PROCEEDINGS OF SCIENCE

Modelling the gamma-ray diffuse emission of the Galaxy up to PeV

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The Tibet ASgamma and LHAASO collaborations recently reported the observation of a gamma-ray diffuse emission from the Galactic plane with energy up to the PeV. We show that under physically motivated conditions these results, together with those of Fermi-LAT and ARGO-YBJ at lower energies, can consistently be interpreted in terms of an emission originated by the Galactic cosmic-ray (CR) population, the so called "CR sea". Our analysis favour CR transport models characterised by spatial-dependent diffusion although some degeneracy remains between the choice of the transport scenario and that of the CR spectral shape above 10 TeV. We discuss the possible relevance of forthcoming measurements, especially those performed by experiments located in the South hemisphere, in resolving that ambiguity. We will then present examples of high resolution maps and spectra of the simulated gamma-ray diffuse emission of the Galaxy from few GeV up to the PeV which we release and can be used by experimental collaborations as templates.

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1. Introduction

The Galactic Cosmic Ray (CR) population is expected to give rise to a diffuse γ-ray emission, concentrated along the Galactic Plane (GP). It consists of two components, hadronic and leptonic, respectively originated by nuclear scattering of CR nuclei – mostly protons and Helium nuclei – onto the Inter Stellar Medium (ISM) gas and Inverse Compton (IC) scattering of CR electrons onto the Interstellar Radiation Field (ISRF). This emission has been clearly identified and full-sky mapped by the Fermi-LAT orbital observatory up to few hundred GeV [1] while above that energy only few measurements have been reported by air-shower experiments in limited regions of the sky and, until recently, not much above the TeV [2, 3] . Nowadays this situation is swiftly improving thanks to a new generation of air-shower experiments which are announcing some striking results.

Indeed, the Tibet ASγ experiment reported the observation of a diffuse γ-ray emission from the Galactic plane ($25° < l < 100°$ and $50° < l < 200°$, both for $|b| < 5°$) with energy up to the PeV [4]. A similar result – though still preliminary and reporting a slightly lower flux than Tibet – was presented by the LHAASO collaboration [5] for the innermost of those two regions.

These measurements offer a new valuable insight into the properties of the Galactic CRs population potentially throughout the whole Galaxy while direct CR detection only probe a relatively local region. Such an achievement may help determining, for example, if the *knee* of the CR spectrum is a feature originated by the acceleration process or by CR transport and to clarify if it is representative of the whole CR Galactic population or is shaped by a local source.

Given the potential strong relevance of these measurements for CR physics, in this contribution we will discuss under which conditions they are compatible with Fermi-LAT and other γ-ray data at lower energies given the locally observed proton and Helium CR spectra.

We will also discuss the role of high energy neutrino astronomy which should also provide complementary insights into these problems. Indeed, if the ~PeV γ-ray detected Tibet ASγ and LHAASO are produced by hadronic processes a corresponding diffuse Galactic ν emission is also expected at those energies (see *e.g.* [6] and refs. therein). Noticeably, the experimental search of the Galactic ν diffuse emission has just started and a detection hint has been recently reported by the IceCube collaboration [7] which may soon be strengthened. The interpretation of all those measurements require advanced numerical packages to treat the CR transport and interactions with accurate models of the interstellar gas distributions. In this contribution we will present the results obtained with the `DRAGON2` [8, 9] and `HERMES` [10] numerical codes producing simulated spectra and maps of the γ and ν diffuse emissions for very general CR transport models. In particular, we will consider a scenario assuming a factorized dependence of the diffusion coefficient on rigidity and position which was invoked in order to explain the hardening of the γ-diffuse emission above 10 GeV observed by Fermi-LAT in the inner GP [11, 12] and motivated theoretically in [13].

