ASTROPARTICLE PHYSICS

the European strategy

ASPERA

SIXTH FRAMEWORK PROGRAMME

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Members of the Roadmap Committee, 2008

Elena Aprile
Laura Baudis
Jose Bernabeu
Pierre Binetruy
Christian Spiering (chair)
Franz v. Feilitzsch
Enrique Fernandez
Andrea Giuliani
Werner Hofmann
Uli Katz
Paul Kooijman
Paolo Lipari
Manel Martinez
Antonio Masiero
Benoit Mours
Francesco Ronga
Sheila Rowan
André Rubbia
Subir Sarkar
Günther Sigl
Gerard Smadja
Jenny Thomas
Lucia Votano

Editorial Board

Maurice Bourquin
Stavros Katsanevas
Arnaud Marsollier
Deborah Miller
Christian Spiering
Rob van der Meer

Graphic design

Arnaud Marsollier
Didier Rouable

Aspera Working Group Leads

Dark Matter:
Gabriel Chardin
Nigel Smith

Neutrino Mass:
Andrea Guiliani
Fabrice Piquemal
Stefan Schönert

Megaton Detector:
Aldo Ianni
André Rubbia

Charged Cosmic Rays
Andreas Haungs
Günther Sigl

Gamma Rays
Werner Hofmann
Manel Martinez

High Energy Neutrinos
Uli Katz

Gravitational Waves
Harald Lück
Michele Punturo

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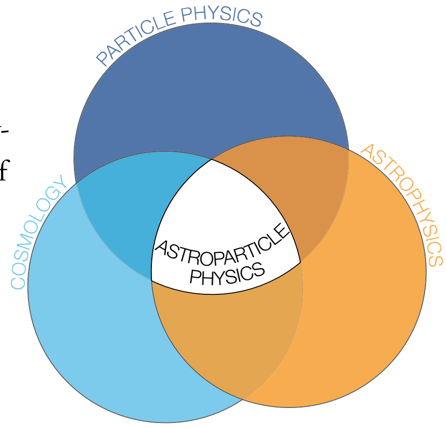
Towards a European Strategy for Astroparticle Physics



Astroparticle Physics is a rapidly growing field of research at the intersection of astrophysics, particle and nuclear physics and cosmology. It addresses questions like the nature of dark matter and dark energy; the stability of protons and the physics of the Big Bang; 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 and the view of the sky at extreme energies; and violent cosmic processes as seen with gravitational waves.

The past two decades have seen the development of the technologies to address these questions with a dramatically increased sensitivity. For several of the questions we are at the threshold of exciting discoveries which will open new horizons. However, the high cost of frontline astroparticle projects requires international collaboration, as does the realisation 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 at the hundred million Euro scale. Cooperation is the only way to achieve the critical mass for projects which require budgets and manpower not available to a single nation, to avoid duplication of resources and infrastructure, and to keep Europe in a leading position.

To promote cooperation and coordination, in 2001 ApPEC (Astroparticle Physics European Coordination) was founded, as an interest grouping of several European scientific agencies. Since 2006 it has been flanked by ASPERA, a European Union ERANET project. In 2007, a Phase-I stage of a roadmap, *Status and Perspective of Astroparticle Physics in Europe*, was presented by its Roadmap Committee, describing the status and desirable options of European astroparticle physics for the next decade. For the present document, more precise timelines and updated cost estimates have been compiled by working groups set up by ASPERA for each of the sub-fields, and the funding landscape was mapped in more detail. We have shared our views and findings with the CERN Council Strategy Group which formulated a *European Strategy for Particle Physics*, and with the astrophysics community which produced a *Science Vision for European Astronomy and an Infrastructure Roadmap for European Astronomy*. The process also included several all-community meetings. As a result, the Roadmap Committee presents proposals for the high priority experiments, for the phasing of large projects and for international cost sharing (see for more detailed information about individual experiments and about cost the long write-up at http://www.aspera-eu.org which is presently being compiled). Our proposals fit within a funding scenario with a smooth factor of two increase over the next 8-10 years. The present document is intended to establish the case for increased activity and investment, as part of the first common European strategy for astroparticle physics. New exciting discoveries lie ahead; it is up to us to take the lead on them in the next decade.

Specifically, the Roadmap Committee proposes seven types of major projects, on different time scales:

- **Ton-scale detectors for dark matter search**
- **A ton-scale detector for the determination of the fundamental nature and mass of neutrinos**
- **A Megaton-scale detector for the search for proton decay, for neutrino astrophysics and for the investigation of neutrino properties**
- **A large array of Cherenkov Telescopes for detection of cosmic high energy gamma-rays**
- **A cubic kilometre-scale neutrino telescope in the Mediterranean Sea**
- **A large array for the detection of charged cosmic rays**
- **A third-generation underground gravitational antenna**

CONTENTS

1. A century of exploration and discovery

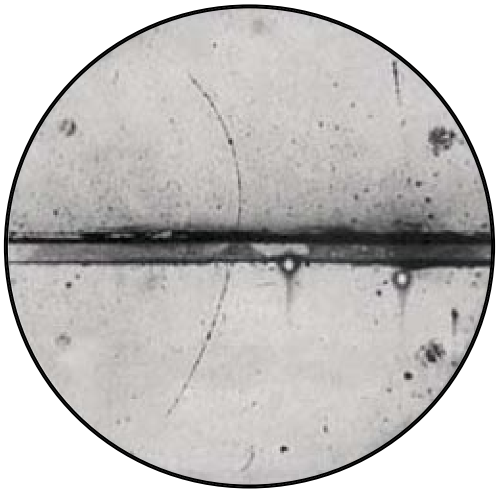
The term astroparticle physics was coined about thirty years ago and has only been used as a commonly accepted label since the nineties. But its roots reach back a century, and the story of this century is a story of remarkable explorations and discoveries. We describe some highlights below.

August 1912: Victor Hess after his highest balloon flight. Hess' discovery of cosmic rays was acknowledged with the 1936 Nobel Prize in Physics.

Cosmic rays

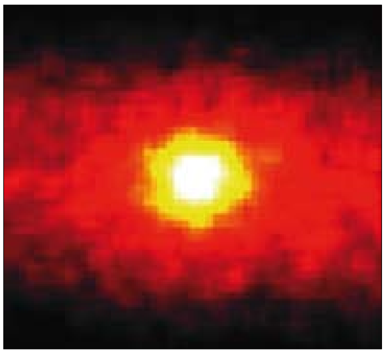
In 1911 and 1912, Austrian physicist Victor Hess performed a series of high-altitude balloon flights in order to measure how ionising radiation would change with altitude. Contrary to initial expectations, his small radiation detectors showed stronger signals the higher he moved. He concluded that a steady rain of something ionizing fell to Earth from outer space, something different from light and meteorites, the only cosmic messengers known at that time. It took some years to realize that these cosmic rays essentially consist of protons, light and heavier nuclei, with a minuscule admixture of electrons.

Two decades later, in 1932, the first antiparticle – the positive electron or positron – was discovered in cosmic rays (Nobel Prize 1937).



One of the first positron tracks in a cloud chamber, recorded by Carl D. Anderson in 1932.

The next was the 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 so-called mesons (Nobel Prize 1950)



e Sun as seen in neutrinos. e picture is composed from several thousand neutrinos recorded by the Japanese Super-Kamiokande detector.

Until the early fifties, cosmic rays remained the main resource for discovering new particles. At that time, particle accelerators took over and replaced cosmic rays as the main tool to explore the micro-cosmos.

The solar neutrino puzzle

The emergence of accelerator based research was not the end of cosmic particle physics. Most notable was the attempt to better understand the interior of the Sun by detecting neutrinos.

Wolfgang Pauli had postulated the existence of these ghostly particles in 1932, in an desperate attempt to explain the apparent deficit in the energy released in radioactive beta decays. He assumed that their interaction probability was so small that they were undetectable. But in 1956, American researchers Frederick Reines und Clyde Cowan succeeded in recording a handful of the billions and billions of antineutrinos escaping from a nuclear reactor in the USA (Nobel Prize 1995).

It was soon realised that neutrinos could be very special cosmic messengers. As hard as they are to detect, as easily they escape from compact celestial bodies like the Sun. Indeed, the Sun is fuelled by nuclear fusion reactions, and the only particles produced in its core which can carry undisturbed information from there to the Earth are neutrinos.

In the early seventies, the lengthy attempts to record solar neutrinos paid off: Raymond Davis (USA) succeeded in recording solar neutrinos in a deep underground detector, well shielded against noise by more than a kilometre of rock. The surprise was that he measured only a third of the expected flux. Was his measurement wrong? Did the Sun work differently than expected? The solar neutrino puzzle was born.

In the end, the solar neutrino deficit was confirmed by other experiments and eventually explained by a mechanism which Bruno Pontecorvo (USSR) had proposed as early as 1957. He assumed that the different types of neutrinos can transform into each other. Today, this effect is known as neutrino oscillation. The Davis detector had only responded to one of the three types, electron neutrinos. The Sun produces exclusively electron neutrinos, and their partial transformation into the two other types led to the observed deficit. It was only in 2001 that this explanation was confirmed beyond any doubt, and that by combining data from many experiments all other hypotheses could be excluded. Oscillations have a fundamental consequence: they are only possible if neutrinos have mass, and this is the first sign of physics beyond the Standard Model of elementary particles. It is remarkable that this hint did not come from an accelerator experiment but from astroparticle physics.

Grand Unified Theories: The cosmic bridge

The real thrill in the cosmic arena came only in the early eighties when some pioneers attempted to test Grand Unified Theories of particle physics (GUTs). These theories aim at a coherent description of three fundamental forces of physics. Actually, conditions when the striking differences between these forces were negligible existed only during the Big Bang. Therefore, GUTs span a fascinating grand bridge between the worlds of the smallest and the largest. GUTs predict that protons, the basic block of ordinary matter, would not live forever. The simplest GUTs predicted proton lifetimes of 10^{29}-10^{32} years, 10^{20} times the age of the Universe.

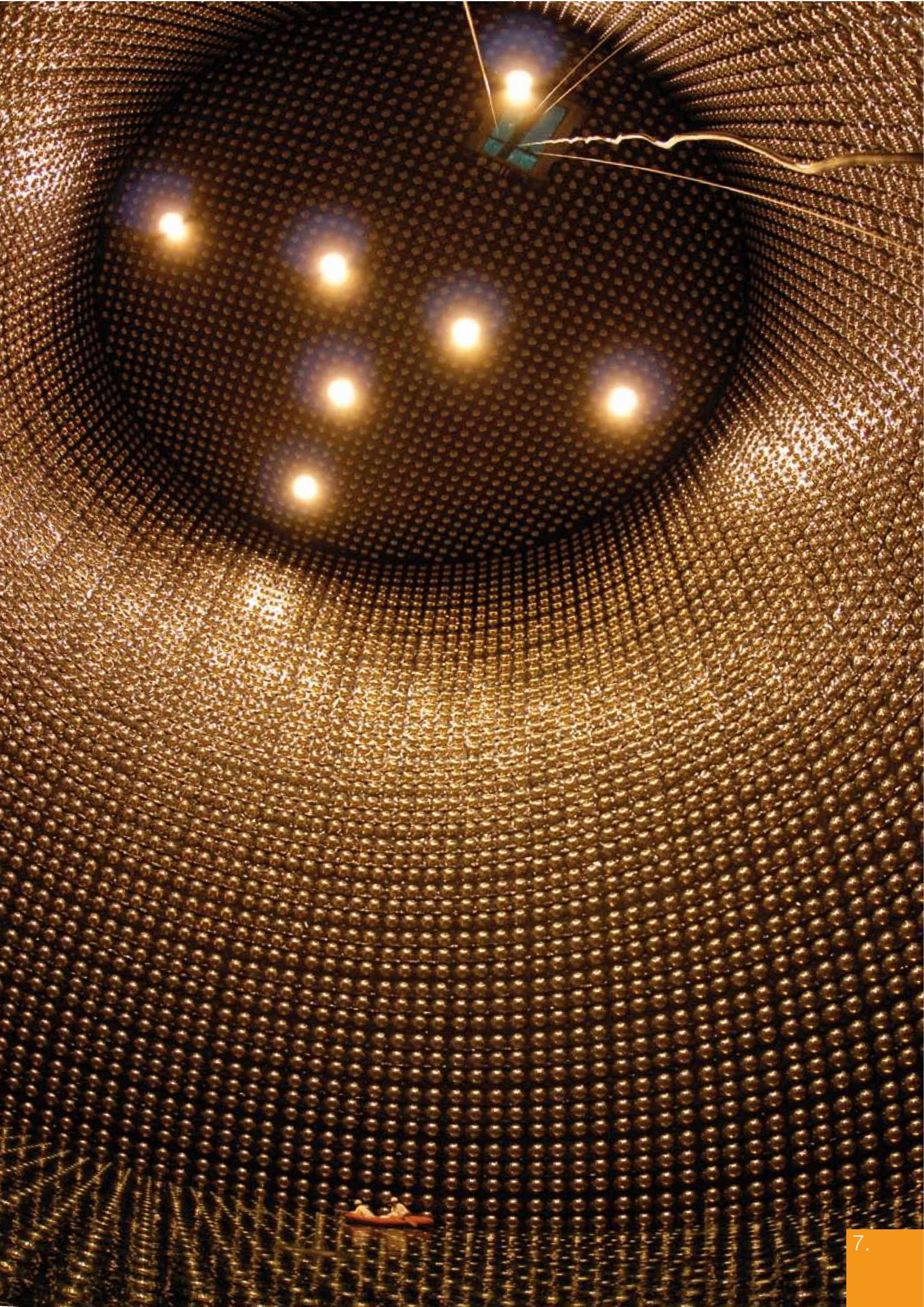
In spite of this long lifetime, decays of protons could be detectable, for instance by observing 10^{33} protons corresponding to roughly 3000 tons of water, in the volume of the Kamiokande detector in a deep Japanese mine. Kamiokande failed to see proton decays, and actually the lower limit for proton decays is now nearly 10^{34} years, ruling out a lot of the simplest GUTs.

The birth of neutrino astronomy

Instead of seeing proton decays, on February 23, 1987, Kamiokande recorded 12 neutrinos from a supernova explosion in the Large Magel-

e Large Magellanic Cloud before and after the supernova explosion. e arrow marks the position of the exploding star.

Inside 'Super-Kamiokande', the successor of Kamiokande. The walls are paved with 11000 photo sensors. The water tank is just going to be filled with 50000 cubic meters of water. At the bottom a small boat.



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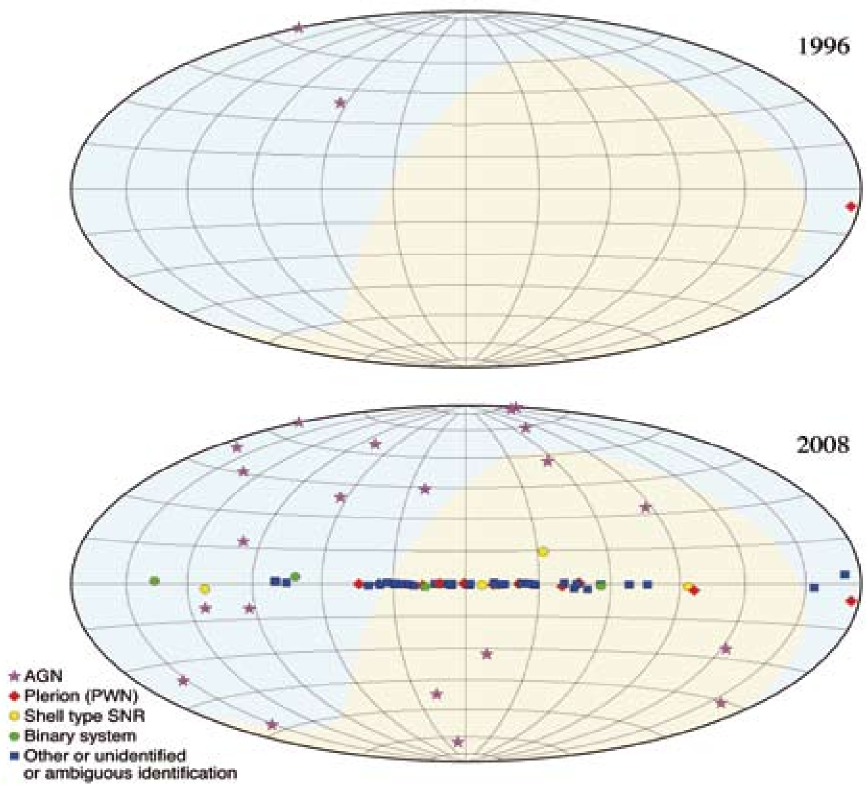
lanic Cloud, a small satellite galaxy of the Milky Way. The particles had made a 160 000 year journey and spectacularly confirmed the calculations about the processes deep in a collapsed star. This discovery came out of the blue and it was made by three detectors simultaneously, the others being located in the USA and in the USSR. February 23, 1987 is therefore considered as the real birth of neutrino astronomy. Raymond Davis and Kamiokande's Masahiro Koshiba were honoured with the 2002 Nobel Prize for physics, "for opening a new window to the Universe" – the window of neutrino astronomy.

