Mid-term review of the European Astroparticle Physics Strategy 2017-2026 in preparation for the 2022 APPEC Town Meeting

APPEC Scientific Advisory Committee

Draft version for European APP community feedback
12 November 2021

Preface:

The European Astroparticle Physics Strategy 2017-2026 was adopted by the Astroparticle Physics European Consortium (APPEC) General Assembly (GA) in 2016. Since then, there have been many developments both in the Astroparticle Physics research field and in the wider world.

In the coming time, APPEC undertakes a mid-term update of the European Astroparticle Physics Strategy, with the aim to establish such an update in fall 2022.

The (European) Astroparticle Physics Community will be closely involved in this update. To this end, a Town Meeting is being prepared for 9 and 10 June 2022 in Berlin, at which occasion all relevant aspects of the strategy will be discussed.

In preparation of this discussion, the APPEC Scientific Advisory Committee (SAC) is preparing a mid-term strategy review document to be serving as framework for the organisation of the Town Meeting and to serve as input for the discussions themselves.

A first draft of the mid-term review is now available to be downloaded from a feedback page at https://indico.desy.de/event/32140/overview. This document is a DRAFT and not the final document. It serves for the APPEC SAC to receive feedback from the community concerning the accurateness and completeness of the document. Please note, that developments are going fast and that some notions in the report may have been outdated before the ink dried up.

We invite you to give feedback to this document through the form that is accessible through the "feedback" button on the left, or the "Fill out the survey" link at the bottom of this page. Feedback can be given as National Community, Collaboration or Individual. Please check the appropriate box.

Feedback can only be provided as plain text. Of course, hyperlinks can be quoted in this text to properly document your response. Multiple feedback submissions are possible, but one comprehensive feedback text will be appreciated. We explicitly solicit to suggest a burning question that is not yet addressed in the draft mid-term review and that you think should really be discussed during the Town Meeting.

Deadline for your feedback is Friday 21 January 2022.

Your feedback will be used to compile the final APPEC SAC mid-term strategy report that will be released well in time for the Town Meeting on 9-10 June 2022. For transparency, your feedback will become available publicly after when the final SAC mid-term review will be submitted to the community as input for the Town Meeting.

The input from the Town Meeting will serve as input for the Strategy Update document that the APPEC SAC will prepare for submission to the APPEC GA after the 2022 summer holidays. The GA will then release it as the European Astroparticle Physics Strategy 2022-2026 Update.

The European Astroparticle Physics Strategy 2022-2026 Update will also serve as an input to the process to establish the new European Astroparticle Physics Strategy after 2026.

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1. Introduction

At its meeting in November 2016, the APPEC General Assembly approved the *European Astroparticle Physics Strategy 2017-2026*. The release of this decadal strategy was just after the publication of the first detection of gravitational waves from a merger of two black holes. Since then, the field of astroparticle physics developed fast, with many more detections of gravitational-wave events, with first multi-messenger observations of specific sources, revealing a wealth of information, and also with more and better detection of many different cosmic messengers. The establishment of the EUropean Consortium for astroparticle theory, EuCAPT, as a centre of excellence hosted at CERN, has provided further impetus to the field. The newly established Joint ECFA-NuPECC-APPEC Activities (JENAA) is another recent step forward in addressing common questions in particle, astroparticle and nuclear physics and to better exploit all sorts of synergies between our fields. It already led to five Expressions of Interest for interdisciplinary cooperation, three of which directly involve the astroparticle physics community.

This rapid progression in astroparticle physics warrants a mid-term evaluation of the strategy, to take stock of what has been achieved since 2017, to evaluate the consequences of surprising discoveries, and to start looking forward towards updating the strategy in the mid-2020s.

The mid-term evaluation of the 2017-2026 astroparticle physics strategy is an effort of the entire field, which will be facilitated by one or more town meetings. Such a meeting was originally foreseen to be held in October 2020 but the consequences of the Covid-19 pandemic prevented such a mass meeting to take place. Depending on the developments of the Covid-19 pandemic, one or two meetings are now foreseen for 2021.

This document provides an overview to the community of recent developments in the field of astroparticle physics as collected by the APPEC Scientific Advisory Committee. Both the status of implementation of the present strategy is provided and an analysis of new developments. It is intended as input for a discussion among all the stakeholders, to determine together what the best course for the astroparticle physics field is to follow in coming years. This document builds on the European Astroparticle Physics Strategy 2017-2026 document, and while aiming to be minimally self-contained, it does not repeat many of the things that were covered in the original strategy document and are certainly worth remembering. An important new input to the Dark Matter section is the *Direct Dark Matter Detection - APPEC Committee Report*.

The sections in this document roughly follow the recommendations of the European Astroparticle Physics Strategy 2017-2026. However, some adjustments have been made.

The two recommendations on neutrino mass and nature and on neutrino mixing and mass hierarchy have been merged into one section on neutrino properties. There is a section on high-energy neutrinos, coupled to an existing strategic recommendation, that deals with neutrinos as probes of astrophysical processes. In the newly merged section, the study of properties of neutrinos themselves is central. An important input to this section is the recent *Double Beta Decay APPEC Committee Report* issued by APPEC in 2019.

A new section is introduced on multi-probe astroparticle physics. The first simultaneous observations of specific sources, multi-messenger observations have now been firmly established as an excellent tool for finding and understanding new and exciting phenomena. This stresses the increasing importance of the synergies between observations at different observatories and the need to combine many different measurements to address the science questions. It highlights the synergy between the different science questions, where different research questions may profit from the measurements at the same versatile observatories. In addition to multi-messenger correlation in space, i.e., to the same source, also time-domain correlations for transient events are a fruitful emerging field. For many types of observation, it is profitable to have several observatories around the world. This provides better coverage for transient phenomena and the competition among observatories leads to ever-improving instruments and observations. A balanced portfolio of larger and smaller observatories and experiments is essential for the progress in the field, both from the viewpoint of looking at the research questions from different angles but also from the standpoint of meeting the diverse research interests and ways of working of many researchers.

The societal awareness of the ecological impact of human activities has been increasing over the past decades and has come to the point where also research can no longer ignore the issue. A section is now dedicated to this topic. It follows two complementary approaches: The minimisation of the negative ecological impact of astroparticle physics observatories and experiments and the contribution from astroparticle physics innovations that may help fight negative ecological impact.

Technological developments are an essential part of astroparticle physics research. Contacts to industry are of vital importance, not only to fulfil our needs but also to share our innovations for economic prosperity for all people, such as for medical applications. While cooperation with industry has been going on for a long time, it is equally important to increase this effort and to make it optimally visible to the outside world. The (mini)ATTRACT initiative, an H2020 project coordinated by CERN that aims to consolidate a European innovation ecosystem focused on detection and imaging, provides good opportunities for astroparticle innovations to be developed for industrial applications. A new section on societal impact is devoted to this effect.

Open science is a policy priority for the European Commission. This has ramifications for astroparticle physics research as for any other research domain. A number of initiatives have started and more remains to be done. A new section is listing the progress in APP open science policy.

More recently, racist events have reminded us of the importance of equity, diversity and inclusion. This theme has been embedded in a slightly more general new human talent management section.

Astroparticle physics is a distinct player in big science, requiring large observatories and other large infrastructure, such as computing. The optimal exploitation of these large, often central infrastructures benefits from strong coordination. A new section is added with an inventory of central infrastructures.

Although astroparticle physics theory does not have its own section, it is of the utmost importance for the understanding of measurements, to pave the way to new observations and to provide the cohesion between the different research questions that are being addressed. Theory is therefore pervasive throughout the document and its importance cannot be overestimated. The establishment of EuCAPT is an important step in the support of astroparticle physics theory in Europe. According to a census performed by EuCAPT, it connects more than 660 scientists of over 200 institutes and universities in 31 European (plus 5 non-European) countries. Therefore, it constitutes a large fraction of the European astroparticle physics community and plays a strong role in the global theoretical astroparticle physics landscape.

Other important issues are developing and using common technologies and the upcoming field of data science and advanced computing. While no separate section has been devoted to these important developments, such as Artificial Intelligence methods, deep learning, etc., have a large impact on nearly all the astroparticle physics research described in the following. Large-scale computing also poses significant ecological worries and not only computing capacity but also better software engineering and alternative approaches should be considered. It is worth noting that the ECFA detector panel is an important instrument in being able to have new experimental and observational technologies reviewed at the highest standards. APPEC takes part in the ECFA detector R&D Roadmap drafting with observers in all nine task forces. The detector R&D Roadmap is an implementation of a recommendation in the European Strategy for Particle Physics that was launched in 2019.

The Covid-19 pandemic has impacted the APP research field as much as any research. The delay that has been incurred by being unable to go to the workplace has been limited as many activities could also be continued in the home office. There has been a tradition of online meetings in the field for some time and on this occasion, all meetings were changed to being online. In the longer run, this adversely affected productivity due to a lack of direct person-to-person contact. Many of the running APP kept on taking data and could be managed mostly remotely, or with crew on the ground obeying Covid-19 mitigation measures. For many experiments and observatories, the situation has slowly led to a backlog in maintenance. For experiments and observatories that are under construction, the impact has generally been more severe leading from months to more than a year delay in some cases. Currently, construction is often suffering from, sometimes extremely, long delivery times of construction materials and components and rapidly increasing prices for these resources. The extent of this impact is not yet clear. It is recommended that an inventory be made, also relating this to the European funding landscape and possibly available recovery funds.

The following sections, where appropriate, start with a reminder of the 2017-2026 Strategy Statement. After a short introduction, the relevant developments since 2017 are listed as much as possible matter-of-fact. At the end of each section, the situation of the SAC's view on the field, Europe's role and APPEC are mentioned. Hyperlinks to relevant documentation are used instead of a bibliography.

2. High-energy gamma rays

2017-2026 Strategy Statement

Through the use of ground-based gamma-ray telescopes (e.g. HESS and MAGIC) and key participation in satellite missions such as *Fermi*, Europe has played a leading and pioneering role in establishing high-energy gamma rays as an ideal messenger to enable exploration of the extreme Universe – as demonstrated by the astonishing number of gamma-ray sources discovered in recent years. The next-generation European-led, ESFRI-listed global project will be the Cherenkov Telescope Array (CTA), which has excellent discovery potential ranging from astrophysics to fundamental physics. The CTA is expected to start full operation as an observatory in 2023.

APPEC fully supports the CTA collaboration in order to secure the funding for its timely, cost-effective realisation and the subsequent long- term operation of this observatory covering both northern and southern hemispheres.

Introduction

We note here that the term 'high-energy gamma rays' used in this document is covering a range of different energy regimes, thought of as low to ultra-high energy. Satellite-based telescopes cover the low to high and increasingly reach to the very high energy regime, typically from ~1 MeV to a few 100 GeV, while ground-based telescopes cover from a few 10s of GeV to 100 TeV+, traditionally regarded as being the very high to ultra-high-energy regimes.

In space, the telescopes use Compton scattering techniques (at low energy) and pair-production (at high energy, i.e., from around 100 MeV). Such instruments have low backgrounds (being able to screen out the charged cosmic rays), excellent energy resolution and exceptionally wide fields of view. However, they suffer from relatively poor angular resolution due to scattering within the detectors.

Ground-based gamma-ray telescopes broadly fall into two categories: imaging atmospheric Cherenkov telescopes (IACTs) and water Cherenkov and scintillator telescopes. IACTs operate by detecting the brief flashes of Cherenkov radiation-induced in the upper atmosphere by the cascades of particles (air-showers) resulting from the interaction of gamma-rays with the Earth's atmosphere. Water Cherenkov telescopes detect the Cherenkov radiation produced in tanks of water by the air shower particles. Both approaches require sophisticated techniques to separate the gamma-ray-induced events from those produced by the much more numerous cosmic rays. Water Cherenkov telescopes of necessity operate at higher energies than IACTs and have a less good angular resolution but have the advantage that they can monitor the skies above at all times rather than operating only at night.

The scientific aims of these instruments are wide-ranging. The first can be broadly described as understanding high-energy particle acceleration in the universe. This has its origins in pinpointing the origins of cosmic rays and high-energy neutrinos, but we are increasingly understanding that energetic particles likely have an important role in feedback mechanisms for star formation and galaxy evolution too. Supernova remnants, long assumed to be the primary source of the Galactic cosmic rays, are known to be gamma-ray sources. In addition, much particle acceleration likely occurs in extreme astrophysical environments close to neutron stars and black holes in systems such as pulsar wind nebulae, binary stars, active galactic nuclei and gamma-ray bursts, to name but a few. This provides a second scientific aim for high-energy gamma-ray astronomy: probing the physical processes in these objects and understanding the characteristics of relativistic jets, winds and explosions. Finally, high-energy gamma-ray astronomy has an important role to play in fundamental physics questions such as the existence, nature and distribution of dark matter, quantum gravity, the formation of the earliest stars, and the origins of magnetic fields in the universe.

Developments since 2017

The wealth of science available from high-energy gamma-ray astronomy is demonstrated by *Fermi*-LAT's 10-year point-source catalogue, which contains over 5000 objects. Recent highlights have included resolving the large-scale jet of the prominent radio galaxy Centaurus A, the long-awaited detection of gamma-rays from a gamma-ray burst with ground-based telescopes,[1] the detection of a gamma-ray burst simultaneously with a gravitational-wave event, thereby confirming it as a binary-neutron-star inspiral event and the detection of gamma-rays from the putative neutrino-emitting blazar TXS 0506+056. A particular focus in the search for dark matter is the Galactic centre, a well-known gamma-ray source, which is thought likely to contain a significant signal from dark matter in addition to a likely PeVatron. Dark matter detection remains elusive; newer instruments are set to make ever-deeper measurements of this region.

Above 100 TeV, a range of recent discoveries[2] has revealed more - and more energetic - sources at these energies than expected, opening this particular window for scientific investigation and discovery.

Distinguishing gamma-ray sources from the background, whether that is diffuse emission or cosmic rays, necessitates the use of sophisticated analysis techniques, as does the classification of the now rather numerous gamma-ray sources. In recent years, machine learning techniques have become increasingly important in gamma-ray astronomy; these have the potential to increase the science output from present and future experiments.

Current and planned space-based high-energy gamma-ray observatories are summarized below, in approximate chronological order of their actual or expected 'first light'.

INTEGRAL

The INTErnational Gamma-Ray Astrophysics Laboratory, operated by ESA together with the United States, Russia, the Czech Republic, and Poland, was launched on 17 October 2002. It covers the low-energy gamma-ray regime, specialising in spectroscopy and imaging (angular resolution: 12 arcmins FWHM) of gamma-ray sources in the energy range 15 keV to 10 MeV. Source monitoring in the X-ray (4-35 keV) and optical (V-band, 550 nm) energy ranges occurs simultaneously with the gamma-ray observations.

AGILE (Astrorivelatore Gamma a Immagini Leggero)

Funded in its entirety by the Italian Space Agency (ASI), the AGILE satellite was launched on April 23rd, 2007. The gamma-ray detector on board (AGILE-GRID) is sensitive to photons with energies in the range 30 MeV - 50 GeV; AGILE also carries an X-ray detector (SuperAGILE).

Since October 2015, all AGILE-GRID data have been published as soon as they are processed and validated. The current public AGILE archive contains all data from December 1, 2007 up to March 31, 2020. In addition, AGILE has a comprehensive mission Guest Observer Programme.

Fermi

The Fermi Gamma-ray Space Telescope was launched on June 11th, 2008. It contains two instruments, the Large Area Telescope (LAT), which operates from 30 MeV to ~300 GeV, and the

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[1] Nature 575, 455, (2019); Nature 575, 459 (2019); Nature 575, 464 (2019).

[2] PRL, article id 031102 (2021); ApJL 907, L30 (2020); Nature, 594, 33 (2021).

Gamma-ray Burst Monitor (GBM), which operates from 8 keV to 30 MeV. Led by the USA, contributions to Fermi were made by 5 European nations[3].

Since the beginning of the second year of operations, all LAT science data has been released as early as possible, typically within a day or two of acquisition. Many hundreds of papers have been produced using this rich dataset. Already operating beyond its design lifetime of 10 years, Fermi operations have been approved until the end of the financial year 2022.

AMEGO

AMEGO (A Medium Energy Gamma-ray Observatory) targets greater sensitivity at energies of a few 10s of MeV but will also carry a pair-production telescope that will be sensitive to gamma rays up to 10 GeV. It is proposed that, in addition to its continuum sensitivity, AMEGO will undertake nuclear line spectroscopy and polarization measurements to address questions in blazar emission mechanisms, physical processes around compact objects, element formation in dynamic systems and dark matter.

The AMEGO concept builds on the strong heritage of the Fermi-LAT and technology developed for gamma-ray and cosmic-ray detectors. The subsystems and spacecraft have undergone preliminary engineering and costing studies that show that it is possible to build the observatory within the probe-class cost envelope.

A NASA-led project, the AMEGO team includes around 200 scientists from the USA and 15 other countries[4], including 8 in Europe. The five-year mission is planned to launch in 2029, assuming approval to proceed is given in 2022.

e-ASTROGAM/ASTROMEV

Originally a proposal for an ESA M5 mission, e(enhanced)-ASTROGAM concept is based on a silicon hodoscope, a 3-D position-sensitive calorimeter and an anticoincidence detector, and is proposed to cover the energy range from 100 keV to 1 GeV. The European-led project is now working within a framework called ASTROMEV, looking to exploit technological advances in the next decade.

There now follows a summary of major current and planned ground-based high-energy gamma-ray observatories, also in approximate chronological order of their actual or expected ‘first light’.

High-Energy Stereoscopic System (H.E.S.S.)

The H.E.S.S. system of IACTs investigates gamma rays in the energy range from 10s of GeV to 10s of TeV. Located in Namibia, near the Gamsberg mountain, the first of the four Phase I telescopes started operation in Summer 2002, with all four operational by December 2003. A much larger fifth telescope - H.E.S.S. II – has been operational since July 2012.

In 2015-2016, the cameras of the four H.E.S.S. I telescopes were fully refurbished using state-of-the-art electronics, in particular using the NECTAr readout chip designed for the Cherenkov Telescope Array (CTA).

To date, the H.E.S.S. Collaboration has published over 100 articles in high-impact scientific journals and is responsible for over 45% of the known VHE gamma-ray sources. In September 2018, H.E.S.S. released data to the public. The data release consists of event lists and instrument response functions in Flexible Image Transport System (FITS) format, an open file format widely used in astronomy, and includes observations of various well-known gamma-ray sources as well as observations of empty fields for background modelling. It complies with the open format

[3] France, Germany, Japan, Italy and Sweden.

[4] Austria, Brazil, Bulgaria, China (Hong Kong), Germany, Italy, Japan, Mexico, the Netherlands, Norway, Poland, South Africa, Spain, Switzerland and the UK.

specifications developed for the CTA Observatory, to support the development of open-source science tools for high-level analysis of gamma-ray data.

The H.E.S.S. observatory is operated by a collaboration of more than 260 scientists from about 40 scientific institutions and 13 different countries[5].

H.E.S.S. operations have been extended until 2022 with a provision for two subsequent 3-year extensions and a likely extension until 2025, to be decided in 2021. There is unlikely to be any overlap with CTA until 2025.

Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescopes

MAGIC is a system of two 17 m diameter IACTs situated on the island of La Palma, which detect gamma rays from 30 GeV to 100 TeV. The first telescope was built between 2001 and 2003, the scientific observations starting in 2004, and the commissioning of the second telescope (MAGIC-II) was completed in autumn 2009. A major upgrade was performed over the northern summers of 2011 and 2012; this included upgrading the camera of the first telescope and the readout of both.

A particular feature of the MAGIC telescopes is their ability to reorient to any point in the observable sky in about 40 seconds at average speed. In the case of gamma-ray, burst follow-up observations a maximum speed of about 7 degrees per second can be achieved, making repositioning in less than 25 seconds possible.

The MAGIC Collaboration has published ~180 papers in high-impact scientific journals. MAGIC has created a public data repository, consisting of event data and instrument response functions, which presently contains data from the blazar TXS 0506+056, as well as providing FITS files of all high-level public results; these data include sky maps of different quantities, 1-D histograms, spectra and light curves.

The MAGIC telescopes are currently run by an international collaboration of about 175 astrophysicists from 24 institutions and consortia from 12 countries[6]. The current MoU among institute members is valid until July 2024. The collaboration is contemplating scenarios for continuing operation beyond that date.

Very Energetic Radiation Imaging Telescope Array System (VERITAS)

Completed in 2007, VERITAS comprises an array of four 12 m diameter telescopes operating in the 85 GeV - 30 TeV energy range. The telescopes are located at the base camp of the Fred Lawrence Whipple Observatory in southern Arizona, USA. In 2012, the 499-pixel cameras were upgraded to employ high quantum efficiency photomultiplier tubes.

The VERITAS Collaboration has published over 100 papers in refereed journals. They are currently in the process of collating all published results, significances, fluxes, light curves and spectra, in an electronic format that will be publicly available from the HEASARC, Zenodo and a GitHub repository. The archive is ready and a research note to accompany it is currently under review by the collaboration.

VERITAS is currently run by a collaboration of about 80 scientists. VERITAS operations are funded through 2022 and it is intended to pursue operations with a full scientific program through 2025.

[5] Armenia, Australia, Austria, France, Germany, Ireland, Japan, Namibia, the Netherlands, Poland, South Africa, Sweden and the UK.

[6] Armenia, Brazil, Bulgaria, Croatia, Finland, Germany, India, Italy, Japan, Poland, Spain and Switzerland.

High Altitude Water Cherenkov Observatory (HAWC)

The HAWC Observatory formally began operations on August 1st, 2013 and is situated in the Parque Nacional Pico de Orizaba in Mexico at an altitude of 4100m above sea level. A water Cherenkov detector, HAWC consists of 300 main water tanks plus an additional 345 small water Cherenkov detectors surrounding the main array, with 3 peripheral and 1 central photomultiplier tube (PMT) per tank. The observatory is optimised for observations in the TeV regime, and energy thresholds range from hundreds of GeV to tens of TeV.

