High-energy neutrino astronomy with IceCube

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Abstract

The prospect of extending our knowledge of the astrophysical processes in the deepest recesses of the Universe by using neutrinos as astronomical messengers has been a dream of scientists since the 1960s. The vision is finally becoming a reality: the first-generation AMANDA neutrino telescope at the South Pole designed to search for high-energy neutrinos is being upgraded to a kilometre-scale array, IceCube, with a much improved sensitivity. A summary of the results from AMANDA, and the perspectives for IceCube are presented.

1 Introduction

Astronomical observations traditionally exploit a wide range of the wavelengths of the electromagnetic spectrum. Photons are abundantly produced in astrophysical processes, and relatively easy to detect. However, they are prone to interact with matter and radiation and therefore do not reach us from the interior of stars or from the far-away regions of the Universe since they are absorbed by the interstellar matter and in pair-production processes with infrared radiation or the cosmic microwave background, Fig. 1. At TeV energies, γ-rays have a range of only about 100 Mpc, and at PeV energies they barely reach us from the edge of our galaxy.

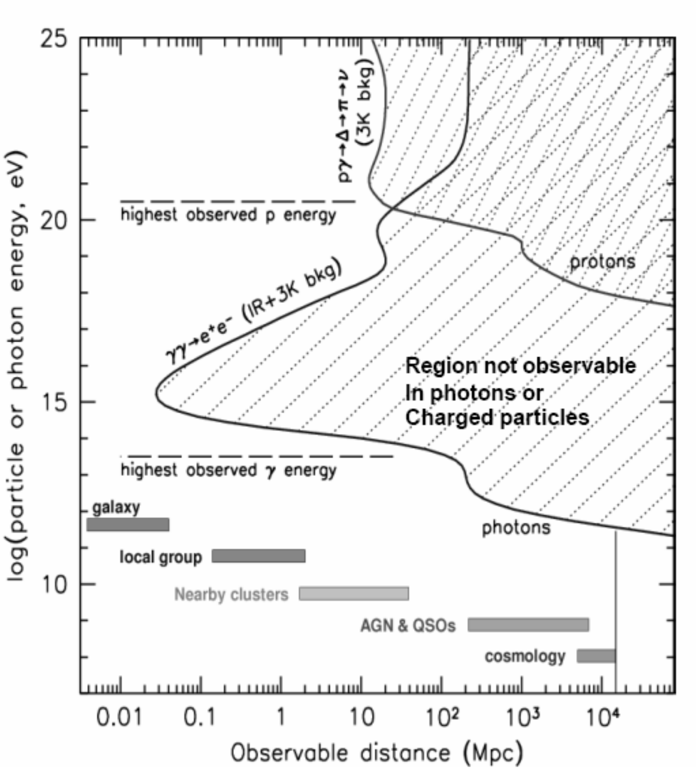

Fig. 1: Logarithm of energy vs. distance for photons and protons. From P. Gorham and D. Saltzberg, www7.nationalacademies.org/bpa/EPP2010_Presentation_Gorham.pdf. The shaded areas represent regions which cannot be observed because of interactions with diffuse radiation.

High-energy cosmic rays constitute another probe of the energetic processes throughout the Universe. Cosmic rays are mostly protons with a small admixture of alpha-particles and heavier nuclei. They were discovered by Victor F. Hess in 1912 [1] and have since been studied extensively with space-borne and ground-based detectors. As seen in Fig. 1, at a given energy the reach of protons is larger than that of photons. However, protons are deflected by the intergalactic and interstellar magnetic fields and hence the information on the direction back to their sources is lost. Figure 2 shows the measured all-particle cosmic-ray energy spectrum, extending over more than 25 decades in flux out to about 10^{20} eV and following approximately a power law. The feature at 3–4 × 10^{15} eV is called the 'knee' and indicates a change in slope from $\sim E^{-2.7}$ to $\sim E^{-3.1}$ [3]. A 'second knee' is seen at ~4–6 $\times\, 10^{17}$ eV, and a flattening called the 'ankle' is observed at ~10^{19} eV. A cut-off is finally expected owing to interactions with the cosmic microwave background radiation (CMBR). For protons this occurs through the resonant reaction $p + \gamma \to \Delta^{+} \to N + \pi$. The cut-off, known as the Greisen–Zatsepin–Kuzmin (GZK) limit [4], for nucleons is at ~ 5 × 10^{19} eV. The detection by AGASA [5] of events with energies apparently beyond the GZK cut-off is to date still under debate.

