Astroparticle Physics European Consortium

Considerations[1] for discussion in the APPEC Town meeting

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Contents :

Introduction

Eight years have passed since the first APPEC/ASPERA scientific vision of 2008, dubbed "The Magnificent Seven", from the seven types of domains where progress and support was needed according to APPEC. Some noticed sceptically at the time that at least four of the seven infrastructures were searches for signals that had not been detected yet (gravitational waves, high energy neutrino astronomy, dark matter and neutrinoless double beta decay). Well, eight years later the "not yet a signal" areas are only two with order of magnitude progresses in sensitivity having been accomplished in all areas. A rare achievement indeed for fundamental physics.

In parallel, the theoretical and experimental developments have unified further the different subdomains of the field; since:

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[1] Based on discussion of the APPEC Scientific Advisory Committee: A. Masiero (chair), Andreas Haungs, Michal Ostrowski, Mauro Mezzetto, Gisela Anton, Laura Baudis, Jocelyn Monroe, Petr Tiniakov, Jo van den Brand, Patrick Sutton, Ramon Miquel, Zito Marco, Andrea Giuliani, Felix Aharonian, Pierre Binétruy, Ignatios Antoniadis, Yifang Wang, Francis Halzen, Hank Sobel, S.Katsanevas and Frank Linde (APPEC)

- *the whole visible Universe from the CMB to the present started to provide comparable cosmological constraints as CMB physics is now related to the large dark energy survey physics and the neutrino properties; and*
- *we are finally at the edge of multi-messenger detections involving high energy photons, neutrinos, high-energy charged particles and gravitational waves, that will give us a deeper understanding of violent phenomena regulating structure formation in the Universe.*

Finally, as the development of the field implies the deployment of large infrastructures, the operation, upgrade and deployment costs must come under close scrutiny, so that the community obtains the maximum number of opportunities permitted by the current funding. A new roadmap has to go further than a scientific vision, with some priorities, and become a "resource aware" roadmap.

In the following, we present "considerations" to be debated in the Town Meeting that will feed into the "resource aware" roadmap of APPEC due in autumn of 2016.

The scientific areas below highlight the emergent unity of the field (starting from cosmology and ending with violent phenomena) and do not reflect any order of priority of funding of the infrastructures.

1. Probing inflation and the formation of cosmic structures: Cosmological Microwave Background (CMB)

CMB findings and tasks. The Planck satellite gave the ultimate measurement of cosmological microwave background fluctuations of temperature discovered by Smoot and Mather (Nobel Prize 2006). The importance of these measurements, as well as the measurement of the fluctuations in the polarisation modes E and B cannot be overestimated since besides the precision measurements of the cosmological parameters they also provide precise measurements of the number of neutrinos and the sum of their masses as well as the first complete map, through gravitational lensing, of the clusters of matter (including dark matter) intervening between the recombination era and the present era of the Universe. The USA has a clear leadership on ground and balloon detection, as is testified by the plethora of experiments either now taking data or planned for the near future in the Atacama, at the South pole and long and ultra-long duration balloons. Nevertheless, there are also ambitious third (G3) generation CMB programs in Europe: QUBIC, QIJOTE and NIKA2 and the balloons LSPE and OLIMPO. The task at hand is now to work towards the measurement of the B-modes of polarisation of the cosmological background with the same type of ultimate precision as obtained in the temperature (scalar) fluctuations. At large angles the B-modes are primordial and bear the imprints of the gravitational waves (tensor modes) produced during the inflation era. The ratio of the amplitudes of the tensor to scalar modes, gives access to the scale of inflation. Furthermore, in the future, the measurement of specific relationships between relevant cosmological quantities should be able to provide unmistakable proof of a signature of inflation. At small angles the B-modes are produced through the lensing of E-modes by the intervening matter and give therefore access to the large scale distribution of matter (including dark matter), the number and masses of neutrinos and/or other exotic particles with precisions that will give, by 2025-2030, conclusive tests of coherence of earth-bound and cosmic measurements. Another domain of research, whose feasibility with current technologies is under investigation, is the measurement with very high precision of the distortions in the CMB black-body spectrum. This could reveal resonant peaks due to standard transitions e.g. from nucleons to the nuclei era (nucleosynthesis), or even dark matter annihilation or any other new physics injections.

- ***CMB Consideration 1.*** *The next generation of experiments should aim at per mil sensitivities for the tensor to scalar ratio r and also at the largest coverage of the angular spectrum. Ground- and space based experiments play a complementary role in this study since ground-based experiments permit the deployment of very large arrays and therefore high angular resolution, while space-born experiments can probe a sufficient number of frequencies that permit an unsurpassed (and probably very much needed) parametrisation and subtraction of the foregrounds.*
- ***CMB Consideration 2.*** *Europe should participate in a G4 ground programme in synergy/complementarity with the CMB-S4 CMB-currently in development in the USA, aiming at a precision on the tensor to scalar ratio of order one per mil, ca 2025, as well as unprecedented precision on the mass of light neutrinos, in synergy with the neutrino programme.*
- ***CMB Consideration 3.*** *Europe should lead a CMB space programme (e.g. CORE+ as a M5 ESA mission, launch 2029-2030), in close discussion with space programs in development in Japan (LiteBird) and the USA (Pixie).*
- ***CMB Consideration 4.*** *Technology wise, Europe should support R&D and TRL (Technology Readiness Level) upgrade of new detection technologies using cryogenic Transition Edge Sensors (TES) and Kinetic Inductance Detectors (KIDs).*
- ***CMB Consideration 5.*** *APPEC should promote the global coordination of the field.*

CMB prospects. The current and future CMB program sets the stage for major thematic unifications. Firstly the prospect of measurement of the inflation parameters, associated with the discovery of Higgs and possibly more massive particles at the LHC, will provide the glimpse of a unified description of physics from the electroweak scale to this of inflation. Secondly the comparison of the neutrino related cosmological measurements with the experimental values measured on ground will become a portal of discoveries of New Physics surpassing the standard models of particle physics and cosmology. Thirdly the study of correlations between the cosmological background primordial fluctuations and the large scale cosmological structures in the Universe, in particular these studied in large Dark Energy surveys, will provide the possibility of a unified description of the totality of visible (and invisible) Universe.

