Observation of the multi-flavour **extragalactic diffuse** high-energy neutrino flux with **IceCube**

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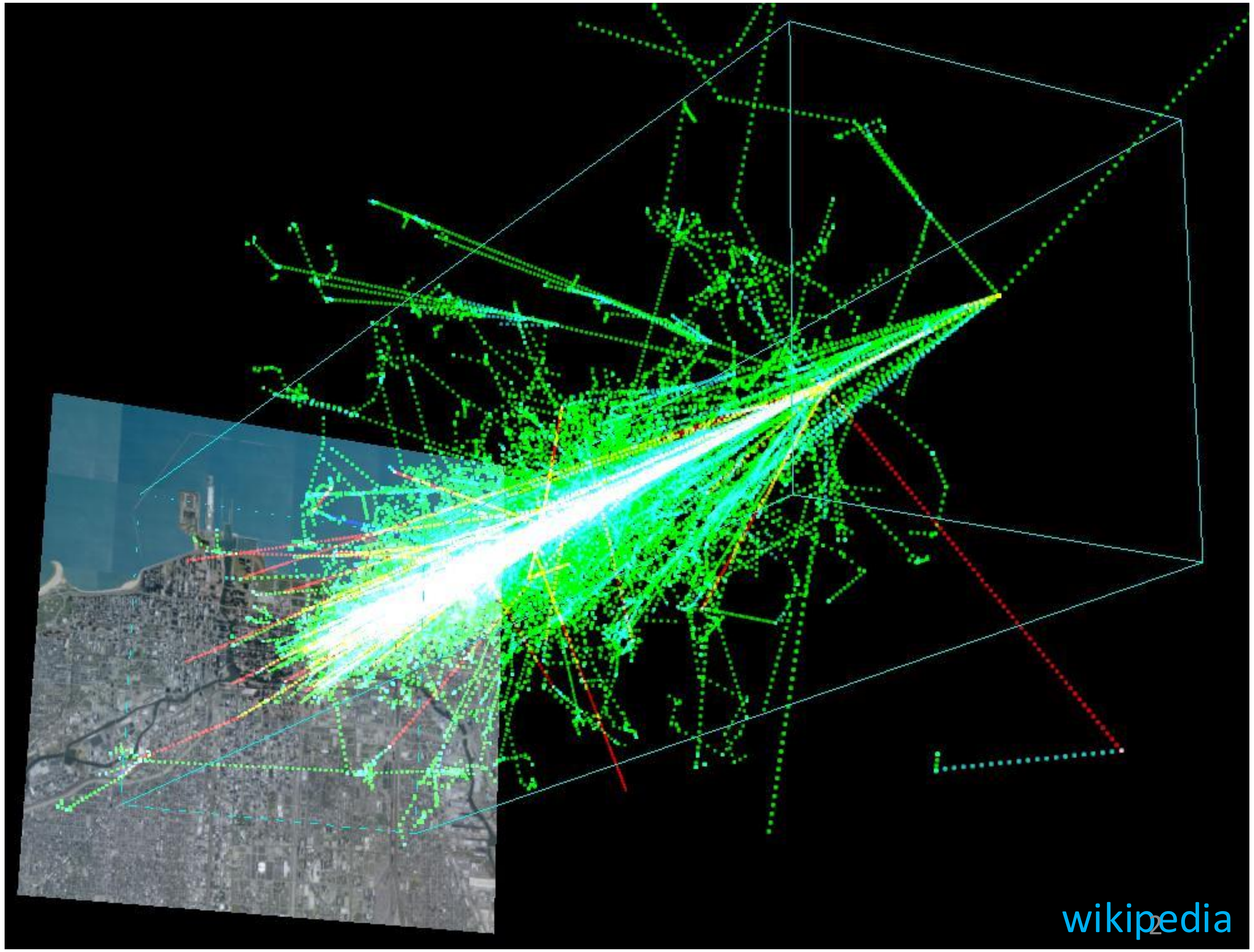
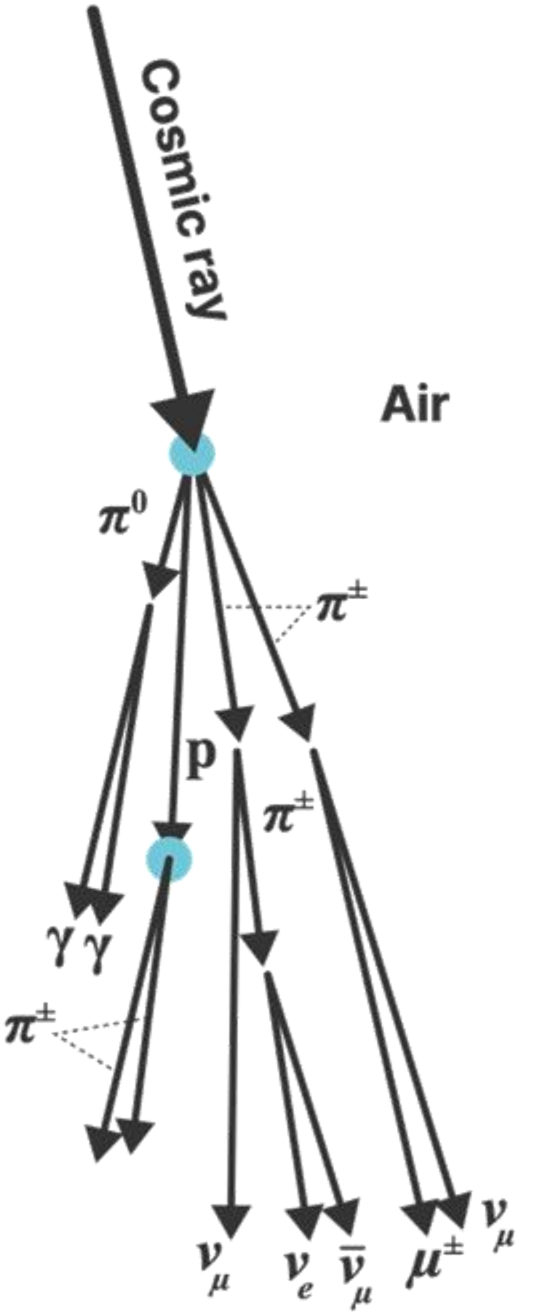
FROM CLOUD CHAMBERS TO EXTENSIVE AIR SHOWERS

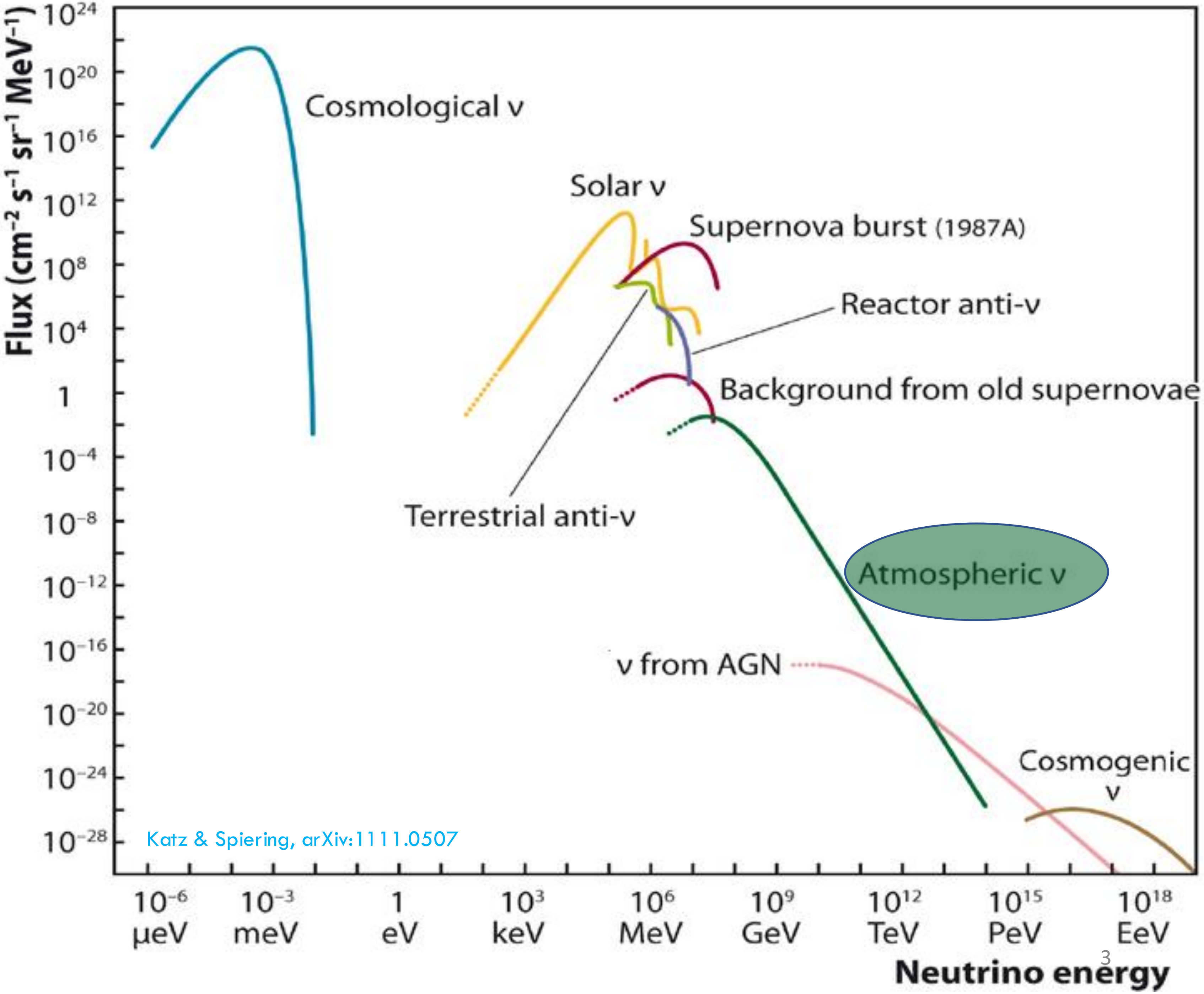
Particle shower universality: fundamental laws at over 10 orders of magnitude in energy



