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Astronomy Community Roadmap 2024

Update of Swiss Community Needs for Research Infrastructures 2029–2032 and beyond

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The Very Large Telescope snaps a stellar nursery and celebrates fifteen years of operations. Source: ESO

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Content

1 Executive summary

The questions to be addressed in astronomy and astrophysics are complex and often require years of coordinated research with our national and international partners, combining information from a network of observing facilities (telescopes and spacecrafts), each contributing with special pieces of the puzzle. A parallel development of associated theory and simulations is needed to understand the data from new observations, and to guide the design of future facilities.

Switzerland hosts high-profile research teams in many areas of research in astronomy. To optimise their efficiency and take research to the next level, networks of activities have been built to consolidate our efforts across the country. These collaborations at national level secure our leadership at international level and will ensure a maximum return from the Swiss investment in international organisations.

A Roadmap for Astronomy in Switzerland aims at providing a framework in which Swiss astronomy could optimally develop by pointing out the strength of the system and providing detailed recommendations for further improving its coherence and impact. Many of the successes achieved in the past two decades are directly or indirectly related to the recommendations issued at the time in previous roadmap exercises. The present Roadmap is an update of the previous detailed one, which appeared in 2022, with an emphasis on the needs for research infrastructures for the period 2029–2032 and beyond.

Modern space- and ground-based astronomy, with its major research infrastructures and/or platforms being planned and built within international collaborations, continues to evolve over time. Boundary conditions change and the academic and/or industrial landscape in which scientific and hardware projects are carried out have to adapt. Over the past years, changes have been significant and the field of astronomy and its related ambitious infrastructure are furthermore developing continuously and at a fast pace asking for a regular reassessment of the priorities.

This assessment aims first at supporting political decisions for the period 2029–2032. However, because of the typical decade-long timescale of the development of large projects in astronomy, it actually gives an overview of the field which goes well beyond the 2029–2032 time frame. The exercise led to a number of key findings, some in continuation of important points outlined in previous roadmaps. They capture important aspects of Swiss astronomy today. Each finding is followed by a recommendation. Together, these recommendations aim at continuously building the framework in which research in astronomy is developing in the 2020s and 2030s, in order to continue the outstanding record of Swiss astronomy in a highly competitive international context.

Artistic representation of the huge and slow impact on Pluto that led to the heart-shaped structure on its surface.
Source: University of Bern/Thibaut Roger

2 Foreword

This document is an update to the Astronomy Community Roadmap published in March 2022. It presents the needs of the Swiss astronomy and astrophysics community in terms of future national and international research infrastructures. Together with similar Community Roadmaps in other disciplines, it is an element of the four-year process leading to the development of the Swiss Roadmap for Research Infrastructures 2027 to be written by the State Secretariat for Education, Research and Innovation (SERI) in view of the ERI Dispatch 2029–2032 to Federal Council. The role for these 'bottom-up' inputs is to serve as an important basis for the strategic planning of the higher education institutions on new or major upgrades to national infrastructures and to inform and support SERI during its decision-making process on Swiss participation in international research infrastructure networks and organisations.

SERI has formally mandated the Swiss Academy of Sciences (SCNAT) to update the seven community roadmaps previously published in the disciplines of biology, chemistry, geosciences, astronomy, particle physics, photon science, and neutron science. SCNAT engaged its network of member societies and commissions to reach out to the scientists willing to get involved. It encouraged diversity of the participating scientists and provided the needed support for the collaborative writing, the layout, the publication and printing of this document.

Just like the Sun, ESO's Extremely Large Telescope (ELT) is rising in Cerro Armazones, Chile. The steel dome of the giant telescope is taking shape in front of the orange disk of the Sun with its sunspots. Source: Häussler/ESO

3 Introduction

This document is not meant to be complete by itself. It is to be understood as a complementary and rather short update of the thorough Astronomy Roadmap published in March 2022. It focuses on the recent evolution of the Swiss astronomy landscape (Chapter 5) and gives an update on the Vision and future needs (Chapter 7). Both parts are divided into four themes, which are the same as in the Astronomy Roadmap 2022:

1. Fundamental physics;

2. Origins – stars, galaxies and the evolving universe;

3. Planets and the search for extra-terrestrial life;

4. Our home and its space environment.

The part on the Swiss astronomy landscape also includes a section on Computer infrastructure and other common issues. Two other chapters are dedicated to the International context and large scale infrastructures, and to the Funding strategy.

The inputs to the different themes have been coordinated and provided by the respective sub-communities. The editorial board was formed by the leader of each theme and worked together on the harmonisation of the text and the elaboration of the other parts of this document.

A close-to-final version was reviewed by the members of the Swiss Commission for Astronomy (SCFA), which is essentially composed of the directors of the various Swiss astronomical institutes and thus represent the interests of all Swiss professional astronomers.

Concerning space missions and instrumentation, additional information can be found in the complementary Space Research Community Roadmap 2024.

For the sake of clarity and completness, the findings and recommendations of the previous Astronomy Roadmap of 2022 are included, if they were considered to be still pertinent.

Laser ranging at the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (SwissOGS) contributing significantly to the next generation terrestrial reference frames, the very long wavelength part of the Earth's gravity field, and to a safe and sustainable use of the near-Earth space. Source: Emiliano Cordelli (AIUB)

4 Findings and recommendations

A diversity of projects in an international context

Astronomy covers a broad area of natural sciences. While the understanding of the formation and evolution of the Universe as a whole (including galaxies, stars, planets) represents the classical core science of the field, modern astronomy also includes aspects of fundamental and particle physics, computer science, chemistry, geophysics, and even biology. Its diverse multidisciplinary nature distinguishes it from other sciences in which large investments in infrastructure are also necessary. Over the years, in order to avoid duplication of efforts, Swiss astronomy research groups have specialised, paving a very diverse landscape.

Most findings and recommendations reported in the last Roadmap of 2022 are still valid. In the following we report them again for completeness: some have been updated and few new findings and recommendations which emerged in the meantime have been added.

Finding 1: The breadth of Swiss astronomy is impressive and has grown very significantly over the past 20 years. The diversity in scientific interests calls for diversity in capabilities, realised through space- and ground-based telescopes and instrumentation, as well as in theoretical and computational developments including specialised analysis tools needed to deal with very large datasets. This diversity is also an important asset within the framework of international agencies, which set priorities for major projects. Defining a single national priority is impossible without excluding a large fraction of the astronomy community and disregarding past investments.

Astronomical research in Switzerland is still poorly performing in diversity measures of personnel (e.g. gender bias), especially at faculty level compared to actions in the international community. Diversity of thought and perspective fosters innovation and productivity.

Recommendation 1: The diversity of astronomical research in Switzerland should be preserved through the concurrent support for participation in multiple large projects having different science goals, and with significant Swiss participation. Moreover, the diversity of thought and perspective should be fostered especially at faculty level.

Finding 2: As projects worldwide grow in size and complexity, significant Swiss participation in those most essential developments is increasingly straining available funding, requiring some clear prioritisation guidelines, consistent throughout the various types of projects.

Recommendation 2: While scientific relevance and excellence must be the ultimate criteria, projects of equal merit should be preferred if one or several of the following holds:
- They establish or strengthen the scientific leadership of Switzerland in an area
- They address the needs of a broad community
- They are being carried out within the framework of international organisations Switzerland is participating in as of today (ESA, ESO and SKAO).

4.1 Ground-based instrumentation

The availability of the VLT, ALMA, and in the near future the European ELT and SKAO, provides Swiss astronomers with access to the worlds' most powerful telescopes and state-of-the-art instruments covering a broad range of wavelengths. While the ESO/ELT and SKAO will be used to address some of the most pressing scientific questions in astronomy, the ESO/VLT and its suite of instruments, as well as ALMA, will remain the workhorse facilities for most astronomers. ESO is also planning to issue a call for a new telescope facility end of 2026, and it is important that Switzerland participate in this future project. All of these imply continued investment in new technologies and instrumentation building, as well as maintaining the existing infrastructure.

Finding 3: The long-term nature of astrophysics research requires stability of the funding over extended periods of time. In particular, it is important to better ensure a coherent and sustained participation in the highest-priority projects. In the context of international collaborative developments, the astronomy community has to define flagship, well-argued projects identified as a higher priority by the community. Access to ESO facilities (VLT, ALMA, ELT, as well as any new future ESO telescope) and to the SKA Observatory provides Swiss astronomers with access to the worlds' most powerful telescopes and state-of-the-art instruments covering a very broad range of wavelengths.

Recommendation 3: In terms of high-level prioritisation, the main organisations for the Swiss astronomy community are ESO with its instrumentation and SKAO for the next decade(s).
The VLT and ALMA will remain world-leading observatories in the ELT era and top priorities for Swiss astronomers. Within ESO, Switzerland should continue to provide strong support for current and future instrumentation, in particular on the ELT. As a new member of the SKAO, Switzerland should consolidate its participation in particular to be ready for data analysis, through participation in the European SKAO Regional Center, and its precursors.

Finding 4: The participation of research teams in instrument building consortia within large international collaborations offers a unique opportunity to develop new Swiss technologies and maximise the science return on investment for Switzerland. It provides significant additional observing time on highly competitive instruments through Guaranteed Time Observing (GTO), enabling much more impactful research, and promotes the further development of cutting-edge technological capabilities in the country. The latter is particularly critical if Switzerland is to remain a major player in the development of future facilities/instruments of increasing complexity.

Recommendation 4: Participation in the development of instruments/facilities should be seen as a means of increasing the return on investment for Switzerland's participation in large international collaborations, both in terms of scientific return, innovative technology development and capacity building. Adequate funding must therefore be secured to enable such participation. In particular, FLARE funding must be increased and adapted to take account of the increasing complexity of the future generation of instruments and the long-term nature of the astrophysics projects.

Finding 5: The Swiss astronomy and astroparticle physics communities, represented by CHAPS and CHIPP, consider, at present, the future Einstein Telescope (ET) as the most scientifically attractive ground based project for a new future large facility, complementary to the LISA space mission. Following the recommendations from the 2021/2022 Roadmaps for Research Infrastructures, CHAPS and CHIPP have advanced towards a common strategy for participation in ET. A federated participation by Switzerland in this future large project, guaranteeing access to all researchers working at Swiss institutions, is of strategic importance. In order to fully leverage this large-scale Swiss participation, it is important to also position ourselves in leading roles within ET in both instrument development and scientific exploration. To achieve this goal, it is essential to establish experience in the current generation of gravitational-wave observatories such as LIGO, Virgo, and KAGRA. It is imperative that the cost of establishing this new research programme be covered through newly available funding and not at the expense of active participation in large research infrastructures with an existing Swiss commitment (such as ESO, SKAO, or ESA).

Recommendation 5: The CHIPP and CHAPS communities recognise Einstein Telescope (ET) as a project of significant mutual interest. In order to take a leading role in instrumentation, the communities should actively participate in LIGO/Virgo/KAGRA technical activities, in preparation for similar efforts for ET. We further endorse the continued, direct, and fruitful collaboration between CHIPP and CHAPS leveraging common interests and tuning our strategy towards strong participation in ground based gravitational-wave observatories, in particular the ET.

Finding 6: Some areas of astrophysical research can be best addressed through the participation in medium/large-size projects taking place outside the framework of the international organisations Switzerland is participating in (ESO and SKAO). To maintain leadership in these areas in Switzerland, it is important that Swiss researchers can access such projects. The recent ASTRONET Science Vision and Infrastructure Roadmap 2022–2035 has listed some of these projects. Namely, the European Solar Telescope (EST) and the wide-field, high multiplex spectroscopic facilities (such as MUST, Spec-S5 and WST). The EST fills a critical gap in the scope of European astronomical facilities for studying the Sun. The wide-field spectroscopic facilities are key for cosmological measurements as well as for transients studies such as the detection of gravitational waves electromagnetic counterparts. A further key experiment is the HIRAX radio interferometric experiment under construction in South Africa which provide a map of the neutral hydrogen of universe for cosmology. Another important facility being developed with a worldwide footprint is the next generation Event Horizon Telescope (ngEHT), and Switzerland could host one of the 15m-size millimeter antenna in the Alps which would be used in the ngEHT worldwide network but could also be used as part as a pan-European interferometric array.

Recommendation 6: Financial support should be made available for medium/large-size projects carried out beyond the ESO and SKAO boundaries. This support should be flexible in both its purpose and its use with the goal of extending access to medium/large research infrastructures to areas outside the main focus of ESO and SKAO. Within this framework, participation of Switzerland in EST should be secured. Participation in a high multiplex spectroscopic facility (such as MUST or the future Spec-S5), in the HIRAX interferometric radio array, and in the future ngEHT global millimeter interferometric array should be considered in due time.

Finding 7: Funding of scientific exploitation of data acquired following a substantial Swiss infrastructure investment remains variable and low compared to other countries. This is limiting Swiss scientific stature and Swiss visibility worldwide. A better coherence between significant investments in infrastructures and the related science return for the community is highly desired. Scientists involved in both ground-based work and space-borne activities have identified that improvements in coordination are necessary.

Recommendation 7: The astronomical community asks for better coordination at national level between investments in hardware developments and the support for the scientific exploitation of the developed experiments. A dedicated initiative (possibly through an augmented SNSF-FLARE budget) needs to be put in place for the exploitation of multiwavelength data coming from the astronomical observatories with Swiss hardware participation.

4.2 Space-based activities

Participation in the ESA Science Programme allows Swiss astronomers to get a privileged access to data produced by revolutionary capabilities in space, to gain a better understanding of how to best exploit them, providing a strong competitive advantage, and to develop know-how in space-related instrumentation by participating in the development of payload elements. This has been made possible by the PRODEX programme and/or the Ordinance on the Promotion of National Activities in the Space Sector (NASO). Moreover, PRODEX funding, by requiring a substantial (50% or more) industrial participation in projects, naturally creates close ties between academia and industry and promotes technology transfer.

The participation of the astronomical community in space science activities in Switzerland is covered by the dedicated Space Research Community Roadmap 2024 by the Committee on Space Research (CSR). We are reporting here the main findings and recommendations addressing specific aspects of the research in astrophysics.

Finding 8: Compared to the major space-faring nations, Switzerland is a small country. However, in the domain of space science, it achieves a much higher visibility and recognition than expected from its sheer size. It does so through its membership of the ESA and through carefully considered bilateral collaborations that provide high visibility. The recent activities of Swiss scientists in proposing and building (with the help of industry) space experiments have been very successful, with Switzerland being involved in almost all the major missions of the ESA programme, including the Swiss leadership of the CHEOPS mission, or the significant participation in future missions like ARRAKIHS and PLATO. Such development efforts are now, however, often funding limited and an efficient handling of the available resources is required to guarantee a high-level of return on investment.

Recommendation 8: The astronomy community recognises ESA as the 'Swiss Space Agency' and as such the main instrument to be supported to implement science projects in space. The astronomy community advocates that maintaining Swiss leadership in space sciences and technology requires an appropriate level in PRODEX funding over the next period.

4.3 Data science and high-performance computing

Finding 9: Numerical simulations have increasingly become a crucial component of research in astronomy. Switzerland is at the forefront of the development and maintenance of state-of-the-art computer programmes utilised by the international community across all fields of astrophysics and cosmology. Some of these codes exploit, and even foster, the latest technology in high-performance parallel computing being deployed on some of the fastest supercomputers in the world at the Swiss National Supercomputing Center (CSCS). This numerical laboratory is a necessary counterpart to ground-based and space-borne observational facilities.

Recommendation 9: Switzerland should further strengthen the national supercomputing infrastructure, as well as combine that with the creation of local facilities dedicated to support the science of large observational projects in astronomy and neighbouring fields. This investment also has to contemplate investing in the human infrastructure necessary for code development and maintenance, to catch up with other more developed numerical simulation communities in natural sciences.

Finding 10: As a result of the advent of new instruments and facilities, the amount of data to be processed in astrophysical analysis is continuously increasing, together with the high precision required with these new instruments. This requires both increased high-performance computing (HPC) resources and the development of fast advanced algorithms.

Recommendation 10: To enable science with the large data sets generated with current and next generation instruments, Switzerland should support the increased access to large high-performance computing facilities and the development of advanced fast algorithms tailored and motivated by the data analysis for these projects.

Finding 11: Data management and data preservation activities have become an essential component of modern astrophysics. Enormous expertise has been acquired in Switzerland, allowing the Swiss astrophysics community to play leading roles in several space missions (e.g. INTEGRAL, Gaia, CHEOPS) and fostering significant scientific return in Switzerland. Currently, no funding is identified for the continuation of these activities, putting in danger the preservation of this expertise and the possibility to lead or contribute to future science missions of wide scientific interest.

Recommendation 11: Discussions should take place between the astrophysics community and the SERI, in order to investigate which funding mechanism could be used to maintain the resources needed for the preservation of the data of missions of particular Swiss interest, as well as the leadership and visibility of Switzerland in this thematic, in particular for space missions.

4.4 Additional findings and recommendations

Finally, additional findings and recommendations are provided in relation with the science funding scheme in Switzerland and its importance for astrophysics.

Recommendation 12: In Switzerland, the funding for large projects is decoupled from the funding supporting their scientific exploitation (data analysis, theoretical modelling, or computational investigations). The funding for this exploitation comes in a large part through competitive project grants from SNSF. Consequently, SNSF plays a central role in adding scientific value to the investments made in large projects and infrastructures. The SNSF funding should leverage prior Swiss Investments with the highest priority and at the appropriate level.

Finding 12: In a research landscape shaped in part by large-scale projects, the availability of a permanent and highly skilled staff is essential. In Switzerland, only Universities, ETHs, and Universities of Applied Sciences can ensure a flexible availability of such qualified personnel.

Finding 13: For Swiss researchers, full access to European framework programmes is necessary to remain embedded in the European astronomical research community. Furthermore, the ability to attract and eventually lead European projects has become a benchmark by which quality and competitiveness of research in a country is evaluated.

Recommendation 13: Switzerland has to provide long-term funding commitment and financial sustainability to allow research groups and institutes to present themselves as reliable partners, or even claim leadership, in high-visibility/large-size projects. Moreover, there should be a coherent and continued funding between FLARE/PRODEX, on one side, and SNSF, on the other side, aimed at the transition between project construction and operational phase.

Recommendation 14: PRODEX and FLARE funding should foresee some mechanism that could help covering unforeseen expenses like varying EUR-CHF conversion. This could be in the form of overheads payment, which would also ease the management of the scientific operation activities of FLARE projects and their integration within Swiss Universities.

Recommendation 15: Concerning ground-based astronomy, FLARE must continue focusing on its 'core' infrastructures (ESO for Astrophysics), as long as other infrastructures like SKAO are being directly funded by SERI through other mechanisms. To enable support for other projects the FLARE budget must be increased accordingly. Indeed, the community strongly supports the idea of securing a 'fair share' within the FLARE budget for new and innovative projects within infrastructures not belonging to ESO or CERN but strategic for Switzerland. The issue of long-term commitments and funding of large projects, still needs to be better addressed.

5 The Swiss astronomy landscape

An update since the Roadmap 2022

Over the past years, the astrophysics landscape has changed significantly and rapidly, both at national and international levels. The transformation can be observed in academia, as well as in the development of new research areas coupled with ambitious infrastructure developments. Switzerland, through its astronomical community, is an active player in this evolving landscape. Already since the appearance of the last Astronomy Roadmap in 2022 there have been several changes which are summarised below.
As now customary in the Astronomy Roadmaps we divide the activities into four main themes. This way it will be easier to compare with the previous Roadmaps. Clearly, for some themes the boundaries are not so sharply defined and thus in some cases we had to choose to discuss some topics in one theme rather than in another. Nonetheless some overlaps might be unavoidable.

5.1 Theme 1: Fundamental physics

5.1.1 Gravitational waves

The Swiss community has been significantly advancing its activities in the field of gravitational waves, demonstrating a robust commitment to both theoretical and experimental aspects. Recent academic appointments include the hiring of Prof. M. Soares-Santos, who started January 2024 at the University of Zurich (UZH), on the domain of gravitational-wave and multi-messenger astronomy and in 2025 Prof. M. Vallisneri will join ETH Zurich (ETHZ) and establish a new group on gravitational waves, in particular for the data analysis for LISA. At UNIGE, both Profs. Fragkos and Schramm are working on different aspects of gravitational waves, in particular towards the Einstein Telescope (ET). Switzerland continues to hold a prominent position in the development and leadership of the ET project, particularly in science and computing domains (see also section on computer infrastructure). Furthermore, there are ongoing discussions regarding Swiss participation in the Virgo collaboration, led by Prof. Fragkos and Prof. Schramm. Key contributions include advancements in computing architecture for future ground-based observatories and the development of critical data acquisition infrastructure for both Virgo and ET, in collaboration with partners in Annecy. Participation in the Virgo project is viewed as a strategic step for Switzerland to build expertise in preparation for further involvement in the ET initiative.

In terms of research initiatives, the Sinergia project GW-Learn, which began in September 2023, is a notable interdisciplinary effort, where a team of researchers from the UNIGE, UZH and ETHZ is applying modern machine learning techniques to boost the predictive power of various layers of the modelling required to analyse and interpret the content of data from current and future gravitational wave experiments. In addition to GW-Learn, SNSF has funded several other projects related to gravitational waves. At UNIGE, in 2022, the inter-departmental Gravitational-Wave Science Center (GWSC) was founded by the Faculty of Sciences, with the aim of consolidating the existing GW-related activities within UNIGE, stimulating new, interdisciplinary research in the domain, and federating the efforts for a Swiss involvement to future gravitational-wave observatories, such as ET. A notable outcome of GWSC is the publicly available POSYDON simulation tool, which is the most advanced code for modelling the binary star progenitors of gravitational wave sources. In parallel, at the Department of Theoretical Physics of UNIGE, the groups of Prof. M. Maggiore has a leading role in forecasting the science that can be made with the ET, and how this is affected by different designs of the experiments, an activity that can have a significant impact on important choices on the design of ET, to be finalised in the next few years, while prof. A. Riotto is performing leading research in the field of primordial black holes. At UZH, the group of Prof. P. Jetzer continues its activities within the LISA consortium and the LIGO Scientific Collaboration, as the only Swiss group at present, and worked in particular on gravitational wave modelling, including effects like eccentricity. Newly appointed Prof. Ita studies the GW signal from the encounters between black holes on parabolic/hyperbolic orbits. The group of Prof. L. Mayer at UZH has engaged actively in research on the new emerging topic of environmental perturbations on gravitational wave signals. This requires computer intensive simulations to predict the perturbation of the GW signal induced by the presence of gas disks and other possible material structures around the supermassive black holes to be detected by LISA.

