Multimessenger constrains on Galactic CR origin and diffuse gamma-ray and neutrino emission

References:

Yu and BTZ, 2026, submitted to ApJL

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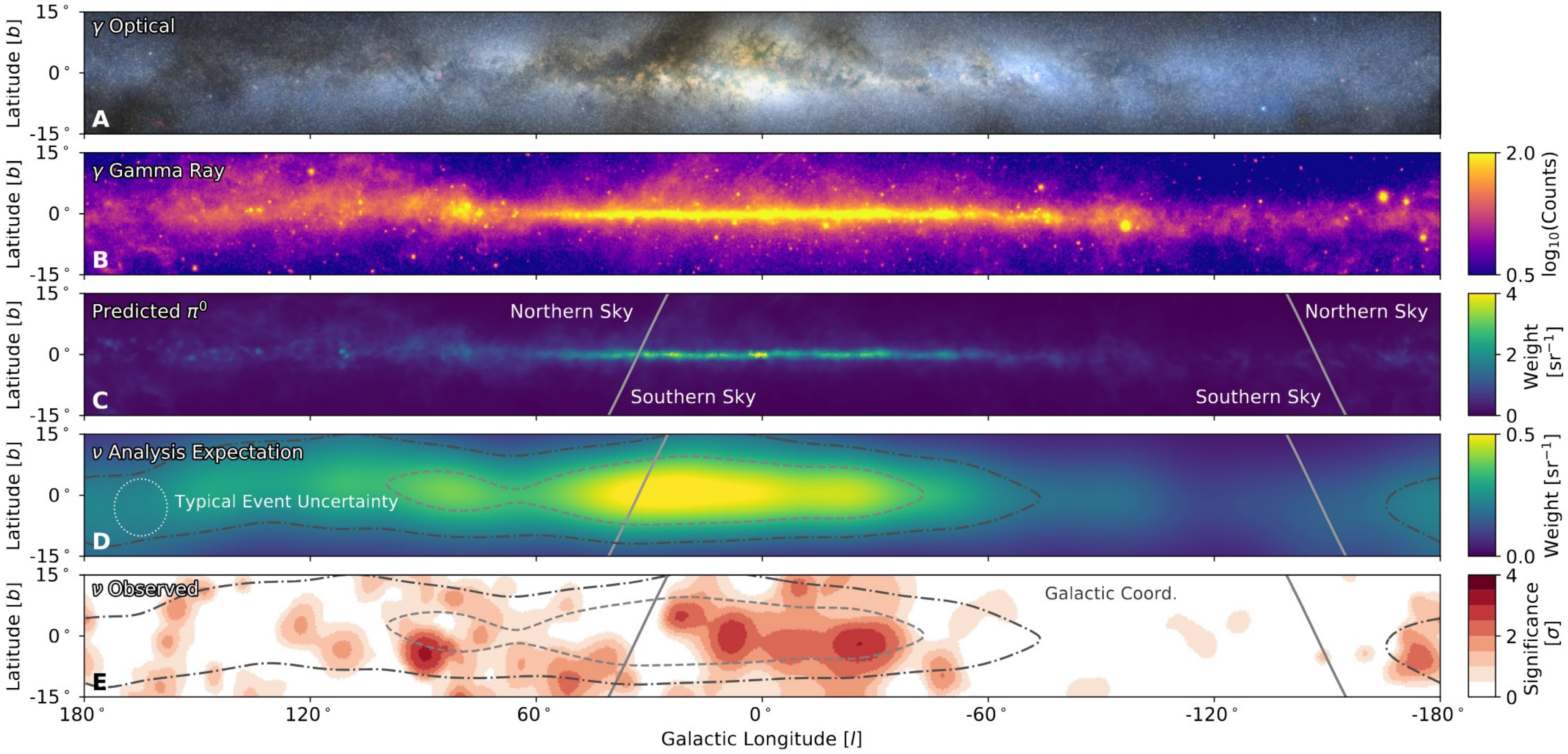
The plane of the Milky Way in photons and neutrinos

IceCube Collab. 2023

Neutrino emission from the Galactic plane at the 4.5σ level of significance

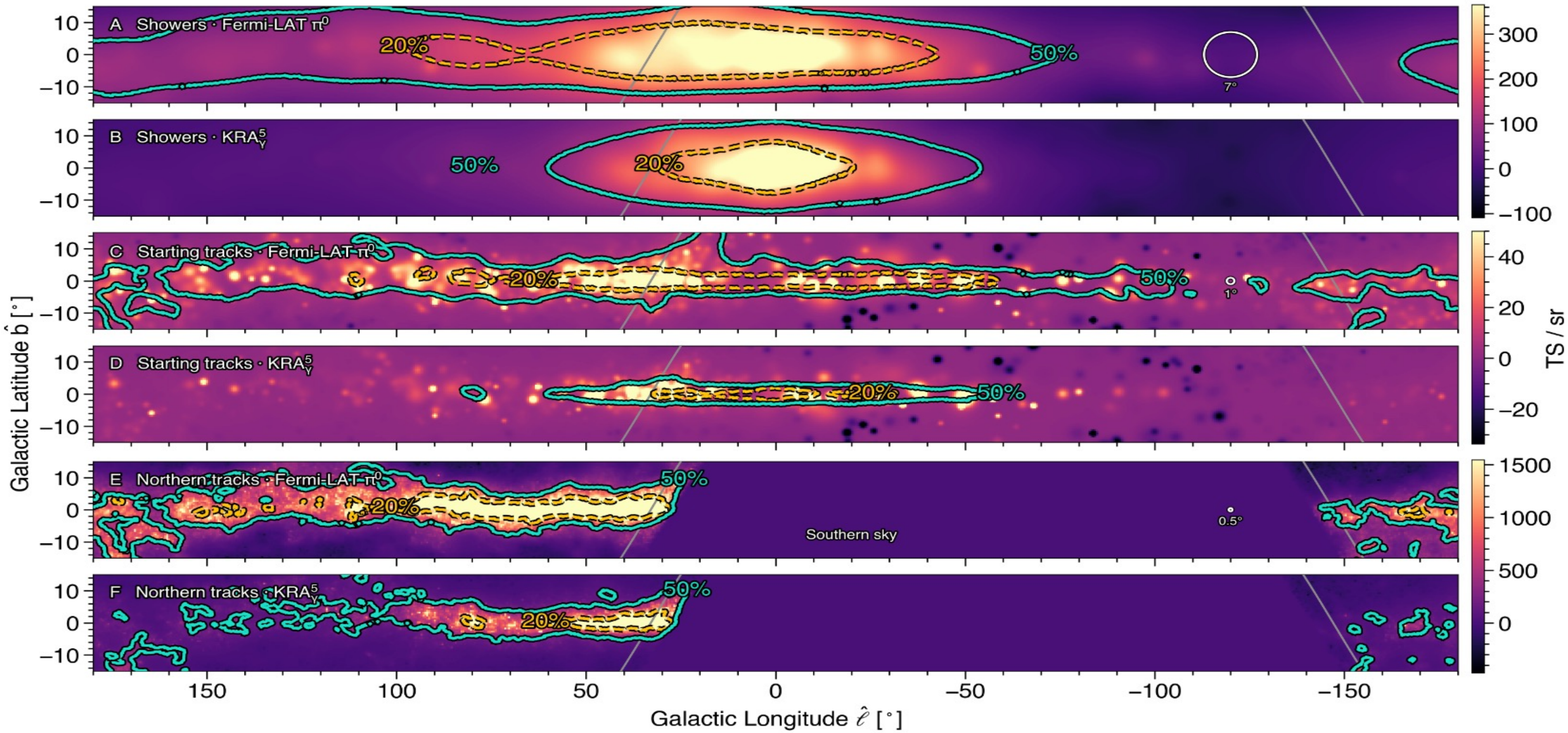


Near their sources and during propagation, cosmic rays interact with matter and produce high-energy gamma-rays and neutrinos

Observation of Galactic plane with neutrinos

IceCube Collab. 2026

High-energy neutrino emission from the Galactic plane at 5.7 σ significance



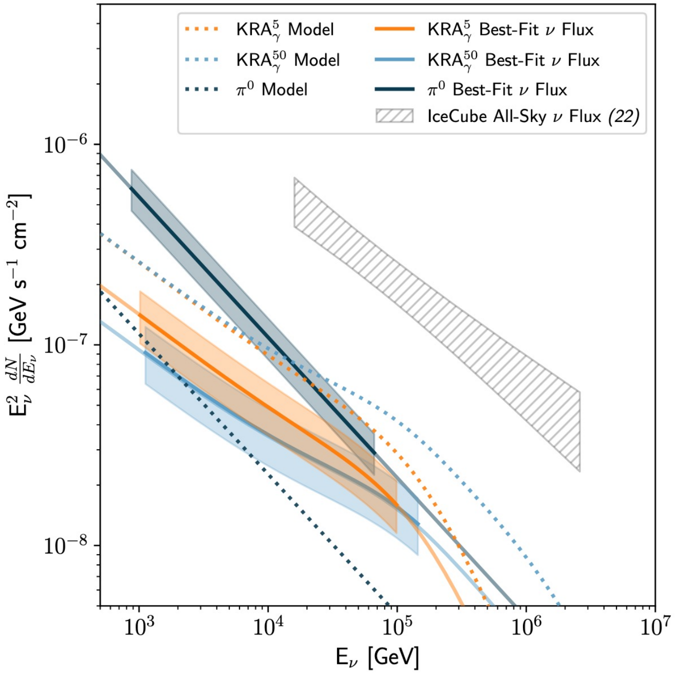
Shower samples (A, B)

Starting-track samples (C, D)

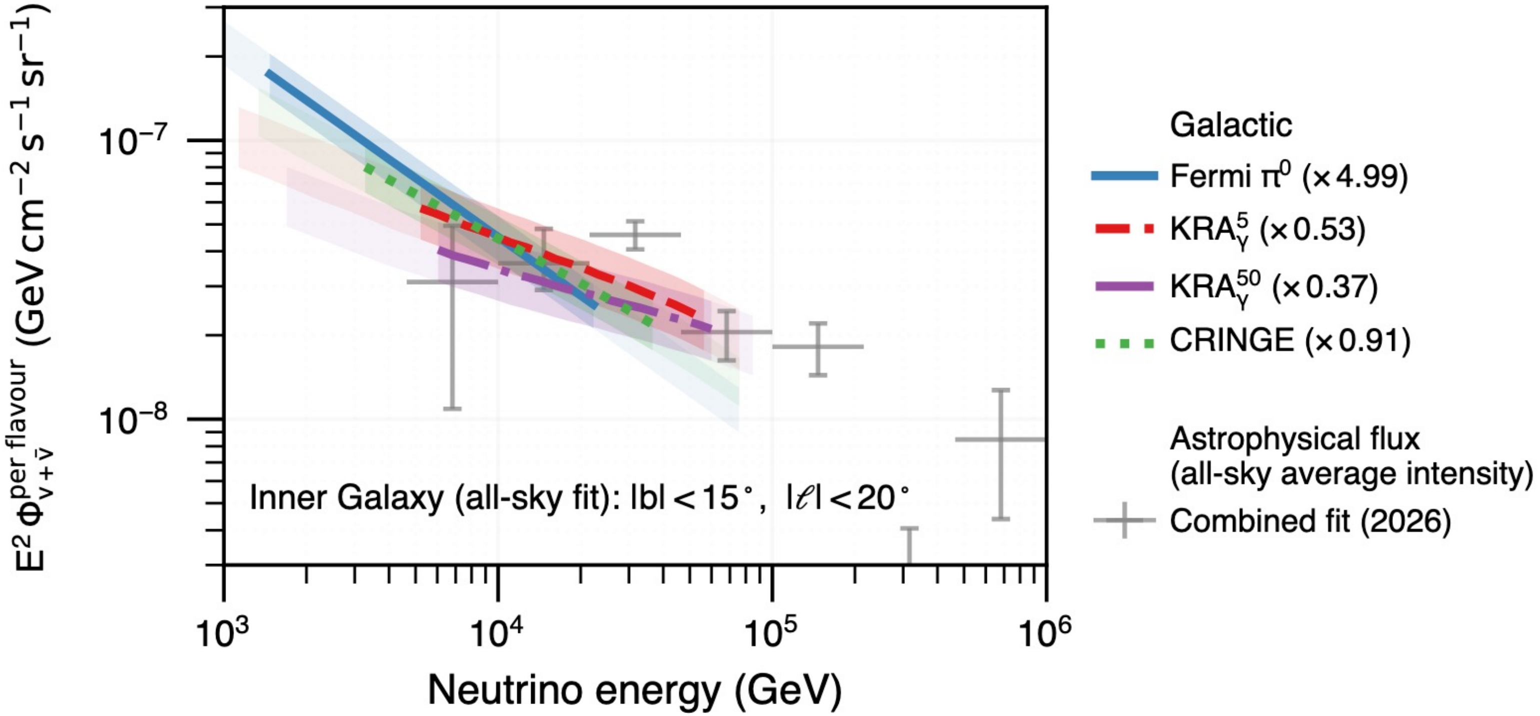
Northern-track samples (E, F)

Energy spectrum of Galactic diffuse emission

IceCube Collab. 2023



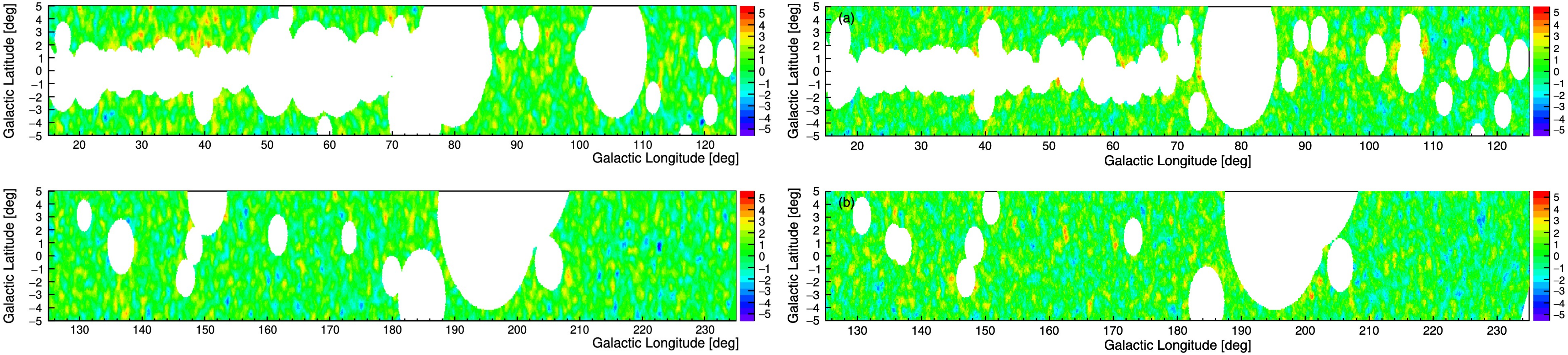
IceCube Collab. 2026



- Based on the all-sky (4π sr) template and are presented as an all-sky flux

- Diffuse Galactic neutrino spectra averaged over the Inner Galaxy
- Comparable to the all-sky averaged astrophysical intensity

