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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 Million Euro 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. This talk describes status and perspectives of astroparticle physics in Europe and reports the recommendations of the Roadmap Committee.

1 Introduction

Although the notation ”astroparticle physics” was coined only 25 years ago, and although it has been widely used only since the nineties, its roots go back to the early years of the last century, when Victor Hess discovered cosmic rays. The origin of these particles – mostly protons, light and heavy nuclei – was unknown, and it is going to be solved only now, 100 years later. However, there was a long period when cosmic rays served as the source of most newly discovered elementary particles: 1932, the first anti-particle, the positron, was recorded in cosmic rays, followed by the muon in 1936 and in 1947 by the pion, the first of the vast family of mesons. Until the beginning of the fifties, cosmic rays remained the main source of new particles and laid the ground for the ”’particle zoo”’, which a decade later was explained by the quark model. It was only in the mid of the fifties that particle accelerators started their triumphal development and cosmic rays lost their role in particle physics. With a single exception, cosmic particle physics disappeared from the screen of most particle physicists.

The exception was the long-lasting attempt to detect solar neutrinos. It was pioneered by Ray Davis in the sixties who measured the ^{8}B neutrino flux with the radio-chemical ClAr method – detecting however only a third of the predicted flux. The deficit was confirmed in the eighties by Kamiokande, a water Cherenkov detector in Japan. The following measurements of pp neutrinos with GaGe detectors in the Russian Baksan laboratory (SAGE experiment) and in the Italian Gran Sasso Laboratory (GALLEX experiment) corroborated the suggestion that the solution to the neutrino deficit was not given by a different solar model but by neutrino oscillations. This solution was eventually confirmed by the SNO experiment in Canada (Bahcall 2005, McDonald et al. 2004).

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 SN1987A in the Large Magellanic Cloud. Their work was a unique synthesis of particle physics and astrophysics since solar neutrinos also provided the first clear evidence that neutrinos have mass. It represents a classical illustration of the interdisciplinary field at the intersection of particle physics, astronomy and cosmology which now is known as astroparticle physics. One may note that Koshiba's Kamiokande detector was originally built to detect proton decay – another bracketing of astrophysics and particle physics by a single technique.

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 70 sources identified by the end of 2007, the high energy sky has revealed a stunning richness of new phenomena and puzzling details (see Fig. 11 below). Other branches of astroparticle physics did not yet provide such gold-plated discoveries but 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.

2 Basic questions

The Roadmap Committee of ApPEC (Astroparticle Physics European Coordination) has recently released a roadmap

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covering the next ten years. Recommendations of the committee (http://www.aspera-eu.org) have been 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 they tell us about violent cosmic processes and about the nature of gravity?

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

3 Dark Matter and Dark Energy

Over the last decade, the content of the Universe has been measured with unprecedented precision. Whereas normal baryonic matter contributes only about 4%, the dominant constituents are unknown forms of matter and energy: Dark Matter (22%) and Dark Energy (74%).

Whereas the concept of Dark Energy was introduced only recently – in response to a negative pressure driving cosmic expansion –, Dark Matter has been discussed for decades. The prevalent view is that Dark Matter consists of stable relic particles from the Big Bang, and that nearly all of it is in the form of Cold Dark Matter (CDM). In the early Universe, CDM particles would have already cooled to non-relativistic velocities when decoupling from the expanding and cooling Universe. Hot dark matter (HDM) has been relativistic at the time of decoupling. Neutrinos are typical HDM particles; their contribution to the total matter budget, however, is small.

3.1 The Search for Dark Matter

The favoured candidate for dark matter is a Weakly Interacting Massive Particle (WIMP) related to new physics at the TeV scale (Steigmann & Turner 1985, Jungmann et al., 1996). Among the various WIMP candidates, the lightest supersymmetric (SUSY) particle in the Minimal SuperSymmetric Model (MSSM) is favoured – likely the *neutralino*. Another theoretically well-founded dark matter candidate is the axion (Peccei & Quinn 1977, Raffelt 2006). Even though axions would be much lighter than WIMPs, they still could constitute CDM, since they are have not been produced in thermal equilibrium and would be non-relativistic.

Direct WIMP searches

”Direct” WIMP searches focus on the detection of nuclear recoils from WIMPs interacting in underground detectors (Gaitskell 2004, Baudis 2006, Sadoulet 2007). No WIMP candidate has been found so far. Assuming that all Dark Matter is made of WIMPs, present experiments with a several-kilogram target mass can therefore exclude WIMPS with an interaction cross section larger than 10^{-43} cm^2 (i.e. 10^{-7} picobarn). MSSM predictions for neutralino cross sections range from 10^{-5} to 10^{-12} pb (see Fig.1).

Experimental sensitivities will be boosted to 10^{-8} pb in a couple of years and may reach, with ton-scale detectors, 10^{-10} pb in 7-10 years. Therefore, there is a fair chance to detect dark matter particles in the next decade – provided the progress in background rejection can be realized and provided CDM is made of super-symmetric particles.

Presently, there are two favoured detection techniques:

Bolometric detectors are operated at a temperature of 10-20 mK and detect the feeble heat, ionization and scintillation signals from WIMP interactions in crystals made, e.g., from germanium, silicon or $CaWO_4$. Present flagship experiments are CDMS in the USA, and CRESST (Gran Sasso Laboratory, Italy) and EDELWEISS (Fréjus Laboratory, France) in Europe.

Noble liquid detectors record ionization and scintillation from nuclear recoils in liquid xenon, argon or neon. XENON (Gran Sasso) and ZEPLIN (Boulby mine, UK) use liquid xenon targets of about 10kg mass, while WARP (Gran Sasso) and ArDM (Canfranc, Spain) operate, or prepare, liquid argon detectors. Actually the most recent significant step in the race for better sensitivities has been made by XENON (see Angle 2008 and Fig.1).

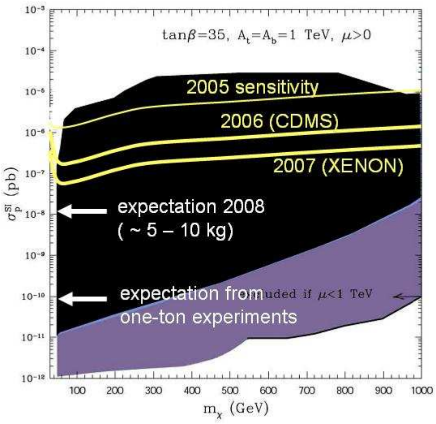

Fig. 1 Spin-independent WIMP cross section vs. WIMP mass for an MSSM prediction (dark area), with parameters fixed to the values shown at top right (Kim et al. 2002). The upper curve represents the limits obtained by 2005. CDMS, a bolometric detector operated in the US, achieved the 2006 record limit and was surpassed in 2007 by XENON, a liquid xenon detector operated in the Italian Gran Sasso Underground Laboratory (Angle 2008). The arrows indicate the sensitivities expected in about a year from now, and within a decade from now with one-ton experiments. All results assume the WIMP to be a neutralino in the standard MSSM formulation.

A variety of presently more than 20 dark matter experiments worldwide (see for a review Baudis 2007) must, within several years, converge to two or three few ton-scale experiments with negligible background. In Europe, there are two large initiatives towards experiments on the ton scale: EURECA, joining most players of the bolometric approach, and ELIXIR, joining most of the liquid xenon experts. R&D on alternative methods will be continued, but most of the resources will naturally be focused to ton-scale flagship projects and the corresponding underground infrastructures. Figures 2 and 3 sketch a scenario towards ton-scale experiments with negligible background (different to ton-scale experiments attempting to identify an annual signal variation on top of a large background, like the DAMA experiment, see below). Figure 2 shows the possible development of limits and sensitivities as a function of time, assuming a standard MSSM WIMP with spin-independent coupling. A 10^{-8} pb sensitivity can be reached within the next couple of years. Improvements by further two orders of magnitude require more massive detectors. The coloured area for >2009 indicates the range of projections given by different experiments, most of them envisaging an intermediate step at the 100 kg scale. Note that this scenario is made from a 2007 perspective and that initial LHC results may substantially influence the design of the very few ”ultimate” detectors. Needless to say that all these plans stand or fall with the capability to reduce the background, even for ton scale masses, to less than a very few events per year.

