High Energy Neutrinos from Space

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Abstract. This paper reviews the status of the search for high-energy neutrinos from astrophysical sources. Results from large neutrino telescopes in water (Antares, Baikal) and ice (IceCube) are discussed as well as observations from the surface with Auger and from high altitude with ANITA. Comments on IceTop, the surface component of IceCube are also included.

Keywords. Neutrinos, cosmic rays

PACS Nos. Appropriate pacs here

1. Introduction

A principal motivation for finding and studying high-energy neutrinos from space is to understand better the sources of cosmic rays and how they accelerate particles to high energy. This review is organized around two connections between cosmic rays and neutrinos. In the first place, it is likely that neutrinos will be produced at some level in interactions of accelerated particles with gas or radiation fields in or near the cosmic-ray sources. Examples are hadronic interactions in the material near an expanding supernova remnant or photo-pion production in the radiation fields inside the jets of an accreting black hole. The main approach in these cases is to look for an excess of neutrinos from a particular direction in the sky above the background of atmospheric neutrinos. Potential sources may be selected for study according to the likelihood that production of neutrinos is expected. Such targeted searches may increase the discovery potential compared to a survey of the whole sky.

Production of neutrinos is also expected by interactions of cosmic rays as they propagate through the Universe. Locally, neutrinos are produced as cosmic-rays interact with gas in the interstellar medium \cite{1}. The expected level (which is quite low) can be calculated directly from the observed gamma-ray flux from the same source, which traces the gas in the disk of the galaxy. A more interesting question is the level of neutrino production by cosmic rays of ultra-high energy (UHECR) as they propagate through the cosmic microwave background (CMB). Protons with energies above $5 \times 10^{19}$ eV are above the threshold for production of pions on CMB photons \cite{2,3}. Neutrinos would be produced when the pions decay. UHE cosmic-ray nuclei also lose energy during propagation in the CMB by photo-disintegration \cite{4}, but the level of neutrino production from subsequent decay of spallation neutrons is lower \cite{5}.

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Figure 1 is a compilation of measurements of the cosmic-ray spectrum at high energy. The spectrum steepens between $10^{15}$ and $10^{16}$ eV total energy per particle. This feature, called the knee, may reflect the decrease in the ability of galactic accelerators such as supernova remnants to achieve such high energy. The spectrum flattens again around $3 \times 10^{18}$ eV = 3 EeV, a feature known as the ankle. It is generally assumed that particles above this energy originate in more powerful extragalactic sources. Finally, the steepening of the spectrum above $5 \times 10^{19}$ eV is usually assumed to be the effect of expected energy losses during propagation through the CMB. One reason to search for cosmogenic neutrinos associated with propagation through the CMB is to see if this assumption is correct.

Figure 1. Compilation of the primary cosmic-ray spectrum measured by air shower experiments [6].

| Detector       | Number of OMs | Enclosed volume (Megatons) | Depth (m.w.e.) | Status       |
|----------------|---------------|----------------------------|----------------|--------------|
| Baikal [7] (NT200+) | 230           | 10                         | 1100-1310      | Operating    |
| AMANDA [8]      | 677           | 15                         | 1350-1850      | 2000 - 2009  |
| ANTARES [9]     | 900           | 10                         | 2050-2400      | Operating    |
| IceCube [10]    | 5160 + 324    | 900                        | 1350-2280      | Operating    |
| (IceCube DeepCore [11]) | (480)         | (15)                       | (1950 - 2280)  | Operating    |
| KM3NeT [12]     | ~10,000       | km$^3$                      | 2300-3300      | Design study |
|                 |               | km$^3$                     | 3000-4000      |              |
|                 |               | km$^3$                     | 1400-2400      |              |
| GVD [15] (future Baikal) | ~2500       | km$^3$                      | 800-1300       | Design study |

