

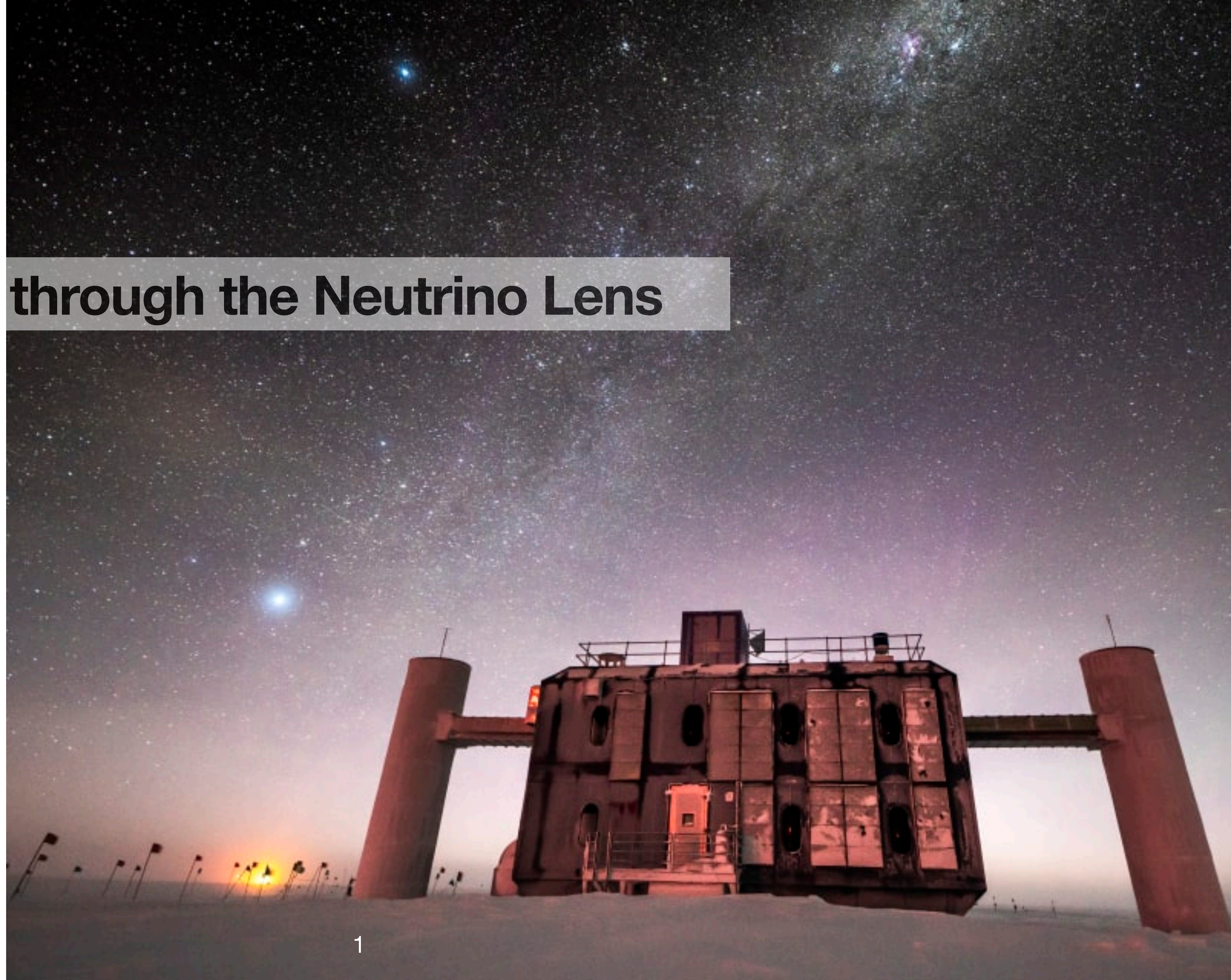
Galactic PeVatrons through the Neutrino Lens

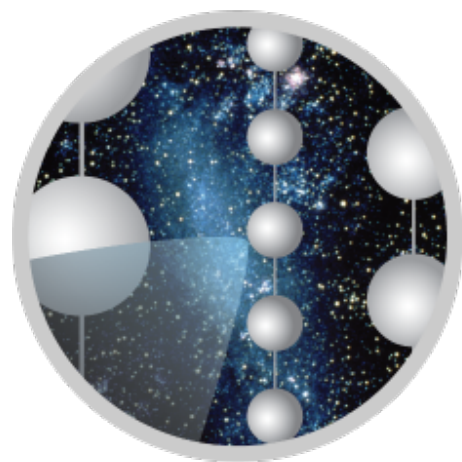
Ke Fang

University of Wisconsin-Madison

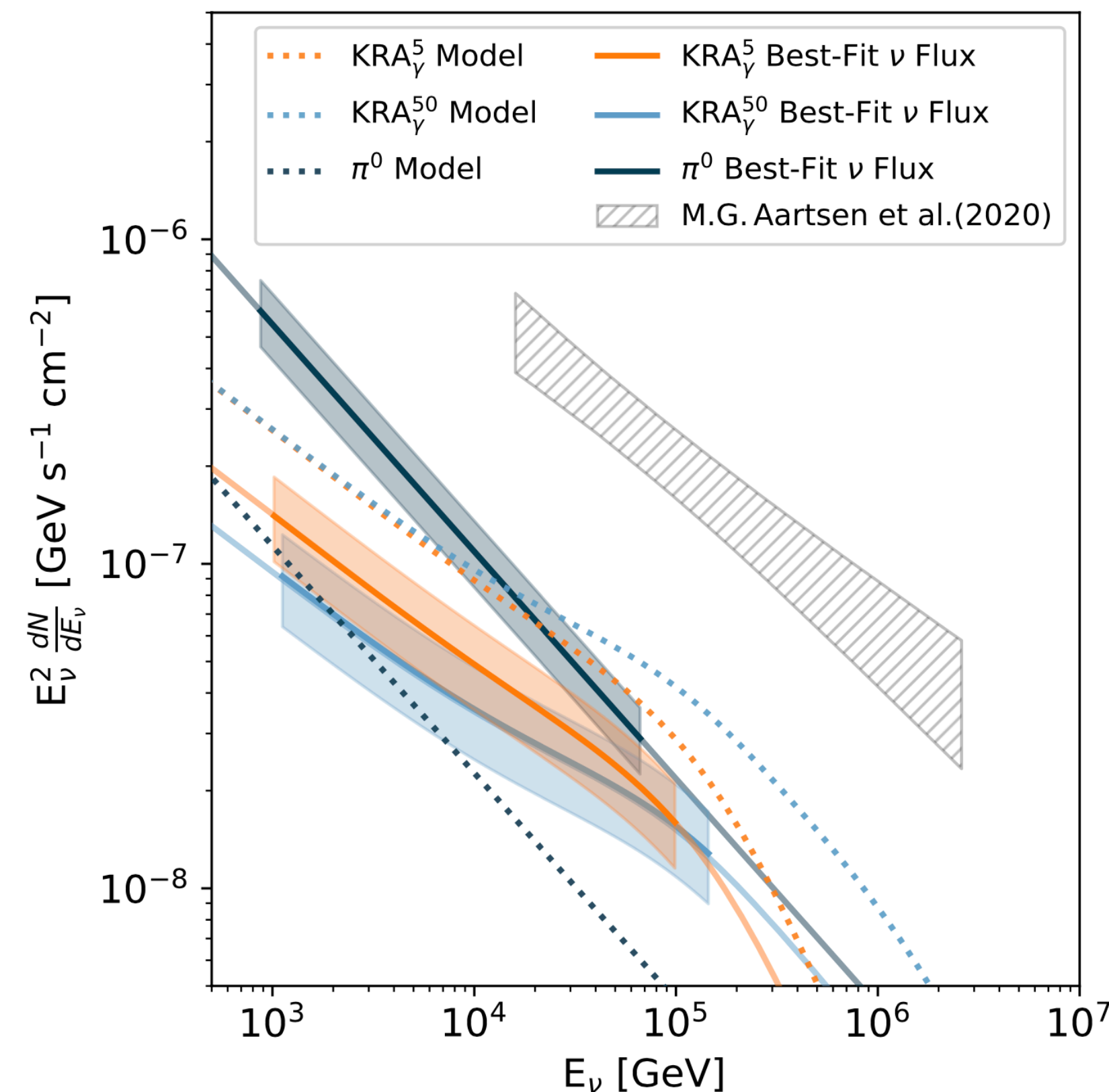
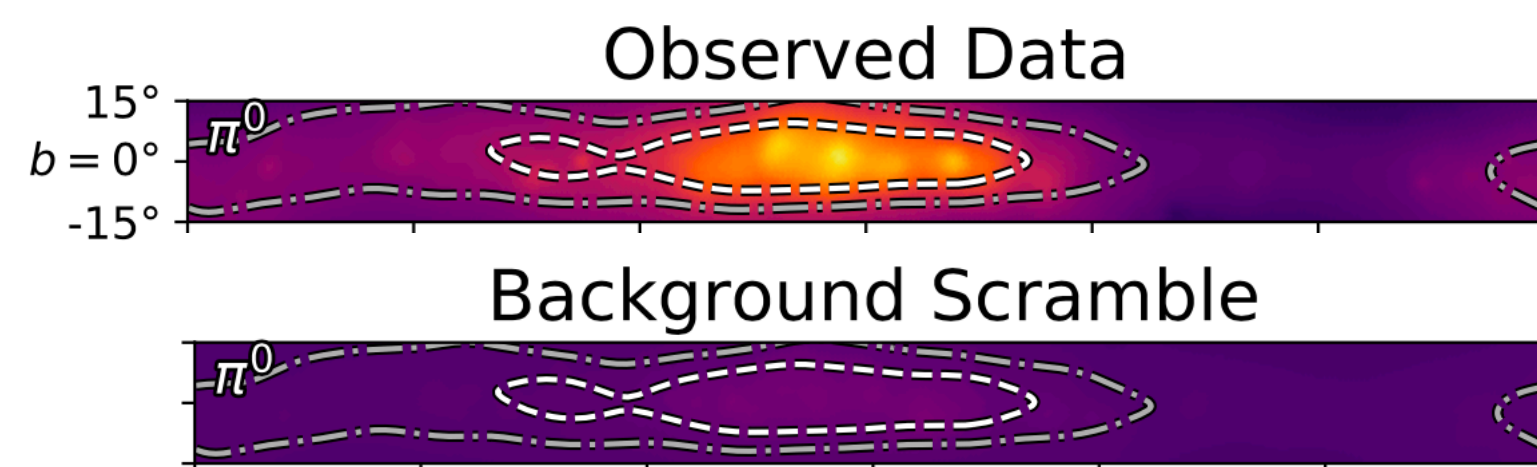
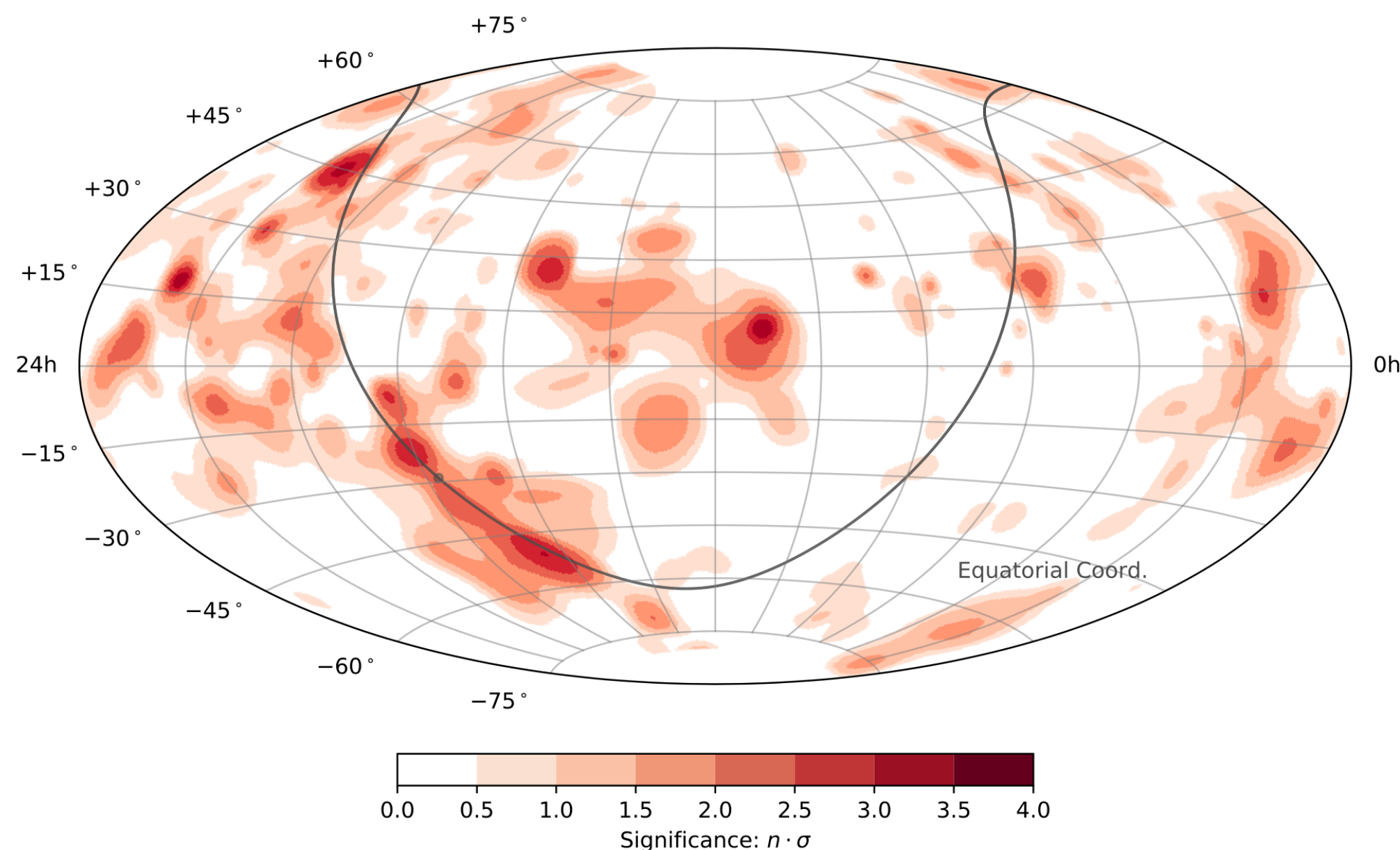
CDHY PeVatron Workshop

Oct 10, 2025





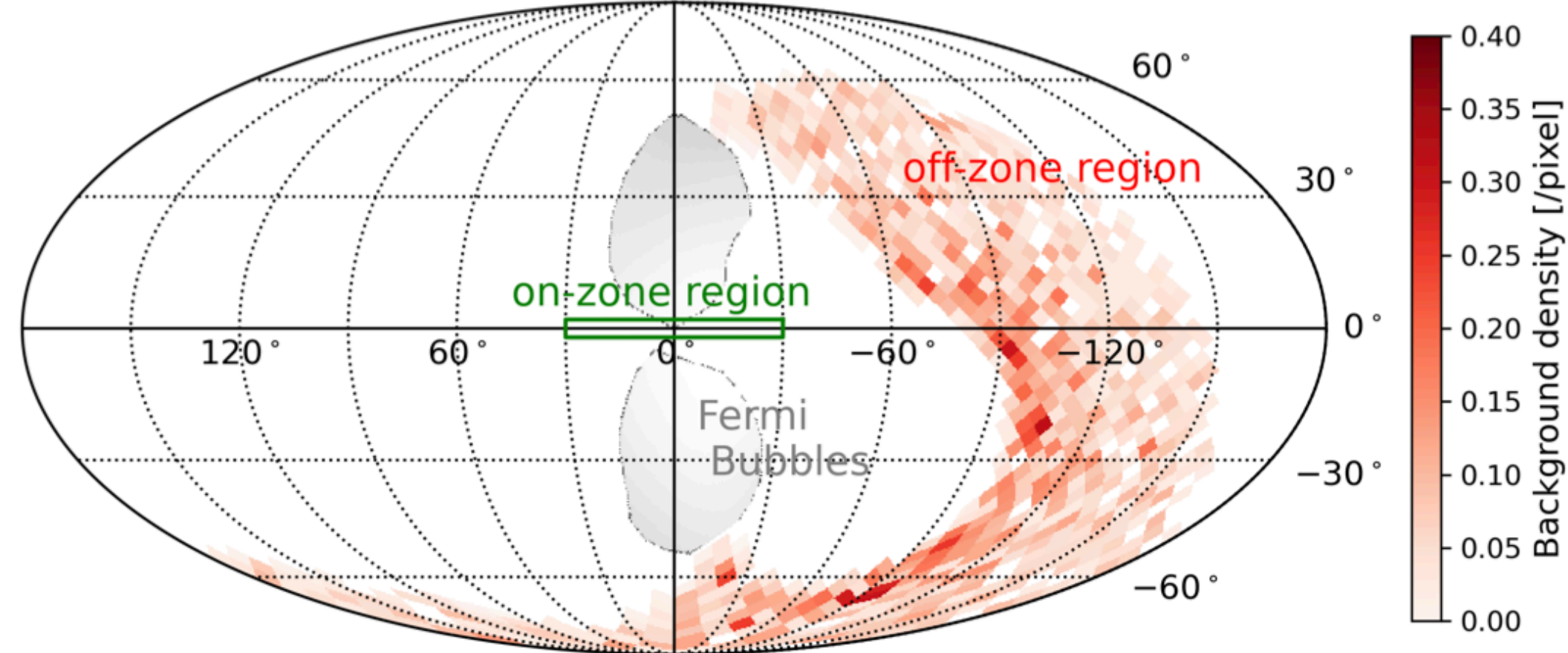
High-energy Neutrino from the Galactic Plane



