A Flavor and Spectral Analysis of the Ultra-High Energy Neutrino Events at IceCube

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C.-Y. Chen, PSBD and A. Soni, Phys. Rev. D **89**, 033012 (2014) [arXiv:1309.1764 [hep-ph]]; arXiv:1411.5658 [hep-ph].

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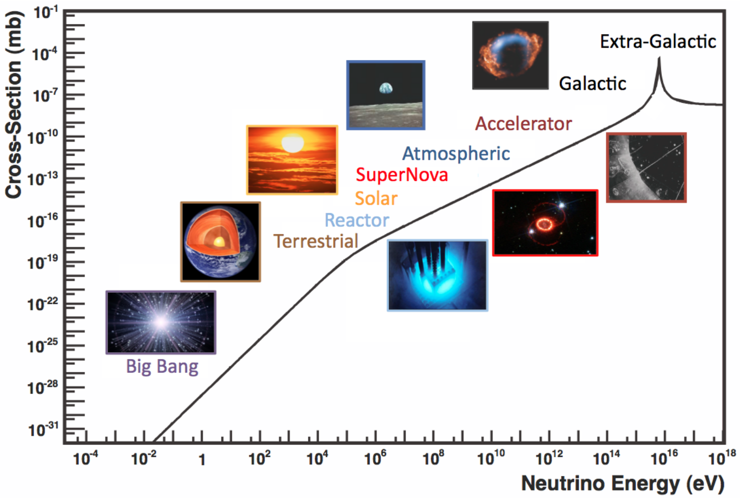
The University of Manchester

Outline

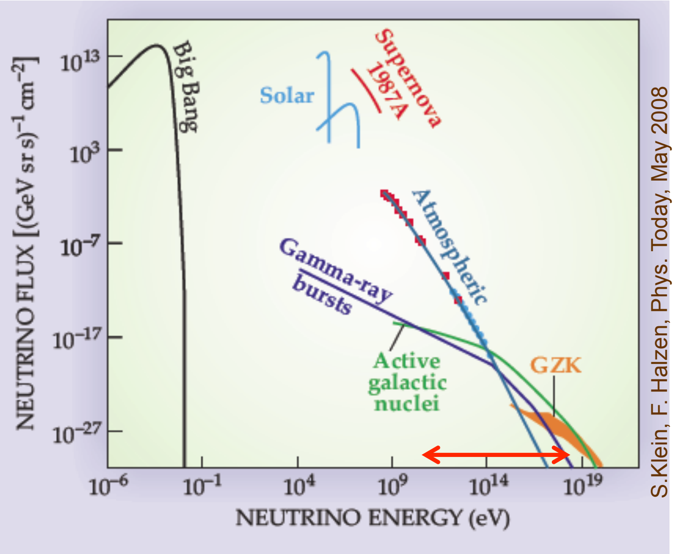
- UHE Events at IceCube
- Sources and Interactions
- SM Predictions
- Implications for New Physics
- A New Astrophysical Flux
- Conclusion

Neutrinos: Friends across 20 orders of Magnitude



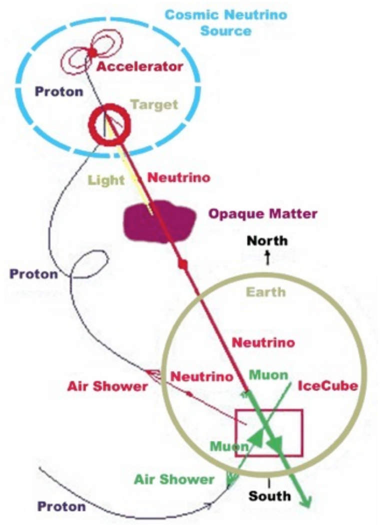
[J. A. Formaggio and G. P. Zeller, Rev. Mod. Phys. **84**, 1307 (2012)]

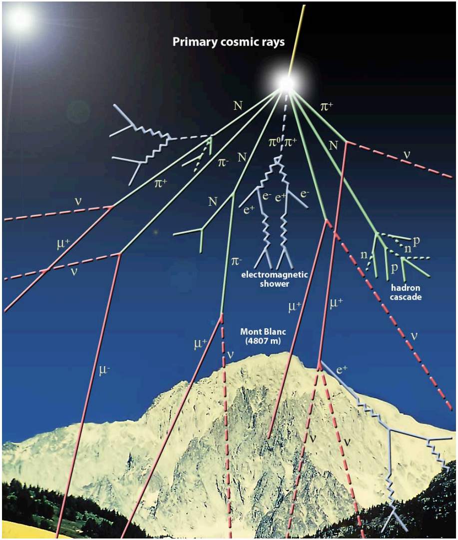
Neutrino Flux



S.Klein, F. Halzen, Phys. Today, May 2008

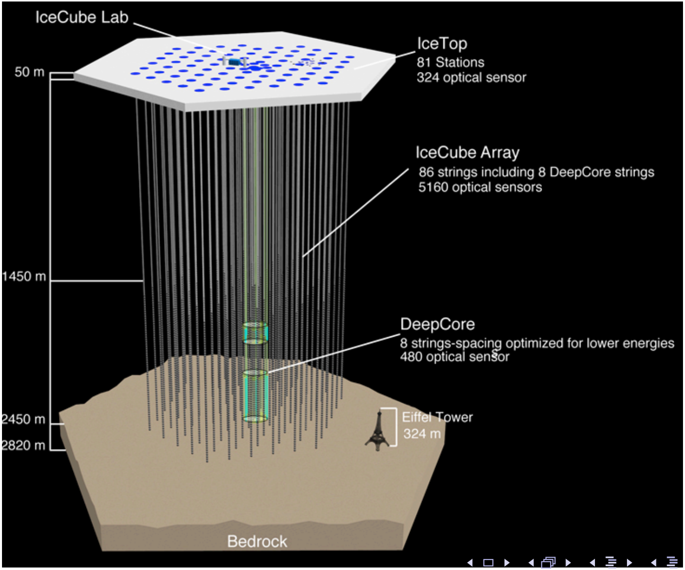
High-energy Neutrinos: Astrophysical Messengers



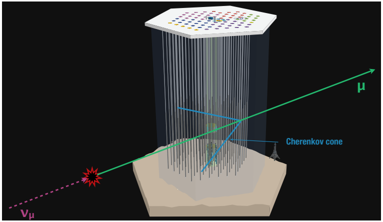


(Ultra) High-energy Neutrino Detectors (Telescopes)

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

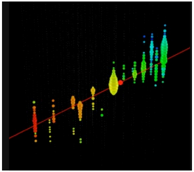


Neutrino Detection at IceCube

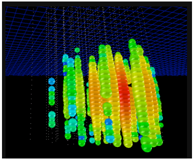


- Cherenkov radiation from secondary particles (muons, electrons, hadrons).
- Within the SM, neutrino interacts with matter only via weak (W and Z) gauge bosons.

