DIFFUSE GAMMA-RAYS AND NEUTRINOS AS PROBES OF GALACTIC COSMIC RAY SOURCES:

THE LOCAL SOURCE SCENARIO

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Based on arXiv:2603.21665
(Submitted for publication)

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TeV Particle Astrophysics

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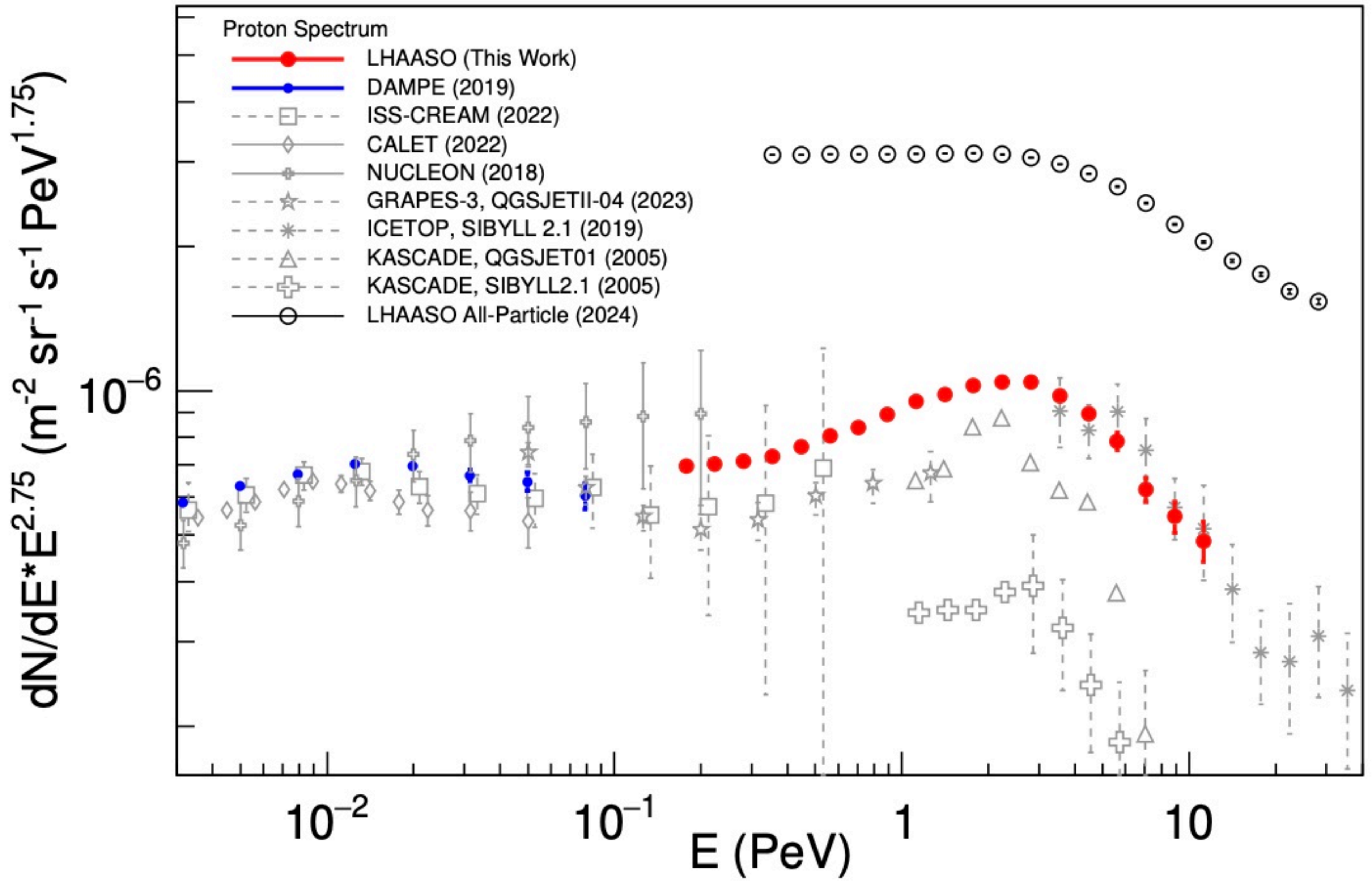
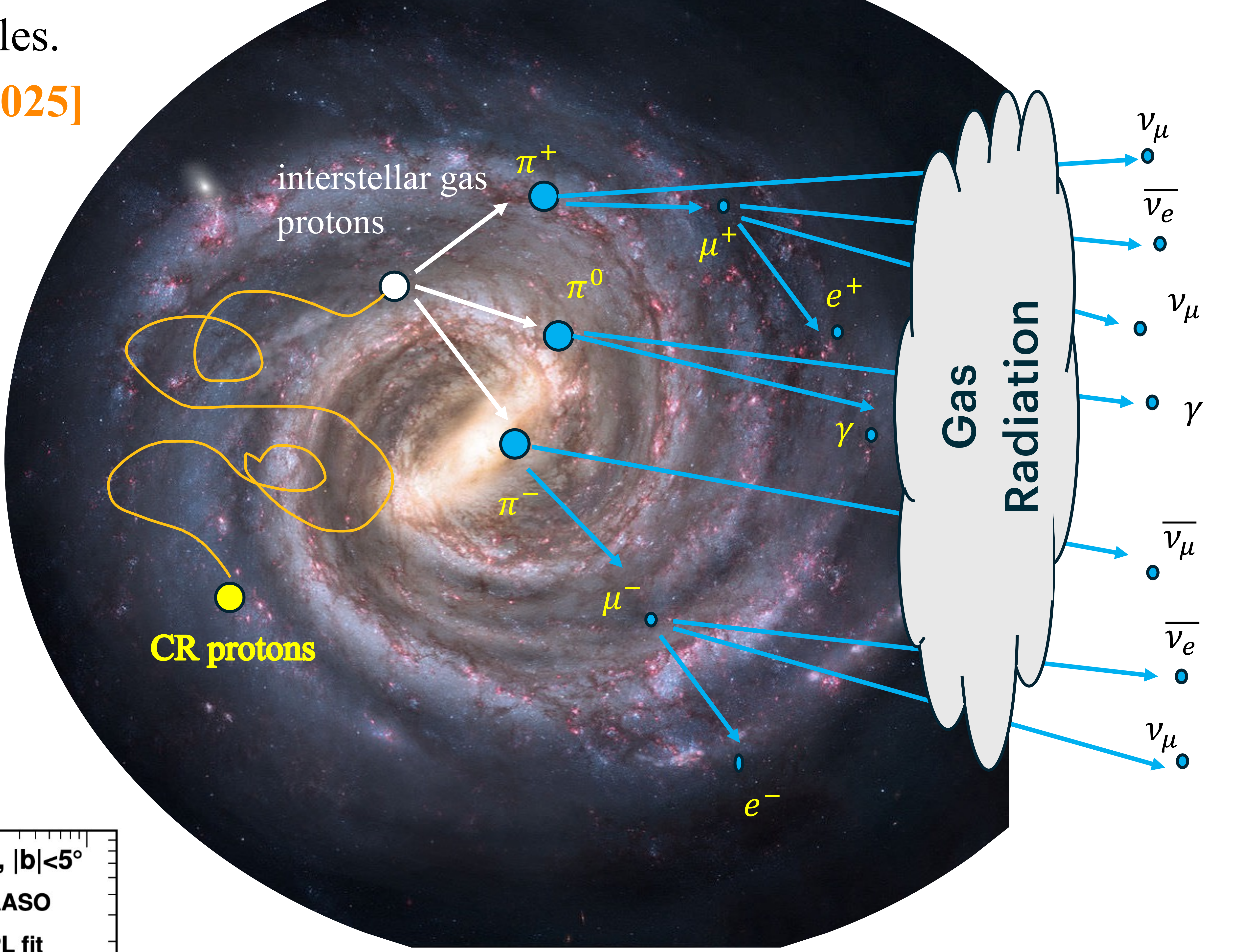
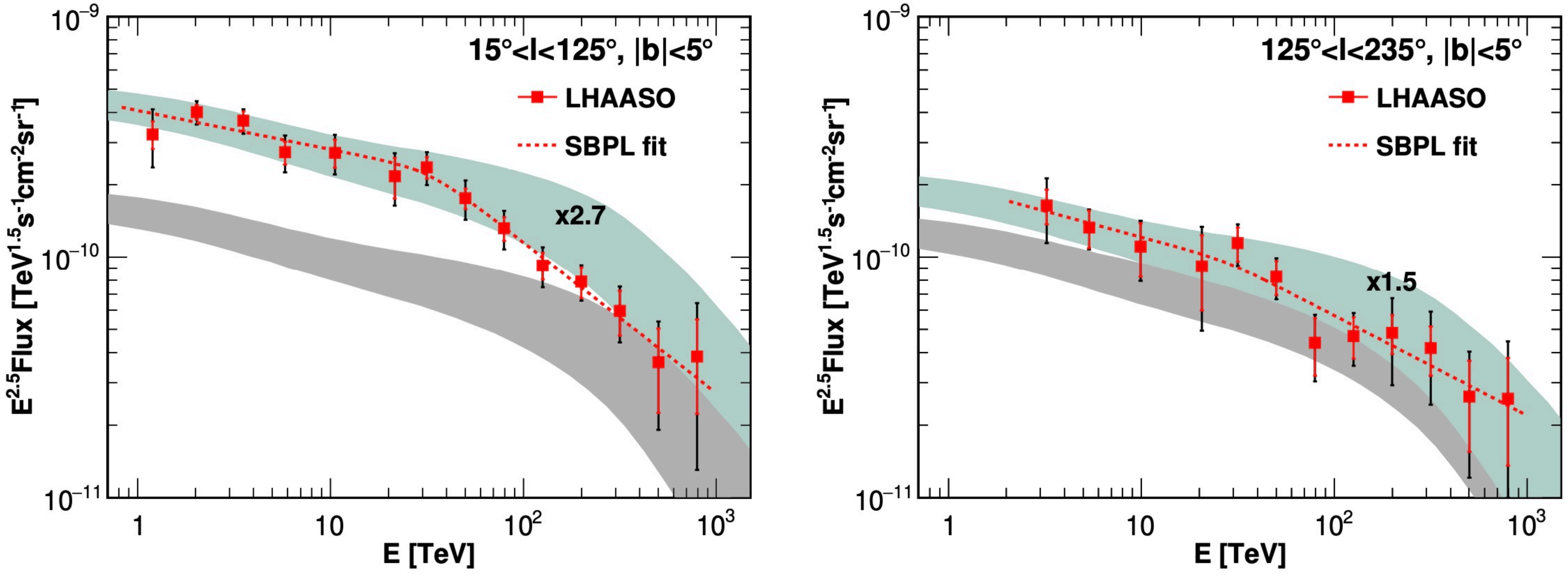
Complete observations of cosmic ray flux from GeV to PeV particles.

In particular, proton spectrum measured by LHAASO Coll. [Cao+2025]



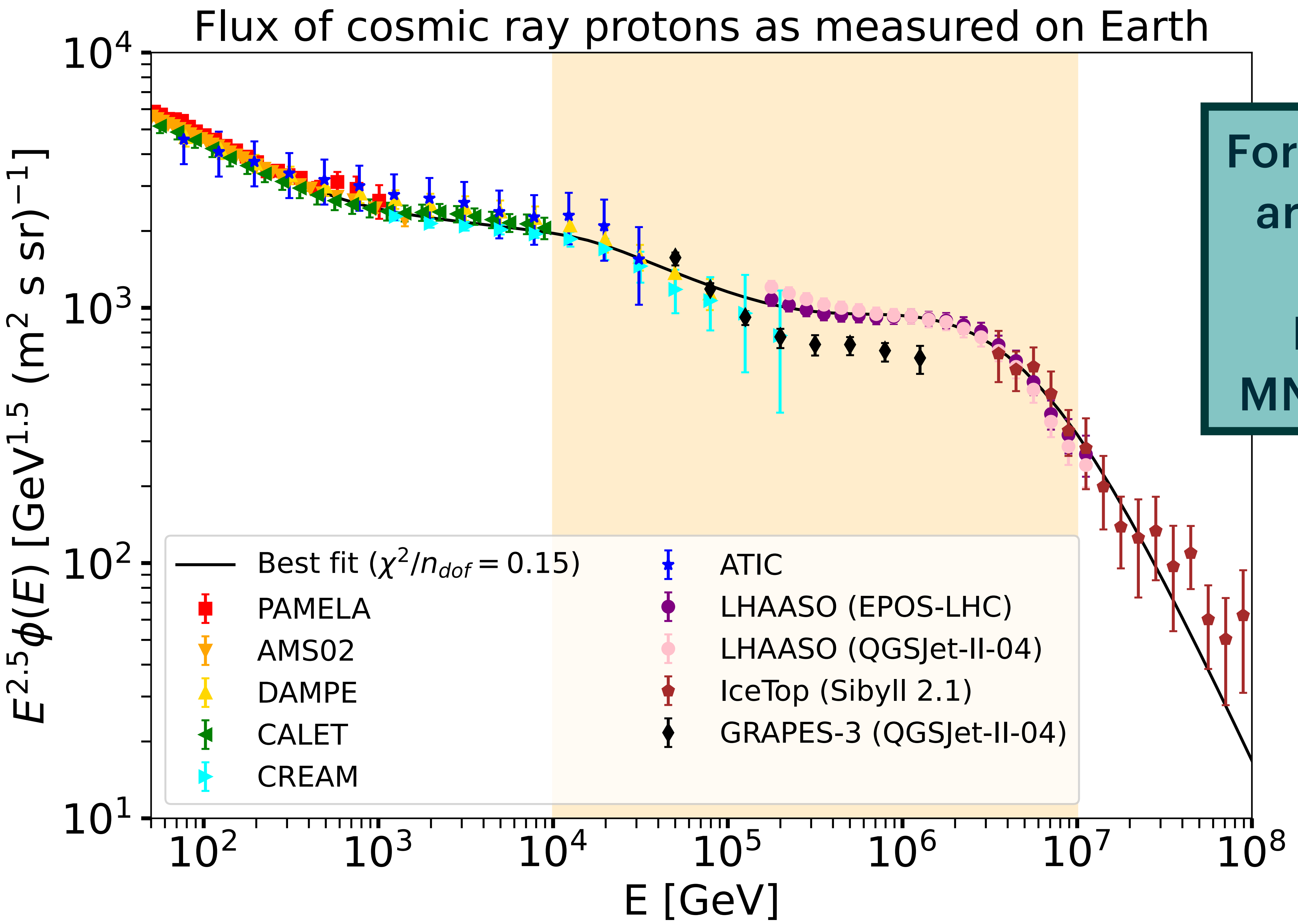




Diffuse gamma-ray flux measured by LHAASO Coll. in two Galaxy regions [Cao+2025]

