APPEC European Astroparticle Physics Strategy 2017-2026 – mid-term update

V10, 13 June 2023 (final draft)

Executive Summary

The APPEC European Strategy for Astroparticle Physics 2017-2026 is well underway to be implemented. Most of the strategic objectives are on track to be attained. However, it has become clear that a few objectives have become out of reach and strategic goals in these areas need to be adjusted. In other areas, the strategic objectives are well in reach and new ones have become on the horizon. In yet other fields projects are maturing rapidly, e.g., for a new European gravitational wave detector. This led the APPEC community to make some mid-term course corrections in the strategic goals of several scientific astroparticle physics topics.

Even faster than the scientific progress the social and societal setting of science in general and thereby also of astroparticle physics is changing. Attracting and retaining talent is increasingly an issue. Social safety in all respects is much more stressed. Open science is rapidly becoming the norm. Considering societal impact is now a must. Therefore, the strategic objectives of how we would like to operate as scientists in astroparticle physics research have become more important and pronounced.

The existing large infrastructures, notably underground laboratories, but also other large installations are important to maintain and further develop. An initiative for much closer cooperation between the European underground laboratories is welcomed by APPEC. The available resources for both running existing large infrastructures and investing in large infrastructures currently under construction or planned for future construction are reassessed globally and give rise to the idea that, while always struggling for more resources, the baseline budget of the field gives it a bright future.

Table of Contents

Introduction

Astroparticle physics is the field of research that lies at the point where astronomy, particle physics and cosmology meet. It has been rapidly evolving in the past decades, at a pace that is still increasing. It utilises advanced particle physics methods to measure cosmic particles as well as cosmic messengers to also answer particle physics questions. Experimentally, it uses the advanced instrumentation of particle physicists, the lowest background rates and state-of-the-art imaging of the cosmos by astronomers. Theoretically, it connects the extremely large, e.g., the Big Bang Model of cosmologists, to the extremely small, e.g., the Standard Model of particle physicists. It aims to gain insights into long-standing enigmas at the heart of our understanding of the Universe – for example:

- **The Extreme Universe:** *What can we learn about the cataclysmic events in our Universe by combining all messengers – high-energy gamma rays, neutrinos, cosmic rays and gravitational waves – that we have at our disposal?*
- **The Dark Universe:** *What is the nature of Dark Matter and Dark Energy?*
- **Mysterious neutrinos:** *What are their intricate particle properties and what can they tell us about the universe at large?*
- **The Early Universe:** *What else can we learn about the Big Bang – for instance, from the cosmic microwave background (CMB)?*

Against the backdrop of the increasing complexity, extensive running time and high capital investment of the experiments operated and planned by the European astroparticle physics community, the field organised itself in 2001 with the establishment of APPEC as its coordinating body. Figure 1 shows APPEC's member countries in 2022.

