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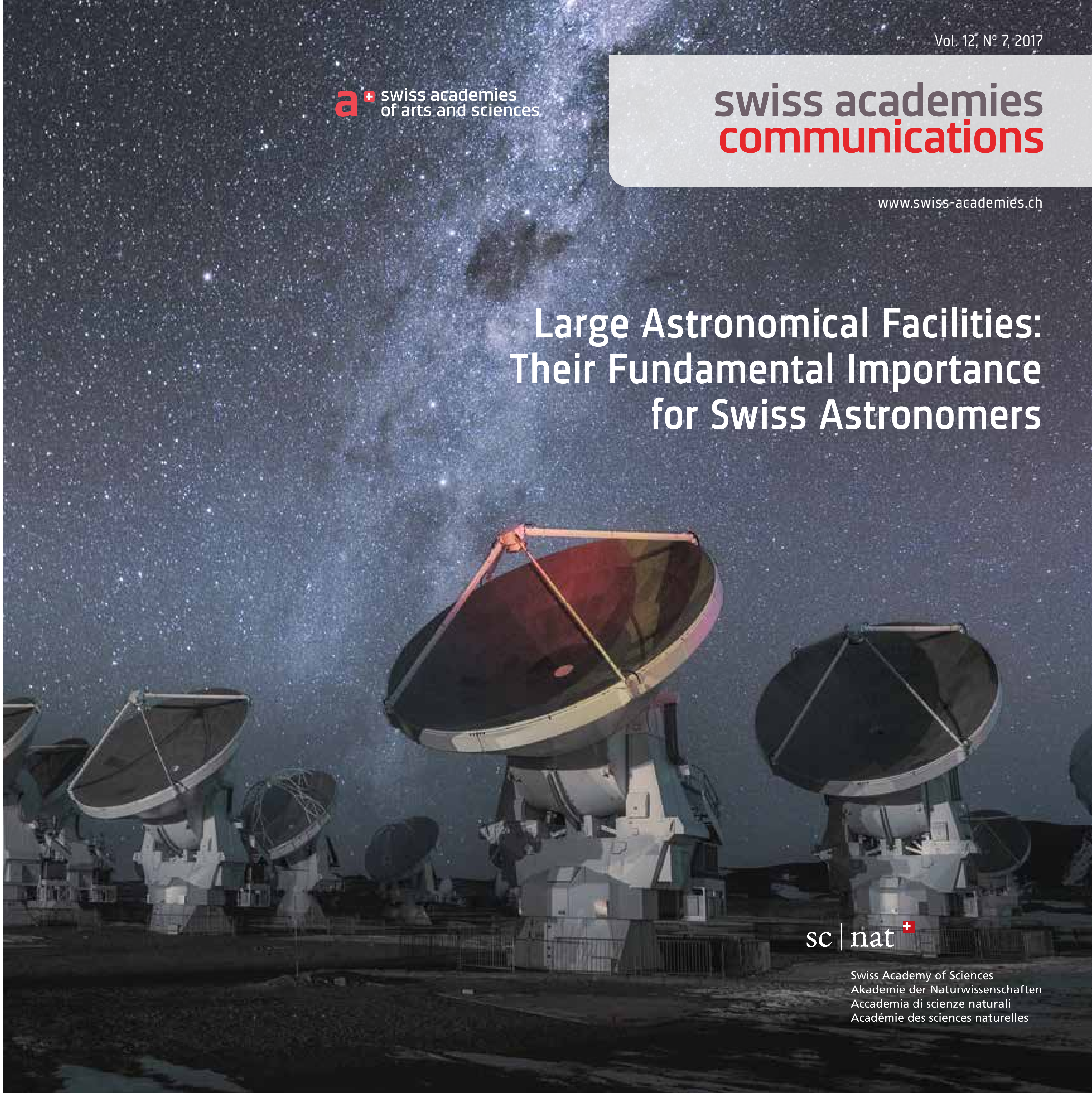

Large Astronomical Facilities: Their Fundamental Importance for Swiss Astronomers

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Large Astronomical Facilities: Their Fundamental Importance for Swiss Astronomers

ESO's Very Large Telescope (VLT) during the testing of the new Laser Guide Star Facility (LGSF), which allows astronomers to correct for most of the disturbances caused by the constant movement of the atmosphere in order to create much sharper images. Credit: ESO/Y. Beletsky

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Aerial photograph of the home of ESO's Very Large Telescope (VLT) on Mount Paranal in Chile. The Paranal Observatory with its four giant 8.2-metre Unit Telescopes of the VLT is located at an altitude of 2,600 metres in the Atacama desert. In the background we can see the 6,720 metres-high volcano Llullaillaco, located a mind-boggling 190 km further East. Credit: ESO/G.Hüdepohl (atacamaphoto.com)

Astrophysics and cosmology have experienced a golden age over the last two decades, due to fundamental observational and theoretical progresses in all areas investigated. Swiss astronomers have made substantial contributions to those fields thanks to the many modern facilities they can use throughout the world. Without a regular access to them, and international collaborations, present day research in astronomy is unthinkable.
This booklet is meant to highlight the impact and their importance for Swiss researchers. All present and future projects are outlined in more detail in the Swiss Roadmap for Astronomy and its updates.[1]

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[1] www.naturalsciences.ch/service/publications/47646-update-to-the-roadmap-for-astronomy-in-switzerland-2007---2016.

1. Introduction

In 1995, Michel Mayor and Didier Queloz from University of Geneva broke new ground by discovering the first planet orbiting another Sun – a so-called *exo-solar planet*. This finding triggered an enormous amount of observational and theoretical activites on those exoplanets. Of fundamental interest is their potential inhabitability by elementary forms of life.

