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Astronomy Roadmap

for Research and Infrastructure 2025–2028 and beyond
by the Swiss Astronomy and Astrophysics Community

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The Very Large Telescope snaps a stellar nursery and celebrates fifteen years of operations. (Image ESO)

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Content

1 Foreword

The present roadmap for future large research infrastructures represents the view of the Swiss scientific community in the field of astronomy. It is a formal element of the process to elaborate the 'Swiss Roadmap for Research Infrastructures 2023' according to Swiss law (art. 41 Federal Act on the promotion of research and innovation; art. 55 of the corresponding Ordinance). The roadmap describes the community needs in terms of national or international research infrastructures for the funding period 2025–2028. It shall serve as an additional basis for the decision-making on new or major upgrades of national infrastructures and/or major participation in international network infrastructures and user facilities.

The responsibility for the elaboration of the 'Swiss Roadmap for Research Infrastructures 2023' rests with the State Secretariat for Education, Research and Innovation (SERI). It has thus launched a process that includes (phase 1) the selection of infrastructures by the ETH Board and swissuniversities, (phase 2) the evaluation by the Swiss National Science Foundation (SNSF), and (phase 3) the assessment of the feasibility again by the ETH Board and swissuniversities. The result will be submitted to the Federal Council for consideration and decision in the context of the Dispatch on Education, Research and Innovation 2025–2028. This whole process is complemented by a preparatory phase to establish the needs of the various scientific communities. The SERI has formally mandated the Swiss Academy of Sciences (SCNAT) with the elaboration of these discipline-specific community roadmaps to which the present one belongs.

SCNAT initiated the work to elaborate such discipline-specific community roadmaps in the fields of biology, geosciences, chemistry, and in subfields of physics in the last quarter of 2018. Its Board defined a process that provided for an overall strategic project lead and for community – specific sub-projects, all led by acknowledged researchers. The whole process was modelled in analogy to the long-standing experience of SCNAT in the fields of astronomy and physics, where roadmaps for research infrastructures had been elaborated in earlier years by the various communities, which were assembled for that purpose around a so-called 'Round Table'. Accordingly, starting in 2019, such Round Tables were also established in biology, chemistry and geosciences. In the past two years hundreds of researchers were invited to take part in this process and dozens of them actively participated in each of the various Round Tables. Whereas this effort was run under the overall responsibility and guidance of SCNAT, including the provision of considerable scientific, editorial and administrative manpower by its office, the final result must be considered a genuine bottom-up contribution by the various scientific communities.

In astronomy, major research infrastructures in space and on the ground are planned and built within international collaborations at a fast and even accelerating pace. Boundary conditions change as well and the academic and industrial landscape in which projects that are carried out have to adapt. The goal of the roadmap at hand is to provide an updated view of this fast evolution in Switzerland, with a clear emphasis on major (and new) developments in the field and on the associated large infrastructure needs, on the ground. The parallel developments for space research are described in another roadmap document – 'A report on space science in Switzerland' – prepared by the Swiss Committee on Space Research (CSR) of SCNAT. The present roadmap 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. This exercise led to a number of findings and recommendations that capture key aspects of Swiss astronomy today, updating the framework laid down by previous roadmap exercises. It has been prepared by the Swiss Commission for Astronomy (SCFA) of the SCNAT acting as the bureau of CHAPS, the College of Helvetic Astronomy Professors.

The Milky Way glitters brightly over ALMA. (Image: ESO/B. Tafreshi)

2 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 all 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.

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 in the field of astronomy and its related ambitious infrastructure is furthermore developing continuously at a fast pace asking for a regular reassessment of the priorities.

This assessment aims first at supporting political decisions for the period 2025–2028. However, because of the typical decade-long timescale of the development of large projects in astronomy, it actually gives an overview of the field for the next decade and beyond. 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, in order to perpetuate the outstanding record of Swiss astronomy in a highly competitive international context.

The Trifid Nebula. (Image: ESO)

3 Findings and Recommendations

3.1 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.

Finding 1: The breadth of Swiss astronomy is impressive and has grown very significantly over the past 15 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.

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.

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:
- 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).

3.2 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 ELT and SKAO will be used to address some of the most pressing scientific questions in astronomy, the VLT and its suite of instruments, as well as ALMA, will remain the workhorse facilities for most astronomers. This implies continued investment in new instruments, 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, and soon ELT) 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 astronomy community is defining the development of the ESO ELT with its instrumentation and SKAO as the flagship projects 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 these facilities. As a new member of the SKAO, Switzerland should consolidate its participation in particular to be ready to analyse the SKAO data, through participation in the European SKAO Regional Center.

Finding 4: The participation by research teams in consortia building of instruments in the framework of large-scale projects provides access to significant amounts of observing time and data of unprecedented quality needed to maintain scientific leadership.

Recommendation 4: Given the size and number of instruments foreseen for the future world-leading astronomical facilities, the FLARE support for astronomical instrumentation is fundamental and has to be maintained at a commensurable level, focusing on the large-scale projects, and adapting to the constraints imposed by the long-term nature of these projects.

Finding 5: The establishment of international organisations developing new large facilities in astronomy (e.g., the Einstein Telescope) will require additional funding for these new key research infrastructures for astronomy. A federated participation by Switzerland in these future large projects, guaranteeing access to all researchers working at Swiss institutions, is important. Among the additional facilities, the Swiss astronomy community considers at present the future Einstein Telescope as scientifically the most attractive. It is imperative that the cost of joining these new projects be covered through newly available funding and not at the expense of the active Swiss participation in ESO, SKAO or ESA. It is then fundamental that a strategic approach is set up at national level to ensure a strong coherence and support to present high priorities as well as for future promising developments.

Recommendation 5: Financial support to the building of new large infrastructures in astronomy, in the frame of international organisations being established in parallel to ESO and SKAO, should be made available first through a dedicated financial line in the budget of research in Switzerland. In a second phase, new instrumentation and software updates will enter the FLARE framework provided that the level of funding is adjusted accordingly. We endorse also that both CHIPP and CHAPS should explore common interests in and develop a common strategy towards future gravitational wave experiments, in particular the Einstein Telescope.

Finding 6: Some areas of astrophysical research can be best addressed through the participation in medium-size projects taking place outside the framework of the international organisations Switzerland is participating in. To maintain leadership in these areas in Switzerland, it is important for local researchers to have access to financial support for such projects.

Recommendation 6: Financial support should be made available for medium-size to larger-scale 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 research infrastructures to areas outside the main focus of ESO and SKAO. The European Solar Telescope (EST), which is since 2016 in the ESFRI Roadmap, is a nice example of a medium-size project.

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. This particular point will become critical with the flow of SKAO data starting in 2025. 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 participation in the SKAO Regional Center, that could also benefit in the exploitation of multiwavelength data coming from other astronomical observatories.

3.4 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 National Complementing Activities (NCA). 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 document prepared by the Committee on Space Research (CSR): ‘A report on space science in Switzerland’. 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 in 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 all the major missions of the ESA programme, including the Swiss leadership of the CHEOPS mission. 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. An improved networking of Swiss infrastructure and space capabilities, such as the newly established Space Exchange Switzerland (SXS) platform, should be promoted to give broader access to space-borne science in general.

Finding 9: The opportunities to participate in the programmes of agencies other than ESA are becoming increasingly important for the Swiss community. In comparison to other countries of similar size (e.g., Belgium), Switzerland's ability to fund activities outside the framework of ESA is severely limited. In addition, funding of auxiliary technical activities (for ESA and non-ESA missions) that are not directly related to the building of experiments (in particular the support to operations) is also clearly needed.

Recommendation 9: A funding programme covering the activities funded through the NCA over the next period is necessary, with clear terms of reference for the domain of application. We also recommend that a regular assessment of the relative contributions to the programmes of each agency be performed in consultation with the community.

3.5 Data science and High-Performance Computing

Finding 10: 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 10: 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 neighboring fields. Among examples that require a dedicated investment in supercomputing infrastructure for large-scale numerical simulations are flagship projects such as SKAO. 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 11: 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 resources and the development of fast advanced algorithms.

Recommendation 11: 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.

Finding 12: 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 (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 12: 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 data preservation of missions of particular Swiss interest, as well as the leadership and visibility of Switzerland in this thematic, in particular for space missions.

3.6 Additional findings

Finally, additional findings are provided in relation with the science funding scheme in Switzerland and its importance for astrophysics. These observations should be considered in any global strategic review of national priorities for Swiss astrophysics, but do not come with actionable recommendations for SERI or SNSF.

Finding 13: 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 14: 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 15: 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.

Artist's impression of the TRAPPIST-1 planetary system. (Image: ESO/N. Bartmann)

4 Context and background

Astronomy is one of the oldest and most widely recognised sciences, originating with the simple fascination and wonder of the night sky. Over time, it has evolved into 'astronomy and astrophysics'[1] one of the most active and dynamic areas of science, integrating multifaceted approaches, from theoretical modelling to state-of-the-art numerical simulations and cutting-edge observations with world-class instruments in space and on the ground, at the forefront of technological developments.

For a few decades, astronomy has been experiencing a golden age, taking advantage of increasingly powerful observing facilities. New instruments on the ground and space missions have produced fascinating discoveries and stimulated dramatic advances in our understanding of the universe and its constituents. These findings motivate the next generation of theoretical and technological developments, as well as laboratory experiments. Pushed by these developments, the field is evolving now extremely rapidly.

Astronomical research is a highly competitive endeavour in which excellence and know-how are essential for progress. In a rapidly evolving environment, success requires dedicated and innovative researchers working within an appropriate framework favouring talents to blossom. A Roadmap for Astronomy aims at providing such a framework, pointing out the strength of the system, providing recommendations for further improving its coherence and impact, and highlighting the main priorities of the field. In particular, such a roadmap is important to

– Effectively plan costly investments in research projects and long-duration infrastructures

– Set priorities for future directions and facilities of the European organisations European Southern Observatory (ESO) and European Space Agency (ESA)

– Initiate and develop new scientific directions, such as the new participation of Switzerland in the intergovernmental organisation Square Kilometre Array Observatory (SKAO)

– Provide input to a European and World-wide vision for astrophysics

– Coordinate activities in education and outreach

– Provide a national context for decisions at the local level.

In this context, Switzerland is doing extremely well with established research groups at the forefront of international research and leading major developments in the field. This builds firstly upon the recognised strength and vigorous activity of our researchers; it has also been fuelled by intense public interest. Recent discoveries address timeless questions about the place of humankind in the Universe and point toward fundamental new physics. This is beautifully illustrated by the Nobel Prize in Physics 2019 'for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos' to James Peebles and our Swiss colleagues Michel Mayor and Didier Queloz.

Astronomy and astrophysics do not have sharply defined boundaries. By essence, they are naturally intertwined with many other branches of physics, mathematics, or computer sciences. There are indeed strong synergies between particle physics and cosmology, or close ties between nuclear physics, hydrodynamics, and stellar evolution. New approaches in computer sciences and statistics (machine learning, etc.) are widely used to handle large samples of observational data in astronomy. Planetary astrophysics has also strong common interests with geophysics, while the growing interest in the development of the conditions necessary for the emergence of life has spawned the vigorous new field of astrobiology, bringing together astrophysics, geophysics, chemistry, and biology. These scientific interconnections are providing much of the excitement and relevance of 21st century astrophysics.

Nevertheless, to define our community and our ambitions, we have to delimit the scope of our strategic considerations. Following the approach used in previous Roadmaps, these boundaries have been set on the basis of the research methods used aiming at understanding the nature and properties of celestial bodies and of the universe itself. As a result, we have excluded from our main considerations neutrino observatories and other subjects more closely related to particle physics, computer science, or geophysics.

1 In this document, 'astronomy' and 'astrophysics' will be used interchangeably. The former is closer to the public perception of the field, while the latter provides a better description of our science. Both refer to the modern research methods used.

Figure 1: Illustrative composite images of the ESO facilities covering a very large window in wavelengths. (Image: ESO/M. Kornmesser)

There are, however, clear connections between astrophysics and particle physics, materializing in the domains of 'astroparticles' and 'multi-messenger astrophysics', attracting more and more scientists originally active in particle physics. This bridging, although not a main priority for the astronomy community today, opens however interesting possibilities for synergies at infrastructure level (similar/common instrumentation), as well as at institutional level (FLARE is the common funding body for the Swiss participation to international large instrumentation projects in astrophysics and particle physics). The scientific portfolio of questions addressed by both communities is subject to the unavoidable tension of breadth versus depth and hence requires an equitable process of prioritisation, ideally by 'bottom up' consensus building.

To help in this process, a coordination has been initiated in 2020 between the two communities (through the Swiss Institute of Particle Physics [CHIPP] and SCFA/CHAPS), speaking, if possible, with a common voice to SERI and facing together, through the establishment of common working groups, the challenges brought by new fundamental developments at the interface between the two fields. The most visible and important among them is undoubtedly the opening of a new window to the universe with the first detection of gravitational waves in 2015 and the subsequent ambitious space and ground-based instruments being developed at present. The Swiss community is organizing itself to embark in this fast-accelerating train and become one of the important players in the game.

5 Swiss astronomy today

Over the past decade, 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.

5.1 A growing community with a vision

In Switzerland, a number of new research groups were established, led by newly appointed professors. In addition, new professors were also appointed and successions have been executed in already existing research areas, thereby strengthening local priorities in the corresponding fields of research. From the 21 professors reported in the first roadmap for Swiss astronomy in 2007, there has been an increase in the overall number of professors, which is now some 30 in the various astronomy institutes. This number does 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.

The most illustrative example of such developments is given by the establishment in 2014 of a National Center of Competence in Research (NCCR) in planetary science, PlanetS, co-led by the universities of Bern and Geneva with strong support of participating institutions (University of Bern, University of Geneva, University of Zurich and ETHZ). This allowed the number of professors in the field to be roughly doubled over a period of 7 years through the creation of new positions and promotions. The long-term goal of PlanetS is to establish, by the end of the NCCR in 2026, a Swiss Institute for Planetary Science (SIPS) with clearly identified activities and responsibilities decentralised in the participating institutions. Such projects and vision have an important influence on the local academic and strategic organisations, helping build a coherence between the science interests of the Swiss community, the national infrastructural investments, and the local evolution of the research groups and prioritisation plans at university/ETH level.

The same is true with international ambitious and federating scientific projects associated with the developments of large infrastructure and/or cutting-edge instruments in space or on the ground. Among the most prominent examples of such projects, we can mention the recent participation of Switzerland in the SKA Observatory (the world largest radio facility to be built in Australia and South-Africa), and the opening of a new window on the universe with the detection of gravitational waves. Academic and research institutions are now evolving to adapt to these new priorities. In the domain of radio astronomy, a new professor position at EPFL is expected to be open in 2022 or 2023 at the latest, and in the domain of gravitational waves, a new professor position at the University of Zurich in the context of the LISA space mission of ESA is now open, to be filled by 2023. At the University of Geneva, the Gravitational Wave Faculty center was created in January 2022. It aims at facilitating and fostering collaborations between groups in the Physics Section and the Astronomy Department in Geneva, at stimulating and catalysing activities in the field of gravitational waves at the Swiss level in synergy between CHIPP and CHAPS and in the framework of large collaborations such as ET and LISA. The ETHZ has plans to open a position for a new professor in Experimental Gravitational Waves.

Since 2016 there have been some major changes in the domain of solar physics. The ETHs and the Schweizerische Forschungsinstitut für Hochgebirgsklima und Medizin Davos (SFI) agreed on an affiliated professor role at ETH for the new director of the Physikalisch-Meteorologisches Observatorium Davos/ World Radiation Center (PMOD/WRC). This role was filled in 2019 by Prof. Louise Harra. PMOD/WRC has an extensive array of ground-based instruments taking solar irradiance measurements, and it is also involved in a number of space instrumentation developments. A new group in computational solar and stellar physics (around Prof. Lucia Kleint, PRIMA recipient) was created at the University of Geneva. The Istituto Ricerche Solari (IRSOL) is now affiliated to the Università della Svizzera italiana, also strengthening its group, with contributions to the Daniel K. Inouye Solar Telescope (DKIST) and planned involvement in the European Solar Telescope (EST). S. Krucker at the University of Applied Sciences and Arts Northwestern Switzerland (FHNW) leads an instrument on the Solar Orbiter mission. The institutes are facing complementary aspects of solar physics and are in contact in order to optimise the synergies and cooperate on intersection areas.

5.2 International context and large collaborations

Progress in astronomy is in a large part driven by observations and thus by the development and availability of major ground-based infrastructures and space missions. Switzerland participates in these major international projects through its membership in organisations such as ESO, SKAO, and ESA. These organisations provide the basis for a large part of the experimental and observational astrophysical research. Swiss astronomers make effective and high-profile use of the common-user observational facilities of ESO and ESA, as well as of the ESA platforms for space research. While the Swiss research community has a direct influence on the direction of ESO and ESA, decisions are ultimately based on the aspirations of all the partners. This means that the Swiss community must retain some flexibility to respond to the changing international context in which it operates. To achieve this, maintaining a wide range of Swiss scientific interests is helpful, to ensure that scientists working at Swiss institutions can take best advantage of the missions and facilities that are implemented by ESO, SKAO, and ESA.

In this context, a complete portfolio of ambitious and large projects with major Swiss involvement is currently underway and planned to become operational within the next decade and for which work is already being carried out (see Appendix 2 for an overview of the corresponding science questions and research developments in Switzerland). Such large projects require considerable advance planning and a sizable amount of work to be carried out before participation in the mission is secured and scientific data are obtained. They represent true long-term investments in the future.

Switzerland has a rich tradition of success in both ground- and space-based instrumentation. The past 10 years have been particularly successful in terms of significant Swiss participation in large projects, ground- and space-based. This success relies on scientific leadership, technological capacities in instrument building, and appropriate funding through the FLARE (Funding large international research projects) (SNSF) programme for ground-based projects, and through PRODEX (Swiss Space Office (SSO)) and 'National Complementing Activities' (NCA, SSO) for space activities.

Following the recommendation in previous Roadmaps, the budgets of PRODEX and NCA have been increased. This allowed Switzerland to get involved in the development of several space instruments and mission ground segments on a level never reached before. Swiss astronomers have made important contributions to the major missions developed by ESA in flight or in development: INTEGRAL, Gaia, Solar Orbiter, Euclid, PLATO, Athena, LISA. Switzerland is now also leading, in a co-venture with ESA, the first S-class mission of the Agency, CHEOPS, a satellite for the precise determination of the radii of small exoplanets. The satellite was successfully launched in December 2019 and since then behaves extremely well, providing exquisite quality data to the community.

On the ground-based side, the funding available in FLARE has evolved as well, first to better cope with the increased challenges in developing the instrumentation to be installed on telescopes growing in size and complexity, and second to maintain existing facilities such as, e.g., the Very Large Telescope (VLT) and its instrumentation at the forefront of modern astronomy. In the current international astronomical context, both for ground-based and space missions, the active participation in the building of instruments is the only way to guarantee a significant share of the observation time,[2] priority access to data, and hence the largest possible scientific return. This is bound to be especially true for the Extremely Large Telescope (ELT).

5.3 FLARE, a common funding instrument to support astronomy and particle physics

FLARE is the main financial instrument to empower Swiss researchers engaged in particle physics and ground-based astronomy and astrophysics. These research fields address curiosity-driven fundamental questions of science that are important for humankind and the society, and that require highly sophisticated experimental infrastructure, often developed specifically for this purpose. The timeline from initial planning, prototyping and design, to construction and data exploitation can often encompass decades. The nature of these 'big science' endeavours requires federated work in international collaborations and long-term planning in order to solve the associated financial and technical challenges. Often such scientific developments are embedded in international organisations, such as CERN and ESO in Europe, which provide a stable governance model, financial transparency and cost sharing, as well as solid project monitoring, technical capabilities, and scientific peer review.

Swiss scientists are well positioned to participate in international networks of scientists to pursue research in astrophysics. Switzerland is a small country, but the environment for research is very favourable thanks in particular to the FLARE programme. The budget increase for FLARE for the period 2021–2024 bodes well for the future of fun-

2 Guaranteed Time Observations (GTO) in the form of an amount of time on the telescope or spacecraft is granted contractually to the consortia building the instruments, proportionally to their resource investments.

Figure 2: Artistic view of the ESO ELT at completion. (Image: ESO)

damental research in Switzerland and is highly appreciated by the particle physics and astronomy communities. Despite these favourable conditions, the scientific portfolio of questions addressed by both communities is subject to the unavoidable tension of breadth versus depth and hence requires a robust and equitable process of prioritisation, ideally by 'bottom-up' consensus building. In this context, the astronomy and particle physics communities agreed on the need for simple and clear basic rules for the definition and the implementation of the FLARE funding instrument. Although both communities have different cultures and implementation models of achieving a 'bottom-up' prioritisation process, they agree on some broad principles.

5.3.1 Principle of prioritisation

The long-term nature of large projects requires stability of the funding over extended periods of time. In order to access membership in large international consortia, Swiss researchers often have to pledge a long-term financial commitment in signing Memoranda of Understanding as part of their hardware contribution to constructing the experiment or a specific instrument (e.g., an instrument for the ESO-ELT), or as other deliverable (such as computing resources, data reduction software, etc.). The time periods in question may easily span subsequent FLARE funding periods and thus consecutive FLARE proposals can depend on each other in a crucial way.

FLARE proposals in general have to answer to high scientific standards, and the attribution of funds should always be guided by scientific peer review of the proposed work, evaluated by the FLARE panel. To assist the prioritisation process, general principles can be outlined emphasizing the importance of different types of projects:

1. **Flagship projects.** Those are the large top-priority projects, well-argued and identified by the community. Flagship projects should fulfil further considerations as well, such as the central role the project plays in the global strategy of the field, and be part of the strategy of an international organisation in which Switzerland participates. This will ensure a good return on investment at infrastructure and science levels. It would also be desirable for flagship projects to have passed at least a conceptual or technical design review. We generally assume that the larger demands on resources by flagship projects are backed up by the demonstrated

Figure 3: Composite image of the two SKA sites under a shared sky. (Image: SKA Organisation)

interest of more than one research group from various institutions or organisations in Switzerland. In evaluating flagship proposals, it should always be noted whether the requested funding is commensurate with the level of community support, available personnel, and required skill sets to perform the proposed work.

2. **Preservation of diversity: fair share projects.** Another overarching spirit of the FLARE instrument, very important for the diversity of the science questions addressed in astronomy, is the one of an 'enabling culture' towards Swiss researchers engaged to contribute a 'fair share' in the design, construction, operation or upgrade of a project. This is important to preserve the unique breadth and diversity of high-quality research in Switzerland.

3. The astronomical community welcomes the idea of 'mirroring grants' that would lend the support for the scientific personnel needed to perform the hardware work and the scientific exploitation of the proposed experiment.

5.3.2 Political priorities

SERI keeps a roadmap of nationally important research infrastructure up to date as input to the quadrennial ERI dispatch. Prioritisation of projects is intrinsically linked to the content of this roadmap, which can include political considerations as well. While we greatly appreciate the effort of SERI to align its prioritisation with that of the community, due to rapid development of the scientific or political fields, it is still possible that a temporal mismatch arises between the SERI's and the community's prioritisation. A close loop interplay between SERI and the scientific communities is highly desirable to keep such discrepancies at a minimum. In this context, we welcome the synchronous and periodic update of the scientific roadmaps of the communities as a valuable tool. If such a mis-alignment of priorities nevertheless exists, requiring some time for the evolution of the community to adapt to the changing landscape, we support the approach of SERI of opening up dedicated funding lines in the ERI dispatch for such new large-scale projects, avoiding thus to jeopardise on-going high-priority activities. This is the case today for the large international infrastructures of SKAO and CTA (Cherenkov Telescope Array), and might become a reality in the near future for the Einstein Telescope (ET) dedicated to the study of gravitational waves.

