



TeV–PeV Gamma-Ray and Neutrino Emission in the Galactic Plane

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Abstract

We model LHAASO observations of diffuse TeV–PeV γ rays in the Galactic Plane as the sum of unresolved leptonic emission from pulsar wind nebulae and hadronic emission from supernova-injected cosmic-ray (CR) protons. We investigate uncertainties in the radial distribution of the infrared component of the interstellar radiation field (ISRF), using profiles with enhanced photon densities in the inner Galaxy. We quantify their effects on $\gamma\gamma$ attenuation of the diffuse γ -ray emission. The alternative ISRF models affect the LHAASO diffuse fit only modestly, as the analysis excludes the Galactic Center direction and applies source masks in the Galactic Plane. Using the hadronic normalization inferred from the LHAASO fit for various ISRF models, the associated pp neutrino emission remains consistent with the IceCube all-sky measurement, while the flux from the Galactic Ridge region remains compatible with current ANTARES and KM3NeT constraints. Since the modified infrared profiles differ most strongly toward the inner Galaxy, we also examine their impact on inverse-Compton emission from point sources near the central molecular zone. These same models can noticeably modify the hadronic and inverse-Compton γ -ray emission above ~ 10 TeV from sources in the central region. Future KM3NeT observations, combined with γ -ray measurements of individual sources, can probe the inner-Galaxy CR population and constrain the radial distribution of the ISRF near the Galactic Center.

Unified Astronomy Thesaurus concepts: [High energy astrophysics \(739\)](#); [Galactic cosmic rays \(567\)](#); [Gamma-ray astronomy \(628\)](#); [Neutrino astronomy \(1100\)](#)

1. Introduction

The diffuse γ -ray emission of the Milky Way has long served as a calorimeter of Galactic cosmic rays (CRs), encoding the imprint of their interactions with gas and radiation fields (see, e.g., P. Blasi 2013; S. Gabici et al. 2019; J. Becker Tjus & L. Merten 2020). Leptonic emission from CR electrons includes bremsstrahlung in the interstellar gas at GeV energies and inverse-Compton (IC) scattering of starlight, infrared (IR), and cosmic microwave background (CMB) photons at γ -ray energies up to several hundred TeV. Above a few tens of GeV, the contribution of hadronuclear interactions (pp) becomes increasingly important through π^0 -decay γ rays. A diffuse multi-TeV excess reported by Milagro in the Cygnus region suggests either a hard local CR spectrum or a contribution from unresolved sources (A. A. Abdo et al. 2008). Fermi-LAT observations revealed an inner-Galaxy excess above a few GeV relative to GALPROP-based diffuse-emission models (M. Ackermann et al. 2012). ARGO-YBJ measurements are broadly consistent with the Fermi-LAT diffuse-emission expectation, and do not show a sub-TeV excess outside the Cygnus region (B. Bartoli et al. 2015). H.E.S.S. has also detected large-scale TeV emission along the inner Galactic Plane, interpreted as a combination of diffuse hadronic emission and unresolved sources (A. Abramowski et al. 2014).

The first detection of a diffuse sub-PeV γ -ray component from the Galactic disk was reported by Tibet AS γ , pointing to the presence of Galactic CR PeVatrons (M. Amenomori et al. 2021). The plausibility of a hadronic origin motivated searches

for a Galactic component in the IceCube TeV–PeV neutrino data. S. Razzaque (2013) associated 5 out of 21 shower-like IceCube events with the Galactic Center region, while J. C. Joshi et al. (2014) found that Galactic CR interactions with matter can account for at most 0.1 of the observed IceCube events. Using diffuse TeV–PeV γ -ray limits, M. Ahlers & K. Murase (2014) argued that the IceCube excess is mostly extragalactic, although subdominant Galactic contributions remain possible. In light of the Tibet AS γ measurement, it was pointed out that there is a possible tension with the nondetection of Galactic neutrinos by IceCube, which may be alleviated by an additional hard CR component associated with Cygnus Cocoon or other Galactic PeV sources (R.-Y. Liu & X.-Y. Wang 2021). The Galactic Plane contribution to the all-sky neutrino flux associated with the Tibet AS γ diffuse emission has been shown to be $\lesssim 5\%$ – 10% around 100 TeV (K. Fang & K. Murase 2021).

Spatially dependent CR transport has been invoked to explain the hard inner-Galaxy γ -ray flux and to predict an enhanced Galactic neutrino component (D. Gaggero et al. 2015a). Subsequent studies have examined the dependence on the radial CR density profile and inner-Galaxy spectral hardening (G. Pagliaroli et al. 2016; P. Lipari & S. Vernetto 2018). Unresolved sources and the diffuse interstellar component can also account for the Tibet AS γ data without requiring a hardening of the CR spectrum toward the Galactic Center (C. Steppa & K. Egberts 2020; V. Vecchiotti et al. 2022). More recently, LHAASO has observed diffuse γ -ray emission extending to PeV energies from both the inner and outer Galactic Plane, with a spectral break at ~ 30 TeV (Z. Cao et al. 2023, 2025a).

IceCube has reported evidence for diffuse neutrino emission from the Galactic Plane (IceCube Collaboration et al. 2023). A joint HAWC–IceCube analysis found no significant neutrino



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counterparts to 22 Galactic γ -ray sources and constrained the hadronic fractions of five sources (R. Alfaro et al. 2024). Neutrino observations of LHAASO sources constrain their hadronic contributions (T.-Q. Huang & Z. Li 2022). Additional unresolved Galactic source components have been introduced in multimessenger modeling of the LHAASO diffuse emission and IceCube Galactic Plane neutrino signal (C. Shao et al. 2023). K. Yan et al. (2024) argued for a significant nonhadronic contribution, plausibly from pulsar halos, whereas data-driven estimates suggest that unresolved pulsar sources cannot dominate the LHAASO diffuse emission above a few tens of TeV (S. Kaci et al. 2024). Multimessenger arguments suggest that the Galactic Plane neutrino signal is compatible with a hadronic diffuse γ -ray component, while resolved γ -ray sources alone are unlikely to account for the IceCube flux (K. Fang & K. Murase 2023; K. Fang et al. 2024).

Population-based arguments suggest that the sources of the Galactic hadronic CR flux may not be the brightest TeV–PeV γ -ray sources (T. Sudoh & J. F. Beacom 2023). The diffuse flux may instead arise from CR propagation in the interstellar medium (ISM) followed by interactions with gas (P. Lipari & S. Vernetto 2025) or from CR trapping in source cocoons (A. Ambrosone et al. 2025). Recent work also suggests that the Galactic γ -ray and neutrino emission from GeV to PeV energies can be explained largely by the Galactic CR sea, without a dominant additional source population (P. De La Torre Luque et al. 2023, 2025). These different interpretations leave the origin of the Galactic TeV–PeV emission unsettled, further motivating careful treatment of propagation effects that modify the observed γ -ray spectrum.

In this work, we quantify how uncertainties in the radial distribution of the IR component of the interstellar radiation field (ISRF) affect the observed γ -ray spectrum from the Galactic Plane. We model the LHAASO diffuse TeV–PeV γ -ray spectrum as the sum of a leptonic contribution from unresolved pulsar wind nebulae (PWNs) and a hadronic contribution from supernova-injected CR protons diffusing through the Galaxy. Using a recent gas density reconstruction, we calculate the resulting γ -ray emission and associated pp neutrino flux. Motivated by the possibility of an enhanced ISRF in the inner Galaxy (A. Misiriotis et al. 2006; S. Vernetto & P. Lipari 2016; N. Gupta 2025), we consider IR profiles with enhanced photon densities in the inner Galaxy. We evaluate their impact on the $\gamma\gamma$ optical depth and hence on the fit to the observed diffuse γ -ray spectrum. The total optical depth is the sum of that due to starlight, IR, and CMB.

Since these IR profiles differ most strongly toward the Galactic Center, we also examine the effect of an enhanced ISRF on IC emission from point sources in the inner few hundred parsecs, near the central molecular zone (CMZ). We further use the hadronic component of the combined leptonic and hadronic fit to the LHAASO diffuse emission to estimate the neutrino flux from the Galactic Ridge ($|\ell| < 30^\circ$, $|b| < 2^\circ$). This region is a key target for upcoming imaging atmospheric Cherenkov detectors, such as the Cherenkov Telescope Array (CTA) and also neutrino detectors like KM3NeT, which has a favorable view of the Galactic Center with upgoing muon tracks. Future KM3NeT observations will test the unresolved-source contribution, particularly toward the Galactic Center.

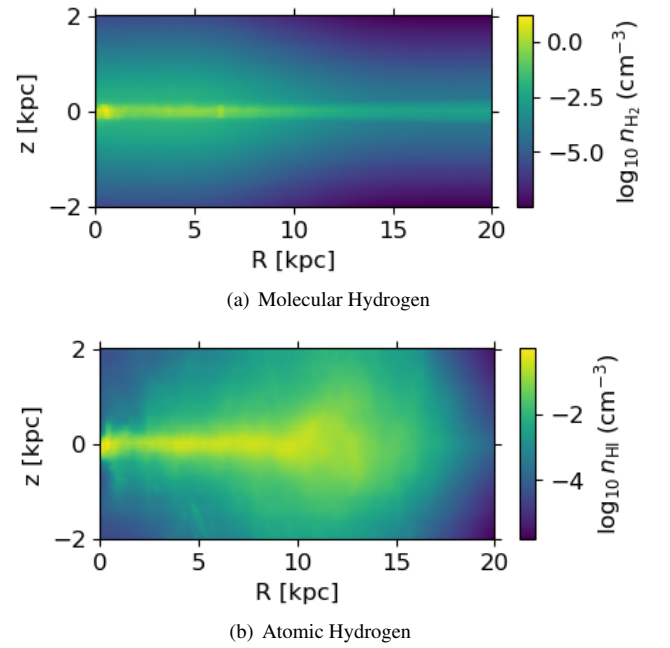


Figure 1. Axisymmetric density distributions of (a) molecular H_2 and (b) atomic H I in Galactocentric coordinates, obtained by azimuthally averaging the 3D ISM reconstruction of L. Söding et al. (2025).

We outline the model considerations in Section 2 and present the results in Section 3. We discuss the implications in Section 4 and draw our conclusions in Section 5.

2. Methods and Model Considerations

2.1. Atomic and Molecular Gas Distribution

Galactic molecular clouds dominate the H_2 distribution and play an important role in shaping the observed CR spectrum (S. Biswas & N. Gupta 2018, 2019; A. De Sarkar et al. 2021). The CMZ, extending to ~ 200 pc from the Galactic Center, contains a high molecular gas density (K. Ferrière et al. 2007; T. S. Rice et al. 2016; B.-Q. Chen et al. 2020; T. Wang et al. 2025). Earlier Galactic gas models often used factorized density profiles, such as the prescription of P. Lipari & S. Vernetto (2018), based on the H I measurements of P. M. W. Kalberla & L. Dedes (2008) outside the Galactic Bulge.

We use the H I and H_2 density cubes from the 3D ISM reconstruction of L. Söding et al. (2025), which provides a spatially coherent model of the full gas distribution. The Sun-centered Cartesian grids are transformed to Galactocentric cylindrical coordinates and azimuthally averaged to obtain the axisymmetric gas distributions n_{HI} and n_{H_2} as a function of (R, z) . The resulting gas maps are shown in Figure 1. The total hydrogen density is $n_{\text{H}} = n_{\text{HI}} + 2n_{\text{H}_2}$. The ISM helium abundance is $n_{\text{He}}/n_{\text{H}} \sim 0.1$ and hence is not included in our analysis.

2.2. ISRF and Optical Depth

Very high energy (VHE; $E_\gamma \gtrsim 0.1$ TeV), γ rays in the Galaxy are attenuated by pair production on ambient radiation fields, including starlight, dust-reprocessed IR photons, and the CMB. Absorption due to the far-IR component becomes important above a few tens of TeV, with the optical depth typically peaking around $E_\gamma \simeq 100$ –200 TeV, whereas CMB

absorption dominates at $E_\gamma \gtrsim 300$ TeV (S. Vernetto & P. Lipari 2016). At $E_\gamma \geq 1$ TeV, attenuation by starlight is subdominant compared to that by IR photons and the CMB. The extragalactic background light can also be neglected for Galactic propagation, since its effect is relevant mainly over extragalactic path lengths. The CMB is treated as an isotropic blackbody with $T_{\text{CMB}} = 2.7255$ K (Planck Collaboration et al. 2020), and its redshift evolution is negligible over Galactic distances.

For a γ ray arriving from direction (l, b) and line-of-sight distance s , the IR optical depth $\tau_{\gamma\gamma}^{\text{IR}}(E_\gamma, l, b, s)$ is obtained by integrating the inverse mean free path $\lambda_{\gamma\gamma}^{-1}(E_\gamma, l, b, s')$ over the line-of-sight variable s' . The mean free path for the anisotropic IR photon field is

$$\lambda_{\gamma\gamma}^{-1} = \int d\Omega \int d\epsilon \frac{dn_{\text{IR}}}{d\epsilon d\Omega}(\epsilon, \Omega; \mathbf{x})(1 - \cos \theta) \sigma_{\gamma\gamma}(E_\gamma, \epsilon, \theta), \quad (1)$$

where $dn_{\text{IR}}/d\epsilon d\Omega$ is the IR photon number density at energy ϵ , direction Ω , and position $\mathbf{x}$. $\sigma_{\gamma\gamma}$ is the pair-production cross section (R. J. Gould & G. P. Schröder 1967), and θ is the angle between the γ ray and target photon.

The IR emission from interstellar dust is modeled as a modified blackbody spectrum, with emissivity

$$\eta_\lambda \simeq \rho_{\text{dust}}(R, z) \kappa_\lambda B_\lambda[T(R, z)], \quad (2)$$

where ρ_{dust} is the dust mass density, κ_λ is the wavelength-dependent dust emissivity cross section (J. C. Weingartner & B. T. Draine 2001), and B_λ is the blackbody spectrum at the local dust temperature. At each point along the γ -ray path, η_λ is integrated along each incoming ray direction $\hat{\Omega}$ to obtain $I_\lambda(\Omega, \mathbf{x})$, which in turn gives $dn_{\text{IR}}/d\epsilon d\Omega$. The optical depth depends on $E_\gamma, (l, b, d)$, the dust density, the temperature, κ_λ , and the angular distribution of the IR field.

For the baseline IR model, we adopt the Galactic dust distribution of A. Misiriotis et al. (2006), with cold- and warm-dust components modeled as exponential disks:

$$\rho_{c,w}(R, z) = \rho_{c,w}^0 \exp\left(-\frac{R}{R_{c,w}} - \frac{|z|}{Z_{c,w}}\right). \quad (3)$$

Here, $\rho_{c,w}^0$ are the central dust mass densities, and $R_{c,w}$ and $Z_{c,w}$ are the radial and vertical scales of cold and warm dust, respectively. In the baseline model, we have $\rho_c^0 = 1.51 \times 10^{-25} \text{ g cm}^{-3}$ and $\rho_w^0 = 1.22 \times 10^{-27} \text{ g cm}^{-3}$, so the cold-dust density normalization is much larger than that of the warm component.

This model provides a useful large-scale description of the Galactic dust distribution based on COBE/DIRBE and FIRAS data (N. W. Boggess et al. 1992; D. J. Fixsen et al. 1996; M. G. Hauser et al. 1998; T. Kelsall et al. 1998). However, the inner-Galaxy dust density is inferred by fitting a parametric dust distribution to the line-of-sight far-IR emission, and the central $10^\circ \times 10^\circ$ region was masked in the DIRBE maps used for the spatial fit. We therefore adopt this profile as our baseline and vary its inner radial dependence, as summarized in Table 1, to estimate the systematic uncertainty in the IR optical depth. Each profile is normalized to match the baseline model value at the solar neighborhood. These variations increase the dust density at the Galactic Center by factors of a

Table 1
Multiplicative Normalization Factors $A_{c,w}$ Applied to $\rho_{c,w}^0$ in Equation (3) for Different Radial Profiles

Model	Radial Profile	$A_c \rho_c^0$	$A_w \rho_w^0$
Base	$A_{c,w} \rho_{c,w}^0 \exp(-R/R_{c,w})$	ρ_c^0	ρ_w^0
M1	$A_{c,w} \rho_{c,w}^0 \exp(-2R/R_{c,w})$	$5.47 \rho_c^0$	$13.14 \rho_w^0$
M2	$A_{c,w} \rho_{c,w}^0 \exp[-(R/R_{c,w})^2]$	$3.29 \rho_c^0$	$57.90 \rho_w^0$
M3	$A_{c,w} \rho_{c,w}^0 \exp(-2.5R/R_{c,w})$	$12.81 \rho_c^0$	$47.64 \rho_w^0$
M4	$A_{c,w} \rho_{c,w}^0 \exp(-3.5R/R_{c,w})$	$70.11 \rho_c^0$	$625.9 \rho_w^0$

Note. The factors are chosen so that the dust density—and hence the IR emissivity—matches the baseline model value at $R_\odot = 8.5$ kpc, in the solar neighborhood. The default scale lengths are $R_c = 5$ kpc and $R_w = 3.3$ kpc for cold and warm dust, respectively.

few to nearly 2 orders of magnitude in the extreme M4 case. We calculate $\tau_{\gamma\gamma}(E_\gamma, \ell, b, s)$ on a grid with $\ell \in [15^\circ, 235^\circ]$ in 2° steps and $b \in [-5^\circ, 5^\circ]$ in 0.5° steps (since $\sin b \approx b$ for $|b| \ll 1$). Along each line of sight, $\tau_{\gamma\gamma}$ is calculated up to the distance at which the Galactocentric radius reaches $R = 15$ kpc. The LHAASO diffuse γ -ray measurements then provide a natural test bed for assessing how uncertainties in the inner-Galaxy IR field affect the interpreted Galactic emission at $\gtrsim 100$ TeV.

2.3. CR Injection from Supernova Remnant Distribution

Supernova remnants (SNRs) are widely considered the main sources of Galactic CRs through diffusive shock acceleration, with efficient acceleration supported by magnetic field amplification and shock geometry effects (see, e.g., S. Xu & A. Lazarian 2017, 2022). Observations of Tycho's SNR indicate proton acceleration up to $\gtrsim 500$ TeV (G. Morlino & D. Caprioli 2012). We adopt $E_{p,\text{max}} = 10$ PeV, which lies between the 5 and 50 PeV source cutoffs commonly used in KRA $_\gamma$ Galactic diffuse γ -ray and neutrino models (D. Gaggero et al. 2015a, 2015b). Since nuclear spallation is negligible at these energies, we restrict the transport calculation to CR protons. For a distributed SNR population, the injection in units of number density per energy and time interval is

$$Q_p(E, R, z) \propto f_S(R, z)(E/E_0)^{-\alpha_p}, \quad (4)$$

where we choose a reference energy $E_0 = 4$ GeV. We adopt a source distribution that follows the SNR radial profile of G. L. Case & D. Bhattacharya (1996) multiplied by an exponential vertical dependence (P. Blasi & E. Amato 2012):

$$f_S(R, z) \propto (R/R_\odot)^p e^{-q(R-R_\odot)/R_\odot} e^{-|z|/z_g}, \quad (5)$$

with $R_\odot = 8.5$ kpc, $p = 1.69$, $q = 3.33$, and $z_g = 0.2$ kpc. Thus, our injection spectrum reduces to a function of E, R , and z . At injection, the spectra required in Galactic CR models are typically steeper than the canonical first-order Fermi prediction, with $\alpha_p \simeq 2.2$ – 2.4 (D. Caprioli 2012). We adopt a conservative choice $\alpha_p = 2.4$.

2.4. CR Diffusion and Transport

Assuming cylindrical symmetry and an azimuthal large-scale magnetic field, $\mathbf{B}_0 = B_\phi(R, z)\hat{\phi}$, transport in the R – z plane is perpendicular to the field. We adopt the spatially

dependent diffusion coefficient of P. De La Torre Luque et al. (2025):

$$D(E, R) = D_0 \beta (E/E_0)^{\delta(R)}, \quad (6)$$

where $\delta(R) = 0.04 \cdot (R/1 \text{ kpc}) + 0.17$ for $R < R_\odot$ and $\delta(R) = \delta(R_\odot)$ for $R \geq R_\odot$. The diffusion coefficient at $E_0 = 4 \text{ GeV}$ is $D_0 = 6.1 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$. In Galactocentric (R, z) coordinates, the transport equation including diffusion and pp losses, and neglecting ionization and Coulomb losses above 1 TeV, is (V. L. Ginzburg & S. I. Syrovatskii 1964; A. W. Strong & I. V. Moskalenko 1998)

$$\frac{1}{R} \frac{\partial}{\partial R} \left(R D \frac{\partial N_p}{\partial R} \right) + \frac{\partial}{\partial z} \left(D \frac{\partial N_p}{\partial z} \right) - \frac{N_p}{\tau_{pp}} + Q_p(E, R, z) = \frac{\partial N_p}{\partial t}, \quad (7)$$

where Q_p is the source term, $\tau_{pp}^{-1} = cn_H \sigma_{pp}^{\text{inel}}$ is the pp collision rate, $\sigma_{pp}^{\text{inel}}$ is the inelastic pp -interaction cross section (S. R. Kelner et al. 2006), and $N_p(E, R, z) = dN/dE_p$. We also note that convection and reacceleration are not important for the energy range of our study. In addition, the proton secondary component becomes important only at energies below $\sim 10 \text{ GeV}$ (see, e.g., C. Evoli et al. 2018).

We choose α_p such that the propagated spectral index, approximately $\alpha_p + \delta(R)$, matches the observed CR proton spectrum in the solar neighborhood. In the steady state, $\partial N_p / \partial t = 0$. We solve Equation (7) numerically in the steady state using a finite-difference method over the galactocentric radius range $0 < R < 15.0 \text{ kpc}$ and $|z| < 2.0 \text{ kpc}$. We impose free-escape boundary conditions, $N_p(E, R_{\text{max}}, z) = N_p(E, R, \pm z_{\text{max}}) = 0$, and regularity at the symmetry axis, $\partial N_p / \partial R = 0$ at $R = 0$.

3. Results

The LHAASO WCDA and KM2A measurements provide the diffuse Galactic γ -ray spectrum in the inner ($15^\circ < l < 125^\circ$, $|b| < 5^\circ$) and outer ($125^\circ < l < 235^\circ$, $|b| < 5^\circ$) Galactic Plane regions (Z. Cao et al. 2023, 2025a). The inner-region spectrum shows a softening above a few tens of TeV, with a change in photon index of approximately 0.5, while the evidence for a break in the outer region is weaker.

3.1. Leptonic Emission from PWNs

We estimate the unresolved contribution of PWNs and pulsar halos to the diffuse Galactic γ -ray emission by generating a synthetic population of their parent pulsars. We use the ATNF³ pulsar catalog (R. N. Manchester et al. 2005) to estimate the age (τ_{age}) and radial distributions of pulsars in a 60° Galactocentric azimuthal sector that contains the Sun. We impose $|z| \leq 1.7 \text{ kpc}$, corresponding to the LHAASO vertical extent, and $\tau_{\text{age}} < 10 \text{ Myr}$, to exclude older pulsars. After applying an age-dependent beaming fraction ϵ_b (T. M. Tauris & R. N. Manchester 1998), the 737 pulsars selected in the reliable sector correspond to a total population of $N_{\text{true}} = 737/\epsilon_b$, accounting for misaligned pulsars.

We first generate a Monte Carlo realization of the reliable sector using the inferred age and radial distributions, including Gaussian fluctuations of width $\sqrt{N_{\text{true}}}$. The same procedure is

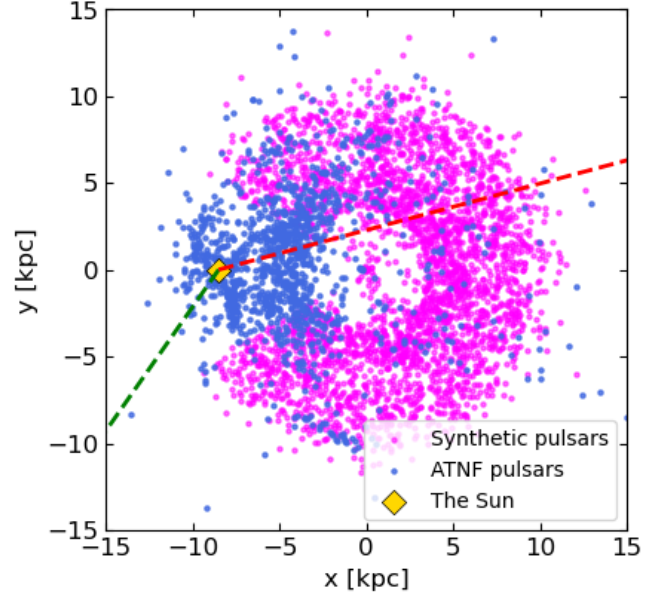


Figure 2. Galactic pulsar distribution, generated from the observed ATNF pulsar distribution in a 60° Galactocentric azimuthal sector centered on the Sun–Galactic Center line. The distribution corresponds to one random realization with an aligned-pulsar fraction of unity. The red dashed line marks $\ell = 15^\circ$; the LHAASO ROI extends counterclockwise to the green dashed line at $\ell = 235^\circ$.

then repeated over the remaining Galactocentric azimuthal sectors to construct the full Galactic population. An example random realization is shown in Figure 2 for $\epsilon_b = 1$. The dashed red and green lines indicate the LHAASO region of interest (ROI) in the Galactic Plane. For each source, we convert the pulsar age to the spindown power $\dot{E}$ using $\log_{10}(\dot{E}/\text{erg s}^{-1}) = -1.529 \log_{10}(\tau_{\text{age}}/\text{yr}) + 42.56$, and estimate the maximum γ -ray energy of the associated PWNs as $E_{\gamma, \text{max}} = 0.9(\dot{E}/10^{36} \text{ erg s}^{-1})^{0.65} \text{ PeV}$, following E. Wilhelm de Oña et al. (2022).

The ATNF catalog is not a complete census of Galactic pulsars, so we use the observed pulsars only as empirical templates for the age and radial distributions of the parent population. The cut $\tau_{\text{age}} < 10 \text{ Myr}$ removes old pulsars with low present spindown powers, which are unlikely to contribute appreciably to the TeV–PeV PWN emission, while $|z| \leq 1.7 \text{ kpc}$ matches the vertical extent of the LHAASO field of view. Catalog incompleteness and sampling biases, including radio selection effects and distance uncertainties, can affect the inferred age and radial distributions. In particular, missing distant inner-Galaxy pulsars or young high- $\dot{E}$ systems would lead to an underestimate of the unresolved PWN contribution, whereas incompleteness among old low- $\dot{E}$ pulsars has little impact on the TeV–PeV flux.

The γ -ray spectrum, $\Phi_\gamma = N_0(E/E_0)^{-\Gamma}$, is assumed for each PWN, with $E_0 = 3 \text{ TeV}$ for the LHAASO WCDA band and $E_0 = 50 \text{ TeV}$ for the KM2A band (Z. Cao et al. 2024). Among the 34 LHAASO sources associated with pulsars/PWNs, the spectral index is available for 31 sources in the KM2A band and 28 sources in the WCDA band. For each synthetic source, we assign a randomly generated Γ within the measured range in the corresponding detector band. For the KM2A and WCDA components, we adopt the fitted relations between the integrated γ -ray flux and the pulsar spindown power derived by S. Kaci et al. (2025), including the same Gaussian scatter.

³ <https://www.atnf.csiro.au/research/pulsar/psrcat/>

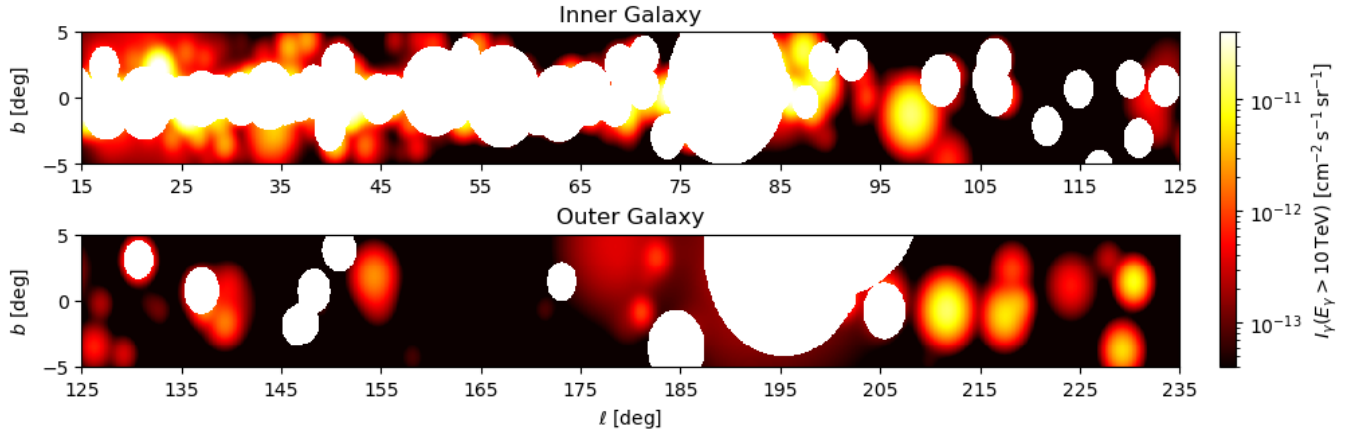


Figure 3. Diffuse integrated γ -ray emission at >10 TeV in the Galactic Plane from PWNs for one random realization of the Galaxy. The emission from the white regions is masked out to match the LHAASO analysis (Z. Cao et al. 2023). The upper and lower panels correspond to the LHAASO inner ($15^\circ < \ell < 125^\circ$, $|b| < 5^\circ$) and outer ($125^\circ < \ell < 235^\circ$, $|b| < 5^\circ$) regions.

For the KM2A component,

$$\log_{10}(4\pi d^2 F_{>10 \text{ TeV}}) = 0.942 \log_{10}(\dot{E}) - 3.894. \quad (8)$$

This gives the integrated flux $F_{>10 \text{ TeV}}$, which is then used to fix the normalization of the KM2A spectrum up to $E_{\gamma, \text{max}}$. If $E_{\gamma, \text{max}} \geq 25$ TeV, the WCDA normalization is set by requiring continuity with the KM2A spectrum at 25 TeV. If $E_{\gamma, \text{max}} < 25$ TeV, only the WCDA component is included, and its normalization is obtained from the analogous relation

$$\log_{10}(4\pi d^2 F_{>1 \text{ TeV}}) = 1.029 \log_{10}(\dot{E}) - 5.682, \quad (9)$$

using the integrated flux between 1 TeV and E_{max} . The resulting normalizations are used to compute the spectra in the WCDA (1–25 TeV) and KM2A (25–1000 TeV) bands. We assume a physical extension of 20 pc for each PWN (see, e.g., A. U. Abeysekara et al. 2017; P. Martin et al. 2022). The source flux is then distributed over neighboring sky pixels using a Gaussian kernel that combines the intrinsic angular extension with the LHAASO point-spread function (PSF). For the PSF, we adopt the largest value in the 10–15 TeV bin (F. Aharonian et al. 2021, see Figure 7 therein). Only sources within the LHAASO field of view are retained.

To identify unresolved sources, we compare the differential flux normalizations of the WCDA and KM2A components with the corresponding decl.-dependent LHAASO sensitivity curves (Z. Cao et al. 2024). We adopt the most optimistic detection thresholds, corresponding to a point source with an E^{-2} spectrum for the WCDA band and with an E^{-3} spectrum for the KM2A band. This choice provides a conservative lower limit on the unresolved PWN contribution. For comparison with the diffuse Galactic Plane emission, we apply a source mask based on detected LHAASO-KM2A sources and known TeVCat sources (Z. Cao et al. 2023). The resulting sky-intensity distribution for one random realization of the Galaxy is shown in Figure 3.

The γ -ray flux is obtained by summing the contributions of unresolved sources over the sky pixels, after applying $\gamma\gamma$ attenuation in the ISRF. The mean unresolved flux, computed from 1000 random realizations of the Galaxy, is shown in Figure 3. Our estimate is consistent with the leptonic flux found by S. Kaci et al. (2025). For the inner region in our baseline IR model, the leptonic contribution accounts for about

20% of the diffuse flux at a few TeV, increases to $\sim 30\%$ at a few tens of TeV, and decreases to $\sim 10\%$ at the highest energies.

3.2. Diffuse γ -Ray and Neutrino Fluxes

The hadronic γ -ray emission depends on the gas density, SNR distribution, and CR spectrum. We use the steady-state CR distribution, $N_p(E_p, R, z) = dN/dE_p$, to calculate the γ -ray and neutrino fluxes. The line-of-sight integrated γ -ray intensity is

$$I_\gamma(E_\gamma, l, b) = \int \frac{ds}{4\pi} Q_\gamma(E_\gamma, l, b, s) e^{-\tau_{\gamma\gamma}(E_\gamma, l, b, s)}, \quad (10)$$

where $Q_\gamma(E_\gamma, R, z)$ is the local hadronic emissivity, in units of $\text{TeV}^{-1} \text{cm}^{-3} \text{s}^{-1}$, calculated using the pp -interaction parameterization of S. R. Kelner et al. (2006). To compare with the LHAASO data, we apply the same source mask to the hadronic component, removing bright Galactic Plane sources. The solid-angle-averaged diffuse γ -ray intensity over the surviving pixels is

$$\Phi_\gamma(E) = \frac{1}{\Omega_{\text{ROI}}} \int_{\text{ROI}} I_\gamma(E, l, b) d\Omega, \quad (11)$$

where $d\Omega = \cos b db dl$ and Ω_{ROI} is the unmasked solid angle of the ROI.

We fit the LHAASO inner-region data by χ^2 minimization, keeping the leptonic contribution fixed and varying only the hadronic normalization. We use the inner-region spectrum for the fit, because it provides a stronger constraint than the outer region, and we use the total LHAASO uncertainties, with statistical and systematic errors added in quadrature, in the χ^2 calculation. This yields a conservative goodness-of-fit estimate, resulting in $\chi_\nu^2 < 1$, primarily due to large uncertainties at the highest energies. The best fit for the baseline model gives a reduced $\chi_\nu^2 \simeq 0.5$ for 13 degrees of freedom, shown in Figure 4. The blue-shaded band shows the 3σ confidence interval on the fitted hadronic normalization, obtained from $\Delta\chi^2 = 9$ for one fitted parameter. The PWN component is fixed to its mean value in the fit, with its 1σ Monte Carlo spread shown by the green-shaded region.

We repeat the fit for the alternative IR radial dependence models in Figure 5. The resulting range is shown by the gray-

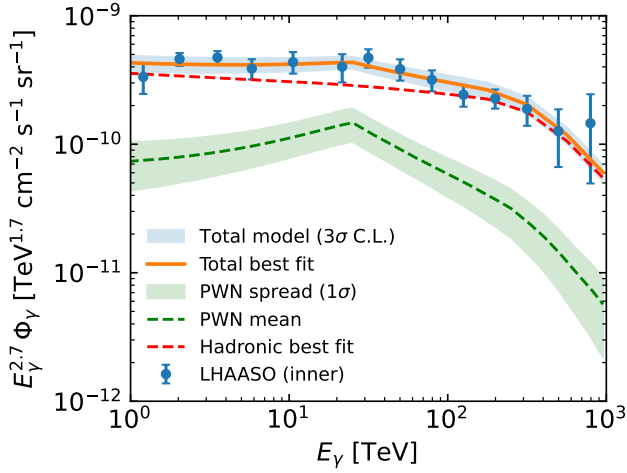


Figure 4. LHAASO inner-region ($15^\circ < \ell < 125^\circ$, $|b| < 5^\circ$) diffuse γ -ray spectrum for the baseline model. The blue band shows the 3σ confidence interval from the fitted hadronic normalization, while the green band shows the 1σ spread of the unresolved PWN component.

shaded band. The black dotted curve shows the most extreme variation: M4. The fit improves slightly, to $\chi_\nu^2 = 0.4$, for the stronger M3 profile, but deteriorates for the M4 profile, to $\chi_\nu^2 = 0.8$. Hence, no statistically significant improvement in the fit to the LHAASO data is found for the radial profiles considered here. The ISRF comparison uses the best-fit normalization for each case. Including the normalization uncertainty may moderately broaden the flux range. The modified profiles differ most strongly in the central region, which lies outside the LHAASO longitude range and is further affected by the Galactic Plane source mask. Within the adopted ROI and source masks, the LHAASO diffuse measurement is therefore robust against the five different IR-background profile uncertainties considered here.

We apply the global normalization of the injected Galactic CR population obtained from the inner-region fit to the outer region and do not perform a separate χ^2 minimization. The gas distribution, PWN population, and ISRF are still evaluated with their spatial dependences for the assumed models. Only the overall injected CR normalization is kept common. The resulting outer-region flux is shown in the right panel of Figure 5. The model underestimates the outer-region flux around the spectral break near ~ 30 TeV and at the highest energies, suggesting that the baseline model may miss additional outer-Galaxy contributions or require modifications to the assumed CR source, gas, or transport model. For the adopted SNR source distribution from G. L. Case & D. Bhattacharya (1996), the radial profile peaks at $R_{\text{peak}} = (p/q)R_\odot$ (see Equation (5)). Source distributions with larger R_{peak} can enhance the outer-region flux. Other possible effects include local CR spectral hardening and residual unresolved or extended source emission. The alternative IR profiles have a negligible effect on the LHAASO outer-region spectrum.

The directional neutrino intensity is calculated over the full sky and integrated over a solid angle:

$$F_\nu(E) = \int I_\nu(E, l, b) d\Omega, \quad (12)$$

where I_ν is calculated analogously to Equation (10), but without any optical depth attenuation. The all-sky single-flavor ($\nu_\mu + \bar{\nu}_\mu$) flux, after accounting for neutrino oscillations, is

shown in the left panel of Figure 6. The blue solid curve shows the baseline model. The blue-shaded band gives the range from the hadronic normalizations used to fit the inner-region γ -ray data for the different IR models. We also show the IceCube constraints on the Galactic neutrino emission derived for the π^0 , KRA_γ^5 , and KRA_γ^{50} templates (D. Gaggero et al. 2015a; IceCube Collaboration et al. 2023). The shaded bands show the 1σ uncertainty of the IceCube best-fit template fluxes over the neutrino energy range contributing 90% of the detection significance. The π^0 template extrapolates the GeV π^0 -decay component inferred from γ -ray data with an $E^{-2.7}$ spectrum and fixed morphology. The KRA_γ templates allow a spatially dependent CR spectrum, producing harder emission toward the Galactic Center. Our prediction is consistent with IceCube estimates and approaches the KRA_γ^5 best-fit flux beyond a few hundred TeV.

3.3. Galactic Center Region

Using the hadronic normalization fixed by the LHAASO inner-region fit, we estimate the neutrino flux from the Galactic Ridge, defined as the region $|\ell| < 30^\circ$ and $|b| < 2^\circ$. This region is expected to provide one of the strongest Galactic neutrino signals because of its high gas column density and enhanced CR activity (A. Neronov et al. 2014; R.-Y. Liu et al. 2016; R. Yang et al. 2016; D. Gaggero et al. 2017). The CMZ is an asymmetric layer of predominantly molecular gas in the central few hundred parsecs of the Galaxy, extending to ~ 200 pc from the Galactic Center. Our transport model is axisymmetric in (R, z) , so a fully 3D Galactic Center transport calculation would be needed to capture the coupled effects of nonaxisymmetric gas, source, and magnetic field structure (J. Dörner et al. 2024). To account for the enhanced central gas concentration, we add the CMZ atomic and molecular hydrogen components from K. Ferrière et al. (2007) to the gas model described in Section 2.1.

The CMZ gas is included only in the line-of-sight emissivity. This is justified by comparing the diffusion time, $t_{\text{diff}} \simeq L^2/6D(E, R)$, with the hadronic loss time, $t_{pp} \simeq (n_H c \sigma_{pp}^{\text{inel}})^{-1}$. Taking $L = 0.2$ kpc as the characteristic CMZ escape scale and evaluating the diffusion coefficient at a representative radius $R = 0.1$ kpc, we obtain $t_{\text{diff}} \simeq 8.5 \times 10^3$ yr at $E_p = 10$ TeV. For a representative CMZ density $n_H = 150 \text{ cm}^{-3}$ and $\sigma_{pp} \simeq 5 \times 10^{-26} \text{ cm}^2$, the hadronic loss time is $t_{pp} \simeq 1.4 \times 10^5$ yr. Since $t_{\text{diff}} \ll t_{pp}$, the CMZ gas mainly changes the emissivity rather than the propagated proton density.

We use line-of-sight distance bins of 0.1 kpc for the Galactic Ridge region, with finer 0.01 kpc binning for $R < 500$ pc. The neutrino flux in our baseline model from the Galactic Ridge per unit solid angle is shown by the blue solid line in the right panel of Figure 6. The shaded band shows the 68% containment region of the ANTARES Galactic Ridge neutrino flux inferred from the posterior distribution of the power-law normalization and spectral index, while the dashed line shows the corresponding best-fit flux (A. Albert et al. 2023). We also show the 90% credible interval upper limit on the neutrino flux from the Galactic Ridge obtained with 640 days of KM3NeT/ARCA data (F. Filippini 2024).

The Galactic Ridge neutrino comparison serves as a consistency check on the hadronic component inferred from the LHAASO diffuse γ -ray fit. An overly hard global hadronic

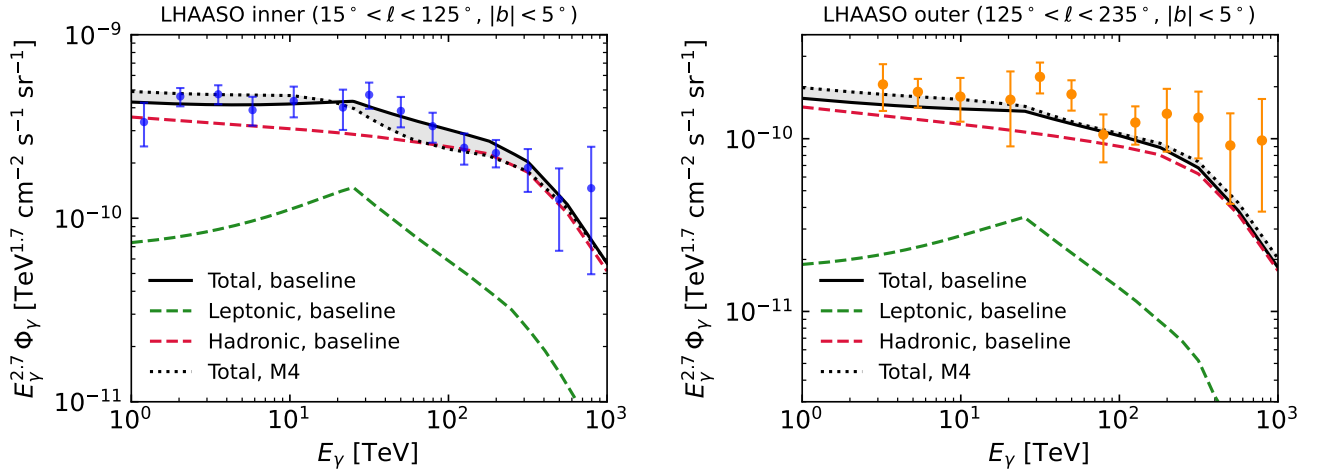


Figure 5. Diffuse γ -ray flux for the LHAASO inner ($15^\circ < \ell < 125^\circ$, $|b| < 5^\circ$) and outer ($125^\circ < \ell < 235^\circ$, $|b| < 5^\circ$) ROIs. The shaded region indicates the variation due to uncertainties in the IR model stemming from the alternate dust density profiles assumed in Table 1. The black solid line shows the base model, while the black dotted line shows the most extreme M4 model. The LHAASO data are shown as the blue and orange points for the inner and outer regions, respectively (Z. Cao et al. 2025a).

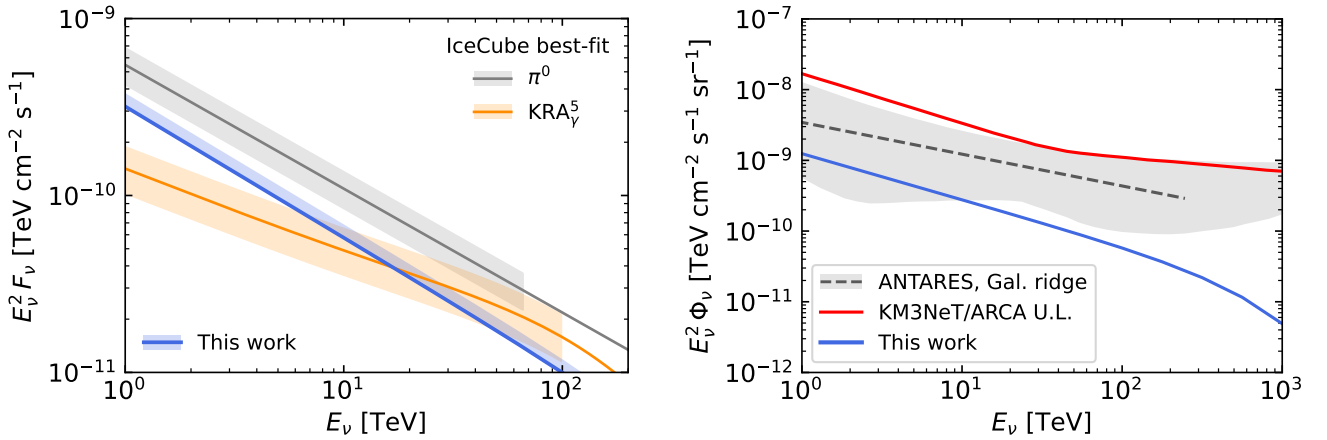


Figure 6. Left: the neutrino flux obtained in our baseline model (blue line) and other IR distribution profiles (blue-shaded band), using the best-fit normalizations obtained in Figure 5. The IceCube all-sky measurement for two of their best-fit models is shown for comparison (IceCube Collaboration et al. 2023). Right: the neutrino flux from the Galactic Ridge ($|\ell| < 30^\circ$, $|b| < 2^\circ$) in our model compared to the 68% confidence level upper limit from ANTARES observations (A. Albert et al. 2023) and the 90% credible interval upper limit from KM3NeT using 640 days of data (F. Filippini 2024).

component would approach the all-sky IceCube diffuse flux, while present Galactic Ridge limits may allow local CR hardening near the Galactic Center relative to our baseline model. Next-generation γ -ray detectors, such as CTA, will provide an important complementary probe, although a quantitative forecast would require a dedicated sensitivity study (A. Neronov & D. Semikoz 2020).

The axisymmetric IR photon density profiles considered here are centrally peaked, so their effect should be stronger for individual sources near the Galactic Center, even though the LHAASO inner-region diffuse flux is affected only modestly. Ultra-high-energy Galactic γ -ray sources extending to $\gtrsim 50$ TeV have been observed, with IC emission on CMB photons dominating at the highest energies (see, e.g., S. Boxi et al. 2025). However, an enhanced IR photon field can increase the IC emission on the ISRF while also strengthening $\gamma\gamma$ attenuation through a larger optical depth. The steady-state electron distribution is

$$N_e(E_e, R, z) = \frac{1}{b_{\text{tot}}} \int_{E_e}^{E_{e,\text{max}}} Q_e(E'_e, R, z) dE'_e, \quad (13)$$

where $b_{\text{tot}}(E_e, R, z) \equiv -dE_e/dt = b_{\text{syn}} + b_{\text{IC}}$ is the sum of the synchrotron and IC energy-loss rates. For electrons of energy E_e scattering target photons of energy ϵ , the IC emissivity scales approximately as $Q_{\gamma,\text{IC}} \propto n_{\text{ph}}(\epsilon, R, z)/b_{\text{tot}}(E_e, R, z)$. In the synchrotron-dominated regime, an enhanced IR photon density increases the IC flux. In the IC-dominated regime, however, the increase in n_{ph} is partly offset by stronger cooling through b_{tot} , and the dominant effect of a stronger IR profile is the larger $\gamma\gamma$ attenuation. Hence, the IR radial distribution models are not expected to violate the Fermi-LAT constraints on the diffuse background emission at GeV–TeV energies in the same ROI as LHAASO (R. Zhang et al. 2023).

We use secondary electrons from pp interactions as a proxy to study how centrally enhanced IR photon density profiles affect the observed spectrum. The left panel of Figure 7 shows the relative contributions of the background photon fields to the total IC spectrum in the baseline model, for a source near the CMZ, at $R \simeq 200$ pc, along $(\ell, b, d) = (0^\circ, 0^\circ, 8.3 \text{ kpc})$. Above a few TeV, IC emission on the IR photon field becomes important. We assume an rms Galactic magnetic field of $3 \mu\text{G}$,

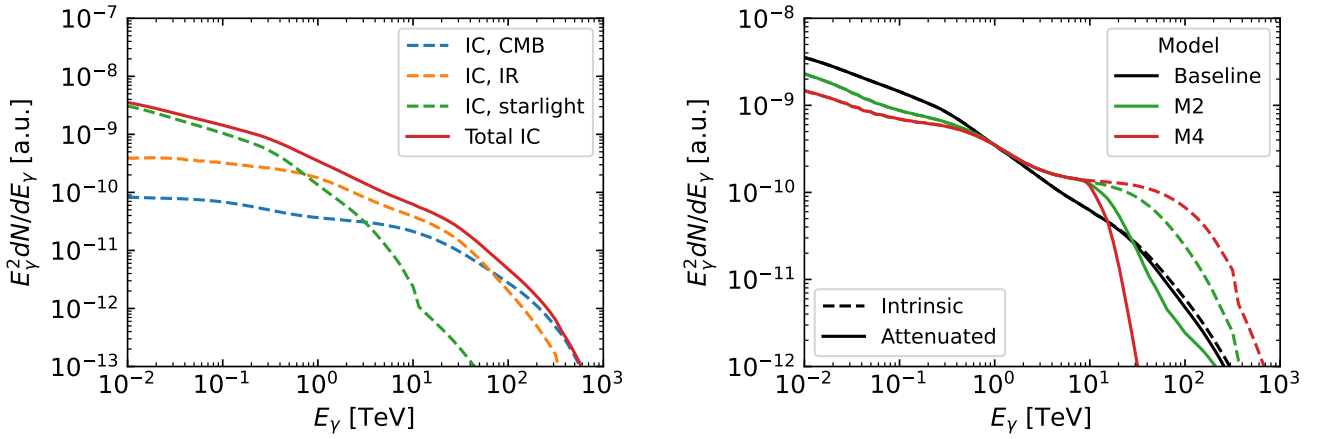


Figure 7. Flux of IC γ -ray emission from a steady-state electron spectrum, shown in arbitrary units. The source is placed near the CMZ at $R = 0.2$ kpc. The left panel shows the relative contributions of the different ISRF photon fields in the baseline model. The right panel shows the change in the total spectrum for different IR radial dependence models.

for which synchrotron losses dominate above $E_e \sim 100$ TeV, due to Klein–Nishina suppression of IC scattering. The right panel of Figure 7 shows the IC spectra for different IR models. More centrally peaked profiles harden the spectrum in the WCDA band, while the extreme M4 case sharply attenuates the flux above a few tens of TeV. Future multiwavelength measurements of point sources near the Galactic Center can therefore constrain the synchrotron emissivity and, in turn, the radial IR density distribution in IC-dominated scenarios (see, e.g., N. Gupta 2025; T. Mizuno et al. 2026). An anisotropic radiation field limits a direct extrapolation of this result to all sources in the Galactic Plane (see also G. Di Marco et al. 2025).

4. Discussions and Summary

We fit the LHAASO diffuse γ -ray flux in the inner and outer ROIs with leptonic PWN and hadronic diffuse CR components. Although the LHAASO region excludes the Galactic Center direction, inner-Galaxy lines of sight pass within a few kiloparsecs of the center, making the inner dust profile relevant for the IR optical depth. We use the A. Misiriotis et al. (2006) profile as the baseline IR model and vary its inner radial dependence to estimate the systematic uncertainty.

For the adopted source distribution and transport model, the alternative ISRF prescriptions slightly improve the fit to the LHAASO diffuse γ -ray data, but the preference remains modest. LHAASO has limited leverage in the innermost region because of its longitude range and source masking. For the adopted diffuse regions and source masks, the LHAASO diffuse measurement is only weakly sensitive to the IR-background profile variations tested here.

The hadronic component in our model is produced by Galactic CRs propagating through interstellar gas. Source cocoons could provide an additional hard component that is not considered here (A. Ambrosone et al. 2025; R. Yang et al. 2025). We normalize the unresolved leptonic component using the empirical flux–spindown relation of S. Kaci et al. (2025), finding a $\sim 30\%$ contribution at a few tens of TeV, consistent with their data-driven estimates.

Our outer-ROI fit underpredicts the highest-energy flux, indicating that an additional source component may be required. This outer-region tension may also depend on the assumed radial source distribution. The SNR source

distribution adopted here peaks at ~ 4 kpc (G. L. Case & D. Bhattacharya 1996, 1998). Source profiles shifted farther outward can enhance the outer-region flux, whereas distributions with lower p/q in Equation (5) reduce it (see, e.g., D. A. Green 2015). More recent studies suggest that a purely exponential radial profile may better describe the present SNR sample (S. Verberne & J. Vink 2021; S. Ranasinghe & D. Leahy 2022).

The CR proton spectral index $\alpha_p = 2.4$ is motivated by the observed local proton spectrum, which is roughly $E^{-2.6}$ in the low-TeV range (Q. An et al. 2019), softens to about $E^{-2.8}$ – $E^{-2.9}$ above ~ 10 TeV (O. Adriani et al. 2022), hardens near 166 TeV (F. Varsi et al. 2024), and shows a broad PeV-scale hump (Z. Cao et al. 2025b). In the diffusion-dominated regime, the propagated slope is approximately $\alpha_p + \delta(R)$. The resulting γ -ray slope is further modified by the $\sim E^{0.1}$ increase of the pp cross section above the threshold and by $\gamma\gamma$ attenuation.

Our results should be interpreted within the assumed spatially dependent diffusion coefficient model. A nonuniversal diffusion coefficient depends on the properties of the turbulent magnetic fields in the ISM (e.g., A. Lazarian & S. Xu 2021). Recent analysis has shown that uncertainties in the gas distribution, hadronic cross section, local CR spectrum, and CR spatial profile can significantly reduce the apparent tension between the LHAASO diffuse data and standard hadronic predictions (V. Vecchiotti et al. 2025).

The Galactic Center and much of the expected Galactic Plane neutrino emission lie in the southern sky, where IceCube track searches are strongly affected by the atmospheric muon background. The Galactic Plane measurement therefore uses cascade events, which reduce the atmospheric neutrino contamination by about an order of magnitude at TeV energies but have poorer angular resolution than tracks (IceCube Collaboration et al. 2023). The neutrino flux obtained here is consistent with the IceCube all-sky flux estimate. However, unresolved Galactic sources may contribute a quasi-diffuse component to the IceCube Galactic Plane signal, especially near 100 TeV (A. Ambrosone et al. 2024).

Current IceCube data do not yet distinguish diffuse neutrinos produced by CR interactions with the ISM from unresolved sources or extended source regions (R. Abbasi et al. 2023). The Galactic Ridge region, $|l| < 30^\circ$ and $|b| < 2^\circ$,

includes the CMZ and the innermost Galactic Plane, and is therefore sensitive to possible variations of the CR spectrum toward the Galactic Center. With the hadronic normalization fixed by the LHAASO inner-region fit, the predicted Galactic Ridge neutrino flux is about a factor of 2 below the ANTARES best fit, while current KM3NeT/ARCA data show no significant excess (F. Filippini 2024).

5. Conclusions

Stronger radial evolution of the ISRF can significantly modify the γ -ray spectral energy distribution (SED) of point sources, even though its effect on the LHAASO diffuse fit is modest. For point-like sources, the IC emission is partly self-regulated, because an enhanced photon background increases the IC target density but also reduces the steady-state electron density through stronger cooling (see Equation (13)). Both leptonic and hadronic γ -ray emission are also attenuated by the enhanced $\gamma\gamma$ opacity. As a result, point-like or extended sources near the Galactic Center may show spectral hardening in the WCDA band, while the most centrally enhanced IR profiles can produce a sharp cutoff above a few tens of TeV. Future KM3NeT observations of Galactic point-like and extended neutrino sources will help isolate the hadronic component. Together with multiwavelength constraints on the synchrotron spectrum and γ -ray SED measurements of individual sources, this will provide a multimessenger probe of the inner-Galaxy CR population and constrain the radial distribution of the ISRF near the Galactic Center.

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