Neutrinos and the Cube

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SINGLE OR DOUBLE POWER LAW - the "break", a new source?

Including IceCube's track analysis with HESE events, (Anchordoqui et al - 1611.07905) …

high-energy index of -2.13 +/- 0.13 , compatibility yields 3 sigma "evidence" favoring double power-law, i.e. spectral break, in the 200 TeV- 500 TeV region.

I.e., there is probably a new source!

(but is it low or high energy?)

Flavor and triangles

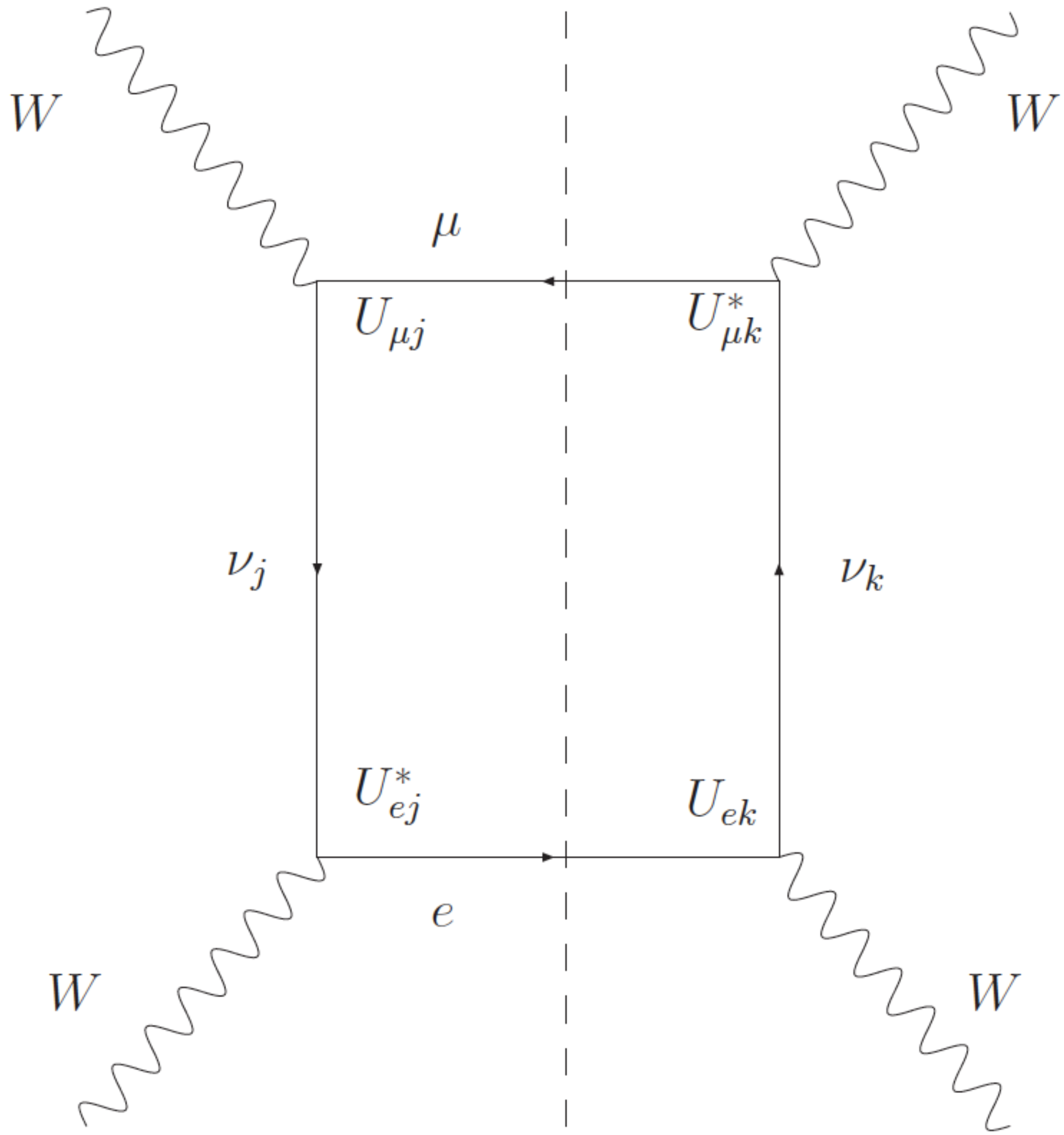
Neutrino at Earth is affected by the transition amplitude $A_{\alpha\to\beta} = \sum_j U_{\alpha j} e^{-iE_{\nu_j}L} U_{j\beta}$. Over large astronomical distances, the oscillating interference terms average out, and one obtains a (3-flavor×3-flavor) probability matrix

