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The very-high-energy neutrino diffuse emission and the contribution of sources to the IceCube and ANTARES measurements

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Based on work done in collaboration with: F. L. Villante and G. Pagliaroli

TeV Particle Astrophysics, 26-30 August 2024, Chicago

Outline:

1. Galactic neutrino diffuse emission model;

   Cataldo et al. JCAP (2019)

2. Sources model *(population study of the Galactic TeV gamma-ray sources with HESS)*;

   Cataldo et al. Astrophys.J. 904 (2020)

3. Results: comparison with ANTARES, and IceCube data and constraints on the models

   Vecchiotti et al. JCAP (2023), Vecchiotti et al. APJL (2023)

Large-scale diffuse emission measurement:

ν

- $\varphi_{\nu,\mathrm{diff}}^{Antares}$ → First hint of neutrino emission from the Galactic ridge (2.2σ evidence)
  Albert, A., et al. 2023, Phys. Lett. B, 841, 137951
- $\varphi_{\nu,\mathrm{diff}}^{IceCube}$ → Measurement of the Galactic diffuse neutrino emission (4.5σ evidence)
  Abbasi, R, et al. 2023, Science, 380, 1338

The observed neutrino signal can be interpreted as:

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

$\varphi_{\nu,S}$: Population study H.E.S.S.

$\varphi_{\nu,\mathrm{diff}}$: Models:
Assumptions on the CR spatial and energy distributions.

Diffuse Galactic ν emission:

$$\varphi_{\nu,\text{diff}}\ (E_\nu, \hat{n}_\nu) = \frac{1}{3} \sum_{l=e,\mu,\tau} \int_{E_\nu}^{\infty} dE \frac{d\sigma_l(E, E_\nu)}{dE_\nu} \int_0^{\infty} dl\, \varphi_{CR}(E, \bar{r}_{Sun} + l\hat{n}_\nu)\, n_H\, (\bar{r}_{Sun} + l\hat{n}_\nu)$$

Differential inelastic cross section of pp interaction from the SYBILL code *Kelner et al (2006)*

Cosmic-ray energy and spatial distribution

Interstellar gas distribution in the Galaxy [*Galprop*]

2 models for the diffuse fluxes **for 2 assumptions of the CR distribution** in the Galaxy.

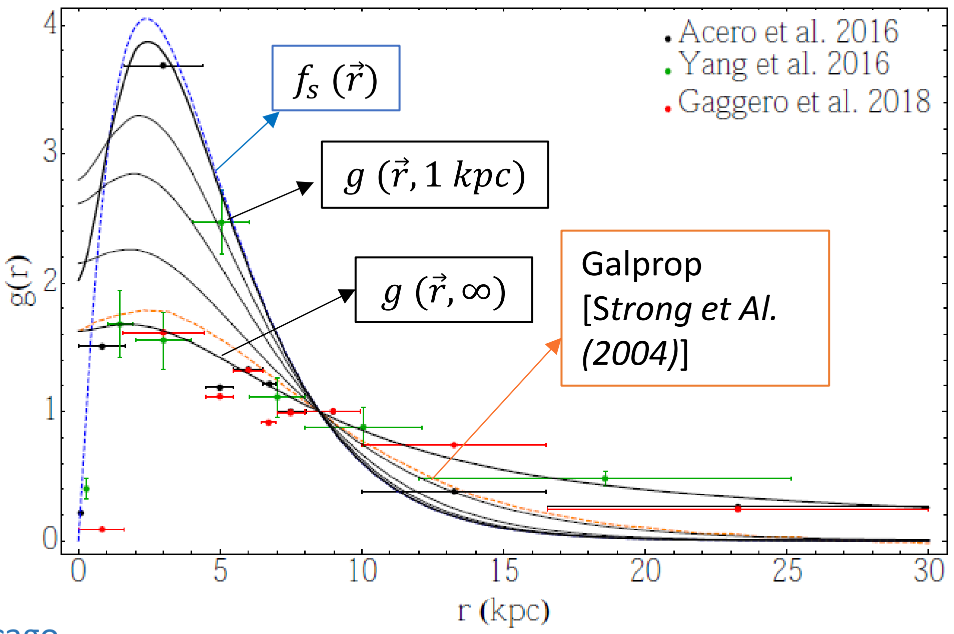
Cosmic ray distribution: $\varphi_{CR}(E,\vec{r}) = \varphi_{CR,Sun}(E\,) g\,(\vec{r},R)\; h(E,\vec{r})$

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

Cosmic ray distribution:

$$\varphi_{CR}(E,\vec{r}) = \varphi_{CR,Sun}(E)\, g(\vec{r},R)\, h(E,\vec{r})$$

- Data driven local CR spectrum *[Dembinski, Engel, Fedynitch et al. (2018)]*
- g(r) is determined by the distribution of the CR sources $f_s(\vec{r})$ proportional to the SNR number density by *Green et al. (2015)*, and by the propagation of CR in the Galactic magnetic field.



