Report on a multi-messenger policy embedded in the European Roadmap of Astroparticle physics

***S.Katsanevas*[1]**

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This report is divided into 3 sections: in the first section I give a synoptic presentation of the key scientific and organizational issues to be addressed with respect to the European Strategy of Astroparticle Physics; in the second section I present the APPEC recommendations, as approved by the APPEC General Assembly and in the third section I give a short description of the 4 areas that constitute the multi-messenger domain, essentially edited from the "glossy" part of the APPEC roadmap. More development on specific domains and infrastructures is the subject-matter of other reports that will be submitted in parallel to the Scientific Council of IN2P3.

1. The European Roadmap and the implication of IN2P3, preliminary remarks

The discovery of the gravitational waves and the observation of neutrinos of cosmic origin shows that the promises of the first APPEC roadmap (ca 2008) when most of the proposed infrastructures ("the 7 magnificent") appeared as risky having not yet seen a signal, are in the processes of being fulfilled. We have entered a new era, where Astroparticle Physics does not have to justify its institutional existence but on the contrary is recognised as a leading force looked upon with expectation. On the other side, a very important task will be to cope with the increase of the scientific/organisational activities and the deployment of large European and Global infrastructures. This is the ultimate background against which the success of IN2P3 will be measured in the coming years.

Scientific issues. In the new context one can identify schematically five key scientific issues that cluster a series of questions and the associated infrastructures. These scientific issues are the following:

- ***The multi-messenger or "cosmic ray origin' issue***. It concerns the way that different probes (photons, CR, neutrinos and gravitational waves) are related between them. In this theme more specific questions are:
  - Can we find point-sources of UHE cosmic rays?
  - Can we find point-sources of HE neutrinos? What is then the mixture of galactic and extragalactic sources?
  - Related to the above: what is the relationship between high energy neutrino and high energy photon production? Can we find common point-sources? What is the relationship between UHE cosmic rays and neutrinos? These are questions addressing explicitly the issue of the origin of cosmic rays. But also, can we detect supernova (low energy) neutrinos?
  - Last but not least, can we localise sufficiently GW sources to be able to identify follow-up events in the other probes (low[2] and high energy photons or neutrinos)?
- ***The dark matter issue.*** Three types of infrastructures (direct searches in underground labs, indirect searches in multi-messenger observatories and production searches at LHC) are necessary to address it properly. Key sub-issues are:
  - Can we separate standard astrophysical processes from dark matter annihilation or decay?, at the multi-messenger infrastructures?
  - Once indices of discovery of dark matter are produced in indirect, direct and/or LHC searches can we pin-down its properties (mass, cross section, distribution, etc.)
- ***The cosmic structure issue***. For the first time, the cosmological survey sensitivities have reached the level that permits to "unify" the visible Universe from the recombination era (400.000y) to the present and thus:
  - Probe the distribution of dark matter, neutrino number and mass, using CMB studies, large "nearby"

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[1] My thanks to S. Loucatos for careful rereading of the manuscript

[2] It is important to stress the importance of low energy photons (KeV-MeV) accompanying e.g. GW events (e.g. SVOM)

surveys for dark energy ($z<2$) , galaxy distributions, reoinisation etc.

  - In this context it is necessary to understand and compare measurements of neutrino number and mass on earth with cosmological ones. Eventual discrepancies may point to new physics beyond the standard model of particle physics and/or cosmology. On what concerns the subject of this report, the high energy neutrino infrastructures will attack the issue of neutrino masses and nature (sterile) (e.g. ORCA/ARCA).
- **The gravitation and cosmology issue.** The sub-issues here are:
  - the full development of gravitational wave astronomy, in order to study the formation of galaxies, the existence of phase transitions in the Universe, eventually to also use the GW events as "standard sirens" to probe cosmological parameters
  - the discovery of the gravitational imprints of inflation on the CMB polarisation
- **The new physics issue.** The study of very high energy events, or events close to the "strong limit" of gravitation, or events testing Lorenz symmetry, open obviously the access to new physics for all infrastructures studied in this report.

All 5 infrastructures studied in the present scientific council (CTA, KM3Net/ORCA, Auger-Prime, Virgo, LISA) address in one way or another the 5 key issues above. This is why their construction is strongly recommended by the APPEC roadmap (see below).

