Neutrino Astronomy with AMANDA

Steven W. Barwick
University of California-Irvine

SPIE Conference
-Hawaii, 2002
Outline of Talk

• Science of HE Neutrino Telescopes
  Point Sources
  Diffuse Sources (up and down)
  GRBs
  WIMP annihilations in earth and sun

• Future developments in detector technology
Messengers of Astronomy

- The neutrino window begins at energies above $10^{13}$ eV
- Era of multi-messenger astronomy
Detection Method for $\nu_\mu$

- Cherenkov photons are detected by array of PMTs.
- Tracks are reconstructed by maximum likelihood method of photon arrival times.
The AMANDA-II Collaboration

- Bartol Research Institute, University of Delaware
- BUGH Wuppertal, Germany
- Universite Libre de Bruxelles, Brussels, Belgium
- DESY-Zeuthen, Zeuthen, Germany
- Dept. of Technology, Kalmar University, Kalmar, Sweden
- Lawrence Berkeley National Laboratory, Berkeley, USA
- Dept. of Physics, UC Berkeley, USA
- Dept. of Physics and Astronomy, UC-Irvine, USA
- Institute of Physics, University of Mainz, Mainz, Germany
- University of Mons-Hainaut, Mons, Belgium
- Fysikum, Stockholm University, Stockholm, Sweden
- Dept. of Physics, University of Alabama, USA
- Vrije Universiteit Brussel, Brussel, Belgium
- Dept. Fisica, Univ. Simon Bolivar, Caracas, Venezuela
- Dept. of Physics and Astronomy, Penn State University, College Station, USA
- Dept. of Astronomy, Dept. of Physics, University of Wisconsin, Madison, USA
- Physics Department, University of Wisconsin, River Falls, USA
- Division of High Energy Physics, Uppsala University, Uppsala, Sweden
- Dept. of Physics, Imperial College, London, UK

Institutions: 8 US, 10 European, 1 South American
The AMANDA Detector

AMANDA-II

AMANDA-A

AMANDA-B10

Super-K
Early photons are red, late photons are blue. More photons are larger circles.

- Bottom of array is toward center of earth.

- Event is clearly traveling in the upward direction.

AMANDA $\nu$-event
Building AMANDA

Drilling Holes with Hot Water

The Optical Module
Optical Properties of Ice

Sensitivity to cascades and EHE physics demonstrated with in-situ sources

Scattering coefficient (1/m) vs. depth

Detailed measurement of optical properties
- strong light scattering
- dust layers
- low absorption
  *(in particular in UV !!)*

In-situ light source

Simulated light source
dramatically increased acceptance towards horizon

Nearly horizontal event (experiment)
Physics Reach of AMANDA-II

Area depends on physics

Search for $\nu$ from TeV $\gamma$ sources

Milagrito all-sky search sets limit at $> 1$ TeV: $7-30 \times 10^{-7}$ m$^{-2}$ s$^{-1}$, ($E^{-2.5}$)

Amanda probes similar flux if $\nu/\gamma > 1$

Sensitivity to point flux
$E^2 F \sim 5 \cdot 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$
AMANDA-B10
Super Kamiokande
MACRO
AMANDA-II
(northern sky)

southern sky

Mk-501 $\nu/\gamma \sim 1$

SPASE air shower array

- calibration of AMANDA angular resolution and pointing!

→ confirms predicted angular resolution Amanda-B10 ~ 3° (due to tails, best fit by two component gaussian)

→ absolute pointing < 1.5°
Atmospheric Neutrinos, 97 data


→ AMANDA sensitivity understood down to normalization factor of $\sim 40\%$ (modeling of ice ...)

\[ \Delta m^2 = 0.003 \]
\[ \sin^2 2\theta = 1.0 \]
• Improved coverage near horizon
• In $6^\circ \times 6^\circ$ bin, for $E^{-2}$ spectrum, and $10^{-8}$ cm$^{-2}$ s$^{-1}$ flux:
  ~ 2 signal
  ~1.5 background

### Projected sensitivities calculated using background levels predicted from 3 years of Am-II data on tape.

<table>
<thead>
<tr>
<th>Source\Sensitivity</th>
<th>muon ($\times 10^{-15}$ cm$^{-2}$ s$^{-1}$)</th>
<th>$\nu (\times 10^{-8}$ cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markarian 421</td>
<td>0.75</td>
<td>0.5</td>
</tr>
<tr>
<td>Markarian 501</td>
<td>0.75</td>
<td>0.5</td>
</tr>
<tr>
<td>Crab</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Cass. A</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>SS433</td>
<td>3.5</td>
<td>1.4</td>
</tr>
<tr>
<td>1ES 1959+650</td>
<td>0.6</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Diffuse flux: Am-B10 limit

$\Phi < 0.9 \cdot 10^{-6}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$

"AGN" with $10^{-5}$ E$^{-2}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$

solid: experiment
dotted: atmos. $\nu$

$E^2 \Phi$

$< 0.9 \cdot 10^{-6}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$
EHE (E \geq 10^{16} \text{ eV}) Search

- Main background: muon “bundles”
  - Comparable N_{\text{PMT}} but smaller N_{\gamma}
- Calibrate with in-situ N\textsubscript{2} laser
- Still evaluating systematic uncertainties