5.1.2 Cosmology

Swiss researchers have continued to pursue their leading role in cosmology, the study of the universe as a whole. In this field, observations using wide-field instruments (both in imaging and spectroscopy) are combined with numerical and theoretical predictions to infer high-precision knowledge about the nature and content of our universe, including Dark Matter, Dark Energy, the early universe and gravity. Since 2022, Swiss researchers have continued their work on optical imaging Stage-III experiments such as the Dark Energy Survey (DES). This has led to precise constraints on cosmological parameters and the confirmation of tensions between different cosmological probes which may point to new physics beyond the standard cosmological model. Swiss researchers also continued their important involvement in the optical Stage-IV experiments such as DESI, 4MOST, Euclid and Rubin/LSST. In particular, in April 2024, the DESI experiment reported their first results from the most precise measurement of our expanding universe, tentatively showing departure from the Lambda-CDM model. The successful launch of the Euclid space mission (July 2023) and its successful commissioning was followed by the release of early scientific results. The preparations for Rubin/LSST is still ongoing with First Light expected in 2025. The 4MOST instrument is now starting to be shipped to Chile, and the Cosmology Redshift Survey target selection is being finalised. The 4MOST survey is expected to start in Fall 2025 and will complement the DESI data to the Southern hemisphere. The Swiss cosmology community is also active in the preparation of the Stage-V spectroscopic surveys, and joined the MUST collaboration as a founding member in July 2024. MUST is the first approved Stage-V spectroscopic project. Other Stage-V projects are also being prepared such as the LBNL-led ‘Spec-S5’ which will turn the Blanco and Mayall telescopes into powerful 6 m spectroscopic telescopes. On the European side, the 12 m Widefield Spectroscopic Telescope (WST) will enter in a three-year design phase early 2025 funded by a Horizon-Europe infrastructure grant. Swiss researchers are leading the science working groups for Cosmology and Transients science (that includes gravitational wave spectroscopic follow-up). For these three projects, they will actively participate in the design of the fibre positioner systems.

Swiss researchers have also been actively involved in the preparation and analysis of radio interferometric experiments. These emerging and most promising instruments are opening a new window on the Universe, bridging the gap between the Cosmic Microwave Background observations and wide-field optical surveys. In 2022, Switzerland has joined the Square Kilometer Array (SKAO) and formed the SKACH consortium which coordinates the Swiss contribution to this observatory. SKAO will start delivering preliminary scientific data in 2026, and will achieve the full assembly of its LOW and MID telescopes by 2030. Switzerland is also involved in different SKAO precursor and pathfinder experiments. In particular, Swiss researchers have played a leading role in the construction of the HIRAX telescope being built in South Africa and which will map the universe via its neutral hydrogen content. Swiss researchers are also actively working on the MeerKAT telescope through collaboration with South-African scientists. Finally, in 2023, Switzerland has joined the MWA collaboration a low-frequency telescope array in Western Australia that is targeting the detection of Hydrogen at the Epoch of Reionisation as well as conducting a full map of galaxies in the Southern Sky.

5.2 Theme 2: Origins – stars, galaxies and the evolving Universe

5.2.1 Stellar astrophysics

Arguably the main project worldwide in stellar astrophysics is ESA’s Gaia astrometric and photometric mission. Gaia is one of the most productive astrophysics mission ever, and stellar astrophysics and galactic dynamics have continued to benefit from the extraordinary data from the Gaia survey. Switzerland is involved in the mission at a high level, being in charge of variability studies. Thanks to the work of the Gaia CU7 group at UNIGE, the Gaia Data Release 3, issued in 2022, provides the detailed variability properties and the classification of more than 10 million objects.

The Sun is a reference star for studying stellar interiors, atmospheres, evolution and magnetism. Also, understanding solar and stellar magnetic activity is important for improving the detection sensitivity of small rocky planets hosted by cool stars. The HARPS and ESPRESSO spectrographs along with the space telescopes Kepler and TESS have provided a wealth of stellar variability data needed for comprehensive understanding fundamentals of stars.

At UNIGE, such data support studying stellar and solar interior structures, evolution of stellar fundamental parameters and chemical composition, using approaches of helio- and asteroseismology and the world-leading stellar evolution codes.

At IRSOL (Prof. S. Berdyugina), such data are employed for studying magnetic activity of stars of various ages and masses, e.g. young and main-sequence dwarfs, subgiants and giants, brown and white dwarfs, etc. Models of spectra, polarisation and flux variations are tested on solar data and employed to infer stellar magnetic fields, their distribution on stellar surfaces and long-term evolution. The outcomes are then evaluated for detection and characterisation of exoplanets. To support observational studies, 3D MHD simulations of different stellar atmospheres are carried out at IRSOL.

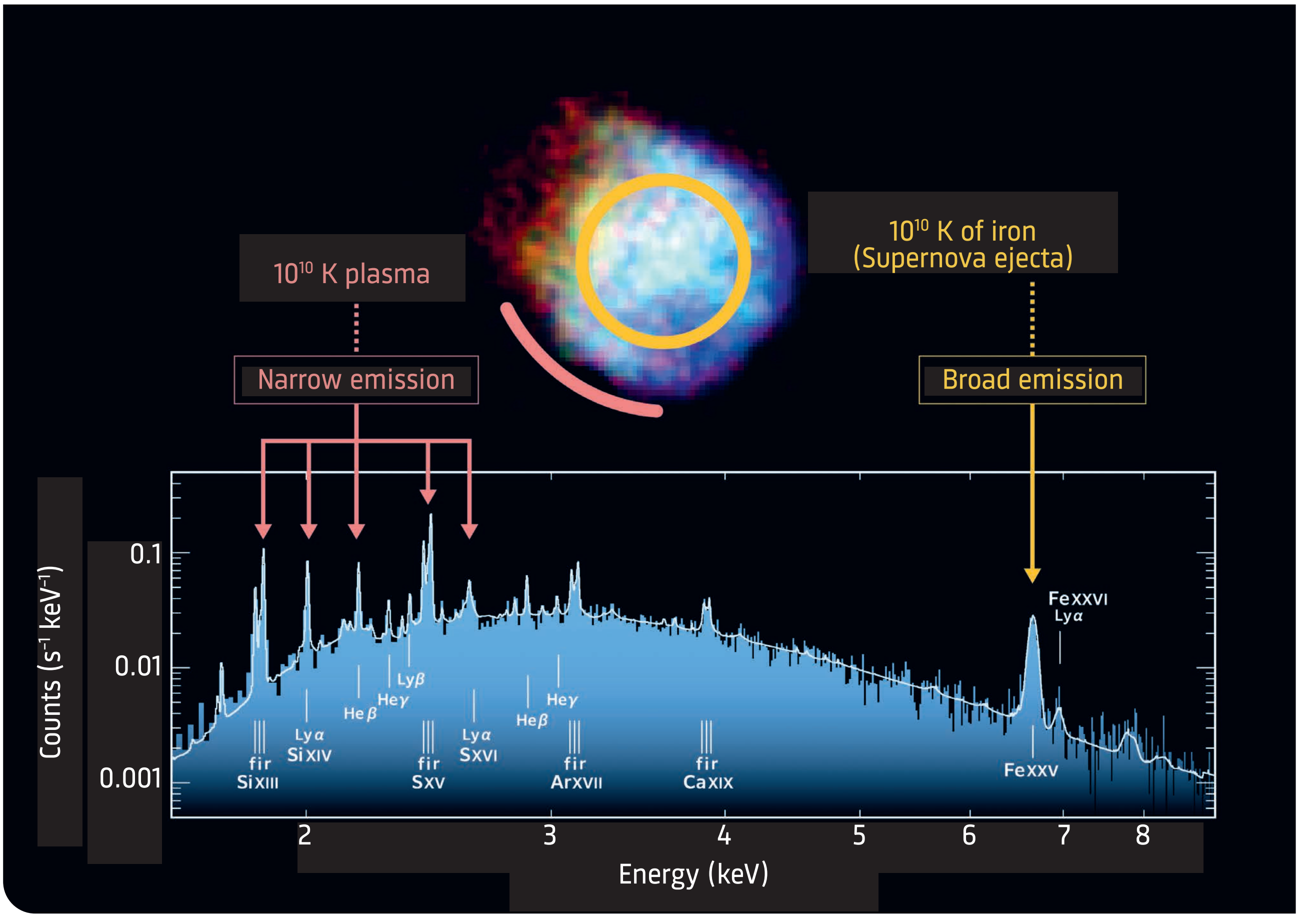


Figure 1: X-ray image and spectrum of the supernova remnant N132D from XRISM's First Light observations. The image was captured by XRISM's Xtend instrument, while the high-resolution spectrum was obtained using the Resolve spectrometer. The unprecedented spectral resolution allows to distinguish two distinct emission regions differing in temperature by a factor thousand. Source: JAXA

5.2.2 Extragalactic astrophysics

Optical and near-infrared domain

Swiss researchers have pursued their leading work in extragalactic astrophysics. This includes the study of the formation of structures in the universe, the formation and evolution of galaxies and their supermassive black-holes, the intergalactic medium, as well as exploration of the Cosmic Dawn and the epoch of reionisation (EOR). Swiss researchers, in particular at UNIGE and EPFL, have been very prominent in the analysis of data from the NASA/ESA James Webb space telescope, which has opened the window of the high-redshift universe (with measurements of spectroscopic redshifts larger than 10) and already provided new and unexpected insights on the first galaxies and black holes, the sources responsible of the reionisation of the Universe, and on other topics.

ETHZ participated in the analysis of stage III wide field instruments for cosmology such as DES, which provides precise measurements on the evolution of structure formation, galaxy bias and the dark matter halo-galaxy connection. Switzerland has also been involved in the analysis of stage-IV wide field imaging and spectroscopic surveys. In DESI, scientists have been modelling the connection between Galaxies and their Dark-Matter halos. In Euclid, the first scientific results showed great prospects for the study of the evolution of galaxies over large cosmological volumes, as well as using clusters of galaxy as cosmic telescopes.

Research using ESO instrumentation has been very active. In particular, the MUSE integral field spectrograph has been used by teams at UNIGE and EPFL to trace ionizing radiation at high redshifts. Teams at UNIGE also made use of the ALMA millimetre array to study dusty galaxies at large redshifts.

Radio-interferometry domain

Swiss scientists have been actively involved in the preparation and analysis of radio interferometric experiments (MeerKAT, MWA, HIRAX, and in the near future SKAO), which offer a unique probe of the EOR, Cosmic Dawn, non-thermal effects in cluster of galaxies, as well as the study of distant galaxies and active galactic nuclei. This effort has been strengthened with Switzerland joining as the 8th member country the Square Kilometer Array Observatory (SKAO). Switzerland is also involved in different SKAO precursor and pathfinder experiments. In particular, Swiss researchers at ETHZ, EPFL and UNIGE have played a leading role in the construction of the HIRAX telescope. In 2023 several Swiss researchers at EPFL, UNIGE, UZH, FNHW, ZHAW and UNIBAS have officially joined the MWA Consortium, and EPFL has hosted the first MWA collaboration meeting in Switzerland in August 2024. Every year since 2016, the Swiss SKA days gather international and Swiss scientists for 2–3 days to discuss scientific results of SKAO precursors and the preparation of SKAO. The SNSF Sinergia grant Astrosignals has enabled the development of interdisciplinary research between astrophysicists and computer scientists allowing for example to develop effective tool to identify an characterise sources in the radio images.

High-energy domain

The study of high-energy sources, such as compact objects and galaxy clusters, is also an important topic at UNIGE, making use in particular of ESA's XMM-Newton and INTEGRAL missions. In 2023, the Japanese X-ray astronomy XRISM was launched. It embarks a revolutionary X-ray micro-calorimeter instrument, which will provide numerous breakthroughs in the study of accreting black holes and galaxy clusters in particular. Thanks to a direct participation in the mission of Switzerland through the leadership of UNIGE, several Swiss scientists enjoy privileged access to the early science phase data. The first science paper on the brightest extragalactic accreting black hole has just been published.

The Universe is studied through radiation emitted over about twenty decades of photon energy. The ten decades above the electron rest mass are known as the gamma-ray domain where satellites and Cherenkov telescopes, in particular the CTAO, are used by Swiss scientists to study details of particle acceleration in galactic sources and in relativistic jets, likely the most energetic and extreme structures of the Universe.

5.3 Theme 3: Planets and the search for extra-terrestrial life

Since the last thematic Roadmap in 2022, the Swiss scientific community in the field of Solar System and extrasolar planet research has continued to play an internationally leading role, reflected by multiple involvements in large infrastructure projects. Despite the relatively brief time span since the last report, significant new developments have occurred on the instrumental and structural levels, underlying the field's large size and importance in Switzerland, its intense dynamics and fast progress. Thanks to the internal coherence made possible by overarching Swiss structures, collaborations have been further intensified between different subfields like solar system-related planetary sciences, astronomical observations of extrasolar planets, observations of protoplanetary disks as the planets' birth environments, theory, instrument development, laboratory research, as well as adjacent fields like geophysics and – especially in the context of the search for extraterrestrial life – astrobiology, climate research, and Earth sciences.

In 2021, ETHZ established the Centre for Origin and Prevalence of Life (COPL). It is an innovative collaboration between different departments of ETHZ to address some of humanity's most profound questions of life in the universe. At its origin lies the conviction that to address it we need to deal with its interdisciplinary challenges and to create functional bridges between astrophysics, planetology, organic chemistry, biology, and cognate disciplines. The Centre's legacy ambition is to cultivate a new generation of scientists at ease with interdisciplinary research, reshaping planetary science and the study of life in the universe for the long term. Life is a global planetary event. Understanding how chemical and physical contexts produce the molecular building blocks of life and lead to biological diversity is complex. The diversity of planetary environments and the potential for life to alter them adds to this challenge, requiring insights from chemistry, geology, biology, and astrophysics to fully grasp the complexity. Researchers at ETHZ are keen to establish a deeper understanding of life's emergence and distribution through innovative collaboration. The core research programme is organized around four main questions: 1) what chemical and physical processes generate the molecular building blocks for life and drive the transition to biological entities? 2) what are the characteristics of planetary environments? 3) how do planetary environments maintain conditions for complex life, and how does life modify these environments? 4) what about non-standard life and life in extreme environments? The Centre will support these activities by providing research funding and fellowships to attract high-profile independent researchers and PhD students.

To celebrate the 2019 Nobel Prize in Physics, the UNIGE established the Centre pour la Vie dans l'Univers (CVU) in 2021. This stemmed from the fact that the discovery of numerous exoplanets, the exploration of the solar system, and a deeper understanding of life's organic structure are opening new research avenues regarding the origin of life. Recent progress now allows to approach the question of life's appearance in a more realistic and practicable manner. At the intersection of astronomy, chemistry, physics, biology, and Earth and climate sciences, the CVU transcends disciplinary boundaries to understand life's origins and distribution in the universe by conducting highly interdisciplinary research projects. The core research program has three main objectives: first, to conduct cutting-edge interdisciplinary research on the origin of life and the search for life in our solar system and exoplanetary systems (about 10 projects are currently ongoing). Second, to develop a fellowship program to attract leading post-doctoral researchers. Third, to underline the role of UNIGE on a national level, in collaboration with the future Swiss Institute for Planetary Science, and internationally on the theme of life in the universe.

With the establishement of CVU and COPL, together with the Center of Space and Habitablity (CSH) at the University of Bern, which was established in 2011, there are now three centers with related objectives in the Swiss landscape, reflecting the leading role of the country in (exo) planetary research. While the specific focus of the three centers differs reflecting the local background, various interaction mechanisms are being implemented among them both in the scientific and educational domain.

5.3.1 Exoplanets

In exoplanet research, two focal points can be identified in the past period: on one hand, the continued extension of the understanding of the demographics of extrasolar planetary systems where the count of known extrasolar planets already exceeds 6000 at the time of writing this document. On the other hand, the characterisation of a smaller number of exoplanets in terms of their internal and atmospheric properties and composition as golden targets for exoplanetology with the prospect of the search for extrasolar life. These developments are driven by several new observational facilities both on the ground and in space in which Swiss institutes play key roles.

Our knowledge of the demographics and diversity of planetary systems and hence of the uniqueness of our Solar System relies on recent or near-future observational facilities. On the ground, one can cite the first light and start of regular observations of the Near-IR spectrograph NIRPS at the ESO La Silla Observatory in spring 2023. It complements the already highly successful HARPS and ESPRESSO spectrographs in the visible domain, which are also mounted at ESO telescopes. Built by consortia in which UNIGE plays a leading role (Prof. F. Bouchy), while UNIBE contributing selected hardware and the theoretical interpretation (following this collaborative scheme for many years, Prof. C. Mordasini), these instruments are the best radial velocity machines worldwide yielding masses for a large number of exoplanets, but also yielding constraints on the atmospheric constituents for some. It is also worthwhile to mention the re-conduction of the HARPS-N Agreement with INAF, in 2023, which allows Switzerland to access the Northern hemisphere with a twin of the successful HARPS spectrograph and pursue radial-velocity follow-up of the Kepler and TESS planetary candidates, as well as study their internal structure and characteristics.

Switzerland (UNIGE and UNIBE) could develop and maintain international leadership in Extreme-Precision Radial-Velocity (EPRV, Prof. F. Pepe) and high-fidelity spectroscopy for the past three decades thanks to continued efforts in improving the precision and the sensitivity. These improvements are in turn the fruit of continuous investment in technology development. NIRPS has become the most precise infrared radial-velocity spectrograph thanks to a revolutionary design and an image scrambling device developed at UNIGE. The wavelength calibration process of all the spectrographs has been revolutionised by the combination of multiple calibration sources and new data-reduction techniques and will further be improved by the future deployment of Laser-Frequency Combs (LFC). Last but not least, one had to learn how to mitigate stellar 'noise' on high-precision data. The solar telescopes on HARPS-N and HARPS have been precursors in observing our 'Sun as a star' (UNIGE) in order to understand how stellar pulsation, granulation and activity impacts the measurement. It eventually allowed to develop new data-extraction and reduction techniques to mitigate or even model stellar effects at velocities lower than one metre per second (m/s). Further improvements are needed, though, to reach the cm/s level required to detect the tiny radial-velocity signals induced by true Earth-analogues.

In space, the CHEOPS (CHaracterising ExOPlanet Satellite) as the first ESA satellite under Swiss lead with UNIBE being the PI-Institute (Prof. W. Benz) with a strong participation of UNIGE (Prof. S. Udry), has recently successfully been granted its first mission extension until the end of 2026. The prospect of a second extension until 2029 will be evaluated in the coming two years. CHEOPS has been tremendously effective in measuring with highest precision the radii of exoplanets in iconic systems. The combination of precise transit observations (including precise transit timing) with precise ground-based radial velocity observations provides us with a constantly growing gallery of multi-planetary systems whose architecture shows surprising diversity. The breadth of planetary system diversity will in the coming decade explode thanks to PLATO (ESA's M3 space-born transit survey, with strong involvement of UNIGE and UNIBE and a launch in 2026),

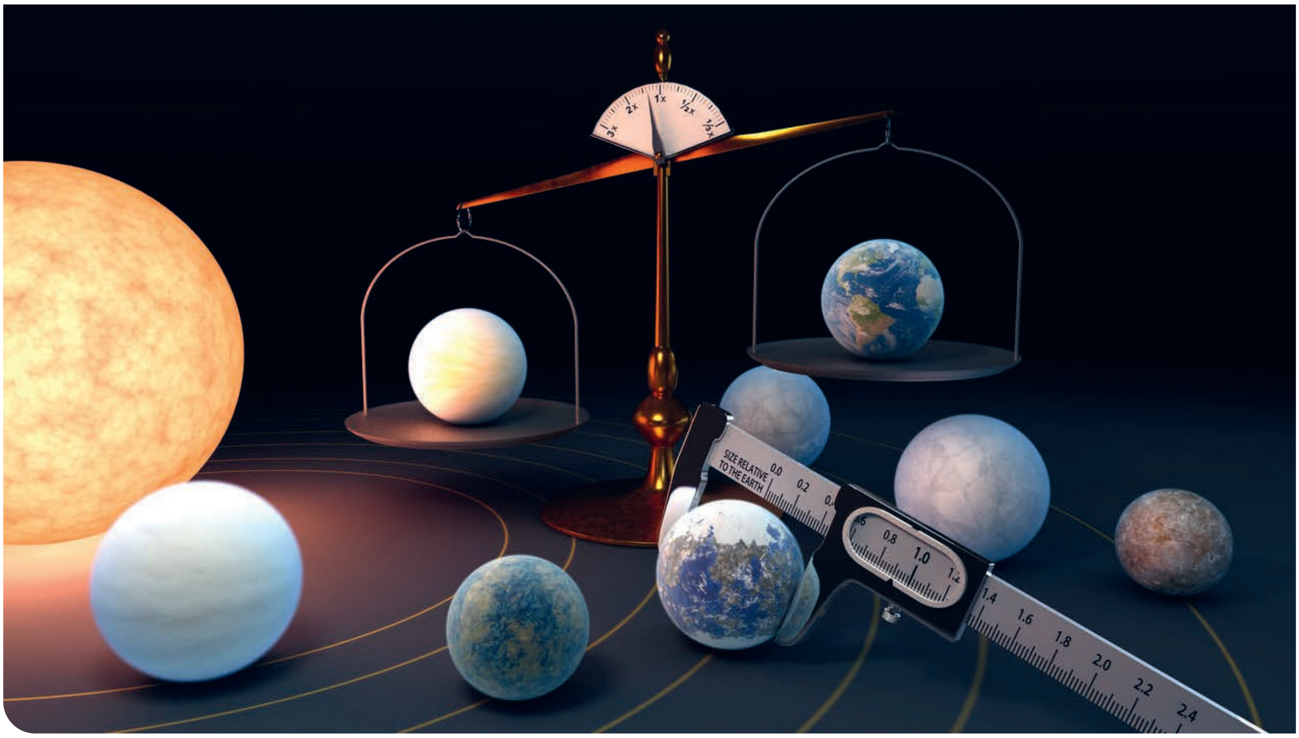


Figure 2: An artist's view of the TRAPPIST-1 system. The TRAPPIST-1 star is home to the largest batch of roughly Earth-size planets ever found outside our solar system. An international study involving researchers from the Universities of Bern, Geneva and Zurich now shows that the exoplanets have remarkably similar densities, which provides clues about their composition. Source: NASA/JPL-Caltech

ARIEL (ESA's M4 transit spectroscopy mission to be launched in 2029 with theory involvement of UZH) and the Nancy Grace Roman Space Telescope (a NASA microlensing survey to be launch 2027), that will, each of them, yield hundreds to thousands of new planetary systems.