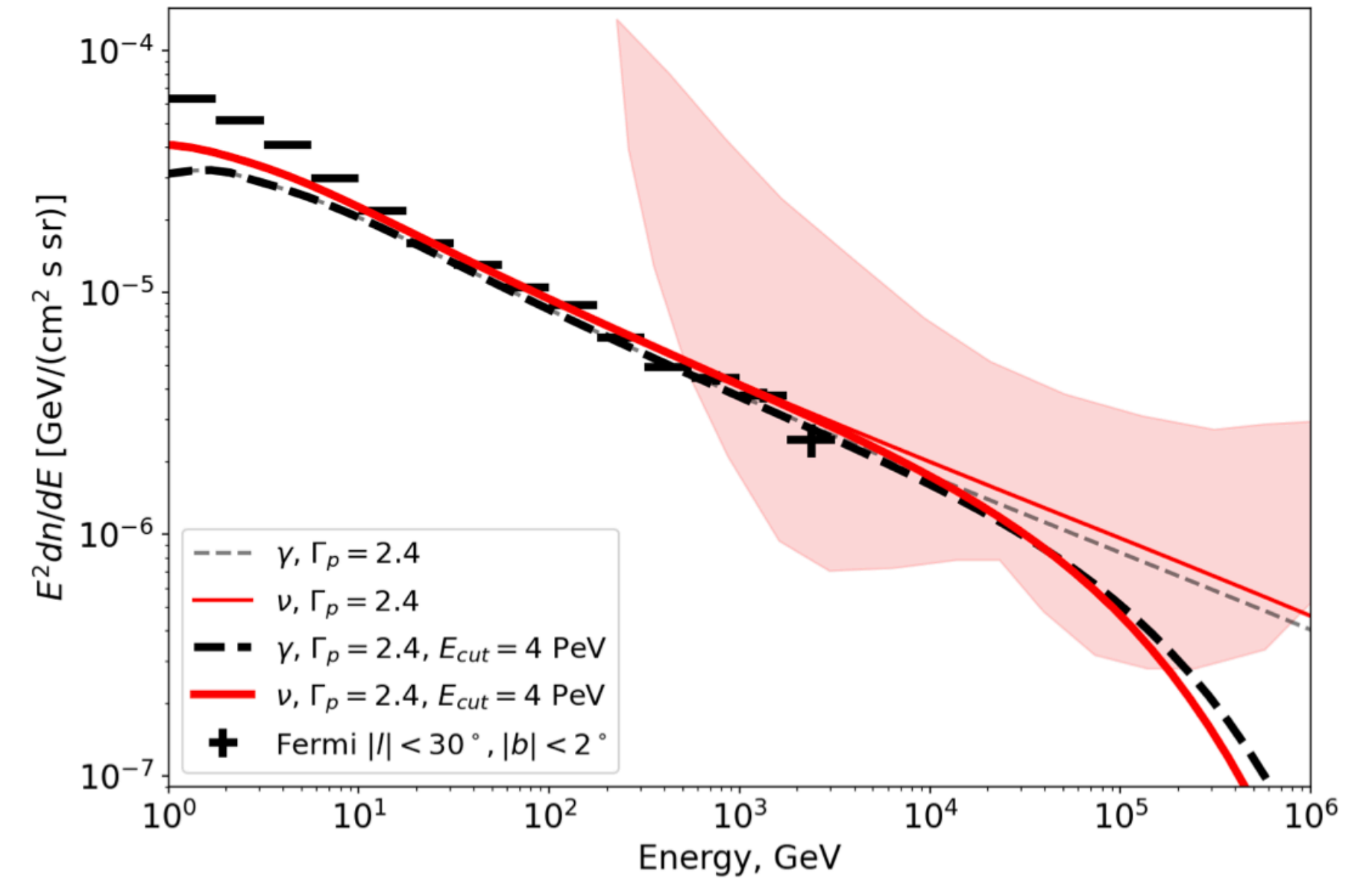
4.5 σ rejection of the background-only hypothesis
Strong evidence for the Milky Way as a source of high-energy neutrinos

IceCube Coll, *Science* (2023)

Hint of TeV Neutrino from the Galactic Ridge



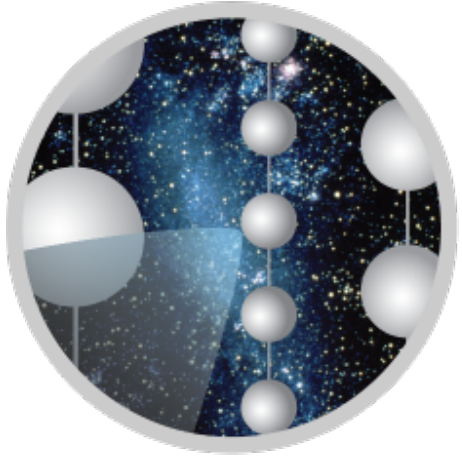
Galactic Ridge defined as $|l| < 30^\circ$, $|b| < 2^\circ$



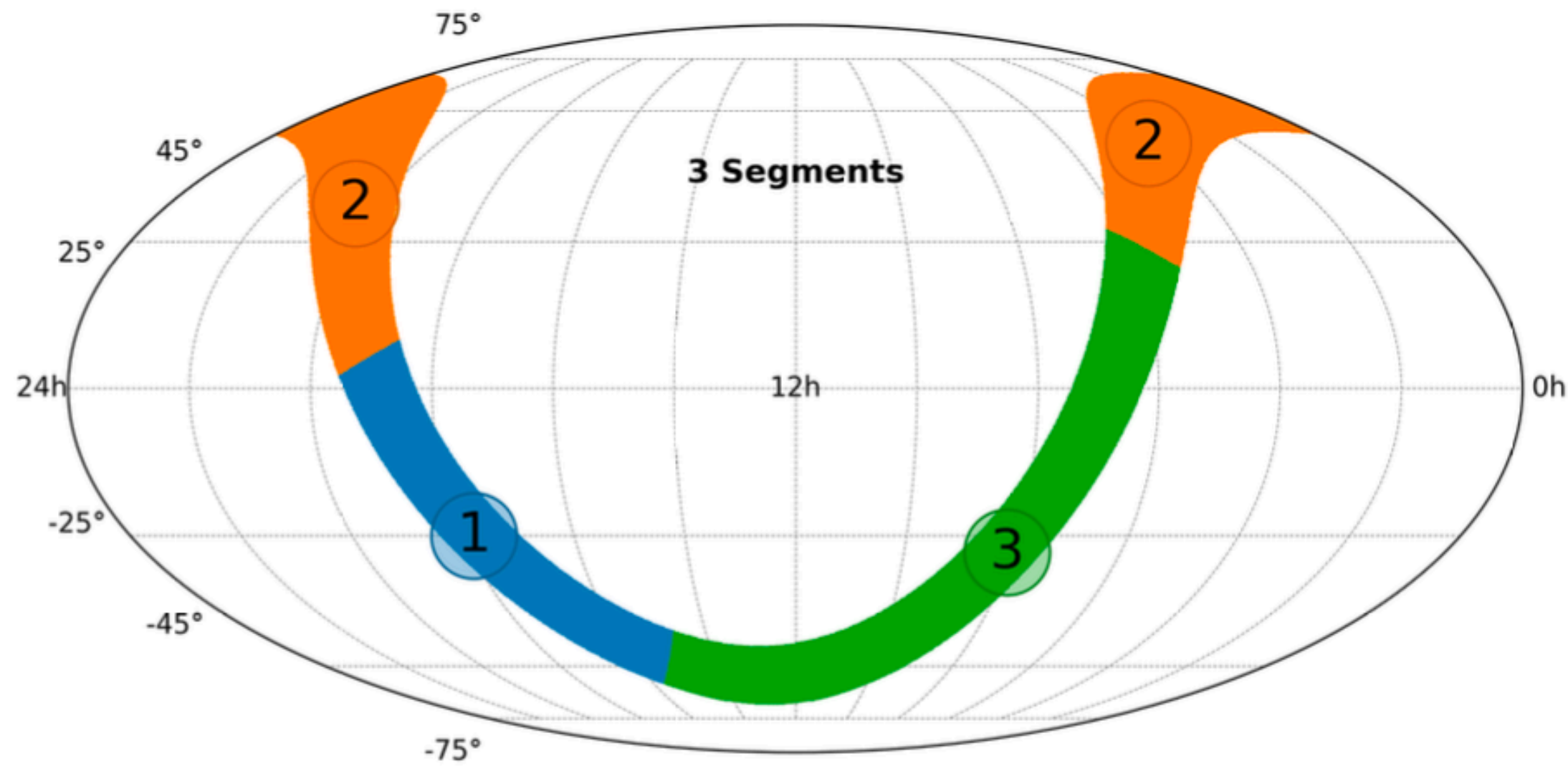
Background-only hypothesis is rejected at 96% confidence level (2.0σ)

The flux is **consistent with diffuse emission** by the cosmic-ray sea interacting with ISM in the region

ANTARES Collaboration, *Physics Letter B* (2023)



Segmented Galactic Neutrino Flux

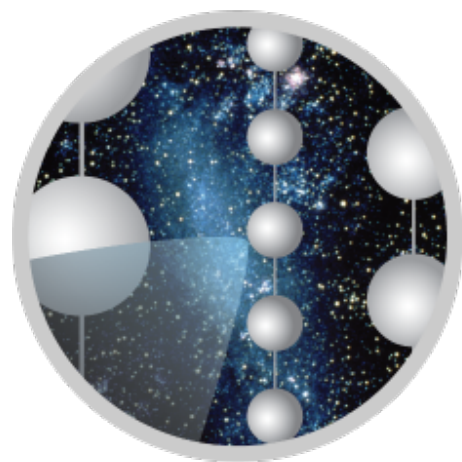


(a) The 3 segments “generic” segmentation scheme.

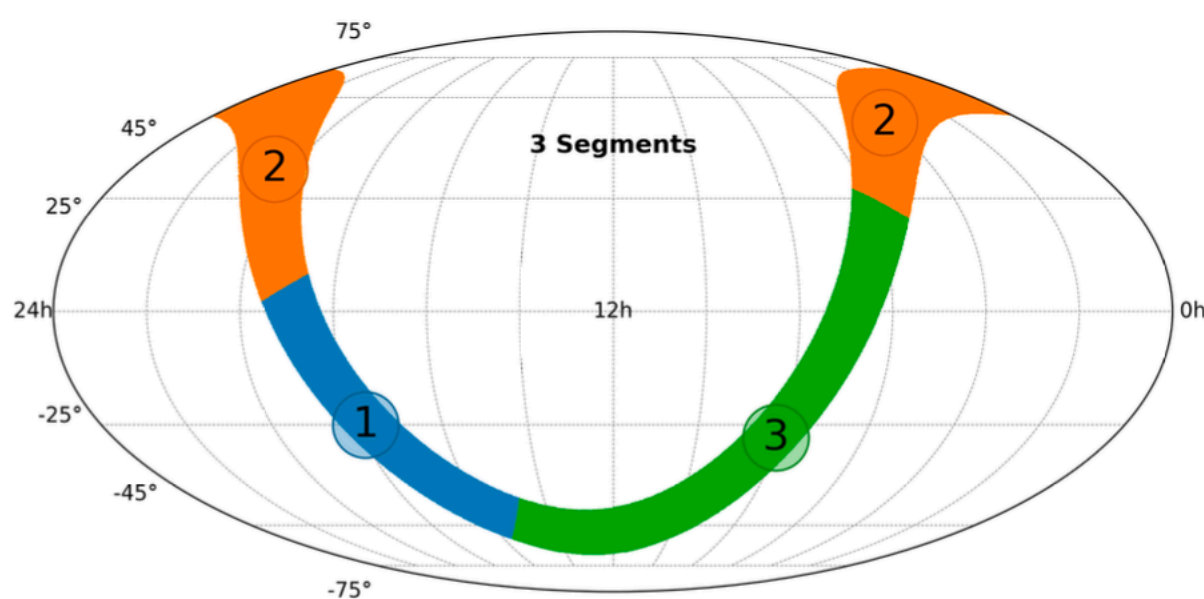
- Characterizing Galactic neutrino emission by dividing the galactic plane into **segments in galactic longitude**
- Full-sky **cascade dataset** as in the first Galactic plane analysis
- Assume uniform emission in each segment. Result **does not depend on spatial templates** of the diffuse emission

$$\mathcal{L}(n_1, \dots, n_M, \gamma_1, \dots, \gamma_M) = \prod_{i=1}^N \left[\frac{1}{N} \sum_{k=1}^M n_k S_i^k(E_i, \delta_i, \alpha_i, \sigma_i, \gamma_k) + \frac{N - n_s}{N} B_i^{\text{SigSub}}(E_i, \delta_i, \gamma_k) \right]$$

PoS-ICRC2025-1130

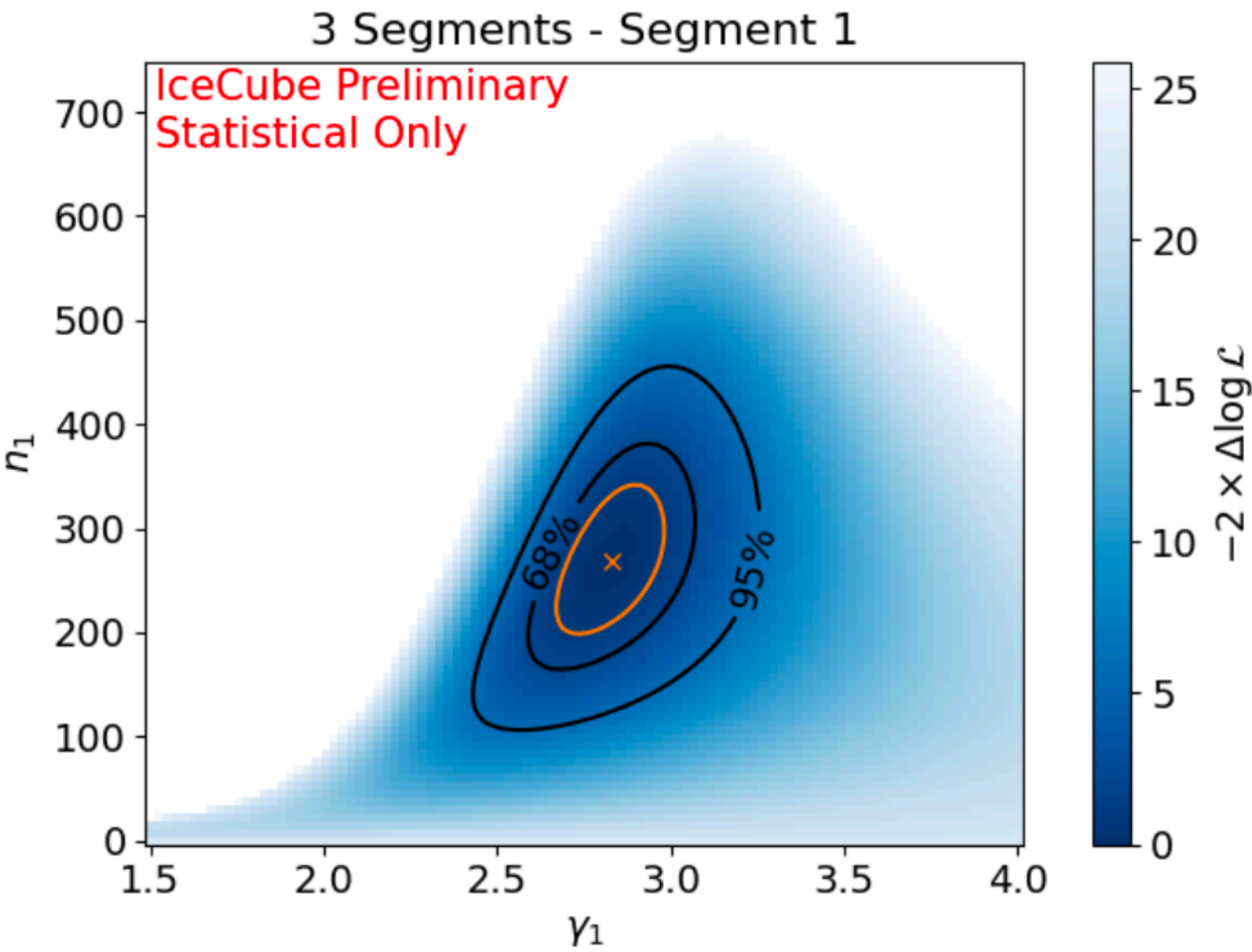


Segmented Galactic Neutrino Flux



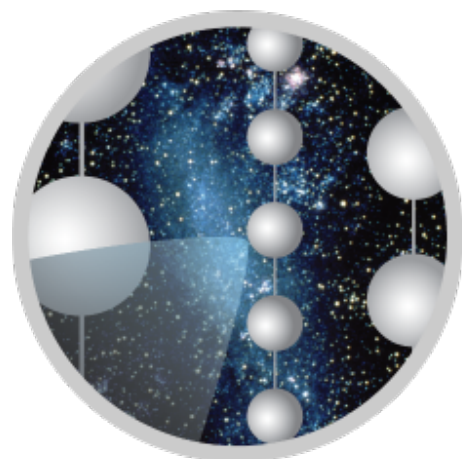
(a) The 3 segments “generic” segmentation scheme.

