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Galactic diffuse gamma rays meet the PeV frontier

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The Tibet ASγ experiment recently reported the observation of a diffuse gamma-ray emission from the Galactic plane with energy up to the PeV. This finding seems to be confirmed by LHAASO preliminary results. Both measurements provide the first evidence of a diffuse gamma-ray emission throughout the Galaxy up to such high energies. These results have relevant implications for neutrino astronomy since they strengthen the expectation that a neutrino diffuse emission from the Galactic plane could soon be discovered by IceCube and KM3NeT. To explore this possibility we use physically motivated numerical models which reasonably describe the observed gamma-ray diffuse emission angular distribution and spectral energy distribution from few GeV up to the PeV under the hypothesis that this emission is mostly originated by the cosmic ray population of the Galaxy. We will discuss the possible detectability of the associated neutrino emission and the valuable implications it may have for understanding the origin and propagation of cosmic rays.

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (Gamma2022)
4-8 July 2022
Barcelona, Spain

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PoS(Gamma2022)035

1. Gamma-ray diffuse emission 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, 2]. Although gamma-ray emission from unresolved sources may be significant, 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, 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.

Neutrinos should also provide complementary insights into these problems. Indeed, since the emission detected by Tibet ASγ and LHAASO is likely to be produced by hadronic processes mostly, a diffuse Galactic ν emission is also expected at those energies (see *e.g.* [3] 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 [4], which may soon be strengthened. The interpretation of 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` numerical code [5, 6] – to model CR transport – in combination with the recently released `HERMES` [7] – 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 use the `DRAGON2` code to account for 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 [8, 9] and motivated theoretically in [10].

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 [5, 6]. 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 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:

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

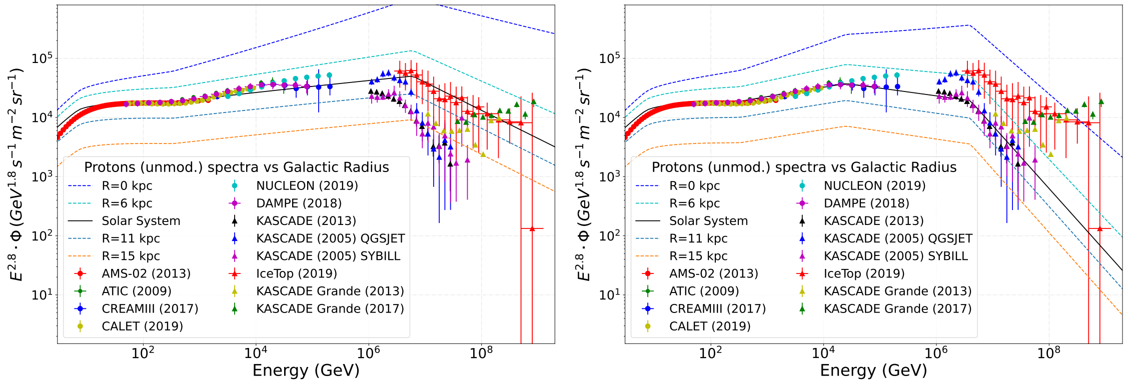

Figure 1: Proton spectra predicted from the γ-*optimized* scenario for the Max (left panel) and Min (right panel) configurations, from 10 GeV to 10^9 GeV, at different galactocentric radii. Available local CR data from AMS-02, ATIC, CREAM, CALET, NUCLEON, DAMPE, KASCADE, KASCADE Grande and IceTop are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

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 [11–13] of AMS-02 results [14] 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 the γ-optimized model. As shown in [15, 16] for the γ-*optimized* setup Fermi-LAT [17] data and ARGO-YBJ [18] 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 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 would 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 distributions 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. The contribution of unresolved sources was computed adopting the