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

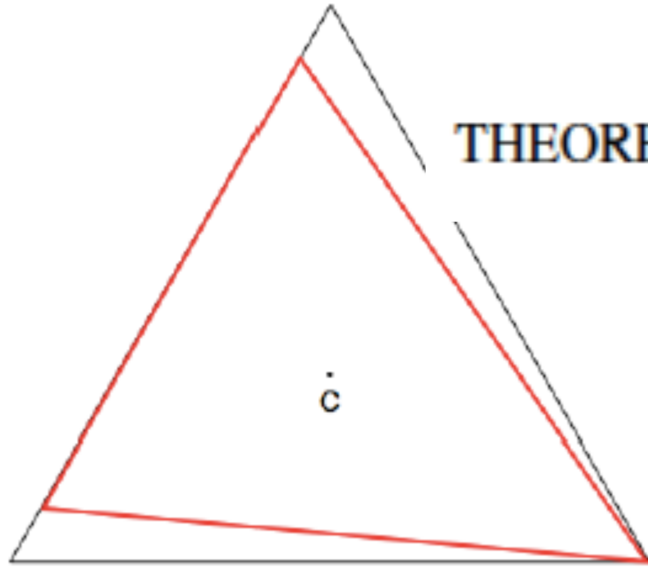
In the TBM model, the probability elements are given by

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

A QFT description:



Evolved flavor matrices:



THEOREM : $S = \frac{\sqrt{3}}{2} |\mathrm{Det}(\mathscr{P})| .$

Figure V.1: The analog of the Earthly triangle is shown (red interior triangle) for the mixing angles that relate quark flavors and masses. Also shown is the centroid point, labelled "C".

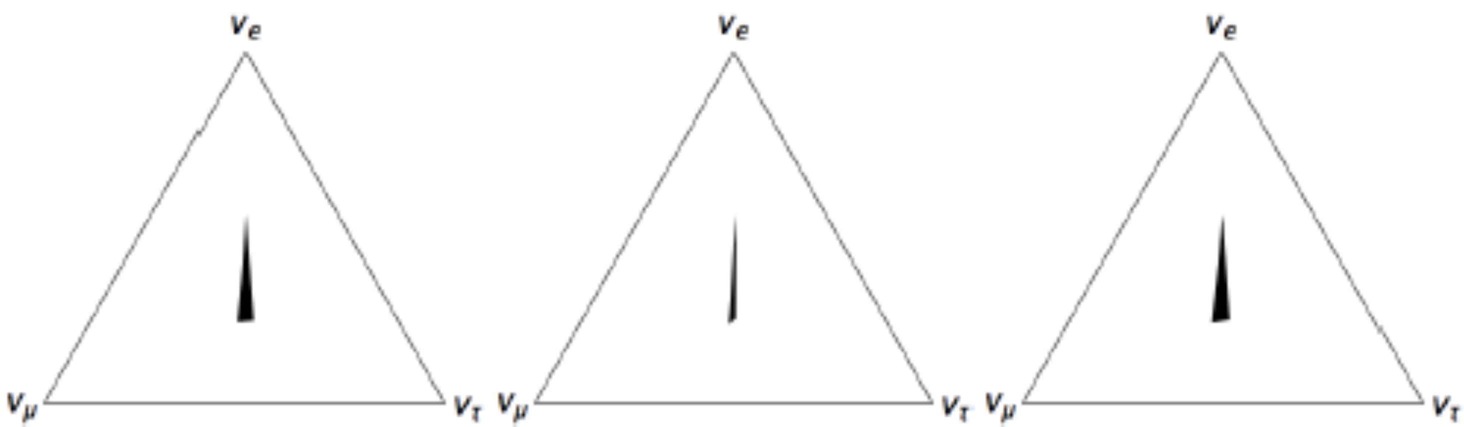


Figure V.2: The Earthly triangles for the best values of, from left to right, the Normal Hierarchy with θ_{32} in first octant, Normal Hierarchy with θ_{32} in second octet, and the Inverted Hierarchy.

