

European Strategy for Astroparticle Physics

APPEC–Astroparticle Physics European Consortium



Introduction

Astroparticle physics is the rapidly evolving field of research at the intersection of astronomy, particle physics and cosmology. Experimentally, it combines the advanced instrumentation of particle-physicists with the highest standard of imaging the cosmos by astronomers. Theoretically, it connects the Big Bang model of cosmologists to the standard model of particle physicists. The former gives a detailed description of the evolution of the macro-cosmos while the latter describes with stunning precision the micro-cosmos. Scientifically, astroparticle physics aims to gain insight into long-standing enigmas at the heart of our understanding of the universe such as:

- HE** **High-energy 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?*
- D** **Dark universe:** *What is the nature of Dark Matter and Dark Energy?*
- V** **Mysterious neutrinos:** *What are the intricate properties of neutrinos and what can they tell us?*
- BB** **Early universe:** *What else can we learn about the Big Bang – for example from the cosmic microwave background?*

Given the increasing complexity, extensive running time and high capital investment of the experiments operated and planned by the European astroparticle physics community, the field organized itself in 2001 with APPEC as its coordinating body. The illustration shows the 2016 APPEC member countries. APPEC published a science vision, coined *European Strategy for Astroparticle Physics*, in 2008 and its first prioritized roadmap in 2011. The field made revolutionary progress since, with as a highlight the recent discovery of gravitational waves tracing back to one of the most energetic events in our universe ever witnessed by humanity: the merging of two black holes. The coming decade promises to be equally successful with an impressive arsenal of cutting-edge experiments expected to come into operation probing deep into the above scientific questions.

Competitive European participation in this dynamic and exhilarating field of research requires careful prioritization – *notably regarding the larger infrastructures* – and in most cases consultation and collaboration with our global partners and colleagues working in astronomy, particle physics and cosmology. The construction and, most importantly, also the running costs of projects must be scrutinized.

The new APPEC 2016 roadmap takes into account the collective funding level expected to be available at the national agencies and the EU and as such is not only a *science vision* but aims to be a *resource-aware* roadmap. The attribution of resources across the various activities is indicated in the attached graphic and summarizes APPEC's funding priorities in the context of global scientific ambitions. Its realization will allow for European researchers to successfully capitalize on past efforts and investments and promises to shed bright light on the composition and the mindboggling dynamics of our universe.

Recommendations

The goals APPEC aspires to achieve in the coming decade are presented below, formulated as 21 recommendations. They are clustered in three categories: *scientific issues*; *organizational issues*; and *societal issues*. The success of this strategy will be determined by coherent action on all recommendations. This can only be achieved in close cooperation with the scientific community that APPEC represents – *the European astroparticle physicists* – with our various national governments and funding agencies, the European Commission, our partners outside Europe and those working in the intimately connected research fields of particle physics, astronomy and cosmology as well as the strong pillars these latter fields rely upon (CERN, ESO and ESA).

As a rapidly evolving and dynamic field, the scope and focus of astroparticle physics varies slightly from one country to another. Despite this heterogeneity the APPEC General Assembly adopted these recommendations by consensus at its 10th meeting in Stockholm, November 2016.

The scientific issues presented below primarily address ‘big science’ projects for which the realisation hinges upon a concerted – multi-national and often multi-disciplinary – strategy. Without exception, these projects build upon a vibrant ecosystem of smaller-scale experiments, innovative detector R&D and model building rooted in national institutes, laboratories and universities throughout Europe. The continuation of this ecosystem is crucial to the future successes of European astroparticle physics and as such constitutes APPEC’s overarching priority.

Scientific issues – large-scale multi-messenger infrastructures

APPEC identified as a very high priority the research infrastructures exploiting all confirmed high-energy messengers (gamma-rays, neutrinos, cosmic rays and gravitational waves) to understand better our universe. European coordination is essential to ensure their timely implementation in order for Europe to retain its scientific leadership in this field.

1. High-energy gamma-rays:

D HE With ground-based gamma-ray telescopes such as H.E.S.S. and MAGIC and key participation in satellite missions like Fermi, Europe has played a pioneering and leading role in establishing high-energy gamma-rays as an ideal messenger particle to explore the extreme universe, as witnessed by the astonishing number of sources discovered in recent years. The ‘Cherenkov Telescope Array’ (CTA) is the ESFRI-listed next-generation and Europe-led global project. It has excellent discovery potential ranging from fundamental physics to astronomy and is expected to start full operation as an observatory in 2023.

