Where are the Icecube Neutrinos Beyond 2-3 PeV ?

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μ

Neutrinos carry three types of information:

(1) Direction

(2) Energy

(3) Flavor

All three have interesting features in IceCube data

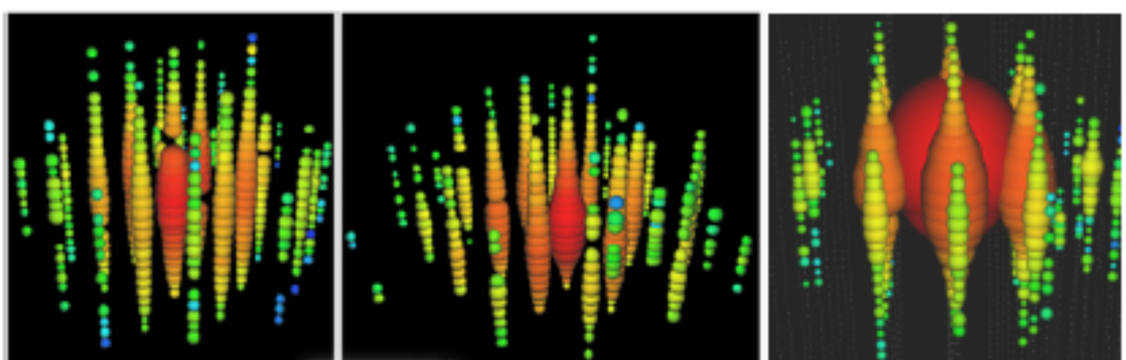
μ

Astro-Nu evidence update:

- first evidence for an extra-terrestrial flux shown at IPA2013 *[IceCube, Science 342 (2013)]*

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

- 3 yrs: 37 events in 988 days — **5.7σ**
- bkg. 8.4±4.2 atm. μ and 6.6+5.9 ν
- 4 yrs: 54 events — **~ 7 σ**
- mostly ν_e CC and NC cascades



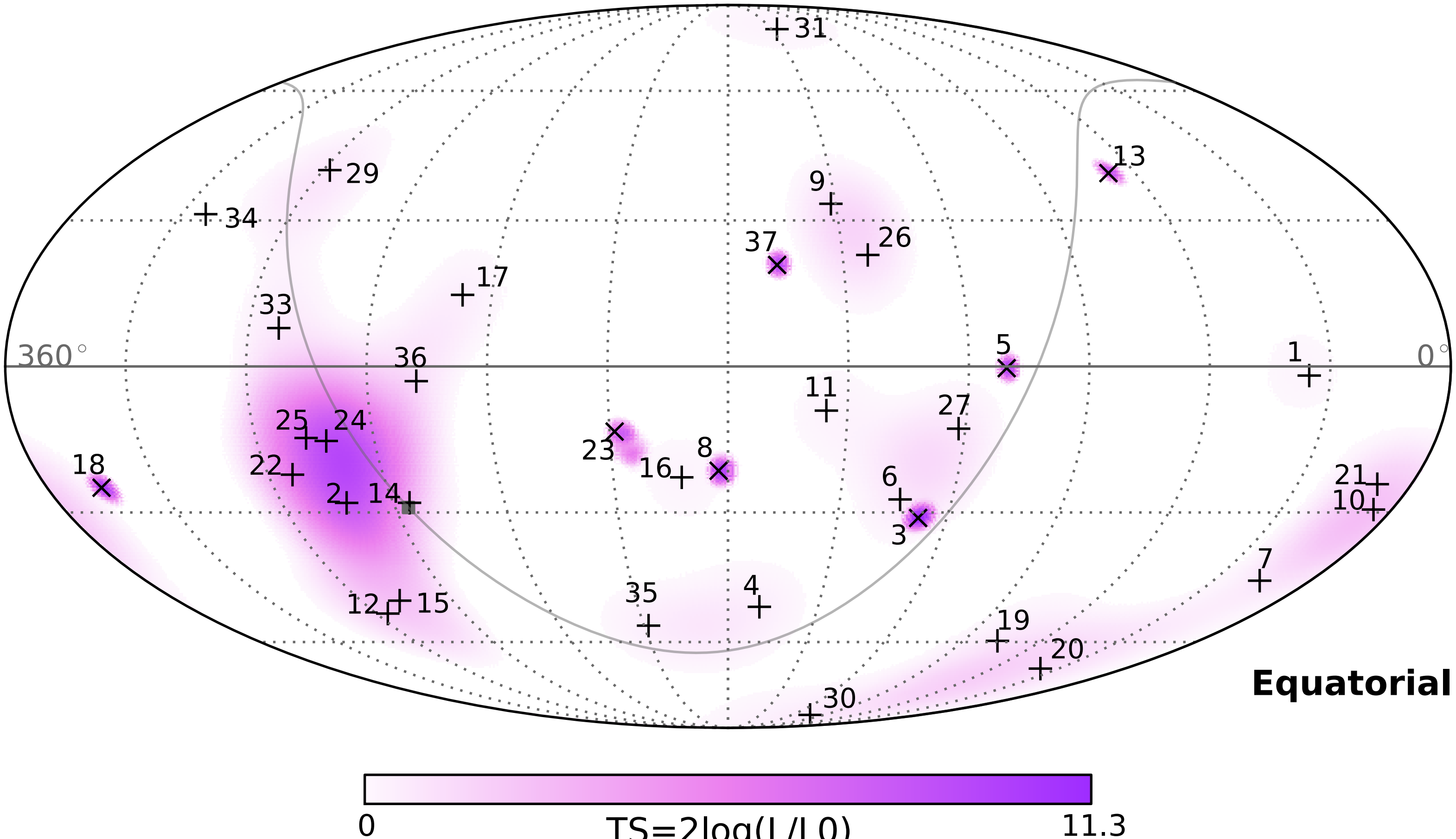
"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

...ents per 1347 Days

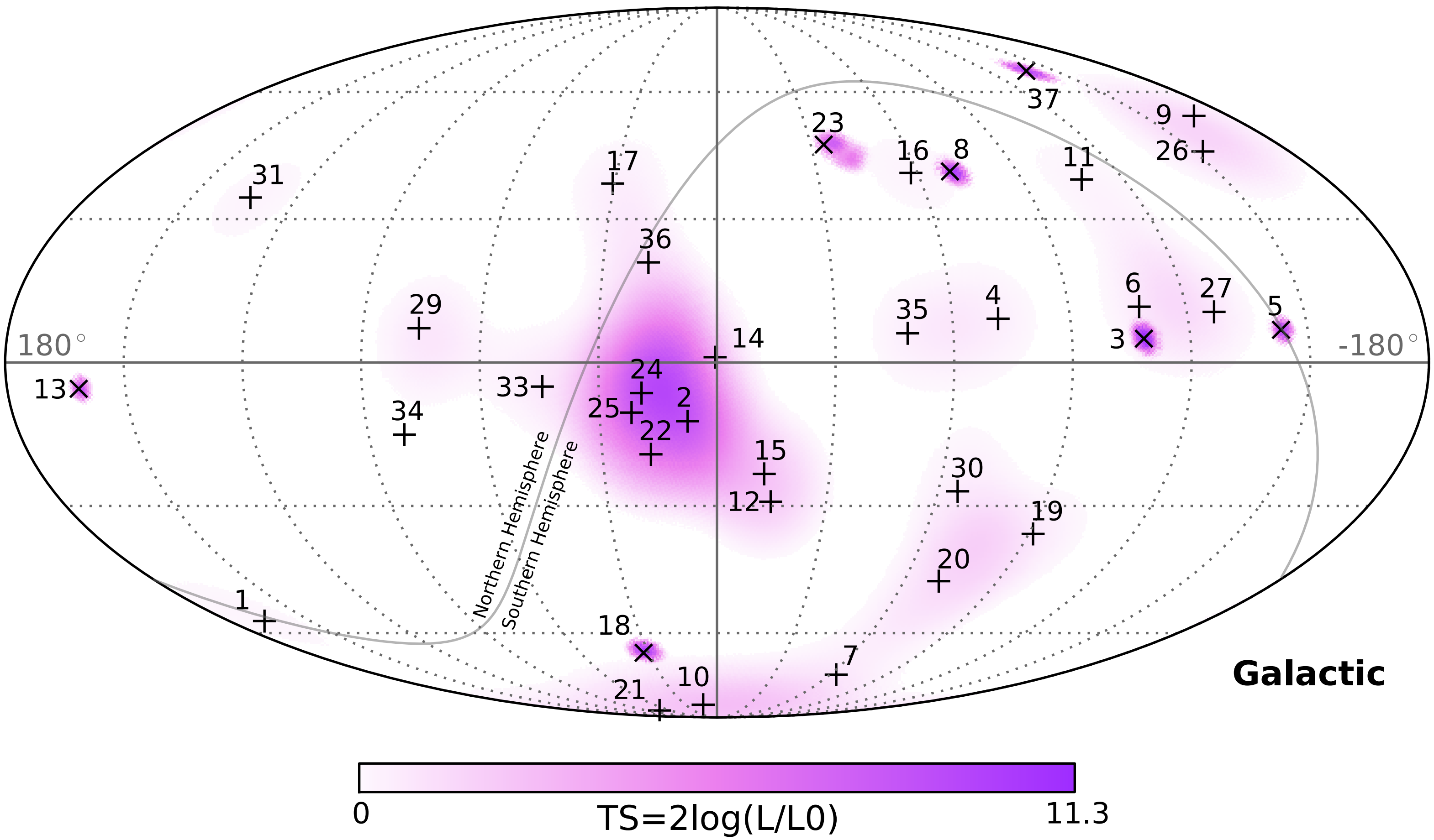
IceCube (Equitorial), 37 events/3 years (bkgd is 15+(2-10) events)



