IceCube's astrophysical neutrino spectrum from CPT violation

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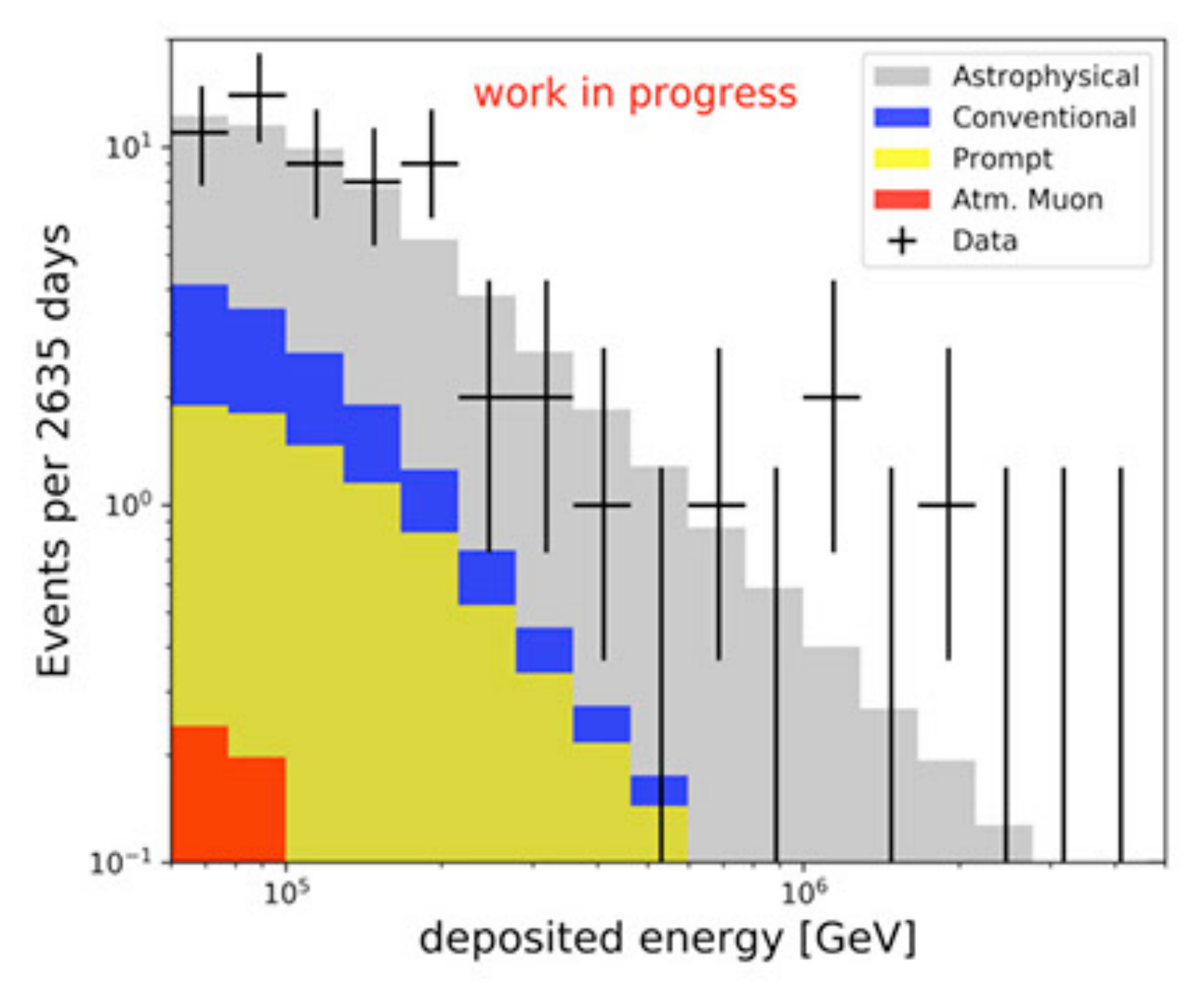
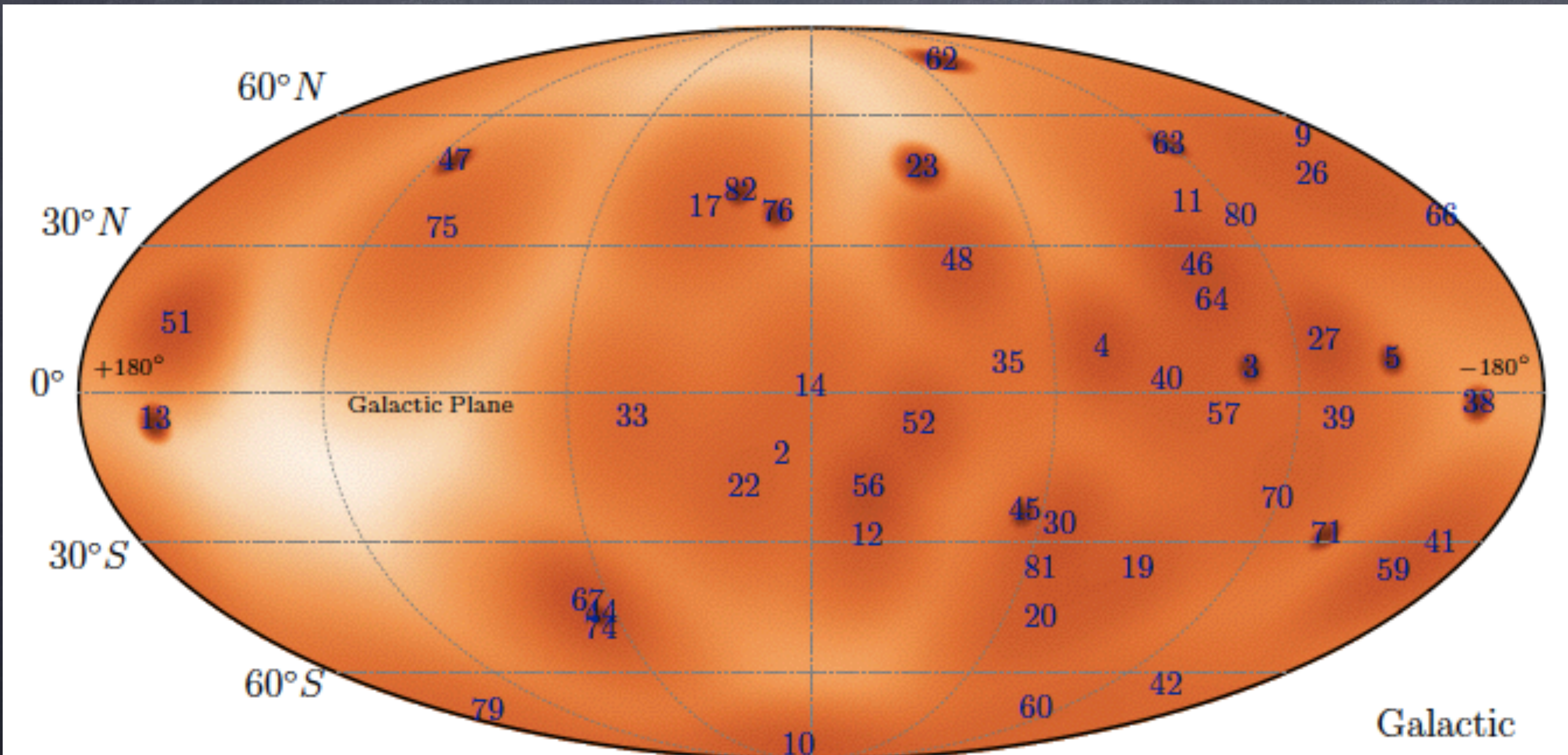
Cosmic neutrinos at IceCube