The combination of space-based transit missions and ground-based high-precision spectroscopy has revealed fundamental during the last decades (Kepler vs HARPS-N, K2 vs HARPS and HARPS-N, TESS vs ESPRESSO, NIRPS and HARPS/-N). On the one hand, space missions provided us with hundreds of new candidates and, on the other hand, the radial-velocity follow-up provided precise mass determination. As the two techniques refined and improved precision, even smaller and lower-mass planets could be discovered and characterised, to a level well below Earth's size and mass planets. This complementarity also became evident in terms of the study of the internal structure of exoplanets, their atmosphere through transit spectroscopy, orbital characterisation through Rossiter-McLaughlin effect, as well as the precise photometric and spectroscopic determination of stellar parameters. These results put in very promising perspective the upcoming PLATO mission and its ground-based follow-up with ESPRESSO@VLT first, and ANDES@ELT. To date, this synergy is though only possible in the Southern hemisphere, since no facility equivalent to ESPRESSO and ANDES do yet exist or are not accessible in terms availability of a large amount of observing time to the Swiss and European community.

Regarding the characterisation of exoplanet atmospheres, the most impactful single element was the launch and start of operation of JWST in July 2022, which sparked the study of exoplanet atmospheres at an unprecedented level. JWST has the ability to measure the composition and structure of atmospheres of giant planets down to terrestrial planets in the best cases. In only two years, JWST has measured the atmospheric composition of sub-Neptunes (the most frequent type of exoplanets known), attempted the detection of an atmosphere around a terrestrial mass planet around a low-mass star, and measured the abundances of dozens of molecules. Switzerland actually co-leads (Prof. B.-O. Demory) a global survey (Saint-Ex Observatory, SPECULOOS collaboration) to specifically detect temperate Earth-sized exoplanets that could be characterised with JWST. JWST, in which ETHZ (Prof. S. Quanz) is involved via the Mid-Infrared Instrument (MIRI) Consortium, has also revolutionised the knowledge of the composition of protoplanetary disks, which is key in the context of understanding the formation and composition of (exo)planets.

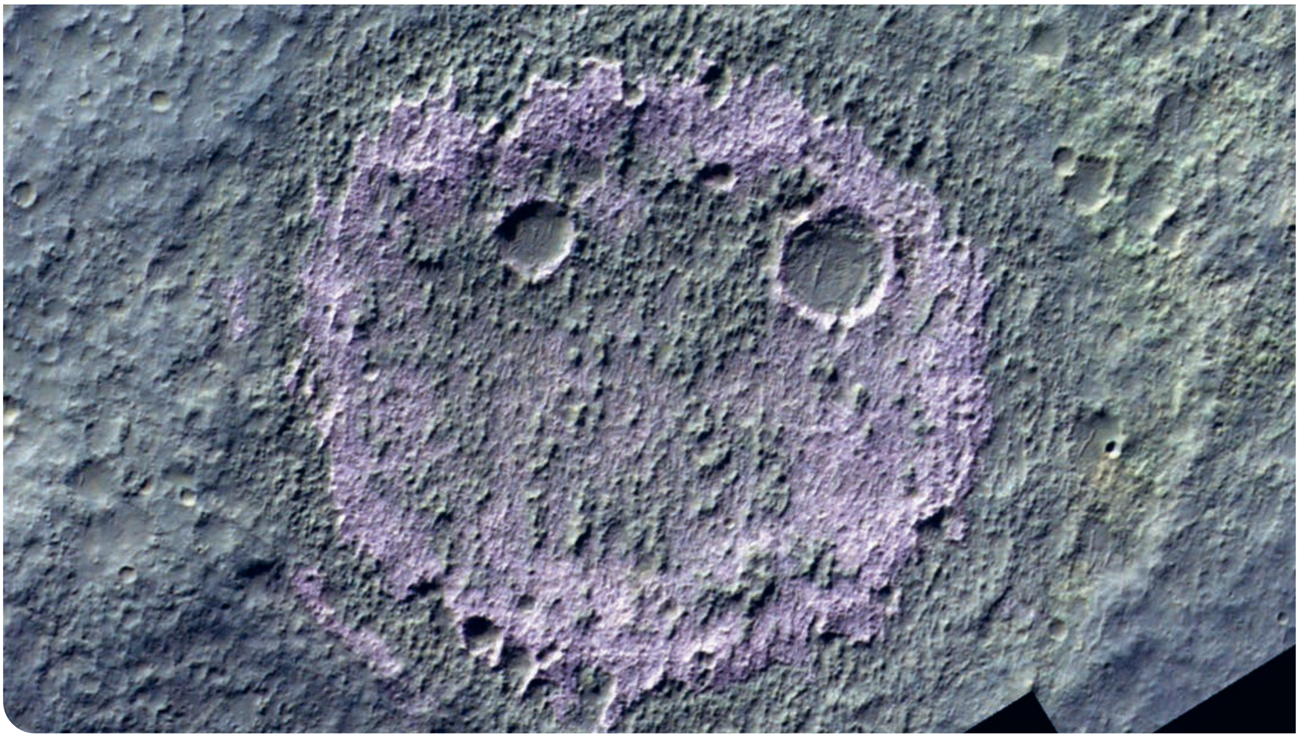


Figure 3: Salt deposits on Mars in the form of a smile. Source: ESA/TGO/CaSSIS

5.3.2 Solar system

Regarding the Solar System, its scientific exploration represents the only opportunity for carrying out detailed in situ measurements of celestial bodies beyond our Earth, complementing the exoplanet statistics. Yielding constraints only accessible in the Solar System (like complex surface and interior compositions and processes, minor body properties of comets, moons, asteroids, cosmochemical laboratory analysis, etc.), it remains the benchmark system for our understanding of the formation of planets, their evolution but also the emergence and prevalence of life. Since the last report, the most important single event was the launch of the ESA L1 JUICE (JUpiter ICy moons Explorer) probe in Spring 2023, where UNIBE is strongly involved (Prof. P. Wurz, PD Dr. A. Vorburger, Prof. N. Thomas) via three instruments (NIM – a mass spectrometer, GALA – a laser altimeter, and SWI – a submillimeter wave instrument, Dr. A. Murk). JUICE will bring our understanding of the three Galilean Moons Ganymede, Callisto and Europe to a new level, searching also for traces of potential life in the sub-surface oceans of the icy moons. Regarding Mars, UNIBE's CaSSIS Camera (Prof. N. Thomas) onboard the ESA-led ExoMars Trace Gas Orbiter continues to yield high-resolution remote sensing observations. CaSSIS is a sophisticated colour and stereo surface imaging system, which is in continuous operation since 2016. The NASA InSight mission probing Mars' interior (ETHZ participation) was completed end of 2022.

The prime mission of the joint ESA-JAXA mission BepiColombo to Mercury, launched in 2018, is expected to arrive at Mercury in 2026, carrying on board two instruments from UNIBE. The instrumentation for the laser altimeter project, BELA, being led by UNIBE (Prof. N. Thomas), is designed to measure the surface topography and contributes to the planetary geophysics experiment. The STROFIO instrument, with a strong Swiss participation (Prof. P. Wurz) will measure the composition of Mercury's atmosphere.

The efforts for observations both for Solar System and extrasolar planets are complemented by the continued development of theoretical models. This includes global planet formation models for planetary population synthesis at UNIBE (Prof. C. Mordasini), internal structure models for more massive planets at UZH (Prof. R. Helled) and small planets for CHEOPS at UNIBE (Prof. Y. Alibert), as well as models for atmospheres, habitability, and climate at UNIBE (PD Dr. D. Kitzmann) and UNIGE (Prof. E. Bolmont). These efforts rely on the access to significant Swiss computational infrastructure and are needed to interpret all observational results, ultimately improving the understanding of the emergence and evolution of planets. Finally, one should note that exoplanet studies are only possible thanks to deeper knowledge of stars themselves (their magnetic and thermodynamic variability), to account for their effects on the radial velocity and transit detections of potentially habitable planets, also using the Sun as a reference star. Consequently, modelling signatures of exoplanets and extra-solar life together with various stellar contamination effects and developing life detection techniques are needed for the coming large space- and ground-based facilities.

5.4 Theme 4: Our home and its space environment

The scope of the Swiss solar-terrestrial studies has grown since 2021 thanks to contributions to space- and ground-based instrumentation, theoretical and computational developments, and new leadership appointments at IRSOL, UNIBE, ISSI and FHNW (Profs. S. Berdyugina, L. Kleint, T. Dudok de Wit, B. Panos). The general trend is to strengthen synergies of solar research with terrestrial, stellar and planetary studies, as well as computational and data science.

5.4.1 Synergy of the solar and near-Earth research

The main challenge in solar physics is to understand the energy transport and magnetised plasma processes within the solar interior, atmosphere, and heliosphere. A much more detailed understanding of the generation and evolution of solar magnetic fields on various spatial and temporal scales is necessary to assess their role and effects on the solar radiation and plasma flows from the Sun into the heliosphere. Solar magnetic regions are the sources of enhanced X-ray, UV, optical, microwave and radio emission as well as violent plasma eruptions, caused by flares and coronal mass ejections (CMEs), which propel billions of tons of high-energy particles into the space. Consequently, detailed studies of the Sun are gaining a higher importance for understanding and monitoring space weather near the Earth and within the solar system. As human's technology advances and our expansion beyond Earth accelerates, predicting solar magnetic activity and impacts of its radiation and plasma on the terrestrial magnetosphere, atmosphere, climate and technology has become an urgent task. Thus, the unprecedented current growth of solar space missions and advancement of ground-based instrumentation is crucial for accessing the entire solar spectrum and various spatial and temporal scales. Addressing this challenge is at the core of the current and planned Swiss solar physics studies and their synergy with research on the Earth and its near-space environment.

5.4.2 Solar research

The largest ground-based solar telescope in Switzerland (0.45 m), equipped with the most precise solar spectropolarimeter in the world ZIMPOL, is operated by IRSOL. An abundance of clear days and observing time warrants unique long-term synoptic measurements of solar magnetic fields, also in coordination with space missions and large ground-based telescopes, with the goal to predict solar magnetic activity on various scales (Prof. S. Berdyugina). ZIMPOL upgrade, started in 2022 in collaboration with the SUPSI Department of Innovative Technologies, aims to advance ZIMPOL-system towards innovative optical sensors. To infer magnetic properties of solar plasma from spectropolarimetric data, developments in the theory, forward modeling, inversions, and 3D MHD simulations are advanced at IRSOL using applied mathematics, HPC, and deep learning techniques in cooperation with the USI Faculty of Informatics.

Participation in and hardware contributions to large ground-based telescopes has strengthen the Swiss leadership in high-precision and high-resolution solar spectropolarimetry. IRSOL has deployed ZIMPOL at Europe's largest 1.5 m solar telescope GREGOR (Tenerife, Spain), to employ advantages of a high spatial resolution. Since 2024, observations with ZIMPOL at GREGOR are offered to the international community. Start of operation of DKIST in 2022, the world-largest 4 m solar telescope (Haleakala, USA), has opened a new era in solar physics. A high-precision polarimetric unit has been designed and built by IRSOL for the first-generation DKIST instrument VTF (in final commissioning phase). This secures guaranteed access to DKIST observing time and data of unprecedented quality.

SKAO, is one of the flagship projects of the Swiss astronomical community for the next decade(s) and is also of interest for solar physics studies. Participation in SKAO is being organised by FHNW (Profs. A. Csillaghy, S. Krucker, B. Panos) within the SKAO Swiss consortium (SKACH), where Csillaghy is Board Member and also Swiss delegate in the Science and Engineering Advisory Committee. The new Swiss participation in the SKA precursor MWA will provide observing time for studying solar flares and solar events that are removed from night-time data to better understand the Sun-Earth connection.

At UNIBE, a new lab is being developed to build astronomical instrumentation (Prof. L. Kleint), in particular developing and building integral field unit spectrographs and spectropolarimeters. They will be used as visitor instruments at telescopes worldwide, including those at the Zimmerwald Observatory. One goal is to study magnetic fields in flare stars and obtain insights into the origins and energetics of superflares. Another goal is to study the physics of flares on the Sun. The research group also focuses on understanding space weather, its magnetic origins, the physics of sunspot formation and evolution, and employs various computer science techniques to study flare prediction. In collaboration with the geodesy group, effects of solar storms on satellite orbits are also studied.

Studies of long-term solar variability are carried out at ETH Zurich (M. Christl) using lab equipment for analysing cosmogenic radionuclide signatures in ice cores and tree-rings. These studies revealed that the Sun also produced superflares in the past thousands of years. Their recurrence rate and links to the overall solar activity levels inform us on the expectation values for the current space era. Time-series of cosmogenic radionuclides are employed at ZHAW (S. Ulzega) for calibrating solar global magnetic dynamo models to understand and predict solar Grand Minima and long-period cycles using advanced Bayesian inference methods and stochastic approaches at the ZHAW HPC infrastructure.

Participation in and hardware contributions to space missions has strengthen the visibility of Swiss solar groups and provided access to unique space data in coordinated observing campaigns with ground-based facilities. PMOD/WRC (Prof. L. Harra) continues operation of the SOHO mission (launched in 1995) and contributed to two Solar Orbiter (SolO, launched in 2020) experiments (SPICE and EUI instruments). FHNW (Prof. S. Krucker) operates and leads the scientific effort of the STIX instrument onboard the SolO. Long-term measurements of the total solar irradiance (TSI) in space are continued with the Compact Lightweight Absolute RAdiometer (CLARA, onboard Norwegian microsatellite NorSat-1, launched in 2017) and the Digital Absolute Radiometer (DARA, onboard Chinese JT-SIM satellite, launched in 2021). CLARA also measures terrestrial outgoing longwave radiation when on the night-side of Earth. UNIBE (Prof. L. Kleint) is Co-I of CMEx, a NASA SMEX mission to study chromospheric magnetism (currently in phase A). FHNW (Prof. S. Krucker) is Co-I on the Soft-Xray Imager (SXI) onboard the ESA-Chinese mission SMILE (Solar wind Magnetosphere Ionosphere Link Explorer, planned launch in 2025). The mission will investigate the interaction between the solar and the Earth's magnetosphere by providing global imaging in X-ray and UV. PMOD/WRC (Prof. L. Harra) contributes a TSI instrument DARA to the mission Proba-3 (launch in 2024) and a solar spectral irradiance monitor to the JAXA mission Solar-C.

The instrumentation developments at IRSOL have fostered an interdisciplinary technology transfer, which led to commercialisation of the ZIMPOL-system based on the 2019 patent in biopharmaceutics, initially jointly with the Optical Materials Engineering Laboratory (OMEL) at ETHZ, and continued in cooperation with the startup ENANTIOS and the R&D company CSEM, Neuchatel. The development of the next generation optical sensor for fast spectropolarimetry, beyond ZIMPOL, is planned in cooperation with SUPSI and ENANTIOS. This public-private cooperation will result in an optical sensor which will significantly enhance capabilities of solar instrumentation to study magnetic fields and eruptive events, with possible applications in astrophysics, Earth observations, and industry.

5.4.3 Near-Earth environment research

The Swiss Optical Ground Station and Geodynamic Observatory Zimmerwald (SwissOGS, also known as the Zimmerwald Observatory) is one of the most productive Satellite Laser Ranging (SLR) stations worldwide. It has been upgraded with new equipment for SLR and very prominently highlighted in the Geosciences Community Roadmap as an essential part of the Pillar I (Geo-OBSERVE). The SwissOGS also became part of the Swiss Quantum Communication Infrastructure (Swiss-QCI) project listed in the Swiss Roadmap for Research Infrastructures 2023. Besides the leading role of the SwissOGS in the domain of space debris, space surveillance, and space situational awareness (SSA), new astronomical projects are performed, such as observations of flare stars and a planned addition of adaptive optics to improve various types of observations.

In the last few years the community that has expertise in different aspects of space weather has been strengthened significantly in Switzerland. Scientific coordination activities are increasing through the national committee of the SCOSTEP, common seminars, and joint proposals. The aspects of space weather covered are from understanding and predicting solar activity to the impact on the Earth's atmosphere. This breadth is a real strength to Switzerland, and it will continue strengthen in the coming period. A new 'Kommando Weltraum' at Federal Department of Defence, Civil Protection and Sport is planned starting in 2026 with major funding, which arose after a 2024 report on space to the Federal Council. At PSI (M. Hildebrandt), space-weather related activities cover qualification of instruments, parts and components for survival in space using radiation testing facilities able to simulate realistic space particle environment. Aerospace radiation detection technologies are devoted to study contemporary particle radiation environments. Development of the AMOR instrument aims to map radiation environment dynamics at low and high altitudes during calm and extreme space weather conditions. In 2023, IRSOL started a synoptic program for high-precision spectropolarimetric observations of solar flares with the goal to improve the forecasting of space weather.

To monitor the space weather from space, ESA will provide the mission Vigil (launch in 2031) in the Lagrange point L5, from which the solar side orbiting into facing the Earth can be seen. This will provide a view in advance the origins of active regions from which, potentially, CMEs could be impacting Earth. The PMOD/WRC is involved in the JEDI imager for Vigil (NASA contribution) and in the phase A study of M-Matisse, a space weather mission for Mars.

Various concepts for satellite missions providing a highly accurate space co-location of all currently available geodetic techniques on-board one single satellite mission have been proposed, i.e. a VLBI transmitter, a GNSS receiver, a DORIS receiver, and a SLR retro-reflector, with fully calibrated reference points for all techniques. The mission Genesis aiming at the co-location of the space geodetic techniques in space have been approved by ESA in 2022 to contribute to reaching the challenging requirements of Terrestrial Reference Frames (TRFs) of 1 mm for positions and 0.1 mm/year for velocities. Genesis will thus contribute to global geodesy, metrology, natural hazard prediction, and monitoring of climate change. The SwissOGS will contribute significantly to the SLR tracking of the Genesis mission and will thus be essential for determining next-generation terrestrial reference frames. The upcoming NASA/DLR Continuation mission GRACE-C was approved in 2023 to continue the unique essential climate data record of mass change in the Earth system as initiated in 2002 by the GRACE mission and continued in 2018 by GRACE-FO.

In 2022, ESA has also given a green light to the Mass change And Geosciences International Constellation (MAGIC), which shall consist of the polar pair of the NASA/DLR GRACE-C mission and an inclined pair of ESA's Next Generation Gravity Mission (NGGM), providing together a significant improvement of accuracy and spatio-temporal resolution of mass change observations of the Earth system. The perspective given by MAGIC is fully in line with the Resolution no. 2 of the International Union of Geophysics and Geodesy (IUGG), proposed by Prof. A. Jäggi and adopted at the IUGG General Assembly in 2023, to urge national and international space agencies and decision makers to implement and maintain long-term sustained observing systems of the Earth's time-variable gravity field realised by dedicated gravity satellite constellations with improved measurement technology to enable new science and applications of enormous societal benefit and to evolve them into sustainable operational services in the longer term.