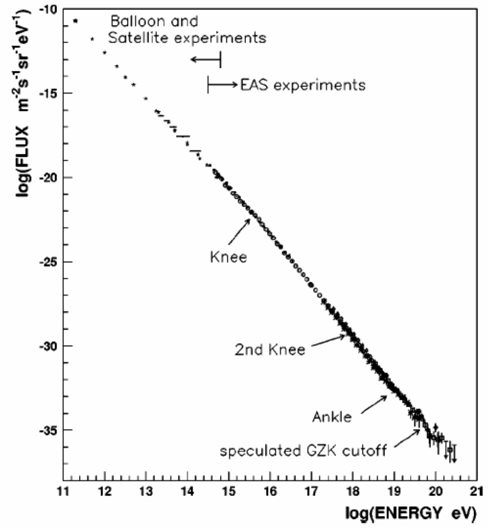

Fig. 2(a): All-particle cosmic-ray spectrum from the review by M. Nagano and A.A. Watson [2a]

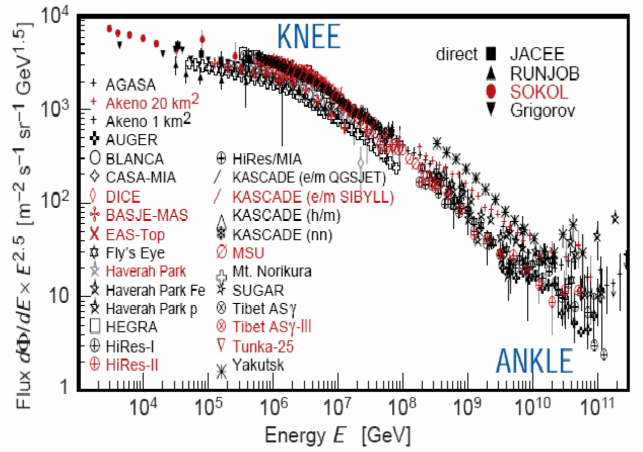

Fig. 2(b): The high-energy part of the all-particle cosmic-ray spectrum. The primary spectrum has been multiplied by $E^{2.5}$ to show the knee in more detail. From Ref. [2b].

Considering the broken power-law shape of the cosmic-ray energy spectrum, it is commonly believed that the mechanisms causing the acceleration of these charged particles might be connected to diffusive shock phenomena, with different types of sources contributing fluxes with different spectral indices. Enrico Fermi was the first to realize that charged particles crossing back and forth over a moving shock-front can be accelerated to very high energies by stochastic scattering processes on moving magnetized plasma-clouds, and to show that the resulting energy spectrum follows a power law [6]. It is generally assumed that cosmic rays in the energy range below the knee are of galactic origin, accelerated in shocks originating in supernova explosions into the interstellar medium [7]. This assumption has been claimed to be supported by X-ray observations of the supernova remnant SN1006 [8a], indicative of electron acceleration to very high energies. This claim has not been corroborated by other observations, however. Today the best evidence for acceleration of charged particles in young supernova remnant (SNR) shocks comes from observations of the SNR RX J1713.7-3946 [8b] where the energy spectrum of the observed γ-rays indicates acceleration of charged particles to ~100 TeV. For energies above the knee, galactic magnetic fields are not strong enough to confine the cosmic rays. Therefore it is likely that the sources of these particles are to be found beyond the Milky Way. Actually, at the very highest energies, proton astronomy might be possible since the magnetic deflection decreases with energy—unfortunately those protons are extremely rare (fewer than 1 per km^2 per year) and their range is limited by the GZK process. So the location of the sources of high-energy cosmic rays remains a puzzle.

In this context, high-energy neutrinos emerge as extremely interesting cosmic messengers. Unaffected by intergalactic magnetic fields and weakly interacting, neutrinos should be able to penetrate regions opaque to protons and photons and point straight back to their sources.

In ‘bottom-up’ schemes, ultra-high energy (UHE) neutrinos originate in decays of pions and kaons produced when protons, accelerated to ultra-high energies by ‘cosmic accelerators’ driven by gravitational energy release, interact with radiation or matter in the vicinity of the sources. Models of such processes typically predict a neutrino energy spectrum of the form $\mathrm{d}N/\mathrm{d}E \sim E^{-2}$ and make a connection between the expected UHE neutrino flux, the flux of the UHE cosmic rays, and the flux of coincidently produced TeV photons. The possible accelerators include extra-galactic sources like Active Galactic Nuclei (AGN) or massive collapsing objects giving rise to Gamma Ray Bursts (GRB), and galactic sources like micro-quasars and SNR.

A second category of models exists, where UHE neutrinos arise from decays of heavy cosmological remnants ($M \sim 10^{23}$ eV). These so-called top-down models predict higher neutrino fluxes than the ‘bottom-up’ acceleration scenarios, certainly within reach of kilometre-scale neutrino observatories [9]. Both schemes make predictions of the shape of the neutrino spectrum and correlate the neutrino flux to that of photons and protons.