- 60 events with dep. energy > 60 TeV
- 3 cascade events between 1-2 PeV

Galactic or extragalactic?



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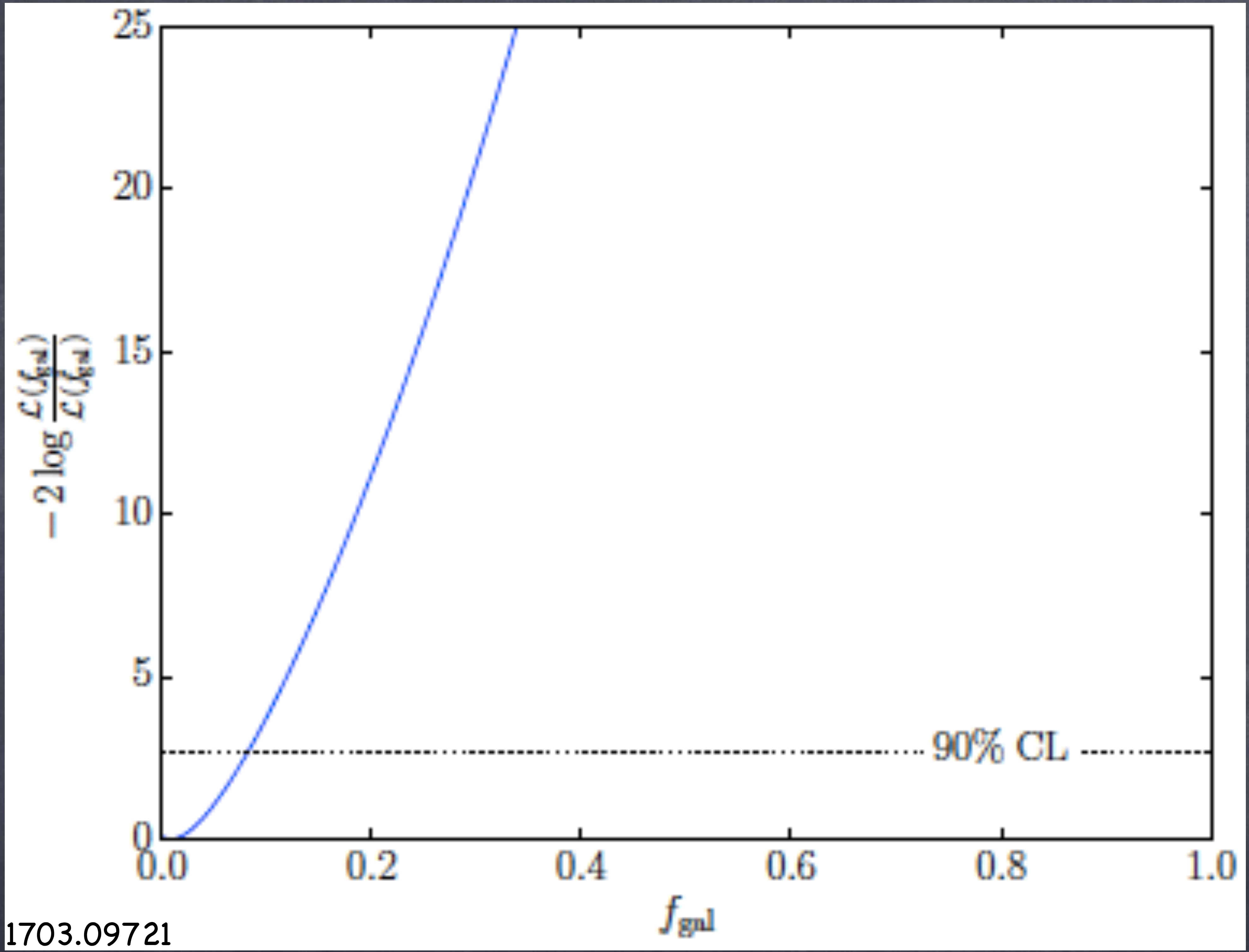
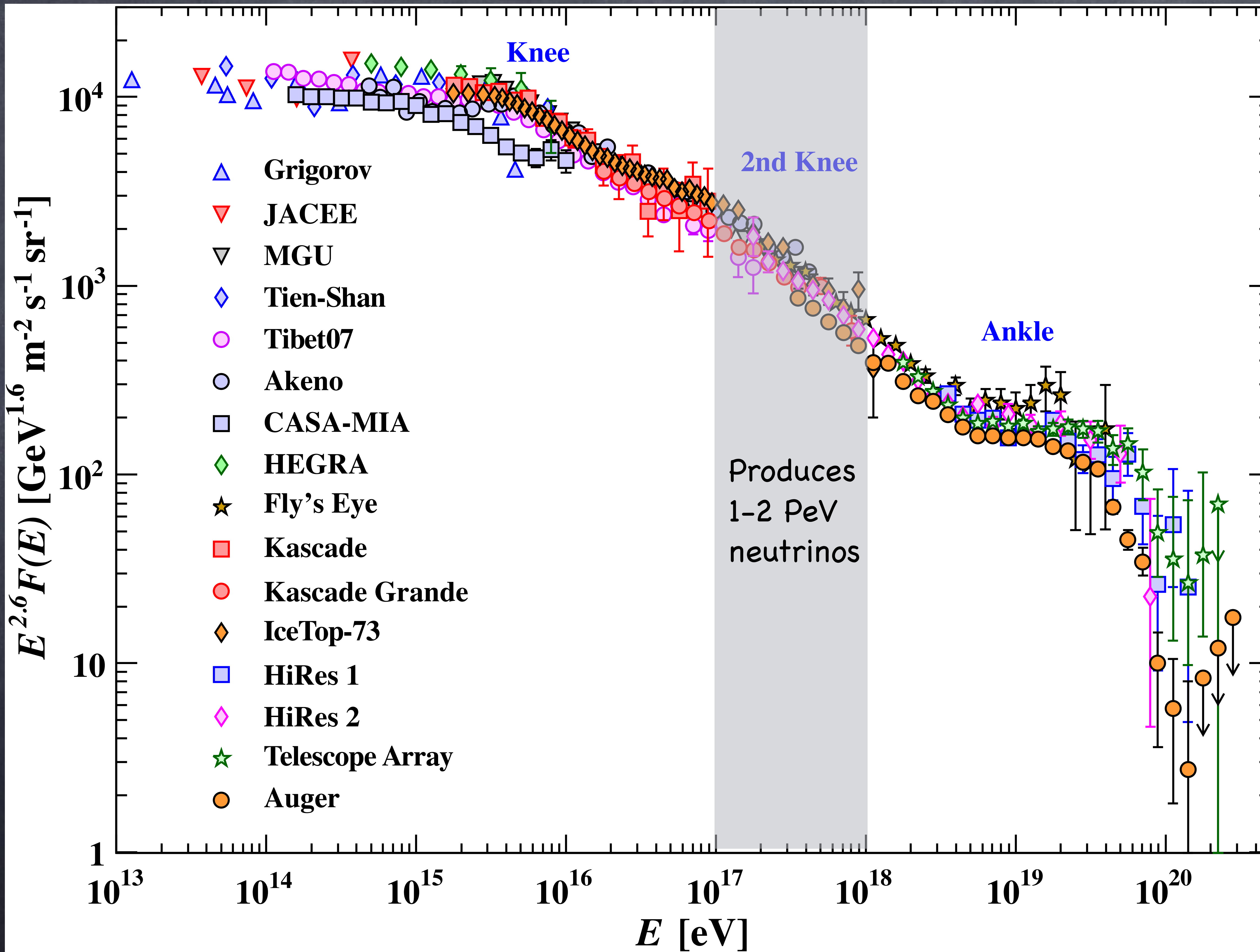
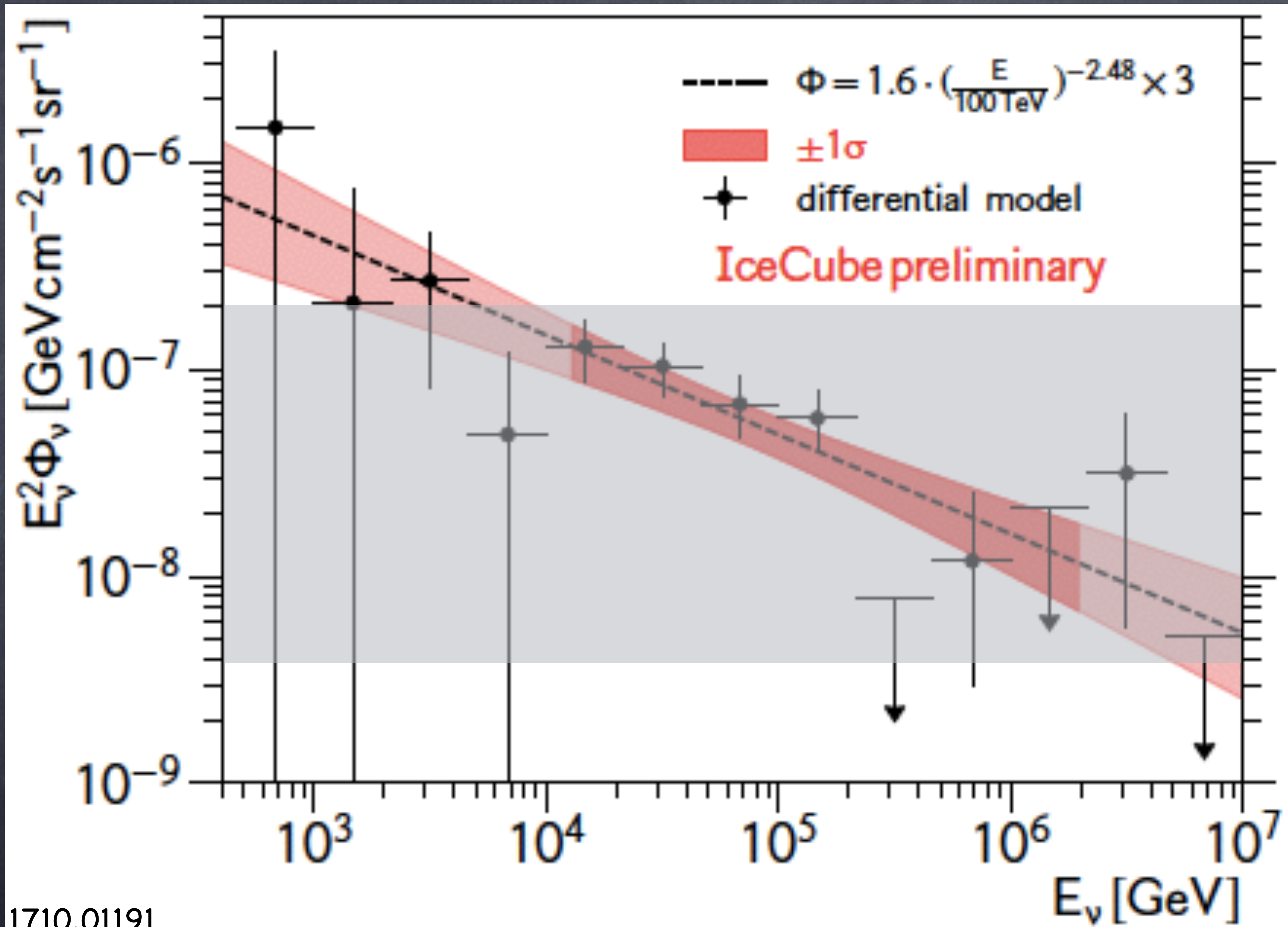