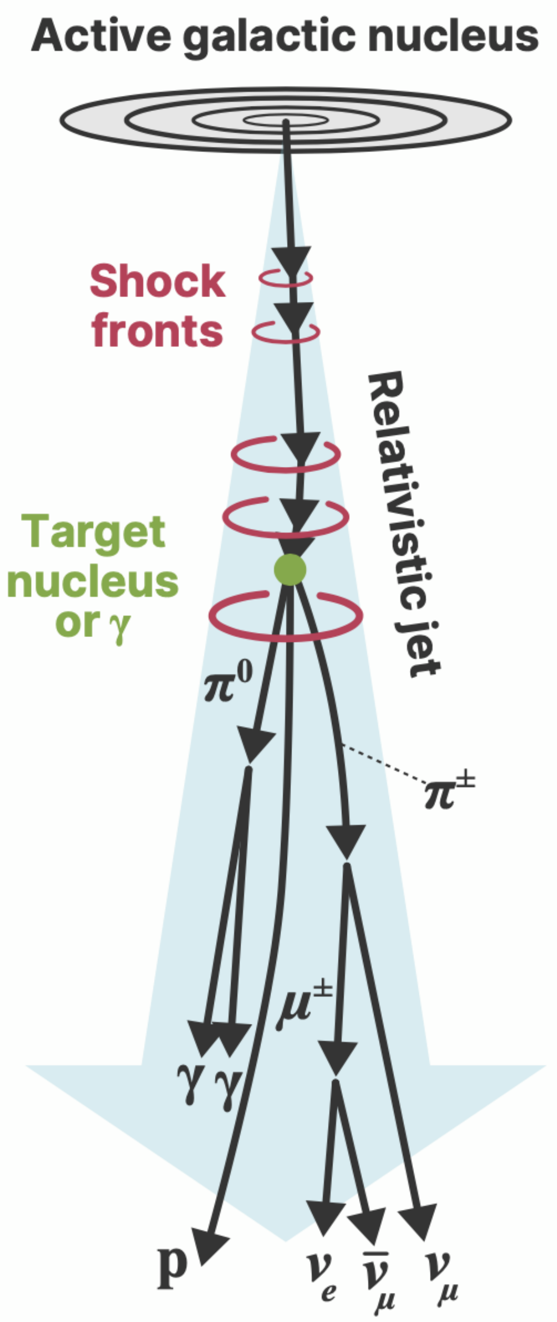
wikipedia

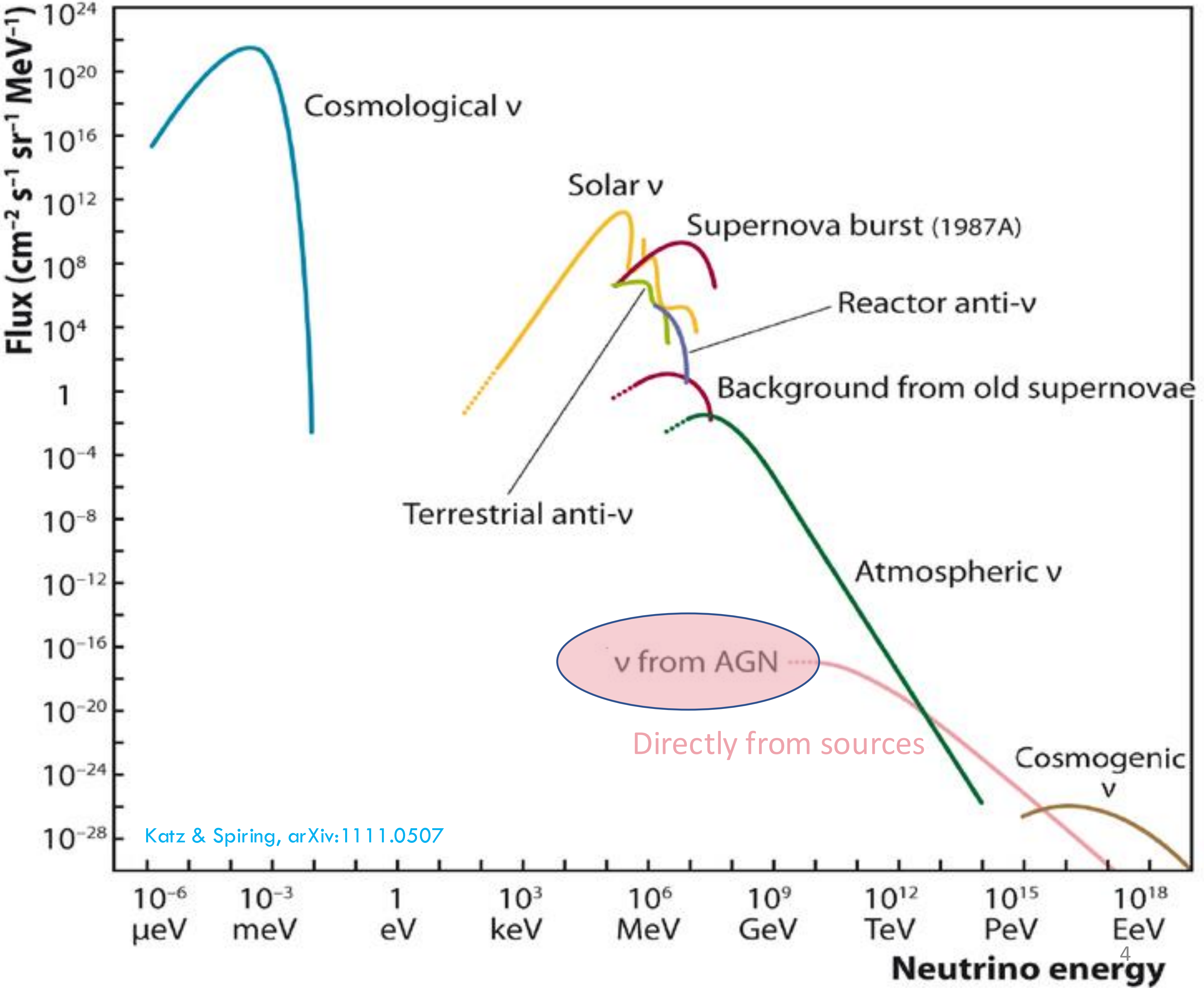


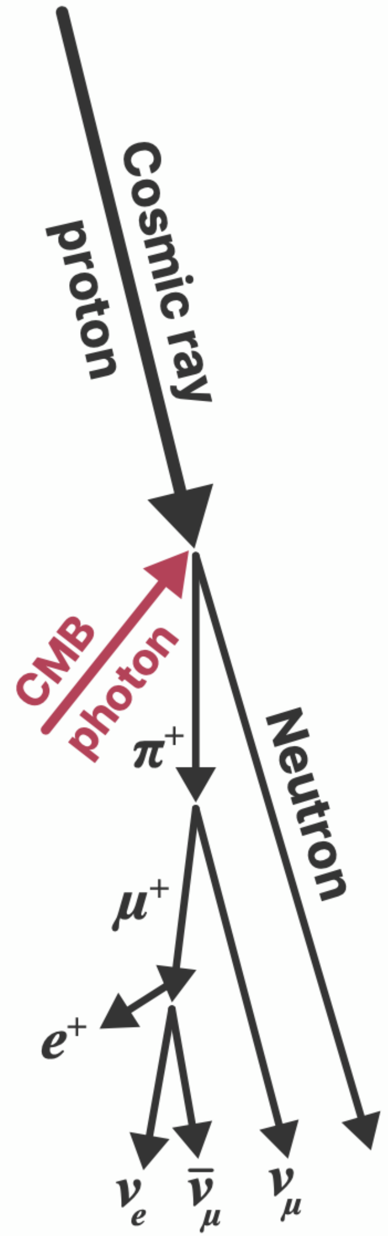
Cosmic ray
Air
π^0
$\pi^\pm$
p
$\pi^\pm$
γ γ
$\pi^\pm$
ν_μ
ν_e
$\bar{\nu}_\mu$
$\mu^\pm$
ν_μ

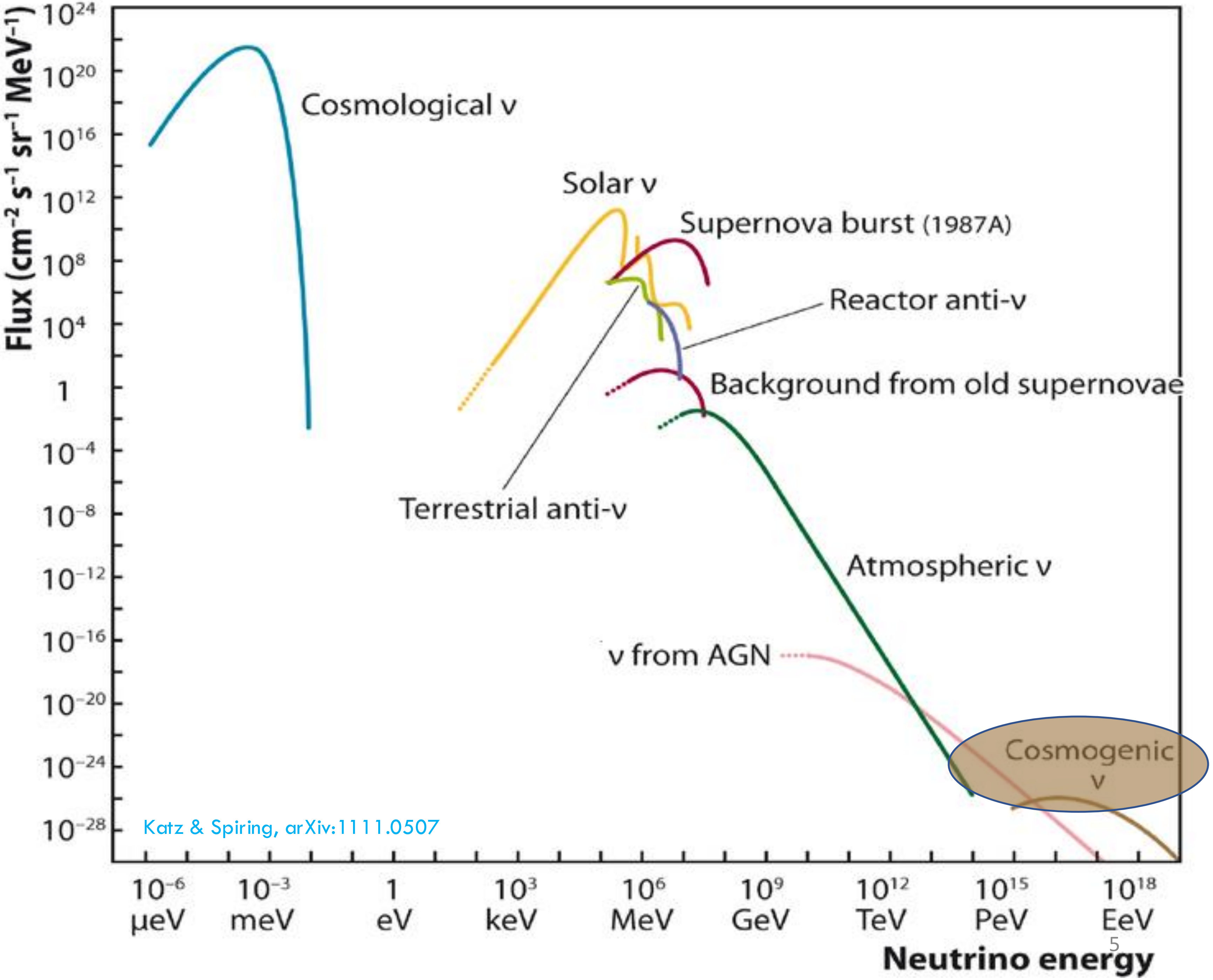


Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Katz & Spiering, arXiv:1111.0507
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy


Active galactic nucleus
Shock fronts
Relativistic jet
Target nucleus or γ
π0
π±
μ±
γ γ
p
νe ν̄μ νμ


Flux (cm−2 s−1 sr−1 MeV−1)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Directly from sources
Cosmogenic ν
Katz & Spiring, arXiv:1111.0507
10−6 μeV
10−3 meV
1 eV
103 keV
106 MeV
109 GeV
1012 TeV
1015 PeV
1018 EeV
Neutrino energy


Cosmic ray
proton
CMB
photon
π^+
μ^+
e^+
Neutron
ν_e
$\bar{\nu}_\mu$
ν_μ


Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
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ν from AGN
Cosmogenic ν
Katz & Spiring, arXiv:1111.0507
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

Atmospheric flux as the foreground

Conventional ($\pi^{\pm}$, K):

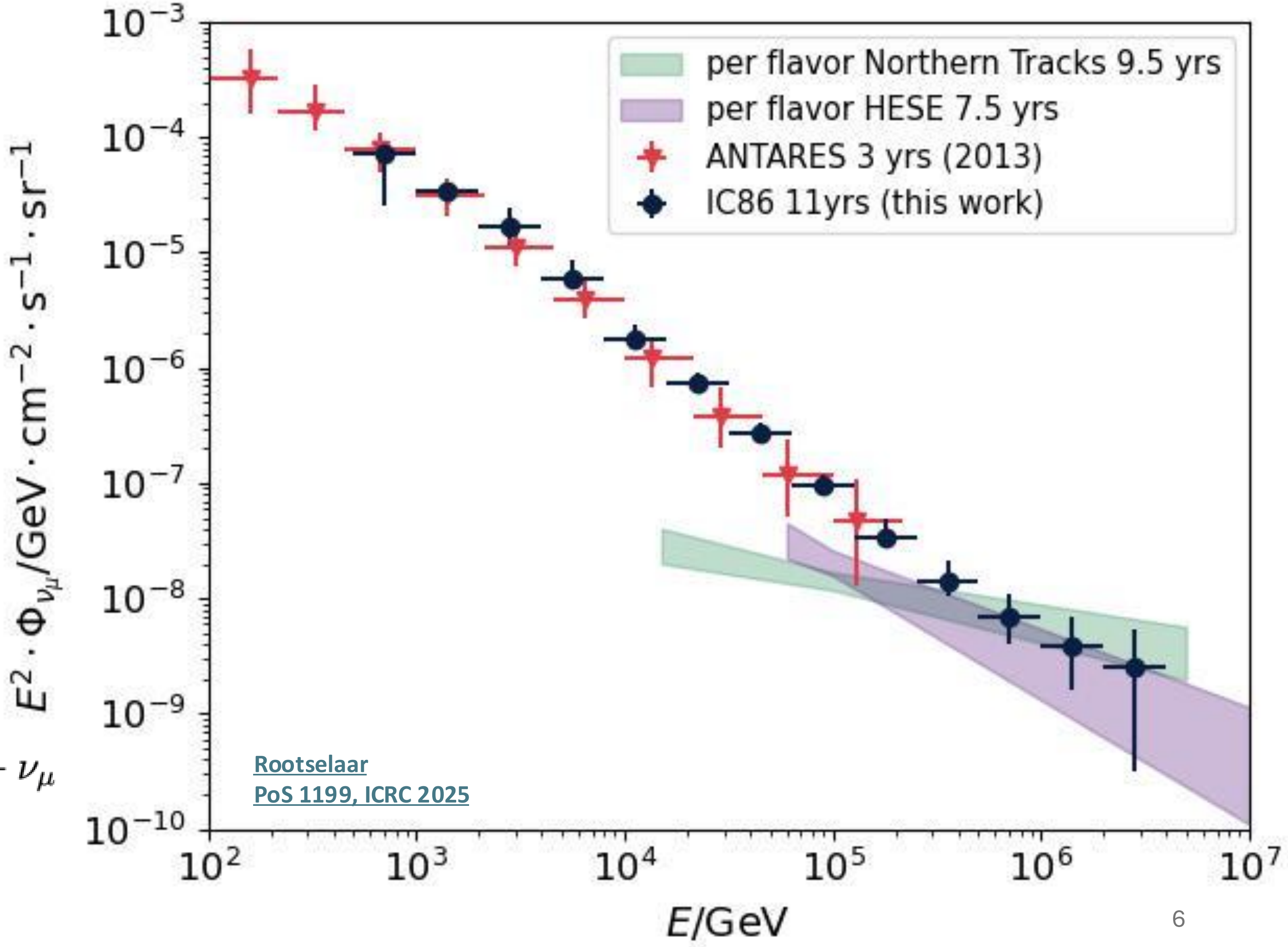
$$\begin{aligned} \pi^{\pm}, K^{\pm} &\rightarrow \mu^{\pm} + \nu_{\mu}\,(\bar{\nu}_{\mu}) \\ \mu^{\pm} &\rightarrow e^{\pm} + \nu_e\,(\bar{\nu}_e) + \bar{\nu}_{\mu}\,(\nu_{\mu}) \\ K^{\pm} &\rightarrow \pi^0 e^{\pm} \nu_e \\ K_L^0 &\rightarrow \pi^{\pm} e^{\mp} \nu_e \end{aligned}$$

$$\phi_{\nu}^{\mathrm{conv}}(E) \propto E^{-3.7}$$

Prompt (D, Λ_c, η, η'):

