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

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Kistler and Laha arXiv: 1605.08781 (submitted)

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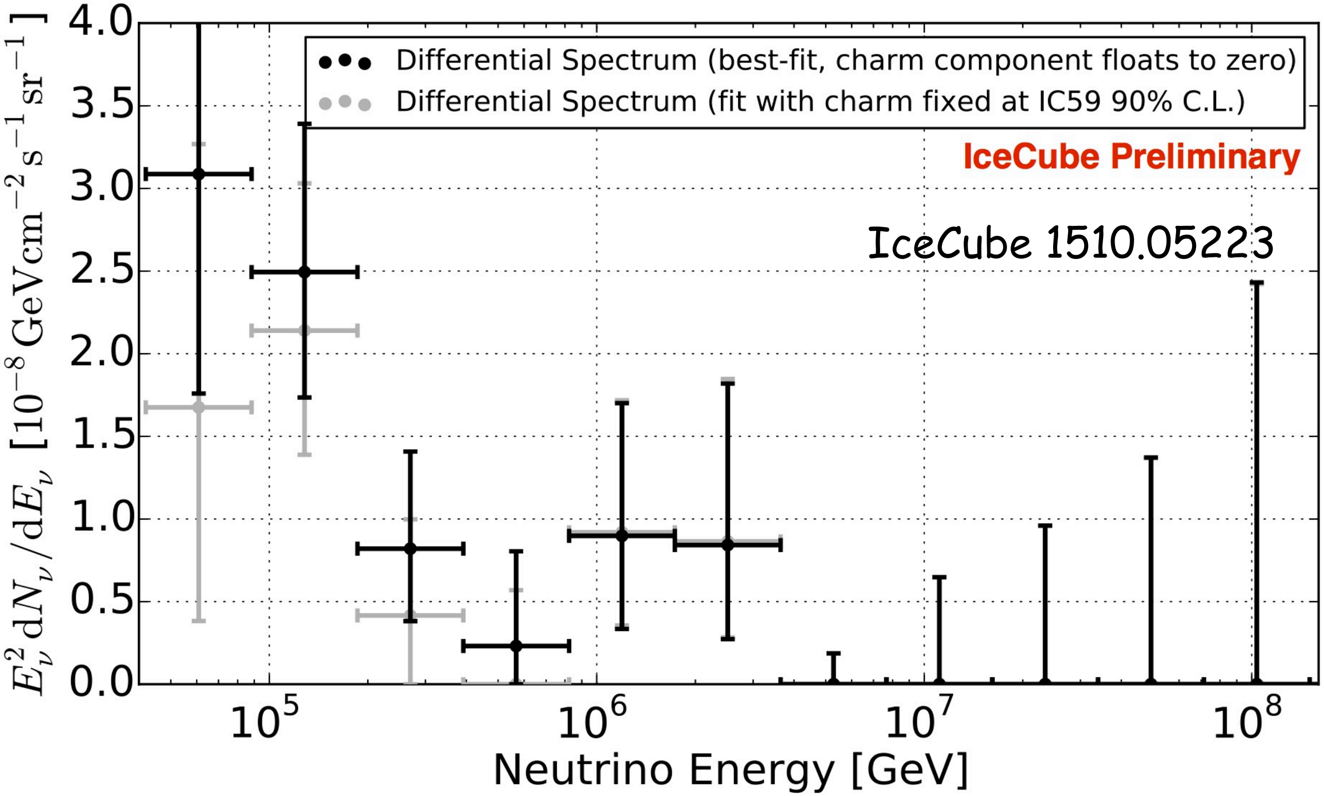
Discovery of astrophysical neutrinos



