Diffuse Emission of Galactic High-energy Neutrinos from a Global Fit of Cosmic Rays

Georg Schwefer1,2,3, Philipp Mertsch1, and Christopher Wiebusch2

1 Institute for Theoretical Particle Physics and Cosmology (ITP), RWTH Aachen University, 52056 Aachen, Germany; georg.schwefer@mpi-hd.mpg.de
2 III. Physikalisches Institut B, RWTH Aachen University, 52056 Aachen, Germany
3 Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany

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Abstract

In the standard picture of Galactic cosmic rays, a diffuse flux of high-energy gamma rays and neutrinos is produced from inelastic collisions of cosmic-ray nuclei with the interstellar gas. The neutrino flux is a guaranteed signal for high-energy neutrino observatories such as IceCube but has not been found yet. Experimental searches for this flux constitute an important test of the standard picture of Galactic cosmic rays. Both observation and nonobservation would allow important implications for the physics of cosmic-ray acceleration and transport. We present CRINGE, a new model of Galactic diffuse high-energy gamma rays and neutrinos, fitted to recent cosmic-ray data from AMS-02, DAMPE, IceTop, as well as KASCADE. We quantify the uncertainties for the predicted emission from the cosmic-ray model but also from the choice of source distribution, gas maps, and cross sections. We consider the possibility of a contribution from unresolved sources. Our model predictions exhibit significant deviations from older models. Our fiducial model is available at https://doi.org/10.5281/zenodo.7859442.

Unified Astronomy Thesaurus concepts: Gamma-ray astronomy (628); Neutrino astronomy (1100); Diffuse radiation (383); Galactic cosmic rays (567)

1. Introduction

Galactic diffuse emission (GDE) of photons and neutrinos is radiation produced within the interstellar medium (ISM) of the galaxy. Electromagnetic radiation has been observed at all wavelengths ranging from radio and microwaves up to PeV gamma rays. Of particular interest are photons and neutrinos from hadronic interactions of Galactic cosmic rays (GCRs) with the interstellar gas while propagating through the galaxy (Strong et al. 2000). The diffuse Galactic emission of both high-energy photons and neutrinos offers invaluable information on the spatial and spectral distribution of GCRs elsewhere in the galaxy (Tibaldo et al. 2021), providing immediate information on the century-old problem of the origin of Galactic cosmic rays.

At gamma-ray energies, three processes contribute to the high-energy GDE of photons: the decay of neutral pions, produced in inelastic collisions of GCR nuclei with interstellar gas; bremsstrahlung from GCR electrons and positron on the interstellar gas; and inverse Compton scattering, which is the upscattering of soft radiation backgrounds by GCR electrons and positrons. Furthermore, a number of extended structures have been discovered in high-energy gamma rays, like the Fermi bubbles (Dobler et al. 2010; Su et al. 2010; Ackermann et al. 2014) or Galactic radio loops Berkhuijsen et al. (1971), as well as an isotropic, extragalactic gamma-ray flux (Ackermann et al. 2015). Finally, a certain fraction of the observed diffuse emission is likely due to so-called unresolved sources, which are sources with fluxes below the experimental detection thresholds (Vecchiotti et al. 2022, 2022). Untangling the various contributions to GDE observed in gamma rays is a formidable task that is in part made difficult by the degeneracy between the hadronic and lepton contributions.

Unlike the multicomponent fluxes of photons, the flux of Galactic diffuse neutrinos offers a clear window into the study of GCR because neutrinos uniquely originate from the decay of charged mesons, i.e., pions, that are produced in hadronic interactions. This flux is a guaranteed signal for the IceCube Neutrino Observatory (Aartsen et al. 2017a) and other high-energy neutrino telescopes (Ageron et al. 2011; Adrian-Martinez et al. 2016; Avrorin et al. 2018), but discovery has thus far remained elusive. However, recent analyses (Aartsen et al. 2019a, 2017b; Albert et al. 2018) suggest that such a discovery could be within reach in the near future. Together with the detection of the first extragalactic sources of high-energy neutrinos (Aartsen et al. 2018a, 2018b; Abbasi et al. 2022a), this will shed light on the origin of the diffuse flux of astrophysical neutrinos measured by IceCube (Aartsen et al. 2020, 2019b; Abbasi et al. 2022b, 2021a).

Precise models of diffuse neutrino emission play a twofold role in the searches: First, they quantify our expectations for searches, allowing us to estimate what bearings (non-) observations have on our understanding of models of GCRs. Second, they provide detailed spatiotemporal templates for targeted experimental searches that otherwise suffer from atmospheric and extragalactic backgrounds.

Model predictions of diffuse Galactic neutrino emission can be based on observed photon fluxes because of the close connection between the parent particles—neutral and charged pions—that originate from the same interactions of GCRs. Of the models available in the literature, the Fermi–π⁰ model (Ackermann et al. 2012) and the KRAγ model (Gaggero et al. 2015b) have been employed in most of the recent experimental searches (Aartsen et al. 2017b, 2019a; Albert et al. 2018). The Fermi–π⁰ model assumes a factorization into the angular distribution of the π⁰-component as modeled by the Fermi-LAT collaboration and a spectrum that above a few GeV is a single power law with the same spectral index of γ ≈ 2.7 in all directions. While designed for use at GeV energies, for neutrino studies, the model spectra have been extrapolated to
higher energies with the same unbroken power law. In previous studies, the spectral index has also been left free to float. The KRA model instead exhibits harder gamma-ray spectra in the Galactic center direction, leading to a different morphology at the energies of interest for observations of high-energy neutrinos (see also de la Torre Luque et al. 2023 for a recent update of the KRA model). In addition, there are also a number of analytical parameterizations of fluxes of high-energy gamma rays and neutrinos (Joshi et al. 2014; Lipari & Vernetto 2018; Fang & Murase 2021).

These existing models, however, suffer from two main drawbacks: First, they have not been systematically fitted to the latest data of local GCR observations. Given the various uncertainties in the modeling of GDE, local data on GCR should serve as an important anchor point and one would hope that the models are able to reproduce these local data (e.g., Marinos et al. 2022). Second, the models suffer from a lack of quantitative estimates of model uncertainties. While the sources of such uncertainties are manifold (fit uncertainties from the GCR model, choice of gas maps, and cross sections), both uses of GDE models (see above) rely heavily on a proper estimate of model uncertainties.

In this paper, we aim to update existing models in light of recent data on local GCR fluxes and present the CRINGE model. We also quantify the uncertainties from the GCR model parameters and the various choices for GDE inputs.

While we hope to present a useful state-of-the-art model for high-energy diffuse Galactic neutrinos, we must caution that the models are able to reproduce these local data (e.g., Marinos et al. 2022). Second, the models suffer from a lack of quantitative estimates of model uncertainties. While the sources of such uncertainties are manifold (fit uncertainties from the GCR model, choice of gas maps, and cross sections), both uses of GDE models (see above) rely heavily on a proper estimate of model uncertainties.

The outline of the paper is as follows: In Section 2, we start by describing the various ingredients for predictions of the GDE in high-energy neutrinos and gamma rays. We lay out the GCR model and describe the global fit to local GCR data. Next, we discuss the various choices for other inputs of the diffuse model, which are gas maps, cross sections, and photon backgrounds. We also present a model of unresolved sources and explain our treatment of gamma-ray absorption. Our results are presented in Section 3, first for the global fit to local measurements of GCRs, then for the diffuse fluxes of high-energy gamma rays and neutrinos. An extended discussion in the context of other GDE observables can be found in Section 4. We conclude in Section 5.

2. Method

The intensity of hadronic gamma rays and neutrinos from longitude and latitude \((l, b)\) and at energy \(E\), \(J(l, b, E)\) is given as the line-of-sight integral (e.g., Strong et al. 2000) of the volume emissivity, generated by the inelastic collisions of hadronic GCRs with the gas in the interstellar medium,

\[
J(l, b, E) = \frac{1}{4\pi} \sum_{m,n} \int_0^{\infty} ds \int_E^\infty dE' \frac{d\sigma_{mn}}{dE} \times J_m(r, E') n_{gas,n}(r)|_{r=r(l,b,s)}. \tag{1}
\]

Here, \(J_m(r, E) = \nu/(4\pi)\psi_m(r, p)\) is the GCR intensity of species \(m\), where \(\psi\) is the isotropic CR density per unit energy. \((d\sigma_{mn}/dE)(E', E)\) is the differential cross section for the production of gamma rays or neutrinos of energy \(E\) from inelastic collisions of GCR species \(m\) of energy \(E'\) on gas of species \(n\). Finally, \(n_{gas,n}(r)\) denotes the 3D distribution of gas, mostly atomic and molecular hydrogen in the galaxy.

Similarly, the intensity of gamma rays originating from inverse Compton scattering of cosmic-ray leptons, \(J_{IC}(l, b, E)\), can be calculated as

\[
J_{IC}(l, b, E) = \frac{1}{4\pi} \sum_{m,n} \int_0^{\infty} ds \int_E^\infty dE' \frac{d\sigma_{KN}}{dE} \times J_m(r, E') n_{ISRF}(r, E_0)|_{r=r(l,b,s)}. \tag{2}
\]

Here, \((d\sigma_{KN}/dE)(E', E, E_0)\) is the Klein–Nishina cross section and \(n_{ISRF}(r, E_0)\) is the number density of radiation field photons per unit energy (Blumenthal & Gould 1970). The predicted intensity of high-energy gamma rays or neutrinos as a function of direction and energy therefore depends on these three inputs: a model for the distribution of GCRs, a map of the interstellar gas and radiation field in the Milky Way, and the hadronic production cross sections. In the following, we will detail our modeling choices for each of these inputs. We will also describe the global fit that we employed to determine the parameters of our GCR model.