5.5 Computer infrastructure and other common issues

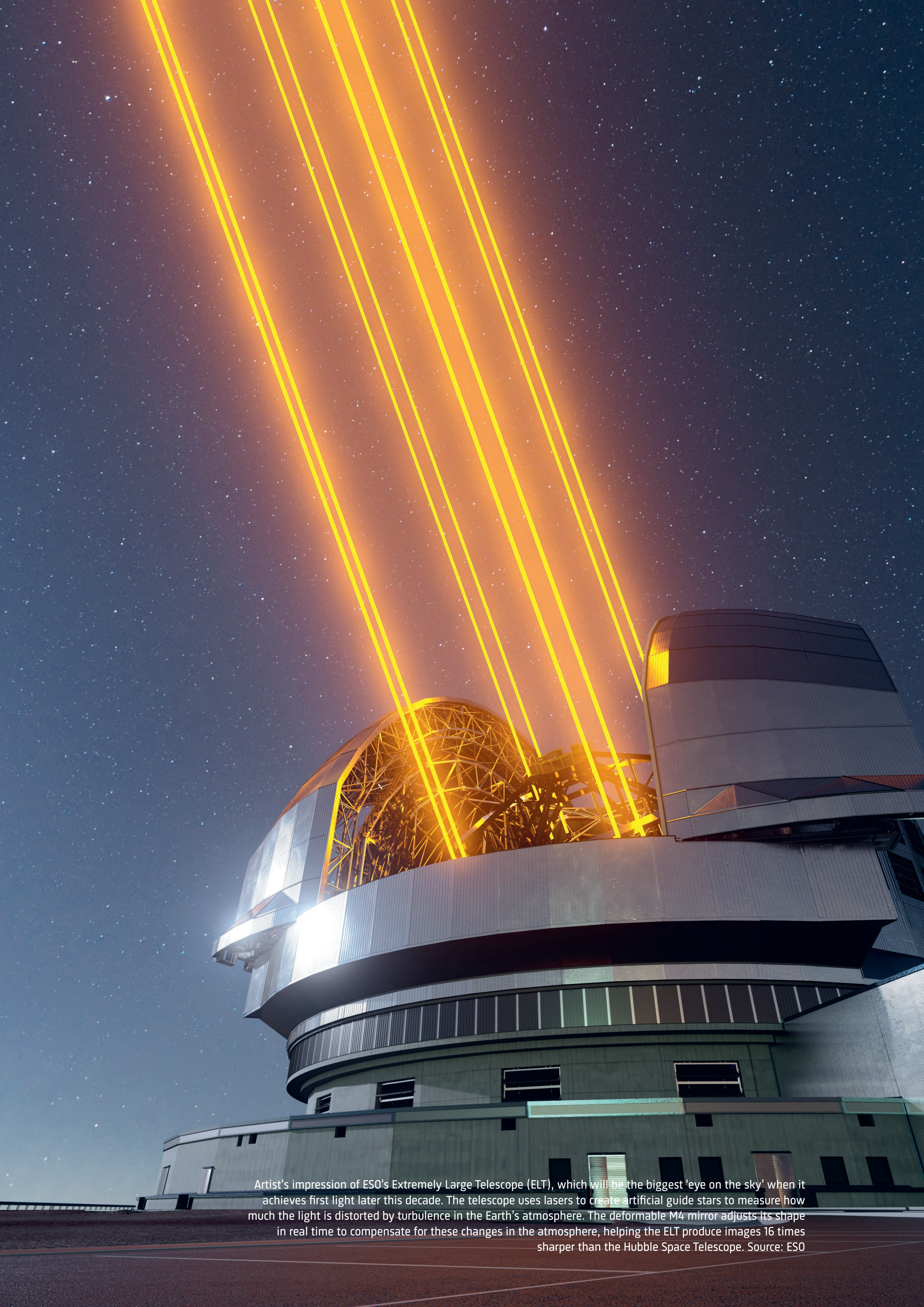
Data preservation and the implementation of FAIR principles for open science are considered more and more important by the agencies funding scientific research, and in particular the SNSF. Since all research institutes are confronted with the same problem, implementing solutions at the institute level is inefficient. A concerted approach, such as the one that was put forward with the idea of the creation of a Swiss-wide institute through the Article 15, is necessary. The negative decision on its funding means that there is currently no clear path forward to address this issue. However, UNIGE, EPFL and FHNW have obtained funding from Swissuniversities (P.I. Prof. S. Paltani) to continue the development of a platform, called AstroORDAS, to perform off-line analysis of astronomical data. Through this project, data sets from multiple missions have been added. The funding of this project on the medium-to-long term remains an issue. A similar infrastructural development is advisable for the ever growing datasets from large scale supercomputing simulations. Some of these are functional to key projects of the Swiss community or in which the Swiss community is involved, such as SKACH and the Euclid Consortium. Even in this case there is a request of funding agencies to make data available but this impractical for the time being as the size of the largest datasets is several Petabytes per simulation.

With the advent of very large projects with huge demands in terms of data management and data processing, in particular SKAO, a centralised computing infrastructure is necessary. This role is very naturally taken by the Swiss National Supercomputing Centre (CSCS). Since 2021, the CSCS is involved in the preparation of the data management for the CTA Observatory through the Data Center for CTAO (CTAO DC), and, more recently, for SKAO through the definition of the SKA Regional Centre (SRC). In addition CSCS provides increasing support to Swiss universities towards high performance scientific computing for advanced numerical simulation campaigns through the Platform for Advanced Scientific Computing (PASC) which enables the development of codes well integrated with priority projects such as SKAO and Euclid by funding dedicated personnel both at universities and within CSCS staff. The latter goes hand in hand with the growing large scale simulation activity of Swiss groups. Also thanks to the advising and supporting role of CSCS, a Swiss team from UZH (Prof. L. Mayer) and computer scientists at UNIBAS (Prof. Florina Ciorba) has managed to obtain in 2023, the largest ever supercomputing time allocation in Europe by being awarded the Extreme Scale Access Award by the EuroHPC Joint Undertaking, on the 3rd most powerful supercomputer in the world: LUMI-G.

The increasing importance of supercomputing in theoretical modelling for astrophysics and cosmology implies that the tools available to the swiss scientific community have to be ready for the 'Exascale revolution', which is just about to start with the first Exascale supercomputers becoming operational, an area where Switzerland has made a considerable investment through CSCS. Owing to support from PASC, SERI and CSCS itself, the group of Mayer at UZH, in collaboration with the computer science group of Prof. Florina Ciorba at UNIBAS has publicly released, in 2024, the first version of the multi-purpose new SPH-EXA gravity+hydrodynamics code, geared at multiple scientific applications, and the first such code worldwide to run on the new generation of large GPU-based supercomputers for Exascale. The code is being developed further by a growing collaboration involving partners in Germany, the UK and the US, and is the flagship code of the SKACH Consortium, positioning Switzerland at the forefront of computational astrophysics. In recognition of their achievement, the Joint Undertaking EuroHPC initiative of the European Union has granted Mayer and collaborators an 'Extreme Scale Access Award'.

The synergy of the solar, computational and data sciences has emerged at several Swiss universities with the support by the national and EU funding. The SNSF Sinergia grant at IRSOL (Dr. L. Belluzzi) and USI Faculty of Informatics (Prof. R. Krause) has advanced 3D computations of polarised radiation transport in the solar atmosphere using cutting-edge methods of computational science and applied mathematics. The SNSF Sinergia grant at FHNW (Prof. A. Csillaghy) and University of Geneva (Profs. S. Voloshynovsky, F. Fleuret, T. Golding) 'Robust Deep Density Models for High-Energy Physics and Solar Physics (RODEM)' aims at fostering cooperation between high energy physicists, solar physicists and experts in machine learning in Switzerland to advance research methodologies in both fields. Continuing the previous work performed while at the University of Geneva (Profs. Kleint, S. Voloshynovsky), a focus on machine learning with large investments in high-performance computing infrastructure has been established at UNIBE (Prof. L. Kleint). This will be used to analyse large data sets to predict flares using machine learning and explainable AI, as well as models from medicine adapted to astronomical applications. Responsible AI technologies, including robust statistics, explainable AI, and physics-informed machine learning are employed at FHNW (Prof. B. Panos) to ensure scientifically accountable big data algorithms. 3D radiation magnetohydrodynamic (R-MHD) numerical simulations are carried out at IRSOL for the interpretation of data collected by ground-based and space telescopes using new HPC hardware (e.g. the new Alps system at CSCS). AI approaches are employed at IRSOL to accelerate forward modeling and inversions of high-resolution spectropolarimetric solar data. AI is used extensively at ETHZ (A. Refregier) for machine-learning based inference for cosmology. Applications of advanced Bayesian inference methods for data-driven calibration of stochastic solar dynamo models are carried out at ZHAW and supported by its HPC infrastructure (S. Ulzega). A new EU funding for federation of solar data has been gained by IRSOL (Prof. S. Berdyugina) to disseminate ZIMPOL data in accordance with the FAIR principles.

It would be desirable that future projects with significant data management needs use the CSCS as their computing infrastructure, and that the support to computational astrophysics and cosmology provided by PASC shall increase and focus on projects of interest to the broader Swiss community.



Artist's impression of ESO's Extremely Large Telescope (ELT), which will be the biggest 'eye on the sky' when it achieves first light later this decade. The telescope uses lasers to create artificial guide stars to measure how much the light is distorted by turbulence in the Earth's atmosphere. The deformable M4 mirror adjusts its shape in real time to compensate for these changes in the atmosphere, helping the ELT produce images 16 times sharper than the Hubble Space Telescope. Source: ESO

6 International context and large scale infrastructures

6.1 The European Southern Observatory (ESO)

The inauguration of the Very-Large Telescope in 1999 was the turn-over that placed the European astronomical community at the forefront of ground-based astronomical observations. Since then, ESO, supported by its member states and their research institutes, has not only consolidated but also extended its leadership in building and operating world-class observatories and infrastructures well-beyond the optical wavelength domain. Besides operating the La-Silla Paranal Observatory, ESO is a main partner and player in the ALMA facility, and it signed an agreement for hosting CTA South and become a founding member of the CTAO ERIC.

ESO continuously maintains both infrastructures to the highest level of standards and performances, and invests in upgrade of existing and in the development of new, cutting-edge instrumentation. These activities have been boosted by an extremely efficient partnership between ESO and many other astronomical institutes based on the principle 'Guarateed-Time Observations (GTO) in exchange of instrumentation'. Switzerland has been particularly active and successful in this partnership thanks also to FLARE by enabling past projects like HARPS, PRIMA, MUSE, SPHERE and ESPRESSO (UNIGE, UNIBE, ETHZ), as well as present VLT projects like RISTRETTO, BlueMUSE and SAXO+. It must be noted that the GTO concept allowed ESO and its community to develop facilities which go well beyond what would be possible with self-funding only. It also allowed astronomical institutes to 'professionalise' their project managements and deploy unique and coherent observing programs within ESO, producing outstanding results.

The past few years have brought amazing progresses in the construction of the European Extremely-Large Telescope (ELT) on the site of Cerro Armazones, in the Chilean Andes. Whereas the American analogues (US-ELT) remain stuck due to financial and political difficulties, the ELT-project has recently (2024) completed the construction of the Main Dome Structure (MDS). The project is still on track for a first light in 2028 despite many adversities that ESO had to face during the reported period (COVID, Social Riot in Chile, bankruptcy of the main contractor, rising construction costs in Chile and inflation).

The ELT infrastructure (similarly to the VLT) is built by a 'self-consistent' project led and financed by ESO. Astronomical institutes in Europe and Switzerland are nevertheless heavily involved in the ELT by participating to the development of its impressive (and challenging) instrumentation suite, without which the telescope would be worthless. So for instance is ETHZ involved in the construction of mid-infrared spectro-imager METIS, one of the first-generation instruments of the ELT, while UNIGE and UNIBE are key players in the high-resolution spectrograph ANDES. UNIGE and EPFL are furthermore involved in the construction of the multi-object spectrograph MOSAIC.

ESO is also an efficient actor and reliable Partner in scientific communication. Its Public Relation office produces high-level press-releases and communication articles. It provides outstanding images and video material for the general public and for professional.[1] There is no doubt that ESO is recognised as the reference in astronomical communication in Europe but it has become also a reference for public outreach at all levels and by all means,[2] e.g. thanks to its SuperNova visitor center in Garching by Munich, and through the organisation of campaigns and events all-around the world.

Finally, it must be recalled that ESO has been and will remain host of 'National Facilities' on their observing site, giving thus the possibility to small countries to build and operate their own telescopes on exceptional observing sites. This is the case for instance for the New Generation Transit Survey (NGTS) at Cerro Paranal (UNIGE is one of the Partners), or, even more relevant, the Swiss Euler 1.2-m telescope in La Silla, Chile, for which ESO and UNIGE will re-conduct the hosting agreement by January 1st, 2025, for five more years at least.

6.2 The Square Kilometer Array Observatory (SKAO)

The Square Kilometre Array Observatory is the next-generation radio astronomy and Big Data facility designed to explore the universe's earliest moments, including uncovering the origins of life, mapping the magnetic field in the Universe, to study galaxy and quasar co-evolution, probe the Cosmic Dawn when the first stars and galaxies formed through hydrogen mapping, understanding nanohertz gravitational waves (through pulsar timing arrays), and investigating the mysterious nature of dark matter and dark energy.

1 https://www.eso.org/public/images, https://www.eso.org/public/videos
2 https://www.eso.org/public/outreach

Figure 4: The SKA-MPI dish prototype in South Africa. The prototype dish is the first to be assembled on site, funded by Germany's Max Planck Institute for Radio Astronomy. Source: SKAO

Construction of SKAO began in June 2021 at the telescope sites in Australia and South Africa, with science operations expected to start in 2029 and continue for at least 50 years, making it a cornerstone of 21st-century fundamental astrophysics.

The SKAO was designated as an intergovernmental organisation in 2019 through international treaty, similar to CERN, ESA and the European Southern Observatory (ESO). Swiss scientists have been involved since the project's inception, and Switzerland officially joined as a member country in January 2022 with a contribution of about 2% of the project budget. As of September 2024, the SKAO has a total of 10 member institutions, and additional six observing partner countries that span over five continents.

With the support of SERI, the Swiss community formed a collaboration for the SKAO (SKACH) that consists of a board of 10 institutions spanning the geography and institutional landscape of Switzerland – CSCS, EPFL, ETHZ, FHNW, HES-SO, ISSI-Bern, UniBAS, UNIGE, UZH, ZHAW. Work within the consortium is multidisciplinary, utilizing the most current knowledge from astrophysics, computer science and radio frequency engineering. SKACH now has over 100 members within Switzerland actively working on the project. In addition to core funding from SERI, SKACH relies on competitive funding from the SNSF for scientific research and development.

Switzerland is leveraging its scientific community to play a significant role in the SKAO across five key areas: Science, Data Science, Computing, Instrumentation, and Education. One essential development to achieve, starting in 2025, is the establishment of a Swiss Science Regional Centre (SRC) node with support from CSCS, which will allow the country to store the most critical visibilities for its science community while assisting the international project in processing the vast 650 PBytes of data generated annually by SKAO. This effort involves development in scalable simulations, advanced imaging, and eco-computing and will require additional infrastructure funding to be sought from the Swiss National Science Foundation (SNSF).

6.3 The Cherenkov Telescope Array Observatory (CTAO)

In 2021 the Swiss Confederation created a dedicated funding line in the ERI dispatch to support the Cherenkov Telescope Array Observatory and the Swiss contributions to its construction. Switzerland funds the construction of the CTAO alpha configuration, in particular via contributions to the large size telescopes, array data acquisition and analysis pipelines and hosting a fraction of the CTAO data center at CSCS. The main topics of interest in the Swiss groups at UNIGE, EPFL, UNIBE, UZH and ETHZ are to understand the origin and feedback of cosmic rays, their acceleration in supernova remnant, starbursts, black hole jets or in other catastrophic phenomena such as galaxy mergers; astrophysical systems such as pulsars, X/gamma-ray binaries, micro-quasars, magnetars, active galactic nuclei, gamma-ray bursts also via multi-messengers techniques; the nature of matter in the universe and searching for the sites where dark matter agglomerates; the cosmological evolution of early galaxies measuring the extragalactic background light and determining magnetic fields in cosmic voids. The CTAO member countries, led by Italy, Germany, France and Japan, submitted in early October 2024 a revised application for recognition of CTAO as a European Research Infrastructure Consortium (ERIC). This application has already been approved by the ERIC Committee and is waiting for the final signature at the European Commission. The European Commission strongly supports the CTAO ERIC and is pushing for the final sign-off in November enabling the ERIC to be created in January 2025. Switzerland is a founding member of the current legal structure (the CTAO gGmbH) and its accession as an ERIC member will be a priority to profit from the Swiss investments. The ERIC will boost the construction efforts both in La Palma (Canaries Island) and on ESO premises close to Paranal in Chile. The on-going construction of the four Large Size Telescopes (4×400 m^2 of mirrors) in la Palma will finish in early 2027 making of CTAO the most sensitive instrument in the energy range 30 GeV – 1 TeV. Two additional large telescopes are being built to be installed in Chile by 2028, accompanied by 14 medium size telescopes (mirrors of 88 m^2) and 37 small size telescopes (mirrors of 4.3 m^2). The CTAO Science Data Management Centre was inaugurated close to Berlin in 2024, where CTAO science operation and data management will be conducted. The CTAO central organisation, with headquarter in Bologna, is currently staffed by about 65 people coordinating the work of more than a thousand people contributing to the construction of CTAO worldwide.

6.4 Gravitational waves: Ground-based facilities

The Einstein Telescope (ET) is the European third generation gravitational wave detector, which has entered a phase of accelerated development over the last three years. In 2021, ET was included on the ESFRI Roadmap and in

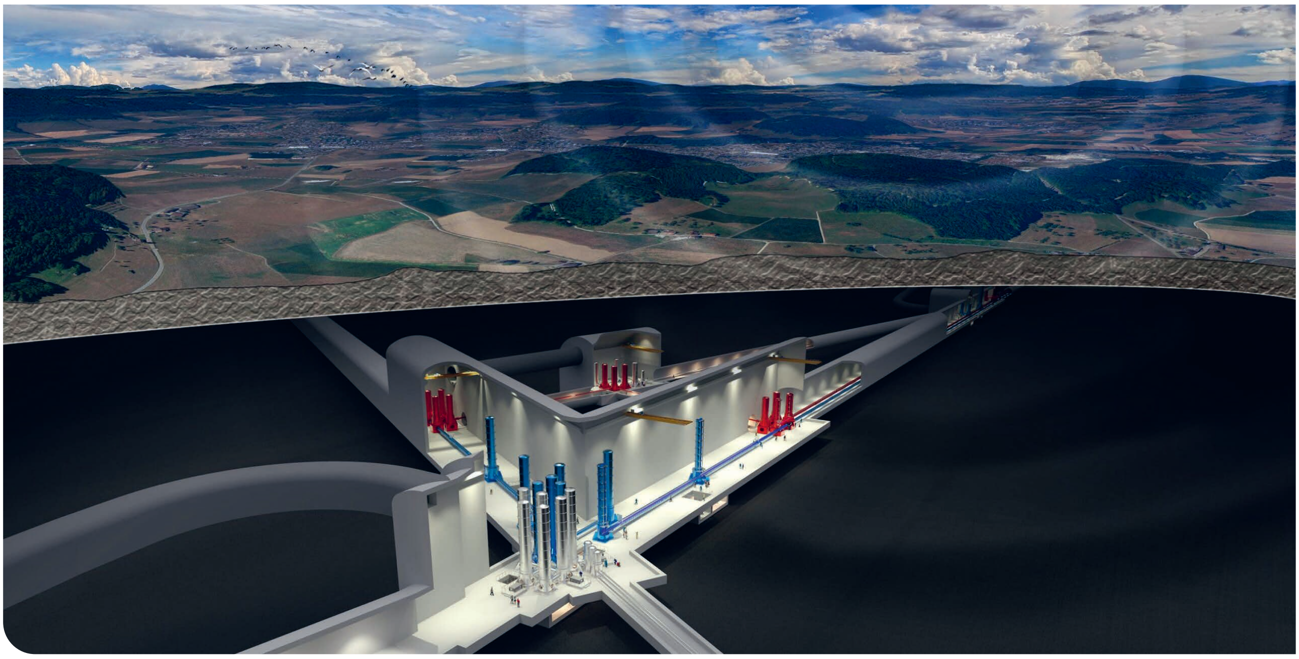


Figure 5: The three 10-kilometer tunnels of the Einstein Telescope will be sited 250 to 300 meters underground in order to make undisturbed measurements of gravitational waves. The site will be either in the border area of the Netherlands, Belgium and Germany or in Sicily, Italy. Source: Marco Kraan/Nikhef

2022, the ET collaboration was founded, which today has over 1600 members. A governance structure has been put in place, similar to the CERN paradigm: including the scientific collaboration, the project directorate and the overseeing proto-council. The latter is currently composed for the Board of Governmental Representatives and the Board of Scientific representatives. Switzerland continues to hold a prominent position in the development and leadership of the ET project, particularly in science and computing domains. Prof. Maggiore is co-chair of the ET Observing Science Board, as well as member of the ET Executive Board and the ET Collaboration Board. Prof. Fragkos is the Swiss national representative at the ET Board of Scientific Representatives, and co-I of the ET Preparatory Phase (ET-PP) project. The ET-PP is also a Horizon-Europe INFRA-DEV project which currently encompasses most of the programmatic activities for ET. Prof. Schramm is the chair of the ET multi-messenger alerts infrastructure division within the e-Infrastructue Board, and Prof. Riotto is chairing the 'Populations Studies' division of the ET Observing Science Board.