High Energy Starting Event analysis --- 4 year data set

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

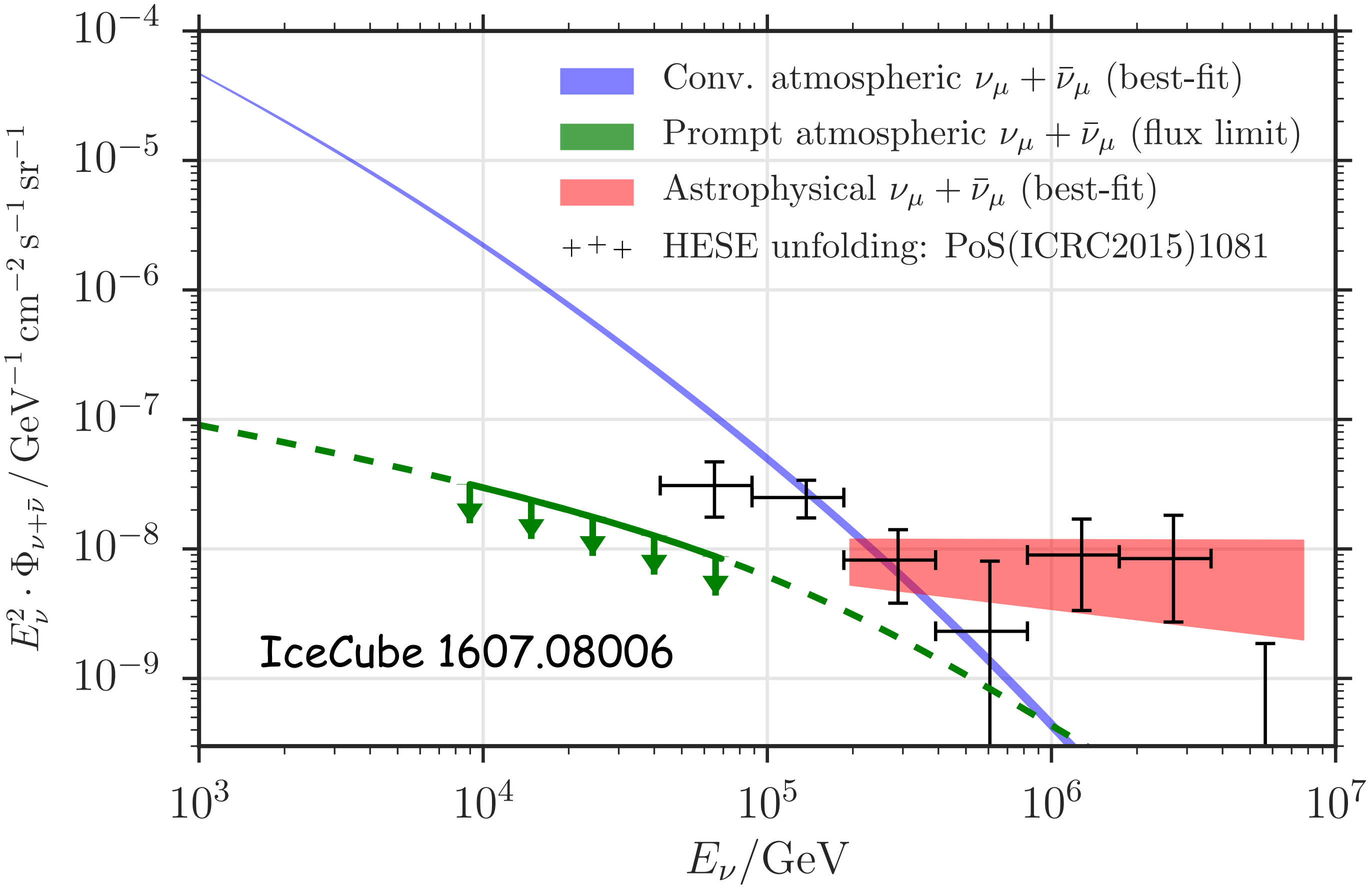
No Glashow resonance event

$$E^2\,\phi(E) = 2.2 \pm 0.7 \times 10^{-8} \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-0.58} \mathrm{GeV\,cm^{-2}\,s^{-1}}$$

