What can/can’t Glashow events tell us?

Existence, yes;   Resonometry, no.

Tom Weiler
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μ

Neutrinos carry three types of information:

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

All three have interesting features.
Glashow events can come from anywhere,
but have a fixed energy, fixed flavor.

μ

Glashow (1960) events:

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

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

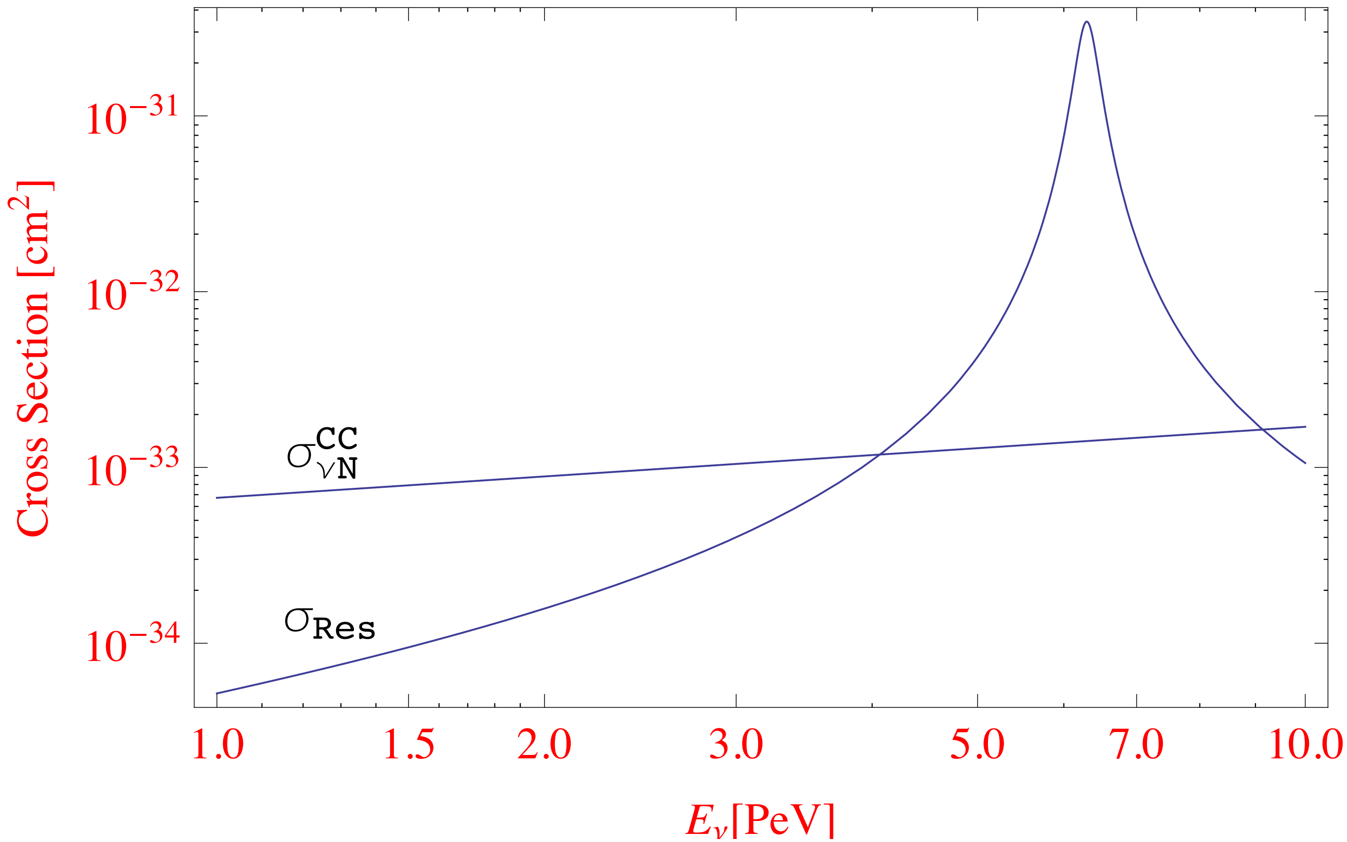

FIG. 1: Cross sections for the resonant process, $\bar{\nu}_e + e^- \to W^- \to$ hadrons, and the non-resonant process, $\nu_e + N \to e^- +$ hadrons, in the 1–10 PeV region.

