Status and Perspective of Astroparticle Physics in Europe

Astroparticle Physics Roadmap Phase I

SIXTH FRAMEWORK PROGRAMME

ApPEC

ASPERA

On this document

The Steering Committee of ApPEC (Astroparticle Physics European Coordination) has charged the ApPEC Peer Review Committee (PRC) in 2005 to prepare a roadmap for astroparticle physics in Europe* which covers the next decade. The need for such a roadmap arises since projects in astroparticle physics move to ever larger sensitivity and scale, with costs of individual projects on the 100 M€ scale or beyond. The roadmap document presented here was prepared by the PRC between October 2005 and January 2007. As a first step towards the roadmap, the state of the experiments in the field was evaluated using a questionnaire filled out by the spokespersons of all astroparticle experiments in Europe, or with European participation (see Appendix 2). Based on this information, on input from the proponents and on presentations given to ApPEC in the last years, the most promising research areas and instrumental approaches were identified. A town meeting in Munich in 2005 served to discuss and iterate these initial concepts with the community at large. The recommendations given in the roadmap were in several stages iterated in particular with the spokespersons of the experiments as well as with the ApPEC Steering Committee. After a large meeting in Valencia (Nov.7/8, 2006), further significant modifications have been prepared by smaller working groups, submitted by individuals and included in the present version.

The resulting ApPEC roadmap marks the first stage (ASPERA Roadmap/Stage I) of a strategy process which foresees a “final” roadmap (ASPERA Roadmap/Stage 3) in July 2008. The next stages will be coordinated within ASPERA, an FP6 ERA-Network, with the aim to give detailed implementation scenarios and priorities.

The present “first stage” roadmap describes the status and desirable options for the next decade and will help to define the financial and organizational conditions to reach the envisaged goals. This represents an important input to the second and third stage of the roadmap process. We argue that physics prospects and worldwide competition suggest a significant increase in funding for astroparticle physics. In 2008, the consolidation of funding options and the further evolved status of the projects will allow much better prioritization and staging recommendations for the 30-800 M€ projects to be constructed after 2010. The ASPERA stage of the roadmap will be supplemented by more detailed data on human resources, budget, milestones and the world situation.

** Europe – in contrast to its geographical meaning – in this roadmap does not include the states of the former Soviet Union (or only insofar as Western groups participate in Russian experiments).*

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Content

Executive Summary

Initial triumphs of Astroparticle Physics

In 2002, Ray Davis and Masatoshi Koshiba were awarded the Nobel Prize in Physics for opening the neutrino window to the Universe, specifically for the detection of neutrinos from the Sun and the Supernova SN1987A in the Large Magellanic Cloud. Their work was a unique synthesis of particle physics and astrophysics. Solar neutrinos also provided the first clear evidence that neutrinos have mass. It is this interdisciplinary field at the intersection of particle physics, astronomy and cosmology which has been christened ***astroparticle physics***.

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

Given its interdisciplinary approach and the overlap with astrophysics, particle physics and cosmology, a concise definition of which experiments may be considered “astroparticle physics” is difficult and perhaps not even desirable. For the purpose of this roadmap, the ApPEC Roadmap Committee adopted the assignments grown historically and being practiced in most European countries.

The basic questions

Recommendations for the evolution of the field over the next decade were formulated by addressing a set of basic questions:

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) Can we detect gravitational waves ? What will they tell us about violent cosmic processes and about the nature of gravity?

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

Astroparticle physics at the dawn of a golden decade ?

Most of the fields of astroparticle physics have moved from infancy to technological maturity: the past one or two decades have born the instruments and methods for doing science with high discovery potential. We observe an accelerated increase in sensitivity in nearly all fields – be it neutrino-less double beta decay, dark matter research, search for high energy neutrinos, gamma rays and cosmic rays, or gravitational waves – just to mention a few.

The long pioneering period to prepare methods and technologies is expected to pay off over the next 5-15 years. This will not only need substantial investment in large detectors but also in the necessary infrastructures – *underground laboratories* (providing the infrastructure to perform, e.g., the search for double beta decay, "direct" searches for dark matter, investigation of neutrinos from the Sun or supernovae, or detectors searching for proton decay), *telescopes/observatories* (like neutrino telescopes underwater and -ice, telescope arrays for gamma rays or the largest air shower detectors for charged cosmic rays) and satellites.

Next-stage projects need strong coordination and cooperation

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

Major European initiatives in the next decade: a scenario

The European astroparticle community has a lead position in many fields. The roadmap and it's recommendations illustrate this claim in detail. We assume that the process of cooperation and coordination converges to the following major (cost > 50 M€) activities between 2009 and 2015. The Table gives a summary information on these projects, the following text a short background and explanation.

Field/ Experiments	**Cost scale per experiment (M€)**	**Desirable start of construction**	**Remarks**
Dark Matter Search: Low background experiments with 1-ton mass	60-100 M€	2011-2013	2 experiments (different nuclei, different techniques), e.g. 1 bolometric, 1 noble liquid; more than 2 worldwide.
Proton decay and low energy neutrino astronomy: Large infrastructure for p-decay and ν astronomy on the 100kt-1Mton scale	400-800 M€	Civil engineering: 2012-2013	- multi-purpose - 3 different technological options - needs huge new excavation - most of expenditures likely after 2015 - worldwide sharing
Properties of neutrinos: Double beta experiments	50-200 M€	2013-2015	- explore inverted hierarchy scenario - 2 experiments with different nuclei (and desirably more worldwide) - large cost range due to large range of isotope prices
The high energy universe: *Gamma rays:* Cherenkov Telescope Array CTA	100 M€ (South) 50 M€ (North)	first site in 2010	Physics potential well defined by rich physics from present gamma experiments
Charged Cosmic Rays: Auger North	85 M€	2009	Confirmation of physics potential from Auger South results expected in 2007
Neutrinos: KM3NeT	250 M€	2011	FP6 Design Study. Confirmation of physics potential expected from IceCube and gamma ray telescopes. Physics Design Report and Proposal expected in 2009.
Gravitational Waves: Third generation ground-based interferometer	300 M€	Civil engineering 2012	Conceived as underground laboratory

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

• Search for Dark Matter

Construction and operation of two 1-ton, low background experiments for "direct" dark matter search with a European lead role. Only 4% of the Universe consist of ordinary matter but 23% of what is called "Dark Matter". The favoured solution to the Dark Matter mystery assumes Weakly Interacting Massive Particles (WIMPs) produced in the Early Universe. These particles could be produced at the forthcoming LHC collider. Cosmic WIMPs can be searched by "direct" and "indirect" means. Our recommendation refers to the direct search, where WIMPs interact with laboratory detectors. The progress made in this field over the last few years is impressive, and extrapolating to the future one concludes that there is a significant chance to detect dark matter particles in the next decade – provided the progress in background rejection can be realized and the considerable funding (on the 60-80 M€ scale for 1-ton projects) is provided. Presently favoured candidate devices appear to be bolometric detectors like EURECA and a noble liquid detector based on xenon or argon. Construction could start between 2011 and 2013. The DAMA collaboration envisages a 1-ton NaI detector as an additional option, with a cost of about 10M€. An experiment able to detect the direction of WIMP events and to correlate this information with our motion through the galaxy would give definitive proof that a potential signal is of galactic origin and furthermore provide information on WIMP galactic halo dynamics. Directional methods require further development efforts and support.

• Proton decay and low energy neutrino astronomy

Start of construction of one large infrastructure for proton decay and low energy neutrino astronomy (possibly also accelerator neutrinos in long baseline experiments). Grand Unified Theories of particle physics predict that the proton has a finite lifetime. The physics of proton decay may be closely linked to the physics of the Big Bang and the matter-antimatter asymmetry in the Universe. The discovery of proton decay would be one of the most fundamental discoveries for physics and cosmology. An improvement of an order of magnitude over the existing limits explores a physically relevant range of lifetimes. A detector with these capabilities could also detect neutrinos from a galactic Supernova with unprecedented statistics. It would not only boost our understanding of stellar explosions but also turn the supernova into a laboratory for testing basic physics laws. It would also allow a precise study of the solar interior and of neutrinos generated deep in the Earth. The design of such a detector appears possible, but requires careful studies to optimize the methods and choice of the most promising technology. The Roadmap Committee recommends envisaging a new large European infrastructure, as a future international multi-purpose facility on the 10^5-10^6 ton scale, for improved studies of proton decay and of low-energy neutrinos from astrophysical origin. The three detection techniques are currently studied for such large neutrino detectors in Europe, Water-Cherenkov (e.g. MEMPHYS), liquid scintillator (e.g. LENA) and liquid argon (e.g. GLACIER). They should be evaluated in the context of a common design study which should also address the underground infrastructure and the possibility of detecting neutrinos from future accelerator beams. This design study should take into account worldwide efforts and converge, on a time scale of 2010, to a common proposal. The committee ranks such a detector (respectively two of them worldwide) very high and recommends that Europe plays a leading role in at least one of them, including the preparation of the corresponding infrastructure in Europe. The total cost depend on the method and the actual size and is estimated between 400 and 800 M€. With start of civil engineering in 2012 or 2013, only a third of this amount might be due before 2016.

• Neutrino properties

Construction and operation of two double-beta decay experiments with a European lead role or shared equally with non-European partners. A clear signal of neutrino-less double beta decay would establish that neutrinos are the only fermions which are their own antiparticle ("*Majorana* particles"). Establishing a possible Majorana nature of neutrinos would be a fundamental discovery. Neutrino-less double beta decay would also constrain the absolute scale of the neutrino mass. There are three possible mass ranges. Two of them (corresponding to the "degenerate" and the "inverted hierarchy" scenario, respectively) are accessible with present methods. The European next-stage detectors are GERDA, CUORE, Super-NEMO and possibly COBRA (neutrino mass range 50-100 meV). With these detectors, Europe will be in the best position to improve sensitivity and maintain its leadership in this field and to prove or discard – together with the direct mass experiments – "degenerate" scenarios. Future detectors of the next following stage, with an active mass of order one ton, good resolution and very low background, can cover the mass range of the "inverted" mass hierarchy and reach a sensitivity of 20-50 meV. Construction could start between 2013 and 2015. Different nuclear isotopes and different experimental techniques are needed to establish the effect and extract a neutrino mass value. The price tag for one of these experiments is at the 50-200 M€ scale, with the large range in cost being due to the production cost for different isotopes.

• The high energy Universe

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

Construction and operation of the large Cherenkov Telescope Array, CTA. European instruments are leading the field of ground-based high-energy gamma ray astronomy. The rich results from current instruments show that high-energy phenomena are ubiquitous in the sky; in fact, some of the objects discovered emit most of their power in the gamma-ray range and are barely visible at other wavelengths ("dark accelerators"). The need for a next-generation instrument is obvious, and its required characteristics are well understood. The Roadmap Committee very strongly recommends the construction of a next-generation facility, CTA. CTA should both boost the sensitivity by another order of magnitude and enlarge the usable energy range. CTA is conceived to cover both hemispheres, with one site in each. The instruments should be prepared by a common European consortium and share R&D, technologies and instrument designs to the extent possible. Cooperation with similar efforts underway in the US and in Japan should be explored. The price tag for one site is in the 50-100 M€ range. The desirable start of construction is 2010.

Construction and operation of Auger North. The present flagship in the search for sources of ultra-high energy cosmic rays is the Southern Pierre Auger Observatory, with a 50% European contribution. The celestial distribution of possible sources and of background radiation and magnetic fields requires full-sky coverage. This is the main idea behind a Northern Auger Observatory, the second being a possible extension to a larger area and measuring to even higher energies. European groups should play a significant role to establish the scientific case, and after its demonstration make a significant contribution to the design and construction of Auger-North. Estimated costs are 85 M€, with about a third of this sum expected from Europe. Construction could start in 2009.

Construction and initial operation of KM3NeT. The physics case for high energy neutrino astronomy is obvious: neutrinos can provide an uncontroversial proof of the hadronic character of the source; moreover they can reach us from cosmic regions which are opaque to other types of radiation. European physicists have played a key role in construction and operation of the two pioneering large neutrino telescopes, NT200 in Lake Baikal and AMANDA at the South Pole, and are also strongly involved in AMANDA's successor, IceCube. A complete sky coverage, in particular of the central parts of the Galaxy with many promising source candidates, requires a cubic kilometre detector in the Northern Hemisphere complementing IceCube. A strong community has grown over the last decade, with the goal to prepare the construction of this future detector in the Mediterranean. Prototype installations (NESTOR, NEMO) and an AMANDA-sized telescope (ANTARES) are expected to be installed in 2006/2007. An EU-funded 3-year study (KM3NeT) is in progress to work out the technical design of a single, optimized large future research infrastructure "KM3NeT". Its design should incorporate initial results from IceCube as well as the improved knowledge on Galactic sources as provided by H.E.S.S. and MAGIC gamma ray observations. The cost scale for KM3NeT is expected to be roughly 230-250 M€; more precise estimates will result from the Design Study. The construction of KM3NeT has to be preceded by the successful operation of small scale or prototype detector(s) in the Mediterranean and could start in 2011.

• Gravitational Waves

Start of the construction of a third generation interferometer. The detection of gravitational waves would prove one of the central predictions of the Theory of General Relativity and be of fundamental significance by its own. Moreover, gravitational waves would provide us with information on strong field gravity through the study of immediate environments of black holes. The most advanced tools for gravitational wave detection are interferometers with broad-band sensitivity. At present, the world's most sensitive interferometer is LIGO (USA), the others being GEO600 in Germany, TAMA in Japan and VIRGO in Italy. The research field of Gravitational Wave has a huge discovery potential but is still awaiting the first direct detection. In the short term, the European ground interferometers (GEO and VIRGO) should turn to observation mode with a fraction of their time dedicated to their improvement (GEO-HF, VIRGO+ and Advanced VIRGO). The design study of a large European third-generation interferometer facility should start immediately and timely decisions for interferometer installation be made at the earliest possible date. Civil engineering could start in 2012. First estimates tag such a device at about 300 M€.

Small initiatives and technology development

Technological innovation has been a prerequisite of the enormous progress made over the last two decades and enabled maturity in most fields of astroparticle physics. It is also a prerequisite for future progress towards greater sensitivity and lower cost and must be supported with significant funds. Also, there must be room for initiatives below the 50 M€ level defined as a lower limit for what we call major initiatives. 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.

Coordination with related communities

Naturally, the astroparticle physics community is developing its concepts in close interaction with the strategies evolved in related fields. The *European Strategy for Particle Physics* has been prepared by the CERN Council Strategy Group. It focuses on accelerator physics activities but also highlights astroparticle physics: *"A range of very important non- accelerator experiments take place at the overlap between particle physics exploring otherwise inaccessible phenomena; Council will seek to work with ApPEC to develop a coordinated strategy in these areas of mutual interest".* This exchange of information has been practiced already in the preparation phase of the strategy paper on particle physics and of the present roadmap. The other important link is to the astrophysics community which is working, within the Era-Net ASTRONET, on a *Science Vision for European Astronomy* which will be followed by an *Infrastructure Roadmap for European Astronomy*. Also in this case, there are close connections between the corresponding panels, including personal overlap.

Funding Challenges

Assuming that 80-85% of European funding available for astroparticle physics is focused on the mentioned major flagship projects, one arrives at a sum of 1.2-1.5 billion € to be spent between 2010 and 2015. Funding of this order of magnitude is desirable to maintain European leadership. It also would reflect the existence and science results of a community which has grown to about 2000 scientists in Europe, many moving from other fields (like accelerator based physics) to astroparticle physics. The present funding for astroparticle physics amounts to 135 M€ per year in all ApPEC member states. A stronger involvement of non-European partners may lower the necessary funding from European resources, on the other hand overseas involvement in Europe will likely go hand in hand with a corresponding European participation in projects in the US, Japan or Russia. Further staging is another option, but always implies a loss in dynamics and in worldwide leadership. In any case staging would be preferable to an option of closing – or ramping down significantly – any of the major activities.

We are convinced that the prospects of astroparticle physics merit a substantial increase of funding, and the ApPEC roadmap paper is intended to establish the case for these increased efforts. New exciting discoveries lay ahead – it is up to us to take the chance offered by the next decade!

1. Introduction

1.1 Aim and remit of this report

This ApPEC report provides a European roadmap for astroparticle physics. It describes the status and perspective of this field within Europe and links it to activities in other parts of the world. It aims to promote astroparticle physics within the member states of ApPEC, to stimulate coordination and cooperation within the European astroparticle community and to prepare future decisions at National and European level. This roadmap covers the next ten years, with a focus on the next five.

The document has been developed by the ApPEC roadmap committee (RC) at the request of the ApPEC Steering Committee (SC). The roadmap committee consists of the ApPEC Peer Review Committee (PRC) members, extended by additional experts from ApPEC member states, USA and Russia. The members of the committee are listed in Appendix 1.

1.2 Questions of astroparticle physics

Astroparticle Physics has evolved as a new interdisciplinary field at the intersection of particle physics, astronomy and cosmology. It combines the experimental techniques and theoretical methods from both astronomy and particle physics. Particle physics is devoted to the intimate structure of matter and the laws that govern it. Cosmology addresses the large scale structure of the Universe and its evolution since the Big Bang. Astrophysics studies the physical processes at work in celestial objects. Most discoveries in particle physics have immediate consequences on the understanding of the Universe and, vice versa, discoveries in cosmology have fundamental impact on theories of the infinitely small.

It will come as no surprise that the borders of a field overlapping with its neighbours are rather blurred, and assignment of certain types of experiments to either astroparticle physics or particle physics or cosmology sometimes appears to be debatable. Rather than wasting effort in sophisticated discussions on definitions, the Roadmap Committee adopted the assignments that have grown historically and are being practiced in most European countries.

Astroparticle physics addresses some of the most fundamental questions of contemporary physics (see also "Connecting Quarks with the Cosmos: Eleven Questions for the New Century", National Academies Press 2003). Achieving an answer to most of these questions would mark a major break-through in understanding our Universe and would open up entirely new fields of research.

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

   Only 4% of the Universe is made of ordinary matter. Following the latest measurements and cosmological models, 73% of the cosmic energy budget seems to consist of "dark energy" and 23% of dark matter. The nature of dark energy remains a mystery, probably intimately connected with the fundamental question of the„cosmological constant problem". Dark matter turns out to be the majority component of cosmic matter. It holds the Universe together through the gravitational force but neither emits nor absorbs light. Dark matter (including a small admixture of massive neutrinos) has likely played a central role in the formation of large scale structures in the Universe. Its exact nature has yet to be determined. The discovery of new types of particles which may comprise the dark matter would confirm a key element of the Universe as we understand it today. The favoured candidate for particulate dark matter is the lightest supersymmetric (SUSY) particle, most probably the *neutralino*. Astroparticle physicists have developed a variety of tools for direct and indirect neutralino searches and will explore a large fraction of the best motivated theoretical models. These explorations will complement SUSY searches at the Large Hadron Collider, LHC. An alternative possibility is that dark matter consists of *axions*, light pseudoscalar particles copiously produced in the Early Universe, or of bosonic particles with axion-like interactions. Other particles beyond the standard model of particle physics may contribute on a smaller level to the cosmic inventory, such as magnetic monopoles or extremely heavy SUSY states. Last but not least, the extent of matter-antimatter asymmetry is explored by searches for antiparticles and tested against theories of the early Universe.

2) Do protons have a finite lifetime?

Grand Unified Theories (GUTs) of particle physics predict that the proton has a finite lifetime. Proton decay is one of the most generic and verifiable implications arising from GUTs. The physics of proton decay may be closely linked to the generation of the matter-antimatter asymmetry in the Universe. The discovery of proton decay would be one of the most fundamental discoveries for physics and cosmology. It requires large-scale detectors located deep underground.

3) What are the properties of the neutrinos? What is their role in cosmic evolution?

Neutrinos have provided the first reliable evidence of phenomena beyond the Standard Model of particle physics. In the Standard Model, neutrinos have no mass. A major breakthrough of the past decade has been the discovery that neutrinos, on the contrary, *are* massive. This evidence has been obtained from the observation that neutrinos can change their identity and oscillate between different flavour states. From the oscillation pattern, the mass differences between different neutrino states can be inferred, but not the absolute values of their masses, nor the form of their mass hierarchy. Dedicated experiments are sensitive to the absolute value of the mass. Another class of experiments search for "neutrino-less double beta decay" and may tell us whether the neutrinos are their own antiparticles – a discovery going well beyond the precision measurement of their absolute masses. Another important issue for particle physics and cosmology is the precise mechanism by which neutrinos oscillate from one state to another. Information on the "mixing matrix" is obtained from measurements of neutrinos from the Sun, Supernovae and the Earth's atmosphere. Moreover, the question is addressed by dedicated experiments with artificially produced neutrinos from reactors and accelerators. Massive neutrinos may have played a role in the genesis of the matter-antimatter symmetry of the Universe and in the formation of large scale cosmic structures.

4) What is the origin of high energy cosmic rays? What is the view of the sky at extreme energies?

Nearly a century ago, the Austrian physicist Victor Hess discovered cosmic rays, charged particles that hit our atmosphere like a steady rain from space. Later, it turned out that some of these particles have energies a hundred million times greater than that achievable by terrestrial accelerators. The observation of particles with such breathtaking energies raises several questions; How can cosmic accelerators boost particles to these energies? What is the maximum energy achievable by galactic sources such as supernova remnants or microquasars ? What is the nature of the particles? How do they propagate through the Universe? Does the cosmic ray energy spectrum extend beyond the maximum energy a proton can maintain when travelling over large cosmic distances, as they would eventually collide with the omnipresent microwave background? A large flux above this energy limit is likely to be attributed to entirely new cosmic phenomena. The mystery of cosmic rays is going to be solved through an interplay of detectors for high energy gamma rays, neutrinos and charged cosmic rays.

5) What do neutrinos tell us about the interior of Sun and Earth, and about Supernova explosions?

In 2002, Ray Davis and Masatoshi Koshiba were awarded the Nobel Prize in Physics for opening the neutrino window on the Universe, specifically for the detection of neutrinos from the Sun and a Supernova. The observation that solar neutrinos change their identity on their way from the Sun to the Earth ("neutrino oscillations") has provided the first indications of massive neutrinos, i.e. of physics beyond the Standard Model of particle physics. However, so far only the high energy tail of solar neutrinos, a small fraction of the total produced, has been studied in detail. Precise measurements of the low-energy part of the solar neutrino spectrum would test our understanding of neutrino oscillations, would allow fine-tuning of the picture of nuclear fusion deep inside the Sun and would give hints on long-term variations of the Sun. Another source of neutrinos are Supernova collapses. The 23 neutrinos detected from Supernova SN 1987A have yielded a rich harvest for particle physics and impressively confirmed astrophysical expectations of the collapse process. A galactic Supernova would result in thousands of neutrinos in existing or planned large neutrino detectors. The neutrino signal would give a detailed insight in the mysterious process by which the early explosion within a supernova is sustained. Moreover it would turn the Supernova into a fantastic laboratory for particle physics and provide excellent sensitivity to many intrinsic properties of particles like neutrinos, axions and others. First evidence for the detection of neutrinos from the interior of the Earth has recently been reported. These neutrinos can provide unique information on nuclear processes and heat production inside our own planet.

6) Can we detect gravitational waves? What will they tell us about violent cosmic processes and basic physics laws ?

Gravitation governs the large scale behaviour of the Universe. Weak compared to the other macroscopic force, the electromagnetic force, it is negligible at microscopic scales. The main prediction of a field theory is the emission of waves. For electromagnetism this has been established through the discovery of electromagnetic waves in 1888. The emission of gravitational waves from accelerated masses is one of the central predictions of the Theory of General Relativity. The confirmation of this conjecture would be fundamental on its own. Moreover, gravitational waves would provide us with information on strong field gravity through the study of the immediate environments of black holes, and they would provide an excellent cosmological probe, in particular to test the evolution of dark energy. With the new tools for gravitational wave detection now available, the discovery of gravitational waves may be just around the corner. Another component of General Relativity is the principle of equivalence which can be tested by experiments on Earth and in space. Deviations for Newton's law at small distances may point to extra dimensions, a conjecture which can be also tested by accelerator experiments.

We note that not all of these questions are going to be answered exclusively by experiments belonging to the field we define as "astroparticle physics". Take *dark matter* searches as an example. First evidence for dark matter has been obtained from the kinematics of Galaxies as revealed by ground-based optical observations in the first third of the 20th century. Since then, dark matter has become a keystone of the standard cosmology model based on much wider evidence than optical astronomy alone, notably on radio-astronomy. The ultimate answer on the nature of dark matter will likely come from the observation of *exotic particles* constituting dark matter. These particles may be first observed in subterranean laboratories, by the planned detectors recording the nuclear recoils due to the impact of dark matter particles ("direct detection"). Alternatively, signs of dark matter particles may arise as products of their annihilation in celestial bodies and may be detected by gamma telescopes at ground level or in space, by neutrino telescopes deep underwater or ice, or by cosmic ray spectrometers in space ("indirect detection"). Last but not least, it may well be that the Large Hadron Collider provides first evidence for dark matter candidates through their production in accelerator based experiments. From an experimental point of view, optical and radio observations are assigned to the field of astronomy, accelerator research to that of particle physics. Direct and indirect detection make use of laboratories deep underground which is the traditional environment of astroparticle and non-accelerator particle physics. These techniques also use neutrino and gamma telescopes, whose techniques have evolved from particle physics. It is this part of the search for dark matter that we assign to the field of astroparticle physics. *Dark energy* has a similar density to dark matter; unveiling of its nature would have profound impact on astroparticle physics. On the other hand, current projects exclusively rely on tools of astronomy; therefore we express strong support for dark energy projects but leave detailed recommendations to the strategic planning of astronomy roadmaps.

1.3 Astroparticle physics at a turning point?

The evolution of scientific disciplines shows a wide diversity. Some have changed our understanding of Nature in the very moment of their birth or soon after. Others have developed over centuries, through important, sometimes groundbreaking discoveries, before reaching a spectacular "golden age" with an explosion of unexpected, fundamental phenomena being discovered. Astrophysics is an example of the latter. Together with elementary particle physics, astrophysics has fundamentally changed our view of the Universe. Both disciplines have made stunning progress over the last two decades – not only on their own, but most prominently as inextricably linked fields of research. "More than ever before, astronomical discoveries are driving the frontiers of elementary particle physics, and more than ever before, our knowledge of elementary particles is driving progress in understanding the Universe and its contents" (cited from "Eleven Questions to the Universe").

Although the term "astroparticle physics" has been widely accepted from only 10-15 years ago, the first triumph of the field dates back to the seventies: the registration of solar neutrinos. Together with the detection of neutrinos from a supernova in 1987, it marks the birth of neutrino astrophysics, acknowledged with the Nobel Prize for physics in 2002. The recent discoveries of TeV gamma astronomy open another chapter of success.

We will argue that astroparticle physics is likely at the dawn of a golden age, as traditional astrophysics was two to three decades ago. The enormous discovery potential of the field stems from the fact that attainable sensitivities are improving with a speed exceeding that of the previous two decades. Improvement of sensitivities alone is arguably not enough to raise expectations. But on top of this, we are entering territories with a high discovery potential, as predicted by theoretical models. For the first time experimental and theoretical techniques allow – or are going to allow – forefront questions to be tackled with the necessary sensitivity. A long pioneering period during which methods and technologies have been prepared is expected to pay off over the next 5-15 years. This will require substantial investment in the necessary infrastructures.

1.4 Infrastructure and tools of astroparticle physics

The prominent tools of particle physics are high energy and high intensity accelerators, those of astronomy are telescopes based on Earth and in space. The toolset of astroparticle physics is more diverse and often combines experimental techniques from both astronomy and physics using expertise from both fields. Examples include the construction of neutrino telescopes, in which the detection technologies developed in particle physics and observational techniques from astronomy are combined or dark matter detectors exploiting drift chamber techniques.

The rapid development of the field requires infrastructures whose size, complexity and cost in most cases requires international cooperation and funding. Three types of infrastructure provide the main backbone of astroparticle physics:

- **Underground laboratories**

  The rock overburden of underground laboratories shield the experiments from the cosmic ray background. Room and services are provided to house devices, which typically are installed and operated by external scientists. 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, or detectors searching for proton decay. Occasionally, one detector is sensitive to several of the mentioned phenomena.

- **Telescopes and antennas**

  The size of these instruments is generally large due to the weakness (for gravitational waves) or the scarcity (for high energy gamma rays, neutrinos or high energy cosmic rays) of the signals that are to be detected. Large neutrino observatories require a large overburden to be shielded from cosmic ray background but, due to their size, cannot be housed underground. They are installed in "open" media like water of oceans or lakes, or in glacial ice. Telescopes for Gamma Rays in the TeV region detect the feeble bluish flash from air showers. They are operated at high altitude and locations with small backgrounds from artificial light sources. This demands an infrastructure sufficient for permanent operation at remote locations. Similar constraints apply regarding huge detectors for extensive air showers.

- **Satellites and Balloons**

  Some measurements of interest to astroparticle physics, e.g. the search for primordial antimatter, require balloon-borne or satellite platforms which are usually covered in the science programme of space agencies. Other measurements such as of gamma-ray signals from annihilating dark matter also benefit crucially from such facilities since these can access energies below the threshold of ground-based detectors. This is particularly true for studies of charged cosmic rays at low and medium energies. Moreover space-borne air fluorescence detectors can significantly boost our knowledge of extremely high energy cosmic rays and possibly neutrinos. To define future infrastructures for such projects requires close collaboration between the astroparticle and space communities in view of their interdisciplinary character. We include satellite experiments tailored to energies of about an MeV and above in this roadmap.

1.5 Funding and Coordination

Although typically cheaper than the largest projects of particle and space physics, astroparticle detectors of the next decade will become significantly more expensive than the present ones. The price tag of frontline astroparticle projects requires international collaboration, as the realization of the infrastructure does. Cubic-kilometre neutrino telescopes, large gamma ray observatories, Megaton detectors for proton decay, or ultimate devices to search for dark matter particles or rare particle decays are in the 50-500 million Euro range.

There are nearly two thousand European scientists involved in the field. International cooperation is the only way to achieve the required critical scale for projects where budgets and manpower are not available to a single nation. Competitive cooperation will also raise standards. European Coordination can avoid duplication of resources and structures. The process of coherent approaches within Europe has already successfully started. In 2000, the major national agencies funding astroparticle programmes founded ApPEC - the ***A***stro***p***article ***P***hysics ***E***uropean ***C***oordination. ApPEC successfully helped to launch ILIAS, an Integrated Infrastructure Initiative with leading European infrastructures in Astroparticle physics. ILIAS covers experiments on double beta decay, dark matter searches and gravitational wave detection as well as theoretical astroparticle physics. The projects within ILIAS have made excellent progress in the first years of the initiative and the growth in cooperation between the subfields and the interaction between the various programmes is significant. Furthermore, a Design Study proposal for the Mediterranean KM3NeT neutrino telescope was supported by ApPEC and accepted by the European Commission (see Appendix 5 for more information on European initiatives).

Often, the size of the project or opportunity requires worldwide cooperation, or even favour junior participation in a project dominated by US or Japanese laboratories. Also in this case, European teams will be better prepared if they can rely on a well-structured European platform.

Discoveries lie ahead, but the scientific opportunities challenge budgetary constraints. Coordination, prioritization, well-managed infrastructures and competitive cooperation are mandatory to maximize the scientific output given finite resources. On the other hand, scientific competition at the world level is very strong, and our competitors, most prominently our American and Japanese colleagues, will take opportunities not taken by Europeans. This sets a constraint to the minimum funding required to remain competitive.

1.6 The five fields covered by the ApPEC roadmap

Within this roadmap, the activities reviewed are broken into five areas, each covered by one chapter:

- **Section 2: Cosmology and the early Universe**
  …. outlines the basic cosmological ideas and observations to test them.

- **Section 3: Particle Properties**
  ….. describes how astroparticle physics experiments provide precision measurements (or parameter limits) of particle properties, or are used for searches of exotic particles or processes. This includes the determination of the Dirac-vs.- Majaorana nature and the absolute mass of neutrinos , the search for proton decay, the search for dark matter particles, and the search for other exotic particles like magnetic monopoles or Q-balls.

- **Section 4: Neutrinos as messengers from the Sun, supernovae and the Earth**
  ….. covers neutrinos as messengers from the Sun and Supernovae, as well as neutrinos generated in the interior of the Earth. It also makes the case for a next-generation, multi-purpose detector for neutrino physics and proton decay.

- **Section 5: The non-thermal Universe**
  ….. addresses experiments to explore the unknown cosmic territory at the highest energies, using charged cosmic rays, high energy gamma rays and high energy neutrinos as carriers of information

- **Section 6: Gravitational Waves**
  ….. is devoted to antennas for detection of gravitational waves and for the study of violent cosmic processes.

Section 7 summarizes the recommendations for each for the fields.

Appendix 1 list the members of the Roadmap committee. **Appendix 2** refers to questionnaires filled out by representatives of astroparticle physics experiments in Europe or with European participation. **Appendix 3** describes the existing underground facilities in Europe. **Appendix 4** sketches outreach activities. **Appendix 5** gives an overview of European initiatives in the field of astroparticle physics and related fields.

2. Cosmology and the Early Universe

2.1 Introduction

The giant leap of cosmology

Astroparticle physics - the interface between astronomy and particle physics – needs to be considered in the overall context provided by *cosmology*, the study of the structure and evolution of the universe as a whole. In the last decade or so, our knowledge of the geometry of space-time and of the composition of the universe, as well as of our past history and likely future, has taken a giant leap forward. This renaissance has come about mainly because of impressive advances on the observational front – large-scale redshift surveys of galaxies, all-sky maps of anisotropies in the relic cosmic microwave background, observations of Type Ia supernovae in distant galaxies which trace the history of the Hubble expansion rate, *et cetera*. All this has contributed to turning cosmology from a data-starved subject into one of the most exciting and fast-moving areas of physical science.

Cosmology requires going beyond the Standard Model of particle physics

We talk now of a 'standard model of cosmology', which provides a compact description of what we know about the universe, but requires the existence of new forms of matter and energy which dominate its dynamics. In contrast with the Standard Model (SM) of particle physics, this description is therefore not based on physics that can be (and has been) rigorously tested in the laboratory. Indeed the most salient facts of cosmology – the existence of a gross asymmetry between matter and antimatter, the preponderance of 'dark matter' over ordinary baryonic matter, the requirement for initial density perturbations (likely to have been generated during a period of 'inflation' in the very early universe) which can grow under gravity to create the observed large-scale structure and, most mysterious of all, the 'dark energy' which exhibits negative pressure making the Hubble expansion accelerate today – all these phenomena *require* new physics beyond the SM. The answers to the most fundamental questions in cosmology may well lie in new physical ideas that have been proposed already to address theoretical shortcomings of the Standard Model of particle physics, e.g. supersymmetry and new dimensions in Nature. However to understand the very peculiar 'initial conditions' of the Big Bang in which our universe was created, it is clear that we will require a complete physical understanding of quantum gravity, the best studied candidate for which, presently, is (super) string theory.

In the present roadmap we refer to, but do not discuss, the experimental missions central to cosmology. However we wish to emphasize that the expected deluge of new data calls for stronger and more coherent efforts on both theory and data analysis, a theme common to particle physics and cosmology.

An express tour through cosmic evolution

Based on ideas which have withstood observational tests over the last decade, a certain consensus has been achieved for our understanding of cosmic evolution after the 'Big Bang', starting from the time when the temperature had dropped to somewhere between the scale of grand unification of the three fundamental forces of the Standard Model (10^{16} GeV) and electroweak unification (10^2 GeV). At this point there was a period of exponentially fast expansion dubbed "inflation", driven by the vacuum energy of a hypothetical scalar field, which increased the scale of the universe by about 50 orders of magnitude. In the course of this process, space - whatever its curvature had been before - became flat, i.e. Euclidian. Moreover, the total energy density was driven to the "critical density" which separates unbounded expansion from future collapse. Subsequently the scalar field energy was released as radiation, (re)heating the universe to a temperature that probably did not exceed 10^9 GeV. The temperature then decreased adiabatically as the inverse of the expansion scale factor, except possibly when phase transitions occurred, associated with e.g. the breaking of the electroweak symmetry to electromagnetism at about 100 GeV and the breaking of chiral symmetry and confinement of free quarks and gluons in nucleons at about 300 MeV. As the universe expanded and cooled, several important processes dropped out of thermal equilibrium as their reaction rates dropped below the Hubble expansion rate. The most important (as far as *our* existence is concerned) was baryogenesis – the mechanism that violated baryon number (***B***) and charge-parity (***CP***) symmetry in order to create the observed tiny excess of matter over antimatter of about 1 part in 10^9; the recent discovery of neutrino mass suggests that the initial asymmetry may in fact have been generated in leptons and subsequently channeled into baryons by non-perturbative Standard Model effects – a process dubbed 'leptogenesis'. Another important process was the 'freeze-out' from thermal equilibrium of the super-weakly interacting particles which would later constitute dark matter – it is a striking coincidence that the expected relic abundance of new stable particles such as neutralinos predicted by supersymmetric theories turns out to be naturally of order of the observed amount of dark matter.

Inflation

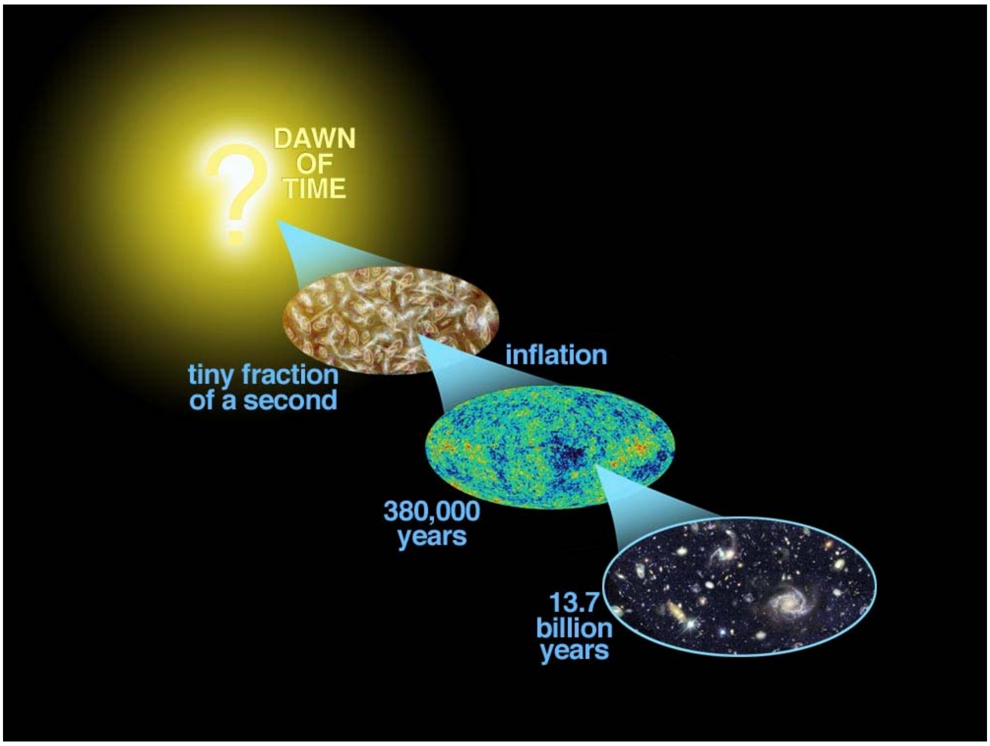
Space becomes flat

Breaking of electro-weak symmetry

Confinement of quarks and gluons

Baryogenesis

"Freeze-out" of dark matter



NASA/WMAP Science Team

Subsequently the thermal equilibrium between neutrons and protons maintained by the weak interactions was broken at about one second and Big Bang nucleosynthesis (BBN) of the light elements began after 'the first three minutes', when the temperature had dropped to about 60 keV.

t > 1 sec: Big Bang Nucleosynthesis (BBN)

t ~ 400,000 years: decoupling of primordial photons

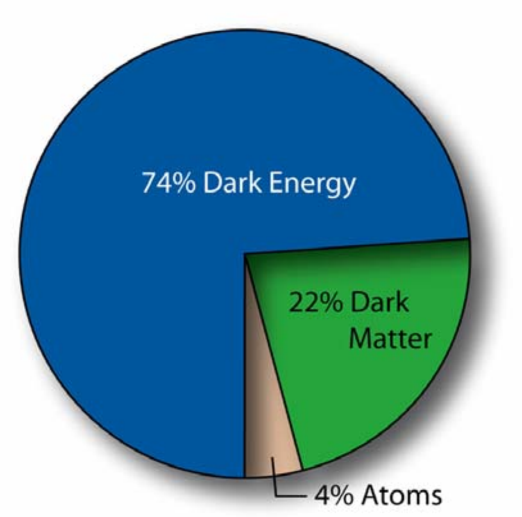
Much later, at an age of about 400,000 years when the temperature dropped to about 0.25 eV, (re)combination of the primordial plasma into neutral atoms occurred. The universe became transparent, and a 'last scattering' gave rise to what is observed today as the cosmic microwave background (CMB) at a temperature of 2.73 K. Its perfect blackbody spectrum bears witness to our hot and dense past and the lack of any spectral distortions such as might be expected due to any late release of energy indicates that the expansion has been essentially adiabatic since about a year after the Big Bang.

Today: accelerated expansion by Dark Energy ?

The energy density in radiation decreases faster than that of non-relativistic (dark) matter, hence the latter came to dominate the expansion at an age of a few thousand years. Most surprisingly however the consequent steady deceleration of the expansion rate appears to have been reversed at an age of a few billion years when a mysterious dark energy exhibiting *negative* pressure apparently took over as the dominant component of the universe.

2.2 The cosmic inventory

Over the last decade, the contents of the universe have been measured with unprecedented precision. Whereas normal baryonic matter contributes only about 4%, the dominant constituents are *unknown* forms of matter and energy -dark matter (22%) and dark energy (74%).



Baryonic matter

Although not all the baryonic matter in the universe can be detected through the radiation it emits, we can get a good handle on the total amount from considerations of primordial nucleosynthesis which created the light elements, combined with observational estimates of their primordial abundances.

The well-known physics of weak interactions and nuclear reactions allows the abundances of the dominant synthesized element ^{4}He as well as the trace elements D, ^{3}He and ^{7}Li to be predicted, as a function of the ratio . of baryons to photons. As shown if fig. 2.1, there is overall agreement between the inferred primordial abundances and the expectations, for η in the range η = (4.7-6.5) x 10^{-10}. Knowing the number density of CMB photons, this implies a baryonic density of ρ_b = 3.9 x 10^{-31} g/cm^3 or a baryonic fraction in ratio to the 'critical density' ($\rho_c = 3 \cdot H_0^2/8\pi \cdot G$) of $\Omega_b = \rho_b/\rho_c$ = 0.040 ± 0.012 (taking the present Hubble parameter to be h = H_0/100 km s^{-1} Mpc^{-1} = 0.72 ± 0.08).

Big Bang Nucleosynthesis

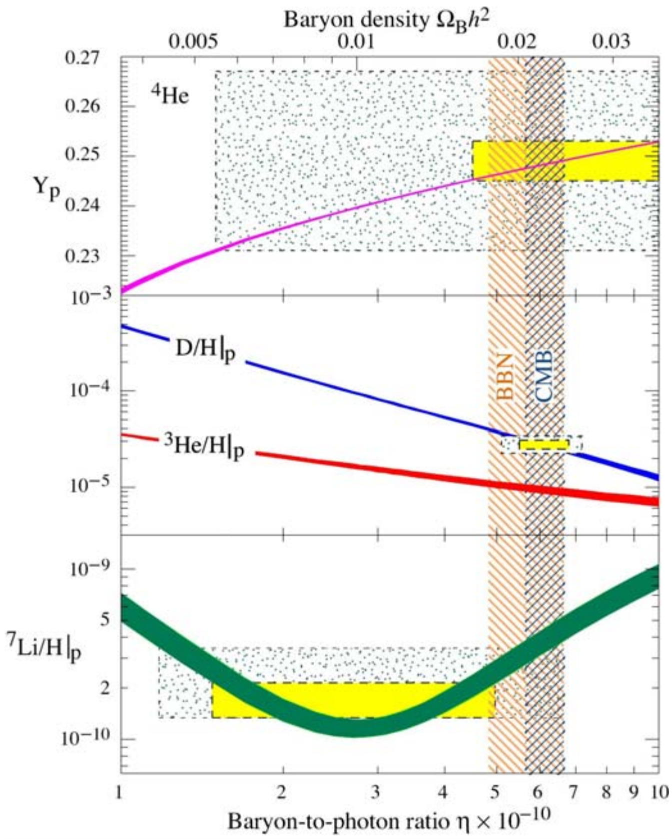


Figure 2.1: *Predicted abundances of primordially synthesized light nuclei as a function of the baryon-to-photon ratio (smooth lines/bands). Predictions are confronted with measured abundances (denoted by subscript p) inferred from measurements (smaller boxes: 2σ statistical errors, larger boxes 2σ statistical errors, larger boxes 2σ statistical plus systematic errors). Y denotes the mass fraction of ^{4}He. The vertical shaded band is the CMB measure of the cosmic baryon density. (taken from the Review of Particle Properties, Particle Data Group)*

This concordance is remarkable and illustrates how good an understanding we have of the physical conditions in the universe when it was only a second old. This allows restrictive constraints to be placed on any new physics which can potentially alter the expansion rate during Big Bang Nucleosynthesis, BBN, e.g. new types of neutrinos.

Baryon density deduced from CMB

The baryon density can also be deduced from precision studies of anisotropies in the CMB as it affects the oscillations in the coupled baryon-photon fluid before (re)combination which leaves a characteristic imprint on the sky at the last scattering epoch. The best fit to data from the *Wilkinson Microwave Anisotropy Probe (WMAP)*, assuming the inflationary density perturbation to have a power-law spectrum, gives Ω_b = 0.043± 0.004.