2.1. Galactic Cosmic-Ray Model

The propagation of GCRs is usually modeled with the transport equation (Ginzburg & Syrovatskii 1964; Parker 1965)

\[
\frac{\partial \psi}{\partial t} - \frac{\partial}{\partial x_i} \left( \kappa_{ij} \frac{\partial \psi}{\partial x_j} + u_i \frac{\partial \psi}{\partial x_i} \right) + \frac{\partial}{\partial p} \left( b \frac{\partial \psi}{\partial p} \right) = q. \tag{3}
\]

The boundary conditions employed are that \(\psi\) vanishes on the boundary of a cylinder of half-height \(z_{\text{max}}\) and radius \(r_{\text{max}}\). We have assumed \(r_{\text{max}} = 20\) kpc and adopted \(z_{\text{max}} = 6\) kpc (Evoli et al. 2020). The solution of this partial differential equation depends on the assumed transport parameters, which are the spatial diffusion tensor \(\kappa_{ij}\), the advection velocity \(u_i\), the momentum-loss rate \(b\), and the source density \(q\). We solve Equation (3), employing a publicly available version of the DRAGON code (Evoli et al. 2017), assuming axisymmetry with respect to the direction perpendicular to the Galactic disk. In the following, we describe the various transport parameters.

2.1.1. Diffusion

GCRs diffuse due to resonant interactions with a spectrum of turbulent magnetic fields Berezinskii et al. (1990). Here, we assume isotropy, such that the diffusion tensor is a diffusion coefficient \(D\) times unit matrix, \(\kappa_{ij} = D \delta_{ij}\). If the power spectrum of turbulence was known, the diffusion coefficient \(D\) could be computed. In phenomenological applications, however, the diffusion coefficient is oftentimes assumed to follow a certain parametric form.
As for its rigidity dependence, we employ a power law with four breaks,
\[
D(R) = D_0 \beta \left( \frac{R}{R_{12}} \right)^{\delta_1} \times \prod_{i=1}^{4} \left( 1 + \left( \frac{R}{R_{i(i+1)}} \right)^{\delta_{i+1}(\delta_i - 1)} \right)^{\alpha_{0+i}(\delta_i - 1 - \delta_{i+1})},
\]

hence four break rigidities \( \{R_{i(i+1)}\} \), four softness parameters \( \{s_{i(i+1)}\} \), five spectral indices \( \{\delta_i\} \), and one normalization \( D_0 \).

Of course, such spectral breaks should only be introduced if required for an accurate description of the data (see Vittino et al. 2019, where the necessity of spectral breaks in the diffusion coefficient is discussed for models of GCR electrons and positrons). At the same time, it is important to motivate the breaks from a physical mechanism, e.g., from features in the power spectrum of turbulence. In the following, we provide some pointers as to the physical origin of the breaks we consider. While the exact break parameters will be determined from a global fit to local GCR data, we indicate some benchmarks.

At rigidities of a few GV and above, the propagated spectra are to a first approximation proportional to the source spectrum divided by the diffusion coefficient. Under the constraint of producing the observed spectral indices, the spectral indices of the source spectra and of the diffusion coefficient are therefore approximately degenerate. This degeneracy gives us the freedom to choose a pure power law for the source spectra (see below) and instead absorb possible spectral breaks in the source spectrum into breaks of the diffusion coefficient.

The first spectral break \((\delta_2 - \delta_1 > 0)\) in the diffusion coefficient at a few GV is a hardening of its spectrum and serves to absorb a spectral softening of the source spectrum. Such spectral breaks have been observed in the gamma-ray spectra of supernova remnants (SNRs) by Fermi-LAT (Abdo et al. 2009a, 2009b, 2010a, 2010b). One possibility is that the break in the diffusion coefficient is due to self-confinement of GCRs in the near-source environment (Jacobs et al. 2022). Such a break has also been introduced into models of GCRs on purely phenomenological grounds in order to achieve a better fit to locally measured spectra when not including reacceleration, as is the case for the model constructed here. We note that even for a model that includes reacceleration, such a break is likely necessary (Strong et al. 2011).

The hardening break in the GCR spectra \((\delta_3 - \delta_2 < 0)\) at \( R_{23} \approx 300 \) GV has been found to be present both in primary (Pavlov et al. 2007; Ahn et al. 2010; Adriani et al. 2011; Aguilar et al. 2015a, 2015b, 2017) and secondary GCRs (Aguilar et al. 2018). The fact that the break is more pronounced in secondary species points to a propagation effect (Vladimirov et al. 2012; Génolini et al. 2017) rather than a feature in the source spectrum. It has been shown (Blasi et al. 2012; Evoli et al. 2018) that such a break can be rather naturally explained as a transition in the turbulence power spectrum from self-generated turbulence dominating \( D \) for low rigidities to external turbulence for high rigidities.

A further softening in the GCR spectra \((\delta_4 - \delta_3 > 0)\) has been observed in the spectra of proton and helium by the DAMPE (An et al. 2019; Alemanno et al. 2021) and CALET (Adriani et al. 2019; Brogi & Kobayashi 2022) experiments. Earlier indications from the CREAM experiment exist (Yoon et al. 2017). While it has been suggested to be the spectral feature of an individual nearby source (Malkov & Moskalenko 2021; Fornieri et al. 2021), statistically, such a scenario is considered unlikely (Genolini et al. 2017). Instead, it might be attributed to a cutoff of one population of sources, e.g., SNRs, before a different population takes over at higher rigidities.

Finally, the softening \((\delta_5 - \delta_4 > 0)\) break in the GCR spectra around \( \sim PV \) is the well-known cosmic-ray “knee.” Although it has been discovered in the all-particle spectrum of cosmic rays as early as 1959 (Kulikov & Kristiansen 1959), there is still no consensus about its origin. The KASCADE and KASCADE-Grande experiments have identified it to be consistent with a break at fixed rigidity for different elements (Antoni et al. 2005; Apel et al. 2011). Therefore, the leading hypotheses are that it corresponds either to the maximum rigidities at which Galactic magnetic fields can contain GCRs or to the maximum rigidity of Galactic accelerators of cosmic rays (Hillas 1984).

2.1.2. Source Injection

We follow the usual assumption of a factorization of the source term \( g = g(r, E) \) in Equation (3) into a spatial source distribution \( S(r, z) \) and an injection spectrum, \( g(p) \).

\[
Q(r, p) = S(r, z) g(p).
\]

The spatial source distribution \( S(r, z) \) is an input to the cosmic-ray model with a significant impact on the morphology of the resulting diffuse emission.

To estimate the associated uncertainty, we use the four commonly used distributions from Ferrière (2001), Case & Bhattacharya (1998), Lorimer et al. (2006), and Yusifov & Küçük (2004). All of these are analytical parameterizations based on population studies of SNRs, massive stars as progenitors or pulsars as relics of supernovae in the Milky Way. Thus, they all serve as a proxy for the distribution of SNRs, the likely preeminent sources of Galactic cosmic rays. The radial profiles of the distributions are shown in Figure 1. For an early inference of the radial source distribution from diffuse GeV gamma rays, see Stecker & Jones (1977).

While overall all four parameterizations agree qualitatively, there is significant quantitative disagreement between them. This is true in particular toward the Galactic center, where the source density of the Case & Bhattacharya (1998) and Yusifov & Küçük (2004) models is forced to zero, while the distributions of Ferrière (2001) and Lorimer et al. (2006) attain finite values.

The injection spectra \( g(p) \) for all nuclei \( i \) are assumed to be pure power laws with energy-independent, but in general different, spectral indices, that is, \( g(p) \propto p^{-\gamma_i} \). Possible breaks in the source spectra can to a certain extent be absorbed into breaks in the diffusion coefficient; see the discussion in Section 2.1.1.

For the calculation of the diffuse emission, the contributions of cosmic-ray nuclei heavier than helium can be approximated via a scaling factor in the hadronic production cross sections for \( p-p \) interactions as in Casandjian (2015), significantly reducing the computation time. This is because the relevant quantity for the production of hadronic diffuse emission is the all-nucleon flux as a function of kinetic energy per nucleon, \( E_{\text{kin}}/n \). As \( E_{\text{kin}}/n \propto (Z/A) R \), spectral features at a common rigidity \( R \) appear also at similar \( E_{\text{kin}}/n \) for all nuclei. Therefore, the spectra of nuclei heavier than helium feature a similar \( E_{\text{kin}}/n \).
dependence to those of lighter nuclei and their contribution to the all-nucleon flux remains small at all \( E_{\text{kin}}/n \).

Because of this, the all-nucleon flux in our model is dominated by the contributions from protons and helium at all \( E_{\text{kin}}/n \). It also allows us to approximate the subdominant contributions of cosmic-ray nuclei heavier than helium via a scaling factor in the hadronic production cross sections as in Casandjian (2015), significantly reducing the computation time needed for the calculation of the diffuse emission.

Besides the three spectral indices \( \gamma_p, \gamma_{\text{He}}, \) and \( \gamma_C \), the source abundances of helium \( N_{\text{He}} \) and carbon \( N_C \) relative to those of protons, which, as is for example done in the supplementary material to Ackermann et al. (2012), are set arbitrarily to 1.06 \times 10^5, are also free parameters in the model.