Over two decades, *cosmology* has also experienced tremendous evolutions, if not revolutions. One of the most fundamental progresses came from the observations of the Cosmic Microwave Background (CMB), the first light to be emitted about 380 000 years after the Big Bang which contains detailed information about the distant past. Due to the expansion of the Universe, the temperature of this electromagnetic radiation cooled down from an initially very high to a currently very low value (2.725 Kelvin, or –270.4° Celsius). Its theoretically predicted small variations and their measurements with three successive satellites **(COBE, WMAP, Planck)** allow to constrain the cosmological models far better than ever before.

Big questions concern the connection from the beginning of the Universe to present day planets formation. Those eventually form out of the rotating disk of dust and gas that surrounds a hot central object (a star), which itself results of the contraction of cold clouds of gas. *Stars evolve* over time, making it a continuous process: they burn light (chemical) elements to heavier ones, producing heat and light, and end their life in gigantic explosions with ejected material containing all the newly produced elements. The final fates and ejecta composition of stars is the basis for our understanding of the evolution and present composition of *our galaxy (the Milky Way) and the large variety of galaxies observed*.

Such studies showed from their early stages that the mass contained in stars and the gas of the interstellar medium seems not sufficient to explain the processes taking place. The existence of an additional invisible entity, called *dark matter*, has been postulated, this already in 1933 by the Swiss astronomer Fritz Zwicky. Our Universe now appears to be made of 5% of common matter (e.g., the atoms, gravitationally attractive), of 26% of *dark matter* (also gravitationally attractive, but of unknown nature), and of 69% of *dark energy* (gravitationally repulsive, also of unknown nature). The latter is linked to another major and unexplained observation made in 1998: the unexpected acceleration of the *expansion of the Universe*.

So far the common set of observational and theoretical advances constitutes the *standard model of the Big Bang cosmology*, the simplest model that provides a reasonably good account of all observed properties of the cosmos. The quest for answers to the remaining questions – be it life on exoplanets or the nature of the dark components of the Universe – requires observations of very faint nearby stars and planets as well as more luminous but very distant galaxies. This calls for *state-of-the-art astronomy facilities* across all segments (or wavelength bands) of the electromagnetic spectrum. Unfortunately Earth's atmosphere permits only certain wavelengths to penetrate down to the ground (Figure 1).

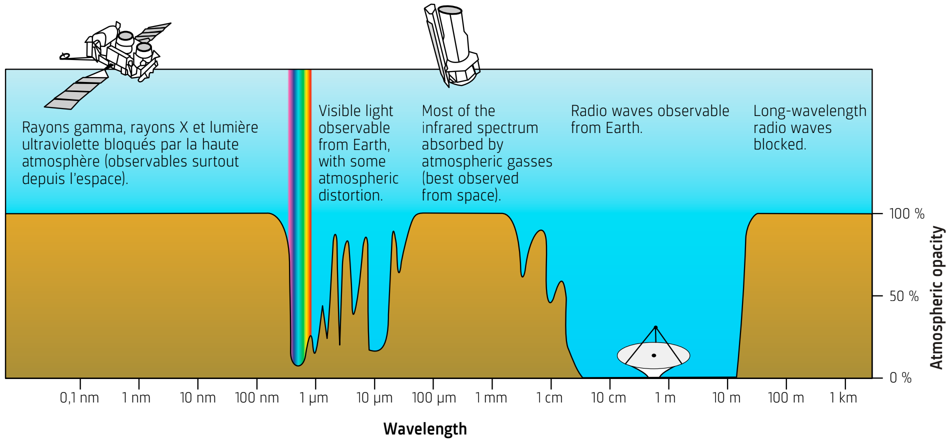

Fig. 1: Most of the wavelengths of light never reach the ground: they are absorbed by our atmosphere. Space telescopes placed above our atmosphere can observe them. Visible and most radio wavelengths do (the 'optical window', i.e., the visible light, and the 'radio window') reach the ground and can be observed by ground-based telescopes. A limited amount of infrared (IR) and ultraviolet (UV) light also reaches the ground. Credit: NASA/Wikimedia Commons

Thus, we need, simultaneously, *ground-based telescopes* as well as *satellites*, the latter being not affected by light absorption in Earth's atmosphere. With Switzerland being a full member of both ESA and ESO, its scientists have direct access to the space satellites[2] of the former and to the ground telescopes[3] of the latter. These are two essential contributing factors to the *very high quality of the research in astronomy and cosmology in Switzerland*. In addition, a number of projects, in every field, are planned for the near future or already put in place.

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[2] www.esa.int/spaceinimages/Images/2013/02/ESA_Fleet_Across_Spectrum_poster_2013

[3] www.eso.org/public/teles-instr/

2. Stars and Planets

2.1 Formation

Stars, and planets surrounding them, form out of contracting clouds of gas and dust. As material accumulates, the *«protostars»* are initially very cool and heavily obscured by immense amounts of tiny debris. To observe such processes happening, infrared and millimeter wavelength perceptiveness is required. ESA's **Herschel** space telescope provided not only this needed sensitivity, but also spectroscopic access to new molecules crucial to understand the energy budget of the interstellar medium, as well as organic chemistry that can lead to pre-biotic molecules.

Formation of stars and planets can also be observed with instruments installed on ESO's **Very Large Telescope (VLT)**, in Chile. Switzerland played a crucial role in the development of many of them. The construction of **ESPRESSO** is led by Swiss astronomers. This spectrograph replaces the Swiss-made **HARPS**, for long the most powerful device for hunting planets through the *radial velocity technique*. This method measures the wobble of the host star in response to the gravitational tug of any surrounding exoplanets; it allowed the discovery of the first one, in 1995.

