New Physics at IceCube

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BSM Seminar, CERN

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

MAX-PLANCK-GESELLSCHAFT

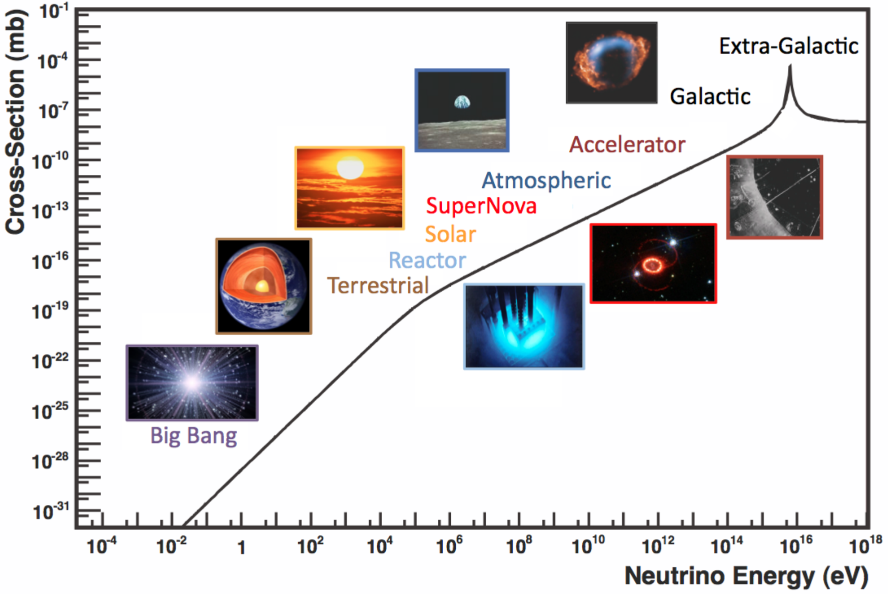
ν

$m_\nu = m_L^T - m_D M_R^{-1} m_D$

MANITOP

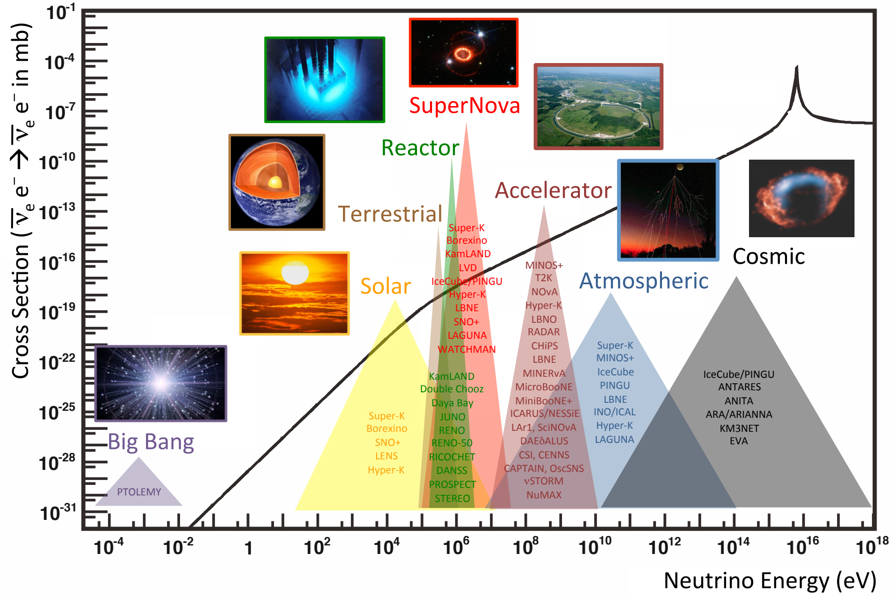
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Neutrinos: Friends across 20 orders in energy



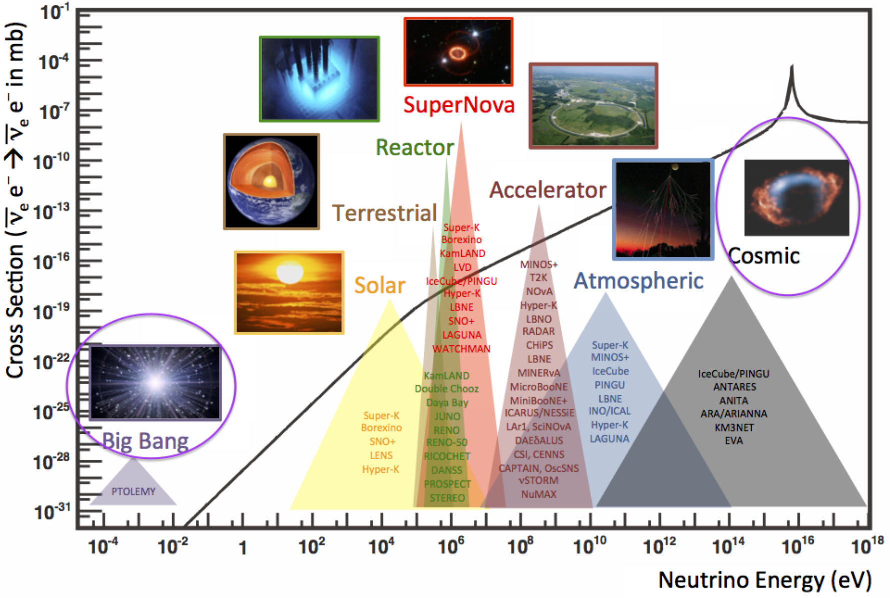
[J. A. Formaggio and G. P. Zeller, Rev. Mod. Phys. **84**, 1307 (2012)]

Neutrinos: Friends across 20 orders in energy



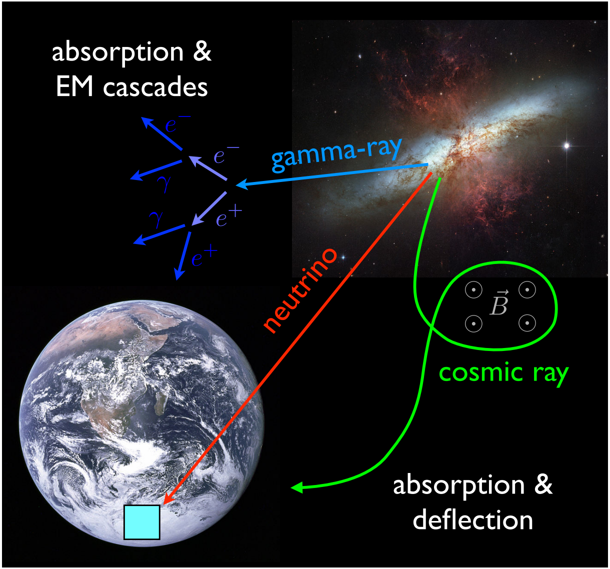
[J. L. Hewett *et al.* (Snowmass 2013 Neutrino Working Group), arXiv:1401.6077[hep-ex]]