HAWC has published around 40 papers in refereed journals. Data from the 3HWC survey of very-high-energy gamma rays and other HAWC papers are now available for public download from the HAWC data repository. The repository also provides a coordinate view of the entire HAWC sky map, allowing users to query the flux and statistical significance of excess gamma rays from any location in the HAWC field of view.

The HAWC Collaboration includes over 120 scientists from 30 institutions in 8 nations[7], primarily Mexico and the USA. The permit for operating HAWC in the Parque Nacional Pico de Orizaba is valid until 2025 with the possibility of applying for an extension. NSF funds for HAWC operations have been secured until 2023, also with the possibility of applying for an extension.

Large High Altitude Air Shower Observatory (LHAASO)

LHAASO aims to detect cosmic rays and gamma rays from 10^{11}-10^{18} eV. Located about 4410 m above sea level in the Haizi Mountain in Sichuan Province in southwest China, LHAASO started operations in 2019 with one-quarter of the total array. As of December 2020, the array will be 75% complete, with the final array expected in 2021. Once completed, it will cover 1.3 square km and consist of 3120 water Cherenkov detectors based in a pool, 1188 muon detectors, 5195 scintillator detectors and 18 wide-field Cherenkov telescopes. The Chinese-led LHAASO Collaboration involves members from several other nations[8].

Cherenkov Telescope Array (CTA)

The next-generation European-led, ESFRI-listed global project will be the Cherenkov Telescope Array (CTA). CTA will operate as an open, proposal-driven observatory; the first ground-based gamma-ray observatory to do so. This mode of operation is expected to boost scientific output by engaging with a wider research community than before.

CTA will make observations over a wide energy range, from 20 GeV to at least 300 TeV, that requires the use of 3 different sizes of telescope: the large-sized telescopes (LSTs), which cover the lowest energies, the small-sized telescopes (SSTs), which cover the highest energies, and the medium-sized telescopes (MSTs), designed to be the ‘work horses’ of the observatory covering the central energy range. The observatory will consist of two arrays, one in the northern hemisphere and one in the south. In the baseline configuration, the array in the south will consist of around 100 telescopes of all three sizes and the array in the north will contain LSTs and MSTs only. Both sites have now been chosen and agreements signed. They are La Palma, at the Observatorio del Roque de los Muchachos, and Chile, near ESO’s Paranal Observatory. The administration required for the observatory has built up the Project Office in Bologna, and the architect’s plans have been chosen for the Data Management Centre on the DESY campus in Zeuthen. The formal governance of the observatory will be through a European Research Structure Consortium (ERIC) that is expected to be established in 2022.

Several prototype telescopes of all sizes have been built by the Consortium, which consists of around 1400 scientists and engineers in over 200 institutes spread over 31 countries. The prototype LST, now undergoing commissioning on La Palma, is expected to become the first

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[7] Brazil, China, Germany, Italy, Mexico, Poland, South Korea and the USA.

[8] Including Germany, Ireland, Italy, Russia, Switzerland and Thailand.

telescope of the northern array. An initial phase with somewhat reduced numbers of telescopes in both arrays has now been fully costed and this phase fits within the initial funding portfolio. Construction on the southern array will start once the requisite infrastructure is in place, including the foundations for the telescopes. Once these are complete, CTA will rapidly become more sensitive than any of the current generation of instruments, with a target date for completion of the initial phase in 2027.

Southern Gamma-ray Observatory (SWGO)

Formed on July 1st, 2019, the SWGO Collaboration consists of scientists from 42 institutions in 11 countries[9]. The Collaboration aims to undertake a design study for a future wide field-of-view gamma-ray observatory in the southern hemisphere over the next 3 years.

Building on the pioneering work of MILAGRO and the success of HAWC, SWGO will consist of an array of particle detectors at ground level to measure the particles from the extensive air showers induced by incoming gamma-rays. Such a detector would have a 100% duty cycle and an inherently wide field-of-view, in contrast to IACTs, which must operate in dark and cloud-free conditions and (at present, at least) have fields of view of < 10 degrees. However, an IACT is able to achieve greater precision and instantaneous sensitivity than a particle detector array. Consequently, the SWGO will be complementary to space-based observatories such as *Fermi* (which have a wide field of view but limited sensitivity at the highest energies) and CTA (which will have a lower duty cycle but will provide high-precision measurements).

The field, Europe's role, and APPEC

Gamma-ray astronomy has emphasised both its maturity as a field and the fundamental importance of the science it covers over the last few years. Europe's contribution to gamma-ray astronomy is very strong. Building on its leadership of the AGILE, H.E.S.S. and MAGIC telescopes, the majority of the scientists and engineers in the CTA Consortium work in European institutions, with both the observatory headquarters and the data centre based in Europe. As discussed above, the MAGIC and H.E.S.S. telescopes will continue operating for some years in the future, while CTA comes to full sensitivity. The two collaborations concerned will then be considering the futures of these systems. The newest collaboration in ground-based gamma-ray astronomy, SWGO, proposes to build an instrument that would be highly complementary to CTA; approximately half the scientists in SWGO are from Europe.

Continued support from APPEC for the construction and subsequent long-term operation of CTA's northern and southern hemisphere observatories is important as the project enters its critical construction phase (which includes finalising funding). Support for SWGO on the roadmap is vital to enable this new project to establish itself and gain funding for its design study and, ultimately, construction.

[9] Including Argentina, Brazil, the Czech Republic, Germany, Italy, Mexico, Portugal, the UK and the USA, plus supporting scientists from these countries and Australia, Chile, France, Japan, Slovenia and Spain.

3. High-energy neutrinos

2017-2026 Strategy Statement

IceCube's first observation of PeV-scale cosmic neutrinos in 2013 has opened an entirely new window onto our Universe: neutrino astronomy. As well as presenting the opportunity to resolve neutrinos' mass hierarchy by studying atmospheric neutrinos, this led ESFRI to include KM3NeT 2.0 in its 2016 roadmap, with operation anticipated to commence in 2020. Within the Global Neutrino Network (GNN), the IceCube, ANTARES, KM3NeT and Baikal-GVD collaborations already joined forces to provide a network of large-volume detectors simultaneously viewing both northern and southern hemispheres and to exploit the full discovery potential of neutrino astronomy.

For the northern hemisphere (including Baikal GVD), APPEC strongly endorses the KM3NeT collaboration's ambitions to realise, by 2020: (i) a large-volume telescope with optimal angular resolution for high-energy neutrino astronomy; and (ii) a dedicated detector optimised for low-energy neutrinos, primarily aiming to resolve the neutrino mass hierarchy. For the southern hemisphere, APPEC looks forward to a positive decision in the US regarding IceCube-Gen2.

Introduction

Ever since Markov discussed in 1960 the possibility of detecting cosmic neutrinos using the Cherenkov effect in seawater, many experimental groups contributed to the development of the required technology. The harsh natural environments and the difficulty to make repairs required by such large detectors have been a driving force for innovations. Today, affordable designs exist whilst operational costs are moderate. Four high-energy neutrino telescopes are currently being operated and/or built, namely IceCube, ANTARES, Baikal-GVD and KM3NeT. These telescopes comprise large 3-D arrays of photo-sensors deployed in deep water or ice (typically km^3). Neutrino telescopes are normally operated day and night during the whole year; several years of data taking are needed to accumulate sufficient statistics to observe neutrinos from the cosmos. As part of multi-messenger astronomy, neutrino telescopes provide complementary data for the determination of the location, nature and flaring of astrophysical sources capable of accelerating particles up to PeV energies and beyond.

The detection principle presents synergistic opportunities with other water Cherenkov detectors. To minimise the cost and maximise the performance of a neutrino telescope, the photo-sensors should have a high quantum efficiency (maximal QE 25–30%), a good time resolution (1–5 ns, depending on the detection medium) and a low price. The preferred choice still is a photo-multiplier tube (PMT) but it is interesting to note that due to the demand, small PMTs are nowadays priced competitive whilst offering better science. Alternative techniques based on acoustic signals in water and radio signals in ice are being explored for the detection of ultra-high-energy neutrinos (i.e., neutrinos with energies in excess of EeV). The long absorption lengths of the media carry the promise to realise very large detectors cost-effectively.

The current computing resources are relatively modest compared to experiments at CERN. Nonetheless, the filtering of the rare signal of cosmic neutrinos from the high background of muons and neutrinos produced by interactions of cosmic rays in the atmosphere above the detectors poses challenges. It has been shown that machine learning and the use of GPUs can improve the science output. With more data becoming available during the next decade and possible (further) discoveries within reach, the future computing resources may significantly grow.

The infrastructures for the different neutrino telescopes offer interdisciplinary opportunities for detailed, continuous and real-time measurements, e.g., for glaciology, marine biology, oceanography and environmental studies.

Developments since 2017

The era of neutrino astronomy has rapidly evolved. The first detection of astrophysical neutrinos pre-dates the current strategy. Since then, the search for sources of high-energy neutrinos has intensified. The release of immediate public alerts by IceCube of astrophysical neutrino detections has led, with the help of simultaneous gamma-ray detections, to the first identification of a blazar-type active galaxy as a likely source of astrophysical neutrinos.

Current and planned high-energy neutrino observatories are summarized below, in approximate chronological order of their first operation.

ANTARES

ANTARES is a deep-sea detector, located 40 km off Toulon, France, in the Mediterranean Sea (at a depth of 2500 m) and mainly dedicated to the observation of neutrinos with energies in excess of 100 GeV. The collaboration is made by about 120 scientists, most of them are also involved in the KM3NeT Collaboration. ANTARES was completed (12 detection lines hosting a total of about 900 optical modules) in 2008. Its observational field-of-view with sub-degree angular resolution covers the Southern hemisphere and the Galactic centre for up-going neutrinos. The ANTARES data taking was extended (in agreement with the funding agencies and with minimal operating costs) beyond its scheduled end date of 2016 and the experiment is still taking data today to provide a complementary neutrino field-of-view for multi-messenger studies in coincidence with the LIGO/Virgo GW O1, O2 and O3 runs. ANTARES has produced scientific results, published in more than 80 papers and has demonstrated that an underwater neutrino telescope can operate for more than 10 years with only a marginal degradation of its effective area and angular resolution, the key quantities necessary for neutrino detection. The latest search for a diffuse cosmic neutrino flux indicates a small excess (1.8 sigma) compatible with the signal observed by IceCube. This will be updated with the final data sample.

IceCube

The IceCube Neutrino Observatory is a cubic-kilometre neutrino telescope in full operation since 2011 at the South Pole, Antarctica. Following the observation in 2013 of astrophysical neutrinos, IceCube began in 2016 the release of public alerts that allow other telescopes, including gamma-ray, x-ray, and optical facilities to rapidly search for counterparts to high-energy cosmic neutrinos. This has helped enrich the recently growing fields of multi-messenger and transient astronomy and led to the evidence of an individual object, a blazar-type active galaxy, as one of the sources of the astrophysical neutrino flux.

The IceCube Collaboration, with members from 53 institutions in 12 countries, is planning a large expansion of the detector, called IceCube-Gen2. This is planned to be fully operational by 2033 and to deliver ten times the rate of cosmic neutrinos as the current detector. Gen2 will include a shallow in-ice radio array for the detection of ultra-high-energy neutrinos and a surface detector array to study high-energy galactic cosmic rays.

As a first step towards IceCube-Gen2, in 2019 the NSF approved full funding for an initial upgrade of the detector. This stage, called the IceCube Upgrade, relies strongly on significant contributions from Germany and Japan, and benefits from further international contributions from Sweden and Korea. The Upgrade will consist of seven new strings deployed in the deep ice at the centre of the cubic-kilometre array. The seven strings will be densely instrumented, adding 700 new optical modules to the existing 5160 modules, allowing novel module designs to be tested for Gen2. Calibration devices will improve the modelling of the optical properties of the ice, allowing for better directional and energy resolution of neutrino events. The improved ice modelling will not only propagate forward to Gen2 but will be applied to the existing decade of data recorded by IceCube. The dense instrumentation of the Upgrade will enhance atmospheric neutrino-oscillation studies, in particular tau neutrino appearance, testing the unitarity of the neutrino mixing matrix. Full deployment of the Upgrade is scheduled for 2023/24.

Baikal-GVD

The deep-underwater neutrino telescope Baikal Gigaton Volume Detector (Baikal-GVD) is currently under construction in Lake Baikal. The telescope has a modular structure and consists of functionally independent clusters - sub-arrays comprising a total of 288 OMs each at depths from 750 m to 1275 m, connected to the shore by individual electro-optical cables. The deployment continues at the rate of two clusters per year.

Eight clusters with 2034 OMs arranged in 64 strings are taking data since April 2021. The effective volume of the facility is currently 0.40 cubic kilometres for shower events from high-energy neutrinos, thereby expecting three to four events per year with energies in excess of 100 TeV, assuming the astrophysical neutrino flux observed by IceCube. Since each GVD cluster represents a multi-megaton scale Cherenkov detector, studies of neutrinos of different origins are possible at the early stages of Baikal-GVD construction. Analysis of events recorded in 2019-2020 resulted in the selection of six cascade-like events with energies in excess of 100 TeV, the first candidates for Baikal astrophysical neutrinos.

Baikal-GVD participates in multi-messenger studies of high-energy phenomena in the universe. The upper limits on the neutrino fluence from GW170817 were derived using 2017 data. For similar detectors, better angular resolution for high-energy neutrino events can be achieved in water as compared to ice. It is expected that real-time alerts from Baikal-GVD will start to be released soon.

Baikal-GVD in the current configuration is the largest neutrino telescope in the Northern hemisphere. During Phase-1 of Baikal-GVD implementation, an array consisting of 14 to 16 clusters is expected to be deployed by 2024.

KM3NeT

The main objectives of KM3NeT-2.0 are *i)* the discovery and subsequent observation of high-energy neutrino sources in the universe and *ii)* the determination of the mass ordering of neutrinos. To meet these objectives, the collaboration plans to build a new research infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea. A phased and distributed implementation is pursued which maximises the access to regional funds, the availability of human resources and the synergetic opportunities for the earth and sea sciences community. The EU-led collaboration is composed of more than 240 scientists from 15 different countries, including partners from Africa, Australia, China and Russia. The currently available funds cover about 60% of the total costs. It is planned to set up a legal entity in the form of an ERIC. KM3NeT-2.0 appears on the ESFRI roadmap project.

The technology is based on a novel design of the so-called optical module which houses 31 small PMTs instead of one large PMT. The full project will encompass more than 6000 such modules. At the Italian site, the 'ARCA' detector will be optimised for neutrino astronomy and at the French site, the 'ORCA' detector will be optimised for (low-energy) neutrino physics. The required production capacity of the detector components has been established and construction of the detectors is ongoing at sites in France and Italy.

The first data taken at the two sites provided a validation of the technology, including ns time accuracy, 10 cm position accuracy and *in situ* determination of the QE of the PMTs. The foreseen refurbishment of the seafloor network at the Italian site has been finished and the construction of the complete infrastructure is ongoing. The construction of the detectors should be completed in

2024(26) for the French (Italian) site, assuming the timely availability of the remaining funds. It is foreseen to operate the detectors for (at least) ten years thereafter.

RNO-G

The Radio Neutrino Observatory Greenland, RNO-G, is currently under construction at Summit Station with three stations deployed in the summer of 2021. Eight more are planned for the summer of 2022 and the rest for a total of 35 stations by 2023. The experiment aims for the first radio-detection of a high-energy neutrino (above 10 PeV) within the following five years. Building on the combined previous experience of radio-based neutrino detection experiments in Antarctica, RNO-G will also serve as a pathfinder for a large radio array (~500 km^2) as part of IceCube-Gen2. A still larger array targeting the radio detection of ultra-high-energy (UHE) tau-neutrinos, as well as UHE cosmic rays and photons, is the Giant Radio Array for Neutrino Detection, GRAND, described in the high-energy cosmic-ray section.

Global Neutrino Network

In 2013, the ANTARES, Baikal-GVD, IceCube, and KM3NeT Collaborations established the Global Neutrino Network (GNN) as an umbrella organisation that provides a forum for cooperation, exchanges, strategic discussions and decisions, and coordination. Under the auspices of GNN, joint data analyses and publications are pursued, the biannual VLVnT (very large volume neutrino telescope) conference series is organised, and responses to international strategy processes such as the CERN strategy update are coordinated.

The field, Europe’s role, and APPEC

Although the idea of doing astronomy by detection of high-energy neutrinos is old, the field is relatively young. Today, Europe is leading the ANTARES and KM3NeT projects, plays an essential role in the IceCube collaboration, and also participates in Baikal-GVD. It is foreseen to phase out ANTARES in favour of KM3NeT (see section “Neutrino properties”). Various theory groups in Europe contribute to the development of the field as well. As was the case for IceCube, for IceCube-Gen2 significant R&D and material contributions from its European members are foreseen to complement the funding from the US. The support of APPEC for KM3NeT remains important to align the funding authorities in setting up an ERIC and to acquire the funds to complete the construction of the infrastructure and to operate it for the envisaged lifetime.

4. High-energy cosmic rays

2017-2026 Strategy Statement

The Pierre Auger Observatory is the world's largest, most sensitive ground-based air-shower detector. Understanding the evident flux suppression observed at the highest energies requires good mass resolution of primary cosmic rays: are they predominantly light nuclei (protons) or heavy nuclei (like iron)? This is the missing key to deciding whether the observed cut-off is due to particles being limited in energy because of interactions with the CMB, or to cosmic accelerators 'running out of steam' to accelerate particles. The Auger collaboration will install additional particle detectors (AugerPrime) to simultaneously measure the electron and muon content of air showers, in order to help determine the mass of primary cosmic rays. This upgrade will also deepen understanding of hadronic showers and interactions at centre-of-mass energies above those accessible at the LHC.

APPEC strongly supports the Auger collaboration's installation of AugerPrime by 2019. At the same time, APPEC urges the community to continue R&D on alternative technologies that are cost-effective and provide a 100% (day and night) duty cycle so that, ultimately, the full sky can be observed using very large observatories.

Introduction

Cosmic rays are defined here as stable atomic nuclei of extra-terrestrial origin.[10] Other definitions, more or less widely used, also include electrons and positrons as cosmic rays, while more rarely in the ultra-high-energy regime, with energy in the EeV range and above, also neutrinos and photons are included,

Cosmic rays with MeV energies are mostly trapped in the sun's magnetic field, while those of higher energies are much more likely coming from sources outside of our solar system. This view was spectacularly confirmed by the Voyager missions breaking through the heliosphere. In the GeV to EeV range, the cosmic ray origin is highly likely from our own Milky Way. While from considerations of the Galactic magnetic field cosmic rays with energy above an EeV were thought to be extra-galactic, more recently the measurement of a dipole in the flux by the Pierre Auger Observatory provided a strong direct observational hint.

Despite more than a century of research of cosmic rays and recent impressive progress, the mystery of their origin, propagation through the universe, and interactions with the Earth's atmosphere are still surrounded by many fundamental questions. Many of these questions are part of, or approachable by multi-messenger observations.

Developments since 2017

A strong direct observational hint for the extra-galactic origin of ultra-high-energy cosmic rays has been delivered by the Pierre Auger Observatory. Auger increased its statistics, making the measurement of the energy spectrum more precise, reinforcing the discovery of a transition from a light to a heavier composition at high energy. The capability of ultra-high-energy cosmic ray observatories for the detection of ultra-high-energy neutrinos and photons is becoming more and

[10] Antimatter is also included but the abundance of anti-nuclei is extremely small. While the antimatter over matter ratio provides important information on origin and evolution of the universe and other physical phenomena, it is currently in practise of limited relevance for the detection and interpretation of (ultra-)high-energy cosmic rays.

more evident, with observed flux limits that are not yet in the range of the theoretically expected flux of these neutral particles but start to approach them.

Current and planned ultra-high-energy cosmic ray observatories are summarized below, roughly in chronological order of their first data taking, with ground-based observatories first, followed by space-based missions.

Pierre Auger Observatory[11]

Since 2017 Auger has published new results establishing a dipole in the arrival direction of UHECR, where the phase strongly supports the extragalactic origin of particles with energy above 8 EeV. A correlation with star-burst galaxies was found for the highest-energy particle. This reinforces the observation of an anisotropic sky with sources located preferentially in the supergalactic plane direction. A new feature in the energy spectrum was reported, which, when combined with composition information, hints at an energy-dependent composition in the 10-100 EeV energy range. Improved results on UHECR composition were also published, although at the very-high-energy end information is still too sparse to be conclusive. New results set tighter upper limits on UHE neutrinos and photons, getting progressively close to the predicted flux range. Auger is taking part in the multi-messenger observations of the gravitational-wave events and has a quasi-real-time follow-up on alerts in place. It is able to test and set limits on UHE counterparts of IceCube and ANITA observations.

Significant effort is being put into the AugerPrime upgrade of the observatory. This upgrade includes new surface detector electronics with, an additional PMT in the water Cherenkov detectors to deal with the high signals near the shower core, a scintillator module on top of each water Cherenkov detector and a cosmic-ray radio detector with a station attached to each of the surface detector units. All these improvements are aimed at identifying event-by-event the cosmic-ray particle type. For the full upgrade, there is still a 10% shortfall in funding, which is being mitigated by not equipping the outer ring of surface detector stations with scintillator modules for the time being, while more funds are being collected. The addition of the radio detector layer is in line with the APPEC roadmap recommendation to continue R&D on alternative cost-effective and high-duty-cycle detection technologies, which brought the radio detection to the readiness level where it can be applied at a large scale. The radio detector extends the composition-sensitive acceptance of the observatory to large zenith angles, thereby significantly increasing the observable sky and the total exposure. The combination of detector technologies and advanced triggering capabilities of the new electronics will also boost the sensitivity and exposure to UHE neutrinos and photons, thereby promising to be able to penetrate significantly into the predicted flux ranges of these neutral particles. The Pierre Auger Observatory will be operational until at least 2030.

