Status and Perspectives of Astroparticle Physics in Europe

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Astroparticle physics has evolved as an interdisciplinary field at the intersection of particle physics, astronomy and cosmology. Over the last two decades, it has moved from infancy to technological maturity and is now envisaging projects on the 100 M€ scale. This price tag requires international coordination, cooperation and convergence to a few flagship projects. The Roadmap Committee of ApPEC (Astroparticle Physics European Coordination) has recently released a roadmap covering the next ten years. ApPEC is a corporation of European funding agencies promoting astroparticle physics.

In 2002, Ray Davis and Masatoshi Koshiba were awarded the Nobel Prize in Physics for opening the neutrino window to the Universe, specifically for the detection of neutrinos from the Sun and the Supernova SN 1987A in the Large Magellanic Cloud. Their work was a unique synthesis of particle physics and astrophysics. Solar neutrinos also provided the first clear evidence that neutrinos have mass. It is this interdisciplinary field at the intersection of particle physics, astronomy and cosmology which has been christened *astroparticle physics*.

The detection of solar and supernova neutrinos is not the only new window to the Universe opened by astroparticle physics. Another one is that of high energetic gamma rays recorded by ground-based Cherenkov telescopes. From the first source detected in 1989, three sources known in 1996, to nearly 40 sources identified by the end of 2006, the high-energy sky has revealed a stunning richness of new phenomena and puzzling details (see Figure 1). Other branches of astroparticle physics have not yet provided such gold-plated discoveries, but have moved into unprecedented sensitivity regions with rapidly increasing discovery potential – like the search for dark matter particles, the search for decaying protons or the attempt to determine the absolute values of neutrino masses.

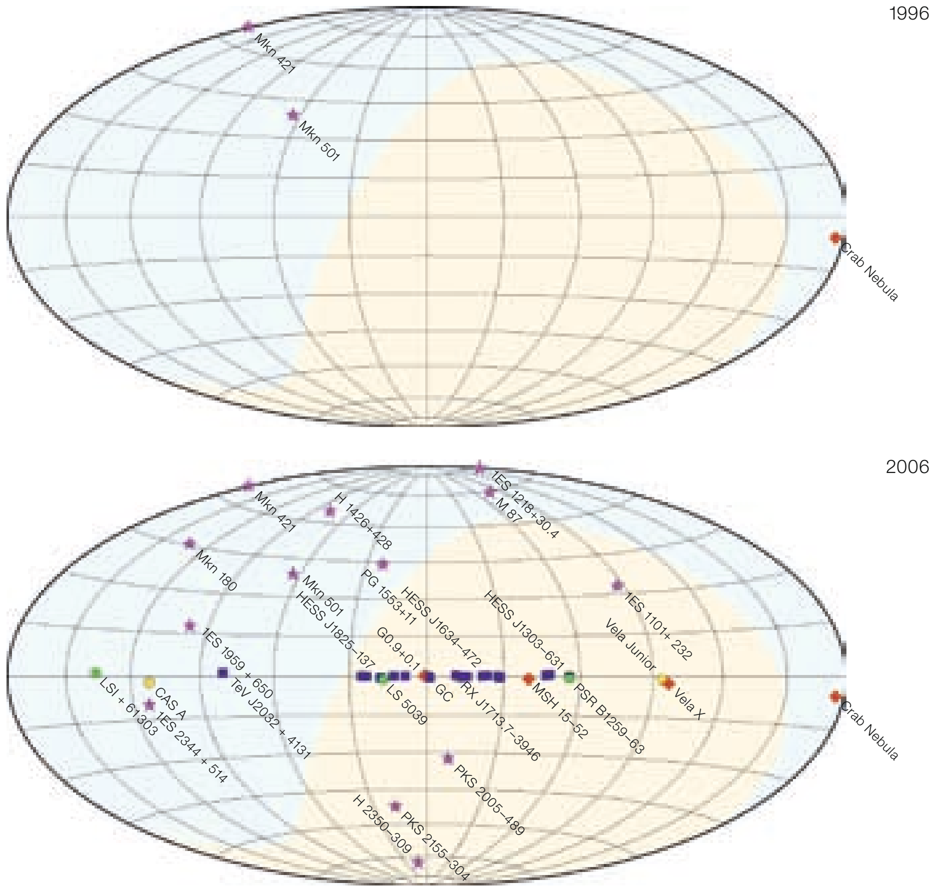

Figure 1: The TeV gamma-ray sky as seen in 1996 and 2006. (Graphic courtesy Konrad Bernlöhr, MPIfK)

AGN
Plerion
Shell Type SNR
Binary System
Other or unidentified or ambiguous identification

Background colours indicate northern (blue)/southern (yellow) sky.