6.5 Gravitational waves in space (LISA)

The space interferometer, LISA, has been selected in 2017 as the third ESA large-class mission. After a long phase of studies (Phase A and B1) LISA has been adopted by ESA in January 2024. This is a milestone as now construction will start in 2025 after the selection of the prime contractor. Switzerland will participate in the construction, in particular of the Inertial sensor front-end-electronics as was done for the LISA Pathfinder mission with the support of the PRODEX Programme as a collaboration between ETHZ and Swiss industry. Moreover, a data center will be established at ETHZ. LISA, whose launch is scheduled in 2035 will explore the Universe in GWs in a different range of frequencies compared to LIGO-Virgo and the planned ET. Profs. D. Giardini (ETH) and P. Jetzer (UZH) are members of the Board of LISA (Giardini also of the Executive Board). Jetzer was also in the LISA Science Study Team of ESA, which wrote the Definition Study Report that was an important document needed for the Mission

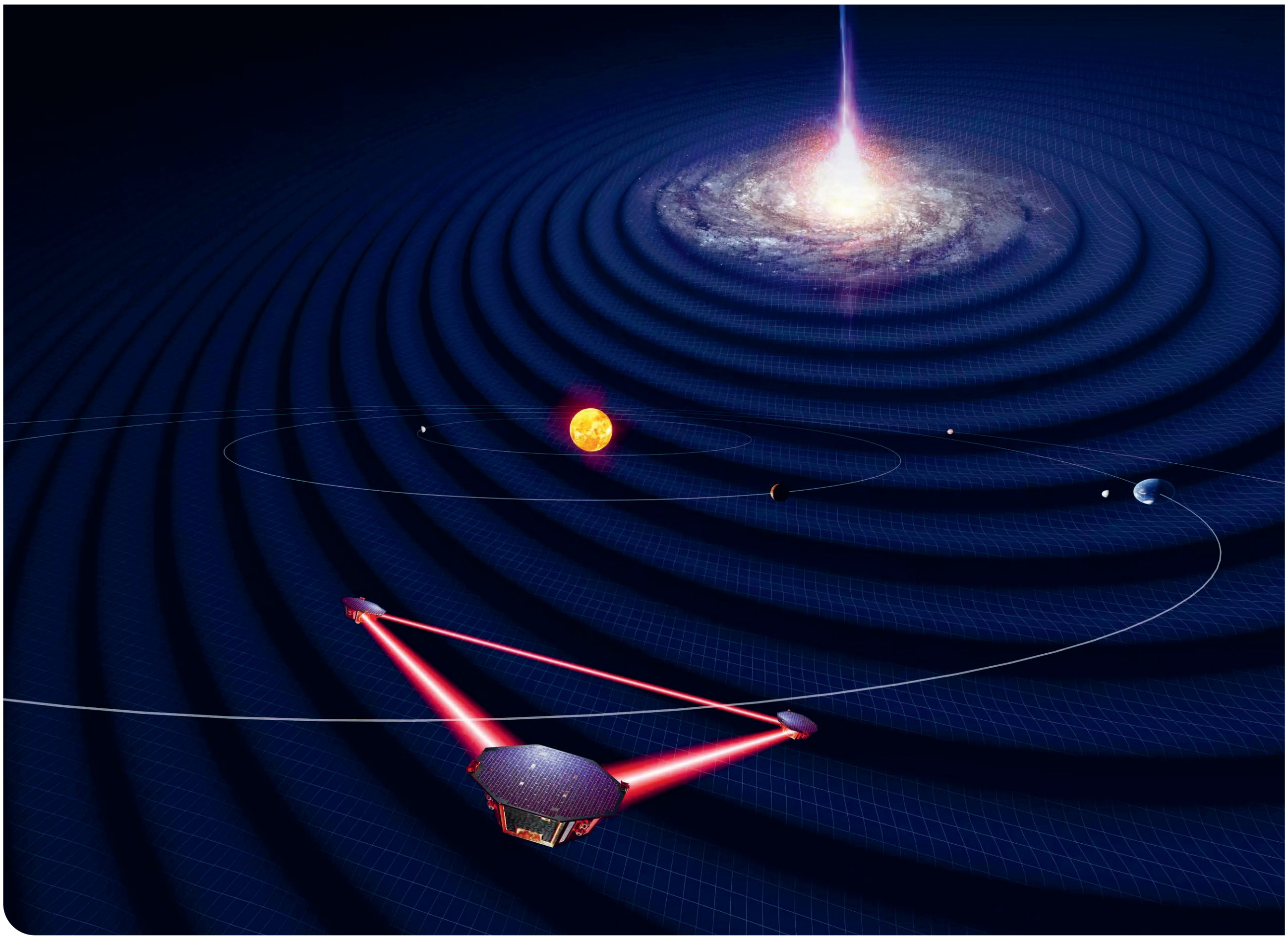


Figure: 6: Artist's impression of the LISA mission satellites in the solar system observing gravitational waves from a distant galaxy.
Source: University of Florida/Simon Barke

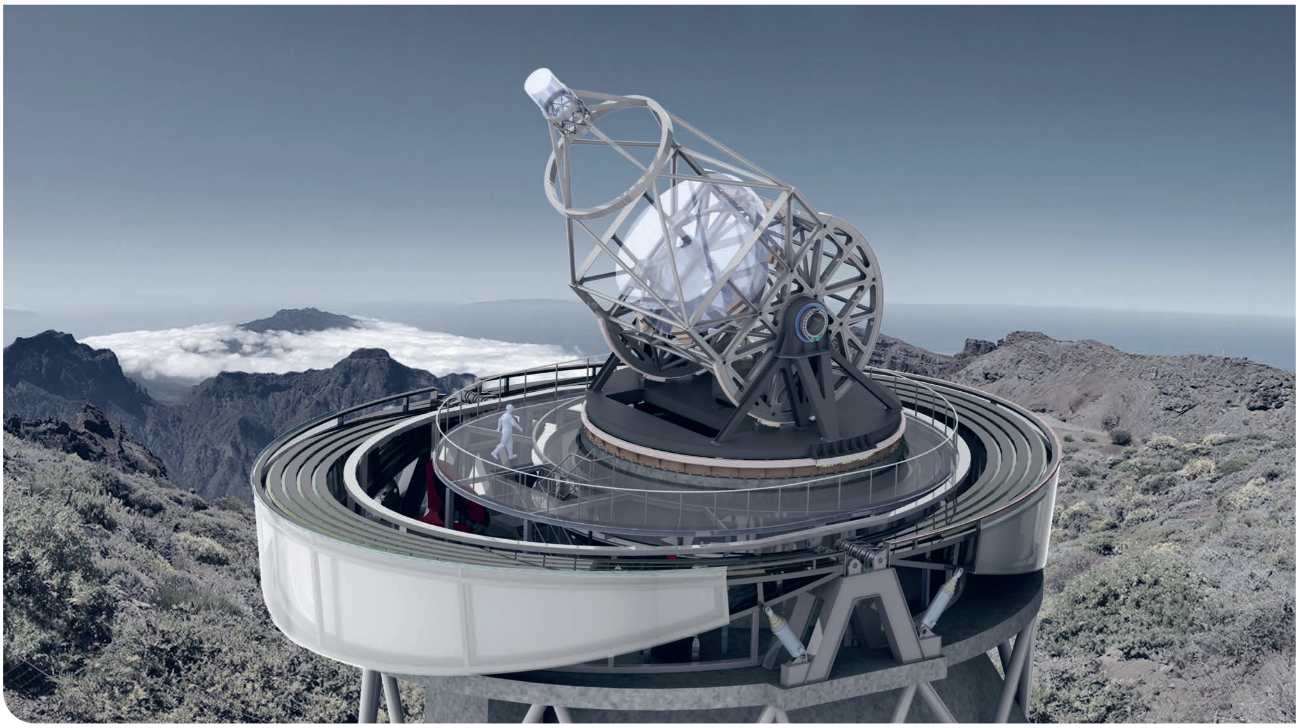


Figure 7: 3D rendering of the design of the 4.2 m European Solar Telescope to be constructed at El Roque de los Muchachos Observatory, La Palma, Spain. Source: EST Foundation

Adoption. Several other Swiss scientists were or still are members of various LISA working groups.

6.6 The European Solar Telescope (EST)

EST, the 4m European Solar Telescope, is the future flagship facility of the European solar physics community. The participation of Swiss research groups dealing with the Sun, instrumentation technologies, and other interdisciplinary synergies (solar-terrestrial, solar-stellar, stellar-planetary, plasma physics, etc.) is necessary to maintain the strong Swiss competence and leadership in these areas. EST has been on the ESFRI Roadmap since 2016 and recommended for implementation as one of the high-priority new infrastructures by the ASTRONET Science Vision and Infrastructure Roadmap 2022–2035.

In July 2023, the EST Foundation has been established as the project legal entity by 9 institutions from 8 European countries, including USI/IRSOL as a founding member on the EST Board of Trustees and the Executive Committee (Prof. S. Berdyugina). The goals of the EST Foundation are to complete the technical design of the telescope and instrumentation, accumulate funding for the EST construction, and prepare the intergovernmental agreements for the EST ERIC consortium. In October 2024, the Preliminary Design Review of the EST optics and the AO system has been successfully completed. Three EU countries (Spain, Slovakia and Czech Republic) have expressed their interest to start international negotiations at ministry levels to implement the EST ERIC and define the commitments for the construction phase. Other EST partners are negotiating funding with their science ministries.

To secure guaranteed access to this next-generation European solar infrastructure, Swiss groups aim at contributing to the EST large instrumentation jointly with other EST partners. Funding opportunities for a contribution to the design of the EST integral-field spectropolarimeter are currently explored by IRSOL, HEIG-VD (Prof. L. Jolissaint) and Institute of Astronomy, Czech Academy of Science, using the Second Swiss Contribution, which aims at strengthening and deepening bilateral relations of Switzerland with its partner countries and the EU as a whole, in particular with Czech Republic. IRSOL together with other EST partners has also received EU funds (2024–2026) for developing a concept for a distributed EST Data Centre using current solar data from various European facilities (open access to ZIMPOL data). Broader participation of Swiss groups developing instrumentation and information technologies are foreseen for contributing to the EST instruments and Data Center, and for cooperation with other large research infrastructures (e.g. SKAO).

6.7 The Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX)

HIRAX is a radio interferometer array under construction in the Karoo region of South Africa. The final instrument will comprise 1024 dishes, each instrumented with dual-polarisation antenna sensitive to radio frequencies between 400 – 800 MHz. HIRAX will map the southern sky, producing a 15,000 square degree tomographic survey of the large-scale structure of the universe as traced by the redshifted 21 cm emission line of neutral Hydrogen. This cosmological survey aims to answer some of the critical questions in modern cosmology, such as the nature and evolution of dark energy, posited to explain the current accelerating epoch of the Universe's expansion. The instrument will also make real-time measurements of the transient radio sky, providing a robust platform for detecting, characterizing and monitoring Fast Radio Bursts (FRBs) and pulsars. Further science goals of the project include searching for neutral Hydrogen absorber systems along the line-of-sight to quasars, as well as producing maps of the polarised radio emission of our galaxy.

HIRAX is currently at an important stage of development with the project having secured funding up to an initial 256 dish deployment (HIRAX-256) and has now started the manufacture and delivery of the first dishes. Switzerland plays a leading role in this experiment. The digital correlators were built in Switzerland with funding through a previous FLARE grant. Additionally the on-site computer systems (Science Data Processing Unit) required for the HIRAX-256 science data processing system have also been built through another FLARE grant in Switzerland. Further FLARE grants have funded R&D for holography calibration and the high-precision metrology for the radio dishes.

The Swiss HIRAX coillaboration is also very active in its science activities for the preparation of HIRAX. This includes extensive in instrument and cosmological simulations, the development of the data analysis pipeline and the control of systematics. Further bilateral and lead agency grants have fostered the collaboration between the Swiss and South African teams in this project.

6.8 The Next Generation Event Horizon Telescope (ngEHT)

ngEHT is a bold extension of the original Event Horizon Telescope (EHT), designed to take our understanding of black holes even further through enhanced observational capabilities. In April 2019, the EHT collaboration made history by releasing the first image of a supermassive black hole: a bright ring formed by radio emission lensed by the gravitational pull of a 6.5 billion solar mass black hole at the center of the galaxy M87. This groundbreaking image confirmed the predictions of General Relativity at the event horizon boundary. Three years later, the EHT captured a similar ring encircling Sgr A*, the four million solar mass black hole at the heart of our own Milky Way galaxy. These images constitute the strongest evidence yet for the existence of supermassive black holes, confining their masses within their photon orbits. The scientific impact of these results is reflected in over 14,000 collective citations, underscoring their transformative influence across astrophysics. These breakthroughs were made possible through the technique of Very Long Baseline Interferometry (VLBI), which linked radio dishes around the globe using atomic clocks, allowing the EHT to reach an unprecedented angular resolution of 25 micro-arcsecond and conduct precision measurements on the scale of black hole horizons.

Building on this success, the ngEHT aims to expand this groundbreaking work by addressing even deeper questions in physics and astronomy. By adding radio dishes in new geographic locations, the ngEHT will enhance the virtual telescope, enabling high dynamic range imaging of the M87 jet and allowing unprecedented studies of how relativistic jets are launched and how energy is extracted from a spinning black hole. The expansion also involves doubling the bandwidth of VLBI systems, which will improve sensitivity and bring new targets into focus, allowing scientists to track black hole parameters across cosmic timescales. Enhanced observing modes and increased computing power for VLBI processing will enable time-lapse movies of M87, providing a new method for testing General Relativity by measuring the periods of matter orbiting around black holes. Additionally, new multi-band receivers capable of reaching 345 GHz will create the first 'color' images of black holes, distinguishing between light bending near the horizon and the evolving emission from within relativistic jets.

Switzerland has an exciting opportunity to play a crucial role in the ngEHT project. The country could potentially host one of the new telescope dishes (in the Swiss Alps, and more precisely above Zermatt), contributing valuable geographic coverage to the global network and significantly enhancing the resolution and accuracy of the data collected. Furthermore, the Swiss National Supercomputing Centre (CSCS) could provide critical computational support for calibrating the enormous volumes of data produced by the ngEHT, ensuring the highest level of precision in scientific analysis. Additionally, Switzerland could provide a timing solution using Swiss-made atomic clocks, which are vital for ensuring synchronisation across the global telescope array, allowing consistent and accurate observations.

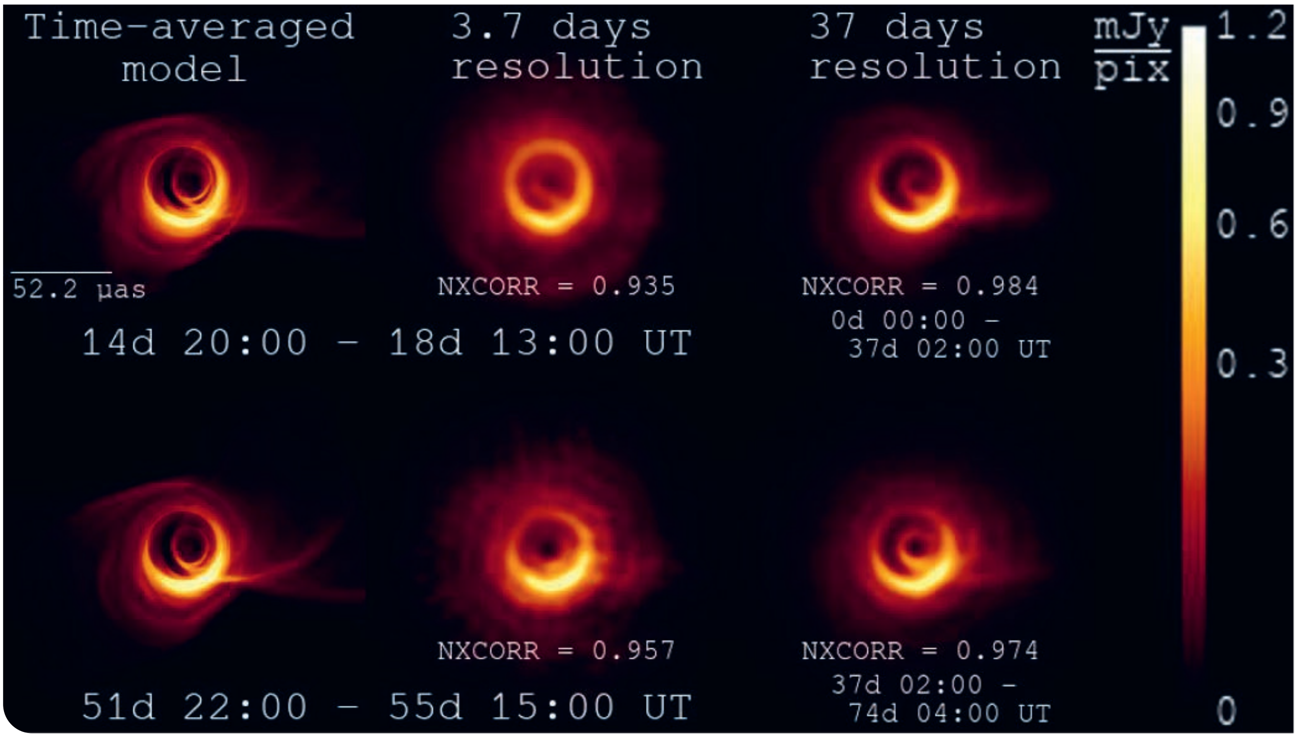


Figure 8: Effect of the temporal resolution on the reconstruction quality. From left to right: the time-averaged over 3.7 days theoretical emission map of the super massive black hole M87* at 230 GHz; frames of the movies simulated for the ngEHT each lasting 3.7 and 37 days, reconstructed using snapshot imaging. The source is varying during the simulated observation. Colours indicate brightness/pixel in mJy (square root scale).
Source: Anastasia Shlentsova et al. 2024

The ngEHT's development presents Swiss scientists and engineers with unparalleled opportunities to contribute to and benefit from this groundbreaking research. The Swiss astronomy, engineering, and computing communities are well-positioned to take leading roles in algorithm development, international collaboration, and data analysis as they prepare for the torrent of data expected from the expanded array. Being part of this cutting-edge project will enable Swiss researchers to explore black hole dynamics, such as accretion processes and relativistic jet formation, providing insights into the fundamental physics of black holes. Moreover, Swiss involvement will foster new research avenues in galaxy evolution, cosmic magnetism, and gravitational physics. By participating in this transformative international endeavour, Switzerland stands to be at the forefront of major astrophysical discoveries, significantly advancing our understanding of the cosmos.

6.9 The Widefield Spectroscopic Telescope (WST)

In the context of mapping stars and galaxies in the universe in the most comprehensive way as possible, in order to probe cosmology, identify and study transient phenomena (including EM counterpart of gravitational wave events, the European community proposed a conceptual design study for a 12-metre wide-field spectroscopic survey telescope (WST). This three-year project got recently funded by the Horizon Europe INFRA-DEV funding with a kick-off in February 2025. The originality of this telescope concept is to be capable to simultaneously operated of a large field-of-view (3 sq. degree), high-multiplex (20,000) multi-object spectrograph (MOS) and a giant 3 × 3 arcmin integral field spectrograph (IFS), both of them covering the full optical and near-infrared wavebands (350–970 nm). In scientific capability these specifications place WST far ahead of existing and planned facilities. In only 5 years of operation, the MOS would target 250 million galaxies and 25 million stars at low spectral resolution plus 2 million stars at high resolution. Without need for pre-imaged targets, the IFS would deliver 4 billion spectra offering many serendipitous discoveries. Given the current investment in deep imaging surveys (Euclid and Rubin Observatory) and noting the diagnostic power of spectroscopy, WST will fill a crucial gap in astronomical capability and work in synergy with future ground (in particular SKAO, Einstein Telescope in the long term) and space-based facilities (Euclid, Roman Space telescope, LISA). WST will address outstanding scientific questions in the areas of cosmology; galaxy assembly, evolution, and enrichment, including our own Milky Way; the origin

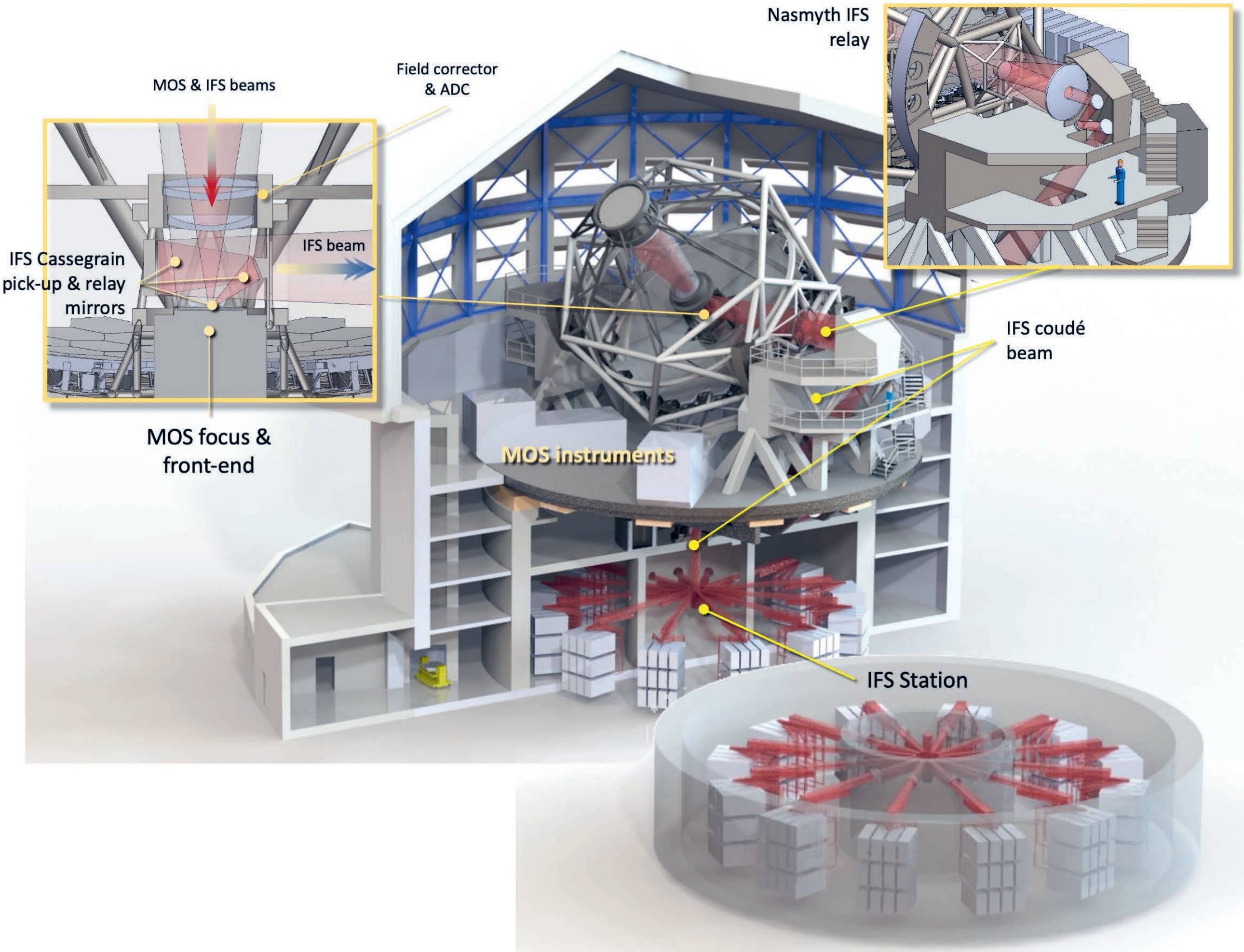


Figure 9: Current WST Facility design. Source: Gaston Gausachs and the WST consortium

of stars and planets; and time domain and multi-messenger astrophysics. WST's uniquely rich dataset may yield unforeseen discoveries in many of these areas. The preliminary study will deliver telescope and instrument designs, cost estimates, an updated science white paper and survey plan, concept studies for data management, and a facility operation concept. The telescope and instruments will be designed as an integrated system and will mostly use existing technology, with the aim to minimise the carbon footprint and environmental impact. The current WST consortium includes institutes in Europe (including Switzerland) and in Australia. WST will be proposed as the next ESO project after completion of the 39-metre ELT (the expected ESO call for proposal for a new facility is expected to be conducted in 2026).

