

AMANDA and IceCube: news and neutrino analyses

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Abstract. IceCube is a kilometer-cubed-scale neutrino detector currently under construction in the Antarctic ice cap near the South Pole. To date, 22 strings have been deployed. In 2006, 9 strings had been deployed, and data from these strings (the “IC-9” detector), have been analyzed to search for neutrinos. IceCube’s predecessor, AMANDA, has been taking data for several years. In this paper, we review a selection of recent results from both AMANDA and IceCube.

INTRODUCTION

The IceCube Observatory is the largest of its type of neutrino detector in the world: an ice-Cherenkov detector located at the South Pole, Antarctica. When completed, it will consist of 80 strings of light sensors, each deployed in 2.5-kilometer deep holes in the Antarctic ice cap, and together instrumenting a volume of ice of approximately one cubic kilometer. With such a large volume, this instrument will be capable of observing the interactions of all neutrino species up to extremely high energies, including those from extragalactic sources.

At this time, the detector is under construction; new strings are deployed during the austral summer months. The first IceCube string was deployed in the 2004/2005 season, eight more in 2005/2006, and 13 in 2006/2007, making for a total of 22 strings operating to date; the detector is over one quarter complete. Since data-taking from strings begins soon after deployment, the performance of the detector can be evaluated, and ever-improving science analyses can proceed as the detector is constructed. During the year 2006, data from the nine-string IceCube detector (“IC-9”) were collected and analyzed to search for neutrinos.

DETECTORS AND DETECTION TECHNIQUE

Each IceCube string consists of 60 Digital Optical Modules (DOMs), which contain one 10-inch photomultiplier tube (PMT) and a system of electronics capable of digitizing the waveform of pulses from incoming photons, operating in local coincidence with their neighbors, and as one of several features, operating onboard flashers. These strings of DOMs are buried in the very pure, clean, and dark ice of Antarctica near the geographic South Pole. The neutrino, when it collides with a nucleon in the ice or surrounding rock,

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produces a high-energy lepton which emits Cherenkov light as it travels through the ice. The DOMs record the waveform shapes of the arriving Cherenkov light, from which the arrival times and amplitudes of photons and the track of the lepton can be deduced.

IceCube also includes an array of surface water tank detectors (similar to those in the Pierre Auger Observatory [1]): two tanks at the top of each string. Each tank contains two DOMs. The water in the tanks is allowed to freeze slowly at the site, resulting in very clear ice. IceTop functions as a surface detector for cosmic ray air showers, tagging cosmic ray events for calibration, acting as a veto for neutrino events, or enabling the study of cosmic rays themselves and their composition.

IceCube's predecessor, AMANDA (Antarctic Muon and Neutrino Detector Array), consists of 19 strings deployed similarly at the same site; AMANDA is embedded inside IceCube. The string spacing of AMANDA is approximately 30-50 meters, as compared to IceCube's string spacing of 125 meters. With 677 optical modules instrumenting a cylindrical volume 200 meters in diameter and 500 meters tall, at depths from 1500-2000 meters, AMANDA will function as a "dense inner core" for the completed IceCube detector. AMANDA was constructed between 1995 and 2000 (the most modern version of the detector is known as AMANDA-II), and data from several years of livetime has been analyzed for a variety of scientific missions, including: diffuse neutrinos [2], point sources of neutrinos [3], neutrinos from Gamma Ray Bursts and other transient sources [4, 5], neutrinos from the annihilation of WIMPs [6, 7], exotic particles such as magnetic monopoles [8], supernova neutrinos [9], and to study cosmic rays [10].

The techniques developed for analyzing AMANDA data are now being adapted for use with IceCube data. For instance, at GeV and TeV energies, charged-current interactions of ν_μ neutrinos, which produce a high-energy muon, are the easiest to distinguish from cosmic ray background. This can be done using the muon's direction; a downgoing track is mostly likely cosmic ray background, but an upgoing track must be from a neutrino interaction. Track reconstruction is done by a maximum-likelihood method using the arrival time of photons at each DOM, with scattering and absorption effects of the ice taken into account. Even if this reconstruction could be done with perfect accuracy, there is an unavoidable error between the muon's direction and the direction of the original neutrino, but at high energies this error shrinks to less than a degree. Interactions of ν_e and ν_τ neutrinos, as well as neutral-current interactions of all three flavors, are also detectable as "cascades". While it is difficult to reconstruct their directionality, the energy estimation is more precise than for muons.

