Neutrinos from heaven and hell in IceCube
Latest results on astrophysical neutrinos and neutrino oscillations

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DESY

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Neutrinos from Hell
TeV - PeV

Image credit: Aurore Simonnet, Sonoma State University
The promise of HE neutrinos

A hundred year puzzle: the cosmic ray spectrum

Where do these particles come from?

Cosmic accelerators? Exotic scenarios?

ν's most likely involved → E ~ [TeV, PeV]

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

when found ...

http://www.physics.utah.edu/~whanlon/spectrum.html
http://starfishquay.blogspot.de/2013/11/the-era-of-neutrino-astronomy-has-begun.html
IceCube
An instrument for neutrino astronomy

- Ice Cherenkov neutrino detector
- 5,160 DOMs
- 86 strings
- 1 km³ volume
- 1.5 – 2.5 km under ice
- Spacing: 17 m in z, 125 in x-y
IceCube
An instrument for neutrino astronomy

*Not to scale

Atmosphere

Source of cosmic rays

Astrophysical neutrino

Cosmic ray

Image: http://globe-views.com/dreams/earth.html
IceCube
An instrument for neutrino astronomy

*Not to scale

Image: http://globe-views.com/dreams/earth.html
IceCube
An instrument for neutrino astronomy
where the signal is hidden in a very large background

» Searches use
  » Direction, energy, time
  » Event topology
  » Diffuse, point-source approaches

*Not to scale

Image: http://globe-views.com/dreams/earth.html
Diffuse, starting events

» Exploit different E spectra → focus on high energies

» Use the detector for vetoing → starting events

Fluxes of detectable down-going μ & ν

Example of different fiducial volumes used
Diffuse, starting events
Diffuse, starting events

decline: $-0.4^\circ$
 deposited energy: $71\text{TeV}$

decline: $40.3^\circ$
 deposited energy: $253\text{TeV}$
Diffuse, starting events

» HE search w/ 3 years of data
» 37 neutrino candidates, mostly cascades, 5.7σ over background
» Search extended to lower energies (2 years)
» 283 cascades + 105 tracks, large overlap with HE analysis


Phys. Rev. D 91, 022001
Diffuse, through-going muons

- Earth-crossing muons → must come from neutrinos
- Good angular resolution, lower limit in energy

View of four HE neutrino-induced muons
Joint analysis of diffuse searches

- Including all diffuse searches in IceCube (also from incomplete detector)
- Best fit by an unbroken power law spectrum
  - Flux $\Phi$ (at 100 TeV) = $(6.7^{+1.1/-1.2}) \cdot 10^{-18}$ (GeV s sr cm$^{-2}$)$^{-1}$
  - Spectral index $\gamma = -2.50 \pm 0.09$

Fit flavor ratio at Earth is 1:1:0 ($\nu_e$:$\nu_\mu$:$\nu_\tau$) compatible with expected 1:1:1
What are the sources of HE ν's?

» No significant clustering of events in HE sample

» Cascades seem to cluster → but they have poor resolution

» Only few tracks, not clustering
Origin of diffuse HE neutrino flux

» Searches for point-like sources compatible with background

  » Full sky
  » Catalogue-based
  » Stacking of sources
  » Transients

» Limits on Fermi Blazars contribution to the diffuse flux
  » GRBs largely excluded
    Nature 484 (2012), 351-354

... we need more data

\[ \frac{E^2 d\Phi}{dE_{\nu}} \quad \text{[GeV}^2\text{s}^{-1}\text{cm}^{-2}\text{sr}^{-1}] \]

- Limit
- Diffuse Flux **

\[ \text{Neutrino Energy [GeV]} \]

- equal weighting *
- \(\gamma\)-Lumi. weighting

IceCube Preliminary

17%
8%

\(\text{IceCube Preliminary} \quad \text{arXiv:1502.03104} \)

*) Band denotes central 90 % of outcomes of different realizations from the \(\gamma\)-Luminosity Function. This limit also holds for all (quasi-)isotropic subpopulations, independent of their gamma emission.

