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DOI
10.1088/2041-8205/815/2/L25

Publication date
2015

Document Version
Final published version

Published in
Astrophysical Journal Letters

The Astrophysical Journal Letters, 815:L25 (5pp), 2015 December 20 doi:10.1088/2041-8205/815/2/L25

THE GAMMA-RAY AND NEUTRINO SKY: A CONSISTENT PICTURE OF *FERMI*-LAT, MILAGRO, AND ICECUBE RESULTS

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Received 2015 November 2; accepted 2015 November 27; published 2015 December 16

ABSTRACT

We compute the γ-ray and neutrino diffuse emission of the Galaxy on the basis of a recently proposed phenomenological model characterized by radially dependent cosmic-ray (CR) transport properties. We show how this model, designed to reproduce both *Fermi*-LAT γ-ray data and local CR observables, naturally reproduces the anomalous TeV diffuse emission observed by Milagro in the inner Galactic plane. Above 100 TeV our picture predicts a neutrino flux that is about five (two) times larger than the neutrino flux computed with conventional models in the Galactic Center region (full-sky). Explaining in that way up to $\sim$25% of the flux measured by IceCube, we reproduce the full-sky IceCube spectrum adding an extra-Galactic component derived from the muonic neutrinos flux in the northern hemisphere. We also present precise predictions for the Galactic plane region where the flux is dominated by the Galactic emission.

Key words: cosmic rays – gamma rays: galaxies – neutrinos

1. INTRODUCTION

In recent years the IceCube collaboration has opened the era of neutrino astronomy and announced the detection of 37 extraterrestrial neutrinos above $\sim$30 TeV (Aartsen et al. 2013a, 2013b, 2014). More recently, a preliminary analysis (Aartsen et al. 2015c), based on four years of data, rose the total number of high-energy starting events (HESE) to 54.

The astrophysical spectrum inferred by IceCube on the basis on the three-year data set was fitted by a power law with index $\Gamma = -2.3 \pm 0.3$ above 60 TeV (Aartsen et al. 2014), while the four-year data favor a steeper spectrum: $\Gamma = -2.58 \pm 0.25$ (Aartsen et al. 2015c). Although a statistically significant departure from isotropy cannot be claimed yet, a recent analysis (Ahlers et al. 2015) showed that the angular distribution of HESE events allows up to 50% of the full-sky astrophysical flux to have a Galactic origin. Moreover, a hint of a harder spectrum in the northern hemisphere may be suggested by a recent analysis (Aartsen et al. 2015b).

The Galaxy, indeed, is a guaranteed source of neutrinos up to a fraction of PeV energies at least.

A sizable flux may either come from freshly accelerated cosmic rays (CRs) undergoing hadronic scattering with gas clumps, or from the hadronic interactions between the Galactic CR sea and the diffuse gas.

The former scenario, however, cannot explain the steepness of the neutrino spectrum measured by IceCube and is in tension with the *Fermi*-LAT upper limit on the corresponding γ-ray emission (Tchernin et al. 2013).

In the latter, instead, if the local CR spectrum is assumed to be representative of the entire Galactic population, the computed spectrum should be significantly lower than the measured spectrum (Stecker 1979; Berezinsky et al. 1993; Evoli et al. 2007; see also Ahlers et al. 2015: the authors show that only $\simeq$8% of the HESE can be accounted in that way, under the conventional assumption that the same CR transport properties hold throughout the whole Galaxy).

However, it is conceivable that CR diffusion—due to stronger star-forming activity and peculiar magnetic field strength/geometry—behaves differently in the inner Galactic region. Several anomalies observed in the γ-ray diffuse emission support this possibility.