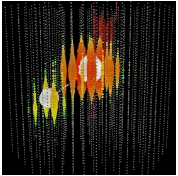
$$\nu_\ell + N \quad \rightarrow \quad \begin{cases} \ell + X & \text{(CC)} \\ \nu_\ell + X & \text{(NC)} \end{cases}$$



CC Muon track (data)

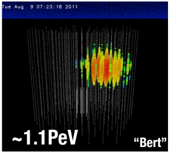


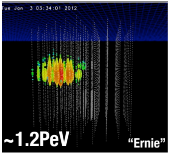
CC electromagnetic/NC hadronic cascade shower (data)

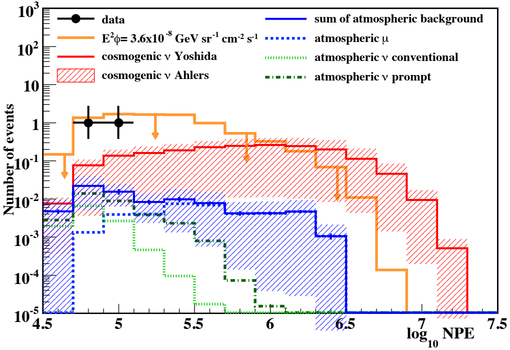


CC tau 'double bang' (simulation only)

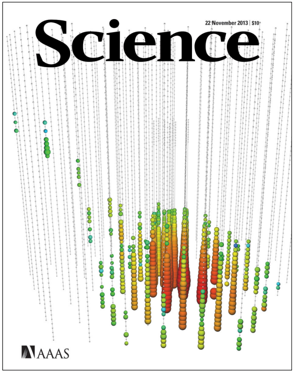
First Observation of UHE Neutrinos

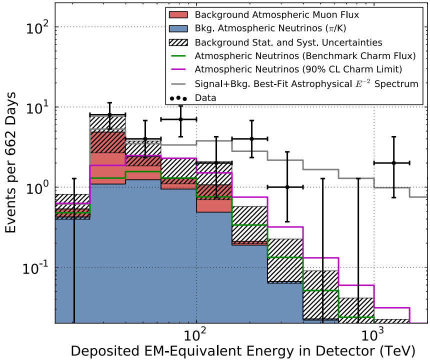






Follow-Up Analysis

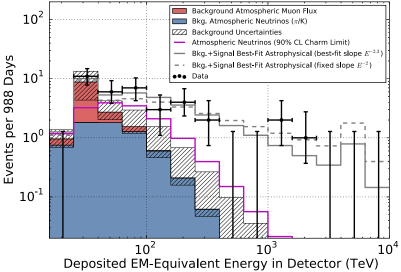


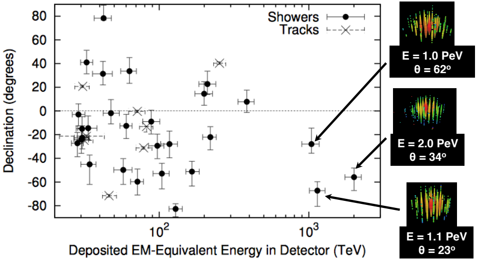


- 26 more events between 20-300 TeV.
- Total 28 events in 662 days of data with 4.1σ excess over expected atmospheric background ($10.6^{+5.0}_{-3.6}$ events).
- 21 cascade events and 7 muon tracks.

With 3-year Dataset

[Phys. Rev. Lett. **113**, 101101(2014)]

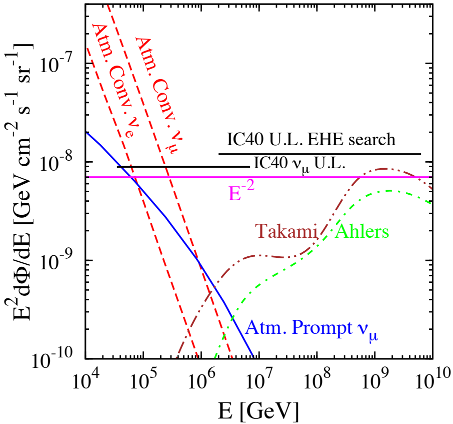




- 9 more events, including one at 2 PeV (“Big Bird").
- Total 37 events in 988 days of data with 5.7σ excess over expected atmospheric background of $6.6^{+5.9}_{-1.6}$ atmospheric neutrinos and 8.4 ± 4.2 cosmic ray muons.
- 28 cascade events and 9 muon tracks.

Understanding the Events

- Two main theoretical aspects:
  - Source (astrophysics): flux and flavor composition
  - Interaction (particle physics): showers and tracks
- Most plausible source: Astrophysical with a power-law flux $\Phi(E_\nu) = CE_\nu^{-s}$.



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)]

Flavor Composition

- Primary production mechanisms for astrophysical neutrinos:
  - $p\gamma$ process: $p\gamma \to \Delta^+ \to n\pi^+ \to ne^+\nu_e\bar{\nu}_\mu\nu_\mu$;
  - pp process: $pp \to \pi^\pm/K^\pm + 2p/n \to \mu\nu_\mu + 2p/n \to e\nu_e\bar{\nu}_\mu\nu_\mu + 2p/n$;
  - pn process: $pn \to \pi^\pm/K^\pm + 2p/n \to \mu\nu_\mu + 2p/n \to e\nu_e\bar{\nu}_\mu\nu_\mu + 2p/n$.
- Predict a flavor ratio of $(\nu_e : \nu_\mu : \nu_\tau)$ =(1:2:0) at source.
- Given a flavor ratio $(f_e^0{:}f_\mu^0{:}f_\tau^0)_\mathrm{S}$, the corresponding value $(f_e{:}f_\mu{:}f_\tau)_\mathrm{E}$ on Earth is given by

$$f_\ell = \sum_{\ell'=e,\mu,\tau} \sum_{i=1}^{3} |U_{\ell i}|^2 |U_{\ell' i}|^2 f_{\ell'}^0 \equiv \sum_{\ell'} P_{\ell\ell'} f_{\ell'}^0 \ .$$

- For the current values of the 3-neutrino oscillation parameters, we get $(1{:}1{:}1)_\mathrm{E}$ at Earth.

Possible (New Physics) Interactions

Several exotic phenomena have been invoked to explain the IceCube events, e.g.

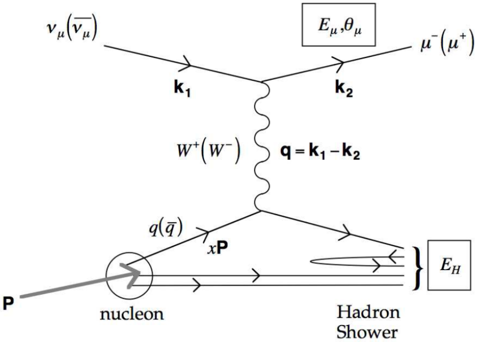
- Decaying (PeV-scale) Dark Matter. [B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, Phys. Rev. D **88**, 015004 (2013); A. Esmaili and P. D. Serpico, JCAP **1311**, 054 (2013)]
- Secret neutrino interactions involving a light mediator [K. Ioka and K. Murase, PTEP **2014**, 061E01 (2014); K. C. Y. Ng and J. F. Beacom, Phys. Rev. D **90**, 065035 (2014)]
- Resonant production of TeV-scale leptoquarks. [V. Barger and W.-Y. Keung, Phys. Lett. B **727**, 190 (2013)]
- 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)]
- Pseudo-Dirac neutrinos oscillating to sterile ones in a mirror world [A. S. Joshipura, S. Mohanty and S. Pakvasa, Phys. Rev. D **89**, 033003 (2014)]
- Superluminal neutrinos and Lorentz invariance violation [F. W. Stecker and S. T. Scully, Phys. Rev. D **90**, 043012 (2014); L. A. Anchordoqui, V. Barger, H. Goldberg, J. G. Learned, D. Marfatia, S. Pakvasa, T. C. Paul and T. J. Weiler, Phys. Lett. B **739**, 99 (2014)]

This Talk

- Before embarking on BSM explanations, desirable to know the SM expectation with better accuracy.
- Include known sources of theoretical uncertainty (mainly from PDFs).
- Include realistic detector effects (e.g., effective number of target nucleons, attenuation effects, energy loss).
- Find the event rate for SM interactions, assuming an isotropic astrophysical, power-law flux.
- Compare the SM predictions with the IceCube data.

