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Galactic diffuse gamma rays meet the PeV frontier

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The LHAASO collaboration recently reported a robust measurement of the diffuse gamma-ray emission from the Galactic plane at energies from $\sim$ 10 TeV up to the PeV. This observation represents a clear evidence of a higher diffuse gamma-ray flux from the Galaxy than the expected from traditional models of CR interactions. On top of this, the recent detection of neutrinos from the Galactic plane by the IceCube collaboration show a similar excess with respect to previous estimations, which further support a larger rate of hadronic interactions in the Galaxy that would explain both observations. However, the uncertainties in the contribution from sources are still too high to discard this as the origin of these excesses.

Here, we present updated comparisons of a model of inhomogeneous propagation of cosmic rays in the Galaxy that is tuned to reproduce the Fermi-LAT measurements across the Galactic plane in the GeV range. We show further proof that the predictions from this model reproduce the observed gamma-ray diffuse emission from few GeV up to the PeV, which indicate that these emissions are dominated by the emission from cosmic-ray interactions in the Galaxy. Finally, we show how this model perfectly reproduce the measurements from LHAASO in the inner and outer parts of the Galactic plane, as well as the IceCube best-fit measurement.

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1. Gamma-ray and neutrino diffuse emissions throughout the Galaxy

The Tibet ASγ and LHAASO collaborations recently announced the discovery of a γ-ray diffuse emission from the Galactic plane (GP) up to energies reaching the PeV [1–3]. Although gamma-ray emission from unresolved sources may be significant (depending on the region of the sky), this diffuse emission is expected to be originated by the interaction of cosmic ray (CR) particles with the interstellar medium (ISM). Therefore, these measurements offer a new probe of the Galactic CR population at energies beyond the *knee* of the CR spectrum and well beyond the Solar System. Such an achievement may allow us, for example, to get a hint of the origin of those energetic particles and to determine if the *knee* is produced by the acceleration process or it is a transport effect. Moreover, it may allow to clarify if that feature is representative of the whole CR Galactic population or is shaped by local effects. The recent measurements from the LHAASO [3] collaboration pointed to an excess of a factor of a few with respect to the diffuse γ-ray emission expected from models assuming uniform propagation of CRs in the Galaxy, which may be already an indication of a higher-than-expected diffuse gamma-ray emission from the Galactic plane.

Neutrinos should also provide complementary insights into these problems. Indeed, the IceCube collaboration recently reported the first robust observation of neutrinos from the Galactic plane [4]. Similarly to what was observed from the LHAASO and TIBET observations, the measured neutrino flux is a factor of $sim5$ above what is expected from the truly diffuse flux predicted from models with uniform propagation of CRs. This may indicate either that there are extra sources of high-energy neutrinos from the Galactic plane (likely emission from sources) or that this kind of model with uniform diffusion of CRs is incorrect (which is theoretically expected and supported by observations of Fermi-LAT [5], in fact). If the emission detected by Tibet ASγ and LHAASO were mostly produced by hadronic processes, a diffuse Galactic ν emission similar to the one observed by IceCube is also expected at those energies (see *e.g.* [6] and refs. therein). However, the uncertainties in the determination of the γ-ray emission from sub-threshold sources and the estimation of the ν emission from sources is still quite large at such high energies, and one can not discard whether these contributions are dominant and can explain both of the excesses or not.

In this report we present the results obtained with the `DRAGON2` numerical code [7, 8] – to model CR transport – in combination with the `HERMES` code [9] – to produce simulated spectra and maps of the γ and ν diffuse emissions as described by a model of inhomogeneous transport of charged particles in the Galaxy. In particular, we show comparisons of the recent LHAASO and IceCube data with the predicted neutrino and gamma-ray diffuse emissions from the γ-optimized model [10, 11], 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 [12, 13] and motivated theoretically in [14].