2. The models

We model the energy and spatial distributions of each relevant CR species solving numerically the transport equation with the `DRAGON2` code [8, 9]. We assume that the spectrum of each CR species can be obtained as a steady-state solution of the transport equation for a smooth distribution of continuous sources which we fix on the basis of supernova catalogues. For a given source

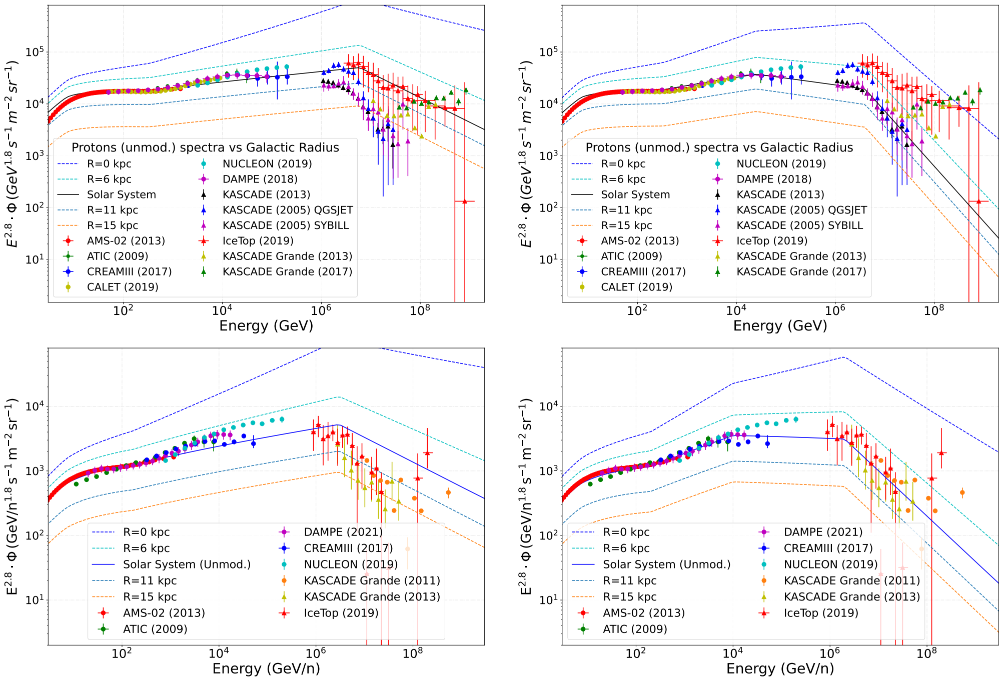

Figure 1: Spectra of protons (upper panels) and helium (lower panels) of the γ-*optimized* scenario for the Max (left panels) and Min (right panels) configurations, from 10 GeV to 10^9 GeV. Since in the γ-*optimized* scenario the propagation of CRs depends on the distance from the galactic center, we show the spectra at different galactocentric radii. Available local CR data from several experiments are included for comparison.

spectrum – a n-times broken power-law tuned against locally measured CR spectra – as an output the code provides the propagated spectrum of each primary and secondary species in every point of the Galaxy. Besides several astrophysical quantities, the CR diffusion coefficient $D(\rho, \vec{x})$ as a function of the particle rigidity, ρ, and of the spatial coordinates needs also to be given to the code as an input. Due to the approximate cylindrical symmetry of the Galaxy, and assuming no relevant dependence on the vertical coordinate, the Galactocentric radius R turns to be the only relevant spatial coordinate for the diffusion coefficient. This quantity is generally assumed to be a power law function of the particle rigidity with a spatially dependent slope that we parameterized as:

$$D(\rho, R) = D_0 \cdot \left(\frac{\rho}{\rho_0}\right)^{\delta(R)} , \tag{1}$$

where D_0 is its normalization at a reference rigidity $\rho_0 = 4\,\mathrm{GV}$. The index $\delta(R)$, *a priori* being poorly known, is inferred from comparing the code predictions with the measured secondary to primary CR flux ratios, being the boron-to-carbon (B/C) ratio the most common. Works based on multi-channel analysis [14, 15] of AMS-02 results [16] found that at the Solar System $\delta(R_\odot) \simeq 0.5$.

