Very-high-energy astrophysical neutrinos with IceCube

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Cosmic Rays – Neutrinos – γ rays

\[ p + p \rightarrow \pi + ... \]
\[ p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases} \]
\[ \pi^0 \rightarrow \gamma + \gamma \]
\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

C.R. accelerator

Photon

Neutrino

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Neutrinos and $\gamma$ rays

- UV
- X-ray
- Gamma Rays
  - Fermi GBM
  - Fermi LAT
  - HAWC
  - IACTS

- Neutrinos
  - Earth
  - Nuclear Reactors
  - Supernovae
  - Sun
  - Accelerators
  - Atmospheric Neutrinos
  - VHE $\nu$ Astro

- Energy (eV)
  - 1 (eV)
  - $10^3$ (keV)
  - $10^6$ (MeV)
  - $10^9$ (GeV)
  - $10^{12}$ (TeV)
  - $10^{15}$ (PeV)

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Full operation since May 2011. Partial operation before this.
Event signatures

(up-going) muon: $\nu_\mu$

cascade $\rightarrow$ all flavors

Poor angular resolution $10^\circ$ – $40^\circ$
Visible energy resolution $\sim 20\%$
Good(*) $\nu$-cascade energy correlation

Good angular resolution $< 1^\circ$
Visible energy resolution $\sim 20\%$
Poor $\nu$-\(\mu\) energy correlation

Main background to $\nu$ studies

Other $\nu$ event topologies are possible
(* not true for sub-dominant neutral current interactions)
Update on Discovery of a quasi-diffuse $\nu$ flux

"4 year" update: 54 events after cuts
Background:
12.6 ± 5.1 down-going muons (tag)

"3-year" study: Aarsten et al. PRL 113 101101
"2-year" study: Aarsten et al. Science 342 6161

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Deposited energy vs. declination

Southern Sky (downgoing)  Northern Sky (upgoing)

- Background Atmospheric Muon Flux
- Bkg. Atmospheric Neutrinos ($\pi/K$)
- Background Uncertainties
- Atmospheric Neutrinos (90% CL Charm Limit)
- Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
- Bkg.+Signal Best-Fit Astrophysical (fixed slope $E^{-2}$)
- Data

IceCube Preliminary 4-year update
Other ways to study this flux

Assuming best-fit power law:
- Unfolding (stat. error)
- Unfolding (incl. best-fit uncert.)
- Astrophysical $\nu_e + \bar{\nu}_e$
- Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$
- Combined $\nu_\mu + \bar{\nu}_\mu$

"3 year" – 6 year planned $\nu_\mu$ diffuse

IceCube Preliminary

Phys. Rev. D 91, 022001
Submitted to PRL arXiv:1507.04005
Phys. Rev. Lett. 113, 101101
3 year $\nu_\mu$ – preparation for 6 year
Highest energy neutrino in 6 years ($\nu_{\mu}$ search)

Deposited energy: $2.6 \pm 0.3$ PeV

Schoenen & Raedel et al. ATel # 7856

RA: 110.34°
Dec: 11.48°
PSF 99%: 1°
June 11, 2014
(56819.20444852863 MJD)
What are the sources?