Organisational issues. In the next years IN2P3 will need to accompany the building up of CTA, KM3Net, Auger-prime, the upgrade path of Virgo and the preparation of LISA.

In all cases the observance of models of sustainable and cost effective operation will be a strong prerequisite for success. In particular CTA and KM3Net being the first very large infrastructures of Astroparticle Physics to be deployed in the coming years, is a key test of the capabilities of the community and the agencies to develop a sustainable model of operation for large APP infrastructures. The experience of VIRGO and Auger should be used extensively. The same applies to the Virgo upgrade path, currently in discussion, with key question: what is the optimum upgrade and R&D path to the Einstein telescope? The space project LISA will follow the usual space practices.

More generally, it is my belief, that APPEC should create a pool of expertise (a special committee?) on the best practices of planning, implementation and operation of large infrastructures, along the lines initiated in the ASPERA days, and along the lines currently practiced by space and large US agencies. Non-optimal policies in the deployment and operation costs can become prohibitive for the emergence of future infrastructures, as is shown in other domains. IN2P3 could help APPEC create a standing committee with scientific/technical personalities with proven expertise in project management to assist the review and agency boards specific to each infrastructure.

A second important issue is the coordination with space projects and the relevant agencies (CNES, ESA…). The case for instance is clear for the Gravitational waves domain, where one has a complementary strong program on ground and space, but it can also be very important to have low energy photon detection in space for the follow-up of the same gravitational wave events. But it is equally important for CTA and KM3Net, see e.g. the scientific case of SVOM.

Thirdly, the program needs to be accompanied with a strong R&D program (in particular for GW detection but also UHECR) a well thought data policy and data management (for all 5 large infrastructures examined at the SC).

Finally, IN2P3 should not neglect to promote the interdisciplinary potential of the domain, since it is rich and would increase the resilience of the funding schemes. There are synergies with geoscience in deep sea high energy neutrino infrastructures but also GW techniques (seismology, deep earth study), deep biology in KM3Net, climate studies in CTA, AUGER and KM3Net, etc. A coordination with relevant national and European agencies should probably be sought.

2. 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:

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?*

Dark Universe: *What is the nature of Dark Matter and Dark Energy?*

Mysterious neutrinos: *What are the intricate properties of neutrinos and what can they tell us?*

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 APPEC member states (dark grey).

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.

High-energy gamma-rays

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 European-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.

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, 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, KM3NeT and Baikal-GVD 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 (including Baikal-GVD), 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.

High-energy cosmic-rays

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.

Gravitational waves

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 acquire ESFRI *status. Regarding space-based interferometry, iAPPEC strongly supports the European LISA 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.

Dark Matter

Elucidating the nature of Dark Matter is a major spear-head 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 program (experiments as well as detector R&D) searching for WIMPs and non-WIMP Dark Mat- ter. 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 proponents, respectively.

Neutrino mass & nature

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 neutrino-less 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 natural neutrinos from the Sun and the Earth's atmosphere as well as neutrinos from nuclear reactors and accelerators to elucidate the neutrino mixing and 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 vison: cosmic microwave background (CMB) and Dark Energy. These areas of research are flourishing as witnessed by Nobel Prizes in 2006 and 2011. 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.

Neutrino mixing & mass hierarchy

Neutrino oscillation, implying neutrino mixing and thereby the existence of non-zero neutrino masses, was discovered by experiments with solar and atmospheric neutrinos and rewarded with the Nobel Prizes in 2002 and 2015. For precise determination of the intricacies of neutrino mixing – including the much anticipated violation of matter-anti-matter symmetry in the neutrino sector and the neutrino mass hierarchy – dedicated accelerator neutrino beams and neutrinos from nuclear reactors are ideal. With the Double Chooz concept, the Borexino liquid scintillator and the ICARUS liquid argon time-projection-chamber technologies, Europe 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 European participation in these projects in the USA and in Asia.

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.

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.

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 program 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.

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- (technolo- gy) 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.

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 that experiments have their computing requirements scrutinized. APPEC will engage with the particle physics and astronomy communities– 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'.*

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.