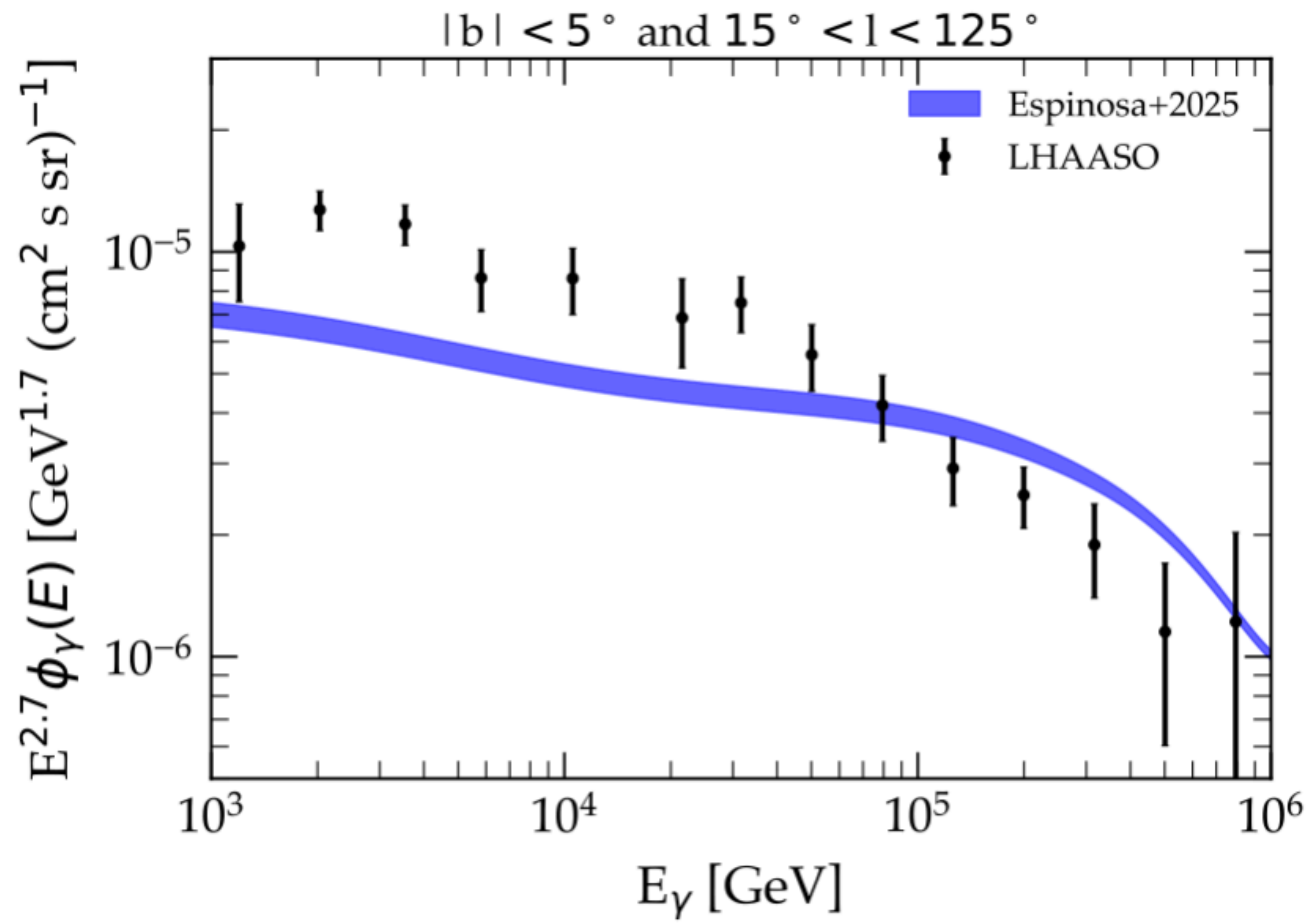
Motivations

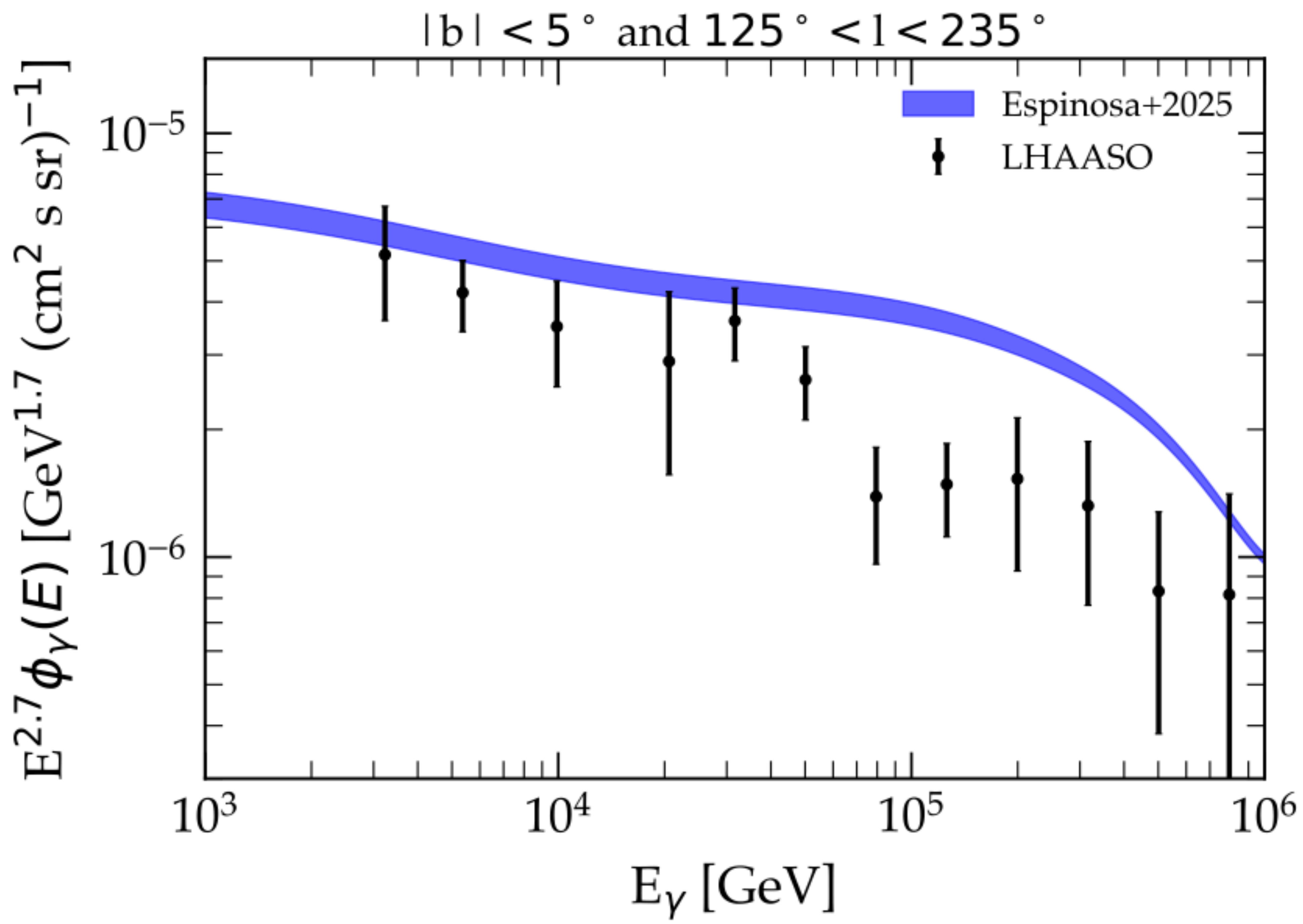
- LHAASO proton knee overshoots the diffuse gamma-ray flux at $E_\gamma > 30\,\mathrm{TeV}$ in LHAASO outer Galactic region.
- **Spectral disagreement** between predicted diffuse gamma-ray emission and observations by LHAASO.
- Diffuse flux seems to present break at $E_\gamma \sim 30\,\mathrm{TeV}$, incompatible with knee at $E_p \sim 3\,\mathrm{PeV}$.



For more details, see arXiv:2506.06593

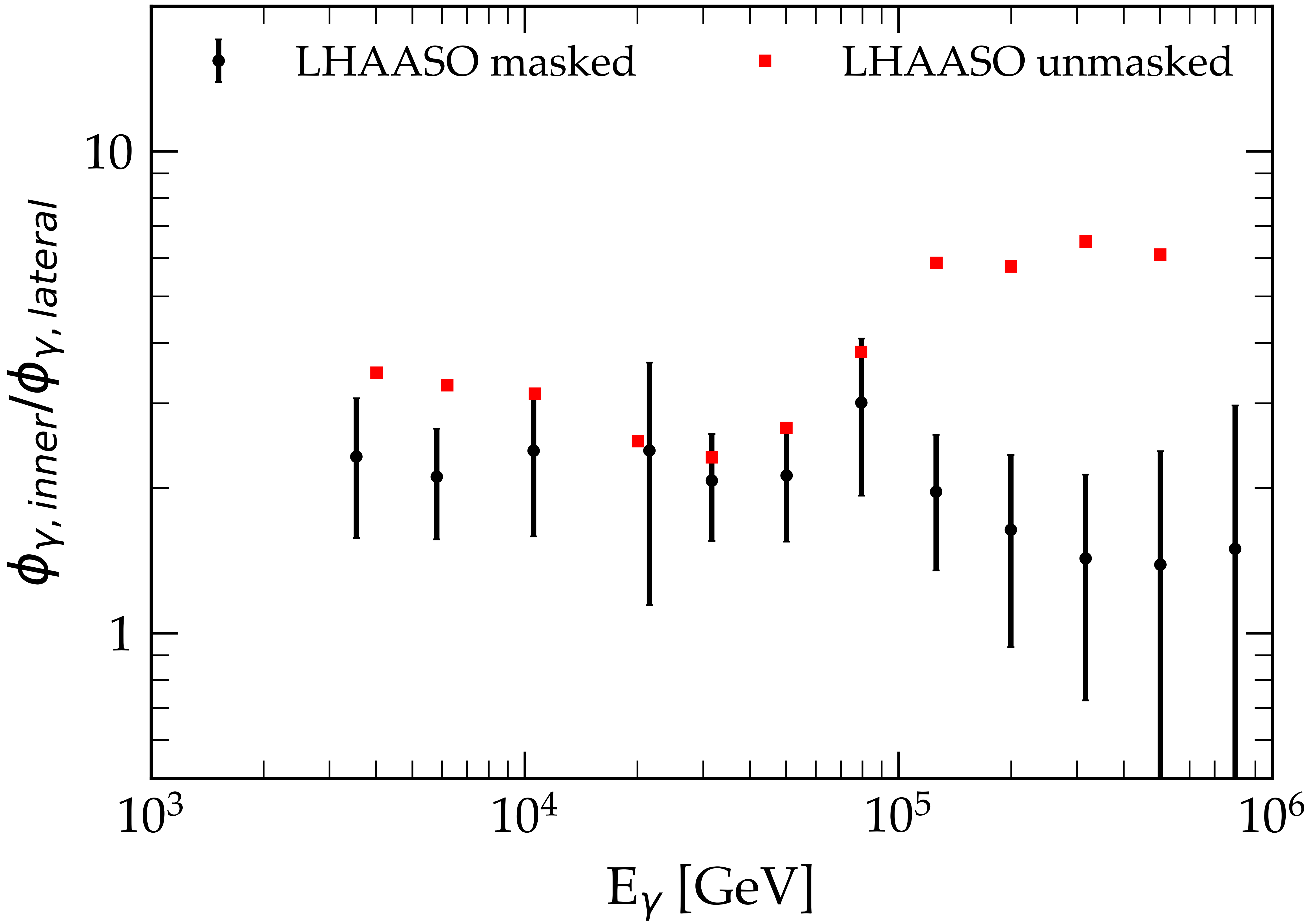
Espinosa et al., MNRAS Lett. (2025)

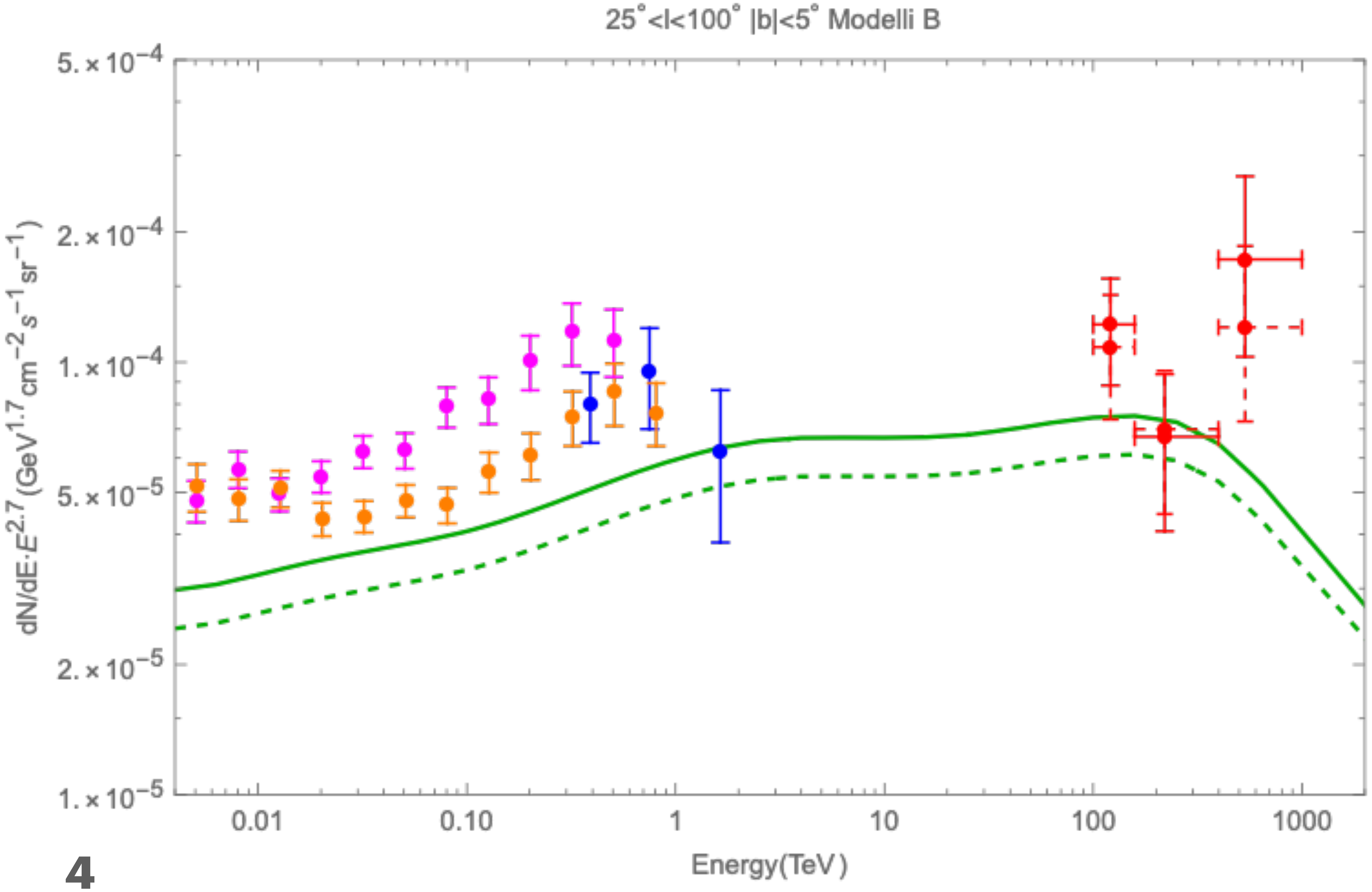




Motivations

- **Spatial and energy dependent excess** hinted by LHAASO observations.
- Inner Galactic region contains a $E_\gamma \gtrsim 100\,\mathrm{TeV}$ component, possibly associated to PeVatron(s) contribution.
- Another experiment, Tibet ASγ, does not find a similar excess. But the two sky regions probed by Tibet ASγ overlap with LHAASO inner region.





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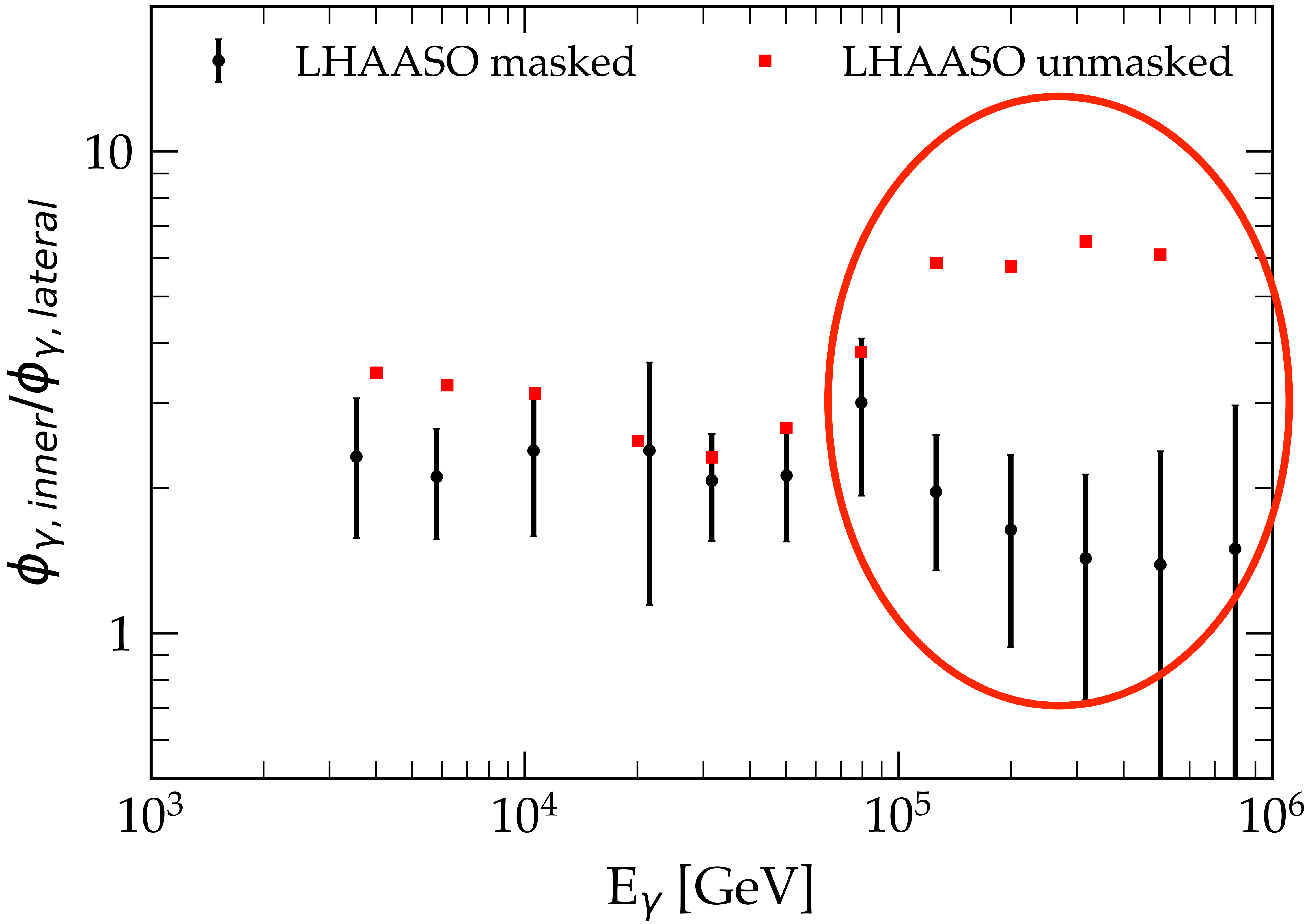

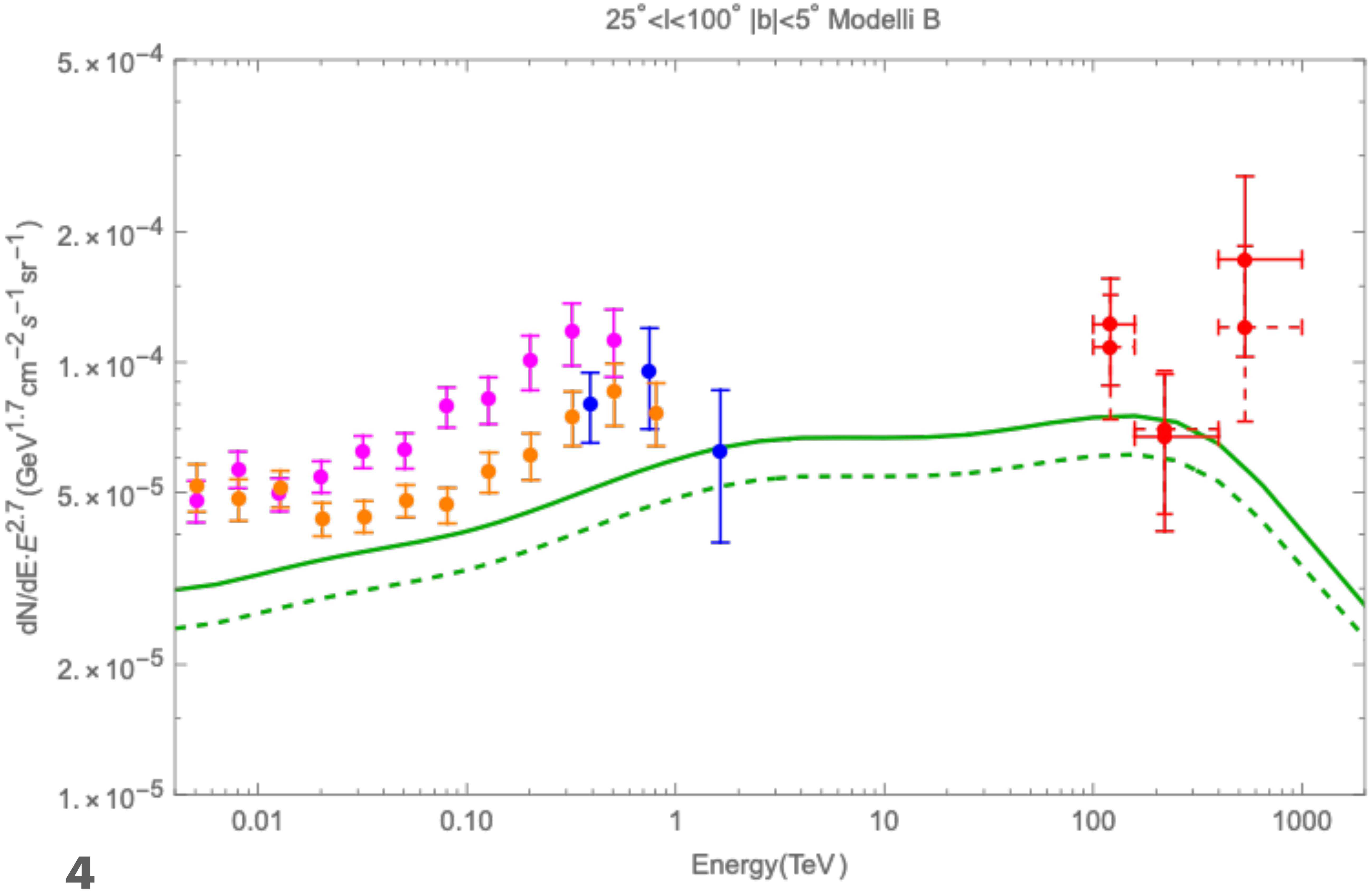

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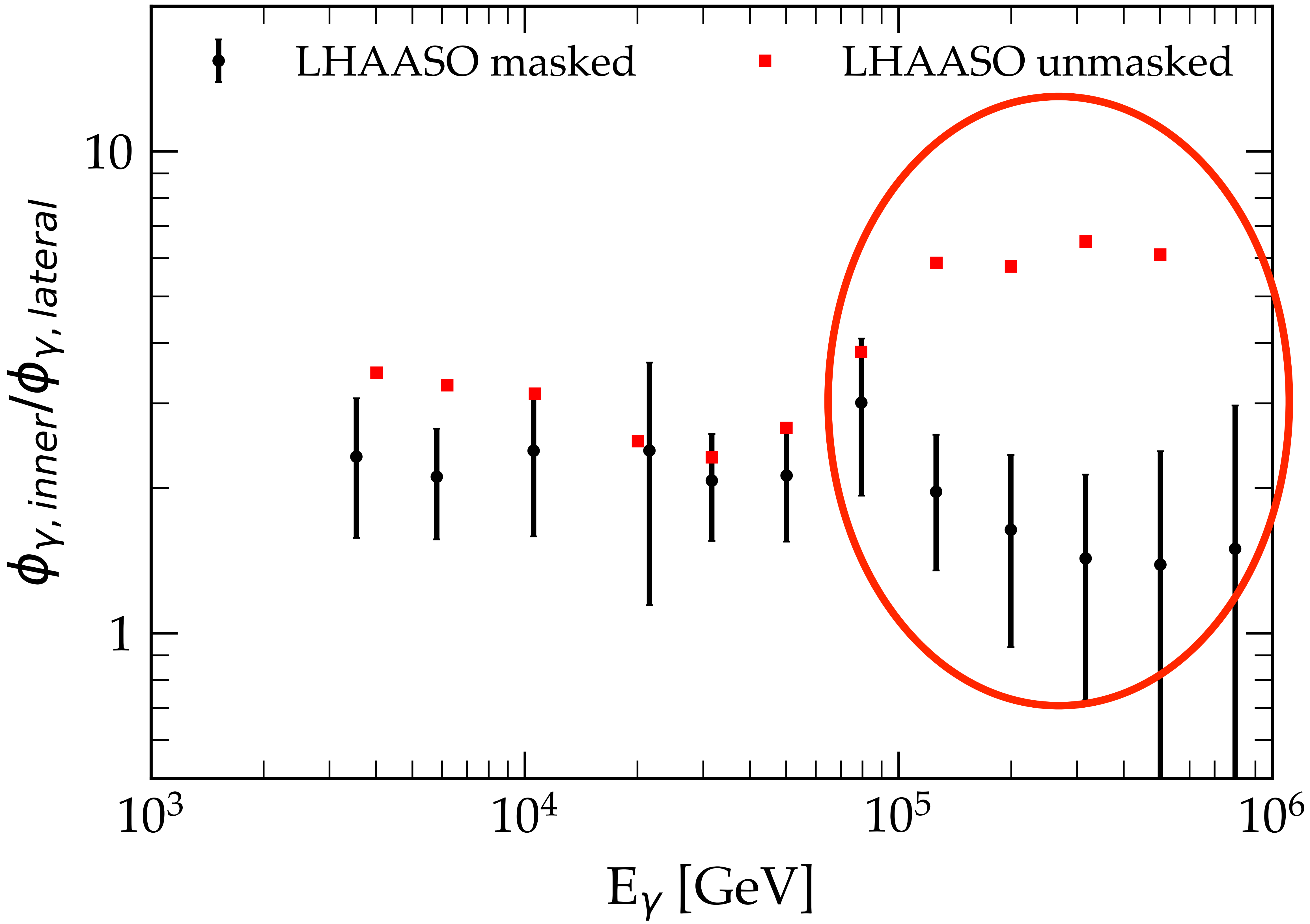

