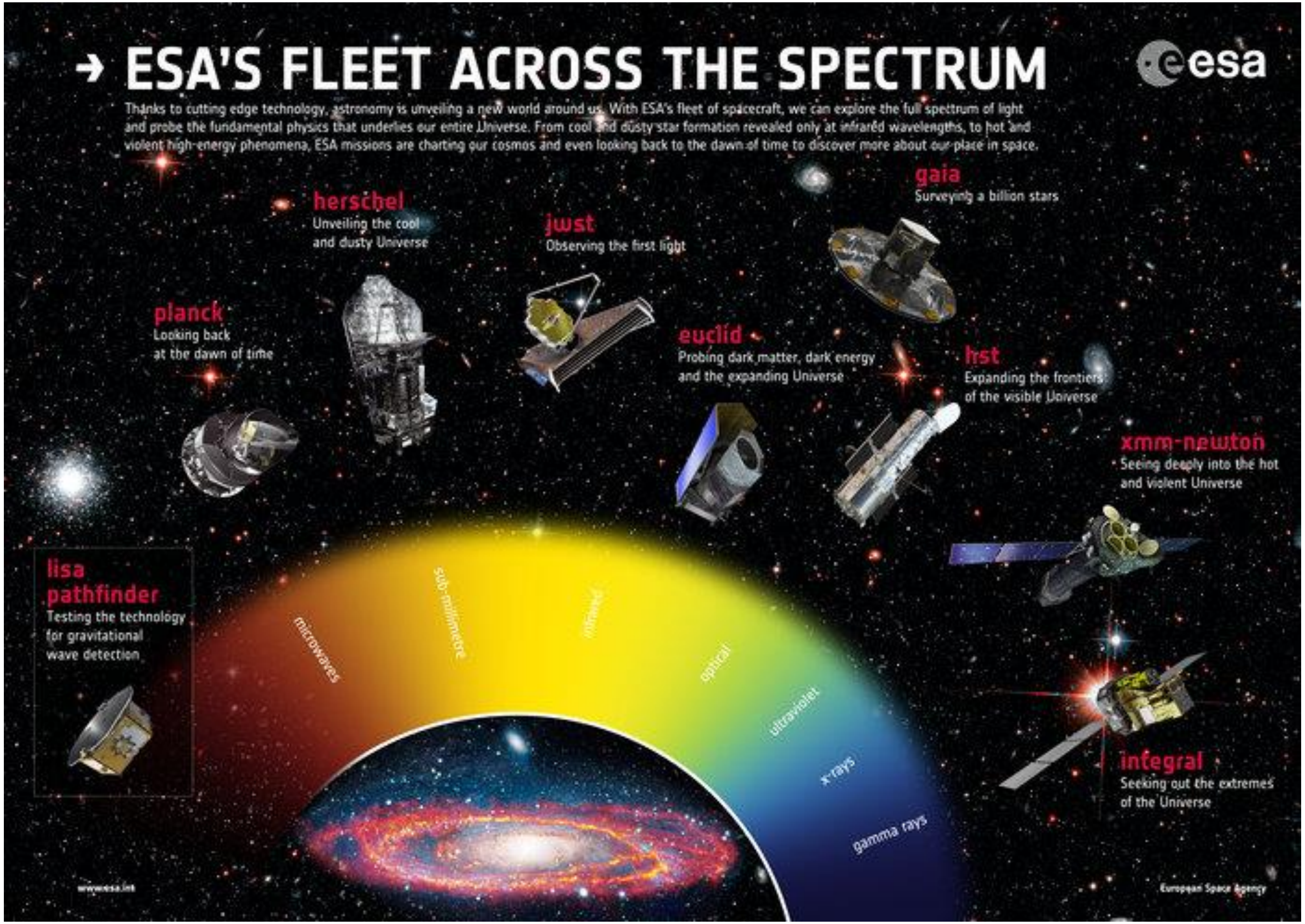
2024 ?