2. The γ-*optimized* models

We model the energy and spatial distributions of each relevant CR species solving numerically the transport equation with the `DRAGON2` code [7, 8]. 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

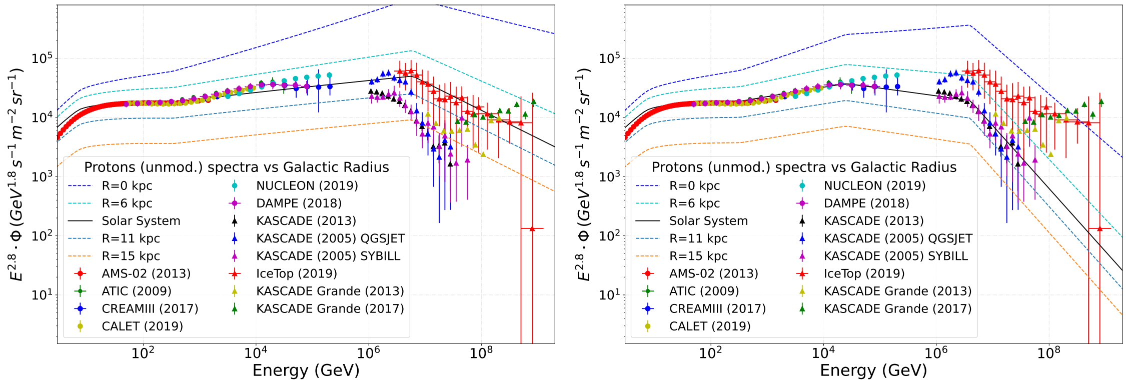

Figure 1: Proton spectra predicted from the γ-*optimized* scenario for the Max (left panel) and Min (right panel) configurations, from 10 GeV to 10^9 GeV, at different galactocentric radii. Available local CR data from AMS-02, ATIC, CREAM, CALET, NUCLEON, DAMPE, KASCADE, KASCADE Grande and IceTop are included for comparison.

spectrum – a n-times broken power-law tuned against locally measured CR spectra (see Fig. 1) – 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 diffusion coefficient describing the movement of CRs in the Galaxy $D(\rho, \vec{x})$ 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 $\rho_0 = 4\,\text{GV}$. 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 [15–17] of AMS-02 results [18] 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 mode a spatially-dependent (factorized spatial-energy dependence) model: the the γ-optimized model. As shown in Refs. [11, 19] for the γ-*optimized* setup Fermi-LAT [20] data and ARGO-YBJ [21] data along the GP are simultaneously reproduced in different parts of the Galaxy for the following choice of the galactocentric radial dependence of δ:

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

for $R < R_\odot = 8.5$ kpc and $\delta(R) = \delta(R_\odot) = 0.5$. We show below that this parametrization of the spatial dependence of the spectral index of the diffusion coefficient leads also to a simulataneous reproduction of the measurements of TIBET, LHAASO, HAWC and IceCube (in different parts of the Galaxy) without any fine-tuning.

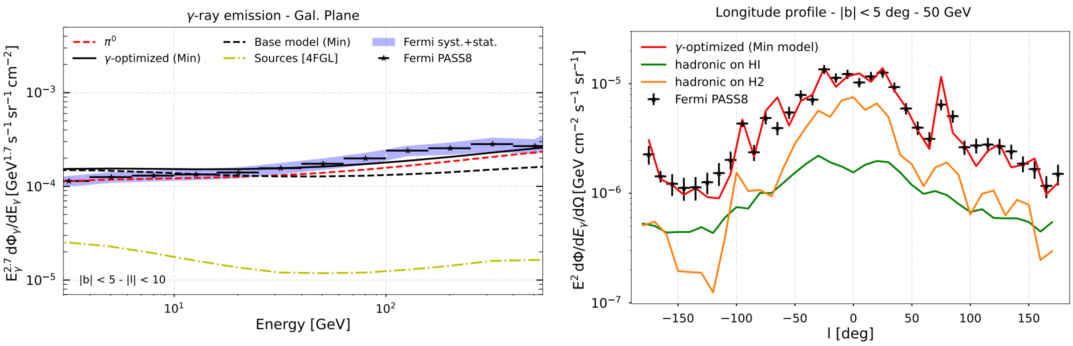

Figure 2: Left panel: Comparison of Fermi-LAT diffuse emission with the predictions obtained from the γ-*optimized* and *Base* models, for the Min configuration, at a window of coordinates $|b| < 5°$, $|l| < 10°$. We also show the π^0 contribution and the contribution from sources. **Right panel:** Longitude profile of the γ-ray emission predicted from the γ-*optimized* model at 50 GeV, compared to Fermi-LAT data and showing the emission originated from collisions of CRs with molecular (H2) and atomic gas (HI)