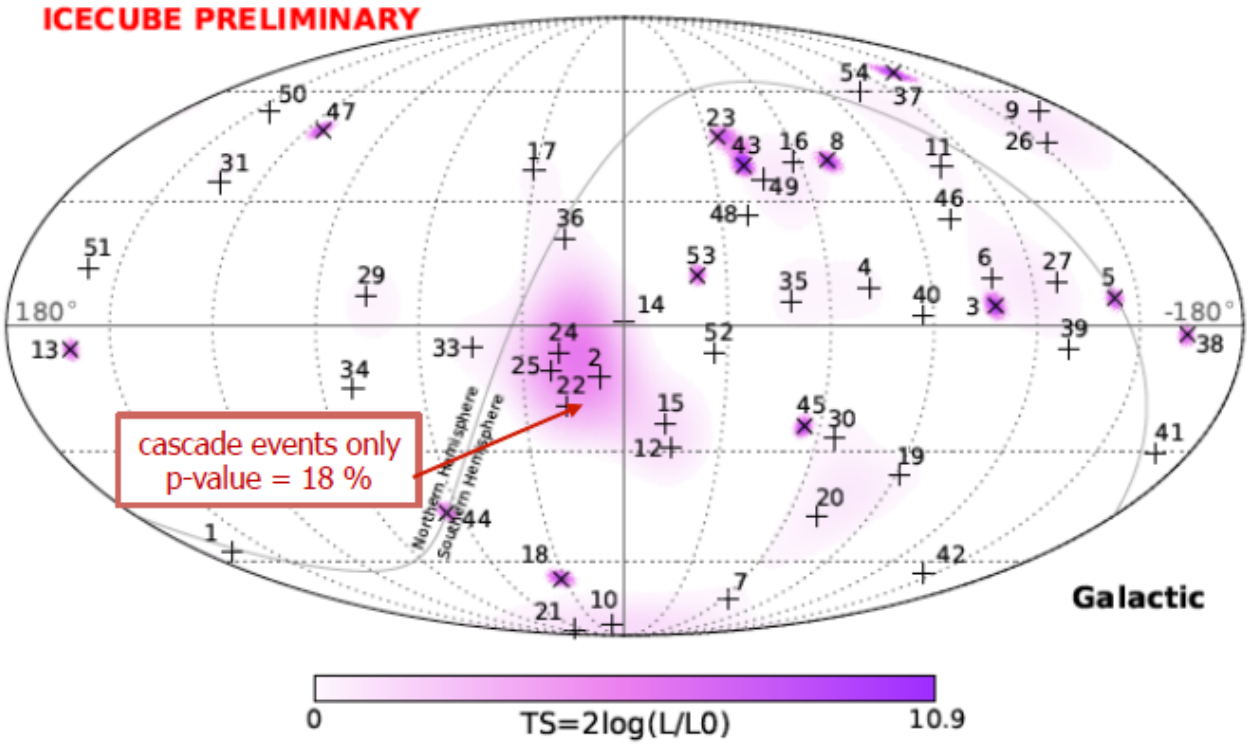
IceCube (Galactic), 37 events/3 years

Maybe Galactic Center shows a transient source (#'s 22, 24, 25) ?

Bai, Two Bargers, Ku, Peterson, Salvado, 1407.2243, suggest associated gammas



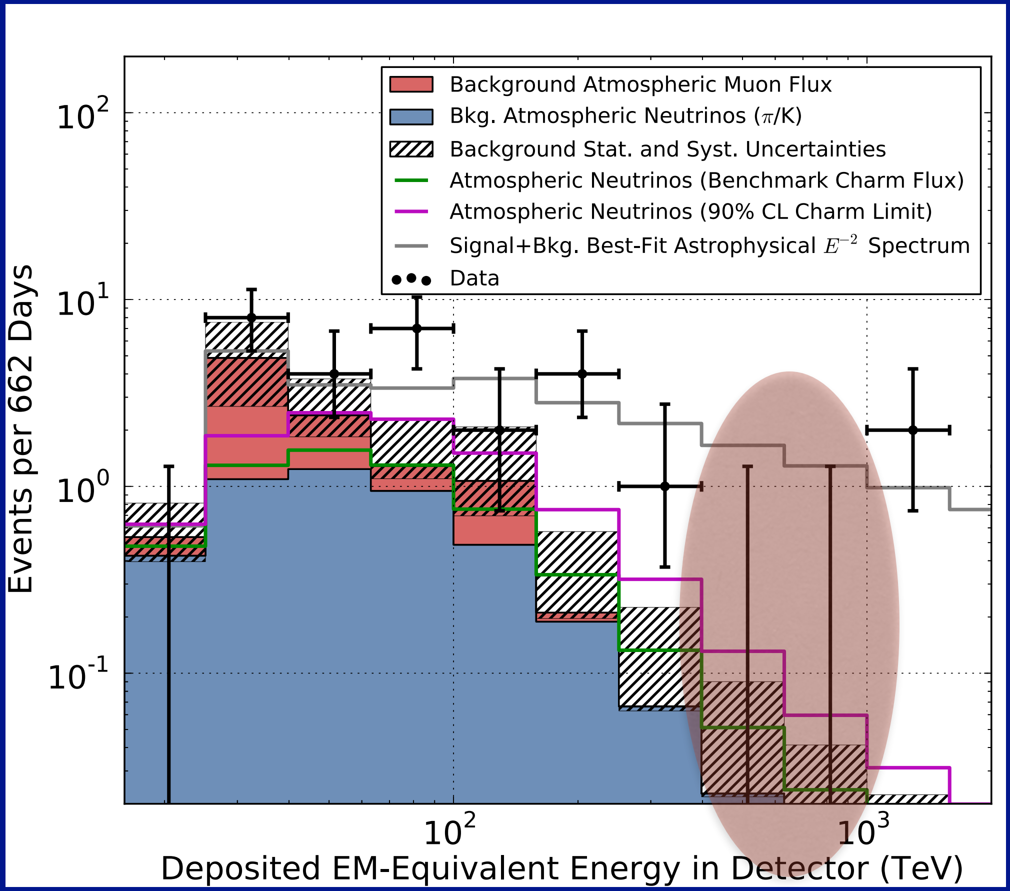
4 years/ 54 events



no significant correlations – spatial or temporal

- too few events to identify sources

Energy - the "gap", and then three events:



e 1: Distribution of the deposited energies of the observed events

Angle-Energy-Flavor Display:

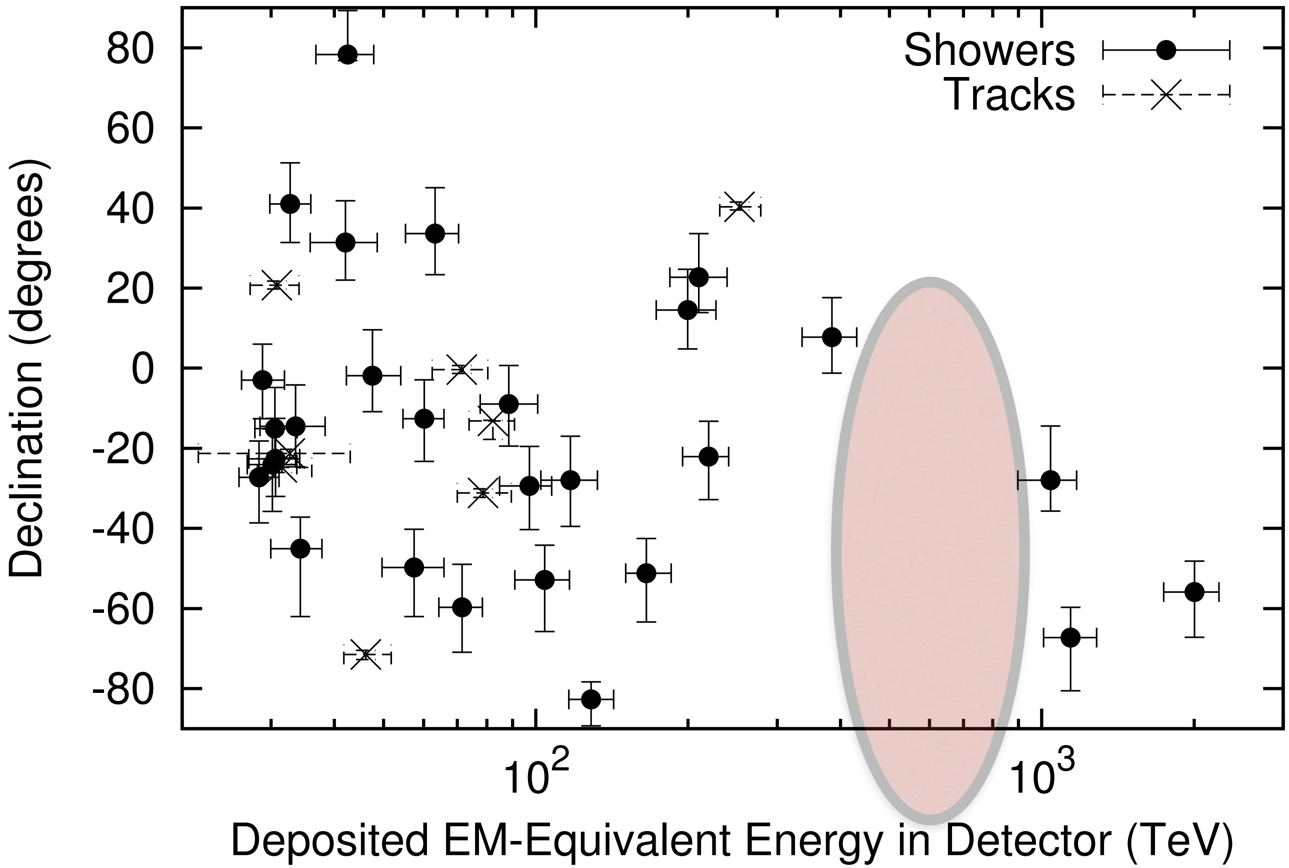
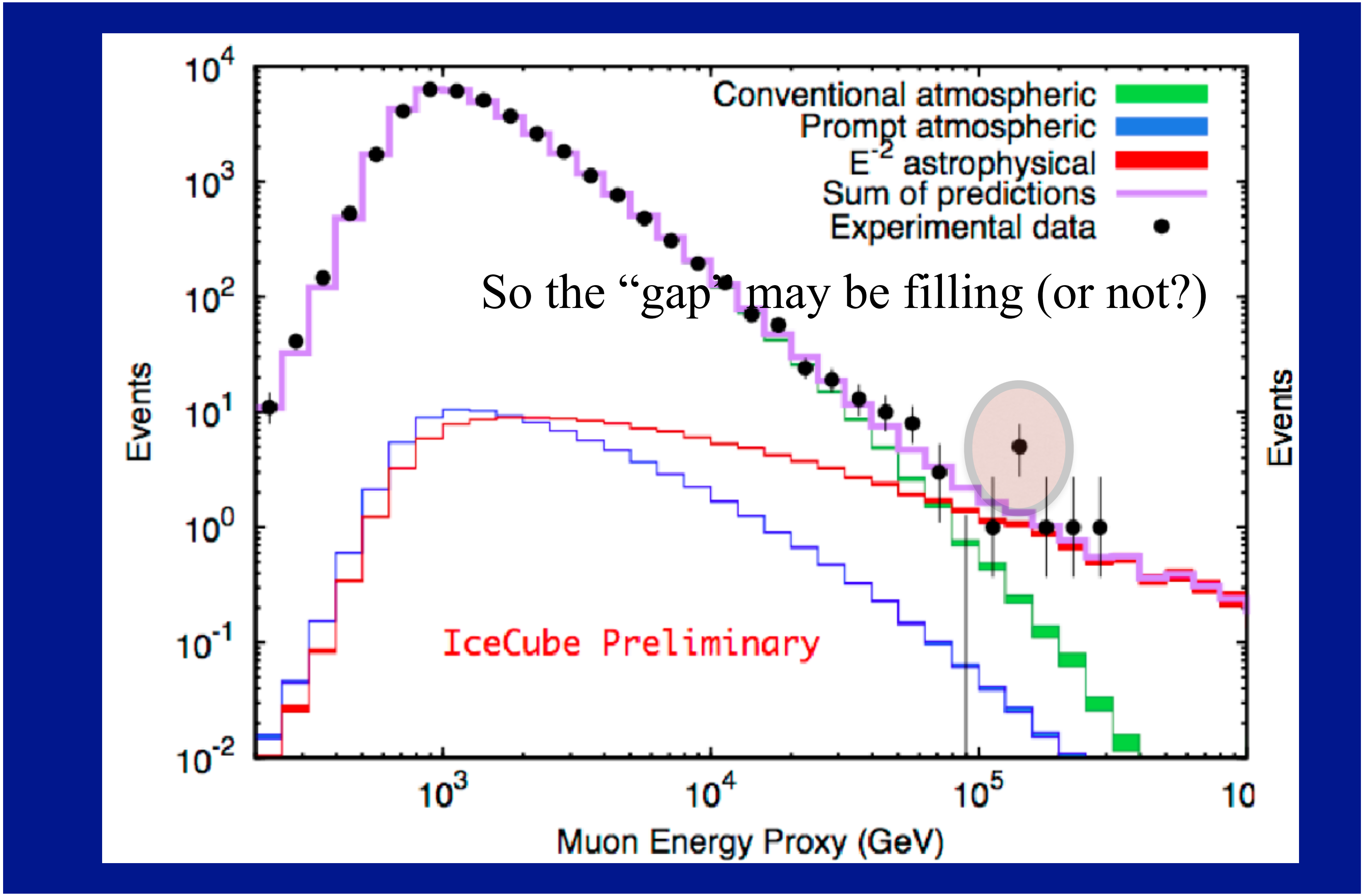
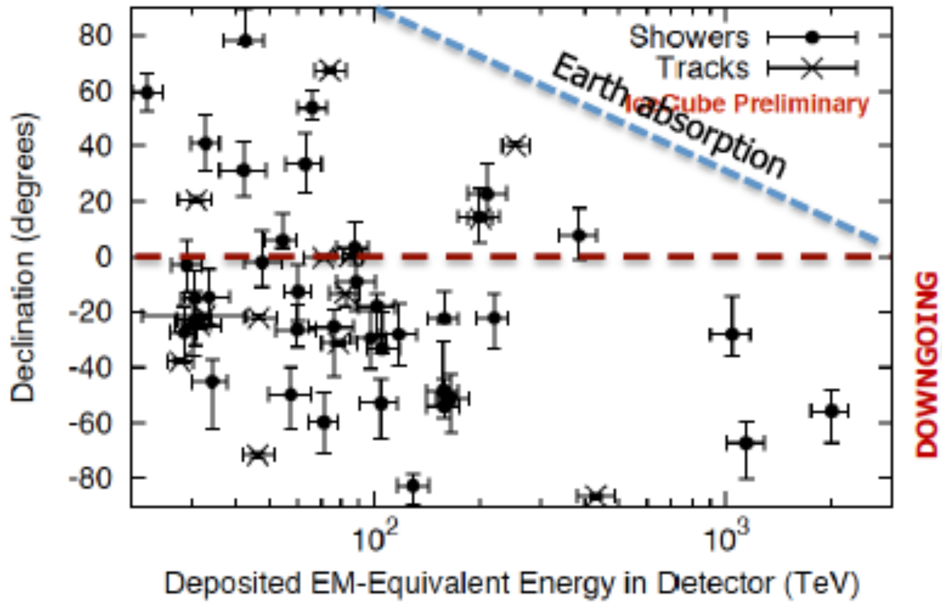


FIG. 1. Arrival angles and deposited energies of the events.

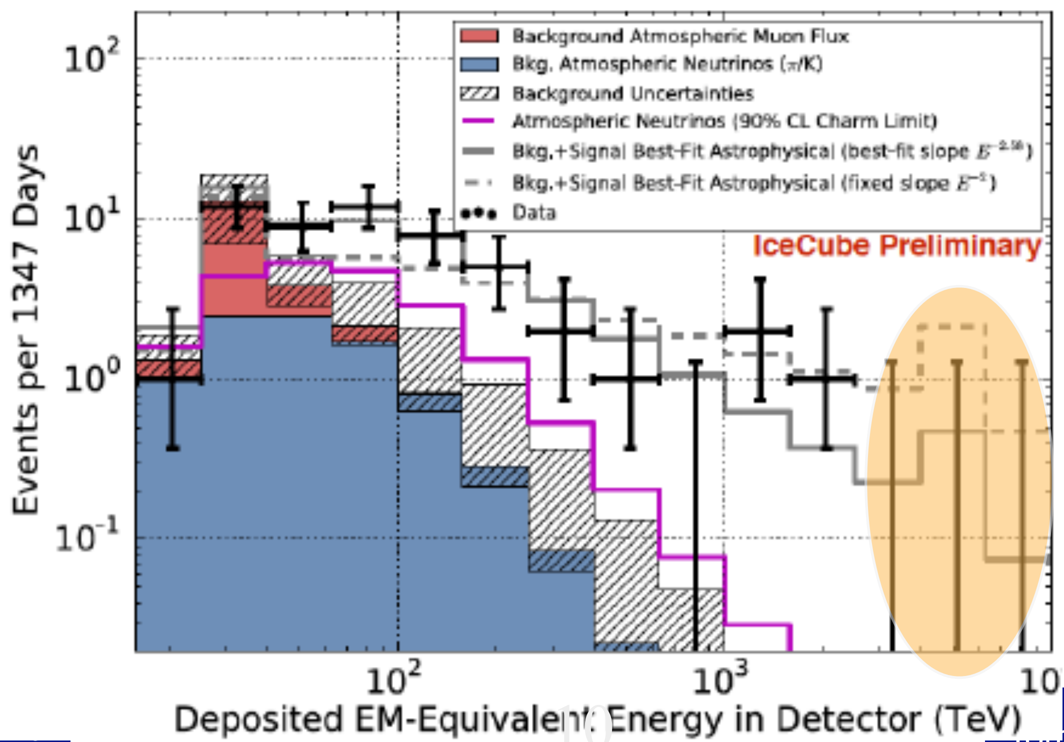
muon rate vs. energy plot:



4 year
54 events



No events



and the "gap" has narrowed

Poisson Probabilities for Bert, Ernie, and Big Bird

Table : Poisson probabilities $\mathcal{P}(n|\mu) = \frac{\mu^n}{n!}\, e^{-\mu}$.

Note: $\mathcal{P}(0|\mu) = e^{-\mu}$, and $\mathcal{P}(\mu|\mu) = \mathcal{P}(\mu - 1|\mu)$.

μ	$n = 3$	$n = 2$	$n = 1$	$n = 0$	$n \geq 3$
3	22%	22%	15%	5.0%	58%
2	18%	27%	27%	13.5%	32%
1	6.1%	18%	37%	37%	8.0%

using Stirling's approximation,

$$P(\mu|\mu) = \frac{1}{\sqrt{2\pi\,\mu}}\,, \text{so}$$

Feldman-Cousins inversion:

FELDMAN-COUSINS
inverts the Poisson distribution:
instead of expected number μ as given, and observed number n as resulting parameter, it's observed number n as given, and range of expected number μ as the inferred parameter.
For a CL, have

$$CL = \int_{\mu_1}^{\mu_2} P(n|\mu)\,,$$

with Feldman-Cousins providing a prescription for where to place the centroid of $[\mu_1, \mu_2]$. At 95% CL (roughly 2σ), F-C get $\mu \in [0.8, 8.0]$ when n=3 (and zero background).
But we have more (Bayesian) info:
there are no observed events above 2 PeV !
So take $\mu = 1$, 2, 3 as representative.
For the first two, three events viewed as an upward fluctuation.