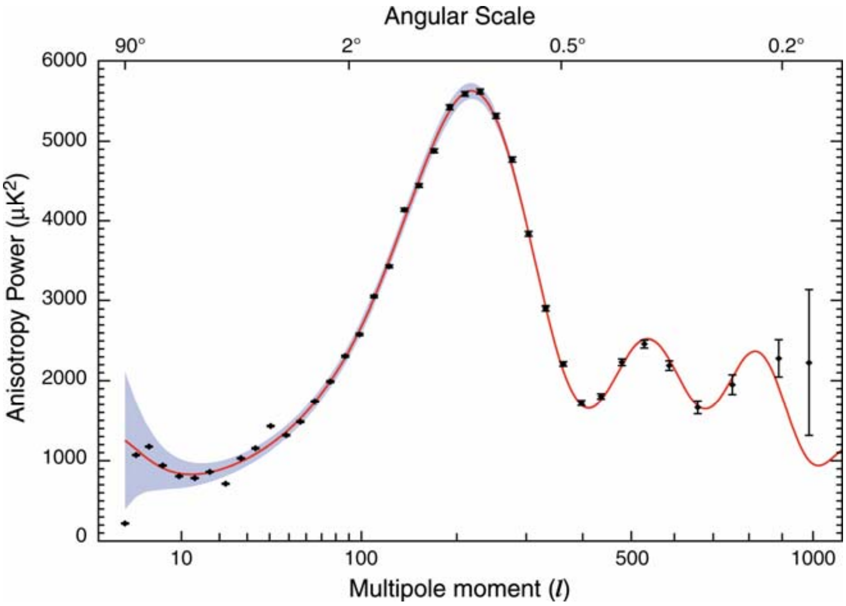


Figure 2.2: *The WMAP temperature angular power spectrum , with the best fit to the 'concordance'* ΛCDM *model (NASA/WMAP Science Team)*

Agreement between baryon densities deduced from BBN and from CMB: *a crucial check of standard cosmology*

The agreement between the two determinations of Ω_b is spectacular and serves as a significant check of the standard cosmology. For example it confirms that the thermal evolution of the universe was adiabatic (i.e. no increase in entropy) between BBN and (re)combination, as is also required by the absence of any spectral distortions in the CMB. Moreover, strong constraints are imposed on new physics beyond the Standard Model, e.g. in supergravity models the gravitino is usually massive and unstable with a long lifetime and the decays of relic gravitinos can potentially drastically alter the primordial nuclear abundances. Therefore restrictive bounds can be placed on the gravitino abundance and thus on the maximum temperature the universe could have achieved after reheating following inflation. This has additional implications, for example on whether the hypothetical heavy right-handed Majorana neutrinos (invoked to give the observed left-handed neutrinos their masses through the 'see-saw' mechanism and related to leptogenesis) can actually be thermally produced in the early universe. Such constraints have been of great value in guiding the construction of plausible models of the early universe.

Dark Matter

The data from *WMAP,* combined with other measurements, also provide a precise determination of the matter density $\Omega_m = 0.24 \pm 0.04$. The excess of the total matter density over the baryonic component implies that most of the matter in the universe is *non*-baryonic i.e. dark matter. (Note that the cosmic density of *luminous* matter is only $\Omega_{lum} \approx 0.0034$ i.e. most baryons are dark as well, probably in the form of a million degree hot X-ray emitting intergalactic medium.)

The existence of dark matter was originally inferred from the 'flat rotation curves' of spiral galaxies and of the large velocity dispersion in clusters of galaxies which suggested that such structures are dominated dynamically by extended haloes of non-visible matter. Further evidence has come from observations of gravitational lensing of distant sources by foreground galaxies and clusters, which enable the potential well of the central regions of the 'lens' to be mapped directly. Studies of the X-ray emission from the hot gas in galaxy clusters also trace the gravitational potential and indicate that the total matter content outweighs the visible matter by about 10 to 1.

Cold and hot dark matter

The dark matter may consist of particles which were 'cold' (non relativistic) or 'hot' (relativistic) at the moment of their decoupling ('freeze-out') from the thermal plasma in the early universe. Hot dark matter particles 'free-stream' until the temperature drops below their mass so if they constitute the dark matter, then the density fluctuations would have been smoothed on small scales and the first structures to form would have been on the scale of superclusters of galaxies. However this does not accord with a variety of observational data which indicates that galaxies in fact formed first. Non-relativistic dark matter must then be dominant, with possibly a minor component of neutrino hot dark matter component. Most of the matter of the universe is then required to be in the form of non-baryonic cold dark matter $\Omega_{CDM} = \Omega_m - \Omega_b = 0.197 \pm 0.04$; this is compatible with the amount needed to explain the rotation curves of galaxies.

Dark matter candidates and particle physics

The most discussed particle candidates for CDM are the lightest supersymmetric particle (the neutralino), which in most models is expected to have has a mass at the 0.1-1 TeV scale, and the axion, a very weakly interacting, ultralight scalar – both were postulated to solve obvious problems in the Standard Model of particle physics. Possible methods for their detection will be discussed in the section on "Particles". Here we re-emphasize the main message from observations: most of the dark matter is non-baryonic, hence we *must* invoke new physics beyond the Standard Model to provide a viable candidate – a new stable massive particle in Nature.

Dark Energy

Even more intriguingly, the total matter content, baryonic and non-baryonic, accounts for only 27% of the total energy of the universe. There are several indications that the missing contribution is (or mimics) a new form of energy which permeates the vacuum called 'dark energy' which behaves just like the 'cosmological constant', Λ, which Einstein had identified as an unavoidable term in his general relativistic equation describing a universe at that time thought to be static. In addition to the gravitational attraction common to any form of energy, this vacuum energy exhibits a dominant repulsive reaction to the cosmological expansion (i.e. a *negative* pressure) which can account for the recent acceleration of the cosmic expansion. This repulsive force is very weak – it would overcome the gravity of the Sun only at a distance exceeding a thousand light years. The allowed contours for the matter density parameter Ω_m and Ω_Λ arising from observations of the CMB, rich clusters of galaxies and Type Ia supernovae (SNe Ia) are shown in Figure 2.3. There is a range of values for Ω_m and Ω_Λ which is compatible with all three types of observations: $\Omega_m = 0.27 \pm 0.016$ and $\Omega_\Lambda = 0.72 \pm 0.08$. These values characterize the 'concordance model' - a Euclidian (flat) universe dominated by dark matter and dark energy.

Supernova cosmology suggests Dark Energy...

SNe Ia are the brightest (optical) objects in the universe and can be observed up to redshifts of $z \sim 1$-2, i.e. back to when the universe was just a billion or so years old. They have rather small variations in their intrinsic peak luminosity and are hence well suited for cosmological tests which require a 'standard candle'. Moreover their time evolution ('light curve') is observed to be tightly correlated with the peak luminosity such that the intrinsically brighter ones fade faster; this allows corrections to be made to reduce the scatter in the Hubble diagram so its curvature can be measured.

The surprising result from studies by the *Supernova Cosmology Project and* the *High-z Supernova Search Team,* as well as the new data from the *Supernova Legacy Survey* is that the Hubble expansion rate appears to have been *speeding up* in our recent past, rather than slowing down as expected. This provides direct evidence that the universe is presently dominated by dark energy with negative pressure like a cosmological constant In particular measurements at redshifts $z < 1$ measure the difference $\Omega_m - \Omega_\Lambda$ to be negative.

.. and nicely complements CMB measurements

As seen in Figure 2.3 below, this nicely complements the CMB measurements which are sensitive to the spatial curvature of the universe i.e. to the combination $\Omega_m + \Omega_\Lambda$. Thus the combination of such measurements picks out the 'concordance model' of the Universe referred to above, and a variety of measurements of the matter density Ω_m, particularly from observations of clusters of galaxies, are also consistent with this model. A further test comes from searches for the expected correlation between large-scale structure and the CMB induced by the 'late integrated Sachs-Wolfe effect' due to the cessation of structure formation when the vacuum energy comes to dominate the expansion. Although such detections are not yet statistically significant, they are consistent with the expectations for the concordance model.

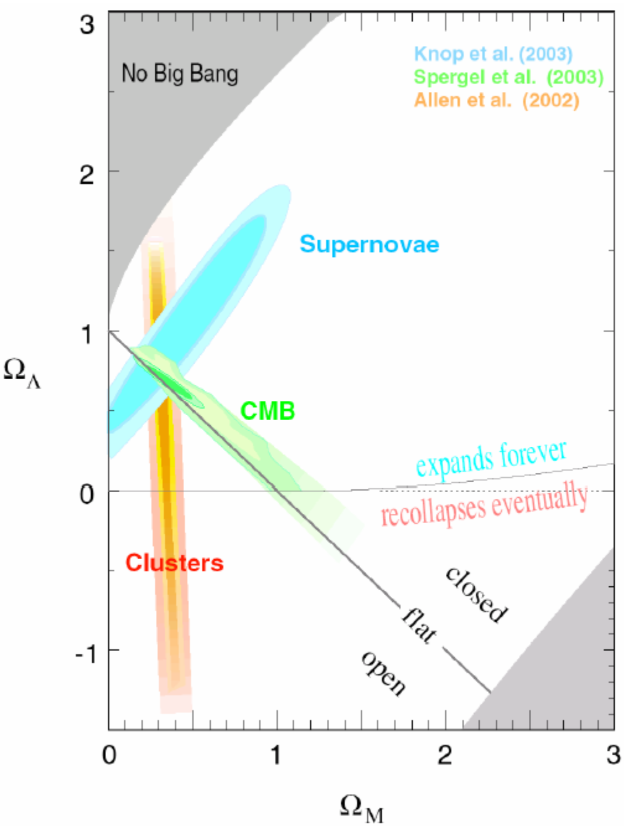


Figure 2.3: *Allowed contours for the cosmological parameters as constrained by three complementary measurements. The values* $\Omega_m \sim 0.27$ *and* $\Omega_\Lambda \sim 0.72$ *define the 'concordance model' - a Euclidian (flat) universe dominated by dark matter and dark energy. The figure also indicates the parameter space for an open or closed Universe, as well as the future evolution – expansion or collapse. (Figure taken from Saul Perlmutter)*

A recent development has been the tentative detection of the 'acoustic peak' in the auto-correlation function of galaxies measured by the *2 degree Field Galaxy Redshift Survey* and the *Sloane Digital Sky Survey* (*2dFGRS* and SDSS, respectively). The observed scale of this peak is just as expected in the concordance model.

Next generation missions

CMB experiments and galaxy redshift surveys have thus provided precision data concerning the amount of baryonic and dark matter and dark energy, and strongly constrained the age of the Universe, its curvature and its present expansion rate. Next generation missions such as *PLANCK*, *SNAP*, *ALMA* and *SKA* will constrain these parameters further, and more importantly, allow various checks to be made for possible systematic effects which can bias the measurements of cosmological parameters (see a full list of projects in the Table at the end of this section).

Caveats

Caution must meanwhile be exercised in accepting these amazing cosmological results since several assumptions have to be made in obtaining them. For example the SNe Ia data are interpreted assuming that the distant and nearby supernovae have the same intrinsic luminosity – although plausible, this needs to be checked directly by measurements in the so far unobserved intermediate redshift range $z \sim 0.1$-0.3. The Hubble constant too has not yet been determined unambiguously. Although the *Hubble Key Project* obtained $H_0 = 72 \pm 3 \pm 7$ km s^{-1} Mpc^{-1} using Cepheid variables to calibrate SNe Ia and other secondary distance indicators, another group have found instead $H_0 = 62.3 \pm 1.3 \pm 5$ km s^{-1} Mpc^{-1} also using *HST* data. Moreover, deeper measurements using physical methods such as time delays of multiple images of quasars indicate an even lower value $H_0 = 48 \pm 3$ km s^{-1} Mpc^{-1}. This calls into question whether the underlying assumption of perfect homogeneity is in fact justified – it is possible that the local and global values of the Hubble parameter differ because we are located in an underdense region which is expanding faster than the average. Although the CMB measurements do imply a Hubble parameter in agreement with the *Hubble Key Project* value, the interpretation of the CMB data require a number of 'priors' to be adopted, the most important being that the universe is spatially flat as required by inflation (to obtain H_0) and that the density fluctuations from inflation have a simple scale-free power-law form (to obtain Ω_m). Relaxing the latter assumption for example enables the *WMAP* data to be well-fitted by a cosmological model with *no* dark energy, if the Hubble parameter is as low as 46 km s^{-1} Mpc^{-1}. Although such a model will not fit observations of large-scale structure with cold dark matter alone, the addition of a small component of hot dark matter, e.g. as 0.8 eV mass neutrinos, redresses the situation. Such models do have more parameters than the concordance model and might thus appear to be disfavored on grounds of simplicity alone. However this is deceptive since they do away with the need for a cosmological constant or dark energy – the value of this parameter required by the concordance model is over 120 orders of magnitude below its 'natural' value as expected from considerations of zero point quantum fluctuations down to the fundamental Planck scale. Such a huge cosmological constant would of course have stopped the universe from ever expanding to its present large size and the very fact that we exist at all requires that the cosmological constant be very close to zero. The expectation has been that it is indeed exactly zero (for a reason as yet unknown but presumably to be explained by a satisfactory formulation of quantum gravity). What has been a major surprise is that according to the cosmological data, the value is not in fact zero but comparable to the energy density in matter at the present epoch. Since the latter was much higher in the past, this raises a second 'naturalness' problem, namely why has the cosmological constant come to dominate the expansion today.

Quintessence

This has motivated proposals for a very weakly coupled scalar field – termed quintessence – the vacuum energy of which evolves with time (or redshift), in contrast to a cosmological constant. Under certain circumstances, the energy density of quintessence can 'track' the energy density of matter or radiation, thus solving the coincidence problem alluded to above. However the mass of a such a field should be of order of the present Hubble parameter ($\sim 10^{-33}$ eV) , while the scale of the required vacuum energy is $\sim(10^{-3}\text{ eV})^4$, so it is clear that the parameters of such a field would need to be very fine-tuned. Moreover if this field couples to matter, it would generate a new long range force and cause violations of the Equivalence Principle. Thus a mysteriously small number (the vacuum energy density) is traded for several unnaturally small parameters.

2.3 Links to Particle Physics

Baryogenesis

The origin of baryonic matter is not fully understood. We know that this requires a small excess of quarks over anti-quarks, otherwise all baryonic matter would have been annihilated. The value $\eta \sim 6 \times 10^{-10}$ of the baryon-to-photon ratio found from BBN and CMB studies is interpreted as due to the almost complete annihilation of quarks and anti-quarks in a Universe which already had a comparable feeble excess of matter over antimatter. Starting from an initially fully symmetric Universe, a matter-antimatter asymmetry can be dynamically generated if a) baryon number ***B*** is not conserved, b) Charge-Parity symmetry, ***CP***, is violated, and c) there is a departure from thermal equilibrium - these three conditions were given by A. Sakharov in 1967. Although the first and third of them can conceivably be satisfied in the Standard Model (during the electroweak symmetry breaking phase transition), the second condition, namely ***CP*** non-conservation, cannot be satisfied. Several alternative mechanisms have been proposed to generate the baryon asymmetry. In the 1980's, the favored mechanism was "GUT baryogenesis" which is closely linked to proton decay, as it involved the out-of equilibrium ***CP***-violating decays of the same GUT-scale gauge bosons which mediate ***B*** violation. However it now appears unlikely that such heavy particles could have been created through (re)heating after the inflationary era.

GUT baryo-genesis and proton decay

Leptogenesis

At present, a second possibility looks more promising. It is related to the idea of explaining the tiny masses of the (left-handed) neutrinos by adding heavy, right-handed Majorana neutrinos to the Standard Model, a trick known as the *seesaw mechanism*. The out-of-equilibrium decay of these heavy Majorana neutrinos in the early Universe violates ***CP***-asymmetry and generates a net lepton number – a process dubbed *leptogenesis*. Subsequently, a part of this lepton-asymmetry is transferred to baryons by non-perturbative Standard Model processes. Thus a connection can be made between the observation of a finite neutrino mass (which is due to the violation of lepton number ***L*** in this model) and the observed dominance of matter in the universe. Some models of this type may even be experimentally testable.

Particle dark matter

Another crucial link between cosmology and particle physics is provided by dark matter. A natural candidate for dark matter would be a new particle beyond the Standard Model which carries a new kind of conserved charge and therefore is cosmologically stable. The best-studied particle of this type is the *neutralino*, which is usually the lightest super-symmetric particle and stable by virtue of a new exact symmetry (***R***-parity). Its expected relic abundance from a state of thermal equilibrium in the early universe can be of order the observed dark matter abundance in certain regions of SUSY parameter space. Forthcoming experiments at the *Large Hadron Collider* are expected to detect other SUSY particles and thus determine the properties of the neutralino. Other SUSY candidates for dark matter have also been considered such as the *gravitino* or super-heavy string-scale relics (‘*cryptons*’). Alternatively the dark matter particles may be excitations in an ultra-light scalar field such as the *axion* (or its super-symmetric partner, the *axino)*. Direct searches for interactions of dark matter particles with laboratory detectors, as well as indirect searches for their annihilation products (such as neutrinos and gamma-rays) from elsewhere need to be guided by considerations of their possible microscopic properties, as well as observational developments in our understanding of the distribution of dark matter in the Galaxy

No dark matter but modified gravity?

It has even been proposed that dark matter may be an illusion due to Modification Of Newtonian Dynamics **(**MOND**)** at very low accelerations. This empirical idea can account very well for galactic rotation curves and predicts the observed tight correlation between the circular velocities and luminosities of spiral galaxies (Tully-Fisher relationship). However it cannot account fully for the dynamics of rich clusters of galaxies. A relativistic covariant theory for MOND has recently been proposed and can even account for gravitational bending of light as observed without invoking dark matter but by introducing additional scalar and vector fields. Establishing the identity of the dark matter or alternatively demonstrating that MOND is physically and cosmologically viable, is among the key challenges in cosmology today. It should be mentioned that recently released data on the “Bullet cluster”, a system of two colliding galaxies, cannot be explained within the MOND scheme.

Inflation

Another important relic is the primordial density perturbation which although tiny in magnitude ($\Delta\rho/\rho \sim 10^{-5}$) is nevertheless essential (in an expanding universe) for the generation of structure. It is these small initial perturbations that grow under gravity in the sea of dark matter to generate the complex "cosmic web" of galaxies, clusters, super-clusters, filaments and voids that we see today. Their imprint on the CMB has been investigated in exquisite detail by the WMAP mission and complemented by the detailed studies of galaxy clustering by the *2dFGRS* and *SDSS* galaxy surveys. The data is consistent with a Gaussian spectrum of adiabatic perturbations with an approximately scale-invariant spectrum. Such a spectrum arises naturally from quantum fluctuations of the scalar field which is supposed to have driven a period of exponentially fast expansion at very early times, i.e. inflation. This requires physics well beyond the Standard Model, and presently we do not know either the identity of the “inflaton field”, nor why it started out displaced from the minimum of its potential. More importantly, we have no fundamental understanding of the cosmological constant problem, i.e. how the vacuum energy driving inflation is (almost) exactly cancelled at the potential minimum. Candidates for the inflaton have been suggested in a wide variety of models based on supersymmetry, supergravity, grand unification, string theory, brane-world etc. They give, in general, different predictions for the slight scale-dependence of the primordial density perturbation which can be confronted with the precision cosmological data. Other scalar fields present during inflation can also be excited so as to generate the observed density perturbation. It may be possible to distinguish between such possibilities, and indeed between inflationary models, by observing the predicted background of primordial gravitational waves through the "B-mode" polarization they induce in the CMB. Other probes of the particle physics behind inflation may be features in the spectrum of density perturbations generated by e.g. other scalar fields which undergo symmetry-breaking phase transitions as the Universe super-cools during inflation.

String Theory and Quantum gravity

Finally, space-time itself may well turn out to be a derived concept in a theory of quantum gravity such as string/M theory and its emergence from such a fundamental theory is of prime importance for cosmology. Even though we are far from the final formulation of such a theory, there is great interest in its implications for the early Universe. In string theory for example, there are membranes of various dimensions - D-branes - which live in the 10-dim 'bulk' space-time, and much attention has been paid to the idea that our universe in fact resides on a 4-dim D-brane. This has motivated study of higher dimensional string theory geometries that may avoid the initial singularity, possibly forming a link with pre-Big Bang cosmology. Given the observational successes of the inflationary paradigm, it is natural to inquire whether inflationary potentials compatible with observation can arise from attractive forces between D-branes. A recent development has been the discovery that the key parameters of the theory, such as the size and shape of extra dimensions **(**'moduli'**)** can be fixed by background 'fluxes' leading to the emergence of a so-called 'landscape' with a very large number of possible vacuum states. A parallel development is the 'holographic' interpretation of space - describing the physics in a bulk space-time in terms of a different theory living on a lower dimensional surface. By analogy with a previous holographic relationship known as AdS/CFT, it is possible that the dual holographic theory would turn out to be non-gravitational. This dual description can potentially be used to give a radically new perspective on traditional cosmological problems such as the mechanism for inflation.

String Theory and Quantum gravity

3. Particle Physics

3.1 Introduction

A historical reminescence

Present particle physics rests on the synthesis of concepts developed over more than half a century: the *Standard Model* of particle physics. The overwhelming majority of the experimental facts supporting this impressive theoretical framework have been obtained with the help of accelerators. In its early phase, however, particle physics relied to a large extent on fundamental discoveries made *without* accelerators:

1) Protons, electrons and neutrons had been discovered before accelerators turned into a tool of sub-atomic physics.
2) Positrons - the first manifestation of antimatter - as well as muons, charged pions and Kaons were first observed in cosmic rays.
3) The neutrino has been inferred from radioactive beta decay and was discovered at a nuclear reactor.
4) Parity violation has been first been observed in radioactive decay.

First hints to physics beyond the Standard Model

The Standard Model robustly and impressively explains nearly all experimental data collected so far. *Nearly* all, but not *all*! Interestingly, the first hints of physics beyond the Standard Model come from non-accelerator observations:

1) The observed matter-antimatter asymmetry of the Universe cannot be explained within the Standard Model
2) The prevalent explanation of non-baryonic dark matter implies particle candidates beyond the Standard model, such as SUSY particles.
3) Neutrino oscillations - as discovered with the help of solar and atmospheric neutrinos - imply non-vanishing neutrino masses.
4) The explanation of Dark Energy in terms of particle physics is open. It may have no straight relation to particle physics,equally well, however, it may have fundamental impact on quantum theory.

Dark Matter and Dark Energy arguably represent the most fascinating and important challenge to Particle Physics today. There are other examples of cosmological considerations being closely linked to new particle physics. The most spectacular is the prediction that protons are not stable but have a finite lifetime. Proton decay is predicted by nearly all formulations of Grand Unified Theories and stimulated the construction of huge underground detectors which, ironically, have not yet revealed proton decay but led to a rich physics harvest from solar and atmospheric neutrinos, and to the detection of neutrinos from a supernova.

Proton decay is only one example for a rare process beyond the Standard Model. Another is the search for a particular form of nuclear radioactivity – the neutrino-less double beta decay. It not only requires that the neutrinos are massive, but also that (as the only one of all the fermions!) it is its own anti–particle. This so-called Majorana nature of neutrinos would have far-reaching consequences of our understanding of the Early Universe.

The present section addresses searches for dark matter and other exotic particles as well as the search for proton decay. It also describes the programme to determine the parameters governing the neutrino sector: mixing angle, CP violating phases, mass and Majorana nature of neutrinos. Last but not least, a few fundamental principles of physics are listed which possibly might be tested with the tools of astroparticle physics and cosmology.

3.2 Dark Matter

Once again: The cosmic inventory

As outlined in section 2, cosmological parameters are presently being measured with a precision unimaginable a decade ago. Observations of the last few years led to a unified framework referred to as the "concordance model". Within this framework, ordinary matter contributes only ~4% to the cosmic inventory, whereas most of the matter, ~23% of the inventory, is in the form of an unknown "Dark Matter". With the total matter accounting for only 27% of the total energy-matter content, the rest, ~73%, is assigned to a smooth substance christened "Dark Energy". Whereas the concept of Dark Energy has been introduced only recently - in response to a negative pressure driving cosmic expansion, that of Dark Matter has been discussed for decades. The prevalent view is that Dark Matter consists of stable relic particles from the Big Bang, and that nearly all of it is in the form of Cold Dark Matter (CDM). In the early Universe, CDM particles typically would have already cooled to non-relativistic velocities when decoupling from the expanding and cooling Universe. Hot dark matter (HDM) has been relativistic at the time of decoupling. Neutrinos are typical HDM particles; their contribution to the total matter budget, however, is small.

The search for cold dark matter candidates obviously addresses one of the most fundamental problems in particle physics and cosmology. The favoured candidate for dark matter is a Weakly Interacting Massive Particle (WIMP) related to new physics at the TeV scale. Among the various WIMP candidates on the TeV scale, the favoured one is the lightest supersymmetric (SUSY) particle, which is framed in a consistent model (the Minimal SuperSymmetric Model, MSSM). Another theoretically well-founded dark matter candidate is the axion. Even though axions would be much lighter than WIMPs, they still could constitute CDM, since they are have not been produced in thermal equilibrium and would be non-relativistic. Alternative candidates include light bosonic particles with axion-like couplings, s-neutrinos and Kaluza-Klein particles.

Weakly Interacting Massive Particles (WIMPs)

The synergy of SUSY searches at accelerators and in the cosmos

SUSY particles could be produced in particle interactions at accelerators. The negative results of current accelerator searches indicate that even the lightest SUSY particle, likely the neutralino, would be heavier than 50 GeV in most realizations of the MSSM. The LHC will extend the search for SUSY particles to much higher masses. However, the discovery of a SUSY particle at the LHC alone does not prove that it is the Cold Dark Matter particle required by cosmology. For that purpose, the detection of *cosmological* WIMPs is necessary. Vice versa, the detection of cosmological WIMPs alone would not prove that they are supersymmetric particles. For that purpose, identification and investigation at accelerators is necessary. The synergy between LHC and next generation dark matter searches is obvious and opens an exciting perspective.

Cosmological WIMPs can be detected by direct and indirect methods. Direct methods would detect the recoiling nuclei (or, more generally, any particles) due to interactions of galactic WIMPs passing through a detector. Indirect searches would try to identify gamma rays, neutrinos or charged anti-particles from WIMP annihilations in cores of galaxies, the Sun or the Earth or other potential regions of enhanced WIMP density.

WIMPs in the Milky Way

The density and velocity distribution of WIMPs in our Galaxy depends on the galactic halo model. The simplest halo models yield a local WIMP energy density of 0.3 GeV/cm^3 and a Maxwellian velocity distribution with a mean of $v_{rms} \sim 270$ km/s, truncated by the galactic escape velocity $v_{esc} \sim 650$ km/s and shifted by the relative motion of the solar system through the galactic halo $v_0 = 230$ km/s. However, recent astronomical data, particularly observations of a large micro-lensing rate towards the Galactic Bulge, indicate that the centre of the Galaxy is dominated by baryonic rather than dark matter, in conflict with the above model. Moreover, computer simulations of structure formation with dark matter show that the Galaxy has likely formed by merging smaller structures and that the dark matter halo is clumped rather than uniform. Direct detection experiments probe the density and velocity of dark matter in the vicinity of the Earth. Indirect detection experiments are sensitive to the dark matter density elsewhere in the Galaxy. Thus together they can delineate the distribution and dynamics of Dark matter in the Galaxy.

Direct Detection

The direct detection of WIMP particles relies on measuring the nuclear recoil produced by the WIMP elastic scattering off target nuclei in underground detectors. Due to the weakness of the interaction, the expected signal rates are very low. Lets assume a WIMP particle χ with mass m_χ, density ρ_χ, average velocity $\langle v_\chi \rangle$, a cross section $\sigma_{\chi A}$ for scattering off a nucleus containing A nucleons. Then the signal rate $\boldsymbol{R}$ of a zero threshold detector can be written as:

$$R \cong \frac{\rho_\chi}{m_\chi} \langle v_\chi \rangle \frac{\sigma_{\chi A}}{A}$$

$$\cong \frac{3.6}{A} \left(\frac{GeV}{m_\chi} \right) \left(\frac{\rho_\chi}{0.3\, GeV/cm^3} \right) \left(\frac{\langle v_\chi \rangle}{230\, km/s} \right) \left(\frac{\sigma_{\chi A}}{10^{-38} cm^2} \right) \frac{events}{kg \cdot day}$$

Figure 3.1 shows the typical range of neutralino cross sections expected in Minimal Super-Symmetric Models (MSSM) as a function of the neutralino mass (here truncated at 50 GeV), together with some present limits and the sensitivities envisaged over the next decade.

For the range of expected cross sections, signal rates of only 10^{-5} to one per kg and per day are expected. But it is not only that the detection rates are desperately small; also the energies transferred to the recoiling nucleus by slow WIMPs are extremely feeble. The energy detectable in ionization and scintillation detectors is further quenched since only a fraction of the recoil energy goes to these channels. This and the small signal rates make the detection a considerable challenge and define the experimental strategies:

The challenge:
• feeble inter-
- actions rates,
• feeble signals

- **thresholds in the keV rang**e, as low as allowed by the eventual onset of background dominance;
- **excellent background suppression**: using low-radioactivity materials, both in the detector itself and in its environment; efficient shielding using deep underground location, passive and active shields; and signal-vs.-background discrimination on an event-by-event base;
- **large target masses;**
- **long-term, stable operation.**

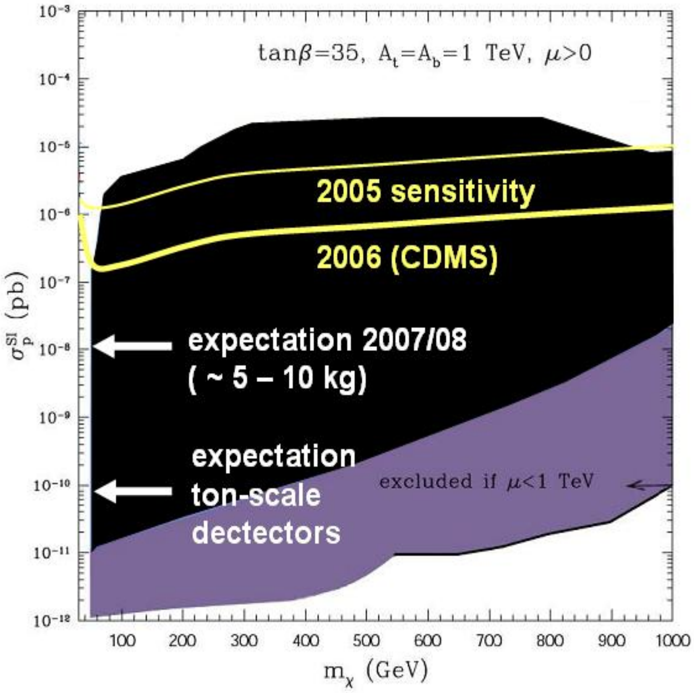


Figure 3.1: *Spin-independent WIMP cross section vs. WIMP mass for an MSSM prediction by Kim, Nihei, Roszkowski and Ruiz de Austri (blue area), with parameters fixed to the values shown at top right. Thin curves give the limits obtained by 2005. Thick line indicate the 2006 CDMS limit, the arrows the sensitivities expected in about a year from now, and within a decade from one-ton experiments. All results assume the WIMP to be a neutralino in the standard MSSM formulation.*

Smoking guns

Following identification of a convincing signal, clearly distinguished against background, one would like to get a final confirmation for the nature of the signal, by observing a "smoking gun" signature which ensures that the signal is due to WIMPs and not due to something else, such as backgrounds.

There are three such signatures:

- **annual modulation**
- **directionality**
- **target dependence**
-

The *annual modulation* signature reflects the periodic change of the WIMP velocity in the detector frame due to the motion of the Earth around the Sun. The variation is only of a few percent of the total WIMP signal ($v_{Earth/Sun}/v_{Sun} \sim$ 15 km s^{-1}/230 km s^{-1} ~ 0.07), therefore large target masses are needed to be sensitive to the effect. Indeed, the DAMA experiment (see below) reports an observation of this signature in its data. The *target dependence* signature follows from the different interactions of WIMPs with different nuclei - both in rate and in spectral shape. The *directionality* signature would clearly distinguish the WIMP signal from a terrestrial background and search for a large forward/backward asymmetry (of order 1). It requires detectors capable of measuring the nuclear recoil direction, a condition potentially only met by low pressure gaseous detectors.

Detection methods

Figure 3.2 sketches the main types of detectable signals. Nuclear recoils will typically ionize the medium and release thermal energy. In addition, scintillation light may be produced. An efficient background rejection can be achieved by recording two of these observables and requiring them to be consistent with a signal from a nuclear recoil (and not from a gamma or electron). Pulse shape analysis provides another mean to distinguish nuclear and electron recoils. Needless to say that interactions are accepted only from well-shielded fiducial volumes.

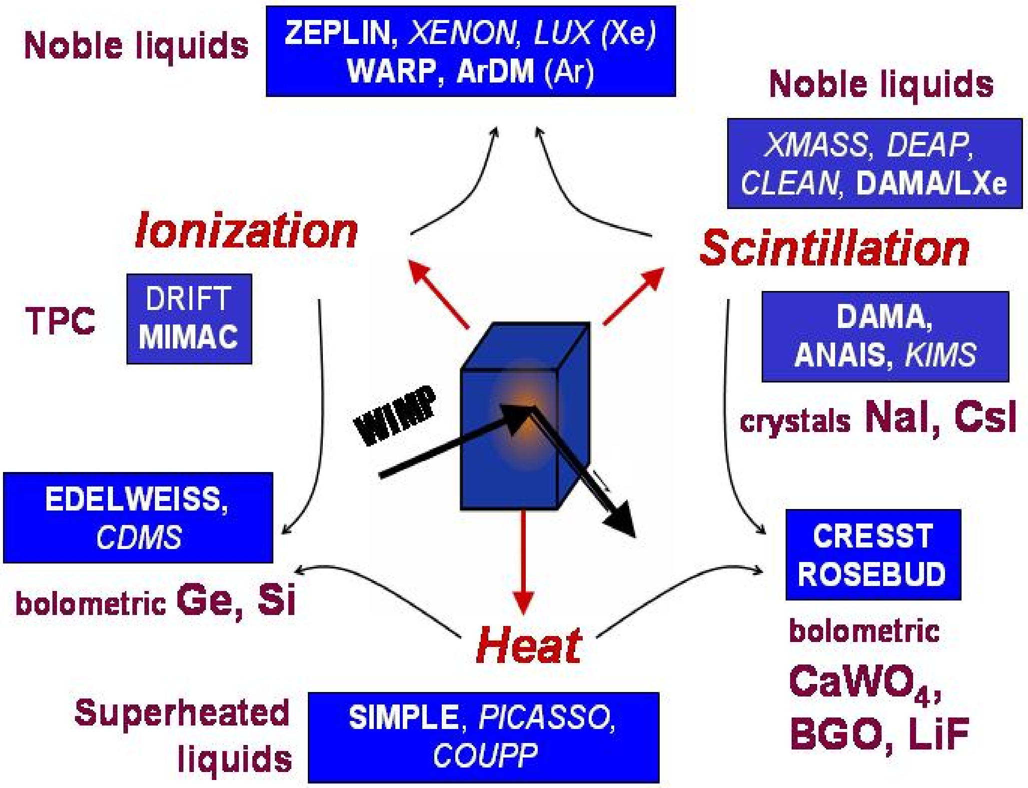


***Figure 3.2**: Methods and present experiments/prototypes for direct WIMP detection. Experiments with a clear European lead role are in bold face, experiments without or with small European participation are in italics. DRIFT (Boulby mine) has similar American and European contributions. Superheated liquid methods are here assigned to ionization to avoid confusion with phonon detection in bolometric detectors.*

Spin-dependent and spin-independent couplings

WIMPs may scatter via both spin-independent and spin-dependent coupling. For a WIMP with both couplings being equal, spin-independent scattering on a heavy nucleus is favoured due to the coherent enhancement. Therefore, the majority of past and present experiments use heavy target materials in order to maximize sensitivity to this scattering mode. However, there are models, e.g. neutralinos that are pure gaugino or pure higgsino states, in which the spin-independent coupling is strongly suppressed. The actual composition of WIMPs is not known. Therefore, a few experiments have been, and are, performed with low-*A*, high-spin target materials.

There are more than 20 active WIMP search experiments worldwide, most of them appearing in Fig.3.2. Convergence towards a few large experiments – ready for construction early in the next decade – is mandatory. At the same time, there are several innovative approaches in the R&D phase which merit careful, continuous support.

Bolometric detectors: CRESST and EDELWEISS (the former in the Gran Sasso Laboratory, the latter in the Fréjus tunnel), as well as CDMS (Soudan mine, USA) are bolometric detectors operated at temperatures of 10-20 milli-Kelvin. In EDELWEISS and CDMS, phonons and ionization are detected, in CRESST phonons and light. After having finished phase-I operation, all these detectors have moved (or are moving) to their second stages, with larger mass and improved background rejection: EDELWEISS increased its active mass from 1 to 9 kg Ge (with 36 kg as final goal); CRESST has installed 3 kg of $CaWO_4$., to be increased to 10 kg, and is investigating other materials. Both EDELWEISS and CRESST have published upper limits at the 10^{-6} pb level. The presently best limit on the spin-independent cross section comes from CDMS, with ~ $1.7 \cdot 10^{-7}$ pb for WIMP masses around 50 GeV. The ROSEBUD collaboration is performing prototype R&D aiming for a better understanding of backgrounds in large scale experiments. None of the cryogenic detectors have claimed DM detection.

Xe/Ar detectors: In noble liquid detectors, typically both scintillation and ionization are measured (in a dual-phase readout). Xenon10 (installed at Gran Sasso) and the ZEPLIN programme (installed at the Boulby mine, UK) use liquid xenon targets of ~10 kg fiducial mass, while WARP (Gran Sasso) and ArDM (Canfranc) operate liquid argon detectors. Generically easier to be expanded to larger masses than bolometric detectors, noble liquid targets must cope with a lower energy resolution. On the other hand, recent preliminary results from some of these collaborations indicate sensitivities comparable to the present benchmark of the CDMS sensitivity. Important progress is therefore expected from this field in the near future. In addition to the now completed ZEPLIN-I experiment at Boulby, the DAMA collaboration is running a single-phase liquid Xenon detector with krypton-free xenon; three other non-European single-phase experiments are in progress: XMASS (Japan) uses xenon, DEAP and CLEAN (Canada/USA, both in an early phase) argon and neon. These approaches aim for appropriate background reduction by applying pulse-shape discrimination and other sophisticated methods.

The DAMA signal

NaI detectors: An annual modulation, observed over seven years, has been reported by DAMA. This detector belongs to the third type of instruments shown in Fig.3.2. The DAMA collaboration has operated 100 kg of highly radio-pure NaI crystals (DAMA/NaI) in the Gran Sasso Laboratory, designed to record the scintillation light induced by Dark Matter particles, either via nuclear recoils or via particle conversion into electromagnetic radiation (e.g. by light bosons). While the observed annual modulation is statistically significant, the interpretation of the result as evidence for dark matter has not been confirmed by other experiments using different techniques and target materials. The DAMA team is already running an enlarged set-up of ~250 kg of radio-pure NaI (DAMA/LIBRA) and promises a first multi-year data set for 2008. R&D on a 1-ton detector is going to be completed, with this stage planned to be constructed after 2008 and provide first data in 2015. An independent result, using the same target material at a different site, may come from the ANAIS group, currently installing a ~100 kg NaI set-up (with different technology and radiopurity) in the Canfranc Underground Laboratory in Spain. Korean physicists have started R&D towards a crystalline detector using CsI (KIMS project).

Superheated liquid detectors: An approach originally tailored to the detection of spin-dependent WIMP interactions uses superheated droplet detectors dispersed in a gel, or heavy liquid bubble chambers. Nucleation of bubbles is caused by nuclear recoils; electron recoils do not trigger nucleation. The threshold of nucleation is adjustable, but once fixed, the detectors provide a yes/no (i.e. "digital") information with respect to that threshold. SIMPLE (C_2ClF_5) and PICASSO (C_4F_{10}) suspend the superheated liquid in a gel. COUPP (USA), uses a CF_3I liquid target in a bubble chamber mode. While it will be difficult with such digital detectors to determine the spectrum of nuclear recoils, this inexpensive approach, is capable of large target mass with excellent gamma/electron rejection, at relatively low cost, and should be considered as another important option in the search for WIMP interactions.

Ge detectors: Some early results on dark matter search have been obtained using extremely pure Ge crystals, the most recent from the Heidelberg-Moscow (HDMS) experiment. Planned experiments which focus on double-beta decay, like e.g. GERDA (see 3.4), are also based on highly pure Ge crystals. However, it seems debatable whether they will achieve sufficient background reduction in order to compete with the other techniques.

Convergences to one-ton detectors methods

CRESST, EDELWEISS and ROSEBUD, together with new labs like CERN, have agreed convergence to a single project christened EURECA, eventually comprising up to one ton of cryogenic detectors with event-by-event background rejection. The situation among the xenon and argon groups is less determined, although relatively large experiments are already considered in the WARP-140, XENON-100, ZEPLIN-IV and ELIXIR concepts. It would be highly advantageous, if these groups eventually could also converge to a single noble gas facility – be it xenon or argon or both – in order to reach a detector mass on the 1-ton scale.

Directionality and WIMP telescopes

Following the eventual observation of a clear positive signal, confirmation of the Galactic and WIMP origin by a smoking-gun signature will be required - annual modulation, target-dependence or directionality. The latter needs a device capable of measuring the recoil direction of the target nuclei, a requirement currently only afforded by low-pressure gas detectors. Further development of this technique, as pursued by the DRIFT collaboration (Boulby mine, UK), the MIMAC project (using ^3He gas) and several new EU groups, is therefore a potentially very important investment, with the next goal to fully demonstrate the directionality and track sense determination.

A scenario for the next decade detectors methods

Figure 3.3 sketches a possible time perspective of direct Dark Matter searches, linking it to the first results from SUSY searches at the LHC. The scenario applies to spin-independent coupling of MSSM WIMPs.

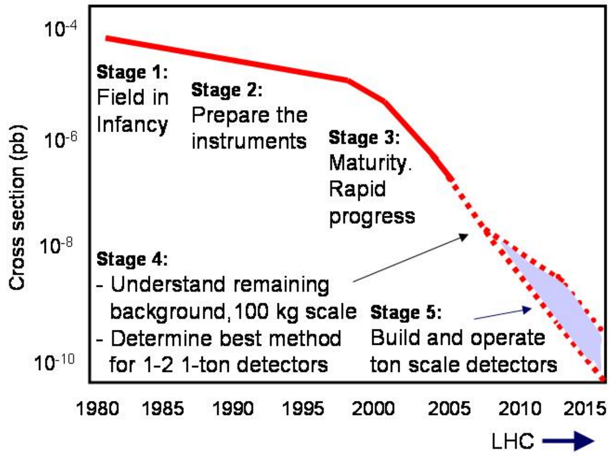


Figure 3.3: *Possible development of limits and sensitivities as a function of time, assuming a standard MSSM WIMP with spin-independent coupling. A 10^{-8} pb sensitivity can be reached within the next couple of years. Improvements by another two orders of magnitude require more massive detectors with dramatically improved background rejection. The colored area for >2008 indicates the range of projections given by different experiments, most of them envisaging an intemediate step at the 100 kg scale. Note that this scenario is made from a 2006-perspective, and that initial LHC result may substantially influence the design of the very few "ultimate" detectors.*

The 10^{-10} pb sensitivity goal and the related coverage of much of the MSSM parameter space is in reach within the next 7-8 years. However, to realise this scenario several conditions have to be met:

- realization of the expected progress in background rejection and signal identification
- demonstration of continuous running over a long period
- sufficient funding for developing and building worldwide three detectors on the one-ton scale based on different methods and nuclei. Given the presently strong role of European projects, Europe should play a strong role in two of them.

The eventual confirmation of a positive observation will require transparency of the experimental process, disclosure of details on used materials and free access to the data.

The following table gives an overview over presently running or prepared experiments (with preparation ranging from R&D to commissioning).

Name	Type	Status	Location	European Members	Others
DAMA/ LIBRA	NaI	running	LNGS	IT	China
ANAIS	NaI	construction	LSC	ES	-
KIMS	CsI	R&D	Korea	-	Korea
HDMS	Ge	running	LNGS	DE	RU
ROSEBUD	bolometer	R&D	LSC	ES, FR	-
DAMA-LXe	LXe scint	running	LNGS	IT	China
ZEPLIN-II	LXe	running	IUS	PT, UK	RU, US
ZEPLIN-III	LXe	installation	IUS	PT, UK	RU, US
XENON10	LXe	commissng	LNGS	DE, IT, PT	US
LUX	LXe	R&D	DUSEL	UK	US
XMASS	LXe	?	Kamioka	-	Japan
WARP	LAr	running	LNGS	IT	US
ArDM	LAr	construction	LSC	CH, ES, PO	-
DEAP	LAr	R&D	SNOLAB	-	Can, US
CLEAN	LNe	R&D	t.b.d.	-	US, Can
DRIFT	CS_2 gas TPC	R&D	IUS	UK	US
MIMAC	^{3}He gas TPC	R&D	t.b.d.	FR	-
EDELWEISS	bolometer	running	LSM	FR, DE	RU
CRESST	bolometer	running	LNGS	DE, UK, IT,	-
CDMS	bolometer	running	Soudan	-	US
SIMPLE	Superheated droplet SHD	running + R&D	LSSB	PT, FR	US
PICASSO	SHD	running + R&D	SNOLAB	CZ	CA, RU, US
COUPP	SH liquid	R&D	t.b.d.	-	US

Table 3.1: *Compilation of experiments and R&D efforts on direct Dark Matter Search. Note that next possible steps beyond presently running detectors (like e.g. XENON-100, WARP-140, EURECA-100 etc.) and also the eventual 1-ton projects have not been included. Abbreviations for European Labs: IUS – Boulby/UK, LNGS – Gran Sasso/Italy, LSM – Frejus/France, LSC – Canfranc/ Spain, LSSB – Bas Bruit/France.*

Indirect detection of WIMPs methods

Up to now, only *direct* detection methods have been discussed. Complementary signatures could be obtained from *indirect* WIMP detection. Indirect searches would identify charged particles, gamma rays or neutrinos from WIMP annihilation in the cores of galaxies, the Sun or the Earth. WIMPs can be gravitationally trapped in celestial bodies and eventually accumulate until their density becomes large enough that the self-annihilation of WIMPs would be in equilibrium with WIMP capture. Celestial or satellite detectors would then detect the decay products of these annihilations: an excess of neutrinos from the centre of the Earth or Sun, a gamma signal from the centre of the Galaxy, or an excess in positrons and anti-protons from galactic plane or halo. Anti–particles such as positrons and anti–protons produced in WIMP annihilation would be trapped in the galactic magnetic fields and be detected as an excess over the background generated by other well understood processes.

Direct and indirect methods are complementary. For instance, gravitational trapping works best for slow WIMPs, making indirect searches most sensitive. In the case of direct detection, however, by kinematic reasons fast WIMPs are easier to detect. For indirect searches, the annihilation rates would depend on all the cosmic history of WIMP accumulation and not only on the present density, providing another aspect of complementarity to direct searches.

Reported indications of a WIMP signature in charged cosmic rays and GeV-gammas remain controversial. Searches with high energy gammas and neutrinos provide upper limits which are close to exclude some MSSM formulations not yet excluded by direct searches. However, a word of caution is needed with respect to non-critical comparison of direct and indirect searches, since the sensitivity of each have different dependencies on slight variations in parameters such as the WIMP density fluctuations, WIMP velocity distribution, capture efficiency and other poorly defined details.

