IceCube: Ultra-high Energy Neutrinos

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Ultra-high Energy Neutrinos: *PeV and above*

- Energies above dominant atmospheric neutrinos
- Cosmic frontier - PeV gamma-ray horizon limited to a few tens of kpc (our galaxy radius)
- Cosmogenic neutrino production is a ‘guaranteed’ v source
The highest energy neutrinos

**cosmogenic neutrinos** induced by the interactions of cosmic-ray and CMB photons

Off-Source (<50Mpc) astrophysical neutrino production via GZK (Greisen-Zatsepin-Kuzmin) mechanism

\[ p > 100\text{EeV} \]

\[ p\gamma_{2.7K} \rightarrow \pi^+ + X \rightarrow \mu^+ + \nu \rightarrow e^+ + \nu' s \]

The main energy range: \( E_\nu \sim 10^{8-10} \text{ GeV} \)

Carries important physics

- Location of the cosmic-ray sources
- Cosmological evolution of the cosmic-ray sources
- Cosmic-ray spectra at sources
- The highest energy of the cosmic-rays
- Composition of the cosmic-rays
- Particle physics beyond the energies accelerators can reach
Atmospheric neutrinos in PeV

- Conventional atmospheric neutrinos from decays of pion and kaons
- Prompt atmospheric neutrinos form decays of heavy flavor short lived mesons (charm, bottom)
- Prompt harder than conventional still steeper than astronomical spectra
- Transition around $3 \times 10^5$ GeV depending on the models

No clear evidence of prompt atmospheric $\nu$ observed so far

Conventional atmospheric $\nu$ is considered to be background in this analysis

Prompt atmospheric $\nu$ as a signal model
The IceCube Detector

1km

1.5km

Array of 80 sparse and 6 dense strings

5160 optical sensors

South Pole

Dome (old station)

Amundsen-Scott South Pole station
Data samples

Effective livetime of 672.7 days

2010-2011 - 79 strings config.
May/31/2010-May/12/2011
Effective livetime 319.07 days

2011-2012 – 86 strings config
May/13/2011-May14/2012
Effective livetime 353.67 days

IceCube Top View

IceCube has been in a stable operation for more than 5 years
The Event Selection

Energy of incoming particle $\propto$ Energy-losses in detector $\propto$ number of photo electrons (NPE)

- Optimization based MC and MC verification based on 10% experimental ‘burn’ sample

See the details of 2010-2011 data analysis: Poster #12-3 (Keiichi Mase)
Two events passed the selection criteria
2 events / 672.7 days - background (atm. $\mu$ + conventional atm. $\nu$) expectation 0.14 events
preliminary p-value: 0.0094 (2.36$\sigma$)

Run119316-Event36556705
Jan 3rd 2012
NPE 9.628x10$^4$
Number of Optical Sensors 312

Run118545-Event63733662
August 9th 2011
NPE 6.9928x10$^4$
Number of Optical Sensors 354

CC/NC interactions in the detector
Event Brightness (NPE) Distributions 2010-2012

- Observed 2 high NPE events near the NPE threshold

- No indication
  - that they are instrumental artifacts
  - that they are cosmic-ray muon induced

- Possibility of the origin includes
  - cosmogenic $\nu$
  - on-site $\nu$ production from the cosmic-ray accelerators
  - atmospheric prompt $\nu$
  - atmospheric conventional $\nu$
Neutrino Energy Distributions (2010-2012)

energy distributions of neutrinos reaching to the IceCube depth

- EM+hadronic (CC) or hadronic (NC) cascade energy $\sim$ PeV
- Most likely to be PeV to 10 PeV neutrinos
- The highest energy neutrino events observed ever!

Preliminary
# Expected Numbers of UHE Events

<table>
<thead>
<tr>
<th>Preliminary</th>
<th>IceCube 2008-2009 Phys. Rev D83 092003 (2011) 333days</th>
<th>IceCube 2010-2012 per 672.7days</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Models</strong></td>
<td><strong>Prompt atm. $\nu$ (Enberg std.)</strong>^</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td><strong>IC59 diffuse limit ^^</strong></td>
<td>5.0</td>
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<tr>
<td></td>
<td>$E^2\phi = 1.4 \times 10^{-8}$ GeV cm$^{-2}$ sr$^{-1}$ sec$^{-1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Background (conv. atm. $\nu$ + atm. $\mu$)</strong></td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td><strong>Experimental data</strong></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td><strong>GZK (Yoshida m=4)</strong>*</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td><strong>GZK (Ahlers max)</strong> **</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td><strong>GZK (Ahlers best fit)</strong> **</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td><strong>GZK (Kotera, dip FRII)</strong> ***</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td><strong>GZK (Kotera, dip SFR1)</strong> ***</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The Exposure and Effective Area

IceCube UHE 2 Years Exposure (2010-2012)

Effective Areas

IC86 Preliminary (2011-2012)

IC79 Preliminary (2010-2011)

Exposure [m² s sr]

$10^{13}$

$10^{12}$

$10^{11}$

$10^{10}$

$10^{9}$

$10^{8}$

$10^{7}$

$10^{6}$

$10^{5}$

$10^{4}$

$10^{3}$

$10^{2}$

$10^{1}$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

log₁₀ (Energy/GeV)

Auger $\nu_\tau$ 2004-2008

arXiv:0903.3385

Preliminary

$\nu_e$

$\nu_\mu$

$\nu_\tau$
IceCube UHE Sensitivity 2010-2012

- Significantly improved from the previous IceCube results
- The world’s best sensitivity!
- Will constrain (or detect) the neutrino fluxes down to mid-strong cosmological evolution models
Summary

• Searched for neutrinos with PeV and greater energies in nearly full 2 years of the IceCube data

• Two candidate events observed
  o PeV to 10PeV energy cascade-channel neutrino events (CC/NC interactions within the detector)
  o The highest energy events observed ever!