2. Probing the acceleration of the expansion of the Universe: Dark Energy (DE)

DE findings and tasks. The study of the history of the expansion rate of the Universe, using supernovae as distant standard candle processes led to the discovery by S. Perlmutter, A. Riess and B. Schmidt (Nobel Prize 2011) of the accelerated expansion of the Universe, dubbed Dark Energy (DE). At the end of this decade, next-generation DE projects currently in construction, both on ground (LSST and DESI) and in space (Euclid) will accomplish detailed large galaxy spectroscopic and photometric surveys with unprecedented precision and extension providing a breakthrough in our knowledge of the history of the expansion rate of the Universe and of the rate of growth of cosmic structures. Spectroscopic galaxy surveys, provide a precise determination of the galaxies' redshifts, and hence a true 3D picture of the galaxy distribution, but they are costly in time and resources, and may suffer from limited depth, incompleteness and selection effects. On the other hand, imaging (also called photometric) galaxy surveys are more efficient and usually deeper, more complete and nearly unbiased, but do not provide a complete 3D view of the Universe, due to their limited resolution in the galaxy positions along the line of sight. It is fair to say that currently the USA leads the research on DE performed from the ground through large galaxy surveys: DESI a spectroscopic survey starting in 2018 and DES a photometric survey in operation and LSST a photometric survey starting in 2021 while Europe will have the leadership on DE studies from space with the Euclid ESA mission launched around 2020. Euclid combines a weak-lensing imaging survey like LSST with a spectroscopic survey like DESI. Taking advantage of its position in space, outside the Earth's atmosphere, Euclid will be able to take the weak-lensing technique to its limit. On the other hand, it will still need a significant amount of data from imaging surveys on the ground in order to both estimate the (photometric) redshifts of the over 1 billion galaxies it will measure and mitigate some of the leading systematic errors. In contrast the ground surveys will rely on the better knowledge of systematics in space due to the absence of atmospheric distortion.

- ***DE Consideration 1.*** *Europe should support the construction data analysis of Euclid which will dominate dark energy science from space in the next decade, providing clear European leadership in that area.*
- ***DE Consideration 2.*** *Europe should support the key contributions of European groups to the ground program, in particular LSST that will be deeper, wider and faster than any ground based optical survey to date.*
- ***DE Consideration 3.*** *Europe should encourage data exchange between Euclid and LSST as this will enhance the scientific output of both missions.*

DE prospects. Both the history of the expansion rate of the Universe and of the rate of growth of cosmic structures depend on the DE properties, although in different ways. By measuring both rates, with the above program, we will be able to disentangle kinematic effects from dynamic effects and therefore eventual modifications of gravity theories from theories postulating e.g. new fields of the particle physics type. Furthermore the studies of correlations between the "recent" (redshift < 3) large scale structures probed by the large scale surveys of DE and the primordial CMB fluctuations studied by CMB serves as a testing ground of the standard models of cosmology and particle physics (possibilities of sterile neutrinos, new particles etc.). Last but not least, the indirect measurements of the sum of neutrino masses that they provide, when compared to direct measurement of neutrino masses from ground experiments, constitute a sensitive probe of New Physics again (non-constant DE, non-Gaussianities, new radiation/particle species, etc.).

3. Direct detection of Dark Matter (DM)

DM findings and tasks. Astrophysical and cosmological observations and particle physics theory predict a spectrum of particles beyond that of the standard model of particle physics: Dark Matter (DM) particles. A plethora of DM candidates has been proposed, with an enormous variety of masses ranging from the millionth of eV for an axion mass to a mass 30 orders of magnitude larger for the DM candidates at the Grand Unification scale. However, there is a class of DM candidates, the Weakly Interacting Massive Particles (WIMPs), which looks particularly attractive: WIMPs can "naturally" reproduce the observed amount of DM and are predicted to exist in several physically motivated extensions of the standard model of particle physics. Three different and complementary approaches have been envisaged to search for DM: DM production at colliders (LHC), indirect searches and direct searches. Indirect detection experiments aim to detect annihilation products of DM particles, such as neutrinos, gamma rays, antiprotons and positrons above the astrophysical background and form one of the driving factors of optimization of the high energy cosmic messenger observatories discussed below. Direct detection experiments look for DM interactions in the laboratory, operating ultra-low background and low-threshold detectors deep underground. They have reached unprecedented sensitivities in a wide mass range for WIMPs, probing WIMP-nucleon cross section below 10^{-9} pb or 10^{-45} cm^2 for WIMP masses of about 40 GeV, while the DAMA/LIBRA collaboration, studying light flashes in NaI crystals at the LNGS (Italy) over the last 15 years, has consistently reported an intriguing annual modulation of their event rate, unconfirmed by higher sensitivity searches under standard assumptions. At present, the highest sensitivity on the WIMP scattering cross section in the 6 GeV – 10 TeV mass range is reached by experiments using liquid xenon as the WIMP target, namely LUX (SURF, USA) and XENON100 (LNGS). First results from DarkSide-50 (LNGS) with argon depleted in ^{39}Ar show very strong and promising background rejection possibilities. A ton-scale xenon detector, XENON1T, under commissioning, aims to reach cross sections as low as 10^{-47} cm^2 after two years of continuous operation. First results from ton-scale argon detectors such as ArDM (LSC, Spain) and DEAP (SNOLab, Canada) are expected during 2016. As for WIMP masses to 10 GeV, the best performance is achieved making use of a combination of light and heat or ionisation signals in sub-K cryogenic germanium detectors: CRESST(LNGS), EDELWEISS(LSM/EU), CDMS-CoGent/US, or CCD detectors (e.g. DAMIC). The current generation (G2) of noble liquid and cryogenic crystal direct detection detectors will produce in the next 2-3 years a one to two-orders of magnitude breakthrough in our sensitivity to test for WIMPs as the most promising DM candidate; the G2 era will pave the way to the ultimate very large G3 DM detectors able to give the final verdict on the WIMPs explanation for DM. Proposals have been submitted for multi-ton scale liquefied noble gas detectors with strong European participation, namely DarkSide-5ton (LNGS), LZ (SURF), XENONnT (LNGS) as well as a ton scale bolometer experiment Super-CDMS. For larger WIMP masses, the envisaged 30-50 ton LXe detector of DARWIN (XENON collaboration and new groups) and 200 ton LAr detector of ARGO (joint effort by ArDM and DarkSide) aim to probe the experimentally accessible parameter range for masses above 10 GeV and 1 TeV, respectively, until the neutrino background starts to dominate the measured recoil spectra. A G3 experiment would be expected to start taking data from 2023 onwards. To go beyond the bound represented by the (solar and atmospheric) neutrino background, new kinds of detectors are needed, for instance directional detectors able to provide the required track angular reconstruction at low energy thresholds. Clearly, if DM is found in direct searches, then direction detectors will be crucial in establishing its nature and astrophysical origin.