Scheme	Segment k	$l_{\min}$	$l_{\max}$	Significance	$n_s = \sum_k n_k$
2 Segments	1	-60°	60°	3.81σ	643
	2	60°	-60°		
3 Segments	1	-40°	40°	3.84σ	643
	2	40°	180°		
	3	-180°	-40°		
6 Segments	1	-30°	30°	3.58σ	808
	2	30°	90°		
	3	90°	150°		
	4	150°	-150°		
	5	-150°	-90°		
	6	-90°	-30°		

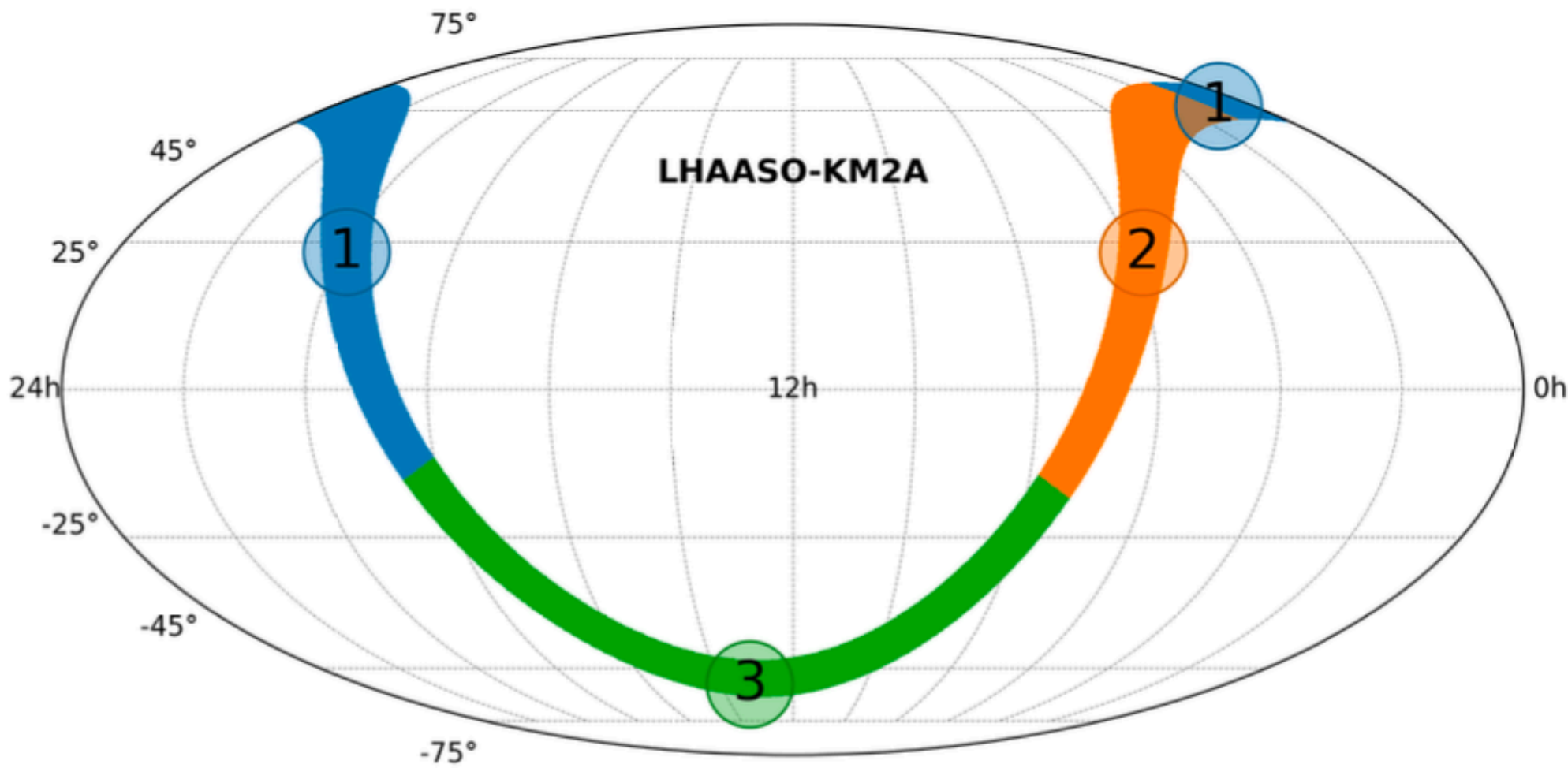


- Most significant scheme is with 3 segments
- Flux and index of each segment in the schemes are reported

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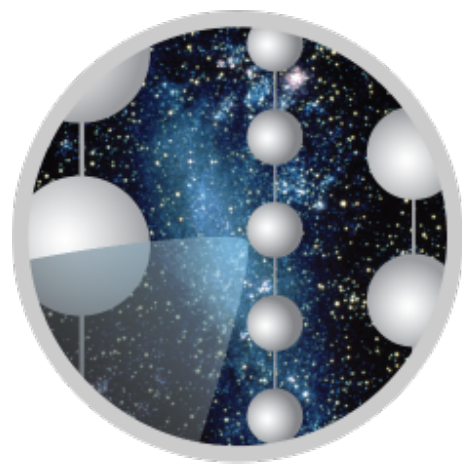
Segmented Galactic Neutrino Flux



(b) Scheme aligning with the LHAASO GP analysis region.

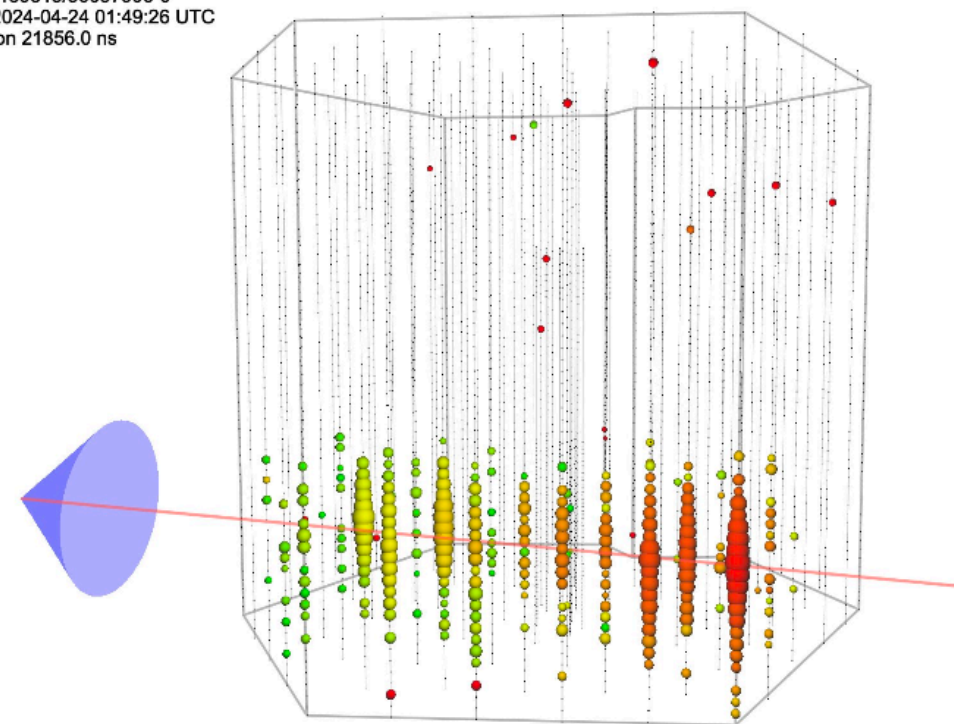
Experiment	$l_{\min}$	$l_{\max}$	$ b _{\max}$	Significance	$n_s = \sum_k n_k$
HAWC [3]	43°	73°	5°	3.01 σ	664
H.E.S.S. [13]	-110°	65°	3°	3.06 σ	569
LHAASO [1, 14]	15°	125°	5°	} 2.73 σ	371
	125°	-55°	5°		
Tibet AS γ I [2]	25°	100°	5°	2.96 σ	660
Tibet AS γ II [2]	50°	200°	5°	2.98 σ	626

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Multi-flavor Neutrino Measurement of the Galactic Plane

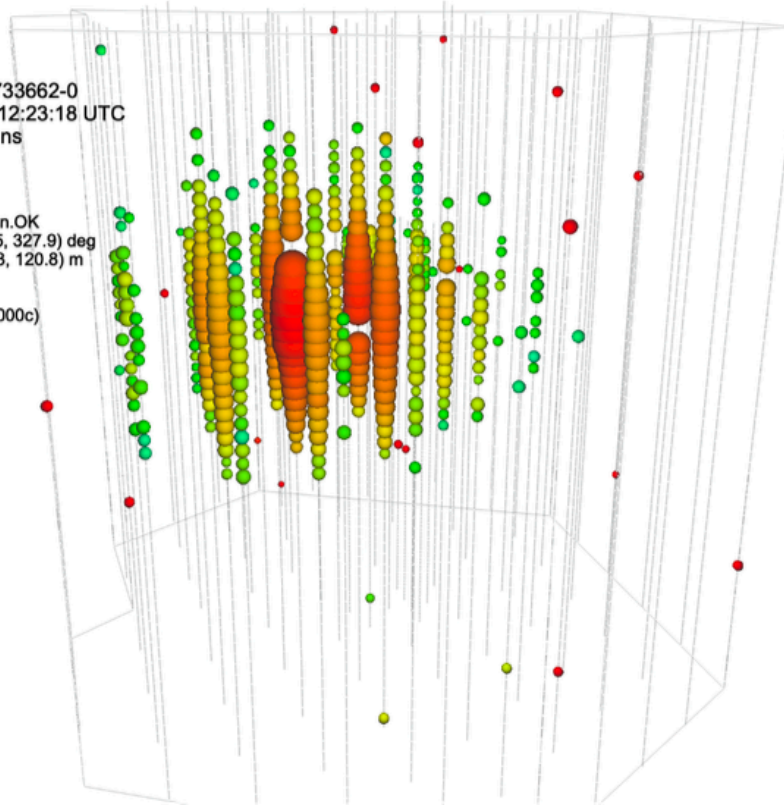
Event 139315/50057906-0
Time 2024-04-24 01:49:26 UTC
Duration 21856.0 ns



(a) Example through-going track event

Event 118545/63733662-0
Time 2011-08-09 12:23:18 UTC
Duration 19851.0 ns

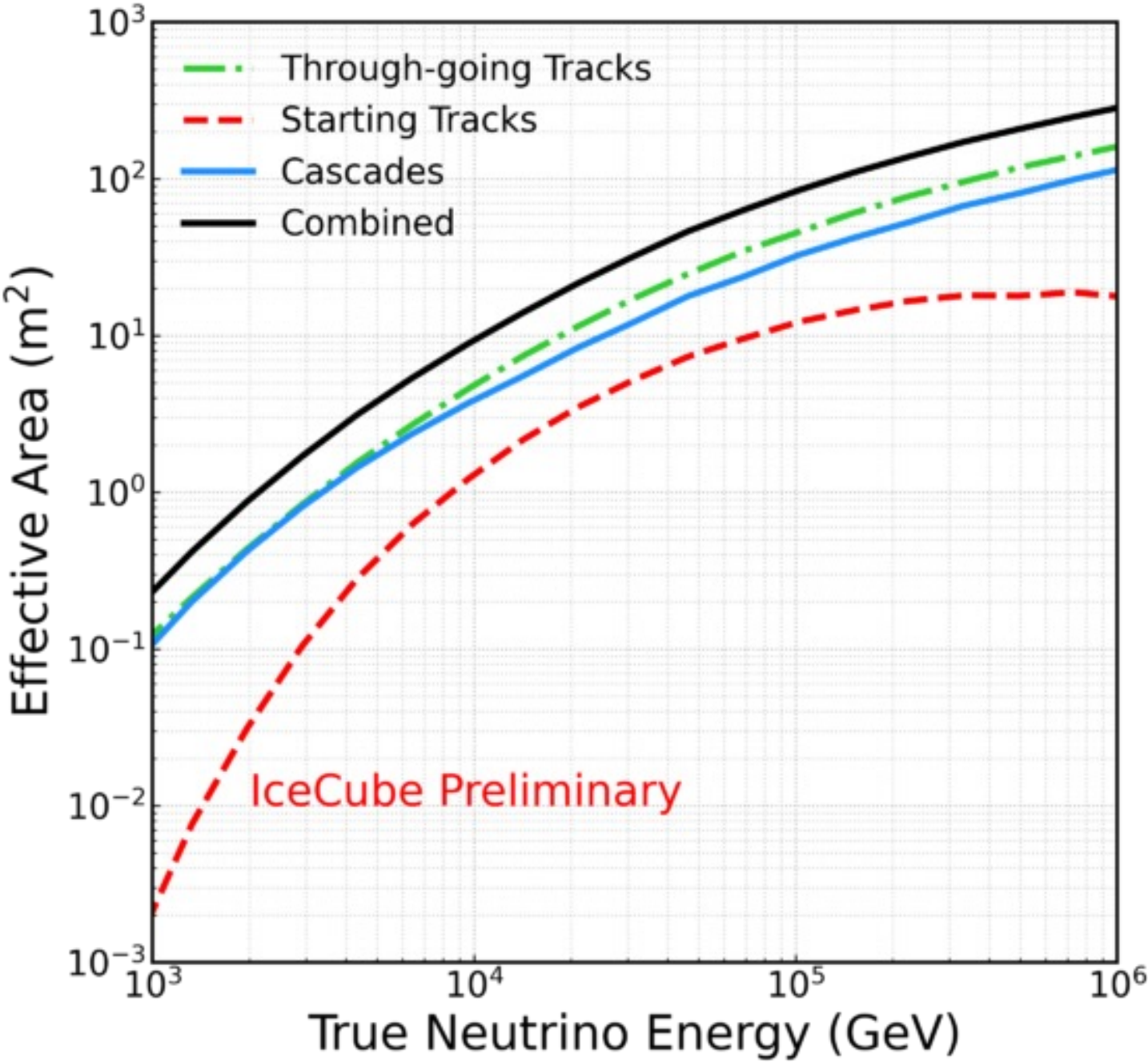
PreferredFit:
Type/Status: unknown OK
Zenith/Azimuth: (68.5, 327.9) deg
Vertex: (-201.1, 100.3, 120.8) m
Time: 9649.466 ns
Energy: 958 TeV
Speed: 0.299792 (1.000c)



