# NEUTRINO PHYSICS AT THE SOUTH POLE - RECENT RESULTS FROM THE AMANDA EXPERIMENT

J. K. BECKER FOR THE ICECUBE COLLABORATION*

*Universität Dortmund,*
*Institut für Physik,*
*D-44221 Dortmund, Germany*
*E-mail: julia@physik.uni-dortmund.de*

In this contribution, recent results from the Antarctic Muon And Neutrino Detector Array (AMANDA-II) on searches for high-energy neutrinos of extraterrestrial origin are presented. In particular, different methods to investigate the diffuse neutrino flux, the single and stacked search for neutrino point sources, the search for transient sources (GRBs and AGN time dependencies) and the search for neutrinos from WIMP annihilation are discussed.

## 1. Very high energy neutrinos in astroparticle physics

One of the primary goals of the **A**ntarctic **M**uon **A**nd **N**eutrino **D**etection **A**rray (AMANDA-II) is the search for very high energy (VHE) neutrinos from extraterrestrial sources. Due to their low interaction probability with matter, neutrinos are one of the most promising particles to provide information about core processes of sources of VHE emission. The low cross section is also the reason that very large volumes have to be instrumented to achieve a significant rate of events. AMANDA is located in the antarctic ice, between 1500 m and 2000 m below the surface and covers a geometric volume of $\sim$0.016 km$^3$. The detector consists of 19 strings with a total of 677 photomultipliers (PMTs). When a muon-neutrino interacts with a nucleon, a muon is produced, emitting Cherenkov light since traveling faster than the speed of light in ice. The Cherenkov light can be detected by the PMTs and both the incidental direction and the neutrino energy are reconstructible. To guarantee that the observed muons are neutrino-induced, the Earth is used as a filter: While muons produced in the atmosphere are absorbed by the Earth, neutrinos traverse the Earth and the signature

*http://icecube.wisc.edu

is unique. After the filtering of atmospheric muons, the remaining signal mainly consists of neutrinos produced in hadronic showers in the atmosphere. Different analysis methods have been developed to separate this background from a potential signal from extraterrestrial sources. In addition to the neutrino-induced lepton, a hadronic cascade produced at the interaction vertex contributes to the signal.

This contribution will focus on four different types of analyses: Limits on an additional diffuse flux contribution over the expected atmospheric signal will be discussed as well as limits on signals from steady and transient point sources. Additionally, an approach for dark matter searches will be discussed. The presented results are mainly based on a four-year data sample taken between 2000 and 2003 in which 3329 neutrinos could be identified[2].

## 2. Diffuse search

Figure 1 shows a summary of the energy spectra of diffuse predictions compared to AMANDA limits. The dashed lines represent the atmospheric neutrino flux[10,15], the lower line giving the vertical flux (nadir angle of $\theta_N = 180°$), the upper line showing the horizontal contribution ($\theta_N = 90°$). Predictions 1 to 4 give possible extragalactic contributions: Model 1 (BBR[4]) predicts a neutrino flux from steep and flat spectrum Active Galactic Nuclei (AGN). Model 2 (WB[16]) shows the diffuse neutrino spectrum which is expected from Gamma Ray Bursts (GRBs). Model 3 (MPR) gives the maximum signal contribution from blazars, while 4 (MPR bound) represents theoretical upper limits on the same source class. The upper bound of the shaded region represents the limit using a high neutron-photon opacity, $\tau_{n\,\gamma} >> 1$, the lower, energy dependent, bound is calculated using $\tau_{n\,\gamma} < 1$, see Ref. [12]. All extragalactic contributions turn out to be flatter than the atmospheric flux, so that the total spectrum is expected to flatten at a certain energy where extragalactic neutrino sources start to dominate isotropically. The data circles show the unfolded energy spectrum of AMANDA[13]. The spectrum is complementary to Frejus measurements at lower energies (squares)[6]. The measured spectrum can be determined up to energies of 100 TeV and follows the atmospheric prediction. An upper limit on an extragalactic $E^{-2}$ muon-neutrino signal is given by $E^2 dN/dE = 2.6 \cdot 10^{-7}$GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for data from the year 2000. Using cuts sensitive to very high neutrino energies to look for an excess over the atmospheric signal, a sensitivity of

$E^2 dN/dE = 9.0 \cdot 10^{-8}$GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ is reached for four years of data (2000-2003)[9]. At ultra high energies, limits to all three neutrino flavors are achieved by considering events from near the horizon (labeled UHE in Fig. 1) or cascades.