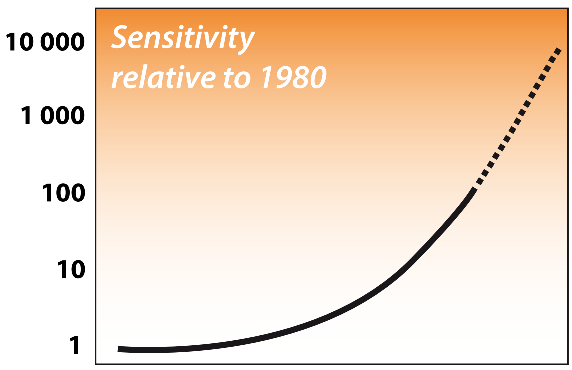
The past decade: gaining speed

The detection of solar and supernova neutrinos is not the only new window to the Universe opened by astroparticle physics. Another is that of high energetic gamma rays

e high energy gamma ray sky, 1996 and 2008

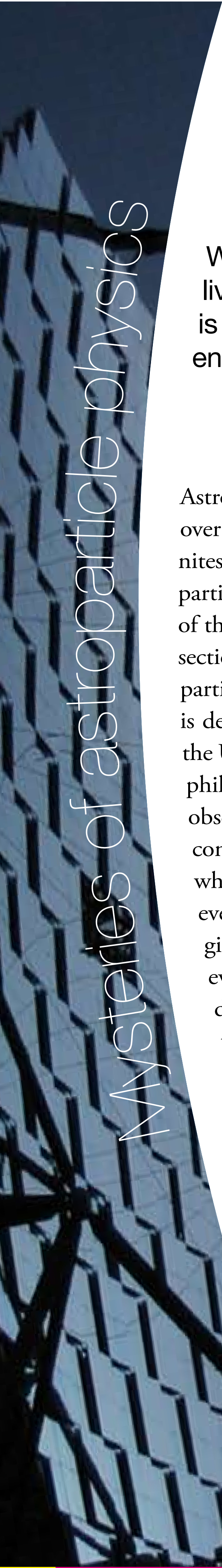


recorded by ground based Cherenkov telescopes – a particularly fruitful field over the last decade. The wavelength of these gamma rays is roughly twelve orders of magnitude shorter than that of visible light. Their energy (many Tera-electronvolts, or TeV) is similar to that of the Large Hadron Collider, the most powerful particle accelerator ever built. From the first TeV gamma source detected in 1989, over three sources known in 1996, about 40 sources identified by the end of 2006, up to the present 75, the high energy sky has revealed a stunning richness of new phenomena and puzzling details.



Sensitivity in many branches of astroparticle physics has improved over the last 30 years. A meagre factor 3 per decade has turned into a factor 10-100 per decade.

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 sources of high energetic cosmic rays or neutrinos or the attempts to detect gravitational waves. Many of the branches of astroparticle physics have moved from infancy to technological maturity, and the attainable sensitivities are improving with a speed far exceeding that of the previous two decades. The improvement of sensitivities alone is arguably not enough to raise expectations. On top of this, we are entering territories with a high discovery potential, as predicted by theoretical models. 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 five to fifteen years!



2. The questions of Astroparticle Physics

What is the inventory of the Universe? What is dark matter? Do protons live forever? How did neutrinos influence cosmological evolution? What is the origin of cosmic rays and what is the view of the sky at extreme energies? What will gravitational waves tell us about the Universe?

Astroparticle physics links phenomena over a vast distance scale – from the infinitesimally small worlds of subatomic particles to the billion light year distances of the whole Universe. It marks the intersection of cosmology, astrophysics and particle and nuclear physics. Cosmology is devoted to the very grand mysteries of the Universe. After centuries of relying on philosophical reasoning and astronomical observations, cosmology increasingly uses concepts of particle physics. Astrophysics, when exploring the most violent cosmic events, needs particle physics technologies to record the messages from these events, and particle physics theory to describe them. And particle physics, at the end, is rejuvenated by questions asked in cosmology and astrophysics, and by the recent spectacular results obtained with astroparticle physics experiments.

Given the interdisciplinary approach of astroparticle physics and its overlap with astrophysics, particle physics and cosmology, a concise definition of which experiments may be considered "astroparticle physics" is di cult and perhaps not even desirable.

For the purpose of this roadmap, historical assignments used in most European countries have been adopted. Recommendations for the evolution of the field over the next decade were formulated by addressing a set of basic questions. 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.

1) **What is the Universe made of ?**
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?**

The following chapters describe the tools to address these questions.

First arguments for dark matter have been derived by the Swiss scientist Fritz Zwicky in 1933, after evaluation of the movements of galaxies in larger clusters. In the seventies, the rotational curves of galaxies suggested that 90% of most galaxies is made from invisible matter.

3. Dark matter & dark energy

Normal matter appears like small ships sailing on an ocean of dark matter and dark energy. Particle physics provides possible candidates for dark matter, but as yet no clear idea exists for what dark energy might be. A next generation of experiments will provide new answers.

The cosmic inventory

Since the 1930s, astronomers came to realise that most of the Universe is invisible and made of matter different from the ordinary stuff we see as stars and galaxies. This invisible matter makes up 90% of the mass of our Galaxy, the visible mass being just 10%. In the Universe as a whole, normal matter only contributes 5%! About 23% is attributed to dark matter which reveals itself by its gravitational attraction. Since 1998, another piece of inventory was introduced, in order to explain an apparent acceleration in the expansion of the Universe: dark energy. At 72%, it seems by far to dominate the rest and may ultimately dictate its fate.

What is dark matter?

For particle physicists, the hunt for dark matter is closely connected with the search for new particles. These particles would not only provide important clues in understanding the early Universe, but also would fill "gaps" in particle physics. The prime suspect of most experts is a particle which is weakly interacting, similarly to neutrinos, but much heavier than the proton: a WIMP (Weakly Interacting Massive Particle). Such a particle is also suggested by super-symmetric theories of particle physics. Other candidates are conceivable, among them axions, also a theoretically predicted particle.

If this jar of jelly beans was the Universe, ordinary matter would be represented by the coloured ones, composing only 5% of the whole. e Universe is mostly dark. 95% consist of dark matter and dark energy.

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With an array of 31 photomultipliers, the Zeplin III detector in the Boulby Underground Mine (UK) records light flashes in liquid xenon. It also measures the related electrical current.

How to detect dark matter?

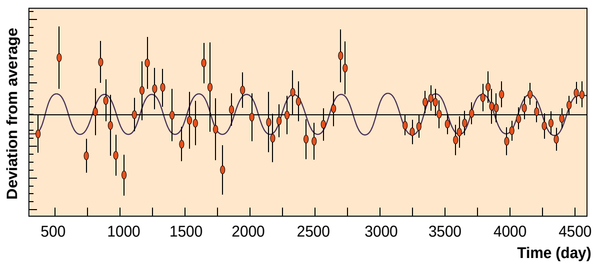
From a technical point of view, the question can be tackled in three ways, each exploiting the tools of nuclear and particle physics.

"Direct methods" look for signals from nuclei kicked on by a WIMP. Since WIMPs interact rarely and the signals are feeble, the detectors are operated deep underground, well shielded against noise and ambient radioactivity which may mimic WIMP signals. "Indirect methods" look for particles such as neutrinos, gamma rays or antiparticles that would emerge from WIMP annihilations in celestial high-density regions, like the Sun or the centre of the Galaxy. Last but not least, dark matter particles may be produced in high energy particle interactions at the Large Hadron Collider.

Devices for direct dark matter detection

Some of the direct-search underground detectors aim to detect the light flashes emitted when a WIMP strikes a nucleus, some the released heat and some the feeble electric current of that interaction.

The DAMA collaboration is studying light flashes in NaI crystals and reports an intriguing annual modulation of their event rate. Such an effect could be a consequence of the Earth's revolution around the Sun since the strength of head-on collisions depends on the relative velocity between the "sea" of WIMPs and the target nuclei in the detector. However, in order to prove whether this modulation is indeed due to dark matter particles rather than to some other annual effect, it must be confirmed by other experiments.



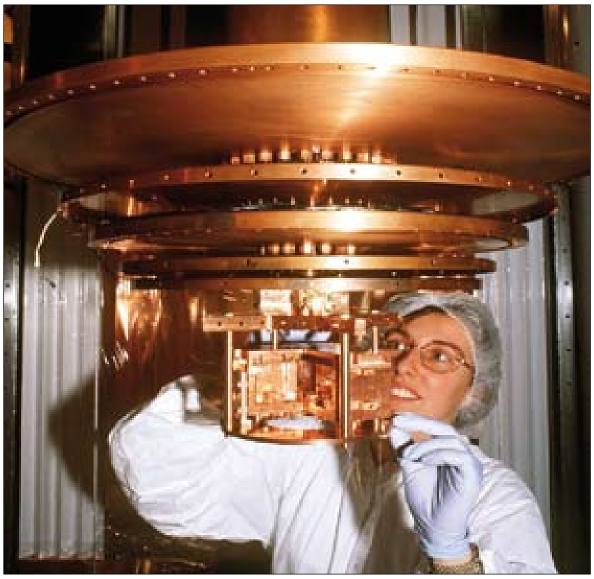
Annual modulation of the counting rate observed by the DAMA experiment in the Italian Gran Sasso Laboratory – first with 100 kg (larger error bars), later with 250 kg detector mass (small error bars).

The combination of two of the aforementioned signatures provides the best rejection of fake signals.

Detecting light or electric current together with the heat released in ultra-cold crystals is one way, detecting electric current together with light in detectors filled with noble liquids another. Present best sensitivities have been obtained with the cryogenic CDMS detector in the USA, and with XENON, a USA-European liquid xenon detector operated in the Gran Sasso underground laboratory in Italy.

No clear WIMP signal has been identified with the existing two-signature detectors of several kilograms mass. Therefore, the need for larger masses and even better noise reduction is obvious. European dark matter teams working with cryogenic techniques are focussing their efforts towards a ton-scale detector, EURECA, with dramatically improved rejection of noise signals. Collaborations using noble liquid detectors filled with argon and xenon are presently constructing devices on the 100-kg scale and envisage next generation detectors of a ton and beyond.

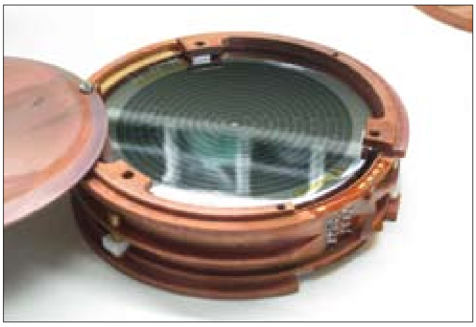
Towards the 100 kg scale: e XENON team is installing a larger detector.



e CRESST detector in the Gran Sasso Laboratory searches for a combination of light and heat signals in crystals cooled down to about 20 milli-Kelvin.

Dark matter strategy

We recommend supporting the current round of these experiments at a high priority, as well as the technology development towards their next-generation versions on a ton scale. These detectors will exceed the sensitivity of present detectors by about three orders of magnitude and therefore will have a fair chance of discovering WIMP dark matter. A recommendation on which of the technologies – noble liquid or cryogenic crystals – should first move to a next stage can only be made after



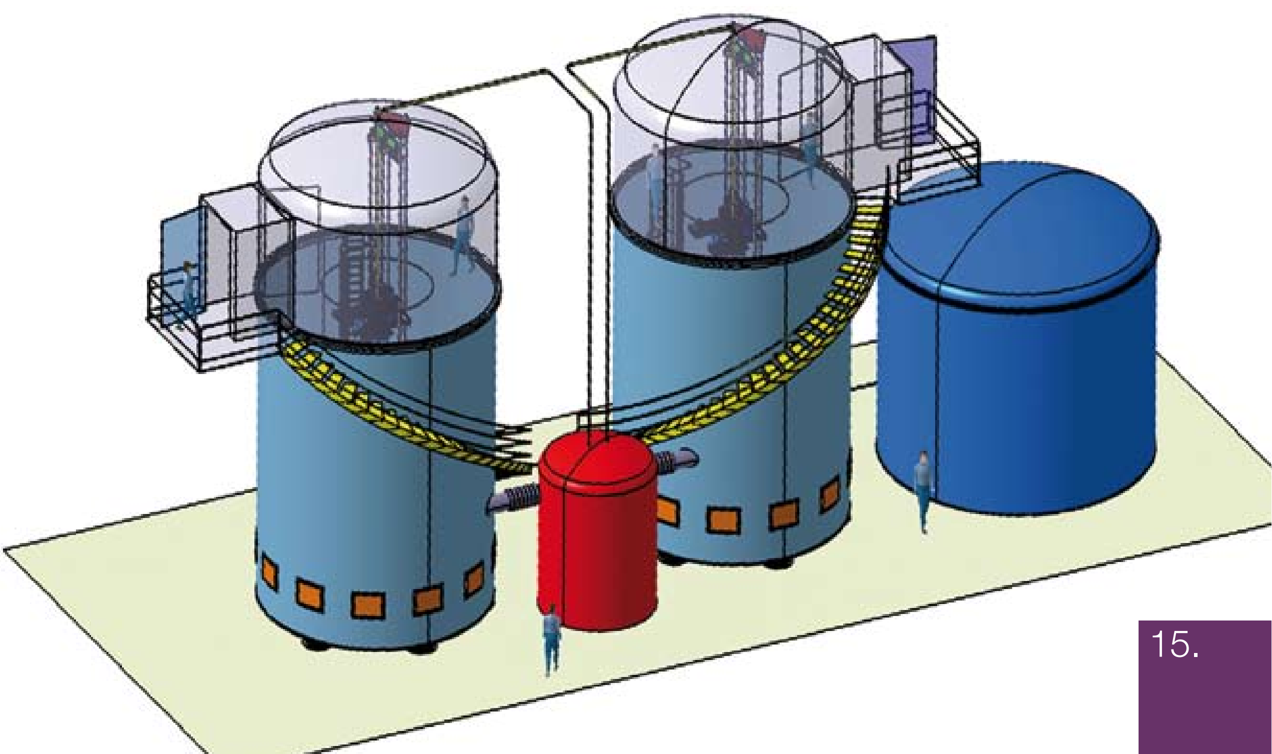
A combination of heat and electrical current in germanium crystals is recorded by the Edelweiss detector in the Laboratoire Souterrain de Modane (France).

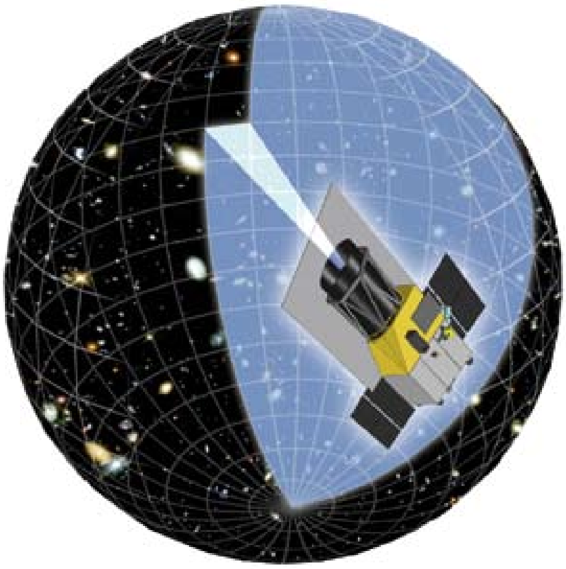
e central part of a 100-litre liquid argon detector being installed by the WARP collaboration in the Gran Sasso Laboratory.

first results from the present experiments in the 10 to 100 kg target mass range become available and after noise rejection and sensitivity/cost ratio for ton-scale detectors can be judged on a more realistic basis. This milestone can be reached by 2010 or 2011.

As soon as one of the technologies turns out to be clearly superior in sensitivity, cost, and timing, we suggest promoting this technology with priority.

Artist's view of the planned EURECA experiment, joining expertise from predecessors CRESST and Edelweiss.





Artist's view of a possible design for a European space mission EUCLID.

Dark energy

Particle physicists have been engaged in the field of dark energy since the beginning. They contributed with their experience of handling large data sets and with cutting-edge technologies. Since the construction of future instruments – large telescopes and space missions – depends on choices beyond the single authority of the agencies charting this roadmap we refer to the Infrastructure Roadmap for European Astronomy for a more complete overview of projects related to dark energy. Looking beyond existing instruments, a next generation of cosmology missions is already in preparation. Examples are the European Planck mission on a satellite exploring the 2.7 Kelvin radiation with unprecedented sensitivity, and the ground-based Dark Energy Survey (DES), the latter with European participation from Spain and UK. Projects to be started after 2013 include the Large Synoptic Survey Telescope, LSST, and the space based missions JDEM (NASA/DOE) and EUCLID (ESA). At present, there is a growing number of European institutions planning to participate in these projects. Worldwide, a variety of other projects are envisaged or are being prepared, like SKA, the Square Kilometre Array, which appears as an entry in the European Roadmap for Research Infrastructures, ESFRI. Needless to say, many of these devices support a variety of standard astronomical tasks and are not limited to dark energy surveys. Given the profound implications for fundamental physics, dark energy missions find the strongest support from the astroparticle physics community.

e Large Synoptic Survey Telescope LSST

Computer-simulated image of dark matter clumps which act as seeds for the later formation of galaxies.

4. Properties of neutrinos

Neutrinos by far outnumber atoms in the Universe. They may have helped shape the Universe and may well be the reason that we are here. Most of what we know about these ghostly particles we have learned during the last decade, but some fundamental questions remain.

