Astroparticle physics

The European Roadmap

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ASPERA

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Executive Summary

Astroparticle physics marks the intersection of astrophysics, particle physics and cosmology. It addresses fundamental questions like the nature of dark matter and dark energy, the physics of the Big Bang, the stability of protons, the properties of neutrinos and their role in cosmic evolution, the interior of the Sun or supernovae as seen with neutrinos, the origin of cosmic rays, the nature of the Universe at extreme energies and violent cosmic processes as seen with gravitational waves.

Among the spectacular successes of astroparticle physics in the last 25 years have been the opening of two new windows to the universe: the neutrino window (the Sun and a supernova) and the window of high-energy gamma rays. The study of cosmic neutrinos also revealed that neutrinos have mass, with fundamental consequences for the role of these particles in cosmic evolution. Astronomers and physicists have discovered that the expansion of the Universe accelerates (2011 Nobel prize for physics!). Other branches of astroparticle physics have greatly improved the levels of sensitivity, something which makes analogous groundbreaking discoveries in the near future likely. This applies to the detection of gravitational waves and dark matter particles, the study of the origin of high energy cosmic rays and neutrinos, the determination of the neutrino mass or, later, the observation of proton decay and the understanding of dark energy. **Compared to the last version of the ASPERA roadmap in 2008, we witness today a remarkable progress on many fronts, as well as an increased coordination and networking on a global scale.**

Research priorities differ from country to country, depending for example on their local infrastructures, or on their traditions and historically grown strengths in particular fields. The Scientific Advisory Committee (SAC) ranked scientific arguments highest but at the same time kept in mind that there are also historical and political aspects to be considered. We decided to classify our recommendations into two categories: a) medium scale projects or medium scale upgrades being at different stages of realization (investment funds in the category of tens of M€) and b) large scale projects whose construction needs to start towards the middle of the current decade (investment funds on the scale of hundreds of M€).

In the first category there are a few projects whose funding has to be kept at substantial levels, be it because they have an impressive momentum that needs to be maintained, because they enter a phase with high discovery potential, because they go hand in hand with LHC physics, because they are technologically ready and have a worldwide community behind them, or finally, because a delay of crucial decisions and funding could even jeopardize the project. In this spirit, we recommend the following projects and urge the agencies to join their forces in order to provide effective and substantial support:

• **Gravitational waves:** With Advanced VIRGO, Advanced LIGO and GEO-HF, a discovery in the next five years becomes highly probable. This would open an entirely new window to the Universe. We urge the agencies to continue to substantially support the ongoing and planned upgrades to advanced detectors.

• **Dark Matter:** With the advent of the LHC and thanks to a new generation of astroparticle experiments using direct and indirect detection methods, the well-motivated SUSY-WIMP dark matter hypothesis will be proven or disproven within the next 5-10 years. The highly significant annual modulation signal observed by DAMA/LIBRA, and its interpretation in terms of dark matter interactions, will also be scrutinized in the next few years. The dramatic progress of the liquid-xenon technology over the past 2-3 years demonstrates a high momentum, which must be maintained. The recently approved **XENON1T** at Gran Sasso laboratory is expected to start operation in 2014/15. The bolometric experiments **CDMS** and **Edelweiss** have recently provided upper limits close to those of XENON100 and move towards a closer US-Europe coordination. We recommend supporting the development of **EURECA**, which envisages one ton of sensitive mass, eventually in a common US-Europe framework. Looking beyond the scale of one ton, we strongly recommend that **DARWIN**, a program aiming to extend the target mass of noble liquids to several tons, is pursued and supported.

• **Neutrino properties:** Several highly important experiments in Europe are either in the commissioning phase or in the final years of construction: **GERDA**, **CUORE** and the demonstrator for **SuperNEMO** will search for neutrino-less double beta decay, **KATRIN** for neutrino mass via single beta decay. **Double CHOOZ**, a nuclear reactor experiment, is studying neutrino oscillations. The mentioned experiments build on a long experience and validation with precursors. They have been recently joined by **NEXT**, a new approach to the search for double beta decay. We renew our strong support for these experiments and look forward to first results. Beyond this, we recommend a phased experimental approach in neutrino-less double beta decay with a sensitivity (ton scale masses) that will allow to explore fully the mass range predicted by oscillation experiments for the inverted mass hierarchy.

- The underground science program on dark matter and neutrino properties calls for more underground space. In this context, there is a unique window of opportunity to extend the present **Underground Laboratory of Modane (LSM)** by taking advantage of the excavation of the safety tunnel of the Frejus road tunnel, which has already started. The new laboratory of 60.000 m^3 at a great depth could host several of the proposed large new projects. We recommend the timely support for the LSM extension.

The **large-scale infrastructures** whose construction needs to start towards the middle of the current decade include three high-energy projects and one on low-energy neutrino astrophysics:

- **TeV gamma-ray astrophysics:** The Cherenkov Telescope Array **(CTA)** is the worldwide priority project of this field. It combines proven technological feasibility with a high speed towards prototyping, with a guaranteed scientific perspective and a mode of operation and wealth of data similar to mainstream astronomy. The cost scale of CTA is 200 M€. We recommend the design and the prototyping of CTA, the selection of the site(s), and to proceed vigorously towards start of construction in late 2013.

- **High energy neutrinos:** In the high-energy neutrino domain, the requirements on the necessary sensitivity have tightened, but the scientific case for a large neutrino detector in the Northern hemisphere remains high. The **KM3NeT** collaboration is working towards a technical proposal for a neutrino telescope with a substantially larger sensitivity than IceCube. The expected cost scale is 250 M€ and based on pioneering technical work by the European astroparticle community, also provides access to deep-sea research.

- **High energy cosmic rays:** The cosmic-ray community including the Pierre Auger collaboration is working towards a **next-generation ground-based observatory.** These efforts include the development of new detection technologies, the search for appropriate sites, and the attraction of new partners. We reiterate the definition of a substantially enlarged ground-based observatory as the priority project of high-energy cosmic ray physics. The cost scale is 100-150 M€, with a substantial contribution from Europe.

- **Low-energy neutrino astrophysics and proton decay:** A megaton-scale low-energy neutrino astrophysics and proton-decay detector for astroparticle and accelerator-based neutrino measurements is addressed by the **LAGUNA** design study. The scientific goals combine high-risk research addressing several fundamental questions of physics (proton decay, CP violation) with exciting neutrino astrophysics (e.g. supernova, solar, geo- and atmospheric neutrinos). The committee recommends that the study be pursued within the LAGUNA-LBNO program, including options with and without a new neutrino beam. Due to the high cost (350-700 M€, depending on site and type of detector) and the long development time, the committee recommends that this program is pursued in a global context. Given the close relation to beam-related neutrino oscillation projects, the urgency of its realization depends strongly on the output of the current accelerator and reactor programs and in particular on whether the missing neutrino-mixing parameters are in the range that would permit a series of very exciting new measurements (neutrino mass hierarchy, CP violation etc). If the current indications for a large mixing angle θ_{13} were to be confirmed within one or two years, attractive scenarios for the medium-term CERN strategy open up, LAGUNA is therefore clearly at the interface with the CERN European Strategy Update to be delivered by the end of 2012. As such the LAGUNA project constitutes a high astroparticle physics priority to be discussed within the CERN strategy update process.

The presently conceived start of construction of KM3NeT, the ground based cosmic ray observatory and a low-energy neutrino detector is in the years 2014-2016. We would support a strategy to search for funding opportunities for these projects – both in Europe and worldwide – and promote any one of these projects as soon as a corresponding window appears.

Astroparticle physicists play a major role in many international **dark energy programs**, as e.g. the dominantly US-funded LSST observatory (first light ca. 2020) or the ESA satellite **EUCLID** (launch 2019). The committee recommends a strong support for these participations.

The path for research in gravitational waves beyond the advanced detectors foresees two very large-scale projects (costs on the billion Euro scale): the Earth-bound **Einstein Telescope (E.T.)** and the space-bound **LISA** project. In today's perspective, E.T. construction would start at the end of the decade and after the first detection of gravitational waves with the advanced detectors. We also look forward to the results of LISA-Pathfinder. We renew our strong support of the LISA mission and preparatory work on E.T.

We finally emphasize the importance of three transversal aspects:

• **Theoretical research** is an integral part of astroparticle physics and is indispensable when experimental data have to be interpreted in the context of models, be it in terms of possible signals or as constraints. Similar to experimental activities, theoretical studies will strongly benefit from a strengthened and more coordinated support. In turn, this will also help to maximally exploit the impact of astroparticle physics experiments.

• **Smaller projects and innovative R&D activities** are essential for the progress of our field and profit from international cooperation. ASPERA addressed this by carrying out a series of calls for R&D activities.

• Most astroparticle observatories, whether they are located underwater/ice (neutrino telescopes) or underground (underground laboratories) or on the ground (air-shower detectors), have developed strong **synergies with geoscience, biological and environmental sciences.** They provide state-of-the-art technologies and attractive infrastructures to the corresponding communities, which in turn will increase the support of these infrastructures. ▪

Content

1. Introduction

The term *astroparticle physics* was created only thirty years ago, and it took a decade to be commonly accepted. Its roots, however, reach back a century, whose story is one of remarkable explorations and discoveries. It started with the groundbreaking discovery of cosmic rays in 1912 by Victor Hess (Nobel Prize 1936). Two decades later, in 1932, the first anti-particle – the *positron* – was discovered in cosmic rays (Nobel Prize 1937). Next came a heavy brother of the electron, the *muon*, discovered in 1937, followed in 1947 by the *pion*, the first representative of the immense family of the mesons (Nobel Prize 1950). The "second spring" of astroparticle physics started with the detection of neutrinos from the Sun in the 1970s and the spectacular registration of neutrinos in 1987 from a supernova. In 2002, Ray Davis and Masatoshi Koshiba were awarded the Nobel Prize for opening the neutrino window to the Universe, specifically for the detection of neutrinos from the Sun and Supernova 1987A. Their work was a unique synthesis of particle physics and astrophysics. Solar neutrinos also provided the first clear evidence that neutrinos have mass. The detection of solar and supernova neutrinos is not the only new window opened by astroparticle physics. Another one is that of very energetic gamma rays recorded by ground-based Cherenkov telescopes. From the first source detected in 1989, three sources known in 1996, to over 100 sources identified until 2011, the high-energy sky has revealed a stunning richness of new phenomena and puzzling details. At the same time, astroparticle physics has progressed to levels of sensitivity with high discovery potentials. This applies to the detection of gravitational waves, the search for dark matter particles and the nature of dark energy (the Nobel prize for physics in 2011 has just been awarded for the 1998 discovery that the expansion of the Universe is accelerating!), the search for the origin of high-energy cosmic rays and neutrinos, the determination of nature, mass and mixing properties of neutrinos and to the observation of proton decay.

We thus are at the threshold of exciting discoveries in several key areas. However, the cost for cubic-kilometre neutrino telescopes, large gamma-ray and cosmic-ray observatories, megaton-scale detectors for proton decay, or ultimate low-temperature devices to search for dark matter particles or neutrino-less double beta-decay ranges between tens and hundreds of millions of Euros. Such costs require international collaboration, as does the realization of the necessary infrastructure. Co-operation is the only way to achieve the critical mass for projects that require budgets and personnel not available to a single nation. This avoids duplication of resources and structures, and would also guarantee a leading role for Europe.
ApPEC and ASPERA have been created to promote this process. ApPEC (Astroparticle Physics European Coordination) was founded in 2001 as a body coordinating the interests of six European scientific agencies. They realized that most of the emergent field of astroparticle physics is not covered by the coordinating and funding mechanisms of adjacent disciplines like particle physics or astronomy. Consequently, ApPEC aimed at developing long-term strategies and offering advice to national funding agencies or other organisations, expressing the view of European astroparticle physics in international forums, and establishing a system of peer review assessment. ApPEC's executive body is the Steering Committee (SC), with one leading scientific executive from each country and observers from CERN, ESO and ESA.

Realizing that its goals and methods fit ERA-NET, the European Union program for support of national and regional cooperation, ApPEC initiated the submission of a proposal for an ERA-NET project called "ASPERA". ASPERA started in July 2006, funded by the EU with 2.5 M€ for a three-year period, and was prolonged for another three years in 2009. The bodies of ASPERA are the Governing Board, consisting of high-level representatives of the agencies, a coordinator and a co-coordinator, a Joint Secretariat consisting of the Work Package Leaders, and the Science Committee, presently named Scientific Advisory Committee (SAC). At present, ASPERA includes 24 partners from 18 countries. ASPERA issued two European-wide calls for research projects, the first focusing on gamma-ray astronomy and dark-matter searches, the second on cosmic ray projects and neutrino mass experiments, with the goal to promote developments towards large future experiments and infrastructures and to strengthen the collaboration between the relevant research groups in Europe.

ASPERA and ApPEC have charged the SAC to update the previous Roadmap(s) for Astroparticle Physics in Europe. The first phase of a roadmap, *Status and Perspective of Astroparticle Physics in Europe*, has been presented in 2007. It described the status and desirable options of European astroparticle physics for the decade 2007-16, including detailed physics information. A second document, *Astroparticle Physics – the European Strategy*, was released in autumn 2008. It was directed to a wider readership than the first one. Moreover, it included more precise timelines and updated cost estimates, and also mapped the full funding landscape. This phase ended officially with a high-profile international workshop in Brussels at 29-30 September 2008.

Because astroparticle physics is a rapidly growing, dynamic field, it does not come as a surprise that its landscape has changed already between 2008 and now. Fortunately, a non-negligible fraction of the necessary modifications to the 2008 roadmap are for the better. On the other hand there have also been substantial delays – which are not unusual for projects on these cost scales. The dynamics of the research landscape is the **first argument** for an updated roadmap.

The **second argument** for the timing is the planned update in 2012 of the European Strategy for Particle Physics which is worked out by the CERN Council Strategy Group. Already for the 2008 ApPEC/ASPERA Roadmap, we have shared our views and findings with the CERN Council Strategy Group (as well as with the astrophysics community which produced a *Science Vision for European Astronomy* and an *Infrastructure Roadmap for European Astronomy*). The present Roadmap should provide a qualified input to the updated document on the *European Strategy for Particle Physics*. This is particularly important since much of our research goes hand-in-hand with research at the LHC and other accelerators – starting with dark matter and supersymmetry, including high energy interactions and ending with questions like CP-violation in the leptonic sector and cosmology. Our roadmap was also drafted in close relation to the *Report of the Working Group on Astroparticle Physics* for the Global Science Forum of the OECD.

In the 2008 roadmap, proposals for priority experiments, for phasing of large projects and for international cost sharing were made. They met a funding scenario with a smooth factor of 2 increase over the next 8-10 years. We were – and continue to be! – convinced that the prospects of astroparticle physics merit this increase. On the other hand we have to face that funding realities in most countries have become more challenging. This is a **third argument** for a revision of the 2008 recommendations and a critical reality check.

Russia – a country with a long tradition in Astroparticle Physics – became an associate member of ASPERA. Whereas until now Europe, the US and Japan have been the primary drivers of astroparticle physics, other countries are becoming increasingly involved, amongst them China and India. This adds another aspect of global cooperation and competition.

The mentioned arguments led to the decision to update the European roadmap for astroparticle physics. The ApPEC Steering Committee and the ASPERA Governance Board charged the SAC to prepare this document. The charge does not include the request of a prioritisation of projects. The SAC is aware that research priorities will differ from country to country, depending, e.g. on their local infrastructures or on their traditions and historical strengths in particular fields. The SAC ranked scientific arguments highest, but at the same time kept in mind that there are also historical and political aspects. For instance, we were careful not to define priorities in such a way that they might limit the phase space of national funding agencies for substantial, positive funding decisions, once such possibilities for a certain project appear on the national level. We also have had to face the fact that the ApPEC and ASPERA steering bodies did not define funding envelopes, to which we could have tailored our recommendations.

The present roadmap is composed of the following parts:

In Section 2 we address the projects of the high-energy Universe, starting with an introduction to the basic questions, continuing with projects on charged cosmic rays, then gamma-ray telescopes and ending with high-energy neutrino detectors.

In section 3 we cover dark matter searches, experiments to determine the nature and mass of neutrinos – both direct mass measurements and searches for neutrino-less double beta decay – as well as detectors for low energy astrophysical neutrinos and proton decay, focussing on a future detector on the 50 kiloton to 1 Megaton scale.

Section 4 is devoted to dark-energy missions and gravitational-wave detection. The tools used in these experiments are rather distinct from the particle and nuclear physics tools typical of the field discussed in Sections 2 and 3. Because dark-energy missions are to a very large extent defined by US plans, we keep our recommendations on this subject brief.

Section 5 addresses activities which are essential for all fields – starting with theoretical research and ending with technology development.

The Appendices reproduce the letter of charge to the SAC in A.1, give a reminder on the 2008 roadmap (A.2), sketch the development from 2008 to 2011 (A.3) and list all recommendations given in the text (A.4). Tables in A.5 provide summary information on all relevant experiments. ■

2. The High Energy Universe

2.1. Introduction

Cosmic rays were discovered nearly a century ago. They have been the basic source of progress in elementary particle physics in the 1930s and 40s, before the development of accelerators. Presently, the primary interest in cosmic rays is opening a window to explore the Universe at the highest energies using all possible messengers.

Astrophysics Questions: The observation of particles with energies much beyond the beam energies of terrestrial accelerators raises several questions. First, how can cosmic accelerators boost particles to these extremely high energies? Cosmic rays with energies up to about 10^{16} eV are probably accelerated at the shock fronts generated by galactic supernova explosions or stellar wind collisions. Indeed, radio emissions, X-rays and gamma-rays give direct evidence that these fronts accelerate electrons to beyond 10^{14} eV. However, the evidence that high-energy protons and nuclei – the main component of charged cosmic rays – have the same origin as these electrons is only circumstantial and needs confirmation. Cosmic rays constitute a remarkable part of the galactic inventory and play an important role in the thermodynamics of the Galaxy. Another key question concerns the maximum energy achievable by Galactic sources, such as supernova remnants or binary star systems. The energy range above a few 10^{18} eV is likely dominated by extra-Galactic cosmic rays, because the Galactic magnetic field cannot confine particles of such energy. Most enigmatic are the particles with energies around and beyond 10^{20} eV. Are particles with such huge energies due to acceleration in the vicinity of super-massive black holes or around stellar collapses? Or are some of them due to more exotic processes? The flux of protons travelling over large cosmic distances should be suppressed above $\sim 4\times10^{19}$ eV where collisions with the cosmic 2.73 K blackbody photon background results in rapid energy loss within tens of Megaparsecs. Data obtained at the Pierre Auger Observatory convincingly confirm a spectral suppression at the expected energy. Is this due to the above mentioned so-called GZK effect or is it just because the cosmic accelerators do not reach higher energies?

The multi-messenger approach: Because cosmic rays are electrically charged, their paths are bent as they travel through cosmic magnetic fields. They do not point back to their sources, except at the very highest energies (more than a few 10^{19} eV), where the deflection for protons is expected to become small according to our current understanding of the inter-galactic magnetic fields. Fortunately the sources are also expected to emit particles that travel in straight lines: gamma-rays and neutrinos. Indeed, gamma-rays with energies up to 10^{14} eV have been observed from a variety of sources. In most cases, however, it is not clear whether they are produced in the interactions of high-energy protons or nuclei with the ambient matter, or whether they are radiated by high-energy electrons. Here, neutrinos may come to the rescue: they can be produced only in processes involving protons and nuclei. With a three-fold approach – charged cosmic rays, gamma-rays and neutrinos – there is a good chance that the mystery of the origin of cosmic rays will be unveiled and the landscape of the extreme Universe will subsequently be fully explored.

Fundamental Physics: Experiments detecting high-energy cosmic particles naturally involve particle and nuclear physics and can probe new physics beyond the Standard Model of particle physics. For example, supersymmetric (SUSY) theories which are to be tested at the LHC also predict dark matter particles that annihilate into charged cosmic rays, gamma-rays and neutrinos. The latter particles can be observed by space-based detectors (charged cosmic rays and gamma-rays) and by Earth-bound detectors (high energy gamma-rays and neutrinos). With their potential for indirect dark matter detection these detectors provide important complementary capabilities to the LHC and to direct detection experiments (see Section 3). Another example is the possibility to probe new physics at energies much beyond those reached at terrestrial accelerators. For instance, a tiny violation of Lorentz invariance would affect the propagation of energetic cosmic particles over cosmological distances and lead to observable effects. An abrupt change of interaction cross sections at the highest energies due to the opening of new dimensions is another example.

2.2. Charged cosmic rays

Cosmic rays can be studied by direct and indirect methods. Direct measurements on satellites and balloons record the primary particles before they interact in the atmosphere of the Earth. Due to the small area of these detectors, however, there are no appropriate statistics in the TeV range. The higher energies are the domain of indirect methods: the detection of air showers initiated by the primary particles. The best established techniques are ground-based detectors that record the shower particles arriving at ground level, or record the Cherenkov or fluorescence light from the showers. Indirect methods for extreme energies include satellite-borne optical or radio detectors observing the atmosphere from space, ground-based radio telescopes observing the lunar crust, or balloon-borne radio detectors observing ice sheets on the polar caps of the Earth.

2.2.1. Direct measurements from satellites and balloons, E < 10^{14} eV

The most direct information on the properties of cosmic rays is obtained with detectors above the atmosphere – on stratospheric balloons or in outer space. Balloon missions with (minor) European participation have been TRACER (The Netherlands), ATIC (Germany) and CREAM (Italy), the first in both hemispheres, the other two in Antarctica. Direct measurements have provided much of the information on galactic cosmic rays and contributed to the contemporary standard model of cosmic-ray propagation in the Galaxy. For instance, TRACER has provided boron-to-carbon measurements up to almost 10^{14} eV. Cosmic particles with GeV-TeV energies from Galactic accelerators or from interactions of primary cosmic rays with interstellar matter, are not only interesting on their own, but also constitute the background of searches for physics beyond the Standard Model of particle physics and for the origin of the cosmic matter-antimatter asymmetry.

PAMELA and AMS

The PAMELA satellite detector (Italy and other European countries) was launched in 2006. In 2008, the collaboration reported a tantalizing excess of positrons over the expected background which triggered a flurry of discussions on its origin – ranging from the annihilation/decay of dark matter to conventional astrophysics like e.g. nearby pulsars or supernova remnants.

Deeper insight is expected from the Alpha Magnetic Spectrometer, AMS. AMS is a multi-purpose particle detector deployed at the International Space Station (ISS) on May 19, 2011 for a mission of about a decade. The AMS community consists of about 600 scientists, 70% from Europe and 30% from elsewhere (China, Korea, Mexico, Russia, Taiwan and US). The physics goals of AMS are the indirect search for Dark Matter, the search for cosmic anti-nuclei, the precise measurement of spectrum and composition of cosmic rays up to a TeV, and the search for strange quark matter. The goals are a sensitivity to anti-He/He $=10^{-10}$, an e^+/p rejection of 10^{-6}, and an accuracy of 1% for composition and spectra of charged particles. With its sensitivity to higher energies and with considerably larger statistics, AMS will shed new light on the PAMELA positron excess and provide a clearer answer on its origin and the possible relation to dark matter. Being complementary to SUSY searches at the LHC, AMS explores some parameter regions that are not accessible to the LHC. The AMS search for anti-nuclei (such as anti-helium or heavier) is motivated by the possible existence of anti-matter domains in the Universe, so the observation of anti-helium nuclei above astrophysical background would be an important discovery. With the parameters mentioned above, the direct anti-matter search is improved by at least three orders of magnitude and extended to energies of 1 TeV. In addition, AMS has significant sensitivity for the detection of anti-deuterons that could provide a very low-background technique of search for dark matter

New since 2008:

Whereas in 2008 the future of AMS was uncertain (due to problems with the US Shuttle program) it was meanwhile successfully launched and is now taking data. Originally, AMS was constructed to operate on the ISS for three years. The operation time of the ISS will now be prolonged from 2015 to 2020 (or beyond). The superconducting magnet of AMS (maximum operation time three years) has been replaced by the "warm" magnet already flown with AMS-01 in 1998.

The committee looks forward to the exciting physics results expected from AMS.

Other satellite and balloon experiments

There is a gap between the energy range covered by present balloon and satellite experiments (up to 10^{12} eV) and by the range accessible from the ground (10^{14} eV and higher). Balloon and satellite measurements of the composition do not suffer from the large uncertainties of hadronic interaction models which complicate the interpretation of ground-based shower detectors. They would not only provide unique information on the origin and nature of Galactic cosmic rays but also – via the improved knowledge about cosmic-rays in the "knee" region – lead to a better knowledge of interaction models which is mandatory for interpretation of air showers at higher energies.

CALET (CALorimetric Electron Telescope) is a mission for the Japanese ISS module. It consists of a total absorption calorimeter, a tracking calorimeter and a silicon pixel detector. It aims for excellent energy measurement, particle identification and charge measurements. CALET will search for dark-matter signatures in electron and gamma-ray spectra and measure fluxes and spectra of nuclei up to Fe and up to the multi-TeV region. The collaboration partners come from China, Italy, Japan and US. The planned launch is 2013.

The Russian satellite project NUCLEON aims at measuring the spectrum and composition of cosmic rays between 10^{12} and some 10^{14} eV. It will consist of a large tracking calorimeter. The launch, originally planned for 2011, has been shifted by three years to 2014/15 (now without the original Italian participation). To what extent these plans are realistic and compatible with even more demanding Russian projects with these goals is hard to judge from the outside.

GAPS (General AntiParticle Spectrometer) is a proposed project to search for dark matter via the anti-deuteron signature. The instrument would use a large area Si(Li) tracker that would serve both as target and detector. Anti-deuterons are detected with high efficiency via an exotic-atom technique. GAPS is scheduled to fly a prototype balloon detector in 2011 with a full instrument coming approximately four years later. GAPS is currently a US-Japan collaboration, but there is the hope that European groups could be involved as well.

