

# Results from Seven Years of AMANDA-II

**Tyce DeYoung, for the IceCube Collaboration**

Department of Physics and Center for Particle Astrophysics, Pennsylvania State University,  
University Park, PA 16802, USA

E-mail: [deyoung@phys.psu.edu](mailto:deyoung@phys.psu.edu)

**Abstract.** AMANDA is a first-generation high energy neutrino telescope, which has taken data at the South Pole in its final configuration since 2000. Results from seven years of operation are presented here, including observation of the atmospheric neutrino flux and searches for astrophysical neutrinos from cosmic ray accelerators, gamma ray bursts, and dark matter annihilations. In 2007, AMANDA was incorporated into the IceCube neutrino telescope, where its higher density of instrumentation improves the low energy response. In the near future, AMANDA will be replaced by the IceCube Deep Core, a purpose-built low energy extension of IceCube.

## 1. Introduction

The Antarctic Muon And Neutrino Detector Array (AMANDA) was constructed at the Amundsen-Scott South Pole Station over a period of years, reaching completion in 2001. The completed detector operated independently until 2006. AMANDA's primary goal was the discovery of high energy neutrinos from astrophysical sources, in the energy range of roughly 100 GeV to 100 PeV. As a first-generation instrument, AMANDA served as a proof of concept and prototype for later neutrino telescopes such as IceCube.

Neutrinos are detected by AMANDA when they undergo either charged-current (CC) or neutral-current (NC) interactions with nucleons in the ice. Muon neutrino CC interactions produce a secondary muon which may travel kilometers through the ice. Neutral-current interactions and CC electron neutrino events produce hadronic or electromagnetic showers of particles near the interaction vertex but no long track. In either case, the secondary particles are detected via Cherenkov radiation by a sparse three-dimensional array of photosensors embedded in the extremely transparent polar ice cap (optical attenuation length  $\sim 25$  m).

The final detector configuration, known as AMANDA-II, consisted of 677 optical modules (OMs) deployed on 19 strings at depths of roughly 1500 m – 2000 m below the surface of the ice sheet. Each optical module consisted of an 8" photomultiplier tube (PMT) contained within a glass pressure vessel. The OM received HV power from the surface, and returned PMT signals amplified by a gain of  $10^8$ – $10^9$  to the surface over either electrical or fiber optic cable. The strings were arranged in concentric circles, with an outermost radius of 100 m, resulting in an instrumented volume of approximately 15 Mton of ice.

After seven years of successful operation, AMANDA was incorporated into the second-generation IceCube neutrino telescope, now half complete. Independent operation thus ceased after the 2006 data run, with a total accumulated exposure of 3.8 years after accounting for detector maintenance periods and deadtime in the data acquisition system.

## 2. Atmospheric Neutrinos

The flux of atmospheric neutrinos produced by decaying  $\pi$  and  $K$  mesons in cosmic ray air showers in the Earth's atmosphere constitutes a background to searches for astrophysical neutrinos, but is also a useful calibration source for AMANDA. This flux is known to a precision of about 30% in the energy range to which AMANDA is sensitive [1]. Neutrinos can be identified within the flux of penetrating cosmic ray muons by searching for muon tracks originating from below the horizon; these upgoing muons must have been produced by neutrino interactions.

The AMANDA measurement of the atmospheric muon neutrino energy spectrum is shown in Figure 1, using data taken over the four year period 2000–2003 [2]. The theoretical bands include the systematic uncertainties due to our modeling of the detector and the propagation of light through the ice. Because the muons that are detected are produced in neutrino interactions at some distance from the detector, the energy of the incident neutrino is not directly measured, but must be inferred from the observed muon energy and the known energy loss rate for muons traversing ice and rock. The atmospheric neutrino spectrum is thus statistically unfolded from the observed muon spectrum, leading to the correlated statistical error bars on the points in Fig. 1. The measurement illustrates that the response of the detector to muon neutrinos is well understood, although the precision is insufficient at present to distinguish theoretical models.

