Search for Signatures of Extra-Terrestrial Neutrinos with a Multipole Analysis of the AMANDA-II Sky-map

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Abstract: In this analysis 3329 neutrino events detected by AMANDA-II during the years 2000-2003 are analysed for anisotropies or unexpected structures in their arrival direction. The structures could arise due to the presence of a signal from many weak and therefore unresolved cosmic neutrino sources, a few brighter sources or extended sources (e.g. a diffuse flux from the galactic plane). The sky-distribution of arrival directions (sky-map) is expanded in a series of spherical harmonics and the power in each multipole moment is calculated. Compared to previous AMANDA-II analyses, it provides a new complementary approach, in particular in the search for very weak individual astro-physical sources. No excess from extra-terrestrial sources is found. Statistical errors as well as systematic errors related to the uncertainty of the angular distribution of the atmospheric neutrinos are quantified using the Feldman-Cousins unified approach. Limits for contributions from extra-terrestrial sources to the sky-map are derived as function of the average source strength and the spectral index of the energy spectrum for different sky-distributions: weak sources isotropically distributed in the northern sky, sources located in the galactic and super-galactic plane. The tested average flux per source varies between $\phi_{low} = 5 \cdot 10^{-13}$ cm^{-2}s^{-1} and $\phi_{high} = 5 \cdot 10^{-11}$ cm^{-2}s^{-1} at the earth, assuming an E^{-2} power spectrum in the sensitive energy range between 1.6 TeV and 1.6 PeV. The number of sources in the sky can be limited at 90% C.L. to be less than 3524 for the assumed ϕ_{low} and less than 28 for ϕ_{high}.

Introduction

There are several proposed candidate objects which could be neutrino sources in the universe, e.g. Active Galactic Nuclei, Supernova Remnants or Micro Quasars.

A direct measurement of these neutrinos is not possible. However, they produce high energetic muons in charged current interactions. Which points into the initial neutrino direction. The charged muons produce Cherenkov-Light passing through the deep ice at the South Pole. The emitted light is measured with the AMANDA-II detector [1] using photomultipliers and the direction and energy of the muon is reconstructed.

The AMANDA-II detector was completed in 2000 and is taking data since then. This analysis uses 4 years of AMANDA-II data (2000 to 2003, 807 days lifetime). The main background are muons produced in the atmosphere. To reject these events only up-going events are included in this sample.

This reduces the field of view to the northern sky. The final event sample consists of $N = 3329$ muon neutrino events. The measured data is reconstructed and filtered as described in [1]. The background of miss-reconstructed down-going muons in this sample is below 5%.

Angular Power Spectrum

This analysis compares the angular power spectrum of the measured data to the background expectation of neutrinos produced in the atmosphere. The data is expanded by means of spherical harmonics $Y_l^m(\theta, \phi)$. The multipole index l characterises the angular scale ($\delta \approx \pi/l$) and m the orientation of the angular structures. Small l correspond to large angular scales (e.g. overall sky-distribution). Small structures appear at large l (e.g. angle between sources). Orientation averaged observables are the multipole moments C_l (power

components):

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_l^m|^2,$$

$$a_l^m = \int_\Omega \sum_{i=1}^{N} \delta(\theta_i, \phi_i) \bar{Y}_l^m(\theta, \phi) d\Omega.$$

Ω stands for the integration over the unit sphere. The software GLESP [2] is used to calculate the integral.

The accuracy of the calculated C_l values from GLESP is limited by the event statistics. The obtained values for C_l which are expected to be zero are found to be non-zero but to scale about as $C_l \sim C_0/N$ and C_0 is normalised to π. The AMANDA-II point source resolution is about $3°$ corresponding to $l \approx 60$. An estimate for the maximum l is provided by the mean angle between the data points: 29 mrad corresponding to $l \approx 116$. A limitation for the maximum l is derived from the degrees of freedom. This is $l = 57$ for 3329 events.

Correlations between the multipole moments due to the limited aperture are taken into account in the statistical analysis.

Data and Background Simulation

The angular power spectrum for the background (atmospheric neutrinos) and different signals is estimated by simulations. Each simulated data set has 3329 events (same as the experimental sample) and contains atmospheric background as well as signal events. The neutrinos are distributed according to the angular acceptance of AMANDA-II. This acceptance is energy dependant. The directions of all simulated neutrinos are varied randomly according to the angular resolution function of AMANDA-II.

The simulation of the atmospheric neutrinos is done according to their angular zenith distribution. Theoretical uncertainties are considered by varying the assumed distribution randomly within it's uncertainties for each simulated data set. For the azimuth angle a flat distribution is assumed due to the rotation of the detector.