We start by noting that conventional models cannot explain the large γ-ray flux measured by the Milagro observatory from the inner GP region at 15 TeV median energy (Prodanović et al. 2007; Abdo et al. 2008). In Figure 1 we show how a representative conventional model, with similar spectral properties as the *Fermi* benchmark model (Ackermann et al. 2012), clearly fails to reproduce that measurement. This problem is common to all the models of this kind and still holds assuming—as done in Ahlers et al. (2015)—that the spectral hardening found by PAMELA in the CR proton and helium spectra above $\sim$230 GeV/n (Adriani et al. 2013) is present throughout the whole Galaxy. Therefore, the Milagro excess is still an open issue, and indeed its possible relevance for high-energy neutrino physics has often been pointed out (see, e.g., Gabici et al. 2008; Taylor et al. 2014).

An even more serious anomaly was found at lower energies in the *Fermi*-LAT diffuse γ-ray spectrum (Ackermann et al. 2012): the conventional models systematically underestimate the measured flux in the inner GP region above a few GeV. A new phenomenological scenario was proposed in (Gaggero et al. 2014) in order to account for the latter results: the idea is to consider a radial dependence for both the rigidity scaling index δ of the diffusion coefficient and the advective wind.

In this Letter we present for the first time a consistent picture based on that scenario that aims to overcome all of the aforementioned problems.

The most significant achievements we present are:

1. A natural explanation to the long-standing Milagro anomaly;
2. A new prediction of the Galactic neutrino diffuse emission that is significantly larger than the one computed with conventional models; and

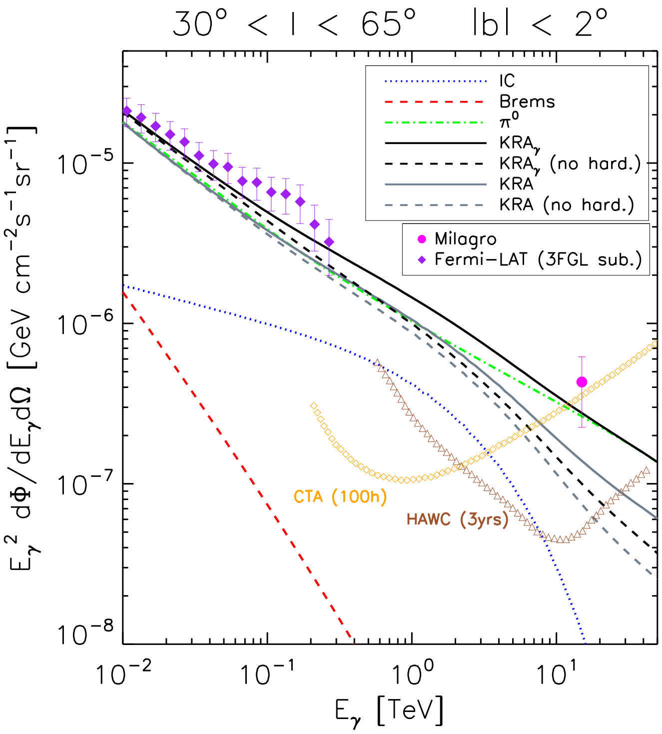

Figure 1. Diffuse emission γ-ray spectrum from the inner Galactic plane ($|b| < 2°$, $30° < l < 65°$) computed for the reference models considered in this Letter compared with *Fermi*-LAT and Milagro data. The Milagro differential flux reported here is 17% lower with respect to the flux reported in 2008 (Abdo et al. 2008) due to the assumption of a spectral index of 2.4 instead of 2.7 (P. Huentemeyer 2015, private communication). The expected sensitivities of HAWC (Abeysekara et al. 2013) and CTA (Actis et al. 2011) are reported. The spectral components are shown for the KRA$_\gamma$ model only. The *Fermi*-LAT data points refer to 5 years of data, within the event class ULTRACLEAN, according to *Fermi* tools v9r32p5.

3. A possible interpretation for the hints of an excess of IceCube events along the Galactic plane and of the different neutrino slope in the northern and southern hemispheres.