For the lepton spectra, the situation is somewhat more complicated. Following Vittino et al. (2019), we model the injection spectrum of electrons as a twice broken power law, with the spectral indices \( \gamma_i \) and break energies \( E_{\text{break}}^{i(i+1)} \) as free fit parameters. To account for the very short propagation distances of cosmic-ray electrons at TeV energies, which are not correctly grasped by the assumed smooth source distribution, the injection spectrum is exponentially cut off at \( E_{\text{cut}}^{i} = 20 \text{ TeV} \). This is similar to the choices made in Mertsch (2018), where such a cutoff was found to be necessary to match the TeV \( e^- + e^+ \) data.

To account for the spectral hardening in the positron spectrum at GeV energies (Aguilar et al. 2019a), an extra source component yielding equal amounts of electrons and positrons is added to the model. Similarly to Vittino et al. (2019), it represents additional astrophysical lepton sources but is agnostic of any precise models for these sources. The assumed spatial distribution is the same as for all other sources. The spectrum of this extra component is modeled as a once broken power law with an exponential cutoff. The break energy is fixed to \( E_{\text{break}}^{\text{extra}} = 50 \text{ GeV} \), the cutoff is at \( E_{\text{cut}}^{\text{extra}} = 600 \text{ GeV} \). The two spectral indices \( \gamma_i^{\text{extra}} \) are free fit parameters.

### 2.2. Interstellar Medium Components

Computing the diffuse emission of neutrinos and hadronic gamma rays requires a 3D map \( n_{\text{gas}}(r) \) of the gas in the galaxy; see Equation (1). Such 3D maps can be obtained from Galactic surveys of gas line emission. Those are based on the fact that Galactic rotation induces different relative velocities between the gas and the observer. Assuming a velocity model, e.g., a rotation curve, this can be used to convert the survey into a 3D map. Given the uncertainties of such a reconstruction, models with rather larger bins in galactocentric radius were developed. (See Appendix B of Ackermann et al. 2012 for some details.) More recently, more sophisticated Bayesian inference techniques have been used (Mertsch & Vittino 2021; Mertsch & Phan 2023). Alternatively, analytical parameterizations of the spatial gas distributions have been suggested (Lipari & Vernetto 2018) as well as more complicated parameterizations that were fitted to data (Johannesson et al. 2018). Our choices for the maps of both atomic and molecular gas are described in Sections 2.2.1 and 2.2.2.

For the computation of leptonic Inverse Compton gamma-ray emission, a model of the interstellar radiation field (ISRF) of the Milky Way is required. We describe the models used in this work in Section 2.2.3.

#### 2.2.1. Atomic Hydrogen

Atomic hydrogen (H\textsc{i}) is traced by the well-known 21 cm emission line from the hyperfine transition. Combining the data from various telescopes, the LAB survey (Kalberla et al. 2005) and the more recent H14PI survey (Ben Bekhti et al. 2016) have become available. The quantity measured by these surveys is the brightness temperature \( T_B(l, b, v_{\text{LSR}}) \) of the emission line as a function of direction and radial velocity \( v_{\text{LSR}} \) with respect to the local standard of rest. The transformation into a differential column density \( dN_{\text{H}\textsc{i}}/dv_{\text{LSR}}(l, b, v_{\text{LSR}}) \) can be calculated from the thermodynamics of two-level systems (Draine 2010; Ackermann et al. 2012):

\[
\frac{dN_{\text{H}\textsc{i}}}{dv_{\text{LSR}}} = CT \tau = -CT \ln \left( 1 - \frac{T_B}{T_{\text{CMB}}} \right).
\]

with \( C = 1.813 \times 10^{18} \text{ cm}^{-2} (\text{K} \text{ km s}^{-1})^{-1} \). This involves the spin temperature \( T_{\text{s}} \), which is equivalent to the population ratio of the excited state to the ground state of the hyperfine structure transition. A large \( T_{\text{s}} \), corresponding to a large population of the excited state and as a consequence little self-absorption and a small optical depth, therefore results in less gas column density being inferred from the observed \( T_B \) of the emission. In fact, the limit \( T_{\text{s}} \rightarrow \infty \) corresponds to the optically thin limit and poses a lower limit on the total amount of H\textsc{i} (Mertsch & Phan 2023). Correspondingly, low \( T_{\text{s}} \) lead to higher inferred column densities. \( T_{\text{s}} \) is quite uncertain and also thought to vary across the galaxy (Ackermann et al. 2012; Ben Bekhti et al. 2016). Typically, models assume a constant value of either

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**Figure 1.** Radial profiles and relative differences to the Ferrière (2001) model of the four GCR source distributions used in this work.
There is great uncertainty associated with the galaxy that increases the H$_2$ to CO ratio is explained through a decrease in metallicity in the outer where $X$ increases with galactocentric radius. This is typically observed in 21 cm surveys, it provides a map of brightness $T$ and as high as $8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (de la Torre Luque et al. 2023). Also, $X_{CO}$ is often taken to vary with galactocentric radius, with different models assuming different radial dependencies. A common description is a ring-based model, where $X_{CO}$ is constant within different galactocentric rings. Examples of this are Gaggero et al. (2015b), where $X_{CO}$ is fixed in two rings, and Ackermann et al. (2012), where it is left as a free fit parameter in 13 rings. In these models, $X_{CO}$ typically increases with galactocentric radius. This is explained through a decrease in metallicity in the outer galaxy that increases the H$_2$ to CO ratio (Gaggero et al. 2015b).

In this study, we conservatively opt for a constant value of $X_{CO} = 2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ throughout the galaxy, in accordance with the above-mentioned local recommendations.

2.2.2. Molecular Hydrogen

Maps of molecular hydrogen (H$_2$) have been derived from the CfA survey compilation (Dame et al. 2001) of emission of the $J = 1 \rightarrow 0$ line of carbon monoxide (Heyer & Dame 2015). Similar to the 21 cm surveys, it provides a brightness $T_B$ and as high as $8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Liu & Yang 2022) and as high as $8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (de la Torre Luque et al. 2023). Also, $X_{CO}$ is often taken to vary with galactocentric radius, with different models assuming different radial dependencies. A common description is a ring-based model, where $X_{CO}$ is constant within different galactocentric rings. Examples of this are Gaggero et al. (2015b), where $X_{CO}$ is fixed in two rings, and Ackermann et al. (2012), where it is left as a free fit parameter in 13 rings. In these models, $X_{CO}$ typically increases with galactocentric radius. This is explained through a decrease in metallicity in the outer galaxy that increases the H$_2$ to CO ratio (Gaggero et al. 2015b).

In this study, we conservatively opt for a constant value of $X_{CO} = 2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ throughout the galaxy, in accordance with the above-mentioned local recommendations.

2.2.3. Interstellar Radiation Field

Models of the ISRF in the Milky Way, require, besides the well-measured homogeneous cosmic microwave background (CMB), calculations of the accumulated Galactic starlight and the infrared emission from dust. These calculations are challenging as the absorption and re-emission of starlight from dust couple these components. Different analytical (e.g., Vernetto & Lipari 2016) and numerical (e.g., Porter et al. 2008, 2017) approaches are used, yielding quantitatively different results. To account for this uncertainty in the calculation of inverse Compton gamma-ray fluxes, we consider two different models, namely those from Porter et al. (2008; henceforth called GALPROP) and Vernetto & Lipari (2016).

2.3. Hadronic Production Cross Sections

The calculation of hadronic gamma-ray and neutrino production cross sections in different hadronic interaction models is associated with sizeable uncertainties, as was for example recently detailed by Koldobskiy et al. (2021). To estimate the resulting uncertainties in the diffuse emission models, we have used three different models for our calculations. These are

1. **K&K:** This model combines the parameterization of the total inelastic p-p cross section from Kafexhiu et al. (2014) with the secondary yields and spectra from Kelner et al. (2006). The latter is based on an analytical parameterization of the SIBYLL hadronic interaction model (Fletcher et al. 1994). Note that this parameterization is only valid for primary energies above 100 GeV (Kelner et al. 2006).

2. **KamaeExtended:** For primary energies below 500 TeV, this model uses the parameterization from Kamae et al. (2006), which is in large part derived from the PYTHIA 6.2 event generator. At higher energies, it is extended with the K&K model. This follows the prescription used in Gaggero et al. (2015a).

3. **AAfrag:** This is based on interpolation tables from the hadronic interaction model QGSJET-II-04m described in Kachelriess et al. (2019) and Koldobskiy et al. (2021). Below 4 GeV primary energy, it is complemented by the parameterization from Kamae et al. (2006).

The K&K and KamaeExtended parameterizations are only available for p-p interactions (Kamae et al. 2006; Kelner et al. 2006) and interactions of heavier gas and cosmic-ray nuclei need to be described via scaling factors of the p-p cross sections. AAfrag in principle contains explicit models for the interactions of heavier nuclei (Koldobskiy et al. 2021). In this work, these are however treated through the same scaling factors as used for the other cross-section parameterizations. The scheme used for these scaling factors directly follows Casandjian (2015): For protons and helium cosmic-ray nuclei, which are included in the sum in Equation (1), the scaling factors relative to the p-p cross sections for different targets are taken from Mori (2009). As already described in Section 2.1.2, interactions of cosmic-ray nuclei heavier than helium are not calculated explicitly but are rather treated through an increase in the rate of p-p interactions.

2.4. Unresolved Sources

Individual sources of high-energy gamma rays or neutrinos vary in luminosity (also known as intrinsic brightness) and in distance from the observer. The resulting fluxes (also known as apparent brightnesses) can therefore vary over many orders of

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5 See also https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/aux/4fgl Galactic_Diffuse_Emission_Model_for_the_4FGL_Catalog_Analysis.pdf.
magnitude. Observations are, however, flux-limited due to a number of effects, like the presence of backgrounds or source confusion. A source with a flux smaller than a certain threshold value can therefore not be detected with the required significance and all such sources contribute collectively to the observed diffuse flux, even though the emission is originating from spatially well-defined regions and not from the interstellar medium as for the truly diffuse emission produced by GCRs. These sources and their collective flux are commonly referred to as “unresolved sources”.