Rather than describe all of the scientific missions described above, I will here focus on a few recently published or pending results from AMANDA and IceCube.

SEARCH FOR DIFFUSE SOURCES WITH AMANDA

Neutrinos from extragalactic sources are distinguishable from atmospheric neutrino background by their harder energy spectrum; theories contend that extragalactic neutrinos should have an E^{-2} power-law spectrum, compared to the $E^{-3.7}$ power-law of the atmospheric neutrinos. So, searches for these neutrinos look for an excess of events in the high-energy tail of an energy spectrum. Although shapes and details of flux predictions vary, the E^{-2} "upper bound" of Waxman and Bahcall [11, 12] is often used as a

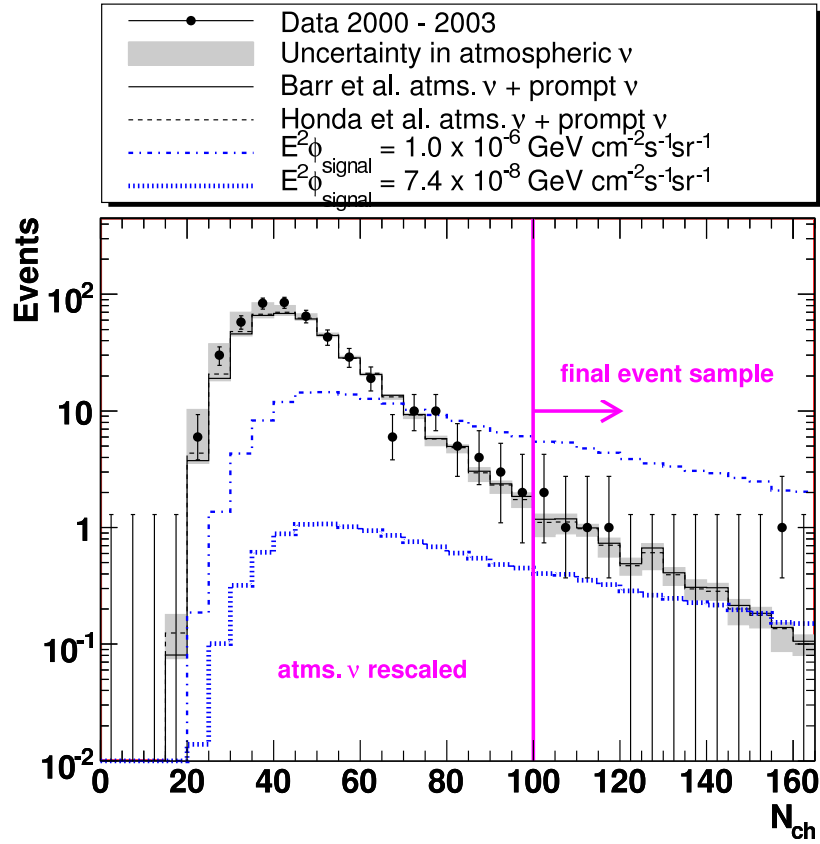


FIGURE 1. Distribution of the number of channels hit, or “NCh”, for data and simulations, showing the final cut and events remaining. Also shown are the NCh distributions expected from atmospheric neutrino background (Honda [13] and Barr et al. [14] models, which are very similar), and two different levels of hypothetical signal. Plot taken from [2].

benchmark for the sensitivity of a neutrino detector.

In one such analysis from AMANDA-II, 807 days of livetime from 2000 through 2003 are used to search for “diffuse” extragalactic neutrinos, meaning the collective flux from distant unresolved sources. The number of optical modules hit (number of channels, or “NCh”) is used as an estimator of the neutrino’s energy. With most of the data blinded, a cut in “NCh” is chosen, above which signal may appear above the reduced background. In the search described above, 6 events were observed above the final cut at NCh=100 (as shown in Figure 1), on an expected background of 7.0 events. From this, an upper limit is computed of $E^2 dN/dE = 7.4 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ on the diffuse flux of extragalactic neutrinos, at the 90% confidence level [2]. This limit is effective for neutrino energies from 16 TeV to 2.5 PeV, and this is the best limit to date in this energy range, a factor of four above the Waxman-Bahcall upper bound.