2. THE MODEL

Following (Gaggero et al. 2014), the starting point is a conventional propagation setup characterized by $\delta = 0.5$,[5] compatible with a Kraichnan spectrum of the interstellar turbulence within the quasi-linear theory framework. We will refer to this setup as the "KRA model" (see also Evoli et al. 2011).

The new model presented in that paper features δ increasing with the galactocentric radius R (implying spatially variable CR transport as originally suggested, e.g., in Erlykin & Wolfendale 2013), and hence predicts a hardening of CR propagated spectrum and γ-ray emissivity in the inner Galaxy.

The following explains the model in more detail.

1. δ has the galactocentric radial dependence $\delta(R) = AR + B$ for $R < 11$ kpc, where $A = 0.035$ kpc^{-1} and $B = 0.21$ so that $\delta(R_\odot) = 0.5$. This behavior may have different physical interpretations, e.g., a smooth transition between a dominant parallel escape along the poloidal component of the regular Galactic magnetic field (in the inner Galaxy, where δ is lower) and a perpendicular escape with respect to the regular field lying in the plane (in the outer Galaxy, where the scaling is steeper).
2. An advective wind for $R < 6.5$ kpc with velocity $V_C(z)\hat{z}$ (z is the distance from the GP) vanishing at $z = 0$ and growing as $dV_c/dz = 100$ km s^{-1} kpc^{-1} is also included. This ingredient is motivated by the X-ray *ROSAT* observations Snowden et al. (1997).
3. The vertical dependence of the diffusion coefficient is taken as $D(z) \propto \exp(z/z_t)$;
4. The halo size is $z_t = 4$ kpc for all values of R (this is a conventional choice widely used in the literature, and we checked that our results do not change significantly considering larger values of z_t).

The observed γ-ray spectra at both low and mid Galactic latitudes, including the Galactic center, are reproduced by this model without spoiling local CR observables: proton, antiproton, and Helium spectra, B/C and ^{10}Be/^{9}Be ratios. Moreover, this scenario naturally accounts for the radial dependence in the CR spectrum found by the Fermi collaboration (Casandjian & Fermi-LAT Collaboration 2015). We will refer to this model as "KRA$_\gamma$" since it is tuned on gamma-ray data.

We implement the setup with DRAGON, a numerical code designed to compute the propagation of all CR species (Evoli et al. 2008; DRAGON-web 2015). While the current version of the code shares with GALPROP (GALPROP-web 2015) the same spallation cross-section routines and gas distribution, its innovative structure allows us to compute CR transport in the general framework of position-dependent diffusion.

Concerning the p and He spectral hardening inferred from PAMELA (Adriani et al. 2011)—recently confirmed by AMS-02 (Aguilar et al. 2015)—and CREAM (Ahn et al. 2010) data above ~250 GeV/n, we consider two alternatives. (1) *Local hardening* could originate from nearby supernova remnants (see, e.g., Thoudam & Hörandel 2013); since this is a stochastic effect and averages out on large scales it amounts to not introducing any feature in the Galactic CR population used in this work. (2) *Global hardening* could originate from a spectral feature in the rigidity dependence of CR source spectra or the diffusion coefficient (here we only consider the former case, as both scenarios have the same effect on the γ-ray diffuse emission). In both cases we assume that above 250 GeV/n the CR source spectra extend steadily up to an exponential cutoff at the energy E_{cut}/nucleon.

We consider two representative values of this quantity, namely $E_{cut} = 5$ and 50 PeV which—for the KRA$_\gamma$ setup—match CREAM p and He data and roughly bracket KASCADE (Antoni et al. 2005) and KASCADE-Grande data (Apel 2013). While KASCADE proton data favor the lowest cutoff, the highest is favored by the KASCADE-grande all-particle spectrum. A more detailed fit of the CR spectra in the PeV region is not justified here due to the large experimental uncertainties on the elemental spectral shapes and normalizations. The consequent uncertainty on the neutrino flux should, however, be captured by our choice to consider a range of cutoffs.

