Ultra-high Energy Neutrino Events at IceCube: Implications for the Standard Model and Beyond

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C.-Y. Chen, PSBD, A. Soni, arXiv:1309.1764 [hep-ph]; and ongoing work.

"Meet Your Neighbour" Meeting,
University of Liverpool

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The Lancaster, Manchester, Sheffield Consortium for Fundamental Physics

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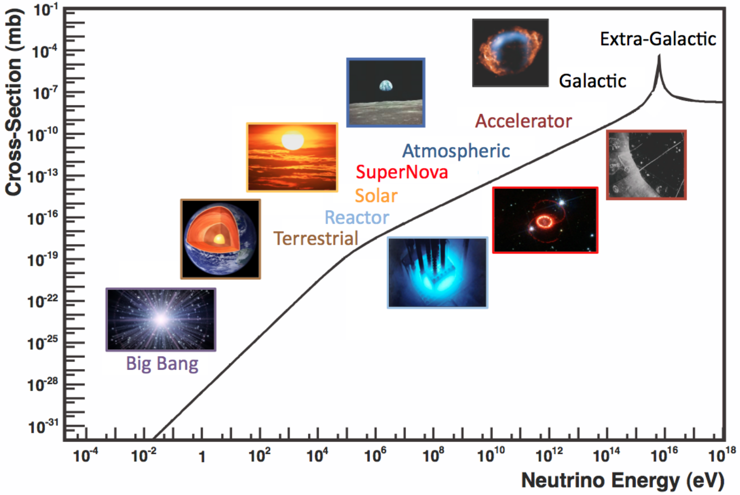
Outline

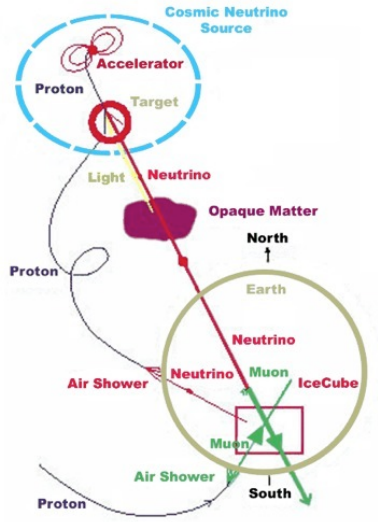
- Introduction
- UHE Events at IceCube
- Possible Sources
- Possible Interactions
- SM Predictions
- Implications for New Physics
- Conclusion

Neutrinos: Friends across > 20 orders of Magnitude

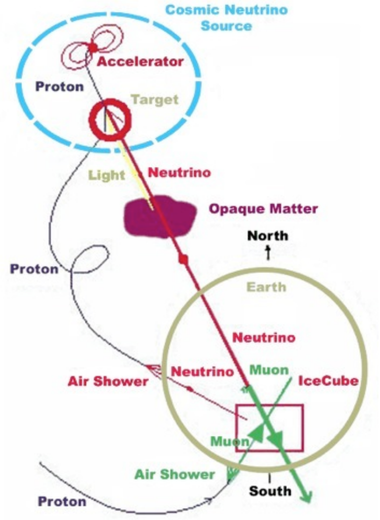


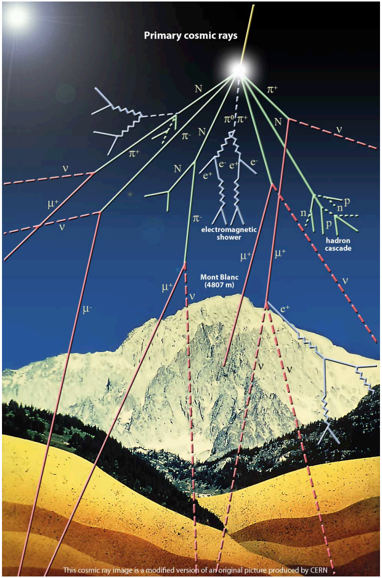
[J. A. Formaggio and G. P. Zeller, Rev. Mod. Phys. **84**, 1307 (2012)]