Aspects of the Flavor Triangle for Cosmic Neutrino Propagation

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(Dated: February 16, 2015)

arXiv: 1411.1174

Water-Ice/Land ratio

Acceptances for Space-Based and Ground-Based Fluorescence Detectors, and Inference of the Neutrino-Nucleon Cross-Section above 10^{19} eV

Sergio Palomares-Ruiz,* Andrei Irimia,† and Thomas J. Weiler‡
Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235-1807

PRD and arXiv:astro-ph/0512231

Finds rate ratio of ice-water/earth ~5 for nutau-skimmers at high energies (E > 10^17 eV)

Finally confirmed12 yrs later (and factor fixed) by

A Comprehensive Approach to Tau-Lepton Production by High-Energy Tau Neutrinos Propagating Through Earth

Jaime Alvarez-Muñiz[1], Washington R. Carvalho Jr.[2,1], Kévin Payet[3], Andrés Romero-Wolf[4], Harm Schoorlemmer[5], Enrique Zas[1]

arXiv:1707.00334

Glashow (1960) events as Resonometer for anti-nue component:

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

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

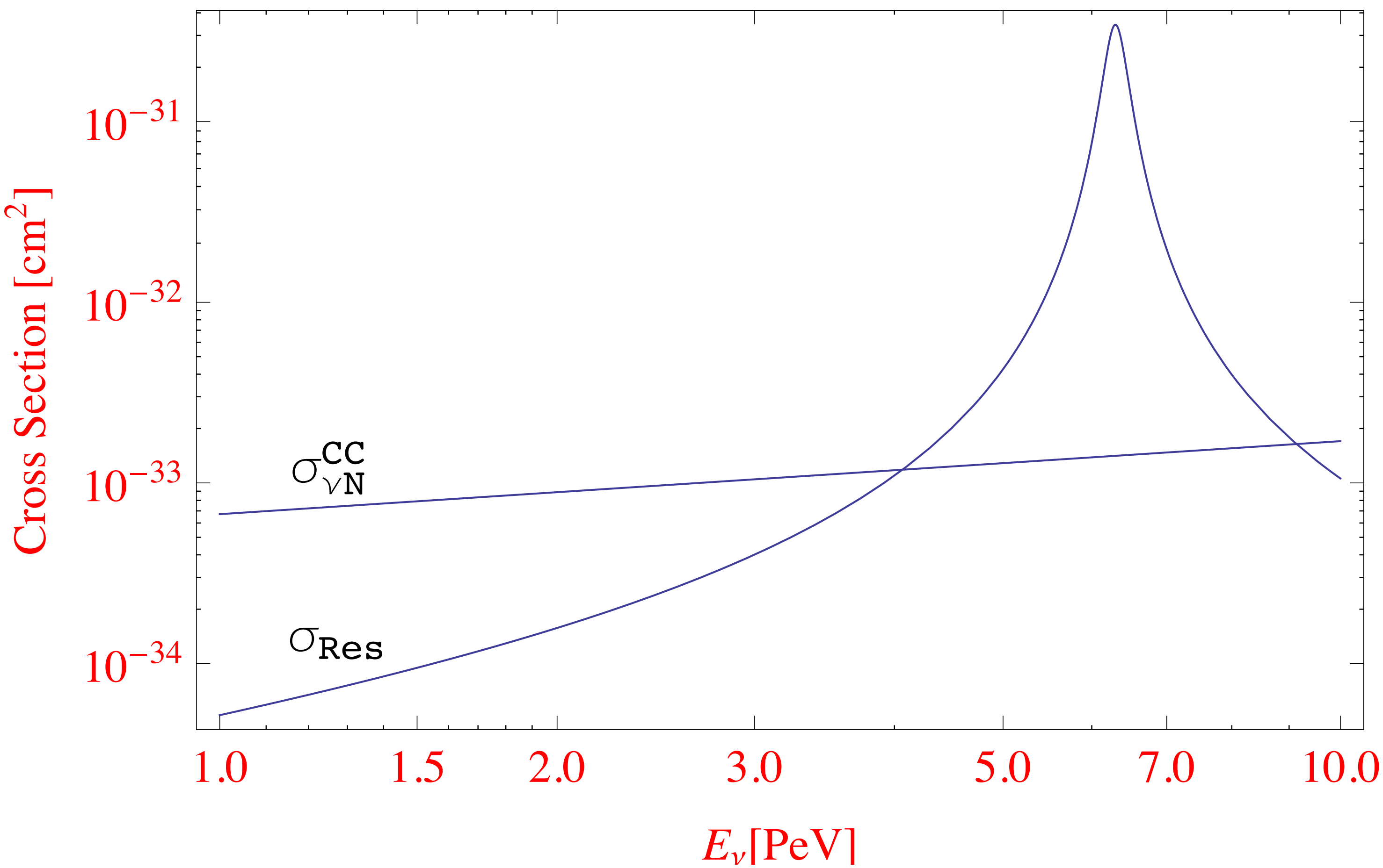
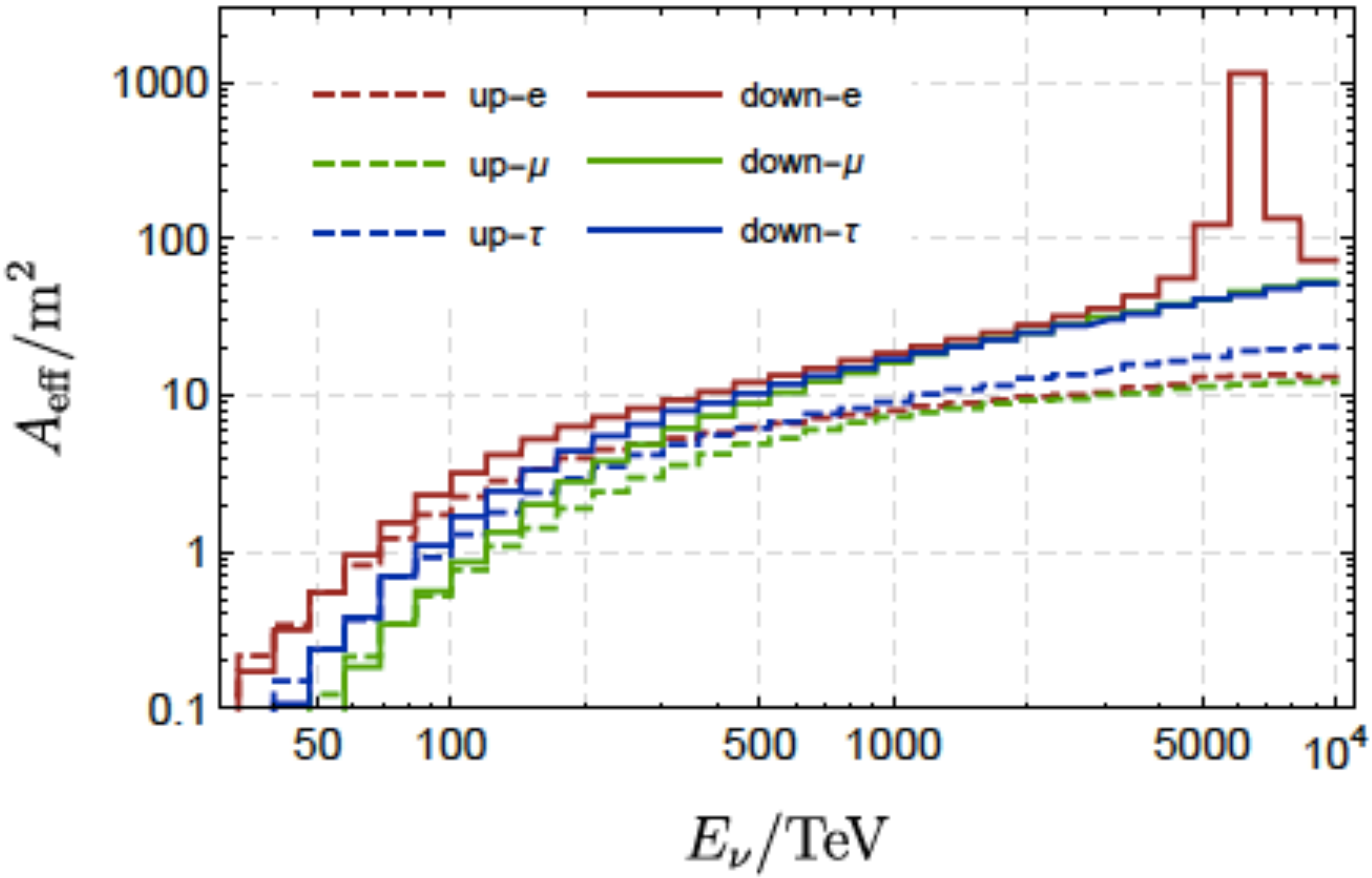


FIG. 1: Cross sections for the resonant process, $\bar{\nu}_e + e^- \to W^- \to$ hadrons, and the non-resonant process, $\nu_e + N \to e^- +$ hadrons, in the 1–10 PeV region.