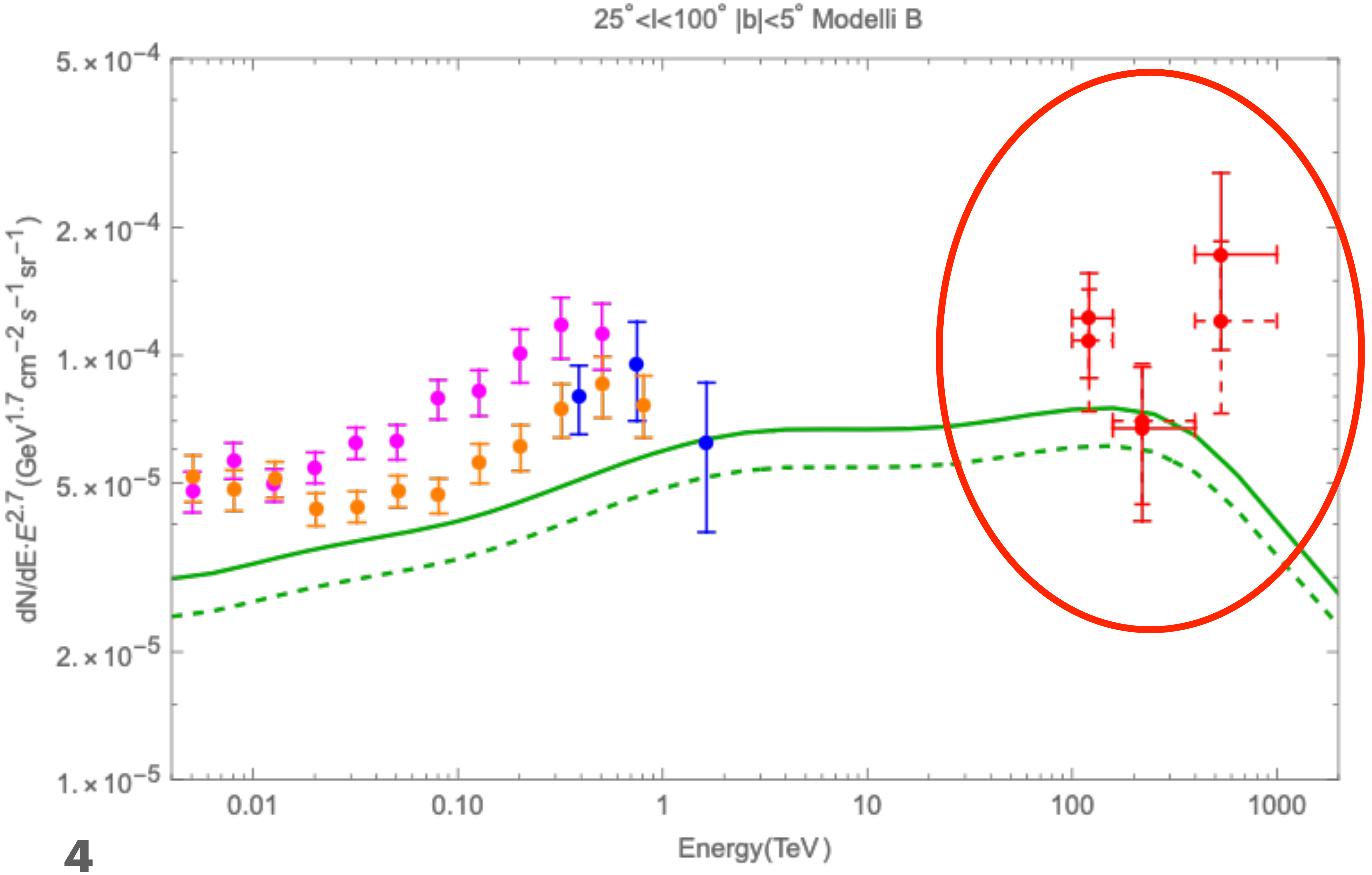

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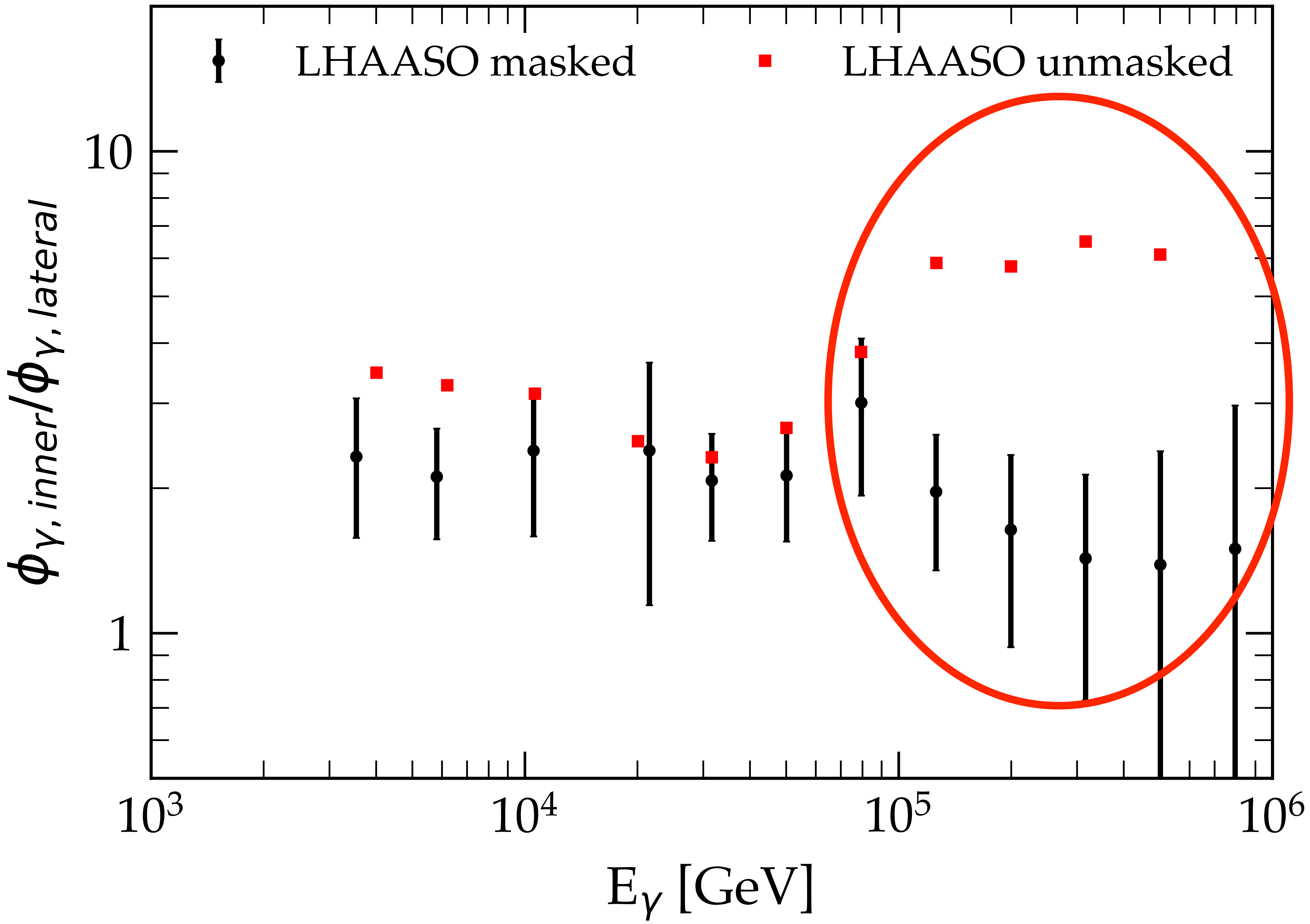
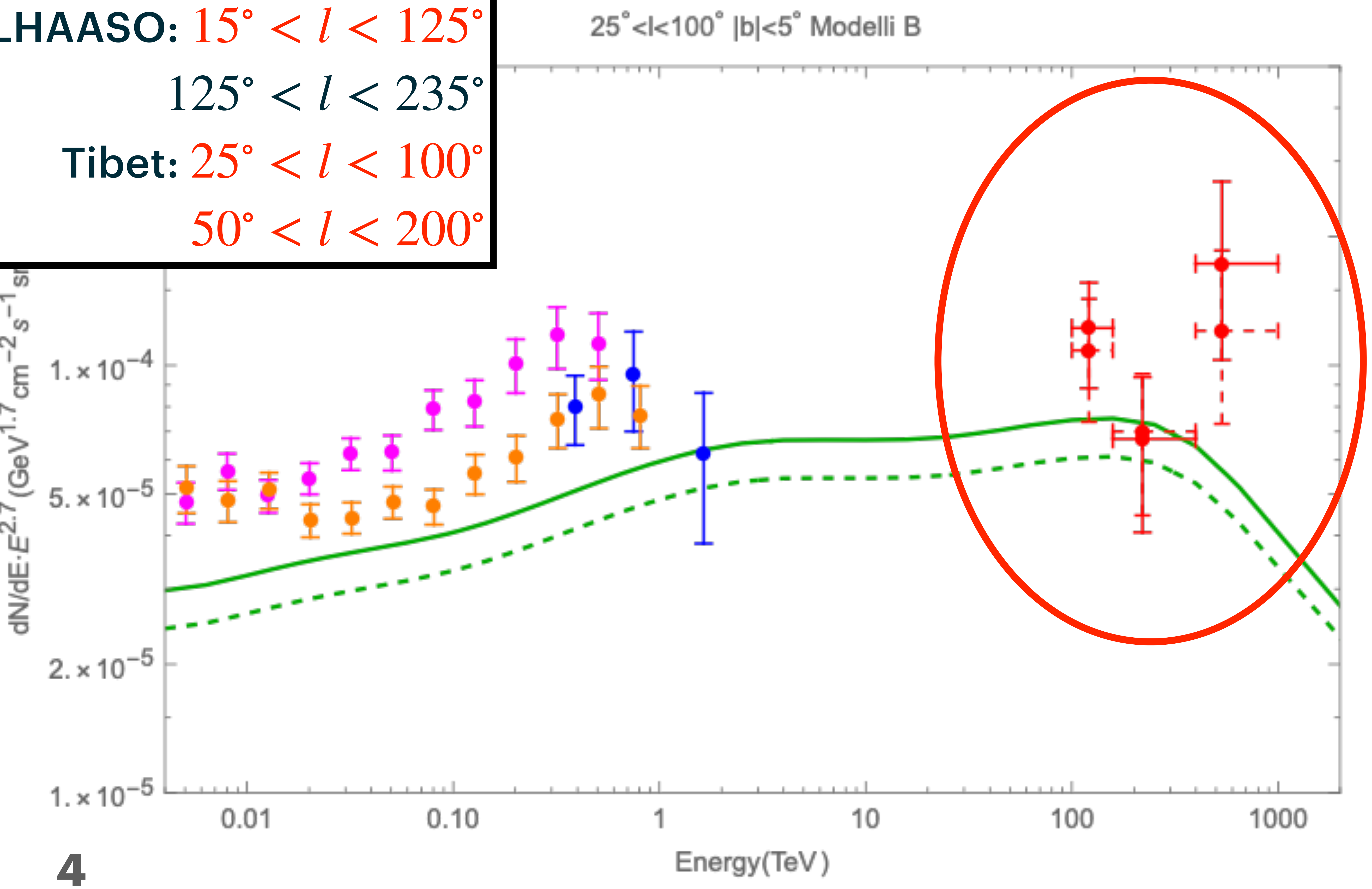
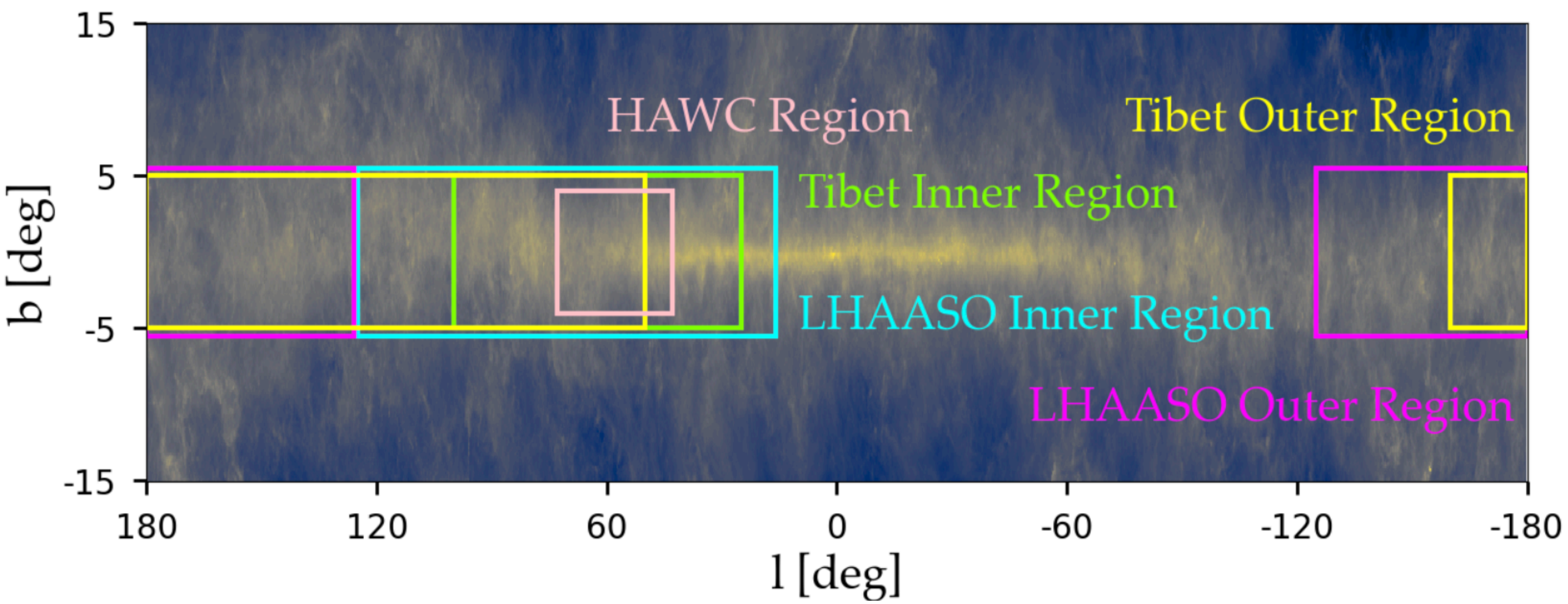


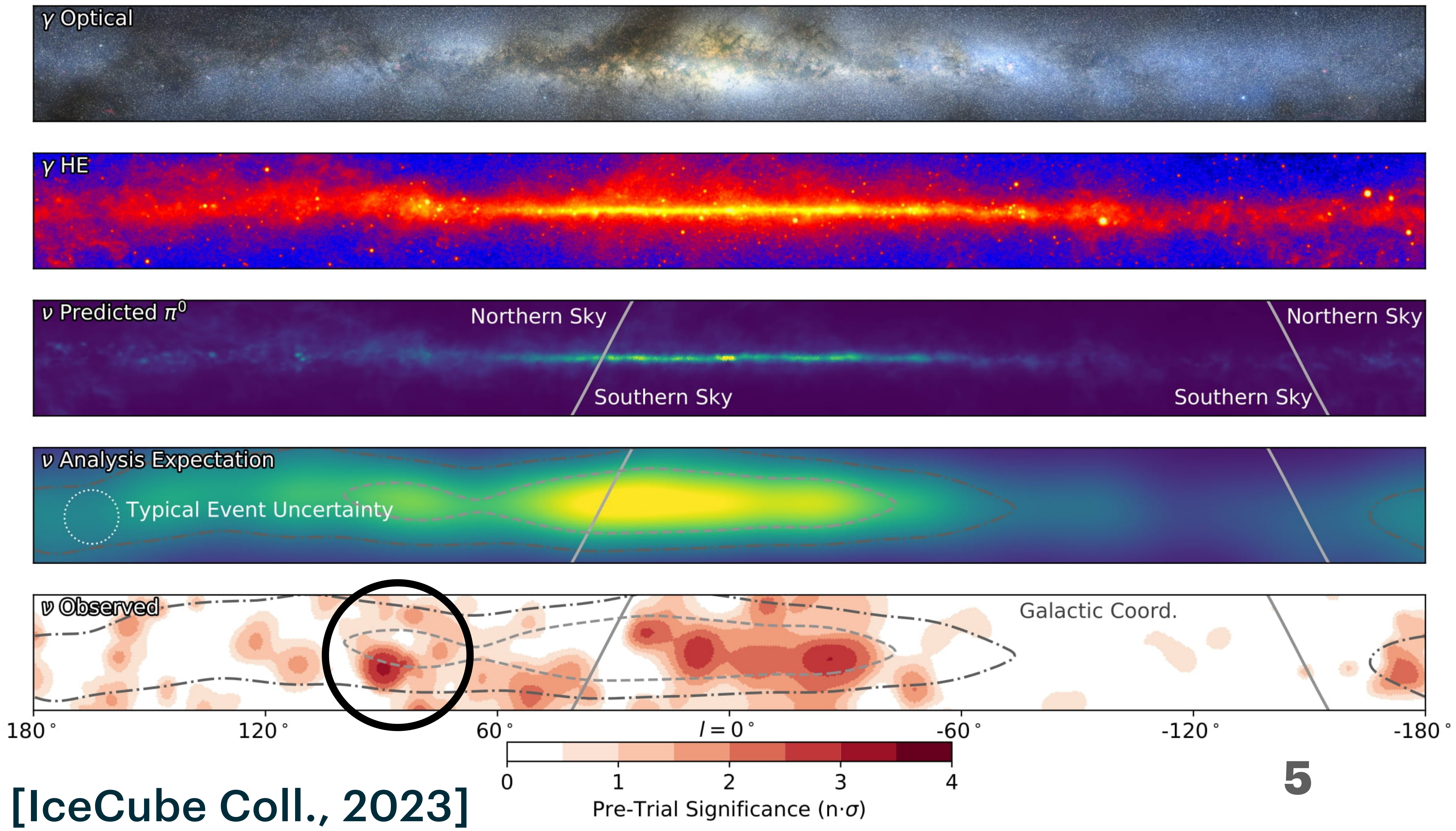
LHAASO: $15^\circ < l < 125^\circ$
$125^\circ < l < 235^\circ$
Tibet: $25^\circ < l < 100^\circ$
$50^\circ < l < 200^\circ$