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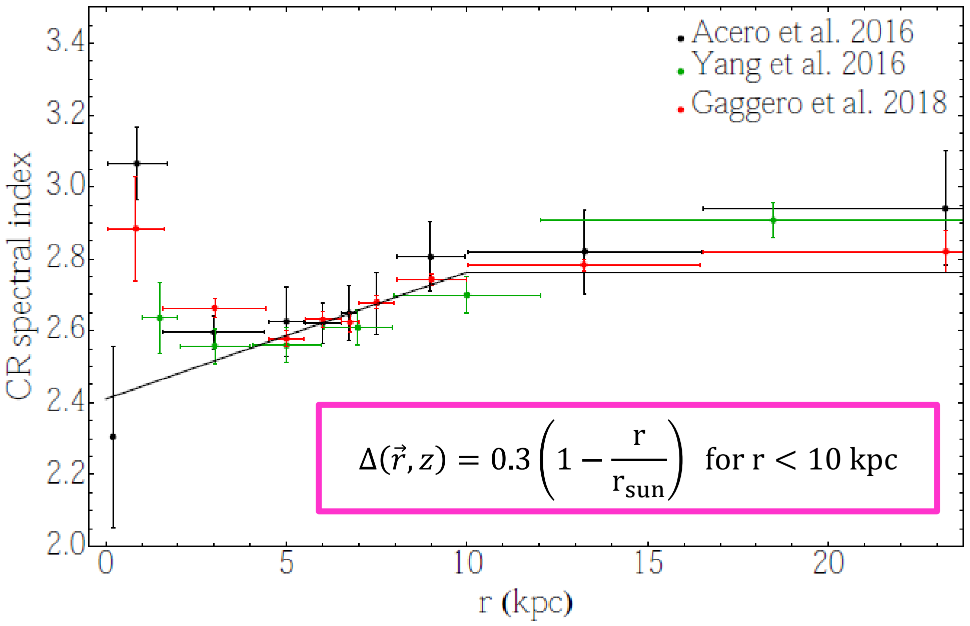
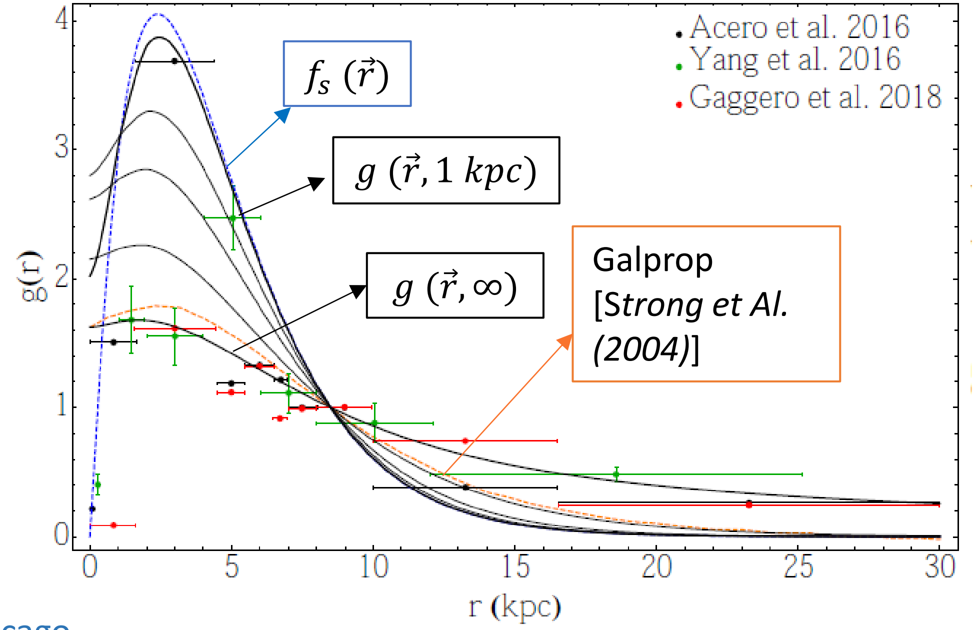
★ **2 cases: with and without spatially dependent CR spectral index** (from the analysis of the FermiLAT data at $\sim$ 20 GeV *[Acero et al. (2016), Yang et al. (2016), Gaggero et al. (2018)]*)

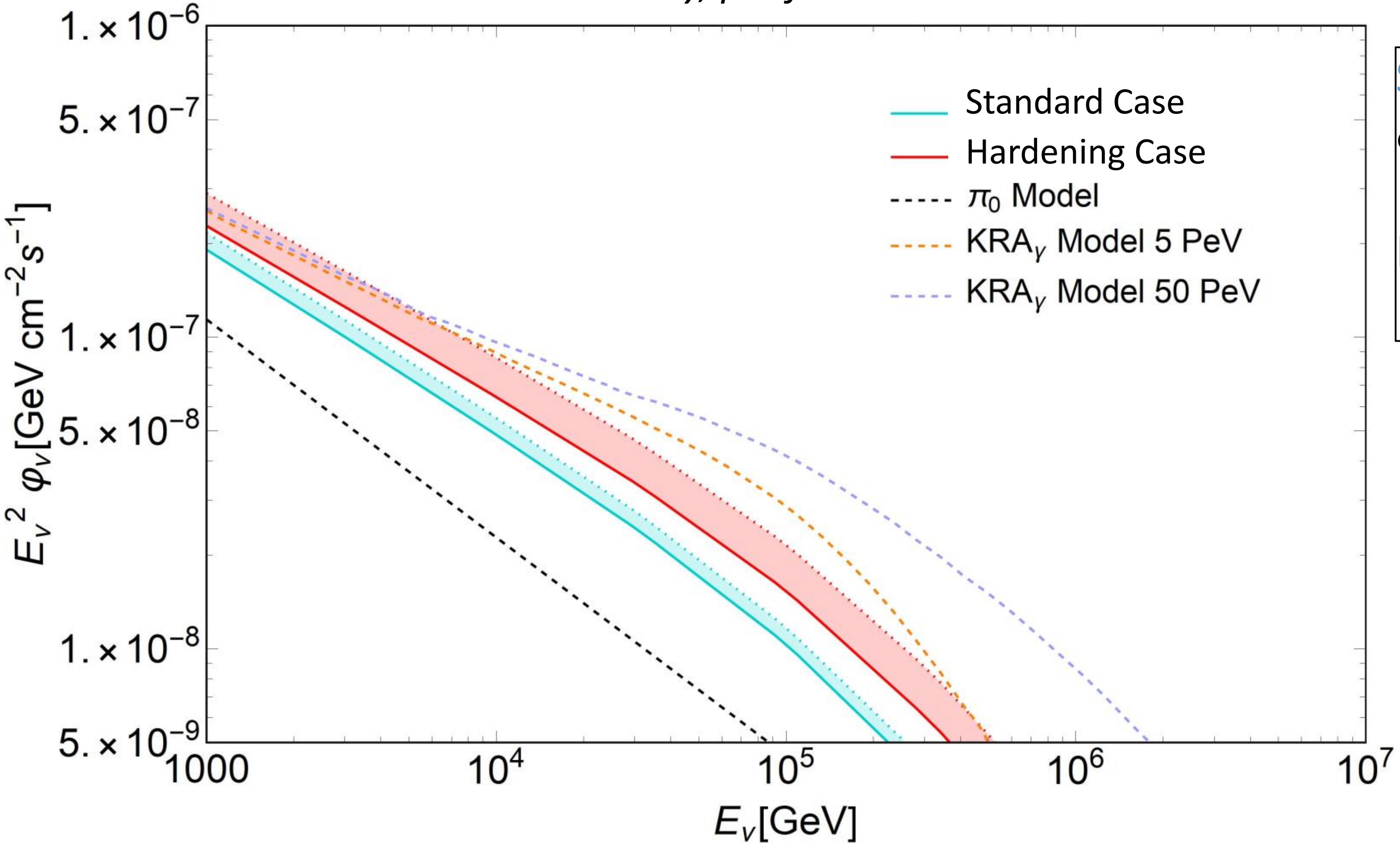
$$h(E,\vec{r}) = \left(\frac{E}{20\ GeV}\right)^{\Delta(\vec{r})}$$