- ***DM Consideration 1.*** *Europe should support and closely follow the development and results of the G2 experiments directly searching for WIMPs DM in the vast range of WIMP masses from 1 GeV up to ten of TeVs.*
- ***DM Consideration 2.*** *APPEC should appoint a scientific and technical committee to work with the European DM community to recommend the technology for one noble-liquid G3direct detection experiment in synergy/complementarity with similar detectors in other regions of the world (e.g. USA)*
- ***DM Consideration 3.*** *Europe should support the participation of European groups in a G3 bolometric detector in the USA (Super-CDMS).*
- ***DM Consideration 4.*** *Europe should support R&D and technology to build a directional detector.*

- ***DM Consideration 5.*** *Europe should continue to support non-WIMP searches (e.g. axions ADMX, IAXO).*

DM prospects. It is unnecessary to stress the obvious that the discovery of DM will be a Nobel Prize winning discovery opening extraordinary vistas for particle physics, astrophysics and Cosmology. Knowing what DM is made of would mean having access for the first time to New Physics beyond the standard model of particle physics. There is no doubt that an enormous (experimental and theoretical) effort is underway to unveil the most sought after unseen particle after the discovery of the Higgs boson. The complementarities of the three search strategies (LHC, indirect & direct) will permit us to pin-down its properties and will guide the design of new machines and observatories. A non-detection, reaching extreme limits of the available WIMP parameter space, will be equally significant since it will redirect fundamental physics to other possibilities.

4. Probing the ultimate nature of the Neutrino (Neutrino)

Neutrino findings and tasks. Despite the many neutrino related discoveries, and the understanding of their role in cosmic bodies (sun and supernovae), the source of two Nobel Prizes in the 21st century to date (Davis & Koshiba in 2002 and McDonald & Kajita in 2015) neutrinos remain mysterious. With neutrino oscillations established, neutrinos cannot be massless. Their very small masses are unnatural in the standard Higgs mechanism. With massive neutrinos, CP violation , the most probable origin of dominance of matter over antimatter, also becomes an open question which only experiments can answer. As a neutral particle, the neutrino and the anti-neutrino could be different particles ('Dirac'-type, like all other matter particles) or they could be the same particle ('Majorana'-type). Again experiment should tell. The many measurements of the neutrino masses projected indirectly by cosmology experiments (CMB and DE) will need to be confronted with direct measurements and will thus become a possible window to New Physics beyond the standard models of particle physics and cosmology.

CP violation and neutrino mass hierarchy. With neutrino oscillations firmly established and the three mixing angles all confirmed experimentally as non-zero, experiments using neutrinos from accelerators to search for CP-violation in the leptonic sector are about to become an exciting reality. Even though current experiments may give hints of neutrino CP-violation, new facilities are needed to unambiguously settle this issue as well as the still outstanding issue of the neutrino mass hierarchy. Capitalizing on the successes of the pioneering neutrino experiments exploring both neutrinos from nuclear reactors and long-baseline neutrino-beams, orders of magnitude larger detectors are about to start construction or are in the planning phase.

The flagship future projects are long-baseline neutrino-beams. In the USA the Long-Baseline Neutrino-Facility (LBNF), sending a neutrino beam from Fermilab (Chicago) a distance of 1300 kilometres to Sanford Underground Research Facility (SURF), received a major boost after the APPEC co-initiated workshop in Paris, 2014, and led a large number of European groups to direct their efforts thereon. The Deep Underground Neutrino Experiment (DUNE) will employ a near and a huge 4×10kton ton far detector, both using the cryogenic liquid argon (LAr) time projection chamber (TPC) technology developed in Europe. Several European laboratories are working together at CERN within the WA105 collaboration in the CERN North Area neutrino hub, towards a realistic implementation of such detectors and their services at SURF. DUNE will also settle the neutrino mass hierarchy, if not clarified earlier, and will significantly improve the precision of the recently determined neutrino parameters.

Several European groups joined the 20 kton liquid scintillator JUNO experiment in China which will use anti-electron neutrinos from a nuclear reactor complex (about 36 GW-thermal power) situated about 50 kilometres away. JUNO will almost entirely be funded by China, but will rely on key contributions from Europe, notably the liquid scintillator purification plant, with data taking scheduled from 2020 onwards. JUNO is expected to reduce the uncertainties on the two mass-squared differences (δm^2_{12} and Δm^2_{13}) and θ_{12} to below 1%. However, JUNO's primary aim is to resolve the neutrino mass hierarchy after 3-5 years of data taking.

In Japan discussions have started to upscale the very successful Super-Kamiokande experiment from its present 50 kton to 1 megaton (Hyper-Kamiokande) to complement the LBNF/DUNE facility with shorter baseline (270 km) and lower neutrino beam energy.

The extraordinary precision and sheer mass of both the long-baseline neutrino-beam and nuclear-reactor neutrino detectors, allows other exciting studies as well. In particular:

- The deep underground and hence well-shielded water-Cherenkov, liquid scintillator and LAr neutrino detectors all allow the increase of sensitivity to proton decay in complementary channels (positron-pion versus strange flavours). One should not forget that in the most simple grand unification models, the parameters of proton decay are related to the parameters of inflation.
- These large neutrino detectors are also well suited for high-statistics and thus higher precision studies of atmospheric, solar and supernova neutrinos. E.g. with the next generation of experiments thousands of neutrinos will be recorded from a supernova in the Milky Way galaxy.