Switzerland is currently contributing in the science definition of the project (leading the Cosmology and Transients Science Working Groups and contributing to the Galactic and Extragalactic Working Groups), as well as contributing to the instrumentation work package focusing on the fiber positionner system.

7 Vision and future needs

7.1 Theme 1: Fundamental physics

7.1.1 Gravitational wave interferometers

We envisage that Switzerland takes an active role as soon as possible into the ET project, as already mentioned in some detail in the previous chapter. In this respect a participation in the Virgo collaboration would be a strategic step towards an involvement in ET.

Moreover, on longer term new ideas on detecting gravitational waves both on ground and in space are already in discussed nowadays. Novel technologies based on atom interferometry could be used to build GW observatories sensitive in particular in the frequencies in between the ones of ET and LISA. First ideas for a space GW detector after LISA are also in discussion within ESA long-term planning science programme Voyage 2050. At present it is important that Switzerland participates in the needed R&D studies, such as to be ready to participate in one or another of these projects.

7.1.2 General relativity Tests

The Atomic Clock Ensemble in Space (ACES) is an ESA ultra-stable clock experiment, a time and frequency mission to be flown from 2025 on the Columbus module of the ISS (International Space Station), to perform fundamental physics tests. The mission objectives are both scientific and technological and is of great interest to two main scientific communities: 1) the Time and Frequency community; which aims to use ACES as a tool for high precision Time and Frequency metrology; 2) the Fundamental Physics community; which will benefit from the use of ACES data for accurate tests of general relativity. The fundamental aspects of ACES deal with the physics of a cold atom clock. ACES consists of the Caesium clock PHARAO and on an active H-maser, built by Swiss Industry. An ESA topical team on tests of General Relativity with ACES is led by Prof. P. Jetzer. Indeed, the use of cold atoms techniques and interferometry will open new possibilities e.g. in the fields of gravitational waves, test of GR and search for some types of dark matter.

7.1.3 Widefield imaging and spectroscopic surveys

Current cosmology surveys have entered the Stage-IV at the start of this decade with the DESI project and shortly followed with the launch of the ESA Euclid Space mission. The V. Rubin Observatory, and the ESO 4MOST project will continue this endeavour of mapping the universe in 3D. Although these facilities where motivated to probe the nature of Dark Energy, the data collected is also serving other galactic and extra-galactic science cases. In the case of the V. Rubin Observatory the transients phenomena (whether variable stars, novae, supernovae, AGN, gamma-ray burst of EM counter part of gravitational wave …) will be studied in a comprehensive way.

The current DESI results, after one year of data, is advocating for an evolving Dark Energy model. Such a possibility is possibly opening up for new physics and is motivating the Stage-V cosmology surveys as one realised that these wide filed mapping of the Universe are key to explore Dark Energy but also other fundamental physics model (nature of the Dark Matter, weighting the mass of the neutrinos, probing the inflationary models, etc.). The upcoming HIRAX experiment will also provide a unique window on Dark Energy through the measurement of Baryonic Acoustic Oscillations using neutral hydrogen intensity mapping.

The first Stage-V project in construction is the MUltiplexed Survey Telescope (MUST) project led by Tsinghua University, and in which EPFL is contributing to the

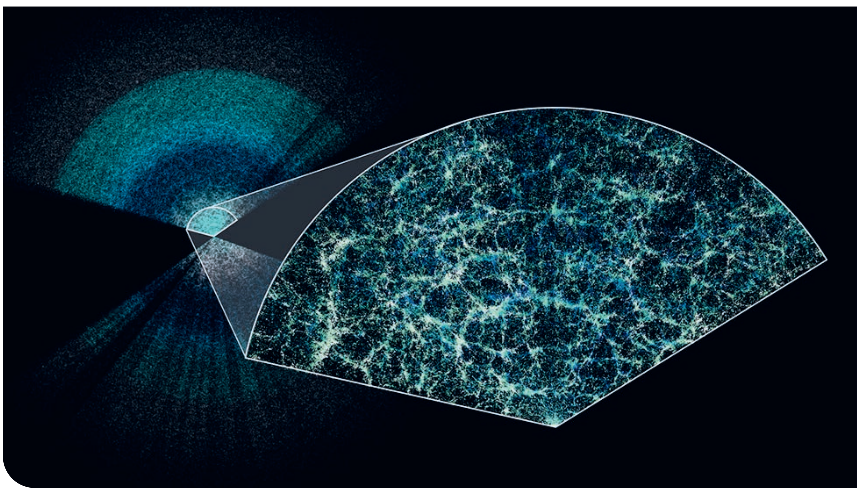


Figure 10: DESI has made the largest 3D map of our universe to date. Earth is at the center of this thin slice of the full map. In the magnified section, it is easy to see the underlying structure of matter in our universe. Source: Claire Lamman/DESI collaboration

fiber positioning robots. Other Stage-V project includes Spec-S5, and WST. With more than 200 millions and up to one billion objects with spectra these Stage-V project will provide a legacy database for any other galactic and extra-galactic science, as well as locating the EM counterpart of gravitational wave events.

7.2 Theme 2: Origins – stars, galaxies and the evolving Universe

The Swiss community has been very proactive in securing significant participation in future projects in the domains of stellar and extragalactic astrophysics. Such participation ensures the early access to cutting-edge data from these missions, and is therefore of great importance in securing the tools and means to keep playing prominent roles in astrophysical research in the future.

7.2.1 Ground-based projects

MOONS is the next-generation multi-object spectrograph for ESO's Very Large Telescope. Equipped with three arms, it will be able to acquire simultaneously 1000 spectra in the red and in the near-infrared. UNIGE, EPFL and ETHZ have contributed to the project, which will start its operations in 2025. MOONS will make key contribution to Galactic archaeology by delivering accurate radial velocities, metallicities and chemical abundances for several millions of stars over its lifetime. MOONS will also provide high-quality spectra for millions of galaxies at the peak of star formation history for the first time, matching a similar rest-frame wavelength, volume, range of environments and stellar masses as the successful Sloan Digital Sky Survey in the local Universe.

UNIGE and EPFL participate in the BlueMUSE consortium. BlueMUSE is a blue-optimised, medium spectral resolution, panoramic integral field spectrograph for the Very Large Telescope based on the very successful MUSE concept. BlueMUSE phase A started in April 2024, with a first light foreseen in 2032. With an optimised transmission down to 350 nm and a higher spectral resolution compared to MUSE, BlueMUSE will perform a survey of massive stars in our galaxy, the local group and up to galaxies within a few Mpc to increase the known population by a factor > 100. Deep field observations with BlueMUSE will also generate huge samples of faint and ultra-faint Lyman-α emitters in the epoch of the Cosmic Noon.

MOSAIC is a multi-object optical and near-infrared spectrograph for the ELT that is currently in development, with participation from UNIGE and EPFL. MOSAIC on the ELT will be a major instrument for stellar and extra-galactic astrophysics. It will be able to trace and explore the star-formation and chemical-enrichment histories of local galaxies by performing detailed spectroscopic observations of individual stars. MOSAIC will also probe the mass assembly of galaxies throughout the history of the Universe, up to Cosmic Dawn, perform a comprehensive inventory of matter in distant galaxies, and observe the first objects in the Universe.

A Swiss consortium is developing an instrument to perform intensity interferometry. Using this technique, large telescopes such as the VLT, GTC, CTAO-LST, ELT, etc., equipped with single-photon detectors with a picosecond resolution can reach an image resolution of 0.1–10 microarcsec. The development includes the detector itself and an on-the-fly correlator based on FPGA.

While its main science goal is the study of exoplanetary transits, the upcoming ESA PLATO mission, together with high-resolution spectrographs on the VLT and ELT, will provide a wealth of stellar variability data needed for comprehensive understanding fundamentals of stars, their properties as hosts of exoplanets, and the place of the Sun in the context of cool stars, which will be further supported by the high-resolution solar data obtained by the EST.

7.2.2 Space-based projects

UVEX is a new NASA Medium Explorer mission to explore the ultraviolet sky, planned for launch around 2030. UVEX is equipped with a wide-field ultraviolet imager and a spectrometer. Switzerland is participating in the mission through UNIGE. UVEX will perform an all-sky survey in the ultraviolet, which will complement cosmological surveys such as Euclid. It will also make important contributions to time-domain astronomy by capturing the UV emission and absorption features of transient sources.

ARRAKIHS is the new ESA's F (small) mission, selected in November 2022. The Swiss participation is led by UZH and EPFL. Its purpose is to detect the very faint surface brightness structures, stream and dwarf satellites, in the halo of a sample of Milky Way-like galaxies, down to unprecedented depth. These detections will help test the validity of the lambda CDM predictions in detail. Switzerland is particularly involved in supporting the mission at the consortium coordination, theoretical and data-processing levels.

The development of ESA's large X-ray mission Athena was stalled in 2022, because the cost of the mission was largely exceeding the available budget. A simplification exercised has been conducted in 2023, which ended up in the restart of a new assessment phase, under the provisional name of NewAthena, of a mission concept that now fits the budget without compromising the science. This hurdle means however that Athena is now planned for 2037, three years later than expected.

The mission concept THESEUS to develop an autonomously repointing satellite to detect and follow X-ray and gamma-ray transients, and to follow them in the infrared, was not selected as the fifth medium-size mission of ESA's Cosmic Vision programme. However, THESEUS was re-proposed for the seventh slot. It is now one out of three starting a new assessment phase. In case of final selection, the launch date is expected to be 2037.

7.3. Theme 3: Planets and the search for extra-terrestrial life

7.3.1 Priorities of exoplanetary research

The Swiss exoplanetary community has developed and maintained world leadership for decades despite the relatively modest financial means and the relatively small size of the research institutes/groups compared to international 'standards'. This was possible thanks to exceptional competences in the field, but also thanks to the deployment of synergies among Swiss groups and institutes to produce a 'critical mass', and to the successful prioritisation of projects and research infrastructures Switzerland is involved in, which in turn allowed to focus the limited resources in fewer projects but in a more relevant manner.

The research community develops its projects primarily within ESA for space and ESO for ground-based astronomy. Despite being a 'small' country, Switzerland is internationally recognised therein as a main actor, in particular in (exo-)planetary science, but also in Solar System exploration. Maintaining and strengthening Swiss leadership in projects deployed within these two organisations is thus also of critical importance for the future positioning of Switzerland.

Regarding future ground-based observations, the advent of the ELT will represent a phase change of exoplanet research. The construction of the dome is nearly completed, with (technical) first light expected in 2028. The ELT first-generation instrument METIS@ELT (a Mid-IR imager; involvement of ETHZ, Prof. S. Quanz), now under construction, will start to observe soon thereafter. The ELT second generation instrument ANDES@ELT (a high-resolution spectrograph) saw in 2024 as an important milestone the signature of its construction agreement between ESO and the consortium which includes UNIGE (Prof. C. Lovis) and UNIBE (Prof. C. Mordasini).

A non-exhaustive list of ongoing missions, present and future projects of critical relevance include, in space:

- Gaia (DR4 will include a list of exoplanets)
- CHEOPS (2nd extension)
- PLATO (launch end 2026)
- ESA L5 (near infrared Gaia OR search for temperate rocky exoplanets in the mid-infrared)
- NASA's upcoming flagship Habitable Worlds Observatory (HWO) – direct detection of temperate rocky exoplanets as main science driver
- LIFE (Large Interferometer For Exoplanets) – characterisation of terrestrial exoplanet atmospheres and search for life outside the Solar System

and from ground:

- METIS@ELT (first-generation instrument of ELT, under construction)
- RISTRETTO@VLT (Visitor instrument, first light 2028 TBC)
- ANDES@ELT (construction agreement signed, first light 2032 TBC)
- A northern ESPRESSO for the PLATO follow-up in the northern hemisphere (proposal with goal for first light in 2029)
- PCS@ELT, a high spatial resolution planet imager, and possible connections to ANDES (foreseen for 2035+)

In the next decades, the projects for detecting potential signs of life outside the Solar System will be the planned space-born observatories LIFE led by ETHZ (Prof. S. Quanz) and the NASA HWO as well as on the ground the future PCS (Planetary Camera and Spectrograph) at the ESO ELT. Already in the coming years, the RISTRETTO instrument (lead UNIGE, Prof. C Lovis, with UNIBE participation, Prof. C. Mordasini) and SAXO+ (both planned for the VLT) will serve as pathfinders to understand the challenges linked to the development and scientific exploitation of these future flagship instruments.

In terms of institutional and structural development in the country, the last years have seen the defining impact on the national community of the establishment of the NCCR PlanetS a decade ago. Country-wide collaborations in the (exo)planetary and adjacent research fields are now routinely started, thanks to the effect of PlanetS (director Phase 3: Prof. N. Thomas). As PlanetS will fade out and end in Summer 2026, progress towards the establishment of a Swiss Institute for Planetary Sciences (SIPS) has been substantial during the last years. One particular activity, beyond the organisational aspects of SIPS, has been the identification of flagship projects which obtained seed-funding from NCCR PlanetS in the domain allowing for a participation of Switzerland as a major partner. Four flagships have been identified for the future SIPS: Participation to Mars Sample return (laboratory analysis of ex-

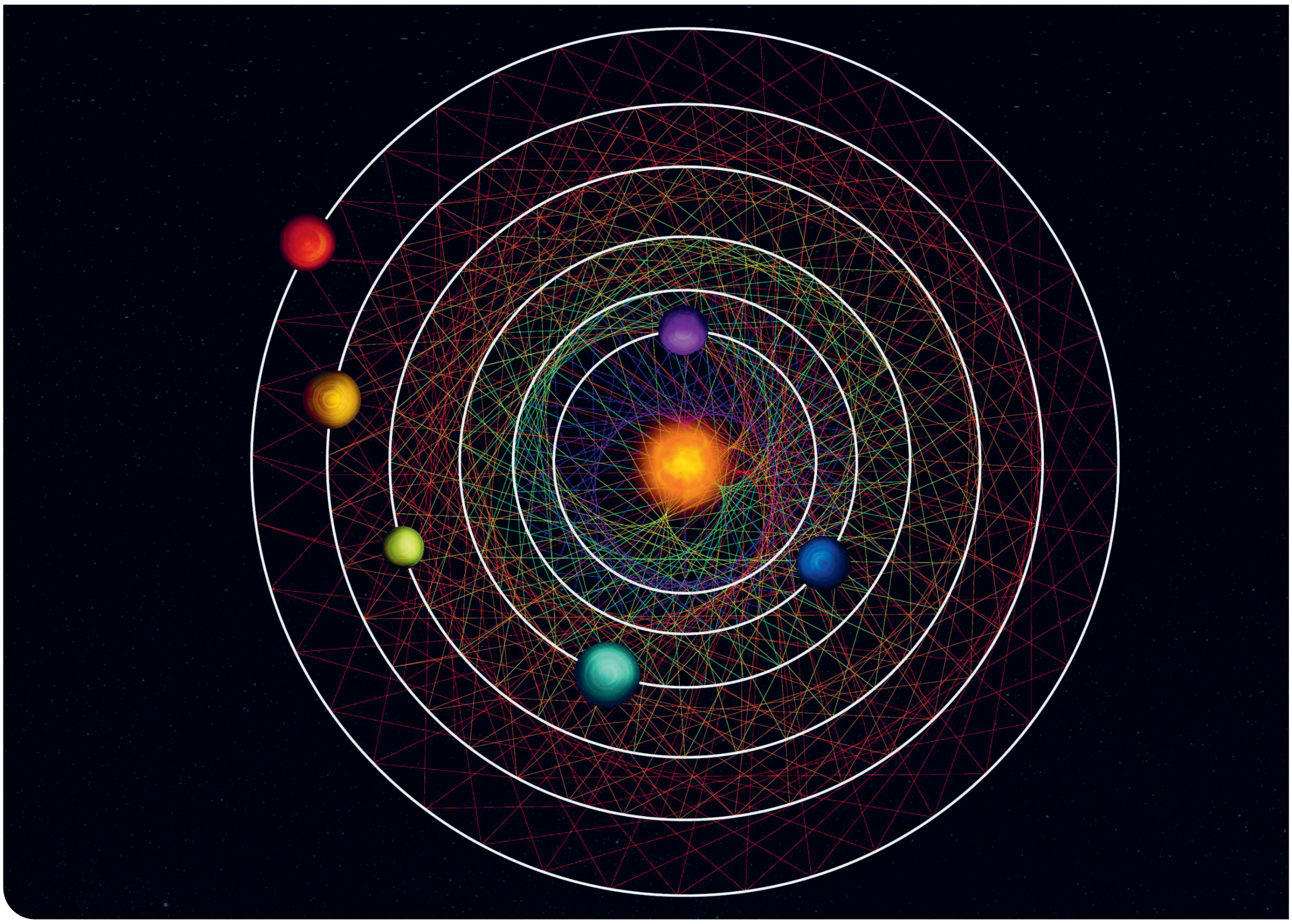


Figure 11: The six exoplanets of the star HD110067 observed by ESA's CHEOPS and NASA's TESS satellites create together a mesmerising geometric pattern due to their resonance-chain. Source: Thibaut Roger/NCCR PlanetS

tra-terrestrial samples), an Uranus mission (in the general context of missions towards icy moons – mass spectrometry, theory, internal structure and evolution), PCS@ELT (building up expertise in Extreme AO, with the pathfinders PLACID (Prof. J. Kuhn, UNIBE, on DAG Turkish telescope), RISTRETTO (Prof. Christophe Lovis and SAXO+), and the LIFE project.

In the coming years, SIPS intends to be the reference for (exo)-planetary science in Switzerland, building up on local actors (schools, centers). Indeed, during the last years, the different main actors in exoplanetary science have organised locally to support the challenges (multi-disciplinarity, extreme technological development, etc. …) linked to the understanding of exoplanets, and potential extra-solar life. Following the example of the Center for Space and Habitability (CSH – founded in 2011 at UNIBE, Profs. S. Wampfler and Y. Alibert), the UNIGE has started the Centre pour la Vie dans l'Univers (CVU, Prof. E. Bolmont) while ETHZ has started the Center for Origin and Prevalence of Life (COPL, Prof. D. Queloz). In the more general field of space-related research, other initiatives such as Space Hub (UZH), ETH Space (ETHZ), and the School of Engineering (UNIBE), provide welcomed support for development (technology, education of the next generation of researchers, etc. …) needed to position Switzerland as a major actor in the field of space-born planet research both in the Solar System and for exoplanets.

7.3.2 Priorities for Solar System exploration

The scientific exploration of the Solar System represents the only opportunity for carrying out detailed in situ measurements of celestial bodies beyond our Earth. These in situ measurements can be compared to telescopic observations, providing ground truth for observations outside the Solar System for example for exoplanets, which rely on remote sensing observations only. Both the two approaches are thus needed in parallel and mutually augmenting. The aforementioned statements about the specificities of the Swiss exoplanet research landscape also apply in large parts to Swiss Solar System research, namely regarding the excellent international standing and the importance of ESA as the main vector for space missions.

Future missions assessing habitability and the search for life in the Solar System are a priority in future planetary missions. JUICE/ESA and Europa Clipper/NASA are equipped with instrumentation for determining habitability of Jupiter's moon Europa. UNIBE has a strong participation in JUICE and a small in Europa Clipper. The planned Europa Lander mission of NASA has the goal, and will have the instrumentation, to search for life. Similarly, OrbiLander/NASA will search for signatures of life on Enceladus, an icy moon of Saturn. ESA also studies a large-class mission covering the science theme 'Moons of the Giant Planets', where Saturn's moon Enceladus is the top target. Even though these missions are relatively far in the future (2040s), development of dedicated instrumentation like mass spectrometers or optical methods (IR spectroscopy, polarimetry) for the detection of bio-signatures have to be developed now to assure participation in such ambitious mission, which will be highly competitive. In particular there is existing expertise in Switzerland and strong interest in combining *in situ* (e.g. mass spectrometry) with remote (e.g. spectro-polarimetry) biosignature detection for the outer solar system exploration. Such effort critically hinges on interdisciplinary expertise involving for instance microbiology lab experimental work (e.g. ERC/SERI SenseLife project). This underlines the importance of long-term laboratory research serving instrumental development for planetary sciences and astronomy.