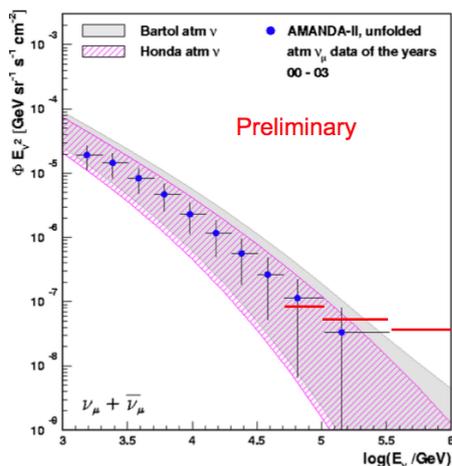


Figure 1: Atmospheric muon neutrino flux observed by AMANDA. The red lines indicate a limit placed on a possible  $E^{-2}$  component.

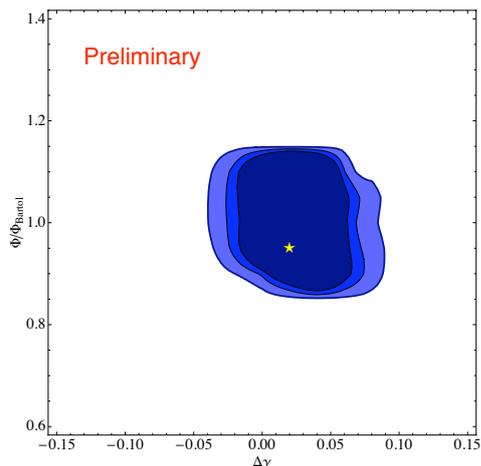


Figure 2: The 90%, 95%, and 99% C.L. contours and best fit point in flux ( $\Phi$ ) and spectral index ( $\gamma$ ) of the atmospheric neutrino flux obtained from one simulated analysis of the seven year data set.

The fact that the observed spectrum is consistent with the predictions for the atmospheric flux at low energies allows us to place a limit on the magnitude of any possible diffuse muon neutrino flux with a harder spectrum than the conventional atmospheric flux, for example due to the prompt decays of charmed leptons in atmospheric air showers or to a population of unresolved astrophysical sources. That limit is indicated with the red bars shown in the highest energy bins of Fig. 1. Results from the full seven year data set will be available soon; the expected precision of the atmospheric flux measurement from that study, derived from analysis of a single simulated data set based on the Bartol flux [1], is shown in Fig. 2.

In addition, the very large number of atmospheric neutrinos detected by AMANDA can be used to search for evidence of physics beyond the Standard Model, such as quantum decoherence or violations of Lorentz invariance [3]. These phenomena would appear as oscillation-like behavior, but at higher energies than standard neutrino oscillations and with very different characteristic flavor signatures.

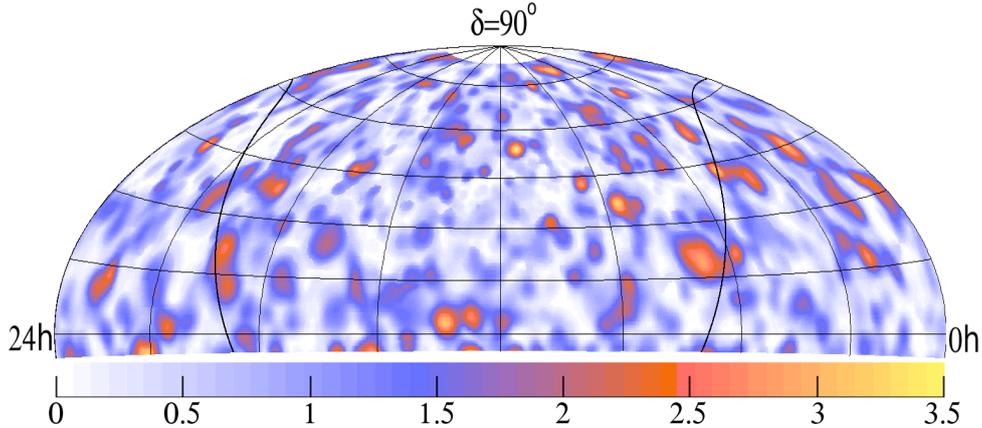


Figure 3: Map of the pre-trials significances obtained from an unbinned point source search using the full data set. The most significant point has a significance of  $3.38\sigma$ ; 95% of randomized background skymaps include a point at least as significant.