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 determine the neutrino-mass hierarchy. This ordering could be normal or inverted. 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 hitherto. Both the IceCube and the KM3NeT collaborations operating neutrino observatories in ice on the South Pole and in the Mediterranean Sea, respectively, have put forward proposals based on their already proven technologies to do so: PINGU is an integral part of the IceCube-Gen2 project at the South Pole and ORCA is part of KM3NeT to be installed in the Mediterranean Sea of the coast of Toulon. PINGU and ORCA could start data taking in the early 2020s and if so would be able to settle the neutrino mass hierarchy before next generation experiments at nuclear reactors and long-baseline neutrino beams will be able to do so.

Sterile neutrinos. The above considerations determine the tasks of measurement under the assumption that there are only three types of neutrinos which are left-handed doublets under the symmetry SU(2)×U(1) of electroweak interactions. Nevertheless, there have been a few experimental indications, of relatively low statistical significance, of the existence of extra neutrinos that are singlets or right-handed in nature, and therefore have no ordinary charged or neutral current weak interactions except those induced by mixing. In parallel, most extensions of the original standard model of particle physics involve one or more sterile neutrinos, with model-dependent masses which can vary from zero to extremely large values. A series of experiments, mostly at Fermilab (LBNF) are proposed, are under construction or early operation to clarify the experimental situation around the existence of sterile neutrinos at the eV scale.

Neutrino mass and nature. Furthermore, together with the presence of dark matter and dark energy in the Universe, the non-vanishing mass of neutrinos is an evidence of New Physics beyond the standard model of particle physics. However, we are still far from knowing the nature of any New Physics. The clarification of the two aforementioned issues of the absolute value of neutrino masses and, even more importantly, of the nature of that mass (Majorana versus Dirac) will certainly shed important light on which new particles and/or interactions allow neutrinos to become massive.

The traditional method to determine the absolute value of neutrino masses consists of measuring the electrons from tritium beta decay where a neutron inside a nucleus transforms into a proton, an electron and an antineutrino. On the other hand, it is only the study of neutrino-less double beta decay ($0\nu2\beta$) that can also shed light on the nature of the neutrino mass. In the case of discovery in this channel a new type of matter would be discovered and lepton number would no longer be a symmetry of Nature, potentially paving the way to understand the origin of the cosmic matter-antimatter asymmetry in the early stages of the Universe; a new mechanism of mass generation, besides the Higgs mechanism, could be in place and the smallness of ordinary neutrino masses could be naturally explained.

The direct measurement of the electron antineutrino mass will be performed with high sensitivity by KATRIN, a world-leading experiment exploiting tritium beta decay and located at KIT (Germany) starting data-taking in 2016. The expected sensitivity is m_ν<200 meV (90% C.L.). The KATRIN group will develop cyclotron radiation spectroscopy emission in tritium beta decay (Project 8) to further increase its neutrino mass sensitivity over the next 10 years. Calorimetric experiments at low temperatures, which exploit the electron capture decay of ^{163}Ho and are sensitive to the electron neutrino mass, are in the R&D phase in Europe (ECHo and HOLMES) and in the USA. These promising searches will still require several years of development before being able to match KATRIN's sensitivity.

Neutrinoless double beta decay is an extremely rare nuclear transition relating the rate of the process to the square of the effective Majorana neutrino mass $m_{\beta\beta}$ (with an uncertainty due to nuclear physics calculations), a linear combination of the three neutrino mass eigenvalues. Present limits on are in the 150-600 meV range. They are achieved in Europe by two second generation (G2) experiments located at the LNGS: GERDA-I making use of the isotope ^{76}Ge and CUORE-0 – the precursor of full CUORE – using the isotope ^{130}Te. Analogous experiments exist in the US and Japan. Current-generation searches do not have the potential to explore the inverted neutrino mass hierarchy region, corresponding to the range 15–50 meV. The $0\nu2\beta$ community is discussing potential G3 experiments capable of fully covering and surpassing such inverted mass hierarchy region requiring an isotope sensitive mass of the order of at least a few hundreds of kg. The present experimental situation is characterised by a rich variety of projects and approaches, which can be grouped into three main classes according to the configuration of the source: Fluid-embedded Source (FS), Crystal-embedded Source (CS) and Externals Source (ES) experiments. In Europe all these three techniques are used, FS at LSC (Spain), CS at LNGS (Italy) and ES at LSM (France). Existing infrastructures in Europe (GERDA and CUORE cryostats at LNGS) already allow housing a few hundreds of kg of isotope mass. Extensions up to this mass level are under discussion (GERDA upgrade, a possible joint GERDA-MAJORANA experiment, and the proposed CUORE follow-up named CUPID). Due to the high enrichment cost (in the 20–80 M€ range), it is unlikely that there will be more than one next-generation experiment in Europe. Two may be possible with contributions from other regions. The next two to three years will be crucial to define the technology of these future searches; essential indications will come from the performance – especially the background levels – achieved by current-generation projects. Europe-based experiments and R&D activities are at the forefront in all the options outlined above.

- ***Neutrino Consideration 1.*** *Europe should aim to support the timely realisation of the world-wide key projects: LBNF/DUNE and JUNO.*
- ***Neutrino Consideration 2.*** *Europe should support the definition of the project Hyper Kamiokande which is in the planning phase.*
- ***Neutrino Consideration 3.*** *Europe should support a medium-scale program of short-baseline oscillation experiments at Fermilab aiming to test the sterile neutrino hypothesis for eV scale neutrinos.*
- ***Neutrino Consideration 4.*** *Europe should support a strong R&D and prototyping program in the CERN North Area, related to the above program (considerations 1 to 3).*
- ***Neutrino Consideration 5.*** *Europe should continue to support the experiments and the R&D activities r relating to single and double beta decay neutrino mass searches.*
- ***Neutrino Consideration 6.*** *Europe should support at least one of the efforts to determine the neutrino mass hierarchy through atmospheric neutrinos (ORCA, PINGU).*
- ***Neutrino Consideration 7.*** *APPEC should appoint a committee to recommend a strategy to adopt for a complete investigation of the inverted mass hierarchy region using neutrinoless double-beta decay processes. Such committee should give first guidelines by the end of 2017, establishing connections and possibly coordination with the analogous process going on in the US in the framework of the Nuclear Science Advisory Committee.*

Neutrino prospects. The importance of the number and masses of neutrinos for cosmology and the standard model of particle physics cannot be overstated. Equally important is the measurement of CP-violation parameter reducing the options for neutrino mass origin and constituting today the most probable origin of matter dominance over anti-matter.