**) 1-flavor diffuse fit result [arxiv:1410.1749]
Neutrinos from Heaven
10 - 100 GeV
Atmospheric neutrino oscillations

Neutrinos change flavor as they travel

\[ P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \sin^2(1.27\Delta m^2 L/E) \]

Atmospheric neutrinos below 100 GeV

Suitable probe for the “large” mass splitting \( |\Delta m^2_{32}| \approx |\Delta m^2_{31}| \)
IceCube + DeepCore
An instrument for neutrino physics

- 8 + 7 strings (DC + IC)
- 0.02 km$^3$ volume
- ~ 500 DOMs in fid. vol.
- 2-2.5 km deep, clearest ice
- Spacing: 7m in z, 40-70m in x-y
- Neutrino energy threshold ~ 10 GeV

Typical LE neutrino in DC
- 7 DOMs with signal hits
- $E_{\nu} = 12$ GeV
- 8 GeV muon (42 m)
- 4 GeV hadronic shower
IceCube + DeepCore
An instrument for neutrino physics

where the signal is buried under enormous background

Source of cosmic rays

Cosmic ray

Astrophysical neutrino

Atmospheric neutrino

Muons

*Not to scale

Image: http://globe-views.com/dreams/earth.html
IceCube + DeepCore
An instrument for neutrino physics
where the signal is buried under enormous background

*Not to scale

Image: http://globe-views.com/dreams/earth.html

» Use IC as veto
» Reconstruct neutrino L & E
» Compare with unoscillated flux
Measurement strategy

- Focus on $\nu_\mu$ CC “golden” events
- Starting events → IceCube as veto for DeepCore
- Clear muon tracks
- Core of direct photons
Measurement strategy

» Focus on $\nu_\mu$ CC “golden” events

» Starting events → IceCube as veto for DeepCore

» Clear muon tracks

» Core of direct photons

Zenith angle distribution of events at different selection levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Data</th>
<th>Neutrino simulation</th>
<th>Atm. muons (from data)</th>
<th>Neutrinos + Atm. muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final level</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>

$\cos(\theta_{\text{reco}})$
Measurement strategy

» Focus on $\nu_\mu$ CC “golden” events

» Starting events $\rightarrow$ IceCube as veto for DeepCore

» Clear muon tracks

» Core of direct photons
  » Minimize ice properties impact
  » $\sim 30\%$ signal efficiency

» “Easy” to reconstruct
  » $10^\circ$ res. in zenith angle
    » From time of arrival
  » $25\%$ res. in neutrino energy
    » From observing charge/no charge
Measurement strategy

» Focus on $\nu_\mu$ CC “golden” events

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Agreement between data and MC

» Best fit to the data from a 2D analysis (E, θ)
» Up-going events
» Using E < 56 GeV
» 5174 events in 3 years
» In 2D fit histogram
  » $x^2 = 54.9 / 56$ d.o.f.

Data of this analysis available at http://icecube.wisc.edu/science/data/nu_osc
Best fit oscillation parameters

\[ |\Delta m_{32}^2| = 2.72^{+0.19}_{-0.20} \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12} \]

» First time a very large volume neutrino detector fits in this figure

» Measuring large L/E range

» Affected by different syst.

» Stat. only errors

\[ |\Delta m_{32}^2| = +0.14 \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(\theta_{23}) = +0.06 \]

Data of this analysis available at http://icecube.wisc.edu/science/data/nu_osc

... we need more, and better, data
After visiting hell and heaven

Back to Earth
IceCube is on its way to ...

- Neutrino astronomy
  - A diffuse flux has been observed
    - With high significance
    - In track and cascade channels
  - No point source identified until now
    - Too dim / frequent?

- Competitive particle physics results
  - Neutrino oscillations measured
    - Systematic uncertainties kept under control
    - Improving selection, reconstruction
  - Starting to look at other “channels”
  - Matter effects not significant until now

On our way, not there yet
A possible future

If it worked once, do it again
A possible future

Next generation neutrino experiments at the South Pole

IceCube Gen2 – larger spacing, bigger volume, surface veto → point sources
PINGU – denser DeepCore, matter effects in oscillations → neutrino mass hierarchy
Backup slides
FAQ from heaven

- Neutrino:antineutrino ratio = 2:1
- Tracks + cascades → next step
- Final muon contamination of the sample of 1%
- Fit of systematic uncertainties as nuisance parameters
  - Very small deviations from nominal value
- No sensitivity to mass ordering
- Study of electron-neutrino component underway
# Measuring neutrino oscillations

» Common to all oscillation experiments
  » Compare neutrino flux at production/detection, explain discrepancies with oscillations
  » Relevant differences between IceCube DeepCore and other oscillation experiments