Comparison of different models for the neutrino diffuse emission:

All-sky, per flavor



Hardening: spatially dependent CR spectral index

Standard Case:

$\varphi_{CR}(E,\vec{r}) = \varphi_{CR,Sun}(E)\, g(\vec{r},R);$

Hardening Case:

$\varphi_{CR}(E,\vec{r}) = \varphi_{CR,Sun}(E)\, g(\vec{r},R)\, h(E,\vec{r});$

Source component:

Study of the HGPS population in the TeV range:

Cataldo et al. Astrophys.J. 904 (2020)

- We constrain the luminosity function with the brightest sources of the HGPS:

$$Y(L) = \frac{N}{L_{max}}\left(\frac{L}{L_{max}}\right)^{-1.5}$$

$$L_{max} = L^{BF}$$
$$N = N^{BF}$$

$$\Phi_{\gamma,s}$$

$$L_{max} = 5.1^{+3.4}_{-2.2} \times 10^{35} erg\ s^{-1}$$
$$N = 18^{+14}_{-7}$$

- Total gamma-ray flux due to sources integrated over 1-100 TeV energy range.
- It includes the contribution from both the sources observed by H.E.S.S. and the one from unresolved sources

Connection gamma-ray and neutrino:

We have $\Phi_{\gamma,s}$ (1-100 TeV) in gamma-rays, we need:

- CR injected spectrum:

$$\phi_p(E;E_{cut}) = \left(\frac{E}{1\ TeV}\right)^{-\beta} Exp\left(-\frac{E}{E_{cut}}\right)$$

$\beta = 2.4$ *(to reproduce the average index of the HGPS);*
$E_{cut} = 0.5 - 10\ PeV$

- Neutrino flux from sources:

$$\varphi_{\nu,s}(E_\nu;E_{cut},\xi) = \xi\Phi_{\nu,s}^{max}(E_{cut})\phi_\nu(E_\nu;E_{cut})$$

Fraction of gamma-ray sources flux produced by hadronic interactions.

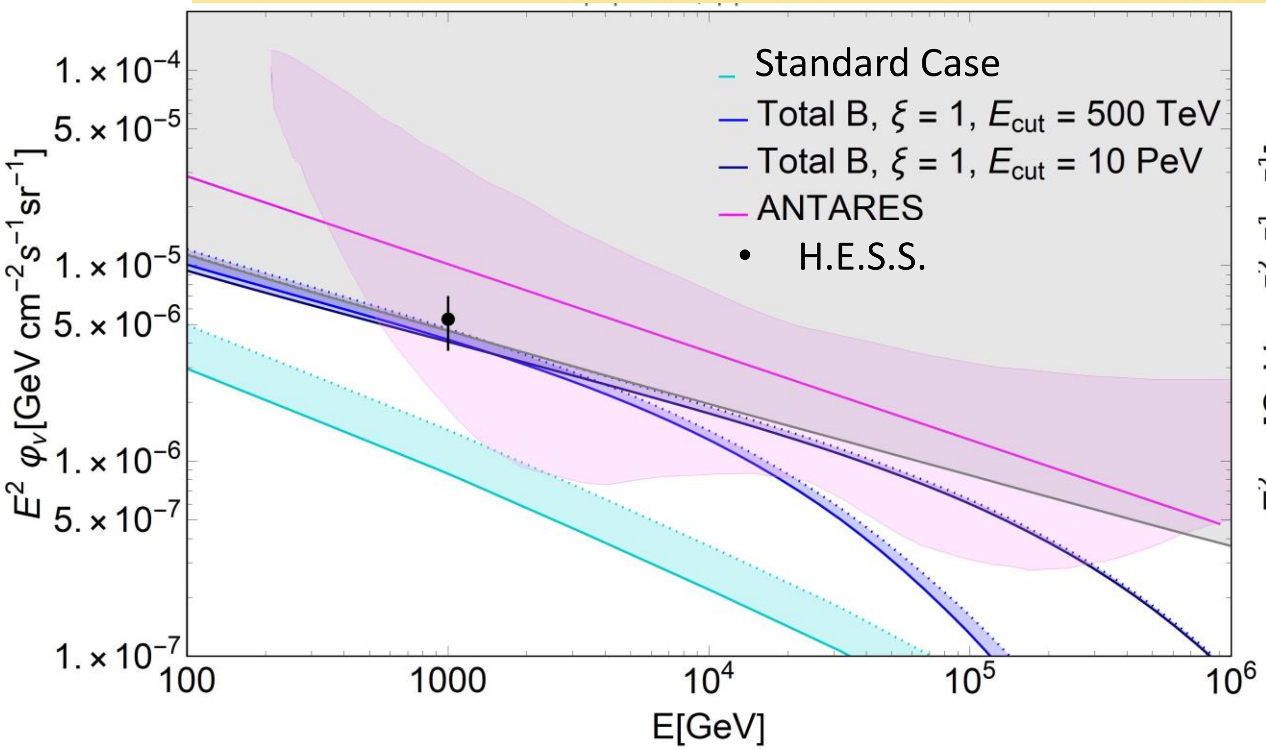
Maximal neutrino flux from sources (1-100 TeV), the neutrino source contribution obtained by assuming that all the TeV gamma-ray sources are powered by hadronic processes