- Galactic fraction < 9.5% at 90% CL

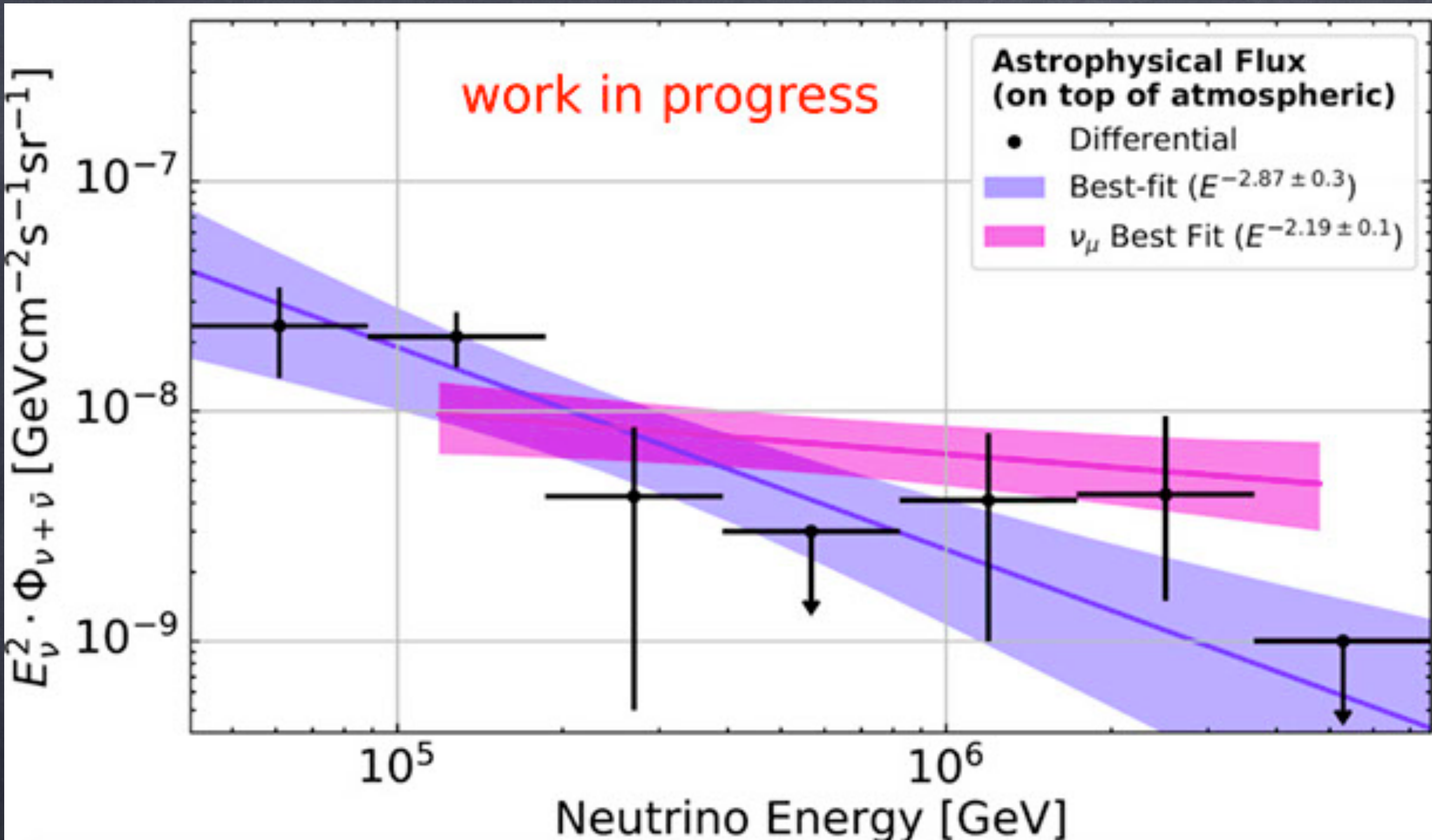
- Zero galactic flux allowed at < 1 sigma

Same source for UHECR and cosmic neutrinos?



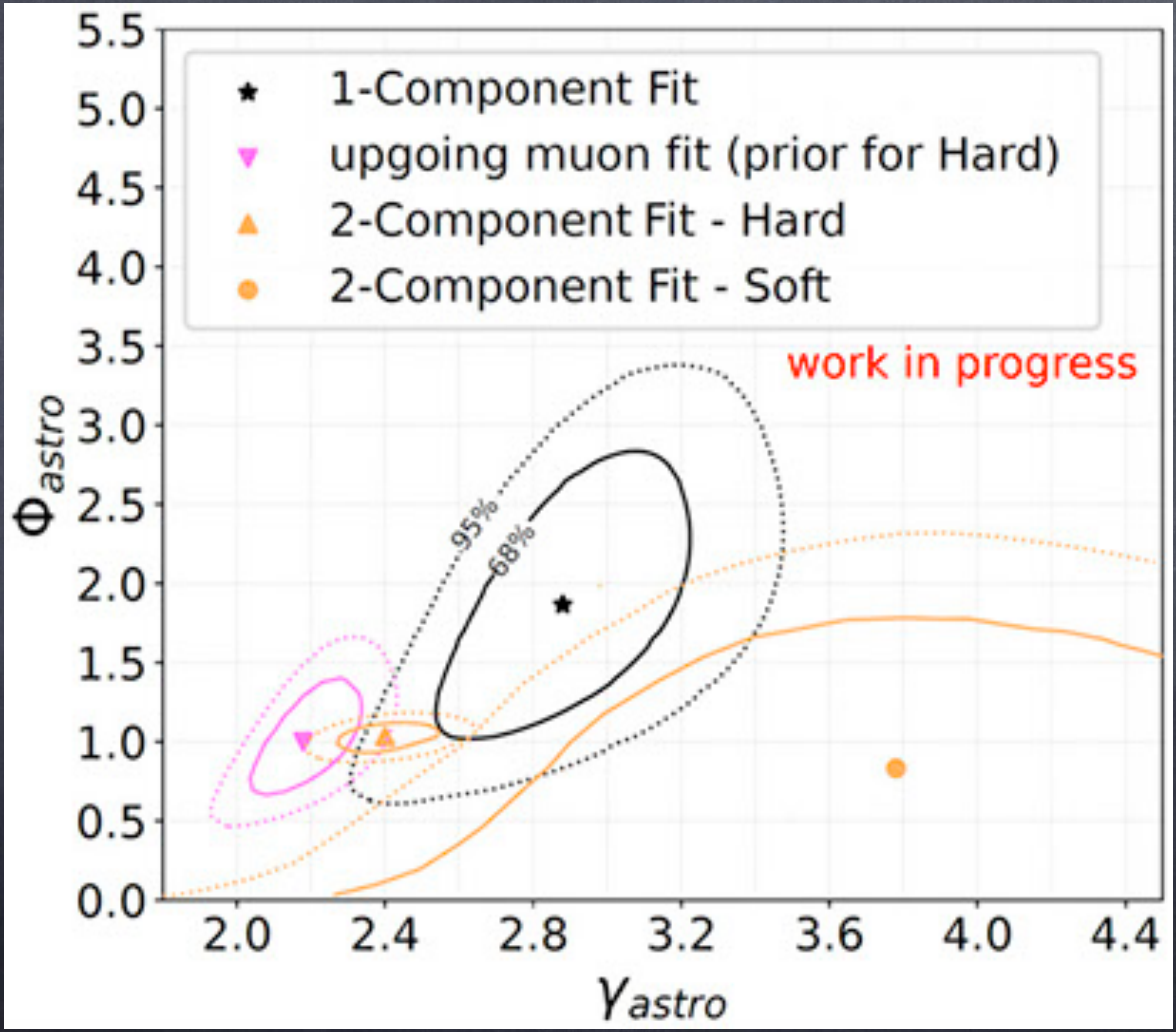


Consistent with the Waxman-Bahcall flux



Upgoing muon neutrino spectrum (E > 120 TeV) harder than HESE spectrum

Multicomponent flux?