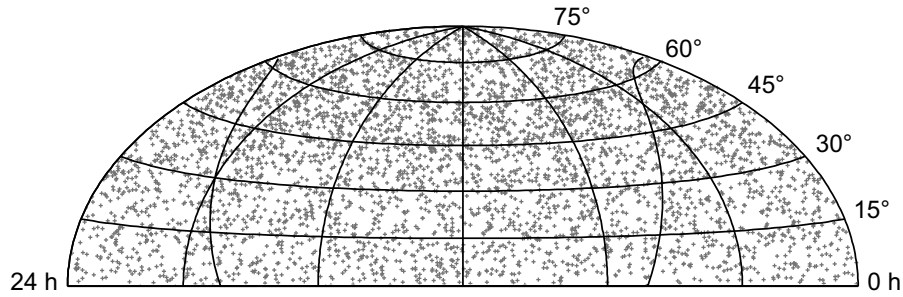


FIGURE 2. Skymap of neutrino candidates from AMANDA 5-year search. Plot taken from [3].

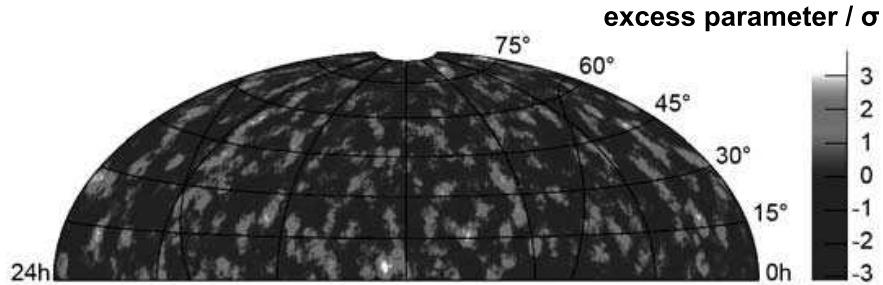


FIGURE 3. Significance map of neutrino candidates from AMANDA 5-year search. Plot taken from [3].

SEARCH FOR POINT SOURCES WITH AMANDA

AMANDA has also analyzed five combined years of data to search for point sources of neutrinos, as might be emitted from energetic objects such as active galactic nuclei (AGN) and blazars. In this analysis, upgoing neutrino candidates are reconstructed, and their directions traced back onto the Northern Hemisphere sky. Here, success depends on track accuracy, and so effort is focused on the selection of well-reconstructed events, with an angular resolution of between 1.5° and 2.5° . From the years 2000 through 2004, 4282 neutrino candidates from a data set comprising over 1001 live days were analyzed in this way [3]; their positions on the sky are shown in Figure 2. The sky is then divided into circular bins of radius between 2.25° and 3.75° (depending on declination), separated by 0.5° . In each bin, the number of observed events can be compared to the number expected from a random distribution to compute the significance; a “significance map” is shown in Figure 3. The largest excess of events found in a bin was 17 events on an expected background of 5.8 events, but over the whole sky this is not statistically significant due to the number of bins investigated. The same analysis run on an event sample which had been scrambled in azimuth (to smear out any real source) yielded similar statistical behavior.

SEARCH FOR GRB'S AND OTHER TRANSIENT SOURCES WITH AMANDA

The strategy for searching for neutrinos from Gamma Ray Bursts (GRB's) in AMANDA has changed over the years as gamma ray satellite detectors which can supply external triggers come and go. The BATSE satellite was decommissioned in 2000 (after the completion of AMANDA-II), SWIFT was launched in 2004, and the Third Interplanetary Network (IPN) provided triggers in the intervening years and continuing to this day. Triggered searches for ν_μ neutrinos associated with these various satellite detections have been performed, including a survey of over 400 GRB's from the years 1997-2003 [4]. No neutrino events have as yet been detected in coincidence with a GRB. Searches have also been conducted for single events of particular interest, such as the giant flare of SGR 1806-20 in December of 2004 [15], with negative results.

