Astroparticle Physics

APPEC Contribution to the ESFRI Landscape Analysis 2023

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The astrophysical community in Europe operates large and diverse observatories and experiments for its research, often in rather inaccessible and harsh locations on Earth. Here we describe the status and development of those research infrastructures that are already listed in the ESFRI roadmap or could be potential candidates for the roadmap in the near future.

1. APPEC

Astroparticle physics is the fascinating field of research at the intersection of astronomy, particle physics and cosmology. This field, which employs cutting-edge technology instruments, saw many successful observations of impressive cosmic events, like the coalescence of black holes and neutron stars or flaring blazars. Thousands of researchers are joining their capacities to make these observations possible. APPEC is the Astroparticle Physics European Consortium, a consortium of 22 funding agencies, national government institutions, and institutes from 18 European countries, responsible for coordinating and funding national research efforts in astroparticle physics. It operates in close cooperation with society, with astroparticle physics related activities outside Europe as well as with neighbouring research fields via its strong connections to Astronomy (ASTRONET), Particle Physics (ECFA), or Nuclear Physics (NuPECC).
Over the past decades, the consortium and the community has been able to grow steadily in number of members, scientists, budget and operating research infrastructures. APPEC's strategic objectives are to a) provide a forum for the coordination of European Astroparticle Physics; b) develop and update long term strategies (roadmap); c) develop closer relationships with neighbouring communities to express collective views on Astroparticle Physics in international fora; and d) provide a fruitful education and training ground for next generations of scientists. Its implementation objectives are to a) facilitate and enhance coordination between existing as well as developing national activities; b) develop a common action plan for large-scale Astroparticle Physics Research Infrastructures; c) foster the digitalisation of the research field and support dedicated e-infrastructures; d) facilitate the convergence of future large-scale projects and facilities; e) provide organisational advice for the implementation of large-scale projects and facilities; f) launch common actions and measures and g) initiate and guide activities funded by the European Commission.

2. Strategy

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 https://www.appec.org/roadmap. Since then, the field rapidly made further progress, with one of the highlights being the multi-messenger observations of a neutron star merger, leading to important new insights in where and how chemical elements originate. Marking the rapid progress in the field, the landscape of experiments and observatories changed since 2017, possibly making some reprioritization warranted. APPEC therefore decided to conduct a mid-term review of the European APPEC Strategy for Astroparticle Physics 2017-2026, leading - with some delay due to the Covid 19 pandemic - to an updated strategy for the second half of the 2017-2026 period, to be published in summer 2023.

In this brief document we discuss the status and relevant developments as well as future plans and strategy for the large-scale, often international Research Infrastructures important to reach the science goals of Astroparticle Physics. An index of success of astroparticle physics can be that all seven priorities set up in the first roadmap 2008 (Gravitational Waves, High-Energy Photons and Neutrinos, Ultra-High Energy Cosmic Rays, Dark Matter, Neutrino Mass and Properties, Cosmology and Dark Energy) considered at the time as high-risk high-gain enterprises, are now considered mainstream fields in its full development. The infrastructures of the CTA, KM3NeT, Einstein Telescope have become part of the ESFRI Roadmap. These projects relate to the "Multi-Messenger Astro(particle)physics" theme and the corresponding instruments, tools and methods developed are breakthrough, highly innovative and benefit many other domains of fundamental science from Astrophysics to Nuclear and Particle Physics and Cosmology.
Other major topics in astroparticle physics are the search for Dark Matter and Dark Energy and the determination of the properties of the neutrinos. These topics are a rapidly growing field of research which need next-generation – i.e. larger and more innovative – infrastructures. Europe is at the forefront of these promising research fields also thanks to the EU support. To keep this position and foster new breakthroughs it is important to continue European coordination in all aspects and levels as well as find support for organising an effective global coordination.
Last but not least, we would like to note an extra argument for the topicality of the Astroparticle thematic in a climate urgency era, mirroring itself in many EU and global priorities. It has become common knowledge that in the last years, there appeared many areas of natural synergy between Geoscience, Climate Science and Astroparticle Physics who share a mutual scientific culture based on common objects of methods and approaches. The Geosphere is both the target and the detecting medium for Astroparticle observatories. Both deal with complex natural large-scale systems, sometimes in extreme environments (sea, desert, underground, space), use long series of precise observations acquired over long time scales and develop models relying on the state-of-the-art in fundamental physics, chemistry, biology and computer sciences.

In summary, the strategy of the astroparticle physics community for the development and operation of research infrastructures and in connection with the society is in accordance with the goals of the new ERA Action 8.