High-energy Neutrinos: Astrophysical Messengers



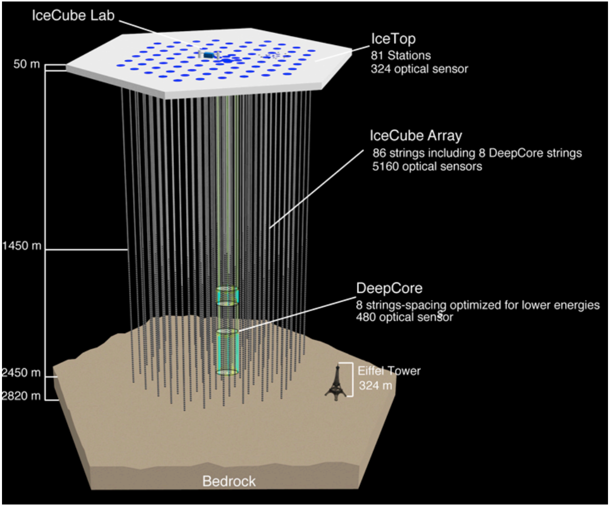
High-energy Neutrinos: Astrophysical Messengers



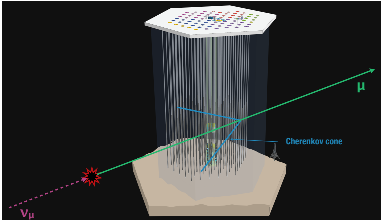


(Ultra) High-energy Neutrino Detectors (Telescopes)

Super-Kamiokande, Baksan, Lake Baikal, ANTARES, AMANDA, **IceCube**, KM3Net,...

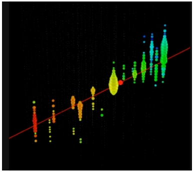


Neutrino Detection at IceCube

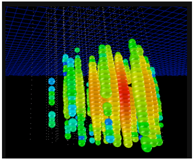


- Cherenkov radiation from secondary particles (muons, electrons, hadrons).
- Within the SM, neutrino interacts with matter only via weak (W and Z) gauge bosons.

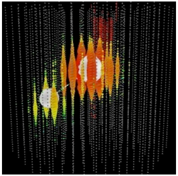
$$\nu_\ell + N \quad \rightarrow \quad \begin{cases} \ell + X & \text{(CC)} \\ \nu_\ell + X & \text{(NC)} \end{cases}$$



CC Muon track (data)



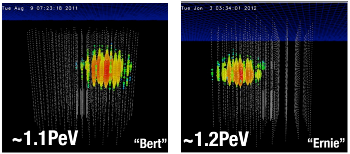
CC electromagnetic/NC hadronic cascade shower (data)

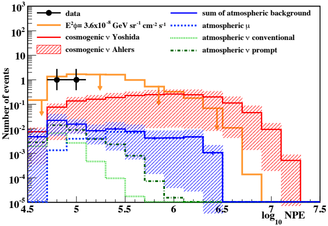


CC tau 'double bang' (simulation)

UHE Neutrino Events at IceCube

- 2 cascade events with 615.9 days of data.





[IceCube Collaboration, Phys. Rev. Lett. **111**, 021103 (2013)]

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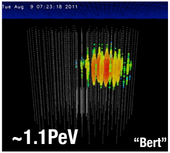
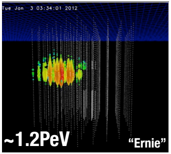
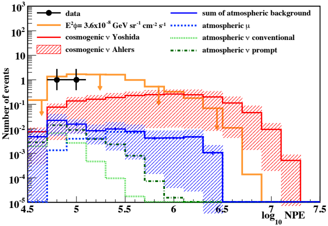
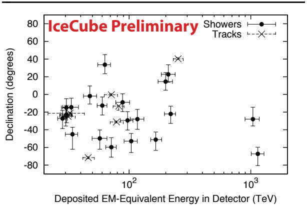


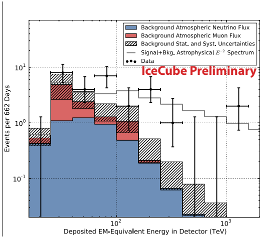




[IceCube Collaboration, Phys. Rev. Lett. **111**, 021103 (2013)]

- Follow-up analysis: 26 more events between 20-300 TeV with 662 days of data.