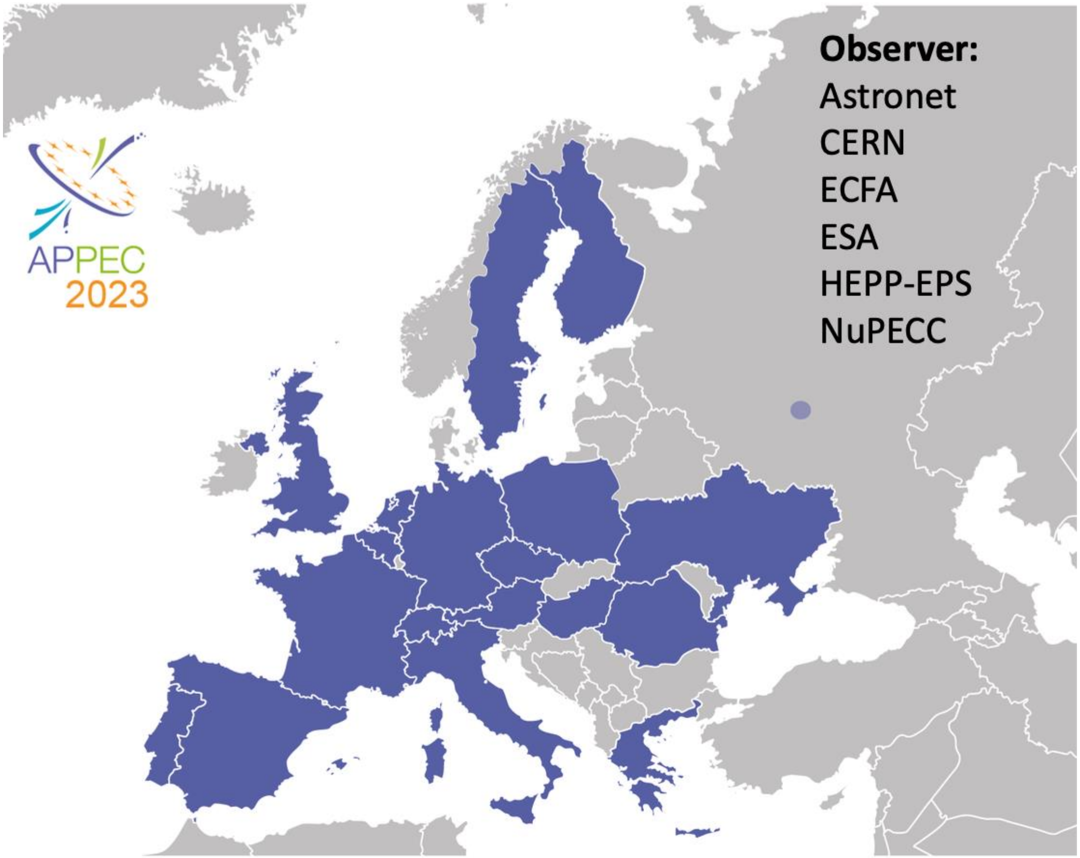

Figure 1: APPEC member countries 2023

APPEC published a science vision, coined the 'European Strategy for Astroparticle Physics', in 2008, and its first prioritised roadmap in 2011. This strategy was succeeded by the APPEC European Strategy for Astroparticle Physics 2017-2026. Since then, the field has made rapid further progress, with one of the highlights being the multi-messenger observations of a neutron star merger. Such multi-messenger observations were foreseen in the 2017-2026 strategy and now have materialised thereby fulfilling the promise of opening an entirely new window to the universe. In addition, the landscape of experiments and observatories changed since 2017, possibly making some reprioritization warranted. The APPEC General Assembly, therefore, decided to have a mid-term review of the APPEC European Strategy for Astroparticle Physics 2017-2026, which resulted, with some delay due to the Covid-19 pandemic, in this report with an updated strategy for the second half of the 2017-2026 period. This mid-term update does not aim to fully repeat the full APPEC European Strategy for Astroparticle Physics 2017-2026 document. Rather, in this introduction relevant developments since 2017 will be mentioned in the next section followed by an updated set of recommendations. This mid-term update also considers an update of the collective funding level expected to be available at national agencies and through the EU.

In the second part of the APPEC European Strategy for Astroparticle Physics 2017-2026 the astroparticle physics landscape is sketched. Nothing had changed since then in its historical development and its scientific and societal relevance, which remain very high. Steady progress was made in answering some of the long-standing enigmas of fundamental particle physics and astronomy, where the role of astroparticle physics research is invariably prominent, such as:

- *What is Dark Matter?*
- *What is Dark Energy?*
- *What caused our Universe to become dominated by matter and not anti-matter?*
- *Can we probe deeper into the earliest phases of our Universe's existence?*
- *What are the properties of neutrinos?*
- *Can we identify the sources of high-energy neutrinos?*
- *What is the origin of cosmic rays?*
- *Do protons decay?*
- *What do gravitational waves tell us about General Relativity and cosmology?*
- *What will multi-messenger astronomy teach us?*

But we have not been able to find definitive answers to any of these questions yet, and as they are relevant as ever, our quest becomes only more urgent.

Over the past few years, some major successes were obtained in the multi-messenger approach. The binary neutron star coalescence observed by the LIGO/Virgo collaboration, GW170817, and specifically the observations by more than 70 other electromagnetic radiation observatories covering the bands from gamma rays, to optical light and radio in the aftermath of this cataclysmic event, has led to many new insights, ranging from the origin of gamma-ray bursts to the nucleosynthesis mechanisms for many of the elements we daily use on Earth. The non-observation of neutrinos by several of the large neutrino observatories posed constraints on the physics that ruled during the merger. The first observation of a high-energy neutrino from the blazar TXS 0506+056, which was also observed with gamma rays and optical light, gave deeper insight into the physics of the jets of this object and the acceleration mechanisms for high-energy cosmic rays. These are two spectacular examples that marked the start of the strategy period as a transition period of expectations from multi-messenger astroparticle physics to one of seeing the first multi-messenger events, confirming that the expectations for the future are warranted. At the same time, upgrades of the Pierre Auger Observatory and Telescope Array, improvements and announced further rigorous upgrades of the IceCube Observatory, progressing deployment of the KM3NeT ARCA detector and various other improvements of existing facilities and proposed upgrades and new observatories further add to the expectations from multi-messenger astronomy. In addition, the upgraded and proposed observatories often can detect more than one messenger, making them very efficient and effective for multi-messenger astroparticle physics.

Since the start of the current strategy period, several key measurements have been made on neutrinos. The direct mass measurement from KATRIN has set a stricter limit of the effective lightest neutrino mass and in the coming period, further improvements on this measurement can be expected. The joint observations from several short and long baseline neutrino beam experiments combined with measurements on atmospheric and astronomical neutrinos have improved our knowledge of their mixing matrix, where in terms of the strength of the mixing the precision era has started and where there are now clear hints for the complex phase to be right in between real and imaginary. At the same time, great progress was made on the design and R&D for the next generation of neutrinoless double beta decay experiments. A dedicated APPEC committee produced a lucid report with clear recommendations on how to best move forward on this very important measurement.

In the realm of the early universe, there have been some important changes in the next generation of observatories, both on the ground and in space. The time seems ripe now for Europe to engage in the leading facilities.

The situation that, within the current best models, we can determine with great precision that the largest part of the universe is not the matter we know and love but consists of matter and energy we have little or no knowledge of remains stunning. The way forward to solve this enigma must be many-pronged, looking at it from any viewing angle possible. While in particle physics there are extreme efforts at producing dark matter particles, astroparticle physics concerns itself with direct and indirect detection. Indirect dark matter detection is getting more sensitive hand in hand with the increase in sensitivity to all kinds of messengers in many different observatories. In the direct search for dark matter, experimental sensitivities have been dramatically increased, and the community agrees that it wants to continue the WIMP search down to the ``neutrino floor'' while at the same time investigating alternative dark matter candidates such as axions. The APPEC Direct Dark Matter Detection Committee has delivered a report with clear recommendations on the next steps in Direct Dark Matter detection.

The importance of theory remains paramount in interpreting the experimental outcomes, devising new experiments and integrating knowledge from many places in theories and models. A new step was made in 2020 with the establishment of the European Consortium for Astroparticle Theory (EuCAPT) as a hub to increase the exchange of ideas and knowledge and to coordinate scientific and training activities in the field of astroparticle physics theory.

