Neutrino Astronomy and its Synergies with GW Astronomy

Basudeb Dasgupta
ICTP, Trieste
The Neutrino Sky

keV  MeV  GeV  TeV  PeV  EeV

Sun

Supernova

Atmosphere

Cosmogenic

Astrophysical
Anatomy of IceCube

The IceCube Neutrino Observatory

Detection of high energy neutrinos via Cherenkov light emitted by secondary leptons.

The first km³ ν detector.

Completed in Dec. 2010!

IceCube 59-strings
May 2009 – May 2010

Anne Schukraft

5160 digital optical modules (DOMs)

NOW2012
Two Types of Events

Tracks

Muon from IC59 Data

Good Directionality
Mostly muon neutrinos

Cascades

Simulated $\nu_e$
$E = 182$ TeV

Good Calorimetry
Mostly electron nus + all NC
## Physics Universe of IceCube

<table>
<thead>
<tr>
<th>Energy</th>
<th>~MeV</th>
<th>GeV - TeV</th>
<th>TeV - PeV</th>
<th>PeV - EeV</th>
<th>&gt;EeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources</td>
<td>Supernova</td>
<td>Atmospheric ν DM GRB</td>
<td>Atm.- Prompt GRB AGN Galaxies Clusters</td>
<td>GZK GRB AGN Galaxies Clusters</td>
<td>?</td>
</tr>
<tr>
<td>Signature</td>
<td>Increase in noise rate</td>
<td>Tracks (Up) Cascades</td>
<td>Tracks (Down) Cascades</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Timing and GW Coincidence

SN neutrino-curve is an excellent probe of the bounce time. This can be used to great advantage for coincidence measurement with gravitational wave detectors.

Halzen and Raffelt, arXiv:0908.2317 (PRD)
QCD Burst

Sagert, Fischer, Hempel, Pagliara, Schaffner-Bielich, Mezzacappa, Thielemann, and Liebendoerfer, arXiv:0809.4225 (PRL)
Probing Dense Matter

\[ \text{Total } E \sim E \text{-density} \times d^3 \]

Time for shock to cross the hadronic crust = \( \frac{d}{c_s} \)

d\(M/dr \) related to compressibility

Photon count rate \([10^3 \text{ per 2 ms}]\)

Time after bounce [s]
GeV - PeV Neutrino Astronomy
What can we say if we see only 1 or 2 events?

Razzaque, Meszaros, Waxman (many papers)
Bartos, Dasgupta, Marka, arXiv:1206.0764 (PRD)
TeV - PeV Neutrino Astronomy
Two Events

Results ($2.8\sigma$)

Appearance of $\sim 1$ PeV neutrinos at lower energy threshold

“Bert”
$\sim 1050$ TeV

“Ernie”
$\sim 1150$ TeV

arXiv:1304.5356
What are we seeing?

Ishihara, Neutrino 2012
We have two cascade events with
\(~1.04\ \text{PeV}\ \text{and}\ \sim1.14\ \text{PeV}\)
Demystifying the PeV Cascades in IceCube: Less (Energy) is More (Events)

Ranjan Laha,1,2 John F. Beacom,1,2,3 Basudeb Dasgupta,4 Shunsaku Horiuchi,5 and Kohta Murase6

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(Dated: June 2, 2013)

The IceCube neutrino telescope recently detected two cascade events with energies near 1 PeV. Without invoking new physics in the neutrino sector, we analyze the source of these neutrinos. We show that atmospheric conventional neutrinos and cosmogenic neutrinos (those produced in the propagation of ultra-high-energy cosmic rays) are strongly disfavored. For atmospheric prompt neutrinos or a diffuse background of neutrinos produced in astrophysical objects, the situation is less clear. We show that there are tensions with observed data, but that the details depend on the least-known aspects of the IceCube analysis. Likely, prompt neutrinos are disfavored and astrophysical neutrinos are plausible. We demonstrate that the fastest way to reveal the origin of the observed PeV neutrinos is to search for neutrino cascades in the range below 1 PeV, for which dedicated analyses with high sensitivity have yet to appear, and where many more events could be found.

arXiv:1306.2309 (submitted to PRD)
What are the relevant fluxes?

![Graph showing neutrino fluxes as a function of energy](image)

- **IC40 U.L. EHE search**
- **Atmospheric conventional**
- **Atmos. Prompt $\nu_\mu$**
- **IC40 $\nu_\mu$ U.L.**
- **$E^{-2}$**
- **Takami**
- **Ahlers**

**Figure:** Neutrino fluxes as a function of neutrino energy. The flux is the same as the Enberg model. The atmospheric prompt flux is compared to the atmospheric conventional flux. The cross section dominates the event occurrence.