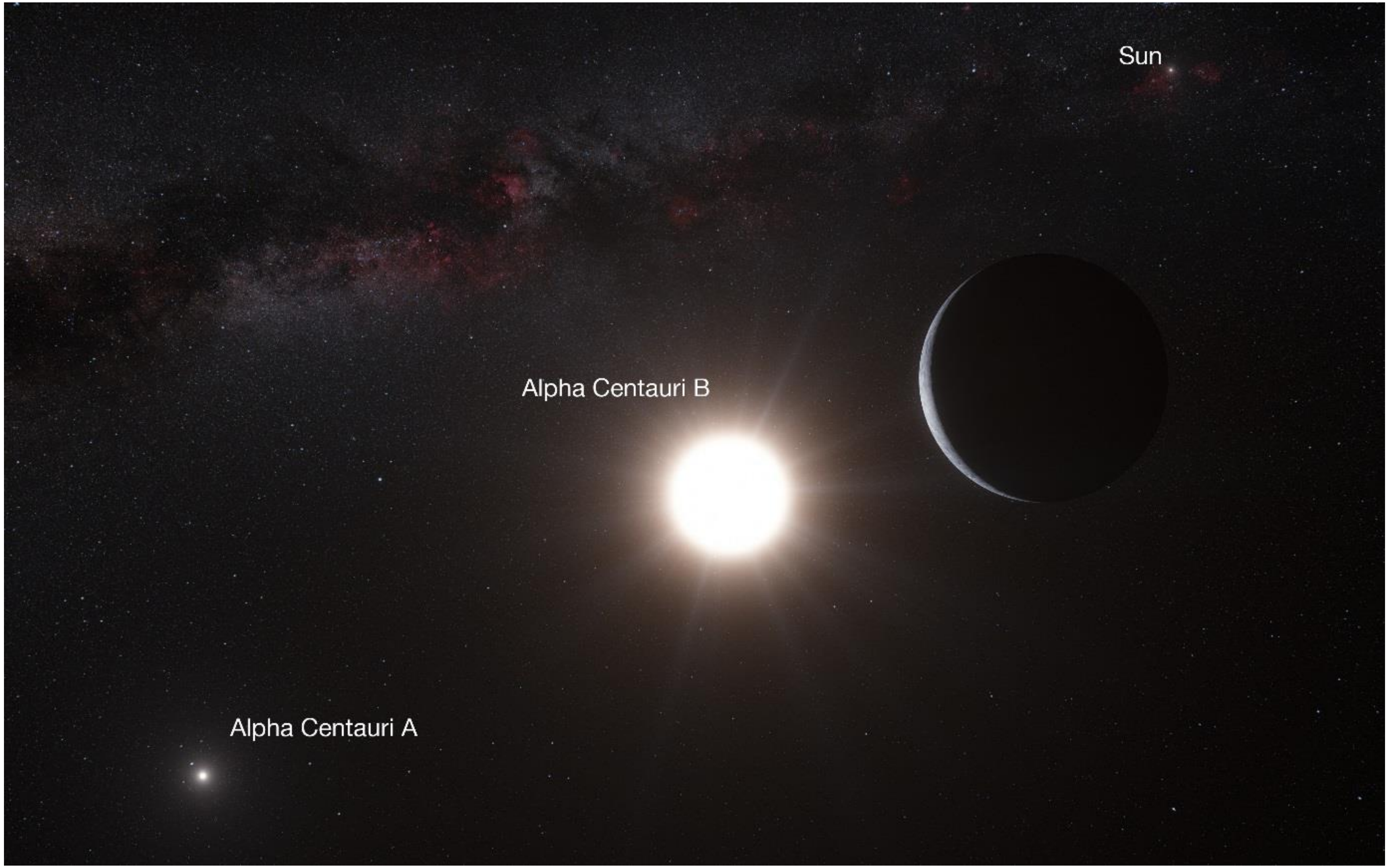
The Fleet of ESA Satellites



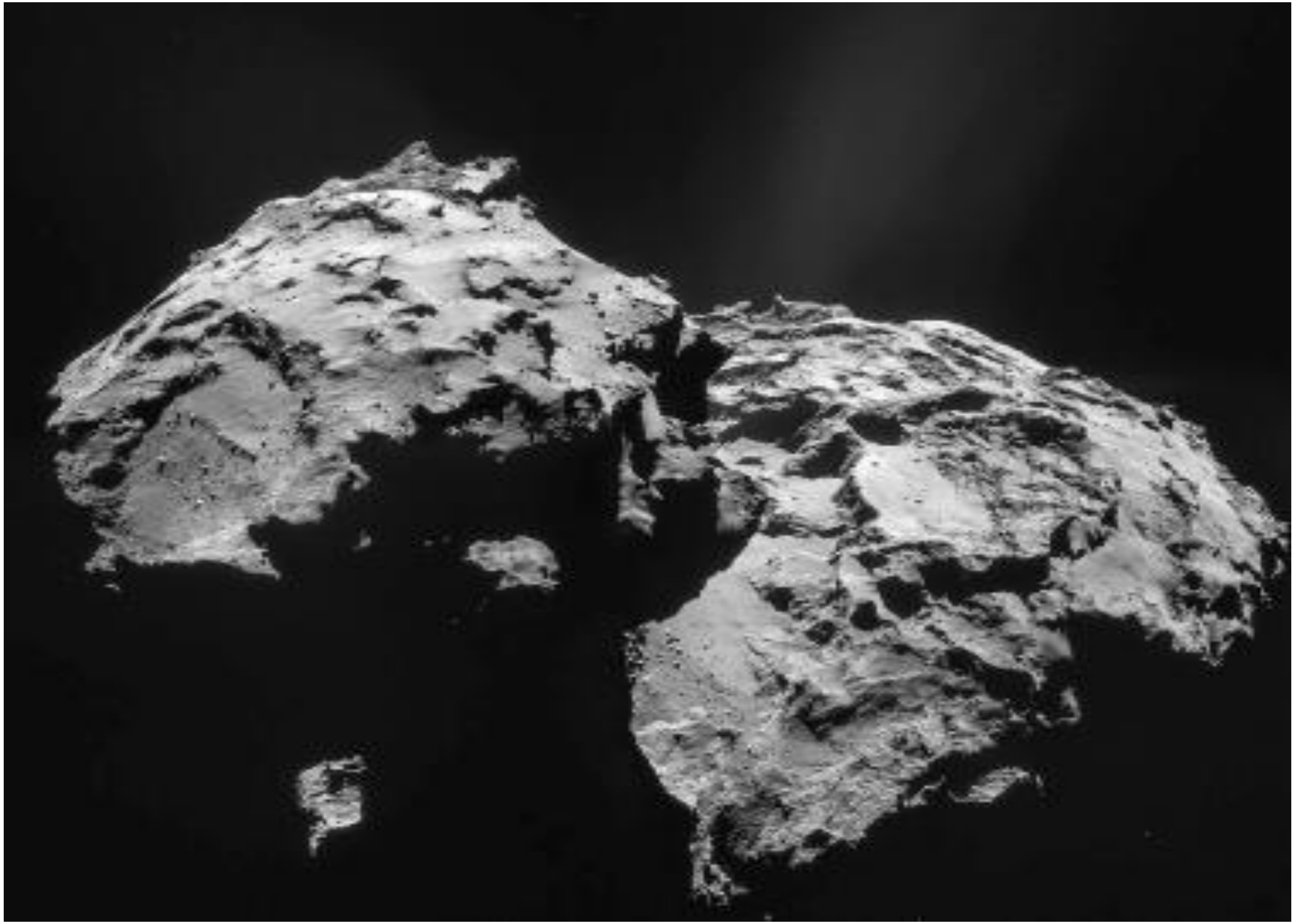
Planets as a by-product of star formation

- *Star formation takes place as when interstellar clouds of gas and dust contract to form a hot central body (protostar), accompanied by accumulation and coalescence of dust particles in a disk, eventually leading to the build-up of planetary bodies*

