Neutrino Telescopes

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Three large optical Neutrino Cherenkov telescopes are now searching the sky for High Energy extraterrestrial neutrinos: the NT200+ in Lake Baikal, the ANTARES in the Mediterranean outside Toulon and the partially completed IceCube at the geographical South Pole, Antarctica. Tens of thousands of atmospheric neutrinos have been observed with energies up to several 100 TeV but so far no evidence for extraterrestrial neutrinos has been found. The IceCube neutrino telescope is approaching Gigaton size which is the expected minimum needed for observing extraterrestrial neutrinos. In the Northern hemisphere the KM3NeT collaboration is planning a Gigaton telescope in the Mediterranean and the Baikal collaboration is planning a Gigaton telescope for cascades in Lake Baikal.

1 Introduction

This paper discusses large neutrino Cherenkov telescopes using the optical Cherenkov technique with water and ice as detector medium.

1.1 Why neutrino astronomy?

Cosmic rays (CR) were discovered almost 100 years ago but we have not yet been able to identify any source by direct observation. The flux of cosmic rays has been measured up to an incredible energy of 10^{20} eV. The acceleration process for these energies is not completely understood. Figure 1 shows the observed cosmic ray flux for different particles compiled by Gaisser [1]. The spectrum is described by power-laws with different spectral index, γ=2.7 below 10^{15} eV (the so-called "knee"), and γ=3 for energies above 10^{15} eV. This can be interpreted as particles (mainly protons) leaking out from our galaxy. The spectrum changes again to a harder spectrum above $10^{18.5}$ eV (the "ankle") which is interpreted as due to an influx of extragalactic particles. The leading theory to explain the cosmic rays below

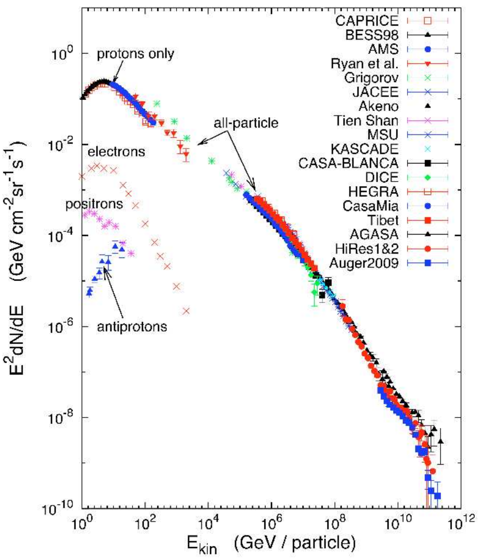

Figure 1: Cosmic ray flux as a function of energy [1].

10^{15} eV is Fermi acceleration in galactic supernova remnant (SNR) shocks. The sources for the extragalactic cosmic rays are believed to be active galactic nuclei (AGN) and/or gamma ray bursts (GRB) which are the most energetic objects observed in space. The reason for not being able to observe the cosmic ray sources directly is that the cosmic rays are electrically charged and deflected by the magnetic field in space. For ultrahigh energy cosmic rays, at energies where the magnetic field in space will have a smaller bending effect, the Cosmic Microwave Background (CMB) from Big Bang will reduce the mean free path in space for protons with energies above $10^{19.5}$ eV via the interaction $p+\gamma_{CMB} \rightarrow \Delta^{+}$. The process is called GZK (after Greisen, Zatsepin, and Kuzmin) [2] and limits the distance in the Universe observable via ultra high energy protons. Figure 2 shows the range in space as a function of the energy of the protons. The GZK process will produce UHE neutrinos via the $\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$ from the decay of the Δ^{+}. The detection of the "GZK neutrinos" is very important for the confirmation of the expected GZK process.

By using high energy photons the deflection by magnetic fields in space is avoided. But the Universe is even less transparent for ultra high energy photons than for high energy protons since these will also interact with the photons from the Cosmic Microwave Background ($\gamma + \gamma_{CMB} \rightarrow e^{+}e^{-}$). A similar process occurs with infrared background photons. Photons with energies about 10^{15} eV, for example, will only reach us from sources within our own galaxy. The observable distance in space as a function of the energy of photons and protons [3] is shown in Figure 2. The maximum energy of photons observed is about 10^{13} eV limiting the distances to the sources to be within 100 Mpc. Photons are not suitable to transmit information about very high energy processes far out in space.