IceCube effective areas (averaged over 4pi):



Eg. p-gamma makes nue's, no anti-nue'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

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

The "Resonometer" of Cosmic Nu Source Models:

Barger, Fu, Learned, Marfatia, Pakvasa, TJW (1407.3255) (expanding on Anchordoqui,Goldberg,Halzen,Weiler (hep-ph/0410003)

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.

But Biehl, Fedynitch, Palladino, TJW, Winter (1611.07983) :

But, nu's are perhaps made in environments with

a) some optical thickness,

b) possible heavy nuclei source

(not proton primaries), => negative pions via

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

and may have

c) muon damping of the pion DK chain

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

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

5

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

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^+.

and so ability of Glashow Resonometer to discriminate among models is set back many years (if at all) !

Summary:

There is evidence of energy break, => new astro-nu source;

that sources are mainly extragalactic (P. Denton's talk)

that flavor triangles are highly interesting theoretically;

that Ice-Water/Land enhances detection rates of
nutau-skimmers by ~ 5;

and Glashow events at 6.3 PeV are due to appear NOW,
but their discrimination of source models will remain
ambiguous for a long, long time.

Extra Slides

anti-nue mean free path in Earth, and the sagita:

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

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.

Neutrinos carry three types of information:

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

All three have interesting features, as we now explore with examples.