EHE events very bright; many PMTs detect multiple photons

At EHE energies, expect only events near horizon

Preliminary Limit

3 months B10

AMANDA-II expected
Diffuse fluxes: theoretical bounds and experimental limits

- DUMAND test string
- FREJUS
- MACRO
- NT-200
- AMANDA-B10
- NT-200+
- AMANDA-II
- IceCube (~2012)

Big Question: Where do prompt muons from CHARM come in?
**GRB Analysis**

• **Search strategies**
  1. Short duration ($T_{90} < 1$ s), composite
  2. All duration, composite
  3. **All duration, maximize on single burst sensitivity**

<table>
<thead>
<tr>
<th></th>
<th>up/down</th>
<th>energy</th>
<th>source direction</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric $\nu_\mu$</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffuse $\nu$,</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EHE events</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point Sources:</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>AGN, WIMPs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRBs</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
GRB Analysis (‘97) - 88 BATSE bursts

T90 of GRB burst

Background cuts can be loosened considerably → high signal efficiency

Composite

GRB Neutrino Flux Upper Limit
AMANDA B10 (1 yr of data)

GRB Neutrino Flux Prediction
(Halzen et al., 2000)
AMANDA-II GRB Analysis (‘00)

Check stability and maximize sensitivity for desired BG rejection

58 bursts (triggered and non-triggered)
Feb-May 2000
AMANDA-II GRB Analysis (‘00)

Compute probability to get observed events from random fluctuation

No evidence for neutrino emission by any GRB
The effective area of AMANDA-II is enormous, nearly 0.06km².

For W-B flux, the most probable detected energy is ~10⁵ GeV.
WIMP annihilation in sun

- Silk, Olive and Srednicki, '85
- Gaisser, Steigman & Tilav, '86
- Freese, ’86; Krauss, Srednicki & Wilczek, ’86
- Gaisser, Steigman & Tilav, ’86

Symbols:
- $\rho_\chi$: WIMP density
- $\chi$: WIMP
- $\sigma_{\text{scatt}}$: WIMP scattering cross-section
- $\Gamma_{\text{capture}}$: WIMP capture rate
- $\Gamma_{\text{annihilation}}$: WIMP annihilation rate
- $\nu$ interactions: WIMP-antineutrino interactions
- $\nu_{\mu}$, $\nu_{\text{int}}$, $\mu_{\text{int}}$: Neutrinos and anti-neutrinos
- Earth
- Sun
Limits on WIMP annihilation in Earth

WIMP annihilation at Earth’s center

• Disfavored by recent direct searches

\[ \nu_\mu \to \mu \]

\[ E_{\mu}^{th} = 1 \text{ GeV} \]

\[ \sigma_{SI} > \sigma_{SI}^{\text{lim}} \]
\[ \sigma_{SI}^{\text{lim}} > \sigma_{SI} > 0.1 \sigma_{SI}^{\text{lim}} \]
\[ 0.1 \sigma_{SI}^{\text{lim}} > \sigma_{SI} \]

\[ \text{Muon flux from the Earth (km}^{-2} \text{ yr}^{-1}) \]

\[ \text{Neutralino Mass (GeV)} \]

2002 real time analysis

Daily transmission ~ 1 GB via satellite
Full data to tape (available next polar summer)
Monitoring shifts in home labs

From 02/03:
Iridium connection for supernova alarm

Data preselected online at Pole

Average data volume in kB

filtered data
downscaled-unfiltered data

V event June 6
20% Amanda II cascade limit (Y2K)

E^2 d\phi(\nu(\nu+\bar{\nu})) / dE (GeV cm^{-2} s^{-1} sr^{-1})

Astrophysical \nu's

Predicted events in 100% of 2000 data

<table>
<thead>
<tr>
<th>\nu_e+\nu_e</th>
<th>10^{-6} E^{-2} GeV cm^{-2} s^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>\nu_\tau+\nu_\tau</th>
<th>10^{-6} E^{-2} GeV cm^{-2} s^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td></td>
</tr>
</tbody>
</table>

Atmospheric \nu's

Predicted events in 100% of 2000 data

<table>
<thead>
<tr>
<th>\nu_e (CC), \nu_e+\nu_\mu (NC)</th>
<th>0.15</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Prompt charm (RQPM)</th>
<th>0.50</th>
</tr>
</thead>
</table>

[X] Multiplicative factor of X applied to limits which did not assume 1:1:1 flux ratio

Baikal (\bar{\nu})[6] (prelim.)

Frejus[3]

AMANDA-B10 (\nu_\mu+\bar{\nu}_\mu)[3]

Macro (prelim.) (\nu_\mu+\bar{\nu}_\mu)[3]

AMANDA-B10 (\nu_e+\bar{\nu}_e)

Baikal NT96+NT200 (\nu_e+\bar{\nu}_e) (prelim.)[1,5]

AMANDA-B10 (\nu_e+\bar{\nu}_e) (prelim.)[3]

\tau_{\nu_\mu} >> 1

\tau_{\nu_e} << 1

MPR[1.5]
AMANDA begins to challenge model predictions,
Prel. diffuse limit is below “weak” theoretical bound
Discovery potential

Preliminary results from AMANDA-II
GRB, Atmospheric Neutrinos
Point sources: soon

Trans-GZK events revived interest in EeV physics
Excellent sensitivity to EeV neutrinos

Promising future:
Real-time data analysis
New DAQ with full waveform readout
>2 more years of AMANDA-II data on tape
There is a great deal more to do!