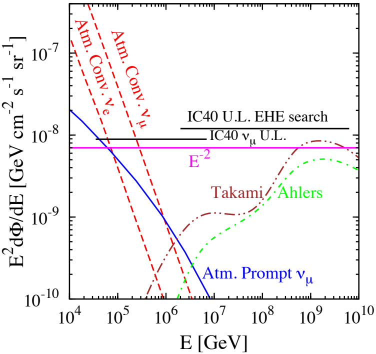




[N. Whitehorn, Talk at IPA 2013, Madison; IceCube Collaboration, submitted to Science]

- 21 cascade events and 7 muon tracks.
- Total 28 events with 4.1σ excess over expected atmospheric background ($10.6^{+5.0}_{-3.6}$ events).

Possible Sources of the UHE Neutrinos



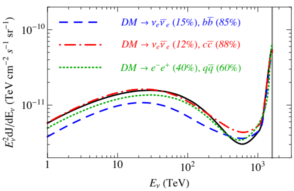
Possible Source	N(1 – 2 PeV)	N(2 – 10 PeV)
Atm. Conv. [45, 46]	0.0004	0.0003
Cosmogenic–Takami [48]	0.01	0.2
Cosmogenic–Ahlers [49]	0.002	0.06
Atm. Prompt [47]	0.02	0.03
Astrophysical E^{-2}	0.2	1
Astrophysical $E^{-2.5}$	0.08	0.3
Astrophysical E^{-3}	0.03	0.06

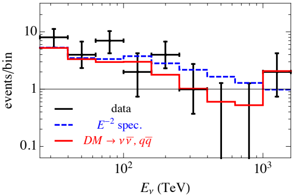
[R. Laha, J. F. Beacom, B. Dasgupta, S. Horiuchi and K. Murase, Phys. Rev. D **88**, 043009 (2013)]

- Atmospheric conventional (π/K): unlikely (dominant flux $<$ 100 TeV).
- Atmospheric prompt (charm): disfavored by IceCube data.
- Cosmogenic (GZK): very unlikely (dominant flux $>$ 10^3 PeV).
- Astrophysical (GRB, AGN, Early Supernovae, Baby Neutron Star, Star-burst Galaxies, Galaxy Clusters,...): plausible.
  - Power-law spectra: $d\Phi/dE \propto E^{-s}$ (with $s \gtrsim 2$), e.g., Waxman-Bahcall flux.
    [E. Waxman and J. N. Bahcall, Phys. Rev. D **59**, 023002 (1999)]
  - Flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ *on Earth* (due to neutrino oscillation).
    [J. Learned and S. Pakvasa, Astropart. Phys. **3**, 267 (1995)]

New Physics?

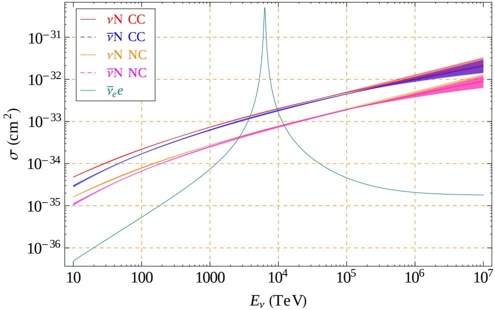
- Several exotic phenomena have been invoked to explain the IceCube events, e.g.,
  - Decaying (PeV-scale) Dark Matter. [B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, arXiv:1303.7320 [hep-ph]; A. Esmaili and P. D. Serpico, arXiv:1308.1105 [hep-ph]]





  - Resonant production of TeV-scale leptoquarks. [V. Barger and W. -Y. Keung, Phys. Lett. B (2013)]
  - Other exotics: Decay of massive neutrinos to lighter ones over cosmological distance scales [P. Baerwald, M. Bustamante and W. Winter, JCAP **1210**, 020 (2012); S. Pakvasa, A. Joshipura and S. Mohanty, Phys. Rev. Lett. **110**, 171802 (2013)]
  - Mirror neutrinos [A. S. Joshipura, S. Mohanty and S. Pakvasa, arXiv:1307.5712 [hep-ph]]
- Before embarking on such speculations, desirable to know the SM expectation with better accuracy.
- With more statistics, could provide a unique test of the SM up to the highest energies ever observed!
- Main aim and motivation of our work. [C.-Y. Chen, PSBD, A. Soni, arXiv:1309.1764 [hep-ph]]