6 Flagship large-scale projects

6.1 The ESO Extremely Large Telescope (ELT)

On a European scale, the most important event shaping European and Swiss astronomy for years and even decades is the construction by ESO of a 39-m segmented-mirror telescope in Chile (ESO's Extremely Large Telescope, in short ELT). In addition to this unparalleled size, the ELT will be equipped with a line-up of cutting-edge instruments, designed to cover a wide range of scientific possibilities. The ELT will address the biggest scientific challenging questions of our time, including tracking down Earth-like planets around other stars in the habitable zones where life could exist, and make fundamental contributions to cosmology by probing the nature of dark matter and dark energy. Other key science areas include the study of stars in our Galaxy and beyond, black holes, evolution of distant galaxies, up to the very first galaxies after the so-called 'Dark Ages', the earliest epoch of the Universe, only 380 000 years after the Big Bang. On top of this astronomers are also planning for the unexpected – new and unforeseeable questions will surely arise, given the capabilities of the ELT.

Today the ELT remains the main priority for astronomy in Switzerland. As explained in the new dedicated web site (elt.eso.org) opened by ESO for the community in the first trimester of 2021, 'The ELT will be the largest visible and infrared light telescope in the world. It will lead to a greater advancement of astrophysical knowledge than any time before, allowing for a deeper exploration of our Universe and giving sharper views of cosmic objects.'

Because of its overarching importance for European astronomy, ESO member States decided in 2012 to go ahead with the construction of the ELT even without the formal ratification of Brazil as a new ESO member state, a key partner for the consolidation of the budget of the project. For various political reasons, Brazil finally did not join, which put the organisation in a delicate situation concerning the budget for the building of the ELT. The situation is now stabilised. The ESO Council, with the help of the governments of the member states, was able to approve in its December 2020 Council meeting the updated estimate for the cost-to-completion of the project (telescope and first light instruments), and most importantly

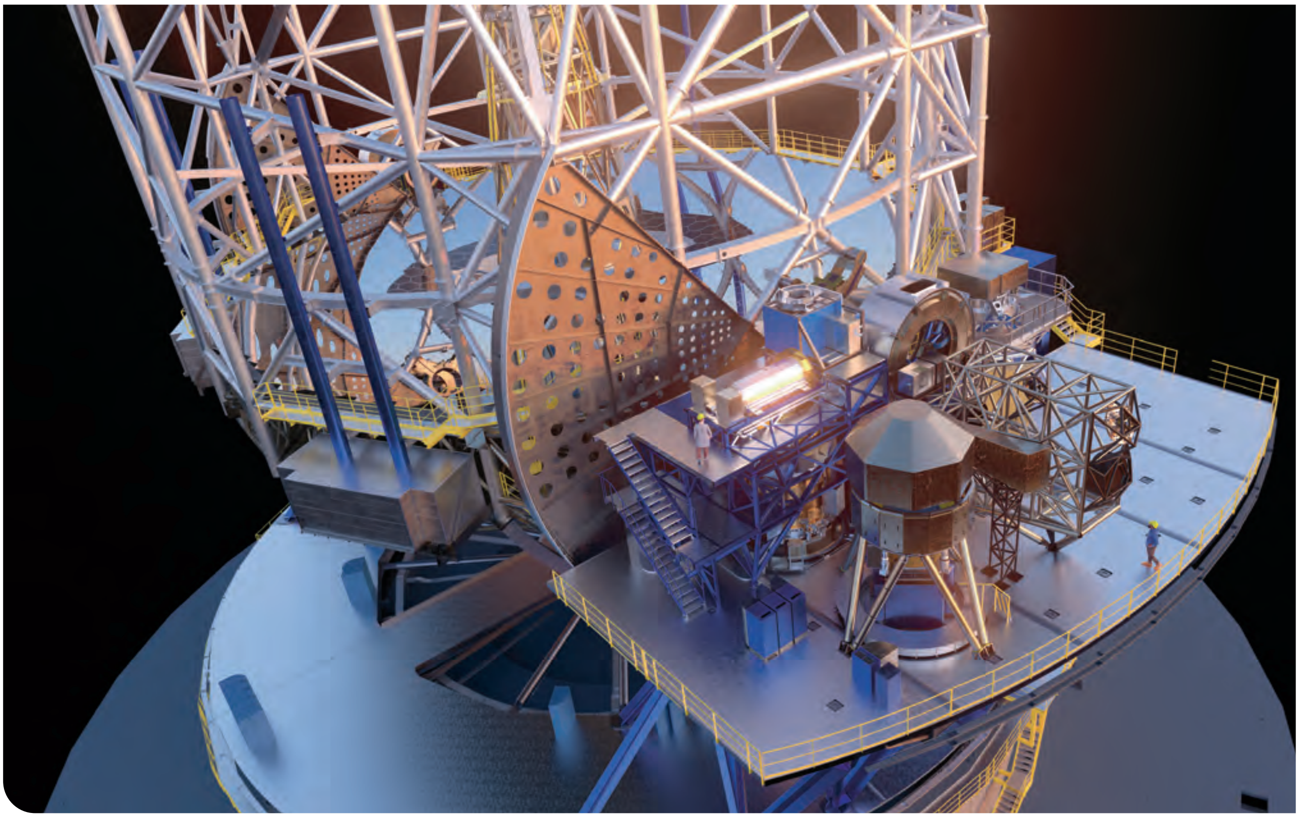


Figure 4: Artistic view of ELT instruments on the Nasmyth platform. (Image: ESO/L. Calçada)

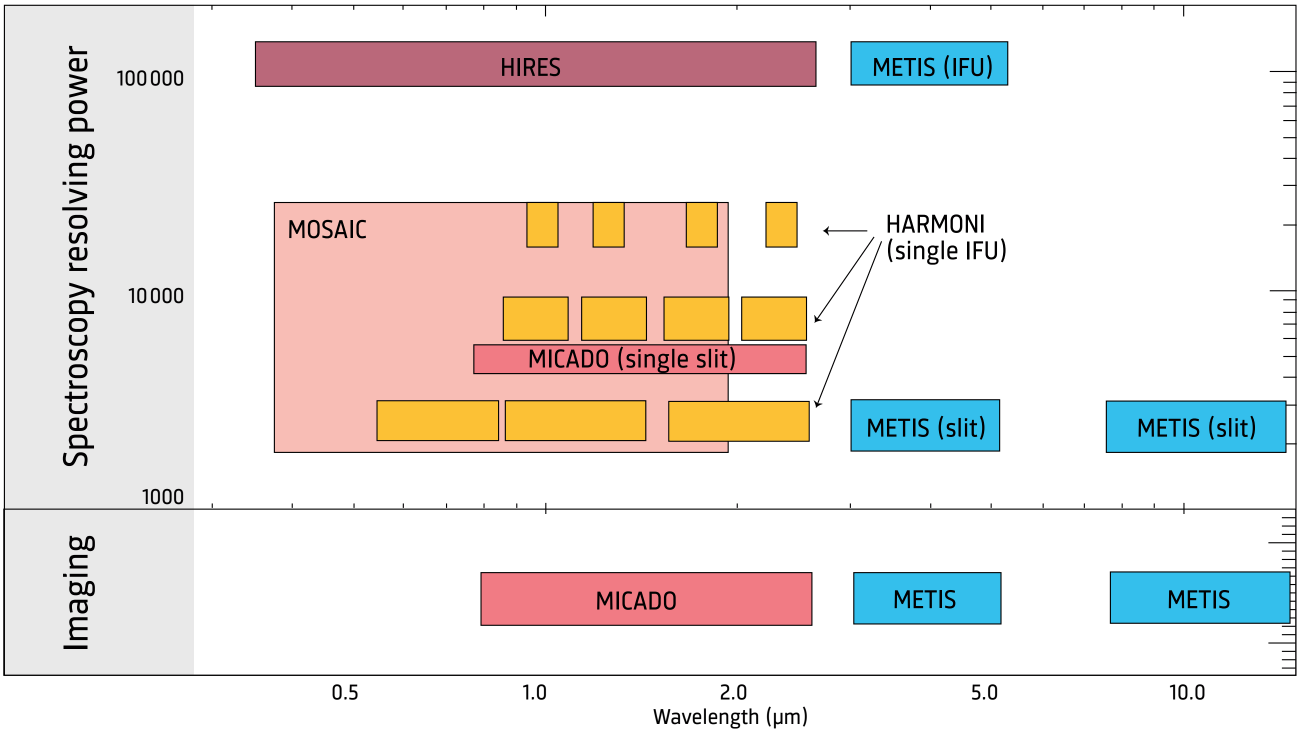


Figure 5: Wavelength-resolution parameter space covered by the ELT first instruments. (Image: ESO)

to accept a dedicated additional funding contribution by the member states for the project. From 2007 on, the ELT has always been singled out as the most important priority for Swiss ground-based astronomy. The decision to secure the budget of the building of the telescope till its completion is therefore most welcome by the Swiss astrophysics' community. At the time of the writing of this roadmap, the first light of the telescope is foreseen for the end of 2026, and the first scientific observations are planned for September 2027. Note however that this date is still somewhat uncertain as the project, as others, might be confronted with still unclear consequences of the COVID19 world-wide pandemic situation.

6.2 ELT instrumentation and Swiss participation

After the ELT's large segmented mirror has collected, corrected and stabilised the light from astronomical objects, dedicated instruments will analyse it in detail. The suite of instruments planned for the ELT includes cameras and spectrographs. Each of these will allow astronomers to observe and study the cosmos in a unique way, paving the wavelength, spectral and spatial resolution parameter space (see figure hereafter).

An initial set of first-generation instruments (HARMONI, MICADO/MAORI, METIS) will start to operate at or shortly after ELT technical first light while an additional two (HIRES and MOSAIC) will start operations at a later stage. Throughout the telescope's lifetime, other instruments will be installed on the telescope to study the Universe in ever more detail. Among them, PCS (Planetary Camera and Spectrograph), an instrument to directly image and characterise small exoplanets, is an important driver for the ELT.

– HARMONI is a high monolithic optical and near-infrared integral field spectrograph at low to medium resolution, allowing scientists to study astronomical objects in fine detail and go beyond what is currently achieved, reaching out to distant galaxies and quasars, individual stars in nearby galaxies, and potentially giant exoplanets in the Milky Way.

– MICADO is a multi-AO imaging camera for deep observations. Coupled with the MAORY multi-conjugate adaptive-optic system, it will take high-resolution images at near-infrared wavelengths, to image the detailed structure of distant galaxies, study individual stars in nearby galaxies, explore environments where gravitational forces are extremely strong, such as close to the massive black hole at the centre of the Milky Way, and discover and characterise young giant exoplanets using coronographic techniques.

– METIS is a powerful spectrograph and high-contrast mid-infrared imager. It is in particular expected to make significant contributions to exoplanet science, investigating their basic physical and chemical properties. In addition, METIS will contribute to the study of circumstellar disks, Solar System objects, properties of brown dwarfs, the centre of the Milky Way, and the environments of evolved stars and Active Galactic Nuclei.

- HIRES is the high-resolution spectrograph for the ELT, in the visible and near infrared. The associated science cases cover a broad range of research, including the characterisation of the atmosphere of Earth-like planets with the potential detection of biosignatures, identifying the very first generation of stars, studying possible variations of some of the fundamental constants of physics, and even a direct measurement of the acceleration of the expansion of the universe.

- MOSAIC is a versatile multi-object spectrograph with high multiplex and high-definition capabilities. The Universe includes hundreds of billions of galaxies, each of which is populated by hundreds of billions of stars. Astrophysics aims to understand the complexity of an almost incommensurable number of stars, stellar clusters and galaxies, including their spatial distribution, their formation and their current interactions with the interstellar and intergalactic media. A considerable fraction of discoveries in these areas require statistics, which can only be provided by observations of large samples from a multi-object spectrograph with multiplex capabilities.

- PCS Planetary Camera and Spectrograph. One of the prime scientific priorities for the ELT is to characterise exoplanets and, specifically, to take images of Earth-like planets. Such a giant leap from the capabilities available today requires significant research into new technologies over several years. Therefore, an ambitious and powerful planetary camera and spectrograph (ELT-PCS) is included in the instrumentation plan, and the research and development for specific components required to build it is now starting.

Several of these instruments have strong, active Swiss participations. They are at different levels of advancement, from first light instruments to R&D and demonstrator instruments on the VLT or smaller telescopes. For them some more information is provided hereafter. For the other instruments to be installed on the ELT, more information is available directly on the ESO dedicated website: elt.eso.org.

6.2.1 Metis (first-light instrument)

The instrument consists of two separate units (imager and integral field spectrograph) encased in a cryostat to maintain the stable low temperatures required to reach required performance. To reach diffraction-limited capabilities, a single-conjugate adaptive optic system is used to compensate for atmospheric turbulence. The project just passed the preliminary design review and is progressing to the final consolidation of the design of the instrument.

The METIS international consortium is composed of 12 institutions from 10 countries (NL [PI], CH, D, F, UK, B, P, A, USA, Taipei) and ESO. Swiss participation is led by ETHZ with Prof. S. Quanz Co-I and METIS project scientist. In addition to leading the METIS Science Team, ETHZ is also responsible for the overall Systems Engineering of the instrument with Dr. A. Glauser acting as consortium Lead Systems Engineer and for the design and delivery of the instrument cryostat.

The high-level involvement of ETHZ in the project is now allowing for a broader participation of Swiss scientists in the project through the NCCR PlanetS. Indeed, METIS will be especially interesting for the exoplanet domain and as such has the full support of the NCCR. It will help

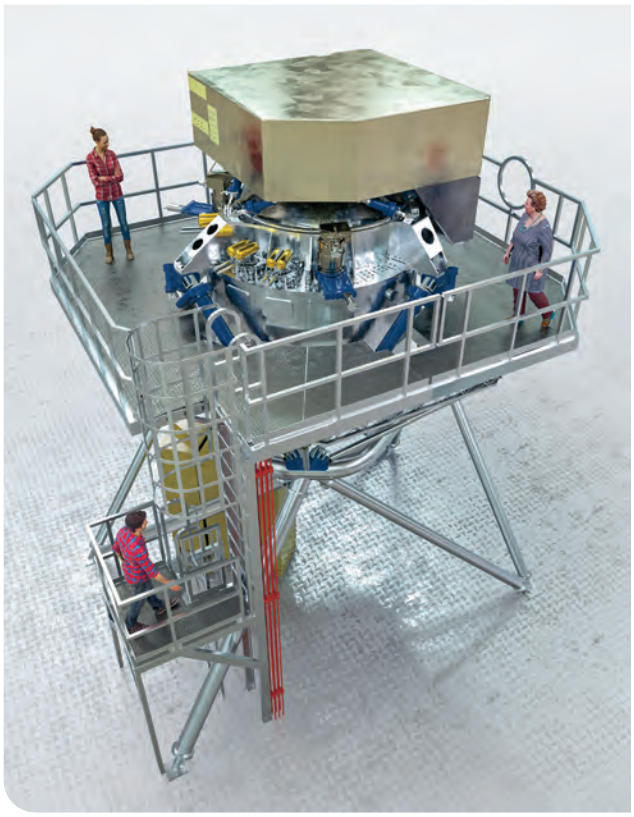


Figure 6: Rendering of METIS on the ELT instrument. (Image: ESO/L. Calçada)

astronomers better understand planet formation by investigating the physical structure and evolution of protoplanetary discs, as well as the chemical composition of planet-forming material. The instrument will also allow astronomers to look into already formed planets around other stars, by investigating the climates and atmospheric properties of short- and long-period gas-dominated exoplanets, as well as searching for small planets around the nearest stars.

6.2.2 HIRES (2nd generation instrument)

The HIRES consortium is composed of close to 29 institutes in 12 countries (I [PI], CH, D, F, DK, UK, PL, E, P, S, Brazil, Chile) and ESO. Swiss participation is at a major level. It is led by the University of Geneva (Swiss Co-PI is Prof. C. Lovis) with an active collaboration with the University of Bern. As for METIS, exoplanetary science is a strong driver for the development of HIRES. In particular, the access to the chemical content of exoplanetary atmospheres, a key element to determine the ecosystem of an exoplanet and thus its potential habitability and possible spectral signature of life, is accessible through high-resolution transit spectroscopy. The development of HIRES with a high-level Swiss participation is thus strongly supported by the NCCR PlanetS.

With the characterisation of exoplanet atmospheres as a strong driver, the HIRES baseline design is along a modular fiber-fed cross-dispersed echelle spectrograph with a wavelength coverage split in two arms, visible and near infrared, providing a broad spectral window at high resolution (R~100’000). HIRES will also include an Integral Field Unit (IFU) mode. From the expertise gained in the development of the ESPRESSO stable high-resolution spectrograph for the VLT, the Geneva-Bern tandem has a strong leadership in the development of the visual arm of the instrument (conceptual designs of the optics and fiber injection, of the thermal and vacuum system, of the calibration unit, of the data flow system), with also a participation as partners to the near-infrared arm, building on the know-how gained with the construction of NIRPS the red arm of HARPS (for the ESO 3.6m telescope), and a strong participation to the definition of the science priorities and top level requirements. The project is about now to start phase B leading to a final design for the instrument.

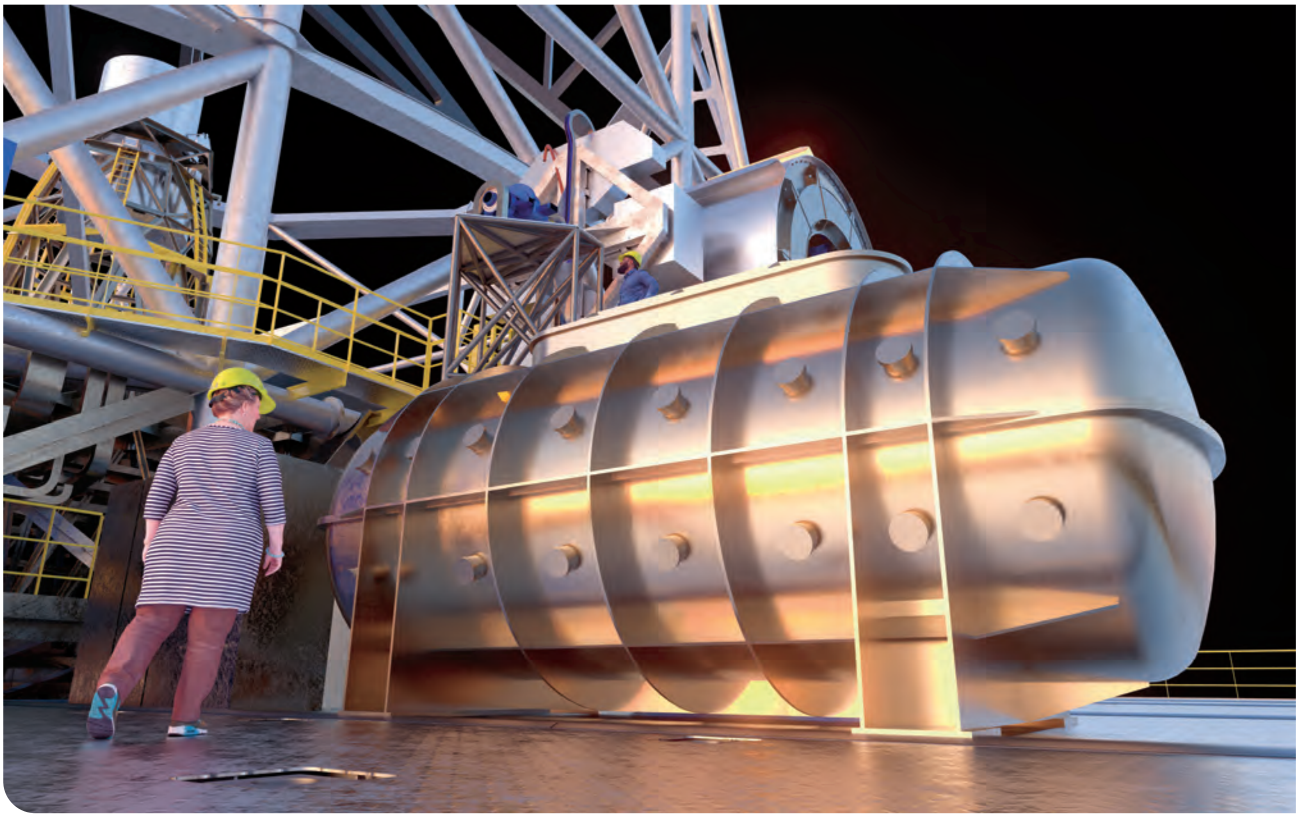


Figure 7: Representation of the vacuum tank of one of the arms of the HIRES spectrograph. (Image: ESO/L. Calçada)

6.2.3 MOSAIC (2nd generation instrument)

The scientific motivations for a multi-object spectrograph (MOS) on the ESO Extremely Large Telescope (ELT) draw on all fields of contemporary astronomy, from extrasolar planets, to the study of the halo of the Milky Way and its satellites, and from resolved stellar populations in nearby galaxies out to observations of the earliest 'first-light' structures in the partially-reionised Universe. These cases are used to identify the top-level requirements for the instrument, entailing two observational modes (high multiplex [200 objects simultaneously] and high definition). When combined with the unprecedented sensitivity of the ELT, MOSAIC will be the world's leading MOS facility. MOSAIC will in particular conduct the first exhaustive inventory of matter in the early universe. This will lift the veil on how matter is distributed in and between galaxies, boosting our understanding about how galaxies formed and evolved.

MOSAIC is designed and built by a consortium composed of close to 23 institutes in 13 countries (F [PI], UK, NL, Brazil, D, A, FIN, I, P, E, S, CH, USA) and ESO. MOSAIC will start Phase B in 2022. Swiss participation is at a significant level. It is led by the University of Geneva (Swiss Co-PI is Prof. D. Schaerer) with an active collaboration with EPFL for the construction of the robotic positioner system.

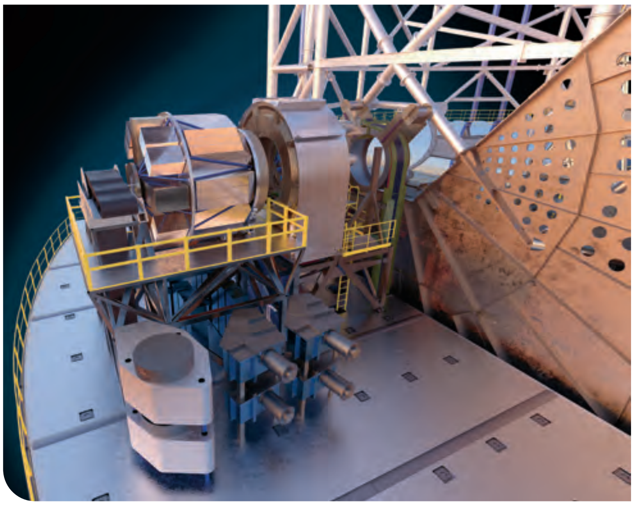


Figure 8: 3D model of MOSAIC on the ELT instrument platform. (Image: ESO)

6.2.4 PCS (R&D and demonstrator level)

The Planetary Camera and Spectrograph planned for the ELT is an instrument to directly image and characterise small exoplanets, an important driver for the ELT. Only ELT-PCS can realise the full potential of the telescope in exoplanet characterisation providing ≳ 100 times better contrast at smaller inner working angles than the general-purpose instruments (HARMONI, MICADO), reaching rocky planets in the habitable zone. Detailed design and construction of ELT-PCS will start as soon as the R&D for specific components reaches the required technology readiness level.