And where are the

i) continuum events

ii) Glashow resonance events

Is there an Energy Cutoff at ~2 PeV ?

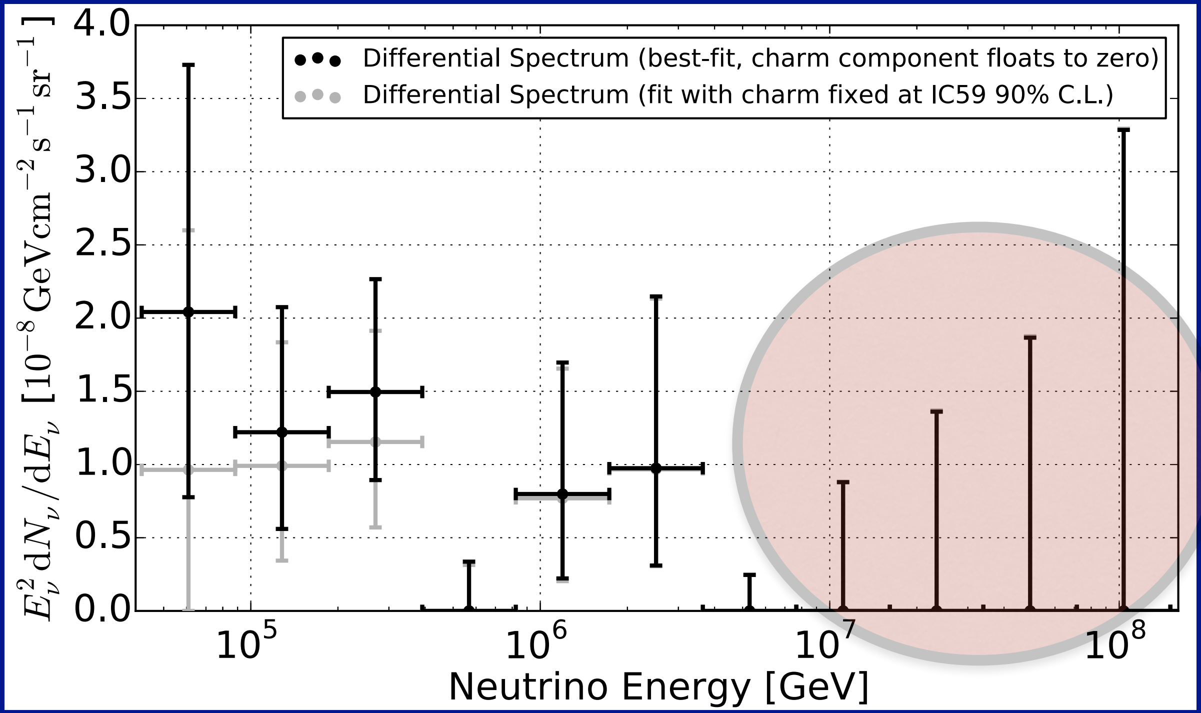


FIG. 4. Extraterrestrial neutrino flux ($\nu + \bar{\nu}$) as a function of energy. Vertical error bars indicate the $2\Delta\mathcal{L} = \pm 1$ contours of the flux in each energy bin, holding all other values, including background normalizations, fixed. These provide approximate 68% confidence ranges. An increase in the

Where are E > 2 PeV neutrino continuum events?

$$\left(\frac{N}{T\Omega}\right)_{\rm non-Res} = N_{n+p}\int_{E_\nu^{\rm min}} dE_\nu \left(\frac{dF_\nu}{dE_\nu}\right)\sigma(E_\nu)_{\nu N}$$

$$= N_{n+p}\left(\frac{6.3\,{\rm PeV}}{E_\nu^{\rm min}}\right)^{\alpha-1.40}\left(\frac{\sigma_{\nu N}^{\rm CC}(E_\nu)}{(\alpha-1.40)}\frac{E_\nu\, dF_\nu}{dE_\nu}\right)\Bigg|_{E_\nu=6.3\,{\rm PeV}},$$

i.e., 1, 0.66 (0.54), 0.52 (0.39), 0.44 (0.29), 0.38 (0.23)
for $E_\nu^{\rm min} = 1, 2, 3, 4, 5,$ PeV

for spectral index = -2 (- 2.3) .

Glashow is a "no-show"?

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

$$s = M_W^2 = 2m_e E_\nu\,, \quad \text{so } E_R = \frac{M_W^2}{2m_e} = 6.3\text{PeV}$$

(Marfatia's talk)

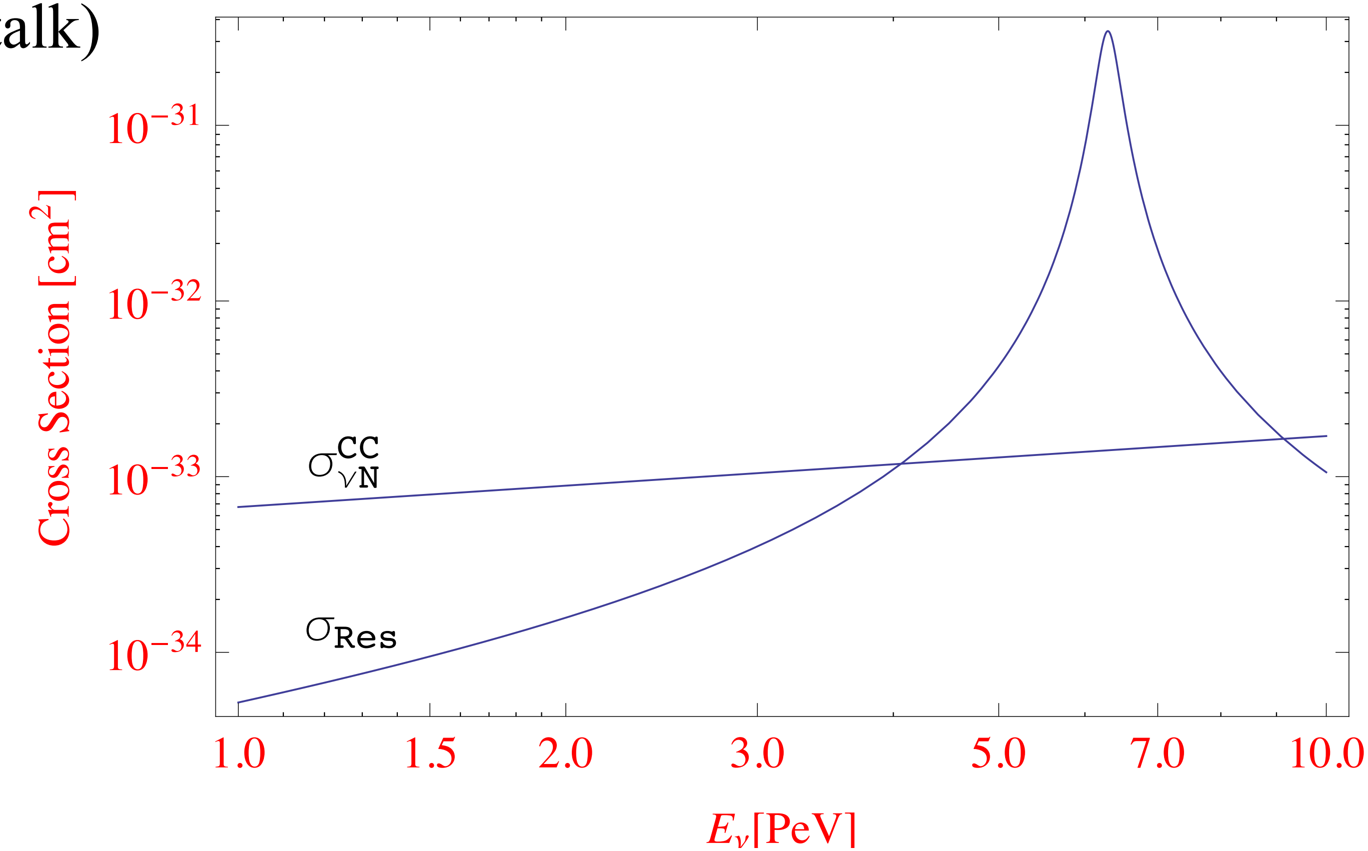


FIG. 1: Cross sections for the resonant process, $\bar{\nu}_e + e^- \to W^- \to$ hadrons, and the non-resonant process, $\nu_e + N \to e^- +$ hadrons, in the 1–10 PeV region.

$$N_{\rm cont}^{\rm exp}(E_1 < E < E_2) = \frac{N_{1-2\,{\rm PeV}}^{\rm exp}}{1-2^{-(\alpha-1.40)}}\left(E_1^{-(\alpha-1.40)} - E_2^{-(\alpha-1.40)}\right)$$

Taking $E_2 \to \infty$ as befits a continued power-law,

$$N_{\rm cont}^{\rm exp}(E > E_1) = \left(N_{1-2\,{\rm PeV}}^{\rm exp}\right)\frac{E_1^{-(\alpha-1.40)}}{1-2^{-(\alpha-1.40)}}\,.$$

Taking $\alpha = 2.0$, 2.3, and 2.5, we get, respectively,

$$N_{\rm cont}^{\rm exp}(E > 2{\rm PeV}) = \left(N_{1-2\,{\rm PeV}}^{\rm exp}\right) \times 1.94,\ 1.15,\ 0.87\,.$$

In addition, the number of Glashow resonance events is

$$\frac{N_{\rm Res}^{\rm exp}}{N_{\rm cont}^{\rm exp}(E > 2{\rm PeV})} \approx 3.4 \times \mathcal{R}\,,$$

where $\mathcal{R}$ is the fraction of Earthly flux that is $\bar{\nu}_e$, ranging from 56% (β-beam) to zero (damped p-γ - no antineutrinos).