Access to long duration balloon flights around the North Pole originating from Kiruna or, even better, from the Svalbard Islands (higher latitude, resulting in a lower geomagnetic cut-off) would open a window of opportunity for European groups. Proposals for measuring medium-energy positrons and electrons (PEBS) or low energy anti-deuteron (Dbar-SUSY) are being considered for such flight opportunities. There are already corresponding US experiments on balloons being flown from Antarctica with minor European participation (ATIC, CREAM). US and Dutch groups are preparing a new TRACER mission with increased aperture.

Recommendation: We reiterate the suggestion of the 2008 roadmap, that efforts be directed to achieve an overlap between present direct and air-shower detection methods in order to get a better understanding on the mass composition and spectral features of cosmic rays. This goal may be pursued with large-aperture, long duration flight missions above the atmosphere (balloons/satellites) and/or by ground-based detectors with adequate particle identification placed at the highest altitudes (see next section). ▪

2.2.2. Galactic cosmic rays at energies 10^{14} - 10^{18} eV

Above ~10^{14} eV, the showers of secondary particles created by interactions of the primary cosmic rays in the atmosphere are extensive enough to be detectable from the ground. At around 10^{15} eV there is a distinct steepening of the spectrum, which is usually interpreted as the limit of the acceleration range of Galactic sources of cosmic rays. Because the maximum energy attainable at cosmic-ray sources is proportional to particle charge, one expects that the average mass of cosmic primaries increases when passing this “knee”. This energy region has been explored by a variety of experiments in the last decade (e.g. EAS-TOP, GAMMA, GRAPES, KASCADE, TIBET, TUNKA-25). Their results have given additional support for a rigidity dependence of the steepening for different primaries. Nevertheless, in all experiments, inconsistencies have been found between the data and the predictions of the hadronic interaction models underlying the analyses. Therefore, further detailed investigations are necessary, in parallel by using new data from the “forward physics” experiments at the LHC (CASTOR, TOTEM, LHCf) and by dedicated shower measurements.

The situation at energies above 10^{16} eV is of crucial importance to our understanding of the origin and propagation of cosmic rays in the Galaxy. What is the mass composition above the iron knee? Is this region dominated by sources other than supernova remnants? Why are anisotropies not observed even though cosmic rays should be diffusing away rapidly from the Galaxy at such energies? What is the nature of the observed “second knee” at ~7×10^{17} eV? Is there an early onset of an extragalactic component?

After KASCADE-Grande has finished its operation, the main progress for the next years is expected from IceTop/IceCube at the South Pole, from the TUNKA-133 experiment in Siberia and from the low-energy enhancements of the Pierre Auger Observatory in Argentina, all with European participation. These detectors provide complementary information and therefore an interesting possibility for a coherent investigation of cosmic rays up to the end of the galactic spectrum and for determining the onset of the extra-Galactic component. We also note that KASCADE-Grande analysis continues, using new input from LHC measurements.

New since 2008:

a) The Tunka Cherenkov air-shower array, with 133 wide-angle photomultiplier stations spread over 1 km² has been completed and takes data. Detectors for muons and a large-spacing extension towards 4 km² are planned for 2011/12. Also the 1 km² IceTop array has been completed and records air-shower particles on the ground, whereas IceCube records the resulting muons punching down to 2,5 km depth in the ice. The extensions at the Pierre Auger Observatory towards lower energies have already been installed (HEAT) or are being installed (AMIGA). Several efforts are being made at these arrays and elsewhere to use MHz receivers as a new method to study the longitudinal profiles of air showers with a 100% duty cycle (LOFAR, AERA at the Auger site, RASTA at the South Pole, Tunka-Radio).

b) The LHC is providing first data, e.g. on total cross sections and multiplicities, which will substantially improve the interpretation of the air shower data.

c) An interesting physics effect, reported earlier by the Tibet air shower array, by Super-Kamiokande and by the American Milagro experiment, was confirmed by the ARGO/YBJ experiment (China/Italy) in 2008 and by IceCube and EAS-Top in 2009: a ~0.1% anisotropy of cosmic rays on both large and medium angular scales. It is an open question whether this effect is due to cosmic-ray focussing on local magnetic fields, to nearby sources of cosmic rays, or to something else. New results are expected from HAWC, the successor of the Milagro-detector that is under construction in Mexico (without any European contribution).

d) China is constructing a new high altitude air shower array (LHAASO) that will record cosmic rays and gamma-rays. This hybrid array will include wide-angle and imaging Cherenkov counters, water pools and scintillation muon counters (see more in the section on gamma-rays). First European and Russian groups are discussing to join the project.

The existing experiments IceCube, TUNKA-133 and the low-energy extensions of the Pierre Auger Observatory (AMIGA/HEAT) should be exploited. We encourage the further development of MHz radio wave detection of air showers, e.g. at the large facilities Auger (AERA) and LOFAR, as well as at the South Pole and the Tunka site. There should be close cooperation with the particle-physics community, in particular with respect to LHC results. An array at the highest possible altitude is desirable to determine the chemical composition in the energy range overlapping with balloon experiments (10 TeV – PeV). At present, the planned LHAASO experiment in China seems to come closest to this requirement. ■

2.2.3. The highest energies

The Pierre Auger Observatory

The present flagship experiment in the search for sources of ultra-high energy cosmic rays is the Pierre Auger Observatory (in short "Auger") in Argentina (450 scientists, ~50% from Europe). This 3,000 km² array of water tanks, flanked by 27 air-fluorescence telescopes, measures direction, energy and profile of giant air showers. Even at energies above 10^{19} eV, where the cosmic flux is only about one particle per year per square kilometre, Auger can collect a reasonable number of events. Above this energy, the deflection of charged particles in cosmic magnetic fields becomes less important and source tracing is likely to become possible if the observed cosmic rays are low-Z particles.

Auger has been taking data since 2004 and in its full configuration since 2008. The combination of a large detector array and fluorescence telescopes provides a substantial improvement in energy calibration and identification of primary particles, resulting in data of unprecedented quality. The observatory is successfully operating and meets all of its design parameters. The first results have provided important information on key questions in the field.

A first breakthrough is the convincing confirmation of the steepening of the spectrum at energies beyond 50 EeV. However, the reason for the effect is not yet convincingly established. It can be explained either by collisions of cosmic rays with the cosmic microwave radiation ("GZK cut-off") or by a natural maximal energy of cosmic accelerators. Beyond several tens of EeV, the Auger Collaboration observes a transition from an isotropic to an anisotropic distribution of the arrival directions. In 2008, the collaboration published the first sky map of events with energies above 55 EeV and reported a correlation of arrival directions with nearby concentrations of matter as traced by certain Active Galactic Nuclei (AGN). Such a correlation would be in agreement with theoretical expectations that only two classes of objects are able to accelerate particles up to 10^{20} eV or higher – the central black holes or emerging jets of AGNs, and Gamma-Ray Bursts (GRBs). In the mean time, the correlation strength has decreased, although the statistical significance of the reported correlation has not changed very much. Another question of great interest is the mass composition of the primary particles. The Auger results indicate surprisingly a heavier composition of the primaries towards the highest energies, where, however, the statistics are limited. In addition, Auger showed that the fraction of primary photons is less than 2% of all cosmic rays at energies of about 10^{19} eV, thus ruling out most 'top-down' models for the origin of ultra-high energy cosmic rays. The Auger Collaboration has also been able to set a stringent limit on cosmic neutrinos at energies of 10^{18}-10^{20} eV, complementary to the limit obtained from the IceCube neutrino detector at the South Pole.

Understanding the primary composition above 10^{19} eV and the nature of the high-energy cut-off as well as identifying individual sources calls for significantly higher statistics. This is the primary motivation to build a much larger array than the present Auger. From its beginnings, the Pierre Auger Collaboration envisaged a detector in the northern hemisphere to give full sky coverage. The plan was to build Auger-North in the US, an array with seven times the aperture of Auger-South. Auger-North sited in Colorado would have profited from the developed infrastructure and the associated cost reductions. Cost estimates were on a firm ground because they were based on principles proven by Auger South. The project cost was 130 M$, with about 50 M$ expected from the US and 40-50% from Europe. In both the 2006 and 2008 ApPEC roadmaps, **Auger-North** was defined as the clear priority project of the field "charged cosmic rays".

News on the Pierre Auger Observatory since 2008:

Whereas the funding prospects for Auger North in some countries had improved over the last 2-3 years, the prospects in the US as host country had stayed open. However, in October 2009, the Particle Astrophysics Scientific Assessment Group (PASAG), charged by DOE and NSF, released recommendations for the fields of Dark Matter, Dark Energy, and High Energy Cosmic Particles. It recommended the funding of Auger North in a scenario where funding for these fields would be doubled over the next ten years. In 2010 the Decadal Survey for Astronomy and Astrophysics (Astro2010) was released and Auger North was not prioritised. As a consequence, the US funding agencies will not consider giving funding for the Colorado site. The Pierre Auger Collaboration concluded that a new proposal for an experiment of the next generation should be prepared. This requires 3-5 years of preparation in order to modify the technology accordingly and to find an appropriate site, including the possibility of a considerable extension of Auger South to a similar scale as had been planned for Auger North. Efforts are being made to exploit not only radio emission dominated by geomagnetic effects at tens of MHz frequencies, but also the molecular Bremsstrahlung emission using GHz receivers, as new methods to study the longitudinal profiles of air showers with a 100% duty cycle.

Alternative experimental approaches at highest energies

An alternative approach to reach the huge detection volumes necessary for cosmic ray studies at 10^{20} eV and beyond are space-based detectors which can record fluorescence light and reflected Cherenkov light from air showers. First generation projects are JEM-EUSO (planned launch 2017), with Japanese leadership, and the Russian project TUS. TUS will have a much smaller aperture than JEM-EUSO but is planned to be launched already in 2012 and may provide interesting input to JEM-EUSO design parameters. In the further future (beyond 2018), these devices could be followed by Super-EUSO and KLYPVE (Russia) or a merger of both. European participation in JEM-EUSO makes up about 40% of the associated scientists. The future development of these devices relies on novel technologies and requires strong coherent R&D efforts. In the more distant future, the Square Kilometre Array (SKA) has the potential to record cosmic rays with energies beyond 10^{20} eV.

Comparison of different detectors

A next generation ground-based cosmic-ray observatory could enable full sky coverage and would provide a much larger detection area than other northern cosmic-ray experiments, such as the Telescope Array (US-Japanese-Taiwan experiment in Utah/US) or the Yakutsk array in Russia. It is also based on proven hybrid technology (multiple signatures of an event), in contrast to JEM-EUSO which will measure fluorescence light only and which will have worse capability for particle identification. On the other hand JEM-EUSO will gather far more statistics at the highest energies and will cover both hemispheres of the sky.

Recommendation: In conclusion, we reiterate the definition of a substantially enlarged ground-based cosmic-ray observatory as the priority project of high energy cosmic-ray physics – irrespective of where this will be deployed. We encourage the community to work towards a global common path for such a substantially enlarged observatory including the development of new detection technologies. We recommend that European groups play a significant role in preparing a proposal for the next generation experiment, and after its approval, make a significant contribution to construction and operation. We also support European participation in JEM-EUSO with its novel technology. We encourage cross coordination between these two approaches. ■

2.3. Gamma-ray astrophysics

In contrast to charged cosmic rays, gamma-rays propagate in straight lines while compared to neutrinos, their interaction cross section is much higher making them easier to detect. This has made gamma-rays a powerful tracer of energetic cosmic processes. On the other hand due to their higher cross section, high-energy gamma-rays are more easily absorbed when travelling over long distances. Similar to charged cosmic rays, gamma-rays can be studied both with satellite- and Earth-based detectors. MeV and GeV gamma-rays are the domain of satellite detectors, whereas from a few tens of GeV upwards, Earth-bound telescopes take over. The physics goals are, to a large extent, the same:

a) investigating the origin and propagation of Galactic cosmic rays by classifying gamma-ray sources and by studying shock-wave acceleration in supernova remnants and other extended sources, pulsar winds and stellar winds, as well as particle acceleration in pulsar magnetospheres;

b) studying the physics of compact objects and their relativistic outflows on different scales, from pulsars and micro-quasars to AGNs and GRBs, in particular probing the physics of black holes close to the event horizon and the emergence and composition of jets;

c) addressing cosmological questions by searching for gamma-rays from Dark-Matter annihilation or decay (indirect Dark Matter search), measuring extra-Galactic background light via its interaction with high-energy gamma-rays and probing the accretion history of the Universe and the formation of the first galaxies;

d) analyzing topics in fundamental physics, such as testing the quantum structure of space-time by looking for any energy dependence of the speed of light at the highest energies and from the most distant sources.

2.3.1 Gamma-ray astronomy from satellites

Space-bound gamma-ray astronomy was pioneered by missions like SAS-2 (1972/73) and COS-B (1975-81). In the 1990s, the EGRET detector on the Compton Gamma Ray Observatory (CGRO) discovered a few hundred astrophysical sources of GeV gamma-rays. The BATSE detector on CGRO recorded about 2000 Gamma-Ray Bursts. The legacy of these missions is fulfilled by INTEGRAL, targeting energies in the keV-MeV range, and AGILE and Fermi, targeting energies in the MeV-100 GeV range.

INTEGRAL (an ESA, NASA and Russian collaboration with instrument PIs in Denmark, France, Germany, Italy, Spain and Switzerland) is a medium-class mission of ESA's 'Horizon 2000' program, launched in 2002. Operations are recommended to be extended to at least 2014. INTEGRAL carries two main instruments covering soft gamma-rays from 12 keV to 10 MeV and two monitors in the X-ray and optical band. For the experiments considered in this roadmap, INTEGRAL is the "next neighbor" towards lower energies. Among its achievements are the deepest all-sky survey in hard X-rays, the mapping of the e+-e- annihilation light in the Galaxy (the origin of which is still unclear), the discovery of many new hard X-ray sources including new families of X-ray binaries and magnetars, the detection of obscured AGNs in hard X-rays as well as GRBs and the mapping of pulsar magnetospheres.

We note that in the following, we will focus to energies above the X-ray range and consider lower energies as the realm of "classical" astronomy. We will only occasionally address X-ray missions, e.g. in the context of dark matter search.

AGILE, a fully Italian mission, was launched in December 2007. It carries a 40×40 cm^2 silicon tracker and a calorimeter covered by a veto counter, an X-ray detector and a small gamma-ray-burst detector. AGILE has detected many Galactic and extra-Galactic sources and recorded a series of interesting transient phenomena.

The Fermi Gamma-ray Space Telescope (US, France, Germany, Italy, Japan, Sweden) was launched in June 2008. It carries two instruments, the Large Area Telescope (LAT) and the GLAST Burst Monitor (GBM). With a 180x180 cm^2 silicon tracker and a calorimeter (also covered by a veto counter), the LAT is 30 times more sensitive than any previous high-energy gamma-ray experiment flown into space and is expected to detect thousands of sources during the five-year primary mission. Fermi has already detected many new pulsars not seen at any other wavelength, as well as many other new galactic and extragalactic gamma-ray sources. It has clearly excluded the galactic 'excess' in GeV gamma-rays which had earlier been reported by EGRET and interpreted as a signal of dark matter. The detection of gamma-rays from distant GRBs provided significantly improved limits on Lorentz invariance violation. Fermi has revealed Galactic bubbles and put constraints on cosmological magnetic fields. Last but not least Fermi has precisely measured spectra of cosmic-ray electrons up to a TeV and has confirmed the PAMELA excess of positrons. Very recently, both Fermi and AGILE reported short flares with up to 30 times the nominal flux from a source that was assumed to be rather steady (and therefore a 'standard candle') – the Crab Nebula.

Fermi is certainly one of the most successful enterprises at the borderline between astronomy and fundamental physics. The initial mission extends up to 2013, but will likely be extended considerably. The chances of realization for a Russian Fermi-like mission ("Gamma-400") are hard to estimate at this time.

Even after INTEGRAL (20 keV–a few MeV) and Agile/Fermi (30 MeV–100 GeV), there remains a noticeable lack of coverage in the gamma-ray sky in the 1-30 MeV range and a lack of effective area to probe physical mechanisms in detail. For many sources, the main power output is expected in this range. Several proposals for missions addressing these energies have been submitted to the recent M3 ESA 'Cosmic Vision' call, but none were selected. On the other hand the LOFT X-ray mission is amongst the four projects having passed the selection for follow-up studies. The main science goal of LOFT is to determine the equation of state of dense matter through precise measurement of the mass and radii of neutron stars, i.e. probing QCD and nuclear physics (at the surface of the neutron star) under extreme conditions (density and magnetic fields). This is clearly a domain at the interface between astro- and particle physics. **The committee recognizes the importance of these missions.**

2.3.2. Gamma-ray astronomy with Earth-bound detectors

Due to the small area of detectors on satellites there are no available statistics at energies above a few tens of GeV. Higher energies are the domain of ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs), covering the energy range up to several hundred GeV with high sensitivity. IACTs record the Cherenkov light from air showers originating from gamma-ray interactions in the atmosphere. Large reflectors focus the light onto cameras of hundreds to a few thousands of photomultipliers (in future possibly also solid-state detectors). From the shower image, the direction, energy and character of the primary particle (hadron versus gamma-ray) can be derived. With another technique, the shower particles reaching the ground are recorded – either via the Cherenkov light they produce in water pools or via the ionisation in tracking devices. Compared to IACTs, these detectors (such as Milagro, ARGO/YBJ and HAWC) have a higher threshold and reduced flux sensitivity as well as poorer energy and angular resolution but enjoy, due to their large field of view, better survey and monitoring capabilities. Thus, they nicely complement IACTs.

Present Imaging Cherenkov Telescopes

The IACT technique was pioneered in the US with the development of the Whipple Telescope and the detection of a first source, the Crab Nebula, in 1989. During the last decade European groups have been central to the progress of the field of ground-based high-energy gamma-ray astronomy. A large proportion of the new sources have been discovered by two Europe-led facilities (H.E.S.S. and MAGIC). VERITAS in Arizona started full operations in 2007, with a similar sensitivity to HESS. All three experiments lead to continuing high rate of discoveries. The measurements provide all the typical data of astronomical observations: images showing spatially resolved source morphologies; light curves showing time variations; energy spectra extending multi-wavelength spectral energy distributions of known sources towards the TeV region; and surveys discovering unidentified sources and extending source catalogues.

IACTs have by now revealed more than a hundred sources of gamma-rays at the 10^{11} to 10^{14} eV scale, many of them in the Galaxy and revealing a complex morphology. Most of the Galactic TeV sources correspond to objects like binary systems, pulsar wind nebulae and supernova remnants. Others are still entirely unknown at any other wavelength and obviously emit most of their energy in the TeV range ("dark accelerators"). Going outside the Galaxy, a large number of AGNs have been observed and their fast variability demonstrated.

The present state-of-the-art of IACTs is represented by the three facilities:

- **H.E.S.S.,** an array of four 12 m Cherenkov telescopes in Namibia, which has taken data since 2003 with all four telescopes. European partners make up 95% of the 170 members of the collaboration. The telescopes operate in stereo mode. The extension towards lower energies by a 28 m telescope, originally planned for 2009, is now envisaged for summer 2012.

- **MAGIC**, located at La Palma/Spain, was initially operated as a single 17 m telescope. MAGIC-II, a second 17 m telescope, saw first light in 2009 and allows now also stereo observations. All of the 150 members of the collaboration come from Europe.

MAGIC is testing innovative photon detectors as part of the existing cameras. In addition, in summer 2011 the MAGIC-I camera will be replaced by a camera of MAGIC-II type, and the readout for both cameras by one with improved performance. Among all three telescopes, MAGIC has the best sensitivity at energies below 100 GeV.

- **VERITAS** is an array of four 12 m telescopes operating in Arizona/US. The collaboration consists of 95 scientists, 20% from Europe. VERITAS has achieved the same sensitivity as H.E.S.S. (1% of the Crab Nebula in less than 30 hours). VERITAS is currently undergoing an upgrade to replace all pixels with high quantum efficiency PMTs and to improve the trigger system with a telescope-image trigger. This upgrade, to be completed in 2012, will significantly improve the telescope sensitivity at gamma-ray energies below 100 GeV.

Less powerful telescopes are operated in Australia (CANGAROO) and in India (TACTIC). India is planning to build MACE, a telescope array of similar power to the present three leading installations, but at high altitude (on the Tibetan plateau at 4,300 m).

While the results achieved with current instruments are already very impressive, they just give a taste of the TeV cosmos. The detailed understanding of the underlying processes and the chance to see more than the tip of the iceberg can be improved dramatically by a much larger array of telescopes based on now well-established techniques and observation strategies. The time has come to make this exciting new astronomical window available to the wider community through the construction of a major new facility, which, unlike earlier projects, will be run as an open observatory and be made available to astronomers on the same basis as optical or X-ray observing facilities. A consortium has been formed to work jointly towards the design and realisation of such an instrument, the Cherenkov Telescope Array (CTA). It involves all groups worldwide currently participating in IACTs, as well as a large number of additional new partners from both particle physics and astrophysics. CTA is included in the list of projects compiled by the European Strategy Forum for Research Infrastructures (ESFRI), and is ranked high in the ASTRONET roadmap and the US decadal survey.

The Cherenkov Telescope Array (CTA)

The goal of CTA is to increase the energy bandwidth simultaneously towards both lower and higher energies, thus improving the current sensitivity and providing large statistics of highly constrained and well-reconstructed events. The actual design of CTA is still under study, but it will likely consist of a few large central telescopes providing superb efficiency below 50 GeV, embedded in an array of medium-sized telescopes giving high performance around a TeV, themselves surrounded by a few-km^2 array of small dishes to catch the bright but rare showers at 100 TeV. The minimum detectable flux in the central energy band at 1 TeV, will be about 0.1% of the Crab flux, combined with an energy resolution of 15% and angular resolution down to 1 arcmin for the best-reconstructed events.

CTA is aimed to cover both hemispheres, with one site in each. The field of view of the Southern site includes most of the Galaxy, while the Northern telescope would instead place the main emphasis on the study of extra-Galactic objects. At energies above a few tens of TeV and over megaparsec distances, gamma-rays are absorbed by the cosmic infrared background light and by the cosmic microwave background above a few hundreds of TeV. Therefore high-energy sensitivity is less important for the Northern ("extra-Galactic") site than for the Southern ("general-purpose") site, which should provide full energy coverage and excellent angular resolution in order to study the morphology of galactic objects.

We assess the project below with reference to the essential criteria: scientific impact, uniqueness/complementarity, strength of community, project management, cost, technical readiness, risks and industrial involvement.

Scientific Impact: The low-energy sub-arrays of CTA would explore a new territory and would bridge the gap to space-based gamma-ray astronomy. The large number of GeV sources detected by Fermi confirms the high potential of this energy range. Our present understanding of the absorption of gamma-rays by the extra-Galactic background light (EBL) indicates that the visibility of the Universe for energies above 100 GeV is limited to redshift $z < 1$. The low-energy section of CTA would extend the observation range to high redshift AGNs with $z \sim 3$-5. The large accessible cosmic volume would result in a substantially increased number of sources, allowing for the first time cosmological issues such as Dark Energy to be possibly addressed.

Extension of the sensitivity at medium and high energies will allow sensitive mapping of the Galaxy and a more precise study of the high-energy part of the spectra of galactic objects and close-by AGNs. Spectra and energy-dependence of source morphology in this energy range provides the most important information for distinguishing acceleration mechanisms in the sources.

With the increase of the sensitivity in the central-energy region, fainter objects will be visible. Also, known objects can be measured on much shorter time scales and their transient behaviour can be studied in more detail. The improved angular resolution will provide much more detailed information on the morphology of the sources. With one thousand expected sources between a few tens of GeV and 100 TeV, CTA will turn ground-based gamma-ray astronomy into an observational discipline comparable to conventional astronomy.

Uniqueness/Complementarity:

CTA vs. H.E.S.S , MAGIC and VERITAS: providing an order of magnitude boost in sensitivity and energy coverage and operated as an open observatory, CTA is qualitatively different from experiments such as H.E.S.S., MAGIC and VERITAS and cannot be realized by a simple expansion or upgrade of any of these instruments.

CTA vs. Wide-angle devices: Wide-angle devices like HAWC, the successor of the Milagro experiment in the US, will have a higher threshold and worse flux sensitivity, angular and energy resolution but – due to their large field of view – better survey and monitoring capabilities, thus nicely complementing CTA. Wide-angle devices may possibly also have the potential to extend the energy range of gamma-ray astronomy into the PeV region.

CTA vs. Fermi: Fermi will overlap with CTA in the energy range of tens of GeV. Combination of data from the two instruments will provide an unprecedented seamless coverage of more than seven orders of magnitude in energy. Simultaneous observations over such a wide energy range are a key to understand the physics of Galactic and extragalactic cosmic accelerators and could be essential in the identification of Dark Matter.

CTA vs. IceCube/KM3NeT and Auger: CTA has a guaranteed rich scientific output based on clear detection of sources. CTA will be a key element for multi-messenger studies with neutrino telescopes and with Auger.

CTA vs. new radio and x-ray observatories: the sensitivity of CTA will allow matching the accuracy of the measurements provided in the radio and X-ray bands in multi-wavelength observations.

CTA vs. H.E.S.S., MAGIC, VERITAS and direct detection experiments of Dark Matter: CTA will expand by a large factor the possibility to detect Dark Matter annihilating to gamma-rays in the Galactic halo. Low-mass candidates will be well covered by direct detection experiments, but near or above the TeV mass range CTA would have unique capabilities for detecting a dark matter signal.

Strength of Community: CTA combines the worldwide experience of all relevant communities working with atmospheric Cherenkov telescopes: Europe, US, Japan and India. The groups from US (formerly AGIS collaboration) and India joined in 2010, with the US groups proposing a major contribution to the medium-sized telescopes. The observatory character of CTA will open this infrastructure to a much wider community, which will appear as “users” who apply for observation time, as in traditional astronomical observatories.