- Any statistically significant deviations from the SM prediction might call for BSM!
- In the absence of significant deviations, could use the data to constrain various BSM scenarios.

SM Neutrino-Nucleon Interactions



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

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

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

where $x = Q^2/(2M_N y E_\nu)$ (Bjorken variable), and $y = (E_\nu - E_\ell)/E_\nu$ (inelasticity).

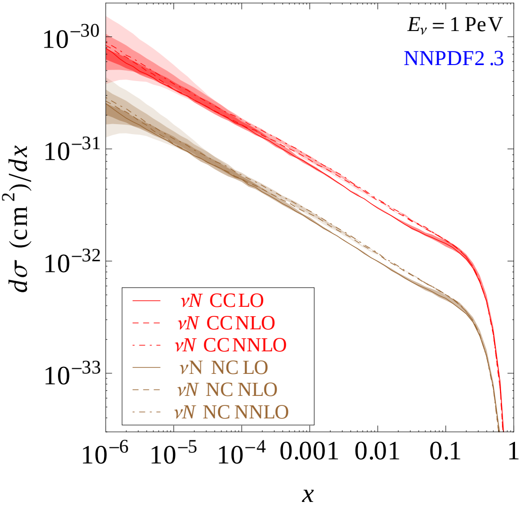
Parton Distribution Functions

- $q, \bar{q}$ ($q^0, \bar{q}^0$) are respectively the quark and anti-quark density distributions in a proton, summed over valence and sea quarks of all flavors relevant for CC (NC) interactions:

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

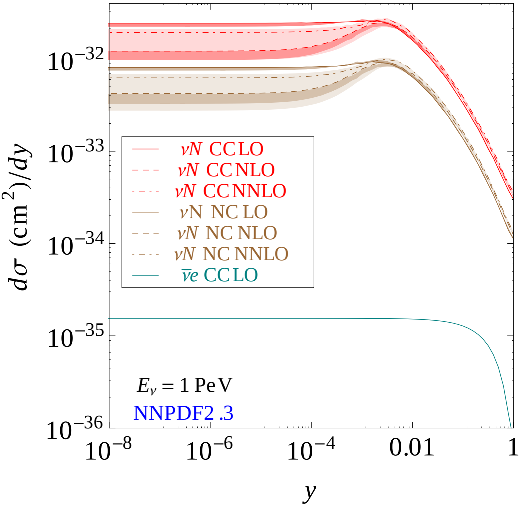
  with $L_u = 1 - (4/3)x_W$, $L_d = -1 + (2/3)x_W$, $R_u = -(4/3)x_W$ and $R_d = (2/3)x_W$ (where $x_W = \sin^2\theta_W$, and θ_W is the weak mixing angle).
- Higher E_ν means probing smaller x-regions (DIS).
- The PDFs must include the lowest possible x-grids (up to $\sim 10^{-9}$ extracted so far from HERA data).
- We used `NNPDF2.3` [R. D. Ball *et al.*, Nucl. Phys. B **867**, 244 (2013)].

Differential Cross Sections



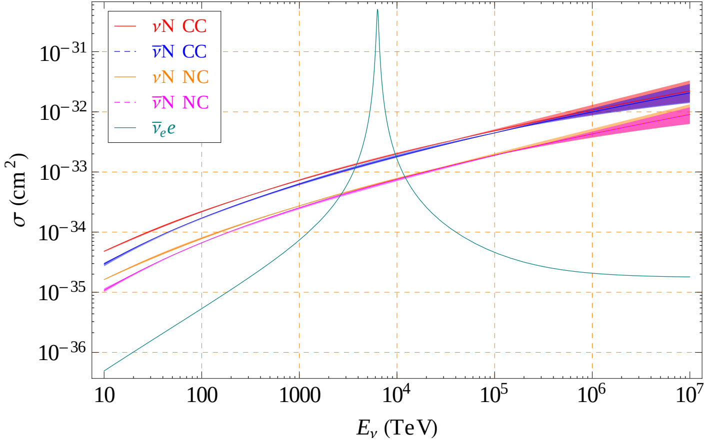
[C.-Y. Chen, PSBD and A. Soni, Phys. Rev. D **89**, 033012 (2014)]

Differential Cross Sections



[C.-Y. Chen, PSBD and A. Soni, Phys. Rev. D **89**, 033012 (2014)]

Total Cross Sections



Glashow Resonance

- Resonant production of W^- in $\bar{\nu}_e e^-$ scattering: [S. Glashow, Phys. Rev. **118**, 316 (1960)]

$$\bar{\nu}_e + e^- \to W^- \to \text{anything}$$

$$\frac{d\sigma_{\bar{\nu}_e e \to \bar{\nu}_e e}}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi} \left[\frac{R_e^2 + L_e^2 (1-y)^2}{\left(1 + 2 m_e E_\nu y / M_Z^2\right)^2} + 4(1-y)^2 \frac{1 + \frac{L_e\left(1 - 2 m_e E_\nu / M_W^2\right)}{1 + 2 m_e E_\nu y / M_Z^2}}{\left(1 - 2 m_e E_\nu / M_W^2\right)^2 + \Gamma_W^2 / M_W^2} \right],$$

where $L_e = 2x_W - 1$ and $R_e = 2x_W$ are the chiral couplings of Z to electron.

- Peak is at energy $E_\nu = m_W^2/(2m_e) = 6.3$ PeV.

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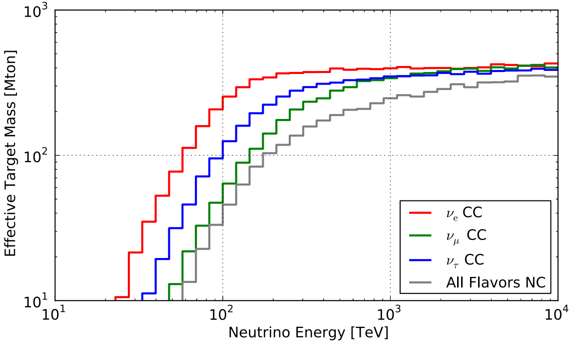
where $L_e = 2x_W - 1$ and $R_e = 2x_W$ are the chiral couplings of Z to electron.