Eg. p-gamma makes e-nu's, no e-antinu's

For example, in idealized pγ interactions, the process

$$p+\gamma \to \Delta^+ \to \begin{cases} \pi^+ + n & 1/3 \text{ of all cases} \\ \pi^0 + p & 2/3 \text{ of all cases} \end{cases}$$

will lead, after pion decay

$$\begin{aligned} \pi^+ &\to \mu^+ + \nu_\mu \,, \\ & \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \,, \end{aligned}$$

Astrophysical Neutrino Production Diagnostics with the Glashow Resonance

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We study the Glashow resonance $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hadrons at 6.3 PeV as diagnostic of the production processes of ultra-high energy neutrinos. The focus lies on describing the physics of neutrino production from pion decay as accurate as possible by including the kinematics of weak decays and Monte Carlo simulations of pp and pγ interactions. We discuss optically thick (to photohadronic interactions) sources, sources of cosmic ray nuclei, and muon damped sources. Even in the proposed upgrade IceCube-Gen2, a discrimination of scenarios such as pp versus pγ is extremely challenging under realistic assumptions. Nonetheless, the Glashow resonance can serve as a smoking gun signature of neutrino production from photohadronic (Aγ) interactions of heavier nuclei, as the expected Glashow event rate exceeds that of pp interactions. We finally quantify the exposures for which the non-observation of Glashow events exerts pressure on certain scenarios.

The Galactic Contribution to IceCube's Astrophysical Neutrino Flux

arXiv:1703.09721

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Abstract. High energy neutrinos have been detected by IceCube, but their origin remains a mystery. Determining the sources of this flux is a crucial first step towards multi-messenger studies. In this work we systematically compare two classes of sources with the data: galactic and extragalactic. We build a likelihood function on an event by event basis including energy, event topology, absorption, and direction information. We present the probability that each high energy event with deposited energy $E_{\rm dep} > 60$ TeV in the HESE sample is galactic, extragalactic, or background. The galactic fraction of the astrophysical flux has a best fit value of $0.07^{+0.09}_{-0.06}$ and zero galactic flux is allowed at 1.2σ.

Xgalactic is way favored:

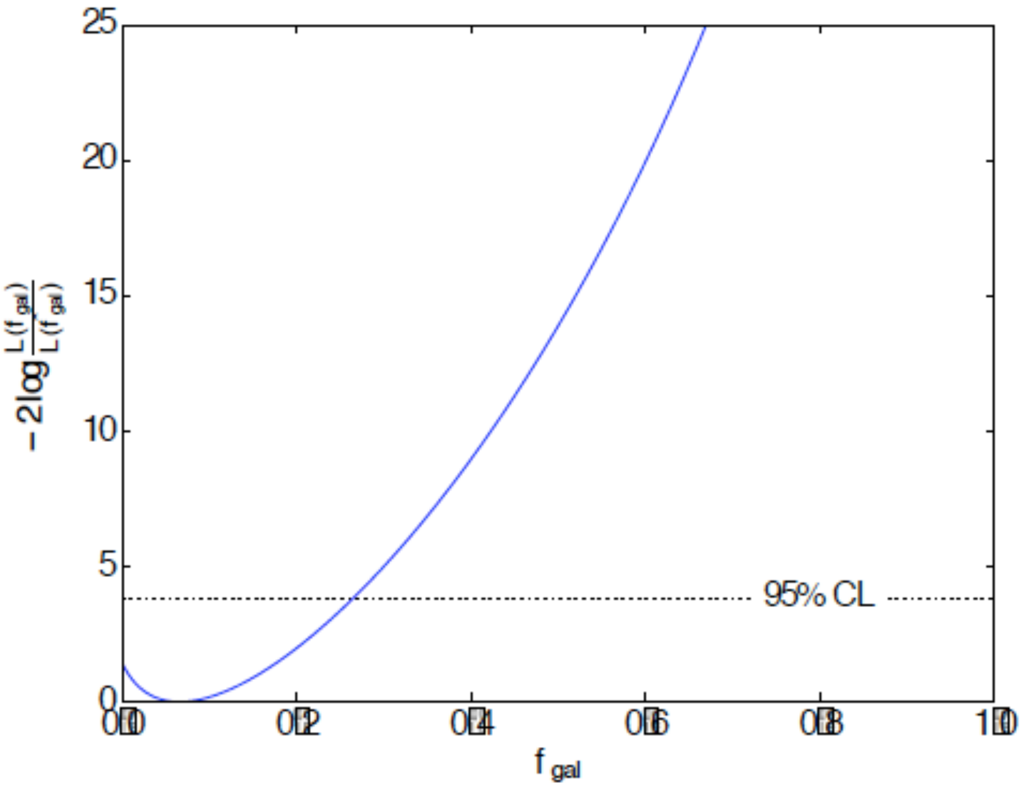


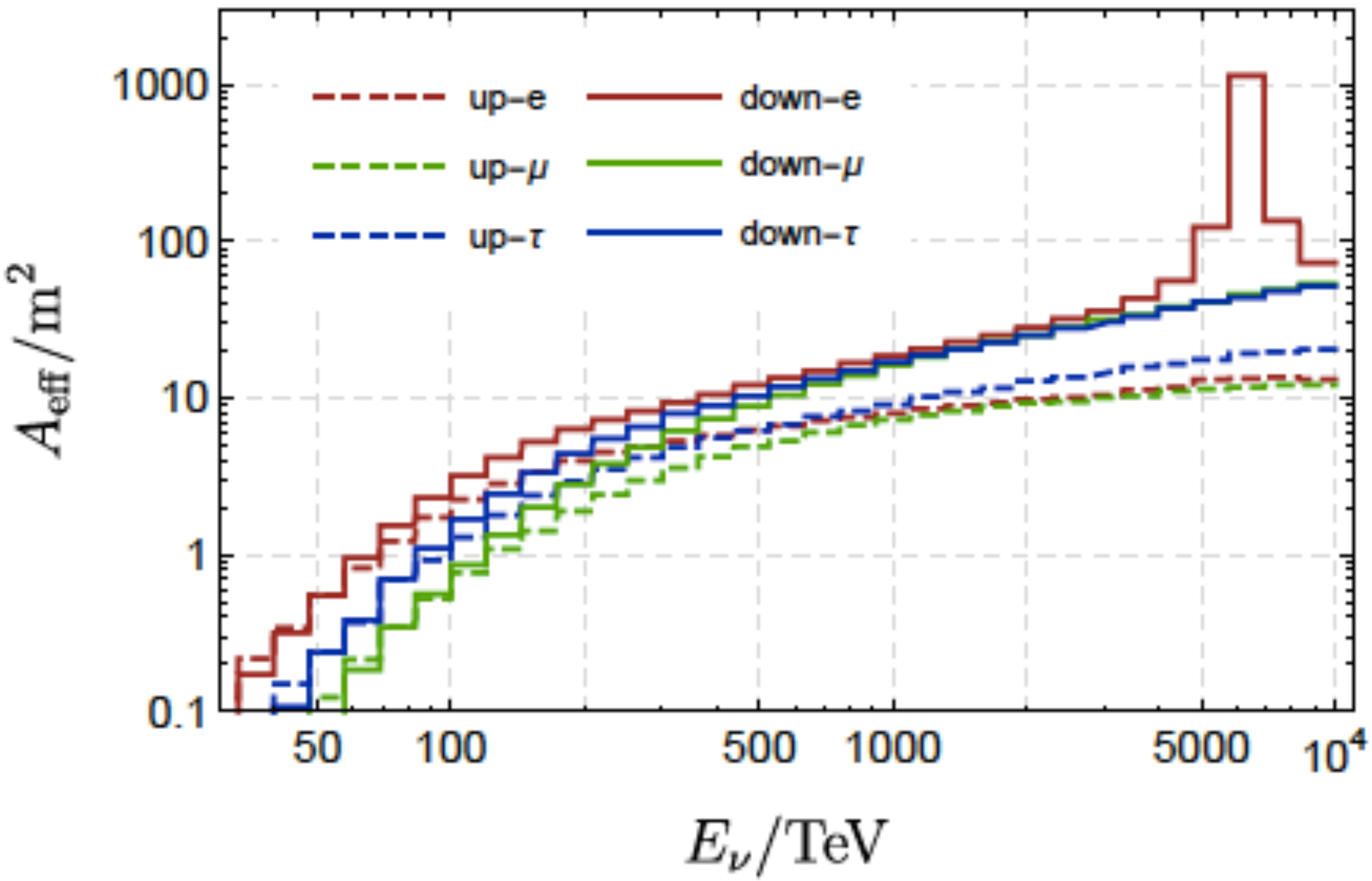
Figure 4. The log likelihood ratio scan $-2\log\mathcal{L}(f_{\rm gal})/\mathcal{L}(\hat{f}_{\rm gal})$. We find the best fit point at $\hat{f}_{\rm gal} = 0.066$ and $f_{\rm gal} = 0$ is allowed at 1.2σ.