We have modeled the flux of unresolved sources by extrapolating spectra and luminosity distributions from γ-ray observations at TeV energies. We largely followed Vecchiotti et al. (2022) who considered the unresolved sources to be dominated by pulsar-powered sources. For unresolved sources in the context of Fermi-LAT observations, see Acero et al. (2015). While it might appear that such sources would be leptonic, we remain agnostic as to the nature of the particles producing the high-energy gamma rays inside the sources. Later, when modeling the flux of high-energy neutrinos, we also consider a contribution from the same unresolved, pulsar-powered sources as in gamma rays. Here, we briefly summarize the salient points of the model and enumerate the adopted parameter values (Vecchiotti et al. 2022).

The intensity from unresolved sources of high-energy gamma rays of energy \( E \) observed from the direction \((l, b)\) is the cumulative intensity up to the threshold \( J_\text{th} \) in intensity,

\[
J_{\text{unres}}(E, l, b) = \int_0^{J_\text{th}} dJ \; p_J(J; E, l, b) J,
\]

where \( p_J \) is the probability density for the intensity \( J \) at energy \( E \) and from the direction \((l, b)\). We assume that the source density factorizes into a volume density of sources \( S_v(r) \) and a probability distribution of source rates \( p_{\text{fr}}(\Gamma) \). Under this condition, Equation (8) can be shown to lead to

\[
J_{\text{unres}}(E, l, b) = \varphi(E) \int_{L_{\text{min}}}^{L_{\text{max}}} dL \; \frac{dN}{dL} \frac{\Gamma}{4\pi} \times \int_{l}^{\infty} ds \; S_v(s; r(l, b), b).
\]

Here, \( \varphi(E) \) denotes the spectrum of a single source,

\[
\varphi(E) = \frac{\beta - 1}{1 - 100^{1-\beta}} \left( \frac{E}{1 \, \text{TeV}} \right)^{-\beta} \exp \left[ \frac{-E}{E_{\text{cut}}} \right],
\]

normalized to \( \sim 1 \) in the energy range 1 to 100 TeV, assuming a cutoff energy \( E_{\text{cut}} = 500 \) TeV. For the luminosity function \( dN/dL \), we follow again Vecchiotti et al. (2022) in adopting a power-law form,

\[
\frac{dN}{dL} = \frac{\Gamma_{\text{th}}(\alpha - 1)}{L_{\text{max}}} \left( \frac{L}{L_{\text{max}}} \right)^{-\alpha},
\]

with \( \Gamma_{\text{th}} = 1.9 \times 10^{-2} \, \text{yr}^{-1}, \tau = 1.8 \times 10^3 \, \text{yr}, \alpha = 1.5, \) and \( L_{\text{max}} = L_{\text{max, Hess}} = 4.9 \times 10^{35} \, \text{erg s}^{-1} \). The source rate \( \Gamma \) can be related to source luminosity \( L \) as \( \Gamma = (\beta - 2)/(\beta - 1) \). Throughout, we have assumed a spectral index \( \beta = 2.3 \). We have varied the flux threshold \( \Phi_{\text{th}} \) between 0.01 and 0.1 \( \Phi_{\text{Crab}} \) where for the 1 to 100 TeV energy range \( \Phi_{\text{Crab}} = 2.26 \times 10^{-11} \, \text{cm}^{-2} \, \text{s}^{-1} \). Finally, for the spatial distribution \( \rho_v(r) \) we have assumed the distribution from Lorimer et al. (2006), and \( r \) (s, l, b) denotes the position at a distance \( R \) from the observer in the direction \((l, b)\). The per-flavor neutrino intensity \( J_\nu(E_\nu) \) is related to this gamma-ray intensity \( J_\gamma(E_\gamma) \) as (e.g., Ahlers & Murase 2014; Fang & Murase 2021)

\[
J_\nu(E_\nu) = 2J(E_\gamma).
\]

2.5. Gamma-Ray Absorption

Above a few TeV, gamma rays are subject to absorption in photon–photon interactions with the ISRF during propagation in the Milky Way (Vernetto & Lipari 2016; Porter et al. 2018). In a fully self-consistent treatment, this is accounted for through the inclusion of the survival probability \( \exp(-\tau(E, s(l, b))) \) in Equation (1), where, following, e.g., Vernetto & Lipari (2016), the optical depth \( \tau \) is calculated as the line-of-sight integral:

\[
\tau(E, s(l, b)) = \int_0^{\infty(\phi)} ds' K(r(l, b), s').
\]

This depends on the absorption coefficient \( K(r, E) \), which for an isotropic ISRF with a photon density per unit energy \( n_{\text{ISRF}}(r, E_0) \) is calculated as

\[
K(r, E) = \int dE_0 \frac{n_{\text{ISRF}}(r, E_0)}{\sigma_{\gamma\gamma}(E, E_0)},
\]

with the interaction cross section \( \sigma_{\gamma\gamma} \) averaged over the angle between the two interaction partners.

The overall effect of the absorption thus depends on the assumed Galactic distributions of cosmic rays and gas, the ISRF model, and the direction in the sky. The dependence on both the choice of ISRF model and details of the cosmic-ray and gas distributions is however only weak (Vernetto & Lipari 2016; Breuhaus et al. 2022), in part because the dominant contribution to the absorption stems from interactions with the homogeneous CMB.

Therefore, and because the fully self-consistent calculation as laid out above adds another line-of-sight integration to Equation (1) and is thus computationally expensive, we use a simplified approach instead. In this, we obtain the absorbed gamma-ray intensity averaged over a given window in the sky \( \Omega \), \( J_{\text{abs}}(E, \Omega) \) from the nonabsorbed intensity \( J \), as

\[
J_{\text{abs}}(E, \Omega) = p_{\text{abs}}(E, \Omega)J(E, \Omega),
\]

with a separately calculated absorption probability \( p_{\text{abs}}(E, \Omega) \). We calculate this following the prescriptions described in Appendix E of Breuhaus et al. (2022). We also assume the same ISRF model (Popescu et al. 2017) and analytical descriptions of the distributions of Galactic gas (Ferrière 1998; Ferrière et al. 2007) and cosmic rays (Lipari & Vernetto 2018) as used there.7

2.6. Global Fit

The GCR model described in Section 2.1 contains a total of 26 free parameters describing the modeling of sources and transport of GCRs; see Table 1. We determine those by fits to local measurements of GCR intensities, which requires an additional set of eight parameters that are also listed in Table 1. In the following, we describe these additional parameters, the

7 We are grateful to Mischa Breuhaus for providing his implementation of the calculation, which makes use of the GAMERA code (Hahn 2015).
Table 1
Free Parameters and Their Best-fit Values

| Source Parameters | Values |
|-------------------|--------|
| $\gamma_p$        | 2.383 ± 0.039 |
| $\gamma_{He}$     | 2.324 ± 0.067 |
| $\gamma_C$        | 2.339 ± 0.006 |
| $N_{He}$          | 87520 ± 1200 |
| $N_C$             | 3101 ± 69.80 |
| $\gamma^{e^-}_1$  | 2.359 ± 0.096 |
| $\log_{10}[E^{eff}_{1}/GeV]$ | 0.680 ± 0.025 |
| $\gamma^{e^-}_2$  | 2.869 ± 0.148 |
| $\log_{10}[E^{eff}_{2}/GeV]$ | 1.663 ± 0.026 |
| $\gamma^{e^-}_3$  | 2.545 ± 0.016 |
| $\gamma^{extra}_1$| 2.386 ± 0.019 |
| $\gamma^{extra}_2$| 1.520 ± 0.021 |

Transport Parameters

| Values |
|--------|
| $D_0$ = 5.18 ± 0.17 |
| $\delta_1$ = 0.0116 ± 0.0009 |
| $\log_{10}[R_{12}/GV]$ = 0.711 ± 0.013 |
| $s_{12}$ = 0.0630 ± 0.0098 |
| $\delta_2$ = 0.566 ± 0.012 |
| $\log_{10}[R_{23}/GV]$ = 2.571 ± 0.073 |
| $s_{23}$ = 0.75 ± 0.11 |
| $\delta_3$ = 0.159 ± 0.094 |
| $\log_{10}[R_{34}/GV]$ = 4.23 ± 0.27 |
| $s_{34}$ = 0.167 ± 0.050 |
| $\delta_4$ = 0.453 ± 0.141 |
| $\log_{10}[R_{45}/GV]$ = 5.89 ± 0.16 |
| $s_{45}$ = 0.022 ± 0.11 |
| $\delta_5$ = 1.050 ± 0.063 |

Solar Modulation Parameters

| Values |
|--------|
| $\phi_p$ = 0.781 ± 0.096 |
| $\phi^{e^-}_{1}$ = 0.610 ± 0.014 |
| $\phi^{e^-}_{2}$ = 1.039 ± 0.031 |
| $\phi_{nuc}$ = 0.795 ± 0.027 |

Energy Scale Shift Parameters

| Values |
|--------|
| $\delta_{AMS-02}$ = 1.021 ± 0.022 |
| $\delta_{DAMPE}$ = 1.037 ± 0.025 |
| $\delta_{KASCADE}$ = 0.880 ± 0.132 |
| $\delta_{IceTop}$ = 0.584 ± 0.084 |

We consider both data from direct measurements by the space experiments AMS-02 and DAMPE as well as indirect measurements from IceTop and KASCADE. Specifically, we fit to protons (Aguilar et al. 2015a), helium (Aguilar et al. 2017), carbon (Aguilar et al. 2017), electrons (Aguilar et al. 2019b), positrons (Aguilar et al. 2019a), and the boron-to-carbon ratio from AMS-02 (Aguilar et al. 2018), and to the proton (An et al. 2019) and helium (Alemanno et al. 2021) data from DAMPE. For IceTop (Aartsen et al. 2019c) and KASCADE (Antoni et al. 2005) data, we use the proton and helium analyses based on the SIBYLL-2.1 interaction model.