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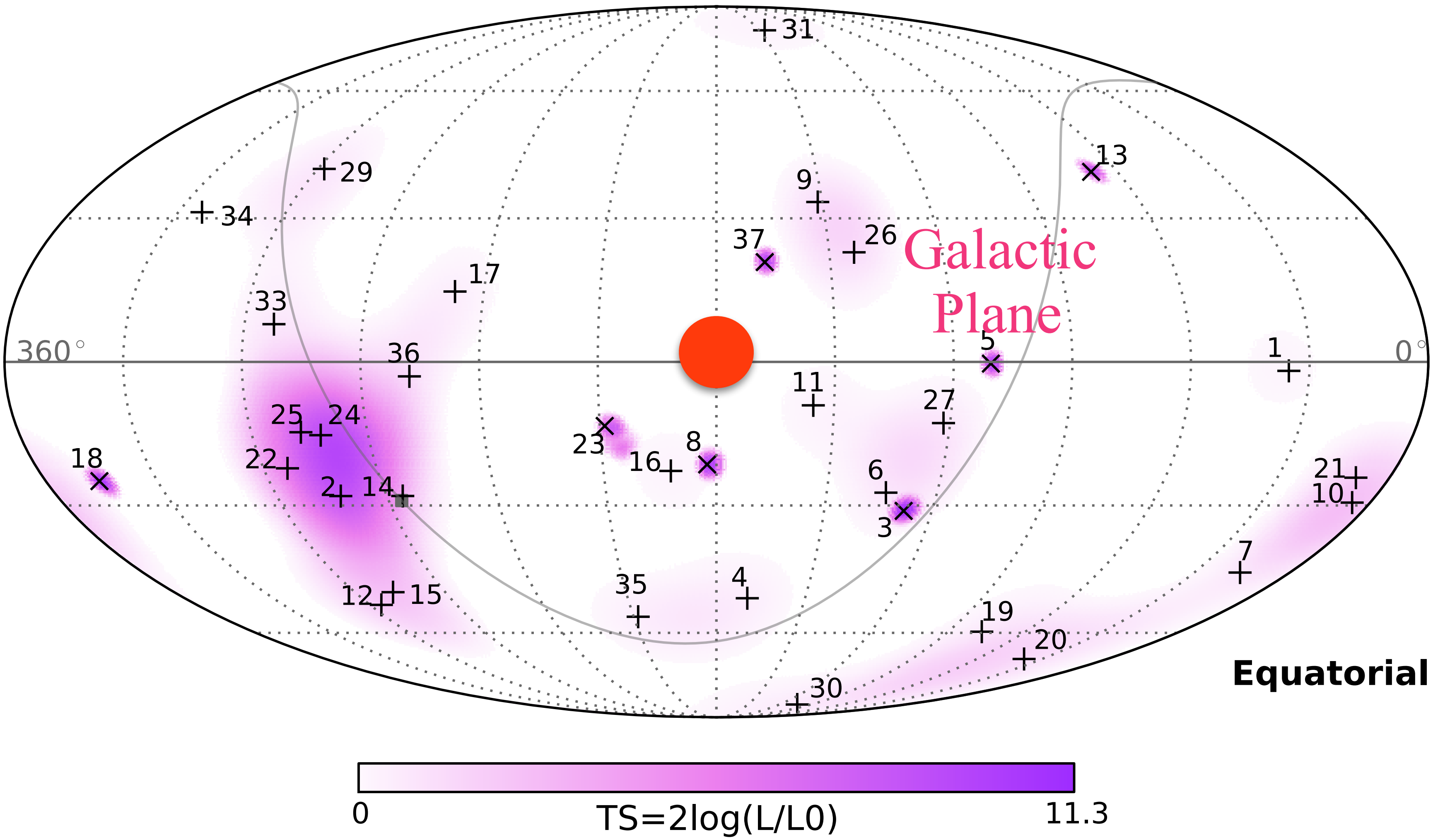
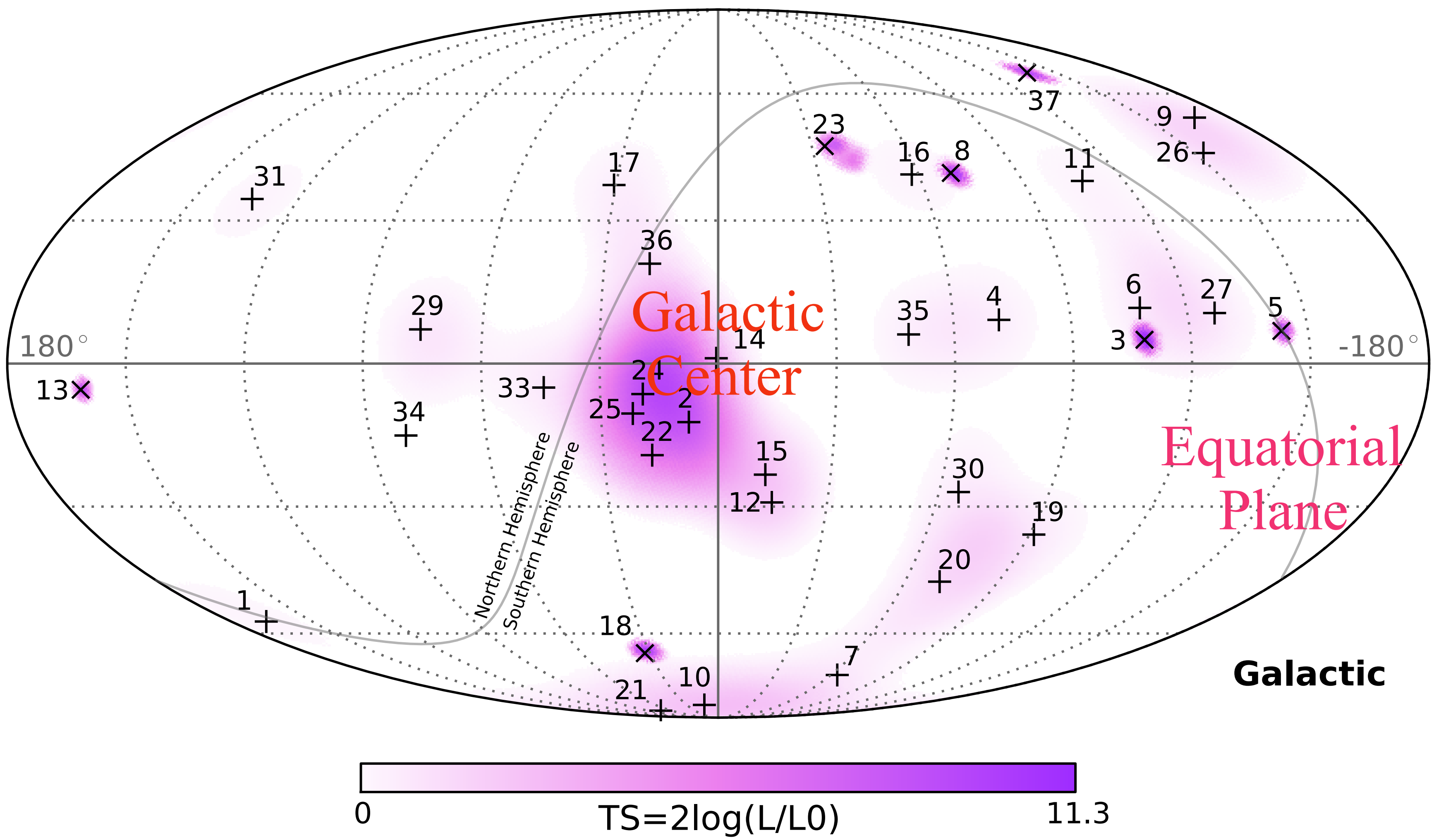
IceCube (Equitorial), 37 events/3 years (bkgd 15+(2-10) low-E atmos. events)



