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The diffuse high-energy non-AGN neutrino emission

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The diffuse astrophysical neutrino flux measured in the very high energy range introduced unresolved issues about the origin of these events and underlined as a viable solution the multi-component scenario. Recent studies show that galaxies with high star formation rate (above teens M_{odot}/year) can be responsible of a seizable fraction of the observed astrophysical flux. Despite their low luminosity, they can be considered as guaranteed "factories" of high energy neutrinos, being "reservoirs"of accelerated cosmic rays and hosting a high density target gas in the central region. On the other hand, in the same range of energies, recent measurements of IceCube and Antares telescopes set the contribution correlated with the diffuse Galactic emission. The Milky Way is a prominent astrophysical lab to correlate the high-energy diffuse emission with the physics of cosmic-ray injection and propagation as well as with the measured molecular gas distribution. In this contribution we describe in details these two diffuse astrophysical components and we show that the associated non-AGN diffuse neutrino flux can represent a sizeable portion of the flux observed by high-energy neutrino telescopes.

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1. Introduction

The observation of the Seyfert galaxy NGC1068 [1] and following searches for X-ray bright Seyfert objects from the IceCube experiment [2] over its entire data taking period underline that this kind of sources can potentially represent the major candidate do describe the IceCube astrophysical neutrino observed till date. The hadronic emission from this class of sources is expected to occurs in the vicinity of the supermassive black holes, which imply the absence of a TeV γ-ray counterpart due to the attenuation expected in a high radiation density environment. Under this assumption a potential neutrino emission from that kind of sources is not expected to be associated with a very-high-energy γ-ray counterpart. In this respect the Disk-corona scenario proposed in the recent years predict neutrino emission from Seyfert galaxies to correlate with keV X-rays which can be used as tracers of the coronal activity. On the other hand other recent studies [3] show that when integrating over larger redshifts Galaxies who did not necessary host a AGN, therefore gamma-ray faint, but more abundant like the Starburst galaxies can account for a large portion of the IceCube diffuse astrophysical flux. SFGs and SBGs are galaxies endowed with an intense star-forming activity, and therefore they have a particularly high gas density ($n_{ISM} \propto 10 - 100cm^{-3}$), strong magnetic fields ($B \sim 10^2 \mu G$), and supernova explosion rates of the order of $(0.01 - 1yr)$ [4]. For these reasons, they are supposed to exhibit strong turbulence which should be able to trap high-energy cosmic-rays inside their environment, giving them an enhanced probability to produce high-energy neutrinos and gamma-rays through hadronic collisions [5].

With that assumptions the hadronic production of such class of sources is strongly limited by the gamma-ray luminosity observed from the close by ones since no strong gamma-ray absorption is expected by internal absorption contrarily to the Seyfert hot corona model description, making the expected flux of the two VHE messengers more tight to each other.

In this work we consider a recently published data driven scenario [3] which uses 15.3 years of Fermi-LAT data considering the γ-ray between 1 and 1000 GeV data for 70 sources, 56 of which were not previously detected. In that work the measured γ-ray emission is related to a theoretical model for SBGs [5] in order to constrain Fcal for each source and it is computed its correlation with the star formation rate of the sources. A additional “reservoir” contribution that we consider in this work is our Galactic diffuse emission which has been confirmed recently by the IceCube collaboration to be a sizeable signal in the TeV-PeV neutrino sky [6]. Here we use the description of this component obtained with a significant update of the KRA_γ models, carried out in [7, 8], where the injection spectrum was re-evaluated using the most recent CR data available as well as Fermi-LAT data. Two alternative source spectral shapes (Min and Max) arre considered for the CR protons and helium nuclei in order to bracket the uncertainty in the PeV region, where the different datasets provided by KASCADE [9] differ significantly from those by IceTop [10] and, more recently, by LHAASO [11]. Finally we present the sum of these two "non-AGN" SED components averaging the expected flux in a full sky observation showing that they can account for most of the diffuse astrophysical neutrino observation of IceCube at teens of TeV. This scenario is in tension with recent statements of the IceCube collaboration which associate this part of the measured neutrino SED with the diffuse AGN (Seyfert-like) emission.