The general advances in machine learning also have their impact on astroparticle physics research and the end of progress in this field is not yet in sight. This means that an entirely new generation of scientists must be trained in data science. It also poses new demands on computing infrastructure and triggers thinking about efficient computing.

Not only has astroparticle physics research advanced but also society in general evolves fast and the field of astroparticle physics researchers is no exception. At the APPEC Town Meeting in Berlin in June 2022, leading to this update of the strategy, the participants deemed the way how the astroparticle physics community functions in a larger societal context at least as important as what this community is researching. More emphasis is put on the recognition and reward for individual researchers and their role in team science, especially also for young researchers. Diversity, Equity and Inclusion are now fully embraced principles to which the field wants to adhere as best as they can while recognising that these values are evolving in time as well. Societal impact is no longer largely measured in terms of industrial applications, but now represents a much richer palette, including our responsibilities in education, open science and citizen science. Next to societal impact, the ecological impact of our science, experiments and observatories has also become an important part of the debate.

While the APPEC European Strategy for Astroparticle Physics 2017-2026 remains valid for the overall course of the field, including many of the more specific recommendations, the developments sketched above warrant an updated direction on some issues. This results in minor changes in the strategy for almost all scientific matters, except for the CMB experiments, where the landscape of future space experiment(s) changed significantly. In addition, the importance of multi-messenger astroparticle physics has gained even more weight. More drastically, our view on how we want to responsibly operate as a community has changed; hence, more emphasis is put on those aspects in this update.

The APPEC General Assembly adopted these updated recommendations by consensus at its meeting in Warsaw on 28-29 June 2023. Crucial to the future successes of European astroparticle physics, its continuation as an experimental and theoretical ecosystem in the larger context of bordering science is APPEC's overarching priority.

Science

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), new physics messengers (dark matter), gravitational waves and cosmological and dark energy observations. In addition, the study of neutrino properties provides crucial input for the understanding of the Universe and its evolution. European coordination is essential to ensuring the timely implementation of large and medium-scale infrastructures and enabling Europe to retain its scientific leadership in astroparticle physics. Establishing these infrastructures and reaping their fruits to the maximum is impossible without vibrant detector R&D, computing, and theory communities.

High-Energy Gamma Rays

Recent discoveries, particularly at energies greater than 100 TeV and/or contemporaneous with gravitational wave detections, have underlined the importance of high-energy gamma rays for the exploration of the extreme Universe. The next European-led project, the Cherenkov Telescope Array (CTA), is expected to start operation in the next few years and will cover gamma rays with energies from a few 10s of GeV to a few 100 TeV. At lower energies, in the so-called ‘MeV gap’, which has received little attention until recently, European scientists are planning the THESEUS satellite mission. The European-led Southern Wide-field Gamma-ray Observatory (SWGO) is being designed to detect gamma rays from 100s of GeV to 100s of TeV using an approach that is highly complementary to CTA, Fermi and the Chinese-led, northern-hemisphere LHAASO experiment. These developments are welcomed by APPEC, but it also notes with concern that there will be no coverage in the GeV regime once Fermi ceases operation.

Recommendations:

APPEC fully endorses the construction and subsequent long-term operation of CTA in both the northern and southern hemispheres. APPEC supports work towards the selection of the mission concept THESEUS and the construction of SWGO. It urges the community to consider a replacement for the Fermi telescope.

High-Energy Neutrinos

IceCube’s first observation of PeV-scale cosmic neutrinos in 2013 has opened an entirely new window onto our Universe: neutrino astronomy. This, together with the opportunity to resolve the neutrinos’ mass ordering by studying atmospheric neutrinos, led ESFRI to include KM3NeT 2.0 in its 2016 roadmap, with operation anticipated to commence in the 2020s. KM3Net will have dedicated neutrino astronomy (ARCA) and neutrino mass ordering measurement (ORCA) parts. The data collected by IceCube provide growing evidence of neutrino sources which is supported by multi-messenger astronomy. Within the Global Neutrino Network (GNN), the IceCube, KM3NeT and Baikal-GVD collaborations have joined forces to provide a network of large-volume detectors viewing both northern and southern hemispheres and to capitalise on the full discovery potential of neutrino astronomy. The possibilities of additional neutrino telescopes located off the coasts of Canada (P-ONE) and China (TRIDENT) are currently being explored. Radio detection techniques utilised by RNO-G which is under construction in Greenland expand the view at ultrahigh energies.

Recommendations:
APPEC fully endorses the goal of the KM3NeT collaboration to complete the construction of the large-volume telescope optimised for high-energy neutrino astronomy ARCA, and the dedicated detector to resolve the neutrino mass hierarchy ORCA. APPEC strongly supports the construction of the IceCube Upgrade, and the ambition to build IceCube-Gen2 in the following decade.

High-Energy Cosmic Rays

To understand the origin and acceleration of the highest-energy cosmic rays and their interaction with the earth's atmosphere, knowledge of their nucleus type is the key. The AugerPrime upgrade of the Pierre Auger Observatory (Auger), including the now-matured radio detection, will considerably improve determining the particle type and will increase sensitivity to ultra-high-energy gamma rays and neutrinos. The Telescope Array observatory (TA) will extend its surface area coverage, thereby greatly enhancing its exposure. There is a need for a next-generation very large ultra-high-energy cosmic ray observatory, for which GRAND and GCOS have been proposed, which still requires significant R&D. Current and future experimental efforts must go together with matching theoretical effort to understand air shower physics and the physics of cosmic ray sources and propagation.

Recommendations:
APPEC fully endorses the completion of AugerPrime and strongly supports the exploitation of the combined Auger and TA full sky coverage by joint working groups. APPEC encourages continued R&D on new cost-effective detector technologies for a next-generation observatory. APPEC encourages theory efforts to understand air shower physics, physics at cosmic-ray sources and cosmic-ray propagation.