Project Management: A collaboration based on MoUs was formed in May 2010. A three-year EU-funded preparatory phase started on Oct.1, 2010 and a project office for the preparatory phase was installed.

Cost: The current cost estimated for CTA is on the 200 M€ scale. The goal of the design and prototype phase is to carry out the necessary work to reduce costs as much as possible and to ensure that the project is ready for the start of construction at the end of the preparatory phase. The Southern site will be more expensive because it will include the high-energy extension with a much larger number of small telescopes than the Northern site.

Technical readiness, challenges and risks: CTA is mostly based on existing and proven techniques, therefore there are no major risks that could prevent the observatory from not working or not providing excellent scientific results. However, the goals of CTA imply significant advances in terms of efficiency of construction and installation, in terms of the reliability of the telescopes and in terms of data preparation and dissemination. The main challenge is to lower the costs per collected photon as compared to MAGIC/H.E.S.S./VERITAS. A risk arises from the possibility that the cost reductions cannot be achieved within the planned time and the project would either be delayed or be downgraded to meet the cost constraint, the latter with a corresponding loss in science power.

Industrial involvement: Cooperation with industry, towards largely industrial fabrication of telescope components is well established and covers many areas, such as optimisation of photo sensors, development of cost-effective techniques for mirror production, or design/production of telescope structures and drives and control systems.

Recommendation: The Cherenkov Telescope Array, CTA, is the clear worldwide priority project of Very High-Energy (VHE) gamma-ray astrophysics. We recommend the design and prototyping of CTA, the selection of site(s) and to proceed vigorously towards start of construction in late 2013. We strongly recommend that the various funding agencies work together to secure the required funds for the construction and operation of CTA. The current IACTs should continue to take data until CTA has superior sensitivity and sky coverage. ■

Wide-angle devices

Wide-angle devices have inferior background rejection, sensitivity, angular and energy resolution and a higher threshold than IACTs. On the other hand they have a wider field of view and about ten times better duty cycle. A number of impressive detections have been made by the Milagro collaboration with a large water pool in the US, including extended sources that are harder to cover with IACTs. Also ARGO/YBJ (Italy/China) has detected several gamma ray sources, the Crab Nebula, Mkr-421 and MGRO J19808+06.

The follow-up project of Milagro is HAWC, the "The High Altitude Water Cherenkov Experiment", a wide-field detector of 900 huge water pools and 22,000 m^2 area being constructed in Mexico (US/Mexico) at 4,100 m altitude. HAWC will be a real breakthrough – it will map the Galactic diffuse gamma-ray emission above 1 TeV, will perform an unbiased sky survey with a detection threshold of ~30 mCrab in two years, enabling the monitoring of known sources and the discovery of new classes of diffuse and point-like TeV gamma ray sources. HAWC would also be sensitive to transient phenomena (an AGN flare 5 times the flux of the Crab in 10 minutes). Both HAWC and CTA will profit from a close cooperation.

LHAASO is a proposed 1 km^2 area, hybrid array comprising IACTs, water pools, scintillation detectors and fluorescence telescopes. It addresses Galactic cosmic-ray studies up to 10^{18} eV and wide-angle gamma-ray astronomy. It is envisaged to be located at more than 4 km altitude in Tibet/China. The large area and the high degree of hybridisation promise important contributions for the highest energies. The collaboration is forming, meanwhile including first collaborators from Europe and Russia.

In addition, there are efforts for large-area wide-angle gamma-ray and cosmic-ray detectors sensitive to gamma-rays above 10 TeV and cosmic rays above 100 TeV. As an example we mention SCORE (Study for a Cosmic ORigin Explorer), which is a proposed project sensitive to gamma-rays above 10 TeV and cosmic rays above 100 TeV. The SCORE principle will be tested with a test array to be deployed in the next 2-3 years at the Tunka site in Siberia and if feasible, could serve as a future PeV extension for IACT arrays.

The wide-angle devices are also excellent cosmic-ray detectors in the energy range from 100 TeV to 1 EeV. The corresponding center-of-mass energies (1.7 TeV to 170 TeV) of the interactions of the cosmic rays with air overlap fully with the LHC energy range and extend well beyond the energies that can be reached by accelerators on Earth.

2.4. High-Energy Neutrinos

The physics case for neutrino astronomy is compelling: high-energy neutrinos can provide an uncontroversial proof that their astrophysical sources accelerate hadrons. Moreover they can reach us from cosmic regions which are opaque to other types of radiation. However, whereas neutrino astronomy in the MeV energy domain has been established with the impressive observation of neutrinos from the Sun and Supernova SN1987A, extraterrestrial neutrinos with energies of GeV and above, which must accompany the production of high-energy cosmic rays, still await discovery. The focus in this field is on Cherenkov neutrino telescopes in deep water and ice. At the high-energy frontier they are extended by methods using acoustic, radio and fluorescence light signals.

Neutrino telescopes address a wide range of astro- and particle physics topics:

a) Exploration of the high-energy universe using neutrinos. First, searching for astrophysical sources of high-energy neutrinos, like supernova remnants, microquasars, pulsars, AGNs, GRBs, or even unknown phenomena. Second, searching for neutrinos from cosmic-ray interactions with inter-galactic matter and radiation fields, thereby addressing cosmological questions.

b) Study of fundamental physics questions: i) search for neutrinos from Dark-Matter annihilation/decay; ii) search for effects of quantum gravity, e.g. possible violation of Lorentz invariance (VLI) or effects of quantum decoherence, by analysing oscillations of atmospheric neutrinos or neutrinos from distant sources; iii) search for exotic particles like magnetic monopoles, supersymmetric Q-balls or nuclearites; iv) measurements of neutrino cross-section at ultra-high energies, which would probe non-perturbative QCD effects as well as new physics beyond the Standard Model.

c) Cosmic-ray studies, by investigating downward going muons or (for IceTop/IceCube) by measuring the spectrum and mass composition of cosmic rays.

d) Monitoring the Galaxy for MeV supernova neutrino bursts (something which does not belong to the high-energy universe, but which can be done by IceCube).

In addition to these central physics topics, the neutrino telescopes and their infrastructures in the deep polar ice or lake/sea water are also useful for a wide spectrum of other fields of science, such as marine biology, oceanography, geology and geophysics, glaciology or environmental sciences.

First generation detectors:
NT200, AMANDA, ANTARES

European physicists have played a key role in construction and operation of the pioneering neutrino telescopes, NT200 in Lake Baikal (Russia, Germany), AMANDA (US, Belgium, Germany, Sweden) at the South Pole. ANTARES is an entirely European project, with 200 scientists from France, Germany, Italy, Netherlands, Romania, Spain and Russia and has broken the technological wall of operating a deep-sea telescope with an acceptably small failure rate. Both AMANDA and ANTARES have shown convincingly the success of the method and that they can detect atmospheric neutrinos with the predicted rate, angular and energy distribution. Unfortunately, even with AMANDA and the highest statistics of high-energy neutrino events ever collected (over 6,000 in 7 years), no signal of extraterrestrial neutrinos has yet been identified. In the coming years ANTARES will collect similar statistics looking at a different region of the sky, which covers the central part of the Galaxy, in order to fully exploit its scientific potential and provide input and testing grounds for the final design steps of KM3NeT.

IceCube

The IceCube Neutrino Observatory consists of IceCube, a 1 km^3 neutrino telescope installed at a depth of 1.5-2.5 km in the polar icecap, and IceTop, a 1 km^2 air-shower detector at the surface. IceCube consists of 5160 optical modules on 86 strings. It was completed December 2010. The 250-member collaboration consists of 34 institutions, 17 of them European (Belgium, Germany, Sweden, Switzerland UK). IceCube is recording about 100,000 neutrinos and about 50 billion down going muons per year and is a member of the Supernova Early Warning Network (SNEWS). IceCube has observed atmospheric neutrinos up to a record energy of 400 TeV and has put the most stringent limits on fluxes of extraterrestrial neutrinos. No such signal has been identified until now, putting a certain pressure on plans for KM3NeT (see below). The arrival directions of down-going muons from charged cosmic rays show a 0.1% anisotropy similar to what has been observed in the Northern hemisphere by ARGO/YBJ, Milagro and Super-Kamiokande. The IceCube limits on high-energy neutrinos from the Sun place competitive limits on dark matter particles with spin-independent scattering on nucleons, and in fact improve on direct detection experiments for the case of spin-dependent interactions. Record limits have also been obtained for magnetic monopoles and possible effects of the violation of Lorentz invariance on neutrino oscillations.

IceTop measures air-shower particles from cosmic rays with primary energies in the range of 1-300 PeV. Combined with muons measured in IceCube, it will provide unique data on the mass composition of primary particles.

The high-density DeepCore nested array will lower the threshold from 100 GeV down to about 10 GeV. This will make IceCube sensitive to oscillations of atmospheric neutrinos. Further increasing the density of optical modules may lower the threshold to 3 GeV, allowing for studying matter oscillations, and possibly even effects that can distinguish amongst the different mass hierarchy scenarios. A further increase in the detector density would allow detection of supernova neutrinos from outside our own Galaxy (see also section 3.5.2). These extensions are presently under study and will critically depend on the actual performance of the existing DeepCore installation.

A planned 160 km^2 in-ice radio detector at the South Pole will be discussed at the end of this section.

Gigaton Volume Detector (GVD) in Lake Baikal

Guided by national history and priorities, the Russian Baikal Collaboration plans the stepwise installation of a kilometer-scale array in Lake Baikal, the Giant Volume Detector. GVD will consist of strings grouped in clusters of eight, each with 24 optical modules. Prototype strings have been operated in 2009 and 2010. Three strings with eight optical modules each and a prototype of the array electronics have been deployed in spring 2011. An official proposal has recently been submitted to Russian funding agencies.

The GVD configuration is optimized for cascade detection. The detection volume for cascades above 50 TeV is 0.3-0.8 km³; the detection area for muons with energy above 10 TeV is 0.2-0.5 km². A threshold of 10 TeV appears to be rather high when compared to IceCube and KM3NeT. On the other hand the optimum energy cut to get the best signal-to-noise ratio (extraterrestrial versus atmospheric neutrinos) for the weakest detectable E^{-2} sources is at a few TeV for point sources, and in the 100 TeV range for diffuse fluxes. Therefore, the GVD configuration may turn out to have a favorable physics/cost ratio. Still, the volume/area is too small to compete with IceCube and KM3NeT. Building GVD could make sense as part of a global Northern infrastructure, i.e. if KM3NeT is built. We give no recommendation with respect to GVD, since no European funding is involved.

KM3NeT

IceCube observes neutrinos from the Northern sky. Complete sky coverage, in particular of the central parts of the Galaxy with many objects that emit TeV gamma rays and are promising neutrino source candidates, requires a detector in the Northern hemisphere with at least the same sensitivity. R&D work towards such a Northern neutrino telescope on the cubic-kilometre scale, named KM3NeT, is being pursued by a consortium formed from the three Mediterranean neutrino telescope projects (ANTARES, NEMO and NESTOR) and sea science/technology institutes. The consortium includes more than 300 members, all from Europe.

Three candidate sites in the Mediterranean Sea, close to Toulon (ANTARES), east of Sicily (NEMO), and off the west coast of the Peloponnese (NESTOR) have been identified and studied in long-term collaborations.

The European Strategy Forum for Research Infrastructures (ESFRI) has included KM3NeT in the European roadmap for research infrastructures. An EU-funded three-year FP6 Design Study has been carried out. An FP7 Preparatory Phase project is ongoing until February 2012, its major objective is to address the legal, governance, financial, engineering and political issues that need to be clarified before construction can proceed. A Conceptual Design Report for KM3NeT was released in April 2008. A Technical Design Report, summarising the outcomes of the Design Study, is available since June 2010. The project cost are estimated to be ~250 M€ for a detector which reaches about five times the sensitivity of IceCube for certain searches.

Scientific Impact: KM3NeT increases the discovery potential for neutrino sources and potentially allows deeper a deeper search into black hole environments and at energies beyond 100 TeV, further out into the Universe than possible with gamma-rays. Together with gamma-ray and cosmic ray observations (and with IceCube), it could pave the way to real multi-messenger astronomy. However, in absence of established cosmic high-energy neutrino sources, it is difficult to assess the sensitivity necessary to achieve these goals. Until now neither IceCube nor ANTARES have seen any cosmic neutrino sources. Should this picture pertain for the first few years of full-scale IceCube operation, KM3NeT in its currently planned configuration, being about five times more sensitive than IceCube, may provide only a limited additional discovery window for extragalactic sources. The abundance and characteristics of such sources should not differ much between the Northern and Southern skies, but firm flux predictions are absent. Predictions for Galactic sources are much more firm if we assume dominantly hadronic emission. In contrast to extra-Galactic sources, we seem to be close to the discovery region, therefore here a factor five but with a telescope observing the Southern hemisphere, counts indeed. With the central part of the Galaxy in its field of view, KM3NeT therefore may provide a significant step beyond IceCube.

The gain from KM3NeT for indirect Dark-Matter searches, exotic phenomena such as magnetic monopoles or Q-balls, or oscillation studies with atmospheric neutrinos, is restricted because these phenomena are not expected to depend on the hemisphere. If, however, IceCube would see an exotic effect, the confirmation by KM3NeT would be essential. Given recent constraints from Fermi-LAT measurements of the diffuse gamma radiation in the energy range below about 100 GeV, the sensitivity of KM3NeT in its current configuration to cosmogenic neutrinos is expected to be limited, but might be increased to a significant level by implementing (part of) the detector in a sparse array of several tens of km³.

The KM3NeT infrastructure will also provide access to continuous, real-time deep-sea measurements over long periods. This is of high interest to various science communities, e.g. marine biologists, oceanographers, geologists and geophysicists, environmental scientists, etc. It is foreseen that KM3NeT will be one node of a global deep-sea observatory system.

Uniqueness/Complementarity;

KM3NeT vs. IceCube vs. Lake Baikal GVD: KM3NeT will have the highest sensitivity to neutrino point sources of all three telescopes. It will be the only detector with > 1 km^3 volume to observe the Southern sky (and with it the central region of the Galaxy) in the neutrino energy range 10^{12}-10^{15}eV. Together with IceCube, KM3NeT will provide full-sky coverage over the full energy range up to energies of cosmogenic neutrino fluxes. It seems obvious that the early observation or non-observation of sources by IceCube will impact the actual size and configuration of KM3NeT. KM3NeT will be about one order of magnitude more sensitive than GVD in Lake Baikal. GVD could be part of a distributed northern infrastructure and add statistics with a detector with different systematics.

KM3NeT vs. CTA and Auger: Even though in contrast to CTA, KM3NeT might likely just scratch the sensitivity region of interest, it would/could open a truly new window, with the occasional surprises related to new territories. It also represents the one hitherto missing frontier of a multi-messenger approach. Even a low-statistics measurement of cosmic neutrino signals would provide highly relevant complementary scientific information to that of CTA and Auger. Thus this is a question of complementarity rather than of competition.

KM3NeT vs. "new detection methods": The new detection methods mentioned further below (acoustics, radio, etc.) are typically applicable at energies of 10^{17}-10^{18}eV and beyond. These methods are therefore complementary to the "traditional" neutrino-telescope technique. Rather than the physics of cosmic acceleration, their main focus is the detection of neutrinos from cosmic-ray interactions with the 2.7 K radiation and from possible exotic relics.

Timeliness and schedule/milestones: Following the publication of the TDR, the KM3NeT Consortium has converged on a technical design, for which now prototyping and test deployment activities are being pursued. An important milestone is a decision on the deployment site, which has a political dimension through the link to possible funding sources of local nature, in particular European Regional Development Funds (ERDF) and the constraints concerning their use. This decision is foreseen to be taken towards the end of the Preparatory Phase. A Technical Proposal will be presented in 2012, and construction could commence in 2013/14 if the project is endorsed. It is expected that construction will take about 4-5 years, although also a staged implementation over a longer period might also be possible.

Scientific groups involved and transnational cooperation (Strength of Community): All research groups currently involved in deep-sea neutrino telescope projects are also part of the KM3NeT effort, providing leading expertise in all relevant fields. In addition, a number of marine-science and technology institutes have joined the KM3NeT consortium and KM3NeT cooperates closely with the EMSO project (European Multidisciplinary Seafloor Observatory). Currently, KM3NeT is pursued as a pan-European effort.

Project Management: Currently, the KM3NeT activities are coordinated and managed through the Preparatory Phase project. For the time beyond the Preparatory Phase, a Memorandum of Understanding between the participating institutions is in preparation. For management and governance in the construction and operation phase, the set-up of an ERIC (European Research Infrastructure Consortium) is under investigation.

Cost: The estimated budget for the KM3NeT research infrastructure lies in the range of 250 M€, with a projected spending profile peaking in the period 2014-17.

Technical readiness, challenges and risks: The feasibility of a deep-sea neutrino telescope has been demonstrated by ANTARES. The KM3NeT technical design represents a major development beyond ANTARES, in particular concerning cost-effectiveness, reliability and deployment of state-of-the-art technology. KM3NeT is expected to be ready for construction by the end of 2012. The major challenge, besides securing funding and reaching political agreement, is to keep the consortium together and active in the phase before project endorsement. A certain risk is that delays beyond the current schedule may lead to a drain of key experts and/or to the implementation of alternative, "specialised" projects of regional character, which fail to match the scientific objectives of KM3NeT but tie up available resources.

Industrial involvement: Close contacts to industry have been established, amongst others, in the following product fields: photomultipliers, information technology (in particular with optical components), deep-sea technology. A substantial fraction of the KM3NeT budget will be spent for purchase of such components from industry. Corresponding pre-procurement activities are conceived in the Preparatory Phase. Outsourcing of production processes to industry is also considered.

Recommendations for IceCube and KM3NeT: IceCube is now providing data with unprecedented quality and statistics. The European partners should

be supported in order to ensure the appropriate scientific return.

There is a strong scientific case for a neutrino detector in the Northern hemisphere, however, with a substantially larger sensitivity than IceCube. Resources for a Mediterranean detector should be pooled in a single optimized design for a large research infrastructure. The KM3NeT collaboration is encouraged to present a technical proposal matching these requirements and in particular to reach final site and design decisions that would enable start of construction in 2014.

The IceCube, ANTARES and KM3NeT collaborations are encouraged to strengthen cooperation, with the goal to form a Global Neutrino Observatory that in the future might also include further projects, such as Baikal-GVD. ▪

Techniques for extremely high energies

Emission of Cherenkov light in water or ice provides a relatively strong signal and hence a relatively low-energy threshold for neutrino detection. However, the limited light transmission in water and ice requires a large number of light sensors to cover the required detection volume. Towards higher energies, novel detectors focus on other signatures of neutrino-induced charged particle cascades, which can be detected from a larger distance. Such methods include recording the Cherenkov radio emission or acoustic signals from neutrino-induced showers, as well as the use of air shower detectors such as the Pierre Auger Observatory, responding to deeply penetrating quasi-horizontal showers with a “neutrino signature”. Auger is also sensitive to tau neutrinos that enter Earth below the horizon and interact to produce energetic tau leptons, which generate Earth-skimming showers. The rates for quasi-horizontal and Earth-skimming events have different dependence on the UHE neutrino cross-section. Therefore, by measuring both rates, the cross-section can in principle be pinned down, without even knowing the cosmic neutrino flux precisely.

The very highest energies are covered by balloon-borne detectors recording radio emission in terrestrial ice masses (the ANITA project with some European participation from the UK) by ground-based radio antenna arrays, e.g. in Europe at LOFAR with the NuMoon project observing the lunar regolith (in the more distant future also SKA). Alternatively, the detectors of Auger are being used to observe neutrino-induced air showers, while R&D is ongoing to use also at this site radio-detection techniques. IceCube has used extremely energetic muons from above the horizon to search for EeV neutrinos.

The published data from these experiments have lead to limits over an energy range of more than six decades, starting at 10^{16}-10^{17} eV and extending beyond 10^{22} eV. All of them have been established within the last decade. The exploitation of the full potential of these methods needs large-scale R&D work, e.g. for their application at SKA.

The next step in radio detection of neutrinos is being undertaken by two projects in Antarctica: ARIANNA, planning to deploy radio antennas on the shelf ice, and ARA, planning to build an 150 km^2 array at the South Pole. In Europe, Belgium is taking part in ARA (with the centre of activities being in the US and Taiwan). ARA obtained significant funding in the US and was testing equipment for fast drilling, energy generation by wind power and radio detection in the season 2010/11. In the future, the satellite-based Russian project LORD will be used to observe GHz radiation from the lunar regolith.

Given the recent indirect constraints from Fermi on the cosmogenic neutrino flux at 10^9-10^{11} GeV, it seems clear that detectors of many tens of cubic kilometers will be necessary to record more than a handful of neutrinos from GZK interactions. We encourage R&D efforts towards this goal. ▪

3. Dark Matter, Neutrino Mass, Low-Energy Neutrino-Astronomy & Proton Decay

3.1 Introduction

Dark matter interactions, neutrino-less double beta decay and proton decay – if they exist at all – are extremely rare processes. Interactions from neutrinos from the Sun have been recorded, but also at a very low rate. The study of such extremely rare phenomena calls for an environment free of noise events that can mimic true signals. Laboratories deep underground, well shielded against particles from cosmic rays, meet this requirement. Europe has four such world-class laboratories deep underground:

- The **Laboratori Nazionali del Gran Sasso (LNGS)** along the Gran Sasso Motorway tunnel, 120 km East of Rome, 1,400 m underground (3,700 metres water equivalent, m.w.e.). With three main halls each covering 2,000 m^2, a total area of 17,800 m^2 including bypass tunnels (total volume of 180,000 m^3) it is the largest of all underground laboratories.

- The **Laboratoire Souterrain de Modane (LSM)** along the Fréjus Road tunnel between Italy and France. With a depth of 4800 m.w.e. it is the deepest of all existing European laboratories. Its main hall has an area of 300 m^{2,} while the total volume is 3,500 m^3. After 2011, a major extension in the context of a forthcoming road-tunnel modification could house ton-scale experiments.

- The **Laboratorio subterráneo de Canfranc (LSC)** along a tunnel connecting Spain and France, at a depth of 2,450 m.w.e. with 1,700 m^2 area and 11,000 m^3 volume. Also for LSC, extensions are planned.

- The **Boulby Underground Laboratory** in a potash and rock-salt mine on the coast of England at 2,800 m.w.e., with 1,500 m^2 laboratory space and a volume of 3,000 m^3.

Other sites are investigated, offering either larger depths, or larger distance to nuclear reactors (allowing the study of neutrinos from the Earth's crust with a low background from reactor neutrinos), or larger available volume. They include the Pyhäsalmi mine in Finland the Sieroszowice mine in Poland (SUNLAB) and the Slanic mine in Romania (see also Section 3.5).

The committee acknowledges the efforts of the three countries to provide underground laboratory space for astroparticle physics.

In the following, we will discuss searches for Dark Matter (Section 3.2), the approaches for direct measurement of the neutrino mass (Section 3.3.), which is related to neutrino less double beta decay (Section 3.4). In Section 3.5, projects for low energy neutrino astrophysics and for the search for proton decay are discussed.

New underground facilities have been built in China (Jinping) and are planned in the US (DUSEL), India (INO) and South America (ANDES).

3.2 Dark Matter

The search for Cold Dark Matter (CDM) candidates addresses one of the most fundamental problems in particle physics and cosmology. There are many hypothetical particles that could play the role of dark matter, with different interactions and different nature. Masses spanning from some billionths of eV to millions of TeV have been considered and actually, the dark matter halo could even have a multi-component nature. However, the dark matter candidate that is favoured by many theorists is a weakly interacting massive particle (WIMP), related to new physics at the TeV scale. Among the various WIMP candidates on the GeV-TeV scale, the most appealing one is the lightest super-symmetric (SUSY) particle framed in the Minimal Supersymmetric Standard Model (MSSM). The MSSM postulates that the effective scale of SUSY breaking is around a TeV and that there is an additional symmetry called R-parity, which would keep the lightest SUSY particle stable. Another theoretically well-founded dark matter candidate is the axion. Even though axions are much lighter than WIMPs, they could still constitute CDM because they are produced out of thermal equilibrium in the early Universe and would be non-relativistic. Alternative candidates include light bosonic particles with axion-like couplings, nuclei of mirror matter, sterile neutrinos in the 10 keV mass range, s-neutrinos and Kaluza-Klein particles or super-symmetric Q-balls. Recently there has been growing interest in asymmetric dark matter – particles with mass of around 5-10 GeV which have the same particle-anti-particle excess as do relic baryons – because this provides a natural connection between the observed abundances of baryonic and dark matter. Such particles would not be able to undergo annihilations today but may well have self-interactions that can potentially solve the problem of excessive sub-structure expected on small scales for collisionless particles.

SUSY particles with masses up to the TeV scale could be produced in particle interactions at accelerators. The negative results of current accelerator searches indicate that even the lightest SUSY particle, likely the neutralino, is heavier than 50 GeV in the simplest realizations of the MSSM, even though lower masses are not ruled out. The LHC will extend the search for SUSY particles to much higher masses. However, the discovery of a SUSY particle at the LHC alone does not prove that it is the CDM particle required by cosmology, in particular it may be unstable because of R-parity violation. For that purpose, the detection of cosmological WIMPs is necessary. Conversely, the detection of cosmological WIMPs alone would not prove that they are SUSY particles. For that purpose, identification and investigation at accelerators is necessary. The synergy between LHC and next generation dark matter searches is obvious and opens an exciting perspective. In the present situation, where we do not yet have experimental proof of SUSY, we should not abandon the search for alternative candidates. Cosmological WIMPs can be detected in direct and indirect searches. In the following we will discuss the dedicated direct-search experiments and refer for indirect searches to section 2.

