Status of the AMANDA Project

Our estimates of the performance of the IceCube detector are based on experience with AMANDA-B10 (taking data since 1997) and AMANDA II (soon to be completed). We discuss the result from the analysis of the first year of data, compare with simulations, and show how these extrapolate to IceCube.

Calibration of the first-generation AMANDA detector was completed in August 98. Although preliminary data were presented at the winter conferences, analysis of the first year of data has been completed. We have published the observation of atmospheric neutrinos with the partially deployed 1995-1996 detector which consisted of only eighty photomultiplier tubes. Manuscripts exist covering high energy atmospheric neutrinos and the search for neutrinos from active galaxies, cold dark matter particles, relativistic magnetic monopoles, and neutrinos from supernova collapses. Some of the results have been discussed in the science section of the proposal.

Construction and Performance

AMANDA-B10 consists of approximately 300 optical modules (OMs) deployed at a depth of 1500-2000 m; see Figure 20. An optical module consists of an 8 inch photomultiplier tube controlled by passive electronics and housed in a glass pressure vessel. It is connected to the surface by a cable which provides the HV as well as transmits the anode current signals of the photomultipliers. All data acquisition electronics are at the surface. We have successfully deployed a total of 17 strings since 1993. Fatal failures of OMs occur at the level of less than 3 percent in the first few hours when they freeze into the ice. These failures are correlated with the uneven profile of the hole and are expected to be remedied by computer-controlled drilling. Very few modules have failed after re-freeze during several years of operation.

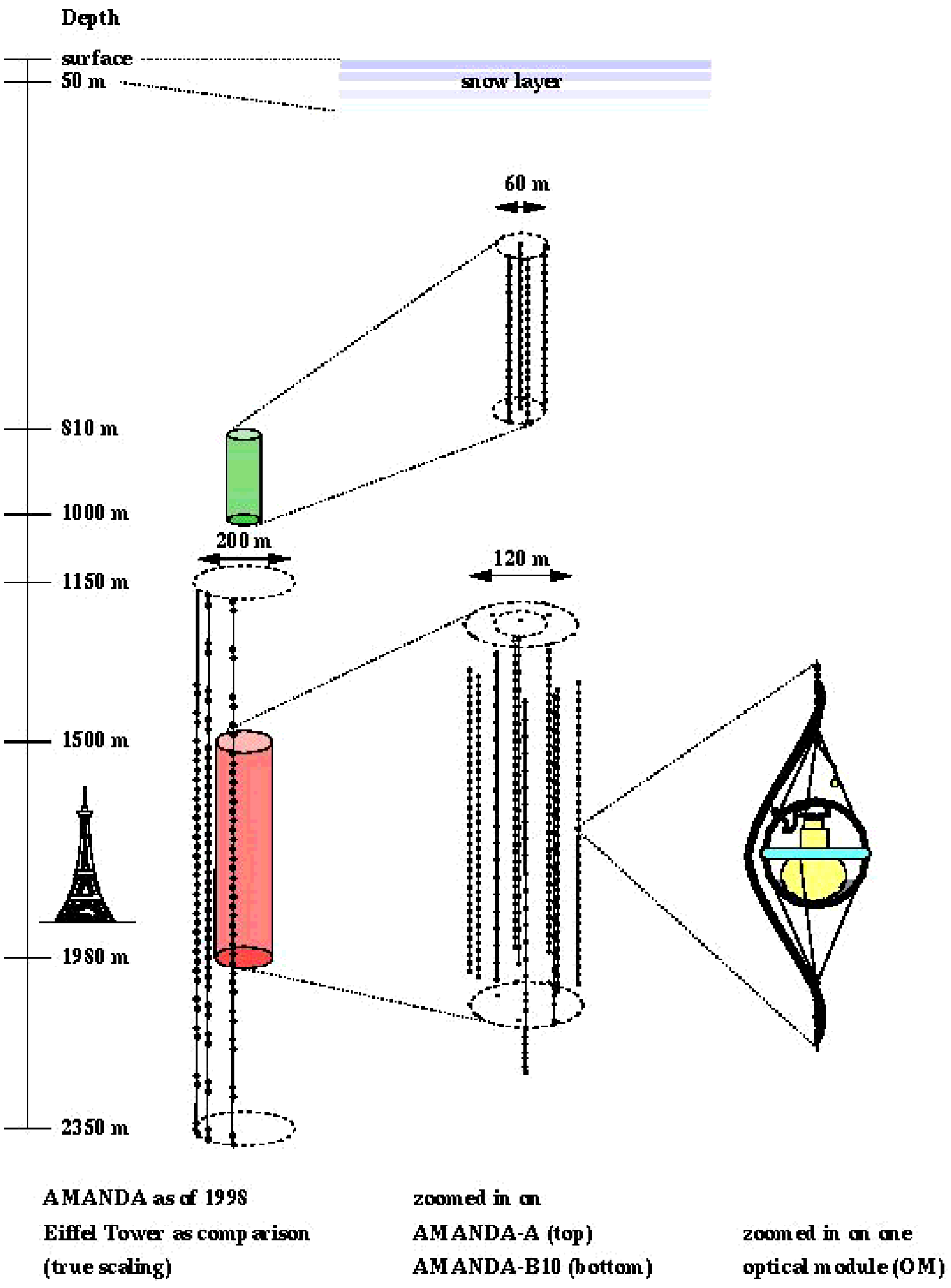

Figure 20: The AMANDA strings deployed at the South Pole. In the center bottom portion of the figure is the AMANDA-B10 array; the data from this array taken in austral winter 1997 is the subject of the analysis discussed here.