Mars is also a promising destination to search for past or present life. The Rosalin Franklin Mars rover is part of the ExoMars mission of ESA and is planned to be placed on the Martin surface in 2028. To access sub-surface samples it will use drills, applying thereby its instrumentation to detect signatures of life. The large NASA Mars Sample Return mission – the highest priority in the US Decadal Survey released in 2022 – should bring samples collected by the Perseverance rover back to laboratories on Earth. The project is currently going through restructuring. It will offer opportunities for Swiss laboratories (ETHZ, UNIBE) to participate in the sample analyses, searching also for traces of life. Additionally, there are also smaller NASA missions planned, for example Abzu and Mars Life Finder, with instrumentation for in situ searches for signatures of present life. Also here are opportunities for significant participation by contributing Swiss instrumentation if the technology for life detection can be demonstrated well in advance, for example by demonstrations on terrestrial analogue sites.

In April 2024, Federal Councillor Guy Parmelin signed the Artemis Accords in Washington on Switzerland's behalf, emphasizing its commitment to international cooperation in space exploration. This agreement paves the way for Swiss participation in future NASA missions, including those aimed at lunar exploration. UNIBE is strongly involved in the NASA Commercial Lunar Payload Services (CLPS) initiative, which supports NASA's Artemis program by contributing the LIMS (Laser Ionisation Mass Spectrometer) for launch in 2027. This instrument will be used for the chemical study of lunar rocks, continuing the unique legacy of UNIBE's involvement in lunar exploration since the Apollo missions and marking the return of Switzerland to the moon. This development must be seen in the strong renewed push for human exploration, which offers many opportunities for (pure) science. This regards the future manned NASA mission to Mars in the 2040, where the search with remote sensing for water accessible to astronauts will be as indispensable as the use of mass spectrometers for traces of (subsurface) life, reflecting one of the most important themes in Solar System research. This involves for example very high-resolution imaging of Mars' surface for the search of landing sites and resources (water) that allow at the same time an unprecedented detailed view of Mars' surface. It also involves miniaturised mass spectrometers for in situ measurements by first robotic probes and then later by astronauts.

Future missions advancing our understanding of the origin and evolution of our Solar System represent the other priority in future planetary missions. This includes the exploration of both smaller building blocks of the Solar System like comets and asteroids but also major planets, some of which have never been visited by a dedicated spacecraft. The ice giants Uranus and Neptune are examples of such planets.

Regarding minor bodies, the Comet Interceptor Mission is a small mission set to launch in 2029 under ESA's Cosmic Vision program. It will stay in orbit around the L2 Lagrangian point until a long-period comet that can be reached is detected. At that point, the spacecraft will intercept the comet and deploy two probes to get closer to the coma for detailed study. It will be the next large step in comet research after the Rosetta Mission for which data analysis is still ongoing, underlying the importance of the support of long-term scientific exploration of mission data.UNIBE leads two instruments on this mission: the CoCa (Comet Camera) visible and near-infrared imager, led by Prof. N. Thomas from UNIBE, and the MANIaC (Mass Analyzer for Neutrals and Ions at Comets) mass spectrometer, led by PD Dr. M. Rubin, also from UNIBE. ETHZ is involved in ESA's M5 Envision orbiter for Venus, set to launch in 2031.

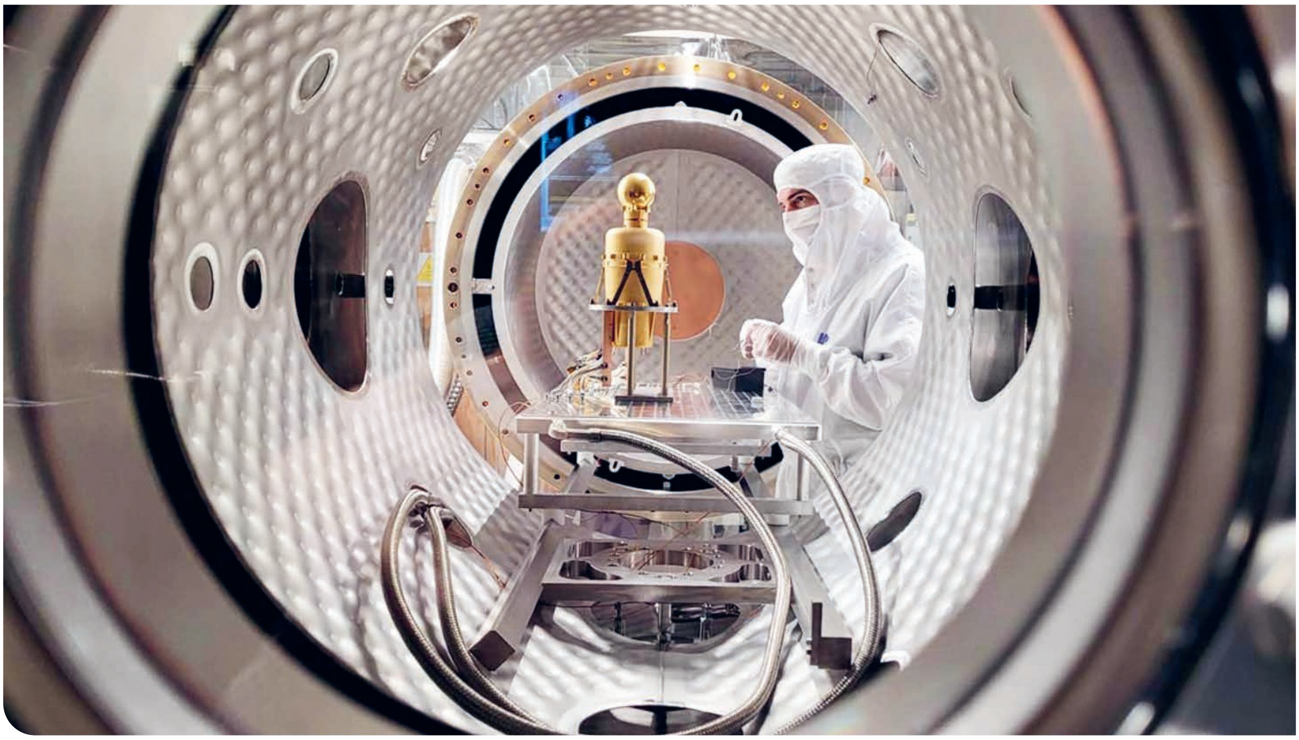


Figure 12: The mass spectrometer NIM in one of the thermal vacuum chambers at the University of Bern, where it was qualified and calibrated for the space mission Juice. Source: University of Bern/Audrey Vorburger

Regarding major planets, investigating Uranus' chemical composition is pivotal for advancing our understanding of both the formation and evolution of our solar system and the characteristics of exoplanets. Current knowledge of Uranus is limited compared to Jupiter, which has been extensively studied by the Galileo and Juno probes. Precise measurements of elemental abundances, especially helium and heavy noble gases, are essential to refine models of Uranus' formation and to determine whether it formed slowly or under different conditions compared to the gas giants. Additionally, isotopic ratios of hydrogen, nitrogen, carbon, and noble gases will reveal the primordial conditions and processes that shaped Uranus. This data, obtained through an in situ probe, will elucidate Uranus' unique features, such as its high ice content, low internal heat, and complex magnetosphere. Understanding these characteristics will not only provide critical insights into Uranus' history but will also enhance our knowledge of ice giants, which might be common among exoplanets, thereby offering a broader perspective on planetary formation and the evolution of solar systems.

The US Decadal Survey has recommended an Uranus Orbiter and Probe as the next NASA flagship mission after Mars Sample Return. The European Space Agency (ESA) is currently considering joining this mission, potentially delivering the probe in a collaboration similar to Cassini-Huygens. While no official statements have been made, ESA's presence at recent Uranus Orbiter and Probe workshops in both Europe and the US indicates strong interest. The primary instrument on such a probe would be a mass spectrometer, as outlined in both the Decadal Survey and the associated Uranus Mission study conducted by NASA. These documents highlight that the main science questions can all be addressed by measuring in situ Uranus' chemical composition. Given the short probe lifetime (~1 hour) due to Uranus' rapid planetary rotation and the limited communication window with the relay satellite, a time-of-flight (TOF) mass spectrometer would be the ideal choice. UNIBE has a high chance of building this mass spectrometer, thanks to the world-leading heritage and expertise in time-of-flight mass spectrometers.

Having a concrete design ready by the time ESA officially announces its participation in the NASA UOP Uranus Orbiter and Probe (UOP) would put Switzerland in the pole position for the mass spectrometer onboard the probe. Moreover, including a mass spectrometer experiment capable of measuring dense atmospheres in the portfolio would open up opportunities for a new series of space missions, such as missions to Venus, Titan, and Saturn.

7.4 Theme 4: Our home and its space environment

7.4.1 Priorities for solar physics research infrastructures

The advancement of the EST project through establishing its legal entity by international partners, including IRSOL/USI as a Swiss partner, opens a unique opportunity to address critical needs of a broader Swiss solar-terrestrial community to access high-resolution solar data on a regular basis in coordination with the space missions equipped with Swiss-built instruments. Federal funding for participation of Switzerland in this medium-size infrastructure is urgently required for consolidating the Swiss research in solar physics, solar-terrestrial and space weather studies as a national consortium followed by a Swiss contribution to the EST, possibly through a dedicated funding line. This will ensure the competitiveness of the Swiss research in these areas, strengthen the Swiss leadership and guarantee access for all Swiss researchers (also outside solar physics) to this premier European solar facility.

EST will significantly improve our understanding of solar magnetic activity and its influence on the heliosphere and the Earth. Its exploitation, also in cooperation with the DKIST, will revolutionise our understanding of the Sun as our home star and the host of the living planet Earth. High-resolution solar data are also required for understanding distant solar-type stars hosting exoplanets. In addition, the EST fills the critical gap in the scope of European astronomical facilities that are available to Swiss researchers with significant participation and hardware contribution.

7.4.2 Priorities for near-Earth environment research infrastructures

Predicting space weather and its effects on satellites improves the security in operation of space- and ground-based infrastructure, such as GPS, power grids, gas and oil pipelines, air and space traffic, etc. A high priority of Swiss research institutions is to advance Swiss expertise in space weather and establish a collaborative platform in this area to employ Swiss investments into the ground-based and space infrastructure related to solar and near-Earth research. Discussions with eight universities and research institutes are ongoing. Such a platform would also enable connections with Swiss stakeholders, to provide models, alerts and tailored forecasts according to their needs. The plans include building a synoptic solar telescope at SwissOGS to fill gaps in data that are needed for a better forecasting of solar flares. New satellite observation programs at the SwissOGS, e.g. scans of the geostationary orbit and high-resolution imaging using adaptive optics, will help improving security in space. The IRSOL's synoptic program on solar flares will continue for at least one solar cycle and provide critical knowledge for improving forecasting space weather on various time-scales.

Terrestrial reference frames (TRFs) are at the heart of metrology and all monitoring processes related to Earth Observation as recognised by the A/RES/69/266 United Nations Resolution. A high-quality TRF is the indispensable fundamental basis to allow for a long-term consistent monitoring of changes in the Earth system such as sea-level rise. Stations like SwissOGS will contribute significantly to SLR tracking of the Genesis mission and thus be essential for determining next generation TRFs. They are also providing a large amount of SLR measurements to ensure that variations of the very long wavelength part of the Earth's gravity field can be determined with the best possible quality to augment the results from satellite gravimetry.

Satellite gravimetry data records provided by the GRACE and GRACE-FO missions now span over 22 years and provide foundational observations of monthly to decadal global mass changes and transports in the Earth system derived from temporal variations in the Earth's gravity field. These observations, addressed as terrestrial water storage, have become indispensable for climate-related studies that enable process understanding of the evolving global water cycle, including ocean dynamics, polar ice mass changes, and near-surface and global ground water changes. The GRACE and GRACE-FO missions are among the most frequently cited missions in the reports of the Intergovernmental Panel on Climate Change (IPCC), underlying the importance to continue and enhance the spatial and temporal resolution of terrestrial water storage (adopted as an Essential Climate Variable by GCOS in 2022) by the planned joint ESA/NASA Mass-change And Geosciences International Constellation (MAGIC).

Our near-Earth environment is increasingly contaminated by space debris, jeopardizing safe and sustainable space operations and putting at risk their benefits for humanity. The number of spacecraft put into orbit has increased exponentially over the past years and unfortunately the number of debris objects follows this trend. Swiss researchers using data from the SwissOGS are studying and monitoring the debris population, to identify their major sources and release mechanism. This allows devising efficient mitigation and remediation measures and thus provides the scientific foundation for a sustainable use of the near-Earth space.

8 Funding strategy

Strengthen the pillars of Swiss funding strategy

The strategy for consolidating the Swiss leadership relies of three major pillars that should be consolidated and possibly strengthened to ensure Swiss leadership also in future.

8.1 Project funding

With increasing size and complexity of research facilities, additional means will be required. The above-mentioned projects will require significant funding for at least the next 15 years. While sane competition in view of selecting the best projects within prioritised infrastructures is suitable, Switzerland should avoid dispersing resources across too many infrastructures. Furthermore, Switzerland has to provide long-term funding commitment and financial sustainability to allow research groups and institutes to present themselves as reliable partners, or even claim leadership, in high-visibility/large-size projects.

Concerning ground-based astronomy, for instance, FLARE must continue focusing on its 'core' infrastructures (ESO for astrophysics), especially as long as other infrastructures like SKAO are being directly funded by SERI through other mechanisms. The SERI letter to SNSF regarding the prioritisation of funding was very appreciated by the Swiss astronomical community, because it emphasized the role of ESO and CERN. The support of new of projects within new organisations should be supported by a corresponding increase of FLARE budget. On the other hand, the community also strongly supports the idea of securing a 'fair share' within the FLARE budget for new and innovative projects within infrastructures not belonging to ESO or CERN but potentially strategic for Switzerland (e.g. EST or a Space Weather Hub). PRODEX and FLARE are designed to fund (instrumentation) projects as opposite to research (activities), who are instead supported by SNSF. This principle is well understood and accepted by the community. On the other hand, any activity or cost item related to the (instrumentation) project (components, travel and logistic costs, human resources, etc.) must remain eligible for FLARE and PRODEX. This aspect is of increased importance in the view of the termination of SNSF's R'Equip or the limitation by SNSF to fund (instrumentation and infrastructure) costs through normal SNSF grants.

8.2 Ensuring operations

Whereas space projects can benefit from PRODEX funding during their operational phase, such a possibility does not exist for ground-based projects and facilities. On the one hand, maintenance and operational costs are not eligible for FLARE, while on the other hand, SNSF expects the Universities to cover infrastructure costs. In case of infrastructures belonging to the University, this expectation might be legitimated, although the 'overheads' transferred by SNSF to the Universities are not sufficient for this task. However, in most cases the infrastructure does not belong to the respective University, and in those cases, the group and/or the institute who built the instrument has no mean to contribute to the follow-up and operations of it. Thus, continued national funding sources should be identified for Swiss contributions to the operation and maintenance of the ground-based research infrastructures governed by international consortia where Switzerland contributes instrumentation.

As mentioned before, scientific operation costs are eligible to PRODEX funding, ensuring successful operations and data management of projects like GAIA, CHEOPS, Euclid, etc. Scientific operational tasks are systematically carried out by research institutes embedded in Universities. While PRODEX covers direct personnel costs, induced infrastructural and service costs, must be bared by the Universities and their departments. Opposite to SNSF, however, PRODEX funding does not foresee overheads that could help covering these expenses. Another particular worry is the varying EUR-CHF conversion, for which there is no possibility of compensation. A dedicated mechanism should be implemented to ease the management of the scientific operation activities and their integration within Swiss Universities.

8.3 Scientific exploitation

The significant investment in instrumentation projects must be accompanied by research activities supported by SNSF and Universities, since research activities are not eligible neither for PRODEX nor FLARE. Consequently, it is very important that coherent and coordinated funding decisions are made, to avoid, for example, the situation that projects supported via PRODEX and FLARE are left without funding via SNSF project grants for the scientific exploration once they become operational. It appears evident that contributing to the construction of a large infrastructure, an instrument, or a space mission and not having the possibility of exploiting this project scientifically (in the sense of the original scientific objective) could be interpreted as an inefficient use of resources. Coherence and continuation of funding between FLARE/PRODEX, on one side, and SNSF, on the other side, should therefore be aimed at the transition between project and operational phase.

8.4 Other challenges

Whereas space projects can benefit from a vast palette of funding programs ranging from R&D (MARVIS etc.), through project funding, to operations (PRODEX), much more limited opportunities are left to ground-based projects. Pure R&D for instance, is not eligible for FLARE unless perfectly integrated in an established (full) project, neither they can be obtained through SNSF grants.

Another aspect on which Switzerland and Europe seem to lack strategic organisation and funding tools are the potential (but not yet fully exploitable) synergies between space missions and ground-based observations. By a matter of fact, there is no possibility to 'hard-link' space and ground-based projects, which are conducted almost 'stand-alone', although in many cases the former would critically benefit from the latter and vice-versa. For instance, the PLATO space mission must be accompanied by a ground-based follow-up programme if it is to exploit its results in an optimum way, but there are no mechanisms, neither at European level, nor at the national level, to enforce (or better enable) coordination and collaboration between ESA and ESO (opposite to NASA and NSF, for instance). This task has thus been left to the (self-organising) astronomical community. Similar example can be given for CHEOPS or Euclid (present), or CoRoT (CNES), Kepler (NASA) and TESS (NASA) in the past. Similarly, cosmology and the understanding of our origins also increasingly rely on the joint exploitation of ground-based and space-borne telescopes and missions (e.g. from the ELT, JWST, and SKAO) and on the combination of multi-wavelength and multi-messenger data. The availability of programs and cross-funding to link space missions and ground-based observations would clearly increase the efficiency of the scientific production and greatly simplify the organisation.

The United Nations Global Geodetic Centre of Excellence (UN-GGCE) has been newly established. Its objective is to strengthen the collective impact, i.e. to take full profit of investments in the global geodesy supply chain consisting of ground observatories (e.g. the SwissOGS), data centers, and analysis centers (e.g. the Center for Orbit Determination in Europe, CODE). Despite its undisputed importance, critical elements of the global geodesy supply chain are under-resourced and rely heavily on 'in-kind' contributions from Member States, universities and organisations. The critical ground infrastructure, like the 'Swiss-OGS', is not eligible for most funding instruments which poses a great challenge for their survival.

9 Annex I. A snapshot of Swiss Astronomy 2024

As of June 30, 2024

	Elected professors	Permanent Senior scientific staff	Non-permanent scientific staff	PhD students	Technical/ engineering staff	Secretarial/IT/ communication
UNIBAS	1	0	1	1	0	0
UNIBE, Divison Space Research and Planetary Sciences	3	9	35	41	53	13
UNIBE, Astronomical Institute	2	2	13	8	4	2
UNIGE, Department of Astronomy	13	11	41	44	49	21
UZH, Departments of Physics and of Astrophysics	8	4	19	25	1	3
USI, IRSOL	1	5	4	1	1	3
EPFL	2	4	22	21	4	6
ETHZ	3	2	36	23	4	3
ISSI Bern	1	1	4	0	1	6
PMOD/WRC (Davos)	1	3	5	4	18	6
Total numbers	**35**	**41**	**180**	**168**	**135**	**61**

These numbers do not take into account that several professors, which are active in theoretical and experimental physics institutes, work also partly or mainly on topics in cosmology and astrophysics. All of these professors are members of CHIPP, this is why we do not count them here explicitly. Moreover, there is some activity towards astrophysics also in Fachhochschulen (e.g. in the FHNW or SUPSI). Therefore, the total numbers, as given here, have to be considered as a lower bound. Notice, that as compared to the last Roadmap all numbers increased.

Status of the community (new leadership appointments and institutes)

In the following we list the main changes in the personnel that occurred in the various institutes across Switzerland since the last Roadmap of 2022.

IRSOL/USI: As of May 2022, Prof. Svetlana Berdyugina, appointed as IRSOL Director, USI affiliated professor and the Euler Institute Board member at the Faculty of Informatics, has established a new group 'Solar Magnetism and Space Weather'. She is an expert in theoretical and experimental spectro-polarimetry with broad applications in astrophysics and astrobiology. She is member of the EST Board of Trustees Executive Committee, and she also leads task teams within the NASA HWO Living Worlds science working group.

UNIBE/AIUB: At the Astronomical Institute of the University of Bern (AIUB), as of July 2022, Prof. Lucia Kleint, appointed as Deputy Director of the SwissOGS and new structural professor in optical astronomy at UNIBE, has established the new research group 'Space Weather' to develop and employ machine learning techniques for advancing the capability of predicting solar flares with applications for studying space weather, and lead astronomical instrumentation projects for solar and stellar observations. Her research focuses on the physics of the Sun, spectro-polarimetry, and AI. She serves as the president of the national committee of SCOSTEP and is a member of the steering committee of the future COSMO solar telescope.

UNIBE/PI: At the Division of Space Research and Planetary Sciences of the Physics Institute (PI) at the University of Bern, as of January 2022, Prof. Christoph Mordasini was appointed as full professor for theoretical planetology and executive director of the Division. His research is focussed on the study of physical processes during planet formation and evolution, the statistical comparison of the exoplanet population with model predictions, and the participation in large instrumentation projects for the observation of extrasolar planets. The Division is strongly involved in the conception, construction, and exploitation of space hardware for experimental planetology, flying its PI-instrumentation on major ESA and NASA missions. At the Center for Space and Habitability of the UNIBE, Prof. Susanne Wampfler and Prof. Yann Alibert were appointed Co-Directors. The Center of Space and Habitability is an interdisciplinary research center fostering interactions between the scientific disciplines interested in the formation, detection, and characterisation of other worlds within and beyond the Solar System. In Summer 2024, Prof. Willy Benz, who had retired at UNIBE in 2022, was elected President of the International Astronomical Union. Within the NCCR PlanetS (UNIBE/PI, UNIGE, UZH, ETHZ), Prof. Benz was replaced by Prof. Nicolas Thomas as the director (co-director: Stephane Udry, UNIGE).