2. Extragalactic reservois

As mentioned in the introduction the diffuse contribution obtained by [3] follows the gamma-ray emission from SBGs taking into account the latest Fermi-LAT data which have been collected in sky-survey mode from August 2008 and November 2023, from a Mission Elapsed Time 239557417 s to 720724699 s, with a total lifetime of $\sim$15.3 years. Photons in the energy range $1-1000\,\mathrm{GeV}$, have been selected, which strongly reduces the possibility of mis-identification of sources due to a limited PSF dimension of $\sim 10^\circ$ at lower energies. In [3] are considered events belonging to `P8R3_v3` version of the Pass 8 photon dataset and the corresponding `P8R3_SOURCE_V3` instrument response functions.
Since photons produced by hadronic interactions usually carry 10% of the parent energy of CRs, the γ-ray spectra are expected to inherit the properties of the CR distribution inside the sources. In order to assess such implications, [3] uses a model describing the non-thermal emission of the sources. The CR transport inside the core of SBGs is described under the leaky-box model equation by a balance among different competing processes: the injection term of the sources such as SNRs, the escape phenomena (advection and diffusion) and the energy-loss mechanism such as hadronic collisions:

$$\frac{N_{\mathrm{CR}} E}{\tau_{\mathrm{esc}}} \quad \frac{\mathrm{d}}{\mathrm{dE}} \left[\frac{\mathrm{d}E}{\mathrm{d}t} \cdot N_{\mathrm{CR}} E \right] \quad QE \tag{1}$$

where $\mathrm{d}E\mathrm{d}t \;\; -E\tau_{\mathrm{loss}}$, with τ_{loss} being the energy-loss timescale, τ_{esc} is the escape timescale, and QE is the injection spectrum of SNRs. The injected spectrum to be a power-law with a $E_{\mathrm{max}} \;\; 10\,\mathrm{PeV}$ exponential cut-off consistent with other results present in the literature [12, 13]. The solution to Eq. 1 is approximated as [14]

$$N_{\mathrm{CR}} E \quad \frac{\tau_{\mathrm{tot}} E}{E} \, {}^{\infty}_{E}\, QE' \mathrm{d}E' \simeq \frac{\tau_{\mathrm{tot}} E \, QE}{\gamma - 1} \tag{2}$$

where $\tau_{\mathrm{tot}} \;\; \tau_{\mathrm{loss}}^{-1} \; \tau_{\mathrm{esc}}^{-1\,-1}$ and the last passage holds for $QE \propto E^{-\gamma}$. For SBGs, pp interactions should be the dominant CR energy-loss mechanism, therefore, $\tau_{\mathrm{loss}} = \tau_{\mathrm{pp}}$. In turn, the escape timescale is given by the competition between CR advection and diffusion phenomena. While it is expected that their relative contribution to change across the whole SFR range $10^{-2} - 10^{3}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ [15], these timescales are strongly model-dependent as well as dependent on the assumption for their scaling relation with the SFR. Indeed, although Refs. [5, 12, 16] have shown advection to be important as escape phenomenon for SFGs and SBGs, Refs. [17] have argued that advection should be suppressed in interstellar medium (ISM) ambient in SBGs, proposing a major role played by diffusion phenomena. Considering that the Fermi-LAT data can hardly disentangle between these scenarios, in [3] the authors introduce an overall parameter-F_{cal}- defined as

$$N_{\mathrm{CR}} E \;\; F_{\mathrm{cal}} \cdot \frac{\tau_{\mathrm{loss}}}{E} \, {}^{\infty}_{E}\, QE' \mathrm{d}E' \simeq \frac{F_{\mathrm{cal}} \, \tau_{\mathrm{loss}} \, QE}{\gamma - 1} \tag{3}$$

in order to test if the γ-ray measurements might be interpreted in terms of star-forming activity. F_{cal} is defined between 0 and 1 and it can be interpreted as an average fraction of CRs between $10 \leq E_{\mathrm{CR}}\mathrm{GeV} \leq 10^4$ actually losing their energy onto pp collisions producing γ-rays and neutrinos. A very small F_{cal} value would correspond to a very strict constraint on the ability to confine high-energy protons by the source. F_{cal} can be expressed as

$$F_{\rm cal} \quad \frac{\tau_{\rm esc}}{\tau_{\rm loss}}\left(\frac{\tau_{\rm esc}}{\tau_{\rm loss}} \quad 1\right)^{-1} \tag{4}$$