As predicted from transparency measurements performed with strings near 1 km depth, it was found that ice is bubble-free below 1400 m. Calibration of the detector (optical properties of the ice, geometry of the detector, cable time-delays) was completed in the austral summer 97-98. We found that

- the absorption length is 100 m or more, depending on depth. Because of the unexpectedly large absorption length, OM spacings should be similar or larger than those of proposed water detectors;

- the scattering length varies between 15 m and 40 m with color and depth and is on average ~25 m (these values may include the combined effects of deep ice and the refrozen ice disturbed by the hot water drilling);
- 20 OM’s report in an average trigger, not 6 as had been anticipated. In a typical neutrino analysis we require that more than 5 photons are, on average, "not scattered" A "direct" photon is required to arrive within 25 nsec of the time predicted by the Cherenkov fit. This allows for a small amount of scattering and includes the dispersion of the anode signals over the 2 km cable. In a full reconstruction, additional information is extracted from scattered photons by minimizing a likelihood function which matches their measured and expected time delays.

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Noise rate stability and supernova monitoring

The AMANDA collaboration has analyzed data from the specialized supernova detection DAQ from 1996 and 1997. Already using only 51 PMTs deployed in 1996 gives a sensitivity to SN bursts from as far away as the center of our galaxy (8.5kpc), as demonstrated in Figure 21. This plot demonstrates the excellent stability and low noise rates that can be achieved in the South Pole ice; the low temperatures (~ -40°C) and negligible radioactive backgrounds make this possible.

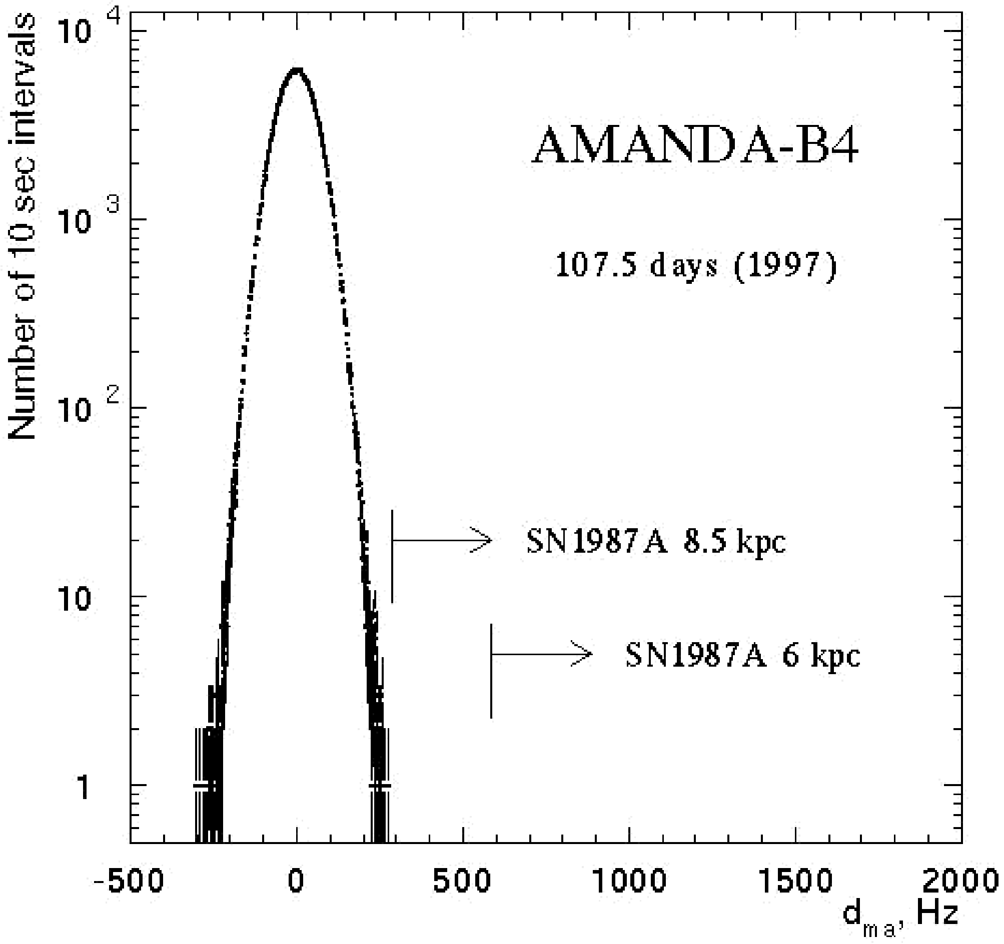

Figure 21: Deviation of the summed noise rate from the moving average for 51 selected PMTs in AMANDA during 108 live days in 1997, with a cut in chi^2/NDF less than or equal to 1.5. Indicated are the cut-values for signals expected for SN1987A-type supernovae at 6kpc and 8.5 kpc.