SM Neutrino Cross Sections



- Neutrino-nucleon cross sections mediated by t-channel W and Z dominant ones.
- PDF uncertainties become important at higher energies.
- Important exception: Glashow resonance.
  - On-shell production of W^- in $\bar{\nu}_e - e^-$ scattering. [S. Glashow, Phys. Rev. **118**, 316 (1960)]
  - Peak is at energy $E_\nu = m_W^2/(2m_e) = 6.3$ PeV.
  - Proposed as an explanation of the PeV events. [A. Bhattacharya, R. Gandhi, W. Rodejohann and A. Watanabe, JCAP **1110**, 017 (2011); V. Barger, J. Learned and S. Pakvasa, arXiv:1207.4571 [astro-ph.HE]]
  - Disfavored by a dedicated follow-up analysis. [IceCube Collaboration, Phys. Rev. Lett. **111**, 021103 (2013)]

Event Rate

$$\frac{dN}{dE_{\rm em}} = T \cdot \Omega \cdot N_{\rm eff}(E_\nu) \cdot \sigma(E_\nu) \cdot \Phi_\nu(E_\nu)$$

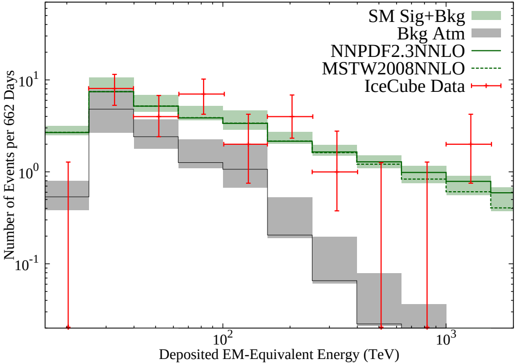
- T=662 days (for IceCube data collected between May 2010-May 2012).
- $N_{\rm eff}(E_\nu) = N_A V_{\rm eff}(E_\nu)$ with $V_{\rm eff}^{\rm max} \sim 0.4\ {\rm km}^3$ at PeV.
- $E_\nu^2 \Phi_{\nu,{\rm tot}}(E_\nu) = 3.6 \times 10^{-8}\ {\rm GeV} \cdot {\rm sr}^{-1} \cdot {\rm cm}^{-2} \cdot {\rm s}^{-1}$ and an equal flavor ratio.
- $\Omega = 2\pi\ {\rm sr}$ for an isotropic flux in the southern hemisphere (downward events at IceCube), while for northern hemisphere (upward events), must include Earth attenuation effects by a shadow factor [R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Astropart. Phys. **5**, 81 (1996)]

$$S(E_\nu) = \int_{-1}^{0} d(\cos\theta)\ \exp[-z(\theta)/L_{\rm int}(E_\nu)]$$

- Use PREM for Earth matter effects and column depth z.
- Deposited em-equivalent energy in terms of incoming neutrino energy – depends on the interaction channel.

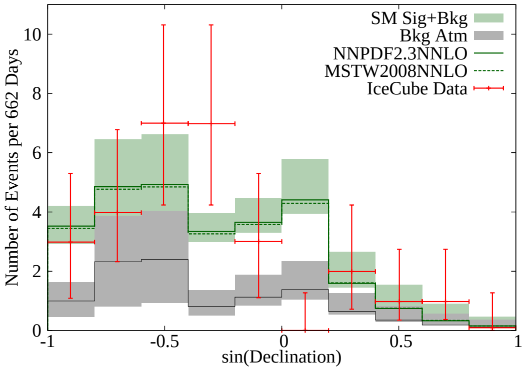
$$E_{\rm em,had} = F_X y E_\nu, \quad E_{\rm em,e} = (1-y)E_\nu$$

SM Prediction for Event Rate



channel	hadron	electron	muon	total
$(\nu+\bar{\nu})N$ NC	$1.54^{+0.12}_{-0.14}$	-	-	$1.54^{+0.12}_{-0.14}$
$(\nu_e+\bar{\nu}_e)N$ CC	$2.42^{+0.30}_{-0.09}$	$6.74^{+0.75}_{-0.13}$	-	$9.15^{+1.05}_{-0.22}$
$(\nu_\mu+\bar{\nu}_\mu)N$ CC	$1.62^{+0.22}_{-0.06}$	-	$4.39^{+0.53}_{-0.12}$	$6.01^{+0.75}_{-0.18}$
$(\nu_\tau+\bar{\nu}_\tau)N$ CC	$2.00^{+0.04}_{-0.05}$	$0.155^{+0.004}_{-0.004}$	$0.153^{+0.003}_{-0.003}$	$2.31^{+0.05}_{-0.06}$
$\bar{\nu}_e e$	0.09	0.01	0.01	0.11
total SM	$7.66^{+0.68}_{-0.34}$	$6.90^{+0.75}_{-0.14}$	$5.02^{+0.33}_{-0.14}$	$19.58^{+1.77}_{-0.61}$