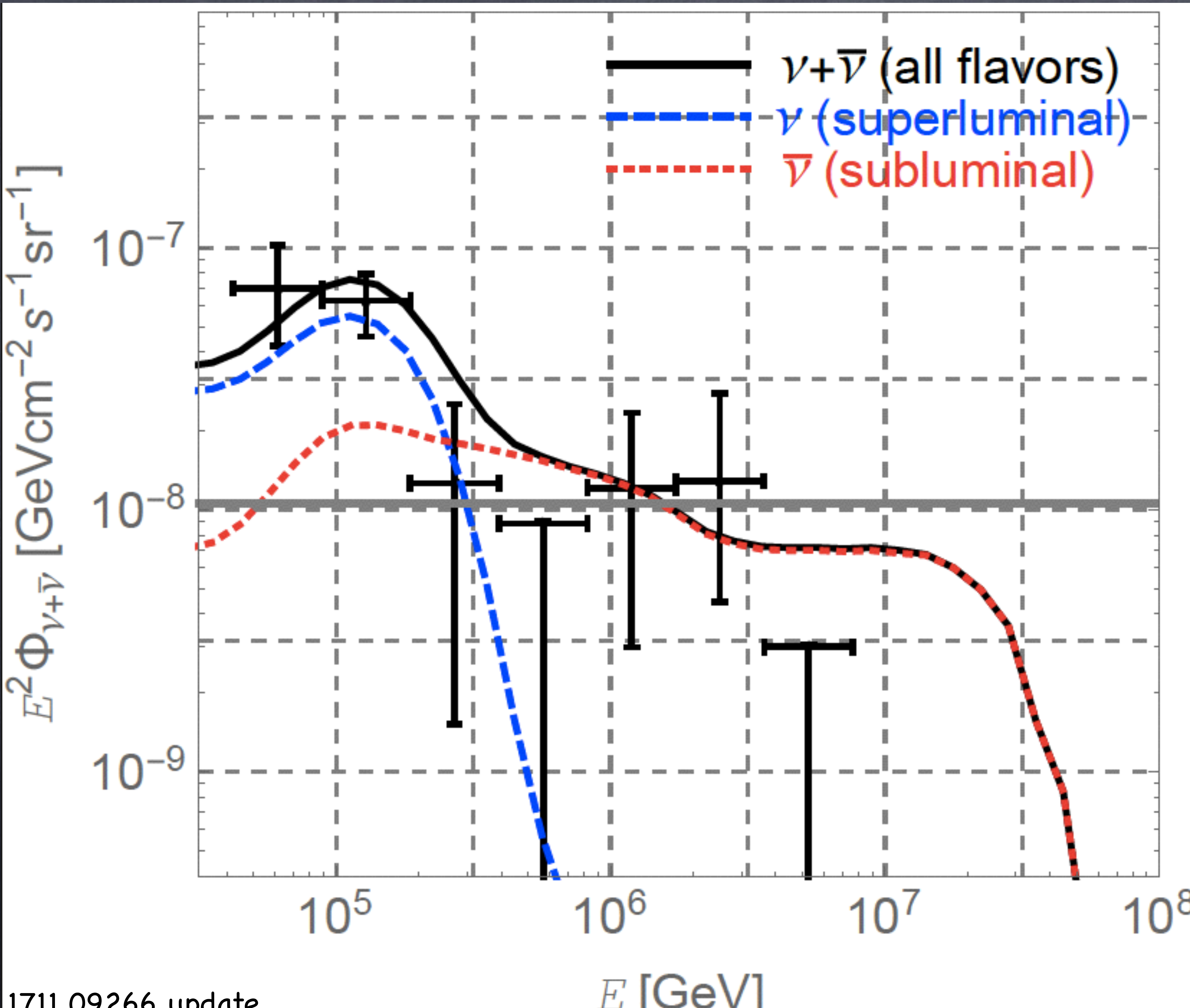


One Glashow resonance event observed

$\bar{\nu}_e$ is unique because of resonant scattering at

$$E_\nu = \frac{M_W^2}{2m_e} = 6.3 \text{ PeV}$$

$$\bar{\nu}_e e^- \to W^- \to \text{anything}$$



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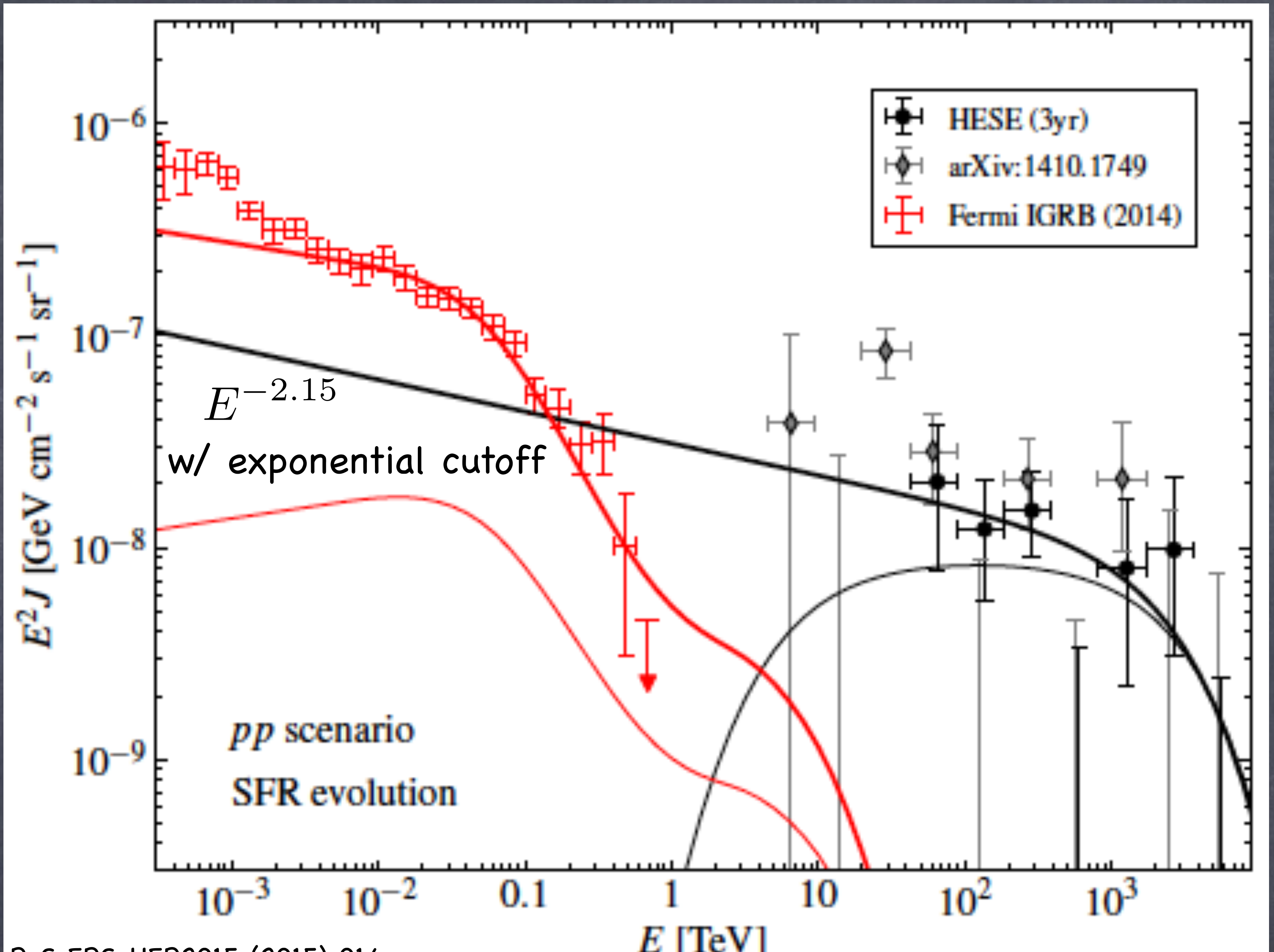
Connection with gamma rays



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- Neutrino spectra softer than shown are inconsistent with Fermi data
- Connection for $p\gamma$ sources weaker because target photons prevent gamma rays from leaving source

Lorentz and CPT violation?

- Suppose LIV and CPTV only occur in neutrino sector
- Only consider effects that change the kinematics of particle interactions
- Postulate that CPTV arises from Planck-suppressed terms in the Lagrangian

- Modified dispersion relation

$$E^2 - p^2 = m^2 + 2\delta E^2$$

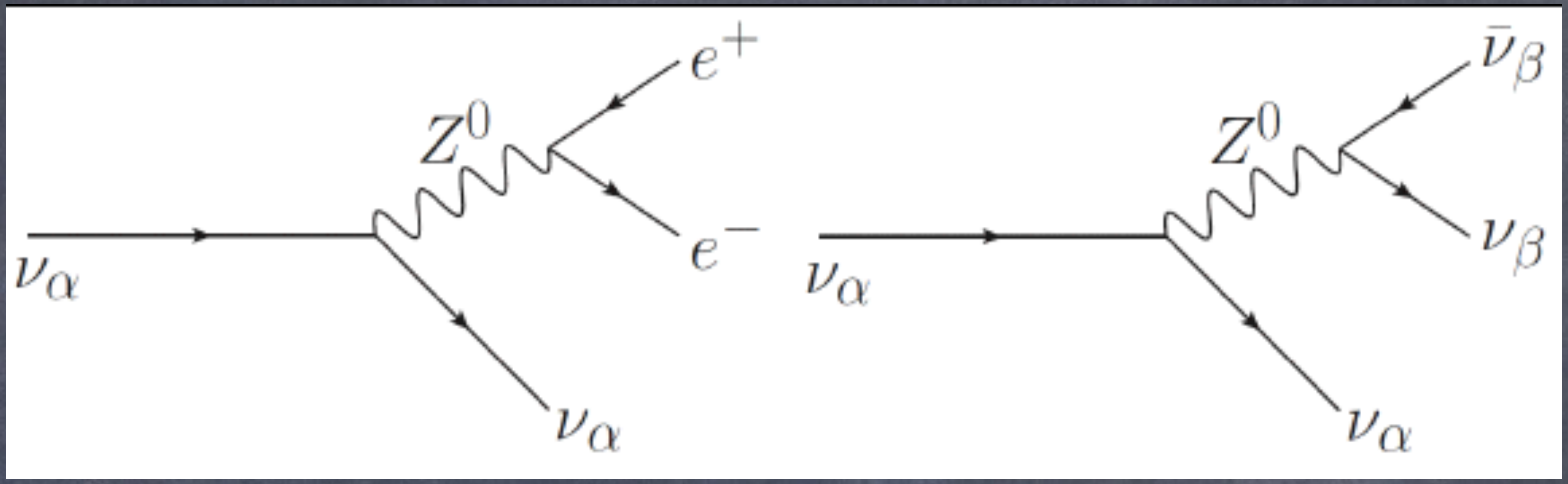
$$\delta = \kappa \frac{E}{M_{Pl}}$$

- Assume all neutrino flavors have same LIV parameter to be consistent with neutrino oscillation data

- Dispersion relation for antineutrinos: $\delta \to -\delta$

- Our choice $\delta > 0 \implies$ neutrinos are superluminal and antineutrinos are subluminal

- Dominant energy loss processes for superluminal neutrinos are vacuum pair emission (VPE) and neutrino splitting