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Atmospheric Neutrinos

The most striking demonstration of the quality of natural ice as a Cherenkov detector medium is the observation of atmospheric neutrino candidates with the partially deployed AMANDA detector which consisted of only eighty photomultiplier tubes. The up-going muons are separated from the down-going cosmic ray background once a sufficient number of direct photons and a minimum track length guarantee adequate reconstruction of the Cherenkov cone. The analysis methods were verified by reconstructing cosmic ray muon tracks registered in coincidence with the surface air shower array SPASE-2 and the air Cherenkov telescope VULCAN.

After completion of the AMANDA detector with 300 OMs, a similar analysis established AMANDA as a neutrino telescope by observing atmospheric neutrinos at a rate consistent with expectation. Atmospheric neutrinos are identified using quality cuts on the reconstruction of muon tracks. We require a good likelihood of a Cherenkov cone fit and a significant number of "direct" photons smoothly distributed along a track. At high cut levels, typically more than 5 "direct" photons and muon range more than 100 m, all features of the neutrino events are consistent with expectations from Monte Carlo simulation of the atmospheric neutrino flux. For instance, the distributions of zenith angle can be seen in Figure 22.

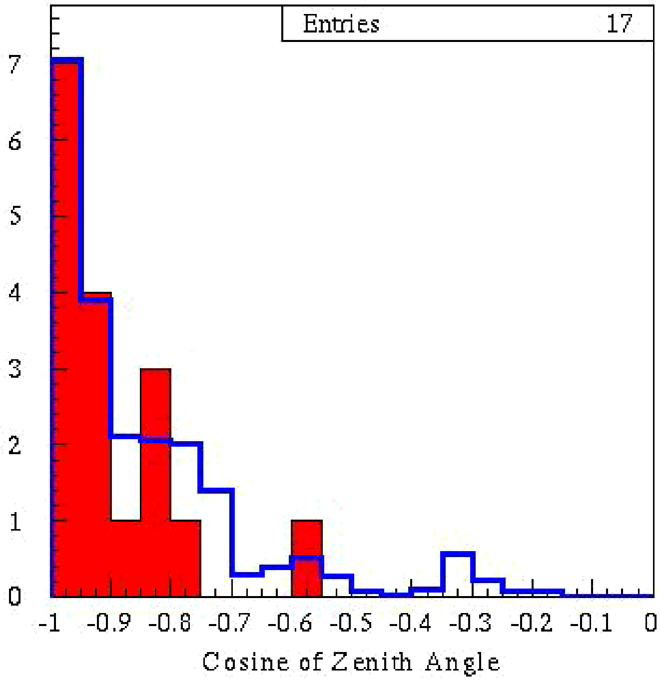
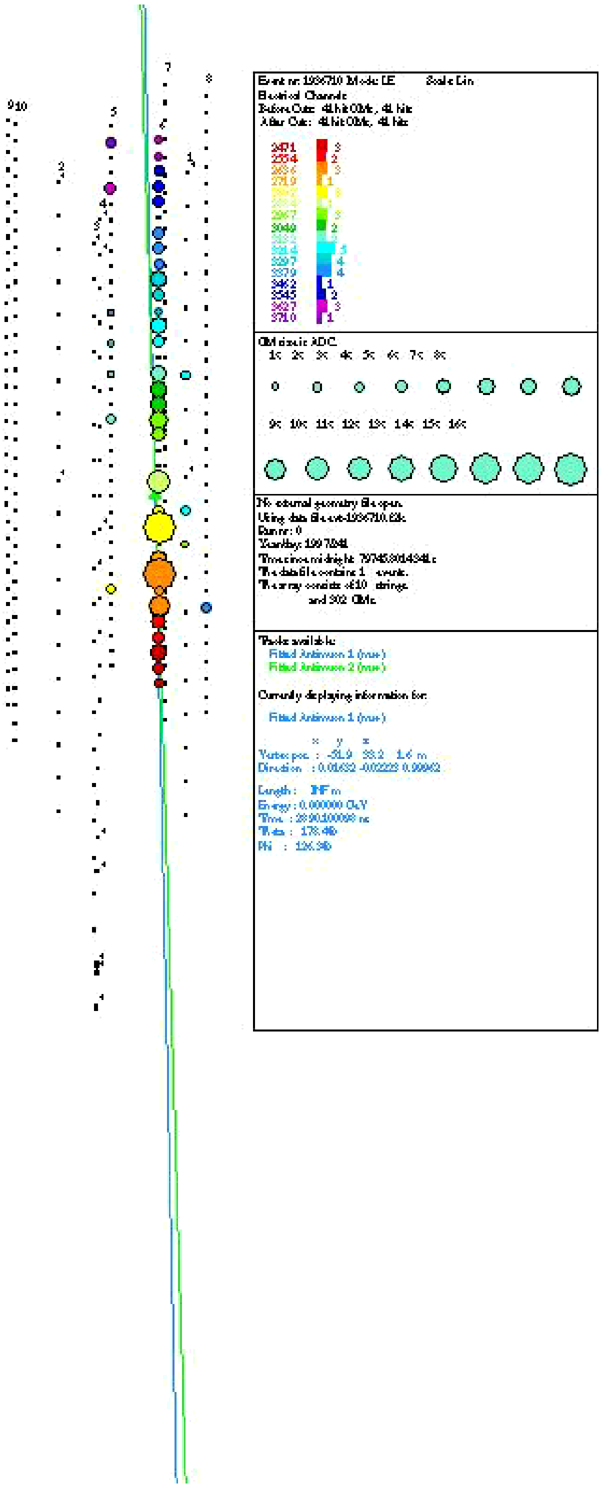