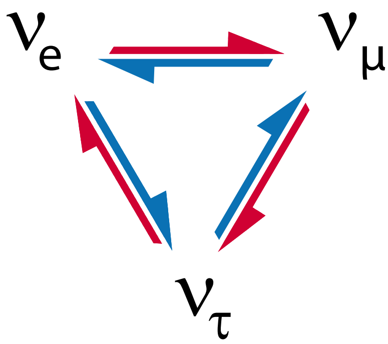
"Almost nothing" and almost everything

When Pauli postulated the neutrino, he was not only convinced that they were not detectable at all, but also could not imagine that they are related to our own very existence. Truly, the neutrino's tendency to interact with matter is tiny: among the 60 billions of solar neutrinos which cross every square centimeter on Earth per second, only a handful collides with an atomic nucleus; the rest passes the Earth unaffected. However, this «almost nothing» is essential for our life and for the Universe as a whole:

- Neutrinos helped to cook the light elements in the early Universe.
- Neutrinos tell us how the Sun shines.
- Without neutrinos dying stars would likely not explode and fertilize the cosmos with heavy elements, a necessary ingredient of our existence.
- Neutrinos may have been essential for the disappearance of antimatter. A tricky mechanism named leptogenesis could have produced an excess of anti-neutrinos in the early Universe, eventually leading to the dominance of matter particles like protons, neutrons and electrons and leaving the Universe without antimatter.

Oscillating neutrinos

Neutrinos appear in three species: electron neutrinos, muon neutrinos and tau neutrinos. In the Standard Model of particle physics, neutrinos should have no mass, like photons. This assumption was questioned when electron neutrinos were shown to disappear on their way from the Sun to the Earth. As we know today, the electron neutrinos change their identity to one of the other species, the latter escaping detection. A similar effect popped up in the Earth's atmosphere: neutrinos produced by cosmic rays change their species during their trip to the detector. This change is dubbed neutrino oscillation, or mixing, and it can occur only if neutrinos have a mass. Therefore, oscillations herald first physics beyond the Standard model. Experiments at nuclear reactors and accelerators have confirmed these findings and also provided independent knowledge about the strength by which the three neutrino species mix with each other. Unfortunately, oscillations are unable to provide us with the values of these three masses: we know «only» the differences between the squares of any pair of them.



Neutrino oscillations: neutrinos are not only ghosts but also chameleons.

Neutrino masses: single beta decay

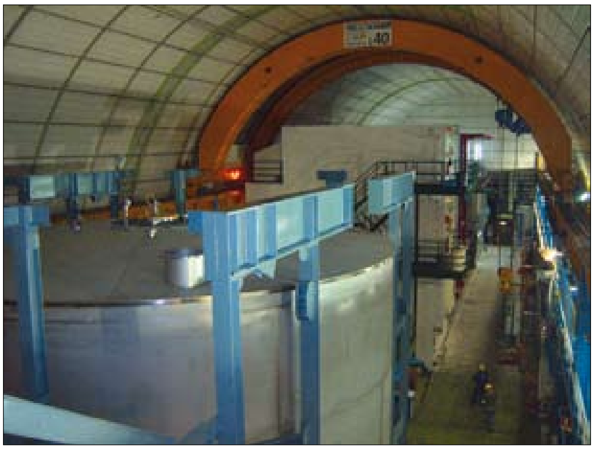
How can we determine the absolute values of neutrino masses, rather than just the mass differences? In the traditional method, one measures the electrons from tritium beta decay, where a neutron inside a nucleus transforms into a proton, an electron and an antineutrino. From these experiments we know, that the heaviest of the three neutrinos is lighter than 2.3 eV, i.e. about 4 millionth of the electron mass.

KATRIN, the KArlsruhe TRItium Neutrino experiment, will have a tenfold improved sensitivity and either determine the mass value or improve the upper limit down to 0.2 eV. If KATRIN fails to see an effect, alternative methods might come to the rescue. In an approach named MARE, physicists plan to cool small radioactive crystals to milli-Kelvin and measure the tiny temperature increase from decay electrons interacting in the crystal.

Neutrino-less double beta decay

In normal beta decay, a neutron inside a nucleus transforms into a proton (which stays bound in the nucleus), an electron and an antineutrino. Let two neutrons in a nucleus decay simultaneously, releasing two electrons and two antineutrinos. Then you have a rare (but observed) process called double beta decay. In its neutrino-less version, only electrons are released, no antineutrinos. This process is only possible if neutrinos are their own anti-particles (Majorana neutrinos) and if they have a mass. The consequences of a possible Majorana nature of neutrinos would be fundamental. It is, for instance, the condition that leptongenesis leads to the observed dominance of matter over antimatter in the Universe.

e NEMO-3 detector in the Laboratoire Souterrain de Modane (France).



Installation of the GERDA detector in the Gran Sasso Laboratory.

So far, only one group claims to have observed neutrino-less double beta decays – from ^{76}Ge nuclei – and claims a neutrino mass in the range of 0.2 to 0.6 eV. The interpretation of the measurement is controversial and calls for replication. This is being attempted with the GERmanium Detector Array, GERDA, which will measure ^{76}Ge decays with a more massive device and better noise suppression. In its first phase (start 2009, Gran Sasso Underground Laboratory) it will comprise 18 kg germanium crystals, later 40 kg, and reach a sensitivity of 0.1 to 0.3 eV. Existing experiments like CUORICINO (also Gran Sasso) and NEMO-3 (Modane Laboratory in the Frejus tunnel) use other nuclei and are exploring mass ranges of the order of 0.2-0.7 eV. They also have their more massive follow-ups: CUORE comprising 204 kg tellurium ^{130}Te in the form of dense packed, super-cooled TeO_2 crystals with 740 kg total mass (planned start 2011) and SuperNEMO comprising sandwiches of radioactive material with tracking chambers (planned start 2012-13), with planned final sensitivities of 0.03-0.1 eV. Two other projects are EXO in the US, with Swiss participation, using ^{136}Xe as an isotope, and COBRA, a project in its early development stage, using the cadmium isotope ^{116}Cd.

The strategy for double beta decay experiments

We give priority to the experiments expected to start operation within the next five years: GERDA (phase I and II), CUORE and Super-NEMO. Complementary nuclei and measurement methods are essential to judge any positive claim or any upper limit. These experiments will be capable of scrutinizing the claimed evidence in ^{76}Ge. They will approach a mass range preferred by certain theoretical models (the “inverted hierarchy” range) and keep European leadership in this field. Other methods may become competitive in the future.

At the same time, the next goal should be envisaged, an experiment on the 1-ton-isotope scale, which will peer deep into the inverted hierarchy mass range. From today’s perspective, it can be accomplished with two options, both to be realized with a worldwide cost sharing. GERDA-III could be a merger of the GERDA project with the USA germanium project Majorana. CUORE-II could change from natural to enriched tellurium, with USA participation. A major milestone would be the decision on the isotopes/ techniques to be taken by 2013.

Precision manoeuvre for a precision experiment: e huge KATRIN vacuum vessel merely passes a narrow street on its way from the factory to the Research Centre in Karlsruhe.

5. Underground physics on the Megaton scale

With a huge multi-purpose detector, physicists will search for decaying protons, study the interior of the Sun and the Earth, obtain incredibly detailed information about a possible galactic Supernova and also study neutrinos from accelerators.

Underground astroparticle physics has resulted in huge detectors, the largest being Super-Kamiokande (or just "Super-K"), a tank in a Japanese mine filled with 50,000 tons of ultra-pure water. Its walls are paved with 11,000 20-inch photo-detectors recording the tiny light flashes from particle interactions. Super-K is one of the most successful devices in modern physics, and it is a true multi-purpose device. It accounts for the precision measurements of solar neutrinos, the detection of neutrinos from the supernova 1987A, the confirmation of neutrino oscillations with neutrinos from the Sun and the Earth's atmosphere, and for the best upper limits on the lifetime of protons.

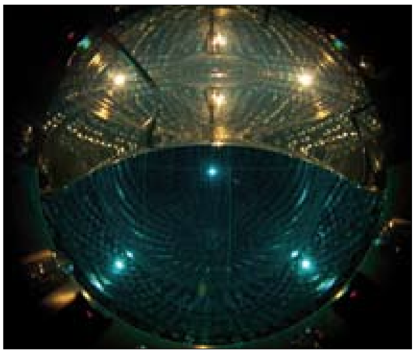
Proton decay

Grand Unified Theories (GUTs) of particle physics predict that the proton has a finite lifetime. The discovery of proton decay would be one of the most fundamental discoveries for physics and cosmology. The related physics may be closely linked to the physics of the Big Bang, the cosmic matter-antimatter asymmetry and a mechanism called baryogenesis. Data from Super-K constrain the proton lifetime to be larger than 10^{34} years, tantalizingly close to predictions of certain "super-symmetry" GUT versions. A sensitivity improvement of an order of magnitude would require water-filled detectors on the Megaton scale or detectors filled with scintillating liquid or liquid argon on the 100 kiloton scale.

Neutrinos from space and Earth: a synoptic view

Proton decay detectors can also detect cosmic neutrinos. Solar neutrinos, burst neutrinos from the supernova SN1987A, reactor neutrinos, neutrinos generated in the Earth's crust and in the Earth's atmosphere have already been detected. Measurements of neutrinos in this energy range – MeV to GeV – would be vastly improved in a next-stage proton decay detector.

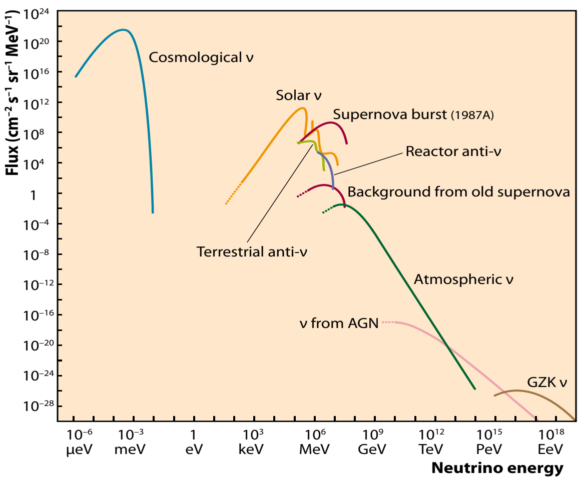
Even higher energies are the domain of detectors underwater rather than underground. Neutrinos from Active Galactic Nuclei (AGN) and collisions of ultra-energetic protons with the 2.7 Kelvin cosmic microwave radiation (marked GZK) will



View into the BOREXINO detector being filled with 100 tons of ultra-pure scintillator.

likely be detected by neutrino telescopes in the next decade (see section 6). No realistic idea exists how to detect 1.9 K cosmological neutrinos, the analogue to the 2.7 Kelvin microwave radiation.

Solar neutrino astronomy has turned into precision science, with eminent input from the GALLEX detector in Gran Sasso. Europe's excellent tradition in this field is presently continued by the BOREXINO liquid scintillation detector that started operation in 2007 and determines, for the first time, the flux of the ^{7}Be neutrinos.



A synoptic view of neutrino fluxes.
Underground detectors are tailored to the energy range of 100 keV to 100 GeV. is is also the focus of detectors on the Megaton scale described in this chapter. e extremely low fluxes at higher energies can be only investigated with detectors of Gigaton rather than Megaton masses. ey are described in chapter 6.

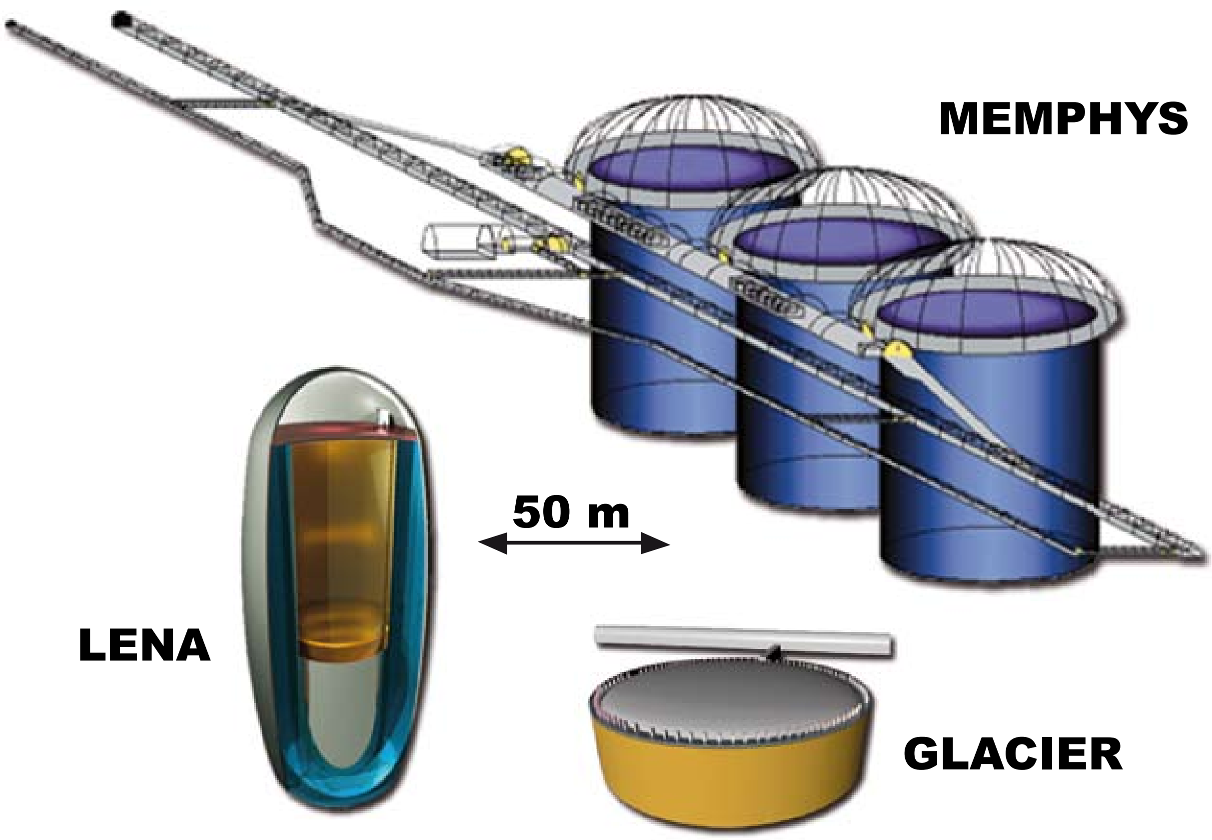
The strategy

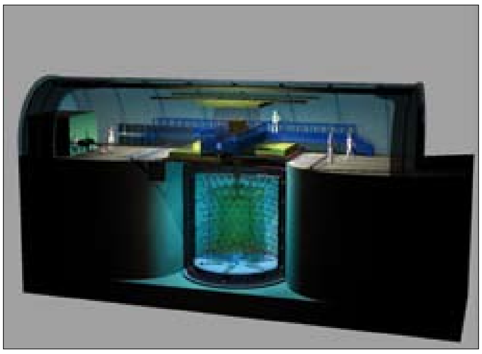
The rich legacy of underground neutrino physics is intended to be continued with a worldwide effort towards one or two multi-purpose detectors in the mass scale of 100-1000 kilotons. Such a facility will increase the sensitivity to proton decay by an order of magnitude, would provide incredibly detailed information on the early phase of supernova core-collapse processes, and will allow the study of details of the standard solar model with percent accuracy. High-statistics studies of atmospheric neutrinos will improve our knowledge of the neutrino mixing, and the study of geo-neutrinos will improve our understanding of the Earth's interior. Next generation underground observatories will also allow long baseline neutrino experiments with beams from accelerators to be performed with unprecedented precision.

A new giant underground observatory will be global in nature and has to follow worldwide coordination and cost sharing. LAGUNA, a common design study within the 7th European Framework Program (FP7), is presently underway. It evaluates three detection techniques: water Cherenkov detectors, liquid scintillator detectors and liquid argon imaging detectors. The study will also address the costs of underground infrastructures in several potential locations in Europe. With related efforts underway in the USA and Japan, the necessity of a coherent approach is obvious.

e three concepts of the LAGUNA design study: a 700 kiloton water detector (MEMPHYS), a 100 kiloton liquid argon detector (GLACIER) and a 50 kiloton liquid scintillator detector (LENA).