Gravitational Waves

Gravitational-wave astronomy is a newly emerging field of research that has enabled us to probe the most energetic transients in the universe, such as the merger of binary systems of black holes and neutron stars. It has revealed the physics governing these events, which is impossible to achieve through electromagnetic or particle observations. Gravitational-wave observations had a gigantic impact on many fields of research, from fundamental physics to astrophysics, from nuclear physics to cosmology. It is expected that the next generation of gravitational wave observatories will trigger a revolution in at least some of these fields. The Einstein Telescope (ET), recently included in the ESFRI roadmap, and the Cosmic Explorer will make precise gravitational-wave astronomy possible and will access all cosmological scales back to the early universe. LISA and the Pulsar Timing array will open a window to observations at lower frequencies, making gravitational-wave emission from yet unobserved astrophysical and cosmological sources detectable for the first time. Until these new missions are in operation, it will be important to keep improving Virgo with the Advanced VirgoNEXT programme.

Recommendations:
APPEC strongly supports actions to enlarge European countries' participation in ET, acquire funds for ET construction and operations, and develop the ET scientific community. APPEC supports building the bridge between second and third-generation detectors to maintain

European expertise and leadership in the field and the VIRGO observation capability up to when the ET will start observations. APPEC strongly supports the LISA mission.

WIMP Dark Matter

The nature of Dark Matter (DM) is one of the most important questions of contemporary physics. The current generation liquid xenon (LXe) direct Dark Matter detection experiments, PandaX-4T, XENONnT, and LZ, came online in 2020-2022, with active target masses of 4-7 tonnes and projected cross-section sensitivities of the latter two of 10^{-48} cm^2 scale at 30 GeV DM mass. The XENON, LZ and DARWIN collaborations joined forces in 2021, forming the XLZD consortium, aiming to build and operate a liquid xenon detector with a projected reach beyond 10^{-48} cm^2 in the next decade. The liquid argon (LAr) detector community has joined in the Global Argon Dark Matter Collaboration in 2017 to build DarkSide-20k, currently planned to start operation in 2026, with 50 tonnes active target and an expected reach of 2×10^{-48} cm^2 scale at 100 GeV. At 5 GeV DarkSide-50 has reached a limit of 1×10^{-43} cm^2, and demonstrated the ability to search for dark matter with masses down to the 50 MeV scale. At masses below 1 GeV, cryogenic solid-state experiments, e.g., SuperCDMS and CRESST, as well as skipper CCDs, e.g., SENSEI and DAMIC-M, expect to achieve a 10^{-42} cm^2 cross-section reach on a 5-year time scale. Expanding the accessible mass range has created new connections between astroparticle physics and quantum sensor technology, which led to new funding initiatives in Europe and elsewhere. Given the broad parameter space for Dark Matter candidates, a diverse experimental approach remains essential, including R&D in directional detection and new technologies, e.g., based on quantum sensors.

Recommendations:

APPEC strongly supports the European leadership role in Dark Matter direct detection, underpinned by the pioneering LNGS programme, to realise at least one next-generation xenon (order 50 tons) and one argon (order 300 tons) detector, respectively, of which at least one should be situated in Europe. APPEC strongly encourages detector R&D to reach down to the neutrino floor on the shortest possible time scale for WIMP searches for the widest possible mass range.

Axions, ALPs and other non-WIMP Dark Matter

The search for ultralight Dark Matter particles has gained significant momentum. Axions or axion-like particles (ALPs) could be detected directly or be produced in the laboratory in prospective light shining-through-wall experiments. A milestone has been achieved by the ADMX experiment, which in 2019 probed the Peccei-Quinn axion coupling regime for masses of micro-eV. Since 2017 several 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, aiming to increase the broad-band sensitivity in the micro-eV to eV mass range by more than an order of magnitude. 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, AION). Such experiments also target gravitational-wave sensitivity in the mHz-Hz frequency regime.

Recommendations:

APPEC supports the unique European-led efforts for axions and ALPs detection in mass ranges complementary to the established cavity approach. APPEC encourages R&D efforts to improve experimental sensitivity and extend the accessible mass range.

Neutrino Mass and Nature

Neutrino oscillation experiments demonstrate that neutrinos have very special properties, several of which are not known yet. These include, above all, the very small neutrino mass values and whether the neutrino is its own antiparticle (Dirac/Majorana). These two questions can be investigated by studying the (double) beta decay of selected isotopes. From the endpoint spectrum of beta decay or electron capture the neutrino mass scale can be directly inferred. The search for the neutrinoless double beta decay will primarily test the particle nature of neutrinos since this Beyond the Standard Model and lepton-number-violating process is only possible if the neutrinos are of Majorana-type. Its observation would additionally give information about the generation mechanism and neutrino mass spectrum. The ongoing experiments with strong European participation and the planned experiments LEGEND1000 (^{76}Ge) and CUPID (^{100}Mo) are among the most competitive. NEXT (^{136}Xe) is a promising option for the next decade. Confirmation of discovery will require results from several isotopes and measurement technologies. In direct neutrino mass searches KATRIN (^{3}H) is leading the field, new technologies are cryo-bolometers of ECHo and Holmes (^{163}Ho) or CRES of Project 8 (^{3}H).

Recommendations:

APPEC strongly supports the CUPID and LEGEND1000 double-beta decay experiments selected in the US-European process and endorses the development of NEXT. APPEC strongly supports fully exploiting the potential of the KATRIN direct neutrino mass measurement and the development of a new generation of experiments beyond KATRIN.