  *-> heavily obscured by dust, needs infrared and millimeter observations (**Herschel Space Telescope**)*
- *Ground-based high-resolution observations with **SPHERE** at the VLT*
- *Hunting for planets with the angular velocity technique (**HARPS, ESPRESSO**)*
- *Next Generation Transit Survey (**NGTS**) at Paranal*
- *Swiss-led **CHEOPS** is the first ESA small mission (launch in 2015)*
- ***PLATO** will be capable of finding Earth-like planets with water on their surface*
- *Solar system missions (**Rosetta**) provided breath-taking images of comet 67P-CG and insight into its composition*



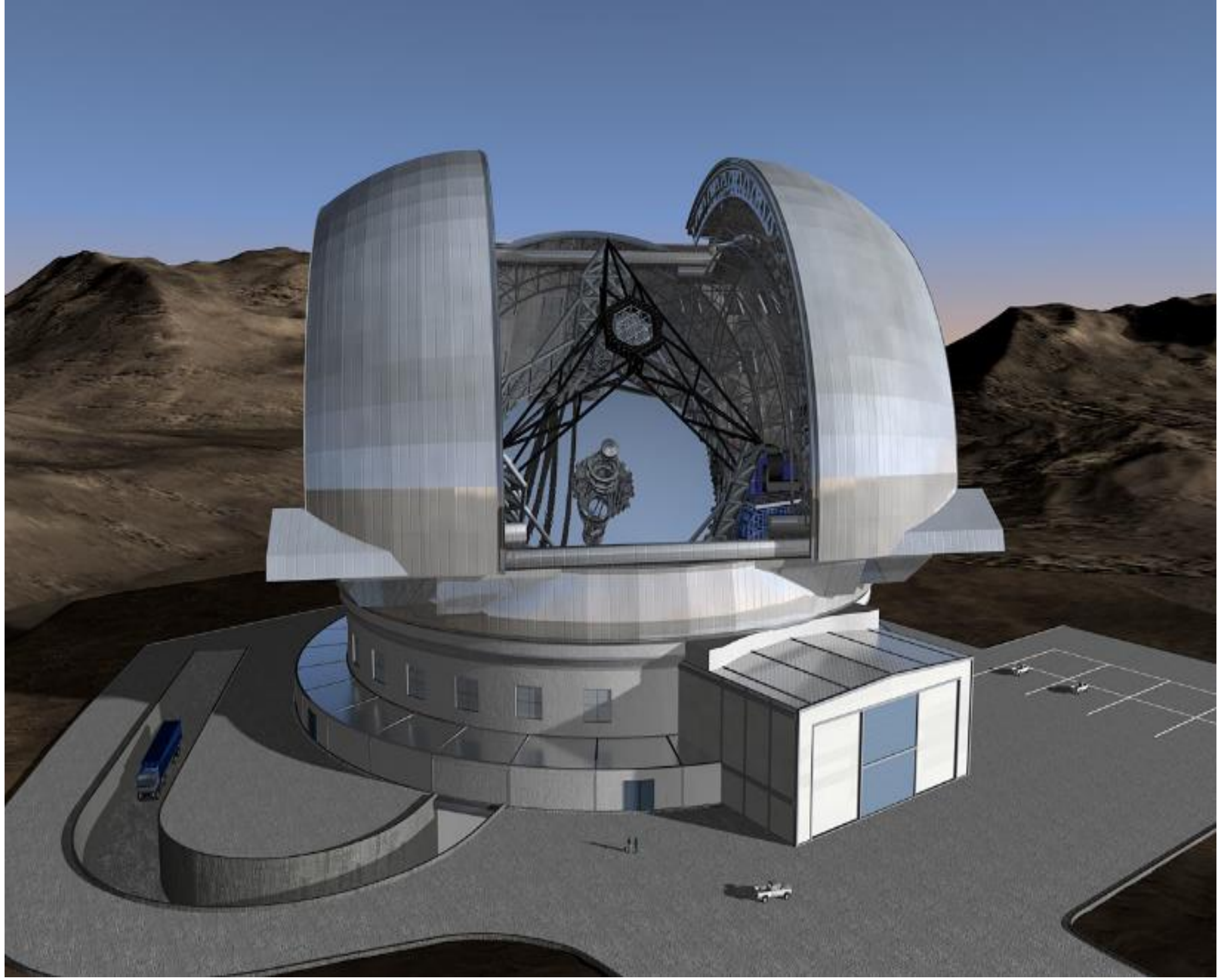
Swiss astronomers discovered in 2012 a planet with about the mass of the Earth orbiting a star in the Alpha Centauri system (Alpha Centauri B) — the nearest to Earth. It is also the lightest exoplanet ever discovered around a star like the Sun. The planet was detected using the HARPS instrument on the 3.6-metre telescope at ESO's La Silla Observatory in Chile.



Comet 67P/Churyumov-Gerasimenko as seen from Rosetta while the lander Philae analyzed the composition of the surface.