Neutrinos: Friends across 20 orders in energy

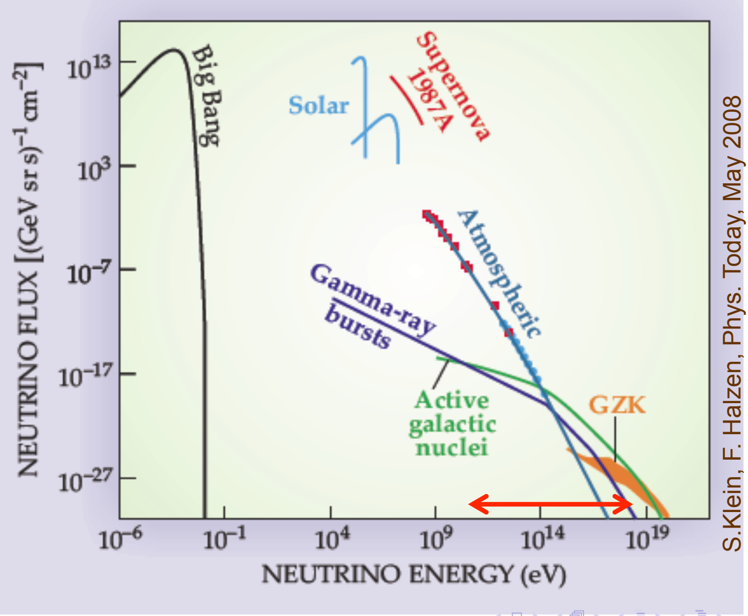


[J. L. Hewett *et al.* (Snowmass 2013 Neutrino Working Group), arXiv:1401.6077[hep-ex]]

High-energy Neutrinos: Astrophysical Messengers



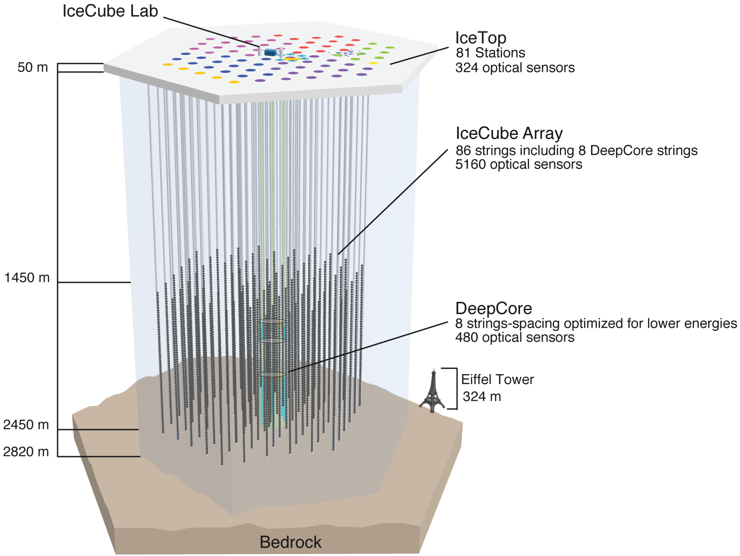
Neutrino Flux



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

Need Very Large Detectors

DUMAND, Lake Baikal, ANTARES, KM3NeT, GVD, AMANDA, **IceCube**

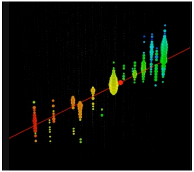


Neutrino Detection at IceCube

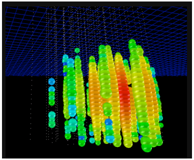
- Within the SM, neutrinos interact with matter only via weak (W and Z) gauge currents.

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

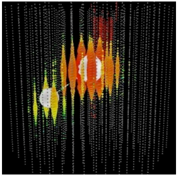
- Cherenkov radiation from interaction products (muons, electrons, hadrons).



CC Muon track (data)

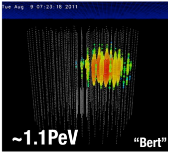


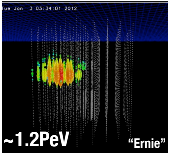
CC electromagnetic/NC hadronic cascade shower (data)

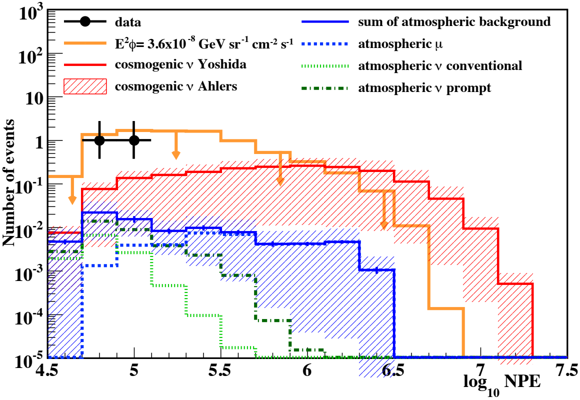


CC tau 'double bang' (simulation only)

First Observation of UHE Neutrinos

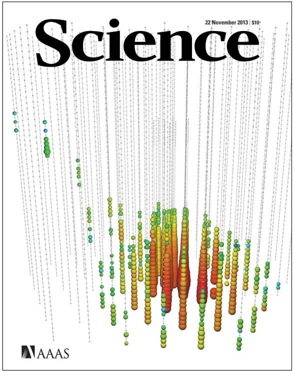


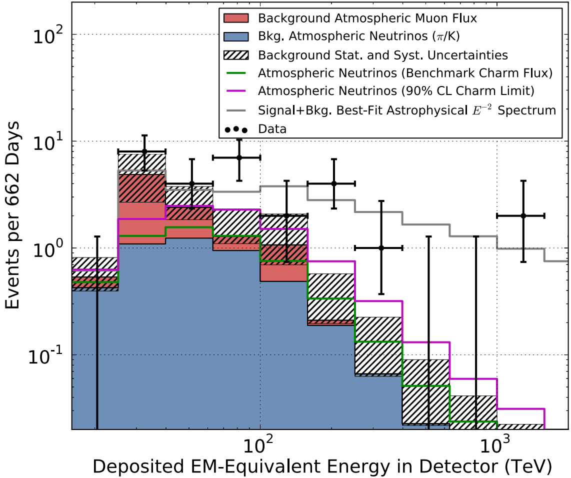




[IceCube Collaboration, Phys. Rev. Lett. **111**, 021103 (2013)]

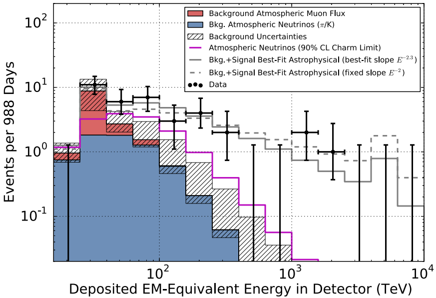
Follow-Up Analysis (2-year Dataset)