Table 1. Parameters of existing and proposed neutrino telescopes ice. Of the total of 5484 OMs in IceCube, 480 are deployed on DeepCore Strings and 324 in IceTop tanks. The three depths listed for KM3NeT correspond to three possible locations, NEMO [13], NESTOR [14] and Antares [9] in that order.
2. Detectors in ice and water

The operating principle of detectors like IceCube, Antares and Baikal listed in Table 1 is the same as Super-Kamiokande [16] and SNO [17]: events are reconstructed from times and amplitudes in an array of optical sensors of Cherenkov light from charged particles moving faster than the local speed of light in the detector. The large detectors are, however, much less densely instrumented. Compared to Super-K with 11,000 photomultiplier tubes (PMTs) in 40 kilotons of water, IceCube has 5160 PMTs of half the diameter in a gigaton of ice. The neutrino telescopes are optimized for large target volume with sparse instrumentation to obtain the greatest sensitivity for relatively rare astrophysical neutrinos of high energy.

![Artist's drawing of the IceCube detector](image)

**Figure 2.** Artist’s drawing of the IceCube detector [18].

IceCube is currently the largest neutrino detector in operation [18]. Construction at the South Pole was completed at the end of 2010, and the detector has been running since May 20, 2011 with its full complement of 86 strings, each equipped with 60 digital optical modules (DOMs) at depths between 1450 and 2450 m in the ice. Fig. 2 shows the completed detector, which also includes a surface air shower array of 81 pairs of tanks, each instrumented with two DOMs and fully integrated into the data acquisition system (DAQ) of IceCube. The IceCube DOM includes, in addition to the 25 cm PMT [19], a programmable data acquisition board [20] that records the amplitude as a function of time produced by photons hitting the photo cathode. Digital signals are sent to the surface where computers build events from physically related signals in the DOMs. Times in individual DOMs are keyed to a single GPS clock on the surface to an accuracy of < 3 ns across the entire array including IceTop.

Antares [9] is located in the Mediterranean Sea near Toulon. It is the first neutrino
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detector to operate in the open ocean, which requires deploying lines of optical modules from a ship and continuously monitoring the positions of the sensors as they respond to currents in the water. Antares optical modules are arranged in groups of three so that local coincidence can be used to overcome the relatively high background of bioluminescence. The Baikal detector also operates in a natural body of water, but deployment occurs from the solid ice on the surface of the lake in winter.

\[ \cos(\theta) = -0.9 \]
\[ \cos(\theta) = -0.7 \]
\[ \cos(\theta) = -0.5 \]
\[ \cos(\theta) = -0.3 \]
\[ \cos(\theta) = -0.1 \]

Figure 3. Left: Effective area of an ideal cubic kilometer detector. Right: Response of IceCube (with 59 strings in 2009-10) to three different spectral shapes for muon neutrinos [21].

The muon channel is the most favorable in terms of event rate in the TeV range and above because the target volume is enlarged by the charged current interactions of neutrinos outside the detector that produce muons that go through the detector. The most sensitive analysis uses the Earth as a shield against the downward background of cosmic-ray muons by selecting horizontal and upward moving events. For energies in the TeV range and above, stochastic energy losses by muons become important, and the light produced increases in proportion to the muon energy according to the standard formula [6]

\[ \frac{dE_\mu}{dX} = -a - bE_\mu. \] (1)

The event rate in this channel is a convolution of the neutrino flux with the neutrino cross section, the detector response and the range of the muon. At high energy the Earth becomes opaque to neutrinos, first for vertically upward neutrinos (\( \sim 30 \) TeV) and then for more horizontal events (\( \sim \)PeV). Thus the effective area for \( \nu_\mu \) in the charged current channel is

\[ A_{\text{eff}}(\theta, E_\nu) = \epsilon(\theta) A(\theta) P_\nu(E_\nu, E_\mu) \exp\{-\sigma(\nu)(E_\nu)NAX(\theta)\}, \] (2)

where \( X(\theta) \) is the slant depth (g/cm\(^2\)) along a zenith angle \( \theta > 90^\circ \), \( N_A \) is Avogadro’s number, \( \sigma(\nu) \) is the neutrino cross section and \( \epsilon(\theta) \) a reconstruction efficiency.