2 Neutrino telescopes

The main objective of neutrino telescopes such as AMANDA and its successor IceCube is the search for very high energy neutrinos from cosmic sources. Predictions of the rates of such neutrinos are what drives the telescope design. It turns out, however, that the design also allows additional goals to be pursued. These include searches for neutrinos from annihilations of dark matter candidate particles, Weakly Interacting Massive Particles (WIMPs), at the centre of the Earth or the Sun, searches for magnetic monopoles and Q-balls [10], and investigations of the limits of validity of Lorentz invariance using huge samples of atmospheric neutrinos [11]. It is also possible to monitor our galaxy for low-energy neutrinos from supernova bursts.

The predicted UHE neutrino production rates from cosmic sources [12] together with the small neutrino interaction cross-section result in low expected rates at Earth, of the order a few (tens) per year per km^2. This limits the choice of detector medium to naturally abundant materials. The neutrinos can only be observed through their interactions with the atoms of the medium which produce long charged tracks ($\nu_\mu \rightarrow \mu$) and/or ‘cascades’ i.e., fairly localized energy depositions (from the hadron showers in both charged current (CC) and neutral current (NC) interactions, and the electromagnetic showers when $\nu_e \rightarrow e$). In both cases charged particles are produced moving with speeds exceeding the speed of light in the medium—giving rise to Cherenkov radiation, which can be observed provided the detector material is transparent in the blue/UV wavelength range where most of the light is emitted. This calls for the choice of water or ice as detector medium.

The AMANDA neutrino telescope has been constructed in the clear Antarctic glacier close to the Amundsen–Scott South Pole station [13]. During the period 1996–2000, 677 optical sensors were deployed on 19 strings, at depths between 1500 and 2000 metres. The strings were lowered into holes drilled with hot water at 80°C and allowed to freeze in. The optical properties of the ice at depths down to 2300 m, essential for understanding and optimizing the telescope performance, were studied using steady and pulsed light sources deployed with the strings [14]. The long absorption length (~110 m) and the relatively long scattering length (~20 m) at 400 nm allow observation of neutrino interactions exterior to the array. This, together with the long range of high-energy muons in ice (about 1 km at 300 GeV), results in an *effective* volume for observation of muons from ν_μ interactions widely exceeding the instrumented detector volume. Figure 3 shows schematically the AMANDA array with an inset optical sensor, the 8″ Hamamatsu R5912-2 photomultiplier coupled via a UV-transparent optical gel to the glass pressure housing designed to withstand a pressure of at least 600 bar. Figure 4 indicates how the neutrino direction and energy can be reconstructed by registering the Cherenkov light pattern of the individual photons. The arrival times at the optical sensors allow reconstruction of the direction, whereas the total number of registered photons is related to the deposited energy.

