Outline

• Neutrino Astronomy

• Current State of the Art: AMANDA Point Source Search (2000–07)

• (Near) Future Work
  – Multimessenger Observations
  – Deep Core and Galactic Objects
Neutrino Emission

IceCube

Supernova Remnants

Active Galactic Nuclei

Gamma Ray Bursts
Hadronic and Electromagnetic Explanations for Gamma Ray Observations

cosmic rays +
eutrinos

$p \rightarrow \pi^\pm \rightarrow \pi^0 \rightarrow \gamma$ + gamma-rays

Hadronic and Electromagnetic Explanations for Gamma Ray Observations
Neutrino Telescopes

• Neutrinos interact in or near the detector

\[ \nu_\ell \rightarrow \ell, \nu_\ell \]

- \(\mathcal{O}(\text{km})\) muons from \(\nu_\mu\) (CC)
- \(\mathcal{O}(\text{10 m})\) particle cascades from \(\nu_e\), low energy \(\nu_\tau\), and NC interactions
- Cherenkov radiation detected by optical sensors
IceCube

4800 DOMs on 80 strings

160 Ice-Cherenkov tank surface array (IceTop)

Surrounds existing AMANDA detector (677 OMs)

40 strings deployed in 4 construction seasons

Digital Optical Module (DOM)
“Double Bang”:
One of several tau signatures: lollipop, inverted lollipop, etc...
Signals and Backgrounds

cosmic ray

atmospheric neutrino

atmospheric muon

astrophysical neutrino
Muon Field of View

- TeV: look down to avoid atmospheric muons
- PeV: Earth opaque, look horizontally
- EeV: Can look above horizon – atmospherics have softer spectrum

Cascades: $4\pi$, except for absorption at high energies (with muons vetoed!)
AMANDA-II Data Set

AMANDA-II complete

Year | Livetime
--- | ---
2000 | 197 d
2001 | 193 d
2002 | 204 d
2003 | 213 d
2004 | 194 d
2005 | 199.3 d
2006 | 187 d
Total | 3.8 yr

Original DAQ decommissioned
AMANDA integrated into IceCube

AMANDA-B operations
results from 4 string, 10 string
and 13 string phases
Atmospheric Neutrinos

- Statistical unfolding of atmospheric muon neutrino spectrum
  - Based on observed muon energies at detector
- Consistent with theoretical models
- Limit placed on possible high energy component
  - Would appear as excess above expected atmospheric flux

Preliminary
Full Sky Source Search

Preliminary

- All significances pre-trials
- 95 of 100 background maps (data randomized in RA) have a point with significance ≥ 3.38σ
Sensitivity

Preliminary

Energy Range (90%): 1 TeV – 3 PeV

$E^2 \frac{d\phi}{dE} / 10^{11} \text{TeV cm}^2 \text{s}^{-1}$

$\sin \delta$

Energy Range (90%): 1 TeV – 3 PeV
Sensitivity

Preliminary Energy Range (90%): 1 TeV – 3 PeV
Effective Area and Energy

- Energy response shifted to higher energies than for gamma rays

\[ R_\mu \propto E_\mu \]
\[ \sigma_{\nu N} \propto E_\nu \}

at low energies

AMANDA-II analysis:
IceCube will be 10-20x bigger
**Source Catalog Search**

- List of 26 sources selected *a priori*

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mu_90$</th>
<th>P-value</th>
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<tbody>
<tr>
<td>Crab Nebula</td>
<td>4.47</td>
<td>0.10</td>
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<tr>
<td>MGRO J2019+37</td>
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<td>Mkn 421</td>
<td>1.26</td>
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<td>Mkn 501</td>
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<td>LS I +61 303</td>
<td>7.21</td>
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<tr>
<td>Geminga</td>
<td>6.07</td>
<td>0.0086</td>
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<tr>
<td>1ES 1959+650</td>
<td>3.38</td>
<td>0.44</td>
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<td>M87</td>
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<tr>
<td>Cyg X-1</td>
<td>2.00</td>
<td>0.57</td>
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</table>

90% C.L. limits of $E^2\Phi < \mu_90 \times 10^{-11}$ TeV cm$^{-2}$ s$^{-1}$

- Upward fluctuations: LS I +61 303, Geminga, MGRO J2019+37
- Downward fluctuations: Mkn 421

Probability of $p \leq 0.0086$ for at least one of 26 sources is 20%
High Energy Neutrino Source Fluxes

\[ \frac{N_{\mu}(E_{\mu}^{\text{min}}, \theta)}{AT} = \int_{E_{\mu}^{\text{min}}}^{E_{\nu}} dE_{\nu} \Phi_{\nu}(E_{\nu}, \theta) \cdot P_{\nu\mu}(E_{\nu}, E_{\mu}^{\text{min}}) \cdot e^{-\sigma_{\text{tot}}(E_{\nu})N_{A}Z(\theta)} \]

Neutrino flux
Probability to produce a detectable muon \( (E_{\mu} > E_{\mu}^{\text{min}}) \)
Earth transparency

