Icecube Astro-Neutrinos, North/South, Energy Spectrum(a), and the Glashow Resonance
Neutrinos carry three types of information:

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

All three have interesting features in IceCube data.
Astro-Nu evidence update:

- first evidence for an extra-terrestrial flux shown at IPA2013 \cite{IceCube, Science 342 (2013)}

\cite{IceCube, Phys.Rev.Lett. 113:101101 (2014)}

- 3 yrs: 37 events in 988 days \(5.7\sigma\)
  - bkg. \(8.4\pm4.2\) atm. \(\mu\) and \(6.6\pm5.9\) \(\nu\)

- 4 yrs: 54 events \(\sim 7\sigma\)

- mostly \(\nu_e\) CC and NC cascades
More (recent) history:

1. 2012: two PeV events found (serendipity)
2. To lower E, found 26 candidate events between 30 TeV and 2 PeV; of these, now 28 HESE events and 4.1 sigma excess over atmosphere; fitted special index = -2.3 to -2.4
3. Now, 54 HESEs from 1347 days, (2010-2014); atmospheric origin rejected at 5.7 sigma; spectral index -2.6±0.03 overall; excess at 30-200 TeV, HESE index lower than thru-going tracks
More$^2$ History:

4. Northern sky index (2.0$\pm$0.35) flatter than Southern (has Gal Plane, 2.56$\pm$0.12), but differ by only 1.1 sigma

5. Que: N/S different? Spectral break? Glashow resonance events?

6. We await the 2000 days (2010-2016)**
North/South event samples:

FIG. 3: Number distributions for up- and down-going HESE events. (Each dark “event” is an overlap of two events, one up-going and the other down-going.)
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)?
54 events

SKYMAP / CLUSTERING
No significant clustering observed (three years)

ICECUBE PRELIMINARY

Galactic

TS = 2\log(L/L_0)

0 13.1
IceCube official results (circa 2016):

Analyzed with a variant of the standard PS method (w/o energy) (i.e. scrambling in RA)

Most significant excess close to (but not at!) the Galactic Center

Significance: 44% (not significant)

Other searches (multi-cluster, galactic plane, time clustering, GRB correlations) not significant either

And, to release years 5 & 6 starting event data in “summer 2016”
Number events = $(T \Delta \Omega) \sigma x \text{flux}$

So now that HERA tells us sigma is SM up to a few PeV, can compare Northern and Southern hemispheres:

Anchordoqui, Block, Durand, Ha, Soriano, Weiler, and no Halzen!

(Aspen working group ± folks)

No statistical significance!
Moving on to Single vs. Double power-law fits …
On likelihood fits:

\[ \ln \text{likelihood} \equiv -\text{Prob}(n, \mu) = - \ln \left( e^{-\mu} \frac{\mu^n}{n!} \right) \]  

(1)

to be minimized (P maximized),

and with Stirling’s approx,

\[ \ln \text{likelihood} \approx \mu + n \left( 1 + \ln \frac{\mu}{n} \right) + \cdots . \]  

(2)

(expected rate \( \mu \) is Bayesian - would make Nate Silver happy; and centered dots can be prompt charm, shower/track missed, etc.)
Event numbers for our analysis:

1. Of the 54 events, 32 are showers (nu_e and nu_tau’s), and 14 are tracks (above our 33 TeV cutoff); we first explore showers only, due to energy un/certainties.

2. We use Poisson statistics (with Bayesian means).

3. Have checked: track/shower ambiguities not important HERE.

4. Double power-law barely provides better fit.
5. crossover (i.e. two equal contributors) occurs at ~ 260 TeV
   - (290 TeV w/more prompts)
6. Can do same for tracks+showers, get shallower high-energy power,
   -2.60 vs. -3.5+3.0-0.7,
   and by itself, 1 sigma contours do not close;
   crossover slightly higher, at ~ 270 TeV
   - (390 TeV w/ prompts).
But including IceCube’s track alone analysis, …

with 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!
And will there be

i) continuum events in 2-10 PeV region ?

ii) Glashow resonance events at 6.3PeV ?
\[
p + p \rightarrow \begin{cases} 
\pi^+ + \text{anything} & 1/3 \text{ of all cases} \\
\pi^- + \text{anything} & 1/3 \text{ of all cases} \\
\pi^0 + \text{anything} & 1/3 \text{ of all cases}
\end{cases}
\]