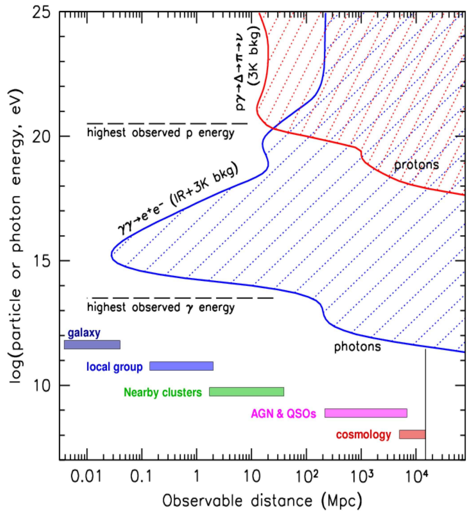

Figure 2: Observable distance for photons as a function of energy.

Neutrinos from galactic and extra galactic sources will not be absorbed by the microwave background in space. It should be possible to identify the CR sources by large neutrino telescopes. The flux ratios of neutrino flavors from pion and muon decays at the source are expected to be 1:2:0 ($\nu_e : \nu_\mu : \nu_t$) but due to neutrino oscillation, the flux ratios will be equal at Earth.

So far only two extraterrestrial sources of neutrinos have been seen, the Sun and the Supernova SN1987a in the Large Magellanic Cloud. Both are, however, low energy neutrino sources of a few tens of MeV.

In addition there are scientific topics besides cosmic ray sources which can be studied by large neutrino telescopes like indirect detection of dark matter particles (see section 3.4), magnetic monopoles, nuclearites, atmospheric neutrinos with very high statistics up PeV energies, Lorentz invariance tests etc.

2 High Energy Neutrino telescopes

The cosmic rays are expected to interact with matter or the radiation field in the vicinity of the source, producing hadrons and leptons decaying to neutrinos. When estimating the expected flux of neutrinos from the observed cosmic ray flux, one finds that detectors of Gigatons of target mass are needed [4]. For the optical Cherenkov detection technique there are mainly water and ice available. The transparent medium is equipped with a lattice of light sensors with a spacing depending on the optical transmission in the media and of the neutrino energies aimed for. The probability for a 1 TeV neutrino to interact in 1 km of water is only $4 \cdot 10^{-7}$. On the other hand the interaction length for neutrinos becomes the size of Earth at neutrino energies of $\sim$100 TeV. Neutrinos with PeV energies will mainly appear only close to the horizon and neutrinos at EeV energies even from above the horizon.

The neutrino telescopes are exposed to an intense flux of atmospheric muons (depending of the depth of the telescope) produced by the CR interactions in the atmosphere, and the atmospheric neutrinos produced in the same interactions will be a background for extraterrestrial neutrinos. The Earth is used as a muon filter and, therefor neutrinos below PeV energy, mainly upward-going neutrinos are used in the analysis.

High energy ν_μ's produce muons (via charge current interactions, CC) with a range in water or ice of several km (about 1 km at 300 GeV) allowing muons created far outside the instrumented detector volume to be detected. The mean angular difference between the incoming neutrino and the out-going muons falls approximately as $E^{-0.5}$ and is about 1° at 1 TeV. Electron neutrinos, tau neutrinos (at moderate energies) and neutral current (NC) interactions will produce "cascades" in which most of the secondary particles will interact and stop within a few tens of metres. The Cherenkov light will, to first order, come from a point source inside the large detector volume. The maximum intensity will, however, be at the Cherenkov angle (41°) around the shower axis allowing a crude determination of the neutrino direction. For ν_τ's at energies above several PeV the decay length for the tau will be hundreds of meters, allowing detection of the two cascades ("double bang events") from the primary interaction and the subsequent decay of the tau.

The neutrino telescopes in the Northern Hemisphere are sensitive to different areas of the sky than the ones in the Southern hemisphere and together they complement each other. The light in ice has shorter scattering length and longer absorption length compared to water. The angular resolution is better in water than in ice owing to the shorter scattering length. The photomultiplier (PM) noise rate in ice is about 1 kHz or less compared with 20-60 kHz (10 inch PM) in sea water due to ${}^{40}K$ decays and bioluminescence.

The expected energy spectrum for the neutrino flux from cosmic ray accelerators is E^{-2} due the assumed Fermi acceleration. The atmospheric neutrinos have a softer spectrum more like $E^{-3.7}$. The energy of the neutrino events will thus be useful when searching for extraterrestrial sources.