To evaluate the injection spectrum of CRs we account for a wide set of local 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 get harder 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 vary depending on the density of sources at different regions of the Galaxy. In Figure 1 we show the proton spectra predicted from the γ-*optimized* model for the Max (left panel) and Min (right panel) configurations at different parts of the GP.

Then, once having adjusted the injection spectra of CRs in the Galaxy we compute the full-sky maps of the γ-ray diffuse emission. In the left panel of Fig. 2 we compare Fermi-LAT diffuse emission with the predictions obtained from the γ-*optimized* and *Base* models, for the Min configuration, at a window around the centre of the Galaxy. In this panel, we also show the different components of the total γ-ray emission (at $|b| < 5$ $|l| < 10$). The contribution of unresolved sources was computed adopting the models presented in Ref. [22] to the Fermi-LAT instrument. For more details, we refer the readers to Refs. [10, 11]. The modelling of an inhomogeneous diffusion coefficient allows us a much better reproduction of the Fermi data close to the Galactic Centre. In the right panel of this figure, we show the longitude profile of the γ-ray emission predicted from the γ-*optimized* model at 50 GeV, compared to Fermi-LAT data (PASS8) and specify the emission originated from collisions of CRs with molecular (H2) and atomic gas (HI). We highlight that the γ-*optimized* model that we present here is only adjusted to the local CR data and Fermi data below 300 GeV. Therefore, in the next section we show the predictions of this model at energies above 1 TeV (that appeared before the release of LHAASO or IceCube data) and never the result of fits to the data.

In Ref. [10], we showed that the predicted γ-ray flux from the γ-optimized model at PeV energies reproduce at a very good level of precision the recently published data by Tibet ASγ [1],

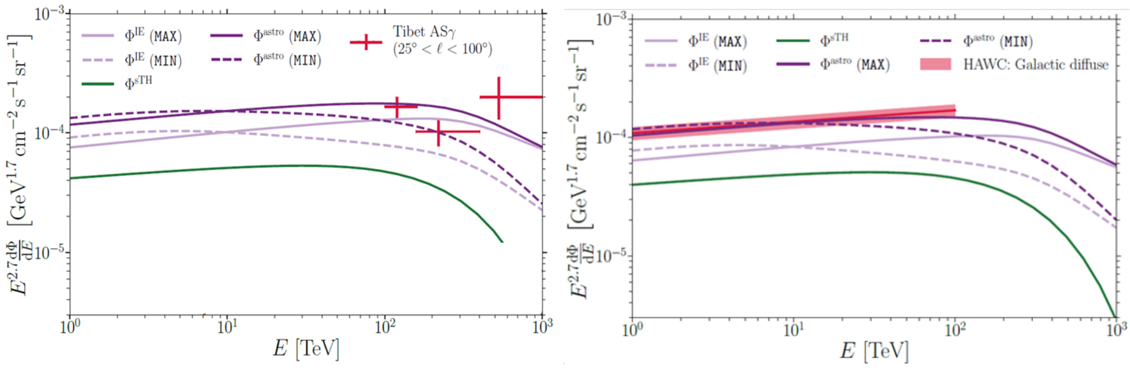

Figure 3: Figures adapted from Ref [23]. **Left panel:** Total Predicted flux from the γ-*optimized* model in the MIN and MAX setups (ϕ^{astro} in the legend - dark purple lines) including the contribution from sub-threshold sources to the TIBET experiment (ϕ^{sTH} in legend - green line) at $|b| < 5°$, $25° < l < 100°$. We also show the truly diffuse emission from the γ-*optimized* model as light purple lines (ϕ^{IE} in legend). **Right panel:** Similar to the left plot but compared to the HAWC diffuse emission at the region $|b| < 4°$, $43° < l < 73°$.