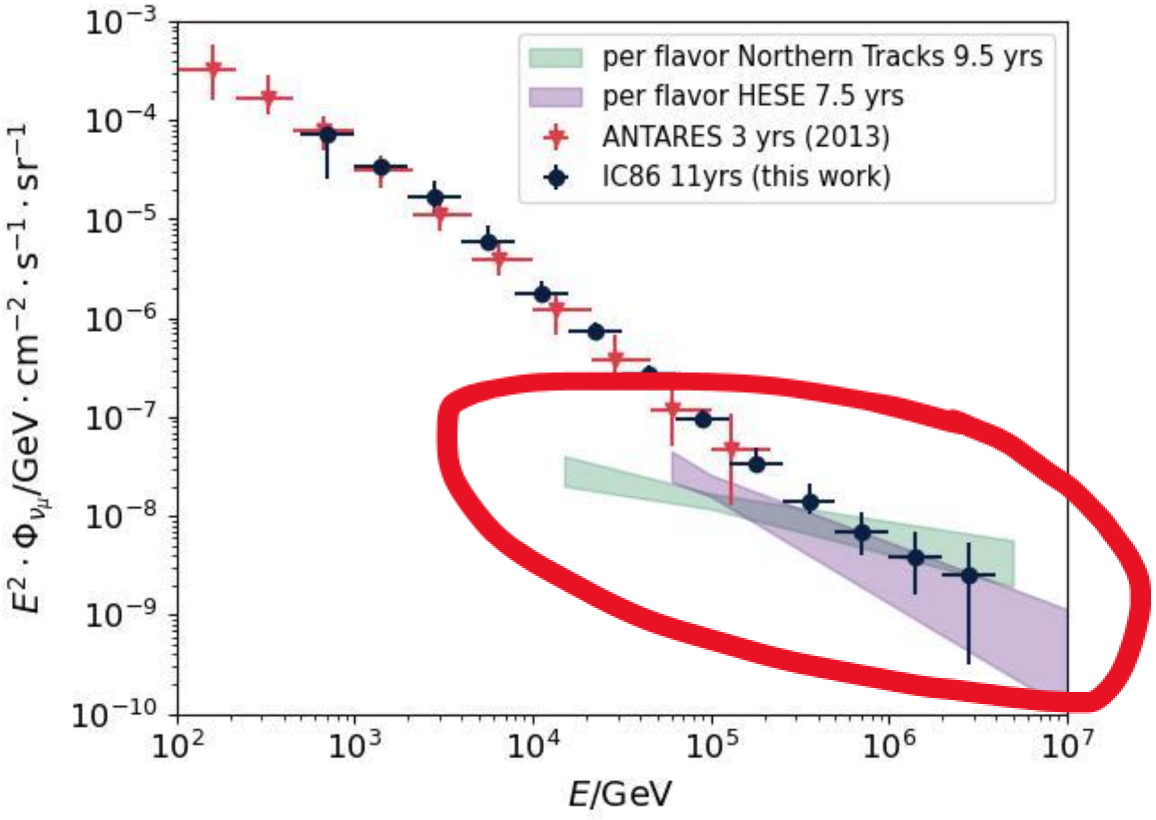
$$\begin{aligned} D, D_s, \Lambda_c &\rightarrow \ell^{\pm} + \nu_{\ell}\,(\bar{\nu}_{\ell}) + X \\ \eta, \eta' &\rightarrow \mu^{+}\mu^{-} \;\Rightarrow\; e^{\pm} + \nu_e + \nu_{\mu} \end{aligned}$$

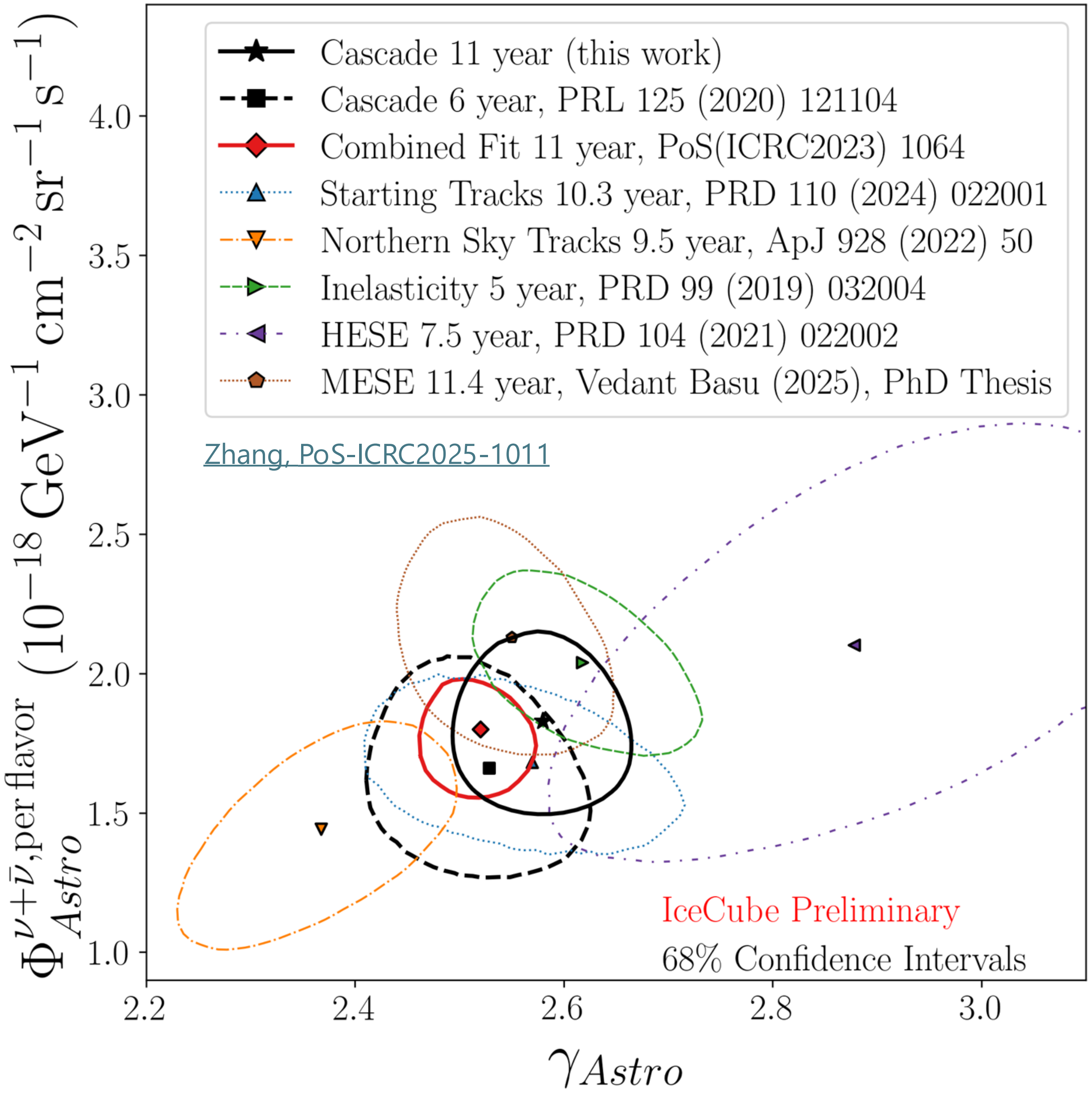
$$\phi_{\nu}^{\mathrm{prompt}}(E) \propto E^{-2.7}$$



Rootselaar
PoS 1199, ICRC 2025

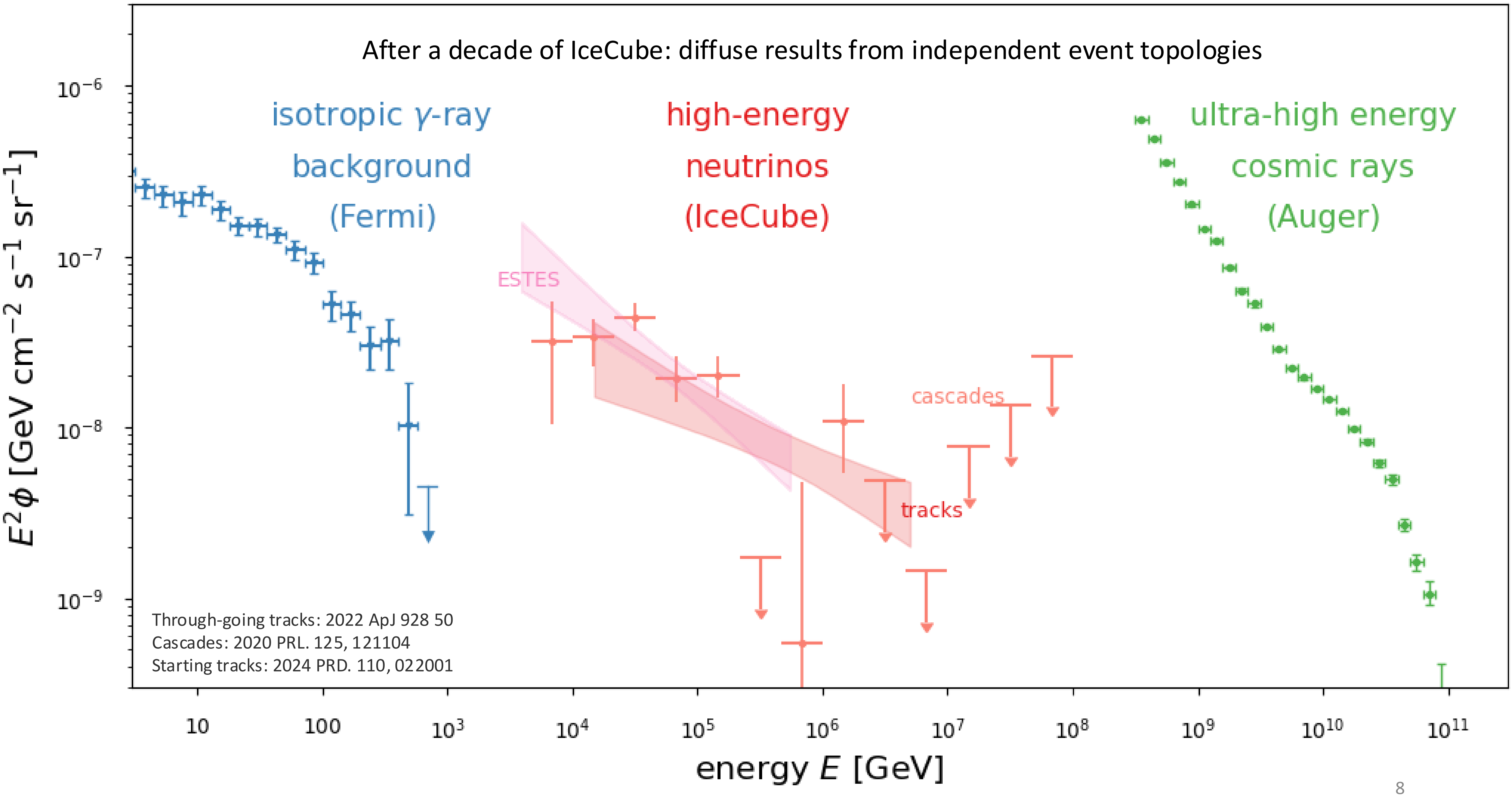
Astrophysical: single power law?



