Multi-PeV Signals from a New Astrophysical Neutrino Flux Beyond the Glashow Resonance
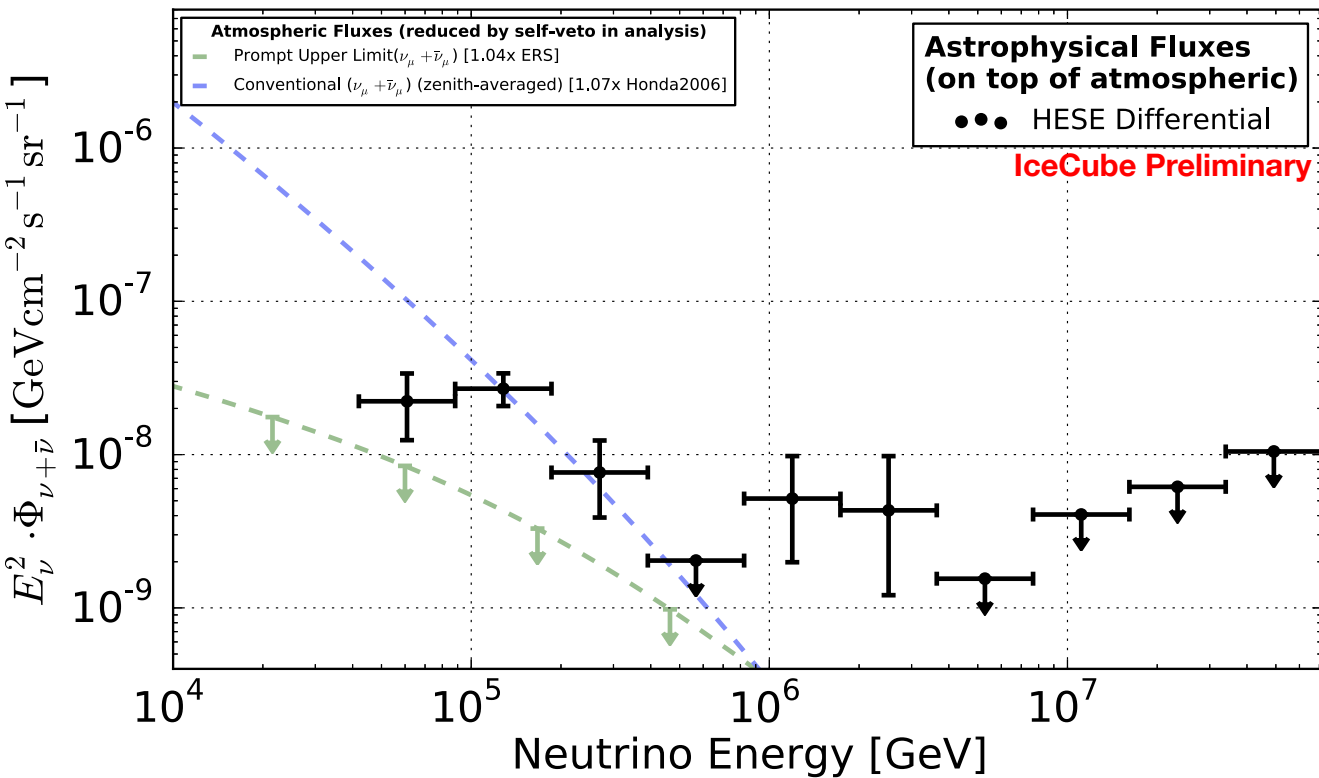
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Kistler and Laha arXiv: 1605.08781 (submitted)

Atmospheric Fluxes (reduced by self-veto in analysis)
- - - Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
- - - Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]

Astrophysical Fluxes
(on top of atmospheric)
●●● HESE Differential
IceCube Preliminary