In a first tranche, 10% of the data of the Pierre Auger Observatory has been made publicly available in 2021, with more to follow at a pace that is currently being discussed within the collaboration.

Telescope Array (TA)[12]

The Telescope Array experiment is the largest ultra-high-energy cosmic ray detector in the Northern Hemisphere. The experiment's high energy extension TAx4 will increase the TA aperture to approximately that of the Pierre Auger Observatory; one half of the extension is already deployed. The main goals of the extended experiment are the study of cosmic-ray anisotropies and understanding the nature of UHECR sources. This implies the study of the twenty-degree "hot-spot" of highest-energy events in the Northern sky, which was found by the experiment

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[11] The Pierre Auger Collaboration has a dominantly European composition in terms of number of authors.

[12] The TA collaboration has a modest European participation and is dominated by US groups.

several years ago. At the same time, the TA collaboration develops new methods that combine knowledge about UHECR arrival directions and mass composition with novel methods of data processing based on machine learning techniques. This allows the TA collaboration to go beyond the basic sensitivity in search for new signatures of UHECR sources and anisotropies.

Giant Radio Array for Neutrino Detection (GRAND)

A proposal has been launched for a Giant Radio Array for Neutrino Detection (GRAND), a 200 000 km^2 radio detector array, primarily aimed at detecting UHE cosmic tau neutrinos (either directly from sources or of cosmogenic origin) but also suitable as a general-purpose observatory for UHE cosmic rays, UHE photons and several other observations. This giant array is proposed to be built up in several stages. The prototype stage GRANDProto300 should be assembled and installed in 2021. A key challenge for this stage is the capability to autonomously trigger on the radio signal from air showers with high efficiency. The first of 10-20 sub-arrays of 10 000 - 20 000 km^2 arrays, to be located worldwide, is aimed to be realised in the second half of this decade, with the full observatory aimed to become operational in the first half of the 2030s. This development is again in line with the call by APPEC for cost-effective and high-duty-cycle detection technologies. The GRAND observations will have strong synergies between (U)HE neutrino, gamma-ray and cosmic-ray research, securing a long-term future for observations in the field of the highest-energy cosmic particles.

JEM-EUSO

In parallel to the developments on the ground, important efforts have been undertaken to apply the fluorescence technique for the detection of UHECR showers from space, with the goal to reach a roughly uniform coverage of the entire sky, with a potentially considerable increase in the overall statistics at the highest energies (say above $10^{19.5}$ eV). These developments have been conducted within the international JEM-EUSO Collaboration, gathering 17 countries (including 11 in Europe) under European leadership (PI/spokesperson), and given rise to several balloon and space pathfinder missions involving national space agencies in Europe as well as NASA. The last one, MINI-EUSO (ASI/ROSCOSMOS), was launched in 2019 and successfully operates on board the International Space Station. The next fully funded mission, EUSO-SPB2 (NASA) will be launched in 2023, including a Cherenkov telescope in addition to the JEM-EUSO fluorescence technology to observe the limb of the Earth for upward-going showers from tau-neutrino decays. This mission will detect cosmic-ray showers around 10^{18} eV and assess the potential of a space mission for cosmogenic neutrino detection. It will be the last step before the development of a full-size mission reaching an exposure larger than the currently accumulated exposure on the ground, demonstrating the power of space for UHE cosmic--ray and neutrino detection. A promising candidate for such a mission, selected in 2017 as a probe mission study by NASA and currently under review for the decadal survey, is POEMMA, which crucially depends on the participation of several European groups, notably for the focal surface and electronics of the fluorescence telescope.

Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)

POEMMA is a probe Class B NASA mission, which evolved from previous work on the satellite mission proposals OWL, JEM- EUS, CHANT and EUSO-SPB1 and 2. It proposes a set of two identical satellites instrumented with a high-sensitivity low-resolution photometer that measures fluorescence and Cherenkov light emission from extensive air showers in the atmosphere. POEMMA can measure both downward going UHECR showers and Earth-skimming UHE tau neutrino interactions producing horizontal and upward going showers. Due to its large field of view and full-sky coverage over a period of 95 minutes, it is capable of following up targets of opportunity for multi-messenger transients. Several European groups[13] are active in the POEMMA collaboration. The cost of POEMMA is estimated to be around 1 BUS$, with a proposed launch in the 2027-2029 timeframe.

Global COSmic-ray observatory (GCOS)

A more generic and yet much less well worked-out idea for a next-generation cosmic ray observatory is the Global COSmic-ray observatory (GCOS). This proposal builds on the hybrid detection Pierre Auger Observatory set-up with an improved, height segmented water-Cherenkov-station-based surface detector, paired to a 10-200 MHz range radio detector and possibly additional new-technology detectors for air-shower detection. It aims to cover a more than 40,000 km^2 area with nearly 2π solid angle coverage, about 15 times the exposure of the currently largest Pierre Auger Observatory, operated in a few sites on both the Northern and Southern Hemisphere.

Inter-collaboration working groups

An important part of the present-day UHECR studies is carried out by inter-collaboration working groups which combine efforts of the key experiments (Pierre Auger Collaboration and Telescope Array) in understanding the cosmic-ray energy spectrum (with cross-calibration in the common field of view area in the sky), anisotropies (with full-sky coverage) and the primary composition, as well as the implications of air-shower data for our understanding of particle physics at ultra-high energy.

The field, Europe's role, and APPEC

The progress on AugerPrime and the full inclusion of the radio detection technique are in line with the APPEC recommendation. This large-scale deployment of radio detection also allows it to gain the experience to deploy it in larger scale observatories. AugerPrime should be able to establish what fraction of ultra-high-energy cosmic rays are protons. If the ultra-high-energy cosmic rays have a significant proton component, which will be identifiable on an event-by-event basis, this will open the possibility for proton astronomy. However, this will require much larger event statistics, hence a much larger observatory. In the case that ultra-high-energy cosmic rays are almost all of intermediate or heavy mass, it will be extremely important to detect the associated flux of ultra-high-energy neutrinos and photons and to establish their cosmogenic and/or source origin. This will require even larger observatories, which incidentally can also serve as cosmic ray detectors.

In any case, a next-generation huge ultra-high-energy cosmic ray observatory is needed, with the additional requirement that such an observatory should be versatile and also capable of detecting ultra-high-energy neutrinos and photons. The case of the Pierre Auger and TA observatories has taught us that this should be a hybrid detection installation, where independent techniques can be cross calibrated.

New observatories can either be space, satellite-based, or ground-based. A steady and significant European effort has been going into JEM-EUSO. The currently most promising space-based proposal is that of POEMMA, led by the US and with a substantial European contribution.

At present, the mostly radio-detection-based GRAND is the most advanced concept for a huge ground-based cosmic ray observatory, while there is also an initiative primarily based on water Cherenkov detectors. In both cases, rough cost estimates range from 150 to 200 M€ investments. It is clear that the world can only afford one ground-based observatory. However, there are good scientific reasons, e.g., full-sky coverage at any time for transient follow-up and multi-messenger

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[13] Among which Czech Republic, France, Germany, Italy, Poland, Slovakia and Switzerland.

astroparticle physics, making this a distributed observatory with several, if not many sites around the globe. Europe is playing a leading role in both GRAND and GCOS, and without the European efforts, it is unclear if a next-generation ultra-high-energy cosmic ray observatory can be built. Within Europe, the magnitude of the investment requires a process of ESFRI listing and aligning the European funding agencies behind one proposal. APPEC coordination will therefore be indispensable.

Space- and ground-based observatories are to a large extent complementary and should both be realised.

The detailed simulation of cosmic-ray air showers is computationally intensive and requires substantial data storage space. At the moment, part of the calculations and data storage is drawing upon Grid resources. It is essential that the community can continue making use of these facilities. At the same time, more R&D is needed for alternative approaches to air shower simulation, e.g., using machine learning techniques, or the use of cheaper and more efficient hardware, such as GPUs and FPGAs.

5. Gravitational waves

2017-2026 Strategy Statement

The first direct observations of gravitational waves by the LIGO-Virgo consortium have revealed a scientific treasure trove. Multi-solar-mass black holes coalescing within seconds into one larger black hole and simultaneously radiating the equivalent of a few solar masses of energy as gravitational waves are now an established fact; they also provide unprecedented tests of General Relativity. Another new, revolutionary window onto our Universe has therefore now opened: gravitational-wave astronomy. In this field, the laboratories that host gravitational-wave antennas play a crucial role by developing new technologies to increase detection efficiencies further. The incredibly high precision in monitoring free-falling objects in space recently achieved by ESA's LISA Pathfinder mission is an important step towards complementary (low-frequency) space-based gravitational-wave astronomy.

With its global partners and in consultation with the Gravitational Wave International Committee (GWIC), APPEC will define timelines for upgrades of existing as well as next-generation ground-based interferometers. APPEC strongly supports further actions strengthening the collaboration between gravitational-wave laboratories. It also strongly supports Europe's next-generation ground-based interferometer, the Einstein Telescope (ET) project, in developing the required technology and acquiring ESFRI status. In the field of space-based interferometry, APPEC strongly supports the European LISA proposal.

Introduction

On September 14, 2015, the first detection of gravitational waves from the coalescence of a binary system of stellar-mass black holes was made by the LIGO interferometers. A century after the fundamental predictions of Einstein, the LIGO Scientific Collaboration and the Virgo Collaboration (LVC) started gravitational-wave astronomy. Observations of merging binary black-hole systems provide unique access to the properties of space-time at extreme curvatures: the strong-field and high-velocity regime. It allows unprecedented tests of general relativity for the nonlinear dynamics of highly disturbed black holes. The direct measurements of binary black-hole properties had a huge impact on our knowledge of the formation and evolution of these astrophysical systems. On August 1, 2017, another epochal discovery was made with the first detection of gravitational waves from a binary system of neutron stars by the Virgo and LIGO network. The relatively small sky-localization of the signal enabled the most extensive electromagnetic observational campaign in the history of astronomy, which led to the observation of the gravitational-wave source at all electromagnetic wavelengths. Information carried by gravitational waves was added to that provided by the study of the electromagnetic spectrum (radio waves, infrared, the visible spectrum, ultraviolet, X-rays and gamma rays), opening a new branch of astronomy by observing the universe with a different and complementary perspective than current telescopes and detectors. In a few years, gravitational-wave observations have been integrated with a weekly detection rate into the exploration of the universe bringing discoveries that have strongly impacted many research fields, from fundamental physics and astrophysics to nuclear physics and cosmology.

We are now at the dawn of gravitational-wave astrophysics, and several key questions are open to be answered. What are the properties of binary systems of stellar-mass, intermediate and massive black holes? How do they form and evolve along with cosmic history? What is the role of neutron-star mergers in the universe nucleosynthesis and in powering relativistic jets? What is the interior structure of neutron stars? What is the nature of compact objects (near-horizon physics, tests of no-hair theorem, exotic compact objects)? Are gravitational-wave sources related to dark matter (primordial black holes, axion clouds, dark matter accreting on compact objects)? What will gravitational-wave observations reveal about dark energy and modifications of gravity on cosmological scales? New gravitational-wave sources are expected to be detected including core-collapse supernovae, isolated neutron stars, massive and super-massive black-hole mergers, populations of galactic compact binaries, stochastic backgrounds of astrophysical and cosmological origin, and cosmic strings. This will be possible by increasing the sensitivity of ground-based detectors and opening new observational windows at lower frequencies by space-born detectors such as LISA and the Pulsar Timing Array. Gravitation is still the least understood fundamental force of nature, and challenges include the discovery and exploitation of new sources of gravitational waves, experimental constraints on the corresponding quantum (graviton) and the development of a quantum field of gravity.

Developments since 2017

The next paragraphs will describe the science, status and the upcoming years' plan for the current generation of ground-based detectors and the plan and perspectives for the new generation of space and ground-based gravitational-wave detectors, which will open new frequencies and will make the most distant universe accessible. Other relevant approaches for the measurement of strong gravity, such as the International Pulsar Timing Array or the Event Horizon Telescope are dominantly driven from the astronomy community and are not discussed here.

Virgo, LIGO and KAGRA

The Virgo project was approved in 1993 by the French CNRS and in 1994 by the Italian INFN. The Virgo Collaboration now has 692 members from 126 institutions of 15 European countries. The Advanced Virgo detector started to observe on August 1st, 2017 as part of a global network of interferometers with the LIGO detectors, improving the sky-localization of the signal and making more detections of binary black-hole systems possible. During the third observation run (started on April 1st, 2019 and ended on March 27th, 2020) the Advanced Virgo and LIGO detectors reached a range for a binary-neutron-star system of 60 and 130 Mpc, respectively. The run produced direct detections of gravitational waves with about 1.5 detections per week. The results of the analysis of the first ~26 weeks of data added thirty-nine candidate events to the 11 confident detections of the first and second observation run, including a new binary-neutron-star event, 34 confident binary black hole events, and one neutron-star black-hole candidate, which may be a binary black hole. These discoveries made it possible to define more stringent constraints on testing general relativity, and on the rate and astrophysical properties of binary systems of compact objects. Among them, we report some exceptional discoveries.

GW190425 is the second detected signal from a binary neutron-star merger after GW170817. The total mass of the system, 3.4 $M_\odot$, is significantly larger than those of any other known binary neutron-star system. GW190412 is a signal from a highly asymmetric mass binary black-hole system, a ~30 $M_\odot$ black hole merging with a ~8 $M_\odot$ black hole. This signal made it possible for the first time to measure gravitational radiation beyond the leading quadrupolar order. GW190814 is a signal from the coalescence of a black hole of 22.2–24.3 $M_\odot$ with a compact object of mass 2.50–2.67 $M_\odot$. It is a particularly interesting signal for its unequal mass ratio and its secondary component consistent either with the lightest black hole or the heaviest neutron star ever discovered in a double compact-object system. GW190521 is a signal from the coalescence of the highest mass binary black-hole system (66–85 $M_\odot$) known so far, which form a final black hole of 142 $M_\odot$. This is the first conclusive evidence of the existence of intermediate-mass black holes (~100–1000 $M_\odot$).

A fourth interferometer KAGRA, located in Japan, entered the observing mode in April with a sensitivity limited to about 1 Mpc. Upgrading of the existing instruments, which will enable LIGO and Virgo to increase their range with respect to the advanced detector design sensitivities, are planned for the next runs. The upgrade of Advanced Virgo, called Advanced Virgo plus, will occur in two phases. The phase 1 installations are expected to increase the sensitivity by a factor of about 2 (a factor 8 in observable volume) for the fourth observation run O4 (expected to start in June 2022), and phase 2 with a sensitivity increase by a factor of about 4 for the fifth run, O5 (expected around 2025). The current plan envisions a network of 4 detectors in O4 (the two LIGO detectors, Virgo, KAGRA) and 5 detectors in O5, with the addition of LIGO India. The detection rate of binary systems of compact objects is expected to increase to several hundred per year.

In order to maximize the science that the scientific community can do with gravitational-wave events, LVC developed low-latency gravitational-wave data analyses and the infrastructure to rapidly detect candidate events (within a few seconds), to generate and distribute public alerts enabling rapid observations and identification of electromagnetic or neutrino counterparts. Public alerts are distributed through NASA's Gamma-ray Coordinates Network (GCN). An overview of the procedures for detecting, vetting and sending gravitational-wave alerts, description of their contents and format, and instructions and software for receiving GCNs and using gravitational-wave sky-localization maps are available in the LIGO/Virgo Public Alerts User Guide. The effectiveness of the developed infrastructure and the reciprocal responsive communications with the astronomical and astroparticle communities is testified by the large percentage of GCNs related to gravitational-wave signal follow-up, which currently represents more than 40% of all the published GCNs during an observation run. This shows the high interest and motivation of the astronomical and astroparticle communities to use observational resources for gravitational-wave science. The latency of the alert GCNs and the information to be released (false alarm rate, sky-localization, source distance, classification) has been agreed upon and discussed with these gravitational-wave user communities. Offline analyses are then performed over a longer timescale, taking advantage of improved calibration of the data and additional information regarding data quality, giving refined parameter estimations for the astrophysical source of gravitational waves.

The LVC releases both public segments of gravitational-wave strain data around validated discoveries (when those discoveries are published individually or in a catalogue), and entire gravitational-wave datasets of an observation run. The release of the entire dataset occurs after a period of internal use to validate and calibrate the data (the current policy consists of releasing every 6 months, in blocks of 6 months of data, with a latency of 18 months from the end of acquisition of each observing block). The main data products are the gravitational-wave strain arrays, released as time series sampled at 16384 Hz. The gravitational-wave data are publicly accessible through the Gravitational Wave Open Science Center (GWOSC), together with data-quality information essential for the analysis of LIGO and Virgo data, documentation, usage guidelines, tutorials, and supporting software.

The Virgo collaboration is taking a large step in moving from dedicated resources for offline analyses to the common International Gravitational Wave observatory Network (IGWN) distributed computing infrastructure, shared with LIGO and KAGRA, and incorporating new Computing Centres in the network. By defining a common architecture and uniform interfaces, based on widely used mainstream tools, it is possible to improve reliability and at the same time reduce the maintenance burden in all computing domains: online, low-latency and offline. This also helps widen the set of computing resources that can be exploited. Supporting services, such as the ones comprising the low-latency infrastructure that generates and distributes public alerts for multi-messenger astronomy, are being deployed in Europe to complement the ones managed by LIGO for flexibility and redundancy; a priority will be to gain expertise in modern service management technologies, also leveraging on support from Computing Centres to streamline the deployment and operation of such services, with the final aim of exploiting as much as possible shared resources and services through the European Open Science Cloud.

While the scientific responsibility of the Virgo detector is assumed by the Virgo collaboration, the European Gravitational Observatory, EGO, funded by the CNRS and INFN (as of 2021, also the Nikhef Laboratory becomes an official member) has the purpose of promoting research in the field of gravitation in Europe. EGO ensures the functioning of the Virgo antenna, its maintenance, its operation and the improvements to be made, the maintenance of the related infrastructures, including a computer centre, and it promotes open cooperation in R&D, the maintenance of the site, the co-operation in the field of experimental and theoretical gravitational-wave research in Europe, contacts among scientists and engineers, the dissemination of information and the provision of advanced training for young researchers.

Einstein Telescope

Einstein Telescope (ET) is a new scientific infrastructure project that will maintain Europe at the forefront of the emerging field of gravitational-wave astronomy, representing one of the most promising new developments in our quest to understand history and future of the universe.

ET is the proposed European ground-based gravitational-wave detector of the third generation. It builds on the experience gained with the Virgo detector. ET will have a triangular shape, corresponding to three nested interferometers, where the arm length is increased to 10 km (compared to 3 km for Virgo and 4 km for LIGO). ET will be built a few hundred meters underground. The triangular shape will give an isotropic antenna pattern, the possibility of localizing the signal with one observatory and fully resolving both gravitational-wave polarizations. The underground configuration reduces terrestrial gravity noise and seismic noise extending significantly the sensitivity toward low frequencies. In the entire frequency spectrum, the sensitivity of ET is expected to improve by at least a factor of ten compared to the design sensitivity of the second-generation instruments.

ET will make it possible for the first time to explore through gravitational waves the universe along with its cosmic history up to the cosmological dark ages, shedding light on the open questions of fundamental physics and cosmology. It will probe the physics near the black-hole horizon (from tests of general relativity to quantum gravity), help understanding the nature of dark matter (such as primordial BHs, axion clouds, dark matter accreting on compact objects), the nature of dark energy and possible modifications of general relativity at cosmological scales. Exploiting the ET sensitivity and frequency band, the entire population of stellar and intermediate-mass black holes (up to 10^3 Mo) will be accessible over the whole epoch of the universe, enabling us to understand their origin (stellar versus primordial), evolution, and demography. ET will observe the neutron-star inspiral phase and the onset of tidal effects with a high signal-to-noise ratio providing an unprecedented insight into the interior structure of neutron stars and probing fundamental properties of matter in a completely unexplored regime (QCD at ultra-high densities and possible exotic states of matter). The excellent sensitivity extending to kilohertz frequencies will allow us to probe details of the merger and post-merger phase. ET will operate with a new innovative generation of electromagnetic observatories covering from the radio to the high-energy bands (such as the Square Kilometer Array, the Vera Rubin Observatory, E-ELT, Athena, CTA). Formation, evolution and physics of binary systems of compact objects in connection with kilonovae and short gamma-ray bursts will be studied along with the star formation history and the chemical evolution of the universe making it possible to understand the universe enrichment of heavy elements and the physics and structure of relativistic jets. ET will produce samples of gravitational-wave detections statistically significant to make precise Hubble-Lemaitre constant measurements able to break the degeneracies in determining other cosmological parameters obtained by Cosmic Microwave Background (CMB,) Supernova Type Ia (SNIa) and Baryonic Acoustic Oscillations (BAO) surveys. ET is expected to detect the gravitational-wave signals from core-collapse supernovae, isolated neutron stars, and the stochastic background.

ET is included in the ESFRI Roadmap 2021 as a new research infrastructure in progress towards implementation. About 41 agencies and institutions have already signed the ESFRI Consortium agreement as proposers of the ET project, and the governments of Italy (as a leading country), Belgium, France, The Netherlands, Poland and Spain have given official support for the ET project. Two candidate sites are under investigation: one in Sardinia and one in the Euregio Meuse-Rhine. Site-characterization studies are underway towards a site selection, which is expected for 2024. The evaluation of the sites must consider the feasibility of the construction and predict the impact of the local environment on the detector sensitivity and operation.

In the 2040s ET is expected to be complemented by the Cosmic Explorer in the USA to operate as a network which will further increase discovery potential and improve the sky localization. The envisaged start of ET's operational phase in 2035 is also very well matched to ESA's LISA space mission which aims at studying gravitational waves at lower frequencies.

