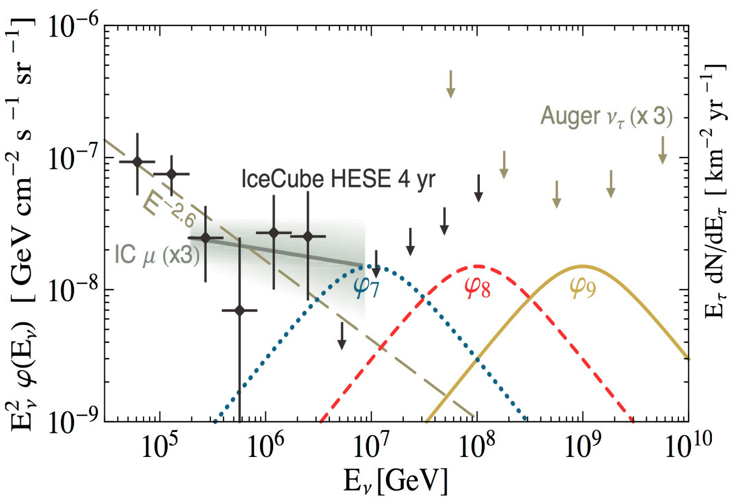
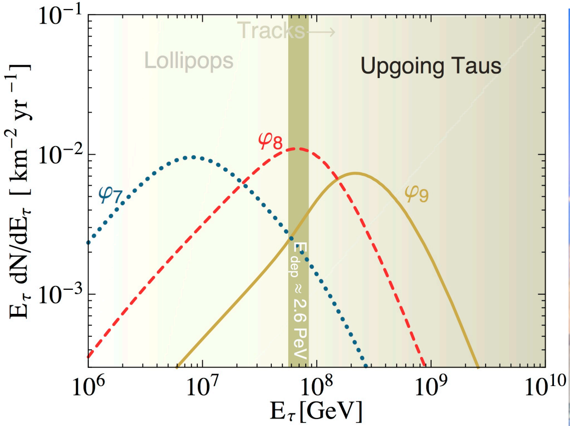




Multi-PeV Signals from a New Astrophysical Neutrino Flux Beyond the Glashow Resonance

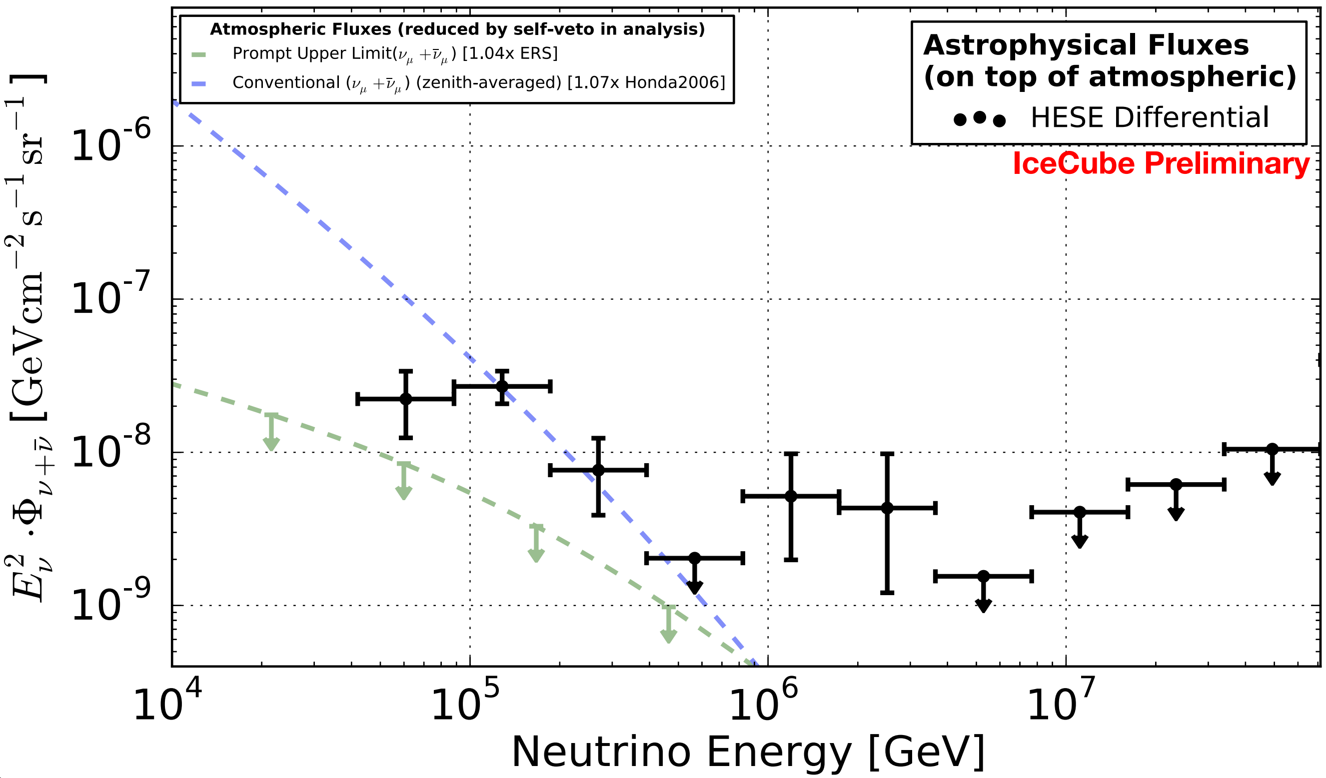
Ranjan Laha

Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)