In addition, recent efforts have searched in the "cascade" channel for neutrinos of *any* flavor, rather than for ν_μ 's only. This is particularly advantageous in a GRB search; with cascades, one can search all 4π steradians of sky rather than just the Northern Hemisphere, and use time coincidence to reduce the background to nearly zero. Such a search for neutrinos from 73 BATSE triggers from 2000 has been performed [5]. One-hour time windows before and after the GRB are used to assess AMANDA's background rate of neutrino candidates, while the 10-minute time window around the GRB itself is kept blinded; then the GRB window is opened to search for an excess of events above the background.

Even *without* external triggers, one can still search for burst-like or transient neutrino events, by looking at a time window around each neutrino candidate, and "rolling" this window through the entire sample of candidates looking for a statistical excess. This type of rolling search has been done using data from 2001-2003, a time period between the departure of BATSE and the arrival of SWIFT, when external GRB triggers were scarce. Rolling time windows of both 1 second and 100 seconds are used to search for time-clustered cascade events [5].

Neither of these GRB searches has uncovered any excess of events, resulting in flux limits above the theoretical Waxman-Bahcall "broken power law" spectrum [16], but this is the first flux limit for GRB's in ν_e 's and ν_τ 's (cascades).

ATMOSPHERIC NEUTRINOS WITH ICECUBE

The first step in any kind of astrophysical neutrino search (such as the diffuse, point source, and GRB analyses described above), is to characterize the spectrum and properties of the dominant background, which are the atmospheric neutrinos produced locally in the Northern Hemisphere atmosphere.

IceCube strings begin taking data soon after they are deployed. In the year 2006, data from the nine-string "IC-9" IceCube detector were collected, quickly filtered, and sent to the Northern Hemisphere for immediate analysis. Lessons have been learned from experience with AMANDA data, such as how to perform hit cleaning on raw data, reconstruct the muon track direction for each event, and apply quality cuts to separate downgoing cosmic-ray muon background events from upgoing neutrino events.

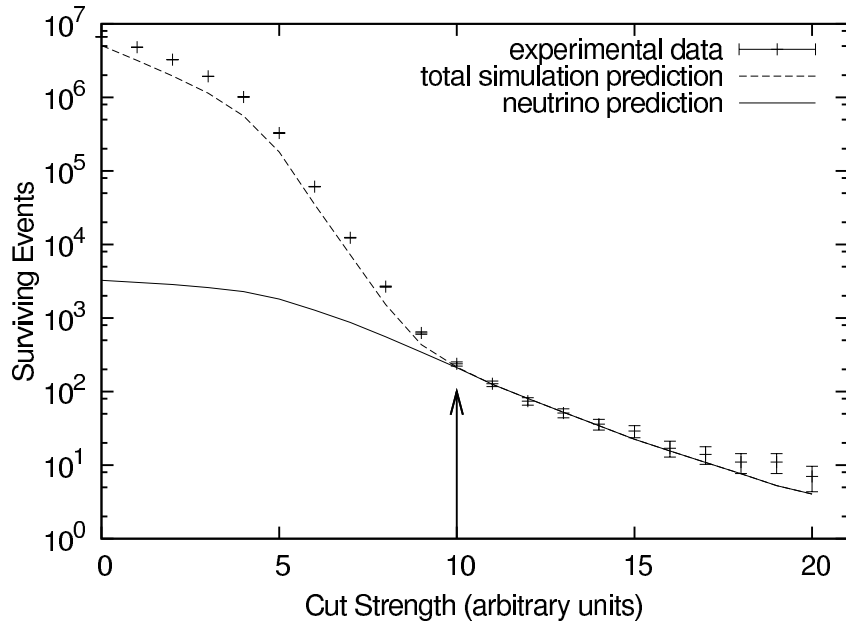


FIGURE 4. Number of events as a function of “cut strength”, which resembles cosmic-ray background when cuts are loose, and resembles atmospheric neutrinos when cuts are tightened. Plot taken from [17].