### 3. Astrophysical Neutrinos

The primary goal of AMANDA is the detection of individual astrophysical sources of high energy neutrinos. We have conducted an unbinned maximum likelihood search for point sources of neutrinos, using a sky map of 6,595 upward going neutrino events collected over seven years [4]. The direction of each of these events was reconstructed using a maximum likelihood method accounting for the propagation of light in the ice [5], and the width of the solution in the likelihood space was used to estimate the angular resolution for each event.

With these data, the significance of the deviation from a background uniform in right ascension ( $\alpha$ ) was calculated for all points on the sky with declinations ( $\delta$ ) between  $-5^\circ$  and  $85^\circ$ . The results are shown in Figure 3. The most significant point on the sky had a significance of  $3.38\sigma$  before accounting for trial factors. The true significance was assessed by repeatedly randomizing the right ascension of each event to create pure background maps, with any possible real sources smeared out across the sky. In 95% of such maps, a point with at least  $3.38\sigma$  was found, indicating that such a level is consistent with statistical fluctuations of the background.

The sensitivity of this search to point sources of neutrinos is shown in Figure 4, compared to the sensitivities of previous AMANDA analyses [6, 7, 8]. The increase in sensitivity is due to improvements in analysis technique as well as to the increased data collected, with a total improvement of an order of magnitude over the initial limit based on one year of data.

In addition to the unbinned search for point sources of neutrinos anywhere in the Northern sky, we have also searched for emission from a list of 26 candidate sources selected *a priori* on theoretical grounds [4]. Results for several of the sources are given in Table 1, including the source with the lowest chance probability ( $p$ -value), Geminga. The 90% C.L. upper limits on muon and tau neutrinos are given as  $E^2\Phi_{\nu_\mu+\nu_\tau} < \Phi_{90} \times 10^{-11} \text{ TeV cm}^{-2} \text{ s}^{-1}$  assuming flavor equality, and the  $p$ -values do not take into account the number of statistical trials. No evidence for neutrino emission from these sources has been observed.

Searches for diffuse fluxes of astrophysical neutrinos have been carried out as well [9, 10, 11]. Such diffuse astrophysical fluxes are generically predicted to have harder spectra than the atmospheric neutrinos, so these analyses search for evidence of higher energy events than would be expected from the atmospheric flux. The limits obtained by these searches are shown in Fig. 5. Flavor equality due to complete mixing over cosmological baselines has been assumed, and the flux refers to the muon component alone. Present limits are within an order of magnitude of

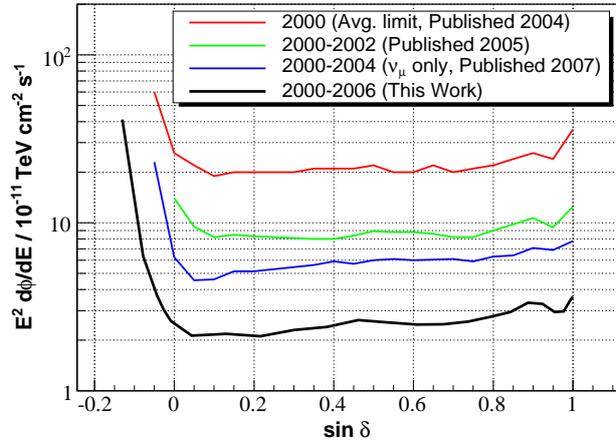


Figure 4: Average 90% C.L. upper limit on the  $\nu_\mu + \bar{\nu}_\mu$  flux (assuming flavor equality) from the unbinned point source search as a function of declination, compared to the results of previous searches using portions of the full data set.

Source	$\Phi_{90}$	$p$ -value
Crab Nebula	9.27	0.10
MGRO J2019+37	9.67	0.077
Mrk 421	2.54	0.82
Mrk 501	7.28	0.22
LS I +61 303	14.74	0.034
Geminga	12.77	0.0086
1ES 1959+650	6.76	0.44
M87	4.49	0.43
Cygnus X-1	4.00	0.57

Table 1: Selected results from a search for neutrino emission from 26 predefined source candidates (details in text). The probability of  $p \leq 0.0086$  for at least one of 26 sources is 20% in the absence of signal.

the Waxman-Bahcall level [12], with IceCube predicted to probe lower fluxes with a year or less of operation with the complete detector.