The measurements of the hadronic intensities are however not necessarily consistent between different experiments. The most commonly cited reason for this is uncertainties in the (relative) energy scale calibrations of different experiments, in particular for indirect observations such as those by IceTop and KASCADE, but also for calorimetric experiments such as DAMPE (Adriani et al. 2022a). We have considered the possibility that these differences are due to uncertainties in the energy scale of the experiments.

The nuisance parameters $\{\alpha_k\}$ are also determined by the fit. We impose a log-normal prior with a width of 30% on each $\alpha_k$. For AMS-02 and DAMPE, the data are sufficiently constraining that the choice of prior has no influence (see Table 1).

Finally, we treat solar modulation in the force-field model (Gleeson & Axford 1968). We allow for four different modulation potentials, for protons, nuclei, electrons and positrons, $\phi_p, \phi_{Nuc}, \phi^{e^-}_1$, and $\phi^{e^-}_2$.

2.6.2. Numerical Tools

We have used a publicly available version of the DRAGON code (Evoli et al. 2008) that solves the transport Equation (3) with a finite difference method. In this, we have implemented our multibreak model for the diffusion coefficient (Equation (4)) and the parameters associated with it (see Table 1).

For computing the hadronic diffuse emission, we have employed the HERMES code (Dundovic et al. 2021). This code provides a flexible framework for computing the volume emissivities, given the spatially resolved GCR spectra and gas densities; see Equation (1). The resulting emission maps are pixelized using the HEALPix scheme (Gorski et al. 2005). In addition to the models and parameterizations provided with the publicly available version of HERMES, we have added the above-mentioned GALPROP and GALPROP-OT gas maps, the AAfrag cross-section parameterization and register interfaces to the code.
2.6.3. Procedure

For fitting our model to the observational data, we adopt a Gaussian likelihood function, combining the quoted statistical and systematic uncertainties of each AMS-02 and DAMPE in quadrature. For KASCADE and IceTop, we have used the statistical uncertainty only and have subsumed the additional systematic uncertainties into a potentially larger energy scale uncertainty. Given the large number of free parameters, finding the best fit is a nontrivial task. It has been recognized that conventional optimizers cannot guarantee to find the global minimum of the negative log-likelihood. Instead, it has been suggested to use Markov Chain Monte Carlo (MCMC) techniques for the minimization (Korsmeier & Cuoco 2016; Mertsch et al. 2021). While computationally rather expensive, MCMC samplers are much more robust and less prone to getting stuck in local minima. At the same time, once the MCMC chain has converged, the ensemble of samples can be used as an estimate of the parameter credible intervals.

We have employed an affine-invariant method (Goodman & Weare 2010) as implemented in the emcee package (Foreman-Mackey et al. 2013). The inherent parallel nature allows for a significant speed-up compared to serial MCMC samplers. Overall, 90,000 MCMC samples were drawn, with a single DRAGON calculation taking around 12 minutes on a single core.

In order to speed up the convergence toward the global minimum, we distinguish between parameters for the DRAGON code (“slow parameters”) and other parameters, that is, the energy rescalings $\{\alpha_i\}$ and the force-field potentials (“fast parameters”). The “slow” parameters are sampled by the MCMC method while the “fast” parameters are profiled over after each DRAGON run. For all further calculations, including the estimates of the uncertainties on the GCR observables shown below, we use the final 6000 samples drawn after convergence of the MCMC chain.

3. Results

3.1. Galactic Cosmic-Ray Intensities

Figures 2, 3, and 4 show (different parts of) the corner plot, that is, the collection of the one-dimensional marginal distributions of parameters and of two-dimensional distributions of pairs of parameters. We have made use of the corner package (Foreman-Mackey 2016), adopting a value of 1 for the smooth and smooth1d keywords. This is made necessary by the high dimensionality of our parameter space. Here, we have chosen to show the distributions for the “slow” parameters of the MCMC scan only, that is, those parameters that are input parameters for the GCR propagation code. We remind the reader that for each set of those “slow” parameters, we have determined the “fast” parameters, that is, the remaining ones, through profiling, meaning the likelihood is maximized with respect to the “fast” parameters only while the “slow” parameters are kept fixed.

For instance, while most of the parameters are uncorrelated, some of the existing correlations and anticorrelations are noteworthy:

1. The better known anticorrelations in GCR parameters are those between source spectral indices and indices of the diffusion coefficient. This is best seen for the spectral indices in the rigidity range where data are most constraining. Indeed, the spectral index $\delta_2$ of the diffusion coefficient for $R$ between $R_{12}$ and $R_{23}$ is anticorrelated with the source spectral indices of various species, that is, $\gamma_{P}$, $\gamma_{He}$, and $\gamma_{extra}$; see Figure 3.

2. These anticorrelations between source spectral indices and diffusion coefficient spectral indices also induce correlations between different source spectral indices; see for instance the correlation of $\gamma_{P}$ and $\gamma_{He}$ in Figure 4.

3. Another apparent correlation is the one between the normalization $D_0$, defined as the value of the diffusion coefficient at the break rigidity $R_{12}$, and this break rigidity; see Figure 2.

4. The spectral indices of the diffusion coefficient above and below a break can be correlated or anticorrelated with the break rigidity. For instance, the break at $R_{23}$ is a softening of the diffusion coefficient, that is, $(\delta_1 - \delta_2) < 0$. Increasing $R_{23}$ can thus be compensated to a certain degree by making the spectral index above, $\delta_3$, even smaller. This explains the anticorrelation between $\delta_3$ and $R_{23}$, seen in Figure 2.

5. The correlation between $\delta_3$ and $R_{34}$ instead (see Figure 2) is due to the fact that the data would prefer a smaller $R_{34}$ were $\delta_3$ chosen to be smaller.

In Table 1, we list the best-fit values of the various “slow” and “fast” parameters as well as their 68% credible intervals. We have found the best-fit values to coincide with the maxima and medians of the marginal distributions. For the “slow” parameters, we have determined the edges of the credible intervals as the 16% and 84% quantiles of the marginal distributions. The edges of the credible intervals for the “fast” parameters are similarly calculated as the 16% and 84% quantiles of their distribution over all samples.

Finally, our best-fit model predictions for the proton, helium, electron, positron, and carbon intensities as well as the boron-to-carbon ratio are shown in Figure 5. The proton and helium intensities are shown as a function of $E_{kin}/n$ as this is the relevant quantity for the production of diffuse emission. For the helium intensities, transforming the experimental data to match these units requires an assumption about the $^{3}$He/$^{4}$He ratio. We use the AMS-02 result $^{3}$He/$^{4}$He $(R) = 0.1476(6/R/4 \text{ GV})^{-0.294}$ provided in Aguilar et al. (2021) and extrapolate this to higher energies. We emphasize that this transformation is relevant only for the illustration in Figure 5 and that all data sets are fitted in their respective measured units.

The best-fit model (black line) reproduces well the GCR data with an overall satisfactory goodness of fit. We have listed the $\chi^2$ values for the individual observables in Table 2. The pull distributions highlight some systematic deviations, for instance in the boron-to-carbon ratio below a few GV. This is due to our restriction to a pure diffusion model; allowing for advection or reacceleration would lead to a better fit at GV rigidities (Heinbach & Simon 1995). The fit to the boron-to-carbon ratio could in the future be improved through the inclusion of the additional measurements such as the recent data from the CALET experiment (Adriani et al. 2022).

The 68% and 95% uncertainty bands are shown in gray and light orange, respectively. They are narrow where the data are sufficiently constraining and wider where the data are less constraining. An example for the latter case is proton and helium spectra beyond the energies where direct observations

---

8. Here, we employ the Bayesian terminology even though strictly speaking, it only applies to unbiased samples from the posterior distribution.
available, that is, beyond a few hundred TeV n\(^{-1}\). Despite the energy-rescaling parameters that were allowed to float freely, there are still some discrepancies between IceTop and KASCADE measurements. As the diffuse neutrino flux is mostly produced by proton and helium, this will be the dominant uncertainty from the GCR fit. Finally, we calculate the total hadronic CR injection luminosity above 0.1 GeV n\(^{-1}\) to be

\[
L_{\text{CR}} = (7.16 \pm 0.33\text{(stat.)} \pm 2.04\text{(s.d.)}) \times 10^{40} \text{ erg s}^{-1},
\]

with the uncertainties stemming from the statistical uncertainty of the CR fit (stat.) and the choice of CR source distribution (s. d.). This value is in good agreement with those given in Strong et al. (2010).

### 3.2. Diffuse Gamma-Ray Intensities

In this section, we present the gamma-ray intensities predicted by the CRINGE model. As discussed above, the diffuse predictions depend on a number of inputs beyond the parameters of the GCR models that we have fitted to local...
observations. These are the spatial distribution of GCR sources, the spatial distribution of atomic and molecular hydrogen as well as the cross sections for the production of gamma rays and neutrinos. In addition, the gamma-ray intensities depend on the choice of the ISRF. Given our ignorance of the true source distribution, gas distribution, cross sections, and ISRF, the
The values of the break energies $E_{(ii+1)}$ are assumed to be in GeV.
choice induces another source of uncertainty beyond the uncertainty from the GCR fit.