For instance, two effective quality cuts can be made on the number of “direct” hits (those which arrive within -15ns and $+75\text{ns}$ of the expected Cherenkov arrival time), and the projected length along the track of these direct hits. These quality cut techniques have been adapted for use in IceCube, and a sample of upgoing neutrino candidates has been extracted from 2006 data from IC-9. Simulated events, both signal (atmospheric neutrinos) and various forms of background (one or multiple cosmic ray muons) are used to assess the effectiveness of the cuts and the purity of the resulting candidate sample. The number of surviving events vs. “cut strength” is shown in Figure 4; as the cut strength is increased (that is, as one demands that events contain more direct hits, and that they make longer tracks), the event rate drops as background is removed with greater efficiency. At the cut strength shown by the arrow in Figure 4, the sample becomes consistent with atmospheric neutrinos only. Accepting only candidates which are confidently upgoing (with a zenith angle $\theta > 120^\circ$), this final sample consists of 142 neutrino candidates in 137.4 days, with an expectation of $169 \pm 60.9(\text{syst.}) \pm 13.0(\text{stat.})$ [17].

HIGH-ENERGY FUTURE

Atmospheric neutrinos are an important “test beam” for the eventual detection of extragalactic neutrinos; this event sample can be used to characterize the IC-9 detector’s response to neutrinos (its effective area) as a function of energy. This calculation is shown

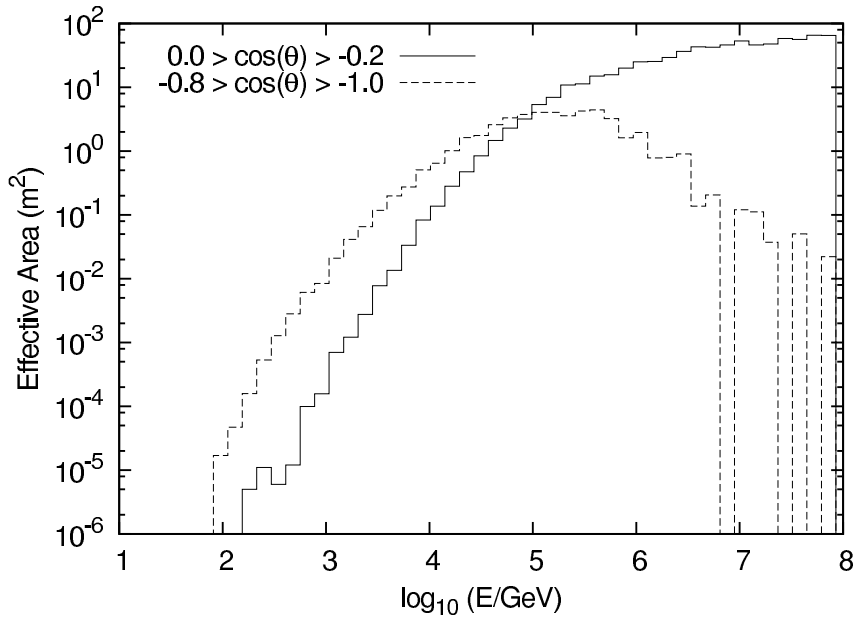


FIGURE 5. Neutrino effective area of IC-9, as a function of energy, for nearly-horizontal and nearly-vertical neutrinos. Plot taken from [17].

in Figure 5; upgoing neutrinos peak at around 100 TeV, while higher-energy neutrinos will be absorbed by the Earth and only visible near the horizon.

As IceCube extends its range into higher energies, the detection strategy will change somewhat. Cosmic ray background events will become rare, and the three different flavors of neutrino will be distinguishable by the topology of the light that the associated lepton emits in the detector. Muons, for instance, travel a long distance before decaying or interacting, and emit light with a long, track-like topology. Electrons travel a shorter distance and produce an electromagnetic cascade or shower, an asymmetric spherical distribution of emitted light. The short-lived tau produces one cascade at the point of the original neutrino interaction, and a second cascade where the tau lepton decays; this is known as a “double bang” signature, one of several detectable signature topologies for a ν_τ [18].

CONCLUSION

At approximately one-quarter of its completed size, IceCube is already making great strides in the analysis of neutrino data. Each year, as the detector is expanded, results will improve, and open up our first glimpses of the high-energy neutrino sky. The integration of AMANDA and IceCube into a combined detector promises additional versatility and reconstruction accuracy for this powerful observatory.

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