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

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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, e.g., for a new CMB satellite mission [not best example], 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, e.g., for high-energy gamma rays. 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 [can be misinterpreted]. Open science is rapidly becoming the norm. Societal impact is now a must. Therefore, the strategic objectives in how we would like to operate as scientists in the astroparticle physics research field has become more important and more 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 is reassessed in a global way and gives rise to the idea that, while always struggling for more resources, the baseline budget of the field gives it a bright future.

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Capture the essence per item:

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Recommendation	40- 80 words

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, 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. The illustration shows APPEC's member countries in 2022.

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.

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Introduction

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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 on 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?*

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Introduction

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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 merger into a black hole observed by the LIGO/Virgo collaboration, GW170817, and specifically the observations by 70 other observatories of gamma-rays and optical light 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.

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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 has 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 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 about 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.

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Introduction

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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 has to be trained in data science. It also poses new demands on computing infrastructure and triggers thinking about efficient computing.

Not only astroparticle physics research advances, 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 for 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. For almost all scientific matters this results in minor changes of the strategy, perhaps 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 and hence more emphasis is put on those aspects in this update.

The APPEC General Assembly adopted these updated recommendations by consensus at its xx-th meeting, held in Place in Month Year. 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

High-Energy Gamma Rays

Recent discoveries, particularly at energies greater than 100 TeV and [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 construction of THESEUS and SWGO. It urges the community to consider a replacement for the Fermi telescope.

Science

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 2020's. [ARCA and ORCA sentence] 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 possibility of an additional neutrino telescope located off the coasts of Canada (P-ONE) is being explored. Radio detection techniques utilised by RNO-G which is under construction in Greenland expand the view at ultrahigh energies. For ultra-high-energy a surface detector (GRAND) and a satellite experiment (POEMMA) are being studied.

Recommendations:

APPEC fully endorses the goal of the KM3NeT collaboration to complete the construction of the large-volume telescopes ARCA and ORCA. APPEC strongly supports the ambition to build IceCube-Gen2 in the following decade.

Science

High-Energy Cosmic Rays

To understand the origin and acceleration of the highest-energy cosmic rays and their interaction with the earth 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 ground-based experiments GRAND and GCOS have been proposed and the space based POEMMA, which all still require 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. APPEC encourages continued R&D on new cost-effective detector technologies for a next-generation observatory. APPEC strongly supports the exploitation of the combined Auger and TA full sky coverage by joint working groups. APPEC encourages theory efforts to understand air shower physics, physics at cosmic-ray sources and cosmic-ray propagation. [Too many APPEC repeats]

Science

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, recently included in the ESFRI roadmap, and the US-led Cosmic Explorer will make precise gravitational-wave astronomy possible and will access all cosmological scales back to the early universe. LISA and Pulsar Timing arrays 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. [Mention (Adv) Virgo(+) (next).]

Recommendations:

APPEC strongly supports actions to enlarge European countries' participation in ET, to acquire funds for ET construction and operations, and to develop the ET scientific community. APPEC supports building the bridge between second- and third-generation detectors to maintain the European expertise and leadership in the field up to when the ET will start observations. APPEC strongly supports the LISA mission.

Science

[Weak mass scale DM/ GeV-TeV range] WIMP Dark Matter

[Explain WIMP] The nature of Dark Matter (DM) is one of the most important questions of contemporary physics. The current generation Xe 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 10^{-48} cm^2 scale at 30 GeV DM mass. The DARWIN, XENON and LZ 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 Ar detector community has joined in the Global Argon Dark Matter Collaboration to build DarkSide-20k, planned to start operation in 2025, with 50 tonnes active target and expected reach of 10^{-47} cm^2 scale at 1 TeV. At masses below 10 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, with the aim of realising 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 especially well below the GeV scale.

Science

Axions, ALPs and other sub-eV Dark Matter candidates

The search for light, sub-eV Dark Matter particles has gained significant momentum. Axions or axion-like particles (ALPs) and similarly behaving particles from space could be detected or they could be produced and detected in the laboratory. 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, AEON [check 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 to the widest possible range of candidates and to extend the accessible mass range.

