Astroparticle Physics European Consortium (APPEC)

APPEC Contribution to the European Particle Physics Strategy

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Abstract

APPEC strongly supports and encourages the prospects of an even stronger synergy between Astroparticle Physics and Cosmology with Particle Physics. Areas of synergy between the above domains are identified: dark matter and dark energy; multi-messenger astrophysics, with the recently achieved discoveries of gravitational waves and the extraordinary opportunities also offered by gamma-ray and neutrino observatories for the exploration of powerful accelerators of the universe; the current neutrino precision program in relationship with cosmology, that promise either an unprecedented confirmation of the two standard models of Particle Physics and Cosmology, or a gate to new physics beyond both. These synergies include R&D on photosensors, cryogenic and vacuum techniques, optimisation of large scale infrastructures (civil infrastructure, vacuum, cryogenics) and of their governance and long-term operation, computing strategies for analysis and handling of large volumes of data, and policies leading to open science. Their development also requires grounding fundamental science within society, including, outreach and education. In view of the above synergies the present document introduces and briefly discusses four recommendations related to the role of PP in i) the dark matter searches; ii) the multi-messenger astronomy, in particular the 3G GW experiments (ET); iii) the neutrino physics; iv) the creation of a European Center for AstroParticle Theory (EuCAPT).

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A history of recent discoveries. Thirty years after Supernova 1987A, the first ``multi-messenger" detection of a violent event in the Universe, on Aug. 14, 2017, the Advanced Virgo and LIGO interferometers detected a gravitational wave signal from the coalescence of two stellar mass black holes. The era of gravitational wave astronomy started thanks to triangulation and the resulting precise sky localisation. Only three days later, the first neutron star–neutron star merger triggered a follow-up campaign with a nearly hundred observatories around the world. This led to the observation of the merger in electromagnetic waves – another unprecedented milestone of multi-messenger astronomy.

These discoveries are not alone in fundamental physics; the past thirty years are paved by a series of extraordinary discoveries, both expected and unexpected, in Particle Physics, Astrophysics, Cosmology and Astroparticle Physics. Examples are the discovery of the CMB fluctuations (1992, Nobel 2006) and the accelerated expansion of the Universe (1998, Nobel 2011), the confirmation of neutrino oscillations (1998, 2001, Nobel 2015) and the subsequent precise measurement of many of their mixing parameters, the discovery of the Higgs particle (2012, Nobel 2013), the development of the high precision cosmological ΛCDM model through measurements by WMAP and Planck (2013), thus confirming the need for a dark matter and dark energy component of the energy/mass budget of the Universe till of course, the already mentioned, recent detection of gravitational waves from black hole and neutron star mergers (Nobel 2017).

These discoveries were accompanied, in Astroparticle Physics and Astrophysics, by the mappings of the violent Universe using ultra high-energy photons (more than two hundred sources with energies above 100 GeV have been detected by H.E.S.S, MAGIC and Veritas); the detection of a diffuse flux of cosmic high-energy neutrinos with IceCube (2013); as well as the measurement by the Pierre Auger Observatory of an anisotropy of high-energy cosmic rays (2017) and the first correlation of a cosmic neutrino, detected in IceCube, with a potential cosmic-ray accelerator, a blazar, identified by Fermi-LAT; a correlation that triggered a multi-messenger campaign with participation of more than a dozen additional telescopes, including MAGIC, ANTARES and the Pierre Auger observatory.

The open questions. A number of research domains at the border of Astrophysics and Particle Physics were identified as the `Magnificent Seven' by the APPEC EU strategy for Astroparticle Physics in 2008. They are also recognised in the new 2018 APPEC Roadmap and form a fertile discovery landscape with increasing coherence between Cosmology, Particle Physics and Astrophysics. Many of the expectations of 2008 have turned into discoveries 10 years later and substantiate a series of questions that guide our research today:

I. What led to Cosmology as we know it? What is the nature of the mechanism that magnified quantum fluctuations to a macroscopic scale providing the seeds of formation of cosmological structures? Was it Inflation?
II. What is the nature and role of neutrinos in the mechanism that led to the dominance of matter over antimatter and the formation of cosmological structures?
III. What is the nature and role of dark matter and dark energy?
IV. What is the origin of high-energy cosmic rays?
V. Have we discovered all the fundamental and/or effective theories that govern matter and forces at different energy scales, or is there new physics to be discovered at higher energies or in most remote, hidden sectors of the theory?