A constant $F_{\rm cal}$ is estimated directly from the γ-ray data [3] for each source without any assumption on the magnetic field, gas density, wind velocity and energy dependence of the diffusion coefficients.
In [3] the authors probe the following relation between $F_{\rm cal}$ and the supernovae rate $R_{\rm SN}$

$$F_{\rm cal} \quad A\left(\frac{R_{\rm SN}}{\rm yr^{-1}}\right)^{\beta}\left(1 \quad A\left(\frac{R_{\rm SN}}{\rm yr^{-1}}\right)^{\beta}\right)^{-1} \tag{5}$$

with A and β free parameters to be deduced from data. This allow to obtain the hadronic contribution from the SGB observed in the Fermi-LAT data sample and therefore to compute the corresponding neutrino flux expected at earth. The evaluated calorimetric fraction of local SFGs and SBGs are then used to constrain the diffuse non-thermal emission of the entire source population. The diffuse emission, per solid angle, is given by

$$\begin{aligned}\phi^{\rm diff}_{\gamma,\nu} \quad & \frac{c}{4\pi H_0} \, {}^{z_{\rm max}}_{0} \, \frac{{\rm d}z}{Ez} \, {}^{\infty}_{10^6 L_\odot} \, \frac{{\rm d}L_{\rm IR}}{\ln 10\, L_{\rm IR}} \mathscr{S}_{\rm SFR} L_{\rm IR}, z \\ & \times Q_{\gamma,\nu}\left(E 1 \; z, {\rm R_{SN} L_{IR}}, {\rm F_{cal} R_{SN} L_{IR}}\right) e^{-\tau_{\gamma,\nu} E, z, L_{\rm IR}}\end{aligned} \tag{6}$$

where z is the redshift, $Ez \quad \sqrt{\Omega_M 1 \; z^3 \; \Omega_\Lambda}$, $\mathscr{S}_{\rm SFR} L_{\rm IR}, z$ is the density of the sources as a function of the infrared luminosity, $Q_{\gamma,\nu}$ are the γ and neutrino production rate for each source, and $\tau_\nu \quad 0$ and $\tau_\gamma E, z, L_{\rm IR}$ accounts for the CMB+EBL absorption of photons as well as for internal absorption phenomena [18]. In Eq. 6 the autors use $L_{\rm IR} \quad 10^6 L_\odot$ as a lower limit for the infrared luminosity corresponding at SFR $\sim 4 \cdot 10^{-3} M_\odot\,{\rm yr}^{-1}$ and $10^{10} L_\odot \sim 1 M_\odot\,{\rm yr}^{-1}$ as a upper one. For the density of the sources, they use the approach described by [19], who have recently updated the distribution of the cosmic SFR using also JWST data.
Figure 1 shows the final γ-ray (in dark red colour) and neutrino (in cyan colour) fluxes for the combined fit of all the SBGs considered. The global spectral index distribution (blending scenario) is provided by a superposition of Gaussian distributions with mean values equal to the best-fit spectral index for discovered sources and with standard deviation equal to their corresponding uncertainty (for the spectral index blending flux calculation, they consider the same technique as in [12]). In this approach, the injected spectral index follows a continous distribution which allows also for spectral indexes lower than 2. The theoretical predictions are compared with the Isotropic Gamma-Ray Background (IGRB) measured by Fermi-LAT [20], the 6-year cascade neutrino flux [21] and 7.5-year HESE data [22] measured by the IceCube neutrino Observatory. The fluxes are dominated by distant sources with a contribution peaking at $z \simeq 1$.

3. Diffuse Milky Way emission

In this analysis we use the results obtained in [7, 8, 23] to describe the diffuse Galactic neutrino emission expectations, in that works the authors introduced two classes of models for the γ-ray diffuse emission: the "Base" and "γ-optimized" models, a development of the "Conventional" and