The LAGUNA design study should provide, on a time scale of 2010, the key information on the discovery potential for the different options and sites and then converge to a common proposal. We recommend additional support to complete the detector R&D programmes that could not be fully supported within the FP7 Design Study. Input to the physics perspectives and feasibility of a large

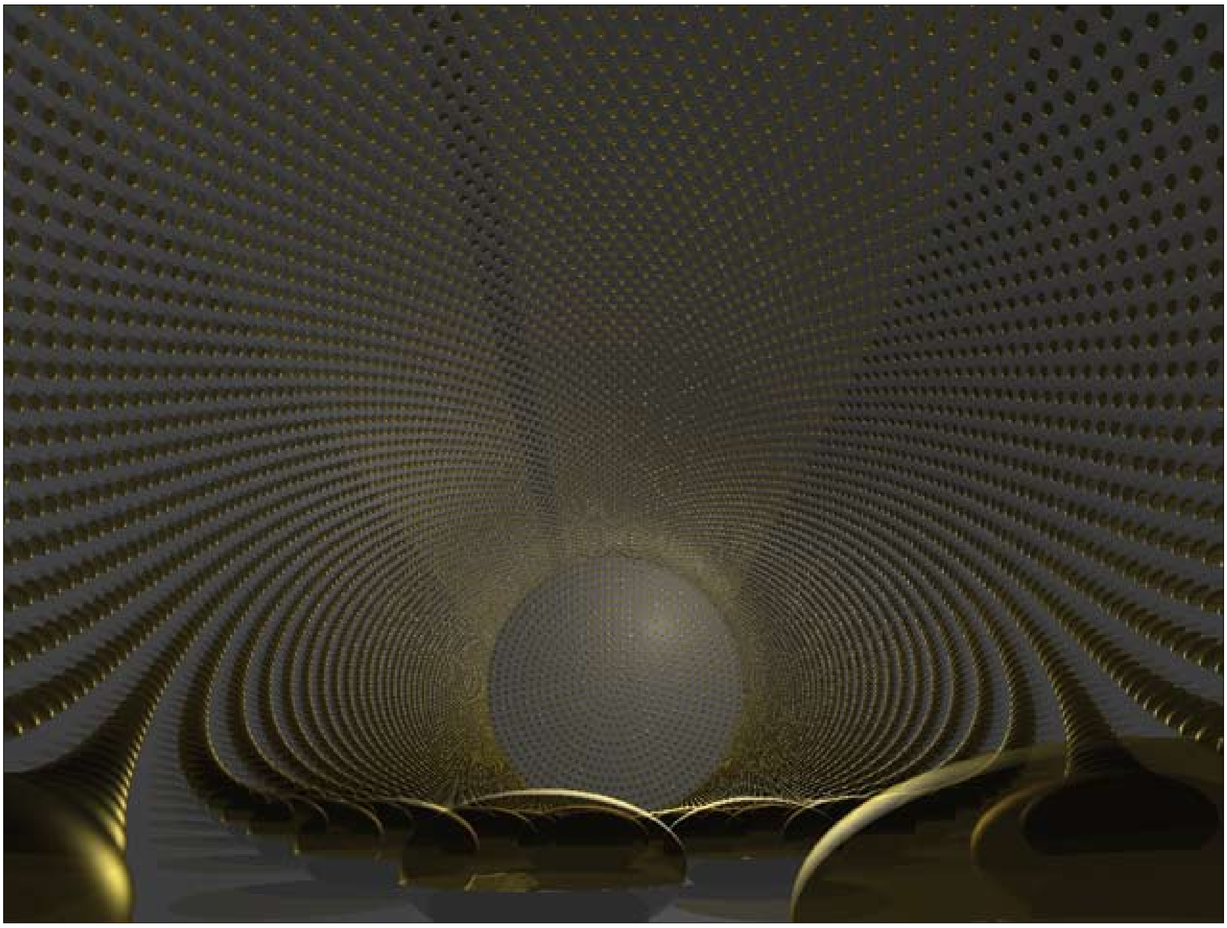




e Double Chooz experiment in France studies neutrinos from a nuclear reactor.

underground facility is expected from present experiments, like BOREXINO (liquid scintillator) and ICARUS-T600 (liquid argon) in Gran Sasso. Evidence for a non-vanishing mixing between the lightest and heaviest neutrinos from the long-baseline experiments Double Chooz (France) and T2K (Japan, with strong European participation) would boost our understanding of CP violation. The observation of different oscillation behaviour of accelerator-generated neutrinos and anti-neutrinos would have fundamental consequences for matter-antimatter asymmetry in the Universe. These observations would impact plans for studying accelerator neutrinos with a Megaton detector and also motivated proposals for dedicated liquid argon detectors, e.g. MODULAR at Gran Sasso.

Artist's view into the inner volume of LENA. e walls are paved with large photo-sensors.

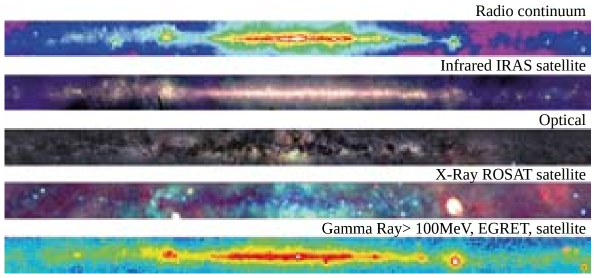


6. The high-energy Universe

The origin of cosmic rays, the most energetic particles ever observed, is going to be revealed in the coming years. Huge observatories for high energy cosmic rays, gamma rays and neutrinos will open an unprecedented view on the violent Universe.

From the Hot to the Extreme

Most of the visible cosmic matter is in a state which physicists call "thermal equilibrium", characterised by a certain temperature. The prime cosmic example is our Sun: analysing its spectrum, we can easily conclude that its surface temperature is about 6000 Kelvin. The spectra of hotter stars, extending far to the ultraviolet or the X-ray range, indicate temperatures up to 50000 Kelvin. In the X-ray range, some strange objects begin to appear on astronomer's sky-maps. They do not fit into the equilibrium scheme but emit considerably more energetic particles than expected for a body with a well-defined temperature. It is here that the realm of the "non-thermal" Universe of extremely high energies begins: the realm of cosmic accelerators.

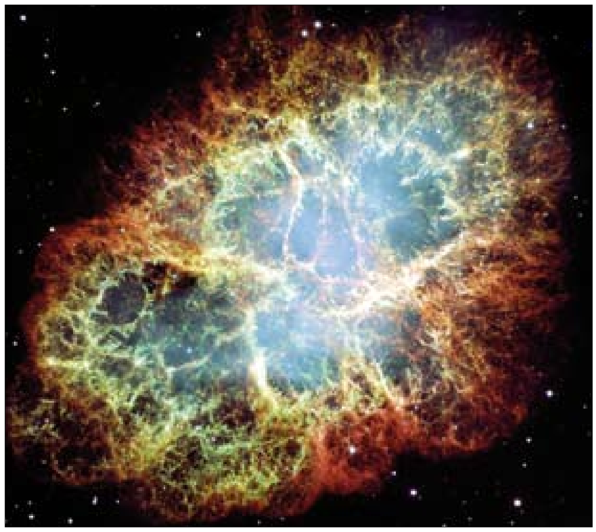


e galactic plane as seen in di erent wavelengths.

The realm of cosmic accelerators

The first obvious proof of something beyond the thermal Universe was provided by charged cosmic rays. They consist of protons, light and heavy nuclei, with a minuscule admixture of electrons. Some of these particles reach breath-taking energies – about 100 billion GeV (10^{20} eV)! This dwarfs any ground-based accelerator: it corresponds to about 10 million times the beam energy of the Large Hadron Collider.

1000 times the LHC – the CRAB nebula is a remnant of a supernova exploded in the year 1054. At the fronts of the expanding cloud, particles are accelerated to close to the speed of light.



10 000 000 times the LHC? – Artist's view of an active galaxy: matter falls to a super-massive black hole in the centre, part of it makes its way to the jets. Places of acceleration are the vicinity of the black hole and the jets.

A threefold attack: multi-messenger astronomy

Cosmic rays with energies up to some million GeV are probably accelerated at the shock fronts of galactic supernova explosions. Indeed, radio emissions and X-rays give direct evidence that these fronts accelerate electrons to nearly the speed of light. However, the evidence that high-energy protons and nuclei – the main component of cosmic rays – have the same origin is only circumstantial and needs confirmation. How do these particles propagate through the Universe? What is the maximum energy achievable by galactic sources such as supernova remnants or binary star systems?

If the ten-million GeV range is a puzzle, then the 100-billion GeV range is a mystery! Are particles with these energies due to cosmic acceleration in the vicinity of super-massive black holes or around star crashes? Or are they due to something totally different, like the decay of super-heavy relic particles from the Big Bang? Accounting for these extreme energies is one of the greatest challenges in astroparticle physics.

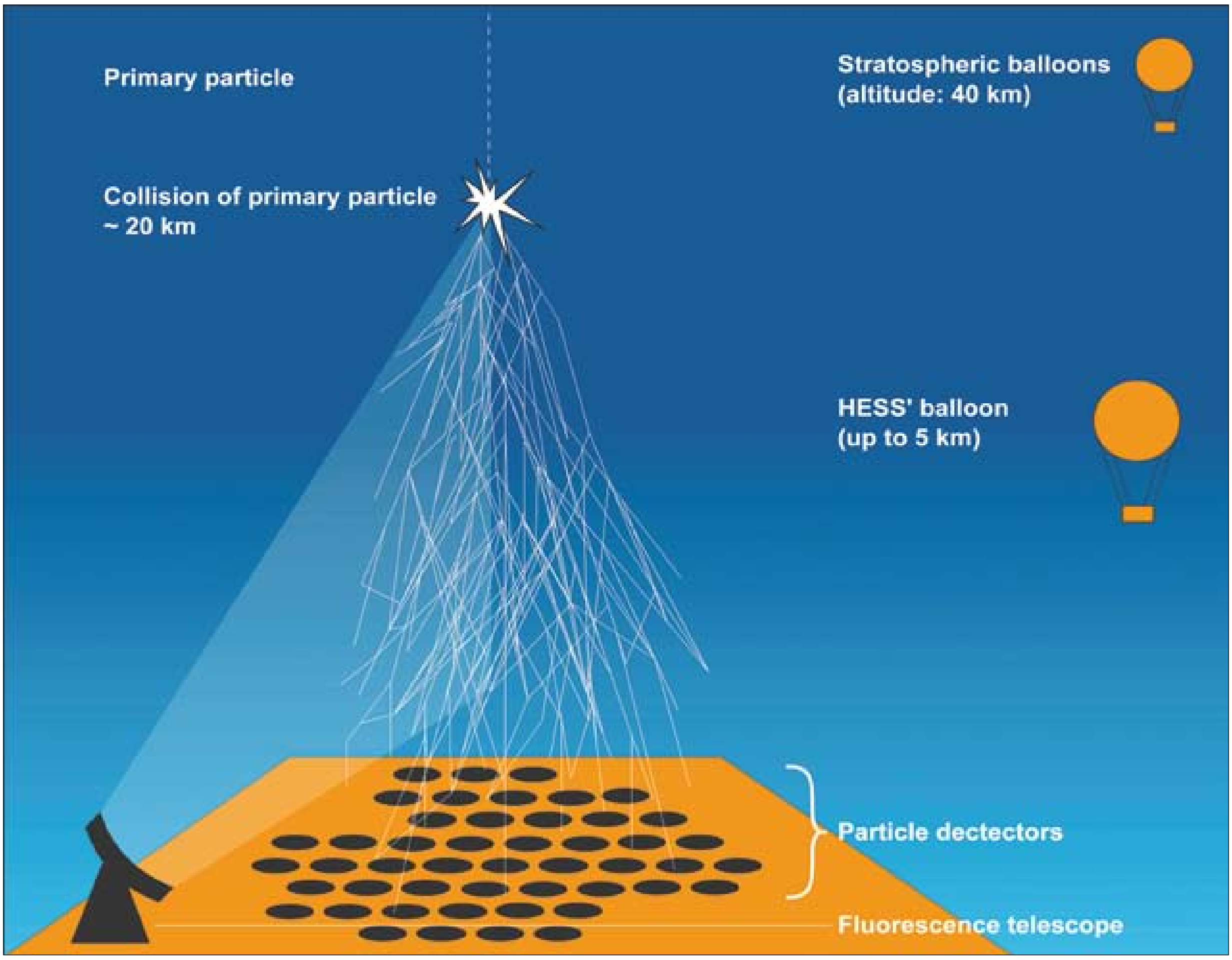
Cosmic rays give clear evidence that something extremely energetic is happening in the Universe. But they do not tell us where. Since they are electrically charged, their paths curve as they travel through cosmic magnetic fields. They don't point back to their sources, except at the very highest energies where deflection becomes small. Fortunately, the suspected sources are also predicted to emit by-product particles which travel in straight lines: gamma rays and neutrinos. Indeed, gamma rays with energies up to a hundred thousand GeV have been observed from a variety of sources. In most cases, however, it is not clear whether they are produced in high-energy proton interactions with the ambient matter, or whether they are radiated by electrons. Here, neutrinos may come to the rescue: they can only be produced in processes including protons and nuclei. With a threefold attack – charged cosmic rays, gamma rays and neutrinos – there is a good chance that we will unveil the mystery of cosmic rays before the centenary of their discovery in 1912, and afterwards fully explore the landscape of the extreme Universe.

Birth of a mystery

Cosmic rays collide with atmospheric molecules at 15-20 km altitude and trigger avalanches of secondary particles. In 1912, Victor Hess measured the secondary particles. The primary particles can only be measured from stratospheric balloons and satellites.

With increasing energy, the flux of primary particles becomes so low that the small detectors in balloons are not even able to collect a few particles. However, in 1938 Pierre Auger demonstrated that avalanche particles from very high-energy parents can reach the ground. This was his recipe: arrange a

Registration of high-energy cosmic rays: particle detectors record the avalanche particles reaching the ground, special telescopes measure the light emitted along the avalanches in the air.

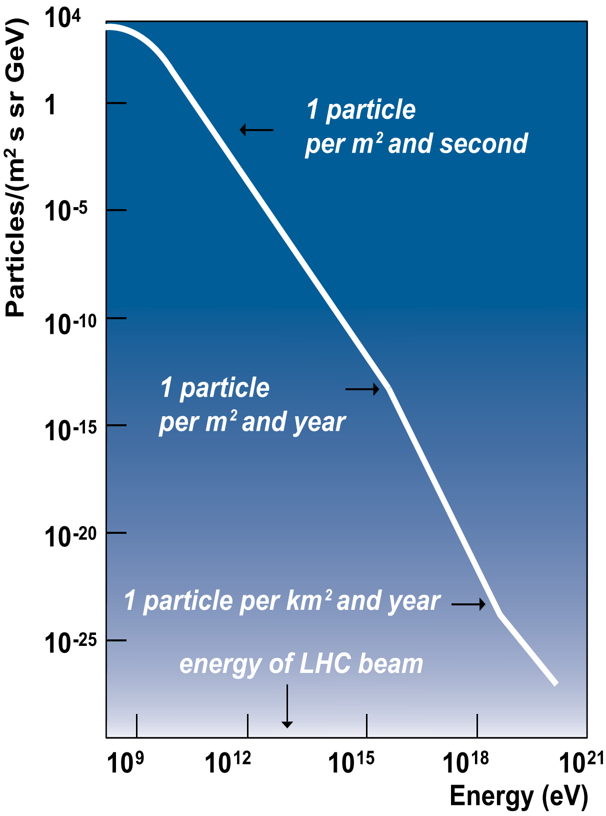


Argentina is the host of the Southern Pierre Auger Observatory

large array of detectors at ground level and register the punch-through particles which fire several of the detectors in coincidence. It took another 24 years until the Volcano Ranch array in the USA recorded a cosmic ray event of 10^{20} eV: the mystery, as it stands today, was born!

The cosmic ray spectrum

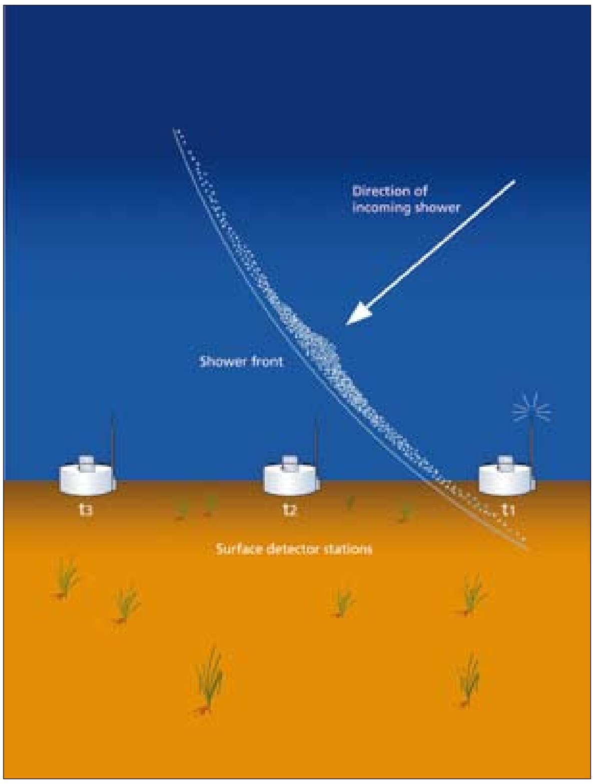
The cosmic ray spectrum extends over 32 orders of magnitude. At 100 GeV, one particle per square metre per second bombards the atmosphere. At one million GeV it is only one particle per square metre per year. And in order to catch one per year of the ten-billion GeV grenades, one needs a full square kilometre!



Still, much can be learned at GeV energies with detectors on satellites like Pamela (launched in 2006) and AMS, the Alpha Magnetic Spectrometer Experiment; for example about primary mass composition, or about the contribution of anti-particles and their possible relation to dark matter. Going higher in energy, the KASCADE detector in Karlsruhe has provided new insight into galactic cosmic rays of up to 10^{17} eV, with complementary information coming in from IceTop at the South Pole and from the Siberian Tunka array. The focus of forthcoming research, however, is on the very highest energies, likely to be entirely of extragalactic origin. This is the domain of the terrestrial Pierre Auger Observatory and space-bound detectors monitoring huge volumes of the atmosphere for traces of high energy particles. Two smaller projects address energies between KASCADE and Auger: the Japan-led Telescope Array presently under construction in Utah/USA, and a planned air shower array in China.

e flux of cosmic rays.