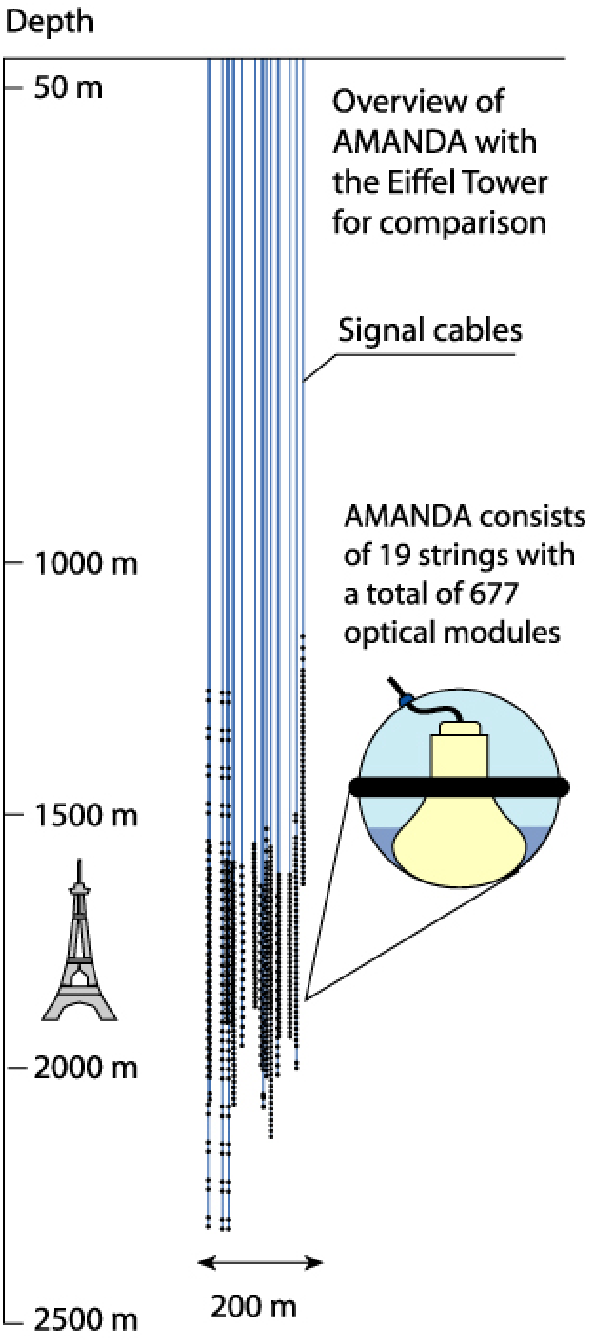

Fig. 3: A sketch of the completed AMANDA array

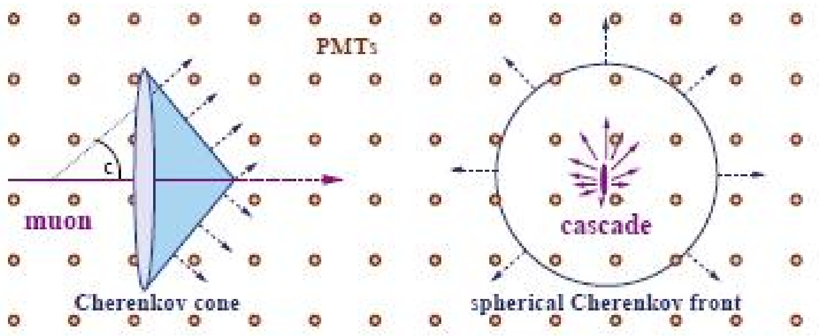

Fig. 4: Left panel: muons travelling through the ice give rise to a conical wave front of Cherenkov light. Right panel: cascades produce a fairly spherical wave front. By registering the arrival times of single photons, the direction of the neutrino and the energy are reconstructed.

3 Results from the AMANDA telescope

The results obtained with the AMANDA array were recently summarized in Ref. [15]. To avoid unintentional bias, data is analysed using blind techniques. The exact approach varies depending on the topic but may imply randomization of event times or optimization of cuts on randomly selected data sub-samples, on low-energy data, or on data outside a certain time range.

3.1 Atmospheric neutrinos

Atmospheric neutrinos arise in the interactions of cosmic rays in the Earth's atmosphere. Since their energy spectrum is well determined theoretically, atmospheric neutrinos can be used as a calibration beam to verify the understanding of the detector response. AMANDA has measured the atmospheric neutrino energy spectrum out to ~300 TeV [16]. The spectrum ties in well to lower energy measurements with other detectors and is consistent with theoretical expectations. The overwhelmingly important background for this analysis is the atmospheric muons abundantly produced in cosmic-ray interactions with the atmosphere. When searching for neutrinos, this background can be largely removed by using the timing information to distinguish between down-going and up-going charged tracks. Whereas the down-going flux is dominated by muons, only neutrinos can penetrate the Earth giving rise to up-going tracks on interaction. The residual background—mainly down-going tracks mistakenly reconstructed as up-going—is removed by strict requirements on the track quality parameters.

3.2 Diffuse neutrino flux

The summed flux of extra-terrestrial neutrinos, not ascribable to individual sources, is called 'diffuse'. The observations integrate over the full Northern sky and over long time periods. Atmospheric neutrinos constitute the most important background, which is discriminated against using AMANDA's ability to correlate the registered signal to neutrino energy. The atmospheric neutrino spectrum varies like $E^{-3.7}$ whereas the spectrum of extra-terrestrial ν's is expected to be harder ($\sim E^{-2}$). Hence, at sufficiently high energies the diffuse neutrino energy spectrum should contain an excess compared to the atmospheric expectation. Diffuse searches in AMANDA have been pursued with a three-pronged approach:

- TeV to PeV muon-neutrinos have been searched for using up-going well-reconstructed tracks [17],
- neutrinos of all flavours have been searched for by estimating the energy of NC and CC cascades [18,19],

- at very high energies (>10^{14} eV) where the neutrino cross-sections are larger and the Earth becomes opaque to up-going neutrinos, close-to-horizontal muon or cascade events were looked for [20]. In this case, energetic muon bundles created by cosmic-ray interactions in the atmosphere are the most important background.

In all cases, the results are handled statistically comparing the number of observed events with the expected background. The results are shown in Fig. 5 with the most stringent (preliminary) limit on $E^2 \mathrm{d}N/\mathrm{d}E$ of 8.8×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} for the neutrino energy range 16–2.5×10^3 TeV [15]. No statistically significant excess above the background expectation can be claimed, which leads to stringent limits on models of neutrino production.

