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Gamma Rays and Neutrinos from the Galactic Plane at the PeV frontier

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Abstract. 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 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.

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[1] Speaker

1. Introduction

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]. This 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 valuable probe of the Galactic CR population at energies well beyond the *knee* of the CR spectrum and well beyond the Solar System neighborhoods. Such an achievement may allow, for example, to get a hint of the origin of those energetic particle and to determine if the *knee* is produced by the acceleration process or it is a transport effect. Moreover – since due to spallation losses at those energies CR reaching the Earth must be originated within few kpc's – it may allow us 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 corresponding 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 (see the claim of 4.1 σ excess obtained in a recent external analysis of IceCube track events [5]).

The interpretation of those measurements needs likelihood analyses comparing the observed γ-ray and ν spectral and angular distributions to simulated templates of the diffuse γ-ray and ν diffuse emissions of the Galaxy. Those simulations require advanced numerical packages to treat with CR transport and interactions and accurate models of the interstellar gas distributions.

In this contribution we will present the results obtained with the `DRAGON2` numerical code [7, 8] – to model CR transport – in combination with the recently released `HERMES` [9] – to produce simulated spectra and maps of the γ and ν diffuse emissions. `DRAGON2` is built to model CR transport under very general conditions. In particular, it allows 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 [11, 13] and motivated theoretically in [14].

We will then be able to compare the predictions of conventional models – assuming space-independent CR propagation – as well as those of spatial dependent γ-*optimized* ones with a wide set of γ and ν available data and to discuss the implications of our findings.

2. The 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. The hadronic component of the γ-ray diffuse emission and the corresponding neutrino emission are produced by the interaction of those CR with the interstella gas. Our gas model consists of a set of column density maps in (l, b) Galactic coordinates for atomic and molecular gas, associated to Galactocentric rings. The atomic gas model is based on the 21-cm line emission data observed by the recent HI4PI survey that covers the whole sky with a 1/12 degree binning [15]. As far as molecular gas is concerned, the decomposition is based on the observations of the CO rotational line at 115 GHz from the CfA survey as discussed in [16].

For a given source spectrum – generally a 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. This quantity is generally assumed to be a single power law function of the particle rigidity with a spatially dependent slope which is parameterized as follows:

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

where D_0 is its normalization at a reference rigidity $\rho_0 = 4\,\mathrm{GV}$. The index δ, *a priori* being poorly known, is inferred from comparing the code predictions with the measured secondary to primary CR flux ratios, the boron-to-carbon (B/C) ratio being the most common. Works based on multi-channel analysis [18, 19] of AMS-02 results [20] found that at the Solar System $\delta(R_\odot) \simeq 0.5$.

In the following we will consider two realizations of these setups: the *Base* one, which is representative of the conventional scenario where δ is independent on R, and the γ-optimized or spatial dependent (factorized spatial-energy dependence) one. As shown in [21, 23] for the γ-optimized setup Fermi-LAT [10] data and ARGO-YBJ [22] 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 $\delta(R) = \delta(R_\odot)$ for $R \geq R_\odot$ which , again, gives $\delta(R_\odot) \simeq 0.5$.

In order to model the γ-ray and ν diffuse emission at larger energies we account for a wide set of CR data in 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). In fact, these measurements suffer for large systematic errors, mostly associated with modeling hadronic interaction within the Earth atmosphere. Therefore, in order to bracket that uncertainty 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 the left panels show our predictions for the Max injection spectra setup while the right panels show the predicted spectra for the Min one.

3. Results

We compute the full-sky maps of the γ-ray diffuse emission as well as the corresponding neutrino emission with the `HERMES` code [9] feeding it with the CR galactic populations simulated with `DRAGON 2` [7, 8] for the models discussed in the above.

3.1. Gamma-rays

For γ-rays the results are presented in Fig. 2. The absorption due to $\gamma-\gamma$ scattering is accounted as described in [9, 23]. Its effect is practically negligible below the 100 TeV while just above that energy it is around 10%.

In Fig. 2 we show the predicted spectra of the γ-ray diffuse emissions with several data set in two sky windows along the GP. First of all 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 capturing 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.

