Characterizing Cosmic Neutrino Sources

A Measurement of the Energy Spectrum and Flavor Composition of the Cosmic Neutrino Flux Observed with the IceCube Neutrino Observatory

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Outline

PART I
What are cosmic neutrinos and why are they interesting?

PART II
How are neutrinos observed with the IceCube detector?

PART III
What are the properties of the cosmic neutrino flux detected with IceCube?
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Motivation: The Cosmic-Ray Energy Spectrum

→ Cosmic rays with extremely high energies observed
→ Sources + acceleration mechanism unknown
Neutrinos and Cosmic Rays
Neutrinos and Cosmic Rays

→ Cosmic neutrinos can reveal cosmic-ray acceleration sites!
Cosmic neutrinos can reveal cosmic-ray acceleration sites!
Expectations for the Energy Spectrum

Strongly depends on source properties!

General arguments:

- **Fermi shock acceleration**
  \[ \rightarrow \text{cosmic-ray spectrum } \sim E^{-2} \]

- **pp- interactions, no energy losses, ...**
  \[ \rightarrow \text{neutrino spectrum } \sim E^{-2} \]

- **Expect distortions from:**
  \[ \rightarrow \text{py-interactions} \]
  \[ \rightarrow \text{muon energy losses} \]
  \[ \rightarrow \text{muon acceleration} \]
  \[ \rightarrow \text{...} \]

**Benchmark:** \[ \Phi_\nu \sim E^{-2} \]
Expectations for the Flavor Composition

Pion-decay sources

\[ \pi^\pm \rightarrow \mu \rightarrow e, \nu_e, \nu_\mu, \nu_\tau \]

\[ \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0 \]

\[ \rightarrow \text{“standard scenario”} \]

Muon-damped sources

\[ \pi^\pm \rightarrow \mu \rightarrow e, \nu_e, \nu_\mu \]

\[ \nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0 \]

\[ \rightarrow \text{strong magnetic fields} \]

Neutron-beam sources

\[ n \rightarrow p, e, \nu_e \]

\[ \nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0 \]

\[ \rightarrow \text{very strong magnetic fields} \]

\[ \rightarrow \text{cosmic rays are heavy nuclei} \]
Expectations for the Flavor Composition

Flavor composition modified by long-baseline neutrino oscillations

\[ \nu_e : \nu_\mu : \nu_\tau \text{ at source} \\
\begin{align*}
0 : 1 : 0 & \quad \boxed{\text{Orange}} \\
1 : 2 : 0 & \quad \boxed{\text{Purple}} \\
1 : 0 : 0 & \quad \boxed{\text{Green}} \\
\end{align*}

\[ \nu_e : \nu_\mu : \nu_\tau \text{ at Earth} \\
\begin{align*}
0.19 : 0.43 : 0.38 & \quad \boxed{\text{Orange}} \\
0.31 : 0.35 : 0.34 & \quad \boxed{\text{Purple}} \\
0.55 : 0.19 : 0.26 & \quad \boxed{\text{Green}} \\
\end{align*}
Flavor composition modified by long-baseline neutrino oscillations

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

\[ \nu_e : \nu_\mu : \nu_\tau \text{ at Earth} \]
- 0.19 : 0.43 : 0.38
- 0.31 : 0.35 : 0.34
- 0.55 : 0.19 : 0.26

**Standard scenario:** \( \nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1 \text{ at Earth} \)
Source Candidates

Within the Milky Way
- Supernova remnants
- Pulsar wind nebulae
- ...

“Extragalactic”
- Active galactic nuclei
- Gamma-ray bursts
- Starburst galaxies
- Galaxy clusters
- ...
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The IceCube Neutrino Observatory

Detection principle: Observe Cherenkov radiation from secondary particles produced in neutrino interactions
Neutrino Event Signatures

Throughgoing track
$\rightarrow \nu_\mu$ charged-current interaction outside instrumented volume

Starting track
$\rightarrow \nu_\mu$ charged-current interaction inside instrumented volume

Shower
$\rightarrow$ Any other interaction inside instrumented volume
Neutrino Event Signatures

Throughgoing track
→ $\nu_\mu$ charged-current interaction outside instrumented volume

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Shower
→ Any other interaction inside instrumented volume
Neutrino Event Signatures

**Throughgoing track**
→ \( \nu_\mu \) charged-current interaction outside instrumented volume

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**Neutrino Event Signatures**

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→ Any other interaction inside instrumented volume

![Graphs showing neutrino event signatures with throughgoing track, starting track, and shower interactions.](image)
Neutrino Event Signatures

Throughgoing track
→ $\nu_\mu$ charged-current interaction outside instrumented volume