Future

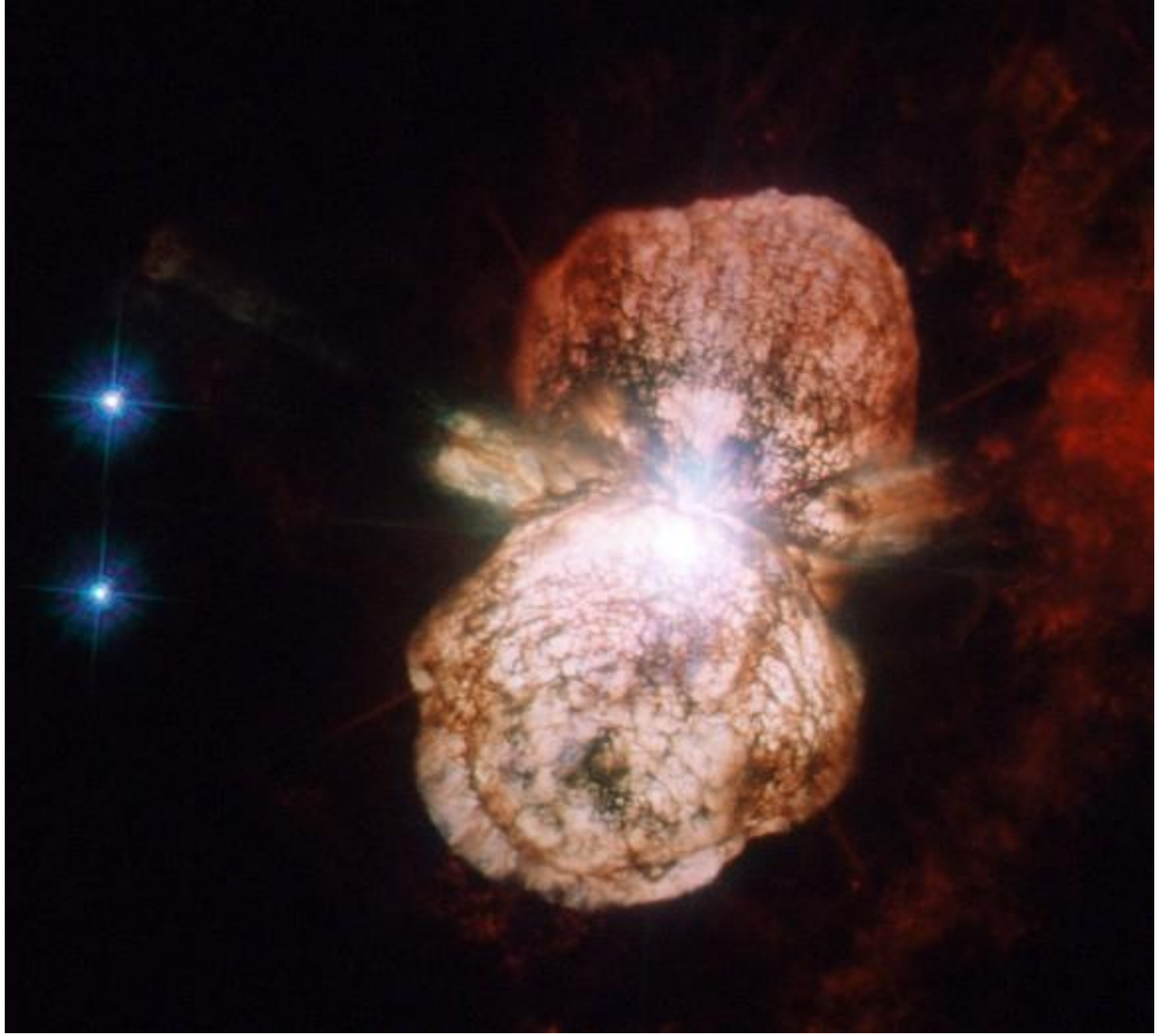
- *The James Webb Telescope (**JWST**, launch in 2018) will provide unprecedented sensitivity and high angular resolution. Will be able to take pictures of planets smaller than Jupiter. The Mid Infrared Instrument (**MIRI**) will be able to study the composition of planets through spectroscopy.*
- *The European Extremely Large Telescope (**E-ELT**, first light in 2024) will have the capacity to directly image thermal emission and reflected light, as well as to characterize spectroscopically planets approaching the size of Earth, perhaps within their habitable zones.*



The ESO ***European Extremely Large Telescope (E-ELT)*** *is a 40m-class telescope that will allow to address many of the most pressing unsolved questions about our Universe. The* ***E-ELT*** *will be the largest optical/near-infrared telescope world-wide and gathering 16 times more light than the largest optical telescopes existing today. It will be able to correct for the atmospheric distortions from the star, providing images 16 times sharper than those from the* ***Hubble Space Telescope****. The* ***E-ELT*** *will enable detailed studies of planets around other stars, the first galaxies in the Universe, super-massive black holes, and the nature of the Universe's dark sector.*