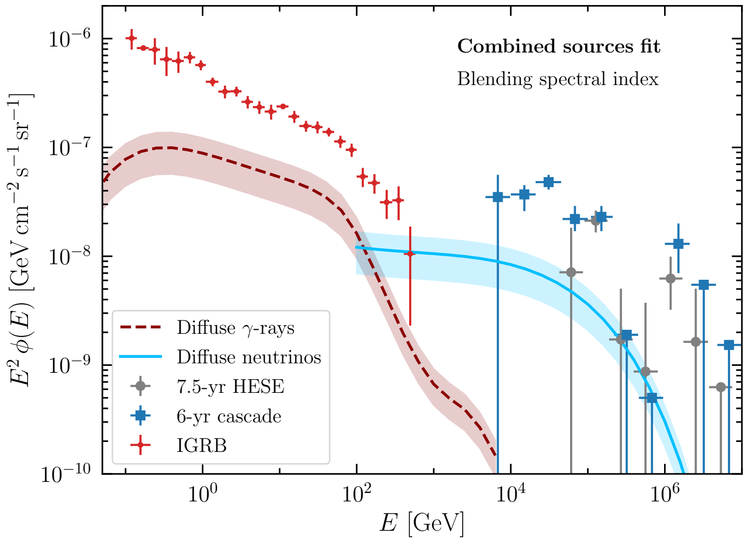

Figure 1: Diffuse 2σ γ-ray (dark red) and neutrino (cyan) bands predicted with the fit over discovered sources. The spectral index blending of Fermi-LAT discovered SBG is applied. The fluxes are compared with the Isotropic Gamma-Ray Background (IGRB) measured by Fermi-LAT [20], the 6 year Cascade neutrino flux [21] and 7.5 year HESE data [22] measured by the IceCube neutrino Observatory.

"KRA$_\gamma$" models.
Both scenarios are based on numerical solutions of the transport equation performed with the `DRAGON2` code [24], a widely used public tool to compute the energy and spatial distribution of charged CR data in any point of the Galaxy[1]. In both models, the normalization of the CR fluxes is set by local data, and the local transport properties are tuned on secondary-to-primary ratios. However, while the Base model is characterized by homogeneous diffusion along the Galactic plane (as often assumed in large-scale propagation setups), the γ-optimized model features a radial-dependent diffusion setup. The latter is largely supported by several analyses of Fermi-LAT data performed over more than a decade, adopting a variety of statistical methods [25, 26]. The remarkable phenomenological consequences of these models in the context of multi-messenger multi-TeV astronomy – both regarding the whole Galactic plane and specific extended regions – have also been pointed out in a variety of papers [27–29].

The γ-optimized models provide an improved treatment upon KRA$_\gamma$ models first introduced in [26] and feature updated gas maps, more accurate CR propagation setup (as detailed in [7]), and improved tuning on a wide range of locally measured charged CR data in the whole energy range available, from the GeV to the PeV domain.

In [23] the injection of CRs is assumed to follow a broken power-law behaviour, a functional form that allows to correctly reproduce the spectral features observed by several CR experiments (see for instance Sec. 3 of Ref. [7]). The normalization of the spectrum is spatial dependent and follows the spatial distribution of supernova remnants as modeled in [30]. The slopes are instead

[1] `https://github.com/cosmicrays/`

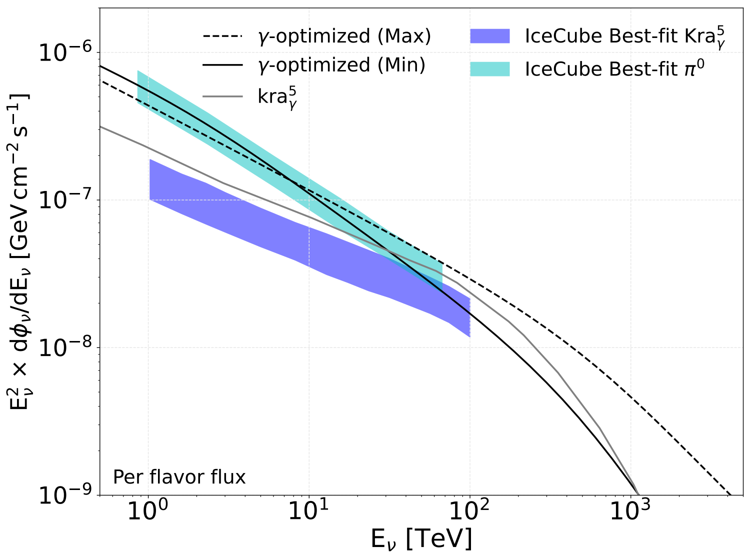

Figure 2: Predicted full-sky ν diffuse emission (per flavor) from the γ-*optimized* model compared to the best-fit IceCube flux extracted from the KRA-γ (cutoff energy of E_c 5 PeV) and π^0 models. The predicted flux from the KRA-γ^5 model is also reported as a grey line, for comparison.

considered uniform, since SNRs (and other classes of Galactic accelerators) are typically expected to provide a similar injection independently of their position in the Galaxy.