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

2. High-energy neutrinos:

v D HE IceCube’s first observation of PeV-scale cosmic neutrinos in 2013 has opened an entirely new window onto our universe: neutrino astronomy. This, combined with the opportunity to resolve the neutrino mass hierarchy studying atmospheric neutrinos, led ESFRI to include KM3NeT 2.0 in its 2016 roadmap with an anticipated start of operation in 2020. Within the ‘Global Neutrino Network’ (GNN), the IceCube and KM3NeT collaborations join forces to realize a network of large-volume detectors viewing both northern and southern hemispheres to efficiently exploit the full discovery potential inherent to neutrino astronomy.

For the northern site, APPEC strongly endorses the KM3NeT collaboration’s ambitions to realize by 2020 a large-volume telescope with optimal angular resolution for high-energy neutrino astronomy and a dedicated detector optimized for low-energy neutrinos primarily aiming to resolve the neutrino mass-hierarchy. For the southern site, APPEC looks forward to a positive decision in the USA regarding IceCube-Gen2.

3. High-energy cosmic-rays:

v HE The ‘Pierre Auger Observatory’ (Auger) is the world’s largest and most sensitive ground-based air-shower array. Understanding the

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

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

4. **Gravitational waves:**

BB HE The first direct observations of gravitational waves by the LIGO-Virgo Consortium have revealed a scientific treasure trove. Multi-solar-mass black holes coalescing within seconds into a super-massive black hole and simultaneously radiating the equivalent of a few solar-masses of energy as gravitational waves is now an established fact and provides unprecedented tests of General Relativity. A new and revolutionary window onto our universe has opened: gravitational-wave astronomy. Herein, the laboratories hosting the gravitational-wave antennas play a crucial role by developing new technologies to increase detection efficiencies further. The recently reached incredibly high-precision in monitoring free falling objects in space by ESA's LISA Pathfinder mission is an important step towards the complementary (low-frequency) space-based gravitational-wave astronomy.

With its global partners and in consultation with the 'Gravitational Wave International Committee' (GWIC), APPEC will define the

timelines for upgrades of existing as well as next-generation ground-based interferometers. APPEC strongly supports further actions strengthening the collaboration between gravitational-wave laboratories. APPEC strongly supports Europe's next generation ground-based interferometer, the 'Einstein Telescope' (ET) project, to develop the required technology and to acquire ESFRI status. Regarding space-based interferometry, APPEC strongly supports the European eLISA proposal.

Scientific issues – medium-scale

Dark Matter & neutrino experiments

APPEC considers as its core assets the diverse, often ultra-precise and invariably ingenious, suite of medium-scale laboratory experiments targeted at the discovery of extremely rare processes. These include experiments to detect the scattering of Dark-Matter particles and neutrinoless double-beta decay and the direct measurement of the neutrino mass using single-beta decay. Collectively these searches must be pursued to the level of discovery, unless precluded by an irreducible background or an unrealistically high capital investment demand.

5. **Dark Matter:**

V D Elucidating the nature of Dark Matter is a major spearhead of astroparticle physics. Amongst the plethora of subatomic particles proposed to explain the Dark-Matter content in our universe, one category stands out: the 'Weakly Interacting Massive Particle' (WIMP), arising for instance naturally in supersymmetric extensions of the standard model of particle physics. Many experiments located in deep-underground laboratories are searching for WIMP interactions. For masses in excess of a few GeV, the best WIMP sensitivity is reached with detectors using ultra-pure liquid noble-gas targets like XENON1T (3.5 tons of xenon) and DEAP (3.6 tons of argon), which both started operating in 2016. Their sensitivity can be further enhanced by increasing the fiducial mass. A suite of smaller-scale experiments explores in particular the low-mass WIMP and other Dark-Matter hypotheses such as dark photons and axions.

APPEC encourages the continuation of a diverse and vibrant programme (experiments as

well as detector R&D) searching for WIMPs and non-WIMP Dark Matter. Together with its global partners, APPEC aims to converge around 2019 on a strategy of how to realize worldwide at least one ‘ultimate’ xenon (order 50 tons) and one argon (order 300 tons) based Dark-Matter detector as advocated by the DARWIN and ARGO consortia, respectively.

