Where are the Icecube Neutrinos Beyond 2 PeV ?

Tom Weiler

Vanderbilt University

Nashville. TN

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Neutrinos carry three types of information:

(1) Direction
(2) Energy
(3) Flavor

All three have interesting features in IceCube data

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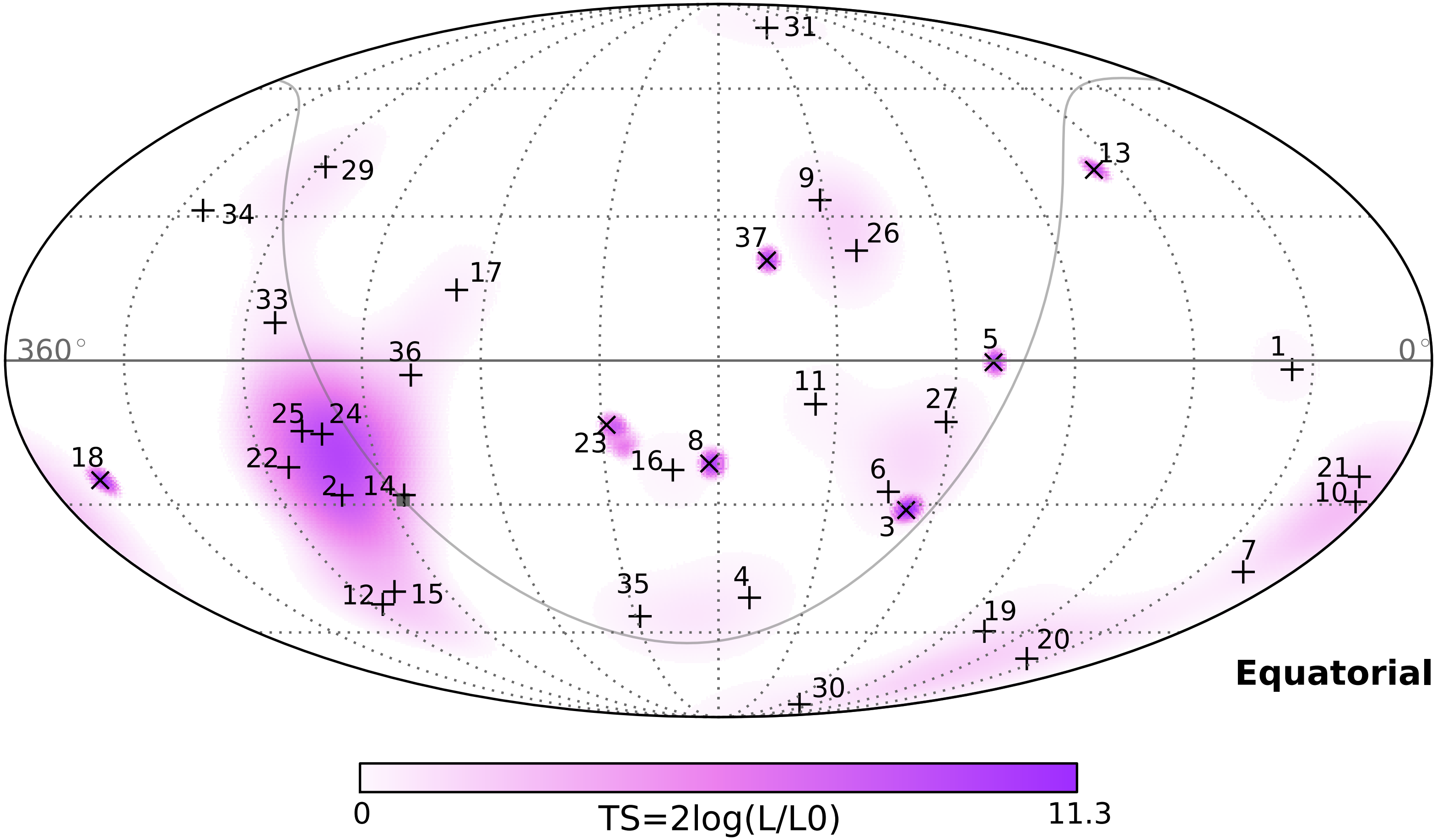
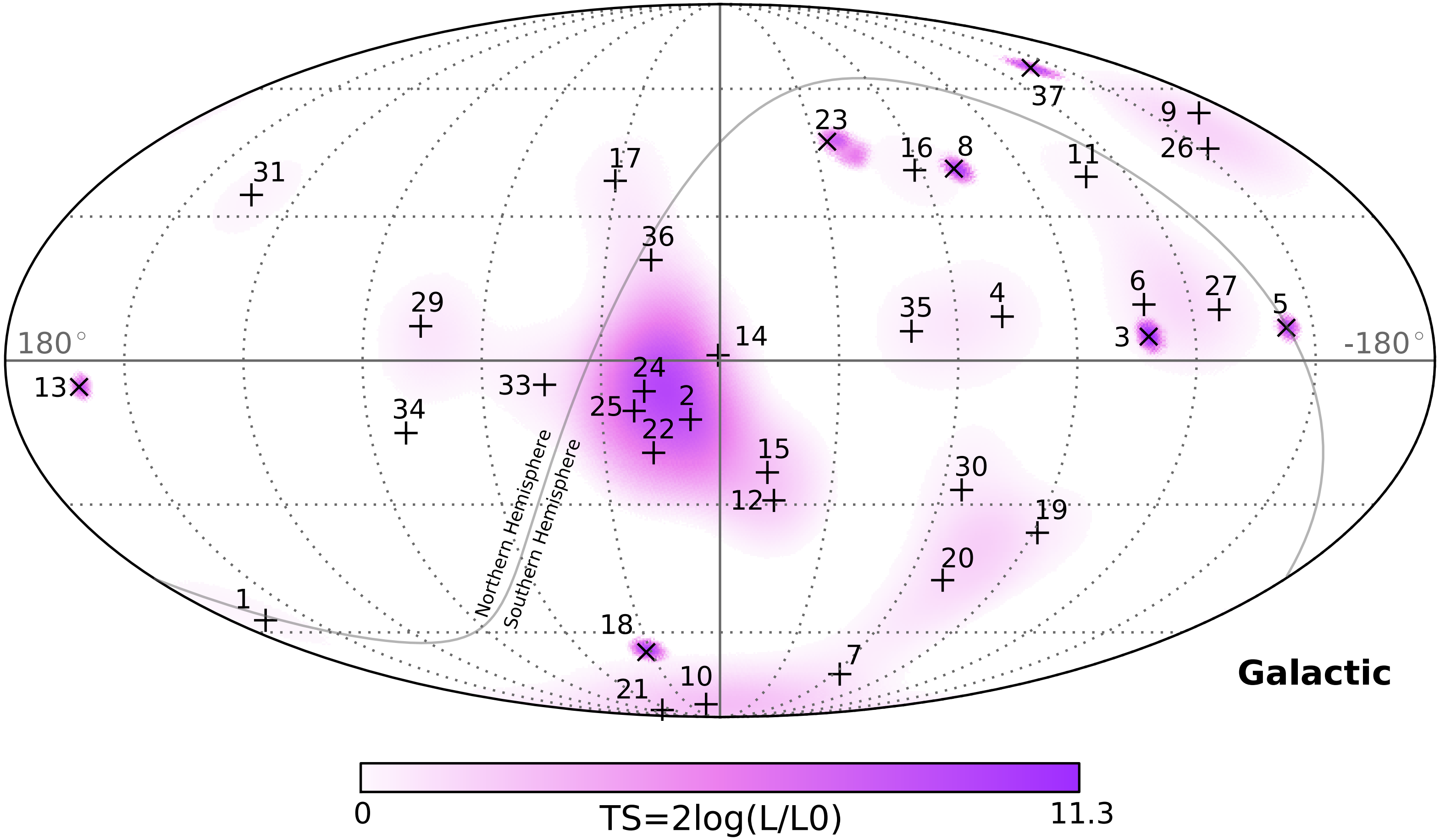
Outline:

- IceCube Data
- “missing” events above 2 PeV
  - continuum events
  - resonant at 6.3 PeV (“Glashow”)
- Statistics
- No Glashow is good Glashow?
  - End of the Neutrino spectrum
  - some consequences
  - some ideas

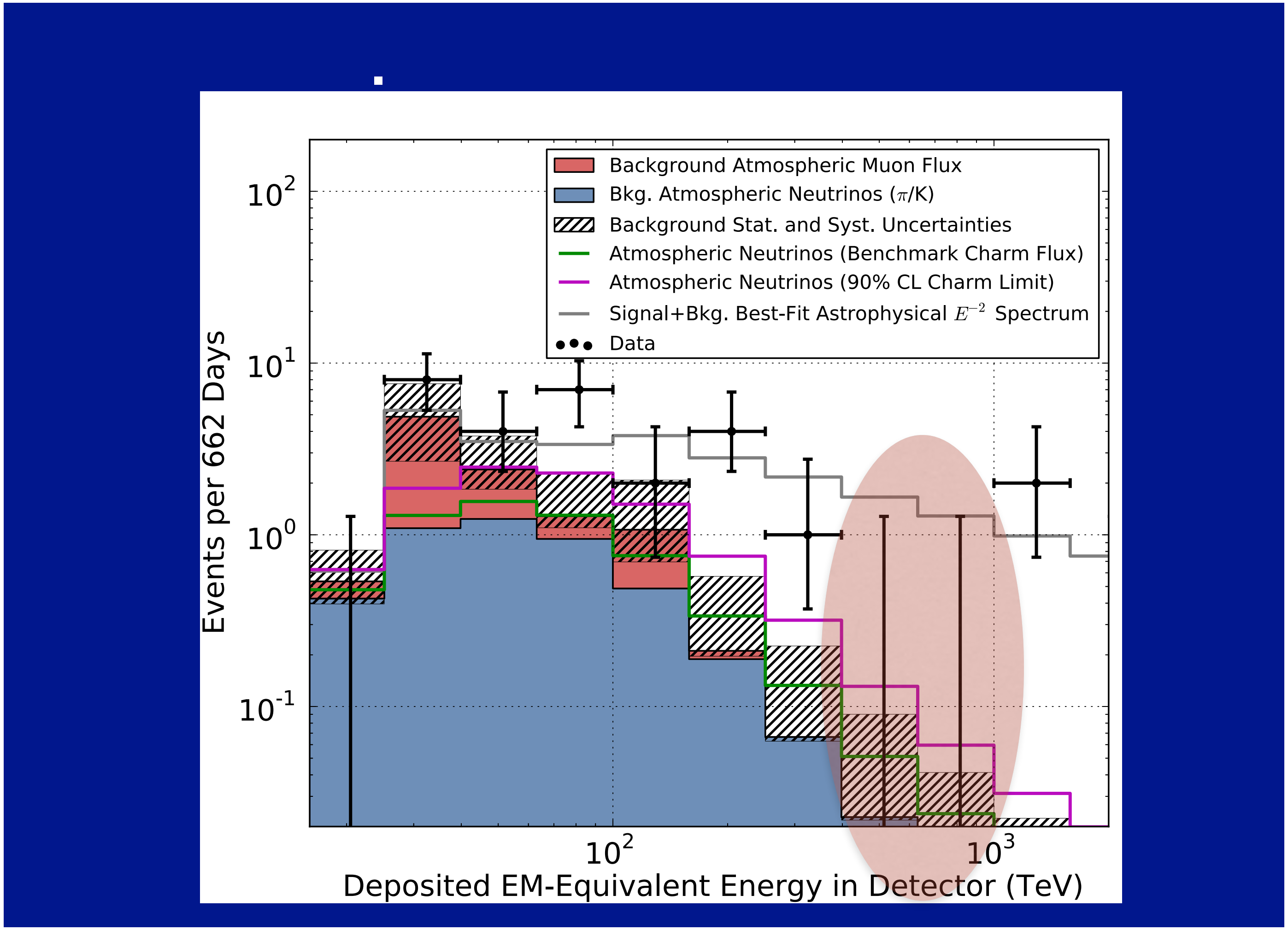
IceCube (Equitorial)