The Pierre Auger Observatory



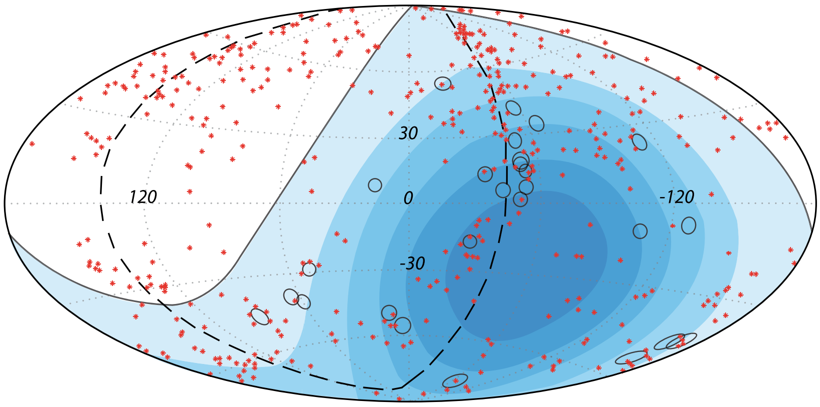
e direction of air showers can be derived from the particle arrival times in the Auger water tanks and from the avalanche pattern recorded with the telescopes (not shown here).

The Southern Pierre Auger Observatory is located in the Pampa Amarilla in Western Argentina. Researchers have carpeted 3000 km² of the prairie with 1600 water tanks. The array is overlooked by four clusters of fluorescence telescopes which record the light flashes emitted by air showers in the atmosphere. The combination of two techniques excludes many uncertainties from which predecessor instruments had suffered; the large area allows the collection of more than just a few events in the 10^{20} eV range. This is where bending in cosmic magnetic fields becomes smaller and back-tracing of cosmic rays to their sources realistic.

Actually, from their first data, Auger physicists already report tantalising correlations of cosmic ray directions with cosmic matter accumulations, and this may be the first step towards true cosmic ray astronomy. More data are being taken with the completed detector and are expected to improve the statistical significance of the observation.

Auger North

Encouraged by this first glimpse, the Auger collaboration envisages a 20 000 km² array in Colorado, USA. The case for “Auger-North” is strong: high statistics astronomy with reasonably fast data collection calls for a substantially larger array than Auger South, full sky coverage calls for a Northern site. A larger array would also allow a more detailed inspection of the high energy cut-off of the particle spectrum, which recently has been firmly established by



Sky-map of the publised 27 highest-energy Auger events (black circles), compared to positions of active galactic nuclei (red crosses).

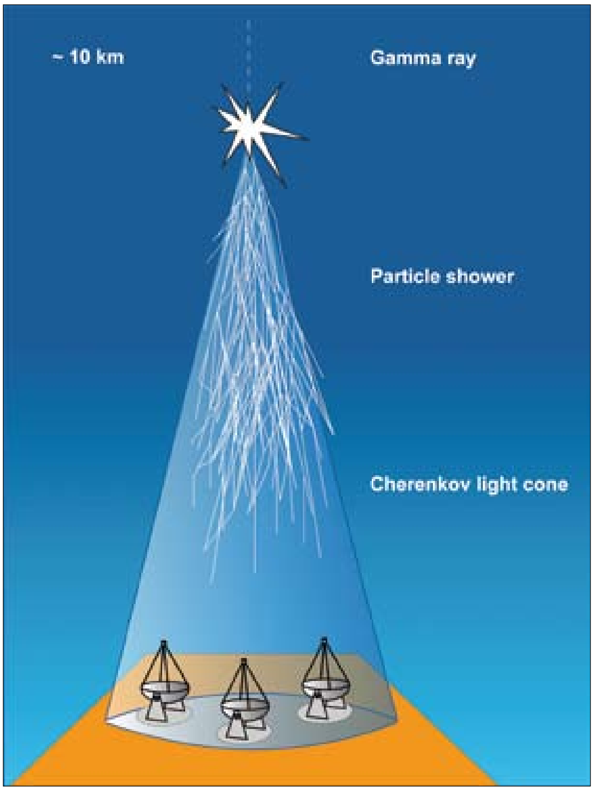
Auger-South. Is it due to the omnipresent sea of 2.7-Kelvin photons, the relics of the Big Bang, which slow down ultra-energetic particles when they travel for more than 100 million years? Or is it just due to cosmic accelerators running out of power? Auger-North, the clear priority project for charged cosmic rays for the next decade, will help answer these questions and further populate the sky map of cosmic accelerators.

A water tank of the Pierre Auger Observatory, with the Andes in the background.

6.2 Exploring the Universe with gamma rays

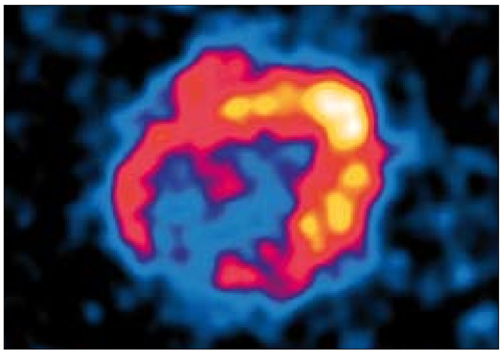
The last decade has witnessed the birth of a new field of astronomy – Very High Energy (VHE) gamma ray astronomy – expanding wavelength coverage of astronomical instruments by another 10 octaves towards the highest energy radiation. These gamma rays are produced when high energy cosmic rays bump into interstellar gas, creating a bunch of elementary particles. Unlike charged cosmic rays, the gamma rays travel on a straight path and point back to the point in the sky where they were produced. Apart from serving as tracers of cosmic rays, speculation is that some VHE gamma rays may result from decays of relic particles with have survived since the Big Bang, such as the mysterious dark matter particles; detection of such gamma rays would give first hints towards the nature of dark matter.

Registration of gamma ray-initiated avalanches in the atmosphere with Imaging Atmospheric Cherenkov Telescopes.



Imaging Atmospheric Cherenkov Telescopes

Very High Energy gamma rays are absorbed in the Earth's atmosphere, creating a cascade of secondary elementary particles, most of which never reach the ground. Satellite instruments such as AGILE and Fermi (the former GLAST), now in orbit, detect gamma-rays before they enter the atmosphere, but their size is too small to capture enough of the highest-energy gamma rays. After long development, a ground-based detection technique pioneered by the American Whipple telescope and perfected by the European-led H.E.S.S. and MAGIC instruments has brought a break-through: Imaging Atmospheric Cherenkov telescopes. These telescopes collect and image the bluish light emitted by the particle cascades created by a VHE gamma ray in the atmosphere. Light from a single VHE gamma ray illuminates a "light pool" of about 150 m radius on the ground, hence a single telescope will detect gamma rays incident upon an area of a few 10000 m^2, compared to the sub-m^2 area of satellite detectors. Latest generation Cherenkov telescope systems



e remnant of a supernova, as seen in TeV gamma rays. e brightest region top-right marks a molecular cloud. e gamma rays from this spot are likely produced in collisions of nuclei accelerated at the shock fronts of the supernova. A first convincing image of a cosmic ray accelerator?

use multiple telescopes to provide stereoscopic viewing of gamma-ray induced particle cascades, for improved determination of impact direction and energy of a gamma-ray.

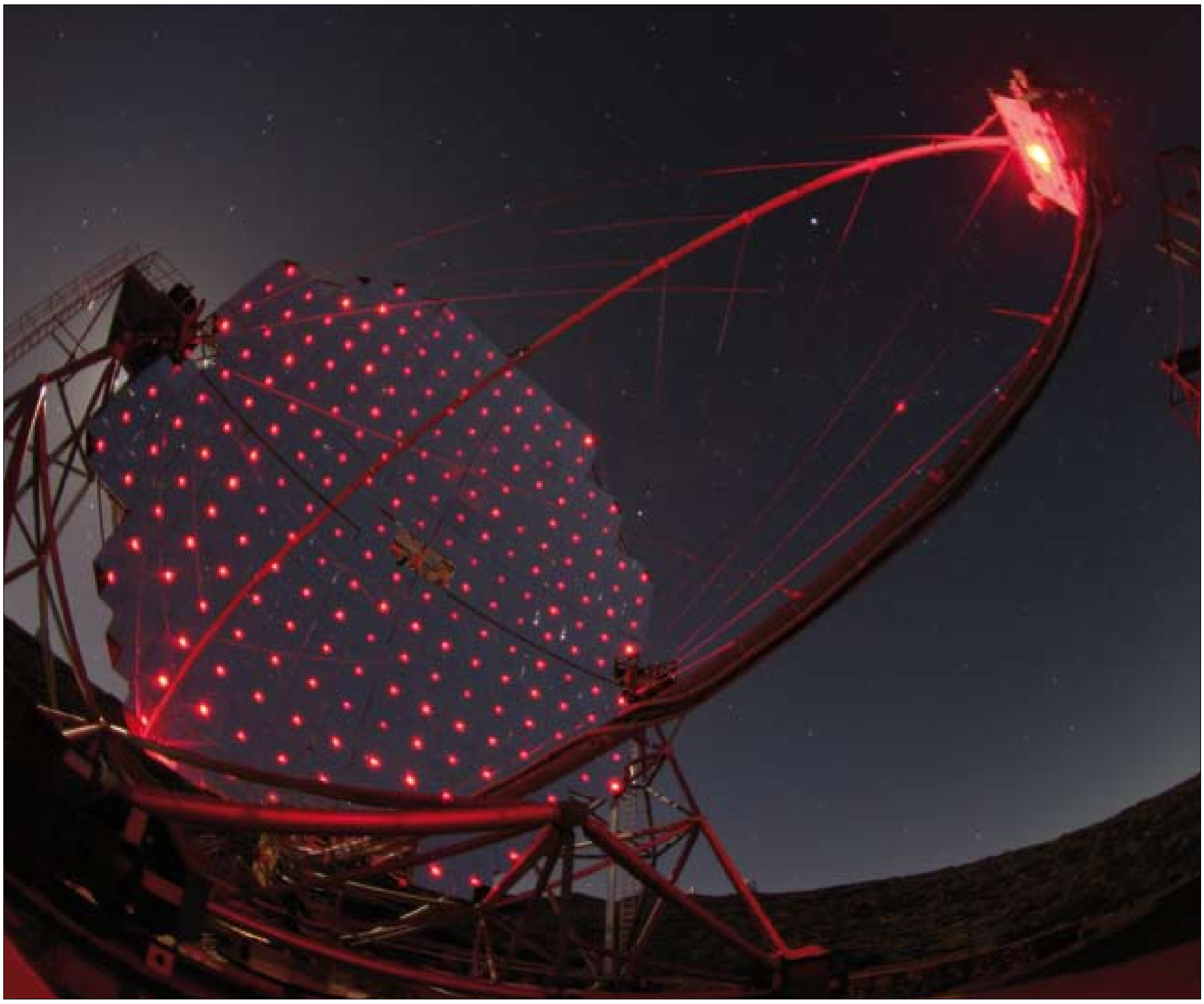
Cherenkov telescopes are flanked by detectors recording the shower particles which reach the ground, like the ARGO/YBJ detector in Tibet, or the American MILAGRO instrument and its planned successor HAWC. Although inferior in sensitivity, they provide an important complement in that they continuously monitor large parts of the sky and allow the study of extended cosmic sources, including the band of the Milky Way.

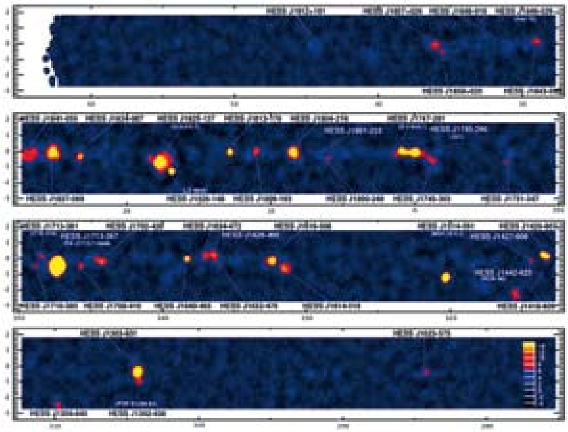
One of the four 11-meter mirror dishes of the H.E.S.S. telescope in Namibia. In 2009, a fifth dish with 25 meter diameter will be installed and improve the low-energy sensitivity of the array.

A rich harvest

VHE gamma-ray astronomy is becoming part of mainstream astronomy, with surveys of the Galaxy revealing dozens of VHE gamma-ray emitting cosmic-ray accelerators. Objects discovered include supernova remnants, binary systems, pulsars, stellar associations and different species of active galaxies, hosting super-massive black holes at their centres.

e first of the two huge 17-meter dishes of the MAGIC telescope at La Palma with its excellent coverage of lower energies.



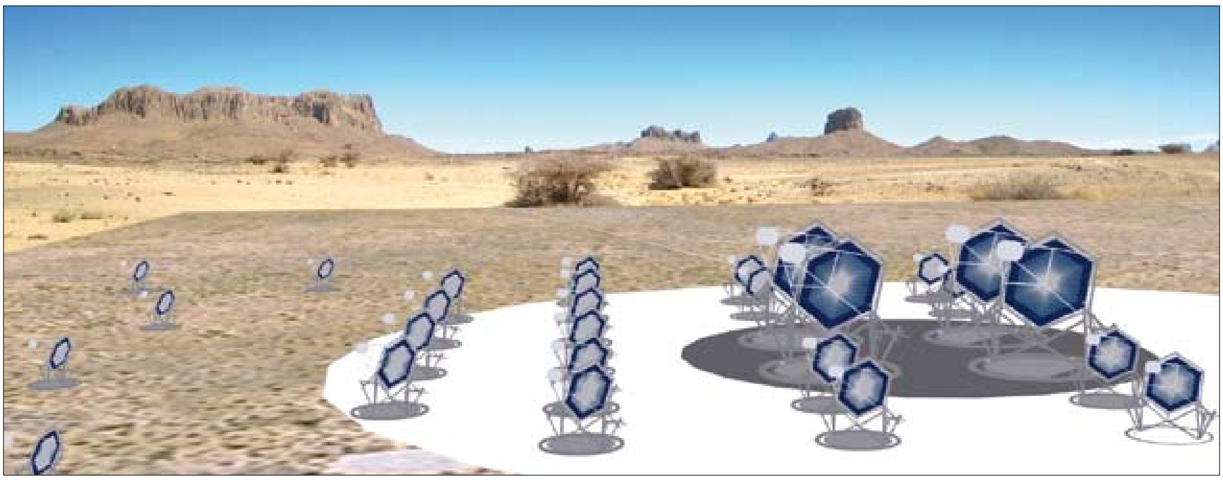


e band of the inner parts of the galactic plane as scanned with the H.E.S.S. telescope. e plane turns out to be lined with sources of TeV gamma radiation, some of them not known from any other wavelength.

The future: CTA

So far, Cherenkov telescopes such as H.E.S.S. or MAGIC are considered “experiments”, requiring dedicated experts to analyse and fully exploit their data. Both the communities of astronomers and of astroparticle physicists feel that the time is ripe to construct a next-generation VHE gamma-ray observatory, which on the one hand boosts sensitivity and resolution beyond that of the current instruments, and also provides observatory services and tools thus making VHE gamma-ray astronomy accessible to the entire community. This resulted in the proposal for the Cherenkov Telescope Array CTA, composed of a large number of Cherenkov telescopes covering the gamma-ray energy range from some 10 GeV to beyond 100 TeV. Combined with a 10-fold improvement of sensitivity and a significant improvement in resolution, CTA is expected to reveal about one thousand sources of VHE gamma rays and to explore their spatial structure and energy spectra. Ultimately, a Northern and a Southern CTA instrument, operated under a common framework, should provide full-sky coverage. Operational overlap with the Fermi satellite mission will provide seamless coverage of 20 octaves of the spectrum. CTA is the priority project in the field of European gamma-ray astronomy. Coordination with similar efforts in the USA (AGIS concept) is underway. CTA is on the ESFRI list of emerging projects and has been proposed as a full ESFRI entry. It is also listed as a priority entry in the ASTRONET infrastructure roadmap. We recommend the design and prototyping of the CTA and selection of site(s), and proceeding rapidly towards the start of deployment in 2012.

A possible design of CTA, the Cherenkov Telescope Array. Large mirrors in the centre collect enough light to catch dim showers from low-energy gamma rays. To collect large statistics at high energies, where particles are rare but the associated showers are bright, smaller mirrors cover an area of a few square kilometres.