3.2.1 General features of a WIMP detector

The direct detection of WIMPs relies on measuring the nuclear recoil produced by WIMP elastic scattering off target nuclei in underground detectors. A large range of techniques and target materials are currently being used to this purpose. The appropriate tool is a low-energy nuclear detector with the following characteristics:

1. *Very low energy threshold for nuclear recoils* (given the nearly exponential shape of the energy spectrum, any gain in threshold corresponds to a relevant increase in sensitivity). Thresholds of the order of 1-10 keV (or even lower) have been demonstrated in various approaches.

2. *Very low intrinsic radioactive background at low energies.* In general, this requires significant expert effort in terms of material selection and cleaning to reduce the intrinsic background to below 0.1 events / (day kg keV). Backgrounds of the order of 0.01 events / (day kg keV) are expected in the best present experiments.

3. *Sensitivity to a recoil-specific observable.* This allows rejecting ambient and residual electromagnetic background for which the energy deposition is detected via a primary fast electron.

4. *Sensitivity to a Dark-Matter-specific observable.* This is necessary for an indisputable signature and may manifest itself in seasonal modulation of the rate, in diurnal modulation of the nuclear recoil directions and in the correct scaling of the candidate WIMP-induced recoil spectrum with the mass A of the target. Typically, such signatures also apply to a wider range of candidates.

The hypothetical WIMP-induced events are in strong competition with background events caused by particles which interact electromagnetically, such as charged particles and gamma-rays originating from residual radioactive contamination or cosmic radiation. In order to extract a nuclear recoil spectrum from this dominant electromagnetic background, its mere reduction through passive methods is usually considered to be insufficient, so that most experiments set up methods distinguishing nuclear recoils from the electron recoils induced by the electromagnetic background. If this operation is successful, the only background source arises from fast neutrons, which, like the WIMP signal, produce slow nuclear recoils. The neutron background can be kept under control by combining proper shielding with detector granularity or spatial resolution. Because the mean free path of fast neutrons is normally in the range of centimetres to tens of centimetres, there is a high probability that a fast neutron, unlike WIMPs, undergoes multiple scattering in a large enough detector or detector array.

The event-by-event identification of nuclear recoils can be achieved by means of the so-called *double read-out* detectors and can be performed using three different approaches. A fast particle depositing energy in a material produces, in general, three types of elementary excitations in the target medium: electron-hole or electron-ion pairs (*ionisation*), phonons (*heat*) and scintillation photons (*light*). Instruments with double read-out are able to provide two distinct signals, proportional to two distinct classes of excitations. In these hybrid devices, the ratio between the two signal amplitudes allows identifying nuclear recoils, since the ratio for energy deposited via a primary electron differs from that deposited via a primary nucleus. This ratio plays the role of a recoil-specific observable.

In case of a simultaneous measurement of ionisation and heat, the detectors consist of arrays of large germanium- or silicon Ge or Si. detectors with simultaneous read-out of charge and phonon signal. The detectors must be operated at very low temperatures, typically in the range 10-100 mK, in order to work as bolometers and to be sensitive to the phonons. The arrays usually consist of tens of individual elements, providing a high sensitive mass and also the granularity necessary to reject or assess the residual neutron background. The raw background and the energy threshold must be sufficiently low. Experiments using this approach are **EDELWEISS** in Europe and **CDMS** (and its expansion SuperCDMS) in the US.

In case of a simultaneous measurement of light and heat, the detectors consist of an array of scintillating crystals with an additional phonon sensor. These devices are often defined as a scintillating bolometer and require the operation of a light detector at very low temperatures, with very low threshold, typically in the few-photon range. Currently, these light detectors have been implemented through auxiliary bolometers consisting of thin wafers of low specific heat materials and equipped with suitable phonon sensors. Experiments based on this technology are the European **CRESST** and **ROSEBUD**.

In case of a simultaneous measurement of light and ionisation, the detectors use liquid noble elements as dark matter target. These materials are ideal for building large, homogeneous and position-sensitive devices. Liquefied noble gases are intrinsic good scintillators and have high ionisation yields. If a high electric field (~ kV/cm) is applied, ionisation electrons can also be detected, either directly or through the secondary process of proportional scintillation. Several experiments use or plan to use noble elements for WIMP search: **XENON** and **ZEPLIN** (both in Europe) and **LUX** in the US use *xenon* as target; **ArDM** and **WARP** (both in Europe) as well as the proposed **DarkSide** experiment (US/Europe proposal to LNGS) use argon as target.

NaI(Tl) scintillating crystals with ultra-high radio-purity and very low threshold are operated in the **DAMA/NaI** and **DAMA/LIBRA** experiments and used to investigate the annual modulation as a possible signature of Dark Matter detection. Notably, this smoking gun signature applies to a large variety of dark matter particles and interaction types.

3.2.2 Experiments without identification of nuclear recoils

When abandoning the implementation of a recoil-specific observable, detectors with simpler structure than those based on double readout can be realized. In order to be competitive, these single-readout devices need to have a very low raw background rate and a large total mass (or exhibit the prospect of scalability). This can make them sensitive to the dark matter signature of annual modulation (which does depend on specific assumptions on the dark matter model) and thereby may compensate for the lack of a method for identifying nuclear recoils. Scintillating crystals like sodium iodide are a convenient solution for accumulating a large detector mass. It is however more difficult to achieve a radio-purity comparable to germanium. NaI-based searches, such as **DAMA-LIBRA,** or the meanwhile terminated **NAIAD**, originally attempted to use pulse-shape discrimination to statistically identify a WIMP component in their observed rate. However, it was found that due to the low number of detected scintillation photons per keV of incident energy, this method is not feasible at low energies.

A first result exploiting the annual modulation signature was provided by the DAMA/NaI set-up (about 100 kg of low-radioactive NaI(Tl) detectors) over seven annual cycles. The result was confirmed by the subsequent expansion of the DAMA experiment, named LIBRA, comprising 232.8 kg of NaI detectors. With much higher statistics, corresponding to 0.87 ton×y (six annual cycles), the modulation effect was confirmed at an 8.9 σ confidence level. The cumulative DAMA/LIBRA exposure is 1.17 ton×yr, corresponding to 13 annual cycles. The modulation frequency and phase are in excellent agreement with what is expected from the interaction of particles composing the Galactic dark matter halo.

In spite of these remarkable correspondences, the reconciliation of the reported modulation effect with the published exclusion limits based on other direct and indirect searches would require some departure from the standard SUSY scenario: the comparison of results from different dark matter experiments is not independent from model assumptions

The DAMA-LIBRA collaboration has put forward several possible explanations of this modulation in terms of dark matter, spanning from WIMP-like candidates – something resembling SUSY neutralinos –to more exotic models for dark matter particles which could interact electromagnetically. An independent cross check using NaI-crystals could be provided by **ANAIS** (Laboratorio Subterràneo de Canfranc, Spain). The DAMA-LIBRA results could be scrutinized further with a similar technology by the Korean group **KIMS**, which deployed CsI crystal detectors with a low detection threshold for direct WIMP search in the Y2L Laboratory. Moreover, a summer/winter effect for a Southern hemisphere detector would yield a phase shift by six months vs. a WIMP-related effect: Thus, if the present technical test of two NaI-crystal units in an IceCube hole at the South Pole is successful, this would provide the option for an additional test of the origin of the modulation phase.

Recommendation: The committee strongly supports improving the DAMA/LIBRA experiment in terms of a lower detection threshold and a lower background, in order to better understand the modulation signal. A fully independent experiment based on the same or on a similar technology would be crucial to cross-check the DAMA/LIBRA effect. ■

Among the searches based on a single-readout approach, non-European experiments based on pure ionization Ge detectors with a very low threshold and an impressively low raw background (CoGeNT in the US and later TEXONO-CDEX in China) should also be mentioned. In spite of their inability to identify nuclear recoils, these searches reach excellent sensitivities at low WIMP masses, both for the spin independent and spin dependent channels. Also **CoGeNT** has recently reported the indication of an annual modulation, although until now with a confidence of only 2.8σ. Other single read-out experiments, with noble liquid targets, are the North-American **CLEAN/DEAP** (neon and argon, both using pulse shape discrimination, and the Japanese **XMASS** (xenon).

3.2.3 Experiments with identification of nuclear recoils

Experiments based on the simultaneous detection of ionisation and light in *double phase noble liquids* have obtained remarkable results in recent years. The **XENON** collaboration, after the successful precursor XENON10, is now operating the XENON100 experiment, based on the dual-phase time-projection-chamber technique, running in the LNGS. The detector uses two arrays of UV-sensitive photomultipliers (PMTs) to detect the prompt and proportional light signals induced by particles interacting in the sensitive xenon volume. The bottom array is located below the cathode, fully immersed in liquid xenon, and mainly detects the prompt light signal. The PMTs of the top array are located in the cold xenon gas above the liquid, detecting the proportional light. XENON100 has full 3D position sensitivity: the time separation between the two pulses of direct and proportional light provides the event depth of an interaction; the hit pattern in the top PMT array providing the x-y position (with a few mm resolution). In addition to the recoil-specific observable consisting of the light-to-ionisation-signal ratio, the position sensitivity, along with the self shielding of liquid xenon and an active liquid xenon veto around the TPC, serves as an important background-rejection feature.

The active target mass is 62 kg of ultra-pure liquid xenon. The raw background is about two orders of magnitude lower than the one of XENON10, because of the selection of low activity materials and the location of the cryo-cooler (a possible source of radioactive background) outside the shields and the veto. The dark matter search has started at the end of 2009, and the results from 100 days of data are very promising, with a limit of 7×10^{-45} cm^2 for 50 GeV WIMP mass. The sensitivity was limited by ^{85}Kr which induced three background events in the signal region. After elimination of this background, the expected sensitivity would extend down to cross sections of the order of 2×10^{-45} cm^2 for standard WIMPs inducing nuclear recoils. In addition, the preliminary runs exhibit a very low raw background, of the order of 0.02 counts/(ke×kg×day) below 100 keV with 40 kg of liquid xenon in the fiducial volume. This performance will enable XENON100 to "switch off" the recoil identification mode and to look at the raw spectrum in order to check if a seasonal modulation appears when searching for particles with electromagnetic interactions, as in the DAMA experiment.

The encouraging results achieved by XENON100 has motivated the collaboration to propose an expansion of the experiment named XENON1T, aiming at operating 1 ton of liquid xenon (fiducial WIMP mass) with a 100 times reduced background compared to XENON100. XENON1T has recently been approved to run in a large water shield in the LNGS.

Other searches exploit both the charge and light modes to reject nuclear recoils. Besides XENON, also **LUX** (US) and **ZEPLIN-III** (Boulby mine, UK) use xenon as the sensitive material. The recent results of ZEPLIN-III are competitive with the best-ever obtained results with double-readout experiments. **WARP** (under commissioning in LNGS) and **ArDM** (ready to be installed in the Spanish LSC), are based on a double-phase argon target. With respect to xenon, argon has an additional tool able to perform nuclear- vs. electron-recoil discrimination, which is the pulse-shape analysis of the primary scintillation signal. However, the lower target mass makes the sensitivity to spin-independent interactions significantly lower.

Recently, **DarkSide**, a project using depleted argon, has been started in LNGS. At present, a 50-kg detector is under construction. The plan is to commission it at the end of 2012.

The existence of two noble liquids with very promising potential for WIMP detection (Xe and Ar) and with nuclear masses significantly different from each other, motivates the realization of a set-up with two targets, an essential feature to provide a WIMP-specific observation. This is the purpose of DARWIN, a project aiming to complete the necessary research and design for the construction of a multi-ton scale liquid argon and/or liquid xenon detector with a sensitivity three orders of magnitude better than that of existing experiments. **DARWIN** brings together several European and US groups working in the XENON, WARP, DarkSide and ArDM collaborations and unites expertise on liquid noble-gas detectors, low-background techniques, cryogenic infrastructure and shielding.

Two noble-liquid target experiments, CLEAN (argon) and DEAP (neon) are under preparation at SNOlab in Canada. Though both experiments are single-read-out experiments, they will identify nuclear recoil events and separate them from electromagnetic interactions by pulse-shape discrimination.

Recommendation: The last 2-3 years have seen dramatic progress of the liquid-xenon based technology for the direct detection of WIMPs. The 100 kg scale has been realised with a low background level and the 1-ton scale is currently being planned. On this basis, the committee recommends that DARWIN, a program to further extend the target mass of noble liquids to several tons, is pursued and supported. The choice in favour of a double-target option should be taken after a clear experimental confirmation that a liquid argon target is competitive with liquid xenon in terms of rejection efficiency, background and operation reliability. ■

Experiments based on bolometers were the first to implement nuclear-recoil discrimination with double readout. Cryogenic calorimeters satisfy the crucial characteristics required of a high-sensitivity WIMP detector: low energy threshold, excellent energy resolution and the ability to differentiate nuclear- from electron recoils on an event-by-event basis. The phonon signal is recorded either after phonons reach equilibrium or “thermalise”, or when they are still out of equilibrium or “a-thermal”, the latter providing additional information about the location of an event.

The **EDELWEISS** experiment operates germanium bolometers at 20 mK in the LSM. This search uses both the ionisation and heat approaches. The detectors simultaneously detect the phonon and the ionisation signals, allowing discrimination against bulk electron recoils of better than 99.9% above 15 keV recoil energy. The charge signal is measured by aluminium electrodes sputtered on each side of the target crystal, while the phonon signal is recorded by a germanium neutron-transmutation doped (NTD) heat sensor glued onto the germanium crystal. The NTD sensors read out the thermal phonon signal, and hence spatial information is not available. To address this, and hence add capability of rejecting close-to-surface events, EDELWEISS implemented a new pattern of charge collection electrodes (InterDigit), allowing rejection of surface events with high efficiency using the ionisation channel. Thanks to these additional tools, measurements performed with ten 400 g detectors during one year have yielded a limit to spin-independent WIMP interactions of 4.4×10^{-44} cm^2 at a mass around 80 GeV. This result has brought this experiment into the leading group with XENON and CDMS. The EDELWEISS-II set-up uses a specially developed 50 l low-radioactivity dilution refrigerator, which will be fitted with forty 800 g detectors in the coming year. The collaboration seems to have in its hands the technology and the means to achieve sensitivity better than 10^{-44} cm^2 in the next years.

In the US, the experiment **CDMS** uses a technology similar to EDELWEISS: the main difference is in the phonon read-out, which is based on fast superconducting transition edge sensors, which can detect a-thermal phonons. This feature allows the rejection of the dangerous surface events on the basis of time structure of the phonon signal. The CDMS-II phase at the Soudan Underground Laboratory has ended, and recently the SuperCDMS phase using larger *germanium* detectors with improved charge and phonon sensors has started. In the next phase, SuperCDMS will use an approach similar to that developed by EDELWEISS for additional surface-event identification.

The two collaborations Edelweiss and CDMS have gathered their data into a combined analysis with improved limits for the high-mass region. Collaborative work is also ongoing towards the optimization of EURECA/Phase-1 and Super-CDMS allowing the possibility to house detectors from one experiment in the infrastructure of the other.

CRESST is a European collaboration which develops cryogenic detectors based on CaWO4 crystals, which show a higher light yield at low temperatures compared to other scintillating materials. The detectors are also equipped with a separate, cryogenic light detector, presently consisting of a sapphire wafer of 40 mm diameter and 0.4 mm thickness, with an epitaxially grown silicon layer on one side for photon absorption. The temperature rise in both the CaWO4 crystals and the light detector is measured with tungsten superconducting phase-transition thermometers, kept at around ~10 mK, within their transition between the superconducting and normal conducting states. A nuclear recoil has a different scintillation light yield compared with an electron recoil of the same energy, allowing discrimination between the two types of events. The advantage of the CRESST approach is the low-energy threshold in the phonon signal and the possibility to discriminate between recoils of the different nuclei present in the target. CRESST observes an excess in the oxygen nuclear recoil region, which is incompatible with the current understanding of the background from gamma-rays, neutrons and alpha particles. The next step is to scrutinize the reported excess counts in the oxygen nuclear recoil band by further reducing the background and by increasing the exposure.

The expertise developed by EDELWEISS, CRESST and ROSEBUD (another experiment at the LSC belonging to the light + heat class) represents the basis of the EURECA project (European Underground Rare Event search with Calorimeter Array). The EURECA facility will be located in the planned extension of the LSM (France). EURECA, currently carrying out a design study, develops a dedicated cryostat with water shielding, and is finalizing the design of its detector modules in the existing EDELWEISS and CRESST experiments. EURECA will use a target mass of up to 1 ton, enough to explore WIMP-nucleon spin-independent cross sections in the region of ~ 10^{-46} – 10^{-45} cm^2. A major advantage of EURECA is the planned use of more than just one target material.

Recommendation: The bolometric techniques have remained competitive with the noble liquid approach in terms of sensitivity to WIMP interactions. The results of the EDELWEISS collaboration showed a clear technological advancement with germanium detectors regarding the rejection of surface beta background, which was the main limitation in the "ionisation + heat" option. The CRESST experiment showed the power of identifying nuclear recoils from light and heavy nuclei using $CaWO_4$. The committee recommends therefore supporting the development of the multi-target approach EURECA, an apparatus capable of housing 1 ton of bolometric sensitive mass and the ongoing cooperation with the CDMS follow-up projects. This facility is complementary to the solution provided by noble liquids, and is versatile enough to provide a multi-target approach (including low Z targets tailored to test the low-mass WIMP region) and to possibly house other rare event searches based on bolometric technology.

The possibility to construct the EURECA set-up is connected to the provision of a suitable, deep, fully instrumented, underground space. In the European scenario, the most natural location would be the planned extension of the LSM, even though other possibilities are not excluded. This extension would be useful also for other next-generation projects in astroparticle physics.

Recommendation: The recommended projects for dark matter such as EURECA and DARWIN and SuperNEMO for ββ decay need new available space, if possible at a deep site. There is a unique opportunity to extend the present underground laboratory of Modane (LSM) by taking advantage of the excavation of the safety tunnel of the Frejus road tunnel, which started a year ago. This new laboratory of 60,000 m^3 would be able to host recommended projects. LSM has the greatest depth of the present underground laboratories in Europe. The committee therefore strongly recommends the timely support for this infrastructure. Such a laboratory - is of the size of one Gran Sasso hall with six times lower muon flux, in operation by 2014 - would enhance the complementarity of the European Deep Underground laboratories. ■

3.2.4 Other approaches to the direct detection of WIMPs

It is worth mentioning also an unconventional technology, which might lead to an unexpected breakthrough in the direct search for dark matter. The idea is to build large WIMP detectors using superheated liquids. An energy deposition can destroy the meta-stable state, leading to the formation of bubbles, which can be detected and recorded both acoustically and optically. Since a minimal energy deposition is required to induce a phase transition, these detectors are so-called threshold devices. The operating temperatures and pressure can be adjusted such that only nuclear recoils (large stopping powers *dE/dx*) lead to the formation of bubbles. **COUPP**, **PICASSO** and the European project **SIMPLE** belong to this class of experiments. The latter has recently reported a stringent limit on spin-dependent WIMP interactions.

Recommendation: The committee endorses an expansion of the experiment SIMPLE with a lower background level in order to further increase its sensitivity to spin-dependent interactions. This search can be done in synergy with the possibilities provided by xenon (about 50% nuclei have half integer spin) and by the bolometric approach which offers the chance to study different odd-A target nuclei. ▪

Finally, directional experiments deserve a special mention. As pointed out above, a diurnal modulation is expected, because all the nuclear recoils induced by WIMP events should globally point towards the Cygnus constellation due to the motion of the Earth in the Galaxy. A strong forward/backward asymmetry is then expected, taking into account the rotation of the Earth. This is a distinctive signature, which cannot be mimicked by any conceivable background source. The challenge is to measure three-dimensional tracks of low energy nuclear recoils with directional detectors based on low-pressure gas chambers. Low pressure (of the order of few tens of mbar) are required for the slow nuclear recoil to have an appreciable range. This makes it quite difficult to increase the sensitive mass. However, an order of 10 events would be sufficient to provide a significant signal. The projects belonging to this class are **DRIFT-II**, **DM-TPC**, **NEWAGE** and **MIMAC**.

Recommendation: The committee recommends supporting the R&D activities related to the directional detection of WIMPs, in particular aiming at a substantial background reduction, as this may become essential to confirm the Galactic dark matter origin of the signal in case of a positive signal from the high-density target detectors. ▪

3.2.5 Indirect detection of Dark Matter

Up to now, only *direct* detection methods have been discussed. Complementary signatures could be obtained from *indirect* dark matter detection. Here one searches for the annihilation products or decay products of dark matter particles: X-rays and gamma rays, anti-particles and neutrinos.

WIMPs can be gravitationally trapped in celestial bodies and eventually accumulate until their density becomes large enough that the self-annihilation of WIMPs would be in equilibrium with WIMP capture. Celestial or satellite detectors would then detect the decay products of these annihilations: an excess of neutrinos from the center of the Earth or Sun or a gamma signal from the center of the Galaxy, from the center of galactic halos or from dwarf spheroidal galaxies. Anti–particles such as positrons and anti–protons, produced in WIMP annihilation would be trapped in galactic magnetic fields and be detected as an excess over the background generated by astrophysical processes.

Obtaining convincing evidence for dark matter from excesses in the measured energy spectrum of gamma-rays or anti-matter turned out to be extremely difficult since the astrophysical backgrounds are not well understood. With extreme assumptions about annihilation cross sections and branching ratios, observations, like e.g. the rise in the energy spectrum of the positron ratio measured by PAMELA can be made compatible with a dark matter origin, without, however, providing a real proof of it. Fresh data, e.g. from AMS and Fermi, may help to clarify the present situation.

Convincing evidence could be obtained from the observation of a gamma-ray line that would point to dark matter annihilating directly to photons. The Fermi LAT satellite has put stringent constraints on this signature and will improve the sensitivity by almost one order of magnitude over the next decade. For dark matter masses above several hundred GeV, Cherenkov telescopes, in particular CTA, will provide significantly improved sensitivity. If dark matter particles are not completely stable (although having a cosmologically long lifetime) one could observe their decay via an X-ray or gamma-ray line. The decay signal would be proportional to the dark matter column density in a given object (and not to the squared dark matter density, as in the case of the annihilating dark matter). As a result, a large variety of astrophysical objects of different nature would produce comparable decay signals. If a candidate line were found, its surface brightness profile could be measured (as it does not decay quickly away from the centers of the objects) and distinguished from astrophysical lines (which usually decay in outskirts). This would allow distinguishing the line due to decaying dark matter from any possible astrophysical background.

Another very clean signature of WIMP annihilations would be the observation of high energy neutrinos from the Sun or the center of the Earth. IceCube so far has neither found any evidence for an excess of neutrinos from the Sun, nor from the Earth or the galactic halo, but over the next few years will improve its sensitivity by a factor of 5 and extend the search to masses below 50 GeV.

Direct and indirect methods are complementary. For instance, gravitational trapping works best for slow WIMPs, making indirect searches most sensitive. In the case of direct detection, however, by kinematic reasons fast WIMPs are easier to detect. For indirect searches, the annihilation rates would depend on all the cosmic history of WIMP accumulation and not only on the present density, providing another aspect of complementarity to direct searches. Current and upcoming indirect searches in the next 5–10 years will cover some parts of the Minimal Supersymmetric Standard Model (MSSM) parameter space which are not accessible by LHC and direct experiments.

Last but not least it must be mentioned that indirect searches do not require dedicated experiments. They come "for free", since X-ray and gamma-ray missions as well as neutrino telescopes, are mainly driven by astrophysical questions. In addition, cosmic-ray missions on satellites address a variety of other fundamental questions.

3.2.6 Axions

Experimental searches for axions or axion-like particles (ALPs) build on the coupling of the axion to two photons. The search for axions of astrophysical origin assumes conversions of axions to photons and vice versa in strong electromagnetic fields. Provided that dark matter is made dominantly from axions, an observation would determine the value of the coupling constant $g_{a\gamma\gamma}$ and vice versa, assuming a certain coupling constant, a value for the axion density can be derived.

The American Axion Dark Matter Experiment (ADMX) searches for axions saturating the dark matter halo of the Galaxy (a "haloscope"). ADMX uses a strong magnetic field permeating a cold microwave cavity. Axions matching the resonant frequency of the cavity decay into microwave photons. ADMX has excluded optimistic axion models in the mass range 1.9-3.5 µeV under the assumption that axions indeed make up the dominant part of the dark matter halo.

Axions (without an imperative connection to dark matter) can be produced in the Sun's core when X-rays turn to axions in the presence of strong electric fields. On Earth, these axions can be converted back in a strong magnetic field. Arriving as axions they tunnel a wall in a large magnet and appear again as keV X-rays. This is the approach of the Axion Solar Telescope (CAST) at CERN and of the Tokyo Axion Helioscope, with CAST in a clear lead position. With $g_{a\gamma\gamma} < 10^{-10}$, the present CAST limit cannot compete with microwave cavities in the mass region below 100 µeV which is preferred for the dark matter hypothesis. Actually CAST sets a similar limit as that derived from the cooling rate of horizontal branch stars. The CAST experiment, however, plans a new experiment with the goal to reach as sensitivity of $g_{a\gamma\gamma} \sim 0.5\times10^{-11}$, and there are even ideas towards extending sensitivity to $g_{a\gamma\gamma}$ by another order of magnitude. This would at least cover a non-negligible part of the $g_{a\gamma\gamma}$-ma parameter space predicted by QCD axion models for axion masses larger a few meV.

A CAST follow-up is discussed as part of CERN's physics landscape. It requires new magnets with increased field and aperture, as well as improved cryogenic and X-ray detection devices.
Even if not all approaches in this field are strictly related to dark matter, there is a potential for revealing new physics. **Therefore, we support the continuation of the corresponding programs.**

3.3 Direct measurement of the neutrino mass

The determination of the absolute neutrino mass scale follows a threefold concept. Three methods can in fact address directly this crucial parameter: analysis of the cosmic microwave background temperature fluctuations, search for and measurement of neutrino-less double beta decay ($0\nu\beta\beta$) and study of single beta decay. We note that the three approaches probe different combinations of masses, mixings and phases. The observation of neutrino-less double beta decay would prove the Majorana nature of neutrinos, which would be even more important than information on masses.