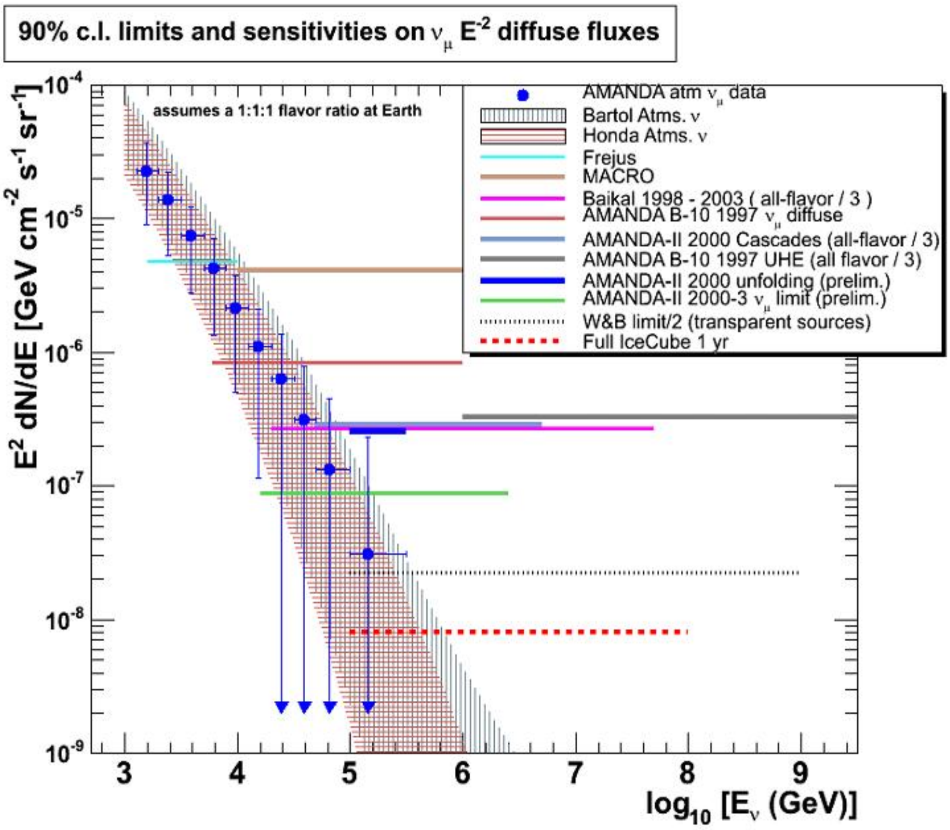

Fig. 5: Flux upper limits on diffuse ν_μ flux, assuming E^{-2} spectrum. All-flavour limits (divided by 3 based on the assumption of 1:1:1 flavour ratio at Earth) are shown for comparison. References: Fréjus [21], MACRO [22], Baikal [23], AMANDA B-10 1997 ν_μ [17a], AMANDA B-10 1997 UHE [20], AMANDA-II 2000 cascades [19], AMANDA-II 2000 unfolding [16], AMANDA-II 2000-2003 ν_μ [17b], Bartol [24], Honda [25].

3.3 Point sources

The AMANDA telescope has been used to search for steady or transient sources of extra-terrestrial neutrinos. Again, different strategies have been pursued. In the case of steady sources we conducted:

- searches over the full Northern sky for clusters of events [26],
- searches for ν's from individual promising astrophysical sources within a predefined set of 32 objects [26],
- searches for ν's from 'stacked' sources, grouping AGNs according to their photon emission characteristics in classes of about 10 and summing events in each class [27].

In all these cases, pointing accuracy is important, so only well-reconstructed muon tracks from ν_μ's were looked for. The expected background is determined from off-source data. Figure 6(a) is a map of the Northern sky showing the 4282 neutrino candidates found in the 2000–2004 data set, corresponding to 1001 days of live time. Figure 6(b) shows the significance obtained by scanning the sky for clusters of events. The significance is positive for excess and negative for deficit of events compared to the expected background of atmospheric neutrinos. The highest excess is 3.7σ consistent with expectation for a random distribution of background events. Hence, as yet there is no evidence for hadronic acceleration in astrophysical sources.

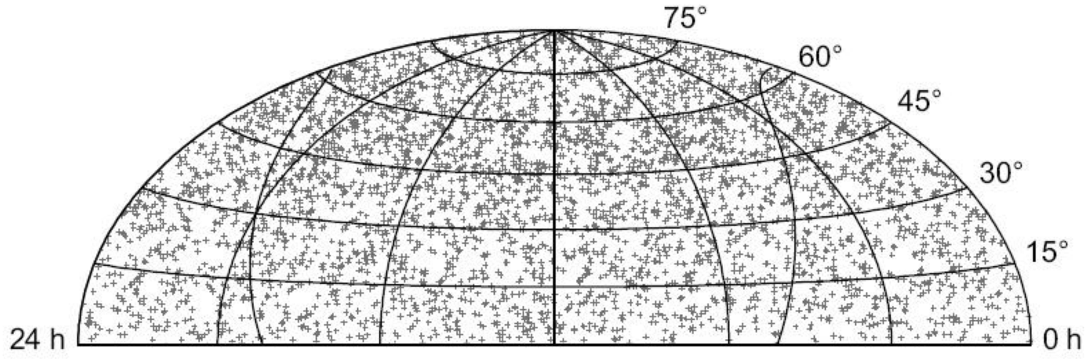

Fig. 6(a): Map of the Northern sky showing the arrival directions of the 4282 neutrino candidates in the 2000–2004 AMANDA data set [26]