Figure 22: Events remaining after strong cuts: muon track longer than 100 m, and number of "direct" photons greater than or equal to 6. The event rate and zenith angle distribution are consistent with the response of the detector to atmospheric neutrinos.

The neutrino event in Figure 23a, taken from the on-line event display, is particularly easy to understand. A muon generated in a neutrino interaction below the detector travels along a string at an average distance of 10 m, generating OM signals over a track length of 400 m. The arrival time of the first photon at an OM is plotted against the distance of that OM from the bottom of the string, reproducing the speed of light; see Figure 23b. Because the muon track is misaligned with the string by 1.5°, the projection of the track on the string travels with a speed somewhat less than *c* as shown in the figure. Note that the arrival times of the photons on a second string, although distant by 30 m from the muon track, still indicate its direction despite the scattering of the photons in the ice.



Electrical Channels
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The data file contains 1 events.
Tracks available:
Currently displaying information for:
x y z
Length :
Energy : 0.000000 GeV
Phi : 126.36

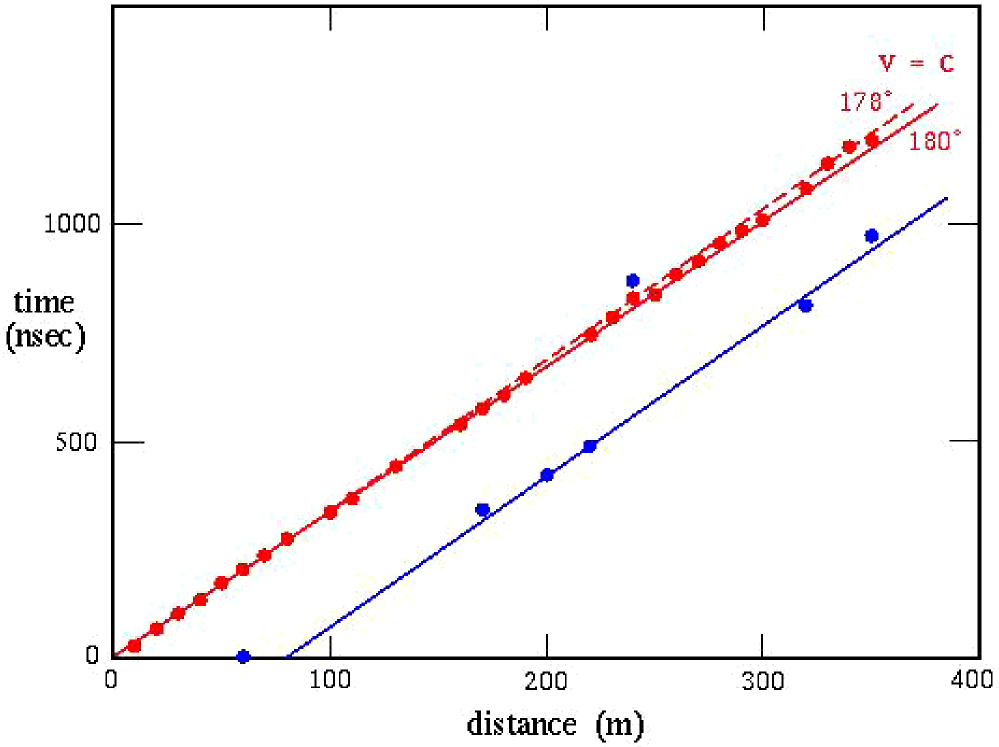
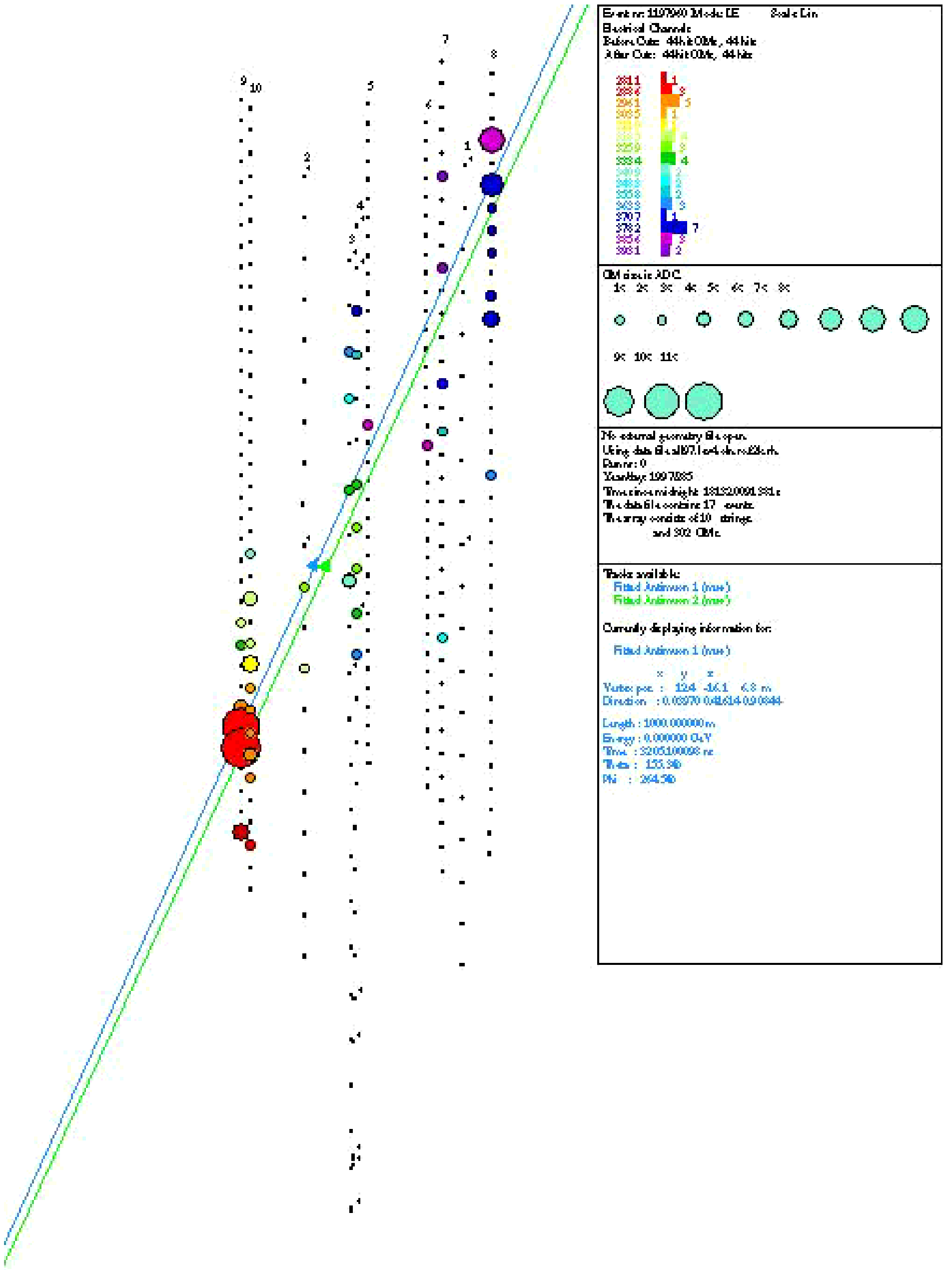


Figure 23: (a) Neutrino event in AMANDA. The shading of the dots represents time of triggered photomultipliers, and the size represents amplitude. The reconstructed muon track moves upward over 400 m. (b) Arrival times of the first photon as a function of distance along the two strings for the event in (a).

Another neutrino event is shown in Figure 24, which looks strikingly similar to a simulated upgoing neutrino event in the same direction. By requiring the long muon track the events are gold-plated, but the threshold is rather high, roughly E_{nu} greater than or equal to 50 GeV. This type of analysis now allows AMANDA to harvest roughly one high energy atmospheric neutrino per day, adequate for calibration of the detector. It is impressive that three analyses with two independent sets of software tools are able to extract largely overlapping neutrino samples from the data.