\[ P_\nu(E_\nu, E_\mu) = N_A \int_{E_\mu}^{E_\nu} dE_\mu' \frac{d\sigma(\nu)(E_\nu)}{dE_\mu'} R(E_\mu', E_\mu) \]

is the probability that a muon produced with energy \( E_\mu' \) reaches the detector with energy \( E_\mu \) sufficient to trigger the detector. The muon range \( R \) is calculated from Eq. [1]. The
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left panel of Fig. 3 shows the $\nu_\mu$ effective area for an ideal cubic kilometer detector with a threshold $E_\mu = 100$ GeV. The neutrino rate is a convolution of effective area with neutrino flux.

In the TeV range and above muons typically pass through the detector, so only a fraction of the muon energy contributes to light in the detector. In this situation, simulations that incorporate the physics of neutrino interactions, of muon energy loss and of ice properties must be used to relate the measured light to the energy of the muon in the detector and thence to the energy of the neutrino. This is done either by convolving an assumed neutrino spectrum with the sequence $\nu_\mu \rightarrow \mu \rightarrow$ observed light, or by an unfolding procedure. An important feature of the analysis is that the distribution of $\nu_\mu$ energies that give rise to a given signal in the detector is different for the steep atmospheric neutrino spectrum from what it would be for a hard spectrum of astrophysical neutrinos. This is illustrated in right panel of Fig. 3 which shows the distributions of neutrino energy that correspond respectively to atmospheric neutrinos from decay of pions and kaons, to prompt atmospheric neutrinos from charm decay and to astrophysical neutrinos assumed to have an $E^{-2}$ differential energy spectrum. The responses are integrated over $2\pi$ solid angle from below the horizon and use the full simulation of IC-59 for $A_{\text{eff}}$.

Figure 4. Sky maps showing exposure of Antares (top) and IceCube (bottom) for atmospheric $\nu_\mu$ from below the local horizon. Figure from Ref. [22].

3. Point source search

The basic analysis in neutrino telescopes is to search for point sources of extraterrestrial neutrinos using the direction of the neutrino-induced muon as a proxy for the direction of the parent neutrino. In the TeV range, the r.m.s. angle between $\nu_\mu$ and $\mu$ is $\sqrt{\langle \psi^2 \rangle} \approx 1.8/\sqrt{E_\nu(\text{TeV})}$. The median angular resolution for Antares is $0.5^\circ$ [23]. For IceCube, 60% of the events are reconstructed to better than $1^\circ$ [24] based on analysis of the moon shadow in cosmic-ray induced muons [25].
An important difference between IceCube and the Antares location at Northern mid-latitudes is exposure, as shown in Fig. 4 from Ref. 22. In particular, the central region of the Galaxy is not visible in upward going events from the South Pole. The sensitivity of Antares and IceCube for point sources is shown by the lines in Fig. 5. In this plot the sensitivity is shown for IceCube running with 40 strings installed in 2008-2009 (IC-40). The individual points are limits on preselected sources, which include galactic objects including supernova remnants as well as potential extragalactic sources such as active galactic nuclei (AGN). The point-source list for IC-40 includes 13 galactic sources and 30 extragalactic sources. Among the galactic sources targeted are several supernova remnants. The extragalactic candidates are mostly active galaxies.

For the Northern sky the larger IceCube detector is by far the most sensitive. Upper limits on specific point sources of neutrinos in the Northern sky from IceCube are currently less than $10^{-11} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$. The sensitivity to point sources is approaching the level of $10^{-12} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$ at which TeV gamma rays are seen from some blazars (e.g. Mrk 401 [28]).