3. THE γ-RAY SPECTRUM

As shown in Gaggero et al. (2014), the KRA$_\gamma$ setup—both in its *local* (KRA$_\gamma$ with no hardening) and *global* realizations—

[5] δ is defined by $D(\rho) \propto (\rho/\rho_0)^\delta$.

provides a good fit of the γ-ray diffuse emission measured by *Fermi*-LAT all over the sky, particularly toward the inner GP region. Moreover, it accounts for the galactocentric radial dependence of the CR spectral index found by the *Fermi*-LAT collaboration (Casandjian & Fermi-LAT Collaboration 2015).

Here we extend the computation performed in (Gaggero et al. 2014) above the TeV.

Similar to (Gaggero et al. 2014), we compute the hadronic emission integrating the expression of the γ-ray emissivity along the line of sight using `GammaSky`, a dedicated code used (Evoli et al. 2012; Cirelli et al. 2014) to simulate diffuse γ-ray maps. This package features, among other options, the gas maps included in the public version of `GALPROP` (Moskalenko et al. 2002; Ackermann et al. 2012; GALPROP-web 2015). We adopt the emissivities given in Kamae et al. (2006), accounting for the energy dependence of the *pp* inelastic cross-section (significant above the TeV). We disregard γ-ray opacity due to the interstellar radiation field, since it is negligible up to a few tens of TeV (Ahlers & Murase 2014).

Our results are shown in Figure 1. As mentioned above, a representative conventional model (KRA) cannot account for the flux measured by Milagro from the inner GP at 15 TeV even if accounting for the CR spectral hardening required to match the PAMELA and CREAM data. The KRA$_\gamma$ setup, instead, is more successful, especially if a global hardening is assumed. This is a remarkable result since: (1) it supports the KRA$_\gamma$ model in a higher-energy regime; (2) it provides the first consistent interpretation of Milagro and *Fermi*-LAT results (an *optimized* model was proposed to account for the EGRET GeV excess Strong et al. (2004), and came out to reproduce Milagro results as well, but was subsequently excluded by *Fermi*-LAT Abdo et al. 2009), and (3) it reinforces the arguments in favor of a non-local origin of the hardening in the CR spectra above 250 GeV.

Interestingly, the KRA$_\gamma$ model also reproduces the high-energy diffuse γ-ray spectrum measured by H.E.S.S. in the Galactic ridge region ($|l| < 0\overset{\circ}{.}8$, $|b| < 0\overset{\circ}{.}3$) in terms of CR scattering with the dense gas in the central molecular zone without the need to invoke the contribution of sources to that region (Aharonian et al. 2006) and without further tuning (see Gaggero et al. 2015 for more details). Although this is a very small region with respect to the regions considered in this paper, this result may be interpreted as a valuable check of our model in a region not covered by Milagro.

Moreover, our KRA$_\gamma$ model is also compatible with ARGO-YBJ results in the window $65° < l < 85°$ and $|b| < 5°$; both the KRA and the KRA$_\gamma$ are consistent with CASA-MIA measurements at high Galactic longitudes (Borione et al. 1998).

4. THE NEUTRINO EMISSION

The results discussed above clearly show that the hadronic emission computed with the KRA$_\gamma$ setup above the TeV is significantly stronger than the conventional model predictions, In this section we show the relevant consequences concerning the Galactic neutrino emission.