- Event pile-up caused by neutrino splitting is larger than for VPE because splitting produces 2 additional lower energy neutrinos

$$\Gamma \propto \kappa^3 \frac{G_F^2 E^8}{M_{Pl}^3}$$

Effect on neutrino sources?

$\pi^+ \to \mu^+ \nu_\mu$ imposes an upper bound on the energy of superluminal neutrinos:

$$E^3 \leq \frac{(m_\pi - m_\mu)^2 M_{Pl}}{2\kappa}$$

VPE occurs above an energy threshold given by

$$E_{th}^3 = \frac{2 m_e^2 M_{Pl}}{\kappa}$$

Threshold energy for neutrino splitting is tiny compared to that for VPE

For a given VPE threshold energy, the upper bound on the superluminal neutrino energy is

$$E < 10.3E_{th}$$

If the highest energy track event observed by IceCube (with median estimated energy of 8.7 PeV) was initiated by a superluminal neutrino, then

$$E_{th}^{min} = 0.85 \text{ PeV}$$

Need extragalactic sources of superluminal neutrinos

CR Reservoirs:

Starburst galaxies and Galaxy clusters

$$pp \to \pi^{\pm} \text{ pairs} \to \nu_{\mathrm{e}} + \bar{\nu}_{\mathrm{e}} + 2\nu_{\mu} + 2\bar{\nu}_{\mu}$$

- naturally produces spectral break
- same number of neutrinos and antineutrinos

CR Accelerators:

Gamma-ray bursts and Active Galactic Nuclei

$$p\gamma \rightarrow \pi^+ \rightarrow \nu_e + \nu_\mu + \bar{\nu}_\mu$$

- naturally produces hard neutrino spectrum
- twice as many neutrinos and antineutrinos

If muons damped

$p\gamma \to \pi^+ \to \nu_\mu$ only

Only superluminal neutrinos at source!