IceCube (Galactic), 37 events/3 years

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



No N/S asymmetry with statistical significance;
move on to Gal-ExGal test.

The Galactic Contribution to IceCube's Astrophysical Neutrino Flux

Peter B. Denton,[a,1] Danny Marfatia,[b] Thomas J. Weiler[c]

(1703.09721)

ExGalactic is way favored:

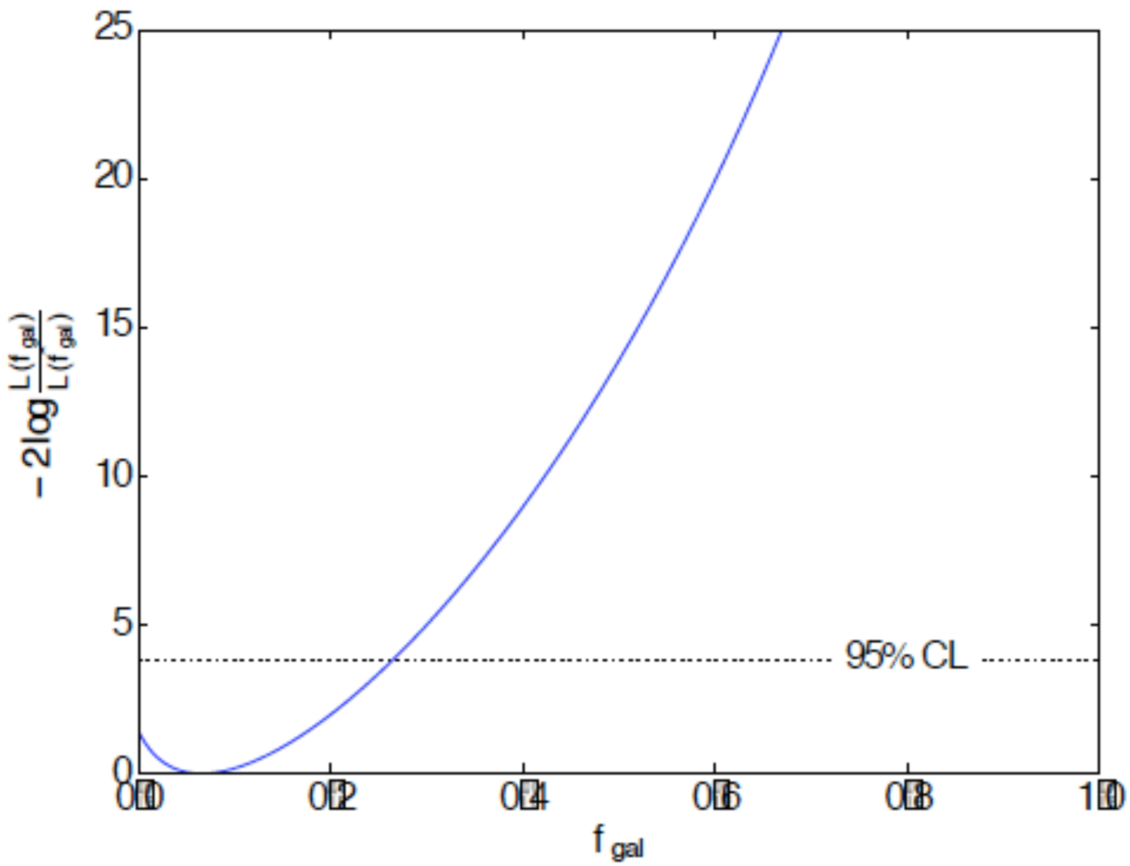


Figure 4. The log likelihood ratio scan $-2\log\mathcal{L}(f_{\rm gal})/\mathcal{L}(\hat{f}_{\rm gal})$. We find the best fit point at $\hat{f}_{\rm gal} = 0.066$ and $f_{\rm gal} = 0$ is allowed at 1.2σ.