A great step in sensitivity for indirect searches is expected within the next 3-6 years: from INTEGRAL (MeV gamma rays), from GLAST and AGILE (GeV gamma rays), MAGIC-II, H.E.S.S.-II and VERITAS (GeV-TeV gamma rays), ANTARES and IceCube (neutrinos), and PAMELA and AMS (cosmic rays) – see also section 5.

Axions

WIMPs are not the only well motivated candidates for cold dark matter. Another attractive possibility is that CDM may be in the form of axions. Axions were originally postulated to solve the so-called strong-CP problem, e.g. the fact that strong CP violation is exceedingly small or even absent – although the QCD Langrangian naturally contains a CP violating term! To cure this, Peccei and Quinn introduced a symmetry which would be spontaneously broken, and the axion would be the associated pseudo-Goldstone boson.

Axions as CDM candidates

The axion framework provides several ways for copious axion production in the early stage of the Universe. The generic scale of the axion mass is unknown, but in order to produce an energy density close to $\Omega_a \sim 1$, it has to be in the range 10^{-6}-10^{-3} eV/c^2. One may wonder how such light particles could constitute CDM. However, axions are produced coherently in a condensate and therefore would have been non-relativistic at decoupling time. Therefore, despite its extremely small mass, the axion is a second realistic candidate for cold dark matter.

Galactic halo Axions

The key property behind all proposed detection techniques is the coupling of the axion to the photon. In strong magnetic fields, an axion can couple to a virtual photon from the magnetic field producing a detectable photon – a mechanism analogous to the well-known Primakoff effect. For axion masses smaller than 10^{-5} eV/c^2, the photon would be in the microwave range and could be detected in microwave cavities placed in an intense magnetic field. A frequency scan would yield a signal when the cavity is tuned exactly to the axion mass. Such experiments, searching for primordial axions trapped in the halo of our galaxy, have been performed in the US and almost reached the required sensitivity to constrain some of the range of axion models. Experiments with improved sensitivity are presently pursued in the US (ADMX) and Japan (CARRACK).

Axions from the Sun

Instead of hunting axions stemming from the big bang, one may also search for axions produced in the interior of stars. They would be generated, by Primakoff conversion, from plasma photons. Stellar axion emission would open new channels of stellar cooling. This fact considerably constrains axion properties, which must not be in conflict with our knowledge of solar physics or stellar evolution.

The axion flux from the Sun can be estimated within the standard solar model. The expected number of solar axions at the Earth surface is proportional to the square of the axion–photon coupling, and their energies follow a broad spectral distribution around ~4 keV. Solar axions, unlike galactic ones, are therefore relativistic particles. The best method to detect solar axions are the so called "axion helioscopes", which use magnets to trigger the axion conversion to photons. Currently this concept is being used by the CAST collaboration at CERN, using a 9-Tesla LHC dipole prototype. No photons with keV energies from axion decay have been detected, placing an upper limit on the axion–photon coupling. A detector upgrade will increase the CAST sensitivity, allowing to explore regions of the axion parameter space suggested by theoretically motivated axion models.

The "PVLAS effect"

A recent indication of an axion-like particle has caused considerable interest. The PVLAS collaboration operating a detector in Legnaro (Italy) claims observation of a rotation of the polarization plane of photons in a 6.6-Tesla field, which might be due to magnetic birefringence. If confirmed, the effect would indicate the existence of a light scalar particle, however with a coupling to photons far above the already established upper limits by CAST or microwave cavity experiments. If the effect is confirmed to be caused by a new low-mass particle, its possible connection to the dark matter problem, if any, remains to be understood. The PVLAS result has stimulated several new proposals for axion experiments. We mention just one of them, a photon-regeneration experiment which is going to be set up at the VUV-Free Electron Laser in DESY. Laser photons will be sent through the transverse field of dipole magnets and might convert to axions. A photon-opaque wall separates this part of the experiment from downstream magnets in which the axion might convert back to photons which then would be detected. The sensitivity to photon-axion coupling is sufficient to test PVLAS. At the future X-ray FEL the limit could be improved by further tree orders of magnitude.

Other exotic particles and antimatter

Axion-like bosons

The variety of possible dark matter candidates includes also light bosons with axion-like interactions. Interactions of such particles are proposed as one of several interpretations of the annual modulation observed in the DAMA data (see above).

Magnetic mono-poles, Q-balls, nuclearites

Although the possible contribution from non-dominant forms of heavy dark matter has been limited by numerous searches, it is not necessarily vanishing. Magnetic monopoles, Q-balls (soliton states of squarks, sleptons and Higgs fields) and nuclearites (condensates of strange-quark matter and electrons), for instance, could contribute to dark matter on a level which is allowed by precision cosmology and still might be tested with present experiments on Earth. Magnetic monopoles, Q-balls and nuclearites are extremely heavy candidates for exotic matter. The predicted mass of magnetic monopoles ranges between 10^4 and 10^{19} GeV, that of nuclearites from a few hundred GeV up to the mass scale of neutron stars, and that of Q-balls up to 10^{27} GeV. Typical velocities would be at 10^{-4}-10^{-3} of the velocity of light. However, galactic magnetic fields may boost magnetic monopoles with not too high masses to relativistic velocities.

There is no theoretical guidance for the expected fluxes of these particles, as exists for WIMPs and axions. On the other hand the discovery of any of these particles would have significant impact on particle physics and cosmology. Stringent flux limits have been obtained from treck etch experiments, mica analyses and large neutrino detectors. Given the fundamental character of these particles, neutrino and air shower detectors should fully exploit their potential for corresponding searches.

Fractionally charged particles

One of the first exotic particles to be searched for were the fractional charges expected from the naïve quark model. The failure to find free quarks provided motivation for the modern theory of quantum chromodynamics in which fractional charges are “confined”, i.e. bound into integrally charged hadrons. Any new stable relic particle from the Big Bang which has electromagnetic or strong interactions would be expected to bind to nuclei resulting in isotopes with anomalous charge-to-mass ratios. Rigorous searches for such anomalous isotopes in sea water, moon rocks etc have set stringent limits. These limits for instance constraint the lightest super-symmetric particle to be neutral rather than charged or coloured.

Antimatter

The unambiguous detection of even a single antihelium or anticarbon nucleus would be a smoking gun for anti-matter dominated regions in the Universe and have profound consequences on our understanding of the early Universe. The search for anti-matter is a traditional domain of balloon-borne or satellite experiments which are addressed in section 5.2.

3.3 Proton Decay

Grand Unified Theories

The question whether protons are stable particles or instead decay is profound. Grand Unified Theories (GUT) of elementary particles and fields, aiming to unify the known electromagnetic, weak and strong interactions, predict that free protons can decay into lighter particles via the transmutation of a quark into a lepton. Today we know that six quarks and six leptons form the fundamental fermions of matter, however, in the Standard Model there is no fundamental connection between these two types of fermions. GUT theories, by postulating symmetry between quarks and leptons, are able to explain the relations between quarks and leptons and predict the unification of forces at the so-called GUT-energy scale. <

Experimental hints, however, are scarce. One is the observation, at the e^+e^- LEP collider, that the strengths of the electromagnetic, weak and strong interactions may converge into a single value at extremely high energies, many orders of magnitude above the energy scale reachable at the future Large Hadron Collider (LHC). Another hint is the observation of finite but very small masses for the neutrinos. Such small masses emerge naturally in GUTs via the existence of new, very heavy neutrino partners, which through a mechanism called “see-saw” could explain the light masses of the ordinary neutrinos. These heavy neutrinos could participate in proton decays, suggesting a connection between the neutrino masses and proton lifetime.

This possibility has regained interest recently after the discovery of non-vanishing neutrino masses.

A well-established theory of the proton decay does not yet exist. However, there are different models for GUTs. They are often labelled according to the assumed underlining symmetry. For example, the simplest GUT theory is based on the SU(5) group. In these models, proton decay could be mediated by new massive unknown vector bosons of masses M on the order of the GUT scale. Since the decay time scales approximately like $\tau_p \approx M^4/m_p$,, the SU(5) GUT theory suggested τ_p~10^{31}–10^{32} years, but this has already been ruled out experimentally. Other models, like those based on super-symmetric extensions of the Standard Model, predict a lifetime below or of the order of 10^{35} years.

The search for proton decay provides an indirect probe of very high-energy scales, which could not be accessed with a high-energy collider. The physics of proton decay could also be intimately linked to the excess of matter over antimatter in the Universe.

How to detect proton decay ?

To be able to detect a proton decay with a lifetime of $\tau_p \sim 10^{35}$ years, one needs to observe a very large number of nucleons over several years (for example 1 million tons of water contains about $3 \cdot 10^{35}$ protons and a similar number of neutrons). In this case, one might be able to detect proton decay.

The possible final state of the proton decay depends on the details of the decay mechanism. In many GUT models, the decay is mediated by the exchange of new heavy gauge bosons, and the mode $p \to e^+ \pi^o$ is expected to be the dominant channel. In super-symmetric GUTs, there are additional mechanisms for proton decay involving not only known fermions but also their super-symmetric partners. Therefore the lifetime can potentially be shorter. Many of these super-symmetric mechanisms predict that the mode $p \to \bar{\nu} K^+$ is the dominant channel.

Presently achieVed limits exclude simplest GUT versions

The sensitivities of current experiments have reached the lower range of predictions, and a future experiment may extend the sensitivity sufficiently to discover the signal (see Fig. 3.4). The most stringent limits have been obtained by Super-Kamiokande. In this kind of detector, one detects the Cherenkov light emitted by the final state particles when they travel faster than the speed of light in water. The $e^+ \pi^o$ channel, for instance, is characterized by two or three Cherenkov rings coming from the electron and from the conversion of the two gammas produced in π^o decay. The lower limit on the partial lifetime of a proton is determined as $5.4 \cdot 10^{33}$ years for this mode (90% C.L.). In the detection one has to take into account that the proton is not free, except in the Hydrogen of the water molecule, but bound in the nucleus. For example the π^o in the $e^+ \pi^o$ channel has a substantial probability of interacting in the Oxygen before decaying into two gammas. The use of water is thus particularly important because of the Hydrogen.

The K^+ in the $p \to \bar{\nu} K^+$ channel is below the Cherenkov threshold and does not emit light in water.

What is detected is the μ^+ or π^+ from its decay $K^+ \to \pi^+ \pi^0$ or $K^+ \to \mu^+ \nu$, respectively. The limit for the $p \to \bar{\nu} K^+$ mode is $2.2 \cdot 10^{33}$ years.

New generation experiments should aim to improve the sensitivities up to 10^{35} years for the mode $p \to e^{+}\pi^{0}$ and the super-symmetric favoured mode $p \to \overline{\nu} K^{+}$. Since the water Cherenkov technique is limited by backgrounds, new techniques based on large liquid scintillator or liquid Argon volume are being investigated. The new detectors will have to be located deep underground to be shielded from cosmic rays. In order to host these large detectors new excavations at existing or new deep underground laboratories will have to be constructed. Feasibility studies have been undertaken to assess the stability of the large cavities as a function of their depth and location.

Expectation to a next generation of experiments

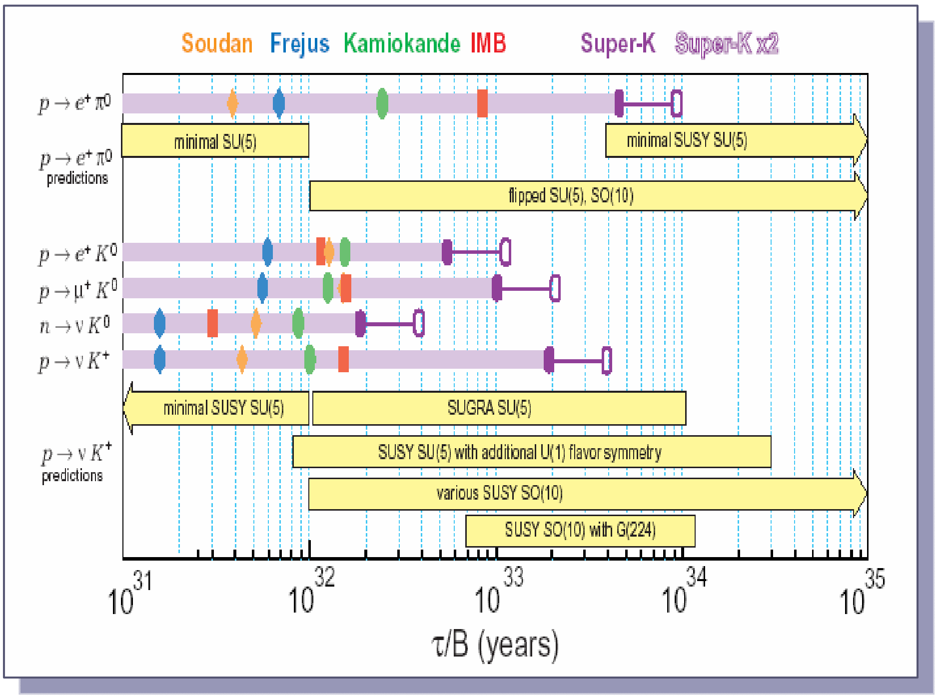


Figure 3.4: *Past and present limits on proton decay in different decay channels, compared to theoretical predictions*

It is important to note that a very massive underground detector constructed for proton decay will also provide an extensive neutrino physics program since it could be simultaneously employed as a far detector for a long baseline neutrino oscillation experiment and as proton decay detector. In addition, it would also provide a detailed study of atmospheric neutrinos and would be a powerful instrument for the detection of Supernova neutrinos capable of observing core collapse supernovae up to the Andromeda Galaxy, with an expected rate of one event every 10–15 years. We discuss these multi-purpose detectors in section 4.5.

3.3 Properties of Neutrinos

Neutrinos are in many ways special particles playing a very important role in the Universe and in fundamental physics. Although their interactions are extraordinarily weak they are essential in the processes that makes stars shine, and likely to be crucial in the titanic explosions of dying stars and the accompanying ejection of heavier elements which eventually form the constituents of our own bodies. Neutrinos may also have influenced the large-scale structure of the Universe. More speculatively, they could have played an essential role in "baryogenesis" - the creation of excess of matter over anti–matter in the Universe, again a mechanism essential for our own existence.

The difficulties of studying particles with such feeble interactions led to a relatively slow accumulation of knowledge about neutrinos, which explains why much of what we know has been learnt only recently. The past decade has delivered fundamental discoveries about the nature of the neutrinos, notably that of neutrino oscillations from study of neutrinos from the Sun and the Earth's atmosphere and subsequent confirmation using neutrinos from a reactor and an accelerator. These discoveries show that neutrinos have a finite mass. However, this mass is much smaller that the mass of all other particles, suggesting that the neutrino mass may have a different origin. These results have far reaching implications that affect our understanding of the Sun (and other stars), our theories of the evolution of the Universe, and the perspectives for developing a more fundamental theory of the subatomic world. Our current theoretical synthesis of the laws of particle physics is the remarkably predictive "Standard Model". In the Standard Model (or more precisely in its simplest form) neutrinos do not have mass and do not oscillate. The discovery of the existence of finite neutrino masses and of neutrino oscillations is a "glimpse" of physics beyond the Standard Model, and of the possible form of a simpler and more fundamental theory.

Open questions ...

A comprehensive understanding of neutrino physics requires answers to the following fundamental questions:

- Are neutrinos their own antiparticles ("Majorana particles")?
- What are the masses of the neutrinos?
- How do different neutrinos mix?
- Are the CP, T and CPT symmetries broken by neutrinos?
- Are neutrinos the key to the understanding of the matter–antimatter asymmetry of the Universe?
- Are there additional light ("sterile") neutrino types beyond the three known (e, μ and τ) flavours?
- Do neutrinos have non-zero electromagnetic form factors ?

Answers to these questions would have far reaching consequences. The problems addressed are fundamental. However, the experimental challenges are considerable and call for a strong and coherent programme of experimental, observational and theoretical studies. Astroparticle physics is central to such a programme.

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

... and key experiments to get the answers

a) oscillation experiments (using neutrinos from accelerators or nuclear reactors as well as atmospheric or solar neutrinos). They provide information on mixing parameters, possible CP violation and mass *differences*, but not absolute masses. *Absolute* masses can be derived from three types of data/experiments:

b) cosmological data, *c)* kinematical direct neutrino mass measurements and *d)* double beta decay experiments. Double beta decay experiments are the only experiments which can prove the Majorana nature of neutrinos. The electro-magnetic form factors of neutrinos could be studied by *e)* exposing a low-energy neutrino detector to an artificial neutrino source like ^{51}Cr.

Before describing status and future plans of the field, we give a short introduction in terminology and basic formulas of neutrino mixing.

The formalism of neutrino masses and oscillations in a nutshell

If neutrinos have mass, the mass eigenstates do not need to be the same as the weak eigenstates. The latter are the states that couple to the W-boson in weak interactions, by definition ν_e, ν_μ and ν_τ. The mass eigenstates are usually denoted by ν_1, ν_2, ν_3... If mass and weak states are not the same they are related by a transformation

$$\nu_l = \sum U_{li}\, \nu_i$$

where *l* stands for e, μ or τ and *i* runs from 1 to the number of mass eigenstates. If there are only three mass states, then **U** is a 3⊗3 unitary matrix. Here we consider only this case. All the experimental evidence can be explained with three mass states, except for the results of the LSND mentioned below, which would require at least a fourth mass state.

The 3⊗3 matrix **U** can be written as follows:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

This mixing matrix is usually called the Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix, analogous to the CKM matrix for the quarks. A neutrino produced at *t*=0 in a pure weak eigenstate is a mixture of mass eigenstates determined by the mixing matrix. As the neutrino travels from the source to the detector each of the mass eigenstates evolves acquiring a phase which is different for the three mass eigenstates due to their different masses. When the neutrino is detected through a weak interaction, this quantum-mechanical mixture is projected again into a weak eigenstate, which in general will be different from that produced at *t*=0. We say that the neutrino has oscillated from one flavour to another. With some algebra one can compute the probability for the transition from a weak eigenstate ν_α at *t*=0 to an eigenstate ν_β at the detector, which is given by the expression:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{bi} U_{\alpha j} U^*_{\beta j}) \sin^2\left(1.27 \Delta m^2_{ij} \frac{L}{E}\right)$$

$$+ 2 \sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{bi} U_{\alpha j} U^*_{\beta j}) \sin\left(2.54 \Delta m^2_{ij} \frac{L}{E}\right)$$

For antineutrinos we have a similar expression, with a minus sign in front of the Im component of the product of mixing matrix elements. In the above expression Δm^2_{ij} is in eV^2, L, the distance from the source to the detector, is in *km*, and E, the neutrino energy, is in *GeV*. The dependence on the mass differences (of which there are two independent) is quadratic and therefore one cannot extract their sign from oscillation experiments in vacuum. We also see from these expressions that non-vanishing complex terms in the matrix would lead to CP violation:

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$$

This equation simplifies considerably if certain conditions are met. It could be for example that one of the mass splittings, Δm^2, is very different from the others. If E and L in a given experiment are such that 1.27 $\Delta m^2(L/E) \approx \pi/2$, then only the corresponding term is relevant in the above expression. The resulting formulae are like those that one would obtain assuming that only two generations participate in the oscillation. The corresponding situation is called a ``quasi-two-neutrino oscillation". It can also be that only two mass states couple significantly to the flavour partner of the neutrino being studied. In that case the equations also become quasi-two-neutrino oscillations. Nature seems to be kind enough to have chosen these situations, the first in the case of atmospheric neutrinos the second in solar neutrinos.

The analysis of solar neutrino data indicates that the electron neutrino couples significantly only to two mass states, chosen as ν_1 and ν_2. The solar neutrino oscillations occur not only because of the mixing but also because electron neutrinos propagate differently through matter than the other two species. When neutrinos propagate through matter they can forward scatter coherently with the medium, via Z- boson exchange. But for electron neutrinos (and only for electron neutrinos) the elastic forward scattering can also proceed via W-boson exchange. As a consequence the flavour transitions, assuming that there is mixing, are modified with respect to those in vacuum. It can be shown that the modified transition probability is given by an expression similar to that in vacuum but depending on and effective mixing angle and an effective mass difference which are modified with respect to those in vacuum. Under certain conditions the effective mixing angle becomes maximal, even for small mixing. The effect is called the MSW effect, from Mikheyev, Smirnov and Wolfstein. What the analysis of the solar data indicates is that the neutrino born as an electron neutrino in the core of the Sun, is also in a state which is almost the heavier of the two mass eigenstates and it remains in that state until it leaves the Sun. This heavier state is usually chosen as ν_2. But since that state is also an eigenstate of the vacuum Hamiltonian it does not change when it propagates freely from the Sun to the Earth. When the solar neutrino interacts on Earth the probability of finding it as an electron neutrino is just the sine-square of the mixing angle appearing in the corresponding quasi-two-neutrino oscillation expression.

In the case of the atmospheric neutrinos the analysis indicates that over the relevant energies and distances only one mass splitting is relevant, traditionally chosen as Δm_{32}.

A convenient parameterization of the mixing matrix is the following

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\frac{\phi_2}{2}} & 0 \\ 0 & 0 & e^{-i\left(\frac{\phi_3}{2}+\delta\right)} \end{pmatrix}$$

where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$. The phases δ, Φ_2 and Φ_3 are CP violating. Φ_2 and Φ_3 can only be non-vanishing if the neutrino is a Majorana particle; they do, however, not affect oscillations or the interpretation of present neutrino results.

Information on the *absolute masses* of neutrinos can be obtained from three sources:

1. Cosmological data provide information on the sum of all masses:

$$m_{cosm} = \sum m_i$$

2. Direct kinematical measurements are sensitive to the square of an "effective" neutrino mass m_β:

$$m_\beta^2 = \sum |U_{ei}|^2 \cdot m_i^2$$

3. Neutrino-less double beta decay is sensitive to

$$m_{\beta\beta} = \mathrm{abs}\ (\ |U_{e1}|^2\ m_1 + |U_{e2}|^2\ m_2 \exp(i\Phi_2) +\ |U_{e3}|^2\ m_3 \exp(i\Phi_3)\ )$$

The coefficients of the linear combination depend on the neutrino mixing matrix that controls the neutrino flavour transitions, and on two additional Majorana phases Φ_2 and Φ_3 whose values are unknown. For vanishing phases, the latter formula simplifies to

$$m_{\beta\beta} = \sum U_{ei}^2 \cdot m_i$$

History and status of neutrino oscillations

When the Standard Model was constructed in the seventies, neutrinos were assumed to be mass-less, since all evidence at the time was consistent with that hypothesis. However, the combination of many experiments on solar, atmospheric, reactor and accelerator neutrinos clearly indicates that there are at least two neutrino states with non zero mass.

Oscillations of solar neutrinos

Solar neutrinos, produced in fusion reactions in the solar core as electron neutrinos, oscillate into muon and tau neutrinos. When they reach the Earth, the electron neutrino component of the neutrino flux is reduced - depending on energy to 35-60% of that produced at the source. Experiments sensitive only to electron neutrinos consistently measured a deficit with respect to that expected in absence of oscillations, and this was the case for many years. The observations started at the end of the sixties with the legendary Homestake experiment of Ray Davis (USA), continued in the eighties with Kamiokande (Japan), and have also been made for the low-energy part of the solar neutrino spectrum: by SAGE (in the Russian Baksan laboratory) and GALLEX (Gran Sasso). The final confirmation that the neutrinos had not just disappeared but instead converted to another type of neutrino came for the SNO experiment in Canada (with participation of UK groups). SNO started operation in 1999 and is sensitive to all three kinds of neutrinos (since it can detect neutral-current reactions). The SNO results have dotted the i. They demonstrated in an uncontroversial way that indeed the disappearing solar electron neutrinos oscillate into muon and tau neutrinos.

Oscillations of atmospheric neutrinos

Electron and muon neutrinos are also produced in collisions of primary cosmic rays with the Earth atmosphere. In 1998, data collected with the Super-Kamiokande detector, in which both electron and muon neutrinos are detected, indicated that the atmospheric muon neutrinos were increasingly "disappearing" as a function of the distance from their production to the interaction point. These neutrinos are produced with a large range of energies and distances from the detector, from tens of kilometres (the atmosphere above the detector) to twelve thousand kilometres (those produced in the atmosphere in the antipodes of the detector). Electron neutrinos did not change significantly, indicating that for the range of energies and distances of atmospheric neutrinos, the oscillation was mainly from muon to tau neutrino (tau neutrinos do interact in SuperKamikande but cannot be efficiently identified).

Confirmation from reactors and accelerators

The oscillation hypothesis, with the value of the oscillation parameters obtained from the analysis of solar and atmospheric experiments, was confirmed independently by the KamLAND and K2K experiments, both in Japan. KamLAND is an experiment able to detect the electron antineutrinos produced by nuclear reactors in Japan. These antineutrinos travel different distances as they arrive at the detector and have a low energy spectrum. Their oscillation depends on the same parameters probed with solar neutrinos. The comparison of the number of neutrinos observed in KamLAND with those expected from the power generated by the reactors is consistent with the oscillation hypothesis and with the parameters measured in solar experiments. K2K is an experiment directing a muon neutrino beam from the KEK accelerator to Super-Kamiokande, 250 km away. The distance and the energy of the neutrinos have been tailored to yield high sensitivity to oscillation parameters in the range derived from atmospheric neutrinos. K2K observed a deficit of muon neutrinos consistent with the parameters derived for atmospheric neutrinos, moreover showed an energy dependence of the effect, which also supports the oscillation hypothesis. The effect is also confirmed by initial results from MINOS (see below) which exclude the non-oscillation hypothesis with high confidence.

CHOOZ: θ_{13} is < 10°

A reactor experiment, CHOOZ in France, was designed to measure the mixing angle θ_{13}. The value $\sin^2\theta_{13}$ is equal to the amount of ν_e contained in the ν_3 state. CHOOZ has looked for disappearance of electron antineutrinos over a short baseline (1 km) and has not observed it. The result can be translated into the currently best limit to the mixing angle, θ_{13} < 10°. The relevance of θ_{13} lays in the fact that for very small θ_{13} the CP violating phase δ would not be measurable (see above), making the case for improved experiments on θ_{13} obvious.

LSND: a fourth neutrino ?

Finally, we mention an experiment in the USA, the Large Scintillation Neutrino Detector, LSND. Performed in the mid nineties, it provided a spectacular puzzle. LSND was using low energy accelerator-produced muon antineutrinos and detected a significant *appearance* of electron antineutrinos over a baseline of 30 m. If the effect was real, and if electron antineutrinos were due to oscillations, this result could not be accommodated with all the other results on oscillations, except by introducing a fourth neutrino mass state around 1 eV, which mixes with the first three! This fourth neutrino had to be *sterile*, i.e. not coupling to W- and Z-bosons. Light sterile neutrinos would have the potential to greatly affect many astrophysical processes, e.g. the heavy element production in supernovae.

The sensitivity of the European KARMEN experiment, also running in the nineties, was tantalizingly close but not fully sufficient to exclude the result. Therefore, the LNSD result is being presently checked by a similar but independent experiment, MINIBOONE in the USA.

What do we know today ?

The present knowledge on the MNSP matrix can be approximately summarized as follows:

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad \Leftarrow \textbf{neutrinos}$$

which is in dramatic contrast to the much smaller mixing between quarks (given by the so-called CKM matrix):

$$U_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix} \quad \Leftarrow \textbf{quarks}$$

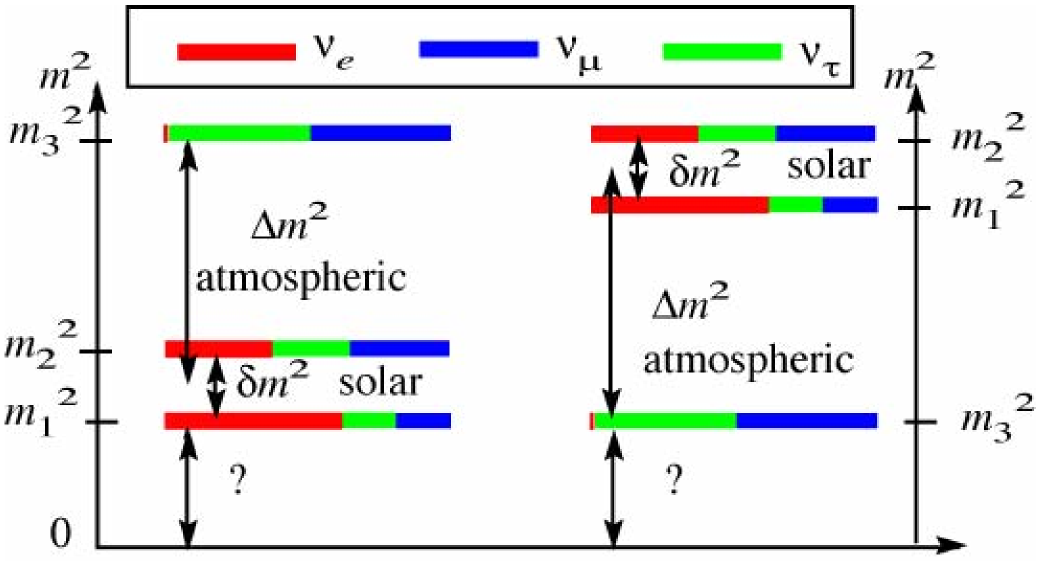


Figure 3.6: *The two possible mass arrangements based on oscillation data, left the "normal" hierarchy, right the "inverted" one. Colors indicate the contribution from the different weak eigenstates, reflecting the known facts about mixing angles.*

Figure 3.6 summarizes our knowledge on mass differences. Notice that from current experiments we do not know the sign of Δm^2_{32}, that is, we do not know if m_3 is heavier or lighter than m_1 and m_2, as depicted in the figure. The first scenario (left hand in the figure) is called "normal hierarchy", the second (right hand) "inverted hierarchy". We know however the sign of Δm^2_{12}. The information for this parameter comes from oscillations in the solar matter, which do depend on the sign of the difference. ν_2 is chosen as the heaviest of the two states intervening in solar oscillations, that is $m_2 > m_1$. The results are

$$|\Delta m^2_{32}| = (2.4 \pm 0.3) \cdot 10^{-3} \text{ eV}^2$$

$$\Delta m^2_{21} = (8.3 \pm 0.3) \cdot 10^{-5} \text{ eV}^2$$

The values of the mixing angles are

$$\theta_{12} = 33^o \pm 2^o$$

$$\theta_{23} = 45^o \pm 3^o$$

$$\theta_{13} < 10^o$$

Future experiments on neutrino oscillations

Neutrino mixing is far from being completely understood. Although θ_{12} and θ_{23} are reasonably constrained by current experiments, only an upper limit is known for θ_{13}, and the values for the phases δ, Φ_2 and Φ_3 are completely unknown. Several oscillation experiments are now being operated, prepared or contemplated in order to answer the open questions.

Improving the "solar" parameters

Solar neutrino experiments KamLAND and SNO/phase-3 will improve the determination of the solar mass difference and mixing angle. The BOREXINO experiment in the Gran Sasso Laboratory is presently in the final filling stage and will measure the mono-energetic neutrinos of the ^{7}Be and p-e-p solar reactions. It should provide a first clear description of the MSW effect in the transition region between vacuum and adiabatic regimes, around 1 MeV. It can also improve the knowledge of θ_{12}. In addition BOREXINO, exploring in real-time the neutrino spectrum below 1 MeV, can search for possible non-standard and/or exotic scenarios (e.g. a light sterile neutrino).

Improving the "atmospheric" parameters

A new long-baseline experiment, MINOS in the Soudan mine (Minnesota), is detecting neutrinos from the NuMI beam in Fermilab (730 km away). MINOS will improve the measurement of the "atmospheric" oscillation parameters and may also slightly improve the limit on θ_{13}. The CNGS program (CERN to Gran Sasso) has started in 2006 with the commissioning of the beam and the observation of first neutrino interactions at in the OPERA detector. OPERA aims at observing the explicit ν_μ to ν_τ transition.

The ICARUS collaboration has developed the liquid argon technique since long. Their 600 ton detector at Gran Sasso is expected to be operational by the end of 2007 and start recording neutrino interactions from the CNGS beam. The collaboration also discusses the possibility of improvements in the CNGS (CERN-to-Gran Sasso) neutrino beam, possibly using the off-axis method, as well as the construction of a modular detector of larger mass, to be placed in a new Gran Sasso hall at shallow depth.

The matter effect for atmospheric neutrinos: a clue to the mass hierarchy ?

The $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu(\nu_\tau)$ subdominant oscillations of atmospheric neutrinos should exist, and their effects could be observable if genuine three-flavor-neutrino mixing takes place in vacuum, i.e., if $U_{e3} \neq 0$. If this mixing is sufficiently large, these subdominant transitions of atmospheric neutrinos are amplified by Earth matter effects. The clue is that matter affects neutrinos and antineutrinos differently, and thus the study of these effects provides unique information. Depending on the sign of $\Delta m^2_{2,3}$, the Earth matter effects can resonantly enhance either the $\nu_\mu \leftrightarrow \nu_e$ or, alternatively, the anti-$\nu_\mu \leftrightarrow$anti-ν_e transitions. If the sign of $\Delta m^2_{2,3}$ is positive, one would observe a reduction of the rate of multi-GeV μ^- events recorded in detectors with charge discrimination. If the sign is negative, the μ^+ event rate will be reduced. Most detailed information on the value of $\theta_{1,3}$ and the sign of $\Delta m^2_{2,3}$ can be extracted from the zenith-angle distribution of the N (μ^-)-N (μ^+) asymmetry for multi-GeV μ^- and μ^+ events rates. Atmospheric neutrino experiments are the only method other than very long baseline accelerator experiments of determining the neutrino mass hierarchy.

In detectors without charge discrimination, the event-by-event distinction between neutrino and antineutrino events is not possible. However, due to the difference of cross sections for neutrinos and antineutrinos, the multi-GeV samples of muon-like events will be smaller and that of electron-like will be larger if $\Delta m^2_{2,3} > 0$, compared to the case $\Delta m^2_{2,3} < 0$. Thus the ratio $N(\mu)/N(e)$ of the multi-GeV μ- like and e-like event rates could be sensitive to the type of the neutrino mass spectrum. This atmospheric neutrino detector could be the one considered world-wide as a next generation multi-purpose detector.

Thus, summarizing, from the study of the Earth matter effects on atmospheric neutrinos one can conclude that: a) matter effects can disentangle the sign of the atmospheric $\Delta m^2_{2,3}$; b) for $\theta_{1,3} = 0$ electron neutrinos decouple from the oscillations of the atmospheric neutrinos in matter; for $\theta_{1,3} \neq 0$, electron neutrinos mix with the third mass eigenstate and take part in atmospheric neutrino oscillations; c) non-resonant medium effects are already apparent in the subdominant channels for baselines L ~ 3000 km, in both the mixing and oscillation phase shift; d) in order for the medium effects to be observable in the muon neutrino survival probability, the resonant MSW effect must be operational, and this requires baselines longer than L ~ 7000 km, the optimal baseline being a function of the value of $\theta_{1,3}$; e) the presence of electrons but no free muons and tau leptons in ordinary matter lead to the appearance of an effective CPT and CP asymmetry. Taking into account the ν_μ, anti-ν_μ, ν_e and anti-ν_e atmospheric fluxes and the relevant charged current neutrino-nucleon deep inelastic scattering cross sections in the detector, these matter-induced "fake" CPT and CP asymmetries are observable. Although a magnetized detector is the preferred experiment to measure these effects with atmospheric neutrinos, the $N(\mu)/N(e)$ ratio alone provides some information to disentangle the type of neutrino mass hierarchy.

Measuring the third angle and searching for CP violation

As mentioned, the value of θ_{13} is not known. Is it not only just small but even vanishing, indicating perhaps an unknown symmetry? A vanishing of any of the mixing angles would imply CP conservation for leptons. As we know that the other mixing angles θ_{12} and θ_{23} do not vanish, the search for a non-vanishing θ_{13} is particularly important for establishing the pre-requisites for CP violation in the lepton sector.

Double CHOOZ versus T2K

To measure (or substantially improve the limit on) θ_{13} requires a new generation of experiments. The next step is expected from Double CHOOZ. As with its predecessor, the CHOOZ experiment, one will search for disappearing electron neutrinos from the French Chooz nuclear reactor, with much increased power compared to the nineties. Also, Double CHOOZ will operate two detectors at different distances, capable of pushing systematic errors down to 0.6%. The experiment could reach a sensitivity of ~0.024 on $\sin^2 2\theta_{13}$ in a three-year run. Double CHOOZ is the most advanced reactor oscillation project. Competitors such as the Daya Bay experiment in China are behind by a couple of years but claim a twice better sensitivity. More important, there are accelerator projects which measure ν_μ-to-ν_e transitions in the appearance channel. Most advanced is the Japanese T2K project which uses a neutrino beam sent from Tokai to Kamioka. T2K is under construction and scheduled to start in 2009, with full beam intensity in 2011. Its five-year sensitivity to $\sin^2 2\theta_{13}$ will be 0.006, assuming the CP violating phase δ to be zero and not canceling stronger effects of the mixing angle (We note the complementary character of reactor experiments which cannot measure δ separately, and accelerator experiments which can.) A similar experiment, NOνA, is planned in the US but not yet approved. The competition with T2K leaves a comparatively small discovery window for Double CHOOZ, making a realization of this experiment urgent.

The mysterious LNSD result which implies more than three neutrino mass states, will be proven or disproven when MINIBOONE data are analyzed. But even when assuming only three mass states, two other important questions remain related to neutrino masses. One is the sign of Δm_{32}. If m_3 is larger than m_1 and m_2 the mass spectrum is called "normal", if the opposite is true the spectrum is called "inverted". Ultimately the masses should be understood in a future theory. Grand Unified Theories (GUTS), relating quarks and leptons, favor a normal hierarchy of masses. The other important question is the absolute value of the masses themselves. The fact that the mass splittings are not zero places a lower bound on the mass of the heaviest state, that is $m_{heaviest} > |\Delta m_{32}|$. On the other hand, cosmological measurements and hypothesis imply an upper bound on the sum of the neutrino masses,

$$\sum m_i < (0.4 - 1.0)\,\mathrm{eV}$$

The combination of both results already gives an indication of the scale of neutrino masses. They are exceedingly small as compared with those of any other elementary particle.

Neutrino masses from Cosmology

Neutrinos left over from the early epochs of the evolution of the Universe, must have a number density of about 56 cm^{-3} for each of the six neutrino species, and a black-body spectrum with temperature 1.947 Kelvin. The neutrino contribution to the matter density of the Universe is proportional to the sum of the neutrino masses. Neutrino oscillations impose a lower limit on the heaviest neutrino mass of about 0.05 eV. This implies that neutrinos contribute at least 0.1% of cosmic matter. Neutrinos with a small finite mass constitute hot dark matter, which suppresses the power spectrum of density fluctuations in the early Universe at "small" scales, of the order of one to ten Mega-parsec. The recent high precision measurements of density fluctuations in the Cosmic Microwave Background (WMAP) and the observations of the Large Scale Structure distribution of galaxies (the projects 2dFGRS and SDSS), combined with other cosmological data, yield very stringent upper limits on the amount of hot dark matter in the Universe, and therefore on the sum of neutrino masses. The limit on $\sum_k m_k$ is 0.68 eV, i.e. stronger than current laboratory limits. The exact estimate of the upper bound depends on the inclusion of different sets of data. The strongest constraint arises from the so–called Lyman–α forests, constituted of absorption lines in the spectra of high-redshift quasars due to intergalactic hydrogen clouds. Results may however suffer from large systematic uncertainties.

The future sensitivity of cosmological measurements of the Large Scale Structure of the Universe using the Galaxy survey SDSS and the CMB mission Planck, combined with the weak gravitational lensing of radiation from background galaxies and of the CMB is expected to reach a value of $\sum_k m_k \sim 0.1$ eV.

Direct Measurements of the Neutrino Mass

Measurements of neutrino flavour transitions provide only the difference between the squared masses of the neutrinos, but not the masses themselves. The only laboratory technique for the direct measurement of a small neutrino mass, without additional assumptions on the character of the neutrino, is the precise measurement of the electron spectrum in β-decays. Here, the neutrino mass (or an upper limit to it) is inferred from the shape of the energy spectrum near its kinematical end point, usually defined as Q-value of the decay. In practice, the most sensitive experiments use the β-decay of tritium since its Q-value is very low, and the relative number of events occurring in an interval of kinetic energy ΔT near the end-point is proportional to $(\Delta T/Q)^3$.

The shape of the spectrum near the kinematical end point depends on the masses of all three mass states and two mixing parameters (the third being dependent on the other two). In practice one is sensitive to an effective mass $m_\beta=(\Sigma_k |U_{ek}|^2 m_k^2)^{1/2}$.

Two groups, the one Mainz (Germany) the other in in Troitzk (Russia) have used spectrometers based on adiabatic magnetic collimation, combined with an electromagnetic filter. Both experiments ended up with the a similar limit on the effective mass, with m_β < 2.3 eV (95% C.L.) being the slightly better one from the Mainz experiment.

The KATRIN experiment

A new experiment, KATRIN, aims for a tenfold improvement in sensitivity, down to 0.2 eV. It is currently being constructed in Karlsruhe (Germany), with worldwide participation. KATRIN follows the basic principle of the devices in Mainz and Troitzk, however translated to a dramatically larger scale. Electrons from a windowless gaseous source will be filtered with the help of a pre-spectrometer, followed by the high resolution (ΔE = 1 eV) main spectrometer. Thanks to the superior luminosity and resolution KATRIN needs only to investigate a small range of the tritium beta decay spectrum below the endpoint. Therefore the systematic uncertainties are much reduced compared to previous experiments due to the energy thresholds of all kinds of inelastic effects. The diameter of the main spectrometer (ten metres in this case) scales inversely with the square of the achievable sensitivity to the neutrino mass, which ultimately places a technical limitation on this method.

The construction of KATRIN and the demonstration of the 0.2- eV sensitivity represent a considerable challenge. KATRIN is a unique device, and its realization merits strong support. Full operation, including the main spectrometer, is expected for 2009/2010.

Given the latest WMAP results, one may ask for the competitiveness of KATRIN. Including WMAP data, precision cosmology measurements yield an upper limit of 0.68 eV for the sum of all three neutrino masses (or 0.68 eV /3=0.23 eV with respect to the lightest mass state). This does not seem to leave much room for a device with 200- MeV sensitivity. However, one must keep in mind that the cosmological limit, despite the impressive success of precision cosmology, has to be derived within a system of assumptions and interpretations, and is not obtained directly. There are calculations arriving at a more robust upper limit of 0.5-1.0 eV per mass state, instead of 0.23 eV. Considering the importance of the neutrino mass question, and the difficulty in associating the cosmological limit to a precise systematic confidence level, it is therefore important to pursue direct measurements up to their eventual technological – and financial – limits.

Beyond KATRIN: bolometric methods?

Apart from a *spectrometric* measurement à la KATRIN, *calorimetric* techniques are being developed and aim for resolution below an electron volt. These experiments use bolometers containing ^{187}Re, the beta-active nuclide with the lowest Q-value in nature: 2.5~keV. On one hand, the calorimetric experiments are reasonably free from the systematic effects induced by any possible energy loss in the source, since all the decay energy (except the one carried out by the neutrino) is measured. On the other hand, solid-state effects and a severe pulse pile-up rates can produce spectral distorsions and background at the end-point. With a present mass limit of 15-20 eV as reached by the MBETA and MANU experiments in Milano and Genova, possible technological limitations with respect to sub-eV resolution cannot yet be judged. However, the complementarity to the spectrometric approach suggests further coordinated exploration of the method. A recently joined world-wide collaboration is proposing a next generation Rhenium-based calorimetric experiment, known as MARE. In a first phase, thanks to an already developed technology, MARE is expected to achieve the present Mainz/Troitzk limit in 2-3 years. The potential of bolometric methods could be further explored in a second 5-year development phase (MARE-2), with the main goal making bolometric sensors 100 times faster than now. This would be a condition to reach a sensitivity similar to that of KATRIN after further five years of running. We finally note that a bolometric experiment, unlike a spectrometer, can be incrementally further, thanks to its intrinsic modularity.

Neutrino-less Double Beta Decay

All known fermions have a distinct anti–particle, particles with same mass and spin but opposite electric charge: electron and positron, proton and anti-proton, etc. Neutrinos may be the only possible exception since they are "neutral", in the sense that they have no known charge-like attribute. The neutrino (of a given flavour) could be the anti–particle of itself. Hypothetical fermions of this type are called *Majorana* particles, in contrast to *Dirac* particles. The implications of massive neutrinos for models beyond the Standard Model differ for *Majorana* and *Dirac* neutrinos. Therefore the answer to the question whether nature took the "*Majorana* option" is an essential building block for a new Standard model.

The only practical method to attack this problem is the study of neutrino-less double beta decay. In this process, a nucleus (*A, Z*) would turn into another (*A,Z*+2) by transforming two neutrons into protons and emitting two electrons: $(A, Z) \rightarrow (A, Z+2) + 2e^-$. This differs from "normal" double-beta decay (second order process of the weak interaction), which is rare but has been detected and studied: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}$.

Neutrino-less double beta decay violates the global lepton number by two units ($\Delta L=2$). It can occur through different processes but all of them require that the neutrino is a Majorana particle. The most proximate theoretical model is to mediate neutrinoless double beta decay by the exchange of a light Majorana neutrino. However, it should be noted that more exotic explanations, as e.g. offered by super-symmetry, are also possible.

For the exchange of a light Majorana neutrino, the half–life for the neutrino-less double beta decay is inversely proportional to the square of the effective Majorana mass, which is defined as $m_{\beta\beta} = \sum U_{ej}^2 \cdot m_j$ - see also the box "The formalism of neutrino oscillation and masses". This experimental observable is different from the one in single beta decay essentially by the complex Majorana phases which appear in $m_{\beta\beta}$ but not in m_β. On the one hand, this feature can lead to cancellation effects in $m_{\beta\beta}$.. On the other hand this feature allows - at least in principle - to explore the CP violating Majorana phases. If a degenerate mass scheme was realized by nature, the CP phases could be explored by combining double beta decay with single beta decay experiments. In case that the inverse hierarchy was the true one, double beta decay experiments alone could give indications on the complex phases. An accurate knowledge of the nuclear matrix elements, which is not available at present, is however a pre-requisite for exploring CP phases. A measurement of m_β by single beta decay experiment together with a null observation in double beta decay experiment would point to a Dirac character of the neutrino. Thus, measurements of double beta decay and single beta decay are complementary approaches to reveal the particle anti-particle symmetry of neutrinos, their mass scale and possibly the CP violating Majorana phases.