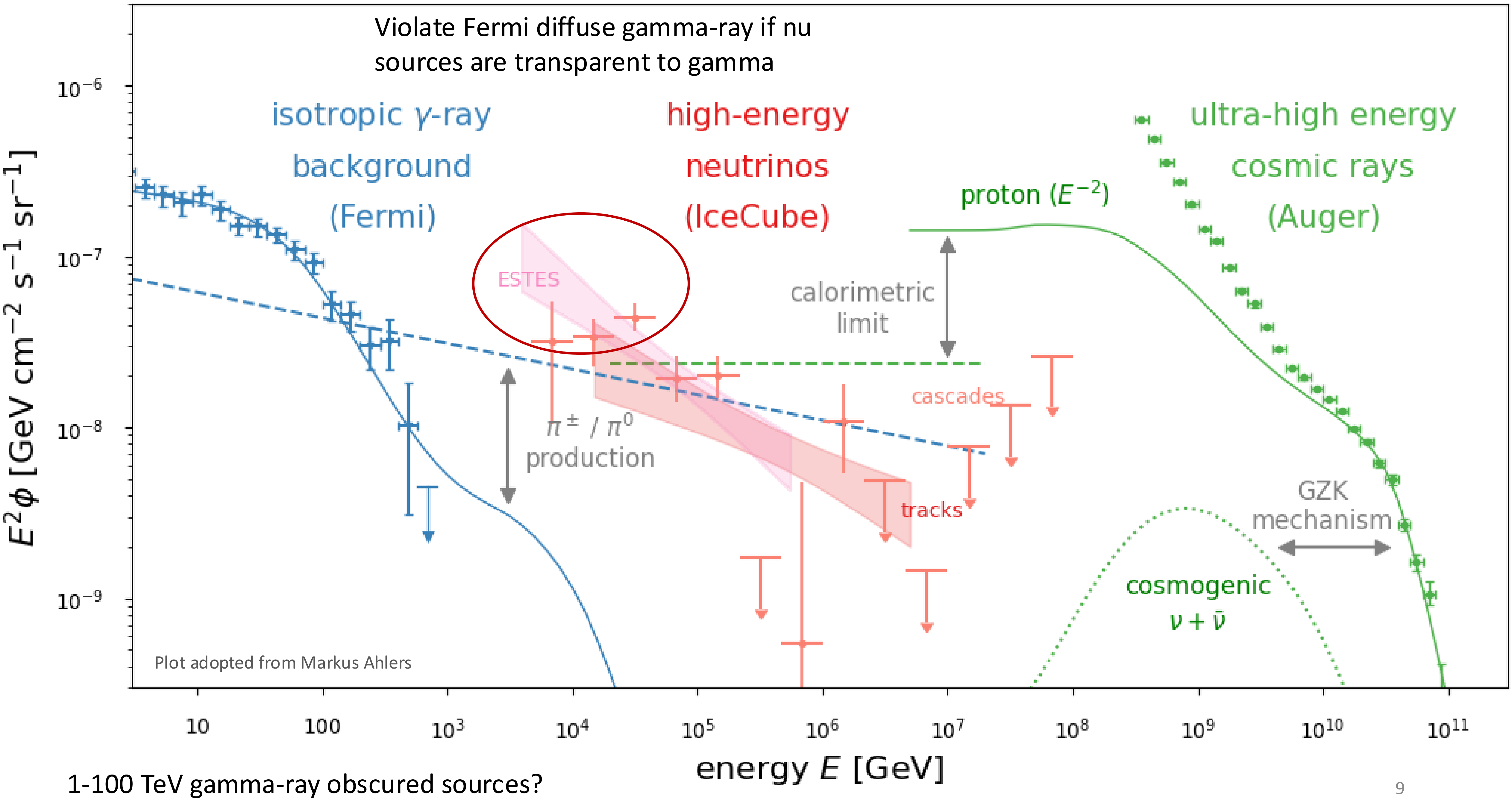


Zhang, PoS-ICRC2025-1011

After a decade of IceCube: diffuse results from independent event topologies



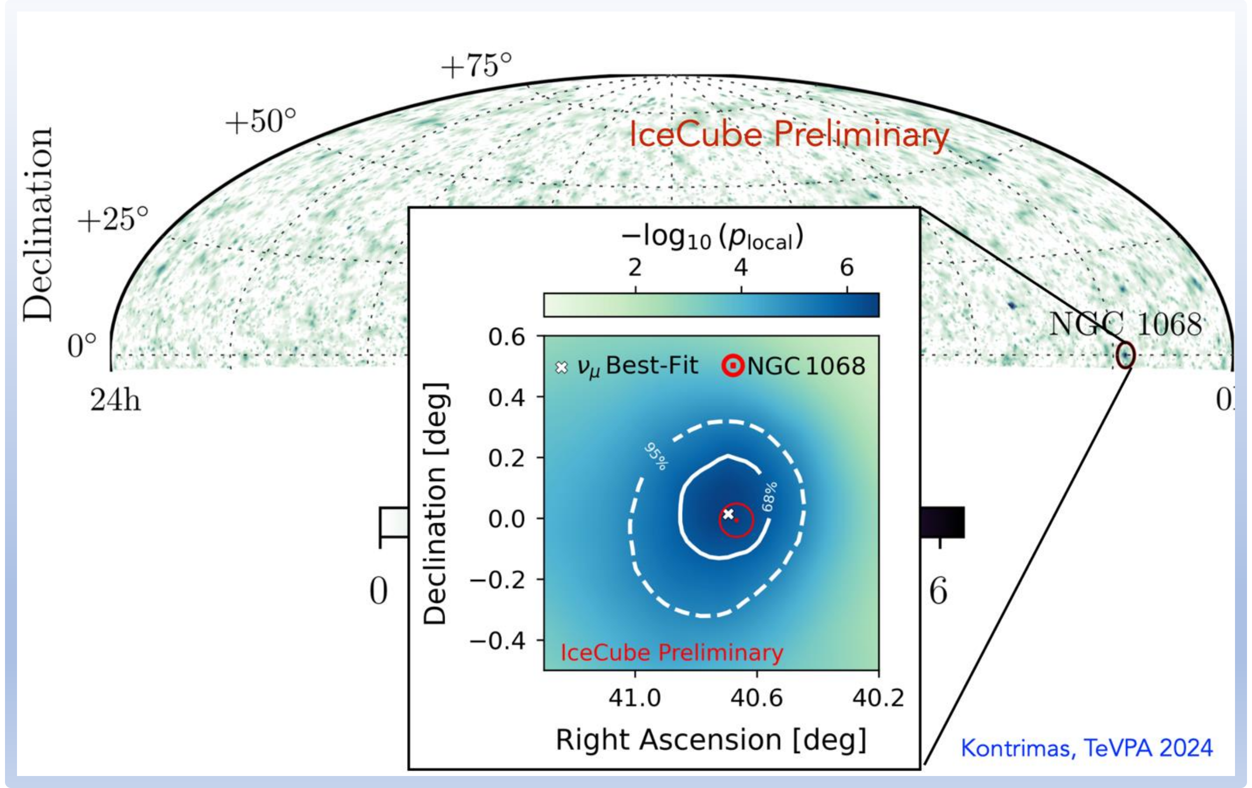
Violate Fermi diffuse gamma-ray if nu sources are transparent to gamma

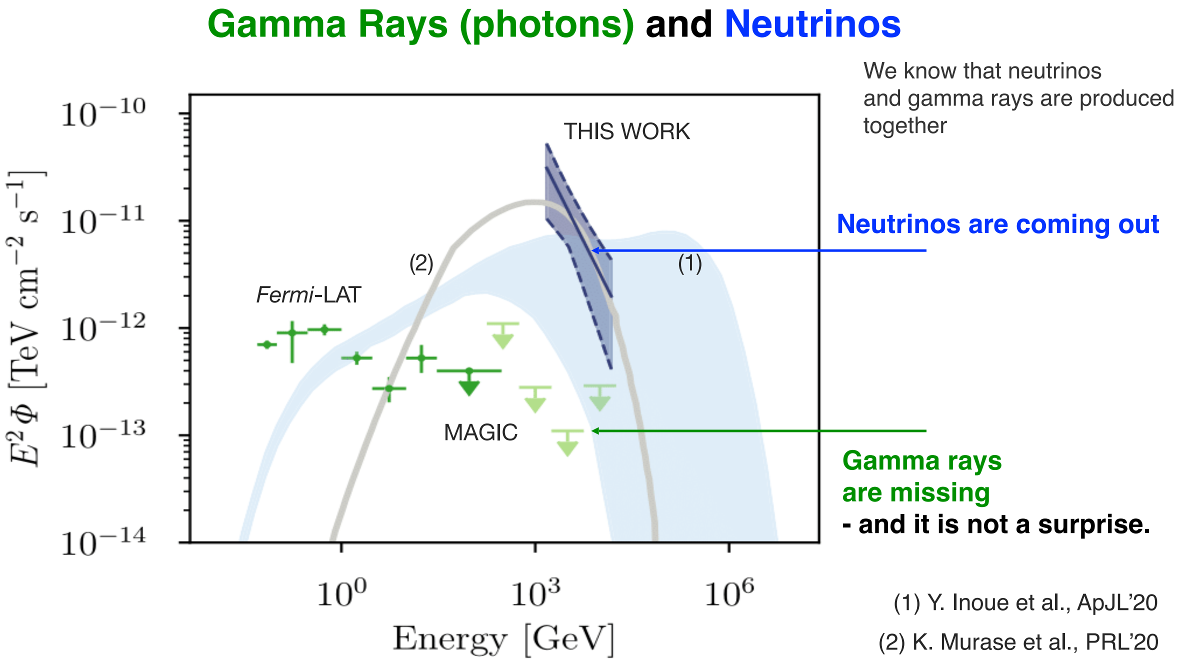


1-100 TeV gamma-ray obscured sources?

Gamma-ray obscured neutrino sources?

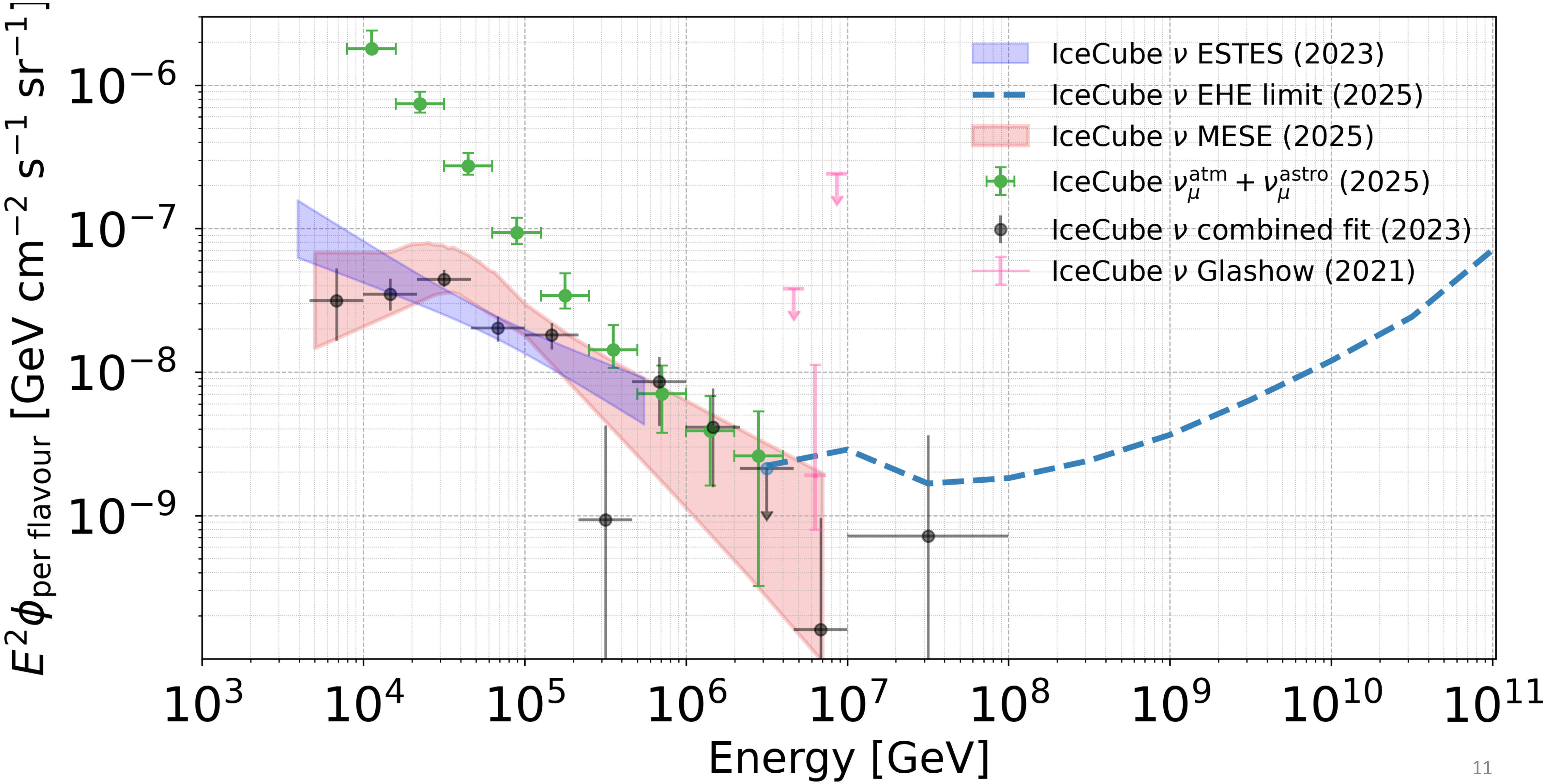
Hints from the first point-like neutrino source: NGC1068 (2022 Science 378, 6619, 538-543)



