The first search for extremely-high energy (EHE) cosmogenic neutrinos with the IceCube Neutrino Observatory

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Outline

• GZK Neutrinos (Cosmogenic neutrinos)
• The IceCube detector
• Data
• Simulation
• Analysis
• Results
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GZK cutoff mechanism:

\[ \gamma_{\text{CMB}} + p \rightarrow \Delta \Gamma \Delta^h \rightarrow p + \pi^h \]
or

\[ \gamma_{\text{CMB}} + p \rightarrow \Delta \Gamma \Delta^h \rightarrow n + \pi^h \]

- Delta baryon resonance energy threshold:

\[ m_\Delta = 1232 \text{ MeV} / c^2 \]

\[ m_p = 938 \text{ MeV} / c^2 \]

\[ E_\gamma = 8.6 \text{ eV} K^{-1} \times 2.7 K \sim 2 \times 10^{-10} \text{ MeV} \]

\[ E_p < \frac{M_\Delta^2 - M_p^2}{4 E_\gamma} = \frac{1232^2 - 938^2}{4 \times 2 \times 10^{-10}} \sim 10^{20} \text{ eV} \]
Why interesting?

- Give information on sources and propagation of EHE cosmic rays
  - Point back to the sources
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- Systematics
- Cubic-kilometer, high-energy neutrino telescope at geographic South Pole

- Use glacial ice (2800m thick) as Cherenkov medium

- Photon sensors: Digital Optical Modules (DOMs)
  - Photo Multiplier Tube (PMT)
Cherenkov light cone
A down-going muon event...

...major background... got 550 of this per second in IC22...
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Data

- Data collected from May 2007 to April 2008 with 22 in-ice strings (IC-22, 1320 DOMs, 52 IceTop tanks)
  
  Effective livetime: 242.1 days

- Only local coincidence (LC) waveforms are recorded.

- Average trigger rate: 550 Hz

- Event selection criteria:
  
  ★ 8 or more DOMs recorded LC signals ➤ all hits within a 20 $\mu s$ window were stored as an event

★ High multiplicity: $NDOM \geq 80$
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- $\nu_e, \nu_\mu, \nu_\tau$ simulated with energy $3 \times 10^5 \leq E \leq 10 \times 10^{11}$ GeV
- EHE neutrinos (signal) simulated
- Muon bundles (background) simulated: CORSIKA
- Secondary particles propagated through the rock and ice
- Ice properties accounted for
- PMT is calibrated
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EHE Event signatures and event filter

- Level 1 cut: $NDOM \geq 80$
- NPE: number of photo-electrons per event
- In-ice energy: energies sampled at a radius of 880 m from the IceCube center

Measure the NPE and relate them to the neutrino energies... level 2 cut: $NPE > 10,000$...
Muon background

- Bundles of muons in cosmic-ray air showers are major background

- Two independent Monte Carlo (MC) simulations are carried out:
  - CORSIKA proton / iron
  - Empirical model: a phenomenological fit to part of the experimental high energy data and optimized to match the data
Up-going  
Down-going  
deep  
shallow

Red: CORSIKA proton
Magenta: CORSIKA iron
Black dot: observational data after level 2 cut :: $NPE \geq 10^4$
Green: distributions obtained from an empirical model
High multiplicity $\text{NDOM} \geq 80$ is still dominated by atmospheric background muons

NPE $\geq 10^4$ reduces the background by three orders of magnitude...still dominated by background...

GZK signal reduction $\sim 24\%$
**Red**: CORSIKA proton  
**Magenta**: CORSIKA iron  
**Black dot**: observational data after level 3 cut :: $\cos(\theta) < 0.8$  
**Green**: distributions obtained from an empirical model  
**Blue**: expected NPE distribution of events induced by GZK / cosmogenic neutrinos
Search for EHE GZK / cosmogenic neutrino signals

Region A: $-250 \text{ m} < z_{\text{COG}} < -50 \text{ m}$ and $z_{\text{COG}} > 50 \text{ m}$
Region B: $z_{\text{COG}} < -250 \text{ m}$ and $-50 \text{ m} < z_{\text{COG}} < 50 \text{ m}$

Upper row: region A
Bottom row: region B

Data
Empirical model MC
CORSIKA MC
GZK signal MC
<table>
<thead>
<tr>
<th>Analysis filter levels</th>
<th>observational data</th>
<th>empirical model</th>
<th>CORSIKA (iron)</th>
<th>CORSIKA (proton)</th>
<th>signal (GZK1 [6])</th>
</tr>
</thead>
<tbody>
<tr>
<td>level 3 ($\cos(\theta) &lt; 0.8$)</td>
<td>2014</td>
<td>$(2.65 \pm 0.21) \times 10^3$</td>
<td>$(2.68 \pm 0.19) \times 10^3$</td>
<td>$(4.16 \pm 0.40) \times 10^2$</td>
<td>$(620 \pm 7.3) \times 10^{-3}$</td>
</tr>
<tr>
<td>level 4 (EHE $\nu$ search)</td>
<td>0</td>
<td>$(6.32 \pm 1.37) \times 10^{-4}$</td>
<td>$(4.18 \pm 1.29) \times 10^{-4}$</td>
<td>$(1.44 \pm 0.58) \times 10^{-4}$</td>
<td>$(155 \pm 1.4) \times 10^{-3}$</td>
</tr>
</tbody>
</table>

- **The majority of the EHE neutrino induced events is close to the horizon:** level 3 cut

- **Level 4 cut was finalized on simulated events alone without referring to the real data (blind analysis)**

- **Final cut was depth dependent: scattering and absorption lengths of glacial ice varies with depth**
Expect to have ~ 1 event per year with the completed IceCube detector...

<table>
<thead>
<tr>
<th>Models</th>
<th>Number of Events per 242.1 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>GZK1 [6]</td>
<td>$(155 \pm 1.4 \ {+24 \choose -40}) \times 10^{-3}$</td>
</tr>
<tr>
<td>GZK2 [22]</td>
<td>$(248 \pm 2.3 \ {+39 \choose -65}) \times 10^{-3}$</td>
</tr>
<tr>
<td>GZK3 [23]</td>
<td>$(83 \pm 0.8 \ {+13 \choose -21}) \times 10^{-3}$</td>
</tr>
<tr>
<td>Z-burst [29]</td>
<td>$(398 \pm 3.4 \ {+63 \choose -95}) \times 10^{-3}$</td>
</tr>
</tbody>
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• Upper limit: \[ E^2 \phi_{\nu_e+\nu_\mu+\nu_\tau} \approx 1.4 \times 10^{-6} \text{GeV cm}^{-2} \text{sec}^{-1} \text{sr}^{-1} \] for \[ 3 \times 10^7 \leq E \leq 10 \times 10^9 \text{GeV} \]

• Obtaining comparable sensitivity to Auger and HiRes in operation for years
Summary

- Data sample were taken in 2007 with effective livetime of 242.1 days with IC22 (~30% of the completed detector).
- Four levels of selection criteria are applied to both data sample and Monte Carlo.
- No events are observed, IceCube has a chance to see some in the future: ~ 1 event per year.
- Consistent with the expected number of background events of $6.3 \times 10^{-4}$.
- 90% C.L. differential upper limit on the neutrino flux of

$$E^2 \phi_{\nu_e+\nu_{\mu}+\nu_\tau} \simeq 1.4 \times 10^{-6} \text{GeV cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}$$

for $3 \times 10^7 \leq E \leq 10 \times 10^9 \text{GeV}$.
Thank you!