RECENT RESULTS FROM AMANDA
(The Antarctic Muon and Neutrino Detector Array)

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(for the AMANDA Collaboration)

- **AMANDA goals:**
  - Demonstrate that South Pole ice is a viable detection medium ✔
  - Demonstrate viability of neutrino telescope in South Pole ice ✔
  - Search for physics producing UHE (E>100TeV) neutrino signals
  - Pave way for IceCube (km scale UHE ν detector)
The AMANDA Collaboration

Bartol Research Institute, USA
DESY-Zeuthen, Germany
Kalmar University, Sweden
LBNL, USA
Mainz University, Germany
South Pole Station, Antarctica
Stockholm University, Sweden
University of California-Berkeley, USA
University of California-Irvine, USA
ULB-IIHE, Belgium
University of Pennsylvania, USA
University of Wisconsin-Madison, USA
University of Wuppertal, Germany
University of Uppsala, Sweden
Physics Motivation

- Overwhelmingly motivated by discovery potential

- Unique probe of AGN and GRBs
- Dark matter and TD search tool
- $\nu$ oscillations
- special relativity, weak eq. princ.
Active Galactic Nucleus
## Event Rate Predictions

### Point Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate (/km² yr)</th>
<th>$E_{\mu} &gt; 1$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNa Remnant</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>AGN (3C273)</td>
<td>1-100</td>
<td></td>
</tr>
<tr>
<td>Mk421, Mk501</td>
<td>1-10 from $\gamma$ flux</td>
<td></td>
</tr>
<tr>
<td>GRB ($\Gamma$ fluct. model)</td>
<td>~ a few</td>
<td>(from a rare burst)</td>
</tr>
</tbody>
</table>

### Diffuse Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate (/km² yr sr)</th>
<th>$E_{\mu} &gt; 1$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGN</td>
<td>400-800</td>
<td></td>
</tr>
<tr>
<td>AGN jets</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>GRB</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Atm $\nu$</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>
Detect Cherenkov photons with array of PMTs. Reconstruct tracks with maximum likelihood technique using photon arrival times.
Candidate Upward-Going $\mu$

No external geometry file is opened.
Detector: amanda-b-10, 10 strings, 302 modules
Data file: /home/its/bobdo/amanda_events/AMANDA019.flt.ev4.rec.main
File contains 10 events
Displaying data event 1897860 from run 0
181113000, 13:11 seconds past midnight.
Before cut: 44 hits, 44 CMS
After cut: 36 hits, 36 CMS

Antitau muon

Vertex pos. $x$ 12.4 -16.1 6.8 cm
Direction $x$ 0.03970 $y$ 0.41614 $z$ 0.90444
Length 17 cm
Energy 9 GeV
Time 7205.100000 ns
Zenith 115.3°
Azimuth 364.6°
Physics Results

- Atmospheric neutrino “test beam” (138 live days, 1997)
- UHE neutrino diffuse flux search
- UHE neutrino point source searches
  - AGN with $E^{-2}$ assumption
  - GRB with spatial and temporal coincidence requirements
- WIMPs from earth’s core

- Low E, too: supernova search, relativistic monopoles

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After removing instrumental noise and requiring good event reconstruction, can then look for one or more of:

- upward vs. downward energy of event
- source location in universe
- time of event

<table>
<thead>
<tr>
<th></th>
<th>T</th>
<th>r</th>
<th>E</th>
<th>u/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRBs</td>
<td>✓</td>
<td>✓</td>
<td>(✓)</td>
<td>✓</td>
</tr>
<tr>
<td>AGN, WIMPs</td>
<td>✓</td>
<td></td>
<td>(✓)</td>
<td>✓</td>
</tr>
<tr>
<td>Diffuse $\nu$</td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Atm. $\nu$</td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
**Atmospheric $\nu$ Analysis**

- Confirmation of expected flux of upward-going muon-neutrino-induced muons is a critical milestone for a UHE neutrino telescope
  - Can the detector be calibrated well enough to reconstruct muons?
  - Do we have sufficient pointing accuracy to do astronomy?
  - Can the huge downward-going cosmic ray muon background be overcome?

<table>
<thead>
<tr>
<th>AMANDA</th>
<th>Down-going cosmic rays</th>
<th>Up-going atm. vs</th>
<th>Detected up-going vs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events/day</td>
<td>$6 \times 10^6$</td>
<td>12</td>
<td>1.5</td>
</tr>
</tbody>
</table>

- Efficiency improves with energy, detector size, improved technology
Permits calibration of: absolute pointing, pointing resolution, signal efficiency
Angular Resolution, Offset

- SPASE events calibrate signal MC
- Absolute pointing $\Delta \Psi \sim 3$ degrees
- Offset $\Delta \theta \sim 1$ degree
- Multi-$\mu$ SPASE events similar to signal
Relative Efficiency

Fraction of events remaining as a function of rejection criteria, normalized to number of triggers.