PCS builds upon the heritage of the EPICS (Exoplanet Imaging Camera and Spectrograph) phase-A study some years ago the aim of which was the demonstration of the instrument feasibility, the derivation of requirements to the ELT, its site, and key components of the instrument (extreme AO (Adaptive Optics), coronagraph, wave-front control), as well as consolidation of the corresponding science cases. In the light of recent developments of high contrast performance at very small inner working angles, coronagraphs for segmented apertures and the timeline of the development of the instrument, the scientific emphasis has shifted from the discovery towards the in depth spectroscopic and polarimetric characterisation of exoplanets from Jupiter-like Gas Giants in larger orbits down to rocky planets in closer orbits, reaching the habitable zone of solar-type stars and ultimately of the late M-dwarfs.

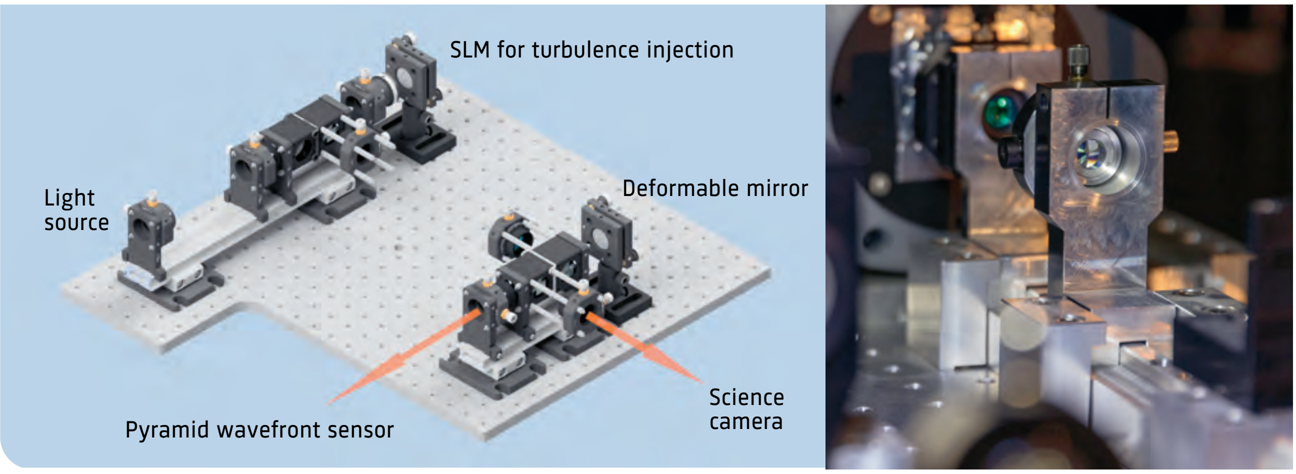
While PCS is still a long way to go (beginning of the 2030s), getting involved in preparatory R&D efforts is fundamental. Switzerland is extremely well-positioned in this context with a set of parallel, on-going, strong involvements in key activities for PCS:

- ETHZ and the University of Geneva are active members of the SPHERE consortium that built the extreme-AO imager for the VLT, and are exploiting observations from the instruments (including 270 nights of GTO time).

- Adding a second AO stage to SPHERE (the SPHERE+ project) is a fundamental step in the R&D plan towards PCS-ELT. The University of Geneva, with the help of ETHZ, is active in the establishment of the SPHERE+ consortium for a strong involvement of Switzerland in the project.

- ETHZ is closely collaborating with the ESO AO-team working on PCS R&D at the level of the development of a dedicated AO-bench and exchange of personnel and know-how (PhD student working on predictive control for AO).

- A fundamental component in PCS for the atmospheric characterisation of small-mass planets is the coupling between high-contrast, high spatial resolution imaging



Figures 9: Left: Opto-mechanical setup of the GHOST AO-testbench at ESO for Extreme Adaptive Optics experiments. Right: The Pyramid wave-front sensor that will be integrated in GHOST. (Image: ESO, M. Kasper)

and high-resolution spectroscopy. A precursor instrument for the VLT, RISTRETTO (see next section), is developed by an international consortium led by the University of Geneva. The scientific driver is to access the oxygen in the atmosphere of Proxima b, the terrestrial planet orbiting in the habitable zone of our closest neighbour star. The instrument will demonstrate the technical feasibility and the science capabilities of the approach.

These activities are today mainly led by the ETHZ and the University of Geneva but the participation to the development of PCS-ELT as a major partner is now developing as a top priority for the NCCR PlanetS and the future SIPS, which will certainly broaden the involvement of Swiss institutions in the project.

Instrument	Main specifications			Schedule				
	Field of view/slit length/pixel scale	Spectral resolution	Wavelength coverage (μm)	Phase A	Project start	PDR	FDR	First light
MICADO	Imager (with coronagraph) 50.5" × 50.5" at 4 mas/pix 19" × 19" at 1.5 mas/pix	*I, Z, Y, J, H, K* + narrowbands	0.8–2.45	2010	2015	2019		
	Single slit	*R* ~ 20 000						
MAORY	AO Module SCAO – MCAO		0.8–2.45	2010	2015			
HARMONI + LTAO	IFU4 spaxel scales from: 0.8" × 0.6" at 4 mas/pix to 6.1" × 9.1" at 30 × 60 mas/pix (with chronograph)	*R* ~ 3200 *R* ~ 7100 *R* ~ 17 000	0.47–2.45	2010	2015	2018		
METIS	Imager (with coronagraph) 10.5" × 10.5" at 5 mas/pix in *L, M* 13.5× 13.5at 7 mas/pix in *N*	*L, M, N* + narrowbands	3–13	2010	2015	2019		
	Single slit	*R* ~ 1400 in *L* *R* ~ 1900 in *M* *R* ~ 400 in *N*						
	IFU 0.6" × 0.9" at 8 mas/pix (with coronagraph)	*L, M* bands *R* ~ 100 000						
HIRES	Single object	*R* ~ 100 000	0.4–18 simultaneously	2018				
	IFU (SCAO)							
	Multi object (TBC)	*R* ~ 10 000						
MOSAIC	~ 7-arcminute FoV ~ 200 objects (TBC)	*R* ~ 5000–20 000	0.45–1.8 (TBC)	2018				
	~ 8 IFUs (TBC)	*R* ~ 5000–20 000	0.45–1.8 (TBC)					
PCS	Extreme AO camera and spectrograph	TBC	TBC					

1 millarcsecond (mas) = 0.001"

Figure 10: Basic information for the ELT foreseen instruments. (Image: ESO)

6.3 ESO's strategic view for future developments

In its strategic plan ESO intends to strengthen its position as the world-leading organisation in ground-based astronomy enabling the best opportunities for new discoveries. As such, it wants to consolidate its position as a key actor on the world-wide scene of existing and future large astronomical facilities regardless of wavelength or messenger, by fostering collaboration and synergy. In this context, ESO has now started a deep and careful reflection on the next facility to develop, after the ELT completion, to best serve the European astronomical community and keep delivering world-class observations driving the cutting-edge research in modern astrophysics. For the next decade, successfully completing the ELT with its original powerful suite of instruments is clearly a central element of strengthening this leadership, together with ensuring that the current facilities remain at the forefront of astronomical investigations.

6.4 The Square Kilometer Array Observatory (SKAO)

The Square Kilometer Array Observatory (SKAO) is the next-generation radio astronomy facility that will revolutionise our understanding of the Universe and the laws of fundamental physics. As we progress with our knowledge of the universe, understanding complex astrophysical phenomena and discovering new ones require today access to multi-wavelength observations. SKAO will tackle some of the most fundamental scientific questions of our time. The SKAO's science goals are broad and ambitious, from providing a probe of Einstein's theory of Gravitation via the study of pulsars to looking back into the history of the Universe as far as the Cosmic Dawn (Dark age and epoch of reionization), when the very first stars and galaxies formed, in order to seek answers to some of the biggest remaining questions in astrophysics. Among them: How do galaxies evolve? What is Dark Energy and what role does it play in the expansion of the Universe? Can we find and understand where gravitational waves come from? What causes planets to form around stars? Is there life out there? Can we probe the existence of extra-terrestrial intelligence? Individually, and working together with other next-generation facilities, SKAO will uncover new findings on the Universe.

SKAO is raising a strong scientific interest across several fields of research. Astronomy is at the forefront of the science to be done with SKAO (cosmology, dark matter, galaxy evolution, magnetic field mapping, etc.) but the need for efficiently handling a very large volume of data is now also attracting new participants, in the domains of signal processing (image reconstruction), data mining, machine learning, data flow analysis, etc. During its operation, SKAO will collect unprecedented amounts of data (at the level of Tb/s), requiring the world's fastest supercomputers to process this data in near real time, before turning these into science products. It is expected that the data archive will grow at an outstanding rate of 600 Pb/year.

The recently completed SKAO Global Headquarters is located at Jodrell Bank near Manchester in the UK, home to the newly intergovernmental organisation -the SKAO- that oversees development, construction, and operations. The two other SKA sites are radio quiet zones and home to the telescopes themselves: a mid-frequency array in South Africa (SKA-mid), and a low-frequency array in Australia (SKA-low).

The Swiss community involved in radio-astronomy is growing likewise, with a participation to the SKAO working groups, the involvement of the signal processing and big-data science community, as well as through an active participation to current SKA-precursor projects (ASKAP and MeerKAT) and in developing smaller scale radio-astronomy facilities (HIRAX in particular), demonstrating so a clear interest for the long-term goals of SKAO. Research groups at EPFL, ETHZ, at the Universities of Geneva, Zurich and Basel, and at the Universities of Applied Science: FHNW, HES-SO and ZHAW are participating in the Swiss SKAO Consortium, addressing both astronomy and data science. They are actively preparing for an efficient use of SKAO data through the future development of the SKAO Regional Centers, and often in synergies with other large astronomy and cosmology projects (e.g., DESI, 4MOST, Euclid).

In this context, Swiss small and medium-sized enterprises are expected to add value to the project through four identified fields of competence; data processing (big data science exploitation), system control and supervision (operation of a large infrastructure), manufacturing and maintenance of antennas and radio receivers, and precise time management through the use of Swiss-Made Maser Atomic Clocks.

In February 2021, the intergovernmental organisation SKAO started to exist, and in June 2021, EPFL joined the organisation as the leading house for Switzerland. In July 2021, the SKAO construction was approved by its Council. On January 19, 2022, Switzerland joined SKAO as a full member. It is expected that by the end of 2022 at least 10 countries will have joined SKAO, and a few more are expected to join in the future. In the last 5 years, EPFL as the leading house of Switzerland, has been coordinating actively the various contributions to the SKAO project on behalf of the Swiss academic community. In particular, annual Swiss SKA meetings have built up a strong and diverse community behind this new infrastructure.

With the participation in the new large infrastructure of SKAO, it is expected that the Swiss astronomy community will continue to grow and that universities will hire new professors on the topic of radio-astronomy and its big-data challenges in the coming years. As a consequence, complementary fundamental basic research support will be required through SNSF or other more-applied national funding. Although part of the growth can come through the current big-data science funding, extra funds will be required to allow the radio-astronomy community to extend and properly benefit from the investment in the SKAO infrastructure. In particular, adequate facilities will be required on the data side for the related intensive data analysis on high-performance computers. Indeed, as of today, the SKA Regional Centers (the data centers which are essential to deal with the huge amount produced by SKAO) are not funded as part of the SKAO infrastructure construction. It is thus essential to ensure appropriate funding for the Swiss participation in the European SKAO Regional Centers. One possibility would be to use the 'CERN model', and benefit from additional SNSF-FLARE funds to cover this participation. Only with new dedicated funding for the SKAO Regional Center, can the Swiss astronomy community lead new SKAO discoveries. It is also important to recognise that undoubtedly new major discoveries will arise from multi-wavelength analyses, combining optical/near-infrared and radio data from SKAO.

Figures 11: An all-facing image of the MeerKAT radio telescope, which will be integrated into the mid-frequency component of the SKA phase 1 telescopes. (Image: South African Radio Astronomy Observatory [SARAO])

7 Data management and data preservation for (space) astrophysics missions

The increasing complexity and performance of astrophysics projects which generate huge and extremely complex data sets represents a major challenge. This is particularly true for space missions, but ground-based instrumentation is following the same trend. For this reason, astrophysics is a domain where data science (machine-learning, advanced statistics, algorithms and data visualisation) plays a major role. At the same time, expertise in computing and storage facilities and in data management have become necessary for scientific exploitation.

Switzerland has acquired a solid international reputation in this field, in particular thanks to initiatives like the INTEGRAL Science Data Center, the scientific data center for ESA's INTEGRAL mission, and to the many projects that followed. Huge developments have been or are currently being made for space missions like Gaia and Euclid. Activities on a smaller scale, but with a high-visibility role for Switzerland, are taking place on, for instance, the ESA-Swiss mission CHEOPS. In addition, in the Solar system exploration, Swiss teams have the responsibility to manage the data from the instruments they have built, like BepiColombo, Solar Orbiter or JUICE, and to preserve them.

Each mission produces very specific data that requires expert knowledge that cannot easily be put in common. However, the principles of data management and the data science support are to a large extent universal, and can be mutualised. In 2017, the Swiss Roadmap for Research Infrastructures 2015 proposed the creation of the 'Common Data Center Infrastructure' (CDCI) dedicated to astrophysics, cosmology and astroparticles (P. I.: Prof. S. Paltani). The goal of the CDCI was not only to provide data management expertise to the Swiss community, but also to address the very important issue of data and software preservation. CDCI has developed a platform, first limited to the INTEGRAL mission, but then extended to other missions, where any user can select, process and analyse large and complex data sets, without requiring the expert knowledge and without needing to install dedicated software that is often aging and barely maintained. Through the tools and interfaces, it developed, the CDCI aimed at providing a unique national platform for the long-term preservation of data in a secure and accessible manner according to the 'FAIR' principles, allowing the continuation of scientific analyses well beyond the life of the missions under consideration.

The funding obtained between 2017 and 2020 was unfortunately not sustainable. In 2019, the creation of a new institute, legally independent from the universities but largely supported by the University of Geneva and the University of Zurich (P. I.: Prof. S. Paltani, Geneva; Co-P. I.: Prof. R. Teyssier, Zurich), was proposed to the SERI through the Article 15 of the Federal Act on the Promotion of Research and Innovation (RIPA). Unfortunately, the funding was not granted.

The need for the support provided by the CDCI remains essential in a period where data play a fundamental role in society. For many future missions, their success and scientific return for Switzerland shall depend crucially on the existence of this support. Without prejudging the funding mechanism that should be used, advanced discussions should take place between the astrophysics community and the SERI, in order to evaluate the scope of a possible successor to the CDCI and the possibility to fund such kinds of activities. Possibly, the support to space missions should be put in top priority, but a view to support all astrophysics missions should be adopted.

8 Projects serving the Swiss astronomy diversity

Swiss astronomers have been successful in getting involved in a significant number of large projects, spread over the scientific landscape of astrophysics. While some are multi-purpose observatories (e.g., JWST, Gaia, Euclid, Athena, PLATO), others are quite specialised and/or address specific bodies (e.g., Rosetta, BepiColombo, JUICE) or carry out specific measurements (e.g., ESPRESSO, CHEOPS, MOONS, 4MOST, DESI, SDSS-V, HIRAX, BlueMUSE). Some of these projects/missions are in operation today, others will be launched and commissioned in the next few years. An important work is also already being carried out to define projects and missions that are even beyond today's horizon. Such preparatory work is essential to position Swiss teams for participation in the most interesting future developments. The large number of instruments and missions with significant Swiss implications mirrors the breadth of Swiss astronomy.

A large part of these projects is developed in the natural framework of ESO, for ground-based instruments, and ESA,[3] for astrophysics from space. The corresponding instrumental developments are motivated as complementary missing pieces for a complete coverage of the science cases in modern astronomy or as precursors of future instruments on larger telescopes (early science and demonstrators), in the frame of ESO or in other contexts.

8.1 Solar system

- BepiColombo is a Cornerstone mission from ESA's previous programme Horizon 2000+ dedicated to the study of Mercury, the smallest, and closest to the Sun, planet of our Solar system. Because of the deep gravitational well due to the Sun, Mercury is extremely difficult to reach, and BepiColombo will be only the third probe to reach it, but it will also be by far the most ambitious one. Launched in 2018, BepiColombo reached Mercury for a first fly-by at the end of 2021, but will finally settle in a stable orbit in 2025 only. More than ten instruments fly on board BepiColombo, including the BEpicolombo Laser Altimeter (BELA), a laser altimeter that is co-led by Prof. N. Thomas (University of Bern) and the German space agency DLR. The significant participation in BELA ensures a very important scientific return in Switzerland. BELA is going to map the surface of Mercury on a grid, providing accurate topography, in synergy with other instruments providing stereoscopic imaging and radar scans, in order to develop a digital model of the terrain that will allow to study the geology, the tectonics, and the age of the surface, as well as to correct models of the planet's gravity for the presence of surface structures. BELA will also investigate tidal deformations of the surface, the surface roughness and the albedo. There are also smaller participations in the form of mass spectrometer for two other instruments led by Prof. P. Wurz (University of Bern): STROFIO and MPPE.

- JUICE is the first large mission of ESA's Cosmic Vision programme. Planned for launch in 2023, JUICE will fly over Jupiter and three of the four giant satellites of Jupiter – Europe, Ganymede and Callisto – at the beginning of the next decade. The main goal of JUICE is the study of the ocean layers that are found on several of these satellites, in order to understand their characteristics and their formation. On Europa, JUICE will focus on chemistry, in particular the presence of organic molecules that are the building blocks of life. JUICE will also study the atmosphere and magnetosphere of Jupiter, as well as the tenuous atmosphere of Ganymede. Among the twelve instruments on board JUICE, Switzerland is participating in four of them. Prof. P. Wurz is co-leading the PEP (Particle Environment Package) and NIM (Neutral gas and Ion Mass spectrometer) instruments. PEP is a particle detector for charged and neutral particles to study the composition of the magnetosphere of Jupiter. NIM will study the composition of the neutral atmosphere of the satellites. The Ganymede Laser Altimeter (GALA) is a laser altimeter with a Swiss participation led by Prof. N. Thomas (University of Bern) that will map the surface of Ganymede to infer the topography, as well as some properties of the surface, like roughness and albedo. Finally, Dr. A. Murk (University of Bern) leads the Swiss participation in the Submillimetre Wave Instrument (SWI), a submillimetre receiver that will study the chemical composition, the wind speed and the temperature fluctuations in the atmosphere of Jupiter.

- Comet Interceptor is a small mission of ESA's Cosmic Vision programme that will remain in orbit around the L2 Lagrangian point until a reachable long-period comet appears. The spacecraft will then intercept the comet and send two probes closer to the coma, in particular in order to study the coma. Two instruments are led by Switzerland, the CoCa (Comet Camera) visible and near-infrared imager (Prof. N. Thomas, University of

3 For space missions, additional information can be found in the Roadmap of the CSR, 'A report on space science in Switzerland '

Bern) and MANIaC (Mass Analyzer for Neutrals and Ions at Comets), a mass spectrometer (Dr M. Rubin, University of Bern).

- Another significant mission for the exploration of the Solar system called EnVision, a probe to Venus, is planned for launch in 2032. Unfortunately, there is only a very small Swiss participation.

8.2 Exoplanets

- PLATO is the third Medium-Class mission of ESA's Cosmic Vision Programme. Its goal is to detect large numbers of Earth-like planets around Sun-like stars through the detection of transits through the periodic dimming of the star when the planet passes in front of it. It will allow us to study the density and composition of these planets, in particular those that are located in the habitable zone (where liquid water can exist) of their host stars. The launch of Plato is currently planned for the end of 2026, with probable further delays. The Swiss hardware participation in PLATO, which is led by Prof. W. Benz (University of Bern), is very significant. It consists in the design and manufacturing of mounting structures for the optical elements, with very demanding stability requirements. In addition, Prof. S. Udry (UniGE) is a member of the Plato Science Working Team. PLATO will also deliver outstanding observations of bright stars that will allow us to probe their stellar structure and evolution through asteroseismology.

- RISTRETTO is a proposed visitor instrument for ESO VLT whose goal is to demonstrate for the first time spatially-resolved spectroscopy of exoplanets in reflected light. This approach combines an extreme adaptive optics system with a high-resolution spectrograph, and will serve as a pathfinder for the future ELT instruments HIRES and PCS. RISTRETTO will aim at characterizing the habitable-zone exoplanet Proxima b (our closest neighbour), and search for constituents such as molecular oxygen, water vapor, and methane in its atmosphere. Furthermore, RISTRETTO will offer novel capabilities for probing accreting protoplanets and protoplanetary disks at very close separation from the host star (30 milli-arcseconds or a few astronomical units). The project is led by Prof. C. Lovis (UniGE) and is supported by the University of Geneva Astronomy Department, the FLARE program, the NCCR PlanetS, and the University of Bern (Prof. C. Mordasini). RISTRETTO is currently in an advanced design phase and construction will start in 2022. It is expected to be deployed at the VLT by 2025.

8.3 Solar and stellar physics

- The European Solar Telescope. The construction of the next-generation large aperture European Solar Telescope (EST), a 4.2 m aperture telescope, is promoted by the European Association for Solar Telescopes (EAST). IRSOL represents Switzerland in the Association. The project was included on the ESFRI Roadmap in 2016. The financing for the realisation of the facility is still a matter of discussions at national levels, including Switzerland, but the work to design the telescope is advancing at the Project Office in Tenerife, Canary Islands, financed mostly by Spain. The facility should be active for at least 30 years after the construction, and Switzerland will benefit from it as several research topics currently investigated, fit with the possibilities offered by the EST. Currently the interested institutes are the Università della Svizzera italiana (IRSOL for solar physics, faculty of informatics for topics related to big data), CSCS (for EST data center), HEIG-VD (adaptive optics), SUPSI (electronics and control system), and possibly further institutes: FHNW for coordinated observations with STIX (Spectrometer Telescope for Imaging X-rays) and PMOD for coordinated observations with Solar Orbiter SPICE (SPectral Imaging of the Coronal Environment) and EUI [Extreme Ultraviolet Imager]). In parallel, through the activities of Prof. L. Kleint (FHNW) and IRSOL (as continuation of its contribution to the first-generation instrument VTF [Visible Tunable Filter]), there are opportunities for involvement in second generation instruments for DKIST, the world's largest solar telescope providing a factor three improvement compared with presently achievable resolution (start of the observations in 2022).

- Solar Orbiter is the first Medium-Class mission of ESA's Cosmic Vision Programme, launched in the beginning of 2020, it will start its operations in 2023. It embarks ten scientific instruments, one of them, STIX, being led by Dr. S. Krucker (FHNW), and three others, EUI, SPICE and SWA) having significant Swiss contributions, the first two from Prof. L. Harra (PMOD/WRC) and the last one from Prof. P. Wurz (University of Bern). Solar Orbiter will study the processes at the origin of the Solar wind, as well as the Solar and heliospheric magnetic fields and the energetic Solar cosmic rays. STIX is a hard X-ray imaging spectrometer that will study the very hot plasma and accelerated electrons that are produced in Solar flares. EUI will image the upper layers of the Sun's atmosphere in the extreme ultraviolet, providing the link between the photosphere and the corona. SPICE will perform imaging spectroscopy of the corona to determine locally the chemical composition, which will enable the mapping of the origin of the Solar flares on the Sun's surface, when combined with in situ measurements performed by the Solar Wind Analyser (SWA), a suite of sensors that are sensitive to the different kinds of particle (electrons, protons, ions) that are present in the plasma of the Solar wind.