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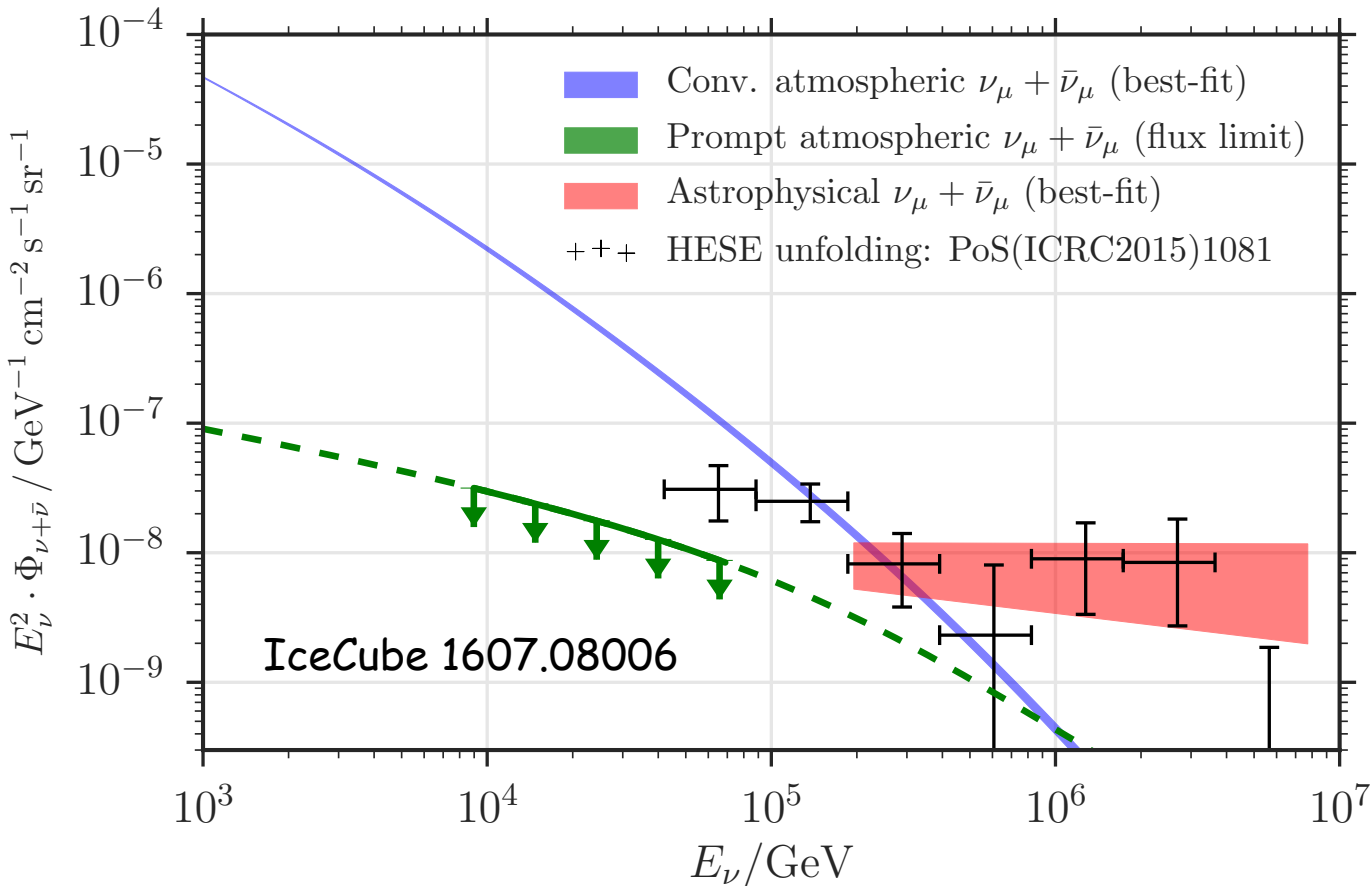
Northen Hemisphere through going muons
--- 6 year data set

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

Legend (in figure):
- Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$ (best-fit)
- Prompt atmospheric $\nu_\mu + \bar{\nu}_\mu$ (flux limit)
- Astrophysical $\nu_\mu + \bar{\nu}_\mu$ (best-fit)
- +++ HESE unfolding: PoS(ICRC2015)1081

IceCube 1607.08006

Axis labels: $E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}} \,/\, \mathrm{GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$ vs E_ν/GeV

$$\Phi_{\nu+\bar{\nu}} = 0.9^{+0.30}_{-0.27} \times 10^{18} \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-2.13 \pm 0.13} \mathrm{GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