Science

Neutrino mass and nature

Neutrino oscillation experiments demonstrate neutrinos to have very special properties, but not all properties are 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 inferred directly. The search for the neutrinoless double beta decay will primarily test the particle character of neutrinos, since this Beyond the Standard Model and lepton number-violating process is only possible if the neutrinos are Majorana-type. Its observation would additionally give access to its mass values and generation mechanism. The ongoing and planned experiments with strong European participation LEGEND (^{76}Ge) and CUPID (^{100}Mo), together with the US-led nEXO, are among the most competitive. The NEXT collaboration explores new technologies to further increase sensitivity. 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).

[Mention NEXT]

Recommendations:

Of the double-beta decay experiments selected in the US-European process APPEC fully endorses CUPID and strongly supports realising LEGEND-1000. APPEC supports R&D exploring technologies for larger sensitivity, like 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.

Science

Neutrino mixing and mass ordering

CP violation in the neutrino sector together with the Majorana character of neutrinos could explain the baryon asymmetry of the universe. Dedicated long baseline neutrino oscillation experiments are ideally suited for precise determination of the intricacies of neutrino mixing, including establishing violation of matter/antimatter symmetry, and the neutrino mass ordering. Building on LAr detector technologies first developed in Europe, the DUNE accelerator neutrino experiment in the USA and the JUNO reactor neutrino experiment in China are being prepared. DUNE, together with the accelerator neutrino water Cherenkov experiment Hyperkamiokande in 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.

[Mention KM3NeT (i.e. ORCA) and IceCube Upgrade (nu-mixing), IceCube-Gen2.]

Recommendations:

APPEC strongly endorses the KM3NeT neutrino telescopes ORCA and ARCA. APPEC strongly supports European participation in the long baseline experiments DUNE and Hyper-Kamiokande, as well as in the JUNO reactor experiment.

Science

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 and FIRAS. APPEC encourages contributions to CMB Stage 4 and R&D towards other, next-generation, ground-based experiments.

Science

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 Supernovae Ia 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, 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.

Science

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 a number of 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 observational strategies, common tools and data formats. APPEC encourages efforts to enhance collaboration among theorists, experimentalists, observers, and experts in data analysis and computing from different communities.

Science

Theory

Astroparticle physics research is a concerted effort between theory and experiment. As well as inspiring a vast spectrum of experiments, 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, with the help of CERN, 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.

Science

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.

Science

Computing and Data Policies

To date, the computing needs of the European astroparticle physics community have been modest and much of which is 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 the 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, nuclear physics and astronomy communities to strike the 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.

Connection to Society

Ecological Impact

With the strongly increasing societal awareness of 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 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 adverse ecological impact as much as possible. APPEC recommends keeping travel to a minimum and to use smart computing strategies to minimise the use of computer resources. APPEC encourages the monitoring of environmental parameters where possible and to apply R&D results to mitigate ecological impact in general.

Connection to Society

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

Engaging with Society

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 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. 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 establishing and using 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 as a way to engage the public to increase 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 in 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.

Organisation

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 strongly encourages the European Underground Laboratories involved in astroparticle physics to establish a Coordination Office that establishes a robust cooperation in key services and support for experiments, coordinates future investments in deep underground infrastructures and establishes a trans-national access policy.

Organisation

European and Global Cooperation

Most of the astroparticle physics research directions have a need for 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 in pursuing complementary technologies (e.g., for next-generation Dark Matter searches and the measurement of neutrino properties). In some cases, 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.