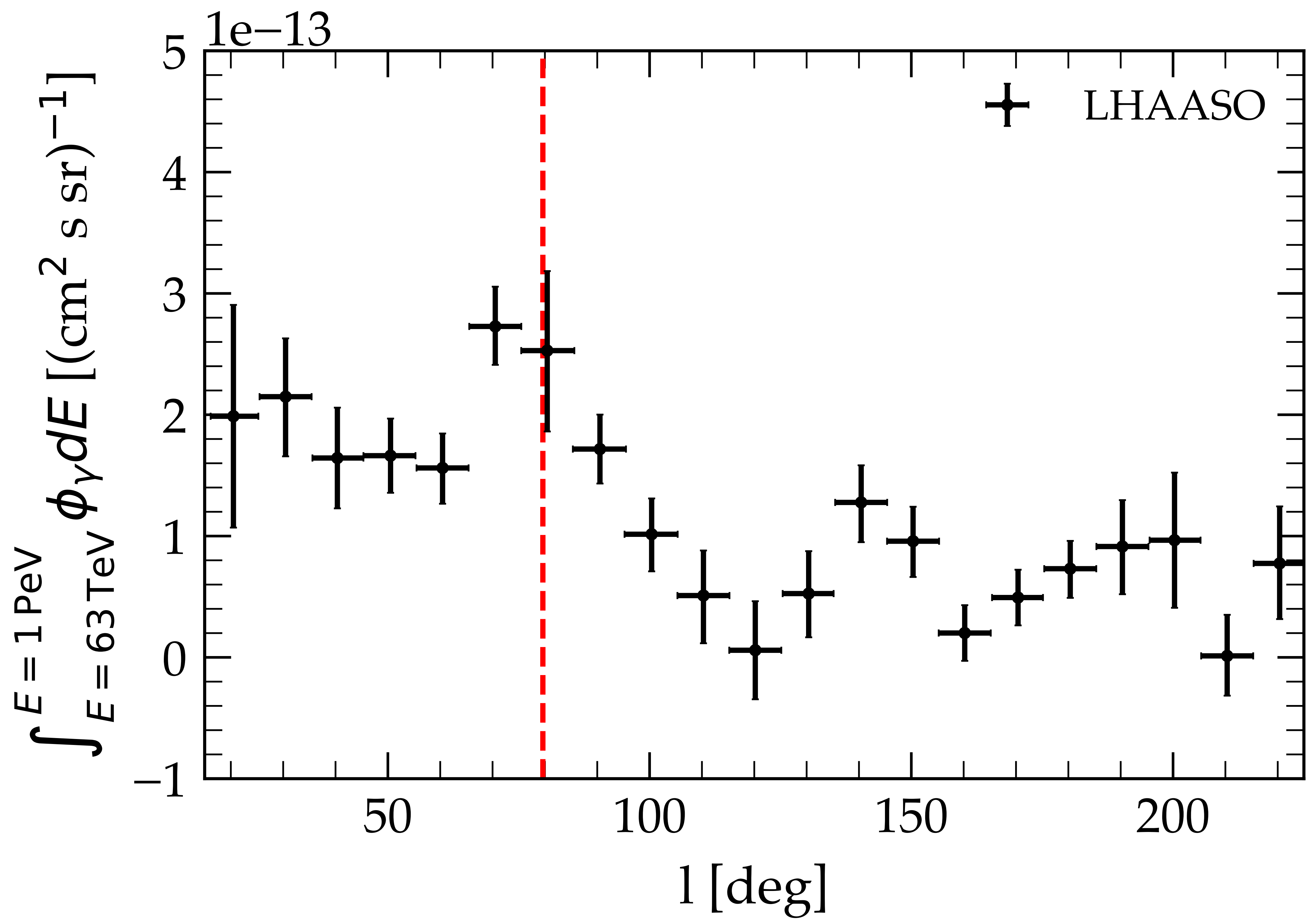
Motivations

- Cygnus is a sky region in common for all VHE gamma-ray observatories.
- **Neutrino observations** along Galactic Plane by IceCube show a slightly higher-significance in the same sky region.
- **Longitudinal profile** of gamma-rays show an small excess in Cygnus region only at the **highest energies**.





[IceCube Coll., 2023]



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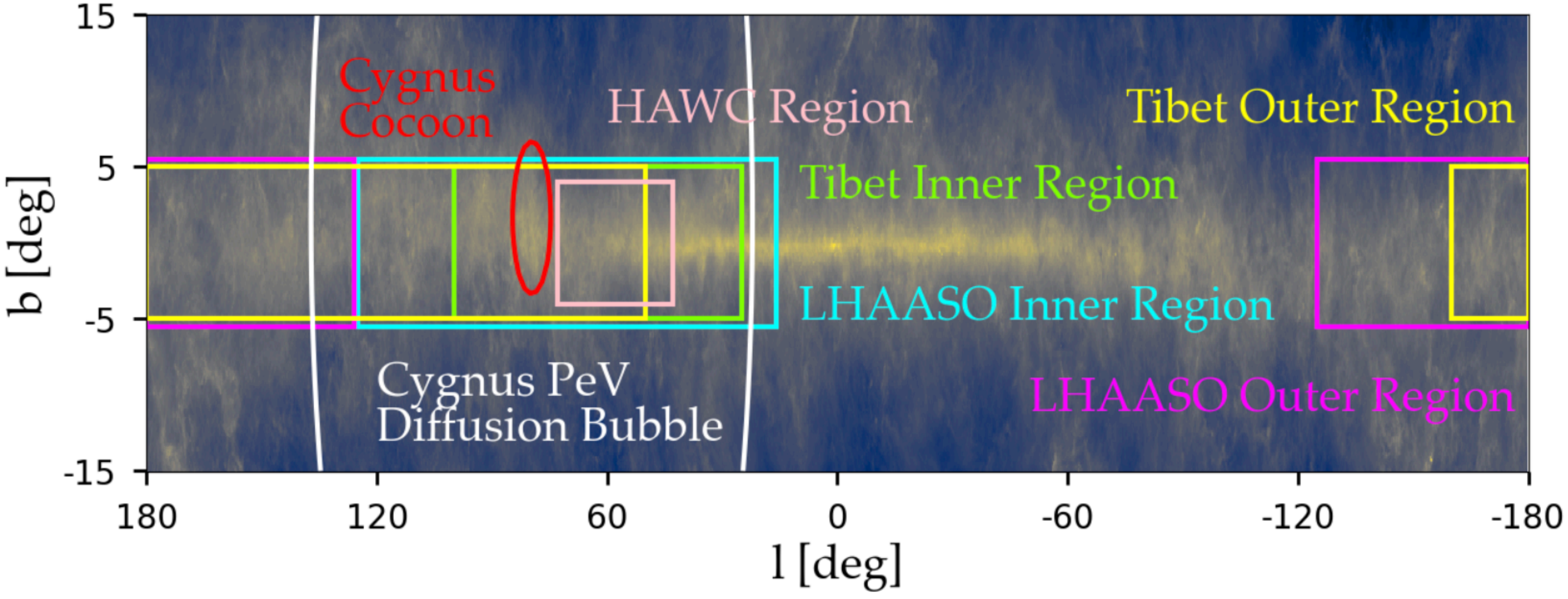

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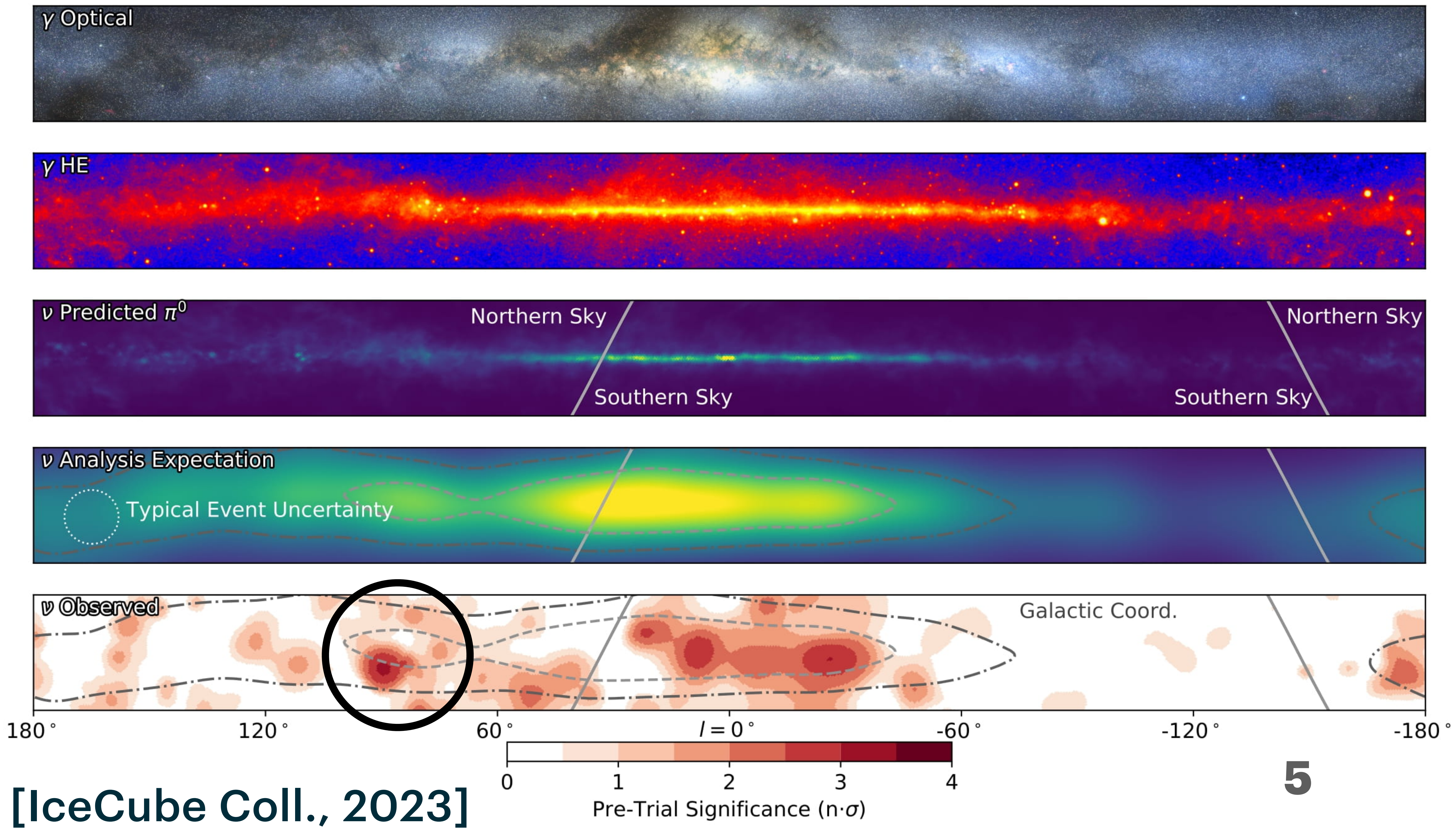
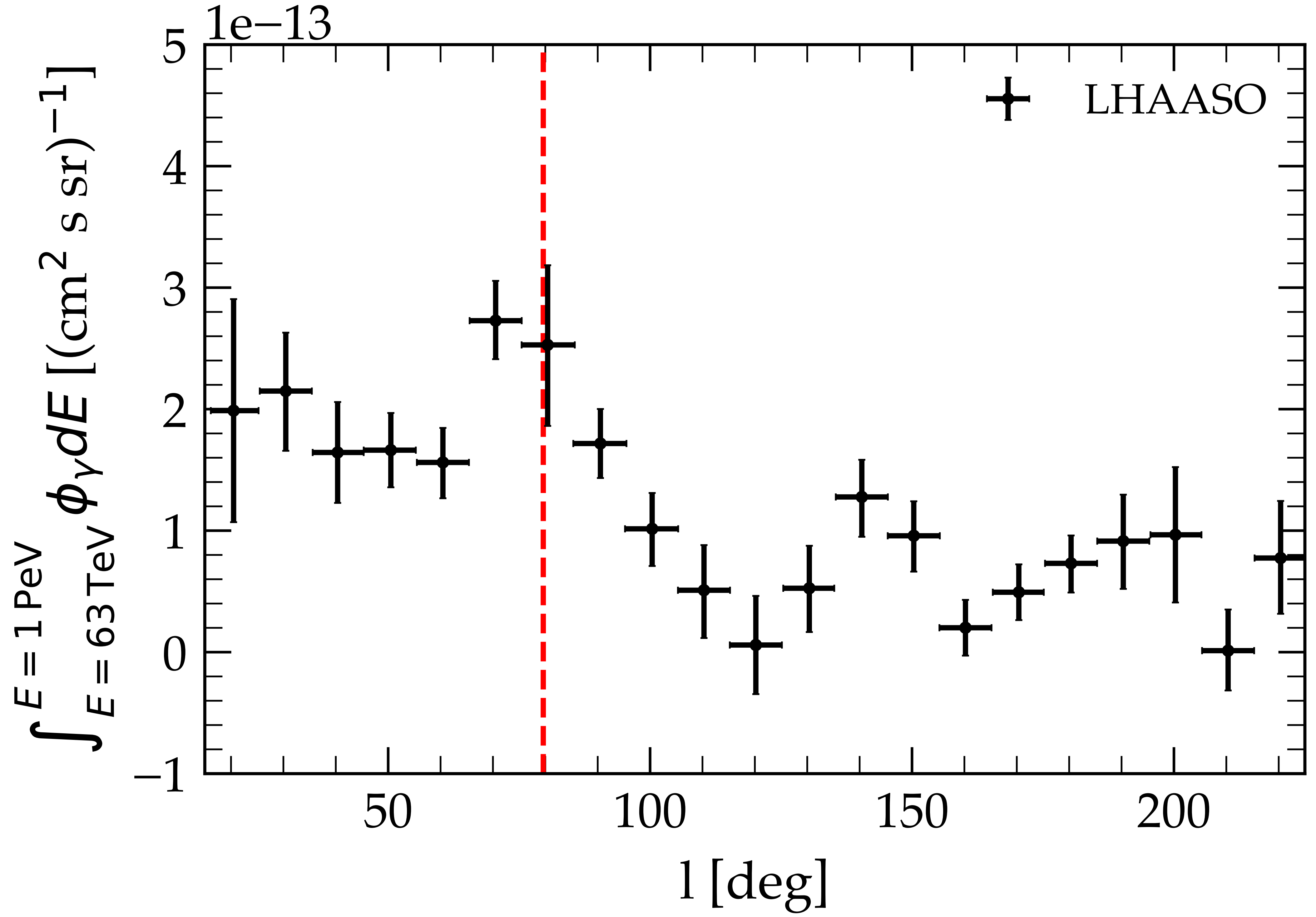
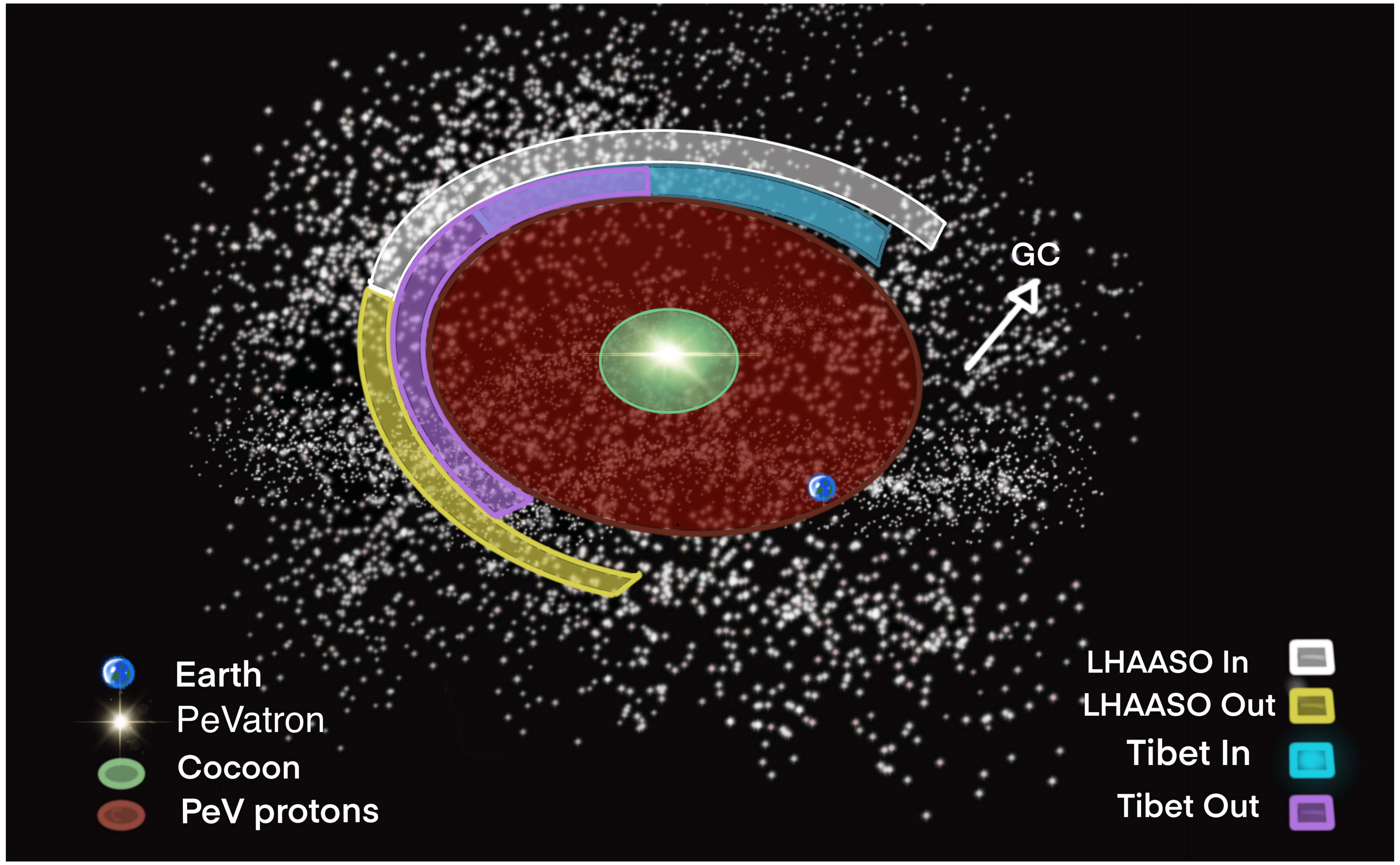