Neutrino Mixing and Mass Ordering

CP violation in the lepton sector is a key question in particle physics and, together with the Majorana character of neutrinos, might even explain the baryon asymmetry of the universe. The ORCA programme within the KM3NeT neutrino telescope offers a European perspective on neutrino mass ordering. The IceCube upgrade with important European participation will also contribute to neutrino oscillation observations. Dedicated long baseline neutrino oscillation experiments are ideally suited for the precise determination of the oscillation parameters, including establishing the violation of matter/antimatter symmetry and of the neutrino mass ordering. Building on LAr detector technologies first developed in Europe, the DUNE accelerator neutrino experiment at the Long-Baseline Neutrino Facility in the USA and the JUNO reactor neutrino experiment in China are being prepared. DUNE, together with the accelerator neutrino water Cherenkov experiment under construction Hyperkamiokande exposed to a neutrino beam from J-PARC in Tokai, Japan, will have a discovery potential on leptonic CP violation. The large neutrino experiments will also feature unsurpassed sensitivities for low-energy cosmic messengers (e.g., supernova neutrinos) and for the much sought-after proton decay.

Recommendations:

APPEC repeats its strong endorsement of the KM3NeT neutrino telescope, with ORCA as an important neutrino mass ordering detector. APPEC strongly supports European participation in the long baseline neutrino oscillation experiments DUNE and Hyper-Kamiokande, as well as in the JUNO reactor experiment.

Cosmic Microwave Background

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. With better precision, the next generation of experiments aims at trying to identify the tell-tale sign of cosmic inflation: the imprint of primordial gravitational waves on CMB polarisation modes, as well as characterising neutrinos and Dark Matter. Ground-based CMB studies provide crucial independent and complementary knowledge to space-based experiments.

Recommendations:
APPEC encourages European contributions to the Japanese LiteBIRD mission as well as R&D for further space-based CMB studies, such as a possible successor to COBE/FIRAS. APPEC encourages contributions to CMB Stage 4 and R&D towards other, next-generation, ground-based experiments.

Dark Energy

Dark Energy, which is used as a catch-all term regardless of whether it arises from vacuum energy or modification of general relativity, is the hypothetical form of energy behind the Universe's accelerated expansion. Along with Dark Matter, it is one of the least-well-understood components of the cosmos. It is studied via a ‘multi-probe’ approach, including Type Ia Supernovae and large galaxy surveys, both satellite-based and ground-based, that combine spectroscopic, photometric, and weak-lensing techniques to reconstruct the expansion history and growth of cosmic structure. To fully exploit data from next-generation cosmology experiments, the exchange and combination of data from both satellite- and ground-based telescopes will be essential.

Recommendations:
APPEC supports the forthcoming ESA Euclid satellite mission, which will establish European leadership in space-based Dark Energy research. APPEC encourages continued participation in next-generation ground-based research projects, e.g., Rubin-LSST and spectroscopic surveys such as DESI and proposed successors.

Multi-messenger Astroparticle Physics

APPEC has identified as a very high priority those research infrastructures that can be used to observe all confirmed astronomical messengers. Observations of electromagnetic radiation, neutrinos, cosmic rays and gravitational waves are jointly referred to as multi-messenger astronomy. For example, different observations together provide the key to identifying the origin of high-energy cosmic rays. The multi-messenger approach is also shown to be crucial for understanding transient phenomena, a prime example of which has been the observations of the binary neutron star merger GW170817, which as a single event probed by several messengers has provided a wealth of new information. APPEC foresees a central role for multi-messenger astronomy in the coming decades. Coordination is essential to ensuring simultaneous operations of the different observatories and the networks that enable (quasi) real-time analysis and follow-up observations.

Recommendations:
APPEC supports the further development and coordination of optimised multi-messenger observational strategies, common tools and data formats. Optimising future observatories for multi-messenger observations is strongly supported. APPEC encourages efforts to enhance collaboration among theorists, experimentalists, observers, and experts in data analysis and computing from different communities.

Theory

Astroparticle physics research is a concerted effort between theory and experiment. As well as inspiring a vast spectrum of experiments, unified theories of fundamental interactions are indispensable to the analysis and interpretation of experimental data. Many European institutes recognise the exciting challenges presented by astroparticle physics and, accordingly, are expanding their activities in the field of theory. APPEC has established the European Consortium for Astroparticle Theory (EuCAPT) as a hub to increase the exchange of ideas and knowledge and to promote scientific and training activities in the field of astroparticle physics theory.

Recommendations:
APPEC fully supports an ambitious theory programme in the field of astroparticle physics, with special attention focused on adjacent disciplines such as particle physics, astronomy and cosmology. APPEC supports EuCAPT as a thriving hub for astroparticle physics theorists from Europe and the rest of the world.

Detector R&D

Frontier experiments in the field of astroparticle physics rely on innovative particle detection technologies and instrumentation that are rarely available as off-the-shelf products. Occasionally, new technologies even open entirely new detection concepts or industrial applications with societal impact. With activities in many European institutes, detector R&D constitutes a cornerstone of the astroparticle physics community. APPEC welcomes the 2021 ECFA detector R&D roadmap for particle physics and acknowledges the synergy with particle physics detector R&D. APPEC would welcome a new Phase 1 ATTRACT cycle. APPEC encourages the formation of consortia to apply for funding in the major EU funding instruments.

Recommendations:
APPEC stimulates and supports a range of detector R&D projects through targeted common calls and technology fora that bring scientists and industries together. APPEC encourages consortia to apply for EU (technology) grants for detector R&D programmes. APPEC welcomes the ATTRACT initiative and supports a new round for the phase 1 call. APPEC encourages universities, institutes and funding agencies to ensure that appropriate career paths and funding opportunities are available for instrumentation scientists.