UZH: As of January 2024, the new Department of Astrophysics has been created at the University of Zürich, which focuses on computational and theoretical studies in astrophysics and cosmology. The Department has also strong links with the international and national consortia around major experiments and observational facilities such as SKA, Euclid, LISA, and hosts the Swiss leadership team for the new ARRAKIHS fast ESA mission. From August 2023 Prof. Harald Ita has been appointed in the Department of Astrophysics, jointly with the Paul Scherrer Institute. He works at the interface between quantum field theory and gravitational physics, pioneering scattering amplitude calculations for merging black holes with numerical and analytical methods. SNSF Professor Aurel Schneider has transitioned to a permanent research staff appointment at the Department of Astrophysics as of September 2024. His group with strong bonds with the Euclid Consortium and SKACH Consortium will contribute to expand Swiss research on the epoch of reionisation, baryonic effects on large scale structure, and the theoretical interpretation of 21 cm intensity mapping with the future SKA-low array. From January 2024 Prof. Marcelle Soares-Santos joined the Physics Department; she works in observational cosmology with imaging and spectroscopic surveys, and multi-messenger astronomy including gravitational waves astronomy.

ISSI: As of September 2022, Prof. Thierry Dudok de Wit, appointed as new ISSI Director for Solar and Plasma Physics. His primary field of expertise is space science and space weather with a focus on data science and statistical inference.

FHNW: Since spring 2024, Prof. Brandon Panos has been appointed to lead the eXplainable Artificial Intelligence (XAI) efforts centered around observational data in heliophysics.

UNIGE: The Department of Astronomy has been led by Prof. Francesco Pepe since July 2019 who will complete his second term by July 2025. In the reported period, Prof. Pascal Oesch (galaxies formation and evolution and early Universe) was appointed Associate Professor in 2022, while Prof. Anne Verhamme (galaxies formation and evolution and early Universe) and Prof. Anastasios Fragkos (stellar physics, massive binaries and gravitational wave science) were both appointed Associate Professor in June, respectively August, 2024. Prof. Monika Lendl was appointed Associate Professor in Exoplanet Science in June 2024. Prof. Roland Walter was promoted to Associate Professor in 2023. Prof. Georges Meynet, full professor, retired by August 1st, 2024. In the same period, the department has welcomed several ERC and SNSF Starting Grants recipients who were consequently nominated Assistant Professor (non-tenure-track) at UNIGE.

The Department of Astronomy of UNIGE is involved in many space and ground-based projects within ESA and ESO, as well as other organisations, either as leading institute or as major contributor. Groups of the Department jointed the Swiss SKA Consortium (SKACH, Prof. Daniel Schaerer et al.) and CTAO (Prof. Roland Walter et al.). Two new intra-faculty centers with strong involvement by the Department of Astronomy have be created: The Centre for the study of Life in the Universe (CVU, Prof. Emeline Bolmont) and the Centre for Gravitational Wave Science

(GWSC, Prof. Anastasios Fragkos). Finally, it must be noted that from June 2022 to June 2023 the 'Geneva Observatory' celebrated it's 250th anniversary of its foundation through many public events.

ETHZ: In 2021, Prof. Didier Queloz, Nobel Prize winner working on exoplanets, was appointed as a Professor at ETHZ. Starting 2025 Prof. Michele Vallisneri will join ETHZ and work on gravitational waves in particular on LISA. In the 2022–2024 period, the Institute for Particle Physics and Astrophyics (IPA) at ETHZ also hosted ERC and SNSF Starting Grants recipients.

EPFL: in December 2021, Prof. Michaela Hirschman was nominated Associate Professor Tenure Track. Her primary field of expertise is the cosmic development of black holes and galaxies, and the modeling of their co-evolution. She is one of the world's leading theoreticians in this field, and her expertise is essential to the interpretation of the new terrestrial and space telescopes that can observe the first moments of the universe. In March 2024, Dr Emma Tolley senior scientist, was nominated Assistant Professor. Emma Tolley conducts research in the field of radio-astrophysics. She leverages high-performance computing (HPC) and data science for the efficient, automated computation and analysis of Big Data produced by scientific infrastructures such as the Square Kilometre Array Observatory radio telescope. EPFL has also welcomed an ERC and SNSF Starting Grants recipient who was consequently nominated Assistant Professor (non-tenure-track), namely: Prof. Richard Anderson.

The EPFL Astrophysics group is involved in space within ESA (Euclid and the new ARRAKIHS fast ESA mission) and ground-based projects within ESO (4MOST, VLT/BlueMUSE and ELT/MOSAIC). EPFL participation with other wide-field spectroscopic projects includes DESI and SDSS-V that are currently taking data as well as the next generation wide-field spectroscopic projects: MUST lead by Tsinghua university (China), Spec-S5 led by LBNL (USA) and WST led by CRAL in France. EPFL is also involved in other large infrastructure organisations such as SKAO, MWA, HIRAX and CTA, either as leading institute or as major contributor. Prof. Jean-Paul Kneib is the lead scientist of the Swiss SKA Consortium (SKACH) and is the Swiss scientific delegate at the SKAO Council. Prof. Emma Tolley is the lead scientist of the Swiss participation to the MWA project, whereas Prof. Andrii Neronov is the lead scientist of the Swiss Data Center for CTAO hosted at CSCS.

10 Annex II. Acronyms

3G	Third-Generation
4MOST	4-metre Multi-Object Spectroscopic Telescope. A fibre-fed spectroscopic facility on the VISTA telescope with a large field-of-view to survey a significant fraction of the southern sky in a few years
ACES	Atomic Clock Ensemble in Space
ALMA	Atacama Large Millimeter Array. A major collaboration between ESO, the US and Japan to construct and operate an array of 50 12-m millimeter-wave antenna, covering 200 km^2 of the Chajnantor plateau at 5000 m altitude
AMOR	Afocusing time-of-flight neutron reflectometer at PSI
ANDES	ArmazoNes high-Dispersion Echelle Spectrograph. ESO's ELT instrument formerly called HIRES
AO	Adaptive Optics
ARRAKIHS	Analysis of Resolved Remnants of Accreted galaxies as a Key Instrument for Halo Surveys
Athena	Advanced Telescope for High-Energy Astrophysics – X-ray observatory. X-ray telescope designed to address the Cosmic Vision science theme 'The Hot and Energetic Universe'
ARIEL	Mission in the ESA Cosmic Vision long-term plan to perform a chemical census of a large (of order 1000) well selected diverse sample of primarily warm and hot exoplanets orbiting relatively nearby host stars with a range of spectral types from A to M
ASTRONET	Planing and advisory network for European astronomy
BELA	BEpiColombo Laser Altimeter – a laser altimeter on board the ESA mission BepiColombo to study the planet Mercury
BepiColombo	Europe's first mission to Mercury
Blue-MUSE	Optical seeing-limited, blue-optimised, medium spectral resolution, panoramic integral-field-spectrograph for the VLT
CaSSIS	Colour and Stereo Surface Imaging System (built at the University of Bern)
CE	Cosmic Explorer
CERN	Eurpean Organisation for Nuclear Research
CHAPS	College of Helvetic Astronomy ProfessorS
CHEOPS	Characterizing ExOPlanet Satellite. – the first small mission in ESA's science programme dedicated to search for exoplanet transits using high-precision photometry. CHEOPS is jointly led by ESA and Switzerland
CHIPP	Swiss Institute of Particle Physics
CLARA	Compact Lightweight Absolute RAdiometer, onboard the Norwegian microsatellite NorSat-1 (launched in 2017)
CME	Coronal Mass Ejection – a massive explosion of solar (stellar) plasma into the outer space.
CMEx	NASA Small Explorer mission to study chromospheric magnetism (currently in phase A)

CoCa	Comet Camera (Visible/near-infrared imager) that will on board of the Comet Interceptor planned for launch in 2029.
CODE	Center for Orbit Determination in Europe
COPL	Centre for Origin and Prevalence of Life
CoRoT	Covention, Rotation and planet Transit. A space telescope mission which operated from 2006 to 2013
COST	Cooperation in Science and Technology
COST-G	Combination Service of Time-variable Gravity Fields. It is a product center of the International Gravity Field Service and is dedicated to the combination of monthly global gravity field models
CSCS	Centro Svizzero di Calcolo Scientifico — Swiss National Supercomputing Centre
CSEM	Centre suisse d'électronique et de microtechnique.
CSH	Center for Space and Habitability (UNIBE) Swiss R&D company, Neuchatel
CSR	(Swiss) Committee on Space Research
CTAO	Cherenkov Telescope Array Observatory – a new generation ground-based instrument for the detection of high energy gamma-rays
CVU	Centre pour la Vie dans l'Univers (UNIGE)
DARA	Digital Absolute Radiometer, onboard the Chinese JT-SIM satellite (launched in 2021).
DES	Dark Energy Survey – a catalogue of the sky over 5000 degrees to probe the Universe
DESI	Dark Energy Spectroscopic Instrument – to measure baryonic acoustic oscillations and redshift space distortions.
DKIST	Daniel K. Inouye Solar Telescope (formerly the Advanced Technology Solar Telescope)
DLR	Deutsche Zentrum für Luft- und Raumfahrt – German Aerospace Center
DORIS	Doppler Orbitographie et Radio-positionnement Intégrés par Satellite
ELT	Extremely Large Telescope
E-ELT	European Extremely Large Telescope. ESO's medium term priority after completion of ALMA is the construction of a 40-m class optical-infrared telescope
EM	Electromagnetic (radiation)
ENANTIOS	Swiss startup employing the ZIMPOL polarimeter in biopharmaceutics.
EnVision	ESA's next Venus orbiter, providing a holistic view of the planet from its inner core to upper atmosphere to determine how and why Venus and Earth evolved so differently
EOR	Epoque of Reionisation
EPFL	Ecole Polytechnique Fédérale de Lausanne
ERC	European Research Council
ERI	Education, Research and Innovation

ERIC	European Research Infrastructure Consortium – a legal framework to facilitate the establishment and operation of research infrastructures
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
ESO	European Southern Observatory
ESPRESSO	Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations – super-stable Optical High Resolution Spectrograph for the combined coudé focus of the VLT
EST	European Solar Telescope
ET	Einstein Telescope
ETH	Eidgenosische Technischen Hochschulen – Swiss Federal Institute of Technology
ETHZ	Eidgenosische Technischen Hochschule Zürich
Euclid	ESA mission to map the geometry of the Universe and better understand the mysterious dark matter and dark energy, which make up most of the energy budget of the cosmos
EUI	Extreme Ultraviolet Imager
ExoMars	Exobiology mission to Mars. Its aim is to further characterise the biological environment on Mars in preparation for robotic missions and then human exploration
FAIR	Findable, Accessible, Interoparable, Reusable
FHNW	Fachhochschule Nordwestschweiz – University of Applied Sciences of the North-West of Switzerland
FISH	ERC Project to study the explosion mechanism and nucleosynthesis in supernovae and Hypernovae explosions
FLARE	Funding Large international Research projects – SNSF
FPGA	Field Programmable Gate Arrays
Gaia	ESA mission to obtain extremely accurate positions and photometry of approximately one billion stars in the galaxy
GALA	GAnymede Laser Altimeter
GENESIS	ESA mission aiming at the co-location of the space geodetic techniques in space, approved in 2022.
Geo-OBSERVE	Integrated Long-Term Observatory (Pillar I from the Geosciences Community Roadmap 2024)
GNSS	Global Navigation Satellite Systems
GR	General Relativity
GRACE	Gravity Recovery and Climate Experiment
GRACE-C	GRACE Continuity, NASA mission, planned launch 2028.
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GREGOR	1.5 m solar telescope installed on Tenerife island with the goal of high precision measurements of the solar magnetic field
GTC	Gran Telescopio Canarias
GTO	Guaranteed Time Observation. Awarded to instrument developers to enable them to carry out specific science investigations with their instrument
GWs	Gravitational Waves
GWSC	Gravitational Wave Science Centre
HARPS	High Accuracy Radial velocity Planet Searcher – an ultra-high precision spectrometer operating on the ESO 3.6m telescope
HEIG-VD	Haute École d'Ingénierie et de Gestion du Canton de Vaud
HES-SO	Haute École Spécialisée de Suisse Occidentale
HIRAX	Hydrogen Intensity and Real-Time Analysis eXperiment
HPC	High Performance Computing
HST	Hubble Space Telescope, NASA-ESA orbiting 2.5 m telescope, in operation since 1990
HWO	Habitable Worlds Observatory – a NASA flagship space telescope for searching extraterrestrial life, to launched in the 2030s
INTEGRAL	INTErnational Gamma-Ray Astrophysics Laboratory. ESA's gamma-ray observatory
IRSOL	Istituto ricerche solari Aldo e Cele Daccò, Locarno
ISSI	International Space Science Institute
JAXA	Japan Aerospace Exploration Agency
JEDI	Extreme Ultra-Violet Imager for the ESA mission Vigil (NASA contribution), launch in 2031
JT-SIM	One of the payloads on the Chinese Fengyun-3E (FY-3E) spacecraft
JUICE	JUpiter ICy moons Explorer – an ESA space mission to explore Jupiter's icy moons
JWST	James Webb Space Telescope. The 6.5 m successor to the HST launched in December 2021
KAGRA	Kamioka Gravitational Wave Detector
Kepler	NASA mission designed to explore the structure and diversity of planetary systems
L5	Lagrange point 5 on an orbit of a celestial body
LIFE	Large Interferometer For Exoplanets
LIGO	Laser Interferometer Gravitational-wave Observatory – ground-based observatory that first detected gravitational waves
LISA	Laser Interferometer Space Antenna – a space-based gravitational wave observatory building on the success of LISA Pathfinder and LIGO
LISA-Pathfinder	Mission testing in flight the very concept of gravitational wave detection
LSST	Large Synoptic Survey Telescope – precedent name of the Vera C. Rubin Observatory
LST	Large-Sized Telescope of the CTAO
MANIaC	Mass Analyzer for Neutrals and Ions at Comets – a mass spectrometer to sample the gases released from the comet
MARVIS	Multidisciplinary Applied Research Ventures in Space (MARVIS). SNSF funding scheme to promote consortia projects that explore space.
MAP	Mathematics, Astronomy and Physics (Platform MAP of the SCNAT)
Mars Express	NASA mission exploring the atmosphere and surface of Mars from polar orbit since arriving at the red planet in 2003

M-MATISSE	Mars Magnetosphere ATmosphere Ionosphere and Space-weather SciencE. ESA medium (M-class) mission project
MeerKAT	Karoo Array Telescope
METIS	A Mid-infrared ELT Imager and Spectrograph
MHD	Magnetohydrodynamics
MIRI	Mid-InfraRed Imager. Instrument built for the JWST by a European-US consortium, operating in the 5–28 μm waveband and performing both imaging and spectroscopy
MOONS	Multi-Object Optical and Near-infrared Spectrograph
MOS	Multi-Object Spectrograph
MOSAIC	Multi-object spectrograph with high multiplex and high-definition capabilities on ESO's ELT
MUSE	Multi-Unit Spectroscopic Explorer, a second-generation instrument for the ESO's VLT, consisting of a 90,000 channel integral field spectrograph
MUST	MUltiplexed Survey Telescope
MWA	Murchison Widefield Array, a radio telescope made of 4096 spider-like antennas tuned to receive signals from the sky between 70 and 300 MHz
NASA	National Aeronautics and Space Administration
NCCR	National Centre of Competences in Research (funded by SNSF)
ngEHT	next generation Event Horizon Telescope
NGTS	Next Generation Transit Survey. An array of small robotic telescopes installed at Paranal, Chile
NIM	Neutral gas and Ion Mass spectrometer
NIRPS	Near Infra-Red Planet Searcher
NORSAT-1	Small Norwegian satellite to investigate solar radiation, space weather, and ship traffic. Launched in 2017
OMEL	Optical Materials Engineering Laboratory at ETHZ
PCS	Planetary Camera and Spectrograph
PASC	Platform for Advanced Scientific Computing
PHARAO	First cold-atom clock ever to orbit Earth, operating outside the International Space Station
PlanetS	NCCR funded by the SNSF
PLATO	PLAnetary Transits and Oscillations of stars – ESA mission to measure planetary transits and stellar oscillations. Launch foreseen in 2026
PMOD/WRC	Physikalisch-Meteorologische Observatorium in Davos/ World Radiation Center
PRIMA	Phase-Referenced Imaging and Micro-arcsecond Astrometry. Former ESO VLTI instrument replaced by GRAVITY
Proba-3	ESA mission to demonstrate formation flying in space. Two paired satellites will form a 150 m long solar coronagraph. Launch foreseen in 2024
PRODEX	PROgramme de Développement d'Expériences scientifiques
PSI	Paul Scherrer Institute
R&D	Research and Development
RISTRETTO	instrument: independent, AO-fed spectrograph proposed as a visitor instrument, with the goal of detecting nearby exoplanets in reflected light for the first time
Rosetta	ESA mission to rendez-vous with a comet and follow it to study its physical properties and evolution on its orbit
Rubin Observatory/ LSST	The goal of the Vera C. Rubin Observatory project is to conduct the 10-year Legacy Survey of Space and Time (LSST). LSST will deliver a 500-petabyte set of images and data products that will address some of the most pressing questions about the structure and evolution of the universe and the objects in it
SAXO+	An upgrade of the SAXO adaptive optic system for the SPHERE instrument
SCFA	Swiss Commission for Astronomy
SCNAT	Swiss Academy of Sciences
SCOSTEP	Scientific Committee on Solar Terrestrial Physics
SDSS-V	Sloan Digital Sky Survey – 5. Facility providing multi-epoch optical and IR spectroscopy across the entire sky, as well as offering contiguous integral-field spectroscopic coverage of the Milky Way and Local Volume galaxies
SERI	State Secretariat for Education, Research and Innovation
SGC	Swiss Geodetic Commission
SIPS	Swiss Institute for Planetary Sciences
SKA	Square Kilometer Array – International project to build the largest radio telescope in the world with a square kilometre of collecting area
SKACH	SKA Switzerland Consortium
SKAO	Square Kilometer Array Observatory – the SKA organisation- a not-for-profit company established in December 2011 to formalise relationships between the international partners and centralise the leadership of the SKA project
SLR	Satellite Laser Ranging
SMILE	Solar wind Magnetosphere Ionosphere Link Explorer
SNSF	Swiss National Science Foundation
SOHO	SOlar Heliospheric Observatory, an ESA/NASA space mission
SOLAR-C	JAXA space mission to study the Sun with a contribution from ESA
SolO	Solar Orbiter. ESA mission dedicated to solar and heliospheric physics launched in February 2020
SPICE	SPectral Imaging of the Coronal Environment
Spec-S5	Spectrographs foreseen for 2037 to probe the accelerated expansion of the universe
SPECULOOS	Search for Planets EClipsing ULtra cOOl Stars. Network of robotic telescopes in search of exoplanets
SPHERE	A second-generation instrument for the ESO's VLT, designed to detect large Jupiter-like planets around nearby stars
SSAA	Swiss Society for Astrophysics and Astronomy

STIX	Spectrometer Telescope for Imaging X-rays
STROFIO	neutral mass spectrograph for sampling Mercury's exosphere
SUPSI	Scuola universitaria professionale della Svizzera italiana
SWI	Submillimetre Wave Instrument (on JUICE)
SwissOGS	Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald
SXI	Soft X-ray Imager
TESS	Transiting Exoplanet Survey Satellite is an MIT-led NASA mission to spend two years discovering transiting exoplanets by an all-sky survey
THESEUS	Transient High Energy Sky and Early Universe Surveyor. Mission designed to vastly increase the discovery space of the high energy transient phenomena over the entirety of cosmic history
UNIBAS	University of Basel
UNIBE	University of Bern
UNIGE	University of Geneva
USI	Università della Svizzera italiana
UVEX	Ultraviolet Explorer. Wide-field ultra-violet space telescope to be launched in 2030 by NASA
UZH	University of Zurich
Virgo	Interferometric gravitational-wave antenna (in Italy)
VIRGO	Variability of solar IRradiance and Gravity Oscillations onboard the SOHO Mission
VLBI	Very Long Baseline Interferometry
VLT	Very Large Telescope: The four 8-m telescopes operated by ESO at Paranal Observatory
VTF	Visible Tunable Filter
WST	Widefield Spectroscopic Telescope
XMM-Newton	X-ray Multi-Mirror Mission. Launched in 1999, it carries three high throughput X-ray telescopes with an unprecedented effective area, and an optical monitor
XRISM	X-Ray Imaging and Spectroscopy Mission
ZHAW	Zürcher Hochschule für Angewandte Wissenschaften
ZIMPOL	Zurich IMaging POLarimeter, the visual focal plane subsystem of SPHERE

SCNAT – network of knowledge for the benefit of society

The **Swiss Academy of Sciences (SCNAT)** and its network of 35,000 experts works at regional, national and international level for the future of science and society. It strengthens the awareness for the sciences as a central pillar of cultural and economic development. The breadth of its support makes it a representative partner for politics. The SCNAT links the sciences, provides expertise, promotes the dialogue between science and society, identifies and evaluates scientific developments and lays the foundation for the next generation of natural scientists. It is part of the association of the Swiss Academies of Arts and Sciences.

Administrative organisation of the astronomical community in Switzerland

The Swiss Commission for Astronomy (SCFA)
Representatives from the astronomy institutes in Switzerland, preferentially the directors, and representatives of important activities in the realm of the SCFA (SSAA President, CSR President, IAU contact person).

The College of Helvetic Astronomy Professors (CHAPS)
Tenured professors in astronomy in Swiss academic institutions, as well as permanent Titular professors and tenure-track professors.

The Swiss Society for Astrophysics and Astronomy (SSAA/SGGA)
Ensemble of the researchers, at all levels, active in the fields of astronomy and astrophysics in Switzerland.