The first method is observational, and seeks to measure the effect of neutrino mass on the power spectrum of large-scale structure. Although it is in principle very sensitive, it depends critically on untested cosmological assumptions (e.g. concerning the primordial power spectrum of density fluctuations) and requires therefore independent checks. Projected sensitivities at the end of the decade reach down to 50 meV for the sum of all neutrino masses, i.e. about six times better than the expectations from the Planck satellite (the present flagship of CMB measurements) alone. If a positive effect was detected, it would provide extremely valuable information when combined with laboratory experiments. For instance, a CMB detection of the neutrino mass, not confirmed by double beta decay experiments, would challenge the Majorana nature of neutrinos. Conversely a positive detection by KATRIN (single beta decay spectrometer) of a mass *above* the cosmological bound, would challenge the standard cosmological model.

The second and third methods are based on laboratory searches. The $0\nu\beta\beta$ searches provide at the moment sensitivities in the range 0.2-1 eV, but are not sensitive to neutrino masses if e.g. the neutrino is a Dirac particle. A positive detection would prove the Majorana nature of the neutrino. Single beta decay endpoint measurements, frequently referred to as *direct searches* for neutrino mass, are not able to disentangle the three values of the neutrino masses (although this operation would be possible in principle), because the required energy resolution and statistics are out of the reach of present technologies. The sensitivity of any future conceivable experiment hardly reaches the 0.1 eV scale. However, *direct searches remain crucial*, since they are the only ones essentially free of theoretical assumptions about neutrino properties and are really model-independent. Moreover, a complete neutrino physics program should comprise experiments addressing all the three variants of the neutrino mass scale, because they are not redundant but rather complementary. They are all required to fully untangle the nature of the neutrino mass.

Direct neutrino mass measurements are performed by analysing the kinematics of charged leptons and/or pions emitted together with flavour-state neutrinos in suitable weak decays. The most sensitive neutrino mass measurements to date, involving electron type neutrinos, are based on the analysis of the shape of the beta spectrum near the end-point of the decay. The limits are ~2.2 eV for electrostatic spectrometers (obtained in Mainz/Germany and Troitsk/Russia with tritium experiments), and ~15 eV for low-temperature micro-calorimeters (MIBETA and MANU experiments in Italy). All these results have been obtained several years ago.

Future experiments on single beta decay:

Two approaches are at the moment experimentally relevant for the direct measurement of the neutrino mass, and represent the evolution of the searches that have obtained the current most stringent limits.

One is based on the study of the tritium (3H) beta decay, extensively used in the last forty years with magnetic and electrostatic spectrometers. Tritium beta decay is an allowed transition with an end point at 18.6 keV, one of the lowest in nature. Its lifetime of only 12.3 years allows realizing sources with high specific activities. Presently the leading technique for the analysis of the beta electrons uses electrostatic spectrometers with adiabatic magnetic collimation. In these devices, the electrons are collimated by means of a magnetic field with a proper space profile and selected by an electrostatic potential barrier. Higher energy resolutions and luminosities can be achieved with respect to the previous-generation magnetic bending spectrometers. The most sensitive planned experiment is KATRIN: it exploits this technology at the highest level and is the only project in the construction phase (in the tritium laboratory in Karlsruhe) in the field of the direct searches. It is mainly a European project, with German leadership and important Russian and US contributions (total cost 50 M€). The main features of **KATRIN** are a stronger tritium source and a larger main spectrometer (10 m diameter), with a higher energy resolution (~1 eV) than its predecessors in Mainz and Troitsk. The simultaneous improvement of resolution and luminosity, together with a better control of background, lead to a sensitivity of about one order of magnitude better than the present limit. The anticipated 90% C.L. exclusion limit is 0.2 eV and the 5σ discovery sensitivity is 0.35 eV. The first tritium runs are planned for 2012. In parallel, the Troitsk experiment is being upgraded to achieve a sensitivity below 1 eV.

Recently, a new idea has emerged in the US for the precise determination of the energy of the tritium beta electrons, consisting of the measurement of the radiofrequency they emit when propagating on cylindrical helices in a static magnetic field. An R&D activity is being conducted in the experiment **PROJECT-8**.

The second approach uses low-temperature micro-calorimeters with a very low transition-energy source embedded in them. The **MARE** project is based on this technology, already developed in the MIBETA and MANU precursors. MARE plans to study the beta decay of ^{187}Re, whose transition energy is only 2.47 keV, the lowest known in nature. The beta decay rate in natural rhenium is of the order of 1 Bq/mg, ideally suited to bolometric detection. Sensitivities similar to those achievable by KATRIN are possible if the bolometric performance meets the expectations. In addition, the *modular approach* intrinsic to the bolometric technology does not set intrinsic limitations to the expansion of the experiment. In the intense R&D activities performed in the last years, it was not possible however to achieve the planned energy resolution. Since this may be due to limitations intrinsic to the Re-based materials, another promising approach is under study by the MARE and the ECHO collaborations, which foresees the embedding of a

^{163}Ho source in optimised bolometers with very high energy resolution. This nucleus decays by electron capture and the mass of the emitted electron neutrino can be measured by studying the end point of the spectrum of the total visible energy produced in the decay. Sensitivities similar to those achievable in the rhenium case can be achieved.

We note that the non-observation of masses above 0.2 eV would have also its good aspects, since only for low masses one could distinguish the sequence of the neutrino mass states.

Recommendation: The KATRIN beta spectrometer is expected to provide unique results on the direct measurement of the neutrino mass starting from 2013, testing the degenerate mass region at the 0.2 eV level. At the moment, no other technology seems to be really in competition. Since with KATRIN the maximum feasible size seems to have been reached, no larger electrostatic spectrometer is currently being planned, but improvements with respect to resolution and other parameters are conceivable. On the other hand the bolometric approach followed in MARE is modular and can in principle be extended arbitrarily. Therefore, we recommend the continuation of R&D activities on the bolometric approach, regarding both 187Re (beta decay) and 163Ho (electron capture) sources.

3.4 Neutrino-less Double Beta Decay

Double Beta Decay (DBD) is rare nuclear transition, in which a meta-stable isobar changes into a more stable one, by the simultaneous emission of two electrons and two electron antineutrinos. Such process can take place in principle for 35 naturally occurring even nuclei, whose ordinary β decay is energetically forbidden or severely hindered by a large change of the nuclear spin-parity state. DBD is a second-order process of the weak interactions and has consequently a very low probability, which leads to extraordinary long lifetimes for the candidate nuclides. The two-neutrino process (2νββ) already observed in several nuclides, is fully consistent with the standard model (SM). The neutrino-less channel (0νββ), which involves only the two electrons in the final state, violates lepton number conservation and would definitely imply new physics beyond the Standard Model of particle physics.

Of primary interest is the process mediated by the exchange of light Majorana neutrinos interacting through the left-handed V-A weak currents. In case of light neutrino exchange, the decay rate is proportional to an exactly calculable phase space factor, to the nuclear matrix element (whose calculation represents a severe challenge for nuclear theorists), and to the so-called Majorana mass. This parameter contains all the neutrino physics, being a linear combination of the three neutrino masses m_i, weighted with the square of the elements of the first row of the neutrino mixing matrix. The presence of the phases of these elements (the so-called Majorana phases) makes cancellation of terms possible: the effective Majorana mass could be smaller than any of the neutrino masses. As already stated at the beginning of Section 3.1, the results on the Majorana mass need to be cross-checked with the information coming from cosmology and the direct searches for a full comprehension of the neutrino properties.

It is important to note that other mechanisms can induce 0νββ, such as the exchange of heavy neutrinos, virtual SUSY particles or V+A currents. In these cases, constraints discussed in section 3.3. do not necessarily apply. However, signs of the associated new physics could be detected at the LHC.

The uncertainties related to the calculation of the nuclear matrix elements are critical for a complete interpretation of 0νββ results, and also for the comparison of the physics reach of future searches using different nuclei.

Recommendation: The committee notes progress in the calculation of the nuclear matrix elements for 0νββ, with clear signs of convergence and with a validation of the traditional methods through a new approach. The committee confirms therefore the importance of continuing this fruitful program, which is based on both theoretical and experimental investigations. ■

Thanks to the information we have from neutrino oscillations, it is useful to express the Majorana mass in terms of three unknown quantities: the mass scale, represented by the mass of the lightest neutrino, and the two independent Majorana phases. It is then common to distinguish three mass patterns: normal hierarchy (NH), where $m_1 < m_2 < m_3$, inverted hierarchy (IH) where $m_3 < m_1 < m_2$, and the quasi-degenerate mass spectrum (QD), where the differences between the masses are small with respect to their absolute values. The 0νββ process has the potential to provide essential information on nature's choice on mass ordering of neutrinos. In fact, if one can experimentally establish that the Majorana mass is larger than 50 meV, one can conclude that the QD pattern is the correct one. On the other hand if this parameter lies in the range 20-50 meV, the pattern is likely to be IH. Eventually, if one could determine that the Majorana mass is smaller than 10 meV but non-vanishing (which is unlikely in a foreseeable future), one could conclude that the NH pattern holds. Therefore $0\nu\beta\beta$ is important at two fronts: the comprehension of fundamental aspects of elementary particle physics and the contribution to the solution of hot astroparticle and cosmological problems, related to both the neutrino mass scale and its fundamental nature.

3.4.1 General features of a $0\nu\beta\beta$ decay search

From the experimental point of view, the shape of the two electron summed energy spectrum enables us to distinguish among the two relevant decay modes. In case of $2\nu\beta\beta$, this spectrum is expected to be a continuum between zero and the transition energy Q with a maximum around Q/3. For $0\nu\beta\beta$, the spectrum is just a peak at the energy Q, enlarged only by the finite energy resolution of the detector. Additional signatures for the various processes are the single electron energy distribution and the angular correlation between the two emitted electrons. Q ranges from 2-3 MeV for the most promising candidates. The importance of having such a high Q-value, in terms both of the phase space for the process and of reduced contribution of radioactive backgrounds at higher energies, limits drastically the number of candidate nuclei that are experimentally relevant. As a reminder: ^{130}Te (Q=2527 keV), ^{116}Cd (Q=2802 keV), ^{76}Ge (Q=2039 keV), ^{136}Xe (Q=2479 keV), ^{82}Se (Q=2995 keV), 100Mo (Q=3034 keV), ^{150}Nd (Q=3367 keV) and ^{48}Ca (Q=4270 keV).

The experimental strategy to investigate $0\nu\beta\beta$ consists of the development of a proper nuclear detector, with the aim of revealing the two emitted electrons in real time and the measurement of their summed energy spectrum as minimal information. Additional pieces of information can be provided in some cases, like the single electron energies and initial momenta. The desirable features of this nuclear detector are:

1 *High energy resolution*, since a $0\nu\beta\beta$ peak must be identified over an almost flat background.

2 *Low background*, which requires underground detector operation, very radio-pure materials (the competing decays from natural radioactivity have typical life-times at least 15 orders of magnitude shorter than those predicted for $0\nu\beta\beta$).

3 *Large source*, in order to monitor many candidate nuclides. Present sources are of the order of 10 kg of isotope in the most sensitive detectors, while the next generation experiments aim at sources in the 100-1,000 kg scale.

4 *Event reconstruction method*, useful to reject background and to provide additional kinematical information on the emitted electrons.

Normally, the listed features cannot be met simultaneously in a single set-up. The practical experimental approaches privilege some properties with respect to others.

The searches for $0\nu\beta\beta$ can be further classified into two main categories: the so-called calorimetric technique, in which the source is embedded in the detector itself, and the external-source approach, in which source and detector are two separate systems.

The calorimetric technique has been proposed and implemented with various types of detectors, such as scintillators, bolometers, solid-state devices and gaseous chambers. It can provide high efficiency, large sources and with a proper choice of the detector, a very high energy resolution (of the order of 0.1%). A drawback is that it is difficult to reconstruct event topology (with the exception of liquid or gaseous xenon TPCs, and with novel germanium detectors). Recent proposals to dissolve the investigated isotopes in a huge amount of liquid scintillator belong to this class as well.

In the external-source approach, many different detection techniques have been combined also : scintillation, gaseous TPCs, gaseous drift chambers, magnetic field for momentum and charge sign measurement, time-of-flight. In this case, large source masses are not easy to achieve, because of self-absorption in the source so that the present limit is around 10 kg, and normally the energy resolution is low (of the order of 10%), intrinsically limited by the fluctuations of the energy the electrons deposit in the source itself. However, a neat event reconstruction is possible, enabling an excellent background identification capability.

The present experimental situation is dominated by three experiments: **Heidelberg-Moscow**, **Cuoricino** and **NEMO3**. All have set limits on the Majorana mass of the order of 0.2 – 1 eV. However, the search for the $0\nu\beta\beta$ transition has been spurred on by a claim made by a part of the Heidelberg-Moscow collaboration. The ^{76}Ge half-life best value quoted by them is 1.5×10^{25} y (or $(0.8 - 18.3)\times10^{25}$ y at 95% c.l.), which can be interpreted in terms of a Majorana mass of 0.39 eV (or 0.05 - 0.84 eV at 95% c.l. including nuclear matrix element uncertainties). NEMO3 (with ^{100}Mo) and especially Cuoricino (with ^{130}Te) have partially scrutinized the range of the claim, but were not able to exclude it because of the nuclear matrix element uncertainties.

New generation experiments are just starting or will begin data taking in the next few years. All of them should be in a position to scrutinize fully the Heidelberg-Moscow claim, and many aim to attack the IH region of the neutrino mass pattern.

3.4.2. Calorimetric 0νββ searches without tracking capability

Four planned projects are characterized by a calorimetric approach with high energy resolution.

CUORE, a natural expansion of Cuoricino, will be an array of natural TeO_2 bolometers arranged in 19 towers and operated at 10 mK in the Laboratori Nazionali del Gran Sasso. The source will correspond to 200 kg of the isotope ^{130}Te, the only one which has a natural abundance enough high (34%) to enable competitive experiments without an expensive enrichment process. It will take advantage of the Cuoricino experience. The proven energy resolution is 0.25% FWHM. The sensitivity to the Majorana mass is 50 meV, and is limited mainly by surface alpha background. CUORE is in the construction phase and data taking is foreseen to start in 2014. A test module of the CUORE detector, comprising a single tower and named CUORE-0, started data taking in 2011.

GERDA is an array of enriched Ge diodes operated in liquid argon and shielded by an active water Cherenkov veto. The experiment, installed in the LNGS, investigates the isotope ^{76}Ge, with the possibility to scrutinize the Heidelberg-Moscow result in just one year. The energy resolution measured during the Phase-I commissioning runs is 0.18% FWHM. and 0.14% for Phase-II prototype detectors. The first phase (currently under preparation) consists of 18 kg of enriched (86%) Ge detectors. The performance of the detectors in liquid argon is excellent, but a known background source (the cosmogenic isotope ^{42}Ar) turned out to be higher than expected. Mitigation techniques have been developed to make sure that ^{42}Ar does not limit the sensitivity of the experiment. The second phase foresees 40 kg of isotope. The predicted sensitivity to the Majorana mass is 190-390 meV in the first phase, and 75 – 150 meV in the second phase. The **MAJORANA** experiment, with US leadership, uses the same basic technology and will consist of an array of enriched germanium diodes operated in conventional copper cryostats. Merging with GERDA is foreseen in anticipation of a 1-ton set-up.

LUCIFER is a European project consisting of an array of ZnSe scintillating bolometers operated at 20 mK. The proof of principle with ~10 kg enriched Se is foreseen in 2014 in the LNGS. The proven energy resolution is better than 1% FWHM. LUCIFER is in the R&D phase and can be considered as a demonstrator for a possible upgrade of CUORE, however with a considerable sensitivity by itself (~100 meV to Majorana mass).

A second class of future experiments is based on a conversion of existing large liquid underground detectors, dedicated so far to direct detection of neutrinos. The approach is still calorimetric, but with low energy resolution and no tracking capability. We report here on two non-European projects in which very large statistics and a full understanding of the background sources can compensate for the low energy resolution. Similar plans (xenon loading of liquid scintillator) have been considered for **BOREXINO** for a long time and still represent a future option.

SNO+ is an upgrade of the homonymous solar neutrino experiment (Canada, with some European contribution), aiming at filling the SNO detector with neodyme-loaded liquid scintillator to investigate the isotope ^{150}Nd. Crucial points are Nd enrichment and purity. Another issue concerns the ^{150}Nd nuclear matrix elements, whose calculation is made difficult by nucleus deformation, which could lead to an important suppression. The present plan is to use 0.1% w/w natural Nd-loaded liquid scintillator in 1,000 tonnes, providing a source of 56 kg of ^{150}Nd, which should lead to a sensitivity of 100–200 meV to the Majorana mass. Data taking is foreseen in early 2012.

KamLAND-Zen is an upgrade of the KamLAND set-up in Japan (no European contribution). The idea is to convert it to neutrino-less Double Beta Decay search by dissolving 400 kg of enriched xenon gas in the liquid scintillator, contained in a mini-balloon immersed in the main vessel. The data taking should have started in 2011, with a final sensitivity of about 50 meV.

3.4.3. Double Beta Decay with Tracking /Topology Capability

This category comprises calorimetric or external-source experiments based on detectors which compensate the low energy resolution with tracking or some form of event-topology capability.

SuperNEMO, which is foreseen to be installed in the planned extension of the LSM, implements the external-source approach at the most sophisticated level. It will provide *excellent track reconstruction*, ensuring the unique capability to measure single electron energy distribution and angular correlation, precious features for a possible identification of the 0νββ mechanism. It will be composed by several modules containing source foils, tracking (drift chamber in Geiger mode) and calorimetric (low-Z scintillator) sections. A magnetic field is present for charge sign identification. SuperNEMO will take advantage of the NEMO3 experience, and will investigate ^{82}Se and possibly ^{150}Nd and ^{48}Ca in a second phase. The proposed configuration foresees 20 modules with 5 kg source for each module, providing 100 kg of isotopes. The projected energy resolution is 4% FWHM. The project is in an advanced R&D phase: the first module, operating as a demonstrator, is scheduled for 2013.

NEXT is a 100 kg high-pressure gaseous-xenon TPC, to be located in the LSC, Spain. The extension to 1 ton is technically possible. Clear two-track signature is achievable, thanks to the use of gaseous rather than liquid xenon. The energy resolution extrapolated from measurements with a prototype is better than 1% FWHM, achieved thanks to the electroluminescence signal associated to the ionisation electrons produced in the double-beta decays. The experiment is in the R&D phase. Three prototypes, all dubbed NEXT-1, have been completed in Spain and at LBNL (USA). A conceptual design report for NEXT-100 has been recently released and the ambitious plan is predicted to start running in 2014.

COBRA is a proposed array of ^{116}Cd-enriched CdZnTe semiconductor detectors operated at room temperature. Nine ββ isotopes are under test, but ^{116}Cd is the only competing candidate. The final aim of the project is to deploy 117 kg of ^{116}Cd with high granularity. Small scale prototypes have been realized in LNGS. The proved energy resolution is 1.9% FWHM. The project is in R&D phase. Recent results on pixellization show that the COBRA approach may allow an excellent tracking capability (solid state TPC).

The three mentioned experiments are located in Europe.

EXO is mainly an US experiment (with Swiss participation), consisting of a TPC of enriched liquid or high pressure gaseous xenon, for the investigation of the isotope ^{136}Xe. The set-up will provide event position and topology. In prospect, the tagging of *Ba* single ion (ββ decay daughter) is foreseen with optical spectroscopy methods. The first step (EXO-200), under commissioning, consists of 200 kg of enriched liquid xenon and will not use the *Ba* tagging approach. It is located in the WIPP facility, in the USA. EXO-200 sensitivity to the Majorana mass is anticipated to be 133 – 186 meV. The proven energy resolution is 3.3% FWHM (improved thanks to simultaneous measurement of ionization and light). Further steps foresee source masses in the 1 – 10 ton range.

Recommendation: The European detectors GERDA and CUORE will explore in the next years the degenerate region of the neutrino mass pattern. CUORE will probe also part of the mass range predicted by neutrino oscillation experiments for the case of the inverted mass hierarchy. In case of discovery at the degenerate mass level, there is a clear path for "precision measurements", with possible evidence from three different nuclei and the opportunity provided by SuperNEMO to investigate the leading DBD mechanism. The committee recommends a prompt realization of the SuperNEMO demonstrator. Whereas GERDA, CUORE and SuperNEMO rely on the long-term experience with precursors and extensively validated techniques, NEXT is a comparatively new approach, with a steep time gradient, combining construction of a full detector with basic R&D. **The committee encourages the collaboration to demonstrate all aspects of the technology and move ahead toward NEXT-100.** ▪

The community is working to improve the sensitivity of these experiments, with the aim to fully cover the inverted hierarchy region, a crucial element for the determination of the neutrino mass hierarchy in synergy with the next stages of the neutrino oscillation program. The general requirement for this task is 1 ton of isotope and a background at the level or below 1 count/(yr ton-isotope) in the region of interest. This challenging objective can be accomplished either by the technologies of the experiments running or in construction (this option would provide the advantage of a phased approach) or by new promising technologies which are currently under study (LUCIFER, COBRA pixel detectors, pulse shape discrimination in bolometer experiments, argon instrumentation in GERDA, Cherenkov light in TeO_2).

Recommendation: The committee recommends that these options are pursued at the R&D level in view of a final assessment of the most effective approaches for the 1 ton scale. As the required financial resources are substantial for ton scale experiments, the committee endorses their realisation in the framework of worldwide collaborations. This would allow the investigation of more than one double beta isotope, which is essential to provide an unambiguous signature of neutrino-less double beta decay and to determine the effective Majorana mass. ■

For future DBD experiments on the ton scale, enrichment at high production rate is a central issue. While this operation is possible for isotopes which are gaseous, or form gaseous compounds at room temperature (like ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe), radon background free isotopes (like ^{150}Nd, ^{96}Zr and ^{48}Ca) require innovative techniques. Enrichment technology is presently dominated by Russian companies.

Recommendation: We encourage Western companies and laboratories to continue R&D on the enrichment of new isotopes (like ^{150}Nd) by centrifugation technology or by laser isotopic separation. ■

3.5 A large detector for proton decay, low energy neutrino astrophysics & next generation long baseline neutrino experiments

The successful detection of neutrinos from the supernova SN1987A by the Kamiokande detector (Japan), IMB detector (US), and Baksan detector (Russia) and the detection of solar neutrinos by the Homestake detector (US) and Kamiokande detector (Japan) opened the field of neutrino astronomy. Both of these accomplishments were recognized with a Nobel Prize in 2002. Actually, these opened a 30-year long tradition of incredibly rich physics with large underground detectors, including solar physics, the discovery of neutrino oscillations by studying Solar (GALLEX/GNO, SAGE, SuperKamiokande, SNO, BOREXINO) and atmospheric neutrinos (SuperKamiokande, MACRO, Soudan, Baksan), and the confirmation of these results using reactor neutrinos (KamLAnd CHOOZ, Palo Verde) and accelerator neutrinos (K2K, MINOS, OPERA). More ambitious physics topics, like Grand Unification, have also been explored. The limits for the lifetime of protons have been pushed to nearly 10^{34} years. Last but not least, in 2005 KamLAND announced the first indication of geo-neutrinos, and BOREXINO confirmed this result with a better ($>5\sigma$) significance. At present and in the near future, the mass-flavour mixing matrix for neutrinos is studied with more intense neutrino beams from the Japanese KEK/J-PARC accelerator complex to Super-Kamiokande (T2K experiment) and from FNAL to Ash-River (NOvA) to measure the last, unknown mixing parameter defined as θ_{13}, opening the path towards measurement of CP-violation in the leptonic sector. The CERN-LNGS program with a neutrino beam to OPERA and ICARUS in LNGS is continued. In addition, the Double-CHOOZ reactor neutrino experiment in France has started data-taking, whereas Daya Bay in China and Reno in the South Korea are being constructed. They will measure electron disappearance to search for the unknown mixing parameter defined as θ_{13} as well. Double-CHOOZ is a principally European experiment with significant overseas participation. T2K sees a very large European contribution with more than half collaborators coming from European institutions from France, Germany, Italy, Poland Spain, Switzerland and United Kingdom. There are also European collaborators in Super-Kamiokande and MINOS (neutrino beam from Fermilab to the Soudan mine).

New since 2008: Several important physics and technological results have been obtained since the 2008 roadmap. BOREXINO has measured Solar ^{7}Be neutrinos with improved accuracy (and also the ^{8}B component), provided essential data in the transition region between vacuum and matter oscillations and confirmed the absence of a day-night effect. BOREXINO has also measured convincingly geo-neutrinos, with a much smaller background from reactor neutrinos than KamLAND. BOREXINO performs as expected with respect to all parameters, in particular with respect to the critical question of purity and background rejection. In 2010, the 600-ton liquid argon TPC ICARUS in Gran Sasso became operational. It demonstrated that the liquid argon technology yields impressive imaging performance and can also be reliably operated in an underground environment. Also of note in 2010, the OPERA experiment detected its first candidate for a tau neutrino event, adding strong evidence of neutrino oscillation from muon to tau neutrinos. Previously, the only direct evidence was a statistical analysis of atmospheric neutrino events in Super-Kamiokande. Furthermore, a set of anomalies in the neutrino sector (LSDN, SAGE and GALLEX registration of neutrinos from Cr sources, Bugey and Mini-Boone) has been extended by results from the anti-neutrino measurement with Mini-Boone and the SAGE-argon measurement. Although none of these hints for physics beyond the Standard Model are particularly convincing, theorists have tried to accommodate them in models which invoke sterile neutrinos interacting only via gravity. The models also make use of recent cosmological observations. To test such ideas we need a new experimental campaign which will falsify the anomalies, or in fact discover new physics. Last but not least, the T2K experiment reported a tempting indication for a non-vanishing mixing angle θ_{13}.