Stars

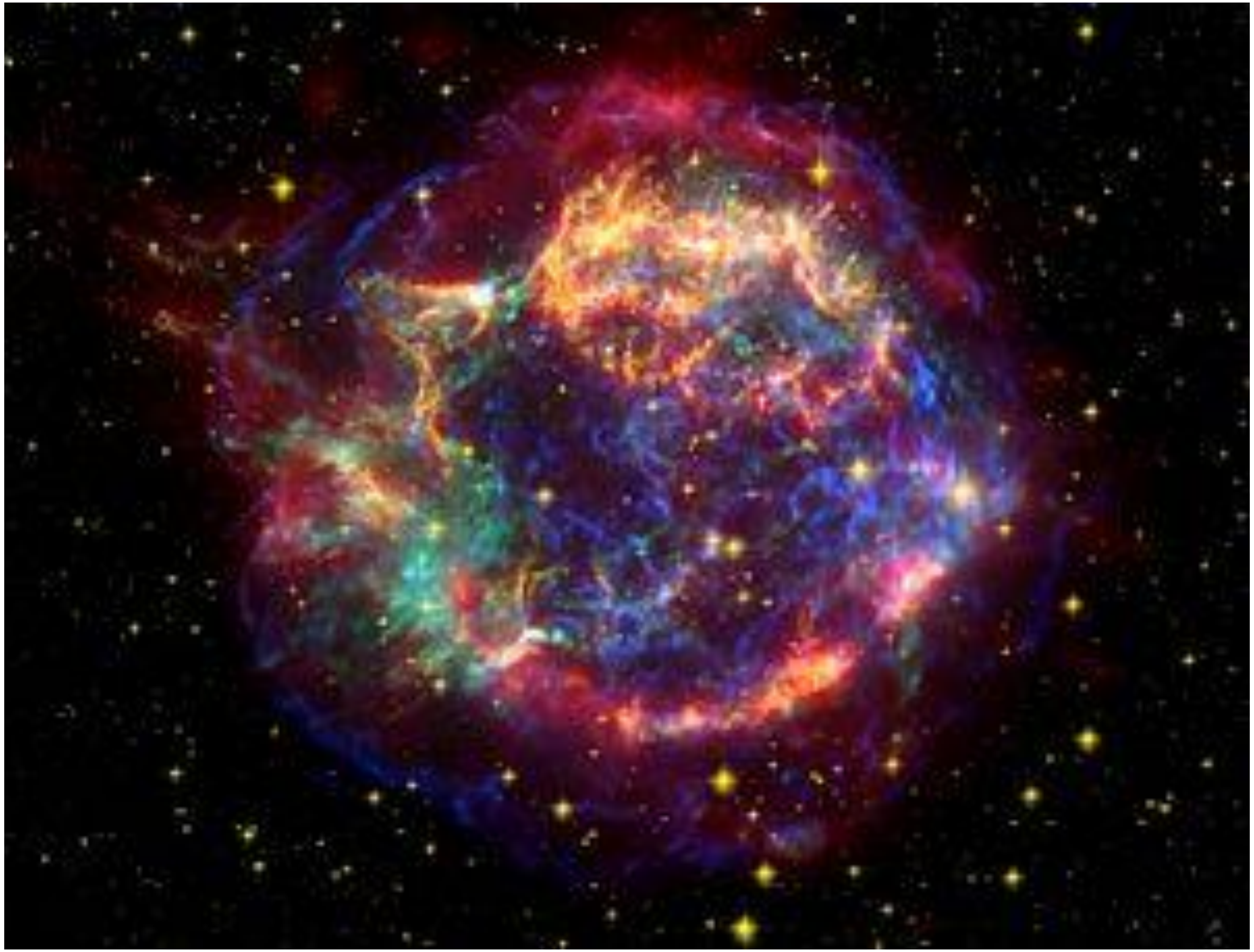
- *Stars and their evolution of the size of our Sun are reasonably well understood since solving the «solar neutrino problem» via neutrino oscillations*
- *Understanding solar activity via emitted solar wind particles and their potential impact on space weather with monitoring satellites (**NORSAT-1** and **PROBA-3** in construction). **Solar Orbiter** mission (launch in 2017) involves two Swiss institutes*
- *Asteroseismology provides a probe to understand the stellar interior (only possibly since a few years for other stars than the Sun): Satellites **CoRoT** (2006-2013), **PLATO** (launch planned for 2024) will be able to constrain stellar masses and radii to an accuracy never reached before.*
- *The understanding of stellar rotation and resulting deformation can be investigated with interferometry (using many telescopes simultaneously to observe stellar surfaces) with the Very Large Telescope Interferometer (**VLTI**)*



*Eta Carinae, as imaged by the **Hubble Space Telescope**, is a stellar system containing at least two stars with a combined luminosity over five million times that of the Sun, located around 7500 light-years distant in the direction of the constellation Carina. The primary star is a peculiar star that initially had around 150 solar masses and has since lost at least 30. Because of its mass and the stage of its life, it is expected to explode as a supernova or hypernova in the astronomically near future. The secondary star is hot and also highly luminous, probably around 30 times as massive as the Sun. The system is heavily obscured by the Homunculus Nebula, material ejected from the primary star during a Great Eruption in the mid nineteenth century. Image Credit: ESA / NASA*

Stellar Deaths and Explosions

*Stars up to 8 Msol will end their lives as a central **white dwarf**, combined with the ejection of a so-called **planetary nebular**, from about 8-25 Msol the central collapse to a neutron star and explosive ejection of matter in a so-called **core collapse supernova** will take place, more massive stars very probably end as central black holes and to some cases as **hypernovae/gamma-ray bursts**. The formation of all elements beyond H,He,Li is due to such processes. The **evolution of elements as a function of time in galaxies** can be understood via observation of (unchanged) surface abundances of old stars with varying ages, based on stellar spectroscopy (with the ESO **VLT**, Hubble Space Telescope **HST**, and the **GAIA** satellite, launched in 2013)*



CAS A, the remnant of a (core collapse) supernova explosion which occurred about 300 years ago in the constellation Cassiopeia. A false color image composited of data from three sources. Red is infrared data from the ***Spitzer Space Telescope*** *(NASA), orange is visible data from the* ***Hubble Space Telescope*** *(NASA/ESA), and blue and green are data from the* ***Chandra X-ray Observatory*** *(NASA). The cyan dot just off-center is the remnant of the star's core, a strongly magnetized neutron star.*

Binary systems

- *Mass exchange in binary systems involving white dwarfs, which leads to exceeding their maximum stable mass (1.4Msol, Chandrasekhar mass), causes explosive eruption of the whole star (**type Ia supernovae**, which are «standardizable candles» and can be used to measure the geometry of the Universe) -> **dark energy***
- *Explosive eruptions of accreted matter on white dwarfs and neutron stars causes **nova explosions** or **X-ray bursts***
- *The merger of two neutron stars leads to **short duration gamma-ray bursts / kilonovae**.*

*X-ray and gamma-ray observations, are observable with ESA's **XMM Newton** and the gamma-ray satellite **INTEGRAL** (Switzerland hosts the INTEGRAL Science Data Center)*

- *Neutron star mergers, neutron-star black hole mergers, black hole mergers cause the emission of **gravitational waves** (discussed below)*

Galaxies

An assembly of stars, interstellar gas, often supermassive black holes, and dark matter (essential for gravitational properties, formation, and evolution), typically 100 billion stars (higher for giant elliptical galaxies by a factor of 100, smaller by orders of magnitude for dwarf galaxies).

Aim: studying key aspects of galaxy formation and evolution, concomitant evolution of large scale structures, i.e. distrribution of matter in the Universe, starting from initial fluctuations, the role of dark matter as gravitational sinks for the inflow of gas, the formation of the firsts stars and galaxies, up to the distribution and evolution of galaxy sizes and clusters of galaxies.