2.1 Baikal

The Baikal neutrino telescope was the first medium sized neutrino telescope successfully installed. It is situated in Lake Baikal in Russia. The existing NT-200+ telescope is deployed at a depth of 1100 m. It consists of a central part with eight strings with 192 optical modules arranged in pairs and is 72 m in height and 43 m in diameter. It has been taking data since 1998. In addition three outlier strings were installed in 2005 at 100 m radius with an additional

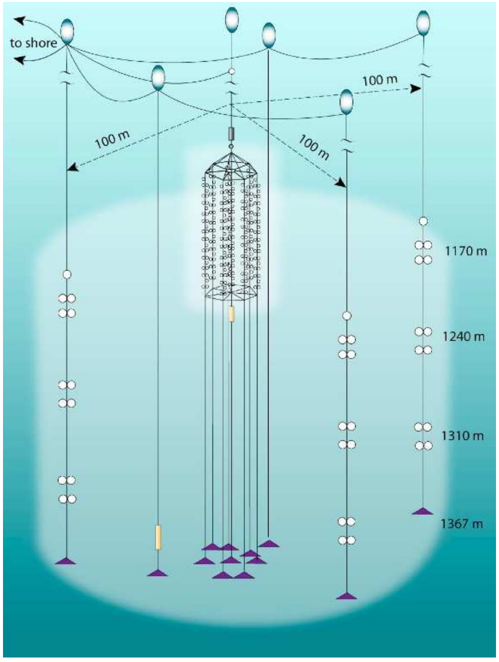

Figure 3: The Baikal NT200+

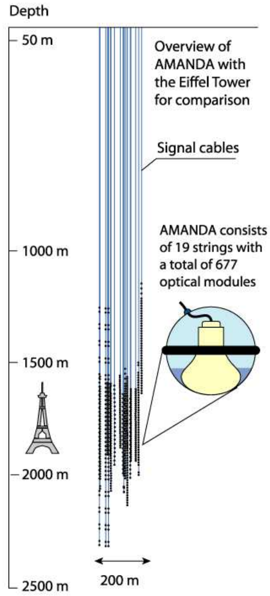

Figure 4: The AMANDA neutrino telescope.

38 modules. This extension is mainly for improving the efficiency for detecting cascades . The telescope has a total sensitive mass of 10 Mtons. The deployment (and repair) is done during winter when the ice of the lake is used as deployment platform. The angular resolution for muon tracks is about 4° and the energy threshold 15 GeV. In total ∼400 up-going muon neutrinos have been detected. Figure 3 shows the existing telescope.

2.2 AMANDA

The AMANDA neutrino telescope is located 1500 m - 2000 m deep in the very optically transparent ice at the Amundsen-Scott base at the geographical South Pole in Antarctica. It was completed in 2000 with 19 strings with in total 680 optical modules. The diameter of the telescope is 200 m and it is about 350 m tall. It has an effective mass of 15 Mtons. The optical modules are deployed in water-filled holes made with a hot water drilling system. The energy threshold is about 50 GeV and the angular resolution for muon tracks about 2° - 3°. After nine years of successful running the telescope was closed down in May 2009. It will be replaced by the low energy extension DeepCore in IceCube. More than 6500 atmospheric neutrinos have been recorded between 2000 and 2006.

2.3 ANTARES

The ANTARES neutrino telescope is situated at 2050 m - 2400 m depth in the sea outside Toulon at the French Mediterranean coast. It consists of 12 strings with in total 900 optical modules. The strings are sepateted by 60 m - 75 m and the vertical instrumented size 350 m. It is comparable in size with the AMANDA telescope. The simulated angular resolution is about 0.3°. The first strings were deployed in 2006 and the final strings in 2008. The strings are deployed from a ship and connected to a junction box on the seabed with a Remotely Operated Vehicle (ROV).