IceCube (Galactic)

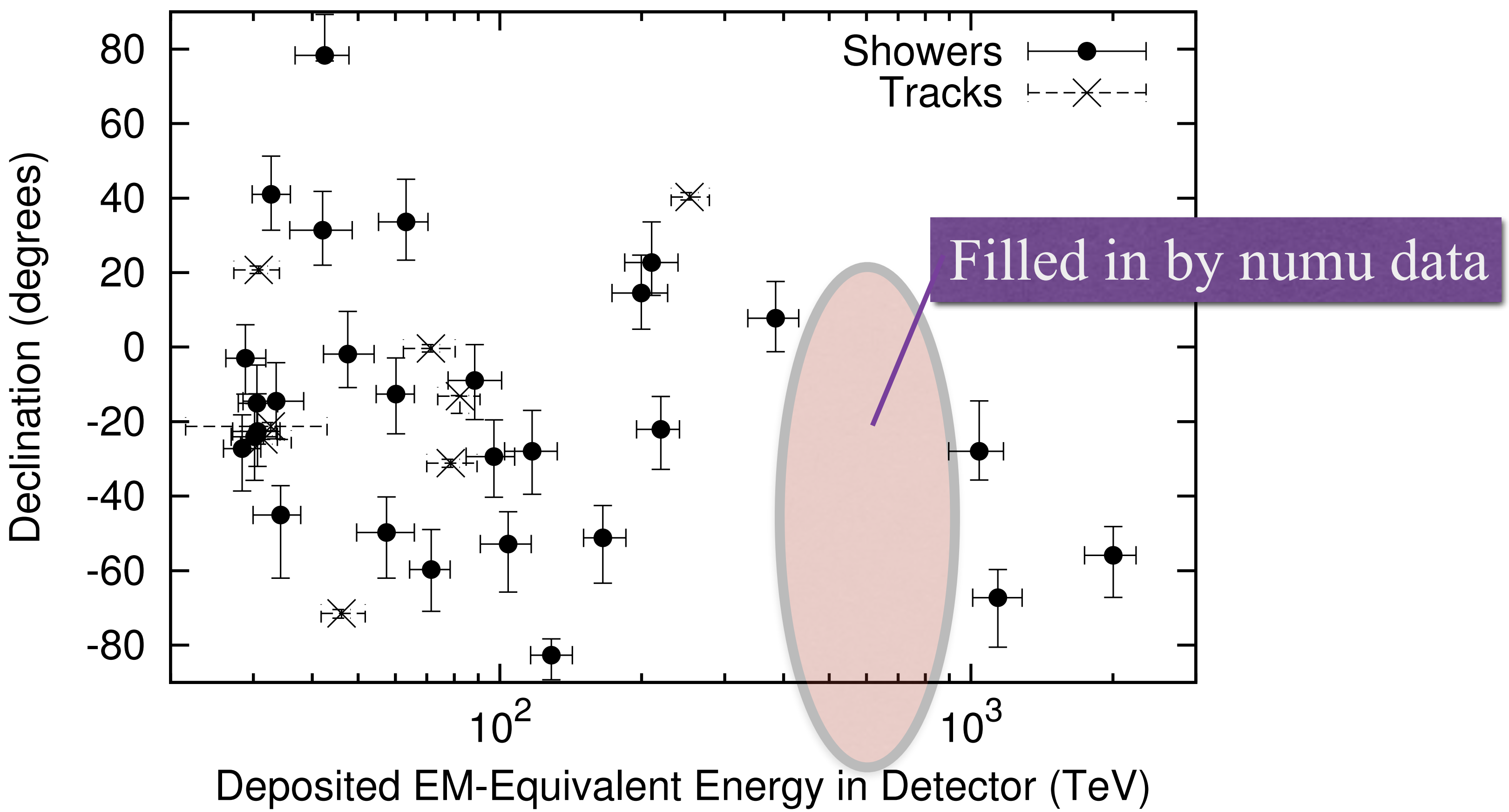


Energy - the “gap”, and then three:



1: Distribution of the deposited energies of the observed events

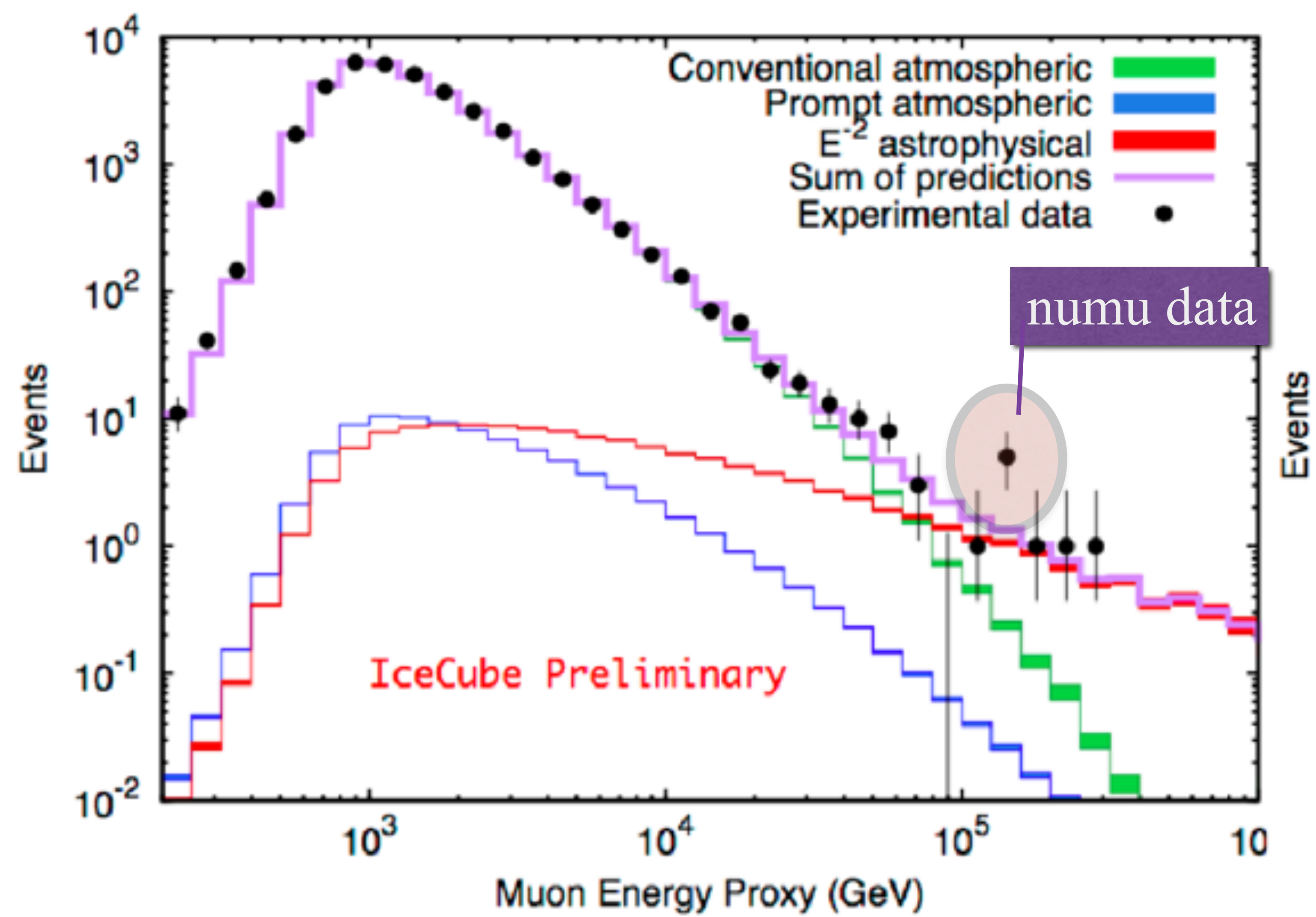
Angle-Energy-Flavor Display:



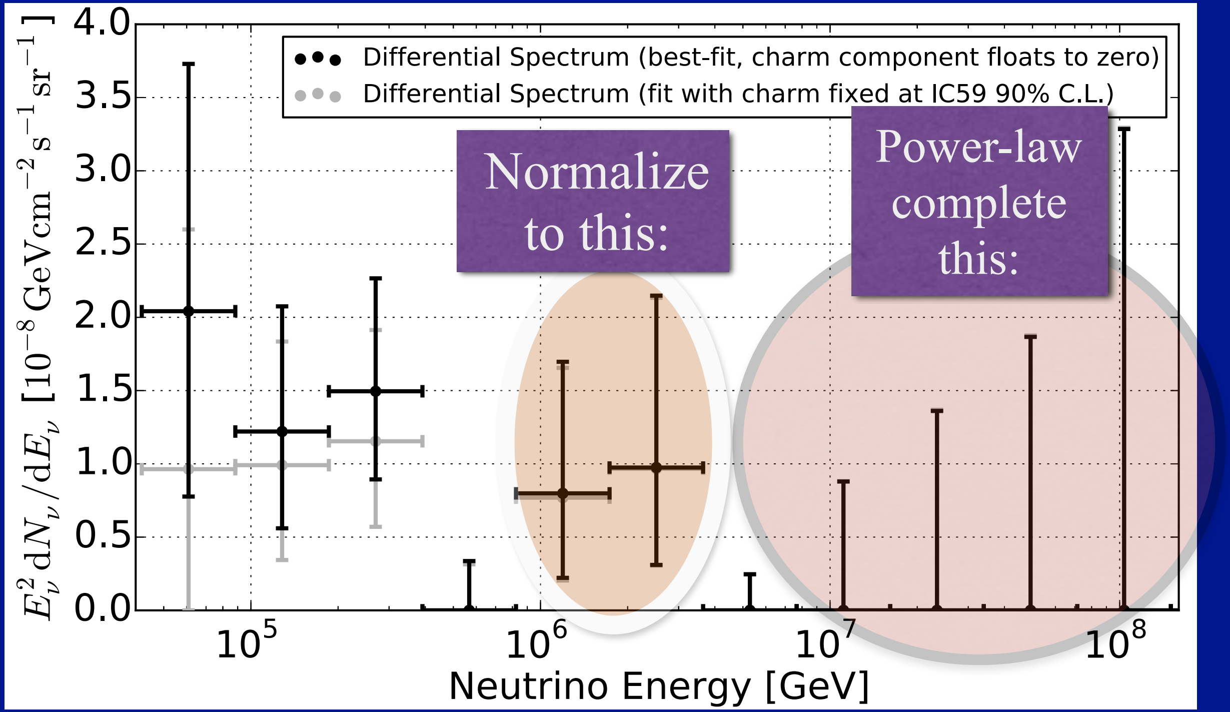
Filled in by numu data

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

muon neutrino energy:



Is there an Energy Cutoff at ~2PeV ?



Normalize to this:

Power-law complete this:

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 Events?

“Missing” number depends on two parameters:

(1)spectral index, α

(2) number expected in 1-2 PeV interval,

$N^{exp}(1\text{-}2\ \mathrm{PeV})$

μ

Integrated numbers:

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

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

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

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

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

In addition, the number of Glashow resonance events is

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

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).