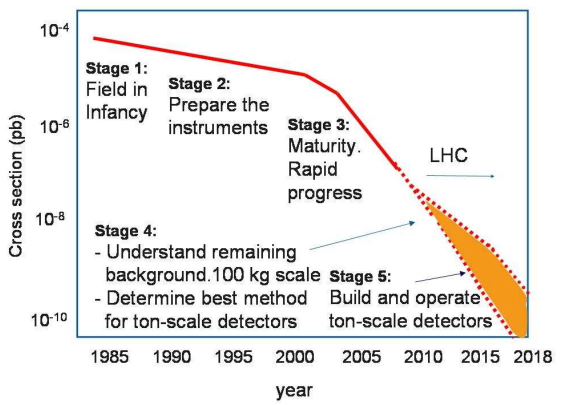

Fig. 2 Possible development of limits and sensitivities as a function of time (see text for explanations).

Figure 3 shows a first tentative projection of investment expenses for ELIXIR and EURECA, including the cost for construction of a suitable low-background, deep underground infrastructure [1]. Estimates will be made more precise within design phases covering the next three years. Note that a possible priorisation within given funding envelopes may change this picture substantially.

[1] This figure may serve as an illustration for the kind of information which has been collected for all astroparticle experiments in Europe.

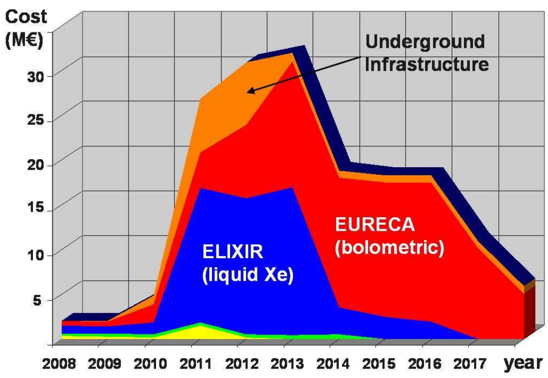

Fig. 3 Present projection of the investment expenses for the ton scale versions of ELIXIR and EURECA, including the cost for an low-background underground infrastructure housing the detectors. Since detectors will be built in a modular way, this scenario includes a stepwise approach to the ton scale, via 100-kg stages.

Following identification of a proper signal, clearly distinguished against background, one would like to get a final confirmation for the nature of the signal, by observing a ”’smoking gun”’ signature which ensures that the signal is due to WIMPs and not due to something else, such as backgrounds. There are three such signatures: *a)* annual modulation, *b)* directionality, *c)* target dependence.

The annual modulation signature reflects the periodic change of the WIMP velocity in the detector frame due to the motion of the Earth around the Sun. The variation is only of a few percent of the total WIMP signal, therefore large target masses are needed to be sensitive to the effect. Indeed, the DAMA experiment (Bernabei 2004), recording the scintillation light in NaI crystals, has reported an observation of this signature in its data from 100 kg NaI (see Fig.4), but the interpretation remains controversial. The collaboration is presently running a 250 kg version of the experiment, with first results expected in 2008, and is asking for ton-scale ressources in a next step.

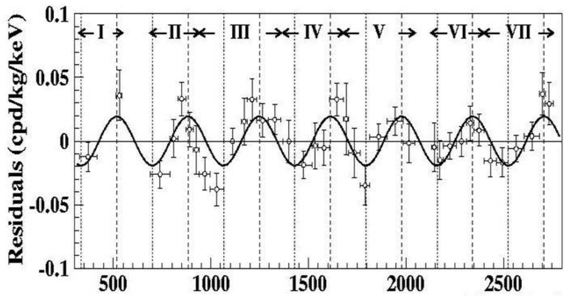

Fig. 4 Seasonal variations of the counting rate residuals observed by the DAMA experiment over a period of seven years (Bernabei 2004).

The target dependence signature follows from the different interactions of WIMPs with different nuclei - both in rate and in spectral shape. The directionality signature would clearly distinguish the WIMP signal from a terrestrial background and search for a large forward/backward asymmetry. It requires detectors capable of measuring the nuclear recoil direction, a condition potentially only met by gaseous detectors. At present, these detectors are in an R&D phase.

Indirect Dark Matter Search

The mentioned *direct* searches are flanked by *indirect searches*. These would identify charged particles, gamma rays or neutrinos from WIMP annihilation in the cores of galaxies, the Sun or the Earth. 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. Earth-bound or satellite detectors would then detect the decay products of these annihilations: an excess of neutrinos from the centre of the Earth or Sun, a gamma signal from the centre of the Galaxy, or an excess in positrons and anti-protons from galactic plane or halo. Anti-particles such as positrons and anti-protons produced in WIMP annihilation would be trapped in the galactic magnetic fields and be detected as an excess over the background generated by other well understood processes.

Present and planned detectors capable to contribute to indirect Dark Matter detection are described in section 7: satellite detectors (Pamela and AMS for charged cosmic rays, Agile and GLAST for gamma rays) and earth bound telescopes (Magic, H.E.S.S., Veritas, CTA for gamma rays, Baikal, IceCube, Antares, KM3NeT for neutrinos).

Direct and indirect methods give complementary information. For instance, gravitational trapping works best for slow WIMPs, making indirect searches most sensitive. In the case of direct detection, however, the higher energy of recoil nuclei makes fast WIMPs 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.

Synthesis of direct, indirect and accelerator signatures

While astroparticle physicists are searching dark matter, particle physicists are preparing searches for super-symmetric particles at the Large Hadron Collider in Geneva, which is expected to start operation end of 2008 and may provide first physics results on SUSY searches in 2010 or 2011. A detection of SUSY particles at the LHC would certainly considerably boost dark matter searches. Eventually, only the synthesis of all three observations – direct and indirect detection of cosmic candidates for dark matter and identification of the neutralino at the LHC – would give sufficient confidence about the character of the observed particles. (see the recent review of Bertone 2007 for a description of a multidisciplinary approach to Dark Matter search).

3.2 Dark Energy

Evidence of Dark Matter and Dark Energy has emerged from astronomical observations. Astronomical studies of galactic dynamics, gravitational lensing, large scale structures and CMBR anisotropies provide arguments for Dark Matter. Combining these observations with the observation that the universe is accelerating (SNIa methods), that the Universe is flat (from CMBR measurements) and that Dark Matter alone cannot provide the critical density (from large scale structures) establishes the need for something like ”Dark Energy”.

However, whereas Dark Matter may consist of distinct particles and can be searched by the methods of astroparticle physics, Dark Energy may be a continuous phenomenon. “Particle search strategies” equivalent to the Dark Matter case do not exist. Dark Energy can primarily explored through its influence on cosmic evolution. Observations in this area traditionally use astronomical techniques (see e.g. Perlmutter & Schmidt 2003, Spergel et al. 2007). Particle physicists have joined this new field and are playing a major role – for instance by contributing with their experience in processing large amounts of data.

The next generation of experiments relevant for Dark Energy search includes the European Planck mission on a satellite, and the ground based Dark Energy Survey, DES, the Low Frequency Array, LOFAR, and the ALMA-Pathfinder APEX. Projects proposed to be started after 2013 include various survey telescopes, most notably the Large Synoptic Survey Telescope, LSST, and the Panoramic Survey Telescope & Rapid Response System, PanSTARRS. Space based missions include the the wide field space imager DUNE and the spectroscopic all-sky cosmic explorer, SPACE, the SuperNova/Acceleration Probe, SNAP, and the James Webb Space Telescope, JWST. Needless to say that survey telescopes serve a variety of standard astronomical tasks and are not bounded to Dark Energy search. This is also true for the European Extremely Large Telescope, E-ELT, and the Square Kilometer Array, SKA. The inclusion of SKA in the ESFRI list demonstrates a high European priority.

Given the deep implications for fundamental physics, Dark Energy missions find the strongest support from the astroparticle physics community. Recommendations are formulated in the European ASTRONET Roadmap.

4 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, tantalizingly close to predictions of various SUSY-GUT predictions. A sensitivity improvement of an order of magnitude requires detectors on the 10^5-10^6 ton scale. The discovery of proton decay would be one of the most fundamental discoveries for physics and cosmology and certainly merits a worldwide coherent effort.

Proton decay detectors do also detect cosmic neutrinos. Figure 5 shows a "grand unified neutrino spectrum". Solar neutrinos, burst neutrinos from SN1987A, 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 3K cosmic microwave background (CMB), the so-called GZK (Greisen-Zatsepin-Kuzmin) neutrinos. Whereas GZK neutrinos as well as neutrinos from Active Galactic Nuclei (AGN) are likely to be detected by neutrino telescopes in the coming decade (see below), no realistic idea exists how to detect 1.9 K cosmological neutrinos, the analogue to the 2.7 K microwave radiation.