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.

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.

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 facili- ties), 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.

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 LISA, 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.

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.

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.

Education & Outreach

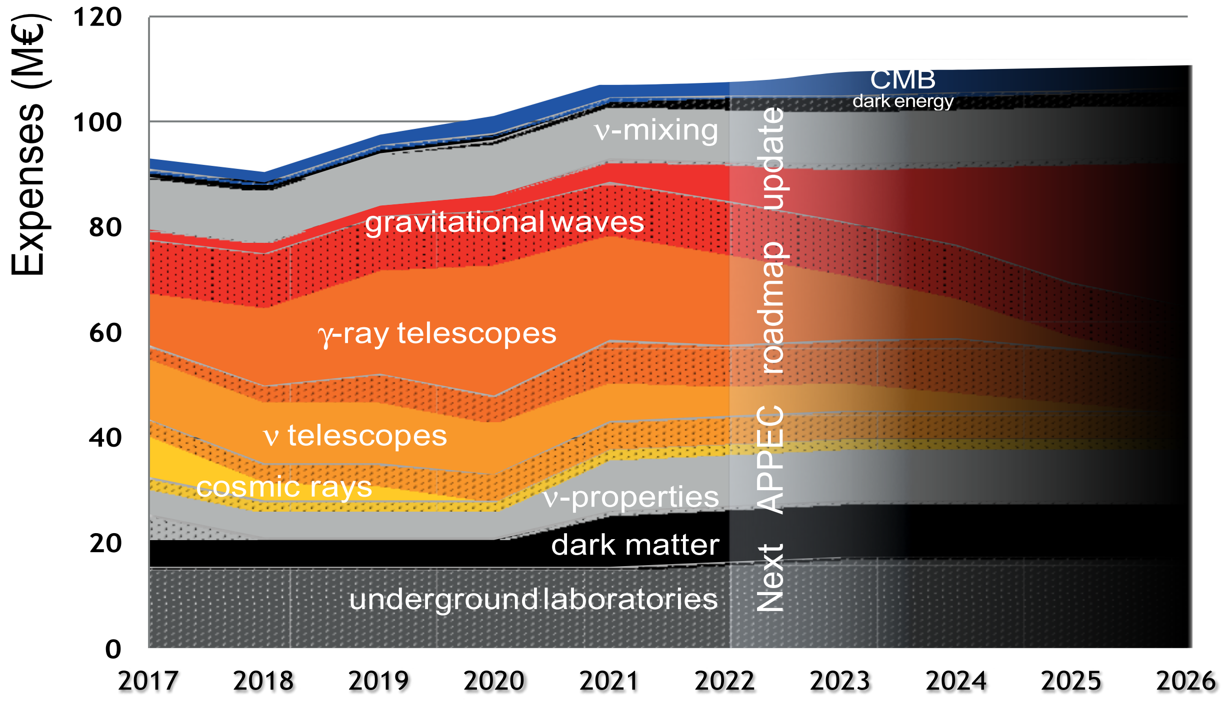
Astroparticle physics research enjoys a strong interest of students and general public alike as recently witnessed by the huge publicity surrounding the discovery of gravitational waves.

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.

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.



Projected annual capital investment – instrument prototyping and construction, excluding manpower – *and annual running costs* – consumables and shift taking expenses *i.e.* travel and manpower *(shaded areas) – anticipated from the European astroparticle physics funding agencies required to realize the APPEC* European Strategy for Astroparticle Physics. *Costs related to the actual scientific exploitation are not considered in this projection. Also excluded from this projection are other, often substantial, contributions from regional and EU structural funds, from European astronomy, from European particle physics (DUNE) and contributions from our non-European partners (in particular large ν-mixing infrastructures).*

3. The extreme Universe: the multi-messenger approach

Most electromagnetic radiation, including the visible light, we observe from our Universe is emitted by objects in near-thermal equilibrium that is following Planck's black-body radiation law. We apparently live in a 'thermal' Universe. The spectrum of our Sun, for example, matches Planck's prediction for an object with a temperature of about 6,000 °C. The afterglow of the Big Bang matches Planck's law to about one in 100,000 with an ice-cold temperature of −270.4 °C.