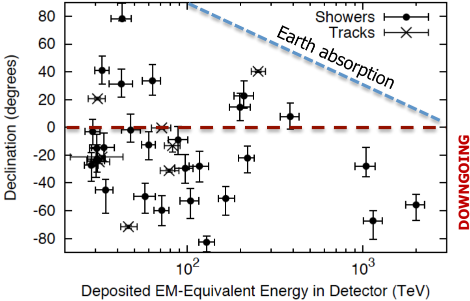




[IceCube Collaboration, Science **342**, 1242856 (2013)]

3-year Dataset

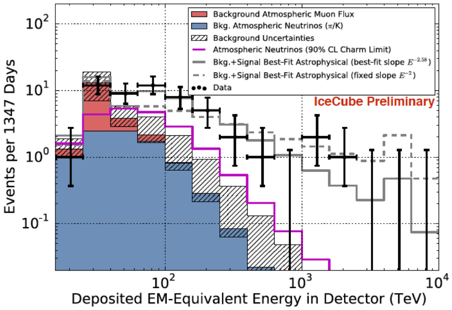


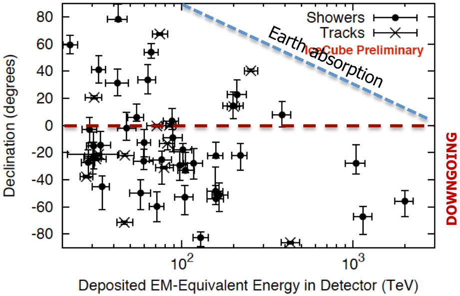


[IceCube Collaboration, Phys. Rev. Lett. **113**, 101101(2014)]

- 9 more events, including one at 2 PeV (“Big Bird").
- Total 37 events 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.

4-year Dataset





54 events (39 cascades and 14 tracks): 7σ excess over expected atmospheric background.

[IceCube Collaboration, ICRC 2015 Proceedings [arXiv:1510.05223 [astro-ph.HE]]]

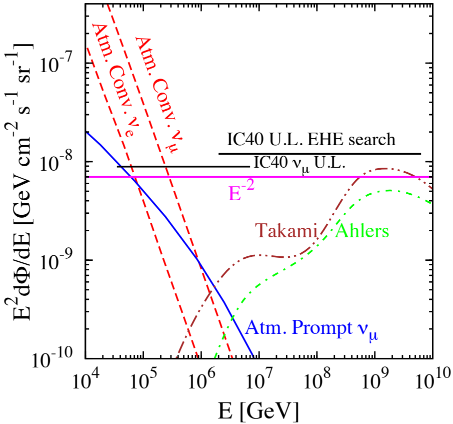
Understanding the Events

- Three main aspects:
  - Source: flux and initial flavor composition
  - Propagation: final flavor composition on Earth
  - Detection: showers and tracks, upgoing and downgoing events
- New Physics beyond the SM could in principle affect any of these aspects.
- But before embarking on BSM explanations, desirable to know the SM expectation with better accuracy.
- Any statistically significant deviation from the SM prediction might hint at BSM!
- In the absence of significant deviations, could use the data to constrain various BSM scenarios.

Source

Most plausible: Astrophysical source with a power-law flux

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



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

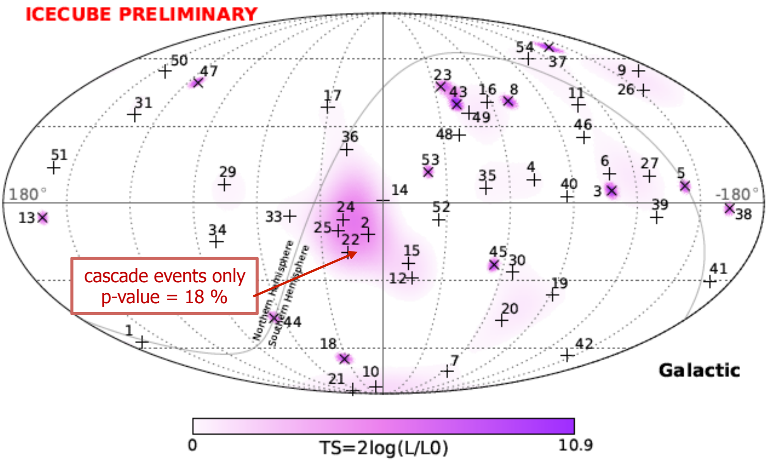
[R. Laha, J. F. Beacom, B. Dasgupta, S. Horiuchi and K. Murase, PRD **88**, 043009 (2013)]

Some Examples

- **Galactic:** (full or partial contribution)
  - diffuse or unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [MA & Murase'13; Neronov, Semikoz & Tchernin'13;Neronov & Semikoz'14; Guo, Hu & Tian'14]
  - extended Galactic emission [Su, Slatjer & Finkbeiner'11; Crocker & Aharonian'11] [Lunardini & Razzaque'12;MA & Murase'13; Razzaque'13; Lunardini *et al.*'13] [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein *et al.*'13; Esmaili & Serpico '13; Bai, Lu & Salvado'13]
- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13] [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - active galactic nuclei (AGN) [Stecker'91,'13;Kalashev, Kusenko & Essey'13] [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14;Kalashev, Semikoz & Tkachev'14]
  - gamma-ray bursts (GRB) [Murase & Ioka'13]
  - starburst galaxies [Loeb & Waxman'06; He *et al.*'13;Yoast-Hull, Gallagher, Zweibel & Everett'13] [Murase, MA & Lacki'13; Anchordoqui *et al.*'14; Chang & Wang'14]
  - hypernovae in star-forming galaxies [Liu *et al.*'13]
  - galaxy clusters/groups [Murase, MA & Lacki'13;Zandanel *et al.*'14]
  - . . .

Slide from M. Ahlers, NeuTel 2015

Nearly Isotropic Flux



no significant correlations – spatial or temporal

- too few events to identify sources

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 $(\nu_e : \nu_\mu : \nu_\tau) = (1{:}2{:}0)_S$ at source.

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- Predict a flavor ratio of $(\nu_e : \nu_\mu : \nu_\tau) = (1:2:0)_\mathrm{S}$ at source.
- Neutrino oscillations average over an astronomical distance scale.
- 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

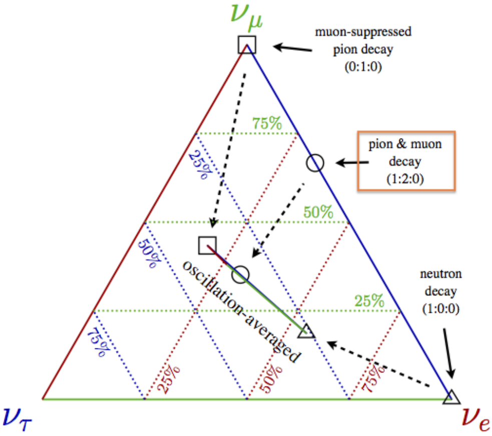
$$f_\ell = \sum_{\ell'=e,\mu,\tau} \sum_{i=1}^{3} |U_{\ell i}|^2 |U_{\ell' i}|^2 f_{\ell'}^0 \equiv \sum_{\ell'} P_{\ell\ell'} f_{\ell'}^0 \ .$$