Switzerland also co-developed the **Next Generation Transit Survey (NGTS)**, at ESO's Paranal Observatory, to look for the dimming of light due to the passage (transit) of a planet in front of its star, as seen from Earth. Building on this technique to follow-up discoveries from HARPS and NGTS, the Swiss-led satellite **CHEOPS** is ESA's first S-class (small) mission. To be launched in 2018, it will be capable of detecting Earth-like planets around a selection of stars and analyze the diversity of compositions for planets smaller than Uranus and Neptune. As a capstone to these studies, ESA's **PLATO**, to be launched in 2024, will be able to find Earth-size planets (example in Figure 2), also at orbital distances from their host stars where liquid water could theoretically exist on their surface, perhaps supporting the development of life.

Fig. 2: Swiss astronomers discovered in 2012 a planet (object on the right) 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. Credit: ESO

Planetary Science research in Switzerland also benefits from participation in ESA's solar system exploration missions. From 2014 to 2016, the spacecraft **Rosetta** has provided breath-taking images of Comet 67P/CG (Figure 3); onboard, the *Rosina mass spectrometer* and cameras developed by Swiss researchers gave insights into the composition of this celestial body. Switzerland is also involved, with cameras, on the **ExoMars orbiter** flying since 2016 around the Red planet, and will participate in future missions such as the **ExoMars2020 lander** and **JUICE**. Planned for launch in 2020, the latter will study the moons of Jupiter when reaching it in 2030.

Fig. 3: Comet 67P/Churyumov-Gerasimenko as seen from Rosetta. Credit: ESA

In 2018, NASA, ESA and the Canadian Space Agency will launch the **James Webb Space Telescope (JWST)** which will offer images with unprecedented resolution and sensitivity from long-wavelength visible light to infrared (0.6 to 27 micrometers wavelenghts), insights on planet composition around other stars, and observations of the most distant events in the Universe. Switzerland is a member of the European **MIRI** (Mid InfraRed Instrument) consortium that contributes this powerful instrument for **JWST**.

Construction just started for ESO's **Extremely Large Telescope (ELT)**. With its 39 m diameter aperture, it will be the world's largest ground-based telescope (Figure 4), and a world-beating facility for decades to come, planned for first light in 2024. Swiss astronomers plan to participate in instruments development for this platform. It will have the capacity to characterize spectroscopically planets approaching the size of Earth, perhaps within their habitable zones, around the nearest handful of stars. It will also allow to study the most distant galaxies.

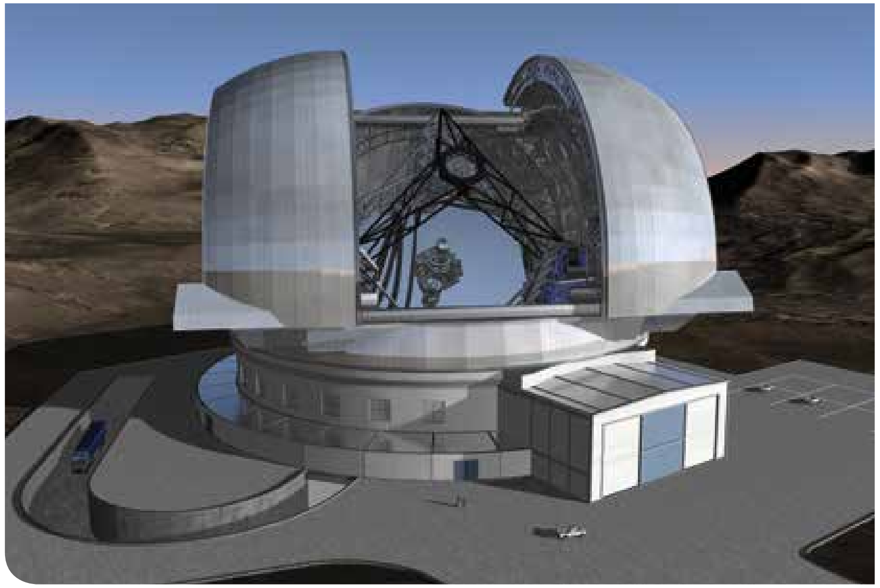

Fig. 4: The ESO Extremely Large Telescope (ELT) is a 39 m-class telescope that will be the largest optical/near-infrared telescope world-wide and gathering 16 times more light than the largest optical telescopes existing today. It will be able to correct for the atmospheric distortions from the star, providing images 16 times sharper than those from the Hubble Space Telescope. The 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. Credit: ESO

2.2 Stellar Evolution

Stellar evolution, from birth to explosion, is a field of very dense activities in Switzerland. Stars can be utilized for many applications, from their function as clocks indicating the age of galaxies up to their role as cosmic laboratories for probing the physics of elusive particles called *neutrinos* or the evolution of *fundamental constants* along the cosmic history.

Talking physics, stars are very complex objects in which the four *fundamental forces of Nature* (gravity, electromagnetic force, weak and strong nuclear forces) interact through numerous processes. In that respect, they offer to explore processes far outside the range of temperatures and densities that can be studied in terrestrial laboratories and allow to study physics at the frontiers of our present day knowledge. Therefore, constructing detailed and reliable models, which predict the evolution of stars from ab initio physical principles, is crucial. New observations are needed to test these; which will be made possible soon.

To assess the activity of our star, the Sun, via emitted *solar wind particles*, and its potential impacts for *space weather*, requires monitoring satellites; Switzerland participates in several missions, with two projects presently in construction, **NORSAT-1** and **PROBA-3**. A big step to better understand our Sun will be made through ESA's **Solar Orbiter** mission, to be launched in 2018, with two Swiss institutes actively involved.

Thanks to *asteroseismology*, it is possible to probe what happens behind the façades of stars. This technique consists in observing the pulsations at their surface and to deduce the physics of their interior from the properties of these «starquakes». This method was first used successfully on the Sun. It can now be applied on other stars, thanks to satellites like the European **CoRoT** (2006 to 2013) and its American sibling **Kepler**, active since in 2009. Both allow in particular to study the physics and history of red giant stars in the Milky Way. Asteroseismology also enables to constrain mass and radius of stars with an accuracy never reached before, and so is of huge usefulness for characterising the planets surrounding them.