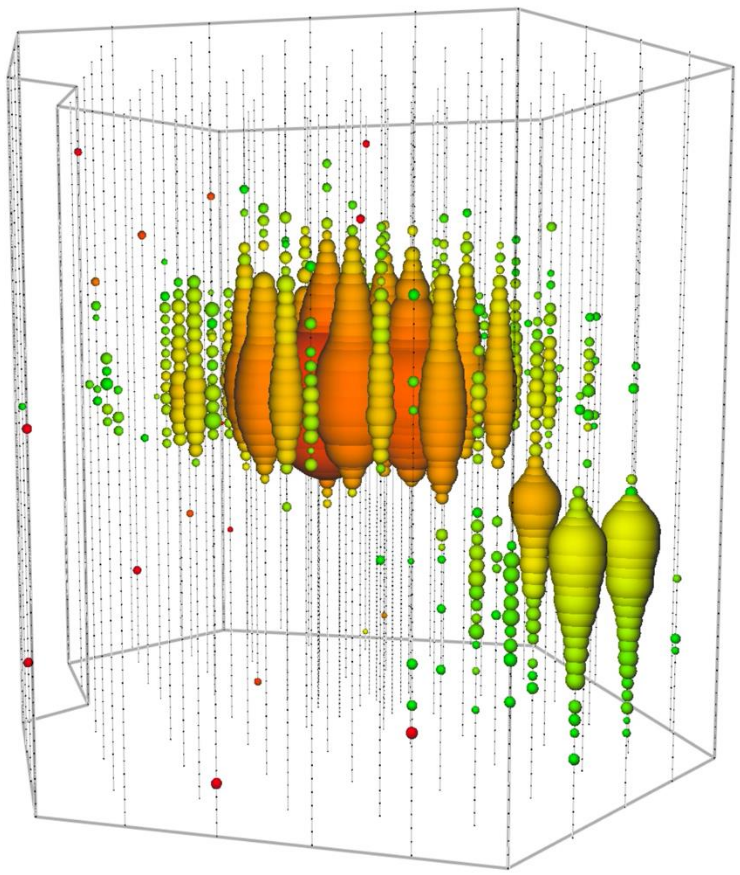


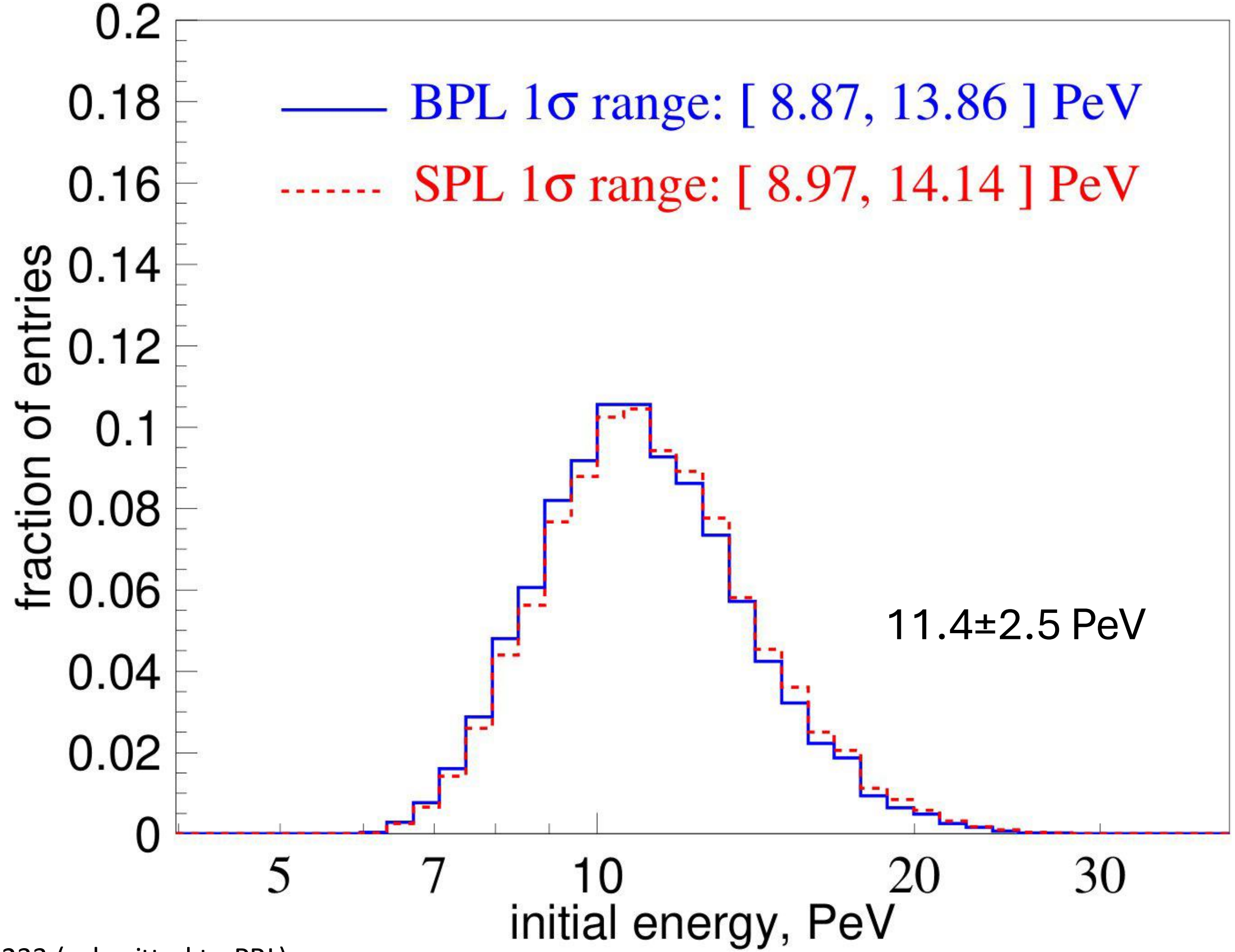
Neutrinos escape dense gas region: excess neutrinos but gamma rays are attenuated / absorbed

The latest results: astro, atmos and cosmogenic



The highest neutrino energy event from IceCube

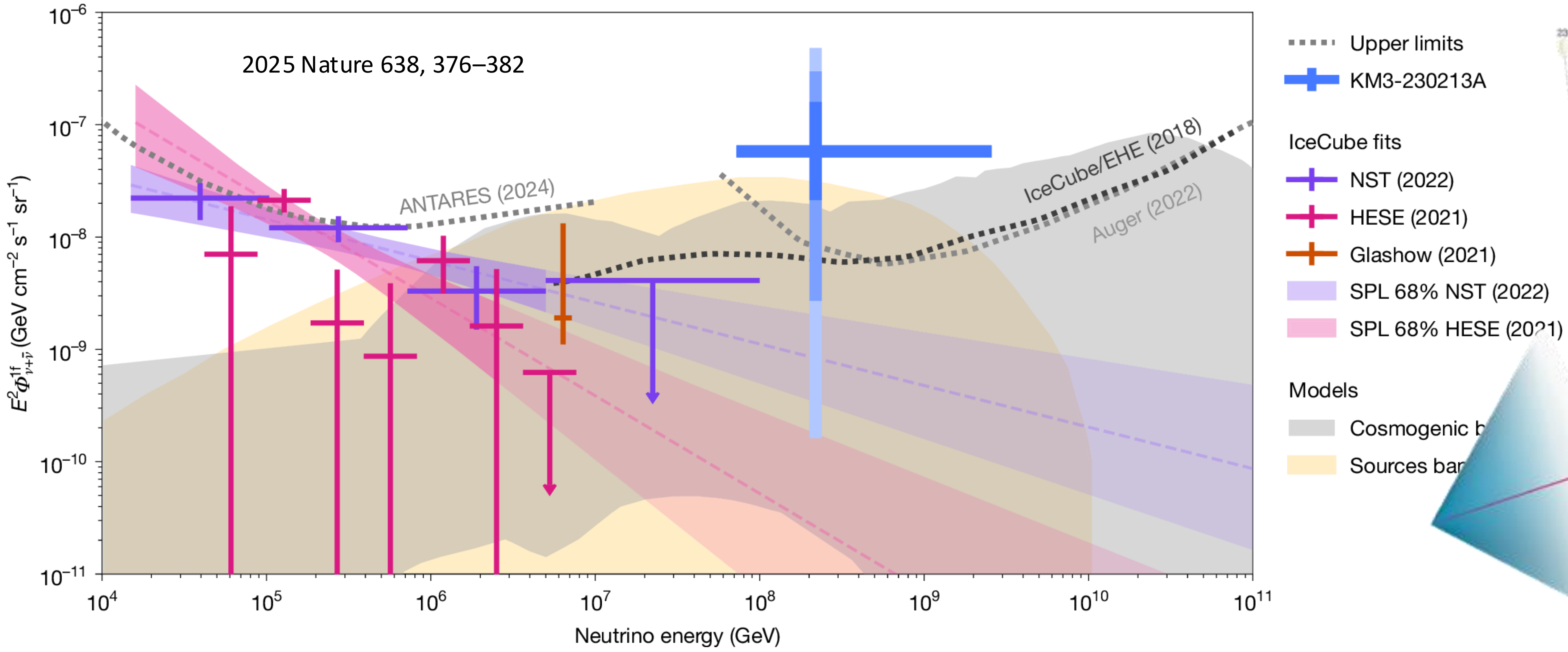


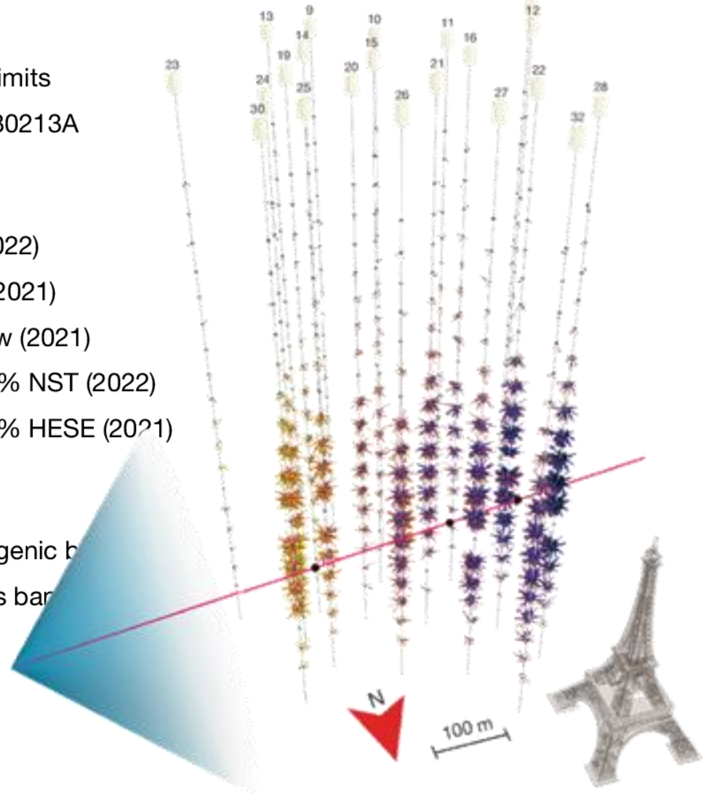


arXiv:2507.22233 (submitted to PRL)
arXiv:2507.22234 (submitted to PRD)