For example, in idealized \( p\gamma \) interactions, the process
\[
p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} 
\pi^+ + n & 1/3 \text{ of all cases} \\
\pi^0 + p & 2/3 \text{ of all cases}
\end{cases}
\]

will lead, after pion decay
\[
\pi^+ \rightarrow \mu^+ + \nu_\mu, \\
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu,
\]
Nu flavors evolve over astro- distances:

assume that tribimaximal mixing [12] holds. Then, the evolution $\nu_\alpha \to \nu_\beta$, with $\alpha$ and $\beta$ any elements of the three-flavor set $\{e, \mu, \tau\}$, is described in terms of the PMNS matrix $P$ by the symmetric propagation matrix $P$ whose positive definite elements are

$$P_{\alpha\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 = \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}. \quad (1)$$

Note that tau neutrinos are not expected at the source in the pion production scenarios, i.e., $\phi_\tau = 0$, because the charged partner $\tau^\pm$ has a mass much larger than the pion mass. As a result, we obtain [35, 36]

$$\begin{pmatrix} \phi^f_e \\ \phi^f_\mu \end{pmatrix} = P^{(2\times2)}_{\text{TBM}} \begin{pmatrix} \phi_e \\ \phi_\mu \end{pmatrix}, \quad P^{(2\times2)}_{\text{TBM}} = \frac{1}{9} \begin{pmatrix} 5 & 2 \\ 4 & 7 \end{pmatrix} \quad (6)$$
A QFT description:
Evolved flavor matrices:

THEOREM: \[ S = \frac{\sqrt{3}}{2} |\text{Det}(\mathcal{P})| \].

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 $\theta_{32}$ in first octant, Normal Hierarchy with $\theta_{32}$ in second octet, and the Inverted Hierarchy.
When no nutau’s are produced at source, only regions 5 and 6 are allowed. In fact, region is dim 2 hyperspace - 1 (constraint) = 1, a boundary.
Sub-triangle 1: $W_{\mu} \geq W_{\tau} \geq W_{e}$ and $w_{\mu} \geq w_{\tau} \geq w_{e}$;
Sub-triangle 2: $W_{\tau} \geq W_{\mu} \geq W_{e}$ and $w_{\tau} \geq w_{\mu} \geq w_{e}$;
Sub-triangle 3: $W_{\tau} \geq W_{e} \geq W_{\mu}$ and $w_{\tau} \geq w_{e} \geq w_{\mu}$;
Sub-triangle 4: $W_{e} \geq W_{\tau} \geq W_{\mu}$ and $w_{e} \geq w_{\tau} \geq w_{\mu}$;
Sub-triangle 5: $W_{e} \geq W_{\mu} \geq W_{\tau}$ and $w_{e} \geq w_{\mu} \geq w_{\tau}$;
Sub-triangle 6: $W_{\mu} \geq W_{e} \geq W_{\tau}$ and $w_{\mu} \geq w_{e} \geq w_{\tau}$.

When $\text{Det}(\mathcal{P}) \neq 0$, the earthly triangle must have representation in each of the six sub-triangular regions, since the triangle must have a nonzero area and it must contain the centroid.

When area $S \propto \text{Det}$ vanishes ($W_{\text{tau}} = 0$) can “predict” CP parameter delta in terms of mixing angles!
Glashow is a “no-show”?

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

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

FIG. 1: Cross sections for the resonant process, \( \bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{hadrons} \), and the non-resonant process, \( \nu_e + N \rightarrow e^- + \text{hadrons} \), in the 1–10 PeV region.
IceCube effective areas (averaged over 4π):
Glashow events are anisotropic:

\[ \lambda_{\bar{\nu}_e} \sim \frac{1}{n_e \sigma_{\text{peak}} \sigma_{\text{Res}}} \sim \begin{cases} 110 \text{ km in mantle rock,} \\ 310 \text{ km in ice.} \end{cases} \quad (18) \]

The width in \( E_{\nu} \), 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 \( \pm 0.3 \) 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.
Glashow not yet problematical:

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

<table>
<thead>
<tr>
<th>Source flavor ratio</th>
<th>Earthly flavor ratio</th>
<th>$\bar{\nu}_e$ fraction in flux ($\mathcal{R}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \pi^\pm$ pairs</td>
<td>(1:2:0)</td>
<td>(1:1:1)</td>
</tr>
<tr>
<td>w/ damped $\mu^\pm$</td>
<td>(0:1:0)</td>
<td>(4:7:7)</td>
</tr>
<tr>
<td>$p\gamma \rightarrow \pi^+$ only</td>
<td>(1:1:0)</td>
<td>(0:1:0)</td>
</tr>
<tr>
<td>w/ damped $\mu^+$</td>
<td>(0:1:0)</td>
<td>(0:0:0)</td>
</tr>
<tr>
<td>charm decay</td>
<td>(1:1:0)</td>
<td>(14:11:11)</td>
</tr>
<tr>
<td>neutron decay</td>
<td>(0:0:0)</td>
<td>(1:0:0)</td>
</tr>
</tbody>
</table>