First evidence of non-thermal behavior in our Universe are cosmic rays occasionally reaching astonishing energies of up to a hundred billion GeV. With the exception of the Big Bang, not even the most extreme astronomical objects can attain the temperatures required to emit particles with such energies. Instead, they can be produced when ultra-relativistic particles – as for example produced in the aftermath of cataclysmic event like a supernova explosion – interact with ambient gas, photons or magnetic fields. Alternatively, super-heavy, hitherto unknown particles, could spawn very high-energy secondaries in their decay. And even more exciting: they could be the result of as yet entirely unknown mechanisms.

Cosmic-rays alone are probably insufficient to unambiguously differentiate between these options. Even though their energies and directions are relatively easy to reconstruct, as a messenger particle they have a severe drawback: their measured directions are scrambled by (inter)galactic magnetic-fields. Unless their energy is extremely high, this makes it difficult to track the measured directions back to the sources.

Fortunately, other messenger particles of non-thermal events in our Universe have been observed: high-energy gamma rays, high-energy neutrinos and, very recently, gravitational waves. Unlike cosmic rays, these are unaffected by (inter)galactic magnetic-fields. Nevertheless, each has its own peculiarities. Gamma rays for example are easily absorbed by inter-stellar dust while neutrinos and gravitational waves are notoriously difficult to detect. It is therefore that by combining the analysing power of all four messengers – *high-energy cosmic rays, gammas and neutrinos and gravitational waves, collectively referred to as the multi-messenger approach* – that astroparticle physicists hope to better understand the non-thermal Universe and thereby to unveil the sources of high-energy cosmic rays. A crucial factor herein is the – already ongoing – process of interconnecting the various multi-messenger observatories amongst themselves as well as to traditional observatories viewing the electromagnetic spectrum to trigger fast follow-up observations to hopefully identify the source of a cataclysmic event.

The multi-messenger approach also allows a wide range of other exciting research topics: searches for the decays of extremely heavy particles, Dark Matter annihilation and even the violation of Lorentz invariance whereas detailed studies of gravitational waves will provide unprecedented tests of the theory of General Relativity.

3.1 High-energy cosmic-rays

Cosmic rays are predominantly protons and heavier atomic nuclei which, upon impact on Earth, hit atmospheric molecules at 15–20 kilometres altitude to generate avalanches of secondary particles called air showers. Cosmic rays span a gigantic energy range from sub-GeV to record energies of at least a hundred billion GeV. Whereas low-energy cosmic rays are known to come from the Sun and other stars, the sources spitting out atomic nuclei with energies reaching energies beyond the Large Hadron Collider – remain a mystery.

Primary cosmic rays can only be measured directly by detectors flown on stratospheric balloons or satellites. Due to weight limitations, space-born detectors can reach up to at most a few TeV. Still, sub-TeV cosmic rays offer a rich scientific program as shown convincingly by, for example, the Pamela satellite, launched in 2006, and the AMS experiment, installed in 2011 on the International Space Station. They measured with exquisite accuracy the primary cosmic-ray mass composition and the energy spectra of photons, electrons, protons, helium and other light nuclei as well as their anti-particles. Interesting features observed in some of these spectra triggered animated debates on their possible origin: decays of new particles, notably Dark Matter, or astrophysical? The jury is still out. In particular, the latest results of AMS-02 are extremely interesting.

In 1938 Pierre Auger demonstrated that high-energy cosmic-ray air showers can reach the ground, allowing them to be recorded using a ground-based detector array. Since, for example, on average only a single ten billion GeV cosmic ray will slam into each square kilometer of the Earth's atmosphere per year, in practice a huge surface must be instrumented to collect sizeable samples of the high-energy cosmic rays. The focus is on the highest-energy cosmic rays, likely of extra-galactic origin, for two reasons: only these can realistically be used to back-track their sources, and also because for primary protons they should exhibit a cut-off around 50 billion GeV due to their strongly enhanced interaction probability with the omnipresent cosmic microwave background photons.