• Likely to be beyond the conventional atmospheric neutrinos

• Hints for the PeV events origin from different energy-region / channels are also coming soon!
  o More cascade event sensitive analysis
  o Lower energy regions for the spectral transition

• Statistical confirmation foreseen with an independent sample

• We are into a very interesting era of neutrino astrophysics!
Backup
Initial level NPE and cos theta distributions

NPE and cos zenith angle distributions comparisons with burn sample
UHE Neutrinos In the Earth...

- Generally neutrinos identified as “through the Earth” up-going events
- Earth is opaque for UHE neutrinos
- UHE neutrino-induced events are coming from above and near horizontal direction

UHE neutrino mean free path
\[ \lambda_n \sim 100 \text{ km} << R_{\text{Earth}} \]
\[ \sigma^{cc}_{nN} \sim 10^{-6}~\text{to}~4 \text{ mb} \]
# Passing rates (stat. errors only)

## Passing rates (per burn sample live time of 498.350 hours) table

<table>
<thead>
<tr>
<th>Filter</th>
<th>Experimental</th>
<th>Atm mu SIBYLL Fe (1.973Hz)</th>
<th>Coincident muon</th>
<th>atmospheric neutrinos</th>
<th>Atm mu SIBYLL H</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Filter Online</strong></td>
<td>3539908</td>
<td>2.34+-/-0.08 x10^6</td>
<td>2.881+/-0.005 x10^5</td>
<td>163.2+/-3.0</td>
<td>9.85+/-1.3 x10^5</td>
<td>0.1528+/-0.0006</td>
</tr>
<tr>
<td><strong>Filter Offline</strong></td>
<td>1.615 x10^6</td>
<td>8.37+/-0.49 x10^4</td>
<td>9.48+/-0.03 x10^3</td>
<td>0.648+/-0.032 x10^4</td>
<td>2.16+/-0.34 x10^4</td>
<td>0.1136+/-0.0004</td>
</tr>
<tr>
<td>(NPE &gt; 1000, Nch &gt; 50)</td>
<td>44458</td>
<td>6.85+/-0.40 x10^4</td>
<td>7655.0+/-23.0</td>
<td>0.625+/-0.031 x10^4</td>
<td>1.75+/-0.32 x10^4</td>
<td>0.1133+/-0.0004</td>
</tr>
<tr>
<td>(NPE &gt; 10^3.5, Nch &gt; 300)</td>
<td>34411</td>
<td>5.65+/-0.271 x10^3</td>
<td>558.7+/-3.4</td>
<td>0.185+/-0.011 x10^3</td>
<td>631.72+/-59.61</td>
<td>0.1102+/-0.0004</td>
</tr>
<tr>
<td>(NPE &gt; 10^4.0, Nch &gt; 300)</td>
<td>3019</td>
<td>253.4+/-13.9</td>
<td>9.53+/-0.20</td>
<td>0.0232+/-0.0013</td>
<td>27.7+/-2.2</td>
<td>0.1019+/-0.0004</td>
</tr>
<tr>
<td>(NPE &gt; 10^4.5, Nch &gt; 300)</td>
<td>134</td>
<td>0.00059+/-0.00024</td>
<td>6.37e-07+/-4.50e-07</td>
<td>0.0028+/-0.0002</td>
<td>8.2e-05+/-5.7e-05</td>
<td>0.0645+/-0.0003</td>
</tr>
<tr>
<td><strong>Final criteria</strong></td>
<td>0.0</td>
<td>0.00024</td>
<td>6.37e-07+/-4.50e-07</td>
<td>0.0028+/-0.0002</td>
<td>8.2e-05+/-5.7e-05</td>
<td>0.0645+/-0.0003</td>
</tr>
</tbody>
</table>
Neutrino energy estimation

A method of the cascade energy reconstruction
- Poisson likelihood for all pulses
- Analytic likelihood maximization for energy
- Numerical minimization (Gulliver) in x, y, z, time, zenith, azimuth

preliminary reconstructed energy: 1.09 PeV

preliminary reconstructed energy: 975 TeV
Surface Energy Distribution of Flavor Dependence

For the downward-going geometry difference due to different parent neutrino flavors on surface is small. For the upward-going geometry it is more relevant, still uncertainty extends not more than 1 energy decades.
In-situ energy scale calibration

Calibrated light source: Standard Candle

- in-situ calibrated N\textsubscript{2} pulsed laser
- light wavelength 337 nm
- at 100\% intensity generates $4 \times 10^{12}$ photons per pulse emitted at 41°
- output adjustable between 0.5\% ~ 100\%
Near future improvement
Background Veto with IceTop

Downward-going region is airshower induced muon background dominated.

Background MC
Background 0.15/livetime

Signal MC
1.0 ~ 30/livetime

Coincidences
IceCube
Do The Jan and Aug events have correlated hits in IceTop?

Before first Hit: Correlation possible

Geometrical not possible as Cascades 2.1 km deep

After the Event no Down-going correlation possible

Jan Auffenberg May 26th 2012
Conclusions

- We saw 0 Hits and 1 Hit in the possible time window of ~8µs. This is a slide under-fluctuation compared with the measured background rate of (0.26/µs = 2.08/8µs).
- There is no evidence for an Air Shower in the two events.
- Veto efficiency is uncertain for prompt neutrino events

Veto Efficiency for different inclination

No cascades in un-vetoed Events:

http://wiki.icecube.wisc.edu/index.php/EHE_IT_Veto_Analysis_unblinding_request#Events_we_don.27t_Veto