High-energy galactic neutrinos and their origin

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Introduction

Hadronic interactions which occur in the Galaxy produce a roughly equal number of charged and neutral pions which decay respectively into muonic and electronic neutrinos, and gamma rays. If photons are not absorbed by the intervening medium, we thus expect that the HE neutrino sky is strongly correlated with the HE gamma sky. This correlation provides us an handle to perform a detailed multi-messengers study of the galactic plane. The results of HE gamma observatories can be combined with the data collected by neutrino telescopes in order to test their consistence in a coherent scenario. The total galactic neutrino and gamma-ray flux are written as:

$$\varphi_{\gamma,\mathrm{tot}} = \varphi_{\gamma,\mathrm{diff}} + \varphi_{\gamma,\mathrm{S}} + \varphi_{\gamma,\mathrm{IC}}$$
$$\varphi_{\nu,\mathrm{tot}} = \varphi_{\nu,\mathrm{diff}} + \varphi_{\nu,\mathrm{S}}$$

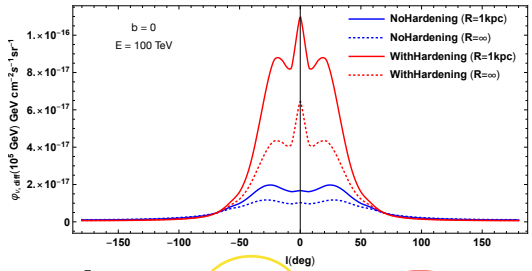
→ The gamma ray flux is measured by HESS, MIlagro, HAWC, Argo-YBJ at energies around TeV.

We analyse the Galactic neutrino component considered as the sum of a diffuse flux ($\varphi_{\nu,\mathrm{diff}}$) and a sources flux ($\varphi_{\nu,\mathrm{S}}$). We base the model of the diffuse galactic flux on four different assumptions on the cosmic rays distribution in the Galaxy. We compare our results with the isotropic astrophysical neutrino flux required to fit IceCube data.

Total galactic neutrino flux: diffuse flux + source flux

$$\varphi_{\nu,\mathrm{tot}} = \varphi_{\nu,\mathrm{diff}} + \varphi_{\nu,\mathrm{S}}$$

Galactic Component: Diffuse



$$\varphi_\nu(E_\nu,\hat{n}_\nu) = \frac{1}{3}\left[\sum_{\ell=e,\mu,\tau}\int_{E_\nu}^{\infty} dE \frac{d\sigma_\ell(E,E_\nu)}{dE_\nu}\int_0^\infty d\ell\, \varphi_{\mathrm{CR}}(E,\mathbf{r}_\odot + l\hat{n}_\nu) n_{\mathrm{H}}(\mathbf{r}_\odot + l\hat{n}_\nu)\right]$$

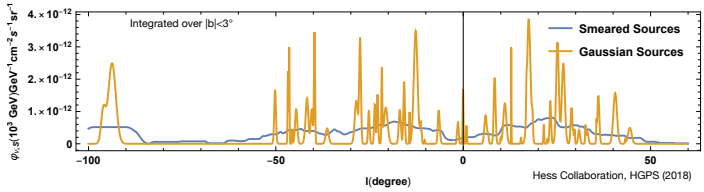
differential inelastic cross section and secondary particle spectra [Kelner, Aharonian, Bugayov (2006).]

interstellar gas distribution in the Galaxy [Galprop]

Cosmic rays energy and spatial distribution

Galactic Component: Sources

The HESS Galactic Plane Survey in 2018 provided a catalogue of 78 gamma ray sources at 1 TeV in the region -100° < l < 60° and |b|< 3°. Each source is spatially represented by a 2-dimensional gaussian with sizes given in the catalogue and a power law or a broken power law function in energy with a given spectral index. We re-binned the data choosing the bin dimension of ~15° (HESE showers resolution).



We assume that sources are all powered by hadronic interactions. In this hypothesis:

$$\varphi_{\gamma,\mathrm{S}} = k_\gamma \left(\frac{E_\gamma}{1\ \mathrm{TeV}}\right)^{-\alpha_\gamma} \exp\left(-\sqrt{\frac{E_\gamma}{E_{\mathrm{cut},\gamma}}}\right)$$
$$\varphi_{\nu,\mathrm{S}} = k_\nu \left(\frac{E_\nu}{1\ \mathrm{TeV}}\right)^{-\alpha_\nu} \exp\left(-\sqrt{\frac{E_\nu}{E_{\mathrm{cut},\nu}}}\right)$$

$$\alpha_\nu = \alpha_\gamma$$
$$k_\nu(\hat{n}_\nu) = (0.694 - 0.16\ \alpha_\gamma) k_\gamma(\hat{n}_\gamma = \hat{n}_\nu)$$
$$E_{\mathrm{cut},\nu} = 0.59 E_{\mathrm{cut},\gamma}$$

Kappes et al., Astrophys. J. 656, 870 (2007)

Cosmic Ray distributions: 4 scenarios [arxiv.org/abs/1904.03894]

We consider the possibility of CR position-dependent spectral index recently emerged from the analysis of the Fermi-LAT data at ~20 GeV (Acero et al. 2016; Yang et al. 2016; Gaggero et al. 2018).