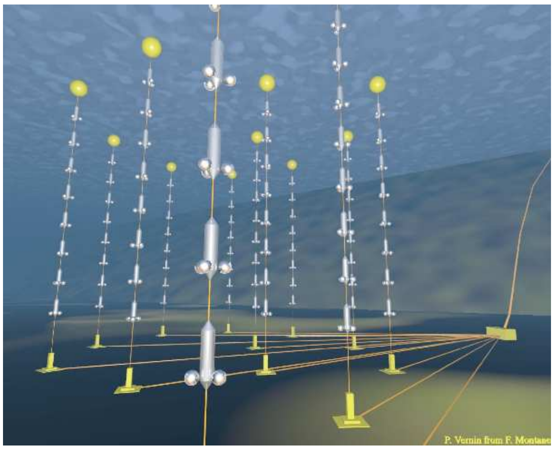

Figure 5: The ANTARES neutrino telescope

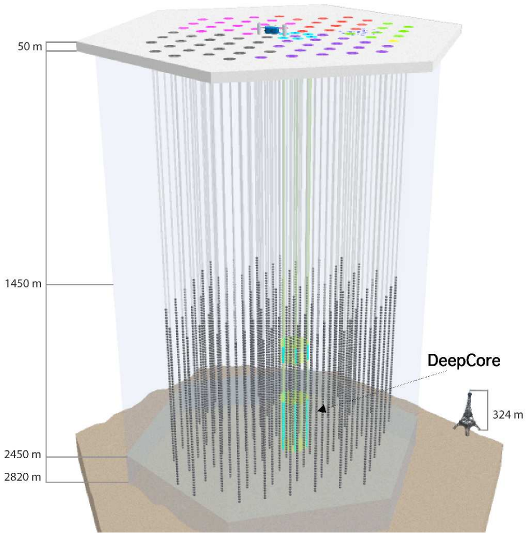

Figure 6: The IceCube neutrino telescope.

The telescope has so far recorded in total 759 upward going muon neutrinos using the first 5-string configuration (2007) and the completed 12 string configuration (2008).

2.4 IceCube

The IceCube neutrino telescope was designed based on the experience from AMANDA. It will be the first neutrino telescope to reach the expected necessary Gigaton scale. It will consist of 80 strings with 60 Digital Optical Modules (DOM) deployed between 1450 and 2450 m depth. The first string was installed in 2005 and the telescope will be completed in January 2011. In January 2010 the telescope consisted of 79 strings with 60 Digital Optical Modules (DOM) each. A cosmic ray air-shower telescope, IceTop, is situated at the surface with high efficiency for PeV - EeV energies. An IceTop station is situated close to the string hole and consists of two tanks with frozen water with two DOMs each. The combination of the neutrino telescope and the air-shower telescope is a unique feature of the South pole installation. It gives the possibility for absolute direction calibration of the neutrino telescope as well as for studies of the chemical components of the air-showers. IceCube has a low energy part called DeepCore with six additional strings deployed at the center of the main telescope where the transparency of the ice is the best. DeepCore will improve the low energy sensitivity for dark matter searches and neutrino oscillation studies, and can use part of the outer IceCube strings for vetoing against atmospheric muons from above. The deployment of the IceCube modules is done as in AMANDA but with a much more efficient hot water drill. A 2450 m deep hole is completed within less than 35 h and the deployment of the string takes less than 10 h. The hole is completely frozen after about 1-2 weeks. The drilling and deployment is only possible during the austral summer, November - February. IceCube has been taking data with the partially completed telescope every year (with 1, 9, 22, 40 and 59 strings called IC1, IC9, IC22, IC40 and IC59) and in total about 13000 up-going muon neutrinos have been analyzed (up to half year of IC40). The median angular resolution is expected to be less than 0.5° for the final detector. Figure 6 shows the IceCube neutrino telescope with the air-shower IceTop on surface and the new DeepCore low energy sub-detector.

3 Recent results

The atmospheric neutrinos are very useful for testing and calibrating the neutrino telescopes. Figure 7 shows the observed muon rate as a function of the cosine of the zenith angle (-1 up-going and +1 down-going) for the Baikal and the ANTARES neutrino telescopes. The separation between atmospheric muons and atmospheric neutrinos is easily seen. Depending on the depth of the telescope the rate of down-going atmospheric muons is five to six orders of magnitude higher than the atmospheric neutrinos.

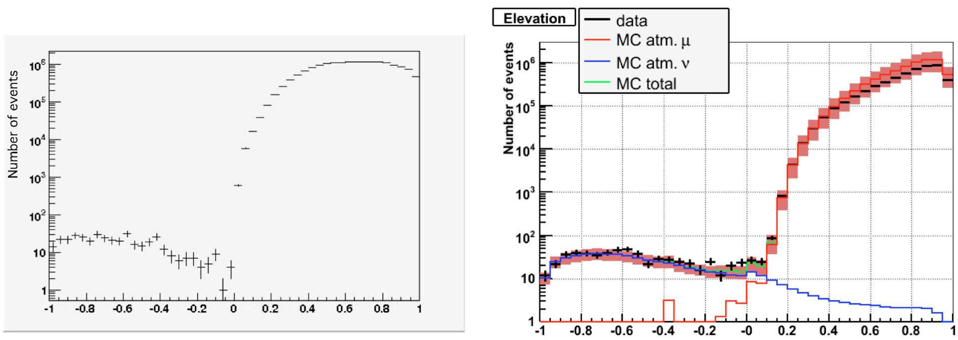

Figure 7: Cos(zenith) distributions of reconstructed muons in Baikal[5] (left) and ANTARES [6] preliminary (right). (Down going muons +1 and up going muons -1)