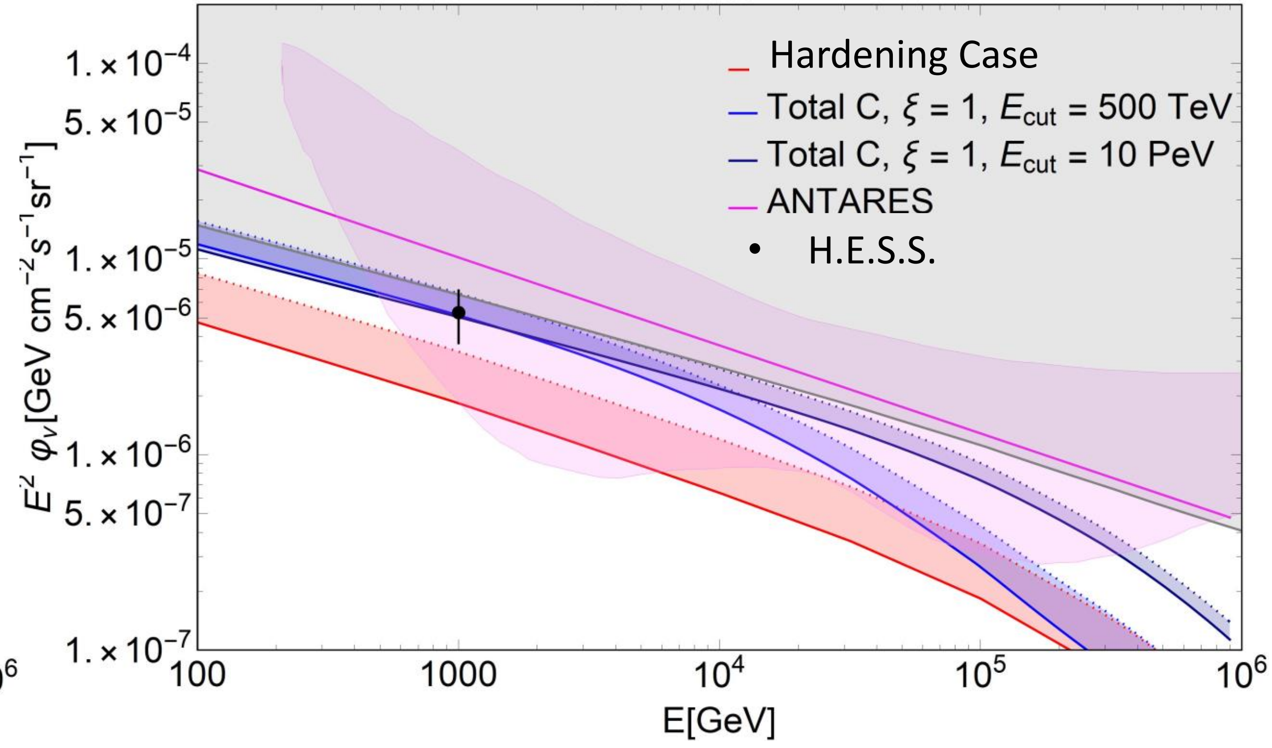
Neutrino spectrum. Normalized in the energy range 1-100 TeV

ANTARES:

- We add the source component to the hadronic diffuse emission in the Standard and the Hardening Cases.