- 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 IceCube analysis. [IceCube Collaboration, Phys. Rev. Lett. **111**, 021103 (2013)]
- A lighter W' resonance can be similarly ruled out for a range of $g_{W'}$, which is otherwise inaccessible experimentally. [Chen, PSBD, Soni (work in progress)]

Event Rate

$$N = T N_A \Omega \int_{E_{\rm min}}^{E_{\rm max}} dE_{\rm dep} \int_0^1 dy \, \Phi(E_\nu) V_{\rm eff}(E_\nu) S(E_\nu) \frac{d\sigma(E_\nu, y)}{dy}$$

- $T = 988$ days for the IceCube data collected between 2010-2013.
- $N_A = 6.022 \times 10^{23}\ \mathrm{mol}^{-1} \equiv 6.022 \times 10^{23}\ \mathrm{cm}^{-3}$ water equivalent for interactions with nucleons. For interactions with electrons, $N_A \to (10/18) N_A$.
- $V_{\rm eff}(E_\nu) = M_{\rm eff}(E_\nu)/\rho_{\rm ice}$ is the effective fiducial volume and $\sim 0.4\ \mathrm{km}^3$ at PeV.

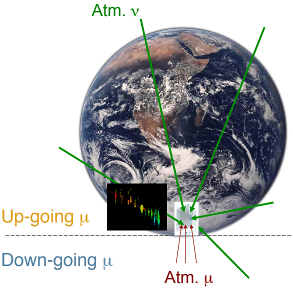


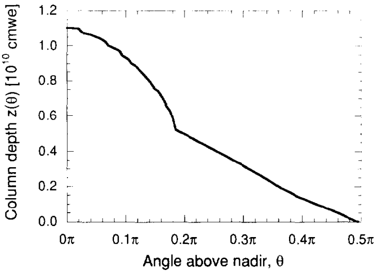
Earth Matter Effect

- $\Omega = 4\pi$ sr for an isotropic neutrino flux.
- To take into account Earth Matter effects (for upgoing events), include an attenuation factor [R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Astropart. Phys. **5**, 81 (1996)]

$$S(E_\nu) = \frac{1}{2}\int_{-1}^{1} d(\cos\theta)\, \exp\left[-\frac{z(\theta)}{L_{\rm int}(E_\nu)}\right]$$

where $L_{\rm int} = 1/(N_A\sigma)$ and $z(\theta)$ is the effective column depth obtained from PREM. [A. Dziewonski and D. L. Anderson, Phys. Earth Planet. Int. **25**, 297 (1981)]





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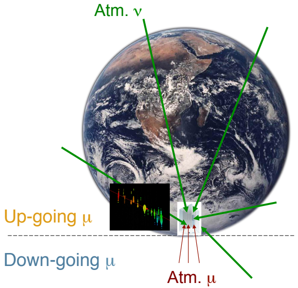
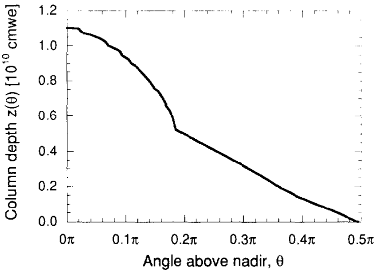




- Makes Earth opaque to UHE neutrinos, thus limiting the upgoing events above $\sim$ 200 TeV.
- For upgoing τ-neutrinos, must include regeneration effects. [S. I. Dutta, M. H. Reno and I. Sarcevic, Phys. Rev. D **62**, 123001 (2000); J. F. Beacom, P. Crotty and E. W. Kolb, Phys. Rev. D **66**, 021302 (2002)]

Astrophysical Neutrino Flux

- Parametrize by a single-component unbroken power-law:

$$\Phi(E_\nu) = \Phi_0 \left(\frac{E_\nu}{E_0} \right)^{-\gamma}$$

where Φ_0 is the total $\nu + \bar{\nu}$ flux for all flavors at $E_0 = 100$ TeV in units of $\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$.

- The exact value of γ depends on the source evolution model.
- Expected to be between 2 and 2.5 for standard astrophysical sources (such as GRBs, AGNs).
- Upper bound on diffuse neutrino flux: [E. Waxman and J. N. Bahcall, Phys. Rev. D **59**, 023002 (1999)]

$$[E_\nu^2 \Phi_\nu]_{\mathrm{WB}} \approx 2.3 \times 10^{-8} \epsilon_\pi \xi_Z \ \mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

- Use the standard flavor composition of $(1{:}1{:}1)_{\mathrm{E}}$ corresponding to $(1{:}2{:}0)_{\mathrm{S}}$.

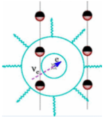
Deposited Energy

- Deposited em-equivalent energy is *always* less than the incoming neutrino energy by a factor which depends on the interaction channel:

$$E_{\mathrm{em,e}} = (1 - y)E_\nu , \qquad E_{\mathrm{em,had}} = F_X y E_\nu \ .$$

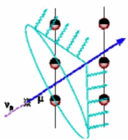
[$F_X = 1 - (E_X/E_0)^{-m}(1 - f_0)$, with $E_0 = 0.399$ GeV, $m = 0.130$ and $f_0 = 0.467$ from simulations of hadronic vertex cascade [M. P. Kowalski, Ph.D. thesis, Humboldt-Universität zu Berlin (2004)]

- Contained vertex search to veto atmospheric background].



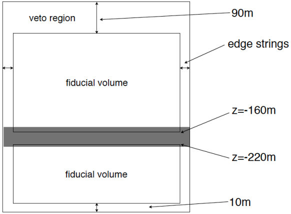
Cascades:

- e-m and hadronic cascades
- $\nu_{e(\tau)} + N \to e(\tau) + X$
  $\nu_f + N \to \nu_f + X \quad f = e, \mu, \tau$
- Resolutions, cascades contained in the detector
  - visible energy < ~ 20%
  - angular ~ 10°-40°

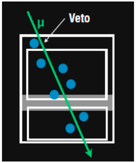


μ Tracks:

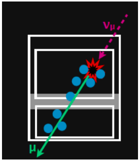
- $\nu_\mu + N \to \mu + X$
- through-going muons
- visible energy resolution~20%
- pointing resolution <1°



Reject incoming muons when *"early charge"* in veto region

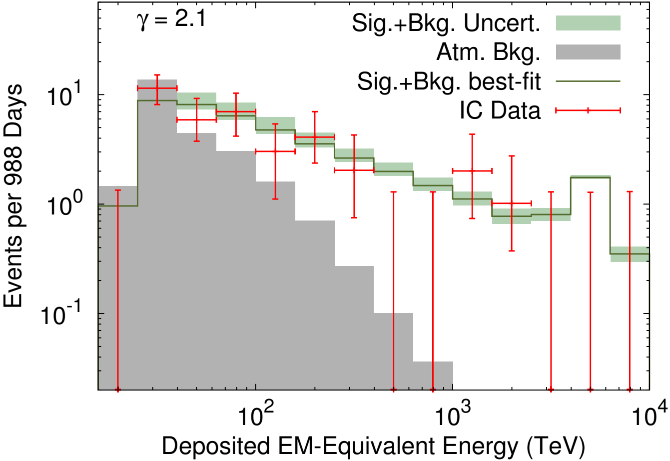


Reject



Accept

SM Event Distribution



[C.-Y. Chen, PSBD and A. Soni, arXiv:1411.5658 [hep-ph]]