(b) Example cascade event

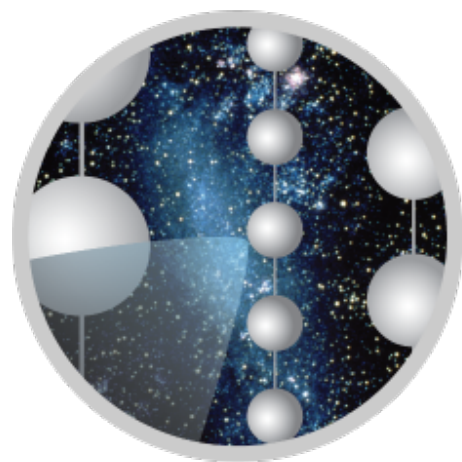
IceCubE Multi-flavour Astrophysical Neutrino source sample (ICEMAN v1)

Dataset	NT	ESTES	DNNC
Livetime	~13 years	12.14 years	12.12 years
Events	979227	12048	85754

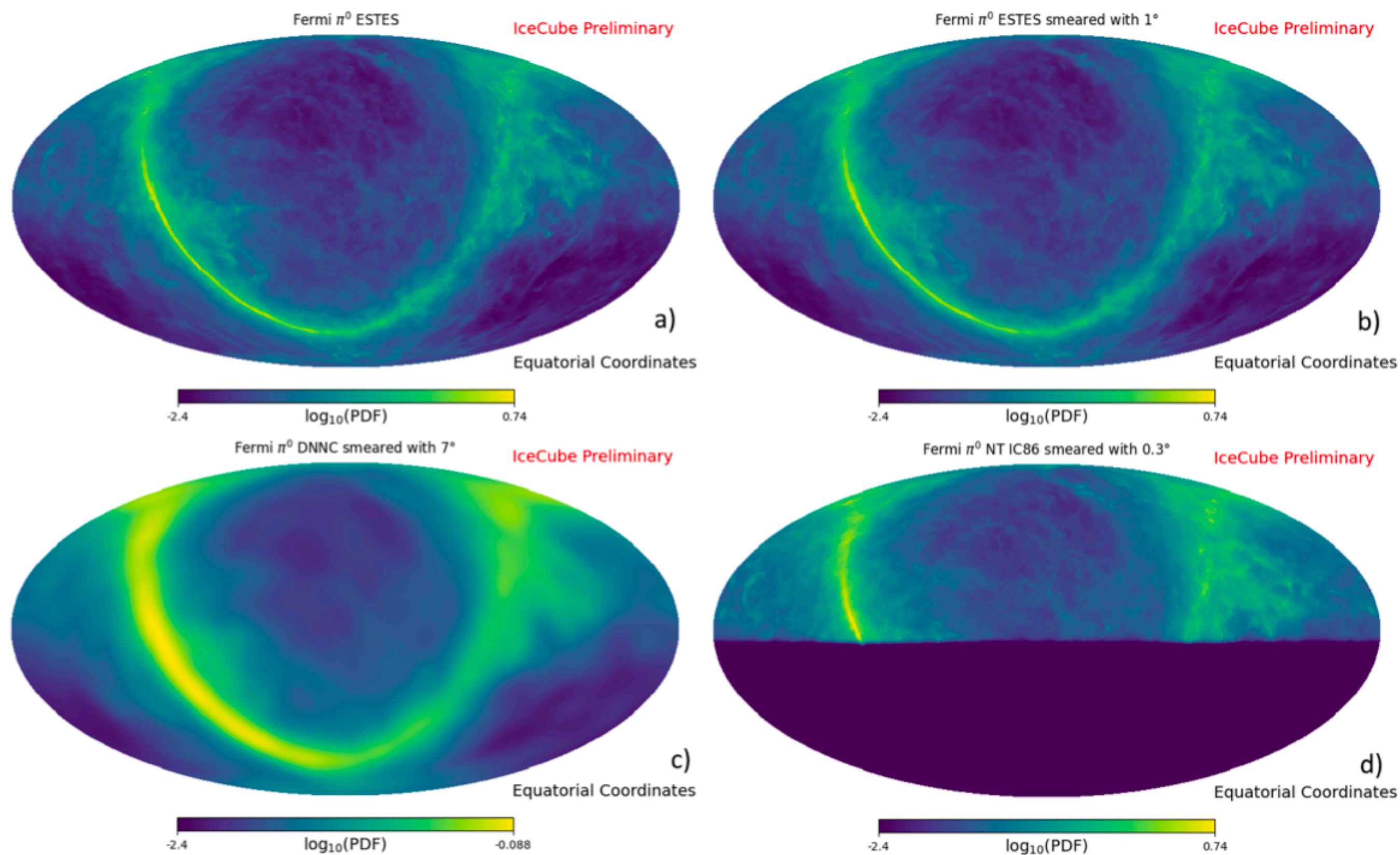


With further improvements in ice modeling Refs. [PoS ICRC2023 975](#), [JINST 19 P06026](#)

[PoS-ICRC2025-1193](#)

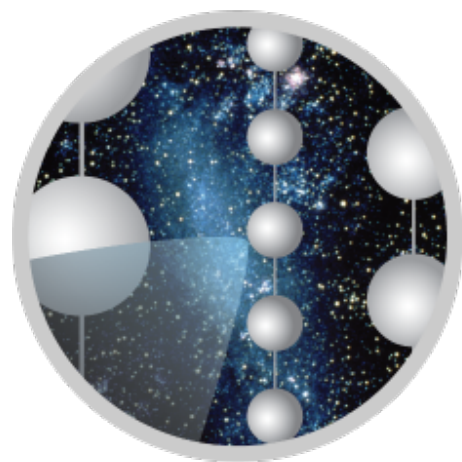


Multi-flavor Neutrino Measurement of the Galactic Plane

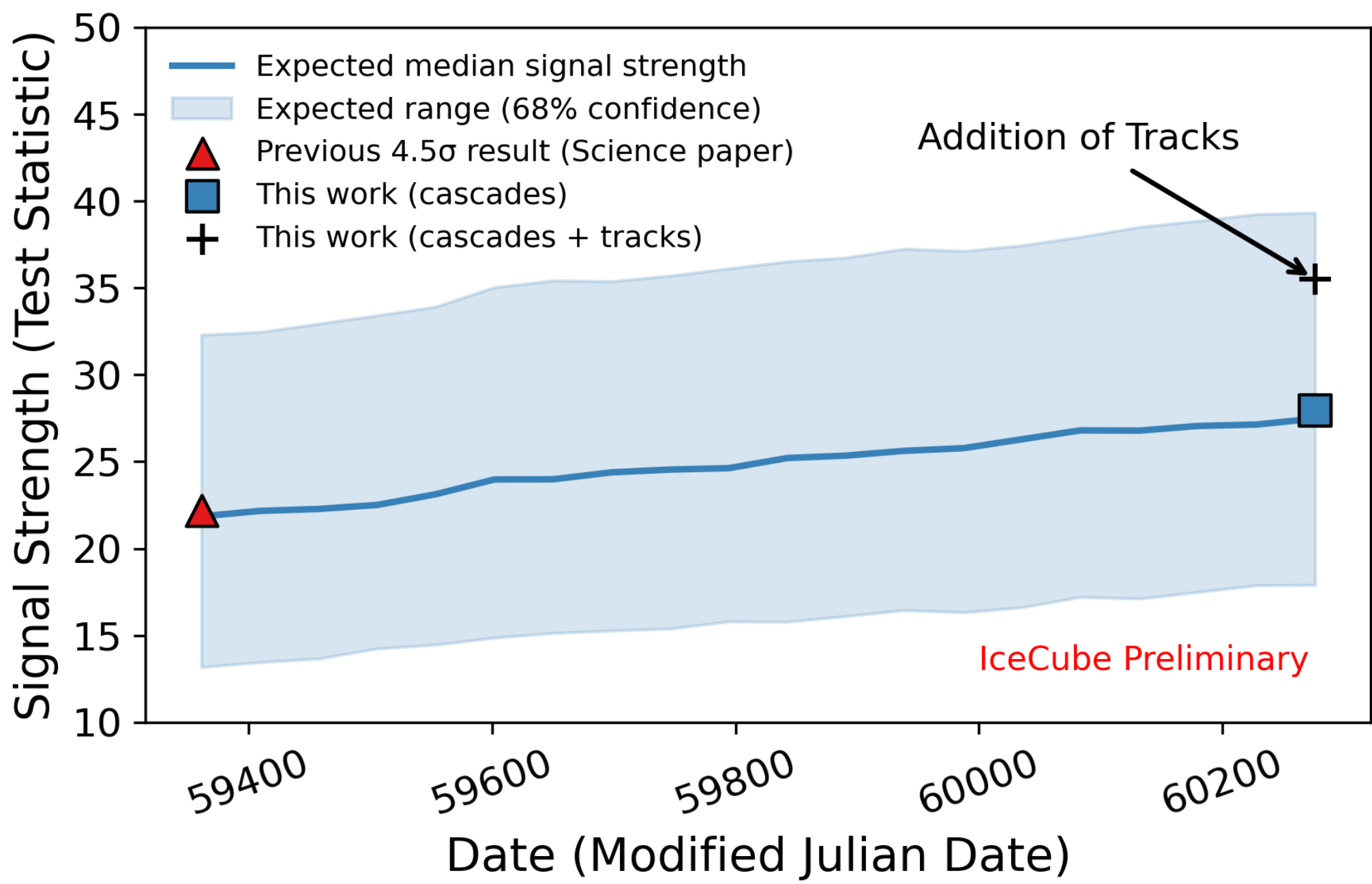


- Spatial signal PDF for each dataset.
- Smearing widths are chosen based on the median angular uncertainty of the signal events in the respective datasets
- The **addition of tracks enhances the sensitivity.**