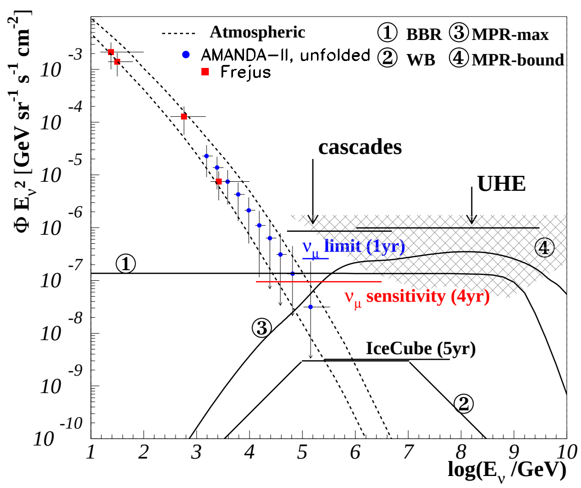


Figure 1. Summary of AMANDA results for a diffuse search in the context of extra-galactic neutrino flux predictions.

## 3. Looking for steady point sources

The search for point sources yields an opportunity to reduce the background of atmospheric neutrinos by selecting positions in the sky where potential objects of neutrino emission are located. The average sensitivity to single point sources for four years of data (2000-2003) is

$$E^2 dN/dE = 6 \cdot 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} .$$

Here, an $E^{-2}$ spectrum has been assumed as the expected signal. The complete northern hemisphere has been scanned for a clustering of events. In addition, a catalog of 33 sources has been preselected. No excess over the atmospheric background could be observed. Preliminary limits to the flux from the 33 single sources and a significance map of the northern hemisphere are given in[2].

Active Galactic Nuclei (AGN) are one of the most prominent source candidates for the extremely high energy flux of Cosmic Rays. This charged component is likely to be accompanied by a neutrino flux.Therefore, there is good potential to detect high energy neutrinos from AGN. In a stacking approach, different AGN samples have been defined according to their geometry and photon luminosity at different wavelengths. Method and results are discussed in detail in[1]. It is assumed, that the neutrino luminosity is proportional to the observed photon luminosity. Each sample contains about 10 sources. Figure 2 shows the stacking limits per source for one year of data taking (year 2000) that are given for the 11 AGN samples. The dashed line represents the single source sensitivity for four years of data taking. The one year stacking limits are already at the sensitivity level of four years of data, which shows that the stacking method provides a very effective way of improving the sensitivity.

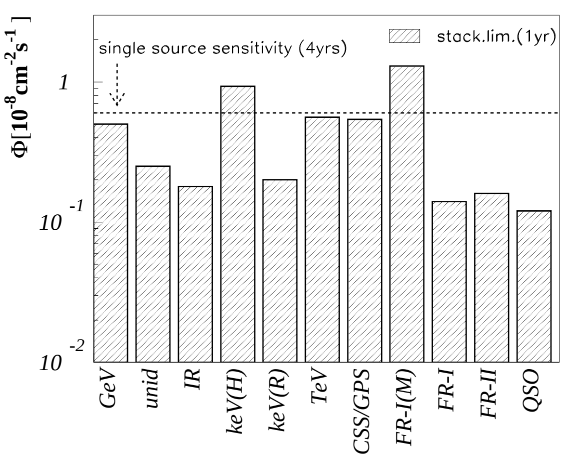


Figure 2. Upper limits to a signal from various AGN samples given per source. The classes on the x-axis are GeV blazars (GeV), unidentified GeV blazars (unid), infrared sources (IR), keV blazars from HAEO-A (keV(H)) and from ROSAT (keV(R)), TeV blazars (TeV), Compact Steep Sources and GHz-Peaked Sources (CSS/GPS), FR-I galaxies including M-87 (FR-I(M)) and excluding it (FR-I) as well as FR-II galaxies (FR-II) and Quasi Stellar Objects (QSO). The stacking limits for one year of data are comparable to the single point source sensitivity of four years (dashed line).

## 4. Transient sources

### 4.1. *Flaring states*

Many permanent objects in the sky reveal a variability in the observed photon luminosity. Based on the assumption that the observed photons are accompanied by neutrinos, a variability in the neutrino luminosity is examined by using a sliding window of a fixed duration. For this purpose, the catalog of the 33 sources presented in Sec. 3 has been used. The sliding window has been optimized to a duration of 40 days for extragalactic and 20 days for galactic sources. Additionally, a multi-wavelength approach has been pursued for three objects (Mkn 421, 1ES 1959+650 and Cygnus X-3) where it has been searched for an excess in the neutrino data at times of flaring states. No significant excess could be observed for any of the methods, the results are summarized in Ref.[3].

