A search for extremely high energy neutrino flux with the 6 years of IceCube data

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Ultra-high energy neutrinos in the Universe

Atmospheric neutrino

Astrophysical neutrino extend above 1 PeV

p+p or p+γ astrophysical photon or matter
Extremely-high energy neutrinos in the Universe

Cosmogenic neutrinos neutrino

FLUX [(GeV cm² sec sr⁻¹)]

ENERGY [eV]

knee

ankle

CMB photon

cosmic-ray

>100EeV

 Decay

\[ \pi^+ \rightarrow \Delta \rightarrow \pi^0 \rightarrow \mu^+ + e^+ + e^- + \nu_\mu + \nu_\mu + \nu_e \]

\[ \Delta \rightarrow \gamma + \nu_e \]

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Cosmic neutrino flux above a few PeV

- Unattenuated neutrinos over cosmological distances
- PeV to EeV sky with charge neutral particle
- Neutrinos associated with UHE cosmic-ray production and gamma-rays
- Above GZK cutoff energies, UHE cosmic-ray compositions...
The IceCube Detector

IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m
The IceCube Collaboration

http://icecube.wisc.edu

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)

Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)

University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
The IceCube Construction and Runs

IC86 = full IceCube (2011~)
IC79 (2010-2011)
IC59 (2009-2010)
IC40 (2008-2009)
IC22 (2007-2008)
IC9 (2006-2007)
IC1 (2005-2006)

Stable full operation since May 2011 - Now taking 5th year physics run with the full IceCube configuration

This work analyze data from IC40 to 3rd year IC86 run (total ~6 year)

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IceCube channels

～880TeV upward through-going muon track event

Starting events sensitive to all flavor CC/NC

Cascade-like events

All except νμ CC, EHE ντ CC

E_{dep} ~130TeV

ν_\ell, W, Z

hadronic shower

ν_ℓ, μ, τ, e

ν_μ CC only

Phys. Rev. Lett. 115, 081102

Phys. Rev. D 84, 072001 (2011)
PRL 111 (2013) 021103

PRL 113, 101101 (2014)

Science 22 Vol. 342 (2013)

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EHE neutrino search with IceCube

Reducing *atmospheric neutrino* background by placing threshold on energy proxy (NPE)

+ *atmospheric muon* background is reduced by well reconstructed downward-going tracks

what not rejected is EHE signal candidate of different event properties

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*atmospheric v background*

- keep
- astrophysical signal

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EHE signals are very bright/energetic
- mostly uncontained through-going and cascade events
- topological features change with energies
Event selection

- Events are from April 2008 to May 2014 (Effective livetime of 2014 days = 5 years and 189 days)

1. Events above the threshold NPE lines are kept
2. Higher NPE threshold for downward-going track

Tighter cut for downward-going track like events

Final level event distributions

- Signal
- Atmos. bg

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Sensitivity

IceCube 2015 sensitivity [2008-2014]

IceCube Preliminary
Observation

- One partially contained upward-going cascade observed in Nov 16, 2012 data
  - Preliminary estimate of energy deposit: 770 TeV (NPE=74300)
  - Vertex position close to the outer most layer of optical sensors

Energy resolution
- ~15% contained cascades
- ~30% partially contained cascades
The binned Poisson LLH analysis

Ex.) BG only hypothesis

\[ L_0 = \prod_{jk} \text{Poisson}(k_{jk}, \mu_{jk}^{BG}) \]

\[ L_1 = \prod_{jk} \text{Poisson}(k_{jk}, \mu_{jk}^{BG} + \lambda_{max}^{GZK} \mu_{jk}) \]

The likelihood ratio

\[ \Lambda \equiv \frac{L_1}{L_0} = \frac{\prod_{jk} \text{Poisson}(k_{jk}, \mu_{jk}^{BG} + \lambda_{max}^{GZK} \mu_{jk})}{\prod_{jk} \text{Poisson}(k_{jk}, \mu_{jk}^{BG})} \]

The log-likelihood ratio

\[ x^2 \equiv \ln \Lambda \]

is the test statistic

P-value

Estimated by replica experiments

\[ p = Pr(x^2 > x_{obs}^2). \]
Results

Is the observed event explained by background?

- Background only hypothesis test p-value: 0.7%
- Hypothesis of observed event being of atmospheric origin rejected at 99.3% CL

Is the observed event astro or cosmogenic origin?

- Observation is inconsistent with GZK hypothesis with p-value of 0.8%
- $E^{-2}$ signal model is compatible with p-value of 90%

- The observed 770TeV event is not likely to be atmospheric background, nor cosmogenic neutrino event...
- Consistent with another HE neutrino event following power-law $\nu$ flux
Model dependent test and upper limits

Different cosmogenic model dependent limits give similar UL in the energy region between $10^8 \text{GeV}$ and $10^9 \text{GeV}$. This implies, despite the differences in spectral shape, models with

$$E \frac{d\phi^{GZK}}{dE} < 10^{-16.5} \text{[cm}^{-2} \text{sec}^{-1} \text{str}^{-1}]$$

are currently only allowed at 90%CL.
Quasi-differential Upperlimits

\[ E^2 \phi(E_\nu) [\text{GeV}^2 \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}] \]

\[ 10^6 \quad 10^8 \quad 10^{10} \]

\[ E_\nu [\text{GeV}] \]

Limits on all flavor (1:1:1) neutrino flux (\( \propto E_\nu \)) over one energy decade

- GZK v Yoshida et al. \( m=4 \) Zmax = 4 \( \gamma=2 \)
- GZK v Ahlers et al. best fit with 3 EeV transition
- GZK v Ahlers et al. 99% CL range with 3 EeV transition
- GZK v Kotera FRII, Emax 316 EeV

IceCube Preliminary

ANITA-II(2010)
RICE(2012)
PAO(2015) v single limit x3
IceCube(2012) [2010-2012]
this work [2008-2014]
Summary and prospects

- Neutrinos above PeV energies are searched by IceCube 6 year sample from April 2008 to May 2014
- One partially contained 770TeV cascade event is observed
- The event is most consistent with a E-2 astrophysical neutrino, not from GZK mechanism
- Tight constraints on several cosmogenic neutrino models are placed
- The analysis will include an additional year sample taken by May 2015 soon
### Model hypothesis tests including the 1 event observation

<table>
<thead>
<tr>
<th>Models</th>
<th>event rates /livetime</th>
<th>p-values</th>
<th>Model dependent UL*</th>
</tr>
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<tbody>
<tr>
<td>Ahlers Fermi max fit (10EeV transition)</td>
<td>8.6 events</td>
<td>0.05%</td>
<td>0.35 times model flux</td>
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<td>Ahlers Fermi best fit (10EeV transition)</td>
<td>4.2 events</td>
<td>3%</td>
<td>0.7 times model flux</td>
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<td>Kotera FRII dip model</td>
<td>11.7 events</td>
<td>0.002%</td>
<td>0.3 times model flux</td>
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<td>Kotera SFR dip model</td>
<td>2.8 events</td>
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*90%CL

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<td>Ahlers Fermi max fit (3EeV transition)</td>
<td>5.1 events</td>
<td>1.5%</td>
<td>0.59 times model flux</td>
</tr>
<tr>
<td>Ahlers Fermi best fit (1EeV transition)</td>
<td>2.3 events</td>
<td>21%</td>
<td>1.33 times model flux</td>
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<td>Yoshida (4,4)</td>
<td>5.6 events</td>
<td>1%</td>
<td>0.54 times model flux</td>
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*90%CL