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

Ranjan Laha

2.6 PeV track event

IceCube 1607.08006
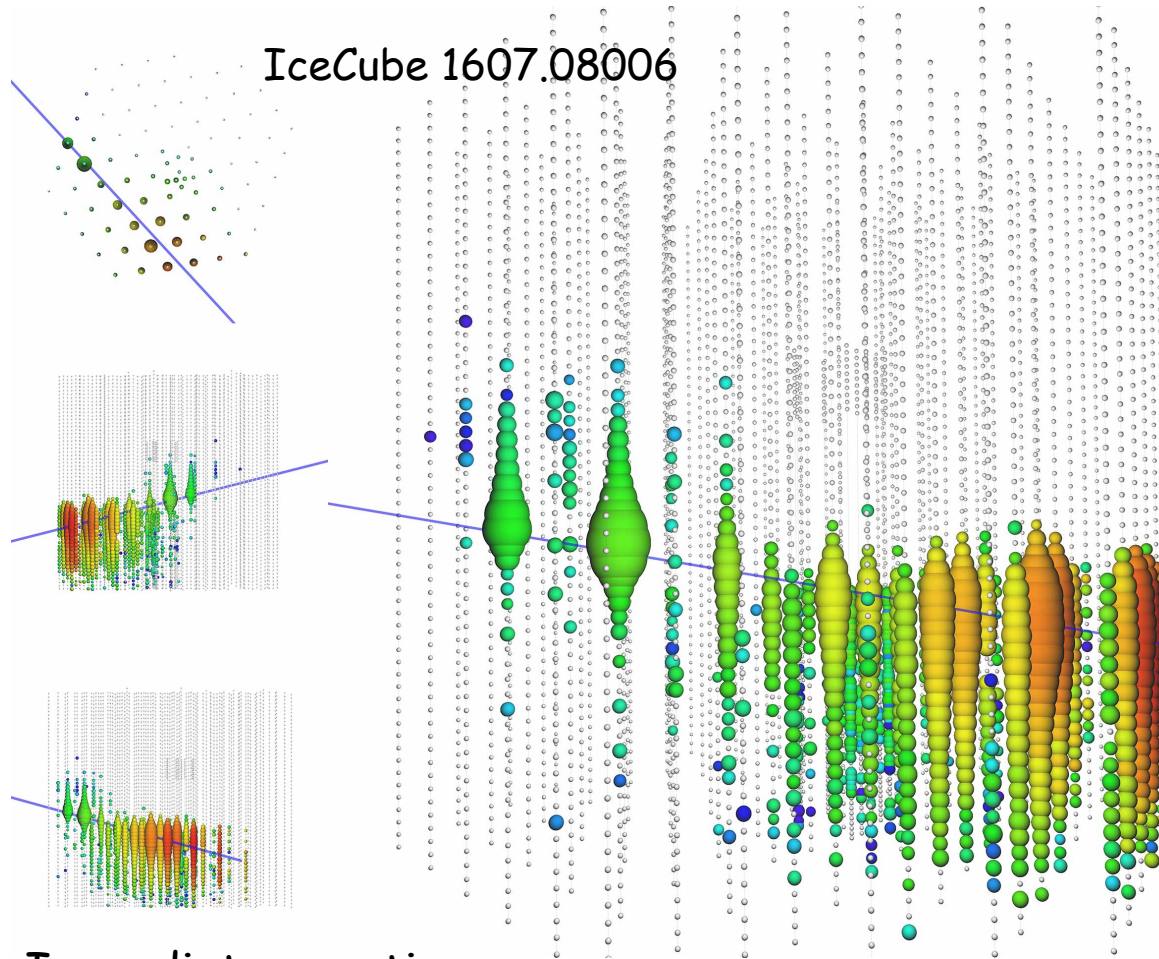
Deposited energy 2.6 ± 0.3 PeV

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

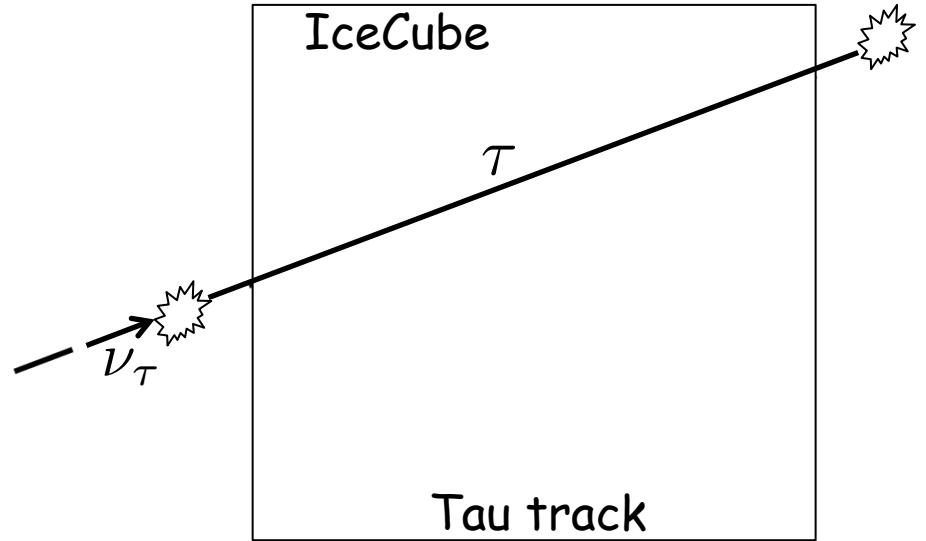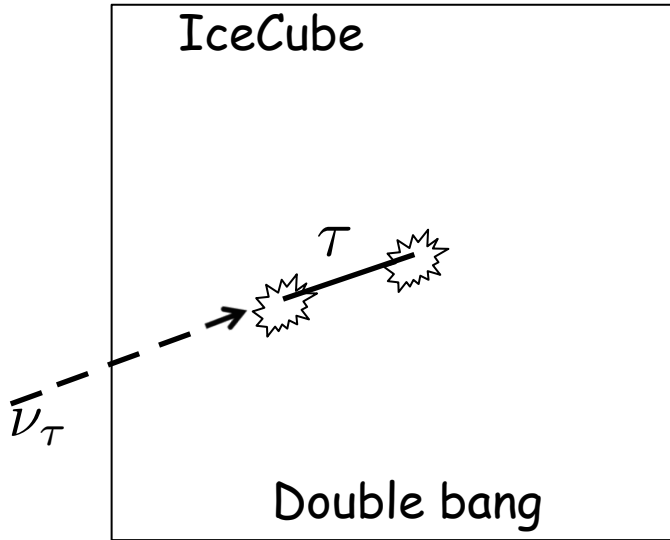$$\nu_\mu + N \longrightarrow \mu + X$$

