

# Constraining very high energy gamma-ray and neutrino diffuse emission

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We calculate the very-high-energy diffuse flux of neutrinos produced by the hadronic interactions of cosmic rays (CR) with the gas contained in the Galactic disk. We compare our results with recent neutrino observational data in the TeV energy range. Namely, we perform a comparison of our predictions with the recent hint for a Galactic neutrino component obtained by ANTARES and the new IceCube measurement of a neutrino diffuse emission from the Galactic disk. We take advantage of recent source population studies to evaluate the contamination of sources to observational determinations of neutrino diffuse emission. By comparing our expectations with IceCube measurement, we constrain the fraction of Galactic TeV gamma-ray sources (resolved and unresolved) with hadronic nature. We finally discuss the constraints that can be obtained on the CR spatial and energy distribution and, hence, on the gamma-ray and neutrino diffuse emission.

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## 1. Introduction

In recent times, many experiments measured the Galactic large-scale diffuse emission both in neutrinos and  $\gamma$ -rays above TeV energies. The Tibet-AS $\gamma$  experiment has provided the first measurement of this component in  $\gamma$ -ray in the sub-PeV energy range [1], followed by LHAASO-KM2A [2]. Moreover, neutrino telescopes have finally reached the required sensitivity to probe TeV neutrino production in our Galaxy. Indeed, the ANTARES collaboration has reported the first possible hint of neutrino emission from the Galactic ridge in the angular region  $|l| < 30^{\circ}$  and  $|b| < 2^{\circ}$  and in the 1 – 100 TeV energy band [3]. The Galactic neutrino component is being detected by the IceCube collaboration at 4.5 $\sigma$  level significance [4].

A guaranteed contribution to the Galactic  $\gamma$ -ray and neutrino signal is provided by diffuse cosmic rays (CRs) interacting with the interstellar medium (ISM). In addition, to this diffuse emission,  $\gamma$ -rays, and neutrinos can also be produced by CRs collisions within or close to their acceleration sites. In the  $\gamma$ -ray sky, only a fraction of Galactic sources are resolved by current detectors. The remaining, faint, sources produce a signal below the detection threshold that contribute to the measured large-scale diffuse emission. These unresolved  $\gamma$ -ray sources have a relevant role in the interpretation of  $\gamma$ -ray data. In particular, the presence of an unresolved source component at  $\sim 10$  GeV summed to the truly diffuse emission can change the spectral shape of the large-scale diffuse emission observed by Fermi-LAT, mimicking a CRs spectral hardening in the inner Galaxy [5]. At very high energy, the presence of the additional diffuse component due to unresolved sources seems needed to obtain a good agreement with the Tibet AS $\gamma$  data [6]. All of this suggests that sources could give a non-negligible contribution also to neutrino measurements. Indeed, in the neutrino sky, all the Galactic sources are currently unresolved. The relevance of this component depends on the hadronic or leptonic nature of the  $\gamma$ -ray sources. Hadronic processes produce a roughly equal number of charged and neutral pions which decay to neutrinos and  $\gamma$  rays, respectively, assuring a strong correlation between the neutrino and  $\gamma$ -ray sky. This correlation, always valid for the truly diffuse emission, fails for the "sources" component if they have a leptonic nature.

In this work, we describe the Galactic neutrino signal considering both the truly diffuse and source component by using a multi-messenger approach. The comparison with observations allows us to constrain the CR spatial and energy distribution and the fraction of Galactic TeV  $\gamma$ -ray sources (resolved and unresolved) with hadronic nature.

## 2. The total Galactic neutrino signal

The observed neutrino signal can be parameterized as:

$$\varphi_{\nu, \text{ tot}} \left( E_{\nu} \right) = \varphi_{\nu, \text{ diff}} \left( E_{\nu} \right) + \varphi_{\nu, s} \left( E_{\nu}; E_{\text{cut}}, \xi \right)$$
(1)

where  $\varphi_{\nu, \text{ diff}}$  represents the truly diffuse emission produced by CR interactions with the ISM and  $\varphi_{\nu,s}$  represents the cumulative contribution produced by sources.