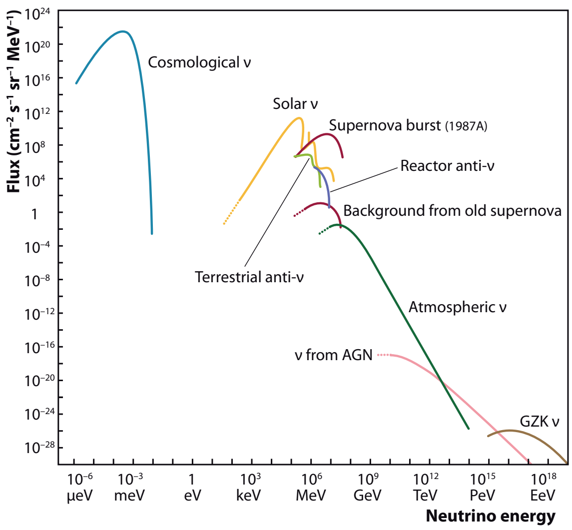

Fig. 5 The "grand unified" neutrino spectrum

Solar neutrinos, detection of neutrino oscillations by solar and atmospheric neutrinos, neutrinos from the supernova SN1987A, geo-neutrinos – large underground detectors have produced an extremely rich harvest of discoveries (McDonald et al. 2004). We note the most recent event in the series of solar neutrino measurements: the first real-time detection of solar ^{7}Be neutrinos by the BOREXINO experiment (Arpesella et al. 2008) – an impressive success, eventually achieved after a long troublesome process of internal, and in particular externally imposed, delays.

The triumphal legacy of underground neutrino physics is intended to be continued by worldwide one or two multi-purpose detectors on the mass scale of 100-1000 kilotons. The physics potential of such a large multi-purpose facility would cover a large variety of questions:

1. The proton decay sensitivity would be improved by one order of magnitude.
2. A galactic Supernova would result in 10^4-10^5 neutrino events, compared to only 20 events for SN1987A. This would provide incredibly detailed information on the early phase of the Supernova explosion.
3. The diffuse flux from past supernovae would probe the cosmological star formation rate.
4. 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 percent accuracy.
5. The high-statistics study of atmospheric neutrinos could improve our knowledge on the neutrino mass matrix and provide unique information on the neutrino mass hierarchy.
6. Our understanding of the Earth interior would be improved by the study of geo-neutrinos.
7. The study of neutrinos of medium energy from the Sun and the centre of the Earth could reveal signs for dark matter.
8. Last but not least, a large underground detector could detect artificially produced neutrinos from nuclear reactors or particle accelerators, over a long baseline between neutrino source and detector.

Three detection techniques are currently studied: Water-Cherenkov detectors (like Super-Kamiokande), liquid scintillator detectors (like BOREXINO) and liquid argon detectors (a technique pioneered by the Italian ICARUS collaboration). The present prominent European projects under study are MEMPHYS, a Megaton-scale water detector (de Bellefon et al. 2006), LENA (Wurm et al. 2007), a 30-70 kiloton liquid scintillator detector, and GLACIER (Rubbia 2004), a 50-100 kiloton liquid argon detector (see Fig.6).

The European LAGUNA consortium (Autiero et al. 2007) has been awarded a FP7 Design Study grant in order *a)* to explore and compare the capabilities of the three methods and *b)* to evaluate the possibilities of excavation of deep large cavities and the accompanying infrastructures. The 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 to be between 400 and 800 MEuro. Civil engineering may start in 2013. The cost would be shared internationally for such a Mega project.

5 Neutrino properties

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 and other celestial objects. Still, some of their intrinsic

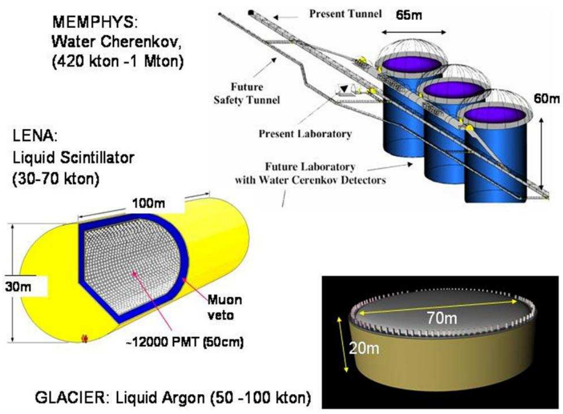

Fig. 6 Representative projects for the three proposed methods: MEMPHYS (420-1000 kton water), LENA (30-70 kton scintillator) and GLACIER (50-100 kton liquid argon).

properties remain undetermined. From the oscillatory behaviour of neutrinos we can deduce that the weak eigenstates of neutrinos (flavour eigenstates) are not identical with their mass eigenstates, that the neutrino masses are non-zero and that they differ from each other. That is why the flavour eigenstates, electron neutrino ν_e, muon neutrino ν_μ and tau neutrino ν_τ, oscillate between each other. From oscillations we can determine how strong the states mix and the mass differences. But what are the absolute values of the masses? Further: are neutrinos their own antiparticles ("Majorana particles")?

Many of the projects devoted to these questions are not really *astro*-particle experiments, but often share certain aspects with "typical" astroparticle experiments: the infrastructure (like low-background, deep caverns), the methods (like high purity liquid scintillator techniques), or sometimes just the scientist's community. That is why they are addressed by the ApPEC roadmap.

The main sources of information on neutrino parameters are the following:

a) oscillation experiments using neutrinos from accelerators or nuclear reactors as well as atmospheric or solar neutrinos. They provide information on mixing parameters, on a possible CP violation and on mass differences, but not absolute masses.

Absolute masses can be derived from three types of data or experiments:

b) cosmological data (see for a review Turner 2007),
c) end-point measurement of electron energy spectra in β-decays,
d) neutrino-less double beta decay experiments. They are the only experiments which can also prove the Majorana nature of neutrinos.

Neutrino oscillations impose a lower limit on the heaviest neutrino mass of about 0.05 eV (since this occurs to be the mass difference between the heaviest and the second heaviest mass state). This implies that neutrinos contribute at least 0.1% of cosmic matter. Neutrinos with a small finite mass contribute to hot dark matter, which suppresses the power spectrum of density fluctuations in the early Universe at "'small"' scales, of the order of one to ten Mega-parsec. The recent high precision measurements of density fluctuations in the Cosmic Microwave Background (WMAP) and the observations of the Large Scale Structure distribution of galaxies (2dFGRS and SDSS), combined with other cosmological data, yield an upper limit of about 1.5% on the amount of hot dark matter in the Universe, corresponding to an upper limit of about 0.6-0.7 eV on the sum of all three neutrino masses (see e.g. Hannestad & Raffelt 2006). The future sensitivity of cosmological measurements with Large Scale Surveys and with the CMB mission Planck, combined with the weak gravitational lensing of radiation from background galaxies and of the CMB is expected to reach a value of ≈ 0.1 eV.

Direct mass measurement

The only laboratory technique for the direct measurement of a small neutrino mass (without additional assumptions on the character of the neutrino) is the precise measurement of the electron spectrum in β-decays. Here, the neutrino mass (or an upper limit to it) is inferred from the shape of the energy spectrum near its kinematical end point. The present upper limit is at 2.3 eV (Kraus et al., 2005, Lobashov et al. 2003). The KATRIN experiment in Karlsruhe will improve the sensitivity of past experiments down to 0.2 eV (Robertson 2007). Operation of KATRIN is expected to start in 2009/2010.

Given the cosmological sensitivities, one may ask for the competitiveness of the KATRIN experiment. Precision cosmology yields an upper limit of 0.7 eV for the sum of all three neutrino masses (or $0.7\,\mathrm{eV}/3 \approx 0.23$ eV with respect to the lightest mass state). This does not seem to leave much room for a device with 0.2-eV sensitivity. However, one must keep in mind that the cosmological limit, despite the impressive success of precision cosmology, has to be derived within a system of assumptions and interpretations, and is not obtained directly. Considering the importance of the neutrino mass question, and the difficulty in associating the cosmological limit to a precise systematic confidence level, it is therefore important to pursue direct measurements up to their eventual technological – and financial – limits. There is only one way to move beyond KATRIN sensitivity: using calorimetric instead of spectrometric methods. The potential of these methods is presently explored.

Neutrino-less double beta decay

The observation of neutrino-less double beta decay may allow going to even lower masses than end-point measurements of the KATRIN type. However, it requires the neutrino to be a *Majorana* particle, i.e. representing the only fermion which is its own anti-particle. Implications of massive neutrinos for models beyond the Standard Model differ for Majorana and Dirac neutrinos. Therefore the answer to the question whether nature took the "Majorana option" is essential.

