IceCube High Energy Neutrinos

Nathan Whitehorn
For the IceCube Collaboration

University of Wisconsin - Madison

July 30, 2013
The Neutrino Landscape above 1 TeV

- $\pi/K$ Atmospheric Neutrinos (dominant $< 100$ TeV)
- Charm Atmospheric Neutrinos ("prompt", visible $\sim 100$ TeV)
- Astrophysical Neutrinos (maybe dominant $> 100$ TeV)
- Cosmogenic Neutrinos ($> 10^6$ TeV)
Gigaton Detectors To See High-Energy Component

Need natural detectors: IceCube, KM3NET (future), ANTARES, Baikal
**IceCube**

- 5160 PMTs
- 1 km$^3$ volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 120 m string spacing
- Completed 2010
Physics Reach of IceCube

- Astrophysical $\nu$
  - Understand Cosmic Ray Source Populations
  - Indirect Dark Matter Searches
  - Lorentz Invariance Violation
  - Direct Observation of $\nu_\tau$

- Atmospheric $\nu$
  - Measurement of Atmospheric Neutrino Spectrum (100k events/year)
  - Measurement of $\theta_{23}$
  - Cross-sections at ultra-high energies
  - Cosmic Ray Measurements
Event Signatures

Muon Neutrino CC (data)
< 1 degree angular resolution
factor of 2 resolution of muon energy

Neutral Current or Electron Neutrino (data)
10 degree angular resolution (high energy)
\( \sim 15\% \) deposited energy resolution

Tau Neutrino CC (simulation)
Neutrino Identification

How to identify neutrinos?

1. Upgoing muon tracks
   - Filter out CR muons with bulk of Earth
   - Unknown vertex – hard to measure energy

2. Contained vertex
   - Filter out CR muons using detector edge for anticoincidence
   - All charged particles seen

3. Excess over background
   - Works only for extremely bright/high energy sources
28 events (7 with visible muons, 21 without) on background of $10.6^{+5.0}_{-3.6}$
Observables of Interest

**Spectral slope**  Separate extraterrestrial fluxes from atmospheric, probe properties of accelerator

**Spectral structure**  Cutoffs/slope changes may imply population changes

**Flavor composition**  Discrimination against $\nu_\mu$ dominated backgrounds, probes physics of production process

**Zenith distribution**  Comparison to backgrounds, probes source locations
Vetoing Atmospheric Neutrinos: an Interesting Wrinkle

- Atmospheric neutrinos are made in air showers
- For downgoing neutrinos, the muons from the shower will likely not have ranged out when they arrive at IceCube
- Downgoing events that start in the detector are extremely unlikely to be atmospheric
- Note: optimal use requires minimal overburden to have the highest possible rate of cosmic ray muons

Schöner et al. arXiv:0812.4308
## Signals and Backgrounds: Why This is Compelling

<table>
<thead>
<tr>
<th>Signal</th>
<th>Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>🟢 Cascade-dominated (∼ 80%) from oscillations</td>
<td>✗ Track-like from CR muons and atmospheric $\nu_\mu$</td>
<td>✔ 21/28 are cascades</td>
</tr>
<tr>
<td>🟢 High energy? Typically assume $E^{-2}$</td>
<td>✗ Soft spectrum ($E^{-3.7}$), $\lesssim 1$ event/year $&gt; 100$ TeV</td>
<td>✔ Energies to above 1 PeV, 9 above 100 TeV</td>
</tr>
<tr>
<td>🟢 Mostly (2/3) in southern sky from Earth absorption</td>
<td>✗ Muons in south, atmospheric neutrinos in north</td>
<td>✔ 24/28 from South, mostly cascades</td>
</tr>
</tbody>
</table>