Basic questions

Recommendations of the Roadmap committee (*http://www.aspera-eu.org*) were formulated by addressing a set of basic questions:

1. What are the constituents of the Universe? In particular: What is dark matter?
2. Do protons have a finite life time?
3. What are the properties of neutrinos? What is their role in cosmic evolution?
4. What do neutrinos tell us about the interior of the Sun and the Earth, and about supernova explosions?
5. What is the origin of cosmic rays? What is the view of the sky at extreme energies?
6. What will gravitational waves tell us about violent cosmic processes and about the nature of gravity?

An answer to any of these questions would mark a major breakthrough in understanding the Universe and would open an entirely new field of research on its own.

Search for Dark Matter

The favoured solution to the Dark Matter mystery assumes Weakly Interacting Massive Particles (WIMPs) produced in the early Universe. A natural candidate for WIMPs is the lightest particle of Minimal SuperSymmetric Models (MSSM), the neutralino. WIMP searches focus on the detection of nuclear recoils from WIMPs interacting in underground detectors (Baudis 2005, Sadoulet 2007). No WIMP candidate has been found so far. Assuming that all Dark Matter is made of these exotic particles, present experiments with a several kg target mass can therefore exclude WIMPS with interaction cross section larger than ~ 10^{-43} cm^2. MSSM predictions for neutralino cross sections range from 10^{-47} to 10^{-41} cm^2. Experimental sensitivities will be boosted to 10^{-44} cm^2 in about a year and may reach, with ton-scale detectors, 10^{-46} cm^2 in 7–8 years. Therefore, there is a fair chance to detect dark matter particles in the next decade – provided the progress in background rejection can be realised and provided Dark Matter is made of supersymmetric particles. Presently favoured candidate devices are 'bolometric' detectors operated at a temperature of 10–20 mK which detect the feeble heat, ionisation and scintillation signals from WIMP interactions, and noble liquid detectors (Xe or Ar) recording ionisation and scintillation. A variety of presently more than 20 Dark Matter experiments worldwide must, within several years, converge to two or three few ton-scale experiments with negligible background.

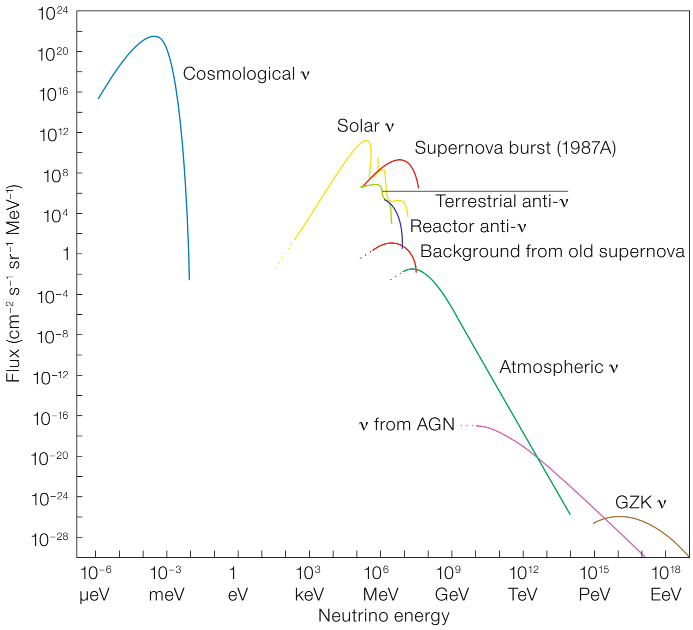

Figure 2: The 'grand unified' neutrino spectrum.

Proton decay and low-energy neutrino astronomy

Grand Unified Theories (GUTs) of particle physics predict that the proton has a finite lifetime. The related physics may be closely linked to the physics of the Big Bang and the cosmic matter-antimatter asymmetry. Data from the Super-Kamiokande detector in Japan constrain the proton lifetime to be larger than 10^{34} years, tantalisingly close to predictions of various GUT models. A sensitivity improvement of an order of magnitude requires detectors on the 10^5–10^6 ton scale.