<table>
<thead>
<tr>
<th>Level</th>
<th>SPASE–MC</th>
<th>Data</th>
<th>Data/MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Filter–1</td>
<td>0.57</td>
<td>0.57</td>
<td>1.00</td>
</tr>
<tr>
<td>Filter–2</td>
<td>0.39</td>
<td>0.35</td>
<td>0.90</td>
</tr>
<tr>
<td>Full analysis</td>
<td>0.22</td>
<td>0.19</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Data = SPASE-AMANDA coincidence events.
SPASE-MC = Monte Carlo simulation
Full analysis = point source analysis with inverted angle
Atmospheric ν Reconstruction

• Principle selection criteria (after removing noise hits):
  – minimum number of unscattered photon hits (typically 5 or more)
  – zenith angle (upward going)
  – low “coarseness”
  – track velocity
  – fit likelihood
  – event center of gravity
  – event shape
Neutrinos Separation for Atmospheric Signal-Background
Atmospheric Neutrino Angular Distribution

See about 1 evt/day; Good shape agreement
Normalization off by 50%:
  atm. flux unc., ice properties, obscuration of light by cables, ...

\[ <E_\mu > = 70 \text{ GeV} \]
\[ <E_\nu > = 130 \text{ GeV} \]
• Use event multiplicity as (so-so) energy estimator

• High multiplicity distribution consistent w/atm. neutrino flux

• New energy estimators will improve limits

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$E^2 \Phi_\nu < 1.6 \times 10^{-6} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$

Note that this flux is expected to be $10^3$ larger than that for point sources. Also, atm. $\nu$ backgrounds are somewhat worse.
UHE ν Point Source Search

- Focus on continuous emission from putative sources with hard ($E^{-2}$) spectra
- Backgrounds come from
  - atmospheric neutrinos
  - misreconstructed atm. Muons
- From 1997 data see 1097 events with no obvious clustering
• bin sky according to angular resolution
• estimate background from declination band
• no statistically significant excess
UHE ν Point Source Flux Limit (preliminary)

* (Average over declination bands given in astro-ph/0002492)
Comparison with Models

Figure adopted from Mannheim & Learned
WIMPs from Sun/Earth

\[ \chi \rightarrow q \bar{q} \rightarrow W, Z, H \]
Angular spread decreases as WIMP mass increases, reducing atm. $\nu$ background.
WIMPs from Earth

Optimize for vertical neutrinos. AMANDA limits are competitive.

*Unofficial, added for completeness

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Neutrinos from GRBs

1. $1 \text{m}_\odot$ released inside $10^2 \text{km}$ (opaque)

2. Fireball $\nu$’s $\approx 100 \text{MeV}$

3. Relativistic shock $\gamma = 10^2 - 10^3$

4. $\gamma$’s produced by electron synchrotron

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GRB Handles

Off source

GRB Position

GRB search bin

GRB burst

1 hour

16 s

1 hour

BKG – off time

on time

BKG – off time

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Search for UHE \( \nu \) vs from Gamma Ray Bursters

- GRBs last about 1s, occur roughly daily. Possible neutrino production of intrinsic interest. Also, can provide ultralong baseline for \( \nu \) osc., test of weak equivalence principle.

- Use BATSE burst times and positions to define signal and background regions

- Search for upward going muons in these windows (permitting looser selection criteria)
Relativistic Monopole Search

Search for signal due to high ionization signal of monopole
Summary

- AMANDA is a functioning neutrino telescope
  - reconstruction of roughly 200 atmospheric neutrinos from 1997 data demonstrates viability of technique
  - from background studies and SPASE-AMANDA coincidences, we believe we understand detector sensitivity to a factor of 20% and background rejection to a factor of 2
  - Limits on UHE neutrinos from AGNs, GRBs, WIMPs, generic point sources, diffuse sources. On several fronts we are beginning to challenge the existing models.
  - Also have limits on monopoles and low energy neutrino bursts (e.g., from supernovae)

- Data from 1998 and 1999 (larger detector and more data) are ready to be analyzed
- The much larger AMANDA-II started data taking this year
- All our fingers are crossed for IceCube approval!
AMANDA-II:

- 30,000-50,000 m²
- nearly uniform response over all zenith angles
Ice: Up to the Task
Temp. vs. Trigger Rate

- Trigger rate follows $T_{\text{eff}}$ closely, demonstrates detector stability
- (No measurements during austral summer)
• SPASE provides absolute pointing, pointing resolution, energy resolution, & signal efficiency

• Atm. $\nu, \mu$ provides sensitivity normalization
Diffuse Fluxes

Figure adopted from Mannheim & Learned

1 pp core AGN (Nellen)
2 pγ core AGN (Stecker & Salomon)
3 pγ “maximum model” (Mannheim et. al.)
4 pγ blazar jets (Mannheim)
5 pγ AGN (Rachen & Biermann)
6 pp AGN (Mannheim)
7 GRM (Waxmann & Bahcall)
8 TD (Sigl)

Limits:
filled: Frejus
open: Fleyes Eye
Point Source Fluxes

Figure adopted from Mannheim & Learned

1 pp core 3C273 (Nellen)
2 pγ core 3C273 (Stecker & Salomon)
3 Πγ + pp jet 3C273 (Mannheim)
4 Coma Cluster (Colafrancesco & Blasi)
5 Crab (Brednarek & Protheroe)
6 sun (Ingelmann & Thunman)
7 SNR IC444 (Gaisser, Protheroe, Stanev)
8 SNR γ-Cygni (G-N-S)
9 Cas-A (Ayotan)