Stanford University and SLAC National Accelerator Laboratory

Kistler and Laha arXiv: 1605.08781 (submitted)

Discovery of astrophysical neutrinos



High Energy Starting Event analysis --- 6 year data set

Fit performed including all events between 60 TeV < E_{dep} < 3 PeV

No Glashow resonance event

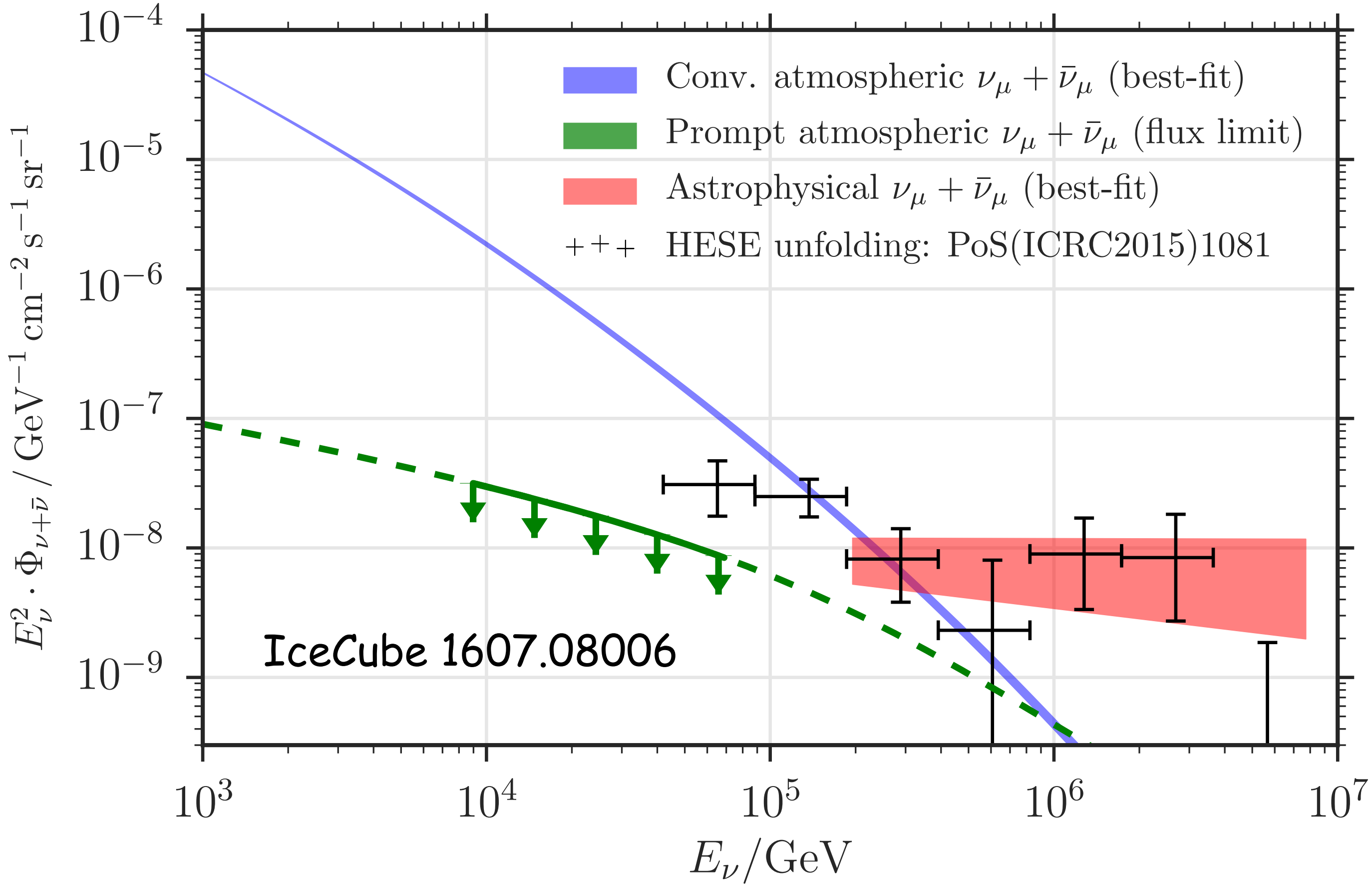
$$E^2\phi(E) = 2.46 \pm 0.8 \times 10^{-8} \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-0.92} \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Steep spectral index from the HESE excess

No statistically significant clustering in space

See talks by Halzen, Kowalski, Wandkowsky, Niederhausen, Richman, Lu, Yuan, Mancina, Wood, Weiler, Ando, Murase, Petropoulou, Sudoh, Denton, Bustamante, Auguelles, Kheirandish, Stecker, Lai, Klop, Yuan, Cerruti, Rodrigues, Fang