5. Probing the Universe with Gravitational Waves (GW)

GW findings and tasks. A century after Einstein's prediction, the first direct observation of a gravitational wave event has been announced. It was noted rightly as an historic breakthrough and opens an entirely new window upon our Universe and field of research: gravitational wave astronomy and fundamental studies of General Relativity in the strong field regime. Gravitational waves 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 and are considered to be the most plausible source for the first direct detection of a gravitational wave. Within our own Milky Way galaxy, gravitational waves emitted by a supernova would allow us to peek into its core. Axial-asymmetric spinning neutron stars will act like 'pulsars', emitting continuous gravitational-wave signals that will provide us insight into their equation of state.

No gravitational waves were detected, by the first generation interferometers (LIGO, Virgo, GEO) in accordance with predicted gravitational-wave source populations within the sensitivity horizon of these instruments. Nevertheless, these projects established the infrastructures and the key technologies needed to attain the required precision and, equally importantly, forged a closely collaborating global community – overseen by the Gravitational Wave International Committee (GWIC)– 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.

The current G2 generation ground-based interferometer projects: Advanced LIGO (USA), Advanced Virgo (Italy), GEO-HF (Germany), and KAGRA (Japan), have been funded. Advanced LIGO entered operation in late 2015 and immediately made the first detection, while Advanced Virgo will follow in 2016. KAGRA is expected to enter in operation in 2017, whilst the Indian version of LIGO, IndIGO, has been recently approved.

The sensitivity of these instruments is expected to ramp up very rapidly to levels commensurate with multiple detections per year: gravitational-wave physics is about to take off! Detection rates and source localization will be enhanced when KAGRA and Indigo join the already established LIGO-Virgo network.

A question that the community will have to face, once the enthusiasm of the extraordinary detection slows down, is the strategy to follow in the coming years: sensitivity upgrades of the current infrastructures by factors 2 to 3, which immediately translates to increase of detection rates 8 to 27 versus efforts to progress towards full third-generation (G3) gravitational-wave observatories on Earth, where the Einstein Gravitational Wave Telescope (ET), project planned for the 2020s, is the most advanced project. It would probe a thousand times larger volume than Advanced LIGO and Virgo 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 measurements.

Furthermore, in space, the undisputed flagship project is eLISA selected by ESA for its 'Gravitational Universe' mission with a launch date in 2034. In view of the GW detection and the presently successful return from the Lisa-Pathfinder ESA space mission, the discussion to advance the launch by a few years is not an unreasonable demand. eLISA is best adapted to gravitational waves in the 10^{-4}-1 Hz range, thereby complementing the higher frequencies accessible to ground-based observatories. The eLISA science program is very rich and 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. eLISA will also probe our own Milky Way galaxy, providing a census of the hundred million relativistic compact binaries estimated to exist in the Milky Way galaxy.

- ***GW Consideration 1.*** *Europe, in collaboration with the other regions in the world, should aim to prepare a new roadmap in the next crucial years after the first detection of gravitational waves; decide on the timelines of support for the further upgrades of G2 antennas, that might promise an increase the sensitivity by factors of 2 to 3 corresponding to increases of reach by factors of 8 to 27, while preparing increases in sensitivity by factors of 10 on the ground (Einstein telescope).*

- *GW Consideration 2. Europe should encourage the advancement of the launch date of the eLISA mission in discussion of course with the relevant authorities (ESA and eventually NASA).*

GW prospects. The Universe can now be probed not only through standard candles of light as it was done until now, but also "standard sirens" of gravitational waves in different frequencies. Through them, there will be most probably new measurements of the expansion rate and acceleration of the Universe, new measurements of the deformations of space time through gravitational lensing, and the possibility of multi-messenger studies (including photons and neutrinos) of violent phenomena, and eventually phase transitions of the type one encounters in particle physics models. Probably most exciting of all, but demanding extreme sensitivities, 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 this would yield a picture of our Universe just after the Big Bang!

6. Probing the High Energy Universe with photons, neutrinos and cosmic rays (HEU)

HEU findings and tasks. Charged cosmic-rays were the first indicators of cosmic non-thermal processes, but charged cosmic rays alone are unlikely to be sufficient since a) they do not point to their source unless they have an ultra high energy (above 10^{19} eV) and b) at high energies their mass composition (proton or nucleus) is uncertain. Fortunately, other messenger particles of non-thermal events in our Universe have recently been observed: high-energy gamma rays (first detection in 1989 and detailed astronomy since 2003), high-energy neutrinos (first detection in 2013) and as stated above gravitational waves. Unlike cosmic rays, these other messengers are unaffected by (inter)galactic magnetic fields. It is by combining the analysing power of high-energy gammas, neutrinos , ultra high energy cosmic rays, as well as gravitational waves i.e. a four-pronged approach that astroparticle physicists hope to better understand the non-thermal Universe. This will ideally unveil not only the intricacies of the sources of high-energy cosmic rays, but also lead to discoveries and subsequent studies of new, super-heavy, elementary particles.