IceCube

μ

ν_μ
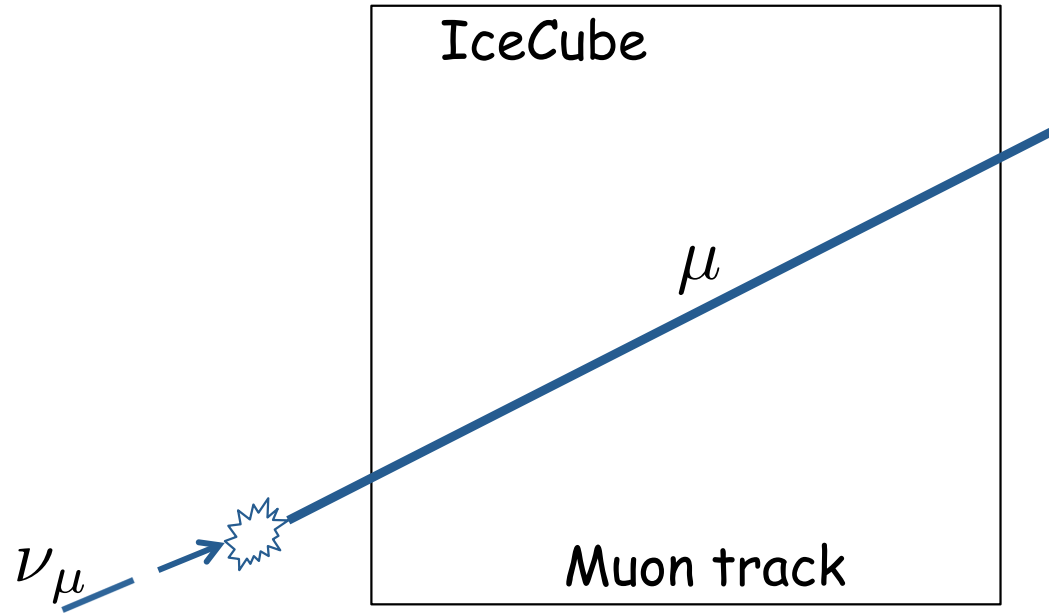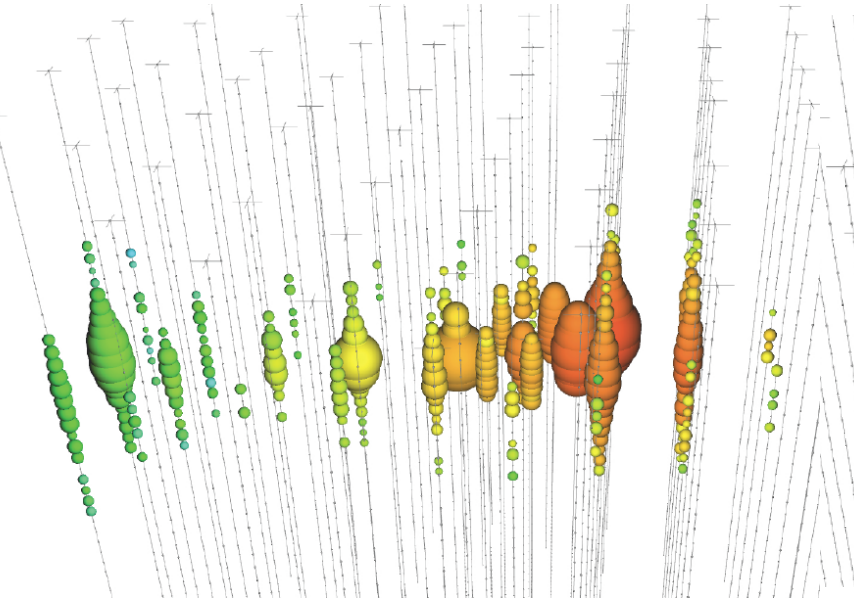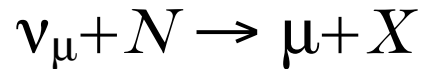
Muon track

Many muon tracks observed in IceCube

Many theoretical studies on muon tracks

Muon tracks in IceCube have been well studied

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

Double bang v/s tau tracks

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

IceCube

τ

$\overline{\nu}_\tau$

Double bang

IceCube

τ

ν_τ

Tau track

Wandkowsky TeVPA 2017
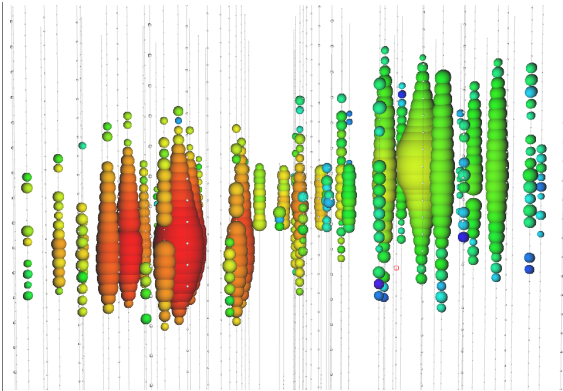
$\nu_\tau + N \rightarrow \tau + X$

?