e-antinu mean free path in Earth, and the sagitta:

$$\lambda_{\bar{\nu}_e} \sim \frac{1}{n_e\,\sigma_{\rm Res}^{\rm peak}} \sim \begin{cases} 110\,{\rm km} & \text{in mantle rock}\,, \\ \\ 310\,{\rm km} & \text{in ice}\,. \end{cases} \tag{18}$$

The width in E_ν, and therefore the bulk of the absorption, extends from 6.3 PeV to $\pm(2\Gamma_W)/M_W\,E_\nu$, the latter equals to ± 0.3 PeV. This short mfp, traceable to the large resonance cross section, tells us that the $\bar{\nu}_e$ absorption by Earth matter at the Glashow energy of 6.3 PeV is considerable. Using the Sagitta relationship between the depth z of IceCube and the length of the horizontal burden h, $h = \sqrt{2R_\oplus z}$, one finds an h of 113-160 km for the IceCube depth 1-2 km, well matched to the $\bar{\nu}_e$ mfp. The absence of significant overburden, the relatively short mfp of Glashow $\bar{\nu}_e$'s, and the large solid angle imply that the Glashow events come mainly from horizontal directions.

IceCube effective areas (averaged over 4pi):



The "Resonometer" of Cosmic Nu Source Models: Barger, Fu, Learned, Marfatia, Pakvasa, TJW, PRD90, 121301 (2014).

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, but source environment matters)

Neutrino at Earth is affected by the transition amplitude $A_{\alpha\to\beta} = \sum_j U_{\alpha j} e^{-iE_{\nu_j}L} U_{j\beta}$. Over large astronomical distances, the oscillating interference terms average out, and one obtains a (3-flavor×3-flavor) probability matrix

$$\mathcal{P}(\alpha \to \beta) = \sum_j |U_{\alpha j}|^2 |U_{j\beta}|^2 \,, \quad \text{relating } \vec{\phi}^f = \mathcal{P}\vec{\phi} \,. \qquad (4)$$

In the TBM model, the probability elements are given by

$$\mathcal{P}_{\rm TBM}(\alpha \to \beta) = \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix} . \qquad (5)$$

For the charged pion decay chains, we immediately find from Eq. (6)

$$\pi^+ \to e^+\nu_e\nu_\mu\bar{\nu}_\mu \xrightarrow{\text{mix}} \xi^f_{\bar{\nu}_e} = \frac{1}{3} \times \frac{2}{9} = \frac{2}{27}\,, \quad (9)$$

$$\pi^- \to e^-\bar{\nu}_e\nu_\mu\bar{\nu}_\mu \xrightarrow{\text{mix}} \xi^f_{\bar{\nu}_e} = \frac{1}{3} \times \left(\frac{5}{9} + \frac{2}{9}\right) = \frac{7}{27} \quad (10)$$

We observe from the ratio of the two processes that the π^- decay chain yields 7/2 times more Earthly $\bar{\nu}_e$ than the π^+ decay chain. From a different perspective, the Glashow event rate from the π^+ decay chain is potentially contaminated by π^- production (if present at the source), namely $\sim 7/2$ times the fraction π^-/π^+.

GLASHOW CANNOT DISCRIMINATE MYRIAD POSSIBILITIES !

But, nu's are probably made in environments with

a) some optical thickness,

b) possible heavy nuclei source

(not proton primaries), => negative pions via

$$n + \gamma \rightarrow \Delta^0 \rightarrow \begin{cases} \pi^- + p & 1/3 \text{ of all cases} \\ \pi^0 + n & 2/3 \text{ of all cases} \end{cases}$$

and may have

c) muon damping of the pion DK chain.

GLASHOW CANNOT UNAMBIGUOUSLY DISCRIMINATE AMONG THE MYRIAD POSSIBILITIES.