- TBM mixing is a good approximation:

$$P = \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix} .$$

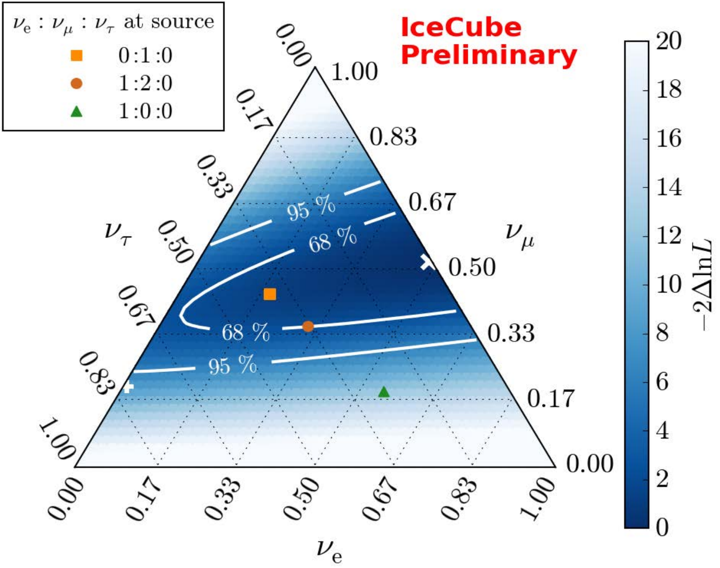
- Predicts $(1:1:1)_\mathrm{E}$ at Earth for $(1:2:0)_\mathrm{S}$. [J. G. Learned and S. Pakvasa, Astropart. Phys. **3**, 267 (1995)]

Other Physical Flavor Compositions



$$(1:2:0)_S \rightarrow (1:1:1)_E$$
$$(0:1:0)_S \rightarrow (4:7:7)_E$$
$$(1:1:0)_S \rightarrow (14:11:11)_E$$
$$(1:0:0)_S \rightarrow (5:2:2)_E$$

Flavor Composition from IceCube data



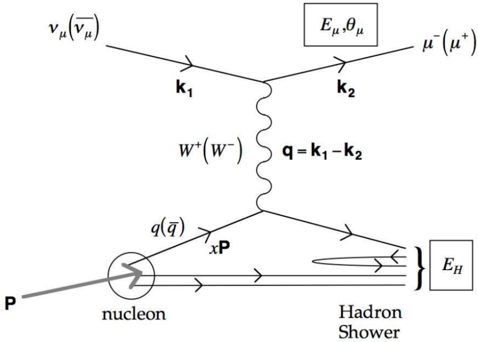
[IceCube Collaboration, ICRC 2015 Proceedings]

Possible (New Physics) Interactions

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

- Decaying (PeV-scale) Dark Matter. [Feldstein, Kusenko, Matsumoto, Yanagida (PRD '13); Esmaili, Serpico (JCAP '13); Bhattacharya, Gandhi, Gupta (JCAP '15); Boucenna *et al* (JCAP '15); Chianese, Miele, Morisi, Vitagliano (PLB '16); BD, Kazanas, Mohapatra, Teplitz, Zhang (JCAP '16);...]
- Secret neutrino interactions involving a light mediator [Ioka, Murase (PTEP '14); Ng, Beacom (PRD '14); Ibe, Kaneta (PRD '14); Kamada, Yu (PRD '15); DiFranzo, Hooper (PRD '15); Altmannshofer, Chen, BD, Soni '16; ...]
- Resonant production of TeV-scale leptoquarks/RPV squarks. [Barger, Keung (PLB '13); Dutta, Gao, Li, Rott, Strigari (PRD '15); Dey, Mohanty (JHEP '15); BD, Ghosh, Rodejohann '16; Mileo, de la Puente, Szynkman '16; ...]
- Decay of massive neutrinos to lighter ones over cosmological distance scales [Baerwald, Bustamante, Winter (JCAP '12); Pakvasa, Joshipura, Mohanty (PRL '13)]
- Pseudo-Dirac neutrinos oscillating to sterile ones in a mirror world [Joshipura, Mohanty, Pakvasa (PRD '14)]
- Superluminal neutrinos and Lorentz invariance violation [Stecker, Scully (PRD '14); Anchordoqui *et al.* (PLB '14)]

SM Neutrino-Nucleon Interactions



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

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

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

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

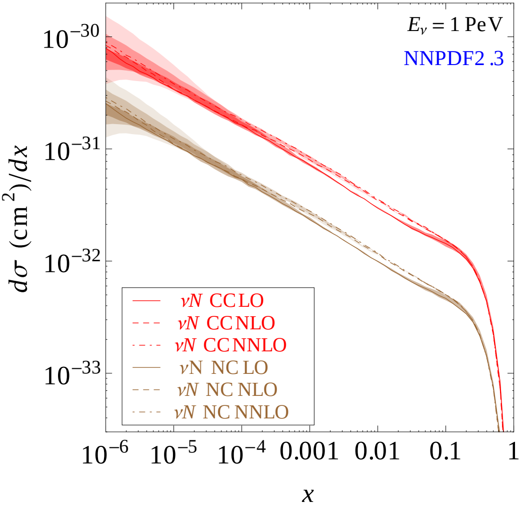
Parton Distribution Functions

- $q, \bar{q}$ ($q^0, \bar{q}^0$) 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:

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

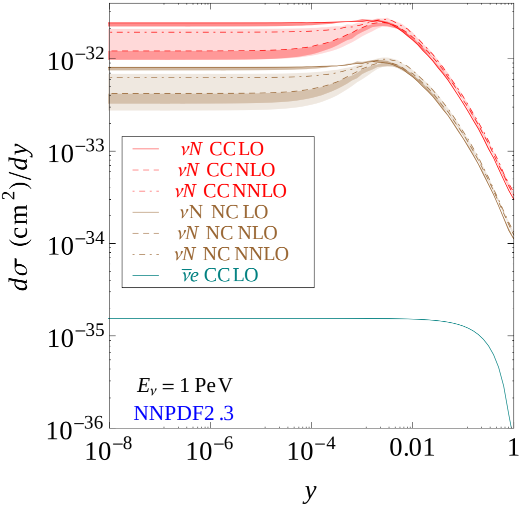
  with $L_u = 1 - (4/3)x_W,\ L_d = -1 + (2/3)x_W,\ R_u = -(4/3)x_W$ and $R_d = (2/3)x_W$ (where $x_W = \sin^2\theta_W$, and θ_W is the weak mixing angle).
- Higher E_ν means probing smaller x-regions (DIS).