6. **Neutrino mass & nature:**

D **V** Despite all previous efforts very fundamental characteristics of the neutrino are still unknown, notably the neutrino mass and whether the neutrino is its own anti-particle (‘Majorana type’) or not (‘Dirac type’). Both can be assessed studying beta-decays of selected isotopes. Single beta-decay allows for direct kinematical inference of the neutrino mass. First results of the world-leading KATRIN experiment in Germany are eagerly awaited. The double beta-decays of e.g. germanium, tellurium or xenon are used to probe physics beyond the standard model in a unique way by searching for decays without neutrinos. This process is only allowed for Majorana-type neutrinos and its observation would not only reveal the neutrino nature and pinpoint its mass, but also demonstrate the violation of lepton number. Between the variety of experiments worldwide searching for neutrinoless double-beta decay, European experiments such as GERDA (germanium), CUORE (tellurium) and NEXT (xenon) rank amongst the most competitive.

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

Scientific issues – synergies with astronomy, particle physics & cosmology

APPEC is a long-term proponent of experiments using accelerator neutrino beams and neutrinos from nuclear reactors to elucidate in particular the neutrino mixing and neutrino mass hierarchy. Recognising the increasingly interdisciplinary reach

of astroparticle physics, APPEC has broadened the scope of its roadmap to explicitly include two topics already referred to in its 2008 science vision: cosmic microwave background (CMB) and Dark Energy. These areas of research are flourishing as witnessed by Nobel Prizes in 2006, 2011 and 2015. CMB and Dark-Energy research not only complement the core astroparticle physics topics but also yield stringent constraints on the neutrino masses and on the role of neutrinos in the early universe.

For the scientific issues addressed hitherto, the focus was on projects primarily funded by European astroparticle physics agencies. By contrast, for the three topics in this section the main funding is likely to come from American and Asian agencies or from the European particle physics and astronomy communities.

7. **Neutrino mixing & mass hierarchy:**

HE **V** For precise determination of the intricacies of neutrino mixing – including the much anticipated violation of matter-antimatter symmetry in the neutrino sector and the neutrino mass hierarchy – dedicated accelerator neutrino beams and neutrinos from nuclear reactors are ideal¹. With the Double Chooz concept, the Borexino liquid scintillator and the ICARUS liquid argon time-projection-chamber technologies, Europe pioneered and validated the enabling detection concepts that are now envisaged for large-scale facilities in the USA (the DUNE long-baseline neutrino experiment) and in Asia (the JUNO reactor neutrino experiment). The former emerged after the first of a series of global neutrino physics strategy meetings co-initiated by APPEC in 2014. Together with the HyperKamiokande project in Japan, these projects define the future of this field. DUNE and HyperKamiokande will also have unsurpassed and complementary sensitivities for low-energy cosmic messengers like supernova neutrinos and for the much sought after proton decay.

From a scientific point of view, and as part of a global strategy, APPEC strongly endorses

¹ With different systematics, also atmospheric neutrinos can be used to probe the neutrino mixing parameters and mass-hierarchy as mentioned in statement 2.

European participation in these projects in the USA and in Asia.

8. Cosmic microwave background - CMB:



The Planck ESA satellite mission gave Europe a major role in space-based CMB experiments while the USA leads ground-based CMB experiments. Apart from better precision, the next generation of CMB experiments is primarily aimed at trying to identify the tell-tale signs of cosmic inflation: the imprint of primordial gravitational-waves upon CMB polarisation modes.

APPEC strongly endorses the proposed European CORE satellite mission to map the CMB from space. APPEC will encourage detector R&D towards a next generation ground-based CMB experiment complementary to initiatives in the USA. APPEC continues to contribute to the global coordination of the field following the 'Florence CMB workshop' series started in 2015.

9. Dark Energy:



Dark Energy, the hypothesized actor behind the observed accelerated expansion of our universe, constitutes together with Dark Matter the least understood component in our universe. It is studied via large galaxy survey campaigns, both space- and ground-based, combining spectroscopic, photometric and weak-lensing techniques to reconstruct the growth of cosmic structures.