E.g.,

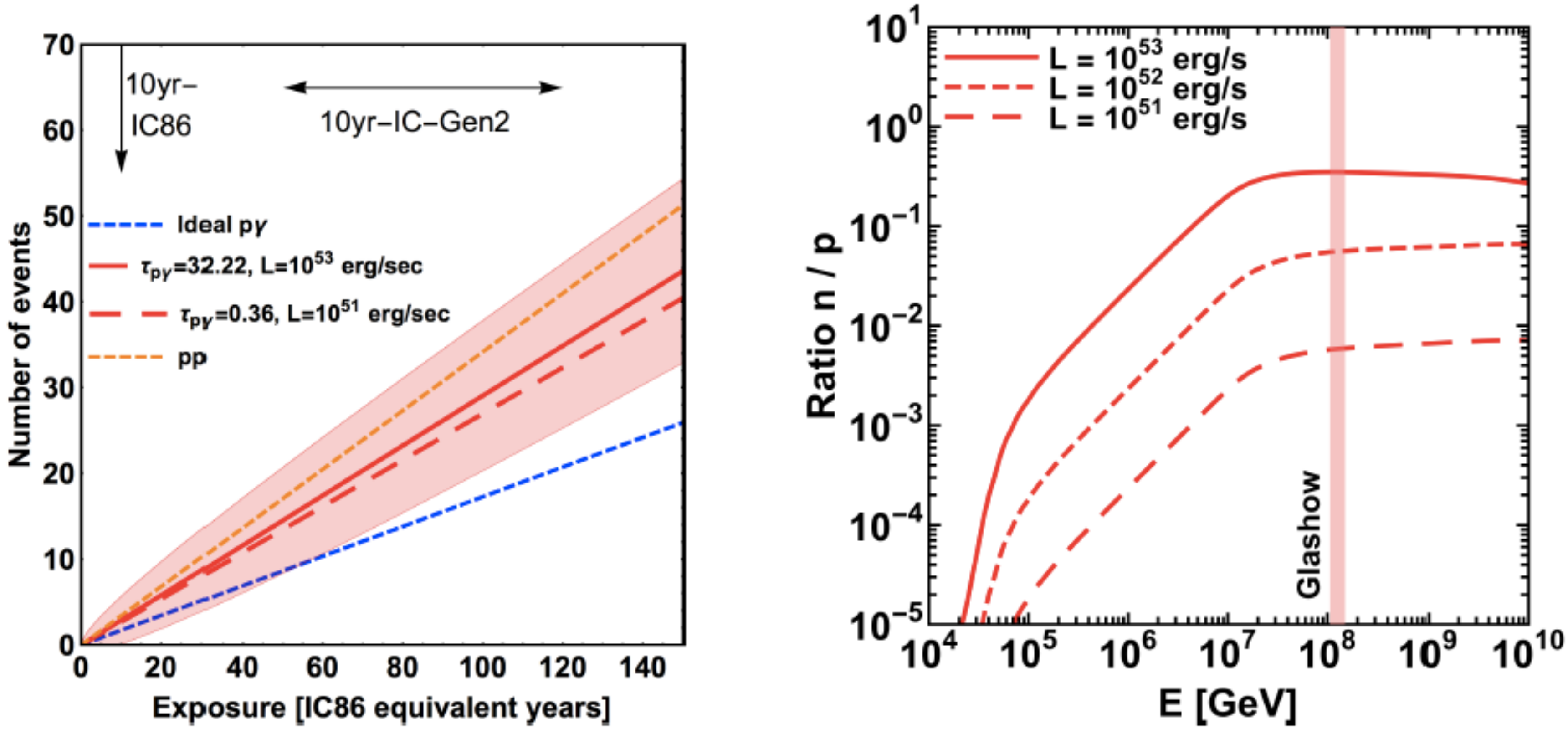


FIG. 3: *Left panel: expected number of Glashow events as a function of exposure for the GRB case for varying optical thickness to photohadronic interactions $\tau_{p\gamma}$. As the luminosity in the burst increases, the optical thickness increases as well, leading to an increasing contamination by π^-. Right panel: neutron to proton ratio as a function of the energy for different luminosities. At the Glashow energy (the vertical band indicates the corresponding primary energy), the ratio scales linearily with the luminosity, saturating at approximately 30% for $L = 10^{53}$ erg/s.*

Single vs. Double power-law fits suggest a new source at higher energy:

No Glashows begin to be problematical:

arXiv:1611.07905, Anchordoqui, Block, Durand, Ha, Soriano, Weiler

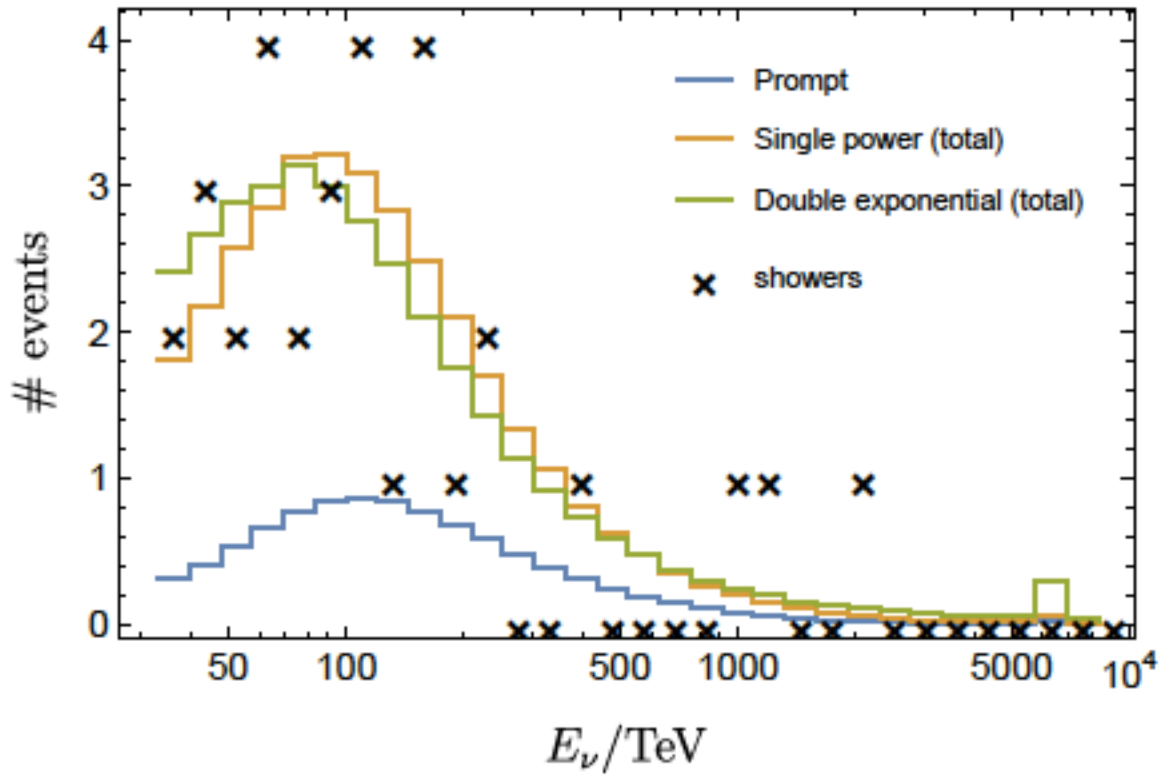
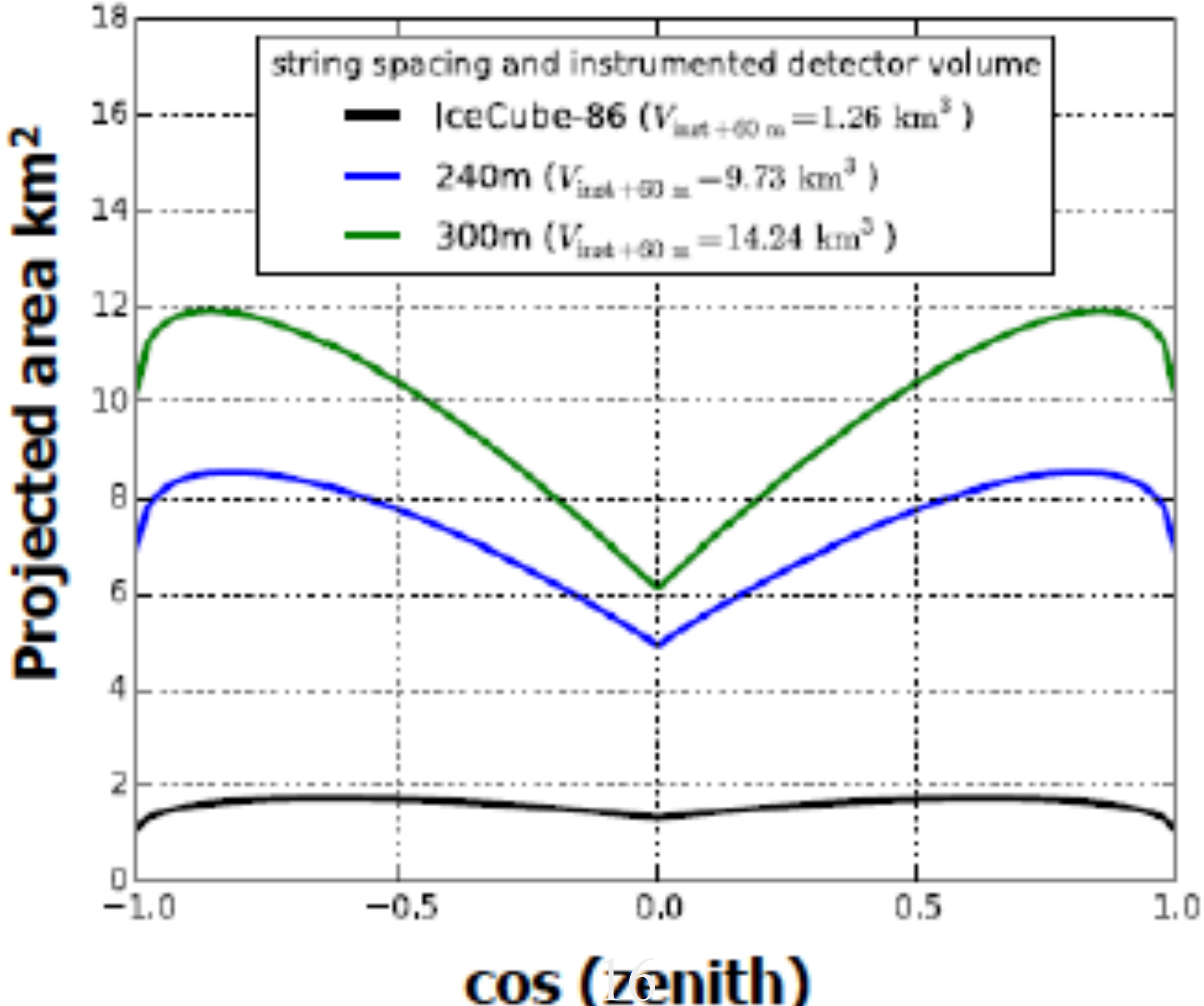