All flavor, $|l| < 30°, |b| < 2°,\ \xi = 1$



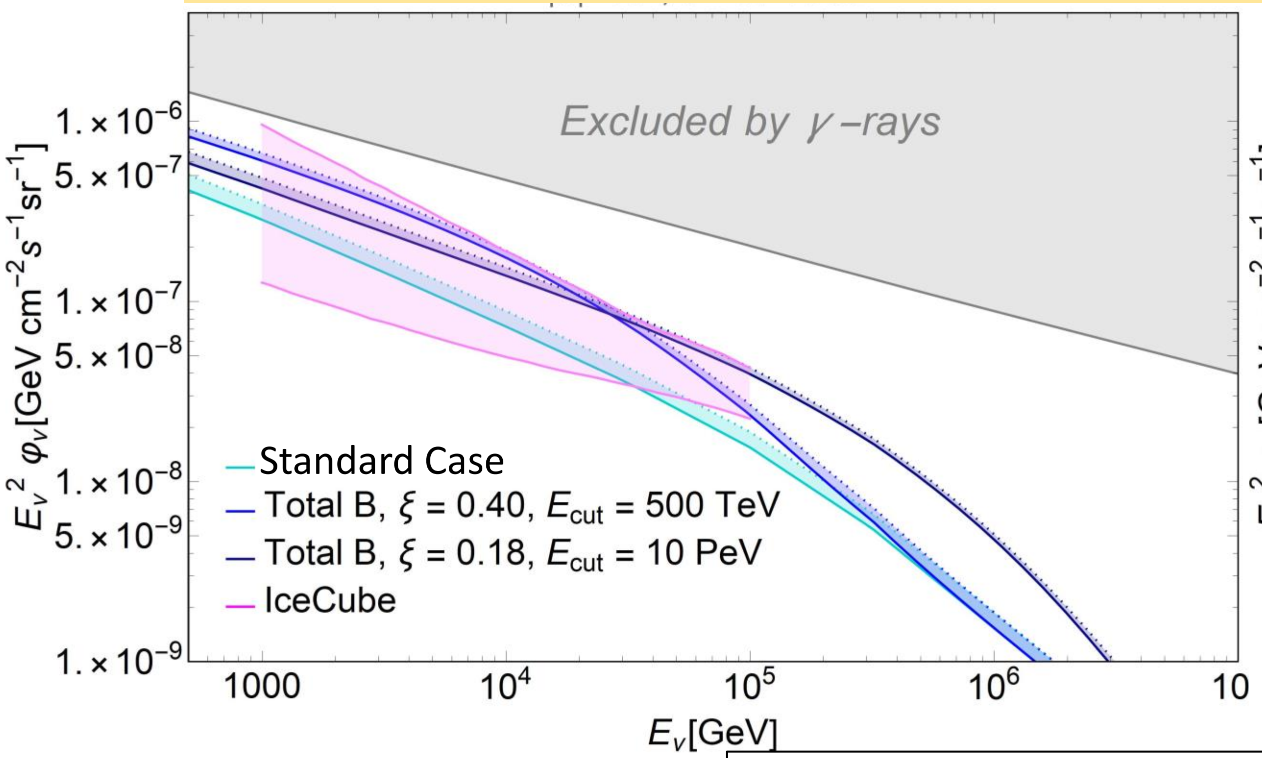


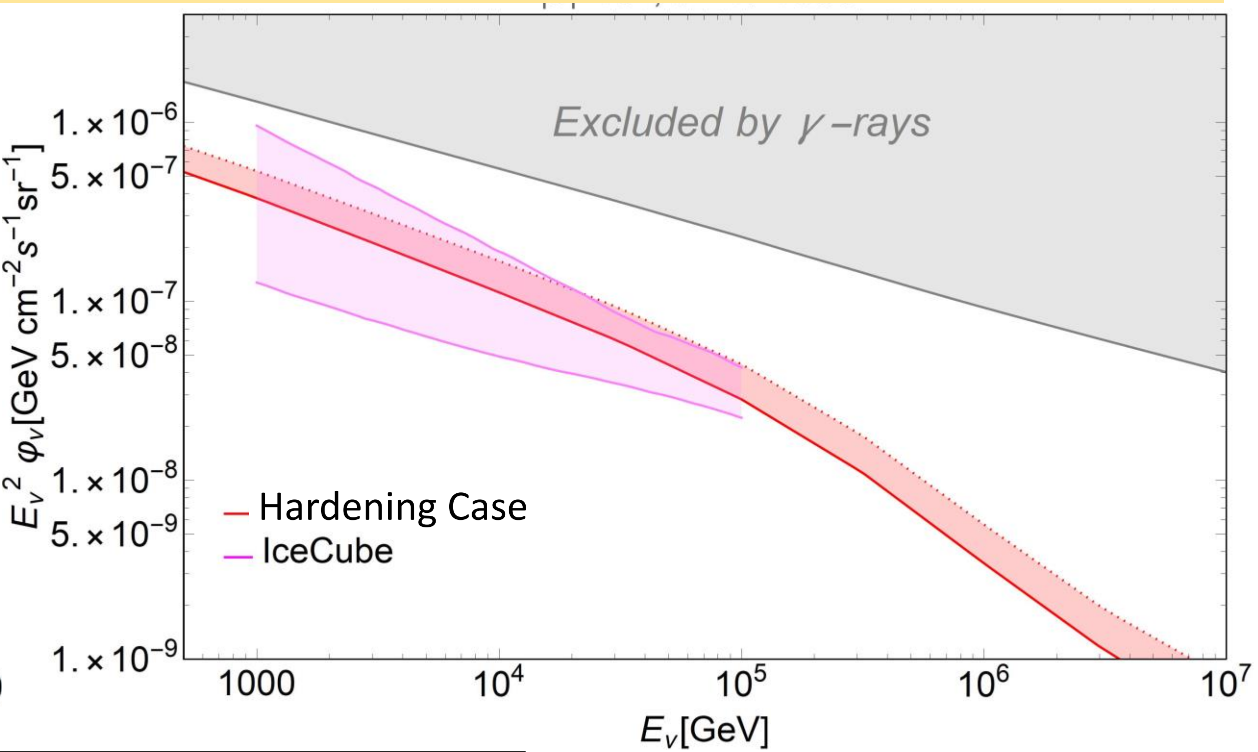
$$\varphi_{\nu,\text{diff}}^{Antares} = \varphi_{\nu,S}(\xi, E_{\text{cut}}) + \varphi_{\nu,\text{diff}}$$

IceCube:

- We add the source component to the truly diffuse emission in the Standard and the hardening Cases.

All flavor, $0^\circ < l < 360^\circ, |b| < 5^\circ$





$$\varphi_{\nu,\mathrm{diff}}^{IceCube} = \varphi_{\nu,S}(\xi, E_{\mathrm{cut}}) + \varphi_{\nu,\mathrm{diff}}$$

IceCube:

- We add the source component to the truly diffuse emission in the Standard and the hardening Cases.