Scale Lin
Before Cuts: 44hit OMs, 44 hits
After Cuts: 44hit OMs, 44 hits
OM size is ADC
Run nr: 0
The data file contains 17 events
The array consists of 10 strings
and 302 OMs
Tracks available:
Fitted Antimuon 1
Fitted Antimuon 2
Currently displaying information for:
Fitted Antimuon 1
x y z
Length : 1000.000000 m
Theta : 155.90
Phi : 264.90

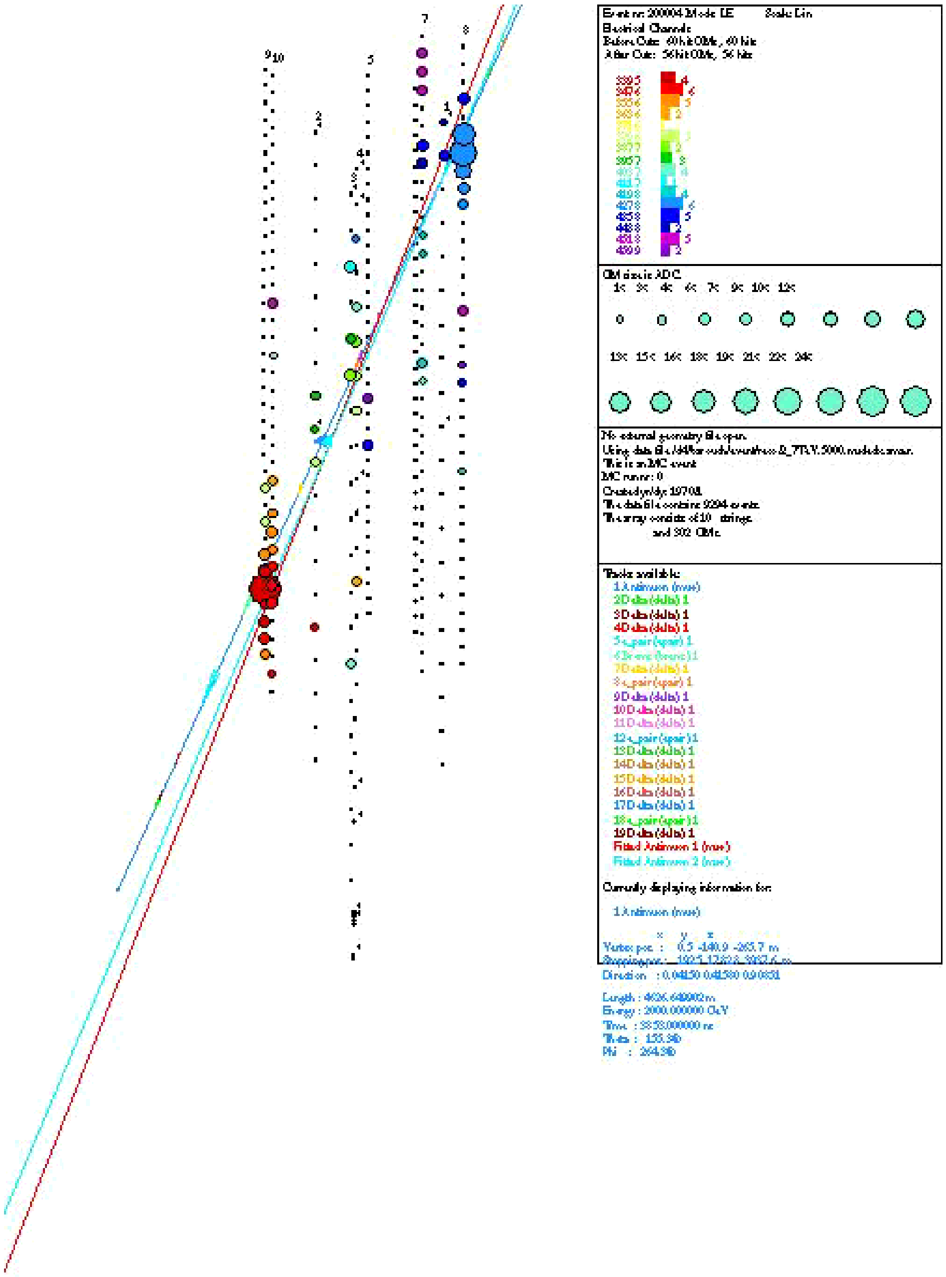


Figure 24: (a) Neutrino event in AMANDA. (b) Simulation of an upgoing muon track with the same direction as the observed event in (a).

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Early Science

We close this summary of the analysis of the 1997 data by presenting a series of results. The science covering these results has already been presented in the science section of this document. Details can be found in the proceedings of the XXIVth International Cosmic Ray Conference. A search has been done for point sources of high energy neutrinos. In contrast with the identification of pure atmospheric neutrino samples, the analysis is optimized for large signal over background of a flux following an E^{-2} energy spectrum. Figure 25 shows a skyplot from this analysis.