Steeper spectral index w.r.t. 3 year data due to lack of PeV events, and higher yield of events at lower energies

No statistically significant clustering in space

Discovery of astrophysical neutrinos



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

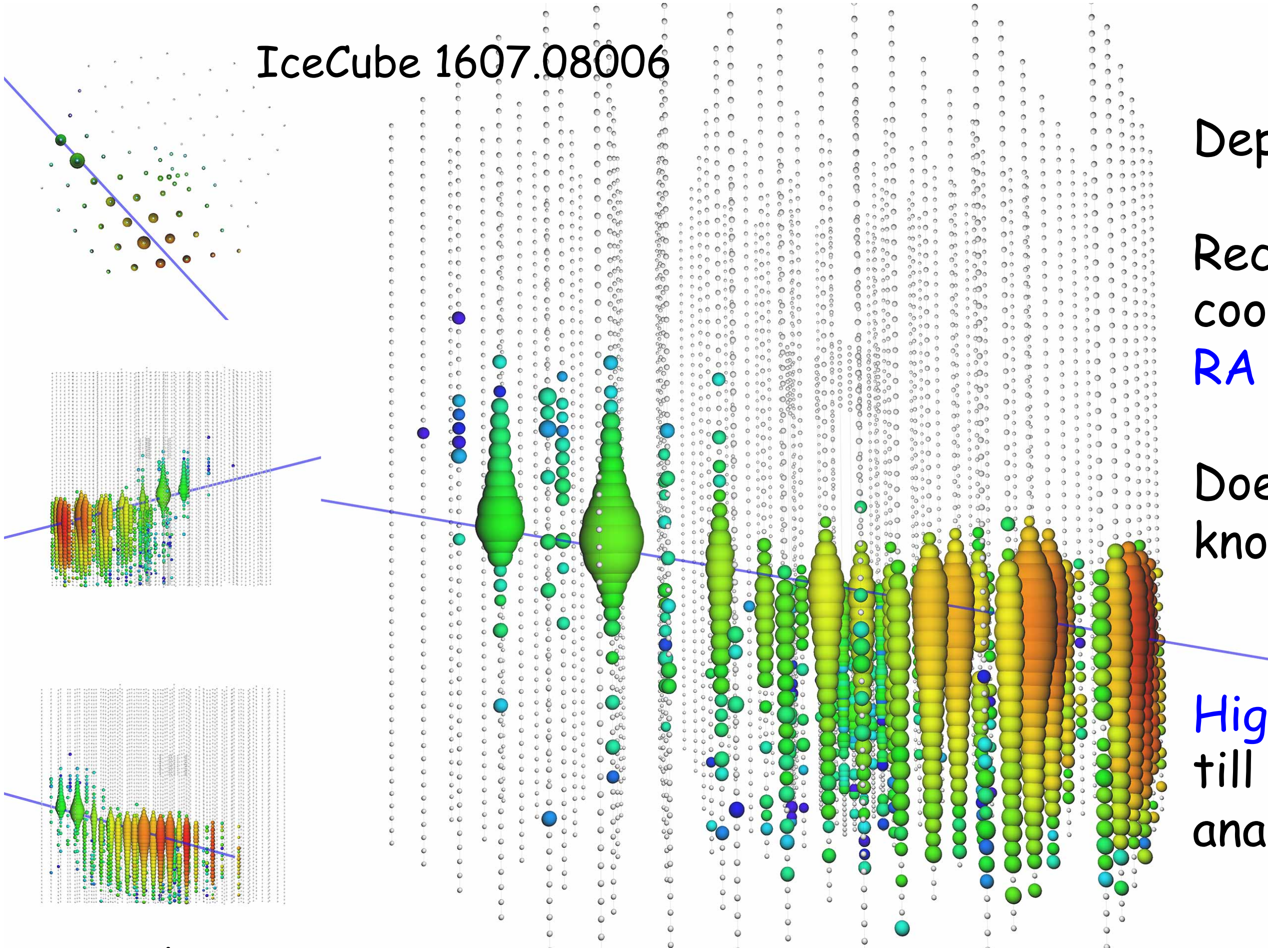
Fit of through going events between 194 TeV < E_ν < 7.8 PeV

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

No statistically significant clustering in space

Tension between spectral indices of these two different searches

2.6 PeV track event



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 lepton 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?