We have also searched for neutrino emission in conjunction with GRBs observed by satellite instruments. We have searched for  $\nu_\mu$  emission from over 400 GRBs observed in the Northern Hemisphere over the seven-year period [13], with an additional search conducted for an excess in cascade ( $\nu_e$  CC and  $\nu_x$  NC) events coincident with 73 observed GRBs anywhere in the sky using the 2001–03 data set [14]. No such coincident events were observed, and limits have been placed on several models of GRB emission [12, 15, 16, 17, 18], as shown in Fig. 6. The limits using the muon channel approach the predicted flux levels, giving encouragement that IceCube

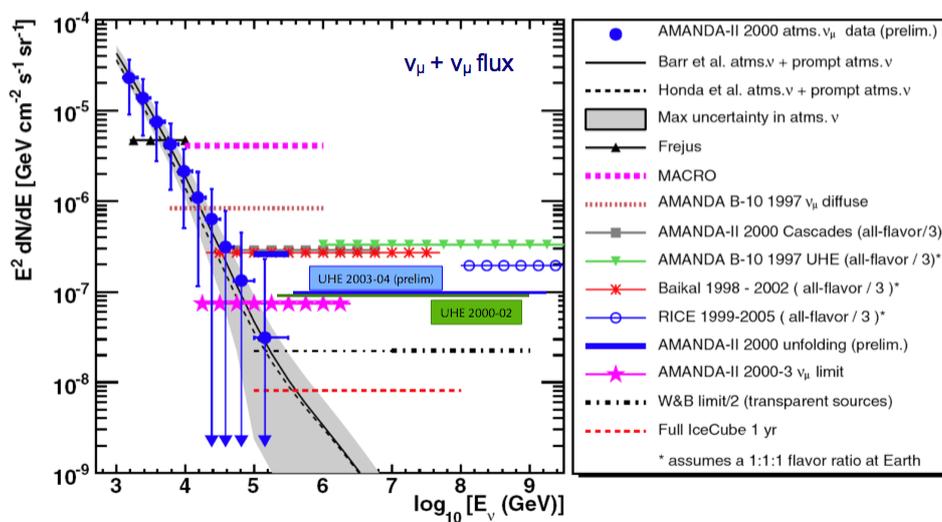


Figure 5: Integral limits on possible  $E^{-2}$  diffuse fluxes. The energy ranges shown are those which produce the central 90% of events in each analysis.

will soon be able to probe neutrino emission from GRBs.

AMANDA is used to search for indirect evidence of dark matter that has accumulated in the gravitational wells of the Earth [19] and Sun and annihilate to produce neutrinos. AMANDA’s search is complementary to those conducted by direct detection experiments because such experiments mainly constrain models with spin-independent neutralino-nucleon scattering, whereas neutralino capture in the Sun allows us to probe models where the coupling is primarily spin-dependent [20]. Also, direct and indirect searches probe different epochs of the history of the solar system and different parts of the WIMP velocity distribution. The limits from the AMANDA search using 2003 data are shown in Fig. 7, for neutralinos which annihilate through a hard ( $\chi\chi \rightarrow W^+W^-$ , or  $\tau^+\tau^-$  at 50 GeV) or a soft ( $\chi\chi \rightarrow b\bar{b}$ ) channel. Systematic uncertainties of approximately 25% are not included in the limits. Each point on the plot represents one or more SUSY models which give similar predicted neutralino-induced neutrino fluxes from the Sun; if at least one model gives a scattering cross section above the limits from direct detection experiments, a green point is plotted; if at least one model predicts a cross section not excluded by direct detection experiments, a blue cross is plotted.

