Characterization of the Astrophysical Diffuse Neutrino Flux

Austin Schneider
For The IceCube Collaboration

ICRC 2019
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

IceCube detector
86 strings of DOMs, set 125 meters apart

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

Detector Construction
- 7 seasons of construction, 2004-2011
- 28,000 person-days to complete construction, or 77 years of continuous work
- 2.1 million kilograms of cargo was shipped, 0.5 million of which was the drill
- 48 hours to drill and 11 hours to deploy sensors per hole
- 4.7 megawatts of drill thermal power with 760 liters of water per minute delivered at 88 °C and 7,600 kilopascals

Detector Design
- 1 gigaton of instrumented ice
- 5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
- 1 square kilometer surface array, IceTop, with 324 DOMs
- 2 nanosecond time resolution
- IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily
Event Morphologies

Track
Muon Neutrino CC

Cascade
Electron Neutrino CC
Tau Neutrino CC
Neutrino NC

Double Cascade
High Energy Tau Neutrino CC

Factor of ~2 energy resolution
0.3° angular resolution at 100 TeV

15% deposited energy resolution
10° angular resolution above 100 TeV

Angular and energy resolution comparable to cascades
First candidate observed!
See talk: J. Stachurska NU8f for details!
Astrophysical Neutrinos - Two Methods

1. Upgoing muon neutrino tracks

- astronomy: angular resolution superior (<0.3°)

2. Isolated neutrinos interacting inside the detector (starting events)

- total energy measurement
- all flavors, all sky
Veto region rejects atmospheric muons and neutrinos

High neutrino signal purity at high energy
More on the veto

- Muons accompany neutrinos from CR air showers
- High-energy muons reach the detector
- Veto suppresses atmospheric neutrino background
- Allows us to look at downgoing neutrino events!
Modelling the Data

Three Neutrino Flux Components

1. Astrophysical $\nu$
   a. Mostly flat
   b. Suppression at Earth's core

2. Atmospheric $\nu$ from K/π (Conventional $\nu_e \nu_\mu$)
   a. Neutrino production peaked at horizon

3. Atmospheric $\nu$ from charmed hadrons (Prompt $\nu_e \nu_\mu$)
   a. Mostly flat
   b. Suppression at Earth's core
Three Neutrino Flux Components

1. Astrophysical $\nu$
   a. Mostly flat
   b. Suppression at Earth’s core

2. Atmospheric $\nu$ from $K/\pi$
   (Conventional $\nu_e \nu_\mu$)
   a. Neutrino production peaked at horizon
   b. Down-going suppressed by veto

3. Atmospheric $\nu$ from charmed hadrons
   (Prompt $\nu_e \nu_\mu$)
   a. Mostly flat
   b. Suppression at Earth’s core
   c. Downgoing suppressed by veto

--

Schönert, Gaisser, Resconi, Schulz

Gaisser, Jero, Karle, van Santen

Argüelles, Palomares-Ruiz, AS, Wille, Yuan
JCAP 1807 (2018) no.07, 047
Data Selection With The Veto
High-Energy Starting Event Selection

Atmospheric events above 250PE in the veto region

Two distinct populations!
Backgrounds
Astrophysical candidates
Reconstruct: deposited energy, direction, morphology

Ternary morphology ID

Above 60 TeV: 60 events

All energies: 102 events
Diffuse Astrophysical Neutrino Flux

\( \frac{d\Phi_{6\nu}}{dE} = \Phi_{\text{astro}} \left( \frac{E_{\nu}}{100\text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18} \text{ [GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}] \)

Best-fit spectral index 2.89 ±0.2

Prompt best fit ⇒ zero

Prompt 90% upper limit 9.65*BERSS

Fit performed for events above 60TeV

Compatible with results from 6 year analysis

IceCube Preliminary

|------|--------|-------------|-------------|

Events per 2635 days

Deposited Energy [GeV]
Diffuse Astrophysical Neutrino Flux

\[
\frac{d\Phi_{6\nu}}{dE} = \Phi_{\text{astro}} \left( \frac{E_{\nu}}{100\text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18} \text{[GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]}
\]