- ***MUSE*** *at the ESO* ***VLT*** *enables detailed study of the mass and age of galaxies throughout the major epoch of galaxy formation and evolution, the distribution matter, galaxies and cluster of galaxies*
- ***MOONS*** *(at ESO* ***VLT****, entering operation in 2019) will survey the galaxy population up to a look-back time of 10 billion years*
- ***SINFONI*** *(at ESO* ***VLT****) will provide complementary IR spectra of individual galaxies to study gas infall and star formation*
- ***ALMA*** *(ATACAMA Large Milimeter Array) will enable to study galaxy formation and evolution in tandem with the facilities above.*
- ***ATHENA*** *(X-ray ESA mission, launch foreseen in 2028) will play a major role in understanding the co-evolution of galaxies and black holes*
- ***EUCLID*** *(ESA satellite with the main aim to investigate the nature of dark energy and the large-scale dark matter distribution) will also generate enormous amounts of date related to formation and evolution of galaxies*

- *GAIA is a precision astrometry mission, revolutionarizing many branches of astronomy, in particular it will be a powerful tool to study stellar dynamics, helping to constrain the dark matter distribution in the Milky Way, dissect nearby stellar groups and clusters, which are key agents to explore evolutionary processes of galaxies*

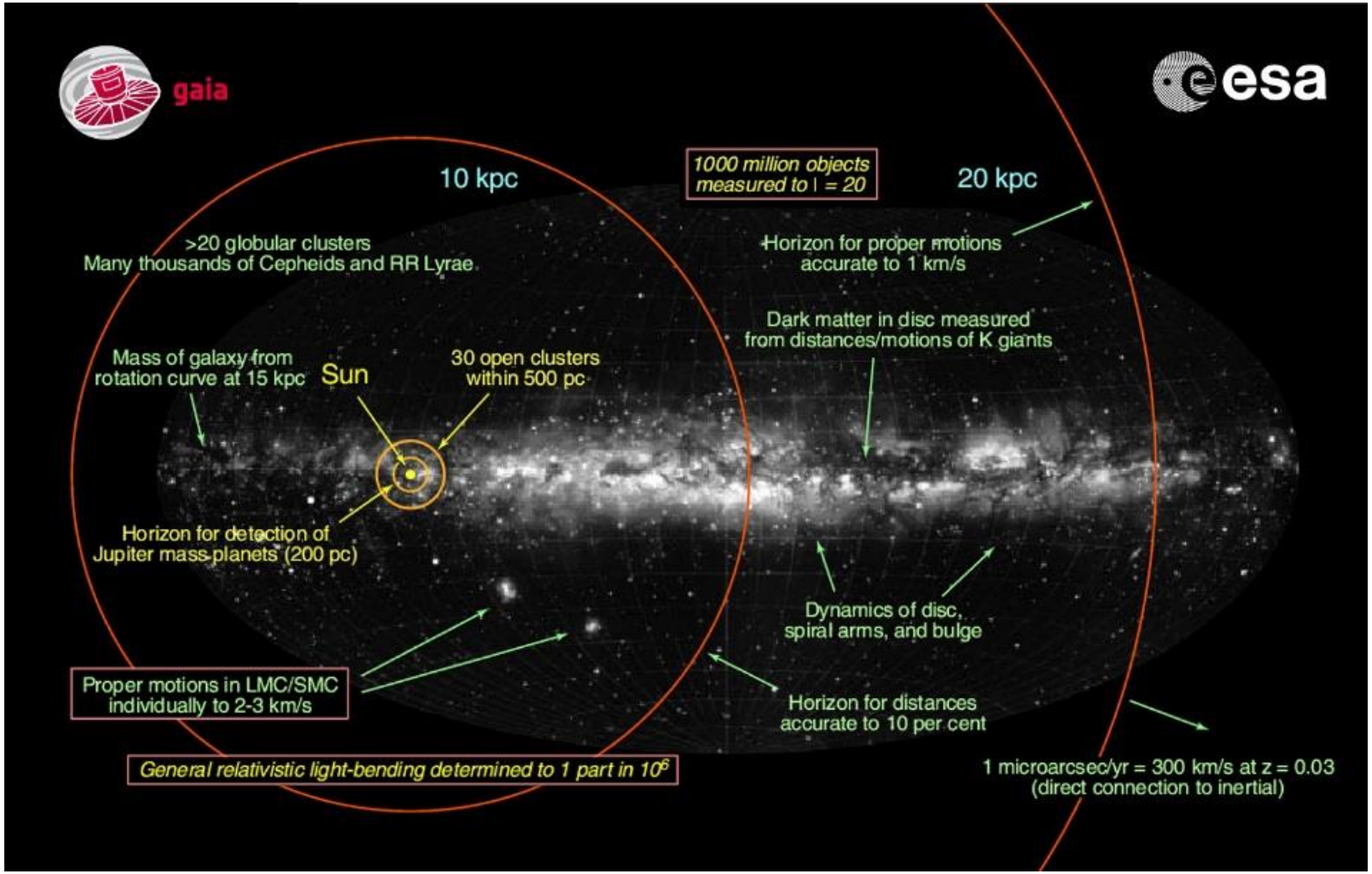


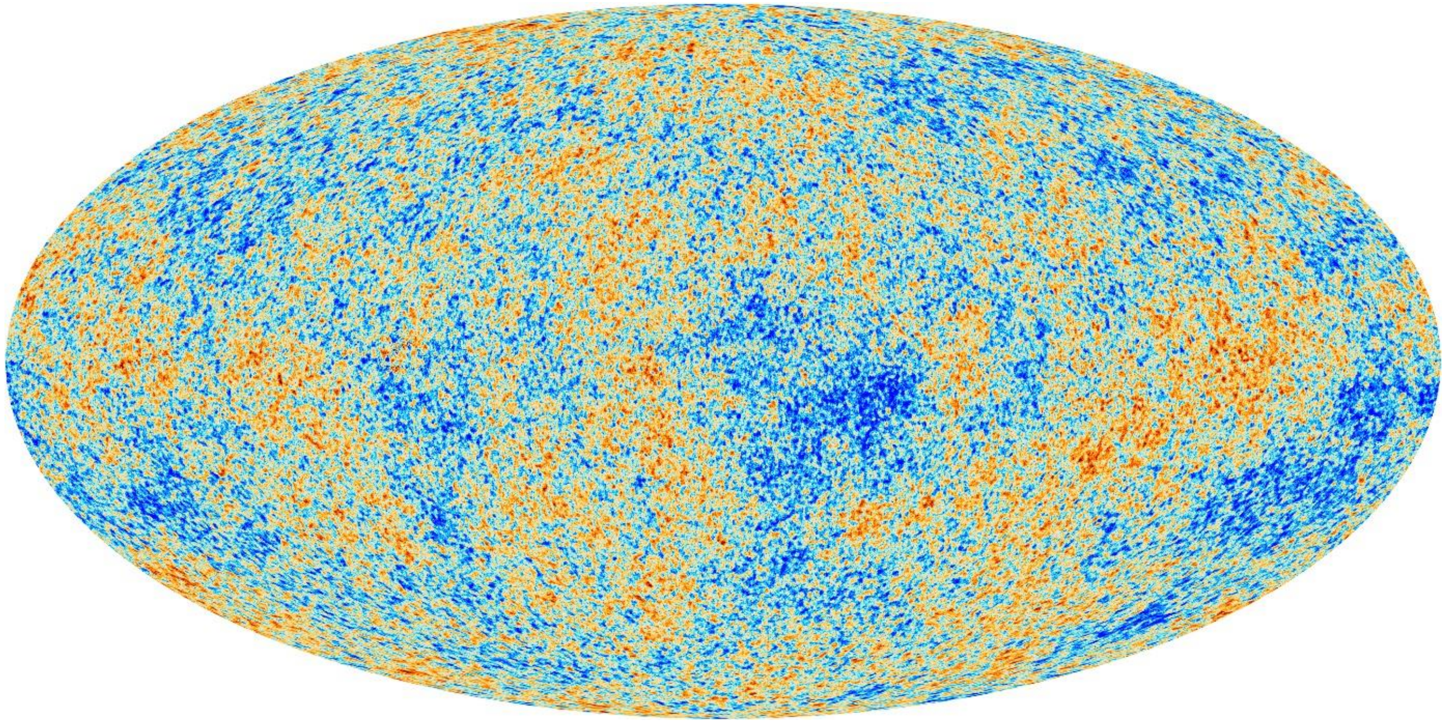
*Illustration of **Gaia**'s range and expected contribution to our knowledge of the Galaxy. Copyright: ESA*

The Universe

- *Understanding the nature of Dark Matter, Dark Energy, Inflation (a period of rapid expansion in the first moments of the Universe), and Gravity -> the most pressing questions in cosmology and fundamental physics.*

in Switzerland

- *Cosmological studies of the Cosmic Microwave Background (**CMB**)*
- *The wide-field Large-Scale Structure (**LSS**)*
- *Astrophysical experiments relevant for **fundamental physics***



*The anisotropies of the Cosmic Microwave Background (CMB) as observed by ESA's **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 all future structure: the stars and galaxies of today*

The most precise confirmation of the standard cosmological model, but remaining anomalies/tensions with other probes.
*Extended data analysis aimed at understanding what happened just fractions of a second after the **Big Bang**.*
*Major theoretical investigations about the period of **inflation**, i.e. a period of very fast expansion, which requires close interaction with particle physics.*

Tests of Gravity and Gravitational Waves

