

Implications of AMANDA neutrino flux limits

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Abstract. The Antarctic Muon And Neutrino Detector Array (AMANDA) is currently the most sensitive neutrino telescope at high energies. Data have been collected in a period of eight years and analyzed with different analysis strategies. Limits to the neutrino flux from point sources, transient emissions, source catalogs and limits to different diffuse flux models have been obtained implying in some cases strong constraints to hadronic interaction models of such sources. In this contribution, implications of the diffuse neutrino limit will be discussed with respect to neutrino production mechanisms in astrophysical sources.

1. Neutrino flux predictions

The existence of Ultra High Energy Cosmic Rays (UHECRs) as well as the detection of TeV photon emissions from galactic and extragalactic sources are a strong indication for neutrino (ν) emission from the same sources. Pions and kaons are believed to take a fraction of the proton energy producing TeV photons in coincidence with high energy neutrinos. Although the atmospheric background of neutrinos is quite high, it decreases rapidly with energy ($\sim E^{-3.7}$) while the extraterrestrial spectra of galactic and extra-galactic sources are typically flatter (typically $\sim E^{-2}$ if shock acceleration is the main mechanism producing high energetic protons at the source). The latter should therefore become the dominant component of the total diffuse spectrum at a certain energy, which depends on the normalization of the neutrino flux. Different predictions are shown in Fig. ???. The left panel shows various calculations which use the diffuse X-ray background as measured by ROSAT to normalize the neutrino spectrum, see [?, ?]. This is justified when assuming the production of neutrinos along with X-rays at the foot of jets of Active Galactic Nuclei (AGN) where protons are accelerated into the photon target of the disk. The right panel shows models based on the correlation between UHECRs, TeV photons and neutrinos, see [?, ?]. Such sources are optically thin to both TeV photons and protons.

2. Detection techniques of AMANDA

AMANDA detects muon-neutrinos (ν_{μ} s) by observing secondary muons from charged current interactions of the neutrinos with the nucleons of the ice. The muons are traveling faster than light in ice and emit Cherenkov radiation which is detected by the photomultiplier tubes. Between the years 2000 and 2004 data from effectively 1001 days have been taken and a ν_{μ} sample of 4282 events from the Northern hemisphere has been collected². In order to keep

¹ <http://icecube.wisc.edu> and these proceedings

² Atmospheric muons make it impossible to use the Southern hemisphere for ν_{μ} searches. Cascade analyses can, however, be done for both hemispheres. These results will not be discussed here, but can be found in e.g. [?]