Zenith Angle Distribution



- More downgoing events than upgoing due to the earth attenuation effects.
- No 'muon deficit' problem so far – Number of muon tracks predicted $6.01^{+0.75}_{-0.18}$ is consistent with the observed 7 tracks.
- Apparent cut-off above 2 PeV due to the E^{-2} flux.
- No significant energy gap between 0.3 - 1 PeV, and $\sim$ 2 events should be observed with more data.

Conclusion

- A lot of interest on the origin of UHE neutrino events at IceCube.
- From particle physics point of view,
  - Current data consistent with the SM explanation.
  - Does not require any exotic new physics scenario.
  - With more data, could provide us a unique test of the SM up to PeV and beyond.
  - Any significant deviations will call for BSM physics.
- From astrophysics point of view,
  - Need to pin down the source(s) of UHE neutrinos.
  - Potentially the first detection of astrophysical high-energy neutrino flux.
  - Could open a new avenue for a number of astrophysical objects and mechanism.
  - Golden era of UHE Neutrino Astrophysics?

Differential Cross Sections

$$\frac{d^2\sigma_{\nu N}^{\rm CC}}{dxdy} = \frac{2G_F^2 M_N E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \left[xq(x,Q^2)+x\bar{q}(x,Q^2)(1-y)^2\right],$$

$$\frac{d^2\sigma_{\nu N}^{\rm NC}}{dxdy} = \frac{G_F^2 M_N E_\nu}{2\pi}\left(\frac{M_Z^2}{Q^2+M_Z^2}\right)^2 \left[xq^0(x,Q^2)+x\bar{q}^0(x,Q^2)(1-y)^2\right],$$

$$\text{where } q = \frac{u+d}{2}+s+b,$$

$$\bar{q} = \frac{\bar{u}+\bar{d}}{2}+c+t,$$

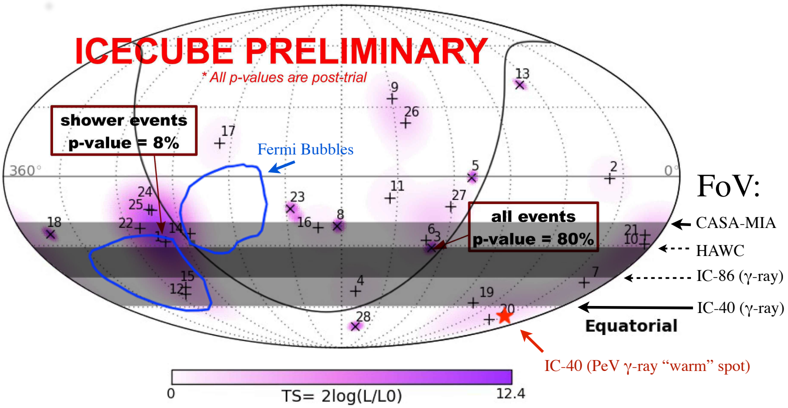
$$q^0 = \frac{u+d}{2}(L_u^2+L_d^2)+\frac{\bar{u}+\bar{d}}{2}(R_u^2+R_d^2) +(s+b)(L_d^2+R_d^2)+(c+t)(L_u^2+R_u^2),$$

$$\bar{q}^0 = \frac{u+d}{2}(R_u^2+R_d^2)+\frac{\bar{u}+\bar{d}}{2}(L_u^2+L_d^2) +(s+b)(L_d^2+R_d^2)+(c+t)(L_u^2+R_u^2),$$

with $L_u = 1-(4/3)x_W,\ L_d = -1+(2/3)x_W,\ R_u = -(4/3)x_W$ and $R_d = (2/3)x_W$.

[R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Astropart. Phys. **5**, 81 (1996)]

Skymap



ICECUBE PRELIMINARY
* All p-values are post-trial
shower events
p-value = 8%
Fermi Bubbles
all events
p-value = 80%
360°
0°
FoV:
CASA-MIA
HAWC
IC-86 (γ-ray)
IC-40 (γ-ray)
Equatorial
IC-40 (PeV γ-ray "warm" spot)
0
TS= 2log(L/L0)
12.4