- Through going muons are assumed to give rise to 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

A generic equation for event numbers for through going leptons

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

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

Lepton energy E_ℓ

Lepton lifetime τ_ℓ

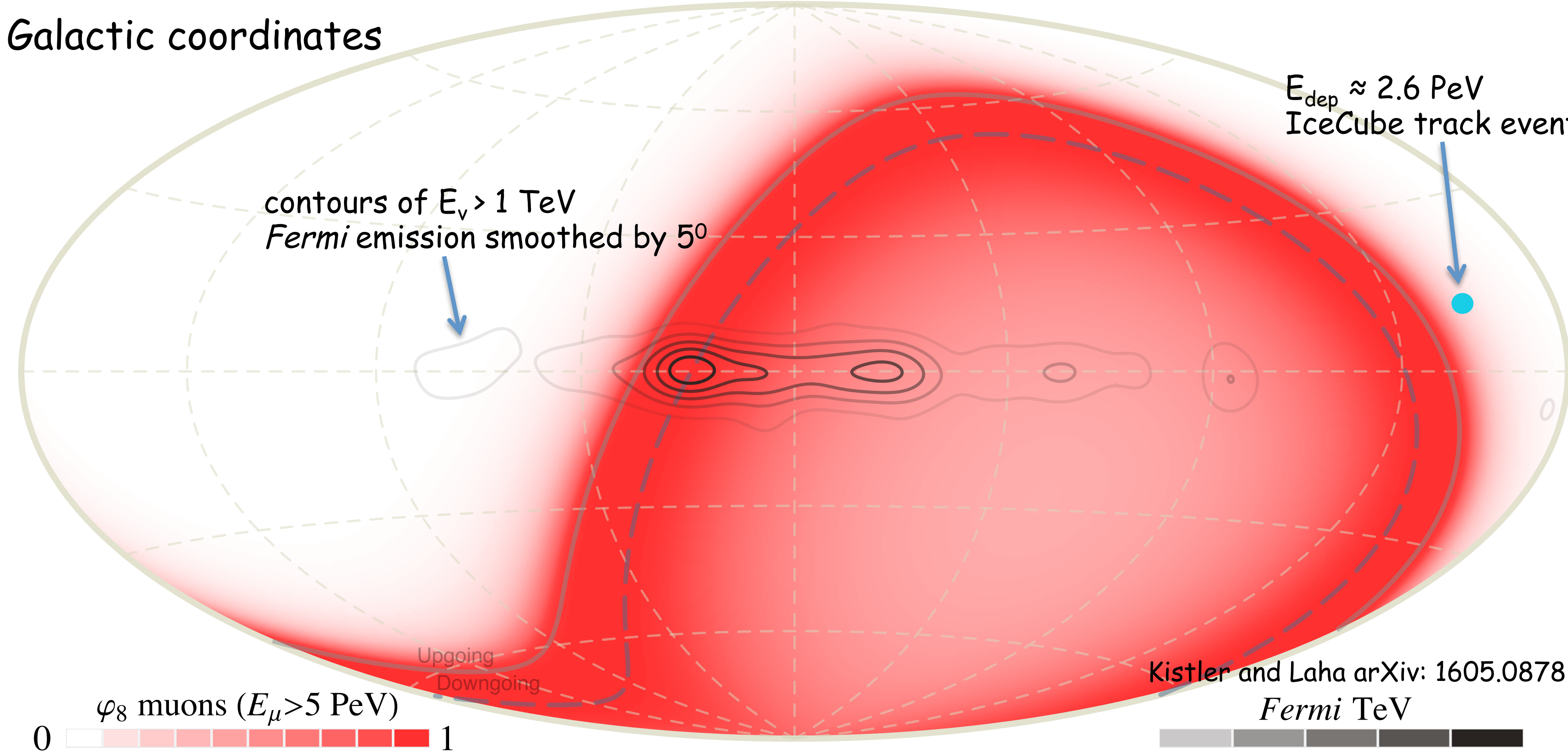
includes
Earth absorption

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

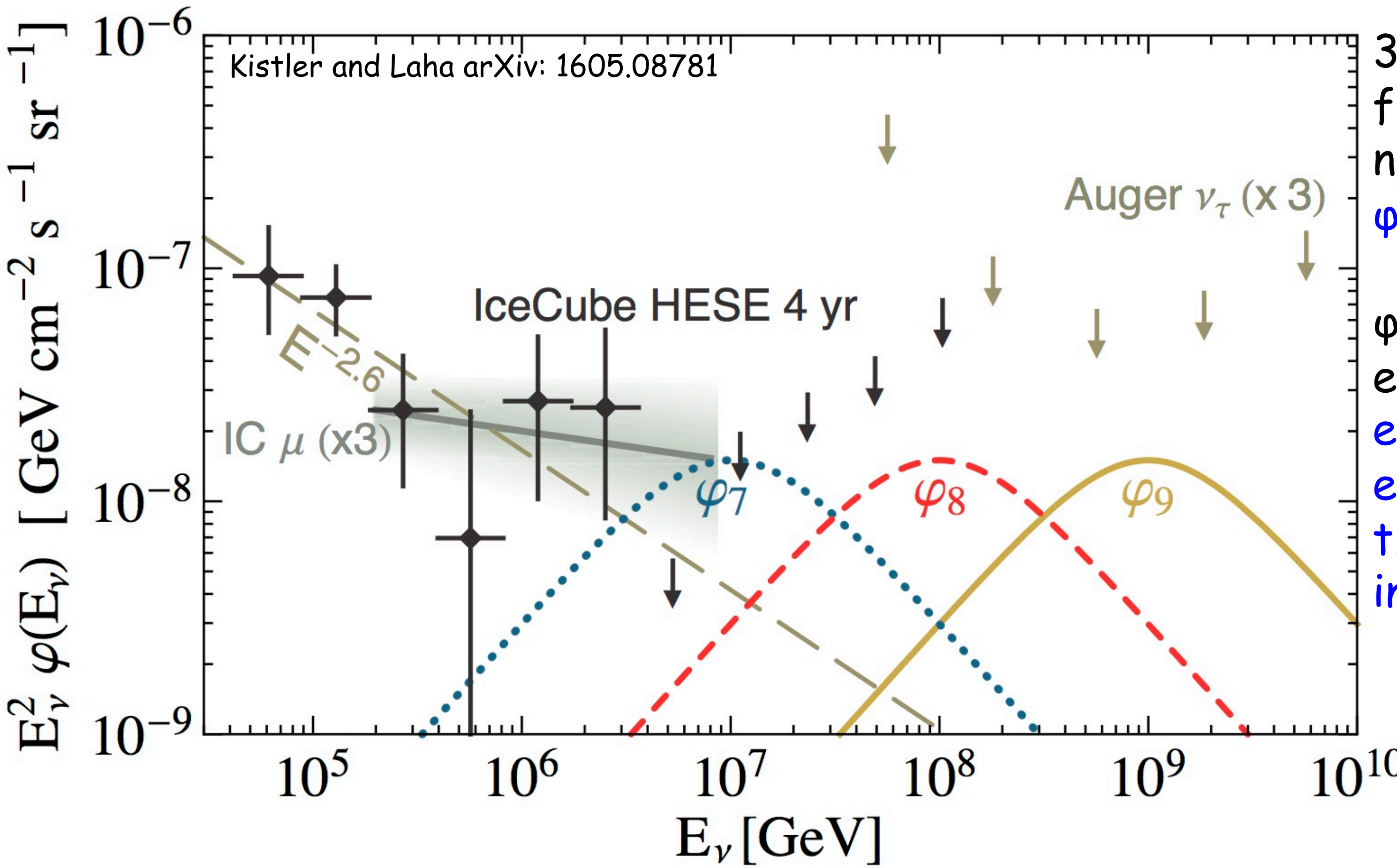
Solid: The horizon demarcates upgoing and downgoing directions