In a neutrino-less double beta decay, a nucleus (A, Z) would turn into another $(A, Z + 2)$ by transforming two neutrons into protons and emitting two electrons: $(A, Z) \rightarrow (A, Z + 2) + 2e^-$. This differs from "normal" double-beta decay (second order process of the weak interaction), which is rare but has been detected and studied: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu$. Neutrino-less double beta decay is possible only for massive Majorana neutrinos. The observed lifetime would be inversely proportional to the neutrino mass squared. Corresponding experiments are performed in low radioactivity environments deep underground, in order to suppress fake events (see for overviews Elliot & Vogel 2002 and Avignone, Elliot & Engel 2007).

Searches for double beta have been performed since the 1950s, but it was the discovery of neutrino oscillations which eventually led to a renaissance of the early enthusiasm and enormously boosted the existing efforts. Present best limits are at 0.3-0.8 eV (Avignone,Elliot&Engel 2007), with the uncertainty in the mass limit reflecting the limited knowledge on the nuclear matrix elements. Figure 7 shows the allowed effective neutrino masses (i.e. the linear combination of masses of the three mass states which is measured in double beta experiments) vs. the mass of the lightest neutrino. Constrains come from the mentioned double-beta limit and from cosmological observations.

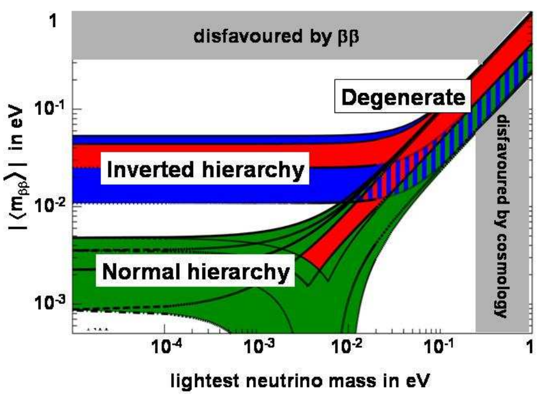

Fig. 7 Allowed effective neutrino mass (as measured in double beta decay experiments) vs. mass of the lightest mass state (adopted from Petcov 2005). Different lines and colours for theoretical predictions correspond to various assumptions on CP violating phases. Degenerate scenarios correspond to nearly equal neutrino masses, for different masses one distinguishes "normal" hierarchies and "inverted" hierarchies

One single experiment (Klapdor-Kleingrothaus et al. 2004) claims a positive observation and derives a mass of 0.2-0.6 eV. This claim is highly controversial but can be tested with next generation experiments which will reach a sensitivity of better than 0.1 eV between 2009 and 2013. At present there are three such European flagship projects: CUORICINO, a bolometric detector in the Gran Sasso Lab, uses 41 kg ^{130}Te and plans to operate a 740 kg detector (CUORE) in the next decade. NEMO is a detector with both tracking and calometry capabilities using 8 kg ^{130}Mo and ^{62}Se in the Fréjus underground laboratory. A 100 kg ^{62}Se detector (Super-NEMO) for the next decade is in the design phase. GERDA is a ^{76}Ge detector. It will be operated in the Gran Sasso Lab from 2009 on and stepwise upgraded from 15 kg to 35 kg. In another approach, called COBRA, the use of CdTe is tested. US projects include MAJORANA, a germanium project like GERDA, and EXO, a xenon detector. These experiments could possibly "scrape" the mass range of the inverted hierarchy scenarios in Fig.7.

Europe is currently clearly leading the field of double beta decay searches and is in the strategic position to play a major role in next generation experiments. To cover a mass range of 20-50 meV, i.e. most of the range suggested by the inverted mass scale scenarios, one needs detectors with an active mass of order one ton, good resolution and very low background. Construction of such detectors might start in 2014-2017. 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 100-200 Million Euro scale, with a large contribution from the production cost for isotopes. The priority and urgency with which these experiments will be tackled will depend on the background rejection achieved in the currently prepared stages, on the available funding, and on the future bounds on the neutrino mass from cosmological observations.

6 Underground Laboratories

Proton decay, neutrino-less double beta decay or interaction of dark matter particles are extremely rare processes and the effects are extremely feeble. The signals from solar or geo-neutrinos are similarly weak. The study of these processes requires a low-background environment, shielded against processes which may fake a true signal. This environment is provided by special underground laboratories. The various tasks require different characteristics of the site. Double beta experiments and dark matter searches need housing for ton-scale detectors and very low radioactive background. Detectors for solar neutrino neutrinos need a moderate depth between 1000 and 2000 meter water equivalent and much larger caverns. For proton decay experiments, neither large depth nor extremely low radiactivity is needed, but the cavern for a Megaton detector naturally has to be huge.

There are five European underground laboratories which have been used in the past and are used presently for astroparticle physics deep underground experiments, with depths ranging between one and nearly five kilometer water equivalent : The Laboratori Nazionali del Gran Sasso (LNGS) along a motorway tunnel in the Apennines (Italy), the Laboratoire Souterrain de Modane, LSM, located along the Fréjus Road tunnel connecting Italy and France, the Laboratorio subterráneo de Canfranc, LSC, arranged along a tunnel connecting Spain and France, the Boulby Underground Laboratory in an operational potash and rock-salt mine on the North-East coast of England. Russia operates the Baksan Neutrino Observatory, BNO, in a dedicated tunnel in the Caucasus. A sixth very deep site in Finland is under discussion and some additional shallow locations are considered for special applications or as test sites (see Coccia 2006 for a review of European underground laboratories and Bettini 2007 for a recent compendium of underground laboratories worldwide).

The following years will lead to clearer picture of a task distribution between European sites. ApPEC will help finding solutions in case of conflicting national preferences and prioritizing possible extensions of the underground labs in accordance with the actual needs in Europe and worldwide.

7 The high energy universe

Much of classical astronomy and astrophysics deals with thermal radiation, emitted by hot or warm objects such as stars or dust. The hottest of these objects, such as hot spots on the surfaces of neutron stars, emit radiation in the range of some 10^3 to 10^4 eV, about thousand times more energetic than visible light. We know, however, that non-thermal phenomena, involving much higher energies, play an important role in the cosmos. First evidence for such phenomena came with the discovery of cosmic rays by Victor Hess in 1912. Hess measured radiation levels during balloon flights and found a significant increase with height, which he correctly attributed to a hitherto unknown penetrating radiation from space. In 1938, Pierre Auger proved the existence of extensive air showers – cascades of elementary particles – initiated by primary particles with energies above 10^{15} eV by simultaneously observing the arrival of secondary particles in Geiger counters many meters a part. Modern cosmic-ray detectors reveal a cosmic-ray energy spectrum extending to 10^{20} eV and beyond (see Fig.8). That are breath-taking energies, a hundred million times above that of terrestrial accelerators (Watson 2006, Olinto 2007).

How can cosmic accelerators boost particles to these energies? What is the nature of the particles? Do the particles at the very highest energies originate from the decay of super-heavy particle rather than from acceleration processes (top-down versus bottom-up scenarios)?

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.

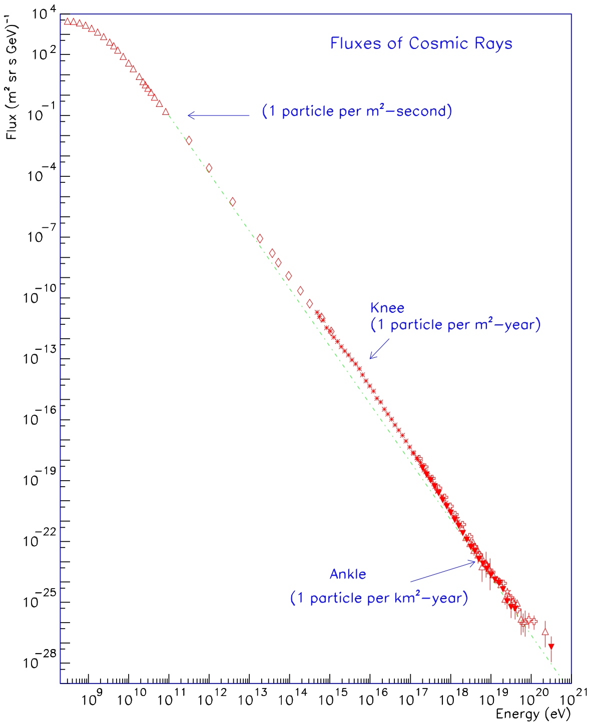

Fig. 8 The spectrum of cosmic rays (courtesy S.P. Swordy). The region below 10^{14} eV is the domain of balloon and satellite experiments, at higher energies ground based techniques take over. Galactic supernova remnants can accelerate particles to energies of 10^{16}-10^{17} eV, well above the "'knee"'. Galactic sources are believed to run out of power at 10^{17}-10^{18} eV. Highest observed energies dwarf the Large Hadron Collider at CERN which will accelerate protons to 10^{13} eV.