An "enthusiastic renaissance"

Searches for double beta have been performed since the 1950s, but it was the discovery of neutrino oscillations which eventually led to a renaissance of the early enthusiasm and enormously boosted the existing efforts. Figure 3.6 shows how $m_{\beta\beta}$ is confined from existing data, showing the allowed regions in the plane spanned by $m_{\beta\beta}$ and the mass of the lightest neutrino mass eigenstate (m_1 or m_3, respectively). The bands for the inverted and the normal hierarchy are suggested by oscillation results. For the inverted hierarchy, m_3 would be the lightest mass state, and $m_{\beta\beta}$ would never drop below ~ 20 MeV, whatever the mass of m_3 is. The suggested region for this scenario would be $m_{\beta\beta}$ ~ (20-50) MeV, defining a benchmark for next generation experiments. For the normal hierarchy, the natural expectation is $m_{\beta\beta}$ ~ (1-4 MeV). However, cancellation effects could lead to smaller effective masses $m_{\beta\beta}$, even if the lightest mass state has m_1 > 1 MeV. Whatever the mass in a "normal scenario" may be: anything below $m_{\beta\beta}$ ~ 10 MeV is beyond present technologies. Cosmology tells us that the lightest mass state cannot be heavier than 0.2-1.0 eV. Present double-beta experiment place an upper limit of ~ 0.4 eV on $m_{\beta\beta}$. Note that both methods suffer from their own, characteristic uncertainties: the one from the cosmological framework itself which incorporates the existence of a hitherto speculative component (dark energy), the other from the uncertainties in the nuclear matrix element.

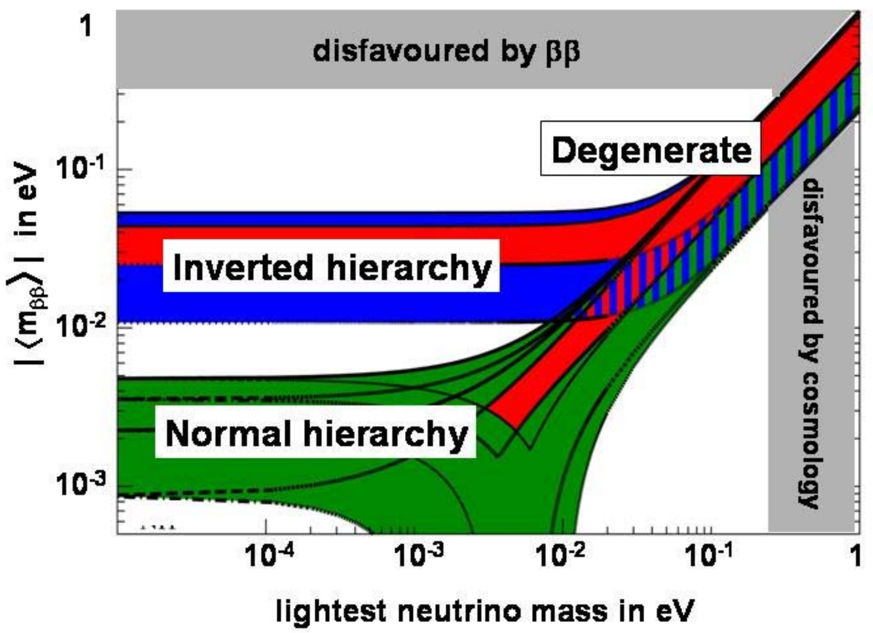


Figure 3.6: *Allowed effective neutrino mass vs. mass of the lightest mass state (adopted from S. Petcov). The different lines and colors for theoretical predictions correspond to various assumptions on CP violating phases.*

Various experimental approaches exist to search for double beta decay. In addition to the calorimetric technique, in which only the summed energy of the two electrons is measured, other approaches are running or are under study, aiming at measuring single electron spectra and angular distribution, or at identifying the daughter nucleus in addition to the two electrons. Different experimental approaches are required in order to reduce possible systematic uncertainties as well as experiment-specific backgrounds. The experimental situation in double beta experiments is the following:

Best present results

Best limits on the lifetime have been obtained by the ^{76}Ge semiconductor experiments Heidelberg-Moscow and IGEX, the one in the Gran Sasso Laboratory, the other in the Canfranc Laboratory:

HM: $T_{1/2} > 1.9 \cdot 10^{25}$ y, $m_{\beta\beta} < 0.33\text{-}0.84$ eV

IGEX: $T_{1/2} > 1.6 \cdot 10^{25}$ y, $m_{\beta\beta} < 0.36\text{-}0.92$ eV

The uncertainty in the mass limit reflects the limited knowledge on the nuclear matrix elements.

The KKGH claim

A subgroup of the HM collaboration (Klapdor-Kleingrothaus et al., KKGH in what follows) has claimed a positive effect from a re-analysis of their data, with $T_{1/2} \sim 1.2 \cdot 10^{25}$ y and $m_{\beta\beta} \sim 0.2$ -0.6 eV. Although this claim remains controversial, it provides an additional motivation for experiments with sensitivities in this mass range.

Running experiments

The largest running experiments are CUORICINO and NEMO-3. CUORICINO (Gran Sasso Lab) uses ^{130}Te as the double beta parent nucleus. It is an array of cryogenic bolometers of Tellurite crystals with a total mass of 41 kg (33.8% ^{130}Te) and is a first stage for CUORE conceived with a total mass of 740 kg. The main isotopes in NEMO-3 are ^{100}Mo (7kg) and ^{82}Se (1kg). NEMO-3 is a cylindrical detector with a central source foil sandwiched by tracking detectors and surrounded by a calorimeter in a 25 Gauss magnetic field and is located in the Fréjus laboratory. NEMO-3 is a stage on the way to the Super-NEMO detector, currently conceived to contain 100 kg ^{150}Nd or ^{82}Se. The sensitivities of both experiments are in the 0.5 eV range. These experiments could possibly confirm, but not fully disprove the KKGH claim.

Coming soon...

The European next-stage detectors are GERDA, CUORE and Super-NEMO. GERDA is being set-up in Gran Sasso and uses Germanium detectors enriched in ^{76}Ge, 18 kg in a first and about 40 kg in a second phase. They will scrutinize the KKGH claim starting in 2008, and will reach a sensitivity $T_{1/2} > 2 \cdot 10^{26}$ y and $m_{\beta\beta} < 0.1\text{-}0.3$ eV targeted for 2010. Depending on the physics results, a third phase using 500 to 1000 kg of enriched germanium detectors is planned merging GERDA with the US lead Majorana collaboration. The start of CUORE operation is scheduled for 2011, reaching a final sensitivity of 0.05-0.1 eV. Super-NEMO will finish a phase of design study in 2008 and projects the completion of the full detector in 2012 with 100 kg of ^{150}Nd or ^{82}Se. Its final sensitivity will be in the range 0.05–0.2 eV. All three experiments can prove or disprove the KKGH claim. Their motivation, as well as ultimate goal is to start the exploration of the parameter range predicted by the inverted mass hierarchy. This endeavour will commence at the beginning of the next decade.

R&D on Cadmium

It is not excluded at this point that an innovative European approach, COBRA, will join the competition. COBRA uses dominantly ^{116}Cd and ^{130}Te isotopes. A detector array of 64 CdZnTe semiconductor devices with a mass of about 0.5 kg has been installed in the Gran Sasso laboratory. Work towards a large scale detector is ongoing, and a Conceptual Design Study is expected in 2010.

Outside Europe

At this point, two large experiments located in the USA with similar sensitivity and a fourth innovative European approach have to be mentioned: EXO will use ^{136}Xe isotopes in a Time Projection Chamber filled with liquid enriched Xenon, 200 kg in a first stage. Neuchatel is the one European EXO collaborator. EXO-200 would address a similar mass range as CUORICINO and NEMO-3. For a later one-ton version, a 0.03 eV sensitivity is claimed. MAJORANA, in a first stage, is planned to contain 120 kg enriched Germanium and to reach a 0.06-0.2 eV sensitivity after three years running. A further large scale experiment which can be realised on an intermediate time scale is SNO++, a follow-up experiment of the Sudbury Neutrino Observatory, with ^{150}Nd-loaded scintillator going to replace the present heavy water filling. For this to happen, enriched ^{150}Nd and the corresponding enrichment facilities are required. (Such facilities might be mandatory for all very large scale experiments). Further activities are ongoing in Japan, especially MOON (investigating ^{100}Mo) and CANDLES (^{48}Ca). A compilation of experimental approaches is given at the end of this section.

A substantial coverage of the “inverted hierarchy” region would be achieved in the following stage. This stage requires detectors with an active mass of the order of one ton, good energy resolution and background levels which are several orders of magnitude below the present state-of-the-art. The physics capability of these large-scale experiments has to be investigated in detail, using the experience in background suppression gained with the detectors to be built over the next five years. This includes the exploration of innovative background reduction techniques like measurement of heat/light plus ionisation and event localization in crystal detectors. One also has to take into account the progress in the determination of mixing parameters in oscillation experiments and the progress in the knowledge of nuclear matrix elements. Different nuclear isotopes are necessary to minimize the impact of uncertainties in matrix elements to the extracted mass values; different experimental techniques will help to establish the effect. On the other hand, the price tag of the order of 50-200 M€ per experiment sets a natural limit of about three one-ton experiments worldwide. Figure 3.7 sketches a possible scenario. Here, a joint effort of GERDA and MAJORANA towards 500-kg active mass is assumed; further a CUORE version with enhanced capabilities, through enriched isotopes or just by larger mass; a one-ton EXO detector; and some other approach like e.g. COBRA or a Super-NEMO+ tracking-calorimeter detector. Decisions on the favoured one-ton detectors, with sensitivity down to 20 MeV, would be taken between 2013 and 2015. Europe is currently leading the field in double beta decay and is in the strategic position to play a major role in these follow-up experiments.

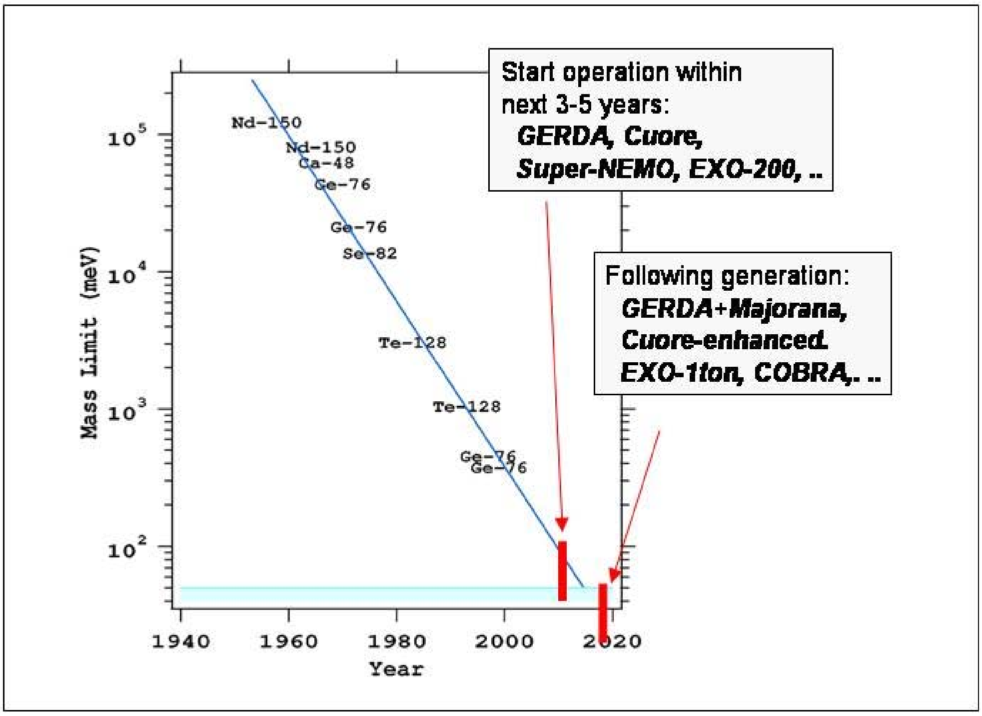


Figure 3.7: *A possible scenario for improvement of the mass sensitivity of double beta experiments (figure adopted from Elliot and Vogel).*

Crucial: isotope enrichment

Isotope enrichment will have a large impact on the cost of future experiments. The production of a large amount of isotopes is possible though ultra-centrifugation, laser separation (AVLIS) or Ion Cyclotron Resonance (ICR) techniques. The centrifugation technique allows to enrich isotopes like ^{76}Ge, ^{130}Te, ^{82}Se, ^{100}Mo, ^{116}Cd. Facilities exist in Russia. The AVLIS process, based on the ionization of the isotope through a laser, has been used for uranium enrichment with the MENPHIS facility in France. This facility could allow enriching ^{150}Nd and producing hundreds of kilograms of enriched neodymium. The ICR method based on the isotopic separation in a plasma through electric and magnetic fields allows enriching isotopes like ^{48}Ca or ^{150}Nd. A prototype built by CEA (France) has shown the feasibility of such a facility. A Design Study should be done for a large production (100kg) with the ICR technique.

Nuclear matrix elements

We finally reiterate the importance of assessing and reducing the uncertainty in our knowledge of the corresponding nuclear matrix elements, experimentally and theoretically as well as the importance of studying alternative interpretations of neutrino-less double beta decay such as those offered by super-symmetry. This requires a program as vigorous, although not as expensive, as construction of the double beta detectors itself.

Name	Nucleus	Method	Location	European Members	Others
Running experiments					
CUORICINO	^{130}Te	bolometric	LNGS	IT, NL, ES	US
NEMO-3	^{100}Mo ^{82}Se	tracko-calo	LSM	FR, CZ, UK ES, FIN	US, RU, JP
Construction funding					
CUORE	^{130}Te	bolometric	LNGS	IT, NL, ES	US
GERDA	^{76}Ge	ionization	LNGS	DE,BE,IT,PO	RU
Substantial R&D funding					
EXO	^{136}Xe	tracking	WIPP	CH	US, RU, CAN
SuperNEMO	^{150}Nd or ^{82}Se	tracko-calo	LSC or LSM	FR,CZ,UK, SK, PL, ES, FIN	US,RU, JP UKR
R&D and/or conceptual design					
CANDLES	^{48}Ca	scintillation	Oto Lab	-	JP
CARVEL	^{48}Ca	scintillation	Solotvina	-	UKR, RU, US
COBRA	^{116}Cd, ^{130}Te	ionization	LNGS	UK, DE, IT, PO, SK	US
DCBA	^{150}Nd	tracking	t.b.d.	-	JP
MAJORANA	^{76}Ge	ionization	SNOLAB or DUSEL	-	US
MOON	^{100}Mo	tracking	t.b.d.	-	JP
SNO++	^{150}Nd	scintillation	SNOLAB	-	CAN, US + …
other decay modes					
TGV	^{106}Cd	el. capture, running	LSM	FR, CZ	RU

Table 3.2: *Compilation of running or proposed experiments to search for neutrino-less double beta decay. Other experimental concepts have been discussed in the literature and are not listed here. Abbreviations for European Labs: LNGS – Gran Sasso/Italy, LSM – Frejus/France, LSC – Canfranc/ Spain.*

4. Neutrinos from the Sun, Supernovae and the Earth

4.1 Introduction

Low energy neutrinos, both natural and man-made, are produced in many sources, among them the core of the Sun, Supernova explosions, the Earth's interior and artificial nuclear reactors. The study of these neutrinos gives information both on the source dynamics and on the properties of the neutrinos themselves.

Low energy neutrinos from the Sun

Most of the heat generated in Stars comes from nuclear reactions occurring in its core. Neutrinos are emitted during this process. Solar neutrino experiments have therefore played a fundamental role in the development of stellar models (in the case of our Sun, the theory is called the Standard Solar Model) and in the understanding of the mechanism of energy production in Stars. In addition, detection of solar neutrinos has provided the first evidence that neutrinos can change flavour from their production in the Sun to their detection on Earth. A direct proof of the validity of the standard solar model has recently been unequivocally demonstrated by the SNO experiment.

Neutrino oscillations

The solar neutrino results can be explained by the assumption that the change in flavour is produced by neutrino flavour oscillations between the production and the detection points. Neutrino oscillations are a quantum-interference phenomenon that can take place provided that the mass eigenstates of the neutrinos have non-degenerate masses and that the flavours, in which the neutrinos are produced, do not coincide exactly with the physical states (this is called mixing between lepton flavour and physical states and was known to happen in the case of quarks.). Neutrino oscillations are explained in the section of Particles Properties.

Recent data obtained with the KamLAND experiment, detecting neutrinos emitted from nuclear reactors, has given further evidence for the neutrino oscillation hypothesis.

Although formidable progress has been achieved in the last 30 years, there is still much to be learned from the study of solar neutrinos: about the Sun and about neutrino oscillations, as explained in section 4.2.

Low energy neutrinos from Supernovae

The life of stars heavier than about eight solar masses ends when their nuclear fuel is exhausted and their cores collapse. This implosion suddenly ends when the core reaches nuclear density and a shock wave is formed. This wave is thought to eject the outer layers of the star. The huge amount of the binding energy of the collapsed core is emitted in the form of neutrinos and anti-neutrinos of all flavours in an stage called the "cooling phase". It is thought that the energy which is deposited by neutrinos behind the shock wave is essential for a successful explosion.

In 1987 the neutrinos emitted in the SN 1987A supernova were detected for the first time, an achievement that was recognized with the Nobel Prize. A handful of neutrino interactions were recorded by three detectors around the world: IMB (USA), Kamiokande (Japan) and Baksan (USSR). In 1987, the Super-Kamiokande detector has been brought into operation and with currently planned detectors it would be possible to detect, and better study, neutrinos from a galactic explosion, were it to occur today. The detailed studies achievable with new large, and/or of new types of, detectors could provide fundamental information to understand the explosion dynamics, something difficult to accomplish by other experimental means, as well as revealing the nature of the neutrino mass ordering. Supernova physics with neutrinos is addressed in section 4.3.

Low energy neutrinos from the interior of the Earth

In 2005 KamLAND has also detected, for the first time, neutrinos originating in the Earth's interior (see section 4.4). The study of these neutrinos can shed light on the radioactive processes occurring in the Earth's interior and believed to be responsible for the energy produced by the Earth, which is presently estimated at a colossal power of about 40 TW (equivalent to about 40,000 nuclear power plants). The KamLAND observations open a new field, the study of Earth dynamics with neutrinos. It will be very important to understand the location of the production of neutrinos in the Earth (core, crust, …) and the energy spectrum which may lead to information on the elements producing this heat.

Figure 4.1 gives an overview of neutrino fluxes from natural and artificial sources, ranging from the thermal background at 1.9 Kelvin left over from the Big Bang, to extremely high energy (PeV) neutrinos expected from extragalactic sources such as active galactic nuclei and to the GZK (Greisen-Zatsepin-Kuzmin) neutrinos. Also shown are solar neutrinos, a background of MeV scale neutrinos from all cosmological supernovae, a typical flux expected from a Galactic supernova, geo- and reactor neutrinos and neutrinos above tens of MeV produced by cosmic rays interacting in the Earth's atmosphere. The very high-energy, non-thermal neutrinos are discussed in section 5.

Towards next generation large underground detectors

The discoveries listed above have been made with detectors deep underground. The era of large underground detectors has produced an extremly rich harvest of discoveries. This triumphal legacy is intended to be continued by one or several multi-purpose detectors on the mass scale of 100-1000 ktons. The physcis potential of a large multi-purpose facility would cover a large variety of questions:

1) The proton decay sensitivity would be improved by one order of magnitude (see section 3.3).
2) A galactic Supernova would result in several ten thousands of neutrino events which would provide a incredibly detailed information on the early phase of the Supernova explosion (see section 4.3).

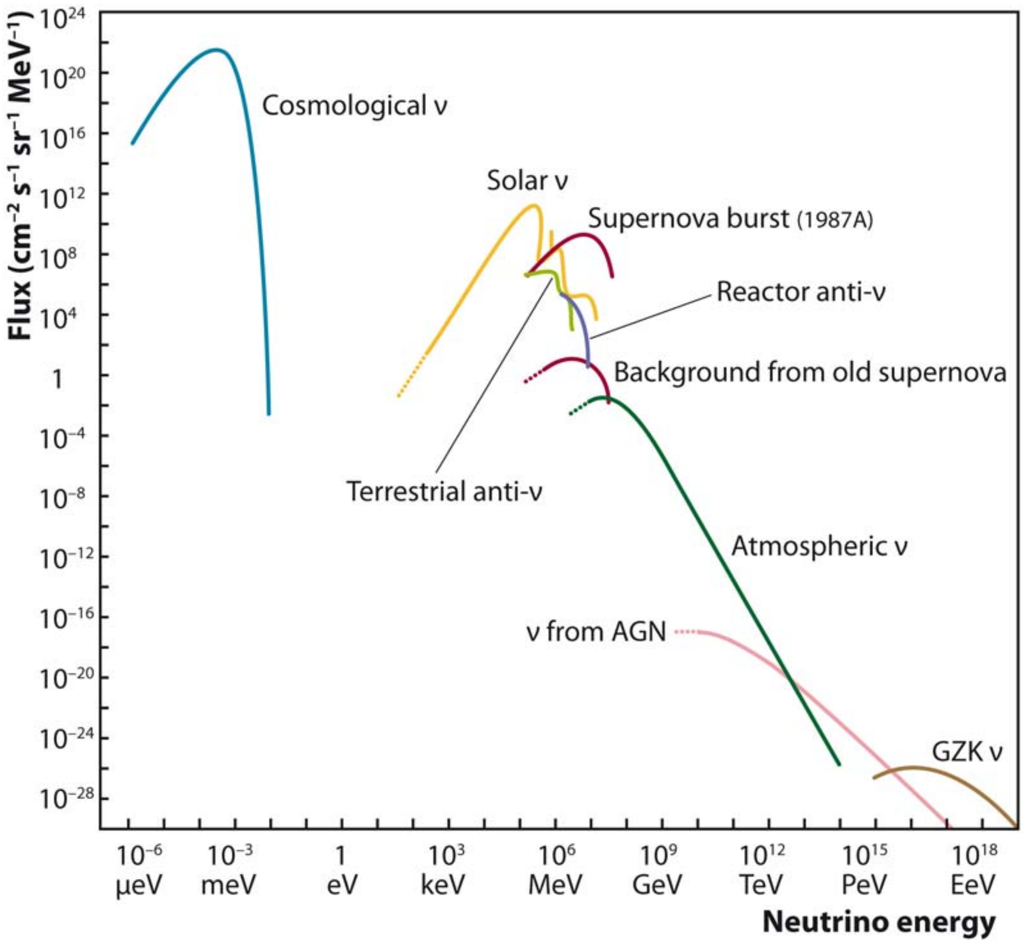


Figure 4.1: *The "grand unified" neutrino spectrum. Solar neutrinos, burst neutrinos from SN1987A, reactor neutrinos, terrestrial neutrinos and atmospheric neutrinos have been already detected. Another guaranteed although not yet detected flux is that of neutrinos generated in collisions of ultra-energetic protons with the 3K cosmic microwave background (CMB), the so-called GZK (Greisen-Zatsepin-Kuzmin) neutrinos. See for AGN and GZK neutrinos section 5.4. Whereas GZK and AGN neutrinos will likely be detected in the next decade, no practicable idea exists how to detect 1.9 K cosmological neutrinos (the analogue to the 3K CMB).*

3) The diffuse flux from past supernovae would probe the cosmological star formation rate (see section 4.3).
4) The details of the processes in the solar interior can be studied with high statistics and the details of the Standard Solar Model determined with percent accuracy (see section 4.2).
5) The high-statistics study of atmospheric neutrinos could improve our knowledge on the neutrino mass matrix and provide unique information on the neutrino mass hierarchy (see section 3.4).
6) Our understanding of the Earth interior would be increased by the study of geo-neutrinos (see section 4.4).

7) The study of neutrinos of medium energy from the Sun and the center of the Earth could reveal signs for dark matter (see section 3.2).

8) Last but not least, a large underground detector could detect artificially produced neutrinos from nuclear reactors or particle accelerators, over a long baseline between neutrino source and detector. For instance, in combination with a beta-beam or a neutrino superbeam from CERN, a large undergroud detector in the FREJUS laboratory could improve the sensitivity to $\sin^2\theta_{13}$ by 1.5-2 orders of magnitude and that for CP violation by one order of magnitude. Looking into the far future, a neutrino factory could serve as neutrino source, allowing for an improvement of three orders of magnitude in $\sin^2\theta_{13}$ and of two orders of magnitude on CP violation (not discussed in detail in this roadmap).

Multi-purpose facilities for proton decay and neutrino astrophysics will be described in section 4.5.

4. 2 Solar neutrino experiments

Solar neutrinos

Solar neutrino experiments were originally proposed to study the processes responsible for solar energy production, believed to be nuclear fusion reactions taking place in the core of the Sun where the temperature is about 10 million degrees, with pressures about 340 billion times the Earth's atmospheric pressure at sea level. A large fraction of the energy produced in these nuclear reactions heats the matter in the core. Because of the size of the Sun, changes in the energy in the core would be reflected on the surface, with its 6000 degrees temperature, only after many thousands of years. The neutrinos however, can directly escape from the core essentially unaffected, reaching the surface within two seconds and from there the Earth in about 8.5 minutes. An astonishing number of solar neutrinos reach the Earth: of the order of 6×10^{10} neutrinos per square centimetre per second. But owing to the very small interaction cross-section, detecting these neutrinos is difficult. The experiments have to be very large to increase the probability of detection, and shielded from the radiation induced by cosmic rays. Natural radioactivity also imposes limitations on the energy of the detectable solar neutrinos, which have to be separated from that due to the natural radioactive background.

Solar neutrino oscillations

Early solar neutrino experiments observed that the number of neutrinos detected was smaller than that expected from solar models. Over the years many experiments observed this deficit, sometimes with seemingly contradicting results. Today we understand that the deficit is due to the change of flavour, from the electron flavour, as they are produced, to muon and tau flavours. Most detectors are not sensitive to the interactions of the latter, giving rise to the apparent deficit. It was not until the year 2001, with the start of the SNO detector, that the interactions of the three neutrino species coming from the Sun were detected, with the result that the sum of the fluxes of the three kinds of neutrinos was in agreement with the expectations of the solar model.

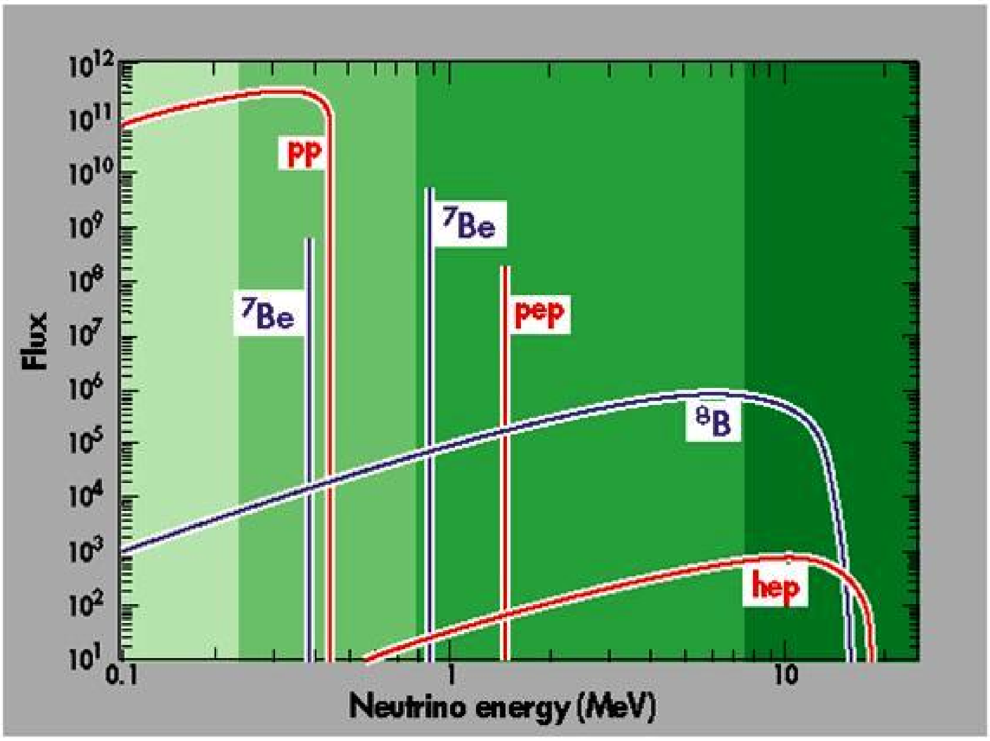


***Figure 4.2**: The solar neutrino flux (following J.Bahcall). The coloured areas indicate the detection threshold for water Cherenkov detectors (~7 MeV), the Cl-Ar Detector (~ 1 MeV) and Ga-Ge detectors (233 keV), respectively). Neutrinos generated in the pp reation have been detected only by Ga-Ge detectors. Water Cherenkov detectors detect exclusively ^{8}B neutrinos (the hep contribution being negligible).*

Solar neutrino data, when interpreted assuming that oscillations take place, also constrain the values of the oscillation parameters. The solar neutrino results have been analyzed together with those obtained in the study of atmospheric and reactor neutrinos. The observed flavour oscillation of solar neutrinos must be additionally affected by a mechanism predicted by Mikheyev, Smirnov and Wolfenstein. In this effect, the electrons in the Sun bring the effective energy of electron neutrinos closer to that of muon and tau neutrinos, which enhances the oscillation probability with respect to that in vacuum. This enhancement depends on the neutrino energy. In the Sun, more than 90% of the neutrinos are produced in the fusion of two Hydrogen nuclei into a Deuterium nucleus ($p + p \rightarrow d + e^+ + \nu$), the so called p-p reaction, for which the energy of the neutrino is at most 0.42 MeV, see Figure 4.2. For these energies the neutrinos have been observed by two experiments, SAGE in the Baksan Laboratory and GALLEX/GNO in Gran Sasso. It is believed that for these neutrinos the oscillation is not strongly affected by the MSW effect but is close to the vacuum case. The transition from vacuum to MSW dominated oscillation is expected to take place around 1 to 2 MeV. The transition will result in a strong change in the survival probability of electron neutrinos. Observation of this effect is a strong motivation for a low energy experiment (sensitive to p-p neutrinos) in the future. Such an experiment would also improve the measurement of the oscillation parameters. These motivations are quantified below.

Solar neutrinos and solar astrophysics

In addition to the study of oscillations, a solar neutrino experiment can be devoted to the original purpose of solar neutrino experiments, namely the study of solar astrophysics. As it is explained by J. N. Bahcall and C. Peña-Garay (hep-ph/0305159), assuming that the luminosity of the Sun is indeed due to the fusion reactions as implemented in the Standard Solar Model, the present neutrino data already constrain the flux coming from the different fusion reactions to a considerable accuracy. This is because each of the reactions entering the model produces a known amount of energy, in addition to neutrinos. This energy is radiated from the Sun's surface as light, and therefore the total solar luminosity of the Sun is directly correlated to the neutrino fluxes from the different reactions. The analysis by J. N. Bahcall and C. Peña-Garay shows that the ratios of measured to expected fluxes are already determined (at 1 sigma) to 2% for the p-p flux, 40% for the ^{7}Be flux and 6% for the ^{8}B flux.

But one would like to check whether the energy production reactions actually taking place in the Sun are consistent with the Standard Solar Model. For this one would like to infer the solar photon luminosity from the measured neutrino fluxes. Such a comparison will also test the prediction of the Standard Solar Model that the Sun is in a steady state, that is, that the rate of energy generation in the core is equal to that radiated through the solar surface.

The global analysis mentioned above gives a ratio of the neutrino-inferred to the well known photon luminosities (at 1 sigma) of

$$\frac{L_{neutrino-\inf erred}}{L_{photons}} = 1.4^{+0.2}_{-0.3}$$

When the photon luminosity is not used as a constraint, the neutrino experiments alone only measure the p-p flux to ±22%, while the ^{7}Be flux is determined to about 40%. The ^{8}B flux determination is similar whether or not the luminosity constraint is used. This is due to the fact that the ^{8}B reaction contributes only a very small fraction to the energy production in the Sun. These numbers change significantly depending on which solar experiments are included in the analysis. Clearly, there is room for improvement on the measurement of the neutrino fluxes.

The ^{7}Be flux is not very well constrained. In the future one can expect a measurement of the ^{7}Be neutrinos by the BOREXINO experiment, through the neutrino-electron scattering reaction. If this rate is measured to ±10% (5%), the uncertainty in the ^{7}Be neutrino flux will be reduced by a factor 4 (7). In addition it will improve the determination of the p-p flux by a factor of about 2.5 (4). BOREXINO also aims measuring the p-e-p flux with with 5-10% accuracy. This would translate to the same accuracy for the p-p flux since the ratio of the production rates of p-e-p and p-p neutrinos can be calculated accurately, without model constraints. The improvement on the oscillation parameters will not be significant with respect to the expected improvement resulting from three additional years of KamLAND data. With this expected data, the uncertainty in the solar Δm^2 is expected to be reduced by at least a factor of 2 (at 1 sigma) with respect to the current measurements. BOREXINO is an experiment based in Europe, and, together with SNO (Canada) and SAGE (Russia), it is the only dedicated solar neutrino experiment in the world. We strongly recommend that this experiment is completed and starts taking data.

Future solar neutrino experiments

Since the p-p reaction dominates the neutrino and energy production in the Sun, an accurate measurement of the p-p flux will allow the determination of the solar luminosity from neutrino data alone. The real time detection and spectral measurement of the neutrinos produced in the p-p reaction will be the ultimate test of the solar model. As stated above the p-p neutrinos are in the energy range where vacuum oscillations dominate over matter effects. Their observation will therefore also provide a stringent test of our present ideas on oscillations. To improve oscillation parameters, namely $\tan\theta_{12}$, it is necessary to reach an accuracy of ±3% in the p-p flux. A 5% measurement of the p-p flux will improve the knowledge of the neutrino solar luminosity by a factor of 3 with respect to that expected in the future from three additional years of KamLAND and from a 5% measurement of the ^{7}Be neutrino-electron elastic scattering rate.

Precision of a few percent requires calibration with a high-intensity artificial source. The ^{51}Cr source used in GALLEX seems well suited for this purpose. By irradiation of the existing source, an activity of the order of 92 PBq (2.5 MCi) can be reached, with the activity known with 2% accuracy.

An experiment able to measure the p-p neutrino energy distribution would be difficult. It has been pointed out that one could instead measure the p-e-p mono-energetic neutrinos at 1.4 MeV, since the ratio of the production rates of p-e-p to p-p neutrinos can be calculated accurately. Such is the objective of the LENA proposal (see section 4.5).

4.3 Geo-neutrinos

Neutrino production in the Earth: geo-neutrinos

Unique information on the interior of the Earth can be obtained by the detection of electron antineutrinos coming from radioactive decays of unstable nuclei in its interior. These are known as geo-neutrinos. Direct information on the Earth's interior is limited at present to about 10 km, which is the maximum depth of holes that can be drilled with present technology. This is of course negligible compared with the Earth's radius of approximately 6300 km.

It is known that the Earth emits heat at a rate of approximately 40 TW. It is believed that this heat is emitted through natural radioactivity of material inside the Earth, namely of Uranium (U), Thorium (Th) and Potassium (K). The same radioactive decays are believed to be the source of the geo-neutrinos. The most accepted model of the Earth composition is the so called Bulk Silicate Earth Model (BSE). This model is built from the direct observations of the Earth crust, of material emerging from the Earth's interior such as the Mid Ocean Ridge Basalts and Ocean Island Basalts, and of the composition of old meteorites, assumed to be similar to the composition of the original planetesimals. Within this model one can estimate the amount of U, Th, and K in the Earth, believed to be concentrated in the crust and the mantle (r>2,900 km). Different estimates agree within 10%. However, the radiogenic heat production from these elements is only about one half of the total measured heat output quoted above. The measurement of geo-neutrinos can in principle test the BSE hypothesis.

KamLAND: first eVidence for geo-neutrinos

The KamLAND experiment has recently published the first evidence of geo-neutrino production. KamLAND detects antineutrinos by the inverse beta-decay process in a liquid scintillator detector. Only neutrinos from the ^{238}U and ^{232}Th decay chains can be detected, those of ^{40}K being below the energy threshold of the inverse beta decay reaction. The result of KamLAND is $N(U+Th)=28^{+16}_{-15}$ events detected in a period of 749 days. This number is obtained from the observation of 152 counts after subtraction of the background from reactors, α-particles and other processes. To infer from this number the produced radiogenic heat one needs models of the distribution of U and Th in the Earth's crust and mantle. Considering a wide variety of geological models, Fiorentini et al. obtain the heat production $H(U+Th)=38^{+35}_{-33}$ TW with a 99% confidence upper bound of $H(U+Th)<162$TW, considerably less restrictive than that obtained by the KamLAND collaboration itself $H(U+Th)<60$TW, using a more restricted variety of geological models.

The rate of geo-neutrinos on the Earth's surface is strongly affected by the distribution of radiogenic elements in the mantle. In one class of models the Earth's mantle consists of two main layers with a boundary at a depth of 670 km. The upper layer has lower concentration of U, Th and K. In another class of models it is believed that the material in the mantle circulates. The model is based on the evidence that there are cold slabs of the mantle which extend deep into the hotter lower region, which would imply a compensation of hotter regions ascending to near the surface. Since the total amount of U, Th and K is fixed by the BSE model, the predictions for the total neutrino flux arriving at a detector from distant sources is quite robust, fixed within ±15%. The above authors conclude that a five-kiloton detector operating over four years at a site relatively far from nuclear power plants can measure the geo-neutrino signal with a 5% accuracy (at one sigma).

BOREXINO vs. KamLAND

BOREXINO is the next following experiment which will measure geo-neutrinos.
Compared to KamLAND, it is farer away from nuclear plants, and the signal itself will be comparable to the background of antineutrinos from reactors (expected signal-to-noise ~1). In KamLAND, the background for geo-neutrinos is presently dominated by antineutrinos from nuclear reactors and by neutrons induced by α-particles. The latter is due to impurities in the liquid scintillator which is planned to be removed for the second phase of the experiment. The geo-neutrino signal of 28^{+16}_{-13} events in KamLAND is based on about 400 tons of target mass and two years of live-time, with a signal-to-noise ~0.17. With a 3-year live-time BOREXINO could measure a geo-neutrino signal with an accuracy of 30%.

With the present scintillator purity in KamLAND, the BOREXINO design sensitivity and that of KamLAND would be comparable if in KamLAND the target mass were increased to 1 kton. *After* the planned purification, the signal-to-noise in KamLAND is estimated to be ~0.26, mainly due to nuclear reactors. Provided successful purification, the two sensitivities would then be comparable if KamLAND's target mass were ~ 700 tons instead of the actual 400 tons.

If directional information on the antineutrino flux can be obtained, a spatial distribution of the natural radioactivity in the interior of the Earth could be derived. Scaling the experimental result from KamLAND to LENA yields an event rate in the range between $4{\cdot}10^2$ and $4{\cdot}10^4$ per year for the location in Pyhäsalmi in Finland (continental crust).

Clearly, the observation of geo-neutrinos is a new field. Neutrinos, with their enormous penetrating power are a unique tool to learn about the Earth interior.

4.4 Neutrinos and type-II Supernovae

Stars substantially more massive than the Sun end their life through spectacular stellar explosions known as core collapse supernovae. Supernovae are among the most violent phenomena in the universe. Most of the elements between Oxygen and Iron and more than half of the elements heavier than Iron are believed to be produced in these explosions.

Massive stars: from birth to death

Stars begin their life when enormous clouds of primordial gas (mainly Hydrogen, with some Helium and traces of heavier elements) are compressed by gravity strongly enough to reach temperatures above that needed for the fusion of two protons into Helium. Once the first fusion takes place the temperature rises and the fusion of Hydrogen into Helium continues, reaching a state of thermal and hydrostatic equilibrium. Eventually all the Hydrogen in the core gets exhausted and the core compresses further to reach temperatures where fusion of Helium into Carbon can take place. The process continues with heavier and heavier elements, until Iron. Iron is the most stable of all nuclei and any fusion or fission process in which it intervenes will absorb, rather than produce, energy. As a consequence the core begins to contract and the temperature in the central region increases. The dissociation of iron and the neutronization of free protons by electron capture, with the emission of neutrinos, cool the core in a runaway fashion resulting in an implosion, or core collapse. As the central core reaches the density of nuclear matter, the implosion stops and rebounds creating a shock wave that propagates outwards, forming a shock front with the in-falling matter. This shock wave propagates out of the iron core and through the successive stellar layers of increasingly lighter elements, ultimately producing the supernova. Neutrinos play a fundamental role in these events. The shock wave would stagnate, were it not for the neutrinos heating it from behind the shock. It is through the neutrinos that the enormous gravitational energy released in the collapse is transferred to the explosion which itself constitutes only roughly one percent of the binding energy that is mostly released in form of neutrinos.

Neutrinos as a unique tool

The observation of neutrinos released in the various stages of the explosion will provide direct information about the dynamics at the centre of the Supernova and therefore of the explosion mechanism. Neutrinos are in fact a unique tool to study the central region of the star, and hence of nuclear matter in the extreme state of temperature and density encountered in the Supernova core. Realistic models of SN physics have to include turbulent fluid flow, rotating nuclear matter, strong magnetic fields and strong (general relativistic) gravitational fields. At present the models are not entirely satisfactory, owing probably to the complexity of the processes involved. Experimentally only a handful of Supernova neutrinos have been observed, and only from one supernova, known as SN 1987A, situated at 50 kpc distance in a satellite galaxy of the Milky Way. The observation with present detectors of a supernova within our own Galaxy would provide much more information.

The four phases of neutrino emission in supernovae

Neutrinos are expected to be emitted in four phases (Figure 4.3): (1) during the core collapse and rebound. These are neutrinos produced in the electron capture by protons as the core collapses. This phase only lasts a few milliseconds. Not all the neutrinos produced in the collapse are emitted. In fact most are trapped by interactions with nucleons inside the core, within the so called neutrino sphere. (2) A few milliseconds after the core bounce. The neutrino emission has a strong peak, which is produced when the supernova shock wave breaks through the neutrino sphere, dissociates iron and therefore allows rapid electron capture by protons, causing a de-leptonization of the outer core layers. (3) The shock wave stagnates, being sustained, and eventually exploding, by neutrino heating. During this phase the neutrino emission is powered by the accretion of matter. The three neutrino species, as well as the corresponding antineutrinos, are produced in this phase that lasts several hundreds of milliseconds. (4) The Kelvin-Helmholtz cooling phase of the proto-neutron star, which occurs over a period of about 10 s. During this time the supernova explodes and the proto-neutron star cools to form a neutron star or a black hole. During this phase all three flavours of neutrinos, and their antineutrinos, are produced thermally. If a neutron star is formed the emission of neutrinos continues for a long time of 10 to 100 seconds. The energy of the neutrinos varies in the range between 5 and 25 MeV.

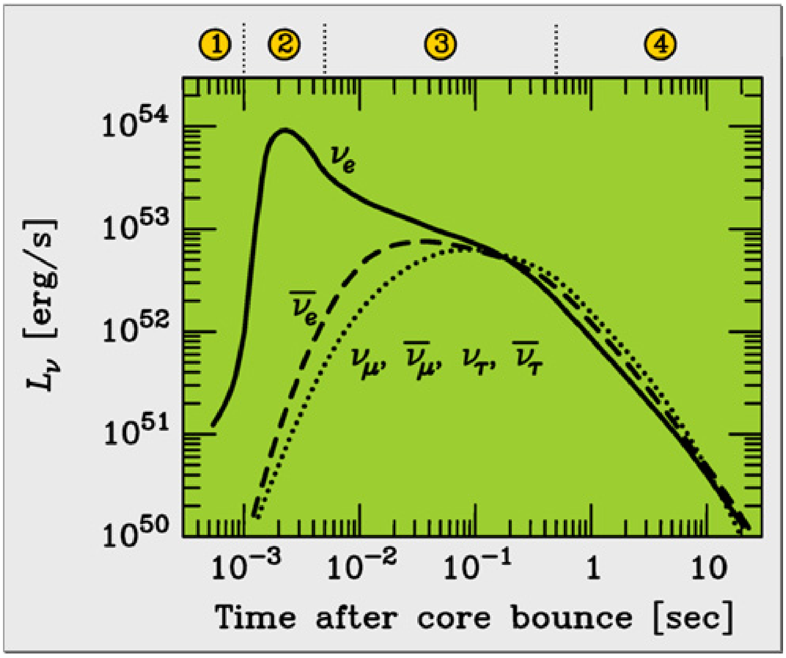


Figure 4.3: *Supernova neutrino emission "light curves" for different neutrino flavours (figure taken from R.Raffelt).*

The observation of neutrinos from these different phases will shed light on the Supernova explosion mechanism and also on neutrino oscillation physics, as demonstrated in Figure 4.4.

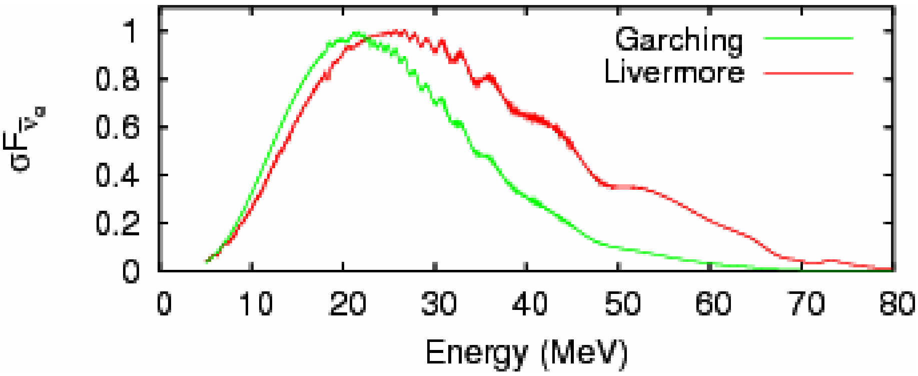


Figure 4.4: *Observable electron anti-neutrino flux from a core collapse supernova, predicted by two different numerical simulations:. The flux oscillates as function of energy as a result of multiple MSW resonances with anti-tau-neutrinos occurring around the position of the shock about 5 seconds after core bounce. Measuring such time dependent spectra from a future Galactic supernova with sufficient statistics would allow both to learn more about neutrino mixing parameters, especially θ_{13}, and the density profile around the shock. Such statistics could be achieved by projects such as LENA or a megaton class detector (see section 4.5).*

The neutrinos emitted will pass through regions spanning an enormous range of densities and will oscillate through resonant matter effects. Depending on the sign of the mass difference, the resonant oscillation occurs in the electron neutrino or antineutrino channel. Water Cherenkov detectors are sensitive to electron antineutrinos through the inverse beta decay reaction, although neutrinos (and their direction) can also be measured by means of elastic scattering. In a detector using scintillator as a target such reactions could be very well studied, with a clearer positron-neutron capture signature not accessible in pure water. Another option to study supernova neutrinos in detail is with a large liquid Argon Time Projection Chamber: a liquid Argon detector would be specially sensitive to electron-neutrinos and therefore very complementary to the two options described above. It would also provide invaluable information on the initial electron neutrino burst, directly related to the neutronization of the collapsing star. Liquid scintillator and liquid Argon detectors would also be able to cleanly detect neutral current events. For instance, BOREXINO, with a threshold as low as 200 keV, would record ~50 neutral current events from muon and tau neutrinos (assuming a standard supernova at 10 kpc distance). The rate of such events is not affected by neutrino oscillations and hence would provide direct information on the supernova explosion mechanism independent of the neutrino intrinsic properties and would therefore provide a direct probe into the supernova explosion mechanism. Alternatively, the independent detection of electron neutrino and antineutrinos, and of the neutrino of other flavours will shed light on neutrino oscillations via the resonant conversion in the supernova matter.