Where/what is Glashow?

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

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

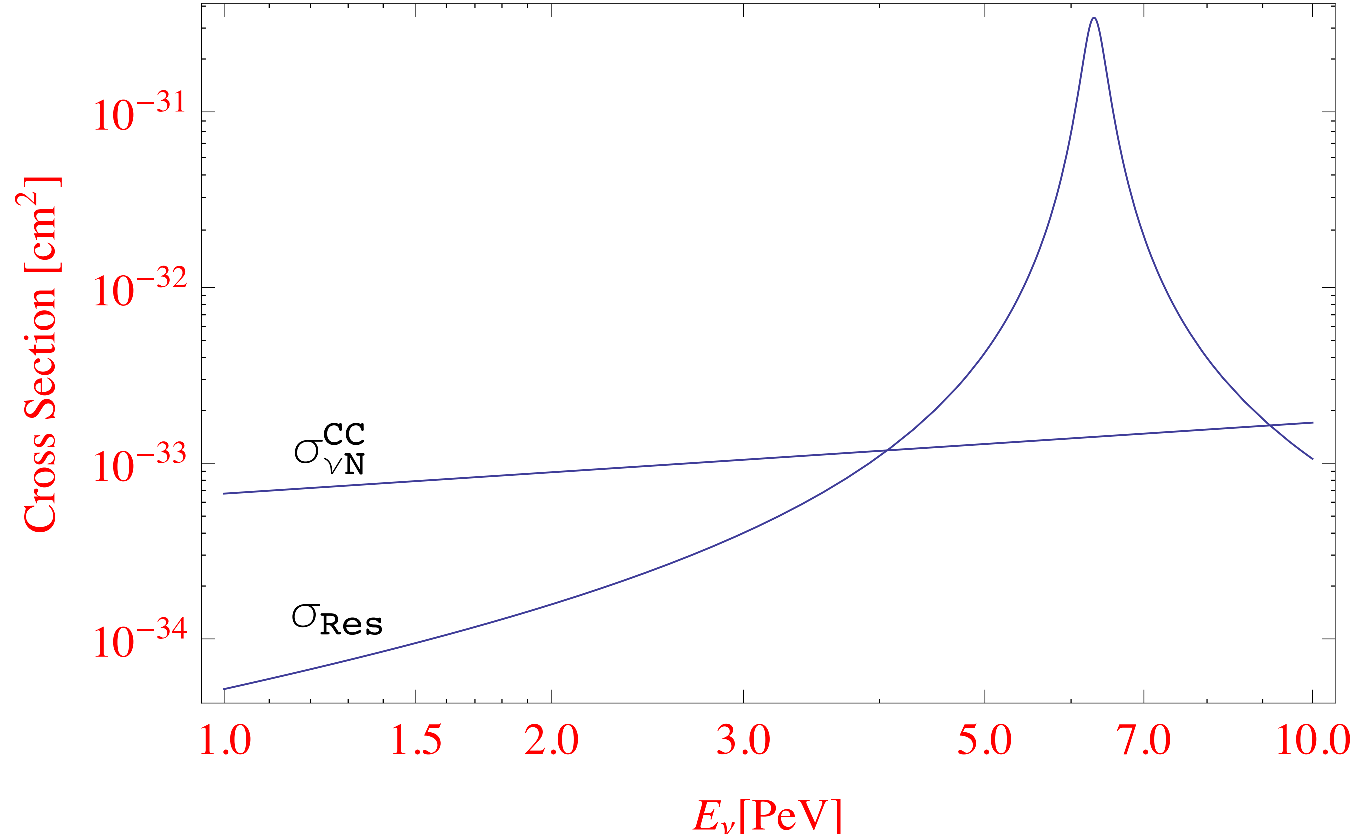


FIG. 1: Cross sections for the resonant process, $\bar{\nu}_e + e^- \to W^- \to$ hadrons, and the non-resonant process, $\nu_e + N \to e^- +$ hadrons, in the 1–10 PeV region.

Glashow Resonance - Formulas:

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

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

Explored in: Anchordoqui, Goldberg, Halzen, TJW (hep-ph/0410003), …
Bhattacharya, Gandhi, Rodejohann, Watanabe (1108.3163. 1209.2422),
Baerwald, Bustamente, Winter (1208.4600)

The “Resonometer” of Cosmic Nu Source Models:

Barger, Lingjun Fu, Learned, Marfatia, Pakvasa, TJW,
Phys Rev (Letters?) and arXiv 1407.3255

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 very little)

Poisson:

POISSON STATISTICS:

$$1 = e^{-\mu}\, e^{+\mu} = e^{-\mu} \sum_{n=0}^{\infty} \frac{\mu^n}{n!} \,.$$

from which we infer that

$$P(n|\mu) = e^{-\mu} \frac{\mu^n}{n!} \,.$$

is the probability of observing n events when the mean, or expected number, is μ.