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### 2.1 Neutrino diffuse emission

The neutrino diffuse flux is calculated following the approach of [7]. The differential one-flavor neutrino flux is parametrized as:

$$\varphi_{\nu,\text{diff}}(E_{\nu},\hat{n}_{\nu}) = \frac{1}{3} \sum_{l=e,\mu,\tau} \int_{E_{\nu}}^{\infty} dE \; \frac{d\sigma_{l}(E,E_{\nu})}{dE_{\nu}} \int_{0}^{\infty} dl \; \varphi_{CR}(E,r_{\odot}+l\hat{n}_{\nu}) \, n_{\text{H}}(r_{\odot}+l\hat{n}_{\nu}) \tag{2}$$

where  $E_{\nu}$  and  $\hat{n}_{\nu}$  indicate respectively the neutrino energy and arrival direction, while  $\frac{d\sigma_{l}(E,E_{\nu})}{dE_{\nu}}$  represents the differential cross section for the production of neutrino and antineutrino with flavor l by a nucleon of energy E in a nucleon-nucleon collision. In Eq. 2, the neutrino flux at Earth is assumed to be equally distributed among the different flavors due to neutrino mixing. In order to compute the diffuse neutrino emission, we need to know the nucleon-nucleon cross-section, the number density of target nucleons  $n_{\rm H}(\mathbf{r})$  contained in the gas, and the differential CR flux  $\varphi_{CR}(E, \mathbf{r})$  as a function of the energy and position in the Galaxy. For the parametrization of the cross-section, we use [8]. The gas distribution is taken from the GALPROP code [9] and includes the contributions from atomic H and molecular H<sub>2</sub> hydrogen. The heavy element contribution is taken into account by assuming that the total mass of the ISM is a factor 1.42 larger than the mass of hydrogen. The CR flux can be written as the product of three terms:

$$\varphi_{\rm CR}(E,\mathbf{r}) = \varphi_{\rm CR,\odot}(E) g(\mathbf{r}) h(E,\mathbf{r})$$
(3)

In the above formula,  $\varphi_{CR,\odot}(E)$  represents the local nucleon flux that is described according to the data-driven parameterization provided in [10]. The function g(r) describes the spatial distribution of CRs and is an adimensional function (normalized to one at the Sun position  $\mathbf{r}_{\odot} = 8.5$  kpc). It is obtained as the solution of a 3D isotropic diffusion equation with constant diffusion coefficient and stationary CR injection  $f_{\rm S}(\mathbf{r})$  that is assumed to follow the SNR number density parameterization given by [11]. The solution depends on the diffusion length R, for which we assume two extreme values, R = 1 kpc, and  $R = \infty$ . In the first case, CRs are confined close to their sources, and the spatial distribution resembles the SNRs one [11], while in the second case, the obtained spatial distribution is very close to that predicted by the GALPROP code. The function  $h(E, \mathbf{r})$  introduces the possibility that the CR spectral index is position-dependent as was inferred from analysis of the Fermi-LAT data (see e.g. [12]). It is defined as:

$$h(E, \mathbf{r}) = \left(\frac{E}{\overline{E}}\right)^{\Delta(\mathbf{r})} \tag{4}$$

where  $\overline{E} = 20 \text{ GeV}$  is the pivot energy and  $\Delta(\mathbf{r}_{\odot}) = 0$ . The function  $\Delta(\mathbf{r})$  in Galactic cylindrical coordinates is modeled as  $\Delta(r, z) = \Delta_0 \left(1 - \frac{r}{r_{\odot}}\right)$  for  $r \le 10$  kpc, while it is assumed to be constant for larger distances. The factor  $\Delta_0 = 0.3$  represents the difference between CR spectral index at the Galactic center and its value at the Sun position. In the following, we refer to the calculations performed by assuming uniform CR spectral index as Case B, while we indicate with Case C the calculations performed by assuming that spectral index depends on the Galactocentric distance.