Computing and Data Policies

To date, the computing needs of the European astroparticle physics community have been modest and could be accommodated by the Worldwide LHC Computing Grid. However, several of the future large observatories dedicated to multi-messenger studies of our Universe will require massive computing resources for data simulation, template matching and data storage and analysis. In parallel, awareness is growing that much can be gained by the sharing of large data sets, Machine Learning and AI algorithms, and best practices between experiments and communities. Training in data-intensive science for the next generation of astronomers and physicists is crucial for the success of current and future large projects. Training in data science also provides opportunities outside of academia. Data policies also touch on Open Science and Citizen Science, which will be addressed in a later section of this document.

Recommendation:

APPEC requests all relevant experiments to continue to have their computing requirements scrutinised. APPEC will engage with the particle physics and astronomy communities to secure a balance between available European computing resources and needs for now and into the future. Appropriate training in data science should be provided for astroparticle physicists.

Connecting to Society

Ecological Impact

With the strongly increasing societal awareness of the ecological impact, astroparticle physics cannot stay behind. Ecological impact is an important aspect to consider for current and future experiments. Current experiments should mitigate adverse ecological effects as much as possible, whereas future experiments should enshrine minimising ecological impact in the design from the start. The research field has a large negative impact on ecology from travel. The recent Covid-19 pandemic has taught us better how to minimise travel and optimise remote meeting tools. The recent sharp increase in energy costs has made the necessity to consider minimising energy consumption even further. The use of computing resources also adds to a negative ecological impact and better data management and more efficient software can help to mitigate this in part. On the other hand, astroparticle physics measurements can contribute to a better understanding of ecological impact by monitoring environmental parameters and sharing these measurements. Detector R&D can lead to establishing techniques and ideas that can be applied in society to mitigate or avoid negative ecological impact.

Recommendations:

APPEC encourages experiments to assess their ecological impact and report their findings publicly and to mitigate the adverse ecological impact as much as possible. APPEC recommends keeping travel to a minimum and using smart computing strategies to minimise the use of computer resources. APPEC encourages the monitoring of environmental parameters where possible and the application of R&D results to mitigate the ecological impact in general.

Societal Impact

There are many ways in which astroparticle physics and astroparticle physicists have a positive impact on wider society. Many of the ultra-sensitive detector developments for astroparticle physics have benefitted other research fields and have societal and industrial applications. The science pursued by astroparticle physicists is of great interest to the public, from schoolchildren to teachers and ordinary citizens, since it includes dark matter, neutron stars, black holes, supernovae, "ghost particles" (neutrinos), etc. Communities local to astroparticle physics experiments, often in remote locations, benefit from their presence, not only in terms of jobs and infrastructure but also from the engagement of the scientists with schools. One of the largest contributions to society is the training of scientists, from Bachelor and Master students to PhD candidates and postdocs, most of whom find their way into a wide variety of industries and services that are in dire need of people with their education and skills. The fascination of our field evokes a special commitment from our early-career scientists, which translates into outstanding skills and capabilities.

Recommendations:

APPEC encourages experiments to continue to seek applications for their work which will benefit the wider society. APPEC also encourages the integration of astroparticle physics into science curricula, not only at the university but also in schools. APPEC encourages knowledge transfer to industrial partners.

Open Science and Citizen Science

Open science is a policy priority for the European Commission and many of the states and funding agencies of the APPEC members. It is not only about open publishing but also about sharing data, analysis tools and ideas according to the Findable Accessible Interoperable and Reusable (FAIR) principles. The current funding programme Horizon Europe's open science policy requires data to be FAIR and open by default (with some specific exceptions). Several initiatives (such as ESCAPE and AHEAD2020) are underway to implement the European Open Science Cloud and make data, analysis and theory tools accessible. Citizen Science refers to scientific research conducted by amateurs as “science for the people, by the people”. This type of engagement of the public potentially increases the scientific capabilities of experiments by having more, different and possibly unexpected use of the available data.

Recommendations:

APPEC encourages the use of data format standards to facilitate data access between experiments. APPEC encourages funding agencies and publishers to support coherent Open Access publication policies. APPEC encourages making data publicly available as much as possible according to the FAIR principles. APPEC encourages citizen science to engage the public, while at the same time increasing the scientific capabilities of experiments.

Organisation

Human Talent Management

A fundamental asset for scientific research is human capital. To attract talented early career researchers, they should be interested already from school age on, with special attention to inclusivity. Talents should be retained by offering a diverse and vibrant working environment that is inclusive and socially and scientifically safe. Astroparticle physics thrives because of a diverse workforce, ranging from technically to theoretically oriented scientists. Throughout their career, scientists should be supported and subjected to fair and transparent granting and career opportunities, where the various aspects of talent are all appropriately recognised and rewarded.

Recommendations:

APPEC insists that the scientific community follows the APPEC, ECFA and NuPECC diversity charter. This charter should be updated following the latest insights into diversity, equity and inclusion. APPEC encourages collaborations to establish a diversity charter and a code of conduct. APPEC calls on all astroparticle physicists to apply transparent criteria for grant applications and career advancement, valuing the various aspects of talent appropriately.

Central Infrastructures

Among the important infrastructure for astroparticle physics are the deep underground laboratories. Shielded by up to about a kilometre of rock they provide the low background condition that is crucial for a variety of astroparticle physics experiments trying to observe extremely rare events, such as neutrinoless double beta decay, dark matter interactions with detectors, or neutrino interactions with detectors. Achieving very low backgrounds took many years of experience and maintaining them takes a significant effort. Different European deep underground laboratories can fulfil different sets of requirements for experiments and the diversity of infrastructures is a significant asset. Exchanging expertise and bundling forces, e.g., in maintaining low background measurement and screening equipment and in documenting and exchanging radio-pure and extremely low background materials, will further reinforce the unique European underground Laboratories infrastructures for astroparticle physics.