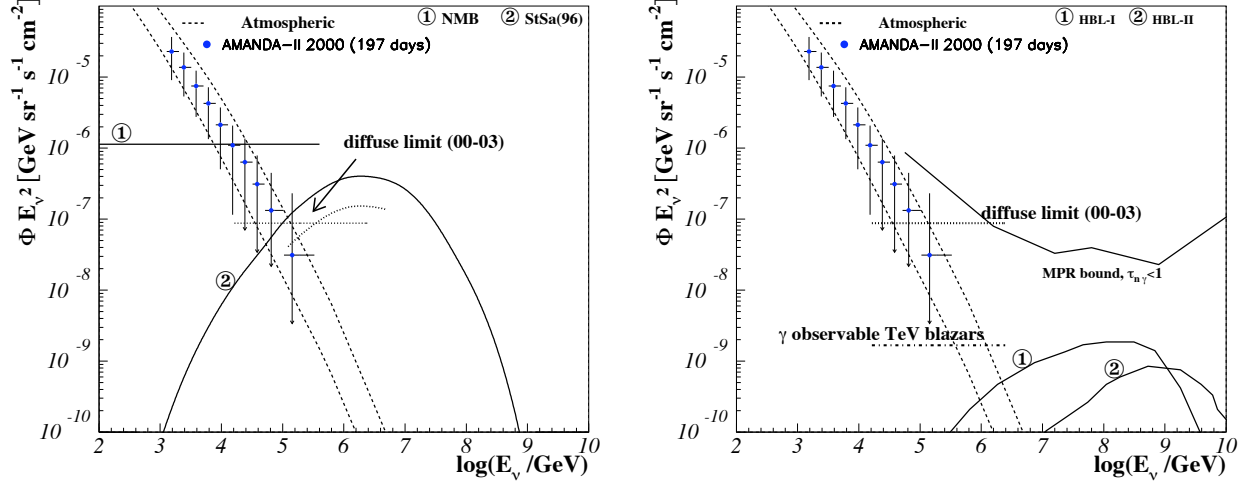


Figure 1. ν spectra for models of ν emission from X-ray emitting AGN (left panel) and for optically thin sources - the cosmic ray flux at the highest energies is assumed to be proportional to the ν output (right panel). Data points are measurements of the diffuse spectrum by AMANDA, year 2000 [?]. Dashed lines represent the atmospheric contribution, the lower line is the vertical flux, the upper one represents the horizontal flux. Limits for 4 years ('00-'03, lifetime=807 days), dotted lines. AGN ν predictions: (1) from Ref. [?]; (2) from [?] (left panel) and (1) and (2) from Ref. [?] (right panel). On the right, the maximum contribution of γ observable blazars is shown as the dot-dashed line. Flux predictions account for ν oscillations.

the analysis blinded to avoid experimenters bias, analyses cuts are optimized using off-source samples created by scrambling the right ascension of events or excluding the time window of transient emissions under investigation. For the case of diffuse flux analyses the analysis is optimized on a low energy sample, where the signal is expected to be negligible.

AMANDA has a twofold strategy for searching for steady point sources. In a first method, a source catalog of 32 sources was established and spatial cuts were determined based on the position of the potential neutrino emitters. The second technique searches for the spatial clustering of events. Neither of the two point source searches has shown a significant excess of events. The mean sensitivity in the Northern hemisphere to an E^{-2} neutrino flux is

$$E^2 \Phi_{lim} = 5.9 \cdot 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \quad (1)$$

for 5 years of data taking. Here, E is the neutrino energy and Φ_{lim} is the flux upper limit.

The search for single point sources was complemented by stacking classes of sources according to the direct correlation between the photon output and the potential neutrino signal. This was done for 11 different AGN samples that were selected at different wavelength bands, see [?]. The optimum sensitivity was typically achieved by the stacking of around 10 sources. The cumulative and mean source limit for every class is given in table ??.

In the diffuse analysis high-energy (HE) events from all directions are examined with respect to the spectral energy behavior of the sample. A flattening of the total neutrino spectrum is expected when a flat, astrophysical component ($\Phi \sim E^{-2}$) overcomes the steep atmospheric background ($\Phi \sim E^{-3.7}$). The reconstructed energy spectrum for one year of data (year 2000) is shown in Fig. ??. It follows the atmospheric prediction (dashed lines). The most restrictive

Table 1. Results of the stacking analysis for each AGN category [?]: the number of included sources N_{src} , the number of expected events N_{ν}^{bg} and the number of observed events N_{ν}^{obs} are listed as well as the cumulative limit f_{lim} as well as the limit per source f_{lim}/N_{source} , both in units of $\text{GeV cm}^{-2} \text{s}^{-1}$.

AGN category	N_{src}	N_{ν}^{obs}	N_{ν}^{bg}	f_{lim}	f_{lim}/N_{src}
GeV blazars	8	17	25.7	2.71	0.34
unidentified GeV sources	22	75	77.5	31.7	0.75
IR blazars	11	40	43.0	10.6	0.96
keV blazars (HEAO-A)	3	9	14.0	3.55	1.18
keV blazars (ROSAT)	8	31	33.4	9.71	1.2
TeV blazars	5	19	23.6	5.53	1.11
GPS and CSS	8	24	29.5	5.94	0.74
FR-I galaxies	1	3	3.1	4.11	4.11
FR-I without M87	17	40	57.2	2.91	0.17
FR-II galaxies	17	77	68.5	30.4	1.79
radio-weak quasars	11	35	41.6	6.70	0.61

limit from the diffuse analysis for the years 2000 to 2003 is given as

$$E^2 \Phi_{lim} = 8.8 \cdot 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \quad (2)$$

in the energy range of $4.2 < \log(E/\text{GeV}) < 6.4$.