IceCube extends the search for point sources to Southern declinations by raising the energy threshold to reduce the high background of downward atmospheric muons. The sensitivity and limits from IC-40 from the Southern sky are included in the left panel of Fig. 5. The right panel of Fig. 5 shows the energy response of IceCube with 59 strings (IC-59) as a function of declination. For upward neutrinos from the Northern hemisphere the limits apply to $\nu_\mu$ energies in the TeV to PeV energy range. For events from above in IceCube (Southern sky) the relevant energy range is approximately two orders of magnitude higher (100 TeV to 100 PeV).

With data from 2010 and later it will be possible to extend the search for neutrinos in the Southern hemisphere to lower energy by using the DeepCore subarray of IceCube. In the final construction years of IceCube eight specially equipped strings were deployed to provide a more densely instrumented sub-array in the center of IceCube called DeepCore. Each of these strings has 60 DOMs, 50 of which are between depths of 2100 and 2450 m, which is below the main dust layer at the South Pole. The DeepCore sub-array is defined to include the bottom half of the central string of IceCube as well as the lower DOMS...
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on six surrounding standard strings. Typical spacing between strings in DeepCore is 75 m as compared to 125 m between standard strings. The spacing between DOMs on the 8 special strings is 7 m. One of the main motivations is to provide an inner fiducial volume surrounded by at least three rings of standard IceCube strings and thirty layers of DOMs above to provide a veto against atmospheric muons and allow for TeV neutrino astronomy in the Southern sky. This and other goals of DeepCore are described in Ref. [11].

4. Flaring, transient and gamma-ray burst sources

A correlation in space or time (or both) with a source observed electromagnetically would enhance the likelihood that the observed neutrinos are of astrophysical origin. Two strategies are used in IceCube to pursue this option. One is to send alerts for follow-up by other instruments when an apparently significant grouping of neutrinos is seen. The potential signal could be two or more neutrinos from the same direction within a short time window or a sequence of events from a targeted source that exhibits flares in the electromagnetic spectrum, for example. Currently alerts are sent from IceCube to ROTSE and the Palomar Transient Factory and SWIFT [29]. Arrangements for sending alerts to the Northern hemisphere gamma-ray telescopes MAGIC and VERITAS are also in preparation. These multi-messenger agreements lead to the possibility that a neutrino signal could be associated with an identified type of object, such as a supernova explosion or a flaring AGN. Limits obtained from the follow up with ROTSE [30] are described in Ref. [31].

Going the other direction, IceCube can follow up potentially interesting astrophysical events such as nearby supernovae [32] or flares from likely cosmic accelerators [33]. A general search for short-term increases in rates of neutrinos from flaring sources is also done [34]. The most important result achieved from a catalog of events is the search for neutrinos associated with gamma-ray bursts (GRB) [35]. Recently data sets from two years of IceCube while the detector was still under construction (IC-40 and IC-59) have been combined to obtain a significant limit on models [36] in which GRBs are the main source of extragalactic cosmic rays. In total 215 GRBs reported by the GRB Coordinated Network between April 5, 2008 and May 31, 2010 in the Northern sky were included in the search. No neutrino was found during the intervals of observed gamma-ray emission.

To set limits on the model [36], the expected neutrino spectrum was calculated for each burst based on parameters derived [37] from features in the spectrum of the GRB. In particular, a break in the observed photon spectrum marks the onset of photo-pion production by accelerated protons interacting with intense radiation fields in the GRB jet. The neutrinos come from the decay of charged pions. Given a predicted neutrino spectrum, the expected number of events was calculated for each burst. The normalization of the calculation is provided by the assumptions that a fraction of the accelerated protons escape and provide the ultra-high energy cosmic rays. In the simplest case, the UHECR are injected as neutrons from the same photo-production processes in which the neutrinos are produced [38]. With this normalization, 8 neutrinos are expected in 215 GRBs and none are observed. Fig. 6 shows the resulting limits along with the original prediction of Waxman and Bahcall [36]. A model-independent search was also carried out, simply looking for neutrinos within 10° in an expanding time window up to several hours around the time of each burst. Again, no correlated neutrinos were found.
5. All-sky survey with $\nu_\mu$