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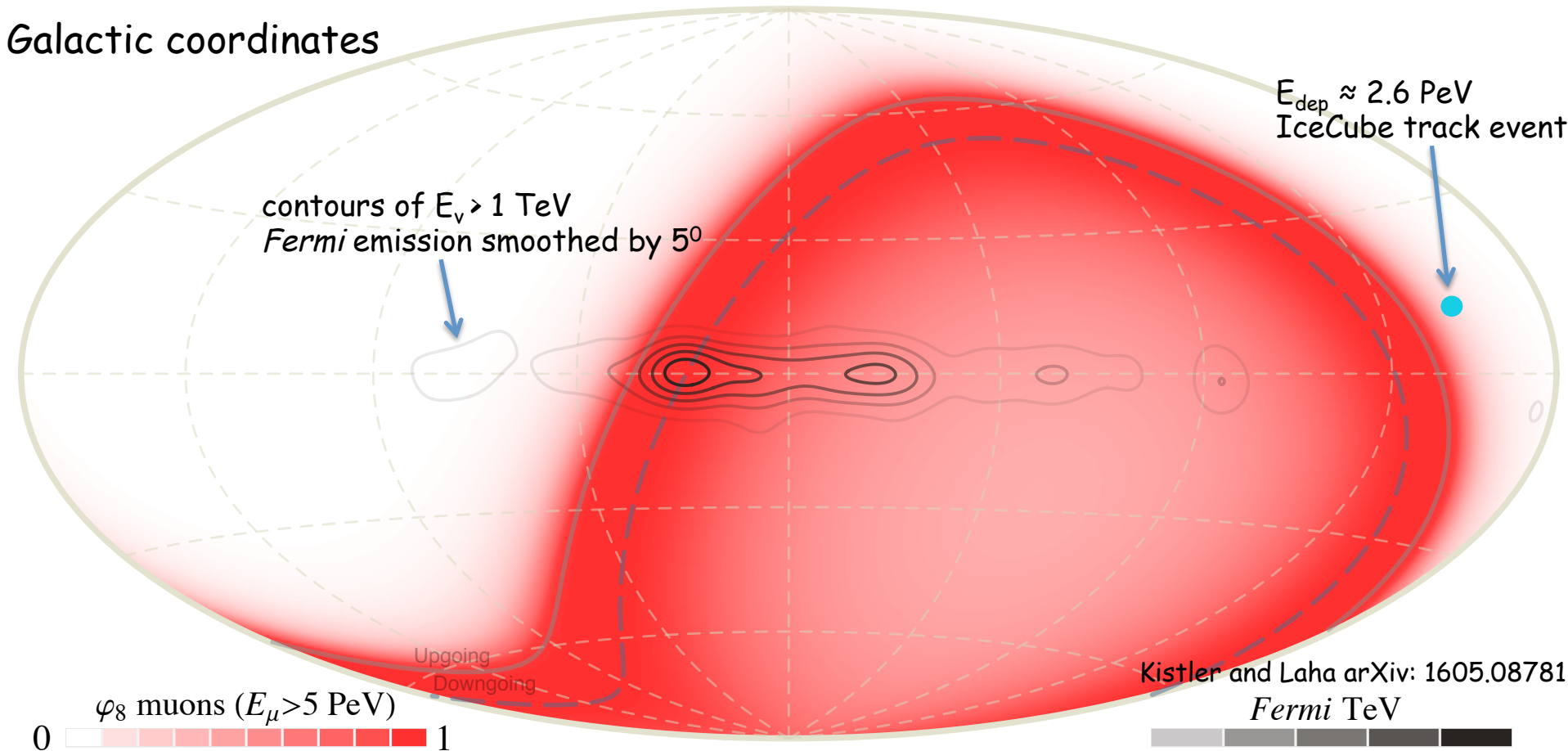
Lepton energy E_ℓ