Galactic diffuse VHE gamma-ray emission



WCDA

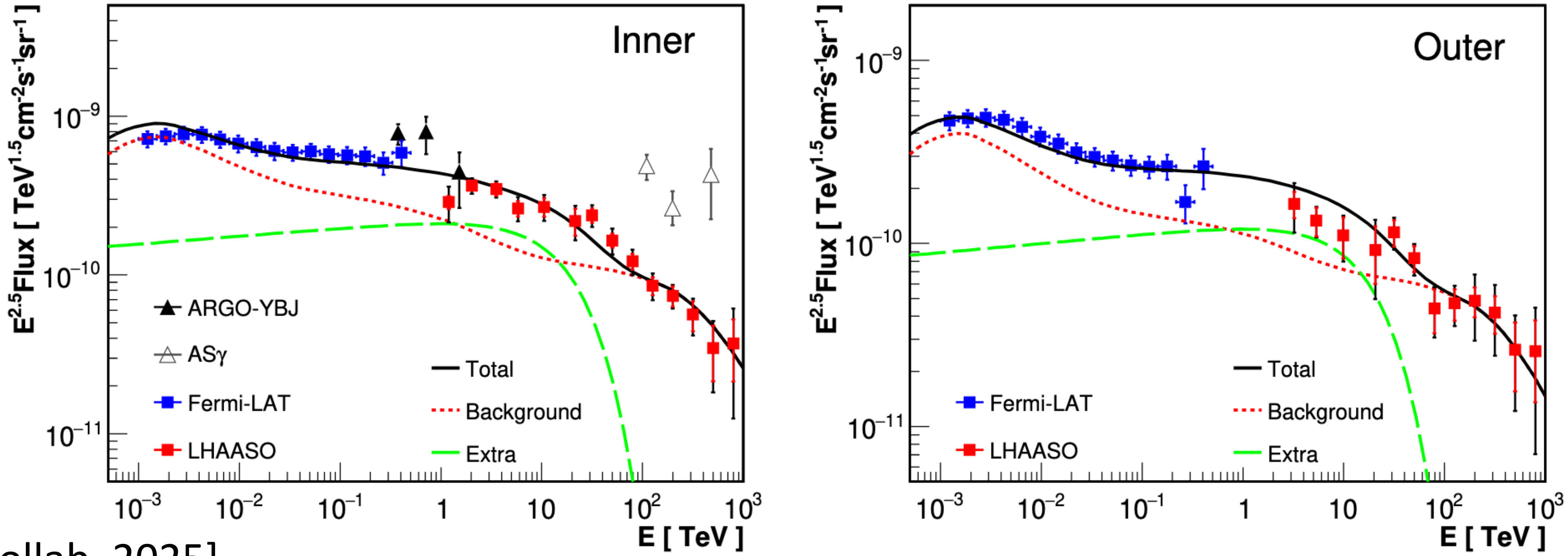
KM2A

[LHAASO Collab. 2025]

- The significance maps in Galactic coordinate of the inner Galaxy region (top panel) and outer Galaxy region (bottom panel))

- Known sources are masked

Energy spectrum of Galactic diffuse HE gamma-ray



[LHAASO Collab. 2025]

Wide-band fluxes of diffuse γ-ray emission in the inner and outer Galaxy regions

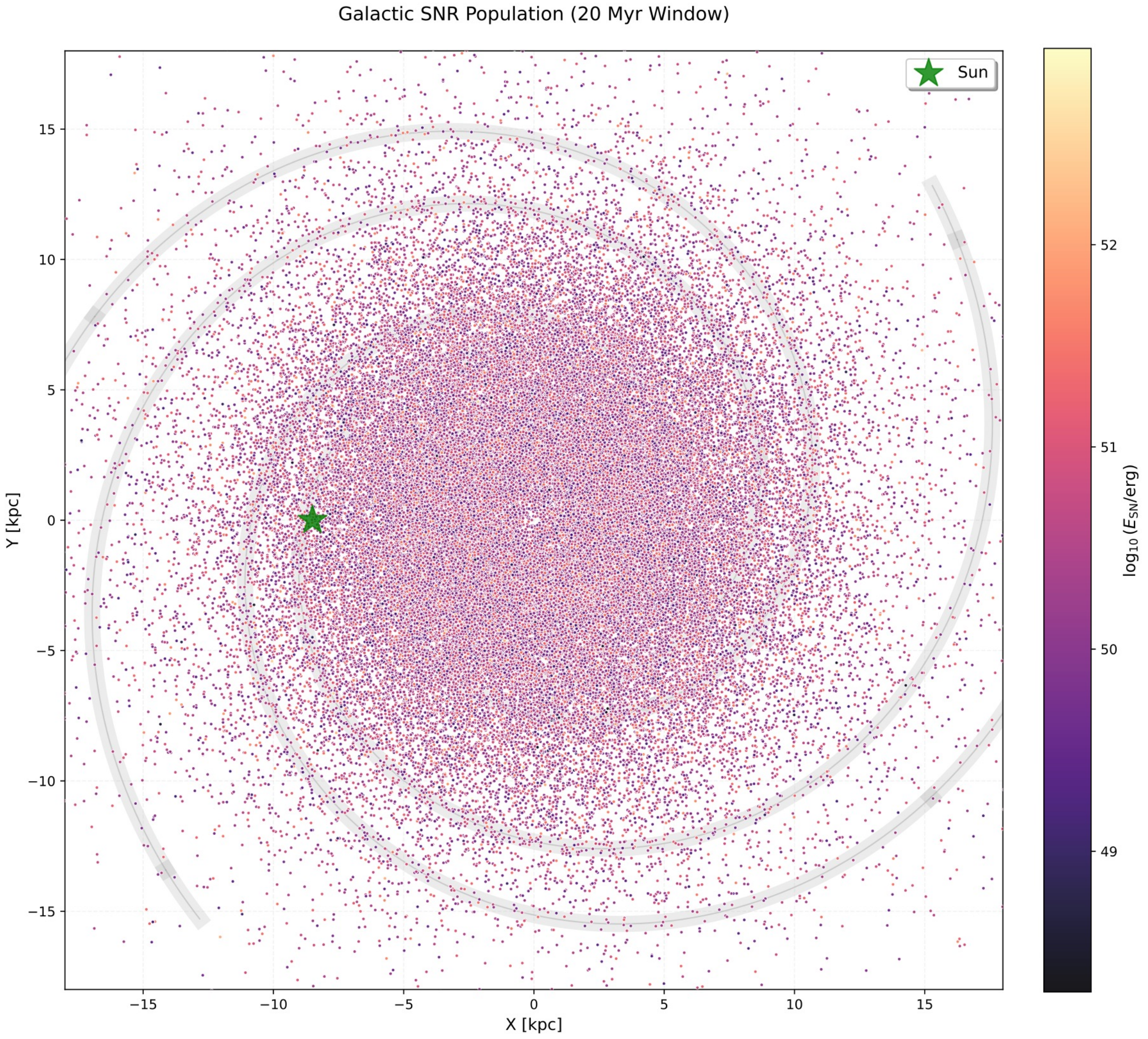
The excess at 0.1-10 TeV energy range

Galactic CRs: Origin of gamma-rays and neutrinos

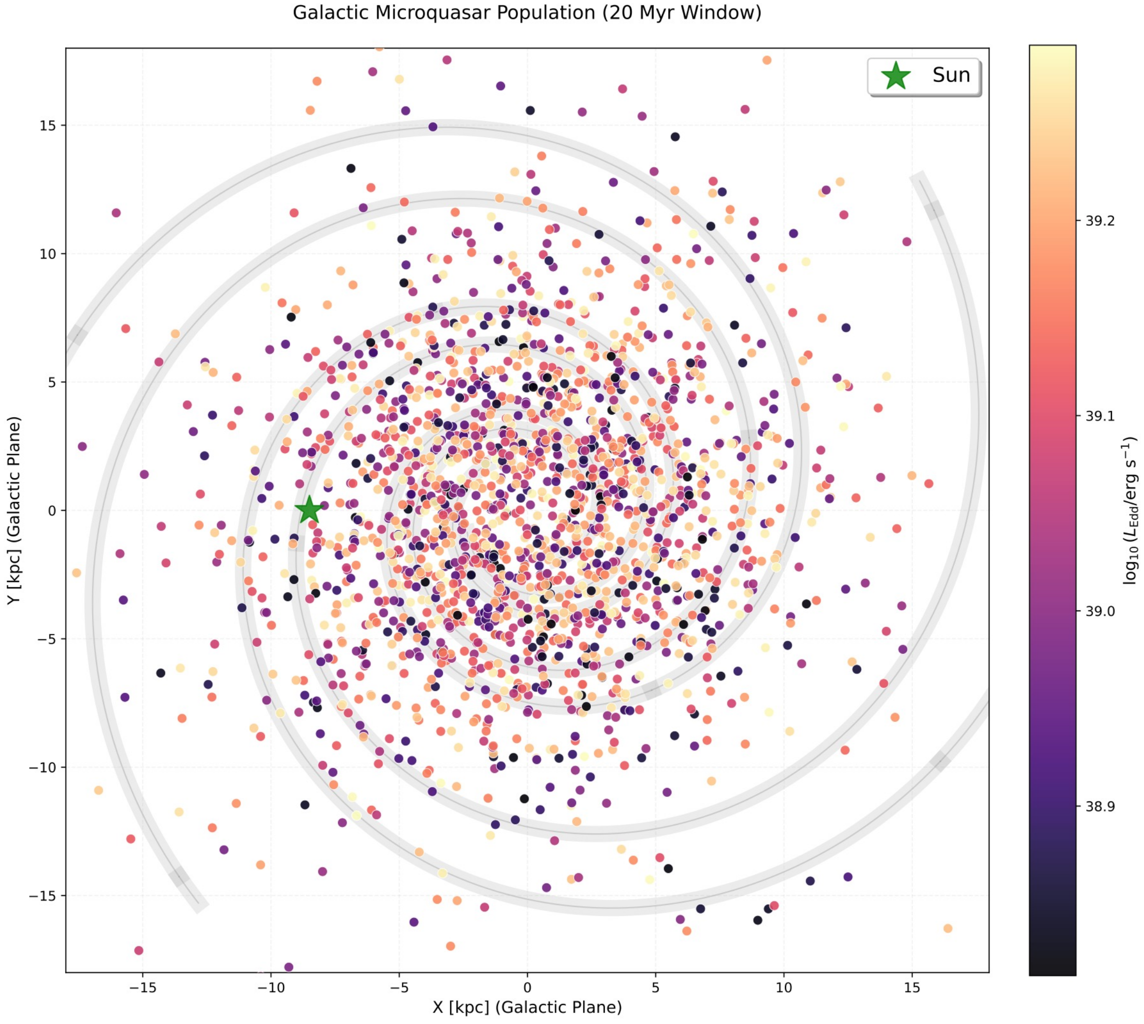
Foundations:

- **Source population:** Galactic CR sea is dominated by past injections from SN and MQ remnant populations.
- **Fit to CR data:** Spatial and spectral neutrino and gamma-ray emission templates are anchored on Galactic CR data.

Spatial distribution of SNRs and microquasars



SNR spatial distribution shown with 10% sample [Green 2015]
Event rate: 1/30 yr



Microquasar spatial distribution [Green 2015]
Event rate: 1/10000 yr

GCR source modeling

Injection spectral parameters for MQs and SNRs follow [Aharonian & Zhang, 2026 ApJ]

Protons and helium nuclei are injected and propagated independently

Heavier nuclei are scaled to helium following rigidity dependence

R-distributions from [Green 2015, MNRAS, 454, 1517]

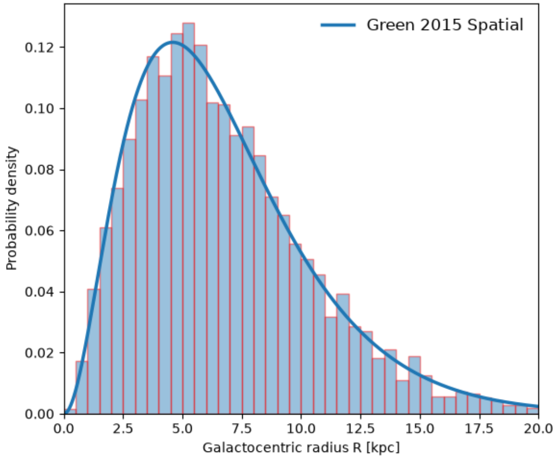


Table 2. Parameters for Population Distributions and CR Injection of MQs and SNRs.

Source	MQ	SNR
Shared Parameters		
Radial Distribution Parameters	$\alpha = 1.09, \quad \beta = 3.87$	
Time Window ($\Delta t_{\rm win}$)	50 Myr	
Pivot Height (h_z)	0.15 kpc	
Solar System Radius ($R_\odot$)	8.5 kpc	
Max. Lookback	20 Myr	
Distinct Parameters		
Birth Rate ($\mathcal{R}$)	1×10^{-4} yr^{-1}	$1/30$ yr^{-1}[a]
Jet Duration ($\tau_{\rm dur}$)	Uniform(0.1, 1.0 Myr)	–
CR Injection Index (s)	2.0	2.4 (2.24) for p (He)
CR Maximum Energy (s)	6 PeV	68(468) TeV for p (He)
Mass / Kinetic Energetics	$M_{\rm BH} \sim$ Uniform(5.0, 15.0) $M_\odot$	$\frac{E_{\rm SN}}{\rm erg} \sim$ Log-Norm(50.5, 0.53^2)[b]

CRs escape (τ_{esc}< 1 Myr at E > 1 TeV) prior to significant pp loss with τ_{loss}~ 50/(n_{gas}/1cm^{-3}) Myr and reach steady state << 20 Myr