Interferometry directs many telescopes simultaneously on the same object, and then combines the collected light. The **Very Large Telescope Interferometer (VLTI)**, a ground based facility at ESO's Paranal Observatory, is one of the best instruments of its kind. With it, it is now possible to observe the surface of other stars than the Sun, resulting for example in the discovery of objects with a rugby-ball shape, indication their very fast rotation.

Among present day facilities with potential enormous impacts on stellar physics, ESA's **GAIA** mission is in the front row (Figure 5). This satellite, launched in late 2013, will observe 1 billion astronomical objects during 5 years, mainly stars (so approximately 1% of the Milky Way stellar population). The outcomes will be used to make a three-dimensional map of our Galaxy, the resulting *variability catalogue of stars* will show how fascinating and unknown our galactic neighbourhood still is, and will be used extensively by Swiss astronomers.

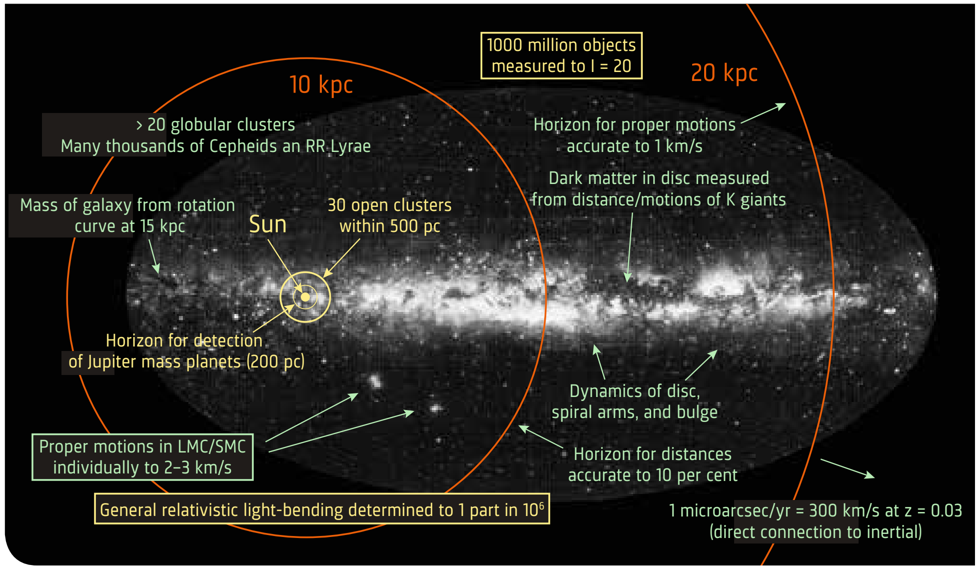

Fig. 5: Illustration of Gaia's range and expected contribution to our knowledge of the Galaxy. (1 kpc = 3262 lightyears = 31 × 10^{15} km). Copyright: ESA/Lund Observatory

When evolving, all stars emit light containing a distinctive *signature of the chemical elements* of the prior interstellar cloud out of which they were born. Thus, from old stars formed very early in the evolution of the Milky Way up to more recently constituted ones, scientist get knowledge about the gas composition of our Galaxy throughout its evolution. Such observations are done amongst others with the **VLT**, ESA/NASA's **Hubble Space Telescope**, and **GAIA**.

2.3 Deaths and Explosions of Stars

The end of life of stars is of great interest to many Swiss scientists. It is mainly determined by the original mass of the object (Figure 6). Stars weighing less than 8 solar masses end their evolution as *white dwarfs*: after having burnt hydrogen and helium in their interiors (first becoming *red giants*), their outer shells are slowly blown off in a stellar wind, leading to a so-called *planetary nebula*. Some planetary nebulae can be observed through a simple terrestrial telescope. Their dense core remains intact, supported by the quantum pressure of a cold and dense electron gas. A typical white dwarf is about as massive as the Sun, yet only slightly bigger than the Earth.

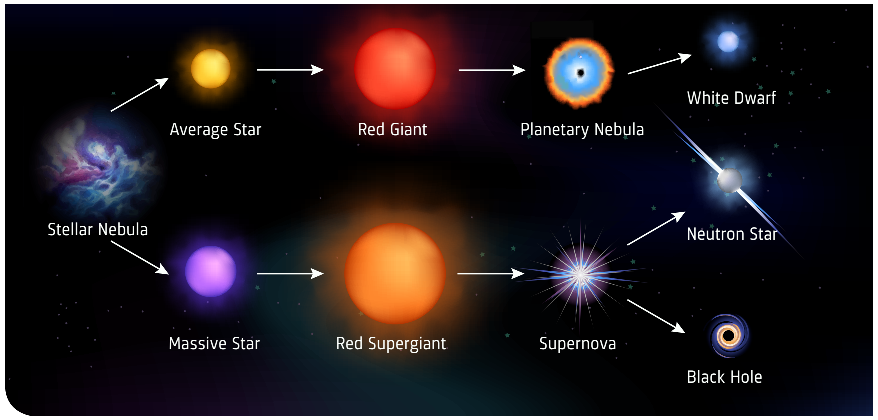

Fig. 6. Stars evolve differently regarding their original mass. Credit: Shuttterstock

More massive stars pass through all remaining nuclear burning stages, from carbon up to silicon consumption. They grow to the state of a *supergiant*, before the collapse of their central iron core, and then explode into a *supernova*, producing a very brief but tremendous outburst of light (as much as a whole galaxy). Seen from Earth, this kind of event, studied in detail with ESO's and ESA's telescopes (Figure 7), can let believe a new star is just born, whereas it is actually the ending of it.