In the following, we have chosen a combination of these inputs as a default model. In particular, we have adopted the source distribution by Ferrière (2001), the GALPROP Galactic gas maps, as well as the AAfrag production cross sections. The fiducial Inverse Compton flux is calculated assuming the GALPROP ISRF model.

Figure 5. Best-fit spectra for various GCR primaries and secondaries: protons (top left), helium (top right), electron (middle left), positrons (middle right), boron-to-carbon ratio (bottom left), and carbon (bottom right). The top panels show the GCR intensities, with the solid black line indicating the best-fit model and the gray and light orange bands showing the 68% and 95% uncertainty intervals. We have also overplotted the observations by AMS-02 (Aguilar et al. 2015a, 2017, 2019b, 2019c, 2018), DAMPE (An et al. 2019; Alemanno et al. 2021), IceTop (Aartsen et al. 2019c), and KASCADE (Antoni et al. 2005). The lower panels are pull plots.
We refer to this choice of parameters together with the best-fit parameters of the GCR model as the fiducial model.\textsuperscript{9} For the different sources of uncertainties, we have computed the respective standard deviations separately. For the uncertainty stemming from a different choice of GCR parameters, we have determined half of the central 68% range of the posterior distribution of intensities. For the other sources of uncertainties, we have fixed the GCR parameters to their best-fit values and computed the standard deviation from the the set of diffuse fluxes obtained for different choices of the input, as listed in Sections 2.1.2, 2.2, 2.3, and 2.2.3. In the following figures, we have stacked these uncertainties into uncertainty bands.

The fiducial model’s intensity as well as the uncertainties around this intensity depend on direction in the sky. For gamma-ray intensities, we have adopted two sky windows for which observational data have been presented at TeV and PeV energies. In Figure 6, we show the prediction of our model for the diffuse gamma-ray fluxes in the windows \(|b| < 5^\circ\), \(25^\circ < l < 100^\circ\) and \(|b| < 5^\circ\), \(50^\circ < l < 200^\circ\). Uncertainties due to the GCR parameters, the source distribution, the gas maps, and the cross sections are indicated by red, yellow, blue, and green bands, respectively. Additionally, the uncertainty of the inverse Compton intensity stemming from the uncertainty of the ISRF is indicated by the purple band. We also take into account the expected intensity from unresolved sources following the model by Vecchiotti et al. (2022). The uncertainties related to the flux threshold varying between 0.01 and 0.1 \(\Phi_{\text{Crab}}\) are shown by the orange bands. The default intensity of unresolved sources added to our fiducial diffuse model is the geometric mean of the intensities corresponding to the upper and lower ends of that range. (See footnote 6.)

Without the inclusion of unresolved sources (left column of Figure 6), our model spectrum is close to \(E^{-2.7}\) for gamma-ray energies between 10 GeV and tens of TeV. Beyond a few tens of TeV, the spectrum softens due to the spectral breaks in the nuclear spectra at tens of TeV and at the knee around 1 PV; see the nuclear spectra in Figure 5. As far as the uncertainties are concerned, below a TeV, the uncertainty from the gas maps is dominating, but the total uncertainty remains below 20%. Above a TeV, the uncertainties from the GCR model and from the cross sections grow; individually they can be as large as 35% and 20%, respectively. The other uncertainties related to the choice of gas maps and cosmic-ray source distribution are independent of energy and remain below 10% in all regions in the sky, respectively. Even within these uncertainties, our model without unresolved sources cannot account for the data by LHAASO (Zhao et al. 2022) and Tibet AS\(\gamma\)+MD (Amenomori et al. 2021), in either of the sky windows.

The inclusion of the unresolved sources significantly enhances the intensities overall and leads to a much harder, close to \(E^{-2.3}\) spectrum for gamma-ray energies between a few hundreds of GeV and a few hundreds of TeV. The right column of Figure 6 shows that the gamma-ray intensities are now in much better agreement with the data by LHAASO (Zhao et al. 2022) and Tibet AS\(\gamma\)+MD (Amenomori et al. 2021) in both sky windows. However, the uncertainty in the prediction of the intensity from unresolved sources is sizeable: Between \(\sim 100\) GeV and a few PeV, it is dominating the total uncertainty and can be as large as a factor 2.

### 3.3. Diffuse Neutrino Intensities

For neutrinos, we have chosen three regions of the sky over which the diffuse intensities are averaged: an inner galaxy window \((|b| < 8^\circ, |l| < 80^\circ)\), an outer galaxy window \((|b| < 8^\circ, |l| > 80^\circ)\), and a high-latitude window \((|b| > 8^\circ)\). These are canonical choices in models of Galactic diffuse emission. In Figure 7, the fiducial model intensities are again shown by the black solid lines, and the uncertainties are indicated by bands of different colors: GCR parameters (red), source distributions (yellow), gas maps (blue), and cross sections (green). In the lower panel, the uncertainty bands are shown after normalization to the fiducial model intensity. We also indicate the predictions of other models, which are the Fermi-\(\pi^0\) model (Ackermann et al. 2012, dashed gray line), the KRA\(\gamma\)-5 model (Gaggero et al. 2015b, dotted gray line), as well as the KRA\(\gamma\)-50 model (Gaggero et al. 2015b, solid gray line). All neutrino intensities shown are per-flavor intensities. We derive these from the all-flavor intensity under the assumption that neutrino oscillations lead to a 1:1:1 flavor ratio at Earth (Gaisser et al. 2016). For the inner galaxy window and without unresolved sources (top-left panel of Figure 7), our model spectrum is close to \(E^{-2.7}\) for neutrino energies between 10 GeV and tens of TeV. Beyond a TeV, the spectrum softens due to the spectral breaks in the nuclear spectra. Below a TeV, the uncertainty is dominated by the cross-section uncertainty, which can be as large as 20%. At \(\sim 1\) TeV, the cross-section uncertainties are smallest, and grow again for higher energies. Also, the uncertainties from the GCR model grow significantly beyond a TeV and reach about 40% at 10 PeV. The other uncertainties related to the choice of gas maps and cosmic-ray source distribution are again independent of energy and remain below 10% in all regions in the sky, respectively.

Comparing our spectrum in the inner galaxy window with the largely featureless \(E^{-2.3}\) spectrum of the Fermi-\(\pi^0\) model, we find our model to give slightly harder spectra below a few TeV, due to the break in the nuclear spectra at \(\sim 300\) GV that had not been considered in the Fermi-\(\pi^0\) model. Above tens of TeV, though, the Fermi-\(\pi^0\) model is clearly harder due to the unbroken power-law extrapolation of the spectra from GeV to PeV energies. We judge that extrapolation to not be well justified in light of data at the knee and recent data just below the knee. Below a few hundred TeV (a few PeV), the predictions from the KRA\(\gamma\)-5 (KRA\(\gamma\)-50) model, respectively, are significantly harder than ours. This is of course in part due to the harder spectral index exhibited by these models in the...
inner galaxy but also due to the choice of the cross sections from Kamae et al. (2006), which as shown in Figure 10, leads to systematically harder spectra than the AAfrag parameterization adopted in our fiducial model. Already at 100 TeV, both models overpredict our neutrino intensity by roughly an order of magnitude. At a few PeV, this difference has grown to almost two orders of magnitude in the case of the KRAγ-50 model. Note that spectra are generally softer above a few hundreds of TeV (a few PeV) for KRAγ-5 (KRAγ-50) due to the assumed exponential cutoff.

The inclusion of unresolved sources in the inner galaxy window (top-right panel of Figure 7) leads to a much enhanced neutrino intensity below ~1 PeV. Our prediction is much closer to the prediction from the KRAγ-5 model, even though the origin of the hard spectrum is very different.

For the outer galaxy window (middle row of Figure 7), the intensities are overall smaller by about a factor of 2 to 3, but the spectral shapes are rather similar. This is to be expected given that we assume no spatial variation of the diffusion coefficient or the source spectra throughout the galaxy. Noticeable is, however, an increased uncertainty from the source distribution (compare the yellow bands in the upper and middle rows of Figure 7). At first, this might seem surprising, given that in absolute terms, the source distributions differ less in the outer galaxy than in the inner galaxy; see Figure 1. However, this can be explained by the fact that, for the same local source density, the distributions featuring a lower source density in the inner galaxy lead to a lower cosmic-ray flux at Earth. As we however normalize the local flux of our models such that local measurements are reproduced, we correspondingly scale up the fluxes for lower central source densities. This decreases the resulting uncertainty in the Galactic center region and increases it toward larger galactocentric radii.

For the case without unresolved sources (middle-left panel of Figure 7), the comparison with the Fermi-π0 model in this sky window shows that both models are compatible between 10 and 100 GeV but at larger energies show spectral differences similar to those in the inner galaxy window. The KRAγ models are at the lower envelope of the uncertainty band below a few TeV but start exceeding the upper end of our uncertainty band above ~10 TeV. Again, the disagreement can be up to two orders of magnitude at 1 PeV.
For the case where unresolved sources are taken into account (middle-right panel of Figure 7), the intensities are again significantly harder. However, in this case, the prediction is larger even than that of the KRAγ-5 model for all energies and larger than that of the KRAγ-50 model for neutrino energies smaller than a few hundred TeV.

