Neutrinos from heaven and hell in IceCube

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Note: All results shown are pre-Neutrino18. New results high-energy results were shown at the conference. See:
https://zenodo.org/record/1286852#.WzPG96dKhzE
https://zenodo.org/record/1286919#.WzPHBadKhzE
Neutrinos from Hell

TeV – PeV energy
The promise of HE neutrinos

A hundred year puzzle: the cosmic ray spectrum

• Where do they come from?
The promise of HE neutrinos

A hundred year puzzle: the cosmic ray spectrum

• Where do they come from?
  • Cosmic accelerators? Exotics?

• ν's most likely involved

\[ p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \]

\[ \rightarrow E \sim [\text{TeV, PeV}] \]

http://www.physics.utah.edu/~whanlon/spectrum.html
The era of neutrino astronomy has begun.
IceCube: An instrument for neutrino astronomy

- Ice Cherenkov neutrino detector
- 5,160 DOMs
- 86 strings
- Spacing: 17m in z, 125 in x-y
- 1 km³ volume
- 1.5 – 2.5 km under ice
- At the geographic South Pole
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Detector calibration

- LED flashers on each DOM
- In-ice calibration laser
- Minimum ionizing muons
- Moon shadow
- In-situ camera

Moon shadow in cosmic rays in IC59
Neutrino detection in IceCube
Neutrino event topologies

\[ \nu_\mu + N \rightarrow \mu + X \]

track (data)
factor of \( \approx 2 \) energy resolution
Ang res. \( < 1^\circ \) at high energies

\[ \nu_e + N \rightarrow e + X \]

\[ \nu_\tau + N \rightarrow \nu_\tau + X \]

cascade (data)
\( \approx \pm 15\% \) deposited energy resolution
\( \approx 10^\circ \) angular resolution (\( E \geq 100 \text{ TeV} \))

\[ \nu_\tau + N \rightarrow \tau + X \]

Two cascades (\( E > 10 \text{ PeV} \))
Not observed yet: \( \tau \) decay length is 50 m/PeV
Neutrinos in IceCube

Source of cosmic rays

Cosmic ray

Astrophysical neutrino

*Not to scale*
Neutrinos in IceCube

Source of cosmic rays

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Atmospheric neutrinos

*Not to scale
Neutrinos in IceCube

Source of cosmic rays

Cosmic ray

Astrophysical neutrino

Atmospheric neutrinos

Atmosphere

*Not to scale
Neutrinos in IceCube

Astrophysical neutrino searches use:
• Direction, energy, time
• Event topology
• Diffuse, point-source hypotheses

*Not to scale
Isolating neutrinos

• Use the Earth as a shield
  • Only neutrinos can come from “below”
  • Look down, sacrifice half of the sky

• Use the detector to tag backgrounds
  • Only neutrinos can “start” inside
  • Sacrifice about half of your detector
Diffuse, starting events

- Exploit different E spectra $\rightarrow$ focus on HE
- Use the detector as veto
  - Accompanying muons
Starting events: Most recent results

- Using 6 years of data
- \(80(\pm 2)\) events observed
- Estimated background:
  - \(15.6^{+11.4}_{-3.9}\) atm. neutrinos
  - \(25.2 \pm 7.3\) atm. muons
- Two of them are an obvious (but expected) background:
- Coincident muons from two CR air showers
High energy events

deciliation: -13.2°
deposited energy: 82TeV

deciliation: -0.4°
deposited energy: 71TeV

deciliation: 40.3°
deposited energy: 253TeV
Starting events: Energy spectrum

• Compatible with benchmark single power-law model.
• Things might be more complicated, but this is not the analysis to decide that.
• Best fit spectral index
  \[ (E^{-\gamma}): \gamma = -2.92^{+0.33}_{-0.29} \]
• \[ E^2 \phi = 2.46 \pm 0.8 \times 10^{-8} \times (E / 100\text{TeV})^{-0.92} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]
Starting events: Zenith distribution

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- Best fit spectral index 
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Starting events: clustering (or the lack-of)
Through-going muons