The gravitational-wave community, currently including about a few thousand scientists, is the targeted primary user community of ET. ET is expected to be one of the major players in multi-messenger astronomy providing alerts of gravitational-wave transient events (with a detection rate of the order of 10^5-10^6 events per year) almost in real-time to the astronomical and astroparticle community for the electromagnetic and neutrino follow-up. Observers and theoretical physicists, from different communities will be the primary beneficiaries of the ET transient alerts and data. Based on the science goals, ET data will be relevant for astroparticle physicists, cosmologists, scientists working on general relativity, fundamental physics, nuclear and particle physics, and astrophysicists. Precision gravity measurements and environmental studies will benefit from collaborations with geophysicists. From the experimental side, the optoelectronic technology in gravitational-wave detectors requires collaboration with experts on quantum sensors and optics.

Some of the ET enabling technologies are based on developments made for the upgrade of the advanced detectors (the so-called aLIGO+ and AdV+ phases). For example, the high-power fibre lasers, the low dissipation coatings, the thermal compensation systems, the heavy mass silica mirrors and suspension systems, the improved squeezed sources and quantum filter cavities, the gravity noise subtraction sensors and methods. In addition, some new technologies, currently not implemented in the advanced gravitational-wave detectors, are needed: the silicon test masses and silicon suspensions, coatings for cryogenic temperatures, low-noise cryogenic systems and cryogenic suspensions, different wavelength optics and optoelectronics. It is crucial to guarantee enough resources to all the institutions involved in ET for all these fields of research.

In the multi-messenger context, ET will be part of the globally coordinated multi-messenger ground-based and space-born resources and will provide public alerts. ET will be able to operate in synergy with other 2G and 3G gravitational-wave observatories (such as AdVirgo/LIGO/KAGRA/LIGO-India, LISA and Cosmic Explorer), to increase the number of detections and improve sky-localisation for multi-messenger follow-up, including providing real-time alerts. The computing resources, software and infrastructures needed to rapidly acquire, analyse and interpret gravitational-wave data will be built on the invaluable experience acquired by the Virgo/LIGO community currently involved in the low-latency alert process. The higher detection rate (for binary neutron-star mergers is expected to be one event every 10 minutes) and the added complication of overlapping signals will certainly require infrastructures for the low-latency detection and distribution far more complex than the current one but still within the technical possibilities ten years from now. Most of the analyses will take place off-site on shared e-infrastructures, and high-reliability service deployments on Cloud infrastructures will provide the alert generation system with the needed resilience.

Open access and long-term preservation will be managed by implementing an OAIS-compliant archive, based on the ISO 13721 standard (Open Archival Information System). After a predefined grace period, validated processed data will be released under an appropriate open licence, most likely in the context of some wider Open Science initiative such as the heirs of current Virtual Observatory projects and GWOSC. Usability will thus be ensured by releasing the software needed to access it with an Open Source licence. All data and metadata formats, along with all required software, will be thoroughly documented, applying FAIR principles and enabling researchers from outside the collaboration, science practitioners and students to profitably exploit the data. Final scientific results, and relevant supplementary data where needed, will be published whenever possible in Open Access journals, archived and indexed in trusted repositories.

LISA

It has been about three years since the LISA mission proposal was selected by ESA in response to a call for missions to implement the scientific theme, “The Gravitational Universe,” making LISA the third large mission planned for ESA’s Cosmic Vision Programme. The proposed mission uses laser interferometry to measure changes in the proper distance between widely separated (millions of km) free-falling test masses. Three spacecraft, each containing 2 free-falling test masses, form a triangular constellation of 6 interferometric links.

LISA will operate at lower frequencies (between 0.1 and 100 mHz) with respect to the ground-based detectors, opening the observation realm to heavier compact objects and compact objects lying in wider orbits. LISA is expected to observe a wide variety of gravitational-wave sources. These include the mergers of massive black hole (MBH, ~10^3–10^9 $M_\odot$) binaries, the extreme-mass-ratio inspirals (EMRIs) of stellar-mass black holes into MBHs, compact object binaries with hour-long orbital periods in the Milky Way, inspiral of stellar-mass binaries at the high end of the mass range probed by LIGO, Virgo, and ET and perhaps a stochastic gravitational-wave background produced in the early universe. These observations will permit a wide range of scientific investigations, ranging from learning about the population of galactic white dwarfs to probing the assembly of the MBH population and their stellar environments in the local universe to understanding the origin of MBH, and finally to tests of fundamental physics and probes of cosmology.

The majority of stars in the universe are found in binaries, and the endpoint of stellar evolution is the formation of a compact object, either a white dwarf, a neutron star or a black hole. If the binary survives the formation of the compact objects, then once the binary has decayed to the point that the orbital frequency is of the order of an hour, the binary will be generating gravitational waves at millihertz frequencies and may be observable by LISA. LISA is expected to resolve between five and ten thousand of these ultra-compact binaries, and also detect the astrophysical foreground from the unresolved population. Several such binary systems are already known through electromagnetic observations which are sufficiently close and at high enough frequency that the gravitational waves they are emitting will be quickly detected by space-based observatories. These “verification binaries” could play an important role in assessing the performance of the LISA mission.

The current understanding is that galaxies and massive black holes formed very early in the evolution of the universe. Galaxies have been found at redshifts greater than 10 and accreting supermassive black holes have been observed at redshifts greater than 7.5. Over cosmic history, galaxies merge and it is expected that, following such mergers, the massive black holes at their centres will also merge via gravitational-wave emission. Lower mass galaxies tend to have lower mass black holes in their centres, and as we look back to earlier times, we observe galaxies less massive than today, perhaps 10^4 to 10^7 solar masses. The merger of such systems will be in the millihertz range observable to space-based detectors. These lighter black holes are hard to observe electromagnetically and so there are several viable models for the formation of massive black hole seeds that are consistent with current EM observations. LISA observations will directly probe the first epoch of massive black hole (MBH) mergers and hence help to distinguish between these different models and shed light on the early growth of structure in the universe.

The massive black holes in the centres of galaxies are typically surrounded by clusters of stars. Stars in these clusters follow the usual evolutionary path, leading to the eventual formation of compact remnants. These galactocentric stellar clusters are dense, and the stars within them undergo frequent encounters which can leave these compact objects on orbits that pass very close to the central black hole. Such objects can become bound to the central MBH and gradually inspiral via the emission of gravitational waves. The ratio of the mass of the stellar-origin compact object to that of the central black hole into which it is falling is typically 1 to 10^5, so these events are called *extreme-mass-ratio inspirals* or EMRIs. Based on recent estimates, the number of EMRIs observed by LISA could be anywhere between 1 and several thousand per year. LISA will be able to track the phase evolution of EMRI signals over hundreds of thousands of orbits, which will provide very accurate measurements of the system parameters, as well as facilitate high precision tests on the predictions of general relativity.

Since the selection, ESA has followed standard mission development processes. The mission definition was established through a so-called Phase 0 study, with the Mission Definition Review being successfully passed in December of 2017. Following that, the mission moved into Phase A, the aim of which is to establish a clear set of mission requirements, starting from Science Requirements and flowing down to Mission Requirements, and on to instrument, spacecraft, and ground-segment requirements. Establishing these requirements, their rationale, and the links between them, set the scene for the following phases of mission development and forms the focus of the work during Phase A. In November of 2019, the mission passed a major milestone, the Mission Consolidation Review, which confirms the capability of the proposed baseline design to meet the mission requirements. Throughout this period, several key technologies have been significantly advanced compared to the normal development process, partly due to the precursor technology demonstration mission LISA Pathfinder, which was successfully launched at the end of 2015 and operated until summer 2017 with great success, as well as follow up developments on various technologies.

In ESA missions, there is a transition point between the definition phase (Phase A and B1) to the implementation and operations phases (Phases B2/C/D/E). This transition point is called adoption and represents the point at which a prime industrial team, selected by ESA, begins the implementation of the mission. The path towards the adoption of the mission is dominated by two key aspects: to establish all key requirements and their interdependencies, and to do pre-development of all critical units up to what is called Technology Readiness Level 6. This means that a number of units have to undergo prototyping and development to confirm the capability to provide the necessary functionality and to demonstrate key performance aspects under the expected environmental conditions. A number of these critical units have already been identified, and a number of developments are already well underway in the Consortium, ESA and NASA. By the end of Phase A, a solid development plan will have been established, and all critical units will have been identified, paving a clear path towards the mission adoption.

Recently, two significant changes have taken place with regard to the definition of science requirements. LISA's performance requirements are now defined in the frequency range 0.1 mHz to 1 Hz whereas the prior studies of mission performance specified requirements in the 0.1 mHz to 0.1 Hz frequency band, with a goal performance over an extended frequency range from 20 μHz to 1Hz. While the system expects to make scientifically-relevant measurements down to 20 μHz and below, achieving the performance at 0.1 mHz is sufficient to secure the stated science goals of the mission and will simplify the verification process. The duration of the baseline science mission is also being examined to ensure the amount of accumulated science data is sufficient to achieve the science objectives. The overall mission duration and the science operations duty cycle are being explored to arrive at a baseline for the mission. Based on current estimates of the observing duty cycle, a baseline mission of 6 years would be adequate to fulfil all of the science objectives. Regardless of the outcome of this study, the mission will be designed with consumables to allow a total science mission (baseline + extension) of 10 years.

Programmatically, progress is being made in finalizing the share of hardware responsibilities between ESA, its member states, and NASA. A coordination meeting between ESA and the delegations from its member state took place in December 2019 and has consolidated the share of responsibilities for key items on the European side. Senior officials from ESA and NASA HQ regularly discuss the LISA collaboration as part of their collaboration meetings. In addition to discussion of hardware responsibilities, the LISA partners are actively discussing the share of responsibilities for the analysis and interpretation of the data as well as the policies for accessing and distributing the scientific data amongst the partners and the broader community.

Over these three years, the LISA Consortium, which is an international collaboration of scientists and engineers, has been focused on the management and development of certain deliverable elements from the European National Space Agencies, ESA and NASA, which range from hardware units of the LISA instrument, through data analysis pipelines, computing infrastructure and data products. The proper definition of these deliverable elements, as well as the planning for their delivery, is another essential part of the Phase A process. NASA is a junior partner working with ESA on the development and implementation of LISA by contributing to certain hardware elements as well as ground-segment and science expertise.

The LISA Consortium now has more than 1300 members arranged in an active set of working groups and is holding regular full-collaboration meetings at a rate of about two per year. In addition to the instrumental work conducted by the LISA Instrument Group, the LISA Data Processing Group is formulating the architecture for the complex data processing chain that will take data telemetered from the spacecraft and transform it into science products. The LISA Science Group continues to refine the scientific applications of the mission and is providing critical analysis support for trade studies such as the bandwidth and lifetime studies mentioned above. LISA data challenges are helping to clarify the search algorithms, signal processing requirements, and realistic science deliverables of the mission.

The field, Europe’s role, and APPEC

Gravitational-wave astronomy is a recent and strongly emerging field, which made it possible to probe the most energetic transients in the universe, such as the merging of binary systems of black holes and neutron stars, revealing the physics governing these events impossible to be accessible through electromagnetic or particle observations. The impact of the LIGO-Virgo observations on fundamental physics and astrophysics is impressive and represents only the beginning of this new exploration of the universe. The upgrades of the current detectors will enlarge the detectable universe bringing new discoveries. The next generation of gravitational-wave detectors is expected to trigger revolutions in astrophysics, cosmology and fundamental physics; the Einstein Telescope will make precise gravitational-wave astronomy possible and will probe all the distance scales back to the early universe and LISA will open a new frequency window, making detectable for the first time the gravitational-wave emission from other astrophysical sources.

The role of the European community in gravitational-wave astronomy is well-established. More than one hundred European institutions are involved in the development, operation, and data exploitation of the Virgo interferometer. Since 2007 Virgo and LIGO have been operating as a network, based on full data sharing and joint publications. Recently, KAGRA also has joined the network. Within the LIGO and KAGRA collaborations (LVK), Virgo groups hold leadership roles in hardware developments, data analysis and interpretation. Furthermore, the Virgo community has built a tight collaboration with the European astronomical, astrophysical and neutrino communities, increasing the potential of the success of the multi-messenger effort. ET will keep Europe at the forefront of gravitational-wave observations. The ET consortium is currently composed of 41 institutions spread over 10 countries in Europe. There is already a broad ET scientific community that is expected to expand in the next few years. LISA has entered a phase of a more detailed study and will be proposed for adoption by 2023, after which construction can begin.

Support from APPEC for building the bridge among second and third-generation detectors is important to maintain the European expertise and leadership in the field up to when ET will start observations. APPEC support for ET being inserted in the ESFRI roadmap, to enlarge European countries' participation, and to acquire funds for the construction and observatory operations is vital. APPEC support is also important for helping the building and development of the ET scientific community, involving and training students and early-career researchers. APPEC should also support the LISA mission, as one of the Cosmic Vision 2015-2025 missions in the portfolio proposed by the European space science community.

6. Dark Matter

2017-2026 Strategy Statement

Elucidating the nature of Dark Matter is a key priority at the leading tip of astroparticle physics. Among the plethora of subatomic particles proposed to explain the Dark Matter content of our Universe, one category stands out: the Weakly Interacting Massive Particle (WIMP). WIMPs arise naturally, for instance, in supersymmetric extensions of the Standard Model of particle physics. Many experiments located in deep-underground laboratories are searching for WIMP interactions. For masses in excess of a few GeV, the best sensitivity to WIMPs is reached with detectors that use ultrapure liquid noble-gas targets; such detectors include XENON1T (using 3.5 tons of xenon) and DEAP (using 3.6 tons of argon). A suite of smaller-scale experiments is exploring, in particular, low-mass WIMPs and other Dark Matter hypotheses such as those based on dark photons and axions.

APPEC encourages the continuation of a diverse and vibrant programme (including experiments as well as detector R&D) searching for WIMPs and non-WIMP Dark Matter. With its global partners, APPEC aims to converge around 2019 on a strategy aimed at realising worldwide at least one 'ultimate' Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.

Introduction

The quest to elucidate the nature of Dark Matter has been a major theme in particle and astroparticle physics for some decades. The intensity of this search has only been increasing over this period. The basic search modes are to produce and subsequently to detect candidate Dark Matter particles at high energy accelerators, which is in the realm of particle physics or to detect Dark Matter particles that are roaming the universe. The latter is the domain of astroparticle physics and can be divided again into two approaches. The Direct Dark Matter Detection targets the interaction of Dark Matter particles with the standard model matter that we build detectors from. Indirect detection of Dark Matter looks for the signatures of the standard model particles that may result from the annihilation of Dark Matter particle pairs.

Developments since 2017

New developments since 2017 include the following:

Scientific Input to Develop APPEC's Dark Matter Strategy

APPEC has charged a specialist committee to review the experimental programmes of direct detection searches for particle dark matter, taking into account European efforts in the context of worldwide activity in the field. The report has been adopted by the APPEC GA in its March 2021 session, following consultation with the community, which broadly supported it. Its recommendations form the basis of APPEC's strategy aimed at realizing the next generation of Xe and Ar experiments.

The 2019 European Strategy for Particle Physics Update has recently concluded a broader review of connections between collider- and accelerator-based searches for dark matter, direct detection, and astrophysical detection. The Physics Briefing Book highlights the rapid proliferation of experimental strategies to search for dark matter across a very broad mass and coupling range and their growing interconnections. The 2019 ESPPU identifies a strong complementarity and synergy between direct dark matter detection experiments, under the auspices of APPEC, and the programme for its production and discovery in accelerator-based experiments. CERN support for direct dark-matter searches based on technologies for which CERN has expertise could deliver a decisive boost to their sensitivity.

Scientific Advances in Direct Detection Experiments

Since the 2017-2026 APPEC Strategy was published, sensitivity in direct detection has advanced by more than an order of magnitude over the dark matter mass range of 1-1000 GeV. At present, direct detection searches have excluded spin-independent dark matter-nucleon cross-sections as low as 10^{-46} cm^2, and spin-dependent cross-sections as low as 10^{-41} cm$^{2.}$ The leading results in the 5 GeV range come from the DarkSide-50 LAr TPC low-mass search and in the 1 GeV range from the CRESST cryogenic solid-state detector. At higher masses, the leading constraints are from cryogenic liquid Xe experiments, led for the past decade by the pioneering XENON programme at LNGS. There has also been the first independent test of the DAMA annual modulation signal on NaI, by the COSINE experiment, which will approach decisive sensitivity in the next few years.

The next generation of experiments using Xe have been built, or are under construction. The PANDA-X, XENONnT and LZ experiments will come online in 2020-2021, with liquid xenon active target masses of 4-7 tonnes. Projected sensitivities of these near-future direct detection dark matter searches reach 10^{-48} cm^2 scale sensitivity at 30 GeV dark matter mass. The global argon dark matter community has joined to form the Global Argon Dark Matter Collaboration, which is building the DarkSide-20k experiment with 50 tonnes of active liquid argon target, planned to start operation in 2023. The DarkSide-20k experiment expects to reach the 10^{-47} cm^2 scale at 1 TeV. Longer-term future searches using Xe (DARWIN) and Ar (Argo) project to reach beyond 10^{-48} cm^2 in the next decade. For spin-dependent interactions, near-term future experiments using Xe and CF3 targets project to reach sensitivity to 10^{-42} cm^2 WIMP-neutron and WIMP-proton cross-sections, at 50 GeV. At low mass (around 1 to 10 GeV), solid-state experiments, e.g., SuperCDMS, expect to achieve 10^{-42} cm^2 cross-section reach on a 5-year time scale.

Growth of Sensitivity to Dark Matter Candidates Other than WIMPs

The search for ultralight dark matter particles like the axion has gained significant momentum. Axion-like particles (ALPs) would arise as a consequence of one solution to the strong CP problem: why QCD appears to preserve CP symmetry. The axions or axion-like particles could be detected directly in dedicated experiments, or produced in the laboratory in prospective light shining-through-wall experiments. A detailed account of the various scenarios and relevant experimental programmes is presented in the ESPPU Briefing Book. A milestone for the field has been achieved by the ADMX experiment, which in 2019 reached sufficient sensitivity to probe the Peccei-Quinn axion coupling regime for masses of ~micro-eV. Since the 2017-2026 APPEC strategy, a significant number of small scale experiments have been initiated to search for ALPs over relatively narrow mass ranges, and major new efforts have been initiated to search with broad-band sensitivity, e.g., BabyIAXO, MADMAX and ALPSII. For example, the full IAXO programme aims to increase the broad-band sensitivity to ALPs in the micro-eV to eV mass range by more than an order of magnitude beyond current results.

The other major area of growth is searches for new kinds of dark matter interactions, e.g., vector interactions of hidden-sector particles, across accelerator-based, direct detection and astrophysical searches. The main phenomenology in direct detection searches is that these interactions may produce electron final states. There has been a significant advance in direct detection searches for new vector particles across the 1-100 keV range in noble liquids, and in the 0.1-1 GeV range in cryogenic bolometer and Si-based searches, reaching cross-sections of 10^{-36} - 10^{-38} cm^2.

Scientific Advances in Detection Techniques

Expanding the range of dark matter candidate masses accessible in experiments has driven new connections between astroparticle physics and quantum sensor technology. This is a focus of new funding initiatives in Europe (e.g., the UK Quantum Technology for Fundamental Physics programme) and in the US (see, e.g., the recent DoE Basic Research Needs report). Non-destructive measurements using quantum sensing metrology tools has led to a step-change in noise reduction in Si detectors searching for vector dark matter interactions, e.g., the SENSEI experiment, recognized with the 2021 Breakthrough Prize. In the sub-eV regime of wave-like dark matter, major new experiments are proposed based on using quantum sensors to probe atomic interferometers (e.g., MAGIS, AEON). Such experiments also target gravitational-wave sensitivity in the mHz-Hz frequency regime.

The field, Europe’s role, and APPEC

Recommendation 1 of the APPEC Dark Matter Report in 2021 affirms that “the search for dark matter with the aim of detecting a direct signal of dark matter particle interactions in a terrestrial detector should continue to be a top priority in astroparticle and particle physics, as a positive measurement will provide the most unambiguous confirmation of the particle nature of dark matter in the universe.” This aligns strongly with the strategy set out in the APPEC 2017 Roadmap. The European community should aspire to retain its global leadership role in dark matter direct detection, underpinned by the pioneering LNGS programme, with the aim of realizing worldwide at least one ‘ultimate’ xenon (of the order of 50 tons) and one argon (of the order of 300 tons) dark matter detector, as advocated by the DARWIN and ARGO proponents, respectively. We strongly endorse the recommendations of the 2021 APPEC Dark Matter Report that “the experimental underground programmes with the best sensitivity to detect signals induced by dark matter WIMPs scattering off the target should receive enhanced support to continue efforts to reach down to the so-called neutrino floor on the shortest possible time scale.”

Given the broad parameter space for dark matter candidates, a diverse experimental and theoretical approach remains important. As recommended in the 2021 Report, “European participation in DM search programmes and associated, often novel R&D efforts, that currently do not offer the biggest improvements to sensitivity should continue and be encouraged with a view of a long-term investment in the field and the promise of potential interdisciplinary benefits.”

The 2021 Report recommended several structural activities that APPEC should undertake to help the field; these include (i) establishing coordinated programmes for dark matter detector development in Europe, similar to the AIDA programme that has stimulated developments across accelerator-based detector R&D; (ii) encouraging continuing dedicated and diverse theoretical activity in this area; and (iii) exploring the formation of a distributed *European Laboratory of Underground Science,* leveraging the synergies of the underground laboratories.