Neutrino mass from SN signals

Correlations between neutrino energy and arrival time will yield information on the absolute mass of the neutrino, e.g. for Super-Kamiokande and a supernova at the center of the Galaxy at the sensitivity level of 1 eV (compared to ~25 eV in the case of SN-1987A). Low-threshold detectors like BOREXINO or a liquid Argon detector may provide another piece of information: an apparent difference in the arrival times of charged-current ν_e events versus neutral-current muon/tau neutrinos would reflect the corresponding mass *differences*.

The early warning system SNEWS

The neutrino signal emerges promptly from a supernova's core, whereas it may take hours for the first photons to be visible. Therefore the detection of the neutrino burst from the next Galactic supernova can provide an early warning for astronomers. There are several neutrino detectors world-wide – running or close to completion – which are sensitive to a core collapse supernova neutrino signal in the Galaxy. From the coincidence of neutrino signal in several of these detectors, a reliable early warning can be derived and sent to the astronomical community. This is the objective of the SNEWS (SuperNova Early Warning System) project, which involves an international collaboration of experimenters representing several of the current supernova neutrino detectors shown in Fig. 4.5. In the future, SNEWS will involve also gravitational wave detectors. The goal of SNEWS is to provide the astronomical community with a prompt alert of the occurrence of a Galactic core collapse event and enable optical observation of the early phases of the Supernova. It is very likely that also a raw directional information could be provided, either by the directionality of elastic scattering events in large water detectors, or by triangulation, i.e. by deriving the direction from the different neutrino arrival times at different sites on the Earth.

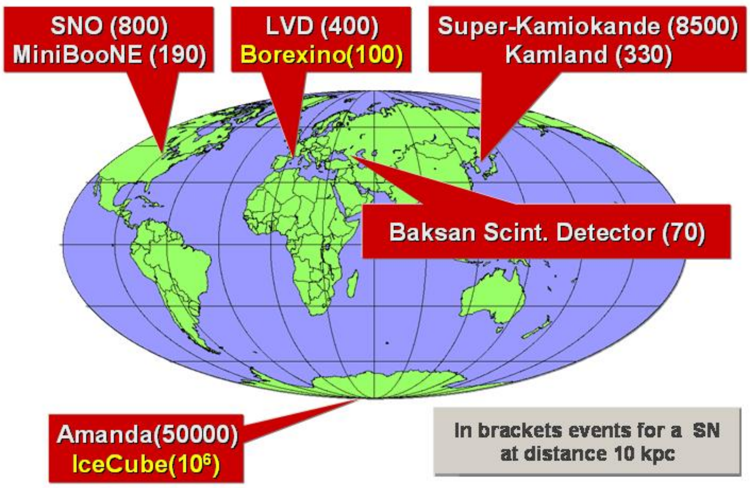


Figure 4.5: *The figure shown the location of underground and under-ice neutrino detectors with significant supernova detection capability (following a compilation of G.Raffelt). At present, only Super-Kamiokande, KamLAND, LVD and AMANDA participate in the SNEWS project. SNEWS intends to provide an early warning system of a galactic core-collapse supernova. Note that AMANDA/IceCube record only increased counting rates, not individual events. IceCube will operate its SN trigger from early 2007, Borexino will join in 2007 or 2008. SNO has been shut down in 2006 but likely will be replaced by SNO++.*

4.5 Next generation multi-purpose neutrino detectors

A rich legacy

The successful detection of neutrinos from the supernova SN-198A by the Kamiokande detector (Japan) has opened the field of neutrino astronomy and has been recognized with the Nobel Prize in 2002. Actually, it opened a 20-year long tradition of incredibly rich physics with large underground detectors, including solar physics, the discovery of non-vanishing neutrino masses by studying solar and atmospheric neutrinos, and the confirmation of these results by detecting reactor neutrinos and accelerator neutrinos in KamLAND and Super-Kamiokande, respectively. The limits for the lifetime of protons have been pushed to nearly 10^{34} years. Last but not least, KamLAND has announced first evidence for geo-neutrinos. In a next step, the oscillation mixing matrix with neutrinos is going to be studied with a more intense neutrino beam from the J-PARC accelerator complex to Super-Kamiokande (T2K experiment).

The step to 50-1000 ktons

With complementary techniques, facilities on the mass scale of 50 kt to 1 Mton could dramatically increase the the potential of past and present underground detectors. Several conceptual ideas for next generation very massive, multi-purpose underground detectors have emerged worldwide and in Europe over the last years. All the designs consist of large liquid volumes observed by detectors which are arranged on the inner surfaces of the vessels. The liquid simultaneously acts as the target and as the detecting medium. The first one relies on the concept of Super-Kamiokande and uses water (MEMPHYS), the second builds on the initial experience with ICARUS and uses Liquid Argon (GLACIER), the third extrapolates experience gained in reactor experiments and BOREXINO and uses liquid scintillator (LENA). The three approaches will be discussed separately and then compared to each other.

Mega-ton water detectors

From a practical point of view, the most straightforward liquid is water, where the detection is based on the Cherenkov light emission by the final state particles. This faint light is detected by a very large number of photomultipliers positioned on the surface of the container. The technology has been pioneered by the IMB and Kamiokande experiments (USA and Japan, respectively) and successfully extended to Super-Kamiokande during many years of operation. Super-Kamiokande, the largest Water Cherenkov detector ever built, has a fiducial mass of 22.5 kton observed by about 11,000 large-size photomultipliers. The possibility of building a water Cherenkov detector with a fiducial mass of about 500 kton observed by about 200,000 photomultipliers is currently being investigated by different groups around the world, and for different underground sites. While water is a cheap medium, the size of such detectors is limited by the cost of excavation and of the photomultipliers. The MEMPHYS project is being discussed for deployment in an extended Frejus laboratory (France/Italy). In the US, the UNO detector is being proposed for a future underground facility in North America. In Japan Hyper-Kamiokande will provide an extension of Super-Kamiokande by a factor 20, using a new cavern to be excavated near Super-Kamiokande. Hyper-Kamiokande will also serve as the far detector for the second phase of the T2K experiment which is presently going to direct a neutrino beam from J-PARC to the Kamiokande site. Water-Cerenkov detectors are most efficient for neutrino interactions with a single Cherenkov ring and are therefore in practice ideally matched for neutrino energies below 1 GeV. They have also a high sensitivity sensitive to proton decays with two isolated Cherenkov rings like for example the channel $p \rightarrow e^{+} \pi^{o}$.

The liquid Argon technique

A second possibility is the liquid Argon Time Projection Chamber pioneered and developed under European leadership over many years of R&D in the ICARUS program. This technology is able to image the rare events with the quality of the bubble-chambers, which are famous for having led to important discoveries in particle physics in the 1970's. However, compared to a bubble-chamber, the liquid Argon TPC is fully electronic and can be in principle extrapolated to very large masses, possibly beyond many tens of kilotons. The Liquefied Natural Gas technology developed by the petrochemical industry has proven that the safe storage of very large volumes of cryogen is possible. The ionization charge produced by charged particles when they traverse the medium and the associated scintillation light can be independently readout and provide a tracking-calorimetry detector. Thanks to their imaging capability, liquid Argon detectors can provide improved sensitivities to the proton decay channels where backgrounds are serious in the Water Cherenkov detectors, like for example for the $p \rightarrow \overline{\nu} K^{+}$. GLACIER is a European design for a new generation liquid Argon TPC, eventually scalable up to at least 100 kton, only limited by the cost of liquid Argon and of the needed cryogenic power. In this context, dedicated R&D for the extrapolation of the liquid Argon TPC to very large scales is been pursued in Europe. Interest in the technology has recently also grown in the USA in the context of a second generation long-baseline experiment at Fermilab. At the same time, the ICARUS collaboration continues developing a modular approach to eventually reach a detector mass of several tens of kilotons with a set of identical units, each of them of the order of five kilotons.

Large scintillation detectors

A third possibility is a very large liquid scintillator volume observed by photomultipliers. The scintillator technology is based on the pioneering developments within the BOREXINO experiment. The light yield of a scintillator is much larger than that of Cherenkov light produced in water. The Cherenkov ring used so successfully in water to identify events cannot be imaged, however it has been shown to be effectively replaceable by precise timing, for example in the context of the search for proton decays in the $p \rightarrow \overline{\nu} K^{+}$ channel. This technique could also be used to detect supernovae neutrinos, and very low energy neutrinos, like for example those emitted by the Earth (geo-neutrinos) or by reactors. At present the maximum volume of such a detector seems to be limited by financial reasons to several tens of kilotons. LENA is a European proposal for such a detector in the range of 30-70 ktons. Russian physicists are planning a scintillation detector in the mass range between KamLAND/BOREXINO and LENA, with about 5 ktons. Placed possibly in the Caucasus, this detector might provide a unique piece of information on geo-neutrinos, due to the different geological structure.

Complementary character of different methods

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

- MEMPHYS would collect the largest statistics.
- GLACIER would have the best pattern recognition.
- LENA would have the lowest energy threshold.

- MEMPHYS and LENA are superior in anti-neutrino detection while GLACIER is best in neutrino detection. Neutrinos and anti-neutrinos together provide the full information to study supernovae.
- MEMPHYS has complementary sensitivity to LENA and GLACIER on proton decay flavor signatures.

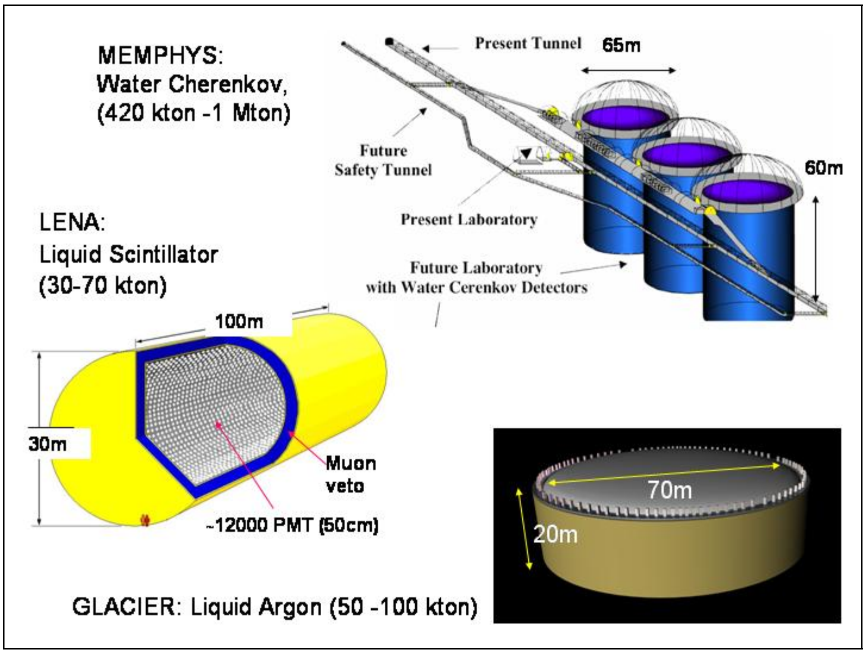


Figure 4.6: *Representative projects for the three proposed methods: MEMPHYS, LENA and GLACIER.*

Table: Physics potential of the three types of detectors for proton decay and neutrino astrophysics

Topics	GLACIER (100 kt)	LENA (50 kt)	MEMPHYS (400 kt)
proton decay, sensitivity $e^+ \pi^0$ anti-ν K^+	 $0.5 \cdot 10^{35}$ $1.1 \cdot 10^{35}$	 - $0.4 \cdot 10^{35}$	 $1.0 \cdot 10^{35}$ $0.2 \cdot 10^{35}$
SN at 10 kpc, # events CC NC ES	$2.5 \cdot 10^4$ (ν_e) $3.0 \cdot 10^4$ $1.0 \cdot 10^3$ (e)	$9.0 \cdot 10^3$ (anti-ν_e) $3.0 \cdot 10^3$ $7.0 \cdot 10^3$ (p)	$2.0 \cdot 10^5$ (anti-ν_e) - $1.0 \cdot 10^3$ (e)
Diffuse SN # Signal/Background events (5 years)	60/30	(10-115)/4	(40-110)/50 (with Gadolinium)
Solar neutrinos # events, 1 year	^{8}B ES : $4.5 \cdot 10^4$ Abs: $1.6 \cdot 10^5$	^{7}Be: $2.0 \cdot 10^6$ pep: $7.7 \cdot 10^4$ ^{8}B: $3.6 \cdot 10^2$	^{8}B ES: $1.1 \cdot 10^5$
Atmospheric ν # events, 1 year	$1.1 \cdot 10^4$	TBD	$4.0 \cdot 10^4$
Geo-neutrinos # events, 1 year	Below threshold	$1.7 \cdot 10^4$	Below threshold

Towards a proposal in 2010

Without any doubt, a massive-detector facility underground has an extremely rich programme. The construction and operation clearly represents a difficult technological challenge and a significant cost on the scale of several hundred million Euro. It is intimately connected to the question of large underground infrastructures (see Appendix 3). The choice of the most appropriate technology, of the site and of the designs of such super-massive detectors should be carefully optimized taking into account the technical feasibility and predicted costs, the multiple physics goals, and also the possible existence of accelerator neutrino beams. The facilities should also incorporate strong artificial neutrino sources, like ^{51}Cr, for calibration purposes. The time scale for the design and construction of a super-massive detector in Europe is likely to be of the order of ten years or more. However the current R&D efforts, assessing the technical feasibility, the physics potential, and the possible underground location of different designs should be vigorously pursued, in particular where Europe has so far maintained leadership.

The facility has not necessarily to rely on only one of the technologies but could incorporate sub-detectors of different technologies.. A proposal on site and technology will be tackled globally, in particular taking into account the plans in the USA and Japan. European researchers in the field have taken first steps towards a design study for a massive multi-purpose facility, and a proposal is expected around the year 2010.

5. The Non-Thermal Universe: Cosmic Rays, Gamma Rays and Neutrinos

5.1 Introduction

The discovery of the non-thermal Universe

Much of classical astronomy and astrophysics deals with thermal radiation from the Cosmos, emitted by hot or warm objects such as stars or dust. The hottest of these objects, such as hot spots on the surfaces of neutron stars, emit radiation in the range of some 10^3 to 10^4 eV, about a 1000 times more energetic than visible light. We know, however, that non-thermal phenomena involving much higher energies play an important role in the Cosmos. First evidence for such phenomena came with the discovery of cosmic rays by Victor Hess in 1912, who measured radiation levels during balloon flights and found a significant increase with height, which he correctly attributed to a hitherto unknown penetrating radiation from space. In 1938, Pierre Auger proved the existence of extensive air showers – cascades of elementary particles - initiated by primary particles with energies above 10^{15} eV by simultaneously observing the arrival of secondary particles in Geiger counters many metres apart. Modern cosmic-ray detectors reveal a cosmic-ray energy spectrum extending to 10^{20} eV and beyond, see Figure 5.1.

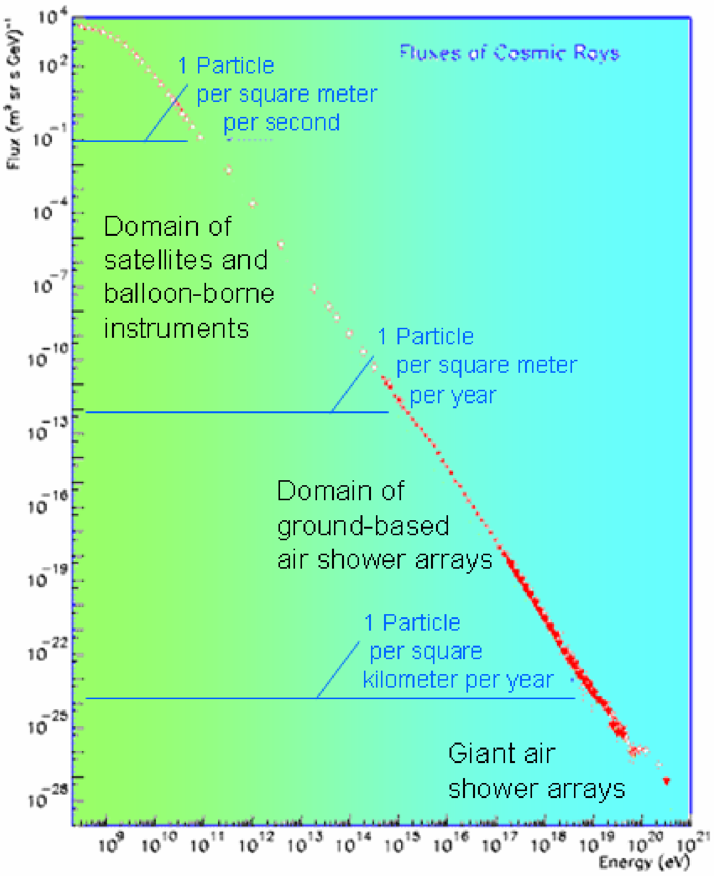


***Figure 5.1**: The all-particle cosmic ray spectrum and experiments relevant for its detection (taken from S. Swordy).*

Obviously, such energies – by far in excess of the energies reached in man-made particle accelerators – cannot be created in thermal phenomena unless they trace back to very early stages of the Big Bang. Other mechanisms must be responsible for their creation. Evidence for such high-energy processes is not only obtained from charged cosmic rays:

- Radio- and X-ray spectra of certain objects show the characteristic shape of synchrotron radiation spectra, emitted when high-energy electrons are deflected in magnetic fields.
- MeV gamma telescopes on satellites (formerly COMPTEL and OSSE on the Cosmic Gamma Ray Observatory CGRO, and presently INTEGRAL with its SPI detector) probe the low-energy component of cosmic rays, providing e.g. information on nuclear de-excitation gamma ray lines or low-energy electrons emitting Bremsstrahlung in the interstellar gas. These are key tools to study the first steps of cosmic particle acceleration.
- Satellite-based gamma ray astronomy in the MeV-GeV range, notably the EGRET satellite, have revealed about 300 sources of radiation at energies around 10^8 eV and also showed the band of the Milky Way uniformly “glowing” in this high-energy radiation. In addition, one detects a uniform glow of the Cosmos as a whole, obviously of extragalactic or cosmological origin.
- Ground-based gamma-ray telescopes are sensitive to lower radiation fluxes and higher energies than the satellite detectors with their limited size. These instruments have discovered dozens of emitters of very high energy gamma rays in the 10^{11} to 10^{13} eV regime, many of them lining the Milky Way.

High-Energy radiation as a key component of the Universe

From such observations, one can estimate the contribution of the non-thermal radiation to the energy balance of the Cosmos, with the surprising result that the energy in non-thermal radiation roughly equals the energy stored in thermal radiation or in interstellar magnetic fields, implying that such non-thermal phenomena can have significant impact on the evolution of the Cosmos, and suggesting a deeper connection between, for example, radiation and magnetic fields.

The sources of non-thermal radiation must be sought in the most violent – and, by implication, highly interesting – regions of the Cosmos. Given that cosmic rays are the most energetic particles known to mankind, they are also of obvious interest to particle physics, exploring otherwise inaccessible energy scales. At speeds within one part in 10^{22} equal to the speed of light, they probe the laws of special relativity in extreme domains, and with the short wavelengths associated with such radiation – a factor 10^{11} below the size of an atomic nucleus – they may even be of use to sense the “foamy” structure of space-time predicted on very small scales by modern theories of quantum gravity.

Imaging the sky: gammas, neutrinos and charged cosmic rays

Non-thermal phenomena are thus seen in the particles of the cosmic rays and in electromagnetic radiation over wide ranges of the electromagnetic spectrum. However, there is strong reason to believe that the acceleration of charged particles – electrons, positrons and atomic nuclei – lies at the root of all these phenomena. Meandering in interstellar magnetic fields, the accelerated particles can reach the Earth as cosmic rays. Due to their deflection in the more or less random magnetic fields, they unfortunately lose much of their directional information, and impinge upon the Earth nearly uniformly from all directions. Therefore information on cosmic rays primarily relates to their energy spectrum and elemental composition - with the possible exception of the very highest energies, where magnetic fields may no longer be able to significantly bend their trajectories. Apart from the extreme energies, source tracing, i.e. *astronomy*, is only possible with the help of neutral, stable particles like gamma rays or neutrinos which travel on straight paths. Fortunately, virtually every source of charged cosmic rays is also a source of these neutral messenger particles. They are created when the accelerated particles collide with interstellar gas or interact with radiation fields or magnetic fields, both in or near the sources or during their journey through interstellar space. The electromagnetic waves and – in future - neutrinos allow "imaging" of distant cosmic accelerators, albeit with a bit of uncertainty since the intensity of radiation is proportional to the number of high-energy particles times the density of the target with which they interact: the latter is often not known very well.

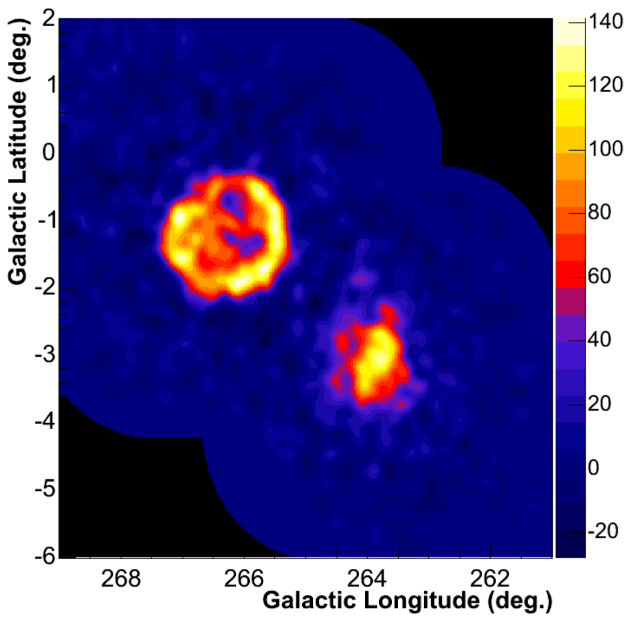


Figure 5.2: *The Vela region as seen by the H.E.S.S. gamma-ray telescopes at TeV energies. The circular structure on the left side of the image is the "Vela Junior" supernova remnant; the outer ring traces the shock wave emitted in a supernova explosion about 700 years ago. The extended emission region on the right is a pulsar wind nebula of energetic electrons accelerated by the Vela pulsar. This pulsar was created in another supernova explosion around 10000 years ago; the shock wave emerging from this explosion has dissipated much of its energy and is no longer visible in high-energy gamma rays.*

This type of imaging of cosmic particle sources is explored, for example, with ground-based gamma ray astronomy at very high energies, a field which has taken large steps forward in recent years, for the first time resolving a supernova explosion wave as a site of cosmic particle acceleration (Figure 5.2); extensions to the existing installations will improve sensitivity in the next two years. At lower gamma-ray energies, the

GLAST satellite, to be launched in 2007, is expected to provide a wealth of new data. However, based on electromagnetic radiation alone it is frequently hard to identify the nature of the primary high-energy particles – electrons/positrons or nuclei. Here, a new emerging field of high-energy astrophysics comes into play: neutrino astronomy. When – and only when – accelerated nuclei interact with cosmic targets, neutrinos are generated among the secondary particles. For sufficiently high fluxes, these neutrinos can be detected on Earth above the atmospheric neutrino backgrounnd. Like gamma rays, neutrinos propagate in a straight path and allow imaging of their sources. They are extremely penetrating which, on the one hand, makes them very hard to detect – requiring cubic-kilometre sized detectors that are currently under construction – but on the other hand, allows them to travel without any absorption from the source to the Earth, no matter how distant or how enshrouded the source is. Multi-messenger astronomy, combining detection of charged cosmic rays, of electromagnetic radiation from radio waves to highest-energy gamma rays, of neutrinos and – ultimately – of gravitational waves will be at the forefront of astrophysics and astroparticle physics during the coming decade and will provide the tools to identify cosmic accelerators and their mechanisms.

Where are the cosmic accelerators ?

How do they accelerate particles ?

What are the cosmic accelerators? Up to energies of 10^{15} eV, maybe 10^{17} eV, a long-term paradigm is that supernova shock waves – as shown in Fig. 5.2 - are responsible for the acceleration. A few times per century, a supernova explodes in our Galaxy, sending a plasma shock wave into space with a speed of a few percent of the speed of light. An atomic nucleus or electron may be “caught” in the shock wave, and, by crossing the shock front many 1000 times without colliding with other particles, may gain significant energy. The ultimate energy is determined both by the fact that after some 10000 years, the supernova shock wave runs “out of steam”, thereby limiting the number of shock crossings. Also, magnetic fields are required to “focus” the particle and keep it from escaping from the supernova shock wave; once a particle has reached a critical energy, it will escape from the acceleration region, providing another limit for the highest energies achievable in this process. Supernova shocks are believed to be the source of Galactic cosmic rays, since they are one of the very few sufficiently energetic processes, and since the theoretical modeling of the “diffusive shock acceleration” can roughly reproduce the measured spectra and composition of cosmic rays. Current experimental evidence, however, is incomplete: some supernova shock waves have been identified as cosmic accelerators, but it is an open question if this mechanism can explain the full yield of cosmic rays, and up to what energy. On the other hand, quite a few of the emitters of very high-energy gamma rays seen in the sky seem not to be directly related to supernova shock waves, indicating that additional mechanisms are at work.

The situation is even less clear for ultra-high-energy cosmic rays, around energies of 10^{20} eV. To accelerate particles in shock waves up to such energies and to hold the particles in the shock wave during the process, either huge accelerators or huge magnetic fields are required. Very few known objects, if any, match this criterion, see Figure 5.5.

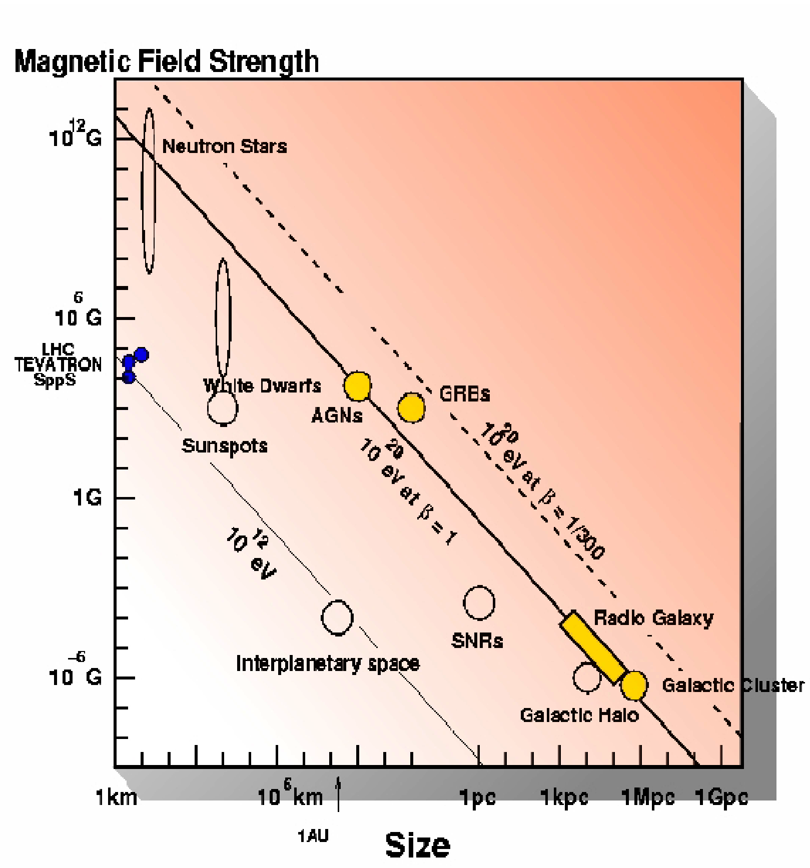


***Figure 5.3:** The famous "Hillas plot" shows potential cosmic-ray accelerators in a diagram where the horizontal direction signifies the size L of the accelerator, and the vertical the magnetic field strength B. The maximal energy E which an accelerator can achieve is proportional to $Z\times L\times B\times\beta$, with β being the shock velocity in units of the speed of light and Z the particle charge; the limiting energy results from the requirement to confine the particle to the acceleration region while it gains energy. A particular energy corresponds to a diagonal line in this diagram and can be achieved e.g. with a large, low field acceleration region or with a compact, high-field region. Assuming a shock velocity β ~1, neutron stars, AGN, Radio Galaxies or Galactic clusters can accelerate protons to E ~10^{20}eV. For non-relativistic shocks (β ~1/300), no object class with sufficient size and magnetic field to produce 10^{20}eV protons is known. Note that the actual maximal energy reached by a particular accelerator can be smaller than implied by this plot which neglects energy loss processes during acceleration. Such losses can be especially important in relatively compact objects, for example in neutron stars.*

The puzzle of missing nearby accelerators

Even more puzzling is the fact that even the ultra-high-energy cosmic rays seem – with current very limited statistics – to fill the sky uniformly. If sources of these particles were "nearby" – within our Galaxy or the local galaxy cluster – the particles can no longer be isotropized by interstellar or intergalactic fields and their arrival directions should correlate with the local structure of the Galaxy or the local galaxy cluster. Given the extreme requirements on the accelerators, it is hard to believe that there are sufficient nearby accelerators to give rise to a uniform cosmic ray distribution on the sky. One is led to conclude that the highest energy cosmic rays come from large distances, many 100 Megaparsecs, in which case there might be many accelerators, and also magnetic deflection may be large. However, due to an effect known as the Greisen-Zatsepin-Kuzmin (GZK) cut-off, ultra-high-energy cosmic rays cannot travel further than a few tens of Megaparsecs before colliding with quanta of the cosmic microwave background, in which process they lose part of their energy and secondary particles are produced. If ultra-high-energy cosmic rays come from far away, their spectrum should therefore cut off at around 10^{20} eV, but at least one experiment has reported the detection of a handful of cosmic rays well beyond this cutoff. Hence, the origin of these highest-energy particles would be a big mystery. The new generation of huge air shower experiments, most notably the Pierre Auger Observatory, aims to provide a solid experimental basis by detecting a sufficiently large number of particles at such energies.

Relics from the Big Bang: "Top-down scenarios" for the highest energies ?

An exciting possibility is that non-thermal particle populations – or at least some of their components – are not generated "bottom up" by an acceleration process, but rather "top down" by decays of very heavy particles. Since such particles cannot be created in today's Universe, they must be relics of the Big Bang. The best known example are super-symmetric particles which might form the dark matter and whose decay or annihilation generates radiation in the 10^9 to 10^{12} eV energy domain. Furthermore, objects of a mass scale as high as the Grand Unification scale, 10^{16} GeV ($=10^{25}$ eV) can in principle be produced during or at the end of inflation. If such objects have a lifetime comparable to or larger than the age of the Universe, for example by being stabilized topologically as in cosmic strings, their decays or annihilations could contribute to the highest energy cosmic rays. Obviously, detection and identification of such objects would be an astounding achievement for astrophysics and particle physics alike, with severe implications for cosmology. Once more, a multi-messenger approach is required to validate any such hypothesis.

Cosmological implications: measuring the starlight background and probing the distribution of cosmic magnetic fields

Beyond the search for relics from the Big Bang, the study of non-thermal radiation in the Universe contributes to cosmology in a number of ways, some of which were mentioned earlier. Very high energy gamma rays, for example, are absorbed in collisions with starlight in intergalactic space, analogous to the GZK mechanism for ultra-high-energy cosmic rays, although the cut-off energies for gamma rays are at lower energies, in the domain of 10^{11} eV. A measurement of their absorption length, via features imprinted by the absorption on the spectra of active galaxies, yields the amount of starlight in extragalactic space, representing the accumulated emission of all galaxies and stars formed since the big bang, and probing the history of galaxy formation. In addition, sufficient statistics of ultra-high-energy cosmic rays and their arrival directions with respect to their sources may allow to learn more about the poorly known distribution of large-scale cosmic magnetic fields before these fields will be mapped out more directly by radio measurements with experiments like LOFAR or SKA. In the long run, this complementarity between very low and very high energy experiments will thus be very fruitful for cosmology and astrophysics.

Is there physics beyond the standard theories, and what could we learn about it from radiation at highest energies ?

Apart from the possibility that new physics may be involved in top-down type sources, physics beyond the Standard Model may manifest itself in propagation and detection of ultra-high energy messengers: Interactions of high energy radiation with low energy photon backgrounds often take place at Lorentz factors of 10^{11} and higher, compared to the laboratory frame. This opens the possibility of testing the Lorentz symmetry in hitherto uncharted territories. Furthermore, the cosmological propagation distances allow very sensitive tests of the equivalence principle by measuring, for example, arrival times of photons and neutrinos from bursting sources at different energies. Finally, due to their low cross sections in the Standard Model, neutrino interactions at ultra-high energies would provide a comparatively clean signature of potential new physics.

The following sections address in more detail status and future of the different approaches contributing to the exploration of the non-thermal Universe.

5.2 Charged Cosmic Rays

Figure 5.4 shows the spectrum of cosmic rays. Compared to fig. 5.1, the flux has been multiplied with E^2, for better visibility of structures. The spectrum follows a broken power law. The two power laws are separated by a feature christened the "knee". Circumstantial evidence exists that cosmic rays up to energies of 10^{16} - 10^{17} eV originate in galactic Supernova remnants. A second feature at higher energies is called the "ankle". Approaching the ankle, the association with our Galaxy will disappear and extragalactic contributions take over. The transition from galactic to extragalactic cosmic rays is important in understanding acceleration mechanisms in our Galaxy; our knowledge about this region is rudimentary. The origin of cosmic rays at the highest energy is not known at all. Future data may reveal unexpected acceleration mechanisms as well as new physics beyond the standard model.

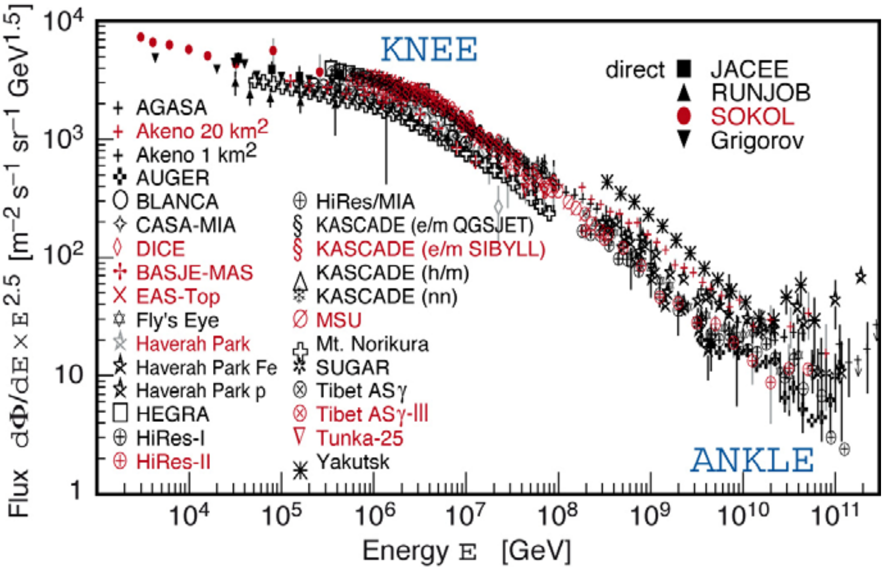


Figure 5.4: *Spectrum of cosmic rays. Compared to Fig. 5.1, the flux has been multiplied with* $E^{2.5}$ *in order to make the structures of the knee around* 10^{15} *eV and of the ankle around* 10^{19} *eV better visible.*

Structures in the CR spectrum

The spectrum of cosmic rays covers more than 12 orders magnitude in energy, over which the flux falls by about 31 orders of magnitude, see Figure 5.1. These extremely wide ranges pose very difficult problems for the experiments dedicated to measurements of the energy spectrum, primary particle type and arrival directions. Direct detection above the atmosphere with balloons and satellites is flux-limited to energies below ~10^{14} eV, see Figure 5.1. At higher energies, extensive air showers are recorded by the footprint of secondary particles on the ground and/or by optical detection of the Cherenkov and fluorescence light emission along the elongated air shower. The main difficulty of inferring the properties of the primary particle is linked to the incomplete understanding of particle interactions in the air, partly at energies well beyond existing data on cross-sections and particle production.

Direct Measurements of Cosmic Rays

The most direct information on the properties of cosmic rays is obtained with detectors above the atmosphere, on stratospheric balloons or in outer space. In particular, those measurements have provided most of the information on galactic cosmic rays, notably conclusions on the composition of cosmic rays at their sources as well as on the propagation of cosmic rays in the Galaxy. The residence time in the Galaxy has been determined through measurements of radioactive nuclei. The amount of material traversed by cosmic rays has been derived from the measured ratio of primary to secondary nuclei, such as the boron-to-carbon ratio or the ratio of sub-iron elements to iron. These data contributed to the contemporary standard model of Galactic cosmic rays. However, the model exhibits discrepancies with measurements when extrapolated to PeV energies. For example, extrapolating the propagation pathlength derived from GeV-energy measurements to energies around the knee, one would expect large anisotropies, which are not observed experimentally. Some of these problems are expected to be resolved by new missions which will extend the existing measurements of the boron-to-carbon ratio to higher energies.

Exotic Physics with balloons and satellites

A traditional mission of many balloon-borne and space missions is the search for anti-matter. The unambiguous detection of even a single antihelium or anticarbon nucleus would be a smoking gun for anti-matter dominated regions in the universe.and have profound consequences on our understanding of the early universe and. the origin of the asymmetry between matter and anti-matter. Other goals of these experiment are the indirect search for Dark Matter and the search for heavily ionizing exotic particles.

Future missions aim to precisely measure *a)* the energy dependence of the ratio of light ions (B/C) or isotopes (D/H, ^{9}Be/^{10}Be) over the largest possible energy interval, *b)* the sign of the charge in order to search for nuclear antimatter with ppb accuracy, *c)* the charge-to-mass ratio *Z/A* of charged particles with ppb sensitivity in order to search for rare particles like strangelets or monopoles, d) the absolute antiproton flux in the high energy region (>1 GeV) in order to search for SUSY inspired DM candidates; *e)* the absolute e^+ flux and its ratio to the electron flux between 1 and 200 GeV in order to search for signals predicted by SUSY-inspired DM models. Some of these measurements are expected to be done by new missions currently in an advanced phase of development.

Present activities with European participation include two balloon-borne detectors and two space-based magnetic spectrometers:

Balloon-borne detectors

The CREAM experiment with its acceptance of 2.1 $m^2 \cdot sr$ comprises a scintillator-tungsten sampling calorimeter combined with a transition radiation detector to identify cosmic rays from hydrogen to nickel, covering an energy range 10^{12} to 10^{14} eV/nucleon (eV/n). European collaborators come from Italy and France. A different approach is followed with the TRACER experiment (with European collaborators in Germany). TRACER measures the energy spectra for heavy nuclei (oxygen to iron) in the range from 10^{10} to 10^{14} eV/n; the principal component is a 5 $m^2 \cdot sr$ transition radiation detector to measure the energy of relativistic nuclei.

Both balloon experiments had sucessful long-duration flights from McMurdo, Antarctica, and data analysis is on-going. More flights are planned in the coming years in order to increase the data samples and to extend the energy spectra of cosmic rays with single element resolution into the 10^{14} eV/n region. These data are required to understand the mechanisms of cosmic-ray propagation at such energies and to resolve the discrepancies outlined above.

Experiments at satellites

PAMELA (with European collaborators in Italy, Germany, Sweden, Russia) is a 21.5 $cm^2 \cdot sr$ magnet spectrometer, supplemented with additional detectors for particle identification to measure light nuclei and anti-nuclei in the energy range from 10^8 to 10^{11} eV/n, as well as electrons and positrons up to $2.5 \cdot 10^{11}$ eV. PAMELA has been launched on a Russian satellite in June 2006.

The AMS experiment (with European collaborators in Denmark, Finland, France, Germany, Italy, the Netherlands, Portugal, Romania, Russia, Spain, and Switzerland) is a magnetic spectrometer with 0.5 $m^2 \cdot sr$ aperture supplemented with detectors for redundant particle identification allowing to identify one anti-nucleus among 10 billions nuclei. AMS aims at measuring with high precision and high statistics all particles and nuclei spectra in the energy range from 10^9 to 10^{12} eV/n, isotopic composition up to 15 GeV/n. It ill also record gamma rays from GeV to TeV. AMS is planned to be launched with a Space Shuttle to the International Space Station. Construction has basically been completed, but due to the known problems with the Space Shuttle there are still uncertainties on the launch date.

The extension of CREAM/TRACER-type measurements to PeV (10^{15} eV) energies requires experiments with apertures as large as 20 $m^2 \cdot sr$ and long exposure times. The use of magnet spectrometers or calorimeters of such a size does not seem feasible due to the weight limits. Ideally, the detector should operate in space for three to five years, significantly improving our knowledge about cosmic-rays in the knee region. This will be a tremendous step forward in the improvement of high-energy interaction models mandatory to interpret air showers at higher energies.

A small fraction of protons penetrates deep into the atmosphere and can be registered e.g. in a large calorimeter (~300 m^2) placed at an altitude of about 500 g/cm^2. Up to now, this possible alternative to balloon-borne and space-borne missions has not led to convincing results yet.

Ground-Based Air Shower Detectors

Above ~10^{14} eV, the showers of secondary particles created by interactions of the primary cosmic rays in the atmosphere are extensive enough to be detectable from the ground. In the most traditional technique, charged particles, such as electrons and muons, are detected in large detector arrays using scintillation counters or water tanks. In addition, hadrons are registered in compact calorimeters. Alternatively, Cherenkov light generated by relativistic shower particles in the atmosphere is registered with imaging or light-integrating detectors. Air showers can also be detected through the isotropic fluorescence emission of the atmospheric nitrogen that the charged particles in the shower excite.

Energies around the knee

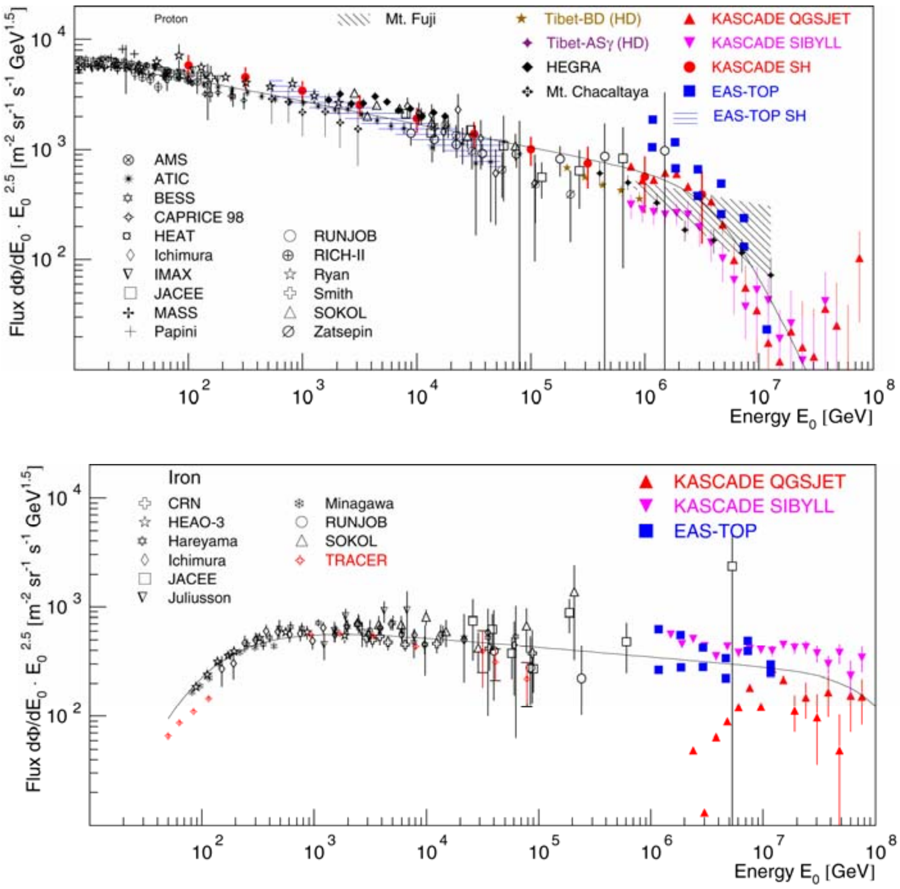


Figure 5.5: *Energy spectra for primary protons (top) and iron nuclei (bottom) as measured directly above the atmosphere and, at the higher energies, derived from air shower experiments.*

The energy region around and shortly above the knee (10^{14} – 10^{16} eV) has been explored by a variety of experiments, notably those with European participation, KASCADE, EAS-TOP, SPASE/AMANDA and TUNKA. As expected for acceleration proportional to particle charge ***Z*** (E_{max}~*Z*), the average mass of cosmic primaries increases when passing the knee. This effect has been established by all recent and running experiments. Most impressively it has been demonstrated by KASCADE where separate spectra for protons and iron have been derived. Figure 5.5 shows clearly that the cut-off for iron is at higher energies than that for protons.

Towards the end of the galactic spectrum

Both from the theoretical and experimental standpoint, the situation at energies above 10^{16} eV dramatically differs from that in the range 10^{14} to 10^{16} eV. The energy range between 10^{16} and 10^{18} eV has been covered by very few experiments. Our knowledge about mass composition above a few 10^{16} eV is rudimentary. Energy spectra determined by different experiments differ significantly, mostly due to the difficulties in proper energy calibration. On the other hand the region above 10^{16} eV is of crucial importance for our understanding of the origin and propagation of cosmic rays in the Galaxy. What is the mass composition above a possible iron knee? Is this region dominated by sources other than supernova remnants? What is the nature of the observed "second knee" at $\sim 5 \cdot 10^{17}$ eV? Is there an early onset of an extragalactic component? What is the relation between cut-off effects due to leakage out of the Galaxy and cut-off effects due to maximum energies in sources?

KASCADE-Grande, IceCube/IceTop, TUNKA-133: approaching the end of the spectrum

A careful investigation of the region 10^{16}-10^{18} eV requires detectors with area ~1 km^2 or more, but much smaller spacing than that of arrays for ultra-high energies, like AGASA, Yakutsk or the Cherenkov water tank array of the Auger Observatory. Such detectors should exploit as many complementary techniques as possible, which can be cross-checked against each other. A trinity of experiments, one running, the other two under construction, is considered to be a unique combination for a coherent investigation of cosmic rays up to the end of the galactic spectrum and to determine the onset of the extragalactic component.