LHAASO [2] (preliminary) and ARGO-YBJ [21]. In these calculations we are accounting for absorption due to $\gamma - \gamma$ scattering as described in Ref. [9, 19]. The effect of absorption is practically negligible below the a few tens of TeV while it becomes quite relevant above 100 TeV. On top of this, we show in Fig. 3 the predicted flux from this model including the contribution from unresolved sources and compare to the TIBET and HAWC measurements of the diffuse γ-ray emission (at $|b| < 5°$, $25° < l < 100°$ and $|b| < 4°$, $43° < l < 73°$, respectively). The estimation of the flux of sub-threshold sources was done in Ref. [23]. As we see, our predictions exceptionally match these observations. The overall agreement between the predictions from our model and the data support our hypothesis that the bulk of the observed diffuse emission is originated by the interaction of the Galactic CR “sea” and not dominated by the flux of unresolved sources. 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. However, there are important uncertainties that make our conclusion to be statistically not significant yet, as those associated to cross sections of pion production ($\gtrsim$ 20% above the TeV) or the spectrum of leptons in different parts of the Galaxy (that can significantly affect the IC emission), specially at high energies. We should remark that a larger contribution from unresolved sources cannot be excluded, making the total uncertainties in modelling this diffuse contribution as large as 50% in the TeV-to-PeV region. 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.

Finally, we also show our predicted γ-ray spectrum compared to the recent LHAASO measurements [3] in the inner (left panel) and outer (right panel) regions of the sky that the collaboration reported in Fig. 4. Here, we show a band around the prediction flux from the Min and Max configurations that represent the difference in the calculated flux using the Kelner-Aharonian [24] and the AAfrag [25] cross sections. This difference provides an estimation of the cross sections uncertainties present in this energy range. The effect of the mask used by the LHAASO collaboration is taking into account through a effective scaling parameter[1]. As we can see from this figure, the

[1]We thank the LHAASO collaboration for providing these details.

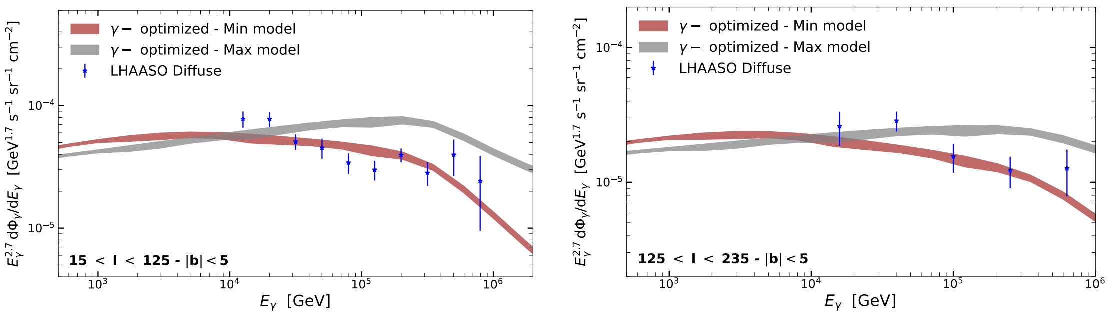

Figure 4: Predicted flux from the γ-*optimized* model in the MIN and MAX configurations compared to the recent diffuse LHAASO data [3] in the inner (left panel) and outer (right panel) regions where the collaboration report the data. The bands correspond to the difference in the flux predicted using the Kelner-Aharonian and the AAfrag cross sections (see more details in the text).

agreement between our predictions for the Min configuration and the LHAASO data is very high. Here, we do not include a prediction for the contribution of unresolved sources. Remarkably, a sub-threshold source contribution larger than $\sim$ 20% of the total LHAASO measurements would be incompatible with this data for the inner region, while a contribution of up to $\sim$ 50% of the total flux could still be consistent with the data.