Alternatively to the conventional (*Base*) scenario, where δ is independent on R, we test a spatially-dependent (factorized spatial-energy dependence) model: the γ-optimized model. As shown in [17, 18] for the γ-*optimized* setup, Fermi-LAT [19] and ARGO-YBJ [2] data along the GP are reasonably reproduced for the following choice of the Galactocentric radial dependence of δ:

$$\delta(R) = 0.04(\mathrm{kpc}^{-1}) \cdot R(\mathrm{kpc}) + 0.17, \tag{2}$$

for $R < R_\odot = 8.5$ kpc and $\delta(R) = \delta(R_\odot) = 0.5$.

To evaluate the injection spectrum of CRs we account for a wide set of CR data up to the PeV domain. In this context, we emphasize the large discrepancies in the energy spectra observed by different collaborations at these energies (see Fig. 1). Therefore, in order to bracket that uncertainty at very high energies we consider two setups for the CR injection spectra which we call *Min* and *Max* configurations. For the γ*-optimized* scenario the spectra of protons and Helium hardens getting closer to the centre as a consequence of the radially-dependent diffusion coefficient adopted in that scenario. Rather, for the *Base* scenario they have the same shape in every position although the normalization would vary depending on the density of sources at different regions of the Galaxy. In Figure 1 we show the proton spectrum predicted from the γ*-optimized* model for the Max (left panel) and Min (right panel) configurations at different parts of the GP.

3. The γ-ray diffuse emission

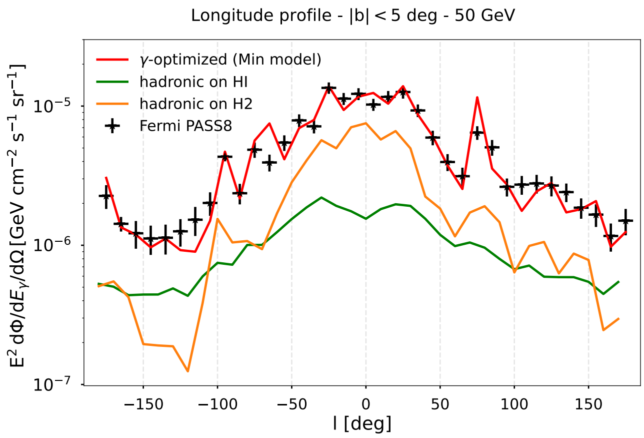

Figure 2: The longitude profile of the total γ-ray emission (for latitudes of $|l| < 5°$) at 50 GeV predicted by the *Base* and γ*-optimized* models for the Min configurations is compared to Fermi-LAT PASS8 results. An almost coincident result is obtained at this energy for the Max configuration. The emission components that come from the hadronic emission generated by HI (atomic) and H2 (molecular) gas are also showed. Fermi-LAT PASS8 data are added for comparison.

Having modeled the distributions of CRs in the Galaxy we can now compute the full-sky maps of the γ-ray diffuse emission with the HERMES code. In Fig. 2 we compare our predictions for the diffuse emission longitude profile with Fermi-LAT (PASS8) results. The contribution of unresolved sources was computed extrapolating the model presented in Ref. [20] based on the Fermi-LAT results. We also account for the isotropic spectral template provided by the Fermi-LAT collaboration [21]. For more details, we refer the readers to Refs. [17, 22]. As expected, the γ*-optimized* models reproduce much better Fermi-LAT data especially close to the Galactic Centre.