(Kaons change little, but source environment matters: BFPWW)
But Nature is not so Clean:

(Biehl, Fedynitch, Palladino, Weiler, Winter, PRD and 1611.07983)

1. Optically thick sources;
2. Heavy nuclei primaries mix n and p, lower E per nucleon;
3. muon-damped sources;

E.g. optically thick: The leading $\Delta$-resonance for neutrons is isospin-symmetric to protons

\[
n + \gamma \rightarrow \Delta^0 \rightarrow \left\{ \begin{array}{l}
\pi^- + p \quad 1/3 \text{ of all cases} \\
\pi^0 + n \quad 2/3 \text{ of all cases}
\end{array} \right.,
\]

which means that $\pi^-$ are pre-dominantly produced instead of $\pi^+$. In the optically thick case, one roughly expects a neutron energy spectrum which is about 1/3 (branching ratio) times 0.8 (fraction of primary energy deposited into the secondary nucleon) $\sim 30\%$ that of the initial proton spectrum, with a corresponding fraction of $\pi^-$ contamination at the highest energy.
For the charged pion decay chains, we immediately find from Eq. (6)

\[
\begin{align*}
\pi^+ & \to e^+\nu_e\nu_\mu\bar{\nu}_\mu \xrightarrow{\text{mix}} \xi_{\bar{\nu}_e}^f = \frac{1}{3} \times \frac{2}{9} = \frac{2}{27}, \\
\pi^- & \to e^-\bar{\nu}_e\nu_\mu\bar{\nu}_\mu \xrightarrow{\text{mix}} \xi_{\bar{\nu}_e}^f = \frac{1}{3} \times \left( \frac{5}{9} + \frac{2}{9} \right) = \frac{7}{27}.
\end{align*}
\]  

(9)  

(10)

We observe from the ratio of the two processes that the \( \pi^- \) decay chain yields 7/2 times more Earthly \( \bar{\nu}_e \) than the \( \pi^+ \) decay chain. From a different perspective, the Glashow event rate from the \( \pi^+ \) decay chain is potentially contaminated by \( \pi^- \) production (if present at the source), namely \( \sim 7/2 \) times the fraction \( \pi^-/\pi^+ \).
FIG. 1: Expected number of Glashow events in the ideal pp and $p\gamma$ scenarios as a function of the exposure for $\alpha = 2.0$. The bands represent the 90% C.L. interval from the statistical (Poissonian) uncertainty and the model uncertainties on the oscillation parameters, assuming a true pp and $p\gamma$ scenario in the left and right panel, respectively. The vertical lines indicate when the other scenario can be excluded.
But ..., e.g.

Approximately ten yrs of Gen2 required for discrimination `tween models

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 $\tau_{\gamma\gamma}$. As the luminosity in the burst increases, the optical thickness increases as well, leading to an increasing contamination by $\pi^-$. Right panel: neutron to proton ratio as a function of the energy for different luminosities. At high energies, the ratio becomes negative due to the background of $\pi^-$ production.
Glashow Resonance - Formulas:

\[
\left( \frac{N}{T\Omega} \right)_{\text{Res}} = \frac{N_p}{2m_e} \left( \pi M_W \Gamma_W \right) \sigma_{\text{Res}}^{\text{peak}} \left. \frac{dF_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} \right|_{E_{\bar{\nu}_e} = 6.3 \text{ PeV}},
\]

scales of course with flux \( dF/dE \),
and so with 3 or 2 or 1 mean events in the 1-2 PeV range,

\[
\sigma_{\text{Res}}^{\text{peak}} = \frac{24\pi \, B(W^- \to \bar{\nu}_e e^-) \, B(W^- \to \text{had})}{M_W^2} = 3.4 \times 10^{-31} \text{ cm}^2.
\]
Glashow particulars:

The resonant to non-resonant rate at 6.3 PeV is about 240. But several features (spectral index effect, width to \( W \)-mass ratio = 1/38, absorption) cut this Glashow resonance production down to about twice continuum rate.
TABLE II: Ratio of resonant event rate around the 6.3 PeV peak to non-resonant event rate above $E_{\nu}^{\text{min}} = 1, 2, 3, 4, 5$ PeV. The single power-law spectral index $\alpha$ 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.