Discovery of astrophysical neutrinos



Northen Hemisphere through going muons --- 6 year data set

Fit of through going events between 194 TeV < E_ν < 7.8 PeV

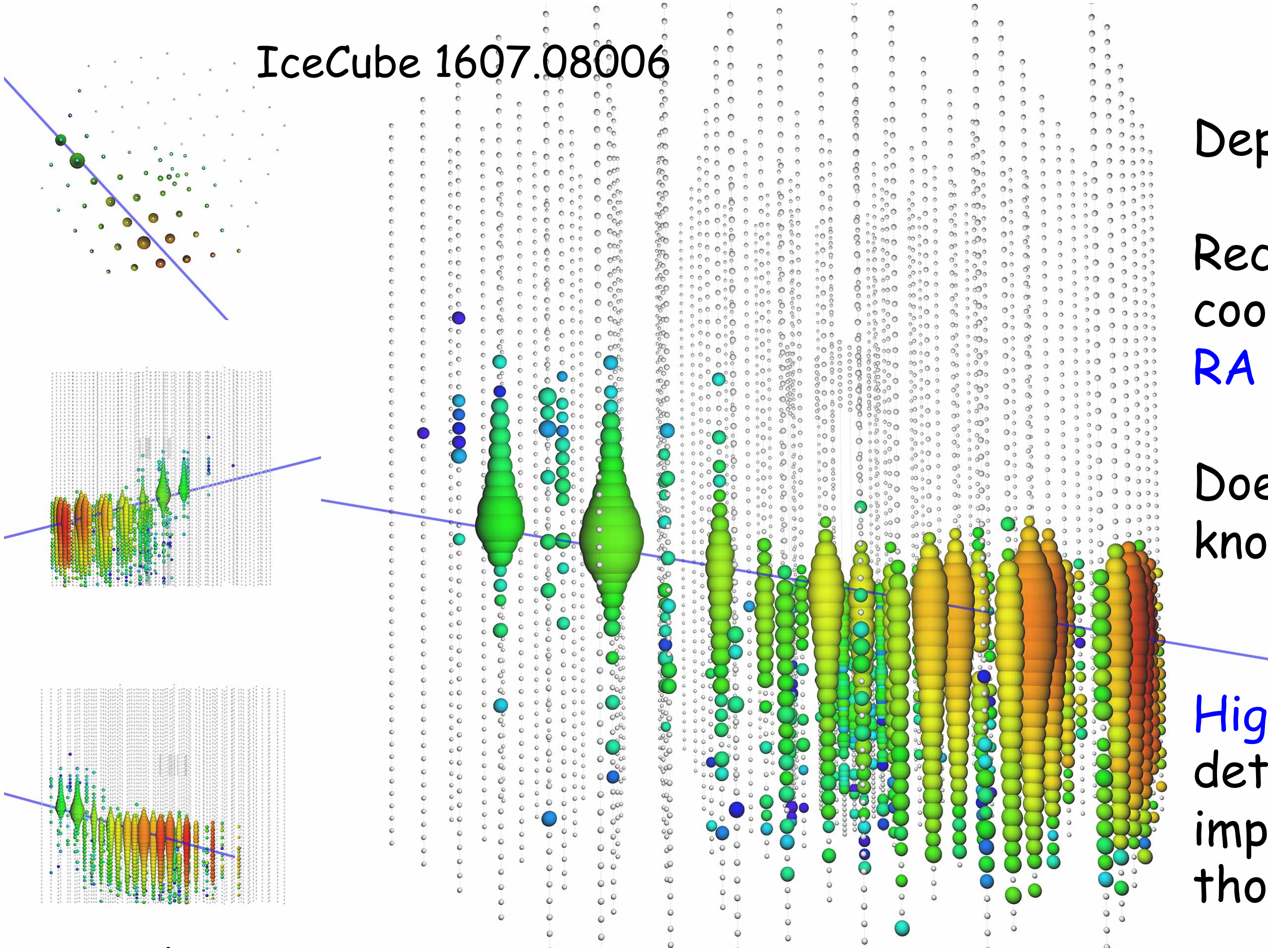
$$\Phi_{\nu+\bar{\nu}} = 0.9^{+0.30}_{-0.27} \times 10^{18} \left(\frac{E_\nu}{100\ \text{TeV}}\right)^{-2.13\pm0.13} \text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

No statistically significant clustering in space

See talks by Weiler, Ando, Murase, Petropoulou, Sudoh, Denton, Bustamante, Auguelles, Kheirandish, Stecker, Lai, Klop, Yuan, Cerruti, Rodrigues, Fang

2.6 PeV track event

IceCube 1607.08006



Deposited energy 2.6 ± 0.3 PeV

Reconstructed equatorial coordinates: decl. 11.42° RA 110.63°

Does not point towards any known astrophysical source

Highest energy track event detected till date --- very important to analyze it thoroughly

Immediate questions:

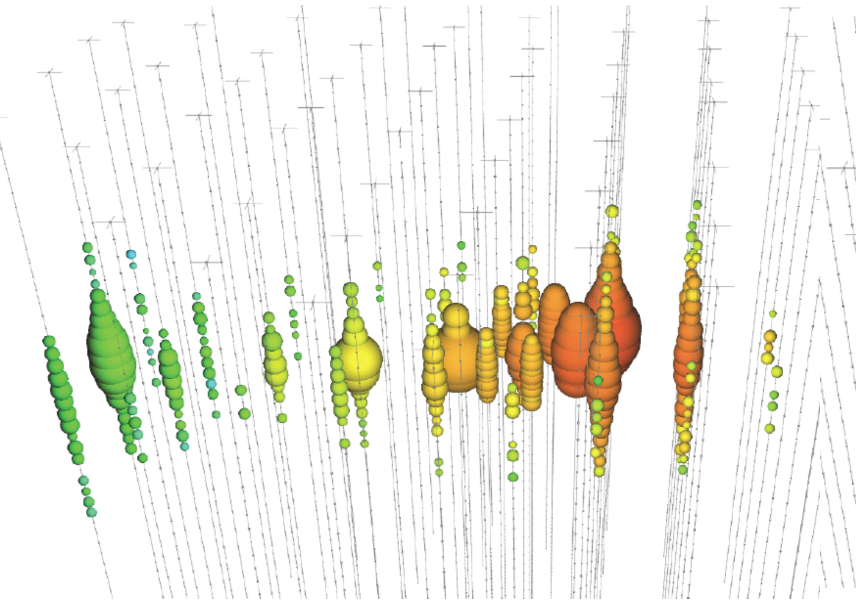
1. What flavor of neutrino produces such a track?