The four neutrino telescopes have recorded different amounts of atmospheric neutrinos reflecting the different sizes and exposure times. Baikal, 391 events, ANTARES 5+12 lines (2007-2008), 750 events, AMANDA (2000-2006) 6600 events and IceCube (up to half-year of IceCube with 40 strings) 13000 events. No extra-terrestrial neutrinos have been found so far but results have been presented giving improved limits for the extraterrestrial neutrino flux, magnetic monopoles, violation of Lorentz invariance, limits on dark matter and determination of the conventional atmospheric muon neutrino flux up to several 100 TeV.

3.1 Search for neutrino point sources

Neutrino telescopes have been using the Earth as a filter to reject down going atmospheric muons when searching for neutrino point sources. When demanding only up going muons, AMANDA and IceCube are sensitive to neutrino sources in the Northern Hemisphere only, owing to the position at the South Pole. Neutrino sources in the Northern sky are fully visible 24 h per day for AMANDA and IceCube. The neutrino telescopes in the Northern hemisphere have a larger fraction of the sky accessible but not for 24 h per day.

The IceCube collaboration has recently started [7] to search for high energy neutrino sources above the horizon. This can be done by a zenith dependent cut on muon energy reducing the flux of down going atmospheric muons by a factor of 10^{-5} to obtain a constant muon rate per solid angle. The flux limits in the Southern hemisphere for IceCube are mainly for neutrino energies above 100 TeV. The sensitivity for neutrinos from point sources is reduced but still very competitive to existing limits for E^{-2} neutrino sources.

The observed sky-maps for the four telescopes are shown in Figure 8 with the directions of the observed neutrino events, except for ANTARES where the directions still are scrambled. The true directions will be available when data is unblinded.

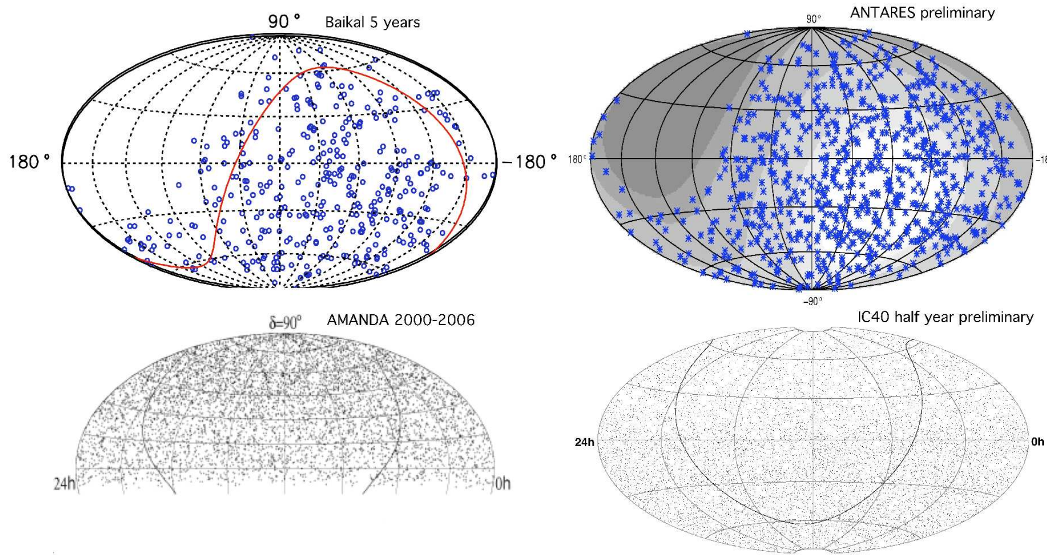

Figure 8: Sky maps from Baikal [5] upper left (391 events), ANTARES 5+12 lines [8] (preliminary) upper right (750 events), AMANDA 7 years [9] lower left (6600 events) and IC40 half-year [10] (preliminary) lower right (6796 events Northern Hemisphere and 10981 events Southern Hemisphere). Baikal and ANTARES maps are in galactic coordinates and AMANDA and IceCube in equatorial coordinates. The ANTARES sky map has the neutrino directions still scrambled. The events in the IceCube Southern hemisphere are mainly high energy atmospheric muons with a reduced rate by a factor of 10^{-5} by energy cut.