#### 2.2 Gamma-ray and neutrino sources

In order to predict the cumulative  $\gamma$ -ray source signal, we follow the approach of [13]. In particular, the source spatial and luminosity distribution is described as the product:

$$\frac{dN}{d^3 r \, dL} = \rho \left( \mathbf{r} \right) Y \left( L \right) \tag{5}$$

where **r** indicates the source position and *L* is the source  $\gamma$ -ray intrinsic luminosity integrated in the 1 – 100 TeV energy range probed by H.E.S.S.. The function  $\rho(\mathbf{r})$ , normalized to one when integrated over the entire Galaxy, is proportional to the pulsar distribution parameterized by [14] and scales as exp (-|z|/H) with H = 0.2 kpc, along the direction *z* perpendicular to the Galactic plane. The function Y(L) represents the source luminosity function and it is described by:

$$Y(L) = \frac{N}{L_{\text{Max}}} \left(\frac{L}{L_{\text{Max}}}\right)^{-\alpha}$$
(6)

in the luminosity range  $L_{\text{Min}} \leq L \leq L_{\text{Max}}$ . In the above relation,  $L_{\text{Max}}$  and N are the maximum TeV  $\gamma$ -ray luminosity of the population and the high-luminosity normalization of the luminosity function, respectively. The total TeV  $\gamma$ -ray flux produced by all the sources (resolved and unresolved) in a given observational window (OW) is calculated by using the prescription of [13]:

$$\Phi_{\gamma,S} = \frac{NF_{\text{Max}}}{4\pi(2-\alpha)} \int_{OW} d^3r \,\rho(\mathbf{r}) \,r^{-2}$$
(7)

where  $F_{\text{Max}} = L_{\text{Max}}/\langle E \rangle$  represents the maximum TeV emissivity, and  $\langle E \rangle = 3.25$  TeV is the average energy of photons emitted in the range 1 – 100 TeV obtained by assuming that all the  $\gamma$ -ray sources have a power-law spectrum with a spectral index equal to 2.3 [15]. It is relevant to notice that, the best-fit value of N is not sensible to a change in the spectral assumption while  $L_{\text{Max}}$  is shifted proportionally to the variation of  $\langle E \rangle$ . As a consequence, if the spectral assumption is changed,  $F_{\text{Max}}$  remains constant and  $\Phi_{\text{tot}}$  is unchanged. Here, we use the best-fit values  $L_{\text{TeV}, \text{Max}} = 5.1^{+3.4}_{-2.2} \times 10^{35} \text{erg s}^{-1}$  and  $N = 18^{+14}_{-7}$  derived in [13] for  $\alpha = 1.5$  by considering the sample of 32 sources in the H.E.S.S. Galactic Plane Survey (HGPS) that produce an integrated flux in the energy range 1-100 TeV above the H.E.S.S. completeness threshold  $\Phi_{\text{th}} = 2.26 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ .

### 2.2.1 Total neutrino source flux

The neutrino source flux is obtained from the  $\gamma$ -ray flux in the following way. We assume that the CR-injected spectrum  $\phi_p$  can be parameterized as a power law with an exponential cut-off. In our calculations, the proton spectral index is chosen as  $\Gamma_p = 2.4$  to reproduce the average spectral properties of HGPS sources while the proton cutoff energy varies in the range  $E_{\text{cut}} = 0.5 - 10$  PeV to explore the relevance of this parameter for our final results. The all-flavor neutrino spectrum (normalized to 1 in the 1-100 TeV energy window) produced by hadronic interaction within the source is given by:

$$\phi_{\nu}(E_{\nu}; E_{\text{cut}}) = \frac{1}{K_{\nu}(E_{\text{cut}})} \sum_{l=e,\mu,\tau} \int_{E_{\nu}}^{\infty} dE \, \frac{d\sigma_l(E, E_{\nu})}{dE_{\nu}} \phi_p(E; E_{\text{cut}}) \tag{8}$$



**Figure 1:** Differential energy spectra of diffuse neutrino from the Galactic plane in the angular regions probed by ANTARES. See text for details.

where  $K_{\nu}(E_{\text{cut}})$  is the normalization constant. By using Eq. 8 and Eq. 7, we calculate the cumulative neutrino emission produced by all sources (resolved and unresolved) contained in a given OW. The all-flavor differential neutrino flux is given by:

$$\varphi_{\nu,s}\left(E_{\nu}; E_{\text{cut}}, \xi\right) = \xi \Phi_{\nu,s}^{\max}(E_{\text{cut}}) \phi_{\nu}(E_{\nu}; E_{\text{cut}}) \tag{9}$$