The resolution of each of these questions would constitute a major step towards the better understanding of the Universe and for some of them it could be a major stepping stone towards a theory that reconciles general relativity with quantum field theory. The relations of these questions with the issues at stake in Particle Physics are more than obvious. We can in particular identify the following four domains where progress is expected in the next 10 to 30 years, where the emphasis here is on the synergy with Particle Physics:

I. The ground-based wave interferometers (advVirgo, advLIGO, GEO) have opened a new way to observe the visible and invisible Universe. Their upgrades (e.g. AdV+), also in synergy with the Japanese KAGRA detector, and the projected 3G generation (Einstein Telescope) will probe the Universe up to the first moments of creation of the galaxies, offering thus new pathways to cosmology: tests of gravitation, measurement of the Hubble constant, probing of the matter/dark matter distribution through lensing, probing the equation of state of dense nuclear and other extreme matter forming stars, the search for primordial black holes as dark matter or the study of WIMP dark matter accretion by neutron stars. The Einstein Telescope and the space satellite LISA will also be sensitive to a series of phase transitions due to many types of new physics (Higgs self-coupling and potential, supersymmetry, extra dimensions, strings, etc.).

II. In parallel, multi-messenger discoveries, following the examples of the recent neutron star merger event of LIGO and Virgo and IceCube's high energy neutrino event, will be able to follow with ever increasing statistics and precision the time evolution of high-energy cosmic processes. This will permit us to probe physical laws at very high-energy scales, test particle equations of state and possibly reveal hints of dark matter. An extraordinary discovery could be, for instance the synchronous multi-messenger detection of a galactic supernova explosion. The next generation observatories (e.g. CTA, IceCube-Gen2, KM3NeT, Baikal-GVD, AugerPrime, Telescope Array extension) are designed as multi-purpose experiments studying particle acceleration and interactions up to the highest energies.

III. Furthermore, within the next decade, the direct search for dark matter particles in underground laboratories (e.g. XENONnT, DarkSide-20k, and the future multi-ton liquid Argon and Xenon projects ARGO and DARWIN) is reaching sensitivities that will cover in the next years a substantial fraction of the standard WIMP parameter space and could provide important input for the next collider program. WIMPs are also accessible through indirect detection measurements with neutrinos, photons and cosmic rays. Given the strong constraints from colliders on the SUSY parameter space, other theoretically well motivated dark matter candidates like the axion (or axion-like particles) gain more visibility. Moreover, objects like MACHOS and primordial black holes or particle candidates like super-heavy dark matter, sterile neutrinos or other particles from the hidden sector could contribute to a more complex mixture of cosmic structures.

IV. Finally, in the coming years, the neutrino program on earth and underground (notably the CERN neutrino test facilities, DUNE, H2K, JUNO, ORCA, KATRIN as well as underground double beta experiments) addresses the mixing angles, the mass hierarchy, the CP violation, the absolute mass, the number and nature (Dirac or Majorana) of neutrinos (experiments GERDA/LEGEND, CUORE, SuperNEMO). The resulting measurements are complementary and comparable in sensitivity to the mass and number of effective families that will be provided by cosmology, i.e. by the large Dark Energy Surveys (LSST, Euclid, DESI) and fourth generation CMB polarisation experiments on the ground and in space. These measurements have the potential to become a portal to new physics, e.g. revealing the hidden sector of sterile neutrinos, alternatives to inflation, etc. Possible new theories in physics will be studied and their predictions for gravitational waves and B-mode polarization of the CMB will be tested.

In summary, in the coming years we are looking forward to an unprecedented increase of sensitivity allowing for the first time to obtain comparable information from the Particle Physics high-precision measurements (*intensity frontie*r) and the explorations of new energy scales (*energy frontier*) as well as from high-sensitivity multi-messenger mappings of the Universe (*cosmic frontier*). The above arguments emphasize the common ground for science and, hence, the need for a profound “cultural” synergy between Particle and Astroparticle, Physics and Cosmology. Such synergy spans detector R&D, computing and large research infrastructure issues.

On the detector side, in order to provide a couple of relevant examples where such synergy could be beneficial, let us mention that Astroparticle Physics and Cosmology observatories support the development of a new generation of cryogenic detectors and of photodetectors, as e.g. indicated in the SENSE[1] Roadmap, which addresses SiPM and cryogenic detectors (Transition Edge Sensors, Kinetic Inductance Detectors, …), as well as the deployment of large systems of intelligent sensors, adapted electronics and data acquisition systems in sometimes hostile environments with high level of synchronisation.

Furthermore, Accelerator and/or Neutrino Particle Physics and, more recently, Astroparticle Physics share the common interest of studying and developing large to very large civil and vacuum infrastructures. The share of civil infrastructure costs is going to play a major role in the total cost of building and running the next generation of experiments of particle accelerators and gravitational wave antennas. Hence, there is a strong demand that scientists and engineers operating in Particle and Astroparticle Physics share some efforts and expertise and devote special attention to innovation and cost optimisation in this domain (e.g. vacuum techniques, underground infrastructure monitoring, natural risk resilience, excavation methods, etc.). The same can be said about computing and the research data management, where, again, the next generation of both particle and astroparticle infrastructures, including all those operating in a multi-messenger context, poses formidable challenges for computing infrastructures, methodologies and workload management.