GCR diffusion

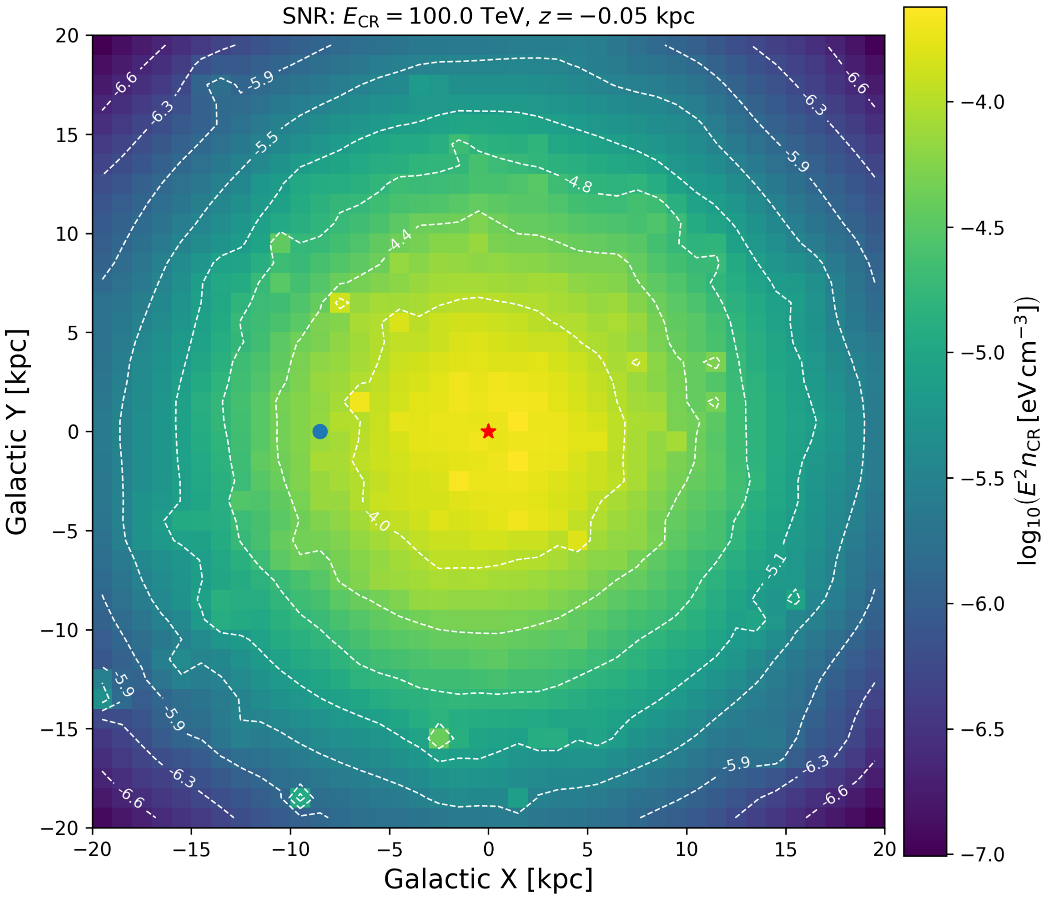


Illustration of steady-state CR density distribution of SNR at z=-0.05 kpc

Isotropic diffusion with constant diffusion coefficient, solving Green function:

$$n_{\rm cr}(E, \mathbf{r}, \tau_{\rm lookback}) = L_{\rm cr} \int_{\tau_{\rm min}}^{\tau_{\rm lookback}} \mathcal{P}(\mathbf{r}, E, \tau)\, d\tau$$

$$\mathcal{P}(\mathbf{r}, z, E, \tau) = \frac{1}{(4\pi\, D(E)\, \tau)^{3/2}} \exp\left(-\frac{r^2}{4D(E)\tau}\right) \mathcal{V}(z, \tau, E)$$

With free-escape boundary at +/- 4 kpc using Blasi & Amato 2011 methods

$$\mathcal{V}(z, \tau, E) = \sum_{n=-\infty}^{+\infty} (-1)^n \exp\left(-\frac{(z - z'_n)^2}{4D(E)\tau}\right)$$

CRs from supernova and microquasar

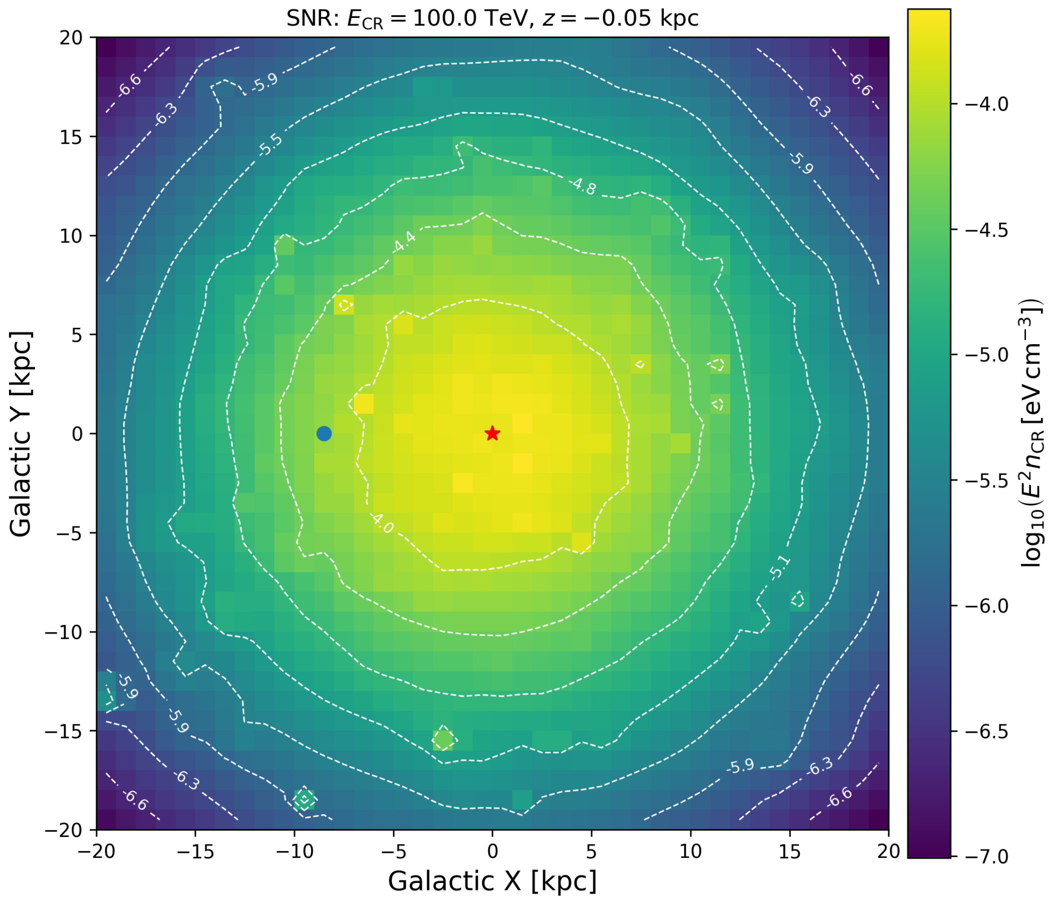


Illustration of steady-state CR density distribution of SNR at z=-0.05 kpc

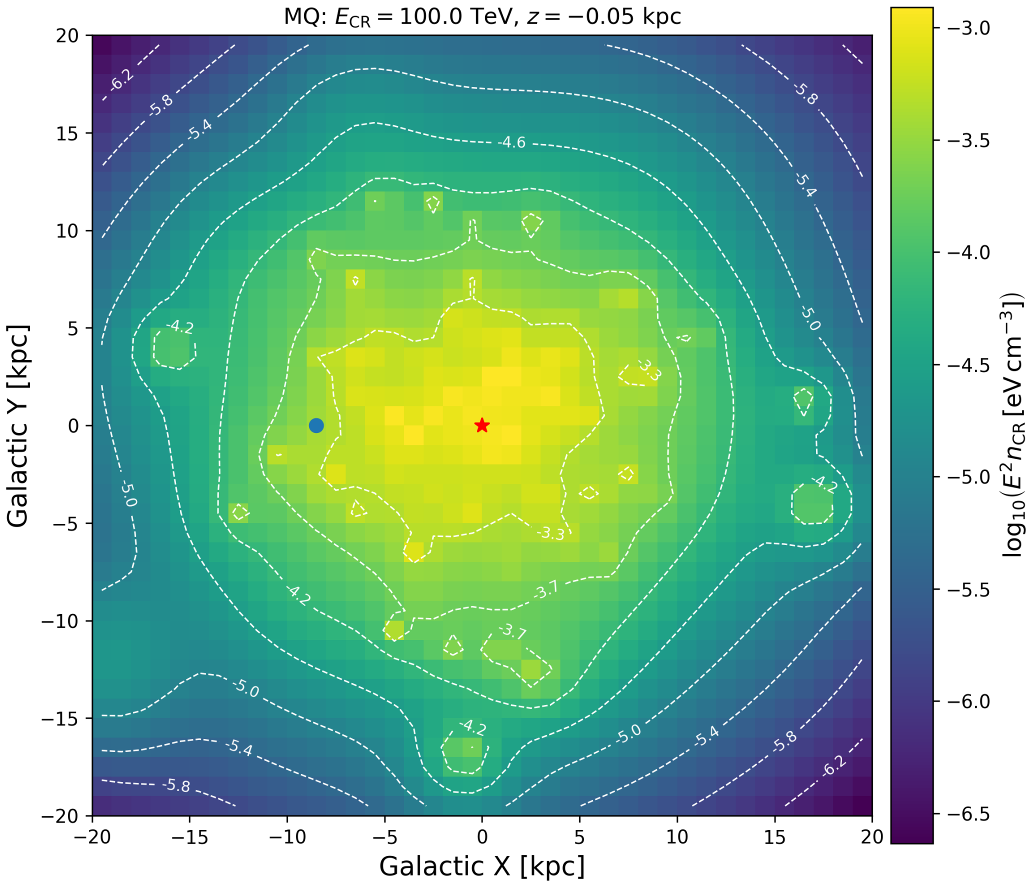
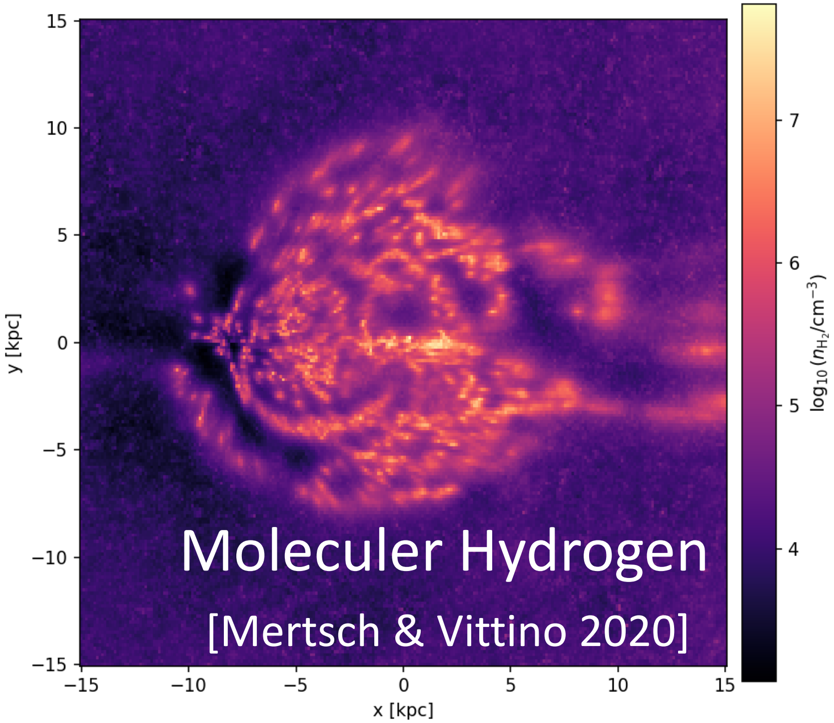


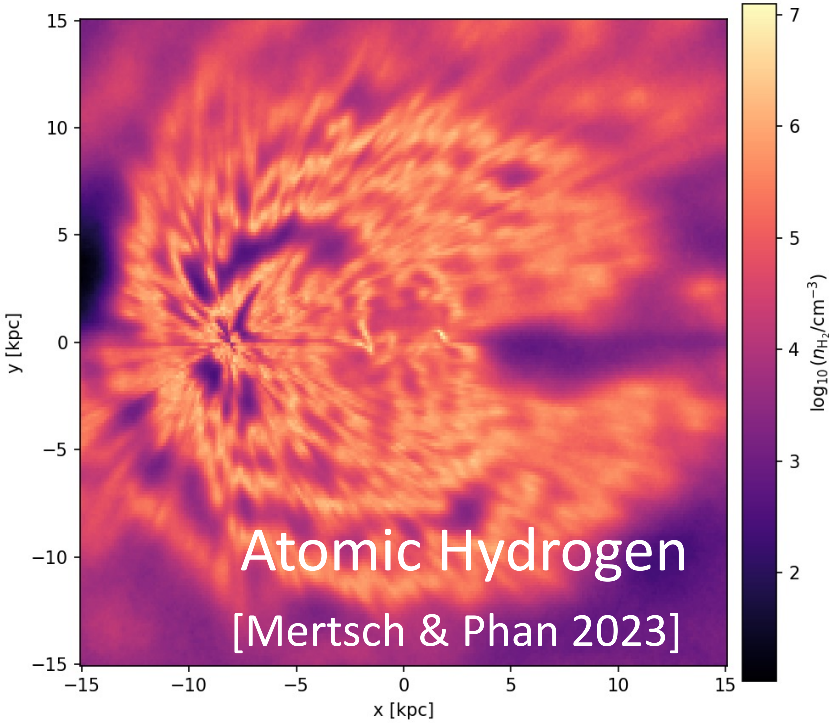
Illustration of steady-state CR density distribution of Microquasar at z=-0.05 kpc

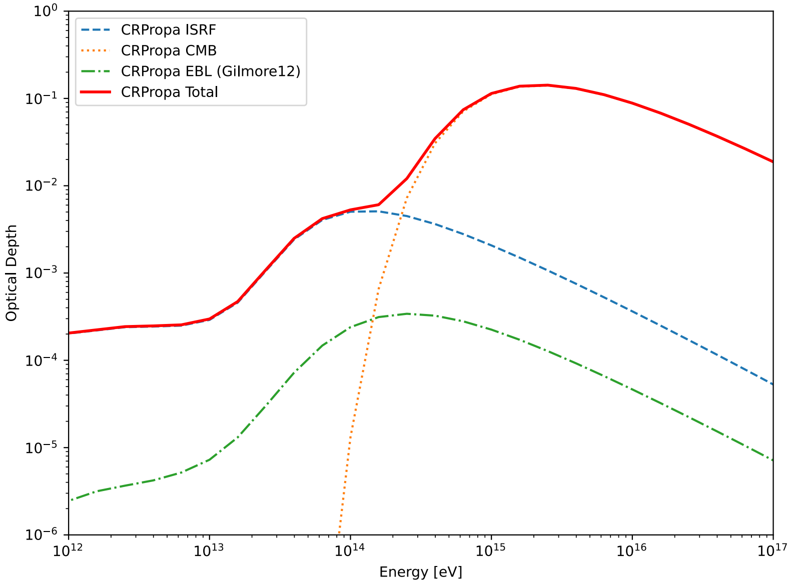
3D Interstellar Radiation and Gas Distribution

Line-of-sight (LOS) integrations over gas and photon maps to estimate resulting $\boldsymbol{\nu}$ and γ-ray emission

- **pp and He-p interaction** with gas nuclei via AAFRAG [Comput.Phys.Commun. 245 (2019) 106846], with heavier nucleus scaled by 1.42 [Castro et. al., 2025]
- $\boldsymbol{\gamma\gamma}$ **absorption** accounts for CMB, EBL, and ISRF photon fields [Vernetto & Lipari 2016, Robitaille 2012]





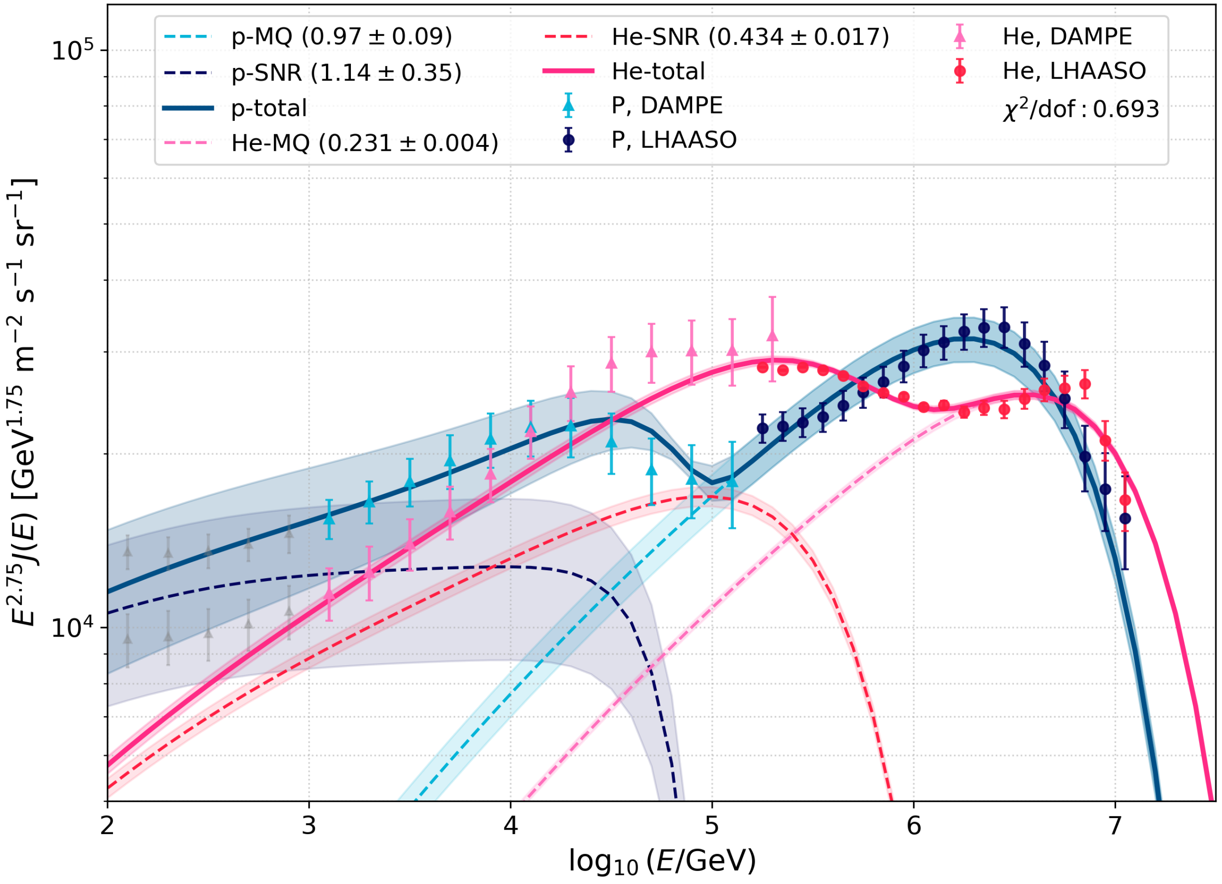


Absorption efficiency: CMB, EBL, ISRF

$$\phi_\nu(E_\nu,\Omega) = \frac{1}{4\pi}\int dE_{\rm p}\,\beta c\,\sigma_{pp}(E_{\rm p})\,\frac{dN_\nu}{dE_\nu}(E_\nu,E_{\rm p})\,X(\Omega,E_{\rm p})$$

$$X(\Omega,E_{\rm p}) = \int_0^\infty ds\,n_{\rm gas}(\mathbf{r})\,n_{\rm p}(E_{\rm p},\mathbf{r})$$

Anchor in CR data



Joint fit to proton and helium data observed by LHAASO and DAMPE

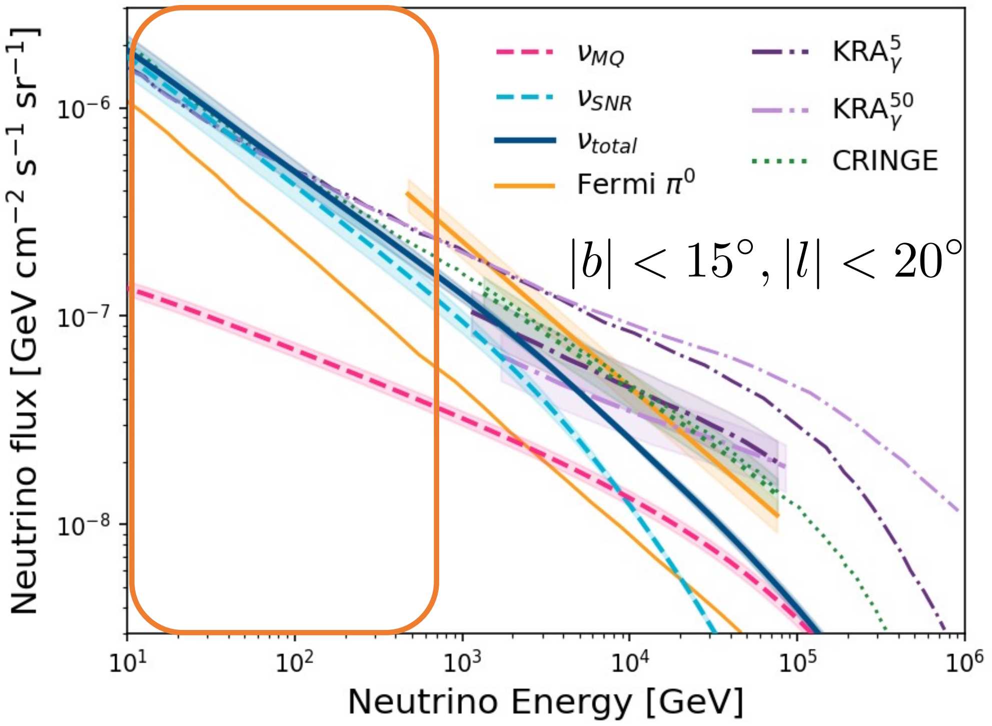
We adopt separate injection parameters for proton and helium [Aharonian & Zhang, ApJ, 2026], but keeps the normalization as free parameter

- Supernova $\mathcal{E}_{\rm cr} = \eta_{\rm cr,SN}\mathcal{E}_{\rm SN}$
- Microquasar $L_{\rm cr} = \eta_{\rm cr,MQ}L_{\rm Edd}$

CR acceleration efficiencies $\eta_{\rm CR}$ best-fit values with 1σ uncertainty bounds

Component	Parameter	Best-Fit Value $\pm 1\sigma$
Microquasars	$\eta_{p,\rm MQ}$	0.10 ± 0.009
	$\eta_{\rm He,\ MQ}$	0.02 ± 0.0004
SNRs	$\eta_{p,\rm SN}$	0.11 ± 0.035
	$\eta_{\rm He,\ SN}$	0.04 ± 0.0017

Predicted Diffuse Neutrinos



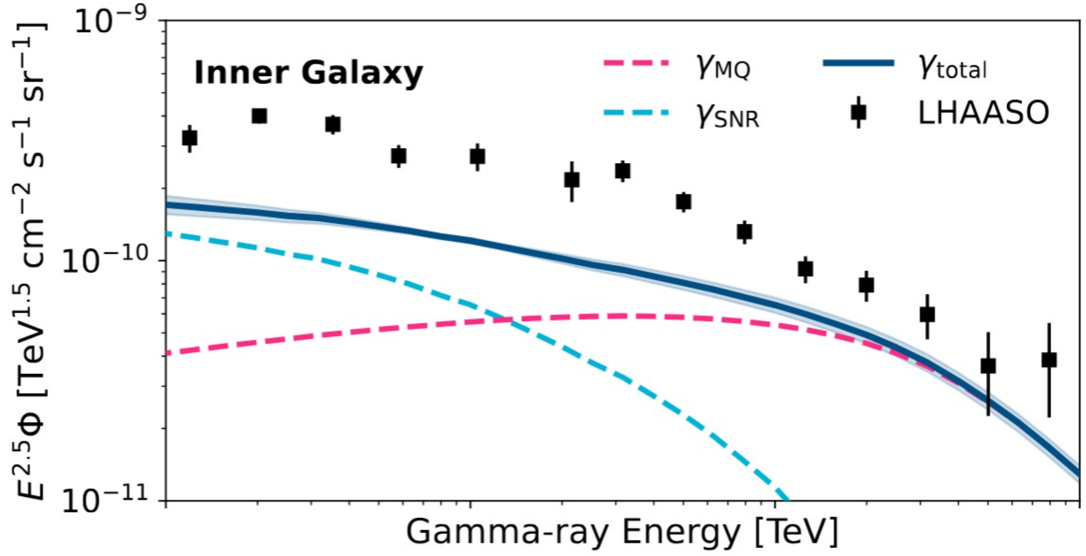
Potential room for contributions from additional/alternative sources or acceleration/propagation physics

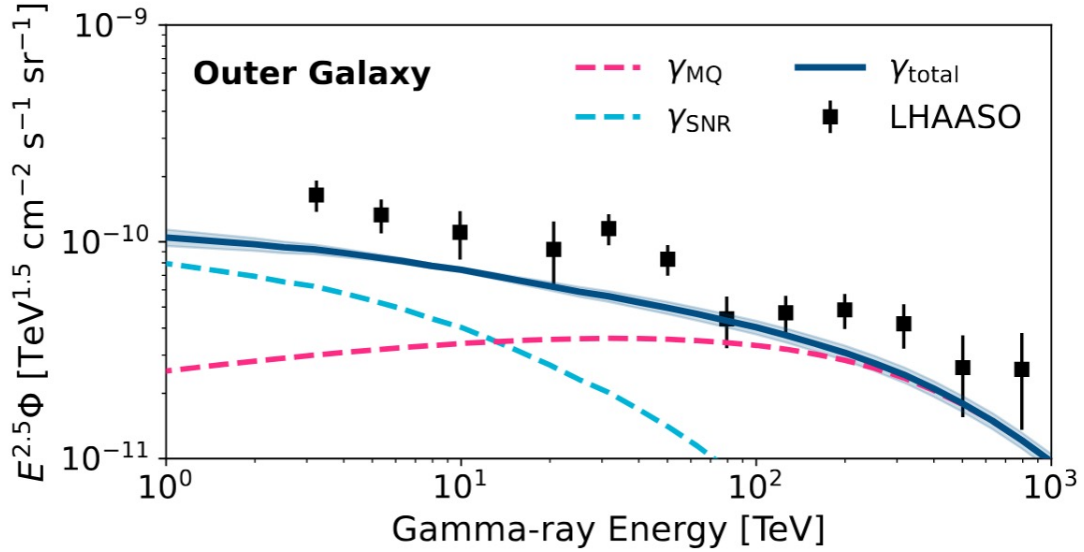
High-precision data points are essential for rigorous model comparison and constraint

Comparison between nominal template predictions and IceCube best fits reveals distinct energy regimes

- Sub-TeV regime: agreement across models
  - SNR dominant and everyone fitted to <10 TeV CR data.
- Beyond 10 TeV: MQ-dominated spectral hardening diverge from CRINGE and KRA
- KRA:
  - rely on simple extrapolations without constraints from recent high-energy CR data
- CRINGE:
  - fitted to KASCADE data and utilize rigidity-dependent diffusion breaks instead of source-driven cutoffs
- Our steepening is physically driven by maximum energy cutoffs of MQ and SNR populations

Predicted Diffuse Gamma Rays





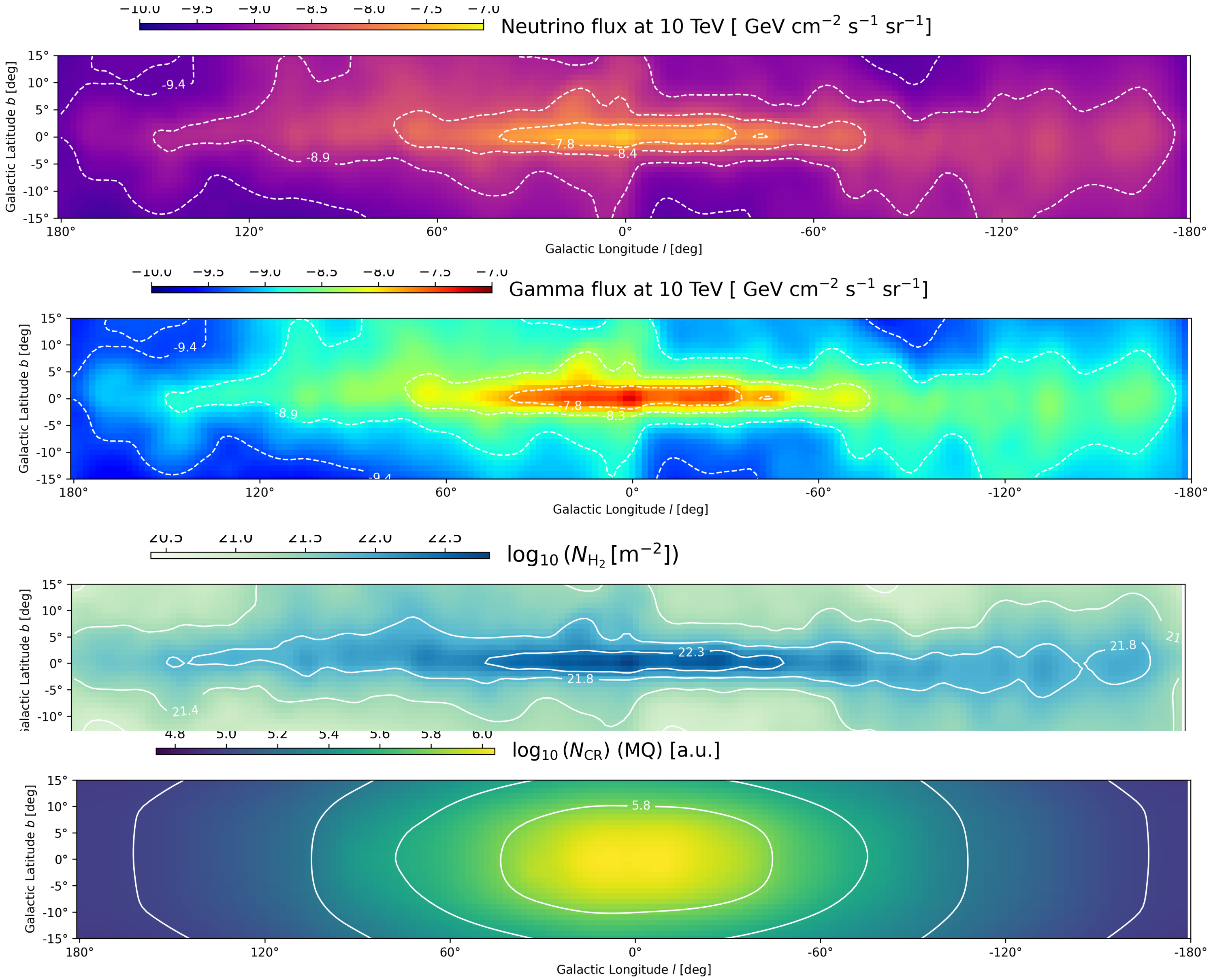
Predicted diffuse gamma-ray fluxes in both inner and outer regions show consistency with LHAASO data

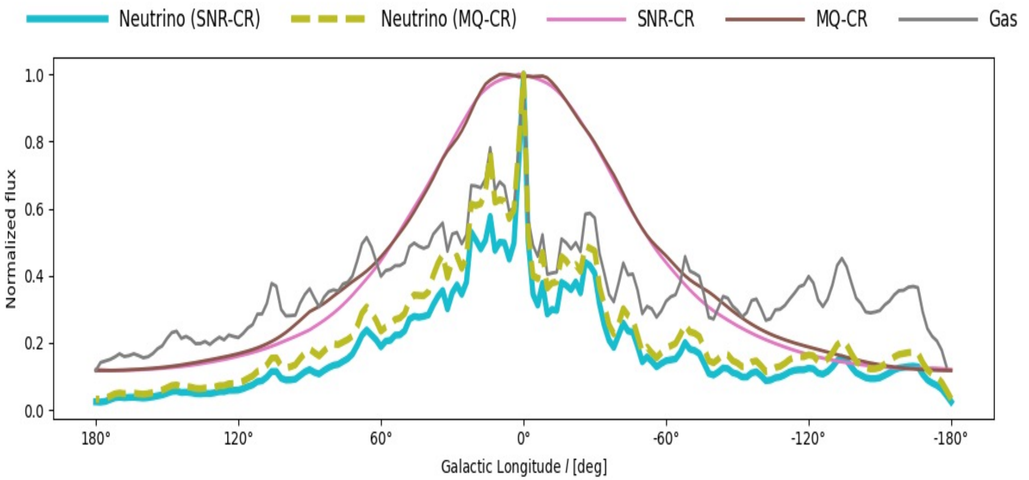
Below 100 TeV, a residual excess in the gamma-ray data suggests possible additional contributions:

- Unresolved, faint source populations
- Unmodeled leptonic process, such as inverse-Compton by high-energy electrons

Above 100 TeV, Inverse Compton emission is strongly suppressed by Klein-Nishina effects, transitioning the diffuse gamma-ray sky into a purely hadronic regime (better agreement)

Diffuse Sky Maps Imprinted by Microquasar and SNRs





- CRs smoothly mirrors the large-scale radial distribution of the source population

- Secondary particle profiles closely track target gas morphology, driven by localized gas density concentrations

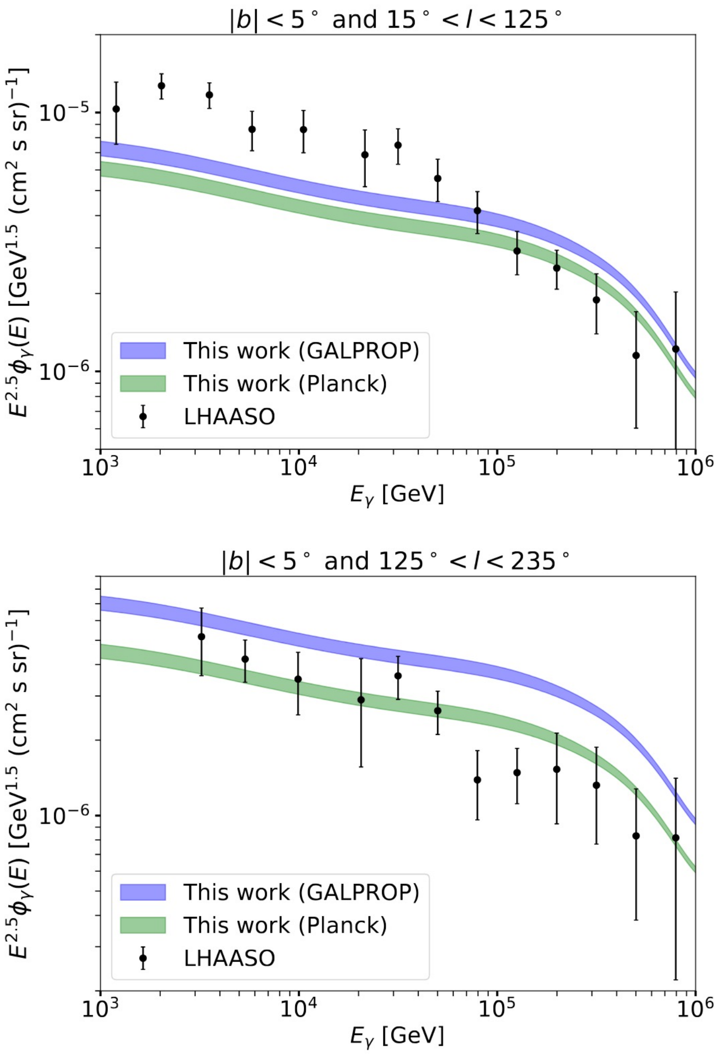
Summary and discussion

Can we be more realistic?

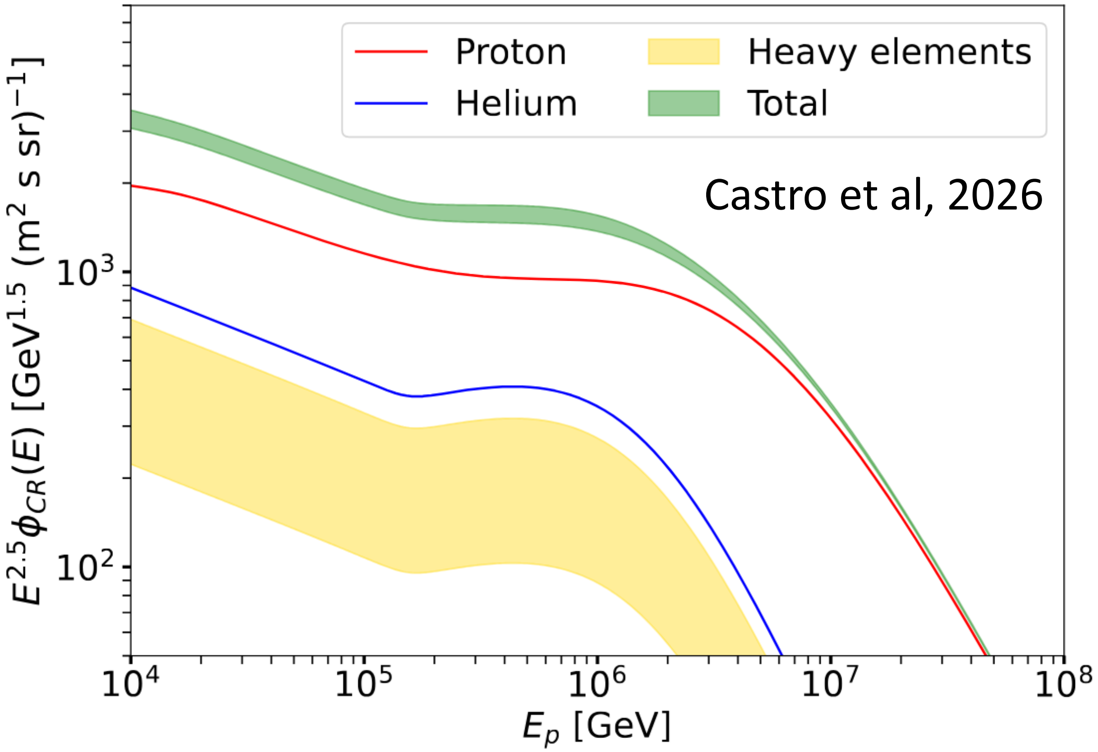
This physically motivated framework can be naturally extended to incorporate richer physical ingredients:

- ✓ Galactic Magnetic Fields?
- ✓ Population variations?
- ✓ Refined source acceleration models?
- ✓ 3D Gas models?
- Active source contributions?
- …

Inconsistency between LHAASO proton and diffuse gamma ?



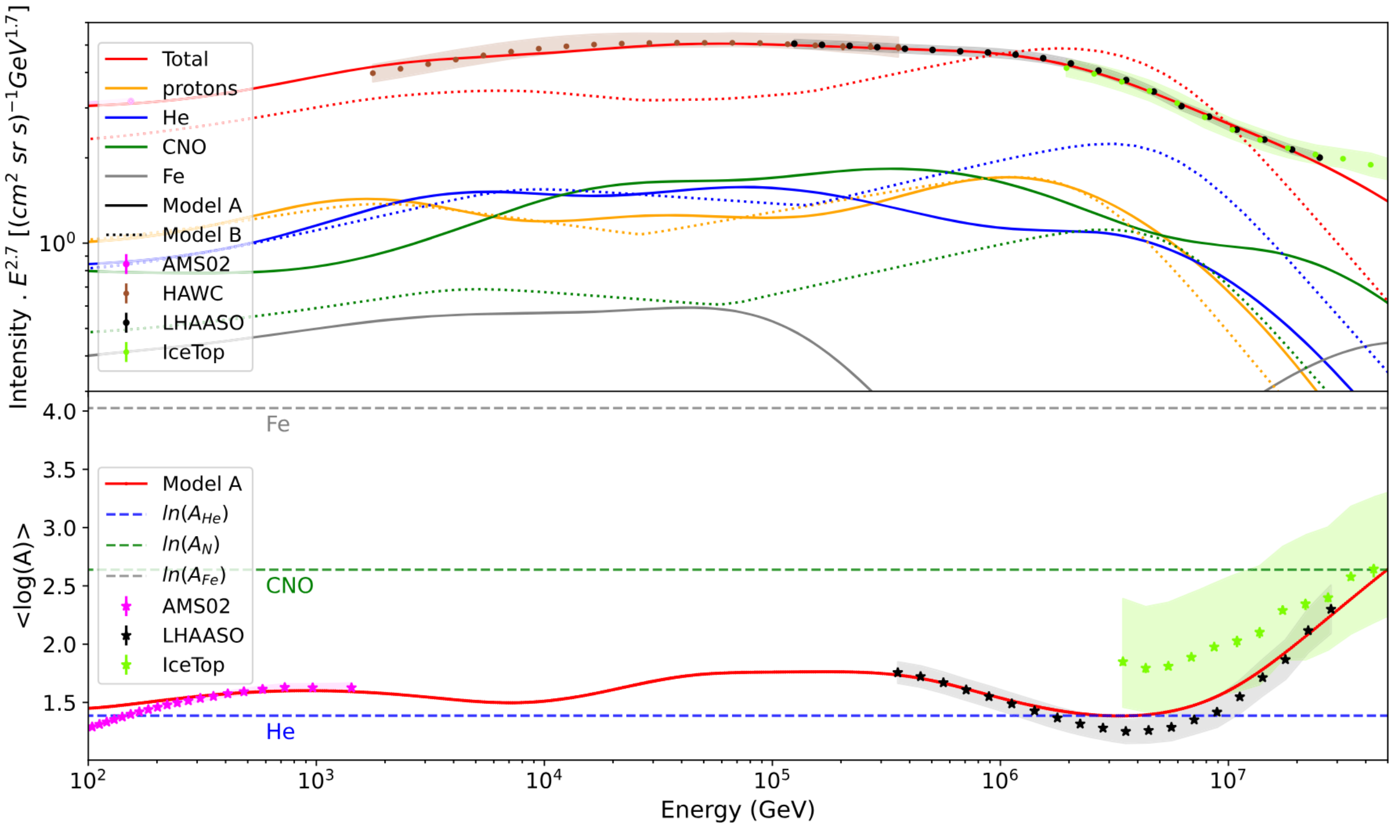
Castro et al, 2026



- LHAASO proton, but outdated helium spectrum

$$\mathcal{R}(E_\mathrm{n}, \mathbf{r}) \equiv \frac{\phi_\mathrm{CR}(E_\mathrm{n}, \mathbf{r})}{\phi_{\mathrm{CR},\odot}(E_\mathrm{n})}$$

Inconsistency between LHAASO proton and diffuse gamma ?



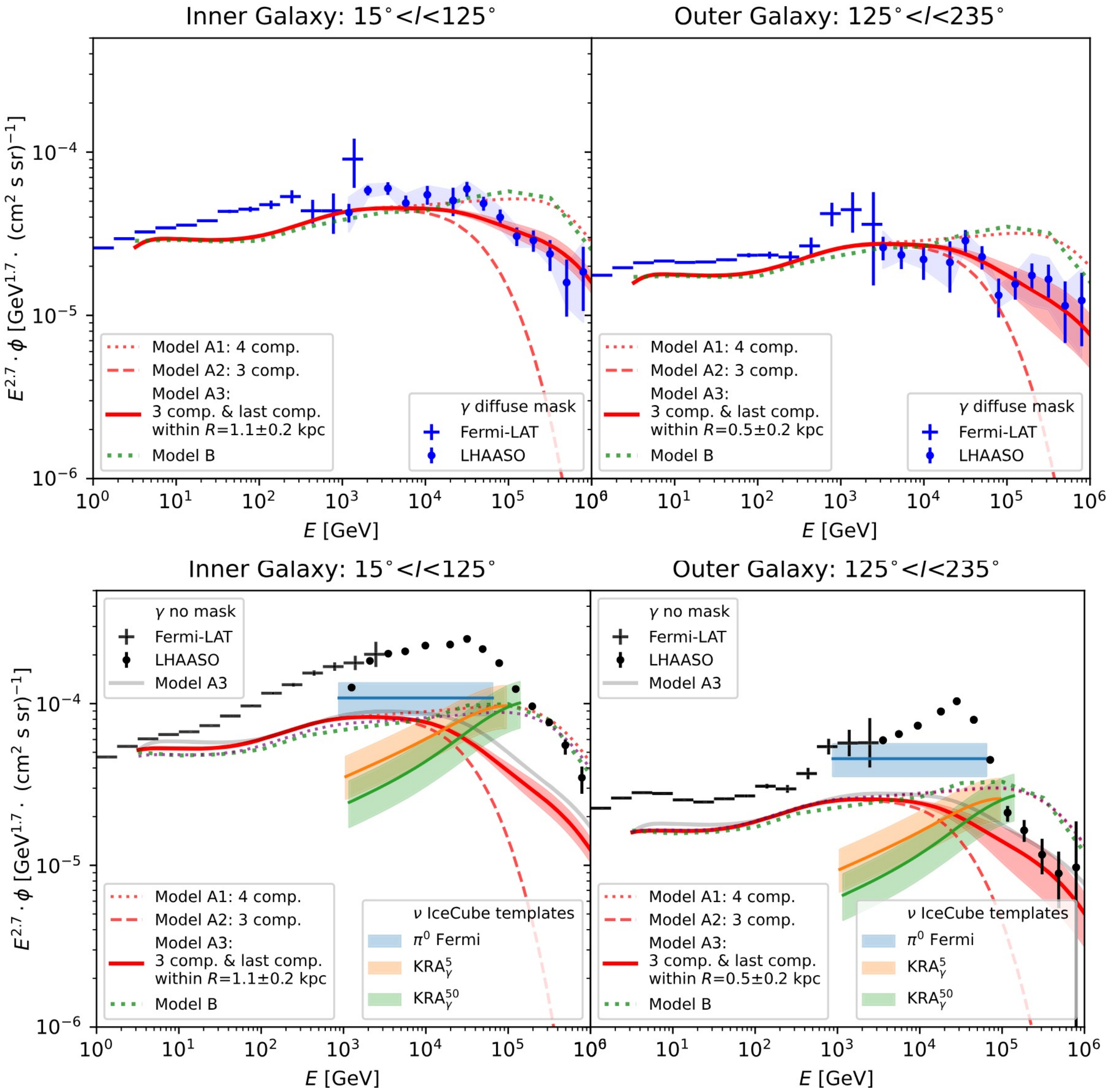
model A

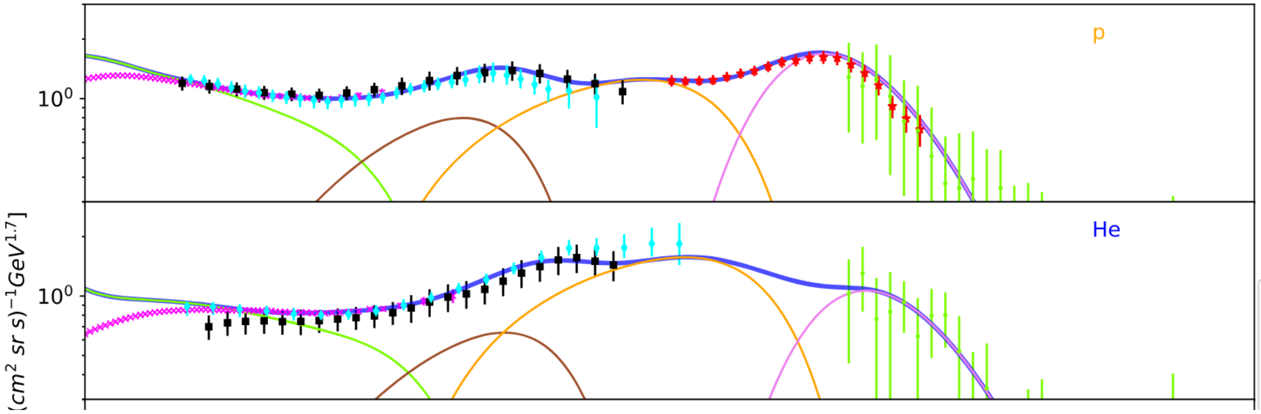
Breaks of the CR spectrum up to the knee are due to contributions of several different populations of sources

model B

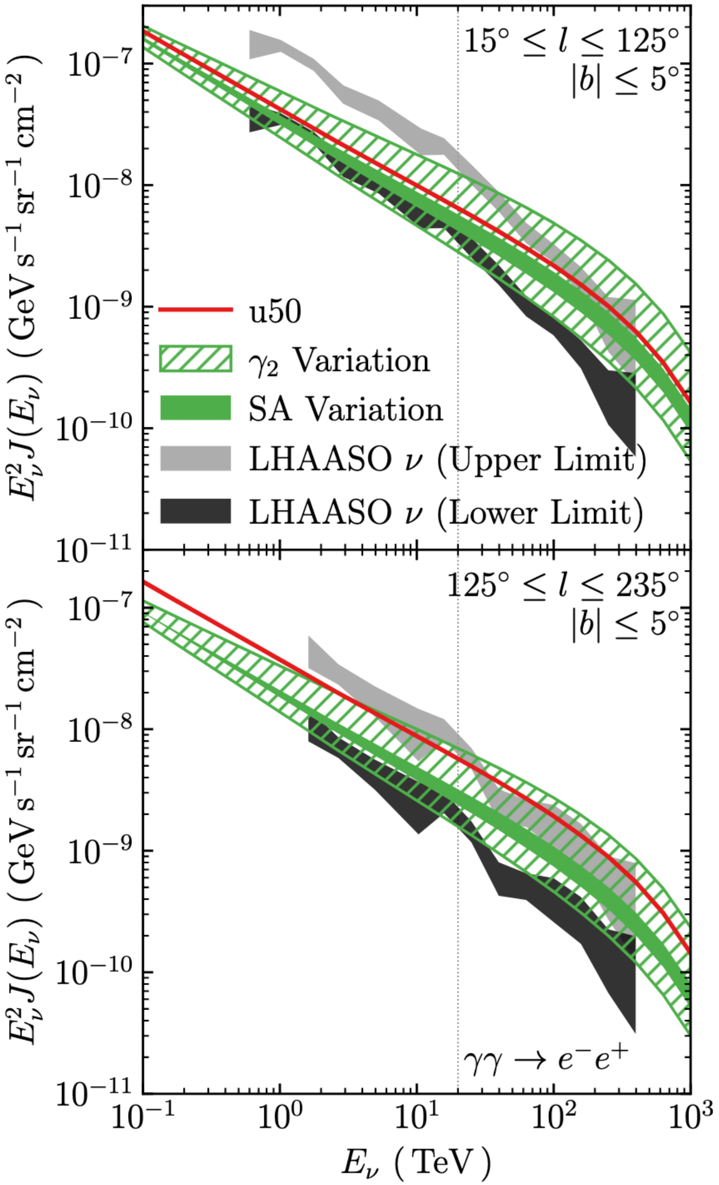
All observed breaks in CR proton spectrum are propagation features

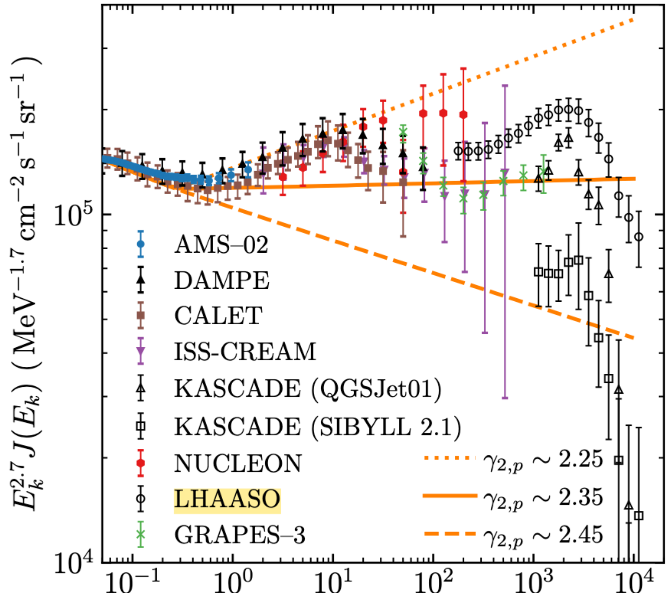
Diffuse neutrinos and gamma-rays

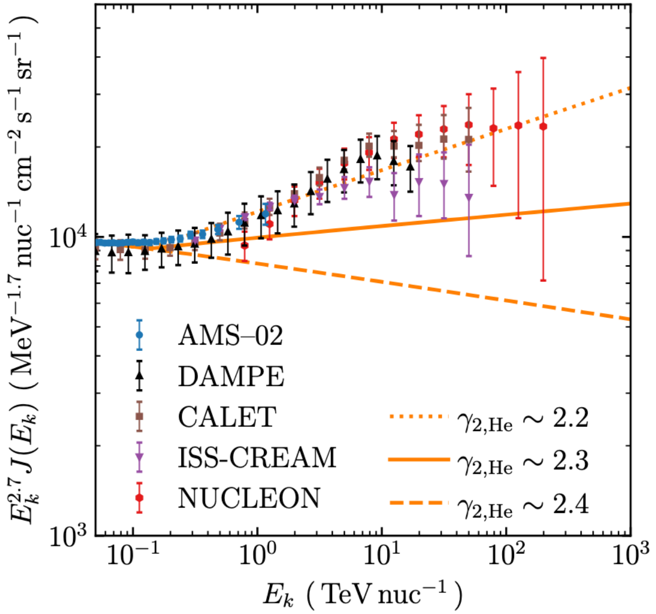


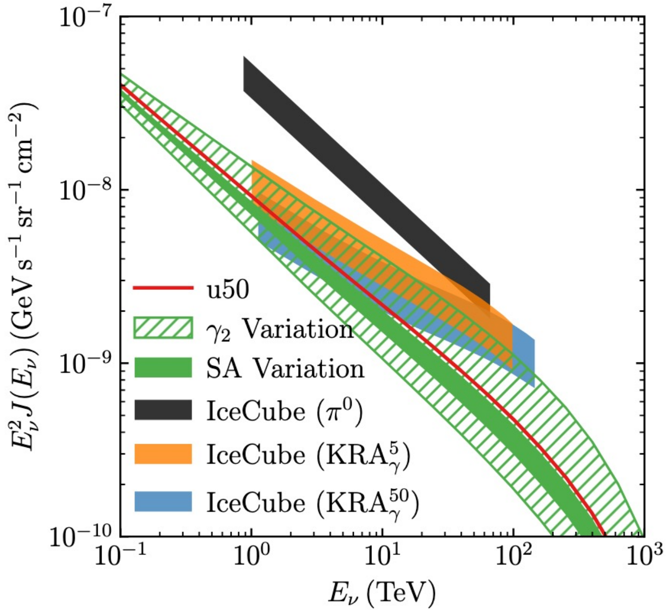


Pi-0 model



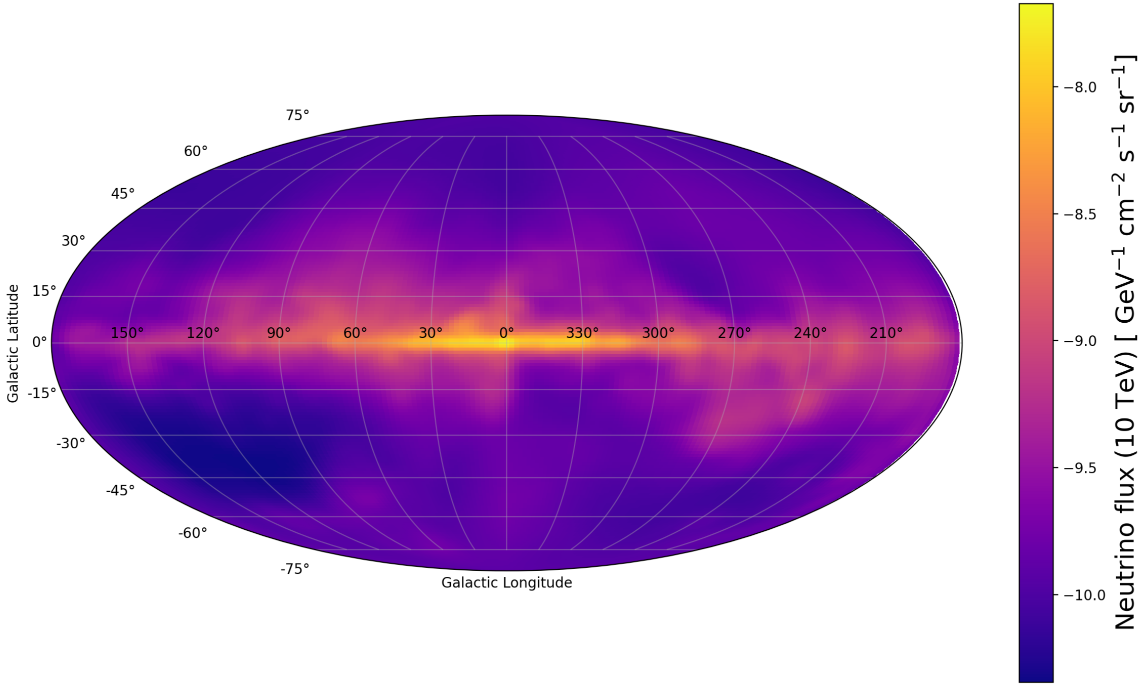


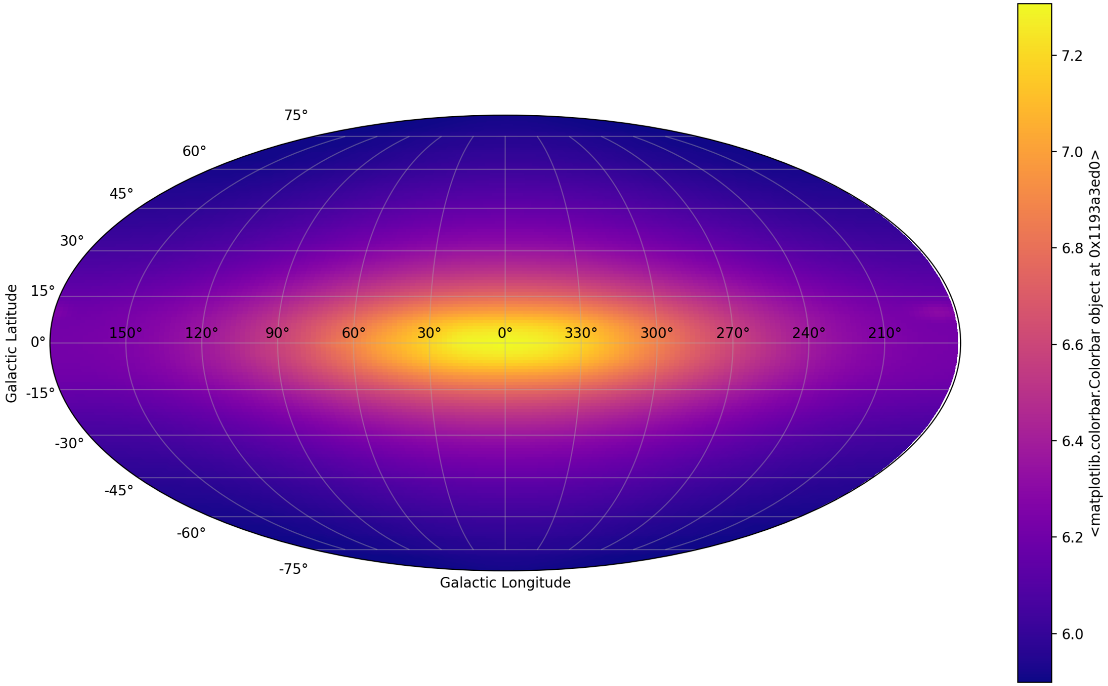




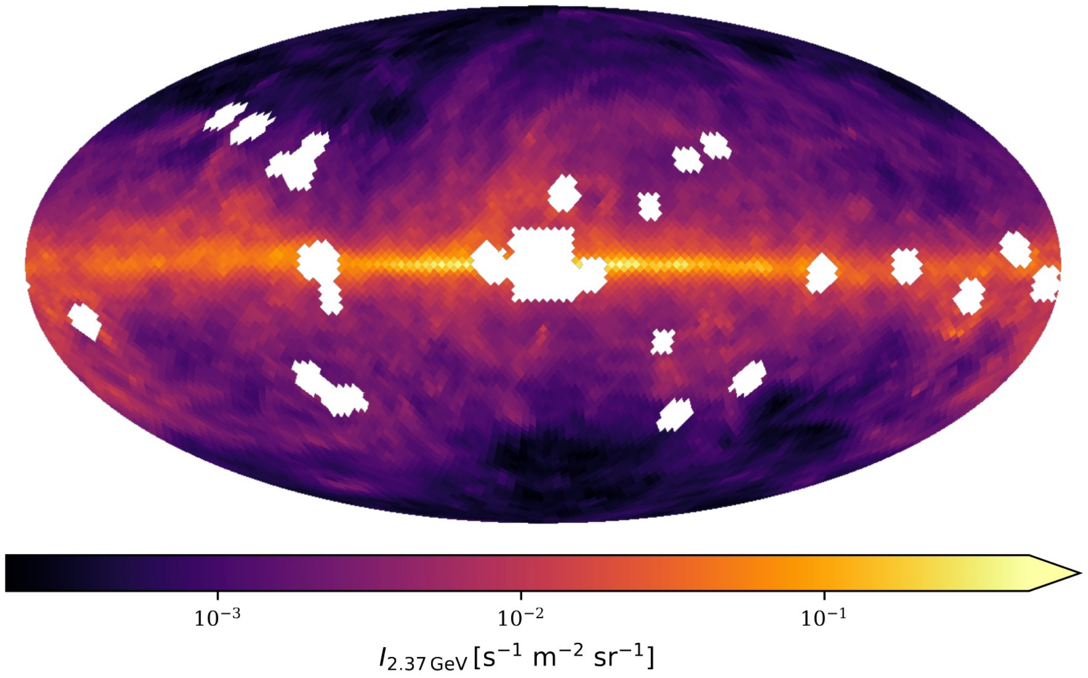
Updated GALPROP models underestimating the IceCube total Galactic plane neutrino flux by factors 2.4–4.6

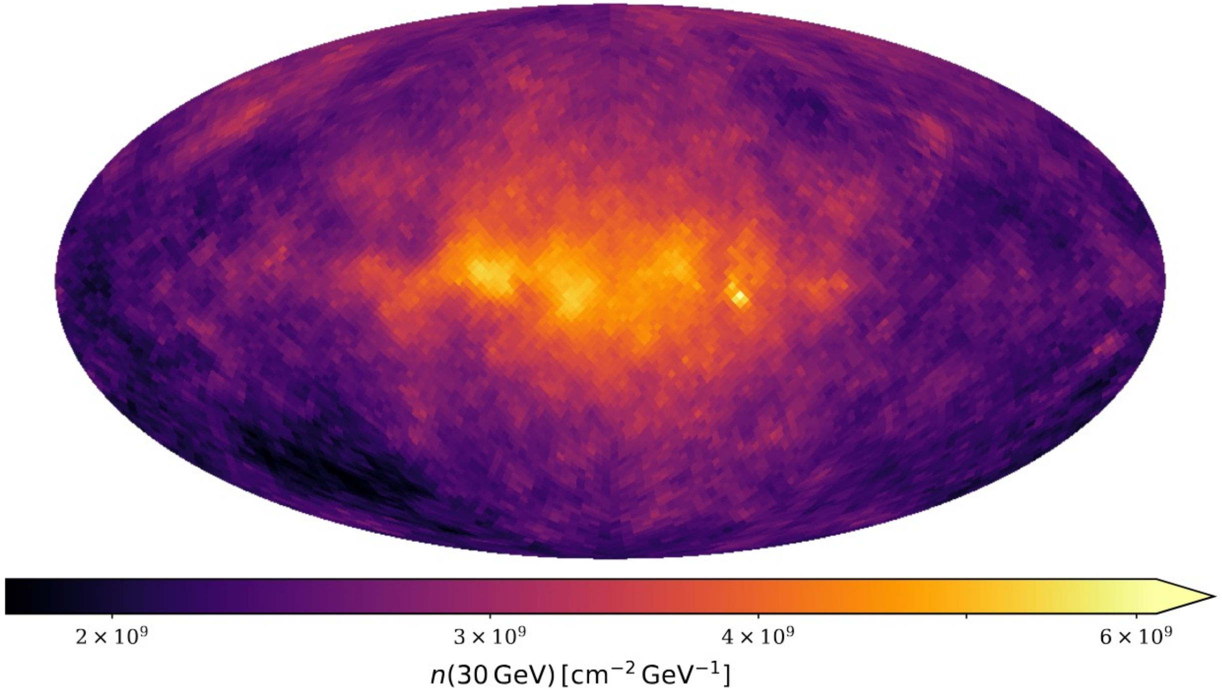
Neutrino and Cosmic Ray skymap





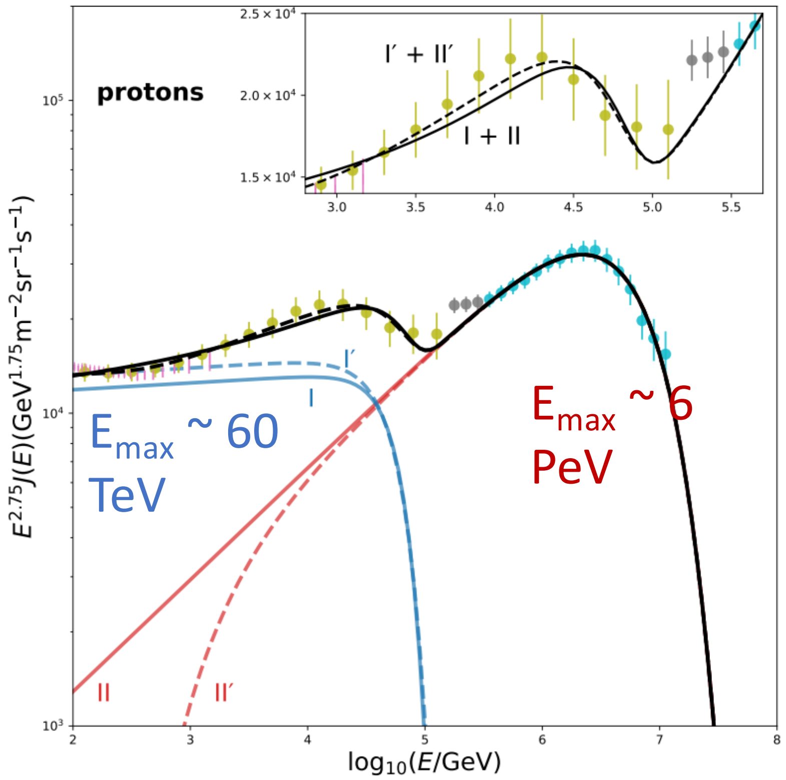
Cosmic ray density in our galaxy

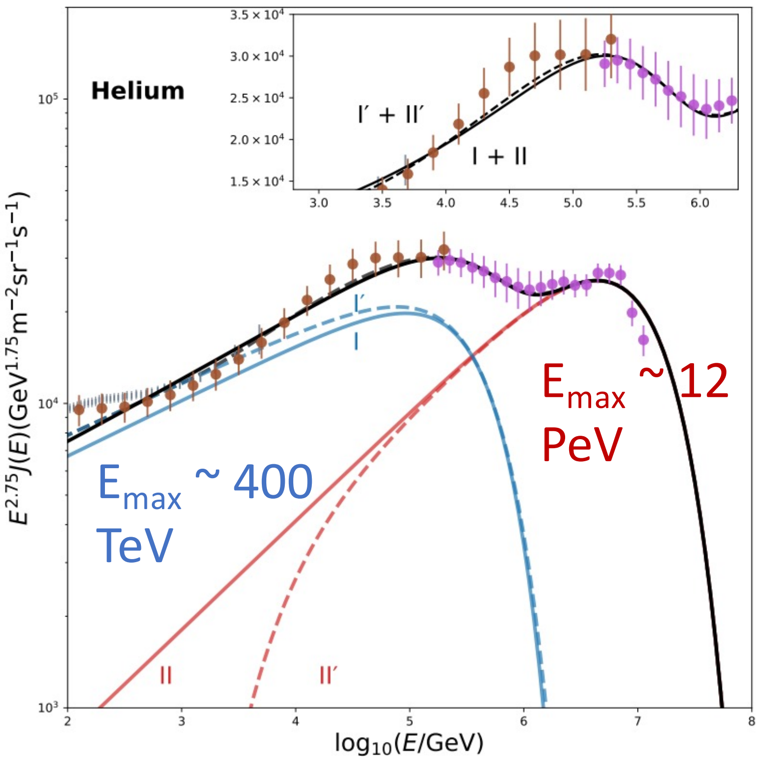


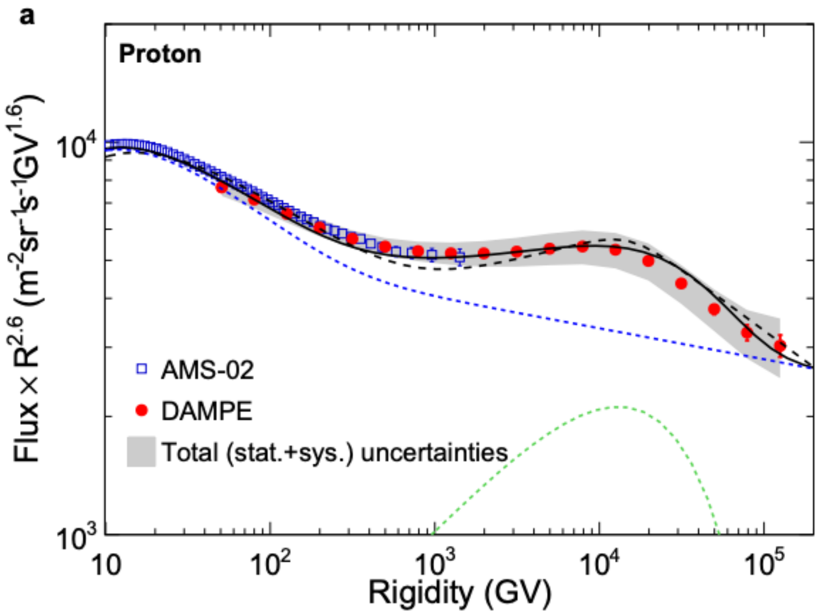


A Minimal Interpretation of the Galactic Cosmic Ray

[Aharonian and BTZ, 2026, ApJ]







[DAMPE Coll. Nature, 2026]

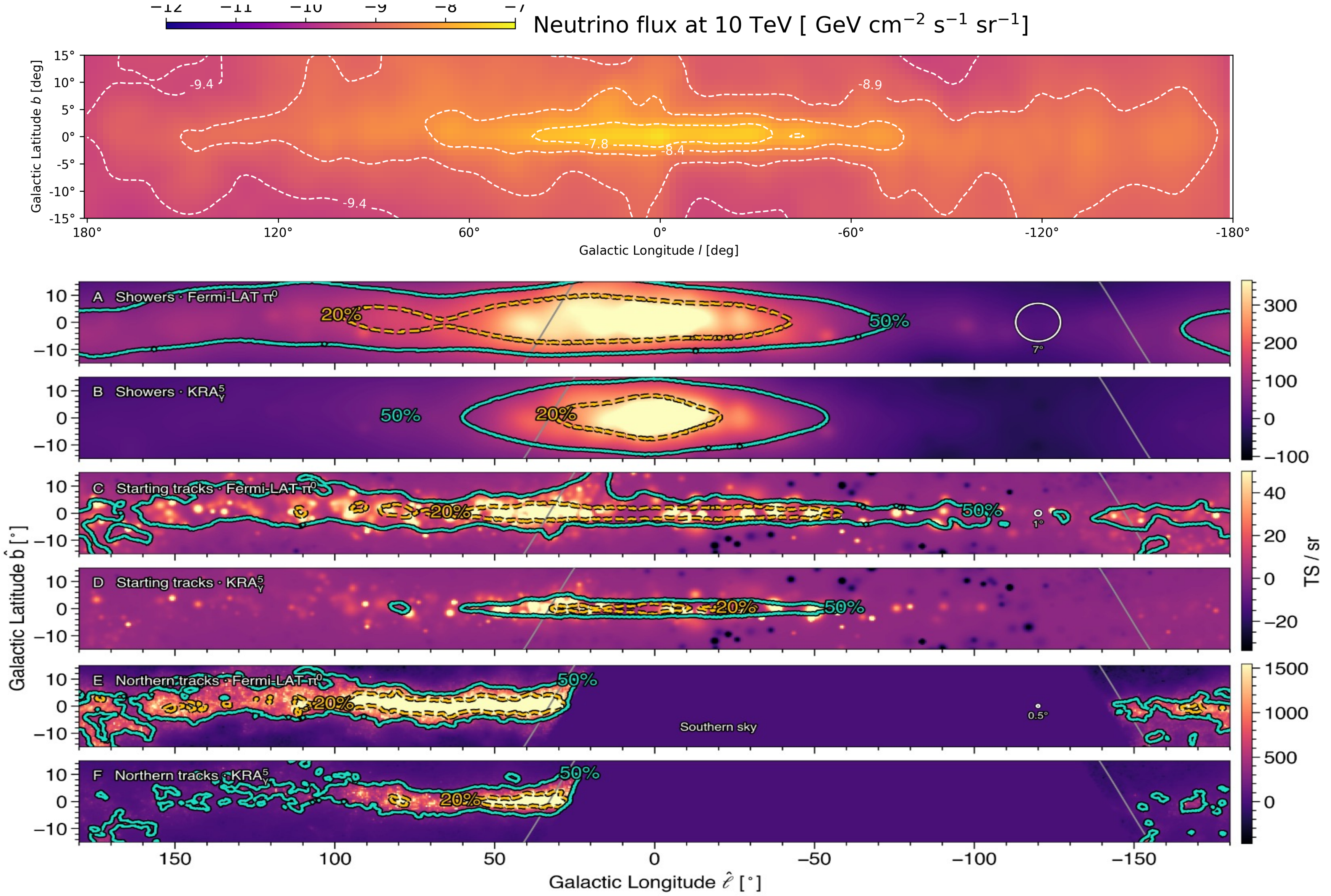
$$J_{tot}(E) = J_1(E) + J_2(E) \qquad J_i(E) = A_i\, E^{-\Gamma_i} \exp\left[-\left(\frac{E}{E_{i,0}}\right)^{\beta_i}\right]$$

Question of TeV bump: Outcome of two source populations? Or a nearby source ?

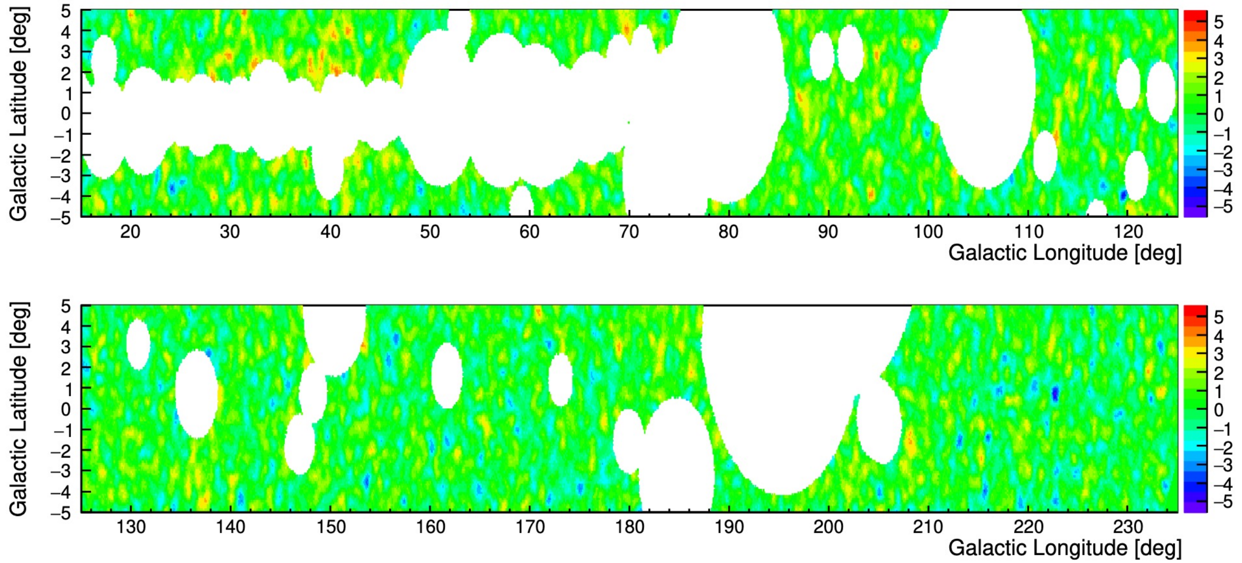
For component I, Protons and helium (heavier nuclei) may from different sources or environments

For component II, Protons and helium may from same sources or environments

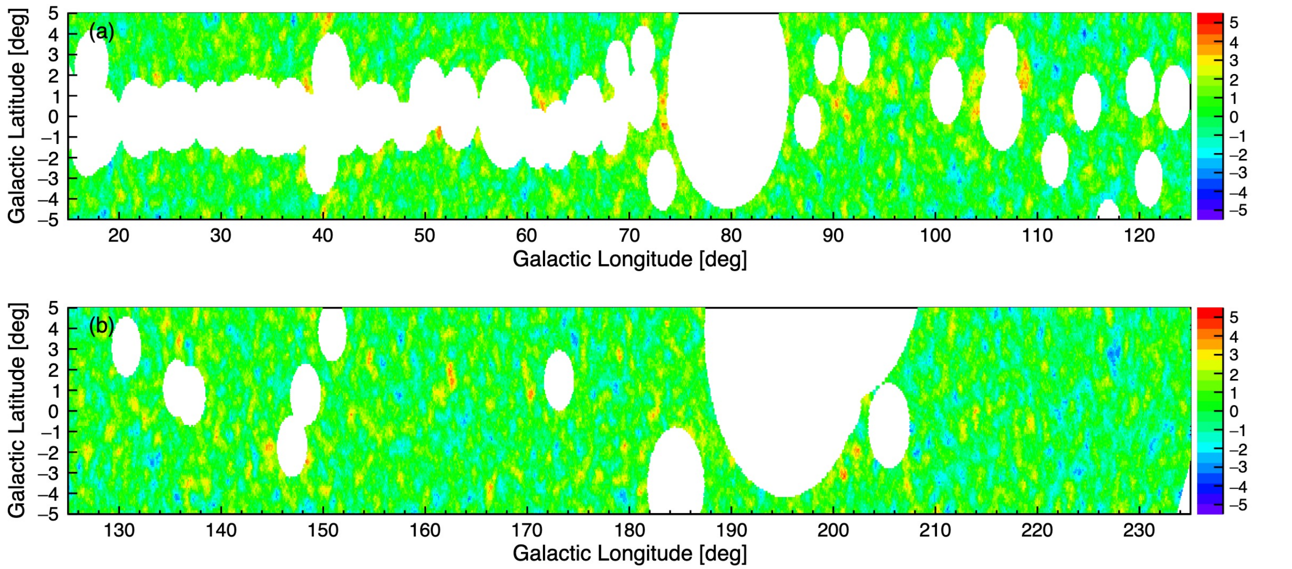
Galactic diffuse line-of-sight integrated emission



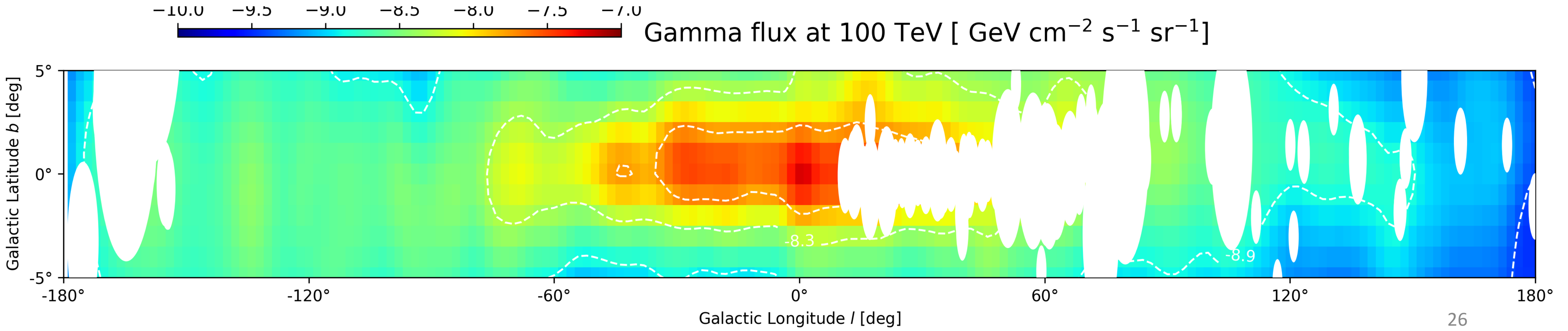
Galactic Diffuse gamma-ray emission



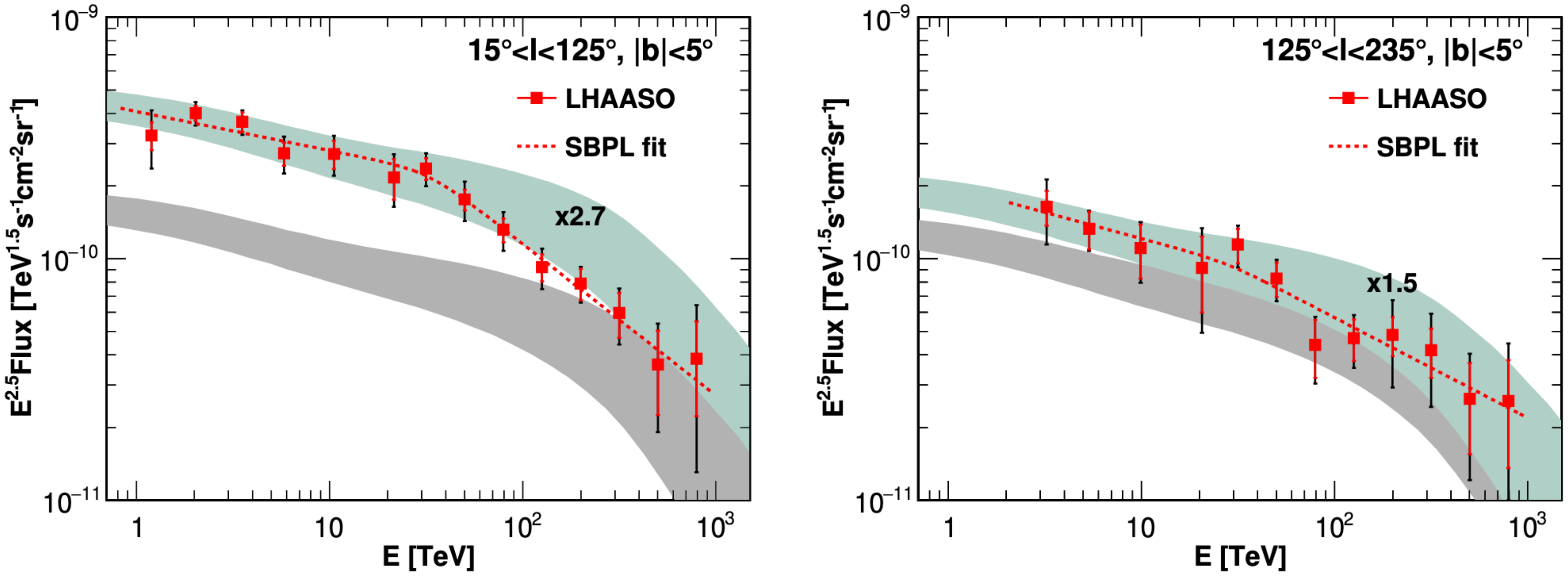
WCDA



KM2A



Energy spectrum of Galactic diffuse VHE gamma-ray



The grey shaded bands show the predicted diffuse fluxes from local CR intensities and the line-of-sight integral gas content, and the cyan bands are upscaled by constant factors as labelled in the plots

SEDs of the diffuse γ-ray emission in the inner (left) and outer (right) regions

"Assume that the CR intensity is uniform in the Galaxy, and calculate the γ-ray emission using the local CR spectra and the line-of-sight integrated gas content" --- LHAASO Collab. 2025

Hadronic interactions

AAFRAG for pp and He-p interaction

$$q_\nu(E_\nu, \mathbf{r}) = n_{\rm gas}(\mathbf{r}) \int dE_{\rm p} n_{\rm p}(E_{\rm p}, \mathbf{r}) \beta c \sigma_{pp}\left(E_{\rm p}\right) \frac{dN_\nu}{dE_\nu}(E_\nu, E_{\rm p})$$

Account for heavier elements in the ISM, we scale the hydrogen number density by a factor of 1.42

Integrating the local emissivity along the line of sight (LOS)

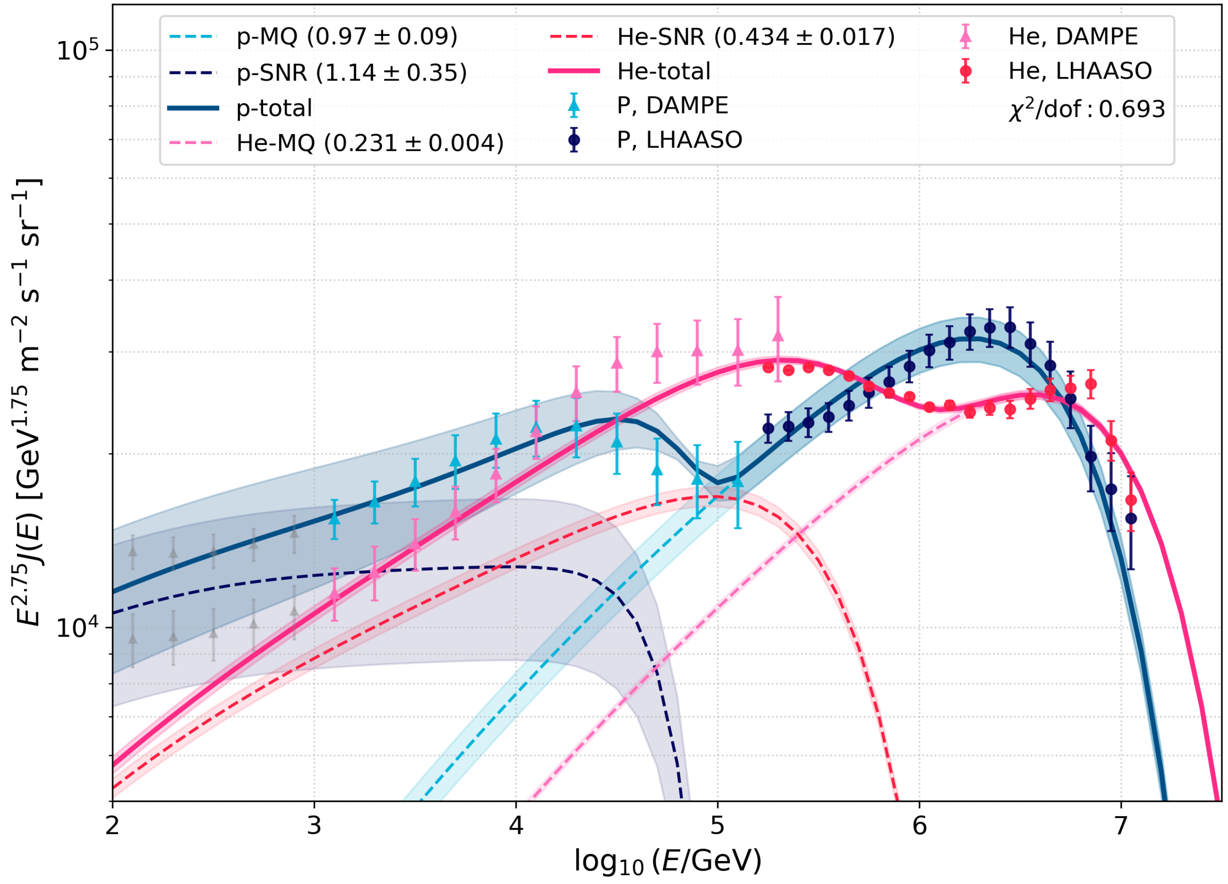
$$\phi_\nu(E_\nu, \Omega) = \frac{1}{4\pi} \int dE_{\rm p}\, \beta c\, \sigma_{pp}(E_{\rm p})\, \frac{dN_\nu}{dE_\nu}(E_\nu, E_{\rm p})\, X(\Omega, E_{\rm p})$$

Cosmic rays and the target gas along the LOS direction $X(\Omega, E_{\rm p}) = \int_0^\infty ds\, n_{\rm gas}(\mathbf{r})\, n_{\rm p}(E_{\rm p}, \mathbf{r})$

The full-sky integrated neutrino flux over Galactic longitude (*l*) and latitude (*b*)

$$F_\nu(E_\nu) = \int_{-\pi/2}^{\pi/2} \int_0^{2\pi} \phi_\nu(E_\nu, l, b) \cos b\, dl\, db.$$

Anchor in CR data



Joint fit to proton and helium data observed by LHAASO and DAMPE

We adopt separate injection parameters for proton and helium [Aharonian & Zhang, ApJ, 2026], but keeps the normalization as free parameter

- Supernova $\mathcal{E}_{\rm cr} = \eta_{\rm cr,SN}\mathcal{E}_{\rm SN}$
  $s_p = 2.40, E_{p,\max} = 68\ \mathrm{TeV}, \beta = 2.55$
  $s_{\rm He} = 2.24, E_{\rm He,max} = 468\ \mathrm{TeV}, \beta = 1.12$
- Microquasar $L_{\rm cr} = \eta_{\rm cr,MQ}L_{\rm Edd}$
  $s_p = 2.0, E_{p,\max} = 6\ \mathrm{PeV}, \beta = 1$

CR acceleration efficiencies $\eta_{\rm CR}$ best-fit values with 1σ uncertainty bounds

Component	Parameter	Best-Fit Value $\pm 1\sigma$
Microquasars	$\eta_{p,\rm MQ}$	0.10 ± 0.009
	$\eta_{\rm He,\ MQ}$	0.02 ± 0.0004
SNRs	$\eta_{p,\rm SN}$	0.11 ± 0.035
	$\eta_{\rm He,\ SN}$	0.04 ± 0.0017

Summary and discussion

- The predicted Galactic diffuse neutrino and gamma ray spectrum naturally comprises two independent populations, dominating distinct energy regimes

- MQs are characterized by lower spatial densities, the local CR flux is inherently subject to stochastic fluctuations from nearby source distributions and the local magnetic field

- CRs accelerated by recent or active sources may remain temporarily confined by local magnetic environments, accelerated particles continuously interact with surrounding target gas

- Systematic uncertainties, including hadronic interaction cross-sections, interstellar gas distributions, and GMF transport