Finally, we show the neutrino flux predicted by the γ-optimized model in Figs. 5 and 6. In Fig. 5 we compare the per-flavour predicted flux with the best-fit IceCube flux extracted from the KRA-γ (cutoff energy of E_c = 5 PeV) [12] and π^0 models [4]. The π^0 model was extrapolated from the diffuse model obtained by the Fermi-LAT collaboration after 21 months of operation [26] and adapted for the prediction of the neutrino flux in the Galactic plane, featuring a model with spatially-independent diffusion of CRs unlike the KRA-γ. As we see from the figure, our predictions lie in perfect agreement with the uncertainty band from the best-fit measurements of IceCube (which are those extracted from the π^0 model). This constitutes a very important proof that this kind of model explains both the γ-ray and neutrino emissions simultaneously without the need of any fine-tuning. On top of this, we emphasize that emission from sources could not be dominant below 100 TeV for this model to be compatible with IceCube observations. Neutrino data from different parts of the Galaxy will allow us to solve this puzzle.

In Figure 6 we show the predicted ν Galactic diffuse emission considering the Min and Max configurations of the γ-*optimized* scenarios and compare them with the the model-independent limits obtained from the ANTARES collaboration [27] considering 7.5 years of IceCube track-like events for the region $|l| < 40^\circ$ and $|b| < 3^\circ$ [28]. For reference we also show the prediction of the KRA$_\gamma^5$ model (cutoff energy of E_c = 5 PeV) [6]. The close similarity of KRA$_\gamma^5$ and γ-*optimized* spectral distributions imply that a possible experimental confirmation of the detection of neutrinos from the Galactic plane would basically hold also for the latter model.

3. Discussion and conclusions

In this contribution we have reported the main results of recent computations of the diffuse γ-ray and neutrino emission of the Galaxy as described from a model of inhomogeneous transport of

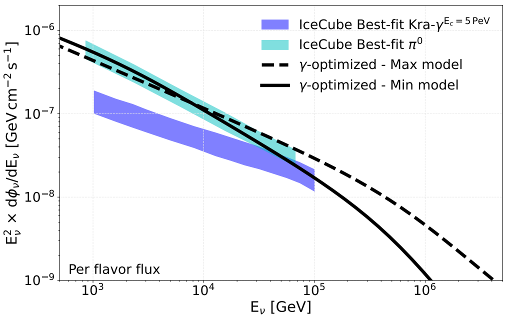

Figure 5: Predicted full-sky ν diffuse emission (per flavor) from the γ-*optimized* model compared to the best-fit IceCube flux extracted from the KRA-γ (cutoff energy of $E_c = 5$ PeV) and π^0 models.

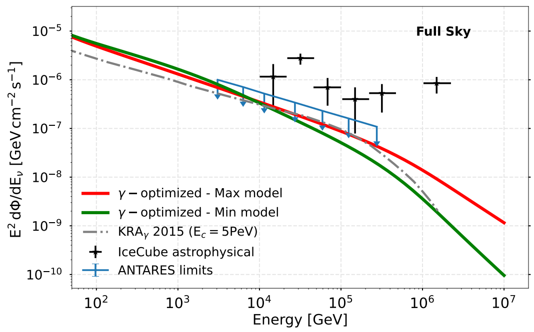

Figure 6: All-sky diffuse ν spectrum from the γ-*optimized* scenario and KRA$_\gamma$ model (cutoff energy of $E_c = 5$ PeV) compared to ANTARES upper limits and IceCube astrophysical ν data.

charged particles in the Galaxy. We have 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 so, we showed the main results obtained from the γ-*optimized* scenario described considering two configurations of the CR injection spectra in order to bracket the systematic uncertainty on the CR data above 1 PeV. We conclude that the predictions from our model are consistent with all γ-ray data reported up to date, covering different parts of the Galaxy and a broad energy range. In particular, the agreement between our predictions and the LHAASO data seems quite significant and favour further an scenario where diffusion is not homogeneous across the Galactic plane.

