Searches for point-like sources of high-energy neutrinos with the AMANDA-II detector

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I Motivation
Cosmic rays

- Discovered 1912
- Spectrum and (low energy) composition well known.
- The origin of the high-energy cosmic rays is still unresolved.
- "Bottom-up" and "top-down" scenarios for production.

Main component: Nuclei of energies up to $\sim 10^{20}$ eV

Gaisser 2006
Acceleration of cosmic rays

- Acceleration in relativistic shocks (first order Fermi acceleration)

- Energy gain: $\Delta E = E_2 - E_1 \sim \beta$

- Expected energy spectrum: $\Phi \sim E^{-2.3}$

- Compatible with cosmic ray spectrum: $\Phi \sim E^{-2.7}$ (if propagation losses are taken into account)
Potential sources of high-energy cosmic rays

- Source classes clearly show emission of non-thermal radiation
- Leptonic acceleration: $e^+, e^-$?
  or
- Hadronic acceleration: $p, Z, e^-$?

Supernova remnants
Pulsar wind nebulae

X-ray binaries
Active galactic nuclei (AGN)

galactic
extra-galactic

Cas A
Microquasar illustration
M 87

Crab Nebula
Identification of cosmic ray sources

- Charged particle tracks do not point to their source: Larmor radius $\ll$ diameter of galaxy

- Source identification by detection of uncharged secondaries from inelastic scattering of cosmic rays with photons and matter close to their source

Alternatively: Inverse Compton-scattering
Observations of high energy gamma ray sources

**E > 100 MeV**

Third EGRET Catalog

- Active Galactic Nuclei
- Unidentified EGRET Sources

**E > 100 GeV**

Galactic plane survey

**VHE Gamma**

- Pulsars
- LMC
- Solar FLare

**H.E.S.S.**

Markus Ackermann 7

GLAST science lunch, Stanford Linear Accelerator Center, 24.01.07
Multi-wavelength observation + spectral modelling necessary to distinguish hadronic & leptonic acceleration processes.

Signal unambiguous indicator for hadronic acceleration.
Gamma-ray vs. neutrino detection

Universe partly opaque for gamma-rays. Opaqueness increasing with energy.

Universe is transparent for neutrinos up to the highest energies.
Gamma-ray vs. neutrino detection

Small cross section of neutrino-nucleon scattering demands for detectors with huge target volume.

- **ν**: Small cross section of neutrino-nucleon scattering demands for detectors with huge target volume.

- **H.E.S.S.**: \( E_\gamma > 350 \text{ GeV} \)

- **νμ/ν<sub>µ</sub> / year \( (E_\nu > 1 \text{TeV}) \) expected in a km<sup>3</sup>-sized neutrino detector.

  (If γ-rays from π<sub>0</sub>-decay)

  Guetta and Amato, astro-ph/0209537

  Kappes et al., astro-ph/0607286
II The AMANDA-II Neutrino detector
The AMANDA-II neutrino detector

- Instrumented volume: 
  ~ 0.02 km$^3$
- Operational since 
  Feb. 2000
- Data taking 
  ~ 200 effective days / year
Signatures of neutrino interactions in ice

Charged Current

- $\nu_e$
- $\nu_\mu$
- $\nu_\tau$

Electromagnetic cascade
- Hadronic cascade

Cascades:
- Length: $O(10m) \rightarrow \text{"point-like"}$
- Directional resolution: $\pm 30^\circ$
- Energy resolution: $\pm 0.1 \ (\log E)$
- Target volume: low

Muon tracks:
- Length: $\sim 3km @ 1TeV$
- Directional resolution: $\pm 2^\circ$
- Energy resolution: $\pm 0.4 \ (\log E)$
- Target volume: high

Neutral Current

- $\nu$

(Neutral Current: BR: 17.7%)
The South Pole challenge

- **Use of a natural target material**
- **Optical properties of glacial ice are very inhomogeneous**
- **Require extensive measurements, modelling and simulation**