6.3 High-energy neutrino astronomy

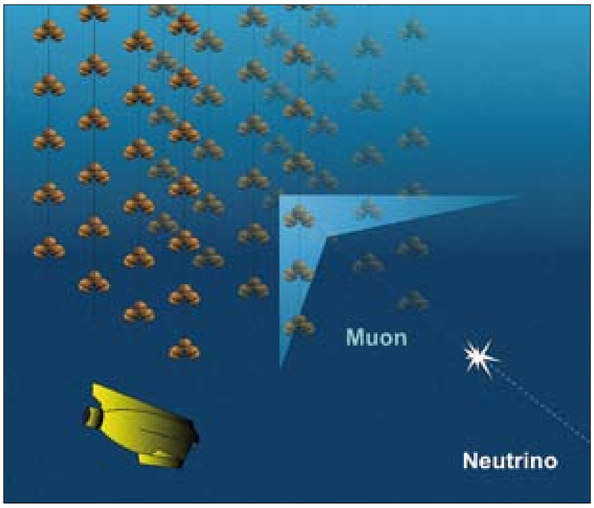
Going deep, looking deep

As of today, the sky-map of extraterrestrial high energy neutrinos is still empty – a challenging terra incognita. Such neutrinos must be emitted as a by-product of high- energy collisions of charged cosmic rays with matter. Since they can escape much denser celestial bodies than light, they can be tracers of processes which stay hidden to traditional astronomy. Undisturbed by anything, they reach us from the remotest regions of the Universe and may let us peer deeper into the universe than with any other messenger. Nevertheless, at the same time their extremely low interaction probability makes their detection extraordinarily di cult.

Detectors for solar neutrinos are buried deep underground in order to shield them against noise which could mimic their rare interactions. Only neutrinos can penetrate deep enough to reach these devices undisturbed. In order to detect the low fluxes from the suspected distant sources of high-energy neutrinos, immense detectors of cubic kilometre volume are required. They cannot be arranged underground but only in deep oceans, lakes or glacial ice where available space is no issue.

Detectors in water and ice

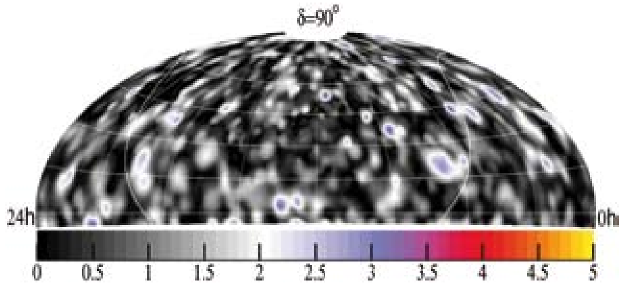
In neutrino interactions in water or ice, feeble Cherenkov light flashes are produced which can be registered by light sensors arranged over a large volume. This principle was first conceived in the late fifties. In the mean time, first-generation detectors are being operated in the Siberian Lake Baikal (NT200), in Antarctic ice (AMANDA) and most recently in the Mediterranean Sea (ANTARES).



A muon is generated in a neutrino interaction and emits a cone of bluish Cherenkov light. e light is recorded by sensors in pressure tight glass spheres.

However, even the sky-map of AMANDA, with 6595 neutrinos collected over seven years, does not reveal statistically significant spots localising cosmic accelerators. Nearly all of these neutrinos seem to be produced in the Earth's atmosphere, in the avalanches of particles

Sky map composed of 6595 neutrinos recorded with AMANDA. Colours indicate the strength of the local excesses. Yet, none of the observed excesses is statistically significant.



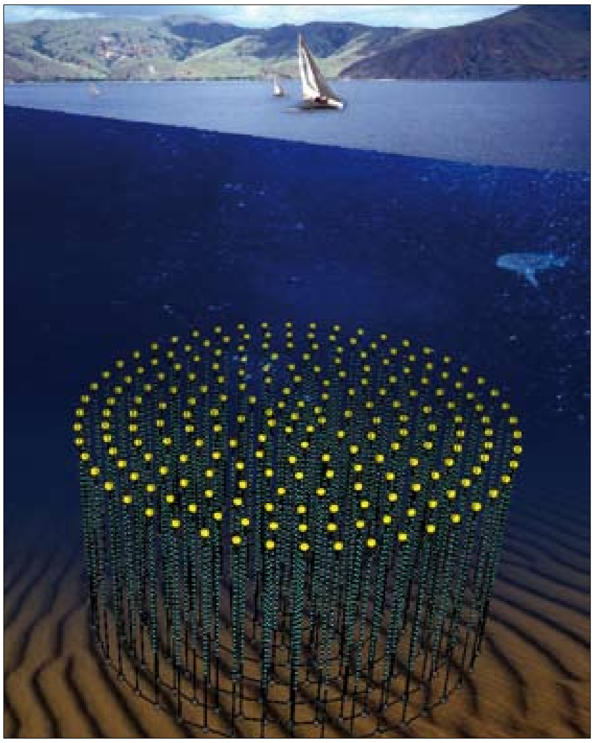
initialised by charged cosmic ray interactions.

To realise the dream of high-energy neutrino astronomy one needs detectors of a cubic kilometre scale or beyond. The construction of these detectors in now underway (IceCube at the South Pole) or planned (KM3NeT in the Mediterranean Sea).

Towards cubic kilometre telescopes

European physicists play a strong role in the most advanced neutrino project, IceCube. IceCube is presently taking data with half a cubic kilometre instrumented volume and will be completed in January 2011. In parallel, a broad community works towards KM3NeT, a cubic kilometre scale neutrino telescope in the Mediterranean Sea, with the recent commissioning of ANTARES (close to Toulon) defining a milestone towards the next generation telescope. Prototype devices with alternative designs have been or are operated close to the Peloponnesus (NESTOR) and to Sicily (NEMO). In parallel, Russian physicists plan an array with sensitivity somewhere between present detectors and KM3NeT.

KM3NeT is the priority project of high energy neutrino astronomy in Europe. It is on the ESFRI list, has obtained funds for an FP6 design study and has recently started a FP7 Preparatory Phase. It is also listed as a priority entry in the ASTRONET infrastructure roadmap. KM3Net will complement IceCube at the South Pole: IceCube will preferentially observe the Northern sky – with neutrinos having crossed the Earth; KM3NeT will preferentially observe the Southern sky. Resources for a Mediterranean detector should be pooled into a single optimised design for a large research infrastructure. The KM3NeT Technical Design Report is expected in late 2009, defining the configuration, deciding between competing technological solutions and providing site arguments. The sensitivity of KM3NeT will substantially exceed that of all existing neutrino detectors including IceCube.



Artist's view of a possible KM3NeT configuration.

7. Gravitational waves

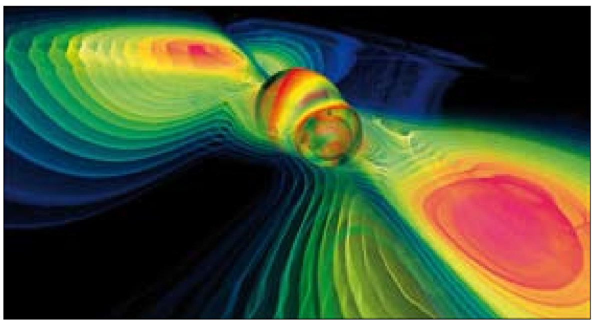
Most of the phenomena predicted by Einstein's General Theory of Relativity have been confirmed, but one has resisted a direct experimental proof: the emission of gravitational waves by accelerated bodies.

Proving Einstein

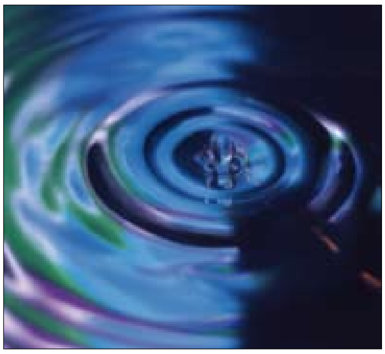
When Einstein formulated his General Theory of Relativity, he predicted a number of stunning phenomena related to the curvature of space-time. Most of them have been confirmed in the meantime, but one of them has resisted direct experimental proof. It is the emission of gravitational waves by accelerated bodies, ripples in space which propagate at the speed of light and rhythmically compress and stretch the distances between objects. Their existence has been indirectly confirmed by the change of the orbiting speed of two close stars, a discovery acknowledged with the 1993 Noble Prize in physics. Einstein considered them too weak to be ever detected directly: even a supernova collapse in a neighbourhood galaxy would change the distance between Earth and Sun by only the diameter of a hydrogen atom, and even this for only a few milliseconds. However, after decades of development, researchers have developed tools so sophisticated and sensitive that the definitive detection of gravitational waves is within reach. Within a decade, we should see true gravitational wave astronomy flourishing.

Messengers of catastrophes

Gravitational waves must be emitted by the coalescence of two orbiting compact objects like neutron stars or black holes, or when a star is sucked into a massive black hole at the centre of a galaxy. The observation of gravitational waves from binary mergers out to extreme distances would strongly impact cosmology. These events can be used as distance markers and help to map the complete expansion history of the Universe in a way complementary to methods of standard astronomy, thus providing completely independent information on dark energy. Last but not least, the Big Bang filled the cosmos with a faint background of gravitational waves, similar to the 2.7-Kelvin microwave background. On a long-term basis, detection of this ultimate first picture is conceivable with devices in space.



Modelling of gravitational waves produced by the merging of two black holes.



Cylinders and interferometers

First attempts to detect gravitational waves used very massive metallic cylinders and aimed to measure the tiny vibrations caused by gravitational waves. Although these instruments may be able to detect a nearby supernova, they cannot compete with a technique using interferometers. In these devices, light waves are split, propagate along extended, perpendicular arms, are reflected back by large mirrors, and finally superimposed at the splitting spot. A gravitational wave passing the device would compress the space along the two arms in a different way, leading to a flickering of the interference pattern. Longer arms, higher light power and better noise suppression are the keys to improve the sensitivity of the interferometer. Progress with light power and noise suppression has been tremendous over the recent years.

First generation interferometers

At present, there are four large interferometric observatories: TAMA in Japan (300 metre arms), GEO-600 in Germany (600 metre arms and a source of many principal innovations), LIGO in the USA (two 4-km arms and one 2-km arm). Youngest in the club is Virgo in Italy (3-km arms) which took first data in 2007. LIGO, Virgo and GEO have formed a worldwide consortium which had a first common data run in 2007. These devices have collected a substantial amount of data which are now being systematically mined for periodic signals or spikes which may be hidden under background noise. These devices could detect the occasional crash of a binary black hole system up to distances of a few hundred million light years, a volume containing thousands of galaxies. However, since these processes are rare, detections within a reasonable operation period are not very likely, although not excluded.

Europe's two interferometric gravitational wave observatories: GEO 600 (top) and Virgo (bottom).

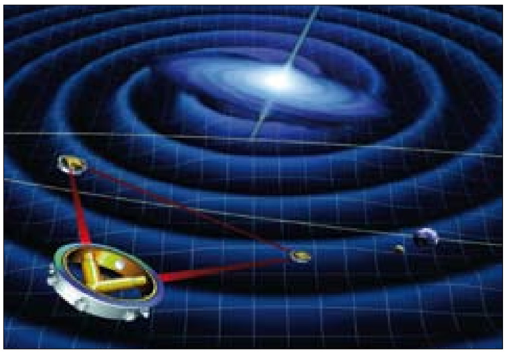
Advanced interferometers

The existing detectors are currently being upgraded. First, "enhanced" versions of the first generation devices will be launched within the next two years. They will be succeeded by "advanced" versions which could be truly ranked as second generation interferometers. The advanced detectors will cover a cosmic volume a thousand times larger than the current ones, with a clear worldwide strategy to reach this stage around 2014. Observation of gravitational waves is expected within some weeks or months of operation. This will set the stage to start construction of a third-generation interferometer which would propel gravitational wave detection to the level of standard astronomy, with many thousands of sources per year.

The future: E.T, the Einstein Gravitational Wave Telescope

E.T. is the long-term future project of ground-based gravitational wave astronomy. With an observed volume a thousand times larger than that of the second-generation detectors, E.T. will record many thousands of events per year, and, in a network arrangement, have an unprecedented sensitivity at 10 Hz to a stochastic gravitational wave background from the Big Bang. The European gravitational wave community is well co-ordinated and plays a world-leading role in planning for the future of the field. An FP7 Design Study for E.T. has commenced, and a first technical design and associated costing is expected in 2011, followed by a 'Preparatory Phase'. A decision on funding for the construction of E.T. will most likely be contingent on a first detection, which may occur during the era of enhanced LIGO and enhanced Virgo ("Virgo+") but is most likely after collecting about a year of data with advanced LIGO/Virgo in approximately 2014/15. The targeted start of E.T. construction could be 2016 or 2017.

With European participation in upgraded versions of LIGO and GEO confirmed, full support for the Virgo upgrade towards "Advanced Virgo" still has to be secured. This would ensure the critical infrastructure for a coherent gravitational wave programme in Europe and lay the ground for E.T.

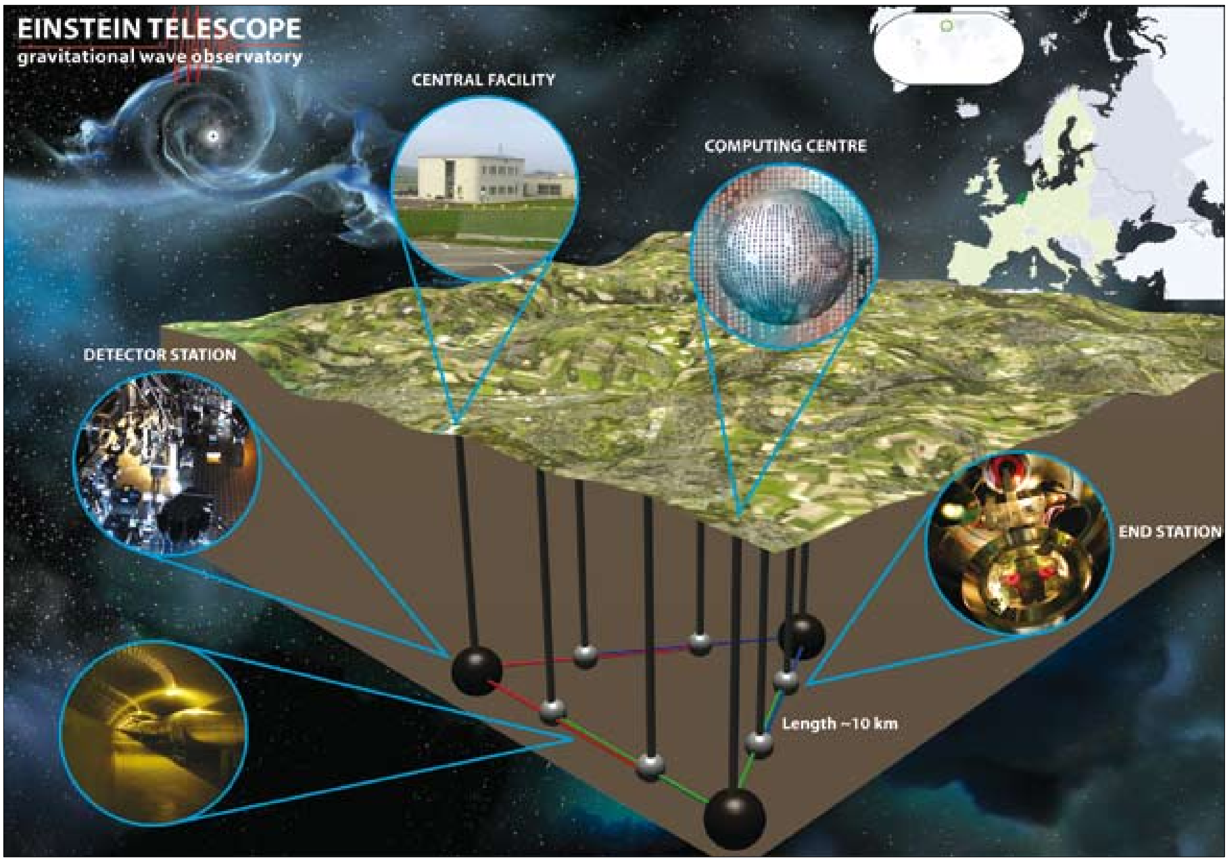


Measuring ripples in space with LISA.

Gravitational waves from space: LISA

The coalescence of super-massive black hole binaries, the spiralling of stars into black holes, stochastic backgrounds from the early universe and Big Bang quantum fluctuations would emit waves in the milli-Herz range. This is the realm of space-based interferometers, where distances are huge and seismic noise is absent.

The priority for a space mission is LISA. This ambitious project aims to fly three satellites at five million-kilometre distance, forming the "arms" of a huge interferometer. A LISA-pathfinder mission will provide a final proof of the feasibility of the concept in 2010, with the start of LISA itself being envisaged for 2018. LISA is complementary to E.T. It will open the low-frequency window for gravitational wave observations and make true multi-wavelength gravitational wave astronomy a reality.



8. The infrastructures of astroparticle physics

Astroparticle physics relies on a variety of distributed platforms: large underground laboratories, observatories at very remote locations and satellites. Construction and sustainable operation of these infrastructures are of key importance for future progress.

Astroparticle physics rests on a variety of distributed platforms. This is different to particle physics, with CERN supplying the infrastructure for the majority of European experimental activities in the field. The infrastructures for astroparticle physics can be grouped into underground laboratories, observatories and space-based platforms.