3.5.1 Present and near term measurements

Solar neutrinos: Once GALLEX/GNO (Gran Sasso Laboratory), KamLAND (Japan) and SNO (Sudbury Laboratory, Canada) have terminated their extremely successful operation or moved on to other physics topics, there will remain worldwide three devices with an active solar neutrino programme:

1) Super-Kamiokande (22 kt fiducial volume water Cherenkov, Japan, ^{8}B-neutrinos)

2) BOREXINO (270 t scintillator, Gran Sasso Laboratory, Italy, ^{7}Be neutrinos)

3) SAGE (GaGe radiochemical detector, Russian Baksan Laboratory, pp neutrinos)

The scientific programme includes measurement of the predicted matter effects from neutrino oscillations (the solar neutrinos pass through significant matter in their path from the core of the Sun and through the Earth at night), precision measurement of solar fusion processes, and long-term monitoring of the solar fusion process. In 2011, first indications for pep neutrinos have been reported. The main goals of the present solar neutrino experiments which can be within reach in a few years are: measurement of the up-turn of the survival probability; improved measurement of the pep flux and first measurement of the CNO flux and possibly of the pp flux by BOREXINO; resolving the metallicity controversy.

Recommendation: The committee strongly endorses further support for the BOREXINO program, which is now unique in the world. BOREXINO could be able to detect CNO neutrinos at 30% level in a timescale of two years. ▪

Supernova neutrinos: If today the signal from a supernova would arrive, the prospects for neutrino detection would be incomparably better than in 1987. At that time, three detectors (Kamiokande, IMBand Baksan) recorded a total of 22 events. Scaled to a supernova at the center of the Galaxy, this corresponds to ~700 events. Today, a SN1987A-type supernova at 10 kpc distance would result in nearly 10,000 neutrinos detected worldwide:

- Super-Kamiokande (8500) and KamLAND (350) in Japan,
- LVD (400), BOREXINO (100) and ICARUS (50) in the LNGS in Italy,
- MiniBOONE (200) in the US,
- the Baksan detector (70) in Russia.

Numbers in brackets give the approximate number of events (dependent on emission model).The possibility to detect supernova neutrinos of all flavors via the elastic reaction $\nu+p\rightarrow\nu+p$ gives scintillation detectors like BOREXINO and KamLAND a crucial role in measuring the temperature of a supernova. A few millions of interactions would be detected in IceCube, however, not as reconstructed events, but only as an increased dark count rate. A counting rate alone does not give information on energy and direction, but the time profile of the supernova pulse would be measured with great accuracy and contribute to the understanding of the early phase of the supernova explosion.

The observation of spectral changes due to neutrino-neutrino interactions and matter effects could be an independent way to determine the ordering of the neutrino masses. It is also possible that an early cut-off of the neutrino emission could provide the first direct evidence of the formation of a black hole.

Geo-neutrinos: BOREXINO has successfully detected ^{8}B neutrinos, ^{7}Be neutrinos, and geo-neutrinos and will continue to improve these important measurements. The future goals of geo-neutrino measurements are: determination of the total Uranium content within the Earth through a spectroscopic observation; determination of the radiogenic heat from the mantle; direct determination at 5% accuracy of the Thorium and Uranium ratio. The last aim can be achieved only by a future super-massive detector such as LENA.

Atmospheric neutrinos: IceCube has collected by far the largest statistics of atmospheric neutrinos and is continuing data taking. With its inner array DeepCore, energies low enough to study neutrino oscillations will be reached.

Accelerator neutrinos: Both the OPERA experiment in Europe and the MINOS experiment in the US will continue their programme of tau neutrino and precision oscillation measurements for the next few years. In addition, new experiments have started: T2K experiment is now operating and a first result of neutrino oscillation via θ_{13} is expected within the year. T2K aims at leading the worldwide θ_{13} exploration and is expected to reach a sensitivity $\sin^2(2\theta_{13})<0.014$ by summer 2014. In 2013 the NOvA experiment will start data taking with the possibility to test matter effects in long baseline neutrino oscillations for favourable values of θ_{13} as well.

A discovery of θ_{13} in the coming years would provide a tremendous boost for next generation long baseline accelerator experiments looking for CP violation in the leptonic sector.

OPERA achieved the first direct detection of a tau neutrino candidate produced from oscillation of a muon neutrino beam. Due to the fact that other existing neutrino beams in the world operate below the threshold for tau production, the CERN/LNGS beam is the only facility capable of making this measurement. ICARUS, which claims a tau appearance sensitivity similar to that of OPERA, should also confirm this measurement. In this context we also mention the proposal to restore the CERN PS neutrino beam and measure oscillations with ICARUS placed at a very short distance. This is focused on physics beyond the Standard Model e.g. sterile neutrinos.

It is recommended that OPERA and ICARUS are continued as planned in order to obtain a more significant evidence for tau appearance.

Reactor neutrinos: The Double-CHOOZ Far Detector has recently started operation and will measure electron neutrino disappearance to provide data on θ_{13} vastly improved from the original CHOOZ experiment. **To achieve full sensitivity and to be competitive with other experiments worldwide, it is critical that the Near Detector be completed as soon as possible.**

Knowledge of θ_{13} is important to define the path to discovery of the CP violation in the leptonic sector, Earth matter effects and perhaps even supernova neutrino emission. It will provide import input on long baseline options for Megaton-scale detectors.

Radioactive sources: This approach is motivated by deficits which were measured in GALLEX and SAGE for neutrinos from strong radioactive sources and by the recently discussed reactor anomaly, as well as by speculations on a fourth, sterile neutrino family deduced from cosmological and accelerator data. It foresees to place extremely strong radioactive sources in liquid scintillators, with the goal to perform very short baseline oscillation experiments. The BOREXINO collaboration is considering such an option.

3.5.2 Next-generation detectors

Large underground detectors have produced an extremely rich harvest of discoveries. This legacy is intended to be continued by one or several multi-purpose detectors on the mass scale of 50-500 ktons. The physics potential of a large multi-purpose facility would cover a large variety of questions:

a) The observation of proton decay would be one of the most fundamental discoveries for physics and cosmology. The verification of GUT models calls for a proton decay sensitivity to be improved by up to one order of magnitude and that alternative decay modes be explored.

b) A galactic supernova would result in several ten thousands of fully reconstructed neutrino events which would provide incredibly detailed information on the early phase of the supernova explosion.

c) Neutrinos from nuclear reactors and/or particle accelerators could be detected over a long baseline between neutrino source and detector. By these measurements the sensitivity to θ_{13} could be substantially improved. [1]

d) The diffuse flux from past supernovae would probe the cosmological star formation rate and the average features of neutrino emission.

e) The details of the processes in the solar interior can be studied with high statistics and the details of the Standard Solar Model determined with per cent accuracy. [2]

f) Geo-neutrinos could be measured with a much-increased statistical accuracy compared to today, which should help discriminate among various geophysical models.

g) The high-statistics study of atmospheric neutrinos will further improve our knowledge on the neutrino mass matrix and might provide information on the neutrino mass hierarchy.

h) The study of neutrinos of medium energy from the Sun and the centre of the Earth could reveal signs for low-mass dark matter which is not detectable by deep-water/ice detectors.

Several conceptual ideas for next-generation very massive, multi-purpose underground detectors have emerged worldwide and in Europe over the last few years. All the designs consist of large liquid volumes observed by detectors which are arranged on the inner surfaces of the vessels. The liquid simultaneously acts as the target and as the detecting medium. First, MEMPHYS relies on the concept of Super-Kamiokande and uses water. Second, LENA extrapolates experience gained in reactor experiments and BOREXINO and uses liquid scintillator. The third detector is GLACIER, building on the pioneering efforts of ICARUS and useing Liquid Argon. The physics return of a next-generation underground facility could be maximized if one could incorporate sub-detectors of different technologies. A proposal on site(s) and technologies necessarily has to be tackled globally, in particular taking into account the plans in the US and Japan. In this context one may also think of a "global observatory" which relies on infrastructures at several sites.

From a practical point of view, the most straightforward liquid is water. Water is a cheap medium, therefore the dominant costs are in excavation and photomultipliers. The possibility of building a water Cherenkov detector with a fiducial mass of 200-500 kton volume is currently being also studied for the DUSEL Laboratory in the US (LBNE project) and for the Kamioka site in Japan (Hyper-Kamiokande). Both projects are also conceived as Long Baseline Experiments (Hyper-Kamiokande with a beam from the T2K experiment with a planned power upgraded neutrino beam from KEK/J-PARC to the Kamioka site, LBNE using a new neutrino beam from Fermilab). Water-Cherenkov detectors have a high sensitivity to proton decays with three Cherenkov rings, like for example the channel $p \rightarrow e^+ \pi^o$.

With respect to its proven feasibility (BOREXINO, KamLAND), a high purity liquid scintillator detector comes next. The scintillator technology for LENA is based on the pioneering developments within the BOREXINO experiment. The light yield of a scintillator is much larger than that of Cherenkov light produced in water and has therefore a lower threshold. The Cherenkov rings used in water to identify events cannot be imaged, however it has been shown to be effectively replaceable by precise timing, for example in the context of the search for proton decays in the $p \rightarrow K^+\nu$ channel. This technique could also detect remnant diffuse supernovae neutrinos, geo-neutrinos emitted from the Earth and reactor neutrinos. At present the maximum volume of such a detector seems to be limited by financial reasons to several tens of kilotons.

The third possibility is a liquid Argon Time Projection Chamber as pioneered in Europe with many years of R&D in the ICARUS program. This technology is able to image the rare events with the quality of a bubble-chamber. Thanks to their imaging capability, liquid Argon detectors can provide improved sensitivities to the proton decay channels where backgrounds are serious in the Water Cherenkov detectors, like for example for $p \rightarrow \text{anti-}\nu + K^+$. It also provides the best performance and background rejection for reconstructing neutrino events above 1 GeV, as encountered in long baseline neutrino oscillations. GLACIER is a novel design for a new generation double phase liquid Argon TPC presently being developed by a European-Japanese effort, aiming at a detector concept scalable up to at least 100 kton. Different detector locations are being considered at this stage: along the planned power upgraded KEK/J-PARC neutrino beam at Okinoshima (Japan) and in Europe along a new neutrino beam from CERN. A 17 kton single phase detector, like ICARUS, is being considered by the LBNE project in the US.

The three mentioned detector types represent a variety of complementary aspects (see also the table below):

- MEMPHYS would have the largest mass and collect the largest statistics.
- GLACIER would have the best pattern recognition and perform best for multi-GeV neutrino events from neutrino beams.
- LENA would have the lowest energy threshold and provide the best measurement of MeV neutrinos
- MEMPHYS and LENA are superior in anti-neutrino detection while GLACIER is best in neutrino detection. Neutrinos and anti-neutrinos together provide the full information to study supernovae.
- MEMPHYS has complementary sensitivity to LENA and GLACIER on proton decay flavour signatures
- LENA physics requires deep detectors, MEMPHYS can be shallower but needs large volumes.

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[1] Results from OPERA. T2K and reactor experiments (Double-Chooz, Daya Bay and Reno) will contribute in guiding the next steps worldwide in long baseline neutrino physics. Positive results from these experiments will signify the direct experimental proof of the fully 3x3 nature of the PMNS matrix and the correctness of its formalism to describe lepton flavor violation in nature. In this case, the coherent next step will be the proof of the complex nature of the mixing matrix via the measurement of the δ_{CP} phase and the determination of the neutrino mass hierarchy.

[2] We expect that most issues of solar physics will be covered by BOREXINO and SNO+ in the next years. What likely will stay unresolved is the detection of supernova relic neutrinos (item d) for which a next gene-ration scintillation detector appears to be the best option.

Physics potential of the 3 types of detectors for proton decay & neutrino astrophysics *

Topics	**GLACIER** (100 kt)	**LENA** (50 kt)	**MEMPHYS** (500 kt)
proton decay, sensitivity(10 years) $e^+ \pi^0$ anti-ν K^+ (**)	5×10^{34} 11×10^{34}	- 4×10^{34}	15×10^{34} 2.5×10^{34}
SN at 10 kpc, # events CC NC ES Elastic scatt. p	~ 38,500 1.6×10^4 (νe) 2.2×10^4 0.8×10^3 (e) -	~16,000 1.3×10^4 (anti-νe) 1.0×10^3 6.2×10^2 (e) 2.6×10^3 (p)	~250,000 2.5×10^5 (anti-νe) - 1.3×10^3 (e) -
Diffuse SN #Signal/Background events (5 years)	~50/30	~30/5	~60/50 (1 module with Gd)
Solar neutrinos # events, 1 year	^{8}B ES : 3.0×10^4 Abs: 1.0×10^5	^{7}Be: 3.6×10^6 pep: 1.0×10^5 ^{8}B: 2.9×10^4	^{8}B ES: 1.2×10^5
Atmospheric ν # events, 1 year	11×10^3	5×10^3	5×10^4
Geo-neutrinos # events, 1 year	Below threshold	1.5×10^3	Below threshold

A next generation underground observatory/observatories will be global in nature and follow worldwide coordination and cost sharing. LAGUNA, a common design study within the 7th European Framework Program (FP7), has been underway since 2008. It started by assessing the feasibility of seven pre-selected large European underground sites in Finland (Pyhäsalmi, up to 4 km m.w.e. depth) France (Frejus, 4.8 km m.w.e.), Italy (Umbria, 1.5 m.w.e.) Poland (Sieroszowice, 2.4 km m.w.e.), Romania (Slanic, 0.6.km m.w.e.), Spain (Canfranc, 2.1 km m.w.e.), United Kingdom (Boulby, 2.8 km m.w.e.) to host one or more instrumented tanks filled with liquids (water, liquid scintillator, or liquid argon).

The LAGUNA design study was focused on the underground cavern infrastructure, tank design and liquid procurement, at the expense of a sufficiently

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* some numbers strongly depend on model assumptions and give a qualitative rather than an exact quantitative comparison.

** this channel is particularly prominent in SUSY theories. Indications for SUSY at the LHC would boost its importance.

detailed detector design allowing a full relative costing exercise of the various options. The main findings of the design study are that:

a) all seven sites appear technically and environmentally feasible, though not all sites are interesting for all detector options,

b) it appears feasible to excavate the desired underground caverns and infrastructures, to build the necessary tanks underground, and to fill them with the liquids,

c) the cost of the excavation, although significant, is not the dominant cost of the project.
Studies indicate that some European options offer potential physics and/or technical advantages that need to be specially and carefully confronted with other options worldwide. The physics goals play a dominant role in selecting the site.

In order to proceed with the project, a better understanding of the costs of the full detector design and construction including their instrumentation for the three detector options is essential. This design study is therefore the next logical step beyond the very successful LAGUNA design study. After the completion of this phase (called LAGUNA-LBNO – from Long Baseline Neutrino Observation since it will also focus to neutrino beam options), all objective technical and costing information should be available. The prospects for LAGUNA-LBNO have increased the interest in the project compared to LAGUNA, which now includes members from Denmark, Finland France, Italy, Germany, Greece, Poland Romania, Spain, Switzerland United Kingdom, Russia and Japan, as well as CERN. This situation could naturally lead to a preparatory phase.

Recommendations: LAGUNA is the European effort to develop neutrino detectors on the "Megaton scale" both for accelerator-based and astroparticle neutrino measurements. The scientific goals are both broad and ambitious. The LAGUNA site study is almost completed, showing that there are possible sites in Europe that could host such experiments. The committee recommends that the study is pursued with LAGUNA-LBNO focusing on detector designs, in order to lead to a better understanding of the costs of the various detector technology options and on the prospects for a new long baseline neutrino beam from CERN. Due to the high cost and long development time necessary to realize this program, the committee recommends that it be pursued in a global context. It is also recommended that programs with and without a new neutrino beam are considered in order to preserve possible scienctific opportunities. ▪

In the context of long-baseline measurements of neutrino oscillations, of the detection of supernova burst neutrinos and of the search for proton decay, we also mention a further infill of the DeepCore detector nested in IceCube at the South Pole. A moderate infill of 15-20 strings would result in a threshold of ~1 GeV and might allow to measure matter oscillation effects that are sensitive to the neutrino mass hierarchy. A massive infill of 50-100 strings might lead to a 20 Megaton detector sensitive to supernova bursts from much beyond our own galaxy and possibly even to proton decay. **The committee encourages the ongoing Monte-Carlo studies** and related photo-sensor developments.

Neutrino astronomy would benefit from the measurements of nuclear cross-sections of astrophysical interest using underground nuclear accelerators. **We recommend therefore supporting the update of the ongoing programs with LUNA and follow-up projects at higher energy.**

The interpretation of current and future long baseline experiments depends highly on the detailed knowledge of neutrino-nucleus interactions. **Hence, the committee encourages more dedicated theoretical work in this field.**

Several anomalies in the neutrino sector and in cosmology have been noted over the last 15 years and generated increased interest in **sterile neutrinos** as a possible explanation. **This makes new experimental campaigns necessary, with the goal to either falsify the anomalies or indeed discover physics beyond the Standard Model.**

The ambitious activities discussed in this and the previous sections should be paired with an increased theoretical effort on predictions in these fields. (See Section 5). ▪

4. Dark Energy & Gravitational Waves

4.1 Dark Energy

The expansion of the Universe ought to be slowing down due to the collective mutual gravitational attraction of matter. However in 1998, observations of very distant supernova explosions (of type Ia) led to the conclusion that the expansion has been *accelerating* during the recent evolution of the Universe. The mechanism responsible for this acceleration has been named "Dark Energy" (DE) – it behaves like Einstein's Cosmological Constant i.e. has *negative* pressure, and appears to make up about ¾ of the energy density of the Universe. The Nobel prize for physics in 2011 has just been awarded for this momentous discovery, yet it is acknowledged that it has no physical explanation. Clearly, establishing the nature of DE and its place in the general theoretical scheme of physics is a research priority of the highest order. Today, basic questions about DE remain unanswered, for instance:

- Does dark energy really exist or is it an artefact of interpreting the observations in the framework of an idealised (perfectly homogeneous) cosmological model?

- Is the DE density in the universe really constant in time (as is expected for Einstein's Cosmological Constant)?

- If so, is this vacuum energy? Then how does one compute this vacuum energy in the context of a theory unifying gravitation and the quantum theory of fundamental interactions (the Standard Model or its extensions)? This is especially problematic since the naïve expectation is that the energy scale of the vacuum energy is the Fermi scale ($\sim 10^2$ GeV) or even the Planck scale ($\sim 10^{19}$ GeV), rather than $\sim 10^{-12}$ GeV as inferred from the cosmological data – this is the notorious as yet unsolved Cosmological Constant problem.

- If not, how did the evolution of DE impact on the history of the Universe?

- Does the existence of DE necessitate the introduction of a new particle-type field, or a revision of the theory of General Relativity, or both?

The scientific investigation of DE centres around two time-dependent properties of the evolving Universe: a scale factor $a(t)$ (linked to the red shift via $a(t) = 1/(1+z)$, $a(t_0)$ normalized to 1 at present time t_0) that describes the variation of distances in the expanding Universe as a function of time, and a *growth of structure parameter* $g(t)$ that describes deviations from an average density.

There are two basic "kinematical" approaches used for measuring $a(t)$:

Supernovae: the experimental programme consists of discovering large numbers of Type 1a supernovae at different redshifts, and measuring their apparent luminosities and redshifts. Their intrinsic brightness can be deduced from the data to within ±15%, so the ratio of apparent to intrinsic luminosity allows an estimate of the distance and therefore the time of the event in the framework of an assumed cosmological model, e.g. the standard homogeneous Friedmann-Robertson-Walker cosmology. Since $a(t)$ can be deduced from the red shift one can plot $a(t)$ vs t and measure the acceleration of the expansion rate of the Universe $(a(t) > 0)$.

Baryon Acoustic Oscillations (BAO): The early universe was a radiation-dominated hot plasma, and tiny statistical density fluctuations of overdensity propagated as acoustic pressure waves with a predictable velocity of $v = c/\sqrt{3}$, where c is the velocity of light. At decoupling (when the radiation ceased to interact with matter) the waves stalled. The time of decoupling has been measured in Cosmic Microwave Background experiments to be 379,000±8,000 yr, so the scale at which the waves stalled can be estimated to be $R_s = 147 \pm 2$ Mpc, serving as a "standard ruler" imprinted on the galaxy distribution. This standard size Rs subtends an angular size $\Delta\vartheta$ to an observer on Earth. The BAO method consists of measuring the position and red shift of tens of millions of galaxies; the angular distances between all pairs of galaxies at a given red shift exhibit an excess at the size $\Delta\vartheta$ of the "standard ruler". From this measurement the angular size distance DA can be inferred ($DA = R_s / \Delta\vartheta$). Since this "apparent" angular distance (which varies with redshift) depends on the expansion history (again, in the framework of an assumed cosmological model), it measures indirectly the cosmological parameters and provides information about the nature of DE.

However these data can also be matched in alternative cosmological models (e.g. the Lemaitre-Tolman-Bondi inhomogeneous cosmology) without requiring dark energy. Hence it is essential to find convincing dynamical effects of dark energy. Two other experimental methods measure both kinematical effects and theory related parameters through the measurement of $g(t)$:

Weak Lensing: Light from distant galaxies is deflected by intervening concentrations of mass, an effect known as gravitational lensing. In weak lensing the effect is not strong enough to produce separated images of distant objects, but merely distorts (shears) the image of the distant objects. This shear map can be constructed from observations of the shapes and red shifts of large numbers of galaxies, and provides a sensitive measurement of the intervening mass distribution. Measuring the mass distributions at a variety of redshifts (times) gives a measurement of $g(t)$.

Galaxy Clustering: Due to the attractive gravitational forces between them, galaxies form clusters. The presence of Dark Energy, with its repulsive gravitational effects, slows down this process. Thus, measurements of the number density, red shifts, and mass distribution of observed clusters provide another measure of $g(t)$. These studies often use the Sunyaev–Zel'dovich (SZ) effect to measure the angular position of the clusters. The SZ effect is a slight distortion of the CMB spectrum in the direction of the cluster, caused by the interactions of electrons of the gas in the cluster with the CMB photons. The effect is independent of redshift and thus the SZ information has to be combined with z measurements provided by an independent survey. An example of this complementarity is the foreseen collaboration between the South Pole Telescope (a SZ survey) and DES (a photometric redshift survey; see below). Another important test of DE is the 'late integrated Sachs-Wolfe (ISW) effect', which generates a secondary anisotropy in the CMB on large angular scales when DE comes to dominate. This is because the negative pressure of DE then halts structure formation through gravitational collapse so that the blueshift/redshift experienced by CMB photons when they pass through galaxy clusters (or voids) do not cancel. Accordingly the CMB should appear slightly hotter in the directions where there is more structure, and slightly cooler where there is less structure. To detect the ISW effect requires cross-correlating galaxy maps with maps of the CMB.

If dark energy is regarded as a relativistic "fluid", an attempt can be made to determine the relationship between its density ρ and pressure p. The relation $w = p / \rho$ is called the "equation of state" of dark energy and contains important information about its nature; it is often parameterised as $w = w_0 + w_a (1 - a)$, where w_0 is the constant term and wa characterizes its time dependence. If dark energy coincides with vacuum energy i.e. appears as a cosmological constant, then $w_0 = -1$ and $w_a = 0$. Thus measuring these quantities provides a test of the relationship of dark energy to vacuum energy, or any alternative theory driving time dependence.

The progress of the quality of the Dark Energy measurements is usually characterized by a Figure of Merit (FOM) defined as the reciprocal of the errors i.e. the area of the error ellipse in the equation of state parameters w_0 and w_a.

- The completed or underway ground based experiments are expected to yield a FOM of about 10.

- The projects in preparation are expected to produce a FOM in the vicinity of 50 to 100, in the next 5 years or so.

- The proposed future projects are estimated to produce a FOM of the order of 1,000 in the next decade.

These four experimental approaches have different strengths and weaknesses. A strong research program on DE needs experiments using all of these approaches since a) their systematic uncertainties are very different and a combination of results is required to reach reliable conclusions, b) the different methods exhibit different correlations between the cosmological parameters and the combined data can be used to increase the measurement precision, and c) a comparison of the results of the measurements of the growth of the scale factor $a(t)$ with the growth of structure $g(t)$ provides an important check on General Relativity (GR).

The role of astroparticle physics. The methodology used for dark energy studies is that of traditional astronomy, e.g. large surveys, photometry, spectroscopic methods, etc. Nevertheless, particle physicists were involved in DE investigations from the very beginning, motivated by its unquestionable theoretical importance, and also by the relevance of certain methodologies of particle physics (large arrays of sensors, importance of very precise calibrations, end-to-end simulations, large data sets). It has therefore become a field where the convergence of the two disciplines has provided a strong innovation factor.

Need for space missions? All of the projects that have been completed, are underway or are in preparation are using ground-based facilities, except for the projects using the Hubble Space Telescope. The generally accepted rule is that anything that can possibly be done from the ground should be done there because the costs associated with space-based efforts are very high.

The motivation to do space-based DE experiments is driven by the desire to trace the expansion history of the universe further back in time. In most models of DE, the dark energy component begins to dominate over non-relativistic matter at $z\sim1$. At these redshifts, the bulk of the light from the objects of interest is redshifted into the infrared (IR). The Earth generates IR backgrounds in ground-based experiments that are difficult to overcome. In contrast, space is cold, with IR backgrounds 4-5 orders of magnitude lower, making the required high redshift measurements possible. In addition, the much better resolution and the stable observing conditions due to the absence of the atmosphere allow for much smaller systematic uncertainties, which will be crucial for the next generation of precision measurements. For these reasons, space is advantageous. This should however be put in balance with the cost of space missions and the time needed to prepare one (usually 10 years or more). It is worth noting also that space missions in this field require complementary ground observations because of the need for a lot of photometry.