7. Neutrino properties

2017-2026 Strategy Statement

Neutrino masses and nature: Despite all previous efforts, some of the neutrino's very fundamental characteristics remain unknown. Notably, these include neutrino mass and whether the neutrino is its own antiparticle or not (in other words, whether it is a Majorana-type particle or a Dirac-type particle). Both of these issues can be explored by studying the beta decay of selected isotopes. Single-beta decay allows direct kinematical inference of neutrino mass; first results from the world-leading KATRIN experiment in Germany are eagerly awaited. The double-beta decay of, for instance, germanium, tellurium or xenon, meanwhile, is used to probe physics beyond the Standard Model in a unique way by searching for decays without neutrinos. This process is only allowed if neutrinos are Majorana-type particles and its observation would not only reveal the neutrino's nature and pinpoint its mass but also demonstrate violation of lepton number. Among the various experiments worldwide searching for neutrinoless double-beta decay, European experiments such as GERDA (focusing on germanium), CUORE (tellurium) and NEXT (xenon) are some of the most competitive.

APPEC strongly supports the present range of direct neutrino-mass measurements and searches for neutrinoless double-beta decay. Guided by the results of experiments currently in operation and in consultation with its global partners, APPEC intends to converge on a roadmap for the next generation of experiments into neutrino mass and nature by 2020.

Neutrino mixing and mass hierarchy: Neutrino oscillation – implying neutrino mixing and thus the existence of non-zero neutrino masses – was discovered by experiments with solar and atmospheric neutrinos and was awarded Nobel Prizes in 2002 and 2015. For precise determination of the intricacies of neutrino mixing – including the much-anticipated violation of matter/anti-matter symmetry in the neutrino sector, and the neutrino mass hierarchy – dedicated accelerator neutrino beams and neutrinos from nuclear reactors are ideal. With the Double Chooz concept, the Borexino liquid scintillator and the ICARUS liquid-argon time-projection-chamber technologies, Europe was a pioneer in this field and large-scale facilities are now envisaged in the US (the DUNE long-baseline neutrino experiment) and Asia (the JUNO reactor neutrino experiment); DUNE emerged after the first of a series of global neutrino physics strategy meetings co-initiated by APPEC in 2014. Together with the Hyper-Kamiokande proposal in Japan, DUNE and JUNO define the future of this field. Both DUNE and Hyper-Kamiokande will also incorporate unsurpassed and complementary sensitivities for low-energy cosmic messengers (e.g., supernova neutrinos) and for the much sought-after proton decay.

From a scientific perspective and as part of a global strategy, APPEC strongly endorses European participation in DUNE and Hyper-Kamiokande experiments – exploiting long-baseline neutrino beam facilities – as well as in the JUNO nuclear reactor neutrino experiment.

Introduction

This section follows up on the recommendations on *neutrino mass and nature* and *neutrino mixing and mass hierarchy* recommendations in the APPEC Roadmap 2017-2026. Since the appearance of the current strategy document, it has become apparent that mass, nature, mixing and mass ordering are not only theoretically but also experimentally closely related. Hence, the merging of the two subjects in this document.

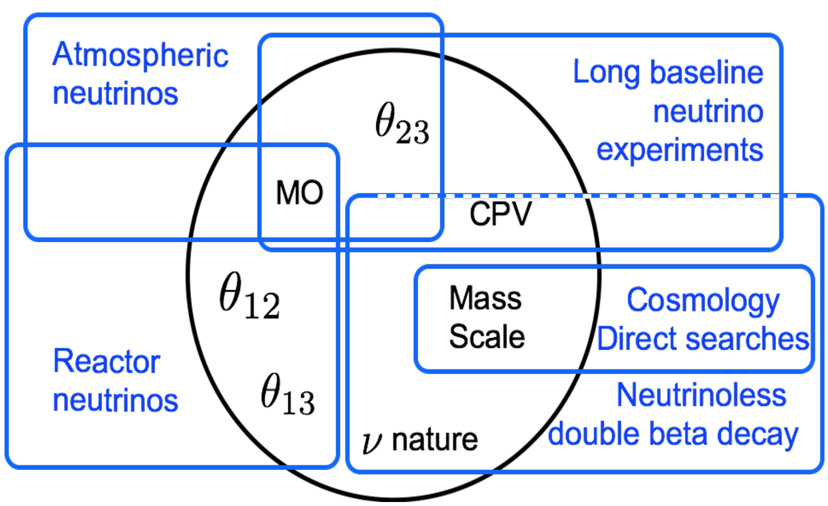
Two decades ago, the discovery of neutrino mass and leptonic mixing by neutrino-oscillation experiments opened a new window on physics beyond the standard model of particle physics.

Since then, a wide neutrino-oscillation experimental programme has provided an accurate picture of neutrino properties, with the precise measurement of two mass squared differences and of the three mixing angles which parametrise the leptonic mixing matrix. The two mass squared differences are tiny, around 7.4 x 10^{-5} eV^2 and 2.5 x 10^{-3} eV^2, implying (at least) 3 massive neutrinos. Differently from the quark sector, the mixing angles are quite large: θ_{23} is close to maximal and its value can vary between 39.6° and 51.8° at 3 sigma, θ_{12}~33° and θ_{13}~8° are measured at the ~2% level. The long-baseline neutrino-oscillation experiments in the current generation are providing a hint that the Dirac CP phase in the mixing matrix is not zero and indicate that its value might indeed be large. Recent neutrino-oscillation data show a preference for the normal neutrino mass ordering but at a lower level compared to previous indications.

Despite this impressive progress, several key questions remain unanswered. These are essential to uncover the physics beyond the standard model at the origin of neutrino masses and leptonic mixing. A key question concerns the nature of neutrinos - whether they are Dirac or Majorana particles and can be best, and in most cases, only addressed by neutrinoless double-beta decay. The absolute values of neutrino masses are also unknown and it is required to establish the neutrino mass ordering and the mass scale. The former can be attacked with several strategies, namely using neutrino oscillations in matter, in long-baseline accelerator and atmospheric neutrino experiments, and in vacuum, using reactor neutrinos, while information of neutrino masses can be gathered by three complementary means: direct mass searches, neutrinoless double-beta decay and cosmology, offering unique synergies. The presence of leptonic CP violation, the precise measurement of all mixing parameters, in particular, the Dirac CP phase and θ_{23}, and the test of the 3-neutrino mixing paradigm are also fundamental issues and several neutrino-oscillation experiments are undergoing or under construction to answer them.

The experimental programme has been supported by a very strong theoretical effort both in neutrino phenomenology and theory. In phenomenology, the focus has been and continues to be on fully exploiting the information coming from current experiments and on exploring the physics potential of future ones, helping to shape the future experimental programme. Research in neutrino theory aims at understanding the origin of neutrino masses and mixing and the connection between neutrinos and other key aspects of the physics beyond the standard model, such as the baryon asymmetry of the universe, dark matter, light wonders dark sectors, and new physics from very low to TeV to GUTs scales. The strong connection to particle physics, cosmology and astrophysics is being pursued, e.g., concerning the role of neutrinos in the early universe and to high-energy cosmic rays. Europe has played a leading role in all these lines of research and continues to do so and hosts the majority of the community active in this field.

The figure on the right depicts the complementarity of current/future different experimental approaches for the determination of the neutrino parameters, assuming standard three-neutrino mixing. Tests of this standard three-flavour scenario, though important, are not shown and are carried out exploiting this programme as well as dedicated searches such as short-baseline neutrino-oscillation and beam dump experiments. The role of astrophysical neutrinos is relevant and complementary but has not been depicted in the figure.



Developments since 2017

There is a broad ongoing experimental program in all these areas with a wealth of data becoming available now and expected in the coming years. The breadth is necessary to tackle the different questions to build a complete picture and to approach them in complementary ways. These multiple approaches also offer unique synergies, which strongly enhance the information which can be inferred from these experiments. Examples are, e.g., the search for leptonic CP violation due to the Dirac CP phase, whose current hints come from the combination of long-baseline and reactor neutrino-oscillation experiments, the hunt for Majorana CP-violation, a particularly elusive question that requires a very precise determination of the effective Majorana mass parameter in neutrinoless double-beta decay, direct neutrino mass determination, the combination of information on the neutrino mass ordering from oscillation experiments, neutrinoless double-beta decay and cosmology, and many others. Importantly, any incompatibility between results in different strategies would be an indication that there exist new physics beyond standard 3 neutrinos, for example, sterile neutrinos, new interactions, or even more exotic scenarios. Current and future large multipurpose neutrino experiments offer also a unique opportunity to search for proton decay. A report on neutrino physics by IUPAP is currently in the final stages of preparation and will provide a broad overview of the key science of the field.

Neutrinoless double-beta decay

The nature of neutrinos, whether they are Majorana or Dirac particles, is intrinsically connected to lepton number conservation. This symmetry arises accidentally in the SM and it is not known if it is a fundamental symmetry of nature. It plays a key role in the mechanism at the origin of neutrino masses, e.g., in the see-saw type I models, and of the baryon asymmetry of the universe via the leptogenesis mechanism. To test this symmetry and establish the nature of neutrinos, it is necessary to search for processes that break lepton number, the most sensitive of which is neutrinoless double-beta decay. In this process, two neutrons simultaneously decay into two protons and two electrons, with no neutrino emission. In the simplest case of light neutrino exchange, the lifetime is controlled by the effective Majorana mass parameter but other LNV mechanisms can also mediate this process at testable levels. In the case of a discovery, a key question will be the determination of the underlying mechanism and the extraction of information on the particles and interactions involved. Specifically, in the case of the light neutrino exchange, it will be possible to extract information on the neutrino masses.

There is a vibrant and diverse experimental program worldwide in which Europe has achieved a recognised leadership and obtained an outstanding track record through its most prominent contributions to many experiments (CUORE/CUPID, GERDA/LEGEND, NEXT, NEMO-3/SuperNEMO). Plans to enhance the sensitivity are being put forward in Europe, America and Asia and aim to completely cover the inverted neutrino mass ordering, corresponding to an effective Majorana mass above 15 meV, while maintaining a discovery potential also for sufficiently large masses for the normal ordering.

Given the scale and cost of future experiments, it is widely recognised that a consolidation of the international effort is required. The APPEC SAC tasked the APPEC DBD subcommittee to review the theoretical and experimental situation and prepare a strategy for the European effort. The committee prepared a report, which was reviewed by APPEC SAC, discussed with the community and endorsed by the APPEC GA in summer 2020. Its main recommendations concern the key importance of this search in modern particle physics, which warrants a significant investment in this very fertile research area with significant discovery potential. It was pointed out that, due to the challenges posed by the unprecedentedly low background requirements, it is vital that several isotopes and experimental techniques are employed to search for this process. A strong emphasis was put on the connection with NuPECC in relation to the computation of the nuclear matrix elements, essential to extract information on the underlying physics model and which still suffer from very large uncertainties.

The best achievable sensitivity to 0νββ-decay rate is the primary goal of each experiment and depends mainly on the number of decaying nuclei, the background rate, and the energy resolution in the region of interest. Next-generation experiments aiming at the discovery of 0νββ-decay or at least to explore neutrino mass ranges below those expected with inverted mass ordering require large masses of the order of ton scale, very good energy resolution and, particularly, a very low background rate, of the order of 10^{-2} cts yr^{-1} ton^{-1} in the ROI. Such numbers may be obtained, in principle, with several complementary techniques. The best isotopes are Ge-76, Mo-100, Te-130 and Xe-136. It is important to underline that a convincing discovery of 0νββ-decay requires the observation of the decay in more than one nucleus. The observation of a single line at the right energy, while enormously exciting, would still leave open the possibility that it is a rare unknown nuclear line.

Ge-76 is the isotope of the GERDA, Majorana and LEGEND-200 experiments, and of the LEGEND-1000 proposal. The world-leading results obtained by GERDA-II with an excellent background rate of 3 cts yr^{-1} ton^{-1} in the ROI and the recent merging of the European and US members of the GERDA and Majorana collaboration into LEGEND-200 makes this option very strong both scientifically and programmatically. While LEGEND-200 is being set up at LNGS, the even larger experiment LEGEND-1000 is aiming to reach the goal of 10^{-2} cts yr^{-1} ton^{-1} in the ROI. The location of LEGEND-1000 is undefined yet.

Mo-100 is the preferred option of CUPID, the next-generation bolometric experiment in Europe. CUPID is a major upgrade of the CUORE experiment currently running at Gran Sasso. CUORE is made of Te-130 bolometers (230 kg active mass) with a background rate of about 160 cts yr^{-1} ton^{-1} in the ROI. While an upgrade of CUORE with Te bolometers is possible, the collaboration, in cooperation with several R&Ds performed in Gran Sasso and Modane, is considering to move to surface-sensitive Mo-100 bolometers, which may allow a ton scale experiment with a background index in the range of 0.1 cts yr^{-1} ton^{-1} in the ROI. The larger phase space of Mo-100 and the larger matrix elements may bring the sensitivity to new physics very similar to that of LEGEND-1000.

Te-130 will also be dissolved in SNO+ using a liquid scintillator as detector medium, an approach similar to that of KamLAND-Zen with Xe-136 (see below). KamLAND-Zen has produced very strong limits and results from SNO+ are expected in the next few years. However, the difficulty to obtain energy resolution comparable to those of crystals makes these options very good to provide limits but less convincing for being able to claim a signal.

Xe-136 is the preferred nucleus for KamLAND-Zen (dissolved in liquid scintillator), EXO-200 (liquid) and NEXT (high-pressure gas-TPC). It will also be the isotope of nEXO (under down selection at DOE with LEGEND-1000 in the next months) and of DARWIN (which aims at developing a very large detector for both dark matter searches and a rich neutrino programme, including 0νββ-decay and solar and supernova neutrino measurements). The NEXT option could provide an interesting avenue for the future, with the potential of offering a background-free experiment, and is currently at the level of 10 kg demonstrators.

As far as the international scenario is concerned, a key element is the US-DOE portfolio determination, currently in progress. LEGEND-1000, nEXO and CUPID will be part of the portfolio review at DOE. It is not known at the time of writing whether this portfolio review will select one single project or more than one. Being that the cost scale of CUPID is significantly smaller than that of the other two, the possibility that two projects are endorsed exists. LNGS is in principle ready to host CUPID, LEGEND-1000 and NEXT at Gran Sasso, but the funding and person-power scheme required to complete these three efforts over the next decade is far from being clear. As described later in the section on the Inventory of "central" infrastructures, the cooperation and the synergy among countries and underground laboratories in Europe (chiefly LNGS, Modane and Canfranc) is a key asset to try to complete such an ambitious program. LNGS has space for this, and the possibility to host one of the experiments re-using the existing Borexino infrastructure and reallocating LVD space is a possibility to be further investigated. Considering that CUPID could be installed in the CUORE cryostat, LNGS is working on the underground infrastructures to allow a suitable and efficient installation of another next-generation double-beta decay experiment.

It should be noted that depth is not yet a major problem for next-generation 0νββ-decay experiments. While cosmogenic-induced backgrounds (short-living isotopes and, chiefly, spallation neutrons) are an issue, active shielding, tagging techniques, and pulse shape analysis make the expected backgrounds for all these experiments still small.

For the future, the possibility to dissolve Te-130 or Xe-136 into the JUNO detector is being studied. The huge potentially achievable soluble mass and the expected very good energy resolution of JUNO make this long-term option very interesting.

In order to translate this sensitivity to Majorana neutrino effective mass (or to other physics mechanisms inducing 0νββ-decay), a precise knowledge of the nuclear matrix elements is required, which is particularly difficult because the large momentum transfer in 0νββ-processes cannot be directly tested in normal β- or 2νββ-decays. This relies on challenging calculations, with several approaches being currently used, and new developments with ab-initio calculations offering a promising avenue to explore. Data from specific experiments made with electronic, muonic or hadronic probes, such as those envisaged at CEBAF or NUMEN at LNS, offer important information to aid the progress in the theoretical calculations.

Neutrino masses

The measurement of two mass squared differences by neutrino-oscillation experiments indicates the existence of three massive neutrinos whose masses can be arranged in two manners: the normal mass ordering if $m_1 < m_2 < m_3$ and the inverted one if $m_3 < m_1 < m_2$. The mass scale is not yet known, allowing the lightest mass to be from nearly zero to close to the upper bound in the sub-eV range.

Experimental strategies for the determination of neutrino masses and their complementarity

The neutrino mass ordering can be established in neutrino-oscillation experiments which can measure their probability in matter both with accelerator and atmospheric neutrinos and in vacuum in medium-baseline reactor neutrino-oscillation experiments. It is expected that a discovery will be made by the end of the decade. These aspects will be discussed in the context of neutrino oscillations, see below.

Three main strategies have been devised to measure neutrino masses. Direct searches look for a deviation of the electron energy spectrum near its endpoint in beta decay (of the electromagnetic de-excitation spectrum of electron capture). This technique is not affected by theoretical assumptions on the nature of neutrinos and provides a model-independent measurement of an average of the neutrino masses. However, the sensitivity is limited at present above O(0.1) eV but several R&D projects are underway to improve this sensitivity. The second way to obtain information on neutrino masses relies on neutrinoless double-beta decay, requiring that neutrinos are Majorana and not Dirac particles. A positive signal would allow us to extract information on the neutrino mass ordering and possibly on the neutrino mass range, under the simplest assumption of the light neutrino mass exchange. The determination of neutrino masses from neutrinoless double-beta decay suffers from the lack of knowledge of the Majorana CP-violating phases and from the uncertainty on the nuclear matrix elements. The sum of neutrino masses can also be measured using cosmological observations, thanks to the significant impact that neutrino masses had in the evolution of the universe. In particular, they suppressed the growth of cosmological structures at relatively small scales due to their free streaming. These measurements require the assumption of an underlying cosmological model and that neutrinos undergo a standard evolution in the course of the universe. They provide the most precise determination of neutrino masses to date, with a limit for the sum of the masses around 0.1-0.3 eV, depending on the data sets and assumptions made.

The complementarity between these three techniques and the synergy among them and with the determination of the neutrino mass ordering is of particular importance. For instance, if the mass ordering were determined to be inverted in long-baseline neutrino-oscillation experiments, it would provide a clear target for neutrinoless double-beta decay experiments with discovery reach in the upcoming generation of experiments and for cosmology which would be able to detect the effects of neutrinos on the formation of large-scale structures in the universe. The combination of information from different approaches would also allow to extract further information on neutrino properties, e.g., on the Majorana CP-violating phases, and to test the underlying assumptions made, possibly uncovering non-standard effects in particle physics and/or cosmology.

Direct searches

The experimental frontier of the neutrino mass search is defined by the KATRIN experiment, which is investigating the endpoint region of tritium beta decay with unprecedented precision by a high luminosity windowless gaseous tritium source and a 10 m diameter spectrometer of MAC-E-Filter type of an energy resolution of about 1 eV. Latest KATRIN's result published in 2021 yields a new direct upper limit on the neutrino mass scale of 0.8 eV, improving the previous direct neutrino mass experiments by a factor of more than two. KATRIN is currently taking much more data and aiming for its design sensitivity of 200 meV on the neutrino mass scale expected to be reached in 2025. After its neutrino mass programme, KATRIN foresees a keV sterile neutrino search program with the TRISTAN detector.

The KATRIN approach, with a separated windowless gaseous tritium source and an integrating spectrometer of MAC-E-Filter type, has two limitations. First, the integrating MAC-E-Filter requires the beta spectrum to be scanned sequentially for determining its shape. Avoiding this will increase the statistics but requires an additional differential method, e.g., time-of-flight measurement or a bolometric detector. With such a method, KATRIN's sensitivity could be improved towards 100 meV. The second limitation is that the tritium source gets opaque if its longitudinal density is further increased. Therefore, the energy of the electron needs to be measured within the tritium source. Project 8 is addressing both limitations by using a gaseous tritium source in a solenoidal magnetic field as KATRIN but determining the beta electron energy by increasing their path inside the source by magnetic reflections and measuring the frequency of the cyclotron radiation of the stored electrons. Project 8 has demonstrated single electron spectroscopy by this CRES method (cyclotron radiation emission spectroscopy) and has presented a promising first tritium spectrum. Project 8's full design features a large volume atomic tritium source looked at by a huge array of radio antennas. It is aiming for a direct neutrino mass scale with a sensitivity of 40 meV.

Another direct approach to the neutrino mass is the investigation of the electromagnetic de-excitation spectrum after electron capture of Ho-163 with cryogenic bolometers. This approach requires arrays with tens of thousands of cryogenic bolometers to avoid pile-up because the whole spectrum is measured at once to reach a sub-eV sensitivity on the neutrino mass. The ECHo and HOLMES experiments are pursuing this approach aiming to reach a sensitivity in the 10 eV range soon, and a sub-eV sensitivity within the next 5 years.

Tritium beta spectroscopy near the endpoint offers another exciting possibility. The capture of electron neutrinos from the cosmic neutrino background will give rise to a monoenergetic electron with an energy corresponding to the endpoint energy plus the neutrino mass. This threshold-less inverse beta decay seems to be the only process having a reasonable chance to detect relic neutrinos in the not too far future. It has been shown that tritium (super-allowed beta decay, low endpoint energy) is the isotope of choice. Therefore, any high-resolution direct search for the neutrino mass with tritium is paving the way to detect relic neutrinos. The R&D project PTOLEMY is combining several methods of the previous and current beta decay experiments and combining it with new ideas with the goal to eventually detect relic neutrinos and ultimately measure neutrino masses independently of the mass ordering.

Neutrinoless double-beta decay

This process can provide information on neutrino masses as discussed above.

Cosmology

Information on the matter power spectrum can be obtained looking at the dark matter, e.g., via cosmic microwave background (CMB) and optical lensing, and galaxy/cluster distributions: Planck measurements of Cosmic Microwave Background temperature and polarisation anisotropies, the CMB lensing potential power spectrum, surveys measuring the Baryon Acoustic Oscillation, Lyα-forest data are typically used. The use of different (or a subset of) data sets allows to constrain the cosmological parameters entering in the underlying cosmological model, i.e., ΛCDM, breaking possible degeneracies. The resulting upper bounds on the sum of neutrino masses are 0.15-0.3 eV, taking more stringent or conservative assumptions. It should be noted that some tension is present in the data, in particular in relation to the different determinations of the Hubble constant via CMB and type-Ia supernovae, and to the amount of gravitational lensing observed by Planck compared to the ΛCDM predictions. The prospects for the future are excellent, thanks to several new experiments coming online in the near future, e.g., DESI, Euclid, CMB-S4 and many others. For the ΛCDM model, it may be possible to distinguish a normal from inverted ordering neutrino mass spectrum and detect the imprint of neutrino masses on the evolution of large-scale structures.