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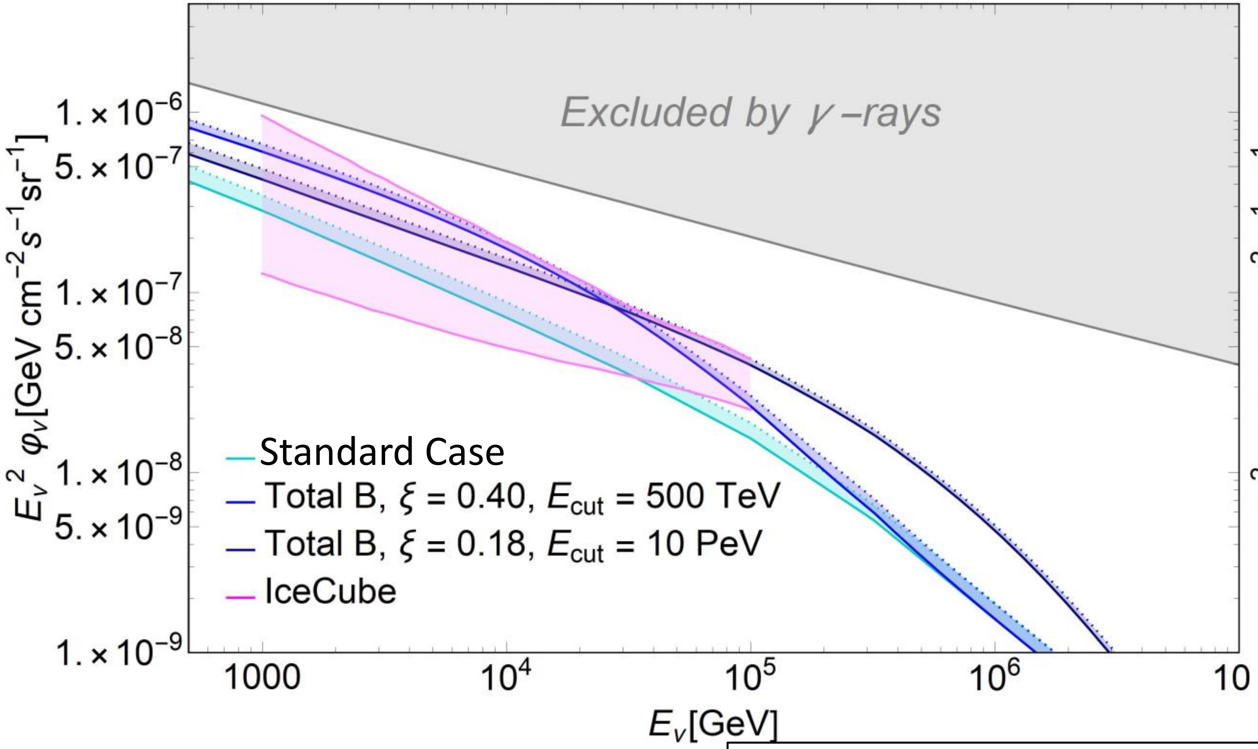
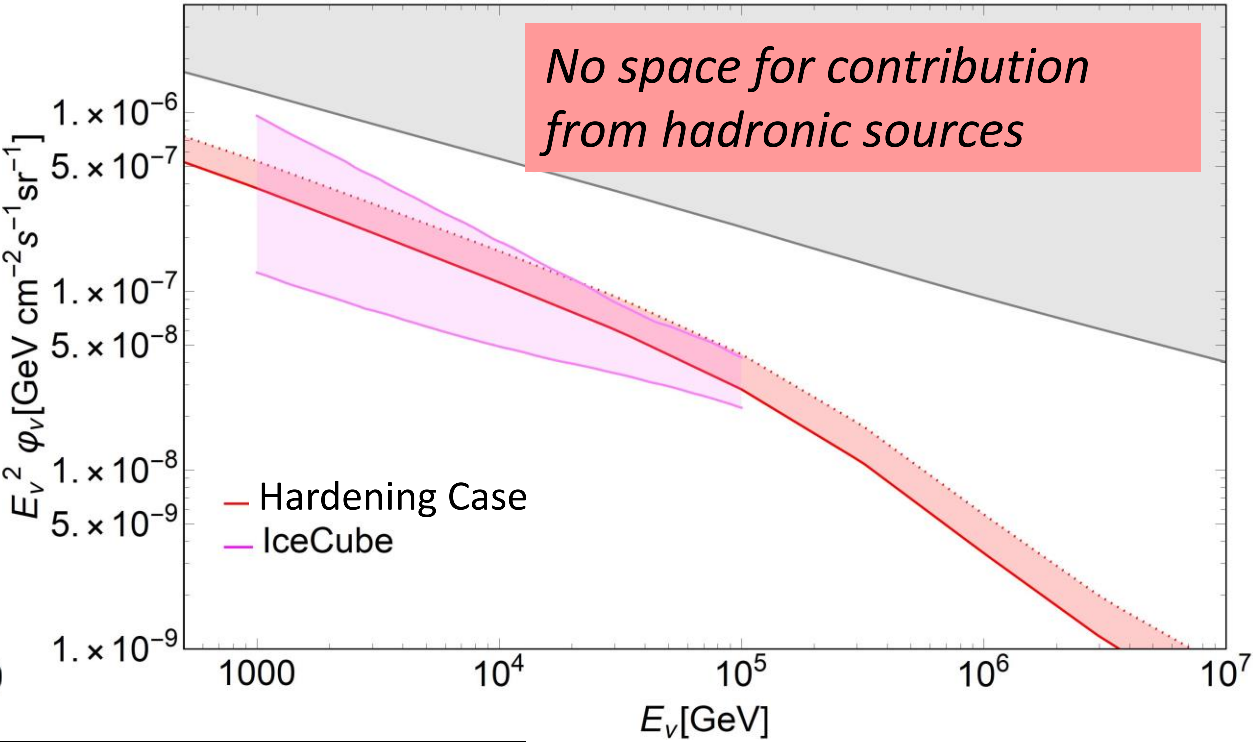




$$\varphi_{\nu,\mathrm{diff}}^{IceCube} = \varphi_{\nu,S}(\xi, E_{\mathrm{cut}}) + \varphi_{\nu,\mathrm{diff}}$$

Conclusions:

The ANTARES neutrino signal cannot be explained solely by the contribution from the diffuse emission and requires a dominant source component;