Recommendations:

APPEC strongly encourages the European Underground Laboratories to maintain, and expand when necessary, their ability to facilitate low background experiments. APPEC encourages the European Underground Laboratories involved in astroparticle physics to establish a Virtual Coordination Office that establishes robust cooperation in key services and support for experiments, coordinates future investments in deep underground infrastructures and establishes a trans-national access policy.

European and Global Cooperation

Most of the astroparticle physics research directions require a global strategy in addition to European coordination. In some cases, this may be due to substantial capital requirements or running expenses (e.g., for large multi-messenger observatories); in others, it may be because of the advantages of pursuing complementary technologies (e.g., for next-generation Dark Matter searches and the measurement of neutrino properties). For the observation of rare transients and global surveys, full sky coverage with observatories around the world is important. In some cases, the collaboration between different observatories, even across research fields, can lead to much better precision or much deeper understanding (e.g., in the field of gravitational wave detection, or ultimately in all multi-messenger observatories). Global coordination of activities in the overarching area of sustainability, social impact and training is also becoming increasingly important.

Recommendation:
APPEC will continue to seek collaboration and coordination with its global partners — scientists, funding agencies and society— to advance the design, construction, sustainable use and governance of the next generation of large-scale, world-class research infrastructures to make the scientific discoveries we all dream of.

Interdisciplinary Opportunities

The necessity to closely cooperate with particle physics, nuclear physics and astronomy is obvious in the astroparticle physics field. In addition, many of our infrastructures offer unique opportunities for other research disciplines or industry. Cabled deep-sea and deep-ice neutrino telescopes, for example, are of great interest to marine biologists and geologists, while deep underground laboratories offer test facilities ideal for biologists studying the evolution of life in low radioactivity environments and microbial life under extreme conditions.

Recommendation:
APPEC will continue interdisciplinary workshops and foster interdisciplinary access to its entire research infrastructure, both in academia and with industry.

Resources

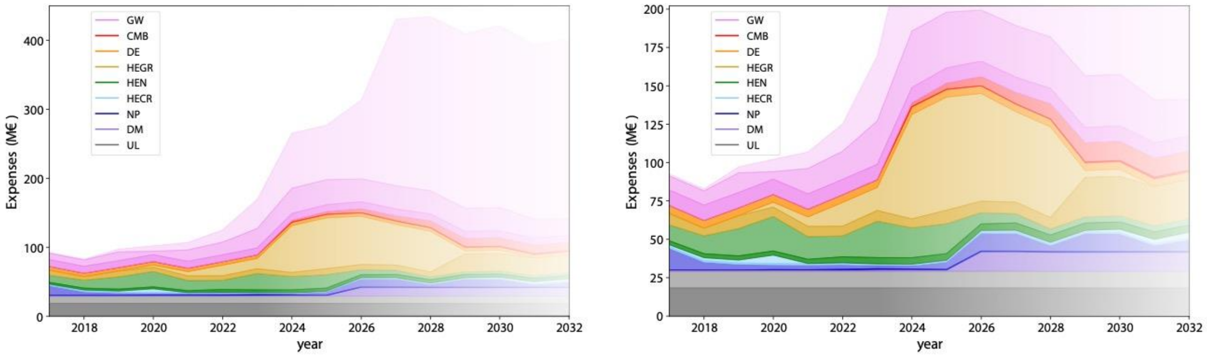

Figure 1: Estimate of realised and planned investment and exploitation expenditures in Astroparticle Physics. The division of the APP sub-fields is UL: underground laboratories; DM: Dark Matter experiments; NP: Neutrino Properties experiments; HECR: High-Energy Cosmic Ray Observatories; HEN: High-Energy Neutrino observatories; HEGR: High-Energy Gamma Ray observatories and satellite missions; DE: Dark-Energy observatories and satellite missions; CMB: Cosmic Microwave Background observatories and satellite missions; GW: Gravitational Wave observatories and satellite missions. The exploitation is given by the darker shade for each colour and the investment budget by the lighter shade. For Gravitation Waves, three shadings have been used: dark for exploitation, middle tone for investments (to be) covered by the usual funding agencies and light for investments from exceptional sources, such as national, regional or EU (economic) structure funds. The part after 2023 has increasing uncertainties on the difference between planned and realised expenditures as time goes on. The right-hand side figure has a truncated vertical scale to make the relative magnitudes of the sub-fields apart from Gravitational Waves better visible.

The major astroparticle physics experiments have been asked to provide information through a questionnaire to update the expected annual investment and exploitation costs. This is the basis for the figure of European expenses on APP as a function of the year that is presented above. Whereas Neutrino Mixing was given as a separate item in the original 2017-2026 strategy, it is now included in Neutrino Properties.[1]

The figures include the full projected investment in the Einstein Telescope. With a total planned investment budget of 1.8 B€, this dominates the total European APP expenses from 2024 onwards. However, a large fraction of the investments will have to come from exceptional resources, such as European, regional, and national investment funds that are not primarily targeted to fundamental science. The part foreseen for the traditional funding agencies is given in the figure in a middle-tone shade of pink. Although this is a small part of the ET investment, it still represents a sizable fraction of the total planned expenses in APP. In the right-hand side figure, the maximum cost scale is set to 200 M€/year to better expose the funding lines that are competing for the same overall European APP resources. In both figures the spending levels get more and more uncertain in the future, indicated by the fading for the future part.