It is important also to search for an excess of astrophysical neutrinos from the whole sky at high energy above the steeply falling background of atmospheric neutrinos. The Universe is transparent to neutrinos, so the flux of neutrinos from sources up to the Hubble radius may be large [39]. A specific estimate based on the density of AGNs [40] is that the event rate from the whole sky should be a factor 20 larger than from a single AGN. Limits from AMANDA [8], Antares [9] and IceCube [41] are shown in Fig. 7. The current limit from the 40-string version of IceCube is now below the original Waxman-Bahcall bound [43].

The limit is obtained by fitting the distribution of light in the detector from upward moving muons to parameters that describe an assumed neutrino spectrum consisting of:

- “conventional” atmospheric muon neutrinos from decay of charged pions and kaons;
- “prompt” atmospheric neutrinos, mainly from decay of charmed hadrons with a spectral shape taken from Ref. [44]; and
- an assumed astrophysical flux with a hard $E^{-2}$ differential energy spectrum.

The atmospheric neutrino flux used in this analysis [41] is a simple power-law extrapolation of the calculation of Ref. [42]. Its normalization is treated as a free parameter in fitting the data in Ref. [41], which is shown as a slightly curved band that extends from 0.33 to 84 TeV in Fig. 7. The other experimental results on the high-energy flux of atmospheric $\nu_\mu + \bar{\nu}_\mu$ in Fig. 7 are from AMANDA [45, 46] and IceCube-40 [47]. All the atmospheric neutrino spectra shown here are averaged over angle. The unfolding analysis of Ref. [47] extends to $E_\nu \approx 400$ TeV. The integral limit on astrophysical neutrinos shown for IceCube-40 in Fig. 7 assumes a hard, $E^{-2}$ spectrum. For this reason, the bound applies at much higher neutrino energies (35 TeV to 7 PeV) than the observed spectrum of atmospheric neutrinos.

As discussed in Ref. [48], one of the difficulties of searching for an astrophysical contribution at the level of the Waxman-Bahcall limit is that the atmospheric background in the relevant energy range above 100 TeV is not well known. Standard calculations of
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Figure 7. Horizontal lines show limits on an $E^{-2}$ spectrum of astrophysical muon neutrinos from AMANDA-II [8], Antares [9] and IceCube [41]. The limits are shown along with measurements of the flux of atmospheric muon neutrinos and anti-neutrinos. The plot is from Ref. [41] where full references are given.

conventional atmospheric neutrinos [42, 49] extend only to 10 TeV. In addition, the level of prompt neutrinos, which are expected to become important somewhere above 100 TeV is highly uncertain. The current IceCube limit appears already to rule out the highest prediction for charm [50].

6. Implications

The Waxman-Bahcall bound is an upper limit to the intensity of neutrinos which holds if the neutrinos are produced in the same sources that produce the extra-galactic cosmic rays. For this to occur, the accelerated protons must be able to escape from the sources, either directly or as neutrons created by $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$. For GRB, escape (at least of the neutrons) is likely because of the rapid expansion, as discussed in Ref. [38].

In the case of AGNs, Waxman and Bahcall [43] show that the existence of TeV photons from blazars guarantees that the density of electromagnetic radiation is such that EeV nucleons can indeed escape, so the bound applies to AGNs as well as GRBs. If protons are trapped in the acceleration region by the turbulent magnetic fields needed to make the acceleration process work, then the bound may be related to an estimate of the expected level of neutrino production. In this scenario, the high energy protons lose energy by photo-pion production, while the neutrons escape and decay to protons to become ultra-high energy cosmic rays (UHECR). The neutrinos from the pion decay are then related by kinematics to the UHECR. Another consequence is that the UHECR would be protons.