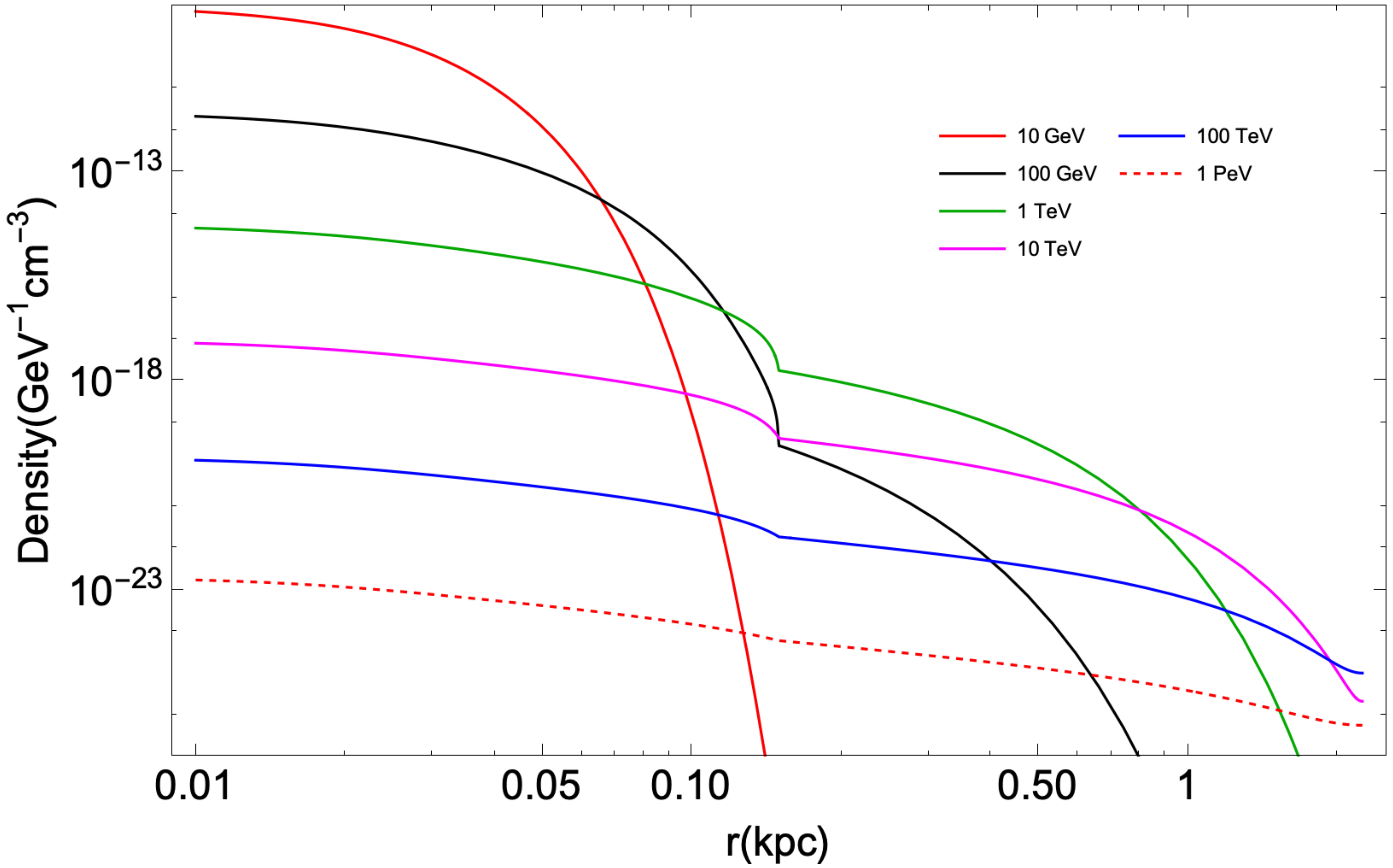


[IceCube Coll., 2023]

Two Population Model: Local Source

- Main idea: Galactic cosmic rays composed of a "low-energy" population (the **CR sea**, associated to SNR) and a "high-energy" contribution from **local PeVatron**.
- LHAASO and TibetASγ suggest such a source could be localised in $(50^\circ < l < 100^\circ, |b| < 5^\circ)$ region
- **Cygnus region** contains a UHE gamma-ray cocoon at ~ 1.4 kpc from Earth.





Galactic Cosmic Rays

Cygnus contribution is not a fit. It is a prediction based on physically motivated parameters

- Cygnus proton injection spectrum [LHAASO Coll., 2024]:

$$\dot{Q}(E_p) = \dot{Q}_0 \left(\frac{E_p}{E_0}\right)^{-s} \exp\left(-\frac{E_p}{E_p^{\max}}\right)$$

$s = 2.1, \quad E_0 = 1\,\mathrm{TeV}, \quad E_{\max} = 5\,\mathrm{PeV}$ and $L_p = \int dE_p\, E_p Q(E_p) = 3 \times 10^{37}\,\mathrm{erg\,s^{-1}}$

- CR propagation following a two-zone model:

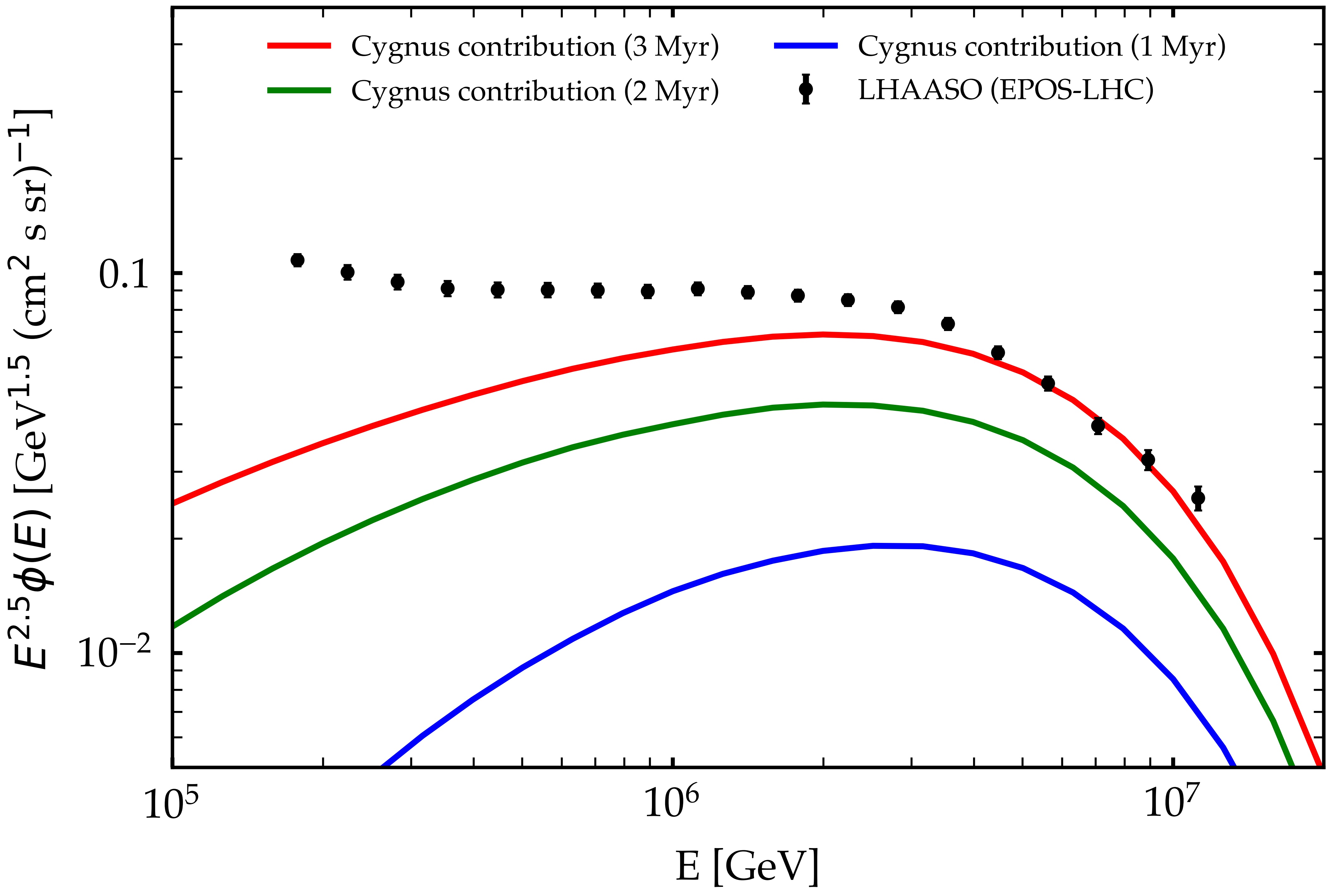
$$\frac{\partial n}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(Dr^2 \frac{\partial n}{\partial r}\right) + Q$$

where $D(r, E_p) = \begin{cases} D_0(E_p/E_0)^{\delta_0} & 0 < r < r_c, \\ D_1(E_p/E_0)^{\delta_1} & r \geq r_c, \end{cases}$

$D_0 = 3 \times 10^{26}, \quad \delta_0 = 0.7, \quad D_1 \sim 10^{28}, \quad \delta_1 = \frac{1}{3}$ and $r_c \sim 150\,\mathrm{pc}$

Solution to transport equation: $Q(r, t, E_p) = \frac{1}{(2\pi R^2)^{3/2}} \exp\left(-\frac{r^2}{2R^2}\right) \dot{Q}(E_p)\theta(t),$

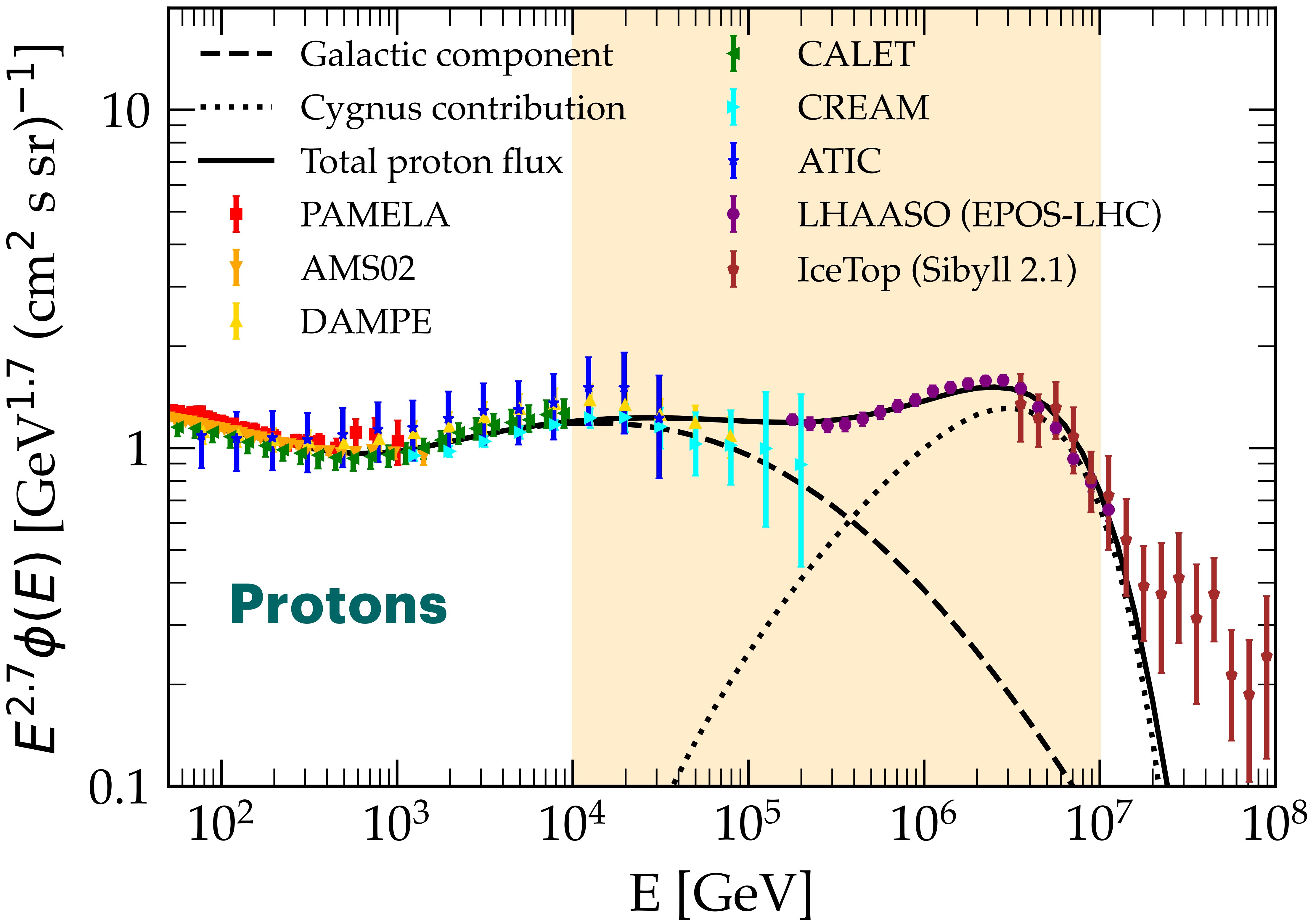
here $R = 1$ pc is source physical size.

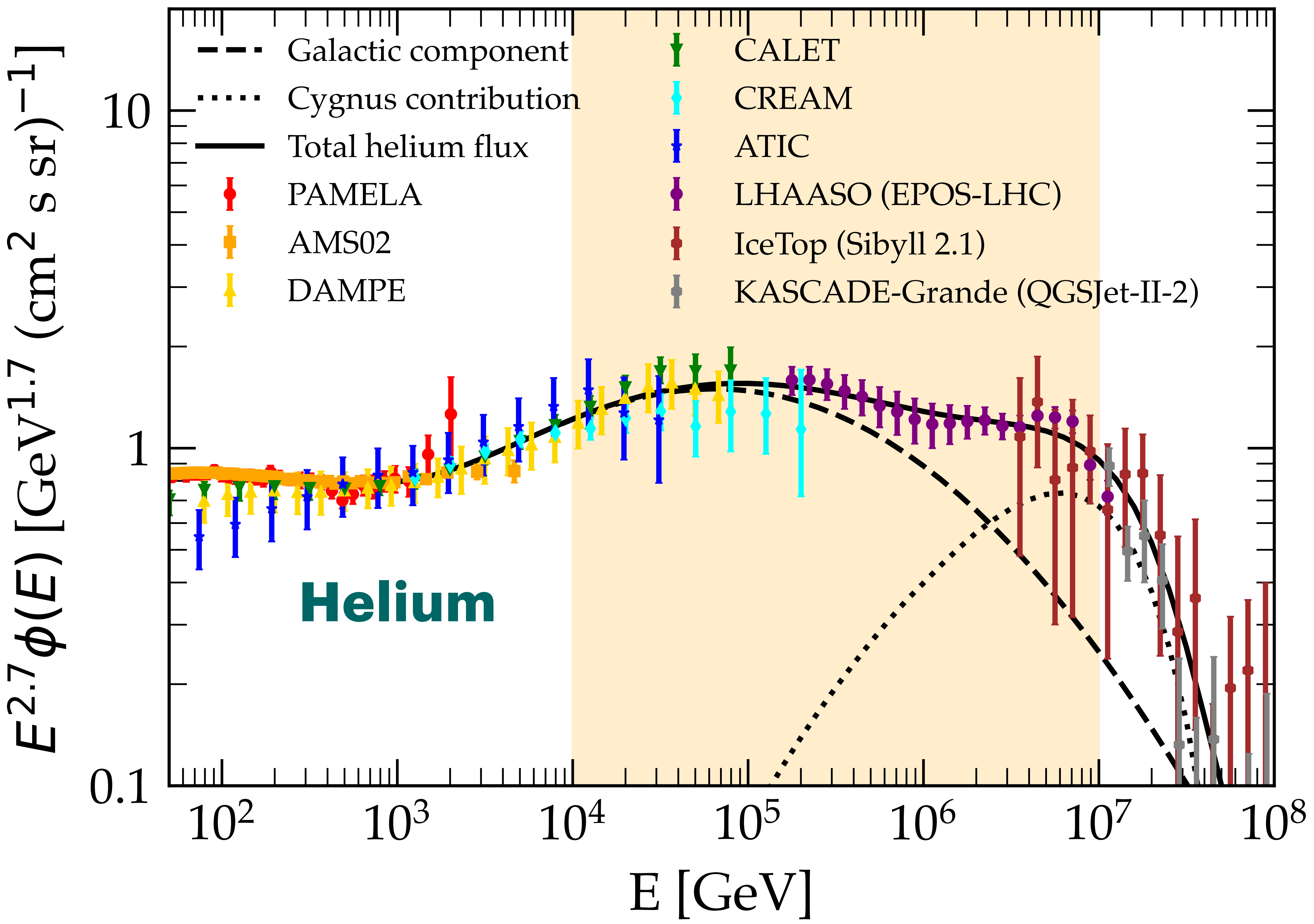


Galactic Cosmic Rays

"CR sea" flux modelled as $\phi_p^{\rm Gal}(E_p) = N\left(\frac{E_p}{\bar{E}}\right)^{-\alpha_1} \Pi_i \left[1 + \left(\frac{E_p}{E_{b,i}}\right)^{\frac{1}{\omega_i}}\right]^{-\Delta\alpha_i \omega_i}$

Then, total CR proton flux at Earth is $\phi_p(E_{\rm n}, \mathbf{r}_\odot) = \phi_p^{\rm Cyg}(E_{\rm n}, \mathbf{r}_\odot) + \phi_p^{\rm Gal}(E_{\rm n})$





Diffuse Flux

$$\phi_\gamma(E_\gamma; s, l, b) = \int_0^\infty ds\, \underbrace{n_{gas}(s, l, b)}_{\text{Gas template}}\, \overbrace{e^{-\tau(s,E_\gamma)}}^{\text{Gamma-ray absorption by CMB}} \int_{E_\gamma}^\infty dE_n\, \overbrace{\frac{d\sigma}{dE_\gamma}(E_n, E_\gamma)}^{\text{Cross-section}}\, \underbrace{\phi_{\mathrm{CR},\odot}(E_\mathrm{n})}_{\text{Cosmic ray nucleon flux}}$$

+ In addition, we consider the contribution of unresolved sources, modelled following [Vecchiotti et al., 2024] where we construct a synthetic PWNe population tuned to the HPGS catalogue.