### 4.2. *Gamma Ray Bursts (GRBs)*

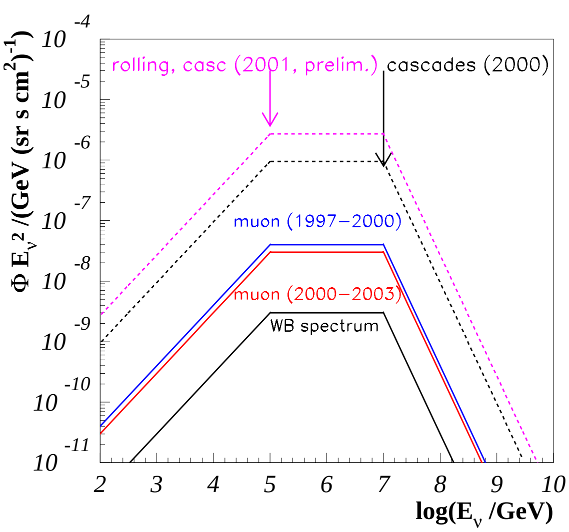


Figure 3. Summary of the limits on the average GRB spectrum.

GRBs are the most luminous objects in the sky and they release their energy within a few seconds: The duration ranges from milli-seconds (short bursts) up to several hundred seconds (long bursts). To increase the sensitivity, all GRBs that occurred during the time of the neutrino data sample are stacked. The limits on the average GRB spectrum given in Ref.[16] are summarized in Fig. 3. It can be seen that the sensitivity of the predicted spectrum (WB) is not reached with AMANDA. Using neutrino induced muons (solid lines) gives limits about an order of magnitude higher than the predicted spectrum[11]. One year of data has been analyzed in the cascade channel with limits as indicated in Fig. 3 (dashed lines, see[8]).

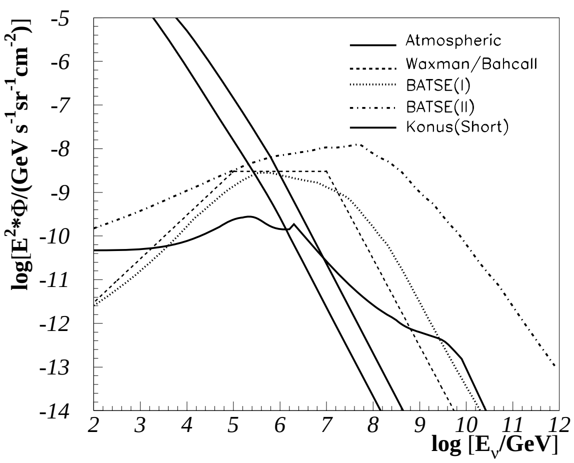


Figure 4. Coincidence flux of different GRB samples[5].

A more detailed approach is to model the neutrino spectra individually: The spectrum derived in Ref.[16] is cited using average parameters for the spectral indices, normalization and breaks in the energy spectrum. These five parameters are derived from observational properties of the photon spectrum and thus, the spectra can be modeled individually. This is demonstrated in Fig. 4. Two different samples from the BATSE catalog have been used to model GRB neutrino spectra individually, resulting in coincidence spectra (dotted and dot-dashed lines) which differ significantly from the average spectrum (dashed line), see[5]. In particular, the spectrum of short bursts (duration less than 2 s, solid line) is much steeper than that of long ones. An analysis of the "monster burst" GRB030329 has been done modeling the spectrum individually with the limits given in Ref.[14].

## 5. Dark matter search: WIMPs

In Supersymmetry with conserved R-Parity, a stable "lightest supersymmetric particle" (LSP), the neutralino, is predicted and turns out to be a prominent dark matter candidate. At sufficently low velocities, high mass neutralinos may be gravitationally captured in areas with high mass density, like the Sun or the Earth's center. Neutralino annihilations to $W^+W^-$ yield a neutrino flux at TeV-PeV energies. By looking for an excess from the Sun or the center of the Earth, constraints on MSSM parameters can be given. AMANDA's sensitivity does not reach CDMS limits yet, but IceCube will be able to approach these, see Ref.[7].

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