PoS-ICRC2025-1193

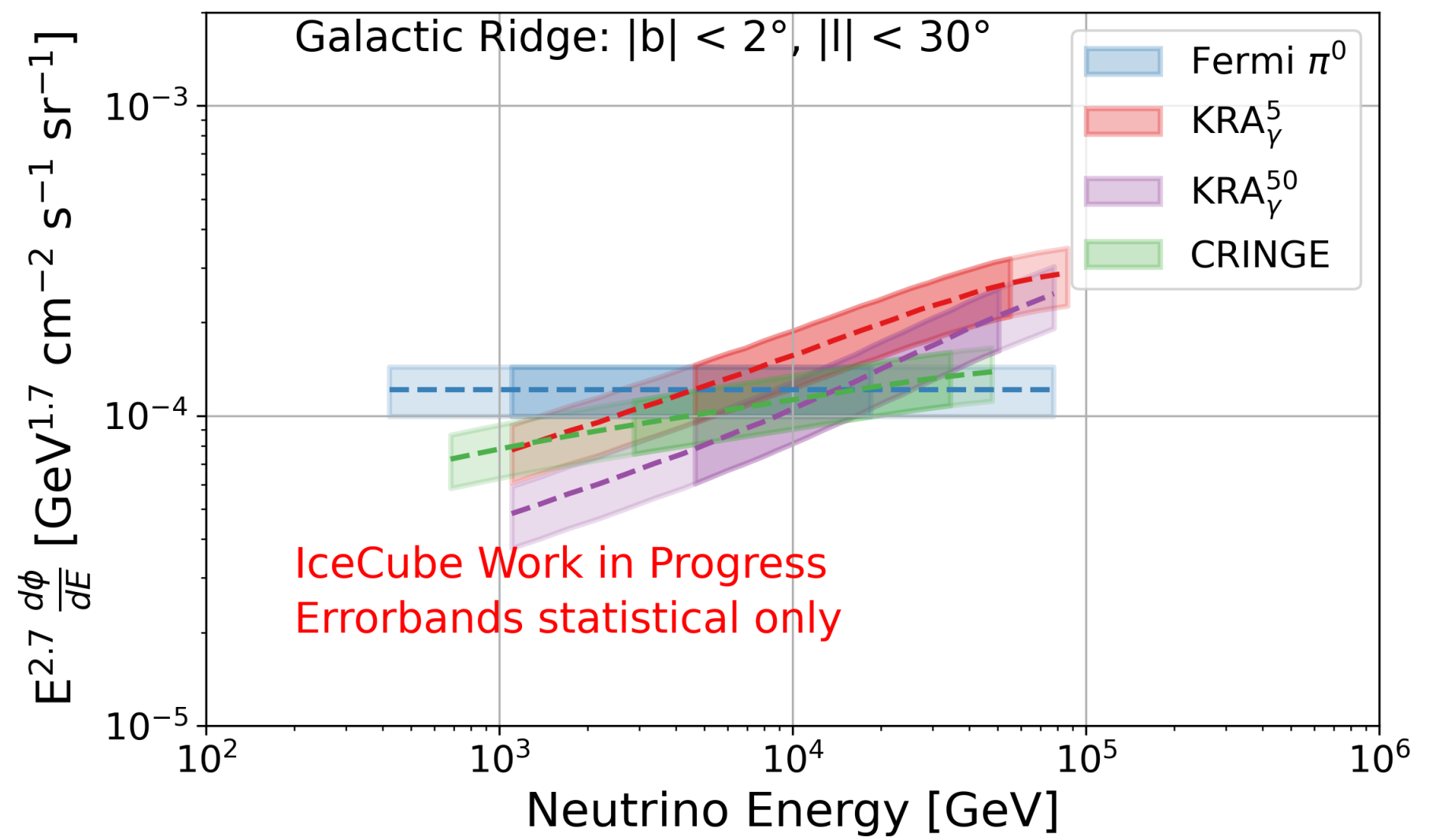


Multi-flavor Neutrino Measurement of the Galactic Plane



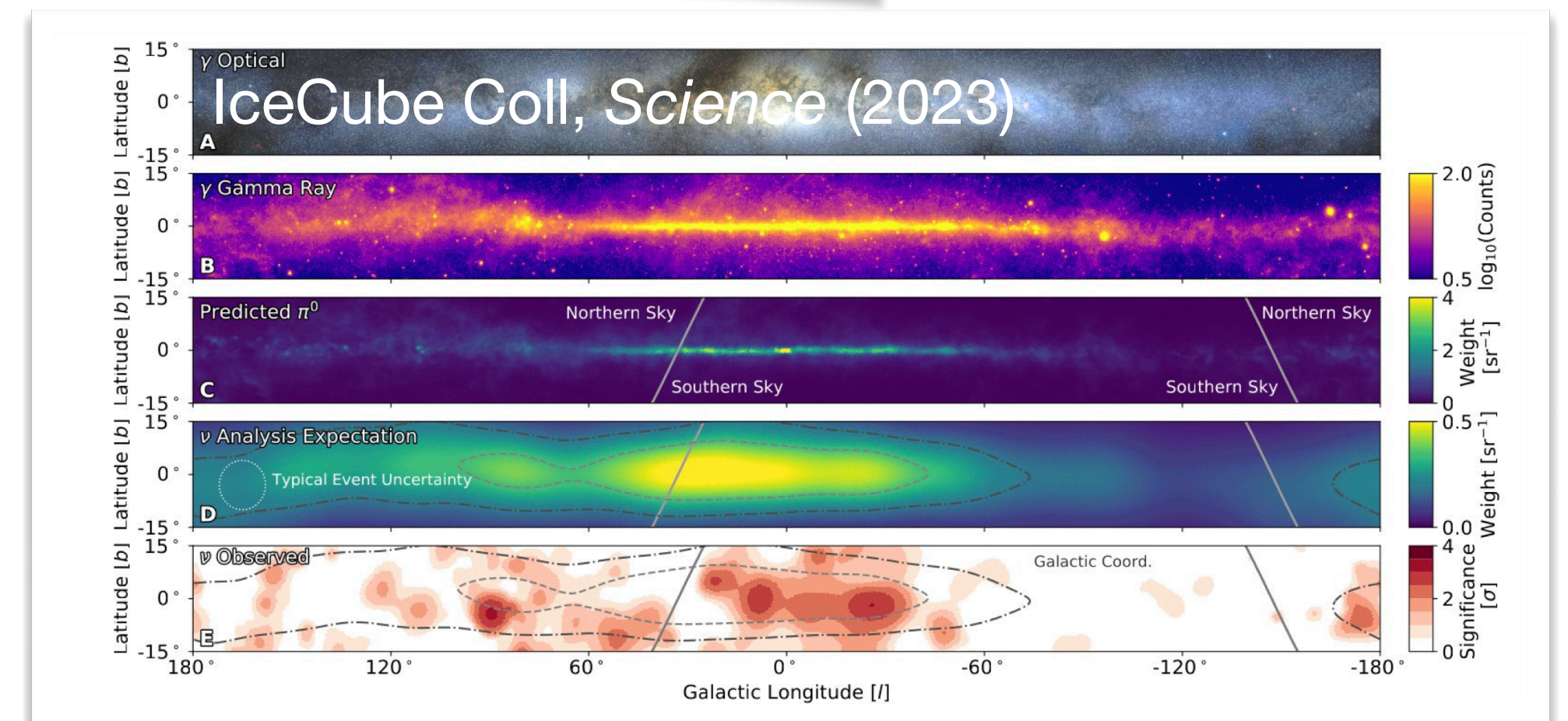
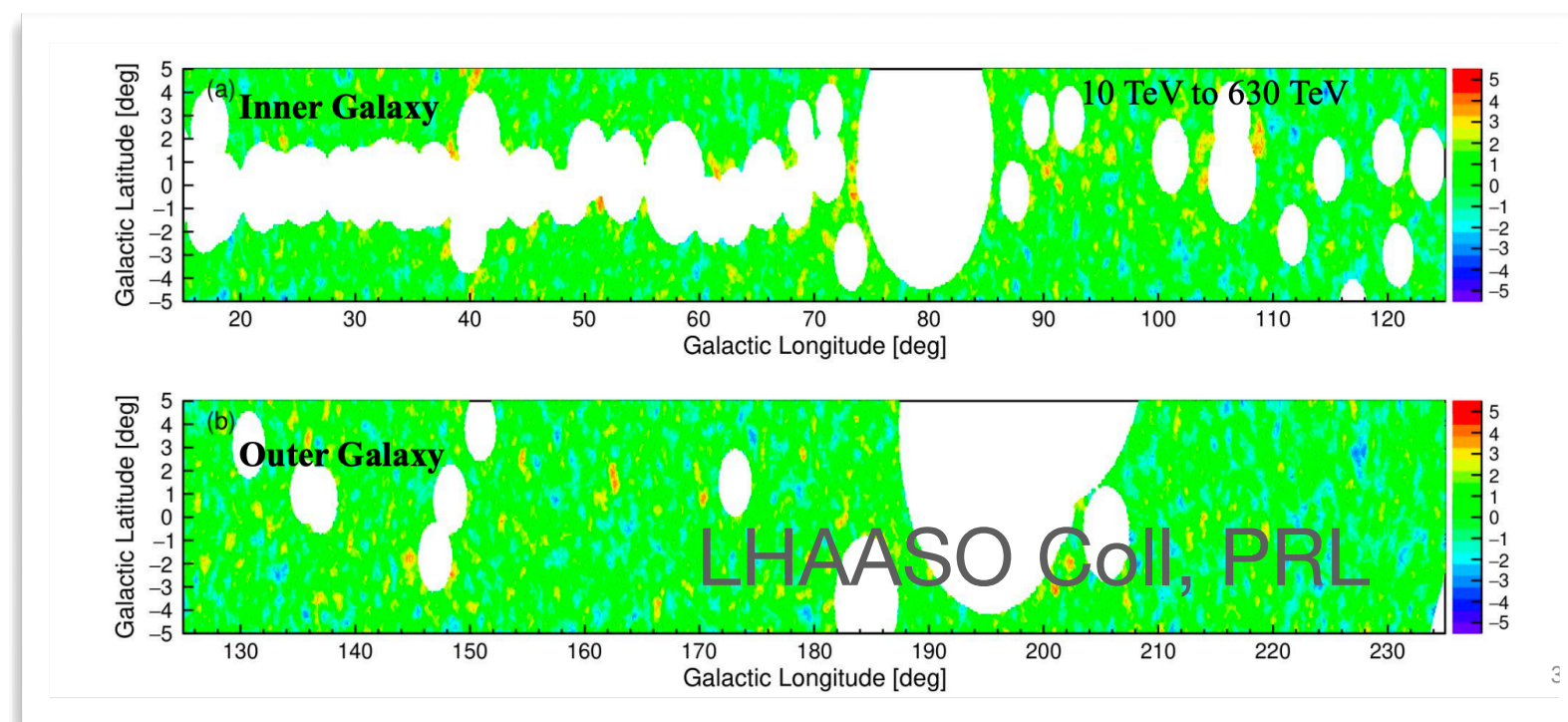
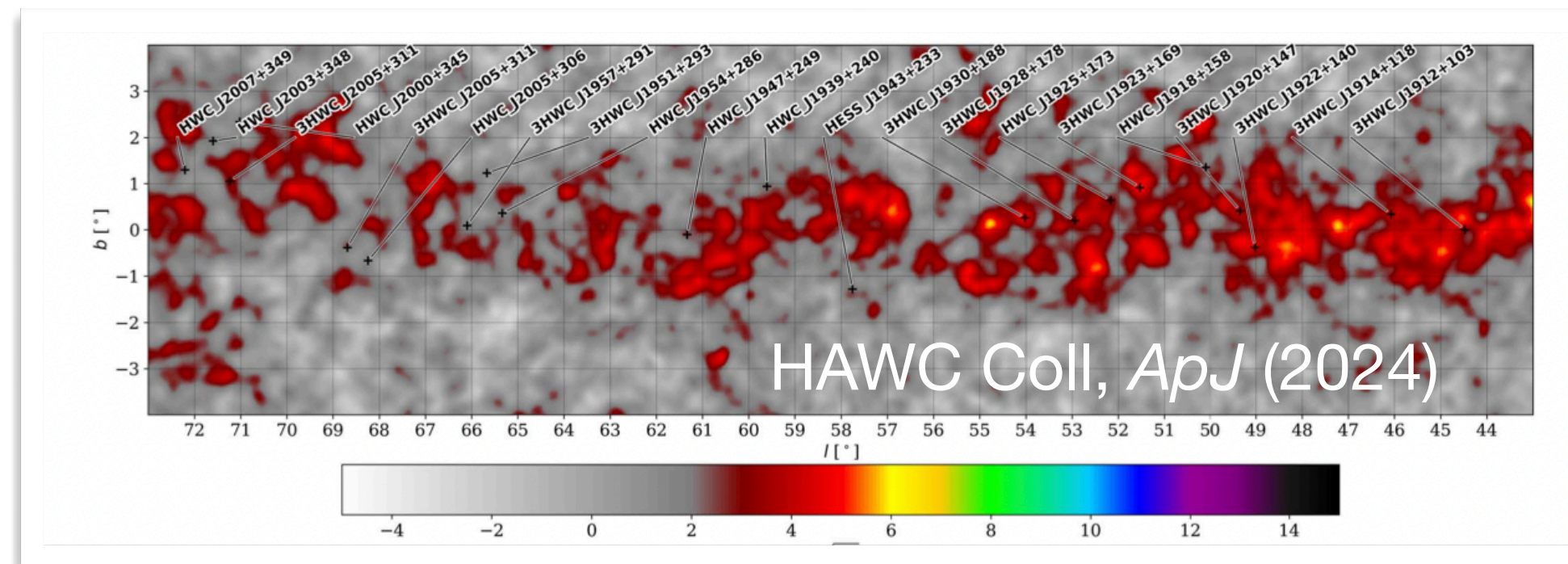
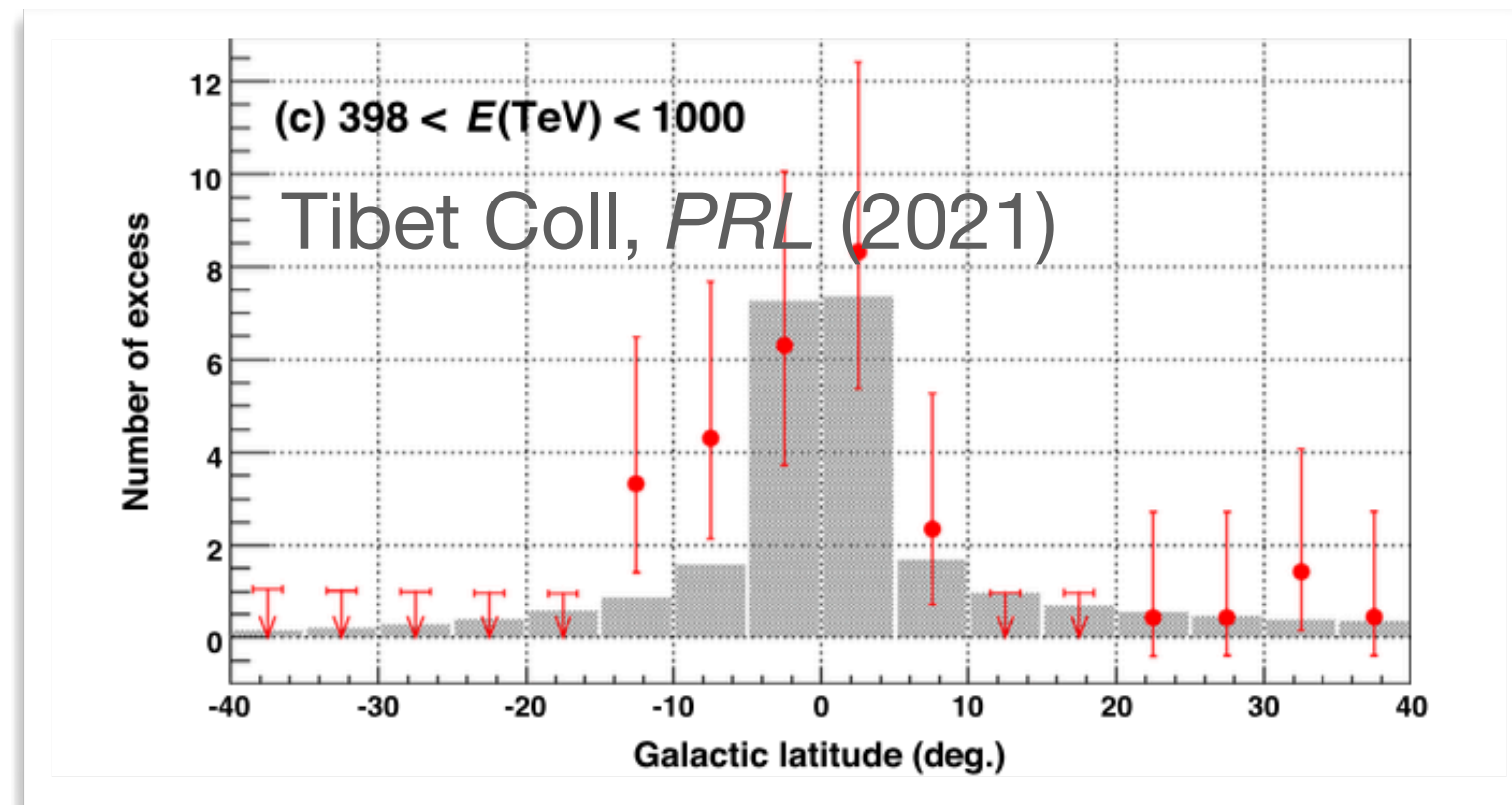
Searches with the Fermi π^0 template yielded
5.7 σ post-trial rejection of the background-only hypothesis

Dataset	Fermi π^0	CRINGE	KRA $^5_\gamma$	KRA $^{50}_\gamma$
IceMan	35.5	31.7	28.3	25.8
DNNC	27.9	23.7	25.3	24.5
NT	4.9	4.8	2.4	1.2
ESTES	2.5	3.0	1.3	1.3



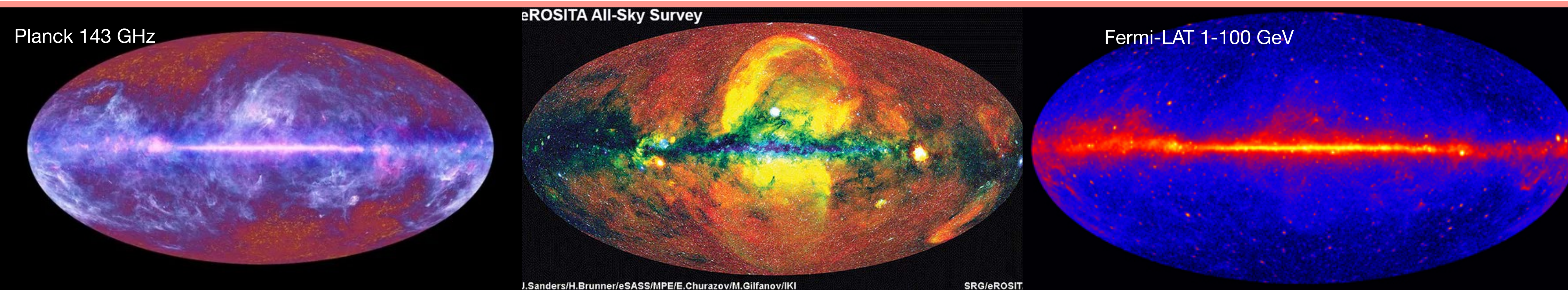
PoS-ICRC2025-1130

TeV to PeV multi-messenger emission by the Galactic Plane

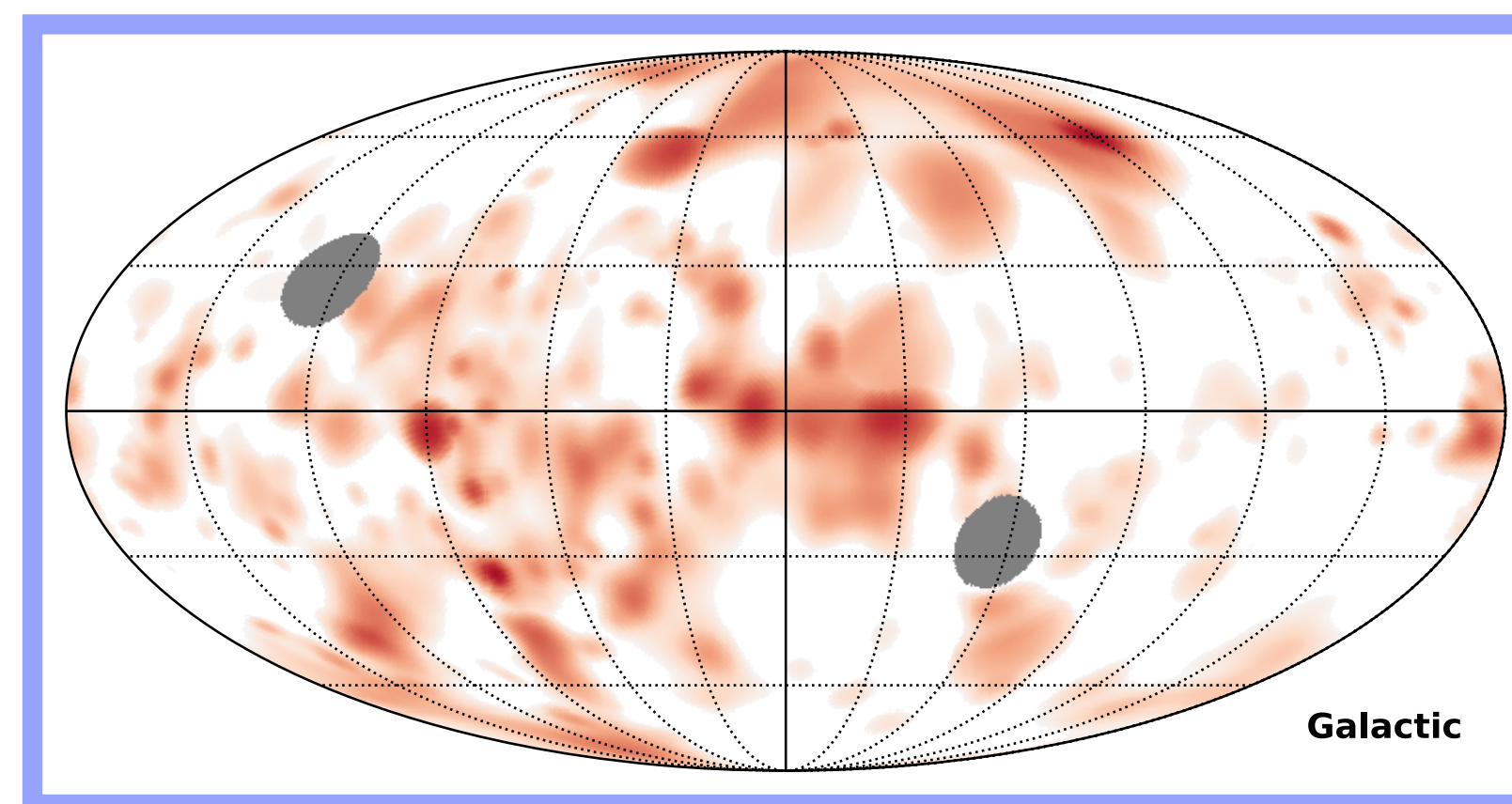


What does the neutrino Galactic plane flux imply for Galactic PeVatrons?