The Pierre Auger Observatory (Auger), installed on the Argentinean Pampa and completed in 2008, is the largest and most sensitive air-shower detector in the world. Auger comprises 3,000 square kilometres of prairie, about ten times the size of Paris, carpeted with 1,600 water-filled tanks to record the air-shower particles (electrons and muons) hitting the ground. This array is overlooked by five telescopes that record the faint fluorescence light caused by air showers in the atmosphere. Combining these two measurements to determine direction and energy of the original incoming cosmic ray significantly reduces systematics. At the highest energies, Auger typically records tens of events per year, these – as well as the tens of thousands of events at lower energies – have already produced tantalizing results including hints of sources and a clear flux suppression around the expected 50 billion GeV. However, it also became clear that further progress hinges critically on a much better mass differentiation. For this Auger will augment the water tanks with large scintillators to get a handle on the electron-to-muon fraction in each shower. This fraction is correlated to the mass (i.e. charge) of the primary cosmic ray. As of 2019, installation should be complete. Also Telescope Array (TA), a smaller air-shower detector installed in Utah (USA) and already completed in 2007, will upgrade its array by a factor of four in size to become comparable in size to Auger. Together, TA and Auger cover the full sky and are working towards combined data analyses. With their upgraded observatories, they are expected to begin to shed light on the mechanisms behind the strong decline of the cosmic-ray flux at the highest energies, which should help to discover the sources of these 100 billion GeV particles.

The global cosmic-ray community is already working towards next-generation observatories. In view of costs a ‘simple’ tenfold expansion of the current observatories is unrealistic. Instead new detection technologies and concepts are being explored. On the ground test campaigns to detect cosmic rays using radio antennas to pick up the minute radio waves induced by air showers moving in the Earth’s magnetic field have shown very promising results. In space, the JEM-EUSO project plans to observe the fluorescence light from air showers with a stereo camera pair mounted on the International Space Station.

3.2 High-energy gamma-rays

Humankind has studied our Universe for centuries using an ever increasing range of the electromagnetic spectrum: from eV energy photons in the visible light to lower energy radio photons and higher energy roentgen photons. Over the past decades an innovative instrument was developed to also observe extremely energetic photons – high-energy gamma rays – with energies ranging from typically 100 GeV to 30 TeV: the Imaging Atmospheric Cherenkov Telescope (IACT). When a high-energy gamma ray hits the Earth’s atmosphere, a cascade of secondary particles (‘shower’) is created giving rise to Cherenkov radiation, a faint bluish light, which is viewed by at least two pointing IACTs to yield a stereo image of the shower from which the direction and energy of the original high-energy gamma ray can be extracted.

This technology was perfected by the H.E.S.S. (Southern hemisphere), MAGIC and VERITAS (both Northern hemisphere) experiments. Collectively they have identified and studied more than 150 high-energy gamma ray sources, including objects such as supernova remnants, pulsars, binaries, active galaxies presumably hosting super-massive black holes at their centers. Their measured fluxes, energy spectra and arrival directions will help to elucidate the origin of these non-thermal particles (notably particle acceleration versus particle decay) and provide us for example the source’s morphology or tell us where super-heavy particles proliferate and what their masses are. More speculatively, some models of quantum gravity theories predict a tiny energy dependence of the speed of light – a violation of Lorentz invariance, a corner stone of physics – which the extremely short wavelength of high-energy gamma rays could eventually reveal.

To fully exploit the discovery potential by studying high-energy gamma rays, a large community of astronomers and astroparticle physics united themselves behind a global project: the Cherenkov Telescope Array or CTA, which acquired ESFRI status in 2008. Unlike its predecessors, which were operated as typical particle physics experiments where the collaboration members decide the measurement program and take care of data collection, reconstruction, analysis and the scientific publications, CTA will adopt standard astronomy practice and operate as an observatory, accessible to the full astronomy and astroparticle physics communities. This means that in addition to CTA’s key science projects, CTA will also accept and support project proposals from researchers outside the CTA collaboration. CTA will measure high-energy gamma rays from as low as 20 GeV to as high as 300 TeV over the full sky. To do so CTA plans to install a total of about hundred telescopes – small (6 m ∅), medium (12 m ∅) and large (23 m ∅) – distributed across two sites (one at the European Southern Observatory Chile and one at the Roque de los Muchachos Observatory in Spain). Several prototype telescopes, still exploring alternative design options, have been procured and tested. Negotiations as to how to share the overall CTA investment costs (about 300 M€) and exploitation costs (about 15 M€/year) have started among the main partners. In order to still benefit from a period of common data taking with the Fermi satellite observing gamma-rays with energies from 10 keV up to 300 GeV in space until at least 2018 it is desirable to start serial production soon. If so, the large and diverse (astronomers and particle physicist alike) CTA user community can soon embark on a very rich and exciting science program.