Among the projects completed or on-going) in which the astroparticle community participates, one may cite SN Factory, SuperNova Legacy Survey (SNLS), Canada France Hawaii Legacy Survey (CFHLS), Baryon Oscillation Spectroscopic Survey (BOSS, part of the Sloan Survey). Among the proposed future projects, some are focussed on astronomical issues, but would contribute to DE studies in any case. One may cite: Pan-STARRS-4, a combination of four large optical/near-IR survey telescopes to be sited on Mauna Kea in Hawaii; the Square Kilometre Array (SKA), a proposed radio telescope with a collecting area of order 1 km^2 capable of operating at a wide range of frequencies and angular resolutions; IXO, a large X-ray space observatory; the Extremely Large Telescope (ELT), a 30 m-class telescope with optical/near-infrared capabilities. In space, the James Webb Space Telescope (JWST), a 6.5 m deployable space telescope, would be useful for many types of dark energy studies including supernovae, clustering, and weak lensing at high redshift.

In the following paragrpahs, details are provided for the most important future projects in which Europe is (or may be) a stakeholder.

Description of present and proposed future projects

The Dark Energy Survey (DES) Collaboration is a project to build, install and operate a new 519 megapixel CCD camera (the Dark Energy Camera) to be mounted at the prime focus of the Blanco 4m telescope at the Cerro Tololo Inter-American Observatory (CTIO) located in La Serena, Chile. The scientific objective of DES is to measure the DE equation of state parameter, w, with four complementary techniques (redshift distribution and clustering evolution of galaxy clusters, weak gravitational lensing on large scales, evolution of large-scale structure including baryon acoustic oscillations and Type Ia supernova distances). To achieve these goals, DES will operate DECam for 525 nights over 5 years (roughly 30% of the observing time) beginning in FY12 and carry out two surveys: a wide-area survey of ~300 million galaxies over 5000 square degrees and a time-domain survey over tens of square degrees to discover and measure light curves for several thousand supernovae. The precision achieved should result in an improvement of a factor of 4-5 in the figure of merit (presently around 10, as discussed above). Since clusters and weak lensing are sensitive to the growth of structure, while BAO and SNe are sensitive to expansion history, the combination of probes will constrain modified gravity theories, in which the relation between perturbation growth and expansion history is altered from General Relativity.

DES has assembled an international collaboration of 120 scientists, including groups from UK (optical corrector), Spain (camera electronics) and Germany (data reduction). In addition to the DOE and NSF in the USA, the European funding agencies involved are the UK Science & Technology Facilities Council, the UK Science Research Infrastructure Fund, the Astronomy & Astrophysics program of the Ministry of Science & Innovation in Spain, and the German Science Foundation's Excellence Cluster "Origin and Structure of the Universe".

During 2011, construction of DECam will be completed in stages, and components will be installed on the telescope. Commissioning was carried out at the end of 2011, followed by early science operations. Normal survey operations will commence mid-2012 and are expected to continue through 2017. The total estimated cost of DES is 45 M$ (with a European share amounting to 5 M€).

LSST, the Large Synoptic Survey Telescope envisions a newly constructed 8.4m ground based telescope and a 3 Gigapixel CCD camera combined with rapid slewing and readout enable imaging of the entire seasonally available sky (20,000 square degrees) every three clear nights in six colours. The images may be examined individually for transient phenomena such as supernovae, or summed to produce deep images suitable for cosmic shear and galaxy-cluster surveys. Coverage from 320-1,080 nm will allow LSST to push ground-based CCD observing to its limits for dark energy studies and a wide range of astrophysical investigations, from near-Earth asteroids to high-redshift gamma-ray bursts.

LSST will discover and measure the shapes and photometric redshifts of over 3 billion galaxies in the redshift range $0.5 < z < 3$, and use this data to measure cosmic shear. The LSST galaxy data will also be used to execute the BAO probe using the photo-z technique. LSST imaging will discover enormous numbers of Type Ia supernovae. As there is no spectroscopic component to the LSST program, precision redshifts and spectral diagnostics will require other resources. LSST light curves for SNe (~30,000 per year) will be of high quality. This data set will enable detailed studies of SN diversity, which will be of value to other dedicated SN studies using spectroscopy or imaging. The overall figure of merit is expected to be some 10 times larger than for DES.

The LSST data set will permit real-time investigations for studying variable objects. In time-domain studies, LSST's specific goals include mapping of near-Earth objects, supernovas, gamma-ray bursts, variable stars, and high-energy transients. Its archival science will include mapping the Milky Way and the distant universe, creating an accurate photometric and astrometric data set, studying stellar kinematics and performing a census of the solar neighbourhood. Another goal of interest for the high energy community is the determination of the sum of neutrino masses.

The LSST project involves a large collaboration of scientists - both astroparticle and astro-physicists. The instrument and data processing plans are advanced - the primary/tertiary and secondary mirrors have been cast and a Chilean site selected – using private and preliminary agency funding. The estimated cost is 465 M$, with operation costs of 42M$/yr. The bulk of the funds for construction and 10-yr operations are sought from NSF, DOE, international research agencies and private donors. In Europe, only the French community is involved in this project at this point but there are discussions in other countries for further involvement. First light is expected in 2020, with science runs starting in 2022 for 10 years.

Spectrographic surveys:

BigBOSS is a proposed ground based spectroscopic Baryon Acoustic Oscillation experiment to be installed on the 4 m Mayall telescope at Kitt Peak National Observatory. The BigBOSS instrument consists of three major components: (i) an optical corrector that provides a 3 degree diameter field of view at the Mayall prime focus; (ii) a focal plane with 5,000 fibers, each controlled by an independent robotic actuator; (iii) ten identical spectrographs, each viewing 500 fibers and covering the wave-length range from 460 to 1040 nm with a resolution of $R = \lambda / \Delta\lambda = 3000 - 4800$. In addition, the BigBOSS project includes a data pipeline and archive to make processed spectra and redshifts available to the community.

BigBOSS will survey a comoving volume that is 10 times larger than that covered by BOSS, the experiment at the 2.5 m Sloan telescope in New Mexico, and will measure redshifts for almost 20 million galaxies (fifteen times more than BOSS). The BigBOSS targets are luminous red galaxies (LRGs) and emission line galaxies (ELGs), both selected from current and planned imaging. LRGs are observed up to a redshift z=0.9 while ELGs are detected up to z=1.7 through detection of the bright [OII] emission line doublet at a rest frame wavelength of 3727 Angstroms. BigBOSS will more than double the BAO FOM over the combined power of all predecessor experiments, achieving an accuracy on the angular diameter distance of 0.4% for $0.5 < z < 1.0$ and 0.6% for $1.0 < z < 1.7$. In a multiyear survey a sample of 30x106 galaxies will be observed out to z~2. In addition, a large number (600,000) of quasars with redshift z>2.2 will be observed and used as backlights for intervening large scale structure as revealed in the absorption features in the Lyman-alpha forest.

The BigBOSS collaboration includes consortiums from France and the UK, and there are some collaborating institutions in Spain. The French will be responsible for the spectrograph design and fabrication, the UK group has expertise in the design and fabrication of large optical elements, and the Spanish group has experience in focal plane design and fabrication.

The Subaru Measurement of Images and Redshifts (**SuMIRe**) survey is being designed for the Subaru 8-m telescope at Mauna Kea. It would have a field of view of about 1.5 degrees, and the capability to simultaneously obtain spectra for about 20,000 objects/night. A redshift range of $0.6 < z < 1.7$ for emission-line galaxies will be targeted, and $2.3 < z < 3.3$ for Lyman-break galaxies. Its primary goal is to measure BAO, as well as to measure thousands of SNe Ia.

Discussions are being held presently to join efforts with the US-led WFMOS (Wide-Field Multi-Object Spectrograph) collaboration, which did not receive approval to be placed at the focal plane of the GEMINI telescope. The cost estimate from WFMOS is 68.5M$, 16.5M$ being already available through Japanese funding. Discussions are being held with US, Brazilian and European groups to complete the funding.

Space missions:

EUCLID is a European project led by ESA to study DE using weak lensing and BAO. The baseline payload consists of a Korsch telescope with a primary mirror of 1.2 m diameter designed to provide a large field of view (0.5 deg^2) to an imaging instrument with a visible channel, a NIR imaging channel and a NIR spectroscopic channel. The first two support the weak lensing probe, whereas the third is designed to perform the wide spectroscopic galaxy survey.

EUCLID's main goals are:

- Measuring the DE equation of state parameters w_0 and w_a, respectively, using both expansion history and structure growth (the figure of merit should reach 1,500 for the Euclid-Planck combination).

- Measuring the growth factor exponent γ (where growth of structure rate $g(t)\ a(t)^\gamma$) with a precision of 2%, enabling to distinguish the predictions of General Relativity from modified-gravity theories

- Testing the Cold Dark Matter paradigm for structure formation, and measuring the sum of neutrino masses to better than 0.04 eV when combined with Planck.

Combined with the Planck data, this should lead to an improvement by a factor of 20 in the determination of the cosmological parameters compared to Planck alone.

EUCLID is currently one of the 3 M missions planned for 2019-20, a downward selection step to only two missions occurring in 2011. Its cost is evaluated at 500 M€ plus some 200 M€ paid by member states for the scientific payload (and 170M$ for NASA, who is a junior partner at the 20% level). It should be noted that there will be significant need for ground-based photometry (agreement with Pan-STARRS and DES, and potentially with LSST). EUCLID has just been approved by ESA for launch in 2019, with a 5-year nominal lifetime.

WFIRST first appeared in the report of the US Decadal survey in summer 2010. WFIRST is a 1.5-meter telescope that will orbit the second Lagrange point (L2), 1.5 million km from Earth, providing a wide-field-of-view near-infrared imaging and low-resolution spectroscopy observatory. It will image the sky at near-infrared wavelengths and perform low-resolution infrared spectroscopy. The mission concept is inspired from the one of the JDEM (Joint Dark Energy Mission) proposed earlier.

WFIRST will address two of the most fundamental questions in astrophysics: Why is the expansion rate of the universe accelerating and are there other solar systems like ours, with planets like Earth? In addition, WFIRST's surveys will address issues central to understanding how galaxies, stars and black holes evolve. To measure the properties of dark energy, WFIRST will employ three different techniques: it will image about 2 billion galaxies and carry out a detailed study of weak lensing that will provide distance and rate-of-growth information; it will measure spectra of about 200 million galaxies in order to monitor distances and expansion rate using baryon acoustic oscillations; and finally, it will detect about 2,000 distant supernova explosions, which can be used to measure distances.

The Decadal Survey estimated the cost of WFIRST to be around 1.6 B$, with a time from project start to launch of 82 months and recommended a prompt start (2013). Given the delays in the JWST program, NASA responded by delaying WFIRST and recommending in the meantime a junior participation (20%) to the ESA-led EUCLID mission which, however, was not considered timely by the US community.

Setting priorities

The projects described above do not need to be prioritised by this Committee. First, one may note that the leadership of all ground projects lies outside Europe. Second, the timing and funding status of these projects is different: DES is funded and will be the main project of the years 2012-2016; LSST was recognized by the US Decadal Survey as the top priority among the large ground projects and will thus be a priority of NSF and DOE in the coming years. BigBOSS and SuMIRe have a different funding status: the first one has just started applying for funds, whereas the second one is searching funds to complement those that it already has. It is unclear what will be the future of either project, but it is clear that a significant European participation to either of them would enhance their chances.

As for the space projects, Euclid, the mission with European leadership will most probably be the first mission ready for launch at the end of the decade. We should know within a few months whether WFIRST is indeed postponed because of the important cost overrun of JWST. If it is so, WFIRST might be the relevant space mission of the 2020 decade in case a departure from a cosmological constant is detected on the ground or in space. It should also be stressed that the hardware cost of space missions is entirely covered by space agencies (by ESA or the European national agencies). Research agencies only contribute to R&D as well as personnel costs.

Recommendation for Dark Energy projects: The SAC welcomes the participation of the European astroparticle physics community in experiments in this field. This community should ensure that it can participate in the harvest of results from the presently planned ground-based projects and should also exploit the unique chance for leadership in space with the ESA-led EUCLID mission. ▪

4.2 Gravitational Waves

Gravitational Wave (GW) science is on the verge of direct observation[3] of the waves predicted by Einstein's General Theory of Relativity, thus inaugurating the new field of Gravitational Wave Astronomy.

Gravitational wave detectors will study sources characterised by extreme physical conditions: strong non-linear gravity and relativistic motions, very high densities, temperatures and magnetic fields. In the coming decades, arrays of ground-and space-based instruments could observe the gravitational wave sky. This new window into the cosmos has the potential to truly revolutionize the understanding of the Universe. Below are just some of the key scientific questions to which answers will be sought:

- **fundamental physics:** What are the properties of gravitational waves? Is General Relativity still valid under strong-gravity conditions? Are nature's black holes the black holes of General Relativity? How does matter behave under extremes of density and pressure?
- **cosmology:** What is the history of the accelerating expansion of the Universe? Were there phase transitions in the early Universe?

- **astrophysics:** How abundant are stellar-mass black holes? What is the mechanism that generates gamma-ray bursts? What are the conditions in the dense central cores of galactic nuclei dominated by massive black holes? Where and when do massive black holes form, and what role do they play in the formation of galaxies? What happens when a massive star collapses? How do compact binary stars form and evolve, and what has been their effect on star formation rates?

Gravitational waves should propagate essentially un-attenuated across a wide range of frequencies, from 10^{-17} Hz for ripples in the cosmological background associated with inflation, up to 10^{3} Hz when neutron stars or black holes are born in supernova explosions, and even 10^{10} Hz for cosmological backgrounds associated with phase transitions at the grand unified scale. GW sources of great astrophysical interest exist within this range, including black hole and neutron star interactions and coalescences, ultra-compact binary stars and rotating asymmetric neutron stars such as pulsars. Because of the very weak nature of gravity, detection is most likely for radiation emitted by astrophysical systems in which very large masses undergo strong accelerations.

Earth-based and higher frequency detectors

The search for gravitational waves began in the 1960s, using large instrumented masses that were expected to vibrate in an observable way due to the passage of a gravitational wave. The last decades have seen a shift in the dominant technology to long baseline laser interferometry. The first generations of large gravitational wave interferometers have been and are being operated. These ground-based km-scale laser driven interferometers of the Michelson type, and their advanced upgraded versions, will be critical in establishing the field of gravitational wave astronomy through the detection of high luminosity gravitational wave sources such as the merger of binary neutron stars and black holes.

In the U.S., the Laser Interferometer Gravitational-wave Observatory (LIGO) consists of three multi-kilometre scale interferometers, two in Hanford,

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[3] Gravitational waves have yet to be observed directly, but strong indirect evidence was obtained in 1974 by R. Hulse and J. Taylor. They measured a decline in the orbital energy of a binary pulsar, presumably due to intense gravitational radiation. For this ingenious work, they were awarded the Nobel Prize in 1993.

Washington, and one in Livingston, Louisiana. In Europe, Virgo is a multi-kilometre scale interferometer located near Pisa, Italy, and GEO600, a 600-m interferometer, is located near Hannover, Germany. The TAMA detector near Tokyo is 300 m in size, whereas CLIO, an advanced 100-m interferometer in the Kamioka mine, has recently demonstrated interferometry with cryogenic mirrors. In order to make the most out of the presently available detectors, the GW community has now established a closely connected network between the gravitational wave antennas in Europe and in the U.S.A, with coordinated data-taking, immediate sharing of data and co-signature of publications.

Major upgrades of LIGO (**Advanced LIGO**), Virgo (**Advanced Virgo**) and GEO600 (**GEO HF**) have been started and will be completed in the next five years. It is expected that the first direct observation of gravitational waves will be made in the next few years by this international network of 2nd generation detectors.

The next step would be to pinpoint the sources on the sky and to extract all the information about each source's behaviour encoded in the gravitational wave signal. To carry this out, a true global array of gravitational wave antennae separated by inter-continental distances would be required. Such a network would improve source location to or below that needed for wide-field electromagnetic telescope to be able to perform effective follow-up and can result in better sky coverage and improved signal to noise ratio.

In the medium term this would be achieved by adding further detectors with appropriately chosen intercontinental baselines and orientations to maximize the ability to extract source information. The most advanced plans along these lines are with the Japanese Large-scale Cryogenic Gravitational-wave Telescope (**LCGT**), recently approved in order to participate in the first direct observation, and the Australian International Gravitational Observatory (AIGO). Further, possibilities for a detector in India (INDIGO) are also being studied.
The state of the art detectors can currently detect a ripple of space with 10^{-22} relative sensitivity, able to monitor cataclysmic mergers or explosions up to 20-25 Mpc away. The next generation would reach sensitivities of 10^{-23}, able to monitor cataclysmic mergers or explosions up to 250 Mpc away. The network of detectors exhibiting this sensitivity (2nd generation or advanced concept) would be in principle able to observe gravitational wave signals at a monthly or even weekly rate from compact coalescing binaries. Following first detection and extraction of information from the network of ground based advanced detectors existing then, or from space or astronomical observations, the aim would be to move to third generation detectors, probing Gpc scales and cosmological distances, thus fully realizing the gravitational wave astronomy potential.

Successful deployment of third generation, underground gravitational wave observatories would require development of a number of new technologies by the gravitational wave community. Many of the necessary R&D programs are undertaken in a limited number of places, but with a growing level of coordination and communication. The proposed Einstein Telescope (**ET**) is an advanced concept for a wide band underground observatory with significantly improved sensitivity over that of planned advanced detectors, especially in the low frequency range.

The ET conceptual design study, funded by the European Union, demonstrated the feasibility of a 3rd-generation GW observatory, with a significantly higher sensitivity, especially below 10 Hz, due to an underground location. The ET cost estimates are strongly depending on the site location and on the soil characteristics, but the rough estimation performed in the ET design study confirmed the feasibility of the ET infrastructure at costs of the order of 800 M€. The realization of third-generation antennas would be triggered by the first detection of GWs expected around 2017-2018, and scientific data would start being available in the second half of the 2020s.

The ET project has as its goal the realisation of a Research Infrastructure, (in the meaning adopted by the European Commission of an infrastructure that will allow European scientists to «use» a «facility») with a lifetime of decades, allowing forefront astrophysics, fundamental physics and astronomy to be carried out, via the study of gravitational radiation from astrophysical sources. The concept is to realize first the required site infrastructure, then to implement the detector hardware. This *modus operandi* is not uncommon; in fact the LCGT project in Japan is currently readying an underground site and a first-stage room temperature detector, with cryogenics to be implemented subsequently.

The creation of the ET observatory in a manner consistent and integrated with the capabilities of the European scientific field currently engaged in the installation and commissioning of Advanced GW detectors is possible via the specific nature of the ET project.

The focus for the first 6-7 years (2015-2022) is on the infrastructure: (1) underground site, (2) vacuum infrastructure and (3) cryogenic facilities.

The engineers involved in (1) are to a large extent from a different manpower pool than the scientists involved in advanced detectors. Underground facility specialists will be required, working on the technical design of the infrastructure 2014-2017, and then on the excavation activities (2018-2022).

The engineers and the scientists involved in (2) and (3) are involved at the periphery of efforts for Advanced detectors and mainly in the early years (to implement the needed additional vacuum chambers and cryo-traps). The timing is thus compatible (-2014 for advanced detectors; 2015-20 design of ET vacuum facilities; 2021-23 vacuum & cryogenic plant installation. Larger manpower dedicated to ET in terms of interferometer experts, will be needed only starting from around 2018. However this core team of physicists will be active throughout the period 2011-18, with an emphasis able to shift smoothly onto relevant hardware and commissioning efforts via the philosophy outlined above, of an infrastructure designed to stand for decades housing hardware which progressively evolves toward a design achieving the ET sensitivity goal.

The program timing could be considered as being close to optimal in the sense that the expertise gained in the construction and commissioning of the advanced detectors can smoothly be steered towards ET and without a large gap in between where key skills might be lost.To enable this program, support for the key R&D activities is needed in the next 7-10 years to develop the technologies that are not shared with advanced detectors, like cryogenic optics and mechanics, new lasers, gravity gradient noise suppression. Cryogenic issues, for example, show important common points between ET and LCGT (For this reason a 4-year scientist exchange program between the two projects has been proposed and positively evaluated by the European Commission, under FP7-People (IRSES): ELiTES. It should be operative from March 2012.

These measurements on the ground and underground could be complemented by very long baseline (5 million km) space interferometers as is the case with the proposed mission LISA, the Laser Interferometric Space Antenna.

Space-based detectors

LISA, a space-based interferometer would open the low-frequency gravitational wave window from 0.1 mHz to 0.1 Hz. The scientific objectives of space-based and ground-based instruments are complementary in the same way that optical and x-ray astronomy are complementary and have provided information about different types of astrophysical objects and phenomena. LISA is the gravitational wave community's priority for a space-based mission, with an earliest launch in the early 2020s, provided that the technology precursor mission LISA Pathfinder, to be launched in 2014, would fulfil its technological goals.

The original LISA project involved an equal share between ESA and NASA. The present financial situation of NASA prompted ESA to consider a reduced mission in a Europe-only context. The new LISA mission is now being considered in the context of the "Cosmic Vision", with a cap cost of around 1.2 billion Euro and an estimated launch date around 2022. Decisions to go ahead with phase-A studies will be made in this context for all large missions under consideration by ESA in February 2012, with a final selection in 2014.

The scientific programme of the new LISA mission retains much of the original mission. LISA will record the inspirals and mergers of binary systems or supermassive black holes, the most powerful transformations of energy in the Universe. It will map isolated black holes with high precision, measuring their mass and the three components of their spin. It will directly observe how massive black holes form, grow and interact over the entire history of galaxy formation. Finally, LISA will study in detail thousands of compact binary stars in our Galaxy, providing a new window onto matter at extreme conditions.

The portion of the gravitational wave spectrum lying between the LISA band and that probed by ground-based interferometers also holds great potential, including observation of coalescences of intermediate black hole binaries and some of the deepest searches for stochastic backgrounds. The DECI-hertz Interferometer Gravitational wave Observatory (DECIGO) is a space gravitational wave antenna proposed in Japan, aiming for launch several years after LISA. In the longer time frame, the Big Bang Observer is targeted at detecting the gravitational waves produced in the big bang and other phenomena in the early Universe.

We finally note that there is also a growing effort to utilize radio astronomy for the detection of gravitational waves in the nano-hertz frequency band with the formation of the International Pulsar Timing Array (IPTA) collaboration. There are currently projects in North America (NANOGrav), Australia (Parkes Pulsar Timing Array) and the European Pulsar Timing Array having or requesting access to the world largest radio telescopes. Search for primordial gravitational waves is also included in the scientific program of CMB detectors like the Planck satellite through the measurement of polarization anisotropies of the cosmic microwave background.

Recommendations for gravitational waves: The committee recommends the move of the international gravitational wave community towards a single worldwide network of ground interferometers which will allow better coverage and better pointing capabilities. This also goes in the direction of increasing the community worldwide.

At a time of down selection of the large mission of the ESA Cosmic Vision program, the community renews its strong support of the LISA program which will open the scientifically challenging domain of low frequency (10^{-4}Hz, 10^{-1}Hz) gravitational wave astronomy, as well as advance our knowledge of fundamental physics.

The committee acknowledges the progress of the Einstein Telescope Design Study, supports a new proposal for coordination actions for ET and encourages ASPERA/ApPEC to take steps for a future inclusion of ET into the ESFRI list.

The committee supports an enhancement of the R&D effort in order to accompany the development of the second generation network and to prepare for the third generation (ET). For this purpose, we propose an ASPERA call for R&D. ▪

5. Transversal activities

The activities addressed in this section are of importance to all of the subfields described in the previous sections. The importance of theoretical studies has been mentioned occasionally and is highlighted here again with respect to all subfields.

Theory

Even more than for experimental astroparticle physics, the distinctions between particle physics, cosmology and astrophysics have been blurred for theory. Theory often motivates experimental projects, links distinct sub-fields of astroparticle physics, and is indispensable for the interpretation of experimental results. In parallel with the ambitious plans for the next-generation astroparticle experiments in Europe, the associated theoretical activities – apart from project-specific analysis and computing activities – need stronger support and coordination. Predictions for specific dark matter candidates, calculation of proton-decay rates, assessment of the uncertainties in predictive theories, an improved understanding of supernova neutrino emission and the diffuse flux of supernova neutrinos, continued research in solar physics, updated studies of atmospheric neutrinos and relevant cosmic-ray physics, charm production in atmospheric neutrinos, geological and geophysical aspects of geo-neutrinos – all these activities are of vital relevance for the big experiments that are going to be built and to the ability to answer big questions in cosmology, particle physics and astronomy. As examples for the need of coherent actions, which we already highlighted in the 2008 roadmap, the assessment and reduction of the uncertainty of nuclear matrix elements for double-beta decay experiments, the interpretation of cosmological data and their relevance for dark matter and dark energy, the modelling of high-energy processes in violent environments and the connection of the activities in our field with the exciting prospects of particle physics in the LHC era, should all be mentioned.

Research and Development

Technological innovation has been a prerequisite for the enormous progress made over the last two decades and has enabled maturity in most fields of astroparticle physics. The astroparticle programme calls for better and cheaper solutions for all of the ubiquitous detectors and materials for astroparticle physics. Electronics and data acquisition are challenged by the need to instrument huge areas or volumes with sophisticated, often autonomous sensors. On the computing side, the treatment of large amounts of experimental data requires Grid- and Cloud-type solutions, as do computer simulations, for instance of extensive air showers or of cataclysmic cosmic events. We welcome the ASPERA common calls for joint funding of research and development. These calls also stimulate cooperation with industry, which has been and will be a strong element in developing cutting-edge technology and for transferring innovative developments to practice. We suggest that about 20-25% of astroparticle funding should be reserved for small initiatives, R&D and small-scale participation in experiments with non-European leadership.