Event distribution is consistent with a diffuse flux
Event flavor consistent with oscillations over astrophysical scale
Point source: No (p-value 0.44 cascades / 0.58 all)
Less than ~100 sources explaining the astro-ν flux would have been detected in “traditional” IceCube νµ point source search.
Follow up by multiple instruments (e.g γ ray): No obvious counterpart
GRBs (prompt < 1-3%, ±20h <12% ): No
Short (<100 s) transients: Probably not.
Galactic plane: No (p-value 0.025; 7.5° band)
<table>
<thead>
<tr>
<th>Title</th>
<th>Author(s)</th>
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<tr>
<td>IceCube PeV cascade events initiated by electron-antineutrinos at Glashow resonance</td>
<td>Barger, Learned, Pakvasa</td>
<td>PRD 87, 037302 (2013)</td>
<td>1207.4571</td>
<td>Glashow resonance</td>
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<td>Neutrino decays over cosmological distances and the implications for neutrino telescopes</td>
<td>Baerwald, Bustamante, Winter</td>
<td>JCAP10(2012)020</td>
<td>1208.4600</td>
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<td>On the Interpretation of IceCube cascade events in terms of the Glashow resonance</td>
<td>Bhattacharya, Gandhi, Rodejohann, Watanabe</td>
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<td>PeV neutrinos from the propagation of ultra-high energy cosmic rays</td>
<td>Roulet, Sigl, van Vliet, Mollerach</td>
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<td>Cholis, Hooper</td>
<td>JCAP06(2013)030</td>
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<td>Kistler, Stanek, Yuxel</td>
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<td>1301.1703</td>
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<td>Kaloshov, Kusenko, Essey</td>
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<td>He, Wang, Fan, Liu, Wei</td>
<td>PRD 87, 063011 (2013)</td>
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<td>Borriello, Chakraborty, Minzti, Serpico</td>
<td>PRD 87, 116009 (2013)</td>
<td>1303.5843</td>
<td>Lorentz invariance</td>
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<td>Neutrinos at IceCube from heavy decaying dark matter</td>
<td>Feldstein, Kusenko, Matsumoto, Yangaida</td>
<td>PRD 88, 015004 (2013)</td>
<td>1303.7320</td>
<td>Exotic (dark matter decay)</td>
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<td>Galactic PeV Neutrinos</td>
<td>Gupta</td>
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<td>1305.4123</td>
<td>Galactic</td>
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<td>Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy</td>
<td>Fox, Kashiyama, Meszaros</td>
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<td>Superheavy Particle Origin of IceCube PeV Neutrino Events</td>
<td>Barger, Keung</td>
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<td>1305.6907</td>
<td>Exotic (Leptoquark)</td>
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<td>PeV neutrinos observed by IceCube from cores of active galactic nuclei</td>
<td>Stecker</td>
<td>PRD 88, 047301 (2013)</td>
<td>1305.7404</td>
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<td>Murase, Ioka</td>
<td>PRL 111, 121102 (2013)</td>
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<td>Laha, Beecham, Dasgupta, Horiwuchi, Murase</td>
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<td>1306.2309</td>
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<td>Testing the Hadronuclear Origin of PeV Neutrinos Observed with IceCube</td>
<td>Murase, Ahlers, Lacki</td>
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<td>Pinning down the cosmic ray source mechanism with new IceCube data</td>
<td>Anchordoqui, Goldberg, Lynch, Olinto, Paul, Weller</td>
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<td>1306.5021</td>
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<td>Constraining Superluminal Electron and Neutrino Velocities using the 2010 Crab Nebula Flare and the IceCube PeV Neutrino Events</td>
<td>Stecker</td>
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<td>1306.6095</td>
<td>Lorentz invariance</td>
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<td>TeV-PeV neutrinos over the atmospheric background: originating from two groups of sources?</td>
<td>He, Yong, Fan, Wei</td>
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<td>1307.1450</td>
<td>Two source populations</td>
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<td>The Galactic Pevatron</td>
<td>Nerovon, Senikoz, Tchemin</td>
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<td>Photodisproportion Origin of the TeV-PeV Neutrinos Observed in IceCube</td>
<td>Winter</td>
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<td>Pseudo-Dirac neutrinos via mirror-world and depletion of UHE neutrinos</td>
<td>Joshpura, Mohanty, Pakvasa</td>
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<td>1307.5712</td>
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<td>Are IceCube neutrinos unveiling PeV-scale decaying dark matter?</td>
<td>Esmaili, Serpico</td>
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<td>1308.1105</td>
<td>Exotic (dark matter decay)</td>
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<td>Establishing the astrophysical origin of a signal in a neutrino telescope</td>
<td>Lipari</td>
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<td>Testing Relativity with High-Energy Astrophysical Neutrinos</td>
<td>Diaz, Kostelecky, Mewes</td>
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<td>A Simple Explanation of the Ultra-high Energy Neutrino Events at IceCube</td>
<td>Chen, Bhuapal De, Soni</td>
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<td>The Galactic Center Origin of a Subset of IceCube Neutrino Events</td>
<td>Razzouk</td>
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<td>Ahlers, Murase</td>
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Outlook: IceCube-Gen2

See highlight presentation by J. Koskinen – Sat. Aug. 29
Thank you!

The IceCube Collaboration

44 institutions / 12 countries / ~310 authors

Funding Agencies

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Energy spectrum

IceCube Preliminary
“4-year” update