This scenario could be realized in jets of GRB and of AGN if acceleration occurs in internal shocks in the jets. As IceCube limits become increasingly strong, this class of models is constrained. A generic alternative could be that the UHECR are accelerated...
outside the jets, for example at the termination shocks of AGNs. In this case the composition of the extragalactic cosmic rays would depend on the ambient medium, and the level of neutrino production would be contingent on the density of the surrounding medium and correspondingly low.

7. Cosmogenic neutrinos

Independent of the level of neutrino production in cosmic sources, there will be production of neutrinos from

\[ p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow \nu_\mu \quad (\rightarrow p + \pi^0 \rightarrow \gamma \gamma) \]

provided only that there are protons above the threshold of \( \sim 5 \times 10^{19} \) eV from sources distributed throughout the Universe. Photons are produce in the neutral pion channel of the same process. These photons would undergo cascading and contribute to the background of diffuse gamma-rays measured by the Fermi Satellite \cite{51}, which leads to an upper limit on the spectrum of cosmogenic neutrinos. This limit is now at the level where no more than approximately one event per year would be expected in the full IceCube \cite{52}. Limits from IC-40 \cite{53} and other detectors are collected in Fig. [8]. The limits are for the sum of three flavors assuming equal contributions from each flavor. Both differential and integral limits are shown. Differential limits are obtained by assuming an \( E^{-2} \) spectrum over a logarithmic bin of energy and calculating the limit for the each bin. The shapes of the curves then indicate the energy response of each detector. The limits for a full
$E^{-2}$ neutrino spectrum are shown as straight lines in the plot. The most precise result is to calculate the expected signal for each flux model and state the corresponding limit or expectation. For example, for the flux of Ref. [52] the expected number of events is 0.43 for IC-40 detector, which was half the size of the completed IceCube.

The ANITA detector [55] is designed to look for neutrino interactions in the ice while flying in a circumpolar pattern in long duration balloon flights above Antarctica. From its altitude of $\approx 35$ km, an array of antennas scans $\approx 10^{6}$ square kilometers of ice looking for radio pulses produced by Cherenkov radiation from the cascade generated by the neutrino interaction in the ice. The radio pulse from a downward slanting neutrino would be reflected from the ice-rock interface and therefore identifiable by its vertical polarization. One neutrino candidate was detected in the second flight of ANITA [56], which was aloft for 31 days. ANITA also sees horizontally polarized events which are interpreted as air showers with cosmic-ray energies of $\sim 10^{19}$ eV that generate a radio signal by geo-synchrotron radiation [57]. A third flight of ANITA is planned for 2012/13.

The Auger detector is sensitive to neutrinos with energies in the EeV range [58]. The signal of a neutrino would be a horizontal air shower with a normal electromagnetic component from a neutrino interaction near the detector. Horizontal air showers produced by cosmic rays would have originated far away so that the electromagnetic component would be absorbed leaving mostly muons at the detector. With a surface area of 3000 km$^2$ the volume of air directly over the array is equivalent to $\approx 30$ km$^3$ of water. However, the array is most sensitive (by a factor of about five [59]) to Earth skimming charged current interactions of $\nu_\tau$ in which a tau emerges from the nearby mountain and initiates an air shower over the array when it decays. The expected number of cosmogenic neutrino events expected in several year is 0.71 for the Earth skimming channel and 0.14 for the near horizontal air shower channel [59].

8. Cosmic-ray physics with IceTop

The surface array of IceCube consists of 81 stations with two ice Cherenkov tanks separated from each other by 10 meters. Each tank contains two downward facing DOMs with the PMT half of the DOM frozen into the ice. During deployment, the tanks were filled with water and then frozen in a controlled process to achieve clear ice free of bubbles. Tanks are lined with a diffusely reflecting material which scatters the Cherenkov light from charged particles back up toward the ice surface and the PMTs. The typical signal from a muon passing through the tank is 130 photo-electrons. One PMT is set at a lower gain than its partner so that the dynamic range of a tank is $\approx 0.1$ to 1000 vertical equivalent muons. Figure 9 is a preliminary measurement of the spectrum with IceTop in 2007 when there were 26 stations [60].