7.1 Charged cosmic rays

The highest energies

The present flagship in the search for sources of ultra-high energy cosmic rays is the Southern Pierre Auger Observatory in Argentina (Abraham et al. 2004), a 3000-km^2 array of water tanks, flanked by air fluorescence telescopes, which measure direction and energy of giant air showers (see Fig.9).

Even at energies above 10^{19} eV, where the cosmic flux is only about one particle per year and square kilometer, the Auger Observatory can collect a reasonable number of events. Starting with these energies, the deflection of charged particles in cosmic magnetic fields is going to be negligible and source tracing becomes possible. Very recently, the Auger collaboration has published a first sky map of events with energies above $10^{19.6}$ eV (Abraham et al. 2007, see Fig.10). There is a clear correlation of events with the super-galactic plane. Also, the authors report a correlation with positions of Active Galactic Nuclei with at least 99% confidence level. Such a correlation would be in agreement with theoretical expectations which classify only two objects to be able to accelerate particles up to 10^{20} eV or

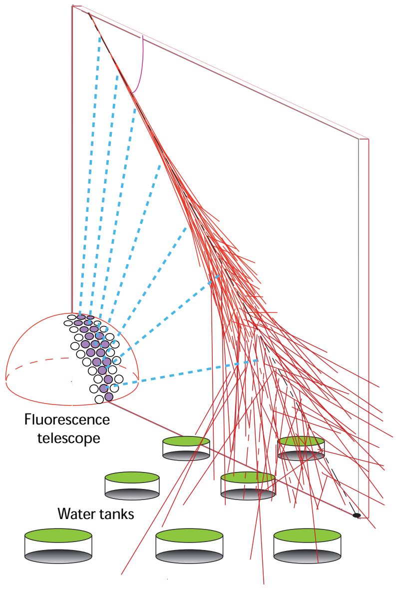

Fig. 9 The Pierre-Auger detection principles: Fluorescence light from air showers is recorded by telescopes, particles at ground level are recorded by Cherenkov water tanks

higher: the jets of AGN and Gamma Ray Bursts. Whether the interpretation of AGN as sources of the observed cosmic rays will withstand further tests and higher statistics has to be seen. If confirmed, it would mark the first step into astronomy with charged cosmic rays.

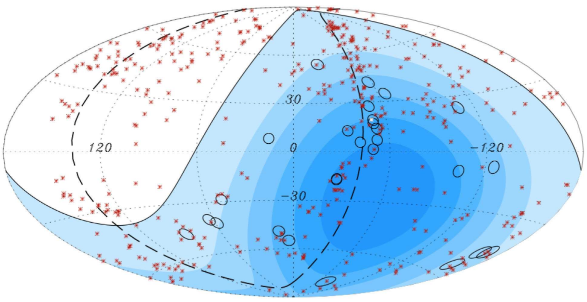

Fig. 10 Sky map in galactic coordinates of 27 cosmic rays with highest energies detected by the Pierre Auger Observatory (black circles), compared to positions of 472 quasars and active galactic nuclei with distance < 75 Mpc. The dashed line marks the super-galactic plane.

Full-sky coverage would be obtained by a Northern observation site, which has been determined to be in Colorado/ USA. This array would significantly exceed the Southern detector in size, possibly at the expense of low energy sensitivity, i.e. using a larger spacing of detector elements which would result in a higher energy threshold. European groups will play a significant role to establish the scientific case, and after its full demonstration make a significant contribution to the design and construction of Auger-North. The cost is estimated at 90 Million Euro, with a 45% European contribution, start of construction is conceived for 2010.

Between knee and ankle

The subjects of the Pierre Auger Observatory are extragalactic sources. There are hardly sources in our own Galaxy which could accelerate particles above 10^{19} eV. Still, it remains interesting at which energy galactic sources actually run out of power. The energy range between 10^{16} and 10^{18} eV has been covered by very few experiments. Energy spectra determined by different experiments differ significantly, mostly due to the problems in proper energy calibration. On the other hand the region above 10^{16} eV is of crucial importance for our understanding of the origin and propagation of cosmic rays in the Galaxy. What is the mass composition? Is this region dominated by sources other than supernova remnants? Is there an early onset of an extragalactic component? What is the relation between cut-off effects due to leakage out of the Galaxy and cut-off effects due to maximum energies in sources? Three experiments (Kascade-Grande in Karlsruhe/Germany, Tunka-133 in Siberia and IceCube/IceTop at the South Pole), each with about 1 km^2 area, are exploring this energy range. They will yield a precise measurement of the energy spectrum as well as improved knowledge about the mass composition (see e.g. Kampert 2006).

Below the knee

At energies below the knee, one notes the recent successful launch of the Pamela satellite experiment. It will hopefully be followed in a few years by the launch of the much larger AMS spectrometer and its operation on the International Space Station ISS. The plans for AMS are strongly affected by the unclear situation for Space Shuttle missions. Pamela and AMS, as well as future balloon missions, will search for anti-nuclei with much increased sensitivity and also measure the energy spectrum of different nuclei below the knee, up to energies 10^{12}-10^{15} eV/nucleon (see for a science summary Picozza & Morselli 2006). A large satellite mission (Nucleon) extending the direct particle measurements to close to the knee is planned in Russia, with some Italian participation.

7.2 TeV gamma rays

In contrast to charged cosmic rays, gamma rays propagate straight; compared to neutrinos, they are easy to detect. This has made them a powerful tracer of cosmic processes.

Among all the different techniques developed so far for gamma detection, primarily two have succeeded in providing catalogues with reliable source detections and spectral measurements: *satellite detectors* and ground based *Imaging Atmospheric Cherenkov Telescopes* (IACTs).

The first steps of cosmic particle acceleration are studied with satellite detectors for MeV energies like INTEGRAL, and for MeV-GeV energies, where the EGRET satellite has revealed more than 300 sources of radiation. In 2008, the GLAST detector will be launched and is expected to provide an even richer view of the universe at energies up to several 10^{13} eV.

Due to the small area of detectors on satellites, at energies above a few tens of GeV they run out of statistics. The higher energies are the domain of ground-based Cherenkov telescopes, covering the range above hundred GeV with extremely large sensitivities. They record the Cherenkov light from air showers originating from gamma ray interactions in the atmosphere. Large dishes focus the light to arrays of photomultipliers (”cameras”). From the shower image, direction, energy and character of the primary particle (hadron versus gamma ray) can be derived.

The IACT technique was pioneered in the USA with the development of the Whipple Telescope. Actually, it took the Whipple group nearly 20 years to eventually detect in 1989 a first source, the Crab Nebula (Weekes et al. 1989). During the last decade, European groups have been leading the development of IACTs and the field of ground-based high-energy gamma ray astronomy. Figure 11 shows a comparison of the TeV gamma sky map in 1996 and 2006. It illustrates the tremendous progress achieved within ten years. Most of the new sources in Fig. 11 have been established by H.E.S.S., an array of four Cherenkov telescopes in Namibia, and MAGIC, a large telescope at La Palma (Voelk 2006, Aharonian2007). Both telescopes are being upgraded.

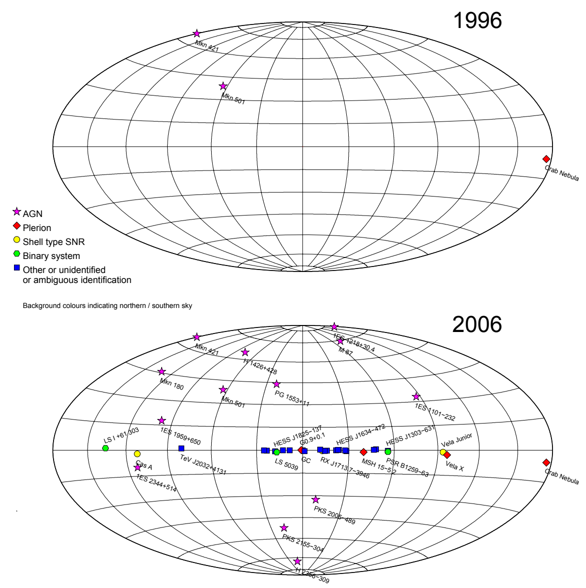

Fig. 11 The TeV gamma sky in 1996 (top) and 2006 (bottom); courtesy K. Bernlöhr.