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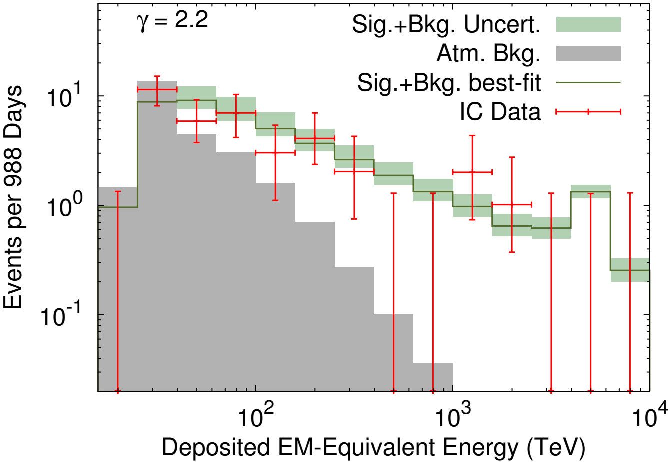

[C.-Y. Chen, PSBD and A. Soni, arXiv:1411.5658 [hep-ph]]

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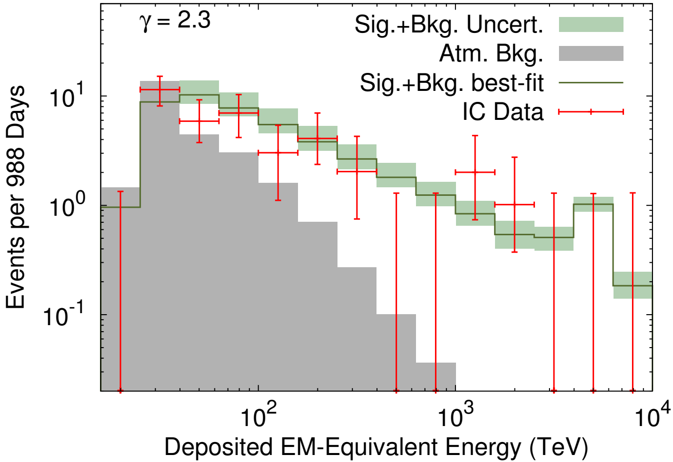

[C.-Y. Chen, PSBD and A. Soni, arXiv:1411.5658 [hep-ph]]

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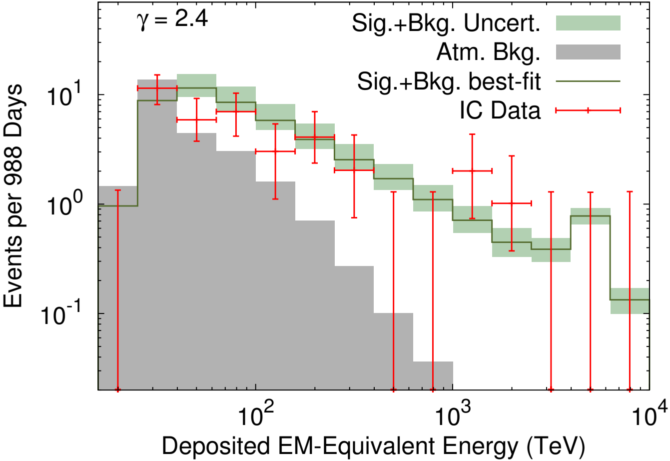

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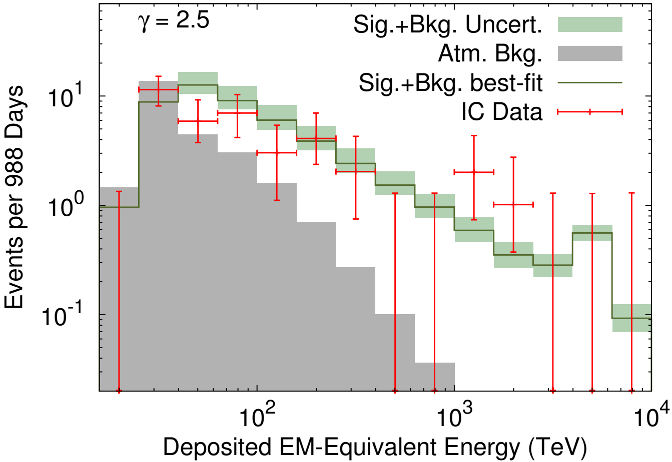

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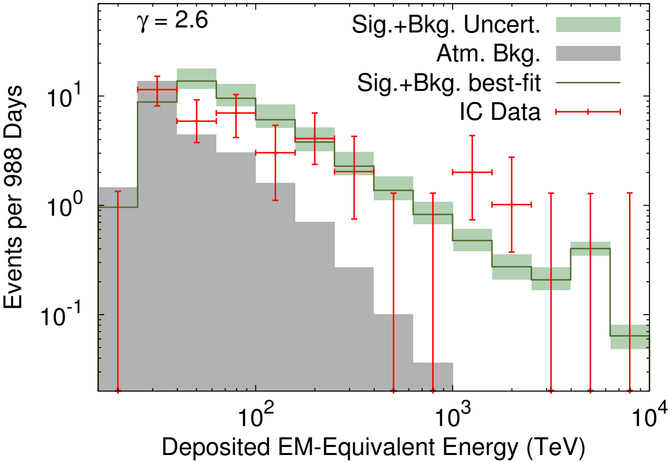

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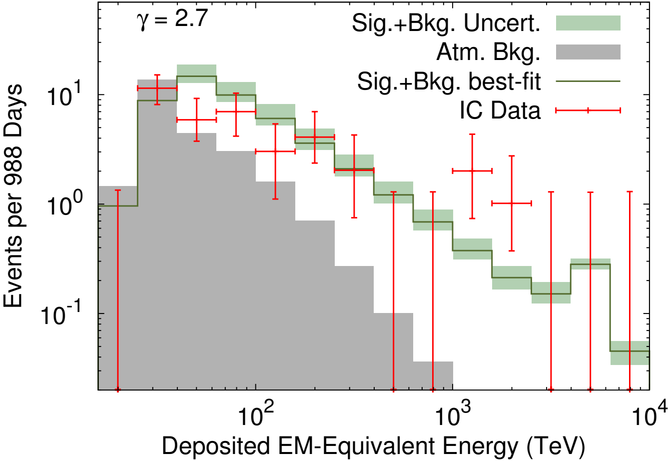
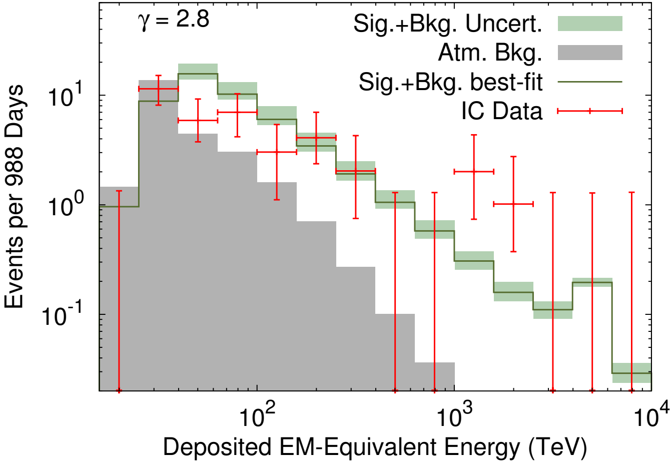