- Swiss teams are involved in a number of other projects to study the Sun and the heliosphere. MiSolFa is an instrument similar to STIX, with a contribution from FHNW, that will observe the same Solar flares from a different point of view. The Davos Absolute Radiometer (DARA) is an instrument on ESA's mission PROBA-3 that will measure the Solar irradiance, and is led by Prof. W. Schmutz (PMOD/WRC). SoSpIM, led by Prof. L. Harra (PMOD/WRC), onboard the JAXA Mission Solar-C will measure the solar spectral irradiance in two spectral bands. IMAP is a NASA mission to probe the acceleration of Solar energetic particles and the interaction of the Solar wind with the local medium, with a contribution from Prof. P. Wurz (University of Bern). Finally, SMILE is a joint ESA-China small mission to study the Earth magnetosphere that will embark two instruments with Swiss participation: SXI is a soft-X-ray imager with participation from Dr S. Krucker (FHNW), and LIA, the Light Ion Analyser, will investigate the relationship between the Solar wind and the magneto-sheath, and has participation from Prof. P. Wurz (UniBE).

8.4 Galaxy formation and evolution

- With the successful launch of NASA+ESA's James Webb Space telescope (JWST) in December 2021, JWST is now the largest telescope in space. With its 6.5m mirror and a suite of powerful and versatile near-infrared to mid-infrared instruments, the JWST will study the early Universe, from the end of the 'dark ages', to the formation of the first galaxies and the epoch of cosmic reionization. A Swiss participation in the European instrument MIRI, a cryogenic mechanism to protect the detector from contamination, has been conducted by M. Guedel (ETHZ, now in Vienna; Prof. S. Lilly and Dr A. Glauser being now responsible for the Swiss contribution) with industrial support from Ruag Space AG and Syderal Swiss SA. Webb is an observatory, whose observing time, guaranteed time notwithstanding, is attributed based on scientific merit alone. The Cycle 1 review has been a huge success for Swiss teams, with in particular the University of Geneva having achieved a success rate of 75%, putting it in third place overall, just behind Harvard University. For the next decade at least, Webb will be a major tool for the study of evolution of the first galaxies, the understanding of complex star formation processes, but also for the study of the formation of planetary systems.
- MOONS is the next-generation multi-object spectrograph that will be installed on the VLT. It will start operations in 2023. MOONS will be able to acquire spectra simultaneously 1000 galactic or extragalactic objects from the R optical band to the near-infrared H band with a medium-to-high resolution. In the local Universe, the Sloan Digital Sky Survey (SDSS), a photometric and spectroscopic large-area survey on a small (2.4m) telescope, is one of the most successful astronomical projects ever. Thanks to the power of the VLT, MOONS will replicate and extend the SDSS over the last 10 billion years of the Universe and thus provide us with an unprecedented view of the evolution of galaxies. A significant Swiss participation in the development of the project has been funded through FLARE under the leadership of ETHZ, with additional contributions from the University of Geneva and EPFL. Prof. S. Lilly (ETHZ) and Prof. S. Paltani (UniGE) are both Co-PI's of MOONS.

- Euclid is the second medium mission of ESA's Cosmic Vision programme. While its main goal is cosmology (see next Subsection), Euclid will bring revolutionary insights to the study of galaxy evolution, and, thanks to the very important Swiss participation, will therefore play a major role to the Swiss groups working on this thematic. In particular, it will provide outstanding morphological information of all galaxies over the entire extragalactic sky (approximately half of the full sky) during the last 90% of the history of the Universe. In addition, it will map the entire extragalactic sky in the near-infrared, providing accurate estimates of the masses of billions of galaxies. Star formation rates will also be measured for tens of millions of galaxies, thanks to its spectroscopic mode.

8.5 High-energy astrophysics, cosmology, and fundamental physics

- Euclid, the second medium mission of ESA's Cosmic Vision programme, will become, after its launch in early 2023, the major cosmology mission in Europe. Euclid is designed to determine the equation of state of dark energy and constrain the models of gravity beyond general relativity. The Visible Imaging Spectrometer (VIS), which contains a Swiss contribution led by the University of Geneva, is going to map the extragalactic sky (about half of the sky) at near Hubble spatial resolution, allowing us to determine precise galaxy shapes that can then be used to infer the distribution of dark matter through the tiny distortions in shapes it causes because of the weak gravitational lensing effect. The Near Infrared Spectrometer and Photometer (NISP) instrument will perform a mapping of the extragalactic sky in near-infrared colors to assist the weak-lensing study, but it will also obtain spectra of tens of millions of galaxies that will be used to measure the structure of the Universe and its evolution through the correlation function, and hence constrain the cosmological parameters and the speed of growth of density fluctuations, which is linked to the properties of gravity. There is a very large Swiss participation in Euclid, involving the University of Geneva, the EPFL, the University of Zurich and the FHNW, thanks to the support of PRODEX (P. I.: Prof. S. Paltani, University of Geneva). A hardware contribution (the shutter of the VIS visible imager) has been built in collaboration with APCO Technologies SA. PRODEX also supports the development and implementation of a large ground-segment contribution involving key scientific contributions (the determination of photometric redshifts, an essential ingredient of the weak-lensing probe) and a data center. A Sinergia program from the SNSF is also in place to prepare for scientific exploitation (P.I.: Prof. F. Courbin, EPFL). Euclid is a proprietary mission, so that the early results will only be available to the members of the collaboration. The support of PRODEX and of the SNSF plays a fundamental role in the success of the Swiss participation in Euclid. About 100 Swiss scientists and engineers are members of the Euclid consortium, Prof. M. Kunz and Prof. S. Paltani being Founding Members.

– The Cherenkov Telescope Array Observatory (CTAO), primarily supported by the CHIPP community, will consist of two arrays of Cherenkov telescopes located in La Palma and Paranal. It is driven by a consortium of about 1500 scientists from 25 countries and will be built between 2023 and 2028 by a European Research Infrastructure Consortium (the first telescope is already operated on-site). CTAO will explore the Universe at the highest energies based on the imaging air Cherenkov technique with four types of telescopes optimised for different energy bands and fields of view. CTAO will probe cosmic particle acceleration at energies 10 to 100’000 times the proton rest mass. Gamma rays are used to trace violent events in the Universe where a small fraction of the particles can take on an ‘unfair’ share of the energy available (non-thermal processes). The main topics of interest in the current Swiss groups (PI: Prof. T. Montaruli, UniGE) are to understand 1) 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; 2) astrophysical systems such as pulsars, X/gamma-ray binaries, micro-quasars, magnetars, active galactic nuclei, gamma-ray bursts also via multi-messengers techniques; 3) the nature of matter in the universe and searching for the sites where dark matter agglomerates; 4) the cosmological evolution of early galaxies measuring the extragalactic background light and determining magnetic fields in cosmic voids. Finally Swiss scientists are also looking for physics beyond the Standard Model, for instance looking for violation of Lorentz invariance or axions and have proposed to use the 4000 m^2 mirror area provided by the CTAO telescopes together with classical extremely large telescopes to reach sub microarcsecond resolution, the best ever in astronomy, to resolve accretion disks around galactic compact sources and quasars. CTAO is in the ESFRI and Swiss infrastructure roadmaps. Switzerland (in particular through SERI) 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. Switzerland also supports the first extension of the alpha configuration in the form of the construction of additional large size telescopes in Paranal.

– Athena is the second large mission of ESA’s Cosmic Vision programme planned for launch in 2034. It will be the successor of ESA’s Cornerstone mission XMM-Newton X-ray observatory. Athena will embark on a large effective area X-ray telescope, with two instruments. The Wide Field Instrument (WFI) will perform large-area surveys in order to search for the first supermassive black holes in the early Universe. It will also measure the masses of clusters of galaxies, from the first proto-clusters to the local Universe; the distribution of these masses and its evolution is an important cosmological probe. In addition, WFI will have the possibility to observe very bright sources, like Galactic neutron stars and black holes, which will give fundamental insights into the complex physics taking place therein. The X-ray Integral Field Unit (X-IFU) is a revolutionary instrument based on a completely new technology, the transition edges sensors, a technology based on superconductors that provides very high energy resolutions for imaging detectors. The X-IFU will study in detail the hot gas inside clusters of galaxies that account for 80-90% of the baryonic mass, constraining the physical processes that take place within. This will allow us to study the composition, dynamics and thermodynamic properties of the gas, which are all necessary ingredients to understand the processes of formation and evolution of these objects. The high spectral resolution combined with high spatial resolution of the X-IFU will also shed light on one of the most spectacular processes taking place in the Universe, namely the process of reheating of the gas by the central supermassive black hole, which probably happens through the formation of turbulent gas, something that only Athena combined with the X-IFU can observe. The X-IFU will also allow us to study in detail the process of accretion onto supermassive black holes, and will in particular characterise the properties of the outflowing winds from these objects. The role of these winds in the evolution of galaxies is one of the most important questions of galaxy evolution, as it has been shown in a few cases that these winds may carry enough momentum and energy to wipe out completely the gas from the host galaxy, thereby stopping any star formation. There is a very large Swiss involvement in Athena, led by Prof. S. Paltani (UniGE), for both instruments, with hardware participations in the X-IFU (and a minor one in WFI), plus a very significant contribution to the data centers of both instruments, with leading role for the general architecture of the Athena ground-segment, the software development for the X-IFU and the data processing for the WFI.

- While the next major X-ray observatory mission, Athena, will not be available until the next decade, similar detector technology will be embarked on the Japan-led mission XRISM, that will be launched in 2023. XRISM is actually a recovery mission for the Hitomi mission, which experienced a failure very early in the mission, but was nevertheless extremely successful (two Nature papers for a single scientific observation) thanks to its ground-breaking detector. Switzerland plays a significant role in the mission, together with the USA and the Netherlands, with the contribution of payload elements manufactured by Ruag Space AG. The science goals of XRISM are similar to those of the X-IFU on Athena, although it will be severely limited by the size of the mirrors, the low spatial resolution, the tiny number of pixels of the detector and the lower energy resolution. Prof. S. Paltani (UniGE) is leading the participation in XRISM, and three members of the Swiss community will participate in the analysis of the private, early mission data.

- The enhanced X-ray Timing and Polarimetry mission (eXTP) is a mission led by the Chinese Academy of Science involving a number of European institutes. eXTP is an X-ray observatory optimised for the observation of very bright sources with high time resolution, in order to study phenomena occurring in extreme physical conditions of density, gravity or magnetic field strength that are found in the vicinity of neutron stars and stellar mass black holes. Thanks to its suite of X-ray instruments, eXTP will make ground-breaking observations to constrain the equation of state of matter at the highest densities. Thanks to its high sensitivity and huge field of view, the Wide Field Monitor will also play a key role in the emerging science of multi-messenger astronomy (see below) by measuring or constraining the electromagnetic flux of the potential multi-messenger sources. Prof. X. Wu (UniGE) leads the Swiss contribution with a significant participation in the Large Area Detector. The Department of Astronomy is also planning to establish a European data center in Geneva. eXTP is currently planned for 2028, but the participation of ESA, which would be needed to support the European institutes, is currently stalled, because of difficult sanitary restrictions in China.

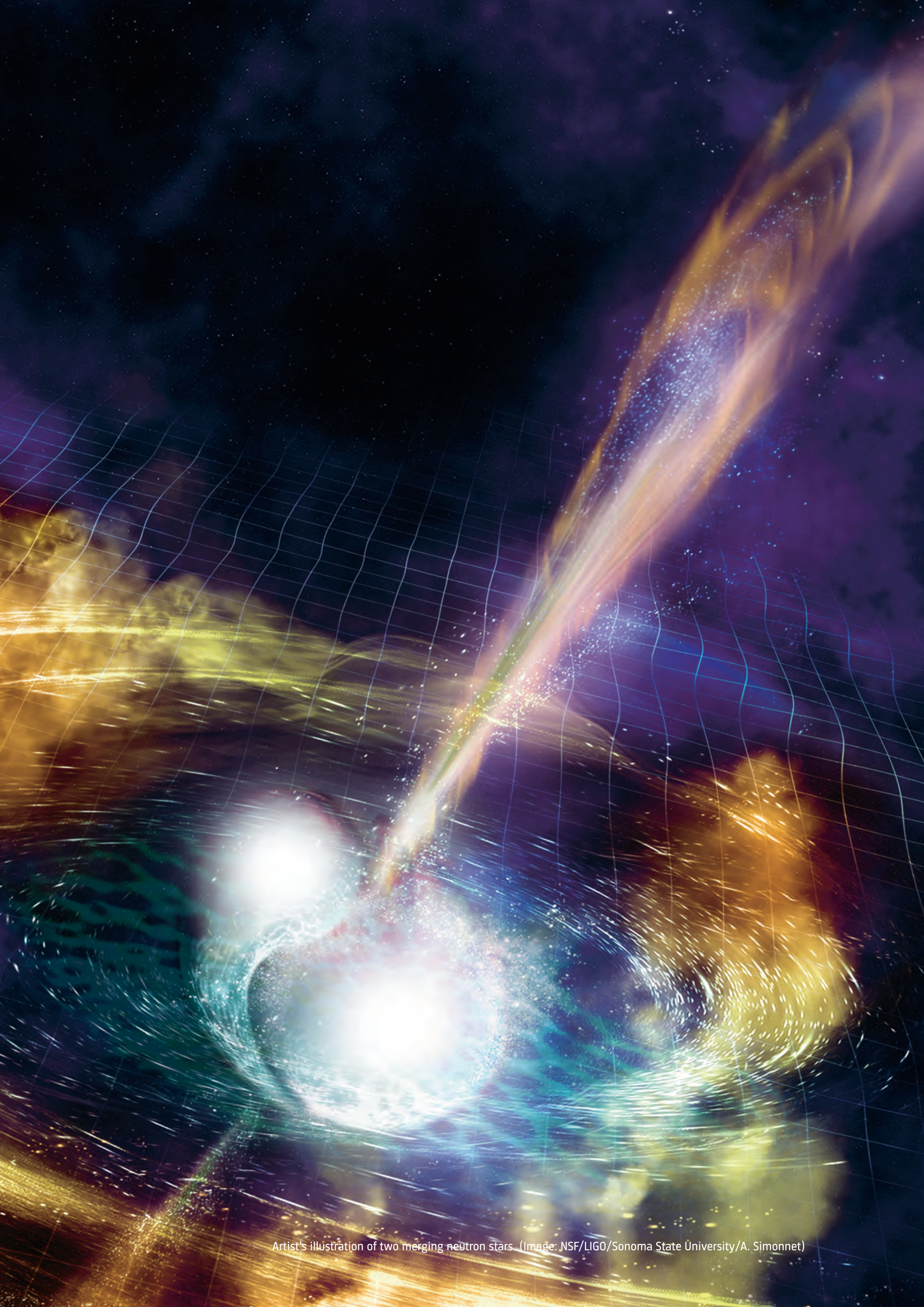
- A large effort has been made in Switzerland to support the THESEUS candidate mission in competition for the M5 slot of ESA's Cosmic Vision programme. THESEUS, which was finally not selected against EnVision, was a mission dedicated to the detection and study of X-ray and gamma-ray flashes that result, in particular, from the collapse of the first massive stars at the dawn of the Universe. At the same time, THESEUS would have detected or constrained the electromagnetic counterparts of gravitational wave events, and thus be fundamental for multi-messenger astrophysics in a time period where the next-generation ground-based gravitational wave telescopes like the Einstein Telescope will start operations. THESEUS will be proposed again as the M7 candidate mission for a launch in 2036, with large Swiss involvement at the University of Geneva (Prof. S. Paltani), with the lead of the science data center, and a hardware contribution to the infrared telescope that will measure the redshifts of gamma-ray bursts on board. The same team shall participate in the NASA mission candidate Gamow, which has similar to but much less ambitious goals than THESEUS, but that could fly in 2028 if selected.

- Swiss research groups are also playing a leading role in the HIRAX experiment. This radio interferometer being built in South Africa will provide a map of cosmological neutral hydrogen and provide important constraints on the standard model of cosmology. Swiss universities (ETHZ, Geneva and EPFL) are leading the construction of the digital correlator and of the Science Data Processing unit for this experiment. They are also very active in the preparation of the analysis of the data from this experiment. This work on HIRAX will also help Switzerland prepare for its participation in SKAO.

- 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. For the first time cold atoms will be operated in conditions which are not realisable on Earth in order to perform fundamental physics tests (relativity, possible drift of fundamental constants with time). At the same time, a number of new technologies needed by the science community will be validated. Furthermore, the science community could take advantage worldwide of the ACES frequency stability by using ground stations to download the ACES time reference. ACES consists of the cesium 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. In the near future more space missions dedicated to tests of General Relativity will certainly be planned.

– The gravitational wave projects, in particular LISA, LIGO/Virgo upgrades and the Einstein Telescope are discussed in detail in the following section.

Figure 12: Colliding black holes send ripples through spacetime that can be detected on Earth. The Advanced Laser Interferometer Gravitational-Wave Observatory, or Advanced LIGO, which has detectors in Louisiana and Washington, has directly observed these gravitational waves. (Image: Mark Garlick/Science Photo Library/Alamy Stock Photo)



Artist's illustration of two merging neutron stars. (Image: NSF/LIGO/Sonoma State University/A. Simonnet)

9 Emerging fields and associated large-scale projects

9.1 Gravitational waves

The first detection by the LIGO/Virgo collaboration of the gravitational waves (GWs) generated by the coalescence of a black hole (BH) binary, in September 2015, was a historical discovery, awarded with the Nobel Prize in 2017. It was then followed in 2017 by a 2nd event associated with the coalescence of a neutron star (NS) binary, together with the simultaneous observation of a gamma rays burst by Fermi-GBM and by the INTEGRAL satellite. The source has then been identified and observed for months in all bands of the electromagnetic spectrum. At the current level of sensitivity, LIGO/Virgo detect approximately one binary black hole (BBH) coalescence per other week, resulting to date in a catalogue of about 90 BBHs, as well as a handful of binary NSs (BNS) and one BH-NS binary. These discoveries mark the beginning of a new era for astrophysics, cosmology and fundamental physics, in which GWs are used as a tool to probe the Universe.[4]

The field of GWs is now emerging as one of the most promising of the next decades, at the intersection of several communities (astronomy, fundamental physics, particle physics, and nuclear physics), and a domain where future significant developments worldwide are envisaged. Switzerland is extremely well positioned to become a key player in this new research field.

9.1.1 The Einstein Telescope (ET)

The early extraordinary results represent, however, only a first step towards our exploration of the Universe with GWs. Third-generation (3G) detectors (after initial LIGO/Virgo and advanced LIGO/Virgo) are currently under study. The European Virgo detector will soon reach the limits imposed by its infrastructure, and the project of a new observatory, the ET (http://www.et-gw.eu), is under development. It will consist of a triangle-shaped GW interferometer, with 10 km arms, located 200-300 meters underground to reduce seismic noise, with many remarkable technological improvements. Two sites are currently considered, one in Sardinia (Italy) and one across the German-Belgium-Netherland border. End of June 2021 ET has been included in the updated ESFRI Roadmap. In parallel in the US, a 3G detector called Cosmic Explorer (CE) is under study as the successor of LIGO. If approved, ET and CE should start taking data in the mid 2030s. ET is conceived as an observatory whose infrastructure will allow for continuous improvement, leading to an expected lifetime of order 50 years, during which it will have a leading position in the field, somewhat similarly to CERN for particle physics.

A recent detailed discussion of the huge scientific potential of the Einstein Telescope has been published by the ET science team headed by Prof. M. Maggiore from the University of Geneva (Maggiore et al. JCAP, 03:050, 2020). As a single example, ET will detect BBH up to redshift $z \sim 20$ corresponding to the depth of the Universe (by comparison, advanced LIGO/Virgo will reach about $z \gtrsim 1$), resulting in the detection of millions of BBH coalescences per year, and 105 BNS per year, of which several tens/hundreds per year could have an observed electromagnetic counterpart.

9.1.2 Space-ground complementarity

At about the same time, the space GW interferometer LISA (Laser Interferometer Space Antenna, ESA L3 mission), whose launch is scheduled for 2035 will explore the Universe in GWs in a different band of frequencies, where, for instance, extraordinary events such as the coalescence of super-massive BHs can be observed. Ground-based 3G detectors and the space interferometer LISA will be highly complementary, and they will provide us with a multi-band picture of the Universe in GWs. Indeed, LISA after the very successful LISA-Pathfinder mission which tested part of the needed technology, in particular the drag-free control, is now under development under the leadership of ESA with important contributions from NASA.

LISA aims to measure gravitational waves directly by using laser interferometry. It is designed as a constellation of three spacecrafts arranged in an equilateral triangle with sides 2.5 million km long, flying along an Earth-like heliocentric orbit. The distance between the satellites will be precisely monitored to detect a passing gravitational

4 To mention only a few highlights: the observation of the NS-NS binary coalescence GW170817 solved the long-standing problem of the origin of (at least some) short gamma ray bursts; the multi-band observations of the associated kilonova revealed that NS-NS mergers are a site for the formation of some of the heaviest chemical elements through r-process nucleosynthesis; the observation of tens of BH-BH coalescences has revealed a previously unknown population of stellar-mass BHs, much heavier than those detected through the observation of X-ray binaries; the speed of GWs has been shown to be the same as the speed of light to about a part in 1015; the first measurements of the Hubble constant with GWs have been obtained; the tail of the waveform of the first observed event, GW150914, showed oscillations consistent with the prediction from General Relativity for the quasi-normal modes of the final BH; several possible deviations from General Relativity (graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.) have been constrained.

wave. LISA completed successfully at the end of 2021 the study Phase A and is currently in the so-called study Phase B1, after which mission adoption is expected, most likely around 2024. If successful, construction will begin afterwards and the launch is expected in the mid 2030s.

9.1.3 Involvement of Swiss researchers and institutions

In Switzerland, several groups have significant experience in the domain of GWs and have already brought important contributions:

LISA Pathfinder. ETH (Prof. D. Giardini) and UZH (Prof. P. Jetzer) led, with the support of the PRODEX programme, the Swiss participation in the LISA Pathfinder demonstration mission. ETH developed the Inertial Sensor Front End Electronics (IS FEE) in collaboration with industry and UZH was involved in theoretical studies needed for defining the LISA mission.