Relation to other fields of science

Our research is primarily directed to basic questions of particle physics, astrophysics and cosmology, but has relations to other fields of science through advanced technologies and infrastructures. Numerous examples have been impressively presented at the December 2010 Workshop “From the Geosphere to the Cosmos” in Paris. They range from marine sciences, early earth quake warning, climate and weather studies and glaciology to the application of high technology developed for basic science in medicine, biology and other sciences. We encourage our colleagues to seek the cooperation with communities from applied sciences, not only for the benefit of the results in applied science, but also to broaden the scientific community behind the huge-scale projects of astroparticle physics.

Education and Outreach

The questions of astroparticle physics address very fundamental questions, like the origin and nature of matter, energy and the Universe. They challenge the imagination and curiosity of a broad audience. The cutting-edge technology and the sometimes remote, exotic locations add another factor of fascination. This makes astroparticle physics an ideal tool to get laymen interested in basic science. For the same reasons, an increasing number of young researchers with brilliant new ideas are motivated to join the field. The number of university positions on astroparticle physics has been continuously increasing over the last decade, reflecting not only the growing importance of the field, but also a growing pool of excellent young researchers challenged by its questions. The support of activities in education and outreach are therefore of growing importance for society and for the future of basic research. ■

Appendices

A.1

Charge to the Science Advisory Committee

Terms of reference of the Scientific Advisory Committee

The main task of the Peer Review Committee (2006-2009) that prepared the Strategy for Astroparticle Physics in Europe was to:

- identify the major questions of the field

- demonstrate its unity despite the diversity of infrastructures deployed,

- identify the major infrastructures that the were necessary for the advancement of the field,

- give a semi-realistic budgetary and human resources plan.

Concerning the last point, it was of course not possible to go through an exhaustive examination of the claims of calendar, the resources needed etc. Nevertheless an aposteriori renormalisation was applied to enforce adequacy between traditional funding of the field and project demands. This gave the well known budget calendar with a 50% integrated increase over the next 10 years when compared to a flat projection of the 2007 expenses.

Since the publication of the European Strategy, and sometimes because of it, many new developments happened, technical design studies are published or are in progress, new scientific results, international roadmaps (especially in the US) are coming along, first decisions of funding are taken and also agency meetings are about to start.

The terms of reference of this Scientific Advisory Committee, which will work for a year (till spring 2011) will be:

- update the roadmap with new, more detailed information on the projects (essentially the Magnificent Seven)

- include considerations on dark energy, space projects and promising R&D

- address issues of critical R&D in view of the large projects of the roadmap and issues of procurement (from photomultipliers to rare isotopes)

- identify the major milestones and decision turning points with respect to the maturity of technologies and/or expected scientific results.

- discuss the site issues and the constraints they impose on the timescale

- take a critical look on budget and calendar claims concerning the large projects

- take into account international developments and represent the European scientific community opinion in the global coordination process happening in the context of the Global Science Forum working group of the OECD on Astroparticle Physics. In particular, address the issue of what is the minimal number of large projects of the same sub-domain that are scientifically justified on a global scale? Conversely, are there projects whose scale demands interregional/global coordination and/or cooperation and what actions should be taken in this context?

For the ApPEC Steering Committee and ASPERA Joint Secretariat:

Stavros Katsanevas ▪

A.2

The 2008 ASPERA Roadmap

In the previous ASPERA roadmap from autumn 2008, seven types of strategic projects were defined which later were christened *"The Magnificent Seven"*. With phased time profiles, that Roadmap Committee proposed:

- **Cosmic rays:** A large array for the detection of charged cosmic rays in the northern hemisphere (Auger North)

- **Gamma rays:** A large array of Cherenkov Telescopes for detection of cosmic high energy gamma-rays (CTA)

- **High energy neutrinos:** A cubic kilometre-scale neutrino telescope in the Mediterranean (KM3NeT)

- **Dark matter search:** Ton-scale detectors which probe a large part of the parameter space of Minimal Supersymmetric Models (i.e. reach a sensitivity range of 10^{-44} cm for the spin-independent cross section)

- **Neutrino-less double beta decay:** A ton-scale detector for the determination of the fundamental nature and mass of neutrinos with the goal to test inverted hierarchy scenarios.

- **Proton decay and low-energy neutrino astrophysics:** A Megaton-scale detector for the search for proton decay, for neutrino astrophysics and for the investigation of neutrino properties

- **Gravitational waves:** A third-generation underground gravitational antenna (E.T.)

The Roadmap also supported Earth and space based missions to explore dark energy, the concept of a cooperative network of deep underground laboratories, common calls for innovative technologies in the field of astroparticle physics, efforts to intensify the synergy with environmental sciences and the formation of a European Centre for Astroparticle Theory.

Starting from the initial cost and profiles supplied by the experiments, the 2008 Roadmap Committee had looked at possibilities for phasing and cost reduction by inter-continental cooperation. It defined milestones to decide which experimental method in any of the sectors "dark matter search", "double beta decay experiments" and "large multi-purpose detector underground" should get priority or how competing methods might be combined. Cost reductions appeared possible in all fields. For some projects a rich scientific harvest would be guaranteed even with slightly reduced capabilities. For others, any compromise in capabilities would jeopardise the success (for instance the observation of point sources in the case of KM3NeT or Auger North). The committee assumed that not all of the available budget should be spent on the flagship projects, but 15-20% should be reserved for small initiatives, participation in overseas experiments with non-European dominance, and R&D. The committee found that the plans fitted into a scheme where the funding for investment had to increase by 70% (or extra 350 M€) over the traditional funding (500 M€) integrated over the next 7 years. The estimated increase in the sum for personnel costs was much smaller. ■

A.3

From 2008 to 2011

We were – and continue to be! – convinced that the prospects of astroparticle physics merit a factor of 2 increase in budgets over the next decade. On the other hand we are aware that funding realities in most countries have become more challenging. An aggressive “factor-2 pressure” appears presently to be beyond realistic expectations. Instead, we propose to proceed with the most advanced projects as fast as possible and to exploit their discovery potential. Their expected successes will then hopefully translate into additional momentum for the remaining priority projects.

The SAC is also aware, that research priorities will differ from country to country, depending, e.g., on their local infrastructures, or on their traditions and historically grown strengths in particular fields. The SAC ranks scientific arguments highest but at the same time keeps in mind that there are also historical and political aspects. We are careful not to define priorities in such a way that they might limit the phase space of national funding agencies for substantial, positive funding decisions, once such possibilities for a certain project may appear on a national level.

We emphasize the strong progress at several fronts during the last 2.5 years. To mention a few:

- **Cosmic rays:** The AMS detector has been launched in May 2011. Several successors of KASCADE-Grande have been completed in 2010 (Tunka-133, IceTop) or are being installed as low-energy extensions of the Pierre Auger Observatory. A small but significant anisotropy of TeV cosmic rays on large and medium angular scales, reported earlier by the Tibet air shower array, Super-Kamiokande and the Milagro experiment, was confirmed by ARGO/YBJ in 2008 and by IceCube in 2009. TRACER has provided boron-to-carbon measurements up to almost 10^{14} eV. The Pierre Auger Collaboration firmly established the high-energy depression of the flux spectrum and obtained interesting results on the composition at the highest energies. On the negative side, two high-ranked US committees did not prioritize Auger North, therefore US funding agencies will not give funding to the Colorado site. As a consequence, a new proposal for a next generation observatory with considerably enlarged area is envisaged. This requires 3-5 years of preparation.

- **Gamma rays:** A huge number of new sources have been detected by H.E.S.S., MAGIC and VERITAS. MAGIC-II started stereoscopic operation. The CTA collaboration has formed and meanwhile includes all relevant players in the world. The project made it to the ESFRI list, and the construction of prototype telescopes has started. Construction of the wide angle detector HAWC in Mexico (US/Mexico) has started. China is planning a new high altitude air shower array (LHAASO).

- **High energy neutrinos:** IceCube with its low-energy extension was completed in December 2010 and shows excellent performance. The KM3NeT technical proposal has been finalized.

- **Dark Matter:** The experiments XENON100, EDELWEISS and CDMS have improved the sensitivity of dark matter searches with a gradient which eventually appears to be as steep as optimistic extrapolations ten years ago suggested. Construction of a 1ton XENON detector is under preparation. EDELWEISS and its US counterpart CDMS have advanced to common publications and discuss other measures of convergence (common procurement and compatibility of cryostats for exchange and/or merging of detector elements). The DAMA/LIBRA experiment continues data taking with a lower threshold and confirms an annual modulation of the signal. Hints for such a modulation area also reported from the American CoGENT experiment.

- **Neutrino-less Double Beta Decay:** The first detector of the new generation double beta experiments, GERDA, is in its commissioning phase. CUORE-0, the first CUORE tower, will be assembled and cooled down in 2011.

- **Low energy neutrino astronomy:** BOREXINO in the Gran Sasso Laboratory LNGS shows excellent performance and has detected not only solar neutrinos but also geo-neutrinos, with a much smaller background from reactor neutrinos than KamLAND (Japan). The ICARUS detector in LNGS eventually started full operation and proves the feasibility of operating large liquid argon detectors underground. The E7 design study LAGUNA is completed and the follow-up study LAGUNA-LBNO was positively evaluated.

- **Gravitational Waves:** Advanced VIRGO and Advanced LIGO perform as a single antenna. Their advanced phase has been approved. The E7 Design Study ET has been completed. There is now a worldwide effort to develop an array of ground interferometers (Europe, US, Asia and Australia) demonstrated by the GWIC roadmap.

- **Dark Energy:** The project Supernova Legacy Survey has published results that give currently the most precise determinations of the parameters of the equation of state of dark energy. With the ESA mission Euclid, Europe is now taking the lead for the study of dark energy from space. ▪

A.4

Compilation of detailed recommendations from the individual chapters

We summarize in the following the recommendation given in sections 2-4.

Galactic Cosmic Rays: **We reiterate the suggestion of the 2007 roadmap, that efforts be directed to achieve an overlap between present direct and air-shower detection methods in order to get a better understanding on the mass composition and spectral hardening of cosmic rays. This goal may be pursued with large-aperture, long duration flight missions above the atmosphere (balloons/satellites) and by ground detectors with adequate particle identification at the highest altitudes (100 TeV-PeV). The existing experiments IceTop, TUNKA-133 and the low-energy Auger extensions (AMIGA/HEAT/AERA) should be exploited. We encourage the further development of MHz radio wave detection of air showers, e.g. at the large facilities Auger (AERA) and LOFAR, as well as at the South Pole and the Tunka site. There should be close cooperation with the particle physics community, in particular with respect to LHC results. An array at the highest possible altitude is desirable to determine the chemical composition in the energy range overlapping with balloon experiments (10 TeV – PeV).** At present, the planned LHAASO experiment in China seems to come closest to this requirement.

Cosmic rays at highest energies: **We reiterate the definition of a substantially enlarged ground-based observatory as the priority project of high-energy cosmic ray physics – wherever it will be deployed. We encourage the community to work towards a global common path for such a substantially enlarged observatory including the development of new detection technologies. We recommend that European groups play a significant role in preparing a proposal for the next generation experiment, and after its approval, make a significant contribution to construction and operation. We also support European participation in JEM-EUSO with its novel technology. We encourage cross coordination between these two approaches .**

Space based gamma astronomy: The committee recognizes the scientific importance of a mission to cover the energy range of 1-30 MeV and of the LOFT X-ray mission.

Earth-bound gamma astronomy: **The Cherenkov Telescope Array, CTA, is the clear worldwide priority project of VHE gamma-ray astrophysics. We recommend to design and to prototype CTA, to select site(s), and to proceed towards start of deployment in 2014. We strongly recommend that the various funding agencies work together to secure the required funds for the construction and operation of CTA. The current IACTs should continue to take data until CTA has superior sensitivity and sky coverage.**

High-energy neutrino astronomy: IceCube is now providing data with unprecedented quality and statistics. **The European partners should be supported in order to ensure the appropriate scientific return.** There is a strong scientific case for a neutrino detector in the Northern hemisphere, with a substantially larger sensitivity than IceCube. **Resources for a Mediterranean detector should be pooled in a single optimized design for a large research infrastructure. The KM3NeT collaboration is encouraged to present a technical proposal matching these requirements and in particular take final site and design decisions that would enable start of construction in 2014.. The IceCube and KM3NeT collaborations are encouraged to strengthen cooperation, with the vision to form a future Global Neutrino Observatory.**

Ultra-high energy cosmic neutrinos: Given the recent indirect constraints from Fermi on the cosmogenic neutrino flux at 10^9-10^{11} GeV, it seems clear that detectors of many tens of cubic kilometres will be necessary to record more than a handful of neutrinos from GZK interactions. **We encourage R&D efforts towards this goal.**

Dark matter search:

a) **The committee strongly supports improving the DAMA/LIBRA experiment in terms of a lower threshold and a lower background, with the goal to better understand the observed modulation signal. A fully independent experiment based on the same or on a similar technology would be crucial to cross-check the DAMA/LIBRA effect.**

b) The last two-three years saw a dramatic progress of the liquid-xenon based technology for the direct detection of WIMPs. The 100 kg scale has been realised with a low background level and the 1-ton scale is currently being planned. **On this basis, the committee recommends that DARWIN, a program to further extend the target mass of noble liquids to several tons, is pursued and supported. The**

choice in favour of a double-target option should be taken after a clear experimental confirmation that a liquid argon target is competitive with liquid xenon in terms of rejection efficiency, background and operation reliability.

c) The bolometric techniques have remained competitive with the noble liquid approach in terms of sensitivity to WIMP interactions. The results of the EDELWEISS collaboration showed a clear technological advancement with germanium detectors regarding the rejection of surface beta background, which was the main limitation in the "ionisation+heat" option. The CRESST experiment showed the power of identifying nuclear recoils from light and heavy nuclei using $CaWO_4$ **The committee recommends therefore supporting the development of the multi-target approach EURECA, an apparatus capable of housing 1 ton of bolometric sensitive mass, and the ongoing cooperation with the CDMS follow-up projects. This facility is complementary to the solution provided by noble liquids, and is versatile enough to provide a multi-target approach (including low Z targets tailored to test the low-mass WIMP region) and to possibly house other rare event searches based on the bolometric technology.**

d) **The committee endorses an expansion of the experiment SIMPLE with a lower background level in order to further increase its sensitivity to spin-dependent interactions.** This search can be done in synergy with the possibilities provided by xenon (about 50% nuclei have half integer spin) and by the bolometric approach which offers the chance to study different odd-A target nuclei.

e) **The committee recommends supporting the R&D activities related to the directional detection of WIMPs, in particular aiming at a substantial background reduction, as this may become essential to confirm the galactic dark matter origin of the signal in case of a positive signal from the high-density target detectors.**

f) Axions: The committee supports the continuation of the corresponding programs.

Direct measurement of the neutrino mass: The KATRIN beta spectrometer is expected to provide unique results on the direct measurement of the neutrino mass starting from 2013, testing the degenerate mass region at the 0.2 eV level. At the moment, no other technology seems to be really in competition. Since with KATRIN the maximum feasible size seems to have been reached, no larger electrostatic spectrometer is currently being planned, but improvements with respect to resolution and other parameters are conceivable.. On the other hand the bolometric approach followed in MARE is modular and can in principle be extended arbitrarily. **Therefore, we recommend the continuation of R&D activities on the bolometric approach, regarding both ^{187}Re (beta decay) and ^{163}Ho (electron capture) sources.**

Neutrino-less double beta decay: **The European detectors GERDA and CUORE will explore in the next years the degenerate region of the neutrino mass pattern. CUORE will probe also part of the mass range predicted by neutrino oscillation experiments for the case of the inverted mass hierarchy. In case of discovery at the degenerate mass level, there is a clear path for "precision measurements", with possible evidence in three different nuclei and with the unique opportunity provided by SuperNEMO to investigate the leading DBD mechanism. The committee recommends therefore a prompt realization of the SuperNEMO demonstrator.** Whereas GERDA, CUORE and SuperNEMO rely on the long-term experience with precursors and extensively validated techniques, NEXT is a comparatively new approach, with a steep time gradient, combining construction of a full detector with basic R&D. **The committee encourages the collaboration to demonstrate all aspects of the technology and move ahead toward NEXT-100.** The community is working to improve the sensitivity with the aim to **fully cover the inverted hierarchy region**, a crucial element for the determination of the neutrino mass hierarchy in synergy with the next stages of the neutrino oscillation program. The general requirement for this task is 1 ton of isotope and a background at the level or below 1 count/(y ton-isotope) in the region of interest. This challenging objective can be accomplished either by the technologies of the experiments running or in construction (this option would provide the advantage of a phased approach) or by new promising technologies which are currently under study (LUCIFER, COBRA pixel detectors, pulse shape discrimination in bolometer experiments, argon instrumentation in GERDA, Cherenkov light in TeO_2). **The committee recommends that these options are pursued at the R&D level in view of a final assessment of the most effective approaches for the 1 ton scale. As the required financial resources are substantial for ton scale experiments, the committee endorses their realisation in the framework of worldwide collaborations. This would allow the investigation of more than one double beta isotope, which is essential to provide an unambiguous signature of neutrino-less double beta decay and to determine the effective Majorana mass.** The committee notes progress in the calculation of the nuclear matrix elements for $0\nu\beta\beta$ decay, with clear signs of convergence and with a validation of the traditional methods through a new approach. **The committee confirms therefore the importance of continuing this fruitful program, which is based on both theoretical and experimental investigations.** ***Extension of the Modane Underground Laboratory:*** The recommended projects such as EURECA and DARWIN for dark matter and SuperNEMO for ββ decay need new available space, if possible at a deep site. **There is a unique opportunity to extend the present underground laboratory of Modane -LSM- by taking advantage of the excavation of the safety tunnel of the Frejus road tunnel, now started a year ago. This new laboratory of 60,000 m^3 would be able to host recommended projects. LSM has the greatest depth of the present underground laboratories in Europe. The committee therefore strongly recommends the timely support for this infrastructure. Such a laboratory - of the size of one Gran Sasso hall with 6 times lower muon flux, in operation by 2014 - would enhance the complementarity of the European Deep Underground laboratories.**

Present experiments on reactor & low energy natural neutrinos and long baseline oscillations experiments: The BOREXINO collaboration is to be congratulated for measuring solar and geo-neutrinos. **The committee strongly endorses further support this scientific program, which is now unique in the world.**

The Double Chooz Far Detector has recently started operation and will measure electron neutrino disappearance with provide data on θ_{13} vastly improved from the original CHOOZ experiment. **To achieve full sensitivity and to be competitive with other experiments worldwide, it is critical that the Near Detector be completed as soon as possible.** Knowledge of θ_{13} is important to define the path to the discovery of CP violation in the leptonic sector. It will shed light on the expected flavor composition of neutrinos emitted by supernova core collapses. **It is recommended that the LNGS program with OPERA and ICARUS be continued as planned in order to obtain a more significant evidence for tau appearance.**

Towards a detector for neutrino astrophysics and proton decay search on the Megaton-scale: **LAGUNA is the European effort to develop megaton neutrino detectors both for accelerator-based and astroparticle neutrino measurements.** The scientific goals are both broad and ambitious. The LAGUNA site study is almost completed, showing that there are possible sites in Europe that could host such experiments. **The committee recommends that the study be pursued with LAGUNA-LBNO focusing on detector designs to lead to a better understanding of the costs of the various detector technology options and on the prospects for a new long baseline neutrino beam from CERN. In addition, due to the high cost and long development time necessary to realize this program, the committee recommends that it be pursued in a global context. In addition, it is recommended that programs with and without a new neutrino beam are considered, in order to preserve possible science opportunities.** Neutrino astronomy would benefit from the measurements of nuclear cross-sections of astrophysical interest using underground nuclear accelerators. **We recommend therefore supporting the update of the ongoing programs with LUNA and follow-up projects at higher energy in this field.** The interpretation of current and future long baseline experiments depends highly on the detailed knowledge of neutrino-nucleus interactions. **Hence, the committee encourages more dedicated theoretical work in this field. We also encourage studies to investigate to which extend parts of the LAGUNA program (supernova neutrinos, oscillation physics, proton decay) can be addressed by an IceCube low-energy extension.** Several anomalies in the neutrino sector and in cosmology have triggered increased interest in **sterile neutrinos** as a possible explanation. **This makes new experimental campaigns necessary, with the goal to either falsify the anomalies or indeed discover physics beyond the Standard Model.**

Dark Energy projects: **We welcome the participation of the European astroparticle physics community in experiments in this field. This community should make sure that it can participate in the harvest of results from the presently planned ground projects and should, on the other hand take the unique chance for leadership in space with the ESA-led Euclid mission.**

Gravitational waves:

a) The committee commends the move of the international gravitational wave community towards a single worldwide network of ground interferometers which will allow better coverage and better pointing capabilities. This also goes in the direction of increasing the community worldwide.

b) At a time of down selection of the large mission of the ESA Cosmic Vision program, the community renews its strong support of the LISA program which will open the scientifically challenging domain of low frequency (10^{-4}Hz,10^{-1}Hz) gravitational wave astronomy, as well as advance our knowledge of fundamental physics.

c) The committee acknowledges the progress of

the Einstein Telescope Design Study, supports a new proposal for coordination actions for ET, and encourages ASPERA/ApPEC to take steps for a future inclusion of ET into the ESFRI list.

d) The committee supports an enhancement of the R&D effort in order to accompany the development of the second generation network and to prepare for the third generation (ET). For this purpose, we propose an ASPERA call for R&D. ▪

A.5

Experiment Overview

Underlined experiments have major contribution of full ASPERA members
Boldfaced experiments cost > 20M€.

The High Energy Universe:

	Low & Medium energy CR + Gamma Rays	Ultra High-energy CR	Gamma Rays	High-energy Neutrino
Data Taking	ATIC (balloon) CREAM (balloon) TRACER (balloon) **Pamela (space)** Tunka-133 ARGO-YBJ Tibet ASγ Gamma Grapes **AMS (space)**	Telescope Array Yakutsk **Pierre Auger Obs**	Whipple H.E.S.S. MAGIC VERITAS CANGAROO ARGO-YBJ **AGILE (space)** **Fermi (space)**	Baikal NT200+ **ANTARES** **IceCube** ANITA
Construction	Tunka-upgrade Tibet ASγ	TUS (space) Auger enhancements (HEAT, AMIGA, AERA)	Tibet ASγ SCORE@Tunka HAWC	**NuMoon as part of LOFAR***
Prototypes or planned	PEBS (balloon) GAPS (balloon) DbarSUSY (balloon) **CALET (space)** **NUCLEON (space)** **LHAASO**	Tunka-Radio RASTA **Follow up to Auger** TA enhancements **JEM-EUSO (space)** LORD (space)	MACE **CTA** HiSCORE **Gamma-400 (space)** **LHAASO**	**Baikal-GVD** **KM3NeT** **DeepCore+** ARIANNA ARA

** experiment with a different primary focus*

Neutrino-less Double Beta Decay:

	Calorimetric Bolometer	Calorimetric Semiconductor	Calorimetric liquid/gas/solid	Tracking gas TPC
Commissioning	CUORE-0	Gerda-I	EXO-200	---
Construction	CUORE	Gerda-II Majorana demonstrator	**SNO+** Kamland-Zen	SuperNEMO demonstrator
R&D	LUCIFER AMoRE	COBRA	CANDLES PANDA-X	DCBA MOON NEXT
Planned	**CUORE Phase-II**	**GerdaIII/** **Majorana**	**XMASS-10t** **EXO**	**SuperNEMO**

Dark Matter:

	Scintillation or ionisation	Bolometric	Liquid Xe	Liquid Ar
Data taking	DAMA/LIBRA KIMS COUPP PICASSO SIMPLE COGENT DAMIC TEXONO	CDMS-II EDELWEISS CRESST ROSEBUD	XENON-100 ZEPLIN-III XMASS-100	WARP-140
Construction	ANAIS	EDELWEISS-III Super-CDMS @ Soudan	**LUX**	DarkSide MiniCLEAN ARDM DEAP 3.6 ton
Advanced planning	Texono-CDEX		XENON1ton PANDA-X	
R&D or Planning	LIBRA 1ton CINDMS	**EURECA** **SuperCDMS @** **SNOLAB** **GEODM**	**LZS-3.5ton** **DARWIN/Xe** **MAX/Xe** **LZD** **XMASS-10ton**	MAX/Ar WARP1ton **DARWIN/Ar** CLEAN

Gaseous detectors, R&D phase: *MIMAC, DRIFT, NEWAGE*

Large underground detectors for neutrino astrophysics, proton decay & Low energy neutrino astro- & LBL physic, proton decays:

	Water Cherenkov	Liquid Scintillator	Liquid Argon	Sandwich Tracking
Data taking	**Super-Kamiokande**	**KamLAND** **Borexino** LVD BUST (Baksan) DoubleChooz	ICARUS ArgoNEUT	**OPERA** MINOS **T2K**
Construction		Daya-Bay RENO **SNO+**		**NOVA**
R&D planned	**Hyper-Kamiokande** **LBNE @ DUSEL** MEMPHYS	**LENA**	**Modular** **T2K Argon** **GLACIER** **Argon @ DUSEL**	**INO**

In Russia, the SAGE radiochemical experiment continues to take data.

Gravitational Waves

	Ground interferometric antennas	Pulsar timing and space antennas
Data taking/G1	VIRGO LIGO GEO TAMA	IPTA
Construction	aLIGO advVIRGO GEO-HF LCGT CLIO	LISA Pathfinder
R&D	AIGO INDIGO	
Planned		LISA

Dark Energy:

	Supernova	Weak lensing	Baryon Acoustic Oscillation	Glaxy clustering
Completed or Underway	CofA SCP SNLS ESSENCE HST SDSS II CofA SP Snfactory CSP KAIT PanSTARRS1	CTIO COSMOS CFHLS DLS LOFAR	SDSS/BOSS	PISCO SPT ACT XCS RCS2 KIDS DEEP2
In Preparation	LRSC Sky Mapper	DES KDS ALPACA ODI	HETDEX BOSS	CIX
Proposed	WFIRST	PanSTARRS4 EUCLID LSST SKA	Big BOSS SuMIRe	10 XbRay NASA MEM Constellation X CCAT

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