3.3 High-energy neutrinos

Travelling basically undisturbed, neutrinos can reach us from the most remote and dense regions of our Universe and allow us to study the Universe with a completely new perspective. High-energy neutrinos can be detected through their interactions with matter, which result in the production of charged particles that in turn produce Cherenkov light flashes. Because of the extremely low neutrino interaction probability, a huge target volume is required. The target medium must therefore be cheap, dark, and transparent, and in addition it must allow for the installation of a 3D grid of light sensors. Surprisingly, deep-sea water and Antarctic ice meet these criteria.

In the Mediterranean Sea, the ANTARES neutrino telescope was deployed in 2008 at a depth of 2,500 m and is taking data with 800 light sensors attached to 12 vertical lines corresponding to a 0.01 km3 instrumented volume. The IceCube collaboration has transformed one cubic kilometer of the Antarctic ice, 1.5 km below the geographic South Pole, into the world's largest neutrino telescope. It was completed in 2010 and is taking data with more than 5000 light sensors attached to 86 vertical lines.

An important breakthrough occurred in 2013 when IceCube published an excess of events at very high energies. By the end of 2016, about a hundred of such events ranging up to 3 PeV energy were identified, sufficient to unambiguously ascribe a cosmic origin to these neutrinos. Various event topologies have been studied: interactions of up-going and down-going neutrinos; 'showers' – dense energy depositions expected for electron-neutrino and neutral current interactions – and 'tracks' – the signature of a charged-current muon neutrino interaction. The overall flux is comparable to the diffuse gamma-ray flux observed by the Fermi satellite thereby suggesting common astrophysical sources. To identify these sources, the few track-like events (about ten per year) are of particular interest because, for these events the direction of the neutrinos can be determined to better most accurately. Regrettably, to date the statistics remain insufficient to unambiguously identify a neutrino point source.

The observation of cosmic neutrinos has boosted plans for the construction of a next generation of neutrino telescopes. On the South Pole, IceCube has conceptual plans for a 10 km3 instrumented volume detector (IceCube-Gen2). GVD recently deployed its first cluster of the 8–12 planned clusters to instrument about one cubic kilometer volume at a depth of 1,5 Km in Lake Baikal by 2020. In the Mediterranean Sea, KM3NeT, an ESFRI project, started the installation of the 1–2 cubic kilometer volume ARCA detector off the coast of Sicily at a depth of 3,5 Km. In comparison to its ANTARES predecessor, ARCA employs as light sensor an innovative multi-PMT digital optical module. On 3 December 2015, the first ARCA line was successfully deployed.

While the atmospheric neutrinos constitute a background for the detection of high-energy neutrinos of cosmic origin, these same atmospheric neutrinos can advantageously be employed as a unique signal to deter- mine the so-called neutrino-mass hierarchy, i.e. the ordering of the three neutrino masses. Due to matter effects, the observed oscillation pattern of low-energy atmospheric neutrinos subtly depends on this hierarchy.

The accurate reconstruction of neutrinos with energies down to a few GeV, needed to determine the mass hierarchy, requires a far denser instrumentation with light sensors than used for the high-energy neutrino telescopes. Both the IceCube and the KM3NeT collaborations have put forward designated proposals – coined PINGU and ORCA, respectively – based on their already proven technologies to address the mass hierarchy.

The worldwide neutrino telescope community stands to make breakthrough contributions to two long-standing questions: the neutrino mass hierarchy and the sources of high-energy cosmic neutrinos. To do so success- fully hinges upon the realization of at least one densely instrumented order megaton detector by 2020 and of sparsely instrumented 2–10 km3-sized detectors covering both the Northern and the Southern hemispheres – ideally using complementary technologies – early in the next decade.