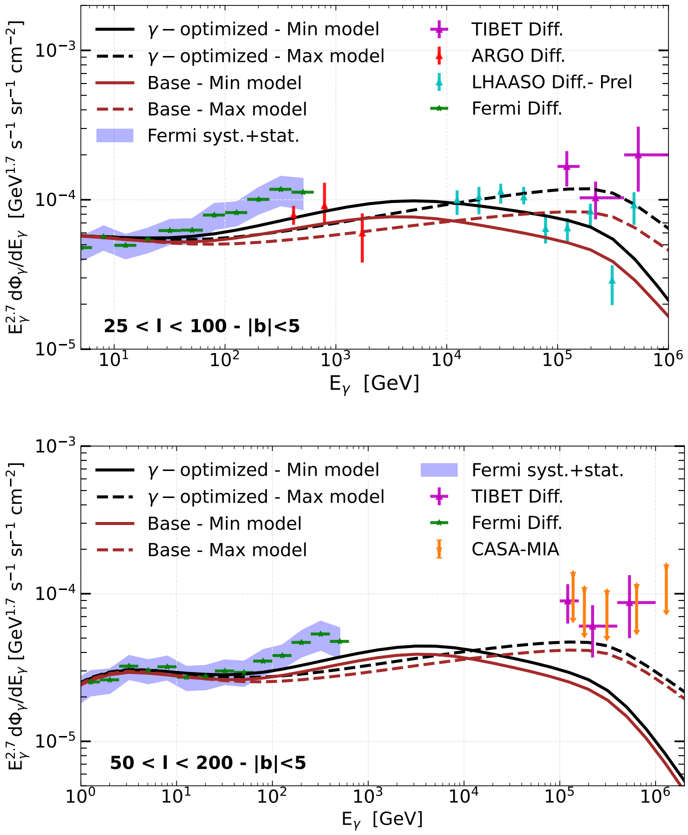

Figure 3: γ-ray diffuse spectra from the γ-optimized scenario compared to Tibet ASγ [4], LHAASO [5] (preliminary), Fermi-LAT [1] (CLEAN events from PASS8 data with subtraction of flux from known sources and isotropic background) and ARGO-YBJ [2] data in the window $|b| < 5°$, $25° < l < 100°$. Here, we account for absorption of γ-rays into CMB photons (see Fig. 7 of Ref. [22]) and do not include the contribution of unresolved sources.

Then our main goal consists of expanding our predictions for the γ-ray flux up to PeV energies and compare them with the recently published data by Tibet ASγ [4], LHAASO [5] (preliminary) and ARGO-YBJ [2]. These results are presented in Fig. 3. We are accounting for absorption due to $\gamma - \gamma$ scattering as described in Ref. [10, 18]. Its effect is practically negligible below the 100 TeV while just above that energy it is around 10%. For the γ-ray production cross-sections we used those by [23] with the updated parameterization of the proton–proton total inelastic cross-section reported in [24].

Remarkably, we notice the overall agreement between the models and the data supporting our working hypothesis that the bulk of the observed diffuse emission is originated by the interaction of the Galactic CR “sea”. Indeed our models allow to capture the main features of the observed data in a remarkably large range of energies, from 10 GeV all the way up to the PeV domain.

It is difficult to assess which model provides the best description of the data. In fact, we are hampered by the scatter in the experimental points above few tens of TeV and the consequent degeneracy arising between the choice of the transport scenario and the shape of the source spectral shape (Min or Max setup). We notice however that, if confirmed, LHAASO low energy data – reasonably the most reliable ones in that dataset – would favor the γ-*optimized* Max model which moreover is that which better agrees with Tibet-ASγ in the $25^\circ < l < 100^\circ$, $|b| < 5^\circ$ sky window.

Finally, we should remark that a larger contribution from unresolved sources, not reported in Fig. 3 since it depends on the angular resolution of each different instrument, cannot be excluded. Interestingly, however, the main candidates for these sources are thought to be leptonic – *e.g.* Pulsars Wind Nebulae (PWNe) and TeV halo – hence they are not expected to give rise to a neutrino emission.

