A search for extremely high energy cosmogenic neutrinos with IceCube

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The extremely high energy (EHE) cosmogenic neutrinos (> $10^8$ GeV)

$$p\gamma_{2.7K} \rightarrow \pi^+ + X \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \nu_\mu$$

EHE cosmogenic neutrinos can shed light on the EHECR origin

- Source position
- Composition (proton/iron)?
- Source evolution / when the EHECR generation started

Predicted, but never detected → Detectable with IceCube

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The detection principle

- **EHE neutrino signal (all flavor)**
  - Horizontal (opaque to the earth)
  - High energy (> $10^8$ GeV)

- **Atmospheric muon background**
  - Down-going
  - Low energy (the energy spectrum is steep (~$E^{-3.7}$))

Datasets

Five datasets are used in this analysis:

1. **Observational data (two years data)**
   - taken in 2010-2011 (319.2 days) with 79 string configuration (IC79)
   - taken in 2011-2012 (350.9 days) with the complete detector (IC86)
   - EHE on-line filter data (NPE > 1000)
   - ~100M events, ~ 1.7 Hz

2. **Signal MC data (JULIeT)**
   - $10^5$-$10^{11}$ GeV, $dN/dE = E^{-1}$
   - 20k events for $\mu$, $\tau$, $\nu_e$, $\nu_\mu$, $\nu_\tau$

3. **Atmospheric muon background MC data (CORSIKA data)**
   - $10^5$-$10^{11}$ GeV, $dN/dE = E^{-1}$
   - 15k events for proton and iron
   - SIBYLL HE interaction model

4. **Coincidence muon MC data (CORSIKA data)**
   - $600$-$10^{11}$ GeV, $dN/dE = E^{-1.7}$, polygonate model (J. R. Hoerandel (2003))
   - 10G events
   - SIBYLL HE interaction model

5. **Atmospheric neutrino background MC data**
   - $10^3$-$10^9$ GeV, $dN/dE = E^{-1}$, $\nu_\mu$, $\nu_e$
   - 10M events
   - atmospheric neutrinos: including knee (T. K. Gaisser (2012))
   - prompt neutrinos: perturbative QCD model (Enberg et al. (2008))
Detected total number of photo-electrons (NPE) $\propto$ Energy

NPE is used for the energy indicator
Analysis scheme

1. Online filter level (EHE):
   NPE > 1000
   \[\downarrow\]
2. Analysis level:
   NPE > 3200
   NDOM > 300
   coincident muon cleaning
   improved geometry reconstruction
   \[\downarrow\]
3. Final level:
   NPE and zenith angle information

Blind analysis

Event number for each filter level

Filter level

Event number

Before cleaning

After cleaning

SPE (llh base)

linefit (simple)
**NPE distribution at analysis level (IC79)**

- **Dominated by atmospheric muons**
- **Reasonable MC/data agreement**

**Graph**

- **33.4 days**
- **NPE > 3200 & NDOM > 300**

**Plot Legend**

- **IC79 data**
- **background sum**
- **atm. μ (single)**
- **atm. μ (coincident)**
- **atm. ν conventional**
- **atm. ν prompt**
- **GZK ν Yoshida et al.**
- **GZK ν Ahlers et al.**
- **GZK ν Kotera et al.**

**Log-log plot**

- **NPE**
- **log_{10} NPE**
- **10^8 GeV (cosmogenic neutrinos (at surface))**
- **10^{10} GeV (CR primary)**

**Zenith angle**

- **19 deg.**

**References**

*Yoshida and Teshima, Prog.Theor. Phys. 89, 833795 (1993), m=4, Zmax=4*

**Ahlers et al., Astropart. Phys. 34, 106867 (2010), m=4.6, Zmax=2 (best)**

***Kotera et al., JCAP 1010, 013869 (2010), FRII***
Zenith angle distribution at analysis level (IC79)

Geometry for atmospheric muons is reconstructed reasonably well.