- **What are the relevant fluxes?**
- **What are the implications?**
- **Future analyses and prospects.**

*4 July 2013, NR Workshop at ICTS, Basudeb Dasgupta*
Atmospheric Neutrinos

Cosmic ray

Dominating at $< 100$ TeV

$\pi^{\pm}$, $K^{\pm}$

Conventional atmospheric neutrinos

$\nu_e : \nu_\mu : \nu_\tau$

$1 : 2 : 0$

$\sim E^{3.7}$

Anne Schukraft
Prompt Atmospheric Neutrinos

Atmospheric neutrinos

Cosmic ray

Dominating at < 100 TeV

$$\nu_e : \nu_\mu : \nu_\tau$$
$$1 : 2 : 0$$

$$\sim E^{-3.7}$$

Anne Schukraft

NOW2012

Cosmic ray

Dominating at > 100 TeV

Earth atmosphere

$$D^{+/-}, D^0, D_s^{+/-}, \Lambda_c^{+/-}$$

$$\pi^+$$

$$K^0$$

$$\pi^- e^-$$

$$\nu_e$$

$$\nu_\mu$$

$$\nu_\tau$$

Prompt atmospheric neutrinos

$$\nu_e : \nu_\mu : \nu_\tau$$
$$1 : 1 : 1$$

$$\nu_\tau \sim 1/20 \times \nu_\mu$$

$$\sim E^{-2.7}$$

3
Cosmogenic Neutrinos

Accelerated proton → CMB photon → Pion → Neutrinos
Ideal; Cascades $4\pi$

Realistic; Cascades $4\pi$

Theory vs Experiment
TABLE I. Expected numbers of cascade events in the two energy bins, obtained by integrating the curves in the right panel (the realistic approach using the effective area) of Fig. 3. These numbers are typically a factor of \(~10\) below those for the left panel (the ideal case or “theorist’s approach”).

<table>
<thead>
<tr>
<th>Possible Source</th>
<th>(N(1 – 2 \text{ PeV}))</th>
<th>(N(2 – 10 \text{ PeV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atm. Conv. [48]</td>
<td>0.0002</td>
<td>0.0002</td>
</tr>
<tr>
<td>Cosmogenic–Takami [36]</td>
<td>0.007</td>
<td>0.07</td>
</tr>
<tr>
<td>Cosmogenic–Ahlers [35]</td>
<td>0.001</td>
<td>0.03</td>
</tr>
<tr>
<td>Atm. Prompt [49]</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Astrophysical (E^{-2})</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Astrophysical (E^{-2.5})</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>Astrophysical (E^{-3})</td>
<td>0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>
What the spectrum must be
Predictions at lower energies

TABLE II. Expected numbers of track and cascade events (ideal case or “theorist’s approach”), obtained by integrating the curves in each panel of Fig. 5 over the range 0.1–1 PeV.

<table>
<thead>
<tr>
<th>Possible Source</th>
<th>$N_{\text{track}}$</th>
<th>$N_{\text{casc}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atm. Conv. [45]</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Atm. Prompt [46]</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Astrophysical $E^{-2}$</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td>Astrophysical $E^{-2.5}$</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Astrophysical $E^{-3}$</td>
<td>9</td>
<td>20</td>
</tr>
</tbody>
</table>
More data for contained events

Results of Contained Vertex Event Search (4.3σ)

28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9}$ (12.1 ± 3.4 with reference charm model)

IceCube Talk at IPA
- Harder than any expected atmospheric background
- Merges well into expected backgrounds at low energies
- Potential cutoff at $1.6^{+1.5}_{-0.4}$ PeV

IceCube Talk at IPA
Directionality

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

IceCube Talk at IPA
What the astro sources could be

<table>
<thead>
<tr>
<th>Source</th>
<th>Mechanism</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGN Jets</td>
<td>Proton-gamma</td>
<td>Peaks at 10-1000 PeV.</td>
</tr>
<tr>
<td>AGN Core</td>
<td>Proton-gamma</td>
<td>OK</td>
</tr>
<tr>
<td>GRB prompt</td>
<td>Proton-gamma</td>
<td>OK, but violates IC limit</td>
</tr>
<tr>
<td>GRB afterglow</td>
<td>Proton-gamma</td>
<td>Peaks at 10-1000 PeV</td>
</tr>
<tr>
<td>Starburst Galaxies</td>
<td>Proton-Proton</td>
<td>OK. Cutoff possible</td>
</tr>
<tr>
<td>Galaxy Clusters</td>
<td>Proton-Proton</td>
<td>OK. Break possible</td>
</tr>
</tbody>
</table>
Partners in Crime

Ranjan Laha  Shunsaku Horiuchi  John F. Beacom

Kenny Ng  Kohta Murase