4. The Neutrino diffuse emission

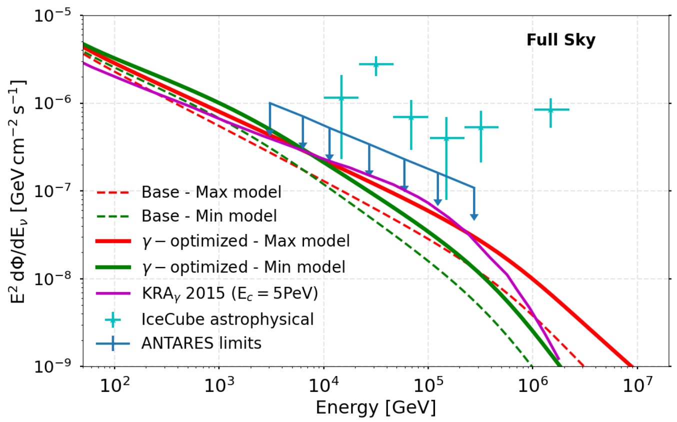

Figure 4: Full sky ν diffuse emission predicted for the Base and γ-*optimized* models (Min and Max configurations) compared to the model-independent upper limits obtained from the ANTARES collaboration. The predicted galactic ν flux from the KRA$_\gamma$ model (cutoff energy of $E_c = 5$ PeV) [6] is also reported. In addition, the IceCube astrophysical ν flux as measured from IceCube using 7.5 years of track events [25] are added for completeness.

Besides offering a clear signature of its hadronic nature, the possible detection of the diffuse neutrino emission of the Galaxy would allow us to probe a region of the GP closer to the Galactic centre than presently accessible to γ-ray observatories. As we discussed above, that is the region where the possible effects of unconventional CR transport are expected to be stronger. For this reasons we used HERMES to compute the neutrino spectrum predicted by the very same models discussed in the above for γ-rays.

In Figure 4 we show the predicted ν Galactic diffuse emission considering the Min and Max configurations of the γ-*optimized* scenarios and compare them with the model-independent limits obtained from the ANTARES collaboration [26] considering six years of track-like events for the region $|l| < 40^\circ$ and $|b| < 3^\circ$. For reference we also show the prediction of the KRA$_\gamma^5$ model (cutoff energy of $E_c = 5$ PeV) [6] which was used by the IceCube collaboration as a template for its full-sky fit analysis finding it to agree with data with 2σ significance [7]. The close similarity of KRA$_\gamma^5$ and γ-*optimized* Max spectral distributions imply that a possible experimental confirmation of that hint would basically hold also for the latter model.

5. Conclusions

In this contribution we have reported some of the main results of recent computations of the diffuse γ-ray and neutrino emissions of the Galaxy.

We discussed under which conditions our results can account for the main features of the measured spectral distributions of those emissions up to energies reaching the PeV. In order to do that we showed the main results obtained from the γ*-optimized* scenario described considering two configurations of the CR injection spectra in order to bracket bracket the systematic uncertainty on the CR data above 10 TeV. We conclude that, although for what concern high energy γ-rays high uncertainties do not allow to firmly nail the correct transport scenario yet, the Tibet-ASγ and preliminary LHAASO results seem to favor a spatial dependent CR transport scenario which in agreement to what required to match Fermi-LAT data at lower Galactic longitudes.

Concerning neutrinos, we showed that, for those models, the expected diffuse emission along the GP is significantly larger than expected for conventional (spatial independent CR transport) scenarios. This finding enhances considerably the perspectives of detecting the corresponding neutrino diffuse emission in the near future.