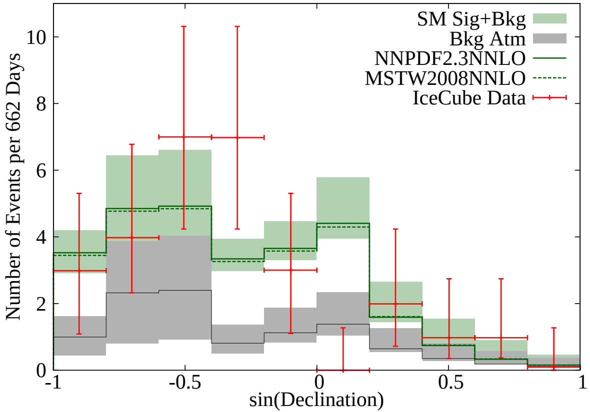
[C.-Y. Chen, PSBD and A. Soni arXiv:1411.5658 [hep-ph]]

SM Event Distribution



[C.-Y. Chen, PSBD and A. Soni arXiv:1411.5658 [hep-ph]]

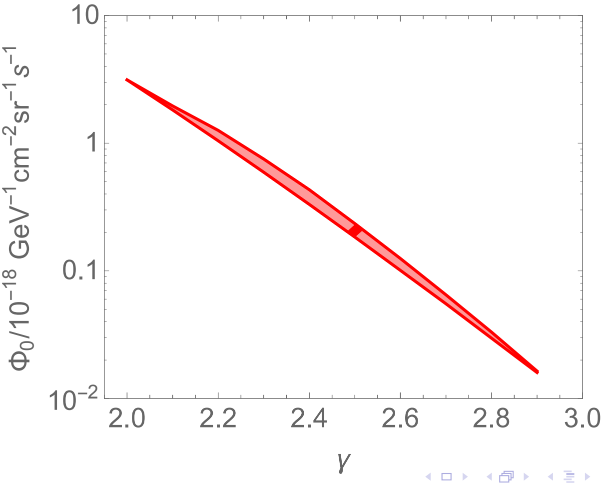
Zenith Angle Distribution



[C.-Y. Chen, PSBD and A. Soni, Phys. Rev. D **89**, 033012 (2014)]

χ^2-Analysis

$$\chi^2 = \sum_i \frac{(N_i^{\rm SM} - N_i^{\rm IC})^2}{\delta N_i^2}$$



Two Potential Problems

- SM predictions with $(1{:}1{:}1)_{\mathrm{E}}$ flavor composition seem to be consistent with current IceCube data.
- Salient Features:
  - An unbroken power-law flux with $\gamma \simeq 2.5$.
  - Less upgoing events due to Earth attenuation effect.
  - Most of the UHE (PeV) events are expected to be downgoing showers.
  - A possible cut-off beyond 10 PeV to explain the absence of more UHE events.
- So far, no need for any exotic explanation!

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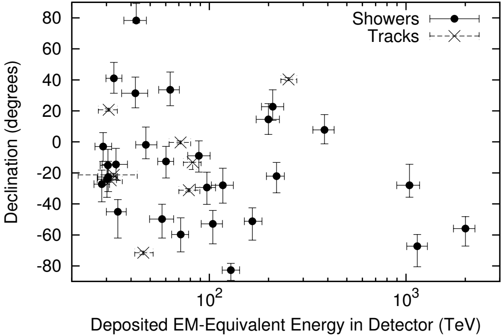
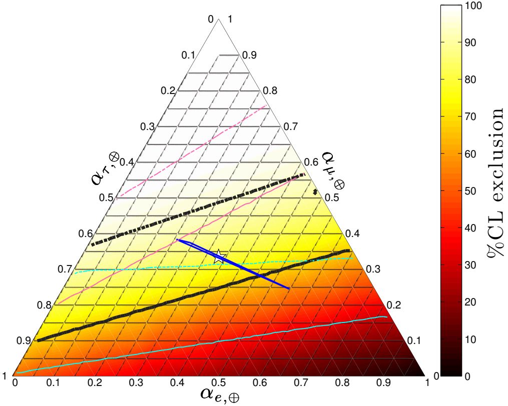
- Salient Features:
    - An unbroken power-law flux with $\gamma \simeq 2.5$.
    - Less upgoing events due to Earth attenuation effect.
    - Most of the UHE (PeV) events are expected to be downgoing showers.
    - A possible cut-off beyond 10 PeV to explain the absence of more UHE events.
- So far, no need for any exotic explanation!
- However, a closer look seems to suggest two potential problems (though not statistically significant).
    - An apparent 'energy gap' between 400 TeV - 1 PeV.
    - A potential 'muon deficit problem' in the high-energy bins ($60\ \mathrm{TeV} < E_{\mathrm{dep}}$).

Two Potential Problems



	Atm. Bkg.	$(1{:}1{:}1)_{\mathrm{E}}$ best-fit	IceCube
Total	$2.8 + < 5.3$	19.9	20
Up	$1.5 + < 3.7$	7.7	5
Down	$1.2 + < 1.6$	12.2	15
Track	$\sim 2.1 + < 1.0$	6.1	4
Shower	$\sim 0.7 + < 4.2$	13.8	16
p-value		0.95	

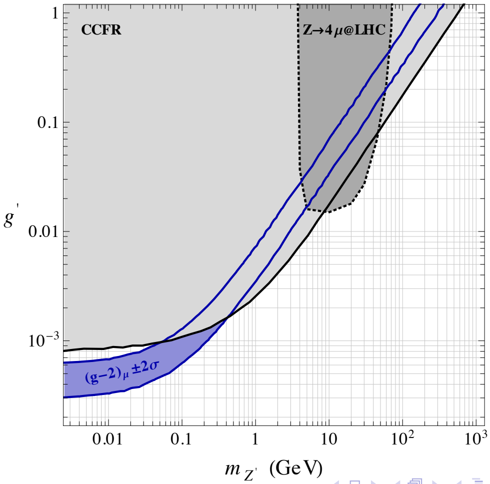
Muon Deficit Problem



- A dedicated statistical analysis disfavors the $(1{:}1{:}1)_{\rm E}$ solution at 81% CL. [O. Mena, S. Palomares-Ruiz and A. C. Vincent, Phys. Rev. Lett. **113**, 091103 (2014)]
- Their best-fit solution is $(1{:}0{:}0)_{\rm E}$.
- Cannot be attained from *any* flavor ratio at an astrophysical source within the standard neutrino oscillation framework.

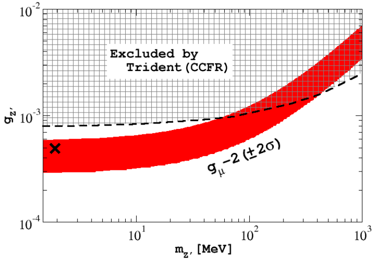
A Possible BSM Solution

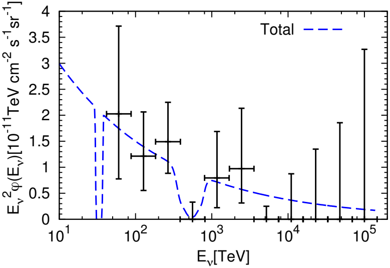
- Invoke exotic lepton flavor violating interactions, e.g. mediated by an MeV-scale Z'.
- Could also explain the longstanding muon $(g-2)$ anomaly.
- However, the parameter space for this to happen is very limited. [W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin, Phys. Rev. Lett. **113**, 091801 (2014)]



A Possible BSM Solution

- Absorption by relic neutrinos could explain the gap between 300 TeV - 1 PeV [T. Araki, F. Kaneko, Y. Konishi, T. Ota, J. Sato and T. Shimomura, arXiv:1409.4180 [hep-ph]]