N. Whitehorn, UW Madison
Snowmass 2013 - 11
<table>
<thead>
<tr>
<th>Signal</th>
<th>Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>√ Cascade-dominated (∼ 80%) from oscillations</td>
<td>✗ Track-like from CR muons and atmospheric $\nu_\mu$</td>
<td>● 21/28 are cascades</td>
</tr>
<tr>
<td>√ High energy? Typically assume $E^{-2}$</td>
<td>✗ Soft spectrum ($E^{-3.7}$), $\lesssim 1$ event/year $&gt; 100$ TeV</td>
<td>● Energies to above 1 PeV, 9 above 100 TeV</td>
</tr>
<tr>
<td>√ Mostly (2/3) in southern sky from Earth absorption</td>
<td>✗ Muons in south, atmospheric neutrinos in north</td>
<td>● 24/28 from South, mostly cascades</td>
</tr>
</tbody>
</table>

→ $4\sigma$ evidence for astrophysical flux
Hints in other channels

IC59 Northern $\nu_\mu$ arXiv:1302.0127

Preliminary

2009, 1.8$\sigma$

IC40 Cascades

2008, 2.4$\sigma$
Some interesting events

74.1 TeV, $-0.4^\circ$

252.7 TeV, $+40^\circ$

N. Whitehorn, UW Madison
Energy Spectrum

- Harder than any expected atmospheric background
- Merges well into expected backgrounds at low energies
- Potential cutoff around 2 PeV if $E^{-2}$
- Too few events to measure spectrum well
Skymap: Compatible with Isotropy

ICECUBE PRELIMINARY

*All p-values are post-trial

shower events
p-value = 8%

all events
p-value = 80%

Too few events to evaluate isotropy or identify sources

N. Whitehorn, UW Madison
Summary

- Energy spectrum seems hard
- Flavor distribution consistent with 1:1:1
- Angular distribution makes atmospheric explanation hard: where are the air showers?
- Matches expectations for astrophysical flux
- Still no evidence for clustering
- Does not continue at $E^{-2}$ past a few PeV
- Hard to characterize without more statistics
Parameters of the Future

- Atmospheric neutrino veto is a very powerful concept
- Dominant observable channel for astrophysical diffuse flux is 100 TeV - 1 PeV cascade events
- If an astrophysical flux, \( \mathcal{O}(20) \) events per year per fiducial gigaton
- Analysis now gives \( \mathcal{O}(100) \) events in IceCube in 10 years
- Angular resolution for cascades limited by modelling of light transport and sparse instrumentation
- Need \( \mathcal{O}(10) \) events from a source to identify
- Flavor composition probes particle and astrophysics

More at VLVnT, Aug 5-7, Stockholm
Surface Air Shower Veto Extension

▶ Use surface veto to reject cosmic ray background
▶ Lowers energy threshold for southern uncontained muons from several PeV to 100 TeV
▶ May gain a factor of 3-5 in southern $\nu_\mu$
▶ Improving $\nu_\mu$ improves point source sensitivity
▶ Low cost
IceCube++: toward 10 km³

- How do you get an order of magnitude in volume?
- Current IceCube string spacing optimized for 10-30 TeV
- What if we optimize for 1 PeV?
- 2.3 km³, 5.3 km³, and 12.6 km³ options at right
- Understanding background rejection of wide spacing in progress
Backup
Zenith Distribution

- Compatible with Isotropic Flux
- Events from North absorbed in Earth
- Minor excess in south compared to isotropic, but not significant

IceCube Preliminary

N. Whitehorn, UW Madison

Snowmass 2013 - 21
Event Distribution in Detector

IceCube Preliminary

Uniform in fiducial volume

N. Whitehorn, UW Madison
Shower Energy Resolution

Reconstructed energy [TeV]

Mean deposited energy [TeV]

Probability density [arb. units]

σ [%]

Probability density [arb. units]

N. Whitehorn, UW Madison Snowmass 2013 - 23
Shower Angular Resolution

![Graph showing Angular Error vs. Mean Deposited Energy]

- Angular Error [degrees]
- Mean Deposited Energy [TeV]

Legend:
- Quantile
  - 0.8
  - 0.5
  - 0.3
  - 0.2

N. Whitehorn, UW Madison Snowmass 2013 - 24
Cascades Tracks
Events Per Bin
Data
Best-fit
Best-fit No Astrophysical

N. Whitehorn, UW Madison Snowmass 2013 - 27