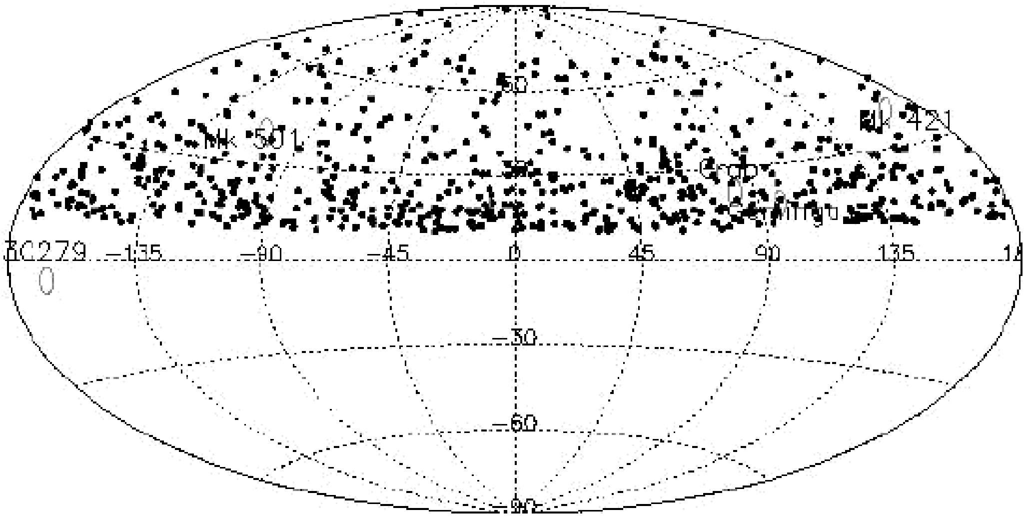

Figure 25: Skyplot from point source search analysis.

The potential of AMANDA as a dark matter detector relies on observing the sun, as previously discussed. This has to await the completion of AMANDA II because it requires good sensitivity near the horizon. In the meantime we have performed an analysis searching for the annihilation of WIMPs in the core of the earth. Figure 26 compares the present upper limit with other experiments.

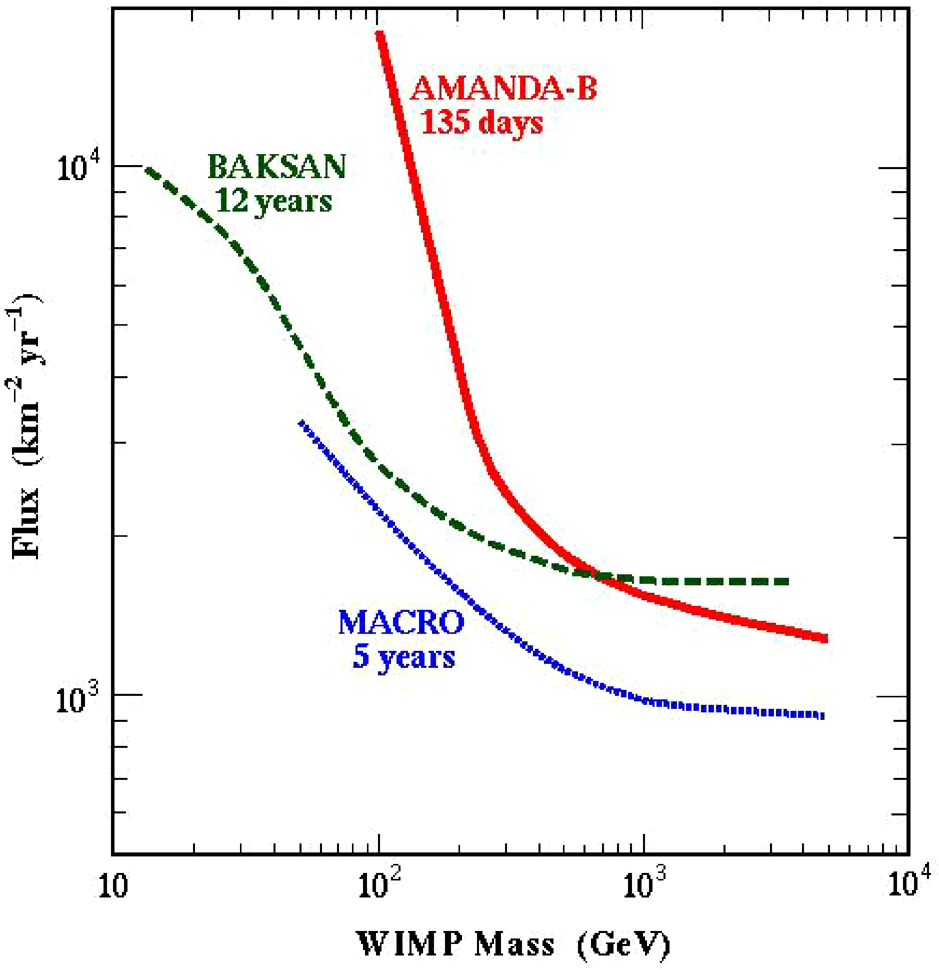

Figure 26: Comparison of AMANDA limits on WIMP masses with those from other experiments.

AMANDA allows us to put stringent limits on relativistic Dirac monopoles. These exotic particles would have a spectacular signature produced by their highly ionizing radiation. As a result, a detector of AMANDA's size does not need a large data set to improve on existing upper limits: Figure 27 shows a comparison with other experiments.