Neutrino-oscillation experiments

These experiments play a key role in determining the neutrino mass ordering and are the dedicated approach to measure the oscillation parameters. The field was opened with the discovery of the solar neutrino deficit by the Homestake experiment. For solar neutrinos, it has now reached a preliminary peak with the complete determination of all solar neutrino fluxes from the pp chain and the recent experimental discovery of CNO neutrinos by the BOREXINO experiment at LNGS. These recent results from BOREXINO were only possible due to the extremely low background of the experiment. Not only do they confirm earlier measurements with much higher accuracy, but they also show very nicely the transition between the solar electron neutrino suppression by neutrino oscillations in vacuum to matter-enhanced oscillation via the MSW effect. However, the detection of solar neutrinos in real-time will continue, e.g., with the planned dark matter search experiments ARGO and DARWIN, for example, to distinguish between low- and high-metallicity solar models or to determine the luminosity of the Sun by neutrinos with sub-percent accuracy.

The field was further boosted by the discovery of atmospheric neutrino oscillations. The study of reactor neutrino and long-baseline-accelerator neutrino propagation, together with a strong theoretical effort, brought the community to the current 3-neutrino mixing scenario.

We are now entering the precision era of neutrino oscillations, focusing on the determination of the neutrino mass ordering and the leptonic CPV (Dirac) phase. The current and future long-baseline neutrino-oscillation experiments focus on the subdominant muon to electron (anti)neutrino-oscillation probability. Leptonic CP-violation and the mass ordering via matter effects modify this probability depending on the energy and neutrinos vs antineutrinos, allowing to disentangle these effects. Large statistics and excellent control of systematic errors are required implying intense beams and large neutrino detectors with excellent capabilities. Current efforts are ongoing in the US and Japan with T2K and NOvA and an enhanced programme for the future, DUNE and T2HK, is underway. Europe was a pioneer in this field and provided an essential contribution to DUNE and to T2HK with the CERN Neutrino Platform. Dedicated atmospheric neutrino experiments, such as KM3NeT/ORCA in Europe, or the use of DUNE, Hyper-Kamiokande (HK), IceCube Gen-2 and INO detectors to study atmospheric neutrinos can also provide information on neutrino oscillations and, in particular, on the neutrino mass ordering. Complementary information on the latter as well as sub-percent precision on mixing angles can be achieved in medium-baseline neutrino-oscillation experiments. Finally, dedicated experiments at a short baseline are currently testing the three-neutrino paradigm, hunting for sterile neutrinos and other deviations. Future experiments can further advance this programme by exploiting the near detector complex and their intense neutrino fluxes “à la beam dump”.

Additional important information may come from precise measurement of Coherent Elastic Scattering (CENS) experiments. Recent detection obtained by the COHERENT collaboration is boosting the field and several experiments are under investigation.

The long-baseline neutrino-oscillation experiments DUNE and T2HK are under construction. They are based on high-intensity neutrino beams and with very large mass detectors. DUNE will exploit the features of the upgraded PIP-II accelerator, which will provide 1.1 10^{21} pot/year (including accelerator complex efficiencies). A large mass (20 kTon initially, 40 kTon in final configuration) liquid argon detector will measure with high precision charged current and neutral current muon and electron neutrino interactions. DUNE has a reach program beyond neutrino oscillations, including supernova neutrinos and searches for proton decay. Thanks to the relatively long baseline, it will be able to disentangle CP-violating effects from mass ordering effects through matter effects. T2HK will use the upgraded beam from JPARC to the new Hyper-Kamiokande (HK) detector, which will be made of two modules of 250 kTons of water. Both DUNE and T2HK may reach 5-sigma sensitivity in a few years of data taking if the CP phase is close to maximal. HK will have a superb sensitivity to proton decay and to supernova detection. Studies are ongoing for an EU-based future programme with the ESSnuSB, as well as for the about 2600 km baseline P2O experiment in which neutrinos are sent from Protvino (near Moscow) to ORCA.

Large neutrino detectors can be used to detect atmospheric neutrinos. They provide information on the value of the atmospheric mass squared difference, on its sign exploiting complex matter effects due to neutrinos traversing the Earth and on the mixing angles. Among the experiments that are being set up or planned to use atmospheric neutrinos for determining the neutrino mass ordering the most advanced is the KM3NeT/ORCA neutrino telescope in the Mediterranean Sea having 6 of 115 detector strings with 18 PMT spheres operational. KM3NeT/ORCA's goal is to finish the detector construction in 2024. Long-baseline neutrino detectors, in particular HK, will also observe atmospheric neutrinos with reduced sensitivity to the mass ordering. The physics reach depends critically on the value of θ_{23} and increases going from the first to the second octant.

Medium-baseline reactor neutrino experiments have measured the angle θ_{13} with excellent precision. The JUNO experiments will exploit a longer baseline to determine the neutrino mass ordering with a complementary strategy that does not require matter effects: The ultra-high-energy resolution of $3\%/\sqrt{E}$ of a 20 kt liquid scintillation in 53 km distance to 2 nuclear power stations will allow to measure the reactor neutrino energy spectrum with an unprecedented precision allowing to determine the neutrino mixing parameters θ_{12}, Δm^2_{21} and Δm^2_{31} with sub-percent precision. This enables determining the neutrino mass ordering with 2.5 to 5 standard deviations after 6 years of data taking. JUNO is expected to start data taking in 2022.

As neutrinos remain the most elusive and less known fermions of the standard model, it is essential to test the three-flavour paradigm. Deviations can take many forms, with sterile neutrinos being the simplest extension. Sterile neutrinos are singlets with respect to the interactions of the standard model and can mix with massive neutrinos. Their presence can explain neutrino masses, the matter-antimatter asymmetry of the universe and dark matter, depending on their mass scale and specific model. Neutrinos can also have other interactions, potentially leading to non-standard matter effects when they travel through media, and can even exhibit more exotic behaviours such as CPT violation, Lorentz violation, mass variation and others.

Although many of these effects are of speculative nature, the result of some experiments, chiefly LSND and a set of short baseline reactor experiments, cannot be explained by the standard three flavour oscillation paradigm. MiniBooNE also reports an unexpected excess of electron-like events at low energy. A possible explanation of these discrepancies (anomalies) is to invoke a larger neutrino sector including one or more sterile neutrino species weakly mixed with the known ones. A set of more precise measurements is needed to clarify whether this option is real or not or if a different explanation is required. A strong program with reactor experiments (baseline 10 m-50 m) and accelerator experiments (baseline ~1 km) is brought forward in several sites and laboratories, including the dedicated Short Baseline Program at Fermilab, which is based on the ICARUS detector.

Neutrino experiments and proton decay

Multipurpose neutrino experiments, such as Super-Kamiokande, JUNO, HK, DUNE, with large masses and excellent event reconstruction capabilities, allow us to search for proton decay. This extremely rare process is predicted in presence of the breaking of the baryon asymmetry at very large scales, as predicted in grand unified theories (GUT). The model-independent current limit on the proton lifetime is set by SNO+ to 5.8×10^{29} years, while the partial lifetime for many decay modes in standard model particles has been determined to be typically larger than 10^{34} years. The most sensitive channel is that of protons decaying into a neutral pion and a positron, for which Super-Kamiokande has set a limit of 1.6×10^{34} years. HK, DUNE and JUNO will be able to significantly improve on this and other channels in the future.

The field, Europe’s role, and APPEC

Neutrinos play a key role in our understanding of fundamental particles and interactions and of the evolution of the universe. Determining their interesting and often surprising properties (masses and mixing angles, CPV phases, mass ordering, particle nature, ...) requires a diverse and complementary worldwide programme, as well as a strong theoretical effort. Europe has been playing a crucial and often leading, role in this field both in experiments and theory. All European agencies and the whole APPEC community are deeply involved in this effort and particularly in the determination of the yet unknown neutrino properties and in the possible discovery of new physics. APPEC should help to coordinate and consolidate Europe's programmes and contributions.

The full determination of neutrino properties calls for several search strategies. A prime example of this complementarity between different approaches is given by the determination of the neutrino masses: direct neutrino mass searches, neutrinoless double-beta decay experiments and the exploitation of cosmological observations provide information on different combinations of the mass parameters. While the direct searches have reached sub-eV sensitivity, cosmological observations may directly see the imprint of non-zero neutrino masses on the universe within the next decade. Within a similar timeframe, neutrino-oscillation experiments will be able to discover the neutrino mass ordering with important implications for neutrinoless double-beta decay searches.

Neutrino-oscillation experiments have entered a precision era concerning leptonic mixing parameters starting to supersede the precision of the CKM quark mixing matrix. In addition to the question of the neutrino mass ordering, those experiments are going to determine the Dirac CPV phase, which may have a strong connection to the puzzle of the baryon asymmetry of our universe. Europe plays a leading role in several of the next-generation neutrino-oscillation experiments, both with the European hosted ORCA detector, as well as with experiments that are being currently built in North America and Asia (DUNE, Juno and T2HK).

The new generation of neutrinoless double-beta decay experiments will explore the full inverse mass ordering parameter region with the potential for discovery of the Majorana particle nature of neutrinos and the violation of lepton number. Thus, the discovery of neutrinoless double-beta decay would provide a paradigm change in the understanding of the fundamental laws, establishing that, contrary to what is predicted by the standard model of particle physics, lepton number is not a conserved symmetry of nature. Europe has a long-established leadership in this field and should continue to strongly contribute to this experimental effort, hosting at the very least one of the next-generation experiments, in order to maintain this position.

Testing the standard 3-neutrino mixing paradigm and neutrino properties is a key physics goal of the programme: neutrinos are the least known of the standard model fermions and could act as a portal to new physics, e.g., dark sectors. In addition to the dedicated effort such as short baseline neutrino-oscillation experiments searching for sterile neutrinos, this goal can be pursued by exploiting other neutrino experiments in order to search for physics beyond the standard model, e.g., using accelerator neutrino facilities a la beam dump, and the new tool of measuring coherent elastic neutrino-nucleus scattering. Opportunities to carry out other searches for physics beyond the standard model at a low energy scale, e.g., light dark matter and dark sectors, should be further explored.

The determination of neutrino properties has a strong overlap with particle physics and with nuclear physics (e.g., with respect to nuclear matrix elements of neutrinoless double-beta decay, neutrino scattering cross-sections, evaluation of reactor neutrino fluxes). APPEC might play a role in facilitating synergetic activities across these fields.

Deep underground laboratories, such as LNGS or others, in Europe, are essential to pursue the programme, specifically in relation to the search for neutrinoless double-beta decay. APPEC supports a coordinated effort to host the experiments.

8. Cosmic microwave background

2017-2026 Strategy Statement

ESA's Planck satellite mission gave Europe a major role in space-based experiments in this field, while the US leads the way in ground-based experiments. Apart from better precision, the next generation of experiments primarily aims at trying to identify the tell-tale sign of cosmic inflation: the imprint of primordial gravitational waves on CMB polarisation modes.

APPEC strongly endorses a European-led satellite mission (such as COrE) to map the CMB from space. APPEC will encourage detector R&D towards a next-generation ground-based experiment complementary to initiatives in the US. APPEC continues to contribute to global coordination of this field following the Florence CMB Workshop series that started in 2015.

Introduction

While the Cosmic Microwave Background (CMB) has played a leading role in recent decades in transforming cosmology into a precision science and in defining the standard model of Cosmology, deeper observations hold the promise of still more fundamental science returns. On the one hand, large-scale polarization in the CMB may still have the imprint of Cosmic Inflation, and afford us a glimpse into the universe at the very beginning of the Standard Big Bang scenario. On the other hand, measurements of the CMB on smaller angular scales hold the promise of insights into Beyond Standard Model Particle Physics, with limits on the sum of neutrino masses, and detections or limits on particles that may have populated the universe in its early, hot phase.

Developments since 2017

The Cosmic Origins Explorer, or *COrE*, was submitted as an M5 mission proposal to the European Space Agency in 2016. As ESA had signalled the need for international partner participation at the level of 20%, a joint mission with JAXA was pursued but did not materialize. The technical and programmatic screening by ESA, before scientific review, concluded that (1) the mission profile and spacecraft design were mature but doubtful for the dilution cooler which was required for continuous operations; (2) There was Low Technical Readiness for certain payload elements (the Kinetic Inductance Device detectors and dilution cooler) which would have required immediate commitment of Member State funding for development; and that (3) the cost was above the M5 target and not recoverable by de-scoping options (ESA estimated over-cost ~200 M€). Plus, there was a risk of increased cost due to optimistic assumptions concerning the Science Operations Centre, and the success-oriented proposed schedule for reaching TR:5-6 by mission selection (~2 years) would require substantial Member State investment before mission selection.

So, while ESA's *Planck* satellite mission gave Europe a major role in space-based Cosmic Microwave Background experiments, this mantle has now been handed over to Japan, which recently approved the *LiteBIRD* mission. In terms of ground-based experiments, the US is leading the way with the South Pole Observatory (SPO), the Simons Observatory (SO) and longer-term efforts, such as CMB Stage 4 (CMB-S4). While Europe is now forging contributions to *LiteBIRD*, coordination in creating a plan for future small-scale CMB science in Europe is lacking.

LiteBIRD

In May 2019, the Institute of Space and Astronautical Science of Japan's Aerospace Exploration Agency selected *LiteBIRD* as its second strategic large mission.

The science goals of the *LiteBIRD* satellite are to detect primordial gravitational waves through a measurement of the tensor-to-scalar ratio, r, whose latest limit is $r \lesssim 4\times10^{-2}$ at 95% CL, and to characterize the CMB B-mode and E-mode spectra at the largest scales with unprecedented sensitivity. The mission targets a precision on r of $\sigma(r) = 10^{-3}$, after removal of foreground contamination and correction for systematic effects and leaving a margin, thus improving current limits by more than an order of magnitude. This defines the "full success" for the *LiteBIRD* mission and will be achieved using *LiteBIRD* data alone, allowing us to test the many slow-roll single-field inflationary models: for example, reject many φ^p models, or otherwise differentiate among many of the flat-top models. A successful detection, on the other hand, would determine the energy scale of Inflation, providing a key clue about physical laws at early times and extremely high energies.

In addition, *LiteBIRD*'s large-scale E-mode polarisation measurement will constrain the optical depth down to the cosmic variance limit, constraining reionization models and breaking degeneracies in the determination of other cosmological parameters, notably the total mass of neutrinos. *LiteBIRD* will also put constraints on spectral distortions of the primordial blackbody, test parity violation in the early universe, and constrain the physics of post-Inflationary reheating. From its vantage point at the second Sun-Earth Lagrange point, *LiteBIRD* will have access to the largest angular scales on the sky and to a broad frequency range, producing a unique data set which will complement others collected on a similar timescale by the next generation of ground-based experiments and producing a long-term legacy which will extend well beyond its stated science goals.

LiteBIRD design and construction are led by Japan with significant inputs expected from both North America and Europe. In Europe, a consortium of seven EU countries is developing plans to assemble and deliver *LiteBIRD*'s Mid-/High-Frequency telescopes, including hardware, electronics, calibration and testing, as well as large parts of the overall *LiteBIRD* simulation and analysis pipeline.

Ground-Based CMB

While *LiteBIRD* will address primordial science on the largest angular scales over the entire sky, there remains abundant science to be done on smaller angular scales, which are only accessible to large telescopes, which in turn can only be economically constructed on Earth. Upcoming large-aperture, ground-based CMB experiments are being designed to address science cases encompassing but not limited to, primordial gravitational waves as predicted from Inflation, relic particles including neutrinos, and Dark Energy and gravity on large scales. In addition to studying Cosmic Inflation on intermediate angular scales, these large CMB telescopes will search for new light relic particles and will shed light on the early universe 10,000 times farther back than current experiments can reach. They will set limits on the sum of the neutrino masses which will allow us to differentiate between the Normal and Inverted Hierarchies and to compare and confirm work from other branches of particle astrophysics.

The best currently developed sites on Earth for millimetre-wave observing are on the Atacama Plateau in the South American Andes and at the geographic South Pole. The design of most future experiments exploits key features of these two locations, namely the ability to drill deep on a single small patch of the sky through an extraordinarily stable atmosphere from the South Pole, and the ability to survey 70% of the entire sky from the exceptionally high and dry Atacama. Experimental efforts at these sites continue to grow and increase in sophistication.

The field, Europe's role, and APPEC

With different angular resolutions and frequency coverages, upcoming ground-based experiments and *LiteBIRD*, which should be taking data on the same time scales, are distinct and synergistic. Ground-based efforts target an Inflationary tensor-to-scalar ratio, or *r*, measurement on degree- and sub-degree- scale anisotropies (the recombination bump), while the *LiteBIRD* constraint on *r* will come from the largest angular scales, including the reionization bump. Moreover, combining the *LiteBIRD* and ground-based data sets from CMB experiments, as well as that from galaxy surveys, will bring further improvement in B-mode sensitivity by improving the correction for lensing, while improvements in measuring reionization will remove degeneracies on parameters determined at small scales. The ensemble of the data addresses a wide range of fundamental physics and cosmology and provides the redundancies necessary for confidence in the results.

One of the primary "lessons learned" from *Planck* was the importance of CMB foreground characterization and removal. A number of European post-Planck efforts address this, including low-frequency work with data from the C-BASS and SPASS telescopes that are pushing the study of polarized contaminants at low radio frequencies, and higher-frequency radio work, which continues at the well-developed Tenerife site in the Canary Islands. At still higher frequencies, millimetre and sub-millimetre dust modelling has long been a European forte, and the continued development of detectors for these frequency regimes should enable continued strength here.

While the largest CMB initiatives are being driven by teams in the United States and Japan, there are a handful of funded suborbital CMB experiments planned from Europe. LSPE will scan the sky in several bands from 40 to 270 GHz from both the ground and balloon, and QUBIC will be observing from the Argentine side of the Atacama with a novel bolometric interferometric system. On longer time scales, in both Europe and elsewhere, the search for spectral distortions in the CMB is regaining interest. Departures of the CMB energy spectrum from a pure black body encode unique information about the thermal history of the universe and can provide independent probes into BSM physics such as Inflation, dark matter (including axion-like particles), and primordial BHs.

APPEC endorses the European Space Agency's efforts to organize a significant contribution to the *LiteBIRD mission*, and encourages the CMB community in its continued efforts towards forging a program of large-scale inputs into the next generation of ground-based CMB experiments before the window of opportunity is closed. We emphasize that while Europe is forging plans for contributions to *LiteBIRD*, no commensurate effort exists for European participation in small-angular-scale CMB science, which includes large-scale structure science synergistic with that of Euclid (see the next section). This will leave Europe out of a large swath of Large-Scale Structure science and the quest for Inflation. APPEC has contributed to European coordination of this field through the Florence CMB Workshop series that started in 2015[14]. These meetings have helped incubate multiple European initiatives for contributing to SO, SPO, and S4, which have not yet come to fruition. These include (1) a proposal for a European Low-Frequency Survey to build upon the radio work mentioned above; (2) contributions to the large angular-scale effort on the Simons Observatory; and (3) contributions to the small angular-scale effort for the South Pole Observatory[15]. While these general "Florence" meetings have probably run their course, APPEC support for developing the three axes, in particular, will help Europe to remain a significant actor in future ground-based CMB science.

[14] See, for example, https://indico.in2p3.fr/event/17625/

[15] See Ganga, K., Baccigalupi, C., Bouchet, F., et al. 2019, *European Work on Future Ground-Based CMB Experiments;* BAAS; https://ui.adsabs.harvard.edu/abs/2019BAAS...51g.111G/abstract.

9. Dark Energy

2017-2026 Strategy Statement

Together with Dark Matter, Dark Energy – the hypothetical form of energy behind the Universe's accelerated expansion – constitutes the least-understood component of the cosmos. It is studied via large galaxy-survey campaigns (both satellite-based and ground-based) that combine spectroscopic, photometric and weak-lensing techniques to reconstruct the growth of cosmic structures.

APPEC supports the forthcoming ESA Euclid satellite mission, which will establish clear European leadership in space-based Dark Energy research. Because of their complementarity to Euclid, APPEC encourages continued European participation in the US-led DESI and LSST ground-based research projects. To benefit fully from the combined power of satellite-based and ground-based experiments, the exchange of data is essential.

Introduction

At present, it is established that about 70% of the universe is made from a mysterious substance known as 'Dark Energy', possibly in the form of Einstein's Cosmological Constant Λ, which causes an acceleration of the cosmic expansion. A further 25% of the universe is made from invisible 'Cold Dark Matter' that can only be detected through its gravitational effects, with the ordinary atomic matter making up the remaining 5% (see the Planck Collaboration results and references therein[16]). This "Λ + Cold Dark Matter" (ΛCDM) paradigm and its extensions pose fundamental questions about the origins of the universe. If Dark Matter and Dark Energy truly exist, we must understand their nature. Alternatively, General Relativity and related assumptions may need radical modifications. These topics have been flagged as key problems by researchers and by advisory panels around the world, and significant funding has been allocated towards large surveys of Dark Energy. Commonly, Dark Energy is quantified by an equation of state parameter w, defined as the ratio of pressure to density. The case where $w = -1$ corresponds to Einstein's Λ in General Relativity, but in principle w may vary with cosmic epoch, e.g., in the case of scalar fields. Essentially, it affects both the geometry of the universe and the growth rate of structures. These effects can be observed via a range of cosmological probes, including the Cosmic Microwave Background (CMB), Supernovae Type Ia, galaxy clustering, clusters of galaxies, and weak gravitational lensing. The Type Ia Supernova surveys revealed that our universe is not only expanding but is also accelerating in its expansion. The 2011 and 2019 Nobel Prizes in Physics were awarded for this SNe Ia remarkable discovery, and for theoretical work on the cosmological models, respectively. Evidence for cosmic acceleration was noted even earlier in the 1990s, where galaxy clustering measurements had indicated a low matter density parameter, suggesting the possibility of a Cosmological Constant when combined with the assumption that space is 'flat' (e.g., two light beams would travel in parallel lines), as predicted by Inflation and later confirmed by Cosmic Microwave Background anisotropy measurements. In the three decades since, the evidence for accelerated expansion has been overwhelmingly supported by a host of other cosmological measurements. The main problem is that we still have no clue as to what is causing the acceleration, and what Dark Matter and Dark Energy actually are.