Lepton lifetime τ_ℓ

includes
Earth absorption

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

Regeneration is important for taus
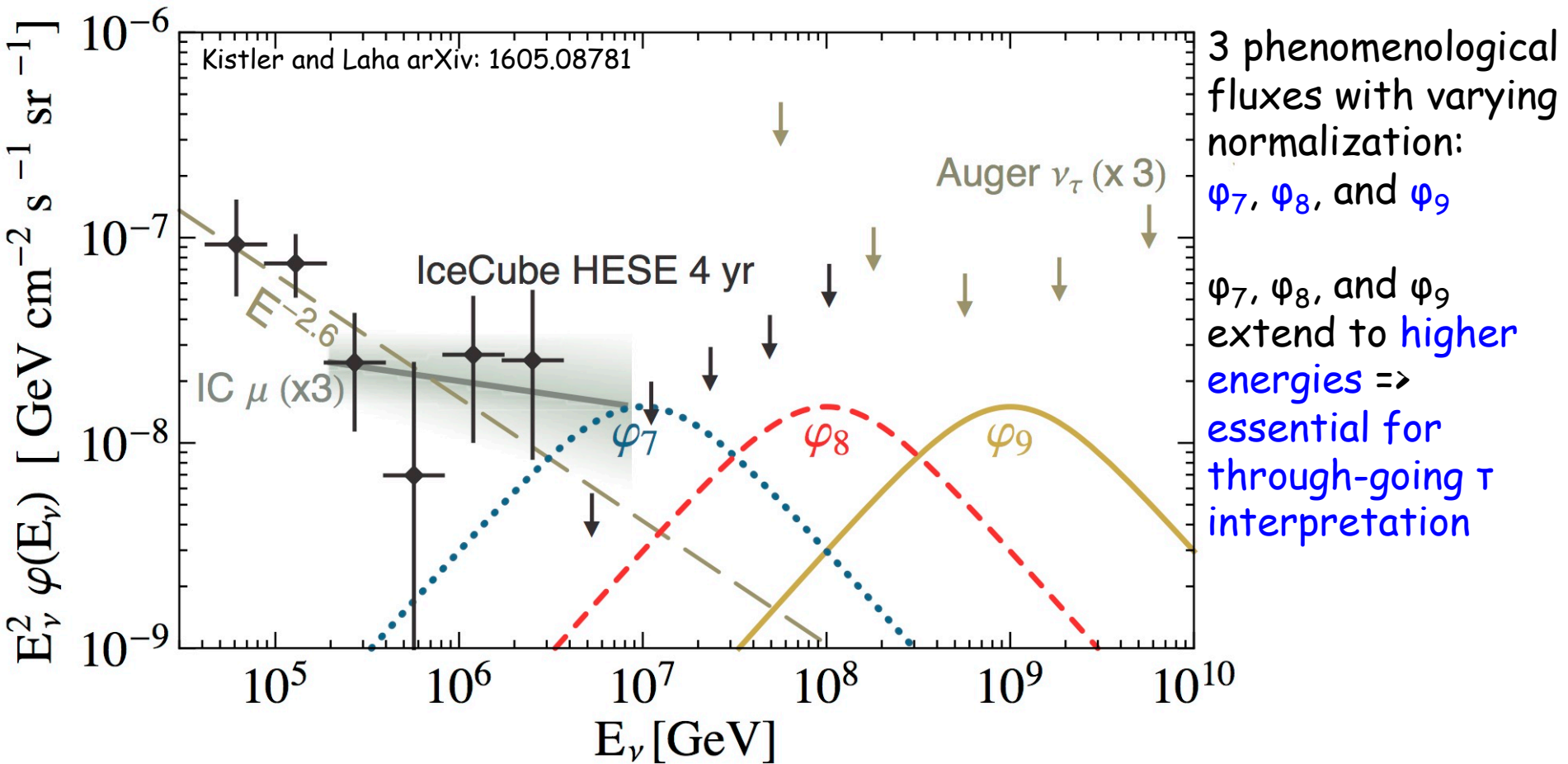
Earth absorption is important for all neutrino flavors

Where does it come from?

Galactic coordinates

$E_{dep} \approx 2.6$ PeV
IceCube track event

contours of $E_\nu > 1$ TeV
Fermi emission smoothed by 5^0

Kistler and Laha arXiv: 1605.08781
Fermi TeV

φ_8 muons ($E_\mu > 5$ PeV)