Expected event number scales with Prob(Bert, Ernie, Big Bird)

Table : Neutrino events above 2 PeV, continuum and resonant.

spectral index	$N_{\rm cont}(E > 2\,{\rm PeV})$	$+N_{\rm res} = 3.4\mathcal{R}N_{\rm cont}(E > 2\,{\rm PeV})$
2.0	$1.94\,N^{\rm exp}_{1-2\,{\rm PeV}}$	$1.94\,N^{\rm exp}_{1-2\,{\rm PeV}}\,(1 + 3.4\mathcal{R})$
2.3	$1.15\,N^{\rm exp}_{1-2\,{\rm PeV}}$	$1.15\,N^{\rm exp}_{1-2\,{\rm PeV}}\,(1 + 3.4\mathcal{R})$
2.5	$0.87\,N^{\rm exp}_{1-2\,{\rm PeV}}$	$0.87\,N^{\rm exp}_{1-2\,{\rm PeV}}\,(1 + 3.4\mathcal{R})$

Expected event number above 2 PeV:

For example,

Table : Neutrino events above 2 PeV, continuum and resonant.

$\alpha = 2.3,\ \mathcal{R} = 0.17$	$N_{\rm cont}(E > 2\,{\rm PeV})$	$+N_{\rm res}$
	$1.15\, N^{\rm exp}_{1-2\,{\rm PeV}}$	$1.81\, N^{\rm exp}_{1-2\,{\rm PeV}}$
$N^{\rm exp}_{1-2\,{\rm PeV}} = 1$	1.15	1.81
$N^{\rm exp}_{1-2\,{\rm PeV}} = 2$	2.30	3.62
$N^{\rm exp}_{1-2\,{\rm PeV}} = 3$	3.45	5.44

$P(0|1.81) = 16\ \%$,

$P(0|3.62) = 2.7\%$,

$P(0|5.44) = 0.43\%$

Most conservative/probable is

(1) spectral break or spectral end at 2-3 PeV;

and next is

(2) Nature playing a statistical trick on us

New particle physics includes:

(3) Particle resonances, which would fail a filled-in “gap”;

But what if

(4) sigma gets stronger (need ~mb for DM/CνB target)

- Resonance(s) ? (mini “Z-bursts”), or

(5) Lorentz invariance fails (also, Pakvasa talk), signified by

- an Energy cutoff,   or
- Gamma cutoff, for neutrinos ?!

PROPOSED SOURCE CANDIDATES

- **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

Mass-Scales and Energy Cutoff in terms of Boost Factor

Anchordoqui, Barger, Goldberg, Learned, Marfatia, Pakvasa, Paul, TJW (2014)

$$\Gamma_\nu = \left(\frac{E_\nu}{2\ \text{PeV}}\right)\left(\frac{0.05\ \text{eV}}{m_\nu}\right) \times 0.4 \cdot 10^{17}$$

No other massive particle can probe Γ's this high !

whereas

$$\frac{M_{\text{Planck}}}{v_{\text{weak}}} = \frac{1.2\times10^{28}\text{eV}}{247\text{GeV}} = 0.5 \times 10^{17}\ ;$$

Suggests

$$\Gamma_\nu^{\max} = M_{\text{Planck}}/M_{\text{weak}}$$

Learned & TJW (2014)

and a possible connection to Gravity/spacetime foam.

Weingberg's neutrino-mass generating operator,

$$\frac{1}{\Lambda}(HL)(HL) \Rightarrow m_\nu = \frac{vev^2}{\Lambda},$$

$\mathrm{m}_\nu \sim \frac{\mathrm{vev}^2}{\mathrm{M_{GUT}}}$, so

$$\Gamma_\nu(E_\nu \sim \mathrm{PeV}) = \frac{E_\nu}{m_\nu} \sim \left(\frac{\mathrm{PeV}}{\mathrm{vev}}\right)\left(\frac{M_{\mathrm{GUT}}}{M_P}\right)\left(\frac{M_P}{\mathrm{vev}}\right),$$

$$\sim 10^4 \times 10^{-4} \times \left(\frac{M_P}{\mathrm{vev}}\right).$$

J.G.Learned and T.J. Weiler, arXiv:1407.0739

Neutrino Energy Maximum:

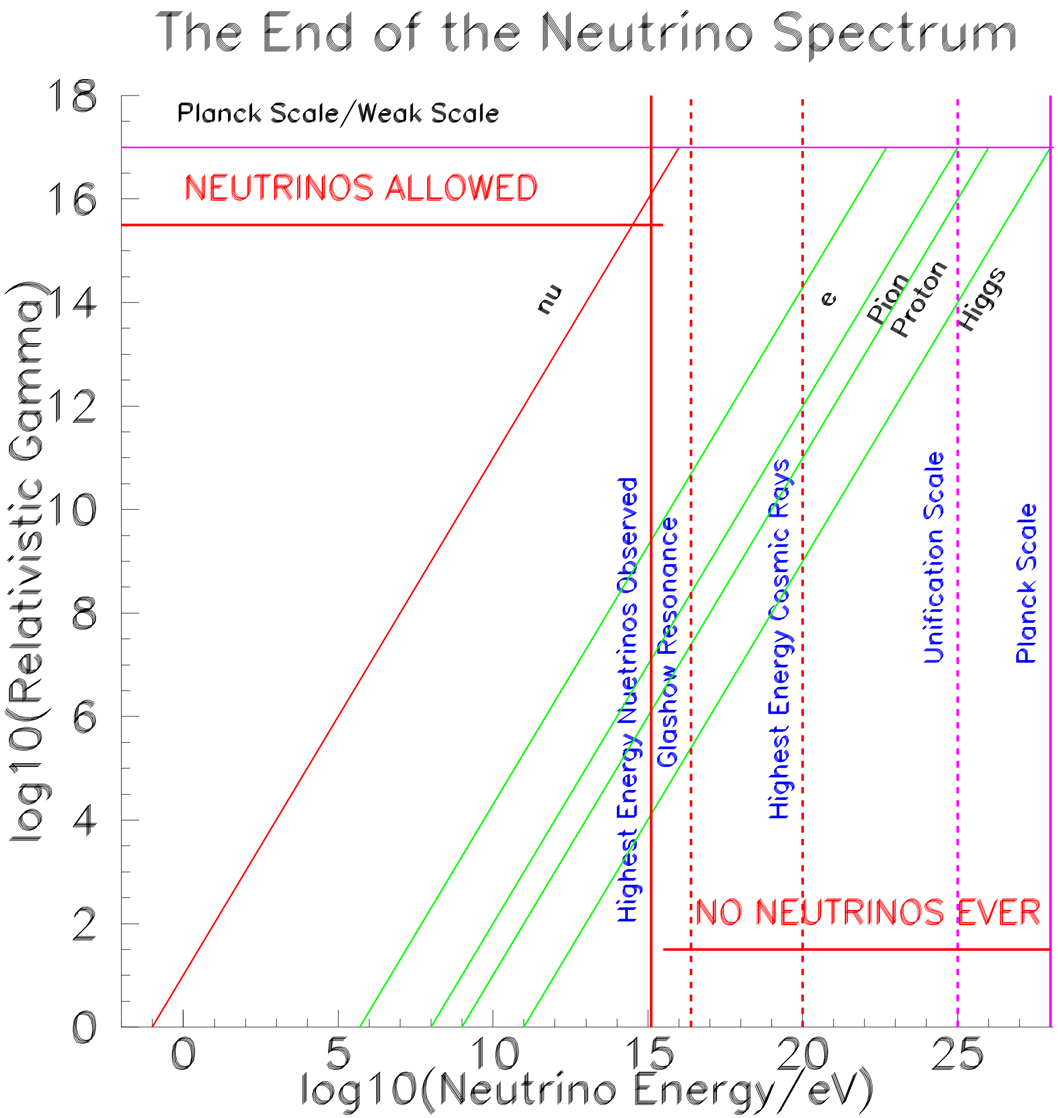
$$E_\nu^{\max} = \frac{m_\nu\, M_{\rm Planck}}{M_{\rm weak}}$$

$$= 2.5\left(\frac{m_\nu}{0.05\,{\rm eV}}\right)\left(\frac{M_{\rm Planck}}{1.2\times 10^{28}\,{\rm eV}}\right)\left(\frac{247\,{\rm GeV}}{v_{\rm weak}}\right){\rm PeV}\,.$$

In what frame?

Nature provides THE preferred frame, the Cosmic Rest Frame.
So $E_\nu^{\max}$
can be written as $u_\beta^{\rm CRF}(p_\nu^{\max})^\beta\,,$ where $u_\beta^{\rm CRF} = (1,\vec{0})$.

And $(p_\nu^{\max})^\beta$ transforms as usual four-vector.



Reasons (excuses):

1- LI is "emergent" low-energy symmetry;

2- Weak int'n "size" is Higgs vev fluctuation, contracted by Lorentz to Planck size:

a) spacetime foam

b) strong gravity/geometry

c) extra dim'ns open up

d) Planck scale LIV

e) …make your own model (like Bj);

doesn't matter, as it is an Xptl issue!