Differential Cross Sections



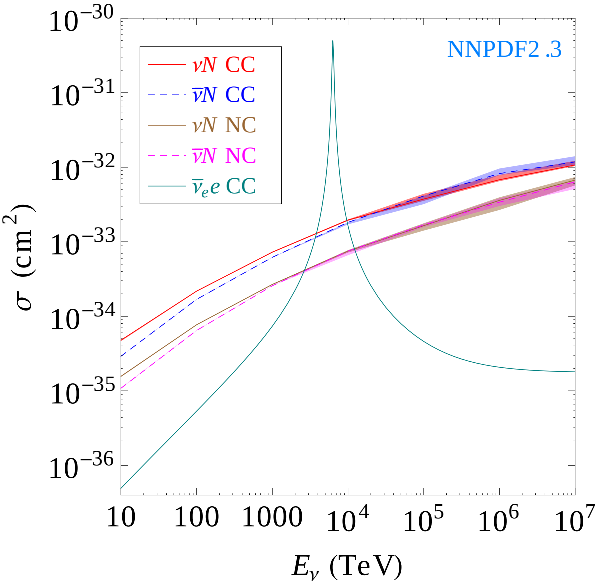
[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **89**, 033012 (2014)]

Differential Cross Sections



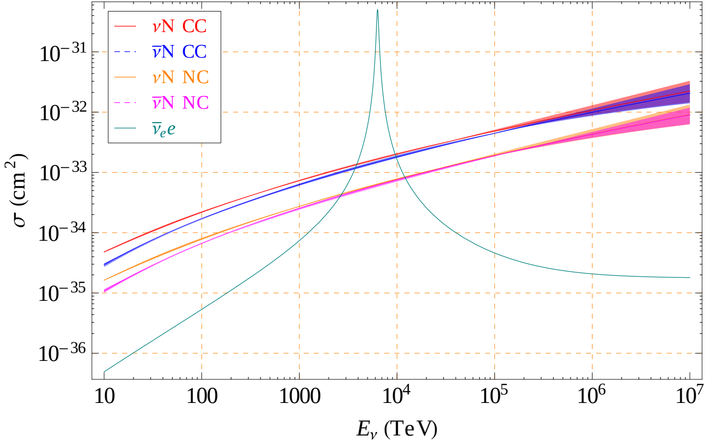
[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **89**, 033012 (2014)]

Total Cross Sections



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

Total Cross Sections (with MSTW2008)



[from A. Connolly, R. S. Thorne and D. Waters, Phys. Rev. D **83**, 113009 (2011)]

Glashow Resonance

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

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

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

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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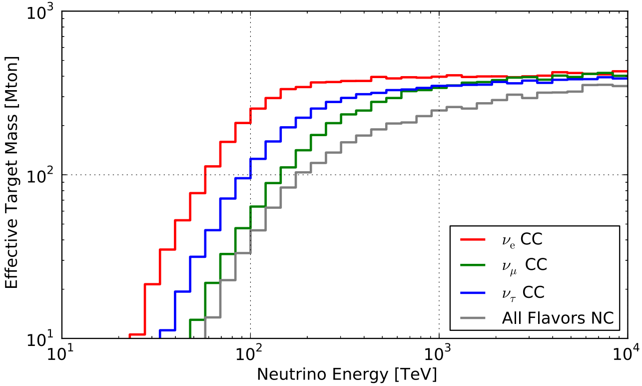
- Peak is at energy $E_\nu = M_W^2/(2m_e) = 6.3$ PeV.
- Proposed as an explanation of the PeV events. [A. Bhattacharya, R. Gandhi, W. Rodejohann and A. Watanabe, JCAP **1110**, 017 (2011); V. Barger, J. Learned and S. Pakvasa, Phys. Rev. D **87**, 037302 (2013)]
- Disfavored by a dedicated IceCube analysis. [IceCube Collaboration, Phys. Rev. Lett. **111**, 021103 (2013)]
- A lighter resonance can be similarly ruled out for a range of coupling values, which might otherwise be inaccessible experimentally.

Event Rate

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

- $T = 988$ (1347) days for the IceCube data collected between 2010-2013 (2014).
- $N_A = 6.022 \times 10^{23}\ \mathrm{mol}^{-1} \equiv 6.022 \times 10^{23}\ \mathrm{cm}^{-3}$ 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.

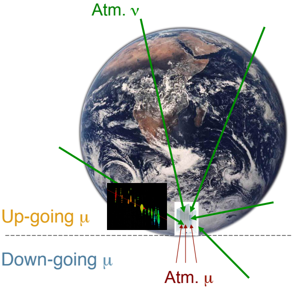


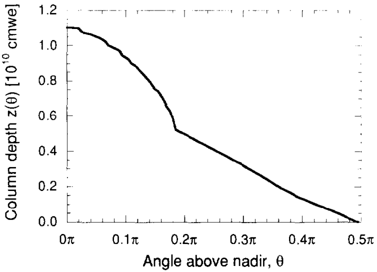
Earth Matter Effect

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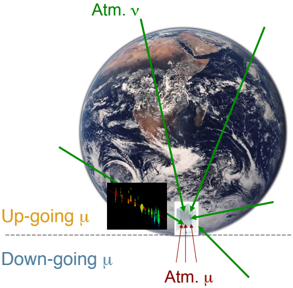
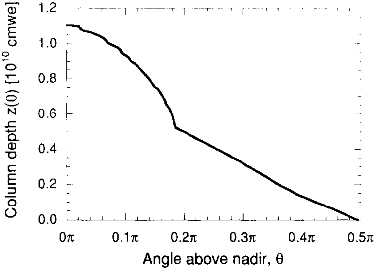
- To take into account Earth Matter effects (for upgoing events), include an attenuation factor [R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Astropart. Phys. **5**, 81 (1996)]

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

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)]





- Makes Earth opaque to UHE neutrinos, thus limiting the upgoing events above $\sim$ 200 TeV.
- For upgoing τ-neutrinos, 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)]

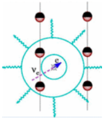
Deposited Energy

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

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

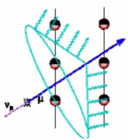
[$F_X = 1 - (E_X/E_0)^{-m}(1-f_0)$, with $E_0 = 0.399$ GeV, $m = 0.130$ and $f_0 = 0.467$ from simulations of hadronic vertex cascade [M. P. Kowalski, Ph.D. thesis, Humboldt-Universität zu Berlin (2004)]

- Contained vertex search to veto atmospheric background].



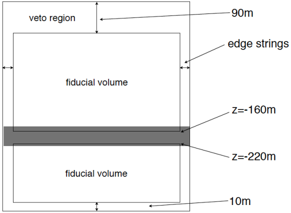
Cascades:

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

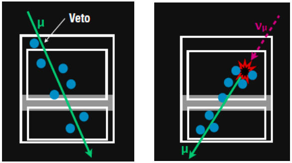


μ Tracks:

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



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



Reject Accept

Astrophysical Neutrino Flux

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

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

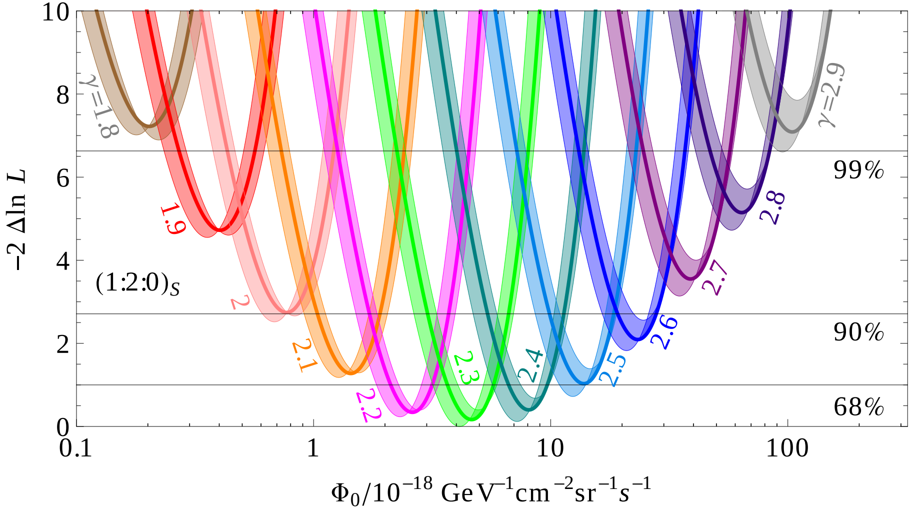
where Φ_0 is the total $\nu + \bar{\nu}$ flux for all flavors at $E_0 = 100$ TeV in units of $\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$.

- 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)]

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

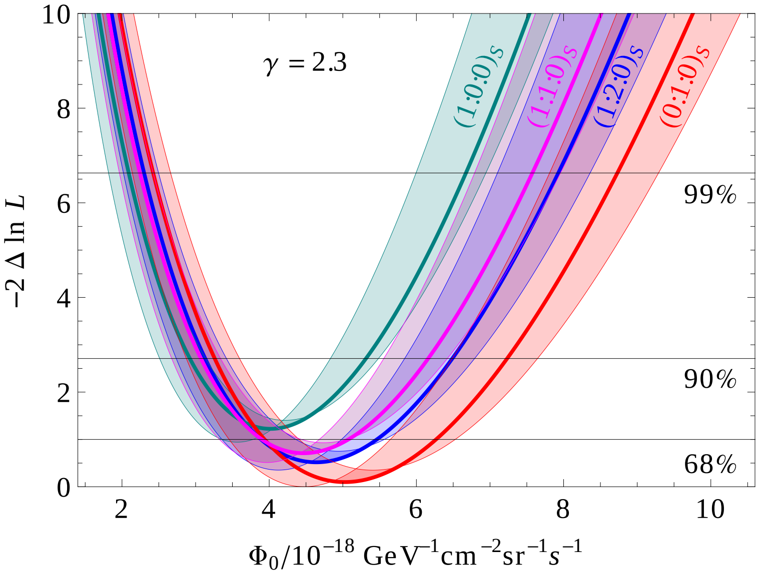
- We keep Φ_0 and γ as free parameters in our analysis.
- Perform a Poisson likelihood analysis.

Likelihood Profile for a Fixed Flavor Ratio



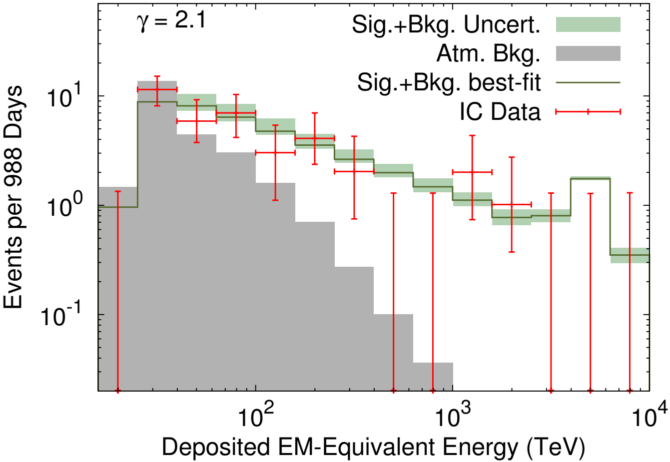
[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

Likelihood Profile for a Fixed Spectral Index



[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

SM Event Distribution



[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

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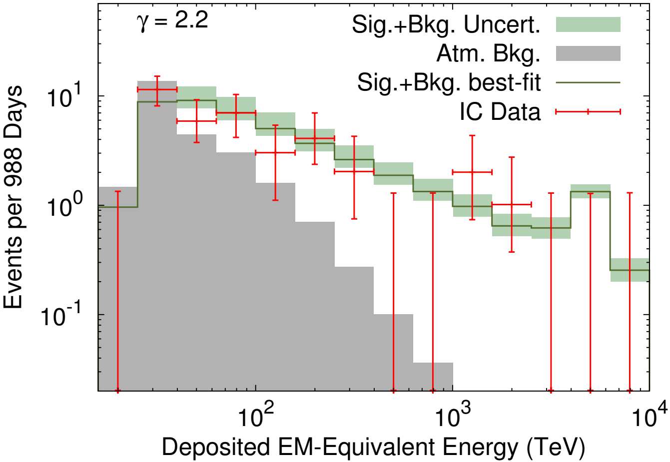

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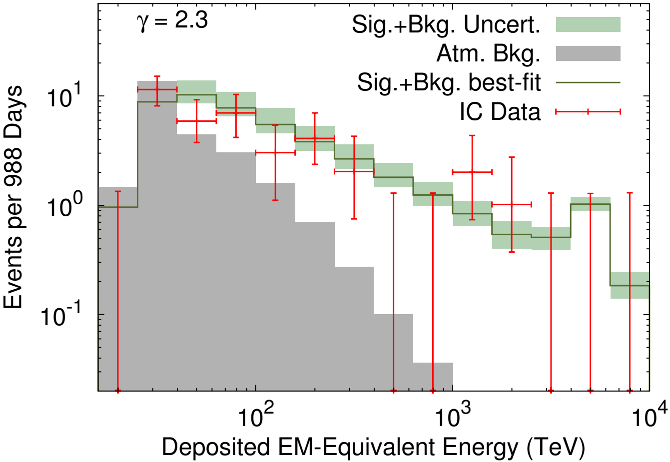

[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

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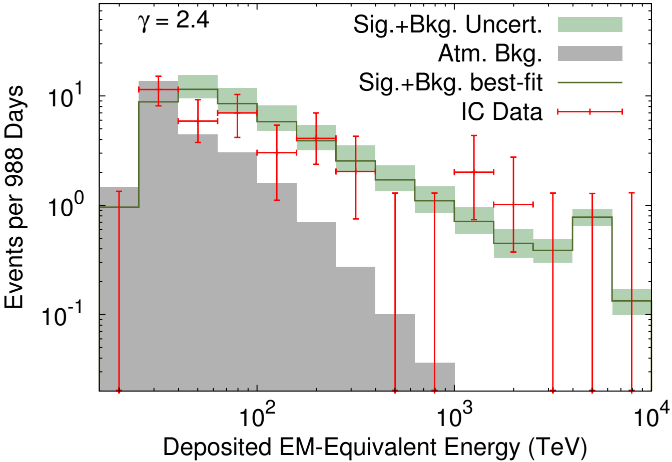