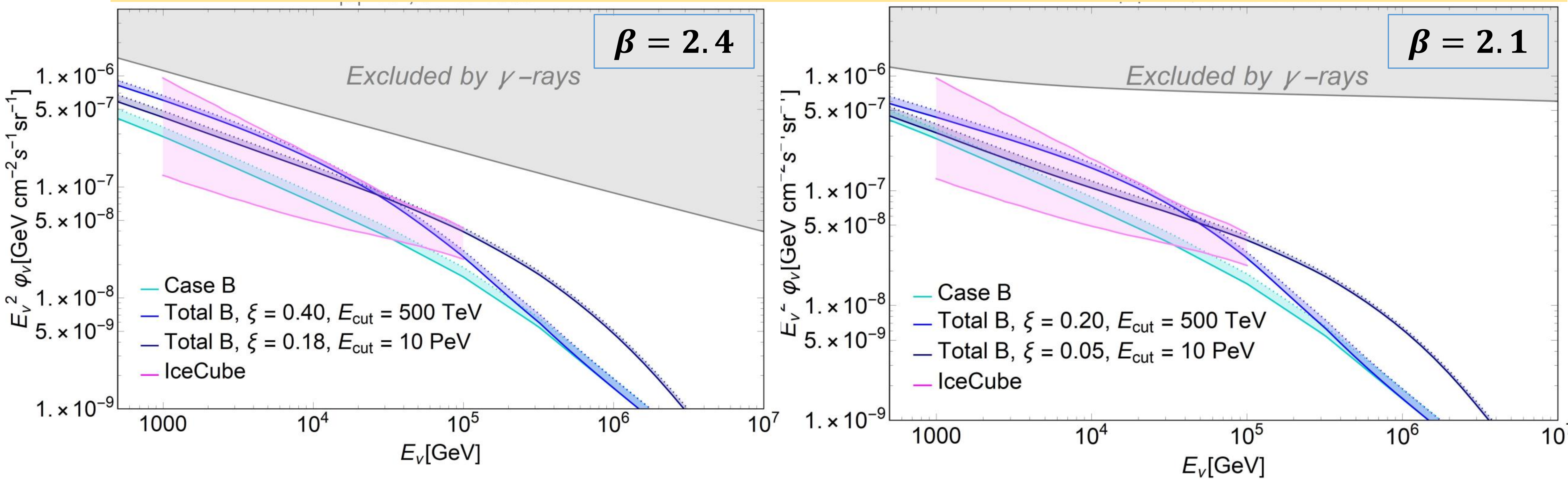
From comparison with the IceCube results, we learn that:

- Only a fraction of the TeV-Galactic gamma-ray sources can have hadronic nature.
- This fraction has to be negligible or sources should have $E_{cut} \leq 500$ TeV if we consider the diffuse model with the hardening hypothesis.
- Instead, in the scenario in which the CR spectrum is uniform within the Galaxy, the maximally allowed fraction is $\xi < 0.40$ $(E_{cut} = 500\ TeV)$. If we require that Galactic sources should be able to accelerate particles up to the CR «knee» then the fraction reduces to $\xi \sim 0.20$

Backup slides

IceCube:

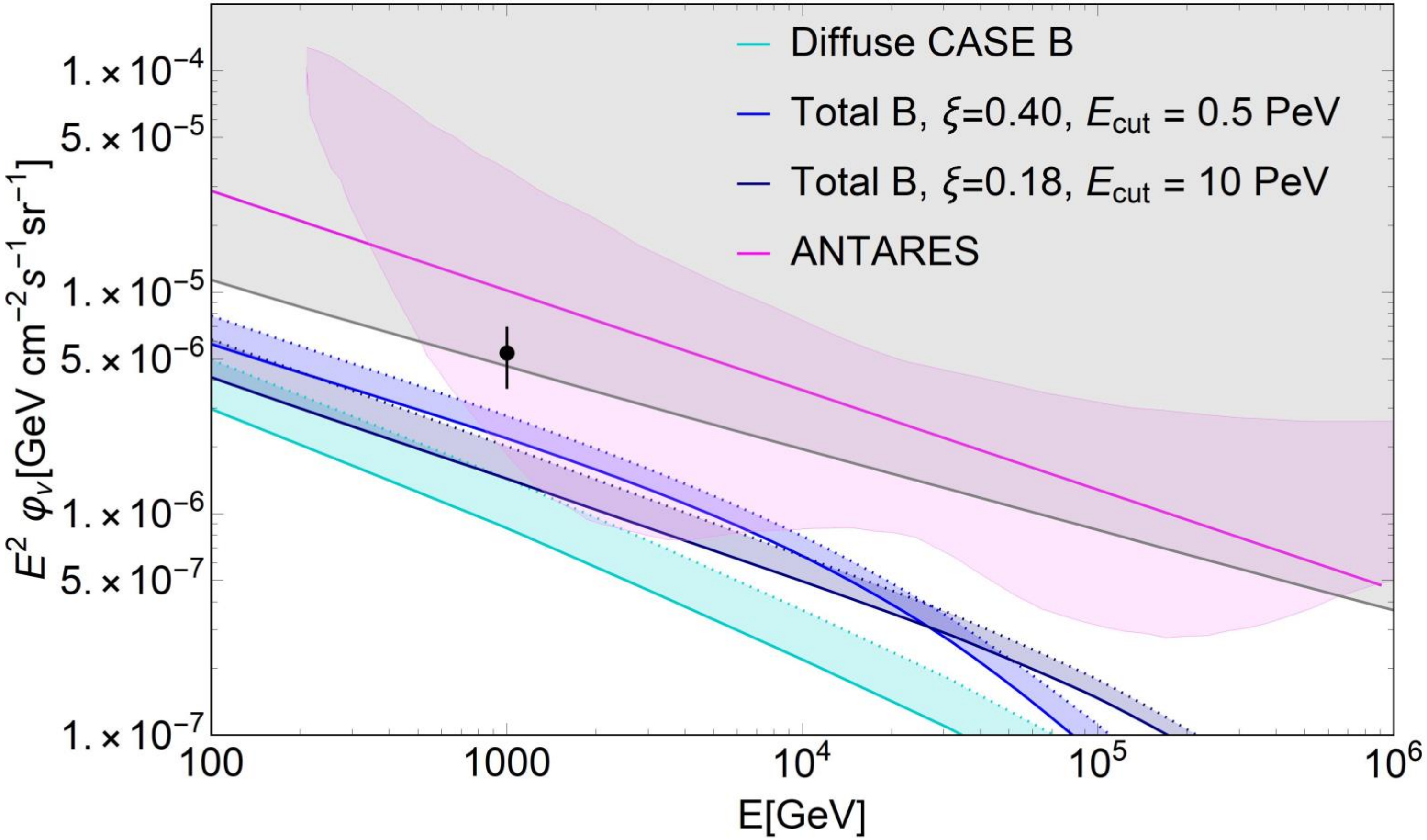
$$0^\circ < l < 360^\circ, |b| < 5^\circ,$$



$$\varphi_{\nu,\text{diff}}^{IceCube} = \varphi_{\nu,S}(\xi, E_{\text{cut}}) + \varphi_{\nu,\text{diff}}$$