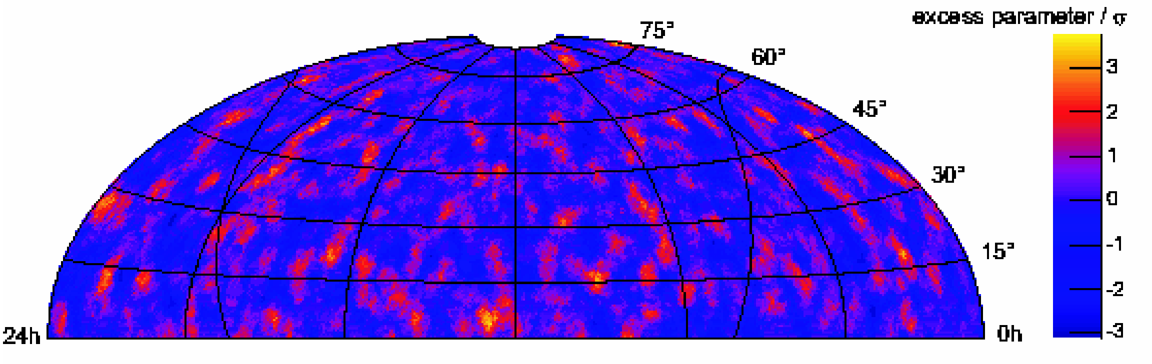

Fig. 6(b): Sky map of the significances obtained by scanning the Northern sky to search for 'hot spots' [26]

The most spectacular transient, potential neutrino sources are the events giving rise to the GRBs detected at a rate of a few per day by satellite-borne instruments. AMANDA uses the spatial and temporal information provided by the Burst And Transient Source Experiment (BATSE) aboard the CGRO satellite (de-commissioned in 2000) and the satellites of the Third Interplanetary Network (IPN [28]) to perform an essentially background-free search for coincident ν's from GRBs. The background is determined from on-source/off-time data and amounts in the muon channel to of the order 1 event for the whole data set corresponding to about 400 bursts. A statistical analysis assuming average burst characteristics [29] allows putting a limit on the ν flux from GRBs, which, however, is still a factor of about 4 above prediction [30]. Specific GRBs can be addressed taking into account individual burst characteristics [31]. Further such analyses are in progress.

3.4 Indirect dark matter searches

It is important to realize that AMANDA is also a particle physics detector capable of detecting neutrinos with energies far above those within reach of Earth-based accelerators, and hence can address issues of interest to particle physics. One such topic is the search for cold dark matter particle candidates (WIMPs), notably the neutralino predicted to be the lightest supersymmetric particle in many extensions of the Standard Model. WIMPs have been proposed as a solution to the dark matter puzzle. Over time they would be gravitationally trapped by astronomical objects like the Earth or the Sun and eventually accrete in their centres. With sufficiently large densities, annihilations would start —the end-product being 'ordinary' Standard Model particles producing high-energy neutrinos in their decays. The ν's are expected to have energies of the order 30% of the WIMP mass and hence could not be confused with low-energy ν's from radioactive processes. AMANDA searches for an excess of ν's from the Earth or the Sun. Examples are shown in Fig. 7 displaying the muon flux from the centre of the Earth and the Sun expected from predictions of the Minimal Supersymmetric extension of the Standard Model (MSSM) with varying parameters and subject to cosmological constraints, as a function of the neutralino mass. The AMANDA limit is competitive compared to other indirect dark matter searches, and complementary to the direct dark matter searches, which, moreover, explore a different epoch of the WIMP population and a different part of its velocity distribution [32].

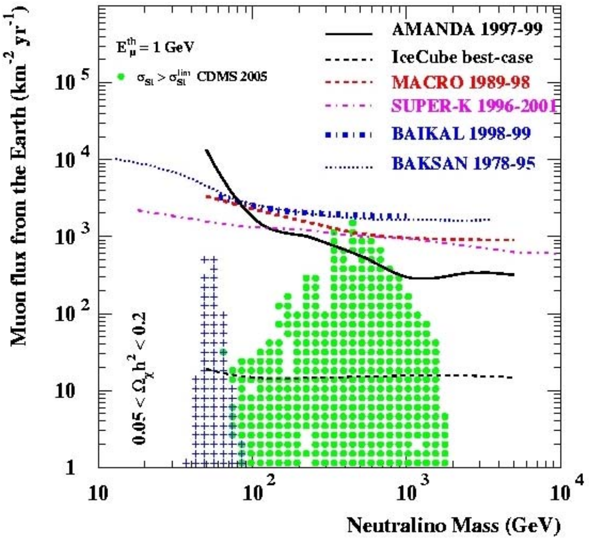

Fig. 7(a): Muon flux from neutralino annihilations at the centre of the Earth as a function of the neutralino mass. Each dot corresponds to a prediction from a supersymmetric model with a given set of parameters [32c].