Learned & TJW (2014)

Engel, Seckel, Stanev:

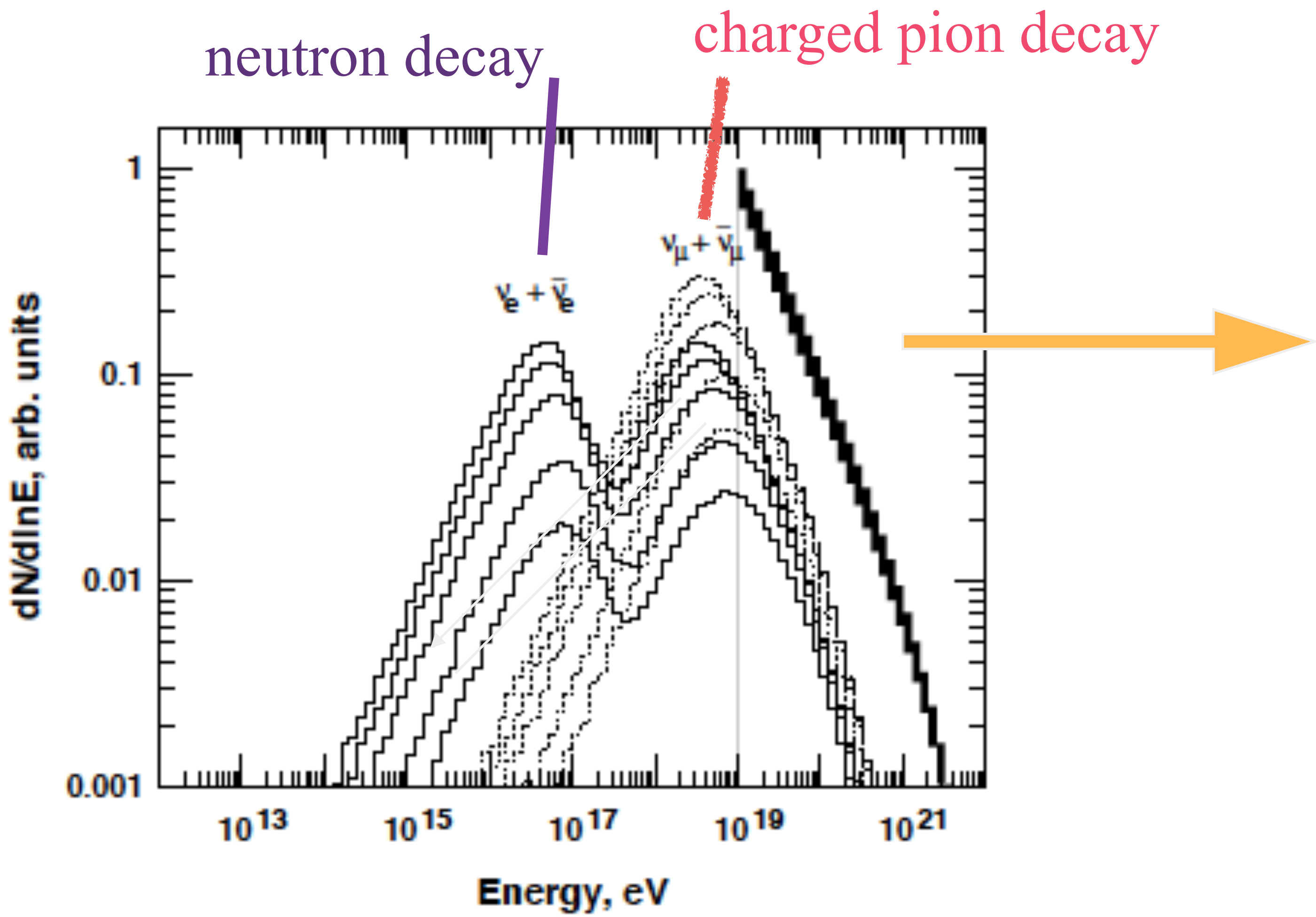
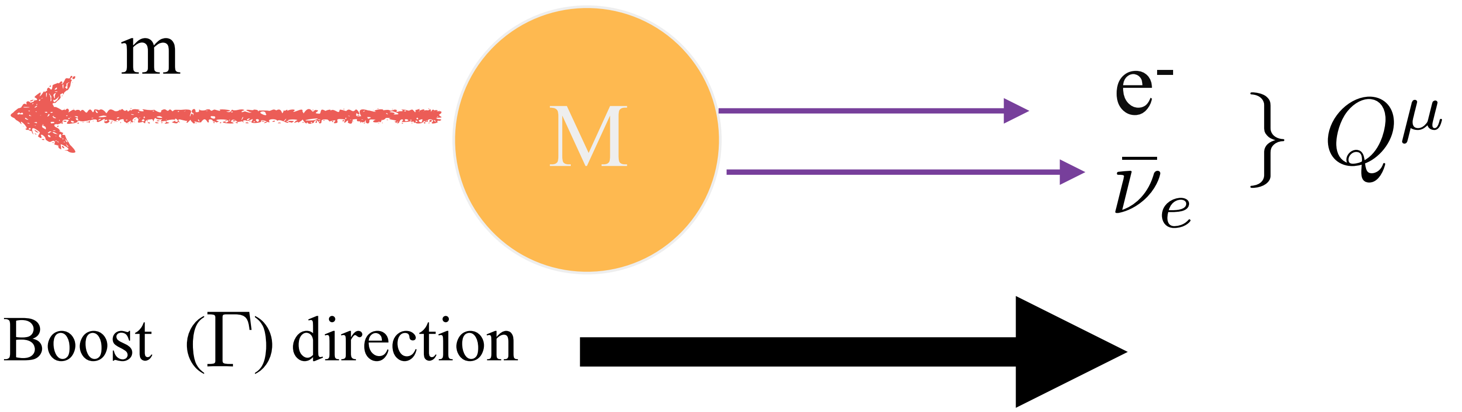


FIG. 2. Neutrino fluxes produced during the propagation of protons over 10, 20, 50, 100, and 200 Mpc (from bottom up) in a 1 nG random magnetic field. The heavy histogram shows the proton injection spectrum defined in Eq. (1).

Not only are many PeV neutrinos (and electrons) forbidden, but also the neutron, muon, and charged pion are stabilized by E(lepton)$^{\max}$



$$Q_0^{\rm LAB} = \Gamma \bar{Q}_0 - \sqrt{\Gamma^2 - 1}\,\bar{Q} \approx \Gamma(\bar{Q}_0 - \bar{Q}) = \Gamma \frac{Q^2}{\bar{Q}_0 + \bar{Q}} > \frac{\Gamma\, Q^2}{2\bar{Q}_0}$$

$$\text{So, } E_M^{\rm LAB} = M\Gamma < \left(\frac{2\bar{Q}_0 M}{Q^2}\right) Q_0^{\rm LAB}$$

$$\text{implies absolute stability if } E_M > \frac{M^2 - m^2}{m_e^2}(E_e + E_\nu)^{\max}$$

Anchordoqui, Barger, Goldberg, Learned, Marfatia, Pakvasa, Paul, TJW (2014)

Sufficient (but not necessary) conditions for absolute stability:

$$\frac{E_M^{\text{stability}}}{(E_e+E_\nu)_{\text{max}}}$$

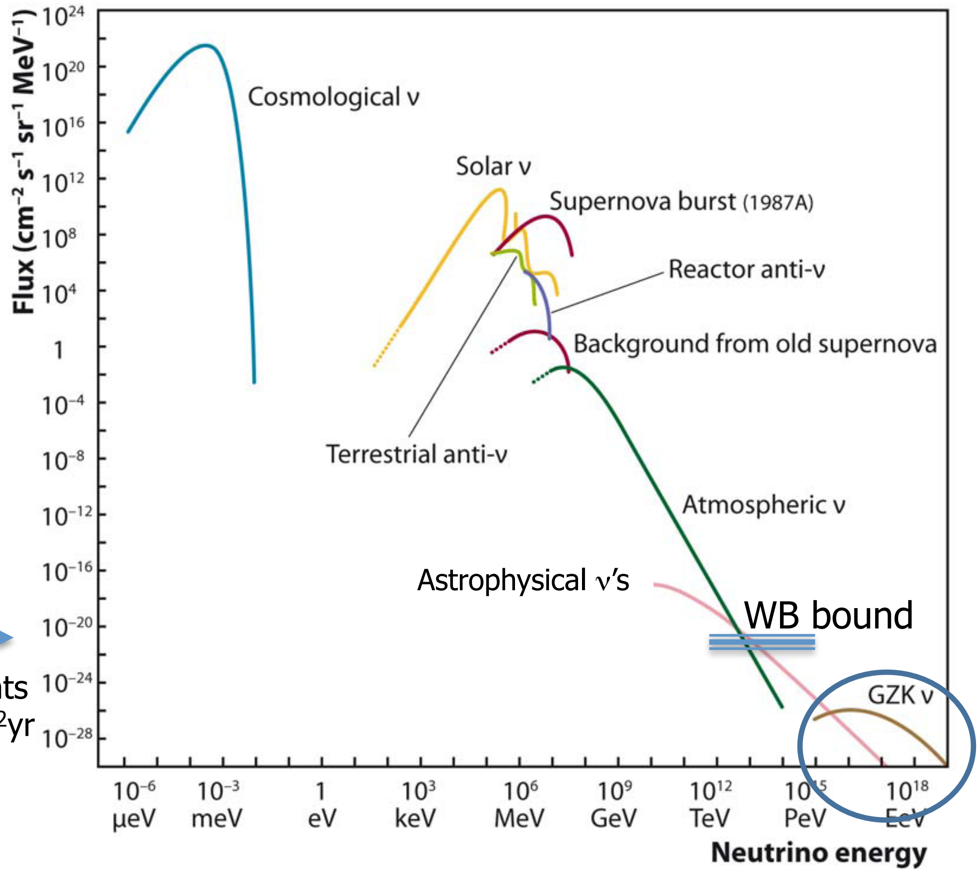
$n \to p\, e^-\, \bar{\nu}_e$	$\frac{m_n^2 - m_p^2}{m_e^2}$	9.7×10^3
$\mu \to \nu_\mu\, e\, \nu_e$	$\frac{m_\mu^2}{m_e^2}$	4.3×10^4
$\pi^\pm \to \gamma\, e^\pm\, \nu_e$	$\frac{m_{\pi^\pm}^2}{m_e^2}$	7.5×10^4
$\pi^\pm \to \pi^0\, e^\pm\, \nu_e$	$\frac{m_{\pi^\pm}^2 - m_{\pi^0}^2}{m_e^2}$	4.5×10^3
$\tau \to \nu_\tau\, e\, \nu_e$	$\frac{m_\tau^2}{m_e^2}$	1.2×10^7

Denton, Marfatia & TJW (2015)

Cosmogenic's another "no-show" ?