2. What are implications for astrophysical neutrinos in light of prior discoveries?

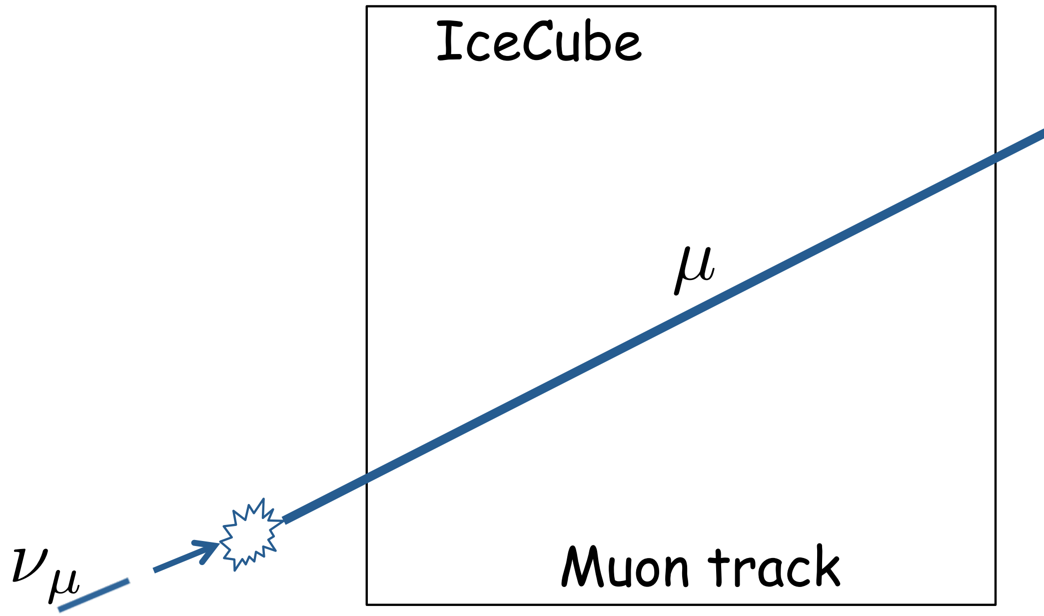
What neutrino flavor produces a track?

- Muons are assumed to give rise to all through-going track like events
- To deposit 2.6 PeV of energy, the muon typically requires $\gtrsim$ 5 PeV energy at detector entry point --- it is probable that this is a super-Glashow (energy ≥ 6.3 PeV) neutrino
- An overlooked possibility in the literature: very high energy through going taus can also give rise to track-like events
- To deposit 2.6 PeV of energy, the tau requires $\gtrsim$ 50 PeV energy at detector entry point
- Can IceCube individually distinguish a through going tau from a through gong muon?
- We discuss astrophysical scenarios for each of these possibilities