Diffuse Gamma-Ray Emission

Spectrum of diffuse flux in better agreement with VHE observations

Cygnus region contributes mainly to the inner Galactic region

Unresolved sources subdominant in both regions

Based on [Vecchiotti et al., 2024]

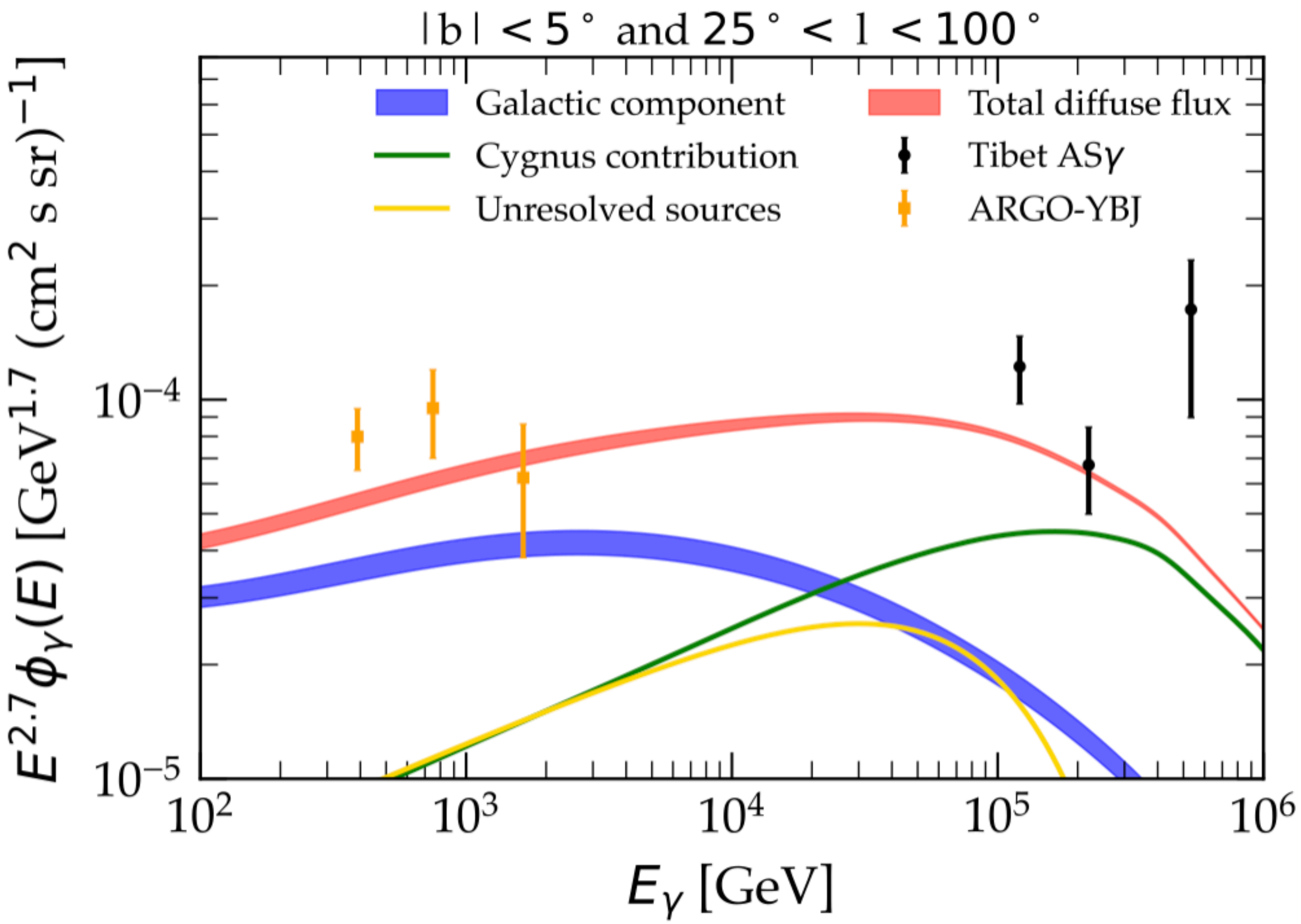
Diffuse Gamma-Ray Emission

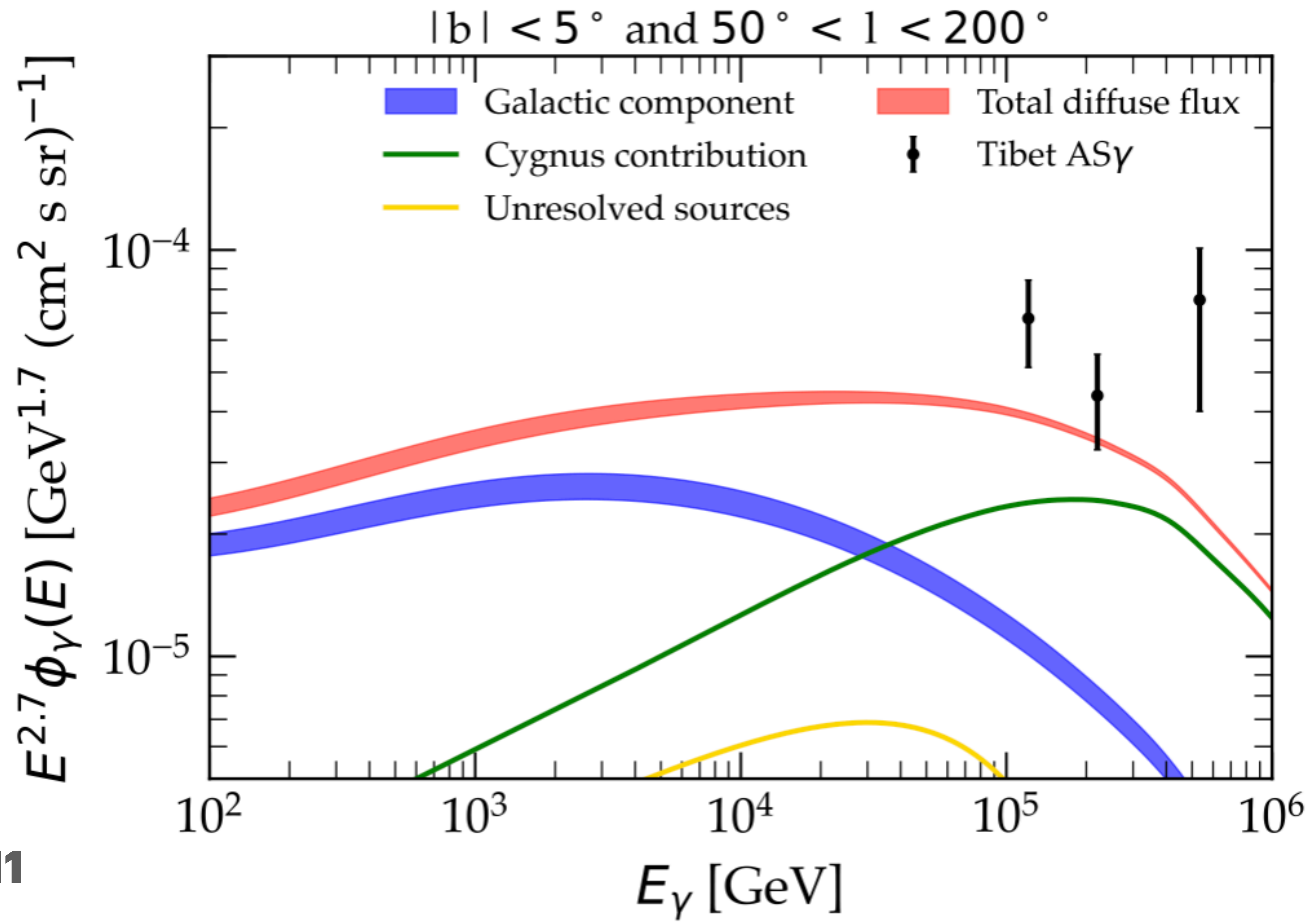
Diffuse flux start reaching VHE observations when subtracting contamination from sources

Cygnus region is the dominant component in both regions at ~ 100 TeV

Unresolved sources become relevant, specially at inner region

See [Kato et al., 2024]



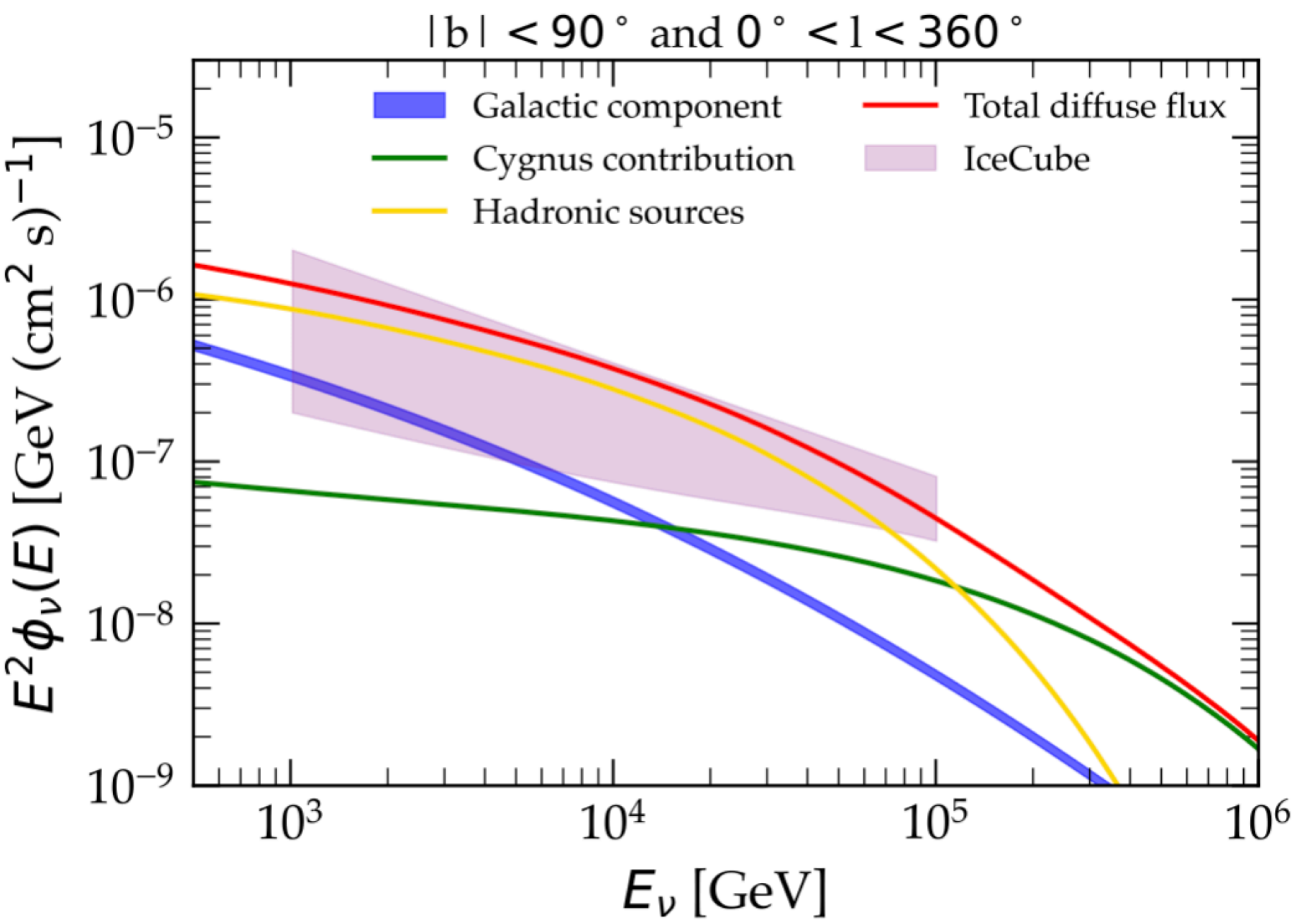


Diffuse Neutrino Emission

Observations of IceCube based on three templates: π^0, KRA_γ^5 and KRA_γ^{50}. Overall good agreement within uncertainties

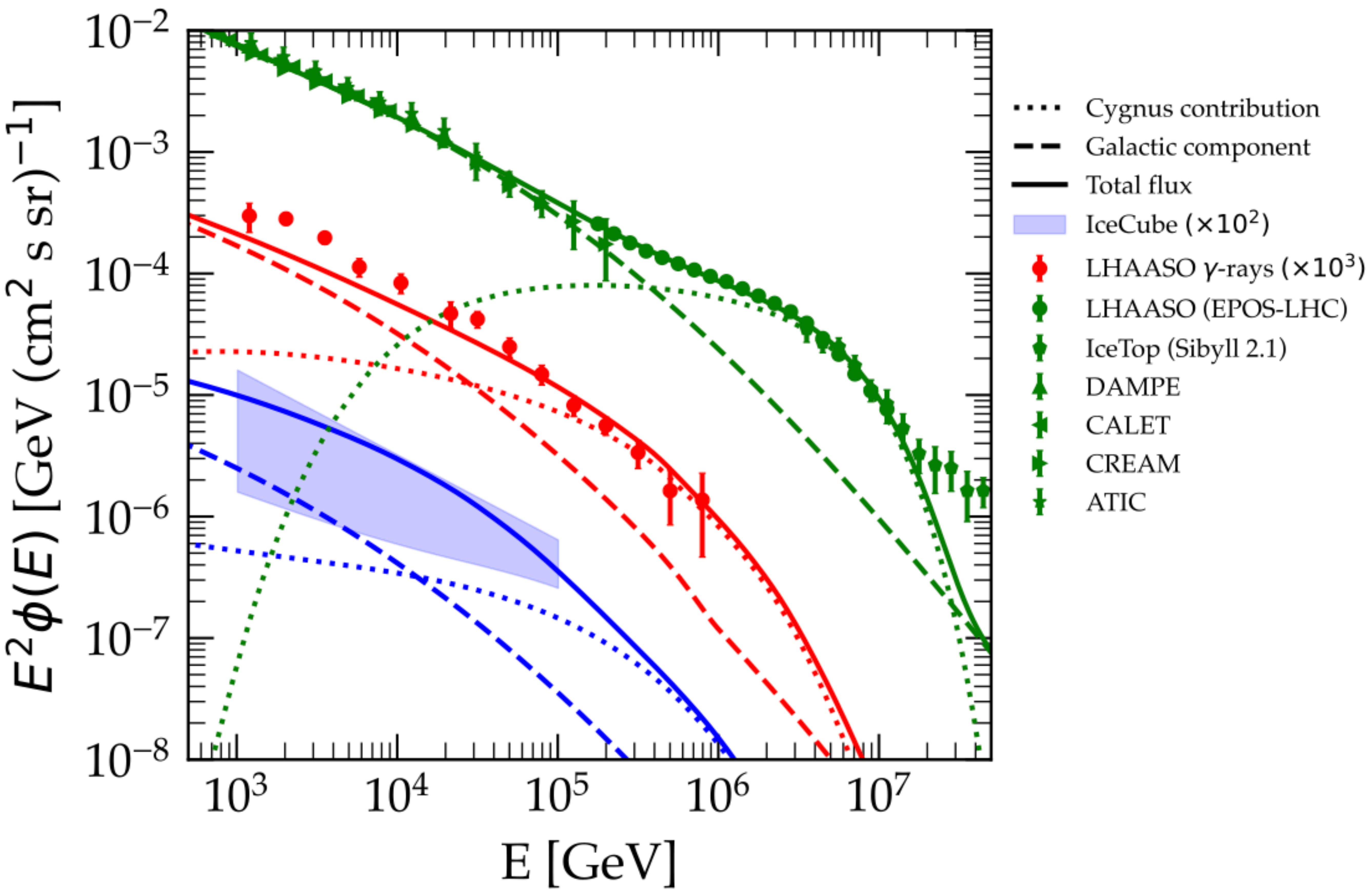
Neutrino contribution of Cygnus region is significant. However, IceCube observation energy range probes it just partially

Up to 50% of sources can be considered as hadronic



Summary

For more details, see arXiv:2603.21665



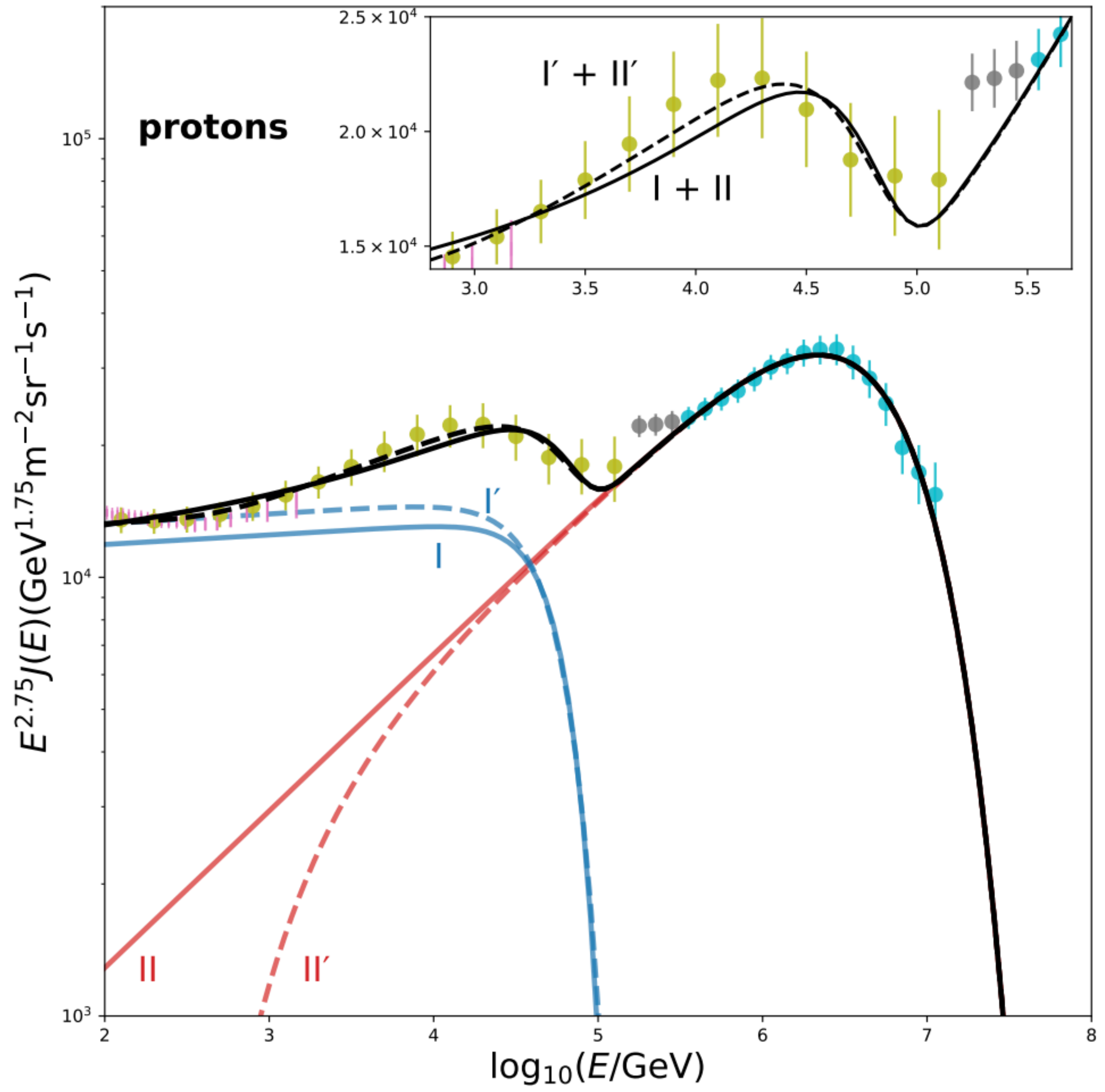
- A two-population model is able to **reproduce observations** of the VHE diffuse gamma-ray and neutrino emissions.
- **Spatial dependence** of the diffuse gamma-ray spectrum is in agreement with a local source contribution in the Cygnus region.
- The **Cygnus UHE Cocoon** is located in this sky region, hosting few PeVatron candidates (microquasar, hypernova, stellar cluster).
- Further exploration of the source properties is currently being done to distinguish the accelerator type and the cumulative contribution of this class of accelerators.