Proton decay detectors do also detect cosmic neutrinos. Figure 2 shows a 'grand unified neutrino spectrum'. Solar neutrinos, burst neutrinos from SN 1987A, reactor neutrinos, terrestrial neutrinos and atmospheric neutrinos have been already detected. They would be also in the focus of a next-stage proton decay detector. Another guaranteed – although not yet detected – flux is that of neutrinos generated in collisions of ultra-energetic protons with the 3-K cosmic microwave background (CMB), the so-called GZK (Greisen-Zatsepin-Kuzmin) neutrinos. Whereas GZK neutrinos as well as neutrinos from active galactic nuclei (marked AGN) will likely be detected by neutrino telescopes in the next decade (see below), no practicable idea exists how to detect 1.9 K cosmological neutrinos, the analogue to the 2.7 K microwave radiation.

A next-generation proton decay detector could record neutrinos from a galactic supernova with unprecedented statistics: 10^4–10^5 events, compared to only 20 events for SN 1987A. It would also allow a precise study of the solar interior and of neutrinos generated deep in the Earth. Three detection techniques are currently studied: Water-Cherenkov detectors (like Super-Kamiokande, see de Bellefon et al. 2006), liquid scintillator detectors and liquid argon detectors. They will be evaluated in the context of a common design study which will also address the underground infrastructure and the possibility of detecting neutrinos from future accelerator beams. This design study should converge, on a time scale of 2010, to a common proposal. The total cost depends on the method and the actual size, and is estimated between 400 and 800 M€. With the start of civil engineering in 2012 or 2013, only a third of this amount might be due before 2016.

Neutrino properties: neutrino-less double beta decay

In the context of astroparticle physics, neutrinos – rather than being the subject of research – mainly play the role of messengers: from the Sun, from a supernova, from active galaxies. Still, some of their properties remain undetermined. From the oscillatory behaviour of neutrinos we can deduce that the masses of the three neutrino species differ from each other. But what are the absolute values of their masses? Further: are neutrinos their own antiparticles ('Majorana particles')? Specifically these two questions could be answered by the observation of a radioactive decay called neutrino-less double beta decay (Vogl 2006). To reach the sensitivity for a mass range of 20–50 meV, as suggested by various theoretical models, one needs detectors with an active mass of the order of one ton, good resolution and very low background. Construction of such detectors is envisaged to start in 2013–2015. Different nuclear isotopes and different experimental techniques are needed to establish the effect and extract a neutrino mass value. The price tag for one of these experiments is at the 50–200 M€ scale, with the large range in cost being due to the production cost for different isotopes.

The high-energy Universe

Cosmic rays have been discovered nearly a century ago. Some of these particles have breathtaking energies – a hundred million times above that of terrestrial accelerators (Olinto 2007; Watson 2005), see Figure 3. How can cosmic accelerators boost particles to these energies? What is the nature of the particles? The mystery of cosmic rays is going to be solved by an interplay of detectors for high-energy *gamma rays, charged cosmic rays and neutrinos*.

Charged cosmic rays

The present flagship in the search for sources of ultra-high energy cosmic rays is the Southern Pierre Auger Observatory in Argentina. This is a 1000-km^2 array of water tanks, flanked by air fluorescence telescopes, which measure direction and energy of giant air showers (see Figure 4). Full-sky coverage would be obtained by a Northern observation site. European groups will play a significant role to establish the scientific case, and after its consolidation make a significant contribution to the design and construction of Auger-North.

TeV gamma rays

European instruments are leading the field of ground-based high-energy gamma-ray astronomy. Most of the new sources in Figure 1 have been estalished by H.E.S.S., an array of four Cherenkov telescopes in Namibia, and MAGIC, a large twin telescope at La Palma. The rich results from current instruments (Aharonian 2007; Voelk 2006) show that high-energy phenomena are ubiquitous in the sky; in fact, some of the objects discovered emit most of their power in the gamma-ray range and are barely visible at other wavelengths ('dark accelerators'). The need for a next-generation instrument is obvious, and its required characteristics are well understood. CTA, the Cherenkov Telescope Array, could both boost the sensitivity by another order of magnitude and enlarge the usable energy range. CTA is conceived to cover both hemispheres, with one site in