For the years that have passed the total expenses are in line with the numbers given in the 2017-2026 strategy report, although there are relative shifts between the different research domains. For the coming years, a major increment can be observed. This is mainly due to two facts. The investment in CTA has been delayed and is foreseen to catching up in the coming years, resulting in a bulge in the investment for the years 2023 to 2029. The exploitation budget for CTA has now also been carefully estimated and is a major expense from 2029

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[1] In the 2017-2026 strategy the neutrino mixing cost included the investment in DUNE, which is largely done through particle physics projects, notably with a large CERN contribution. This contribution is no longer included in this estimate of the European Astroparticle Physics costs.

onwards. The second new fact is the Einstein Telescope, which is getting on firm grounds and for which major work has been done on costing. Of these two major investment schemes, the CTA investment has been mostly secured. The ET investment is not secured yet but is part of the major European investment roadmaps. The onset of the ET investments is already noticeable in the recent past and for the near future, e.g., through spending on project studies and investment in the Einstein Telescope Pathfinder and Einstein Telescope infrastructure Consortium programmes.

Outlook Towards the Next Strategy Update

Progress in Astroparticle Physics since 2017 has been enormous and while this mid-term update of the 2017-2026 APPEC Astroparticle Physics Strategy has not rigorously changed the course of the field, it has resulted in some significant updates of the strategy for a good number of topics. And the pace at which Astroparticle Physics research is moving will not slow down, and likely even accelerate in the next few years and beyond. In addition to the scientific progress that will change our perspective, society at large, of which the Astroparticle Physics community is part, is changing. This has led to transformative changes in the way our research field is functioning socially and in what it is expected to contribute to society. This has become evident in an increased weight on the connecting to society and organisation sections of this document. And the importance of these sections will likely grow further.

For all these reasons, a new APPEC Astroparticle Physics Strategy from 2027 onwards will likely not be business as usual. It will require yet another thorough discussion in our community, which should be held in the years 2025 and 2026 and be prepared before that time, starting in 2024. By that time several large projects that are mentioned as being under construction here will have become data-taking and producing new results. Several of the preparatory projects that are encouraged in this update will have become much more concrete. Many encouraged R&D projects will have delivered results that lay the ground for the feasibility of new projects that can be prepared. And our community, as embedded in the larger human society, will have transformed further, changing the way we work and the connections we make to society. We live in interesting times now and probably even more so when a new strategy has to be established by 2027.

Acronyms and Abbreviations

ADMX	Axion Dark Matter eXperiment
AION	Atom Interferometer Observatory and Network
ALP	Axion-Like Particle
ALPS	Any Light Particle Search experiment
ALPSII	Second version of ALPS
APP	AstroParticle Physics
APPEC	AstroParticle Physics European Consortium
ARCA	Astronomy Research with Cosmics from the Abyss
Auger	Pierre Auger Observatory
AugerPrime	Upgrade of the Pierre Auger Observatory
BabyIAXO	Small forerunner experiment of IAXO
CCD	Charged Coupled Device (detector)
CDMS	Cryogenic Dark Matter Search
CMB	Cosmic Microwave Background
CRESST	Cryogenic Rare Event Search with Superconducting Thermometers
CTA	Cherenkov Telescope Array
COBE	Cosmic Background Explorer
COBE/FIRAS	COBE Far InfraRed Absolute Spectrophotometer
CUORE	Cryogenic Underground Observatory for Rare Events
CUPID	CUORE Upgrade with Particle IDentification
DAMIC-M	Dark Matter in CCDs experiment
DarkSide	Dark Matter experiment
DARWIN	Dark Matter experiment
DE	Dark Energy
DM	Dark Matter
DUNE	Deep Underground Neutrino Experiment
ECFA	European Committee for Future Accelerators
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
ET	Einstein Telescope
EU	European Union
EuCAPT	European Consortium for Astroparticle Theory
FAIR	Findable, Accessible, Interoperable and Reusable
GCOS	Global Cosmic-ray Observatory
GRAND	Giant Radio Array for Neutrino Detection
IAXO	International Axion Observatory
IceCube	South Poel Neutrino Detector
IceCube-Gen2	Second generation follow-up of IceCube
J-PARC	Japan Proton Accelerator Research Complex
JUNO	Jiangmen Underground Neutrino Observatory
KM3NeT	Cubic kilometre neutrino telescope
LAr	Liquid argon
LEGEND1000	Large Enriched Germanium Experiment for Neutrinoless double-beta Decay
LHAASO	Large High-Altitude Air Shower Observatory
LIGO	Laser Interferometry Gravitational-wave Observatory

LiteBird	Light Satellite for the studies of B-mode polarization and Inflation from background Radiation Detection
LNGS	Laboratori Nazionali del Gran Sasso
LXe	Liquid xenon
LZ	Lux-Zeplin
MADMAX	MAgnetized Disc and Mirror AXion experiment
MAGIS	Matter-wave Atomic Gradiometer Interferometric Sensor
NEXT	Neutrino Experiment with a Xenon TPC
NuPECC	Nuclear Physics European Collaboration Committee
ORCA	Oscillation Research with Cosmics from the Abyss
PandaX-4T	Dark Matter experiment
SENSEI	Sub-Electron Noise Skipper Experimental Instrument
SWGO	Southern Wide-field Gamma-ray Observatory
SuperCDMS	Successor experiment of CDMS
TA	Telescope Array
THESEUS	Transient High-Energy Sky and Early Universe Surveyor
TPC	Time Projection Chamber
Virgo	Interferometer at the European Gravitational Observatory
WIMP	Weakly Interacting Massive Particle
XENON	Xenon Dark Matter experiment
XLZD	joint XENON, LZ and DARWIN experiment