The area enclosed by IceTop is approximately one km$^2$, and the mean atmospheric overburden at the South Pole is 680 g/cm$^2$. Given its total area and the average spacing between stations of 125 m, IceTop covers an energy range from 300 TeV to just above 1 EeV. The aperture of the 3-dimensional array formed by and IceTop and the deep part of IceCube is $\approx 1/3$ km$^2$sr. Together, the two parts of IceCube form a three-dimensional air shower array.

Figure 10 shows a coincident event that is contained in both parts of the IceCube. The event has an energy of $\approx 30$ PeV as estimated from the pulses in IceTop. Such an event would produce 35 to 100 muons with sufficient energy at production in the atmosphere to penetrate through IceCube. The actual number fluctuates from event to event, but these are average values expected for protons or iron nuclei respectively. A major goal
of cosmic-ray studies with IceCube is to use the ratio of signal in the deep detector to shower energy estimated by IceTop to measure the primary composition up to the EeV range. A preliminary analysis with 21 days of data taken with IC-40 indicates an increase in the mean mass of the primary cosmic rays between 0.3 and 30 PeV. Analysis of a large sample of data from the completed detector to exploit its full capability depends on correcting for systematic seasonal effects, which is underway.

Figure 9. Preliminary measurement of the primary energy spectrum with IceTop in 2007 with 26 stations deployed. Figure from Ref. [61].

Figure 10. Example of a coincident event contained in both parts of IceCube.
9. Conclusion and Outlook

So far the only extraterrestrial neutrinos detected are from Supernova 1987A [63, 64] and from the Sun [17, 65]. Early predictions for high levels of astrophysical neutrinos at high energy have not been realized. Current limits from IceCube are beginning to exclude some models in which production of neutrinos is intimately connected with acceleration of the majority of ultra-high energy cosmic rays from extra-galactic sources. At the same time, the sensitivity of IceCube is approaching the level where signals are expected from some galactic sources after several years [40]. Realization of the proposals for KM3NeT [12] and (or) GVD [15] in the Northern hemisphere would provide full-sky coverage with cubic kilometer sensitivity for astrophysical neutrinos in the TeV range and above. In the meantime, ANTARES and Baikal continue to provide some level of complementary coverage as indicated in Fig. 4.

An important aspect of IceCube from the point of view of high energy physics is the possibility to use the atmospheric neutrino beam to search for hints of new particle physics [66] that might show up as anomalies in the angular dependence or the energy spectrum of atmospheric neutrinos. This is possible because the large size of IceCube gives an unprecedented rate of some 100,000 neutrinos per year in the TeV range and above. Limits on violation of Lorentz invariance [67] and on certain models of sterile neutrinos [68] have already been published. The energy dependence of the neutrino cross section above accelerator energies is also of interest in this connection.

Another consequence of the large size of IceCube is the huge sample of cosmic-ray induced atmospheric muons. The event rate of almost 100 billion $\sim$ TeV muons per year has already led to measurement in the Southern sky of cosmic-ray anisotropy at the level of $10^{-4}$ [69] and to new measurements of its small-scale structure [70] and energy dependence [71]. Statistics are high enough to measure the spectrum of atmospheric muons to 100 TeV and somewhat higher [72]. This opens the possibility of measuring the prompt neutrinos from charm by a combination of angular dependence and seasonal variations [73].

