Combined Analysis of the High-Energy Cosmic Neutrino Flux at the IceCube Detector

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for the IceCube Collaboration

The 34th International Cosmic Ray Conference
30 July – 6 August, 2015
The Hague, The Netherlands

August 4, 2015
Cosmic Neutrinos at IceCube

- Cosmic neutrino flux discovered!

- Sources still unknown

- Need precise measurement of
  - Energy spectrum
  - Flavor composition

→ conclusions on sources possible
Searching for Cosmic Neutrinos with IceCube

➢ Search for upgoing tracks
  - Effective area: $\gg$ detector
  - Muon background: negligible
  - Channel: charged-current $\nu_\mu$
  - Sky coverage: northern sky

➢ Search for starting events
  - Effective area: $\lesssim$ detector
  - Muon background: yes
  - Channel: all
  - Sky coverage: full

“throughgoing track”

“contained shower”

“starting track”

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Searching for Cosmic Neutrinos with IceCube

➤ Search for partially contained showers
  ▪ **New!** → PoS(ICRC2015)1109
  ▪ Enlarge effective area at high energies

➤ Search for “double pulse” events
  ▪ **New!** → PoS(ICRC2015)1071
  ▪ Identify tau neutrinos

“partially contained shower”

interaction
tau decay

Voltage [mV]

Time [ns]
Combined Analysis

- Combine results from 8 different searches
  
<table>
<thead>
<tr>
<th>ID</th>
<th>Signatures</th>
<th>Observables</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>throughgoing tracks</td>
<td>energy, zenith</td>
<td>2009–2010</td>
</tr>
<tr>
<td>T2</td>
<td>throughgoing tracks</td>
<td>energy, zenith</td>
<td>2010–2012</td>
</tr>
<tr>
<td>S1</td>
<td>cont. showers</td>
<td>energy</td>
<td>2008–2009</td>
</tr>
<tr>
<td>S2</td>
<td>cont. showers</td>
<td>energy</td>
<td>2009–2010</td>
</tr>
<tr>
<td>H1*</td>
<td>cont. showers, starting tracks</td>
<td>energy, zenith</td>
<td>2010–2014</td>
</tr>
<tr>
<td>H2</td>
<td>cont. showers, starting tracks</td>
<td>energy, zenith, signature</td>
<td>2010–2012</td>
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<tr>
<td>DP*</td>
<td>double pulse waveform</td>
<td>signature</td>
<td>2011–2014</td>
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<tr>
<td>PS*</td>
<td>part. cont. showers</td>
<td>energy</td>
<td>2010–2012</td>
</tr>
</tbody>
</table>

- Determine energy spectrum and flavor composition in a joint fit

- Full details can be found in:
  arXiv:1507.03991
Analysis Method

> “Forward-folding” likelihood fit

- Fold models for background and signal fluxes with detector response → templates in observable space
- Compare templates with experimental data
- Vary model parameters until best agreement is reached

> Models

- **Atmospheric muons**
  CORSIKA simulation
- **Conventional atmospheric neutrinos**
  HKKMS (Honda et al. 2007)
- **Prompt atmospheric neutrinos**
  ERS (Enberg et al. 2008)
- **Astrophysical neutrinos**
  ???
**Signal Hypotheses**

- **Energy spectrum**
  - **Benchmark model:** Fermi acceleration at shock fronts
    \[ \Phi_v \propto E^{-2} \]
  - Actual spectrum depends on source class
  - **Hypothesis A:** \[ \Phi_v = \phi \times \left( \frac{E}{100 \text{ TeV}} \right)^{-\gamma} \]
  - **Hypothesis B:** \[ \Phi_v = \phi \times \left( \frac{E}{100 \text{ TeV}} \right)^{-\gamma} \times \exp\left( -\frac{E}{E_{\text{cut}}} \right) \]

*Image credit: NASA, ESA, and Zolt Levay (STScI)*
Signal Hypotheses

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- **Flavor composition**
  - Pion-decay: \[ \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0 \quad \rightarrow \quad \nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1 \]
  - Muon-damped: \[ \nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0 \quad \rightarrow \quad \nu_e : \nu_\mu : \nu_\tau \sim 0.22 : 0.39 : 0.39 \]
  - Neutron-decay: \[ \nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0 \quad \rightarrow \quad \nu_e : \nu_\mu : \nu_\tau \sim 0.56 : 0.22 : 0.22 \]
  - **Fit:** allow any composition

Image credit: NASA, ESA, and Zolt Levay (STScI)
Assume isotropic flux and $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$
Results – Energy Spectrum

Assume isotropic flux and $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

Best fit hypothesis A:

- $\Phi_V = \left(7.0^{+1.0}_{-1.0}\right) \times 10^{-18} \text{ GeV}^{-1}\text{s}^{-1}\text{sr}^{-1}\text{cm}^{-2} \times \left(\frac{E}{100\text{ TeV}}\right)^{-2.49\pm0.08}$
- $E^{-2}$ excluded at $4.6\sigma$
Assume isotropic flux and $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

**Best fit hypothesis A:**
- $\Phi_v = \left(7.0^{+1.0}_{-1.0}\right) \times 10^{-18} \text{ GeV}^{-1} \text{s}^{-1} \text{sr}^{-1} \text{cm}^{-2} \times \left(\frac{E}{100 \text{ TeV}}\right)^{-2.49 \pm 0.08}$
- $E^{-2}$ excluded at $4.6\sigma$

**Best fit hypothesis B:**
- $\Phi_v = \left(8.0^{+1.3}_{-1.2}\right) \times 10^{-18} \text{ GeV}^{-1} \text{s}^{-1} \text{sr}^{-1} \text{cm}^{-2} \times \left(\frac{E}{100 \text{ TeV}}\right)^{-2.31 \pm 0.15}$
- Preferred over hypothesis A by $1.2\sigma$

Both models describe the data well.
Results – Energy Spectrum

Profile likelihood scan
Results – Energy Spectrum

Profile likelihood scan

- $E^{-2}$, no cut-off
Results – Energy Spectrum

➤ Profile likelihood scan

- $E^{-2}$, no cut-off
  - 4.6 $\sigma$

- $E^{-2.49}$, no cut-off
Results – Energy Spectrum

> Profile likelihood scan

- $E^{-2}$, no cut-off
  - 4.6 $\sigma$
- $E^{-2.49}$, no cut-off
  - 1.2 $\sigma$
- $E^{-2.31}$, cut-off at 2.7 PeV

Graph showing contour lines and shaded regions with labels for significance levels (90%, 95%, 99%) and a color bar indicating $\Delta \ln L$. The graph is labeled as IceCube Preliminary.
Results – Energy Spectrum

> All-flavor neutrino energy spectrum

![Energy Spectrum Graph](image-url)

- Power law ($\nu_e + \nu_\mu + \nu_\tau$)
- Power law + cutoff ($\nu_e + \nu_\mu + \nu_\tau$)
- Differential ($\nu_e + \nu_\mu + \nu_\tau$)

IceCube Preliminary
Results – Flavor Composition

\[ \nu_e : \nu_\mu : \nu_\tau \text{ at source} \]
- 0:1:0
- 1:2:0
- 1:0:0

IceCube Preliminary

\[ -2\Delta \ln L \]
Results – Flavor Composition

IceCube Preliminary

$\nu_e : \nu_\mu : \nu_\tau$ at source
- 0:1:0
- 1:2:0
- 1:0:0

Best fit
Results – Flavor Composition

IceCube Preliminary

$\nu_e : \nu_\mu : \nu_\tau$ at source
- 0:1:0
- 1:2:0
- 1:0:0

- muon-damped (0:1:0)
- Pion-decay (1:2:0)
- compatible

$-2\Delta\ln L$

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**Results – Flavor Composition**

Neutron-decay (1:0:0) → excluded at 3.7σ

Pion-decay (1:2:0) → compatible

Muon-damped (0:1:0)
Projection of Sensitivities

➢ Use most recent event samples
  ▪ T2 → throughgoing tracks
  ▪ H2 → contained showers + starting tracks
  ▪ PS → partially contained showers
  ▪ DP → double pulse waveform events

➢ Scale simulation data to mimic the collection of additional data
  ▪ Use current best-fit fluxes as input

➢ Perform analysis with the “Asimov data set” (Cowan et al. 2011)
  ▪ One “representative” data set (based on input flux)
  ▪ → obtain median sensitivity
Hypothesis A true

- $E^{-2.49}$, no cut-off
- $E_{\text{cut}} > 7.7 \text{ PeV (2 \sigma C.L.)}$ for 10 years of data
**Sensitivity – Energy Spectrum**

> Hypothesis A true
> - \( E^{-2.49} \), no cut-off
> - \( \rightarrow E_{\text{cut}} > 7.7 \text{ PeV} \) (2\( \sigma \) C.L.)
> - for 10 years of data

> Hypothesis B true
> - \( E^{-2.31} \), cut-off at 2.7 PeV
> - \( \rightarrow \) presence of cut-off can be established at 3\( \sigma \) with 10 years of data
Summary

- Combined analysis of cosmic neutrino flux
  - Take into account all signatures
  - Sensitive from ~10 TeV – multi-PeV

- Most precise characterization of the flux obtained so far
  - Energy spectrum
  - Flavor composition

- Projection of sensitivities