High-energy gamma rays. Over the past decades an innovative instrument was developed to observe high-energy gamma rays, with energies ranging from typically 100 GeV to 30 TeV: the Imaging Atmospheric Cherenkov Telescope (IACT). 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 breath-taking objects such as supernova remnants, pulsars, binaries, active galaxies presumably hosting super-massive black holes at their centres. To fully exploit the discovery potential by studying high-energy gamma rays, a large community of astronomers and astroparticle physicists united themselves behind a global project: the Cherenkov Telescope Array or CTA, which acquired ESFRI status in 2008. Compared to its predecessors, CTA will be an order of magnitude more sensitive and is expected to increase the number of identified sources tenfold. Unlike its predecessors, which were operated as typical particle physics experiments i.e. 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. CTA will cover high-energy gamma rays from as low as 20

GeV to as high as 300 TeV. To cover this large dynamic range, about a hundred telescopes of three sizes will be installed. To cover the full sky, two sites were selected in 2015 and CTA's Resources Review Board started contract negotiations with both of them: the European Southern Observatory Paranal grounds in Chile and the Instituto de Astrofisica de Canarias, Roque de los Muchachos Observatory in La Palma, Spain. Several prototype telescopes, still exploring alternative design options, have been procured and tested. Negotiations as to how to share the CTA investment costs (about 300 M€) and exploitation costs (about 15 M€/year) have started among the main partners. Unless cost savings can be identified, for example by using the most economic telescope designs, some staging of the project will probably be inevitable. Also, given that CTA plans to operate for up to 30 years, the exploitation costs warrant scrutiny.

High-energy neutrinos. IceCube's 2013 announcement of the first observation of high-energy (PeV-range) neutrinos of cosmic origin opens a new window upon our Universe: neutrino astronomy. The challenge now: to identify the sources of these 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. Neutrinos can shed light on cataclysmic events that remain obscure in traditional, predominantly electromagnetic, astronomy. However, since neutrinos interact very little with their surroundings, their detection is extraordinarily challenging. The holy grail of high-energy neutrino physics is to identify and subsequently study fluxes of high energy events, thereby complementing studies of high energy gamma-rays and cosmic rays.

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. As pointed out in the late 1950s, 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 2500 m below sea level 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 kilometre 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. 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 than 0.4 degrees; a very powerful constraint in hunting for neutrino point sources. To date, the statistics remain insufficient to unambiguously identify a neutrino point source.

The observation of cosmic neutrinos has boosted the 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) focused on the PeV energy regime, addressing notably extragalactic sources. The Baikal-GVD neutrino telescope recently deployed its first cluster of the 8-12 planned clusters to instrument about one cubic kilometre volume at a depth of 1500 metres in Lake Baikal by 2020. In the Mediterranean Sea, KM3NeT, most probably in the new (2016) ESFRI list, started the installation of the 1-2 cubic kilometre volume ARCA detector off the coast of Sicily at a depth of 3500 m. It is currently in its phase 1, fully funded, and the collaboration bids for a phase 2 approval, that would provide a neutrino telescope larger by a factor 2-3 in sensitivity. Compared to IceCube-Gen2, ARCA's complementary scientific priority is the observation of Galactic neutrino sources in the TeV to PeV regime.

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 successfully requires the realisation of at least one densely instrumented order megaton detector by 2020 (ORCA or PINGU presented above) and of sparsely instrumented 2-10 km^3-sized detectors covering both the Northern and the Southern hemispheres– ideally using complementary technologies – early in the next decade.

High-energy cosmic rays Cosmic rays span a gigantic energy range from sub-GeV to record energies of at least a hundred billion GeV. They 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. The sources of high-energy cosmic rays remain a mystery i.e. which cataclysmic objects in our Universe are capable of accelerating particles to energies many millions times higher than those mankind achieves in its most powerful accelerators like CERN's Large Hadron Collider (LHC)?

Primary cosmic rays can only be measured directly by detectors flown on stratospheric balloons or satellites. However, due to weight limitations, space-born detectors fail to attain the accuracy needed to study cosmic-rays beyond a few TeV. And even if they could, the primary cosmic-ray flux decreases so fast with increasing energy that hardly any events will be observed beyond a few TeV. Still, sub-TeV cosmic rays offer a rich scientific program as for example convincingly shown by the Pamela satellite, launched in 2006, and the AMS experiment, installed in 2011 on the International Space Station. AMS 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.

Due to inter-stellar and galactic magnetic fields only the cosmic rays with highest energy-to-charge ratio can realistically be used to back-track to their sources, they can be detected only through their showering in the atmosphere. Furthermore, due to their strongly enhanced interaction probability with the omnipresent photons of the CMB radiation, cosmic-ray protons with energies above 5×10^{10} GeV should be suppressed: the Greisen–Zatsepin–Kuzmin, GZK, cut-off. With the highest energy cosmic-ray protons the proton-proton interaction probability, cross section, can be measured at much higher centre-of-mass energies than the LHC.

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 and has a substantial European involvement. Auger has already produced tantalizing results (highest centre-of-mass energy proton-proton cross section; hints of sources; evolution of the mass composition at the highest energies; new spectral features amongst which a clear flux suppression around the predicted GZK cut-off at 5×10^{10} GeV). However, it also became clear that further progress hinges, apart from higher statistics, critically on a much better mass differentiation. For this Auger will augment the water tanks, forming the basic element of its surface detectors, with a large scintillator to get a handle on the electron-to-muon fraction in each shower which is correlated to the mass (i.e. charge) of the primary cosmic ray. Auger is now scheduled to take data until at least 2025 with its primary aims to discover cosmic-ray sources and to settle the GZK cut-off. In parallel, Telescope Array (TA), a smaller air-shower detector installed in Utah (USA) and already completed in 2007, covering the same energy range as Auger, will upgrade its array by a factor four in size to become comparable 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.

The global cosmic-ray community is already working towards next-generation observatories. In view of cost 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 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. These future projects should yield orders of magnitude larger data samples which should allow detailed studies of the cosmic-ray sources.