where  $\Phi_{\nu,s}^{\max} \equiv \frac{K_{\nu}}{K_{\gamma}} \Phi_{\gamma,s}$  represents the maximal source neutrino flux integrated into the [1, 100] TeV energy window, i.e. the neutrino source contribution obtained by assuming that all the TeV  $\gamma$ -ray sources, resolved and unresolved, are powered by hadronic processes and  $K_{\gamma}$  is the normalization constant for the  $\gamma$ -ray spectrum. Furthermore, since not all the sources produce  $\gamma$ -rays via hadronic mechanisms, we introduce the quantity  $\xi \leq 1$  that represents the fraction of the  $\gamma$ -ray source flux that is produced by hadronic interaction and, hence, is accompanied by the production of neutrinos.

## 3. Comparison with ANTARES

We show our predictions for the all-flavor Galactic neutrino flux in the OW of ANTARES in Fig. 1. The cyan and red bands correspond to the diffuse neutrino emission calculated assuming Case B (right panel) and Case C (left panel), respectively. The total flux, obtained using Eq. 1, is displayed with blue bands for two different values  $E_{cut} = 0.5$ , 10 PeV and  $\xi = 1$ . The width of cyan, red, and blue bands is related to the uncertainties in the assumed CR spatial distribution in our Galaxy. In particular, the lower limit of each band is obtained assuming  $R = \infty$ , while the upper limit is obtained assuming R = 1 kpc. The ANTARES best fit, obtained in the 1-100 TeV energy range, is shown with a magenta line. The magenta band represents the  $1\sigma$  uncertainties [3].

The predicted diffuse neutrino emission is well below the signal observed by ANTARES. In particular, in Case B, the diffuse neutrino flux at the energy  $E_{\nu} \sim 40$  TeV which is most efficiently probed by ANTARES, is a factor ~ 10-20 lower than the observed signal. Even in Case C, it is well below the ANTARES signal, being a factor ~ 3-6 lower than the best-fit flux at  $E_{\nu} \sim 40$  TeV. Hence, the ANTARES hint for a Galactic neutrino signal cannot be explained by CR diffuse emission alone and requires a dominant contribution from a population of Galactic neutrino sources. Indeed, the blue bands (diffuse + sources) are always below the ANTARES best-fit results. We recall that



**Figure 2:** Differential energy spectra of diffuse neutrino from the Galactic plane in the angular regions  $0^{\circ} < l < 360^{\circ}$  and  $|b| < 5^{\circ}$ . See text for details.

the source population considered in this study is constrained to reproduce the flux, longitude, and latitude distribution of TeV  $\gamma$ -ray emitting objects observed by HGPS. Moreover, we fixed  $\xi = 1$ , hence, all the sources are assumed to emit radiation by hadronic interactions. This assumption is rather extreme and allows us to obtain a very conservative upper bound for the neutrino source contribution. Indeed, according to our present knowledge, the TeV  $\gamma$ -ray Sky seems to be dominated by Pulsar Wind Nebulae that are mostly powered at TeV by the inverse Compton mechanism. In general, in order to have a total neutrino emission comparable to the ANTARES best-fit flux, in addition to the above hypotheses, it is also necessary to postulate that all these sources are Pevatrons, i.e., they accelerate protons at energy larger than  $\sim 1$  PeV. As a last step, we set an upper limit for the total neutrino flux from the disk of our Galaxy. The solid grey lines show the maximal predictions for the total neutrino flux that can be obtained in the considered scenarios. They are obtained by maximizing both diffuse and source components, i.e., by taking R = 1 kpc for diffuse flux calculation and,  $\xi = 1$  and  $E_{\text{cut}} = \infty$  for the primary proton source spectrum. We also show with a black point the neutrino flux obtained by converting the total  $\gamma$ -ray flux measured by the H.E.S.S. experiment at 1 TeV [16] integrated into the ANTARES OW using our spectral assumption for the CR. The total flux measured by H.E.S.S. includes the contribution from sources and diffuse emissions, and it has to be interpreted as an upper limit on the neutrino flux expected at 1 TeV. The error bar represents the systematic error on the flux that is of order 30% [15]. We see that the best-fit flux and a relevant part of the ANTARES 1 $\sigma$  region lie above the maximal allowed neutrino emission according to our calculations and/or H.E.S.S.  $\gamma$ -ray data.