Starting track
→ $\nu_\mu$ charged-current interaction inside instrumented volume

Shower
→ Any other interaction inside instrumented volume

Good directional reconstruction

Good energy reconstruction
Atmospheric Backgrounds and Cosmic Signal
Atmospheric Backgrounds and Cosmic Signal
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**Atmospheric muons**
- ~ 250 million / day
- Track-like, from above
**Atmospheric Backgrounds and Cosmic Signal**

**Atmospheric muons**
- ~ 250 million / day
- Track-like, from above

**Conventional atmospheric neutrinos**
- ~ few 100 / day
- Low-energy
Atmospheric Backgrounds and Cosmic Signal

**Atmospheric muons**
- ~ 250 million / day
- Track-like, from above

**Conventional atmospheric neutrinos**
- ~ few 100 / day
- Low-energy

**Prompt atmospheric neutrinos**
- ~ few / day
- Higher-energy

\[ \mu \]

\[ D^\pm, D_s^\pm, D^0, \Lambda_c^\pm \]
Atmospheric Backgrounds and Cosmic Signal

**Atmospheric muons**
- ~ 250 million / day
- Track-like, from above

**Conventional atmospheric neutrinos**
- ~ few 100 / day
- Low-energy

**Prompt atmospheric neutrinos**
- ~ few / day
- Higher-energy

**Cosmic neutrinos**
- ??? / day
- (Presumably) very high-energy
Event Selection Techniques

1) Select upgoing / horizontal track events

- Active volume $>>$ detector
- Negligible muon background

- $\nu_\mu$ charged-current interactions
- Northern Hemisphere
- Cannot suppress atmos. neutrinos

2) Select starting events

- Active volume $\leq$ detector
- Residual muon background

- All neutrino interactions
- Full sky
- Downgoing atmos. neutrinos suppressed
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The Cosmic Neutrino Flux Observed with IceCube

Discovery in 2013
→ Energy range: $10^{13} - 10^{15}$ eV (10 TeV – 1 PeV)

Sources yet unknown
→ arrival directions consistent with isotropy

Measurements of flux properties
→ draw conclusions on source properties

Previously:
→ measurements of specific properties, based on specific event selections
Unique Feature of the Analysis

Comprehensive characterization through a combined analysis of data from six different event selections

Key challenges:

- Compile and combine the data
- Develop techniques to treat systematic uncertainties consistently
- Implement, test and apply maximum likelihood fit
Analysis Technique

Experimental data

Observable distribution

Model

Neutrino energy

Model + detector simulation

Deposited energy

Events

Maximum likelihood analysis
Background Models

Atmospheric muons

→ Air shower simulations with CORSIKA

→ Parametrizations at high energies

Atmospheric neutrinos

→ Calculations from literature

→ Apply detector-related corrections
Background Models

**Atmospheric muons**
- Air shower simulations with CORSIKA
- Parametrizations at high energies

**Atmospheric neutrinos**
- Calculations from literature
- Apply detector-related corrections

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Absolute flux levels $\rightarrow$ free fit parameters!
Results – Energy Spectrum

"Power Law Model":

\[
\Phi(E) = \phi \times \left( \frac{E}{100 \text{ TeV}} \right)^{-\gamma}
\]

\[
(\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1)
\]

\[
\gamma = 2.50 \pm 0.09
\]

→ benchmark \( \gamma = 2 \) rejected with 3.8 \( \sigma \)
Results – Energy Spectrum

"Power Law Model"
Results – Energy Spectrum

“Power Law Model”

Example best-fit observable distribution:

Goodness-of-fit p-value:

37.6%

→ no indication for significant discrepancies
“Differential Model” → “Unfold” flux in 9 separate energy bins

→ steep spectrum caused by excess around 30 TeV and lack of events above 2 PeV
“Flavor Model” → measure unconstrained flavor composition

→ can reject neutron-decay scenario (1 : 0 : 0) with 3.6σ
Impact of the Results

Energy Spectrum:
Combine with measurement of diffuse gamma-ray background
→ strong constraints on production mechanism

Flavor composition:
Test exotic models, e.g. neutrino decay
Common scenario: only $\nu_1$ stable
→ ruled out for NH at 2$\sigma$

New physics
$\theta_{ij}, \delta_{\text{CP}}$: BF, $1\sigma, 3\sigma$
NH

Murase et al., PRL 116, 071101 (2016)
Bustamante et al., PRL 115, 161302 (2015)
Conclusion

Presented first comprehensive characterization of cosmic neutrino flux:

Energy spectrum

Flavor composition

Want to learn more?

→ **Publication:** Aartsen et al., Astrophysical Journal **809**, 98 (2015)

→ **Thesis:** contact me! [lars.mohrmann@fau.de]