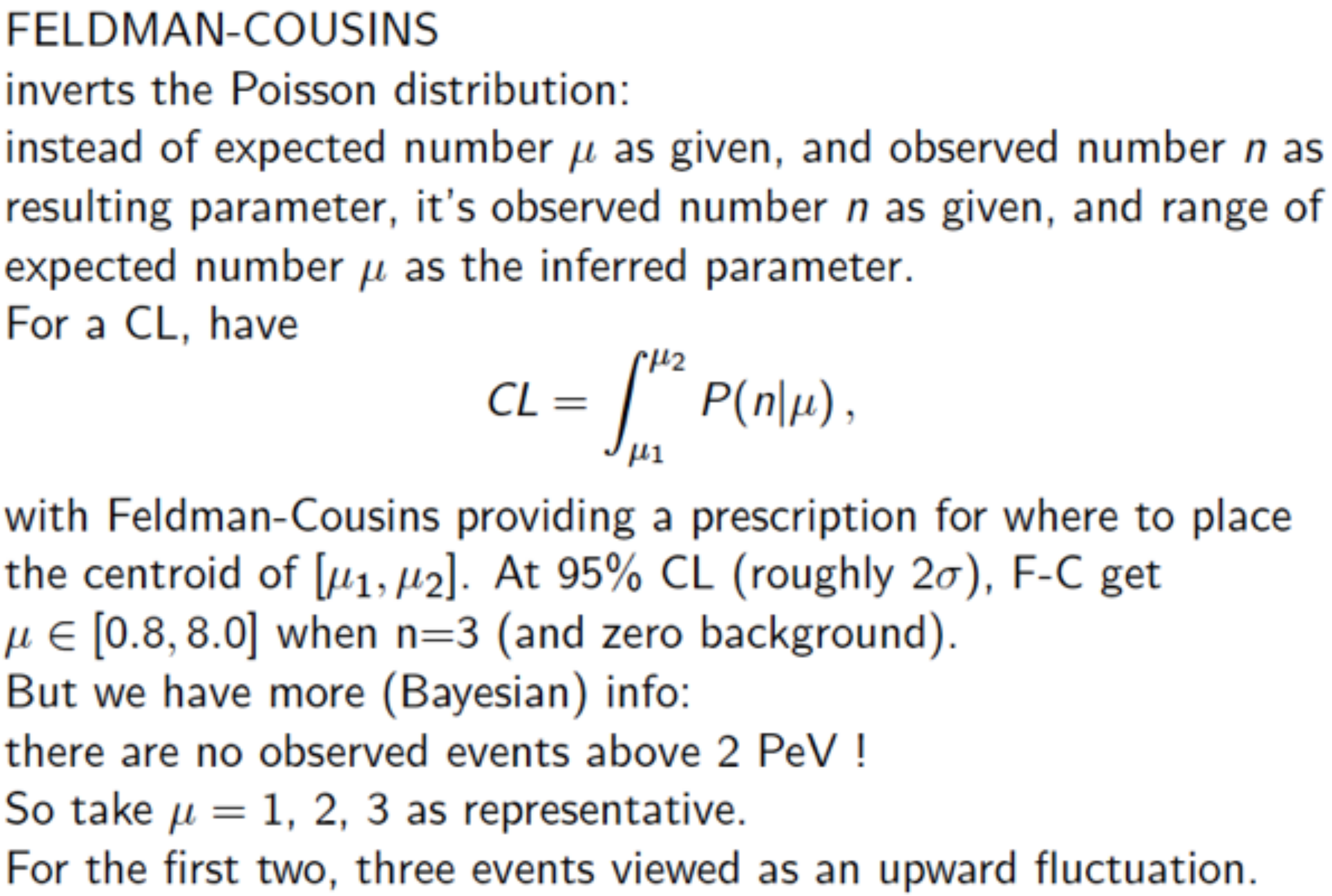
Poisson:

Mean value of $P(n|\mu)$ is $\sum_n n \times P(n|\mu) = \mu$.

Moreover, variance $\sum_n (n^2 - \mu^2) \times P(n|\mu)$ is also μ.
(Source of $\frac{S}{N} \sim \frac{\mu}{\sqrt{\mu}} = \sqrt{\mu}$)

Moreover, $\int_0^\infty d\mu \, P(n|\mu) = \int_0^\infty d\mu \, \frac{e^{-\mu}\,\mu^n}{n!} = \frac{n!}{n!} = 1$.

Feldman-Cousins: (H. Goldberg's reminder)



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.

Poisson:

SPECIAL CASES:

(1) using Stirling's approximation,

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

$P(3|3) \approx \frac{1}{\sqrt{6\pi}} = 23\%$, while $P(3|2) = 18\%$, and $P(3|1) = 6\%$,
all roughly "equally" viable;

(2) when no events are observed,

$$P(0|\mu) = e^{-\mu}\,,$$

so $P(0|1) = 1/e = 37\%$ and $P(0|3) = e^{-3} = 5.0\%$,
for the dearth of events above 2 PeV, also viable;
however, $P(0|5) = 0.7\%$, not so viable.