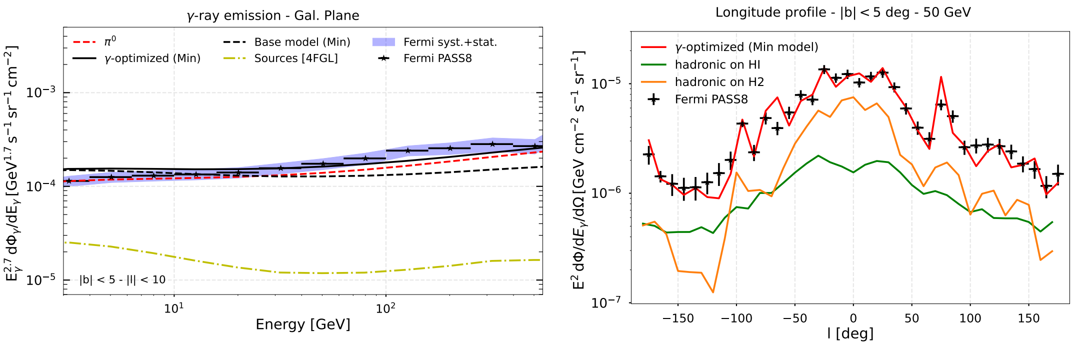

Figure 2: Left panel: Comparison of Fermi-LAT diffuse emission with the predictions obtained from the γ-*optimized* and *Base* models, for the Min configuration, at a window of coordinates $|b| < 5°$, $|l| < 10°$. We also show the π^0 contribution and the contribution from sources. **Right panel:** Longitude 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)

models presented in Ref. [19] to the Fermi-LAT instrument. For more details, we refer the readers to Refs. [15, 20]. As expected, the γ-*optimized* model reproduces much better Fermi data close to the Galactic Centre ($|b| < 5$ $|l| < 10$). 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).

Then our main goal consisted of expanding our predictions for the γ-ray flux up to PeV energies, and compare them with the recently published data by Tibet ASγ [1], LHAASO [2] (preliminary) and ARGO-YBJ [18]. These results are presented in Fig. 3. We are accounting for absorption due to $\gamma - \gamma$ scattering as described in Ref. [7, 16]. Its effect is practically negligible below the 100 TeV while just above that energy it is around 10%. We emphasize that in this figure we are not adding the contribution from unresolved sources (since it depends on each different instrument), that becomes relevant at high energies. 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.

However, there are important uncertainties that make our conclusion to be statistically not significant, 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 ($\sim 5 - 10$% above the TeV), specially at high energies. In addition, 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.

Besides offering a firm signature of its hadronic nature, the possible detection of the diffuse neutrino emission of the Galaxy would allow us to probe regions of the GP closer to the Galactic

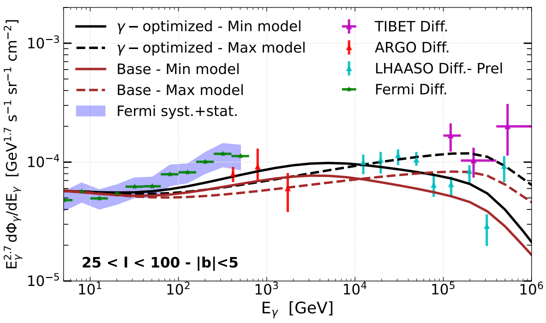

Figure 3: γ-ray diffuse spectrum from the γ-*optimized* scenario compared to the KRA$_\gamma$ model (cutoff energy of $E_c = 5$ PeV) and the available data in the window $|b| < 5°$, $25° < l < 100°$.

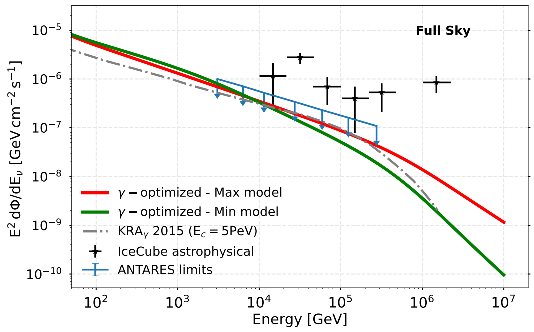

Figure 4: All-sky diffuse ν spectrum from the γ-*optimized* scenario and KRA$_\gamma$ model (cutoff energy of $E_c = 5$ PeV) compared to ANTARES upper limits and IceCube astrophysical ν data.

centre. 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 the model-independent limits obtained from the ANTARES collaboration [21] considering 7.5 years of IceCube track-like events for the region $|l| < 40°$ and $|b| < 3°$ [22]. For reference we also show the prediction of the KRA$_\gamma^5$ model (cutoff energy of $E_c = 5$ PeV) [3] 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 [4]. 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.

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 charged particles in 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 concerns high-energy γ rays the 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.

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