FIG. 14: Histogram of events, predicted and measured, including prompt events (showers).

Glashows may receive help from IceCube Gen-2:

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

INCREASE IN VOLUME AND PROJECTED AREA



There is evidence of new astro-nu source;

and there is evidence that astro-nut are Xgal;

and Glashows are due to show about NOW;

but,

GLASHOW RESONOMETER TO UNAMBIGUOUSLY DISCRIMINATE AMONG THE MYRIAD POSSIBILITIES

IS UNLIKELY.

Extra Slides

Glashow's peak:

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

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 $u_\beta^{\rm CRF} (p_\nu^{\max})^\beta\,,\quad$ where $u_\beta^{\rm CRF} = (1, \vec{0})$.

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

Neutrino maximum energy (cont.) another way:

Weingberg's neutrino-mass generating operator,

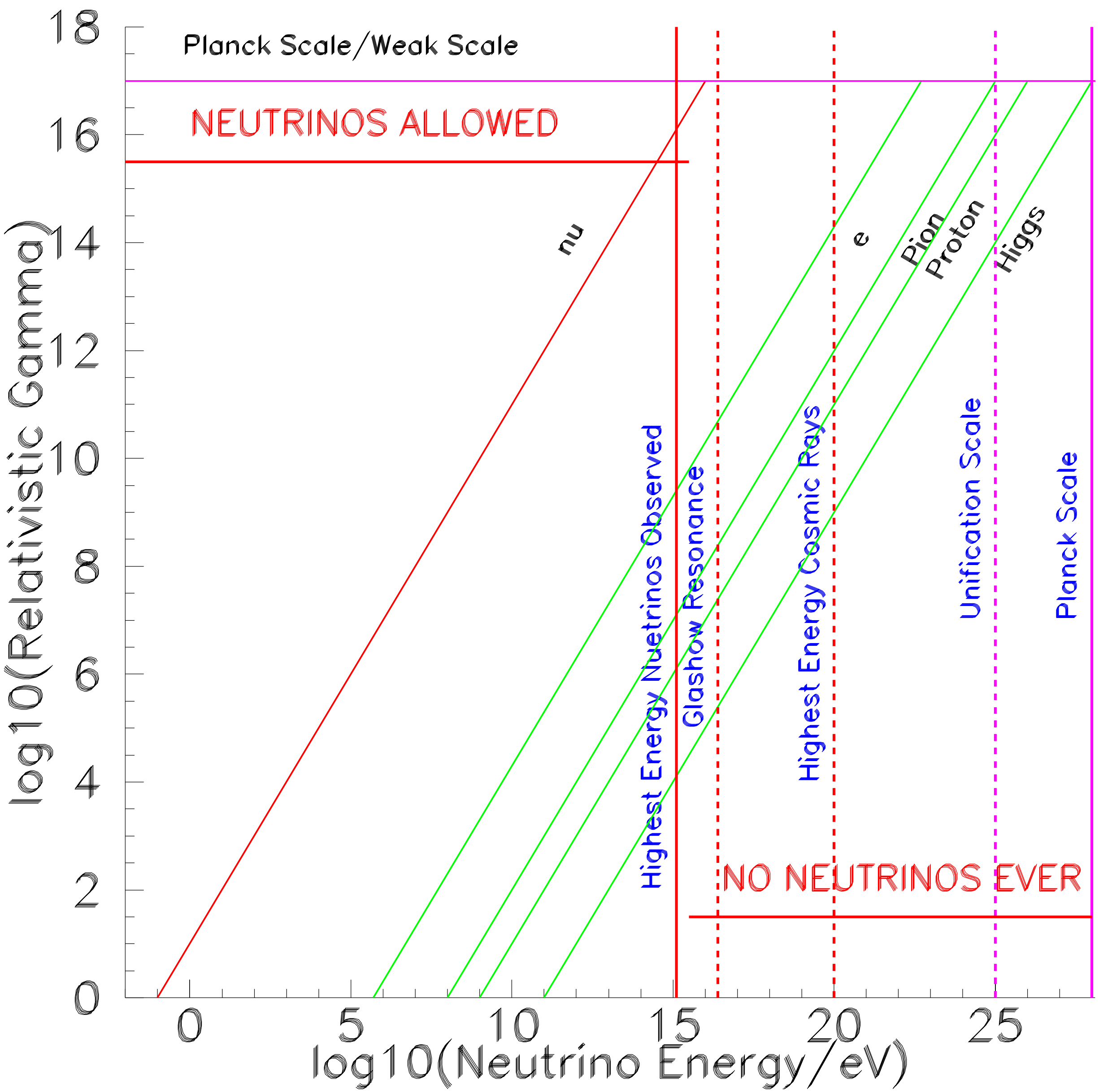
$$\frac{1}{\Lambda}(HL)(HL) => m_\nu = \frac{vev^2}{\Lambda},$$