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

Scientific issues – foundations

Underpinning, driving and facilitating the aforementioned experiments are vibrant programmes in theoretical physics, cutting-edge detector R&D activities as well as efforts to provide adequate computing resources. APPEC has every intention to continue to support and stimulate

these activities in whichever way it can. In addition APPEC recognizes the uniqueness of the European infrastructures provided by its deep-underground laboratories. Without these laboratories key APPEC research objectives would become impossible to achieve.

10. Theory:



Astroparticle physics research is a concerted effort between theory and experiment. Unified theories of the fundamental interactions inspire a vast spectrum of experiments and are also indispensable in the analysis and interpretation of experimental data. Many European institutes recognize the exciting challenges in astroparticle physics and are expanding their theory activities.

APPEC supports an ambitious astroparticle physics theory programme with special attention for adjacent disciplines like particle physics, astronomy and cosmology. APPEC encourages the establishment of an astroparticle physics theory centre in one of its member countries.

11. Detector R&D:



Frontier astroparticle physics experiments rely on innovative particle detection technologies and instrumentation that are rarely available as off-the-shelf products. Occasionally, new technologies even open up entirely new detection concepts or industrial applications. With activities in many European institutes, detector R&D constitutes a cornerstone of the astroparticle physics community.

APPEC stimulates and supports a range of detector R&D projects by means of targeted common calls and Technology Fora bringing together scientists and industries. APPEC encourages consortia to apply for EU- (technology) grants such as achieved by SENSE for low-level light sensor technologies. APPEC welcomes the ATTRACT initiative which aims to accelerate the development of particle-radiation detector- and imaging technologies for science and the market.

12. Computing & data policies:



To date the computing needs of the European astroparticle physics community have been modest and could be accommodated by the 'Worldwide LHC Computer Grid' (WLCG).

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 analysis and storage. In parallel there is a growing awareness that much can be gained by sharing 'big data' and best practices between experiments and communities.

APPEC requests all relevant experiments to have their computing requirements scrutinized. APPEC will engage with the particle physics and astronomy communities – for example within the context of EU-TO – to secure also for the future a balance between available European computing resources and needs. Furthermore, APPEC encourages using data format standards to facilitate data access between experiments. APPEC supports the transition to Open Access publication strategies and APPEC encourages to make data publicly available – 'open data' – to foster for example 'citizen science'.

13. Unique infrastructures –



deep underground laboratories:

Deep underground laboratories shielded by thousands of metres of rock host a diverse suite of (often unique) extremely low-background experiments and provide a platform for multi-disciplinary collaboration.

In view of maintaining a good match between available capacity and planned activities, APPEC fosters continued support and cooperation between underground laboratories as for example advocated in the DULIA – Deep Underground Laboratory Integrated Activity – initiative.

Organizational issues

As a 'big science' research field, astroparticle physics critically relies on large infrastructures requiring large investments. This makes collaboration – national, European and even global a sine-qua-non. Similarly an interdisciplinary field like astroparticle physics not only naturally interacts closely with the astronomy and particle physics communities but also offers opportunities to other fields of research and industry.

14. **European Commission:**

European astroparticle physics successfully

contributes to the aims of the European Commission to strengthen excellence and attractiveness in research and innovation and economic and industrial competitiveness. The present APPEC consortium is building upon the past success of the EU-supported ASPERA project. ESFRI status and EU structural- and regional funding play an increasingly important role in the realization of our large research infrastructures. ERC grants often drive original ideas that are difficult to pursue otherwise. Astroparticle physics technology already has demonstrated innovative commercial applications.

APPEC will continue to work with the European Commission in order to strengthen the EU capitalizing upon astroparticle physics' technologies and ideas as well as to make optimal use of the already existing opportunities within the various EU programmes both in view of science and in view of generating economic value.

15. **European collaboration & coordination:**

This roadmap itself is the result of an intense process, culminating in the Town Meeting of the European astroparticle physics community in Paris, April 2016. Prominent flagship astroparticle physics infrastructures – such as the CTA and KM3NeT ESFRI projects and the future Einstein Telescope project – require capital investments that surpass the capabilities of a single European country.

APPEC will explore ways to align the realistically available funding in Europe to maintain the excellent discovery potential for European scientists. Project governance, management, computing needs and running costs require serious attention.