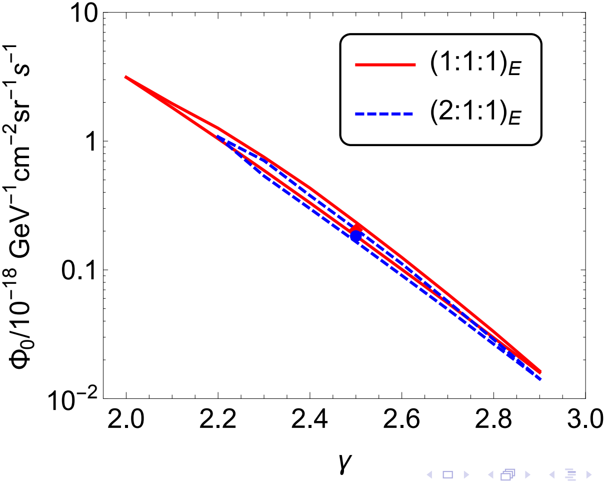
- However, requires non-trivial (asymmetric) flavor structure for $Z'\bar{\ell}_\alpha \ell_\beta$ couplings, which is hard to motivate in a realistic model.
- Moreover, if a similar coupling to quarks is allowed, then ruled out by the IceCube data. [Chen, PSBD, Soni (work in progress)]

A New Solution (within the SM Framework)

- Coexistence of another astrophysical source with $(1{:}0{:}0)_{\mathrm{S}}$ flavor composition.
- Several well-motivated sources, e.g.
  - Nuclear beta decay of relativistic neutrons.
  - UHECRs interacting with relativistic electrons.
  - e^+e^- scattering in a dense astrophysical system.
- Predicts a flavor ratio of $(2{:}1{:}1)_{\mathrm{E}}$ at Earth.
- Solves the muon deficit problem without invoking BSM interactions.
- Once the $(2{:}1{:}1)_{\mathrm{E}}$ flux is recognized, it is rather natural to consider a two-component flux consisting of both $(1{:}1{:}1)_{\mathrm{E}}$ and $(2{:}1{:}1)_{\mathrm{E}}$.
- Offers a simple explanation of the apparent energy gap.

χ^2-Analysis

$$\chi^2 = \sum_i \frac{(N_i^{\rm SM} - N_i^{\rm IC})^2}{\delta N_i^2}$$



Comparison of the Number of Events

$$\Phi(E_\nu) = \Phi_1 \left(\frac{E_\nu}{E_0}\right)^{-\gamma_1} e^{-E_\nu/E_1} + \Phi_2 \left(\frac{E_\nu}{E_0}\right)^{-\gamma_2}$$

	Background	$(1:1:1)_\mathrm{E}$	$(2:1:1)_\mathrm{E}$	Two-comp	IceCube
Total	$2.8 + < 5.3$	19.9	19.7	19.4	20
Up	$1.5 + < 3.7$	7.7	7.5	7.3	5
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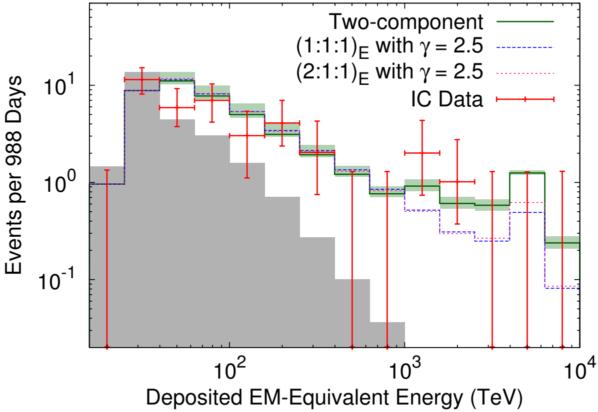
Shower	$\sim 0.7 + < 4.2$	13.8	15.6	15.1	16
p-value		0.95	0.95	0.75	

Event Distribution



[C.-Y. Chen, PSBD and A. Soni, arXiv:1411.5658 [hep-ph]]

Conclusion and Outlook

- Understanding all aspects of the UHE neutrino events at IceCube is very important for both Astrophysics and Particle Physics ramifications.
- From astrophysics point of view,
  - Need to pin down the source(s) of UHE neutrinos and their flavor composition.
  - Golden era of Neutrino Astrophysics.
- From particle physics point of view,
  - Current data seems to be consistent with the SM interactions.
  - Any significant deviations might call for BSM interpretations.
  - With more statistics, can be used to constrain (otherwise inaccessible) BSM scenarios, such as light Z'.
- If the 'muon deficit' and/or the energy gap become statistically significant, our two-component flux can offer a natural solution within the SM framework.

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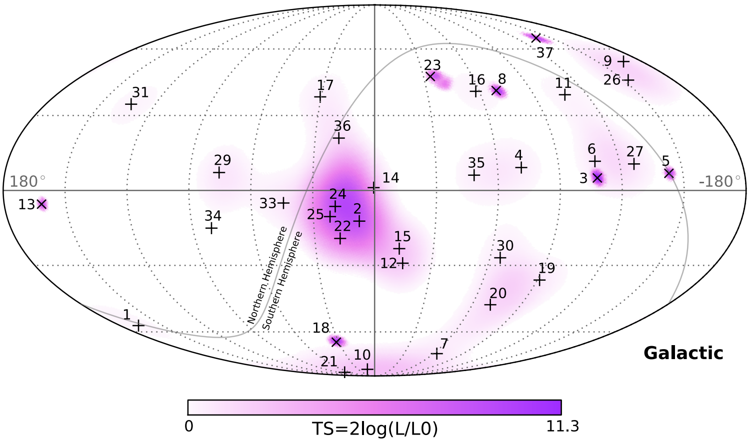
THANK YOU.

Skymap



180°
-180°
Galactic
Northern Hemisphere
Southern Hemisphere
1
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12
13
14
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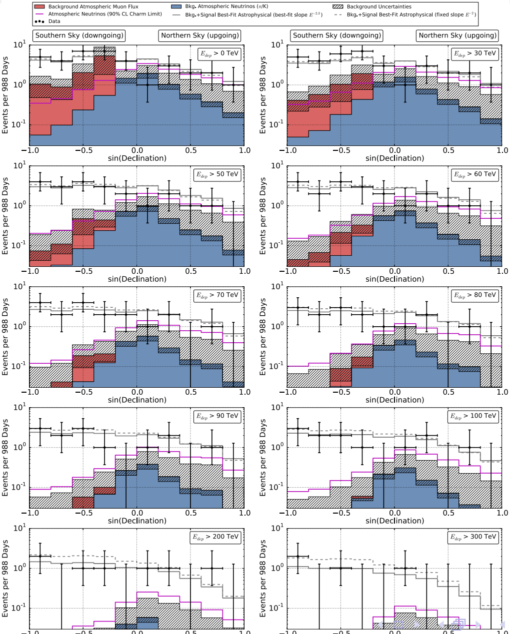
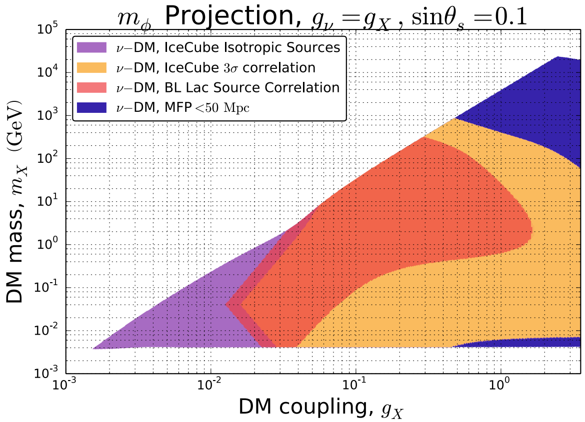
33
34
35
36
37
0
TS=2log(L/L0)
11.3