3.4 Gravitational waves

Gravitational waves were first predicted by Einstein in 1916, but he considered them too weak to ever be detected. Nevertheless, convincing indirect evidence for the existence of gravitational waves was reported by Hulse & Taylor in 1974 (Nobel Prize 1993). A century after Einstein's prediction, the LIGO-Virgo Consortium announced the first direct observation of a gravitational wave: GW150914. This incredible event was traced back to the coalescence of two large black holes, about 30 solar masses each, leaving a single black hole behind and radiating gravitational waves in energy equivalent to three solar masses within a fraction of a second. This first observation produced a watershed of scientific papers already and opened an entirely new window upon our Universe: gravitational-wave astronomy.

Gravitational waves, tiny vibrations in space-time propagating at the speed of light, are produced by the acceleration of mass. Two orbiting compact objects such as neutron stars or black holes emit a very characteristic ‘chirp’ gravitational-wave signal when they coalesce. At the coalescence itself, this signal is incredibly powerful: briefly exceeding the combined power that all stars in the visible Universe emit as light. They are visible out to extreme distances and they allow many precision tests of General Relativity as shown convincingly already using GW150914. They can also be used as distance markers (‘standard sirens’) and thereby help to map the expansion history of our Universe to for example provide independent information on dark energy. Within our own Milky Way galaxy, gravitational waves emitted by a supernova would allow us to peek into its core. Probably most exciting of all, the brief period of inflation very shortly after the Big Bang filled the cosmos with a faint gravitational-waves background, similar to the cosmic microwave background. Observation of these waves would yield a picture of our Universe just after the Big Bang!

Directly observing the minute space-time ripples caused by a passing gravitation- al wave requires astonishing precision: typically 1 part in 10^{21}. First attempts to directly detect gravitational waves started in the 1960s, using ton-scale bars designed to resonate at around a kHz after a gravitational wave passed through. They failed. From the 1980s onwards, the focus has shifted towards long-baseline (3–5 km) laser interferometry with broadband sensitivity in the 100–1000 Hz region for observatories on Earth.

First generation interferometers on the ground ran until 2010–11. These projects established the infrastructures, the key technologies needed to attain the required precision and, equally important, forged a closely collaborating global community ready to exploit the gravitational-waves physics discovery potential. In particular, LIGO and Virgo operations are now conducted through the LIGO Virgo Collaboration, with coordinated data-taking periods, data sharing, joint data-analyses, and co-authorship of publications.

Next generation ground-based interferometer projects, Advanced LIGO (USA), Advanced Virgo (Italy), GEO-HF (Germany), and KAGRA (Japan), have been funded. Advanced LIGO started its first science operations in 2015 and almost immediately recorded GW150914 (and subsequently at least two more) which, apart from the excellent science, generated literally astronomical public attention. Advanced Virgo is expected to join LIGO’s next science scheduled to start early in 2017. With these two instruments taking data, tens of detections per year are anticipated: gravitational-wave astronomy (and physics) is taking off! Detection rates and source localization will be enhanced further if LIGO-India (foreseen for post-2020) becomes a reality and when KAGRA joins the already established LIGO-Virgo network.

Boosted by these first direct observations, R&D is progressing towards full third-generation observatories. On Earth, the Einstein Gravitational Wave Telescope (ET), project is the most advanced project, it will probe a thousand times larger volume and thereby elevate gravitational-wave physics from weekly or monthly detections to an era of high-statistics allowing high-precision astronomy and confronting the theory of General Relativity with a plethora of experimental tests. In space, the undisputed flagship project is LISA selected by ESA for its ‘Gravitational Universe’ mission with a launch date around 2030. LISA is best adapted to gravitational waves in the 10^{-4}-1 Hz range, thereby complementing the higher frequencies accessible to ground-based observatories. The LISA science program includes the observation of coalescing supermassive black-hole binaries out to redshifts of at least ten and the cannibalism of small black holes captured by supermassive black-holes out to redshifts of about one. LISA will also probe our own Milky Way galaxy, providing a census of the hundred million relativistic compact binaries (of white dwarfs, neutron stars, and stellar-mass black holes) estimated to exist in the Milky Way.