- *100 years after General Relativity (GR) was developed by Einstein during his Swiss days in Bern and Zürich, the very first gravitational wave detection of merging stellar mass black holes took place by **LIGO**, but tests of GR at very large scales and in the strong field regime are required to also understand possible deviations from its predictions, possibly related to dark matter and dark energy.*
- *Switzerland is involved in the **LISA-Pathfinder** mission, launched end of 2015, testing the technical feasibility of the **LISA** mission (planned for 2030 jointly by ESA and NASA), which would permit to detect and study low-frequency gravitational wave radiation from (super)massive black holes merging at cosmological distances (related to galaxy mergers)*
- *GR predicts also the deflection of light by gravity. This permits large assemblies of matter to act as **gravitational lenses**, utilized in astronomical surveys **DES** (Dark Energy Survey), **Euclid** (discussed before**)**, and **COSMOGRRAIL** (COSmological Monitoring of GRAvitational Lenses, with the **Euler** Swiss telesope at ESO La Silla).*

Findings

Swiss astronomers are working very successfully at the very forefront of astrophysical research, underlined by a number of examples in this document. They are able to do so, because Switzerland is participating in and contributing to European (and other international) collaborations / organizations which provide access to large scale observational facilities which no country can run alone. All present and future successes are linked to it as outlined in more detail in the Swiss Roadmap for Astronomy and its updates. While the present document relates to classical astronomical tools, there are other fields, like astroparticle physics, which contribute in different ways to the understanding of astrophysical objects and the universe as a whole. They include observations of neutrinos (e.g., ICECUBE), high energy cosmic rays (e.g., AMS), very high energy gamma-rays (e.g., CTA), which are performed with tools related to particle physics which are not part of this document. They can be found in the Swiss Roadmap for Particle Physics and its updates.

http://www.naturalsciences.ch/service/publications/47646-update-to-the-roadmap-for-astronomy-in-switzerland-2007---2016.

http://www.chipp.ch/documents/Achievements_RoadMap2005-2010.pdf.

Early Facilities at ESO/La Silla, e.g.

Euler Telescope: the Swiss 1.2-meter Leonhard Euler Telescope at the ESO La Silla site was built and is operated by Geneva Observatory.

HARPS (suppored by former FLARE funding): High Accuracy Radial velocity Planet Searcher - an ultra-high precision spectrometer operating on the ESO 3.6m telescope; has been the most successful ground-based instrument to detect exoplanets anywhere in the world.