Concerning neutrinos, we showed that, for these models, the expected diffuse emission along the Galactic plane is significantly larger than expected for conventional (spatial independent CR transport) scenarios. We find again a very good agreement between the predictions from the γ-optimized model with the recent IceCube data. This may indicate that both observed "excesses" are originated because our naive modelling of the propagation of CRs in the Galaxy.

In conclusion, we have demonstrated that the model of inhomogeneous transport of CR particles in the Galaxy tuned to reproduce the hardening towards the center of the Galaxy observe at tens of GeV in the Fermi data automatically reproduce simultaneously, and without any fine-tuning, the very recent LHAASO and IceCube measurements with a high level of precision.

References

[1] M. Amenomori *et al.* (Tibet ASgamma), PRL **126**, 141101 (2021), arXiv:2104.05181 .

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

[3] Z. Cao *et al.*, “Measurement of ultra-high-energy diffuse gamma-ray emission of the galactic plane from 10 tev to 1 pev with lhaaso-km2a,” (2023), arXiv:2305.05372 [astro-ph.HE] .

[4] IceCube, Science **380**, 1338 (2023), https://www.science.org/doi/pdf/10.1126/science.adc9818 .

[5] M. Ackermann *et al.* (Fermi-LAT), Astrophys. J. **750**, 3 (2012), arXiv:1202.4039 .

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

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

[8] C. Evoli *et al.*, JCAP **2018**, 006 (2018), arXiv:1711.09616 .

[9] A. Dundovic *et al.*, Astron. Astrophys. **653**, A18 (2021), arXiv:2105.13165 .

[10] P. D. l. T. Luque *et al.*, Astron. Astrophys. **672**, A58 (2023), arXiv:2203.15759 [astro-ph.HE] .

[11] P. De la Torre Luque and others., Front. Astron. Space Sci. **9**, 1041838 (2022), arXiv:2209.10011 [astro-ph.HE] .

[12] D. Gaggero, A. Urbano, M. Valli, and P. Ullio, PRD **91**, 083012 (2015), arXiv:1411.7623 .

[13] P. Lipari and S. Vernetto, Phys. Rev. D **98**, 043003 (2018), arXiv:1804.10116 .

[14] S. S. Cerri *et al.*, JCAP **2017**, 019 (2017), arXiv:1707.07694 .

[15] Y. Génolini *et al.*, Phys. Rev. D **99**, 123028 (2019), arXiv:1904.08917 .

[16] P. D. L. T. Luque *et al.*, JCAP **07**, 010 (2021), arXiv:2102.13238 [astro-ph.HE] .

[17] P. D. L. T. Luque, JCAP **11**, 018 (2021), arXiv:2107.06863 [astro-ph.HE] .

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

[19] P. De la Torre Luque *et al.*, JCAP **07**, 008 (2022), arXiv:2202.03559 .

[20] F. Acero *et al.* (Fermi-LAT), Astrophys. J. Suppl. **223**, 26 (2016), arXiv:1602.07246 .

[21] B. Bartoli *et al.* (ARGO-YBJ), Astrophys. J. **806**, 20 (2015), arXiv:1507.06758 .

[22] C. Steppa and K. Egberts, Astronomy & Astrophysics **643**, A137 (2020).

[23] C. Eckner and F. Calore, Phys. Rev. D **106**, 083020 (2022).

[24] S. R. Kelner and F. A. Aharonian, Phys. Rev. D **78**, 034013 (2008).

[25] M. Kachelriess, I. Moskalenko, and S. Ostapchenko, Computer Physics Communications **245**, 106846 (2019).

[26] M. Ackermann *et al.*, The Astrophysical Journal **750**, 3 (2012).

[27] S. Adrian-Martinez *et al.* (ANTARES), Phys. Lett. B **760**, 143 (2016), arXiv:1602.03036 .

[28] R. Abbasi *et al.* (IceCube), Phys. Rev. D **104**, 022002 (2021), arXiv:2011.03545 .