The UHE neutrino candidate from KM3NeT

- The highest energy neutrino candidate 220_{-110}^{+570} PeV

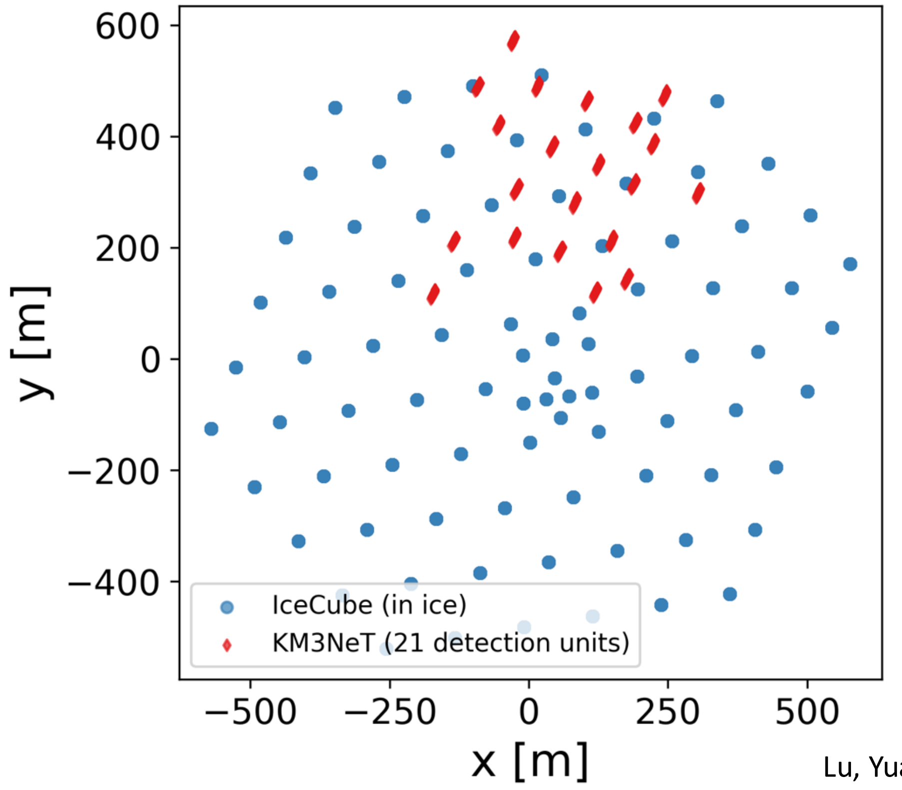


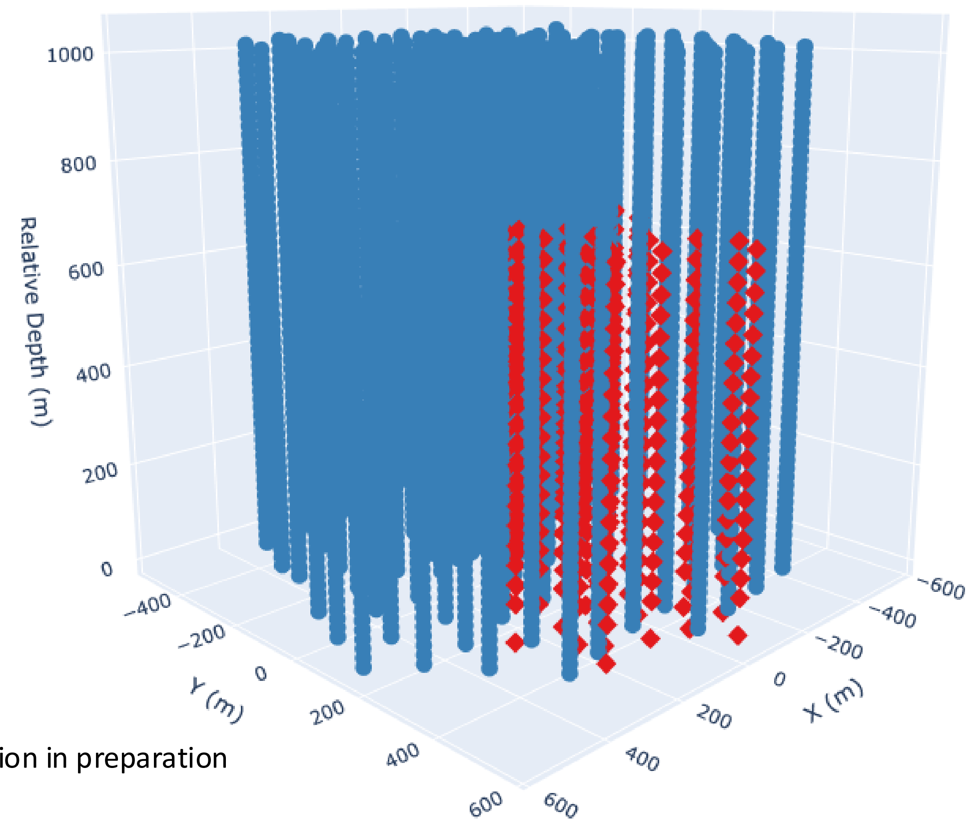


Is it consistent with IceCube result?

Understanding the KM3-230223A

- Detector geometry of **IceCube** vs **KM3NeT** (21 detection lines)

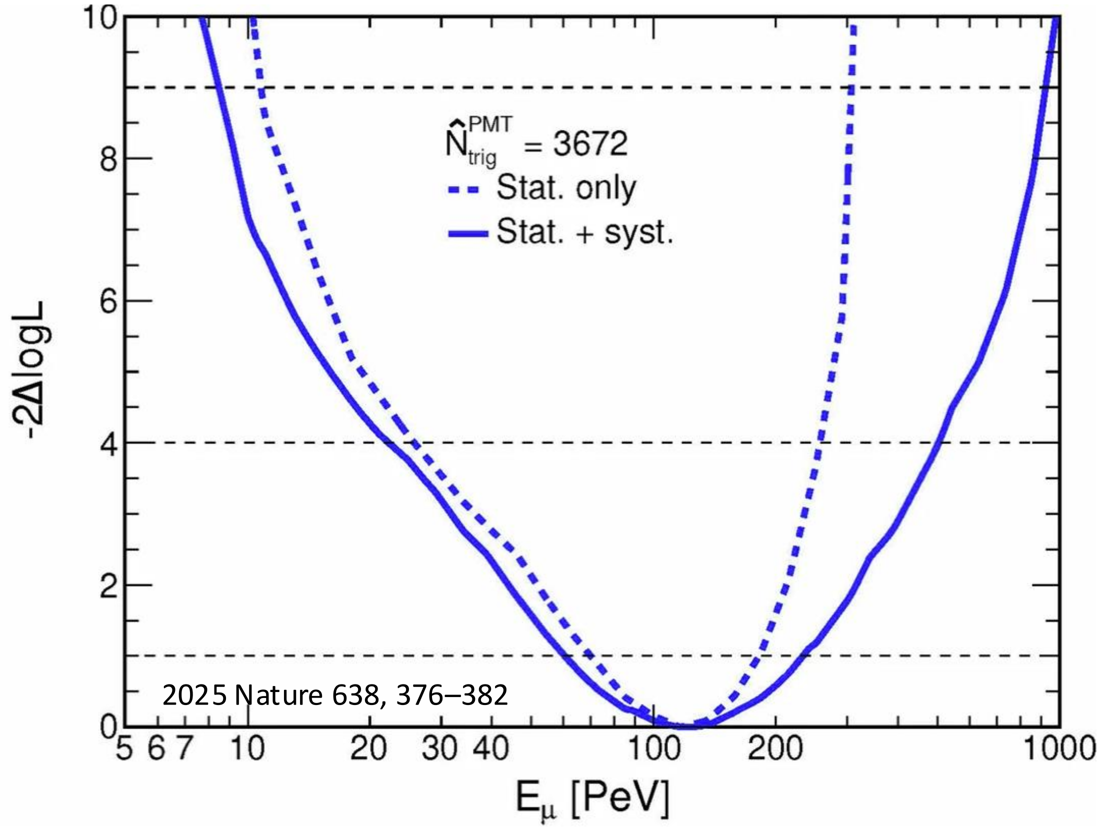




Lu, Yuan, Publication in preparation

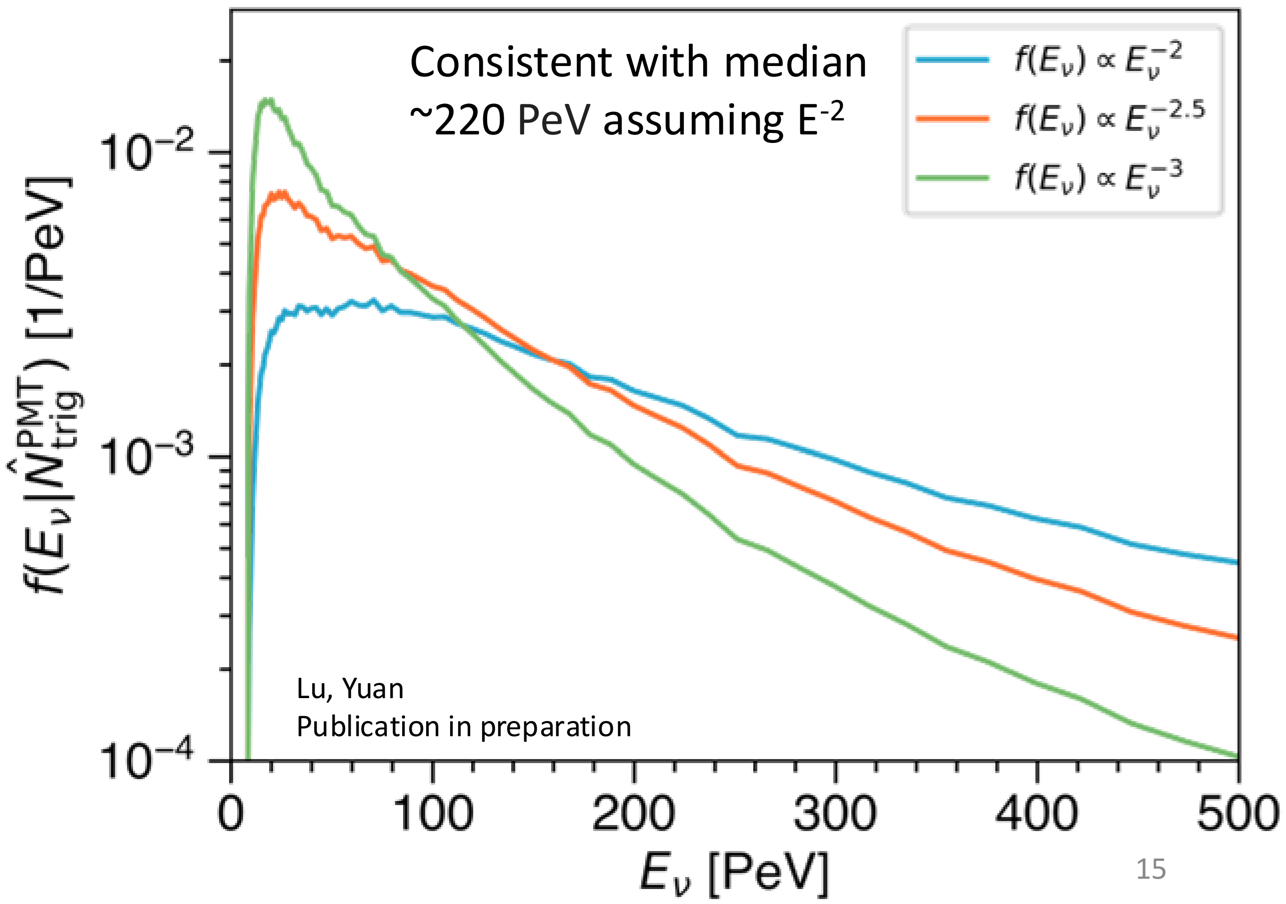
Understanding the KM3-230223A

Muon energy reconstruction: frequentist likelihood with no prior assumed -> spectrum dependencies ignored



Neutrino energy reconstruction:

Energy highly depends on assumed astrophysical flux shape

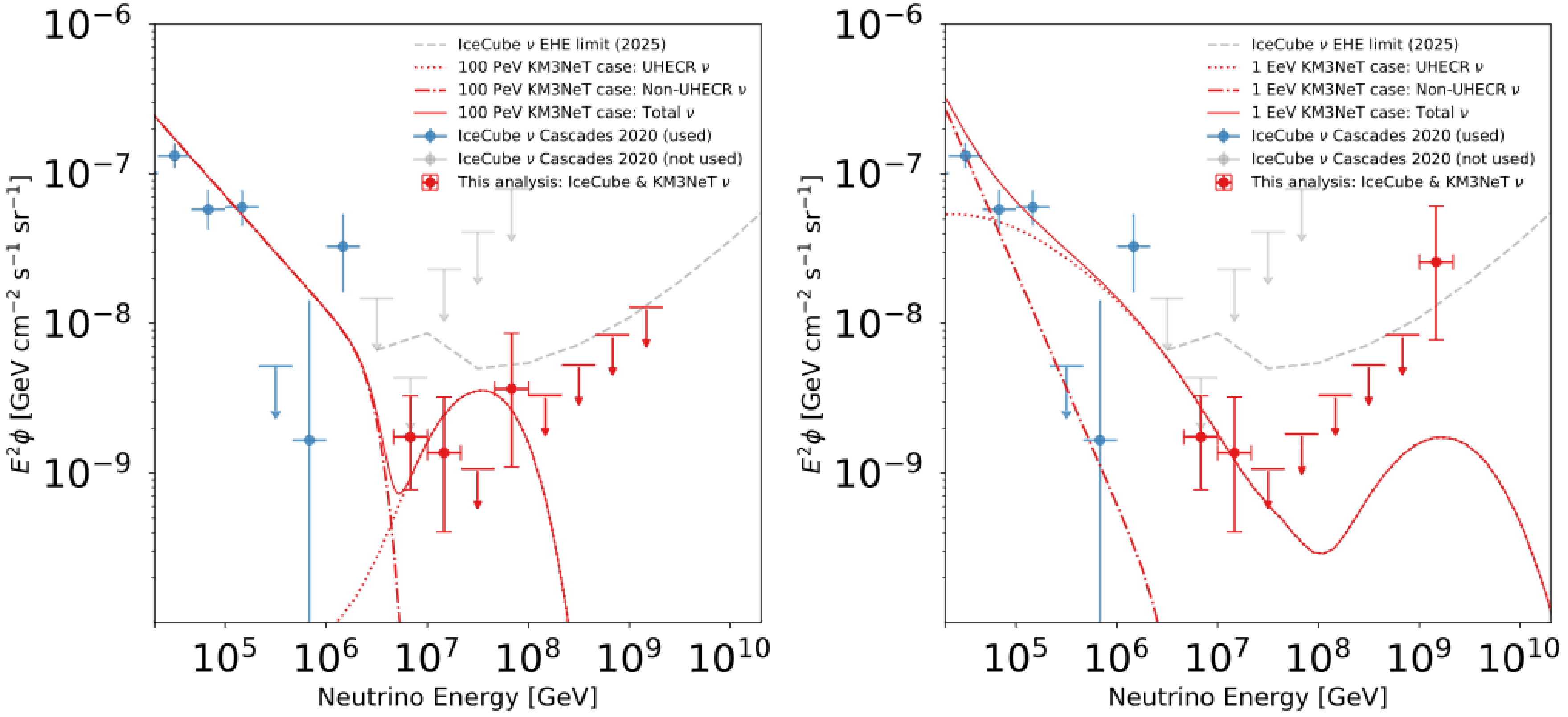


Tension and possible origins

- KM3NeT–only flux ($E^2\Phi = 5.8 \cdot 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}) expect >70 events 72 TeV – 2.6 EeV from IceCube’s EHE analysis (2025 PRL 135 031001)
- Combined analysis (IceCube + KM3NeT + Pierre Auger): Tension reduces to ~2–3σ. (arXiv:2502.04508, 2025 PRX 15 031016)

Possible origin of the event:

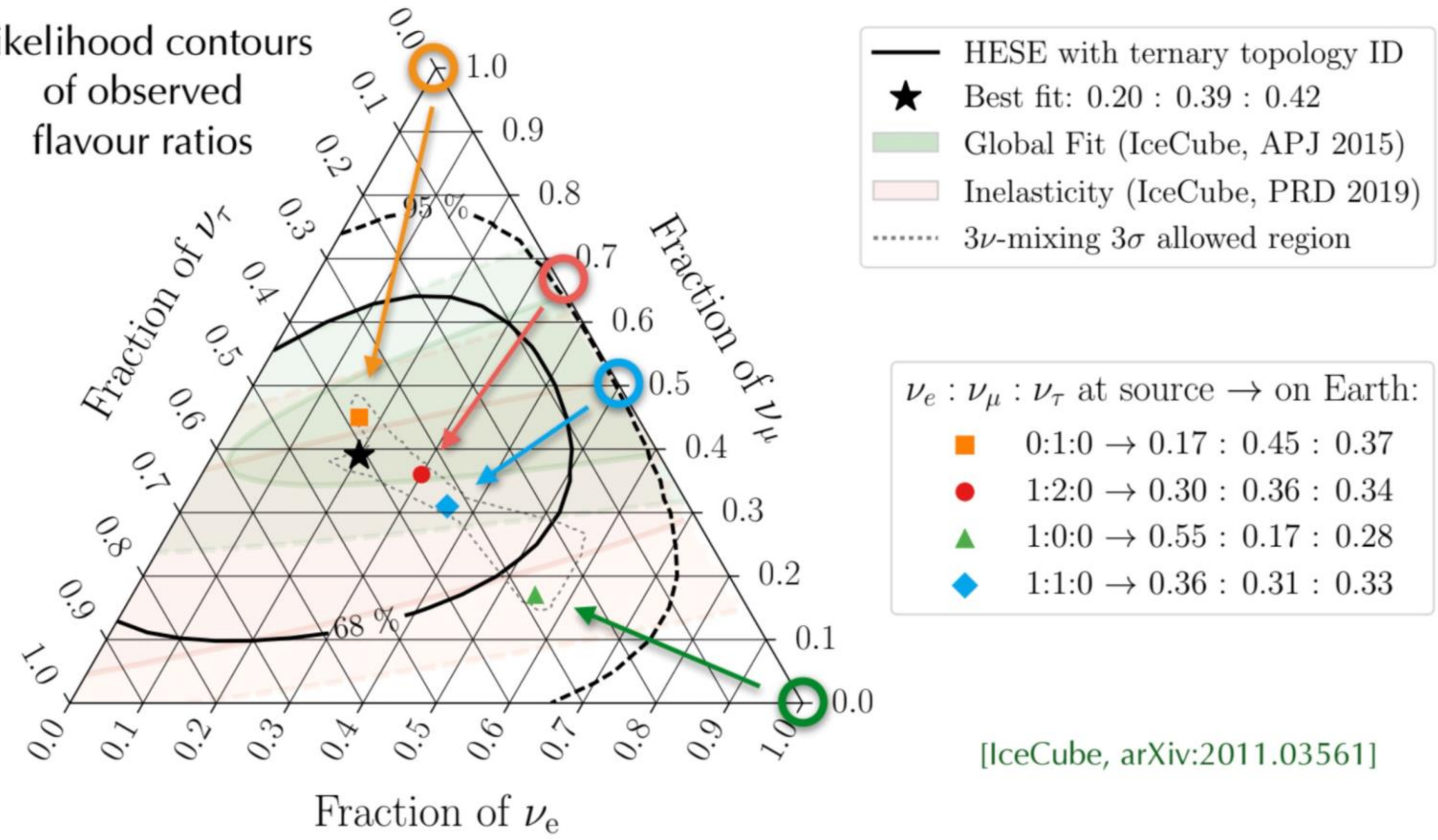
- p–γ at source: bump from the at around 30 PeV
- GZK cosmogenic neutrino



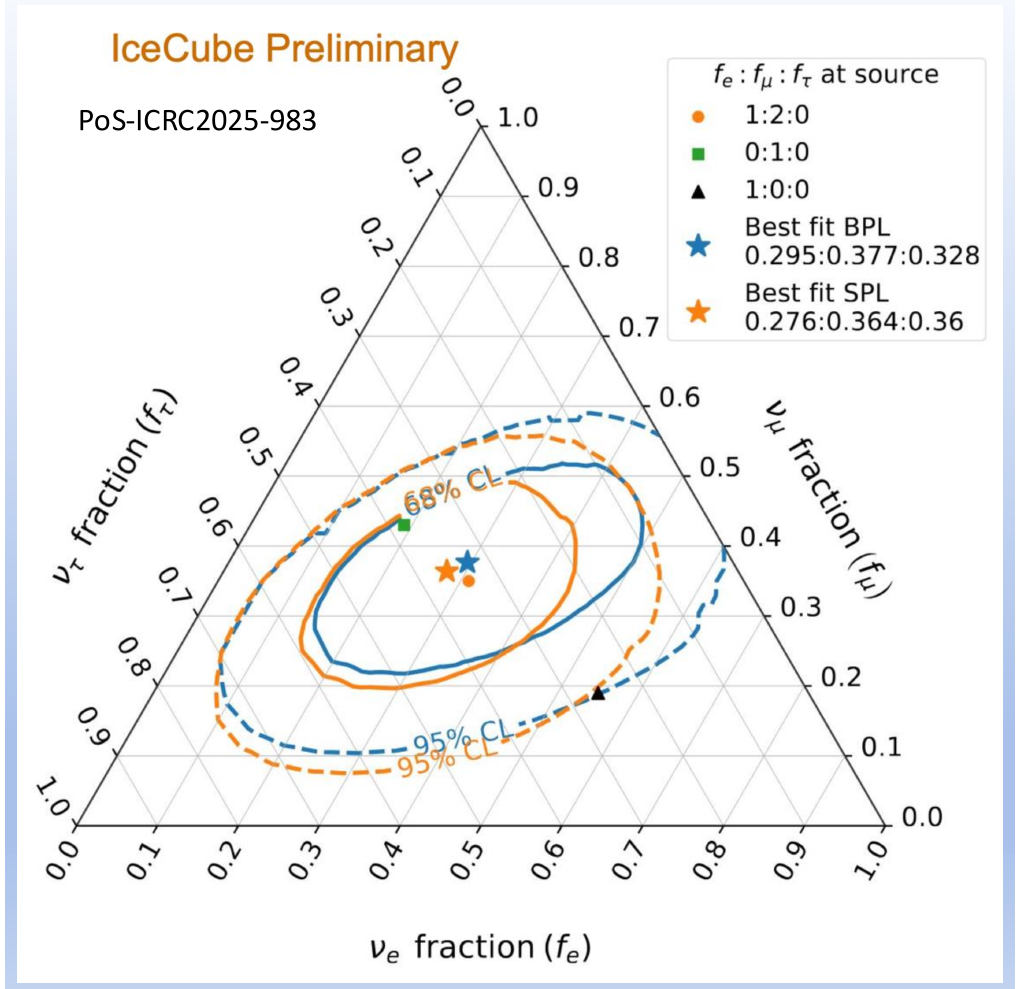
Muzio, Yuan, Lu arXiv:2502.06944

Flavour composition measurements

Likelihood contours of observed flavour ratios



[IceCube, arXiv:2011.03561]

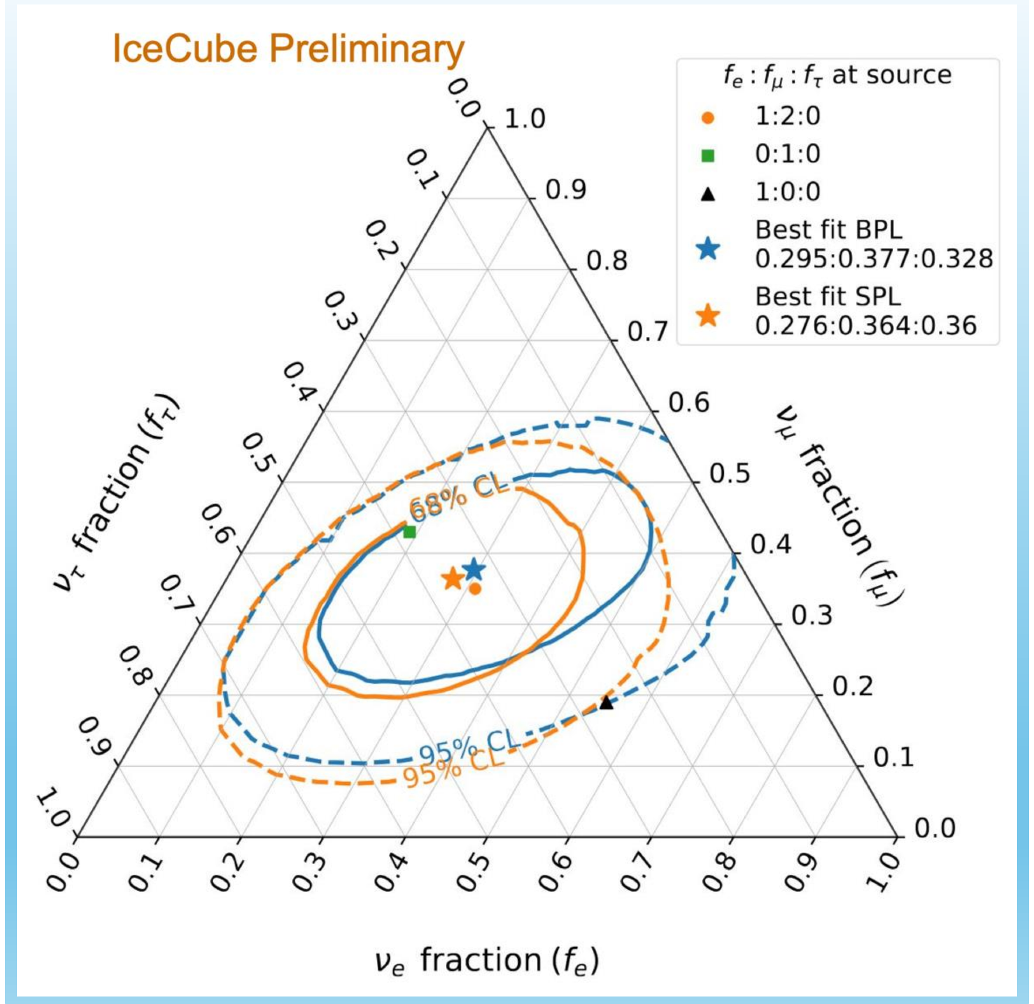


Pion-beam (π→μ→e) 1 : 2 : 0. **Muon-damped** 0 : 1 : 0. **Neutron-beam** 1 : 0 : 0. **Charm-prompt** 1 : 1 : 0.1