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[16] *Planck* 2018 results - VI. Cosmological parameters; Planck Collaboration, A&A, 641 (2020) A6; DOI: https://doi.org/10.1051/0004-6361/201833910;

Current observations (e.g., Planck, eBOSS, DES) are consistent with $w = -1$ (i.e., a cosmological constant) to within 0.03 or so. However, it is still possible that w slightly deviates from –1, and it may even vary with cosmic time and with spatial direction. These questions, crucial for fundamental Physics, will hopefully be resolved with the next generation of surveys such as DESI, Euclid and Rubon-LSST. We also note some possible problems in ΛCDM: a 4-sigma 'tension' between the Hubble constant derived from the CMB and the value from local stellar distance indicators, and 2-sigma tension in measurements of the clumpiness amplitude S8.

There are additional emerging probes which include Ly-alpha clouds, 21 cm and the speed of gravitational waves, as follows.

The clustering of the Ly-alpha tracers can be used in the same way as galaxy clustering to measure BAO and the Alcock-Paczynski effect (AP) and thus constrain the expansion history of the universe, typically at higher redshifts than galaxies. This has produced some initial important cosmological results in BOSS, has been shown to work in e-BOSS and the next frontiers will be DESI (where this is one of the observables driving the science case).

The Square Kilometre Array (SKA) will detect and map the neutral hydrogen (HI) emission at 21 cm for cosmic structures out to $z = 3$ and higher, extending clustering studies (BAO, Redshift Distortions (RSD), and in general full shape power spectrum analyses) deep into what is believed to be the matter-dominated regime. This will provide highly complementary information and make possible a multitude of synergies that can improve constraints on cosmology and the nature of gravity beyond what optical/IR or radio surveys can achieve separately.

The speed of gravitational waves (or rather constraints on possible deviations of this speed from the speed of light) has already produced interesting constraints on families of models for gravity beyond GR. The new window on the universe offered by GW (with or without optical counterpart) offers a new synergistic venue to probe the expansion history of the universe which modelling interpretation and exploitation is still at the embryonic stage.

Forthcoming large-scale structure data have, in principle, enough statistical power to detect the effect of non-zero neutrino mass (even at the lower mass scale limit imposed by oscillations) and to constrain the absolute neutrino mass scale (see the neutrino section where this is discussed). Observables such as the power spectrum of cosmic structures show a dependence on the neutrino mass, which is partially degenerate with parameters of extended models of gravity. There is a cancellation of the impact of the neutrino mass with a modified gravity model in the power spectrum in the linear regime, which is very efficient if a single redshift is considered. This degeneracy can be broken by combining different redshifts, resorting to non-linear scales, and jointly considering several probes (e.g., clustering and weak lensing).

Developments since 2017

The landscape of galaxy surveys for Dark Energy

The SNe Ia 1998-1999 results of the accelerating universe have stimulated many imaging and spectroscopic galaxy surveys designed to verify and characterise Dark Energy. Back in 2006, the U.S. Dark Energy Task Force (DETF) report classified Dark Energy surveys into numbered stages: Stage II projects were ongoing at that time; Stage III were near-future, intermediate-scale projects; and Stage IV were larger-scale projects in the longer-term future. These projects can be further divided into ground-based and space-based surveys.

Spectroscopic surveys

Among the spectroscopic surveys we note the completed SDSS Baryon Oscillation Spectroscopic Survey (BOSS), eBOSS ('extended BOSS'), the Dark Energy Spectroscopic Instrument (DESI)) which started observations and under construction the Subaru Prime Focus Spectrograph (PFS), 4MOST, HETDEX, Euclid and the Wide-Field Infrared Survey Telescope (WFIRST -- now known as the Nancy Grace Roman Space Telescope).

Imaging surveys

Current imaging surveys include the Dark Energy Survey (DES), the Hyper Suprime Cam (HSC), the Kilo-Degree Survey (KiDS), PAU, and under construction the Vera C. Rubin Observatory (which will perform the Legacy Survey of Space and Time, LSST), and the above-mentioned Euclid and WFIRST. The Dark Energy Spectroscopic Instrument (DESI), which had its first light in 2019, has started survey observations at Kitt Peak National Observatory in 2021. It will measure redshifts of 35 million galaxies and quasars. The Rubin Observatory (LSST), under construction on Cerro Pachon in Chile, to start in 2022-3, will chart billions of galaxies. ESA is currently building a space mission called Euclid, planned for launch in 2023, which will aim to measure the redshifts and shapes of galaxies up to ten billion years into the past. The Roman Wide Field Infrared Survey Telescope (WFIRST), to be launched in 2025 or later, is a space-based project led by the U.S. National Aeronautics and Space Agency (NASA), which will investigate the expansion history of the universe at near-infrared wavelengths.

The field, Europe's role, and APPEC

The field of Dark Energy will remain vibrant over the coming decade, towards testing if Dark energy is 'just' Einstein's Cosmological Constant, and if the ΛCDM paradigm remains robust despite parameter 'tensions' especially in the Hubble Constant and the clumpiness parameter of the universe.

Groups across Europe are involved in almost every Dark Energy experiment, with significant leadership roles even when the experiment is led by another country. Building on existing expertise in e.g., BOSS, DES, DESI and KiDS, the European flagship project in this area is ESA's Euclid mission. The mission (expected to be launched in 2023) will explore the expansion rate of the universe and the growth of cosmic large-scale structures by measuring galaxy shapes (for weak gravitational lensing studies) and redshifts. The Euclid observations will cover the period over which Dark Energy played a significant role in accelerating the expansion of the universe over the past 6 billion years.

The US-led DESI, Rubin (LSST) and Roman (WFIRST) have similar scientific goals, and each of them involves scientists from groups across Europe. These surveys will also lead to important constraints of the nature of Dark Matter and neutrino mass. The time domain of these surveys is also extremely important for follow up observations of gravitational-wave events. The analyses of these huge surveys already benefit from using Machine Learning and AI methods and we'll see more such applications in the future.

It is important that APPEC supports Euclid, other international projects, and especially early-career scientists in Europe in exploiting these huge surveys.

10. Multi-probe astroparticle physics

Introduction

In the current strategy, there is no separate section on multi-messenger and multi-purpose observatories. However, it was deemed an important development that should be addressed in this mid-term review. The European Astroparticle Physics Strategy 2017-2026 identified as an overarching theme the large-scale multi-messenger infrastructure: *"To improve understanding of our universe, APPEC identified as a very high priority those research infrastructures that exploit all confirmed high-energy 'messengers' (cosmic particles that can provide vital insights into the universe and how it functions). These messengers include gamma rays, neutrinos, cosmic rays and gravitational waves. European coordination is essential to ensuring timely implementation of such infrastructures and enabling Europe to retain its scientific leadership in this field."* At that time no special section or specific multi-messenger strategy statement was included but the need for a diverse landscape of observatories was stressed. Today it has been realised that in addition to maintaining this diverse landscape of observatories for all possible messengers, there are also elements that transcend the role of each of these observatories alone. In addition to considering the case of several observatories each measuring their own messenger, it has also been realised that the same observatory, if needed with some additions or modifications, can often be used to detect several messengers and significant synergy can thus be attained. To emphasize both aspects the term *multi-probe astroparticle physics* has been coined for the title of this section.

Recent developments

Three discoveries thus far have marked the history of multi-messenger astroparticle observations: 1) the core-collapse supernova SN 1987A exploded in the Large Magellanic Cloud, for which a burst of low-energy neutrinos was detected a few hours before the optical observations; 2) the merger of a binary-neutron-star observed through gravitational waves (GW170817), gamma rays (GRB 170817A), and in the ultraviolet-optical-near infrared (AT2017gfo); 3) the possible association of high-energy neutrinos with the blazar TXS 0506+056.

These remarkable transient detections have demonstrated the power of multi-messenger observations to provide key insight into the physics of the most energetic events of the universe. SN 1987A made it possible to probe the engine of core-collapse supernovae, to set upper bounds on the neutrino mass, charge, and number of flavours, and to perform unique tests of gravity. GW170817 and the associated signatures detected in the entire electromagnetic spectrum over more than 3 years have been the first strong observational evidence that binary neutron-star mergers power short gamma-ray bursts and kilonovae. They gave insight into the properties of relativistic jets and showed that binary neutron-star mergers are one of the major channels of the formation of heavy (r-process) elements in the universe. Furthermore, they made it possible to measure the propagation speed of gravitational waves ruling out several classes of modified gravity models, to set constraints on the equation of state of supranuclear matter, and to evaluate the expansion rate of the universe. The high-energy neutrinos possibly associated with the Blazar TXS 0506+056 can represent the first direct identification of astrophysical sources of extragalactic neutrinos, giving insights into the composition of relativistic jets powered by active galactic nuclei. A search for ultra-high-energy neutrinos associated with gravitational-wave events and the Blazar TXS 0506+056 by the Pierre Auger Collaboration gave null results

Maximizing the scientific results of multi-messenger observations requires a real-time search for candidate events, infrastructure to send rapid alerts, a worldwide rapid response able to exploit observational resources to follow-up large regions of the sky and to characterize transients. Coordination among space and ground-based observatories covering all messengers and the entire electromagnetic spectrum results to be imperative.

Future developments

The upcoming years are expected to undergo a revolution for multi-messenger detections. Innovative observatories of transient events are expected to start operations during the next few years and the next decade. Instruments such as the Vera Rubin Observatory, SKA, CTA, KM3NeT, and the Einstein Telescope will enormously increase the detection rate; some of them are expected to produce billions of transients per year. In addition to the huge increase of the capabilities to reveal individual events through multi-messenger observations, the universe will be explored through separate powerful multi-probe observations up to large distances. For example, the Vera Rubin Observatory and Euclid will give us details of the large-scale structure of the universe, and instruments such as the JWST, ELT, ATHENA, will make it possible to observe the first stars, galaxies, and massive black holes. The current gravitational-wave detectors and the next generations, such as Einstein Telescope and LISA will benefit from the results of galaxy surveys to drive the search for an electromagnetic counterpart and to make cosmology. At the same time, the knowledge of the first structures in the universe, the star-formation history and the universe chemical enrichment through electromagnetic studies together with the gravitational-wave studies of the formation and evolutions of black holes of different masses and origin (stellar or primordial) will enable an unprecedented insight into the early universe and its evolution.

Observation of neutral UHE particles, photons and neutrinos, is another promising way of multi-messenger studies. Above 10^{18} eV, these neutral particles are produced in decays of pi mesons, which in turn are born in interactions of cosmic rays of energies an order of magnitude higher with the background radiation. These cosmogenic photons and neutrinos serve as a diagnostic tool to decipher the mass composition of cosmic rays in the poorly studied energy band, allowing for a further step to understanding the sources of the highest-energy particles in the universe. In addition, transparency of the universe to UHE gamma rays grows with the photon energy, and extreme-energy photons may bring important astrophysical information while 10^{19} eV ones can be used to test several new-physics models. UHE photons and neutrinos represent the only available tool to test viable scenarios of superheavy dark matter.

Photons and neutrinos can be detected by UHE cosmic-ray observatories, Pierre Auger Observatory and Telescope Array, but it is a challenge to firmly separate air showers caused by them from the bulk of cosmic-ray events. To this end, sophisticated analysis methods are being developed, based on machine learning and other tools for big data processing. Essential for the detection of transients is a large exposure coupled to a large sky coverage at any particular time. The proposed GRAND detector hopes to establish this by deploying ten or more detection arrays around the globe, each spanning about 20000 km^2 of detection surface.

The sections on Neutrino properties and Ground-Based CMB highlighted the point that neutrinos affect the amount and evolution of large-scale structure in the universe and that they thereby allow us to use cosmological measurements to set limits on the sum of neutrino masses. Similarly, the existence, quantity and properties of Dark Matter in the universe also have profound effects on the growth of structure, such as galaxies and clusters. Signatures of Dark Matter are readily apparent in the power spectra of many cosmological surveys of structure. The Planck measurement of the density of Dark Matter in the universe, for example, is a detection of the order *100-σ* of Dark Matter, and perhaps our best evidence for its existence. Microwave, submillimetre, infrared and optical cosmological surveys measuring the growth of structure are therefore all strong complements to direct detection investigations into the nature of Dark Matter.

A diverse variety of neutrino experiments (including ones that otherwise are not closely coupled to astronomical observations) work together on identifying a galactic supernova before it can be observed with light. Occurring at an average rate of only 1-3 per century, the next galactic supernova will be a once-in-a-generation event. Neutrinos are the first particles that escape from a core-collapse supernova and may therefore arrive up to several hours ahead of the light signal.

SNEWS - the SuperNova Early Warning System - receives real-time information from contributing neutrino experiments and will issue an alert that informs the worldwide astronomical community well in advance of a supernova's appearance in light. The list of experiments that currently contribute to SNEWS includes Super-Kamiokande, IceCube, KamLAND, HALO, and KM3NeT. The new large detectors under construction for neutrino oscillations, DUNE, JUNO and T2HK, as well as the planned large dark matter detectors, ARGO and DARWIN, will certainly join SNEWS. Neutrinos are the only particles that can escape from the inner part of the SN, due to its extreme densities, and therefore carry unique information on the SN explosion. The measurement of the energy and time distribution of the neutrinos will provide an unparalleled probe into the core-collapse process.

Early warning systems, such as SNEWS and GCN are instrumental to multi-messenger observations. Sharing information with a common data format and in readily accessible repositories is also a *sine qua non* for optimal multi-messenger analyses, and should be fully developed. The enormous increase of rate and volume of alerts expected from LSST at the Vera Rubin Observatory requires innovative software systems able to ingest, process, and serve large streams of alerts to the broad scientific community. A new generation of astronomical alert brokers such as ALeRCE, AMPEL, ANTARES, Babamul, Fink, Lasair, Pitt-Google, Point of Interest, SNAPS, or POI:Variables are currently under development and evaluation. The selected brokers for LSST are expected to set the basis for the future multi-messenger alert distribution.

The field, Europe’s role, and APPEC

The upcoming years are expected to undergo a revolution for high-energy transient observations. The astroparticle and astronomical community will deploy from now to the next decade several innovative facilities with enhanced sensitivity and/or survey capabilities; CTA, Athena, the Vera Rubin Observatory, Euclid, JWST, ELT@ESO, SKA, KM3NET, ET and LISA (to cite some). These observatories will maximize their science operating in synergy and/or as multi-probe networks.

Europe leads or has a major involvement in the development and building of many of the above observatories, and is of the major users for the exploitation of their observations. Collaborations and networking among different communities (e.g., gravitational-wave physics, astronomers, and neutrino physicists) have been developed in recent years and brought the outstanding multi-messenger observation of GW170817.

It is important for APPEC to support the building or reinforcement of common infrastructures for rapid data analysis, rapid sharing of the observed results, and data storing. APPEC support is critical also to further enhance networking, collaboration and coordination among experimentalists, observers, experts in data analysis and computing, and theorists from different communities to define science requirements for instrument technologies and observation modes optimized for operating in synergy. Common and complementary initiatives to develop optimized observational strategies, common tools and formats to share, analyse, visualise, and interpret data from different observatories are crucial to facilitate and enhance the science return from multi-probes observations and need APPEC support.

11. Ecological impact

Introduction

In the current strategy, there is no section on ecological impact. However, it was deemed an important development that should be addressed in the mid-term review.

Recent development

There is a growing awareness of the effect of our ecological impact in society and of the idea for mitigating measures. It is time to be explicit about the ecological impact of the research in astroparticle physics. Recently, the updated European Strategy for Particle Physics calls for carefully studying and minimising the environmental impact of particle physics activities, a detailed plan to minimise the environmental impact as part of the approval process for major projects and exploration of alternatives for travel.

It makes sense for the European astroparticle physics community to align with this strategy and extend it to astroparticle physics activities.

There are three facets to be considered:

- The ecological impact of astroparticle physics satellites, experiments and observatories, including the environmental impact of installations, chemical and radiological impact, energy consumption (also of computing, housing, etc.), etc.;
- The ecological impact of community activities, such as travel, meetings, etc.;
- Contributions and spin-offs from astroparticle physics research to measure ecological impact, or to avoid or mitigate negative effects of ecological impact from any activity.

To assess the situation, an inventory of current activities with estimates of their ecological impact should be made.

Over the past years, travel is likely to have contributed the most to the ecological impact of astroparticle physics activities. Recent events have shown that travel is clearly something that can be reduced but the balance has to be carefully struck to not hamper the effectiveness of the research. Computing uses considerable resources and energy, thereby contributing substantially to the carbon footprint of astroparticle physics. In addition to improved hardware and e.g., the use of GPUs and FPGAs for reconstruction and Monte Carlo modelling, there may be much to gain in devising better algorithms and innovative ideas for modelling, reconstruction and data analysis. The current generation of software is usually not optimised for using minimal resources. An added benefit of much-improved software may be that it runs much faster, facilitating e.g., interactive analysis.

The role of APPEC

Most recently a report "*Carbon Footprint Study for the GRAND Project*" has appeared that presents a detailed breakdown of the carbon footprint of an experiment in its early phase of existence. It would be most valuable to have such reports for all major astroparticle physics observatories and experiments. Such inventories will give insight into which activities and techniques can be targeted to minimise the carbon footprint of our research activities. Of course, this is just a start. The next step would be to find solutions and alternatives for addressing the culprit activities and techniques. It should also not be forgotten that the Carbon footprint is only one aspect of ecological impact, albeit an important one.

APPEC could play a leading role in persuading observatories and experiments to conduct similar inventories, in facilitating to share expertise on how to do these studies, on advising on methods of reporting that make the studies both comparable and allowing them to be easily combined into a global overview for astroparticle physics. As a first step, APPEC could appoint a standing committee to gather and combine ecological impact information of astroparticle physics activities. While doing so, such a committee is likely to acquire the expertise that allows it to advise observatories and experiments on how to conduct their studies. In a second step, the role of this committee can be extended to collect and share ideas on minimising the ecological impact and even to initiate studies for this purpose.

12. Societal impact

Introduction

In the current strategy, there is no section on societal impact. However, it was deemed an important development that should be addressed in the mid-term review.

Ongoing and recent developments

There are many ways in which astroparticle physics and astroparticle physicists have a positive impact on wider society. In general, much of the ultra-sensitive detector developments for astroparticle physics has benefitted other research fields and societal applications, such as in imaging equipment, e.g., for medical imaging. For example, the liquid noble gas detector technology of the dark matter experiment XENON is being applied for positron emission tomography (PET). As a high-tech scientific area building large-scale experiments, astroparticle physics necessarily interacts with industry. Very large orders can result, e.g., the AugerPrime upgrade resulted in orders for metal structures worth more than half a million euros to industries in several European countries. This included the use of high-tech metal-foam sandwich panels which are normally used for panelling facades of buildings. Such orders not only provide employment but often improve the capability of industry; these new skills then prove beneficial for the industrial partner, who may use them to gain further orders. The science pursued by astroparticle physicists is of great interest to all groups of the public, from schoolchildren to teachers and ordinary citizens, since it includes dark matter, neutron stars, black holes, supernovae, the “ghost particles” neutrinos, etc. Astroparticle physics experiments often have a positive impact on the lives and aspirations of people in the areas local to the experiments; these are usually areas remote from large cities where residents do not have a wide spectrum of opportunities. One of the largest contributions to society is the training of scientists, from Bachelor and Master students to PhD candidates and postdocs, of whom most find their way in a wide variety of industries and services that are in dire need of people with their education and skills. Not only do the young scientists receive excellent training in science and especially in astroparticle physics, sensitive and innovative detectors, big data analysis including artificial intelligence, etc., the particular fascination of our field also evokes a special commitment from our young scientists, which translates into outstanding skills and capabilities. A few specific examples of the societal impact of astroparticle physics are given below. This is, of course, not an exhaustive list.

WATCHMAN (WATer CHerenkov Monitor for Anti-Neutrinos)

The main purpose of WATCHMAN is to develop technology and data analysis techniques to demonstrate the ability to monitor nuclear reactors from distances of tens of kilometres as part of future Nuclear Non-Proliferation Treaties.

Anti-neutrinos are an inevitable by-product of the production of plutonium, which is used in nuclear weapons. Using techniques developed by astroparticle physicists, a system is being designed to detect these anti-neutrinos. It will be situated at Boulby Underground Laboratory in the UK.

Pierre Auger Observatory (PAO) Visitor Centre

The PAO’s visitor centre opened in 2001 and attracts an average of 7000 visitors each year. Although the visitor centre is primarily visited by local schools, many tourists also visit the centre, bringing an extra boost to the local economy. The Centre hosts a science fair, which takes place usually each November during the collaboration meeting. The event, which is sponsored by the observatory, started in 2005 and has been more successful every year, with increased participation from young people of all ages who come from all over the Mendoza Province and beyond. The local school has been named after Professor Jim Cronin, one of the founders of PAO, in recognition of his and the observatory’s contribution to the local community.

There is also a full scholarship program for a student from the local town, Malargüe, to attend Michigan Technical University, which has been a huge success so far.