The Universe in Radio, X-ray, Gamma-ray Lights

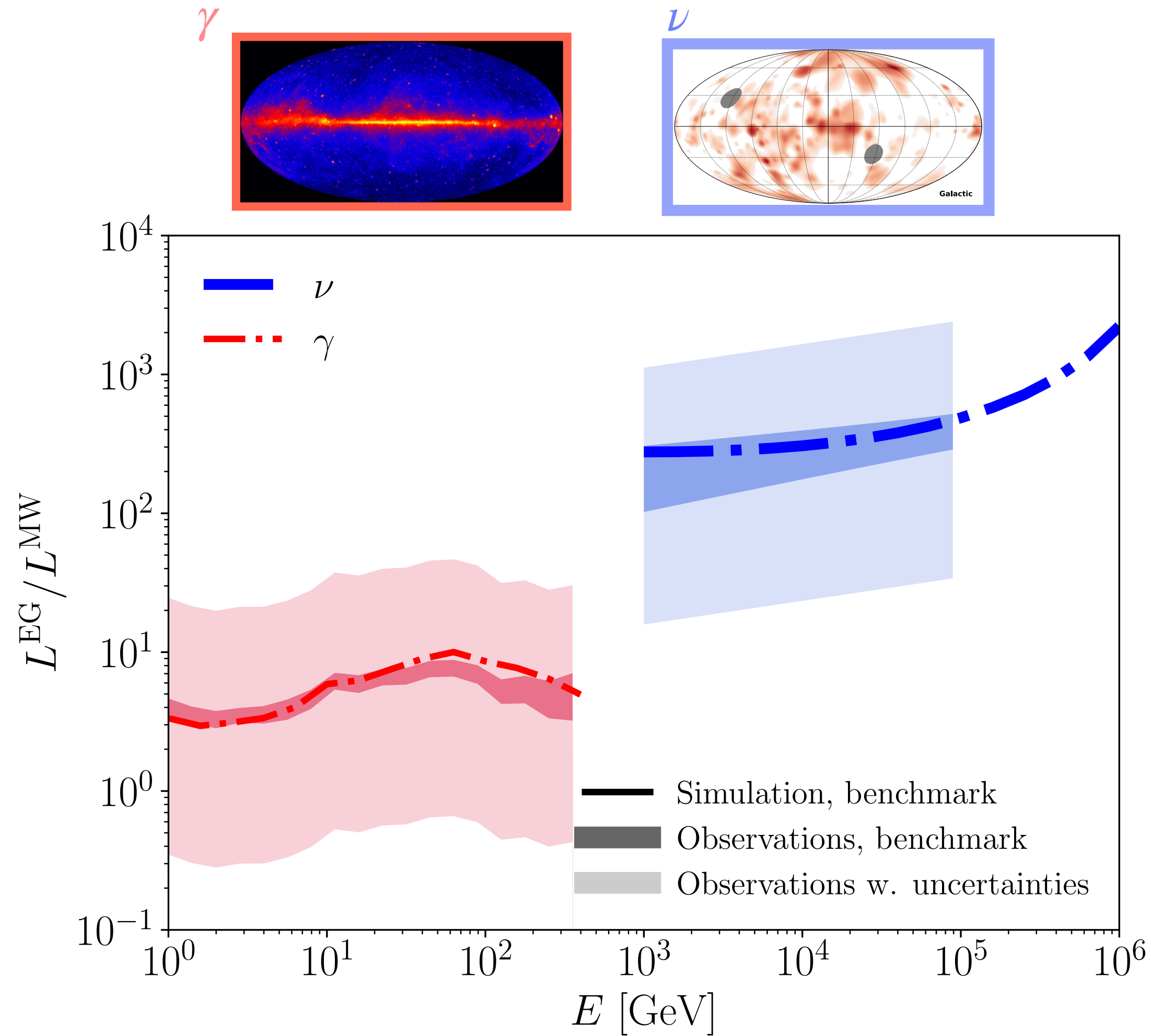


The Universe in Neutrino



In **neutrino**, the Galactic Plane is not much brighter than the extragalactic background, as it is in **photon**.

Milky Way turns out to be a Neutrino Desert!



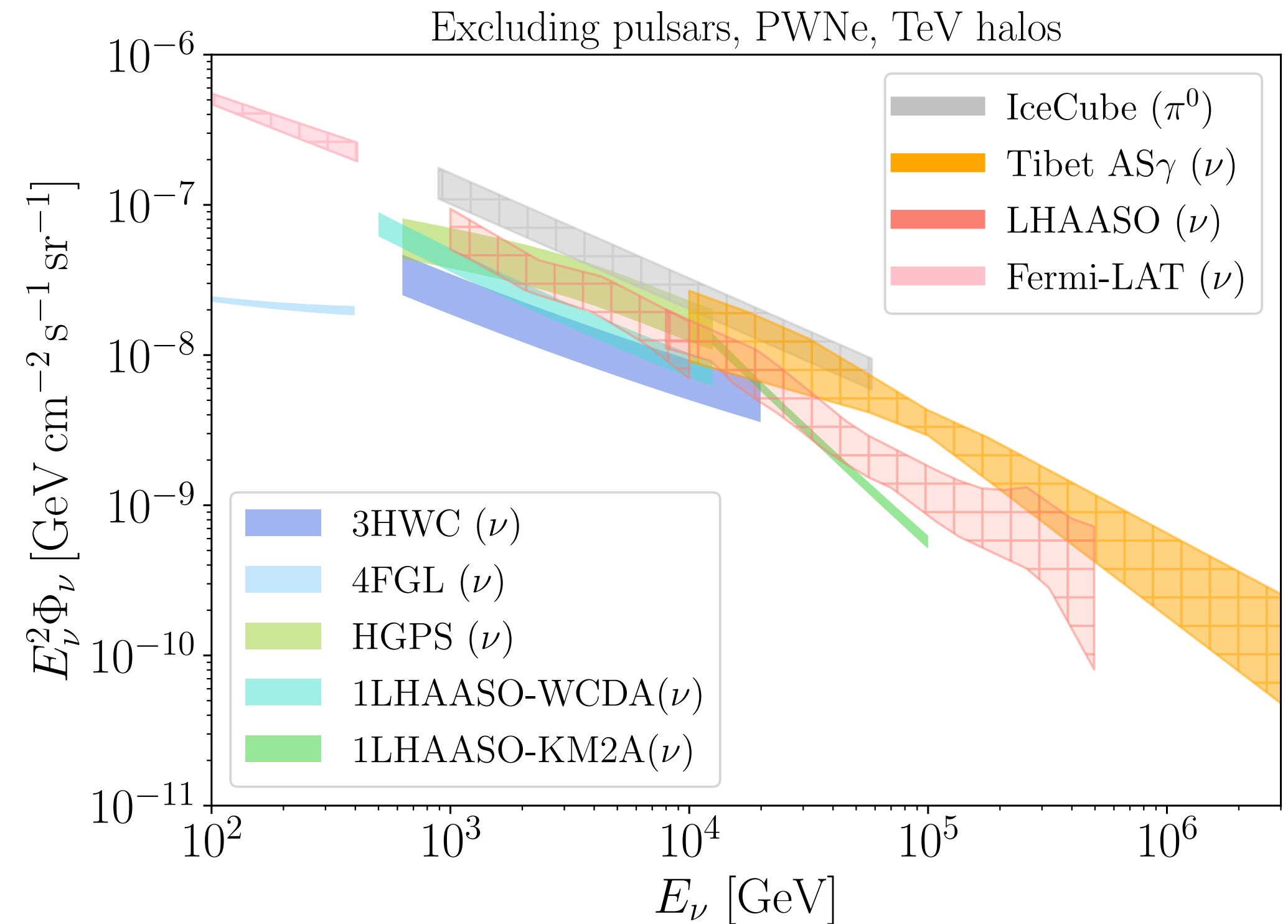
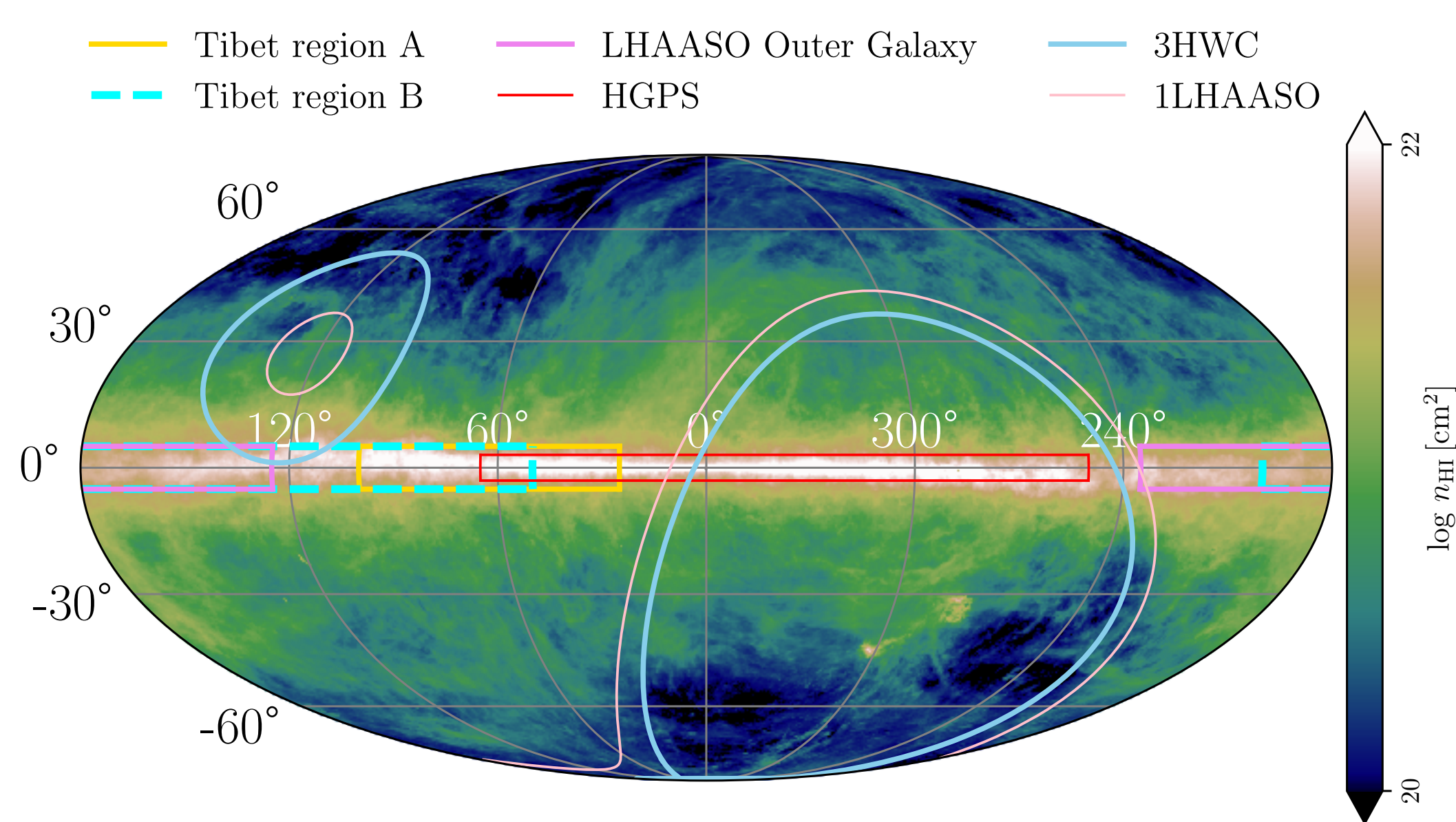
$$\frac{L_{\nu}^{\text{EG}}}{L_{\nu}^{\text{MW}}} \approx \frac{\Phi_{\nu}^{\text{EG}}}{\Phi_{\nu}^{\text{MW}}} \frac{3F_{\epsilon}}{4\pi r_{\odot}^2 n_0 c t_H \xi_z}$$

$$= 120 \left(\frac{\Phi_{\nu}^{\text{EG}} / \Phi_{\nu}^{\text{MW}}}{5} \right) \left(\frac{n_0}{0.01 \text{Mpc}^{-3}} \right)^{-1} \left(\frac{\xi_z}{3} \right)^{-1} \left(\frac{F_{\epsilon}}{1} \right)$$

A comparison of the Galactic and extragalactic neutrino flux suggests that the **Milky Way currently does not host the type of neutrino emitters that dominate the extragalactic neutrino sky.**

KF, Gallagher, Halzen *Nature Astronomy* 2306.17275

Sources vs Diffuse Emission: Comparing ν and γ observations



- Neutrino flux of the Galactic plane is likely **dominated by the diffuse emission** but could include a **non-negligible contribution of hadronic gamma-ray sources**