<table>
<thead>
<tr>
<th><strong>IceCube DeepCore</strong></th>
<th><strong>Atmospheric (Super-Kamiokande)</strong></th>
<th><strong>Accelerator (MINOS, NovA, T2K)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial flux obtained from models (tuned with measurements)</td>
<td>Detection by Cherenkov rings</td>
<td>Near detectors → initial flux well understood</td>
</tr>
<tr>
<td>Large range in L (baseline) of 10-12,700 km</td>
<td>~ 22.5 - 40 kton detector</td>
<td>Tracking detectors</td>
</tr>
<tr>
<td>Complex natural medium</td>
<td>Dimensions: &lt; 10m diameter x ~30 m length</td>
<td>Committed to single baseline</td>
</tr>
<tr>
<td>Open detector, order of Mton</td>
<td>Narrow energy range</td>
<td></td>
</tr>
<tr>
<td>Large range in energy, higher than any other experiment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detection by Cherenkov light produced over ten's of meters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limited particle ID: muon, non-muon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interactions mainly deep inelastic scattering</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Energy resolution ~ 10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Densely instrumented detectors, good measurement of hadrons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complicated neutrino interactions in “transition region” ( &lt; a few GeV)</td>
</tr>
</tbody>
</table>

Some of the main differences between experiments measuring the atmospheric parameters of oscillations. T2K is complicated to place, as Super-Kamiokande acts as far detector.
# Systematic uncertainties used

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Nominal value from</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neutrino interactions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cross-section scaling</td>
<td></td>
<td>Free E^(+/-0.03)</td>
</tr>
<tr>
<td>Linear energy dependence</td>
<td></td>
<td>~ +/-20%*</td>
</tr>
<tr>
<td>Axial mass of non-DIS events</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Atmospheric neutrino flux</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall normalization</td>
<td>Honda 2012</td>
<td>Free E^(+/-0.04)</td>
</tr>
<tr>
<td>Spectral index</td>
<td></td>
<td>+/- 20%</td>
</tr>
<tr>
<td>NuE relative normalization</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Detection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadronic energy scaling</td>
<td>Geant4 (model)</td>
<td>+/- 5%</td>
</tr>
<tr>
<td>DOM overall efficiency</td>
<td>Muons, flashers</td>
<td>+/- 10%</td>
</tr>
<tr>
<td>DOM angular acceptance (scattering in hole-ice)</td>
<td>Fit to flasher data</td>
<td>As large as 50%‡</td>
</tr>
<tr>
<td>Bulk-ice model</td>
<td></td>
<td>Two models</td>
</tr>
</tbody>
</table>

* Exact value depends on the individual process

‡ Largest deviation for photons perpendicular to PMT direction
Agreement between data and MC

» Full 2D histogram
neutrino oscillations
Evolution of oscillation analysis in IceCube DeepCore

MINOS 2012
Super-K 2012, zenith $2\nu$
T2K 2013, $\theta_{23} \geq \pi/4$
ANTARES
IceCube-79, $\chi^2$, zenith
IceCube-79, likelihood, zenith and energy, preliminary
IceCube-86, likelihood, zenith and energy, preliminary

*Normalization has been fixed at the horizon

IceCube Preliminary

Ratio X:\delta Oscillations

Events

IC2012

IC2014
Electron neutrinos from the atm

Consistent with Honda flux

Extrapolated to higher energies using H3a model

M. G. Aartsen et al. Phys. Rev. D 89, 062007
FAQ from Hell

» Galactic or extra-galactic?
  » No hints yet

» Northern vs southern sky?
  » Looks different, but not significant

» Going from tracks and cascades → flavor
  » Cascades ≈ NuE + NuTau + 0.4*NuMu
  » Tracks ≈ 0.6*NuMu

» “Prompt component” still uncertain
  » Not a major uncertainty in the astrophysical flux (veto)
Diffuse, HE starting events

- Using 3 years of data, HE starting events
- 37 neutrino candidates
  - 8 ± 4 atm. muons
  - 6 $^{+6}_{-2}$ atm. neutrinos
- 5.7 σ over background
- Cascade-dominated
  - Poor angular resolution
- Search extended to LE

[Graph: IceCube Preliminary, Events per 988 Days vs Deposited EM-Equivalent Energy in Detector (TeV)]

Phys. Rev. Lett. 113, 101101
Joint analysis of diffuse searches

»Likelihood scans

Normalization vs spectral index

Normalization, index vs charm component
Joint analysis of diffuse searches

» Different samples used in the joint LLH analysis
Joint analysis of diffuse searches

Individual fits to different samples
Joint analysis of diffuse searches

» Flavor ratio

IceCube Preliminary

$\nu_e : \nu_\mu : \nu_\tau$ at source

0:1:0 1:2:0 1:0:0

$\nu_e$ fraction at Earth

68% C.L.
90% C.L.
Joint analysis of diffuse searches

Flavor ratio (compared to previous result in arXiv)

IceCube Preliminary

\[ \nu_e : \nu_\mu : \nu_\tau \text{ at source} \]

- 0:1:0
- 1:2:0
- 1:0:0

\[ \Delta \ln L \]