Best-fit spectral index 2.89 ±0.2
Prompt best fit ⇒ zero
Prompt 90% upper limit 9.65*BERSS
Fit performed for events above 60TeV
Compatible with results from 6 year analysis

IceCube Preliminary
Comparison with Other Samples

<table>
<thead>
<tr>
<th>Name</th>
<th>Approx. Neutrino Energy</th>
<th>Direction</th>
<th>Dominant Flavor</th>
<th>Unbroken Spectral Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESE</td>
<td>50 TeV - 5 PeV</td>
<td>All-sky</td>
<td>$e, \mu, \tau$</td>
<td>2.89</td>
</tr>
<tr>
<td>Cascades</td>
<td>5 TeV - 5 PeV</td>
<td>All-sky</td>
<td>$e, \tau$</td>
<td>2.48</td>
</tr>
<tr>
<td>NuMu</td>
<td>50 TeV - 10 PeV</td>
<td>Northern</td>
<td>$\mu$</td>
<td>2.28</td>
</tr>
</tbody>
</table>

**Table:**

<table>
<thead>
<tr>
<th>Name</th>
<th>Approx. Neutrino Energy</th>
<th>Direction</th>
<th>Dominant Flavor</th>
<th>Unbroken Spectral Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESE</td>
<td>50 TeV - 5 PeV</td>
<td>All-sky</td>
<td>$e, \mu, \tau$</td>
<td>2.89</td>
</tr>
<tr>
<td>Cascades</td>
<td>5 TeV - 5 PeV</td>
<td>All-sky</td>
<td>$e, \tau$</td>
<td>2.48</td>
</tr>
<tr>
<td>NuMu</td>
<td>50 TeV - 10 PeV</td>
<td>Northern</td>
<td>$\mu$</td>
<td>2.28</td>
</tr>
</tbody>
</table>
Tests of Models

- Many possibilities for high energy astrophysical neutrino production
- Test just a few: AGN, low-luminosity AGN BLLacs, choked jets in core-collapse SN, star burst galaxies, low-luminosity BLLacs, and GRBs
- Compare to single power law as a baseline

- **Test Model only (no free parameters)**
- **Test Model + SPL (only SPL parameters)**
- Mostly SPL preferred
- Data in this sample is compatible with an unbroken single power law its sensitive energy range

\[
\mathcal{L}(\theta, \bar{\eta}) = \prod_{i=1}^{n} \mathcal{L}_{\text{test}}(\mu_i(\theta, \bar{\eta}), \sigma_i(\theta, \bar{\eta}); d_i) \prod_{i=1}^{m} \mathcal{L}_s(\eta_s) \tag{1}
\]