UPPSALA UNIVERSITET

ICECUBE



100 → ν_μ events per km^{2}yr

"guaranteed" flux

Greisen-Zatsepin-Kuzmin cosmogenic ν's

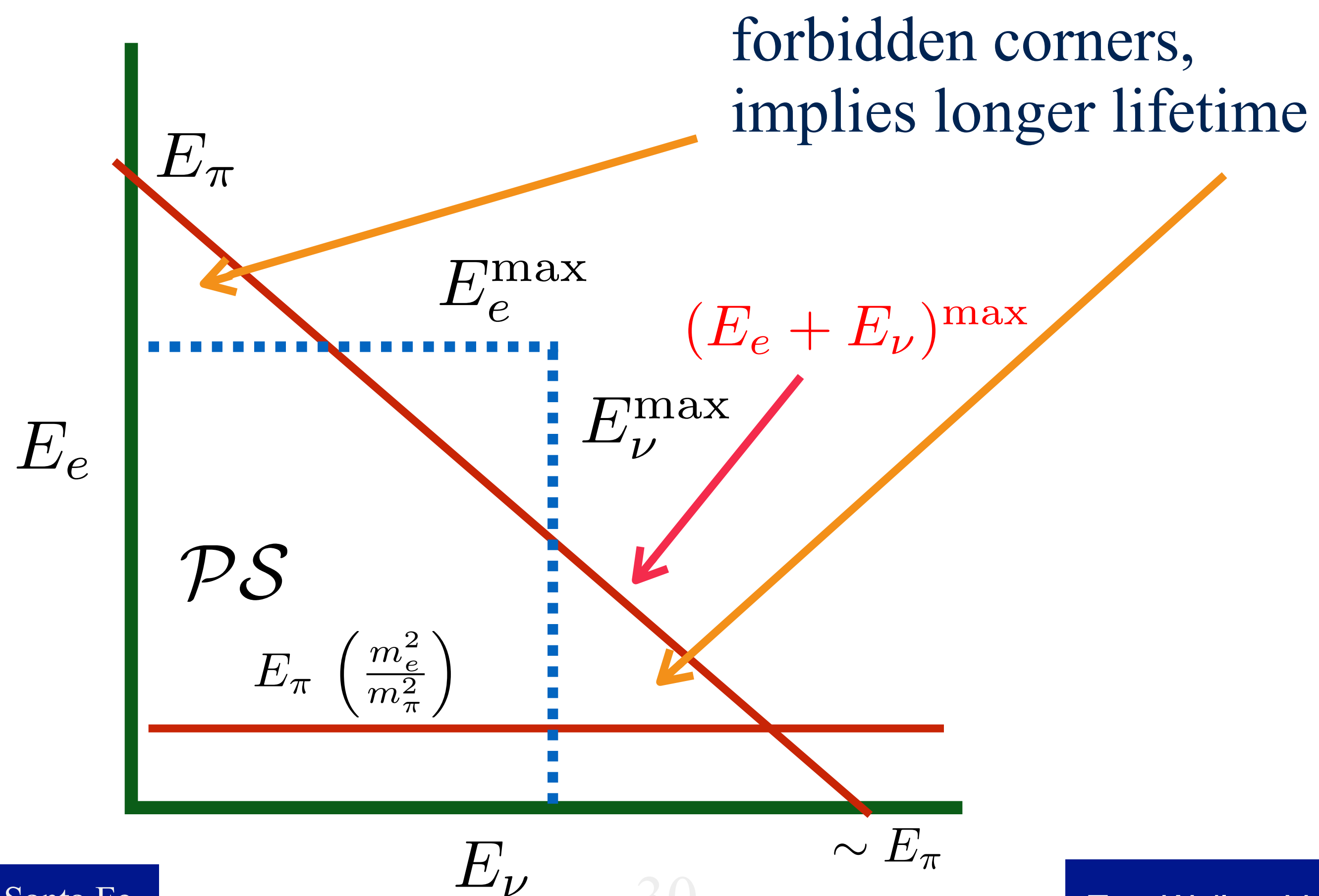
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \begin{array}{l} n\pi^+ \rightarrow n\mu\nu \\ p\pi^0 \rightarrow \gamma\,\gamma \end{array}$$

- atmospheric ν's dominate < 100 TeV
- astrophysical ν's (perhaps) > 100 TeV

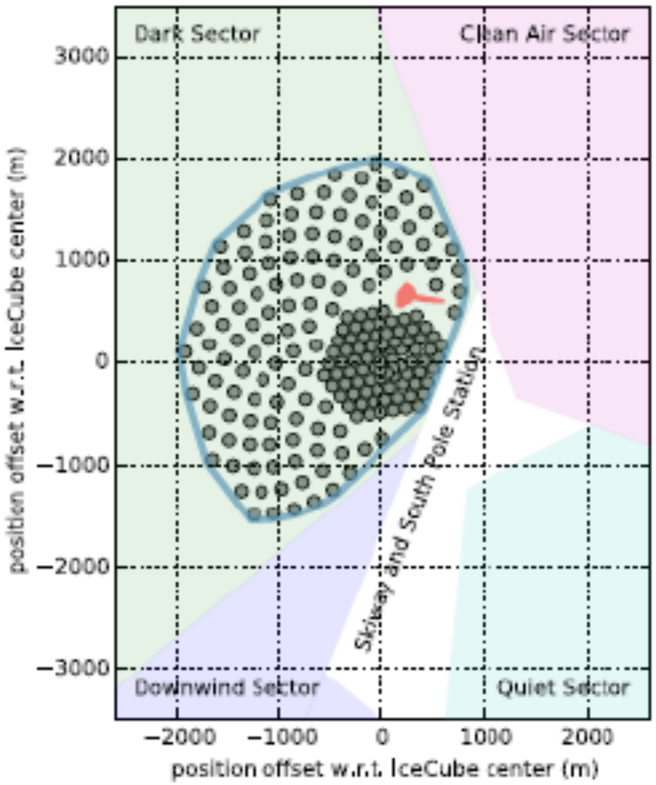
Necessary Condition much harder (in progress)

3-body phase space is

$$dLIPS^{(3)} = \frac{1}{32\pi^3}\, dE_1\, dE_2$$



May receive help from IceCube Gen-2, to answer questions:

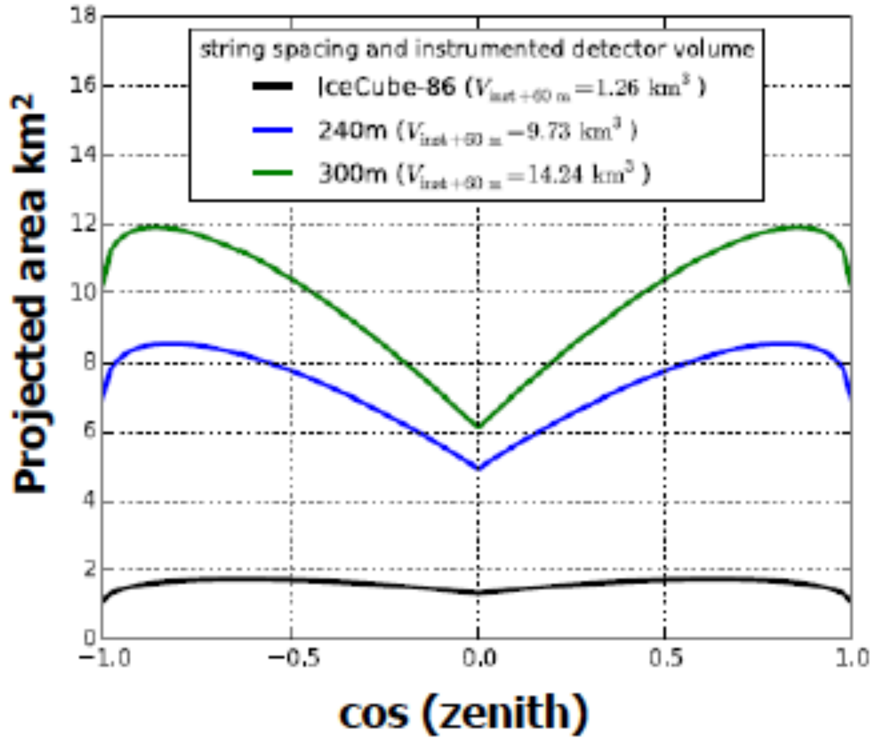


STRAWMAN DETECTOR

- 120 additional strings
- length 1.3 km
- average spacing 240 m
- volume 9.7 km^3

Expect 5-10 increase in effective area,
=> 5-10 increase in EVENT RATE:

INCREASE IN VOLUME AND PROJECTED AREA



In Summary:

Multi-PeV and Glashow resonance rates not yet in danger,
but worth watching.

Glashow resonance can reveal ν source dynamics on other side of Universe (Marfatia's talk).