[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

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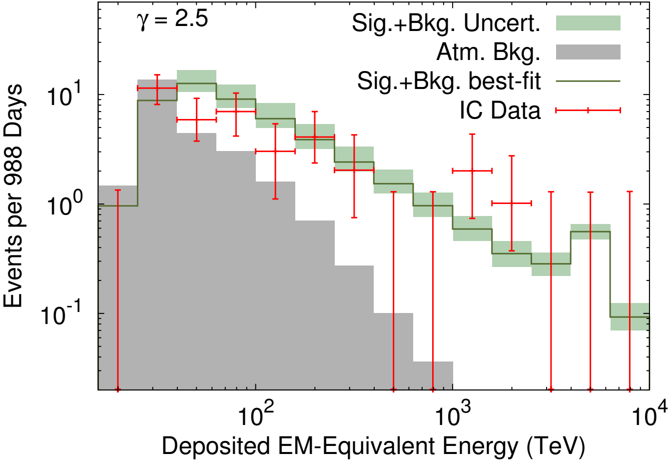
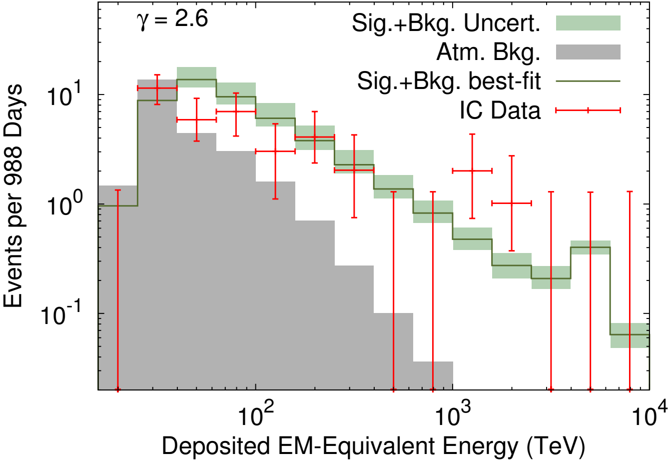


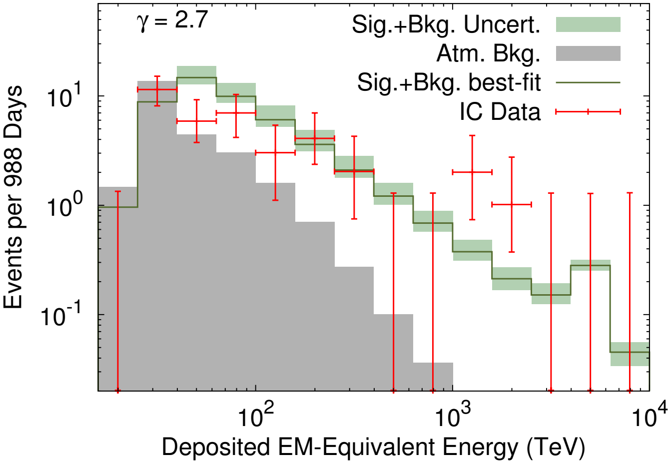
[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

SM Event Distribution



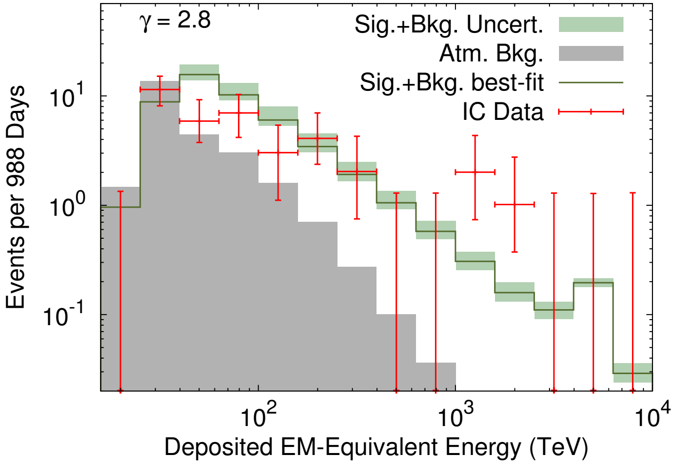
[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

SM Event Distribution



[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

SM Event Distribution



[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

Potential Issues?

- SM predictions with $(1{:}1{:}1)_{\rm E}$ flavor composition seem to be consistent with current IceCube data.
- Salient Features:
  - An unbroken power-law flux with $\gamma \simeq 2.2 - 2.5$.
  - No cut-off required to explain the absence of more UHE events.
  - Less upgoing events due to Earth attenuation effect.
  - Most of the UHE (PeV) events are expected to be downgoing showers.
- So far, no need for any exotic explanation!

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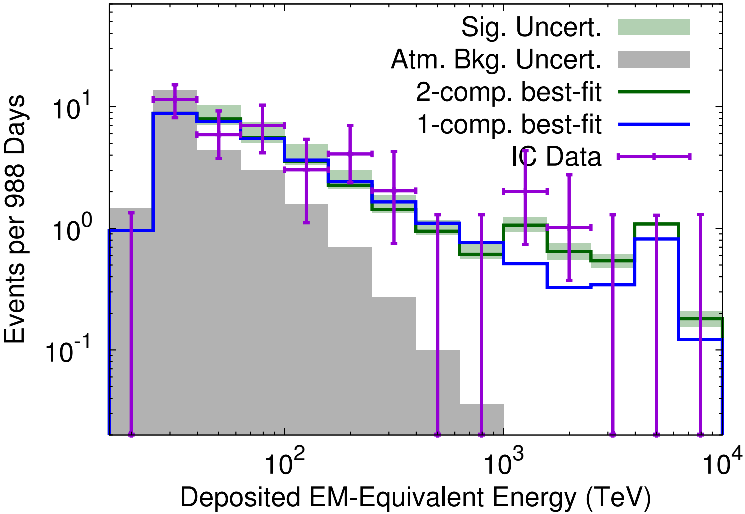
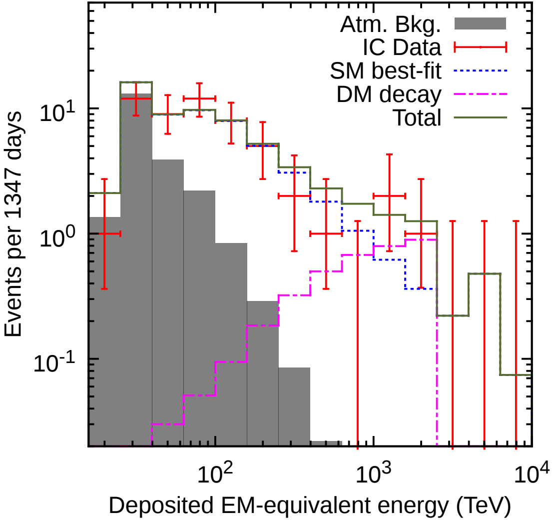
  - Most of the UHE (PeV) events are expected to be downgoing showers.
- So far, no need for any exotic explanation!
- However, a closer look seems to suggest two potential issues (though not statistically significant yet).
  - An apparent energy gap between 400 TeV - 1 PeV (still persists in the 4-yr data).
  - A potential excess in the PeV (and also around 100 TeV) energy bin.