KASCADE-Grande (Germany, Italy, Poland, Romania) is the extension from the original KASCADE array covering 0.04 km^2 to an area of 0.5 km^2. It detects cosmic rays between 10^{13} eV and 10^{18} eV and is expected to provide important information on galactic cosmic rays and the transition to extra-galactic cosmic rays. It measures simultaneously the electromagnetic and muonic shower components with arrays of unshielded and shielded scintillation detectors, and the hadronic component with a calorimeter. KASCADE has contributed to the improvement of interaction models and has set a first milestone in resolving the knee into element groups. Energy spectra could be derived for five groups (protons, helium, CNO, silicon group, and iron group), exhibiting cut-off features scaling approximately with the charge of the nuclei. The results demonstrate that the knee is caused by a cut-off of the light elements and that the average mass of cosmic rays increases as function of energy in the region of the knee as expected from acceleration in supernova remnants and the diffusive propagation in the Galaxy which depend mainly on *rigidity*, i.e. the energy per nuclear charge unit. KASCADE-Grande will continue to collect data until 2008/9. After this period the dominance of systematic uncertainties suggests terminating the operation.

At the South Pole the existing installation of the ***SPASE/AMANDA*** experiments (with European collaborators from Belgium, Germany, Sweden, UK) is presently being extended to form the ***IceCube/IceTop*** experiments (with European collaborators from Belgium, Germany, The Netherlands, Sweden, UK). The electromagnetic shower component is registered in a 1 km^2 array of ice Cherenkov detectors at the surface (IceTop). High-energy muons are registered in a well shielded 1 km^3 ice Cherenkov detector (IceCube).

The Russian-German-Italian ***TUNKA*** experiment plans to extend the existing array of integrating Cherenkov detectors in Siberia to cover an area of 1 km^2 and to extend the energy range up to 10^{18} eV. Precise energy measurement is crucial to detect fine structures in the spectrum. TUNKA adds to the set of techniques a calorimetric method, which – for this energy range – is the Cherenkov technique. It also provides information on the longitudinal development of showers in the atmosphere and therefore on the mass composition.

A better understanding of the cosmic ray composition and the high-energy interaction models is required to overcome the limitations mentioned above. Some data in this sector can be obtained from measurements at the LHC in close cooperation between the particle and astroparticle communities.

Extragalactic Cosmic Rays

At energies above ~10^{18} eV, the ground array technique was used by experiments operating with ever-increasing area from the 1960s, sometimes for more than twenty years. The largest installation was the Akeno Giant Air Shower Array (AGASA) near Tokyo, Japan, covering an area of roughly 100 km^2 with about 110 detectors on a grid with 1 km spacing. AGASA was decommissioned in early 2004. Extensive air showers can also be detected by the isotropic fluorescence emission, a technique first used by the Fly's Eye detector in the 1980s. The US-Japanese High Resolution Fly's Eye (HiRES) was taking data in Utah, USA, with stereoscopic observation of cosmic rays above 10^{19} eV. It was shut down in March 2006. The Japanese-US Telescope Array project (TA) is under construction during 2005/7; it will comprise a ground array of 800 km^2 to be later combined with fluorescence detectors and/or the HiRES telescopes.

A comparison of cosmic ray energy spectra obtained with ground arrays and the calorimetric optical measurements indicate systematic errors of about 30%, see Figure 5.6.

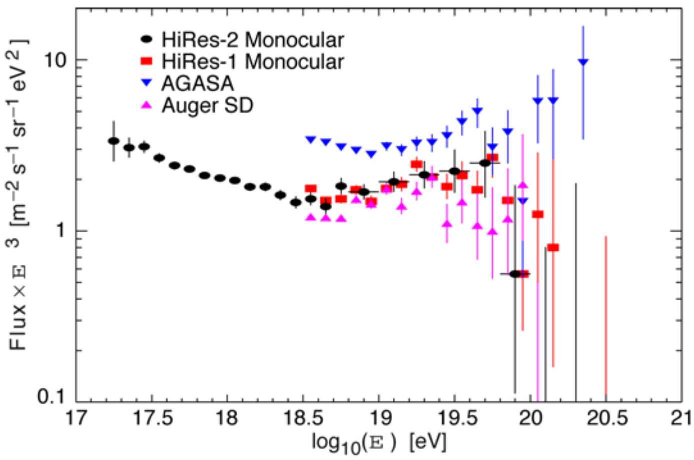


Figure 5.6: *The CR spectrum at the highest energies; the flux is now multiplied by E^3. The AGASA and HiRes data are obtained with pure ground array and fluorescence measurements, respectivel. The Pierre Auger Observatory is a hybrid system combining both techniques; the preliminary spectrum from the first year of operation uses the large data set recorded by the ground array and the energy calibration from the fluorescence telescopes.*

The Pierre Auger Observatory

A major step forward is going to be achieved by the Pierre Auger Observatory (see Fig. 5.7). The aim of this instrument is to measure the energy spectrum, arrival distribution and mass composition of the highest energy cosmic rays with unprecedented statistics and precision. The Southern site, presently under construction in Mendoza, Argentina will reach its full size in late 2007. It will cover 3000 km^2 with 1600 water Cherenkov tanks spaced by 1.5 km, with four groups of six fluorescence telescopes each at the perimeter of the array simultaneously observing fluorescence traces during dark nights. The ground array will have an aperture about 30 times as large as the AGASA array, with ~ 13% of the events being detected optically. First detectors of Auger-South became operational in January 2004. The energy threshold is a few times 10^{18} eV. On September 28, 2006, there were 1285 tanks deployed with 996 recording data and 18 of the 24 telescopes were operational. The Auger Collaboration includes 250 scientists from 17 countries. The strong European contribution is about 50 percent in terms of people and investment (total 50 M$).

An important step has been to demonstrate that measurements with the surface detectors of shower size can be calibrated with the fluorescence information to give estimates of energies on an event by event basis. This step allows the high statistics of the surface detector to be used to construct an energy spectrum that has small systematic errors (< 10%) due to lack of knowledge of hadronic interaction details or of the mass spectrum of the primaries creating the showers.

The Southern and Northern hemispheres contain different large-scale matter distributions and hence potential sources of cosmic rays. Recording suitable numbers of events beyond the GZK threshold will open the *particle astronomy window* to the universe. Therefore, full-sky coverage has been a design feature of the Auger Observatory since its conception. Construction of the northern Auger site is planned to begin in Colorado, USA, in 2008/9 with a tentative collection area of 10,000 km^2. A milestone will be the definition of the scientific case and a detailed design, based on data equivalent to 6-7 times the total AGASA statistics, which will have been collected by mid-2007 from Auger South.

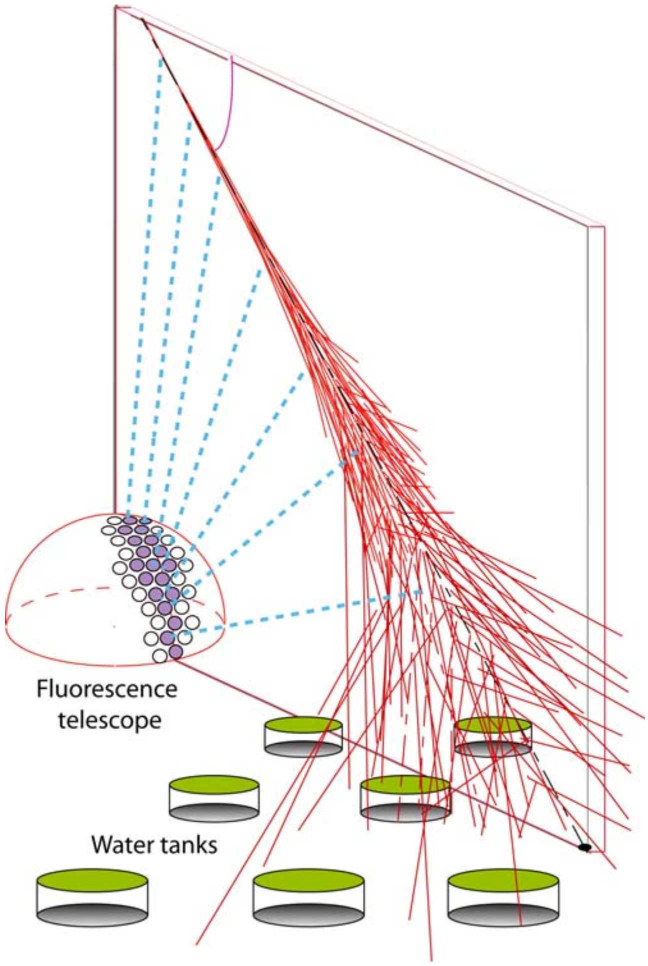


Figure 5.7: *The Auger detection principles: Optical detection of fluorescence light from air showers recorded by telescopes particles at ground level recoreded by Cherenkov water tanks.*

Neutrinos in Auger

It is worth noting that large air shower detectors like Auger have significant sensitivity for neutrinos above energies of ~EeV (= 10^9 GeV). Only neutrinos can induce nearly horizontal and Earth-skimming showers, which start close to the detector; ordinary showers, initiated by protons or nuclei, will be absorbed or reduced to their muonic component after traversing a lot of matter. This technique is complementary to neutrino telescopes in water and ice which are optimized to energies below ~10^{15} eV, above which the Earth becomes opaque to neutrinos due to the rising neutrino cross-section.

Novel detection methods

Radio emission from air showers was first observed in 1965. The origin is thought to be coherent synchrotron radiation at radio frequencies (20-100 MHz) emitted by electrons and positrons deflected in the geomagnetic field. With modern digital signal processing methods it has been possible to construct omni-directional arrays of antennas with phase-shift and filtering analysis being done off-line in software. The LOPES antennas detect radio emission from showers in coincidence with the KASCADE-Grande experiment in a German-Dutch-Italian-Polish-Romanian effort. The *proof of principle* was achieVed in 2005 and has been confirmed by work of the CODALEMA collaboration in France. There are on-going efforts to deVelop this novel and potentially cost-effective technique for physics use on larger scales, e.g. within the Auger Observatory.

Ultra-high energy cosmic rays may also be detected optically from satellites looking downward from orbits. In principle, this concept may provide apertures and eVent rates greatly above those realistically achieVable by ground-based installations. Studies like OWL (NASA) and EUSO (mostly ESA and European groups) have been performed. They show that design efforts should be directed to lower thresholds, better image resolutions and calibration. The inclusion of ultra-high energy cosmic rays into the ESA *Cosmic Vision 2015* programme provides a frame to study future space missions.

Large radio astronomy facilities such as the Westerbork radio telescope (experiment NuMoon) or arrays like LOFAR and SKA, as well as satellite based radio receivers (experiment LORD) can be used to record neutrino and cosmic ray induced showers on the moon. These approaches are described in more detail in section 5.4.

5.3 Gamma Ray Astronomy

Gamma rays have proven to be a very powerful tracer of populations of high-energy particles produced in the "non-thermal" universe, via their interactions with interstellar material or with radiation fields. Among all the different techniques deVeloped so far for their detection, primarily two have succeeded in providing catalogues with reliable source detections and spectral measurements: *satellite detectors* and *ground based Cherenkov telescopes*. Due to the small area of detectors on satellites, they run out of statistics at energies above a few tens of Giga electron volts (GeV = 10^9 eV). The higher energies are the domain of ground-based Cherenkov telescopes, covering the range above hundred GeV with extremely large sensitivities.

Imaging air Cherenkov telescopes open a new window of electromagnetic radiation from space

Cherenkov imaging of high-energy gamma rays

Cherenkov telescopes image the light generated by ultra-relativistic electrons and positrons when the primary gamma ray is absorbed in the Earth's atmosphere, releasing an electromagnetic shower. This light reaches the ground in the form of a very faint bluish light flash of few nanoseconds duration and therefore requires a large optical telescope with a fast and sensitive imaging camera for its detection. On the one hand, this technique has proven to be challenging, and the deVelopment of the right instrumental features and suitable analysis techniques to extract the gamma signal from the overwhelmingly more abundant signals from charged cosmic rays has taken considerable time and R&D effort. On the other hand, since the Cherenkov light is produced high up in the atmosphere (at about 10 km height for the typical energy range of present Cherenkov Telescopes) and within a cone of about 1 degree aperture, an area as large as few tens of thousands of squared metres is illuminated and hence the effective detection area is huge in comparison with that attainable using other techniques. The already established potential of the technique outweighs its experimental complexity in comparison with other astronomical instruments.

The imaging atmospheric Cherenkov technique was born in the USA with the deVelopment of the Whipple Telescope, which took over 20 years to detect its first source. During the last decade European groups have been leading the deVelopment of imaging atmospheric Cherenkov telescopes. They are consolidating them as the most powerful instrument to study very high energy gamma rays from the Universe. The German/Spanish/Armenian HEGRA experiment has pioneered stereoscopic shower imaging by arrays of Cherenkov telescopes, dramatically improving sensitivity and resolution. The French CAT instrument has perfected imaging by use of fine-grained photon detectors for most efficient imaging.

Still, the source catalogue and the quality of the observations produced by that generation of Cherenkov telescopes was limited. This was in contrast to the situation of gamma ray astronomy at GeV energies, which during the last decade went through a dramatic emergence – thanks to the space-based EGRET detector on the American CGRO satellite – and provided a catalogue of a few hundred sources. The quest for better sensitivity and lower energy threshold then challenged the international community to construct a new generation of instruments. The best option for an improved sensitivity towards higher energy is the use of arrays of telescopes, while very large dishes are needed to reduce the energy threshold. Within a limited budget, a decision between the two options had to be taken. For this reason, some groups decided to initially deVelop arrays of medium-size telescopes, while others decided to initially deVelop single giant telescopes.

Among the latest generation of instruments are:

Cherenkov telescopes of the latest generation reVeal a rich sky

- the H.E.S.S. instrument (with European partners from Germany, France, the UK, Ireland, the Czech Republic, Armenia and, recently, Poland), an array of 4 twelve-metre telescopes which combines stereoscopic imaging with large light collectors and highly segmented detectors with rather wide field of view- see Fig. 5.8. The full H.E.S.S. system has been operational since 2004; initial data from the first telescope were recorded in 2002.
- the MAGIC telescope (with German, Spanish, Italian, Swiss, Polish, Finnish, Bulgarian, Armenian, and US groups), a giant seVenteen-metre telescope which provides the largest photon collector, uses photon detectors with enhanced quantum efficiency, and image timing information. Much effort has been spent to enable fast positioning to a source alerted by a GRB trigger from satellite detectors. MAGIC started physics data taking in 2004.

UK and Irish physicists also participate in the VERITAS telescope, an array of four twelve-metre telescopes being commissioned in the US.

Figure 5.8: *The H.E.S.S. Telescope array*

Data from Cherenkov telescopes of this latest generation have reVealed a sky rich in features at energies of Tera electron volts (1 TeV = 10^{12} eV). Figure 5.9 illustrates the tremendous progress over the last decade.

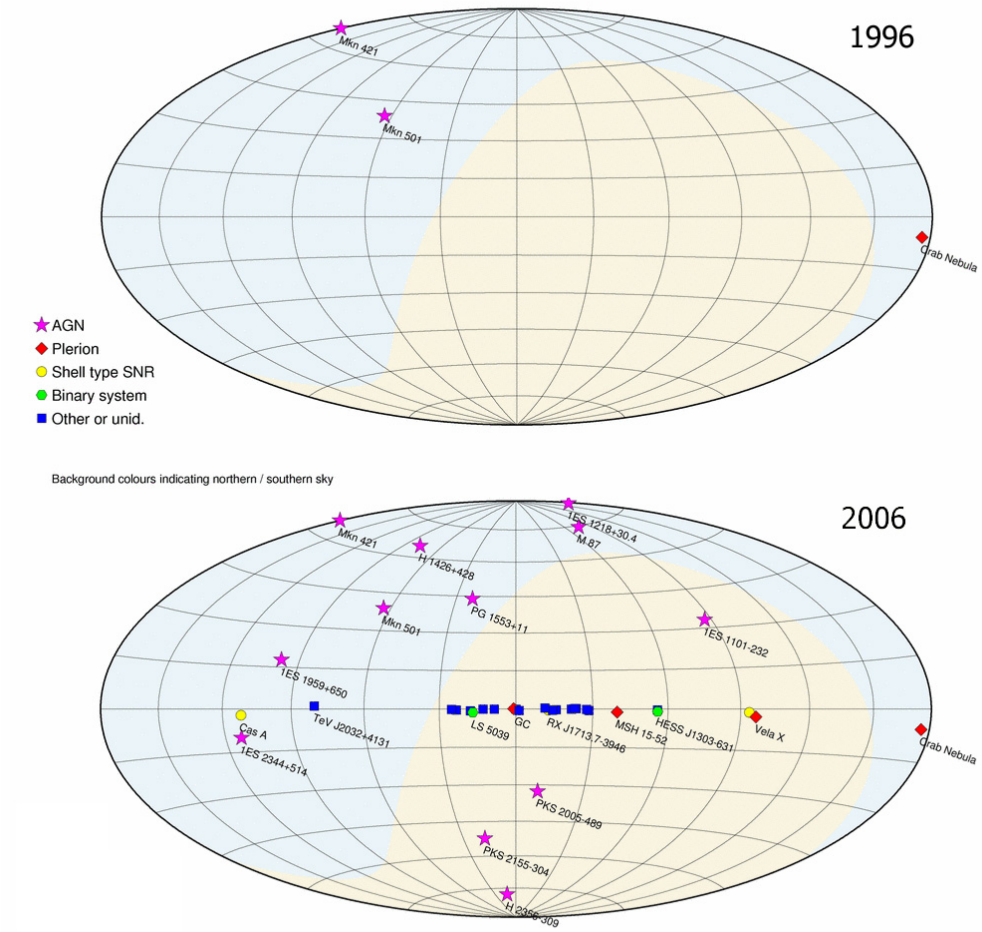


Figure 5.9: *The TeV gamma-ray sky as seen in 1996 and 2006.*

Maps produced by H.E.S.S. clearly show the band of the Milky Way lined with cosmic accelerators. These galactic sources of high-energy particles are characterized by rather flat energy spectra - nearly a constant energy output in each decade of the high-energy spectrum - extending up to many tens of TeV. The sources also exhibit morphologies that are well resolved on the scale of the angular resolution provided by systems of Cherenkov telescopes. These observed structures range from the clearly visible circular shells of supernova shock waves (see Figure 5.2) to the jet-like features detected around some of the pulsars. Many of the new H.E.S.S. sources are pulsar wind nebulae, where an electron-positron "wind" driven by a pulsar's giant electric and magnetic fields creates an extended emission nebula, challenging magneto-hydrodynamic models which aim to describe this process. EVen more puzzling is another class of sources which seem to have no counterpart in other wavelength regions ("dark accelerators"). Gamma rays are also found to trace the structure of giant molecular clouds near the Galactic Centre, indicating that these are illuminated by a powerful cosmic-ray accelerator at the centre of our Galaxy.

Galactic sources of high-energy gamma rays

Extragalactic sources – active galaxies – at unprecedented distances of up to three billion light years have been detected by H.E.S.S. and MAGIC. The shape of their gamma ray spectra relates to the density of light in the space between galaxies, and thus to the hotly debated history of cosmological structure formation. The extragalactic range of high-energy gamma rays is limited due to interactions with this background light; the analysis of the resulting "Gamma Ray Horizon" as a function of the source redshift after collecting a few tens of AGNs may provide new significant constraints for cosmological parameters. The fact that source spectra follow steep power laws together with the energy threshold reduction achieVed (in particular by the MAGIC telescope) has allowed collection of enough gamma rays from a flaring source to provide light curves with about two-minute precision, by both H.E.S.S. and MAGIC. This is an unprecedented time resolution for transient phenomena at these energies. Also, with the MAGIC telescope it has been shown that gamma ray bursts can be observed from the ground during their prompt emission phase, opening the window to study the most powerful phenomena in the Universe.

Extragalactic gamma-ray emitter and cosmology

Towards a new European facility for high-energy gamma-ray astronomy

Given that Europe is presently the undisputed leader in the emerging field of very high energy astrophysics with ground-based instruments, the construction of a next-generation facility to explore the entire sky at the highest currently accessible energies of the electromagnetic spectrum in parallel with the observations carried out by US-initiated GLAST instrument (see below) must be an important direction for deVelopment in European astroparticle physics.

Maintaining European leadership in high-energy gamma ray astronomy

While the results achieVed with current instruments are already very impressive, the performance in this domain can be improved dramatically by a much larger deployment based on now well established techniques and observation strategies. The goal is simultaneously increasing the energy bandwidth towards lower and higher energies, improving the sensitivity at currently accessible energies, and providing large statistics of highly constrained and very well reconstructed photon initiated eVents (Figure 5.10).

Rationale for a next-generation facility

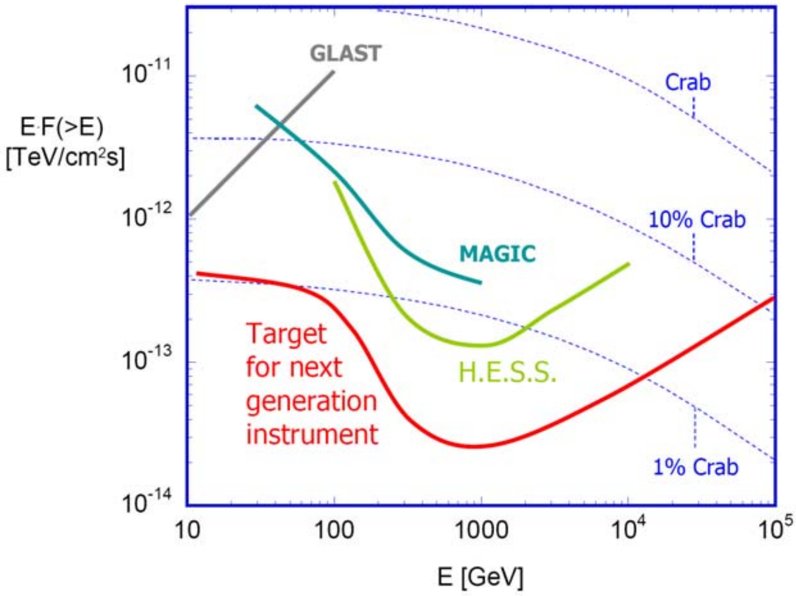


Figure 5.10: *Sensitivity of latest-generation Cherenkov instruments (H.E.S.S. and MAGIC) in comparison to the next-generation satellite experiment GLAST, and goals for the next-generation Cherenkov instrument. For reference, the gamma-ray flux from the Crab Nebula is shown.*

The superior angular resolution of these instruments will make it possible to resolve the details of structures within extended radiation sources. At high energies, in the most interesting range of tens of TeV, low statistics preVent the detailed study of spectra and source morphologies. Only arrays with a large number of telescopes, covering a larger area, can provide sufficient statistics. Operated in different modes, such arrays would furthermore allow the survey of significant fractions of the sky with high sensitivity, currently a daunting task in terms of the observation time required. At lower energies, in the range of ten to hundreds of GeV, telescopes with large mirrors combined with sensitive light sensors are the natural candidates to boost performance and open new possibilities, although that is precisely the range in which the IACT (Imaging-Air-Cherenkov-Telescope) technique is pushed up to its limit, and the actual performance of such deVices is still under study. At the low energies, the Universe becomes transparent to gamma rays and one can explore cosmological regimes. Cherenkov telescopes excel in particular in the study of transient phenomena which are characteristic for active galaxies. Operation of the proposed Cherenkov Telescope Array (CTA) would be crucial for the study of short timescale variability of extragalactic and galactic gamma-ray sources, especially in conjunction with observations by GLAST, which would provide an alert for transient sources to be subsequently observed by the new Cherenkov array. The proposed array would have unprecedented timing sensitivity for such short timescales, and will provide information on extreme astrophysical processes in a time regime neVer explored before and not accessible to eVen the largest gamma-ray space missions. Future joint operations by GLAST and by the new Cherenkov array make the proposal very timely. The high-energy cut-off of pulsed emission from pulsars is another key theme to be explored with such an instrument.

The detailed layout and configuration of a novel array of Cherenkov telescopes – possibly combining telescopes of different dish sizes and with varying telescope spacing, and with the option of a staged deployment - needs to be defined in detail. HoweVer, the understanding of the experimental approach and the instrumental technology are at a leVel that such an all-sky observatory could be implemented starting around 2010, after a design phase taking into account the extensive experience gained with instruments such as H.E.S.S. and MAGIC. A large and rapid deployment of techniques as they are – on smaller scales - already in use or currently being implemented by a few groups should be the primary objective in view of the general schedules of gamma-ray astronomy; timely implementation is essential for synchronous observations with GLAST.

CTA - a new European Cherenkov telescope facility

Given the scale of this project, and its nature as an open facility for European astrophysicists, astronomers and astroparticle physicists, the detectors clearly need to be realized and implemented in the European context but as an installation open to world-wide collaboration. The site selection for such an instrument will form part of a study which will include detailed simulations to decide the optimal telescope configuration for the best scientific output. Given the wealth of sources in the central region of our Galaxy, and the richness of their morphological features, a site in the southern hemisphere is attractive. On the other hand, a complementary northern site has to be considered for the study of the closest galaxy clusters, AGNs, the cosmological eVolution of galaxies and star formation. Furthermore, at energies approaching the cosmic ray knee around a PeV, gamma-rays can reach us only from the closest parts of our Galaxy, i.e. predominantly from the northern sky. The ensemble of sites would provide full sky coverage and the wider energy range coverage as demonstrated by H.E.S.S. - MAGIC large/small zenith angle simultaneous observations. These facilities should be operated in a coherent way by a joint European consortium. The CTA project - CTA stands for Cherenkov Telescope Array – has been formed to work jointly towards the design and realisation of such an instrument; CTA involves all European groups currently participating in Cherenkov instruments, as well as a large number of additional new partners from particle physics and astrophysics.

Initiatives with similar goals are being discussed by the VHE gamma-ray astronomy community around the globe – in the US, now starting operation of the VERITAS telescope array, and by Japan and Australia, now running the CANGAROO-III telescope array. It is very important that the necessary coordination mechanisms between the CTA initiative and the parallel efforts started around the globe are established as soon as possible, with the aim to study the complementarity of such installations and the eVentual possibility of coordinating/joining efforts in world-wide collaborations.

We also emphasize the expected large impact of CTA's scientific output to the Astrophysics community. Indeed it is already discussed in depth in the ASTRONET roadmap. Therefore, in order to exploit the full scientific potential of such an installation, the optimization of its design should strongly take into account the input of the Astrophysics community. For that purpose, the necessary mechanisms to increase the communication and the collaboration between both communitites should be established as soon as possible.

An interim step: HESS II and MAGIC II with enhanced sensitivity

In the interim period, both H.E.S.S. and MAGIC are being upgraded to enhance their capability and sensitivity, at the same time providing a test bed for deVelopment towards the new telescope facility:

- H.E.S.S. will add a large (600 m^2) Cherenkov telescope at the centre of the current (107 m^2) telescopes. Operated in stand-alone mode, the large telescope will have a significantly lower energy threshold than the current instrument. In coincidence mode, the additional high-intensity image will improve background rejection and angular resolution.

- MAGIC is building a second telescope, essentially identical to the first one, to allow stereoscopic operation. At the same time, improved photon detectors and faster readout electronics are being introduced.

Experience with H.E.S.S.-II and MAGIC-II will be valuable for the implementation of the new facility.

Wide-angle instruments high-energy gamma-ray astronomy

Complementary detection techniques for high-energy gamma rays

While Cherenkov instruments provide the best sensitivity, angular resolution and background rejection capability for gamma-ray astronomy at highest energies, they suffer from the limited field of view and limited duty cycle. Other techniques aim at providing complementary capabilities. Wide-angle, full-time detection is provided by instruments detecting shower particles on the ground. Since very few of the shower particles penetrate deep enough, such instruments should be (a) located at maximum feasible height, around 4-5 km above sea leVel, and must (b) cover a significant fraction of the ground with detector elements. Directional reconstruction of the shower can be obtained by use of the arrival time information, or by tracking individual shower particles. The ARGO/YBJ instrument in Tibet (4300 m above sea leVel), with strong European participation, uses a 100×100 m^2 array of Resistive Plate Chambers for detection of shower particles. The detector is in its commissioning phase and aims for a sensitivity of 30% of the Crab flux. The Tibet Air shower array (also at 4300 m asl) resembles classical scintillation arrays detectors. With a 5.5 σ detection of the Crab Nebula after 550 days observation, the array in its present configuration reaches its limits. Most convincing results have been obtained from the MILAGRO instrument in the US, which operates a 4800 m^2 pool as a water Cherenkov detector for air shower particles. Apart from the observation of the strong sources Crab and Mk421, they have reported the exciting discovery of a very extended gamma-ray emission coming from the Cygnus arm region. The detection of such a widely extended emission is quite difficult with pointing deVices such as Cherenkov Telescopes and might provide already a proof on the complementarity between both approaches. So far, energy thresholds of such instruments are significantly higher than for Cherenkov telescopes, of order one TeV, and their sensitivity is just enough to detect the strongest sources, e.g. the Crab Nebula, the Active Galaxy Markarian-421, and the Galactic Centre. Given their complementary capabilities, it is howeVer important to continue the eVolution of these instruments. ARGO/YBJ should be completed during 2007 and might already show the actual potential of that technique. The MILAGRO collaboration is planning a larger array called HAWC which is being designed to allow for a survey of an important part of the sky in the gamma-energy range above few hundred GeV and which would therefore have an important overlap/complementarity with the physics goals of CTA . The same recommendation holds for wide-angle Cherenkov instruments, which could, for example, be realized by exploiting technology deVelopments for the EUSO instrument, with Fresnel lenses and large focal-plane detector arrays with as many as 10000 sensor elements.

Satellite experiments

Space based telescopes

After the great success of the present generation of instruments, the opportunity for a growth similar to the one experienced in the high-energy gamma ray astronomy from satellites is now clearly perceived in the adjacent domain of very high energy astronomy. It is now well established that science should progress in parallel in both domains which present obvious complementarities. Two new satellites will be launched before the end of 2007: on the one hand AGILE, a small Italian mission which should already improve the EGRET observations in the high-energy domain, and on the other hand GLAST, a new large satellite for GeV gamma-ray astronomy, which will reach the range of few hundred GeV and is being prepared in the US with European partners and is planned for an operational lifetime of 5 years and a probable extension to 10 years. GLAST is expected to improve on the EGRET capabilities beyond an order of magnitude and provide a new gamma-ray all-sky catalogue with few thousands of new sources, with many of them reaching energies in the Cherenkov telescope domain. Therefore, a parallel effort for a ground-based all-sky observatory, able to follow and study in detail the new GLAST catalogue sources, is urgently needed in favour of gamma-ray astronomy at the very highest energies. We also reiterate the close connection to satellite observations at longer wavelengths. X-ray satellites and missions like INTEGRAL play a key role in multi-wavelength studies. The energy range of INTEGRAL (keV- GeV) has a strong overlap with AGILE and GLAST.

5.4 High Energy Neutrino Astronomy

The case for large detectors in open water and ice

Whereas neutrino astronomy in the energy domain of Mega electron volts (1 MeV = 10^6 eV) has been established with the impressive observation of solar neutrinos and neutrinos from supernova SN 1987A, neutrinos with energies of Giga electron volts (1 GeV = 10^9 eV) and above, which must accompany the production of high energy cosmic rays, still await discovery. Detectors underground have turned out to be too small to detect the corresponding feeble fluxes. The high energy frontier of Tera electron volts (1 TeV= 10^{12} eV) and Peta electron volts (1 PeV = 10^{15} eV) energies is currently being tackled by much larger, expandable arrays constructed in open water or ice. They consist of photomultipliers detecting the Cherenkov light from charged particles produced by neutrino interactions (see Fig. 5.11).

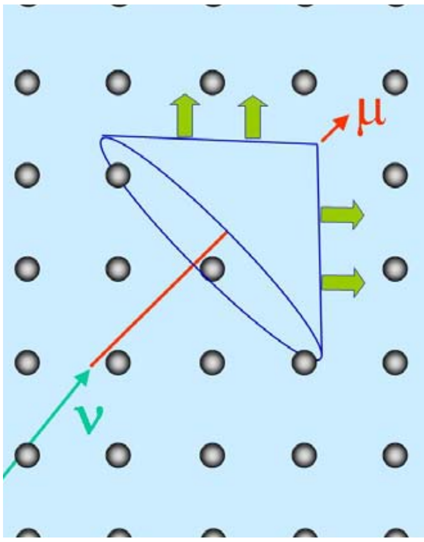


Figure 5.11: *Neutrino telescopes consist of large arrays of photomultiplier tubes underwater or under ice. They detect the Cherenkov light emitted by charged particles which have been produced in neutrino interactions – here from an up-going muon which stems from a neutrino having crossed the Earth.*

Techniques for highest energies

Emission of Cherenkov light in water or ice provides a moderately strong signal and hence relatively low energy thresholds for neutrino detection, but the limited light transmission in water and ice requires a large number of light sensors to cover the required detection volume. Towards higher energies, novel detectors focus on other signatures of neutrino-induced charged particle cascades, which can be detected from a larger distance. This includes recording the Cherenkov radio emission or acoustic signals from neutrino-induced showers, as well as the use of air shower detectors responding to showers with a "neutrino signature". The very highest energies will be covered by balloon-borne detectors recording radio emission in terrestrial ice masses, by ground-based radio antennas sensitive to radio emission in the moon crust, or by satellite detectors searching for fluorescence light from neutrino-induced air showers. Taken all together, these detectors cover an energy range of more than twelve decades, starting at 10^{13}-10^{14} eV (10-100 GeV) and extending beyond 10^{22} eV. Figure 5.12 sketches the measured and predicted neutrino fluxes in comparison to present limits and expected sensitivities for extraterrestrial "diffuse" neutrino sources, and also compares the neutrino fluxes to measured fluxes of gamma radiation and cosmic rays.

Within the last five years, experimental sensitivities over the whole energy range have improved by more than an order of magnitude, as shown in Figure 5.14. Over the next 7-10 years, flux sensitivities are expected to move further down by a factor of 30-50, over the entire range from tens of TeV to hundreds of EeV. This opens up regions with high discovery potential.

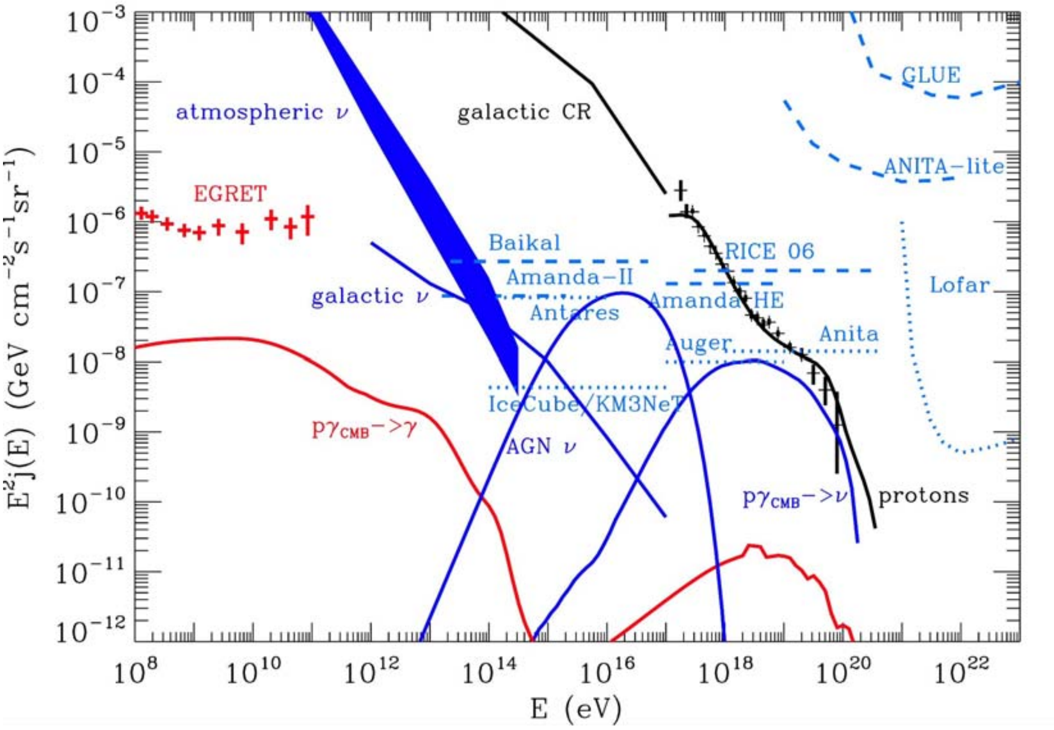


***Figure 5.12:**. Estimated fluxes and eVolution of instrumental sensitivity for neutrinos, compared to fluxes of charged cosmic rays and gamma rays. Primary cosmic ray fluxes (data and a model fit) are shown in black, the secondary γ-ray flux expected from proton interactions with the Cosmic Microwave Background (p+CMB→γ) in red and the "guaranteed" neutrino fluxes per neutrino species in blue: atmospheric ν, "galactic ν" resulting from cosmic ray interactions with matter in our Galaxy, and GZK neutrinos resulting from cosmic ray interaction with the Cosmic Microwave Background, p+CMB→ν. These secondary fluxes depend to some extent on the distribution of the (unknown) primary cosmic ray sources for which active galaxies were assumed above 10^{18} eV. Cosmic ray interactions within these sources can also produce neutrinos whose fluxes depend on models for which one example is given (AGN ν). The flux of atmospheric neutrinos has been measured by underground detectors and AMANDA. Also shown are existing upper limits and future sensitivities to diffuse neutrino fluxes from various experiments (dashed and dotted light blue lines, respectively), assuming the Standard Model neutrino-nucleon cross section extrapolated to the releVant energies. The maximum possible neutrino flux is given by horizontally extrapolating the diffuse γ-ray background observed by EGRET.*

Atmospheric neutrinos: a difficult background but also a stable calibration signal

The various techniques have eVolved to rather different leVels, ranging from the R&D phase to technological maturity and well-established operation. The feasibility of optical neutrino detection underwater and ice has been demonstrated by the NT200 telescope in Lake Baikal, and by AMANDA at the South Pole. Their comparatively low energy thresholds of tens of GeV allow them to record large numbers of atmospheric neutrinos. The flux of atmospheric neutrinos is known rather well, therefore they can serve as a calibration signal. The steep spectrum preVents this background from swamping extraterrestrial neutrinos whose spectra are expected to extend to much higher energies. Apart from atmospheric neutrinos, there are other guaranteed sources at higher energies: neutrinos generated in the galactic disk must exist, as well as neutrinos generated in cosmic ray interactions at the 3K background radiation (GZK neutrinos, see Figure 5.12). Although less accurately predictable than atmospheric neutrinos, their detection would provide a proof of principle for detectors with energy thresholds above a PeV where the contribution of atmospheric neutrinos is negligibly small.

An important aspect of high-energy neutrino detection is the search for point sources, which would help to solve the long-established problem of the origin of ultra-high energy cosmic rays. A detector's sensitivity to point sources depends not only on its volume, but also on its angular resolution, which affects the effective pixel size and therefore the amount of background expected. Since strong light scattering in ice worsens the angular resolution, underwater detectors are therefore expected to yield higher sensitivities than ice-based telescopes.

The TeV-PeV region: Cherenkov telescopes deep under water and ice

Proof of principle: Baikal and AMANDA

This technique has been established by two pioneering detectors, both with strong European participation:

- NT200 in Lake Baikal (Russia, Germany),
- AMANDA at the South Pole (USA, Germany, Sweden, Belgium).

The pioneering Baikal detector has taken data since 1993, and in its full configuration NT200 (192 photomultipliers on eight "strings") since 1998. Expanded in 2005, it is now called NT200+. With respect to its size, the Baikal array has been surpassed by AMANDA which was installed between 1996 and 2000, with a total of 677 photomultipliers on 19 strings. AMANDA has an effective area of 20,000 square metres, about one order of magnitude below the size suggested by most theoretical models. Flux estimations from astrophysical sources suggest that detectors of cubic kilometre size are required in order to collect a few up to a few tens of neutrinos in the TeV-PeV energy range per year and per source. Therefore, based on the experience from AMANDA, a cubic kilometre telescope,

IceCube: a cubic kilometre observatory at the South Pole

- IceCube (USA, Belgium, Germany, Sweden, Netherlands, UK, Japan, New Zealand)

is being deployed at the South Pole. Completion is foreseen in 2010/11; it then will consist of 4800 photomultipliers arranged in 80 strings. Nine of them have been deployed in 2005/06. IceCube is complemented by a surface air shower array, IceTop, which greatly enhances the physics capabilities of the deep ice detector.

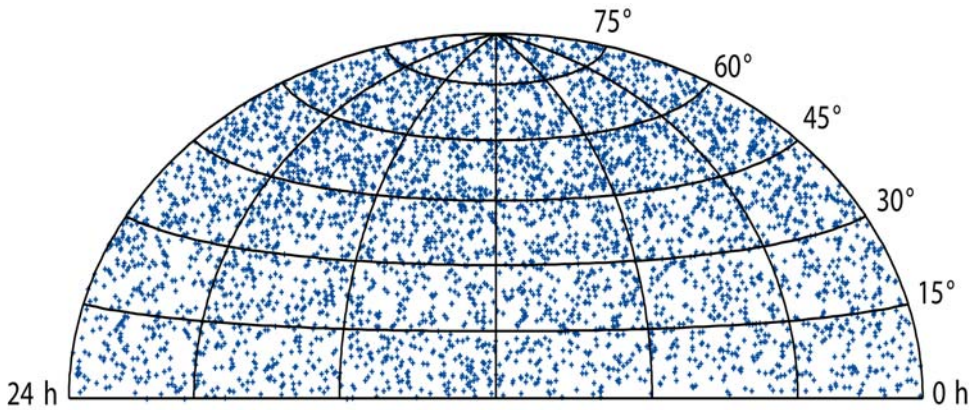


Figure 5.13: *Sky map of 4382 events recorded by AMANDA in 2000-2004. EVen with this highest statistics of high energy neutrino eVents eVer collected, no point source signal could be identified, motivating the construction of detectors more than one order of magnitude beyond AMANDA size.*

The detection mode with the best angular resolution for underwater/ice telescopes relies on muons generated in neutrino interactions and crossing the array from below. AMANDA/IceCube therefore essentially observes the Northern sky. HoweVer, in the local Universe, candidate sources for high energy neutrinos are not distributed isotropically. This, together with the probably modest number of detectable sources, calls for a complete coverage of the sky. The galactic centre is of particular interest, and only Northern hemisphere detectors are able to see the upward-going neutrinos from this region. This is the main motivation to build a counterpart to IceCube in the Mediterranean. Currently, three neutrino telescope projects are being pursued in the Mediterranean:

First stage Mediterranean projects

- ANTARES (France, Germany, Italy, The Netherlands, Spain, Russia),
- NESTOR (Greece),
- NEMO (Italy).

The first two of these are preparing first-generation neutrino telescopes of approximately the same size and sensitivity as AMANDA. NEMO is an R&D project aiming at a Mediterranean detector of cubic-kilometre scale.

Close to Toulon (France), ANTARES has started the installation of a detector comprising 12 strings, each carrying 75 photomultipliers and anchored to the sea bed at 2.5 km depth. The strings are connected to a *Junction Box* from which the main cable goes to shore. Between 2003 and 2005, all detector components have been successfully validated in prototype installations. The Junction box and the main cable have been functional since 2002, and two first strings have been deployed and connected to the Junction box in 2006; two further strings were deployed in autumn/winter 2006. The installation of the full detector is planned to be completed by the end of 2007.

The NESTOR design is based on hexagonal rigid structures (*floors*) with a diameter of 32 m, each carrying six pairs of photomultipliers. Twelve floors will form a *tower* of 300 m height. NESTOR will be deployed near the West Coast of the Peloponnese, at 4 km depth. In 2003, a prototype floor has been operated for more than a month. Recorded atmospheric muons agree with preVious measurements and simulations.

In the framework of the NEMO project, a candidate site for a future km³-scale detector has been identified at a depth of 3.3 km near the East coast of Sicily, and new solutions for various detector components have been deVeloped. Among them is a mechanical structure, consisting of 20 m long rigid arms connected to each other by ropes. This flexible tower can be folded, deployed and finally released after reaching the sea bottom. A first prototype was successfully deployed in Dec. 2006 and is tested at present.

Already in 2002, the *High Energy Neutrino Astronomy Panel (HENAP*) of the PaNAGIC committee of IUPAP concluded that "a km³-scale detector in the Northern hemisphere should be built to complement the IceCube detector being constructed at the South Pole". Meanwhile, the groups involved in the Mediterranean neutrino telescopes have deVeloped a joint activity aimed at a common future project. An EU-funded Design Study

- KM3NeT

KM3NeT: a cubic kilometre observatory in the Mediterranean

has started in Feb. 2006 to prepare this project. Concurrently, the *European Strategy Forum for Research Infrastructures (ESFRI)* has included the KM3NeT neutrino telescope in the *European Roadmap for Research Infrastructures*, thus assigning high priority to this project.

EVen with exploitation of the experience and expertise gained in the current projects, a major R&D program needs to be executed to arrive at a cost-effective design for a km³-scale deep-sea neutrino telescope, optimized for scientific sensitivity, fast and secure production and installation, stable operation and maintainability. The KM3NeT Design Study will address these issues in a 3-year program, with a 20 M€ budget, of which 9 M€ are provided by the EU. Participants are 30 particle/astroparticle institutes and 7 sea science/technology institutes from Cyprus, France, Germany, Greece, Ireland, Italy, The Netherlands, Spain and the United Kingdom.

The main deliverable of the Design Study is a *Technical Design Report (TDR)*, laying the foundation for funding negotiations and concrete project preparation. The vision of the proponents is that KM3NeT will be a pan-European research infrastructure, giving open access to the neutrino telescope data, allowing the assignment of "observation time" to external users by adapting the online filter algorithms to be particularly sensitive in predefined directions, and also providing access to long-term deep-sea measurements to the marine sciences communities.

Russian plans for a larger detector

Finally, Russian physicists are planning an array of similar scale – an effective mass of a Gigaton of water – in Lake Baikal, with capabilities likely half way between AMANDA/ANTARES and IceCube/KM3NeT. Provided that high energy neutrino astronomy deVelops into a flourishing field, with many sources and correspondingly high fluxes, such an array might improve eVidence for Southern Sky steady sources and extend the time coverage for transient sources. At present, no European partners are involved in this project..