Other capabilities of IceCube include detection of neutrinos from galactic supernova explosions and sensitivity to neutrinos from dark matter annihilation. Rates above threshold in the DOMs are monitored continuously. A galactic supernova would show up as a sharp increase in the counting rate due to light produced near the DOMs by many interactions of $\sim$10 MeV neutrinos [74, 75]. This is possible because of the low counting rate ($\approx 500$ Hz) of DOMs in the ice. Similar monitoring of scalar rates in IceTop DOMs has already led to the observation of particles at ground level associated with a solar flare [76]. A sufficiently strong GRB could also show up as an increase in IceTop single tank rates.

Indirect searches for dark matter are done in two ways in IceCube. Neutrinos from WIMP annihilation in the Sun provide the most stringent limits on the spin-dependent WIMP-proton scattering cross section [77]. It is also possible to look for neutrinos from WIMP annihilation the Galactic halo (currently by looking for an angular excess in the edge of the galactic center region that is visible in the Northern sky [78]).

An important aspect of IceCube is its ability to detect all flavors of neutrinos [79]. Although the largest event rate at high energy will be from charged current interactions of $\nu_\mu$, because the long muon range, the other flavors are particularly important for several reasons. The background of atmospheric $\nu_\tau$ is significantly lower at high energy than $\nu_\mu$. To be identified, $\nu_\tau$ must interact inside the detector, which means their energies will be measured more accurately. Production of $\nu_\tau$ by cosmic-ray interactions in the atmosphere is negligible, but, because of oscillations, they will be at the same level as $\nu_\mu$ and $\nu_\tau$ from astrophysical sources. Identification of events as $\nu_\tau$ would therefore be a strong indication
of astrophysical origin.

Flavor identification hinges on identifying cascades in the detector, where a cascade is defined as a nearly isotropic burst of light. High energy muons produce cascades by bremsstrahlung and other stochastic loss processes, but they can be identified by the associated track. Charged current interactions of $\nu_e$ as well as neutral current interactions of all flavors make isolated cascades. Cascades at the rate expected from atmospheric neutrinos have already been detected in the sub-TeV range with DeepCore [80]. Depending on their energy, $\nu_\tau$ would be identified as a single (perhaps elongated) cascade, a “double bang” event [81] or a cascade associated with the track of a $\tau$-lepton either before or after the cascade depending on whether the cascade is from the lepton decay or the neutrino interaction. The $\tau$ track would have lower brightness than a muon track of similar energy. In addition, the $\nu_\tau$ channel is amplified by regeneration in the Earth through $\nu_\tau \rightarrow \tau \rightarrow \nu_\tau$ [82, 83]. It is interesting to note that the cascade-like events generated primarily by $\nu_e$ and $\nu_\tau$ give significant contributions to the limits obtained for $E_\nu > 1$ PeV in IceCube [53, 54], as shown in Fig. 8.

For the future there are new efforts that push toward larger exposure at the highest energies as well as plans for increasing the sensitivity at low energy. The KM3NeT project aims for a substantial increase in sensitivity compared to IceCube, with emphasis on the galactic center region. The Askaryan Radio Array (ARA) project has the aim of building a detector capable of detecting about 100 cosmogenic neutrinos at the level allowed by the diffuse gamma-ray limit of Fermi [52]. The first test set up for ARA was deployed next to IceCube in January, 2011. Radio antennas will be deployed in shallow holes ($\approx 200$ m) starting in the current (2011/2012) Antarctic seasons to detect Askaryan radio emission from neutrinos [84]. There is also a proposal for a radio air shower test array (RASTA) to determine the feasibility of expanding the surface air shower coverage by an order of magnitude [85].

In the low-energy direction, there is a proposal to lower the energy threshold of the current DeepCore to $< 10$ GeV by deploying 18 to 20 strings inside the DeepCore volume [86]. This extension (called PINGU) would enhance the capability of IceCube for neutrino oscillation studies and for low energy neutrinos from the galactic center region in the Southern sky. There is also ongoing discussion of the possibility of making megaton scale proton decay detector in the deep center of IceCube, which would require much denser coverage [87].

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