3. Ongoing and potential future ESFRI projects

- In the following we first address the three Research Infrastructures from the field of Astroparticle Physics that have already been included in the ESFRI roadmap:

KM3NeT – the *Cubic Kilometre Neutrino Telescope* for high-energy neutrinos (ESFRI)
In the Southern hemisphere, 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 the Northern hemisphere observatory KM3NeT 2.0 in its 2016 roadmap. Construction has started and operation is starting up in a phased approach. ***APPEC Recommendation:*** *APPEC fully endorses the goal of the KM3NeT collaboration to complete the construction of the large-volume telescope optimised for high-energy neutrino astronomy ARCA, and the dedicated detector to resolve the neutrino mass hierarchy ORCA.*

CTA – the *Cherenkov Telescope Array* for observation of high-energy gamma rays (ESFRI)
Recent discoveries, particularly at energies greater than 100 TeV and 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 under construction and 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. ***APPEC Recommendation:*** *APPEC fully endorses the construction and subsequent long-term operation of CTA in both the northern and southern hemispheres.*

Einstein Telescope – the *3rd Generation Gravitational Wave Detector* (ESFRI)
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. 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, included in the 2021 ESFRI roadmap, will make precise gravitational-wave astronomy possible and will access all cosmological scales back to the early universe. ***APPEC Recommendation:*** *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.*

- There are a number of European underground laboratories that provide essential infrastructure for key astroparticle physics projects. The owners and operators of these laboratories are considering structural coordination to provide a common framework for the appropriate experimental facilities:

DUL – *European Deep Underground Laboratories* (European coordination of distributed RIs)
Among the important infrastructures 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. ***APPEC Recommendation:*** *APPEC strongly encourages the European Underground Laboratories to maintain, and expand when necessary, their ability to facilitate low background experiments. APPEC encourages the European*

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

- Finally, projects are listed below that are central to APPEC's strategic planning, but are either too far in the future to already initiate the accession process to the ESFRI roadmap, or may not be seen as research infrastructures in their own right, but as experiments within large research infrastructures such as an underground laboratory:

GCOS and GRAND – the *next-generation cosmic-ray observatory*
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, including the now matured radio detection, will considerably improve determining the particle type. There is a need for a next generation very large ultra-high-energy cosmic ray observatory, for which among others the European-led multi-site ground-based detectors GRAND and GCOS and the space-based POEMMA fluorescence telescope have been proposed, which still require significant R&D and will be constructed earliest in the 2030ies. ***APPEC Recommendation:*** *APPEC encourages continued R&D on new cost-effective detector technologies for a next-generation observatory.*

XLZD and ARGO – the *future of WIMP Dark Matter search*
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 came online in 2020-2022, with active target masses of 4-7 tonnes. The next stage is to build and operate the DARWIN observatory at the 50-ton scale by the end of this decade. DARWIN might eventually be realised via the XLZD consortium formed by the XENON, LZ and DARWIN collaborations in 2021. 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 of active target. ***APPEC Recommendation:*** *APPEC strongly supports the European leadership role in Dark Matter direct detection 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.*

LEGEND – the *next large-scale experiment to study neutrino properties*
Current neutrino oscillation experiments demonstrate neutrinos to have very special properties. Some of the key properties are not known yet. These include, above all, the very small neutrino mass values and whether the neutrino is its own antiparticle (Dirac/Majorana). These two questions can be investigated by studying the (double) beta decay of selected isotopes. 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. The ongoing and planned experiment with strong European participation LEGEND (^{76}Ge) is among the most competitive. ***APPEC Recommendation:*** *APPEC strongly supports those double-beta decay experiments that are selected as part of the ongoing US-European strategy process.*

4. Connection to society

In addition to scientific advances in astroparticle physics and in fundamental research in general, which often change our perspectives, society as a whole is changing. This has led to profound changes in the way our research field functions socially and the contribution it should and must make to society. In particular, this is also reflected in a greater emphasis on the connection to society of large research infrastructures:

- Environmental Impact

Current experiments have to 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. Detector R&D can lead to establishing techniques and ideas that can be applied in society to mitigate or avoid negative ecological impact. **APPEC 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 encourages the monitoring of environmental parameters where possible and to apply R&D results to mitigate ecological impact in general.*

- Digitalization and Computing

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. 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. Training in data intensive science for the next generation of astronomers and physicists is crucial for the success of current and future large projects, where training in data science also provides opportunities outside of academia. Data policies also touch on Open Science and Citizen Science. **APPEC Recommendation:** *APPEC requests all relevant experiments to continue to have their computing requirements scrutinised. Appropriate training in data science should be provided for astroparticle physicists.*

- Societal Impact

Astroparticle physics and astroparticle physicists have had and are having a positive impact on society in many ways. Many technical and methodological developments initiated by our research have been beneficial for other research areas and industrial applications, and the training of scientists, from bachelor's and master's students to PhD students and postdocs, is essential for the science- and technology-based foundations of our society and economy. The fascination of our field evokes a special commitment in our young scientists, which translates into outstanding skills and abilities. Moreover, the science we do is of great interest to the public, including schoolchildren and teachers, as it encompasses fascinating concepts such as dark matter, neutron stars, black holes, or neutrinos. **APPEC Recommendations:** *APPEC encourages experiments to continue to seek applications for their work which will benefit wider society.*