LISA. Presently, both groups at ETHZ and the University of Zurich are actively working for the LISA mission. In this context, Switzerland will further develop the IS FEE in collaboration with Swiss industry. Besides the technical work, the ETH and the University of Zurich are also involved in studies on future data analysis and scientific exploitation. D. Giardini and P. Jetzer are members of the

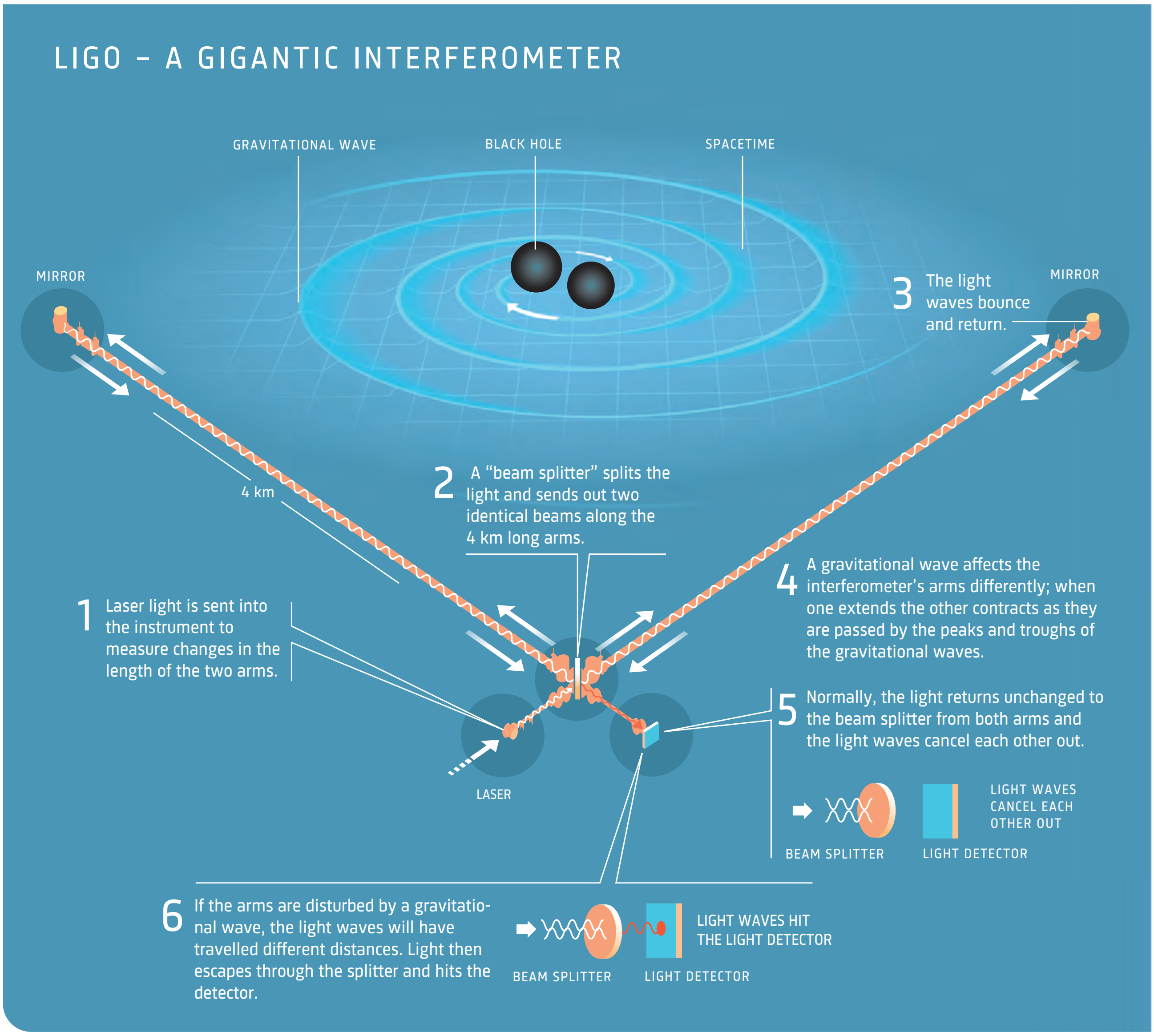


Figure 13: Principle of functioning of the LIGO interferometer. (Image: Johan Jarnestad/The Royal Swedish Academy of Sciences)

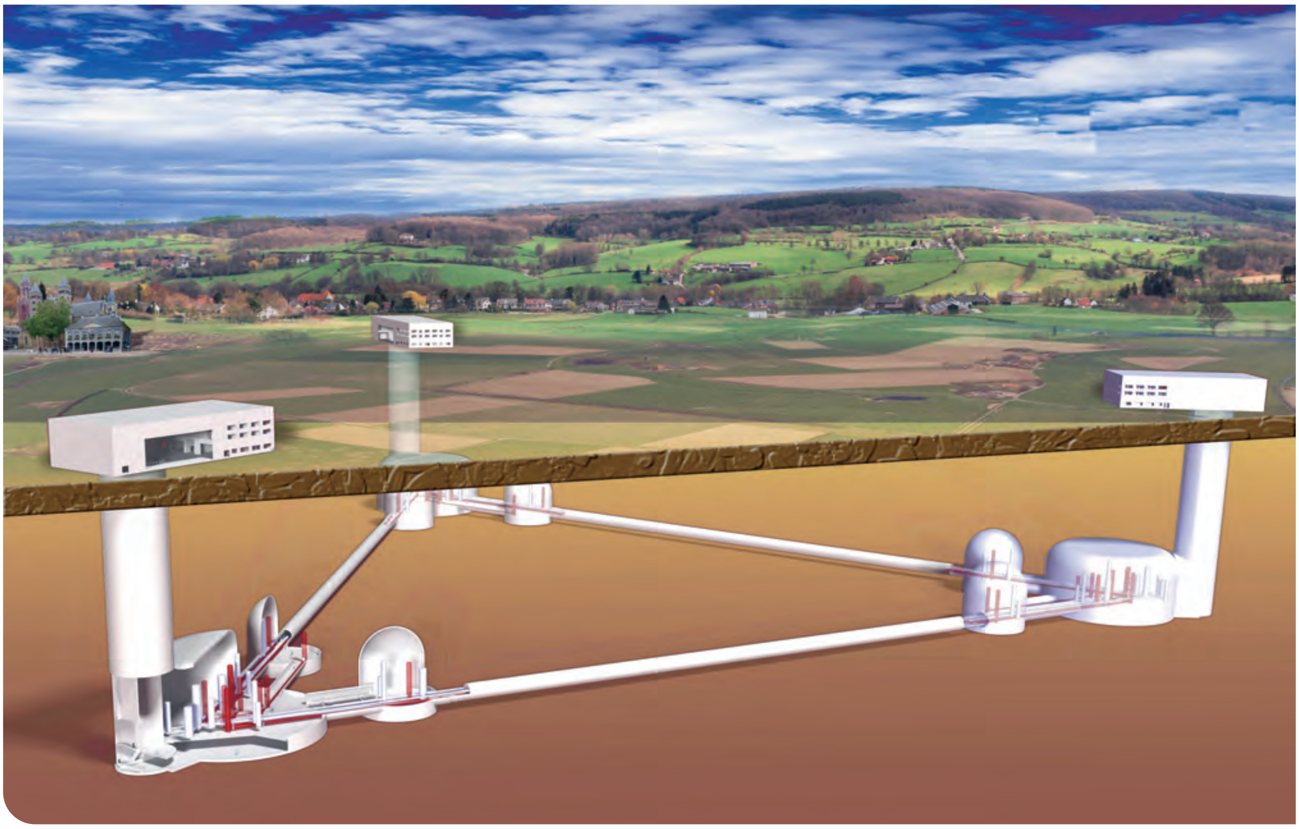


Figure 14: Artistic view of the Einstein Observatory. (Image: NIKHEF)

Board of LISA (D. Giardini also in the Executive Board and P. Jetzer in the LISA Science Working Team of ESA). On the Astronomy side, Profs S. Paltani and A. Fragkos from the University of Geneva are members of the LISA Consortium as well, with an interest in the Data Processing Group (Data center in Geneva) and in the Astrophysics Working Group. Prof. L. Mayer from the University of Zurich is co-leading the Astrophysics Working Group. Profs. M. Maggiore, R. Durrer and A. Risotto and several of their collaborators at the University of Geneva are also members of the LISA consortium and actively involved in different Working Groups.

LIGO/Virgo. The group of Prof. P. Jetzer is, since the beginning of 2017, member of the LIGO Scientific Collaboration (LSC) and is leading a working group on eccentric waveform modelling.

Einstein Telescope. Prof. M. Maggiore is a member of the Steering Committee of ET and is a co-chair of the ET Observational Science Board. In this role, he is in charge of coordinating the theoretical activities related to ET. His group, as well as the groups of Profs R. Durrer and A. Riotto, are well established groups working in this domain for many years.

The high-level participation of M. Maggiore in the Einstein Telescope provides an entrance door for an enlarged Swiss participation in the project. In March 2020 the University of Geneva signed the 'Letter of Intent supporting the preparation toward the establishment of the Einstein Telescope', thus qualifying the University of Geneva as one of the founding universities of the project. Given the remarkable developments in the field, and the synergies that it already fosters between the CHIPP and CHAPS communities, several Swiss institutions have started a process of aggregation and coordination in this domain (e.g., the creation in January 2022 of the 'Gravitational Wave Science Center' at the Faculty of Sciences at UNIGE, with coordinator Prof. M. Maggiore [theory] and deputy coordinator Prof. A. Fragkos [astronomy]).

Quite naturally, this will eventually lead to evaluating the opportunity of a Swiss involvement, besides the already established LISA project, in an infrastructure such as the Einstein Telescope, that would allow Switzerland to play a major role in these exciting developments for the next decades. In this respect an early participation in Advanced Virgo would be desirable as this would allow to get quickly the needed expertise in view of the Einstein Telescope building and also to participate from the beginning in the data analysis and the scientific exploitation of the facility.

9.2 Multi-messenger astronomy

The vast majority of our knowledge of the Universe has been communicated to us through electromagnetic waves, or photons. However, other signals are emitted by astrophysical sources. For instance, it has been known for more than a century that most of the energetic charged particles on Earth have a cosmic origin, forming the so-called cosmic-rays. The energy of a single particle can reach incredibly high values, with events having been recorded at the Pierre Auger Observatory in Argentina with macroscopic energies (up to about 60 J, i.e., the energy of a tennis ball at 10 m/s), Low-energy neutrinos are produced in large numbers by every star, and Solar neutrinos are routinely detected on Earth. Very high energy neutrinos are also expected based on the existence of these extremely high energy cosmic rays, and huge detectors have been built, in particular IceCUBE in Antarctica, which uses about 1 km^3 of ice as a neutrino detector. Finally, gravitational waves, whose existence has been directly demonstrated in 2015 with the discovery of a black-hole merger by the LIGO gravitational-wave observatory, constitute another messenger. Multi-messenger astronomy is defined by the simultaneous observation of celestial events with more than one messenger, usually including electromagnetic waves. Solar flares are routinely studied with normal telescopes and cosmic ray detectors. A bunch of neutrinos were detected several hours before the explosion of the supernova SN 1987A. A possible association between high-energy neutrinos and gamma-ray flares has been announced for the blazar TXS 0506+056. But the most compelling multi-messenger event definitely took place on August 17, 2017, where the ground-based gravitational-wave detectors observed a signal that was simultaneously detected by gamma-ray instruments, including INTEGRAL at the INTEGRAL Science Data Centre of the University of Geneva. This combined observation allowed the astronomers to understand the event in a lot of detail; they concluded that we observed a neutron star-neutron star merger in what is known to be a kilonova.

The importance of multi-messenger astronomy is bound to grow significantly in importance. Multi-messenger events provide a unique window on some of the most fascinating astrophysical processes, involving the highest energy densities and the largest gravitational fields. While these events are still rare, new detector facilities will soon dramatically change the situation, by being more and more sensitive. Switzerland is very well positioned to participate in the science of multi-messenger astronomy. Cosmic ray detectors in space have been developed for more than two decades at UNIGE in the Particle Physics Department, starting with the AMS project (Swiss contribution now led by Prof. X. Wu). The same department is also involved in IceCUBE (Prof. T. Montaruli). At the University of Geneva again, INTEGRAL has been contributing to the observation and assessment of the existence of gamma-ray counterparts of gravitational-wave events since the beginning.

Further development of multi-messenger astronomy in Switzerland requires the consolidation of the already solid collaboration with particle physicists for the access to non-electromagnetic messengers for the development and scientific exploitation of cosmic-ray, neutrino and gravitational-wave detectors. As mentioned above, a significant participation in ground-based gravitational-wave detectors like the ET is needed. The electromagnetic counterparts, especially in X-rays and gamma-rays, play a fundamental role in linking a multi-messenger event with its source, which can usually be identified in optical/near-infrared only. Additional developments in space missions providing large-field of view and sensitive detectors in the X-ray and gamma-rays, like Gamow, eXTP or THESEUS are also mandatory, especially in view of the huge expertise in the field at the University of Geneva.

Other instrumentation with Swiss involvement will be providing important contributions in the field. Neutrino sources will produce gamma-ray flares up to the energy range accessible to CTA, which will play an essential role in the understanding of the physical conditions of cosmic accelerators. The properties of the electromagnetic counterparts of gravitational events are best studied in the soft X-rays, where high-resolution and sensitive telescopes are available; Athena will be instrumental in constraining the physics of merger events through the observation of the X-ray signal, from the precursor to the afterglow. SKA will also observe low-frequency radio counterparts and will be extremely powerful to identify the counterpart considering the large field of view, high sensitivity and high spatial resolution.

In particular SKA together with LISA can help to greatly improve the sky localisation, enabling the redshift determination of gravitational wave sources from massive and supermassive black hole mergers, as required to break the well-known mass-redshift degeneracy. Similarly, also joint Athena – LISA observations would be extremely important.

With its access to a wide range of facilities, often with quite prominent roles, the Swiss astronomical community is able to play a quite prominent role in the science of multi-messenger astronomy. This will require strong support from the SERI in the preparation of the future missions, as well as a good collaboration with the physics community. Both elements are currently in place.

10 ESA's 'Voyage 2050' programme

'Voyage 2050' is the name of the third planning cycle of the scientific missions of the European Space Agency, after Horizon 2000 and Horizon 2000+ established at the end of the 1980s, and Cosmic Vision 2025, established in 2005. Because of the huge impact of space missions on astrophysics, the evolution of ESA's scientific programme is extremely relevant to the future directions taken by Swiss astrophysicists. A Senior Committee has been appointed in 2018 by ESA to recommend, in a bottom-up process based on submission of white papers by the scientific community at large, science themes to be implemented starting from 2040. The mandate of the Senior Committee consisted in defining:

1. The science themes for three Large missions to be implemented
2. Possible science themes for the Medium missions
3. Enabling technologies that will be needed beyond Voyage 2050

Fifty members of the community, with a focus on diversity and representativity of early-career scientists, were furthermore selected to form five topical teams to assist the Senior Committee in its evaluations. The Senior Committee formulated its recommendations to ESA's Executive in 2021, which were endorsed by the Science Programme Committee during its 167th meeting.

Regarding the Large missions, the Senior Committee proposed the following three mission concepts:

1. The first mission shall be a mission to the moons of the giant planets, i.e., either Jupiter or Saturn, to study habitability, the presence of biosignatures, chemistry, etc. This would be implemented through a planetary probe, with Saturn probably being the priority, although it shall need to be studied more in detail by a dedicated expert committee.
2. The second mission will focus on either of the two following science themes:
   a. The characterisation of the atmosphere of a significant number of temperate and rocky exoplanets
   b. A global astrometry survey of the Galaxy in the near-infrared, following in the footsteps of Gaia, which will address a number of 'foundational' scientific themes, such as stellar and galactic formation and structure.

   While the exoplanet science theme seems the most compelling to the Senior Committee, its feasibility needs to be demonstrated, both in terms of technical feasibility and affordability. The final decision on this science theme will be taken when these questions are clarified. In addition, the global context shall be re-evaluated in view of the results of the three Cosmic Vision missions CHEOPS, PLATO, ARIEL, and ESO's ELT. For the near-infrared astrometry science theme, realistic estimates of the performance should be performed, in order to put forward a consolidated science case.
3. The final large mission will study the physics of the very early Universe. At least two different kinds of probes can be envisaged: a gravitational-wave detector for waves with frequencies between the range accessible to LISA and that (much higher) accessible to ground-based facilities, and a mission to perform accurate spectroscopic and polarimetric observations of the cosmic microwave background. Again, an expert team shall be consulted to understand the capabilities and limitations of each of these techniques.

Concerning the priorities, the planetary probe is an obvious first choice, but the order between the second and the third missions shall be decided later, based on technical and programmatic considerations.

The Senior Committee did not provide a list of science themes to be implemented for medium-size missions, because they recognised the necessity to remain flexible. Medium-size missions are indeed already quite ambitious, but they can be implemented on a significantly shorter time scale than the large missions. Thus, the Senior Committee only highlighted the richness of the proposals that have been received. The highlighted proposals cover domains from the magnetosphere to the Sun and Solar system, to the stars and the interstellar medium, to black holes and accretion physics, to the missing baryons and the large-scale structure, as well fundamental physics, with probes of quantum mechanics and general relativity.

The Senior Committee also points out the importance of international collaboration, and recommends participation in a mission to Uranus or Neptune in partnership with another agency, for instance in the form of a medium-size contribution. Although the recommendations predated the publication of the results of the Decadal Survey on Astronomy and Astrophysics 2020 of the USA National Academy of Sciences, the Senior Committee invites ESA to join NASA in the implementation of its flagship and probe-class missions. These missions are, respectively, an infrared-to-ultraviolet large telescope dedicated to the observation of habitable exoplanets, as well as to general astrophysics, and two possible missions in competition, a far-infrared spectroscopy and/or imaging mission and a high spatial and spectral resolution X-ray mission. ESA is also invited to join NASA to implement a NASA-led in situ probe of the interstellar medium, if selected by the Solar and Space Physics Decadal Survey. In addition, a participation in a mission focused on the origin of the Solar system is recommended, possibly with sample return, although this would probably largely exceed the available budget, so that in situ measurements, possible in the atmosphere of the giant planets, could be a possible descope.

11 Societal impact

Fewer than 1% of all scientists are astronomers, yet astronomical stories take more headlines and media coverage than any discipline other than medicine. Astronomy captures the public interest for three main reasons:

- The exploration of the universe in space and time reveals our origins and our place in the cosmos;
- The incredible discoveries and beautiful images acquired by modern telescopes are highly inspiring;
- Giant telescopes and complex space missions are fascinating technological achievements.

In addition, astronomy probably represents some ideal of pure science only aiming to the advancement of knowledge, away from a direct societal impact or a commercial application.

It would however be wrong to consider astronomy as decoupled from society and industry. Much to the contrary, it plays an extremely important societal role as a gateway to attract the interest of pupils into MINT disciplines, by forming the next generation of highly-skilled workforce, as well as by promoting innovation and providing cutting-edge technology development opportunities to industry.

11.1 Astronomy contributions to innovation and industry

Progress in astrophysics has always been intimately tied to technological development. The invention of charge couple devices (CCDs), for instance, has revolutionised modern observational space- and ground-based astronomy. Another prominent example is the development of the precise spectro-velocimeter that eventually led to the discovery of the first extrasolar planet. Another example is the amazing technology development of ground-based interferometers that allowed more recently the detection of gravitational waves. These are only three examples for the essential role of technology that drives new discoveries and leads to breakthroughs in how we see the Universe.

Although it may appear less evident at first glance, research in astronomy also directly drives technological R&D and produces considerable direct and indirect technology and knowledge transfer. CCD cameras and image analysis are nowadays ubiquitous in any smartphone, for instance. The know-how gained in participation in international cutting-edge projects can be applied to many other areas very different from astronomy. Space and ground-based astronomical research projects help Swiss industry to fully exploit the technological potential existing in universities and technical institutes, e.g., in photonics, micro- and nano- technologies, optics, electronics, optoelectronics, microwave technology, detector and cryogenic technology, artificial intelligence and general algorithmics, image and data analysis, etc. It encourages and supports the creation of spin-off companies in the space and non-space market and it fosters the global competitiveness of Swiss equipment suppliers.

The development of major astronomy satellites or ground-based instrumentation is usually undertaken in collaboration between scientific research institutes and industry. This provides the scientific driver, the technological advance and the reliability of the construction that are needed to make a world-class instrument. ESO and ESA thus provide important opportunities to Swiss industry to compete internationally for the development and building of parts of the research infrastructure.

Swiss Universities and ETHs are active and even leading partners in many of the international projects within ESA and ESO, playing major and highly visible roles in defining the initial science requirements, leading projects, building key instrument hardware and software elements, and developing data reduction and analysis tools. They often collaborate with Swiss industry, technical universities and research infrastructures (PSI, PIF, SLS, CERN) owner of specific cutting-edge technology, facilities and infrastructures. These projects and collaborations need resources, but the investment is highly rewarding by getting prime access to the new technology with the associated opportunity to reap the largest scientific return. Indeed, even on observational facilities with open competitive scientific access – such as the ESO telescopes and many of the ESA observatories – the knowledge gained through instrument development gives participants a huge advantage in optimizing the use of the instrument and in performing the most effective data analysis.

11.1.1 FLARE and PRODEX funding

The FLARE funding scheme provides critical support for the development of ESO instrumentation projects, while for space missions, it is via the ESA PRODEX programme that experiments and instruments can be developed in

Switzerland both by industry and research institutes. This funding scheme offers Swiss Institutes an entry into consortia of large instrumentation projects to which they contribute in exchange for significant scientific return. It enables, for instance Swiss researchers to perform high-impact science by using the so-developed new observing facilities through reserved observing time or GTO.

FLARE and PRODEX offer a unique opportunity to involve Swiss industry in research projects e.g., by contributing state-of-the-art technological expertise. By a matter of fact in the case of FLARE, and by formal requirement in the case of PRODEX, a significant fraction of their funding is re-injected in (Swiss) industry, eventually also fostering collaboration between research institutes and industry. FLARE and PRODEX are thus two essential sources of funding to be continued and secured to the benefit of scientific research, as well as innovation and top-level industry developments. We must however note that both funding tools, and FLARE in particular, do not offer long-term financial commitment. In an era in which projects become larger and longer, this uncertainty of funding may weaken the position of Swiss partners in international consortia.

11.1.2 The missing link

PRODEX and FLARE have demonstrated to be essential tools to (co-)fund space and ground-based projects. However, they can only be activated once the projects have entered an official phase. For technological R&D preceding the project phase, and often critical for the proposal preparation, no adequate tool exists. This situation provokes a competitive disadvantage for Swiss institutes and Swiss industry in high-risk technology development with no guaranteed financial or scientific return.

11.2 Contribution to education and outreach

Astronomy addresses some of the oldest and deepest questions on our origins and our place in the cosmos. It therefore captures the imagination of young and old people alike. The public fascination for astronomy is further reinforced by the beauty of the night sky – away from light population in the cities – and the amazing images captured by giant telescopes or sophisticated satellites. As a consequence, planetariums and astronomical exhibits are among the most popular at museums that showcase science.

11.2.1 Outreach

The large public interest in astronomy is reflected by 32 societies or associations affiliated to the Swiss Astronomical Society (SAS), which is mainly constituted of amateur astronomers. This network of regional sections with overall some 2500 members is an important component of astronomy outreach. They propose telescope observations, planetariums, events and conferences. Professional astrophysicists are often invited by them to give outreach talks all around Switzerland and also participate in the edition of the journal ORION.

To complement the offer by the amateur astronomers, professional astronomers provide more specific outreach activities within their institute or through the Swiss Society for Astrophysics and Astronomy (SSAA). Professional outreach is usually more linked to current research, new discoveries, or the development of new instruments or telescopes. To mention a few of them:

– The NCCR PlanetS publishes the Newsletter 'The Observer' to communicate with the public. It also develops exhibitions in museums and offers outreach and educational material.

– Stellarium Gornergrat is a pedagogical observatory of the universities of Bern and Geneva offering educational content and remote observing time from an altitude of 3100 metres for schools and the interested public. It is in particular possible to use the facility remotely to conduct its own observation programme for a matura work in astronomy.

– 'Salomé' is a new series of French comic books on the search of exoplanets at the Geneva Astronomical Observatory. Depicting real people like Nobel Prize winners Michel Mayor and Didier Queloz, it aims at initiating children to sciences. It is further complemented by a pedagogical project for teachers at the end of primary school (7th and 8th degree Harmos) and reached already about 10'000 pupils in the Romandie since March 2020.