Organisation

Interdisciplinary Opportunities

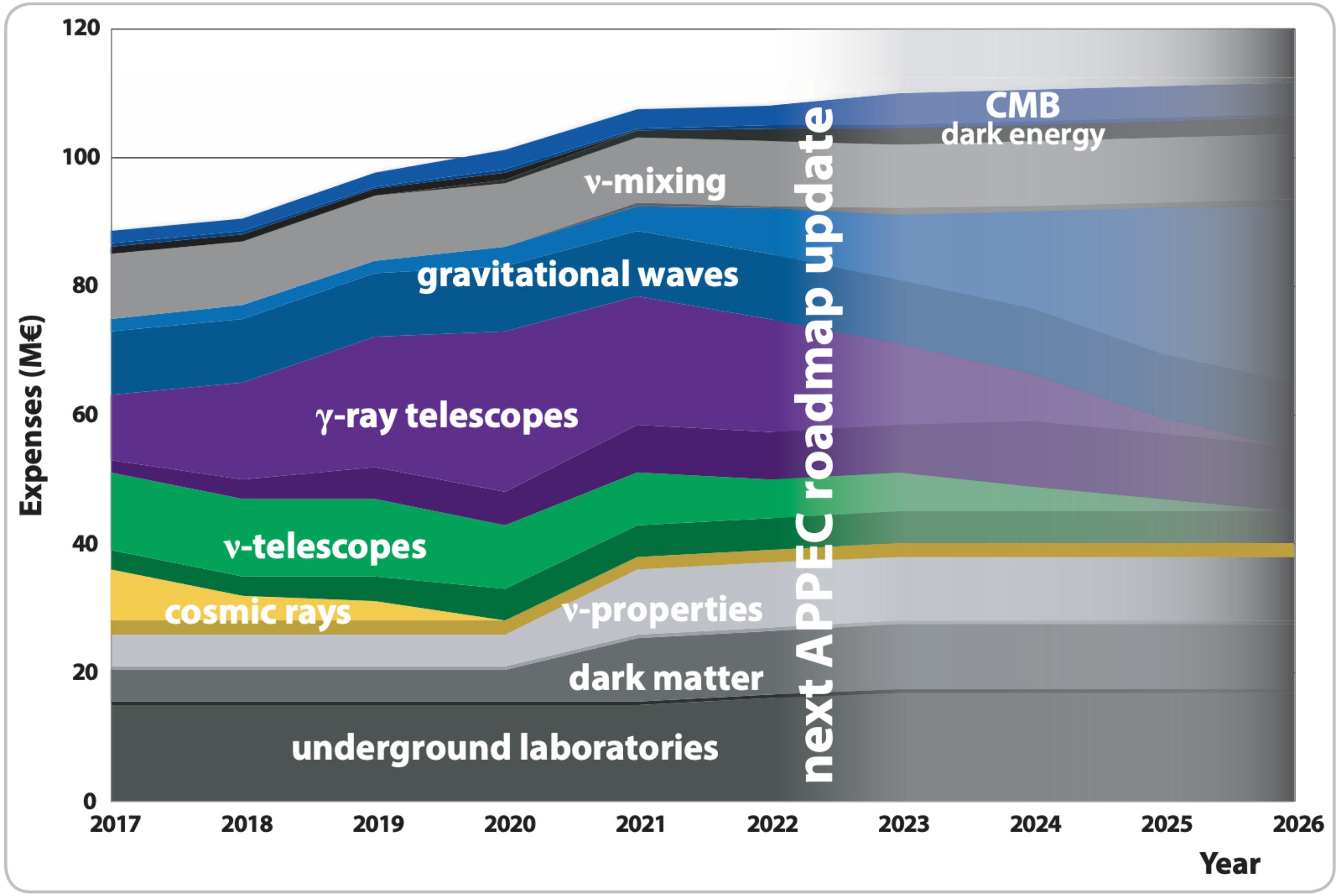
Many of our infrastructures offer unique opportunities for other research disciplines or for industry. Cabled deep-sea and deep-ice neutrino telescopes, for example, are of great interest to marine biologists and geologists, while deep underground laboratories offer test facilities ideal for biologists 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.

Organisation

Resources



Census was held under

- experiments' spokes
- lab directors

Results being prepared

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 of 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.