Einstein Telescope industrial impact

During the Einstein Telescope's construction phase, it is estimated[17] that there will be a direct economic effect on the building industry and its suppliers of some M€ 900, and an indirect effect as a consequence of the increased economic building activity (on local shopkeepers, etc.) of approximately M€ 500.

In technology and innovation, new technologies will result from the challenge of building the telescope. These will include technologies for reducing vibrations (including cryogenic operated mirrors), the optic interferometer, diagnostic equipment (including measurement and control software) and from the spill-overs of these effects in the economic and societal domain.

AMANAR: Under the Same Sky

Initiated in 2019, "AMANAR: Under the same sky" is an initiative to promote and support the scientific education and the development of scientific skills of children living in the Saharawi refugee camps in Tindouf (Algeria) through the observation and understanding of the universe, as well as to encourage peace, common understanding and a sense of world citizenship under the same sky. Conceived by the international organization GalileoMobile and the Asociación Canaria de Amistad con el Pueblo Saharaui (ACAPS), the project combines outreach activities and visits to the Canary observatories with the children in July and August as part of their summer in the Canary Islands with the "Holidays in Peace" program, as well as visits to the refugee camps by a group of scientists and experts. The CTA Observatory is an active partner in this project, supporting the organization of activities in the Canary Islands, where CTA-N will be located, and the provision of educational material for the camp visits.

Neutrino village

An interesting example from a whole socio-economic unit that grew out of astroparticle physics is the Neutrino village at the site of the Baksan Neutrino Observatory. This settlement was established 50 years ago as the residence for participants in the observatory in the geographically remote Northern Caucasus in a poor high-mountain rural region. It did not exist before the observatory was built, and it indeed carries the official name Neutrino for postal addresses. First, people who participated in the construction and exploitation of the observatory settled there but now the residents are not only those directly related to the observatory - many moved from nearby villages to benefit from the infrastructure, jobs, the school (where, in particular, some retired scientists teach), etc.

The role of APPEC

Bringing the important societal impact of astroparticle physics to the attention of the general public should be stimulated by APPEC but the implementation can be left to national organisations and the various experimental collaborations, observatories and institutes. The APPEC GA plays an important role in making the impact of astroparticle physics visible to funding agencies and fuelling the funding agencies with examples and case studies to be provided to government officials. This is essential for the continued support of the field at all required governance levels. For specific large and important projects that still require funding, APPEC may consider initiating societal and economic impact studies itself.

[17] https://www.einsteintelescope.nl/wp-content/uploads/2019/02/impact-assessment-of-the-einstein-telescope.pdf

13. Open Science and Citizen Science

Introduction

In the current strategy, there is no section on Open Science and Citizen Science. However, it was deemed an important development that should be addressed in the mid-term review.

Open science is a policy priority for the European Commission. Open Science policy, mandatory open access to publications and open science principles applied throughout the programme, is a new element of the Horizon Europe framework programme. The Commission requires beneficiaries of research and innovation funding to make their publications available in open access and make their data "as open as possible and as closed as necessary". Several initiatives in astroparticle physics already predate the interest of national and European funding agencies in open science. In particular, almost all APP publications are available in open access on the arXiv preprint server, e.g., Fermi LAT data is publicly available, as well as 10% of the data of the Pierre Auger Observatory, the muon track lists from IceCube and ANTARES, the data from gravitational-wave observatories through GWOSC etc. There are also already existing initiatives concerning citizen science, e.g., with the HiSPARC project and with the international cosmic ray day.

Open science

The European Open Science Cloud (EOSC) is an environment for hosting and processing research data to support EU science. EOSC enters the implementation phase that will end in 2027.

ESCAPE project

ESCAPE - the European Science Cluster of Astronomy and Particle Physics ESFRI Research Infrastructures – helps implement the EOSC strategy. Among its organizational structures, the ESCAPE External Advisory Board is a group of independent experts associated with the ESFRI projects and other related Research Infrastructures and Industry, whose mission is to ensure the optimal alignment of the work in ESCAPE with the needs of the ESFRI facilities. The APPEC chair is part of this External Advisory Board.

ESCAPE is part of the ESFRI Science Clusters and issued a position statement in June 2021 on the expectations and long-term commitment to open science. Following the call for Expressions of Interest by APPEC-ECFA-NuPECC at JENAS 2019, the initiative for Dark Matter in Europe (iDME) aims to create a 'public place' where researchers working on the Dark Matter problem. ESCAPE will also support the Dark Matter initiative as a TSP (Test Science Project), with the aim to build a common FAIR-data open research environment.

AHEAD2020 project

AHEAD2020 (Integrated Activities in the High Energy Astrophysics Domain) is an ongoing project approved in the framework of the European Horizon 2020 program (Research Infrastructures for High Energy Astrophysics). AHEAD2020 aims at integrating and opening research infrastructures for high energy and multi-messenger astrophysics. It works to make accessible and usable multi-messenger data by providing analysis and theory tools specifically dedicated to data exploitation and to offer access to a network of research infrastructures and virtual access to gravitational-wave data. Within this context, AHEAD2020 provides resources dedicated to support the development of the GWOSC to facilitate access to gravitational-wave.

AHEAD2020 supports the community via grants for collaborative studies, dissemination of results, and promotion of workshops. Within the public outreach package, the EGO node has started a programme of remote live visits of its facilities in Cascina and of the Virgo detector and produced a series of posters to be distributed to schools and University institutions.

Citizen Science

The term citizen science refers to scientific research conducted by amateur scientists. Citizens can participate in the scientific research process in different possible ways: as observers, as funders, in identifying images or analysing data, or providing data themselves. This serves not only the goal of the democratization of science but also allows real advancements in scientific research by improving the scientific communities 'data analysis capacities.

Citizen Science, as "science for the people, by the people", is part of the European Commission's strategy to shape Europe's digital future. We provide below an example of a successfully implemented project.

REINFORCE (Research Infrastructures FOR Citizens in Europe)

REINFORCE (Research Infrastructures FOR citizens in Europe) is a Research & Innovation Project, supported by the European Union's Horizon 2020 SWAFS "Science with and for Society" work programme.

The project created a series of cutting-edge citizen science projects on frontier Physics research, with citizen scientists making a valued contribution to managing the data avalanche.

4 demonstrators have been developed:

- Gravitational Wave noise hunting: Its aim is to develop a cutting-edge citizen science programme by providing public access to GW antenna data, including environmental data, for an open-data project.
- Deep Sea Hunters: Invites citizens to optimize the KM3NeT neutrino telescope against sources of environmental noise which have never been systematically studied, while engaging in the exciting world of neutrino astronomy.
- Search for New Particles at the Large Hadron Collider of CERN: Engages citizens in the quest of the LHC for the discovery of the ultimate structure of matter as well as particle theories beyond the standard model.
- Cosmic Muons Images: Interdisciplinary studies with Geoscience and Archaeology has the goal to show how the technology developed to study fundamental physics can be applied to the development of frameworks that may have a significant impact on society.

The information above and more can be found on the REINFORCE project website.

The Role of APPEC

APPEC should identify and reinforce the collaboration with current and future projects aimed at developing data infrastructure, open-source platforms and software for storing, extracting and enabling data analysis of multi-messenger astroparticle physics.

APPEC should encourage and promote the design and implementation of open citizen science projects and actions, not only for large infrastructures but also for smaller national projects. We also stress the importance of identifying interdisciplinary collaborations that could benefit from the data collected by one single infrastructure (e.g., geoscience, etc.)

14. Human talent management

Introduction

In the current strategy, there is no section on human talent management. However, it was deemed an important development that should be addressed in the mid-term review.

Attracting and retaining talent

By far the most important asset for astroparticle physics research is human capital. The ambitions in astroparticle physics lying ahead of us have a very long-term perspective and require a sustained and even an increased number of scientists to build and exploit experiments and observatories, to harvest and interpret their results and to devise theories and models to explain the observations and understand our world a little better.

To attract young talented researchers, they have to be interested already from a young age. This can be achieved by extensive public engagement, which does not only target children but as important their environment of family, friends, teachers, etc. The outreach efforts in particle physics and astronomy are exemplary in this respect and astroparticle physics can ride along on these programmes. In addition, it is important to make sure that in the outreach efforts also the typical astroparticle physics research questions are obtaining a stage.

A focus on primary and secondary education is important because astroparticle physics touches on some of the big questions that motivate school children to study STEM subjects, which is important both to interest and prepare them for an academic physics or astronomy study later. There are several initiatives to teach topics in astrophysics and related subjects in high schools. These efforts could be streamlined further, e.g., modelled on or in cooperation with the International Particle Physics Outreach Group (IPPOG) that has set up such a structure for particle physics.

Including basic astroparticle physics in the core curriculum, by offering elective courses or by illustrating more general physics and astronomy subjects with astroparticle physics applications or input may awaken the interest in BSc physics and astronomy students for astroparticle physics. Specialised MSc programmes in astroparticle physics, either stand-alone or in association with particle physics and/or astronomy are essential to shape the next generation of astroparticle physicists.

For the training of PhD students, many opportunities already exist, like schools for astroparticle physics or more dedicated topics. There are also many opportunities for postdocs and more senior scientists to keep up-to-date in astroparticle physics. Special attention may be given to the training on modern artificial intelligence and advanced computing topics since developments in these fields are rapid and of high interest to astroparticle physics.

The knowledge and especially the skills of (young) astroparticle physicists and students are also highly valued in non-academic sectors. Retaining talent in our research community is an issue. To remain attractive the working environment has to be exciting and stimulating, inclusive and competitive with other potential employers in terms of benefits and work-life balance. The rat race for funding and permanent positions are detrimental to a stimulating working environment and tends to overshadow the excitement more and more. More transparency in selection processes and rewards, e.g., such as proposed in the DORA San Francisco Declaration[18], will help but will not completely solve this problem. Concerning the career perspective transparency should be displayed, facilitating PhD students and postdocs to also prepare for a career outside of

[18] Declaration on Research Assessment (DORA)

academia, e.g., by offering appropriate training.[19] Part of the uncertainty in career perspective may be compensated by giving trust, responsibility and independence to young researchers, like this is also compensation enough for many senior researchers to stay in academia, despite often non-competing remuneration and benefits when compared to similar non-academic positions. The JENAA Recognition Working Group may provide handles to address proper recognition of individual scientists, including the more junior ones. Diversity, equity and inclusion is of specific interest, not only to retain but also to be able to attract people to the astroparticle research field. The next section will be specifically devoted to that issue. While for remuneration and benefits no spectacular improvements can be expected, addressing the work-life balance is possible and can make a difference in retaining the best talent in our research field.

Diversity, Equity & Inclusion

On June 17, 2020, at the European Parliament, European Commission President Ursula von der Leyen said[20]:

“As a society, we need to confront reality. We relentlessly need to fight racism and discrimination: visible discrimination, of course. But also more subtle racism and discrimination – our unconscious biases. All sorts of racism and discrimination! In the justice system and law enforcement, in the labour and housing markets, in education and healthcare, in politics and migration.”

A glance around most of our institutions or even a moment’s reflection requires us to conclude that European particle astrophysics is just as guilty as any of these other institutions. The Diversity Charter of APPEC, ECFA, NuPECC can be found via the NuPECC website[21].

The role of APPEC

Efforts should be made to address racial, sexual and physical discrimination in European particle astrophysics despite our inability to collect specific statistics. APPEC plays an important role in publicly denouncing all kinds of discrimination and calling for full inclusiveness. As a continent-wide consortium with strong links to other such organizations, APPEC is in the position to be able to survey and recommend to members practices that are seen to work in other environments. The Diversity Charter of APPEC, ECFA, NuPECC is a good start but the issues should remain in the active consciousness by continuously repeating the message. To help address these, we suggest working with, among others, the following organisations and movements:

- APS Inclusion, Diversity, and Equity Alliance: https://aps.org/programs/innovation/fund/idea.cfm
- The AIP National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP): https://www.aip.org/diversity-initiatives/team-up-task-force is another US-based organization.
- Particles for Justice (https://www.particlesforjustice.org/) also seems US-centred, though it did, for example, pronounce Sturmia’s CERN statement to be unsound[22]

Please note that this is merely a starting list for cooperation and involvement.

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[19] Banking on an increase of research positions smells like a Ponzi scheme, as an increased number of permanent positions will lead to an increasing demand for PhD and postdoc positions, which in turn will need more permanent positions to have a favourable career perspective.

[20] https://ec.europa.eu/jrc/communities/en/community/jrc-alumni-network/article/speech-president-von-der-leyen-european-parliament-plenary-%E2%80%93-

[21] http://nupecc.org/jenaa/docs/Diversity_Charter_of_APPEC__ECFA__NuPECC-9.pdf & http://nupecc.org/jenaa/?display=diversity

[22] https://www.particlesforjustice.org/statement-sexism

It is recommended that a standing APPEC working group on diversity, equity and inclusion is set up to develop ideas and stimulate their implementation and that this working group monitors the situation and reports once a year to the APPEC GA.

15. Inventory of “central” infrastructures

Introduction and current situation

The APPEC community benefits from the existence of several excellent infrastructures in the field of underground physics. Five main underground laboratories exist in Europe: the “Baksan Neutrino Observatory”, located in a 4000 m long horizontal tunnel constructed especially for the laboratory in the Caucasus mountains in Russia at a maximum depth of 4700 m.w.e.; the “Boulby Underground Laboratory”, located at a depth of 2805 m.w.e. in a working potash, polyhalite and salt mine in the North East of England; the “Laboratori Nazionali del Gran Sasso” (LNGS, Italy), located at a depth of 3800 m.w.e. through the Gran Sasso tunnel of the A24 highway in Italy; the “*Laboratoire Souterrain de Modane” (LSM, France)*, located through the Frejus tunnel between Italy and France, at a depth of 4800 m.w.e.; the *“Laboratorio Subterráneo de Canfranc”* (LSC, Spain), located in a former railway tunnel under the Pyrenees at a depth of 2450 m.w.e.

Other “shallow depth” facilities exist around Europe. We do not list them here but we acknowledge they are an important auxiliary tool as well. Also not listed but acknowledged are deep underwater facilities, such as KM3NeT.

The five main facilities are a crucial asset for the development of underground physics and astroparticle physics in Europe. Although of very different size (the largest by far is LNGS, with three underground halls offering a total of 180.000 m^3 of underground usable volume, the largest in the world, while Boulby, LSC and LSM offer a volume of 4000 m^3, 10000 m^3 and 3500 m^3 respectively and Baksan offers a variety of volumes at different m.w.e. depths), the five laboratories play a very important role for the field, hosting a large number of top quality experiments in the fields of solar neutrino physics, dark matter search, neutrinoless double-beta decay search, and rare events physics, including nuclear physics for astrophysically relevant reactions, biophysics and environmental sciences.

The role of APPEC

The aforementioned facilities have been operated independently in the last decades by the respective funding institutions (INR RAS for Baksan, INFN for LNGS, IN2P3 for LSM, STFC for Boulby, and the Agencia Estatal de Investigation of the Spanish Minister of Research for LSC).

This mode of “independent” operation has been so far very successful and has brought many important results. It should be mentioned that all successful experiments performed in European laboratories have benefited from the knowledge and the expertise developed by the groups in other laboratories so that an effective factual collaboration has always been in place.

However, the new generation of experiments envisaged or programmed for the next two decades will benefit from, if not require, a much more coordinated effort.

The required sensitivity of low background experiments, especially those aiming at the direct search of dark matter and at the search for neutrinoless double-beta decay, calls for detectors of much larger target mass (ton or multi-ton scale in both fields) and much lower intrinsic and external backgrounds.

This in turn requires both the active detector materials and the passive shielding and supporting materials to be more and more radio-pure, often at the level of a few counts per ton per year in the energy region of interest. While the technology needed to achieve such pure materials may exist, the material selection and the tests of the purification procedures that are needed to achieve such purities, always require very long measurement campaigns on a diverse and large set of different materials and using many different techniques. Regardless of the actual location of the various experiments, a strong synergy and cooperation among the Laboratories are crucial to be able to perform those ancillary but crucial measurements in a timely and effective way. A well-organised network with the highest level of cooperation practically achievable would strongly increase European competitiveness and APPEC may certainly play a pivotal role in promoting such cooperation. While the realisation of a specific ERIC might be seen as too ambitious at this moment in time, other forms of cooperation are possible and should be pursued. A European Laboratory of Underground Science Working Group has been set up to discuss these issues.

16. Discussion items for the strategy update

This document is intended as input to the discussion at the APPEC town meeting in 2022 in Berlin. The summary and conclusion should be written after the Town Meeting, taking all input before and at the meeting into account. In the final section of this document, a number of issues are presented that should serve as input for a structured discussion. They all circle a number of general questions: Which parts of the strategy are on track for realisation by 2026? Where should the strategy be adapted in view of developments since 2017? How can the strategy after 2026 already be anticipated, and what should be done to establish the best strategy for the period after 2026?

Ongoing and new experiments, observatories and theory-hub

Since the launch of the 2017-2026 APPEC strategy in 2016, several significant developments have occurred in our understanding of the universe, some coming from new experimental or observational results, some other from new theoretical insights, and some from the interplay between experiment and theory. In addition, there has been good progress on building a number of high priority and other new experiments and observatories, promising a wealth of new results to be expected in the coming years. And last, but not least, new initiatives have emerged for new experiments and observatories and a new theory centre, EuCAPT, has been established.

While the different experiments all have merits and deserve priority in their own right, it is proposed to also look at them and their relative merits in terms of multi-messenger astroparticle physics and in terms of multi-probe experiments or observatories in dedicated discussion sessions. An important input to such discussions would also be synergy between experiments and observatories and the optimal use of large common infrastructures, such as deep underground and deep-sea facilities.

Gravitational-wave detection is already an important part of the European astroparticle physics strategy. The ongoing detection of gravitational-wave events has accelerated the ideas and R&D for next-generation detectors. It firmly established the mission for LISA, led by the astronomy community. It also made the European ambitions for a ground-based gravitational-wave interferometer very clear and focused on the ambitious Einstein Telescope project. This project, with a proposed budget of about an order of magnitude more than the previously most expensive astroparticle physics projects, sets new requirements on attracting funding while maintaining a balanced astroparticle physics programme. Finding the optimal path for both realising ET and retaining the broad programme required for multi-messenger astroparticle physics, as well as other high-priority astroparticle physics goals, will be an important discussion item at the Town Meeting.

Several new large experiments, such as CTA, KM3NeT and AugerPrime, have come out of the planning phase and have gone or are going into the construction and commissioning phase. These are important milestones in the realisation of the APPEC 2017-2026 strategic plan.

New large experiments can be anticipated in the relatively short-term future for neutrinoless double-beta decay. Given the potential fragility of a detected signal, it is important to confirm a finding with several isotopes, i.e., do several experiments on the same time scale. Global negotiations on the funding and site choice of these are ongoing. Also, on a relatively short time scale, the IceCube-Gen2 extension is planned but this still needs to be budgetarily secured. In the medium-term future, one or more new large direct dark matter detection experiments are in the planning at a scale that will also require global participation. In the longer-term future, both ground detection and a satellite mission are foreseen for the detection of ultra-high-energy cosmic rays, both requiring substantial investments. The staging of these large endeavours seems reasonable to spread financial investments and other resource requirements over time.

The larger context and resource limitations

To remain at the forefront of astroparticle physics, the European resources have to be efficiently pooled and distributed. From the inventory presented before, it is clear that there is no shortage of ideas for new experiments and observatories when compared to the available resources. These resources comprise person-power and intellectual capacity as well as available budget and materials. Some of the individual proposals transcend the available resources in Europe and require global participation. For some other existing and proposed experiments and observatories, there is fierce competition from the other continents and one has to investigate the optimal strategy of cooperation or competition or a combination of both. Above all, there is a clear desire in the European astroparticle physics community to stay at the front of developments over a good breadth of topics. In the end, the opportunity to realise as much as possible of the ambitions will be largely driven by the volume of the European astroparticle physics community, which will depend much on the attractiveness and excitement of the discoveries ahead of us and our ability to showcase them. A decisive factor in how much of the European astroparticle physics ambition can be realised is how well the European funding agencies can be aligned on its high priority projects. In addition to the national funding agencies, central European funding, such as in the Horizon Europe programme will be required. Another important factor, at least for part of the planned new large experiments, is how efficient and cost-effective the resources of the various European underground laboratory's facilities can be made available.

There are clear synergies of astroparticle physics with particle physics, nuclear physics and astronomy. These synergies should be taken optimally advantage of. JENAA is a good platform to seek optimal synergy with particle and nuclear physics. A structure for closer cooperation with astronomy should be investigated. Exploiting the synergies may offer additional resources for realising European astroparticle physics ambitions.

Winning the hearts of the public, funding agencies and politicians

Notably, also, there have been significant developments in the appreciation of our research by the public, governments and funding agencies. Engagement of the public, funding agencies and politicians will be required to sustain our field. Open Science and Citizen Science play a large role in engaging as many people as possible in astroparticle physics. The natural curiosity of humans in the universe helps, and should be seized as an opportunity as much as possible. The impact of astroparticle physics on society should be clearly exposed and where possible further enhanced. Equity, diversity and inclusion are key to offer a safe working environment for current and new astroparticle physicists. This is essential to retain and recruit talent. Making astroparticle physics endeavours ecologically neutral is a prerequisite for survival in the long run. But the research field can do better and, in fact, contribute to monitoring the ecological state and to prevent or mitigate adverse ecological impact from many different origins.

Collecting new ideas

An important goal of the strategy update process is to collect new ideas in all possible directions, be it for theoretical or phenomenological models and theories, new experimental or observational approaches but in particular also how we can sustain our research field. For the latter, new ideas for societal applications, for contributing to a green society, for involving citizens in science, for making our research field more attractive and inclusive for scientists, in short, new ideas to increase our societal impact are much needed. Therefore, these issues deserve a good discussion at the Town Meeting.