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

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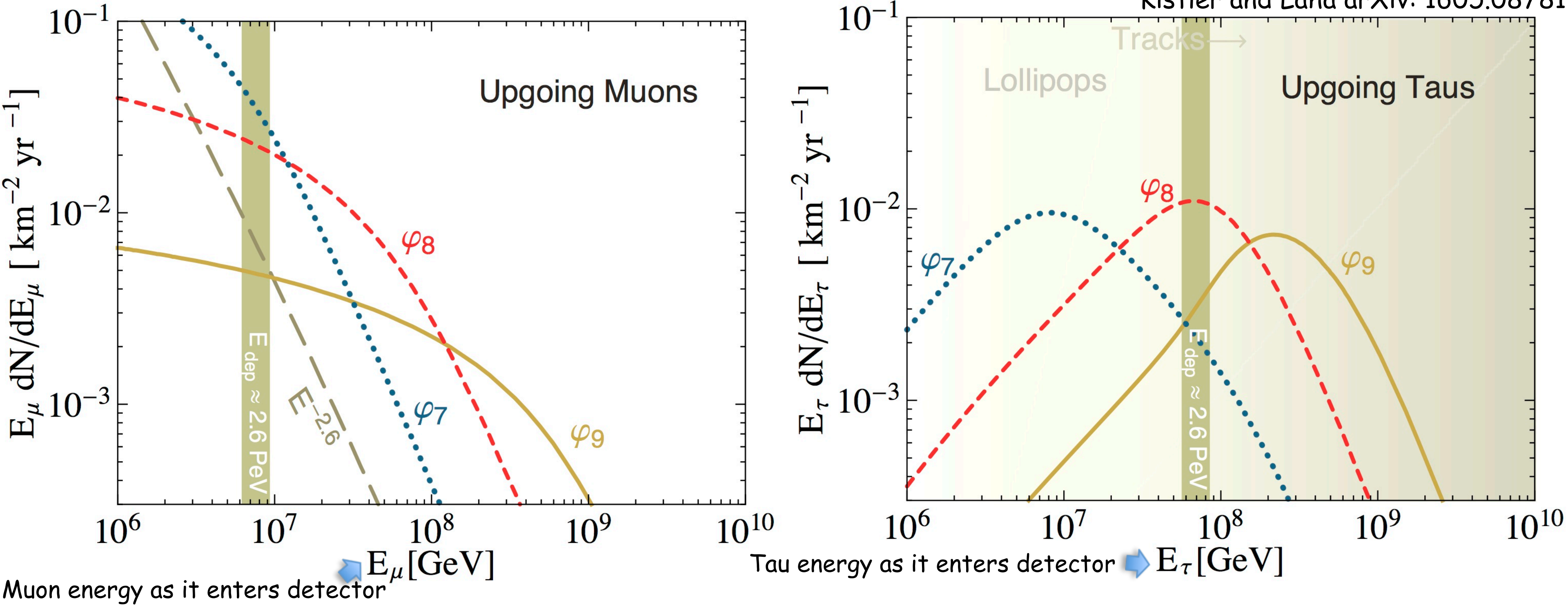

Muons of energy ≥ 100 GeV can traverse the full IceCube detector

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 an order of magnitude larger than that of muon: enormous physical significance