“missing” neutrinos at IceCube

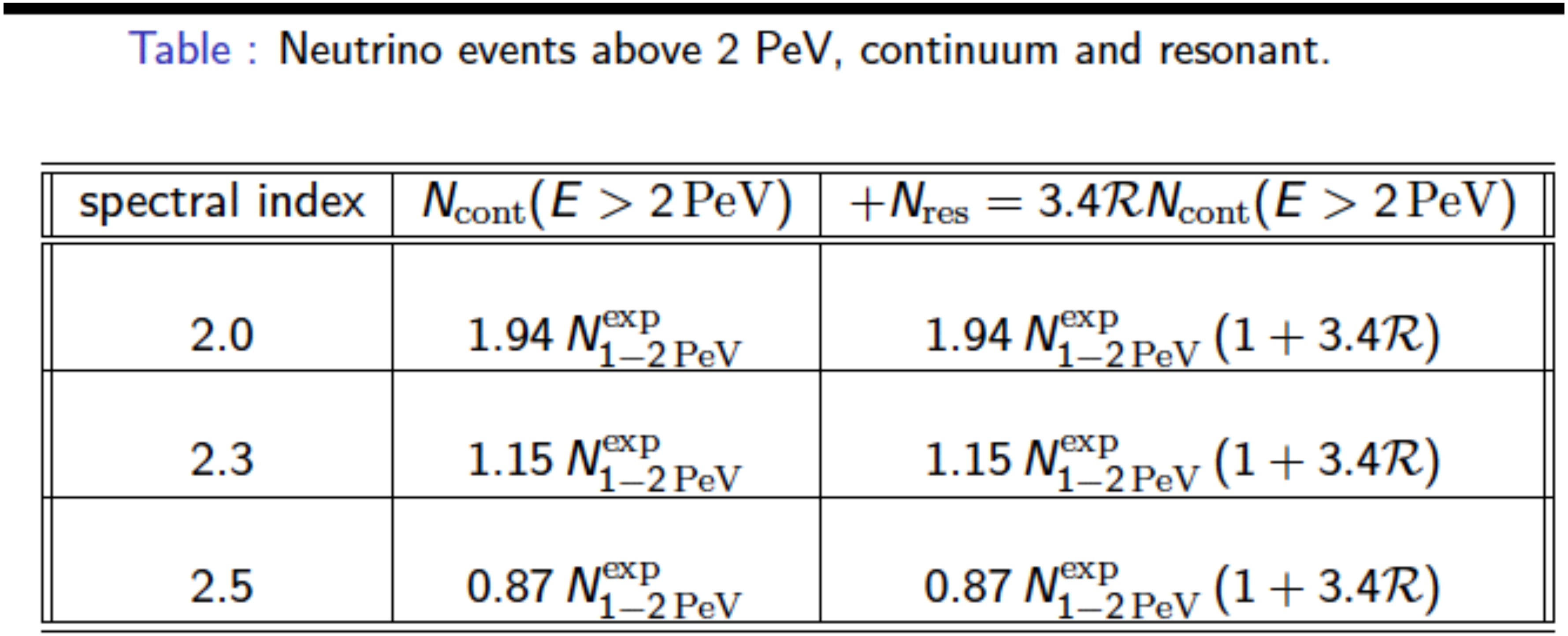
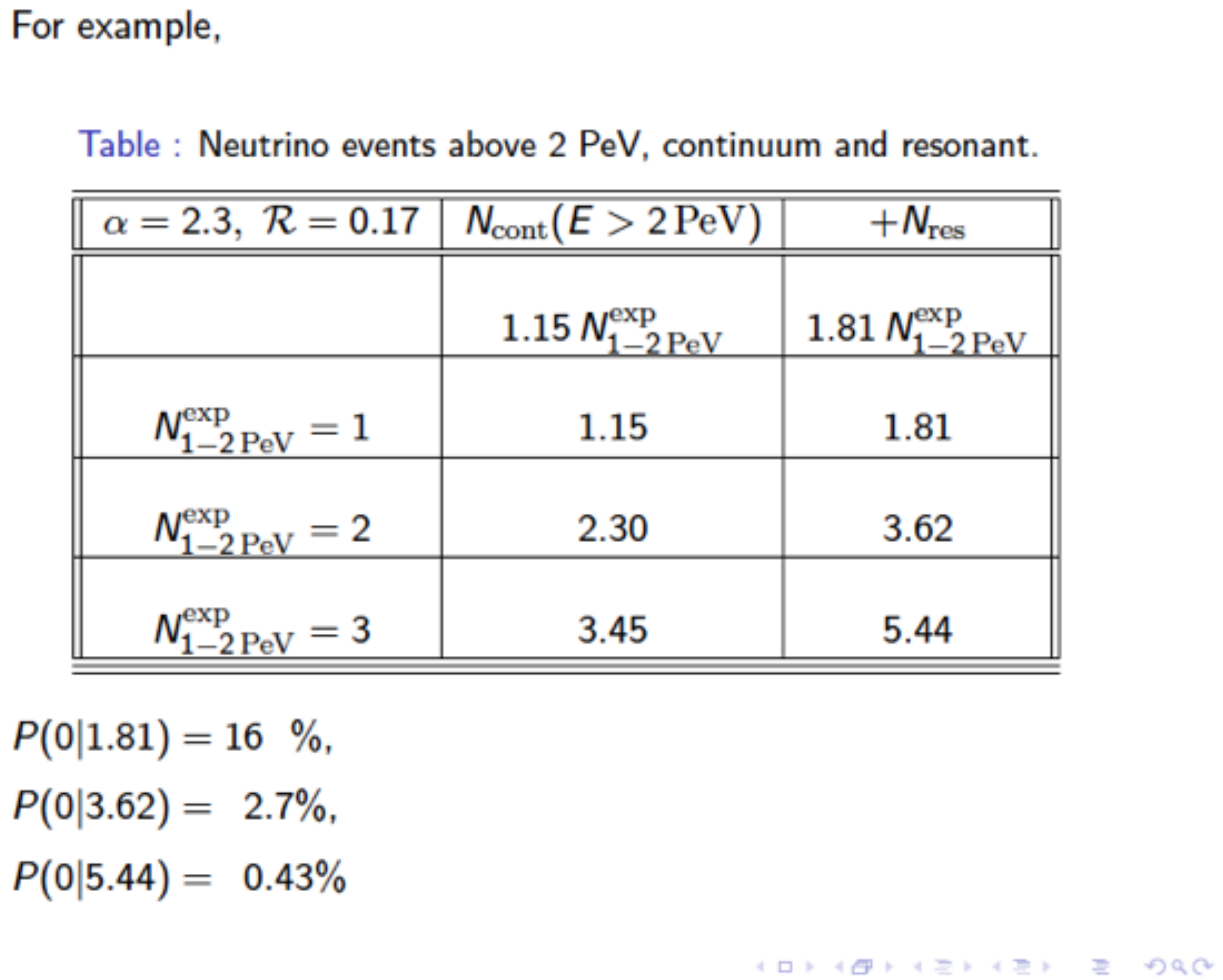


Table : Neutrino events above 2 PeV, continuum and resonant.

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	$0.87\, N^{\rm exp}_{1-2\,{\rm PeV}}$	$0.87\, N^{\rm exp}_{1-2\,{\rm PeV}}\,(1 + 3.4\mathcal{R})$

“missing” neutrinos at IceCube



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

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

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

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

No Glashow is good Glashow ?