- ***HUE Consideration 1.*** *Europe should continue to support the CTA deployment as a high priority project.*
- ***HUE Consideration 2.*** *CTA being the first general purpose large observatory that will be deployed by the astroparticle community, requires its operation costs to be properly scrutinised and optimised to reduce the risks of these costs having severe impacts on the rest of the program. Full deployment should be contingent on a complete study of the operation costs.*
- ***HUE Consideration 3.*** *Europe should examine a funding plan for phase 2 of KM3NeT (ARCA) during 2016. The operation costs should be equally scrutinised.*
- ***HUE Consideration 4.*** *The European agencies should support the approval of IceCube-Gen2 by NSF and make available the corresponding European contributions.*
- ***HUE Consideration 5.*** *The European agencies should oversee the timely completion of the Auger upgrade.*
- ***HUE consideration 6.*** *R&D for the next generation of ultra-high energy cosmic rays should be supported.*

HUE prospects. The establishment of high energy gamma astronomy a decade ago, the first steps of the high energy neutrino astronomy 2-3 years ago and the very recent gravitational wave detections are clear indications that multi-messenger astronomy has started. The IceCube events are consistent with Fermi satellite photon spectra, the Auger spectra when identified as protons would have clear implications on high energy neutrino spectra in IceCube and KM3NeT. Gravitational waves from gamma-ray bursts should have equivalents in neutrino, photon and cosmic ray observatories. We know that violent phenomena regulate the formation of cosmic structures. Their better understanding through multi-messenger astronomy, will be another stepping stone to a unified view of the physics and astrophysics of our Universe.

7. Transverse issues

7.1 Theory

Theory findings and tasks. To take full advantage of the impressive potential of the next-generation projects in astroparticle physics, a deep and fruitful synergy between Theory and Experiment is mandatory. As different as those fields can be in terms of their techniques, there is one feature they share: their possible success in exploring the "terra incognita" hinges upon a strong synergy between theory and experiment. Indeed, we do not have a well-established New Physics theoretical framework to guide the experiments whereas the available experimental data is still insufficient to point towards a unique over-arching theory. In other words, our experimental search needs some guidance, or at least some more or less clear indication of where and what to look for from theory; on the other hand, in building up New Physics theories, the astroparticle experimental input is as badly needed as the input coming from more the more traditional sources as high-energy and high-intensity particle physics.

Theory groups and dedicated research centers in astroparticle physics are dispersed amongst a number of European universities and institutions. During recent years, there has been an effort of coordination and common actions through the PACT initiative of APPEC (Particle Astrophysics and Cosmology Theory). PACT has been so far a "virtual" institute organizing some common actions. However, the PACT seed has to evolve from such a virtual institute of moderate impact on the life of the astroparticle community to a possible European Center for Astroparticle Theory coordinating the activities of the individual centers in an organized form at the European level. Its mandate would be not only to coordinate the astroparticle theory research in Europe, but also create a reference center where theorists and experimentalists could be together for fixed periods, interacting and exchanging ideas, and organize thematic research programs, topical workshops and schools training students and young researchers in the field. The particular form of this center (virtual or local), the related organizational structure and the actions to be taken should be discussed directly within the astroparticle theory community and its action should be supported by the agencies in APPEC.

- ***Theory Consideration 1.*** *APPEC should support the realization of an European Centre for Astroparticle Theory with the tasks of coordinating the intense and diversified European astroparticle theory activities and enhancing the already existing synergies between theory and experiment in astroparticle physics.*

7.2 Computing

Computing findings and tasks. Astroparticle physics data taken by current experiments and observatories are relatively voluminous and expected to grow by a factor six by 2020. E.g. current CPU use by major astroparticle physics experiments, is equivalent to half of the LHC Tier-0 (2012) and will grow to nearly three LHC Tier-0s by 2020. Current low latency disk storage is of the order of 10 Petabytes (PB) and will be about 70 PB by 2020, while tape archive/tape storage current needs are of the order of 20 PB and will exceed 100 PB by 2020. During the first years of 2020's and after a series of large surveys and experiments enter into operation, the requirements for computing resources are estimated to increase overall by a factor 10. Although this is quite large and has to be programmed efficiently, it is still manageable and relatively modest with respect to needs of e.g. the LHC upgrades.

The originality of astroparticle physics data is their diversity: they can be categorized as event-type (high energy astroparticle observatories, similar to particle physics data), time-series (gravitational wave antennas) and images (large surveys, similar to classical astrophysics data). Each type of data requires a different type of analysis method. The diversity of data and its analysis makes astroparticle physics a formidable test-bed for new and innovative computing techniques concerning hardware, middleware, analysis software and database schemes. Tier-2 scale computing centres can play an important role as hubs of software development, visualization, general interfacing, coordinated design, and public outreach.

Furthermore, given that astroparticle physics projects depend on certain site conditions and are mostly placed at remote locations often without direct access to high-speed Internet each project is required to develop its own solution for local and intelligent processing and transfer of project data to computing centres. Sometimes also innovative methods of distribution of precision timing and synchronization need to be developed.

- ***Computing Consideration 1.*** *The Astroparticle physics community needs to discuss, in addition to future computing requirements on how to make data formats compatible in order to ease multi-messenger analyses and facilitate data access. Access policies developed in astrophysics for data taken at large astronomical observatories or by satellites should also be adopted for astroparticle physics data; after a defined proprietary period – suitable for a scientific analysis by the PI – data are made publicly available via archives.*
- ***Computing Consideration 2.*** *Industrial and societal applications of hardware and algorithms developed for astroparticle experiment/observatories should be supported.*

7.3 R&D and Industry

R&D and Industry findings and tasks. Astroparticle physics experiments make huge demands of technology, often combining several extraordinary characteristics like ultra-high measurement precision, huge detector size, very harsh operating environment, excellent reliability or ultra-low radioactive background. Not surprisingly R&D activities are an integral and vital part of astroparticle physics research. R&D ranges from the continuous quest for better and cheaper detectors (in particular photo sensors) as well as better and cheaper components like cryogenic coolers, electronics, seismic attenuators, isotope purification systems to the development and exploration of entirely new detection concepts. Examples of new concepts are the pioneering work on the detection of cosmic rays using their radio emission, the detection of high-energy neutrino interactions using acoustic signals or creative ideas to extract radio-pure materials, argon and lead, from supplies shielded for a long time from activation by cosmic rays. For some years APPEC has organized so-called Technical Fora to bring together leading industries with our R&D communities in various areas: photon detection, deep-sea technology, optics, cryogenics, etc.. These Technical Fora helped technical progress as well as the setting up of consortia to jointly respond to EU calls for funding.