\[
B_{10} = \frac{\int d\bar{\eta} \mathcal{L}(\bar{\eta})}{\int d\bar{\eta} \mathcal{L}_{\text{test}}(\bar{\eta})} \tag{2}
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>Model only Bayes factor</th>
<th>Model + SPL Bayes factor</th>
<th>Most-likely SPL $\gamma_{\text{astro}}$</th>
<th>Most-likely SPL $\Phi_{\text{astro}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stecker [26]</td>
<td>$4.32 \times 10^{-13}$</td>
<td>$1.45 \times 10^{-10}$</td>
<td>$3.97^{+0.54}_{-0.47}$</td>
<td>$4.08^{+1.8}_{-1.13}$</td>
</tr>
<tr>
<td>Fang et al. [27]</td>
<td>0.281</td>
<td>0.248</td>
<td>$3.83^{+0.81}_{-0.5}$</td>
<td>$2.56^{+1.28}_{-1.44}$</td>
</tr>
<tr>
<td>Kimura et al. (B1) [28]</td>
<td>$4.84 \times 10^{-6}$</td>
<td>$8.38 \times 10^{-7}$</td>
<td>$4.5^{+0.4}_{-0.67}$</td>
<td>$0.98^{+1.04}_{-0.98}$</td>
</tr>
<tr>
<td>Kimura et al. (B4) [28]</td>
<td>$3.44 \times 10^{-4}$</td>
<td>0.666</td>
<td>$2.43^{+0.31}_{-0.26}$</td>
<td>$1.39^{+1.18}_{-0.77}$</td>
</tr>
<tr>
<td>Kimura et al. (two component) [28]</td>
<td>$1.73 \times 10^{-4}$</td>
<td>$6.12 \times 10^{-6}$</td>
<td>$4.15^{+0.84}_{-0.73}$</td>
<td>$0.0^{+0.06}_{-0}$</td>
</tr>
<tr>
<td>Padovani et al. [29]</td>
<td>$6.20 \times 10^{-11}$</td>
<td>$3.32 \times 10^{-7}$</td>
<td>$3.59^{+0.59}_{-0.34}$</td>
<td>$4.97^{+1.68}_{-1.46}$</td>
</tr>
<tr>
<td>Senno et al. [30]</td>
<td>0.256</td>
<td>3.52</td>
<td>$3.67^{+0.57}_{-0.62}$</td>
<td>$3.36^{+1.56}_{-1.54}$</td>
</tr>
<tr>
<td>Bartos et al. [31]</td>
<td>$1.15 \times 10^{-14}$</td>
<td>$2.81 \times 10^{-16}$</td>
<td>$4.25^{+0.75}_{-0.83}$</td>
<td>$0.0^{+0.49}_{-0}$</td>
</tr>
<tr>
<td>Tavecchio et al. [32]</td>
<td>0.0730</td>
<td>1.04</td>
<td>$3.88^{+0.65}_{-0.49}$</td>
<td>$3.7^{+1.39}_{-1.48}$</td>
</tr>
<tr>
<td>Biehl et al. [33]</td>
<td>$8.66 \times 10^{-7}$</td>
<td>0.362</td>
<td>$3.35^{+0.4}_{-0.38}$</td>
<td>$5.09^{+2.07}_{-1.03}$</td>
</tr>
</tbody>
</table>
Summary

- Veto-based method produces a high-purity astrophysical neutrino sample at high energies
- Sample is sensitive to all neutrino flavors in the full sky
- Zenith distribution $\Rightarrow$ background only hypothesis excluded
- Differing observations from different energy ranges and flavors may indicate additional features
- Tests of ad-hoc models show no strong preference beyond the single power law using this sample

https://pos.sissa.it/358/1004/pdf
Bonus Slides
Tests of Models

- Many possibilities for high energy astrophysical neutrino production
- Test just a few: AGN, low-luminosity AGN BLLacs, choked jets in core-collapse SN, star burst galaxies, low-luminosity BLLacs, and GRBs
- Compare to single power law as a baseline
- We fit the normalization of many flux segments
- Errors show 68.3% credible regions
- Violins show the shape of the pdf
- Line shows approximately an $E^{-2.9}$ spectrum
- Unbroken power law works well for this data sample
Getting More Generic - $E^{-2}$ Segments

- We fit the normalization of many flux segments
- Errors show approximate 68.3% confidence regions
- Line shows approximately an $E^{-2.9}$ spectrum
- Unbroken power law works well for this data sample
Want to disentangle the flux properties and apparent discrepancies

2 ways to improve measurements:
1. Combine existing samples
2. Move to lower energies

More statistics ⇒ systematically dominated

Systematically dominated ⇒ challenging analysis

Working to incorporate all known systematic uncertainties
- Atmospheric model
- Unconstrained hadronic interactions
- Cosmic ray flux/composition
- Neutrino cross section
- Earth model
- Charged lepton cross sections