Muon tracks



Wandkowsky TeVPA 207



$$\nu_\mu + N \rightarrow \mu + X$$

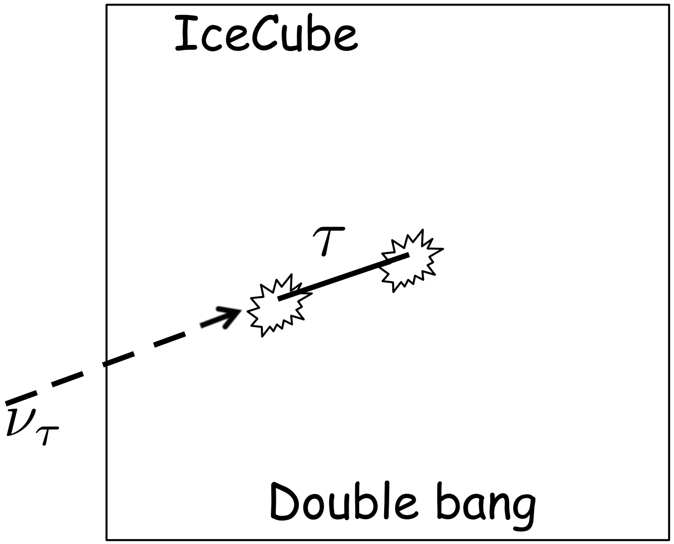
Many muon tracks observed in IceCube

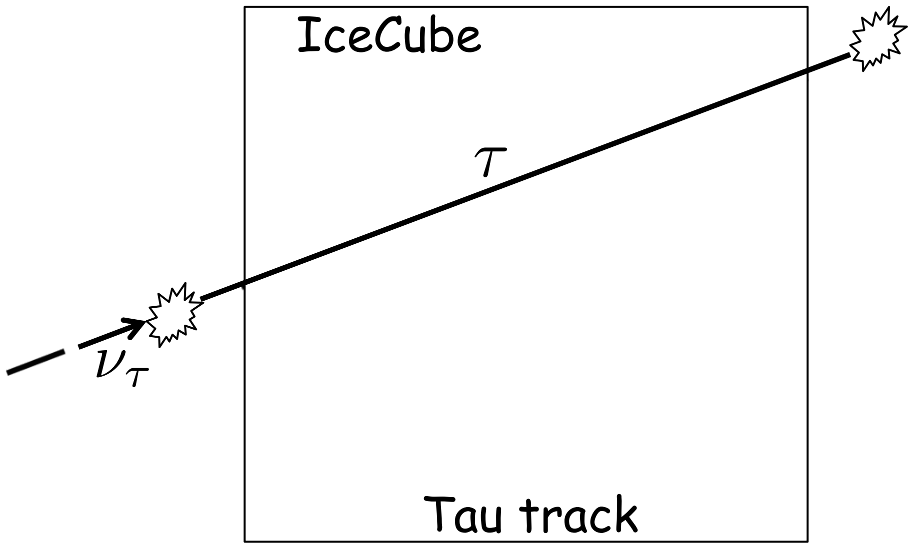
Many theoretical studies on muon tracks

Muon tracks in IceCube have been well studied

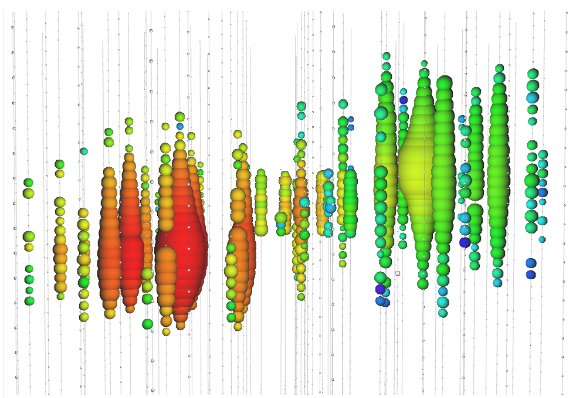
Double bang v/s tau tracks

Tau tracks are produced by ν_τ with energy $\gtrsim$ 50 PeV





Wandkowsky TeVPA 2017



$$\nu_\tau + N \rightarrow \tau + X$$

?

How do tau tracks look in IceCube?

A generic equation for event numbers for through going leptons

$$\frac{d}{dE_\ell}\left[b_\ell(E_\ell)\frac{dN_\ell}{dE_\ell}\right] + \frac{m_\ell}{c\,\tau_\ell\,E_\ell}\frac{dN_\ell}{dE_\ell} = Q(E_\ell)$$