Atmospheric neutrinos also come from horizontal direction, but low energy.
Final selection criteria (IC79)

Model discovery potential method used

Yoshida and Teshima, Prog. Theor. Phys. 89, 833–795 (1993), m=4, $Z_{\text{max}}=4$

0.57 per 333 days for IC40

Signal

Background

Test data

Expected event rates

<table>
<thead>
<tr>
<th>GZK signal*</th>
<th>Bg total (Atm. $\mu$)</th>
<th>(Atm. $\nu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98±0.01</td>
<td>0.041±0.003</td>
<td>(0.033±0.003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.008±0.001)</td>
</tr>
</tbody>
</table>

*Yoshida and Teshima, Prog. Theor. Phys. 89, 833–795 (1993), m=4, $Z_{\text{max}}=4$

0.57 per 333 days for IC40

~1 event/yr
Effective area

\[ A_{\text{IC79}} \approx A_{\text{IC86}} \approx 2 \times A_{\text{IC40}} \]

for each flavor

\[ \nu \text{e} \]
\[ \nu \mu \]
\[ \nu \tau \]

Increases with energy

\( \sim 5000 \text{ m}^2 \) @ EeV
Two cascade like events found in 2011-2012 data

May, 2011 - May, 2012 (350.9 days), IC86 configuration
Either CC interaction of $\nu_e$ or NC interaction of any flavor $\nu$

Aug., 9th, 2011
Run 118545
-Event 63733662
NPE: $7.0 \times 10^4$
NDOM: 354
("Bert")

Preliminary

<table>
<thead>
<tr>
<th>event rate in 615.9 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric muons</td>
</tr>
<tr>
<td>conventional atmospheric neutrinos</td>
</tr>
<tr>
<td>prompt neutrinos*</td>
</tr>
<tr>
<td>total background</td>
</tr>
</tbody>
</table>

Significance: 2.7 sigma


Jan, 3rd, 2012
Run 119316
-Event 36556705
NPE: $9.6 \times 10^4$
NDOM: 312
("Ernie")
The August event ("Bert")

Aug., 9\textsuperscript{th}, 2011
Run118545
-Event63733662
NPE: $7.0 \times 10^4$
NDOM: 354
The January event ("Ernie")

Jan, 3rd, 2012
Run119316
-Event36556705
NPE: $9.6 \times 10^4$
NDOM: 312
NPE distribution at final level

IC79/86 combined (615.9 days)

Preliminary
The energy deposit reconstruction

Aug. (“Bert”)  
$1.0 \pm 0.2$ PeV

Jan. (“Ernie”)  
$1.1 \pm 0.2$ PeV

energy resolution for these specific events including systematics (ice + DOM eff.)

Preliminary
Two events compatible with EHE cosmogenic neutrino models?

How cosmogenic models are compatible with the two event observation by using energy distribution and rate

Fisher’s method

$$\chi^2 = -2 \ln(P_E) - 2 \ln(P_{\text{pois}}(2; \mu))$$

follows 4 degrees of freedom

Energy distribution rate (Poisson)

Preliminary

IC40+IC79+IC86

<table>
<thead>
<tr>
<th>neutrino model</th>
<th>$P_E$</th>
<th>expected rate</th>
<th>$P_{\text{pois}}$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GZK Yoshida and Teshima</td>
<td>0.060</td>
<td>2.8</td>
<td>0.55</td>
<td>0.15</td>
</tr>
<tr>
<td>GZK Ahlers Fermi best</td>
<td>0.060</td>
<td>2.1</td>
<td>0.73</td>
<td>0.18</td>
</tr>
<tr>
<td>GZK Kotera FR-II</td>
<td>0.034</td>
<td>5.9</td>
<td>0.038</td>
<td>0.01</td>
</tr>
<tr>
<td>GZK Kotera GRB</td>
<td>0.044</td>
<td>1.1</td>
<td>0.42</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Cosmogenic neutrino models are not preferable to account for the two event observation

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Constraint on EHE cosmogenic neutrino models

Compared the event rate with observation

Essentially no event observation above 100 PeV, though the effect of the two events considered by the energy PDF