IceCube's most sensitive search so far is the half-year exposure of IC40 (2008), see Figure 8 (lower right) [10]. The "warmest" spot was at right ascension of 114.95° and declination of

15.35°. The p-value accounting for effective trials in scanning the sky was 61 % which is far from significant. ANTARES has presented their first preliminary results for 25 selected sources [11] using the 5 string telescope (2007) without any significant signal.

In Figure 9, neutrino flux upper limits (90 %) for predefined specific point sources as well as average upper limits and expected sensitivities are shown, assuming an E^{-2} energy dependence. The IC40 175 days (half year) exposure is used to predict the sensitivity and discovery potential (5σ) for IC40 345 days. The preliminary sensitivities for the completed IceCube [12] and KM3NeT [13] are also shown for one year exposure. The flux limits for IceCube above the horizon (negative declination) are based on very high energy events (above 100 TeV and in the PeV range) whilst ANTARES covers the GeV to TeV energy range. IceCube and ANTARES are sensitive to different parts of the E^{-2} spectrum for the negative declination.

3.2 GRB

Short transient neutrino sources have a much reduced background from atmospheric neutrinos. One type of potential transient sources for high energy cosmic rays are the Gamma Ray Bursts (GRBs). They are the most violent events observed in space. The search for neutrino events in coincidence in time and direction (given by satellites) with a GRB is almost free of background from atmospheric neutrinos. AMANDA [14], IceCube [15][16] and ANTARES [17] have presented limits for hundreds of GRBs but without any significant observation of coincident neutrinos. The GRBs are probably the most promising source for detection of extra galactic neutrinos.The sensitivity for IceCube is expected to be high enough to exclude GRBs as the main sources for ultra high energy cosmic rays, if no signal is observed by IceCube within five years.

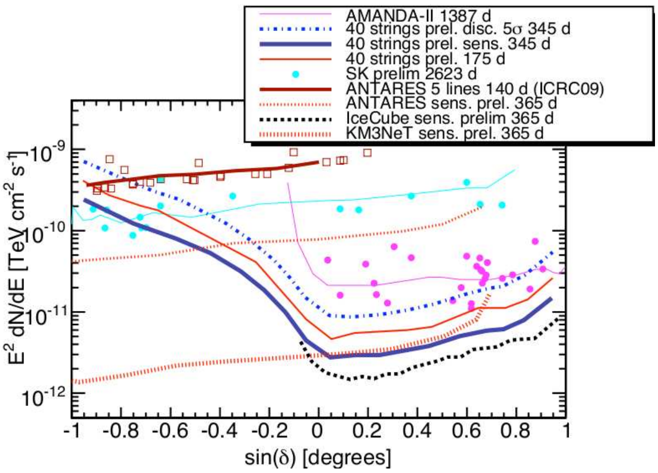

Figure 9: Upper limits (90%) and sensitivities for E^{-2} neutrino sources as a function of declination. AMANDA [9], IC40 [10], Super Kamiokande [18], ANTARES 5 lines [11], ANTARES 365 days [11], KM3NeT [13], IceCube 365 days [12]. Courtesy T. Montaruli.

3.3 Search for a diffuse neutrino flux

If there is not a sufficient number of events from neutrino point sources to give individual significant observations, the sum of all neutrino sources in the sky could still be significant. However, the only way to distinguish these neutrinos from the atmospheric neutrinos is that we expect the astrophysical sources to have a harder energy spectrum E^{-2} compared to the atmospheric neutrinos $E^{-3.7}$. The signal for a diffuse astrophysical neutrino flux is then an excess of high energy neutrino events above the expected atmospheric neutrino energy distribution. Diffuse flux limits are normally given for the sum of all three neutrino flavors because the large distance from an astrophysical source will give equal mixture due to neutrino oscillation.

Figure 10 shows the 90 % confidence level upper limits and expected sensitivities for diffuse flux of astrophysical neutrinos as a function of neutrino energy for a number of experiments. The unfolded atmospheric muon neutrino spectrum from AMANDA [19] and IceCube [20] (preliminary) are also shown. New preliminary diffuse flux limits for astrophysical neutrinos from Baikal [21], AMANDA [22] and IceCube [23] [24] with 22 strings are included. No statistically significant observation of any astrophysical diffuse neutrinos has been observed. However, as can be seen in Figure 10 the preliminary flux sensitivity for IC40 [10] is now below the Waxman-Bahcall flux prediction [4], showing that with 50% of IceCube one has already reached a possible discovery region.