Kistler and Laha arXiv: 1605.08781

Lepton energy loss: $b_\ell \equiv dE_\ell/dX$

Lepton energy E_ℓ

Lepton lifetime τ_ℓ

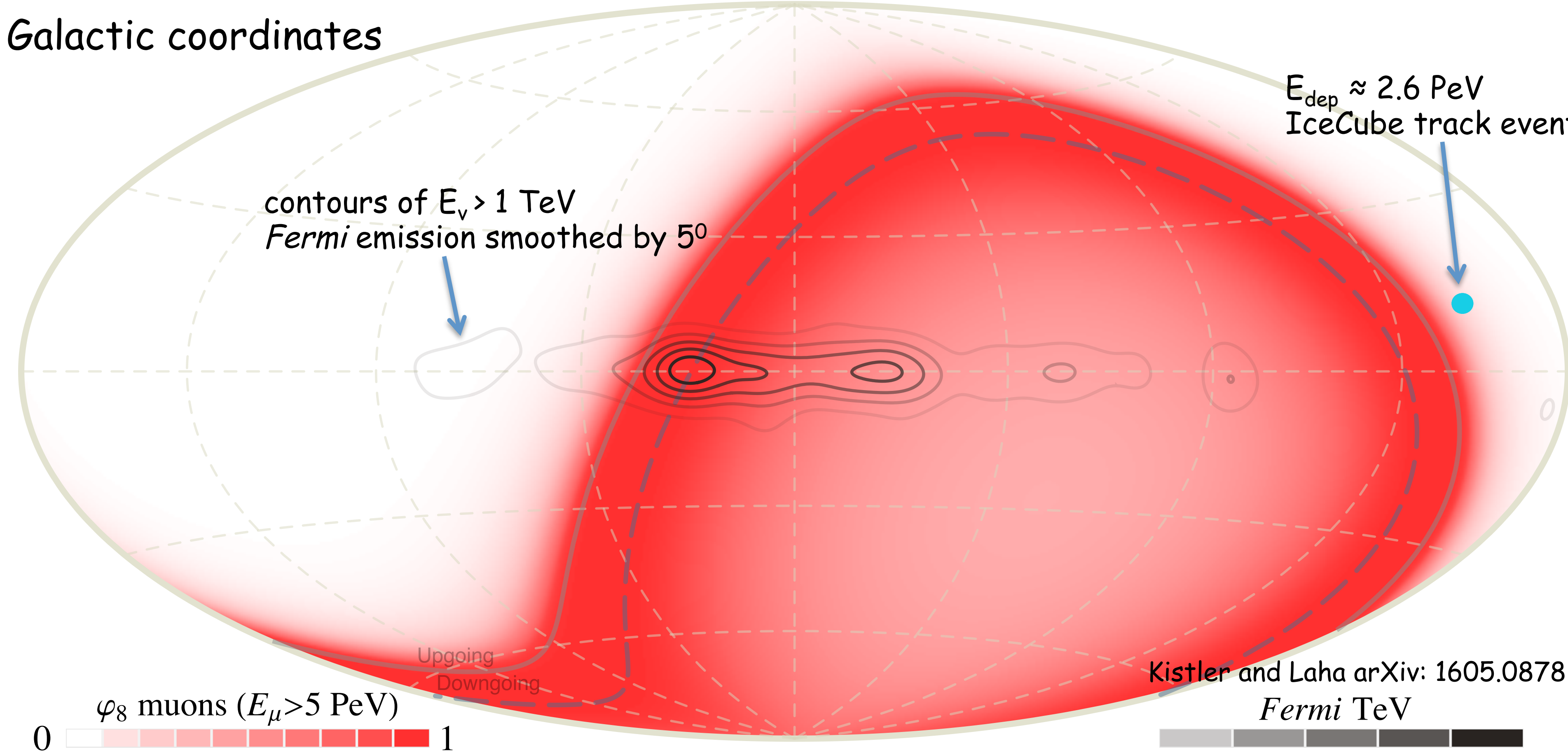
includes Earth absorption

Volumetric source term $Q(E_\ell) \approx N_A\,\rho\,\phi_\ell\left(\frac{E_\ell}{\langle 1-y\rangle}\right)\sigma_{\rm CC}\left(\frac{E_\ell}{\langle 1-y\rangle}\right)/\langle 1-y\rangle$

Regeneration is important for taus

Earth absorption is important for all neutrino flavors

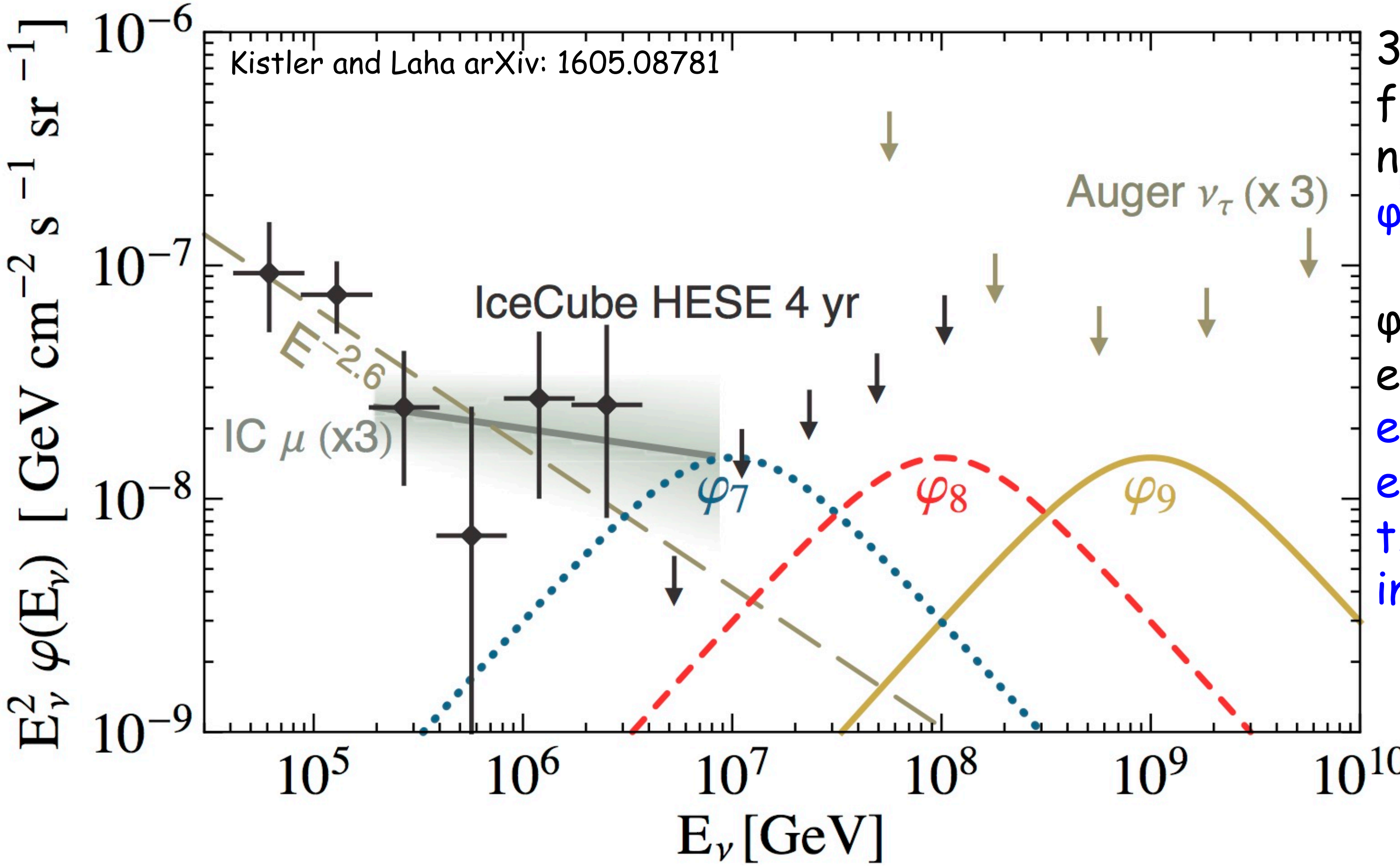
Where does it come from?