0   1

Upgoing
Downgoing

Shaded: Sky density of $E_\mu > 5$ 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
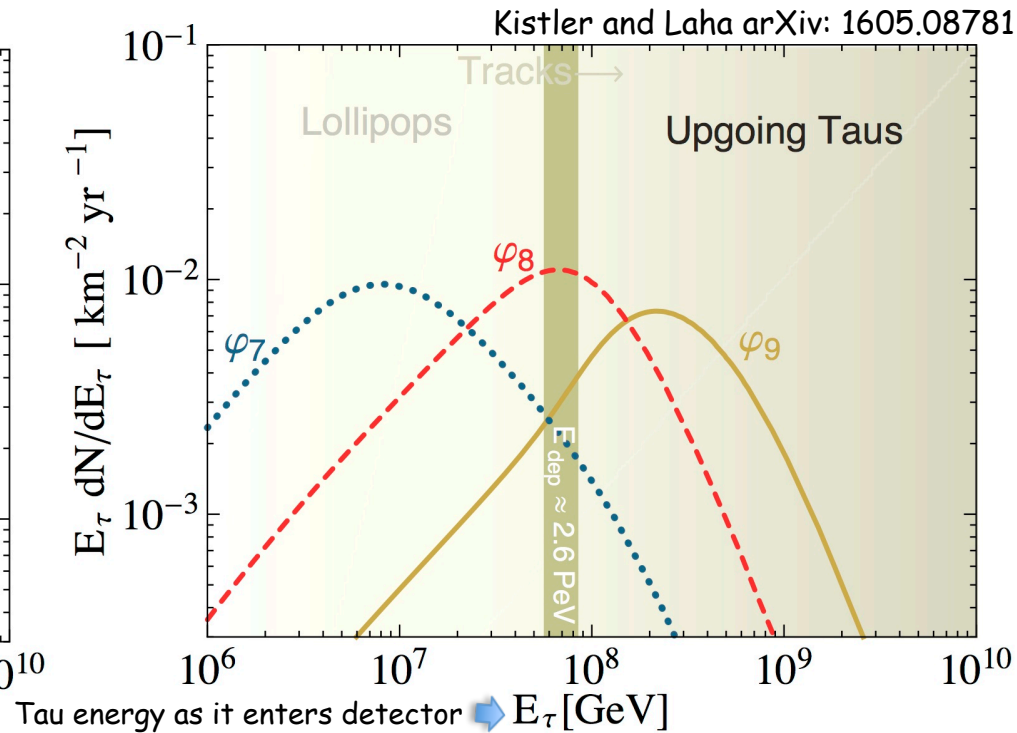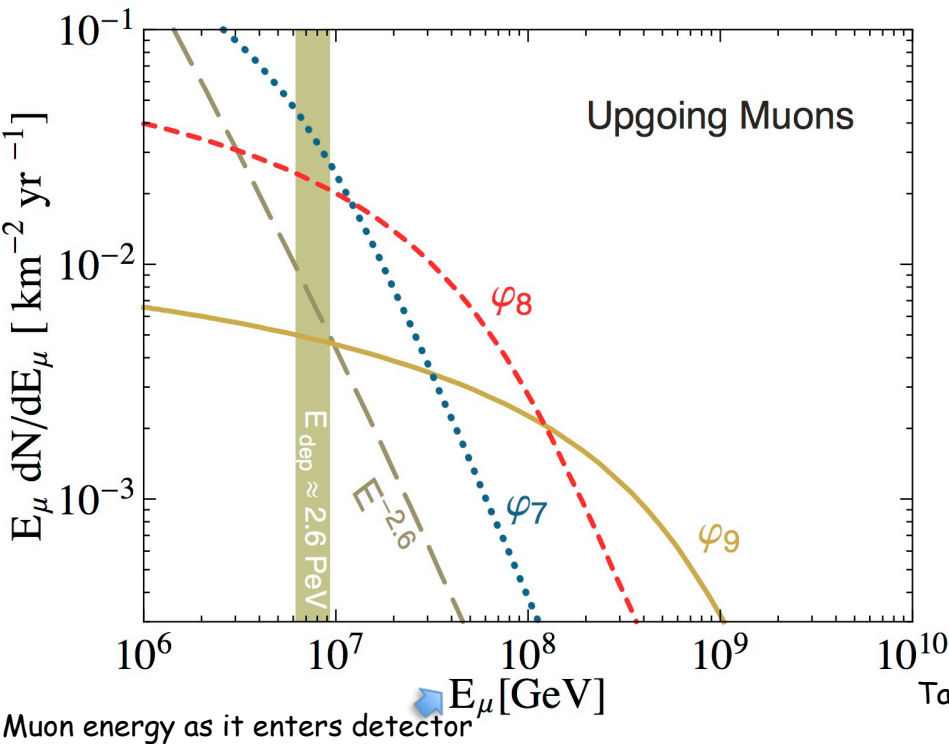
Astrophysical neutrino fluxes

Kistler and Laha arXiv: 1605.08781

Auger ν_τ (x 3)

IceCube HESE 4 yr

$E^{-2.6}$

IC μ (x3)

φ_7 φ_8 φ_9

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

$$\varphi_i(E_\nu) = f_i \left[\left(\frac{E_\nu}{E_i} \right)^{\alpha\eta} + \left(\frac{E_\nu}{E_i} \right)^{\beta\eta} \right]^{1/\eta} \qquad i = 7, 8, \text{ and } 9$$

$$E_i = 10^i \text{ GeV}$$

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

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; $\cos\theta_{\mathrm{nadir}} > -0.2$	0.06	0.30	0.46	0.25
upgoing τ: $E_{\tau,\mathrm{up}} > 50$ PeV	—	0.01	0.08	0.07
down τ: $E_\tau > 50$ PeV; $\cos\theta_{\mathrm{nadir}} > -0.2$	—	0.03	0.17	0.19
Total tracks	0.1	0.56	0.96	0.59
$\bar{\nu}_e e$ shower: $E_{\mathrm{em}} > 5$ PeV	—	2.6	0.36	0.04
$\nu_e + \bar{\nu}_e$ CC: $E_{\mathrm{em}} > 5$ PeV	—	0.87	0.50	0.12
$\nu + \bar{\nu}$ NC: $E_{\mathrm{em}} > 5$ 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?