IACTs have by now discovered more than seventy emitters of gamma rays at the 10^{11} to 10^{13} eV scale, many of them lining the Milky Way and revealing a complex morphology (see e.g. Fig. 12, taken from Aharonian et al. 2005). Most of the TeV sources correspond to known objects like binary stellar systems or 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 our own Galaxy, a large number of Active Galactic Nuclei have been observed and their fast variability demonstrated.

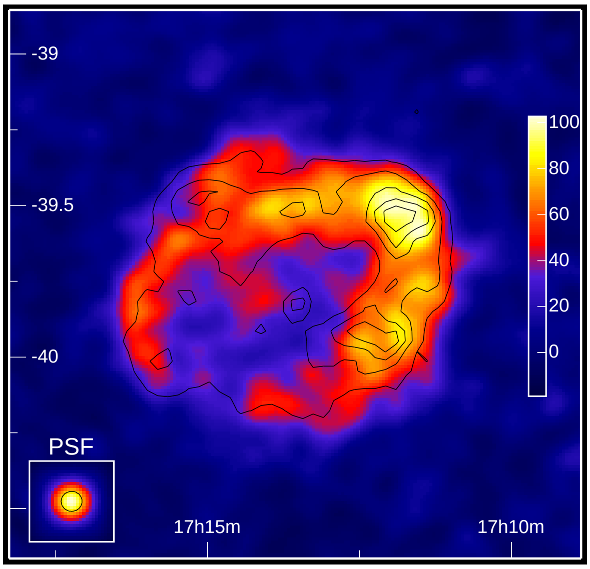

Fig. 12 Supernova remnant RXJ1713.7-3946 at radio wavelength (contours) and TeV energies (coloured regions).

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 cover 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. A proto-collaboration has been formed to work jointly towards the design and realisation of such an instrument, which was christened CTA (Cherenkov Telescope Array, see Hermann et al. 2007). It involves all European groups currently participating in IACTs, as well as a large number of additional new partners from particle physics and astrophysics. Actually, CTA is on the list of emerging projects compiled by the *European Strategy Forum for Research Infrastructures (ESFRI)* and has been proposed by the ApPEC steering committee to be promoted to the status of a full ESFRI entry.

The goal of CTA is simultaneously increasing the energy bandwidth towards lower and higher energies, improving the sensitivity at currently accessible energies, and providing large statistics of highly constrained and very well reconstructed events (see Fig. 13, taken from Hermann et al. 2007). CTA will likely consist of a few very large central dishes providing superb efficiency below 50 GeV, embedded in an array of medium dishes giving high performance around a TeV, the latter being surrounded by a few-km^2

array of small dishes to catch the bright but rare showers at 100 TeV: altogether 40-70 telescopes. A similar concept (AGIS) is being discussed in the USA, and the need for co-operation and coordination is obvious.

CTA is conceived to cover both hemispheres, with one site in each. The field of view of the Southern site includes most of the Galaxy, the Northern telescope would instead focus to extragalactic objects. At energies above a few tens of TeV and over Mega-parsec distances, gamma rays are absorbed by the cosmic infrared light fields, and above a few hundreds of TeV by the 3K background. Therefore high energy sensitivity of the Northern ("extra-galactic") site is less important than for the Southern ("center of the galaxy") site. For the Southern site, emphasis would be put to high-energy sensitivity and excellent angular resolution in order to study the morphology of galactic objects.

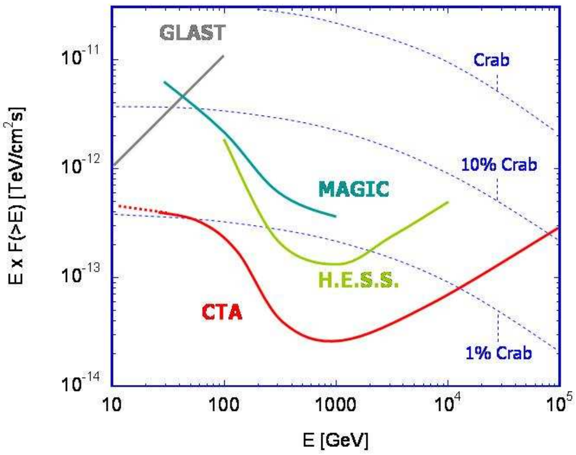

Fig. 13 Sensitivity of latest-generation Cherenkov instruments (H.E.S.S. and MAGIC) in comparison to that of the next-generation satellite experiment GLAST, and to the envisaged sensitivity of a next-generation Cherenkov instrument. The final values for CTA will depend on the actual layout. For reference, the gamma ray flux from the Crab Nebula is shown.

CTA, with its many telescopes of small field of view, will likely be complemented by wide-angle devices like HAWC, the successor of the MILAGRO experiment in the USA (Sinnis, Smith & McEnery 2004). This is a large water pool with photomultipliers detecting the light from air shower particles entering the water. Compared to IACTs, HAWC would have a higher threshold and worse flux sensitivity but – due to its large field of view – better survey capabilities and better sensitivity to extended sources. From the low energy side, the US-initiated GLAST instrument would overlap with CTA. Since parallel observations are desirable and GLAST will be launched very soon, CTA construction should start as early as possible.

7.3 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). However, whereas neutrino astronomy in the energy domain of MeV has been established with the impressive observation of solar neutrinos and neutrinos from supernova SN-1987A, neutrinos with energies of Giga electron volts and above, which must accompany the production of high energy cosmic rays, still await discovery. Detectors underground have turned out to be too small to detect the corresponding feeble fluxes. The high energy frontier of TeV and PeV (1 PeV= 10^{15} eV) is currently being tackled by much larger, expandable arrays constructed in deep, open water or ice. They consist of photomultipliers detecting the Cherenkov light from charged particles produced by neutrino interactions (see Fig.14). Flux estimations from astrophysical sources suggest that detectors on the cubic kilometre size scale are required for clear discoveries.

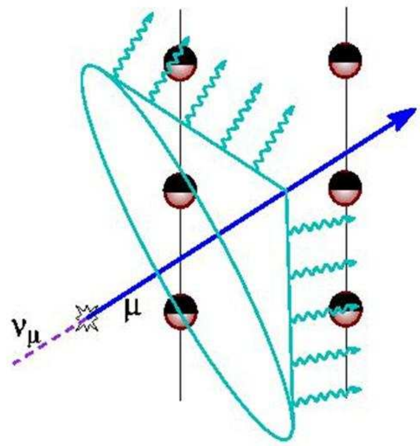

Fig. 14 Neutrino telescopes consist of large arrays of photomultiplier tubes underwater or under ice. They detect the Cherenkov light emitted by charged particles which have been produced in neutrino interactions – here from an up-going muon which stems from a neutrino having crossed the Earth.

European physicists have played a key role in construction and operation of the two pioneering large neutrino telescopes, NT200 in Lake Baikal (Belolaptikov et al. 1997) and AMANDA at the South Pole (Andres et al. 2001), and are also strongly involved in AMANDAs successor, IceCube (Ahrens et al. 2003, Spiering 2005).

Figure 15 shows a sky plot of the 4282 events recorded by AMANDA over five years (Achterberg et al. 2007). Even with this highest statistics of high energy neutrino events ever collected, no point source signal could yet be identified, motivating the construction of detectors more than one

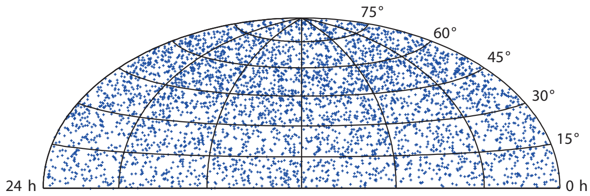

Fig. 15 Sky map of 4282 events recorded by AMANDA in 2000-2004.

order of magnitude beyond AMANDA size. Such a cubic kilometre detector, IceCube, is presently being deployed at the South Pole (Ahrens et al. 2003). Completion is foreseen in January 2011; it then will consist of 4800 photomultipliers arranged in 80 strings (see Fig.16) half of which have been installed by February 2008.