Backup Slides

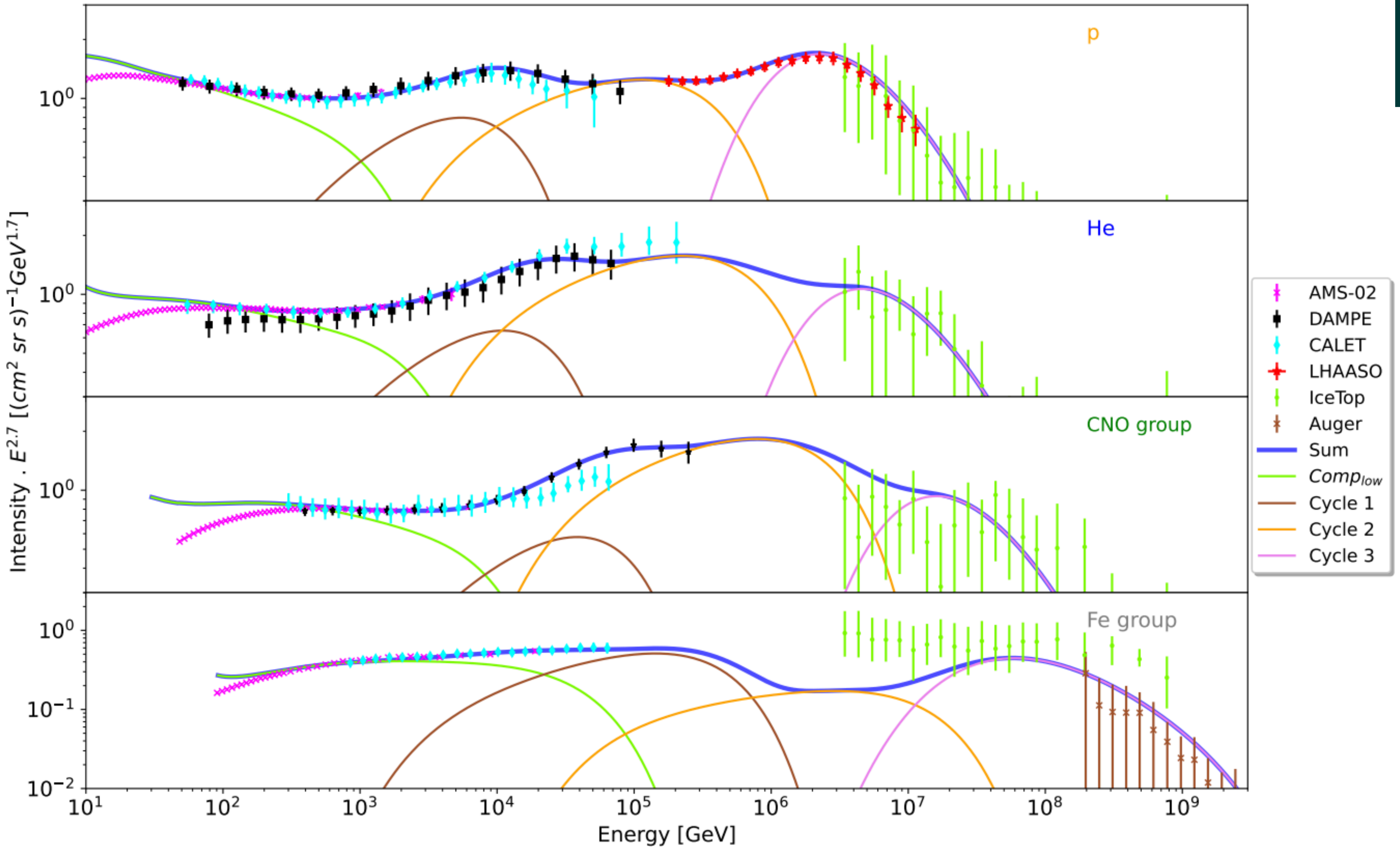
Galactic Cosmic Ray Populations

Direct and indirect observations of cosmic rays have shown that a **single population is unable to reproduce all spectral features** found from GeV to PeV energies.

Several multi-population models of Galactic cosmic rays have been proposed.

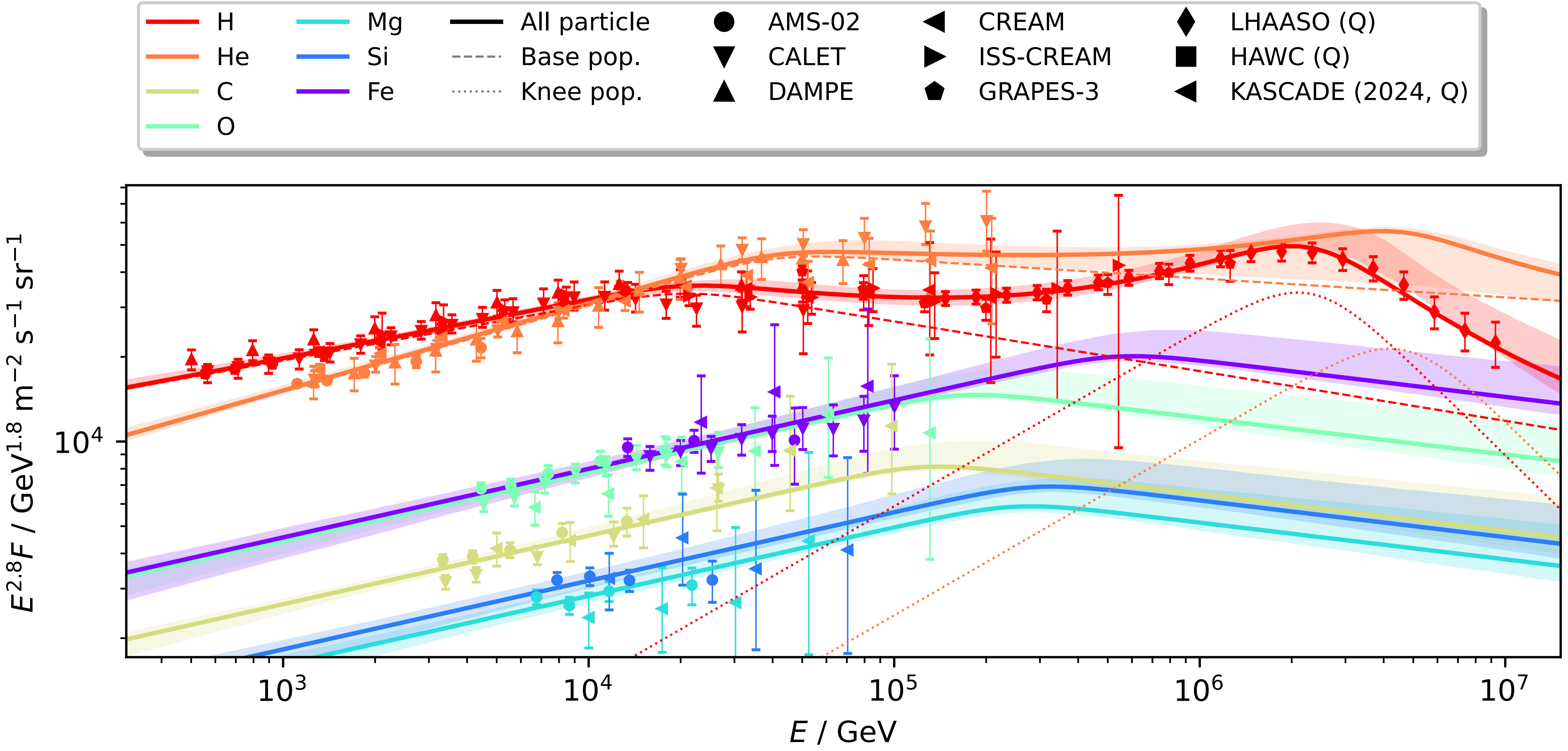


[Aharonian & Zhang, 2026]



[Prevotat et al., 2025]

... and many more!



[Vaiman et al., (PoS ICRC2025)]

Unresolved Sources

In addition, we consider the contribution of unresolved sources. We model them following [Vecchiotti et al., 2024], using a synthetic PWNe population with

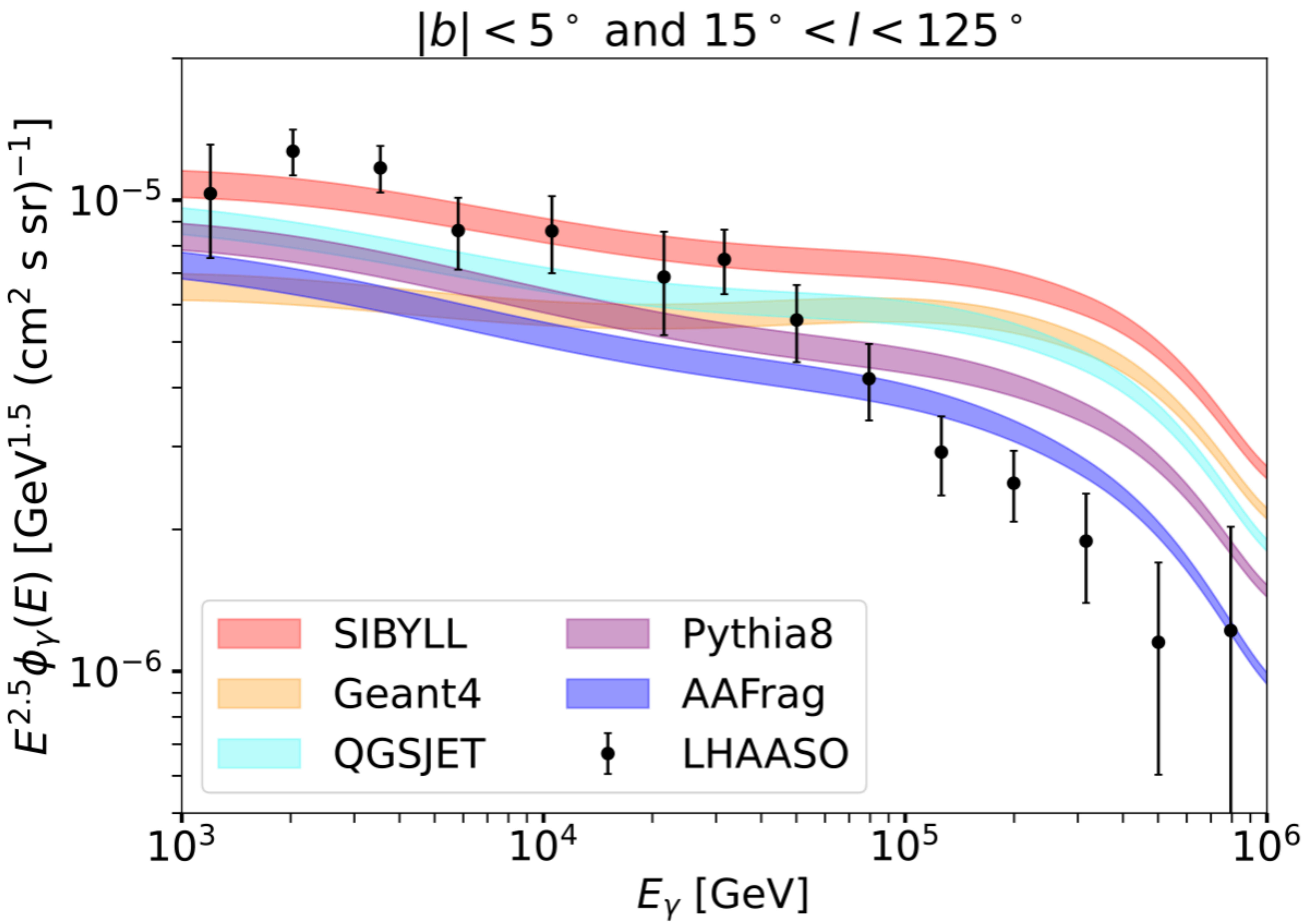
- Spectrum $\propto \left(\frac{E}{E_0}\right)^{-2.4} \exp\left(-\frac{E}{E_{\max}}\right)$ with $E_0 = 3\,\mathrm{TeV}$ and $E_{\max} = 100\,\mathrm{TeV}$.

- Intrinsic luminosity $L(t_{\mathrm{age}}) = L_{\max}\left(1 + \frac{t_{\mathrm{age}}}{\tau_{\mathrm{sd}}}\right)^{-2}$ with

  $L_{\max} = 1.87 \times 10^{35}\,\mathrm{erg\,s^{-1}}$, $\tau_{\mathrm{sd}} = 2.9\,\mathrm{kyr}$ and t_{age} uniformly sampled from $[0, 10^6]$ yr.

- Spatial distribution $\propto \exp\left(-\frac{|z|}{H}\right)$ with Galactic disk thickness $H = 0.05$ kpc.

Role of Cross-Section Model



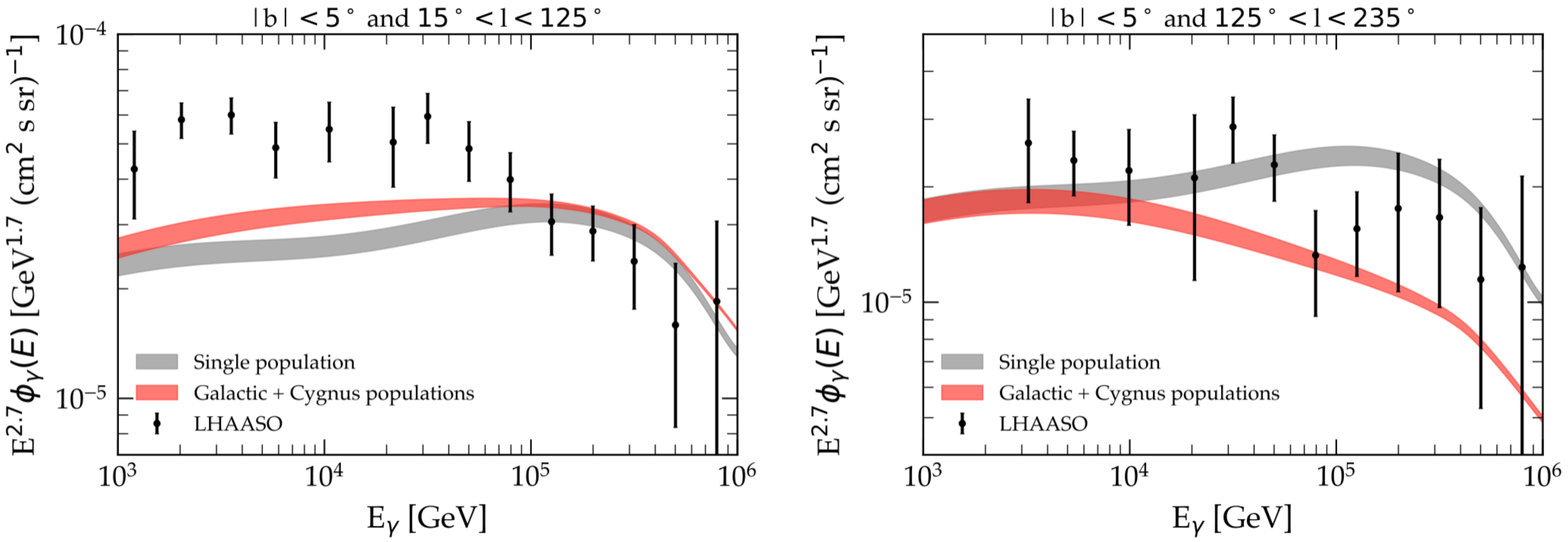
Cross-section model corresponds to a significant uncertainty in the overall normalisation of the diffuse flux.

Disagreement of spectral shape cannot be attributed to cross-section parametrisation.

AAFRag model [Kachelriess et al., 2023] adopted for its better reproduction of accelerator data and lower tension implied between theoretical predictions and observations.