We first compute the ν_e and ν_μ production spectra: for both flavors we use the emissivities provided in Kamae et al. (2006; well-tuned on accelerator and CR data) for projectile energies below ~500 TeV, while we adopt the emmisivities provided in Kelner et al. (2006) that are above that energy range. Then we account for neutrino oscillations: their effect is to almost equally redistribute the composition among the three flavors

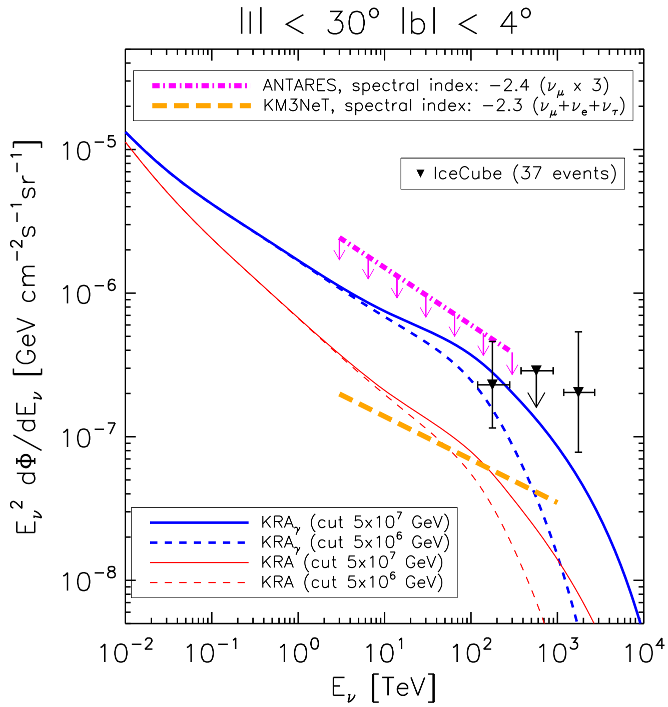

Figure 2. Solid and dashed red (blue) lines: expected neutrino spectra (all flavors, both neutrinos and antineutrinos) in the inner Galactic plane region computed for the conventional KRA (the novel KRA$_\gamma$) models for two different cutoff values. We also show the maximal flux, estimated considering three years of IceCube HESE events as described in Spurio (2014) and the constraint from the ANTARES experiment (Fusco & ANTARES Collaboration 2015; 1500 days of experiment livetime between 2007 and 2013), as well as the deduced sensitivity of the future Mediterranean observatory KM3NeT (Piattelli & KM3NeT Collaboration 2015b) with four years (~1500 days) of livetime.

(Cavasinni et al. 2006). We only consider proton and helium CRs/gas—just as for γ-rays—since heavier nuclear species give a negligible contribution in the energy range we cover in this work (Kachelriess & Ostapchenko 2014).

Because neutrinos in the Galactic emission are expected to be maximal in the inner Galactic plane region, we first present our results for the windows $|l| < 30°$ and $|b| < 4°$. For this region the ANTARES collaboration (Aguilar et al. 2011) recently released an upper limit on the muon neutrino flux based on the result of an unblinding analysis regarding the events collected between 2007 and 2013 in the energy range $[3 \div 300]$ TeV (Fusco & ANTARES Collaboration 2015).

In Figure 2 we compare the ν_μ flux computed with the KRA and KRA$_\gamma$ setups with the flux of the experimental constraint. First of all we notice the large enhancement (almost a factor of 5 at 100 TeV) obtained with the KRA$_\gamma$ model with respect to the conventional scenario. Indeed, while—in agreement with previous results—we find that the flux corresponding to the KRA model may require long times of observation even by the KM3NeT observatory (Adrián-Martínez et al. 2013), our prediction for the KRA$_\gamma$ model is instead well above the sensitivity reachable by that experiment in four years and it is almost within the ANTARES observation capabilities.

Interestingly, our result is in good agreement with the maximal flux inferred from the fraction of IceCube HESE events compatible with that region (see Figure 3). We notice that in that region the expected EG contribution, as constrained from the muon neutrino flux in the northern hemisphere (see