KF & Murase ApJL 2307.02905

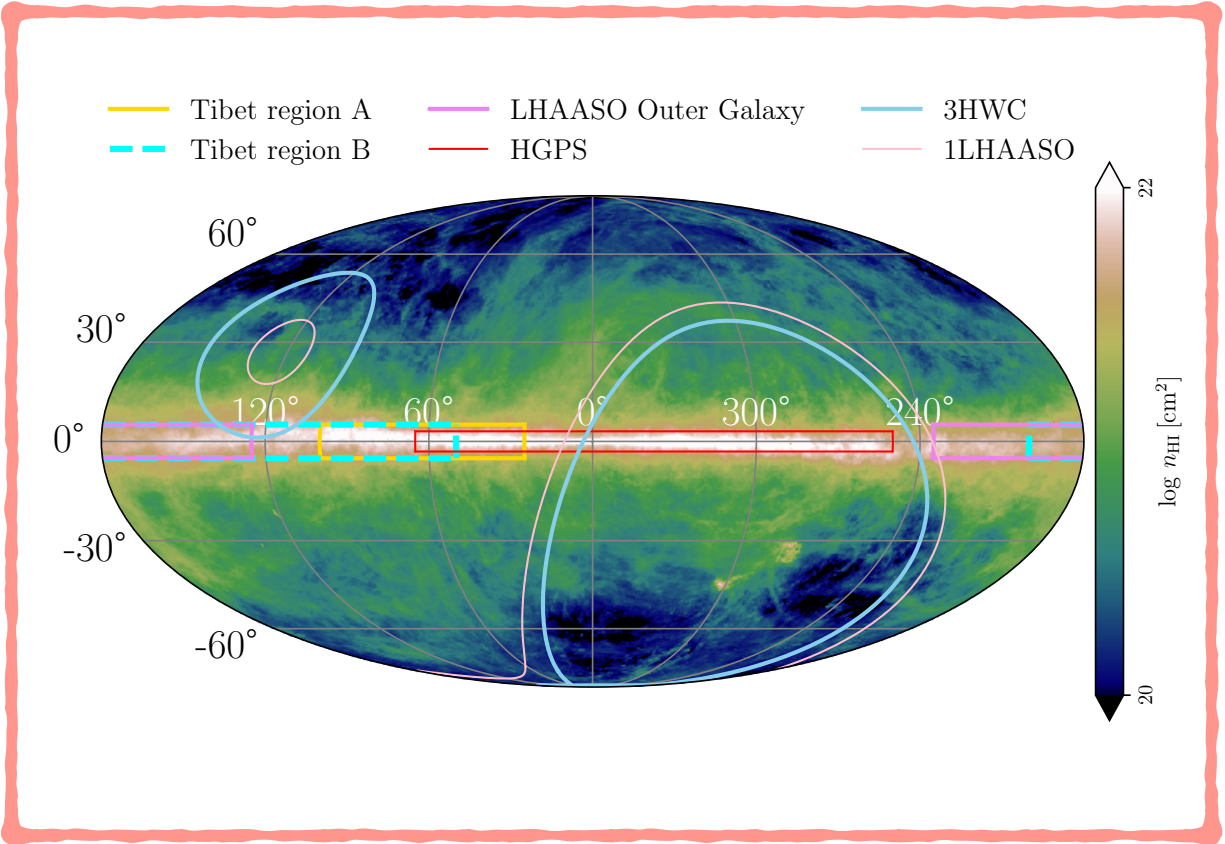
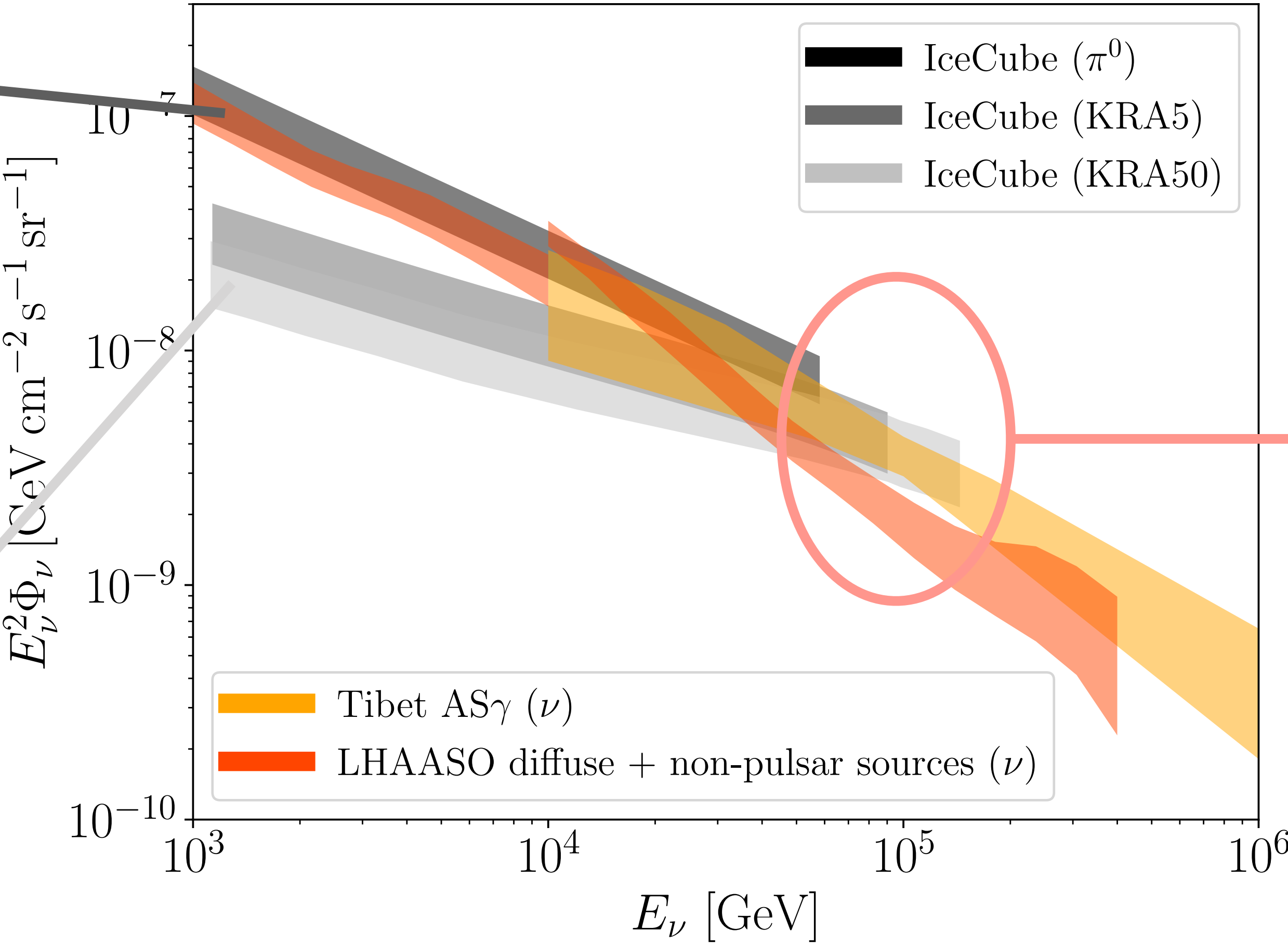
Galactic Diffuse Emission: Source Contribution

Partial contribution by unresolved hadronic sources such as star-formation regions and molecular clouds

(Neronov+2023, Abhijit+2024)

Room left for **leptonic emitters** such as TeV halos

(Dekker+2024, Kai+2024, Kaci+2024)

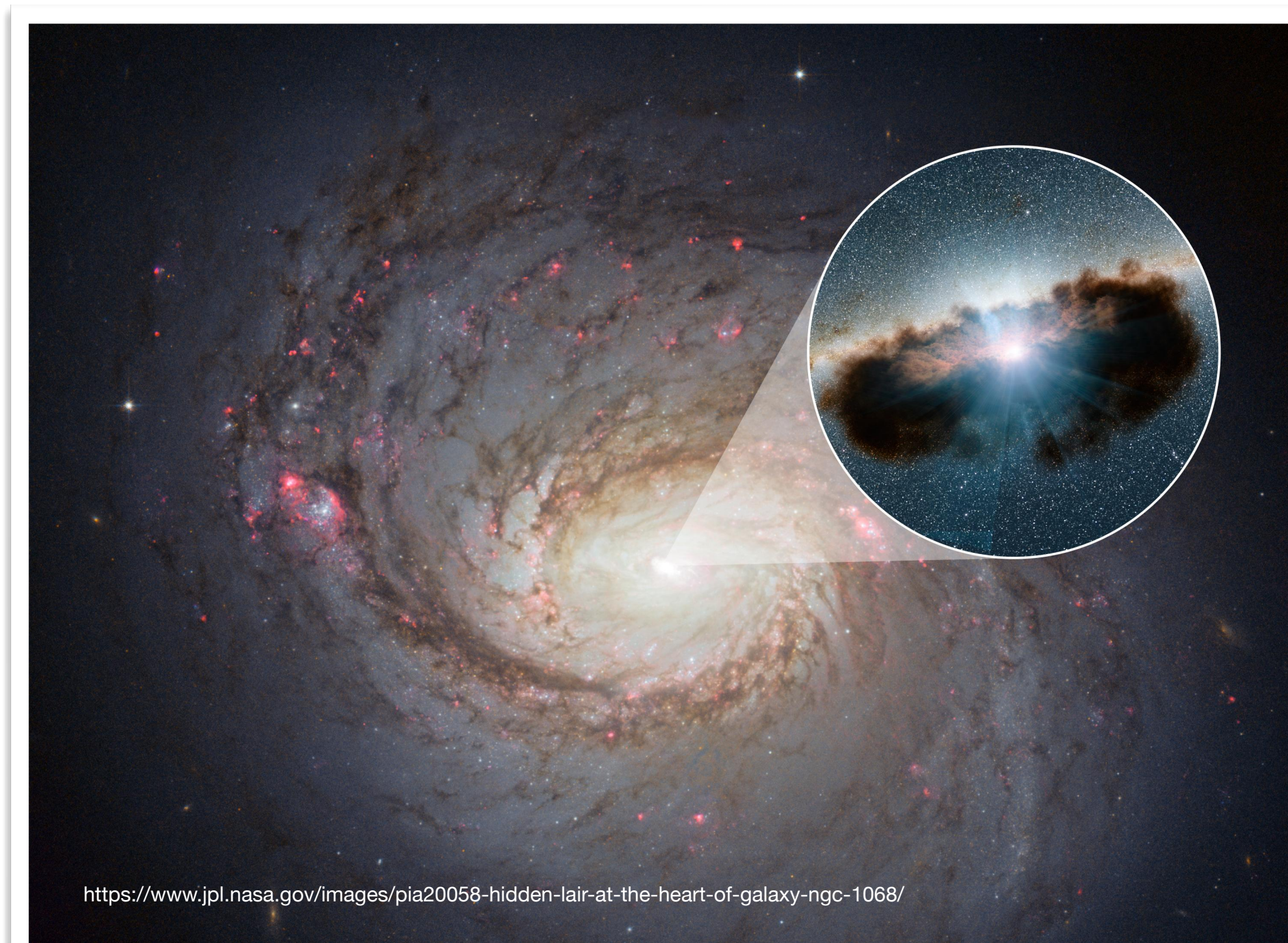


Hadronic diffuse emission or/and a population of γ -ray opaque neutrino emitters?

KF & Murase ApJL (2023)

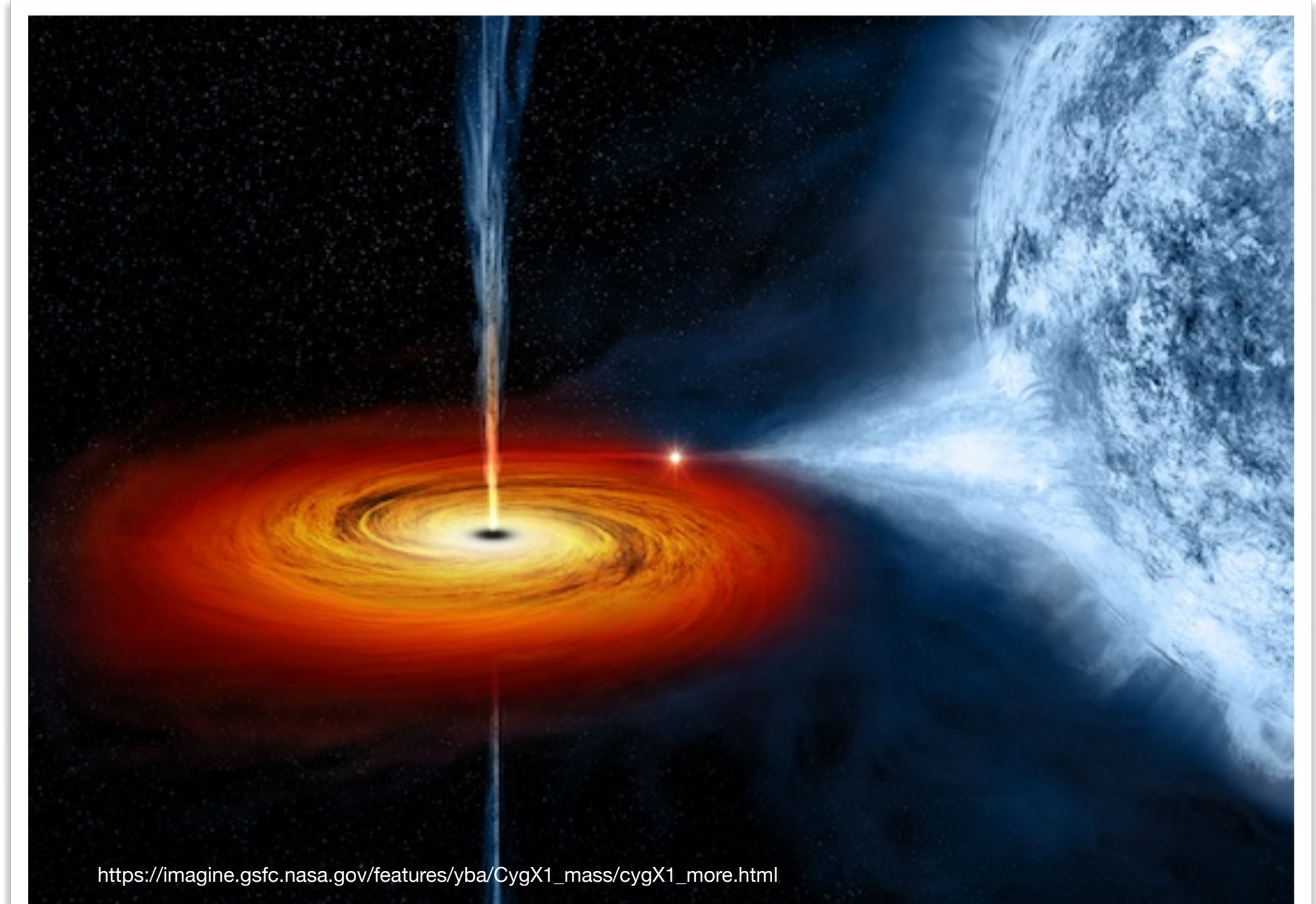
See also analysis of Vecchiotti+2023, Silvia+2024

Gamma-ray-opaque neutrino sources?



NGC 1068

$$M \sim 5 \times 10^7 M_{\odot}$$



Cygnus X-1

$$M \approx 21.2 M_{\odot}$$

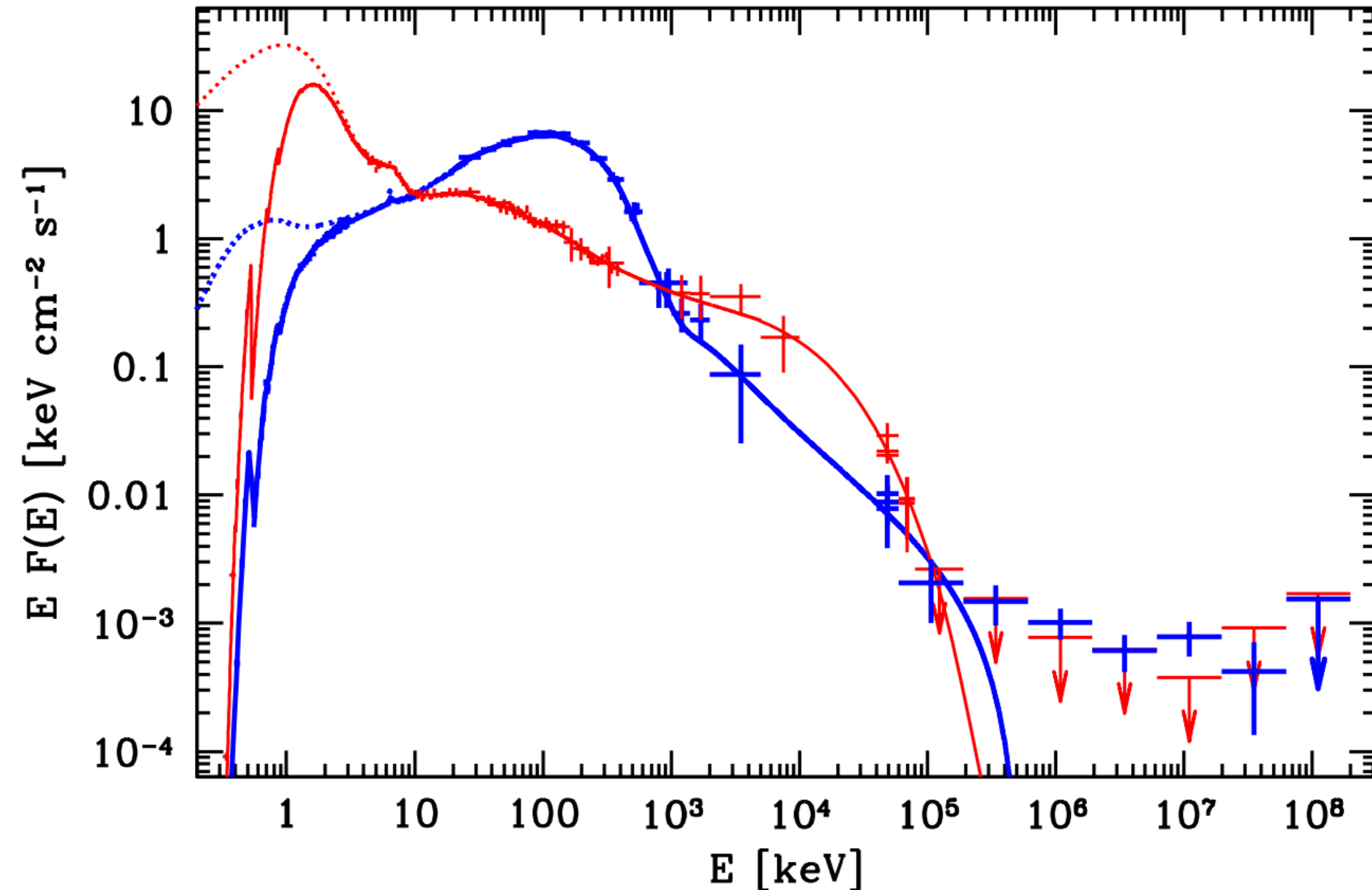
Coronal Neutrino Emission: Dependence on the Compactness

Acceleration	$\ell = \frac{L_X}{R} \frac{\sigma_T}{m_e c^3}$ $\sigma_{\pm} = \frac{B^2}{4\pi n_e m_e c^2} = \frac{\xi_B}{2\pi \tau_T} \ell$	$u_B = \xi_B u_X$ $n_e \approx \tau_T / \sigma_T R$
Interaction	$\tau_{p\gamma} \propto \frac{m_e c^2}{\epsilon_X} \frac{\sigma_{p\gamma}}{\sigma_T} \ell$ $\tau_{pp} \propto \frac{n_p}{n_e} \frac{\sigma_{pp}}{\sigma_T} \tau_T$	

- Particle acceleration and interaction timescales in the coronal region are tied to the compactness of the X-ray source
- $\ell \approx 17$ for NGC 1068 and $\ell \approx 19$ for Cygnus X-1 at $R = 10 R_g$
- **Neutrino emission processes may similarly happen in the cores of active galactic nuclei and black hole XRBs**, despite of their drastically different masses and physical sizes.