Must optimize tools for this new signal in IceCube

Angular distribution

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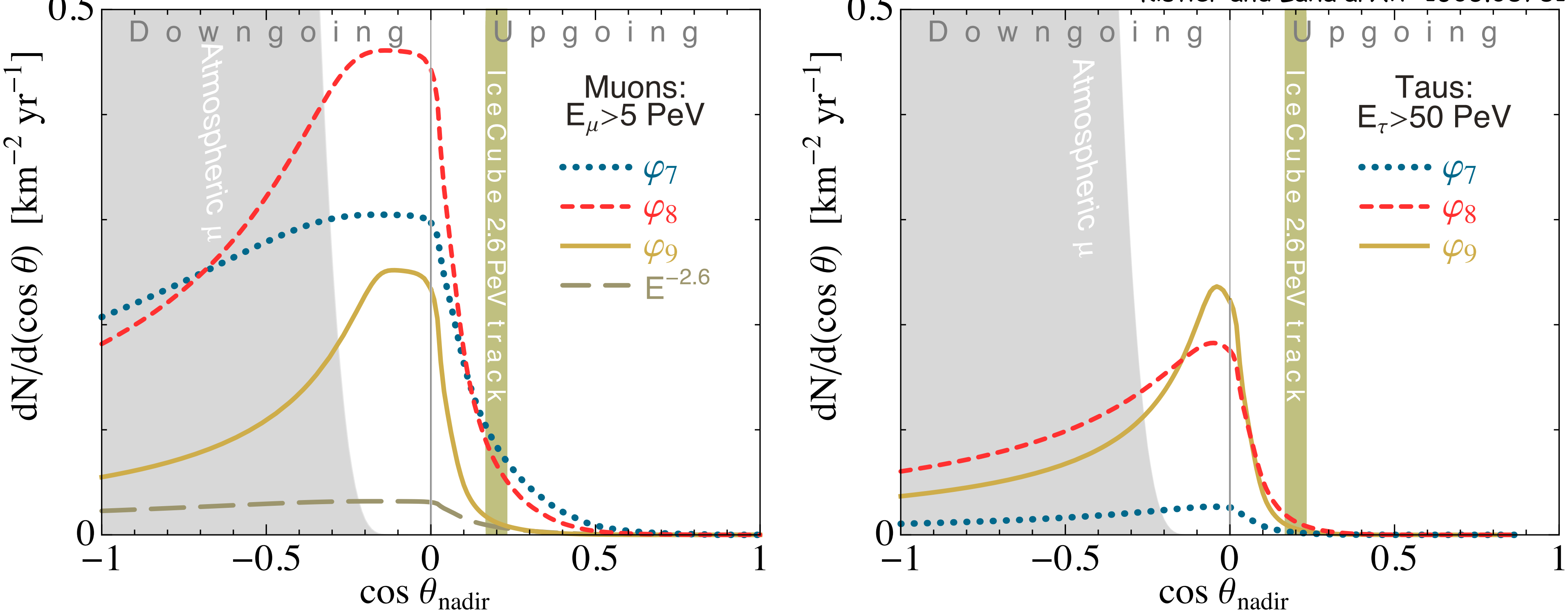

Angular spectra of E_μ > 5 PeV muons and E_τ > 50 PeV taus

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

Event numbers

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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 (~ 4), and might be disfavored
Is the 2.6 PeV track event hinting at a super-Glashow astrophysical neutrino flux?

Conclusions

- The 2.6 PeV track event is the highest energy event in IceCube
- If interpreted as a through going muon, then the neutrino energy can be $\gtrsim$ 6.3 PeV
- The HESE best fit flux ~ $E^{-2.6}$ is unlikely to give such an event
- The Northern Hemisphere muon best fit flux ~ $E^{-2.13}$ produces too many Glashow resonance events
- Phenomenological spectra peaked at higher energies might give rise to this event --- hints of super-Glashow neutrino flux?
- We show for the first time that a through going tau can also give rise to tracks and possibly this event
- The neutrino energy must be $\gtrsim$ 70 PeV if a through going tau gives rise to this event
- The enormous difference in parent neutrino energy implies that it is desirable to better characterize a through going muon track and a through going tau track
- 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 individually?

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