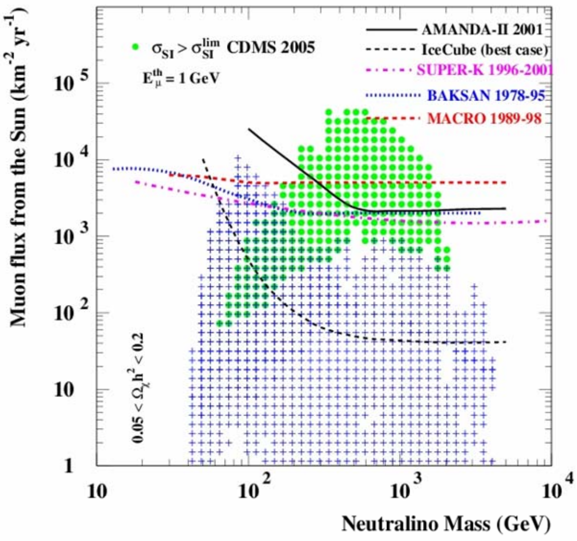

Fig. 7(b): Muon flux from neutralino annihilations at the centre of the Sun as a function of the neutralino mass. Each dot corresponds to a prediction from a supersymmetric model with a given set of parameters [32b].

3.5 Supernova watch

Since the interior of the Antarctic ice-cap is essentially noise-free, AMANDA can explore its sensitivity to coherent rate increases in excess of the dark noise to search our galaxy for supernova events. A supernova produces a burst of neutrinos, which on interaction in the detector give rise to isotropically distributed (mostly) positron-induced cascades with energies in the MeV range. The result is a simultaneous rate increase for many optical modules. AMANDA is participating in the SuperNova Early Warning System (SNEWS) [33].

4 IceCube

Building on the experience from AMANDA, a kilometre-scale, gigatonne, neutrino observatory, IceCube, is currently under construction at the South Pole. Figure 8 shows the IceCube array consisting of 80 strings with a total of 4800 optical modules deployed at depths between 1450 m and 2450 m in the Antarctic glacier. The strings are arranged in a hexagonal pattern with inter-string distances of 125 m, surrounding the AMANDA array. The geometry is optimized for the detection of muons at TeV energies and above. An extended air shower detector on the surface, IceTop, complements the deep-ice array with optical modules frozen inside water tanks, in total 320 optical sensors. The combination of IceCube and IceTop provides an opportunity for cosmic-ray composition studies close to the ‘knee’ of the cosmic-ray spectrum and above. Moreover, IceTop tagged muons can be used for calibration and survey of the deep-ice array. Also important is the possibility of using IceTop information for rejecting cosmic-ray backgrounds to physics studies with the deep detector.