11.2.2 Education

Pre-university education

Despite the broad public interest and fascination for young people, astronomy is not officially part of primary and secondary education. It is on a voluntary basis that teachers decide to incorporate some aspects of astronomy in their courses. Most commonly on the orbit of the Earth around the Sun and the inclination of its spin axis leading to the seasons, or on the phenomenon of the moon phases and the eclipses. Some physics teachers at high-school cover the laws of Kepler and Newton's gravitation and more rarely offer an introduction to stellar evolution or to Einstein's special relativity. It would be interesting to develop partnerships between astronomers and teachers to help them exploit the inherent interest of students for astronomy and the potential of astronomy education as a gateway into science.

Undergraduate education

Essentially all of the undergraduate astronomy teaching at university level is embedded within a curriculum in physics, or in other related disciplines, such as computational science at the University of Zurich. There is no dedicated Bachelor or Masters degrees in Astronomy in Switzerland, although it is possible to take a Physics degree with a 'Minor' in Astronomy at the University of Bern and with an 'Orientation' in Astrophysics at the University of Geneva and the University of Zurich. As a consequence, many astronomy professors in Switzerland teach more courses in physics than in astrophysics. This close association with physics makes sense, since a solid education in physics or a related field is the best preparation for a postgraduate career in astrophysics.

Graduate education

Education at the graduate level is a preparation for the research environment and is necessarily less structured than at earlier stages. For more than 50 years, the annual Saas-Fee Course – organised by the SSAA with financial support by SCNAT – has served as an important element in the training of our own PhD students. Originally held in Saas-Fee, the courses last a week and are nowadays organised in different places, but always in the Swiss Alps during the winter. These outstanding courses cover different topics every year and are traditionally delivered by international experts, thus attracting also many participants from abroad. The lecture notes are published in a book, which are often regarded as classics in graduate education all over the world.

Spiral galaxy Messier 83. (Image: ESO)

12 Annex I. A snapshot of Swiss Astronomy 2021

As of December 31, 2021

	Elected professors	Permanent Senior scientific staff	Non-permanent scientific staff	PhD students	Technical/ engineering staff	Secretarial/IT/ Communication
IRSOL	0	5	4	2	1	1
ISSI (Bern)	1	2	2	0	0	4
University of Bern (without AIUB)	3	8	21	26	36	11
AIUB	1	3	13	6	3	3
PMOD/WRC	1	1	4	6	4	1
ETHZ	4	1	36	23	4	3
University of Basel	1	1	2	1	0	0
University of Zurich	6	2	22	31	1	2
EPFL	1	4	22	21	2	4
University of Geneva Department of Astronomy	11	9	45	33	44	21
Total numbers	**29**	**36**	**171**	**149**	**95**	**50**

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.

13 Annex II. Research in astronomy in Switzerland

The beginning of the 21st century has witnessed tremendous advancements of research in astrophysics and Swiss astronomers are working at the forefront of research in modern astrophysics. Previous Roadmaps highlighted the strong foundations of Swiss astronomy. Research groups have established an international presence in many of the most current and new areas of research. In particular, we leverage our membership in ESO and ESA to lead observational research in areas such as exoplanets and the exploration of the Solar System, solar and stellar astrophysics, galactic and extragalactic astrophysics, and cosmology. This has gone hand in hand with the development of innovation and technology. Swiss theorists have leading roles in the areas of stellar evolution, supernova explosions and compact binary mergers, planet formation, galaxy evolution, and cosmology, supported by strong developments in state-of-the-art computer simulations. This strength and vigorous activity provide the foundation upon which the future directions of the community can be based.

The questions to be addressed in astrophysics are multiple. They are gathered here in broad scientific themes unifying both past achievements (some very recent) and future potentials. These themes are:
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

13.1 Fundamental physics

Astrophysics can be either the application of physical laws to cosmic phenomena, or the use of cosmic phenomena to extend our knowledge of physical laws. While the former is evident, the latter comes from the fact that astrophysical environments can be so extreme that physical conditions unattainable in our laboratories can be examined and new insights about the nature of the fundamental forces or laws of Nature can be gained.

Probably the most extreme example of such conditions is the Big Bang itself, and the rapid expansion of the early Universe that followed: the so-called inflation phase. During inflation, quantum fluctuations are amplified and, as the Universe expands and cools, finally result in classical density fluctuations. This is the time at which the structure of the future observable Universe is being defined and baryogenesis is being completed. Testing this phase in the laboratory would require energies 10 billion times larger than those currently reached at CERN's Large Hadron Collider (LHC).

Swiss research groups located throughout the country develop relevant theories and means to test them with great successes. Accurate measurement of the anisotropies and polarisation of the Cosmic Microwave Background (CMB), such as those provided by the ESA Planck satellite, is the best window into the Universe at very high energies. Swiss research teams have participated in the mission and in the cosmological analysis and interpretation of the data. Planck has yielded the most precise determination of the age of the Universe (although with the use of priors), of the spatial curvature of the Universe, of the number of baryons in the Universe, of the spectral index of primordial fluctuations and, together with additional astrophysical data, the current best constraints on the mass of the neutrinos.

In 2011, the Nobel Prize in physics was awarded for the discovery of dark energy resulting in an accelerated expansion of the Universe utilizing type Ia supernova explosions, a method pioneered by the Basel astronomer G.A. Tammann. Addressing the question of its nature requires wide-field galaxy surveys carried out from the ground and from space. Swiss teams are heavily involved in current and upcoming ground-based experiments, such as DES, BOSS, DESI and Rubin Observatory/LSST, HIRAX and SKA. Switzerland is also deeply involved in the ESA Euclid mission to be launched in 2023. Euclid will observe 15'000 square degrees, in visible and near-infrared wavelengths. Several Swiss institutes are directly involved in the preparation of the mission through essential activities related to theory, observations, simulations, data reduction, and hardware.

The bulk of the mass of our galaxy is in the form of dark matter. The identification of the nature of dark matter is one of the main challenges of modern physics. Astronomical observations in the X-ray and gamma-ray domain, and with neutrinos, are our few chances for such an identification (along with the complementary direct detection searches and particle collider experiments). Over the last years X-ray and gamma-ray telescopes have started to search for the signal from interactions of dark matter particles (decay and/or annihilation) in the halo of the Milky Way, from the galactic center and other nearby structures. Swiss researchers are successfully contributing to this on-going search, which results in significant tightening of bounds on parameters of particle models of dark matter.

The nature of dark matter, dark energy, inflation, and gravity poses some of the most pressing questions in fundamental physics and cosmology today. To shed light on these questions, astronomers in Switzerland will build upon their current projects to ensure a leading role in key international experiments and theoretical projects. In particular, the following describes how they will pursue cosmological studies of the CMB and wide-field Large-Scale Structure (LSS) surveys, as well as astrophysical experiments relevant to fundamental physics.

13.1.1 Large-Scale Structure Surveys

The information of the early Universe provided by the CMB needs to be complemented by measurements of large-scale structures in the low-redshift ($z < 2$) Universe. This is not only necessary to break degeneracies present when only CMB data are available, but is also essential to probe the dark matter, dark energy, inflation and gravity dominated era. These measurements can be obtained through wide-field imaging and spectroscopy in the visible and near infrared, as well as radio surveys. These surveys enable several cosmological probes such as baryonic acoustic oscillations, weak lensing, redshift space distortions and galaxy clusters. These probes can then be combined to further break degeneracies and to control systematic effects.

Swiss astrophysicists continue to play a leading role in large-scale surveys. Several of them are of the Dark Energy Survey (DES) experiment on the 4-m Blanco Telescope at Cerro Tololo, Chile. DES provides a unique imaging survey of 5000 square degrees in five visible bands, and is optimised for weak lensing. They are also involved in the Baryonic Oscillations Spectroscopy Survey (BOSS) and lead its extension eBOSS. They have also initiated and led the COSMOGRAIL project, the COSmological MOnitoring of GRAvItational Lenses. Started in 2005, this long-term photometric monitoring (from the Euler Swiss telescope and 2.2-m telescope at ESO La Silla) of most gravitationally lensed quasars, delivers the most precise time delays to infer an independent Hubble constant value.

Swiss scientists are also part of wide field survey experiments. The Dark Energy Spectroscopic Instrument (DESI), a powerful multi-object spectrograph, is measuring the positions and redshifts of tens of millions of galaxies. The survey was conducted from the 4-m Mayall telescope at Kitt Peak over a five-year period. The final data release of the DESI imaging survey was released in January 2021.

Radio experiments also offer great prospects for Cosmology and large-scale structure. In particular, they can bridge the gap between observations of the early universe with CMB and large-scale structure surveys in the optical, by being sensitive to the dark ages. Switzerland is in the process of joining SKA which will provide an unprecedented view of the universe. Swiss participation in precursor experiments will also be important to prepare for the SKA and produce state-of-the art scenes in their own right. In particular, there is already Swiss involvement in the development of in the cosmological radio experiments HIRAX designed to perform a survey of neutral hydrogen in the Universe using the intensity mapping technique.

Switzerland will also continue to participate in the development of experiments for the longer term. Several institutions are involved in the preparation of Euclid, through diverse responsibilities and the hosting of one of the Science Data Centers. Participation by several groups in the Rubin Observatory/ LSST and DESI will also ensure that some access to the ultimate ground-based data set in its depth and area coverage will be possible for Swiss astronomers when it starts operations in 2020. Finally, the Square Kilometer Array (SKA) will provide unique contributions to constrain the non-Gaussianity of the initial conditions for large scale structure growth and aspects of dark energy.

13.1.2 Tests of Gravity and Gravitational Waves

General Relativity (GR) is a very successful theory, but it has not yet been fully tested at very large scales and in the strong field regime. Deviations from its predictions could be related to dark matter or to dark energy. Switzerland is involved in the construction of the LISA, the ESA L3 mission for the detection of gravitational waves. The scope of such a mission will be to detect and study low-frequency gravitational radiation. It will open new possibilities for astrophysical studies, for instance by allowing the detection of supermassive black holes merging at cosmological distances and to test very precisely GR in the strong field regime. From the ground, the SKA will allow unique tests of general relativity and gravity waves from pulsar and black hole measurements. On the theory side, Swiss groups are active in the prediction of gravitational wave emission from compact object mergers (neutron star mergers, neutron star – black hole). It is expected that these predictions can be tested with advanced versions of LIGO and VIRGO, sensitive to the kHz regime. Another aspect of GR which has not yet been tested in all its aspects is the validity of Einstein's Equivalence Principle. It might well be that a more fundamental theory unifying gravity and the standard model of particle physics leads to, although very tiny, violations of the Equivalence Principle. Space experiments like ACES and other proposed ones aim at verifying it. Given the relevance of this issue, it is important to be actively involved in such space experiments and also to pursue theoretical investigations. Switzerland is indeed well positioned in this respect thanks to its involvement in ACES and the many theoretical groups working on beyond GR models.

13.1.3 The Search for Dark Matter

Search for the nature and origin of dark matter is one of the main foci of modern physics and astronomy research. Swiss researchers are strongly involved in this search, with theoretical groups exploring possible particle models of the dark matter, experimental physics groups performing the 'direct' laboratory searches of dark matter in the form of Weakly Interacting Massive Particles (WIMP), and astronomy groups pursuing 'indirect' searches of the X-ray and/or gamma-ray signal from interactions of dark matter particles in the halo of the Milky Way galaxy and in the nearby galaxies and galaxy clusters.

Finally, it is worth mentioning that a major facility for the indirect search of WIMP particles with masses in the range between tens of giga-electron volt (ten times larger than proton mass) up to ten tera-electron volts will be CTA that will use the Earth atmosphere as a giant gamma-ray detector. Research groups in particle physics in Switzerland have become involved in the development of CTA hardware, in particular in the design and construction of an array of 'small size' (4-m dish diameter) telescopes. The participation of astronomy groups is more focused on the data treatment and the combination of measurements in a multi-messenger context.

13.2 Origins – stars, galaxies and the evolving Universe

We live in a Universe changing in time as structures form and evolve. Stars are the building blocks of the visible Universe. Over the history of the Universe, they have produced most of the chemical elements, and released them through winds or powerful explosions. The newly synthesised and often radio-active elements imprint in the interstellar medium the detailed traces of stellar evolution and provide a natural clock to mark the passage of time. Over the past two decades, Swiss astronomers have exploited with great success world-class ground- and space-based observatories, and fundamental theoretical breakthroughs were obtained thanks to the development of sophisticated models of the sun, stars, and stellar explosions that probe stars as high-energy laboratories of physical processes. This led to a number of major contributions both observational and theoretical in a wide range of topics in stellar evolution (including the sun) as well as in the dynamical and chemical evolution galaxies and of the Universe at all scales.

13.2.1 Galaxy formation and evolution

Swiss research in galaxy formation and evolution is at the forefront of the field. Astronomers working at Swiss institutions are maintaining leadership in studying key aspects of galaxy formation and evolution, as well as concomitant evolution of large-scale structures. In this domain, the primary resources for discoveries and the main workhorses are the ESO VLT, ALMA, the Hubble Space Telescope (HST), and the JWST, which will become a major and revolutionary facility from 2022 on. Further ahead, facilities such as the E-ELT and SKA, will open new windows to the early Universe, galaxy formation and observational cosmology, with their unprecedented sensitivity, spatial resolution and new wavelength coverage.

With their well-established and growing expertise in multi-wavelength observations, modelling, and numerical simulations, Swiss astronomers are already at the forefront in this domain. For example, combining the deepest ground-based observations with the VLT, ALMA, and the HST, Swiss astronomers have successfully led searches for the most distant galaxies in the Universe and contributed to important progress on the physical properties of early galaxies and their stellar, gas, and dust content. With HST they have also discovered and established the first large samples of galaxies which are analogues to the sources of cosmic reionization. These achievements have provided first insights on the first objects formed shortly after the Big Bang, in the era of cosmic reionization, and later on. Equipped with these insights and experience, the Swiss teams are now perfectly placed to play an important role in the exploration of the early Universe and first galaxies with the JWST and later facilities. This is reflected by the high success rate of Swiss astronomers for the first cycle of JWST observations. Observing the first galaxies and understanding cosmic reionization, some of the main topics for which the JWST, E-ELT and the SKA have been or are being constructed, will be a prime topic of the Swiss community.

The MUSE instrument on the VLT, a revolutionary wide-field integral-field spectrograph which has seen first-light at the beginning of 2014, is a unique facility to study the galaxy populations emerging from the reionization epoch. MUSE enables unique studies of the relation between galactic structure, mass, dynamics and star-formation history in galaxies across a broad swathe of cosmic time. It is yielding extremely rich data sets on nearby galaxies, providing new clues to their evolutionary past. It also enables resolved studies of galaxies seen during the major epoch of galaxy formation, at redshifts $0.5 < z < 2.0$, when the Universe was forming stars ten times faster than at present. MUSE also enabled ground-breaking studies of the evolution of the cosmic web, tracing the infall of gas onto galaxies, and studying the growth of black holes as part of the formation and evolution of galaxies. Astronomers in Switzerland have enjoyed access priority to MUSE through guaranteed time, as well as access through open time proposals. Swiss astronomers are now also involved in Blue MUSE, a next generation instrument for the VLT, just selected by ESO to go in Phase A. A powerful wide-field integral-field spectrograph in the blue part of the optical spectrum, it will represent a unique and complementary instrument to MUSE, the most-demanded VLT instrument.

Swiss astronomers are participating in large galaxy surveys collecting a vast amount of data on the population of galaxies and active galactic nuclei at low and high redshifts, and on their environment. A real breakthrough has come from the development of new phenomenological approaches to understanding the evolving galaxy population. These have been based on identifying simplicities of the galaxy population and exploring the implications of these via the most basic continuity equations. Paradoxically, by stepping back from physical preconceptions about how galaxies should be evolving, a much clearer picture has emerged of how they actually are behaving, in terms of both the fueling of galaxies and the quenching of their star-formation activity.

Another major step forward for Swiss astronomers will come very soon with MOONS, the next generation multi-object infrared spectrograph on the VLT. MOONS will survey the galaxy population at a look-back time of over 10 billion years with the same level of precision that today can be achieved in nearby galaxies.t Furthermore, ESA's Euclid satellite – whose prime objectives are to study the nature of dark energy and the large-scale distribution of dark matter – will also generate enormous amounts of data directly related to the formation and evolution of galaxies. Astronomers of nearly all fields of astrophysics will benefit directly from this unique and outstanding legacy survey.

Star formation activity of all the galaxies in the course of their evolution leads to accumulation of diffuse infrared and visible light, collectively known as Extragalactic Background Light (EBL). Direct measurements of such light are not possible because of the high level of zodiacal emission in the visible and infrared. However, the spectrum of EBL is measured indirectly by gamma-ray telescopes, via the effect of absorption of the highest energy gamma-rays in interaction with the EBL photons. Swiss astronomers use the newly available gamma-ray techniques of the measurement of EBL for the study of evolution of the star formation activity of galaxies.

The exchange of gas between galaxies and their surroundings is central to their evolution: infalling material fuels star formation, while energy injection from massive stars and supernovae may regulate further star formation. Enriched material has been seen in absorption for many years in the intergalactic medium at high redshifts. Recent work in Switzerland has now established an unambiguous connection between this material and bipolar winds driven by the intense energy injection associated with supernovae in star-forming galaxies in the early Universe. Furthermore, a quite different line of research has established that these winds are highly magnetised, potentially providing an explanation for the presence of significant fields in intergalactic space and, by removing small-scale magnetic turbulence, resolving difficulties in the operation of galactic-scale dynamos.

Complementary evidence for the existence of magnetic fields in intergalactic space, spread by the galactic winds or left from the earlier epochs of evolution of the Universe, was found via observations with gamma-ray telescopes. Very high-energy gamma-rays propagating from extragalactic sources initiate electromagnetic cascades in intergalactic space. The details of the gamma-ray signal from such cascades are sensitive to the magnetic field. Swiss researchers have used this effect to establish the presence of magnetic fields in the voids of the large-scale structure.

While the theory tracing the development of dark matter structures is now well mastered, the evolution of gas and stars is not easily linked to the evolution of non-baryonic matter. The processes of gas accretion, heating, cooling, and star formation are still poorly understood from both theoretical and observational points of view. Star formation occurs in massive, dense and cold gravitationally bound giant molecular clouds, but we do not know how star formation proceeds on a galactic scale. Work continues in order to understand the dependence of outcomes of star formation in local environments (e.g., initial mass function, multiplicity, companion mass ratio distributions, boundedness of star clusters, feedback mechanisms, lifetime of molecular clouds and the duration of star formation, star formation efficiency) on initial conditions, and how to relate these to galactic scale star formation. These topics are also addressed by searching for the remnants of ultra-faint galaxies, by studying the chemical abundance patterns of the earliest generations of stars in the Local Group dwarf spheroidal galaxies, and by numerical simulations of the tidal interactions of these galaxies with the Milky Way.

13.2.2 Solar and stellar physics

Stars are fundamental bodies in astrophysics. They are prime components in galaxies, as main contributors to the emitted light, and also contributing to the gravitational potential influencing the morphology and dynamics of the system. Basic characterisation of exoplanets relies heavily on the precise knowledge of the stellar basic parameters (detection techniques often only allow to determine planet parameters relative to the ones of the star). Compact objects, as products of stellar evolution, are often the hosts of processes at high energies. Understanding stellar endpoints, their ejecta, and the transition (as a function of initial mass) from core collapse supernovae to hypernovae / gamma-ray bursts (accompanied by black hole rather than neutron star formation as endpoints in stellar evolution or compact binary mergers), is of essential importance for a global picture of the chemical and dynamical evolution of galaxies. Theoretical simulations rely on fundamental physics, like the equation of state of ultra-dense matter, neutrino properties, general relativity, and multi-dimensional magneto-hydrodynamics. The increase of the computing power, together with progresses in simulation techniques, open the path towards still more precise and reliable multidimensional simulations of turbulence in stars, paving the way towards more accurate stellar models. Among the many highlights in this domain, we can quote the challenging numerical simulations incorporating the complex treatment of neutrino transport or the magneto-hydrodynamic processes that have finally led to successful supernova explosions (Fig. 15), and the spinstar model proposed for the first stars in the Universe, which opened new views on how these element factories enriched, and helped ionise sub-structures in the early Universe. Swiss researchers are actively involved in solving the remaining puzzles in collaboration with the European COST Actions (cooperation in Science and Technology) ChETEC (Chemical Elements as Tracers of the Evolution of the Cosmos), PHAROS (The multi-messenger physics and astrophysics of neutron stars), PASC (the Platform for Advanced Scientific Computing), the International REsearch Network for Nuclear Astrophysics (IRENA), and within the ERC projects FISH and STAREX.

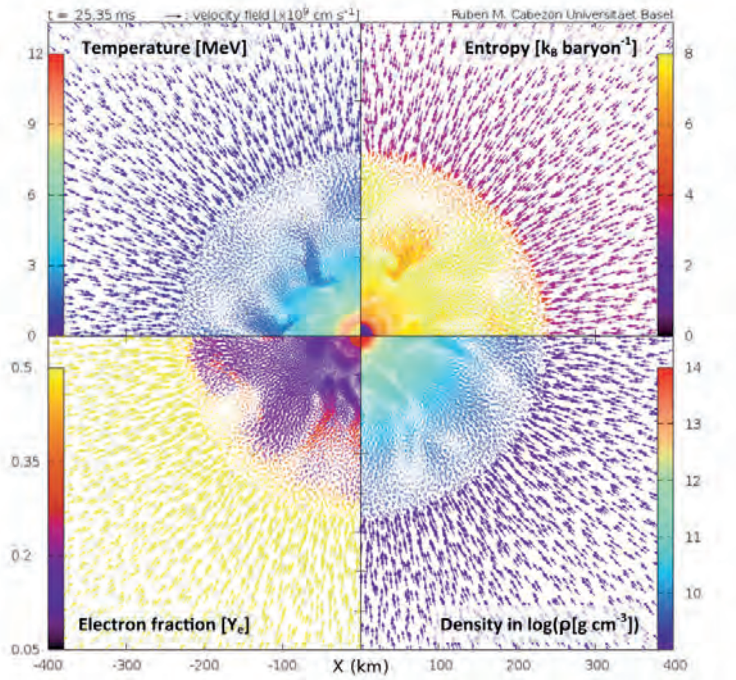


Figure 15: 3D core-collapse supernova simulation with SPH code SPHYNX during the turbulent neutrino-heating phase at 25.35ms after core bounce, extending beyond the central proto-neutron star. Thermodynamic quantities, like temperature k_{BT} (in MeV), entropy (in k_{BT} per baryon), density (in g/cm^3) are given in three quadrants, and the electron fraction, Y_e, in the fourth quadrant. Shown is a 3D cut through a cube of 800 km side length. The velocities of matter are given by the size of the arrows relative to the scale of 10^9cm/s, small within the proto-neutron star, larger outside – and in this turbulent phase before the explosion still showing infall and outward movements (Image: R. Cabezón, University of Basel)

In Switzerland, the theoretical modelling of stellar evolution through state-of-the-art numerical simulations has historically been very strong in several institutes. This research is very actively continuing today, and is especially important in the context of high-priority project developments in the domain of stellar astrophysics (Gaia, PLATO), high-energy astrophysics (Athena), and gravitational waves (LISA, Einstein Telescope).