<table>
<thead>
<tr>
<th>$E_{\nu}^{\text{min}}$ (PeV)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \pi^\pm$ pairs</td>
<td>0.33 (0.29)</td>
<td>0.50 (0.53)</td>
<td>0.64 (0.77)</td>
<td>0.76 (1.0)</td>
<td>0.87 (1.2)</td>
</tr>
<tr>
<td>damped $\mu^\pm$</td>
<td>0.22 (0.18)</td>
<td>0.33 (0.34)</td>
<td>0.42 (0.50)</td>
<td>0.49 (0.64)</td>
<td>0.56 (0.79)</td>
</tr>
<tr>
<td>$p\gamma \rightarrow \pi^+$ only</td>
<td>0.14 (0.12)</td>
<td>0.22 (0.23)</td>
<td>0.28 (0.33)</td>
<td>0.33 (0.43)</td>
<td>0.38 (0.53)</td>
</tr>
<tr>
<td>damped $\mu^+$</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>charm decay</td>
<td>0.37 (0.32)</td>
<td>0.56 (0.60)</td>
<td>0.72 (0.86)</td>
<td>0.85 (1.1)</td>
<td>0.98 (1.4)</td>
</tr>
<tr>
<td>neutron decay</td>
<td>1.1 (0.94)</td>
<td>1.7 (1.8)</td>
<td>2.1 (2.5)</td>
<td>2.5 (3.3)</td>
<td>2.9 (4.0)</td>
</tr>
</tbody>
</table>
Cosmogenic's?

"guaranteed" flux

Greisen-Zatsepin-Kuzmin

cosmogenic ν's

\[ p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow n\pi^+ \rightarrow n\mu\nu \]

\[ p\pi^0 \rightarrow \gamma\gamma \]

νμ events per km²·yr

100
And now IceCube sees a 2.6 PeV (dep energy) muon track, 
=> 6-10 PeV muon neutrino energy (Astronomy Telegrams)

and ANITA sees a 0.8 EeV up-coming event 
(arXiv:1603.05218), probably CR, but still…

J. Liao, Marfatia, Weiler, in progress, 
(along with PAO limit on tau neutrino flux - Earth-Skimmers).
could even be a tau neutrino at 100 PeV ($10^{17}$ eV).

Engel, Seckel, Stanev:

**neutron decay**

**charged pion decay**

**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).
The End of the Neutrino Spectrum

Planck Scale/Weak Scale

NEUTRINOS ALLOWED

High Energy Neutrinos Observed Glashow Resonance

High Energy Cosmic Rays

Unification Scale

Planck Scale

NO NEUTRINOS EVER???
Neutrino maximum energy (cont.)

another way:

Weingberg’s neutrino-mass generating operator,

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

\[
m_\nu \sim \frac{vev^2}{M_{GUT}}, \text{ so}
\]

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

\[
\sim 10^4 \times 10^{-4} \times \left( \frac{M_P}{\text{vev}} \right).
\]
Neutrino Energy Maximum:

\[ E_{\nu}^{\text{max}} = \frac{m_{\nu} M_{\text{Planck}}}{M_{\text{weak}}} = 2.5 \left( \frac{m_{\nu}}{0.05 \text{ eV}} \right) \left( \frac{M_{\text{Planck}}}{1.2 \times 10^{28} \text{ eV}} \right) \left( \frac{247 \text{ GeV}}{v_{\text{weak}}} \right) \text{ PeV}. \]

In what frame?

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

And \( (p_{\nu}^{\text{max}})^{\beta} \) transforms as usual four-vector.
May receive help from IceCube Gen-2, to answer questions:

Expect 5-12 increase in effective area, => 5-12 increase in EVENT RATE:

- 120 additional strings
- length 1.3 km
- average spacing 240 m
- volume 9.7 km$^3$
Double power-law fits better (3 sigma) than single power-law; break in 200-200 TeV range; suggests a new source.

No North/South significance at present.

No multi-messenger events (but search is just beginning, AMON, …)

No Glashow events, just beginning to be problematical. [ Neutrino flavor physics is very interesting, and useful - three lbs of mush in our heads can learn secrets of other side of Uni ]

IceCube-Gen2 coming, w/ 5-12x data rate.

Gamma = E/m is huge for neutrinos, ~ 10^17; tests Lorentz Inv.