Source neutrinos are simulated with a Poisson-distributed number of events per source at the earth

and an power law energy spectrum. The mean number of events varies between $\mu = 0.1$ (corresponding to $\phi \approx 5 \cdot 10^{-13}$ cm^{-2}s^{-1}) and $\mu = 10$ (corresponding to $\phi \approx 5 \cdot 10^{-11}$ cm^{-2}s^{-1}). ϕ is the integrated flux per source at the earth in the sensitive range between 1.6 TeV and 1.6 PeV assuming an E^{-2} energy spectrum. Source locations are simulated isotropically distributed in the northern hemisphere or located in the (super) galactic plane.

Figure 1 shows the angular power spectrum for atmospheric neutrinos compared with an example spectrum for extra-terrestrial neutrinos. The steep falling of the spectrum for $l < 6$ appears due to the restriction to the northern sky while the flat tail corresponds to the statistical limitation of GLESP (see above). Error bars are derived from the RMS spread found for 1000 simulated and analysed data sets. The tested multipole moments C_l for the analysis are chosen by simulation according to their sensitivity for a certain signal [3]: $C_{2/3/5}$ for isotropic distributed sources with a flux below $\phi = 5 \cdot 10^{-12}$ cm^{-2}s^{-1}, C_{1-40} for a higher flux and C_{1-15} for the (super) galactic plane. For weak sources ($\mu \le 1$) using only $C_{2/3/5}$ restricts the sensitivity to the overall distribution of the neutrinos.

Experimental Result

The analysis steps have been optimised using simulation without referring to the data (blind analysis). The angular power spectrum of the experimental data is calculated in the same way as for the simulated data. Figure 1 shows the result. The experimental moments are generally within the errors of the background expectation and no general deviation is observed. For further analysis

$$d_l \equiv (C_l^{exp.} - C_l^{sim.})/\sigma_l$$

is defined as the difference between measurement and simulation normalised to the combined uncertainty from statistics and the model dependence. The average $< d_l >$ over l for the experimental data and the purely atmospheric expectation is $< d_l > = 0.2 \pm 0.14$ with a $RMS = 1.0 \pm 0.3$. The value $D^2 = \sum_{l=1}^{40} d_l^2 = 57.2$ is calculated. The probability to obtain a larger D^2 is 7% (from
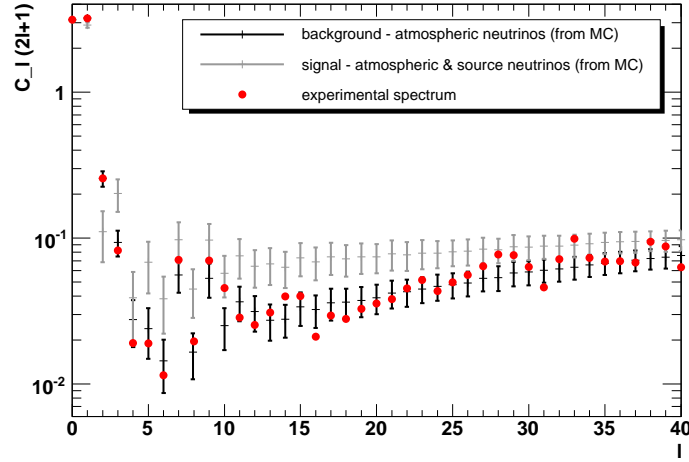
Figure 1: Expected angular power spectrum for atmospheric neutrinos (black) and one signal example (gray) (both from Monte Carlo Data) compared to the experimental spectrum (red dots). The example data is simulated for 110 sources in the northern sky with a flux per source $\phi = 5.23 \cdot 10^{-11}$ cm^{-2}s^{-1}. The error bars include systematic errors as described in the text.

the simulations). This is the probability for consistency of experimental data and the purely atmospheric expectation. It does not show a good agreement. However, this probability does not reject the purly atmospheric assumption.

Limits on Cosmic Contributions

The contribution of signal events in the experimental sample is tested by means of the observable $D^2 = \sum d_l^2$. Upper limits on these are derived by constructing confident belts according to [4] as a function of the number of signal neutrinos in the data sample.

The derived upper limits for an energy range from 1.6 TeV to 1.6 PeV and an E^{-2} energy spectrum are shown in table 1 and in figure 2. The limit on the total number of signal neutrinos in the data sample is almost independent of the source strength. We limit the contribution from isotropically distributed sources to be less than about 300 events total and less than about 200 events for the (super) galactic plane. As expected the results for the galactic and super galactic plane are nearly identical. The step in the limits for the isotropically distributed sources corresponds to the change in the used l (see above).