KF &, Halzen, Heinz, Gallagher ApJL 2410.02119

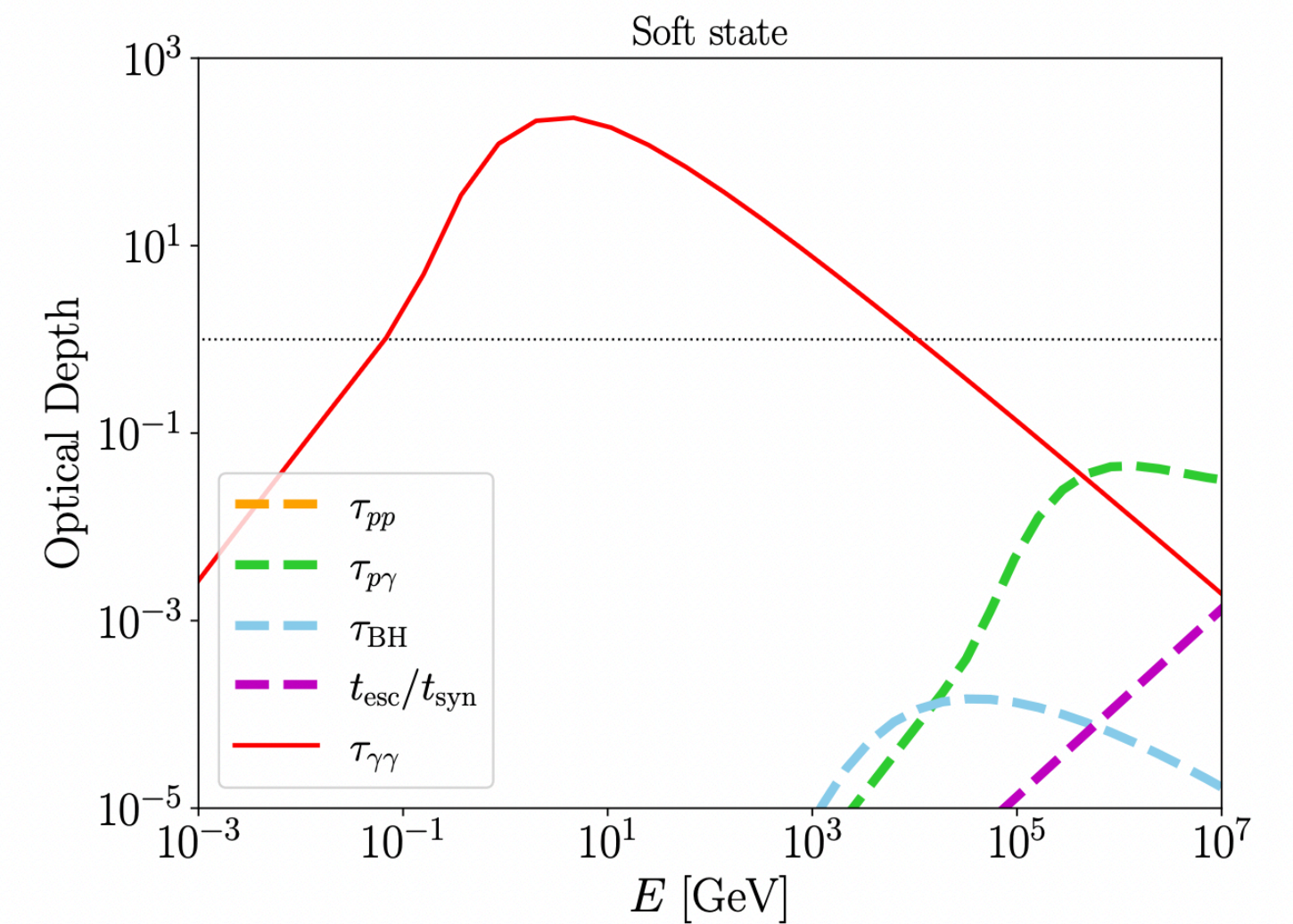
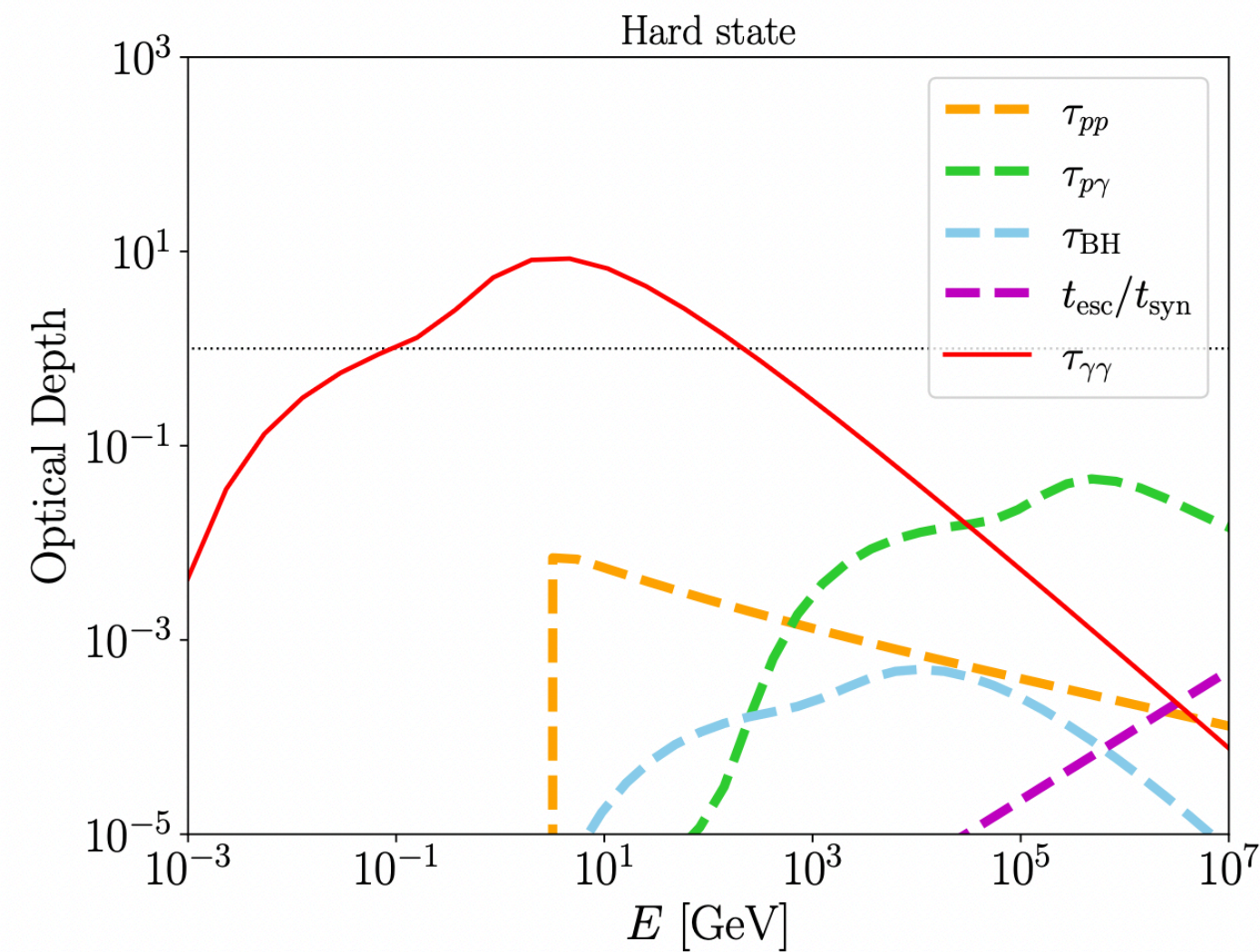
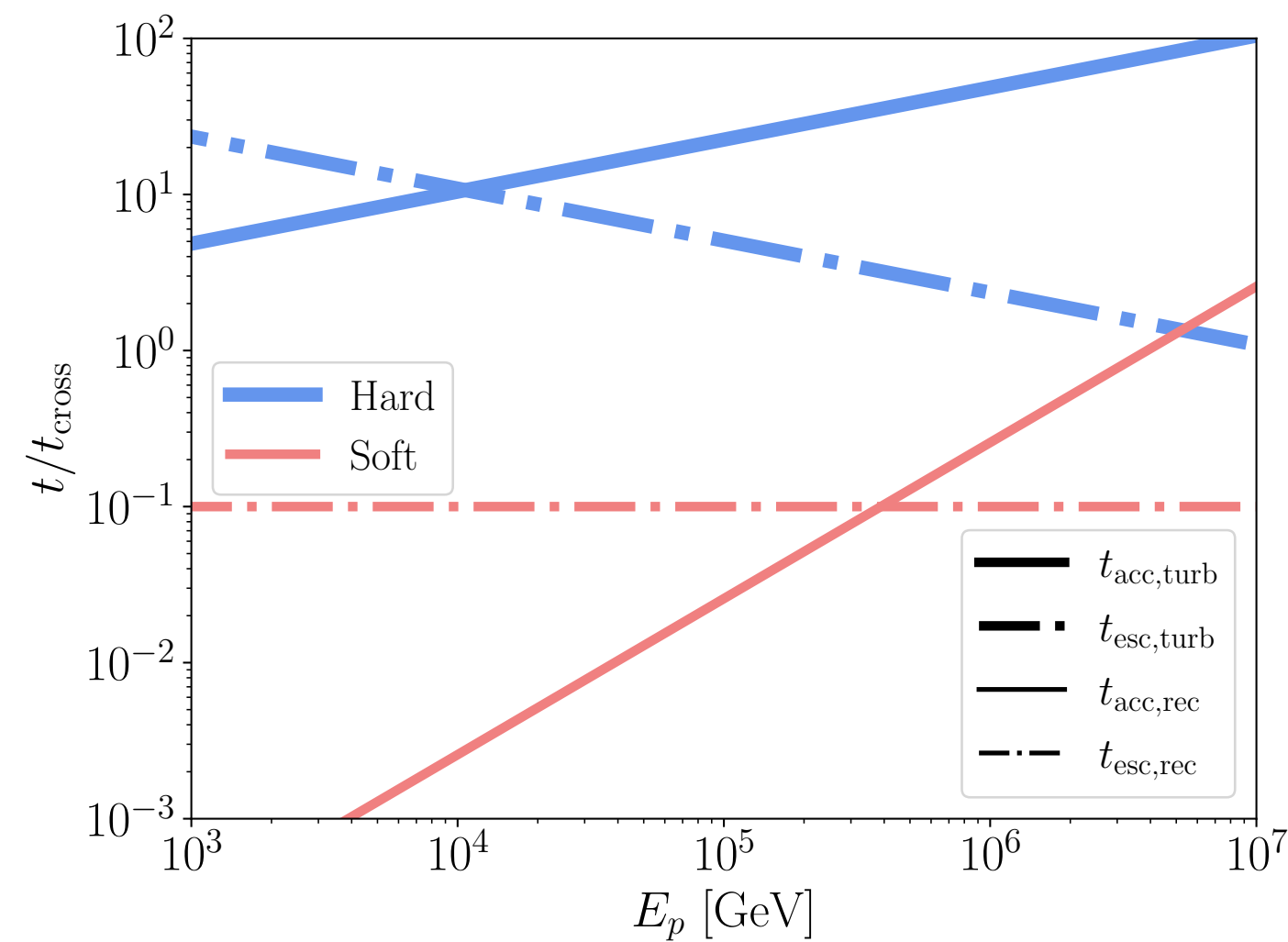
Galactic Black Hole Corona: Cygnus X-1 as an example



Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

- Hard and soft states
- Transition of states due to **different accretion states**. In hard/soft state, coronal emission dominates at large/small radius
- Hard X-ray to MeV gamma-ray emission associated with corona
- 1-100 GeV emission only in hard state; sub-GeV emission seen in both states. Origin unknown

Galactic Black Hole Corona: Cygnus X-1 as an example

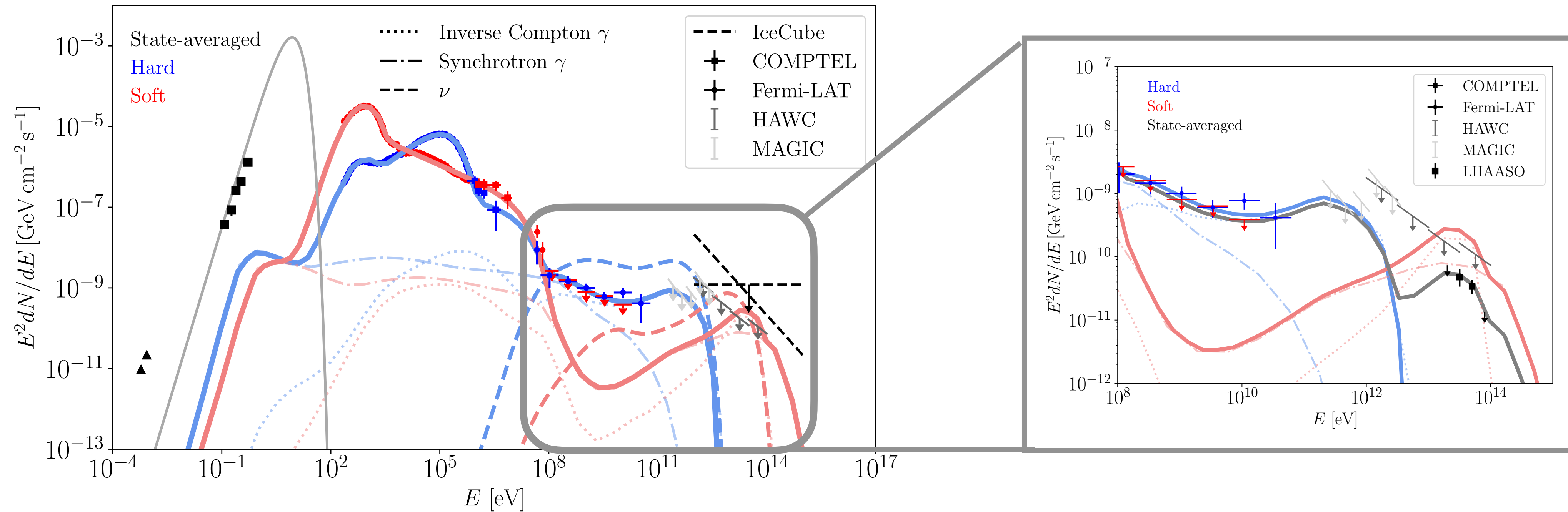


- Hard state: $R \sim 100 R_g$, $\ell \sim 2$, $\sigma_{\pm} \sim 0.1$, turbulent acceleration
- Soft state: $R \sim 30 R_g$, $\ell \sim 20$, $\sigma_{\pm} \sim 60$, magnetic reconnection
- In both states, coronal region is **opaque to gamma rays**. Soft state has $\tau_{\gamma\gamma} \gg 1$

KF & Halzen, Heinz, Gallagher ApJL 2410.02119

Galactic Black Hole Corona: Cygnus X-1 as an example

KF &, Halzen, Heinz, Gallagher ApJL 2410.02119



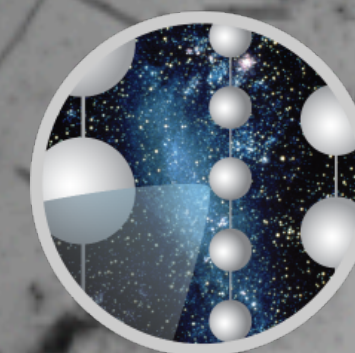
- Hadronic γ rays **cascade down** to sub-GeV energies in soft state and 0.1-100 GeV in hard state
- ν emission **detectable with future observations**
- State-averaged γ -ray flux is **consistent with TeV limits and LHAASO observation**
- Galactic XRB coronal emission **could explain both Galactic cosmic-ray and neutrino flux**

Future

Future southern wide-field gamma-ray detectors needed to explore the other side of Milky Way



Finding individual PeVatrons with neutrinos



GEN2