A Two-component Solution



[C.-Y. Chen, BD and A. Soni, Phys. Rev. D **92**, 073001 (2015)]

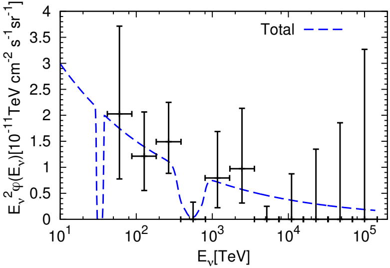
A Possible BSM Solution

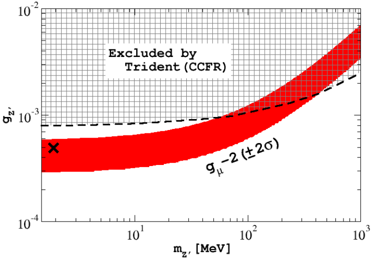


[BD, D. Kazanas, R. N. Mohapatra, V. L. Teplitz and Y. Zhang, JCAP **1608**, 034 (2016)]

Another BSM Solution

- Invoke exotic lepton flavor violating interactions mediated by an MeV-scale Z'.
- Absorption by relic neutrinos could explain the gap between 400 TeV - 1 PeV [T. Araki, F. Kaneko, Y. Konishi, T. Ota, J. Sato and T. Shimomura, Phys. Rev. D **91**, 037301 (2015)]
- New Z' interactions could also explain the longstanding $(g-2)_\mu$ anomaly.

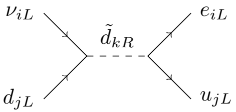




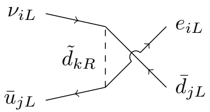
- Requires a non-trivial (asymmetric) flavor structure for $Z'\bar{\ell}_\alpha \ell_\beta$ couplings.
- Other consequences like LFV τ decays. [W. Altmannshofer, C.-Y. Chen, BD and A. Soni, arXiv:1607.06832 [hep-ph]]

RPV SUSY at IceCube

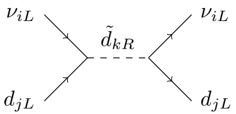
$$\mathcal{L}_{LQD} = \lambda'_{ijk}\left[\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} - \tilde{e}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}e_{iL} - \tilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\right] + \text{H.c.}$$



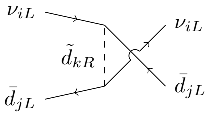
(a) CC s-channel



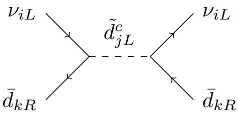
(b) CC u-channel



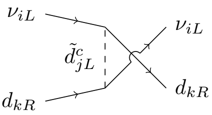
(c) NC s-channel



(d) NC u-channel

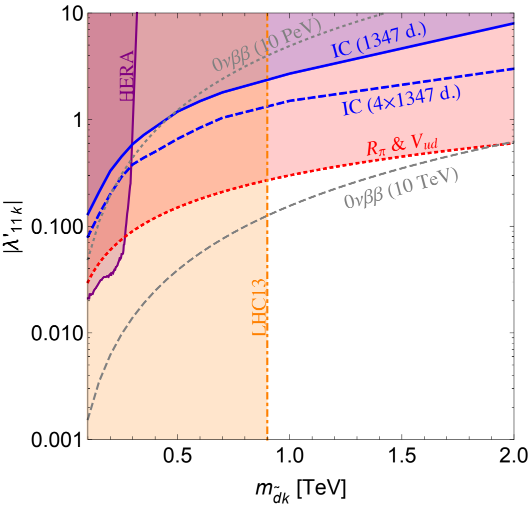


(e) NC s-channel



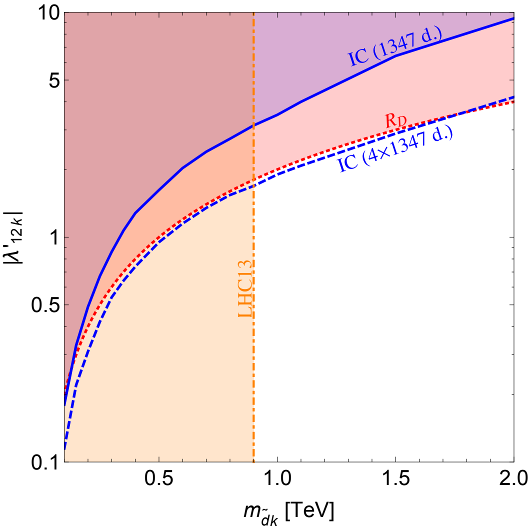
(f) NC u-channel

RPV SUSY at IceCube



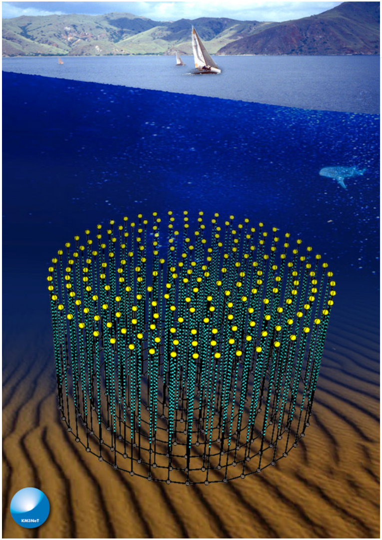
[BD, D. K. Ghosh and W. Rodejohann, arXiv:1605.09743 [hep-ph]]

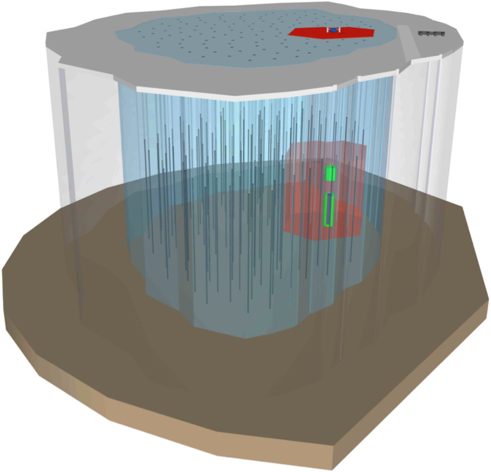
RPV SUSY at IceCube



[BD, D. K. Ghosh and W. Rodejohann, arXiv:1605.09743 [hep-ph]]

Future Prospects (KM3NET, IceCube-Gen2)





Conclusion

- Understanding the UHE neutrino events at IceCube is very important for both Astrophysics and Particle Physics.
- From astrophysics point of view,
  - Need to pin down the source(s) and flavor composition.
  - Multi-messenger approach (involving cosmic rays, γ-rays and neutrinos) is the key.
  - Golden era in Neutrino Astrophysics.
- From particle physics point of view,
  - Current data seems to be consistent with the SM predictions.
  - Any significant deviations call for BSM interpretations.
  - With more statistics, can be used to discover/constrain various BSM scenarios, e.g. light Z', ν NSI, PeV DM, RPV SUSY, leptoquarks.
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THANK YOU.