If events above a few PeV do not arrive, then either/or

(a) Nature cuts off/breaks the sources
($E_p \sim 20\, E_\nu$ for pion chain);

(b) $\sigma_{\nu N}$ is anomalously large at ~PeV (~ mb);
(includes resonant mini-bursts, CFS; DiFH; … Hernandez,TJW)

(c) new fundamental physics at scale $\Gamma_\nu \sim 10^{17}$.
(as advocated at the end of this talk)

Extra Slides

ASTROPHYSICAL NEUTRINOS

5

- first evidence for an extra-terrestrial flux shown at IPA2013 *[IceCube, Science 342 (2013)]*

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

- 3 yrs: 37 events in 988 days **5.7σ**
- bkg. 8.4±4.2 atm. μ and 6.6+5.9 ν
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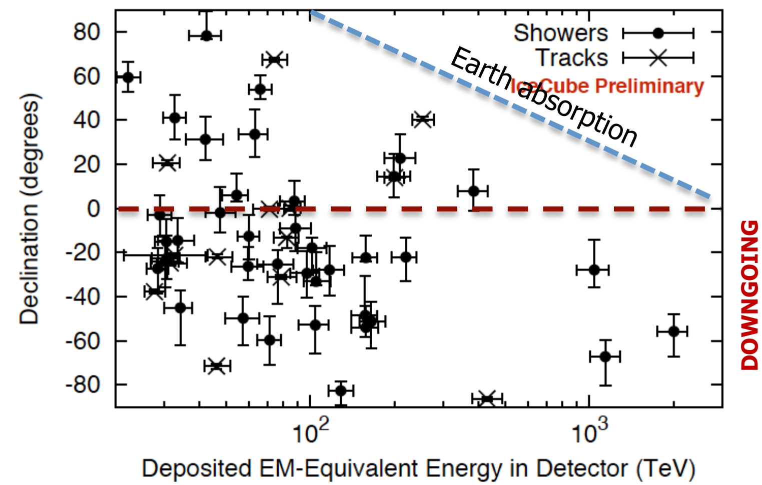

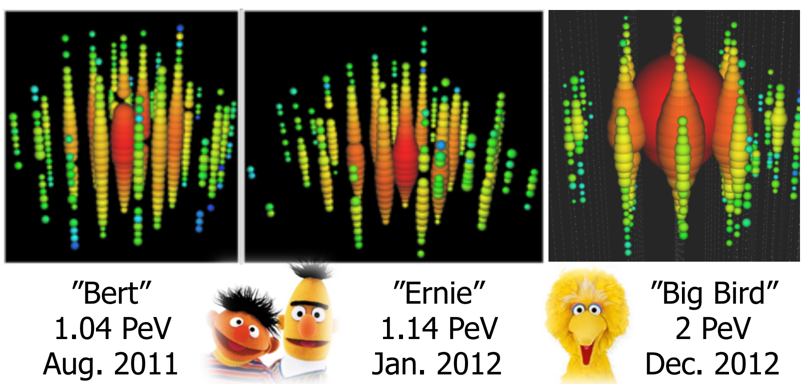

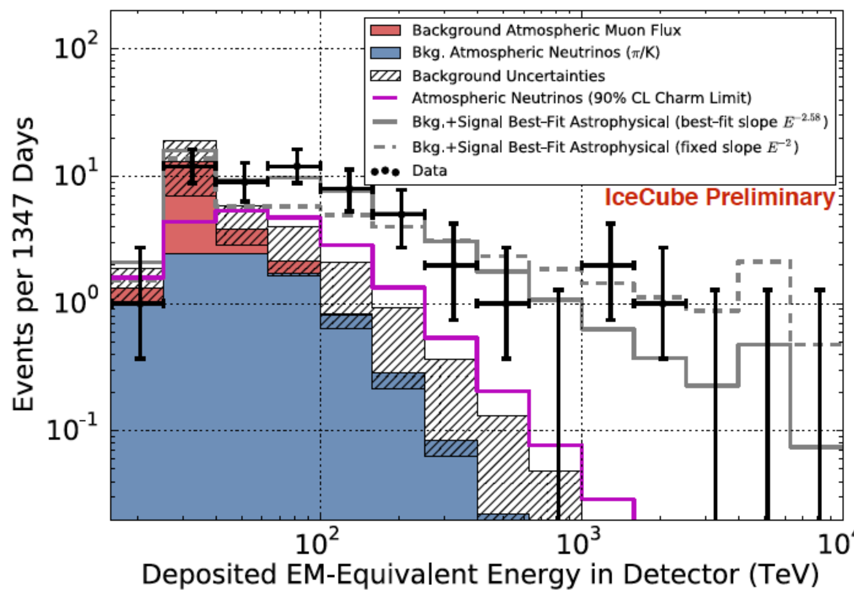

- zenith distribution consistent with isotropic astrophysical flux

Glashow Resonance - Formulas:

$$\left(\frac{N}{T\Omega}\right)_{\rm Res} = \frac{N_p}{2m_e}\,(\pi M_W \Gamma_W)\,\sigma_{\rm Res}^{\rm peak}\;\frac{dF_{\bar\nu_e}}{dE_{\bar\nu_e}}\Big|_{E_{\bar\nu_e}=6.3{\rm PeV}}\,,$$

$$\sigma_{\rm Res}^{\rm peak} = \frac{24\pi\,{\rm B}(W^- \to \bar\nu_e e^-)\,{\rm B}(W^- \to {\rm had})}{M_W^2} = 3.4\times 10^{-31}{\rm cm}^2\,.$$

The "Resonometer" of Cosmic Nu Source Models:
Barger, Fu, Learned, Marfatia, Pakvasa, TJW, arXiv'd today

TABLE I: Neutrino flavor ratios at source, component of $\bar{\nu}_e$ in total neutrino flux at Earth after mixing and decohering, and consequent relative strength of Glashow resonance, for six astrophysical models. (Neutrinos and antineutrinos are shown separately, when they differ.)

	Source flavor ratio		Earthly flavor ratio		$\bar{\nu}_e$ fraction in flux ($\mathcal{R}$)
$pp \to \pi^{\pm}$ pairs	(1:2:0)		(1:1:1)		$18/108 = 0.17$
w/ damped $\mu^{\pm}$	(0:1:0)		(4:7:7)		$12/108 = 0.11$
$p\gamma \to \pi^{+}$ only	(1:1:0)	(0:1:0)	(14:11:11)	(4:7:7)	$8/108 = 0.074$
w/ damped μ^{+}	(0:1:0)	(0:0:0)	(4:7:7)	(0:0:0)	0
charm decay	(1:1:0)		(14:11:11)		$21/108 = 0.19$
neutron decay	(0:0:0)	(1:0:0)	(0:0:0)	(5:2:2)	$60/108 = 0.56$

(Kaons change little)

Glashow event rates vs. continuum:

TABLE II: Ratio of resonant event rate around the 6.3 PeV peak to non-resonant event rate abov $E_\nu^{\rm min} = 1,\ 2,\ 3,\ 4,\ 5$ PeV. The single power-law spectral index α is taken to be 2.0 and 2. for the non-parenthetic and parenthetic values, respectively. As an example, the single power-law extrapolation from the three events observed just above 1 PeV predicts a mean number of observe resonance events around 6.3 PeV equal to the first numerical column times 3.

$E_\nu^{\rm min}$ (PeV)	1	2	3	4	5
$pp \to \pi^\pm$ pairs	0.33 (0.29)	0.50 (0.53)	0.64 (0.77)	0.76 (1.0)	0.87 (1.2)
damped $\mu^\pm$	0.22 (0.18)	0.33 (0.34)	0.42 (0.50)	0.49 (0.64)	0.56 (0.79)
$p\gamma \to \pi^+$ only	0.14 (0.12)	0.22 (0.23)	0.28 (0.33)	0.33 (0.43)	0.38 (0.53)
damped μ^+	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
charm decay	0.37 (0.32)	0.56 (0.60)	0.72 (0.86)	0.85 (1.1)	0.98 (1.4)
neutron decay	1.1 (0.94)	1.7 (1.8)	2.1 (2.5)	2.5 (3.3)	2.9 (4.0)

Glashow Resonance - rates vs. continuum

The numbers of expected resonant events is greatly reduced from the ratio of resonant to non-resonant cross sections by the additional factors. The cross section ratio at 6.3 PeV is 240: see Fig. 1. The $\frac{\Gamma_W}{M_W}$ ratio is 1/38. The α-dependent factor $\left[(\alpha - 1.40)\left(\frac{1\,\mathrm{PeV}}{6.3\,\mathrm{PeV}}\right)^{\alpha-1.40}\right]$ yields about 0.2 for both α's of interest, 2.0 and 2.3. The end result is about $2\mathcal{R}$ for the ratio of resonant events to non-resonant events above 1 PeV.

Since three down-going shower events have been observed at IceCube in the 1-2 PeV region, the expected number of Glashow events is found by multiplying the first numerical column of Table II by three. These expected resonant event numbers are 1.0 (0.9), 0.7 (0.5), 0.4 (0.4), 0 (0), 1.1 (1.0), and 3.3 (2.8), for the six models, and for $\alpha = 2.0\,(2.3)$, respectively. Since no 6.3 PeV events are observed,[1] all models remain viable except perhaps the final one, where neutron decay to pure $\bar{\nu}_e$ predicts some resonance events at Earth. In terms of Poisson statistics, when $\langle N \rangle$ events are expected, the probability that none are observed is $P(0|\langle N \rangle) = e^{-\langle N \rangle}$; thus, the six models yield Poissonian occurrence probabilities of 37%, 50%, 67%, 100%, 33%, and 4% for $\alpha = 2$, and slightly larger probabilities for $\alpha = 2.3$.