![Graph showing scattering and absorption coefficients](image)

- **Scattering coefficient**
- **Absorption coefficient**
  - Different depths and wavelengths are indicated:
    - 532 nm
    - 470 nm
    - 370 nm
    - 337 nm
  - LGM
  - Bubbles dominate at lower depths
The South Pole challenge

- 2-dimensional ice model was developed for simulation
- Just recently implemented in the simulation chain
  (due to CPU constraints)
AMANDA-II physics program

- **Search for point sources of astrophysical neutrinos**
  - Time integrated searches
  - Searches for time variable sources
  - Gamma-Ray Bursts

- **Search for a diffuse cosmic neutrino flux**
  - Muon neutrinos
  - Cascades (all neutrino flavors)
  - Ultra high energy analysis
  - Galactic plane

- **Search for neutrinos from WIMP annihilation**

- **Other topics:** Atmospheric muons & neutrinos, cosmic ray composition, gamma-ray astronomy with muons, supernova searches, exotic particles
Neutrino event selection (point source search)

- Extraterrestrial neutrinos: few events expected
- Atmospheric neutrinos: $\approx 10^3$ events / year
- Muons from air showers: $\approx 10^9$ events / year

### Event selection

<table>
<thead>
<tr>
<th>Event category</th>
<th>$R_{\text{evt}}$</th>
<th>$R_{\text{atm-}\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triggered events</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Directional cuts</td>
<td>0.11 %</td>
<td>87%</td>
</tr>
<tr>
<td>Topological cuts</td>
<td>5 $\times$ 10^{-5} %</td>
<td>35%</td>
</tr>
</tbody>
</table>

- Final neutrino sample: 4282
- Atm-$\nu$ simulation: 3627 - 4912

- "Blind" event selection to avoid statistical biases
- Selection optimized for hard and soft spectra
Search for point sources

- Search for signal from candidate sources
- Scan of full northern sky
- Dedicated searches for variable sources
- Flux upper limits set if no signal is seen

On-Source

Off-Source

$\alpha = 2.25^\circ - 3.75^\circ$

2000-2004 data set

1001 effective days

24h 75°

60° 45°

30° 15°

0h
- **Sensitivity** (limit setting capability) to neutrino flux $d\Phi/dE \sim E^{-2}$
- Contribution of $\nu_\tau$ to sensitivity **10-16%** (declination dependent)
- $\nu_\mu + \nu_\tau$ is the strongest limit on the neutrino flux for a $\nu_\mu:\nu_\tau = 1:1$ flavor ratio
Neutrino effective areas

- Muon neutrinos
- Tau neutrinos via $\nu_\tau \rightarrow \tau \rightarrow \mu + \nu_\tau + \overline{\nu_\mu}$ (17.7 %)
Zenith distribution of events in the point source sample

Predictions from atmospheric neutrino simulation is shown with its (experimental) systematic error interval
### Systematic uncertainties

- **Main contributions the systematic error** are (point source analysis)
  - average OM efficiency ($\sim 10\%$)
  - rock density (up to $7\%$)
  - detector simulation inaccuracies ($\sim 7\%$)

- **Total systematic uncertainty** on the signal efficiency
  - $E^{-2}$ spectrum: $+10 \, \text{}/\, -15\%$
  - $E^{-3}$ spectrum: $+5 \, \text{}/\, -20\%$
  - atmos. spectrum: $+5 \, \text{}/\, -25\%$