BUT, intrinsic contamination from π^- is expected to reduce the superluminal fraction by 20%-33%

e.g.

$$p\gamma \to n\pi^+$$

$$n\gamma \to p\pi^-$$

Flavor ratio at Earth

	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)	$60/108 = 0.56$

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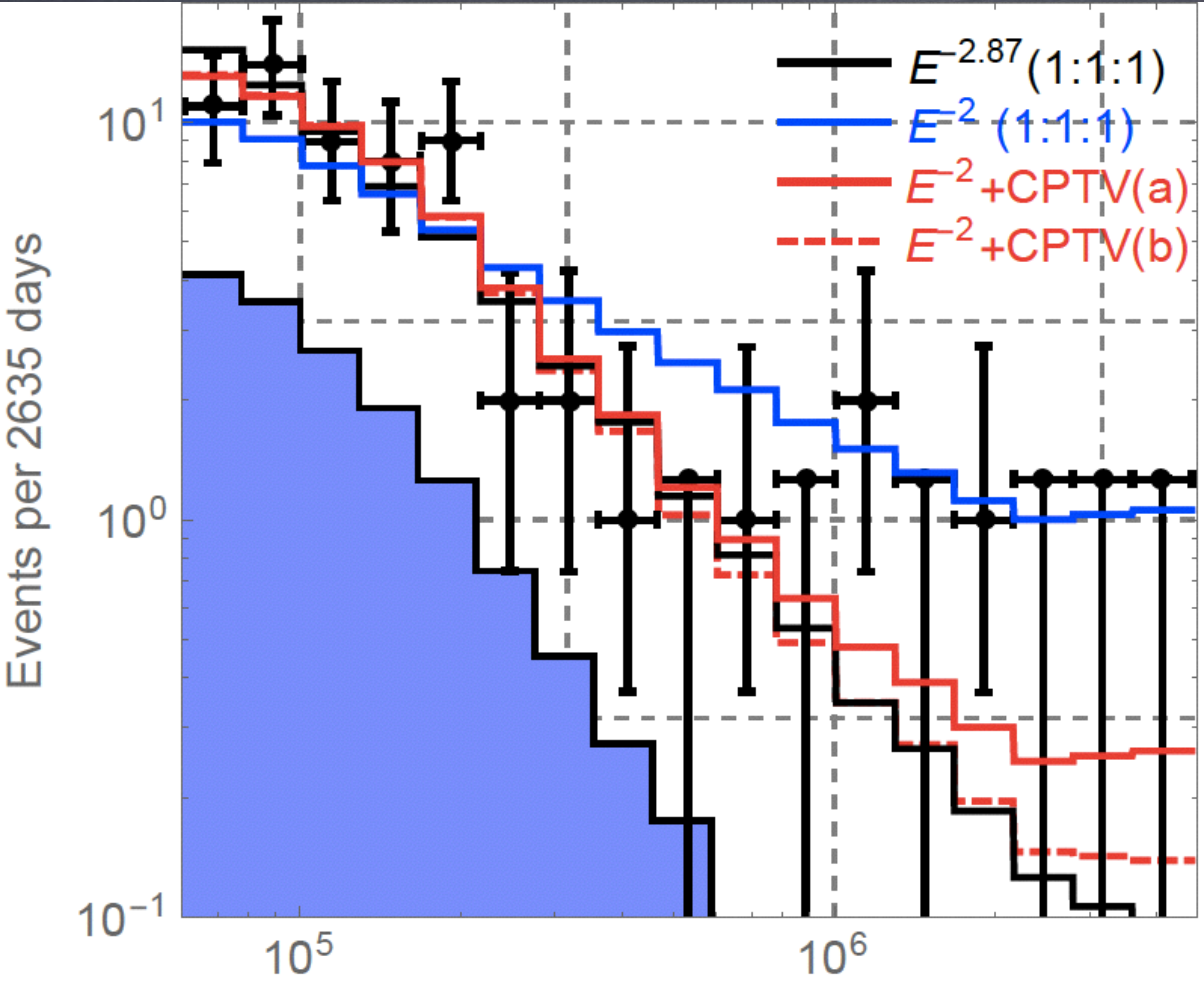