E.g.,

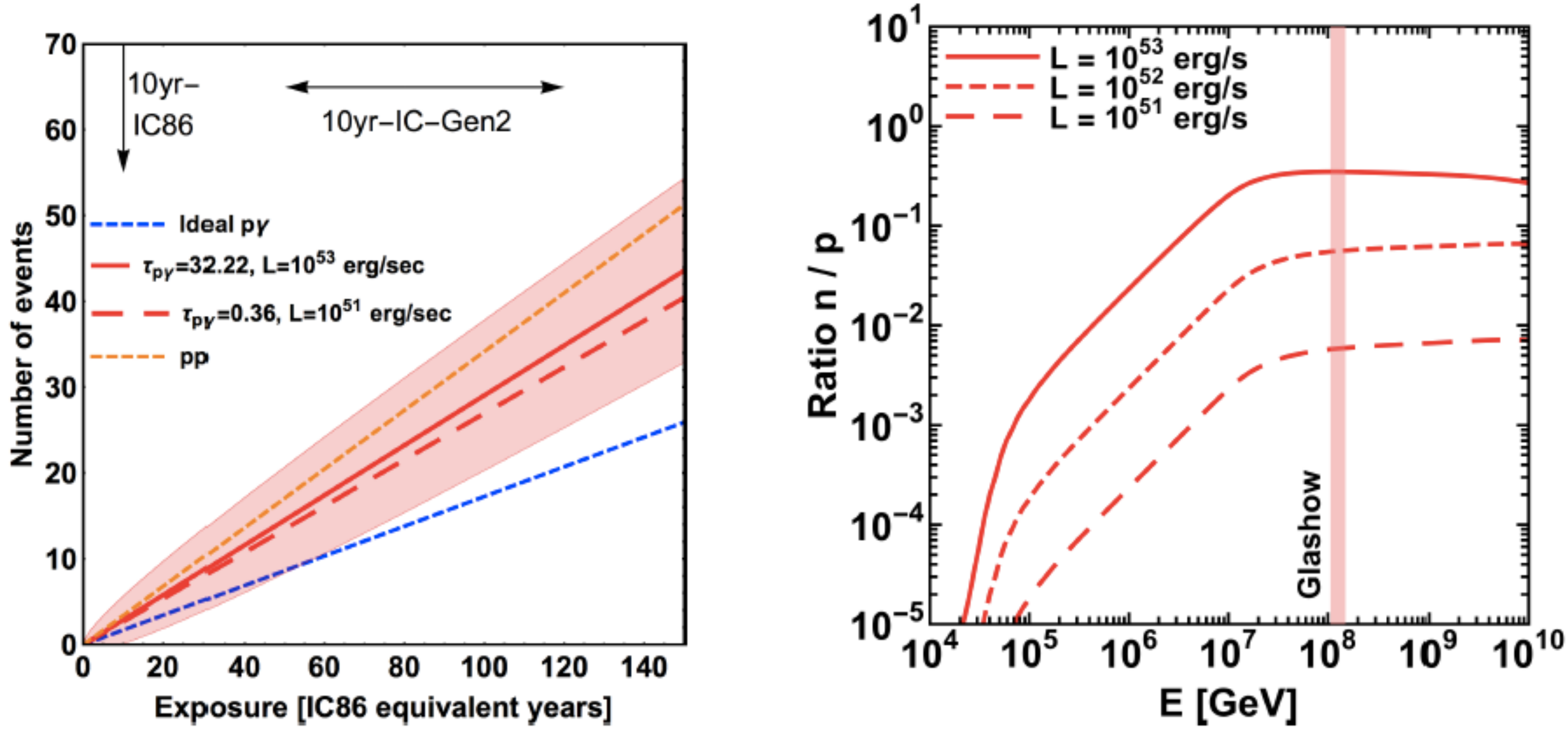


FIG. 3: *Left panel: expected number of Glashow events as a function of exposure for the GRB case for varying optical thickness to photohadronic interactions* $\tau_{p\gamma}$. *As the luminosity in the burst increases, the optical thickness increases as well, leading to an increasing contamination by* 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.*

Glashow's peak:

$$\sigma_{\rm Res}^{\rm peak} = \frac{24\pi\,\mathrm{B}(W^- \to \bar{\nu}_e e^-)\,\mathrm{B}(W^- \to \mathrm{had})}{M_W^2}$$

$$= 3.4 \times 10^{-31}\,\mathrm{cm}^2\,.$$