On the observational side, Switzerland plays a major role in the ESA Gaia mission, launched in 2013, which is presently sweeping the entire sky, repeatedly measuring more than 2.5 billion celestial objects. Swiss astronomers are leading the 'Variability' Coordination Unit (CU7 with the participation of 15 European institutes) within the Gaia Data Processing and Analysis Consortium (DPAC) of the Gaia mission. This coordination effort provides one of the largest catalogues of time-dependent phenomena in all phases of stellar evolution. Swiss astronomers also contribute to the astrometric detection of exoplanets through the 'Object Processing' Coordination Unit (CU4) dedicated to non-single stars. The Gaia spacecraft operations may be extended until 2025, and a final data release should occur at the end of this decade, to which Switzerland aims to contribute via CU7 and CU4. Thanks to the precision and homogeneity of its data (in astrometry, but also in photometry and spectroscopy), Gaia has provided and will continue to provide key advances for the structure of our Galaxy, stellar structure and evolution, including the determination of masses and radii of stars, exoplanet detection, black hole detection, asteroseismology, stellar cluster population and Galactic archaeology, mergers of galaxies with our Milky Way, dark matter distribution, the distance ladder from our nearest objects to the distant Universe, etc. In short, the Gaia mission has started to profoundly transform many branches of astronomy. The full exploitation of this unique capability should be a priority whilst taking advantage of the Swiss knowledge in Gaia, thanks to the involvement in DPAC. Swiss researchers are actively involved in the EuroCOST Action CA18104 (Revealing the Milky Way with Gaia).

Asteroseismology has become a key observational technique for future progress in stellar astrophysics (Fig. 15, left). Based on the experience acquired within the CoRoT and KEPLER space missions, Swiss astronomers have started developing innovative theoretical stellar models. These will provide essential information useful for the understanding of a variety of processes, ranging from the star-planet connection to the star formation history in the Milky Way and the origin of the spin of compact objects, so relevant for comparisons with gravitational wave detections. Finally, these models will provide the central framework for the stellar astrophysics to be carried out by the PLATO mission.

The Solar physics community in Switzerland is involved in understanding how climate varies due to natural forcing including solar irradiance variations, energetic particle participation, and understanding the sources of activity and variations on the Sun due to magnetic fields. These include the most energetic explosions in the solar system – solar flares, and coronal mass ejections. These occur over a wide range of spatial and temporal scales. Solar activity and its impact will be explored in the corona via the 3 instruments with Swiss contribution on Solar Orbiter which will operate until 2029. PMOD/WRC operates instruments on the ground to measure solar irradiance in different wavelengths – all of which are key for inputs to climate modelling. The EST, planned to be in operation from 2030, will provide ground-based high-quality data on solar magnetism. IRSOL is currently acting as Swiss partner in this large-scale infrastructure and contributing to its instrumentation with expertise in high precision spectro-polarimetry, thereby securing access to generated data to the whole Swiss solar physics community.

13.2.3 High-energy astrophysics

High-energy astrophysics in Switzerland started to develop with the establishment of a group at the University of Geneva around 1990. The group significantly increased in size and scope since 1995, with the establishment of the INTEGRAL Science Data Centre, a center dedicated to the development of software for and to the processing of the data of ESA's satellite mission INTEGRAL, a gamma-ray and X-ray observatory. Since its launch in 2002, INTEGRAL has played an important role in the development of high-energy astrophysics in Switzerland. Together with the other currently available X-ray observatories, especially XMM-Newton, they have led to considerable progress in our understanding of neutron star and black hole powered phenomena such as pulsars, supernovae remnants, gamma-ray burst as well as of X-ray binaries, active galactic nuclei, and galaxy clusters. The outstanding success of the current generation of X-ray observatories has transformed X-ray astronomy into an essential tool for the understanding of fundamental questions, such as the physics of matter at extreme densities via the determination of pulsar/neutron star radii, general relativistic effects in the vicinity of black holes, accretion and jet formation, the history and accretion and growth of supermassive black holes, their role in the evolution of galaxies and galaxy clusters through the process of feedback, as well as the build-up of the largest cosmological structures and the reionization of the Universe. The future of high-energy astrophysics in Switzerland is assured by two major projects, Athena and CTA, and it is hoped to open a major new window on the time domain astronomy and multi-messenger astronomy.

Because most of the baryonic component of the Universe is locked up in hot gas at temperatures of millions of degrees, and because of the extreme energetics of the processes close to the event horizon of black holes, high-energy astrophysics is essential for our understanding of this hot and energetic component of the Universe. Athena is an X-ray Observatory combining high spatial and spectroscopic resolution, thanks to its revolutionary detector based on superconducting material, with deep, wide-field imaging, which has been selected by ESA as its second large mission of the Cosmic Vision programme to be launched in 2034. With its long-standing tradition in high-energy astrophysics, Switzerland is participating actively in the development of the instrumentation, in several components of the ground segment, including analysis software and data processing, and in the future scientific exploitation of the data. This facility will play a major role in understanding the co-evolution of galaxies and black holes in the next decade and in the study of baryons in galaxy clusters. In order to prepare for the new and exciting science of Athena, Switzerland has been participating jointly with the Netherlands in the Japanese mission Hitomi, which was launched in 2016. Hitomi's payload included a cryogenic detector similar to that of Athena, but largely simplified. Hitomi failed after six weeks of operations and only a single truly scientific observation. Nevertheless, the single observation was revealed to be absolutely outstanding, resulting in about ten scientific publications, including two in the journal Nature. The new Japanese recovery mission XRISM will launch in 2023, again with a solid Swiss participation. XRISM is absolutely essential to bridge the gap between the current generation of X-ray telescopes and Athena. It is worth noting that the Swiss and Dutch participation in both Hitomi and XRISM is outside of, and in addition to, the ESA Mission of Opportunity framework, providing the Swiss community with a much larger visibility and scientific return than any other European country.

The development of high-energy astrophysics in Switzerland also happens in the gamma-rays, especially with Cherenkov telescopes, which detect the highest-energy gamma-rays through the production of leptonic cascades in the atmosphere, and their subsequent Cherenkov flashes. A Swiss group participated in the FACT project, the first Cherenkov camera using silicon detectors instead of photo-multipliers. While mostly a technology demonstrator, FACT has been extremely important in the context of the development of the CTA, a major Cherenkov facility led by an international consortium that includes Switzerland thanks to a direct support from SERI. CTA will be the largest gamma-ray telescope in the world and will be ten times more sensitive than current instruments, as well as an unprecedentedly large energy range. CTA will target the giant particle accelerators in the Universe, shedding light on some of the most violent physical processes, like ultra-relativistic ejection by supermassive black holes and the explosive death of the most massive stars. Swiss astrophysicists are also participating in the MAGIC collaboration, a set of two large Cherenkov telescopes whose consortium prefigures that of CTA.

By providing the scientists with information on matter in the vicinity of extreme objects and events, X-rays and gamma-rays play a fundamental role in the emerging science of multi-messenger astronomy. Indeed, they often provide the missing link between an event detected with gravitational waves or neutrinos and the identification of the source of the event. The main tool for multi-messenger astronomy is an X-ray and gamma-ray telescope with a very large field of view and good sensitivity, in order to be able to detect and locate these events, which are generally transient. The same instrumentation is obviously able to detect other kinds of transient events, and thus contribute to another emerging theme of time domain astronomy. INTEGRAL has been the European pioneer in the field, and Swiss astronomers at the University of Geneva have contributed to confirmation that the first gravitational wave event GW150914 detected in 2015 was indeed a merger of two black holes, and detected unambiguously the electromagnetic counterpart of GW170817, the first neutron star–neutron star merging event that is considered the first fundamentally multi-messenger event ever detected. Swiss groups have been working hard to promote space X-ray and gamma-ray facilities to fulfil such a fundamental role as the monitoring of the transient sky, with non-selected ESA's candidate missions LOFT and THESEUS, as well as the China-led mission eXTP, which essentially re implements the science case of LOFT, and is optimised for time domain astronomy. THESEUS will be reproposed in the framework of the ESA Cosmic Vision programme, again with significant Swiss participation. eXTP should go ahead in China, but the current sanitary situation makes any progress in the establishment of an ESA–China official collaboration very difficult.

Computational Astrophysics and Cosmology

Computer simulations play a key role in modern science, using virtual data as a link between our theoretical understanding of the Universe and our observations of the physical world. They are also used to construct mock Universes to test new theories and open new avenues of research.

In cosmology, simulations have a particularly high impact because we have a direct knowledge of the initial conditions of our Universe through the observations of the CMB. For example, next generation galaxy surveys such as Euclid will be able to measure the cosmological power spectrum up to k=10 h/Mpc, and the key cosmological parameters to percent level precision. As a consequence, to model this regime we will have to better understand the physics of baryonic matter, which boils down to understanding star formation, galaxy formation, feedback processes and their impact on the distribution of matter on small-scales.

Hydrodynamical simulations designed to model these processes are being done, for example, as part of the Euclid consortium in order to generate correction terms that can be added to the standard pure N-body codes. Some of the few codes capable of scaling successfully to tens of thousands of cores and performing the target resolution for full Euclid simulations have been developed in Switzerland, resulting in the Euclid flagship simulations . Similar plans are on the way for SKA, building on the already high impact of galaxy and start-formation simulations of the University of Zurich and EPFL groups, carried out with state-of-the-art SPH, Lagrangian meshless and Adaptive Mesh Refinement codes mostly developed or co-developed in-house. These activities are well integrated with some of the most impactful international collaborations on galaxy formation simulations, such as the N-Body shop, the AGORA (Assembling Galaxies Of Resolved Anatomy) collaboration on galaxy project, and the FIRE (Feedback in Realistic Environment) collaboration. In all of these the Swiss groups play a leading role.

Supercomputer simulations, since the last Roadmap, have progressed significantly in other fields in which Switzerland is at the forefront, such as the modelling of stars and

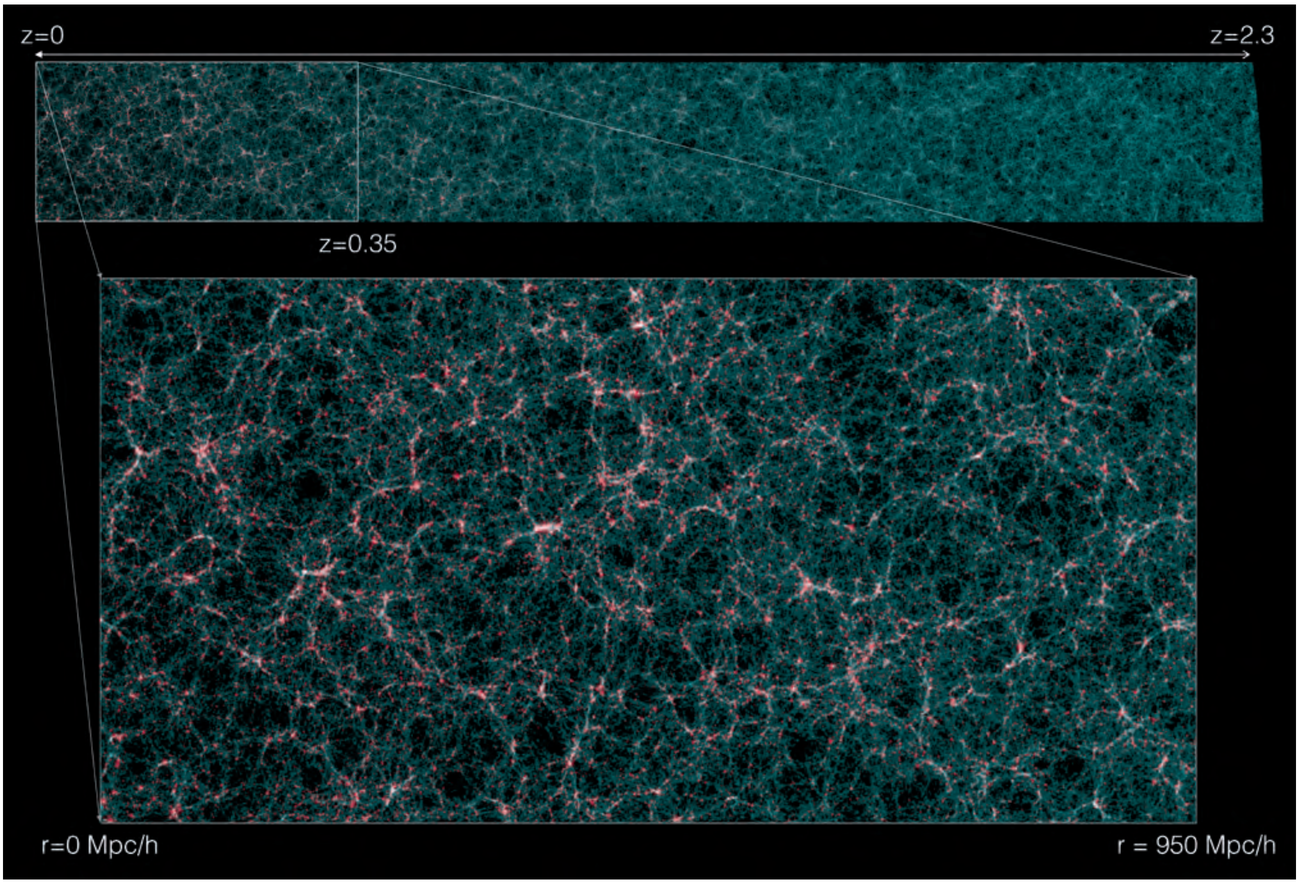


Figure 16: Galaxy Types in the Flagship Mock Catalogue – Top panel: False colour images showing a small portion (0.3%) of the full light-cone simulation (similar to Image 1), but showing different galaxy types with different colours. Central galaxies are coloured in green, and satellites in red. Bottom panel: zoom in on the top panel image that displays the local universe with greater detail. Central galaxies populate all dark-matter halos of the cosmic web, whereas satellite galaxies tend to reside in the most massive halos, that is, in the highest density peaks of the underlying dark-matter distribution. (Image: J. Carretero/P. Tallada/S. Serrano for ICE/PIC/U.Zurich and the Euclid Consortium Cosmological Simulations SWG)

Supernovae explosions, including neutrino diffusion and sophisticated radiation transport schemes, by the Universities of Basel and Geneva groups, the magneto-hydrodynamical simulations of proto-planetary disks and planet formation, an area where the University of Zurich group has performed pioneering calculations with self-gravity and dust particles, and, finally, simulations of the formation and evolution of supermassive black holes across cosmic time, in connection to gravitational wave sources and thus with the LISA program and Fundamental Physics (see also section on stellar physics), For all of these complex computations challenges are posed by multi-scale problems, since adaptivity of codes in space and time must be improved further. and in a way that exploits the latest HPC hardware, getting the community ready for the Exascale supercomputing era. Swiss researchers have also been successful at obtaining PASC project grants to advance their codes in preparation for Exascale. One example is the SPH-EXA (Optimizing Smooth Particle Hydrodynamics for Exascale Computing) PASC project involving Zurich astrophysicists, computer scientists in Basel, and staff at CSCS, which has established a unique multi-disciplinary collaboration that will foster the creation of large flagship simulations in support of astronomy flagship projects such as SKA.

13.2.4 A multi-wavelength approach

As modern astrophysics requires a multi-wavelength approach, expertise in infrared and millimeter-wave techniques has become increasingly important. Further, the scientific need to connect studies of galaxy formation to our understanding of stars, as well as stars to planets, makes studies of the origins of stars crucial in the current landscape. Access to optical and IR facilities such as the VLT and the JWST enable Swiss astronomers to remain at the forefront of this rapidly developing area. MOONS, the third-generation infrared spectrograph being built for the VLT with Swiss participation, will carry out very large surveys of the distant Universe that can be directly compared with large surveys of the nearby Universe. Complementary studies with ALMA – and other millimeter and far-infrared facilities – will furthermore enable to connect the initial conditions of star formation with the outcomes (number of stars as a function of mass, properties of multiple systems etc.). From space, we can build on past ESA IR mission successes (e.g., ISO and Herschel) to plan for the future. Successor missions to the planned SPICA satellite in the framework of NASA's Discovery programme and ESA's science programme are being studied. Finally, the SKA, which will open unprecedented views on the deep Universe in the radio domain, will undoubtedly play a major role in this field in the future.

13.3 Planets and the search for extra-terrestrial life

Since the first discovery of a planet orbiting a main-sequence star in 1995 by the Swiss astronomers Michel Mayor and Didier Queloz, awarded by the Nobel Prize in Physics 2019, studies of planetary objects have spectacularly broadened their scope. The scientific focus has shifted from discovery to characterisation of these other worlds. We can now assess the temperatures, luminosities, and compositions of a handful of planets whose light is detected directly through secondary eclipse or resolved imaging, in addition to dozens of worlds whose bulk composition is constrained through estimates of their masses (radial velocity) and radii (transit). Planetary sciences also experience the emergence of a new unifying paradigm: the concept of 'planetary systems', a class of astrophysical objects which covers and links together the solar system, giant planets systems and extrasolar planetary systems.

13.3.1 Exoplanets

Exoplanet research in Switzerland remains today world-leading with leadership or participation in a number of international collaborations for the detection and characterisation of planets in various environments. Collaborations in the development of the instruments HARPS (spectrograph) and SPHERE (XAO imager) for ESO, established close to 2 decades ago, remain strong and successful. As the only instrument on the 3.6m ESO telescope and its almost complete dedication to exoplanet science, HARPS continues today to lead the world in radial velocity exoplanet discoveries including bodies with minimum masses in the Earth regime. It also plays a key role in determining the mass of small planets detected in the frame of space-based transit observations (Kepler, TESS). SPHERE on the VLT is one of the premiere facilities for imaging planets with key discoveries led by Swiss astronomers, as e.g., a forming planet still embedded in the protoplanetary disk or the coolest imaged brown dwarf. ESPRESSO, the 2nd generation of high-precision spectrographs for the VLT, built under Swiss leadership (University of Geneva), has been installed at the telescope end of 2018. It is complementing the palette of instruments in the hand of Swiss astronomers, allowing for the detection of exoplanets as small as the Earth, the measurement of their mass. It is also a powerful instrument to access chemical elements in the atmosphere of transiting planets through transit spectroscopy measurements (at high spectral resolution, the spectral lines of a specific element in the star and from the planet are separated in frequency as the two objects move at different velocities on their orbits).

CHEOPS, the first Swiss scientific satellite, was selected in October 2012 as the first S-class mission in ESA's Science Programme and was successfully launched in December 2019. CHEOPS is the first mission dedicated to the search for transits of exoplanets by means of ultra-high precision photometry on bright stars already known to host planets. It provides the unique capability of determining accurate radii for a subset of those planets for which the mass has already been estimated from ground-based spectroscopic surveys. It also provides precise radii for new planets discovered by the next generation of ground- or space-based transit surveys (TESS, NGTS). By unveiling transiting exoplanets with high potential for in-depth characterisation, CHEOPS also provide prime targets for instruments suited to the spectroscopic characterisation of exoplanet atmospheres, from the ground at high-resolution (e.g., ESPRESSO/VLT, HIRES/ELT) or from space (JWST, Ariel).

Today, the count of confirmed extrasolar planets is exceeding several thousands. The explosive pace of progress in exoplanet research will continue for the next several years. HARPS, HARPS-North, and ESPRESSO will continue to push towards detection of true Earth analogues with the radial velocity technique. NGTS and other ground-based transit surveys will reveal hundreds of new worlds ready for follow-up with the VLT, as well as CHEOPS and JWST. New high contrast imaging facilities such as SPHERE+ and ERIS in development will reveal young planetary systems at large orbital radii that can confront formation theory head-on. Ultimately, PLATO, to be launched in 2026, will provide an extensive census of planets orbiting bright stars, including some terrestrial planets on orbits comparable to the one of the Earth. Progress in understanding key physical and chemical properties will continue with an eye towards understanding whether planetary systems like our own, and the potential for habitability that they represent, are common or rare in our Universe. Switzerland is poised for leadership in all relevant domains: developing novel instrumentation, theoretical modelling, detection and characterisation of planetary systems, exploiting synergies with colleagues in Earth Science and related disciplines. A key aspect of Swiss leadership in the next decade will be to provide adequate funding for exoplanet scientists in Switzerland to play key roles in instrumentation for the ELT, as well as continued support for involvement in the next generation of exoplanet space missions (the ESA Cosmic Vision Programme and beyond).

13.3.2 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. The in-situ exploration of Mars (Mars Express, MRO and ExoMars), of Venus (Venus Express, EnVision), of comets (Rosetta, Comet Interceptor), and of Mercury (BepiColombo) are important elements of the scientific and exploration programmes of two major Space Agencies (ESA and NASA), in which a significant Swiss participation was taking place.

The HiRISE imaging system on MRO has identified possible traces of extant liquid water on Mars and there is significant evidence for subsurface water ice from HiRISE and other instruments. Through laboratory investigations, Switzerland has supported studies of surface materials and has also built the imaging system for the ExoMars Trace Gas Orbiter, CaSSIS, which has returned more than 25000 images of the surface of Mars over the past 4 years. The imaging has complemented the study of Martian activity today through measurement of Marsquakes made by instruments partially developed in Switzerland. The push towards human exploration of the Moon and Mars is increasing in intensity and the Swiss community is active in positioning itself to participate in programmes such as Artemis and Mars Ice Mapper with a view to exploiting the scientific opportunities that these programmes can provide.

Venus is to become a 'hot' topic in the next decade because of the selection of DAVINCI+ and VERITAS in NASA's Discovery programme and EnVision in ESA's science programme. It is also an ideal object for comparative planetology studies and relating our terrestrial planets to those to be found in exoplanetary systems. Switzerland will contribute hardware to EnVision and is therefore well placed to exploit these initiatives.

The Mercury mission BepiColombo has been launched in October 2018 and is on its 7-year journey to Mercury, experiencing 9 planetary flybys on its way (the 1st one was with the Earth in April 2020) in order to reduce speed and change its trajectory. The University of Bern developed the instrumentation for the laser altimeter project, BELA, which is designed to measure the surface topography and participate in the planetary geophysics experiment. This mission also links to studies of exoplanets because detailed study of Mercury may constrain processes active during the early phases of terrestrial planet formation – something about which we remain rather ignorant.

The JUpiter ICy moons Explorer (JUICE) mission to the icy moons of Jupiter has been selected by ESA as the L1 mission of the Cosmic Vision programme. It belongs to the largest class of missions ESA can fly and, as such, it is truly one of the flagship missions of the agency. It is therefore very encouraging that Swiss scientists are members of several instrument consortia for this mission. In one case, they are even co-leading the full instrument (Particle Environment Package or PEP). The mission should be launched towards the end of 2023 and will reach Jupiter 8 years later. It will perform detailed investigations of Jupiter and its system in all their inter-relations and complexity, with particular emphasis on Ganymede as a planetary body and potential habitat. Investigations of Europa and Callisto will complete a comparative picture of the Galilean moons.

Rosetta, ESA's 'comet chaser', was woken-up early 2014 for the rendezvous with the comet and provided startling pictures of the encounter. Swiss scientists have then been very busy during the whole year of measurements as the satellite followed the comet on its orbit. Switzerland carried the responsibility for a suite of instruments (ROSINA – Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) dedicated to chemical composition measurements of gases, and participated strongly in the imaging system OSIRIS (Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy). Results obtained with these instruments were remarkable by providing detailed measurements of what is assumed to be a relic of the proto-planetary disc. The observations determined the bulk density of the nucleus, showed the importance of large particles in the coma, revealed remarkable diversity of the surface structure, and established the outgassing properties. Swiss teams are following up on this work by supporting ESA's new F-class mission, Comet Interceptor, that is designed to complete a fast fly-by of a dynamically new comet (or possibly an interstellar object). This will provide direct comparisons between pristine objects and those that have evolved because of frequent, repeated orbits through the inner solar system.