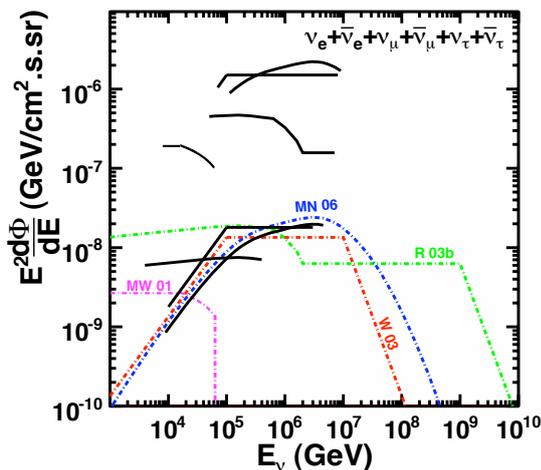


Figure 6: Integral limits on neutrino fluxes from GRB’s, for several models of neutrino emission.

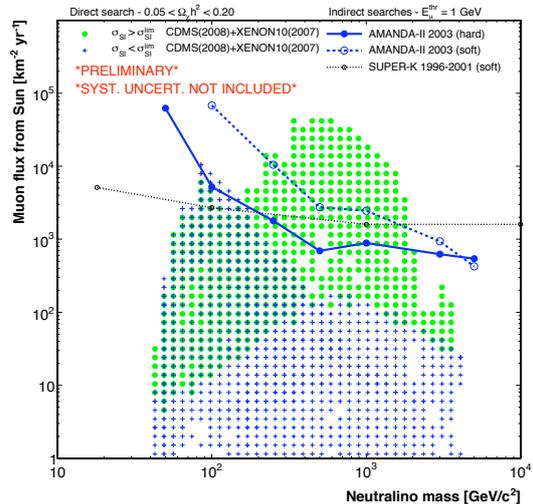


Figure 7: Limits on the neutrino flux produced by neutralino annihilation in the Sun’s gravitational well (details in text).

#### 4. Future Efforts

Following seven years of operation as an independent detector, AMANDA was incorporated into the growing IceCube neutrino telescope [21] during the 2006–07 austral summer. AMANDA has operated as an IceCube subdetector since then, with its higher density of instrumentation augmenting IceCube’s response to low energy events, which produce less light than the TeV neutrinos for which IceCube is optimized. With IceCube strings deployed in the AMANDA volume improving the detector response, and with outer IceCube strings providing an active veto around that volume, the reach of the IceCube/AMANDA data will provide improvements over the existing data set for topics such as the search for dark matter.

Recently, funding has been approved to replace AMANDA with a new Deep Core subdetector, shown in Figure 8. This detector will be based on IceCube hardware, but with PMTs using a new photocathode material with 40% higher quantum efficiency. Six new strings will be added, each with 50 OMs deployed between 2100 m and 2450 m and an additional 10 OMs deployed at

shallower depths to reinforce the veto shield against downgoing cosmic ray muons. The seven closest standard IceCube strings will also be used as part of the fiducial Deep Core detector, resulting in a volume comparable to AMANDA's. The detector will be located at the bottom center of IceCube, improving the veto efficiency for more horizontal cosmic ray muons, and exploiting the higher clarity of the ice at depths below 2100 m. Deep Core will increase the effective area of IceCube significantly at energies below 100 GeV, as shown in Fig. 9.

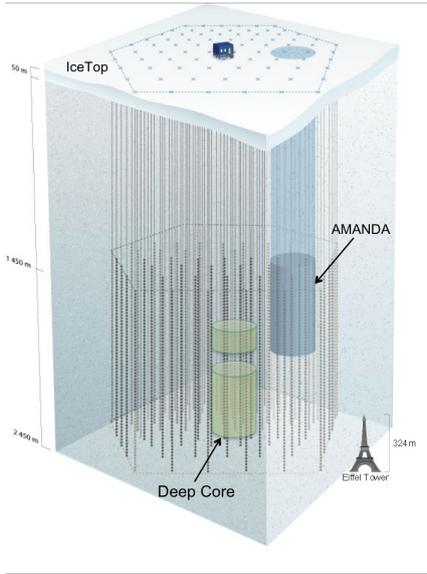


Figure 8: Schematic of IceCube, including AMANDA and the new Deep Core detector.