A common denominator of many of the experiments focused on a better understanding of the high-energy is the deployment and operation of large numbers of sensors, often in hostile environments: frozen in the Antarctic ice, floating deep in the Mediterranean Sea, in high-altitude deserts or in underground caverns. Key characteristics of these sensors are: high reliability, low power consumption, wireless control and affordable cost. The low-cost, low-power and wireless controllable seismic sensors which will eventually be needed for the next generation gravitational wave detectors are just one example. They will be needed to control the gravitational gradient noise i.e. the effects of density perturbations in the Earth's interior. These same sensors can for example also be used for oil exploration campaigns and perimeter security and are as such marketed by Innoseis B.V., a spin-off of astroparticle physics research.

- ***R&D and Industry Consideration 1.*** *APPEC should encourage the use of astroparticle physics technology and concepts for direct societal benefit.*

7.4 Education & Outreach

Education & Outreach findings and tasks. With enigmatic questions such as "*What is Dark Matter?*", "*How did our Universe evolve?*", "*What is the true nature of the mysterious neutrinos?*", "What do high-energy cosmic messenger particles tell us?" astroparticle physics research is exciting and inspirational. Tantalizing discoveries are what really attracts the interest of the general public and astroparticle physics is doing extremely well in this respect. Already four Physics Nobel Prizes in this century: cosmic neutrinos (2002), cosmic microwave background (2006), accelerating expansion of the Universe (2011) and neutrino oscillations (2015), with several game changing observations such as the PeV neutrinos observed by ICECUBE and the recent discovery of gravitational waves.

- ***Education and Outreach Consideration 1.****Given the rapid recent expansion of the field, it is time to take stock to collect and exchange best practices regarding outreach material, lab courses, and demos for both university and high-school students. IPPOG, the International Particle Physics Outreach Group, has contacted APPEC to join forces herein. Our community should explore online teaching opportunities like MOOCs i.e. Massive Open Online Courses and APPEC itself should strive towards a structural organization of astroparticle physics summer schools and summer studentships at our frontier astroparticle physics research facilities. The advance our visibility. Finally, APPEC must further professionalise its Newsletter approach and its presence on the Web and social media like Facebook and Twitter.*

8. The global view

Global view findings and tasks. Astroparticle physics is clearly a domain where collaboration and coordination are vital. The investment funding for the proposed observatories – often exceeding national or even regional capabilities – the difficulties in establishing a single institutional centre to cover the full spectrum of astroparticle physics activities and above all the fact that the rarity of some astroparticle physics messengers demands large detector networks spanning across the globe, covering both hemispheres, all call for collaboration. The need to collaborate is also a strength of the field, since it can advance state of the art science in emerging economies and it can stimulate science education and science engagement around the globe. The astroparticle observatories deployed in hostile, remote or controlled environments like deserts, deep-seawater, Antarctic ice, deep underground or in space, can also easily accommodate dedicated instruments monitoring global issues such as climate change and earthquakes and thereby attract other research communities.

Since the EU-funded ERANET ASPERA (2006-2012), APPEC promoted global coordination. Coordinating highlights where APPEC played a key and sometimes leading role, were :

- *The start of operations of the Auger Observatory of Cosmic Rays, historically the first truly international endeavour without a key national stakeholder playing the role of the "host institution";*
- *The formation of a worldwide collaboration to study high-energy gamma-rays: the Cherenkov Telescope Array (CTA) project; and*
- *The establishment of the Global Neutrino Network in which the high-energy neutrino observatories collaborate and exchange information.*

After the termination of the EU-funded ERANET ASPERA in 2012, APPEC re-positioned itself maintaining international collaboration at the core of its work programme. APPEC organized or co-organised two international meetings on large neutrino infrastructures, highly contributing to the formation of the worldwide collaboration DUNE. The successful global convergence in the neutrino sector, inspired several major agencies to tackle another area where global collaboration & coordination appears desirable: the "Cosmic Frontier" and in particular the next generation precision experiments measuring the CMB, where the process is ongoing.

- ***Global View Consideration 1.*** *APPEC should continue its efforts towards a global coordination in the next generation CMB experiments.*
- ***Global View Consideration 2.*** *In view of the high investment costs, next generation direct dark matter search experiments (entering the multi-ton scale) and neutrinoless double-beta decay (entering the ton-scale) experiments will demand global coordination. After the results of the current experiments have been published and once the favoured technologies are sufficiently mature, APPEC should coordinate with other regional agencies how to best select the next generation experiments paying attention to scientific excellence, the use of complementary technologies and the opportunities offered by the existing deep-underground laboratories.*
- ***Global View Consideration 3.*** *To achieve the scientific discoveries we dream of avoiding unnecessary long delays and spending available investment funding economically, not only global collaboration is required, but also a global strategy. Such a strategy should advance the design, construction, exploitation and management of the next generation world-class*

large Research Infrastructures and facilitate the access of a worldwide community to these Research Infrastructures irrespective of where they are located. Following specific items urgently require attention:

- *a modern policy on the operation of the large Research Infrastructures using the full potential of standardisation, digitisation, automation and virtual presence has to be adopted, reducing where possible exploitation costs;*
- *a policy on the global interoperability of Research Infrastructures through the pursuit of international agreements on the coordination of operations, reciprocal use, data exchange and authorship sharing. For example along lines currently pioneered by the network of gravitational-wave detectors. Two upcoming major challenges are the coordination of observations in view of multi-messenger science and the exchange of large sets of complementary data between for example LSST and EUCLID;*
- *a policy to promote interdisciplinary access of Research Infrastructures by scientists from other areas of research and industry, as well as transferring technical know-how to non-academia (industrial and society). A specific example relating to astroparticle physics are the neutrino observatories located in the deep-sea or Antarctic ice which offer opportunities to marine and earth scientists; and*
- *an international policy on science engagement and education centred upon the scientific challenges and the interdisciplinary aspects of the large astroparticle physics observatories.*