Shaded: Sky density of E_μ > 5 PeV muons from model φ_8
Solid: The horizon demarcates upgoing and downgoing directions
Dashed: The rough 10^0 downgoing boundary for atmospheric muons
No gamma-ray source was reported by HAWC

The 2.6 PeV track event probably comes from a diffuse astrophysical neutrino flux

Astrophysical neutrino fluxes



3 phenomenological fluxes with varying normalization: φ_7, φ_8, and φ_9

φ_7, φ_8, and φ_9 extend to higher energies => essential for through-going τ interpretation

φ_7 and φ_8 resemble BL Lac AGN models

Rescaled combinations of φ_7 and φ_9 approximate GZK neutrinos from EBL and CMB interactions

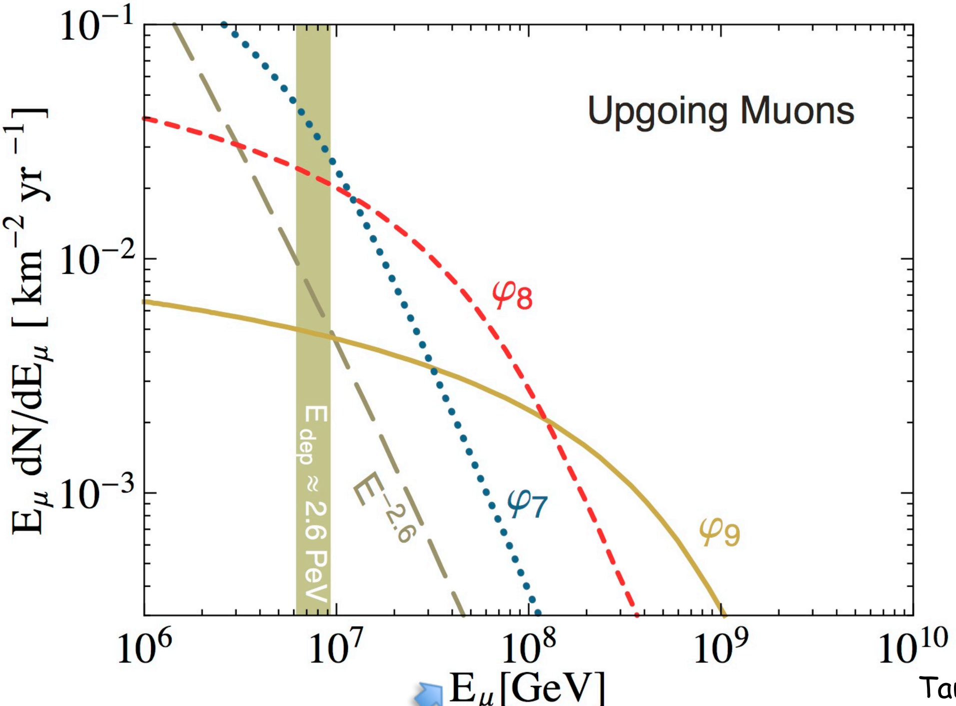
$$\varphi_i(E_\nu) = f_i \left[\left(\frac{E_\nu}{E_i}\right)^{\alpha\eta} + \left(\frac{E_\nu}{E_i}\right)^{\beta\eta} \right]^{1/\eta}$$

$i = 7,\ 8,$ and 9

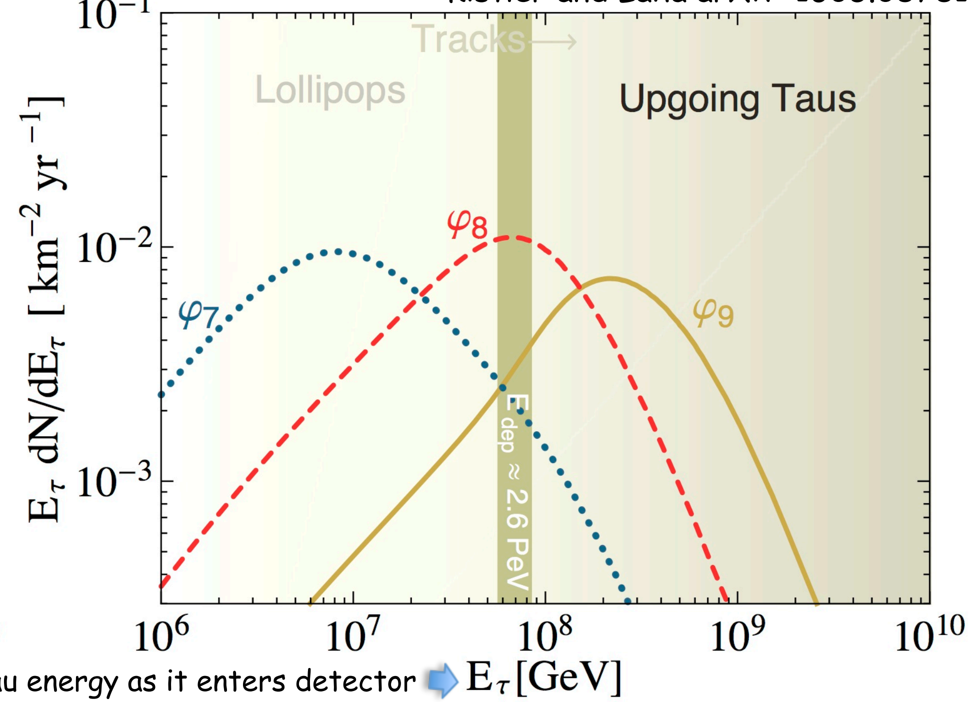
$E_i = 10^i$ GeV

Energy distribution

Kistler and Laha arXiv: 1605.08781



Muon energy as it enters detector



Tau energy as it enters detector

Muons of energy ≥ 100 GeV can traverse the full IceCube detector

Taus of energy ≥ 50 PeV can traverse the full IceCube detector

General conclusion: in order to deposit 2.6 PeV energy inside IceCube, the energy of tau as it enters the detector must be approximately an order of magnitude larger than that of muon: enormous physical significance

Must optimize tools for this new signal in IceCube

Event numbers

Kistler and Laha
arXiv: 1605.08781

Events in 5 km^2 yr (μ, τ tracks) or 5 km^3 yr (showers).