Techniques tailored to energies above 10^{17}-10^{20} eV (100 PeV-100 EeV)

Towards the highest energies

Neutrinos with energies above 100 PeV should be generated in GZK interactions of extremely energetic protons from GRB or AGN. Moreover, many models of AGN jets and GRB afterglows also predict corresponding high-energy tails of neutrino spectra. The expected low fluxes require detectors exceeding cubic-kilometre size. They are based on techniques other than optical detection in water and ice:

Optical detection of neutrino-induced air showers

Optical detection of neutrino-induced air showers: This method aims to identify horizontal air showers initiated by neutrino interactions deep in the atmosphere. Using large air shower detectors such as Auger, the optimum sensitivity window for this method is 0.1-10 EeV, with an effective detector mass of 1-20 Gigatons. This mass can be increased for tau neutrinos, scratching the Earth and interacting close to the array. An extremely energetic tau lepton produced in such interactions may escape the rock, and the particle cascade produced by its decay in the atmosphere above the array can then be recorded. Provided the pattern can be clearly identified, the sensitivity would reach down to 10^{-8} E_ν^{-2} GeV^{-1} cm^{-2} s^{-1} sr^{-1}. At the highest energies one is led to space-based detectors monitoring larger volumes than visible from any point on the Earth's surface. The EUSO project intends to launch large mirrors with optical detectors to 500 km height. The mirrors would look down upon the atmosphere and search for nitrogen fluorescence signals due to neutrino interactions. The monitored mass could be up to 10 Teratons, with an energy threshold around 10 EeV. Due to the uncertain schedule of Space Shuttle and International Space Station, the realization of EUSO appears not determined at present.

Hearing neutrinos

Acoustic detection of neutrino-induced showers in water, ice or salt: This promising technique is still in its R&D phase. It relies on the ionisation loss in high energy particle cascades transforming into heat. The following fast expansion of the medium results in a short acoustic pulse. The signal power spectrum peaks at 20 kHz, where the attenuation length of sea water and ice is a few kilometres, compared to seVeral tens to hundred metres for light. Again, the large attenuation length makes the method attractive for extremely high energies, where large detector spacing is mandatory in order to achieVe the huge detection volumes necessary for low fluxes. Expected peak sensitivities are in the EeV region. Open key issues are signal strength and natural background leVels. Acoustic detectors might surround the optical detectors of a cubic kilometre detector in the Mediterranean and extend its sensitivity to much higher energies. For IceCube, a hybrid scheme comprising optical, radio and acoustic detection has been proposed (radio does not work in salt water), with a total volume of the order of hundred cubic kilometres. European groups play a leading role in R&D activities on acoustic detection in water (France, Germany, Italy, Spain, UK) and in ice (Germany, Sweden and Belgium).

Radio detection of neutrinos

Radio detection of neutrino-induced air showers: Electromagnetic cascades generated by high-energy electron-neutrino interactions emit coherent Cherenkov radiation. The signal strength rises proportionally to E^2 , making the method interesting for high energies. In ice, as well as in salt domes, attenuation lengths of seVeral kilometres can be reached, depending on frequency band, ice temperature and salt quality. This allows large spacing between the individual detectors and a comparatively cheap extension to large volumes. Thus, for energies above few tens of PeV, radio detection in ice or salt may be competitive or superior to optical detection. Best limits have been set by a prototype detector, RICE, operating in 100-300 metre ice depth at the South Pole. The ANITA project uses an array of radio detectors planned to be flown by balloon in an Antarctic circumpolar flight in December 2006. From 35 km height, it will be able to record radio impulses in the thick ice sheet and monitor a huge volume. The expected sensitivity from a 30-day flight is $\sim 10^{-8}$ E_ν^{-2} GeV^{-1} cm^{-2} s^{-1} sr^{-1} at 10 EeV (10^{19} eV). Radio emission is also expected from extremely high-energy cascades induced by neutrinos or cosmic rays skimming the Moon's surface. Using two NASA antennas, the GLUE experiment has set an upper limit below 10^{-4} E_ν^{-2} GeV^{-1} cm^{-2} s^{-1} sr^{-1} at 100 EeV. Similar moon observations are planned for the Westerbork radio telescope in the Netherlands (NuMoon project) in 2006-08, and for the Low Frequency Array LOFAR – the world's largest low-frequency radio telescope starting in 2008. The core of LOFAR is located in the Netherlands, with a funded extension into Germany and the UK and with pending applications in France, Italy, Sweden and Poland. Russian physicists have performed a similar search with the Kalyazin radio telescope (although not yet reaching the GLUE sensitivity). LOFAR's follow-up will be the Square Kilometer Array (SKA), to be built between 2014 and 2020 at the Southern hemisphere and included in the ESFRI list (see Appendix 5). It has also been proposed to observe the moon from space, either with an orbiter (LORD - Lunar Orbital Radio Detector) or with a LOFAR-like telescope which is discussed within ESA's exploration program. Last but not least we mention an analysis of data taken with the FORTE satellite to look for radio signals from giant air showers which has yielded upper limits on neutrino fluxes at energies above 10^{21} eV, relevant for speculative top-down sources.

The interactions of neutrinos above a PeV would probe interaction energies unattainable by terrestrial accelerators within any foreseeable future. Cross sections deviating from expectations would provide a relatively clean signature for physics at high energies where the Standard Model may be modified by new effects such as unification with gravitational interactions involving extra dimensions. Since neutrino cross sections are accessible by comparing the rates of different types of neutrino events (strongly inclined versus Earth skimming), experiments with the largest effective volume for such events will also provide a potential new window to new fundamental physics.

The overall picture

A promising decade ahead

At the end of the year 2005, we have covered about a third of a particularly exciting period for high-energy neutrino astrophysics. Since the year 2000, the sensitivity frontiers have improved by more than an order of magnitude, over an energy range from 10^{13} to $>10^{22}$ eV. They are expected to move down by another two orders of magnitude within the following ten years. Figure 11 shows a scenario for the sensitivity to diffuse fluxes for two selected energy ranges, 10-1000 TeV, and 0.1-10 EeV, as a function of time. At lower energies, the time gradient of improvement reveals a dramatic increase with the emergence of detectors in open media, Baikal-NT200 and AMANDA, providing a twenty-fold improvement of previous limits within five years. Another factor of 30 in sensitivity is expected from IceCube and from a cubic kilometre Mediterranean detector. Both projects cost in excess of one hundred M€. The Mediterranean detector is essentially an European project, IceCube is dominated by US institutions, however with significant European contributions. A similarly rapid evolution is taking place for neutrino detection at highest energies. RICE and GLUE have improved former limits from RICE and the Japanese air shower detector AGASA by an order of magnitude, with the next decade promising another factor of 30, based on results expected first from ANITA, Auger, NuMoon and LOFAR, and later from the other methods mentioned above – notably radio and acoustic signatures as well as fluorescence from air showers detected from space. Increased, coordinated R&D work on these methods will be necessary to realise this sketched scenario.

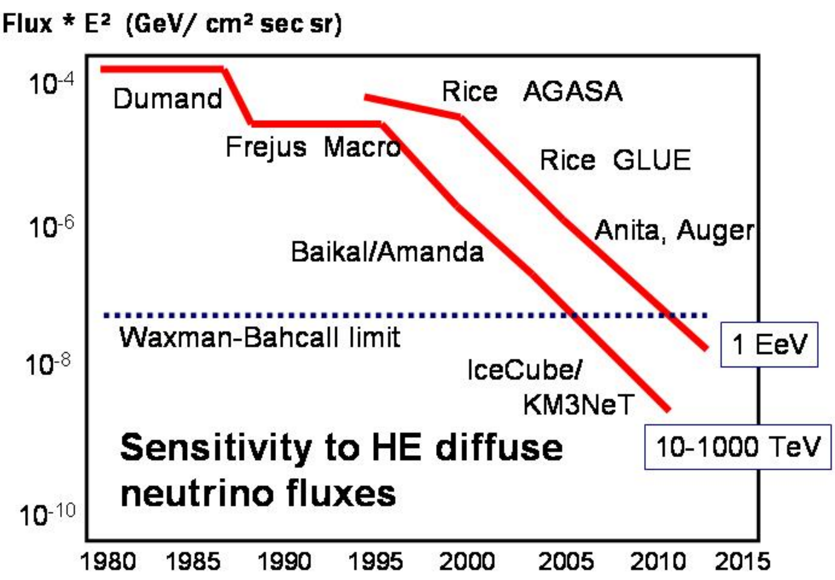


Figure 5.14: *Development of the sensitivity to the diffuse flux of extraterrestrial neutrinos over the past two decades and improvement expected over the next decade. The sensitivity in the TeV range is improved by Cherenkov detectors under water and in ice; at energies of tens of PeV and above, alternative methods like radio detection (e.g. RICE, ANITA, GLUE), airshower detection (AGASA, Auger) or acoustic detection take over. A similar dramatic picture of improvement can be drawn for even higher energies (FORTE, later LOFAR). The Waxman-Bahcall limit is a theoretical bound derived from measured cosmic ray spectra at the highest energies. It has served as a benchmark goal for years.*

6. Gravitational Waves

6.1 Introduction

Electromagnetism and gravitation

Of all the fundamental interactions, gravitation is the one that has been known since the beginning of times and was the first to achieve the status of a dynamical theory. Paradoxically, today it is the least understood. The reason is its extreme weakness which makes its effects totally negligible at a microscopic scale. Two interactions produce long range, classical forces: electromagnetism and gravitation. It is instructive to consider the progress in our understanding of both: Already in the seventeenth century Newton formulated gravitation as the archetype of a dynamical theory. It is described as a static instantaneous force acting between two massive bodies. The inverse square law was introduced phenomenologically in order to explain the observed trajectories of the known planets and it was later verified by terrestrial experiments. It took almost one hundred years for electromagnetism to achieve a comparable status with the introduction of the static Coulomb potential. The fact that both known forces at that time were described by a *1/r* potential does not seem to have attracted any particular attention. In 1846, Newton's law for gravitation was brilliantly verified by the prediction of a new planet, Neptune. But soon progress in understanding of the electromagnetic phenomena took on a much faster pace. Two milestones should be mentioned: The unified theoretical description of all electromagnetic phenomena by Maxwell in 1864 and the detection of electromagnetic waves by Hertz in 1888. In the same way that Newton's theory of gravitation is the first classical dynamical theory, Maxwell's is the first classical field theory, in which fields rather than forces become the fundamental entities in our Universe. At the end of the nineteenth century, electromagnetism appeared to be a complete theory with no room for improvement.

The 20th century: relativity and quantum theory

The twentieth century, the century of all revolutions, changed this simple picture. Relativity introduced the equivalence between mass, an intrinsically gravitational quantity, and energy. Quantum theory showed that energy in an external classical potential is quantised. The photon was introduced as a first example of a duality between a field and a particle. General relativity was formulated as a classical field theory of gravitation, in which the geometry of space-time becomes the fundamental dynamical variable. Quantum electrodynamics, the quantum analogue of Maxwell's theory, was brilliantly verified by experiment. Two new forces, the strong and the weak, were discovered. The Standard Model offered a quantum description of all interactions with the exception of gravitation. Geometry became the basic language of Physics.

The physical releVance of detecting gravitational waves

Today, at the rise of a new century, the parallel understanding of these two forces leaves gravitation much behind. Classically they are both described by field theories, but, while all aspects of Maxwell's theory have been verified, only the post-Newtonian approximation of general relativity has been compared with observation. The main prediction of a field theory, namely the emission of wave radiation, is still lacking experimental confirmation. The possibility to detect gravitational waves is one of the main challenges of our experimental program. The discrete energy spectrum of a particle in an external classical potential, the cornerstone of atomic physics for the case of an electromagnetic potential, has only recently been measured for a particle moving in earth's gravitational field. The most important prediction of the quantum nature of the field, the existence of gravitons, seems to be out of reach for any foreseeable future. Given this incomplete understanding of such a fundamental physical law, it is not surprising to find in this field a long term, rich and multidisciplinary experimental program.

6.2 Gravitational-wave Astrophysics

The discovery potential

Gravitational waves that we can expect to observe must be emitted by massive objects undergoing large accelerations. Typical examples are coalescences of binary systems of compact objects like neutron stars (NS) or black holes (BH). Even more spectacular events could be observed from galaxy collisions and the subsequent mergers of super-massive black holes residing in the centres of the galaxies. Other known sources include ultra-compact binaries, such as double white dwarfs and ultra-compact X-ray binaries. Further expected sources are compact objects spiralling into super-massive black holes, asymmetric supernovae, and rotating asymmetric neutron stars such as pulsars. Processes in the early Universe, on the time and length scales of inflation, must also produce gravitational waves. Their observation would point to *new physics* beyond the standard model. Detection of gravitational waves will not only be a validation of the field theoretical predictions mentioned in section 6.1, but will open a new window for the observation of many astrophysical processes in the Universe, from our own Galaxy up to cosmological distances.

Source sizes and observing frequencies

Just like electro-magnetic waves, gravitational waves come in many different frequencies. But unlike electro-magnetic waves, it is not the microscopic processes deep inside the sources that determine the wavelength, but the global properties of the sources, leading to wavelengths of the order of the source sizes. These range from tens of millions of kilometres for super-massive black holes and Galactic binaries, to "only" several kilometres for neutron stars and stellar mass black holes. The associated frequencies range from below a milli-Hertz to above a kilo-Hertz. Study of the full diversity of the gravitational wave sky therefore requires complementary approaches: Earth-based detectors are typically sensitive to high-frequency waves, while space-borne detectors sample the low-frequency regime.

High frequencies

At high frequencies the most promising sources are coalescing neutron stars and black holes that give us an opportunity to directly observe black holes and other highly relativistic objects and investigate general relativity in strong field conditions. A census of a significant portion of the visible Universe would allow us to study the evolution of the population of (massive) stars over cosmological time-scales and dynamical interactions in different stellar environments. The possible identifications of electro-magnetic counterparts (such as the host galaxy of a source) would lead to an accurate measurement of several cosmological parameters, and facilitate a deeper understanding of dark energy and its equation of state.

In addition, with the coalescences of compact neutron star or black hole binaries currently believed to be the sources of short GRBs, and supernova explosions believed to be the sources of long timescale GRBs, the observation of the gravitational waves expected from such events will contribute to a better understanding of the processes leading to GRBs. Particularly interesting would be coincident observations of neutrinos and gravitational waves from supernovae and GRBs..

Gravitational waves in a multi-messenger context

Astronomers have deepened dramatically their understanding of the Universe by correlating observations from various electromagnetic bands – an approach known as multi-wavelength astronomy. In the expected era of routine gravitational wave astronomy, gravitational wave observations of high-energy astrophysical systems will form a crucial component of a true *multi-messenger* toolset. Already now, gravitational wave astronomers are cooperating with radio astronomers. For instance, they use the observed radio timing data from pulsars to provide effective templates for the detection of gravitational waves from rotating neutron stars. Neutron stars are the other key target in the high-frequency band: they are cosmic laboratories of matter under extreme conditions of density, temperature and magnetic fields. Gravitational wave instruments will open a radically new window to explore such phenomena.

Finally, a variety of cosmological scenarios predict a stochastic background of gravitational waves that might be observable in the high-frequency range. Although the detailed physical processes are still poorly understood, this is a unique opportunity to probe New Physics at energy and time scales that are so far inaccessible.

Low frequencies

At low frequencies the most impressive sources will be the mergers of super-massive black holes. In the currently favoured cosmological paradigm, galaxies are assembled from the merging of more and more (dark matter) haloes. Combined with the notion that most galaxies – even at high red-shift, i.e. early times – have massive black holes (BH) in their centres, this predicts a wealth of BH–BH mergers throughout the Universe. Thus gravitational waves detected from these would provide an independent test of the scenario that galaxies have formed hierarchically. In addition they will provide very accurate mass and distance measurements. If these gravitational-wave detections are correlated with electro-magnetic observations of the same events, super-massive black hole mergers can set an independent distance scale, helping to unravel the mystery of dark energy.

Observations of the region around the super-massive black hole in the Galactic centre have shown a very rich environment, in which many young stars and young star clusters are present. These will form abundant populations of stellar mass compact objects, ranging from white dwarfs to neutron stars and black holes. Eventually these objects are inevitably captured by the central black hole, leading to so-called "extreme mass-ratio inspirals" (EMRI), which turn out to be excellent probes of the space-time of the super-massive black hole: the metric is fully determined by the virtually unperturbed super-massive black hole, and the stellar mass object serves as a test particle.

Compact binaries containing white dwarfs are weaker sources. They can only be studied in our own Galaxy. However, the shape of the mass distribution in which stars are formed, the so-called initial mass function, is such that white dwarfs that form from low-mass stars are vastly more abundant in the Galaxy than neutron stars or black holes. This means that for each NS-NS binary in the Galaxy, there are a thousand double white dwarfs! Current estimates for the number of individually detectable double white dwarfs in the Galaxy stand at around 10,000. The gravitational-wave measurements of this population that is largely inaccessible to electro-magnetic detectors, harbours a wealth of information about the formation and evolution of compact binaries in general and the physics of mass transfer and tides in white dwarfs in particular.

Gravitational waves from the early Universe, if detectable, will open a new window to probe fundamental physics processes in regions and at energy scales hitherto not accessible. They may provide a unique source of information for transitions in the early Universe, making gravitational waves, possibly together with neutrinos, the only probes for these epochs.

6.3 The detection of Gravitational waves

First eVidence for gravitational waves

Hulse and Taylor received the 1993 Nobel Prize for the indirect detection of Gravitational Waves through the energy loss of the binary pulsar PSR 1913+16. The direct observation of gravitational radiation is still a challenge for experimental physics; however after almost 40 years of experimental development, we now have the technology to hand.

Direct detection of gravitational waves: resonance antennas and interferometers

The search for gravitational waves began in the early 60s with resonant mass detectors. Currently four detectors are now routinely operating in Europe (AURIGA, EXPLORER and NAUTILUS, all funded by Italy) and in the US (ALLEGRO) with a good duty cycle and a bandwidth of several tens of Hz in the 1 kHz range. However over the last two decades the field of gravitational wave detection has focussed on the development of broadband interferometric gravitational wave detectors, which have now reached unprecedented levels of sensitivity. Many of the currently used techniques have been developed from the seventies and nineties at prototype instruments in Garching and Glasgow.

Recently, the construction of several large interferometers has been completed: the LIGO systems in the US (a project now with significant involvement from UK and German groups), VIRGO funded by France and Italy and GEO600 funded by Germany and the UK. The Japanese TAMA interferometer has been alternating commissioning and detector improvement with data taking for several years. These detectors are now in a phase of operation, with a sensitivity exceeding that of resonant bars, having a larger bandwidth (reaching from a low frequency cut-off at several tens of Hz up to several kHz) and extending the search to a much broader range of potential sources. In addition to these ground based detectors, the preparation of a space-based interferometric detector (LISA) which will open a completely new frequency range ($3x10^{-5}$ to 1 Hz) is underway, with an earliest launch date scheduled for 2015.

Network Analysis

Here we need to emphasize the importance of a network analysis for the data provided by multiple instruments. In fact, the same astrophysical event could be seen by all detectors having an adapted sensitivity in the relevant frequency range. Combining the observations can provide key information such as the location of the source in the sky and the gravitational wave polarization, in addition to increasing the detection confidence, a critical issue at the time of first positive signals. In a broader context, gravitational wave observations would be combined with data from other information carriers – electro-magnetic waves or neutrinos – and contribute to the multi-messenger approach discussed above.

Resonant or acoustic detectors

In a resonant or acoustic detector, the gravitational waves induce a mechanical vibration of the antenna, typically a cylindrical bar, which is then converted into an electrical signal using a transducer. The sensitivity and bandwidth of the detector are determined by the mechanical properties of the bar, its temperature, the transducer properties and the effect of various noises. The most noticeable progress of the bar detectors in the recent years has been the widening of the bandwidth from a few Hz to several tens of Hz.

AURIGA Explorer, Nautilus

Since current resonant detectors are sensitive to signals with a frequency around 1 kHz, and given their sensitivity, the typical sources that could be expected to be observed are galactic supernovae or millisecond pulsars. The expected event rate being low, a good duty cycle with years of data taking is required, and a network analysis is mandatory to reject fake events. This is the present strategy followed with the detectors AURIGA, Explorer, Nautilus.

MINIGRAIL

SFERA

A way to improve the sensitivity is to increase the detector masses or to change their shape. The MINIGRAIL spherical detector (Leiden, Netherlands) is exploring a new shape with a 1.4-ton sphere having a resonant frequency of 2.9 kHz. The proposal to build a two-metre diameter spherical detector of 33 tons called SFERA has been explored by Italian, Swiss and Dutch groups. With this kind of heavier sphere, the frequency band could be around 1 kHz. The advantage of the sphere is the measurement of all components of the gravitational wave tensor with the same detector. However, the expected sensitivity is no better than that of the upgraded interferometers. Considering the available resources, the INFN, as the potential funding agency for this project, has recently decided not to pursue it.

DUAL

Another possible detector is a dual-resonator detector (DUAL). At the quantum limit a DUAL detector of 16.4 tons, equipped with a wide area selective readout, would reach a sensitivity similar to that of the *advanced* versions of LIGO and Virgo between 2-6 kHz, a frequency range where signals from merging or ring-down of compact objects are expected. The DUAL detector involves many new ideas and technologies. An R&D program carried out by the AURIGA group has started to investigate and demonstrate the feasibility of such innovative detectors.

Ground Based Interferometers

Interferometers detect gravitational waves by measuring the distance variation between undisturbed mirrors following free geodesics in space-time. Their sensitivity depends on the interferometer arm length and is limited by the residual motion of the mirrors (typically due to seismic activity, thermal noise, radiation pressure noise) and the limitation of the distance measurement (typically photon shot noise). Of course, the mitigation of technical noises is critical. Ground based interferometers are sensitive to gravitational waves in the audio-frequency band ranging from a few Hz up to several kHz.

The ground-based interferometers will have access to a variety of astrophysical sources of gravitational waves. Examples are "inspiraling" neutron star (NS) and black hole (BH) binaries. This is a rich topic since the inspiral waves will reveal the bodies' masses and spins and will enable precision tests of General Relativity at post-Newtonian orders. We can learn about the dynamics of space-time under the extreme circumstances of BH-BH mergers and ring-downs by comparing observations with supercomputer simulations. NS binaries will be detectable up to a distance of about 30 Mpc for initial Virgo or LIGO, with event rates predicting an upper bound of 1 event per 3 years for binary neutron star coalescences and 1 per year for BH-BH coalescences.

Given our current understanding of the expected event rates, gravitational wave detection is not guaranteed with the initial interferometers. Thus a mature plan exists for planned upgrades to the existing detectors systems to create '*enhanced*' and '*advanced*' detector systems, such that the observation of gravitational waves within the first weeks or months of operating the *advanced* detectors at their design sensitivity is expected. They are described below in more detail.

Figure 6.1: *Aerial view of the Virgo interferometer*

GEO, VIRGO, LIGO

GEO600 and Virgo completed construction in 2003. They are now in the late stages of commissioning, and although they are not yet operating at their design sensitivity, they have already achieved sensitivities better than the resonant detectors. Present and planned science runs of these detectors are indicated in Fig. 6.2.

The year 2006 was devoted to the improvement of detector sensitivities and the first long data taking period, with GEO joining the long science run of the LIGO interferometers that started in November 2005. The LIGO interferometers have been built with less sophisticated suspensions and without the technique of signal recycling implemented in GEO600. They are now operating at design sensitivity. From January to October 2006, GEO600 participated in the LIGO science run. It then returned to detector commissioning in order to be prepared to cover, with improved sensitivity, LIGO's downtime in late 2007 and 2008. In that period, the LIGO detectors will be upgraded to create an enhanced LIGO system. Virgo will continue its commissioning process into 2007. In summer 2007, an agreement between all of the gravitational wave detectors worldwide will be sought, with the aim of optimal coverage of the upgrading downtimes. The upgrade of Virgo to an *enhanced* 'Virgo+' design in the second half of 2008 will be followed by an extended science run with worldwide participation. It is expected that during the following years, GEO600 and Virgo will be in observation mode for the majority of their operational time. However, various detector upgrades are foreseen since sensitivity improvements are critical to guarantee a first detection and increase the number of reachable sources. Obviously, upgrade periods need to be carefully coordinated between detectors to maximize the possible science output.

Worldwide network

Close coordination and collaboration between the various detector teams opens the possibility of a continuous observation of gravitational waves over the coming years. It also enables an efficient network data analysis. A worldwide network of detectors is essential for *a)* achieving a low false alarm rate and *b)* locating signal sources in the sky. A global network is a common goal of all projects and is ensured by mutual Memoranda of Understanding that have been signed or are in the process of being signed.

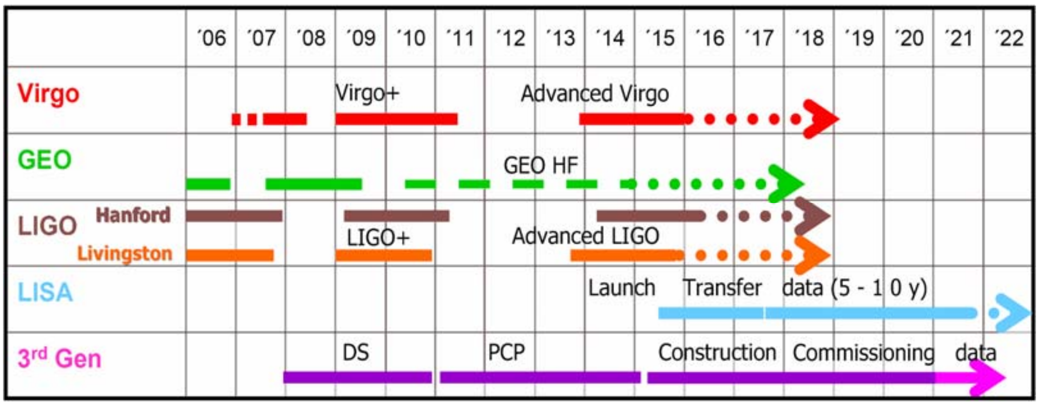


Figure 6.2: *Timeline of current detector operation and planned detector upgrades. The solid lines for the existing detectors indicate data taking times. In the regions of dotted lines the mode of operation is not yet defined. In the scenario shown, LISA will be launched in 2015 and start data taking in 2017 for a duration of at least 5 years. Limited by the supply of consumables this period may be extended up to 10 years. The 3rd generation plans start with a 3 year design study in 2008, followed by a 4 year preparatory construction phase. Construction and commissioning will last for 6 years and allow data taking from 2021 onwards.*

VIRGO+

The first set of improvements for Virgo corresponds to changes that do not modify the overall interferometer layout. Consequently, the corresponding installation could be of relatively short duration. This includes an increase in laser power, some mirror suspension changes, tuning of various parameters, and an upgrade of the control systems. The expected sensitivity gain is typically a factor 3 (in amplitude), which converts to a factor 3^3=27 for the event rate increase, as gravitational wave detectors observe signal amplitude, which falls off as 1/distance, and not intensity, which falls off as $1/(\text{distance})^2$. These upgrades are modest enough to be funded within the operation cost and will take place in 2008 for VIRGO+.

Advanced LIGO, Advanced VIRGO

More ambitious upgrade programs are planned to create *Advanced* LIGO and *Advanced* Virgo detector systems. The goal in each case is a sensitivity improvement of roughly one order of magnitude with respect to the initial instruments (about three orders of magnitude *rate* improvement for extragalactic events). In both cases, significant changes of the optical setup are foreseen. In addition, the LIGO seismic isolation system will be completely rebuilt to extend the observation band down to about 10 Hz, a value which will essentially match the performance of the currently installed Virgo seismic isolation. The *Advanced* LIGO construction proposal is fully peer-reviewed and is approved by the National Science Board, with capital contributions from the UK and Germany already in place. The proposal and costing for *Advanced* Virgo is expected to be completed by the end of 2007, followed by construction and installation around 2011. The *advanced* interferometers are expected to be in operation around 2013. On a similar timescale and with similar target sensitivity, an underground, cryogenic interferometer, *LCGT* is proposed for installation in the Kamioka mine in Japan.

GEO-HF

GEO600 will go through a series of small upgrading steps (laser power, upgrade to a basically digital control system, 'squeezed' light, mirror changes) between 2009 and 2013 and will evolve to GEO-HF, a detector tailored to ***H***igh ***F***requencies above 500 Hz.

European contributions to LIGO

European efforts are not restricted to the local instruments Virgo and GEO600. Besides pioneering Signal Recycling (a technique that will be used in all *advanced* detectors), the GEO team will provide to *Enhanced* and *Advanced* LIGO the high power laser systems and the quadruple suspensions with fused silica fibres for the last suspension stage. The Laboratoire des Matériaux Avancés, a coating facility built for coating the mirrors for Virgo and now producing the best coatings worldwide, will provide the coatings for the mirrors of *Advanced* LIGO.

The road toward third generation Interferometers

The era of *advanced* ground-based interferometers will see gravitational wave observations firmly embedded in the wider field of astronomy and astrophysics. Enhancing detector performances beyond those achievable with the *advanced* instruments will then become pressing to fully realise the potential of gravitational wave astronomy by making it possible to continuously observe the distant, dark, dense and catastrophic Universe. Thus preparations are needed now to pave the way for new '3rd generation' interferometric detectors. Since the *advanced* versions of the present interferometers will start reaching some fundamental limits of their facilities, *e.g.* due to the seismic environment, the preparation of a new generation of interferometers envisages a new, seismically quiet underground facility. The typical sensitivity target is an order of magnitude better than that of *Advanced* LIGO and Virgo (again three orders of magnitude in event rate), with the seismic cut off going down to about 1 Hz (see figure 6.3). This new facility will be a dramatic step and allow Europe it to play a key role in what will then be the field of gravitational-wave observational astronomy.

The underground option

The additional science possible with third generation detectors would have an enormous impact in several key areas of astrophysics, cosmology and fundamental physics. For example, third generation detectors, with ten times better sensitivity than the *advanced* detectors, would measure to a few percent or better, the masses, sky positions and distances of binary black holes (BBH) with stellar- and intermediate (i.e. a few hundred times solar) mass, out to a redshift of z=2 and z=0.5, respectively. Compared to *advanced* detectors the event rate of BBH coalescences increases by several hundred to a few thousands per year, depending on the total mass of the system. It is important to note that only a network of detectors could determine sky positions and distances to this precision, and it is expected that such detectors would be constructed in Europe, the US and, perhaps Australia and/or Japan.

Observation of intermediate-mass BBHs would provide an inventory of the recent history of black hole formation in the universe and give vital clues to the role of black hole 'seeds' in galaxy formation and evolution. When combined with the redshift of their electro-magnetic counterpart, BBHs would also provide an absolute, physical calibration of the Hubble constant to a precision significantly better than from traditional 'standard candle' methods and completely bypassing the lower rungs of the cosmic distance scale.

Third generation detectors would facilitate high precision tests of General Relativity that are not possible with solar-system or binary pulsar observations. By probing the highly curved structure of space-time near dense objects we would be able to answer fundamental questions about the final fate of gravitational collapsing (is it a rotating black hole or a naked singularity or some other exotic object?) and confirm if the emitted signals from such events are consistent with general relativity to very high order in post-Newtonian perturbation theory.

Design study for third generation interferometer

A design study for such a third-generation facility was made in the FP6 framework as a joint proposal from European groups working on gravitational waves searches. At that time the proposal was considered slightly premature and thus did not receive funding. However with current interferometric detectors now operating at or close to design sensitivity, and plans now mature for second generation instruments, it is imperative that in Europe sufficient planning and preparatory R & D be carried out to enable the construction of a European 3rd generation instrument on the appropriate timescales.

This process is in progress through the increased European-wide collaboration and co-operation enabled under two currently active FP6 'ILIAS-Integrated Large Infrastructures for Astroparticle Science' awards: the 'STREGA' project focussed on research and development crucial for improving thermal-noise limited sensitivity in interferometric detectors, and the 'GWA' gravitational wave network, enabling co-operation between European groups on detector commissioning, data-analysis and planning for future instruments.

The community is thus united behind a proposal for a design study for a new 3rd generation facility which will be submitted as part of the upcoming FP7 framework call. This proposal is being prepared by the ILIAS GWA network and is intended to start in 2008 and last for 3 years. The outcome of this work will be a conceptual design of the facility (including a selection of possible sites), followed by a more detailed preparatory construction phase to be in a position to start construction around 2014. The design study will include conceptual aspects of the observatory to show that the envisaged sensitivity can be reached with the techniques, the funding and on the timescales foreseen.

Cost

The cost for the current baseline configuration is estimated to about 300 M€. Until then, construction and operation of the ground based detectors LIGO, Virgo, and GEO will have accumulated to about 1000 M€. This is the time when the *advanced* interferometers will be in operation and the observation of gravitational waves should have become a routine task with improved detectors required to increase the range and variety of astrophysical objects under study and keep Europe at the forefront of this field.

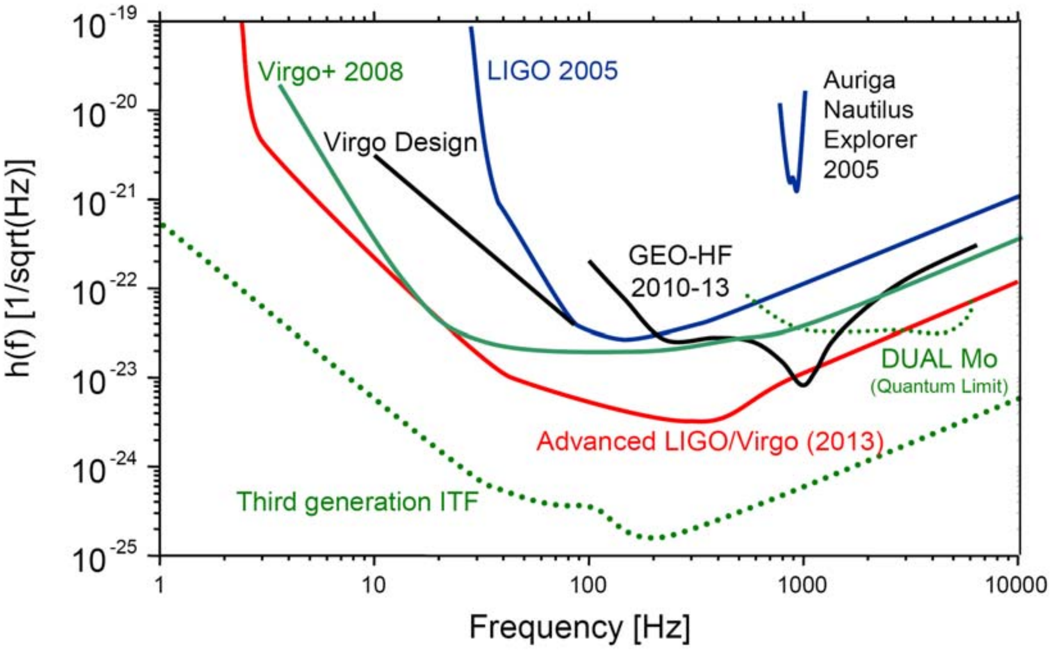


Figure 6.3: *Current and expected sensitivities for ground-based gravitational waves detectors. The solid curves correspond to existing detectors and their expected upgrades. Advanced devices are expected to detect between a handful and about thousand objects of the BH-BH, NS-BH and NS-NS merger type per year. Dotted lines are for new projects. The position of the minimum in the GEO curve could be tuned at run time. The Third generation ITF curve is a very preliminary estimate. Such a device is expected to detect between thousand and hundred thousand. merger events per year.*

Space-based detectors: LISA

LISA and LISA-Pathfinder

The frequency domain much below one Hz can be only explored from space. There is currently an approved ESA-NASA mission, LISA, which is scheduled for a launch around 2015. After the transit, to the final orbit LISA will be ready for taking data in 2017 (see also the scenario of Fig. 6.2). LISA involves three spacecraft flying approximately 5 million kilometres apart in an equilateral triangle formation. These very long arms allow to cover a frequency range of $3 \cdot 10^{-5}$ to 1 Hz, complementary to the frequency window covered by ground-based instruments. It makes LISA ideally suited for the study of super-massive black holes mergers, galactic compact binaries and potentially the signatures of new physics beyond the standard model. Prior to LISA, the *LISA Pathfinder* mission, to be launched in 2009 by ESA, will test some of the critical new technology required for the instrument.

LISA science

LISA will record the inspirals and mergers of binary black holes throughout the Universe, allowing a precise mathematical understanding of the most powerful transformation of energy in the cosmos. It will map isolated black holes with high precision, verifying that they can be completely specified by four numbers: mass and the three components of spin. With its enormous reach in space and time, LISA will observe how massive black holes form, grow, and interact over the entire history of galaxy formation. It will measure precise, gravitationally-calibrated, absolute distances up to very high red-shifts and such contribute in a unique way to measurements of the Hubble constant and of Dark Energy. It will measure the 3D positions and orbital properties of thousands of compact binary systems in the Galaxy, providing a new window into matter at the extreme endpoints of stellar evolution. In fact the LISA census of super-massive black holes and galactic compact binaries will be complete! Any merging super-massive black hole in the observable Universe will be detected. Above a few mHz, where the Galactic binaries become individually detectable, LISA will observe all sources in the Galaxy. This allows statistical studies that are not hampered by biases that are often difficult to account for. In addition, several LISA events will likely have electro-magnetic counterparts at a wide variety of timescales and wavebands that will stimulate major new observing opportunities across the electromagnetic spectrum. It is also conceivable that LISA will discover new phenomena of nature, like phase transitions of new fields, extra dimensions or string networks produced in the relativistic early Universe.

7. Recommendations

1. Dark Matter and Dark Energy

1.1 Dark Matter

The problem of understanding the nature of the cosmological and Galactic Dark Matter is of central importance for our understanding of particle physics and the Universe around us. The simplest solution to the Dark Matter problem assumes weakly interacting massive particles, thermally produced in the Early Universe, the most notable candidate being the lightest super-symmetric particle, the neutralino. These particles can be searched for in the LHC experiments, although evidence for super-symmetric particles in accelerators does not imply their existence as dark matter. Their presence as the main component of our Milky Way halo can be detected with both direct and indirect methods, covering for a large fraction of the best motivated theoretical models. Indications of a possible signal have been reported by the DAMA group, and an upgraded version, DAMA-LIBRA, is presently taking data. Another ongoing experiment at a different site (the ANAIS project) might provide a valuable cross check. Present best limits for the spin-independent cross section of neutralino WIMPs have been obtained by the CDMS experiment (USA) and are expected to be improved, by CDMS itself and by European experiments, by another order of magnitude (down to $\sim 10^{-8}$ pb) over the next two years.

Detectors of nuclear recoil with a threshold of few keV, excellent background suppression, and a mass of order one ton, can reach a sensitivity of 10^{-10} pb and cover an important fraction of the parameter space of existing models. The efforts made in this direction by the groups that use bolometric techniques (CRESST and EDELWEISS) to converge to a single very competitive proposal (EURECA) are strongly supported. A technical proposal is expected in 2009/2010. The development of noble liquid techniques (at present ZEPLIN and XENON using xenon, and the projects WARP and ArDM exploring argon) can provide complementary means to reach detectors with a ton-scale. Convergence towards a single proposal for a large-scale facility with ultimate sensitivity based on the noble liquid technique is strongly encouraged. The preferred scenario includes a cryogenic and a noble liquid low-background experiment on the one-ton scale with a European lead role, as warranted by results from the 100 kg scale detectors. The use of different techniques with different systematics and of different targets would strengthen the physics interpretation considerably.

Smoking guns for the direct detection of WIMPs are target dependence, annual modulation and directional dependence of a signal. An anual modulation has been observed by DAMA, and the collaboration is working on R&D for a 1-ton NaI version after DAMA-LIBRA. The detection of a signal by *non*-directional, large mass detectors would call for the definitive proof that it is of galactic origin. This proof could be provided by a massive directional device. Further development of the corresponding technique (like that of the DRIFT collaboration) is therefore important and should be supported.

The progress made over the last few years is impressive, and extrapolating to the future one concludes that there is a significant chance to detect WIMPs in the next decade –

provided the necessary progress in background rejection for large target masses can be achieved
Direct searches for Dark Matter are accompanied by a broad program on indirect Dark Matter search, performed with gamma and neutrino telescopes and with balloon and satellite detectors The AMS detector belongs to the last class and is scheduled for a three-year flight on the International Space Station. It is expected to provide a wealth of data on dark matter search, antimatter and cosmic ray physics.

We recommend that decision makers take the necessary steps to assure operation of AMS.

Another theoretically well-motivated particle candidate for cold dark matter is the axion. Direct search experiments for galactic dark matter axions using the cavity technique are pursued in the USA and Japan. In Europe, a search for solar axions is performed with the CAST experiment at CERN. This search covers a range of axion parameters which would correspond to a hot dark matter particle, similar to neutrinos. Therefore, CAST is complementary to the US and Japanese efforts.

The CAST experiment should be continued to cover the full range of axion masses that is accessible by this technique.

1.2 Dark Energy

The nature of dark energy is one of the most important problems in physics and cosmology today. So far, dark energy can primarily be explored through its influence on cosmic evolution. Observations in this area traditionally use astronomical techniques , but particle physicists, both experimentalists and theorists, have joined this new field and are playing a major role. In the USA, there is presently a broad engagement of the particle physics community in two large DE projects, SNAP and LSST.

There is growing activity in the astroparticle physics community in Europe in this area, and initiatives to address this question together with the astrophysics and cosmology communities are encouraged.

2. Particle Properties

2.1. Direct measurement of the neutrino mass

The measurement of beta-decay spectra near the endpoint allows a direct kinematical determination of the neutrino mass without model assumptions.

We strongly support the construction of the KATRIN beta spectrometer to increase the sensitivity by one order of magnitude, down to masses of 0.2 eV.

Bolometers have not yet reached their technological limit and may eventually go beyond the projected sensitivity of KATRIN. Their potential should be further explored and R&D should be supported.

2.2 Mass and nature of neutrinos from Double Beta Decay

A clear signal of neutrino-less double beta decay would establish that the neutrino is its own antiparticle (Majorana particle) and constrain the absolute scale of the neutrino mass. There are three possible mass ranges, two of them (corresponding to the "degenerate" and the "inverted hierarchy" scenario, respectively) being accessible with present techniques. Existing experiments like CUORICINO and NEMO-3 are exploring masses of the order of $\geq$ 500 meV, belonging to the range of the first of these mass intervals: They could address - but not fully disprove - a recent claim on a positive observation derived from data taken with the Heidelberg-Moscow detector.

The European detectors which are expected to start operation within the next 5 years and merit clear support are GERDA, CUORE, Super-NEMO and possibly COBRA (mass range 50-100 meV). With these detectors, Europe will be in the best position to improve sensitivity and maintain its leadership in this field and clearly prove or disprove the mentioned claim.

Only even larger, future-generation detectors, with an active mass of order one ton, good resolution and very low background, can cover the second possible mass range (inverted mass hierarchy) and reach the level of 20-50 meV. Different nuclear isotopes and different experimental techniques are needed to establish the effect and extract a neutrino mass value. We recommend a strong participation of Europeans in the future-generation detectors with a sensitivity down to 20 meV. Decisions on these detectors are due in the first half of the next decade.

We also recommend a vigorous program, based on both theoretical and experimental investigations, to assess and to reduce the uncertainty of nuclear matrix elements, at least for a few key nuclei.

2.3 Study of Neutrino Mixing Parameters

The structure of the neutrino mass matrix, describing the mixing between different neutrino flavours, is of great importance for particle physics and cosmology. Future measurements with neutrinos from the Sun, supernovae or other astrophysical objects, coupled with those generated in the Earth's atmosphere will not only provide a deeper understanding of their sources, but also improved information on the neutrino mixing and fundamental properties. Precision data on neutrino mixing are expected from dedicated experiments with neutrinos generated in reactors and in accelerators.

The high precision measurement of the electron anti-neutrino spectrum from nuclear reactors provides unique information complementary to accelerator experiments. The European "DOUBLE CHOOZ" experiment at the Chooz nuclear power reactor appears to be the most advanced project of this type. In order to maintain this leadership and to make use of the discovery opportunity it should be built as soon as possible.

2.4 Search for Proton Decay

The detection of proton decay would be one of the most fundamental discoveries for physics and cosmology. Proton instability is predicted by most extensions of the Standard Model. An improvement of an order of magnitude over the existing limits explores a physically relevant range of lifetimes. The design for a detector with this capability appears possible, but requires careful studies to optimize the methods and choice of the most promising technology.

We recommend that a new large European infrastructure is put forward, as a future international multi-purpose facility on the 10^5-10^6 ton scale for improved studies proton decay and of low-energy neutrinos from astrophysical origin. The three detection techniques being studied for such large neutrino detectors in Europe, Water-Cherenkov (like MEMPHYS), liquid scintillator (like LENA) and liquid argon (like GLACIER), should be evaluated in the context of a common design study which should also address the underground infrastructure and the possibility of an eventual detection of future accelerator neutrino beams. This design study should take into account worldwide efforts and converge, on a time scale of 2010, to a common proposal.

3. Low energy neutrinos from the Sun, Supernovae and the Earth

Low energy neutrinos are produced in many natural sources, among them the core of the Sun, supernova explosions, and the Earth interior. Their study has provided information on both the source dynamics and - together with the investigation of neutrinos from artificial sources - the properties of the neutrinos themselves. With GALLEX and GNO, Europe has played a leading role in the discovery of neutrino oscillations. European groups have also played a significant role in developing other technologies for low energy neutrino detection. With GALLEX closed, there is no running solar neutrino experiment in Europe until BOREXINO will start data taking. The presently running detectors with good Supernova detection capability and European participation are LVD (Gran Sasso), IceCube/AMANDA (South Pole) and SNO (Canada).

We recommend that BOREXINO is completed and starts operation as soon as possible, and that the technical and personal support needed to ensure full operation is provided.

Any major neutrino experiment with a mass on the scale of Super-Kamiokande or larger should be multi-purpose and thus discussed in a larger context than low-energy neutrinos. This context should include proton decay, solar, atmospheric and supernova neutrinos, and possibly accelerator neutrinos. **See for the corresponding recommendation section 2.4.**

4. The non-thermal Universe

4.1 High-energy cosmic rays

The study of ultra-high energy cosmic rays addresses important physics problems and requires a sustained long-term programme.

We recommend that the present efforts, mainly focused in the Southern Pierre Auger Observatory with a 50% European contribution, be pursued with vigor.

The interplay of source distribution, energy spectrum and propagation through background radiation and magnetic fields requires both detailed theoretical modeling and a careful study of the arrival directions of cosmic rays with full-sky coverage. This is the main motivation for a Northern Auger site.

We recommend that European groups play a significant role to establish the scientific case, and, after its consolidation, make a significant contribution to the design and construction of a Northern Auger Observatory.

The development of novel cost effective techniques with large aperture and particle identification would provide a useful redundancy to the present detectors. One such approach could be the radio detection of air showers as pursued by the LOPES (later LOFAR) and CODALEMA collaborations. We recommend support of R&D for these new technologies.

We appreciate the inclusion of ultra-high energy cosmic rays into the ESA *Cosmic Vision 2015* programme, which provides a frame to study the scientific case, technical design and timeliness of space based detectors for ultra high energy radiation

The interpretation of air-shower measurements depends on an understanding of high-energy interaction models.