The scientific and technical expertise of Swiss researchers involved in the exploration of the solar system lies in remote sensing and in-situ measurements. ESA recently decided that a large-scale mission to one or more of the moons of the gas giant planets will be one of its major objectives for the late 2030s. Studies are about to be initiated and it is imperative that the younger generation in Switzerland plays an active role in defining and implementing this mission.

13.3.3 The National Center for Competence in Research – PlanetS

The NCCR PlanetS, which has been active since June 2014, has been extremely successful in coordinating and expanding activities in the field of exoplanets and has been instrumental in bridging the gap between solar system exploration and exoplanet astronomy. PlanetS is based upon a strong collaboration between four institutions (University of Bern, University of Geneva, ETHZ and University of Zurich) and has led to a significant strengthening of exoplanet research in Switzerland. From individual research group efforts and ad hoc collaborations, the field has moved towards a coordinated, coherent and multi-disciplinary national research programme. Today, Swiss research teams are involved in a coordinated way in planetary studies, regardless of the technique (laboratory-based, observational, or theoretical) or objects they study (solar system bodies, proto-planetary discs, exoplanets). The Swiss landscape has also benefited from the award of the Nobel Prize to Michel Mayor and Didier Queloz.

The NCCR is entering its third phase (2022-2026) and numerous projects grouped within three major topics (Formation and Architecture of Planetary Systems, Physics and Characterisation of Planets, and Habitability and the Search for Life) will be addressed. A bonus programme has been proposed based on further exploration of the frontiers of life in the Universe. Several of the projects also seek to link possible future space missions to ground-based astronomy efforts. These include possible biosignature detection in exoplanet atmospheres through space-borne interferometry and support for investigations of the surfaces and sub-surfaces of the Jovian moons. PlanetS therefore exploits synergies between Earth-based astronomical observations of exoplanets and proto-planetary discs, detailed measurements of objects in our own Solar System, laboratory studies of critical processes, and theoretical frameworks for the modelling of processes and systems.

The collaboration and networking between the institutions is seen by all sides as having been very productive and constructive in maintaining and enhancing Switzerland's position in this highly competitive field. With the NCCR now starting to run down, the groups are very keen to establish a 'Swiss Institute for Planetary Sciences' (SIPS) that will maintain this network and exploit synergies between the activities of the institutions.

The stated aim of SIPS is to understand the formation and evolution of planetary systems and search for the existence of life within them. It will be based around five elements addressing scientific exploitation of the investments made by the Swiss government in this field, exploitation of acquired data, development and transfer of technologies developed through these activities, education and training at all levels (including engineering), and communication and public outreach in one of the most popular scientific fields. It is intended to seek financial support for SIPS within the next four-year period so that a smooth transition from the NCCR to SIPS can be achieved. Expansion of SIPS beyond the existing partners is also a clear goal. The astronomy and planetary sciences communities see this as securing the investment that has already been made and ensuring that this area remains a leading activity in the Swiss landscape for the next two decades.

13.4 Our home and its space environment

Space geodetic techniques such as Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), and Doppler Orbitographie et Radio-positionnement Intégrés par Satellite (DO-RIS), provide the metrological basis for the establishment of the global terrestrial reference frame, for the determination of the transformation parameters between the terrestrial and the celestial reference frame, and for a multitude of studies related to the system Earth – our 'cosmic home'. The International Association of Geodesy (IAG) founded the International GNSS Service (IGS) in 1994 to support the development of GNSS data analysis, and to exploit the scientific use of GNSS. The Center for Orbit Determination in Europe (CODE), which is led by Switzerland, is one of the leading global analysis centers of the IGS.

The Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (SwissOGS) is a station of the global tracking network of the International Laser Ranging Service (ILRS). Satellite Laser Ranging (SLR) observations to dedicated satellites equipped with laser retro-reflectors are acquired 24 hours a day and 7 days per week with the monostatic 1-m multi-purpose Zimmerwald Laser and Astrometry Telescope (ZIMLAT). SLR at SwissOGS contributes to the determination of the International Terrestrial Reference Frame (ITRF), especially to the origin and scale, precise orbit determination, and the determination of the long-wavelength part of the Earth's gravity field. All these efforts have to be seen in the larger context of the

Figure 17: Laser beam transmitted from the 1-metre ZIMLAT telescope to measure the distances of artificial satellites with a mm-accuracy. (Image: Emiliano Cordelli [AIUB])

Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG), where SwissOGS is the most productive SLR station in the northern hemisphere, to advance our understanding of the dynamic Earth system by quantifying our planet's changes in space and time.

Ultra-precise inter-satellite ranging as performed for more than 15 years by the Gravity Recovery and Climate Experiment (GRACE) mission and now continued by its Follow-On mission (GRACE-FO) has been established as the state-of-the-art technique to globally observe mass variations in the system Earth from space. This includes, among others, monitoring of the terrestrial water cycle, ice sheet and glacier mass balance, sea level change and ocean bottom pressure variations, as well as understanding responses to changes in the global climate system. Today, a growing number of institutions are processing the GRACE/GRACE-FO Level-1B instrument data to derive mass variations on a monthly basis. In the frame of the European Gravity Service for Improved Emergency Management (EGSIEM) initiative, a H2020 project led by Switzerland, a prototype of a scientific combination service has been set up. Starting in 2019, the Combination Service of Time-variable Gravity Fields (COST-G) operationally continues the initial activities, again under the lead of Switzerland, to realise a long-awaited standardisation of gravity-derived mass transport products under the umbrella of the IAG.

13.4.1 Earth and Space Weather

In their latest report on 'Climate Change, impacts and vulnerability in Europe 2012', the European Environment Agency (EEA) stated the expected severe impacts in Europe due to climate change. One of the driving factors is ice melt, e.g., the Greenland ice sheet, and the changing hydrology within Europe. Time variability, as derived from space borne gravity field missions, is one of the most reliable ways of obtaining such evidence. This approach is closely related to satellite orbital dynamics. With their long-standing expertise in these problems, Swiss institutes have made major contributions to this field. These activities are gaining relevance and visibility, due to the world-wide challenges induced by global warming.

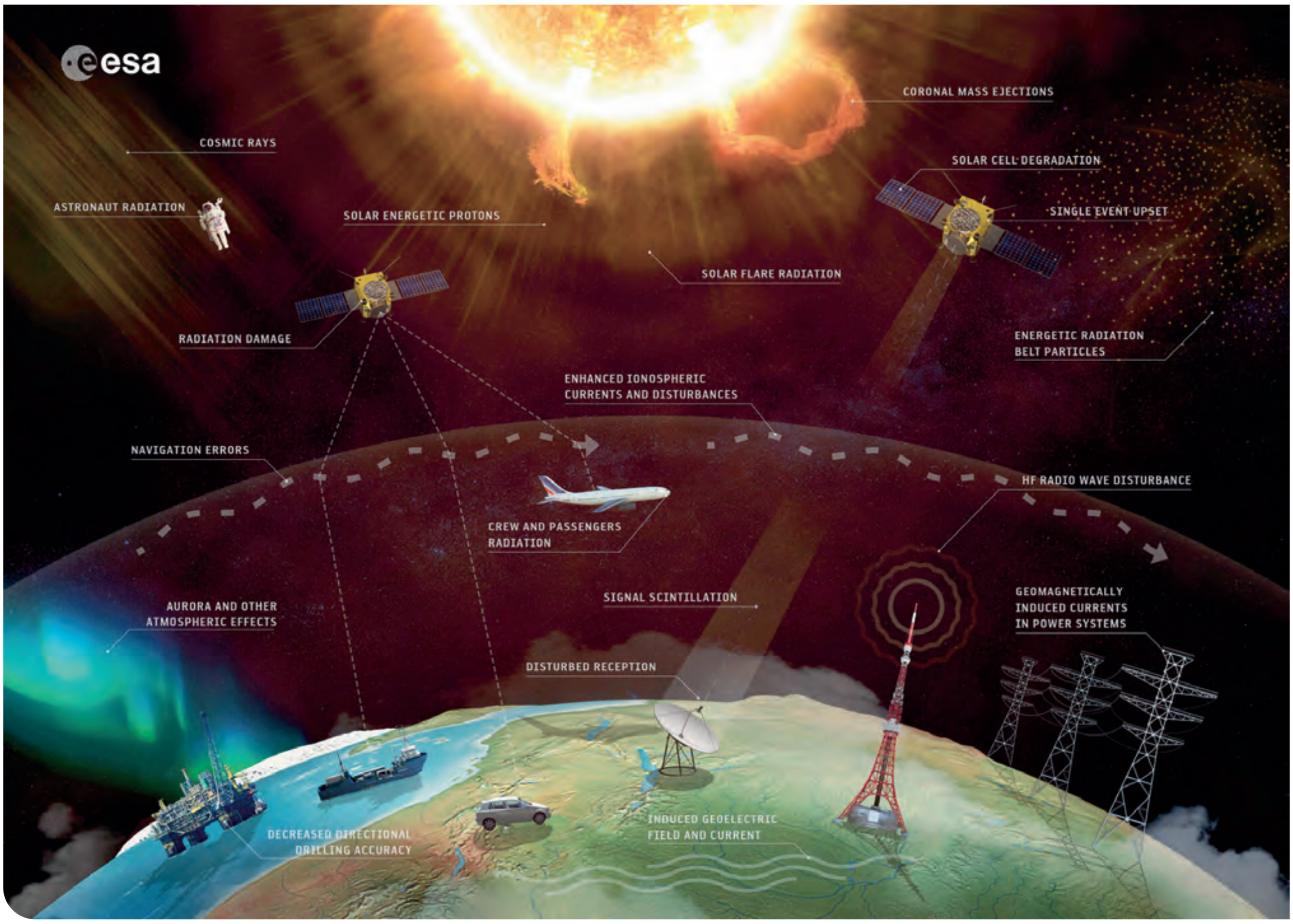


Figure 18: Cartoon diagram depicting the various ‘Space Weather’ effects on human activities. (Image: ESA/Science Office)

Our society has become more and more dependent, directly or indirectly, on satellite services. These are vulnerable to what is called ‘space weather’, which is the impact of solar events, or more generally speaking, events from outer space, on the Earth. For instance, one significant influence of solar activity is seen in disturbances in satellite navigation services, like Galileo, due to space weather effects on the upper atmosphere. This in turn can affect aviation, road transport, shipping and any other activities that depend on precise positioning. The world-wide community is putting into place warning centers, and the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) has a working group active on the subject. Swiss scientists are actively involved in research for understanding the solar processes, as well as assessing the potential impact on Earth.

Earth’s bounded observations play an important role in better understanding the sun, and Swiss solar physicists are performing polarimetric observations, using the most sensitive polarimeter (ZIMPOL), in order to better understand the sun’s magnetic field. Observations are also carried out at GREGOR, one of the largest such facilities currently operating.

Assessment of the activity of the sun for an efficient ‘nowcast’ of the potential impact of space weather requires monitoring satellites. Switzerland is involved in several missions. VIRGO onboard SOHO has measured the solar irradiance for over 2 solar cycles and is still going strong. CLARA onboard NorSat-1, launched in 2017, measures the total solar irradiance as well as the thermal emmission from Earth. The DARA radiometer for the PROBA3 mission was delivered end of 2021 and is currently being integrated on the spacecraft. A big step to understanding our sun is ESA’s Solar Orbiter mission, launched in 2020, in which two Swiss institutes are actively involved in the research teams.

The area of research, known as space weather, is one that Switzerland is becoming more involved in via their involvement with the future space weather monitor (Lagrange space mission, recently named Vigil), and understanding in details the magnetic fields in the Sun before an eruption through DKIST that will start observing in

2022, and in the future EST. Alongside this, the Università della Svizzera italiana is advancing research in computational models for solar physics through a close cooperation between its Institute for Computational Sciences, IRSOL and the CSCS. The University of Geneva and FHNW have an ongoing collaboration on developing machine learning techniques to statistically analyze the wealth of solar data, which will be especially important when DKIST and EST with much higher data rates start observing. Climate modelling takes place at PMOD/WRC and ETHZ. These models can be used for understanding previous climate scenarios as well as predicting future situations. These models also are applied to other stellar systems. Both modelling efforts require access to HPC (High Performance Computing). A better understanding of space weather and the influence of solar activity on Earth will also be beneficial to our investigations of stellar activity and its impact on potentially habitable planets.

13.4.2 Space debris

The need for environmental protection extends to space. The proliferation of space debris and the increased probability of collisions and interference raise concerns about the long-term sustainability of space activities, particularly in the low-Earth orbit and geostationary orbit environments. This is especially becoming an acute problem since the launch over the past few years of constellations of small satellites by the private sector. International organisations at different levels are examining measures to enhance the long-term sustainability of such activities, among them the UN COPUOS, and the Inter-Agency Space Debris Coordination Committee (IADC). Swiss researchers participate in the development of efficient and cost-effective measures to reduce the creation and proliferation of space debris by studying the current debris population, to identify their major sources and release mechanism.

A better understanding of the space debris population in the near-Earth environment in terms of spatial density, of statistical orbital characteristics, as well as characteristics of individual objects will remain in the center of interest. Extending the catalogue of known objects and determining their characteristics, developing statistical environment models, and the long-term monitoring of the environment are necessary for the scientific foundation for a sustainable use of the near-Earth space.

Through a ‘Space safety and security’ initiative, ESA will devote increasing attention to the environmental impacts of its own activities. Switzerland is involved at industry level and takes the lead in the removal of space debris thanks to ClearSpace, a spin-off from the EPFL focusing on developing technologies and services to remove unresponsive (failed) satellites from space. The start-up has received funding for its ClearSpace-1 ADR mission under the ESA ADRIOS programme. ESA has also selected ClearSpace to be the leader of the industrial consortium for the project.

14 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. ESA ultra-stable clock experiment, a time and frequency mission to be flown on the Columbus module of the International Space Station, in support of fundamental physics tests.
ADRIOS	Active Debris Removal/In-Orbit Servicing
AGORA	Assembling Galaxies Of Resolved Anatomy. A project investigating galaxy formation with high-resolution simulations and comparing the results across code platforms and with observations.
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 5000m altitude.
AMS	Alpha Magnetic Spectrometer Experiment. A state-of-the-art particle physics detector designed to operate as an external module on the International Space Station.
ASKAP	Australian SKA Pathfinder. A radio telescope situated in western Australia using novel technology to achieve extremely high survey speed, making it one of the best instruments in the world for mapping the sky at radio wavelengths.
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‘.
AO	Adaptive Optics
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.
BBH	Binary Black Hole
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.
BH	Black Hole
Blue-MUSE	Optical seeing-limited, blue-optimised, medium spectral resolution, panoramic integral-field-spectrograph for the VLT.
BNS	Binary Neutron Star
BOSS	Baryonic Oscillations Spectroscopy Survey
CaSSIS	Colour and Stereo Surface Imaging System (built at the University of Bern)
CCD	Charge Couple Device
CDCI	Common Data Center Infrastructure
CE	Cosmic Explorer
CERN	Eurpean Organisation for Nuclear Research
CHAPS	College of Helvetic Astronomy ProfessorS
ChETEC	Chemical Elements as Tracers of the Evolution of the Cosmos
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
ClearSpace-1	A pioneering ESA mission to remove debris from Earth orbit.
CMB	Cosmic Microwave Background
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
CoRoT	Covention, Rotation and planet Transit. A space telescope mission which operated from 2006 to 2013.
COSMOSGRAIL	COSmological MOnitoring of GRAvItational Lenses. long-term photometric monitoring of most gravitationally lensed quasars.
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
CSR	(Swiss) Committee on Space Research
CTA	Cherenkov Telescope Array – a new generation ground-based instrument for the detection of high energy gamma-rays.

DAVINCI	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging. The mission is set to explore Venus to determine if it was habitable and understand how these similar worlds (Earth and Venus) ended up with such different fates.
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
DO-RIS	Doppler Orbitographie et Radio-positionnement Intégrés par Satellite
DPAC	Data Processing and Analysis Consortium
EAST	European Association for Solar Telescopes
EBL	Extragalactic Background Light
eBOSS	Extended Baryonic Oscillations Spectroscopy Survey
EGSIEM	European Gravity Service for Improved Emergency Management
ELT	Extremely Large Telescope.
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.
EPFL	Ecole Polytechnique Fédérale de Lausanne
ERC	European Research Council
ERI	Education, Research and Innovation
EPICS	Exoplanet Imaging Camera and Spectrograph
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
eXTP	enhanced X-ray Timing and Polarimetry mission
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
Fermi-GBM	Fermi Gama-ray Burst Monitor
FHS	Fachhochschule – University of Applied Sciences
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
FIRE	Feedback In Realistic Environment
Gaia	ESA mission to obtain extremely accurate positions and photometry of approximately 1 billion stars in the galaxy.
GALA	GAnymede Laser Altimeter
Gamow	A mission that uses Gamma Ray Bursts to probe the high redshift ($z > 6$) Universe when the first stars were born, galaxies formed and Hydrogen was reionization.
GGOS	Global Geodetic Observing System
GNSS	Global Navigation Satellite Systems
GR	General Relativity
GRACE	Gravity Recovery and Climate Experiment
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.
GTO	Guaranteed Time Observation. Awarded to instrument developers to enable them to carry out specific science investigations with their instrument.

GWs	Gravitational Waves
HARMONI	High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph – one of the first generation of ELT instruments.
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
HIRES	HIgh RESolution spectrograph at optical and near-infrared wavelengths for ESO's ELT recently renamed to ANDES, the ArmazoNes high Dispersion Echelle Spectrograph.
HiRISE	High Resolution Imaging Science Experiment – one of six instruments onboard the Mars Reconnaissance Orbiter.
HPC	High Performance Computing
HST	Hubble Space Telescope, NASA-ESA orbiting 2.5m telescope, in operation since 1990.
IADC	Inter-Agency Space Debris Coordination Committee
IAG	International Association of Geodesy
IceCUBE	neutrino observatory constructed at the Amundsen–Scott South Pole Station in Antarctica.
IFU	Integral Field Unit
IGS	International GNSS Service
ILRS	International Laser Ranging Service
IMAP	Interstellar Mapping and Acceleration Probe
INTEGRAL	INTErnational Gamma-Ray Astrophysics Laboratory. ESA's gamma-ray observatory.
IRENA	International REsearch Network for Nuclear Astrophysics
IRSOL	Istituto Ricerche Solari Locarno
IS FEE	Inertial Sensor Front End Electronics
ITRF	International Terrestrial Reference Frame
JUICE	JUpiter ICy moons Explorer – an ESA space mission to explore Jupiter's icy moons.
JWST	James Webb Space Telescope. The 6.5m successor to the HST launched in December 2021.
Kepler	NASA mission designed to explore the structure and diversity of planetary systems.
LHC	Large Hadron Collider
LIA	Light Ion Analyser
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.
LIGO	Laser Interferometer Gravitational-wave Observatory – ground-based observatory that first detected gravitational waves.
LOFT	Large Observatory For x-ray Timing – mission intended to answer fundamental questions about the motion of matter orbiting close to the event horizon of a black hole, and the state of matter in neutron stars.
LSC	LIGO Scientific Collaboration
LSS	Large-Scale Structure
LSST	Large Synoptic Survey Telescope – precedent name of the Vera C. Rubin Observatory.
MANIaC	Mass Analyzer for Neutrals and Ions at Comets – a mass spectrometer to sample the gases released from the comet.
MAORY	Multi-conjugate Adaptive Optics RelaY – an adaptive optics module for the ELT.
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.
MeerKAT	Karoo Array Telescope
METIS	A Mid-infrared ELT Imager and Spectrograph
MICADO	Multi-AO Imaging Camera for Deep Observations
MINT	Mathematics, Engineering, Natural Sciences, Technics
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.
MPPE	Mercury Plasma Particle Experiment
MRO	Mars Recognition Orbiter. A spacecraft designed to study the geology and climate of Mars, provide reconnaissance of future landing sites, and relay data from surface missions back to Earth.

MUSE	Multi-Unit Spectroscopic Explorer, a second-generation instrument for the ESO's VLT, consisting of a 90,000 channel integral field spectrograph.
NASA	National Aeronautics and Space Administration
NCA	National Complementing Activities
NCCR	National Centre of Competences in Research (funded by SNSF)
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.
NS	Neutron star
NSIP	Near Infrared Spectrometer and Photometer
OSIRIS	Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy
PCS	Planetary Camera and Spectrograph
PASC	Platform for Advanced Scientific Computing
PEP	Particle Environment Package
PHARAO	First cold-atom clock ever to orbit Earth, operating outside the International Space Station.
PHAROS	The multi-messenger physics and astrophysics of neutron stars.
PIF	Proton Irradiation Facility (at PSI)
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	SNSF grants aimed at excellent women researchers who show a high potential for obtaining a professorship.
Proba-3	ESA mission to demonstrate formation flying in space. Two paired satellites will form a 150m long solar coronagraph. Launch foreseen in 2023.
PRODEX	PROgramme de Développement d'Expériences scientifiques
PSI	Paul Scherrer Institute
R&D	Research and Development
RIPA	(Swiss) Federal Act on the Promotion of Research and Innovation
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.
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.
Rosetta	ESA mission to rendez-vous with a comet and follow it to study its physical properties and evolution on its orbit.
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
SAS	Swiss Astronomical Society
SCFA	Swiss Commission for Astronomy
SCNAT	Swiss Academy of Sciences
SDSS-V	Sloan Digital Sky Survey – 5. Facility providing multi-epoch optical & 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
SFI	Schweizerisches Forschungsinstitut für Hochgebirgsklima und Medizin Davos
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.
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
SLS	Swiss Light Source (at PSI)
SMILE	Solar wind Magnetosphere Ionosphere Link Explorer
SNSF	Swiss National Science Foundation
Solar Orbiter	ESA mission dedicated to solar and heliospheric physics launched in February 2020.

SoSpIM	Solar Spectral Irradiance Monitor
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
SPICE	SPectral Imaging of the Coronal Environment
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
SSO	Swiss Space Office (SERI)
STAREX	ERC Project to model massive and supermassive stars in the very early Universe connecting their chemical, radiative and mechanical feedback to potential observed features of Pop III and very metal poor massive star populations.
STIX	Spectrometer Telescope for Imaging X-rays
STROFIO	neutral mass spectrograph for sampling Mercury's exosphere
SUPSI	Scuola universitaria professionale della Svizzera italiana
SWA	Solar Wind Analyser
SWI	Submillimetre Wave Instrument (on JUICE)
SwissOGS	Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald
SXI	Soft X-ray Imager
SXS	Space Exchange Switzerland – platform intended to support the further development of space in Switzerland in areas which are not core tasks of SERI/SSO.
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.
UniBE	University of Bern
UN COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UniGE	University of Geneva
UZH	University of Zurich
Venus Express	ESA's first spacecraft to voyage to our nearest planet
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy – It will be the first NASA spacecraft to explore Earth's sister planet Venus since the 1990s.
Virgo	Interferometric gravitational-wave antenna (in Italy)
VIRGO	Variability of solar IRradiance and Gravity Oscillations onboard the SOHO Mission
VIS	Visible Imaging Spectrometer
VLBI	Very Long Baseline Interferometry
VLT	Very Large Telescope: The four 8-m telescopes operated by ESO at Paranal Observatory.
VTF	Visible Tunable Filter
WFI	Wide Field Instrument
WIMP	Weakly Interacting Massive Particle
X-IFU	X-ray Integral Field Unit
XMM-Newton	X-ray Multi-Mirror Mission. Launched in 1999, it carries 3 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
ZIMLAT	ZIMmerwald Laser and Astrometry Telescope
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 and CSR presidents, IAU contact person, ...).

The College of Helvetic Astronomy Professors (CHAPS)
Tenured professors in astronomy in Swiss academic institutions.

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