16. **Global collaboration & coordination:**

Some research directions warrant a global strategy. Either simply because of the substantial capital or running expenses (e.g. for multi-messenger facilities), or because of the advantages in pursuing complementary technologies (e.g. for next-generation Dark-Matter searches & the measurements of neutrino properties). In some instances the co-operation of different observatories as a single inter-connected network leads to a much better precision or deeper understanding

(gravitational-wave detectors or ultimately all multi-messenger observatories).

APPEC will continue to seek global collaboration and coordination with its partners – scientists and funding agencies – to advance the design, construction, sustainable exploitation (including computing requirements) and governance of the next generation world-class large research infrastructures required to achieve the scientific discoveries of which we all dream.

17. Astronomy & particle physics communities:

APPEC's field of interest naturally touches astronomy and particle physics. ESO and CERN are already long-term observers at our APPEC meetings and events. With possible future space-based projects such as Euclid, CORE and eLISA, ESA is becoming another important partner.

APPEC will enhance its interactions with its present observers ESO and CERN in areas of mutual interest. APPEC will seek to engage with ESA in view of the upcoming astroparticle physics oriented space missions. This will ensure scientific complementarity where appropriate and allow closer collaboration with our colleagues working in astronomy and particle physics. As such APPEC welcomes ASTERICS which serves as a platform for closer collaboration between the ESFRI-listed projects SKA, CTA, KM3NeT and E-ELT.

18. Interdisciplinary opportunities:

Some of our infrastructures offer unique opportunities to other research disciplines or industry. Cabled deep-sea and deep-ice neutrino-telescopes are of great interest to marine biologists and geologists. Deep underground laboratories offer testing facilities to biologists studying the evolution of life in low radioactivity environments and of microbial life under extreme conditions.

APPEC will further develop interdisciplinary workshops and promotes interdisciplinary access to its full research infrastructure to the outside world – academia and industry alike.

Societal issues

Astroparticle physics is a prime example of curiosity-driven research. The excitement about the mysteries of the Universe as well as the recent

spectacular discoveries easily spark public interest and give rise to a watershed of outreach activities, which in turn capture people – *young and old, female and male* – and increase the educated skills base for the future. The inherent high-tech aspects of our instrumentation provide ample opportunity for industrial collaboration, not only in delivering the technologies required for the astroparticle physics projects, but also in applying these technologies to other challenges. In this way, pure science creates significant economic growth.

19. Gender balance:

APPEC contributes to an inclusive and gender-neutral working environment. Historically, physics is a field with low representation of female researchers, in particular in leading positions. Despite prominent role models, women remain underrepresented in our field of research.

Inspired by the H2020 project GENERA, APPEC will develop a gender balance policy for all its activities and APPEC will urge projects to develop and implement Gender Equality Plans.

20. Education & Outreach:

Astroparticle physics research enjoys a strong interest of students and general public alike as recently witnessed by the huge publicity surrounding the discovery of gravitational waves.

Given the rapid expansion of the field, APPEC encourages, for example in cooperation with the 'International Particle Physics Outreach Group' (IPPOG), the exchange of best practices regarding outreach. APPEC will implement a more structured organization of dedicated astroparticle physics summer schools and studentships at its frontier research facilities. APPEC will enhance its presence on the web and social media.

21. Industry:

Astroparticle physics creates and uses advanced technologies. Hence, a close cooperation with high-tech industry is vital. This interplay between basic research and innovation generates knowledge and technology with potential societal benefit. For example: cosmic-ray muon tomography is used to image volcanos, nuclear material, burial sites and blast furnaces for steel manufacturing; and

large-scale networks of seismic sensors have been developed for oil exploration and perimeter security.

APPEC will increase its efforts to identify potential applications of astroparticle physics expertise for societal benefit. In parallel APPEC will continue to organize its successful Technology Fora on targeted technologies as a discussion and collaboration platform for industry and academia.

Illustration is still in the works!

Projected capital investments (top) and running costs (bottom) expected from European astroparticle physics funding agencies to realize APPEC's European astroparticle physics strategy. Other European funding (e.g. via the European Commission, particle physics or astronomy funding agencies) as well as contributions from outside Europe (notably America and Asia) are excluded.