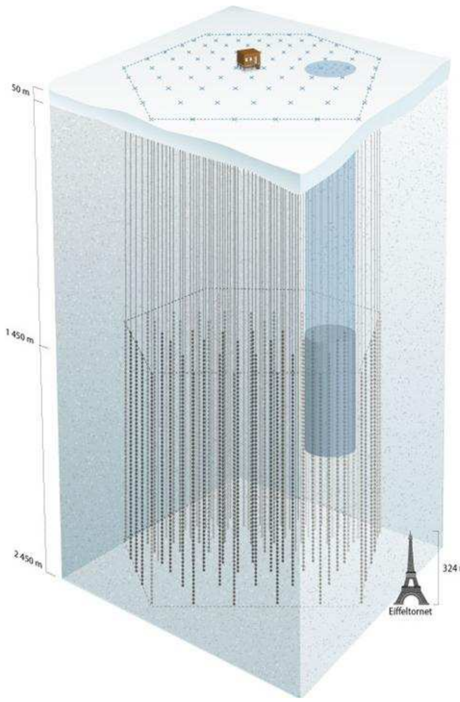

Fig. 16 IceCube schematic view. IceCube consists of 80 strings each equipped with 60 photomultipliers between 1400 and 2400 meters depth. AMANDA (small cylinder) is integrated into IceCube. IceCube is complemented by a surface air shower array, IceTop, which records air showers and greatly enhances the physics capabilities of the deep ice detector.

Using the Earth as a filter, IceCube observes the Northern sky. 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 (Halzen 2007). A prototype installation of AMANDA size, ANTARES, is presently being installed close to Toulon/France (Kouchner 2007), with 10 of a total of 12 strings already operating. R&D work towards a cubic kilometer detector is also pursued at two other Mediterranean sites, the one (NEMO) close to Sicily, the other (NESTOR) close to the Peloponnesus (Spiering 2003, Katz 2006, Amore 2007).

Resources for a cubic kilometre Mediterranean detector will be pooled in a single, optimized large research infrastructure. An EU-funded 3-year study (KM3NeT) is in progress to work out the technical design of a neutrino observatory in the Mediterranean, with construction envisaged to start in 2011 (Katz 2006). ESFRI has included KM3NeT in the *European Roadmap for Research Infrastructures*, thus assigning high priority to this project. Start of the construction of KM3NeT is going to be preceded by the successful operation of small scale or prototype detector(s) in the Mediterranean. Its design should also incorporate the improved knowledge on galactic sources as provided by gamma ray observations, as well as initial results from IceCube – including e.g. the possibility to construct, for similar cost, a 3 or 5 times larger array with higher energy threshold. Still, the time lag between IceCube and KM3NeT should be kept as small as possible. Figure 17 shows an example for a possible KM3NeT configuration, based on a "hollow cylinder" structure.

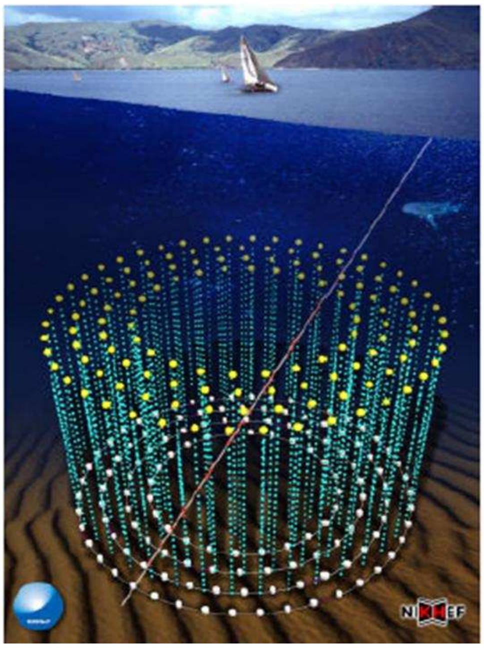

Fig. 17 Artists view by M. Kraan (NIHKEF) of a possible design of KM3NeT.

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 – see Böser & Nahnhauer 2006 for a review. Methods include recording the Cherenkov radio emission or acoustic signals from neutrino induced showers, as well as the use of air shower detectors responding to showers with a ”neutrino signature”. The very highest energies will be covered by balloon-borne detectors recording radio emission in terrestrial ice masses, by ground-based radio antennas sensitive to radio emission in the moon crust, or by satellite detectors searching for fluorescence light from neutrino-induced air showers. Taken all together, these detectors cover an energy range of more than twelve decades, starting at 10^{13}-10^{14} eV (10-100 GeV) and extending beyond 10^{22} eV. Limits come i.e. from air shower detection with optical methods, from radio searches for particle showers in the Moon, and from radio searches for particle showers in ice. All of them have been derived within the last decade. Exploitation of the full potential of these methods needs large-scale R&D work.

Summary on high energy neutrino detection

Within the last five years, experimental sensitivities over the whole energy range have improved by more than an order of magnitude, much faster than during the previous decades. Over the next 7-10 years, flux sensitivities are expected to move further down by a factor of 30-50, over the entire range from tens of TeV to hundreds of EeV. This opens up regions with high discovery potential.

8 Gravitational Waves

Gravitational waves would provide us with information on strong field gravity through the study of immediate environments of black holes. Typical examples are coalescences of binary systems of compact objects like neutron stars (NS) or black holes (BH). Even more spectacular events could be observed from galaxy collisions and the subsequent mergers of super-massive black holes residing in the centres of the galaxies. Further expected sources are compact objects spiralling into super-massive black holes, asymmetric supernovae, and rotating asymmetric neutron stars such as pulsars. Processes in the early Universe, on the time and length scales of inflation, must also produce gravitational waves.

Since the expected wavelengths are of the order of the source size, frequencies range from below a milli-Hertz to above a kilo-Hertz. Study of the full diversity of the gravitational wave sky therefore requires complementary approaches: Earth-based detectors are typically sensitive to high-frequency waves, while space-borne detectors sample the low-frequency regime.

Pioneers of direct observations have been using resonant bar detectors, and some (significantly improved) bar detectors are still in operation. However, the most advanced tools for gravitational wave detection are interferometers with kilometre-long arms. The passage of a gravitational wave differently contracts space along the two directions of the arms and influences the light travel time (Hong, Rowan & Sathyaprkash 2005).

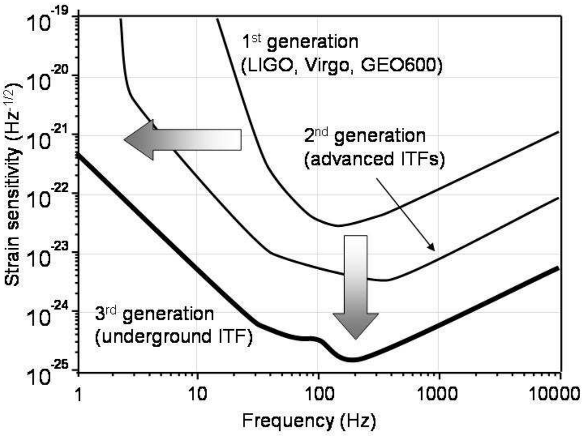

Fig. 18 Current and expected sensitivities for ground-based gravitational waves detectors (Courtesy H. Lück). Not shown are the curves for GEO-HF which will is the GEO600 interferometer tuned to high frequencies and for DUAL, a future medium bandwidth detector called DUAL. The third generation interferometer curve is a very preliminary estimate.

At present, the world’s most sensitive interferometer is LIGO (USA), the others being Virgo in Italy, GEO600 in Germany and the smaller TAMA in Japan. Given our current understanding of the expected event rates, gravitational wave detection is not very likely with these initial interferometers. Thus a mature plan exists for upgrades to the existing detectors systems to create *enhanced* and after that *advanced* detector systems, such that the observation of gravitational waves within the first weeks or months of operating the advanced detectors at their design sensitivity is expected (Fig. 18)

The European ground interferometers (GEO and Virgo) are turning to observation mode with a fraction of their time dedicated to their improvement (GEO-HF, Virgo+ and Advanced Virgo) – see Fig. 19. 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 5 years.