Declination



Neutrino Portal Dark Matter

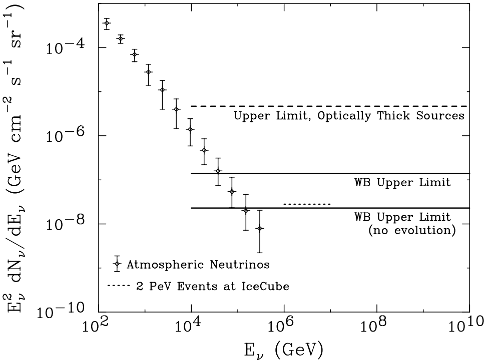


[J. F. Cherry, A. Friedland and I. M. Shoemaker, arXiv:1411.1071 [hep-ph]]

Astrophysical Neutrino Flux

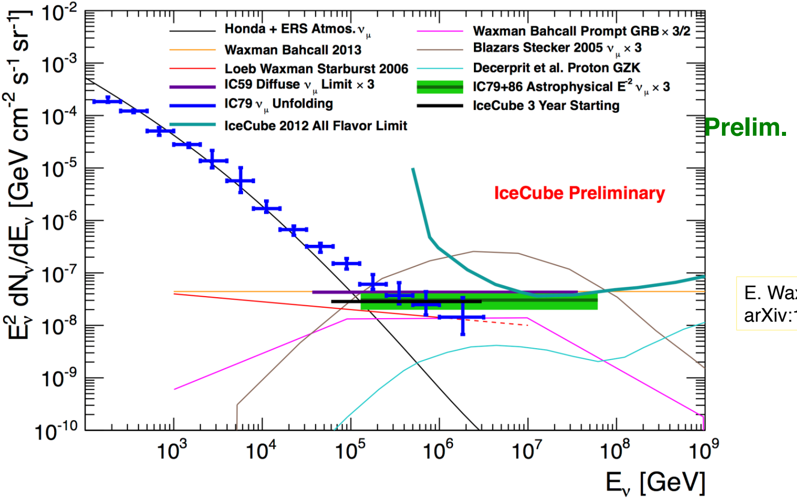
- Three primary mechanisms:
  - Proton collisions with energetic photons (Photo-meson production)
  - Proton-gas collision
  - Decay of UHE neutrons
- All involve high-energy cosmic rays $\Longrightarrow$ direct connection between cosmic ray and neutrino spectra.
- Upper bound on diffuse neutrino flux: [E. Waxman and J. N. Bahcall, Phys. Rev. D **59**, 023002 (1999)]

$$[E_\nu^2 \Phi_\nu]_{\rm WB} \approx 2.3 \times 10^{-8} \epsilon_\pi \xi_Z \ {\rm GeV cm^{-2} s^{-1} sr^{-1}}$$



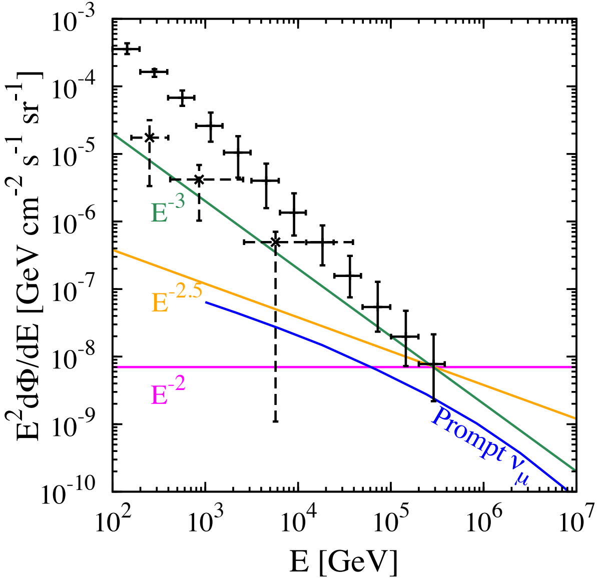
[I. Cholis and D. Hooper, JCAP **06**, 030 (2013)]

Upper Limit on Diffuse Flux



E. Waxman, arXiv:1312.0558

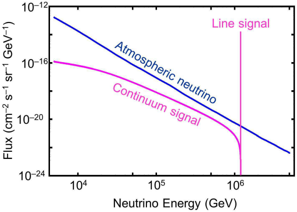
Different Power Law Spectra

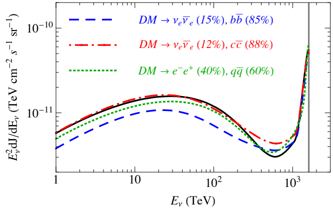


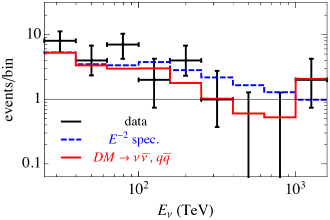
[R. Laha, J. F. Beacom, B. Dasgupta, S. Horiuchi and K. Murase, Phys. Rev. D **88**, 043009 (2013)]

Decaying DM

- DM annihilation saturating the unitarity limit $\sigma_{\rm ann} \leq 4\pi/(m_{\rm DM}^2 v^2)$ cannot explain the PeV events: $\Gamma_{\rm events} \sim V_{\rm eff} L_{\rm halo} n_{\rm N} \sigma_{\rm N} \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^2 \langle \sigma_{\rm ann} v \rangle \lesssim 1$ per few hundred years
- Decaying PeV-scale DM with lifetime $\tau_{\rm DM} \simeq 1.9 N_\nu \times 10^{28}$ s can explain the IceCube PeV events. [B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, arXiv:1303.7320 [hep-ph]]

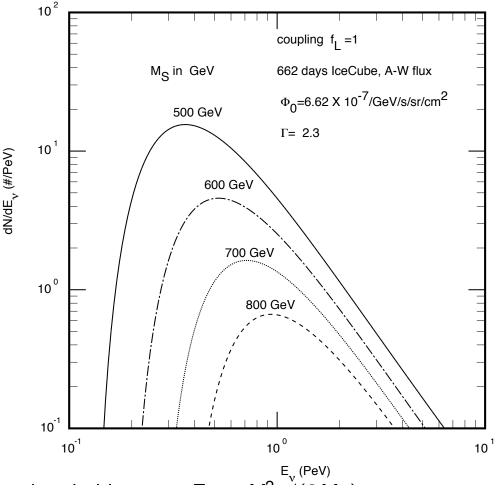






[A. Esmaili and P. D. Serpico, arXiv:1308.1105 [hep-ph]]

Leptoquarks



Resonant production at threshold energy $E_\nu = M_{\rm LQ}^2/(2M_N)$. [V. Barger and W. -Y. Keung, arXiv:1305.6907]