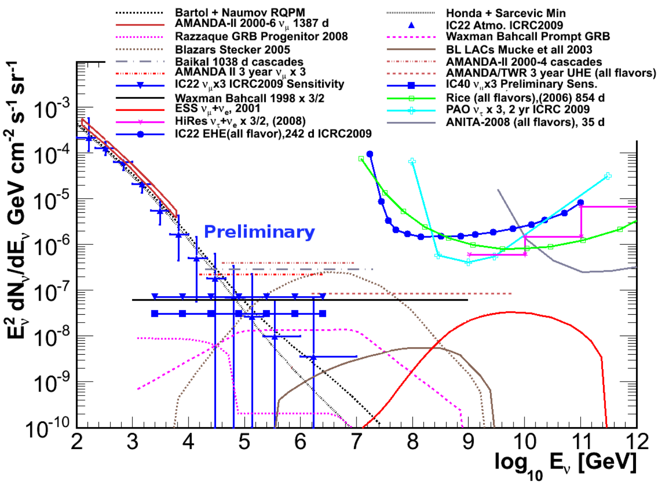

Figure 10: Experimental upper limits for diffuse extraterrestrial neutrino fluxes, estimated sensitivities and predictions for different theoretical models as a function of neutrino energies.

3.4 Dark matter search

If the dark matter consists of weakly interacting massive particles (WIMPs) like e.g. supersymmetric neutralinos, one expects these to be gravitationally captured by heavy objects like Sun, Earth, the center of the galaxy, etc. Since neutralinos are majorana particles, they annihilate and produce standard matter e.g. neutrinos. The observation of high energy neutrinos (GeV to TeV) from the centers of Sun or Earth or the centre of the galaxy might then be an indirect indication for dark matter particles. Baikal [25], ANTARES [26], AMANDA [28] and IceCube[29] have recently presented limits on muon flux generated by neutrinos from neutralino annihilation in the Sun. No excess of neutrinos from the Sun or the centre of the Earth has been observed.

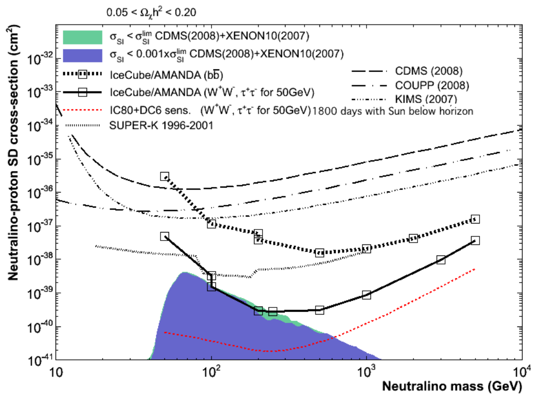

Figure 11: Upper limits at 90% confidence level on spin-dependent neutralino proton cross section for the hardest (W^+W^-) and softest ($b\bar{b}$) decay channels. The shaded area represents MSSM models not disfavored by direct dark matter experiments based on DarkSusy [34].

The neutrino telescopes are especially sensitive for spin-dependent interactions between dark matter particles and standard matter since the capture in the Sun is sensitive to this cross section. This allows for comparison with direct detection experiments for models having equilibrium between capture and annihilation rates in the Sun. In Figure 11 the 90% upper limits on the spin-dependent neutralino-proton cross section are shown for the neutrino telescopes Super-Kamiokande [27], AMANDA [28] and IC22 [29]. The limits from the neutrino telescopes are far better than for the direct detection experiments CDMS [30], XENON-10 [31], KIMS [32] and COUPP [33]. The shaded area represents MSSM models not disfavored by direct dark matter experiments based on DarkSusy [34]. The IC80 + DeepCore sensitivity is given for 1800 days with the Sun below the horizion. As seen in Figure 11, IC80 with the DeepCore telescope will soon be able to test many interesting MSSM models. DeepCore is improving the sensitivity at the lowest neutralino masses.