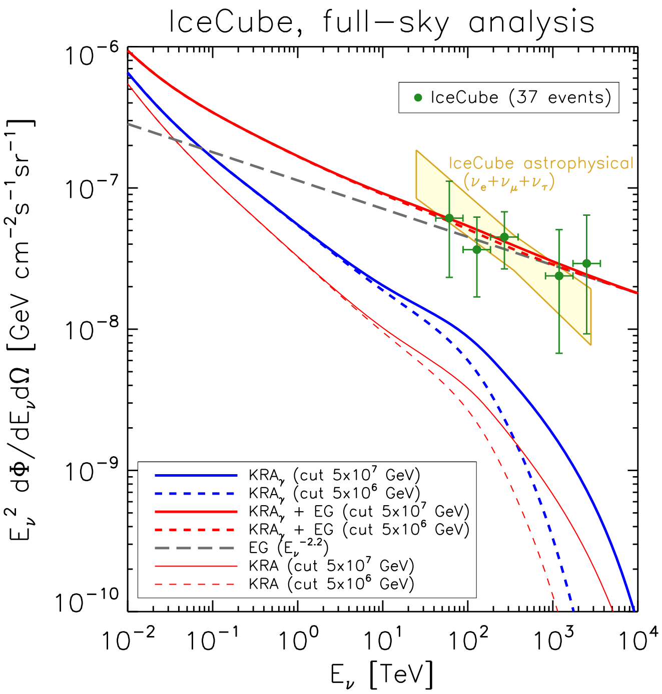

Figure 3. Full-sky neutrino spectrum (all flavors, both neutrinos and antineutrinos) predicted by the KRA$_\gamma$ and KRA models (with global CR hardening), adopting two different choices for the CR high-energy cutoff. We also plot the combination of the Galactic (KRA$_\gamma$) and a benchmark EG spectrum. The EG flux is consistent with that inferred from the IceCube collaboration in the northern hemisphere (Aartsen et al. 2015b). The models are compared with the 68% confidence region for the IceCube astrophysical neutrino flux obtained with a maximum-likelihood (yellow region; Aartsen et al. 2015a) and the three-year HESE sample (green points; Aartsen et al. 2014).

below) gives a subdominant contribution with respect to that computed with the KRA$_\gamma$ model. Therefore the possible detection of a signal in that sky window would be a smoking gun for the presence of such Galactic emission.

IceCube should also have the potential to detect that emission on a larger region. In this context, we also note that an independent analysis (Neronov & Semikoz 2015b) already found a significant hint of an excess in the 4-year HESE sample (Aartsen et al. 2015c) along the Galactic plane.

We now turn our attention to the recently published IceCube results, both concerning the full-sky and the northern and southern hemispheres separately.

In Figure 3 we represent the full-sky total neutrino spectrum (all flavors, including antiparticles) computed for the KRA$_\gamma$ and KRA models, with global CR hardening, and compare it to the IceCube results.

Our prediction for the conventional setup (KRA model) is in good agreement with Ahlers et al. (2015): in that work, the benchmark Galactic model accounts for 8% of the flux measured by IceCube above 60 TeV, for a CR spectrum similar to the one used here above 50 PeV.

On the other hand, the KRA$_\gamma$ predicts a $\sim$2 times larger full-sky flux above 10 TeV: the model prediction is therefore only $\simeq$4 times smaller than the best fit of the astrophysical flux measured by IceCube on the whole sky.

We remark that another analysis (Neronov & Semikoz 2015a), based on an extrapolation of *Fermi*-LAT data, points toward a non-negligible Galactic contribution to the full-sky neutrino flux due to a hard diffuse CR spectrum. In that scenario the (softer) locally observed CR spectrum may get a major contribution from one or more local sources: this interpretation still has to be validated against *Fermi*-LAT data, while our model is based on those measurements.

Setting a threshold energy at 60 TeV and convolving the KRA$_\gamma$ spectrum (with $E_{\rm cut} = 50$ PeV) with the IceCube HESE effective areas (Aartsen et al. 2013a), the expected number of neutrino events in three years of IceCube observation represents $\sim$15% of the published sample (Aartsen et al. 2014). These rates are well above those expected due to atmospheric muons and atmospheric neutrinos and confirm the spectral comparison between KRA$_\gamma$ and IceCube data.