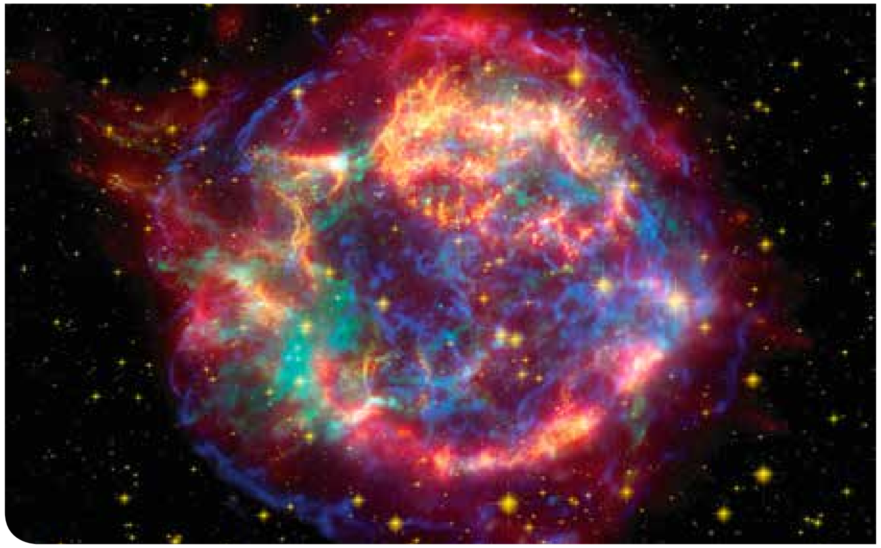

Fig. 7: CAS A, the remnant of a (core collapse) supernova explosion which occurred about 300 years ago in the constellation Cassiopeia. A false color image composited of data from three sources. Red is infrared data from the Spitzer Space Telescope (NASA), orange is visible data from the Hubble Space 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. Credit: NASA/JPL-Caltech

The final stage can either be a *neutron star*, an extremely dense object composed almost entirely of neutrons and supported by the quantum pressure of a cold neutron gas and repulsive nuclear forces; the observation of *neutrinos*, which leave the high-density neutron star already within a few seconds after collapse, has proven that our basic understanding of core-collapse supernovae is correct – a topic actively pursued by Swiss researchers. Or, it can finally be a *black hole*, accompanied by other phenomena like *hypernovae* (super luminous supernovae) and/or gamma-ray bursts (titanic energetic explosions with emission of gamma-rays). Light curves – measuring the declining luminosity of stars as a function of time – can be followed with ESO's **New Technology Telescope (NTT)**, the **VLT**, and the **JWST**. Efficient follow-up observations over extended times require access to both 8–10 m class telescopes, and the **ELT** for even more detailed studies.

When a white dwarf is accompanied by another star, forming a *binary system*, mass can be transferred from the latter to the former. This leads the mass of the white dwarf to exceed a limit (1.4 solar masses) after which an explosion occurs, called *type Ia supernovae*. Because they can be used as truthful light indicators in the cosmos, their use made possible the discovery that the *expansion of the Universe is accelerating* – a field of research in which Swiss astronomers are active.

Binary systems containing neutron stars can lead to a number of other explosive events characterized by X-ray and (short-duration) *gamma-ray bursts* (as well as gravitational waves, see 4.2), observable with ESA's **XMM Newton** or respectively the gamma-ray satellite **INTEGRAL**. Switzerland hosts the **INTEGRAL Science Data Center (ISDC)**, which is now also actively contributing to other space missions and ground-based projects, with a prime scientific focus on high-energy.

3. Galaxies:

3.1 Formation and Evolution

Galaxies are an assembly of stars, interstellar gas, often central supermassive black holes (with typical masses from a few million to a few billion solar masses), and dark matter – which is essential for their gravitational properties, their formation and evolution. They range largely in size, containing typically 100 billion stars. This can be higher by a factor of 100 for giant elliptical galaxies and smaller by orders of magnitude for dwarf galaxies.

Studying the evolution of galaxies can be done through an astronomical phenomenon called *redshift*, which occurs whenever a light source moves away from an observer, as it is the case because of the expansion of the Universe. This fleeing induces a shift of the wavelengths of the light and other radiations emitted by this object towards the red side of the electromagnetic spectrum. The characterisation of this shift over time can inform scientists on the distances and age of these sources.

The **VLT** will remain a prime facility for such studies. One of its major second-generation instruments **MUSE**, recently commissioned, will enable detailed study of the mass and age of galaxies, a field of which astronomers at Swiss institutions are examining key aspects. It will also enable ground-breaking studies of the evolution of the 'cosmic web', i.e., the distribution of matter, galaxies and clusters of galaxies, tracing the infall of gas onto galaxies, and study the role of the growth of black holes.

Another major step forward will come with **MOONS**. This next generation *near-infrared (nIR)* spectrograph, entering operation in 2019, will survey the galaxy population at a look-back time of 10 billion years (i.e., over most of the history of the Universe) with the same precision that can be achieved today in nearby galaxies. The upgrade of **SINFONI** for use with a new adaptive optics facility **(ERIS)** will provide complementary IR spectra of the furthest individual galaxies. Use of the telescope array **ALMA** (as well as the facilities of **IRAM**/PdB) in tandem with these optical/IR facilities will enable detailed study of galaxy formation and evolution.

Astronomers working at Swiss institutions are also poised to play a strong role in developing a high-energy astrophysics (X-ray) ESA mission **(ATHENA)** with a possible launch date in 2028. In the next decade, this facility will play a major role in understanding the co-evolution of galaxies and black holes.

Expertise in infrared and millimetre-wave techniques has become increasingly important to connect star formation and evolution of galaxies. Access to optical/IR facilities such as the **VLT** and soon **JWST** will enable Swiss astronomers to remain at the forefront of this rapidly developing area. We can build on past ESA infrared mission successes (e.g. **ISO** and **Herschel**) to plan for the future, **SPICA**, a Japanese satellite to be launched in 2022. Further aspects of galaxies are discussed in 2.2 with respect to the Milky Way and in 4.3/4.4 with re-spect to the large scale structure of the Universe.