## 4. Comparison with IceCube

In Fig. 2, we compare our predictions for the Galactic neutrino emission with the IceCube results. The legend is the same as in Fig.1. The IceCube Galactic signal is obtained by using a template fitting procedure where the angular and energy dependence of the neutrino flux is fixed according to three different models, namely the  $\pi_0$ , KRA<sup>5</sup><sub> $\gamma$ </sub> and KRA<sup>50</sup><sub> $\gamma$ </sub> models [17], while the overall normalization is free to vary. We show with the magenta region the maximal and minimal allowed values for the neutrino flux obtained by IceCube by using different templates (also including the 1 $\sigma$  uncertainties of the respective fits). We restrict our comparison to the angular region 0°  $\leq l \leq 360^{\circ}$ 

and  $|b| < 5^{\circ}$  where the best-fits of the Galactic neutrino component obtained for the different templates give almost the same constraints above  $\sim 50$  TeV. At lower energy, the extracted signal depends instead on the assumed neutrino spectrum. In this respect, we recall that the neutrino spectral index is assumed to be equal to 2.7 in the  $\pi_0$  model while it is close to 2.5 for the KRA<sub>y</sub> models. The IceCube signal is always below our upper limit (gray solid lines in Fig. 2). This is different from what we obtained for ANTARES [3] and suggests that the Galactic  $\gamma$ -ray source population cannot be entirely powered by hadronic mechanisms. Indeed, the diffuse emission in our Case C saturates the IceCube signal, leaving no space for any other additional contribution. The above result automatically implies that the source contribution to the observed signal should be zero or negligible compared to the CR diffuse emission, hence, either  $\xi \ll 1$  or  $E_{cut} \ll 500$  TeV. However, this request could not be easily satisfied in the context of Case C. Indeed, the CR spectral hardening in the inner Galaxy is motivated by the presence of Galactic sources able to accelerate hadrons up to few PeVs energy. For example, the KRA $^{5}_{\nu}$  model assumes that the source injection spectrum is a power law with an exponential cutoff at 5 PeV. Hence, in order to not exceed the IceCube signal, these sources should accelerate hadrons up to few PeVs but do not effectively produce neutrinos in the 1-100 TeV energy range. If we consider Case B instead, the IceCube data allows for a non-vanishing source contribution. The source contribution is required in order to produce enough neutrino to explain the IceCube signal in the most constrained energy range  $50 \le E_V \le 100$  TeV. In this regard, the minimum allowed cutoff value is  $E_{\rm cut} = 500$  TeV. The fraction  $\xi$  of TeV  $\gamma$ -ray sources that can have hadronic nature depends on the assumed proton cutoff energy and it is fixed in order to reproduce the IceCube data. For  $E_{cut} = 10 \text{ PeV}$ , the maximal fraction is  $\sim 20\%$ , corresponding to a source contribution integrated between 1 and 100 TeV that is equal to  $\Phi_{\nu,s} = 1.1 \times 10^{-10} cm^{-2} s^{-1}$ . For a smaller cutoff energy  $E_{\text{cut}} = 500 \text{ TeV}$ , we obtain  $\xi \le 40\%$ , corresponding to  $\Phi_{\nu,s} \le 2.6 \times 10^{-10} cm^{-2} s^{-1}$ .

## 5. Conclusion

We have discussed the implications of the recent measurement of high-energy neutrino emission from the Galactic disk performed by ANTARES and IceCube. In the case of ANTARES, we showed that also in the most optimistic Case C, the solely diffuse emission is not able to explain the neutrino observation. However, also including a source component, calculated under the assumption that all  $\gamma$ -ray sources have hadronic nature, the total signal is below the best-fit value. A different conclusion is reached if we consider the IceCube signal. In order to explain the IceCube result, only a fraction of the TeV-Galactic gamma-ray sources can have hadronic nature. This fraction has to be negligible if we assume that CRs diffusing in the inner Galaxy have a spectrum harder than at the Sun position, as it is e.g. assumed in the KRA $\gamma$  models or in our Case C. If we consider instead the scenario in which the CR spectrum is uniform within the Galaxy (Case B), the maximally allowed fraction is  $\xi \leq 40\%$ , for  $E_{cut} = 500$  TeV.

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