<table>
<thead>
<tr>
<th>model</th>
<th>expected rate (&gt;100 PeV)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GZK Yoshida Teshima, m=4, Zmax=4</td>
<td>2.6</td>
<td>0.11</td>
</tr>
<tr>
<td>GZK Sigl, m=5, Zmax =3*</td>
<td>4.0</td>
<td>0.030</td>
</tr>
<tr>
<td>GZK Ahlerts, Fermi best</td>
<td>2.0</td>
<td>0.21</td>
</tr>
<tr>
<td>GZK Ahlerts, Fermi max</td>
<td>4.1</td>
<td>0.027</td>
</tr>
<tr>
<td>GZK, Kotera, GRB</td>
<td>0.63</td>
<td>0.53</td>
</tr>
<tr>
<td>GZK, Kotera, FRll</td>
<td>3.8</td>
<td>0.022</td>
</tr>
<tr>
<td>Top-down SUSY**</td>
<td>21</td>
<td>&lt;&lt; 0.001</td>
</tr>
<tr>
<td>Top-down QCD**</td>
<td>5.0</td>
<td>0.011</td>
</tr>
</tbody>
</table>


high evolution models (m>4) are mostly ruled out such as FRll
The model independent upper limit

similar as previous analysis, but model independent

differential limit per one energy decade

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Summary

- Extremely high energy cosmogenic neutrinos were searched for by using 2010-2012 IceCube data
- Two cascade-like events found!
- Significance of cosmogenic neutrino hypothesis is 2.7 sigma
- High evolution models are ruled out such as FRII
- Several follow-up analyses to look for such contained events are being performed and their results are coming soon!
backups
Effect of source evolution and maximum energy on neutrino flux

Effect of the source evolution

Effect of the maximum energy

Neutrino flux depend on the source evolution and maximum energy

\[ \rightarrow \text{constraint on the parameters} \]

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Kotera et al., JCAP 10 (2010) 013
The IceCube experiment

- Deployed in the Antarctica glacier
- In-ice + IceTop + deep core
- 86 strings (completed 2010!)
- ~5,000 photo-multiplier tubes (PMTs)
- Detector volume: ~1 km³
- ATWD 300MSPS
  - 3 different gains (x16, x2, x0.25)
- FADC for long duration pulse
- Targets for high energy cosmic neutrinos
Closest string positions for the vertices

Jan. ("Ernie")

Z: 25 m

Aug. ("Bert")

Z: 122 m

Well contained!
IceTop (surface array) veto information

- IceTop veto information was checked
- hits search in allowed 8μs time window
- 0 and 1 hit observed again 2.1 hits expected

→ No CR shower
Reconstructed energy at surface

Top-down approach (in-ice) + propagation to surface
In case of $\nu_e$ CC, full energy deposit
Other case of NC, partial energy deposit by Bjorken $y$

Aug.  
6.01 < log(E/GeV) < 8.03  
(90%)

Jan.  
6.09 < log(E/GeV) < 8.65  
(90%)
### The systematic uncertainties

<table>
<thead>
<tr>
<th>Sources</th>
<th>Signal (%)</th>
<th>Conventional Background (%)</th>
<th>Prompt (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical error</td>
<td>±0.4</td>
<td>±7.3</td>
<td>±1.1</td>
</tr>
<tr>
<td>DOM efficiency</td>
<td>+3.1, –3.4</td>
<td>+63.7, –30.8</td>
<td>+21.3, –18.9</td>
</tr>
<tr>
<td>Ice properties/Detector response</td>
<td>–6.5</td>
<td>–48.0</td>
<td>–29.8</td>
</tr>
<tr>
<td>Neutrino cross section</td>
<td>±9.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Photo-nuclear interaction</td>
<td>+10.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>LPM effect</td>
<td>±1.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cosmic-ray flux variation</td>
<td>–</td>
<td>+24.0, –39.0</td>
<td>±30.0</td>
</tr>
<tr>
<td>Cosmic-ray composition</td>
<td>–</td>
<td>–61.0</td>
<td>–</td>
</tr>
<tr>
<td>Hadronic interaction model</td>
<td>–</td>
<td>+13.5</td>
<td>–</td>
</tr>
<tr>
<td>$\nu$ yield from cosmic-ray nucleon</td>
<td>–</td>
<td>±3.5</td>
<td>–</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+0.4 (stat.)+13.8–11.7 (syst.)</td>
<td>±7.3 (stat.)+69.5–92.5 (syst.)</td>
<td>±1.1 (stat.)+36.8–46.4 (syst.)</td>
</tr>
</tbody>
</table>