Last but not least, the current scientific evolution on new ways to explore the cosmos has many implications on society. Outreach and education, interdisciplinarity, public data access, big data education, and the promotion of human equal rights should also be considered as domains of synergy and collaboration between the different fundamental science disciplines. Equality charters can reinforce the synergy to fight prejudice against diversity. Finally, a special effort should be dedicated to encourage the dissemination of critical thinking across society and increase the public understanding of the long term role of science and its predictions.

[1] https://www.sense-pro.org/

APPEC recommendations in synergy with the European Strategy for Particle Physics. In view of the above, and taking into account the recommendations of the APPEC roadmap published in early 2018,[2] we present here the APPEC recommendations concerning possible synergies of the APPEC Roadmap and the European Strategy of Particle Physics. APPEC supports:

1. ***Particle Physics Cooperation with respect to dark matter searches, including R&D and enabling technologies leading*** **toward a global program on dark matter searches, similar in breadth to the neutrino physics program.** The nature of dark matter is clearly among the major riddles of current day fundamental physics. This program would include the multi-ton detector realisations aiming at the direct detection of dark matter (WIMP and some of the dark matter alternatives), as well as the search of non-WIMP forms of dark matter (e.g., axions or dark photons) using new sensor technologies. Such a program in CERN scope and technological environment could constitute an extraordinary catalysing factor of discovery and feedback concerning the future directions to follow.

2. ***The development of the synergies between the Particle Physics community and the next generation of observatories of Multi-messenger Physics and in particular the third-generation gravitational-wave observatory Einstein Telescope (ET), on science, infrastructure, detector R&D, computing and governance.*** These synergies concern the program of observatories concerning high-energy photons, gravitational waves, neutrinos and ultra-high-energy cosmic rays currently in operation, in construction, or being upgraded. Remarkably, exploiting the large area of synergy between CERN expertise, e.g. on the infrastructural aspects (tunnel, vacuum, cryogenics, etc.) and the billion euro scale 3rd-generation Einstein Telescope (ET) could accelerate the latter's establishment. These synergies also concern developments of innovative detectors, low-power electronics, computing, where low latency distribution of alerts and high throughput of data is needed, as well as other aspects of the data life cycle (e.g. data analytics, machine/deep learning, etc.). Furthermore, the global character of the next generation infrastructures could profit enormously from the large experience of CERN on what concerns the governance schemes of large research infrastructures. Finally, many facets of the LHC and non-LHC programs at CERN, e.g. the study of hadronic physics at the highest energies, high-energy cross-sections and particle-production measurements using very forward detectors, but also measurements at ISOLDE, Totem, ALICE and LHCb, are crucial inputs for the studies of interactions and shower development of the cosmic messengers. Conversely, ultra-high-energy cosmic ray, neutrino and photon observatories can provide cross section and particle-interaction measurements at energies higher than those at humanly made accelerators.

3. The vigorous continuation and full development of the CERN neutrino platform as well as an active role of particle physicists and engineers for global collaboration on neutrino projects aiming at clarifying the crucial puzzle of the origin, nature and features of neutrino masses and mixings and the possible existence of sterile neutrino states. The neutrino intensity frontier, combined with the cosmology frontier program, is a portal to new physics beyond the standard models of both Particle Physics and Cosmology. APPEC has actively encouraged and supported in the previous 5 years the global coordination of the neutrino accelerator program and is currently supporting the global

[2] http://www.appec.org/roadmap.

coordination for the next generation of Cosmological Microwave Background observatories. APPEC also supports as a key priority in its roadmap the global coordination of the neutrinoless beta decay program probing the neutrino mass and nature.

4. ***The support of the strong interplay between the theoretical communities.*** In particular, the birth of the European Centre for AstroParticle Theory (EuCAPT) that APPEC is currently pursuing could play an instrumental role in vigorously developing or enhancing the already existing links between Particle and Astroparticle Physics theorists. Active support of EuCAPT by the European Particle Physics community will be highly appreciated by APPEC.

The present document has been reviewed by the APPEC Science Advisory Committee (SAC) and approved by the APPEC General Assembly (GA).

About APPEC

APPEC is the Astroparticle Physics European Consortium, a consortium of 19 funding agencies, national government institutions, and institutes from 17 European countries, responsible for coordinating and funding national research efforts in Astroparticle Physics. Apart from promoting cooperation and coordination, a crucial APPEC activity is to formulate, update and realise the European astroparticle physics strategy. Key ingredients in the new strategy, launched in January 2018 are the 21 recommendations addressing, in addition to the scientific issues, crucial organisational aspects as well as important societal issues such as gender balance, education, public outreach and relations with industry. By acting coherently on these recommendations, Europe will be able to exploit fully the tantalising potential for new discoveries in good international collaboration.