- up-going (i.e. not a CR muon)
- deposited energy: 2.6±0.3 PeV
- neutrino energy: 8.7 PeV (median)
- date: June 11, 2014
- direction: 11.48° dec / 110.34° RA
Through-going muons

- Selected horizontal and up-going muon tracks
- Sensitive to astrophysical neutrinos above $\sim 120$ TeV
- Power-law index: $2.19 \pm 0.10$ prompt component fits to zero
Through-going muons: lack of clustering
Alerts & follow-ups

- PTF (optical)
- Gamma ray telescopes (Veritas, HESS, MAGIC)
- SWIFT (X-ray)

“The North”
Astrophysical flux flavor composition

- Multiple predictions for astrophysical flavor $(\nu_e:\nu_\mu:\nu_\tau)$
  - Standard pion+muon decay (1:2:0)
  - Muon damped (0:1:0)
  - Neutron decay (1:0:0)

- Detection flavor close to (1:1:1)
Astrophysical flux flavor composition

- Simultaneous spectrum fit
  \( \nu_e : \nu_\mu : \nu_\tau \)
  - Standard pion+muon decay (1:2:0)
  - Muon damped (0:1:0)
  - Neutron decay (1:0:0)
    - Only one significantly excluded (3.7\( \sigma \))
- No tau-neutrino signals yet
  - Hard to identify
  - Compatible with statistics

Summary from hell

- Well established diffuse astrophysical neutrino flux observed
- Neutrinos found up to a few PeV
- Sources not yet identified
- Multi-messenger program in place looking for coincidences
- Identification of neutrino flavor ongoing – no HE tau neutrino yet

All studies are limited by statistics
we need more events
Neutrinos from heaven

10-100 GeV
Atmospheric neutrinos

- Some people’s background is another people’s signal
Atmospheric neutrinos

- Free beam of neutrinos. Wide E range, varying travel distance.
Neutrino oscillations in 2 minutes or less

**Neutrino production**
- definite flavor (associated $l^{±/-}$)
- superposition of mass eigenstates

**Propagation**
- as massive states $\rightarrow$ phase $\exp(-ipx)$
- traveling close together, maintain coherence

**Detection (interaction)**
- coherent sum of mass states
- associated $l^{±/-}$ determines flavor
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\[
\nu_\alpha = \sum_{k=1..3} U_{\alpha k}^* \nu_k
\]

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
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**Propagation**
- as massive states \( \rightarrow \) phase \( \exp(-i px) \)
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\]
Caveat: influence of matter

- Scattering processes in ordinary matter

- In constant electron density

\[ \Delta m^2_M = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2}, \]

\[ A = \pm 2\sqrt{2} E G_F n_e. \]

\[ \tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}}. \]
Standard oscillations in matter

Survival probabilities for atmospheric neutrinos (no approximations)
Standard oscillations in matter

Survival probabilities for atmospheric neutrinos (no approximations)
And sterile neutrinos? They also fit

• Possibility: Additional neutrino state that doesn’t couple to W/Z
  • New state mixes with known ones
  • Ex: 3+1 → +3 mixing angles +1 phase

\[
\begin{align*}
\begin{bmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s
\end{bmatrix} &=
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{bmatrix}
\begin{bmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{bmatrix}
\end{align*}
\]

\[
\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}}.
\]
Sterile neutrino flux modifications

- For a higher mass difference → higher $E$

- Additional sterile mixing + matter enhancements changes oscillation amplitudes also at low energies

\[ P_{\nu_\alpha \rightarrow \nu_\beta} (L, E) = \sin^2 (2\theta) \sin^2 \left( \frac{\Delta m^2}{4E} L \right) \]
Probing oscillations

With atm. nu:

- large L&E regions of phase space
- 2 ν, anti-ν flavors in “beam”
- on/off signal regions
- E > τ threshold
Added bonus: neutrino-nucleon $\sigma$

- High energy atmospherics: deep inelastic scattering regime
Added bonus: neutrino-nucleon xs