The results were obtained by optimizing the analysis cuts on E^{-2} spectra. Nonetheless the dependency of the response function of the detector to different spectra was considered and limits were set for different spectral shapes (e.g. E^{-3}) or specific models as shown in Fig. ???. Varying the spectral index in the simulation shows that the event distribution simulated for AMANDA peaks at very different energies depending on the assumed spectral index. While, for an E^{-2} spectrum, 90% of the signal lies between $4.2 < \log(E/\text{GeV}) < 6.4$ as discussed above, an E^{-3} spectrum shows an event distribution located about an order of magnitude lower in energy while an E^{-1} spectrum shifts the sensitivity to higher energies. This shows that it is useful to model the spectra according to the predicted shape. This is discussed in detail in [?].

3. Interpretation of AMANDA diffuse limit

Two main astrophysical implications to be drawn from the current diffuse limit will be examined here. The first is the apparent overproduction of neutrinos in coincidence with X-ray photons in the case of hadronic acceleration at the foot of AGN jets. The second is the maximum contribution of TeV observable blazars to the total diffuse neutrino flux. For a detailed discussion of these and further implications, see [?].

3.1. X-ray/Neutrino correlation in AGN

The left panel of Fig. ?? shows that two models, predicting neutrino emission from X-ray emitting AGN, violate the AMANDA limit. In the case of model 1 [?], the E^{-2} -shaped limit applies (constant, dotted curve), while the limit has been calculated according to the specific shape of the model in the case of model 2 [?] (curved, dotted line). Since we discuss the X-ray emission of sources, we refer to the original calculation of model 2. These calculations have been renormalized to the COMPTEL diffuse flux, $E > \text{MeV}$ [?]. While a correlation between MeV photons and neutrinos is possible, X-rays and neutrinos are not correlated. Another model [?]

relating neutrino to X-ray emission can be ruled out in the same way. This suggests that the observed X-rays are related to Inverse Compton Scattering rather than to a hadronic scenario. This, however, does not rule out neutrino emission in coincidence with other wavelength bands, like MeV, GeV or TeV sources, for example.

3.2. TeV blazars and Neutrinos

The diffuse neutrino flux from TeV blazars must be lower than the diffuse AMANDA limit:

$$E^2 \left. \frac{dN}{dE} \right|_{TeV} < 8.8 \cdot 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}. \quad (3)$$

Since TeV photons are absorbed on their way to Earth, current TeV Air Cherenkov telescopes can only detect sources up to $z < 0.3$. TeV photons are believed to be directly correlated to HE neutrinos, since both are produced via the pions from the Δ -resonance resulting from $p\gamma$ interactions. Thus, the detected neutrino flux from *TeV observable sources* is $E^2 \left. \frac{dN}{dE} \right|_{TeV\text{obs}} < 8.8 \cdot 10^{-8} \cdot \eta^{-1} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. Here, η is the absorption factor, depending on the Star Formation Rate (SFR) scenario and on the maximum redshift, i.e. $z_{\text{max}} = 0.3$. Using a constant density of sources, η is maximized and a limit of $\eta(z_{\text{max}} = 0.3) > 53$ is given. Thus, the upper limit of the contribution of TeV observable sources to a diffuse neutrino flux is given as

$$E^2 \left. \frac{dN}{dE} \right|_{TeV\text{obs}} < 1.7 \cdot 10^{-9} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \quad (4)$$

displayed as the dot-dashed line in the right panel of Fig. ???. This underlines the necessity of a diffuse search with HE neutrino telescopes and the need for source-catalog independent searches.

4. Conclusions

AMANDA limits from 5 years for the point source analysis and 4 years for the diffuse analysis can already be used to constrain the physics of X-ray emission in AGN. Other acceleration mechanisms, predicting the emission of neutrinos in coincidence with TeV, GeV or MeV photons, are still interesting investigate and represent good targets for observation. Optically thin sources are only observable in TeV photons up to $z < 0.3$, which leaves neutrinos as a unique messenger from higher redshifts. IceCube is currently being built at the South Pole as AMANDA's 1km³-successor and the sensitivity will reach levels of $E^2 \Phi_{sens} \sim (2 - 7) \cdot 10^{-9} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ in only one year of full observation, see e.g. [?, ?]. This will allow to constrain further neutrino emissions from extragalactic sources, such as AGN and Gamma Ray Bursts (GRBs), or galactic sources such as micro-quasars and Supernova Remnants.

Acknowledgments

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