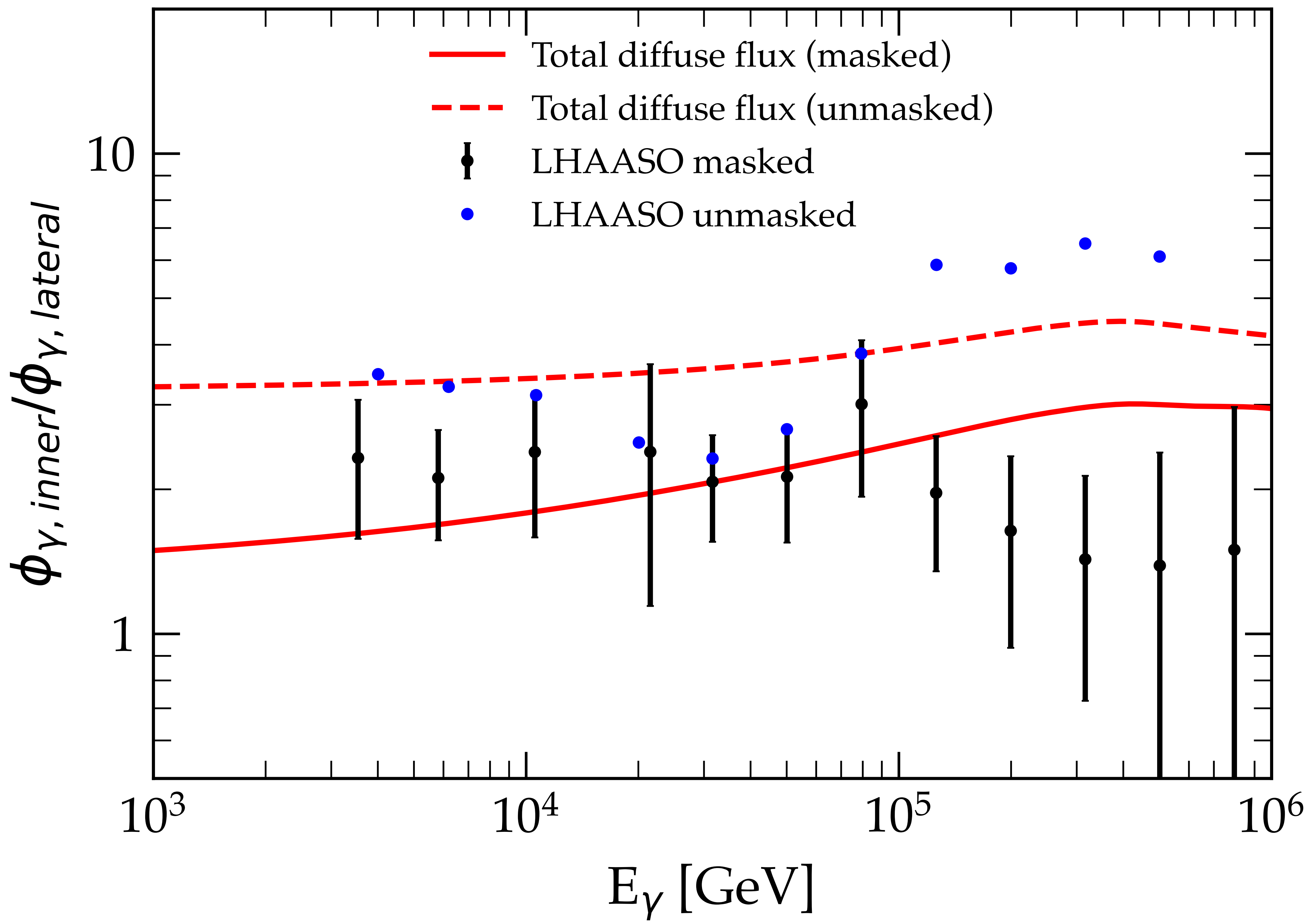
Diffuse Gamma-Ray Emission

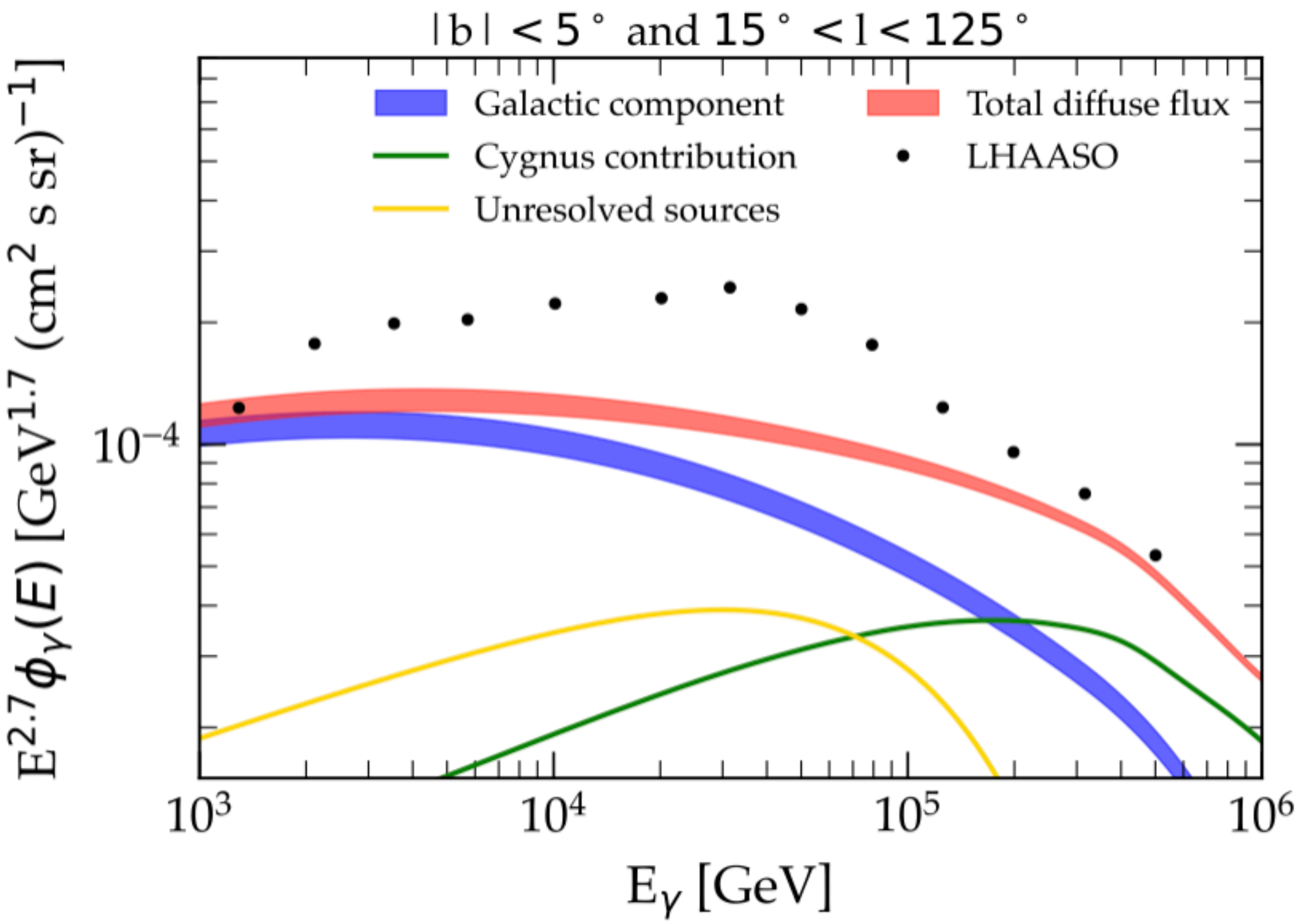
- Better agreement for the two-population model (specially in inner Galactic region) in contrast to previous π^0 model in [Espinosa Castro et al., 2025] which only considers one Galactic CR population.

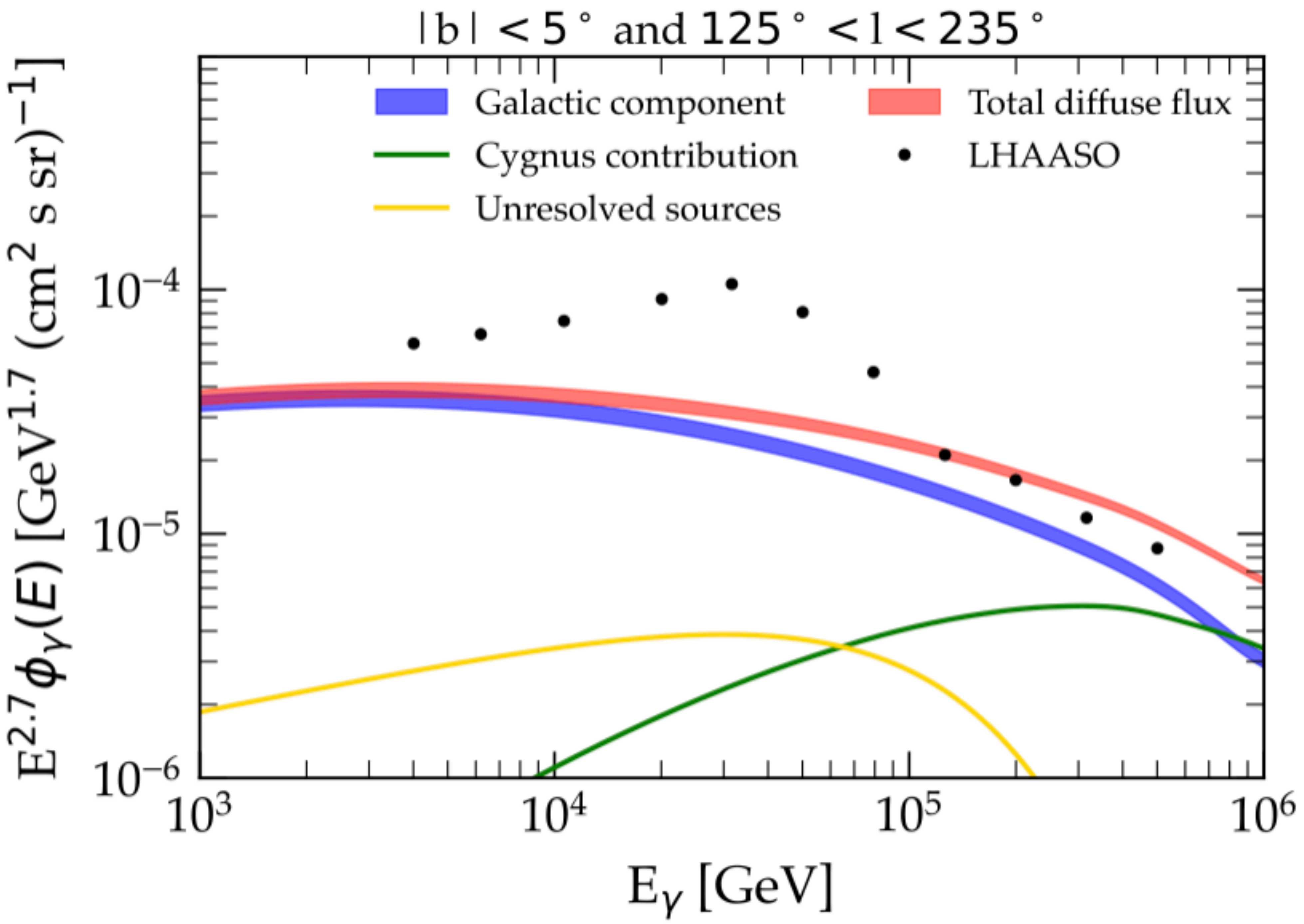


Diffuse Gamma-Ray Emission

- When we remove the mask, Cygnus region contribution still significant but still leave room for other Galactic sources, according to LHAASO observations.
- Spectrum at lower energies differs from Fermi-LAT observations, particularly in inner Galactic region.





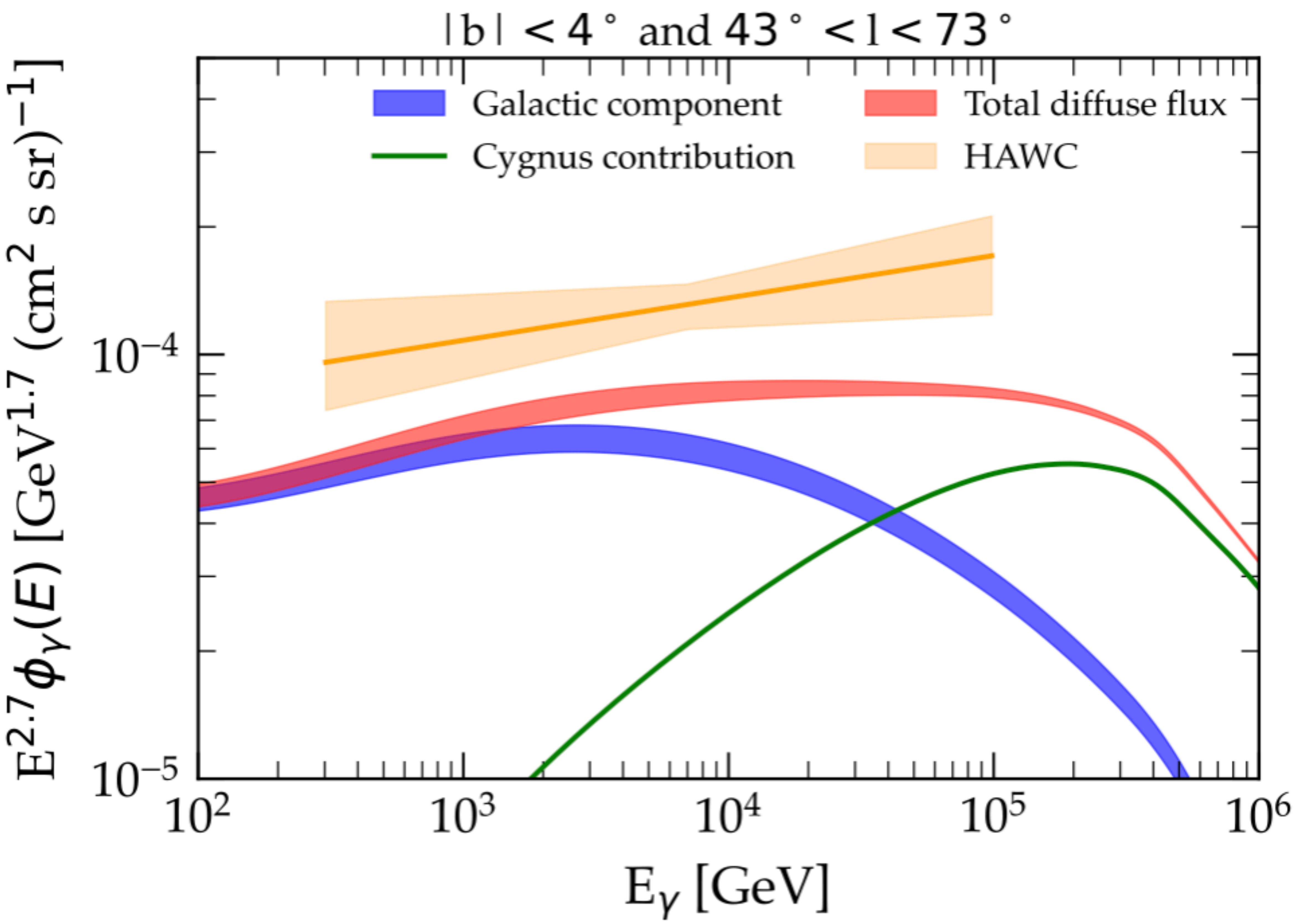


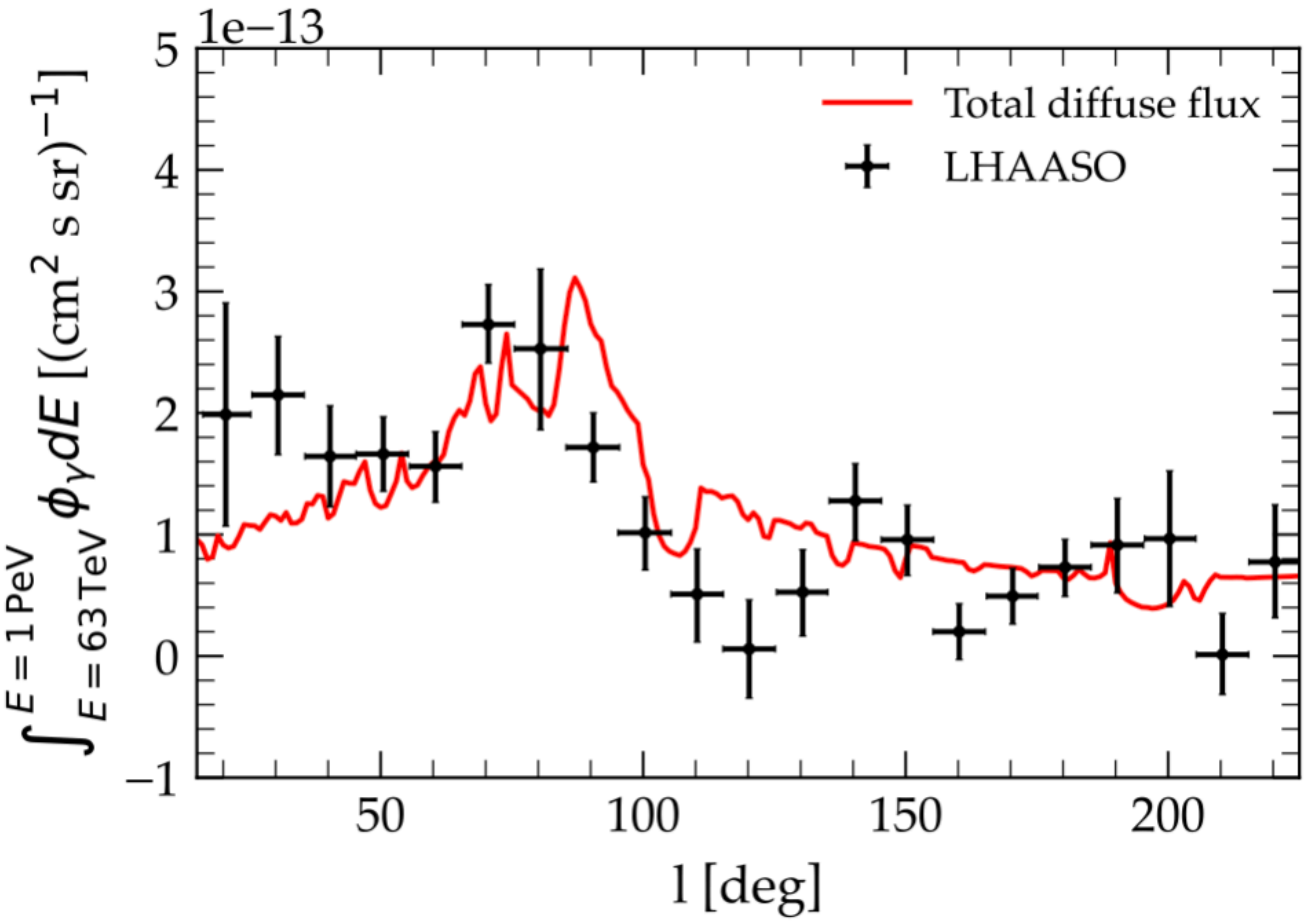
Diffuse Gamma-Ray Emission

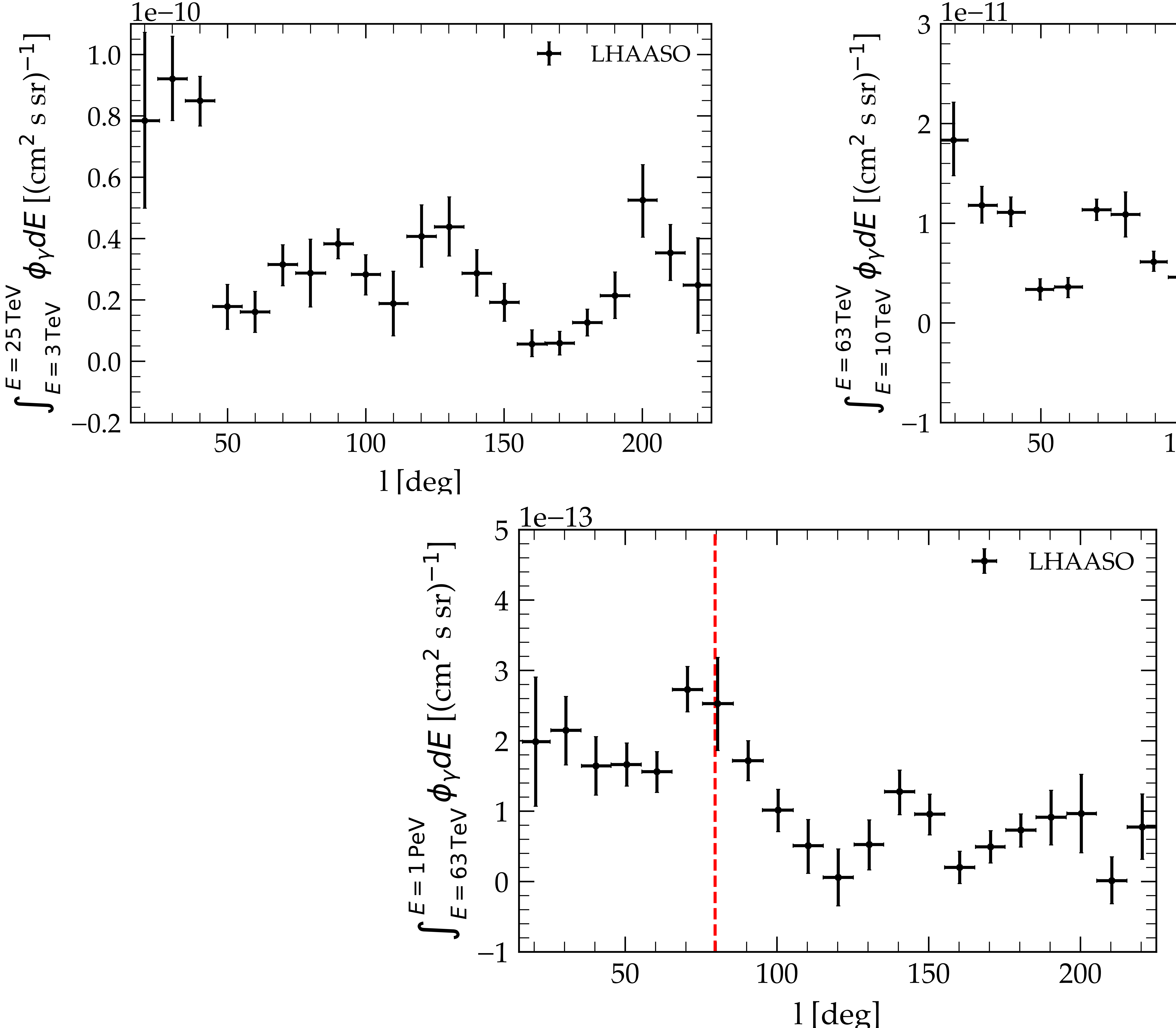
Diffuse flux in good agreement with spectral shape but unresolved TeV component required

Reproduction of longitudinal profile at high energies around Cygnus region

PRELIMINARY







1e−10
LHAASO
$\int_{E=3\,\mathrm{TeV}}^{E=25\,\mathrm{TeV}} \phi_\gamma dE$ [(cm^2 s sr)$^{-1}$]
l [deg]
1e−11
LHAASO
$\int_{E=10\,\mathrm{TeV}}^{E=63\,\mathrm{TeV}} \phi_\gamma dE$ [(cm^2 s sr)$^{-1}$]
l [deg]
1e−13
LHAASO
$\int_{E=63\,\mathrm{TeV}}^{E=1\,\mathrm{PeV}} \phi_\gamma dE$ [(cm^2 s sr)$^{-1}$]
l [deg]