**Diffuse fluxes**

- GZK neutrinos \( \text{0.5 / year} \)
- GRB \( \text{(Waxman)} \)
  \( \text{50 / year} \)
- AGN (thin) \( \text{(Mannheim)} \)
  \( \text{few / year} \)
- (thick)
  \( \text{>100 / year} \)

**Point-like sources**

- GRB \( \text{(030329)} \) \( \text{(Waxman)} \)
  \( \text{1-10 / burst} \)
- AGN \( \text{(3C279)} \) \( \text{(Dermer)} \)
  \( \text{few / year} \)
- Galactic SNR \( \text{(RXJ1713, Vela)} \) \( \text{(Aharonian, Vissani)} \)
  \( \text{few / year} \)
- Galactic Microquasar \( \text{(Distefano, Aharonian et al.)} \)
  \( \text{1-100 / year} \)
- Auger sources \( \text{(Halzen, O’Murchadha)} \)
  \( \text{5 – 0.03 / year} \)
- Milagro source \( \text{(MGRO J1908+06)} \) \( \text{(Halzen et al.)} \)
  \( \text{0.5 / year} \)
Multimessenger Observations

A Distant GRB, AGN, etc.

Swift, GLAST, HETE, etc.)

Timing/localization from satellites & ground-based detectors for neutrino searches
Observations in the direction of 1ES 1959+650

An interesting coincidence with a gamma ray flare:

- 3.7 atmospheric neutrino events expected between 2000 and 2003.
- 5 events observed, incl. 3 in 66 days in 2002, during active period of source

Whipple light curve [Holder et al 2003]

"Orphan flare" (MJD 52429)
**Orphan Flares**

- Seem to suggest acceleration of hadrons
  - But not impossible in EM scenarios

In electromagnetic acceleration scenarios, the X-ray synchrotron photons are the seeds for the gamma rays

- Only observed serendipitously with current instruments
  - Are these common? Only specific objects? Spectral clues?
  - Need a wide field-of-view TeV gamma ray telescope
Neutrinos from GRBs, AGN, and supernovae

A Distant GRB

γ, ν

Swift, GLAST, HETE, etc.)

Timing/localization from satellites & ground-based detectors for neutrino searches

IceCube alerts to TeV ACTs, robotic optical telescopes?

ROTSE, PTF

HAWC

MAGIC
Neutrino-Triggered ToO’s

- Search for “choked” jets inside supernovae (Mészáros & Waxman)
- Up to 30 events in 10 s for a SN at 10 Mpc (Ando & Beacom)
- Look for correlated neutrino events in IceCube, then follow up with robotic optical telescopes looking for supernovae (Kowalski & Mohr)
- Expect ~10 neutrino doublets (w/in 2º-3º) and ~10 high energy neutrinos (E_μ > 100 TeV) per year
Galactic Sources?

• If cosmic ray muons can be beaten down below the atmospheric neutrino background, can look up at the Southern sky and Galactic center region
  – Demand events with ν-N interaction vertex contained in detector
  – Rough estimate of fraction of starting tracks:
    \[ \epsilon(E) \sim \frac{L_{\text{detector}}}{R_\mu(E)} \approx \frac{1 \text{ km}}{\frac{1}{b} \ln \left( \frac{bE}{a} + 1 \right)} \]
    where
    \[ -dE_\mu/dx \approx a + b \ E_\mu \]
    \[ a \approx 0.2 \ \text{GeV/m} \]
    \[ b \approx 3.4 \times 10^{-4} \ \text{m}^{-1} \]
    also account for
    \[ \langle y \rangle \sim 0.42 \text{ at low E (average over } \nu, \bar{\nu} \rangle \]
Galactic Sources?

- Most events below $E_\nu \approx 1$ TeV are contained
  - Some events up to $\sim 10$ TeV (comparable to typical analysis efficiency)

Initial analysis underway at PSU (with AMANDA+IceCube): C. H. Ha
IceCube Deep Core

- Extend IceCube sensitivity to neutrinos with energies below a few hundred GeV
  - Six strings with 60 high-QE PMTs each
  - Use very clear ice at bottom of IceCube ($\lambda_{\text{att}} \sim 40-50 \text{ m, cf. } 20 \text{ m}$)
  - IceCube active veto
    - Reduce cosmic ray muons to atm. $\nu$ level (factor $10^{-6}$)
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Deep Core

IceCube Baseline

Including Deep Core
(renormalized)

$\nu N$ vertex positions for simulated $\nu_\mu$ on E$^{-2}$ from 5 GeV–50 TeV
Low Energy with Deep Core

- Large increase in effective volume for $E_{\nu} < 100$ GeV
  - WIMPs, southern sky, atmospheric neutrino oscillations
  - Threshold down to 10-20 GeV
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Conclusions

• No neutrino sources yet

• Rapid increases in sensitivity in next few years

• Multimessenger observations can give a large advantage
  – IceCube analysis tailored to published X-ray, gamma ray observations
  – IceCube-triggered ToO’s

• Deep Core coming – open up the southern sky?