	$E_\nu^{-2.6}$	φ_7	φ_8	φ_9
upgoing μ: $E_\mu > 5$ PeV	0.04	0.22	0.25	0.08
down μ: $E_\mu > 5$ PeV; $\cos\theta_{\rm nadir} > -0.2$	0.06	0.30	0.46	0.25
upgoing τ: $E_{\tau,\rm up} > 50$ PeV	—	0.01	0.08	0.07
down τ: $E_\tau > 50$ PeV; $\cos\theta_{\rm nadir} > -0.2$	—	0.03	0.17	0.19
Total tracks	0.1	0.56	0.96	0.59
$\bar\nu_e e$ shower: $E_{\rm em} > 5$ PeV	—	2.6	0.36	0.04
$\nu_e + \bar\nu_e$ CC: $E_{\rm em} > 5$ PeV	—	0.87	0.50	0.12
$\nu + \bar\nu$ NC: $E_{\rm em} > 5$ PeV	—	0.18	0.42	0.16

The normalizations of φ_7, φ_8, and φ_9 can be made variable

The harder spectra adopted by us is more favorable to give rise to the 2.6 PeV track event

The $E^{-2.13}$ produces too many Glashow resonance events (~ 3), and might be disfavored

Is the 2.6 PeV track event hinting at a super-Glashow astrophysical neutrino flux?

Conclusions

- Common knowledge: Muons give rise to all through going track events in IceCube ---- incomplete!

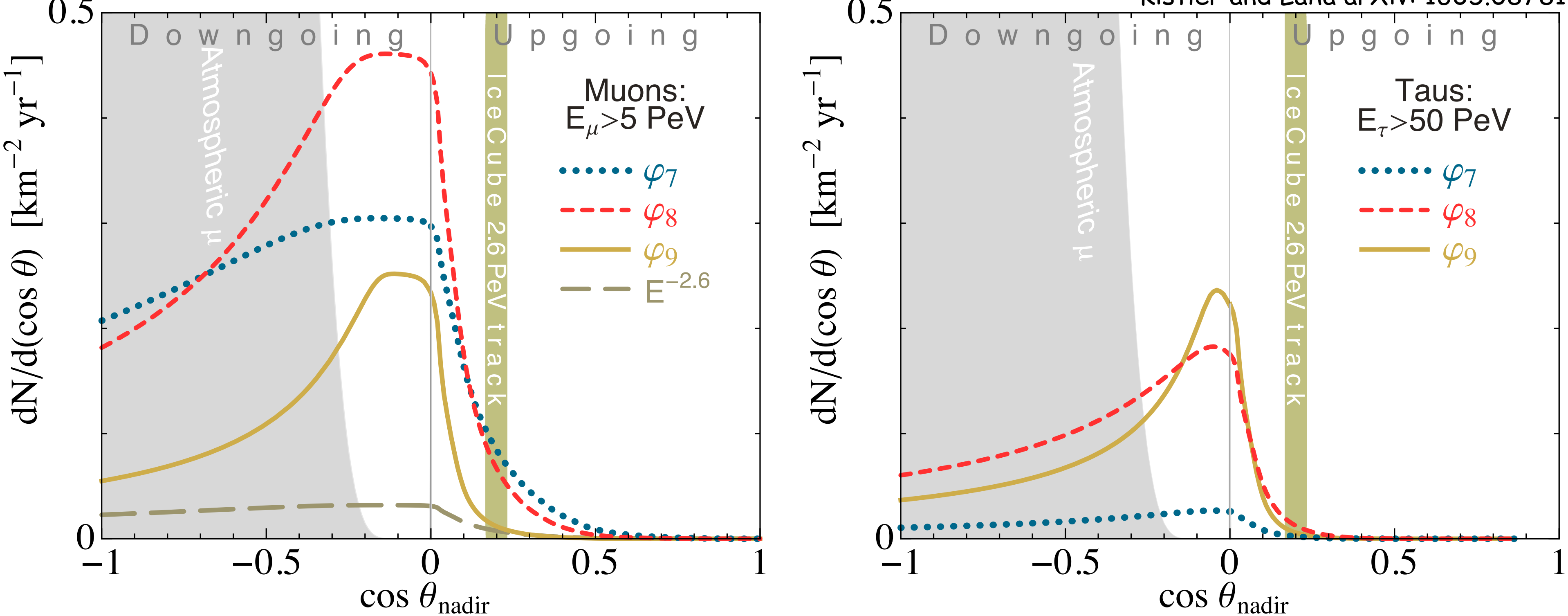
- We show for the first time that a through going tau can also give rise to tracks

- The through going tau track is a new signal in IceCube ---- needs more research ---- can we distinguish a through going muon track and a through going tau track ?

Questions: rlaha@stanford.edu

Angular distribution

Kistler and Laha arXiv: 1605.08781



Angular spectra of E_μ > 5 PeV muons and E_τ > 50 PeV taus

For the same spectra, the angular distribution is different --- through going muon tracks and through going tau tracks probe different energy ranges of the underlying astrophysical neutrino spectrum

For $\varphi_7 \rightarrow \varphi_8 \rightarrow \varphi_9$, the tau/ muon track ratio approaches unity