4. The Universe

The nature of dark matter, dark energy, as well as *inflation* (a period of extremely rapid expansion in the very first moments of the Universe) and *gravity* pose some of the most pressing questions in cosmology and fundamental physics today. To shed light on them, astronomers in Switzerland have a leading role in key international experiments and theoretical projects both from the ground and in space.

4.1 The Cosmic Microwave Background

The Cosmic Microwave Background, the *first light* to be emitted about 380,000 years after the Big Bang, provides a high precision picture of the early Universe. To detect it, ESA's **Planck** mission was launched in 2009. Astrophysicists from Switzerland, as members of its core team, have participated in the first data and science release in 2013 (Figure 8). These data suggest tensions with other probes and intriguing anomalies that require further investigation. Subsequent updates will significantly tighten the constraints on the *cosmological standard model* and further advance our knowledge of the composition of the present and primordial Universe. In addition, Swiss astronomers are involved in theoretical investigations of this early phase of the Universe, in particular at the interface with particle physics.

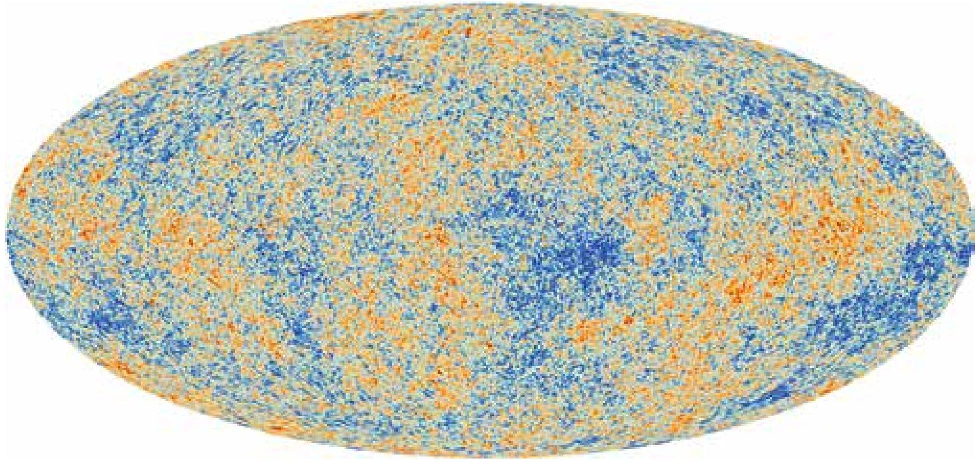

Fig. 8: The anisotropies of the Cosmic Microwave Background as observed by ESA's **Planck** satellite. The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380,000 years old. It shows tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today. Credit: ESA/The Planck Collaboration

4.2 Tests of Gravity and Gravitational Waves

General relativity (GR) was invented in 1915 by Albert Einstein during his years in Bern and Zurich. It contains the concept of *gravitational waves*, ripples in the curvature of space-time that propagate like waves and are produced by events like the merging of two very dense objects (e.g. black holes or neutron stars). These gravitational waves have been discovered for the first time only in 2015 by the American terrestrial detector **LIGO**, consistent with the GR theory. Deviations from GR predictions could be related to dark matter or dark energy.

Switzerland has been involved in the construction of ESA's **LISA-Pathfinder** satellite, launched in 2015, with the aim to test the technical feasibility of the **LISA** mission. The scope of this satellite is to detect and study low-frequency gravitational radiation (at lower frequencies than LIGO), i.e., energy loss of objects via gravitational waves. **LISA** opens new possibilities for astrophysical studies by allowing detecting massive black holes merging at cosmological distances (opposite to LIGO, being only sensitive to stellar mass objects). Its launch (with possible NASA support) should take place in the 2030s or even earlier.

GR also predicts the *deflection of light by gravity*. This effect is utilized by astronomers in the sense that large assemblies of matter can act like a lens for light emitted from more distant sources. Fritz Zwicky pointed out in 1937 that this could allow galaxy clusters to act as *gravitational lenses*. It was not until 1979 that this effect was confirmed by observation and is known today as «strong gravitational lensing». Nowadays, scientists also make the most of «weak lensing», which shows up only across ensembles of sources, changing the shape distribution of a background ensemble of galaxy images in a statistical way.

4.3 Large-Scale Structure Surveys

The *Large-Scale Structure (LSS)* of the Universe refers to the patterns of galaxies and matter on scales much larger than the individual galaxies. These LSS, which can be seen up to billions of light years in length, are created and shaped by gravity. Their study, complementing information on the early Universe provided by the CMB, is crucial to understand the era dominated by the dark energy. These measurements can be obtained from surveys by wide-field imaging and spectroscopy in visible, near-infrared, and radio surveys.

Swiss astrophysicists play a leading role in LSS surveys. They have recently become a full member of the **Dark Energy Survey (DES)** experiment for a period of 5 years on the 4m Blanco Telescope at Cerro Tololo, Chile. **DES** will provide a unique imaging survey of 5000 square degrees in five visible wavebands and is optimized for weak lensing. They are also involved in the **Baryonic Oscillations Spectroscopy Survey (BOSS)** and lead its extension **eBOSS**; *baryon acoustic oscillations* are regular, periodic fluctuations in the density of the visible matter of the Universe. They have also initiated and lead the **COSMOGRAIL** project, to understand the expansion of the Universe: the idea is to follow, over long periods of time, celestial objects called *quasars*, the light of which has been deviated through gravitational lensing. This work is done at the **Euler** Swiss telescope at ESO's La Silla, Chile.