Underground laboratories

The study of extremely rare phenomena calls for an environment free of noise events which might mimic true signals. Laboratories deep underground, well shielded against particles from cosmic rays, meet this requirement. Experiments performed in underground laboratories include the search for double beta decay, "direct" searches for dark matter, investigation of neutrinos from the Sun or supernovae, and detectors searching for proton decay. Europe has four world-class deep underground laboratories:

> The Laboratori Nazionali del Gran Sasso (LNGS) along the Gran Sasso Motorway tunnel, 120 km East of Rome, 1400 m underground (3700 metres water equivalent, m.w.e.). With three main halls each covering 2000 m² it is the largest of all the underground laboratories.

View into one the large halls of the Gran Sasso Laboratory in Italy.

> 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 laboratories. Its main hall has an area of 300 m². After 2011, an extension in the context of a coming road-tunnel modification could house ton-scale experiments. Also, a long-term giant excavation to house a Megaton-scale detector is being discussed.

> The Laboratorio subterráneo de Canfranc, LSC, along a tunnel connecting Spain and France, at a depth of 2450 m.w.e. with 850 m² area.

> The Boulby Underground Laboratory in a potash and rock-salt mine on the coast of England, at 2800 m.w.e., with 1500 m^2 laboratory space.

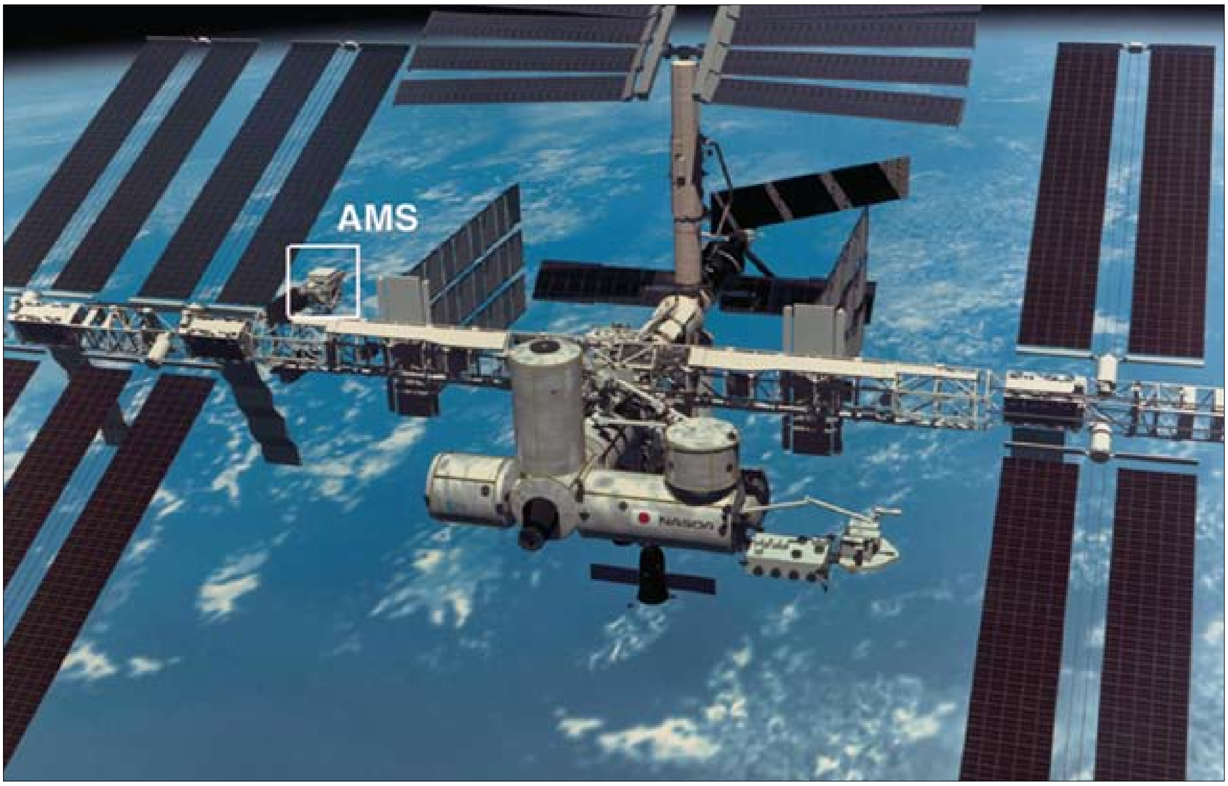
Other sites are being investigated, offering either larger depths, or larger distance to nuclear reactors (allowing the study of neutrinos from the Earth's crust with a low background from artificially produced neutrinos), or larger available volume. The largest depths are conceivable in a mine in Pyhäsalmi, Finland. Present excavations at this place reach down to a 4000 m.w.e., but large caverns at even greater depth are possible. Salt mines in Sieroszowice/Poland and Slanic/Romania offer large volumes at shallow depths. Small laboratories also exist in France and in the Ukraine. The oldest of the European underground laboratories is the Baksan Neutrino Observatory in the Russian part of the Caucasus. At present, it seems less favoured for logistical reasons and because of the unstable situation in this geo-political region.

Map of existing and considered European underground laboratories.

A cooperative network of underground laboratories

Which of the large experiments will be done at which site has to be decided over the next years. Significant activities are under way within the FP6 programme ILIAS, within the LAGUNA FP7 design study for a Megaton-scale detector, in the laboratories and within the individual experiments. There are clear advantages to have several deep underground laboratories in Europe and also to exploit both types of access – with road tunnels and mines. ILIAS and ASPERA promote this concept through formation and operation of a cooperative network of deep underground laboratories with each partner contributing low-background facilities and specific infrastructures depending on user demands, techniques available and the specific features of each site.

e International Space Station provides the infrastructure for many experiments including AMS 02, the Alpha Magentic Spectrometer, which should be launched in 2010, will search for antimatter and measure spectrum and composition of cosmic rays.



e CREAM cosmic ray detector at its launch towards a circumpolar long-duration flight in Antarctica.

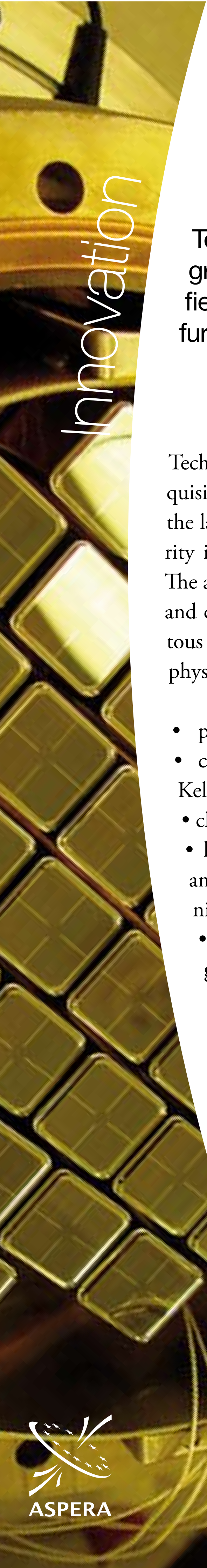
Observatories

Most cosmic particle detectors of the past could be considered “experiments”, with a relatively simple infrastructure. In contrast, several of the present and most of the future detectors have the character of “facilities”, with a sustainable mode of operation and administration, offering research possibilities to a wide community and being run as open observatories. For instance, a Mediterranean cubic kilometre facility for neutrino astronomy will also be used by oceanographers, biologists and seismologists, and the Cherenkov Telescope Array will reserve much of its observation time for external users. The infrastructural aspect of many of these facilities is further enhanced by their remote location. Whereas the necessary infrastructure for IceCube is provided by NSF’s Amundsen-Scott Station at the South Pole, other projects have to create most of their infrastructure themselves, like H.E.S.S. in Namibia, the Pierre Auger Observatory in the Argentinean Pampa, just to name two examples. A first-class infrastructure, with appropriate funding – not only for construction but also for sustainable operation – is a key aspect of next-generation detectors.

Space-based platforms

Some of the detectors for cosmic particles are mounted on satellites. They are able to identify and measure particles before they interact with the Earth’s atmosphere. The present major experiments orbiting around the Earth are PAMELA (charged particles) and AGILE and Fermi (gamma rays). The Alpha Magnetic Spectrometer, AMS, is expected to be launched in 2010 and will measure both charged particles and gamma rays on the International Space Station. Several experiments use stratospheric balloons for short-term flights, such as CREAM or ATIC, detecting charged particles. While the detector construction is supported by particle physics funding agencies, the infrastructures required to launch this type of experiment is usually provided by national or international space agencies.

e Fermi detector (formerly called GLAST) records gamma rays from space.



9. Pushing the frontier of innovation

Technological innovation has been a pre-requisite for the enormous progress made over the last two decades. It has enabled maturity in many fields of astroparticle physics. The challenges of the next decade require further fresh ideas and cutting-edge technology.

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, for example:

- photo detectors,
- cryogenic detectors working at milli-Kelvin temperatures,
- charge gain amplification devices,
- high-purity crystals and noble liquids and the related isotope purification techniques,
- state-of-the-art optical elements for gravitational antennas.

Beyond cutting-edge improvements of the existing, principally novel methods are being tested:

- Can one efficiently track particles via their radio emission?
- Can one "hear" neutrino interactions at super-high energies?

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-type solutions, as do computer simulations, for instance of extensive air showers or of cataclysmic cosmic events.

Many of the experiments are located in hostile environments: anchored deep in the Ocean, frozen in Antarctic ice, installed in the desert, in underground tunnels, on high mountains or flying on balloons or satellites. The astroparticle physicists were the first to install a high-bandwidth continuous link with the ocean bottom, instrument a very large prairie area with a 3000 km² dense grid of solar powered, synchronized detectors and develop underground laboratories of unprecedented radio-purity. Extreme reliability and remote control are the key words for these applications.

Given the importance of technological innovation, ASPERA envisages common calls for joint

High-purity germanium crystals for dark matter search.

funding of research and development projects. Calls will also stimulate cooperation with industry, which has been and will be a strong element of developing cutting-edge technology and of transferring innovative developments to industry.

We suggest that about 15-20% of astroparticle funding should be reserved for small initiatives, participation in overseas experiments with non-European dominance, and R&D.

Synergy with environmental research

In astroparticle physics, the ambient medium is often used as both interaction target and detector. But be it water, be it air – its properties change with time and must be carefully monitored. Environmental monitoring is therefore a key task in detector development. Instrumentation and monitoring of huge volumes in the atmosphere, the ocean and the Earth induces strong synergies with the geosciences, oceanography, climate research and risk monitoring and will lead to further innovations:

• Underwater monitoring: Remotely operated or autonomous vehicles do not allow long-term, continuous exploration of abyssal depths and require costly support ships. The neutrino telescope KM3NeT will provide a unique multidisciplinary observatory for deep sea science, exploring the properties of the deep Mediterranean Sea continuously over many years.

• Underground monitoring: Astroparticle detectors are currently used, for instance, for environmental measurements, for ancient sample dating and for the tracking of the origin of food. Future interdisciplinary networks of underground sensors will address a wide range of questions, ranging from imaging groundwater resources to studying the complex interactions between tectonic stresses, seasonal infiltration and fault-zone hydro-mechanical stability.

• Atmospheric monitoring: The new generation of air shower experiments requires accurate atmospheric monitoring. Already now, the stormy development of this field has provided world-class data. Autonomous distributed systems developed in this field will also fertilize networks for ground and underwater seismic monitoring.

Setup to test the feasibility of acoustic detection of neutrinos in ice.

10. Coordination of astroparticle theory

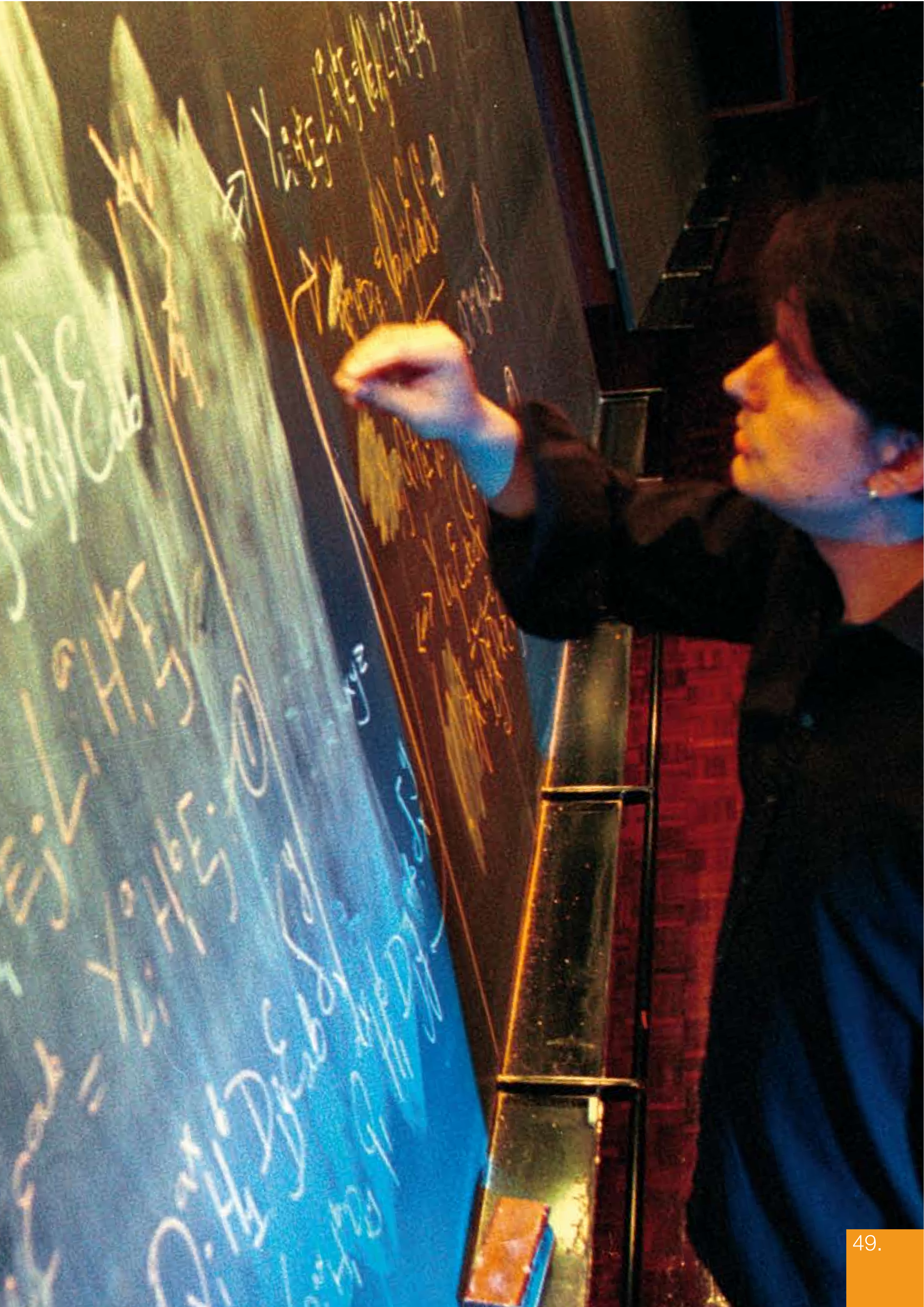
Theoretical research is an invaluable source of new concepts, of inspiration for experimenters and a necessary tool to interpret experimental results. Theorists are spearheads in combining particle physics, cosmology and astrophysics. Like experiment, theory needs reliable support and coordination.

Even more than for experimental astroparticle physics, the distinctions between particle physics, cosmology and astrophysics have been blurred for theory. The same theorists often work on several fields, like high energy particles, dark matter, physics of the early Universe – just to name a few. Notably, most of them have a background in particle physics.

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. As examples for the need for coherent actions we mention the assessment and reduction of the uncertainty of nuclear matrix elements for double beta decay experiments, the interpretation of cosmological data and their relevance to dark matter and dark energy, and the modelling of high energy processes in violent environments.

Coherent European activities in theoretical astroparticle physics are supported by various means. These include the establishment of a regular common European school for astroparticle physics, building on the experiences with the International School on AstroParticle Physics (ISAPP). At present, the European Union supports the "European Network of Theoretical Astroparticle Physics" (ENTApP), a networking programme of the FP6 Integrated Infrastructures Initiative ILIAS. ENTApP focuses on theory related to the experimental goals of ILIAS – neutrino-less double-beta decay, dark matter and gravitational waves.

Theory is an invaluable source of inspiration for experimenters and a necessary tool to interpret experimental results, and must be supported with the same recognition like experiments. Among the discussed proposals for improved support and coordination of astroparticle theory we mention a Europe-wide common call for theoretical proposals and a future European Centre for Astroparticle Theory, with the involvement of an international panel of expert referees. Such a centre could be established either in one of the European countries or at CERN. Given the synergy between LHC physics and astroparticle physics, CERN would be a natural host, particularly in view of several astroparticle experiments being CERN 'recognised experiments'.



11. Education and outreach

Education & outreach

The number of young researchers joining astroparticle physics has steadily increased over the last decade. Astroparticle physics is not only an important element of teaching at many universities, but also challenges imagination and curiosity of a broad audience.

The questions of astroparticle physics address very basic 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 other factors 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.