The situation is somewhat similar for high Galactic latitudes, as shown in the lower row of Figure 7, albeit at an overall
normalization reduced by a factor of $\sim 6$ with respect to the outer galaxy window. The uncertainties from the source distribution are in between those for the inner and outer galaxy windows, as could be expected.

In Figure 8, we also show profiles of the neutrino intensity in Galactic longitude at an energy of 3 TeV. We have chosen an energy at which all sources of uncertainties contribute $\sim 10\%$ to the overall uncertainty. The prediction from our fiducial model with the Ferrière (2001) source distribution, the GALPROP Galactic gas maps as well as the AAfrag production cross sections. The Fermi-$\pi^0$ model is indicated by the dashed gray line, and the KRA$\gamma$-5 and KRA$\gamma$-50 models by the solid and dotted gray lines. In the lower panel, the uncertainty bands are presented after normalization to the fiducial model.

Integrated over the whole sky, our fiducial model predicts a single-flavor neutrino energy flux of between 10 TeV and 10 PeV neutrino energy. This energy range is similar to the sensitive energy ranges of the IceCube measurements of the diffuse astrophysical neutrino flux (Abbasi et al. 2021a, 2022b). In this energy range, the Galactic diffuse neutrino flux as predicted by our fiducial model accounts for 1.9–4.0% of the overall astrophysical neutrino energy flux as measured in various channels in IceCube (Abbasi et al. 2022b, 2021a; Aartsen et al. 2020, 2019b). In the same energy range, our fiducial model results in 23% of the integrated energy flux predicted by the KRA$\gamma$-50 model, 32% of the KRA$\gamma$-5 model flux, and 137% of the Fermi-$\pi^0$ flux. The currently most sensitive IceCube analysis (Abbasi et al. 2021b) quotes sensitivities at the level of 12% and 17% of the KRA$\gamma$-50 and KRA$\gamma$-5 model flux, respectively. This shows that the discovery of the Galactic diffuse neutrino flux or strong constraints on models for this flux are possible at the level predicted by our fiducial model with the existing data.

Finally, the total all-flavor neutrino luminosity above 1 TeV calculated from our model is

$$L_\nu = (6.13^{+0.52}_{-0.3}(\text{stat.}) \pm 0.59(\text{gas})$$

$$\pm 0.08(\text{xsec}) \pm 0.12(\text{s.d.})) \times 10^{36} \text{ erg s}^{-1}. \quad (18)$$

4. Discussion

In this paper, we have predicted the high-energy diffuse neutrino intensity from the galaxy, based on a model of GCRs.
that fits measured cosmic-ray data between GV and 100 PV rigidities. We have also predicted diffuse gamma-ray fluxes in the TeV to PeV energy range and compared to results from ARGO-YBJ, Tibet AS-γ+MD, as well as LHAASO. It is, however, natural to ask whether our models agree also with GeV gamma rays as for instance measured by Fermi-LAT data for our model parameters and the measured Fermi-LAT counts\textsuperscript{10} and the prediction of our fiducial model for three different sky regions also shown in Figure 7. In the inner galaxy window (top panel), it can be seen that while the model is in agreement with the GeV gamma-ray data within uncertainties except at energies above 40 GeV, the observed gamma-ray fluxes are harder than the model fluxes. In addition to the central galaxy, there is a significant discrepancy between GeV gamma-ray data and our model predictions in the outer galaxy window, where we underestimate the data by some 20%. We note that this issue has received relatively little attention yet and therefore awaits further clarification. Finally, we find our model to largely reproduce the data at high latitudes, unlike some of the previous studies (Orlando 2018).

We have also explored the framework of KRAγ-like models, which aim to solve the puzzle of the observed spectral hardening in Fermi-LAT data toward the Galactic center by modifying the diffusion constant in the inner galaxy as

\[
\delta_i(r) = \begin{cases} 
A_i r + B_i & r < 11 \text{ kpc} \\
A_i \times 11 \text{ kpc} + B_i & r \geq 11 \text{ kpc}
\end{cases}
\]  

(19)

leading to harder spectra from that region. However, we have found that such modifications can only partly solve the hardening issue. This is illustrated in the upper panel of Figure 9. There, we have superimposed the prediction for a KRAγ-like model that is equal to our fiducial model apart from the diffusion coefficient, which depends on galactocentric radius as described in Equation (19) with \(A_i = 0.035 \text{ kpc}^{-1}\). The \(B_i\) are chosen such that \(\delta_i(r = r_i)\) agree with the values from Table 1. The residuals of this model show a trend rather similar to our fiducial model with predicted spectra that feature a larger flux normalization but remain too soft. This is evidence that a significant part of the enhancement and spectral hardening of the KRAγ models with respect to the Fermi-π\textsuperscript{5} model (which assumes homogeneous diffusion) is only due to the hardening break in the diffusion coefficient at around 300 GV.

In the outer galaxy window, the KRAγ-like model even features slightly larger residuals with the Fermi-LAT data than our fiducial model. At high latitudes, where local emission dominates, the two models coincide as expected.

Another interesting outcome of our global fit of the GCR model is the spectral position of the knee. The break in the predicted proton spectrum, for instance, occurs at a few hundred TeV, which is somewhat lower than traditionally considered. Note that this energy might in fact be compatible with claims by ARGO-YBJ (Bartoli et al. 2015b). Returning to Figure 5, we note that the low value for the break rigidity \(R_{45}\) has been driven by the KASCADE helium data. In a sense, the low \(R_{45}\) is not surprising, but a consequence of the 300 GV break, which leads to the dominance of helium even before the proton knee (Drury 2018). The only way, in fact, to get a more pronounced peak at higher rigidities would be to change the energy scale corrections with respect to what our fit determined. This could be possible if there was another hardening break between 10 TV and 1 PeV. We note that there have been indications from DAMPE (Stolpovskiy 2022), though we have not added these preliminary data yet.

\textsuperscript{10} We are grateful to Markus Ackermann for providing us with the counts maps and instrument response functions.
5. Summary and Conclusion

We have presented CRINGE, a new model for the diffuse emission of high-energy gamma rays and neutrinos from the galaxy. For the transport of GCRs, we have adopted a simple diffusion model with homogeneous diffusion coefficient, but we have allowed for a number of breaks in the rigidity dependence. We have determined the free parameters of our model by fitting to locally measured spectra of proton, helium, electrons, and positrons as well as to the boron-to-carbon ratio. Adopting an MCMC method, we have determined the uncertainties of the fitted parameters and provided uncertainty bands for the predicted GCR intensities and the boron-to-carbon ratio. Our GCR model successfully describes these data in the energy range between 1 GeV and 100 PeV.

Combining the best-fit GCR parameters with a fiducial choice for the source distribution, gas maps, cross sections, and photon backgrounds, we have computed the diffuse emission of high-energy gamma rays and neutrinos at energies between 10 GeV and 10 PeV. We have also estimated the uncertainties due to the possibility of alternative choices of inputs. In addition, we have allowed for the presence of unresolved, pulsar-powered sources of high-energy gamma rays and neutrinos. Comparing our results with the intensity of high-energy gamma rays observed by Argo-YBJ, Tibet ASγ+MD, and LHAASO, we have found very good agreement for the case where unresolved sources are taken into account. For our neutrino predictions, we have compared with the Fermi-π0 and the KRA-γ models that have previously been employed in experimental searches. Without the unresolved sources, our predictions are usually lower than the KRA-γ models for $E \geq 1$ TeV and higher than the Fermi-π0 model for $E \leq 100$ TeV. Taking the unresolved sources into account, our predictions are mostly comparable to or even higher than the KRA-γ models.

Future studies of the Galactic diffuse neutrino flux by IceCube and KM3Net will be able to employ our model predictions as spatiotemporal templates. Such searches present an important test of the model of GCRs. The possible observation of or bounds on the diffuse Galactic flux of high-energy neutrinos will present important constraints on models of acceleration and transport of GCRs at TeV and PeV energies. In addition, we can hope to gain some insights into the presence of unresolved hadronic sources.

We are grateful to Markus Ackermann for providing us with the Fermi-LAT counts maps and instrument response functions. We also thank Mischa Breuhaus for providing his implementation of the calculation of gamma-ray absorption in the Milky Way. Daniele Gaggero, Pedro de la Torre Luque, and Ottavio Fornieri are gratefully acknowledged for their help with the DRAGON code. We also thank Carmelo Evoli for advice on the HERMES code. We acknowledge use of the HEALPix package (Gorski et al. 2005). G.S. acknowledges membership in the International Max Planck Research School for Astronomy and Cosmic Physics at the University of Heidelberg (IMPRS-HD).

Appendix A
Comparison to Fermi-LAT Data

In the following, we provide some details on the preparation of Fermi-LAT data that we use in Section 4. In order to compare a diffuse model to pixelized Fermi-LAT count maps, we have used forward folding. For a given gamma-ray intensity $J$, the expected counts per solid angle and reconstructed energy are calculated as

$$C(E_{\text{reco}}, \theta_{\text{reco}}) = \int dE \int d\Omega \Phi_j$$

$$\times (E, \theta) \mathcal{E}(E, \theta) \text{PSF}(\theta - \theta_{\text{reco}}, E) \text{ED}(E_{\text{reco}}E)$$ (A1)

with the instrument response functions (IRFs) exposure $\mathcal{E}$, energy-dependent point-spread function PSF, and the energy dispersion ED. From this, the expected counts in pixel $i$ of energy bin $k$, $\mu_k$, follow as

$$\mu_k = \int_{E_{\text{min},k}}^{E_{\text{max},k}} dE_{\text{reco}} \int_{\Omega_k} d\Omega C(E_{\text{reco}}, \theta_{\text{reco}}).$$ (A2)

This quantity is then compared directly to the Fermi-LAT data counts to obtain the results presented in Figure 9.