3.5 Atmospheric muon anisotropy

The high flux of atmospheric muons recorded in IceCube opens up the possibility for studies of anisotropy in cosmic rays. IceCube [35] with 22 strings (2008) has reconstructed more than $4.3 \cdot 10^9$ down-going atmospheric muons from the CR interactions in the atmosphere. The median angular resolution is 3° and the median energy is 14 TeV. Figure 12 shows the Southern sky in equatorial coordinates with a large-scale anisotropy of amplitude $(6.4 \pm 0.2) \cdot 10^{-4}$. The explanation is not known but the anisotropy is probably due to the the local interstellar magnetic field. It is consistent with what has already been observed for the Northern hemisphere by Super-Kamiokande [36], MILAGRO [37] and the Tibet array [38] [39].

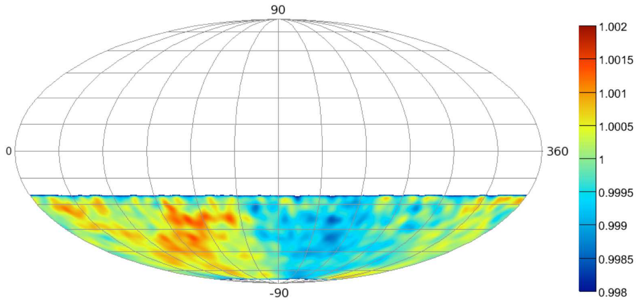

Figure 12: The sky map of relative intensity of atmospheric muons in equatorial coordinates. In total $4.3 \cdot 10^9$ atmospheric muons have been recorded.

4 New neutrino telescopes

The KM3NeT [13] Consortium (joint effort by the ANTARES, NEMO [40] and Nestor [41] [42] collaborations) is working on a large Gigaton telescope in the Mediterranean. The aim is to have one large telescope in the Northern Hemisphere as a complement to IceCube in the Southern Hemisphere. They have published a Conceptual Design Report [43] and are working on a technical design report to be published early 2010. The KM3NeT consortium has broad experience with neutrino telescopes in the deep ocean. The sites discussed for the KM3NeT telescope are 1) 40 km outside Toulon France at 2500 m depth 2) 15 km - 48 km outside Pylos Greece at 3700-5200 m depth and 3) 70 km outside Sicily Italy at 3500 m depth. Of the three projects ANTARES is the only “complete” telescope running. NEMO and NESTOR have been using single telescope components for testing. The angular resolution aimed for is 0.1° at 100 TeV neutrino energies.

The Baikal collaboration is preparing a new telescope in the Lake Baikal called Gigaton Volume Detector (GVD). It will have 91-100 strings with 12-16 optical modules each. The instrumented vertical size will be 350 m and the total horizontal area about two square kilometers. The effective volume for 100 TeV cascades will be 0.5 - 1.0 Gigaton. The muon threshold is expected to be 10 TeV. The construction is planned to start 2011 and the telescope to be completed in five years.

5 Conclusion

The partially completed IceCube telescope has already reached the sensitivity for testing "realistic" predictions of astrophysical neutrino fluxes. ANTARES is now fully operational and is the first running telescope in the Mediterranean. The planning for KM3NeT in Mediterranean and GVD in Lake Baikal are in progress. ln the near future it will be shown if telescopes of one Gigaton will be large enough to detect the neutrino flux from extraterrestrial sources.

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Discussion

Frank Simon (MPI Munich: How is the connection between GRBs, high energy CRs and neutrinos made? Does it involve pinpointing the source in space with the neutrino signal?
Answer: The GRB are easy to study with a very small background of atmospheric neutrinos. The analysis is done off line using the information from GRB satellites about the exact time and direction. The expected background from atmospheric neutrinos is very small. E.g. the AMANDA GRB search mentioned, with more than 400 GRB studied, had in total less than two expected atmospheric neutrino events.
Giovanni Siragusa (Universiät Mainz): What are the prospectives for radio and acoustic detection for high energy neutrinos? Nemo is testing such a technology.
Answer: I do not know the status of the NEMO effort. There are several radio projects for ice which are looking promising. The prospect for acoustic detecting of high energy neutrinos in ice does not looks as promising at the moment.
Vali Huseynov (Nakhchivan State University): To detect neutrinos it would be better in the future to use the crystals with strong magnetic field. When inner effective magnetic fields are strong enough, the influence of the field on the neutrino interaction processes (e.g. Neutrino-electron scattering) is essential. In this case it is possible to detect neutrinos of very low energies and relic neutrinos.
Answer: I do not know enough in order to comment what you are saying. However, the detection of the relic neutrinos is the ultimate neutrino experiment.