A joint astroparticle physics outreach program in Europe (EuroCosmics) brings together outreach efforts in 12 European countries and promotes a long term scientific/educational collaboration between researchers, high-school teachers and high-school students. For instance, Dutch Universities developed a country-wide network of cosmic ray detectors at the roofs of more than 50 high schools. The astroparticle physics community is also in close contact with the European Particle Physics Outreach group which is also working on a network and forum for outreach activities. Among the traditional activities of outreach, "open days" in the large underground laboratories and popular-scientific TV movies have turned out to be particular successful.

e Dutch HISPARC project: recording cosmic particles on school roofs.

ASPERA

Warped space-time or soap bubbles? Children at an open day in the Gran Sasso Laboratory.

The implementation of the ASPERA website (www.aspera-eu.org) has turned out to be a valuable platform for internal and external communication and was visited 50,000 times within 18 months. It allows access to information on reports, the roadmap, conferences and meetings, press releases, and the ERA-NET itself. The ASPERA outreach group releases a monthly newsletter with about 800 subscriptions, developed a travelling exhibition for presenting ASPERA at important events, and installed extended press relationships. These activities play a key role in giving greater visibility to astroparticle physics at the European level and beyond.

To establish a sustainable outreach structure ASPERA plans to enhance its outreach group towards a coordination network, allowing more effective communication and avoiding duplication of efforts. This network will make use of the ASPERA web platform as the area for the exchange of information and ideas.

e ASPERA travelling exhibition attracts visitors at the Euro Science Open Forum ESOF 2008 in Barcelona.

Coordination in Europe: ApPEC and ASPERA.

The high cost of frontline astroparticle projects requires international collaboration, as does the realisation 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 M€. Coordination and cooperation are 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.

ApPEC (Astroparticle Physics European Coordination) was founded 2001 as an interest grouping of six European scientific agencies. They realised that most of the emergent field of astroparticle physics was 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,
- establishing a system of peer review assessment.

Since then, ApPEC has grown to 17 agencies representing 14 European countries. Its executive body is the Steering Committee (SC), with one leading scientific executive from each country and observers from CERN, ESO and ESA. Its strategic advisory body is the Peer Review Committee (PRC). The PRC reviewed each of the subfields of astroparticle physics, with topical workshops in 2002-2004. ApPEC has coordinated the submission of the successful proposal ILIAS, an Integrated Infrastructure Initiative (I3), funded under the European Commission's Sixth Framework Programme (FP6). ILIAS focuses on the searches for double beta decay, for dark matter, and the search for gravitational waves. It also includes a programme for coordinating, for the first time, the deep underground laboratories in Europe, and a network on theoretical astroparticle physics. Also, ApPEC promoted the successful proposal for a FP6 Design Study for a Mediterranean neutrino telescope, KM3NeT.

By 2005 ApPEC realised that its goals and methods fitted perfectly to the European Union ERANET scheme and initiated the submission of the ASPERA proposal. ASPERA started in July 2006, funded by the EU with 2.5 M€ for a three-year period. ASPERA has enabled the pursuit of political and coordinative goals on a solid operational basis. Aiming to be a truly European initiative, it consistently works towards extension to more national agencies. 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 Roadmap Committee. Actually, the ASPERA Roadmap Committee emerged from the ApPEC Peer Review Committee (PRC) with part of the old members replaced by new members and taking account the new partner countries.

The work of ASPERA is structured into clear work packages, with the three of them forming the core activities:

a) chart the status of astroparticle physics funding schemes in Europe
b) establish a roadmap and an action plan
c) link the existing platforms of observation, establish the best legal schemes for future infrastructures and find ways to commonly and manage the new large programs

Under the operational leadership of ASPERA, the Phase-I stage of a roadmap was finished, describing the status and desirable options for the next decade. This *Status and Perspective of Astroparticle Physics in Europe* (http://www.aspera-eu.org) has been prepared by the Roadmap committee between October 2005 and January 2007, with questionnaires sent to the experiments, many committee meetings and several town meetings and with feedback from the science community.

In a second phase, detailed questionnaires from subfields and agencies have been collected and timelines and updated cost estimates compiled within ASPERA working groups each addressing one of the sub-fields. The outcome has been presented at an international meeting on 20/21 September 2007 in Amsterdam. In the third phase, ending in autumn 2008, a realistic funding scenario has been worked out. Proposals for priority experiments, for the phasing of large projects and for international cost sharing are made. They meet a funding scenario with a smooth factor of 2 increase over the next 8-10 years (see the recommendations at the end). Phase-III will officially culminate with a prestigious international workshop in Brussels on 29/30 September 2008 and the presentation of the present document. It will be flanked by a longer write up, becoming available online.

The ASPERA census as of August 2008 (see http://www.aspera-eu.org) includes 11 countries: Belgium, the Czech Republic, France, Germany, Italy, The Netherlands, Portugal, Spain, Sweden, Switzerland and the United Kingdom, with detailed information presented on “National Days”. Numbers from Greece will be added on a National Day in autumn 2008, and those for the new ASPERA members will follow in 2009.

The total number of Full Time Equivalents (FTE) assigned to astroparticle physics was counted as 2,325. The total 2006 budget for astroparticle physics in the 11 countries amounted to 186 M€; about 96 M€ for investment and running and 90 M€ for salaries. Averaged over recent years, the total sum for investment is about 70 M€. The tables give the numbers of FTE, the total 2006 budgets and the number of institutions with astroparticle activities (research centres and universities) per country (see table).

Normalised to the total government budget for research, the expenditures amount to 0.5 to 5.5 per thousand, with a large proportion of the Italian budget spent on running the Gran Sasso Underground laboratory (see first figure).

The ratio of the number of researchers to the population of each country demonstrates the support which astroparticle physics has all over Europe (see second figure).

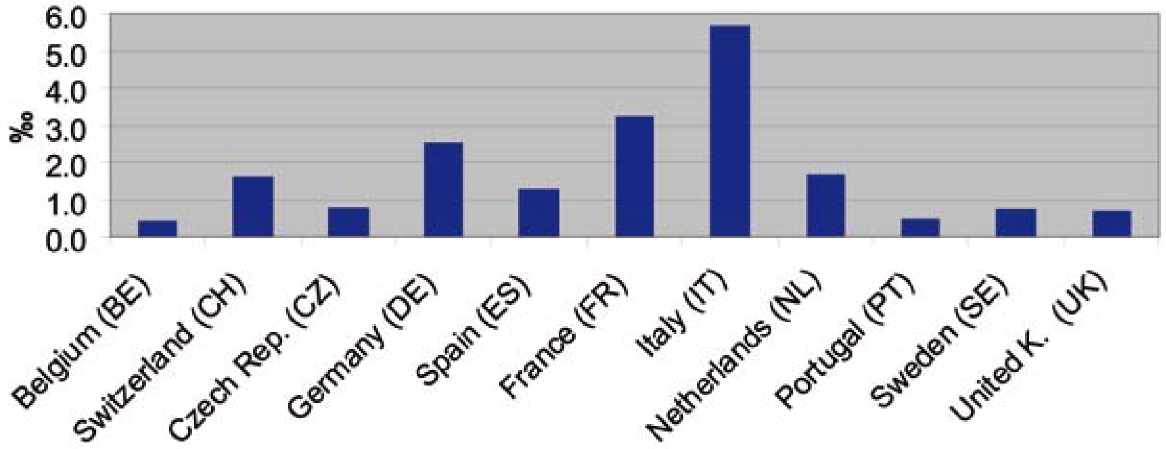
The ASPERA program gave a tremendous boost to the European convergence of the field. The process became visible internationally and elicited demands from other continents for global coordination, as it is currently seen in the OECD Megascience forum under preparation. Next steps in Europe will be common calls for joint funding of research and development initiatives as well as coordinated joint programming of multimillion programs.

Although a large part of its activities are now passing through ASPERA work packages, ApPEC decided not to dissolve into the ERANET but continue its operation at a higher decisional level. The reason is obvious: Astroparticle physics needs sustainable support beyond the few-years duration of an ERANET program. So ASPERA sees its sustainable future in a "reinforced" ApPEC, or, in other words: ApPEC constitutes both the past and the future of ASPERA.

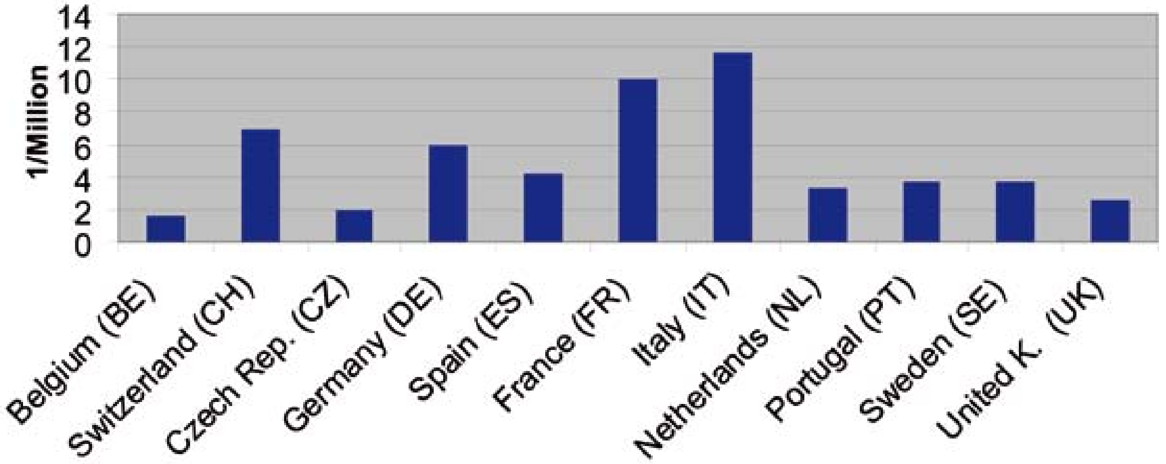
Astroparticle physics in ASPERA countries:
Number of Full Time Equivalents (FTE), the 2006 budget, and number of institutions with astroparticle activities (research centres and universities).

Country	BE	CH	CZ	DE	ES	FR	IT	NL	PT	SE	UK
FTE	17	52	20	494	168	608	679	55	40	34	158
Budget(M€)	0.7	3.6	0.4	44.0	10.0	51.5	58.6	6.1	0.5	2.0	9.0
#Institutions	4	7	5	38	13	28	30	9	5	3	19

Ratio of the astroparticle budget to the government research budget.



Ratio of the number of researchers in astroparticle physics to the total population.



Source: 2006

Recommendations

Recommendations

Astroparticle physics is developing with high speed and stands on the threshold of fascinating discoveries. Below we present the roadmap committee's recommendations for priority instruments in each of the seven fields, for support of related activities and for phasing of the big projects.

Direct Dark Matter Search

We recommend the construction and operation of one – possibly two complementary – detectors on the ton scale or beyond with low background, capable of reaching a 10^{-10} pb sensitivity, with a European lead role or shared equally with non-European partners. We recommend a stepwise approach via 100 kg detectors, as presently underway, and a prioritisation between different technologies around 2010/2011. We urge convergence of parallel worldwide efforts.

Neutrino Mass

Depending on the outcome of the present generation of double beta decay experiments being prepared, we recommend the eventual construction and operation of one or two double beta decay experiments on the ton-scale, capable of exploring the inverted-mass region, with a European lead role or shared equally with non-European partners. A decision on the construction could be taken around 2013.

Proton Decay & Low Energy Neutrino Astrophysics

We recommend supporting the work towards a large infrastructure for proton decay and low energy neutrino astrophysics, possibly also accelerator neutrinos in long baseline experiments, in a worldwide context. Results of a current FP7 design study (LAGUNA) are expected around 2010 and should be followed by work towards a technical design report. Depending on technology, site and worldwide cost sharing, construction could start between 2012 and 2015.

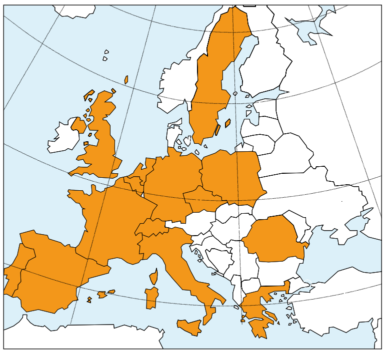
Gamma Astrophysics

The priority project for VHE gamma astrophysics is the Cherenkov Telescope Array, CTA. We recommend design and prototyping of CTA, the selection of sites, and proceeding rapidly towards start of deployment in 2012.

Charged Cosmic Rays

The priority project for high energy cosmic ray physics is the Pierre Auger Observatory. We encourage the agencies in different conti-

ASPERA



ASPERA comprises 18 agencies from 13 countries in Europe funding astroparticle physics research, and CERN.

nents to work towards a common path for Auger-North. We recommend the construction of such a large array as soon as world-wide agreements allow.

Neutrino Telescopes

The priority project for high energy neutrino astrophysics is KM3NeT. Encouraged by the significant technical progress of recent years, the support for working towards KM3NeT is confirmed. Resources for a Mediterranean detector should be pooled into a single optimised design for a large research infrastructure, with installation starting in 2012. The sensitivity of KM3NeT must substantially exceed that of all existing neutrino detectors including IceCube.

Gravitational Waves

The long-term priority of ground-based detectors is the Einstein Telescope, E.T., a large underground gravitational wave detector. We recommend support for R&D work towards E.T., with construction starting after first discoveries have been made with LIGO/Virgo/GEO, likely around 2016/17. The short term priority is the upgrade of the present generation of gravitational waves detectors, with a particular recommendation to support a fast upgrade of Virgo to "advanced Virgo".

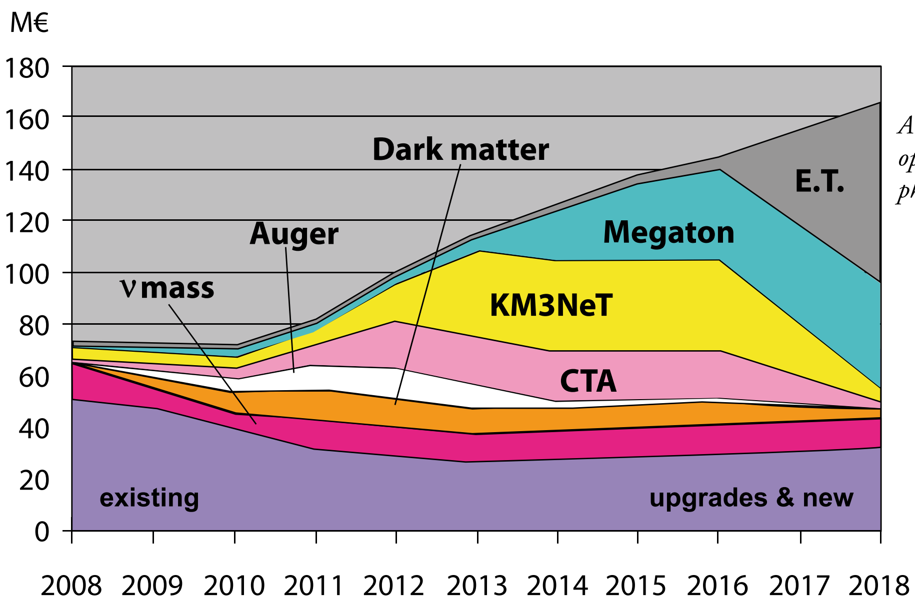
We also support:

- Earth and space based missions to explore the phenomenon of "dark energy",
- the concept of a cooperative network of deep underground laboratories,
- a common call for innovative technologies in the field of astroparticle physics,
- efforts to intensity the synergy with environmental sciences,
- the formation of a European Centre for Astroparticle Theory.

Starting from the initial cost and profiles supplied by the experiments, the Roadmap Committee has looked at possibilities for phasing and cost reduction by inter-continental cooperation. It defined milestones to decide which experimental method in any of the first three classes (dark matter search, double beta decay experiments and a large multi-purpose detector underground) should get priority or how competing methods might be combined. These milestones are explained in the previous chapters. 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). We assumed that not all of the available budget should be spent on the flagship projects, but about 15-20% should be reserved for small initiatives, participation in overseas experiments with non-European dominance, and R&D. We find that the plans fit into a scheme where the funding for investment is smoothly doubled over 8-10 years, amounting to an integrated increase of about 50% in a ten year period. The estimated increase in the sum for personnel costs is smaller. The figure below illustrates our findings.

Earliest projects on the cost scale of 30 M€ or more are the high energy observatories, with the European priority projects CTA and KM3NeT, together with an Auger-North implementation in a worldwide context. These projects are based on known technology and their construction could start by 2012. In the domain of underground science, the present network of European underground laboratories should be further strengthened by coordination and extensions. The technology of ton-scale underground detectors for dark matter and neutrino mass will be decided in 2010-2013, based on the performance of current medium scale detectors and on cost considerations. The construction of a very large underground detector for proton decay and low-energy neutrino astrophysics could start by the middle of the next decade, followed by a third generation gravitational antenna, both in a worldwide context.

The technology of the next generation dark matter and neutrino mass detectors, as well as the steps towards a Megaton scale detector and the next generation gravitational antenna, will be further defined in the next version of this roadmap, due in 2010/2011. This update will be driven not only by issues of technology readiness and design study specifications but also by the wealth of data and discoveries expected from recently launched or soon operating instruments, for instance the Fermi satellite, the Large Hadron Collider LHC, the Planck satellite and long baseline reactor and accelerator neutrino experiments.



A scenario for investment and operation cost of astroparticle physics in the ASPERA countries.

Illustration credits

p1. 3 circles: ASPERA/A.Marsollier

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