- Included in the **limit calculation**
III Results from the point source search
Results I: Candidate sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Events observed/</th>
<th>Excess</th>
<th>Flux upper limit (15% sys, 7% stat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassiopeia A</td>
<td>5/6.00 0.15 0.89</td>
<td>0.84</td>
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</tr>
<tr>
<td>Markarian 421</td>
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<tr>
<td>Markarian 501</td>
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<tr>
<td>1ES1959+650</td>
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<tr>
<td>M87</td>
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<tr>
<td>3C273</td>
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<tr>
<td>SS433</td>
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</tr>
<tr>
<td>LSI +61 303</td>
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<tr>
<td>Cygnus X-1</td>
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<tr>
<td>Cygnus X-3</td>
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<td>0315+118</td>
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<tr>
<td>AGN</td>
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<tr>
<td>Microquasar</td>
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<tr>
<td>SNR</td>
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<td></td>
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<tr>
<td>Crab Nebula</td>
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</tbody>
</table>
| 32 sources in candidate list
| No significant excess, no indication for a neutrino source
| Systematic error of 15% on signal prediction included in limits
Results II: Grid search

2000-2004

Random events

69 out of 100 sky maps with randomized events show an excess higher than $3.7\sigma$. 

Largest fluctuation: $3.7\sigma$ at 12.6 h, +4.5 deg
90% confidence level flux upper limits for the northern hemisphere in 0.5 deg bins (15% systematic error included)
Search for neutrinos in active phases of variable sources

- **Time-integrated search not optimal** if neutrino emission of a source is variable.
- **Hypothesis**: electromagnetic and neutrino emission are correlated (naturally expected for neutrino / high-energy gamma-ray emission).
- **Selection of time periods** of high electromagnetic source activity to improve signal-to-noise ratio.
- **Continuous monitoring** of source activity necessary → X-ray / radio data used for period selection.
- **3 Sources investigated**: Markarian 421, 1ES1959+650 and Cygnus X-3
Search in predefined time windows

Markarian 421
- expected: 1.63

AMANDA
- events

Cygnus X-3
- expected: 1.39
Search for excess of events in short time window.

12 potentially variable sources investigated.

Search with sliding time window of 20 days (galactic sources) / 40 days (extra-galactic sources) duration.

No significant excess of events found.
Neutrinos from the direction of 1ES 1959+650

- 3 neutrinos in 66 days.
- In overlap with the only observed period of strong gamma-ray flares of this source.
- Only affirmed observation of an “orphan flare” (gamma-ray and x-ray intensity not correlated)
Neutrinos from the direction of 1ES 1959+650

- Event at MJD 52429.0 at the day of the „orphan flare“
- Event at MJD 52460.3 in coincidence with smaller flare
- „A posteriori“ observation. Assignment of a significance not possible.

Krawczynski et al. (2003)
Target of opportunity test run with MAGIC IACT (Sep - Dec 2006)

- Trigger $\gamma$-ray observations by neutrinos
- Neutrino events selected by AMANDA on-line filtering ($\Delta t \approx 1h$)
- Alert sent to MAGIC if neutrinos are from the directions of predefined source candidates
- MAGIC observation, if source visible within 24 hours after the neutrino arrival
- 5 alerts sent, 1 MAGIC observation.
- Results will be exchanged and compared to pre-determined thresholds for $\gamma$-ray flux.
- Neutrino events by themselves are consistent with prel. background estimates.
IV Interpretation of flux limits
Comparison to selected models

- Specific theoretical models for neutrino emission from a single source rarely show a pure $E^{-2}$ spectrum.
- Variation of the spectral index between $\gamma=1$ and $\gamma=3$ shifts the peak energy of the detected neutrinos by 6 orders of magnitude.

Specific limits have to be calculated for the sources/spectra modelled based on the effective area of AMANDA-II.
Sensitivity to different spectra

Sensitivity to $d\Phi/dE \sim E^{-1}$: Declination dependence due to neutrino absorption

Sensitivity to $d\Phi/dE \sim E^{-3}$: Declination dependence from detector efficiency

Graphs showing the sensitivity of different spectra with respect to the angle $\delta$.
Crab nebula

- Guetta & Amato: Rescaling of gamma ray flux \( N_{\nu, \text{exp}} = 0.16 \)
- Bednarek & Protheroe: Heavy nuclei accelerated in outer gap \( N_{\nu, \text{exp}} = 0.08 \)
- Bednarek: Time evolution of pulsar wind nebula \( N_{\nu, \text{exp}} = 0.03 \)
- Link & Burgio: Ions accelerated near pulsar surface \( N_{\nu, \text{exp}} = 1.2 \)