Even the advanced versions of the present interferometers will start reaching some fundamental limits, e.g. due to the seismic environment. Therefore the European Gravitational Wave Community envisages a *3rd* generation interferometer as seismically quiet underground facility. The sensitivity target is an order of magnitude better than that of Advanced LIGO and Virgo (three orders of magnitude in event rate) with the seismic cut off going down to less than 1 Hz (see Fig. 18). This new facility (the ”Einstein Telescope”, *E.T.*) would be a dramatic step and allow Europe to play a key role in what will then be the field of gravitational-

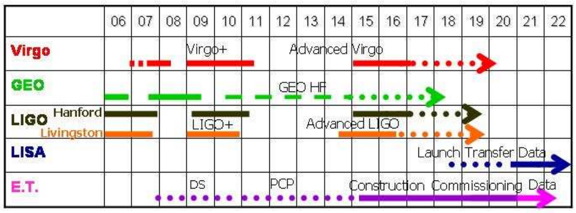

Fig. 19 Timeline of current detector operation and planned detector upgrades. The solid lines for the existing detectors indicate data taking times. In the regions of dotted lines the mode of operation is not yet defined. In the scenario shown, LISA would be launched in 2018. The *3rd* generation plans start with a 3 year design study in 2008, followed by a 4 year preparatory construction phase. Construction and commissioning will last for 6 years and allow data taking from 2021 onwards.

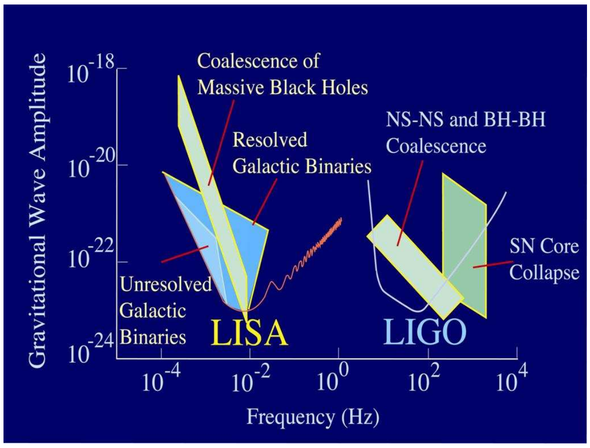

Fig. 20 Comparison of the sensitivity regions defining the science potential and the science targets of earth-bound and space interferometers, respectively (Courtesy H. Lück).

wave observational astronomy. E.T. would have a guaranteed rate of many thousand events per year and would move gravitational wave detectors in the category of astronomical observatories. A network of third and second generation detectors would measure to a few percent the masses, sky positions and distances of binary black holes with stellar- and intermediate (i.e. a few hundred times solar) mass, out to a redshift of $z = 2$ and $z = 0.5$, respectively.

E.T has been approved as a FP7 design study in 2007. The outcome of this work will be a conceptual design of the facility (including a selection of possible sites), followed by a more detailed preparatory construction phase to be in a position to start construction around 2015 (see Fig. 19). The design study will include conceptual aspects of the observatory to show that the envisaged sensitivity can be reached with the techniques, the funding and on the timescales foreseen. Cost for E.T. would be on the 500 Million Euro scale.

Gravitational wave astronomy from space

The frequency domain much below one Hz can be only explored from space. There is currently an ESA-NASA mission, LISA, which is scheduled for a launch in 2018. LISA would be ideally suited for the study of super-massive black holes mergers, galactic compact binaries (see Fig. 20) and potentially for the signatures of new physics beyond the standard model (Hughes 2007).

After transit to the final orbit, LISA will be ready for data taking in 2020, roughly coinciding with the Einstein Telescope, ET. LISA involves three spacecraft flying approximately 5 million kilometres apart in an equilateral triangle formation. These very long arms allow to cover a frequency range of $3 \cdot 10^{-5}$ to 1 Hz, complementary to the frequency window covered by ground-based instruments. Prior to LISA, the *LISA Pathfinder* mission, to be launched in 2010 by ESA, must test some of the critical new technology required for the instrument and proof the feasibility of the concept.

The advanced ground based detectors will assure the detection of gravitational waves within a few weeks or months. This is a necessary condition to move ahead and to aquire the substantial funding for E.T. and/or LISA. These two detectors then would move gravitational wave instruments eventually into the league of true astronomical observatories.

9 The Big Picture

In its strategy paper, the ApPEC roadmap committee argues that astroparticle physics is likely at the dawn of a golden age, as traditional astrophysics was two to three decades ago. The enormous discovery potential of the field stems from the fact that attainable sensitivities are improving with a speed exceeding that of the previous two decades. Improvement of sensitivities alone is arguably not enough to raise expectations. But on top of this, we are entering territories with a high discovery potential, as predicted by theoretical models.

The increasing speed of progress is illustrated by Fig. 2, with a strongly higher gradient of sensitivity improvement for Dark Matter search than any time before. Curves of nearly identical shape can be drawn e.g. for detection of high energy neutrinos or charged cosmic rays. For the first time experimental and theoretical techniques allow – or are going to allow – forefront questions to be tackled with the necessary sensitivity. A long pioneering period during which methods and technologies have been prepared is expected to pay off over the next 5-15 years.

The price tag of frontline astroparticle projects requires international collaboration, as does the realization of the infrastructure. Cubic-kilometre neutrino telescopes, large gamma ray observatories, Megaton detectors for proton decay, or ultimate low-temperature devices to search for dark matter particles or neutrino-less double beta decay are in the range of 50-800 MEuro. Cooperation is the only way *a)* to achieve the critical scale for projects which require budgets and manpower not available to a single nation and *b)* to avoid duplication of resources and structures. Astroparticle physics is therefore facing a similar concentration process as particle physics since several decades.

The following list of experiments on the >50 MEuro scale cost for investment is the result of a first strategic approach of European Astroparticle Physics (Phase-I of the ASPERA Roadmap).

– **High energy gamma astronomy:** A large Cherenkov Telescope Array (CTA). Desirably two sites, one South, one North. Overall cost 150-170 MEuro. Prototypes 2011, start of construction in 2012.
– **High energy neutrino astronomy:** A kilometer scale neutrino telescope KM3NeT in the Mediterranean, complementing IceCube on the opposite hemisphere. Cost scale 200 MEuro. Start construction after a preparatory phase, in 2011 or 2012.
– **High energy cosmic ray astronomy:** Auger-North, complementing the Pierre-Auger Site in Argentina. Cost about 90 MEuro, 45% of that from Europe. Start construction in 2010 or 2011.
– **Direct Dark Matter searches:** Two "zero-background"dark matter experiments on the ton scale, with a cost estimate of 150-180 MEuro for both experiments and the related infrastructure together. Two different nuclei and techniques (e.g. bolometric and noble liquid). Decision in 2010/2011.
– **Masses and possible Majorana nature of neutrinos by double beta decay experiments:** Next generation experiments are GERDA, CUORE, Super-NEMO. Decision about an "ultimate" ton-scale experiment in the next decade, start of construction not before 2013. Cost on the 150 MEuro scale. Share with non-European countries.
– **Proton decay and low energy neutrino astrophysics:** A detector on the Megaton scale. Worldwide collaboration, close coordination with USA and Japan. Cost between 400 and 600 MEuro. Decision on technology after the end of the design phase, 2010-2012.
– **Gravitational waves:** The third generation Graviational Wave interferometer, located underground. Cost at the 500 MEuro scale. Need detection of Gravitational Waves with "advanced" interferometers before construction would be approved. Coordination with space plans (LISA) is important.

Naturally, there must be room for initiatives below the 50 Million Euro level. The Roadmap committee suggests that about 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.

With ApPEC and the related ERA-Net ASPERA, the process of coherent approaches within Europe has already successfully started. ApPEC represents nearly two thousand European scientists involved in the field. ApPEC helped to launch ILIAS, an Integrated Infrastructure Initiative with leading European infrastructures in Astroparticle physics. ILIAS covers experiments on double beta decay, dark matter searches and gravitational wave detection as well as theoretical astroparticle physics. ApPEC has also actively promoted the approval of KM3NeT as ESFRI project and FP6 design study, of CTA as emerging ESFRI project, of the Megaton neutrino detector study LAGUNA and the *3rd* generation gravitational interferometer E.T. as FP7 design studies and also the FP7 support for the preparatory phase of KM3NeT. ApPEC will also play an important role in forming a coherent landscape of the necessary infrastructures, in particular of the underground laboratories.

Phase-I of the roadmap (http://www.aspera-eu.org) describes physics case and status of astropraticle physics and formulates recommendations for each of the subfields. In a second phase (Phase-II), detailed information on time schedule and cost have been collected from all experiments. There is also a census on the present funding level collected from the national funding agencies. Phase-III has just started. During this phase, a precise calendar for milestones and decisions will be prepared. Also, priorities will be formulated, based on different funding scenarios. A Phase-III roadmap paper will be released in autumn 2008. This work will provide the necessary input for the decisions on the large projects of the list above. Clearly, the required resources exceed the present funding level. The roadmap committee of ApPEC is, however, convinced that the prospects in this field merit a substantially increased support.

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