Swiss scientists also work on the development of future wide field survey experiments. The **Dark Energy Spectroscopic Instrument (DESI)** will be a powerful multi-object spectrograph measuring the positions and redshift of tens of millions of galaxies. There is also Swiss involvement in the development of cosmological radio experiments such as **BINGO**, optimized to measure baryon acoustic oscillations. Participation by several Swiss groups in the US-led **Large Synoptic Survey Telescope (LSST)**, to be fully operational in 2022 at the Cerro Pachon site in Chile, will ensure that at least some access to the rich ultimate ground-based data will be possible.

Last but not least, many Swiss institutions are heavily involved in the preparation of ESA's **Euclid** satellite, due to investigate the nature of dark energy and the large-scale distribution of dark matter (following earlier results of the GAIA satellite). They carry leading responsibilities related to theory, observations, simulations, signal processing, data reduction, hardware, and the hosting of one of the Science Data Centers. During the period 2020–2026, it will generate the ultimate space-based data set related to cosmology and extragalactic astrophysics.

4.4 The Square Kilometer Array

Potentially the largest international collaboration in astronomy, the **Square Kilometre Array (SKA)** is a project to build the world largest radio telescope, with eventually a collecting area over a square kilometre, i.e., one million square metres. The SKA will use thousands of dishes and up to a million antennas. The scale of the SKA represents a huge leap forward in engineering and research and development. Both South Africa and Western Australia have been chosen as co-hosting locations, this for many scientific and technical reasons, one of them being the radio waves' quietness of these two very remote locations on Earth.

The SKA aims to solve some of the biggest questions in astronomy. The unprecedented sensitivity of the thousands of individual radio receivers working together will give astronomers insight into the formation and evolution of the first stars and galaxies after the Big Bang. They will also help explain how the first black holes and stars formed, the role of cosmic magnetism, the nature of gravity, the nature of dark energy, and possibly life beyond Earth. The SKA would essentially impact all fields of astrophysics and cosmology.

Amongst Swiss astronomers, there is a significant scientific and technological interest in a strong involvement in the SKA. Currently, Switzerland has an observer status. However, universities along with the State Secretariat for Education, Research and Innovation (SERI) are investigating the possibility of a more concrete participation.

5. Connections to adjacent Research Fields

The classical astronomical tools expanded to observations in the whole spectrum of electromagnetic wavelength shown in Figure 1. This document discusses a further extension towards gravitational wave radiation. The recent neutron star merger event GW170817 started a new era of multi-messenger observations, including gravitational waves, gamma-rays, X-rays, radio, optical and near infrared (with Swiss involvement in modeling, the gravitational wave LIGO collaboration, and gamma observations with the INTEGRAL satellite). The sun and Supernova 1987A have also been observed in neutrinos, and future neutron star merger events with different viewing angles might do so as well. Adjacent research fields like *astroparticle physics* can contribute therefore in additional 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**), and *very high energy gamma-rays* (e.g., **CTA**). A description of those tools can be found in the Swiss Roadmap for Particle Physics and its updates.[4]

6. Conclusions

As already outlined in the abstract, Swiss astronomers are working very successfully at the very forefront of astrophysical research. **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.**

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[4] https://naturwissenschaften.ch/organisations/chipp/meetings_documentation/95387-chipp-road-map-achievements-status-and-outlook-implementation-of-the-road-map-2005-2010

Appendix

A list of astronomical satellites and telescopes, as well as observational surveys and collaborations, (with abbreviations) which appear in the text:
Status: c = completed; o = in operation, p = in preparation/construction
Yellow = ground based infrastructure; blue = instruments and surveys from space

ALMA: The Atacama Large Millimeter Array is a major collaboration between ESO, the United-States and Japan to construct and operate an array of 66 12 m millimeter-wave antenna, scattered over an area of 200 km² of the Chajnantor plateau at 5000 m altitude, in Chile. The project was completed in 2012.	o
AMS: The Alpha Magnetic Spectrometer is a state-of-the-art (astro-)particle physics detector designed to operate as an external module on the International Space Station, searching for antimatter and dark matter while performing precision measurements of the composition and flux of cosmic rays.	o
ATHENA: ESA's Advanced Telescope for High-ENergy Astrophysics will research hot and energetic environments during large-scale structure formation in the Universe and the formation and growth of black holes.	p
BINGO: Baryon acoustic oscillations In Neutral Gas Observations, is a collaboration between research groups from the UK, Switzerland, Brazil, Uruguay, and Saudi Arabia.	p
BOSS: This survey (with the Apache Point 2.5 m telescope) focuses on mapping the Universe on the largest scales, creating the largest volume three-dimensional map of galaxies ever created.	o
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.	p
COBE: The purpose of the COsmic Background Explorer mission (NASA, 1989–1993), the first of three satellites to study the Cosmic Microwave Background (CMB) was to take precise measurements of the diffuse radiation between 1 micrometer and 1 cm over the whole celestial sphere; its results lead to the 2006 Nobel prize in Physics.	c
CoRoT: ESA mission standing for 'COnvection, ROtation and planetary Transits', operating from 2006 to 2013, could probe stellar interiors, studying the acoustic waves that ripple across the surface of stars (asteroseismology).	c

COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses project is aimed at measuring time delays for most known lensed quasars with an accuracy below 3%, in order to determine the Hubble constant H0.	o
CTA: The Cerenkov Telescope Array, an astroparticle experiment to measure the highest energy gamma-rays.	p
DES: Dark Energy Survey – a galaxy survey of the sky over 5000 degrees to probe the Universe.	o
DESI: Dark Energy Spectroscopic Instrument to measure baryonic acoustic oscillations and redshift space distortions.	p
eBOSS: The Extended Baryon Oscillation Spectroscopic Survey (eBOSS) will precisely measure the expansion history of the Universe throughout eighty percent of cosmic history, back to when the Universe was less than three billion years old, and improve constraints on the nature of dark energy.	o
ELT: Extremely Large Telescope. ESO's medium term priority after completion of ALMA is the construction of this 40 m class optical-infrared telescope.	p
ERIS: An Enhanced Resolution Imager and Spectrograph for the VLT.	p
ESPRESSO: A superstable Optical High Resolution Spectrograph for the combined coudé focus of the four units of the VLT.	p
Euclid: An ESA space mission to map the geometry of the dark Universe by investigating the distance-redshift relationship and the cosmic evolution out to redshifts ~2, equivalent to a look-back time of about 10 billion years.	p
Euler Telescope: the Swiss 1.2-metre Leonhard Euler Telescope at the ESO La Silla site was built and is operated by Geneva Observatory.	o
ExoMars: An exo-biology mission to Mars.	o
Gaia: An ESA mission to obtain extremely accurate positions and photometry of approximately 1 billion stars in the Milky Way.	o
HARPS: High Accuracy Radial velocity Planet Searcher – an ultra-high precision spectrometer operating on the ESO 3.6 m telescope.	o
Herschel Space Telescope: An ESA telescope with a mirror of 3.5-metres in diameter, collecting long-wavelength radiation from some of the coldest and most distant objects in the Universe. Herschel is the only space observatory to cover a spectral range from the far infrared to sub-millimetre.	c
HIPPARCOS: ESA scientific satellite, launched in 1989 and operated until 1993. It was the first space experiment devoted to precision astrometry measuring high-precision parallax for over 100 000 stars.	c

HST: Hubble Space Telescope, a NASA-ESA orbiting 2.5 m telescope, in operation since 1990.	o
IceCube: An (astro-)particle detector at the South Pole searching for neutrinos from the most violent astrophysical sources.	o
Integral: ESA's high energy X-ray and gamma-ray observatory.	o
IRAM: Institut de Radioastronomie Millimetrique, a French/Max-Planck/Spanish institute for millimetre radio astronomy and major partner of ALMA.	o
ISO: ESA's Infrared Space Observatory was the world's first true orbiting infrared observatory (1995–2006)	c
JUICE: JUpiter ICy moons Explorer – an ESA space mission to explore Jupiter's icy moons. Launch foreseen for 2022.	p
JWST: James Webb Space Telescope. The 6.5 m successor to the HST (and also to the Spitzer Space Telescope) due to be launched in 2018. The JWST will operate primarily in the 1-28 µm waveband.	p
KEPLER: A NASA Mission to explore the structure and diversity of extrasolar planetary systems. This is achieved by observing a large sample of stars and their variations.	o
LISA: The Laser Interferometer Space Antenna is a future ESA mission, with the interferometer formed by several satellites and the objective to detect low frequency gravitational waves (lower than LIGO and sensitive to the merger of [super]massive black holes).	p
LISA-Pathfinder: ESA technology demonstration mission in preparation of a gravity-wave measurement mission. Launched in 2015.	o
LSST: Large Synoptic Survey Telescope – large aperture, fast, wide field survey telescope to image faint objects across the entire sky.	p
MIRI: Mid-InfraRed Imager. This is an instrument being built for the JWST by a European-US consortium, operating in the 5-28 µm waveband and performing both imaging and spectroscopy.	p
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.	p
MUSE: Multi-Unit Spectroscopic Explorer, a second-generation instrument for the ESO VLT, consisting of a 90,000 channel integral field spectrograph.	o
NGTS: Next Generation Transit Survey. An array of small robotic telescopes installed at Paranal, Chile (ESO).	o
NORSAT-1: Small Norwegian satellite to investigate solar radiation, space weather, and ship traffic. Launched in 2015.	o

NTT: An ESO 3.58 m Richey-Chretien telescope which pioneered the use of active optics.	o
PLATO: PLAnetary Transits and Oscillations of stars – an ESA mission to measure planetary transits and stellar oscillations. Launch foreseen in 2024.	p
PLANCK: ESA space observatory which mapped the anisotropies of the cosmic microwave background (CMB) at microwave and infrared frequencies from 2009 to 2013. With its high sensitivity and better angular resolution the mission substantially improved upon observations made by NASA's COBE and WMAP.	c
Proba-3: ESA mission to demonstrate formation flying in space. Two paired satellites will form a 150 m long solar coronagraph. Launch foreseen in 2018.	p
Rosetta: ESA mission made rendez-vous with a comet and followed it to study its physical properties and evolution on its orbit.	c
SINFONI: Spectrograph for INtegral Field Observations in the Near Infrared attached to the ESO VLT.	o
SKA: Square Kilometer Array – an international project to build the largest radio telescope in the world with a square kilometer of total collecting area.	p
Solar Orbiter: An ESA mission dedicated to solar and heliospheric physics. Launch foreseen in 2018.	p
SPICA: Space Infrared Telescope for Cosmology and Astrophysics. A Japanese satellite to be launched in 2022.	p
Spitzer: A NASA infrared observatory.	o
SPHERE: A second-generation instrument for the ESO VLT, designed to detect large Jupiter-like planets around nearby stars.	o
VLT: Very Large Telescope, the four 8m telescopes operated by ESO at Paranal Observatory.	o
VLTI: Very Large Telescope Interferometer: The four telescopes of the VLT when linked together interferometrically, in order to give exceptionally high resolution on bright sources.	o
WMAP: The Wilkinson Microwave Anisotropy Probe (NASA, 2001–2009) greatly improved knowledge about the CMB beyond what the COBE mission learned, permitting observations with a factor of 20 higher resolution.	c
XMM Newton: ESA's X-ray Multi-Mirror Mission launched in 1999, carries 3 high throughput X-ray telescopes with an unprecedented effective area. The large collecting area and ability to make long uninterrupted exposures provide highly sensitive observations.	o

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