Wondering which among those models provide the best description of the data we are hampered by the scatter in the experimental points above few tens of TeV and the consequent

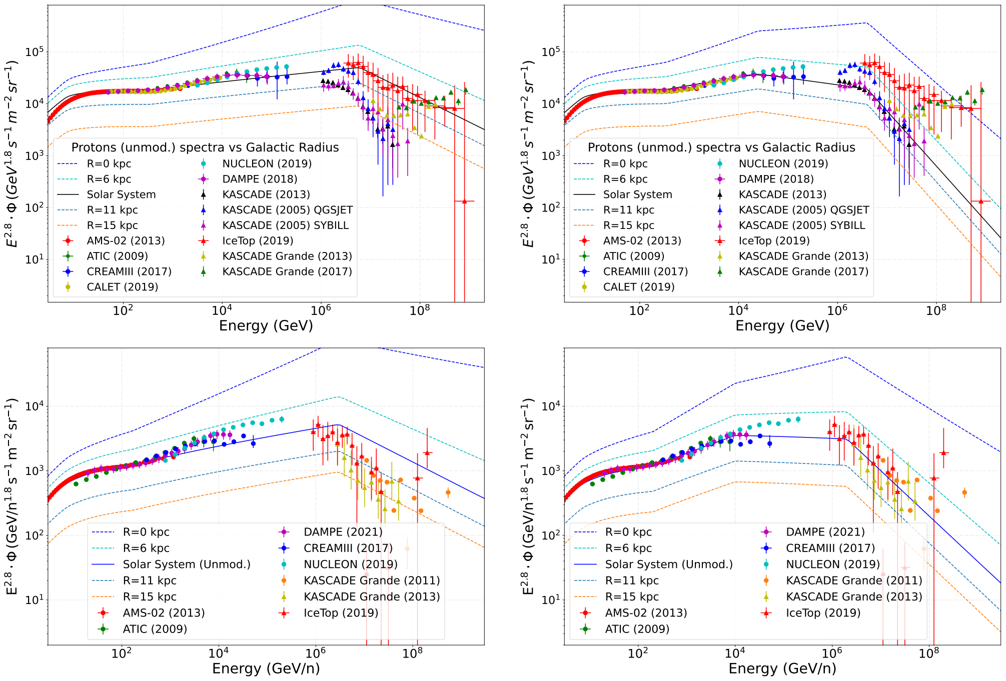

Figure 1. Spectra of protons (upper panels) and helium (lower panels) of the γ-*optimized* scenario for the Max (left panels) and Min (right panels) configurations, from 10 GeV to 10^9 GeV. Since in the γ-*optimized* scenario the propagation of CRs depends on the distance from the galactic center, we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

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) 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. Interestingly, as evident from the right panel of Fig. 2, the same model is also favored by the spectrum measured by Tibet-ASγ in the $50^\circ < l < 200^\circ$, $|b| < 5^\circ$ window where the dependence on the choice of the transport scenario is less critical. Although Tibet-ASγ data points are slightly above that model one should take in mind that a contamination due to the Cygnus cocoon (see [1]) is likely to explain that excess.

We adopt the γ-ray production cross-section described in [28] (based on SYBILL) with the updated parameterization of the proton–proton total inelastic cross-section reported in [29]. The results obtained with these cross sections have been also compared to the γ-ray emissivities extracted from the `AAfrag` package [30] finding a maximum 20% difference in normalization and a negligible impact on the slope in the energy range of interest for this work.

A further uncertainty may arise however from a larger than expected contribution of unresolved sources. Although our models try to account for them extrapolating the predictions of the model discussed in [24], a larger emission 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.