No hardening on the CR spectral index

$$\varphi_{\mathrm{CR}}(E,\mathbf{r}) = \varphi_{\mathrm{CR},\odot}(E) g(\mathbf{r},R) \quad \begin{cases} R = 1\ \mathrm{kpc} \\ R = \infty \end{cases}$$

Hardening on the CR spectral index

$$\varphi_{\mathrm{CR}}(E,\mathbf{r}) = \varphi_{\mathrm{CR},\odot}(E) g(\mathbf{r},R) h(E,\mathbf{r}) \quad \begin{cases} R = 1\ \mathrm{kpc} \\ R = \infty \end{cases}$$

CR spatial distribution function:

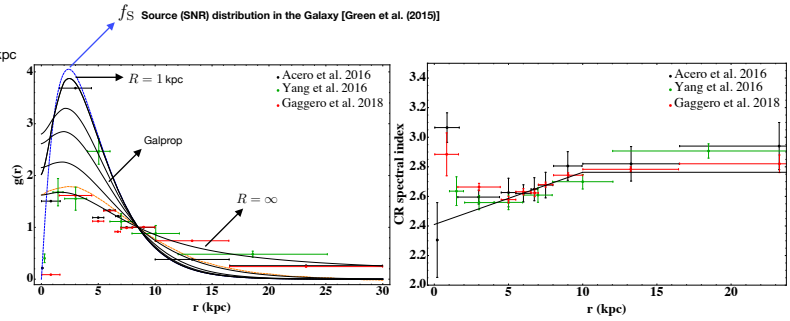
$$g(\mathbf{r}) = \frac{1}{\mathcal{N}} \int d^3x\ f_{\mathrm{S}}(\mathbf{r}-\mathbf{x})\ \frac{\mathcal{F}(|\mathbf{x}|/R)}{|\mathbf{x}|}$$

$$\mathcal{F}(\eta) \equiv \int_\eta d\gamma\ \frac{1}{\sqrt{2\pi}} \exp\left(-\gamma^2/2\right)$$
$$\mathcal{N} = \int d^3x\ f_{\mathrm{S}}(\mathbf{r}_\odot - \mathbf{x})\ \frac{\mathcal{F}(|\mathbf{x}|/R)}{|\mathbf{x}|}$$

Hardening:

$$h(E,\mathbf{r}) = \left(\frac{E}{\overline{E}}\right)^{\Delta(\mathbf{r})} \qquad \Delta(r,z) = 0.3\left(1 - \frac{r}{r_\odot}\right) \quad \overline{E} = 20\ \mathrm{GeV}$$

Data driven local CR spectrum [Dembinski, Engel, Fedynitch et al. (2018)]



Results

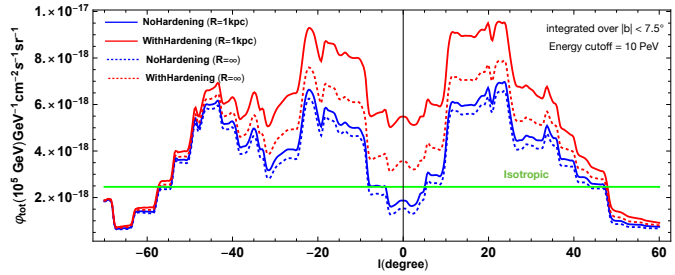
IceCube datasets

The most recent **High-Enery Starting Events (HESE)** dataset (6 yrs exposure) has been presented in 2017, and this is the dataset used to claim the discovery of a diffuse flux of HE neutrinos coming from both hemispheres. It's characterized by a soft spectrum:

$$\varphi_{\mathrm{HESE}} = N_{\mathrm{HESE}} \cdot \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-\alpha_{\mathrm{HESE}}} \qquad \alpha_{\mathrm{HESE}} = 2.9 \pm 0.3,\quad N_{\mathrm{HESE}} = 2.5 \pm 0.8\ 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

The **Through-going muons** dataset (presented in 2017, 8 yrs exposure) is sensible only to muonic neutrinos which interact through CC interaction producing a muon and coming from the Northern hemisphere. It is characterized by a harder spectrum than the HESE dataset:

$$\varphi_\mu = N_\mu \cdot \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-\alpha_\mu} \qquad \alpha_\mu = 2.2 \pm 0.1,\quad N_\mu = 1.01^{+0.26}_{-0.23} \cdot 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$



On the **overall sky** the galactic contribution (diffuse flux + source flux) at 100 TeV gives a subdominant contribution to the isotropic HESE flux measured by IceCube:

Diffuse with Hardening (R = 1 kpc) / Isotropic : **7%**
Diffuse with Hardening (R = ∞) / Isotropic : **5%**
Diffuse without Hardening (R = 1 kpc) / Isotropic :**4%**
Diffuse without Hardening (R = ∞) / Isotropic : **3%**

Sources (energy cutoff = 10 PeV) / Isotropic : **8.5%**

In the window **-60°<l<60°, |b|<7.5°**, galactic diffuse fluxes give a comparable contribution to the isotropic HESE flux. At 100 TeV:

Diffuse with Hardening (R = 1 kpc) / Isotropic : **110%**
Diffuse with Hardening (R = ∞) / Isotropic : **64%**
Diffuse without Hardening (R = 1 kpc) / Isotropic : **36%**
Diffuse without Hardening (R = ∞) / Isotropic : **25%**

Sources (Energy cutoff = 10 PeV) / Isotropic : **120%**