The Fermi-LAT data set used in this work consists of 8 years of Pass 8 P8R3 ULTRACLEANVETO data from the same time window as used for the construction of the 4FGL catalog (Abdollahi et al. 2019) together with the corresponding IRFs. Pass 8 P8R3 is the latest Fermi-LAT data release featuring the current up-to-date processing and event reconstruction (Bruel et al. 2018). The ULTRACLEANVETO event selection features the lowest instrumental background and is recommended for the study of large-scale structures (Bruel et al. 2018). The data set used in this work features events binned into 22 logarithmic energy bins ranging from 1.6 GeV to 2.32 TeV. Besides that, events are separated into four classes according to the quality of their angular reconstruction. These are labeled PSF0-PSF3, with a larger number representing better reconstruction quality, and each contains about the same number of events but features a separate PSF.12

The total gamma-ray flux measured by Fermi-LAT consists of course not only of Galactic diffuse emission but also of emission from both point-like and extended sources as well as isotropic extragalactic emission and the remaining instrumental backgrounds. For the latter, a recommended model for the P8R3 ULTRACLEANVETO selection is provided publicly13 and included as an additional flux component in the model. Also, in addition to the hadronic diffuse emission and the inverse Compton component discussed in the main text, we also include the contribution from bremsstrahlung of cosmic-ray leptons. This component can be safely ignored above 20 GeV due to its steeply falling spectrum but contributes at the level of up to 5% at energies of a few GeV. With this, the total intensity that is compared to data is

$$J = J_{\text{had}} + J_{\text{IC}} + J_{\text{brem}} + J_{\text{anisotropic}} + J_{\text{instrument}}.$$ (A3)

Note that this does not include the intensity from either resolved or unresolved sources. While we do not consider unresolved sources in this analysis, we mask out known sources to stay as independent of the details of source emission models as possible. This includes all 5064 sources included in the 4FGL, of which 75 are spatially extended (Abdollahi et al. 2019), as well as two large-scale features in the Galactic

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11. The pixelization was done using HEALPix (Gorski et al. 2005).
12. https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/
13. https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
gamma-ray sky that cannot be reproduced with the modeling approach pursued here, the Fermi bubbles (Su et al. 2010) and the north polar spur (NPS) (Casandjian & Grenier 2009; Acero et al. 2016). For the Fermi bubbles, a publicly available spatial template\(^{14}\) similar to that shown in Acero et al. (2016) is used, while the mask for the NPS is constructed following the template shown in Acero et al. (2016). For the sources from the 4FGL, a circular mask with radius \(\sigma_{\text{mask}}\) is assumed. For the spatially extended sources, the mask size is not \(\sigma_{\text{mask}}\), but rather \(\sigma_{\text{mask}} = \sigma_{\text{src}}^2 + \sigma_{\text{erc}}^2\), with \(\sigma_{\text{src}}\) the radius of the source. \(\sigma_{\text{mask}}\) must of course be chosen to be large enough to mask out a large fraction of the source emission, but also needs to be small enough to still leave a significant fraction of pixels unmasked, in particular toward the Galactic center where the source density is highest. As a compromise between these considerations, a value of \(\sigma_{\text{mask}} = 0.5^\circ\) is chosen, and the data considered in this work are restricted to the PSF3 and PSF2 classes at energies \(E > 5\) GeV. This ensures that all sources are masked out at least \(2.3 \times 68\%\) PSF containment angle. For simplicity, and to be even more restricting at higher energies, \(\sigma_{\text{mask}}\) is fixed independently of gamma-ray energy. As a consequence of only considering the Fermi-LAT data above 5 GeV, where the energy resolution is much better than at lower energies (see footnote 9) (e.g., Atwood et al. 2009b), energy dispersion is ignored. Given this energy threshold and the rather wide logarithmic energy binning of the data set used here with \(E_{\text{max}}/E_{\text{min}} = \sqrt{2}\), the systematic error introduced by this simplification was found to be below 5\% in all cases. On the high-energy end, we restrict our analysis to gamma-ray energies below 100 GeV. This cutoff ensures that the Poisson uncertainty on the data counts also remains below 5\% in all cases.

**Appendix B**

**Input Variations for the Best-fit GCR Parameters**

The quantification of the uncertainties of Galactic diffuse emission stemming from the choice of gas distributions, hadronic production cross sections, cosmic-ray source distribution, and ISRF as described in Section 3.3 are based on discrete variations of the respective model inputs assuming the best-fit GCR parameters. In the following, we show the fluxes for each of these discrete variations to illuminate the shape of the uncertainty bands displayed in Section 3.

**B.1. Hadronic Production Cross Sections**

Figure 10 shows the all-sky averaged spectra and relative differences of both the diffuse neutrino and hadronic gamma-ray flux for the three hadronic production cross sections described in Section 2.2. All other inputs are the same as for our fiducial model. We remind the reader that the K&K cross sections are only valid at primary energies above 100 GeV and that the KamaeExtended model is equal to the K&K model at primary energies above 500 TeV. The latter is then reflected at somewhat lower energies in the diffuse emission spectra as is clearly visible in Figure 10. When comparing the differences between the cross sections for neutrinos to those for hadronic gamma rays, one can see that for hadronic gamma rays, the cross sections are in close agreement below 1 TeV. This is different for neutrinos, where the difference between the AAfrag and KamaeExtended parameterizations are already sizable at lower energies. We also highlight that the KamaeExtended model predicts consistently harder spectra than the AAfrag model for both neutrinos and hadronic gamma rays.

![Figure 10](https://dspace.mit.edu/handle/1721.1/105492)

**Figure 10.** All-sky averaged neutrino (left panels) and hadronic gamma-ray (right panel) intensity as a function of energy. We show our model prediction for the different hadronic production cross sections described in Section 2.3 using the best-fit GCR parameters combined with the GALPROP Galactic gas maps and the Ferrière (2001) source distribution. The blue line obtained using the AAfrag cross sections corresponds to our fiducial model. In the lower panels, the relative deviations after normalization to this fiducial model are presented.

\(^{14}\) https://dspace.mit.edu/handle/1721.1/105492
B.2. Gas Distribution

Figure 11 shows the longitudinal profiles of the diffuse neutrino flux at $E = 3$ TeV for latitudes $|b| < 5^\circ$ for the three Galactic gas maps described in Section 2.2. All other inputs are the same as for our fiducial model. The difference between the GALPROP and GALPROP-OT model arises solely from the assumption of a different value for the spin temperature $T_s$. As expected, the GALPROP-OT model assuming optically thin gas leads to a lower intensity. The differences with respect to the HERMES gas maps stem from the reliance on different 21 cm surveys, the reconstruction into galactocentric rings of different sizes, the assumed values of $T_s$, and the treatment of dark gas.

B.3. Cosmic-Ray Source Distribution

Figure 12 shows the longitudinal profiles of the diffuse neutrino flux at $E = 3$ TeV for latitudes $|b| < 5^\circ$ for the four source distributions described in Section 2.1.2. All other inputs are the same as for our fiducial model. The relative intensities of the models toward and away from the Galactic center reflect the shape of the radial profiles as shown in Figure 1. For the reasons described in Section 3.3, the relative differences between the intensities are larger away from the Galactic center than toward it. Furthermore, as also mentioned in Section 3.3, the coincidence of the intensities at $|l| \approx 45^\circ$ can be explained by the fact that in this direction, the emission is on average produced at galactocentric radii similar to the solar radius and is thus constrained by the fit to local GCR intensities. Overall, the source distribution from Case & Bhattacharya (1998) gives the flattest emission profile, and the emission obtained with the distribution from Lorimer et al. (2006) is peaked toward the Galactic center the most.

B.4. Interstellar Radiation Field

Figure 13 shows the spectra of the inverse Compton gamma-ray intensity in different windows in the sky. The spectra are calculated using the best-fit GCR parameters combined with the Ferrière (2001) ones and are shown for both ISRF models described in Section 2.2.3. Similar to the hadronic component of the gamma-ray and neutrino intensities, the inverse Compton intensity also varies over the different windows in the sky, with the largest intensity toward the Galactic center. The cutoff of the intensities above 10 TeV reflects the cutoff in the electron source spectra at $E_{\text{cut}} = 20$ TeV as described in Section 2.1.2. The GALPROP ISRF model produces intensities at least 25% larger than the model from Vernetto & Lipari (2016) in all regions in the sky and at all energies. However, because the inverse Compton intensity is a subdominant contribution to the overall gamma-ray intensity, the overall uncertainty stemming from the ISRF model choice as shown in Figures 6 and 9 is correspondingly reduced.
Figure 12. Neutrino intensity as a function of Galactic longitude for a neutrino energy of 3 TeV. We show our model prediction for the different source distributions described in Section 2.1 and shown in Figure 1 using the best-fit GCR parameters combined with the GALPROP Galactic gas maps and the AAfrag production cross sections. The blue profile obtained using the Ferrière (2001) source distribution corresponds to our fiducial model. In the lower panel, the relative deviations after normalization to this fiducial model are presented.
Figure 13. Inverse Compton gamma-ray intensity as a function of energy in different regions in the sky. We show our model prediction for the ISRF models described in Section 2.2.3 using the best-fit GCR parameters combined with the Ferrière (2001) source distribution. The blue profiles obtained using the GALPROP ISRF model correspond to our fiducial model. In the lower panels, the relative deviations after normalization to this fiducial model are presented.