NTT: An ESO 3.58m Richey-Chretien telescope which pioneered the use of active optics.

NIRPS: an IR spectrograph for the 3.6m (exoplanet science) with strong Swiss participation,

Swiss groups continue to perform important research with this early ESO infrastructure!

VLT: Very Large Telescope, the four 8m telescopes operated by ESO at Paranal Observatory.
VLTI: Very Large Telescope Interferometer: The four telescopes of the VLT when linked together interferometrically, in order to give exceptional resolution on bright sources.

Swiss groups play major roles in the following infrastructures

SPHERE: A second-generation instrument for the ESO VLT, designed to detect large Jupiter-like planets around nearby stars.

ESPRESSO: A superstable Optical High Resolution Spectrograph for the combined coudé focus of the VLT.

This new high-precision radial-velocity spectrograph for the Very-Large Telescope comes under the ***leadership of UniGe, UniBe (within NCCR PlanetS)***

MOONS: a new conceptual design for a Multi-Object Optical and Near-infrared Spectrograph for the VLT. The aim is to have MOONS operational by 2019.

Spectroscopy over a wide wavelength range is key to understanding the physical and cosmological processes that shape the evolution of gas and stars in our own Galaxy and in the distant Universe.

(Swiss team from ETHZ, EPFL, and UniGe)

Submillimeter Astronomy

ALMA: Atacama Large Millimeter Array. A major collaboration between ESO, the US and Japan (+ Canada, Corea, Taiwan) to construct and operate an array of 50 12m millimeter-wave antenna, covering 200km^2 of the Chajnantor plateau at 5000m altitude. The initial version of the project was completed in 2012 (inauguration in 2013), but still being extended to its final operational mode. Spectrum 84-950 GHz (3 mm to 530 μm).

(Alma is run as a users facility with proposals for observing time. Swiss groups have been successful being PIs and CoIs.)

E-ELT: European Extremely Large Telescope. ESO‘s medium term priority after completion of ALMA is the construction of this 40m class optical-infrared telescope, first light 2024.

Selecting instruments for any telescope is a critical step in making sure that the astronomical community it serves can undertake the scientific projects for which the telescope was designed.

Procurement for all instruments will start in 2015. Negotiations with consortia that will build ELT-IFU (HARMONI), ELT-CAM (MICADO), the MCAO system (MAORY), and ELT-MIDIR (METIS), signing agreements for construction for each of these in 2015.

E-ELT-METIS: A mid-infrared imager and spectro-graph candidate instrument for the E-ELT.

(Swiss research groups involved from ETHZ)

A request for letters of interest from the community for the construction of an ELT-MOS and **ELT-HIRES** was **issued**, followed by a call for proposals for Phase A studies.

E-ELT-HiReS: Building on the experience of the high-resolution community with the VLT high-resolution spectrographs, the (science) case is made for a high-fidelity, high-resolution spectrograph with wide wavelength coverage at the E-ELT with the following flagship science drivers:

- from the study of exo-planetary atmospheres over the evolution of galaxies to the complex role of stellar and AGN feedback and the imprint of the very first stars on the inter-galactic medium.

The requirements of these science cases can be met by a stable instrument with a spectral resolution of R~100,000 and broad, simultaneous spectral coverage extending from 0.37µm to 2.5µm. HIRES will ensure continued competiveness of the European high resolution community in the E-ELT era and in this way will largely enhance the overall competiveness of the E-ELT.

HIRES will be the only occasion for CH (UniGe, UniBe, ETHZ) to take the lead in an E-ELT instrument!

GTO is essential for achieving important scientific results, comes with sizeable contributions to instrument building

(see the involvement in ESPRESSO, MOONS, HiReS)

DESI: Dark Energy Spectroscopic Instrument – to measure
baryon acoustic oscillations and redshift space distortions by measuring positions and redshifts of tens of millions of galaxies (survey conducted from the 4-m Mayall telescope at Kitt Peak over a five-year period 2018-2022).

(a small-size? project outside ESO with involvement of EPFL)

BINGO: Baryon acoustic oscillations In Neutral Gas Observations,
is a collaboration between research groups from the UK, Switzerland, Brazil, Uruguay, and Saudi Arabia.

(a small-size project outside ESO with involvement of ETHZ)

Missions where Swiss groups plan participation

CHEOPS: Characterising ExOplanet Satellite, the first small mission in ESA's science program dedicated to search for exoplanet transits using high-precision photometry; jointly led by ESA and Switzerland. Launch in 2017.

(small-size mission, funded by ESA (hardware) and NCCR PlanetS (science), UniBe, UniGe)

Euclid: An ESA space mission to map the geometry of the dark Universe by investigating the distance-redshift relationship and the evolution of cosmic structure out to redshifts ~2, or Equivalently to a look-back time of 10 billion years. Launch in 2020.

(EUCLID passed successfully Mission-Preliminary Design Review in October 2015, EPFL, UniGE, UniZH and FHNW Brugg have been extremely active in various Science Working Groups and Organisation Units as leads, coleads, and coworkers)

JUICE: JUpiter ICy moons Explorer - an ESA space mission to explore Jupiter's icy moons. Launch foreseen for 2022.

PLATO: PLAnetary Transits and Oscillations of stars - an ESA mission to measure planetary transits and stellar oscillations. Launch foreseen in 2024.

Large-Scale Future Infratructures Outside ESO

SKA: Square Kilometer Array - an international project to build the largest radio telescope in the world with a square kilometer of collecting area (probable site South Africa, Headquater in UK).

There is a strong Swiss community building up for future participation in the SKA (UniGE (PI), EPFL, ETHZ, UniZH, CSCS, FHNW)

LSST: Large Synoptic Survey Telescope - large aperture, fast, wide field survey telescope to image faint objects across the entire sky.

These projects are of high scientific importance and maybe possible with a substantial budget increase?