$E^3 \, dN/dE \, [\, eV^2 \, m^{-2} \, s^{-1} \, sr^{-1} \,]$

Conclusions

- Common knowledge: Muons give rise to all through going tau 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
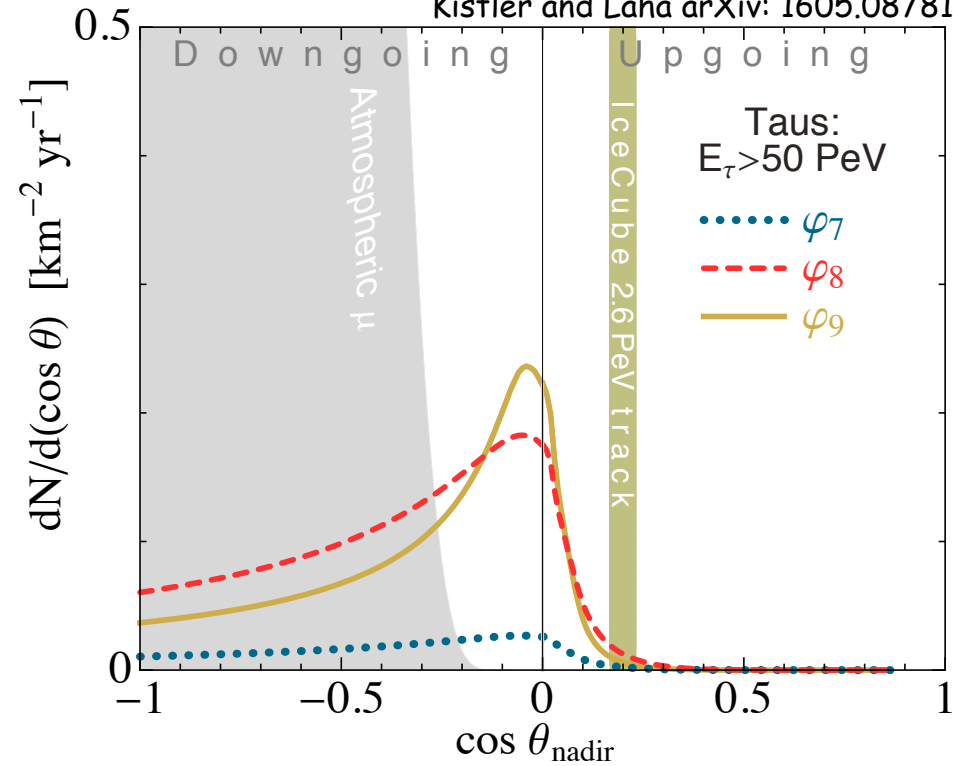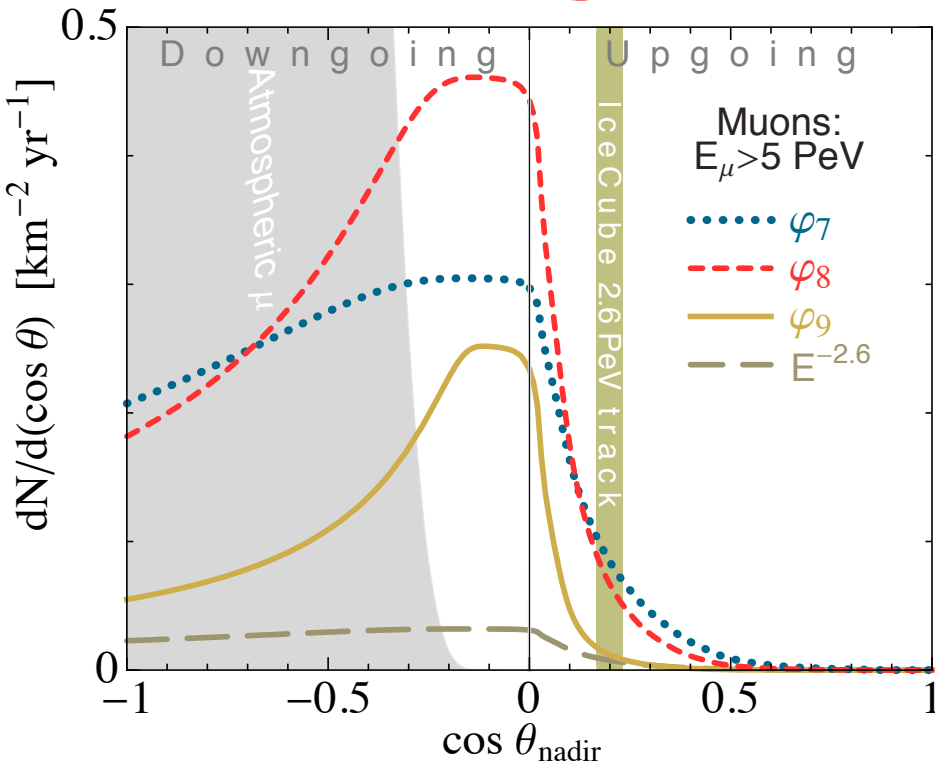
Angular spectra of $E_\mu > 5$ PeV muons and $E_\tau > 50$ PeV taus

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