• High energy atmospherics: deep inelastic scattering regime
IceCube DeepCore

- 8 + 7 strings (DC + IC)
- About 500 DOMs in fid. vol.
- Spacing: 7m in z, 40-70m in x-y
- Neutrino energy threshold: 10 GeV
DeepCore events

- Interaction:
  - NuEBar -> EPlus + Neutron + Pi0
- Primary
  - Type: NuEBar
  - Energy: 1.11e+01 GeV
- Cascade
  - Type: EPlus
  - Energy: 1.01e+01 GeV
DeepCore events

Interaction:
  NuEBar -> EPlus + Pi0 + PPlus + PiMinus + Pi0
Primary
  Type: NuEBar
  Energy: 6.85e+01 GeV
Cascade
  Type: EPlus
  Energy: 5.91e+01 GeV
DeepCore events

Interaction:
- \( \text{NuMuBar} \rightarrow \text{MuPlus} + \text{EPlus} + \text{Neutron} \)

Primary
- Type: NuMuBar
  - Energy: \(1.29\times10^{1}\) GeV

Muon
- Type: MuPlus
  - Energy: \(1.25\times10^{1}\) GeV

Cascade
- Type: Neutron
  - Energy: \(2.82\times10^{0}\) GeV
DeepCore events

Interaction:

Primary
- Type : NuMuBar
  - Energy: 7.34e+01 GeV

Muon
- Type : MuPlus
  - Energy: 5.22e+01 GeV

Cascade
- Type : PiPlus
  - Energy: 9.93e+00 GeV
Analysis strategy

• Background
  • Aggressive vetoing to reject muons
  • Select starting events only

• Reconstruction
  • 8D likelihood w/track+cascade
  • Using detailed ice description

• Particle identification
  • Ratio of track+cascade/cascade only fit

• Parameterize systematic effects
  • Fit together with physics parameters
Reconstruction resolutions
Reconstruction resolutions

![Graphs showing reconstruction resolutions for different neutrino interactions (CC, NC) at various energies (GeV)].
Results: NuMu disappearance

- Analysis in L vs E space
- 48k events in 3 years
- $\chi^2 = 117.4/119$ dof
- Data driven background

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Results: NuTau appearance

- Let tau neutrino component float
- Slightly below expected value (1.0)
- Not significant yet
Results: Sterile neutrinos - LE

- How would a sterile neutrino affect the sample?

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\begin{bmatrix}
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\nu_\tau \\
\nu_s
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\nu_4
\end{bmatrix}
\]

Phys. Rev. D 95, 112002 (2017)
Results: Sterile neutrinos - HE

• How would a sterile neutrino affect the **high energy** sample?

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
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\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
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\nu_4
\end{pmatrix}
\]

Summary from heaven

• Atmospheric neutrinos used for particle physics studies
• Events are hard to reconstruct, but we have thousands per year
• Measurements of standard oscillations improving rapidly
• Tau neutrinos from oscillations beginning to appear
• Exotic BSM ongoing: steriles, non-standard interaction, decoherence

Studies start to be limited by systematics
we need more calibration sources
Looking into the future
The IceCube Upgrade
The IceCube Upgrade

• More sensors in same volume
  • Lower DeepCore E threshold
  • Better oscillation physics

• New calibration sources
  • Controlled light emission
  • Improved ice description
  • Better pointing at HE by factor 2
  • Re-analysis of current HE data
A step further: IceCube Gen-2
A step further: IceCube Gen-2

Main detector
• +120 strings
• 240m inter-string distance
• 80 Oms per string
• 8 km$^3$ volume

Extensions
• Surface array (CR and veto)
• Radio array (EHE neutrinos)
Final words

IceCube: a neutrino observatory from GeV to PeV energies
  • Astrophysical neutrinos
  • Neutrino oscillations
  • Dark matter
  • Cosmic ray physics
  • ...

More data and better calibration $\rightarrow$ constantly improving results

Upgrades proposed: maximize the science output at all energies