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“End of the Neutrino Energy Spectrum”

Anchordoqui, Barger, Goldberg, Learned, Marfatia, Pakvasa, Paul, TJW,
Phys Lett B and 1404.0622

(violates Learned’s Theorem)

E_{maxed} leptons stabilize charged pion at hi E,
also stabilize neutron at hi E
(paper pending, with P. Denton, D. Marfatia)

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Mass-Scales and Energy Cutoff in terms of Boost Factor

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

whereas

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

Maybe suggests

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

and a possible connection to Gravity/spacetime foam.

Neutrino Energy Maximum:

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

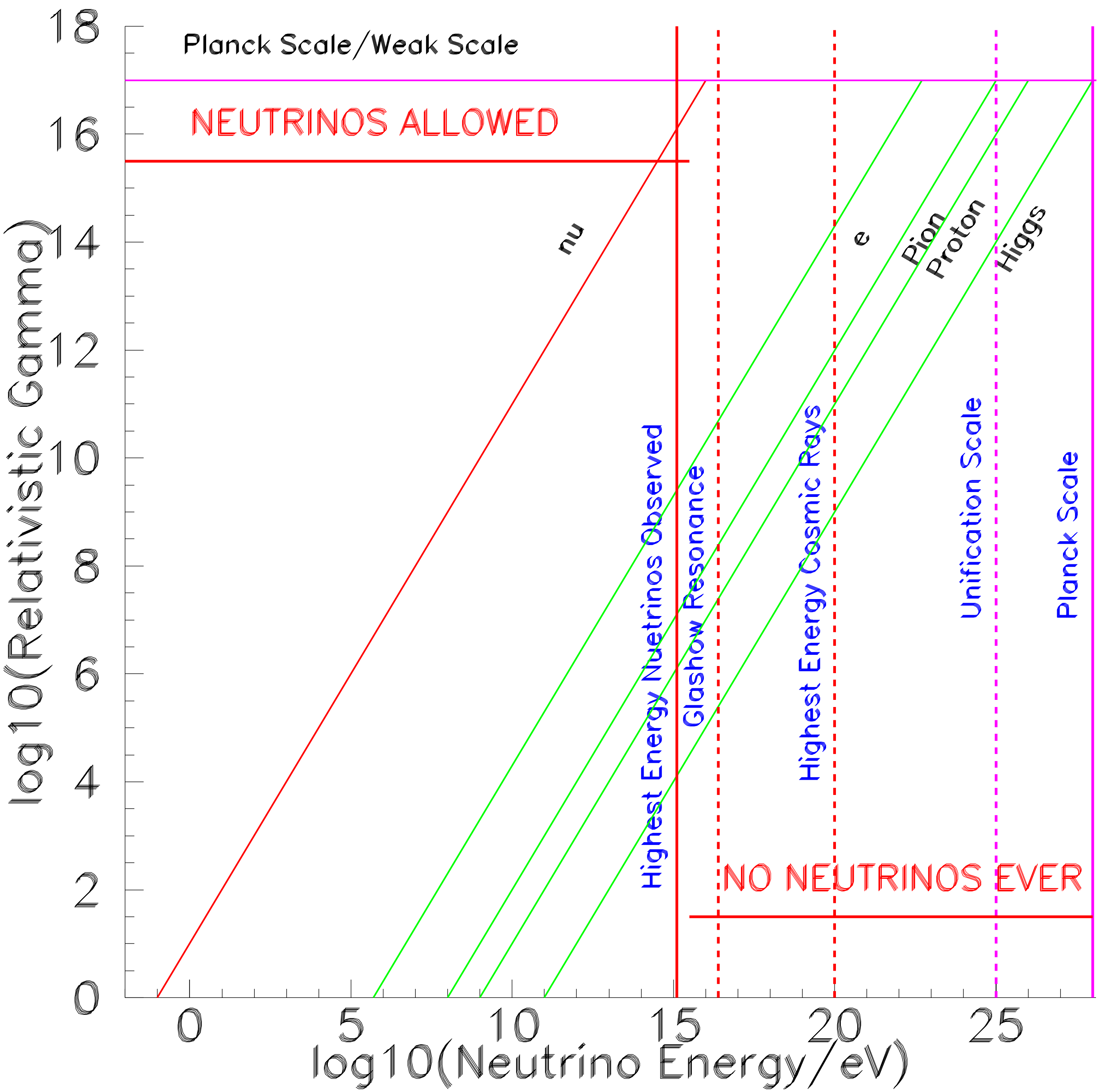
$$= 2.5\left(\frac{m_\nu}{0.05\,{\rm eV}}\right)\left(\frac{M_{\rm Planck}}{1.2\times 10^{28}\,{\rm eV}}\right)\left(\frac{247\,{\rm GeV}}{v_{\rm weak}}\right){\rm PeV}\,.$$

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.

The End of the Neutrino Spectrum



and Weinberg’s mass operator:

Inserting Weingberg's neutrino-mass generating operator,

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

find $\Lambda \sim M_{\rm GUT}$, so

$$\sqrt{G}\,E_\nu^{\rm max} \sim \frac{vev}{M_{\rm GUT}}\,.$$

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) stringy relations, G and SM
d) BH entropy: area and G
c) extra dim’ns open up: geometry and M_P
d) Planck scale LIV
e) …make your own model
(like Bj; like Illana, Masip, Meloni)

Outguessing Nature doesn’t matter, as it’s an Xptl issue!

and yes,
Incredible claims require incredible evidence …
data coming in, but not yet there

In Summary:

Multi-PeV continuum and Glashow resonance rates in borderline danger, worth watching.

Glashow resonance can reveal ν source dynamics on other side of Universe.

If events above a few PeV do not arrive, then %$#@~*&, and either

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

e.g., Reno,Sarcevic, … non-pion chain,
choked jets/charm prodct'n and decay

(b) the power-law is broken;

(c) new fundamental physics at scale $\Gamma_\nu \sim 10^{17}$.