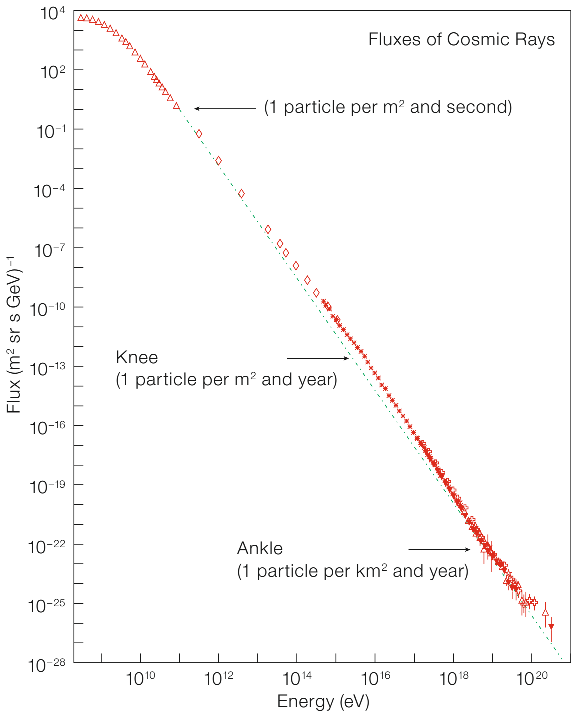

Figure 3: The spectrum of cosmic rays and the domains for various experimental methods. Highest observed energies dwarf the Large Hadron Collider at CERN which will accelerate protons to 10^{13} eV.

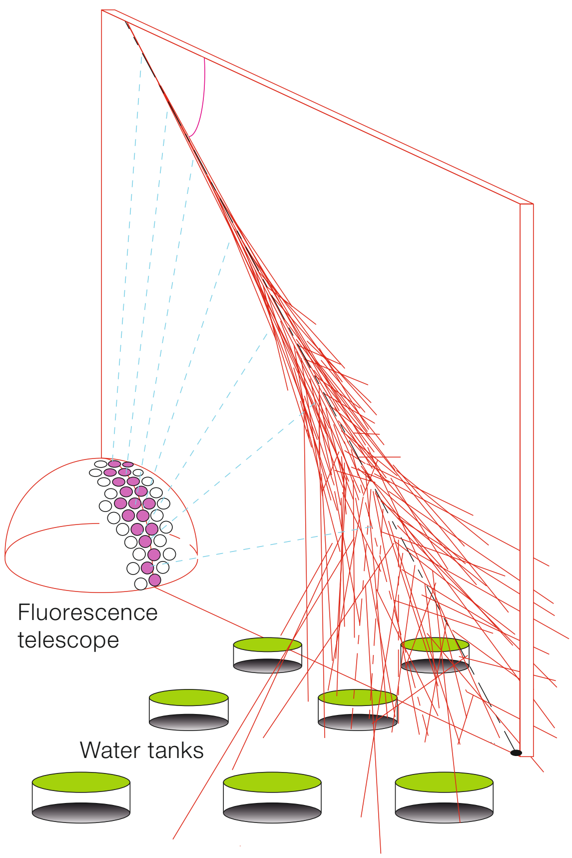

Figure 4: The Auger detection principles: fluorescence light from air showers is recorded by telescopes, particles at ground level are recorded by Cherenkov water tanks.

each. The instruments will be prepared by a common European consortium.

High-energy neutrinos

The physics case for high-energy neutrino astronomy is obvious: neutrinos can provide an uncontroversial proof of the hadronic character of the source; moreover they can reach us from cosmic regions which are opaque to other types of radiation (Waxman 2007). European physicists have played a key role in construction and operation of the two pioneering large neutrino telescopes, NT200 in Lake Baikal and AMANDA at the South Pole, and are also strongly involved in AMANDA's successor, IceCube (Halzen 2007). A complete sky coverage, in particular of the central parts of the Galaxy with many promising source candidates, requires a cubic kilometre detector in the Northern hemisphere. Prototype installations of AMANDA size are presently installed at three different Mediterranean sites (Greece, France, Italy). An EU-funded three-year study (KM3NeT) is in progress to consolidate the scientific case and to work out the technical design of a single, optimised large future research infrastructure in the Mediterranean, with construction envisaged to start in 2011.

Gravitational waves

Gravitational waves would provide us with information on strong field gravity through the study of immediate environments of black holes. The most advanced tools for gravitational wave detection are interferometers with kilometre-long arms. The passage of a gravitational wave differential contracts space along the two directions of the arms and influences the light travel time (Hong 2005). At present, the world's most sensitive interferometer is LIGO (USA), the others being GEO600 in Germany, TAMA in Japan and VIRGO in Italy. The research field of Gravitational Wave has a huge discovery potential but is still awaiting the first direct detection. In the short term, the European ground interferometers (GEO and VIRGO) should turn to observation mode with a fraction of their time dedicated to their improvement (GEO-HF, VIRGO+ and Advanced VIRGO). Predicted event rates, e.g. for mergers of neutron star/ black hole systems (BH-BH, NS-NS, NS-BH) are highly uncertain and range between 3 and 1000 for the 'advanced' detectors planned to start data taking in about five years (see Figure 6). This would change dramatically with a third-generation underground interferometer facility (Einstein Telescope, E.T.) which would have a guaranteed rate of many thousands of events per year and move gravitational wave detectors into the category of astronomical observatories. Civil engineering could start in 2012 or 2013.