Clearly, another component—most likely of extragalactic (EG) origin—needs to be invoked in order to account for all of the IceCube events.

Here we assume this EG component to be isotropic and use the astrophysical muon neutrino IceCube measurements from the northern hemisphere (Aartsen et al. 2015b)—where the Galactic emission is only $\sim 1/10$ of the total flux—to probe its spectral properties. Although the northern spectral slope is statistically compatible with the full-sky one, given the hint of a steeper spectrum in the southern hemisphere, it is interesting to check if the combination of our Galactic prediction and the EG flux inferred from the aforementioned muon neutrino measurement provide a better agreement with the data.

For illustrative purposes, in Figure 3 we show the effect of adding an isotropic EG emission to the Galactic neutrino emission computed with the KRA$_\gamma$ model, with a spectrum given by the IceCube best fit of $\Phi_{\nu_\mu}^{\rm North}$, multiplied by three to account for all flavors. The nature of such emission is still under debate: as pointed out in Glüsenkamp & IceCube Collaboration (2015) and Bechtol et al. (2015), neither blazars nor star-forming galaxies can provide more than a subdominant contribution, given the constraints imposed by the gamma-ray extragalactic background inferred from *Fermi*-LAT data. The plot clearly shows how the KRA$_\gamma$ helps to improve the fit in the low-energy part of the IceCube spectrum.

We also checked that the neutrino flux computed with the KRA$_\gamma$ model for $|b| < 7\overset{\circ}{.}5$ is in rather good agreement with that inferred from IceCube HESE analysis if the EG emission, as estimated above, is accounted for. A dedicated analysis will be performed in a forthcoming work.

5. CONCLUSIONS

In this Letter we connected γ-ray GeV and TeV measurements in a unified scenario, together with the recently released IceCube neutrino data, providing a consistent picture based on a CR transport model proposed in Gaggero et al. (2014). The model features a variation of the diffusion coefficient rigidity, scaling δ with the galactocentric radius. The variation was suggested by a spectral anomaly found in the *Fermi*-LAT γ-ray data, and turned out to be compatible with both γ-ray spectra at low and intermediate Galactic latitude and local CR observables.

In this work we showed that our picture sheds new light on recent high-energy gamma-ray and neutrino observations. In particular, it provides a novel natural explanation for the anomalous γ-ray flux measured by the Milagro observatory from the inner GP region at 15 TeV; moreover, it appears to be compatible with the H.E.S.S. spectrum in the Galactic ridge region.

Remarkably, our model also provides a different interpretation of the full-sky neutrino spectrum measured by IceCube with respect to the standard lore, since it predicts a larger contribution of the Galactic neutrinos to the total flux, compared to conventional models.

These predictions will be testable in the near future by neutrino observatories such as ANTARES, KM3NeT, and IceCube itself via dedicated analyses that are focused on the Galactic plane, and also by analyzing the different spectral slopes in the northern and southern hemispheres. A hint of a softer slope in the northern hemisphere is already present, and appears to be compatible with our picture.

A physical interpretation of our model most likely requires either abandoning the isotropic diffusion scenario generally adopted to treat CR propagation, or considering different turbulence regimes in different regions of the Galaxy: a quantitative modeling of those phenomena is far beyond the scope of our phenomenological work.

We are indebted to Carmelo Evoli, Piero Ullio, Andrii Neronov, Petra Huentemeyer, Markus Ahlers, Maurizio Spurio, Luigi Fusco, and Rosa Coniglione for many inspiring discussions and useful advice.

D. Gaggero acknowledges the SFB 676 research fellowship from the University of Hamburg as well as the hospitality of DESY. A. Marinelli acknowledges the Galilei research fellowship of Pisa University. The work of A.U. is supported by the ERC Advanced Grant n° 267985, “Electroweak Symmetry Breaking, Flavour and Dark Matter: One Solution for Three Mysteries” (DaMeSyFla).

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