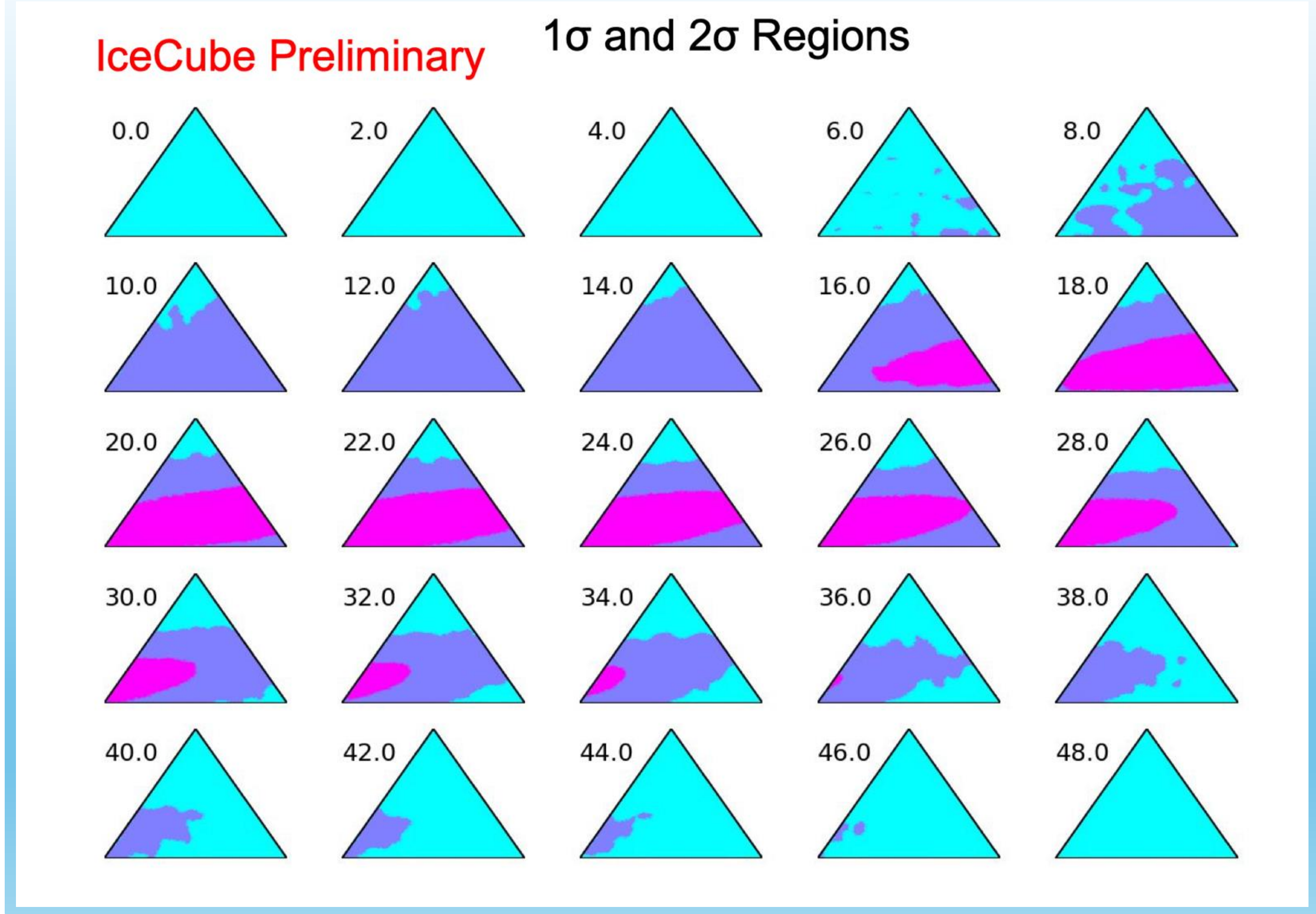
Flavour

- Direct tau event search: 7 candidates identified via neural networks (2024 PRL 132, 151001)
- Flavor composition: measured for extragalactic and galactic (PoS-ICRC2025-983, Hardin at 2025 CIPANP)

Extragalactic

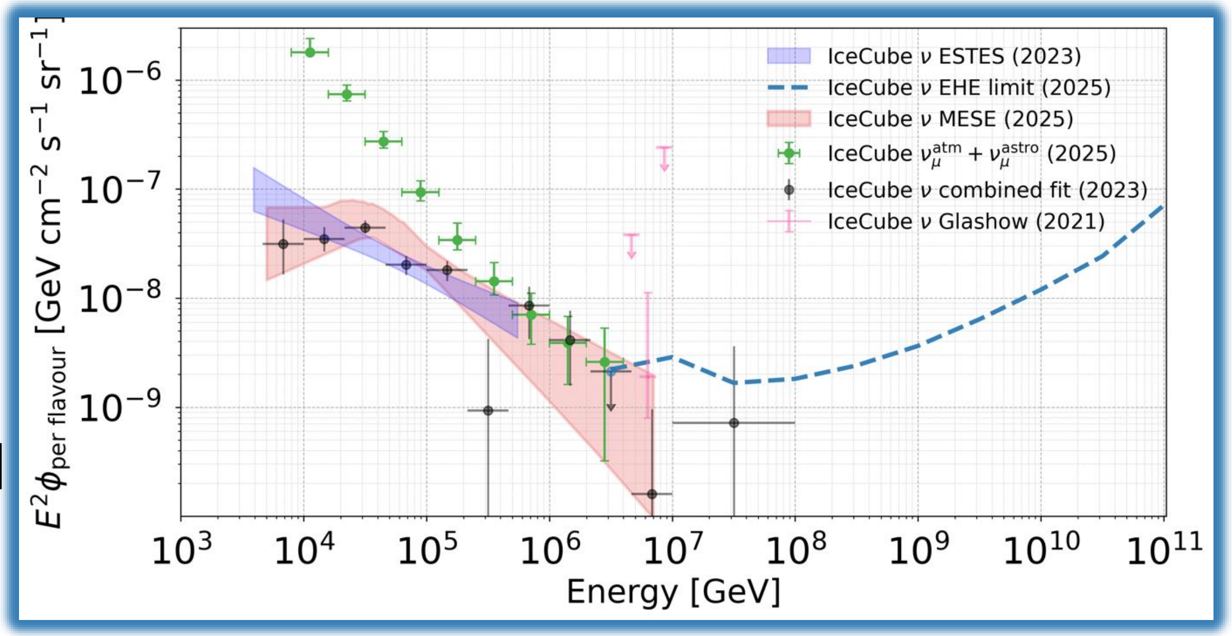


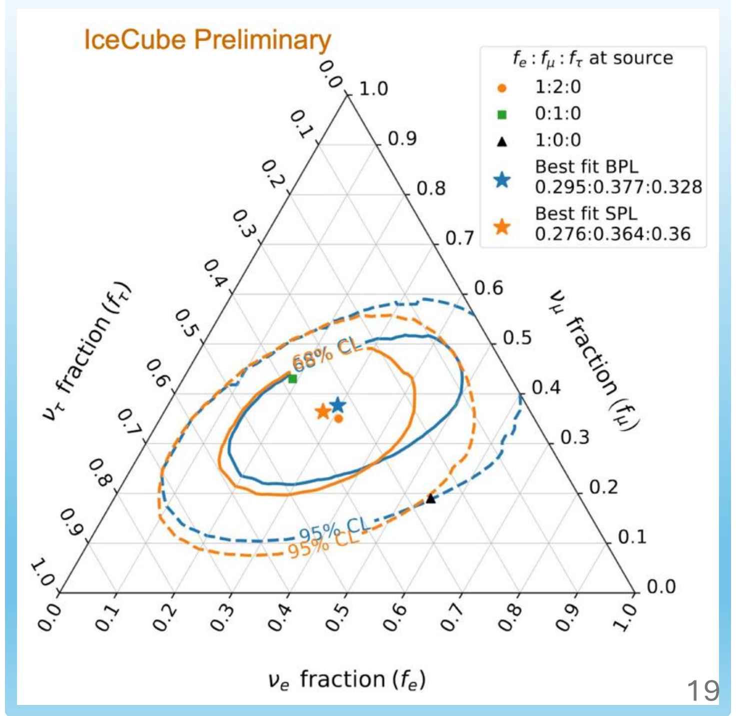
Galactic



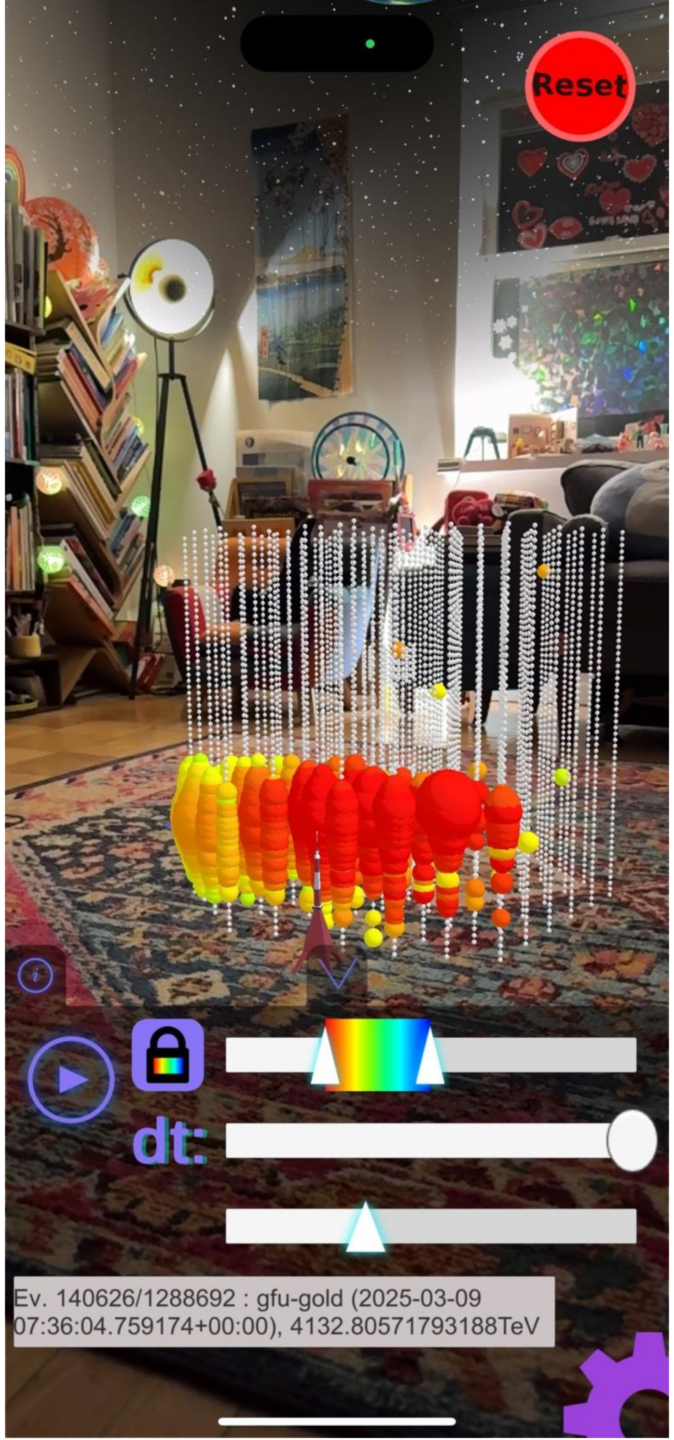
Conclusion

- 1-10 TeV: Shower events indicate a deviation from a single power law, possibly linked to gamma-ray–obscured sources.
- > 10 PeV: More statistics are needed to distinguish scenarios and assess consistency with the KM3NeT candidate.
- Flavour composition: Measurements are beginning to exclude regions predicted by beyond-Standard-Model scenarios.





- Galactic diffuse measurements: see talk from Tianlu Yuan (Thurs)
- Future prospects of high energy diffuse measurements from IceCube: see talk from Emre Yildizci (Wed)



Receive IceCube alerts

- GCN notice and circular
- **Augmented Reality** app (ICEcuBEAR) on Android and iOS.