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

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

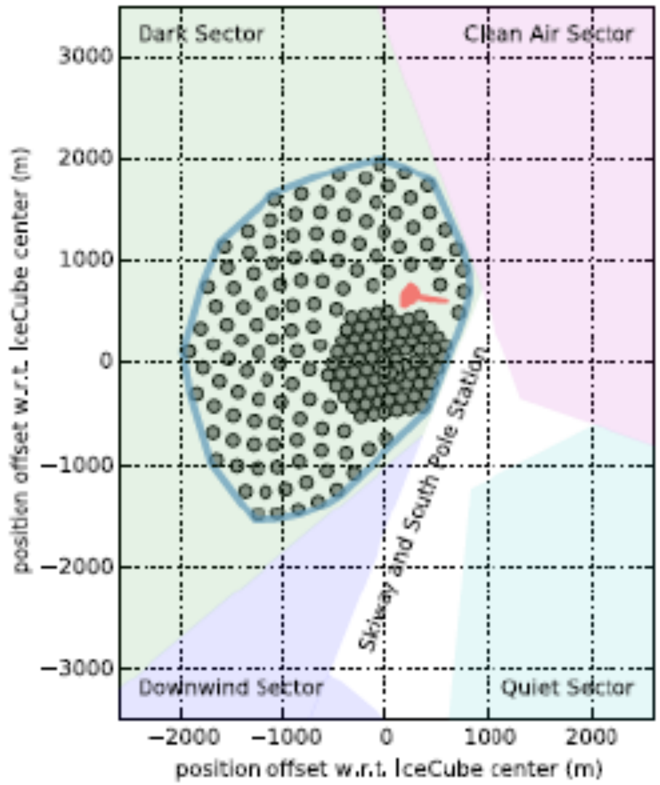
$$\sim 10^4 \times 10^{-4} \times \left(\frac{M_P}{\mathrm{vev}}\right).$$

The End of the Neutrino Spectrum



Learned & TJW (2014)

Glashows may receive help from IceCube Gen-2:



STRAWMAN DETECTOR

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

Glashow Resonance - Formulas:

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

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

Glashow event rates vs. continuum:

TABLE II: Ratio of resonant event rate around the 6.3 PeV peak to non-resonant event rate above $E_\nu^{\min} = 1,\ 2,\ 3,\ 4,\ 5$ PeV. The single power-law spectral index α is taken to be 2.0 and 2.3 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 observed resonance events around 6.3 PeV equal to the first numerical column times 3.

$E_\nu^{\min}$ (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)