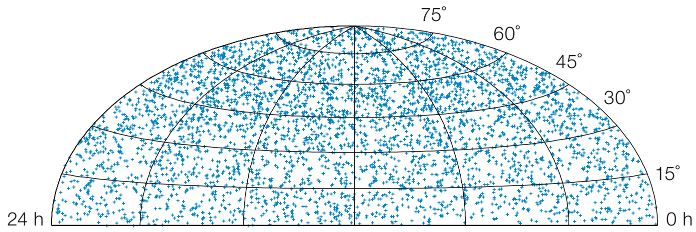

Figure 5: Sky map of 4282 events recorded by AMANDA in 2000–2004.

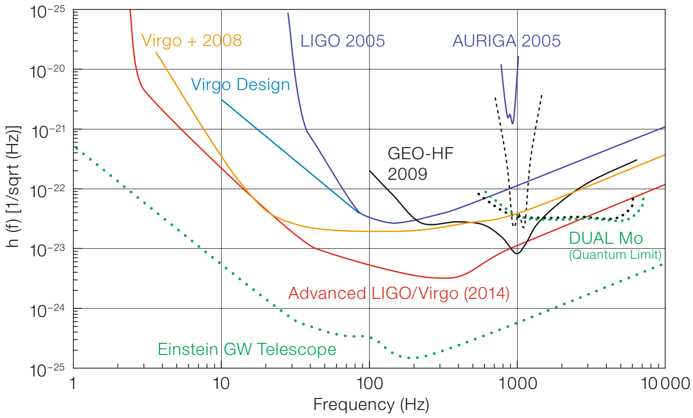

Figure 6: Current and expected sensitivities for ground-based gravitational wave detectors. The solid curves correspond to existing detectors and their expected upgrades. Dotted lines are for new projects.

The big picture

Table 1 is based on a scenario where the process of cooperation and coordination converges to a few major activities (cost > 50 M€) between 2010 and 2015. Naturally, there must be room for initiatives below the 50 M€ level. The Roadmap committee suggests that about 15–20 % of astroparticle funding should be reserved for smaller initiatives, for participation in overseas experiments with non-European dominance, and for R&D. Technological innovation has been a prerequisite of the enormous progress made over the last two decades and enabled maturity in most fields of astroparticle physics. It is also a prerequisite for future progress towards greater sensitivity and lower cost and must be supported with significant funds.

The present 'first stage' roadmap will be followed by a second stage which will be associated with a detailed census of existing budget and human resources available in the participating agencies.

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Field	Experiment	Cost scale per experiment (M€)	Desirable start of construction	Remarks
Dark Matter	Low background experiments with one-ton mass	60–100	2011–2013	two experiments (different nuclei and different techniques)
Proton decay and low-energy neutrino astronomy	Large infrastructure for p-decay and ν astronomy on the 100 kton–1 Mton scale	400–800	Civil engineering: 2012–2013	– needs huge excavation – most of expenditures likely after 2015 – worldwide sharing
Properties of neutrinos	Experiments on neutrinoless double beta decay with one-ton mass	50–200	2013–2015	two experiments with different nuclei (desirably more worldwide)
The high-energy Universe	*Gamma rays:* Cherenkov Telescope Array CTA	100 (South) 50 (North)	First site in 2011	Physics potential well defined by rich physics from present gamma ray experiments
	Charged Cosmic Rays: Auger North	85 (1/3 Europe)	2010	Confirmation of physics potential from Auger South results expected in 2007
	Neutrinos: KM3NeT	250	2011	Confirmation of physics potential expected from IceCube and gamma ray telescopes. Full Proposal expected in 2009.
Gravitational waves	Einstein Telescope	300	Civil engineering: 2012	Conceived as underground laboratory

Table 1: Future European projects with > 50 M€ estimated cost. Note that in most of the cases further R&D efforts, or further input from prototype devices, or final confirmation of the physics case, are required before arriving at a detailed technical proposal. Therefore the indicated starting dates are termed 'desirable'.

Photo: H.E.S.S. Collaboration

Two of the four H.E.S.S. Cherenkov telescopes for detection of very high energy gamma rays are shown. The H.E.S.S. observatory is situated in Namibia, southern Africa. Each telescope has a mirror diameter of 12 m with a camera consisting of 960 photomultipliers. The four telescopes are coupled and work in stereoscopic mode.