The impact of measurements at accelerators, particularly at the LHC, should be evaluated in close cooperation with the particle physics community.

There is a gap of about one decade of energy between the measurement of cosmic rays by the air-shower technique (e.g. with KASCADE-Grande, Tunka and IceTop) and the direct detection of primary cosmic rays above the atmosphere, e.g. by balloon experiments like TRACER and CREAM and satellite detectors like Pamela and AMS.

Efforts to brigde the gap between present direct and air shower detection methods (with large-aperture, long duration flight missions above the atmosphere and/or by ground detectors with sufficient particle identification placed at highest altitudes) should be encouraged.

4.2 High energy neutrinos

European physicists have played a key role in construction and operation of the two pioneering large neutrino telescopes, NT200 in Lake Baikal and AMANDA at the South Pole. They are also strongly involved in AMANDA's successor, IceCube. With the projects ANTARES, NEMO and NESTOR as seed, a strong community has grown over the last decade, with the goal to prepare the construction of a large underwater telescope in the Mediterranean. An EU-funded 3-year study (KM3NeT) is in progress to work out the technical design of this future installation by early 2009. Prototype installations (NESTOR, NEMO) and an AMANDA-sized telescope (ANTARES) are expected to be installed in 2006/2007.

For a complete sky coverage, in particular of the central parts of the Galaxy with many promising sources, we strongly recommend to work towards a cubic kilometre detector in the Northern Hemisphere which will complement the IceCube detector. Resources for a Mediterranean detector should be pooled in a single, optimized large research infrastructure "KM3NeT". Start of the construction of KM3NeT is going to be preceded by the successful operation of small scale or prototype detector(s) in the Mediterranean. It's design should also incorporate the improved knowledge on galactic sources as provided by H.E.S.S. and MAGIC gamma ray observations, as well as initial results from IceCube. Still, the time lag between IceCube and KM3NeT detector should be kept as small as possible.

Based on AMANDA experience, the construction of IceCube with its early high discovery potential is planned to be completed in 2011. Since long, European partners have been playing a strong role in AMANDA/IceCube. They should be supported in order to ensure the appropriate scientific return, as well as a strong contribution to the considered extension of IceCube.

Several promising techniques to detect cosmic neutrinos of highest energy – like radio Cherenkov detection in ice, in the atmosphere or in the moon crust – will be tested with existing detectors; others, like acoustic detection, or radio detection in salt domes, are still in an R&D phase. In order to cover the full range of all possible energies of cosmic neutrinos, exploitation of these techniques is mandatory. The ongoing coordinated R&D work should be supported.

4.3 High-Energy Gamma-Ray Astronomy

European instruments are leading the field of ground-based high-energy gamma ray astronomy. The rich results from current instruments (in particular H.E.S.S. and MAGIC) show that high-energy phenomena are ubiquitous in the sky; in fact, some of the objects discovered emit most of the power in the gamma-ray range and are barely visible at other wavelengths. With the experience gained from these instruments, the need for a next-generation instrument is obvious, and its required characteristics are well understood.

To further explore the diversity of galactic and extragalactic gamma ray sources, construction of a next-generation facility for ground-based very-high-energy gamma ray astronomy (CTA – Cherenkov Telescope Array) is very strongly recommended. It builds on the demonstrated technical maturity and physics case of Cherenkov telescopes. CTA should both boost the sensitivity by another order of magnitude and enlarge the usable energy range. The technology to build arrays of highly sensitive telescopes is available or under advanced development, and deployment should start at the beginning of the next decade, overlapping with the operation of the GLAST satellite.

It is desirable to cover both hemispheres, with one site each. While low-threshold capability is of interest for both, a southern site of the facility should also provide improved detection rate at very high energies, given the flat spectra of galactic sources; this aspect may be less crucial for a northern site concentrating more on extragalactic physics. The instruments should be prepared by a common European consortium and share R&D, technologies and instrument designs to the extent possible. Cooperation with similar efforts underway in the US and in Japan should be explored.

The development of alternative detection techniques, for example techniques based on detection of shower particles at ground level, should be pursued, in particular concerning approaches for wide angle instruments which are complementary to the conventional Cherenkov instruments with their limited field of view.

5. Gravity

The Gravitational Wave field has a huge discovery potential but is still awaiting the first direct detection. Therefore, the effort must be balanced between the quasi-continuous observations and the upgrade of the existing detectors as well as the design and construction of new one(s).

The European community should continue the effort towards integration and should focus its resources on the projects with the largest discovery potential. In the short term, the European ground interferometers (GEO and Virgo) should turn to observation mode with a fraction of their time dedicated to their improvement (GEO-HF, Virgo+ and Advanced Virgo). A continued operation of resonant detectors is desirable in order to limit the effect of the down time of the interferometer network. New acoustic detector concepts should be pursued towards higher sensitivity and broader bandwidth.

We recommend that the design study for a large European third-generation interferometer facility should start as soon as possible. Timely decisions for interferometer installation at the earliest possible date should be made.

The LISA mission will provide gravitational wave observations complementary to those of the ground interferometers. Covering the sub-Hz frequency range, it will enable the exploration of a wealth of sources, both of galactic and cosmological origin and should be actively supported.

6. Multi-wavelength and multi-messenger studies

For virtually all topics, multi-wavelength coverage of radiation sources is a key issue; in particular information at radio, X-ray and lower-energy gamma-ray wavelengths is crucial for the understanding of the processes in the sources. GLAST – serving as an all-sky monitor at lower energies – is an essential element in a multi-wavelength approach towards gamma-ray astronomy. The next decade will likely open the possibility to extend the classical multi-wavelength approach towards a true multi-messenger approach, including charged cosmic rays, photons from radio to TeV energies, neutrinos and gravitational waves.

We recommend close collaboration between the high and low energy gamma communities as well as efforts towards a more general multi-messenger approach including neutrinos, gravitational waves and cosmic rays. This should include experimentalists as well as theorists who both are encouraged to intensify collaboration on multi-messenger studies.

Appendix 1: Members of the Roadmap Committee

- Frank Avignone (USA)
- Thomas Berghöfer (Germany, Steering Committee Observer)
- Jose Bernabeu (Spain)
- Leonid Bezrukov (Russia, Guest)
- Pierre Binetruy (France)
- Hans Blümer (Germany)
- Karsten Danzmann (Germany)
- Franz v. Feilitzsch (Germany)
- Enrique Fernandez (Spain)
- Werner Hofmann (Germany)
- John Iliopoulos (France)
- Uli Katz (Germany)
- Paolo Lipari (Italy)
- Manel Martinez (Spain)
- Antonio Masiero (Italy)
- Benoit Mours (France)
- Francesco Ronga (Italy)
- André Rubbia (Switzerland)
- Subir Sarkar (United Kingdom)
- Günter Sigl (France)
- Gerard Smadja (France)
- Nigel Smith (United Kingdom)
- Christian Spiering (Germany, ***chair***)
- Alan Watson (United Kingdom)

Appendix 2: Statistical data on astroparticle activities in Europe

As a first step towards the roadmap, the state of the experiments in the field was evaluated using a questionnaire filled out by the spokespersons of all astroparticle experiments in Europe, or with European participation. The questionnaires have been collected between July and December 2005, and a compilation of the filled questionnaires can be found at http://www.aspera-eu.org.

The questionnaire provides information on:

- Name of the experiment
- Spokesperson
- Collaborating institutions
- Number of authors
- Number of PhD students
- Location/Infrastructure
- Funding agencies
- Scientific goals
- Design
- Cost
- Present status (R&D, construction, operational)
- Most relevant results
- Perspective (total cost, status of funding, merging with other projects, close R&D relation to other projects, coming relevant reviews, branch points)
- Wich relevant results are expected, and when
- Most actual information (web page etc)

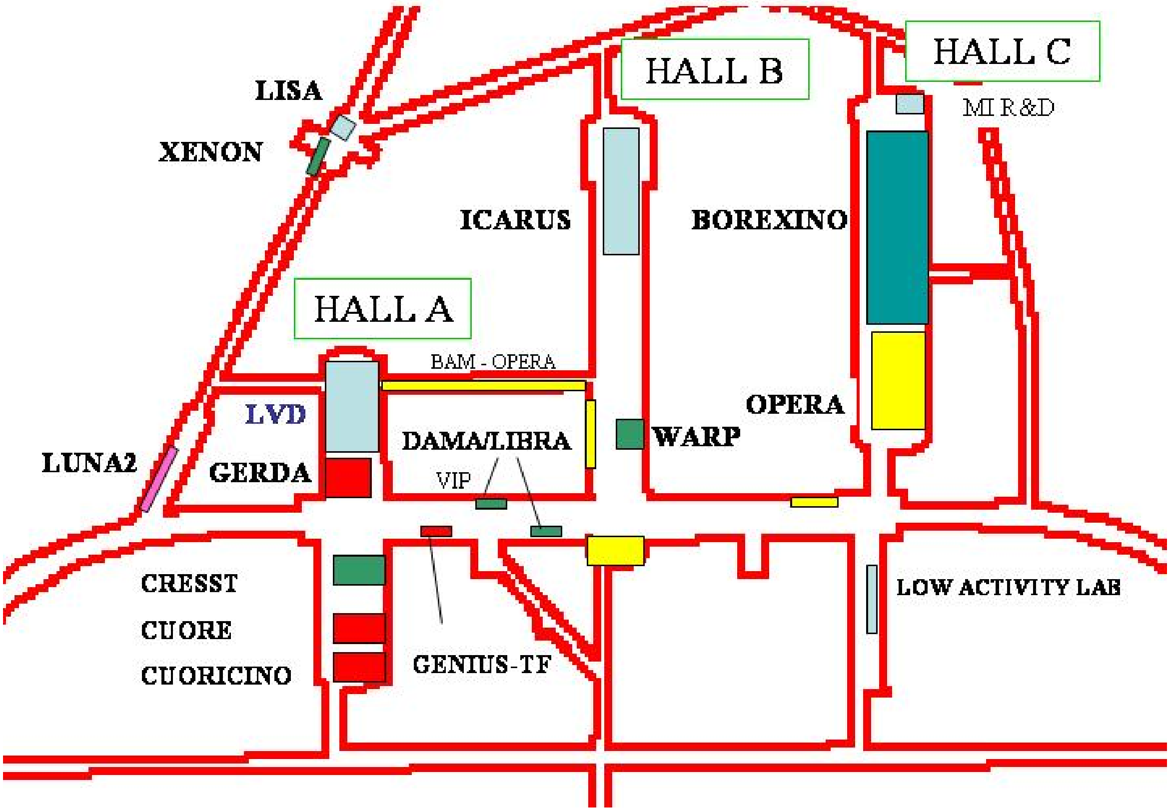
Some of this information will be scrutinized in questionnaires to be filled out by the working groups of ASPERA between February and September 2007. The ASPERA questionnaires will serve as input to the final phase of the present ApPEC/ASPERA roadmap process. The process will be finished in July 2008 by a roadmap document which, rather than repeating the present roadmap with respect to physics background and justification, will focus to actual quantitative data, time line charts, milestones, budget and priorities.

Appendix 3: Infrastructure for underground experiments in Europe

The following summary is to a large part based on work done within the ILIAS initiative and on material which has been provided by Gilles Gerbier, CEA/DAPNIA (France) and Stanislav Mikheev, INR (Russia).

There are five European underground laboratories which have been used in the past and are used presently for astro-particle physics deep underground experiments. A sixth very deep site in Finland is under discussion. Other shallow locations a considered for special applications or as test sites. We describe the six sites in more detail, see also the table for the relevant parameters.

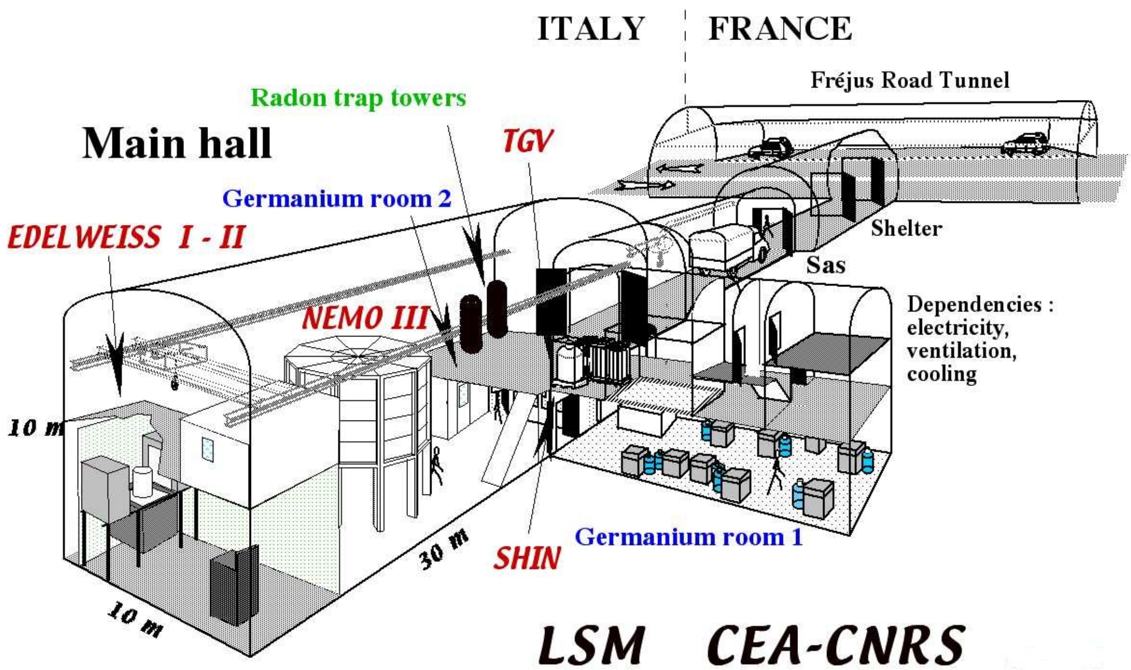
- The ***Laboratori Nazionali del Gran Sasso*** **(LNGS)** is located along the Gran Sasso Motorway tunnel, 120 km East of Rome, 1400 m under the top of the Aquila mountain (3700 metres water equivalent, m.w.e.) and 4.5 km from the tunnel entrance. LNGS is by far the largest of all underground laboratories: its three main halls each cover 2000 m^2 and are interconnected by tunnels which provide additional space for small experiments. The figure sketches the occupancy of halls and tunnels and demonstrates the rich physics programme of this world-class laboratory:



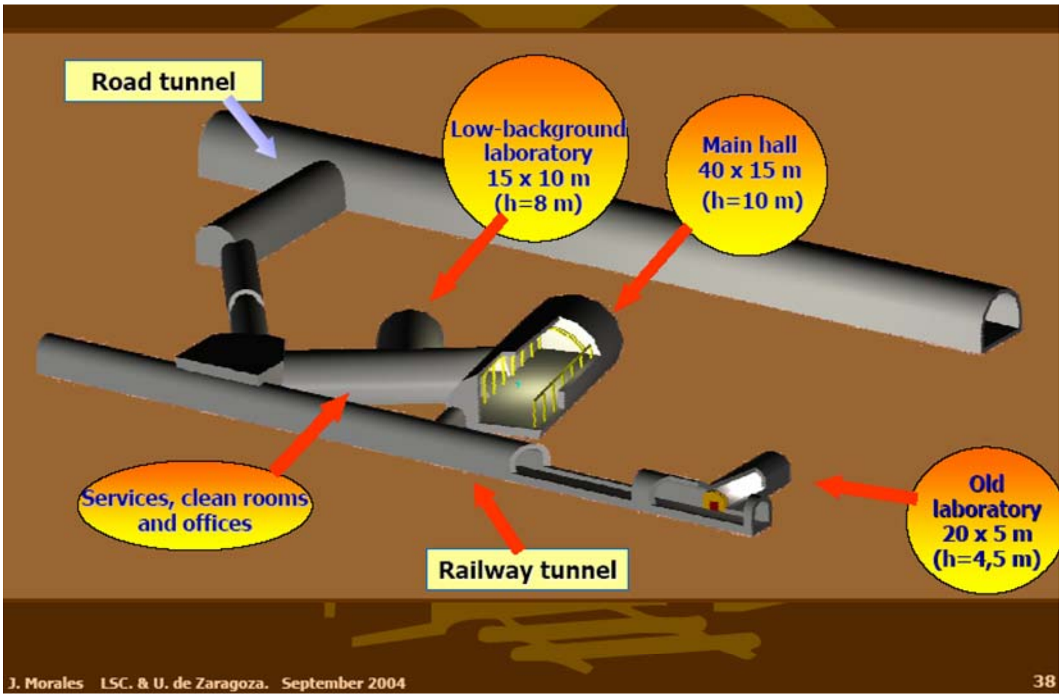
Until 2012, the laboratory will be almost full with the scheduled experiments. Plans for further excavations exist, but prospects are unclear due to sensitive environmental issues. Other sites in the Gran Sasso area, at different depths, are under investigation.

- The ***Laboratoire Souterrain de Modane,*** **LSM,** is located along the Fréjus Road tunnel connecting Italy and France, 1750 m (4800 m.w.e.) under the top of the Fréjus mountain and 6.4 km from the tunnel entrance, and of easy access by road (highway) and train. The present laboratory consists of a main hall with area of 300 m^2 and three additional rooms, altogether an area of 500 m^2 with a volume of 3500 m^3. LSM presently houses the experiments NEMO, Edelweiss, TGV as well as a set of 13 HP Germanium counters for low radioactivity sample measurements. LSM is the deepest of all existing laboratories. Two possible extensions are being investigated:
  - A new laboratory in the 15 000-50 000 m^3 volume range which may house larger experiments like EURECA or Super-NEMO.
  - A giant excavation (or multi-excavation) sufficient to house a Megaton water Cherenkov detector (see also Fig. 4.6)

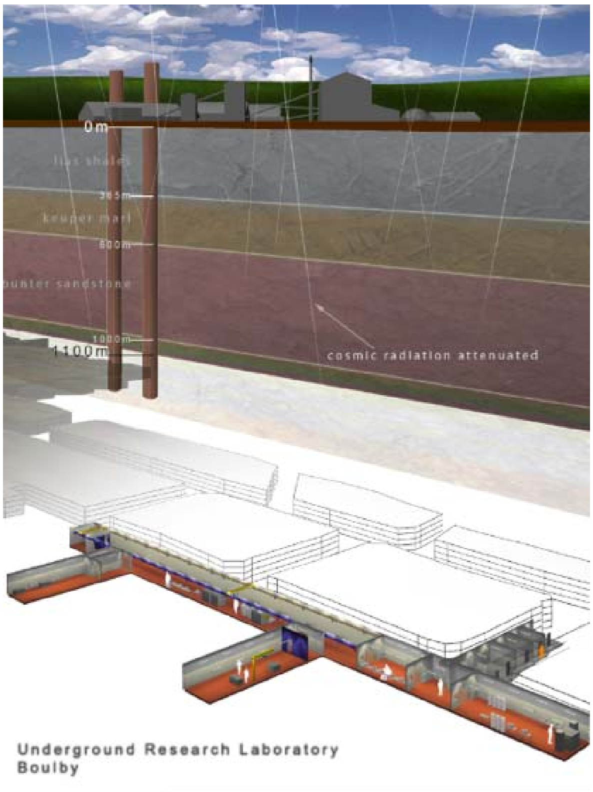
  The decision to dig a new safety gallery along the existing road tunnel has been taken by Italian and French authorities. This will constitute a unique opportunity to excavate with available machines the moderate size extension of the first option in 2011. The prospects for a large megaton excavation await international discussions.

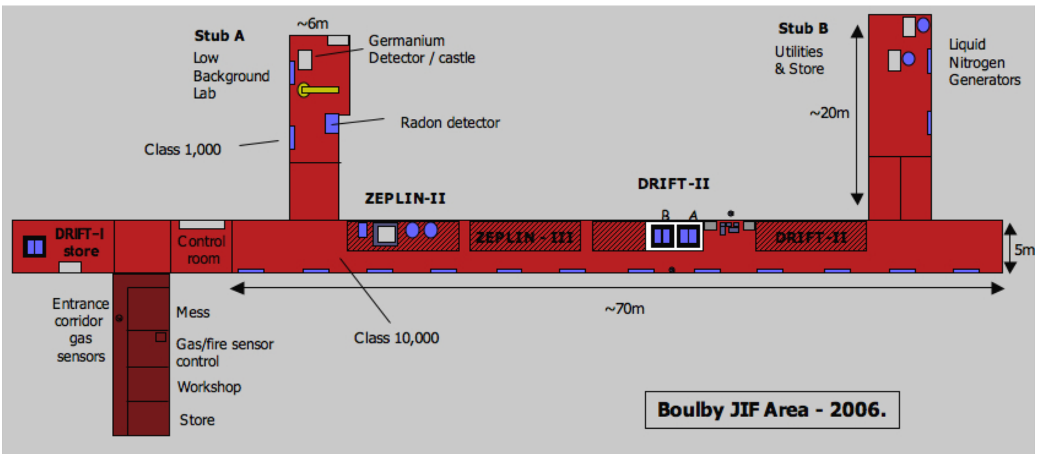


- The ***Laboratorio subterráneo de Canfranc,*** **LSC,** is arranged along the Somport Road tunnel connecting Spain and France, 900 m (2450 m.w.e.) under the Tobazo mountain and 3.4 km from the tunnel entrance. It consists of a the old 100 m^2 laboratory, the new main experimental hall (40x15x11 m^3) and a low background lab (15x10x8 m^3), plus interconnecting and service tunnels. The newly installed lab has been recently inaugurated. The site is the shallowest of deep European sites. There are currently no plans for further, or deeper, expansion of the site in the future, though this is not ruled out. LSC is housing the experiments ROSEBUD, IGEX-DM, and ANAIS. New experiments, ArDM and Super-NEMO, have applied to be housed in the new lab.

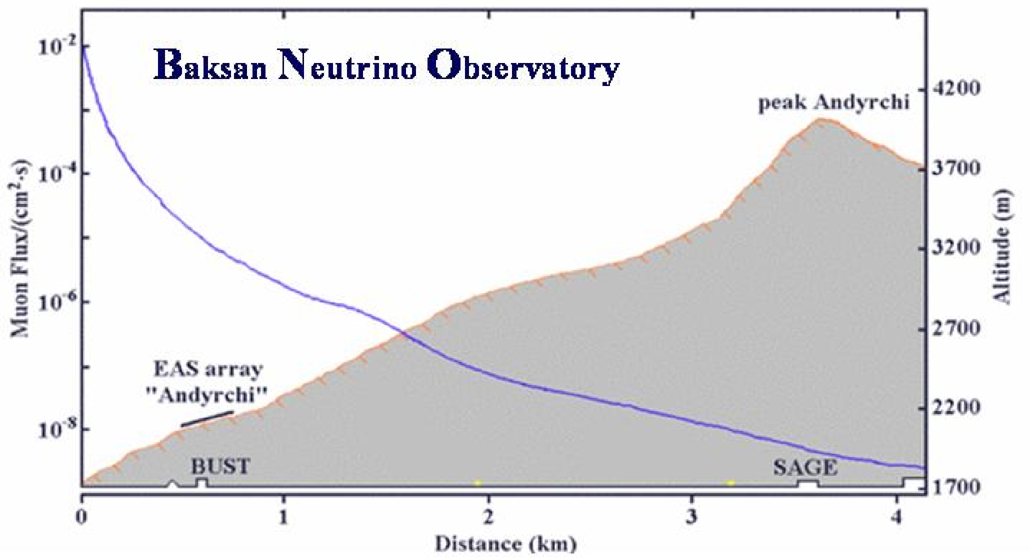


- The ***Boulby Underground Laboratory***, part of the Institute for Underground Science, **IUS,** is located in an operational potash and rock-salt mine on the North-East coast of England, 1100 m below ground (2800 m.w.e.). It is accessible via a Shaft 1 km away. The available area is about 1500 m^2 clean lab space, with a volume of 3000 m^3, housing the dark matter experiments ZEPLIN II and III and DRIFT II. Since the surface profile is flat, the muon flux is comparable to that of Gran Sasso (with its greater depth with respect to the top of the overburden). The Boulby mine contains over 1000 km of tunnels, and excavation of the rock appears to be cheap and easy. Thus, although there are no specific plans for further expansion, the prospects for it are good if desired. The salt structure is best suited for tunnels of 5-10 metre dimensions, although the construction of caverns up to 30 m height seems possible without support structures.

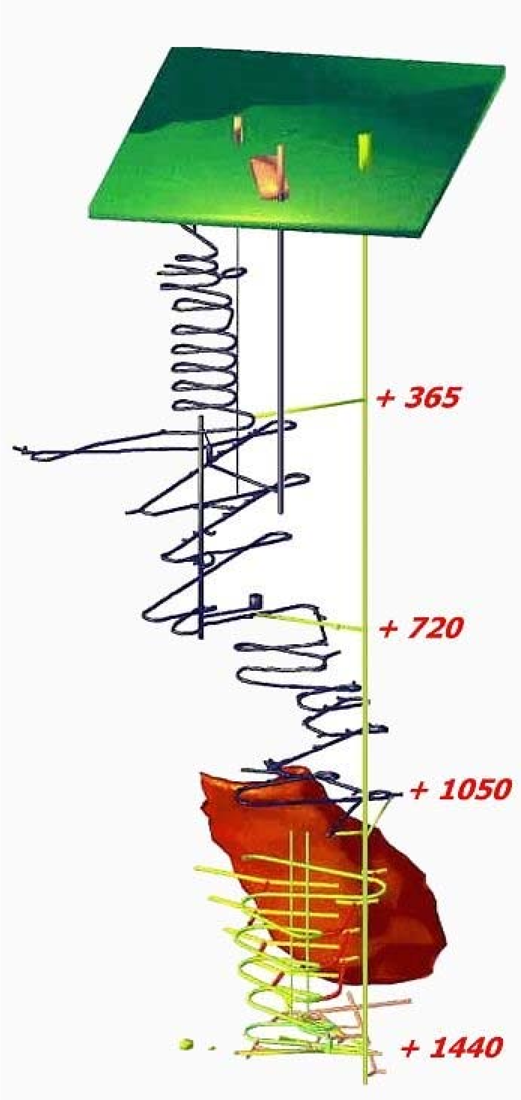




- The ***Baksan Neutrino Observatory*, BNO,** is the oldest of all listed laboratories. It is located under Peak Andyrchi in the Russian part of Caucasus (Baksan valley). Its dedicated tunnel is the first example for a purpose-build deep facility. The Laboratory consists of 2 halls and some small low-background chambers. The first hall houses the Baksan Underground Scintillation Detector (BUST, 850 m.w.e.), the second SAGE, the GaGe experiment (4800 m.w.e.). The construction of a third hall even deeper in the mountain (5100 m.w.e.) has been started a while ago, originally with the aim to house an ClAr experiment. Currently this hall is discussed in the context of a large scintillation detector for solar, supernova and geo-neutrinos. The Baksan laboratory has not been discussed in this roadmap since no Western European groups participate in Baksan experiments. From a physics point of view, the site is certainly attractive. It seems to be less favoured when considering also access and logistical arguments and the sometimes unstable situation in this geo-political region.



- The ***Centre for Underground Physics in Pyhäsalmi***, **CUPP**, has recently joined discussions within ILIAS. Its peculiarity is the access via a truck road going down to large depths. Various small labs have been constructed at different depths (see figure). New excavations have been started in 2001 and are now down to a depth of 1450 m (corresponding to 4060 m.w.e). The muon flux is comparable to that of the LSM (Fréjus). Large caverns at greater depth are possible, and the Finnish group is actively investigating this possibility. CUPP is running test experiments, e.g. detecting cosmic rays at various depths. Because of the vertical entrance and the large depth, the site is environmentally robust and can safely host experiments with large amounts of liquids like LENA. Although not as remote as the Baksan Lab, CUPP is not central. However, this may turn out to be a slight advantage in the context of Long Baseline Experiments and detection of geo-neutrinos (the latter requiring a background from reactor neutrinos which is as small as possible).



Two small shallow laboratories exist in the Ukraine, both in salt mines, the one dedicated to rare decays, the other housing a small (130 m^3) Supernova scintillation detector. The Laboratoire Souterraine Bas Bruit (LSBB) in France is a small site at 1500 m.w.e. depth housing the SIMPLE experiment. Salt mines at other places in Europe are discussed, for instance in the context of acoustic or radio detection of neutrinos.

Which of the large experiments will be done at which site has to be decided over the next years. Strong activities are under way within ILIAS, in the labs and within the individual experiments. Clear recommendations are premature. Nevertheless, we reflect some considerations in the final paragraphs:

The next Dark Matter experiments will require low neutron backgrounds, for which depth is an advantage to reduce cosmic ray muon initiated neutrons. Calculations show, however, that an 95% effective muon veto can reduce the neutron background as much as additional ~2 km.w.e. would do. The Radon background should also be taken into account. A new low background cavity should be not only deep but also have an integrated shield against radioactivity.

Double beta decay is searched for using two methods : tracking devices like super-NEMO, and calorimeters of the bolometric or Germanium type. The former seem to be less sensitive to neutrons and can be hosted by a shallower site, e.g. Canfranc (although there the present space is not large enough for the full scale experiment). For the full Super-NEMO, a future larger Fréjus cavern seems more appropriate. Calorimetric detectors are more sensitive to neutron background and would benefit by being hosted at the deeper sites.

Large neutrino and proton decay detectors (water, scintillator, liquid argon) will need new cavities (at least 100000 m^3), CUPP/Pyhäsalmi may be able to provide this, but is remotely located. Fréjus is a good candidate for large cavities (dry and stiff rock, low convergence, as shown by pre-studies). There are good prospects for synergy with low background experiments and also with long baseline experiments using neutrinos from CERN. Compared to CUPP, there is a local team trained to run such installations, providing synergy also with CERN.

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 promotes 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 specific features of each site. For example: Gran Sasso for medium-sized experiments requiring large horizontal access; Fréjus for smaller-scale experiments and those that can benefit from extra depth, in future also for medium-sized experiments in an adequately sized lab or for a large Megaton neutrino detector in a huge cavern if worldwide consensus can be reached; Boulby for small-scale experiments, for those suited to tunnel-type excavations, or for those benefiting from clear separation from the general public as offered by a mine site; Pyhäsalmi also by reasons of controlled access and offering the potential for experiments requiring greater height; Canfranc for experiments with small-to-moderate size requiring less stringent shielding against cosmic muons.

Parameters of the six large European Underground sites

Infrastructure ▸	LNGS Gran Sasso	LSM Fréjus	LSC Canfranc	IUS Boulby	BNO Baksan	CUPP Pyhäsalmi
Year of completion	1987	1982	1986, 2005	1989	1977, 1987	1993 (2001)
Area (m^2)	13000	500	150+600	500+1000	550, 600	500-1000
Volume (m^3)	180000	3500	8000	3000	6400, 6500	100-10000
Access	Horizontal	Horizontal	Horizontal	Vertical	Horizontal	Slanted truck road
Depth (m.w.e.)	3700	4800	2450	2800	850, 4800	1050, 1444 up to 4060
Surface profile	Mountain	Mountain	Mountain	Flat	Mountain	Flat
Muon flux (m^{-2} day^{-1})	24	4	406	34	4320, 2.6	8.6 @ 4060m
Neutron flux (>1 MeV) (10^{-6} cm^{-2} s^{-1})	$O(1)$	$O(1)$	$O(1)$	$O(1)$	- , $O(1)$	?
Radon content (Bq/m^3)	$O(100)$	$O(10)$	$O(100)$	$O(10)$	$O(100)$	$O(100)$
Main past and present scientific activities	- DM - ββ - solar ν - SN ν - atmos. ν - monopole - nuclear astrophysics - CRs (μ) - LBL ν's	Eighties: - Proton decay - atmos.ν Now: - DM (Edelweiss) - ββ (NEMO, TGV)	- DM (IGEX-DM, ROSEBUD, ANAIS) - ββ (IGEX)	- DM (Zeplin I,II, III, DRIFT)	*BUST:* - solar ν - SN ν - atmos. ν - CRs (μ) - monopoles *SAGE:* - solar ν	- CRs (test set-up)
Number of visiting scientists	700	100	50	30	55	15

Note: We give only order-of-magnitude values for neutron flux and radon content since these values vary strongly with location in the mine, wall cover, ventilation etc.

Appendix 4: Outreach

Outreach activities are of growing importance in society and turn out to be strategic for the future of basic research. On the one hand the general public needs to be (and wants to be) informed about the exciting developments at the forefront of research: cutting-edge science like astroparticle physics causes curiosity and fascination in the public which eventually may transform to public and political support. On the other hand the continuous demand for well-educated young researchers with a PhD in science or technology, makes it increasingly important to convince young people to study physics, astronomy or related topics. Many students lack a clear view of the prospects and career opportunities that science studies offer. Young children, pupils and students are the top target groups of education and outreach activities; but also teachers should be put into the position to understand the essence of our research which cannot be found in textbooks. Research in astroparticle physics is particularly suited for outreach activities as the developments in this field are related to very basic questions concerning the origin of matter, energy and the universe, which appeal to a broad audience. "Open days" in underground labs or at universities and dissemination of publicity material at these occasions, participation in science fairs, public-interest websites, popular-scientific talks, radio and TV interviews, animated videos, exhibition of scale models or interesting bits of equipment, and posters are traditional means of outreach. In some countries and laboratories, brochures for the public have been published (like the 100-page brochure "Astroparticle Physics in Germany"). The astroparticle community is in close contact with the European Particle Physics Outreach group[1] which is also working on a network and forum for outreach activities.

Recently, a joint astroparticle physics outreach programme in Europe (EUROCOSMICS[2]) has been founded, which brings together outreach efforts in 12 European countries. This platform should also offer excellent opportunities for 'new' participants that recently joined - or are about to join - the European Economic Community. The project combines several programmes among which several aim at at measuring ultra high energy cosmic rays. For instance already in 2001 the Radboud University in Nijmegen, the Netherlands, initiated the *Nijmegen Area High School Array* (NAHSA). Within the framework of this project scintillator detector arrays are constructed, which are subsequently placed at the roofs of a number of local high schools to observe extended air showers. In 2002, NIKHEF in Amsterdam took the initiative further to extend this idea by developing a country-wide network of such cosmic ray detectors. This project, which carries the name HiSPARC[3] (*High School Project on Astro*[*particle*] *physics Research with Cosmics*), is designed as an open network enabling other schools and academic institutions to join. Presently, about 50 high schools are involved, clustered around 6 universities, while both the network of clusters, schools and participants is still expanding. Today similar networks are growing in Sweden, Greece, Belgium, Poland, Russia and Portugal while initiatives are underway in Denmark, the UK, Germany, Italy and Spain. EUROCOSMICS focuses on building a long term scientific/educational collaboration between researchers, high-school teachers and high-school students. Its spatial distribution of clusters and an increasingly dense network of detectors near schools and scientific institutes enable to observe extended air showers with a decent spatial distribution across Europe. Depending on the size of each individual cluster, several of them cover an area wide enough to reconstruct extended cosmic ray air showers resulting from the impact of (ultra-) high energy (i.e. in excess of 10^{16} eV) primary cosmic rays on the earth's atmosphere. At the same time, coincidences among the clusters may be studied.

[1] http://eppog.web.cern.ch/eppog/
[2] See: http://www.eurocosmics.org/
[3] See: http://www.hisparc.nl/

Moreover, dedicated clusters, those that are more densely populated with detection stations, enable studies on density fluctuations within the extended air showers. The unknown nature and not very well understood composition of this specific class of cosmic rays underlines the state-of-the-art scientific component of the research. The innovative character of this approach was recognised in 2004 in which year HiSPARC was distinguished with the Altran Foundation prize[4], after winning a European competition with the theme: '*Discovering, understanding and enjoying science through innovation'*.

The goal of the teams participating in EUROCOSMICS is to involve high-school students directly at all stages of scientific research. The project provides first-hand experience in scientific measurements and teamwork. The high-school students construct their own (in majority scintillator) detector under supervision of a scientist at one of the participating universities or scientific institutes. At the same time, this will provide them an 'inside view' on the day-to-day activities in these centres. Next, the detectors are tested, calibrated and installed at the student's school. The detection stations are connected via internet to a central regional data base, which is freely accessible for all participants. One of the EUROCOSMICS challenges is to establish a transparent, distributed database storage including access and analysis tools applicable across Europe. Schools, universities and research institutions involved contribute to the project by providing students, teachers, technical and scientific staff. Furthermore, at a small scale an experiment has started to free high-school teachers from regular teaching duties for one day per week, allowing them to spend the day at the research institute to do analysis and/or develop educational material. Of course, due to the special nature of the project, governments, universities, scientific societies, industry, private organizations and schools need to support the project financially. Especially, the relationship with industry should be emphasised; not only at the technological level, but also from point of view of their future quest for high level academic human resources.

Spring 2005, a first European meeting on 'educational' cosmic ray networks was organised in Amsterdam, bringing together representatives (including high-school teachers) of outreach initiatives in 10 European countries. A second meeting (September 2006) took place in Lisbon. Here, even more countries were represented, while the organisation for a European consortium was first laid out. Goal is to establish a mobility network under which umbrella, astroparticle physics outreach efforts are coordinated, exchange of experience and information is achieved, data and transparent data access for all participants across Europe is guaranteed. This will indeed require significant support from participating scientific institutes both in terms of commitment, person-months as well as financial. Moreover, investments for providing an infrastructure to enable development of educational material with the aim to maximise the impact on the European high-school curriculum, will be indispensable. The work comprises press-centre activities, development of educational materials, maintenance of data transfer and database facilities, analysis tools and educational programs at the organisation's web sites (so-called ELOs). The network's aim is also to organise and support regular international workshops for scientists and teachers; and scientists, teachers and high-school students at regular intervals. Regular coordination meetings take place via video conferencing; the next collaboration meeting is scheduled for September 2007 at CERN, Geneva, Switzerland.

Another strategically relevant aspect of outreach activities for the future of basic research is the information of policy makers. This aspect is in the focus of one of the ASPERA tasks (see Appendix 5). The ASPERA effort will mainly address national policy makers and

[4] See: http://www.fondation-altran.org/

ministry officials. The “National Open Days” at which network science managers from European agencies visit each country one by one will be widely publicised. This technique has been used by ECFA (European Committee on Future Accelerators) and has been an important lever arm increasing European-wide participation. ASPERA will also organize inaugurations, special pan-European celebrations, visit of infrastructures and launching of satellites for policy makers. Related information will be available on the ASPERA website.

Appendix 5: Glossar on Initiatives and Committees in the field of astroparticle physics and related fields

ApPEC

ApPEC stands for Astroparticle Physics European Coordination. This is a group of national funding agencies which came into being in 2001 when six European scientific agencies (later growing to thirteen) took the initiative to coordinate and encourage Astroparticle Physics in Europe. ApPEC's amin activities are:

- developing long-term strategies,
- expressing the view of European Astroparticle Physics in international forums,
- assessing astroparticle physics projects with the help of a Peer Review Committee,
- preparing a roadmap for astroparticle physics in Europe (the present document) which will serve as stage I of a process to be continued under the coordination of ASPERA.

ApPEC's work rests on two bodies: the Steering Committee (SC) and the Peer Review Committee (PRC, at present functioning as "Roadmap Committee").

https://ptweb.desy.de/appec/

ASPERA

ASPERA is a network of national government agencies responsible for coordinating and funding national research efforts in Astroparticle Physics. Within the ERA-NET scheme under the 6th Framework Programme of the EU, ASPERA started in July 2006 and is funded by the European Commission at the level of 2.5 Million € over a three year period. The ASPERA network was first proposed by ApPEC and began with 17 national agencies in Europe and the two transnational organisations CERN and ESA. ApPEC will make use of developments made by the ASPERA network.

ASPERA has the following main goals:

- A common information system comparing the various review and funding mechanisms.
- A joint electronic infrastructure with web based tools for communication and coordination.
- Common methods of benchmarking and managing large infrastructures.
- A scientific roadmap.
- An identification of innovative R&D fields suitable for joint research projects with high European added value.
- Uniform processing and evaluation schemes for joint transnational proposals.
- An identification of possible links amongst existing infrastructures.
- Pan-European collaborations for the next generation of large scale infrastructures.
- Examination of transnational R&D domains to develop a model call for R&D proposals.
- Guidance and possible frameworks for national agencies to fund transnational programmes.
- Extension of the network to all interested European countries with activities in Astroparticle Physics.

http://www.aspera-eu.org

ASTRONET

ASTRONET has been established as a four-year ERA-NET project under the European Commission's Sixth Framework Programme (FP6), by funding agencies and ministries from France, Germany, Italy, the Netherlands, Spain, the UK, plus ESA, ESO and NOTSA. The programme started Sept.1, 2005 with a total budget of 2.5 M€. ASTRONET aims to establish a comprehensive long-term planning process for the development of European astronomy. It covers four main activities:

- A "Science Vision for European Astronomy" which aims to prepare a strategic vision for the scientific development of European Astronomy over the next 15-20 years. This document is now available at the URL below.
- An "Infrastructure Roadmap for European Astronomy" which will be based on the Science Vision and contain a strategic plan for major research infrastructures in Europe.
- Targeted Coordinated Activities aims to prepare coordinated evaluation procedures and eventually a common multi-agency research programme.
- Networking deals with the exchange of information between all relevant partners.

http://www.astronet-eu.org

ESA and "Cosmic Visions 2020"

The European Space Agency, ESA, has defined its research missions for the next decade in a document released in 2002, the *Cosmic Visions 2020*. These projects include satellite missions like the gamma observatory INTEGRAL (already operating) and the gravitational interferometer LISA (planned for the next decade), which are also mentioned in the present ApPEC roadmap.

http://www.esa.int

ESFRI and the ESFRI roadmap

The European Strategy Forum on Research Infrastructures (ESFRI) was launched in 2002 and brings together representatives of EU Member States and Associated States. Its role is to support a coherent approach to policy-making on research infrastructures in Europe and to act as an incubator for international negotiations about concrete initiatives. After two years of consultations, in September 2006, ESFRI has released the ESFRI roadmap. The roadmap identifies 35 large scale infrastructure projects at various stages of development. Three of these projects belong to astronomy/astroparticle physics: KM3NeT, the cubic kilometer neutrino telescope in the Mediterranean (cost 220-250 M€, start of operations of full detector 2015), the Extremely Large Telescope ELT (850 M€ cost, start of operation 2018), and the Square Kilometer Array SKA (1150 M€ cost, start of operation 2014-2020). ESFRI also defines a list of 24 "emerging proposals" which include CTA, the Cherenkov Telescope Array. Both KM3NeT and CTA are addressed in detail in the present ApPEC roadmap.

http://cordis.europa.eu/esfri/

HEAPNET

HEAPNET started as an application for an EU Integrated Infrastructure Initiative (I3) in the field of astroparticle physics (after ILIAS, see below). In the first attempt in 2005, this initiative was not approved for EU funding. Nevertheless, HEAPNET comprises about 800 scientists and focuses on the high energy aspects of astroparticle physics (ground and space based experiments). It comprises joint research activities like photodetection, radiodetection and space detectors. Even without being funded by the EU, the HEAPNET initiative has developed to a closely linked community with a clear understanding of networking and joint research activities in this subdomain of astroparticle physics.

http://www.heapnet.org/

HEPAP, P5, NuSAG, DMSAG

The High Energy Physics Advisory Panel (HEPAP) includes several sub-panels and is charged by DOE and NSF. Among these are the Particle Physics Project Prioritization Panel (*P5*) and the Neutrino Scientific Assessment Group (*NuSAG*) which both have produced detailed roadmaps (see the URL below), as well as the Dark Matter Scientific Assessment Group (*DMSAG*). The *P5 roadmap* addresses a wide range of questions, with a strong overlap with astroparticle physics: the high energy frontier (LHC and ILC), Dark Matter, Dark Energy, neutrino science and precision measurements for charged leptons and quarks.

http://www.science.doe.gov/hep/hepap.shtm

ILIAS

ILIAS is an Integrated Infrastructure Initiative (I3), with 20 contractors, funded under the European Commission's Sixth Framework Programme (FP6). Based on a set of networks and joint research projects, the programme focuses on three key areas:

- the search for double beta decay,
- the search for dark matter,
- 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.

ILIAS was started on April 1, 2004 with a total budget of 10 M€ (EU support 7.5 M€). ILIAS comprises more than 1000 scientists.

http://ilias.in2p3.fr/

NuPECC

NuPECC stands for Nuclear Physics European Collaboration Committee and is an Associated Committee of the European Science Foundation (ESF). Its objective is to strengthen European cooperation in nuclear science. NuPECC has produced a roadmap which focuses to large accelerator-based facilities like FAIR, EURISOL or the ALICE detector at CERN. NuPPEC also addresses nuclear astrophysics which is not contained in this roadmap, for instance a high-current underground high-current 5MV accelerator with the potential to measure astrophysically important reactions down to stellar energies.
http://www.nupecc.org

PaNAGIC

PaNAGIC is the *Particle and Nuclear Astrophysics and Gravitation International Committee.* It has been created by the International Union of Pure and Applied Physics (IUPAP) in 1998, with the aim to support international exchange of ideas and to support the convergence of the international scientific community with respect to large-scale activities on particle and nuclear astrophysics, gravitation and cosmology. For certain purposes, PaNAGIC installs sub-panels, like e.g. HENAP. This *High Energy Neutrino Astrophysics Panel* of PaNAGIC, has produced detailed recommendations for large neutrino telescopes in 2002.

Strategy Group on European Particle Physics

This panel was established in June 2005 by the president of the CERN Council in order to produce a draft European roadmap for particle physics. A one-year procedure included several meetings of the Strategy Group as well as open meetings. It resulted in a three-volume Briefing Book and eventually in a two page strategy paper (CERN Courier, Sept 2006) which was adopted by the Council in July 2006. Representatives from ApPEC (both Steering Committeee and Physics Review Committee) have been participating in the meeting of the strategy group. The two-page strategy document focuses to accelerator physics activities but also highlights astroparticle physics by summarizing *"A range of very important non- accelerator experiments take place at the overlap between particle physics exploring otherwise inaccessible phenomena; Council will seek to work with ApPEC to develop a coordinated strategy in these areas of mutual interest".*

http://www.cern.ch/council-strategygroup
http://events.lal.in2p3.fr/conferences/Symposium06/
http://www-zeuthen.desy.de/exps/ccgs/

The main questions defining Astroparticle Physics in the 21st century:

• What is the Universe made of? What is the nature of dark matter and energy ? • Do protons have a finite life time? • What are the properties of neutrinos? • What is their role in cosmic evolution? • What do neutrinos tell us about the interior of the Sun and the Earth, and about Supernova explosions? • What is the origin of cosmic rays ? • What is the view of the sky at extreme energies ? • Can we detect gravitational waves? • What will they tell us about violent cosmic processes and about the nature of gravity? •

ASPERA

ASPERA members