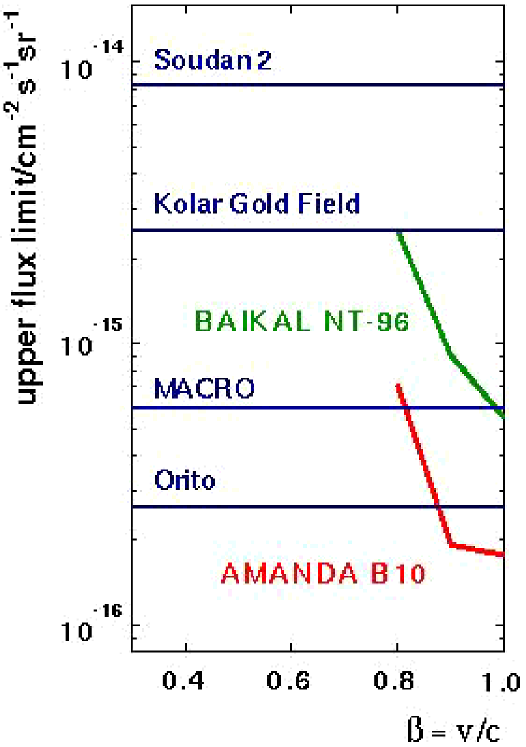

Figure 27: Comparison of AMANDA limits on relativistic monopoles with those from other experiments.

Finally, the seasonal variation of muon flux demonstrates an understanding of the detector response. The muons originate mostly from the decay of cosmic ray interaction products such as pions and kaons. The lower the air temperature, the denser the air between where the pions and kaons are produced and where they decay, the more of them interact before they can decay, and the fewer the muons that reach AMANDA. Figure 28 shows the changes in muon flux closely following the changes in temperature, just as expected.

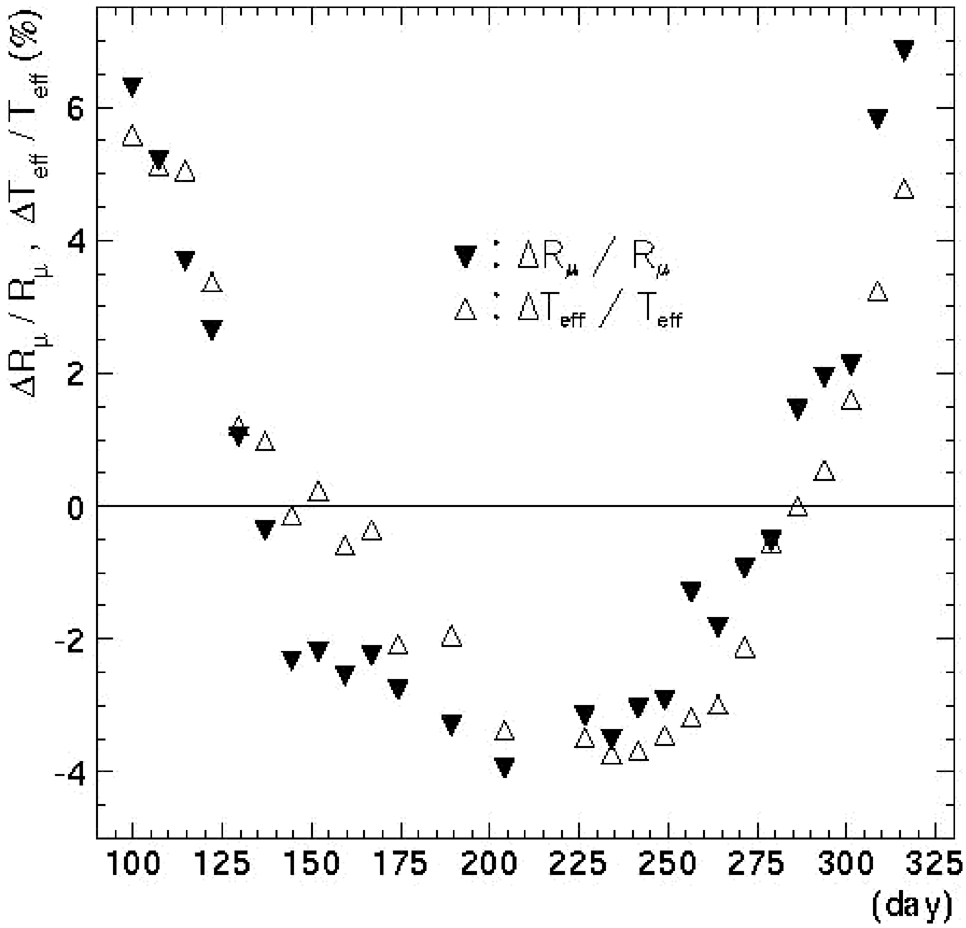

Figure 28: Percentage change in downgoing muon flux, and percentage change in temperature over time.

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