References

[1] Ackermann M *et al.* (Fermi-LAT) 2012 *Astrophys. J.* **750** 3 (*Preprint* 1202.4039)

[2] Bartoli B *et al.* (ARGO-YBJ) 2015 *Astrophys. J.* **806** 20 (*Preprint* 1507.06758)

[3] Nayerhoda A, Salesa Greusa F, Casanova S, Gaggeroc D, Grasso D and Marinelli A (HAWC) 2020 *PoS* **ICRC2019** 750

[4] Amenomori M *et al.* (Tibet ASgamma) 2021 *Phys. Rev. Lett.* **126** 141101 (*Preprint* 2104.05181)

[5] Zhao S, Zhang R, Zhang Y and Yuan Q (LHAASO) 2021 *PoS* **ICRC2021** 859

[6] Gaggero D, Grasso D, Marinelli A, Urbano A and Valli M 2015 *Astrophys. J. Lett.* **815** L25 (*Preprint* 1504.00227)

[7] Aartsen M G *et al.* (IceCube) 2019 *Astrophys. J.* **886** 12 (*Preprint* 1907.06714)

[8] Evoli C, Gaggero D, Vittino A, Di Bernardo G, Di Mauro M, Ligorini A, Ullio P and Grasso D 2017 *JCAP* **2017** 015 (*Preprint* 1607.07886)

[9] Evoli C, Gaggero D, Vittino A, Di Mauro M, Grasso D and Mazziotta M N 2018 *JCAP* **2018** 006 (*Preprint* 1711.09616)

[10] Dundovic A, Evoli C, Gaggero D and Grasso D 2021 *Astron. Astrophys.* **653** A18 (*Preprint* 2105.13165)

[11] Gaggero D, Urbano A, Valli M and Ullio P 2015 *Phys. Rev. D* **91** 083012 (*Preprint* 1411.7623)

[12] Lipari P and Vernetto S 2018 *Phys. Rev. D* **98** 043003 (*Preprint* 1804.10116)

[13] Cerri S S, Gaggero D, Vittino A, Evoli C and Grasso D 2017 *JCAP* **2017** 019 (*Preprint* 1707.07694)

[14] Génolini Y *et al.* 2019 *Phys. Rev. D* **99** 123028 (*Preprint* 1904.08917)

[15] Luque P D L T, Mazziotta M N, Loparco F, Gargano F and Serini D 2021 *JCAP* **07** 010 (*Preprint* 2102.13238)

[16] Aguilar M *et al.* (AMS) 2016 *Phys. Rev. Lett.* **117** 231102

[17] De la Torre Luque P, Gaggero D, Grasso D and Marinelli A 2022 *Front. Astron. Space Sci.* **9** 1041838 (*Preprint* 2209.10011)

[18] De la Torre Luque P, Mazziotta M N, Ferrari A, Loparco F, Sala P and Serini D 2022 *JCAP* **07** 008 (*Preprint* 2202.03559)

[19] Acero F *et al.* (Fermi-LAT) 2016 *Astrophys. J. Suppl.* **223** 26 (*Preprint* 1602.07246)

[20] Steppa C and Egberts K 2020 *Astronomy & Astrophysics* **643** A137 ISSN 1432-0746 URL http://dx.doi.org/10.1051/0004-6361/202038172

[21] Ackermann M *et al.* (Fermi-LAT) 2015 *Astrophys. J.* **799** 86 (*Preprint* 1410.3696)

[22] Luque P D l T, Gaggero D, Grasso D, Fornieri O, Egberts K, Steppa C and Evoli C 2022 *ArXiv:2203.15759* (*Preprint* 2203.15759)

[23] Kelner S R and Aharonian F A 2008 *Phys. Rev. D* **78** 034013

[24] Kafexhiu E, Aharonian F, Taylor A M and Vila G S 2014 *Phys. Rev. D* **90** 123014

[25] Abbasi R *et al.* (IceCube) 2021 *Phys. Rev. D* **104** 022002 (*Preprint* 2011.03545)

[26] Adrian-Martinez S *et al.* (ANTARES) 2016 *Phys. Lett. B* **760** 143–148 (*Preprint* 1602.03036)