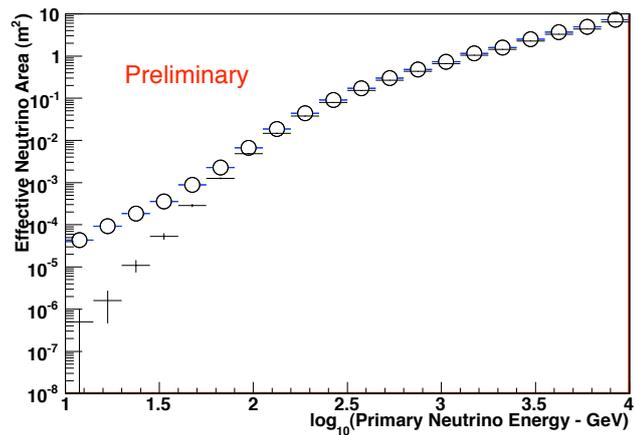


Figure 9: Effective area to  $\nu_\mu + \bar{\nu}_\mu$  for IceCube with Deep Core at trigger level (circles), compared to IceCube alone (crosses). At low energies, the improvement is more than an order of magnitude.

## References

- [1] G. D. Barr, T. K. Gaisser, S. Robbins and T. Stanev, Phys. Rev. D **74**, 094009 (2006) [arXiv:astro-ph/0611266].
- [2] K. Münich for the IceCube Collaboration, Proc. 30th Int. Cosmic Ray Conf. [arXiv:astro-ph/0711.0353].
- [3] J. Ahrens and J. L. Kelley for the IceCube Collaboration, Proc. 30th Int. Cosmic Ray Conf. [arXiv:astro-ph/0711.0353].
- [4] R. Abbasi *et al.* [The IceCube Collaboration], [arXiv:astro-ph/0809.1646].
- [5] J. Ahrens *et al.* [The AMANDA Collaboration], Nucl. Inst. Meth. A **524**, 169 (2004) [arXiv:astro-ph/0407044].
- [6] J. Ahrens *et al.* [The AMANDA Collaboration], Phys. Rev. Lett. **92**, 071102 (2004) [arXiv:astro-ph/0309585].
- [7] M. Ackermann *et al.* [AMANDA Collaboration], Phys. Rev. D **71**, 077102 (2005) [arXiv:astro-ph/0412347].
- [8] A. Achterberg *et al.* [The IceCube Collaboration], Phys. Rev. D **75**, 102001 (2007) [arXiv:astro-ph/0611063].
- [9] M. Ackermann *et al.* [The IceCube Collaboration], Astrophys. J. **675**, 1014 (2008) [arXiv:astro-ph/0711.3022].
- [10] A. Achterberg *et al.* [The IceCube Collaboration], Phys. Rev. D **76**, 042008 (2007) [arXiv:astro-ph/0705.1315].
- [11] M. Ackermann *et al.*, Astropart. Phys. **22**, 339 (2005).
- [12] E. Waxman and J. N. Bahcall, Phys. Rev. D **59**, 023002 (1999) [arXiv:hep-ph/9807282].
- [13] A. Achterberg *et al.*, [The IceCube Collaboration and the IPN Collaboration], Astrophys. J. **674**, 357 (2008). [arXiv:astro-ph/0705.1186].
- [14] A. Achterberg *et al.* [IceCube Collaboration], Astrophys. J. **664**, 397 (2007) [arXiv:astro-ph/0702265].
- [15] E. Waxman, Nucl. Phys. Proc. Suppl. **118**, 353 (2003) [arXiv:astro-ph/0211358].
- [16] P. Meszaros and E. Waxman, Phys. Rev. Lett. **87**, 171102 (2001) [arXiv:astro-ph/0103275].
- [17] K. Murase and S. Nagataki, Phys. Rev. D **73**, 063002 (2006) [arXiv:astro-ph/0512275].
- [18] S. Razzaque, P. Meszaros and E. Waxman, Phys. Rev. Lett. **90**, 241103 (2003) [arXiv:astro-ph/0212536].
- [19] A. Achterberg *et al.* [AMANDA Collaboration], Astropart. Phys. **26**, 129 (2006).
- [20] F. Halzen and D. Hooper, Phys. Rev. D **73**, 123507 (2006) [arXiv:hep-ph/0510048].
- [21] S. R. Klein for the IceCube Collaboration, these proceedings.