Flux limits and predictions shown correspond to \( \nu_\mu + \nu_\tau \) flux on earth for a flavor ratio of \( \nu_\mu : \nu_\tau = 1:1 \)

| \( N_{\text{observed}} \) | 10 |
| \( N_{\text{background}} \) | 6.74 |
| Event upper limit (90% CL) | 10.1 |

![Graph showing flux limits and predictions for the Crab nebula](image-url)
X-ray binaries

- Distefano et al.: $p\gamma$-interaction in the jet with int. and ext. photons ($N_{v,exp}=7.8$ for SS 433)
- Bednarek: $pp$-interaction in WR star and accretion disk after photodissoziation of heavy nuclei in the jet ($N_{v,exp}=2.1 / 1.4$ for Cygnus X-3)
- Anchordoqui et al.: Protons accelerated in electrostatic gap interact in accretion disk ($N_{v,exp}=0.12$ for AO 0535+625)

### SS433
- $N_{obs}/N_{bg} = 4 / 6.14$
- Event upper limit (90% CL) = 3.1

### Cygnus X-3
- $N_{obs}/N_{bg} = 7 / 6.48$
- Event upper limit (90% CL) = 6.4

### AO 0535+625
- $N_{obs}/N_{bg} = 7 / 6.48$
- Event upper limit (90% CL) = 6.4
Neronov and Semikoz: Model for “typical GeV loud Blazar”, $p\gamma$-interaction in the AGN core

$N_{\nu,\text{exp}} = 0.04 - 1.1$ (QSO 0528+134)
$N_{\nu,\text{exp}} = 0.006 - 0.14$ (QSO 0954+556)

<table>
<thead>
<tr>
<th>QSO 0528+0134</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{obs}} / N_{\text{bg}}$</td>
</tr>
<tr>
<td>Event upper limit (90% CL)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>QSO 0954+556</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{obs}} / N_{\text{bg}}$</td>
</tr>
<tr>
<td>Event upper limit (90% CL)</td>
</tr>
</tbody>
</table>

variation of beaming angle for $\nu$-emission

$N_{\nu,\text{exp}}$ - $\nu$-electron flux expected from the AGN core.

$E^2 d\Phi/dE$ - Energy spectrum of the $\nu$-emission.
Markarian 421

- WHIPPLE observations
- Muecke et al.: Model of Markarian 421 as High frequency peaked BLLac in the Proton Synchrotron Blazar model ($N_{\nu,\text{exp}} \sim 0$)

![Graph showing event upper limit and observed counts](image)

- $N_{\text{observed}} = 6$
- $N_{\text{background}} = 7.37$
- Event upper limit (90% CL) = 4.1
Summary:

- 5 years of data (1001 effective days) of the AMANDA-II detector have been analyzed for a signal from neutrino point sources.

- No statistically significant source of neutrinos has been found so far.

- A dedicated analysis for variable sources has been performed also with negative result.

- An interesting coincidence between a gamma-ray flare and the arrival time of neutrinos has been found for the Blazar 1ES 1959+650.

- The analysis provides the most stringent limits on neutrino fluxes from point sources on the northern hemisphere.

- Current models of neutrino emission from Microquasars can be constrained by the results.
… and Outlook: IceCube

- **2006**: 9 strings
- **2007**: up to 22 strings (currently 20)
From AMANDA to IceCube

- 677 Optical Modules
- 4200 Digital Optical Modules
- + 160 surface detectors
- Instrumented volume: ~ 1 km$^3$
Currently 20 strings deployed,
21-22 expected after end of deployment season
Neutrino candidate in IceCube-9

- **Candidate event** for a neutrino-induced muon in IceCube-9
- First physics analyses are under way
### Expected IceCube performance