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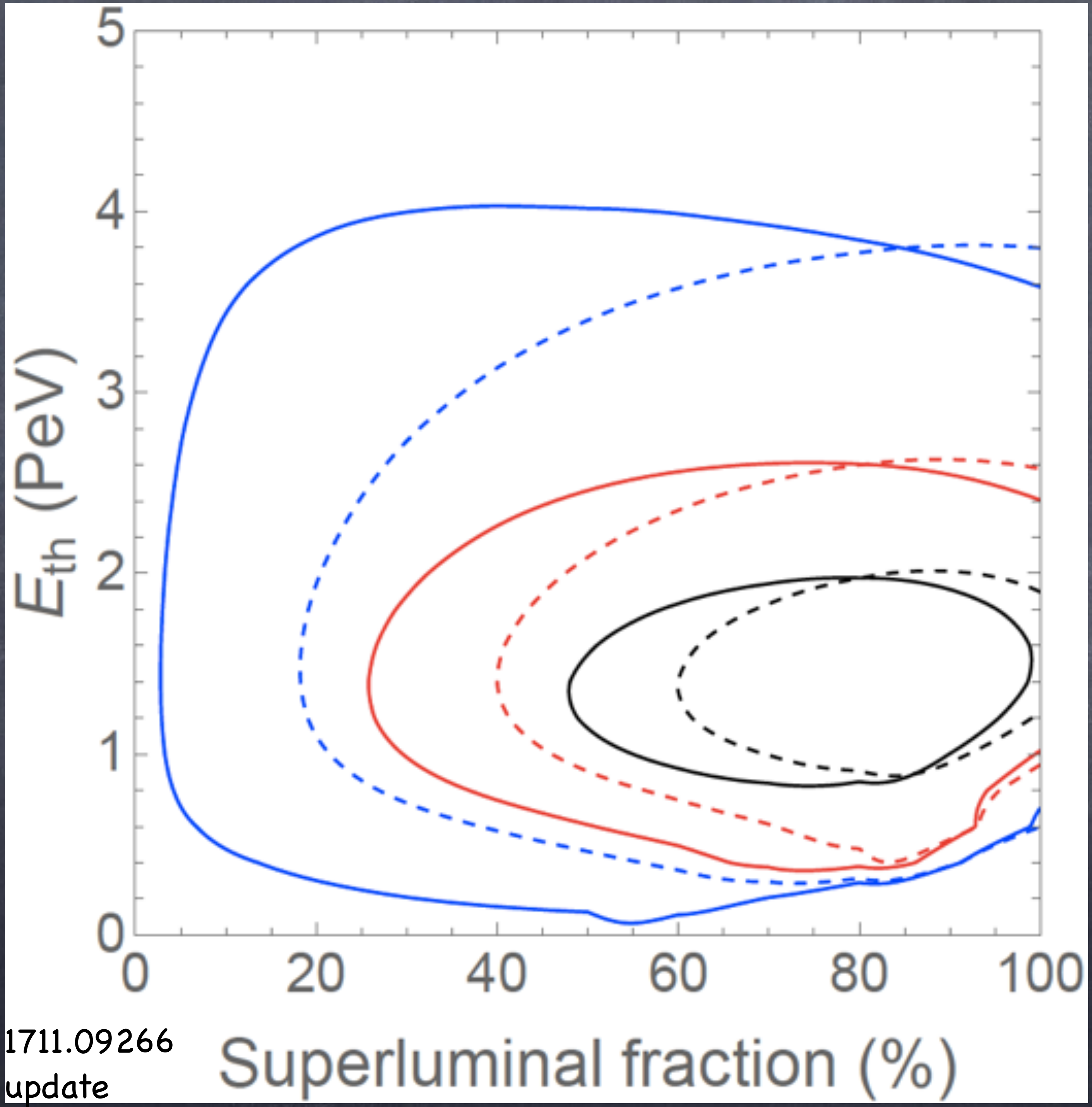
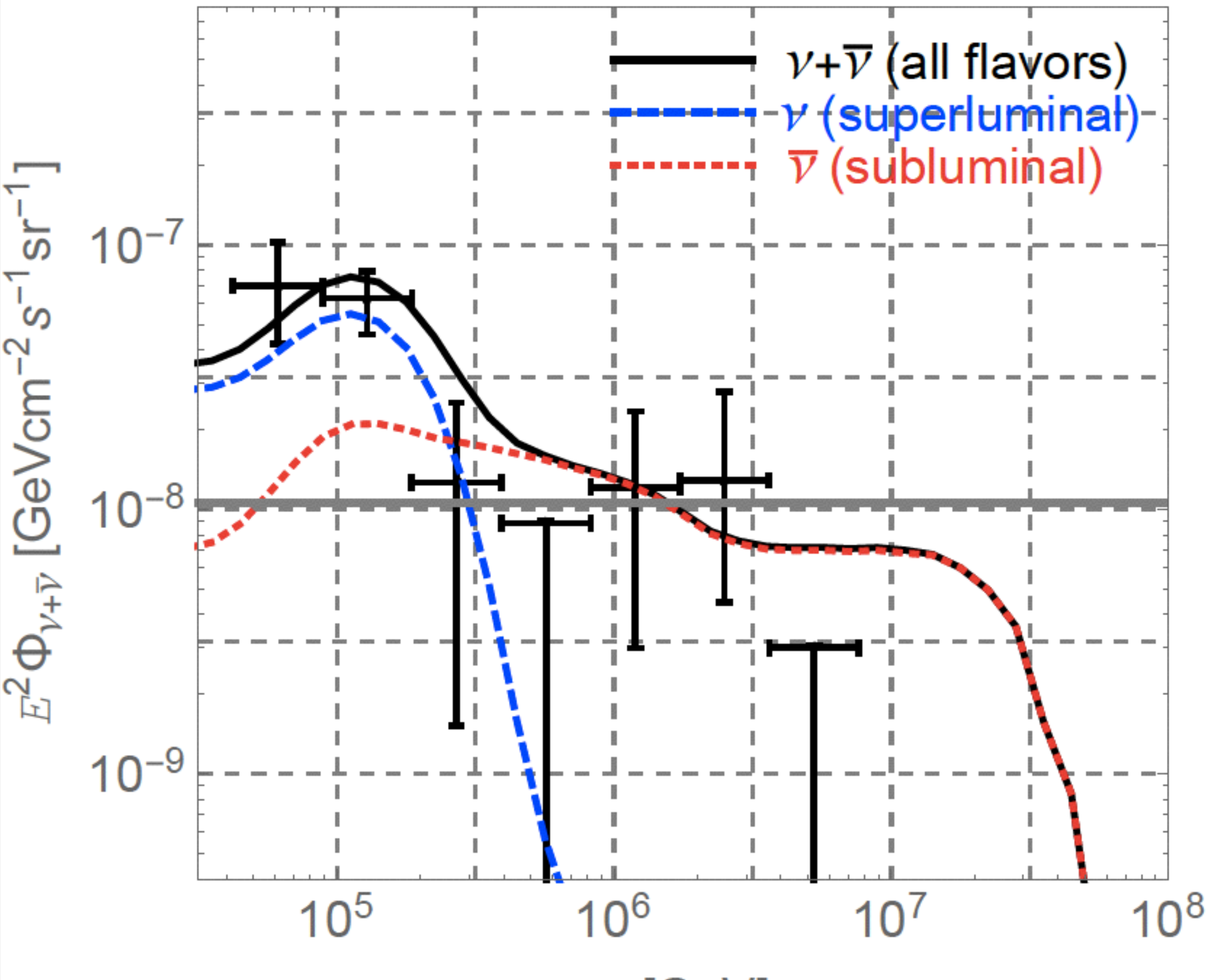
	$E^{-2.87}(1:1:1)$		$E^{-2}(1:1:1)$		E^{-2} with CPTV	
Case	(a)	(b)	(a)	(b)	(a)	(b)
χ^2	16.0	16.6	24.9	30.7	13.0	14.5
GR events	0.20	0.20	3.2	2.8	0.95	0.48



Superluminal fraction compatible with π^- contamination



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Summary

- Multicomponent neutrino flux not required if neutrino interactions violate CPT
- Single E^{-2} spectrum from muon-damped $p\gamma$ source works
- Superluminal fraction compatible with π^- contamination
- Excess below 200 TeV explained by event pile-up from superluminal neutrino decay
- Subluminal antineutrinos contribute at high energies so no cutoff; expected Glashow event may have been seen
- π^+ is predicted to be a cosmic ray primary