In that study the authors did not account for CR species heavier than helium since, under reasonable conditions, their contribution to the γ-ray emission is subdominant (less than 10%) with respect to that due to protons plus helium [31]

One of the main discrepancies in the very-high-energy domain ($E \gtrsim 100$ TeV) is the significant difference between the proton spectrum measured by KASCADE [9] and KASCADE-Grande [32], and that measured by IceTop [10] and, more recently, by LHAASO air-shower experiments on the other hand. This discrepancy turns into a factor of (at least) a few uncertainty in the predicted TeV-PeV diffuse γ-ray and neutrino emissions. In [23] the authors consider two alternative setups, one reproducing KASCADE + KASCADE-Grande, as well as CALET and DAMPE at lower energies (what we call "Min" setup) and another one following the measurements by IceTop (the "Max" setup). which allows us to bracket the uncertainties in the predicted secondary emissions. The neutrino spectra and angular distributions of the ν are obtained with the `HERMES` code [33]. The details about the interstellar gas distribution used can be found in [7]. Moreover that the predictions of the hadronic diffuse emission that we show here were already available in Refs. [7, 8]. In figure 2 it is reported the obtained neutrino flux considering the "Min" and "Max" full sky averaged in comparison with the previous KRA-γ^5 and the best fit flux obtained by IceCube for the KRA-γ^5 and the π^0 template analysis [6].

4. The total neutrino "reservoir" component, discussion and conclusions

After the introduction of the two separate neutrino diffuse components, which constitute a sizable portion of the IceCube diffuse astrophysical flux, in this section we finally report the

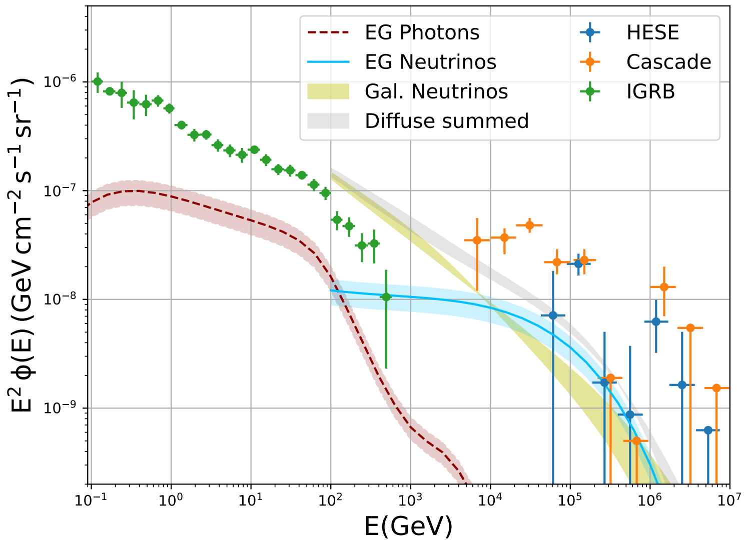

Figure 3: Total predicted full-sky ν diffuse emission (per flavor) reported with the grey band, while the green and blue bands represent respectively the gammaγ-*optimized* model and the data driven SBG emission discussed in the previous sections; compared to the last SEDs reported by IceCube for the HESE and CASCADE samples.

expected flux obtained with the sum of the two averaged over the solid angle. As can be seen in figure 3 when considering the HESE fluxes measurements, the low energy part can be described through the introduced "reservoir" diffuse components without the need of a additional astrophysical flux. In fact, while these two components separately account up to 10% (the Galactic one) and up to 20 – 30% (the SBGs one) of the HESE flux when integrating over the whole energy range, when considering the HESE sample up to teens of TeV they represent the major contribution. This is mainly due to the cosmic-ray physics of these "reservoirs" and to the maximal energy reached by the internal cosmic-ray accelerators. Summarizing the reported result suggests two different multi-messenger considerations:

- A diffuse emission of neutrinos from abundant gamma-ray faint sources, like star-forming galaxies, represents a valuable alternative to a diffuse emission from less abundant gamma opaque sources, like Seyfert galaxies. When we add to this component the diffuse Galactic emission we mostly explain the totality of HESE flux at low energy.

- The so called "hot corona" scenario which well describe the case of NGC1068 cannot be replicated for the possible emission associated to the entire class os Seyfert galaxies unless we neglect the "reservoir" component.

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