#### Galactic center

<table>
<thead>
<tr>
<th>Years</th>
<th>Diffuse neutrino flux [GeV cm(^{-2}) s(^{-1}) sr(^{-1})]</th>
<th>Point Sources [GeV cm(^{-2}) s(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>exp. Sensitivity (90% CL) exp. Detection threshold (5σ)</td>
<td>exp. Sensitivity (90% CL) exp. Detection threshold (5σ)</td>
</tr>
<tr>
<td>1</td>
<td>8.1 \times 10^{-9} 2.6 \times 10^{-8}</td>
<td>5.5 \times 10^{-9} 1.7 \times 10^{-8}</td>
</tr>
<tr>
<td>3</td>
<td>4.2 \times 10^{-9} 1.2 \times 10^{-8}</td>
<td>2.4 \times 10^{-9} 7.2 \times 10^{-9}</td>
</tr>
<tr>
<td>5</td>
<td>3.2 \times 10^{-9} 9.9 \times 10^{-9}</td>
<td>1.7 \times 10^{-9} 4.9 \times 10^{-9}</td>
</tr>
</tbody>
</table>

10% of the AMANDA-II limiting flux detectable in IceCube in 3-5 years with 5σ significance.
BACKUP SLIDES
IceCube verification: Time calibration

DOM 60 delay is 92.38 ± 1.74, direct hit expect. 86.05

Photon arrival time difference between DOMs 45 & 46

1.74 ns rms

All 60 DOMs

entries

time difference [ ns ]

0 20 40 60 80 100 120 140 160 180 200

0 1 2 3 4 5

time rms resolution measured with flashers [ ns ]

DOM 45

DOM 46

DOM 47

DOM 48
Neutrino effective area

\[ \nu_\mu \text{ (2000-2004)} \]
Nellen et al.: pp interaction in AGN core ($N_{v,\text{exp}} = 0.86$)

Stecker and Salamon: $p\gamma$ interaction in AGN core ($N_{v,\text{exp}} = 0.81$)

Mannheim: pp and $p\gamma$ interaction in the Blazar jet ($N_{v,\text{exp}} = 0.01$)

Diffuse flux predictions from Nellen et al. and Stecker and Salamon already excluded by AMANDA-II limits
Source stacking analysis

- Search for an excess of events from several sources combined
- AGNs grouped in classes of potential high energy neutrino sources
- Assumption: neutrino flux is linearly correlated with luminosity

### Source class

<table>
<thead>
<tr>
<th>Source class</th>
<th>N_{src}</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR Blazars</td>
<td>11</td>
<td>1.2</td>
</tr>
<tr>
<td>keV Blazars (HEAO-A)</td>
<td>3</td>
<td>0.59</td>
</tr>
<tr>
<td>keV Blazars (ROSAT)</td>
<td>8</td>
<td>0.63</td>
</tr>
<tr>
<td>GeV Blazars</td>
<td>8</td>
<td>0.32</td>
</tr>
<tr>
<td>Uni. GeV sources</td>
<td>22</td>
<td>3.2</td>
</tr>
<tr>
<td>TeV Blazars</td>
<td>5</td>
<td>0.69</td>
</tr>
<tr>
<td>GPS and CSS</td>
<td>8</td>
<td>0.57</td>
</tr>
<tr>
<td>FR-I Galaxies</td>
<td>1</td>
<td>0.54</td>
</tr>
<tr>
<td>FR-I Galaxies (no M87)</td>
<td>17</td>
<td>0.43</td>
</tr>
<tr>
<td>FR-II Galaxies</td>
<td>17</td>
<td>3.5</td>
</tr>
<tr>
<td>Radio-weak sources</td>
<td>11</td>
<td>1.3</td>
</tr>
</tbody>
</table>

**Flux upper limit** in units of $10^{-7}$ GeV cm$^{-2}$s$^{-1}$ for differential flux $d\Phi/dE \sim E^{-2}$

A. Gross, Ph.D thesis, University of Dortmund