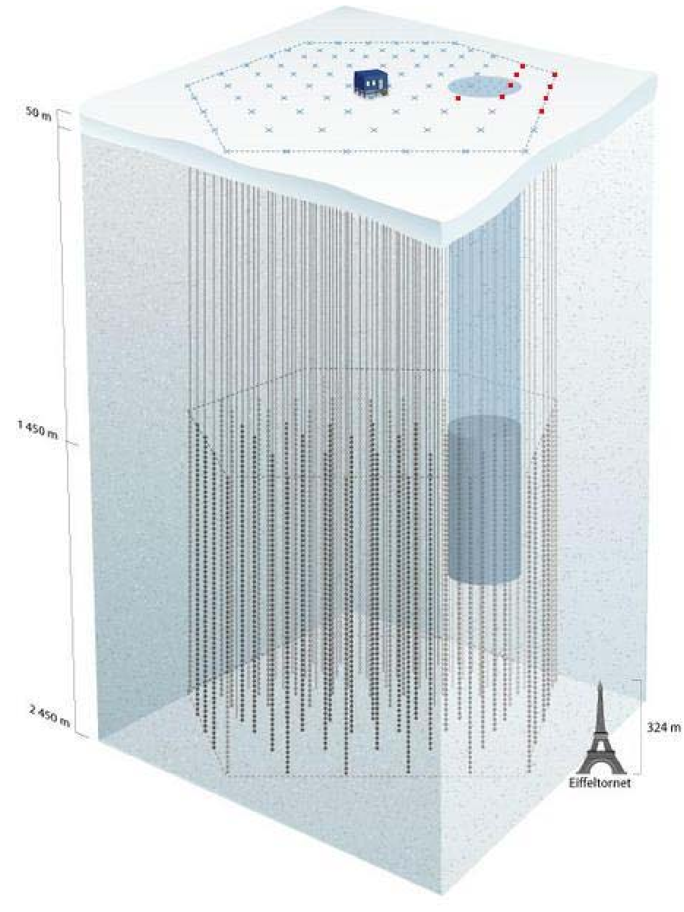

Fig. 8: A sketch of the IceCube observatory with 80 in-ice strings and, on the surface, 80 IceTop stations, one above each string location. The grey cylinder represents AMANDA. The red dots indicate the positions of the nine strings deployed by spring 2006.

The fundamental component of IceCube is the Digital Optical Module (DOM), a 30 cm diameter pressure sphere enclosing a 10″ Hamamatsu PMT similar to AMANDA’s 8″ PMT but, unlike AMANDA, also including a system for time-stamping, digitizing, and storing the registered waveforms locally, transmitting to the surface on request. The local time-stamp is correlated to a global clock by a time calibration procedure allowing one to achieve a relative timing accuracy between modules of the order of 3 ns, which is small compared to the effects of light scattering in ice. Each DOM also contains 12 LEDs which provide light-sources for geometrical calibration of the array.

4.1 Current status

IceCube installation started during Austral summer 2004–2005 with the deployment of one string and four IceTop stations. In 2006, 9 strings and 16 IceTop stations are being commissioned, the detector having reached an instrumented volume comparable to that of AMANDA. Performance measurements so far show behaviour according to design specifications [34]. Figure 9 shows a typical waveform captured by a DOM, which is well described by a fit representing a superposition of terms, each corresponding to a single photo-electron response.

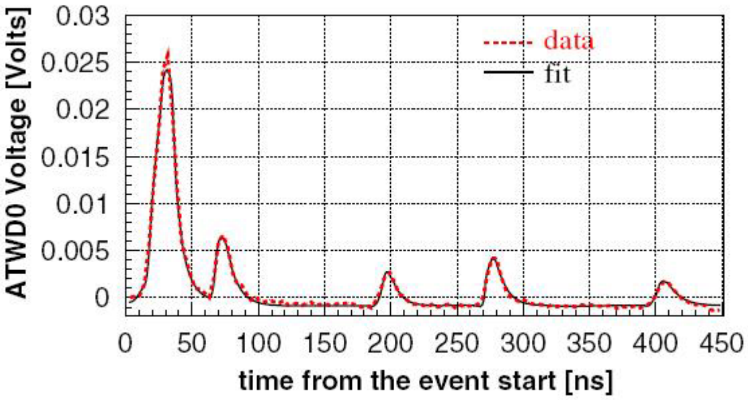

Fig. 9: A typical waveform captured by an IceCube DOM. The waveform features can be used in event reconstruction [34].

Simulations lead us to expect an increasing sensitive aperture with increasing energy, and for muon-neutrinos in the PeV range, full-sky observations become possible. The effective area for upward-moving muons above 10 TeV exceeds the geometric instrumented area of 1 km^2, increasing with energy. The median angular resolution for muons improves with energy, approaching 0.8° for TeV muons. This result does not take into account the DOM waveform information which when fully used should give a further improvement. The sensitivity of IceCube to point sources and diffuse flux of neutrinos has been estimated [35] leading us to believe that a flux at the level of 10% of the present four-year limit would be detectable after three years of observation with complete IceCube at 5σ significance.

Assuming independently available spatial and temporal information, for instance from the Swift or GLAST satellites, fully instrumented IceCube expects to achieve within three years a sensitivity at the level of 20% of the flux of neutrinos from GRBs predicted by Waxman and Bahcall [30].

5 Outlook

The implementation of the IceCube observatory is proceeding according to plan and will be completed in four more years. At that time IceCube will be the world's largest neutrino telescope with an effective volume exceeding 1 km^3. To further extend the energy reach of IceCube into the domain of the very highest energies, like those expected for neutrinos produced in the interactions of the cosmic rays at GZK energies with the cosmic microwave background, the IceCube Collaboration is looking into ways of expanding the sensitive volume by a factor 100 by deploying acoustic and/or radio-sensitive devices. Owing to the long absorption length of acoustic (radio) waves in ice, of the order 1 km, such an extension does not need to be extremely sensor-intensive and would provide not only additional sensitivity but also redundancy for the observation of rare signals.

The IceCube Collaboration includes about 200 researchers from 30 institutions in Belgium, Germany, Japan, The Netherlands, New Zealand, Sweden, the U.K., and the U.S.A. [36].

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