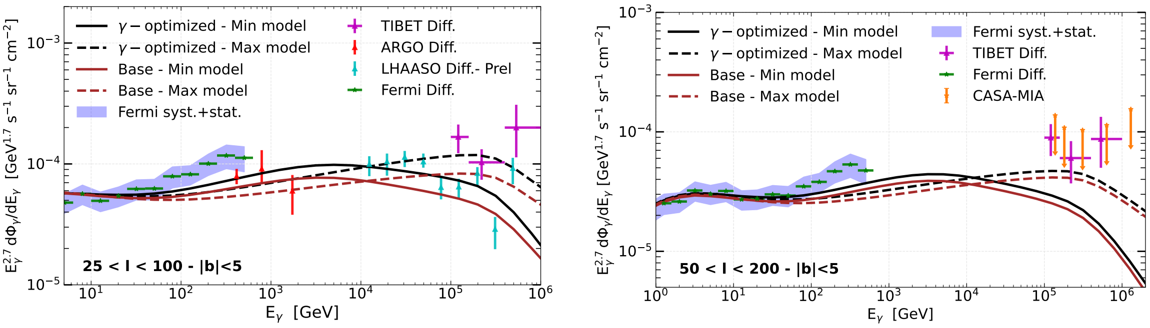

Figure 2. γ-ray diffuse spectra from the γ-optimized scenario compared to Tibet ASγ [1], LHAASO [2] (preliminary), Fermi-LAT [25] (CLEAN events from PASS8 data with subtraction of flux from known sources and isotropic background) and ARGO-YBJ [22] data in the window $|b| < 5°$, $25° < l < 100°$. Here, we account for absorption of γ-rays into CMB photons (see Fig. 7 of Ref. [17]) and do not include the contribution of unresolved sources.

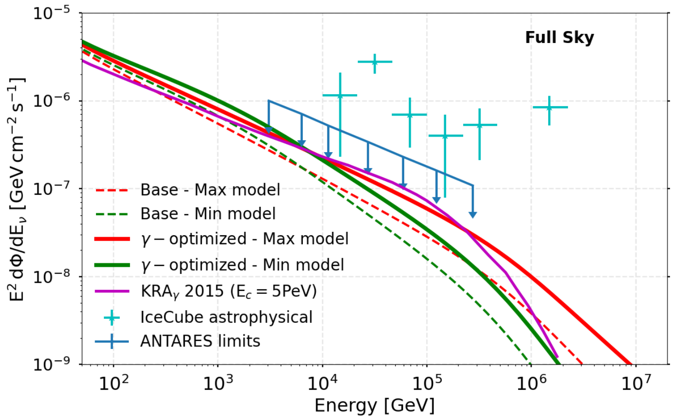

Figure 3. Full sky ν diffuse emission predicted for the Base and γ-*optimized* models (Min and Max configurations) compared to the model-independent upper limits obtained from the ANTARES collaboration. The predicted galactic ν flux from the KRA$_\gamma$ model (cutoff energy of $E_c = 5$ PeV) [3] is also reported. In addition, the IceCube astrophysical ν flux as measured from IceCube using 7.5 years of track events [26] are added for completeness.

3.2. Neutrinos

Besides offering a firm signature of its hadronic nature, the possible detection of the diffuse neutrino emission from the Galaxy would allow us to probe a region of the GP closer to the Galactic center than presently accessible to γ-ray observatories. As we discussed in the 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 3 we show the predicted ν Galactic diffuse emission considering the Min and Max configurations of the Base and γ-optimized scenarios and compare them with the the model-independent limits obtained from the ANTARES collaboration [27] considering six years of track-like events for the region $|l| < 40°$ and $|b| < 3°$.

While all models are compatible with those upper limits, it is evident as in that region the emission expected for the γ-optimized models is significantly higher – hence not far from its possible detectability – than predicted with the conventional Base models. For reference we also show the prediction of the KRA_γ^5 model [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_γ^5 and γ-*optimized* Max spectral distributions imply that a possible experimental confirmation of that hint would basically hold also for the latter model.

4. Conclusions

In this contribution we have reported the main results of some recent computations of the diffuse γ-ray and neutrino emission of the Galaxy originated by its CR population.

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 considered two different CR transport scenarios as well as two different shapes of the source spectra trying to bracket the systematic uncertainty on the CR data above 10 TeV. We showed that, though for what concern high energy γ-rays those uncertainties do not allow us to firmly nail the correct transport scenario yet, Tibet-ASγ and preliminary LHAASO results favor a spatial dependent (so called γ-optimized) CR transport scenario which is in agreement to what required to match Fermi-LAT data at lower Galactic longitudes as well.

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 it in the next future.

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