The limits on the number of neutrinos can be converted to limits on the number of sources (fig. 2). The number of sources is decreasing with increasing strength. The tested flux per source in this analysis is chosen to be below the flux limit for resolved sources $\phi = 4.38 \cdot 10^{-11}$ cm^{-2}s^{-1} derived by [1]. However, limits on the number of sources presented here depend on the assumed sky distribution of the sources and the equal source strength.

With this analysis further limits are derived [3]. Table 1 shows limits for other power law energy spectra. The limit on a diffuse neutrino flux (E^{-2}) is about $5 \cdot 10^{-7}$ GeV^{-1}cm^{-2}s^{-1}sr^{-1}. This is a factor 2 to 3 worse compared to the actual limit set by AMANDA-II. A diffuse flux ($E^{-2.7}$) from the galactic plane is limited to be below $E^{2.7} \cdot d\phi/dE < 3.4 \cdot 10^{-3}$ GeV$^{1.7}$cm^{-2}s^{-1}sr^{-1} with 90% C.L.. $C_{2,3}$ are sensitive to atmospheric neutrino oscillation. Figure 1 shows no difference between the expectation and the experimental result. We derive a limit $\Delta m_{atms.}^2 < 5 \cdot 10^{-3}$ eV^2 (90% C.L.) for maximum mixing.

Conclusion

For the first time the technique of a multipole analysis, well known from CMBR, is applied to the
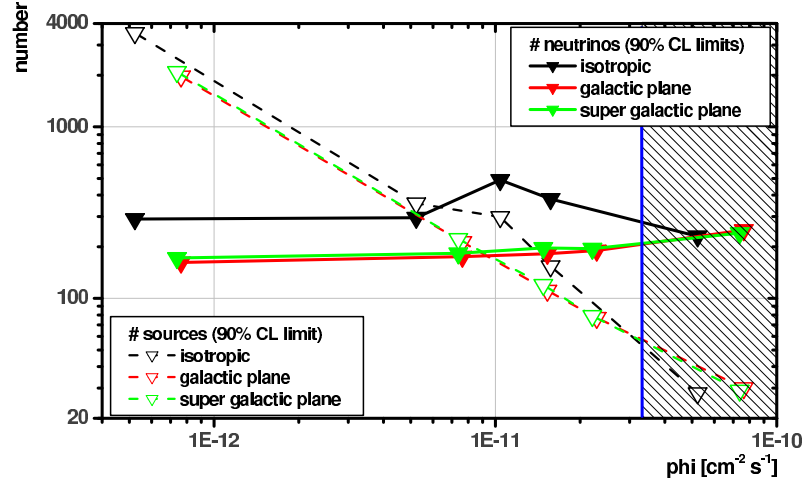
Figure 2: 90% CL upper limits on the number of neutrinos from extra terrestrial sources in the data sample (full lines) and on the number of sources in the northern sky (dashed lines) for different distributions assuming an E^{-2} energy spectrum. Complementary to this analysis the direct search for point sources excludes any source above a flux of $\phi = 4.38 \cdot 10^{-11}$ cm^{-2}s^{-1} [1]. This restriction is indicated as the shaded region in the graph.

AMANDA-II data. It is found suitable to search for a signal of extra-terrestrial neutrinos. The analysis is not well optimised yet. For the future with increased statistics and improved analysis we expect a substantially increasing sensitivity.

References

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	μ	0.1	1	2	3	10
isotropically distributed sources						
E^{-2}	ϕ	0.52	5.2	10	16	52
	N_ν	290	295	490	380	230
	N_S	3524	358	298	154	28
$E^{-2.5}$	ϕ			29	43	
	N_ν			775	625	
	N_S			625	298	
sources in the galactic plane						
E^{-2}	ϕ	0.76	7.6	15	23	76
	N_ν	162	175	182	190	250
	N_S	1968	213	111	77	30
$E^{-2.4}$	ϕ			36	53	
	N_ν			168	172	
	N_S			115	78	
sources in the super galactic plane						
E^{-2}	ϕ	0.74	7.4	15	22	74
	N_ν	172	183	197	195	240
	N_S	2090	222	120	79	29
$E^{-2.4}$	ϕ			33	49	
	N_ν			175	178	
	N_S			119	81	

Table 1: Derived 90% CL limits on the number of measured extra terrestrial neutrinos N_ν and the number of sources in the northern hemisphere N_S depending on the source flux ϕ (in 10^{-12}cm^{-2}s^{-1}) and the energy spectrum.