ANTARES:

$$|l| < 30°, |b| < 2°$$

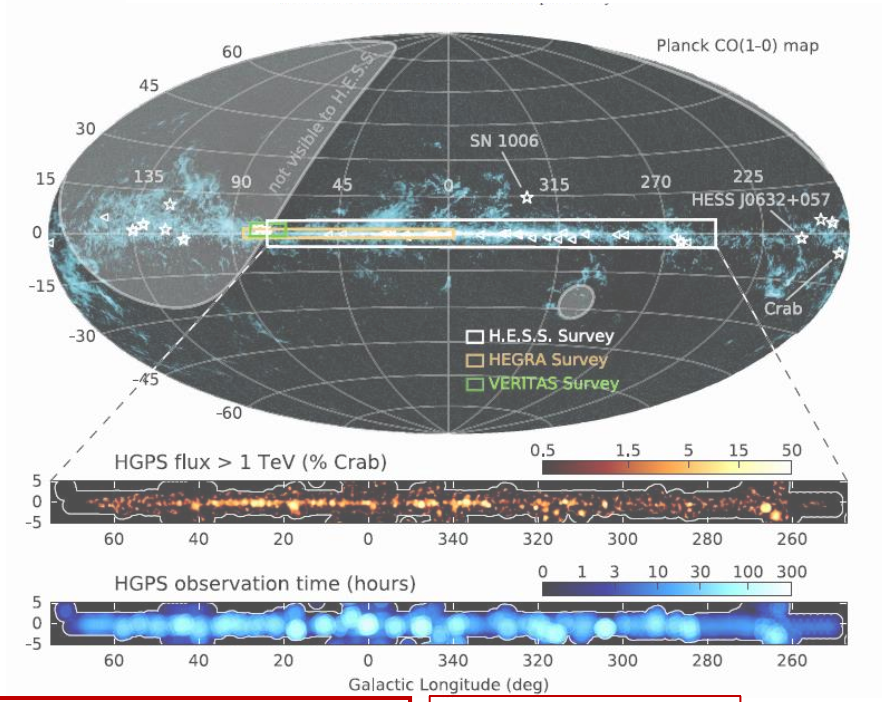


$$\varphi_{\nu,\text{diff}}^{Antares} = \varphi_{\nu,S}(\xi, E_{\text{cut}}) + \varphi_{\nu,\text{diff}}$$

Study of the source population in the TeV range:

Cataldo et al. *Astrophys.J.* 904 (2020)

Abdalla et al, *A&A*, 612, A1 (2018)



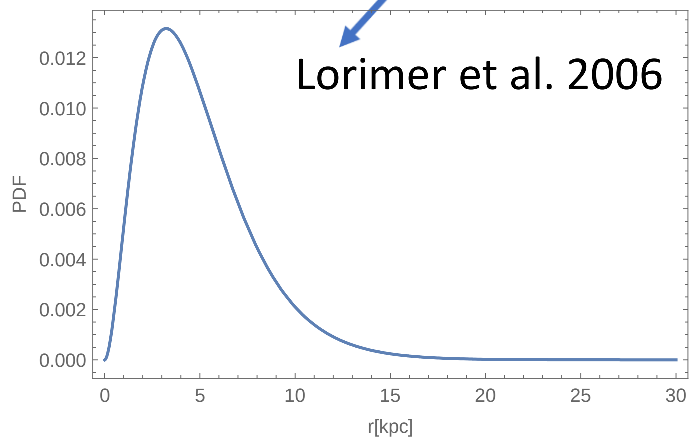
- The HGPS catalogue ($\phi > 0.1\phi_{Crab}$);
- Model for TeV source population:

we assume the spatial distribution and the luminosity distribution of the sources;

$$\frac{dN}{d^3r dL} = \rho(r) Y(L)$$

$$Y(L) = \frac{R\tau(\alpha-1)}{L_{\max}}\left(\frac{L}{L_{\max}}\right)^{-\alpha}$$

$\alpha = 1.5$
$\alpha = 1.8$



Lorimer et al. 2006

$$\alpha = 1/\gamma + 1$$

For pulsar-powered sources:

$$R = 0.019\,\mathrm{yr}^{-1} \quad L(t) = L_{\max}\left(1+\frac{t}{\tau}\right)^{-\gamma}$$

We assume a **power-law** energy spectrum with index $\boldsymbol{\beta_{TeV} = 2.3}$ that is the average index for all the sources in the HGPS catalogue.

Results:

- The total TeV luminosity (1-100 TeV) of the Galaxy:

$$L_{MW} = \frac{R\tau(\alpha-1)\, L_{max}}{(2-\alpha)} \left[1 - \left(\frac{L_{min}}{L_{max}}\right)^{\alpha-2}\right] = 1.7^{+0.5}_{-0.4} \times 10^{37}\ erg\ s^{-1}$$

$\frac{L_{min}}{L_{max}} \to 0$

- The total flux at Earth produced by all sources (1-100 TeV) (resolved and unresolved) in the H.E.S.S. OW:

$$\phi_{tot} = \frac{L_{MW}}{4\Pi\langle E\rangle} \int_{OW} d^3r\, \rho(r)\, r^{-2} = 3.8^{+1.0}_{-1.0} \times 10^{-10} cm^{-2} s^{-1}$$

$\langle E\rangle \to$ 3.25 TeV

- By subtraction we can obtain the contribution of unresolved sources in the H.E.S.S. observational window knowing that: $\phi_S^r = 2.3 \times 10^{-10} cm^{-2} s^{-1}$ (cumulative flux due to all 78 sources):

$$\phi_S^{unr} = \phi_{tot} - \phi_S^r = 1.4^{+1.0}_{-0.8} \times 10^{-10}\ cm^{-2} s^{-1}\ \sim 60\%\ \phi_S^r$$

Comparison Diffuse models in gamma-rays: