

# Galactic population of HE- $\gamma$ sources and the contribution of its unresolved component to Diffuse $\gamma$ and $\nu$ emission

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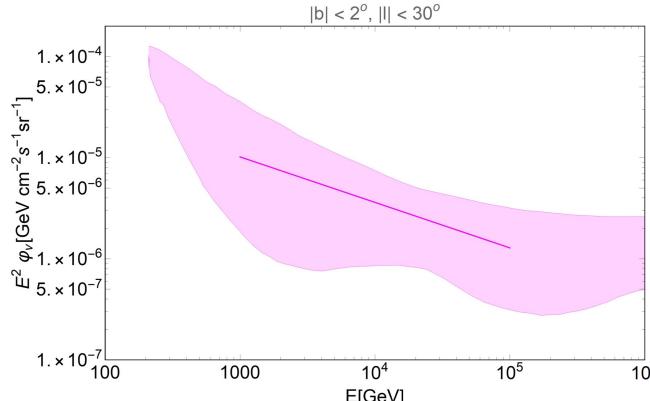
Based on [arXiv:2306.16305](https://arxiv.org/abs/2306.16305) and [arXiv:2307.07451](https://arxiv.org/abs/2307.07451)  
in collaboration with: F. L. Villante and V. Vecchiotti

# Large-scale neutrino diffuse emission

$\varphi_{\nu, \text{tot}}^{\text{Antares}}$



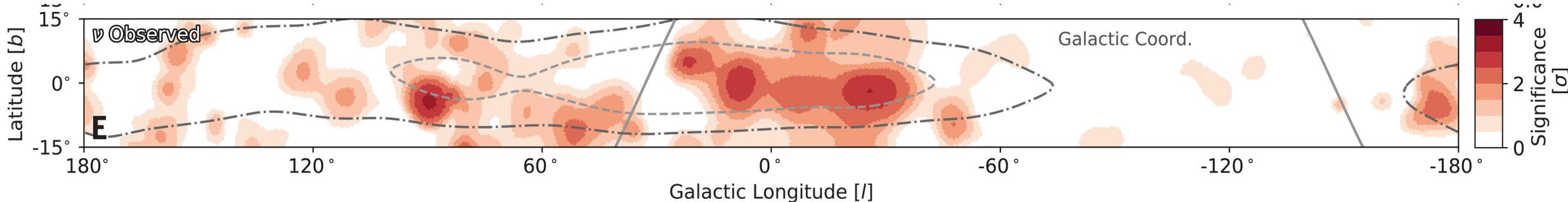
First hint of neutrino emission from the Galactic ridge (2.2 $\sigma$  evidence)  
*Albert, A., et al. 2023, Phys. Lett. B, 841, 137951*



$\varphi_{\nu, \text{tot}}^{\text{IceCube}}$



Detection of the Galactic diffuse neutrino emission (4.5 $\sigma$  evidence)  
*Abassi, R, et al. 2023, Science, 380, 1338*



The observed neutrino signal can be interpreted as:

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

# Large-scale neutrino diffuse emission

$\nu$

$$\left[ \begin{array}{l} \varphi_{\nu,\text{tot}}^{\text{Antares}} \\ \varphi_{\nu,\text{tot}}^{\text{IceCube}} \end{array} \right]$$

First hint of neutrino emission from the Galaxy

*Albert, A., et al. 2023, Phys. Lett. B, 841, 13795*

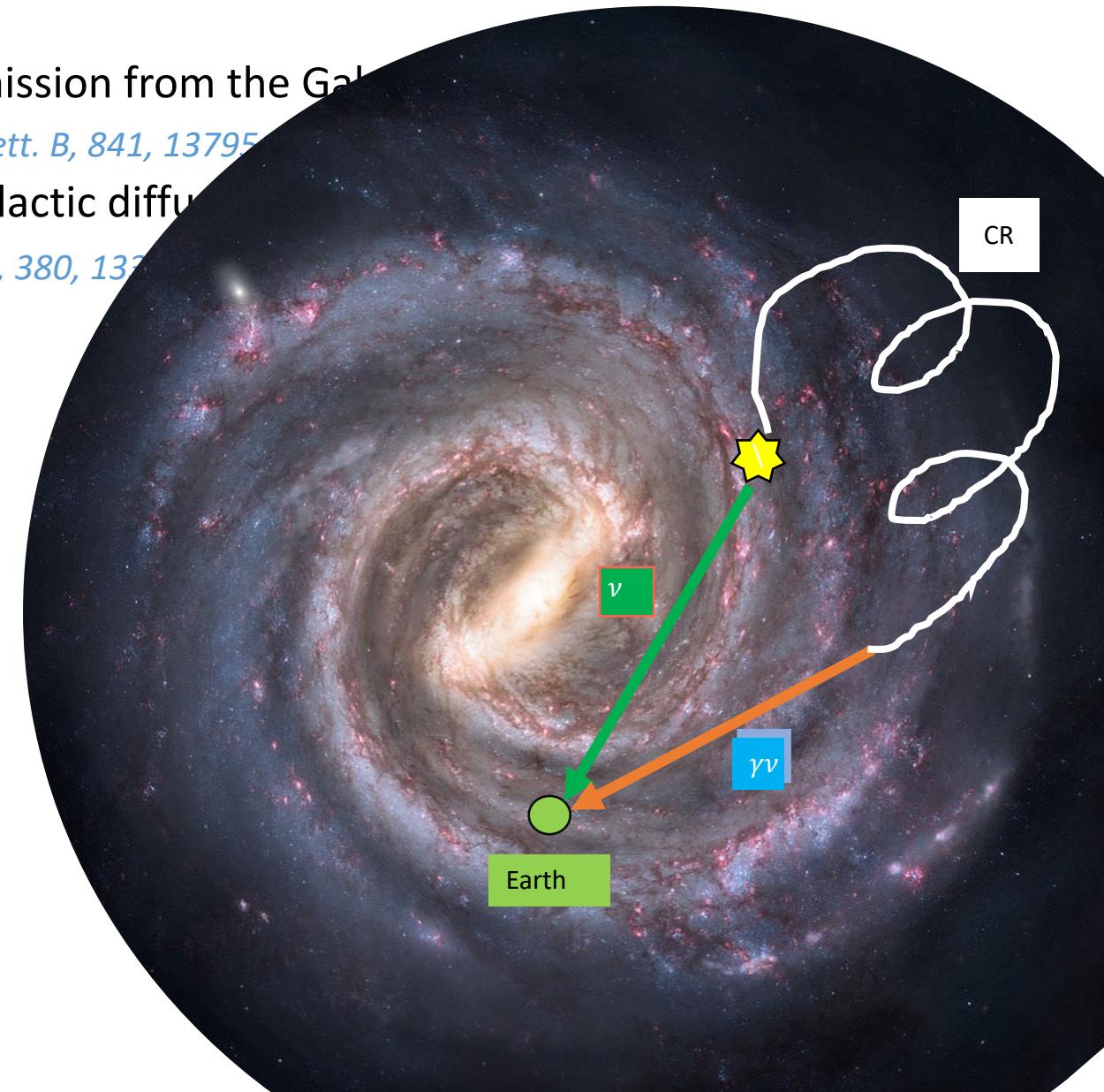
Measurement of the Galactic diffuse flux

*Abassi, R, et al. 2023, Science, 380, 137*

The observed neutrino signal can be interpreted as:

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

Diffuse component is due to the interaction of accelerated hadrons with the interstellar medium;



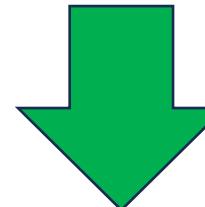
# Truly Diffuse Galactic $\nu$ emission:

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

Differential inelastic cross section of pp interaction from the SYBILL code  
[Kelner,Aharonian,Bugayov (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.**

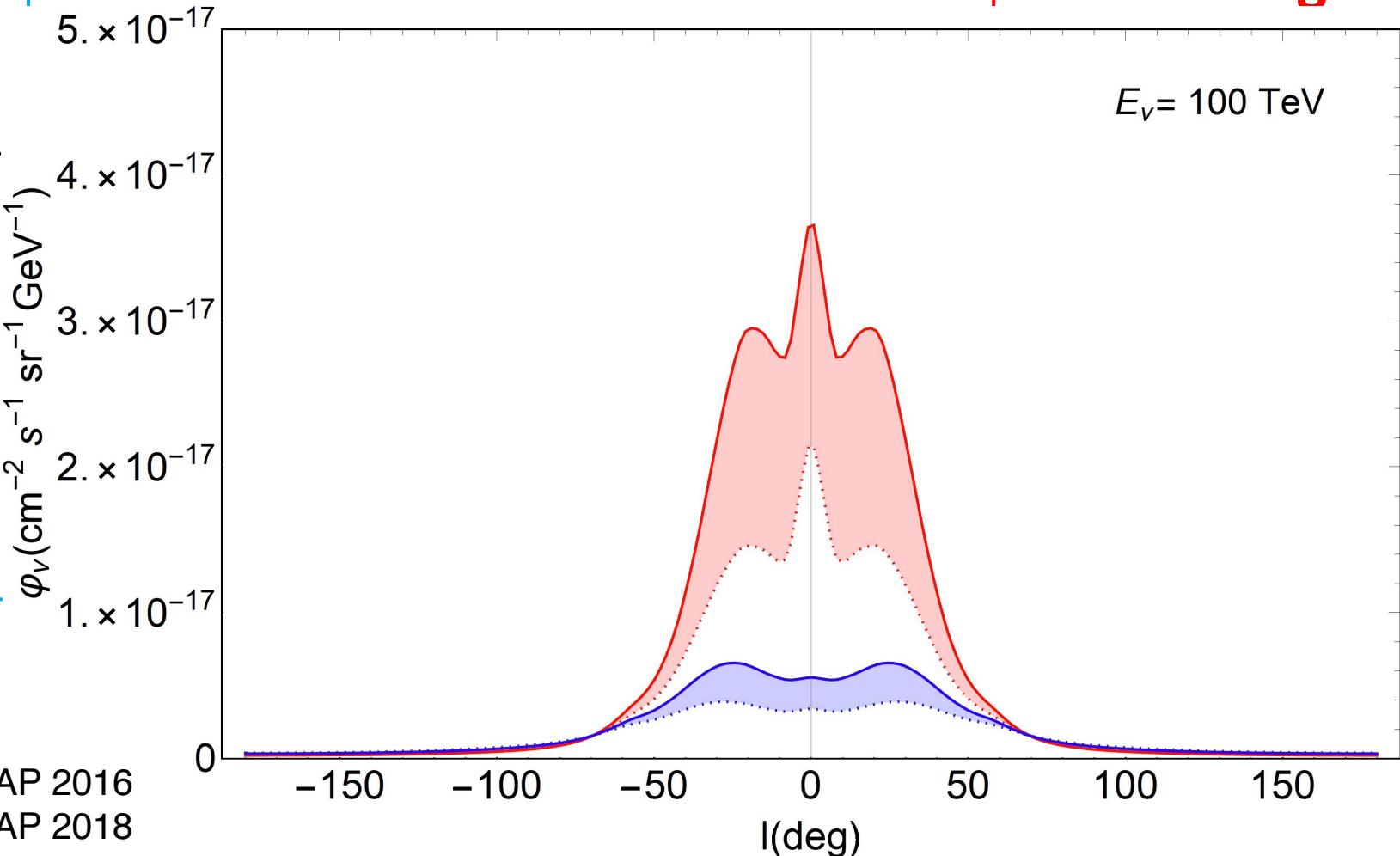
Standard Case B

Hardening Case C

# Truly Diffuse Galactic $\nu$ emission:

- Standard Case B

The Spectrum of the CR is uniform inside the Galaxy and corresponds to the one we measure at the Earth



- Hardening Case C

The Spectrum of CR changes inside the Galaxy and becomes harder toward the inner Galaxy

# Large-scale neutrino diffuse emission

$\nu$

$$\varphi_{\nu,\text{tot}}^{\text{Antares}}$$

First hint of neutrino emission from the Galaxy

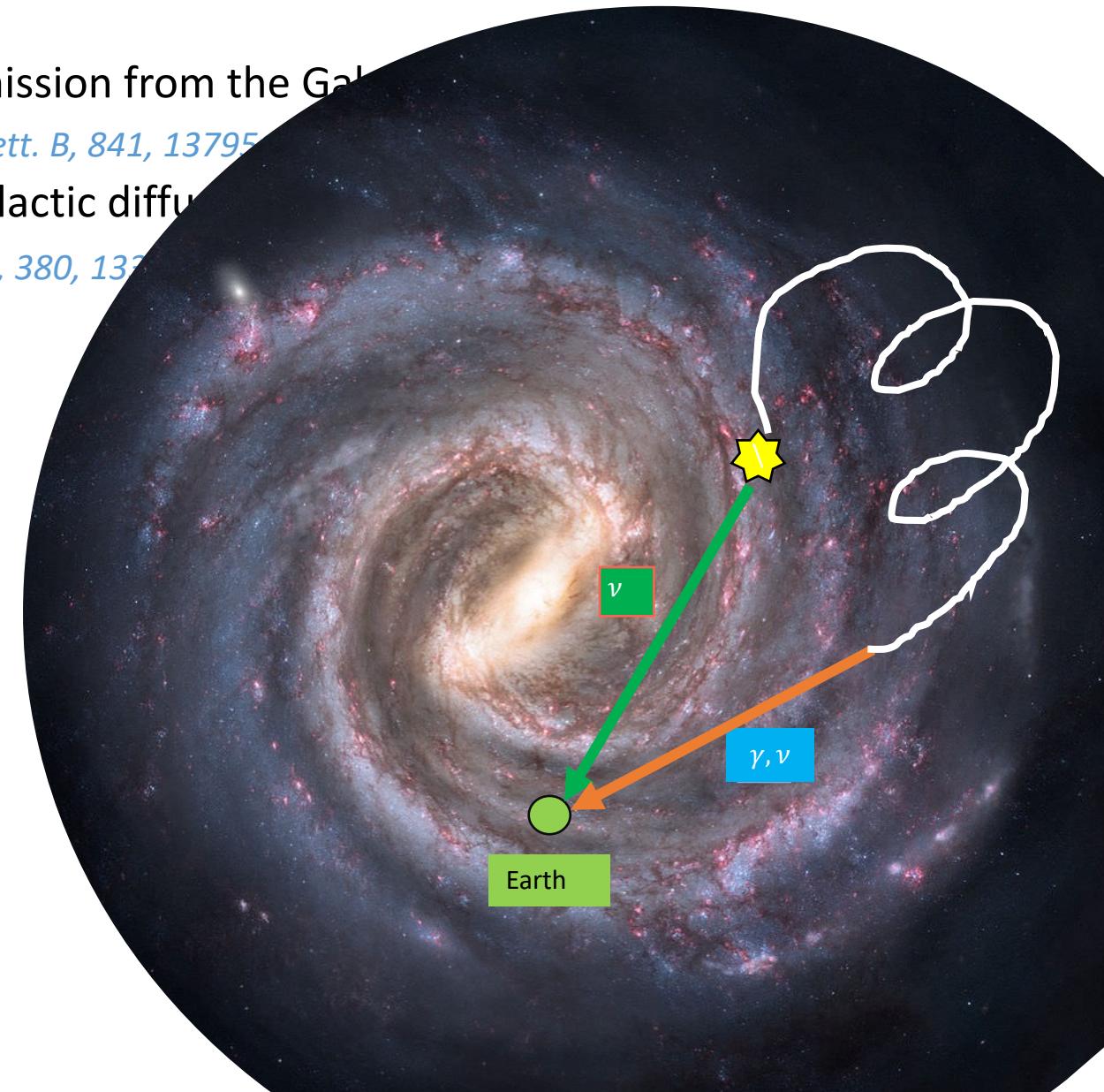
$$\varphi_{\nu,\text{tot}}^{\text{IceCube}}$$

Measurement of the Galactic diffuse neutrino flux  
*Albert, A., et al. 2023, Phys. Lett. B, 841, 13795*

The observed neutrino signal can be interpreted as:

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

**Source component** is due to the interaction of accelerated particles (hadrons) with the ambient medium (ISM or CMB) within or close to an acceleration site (such as PWNe, SNRs).

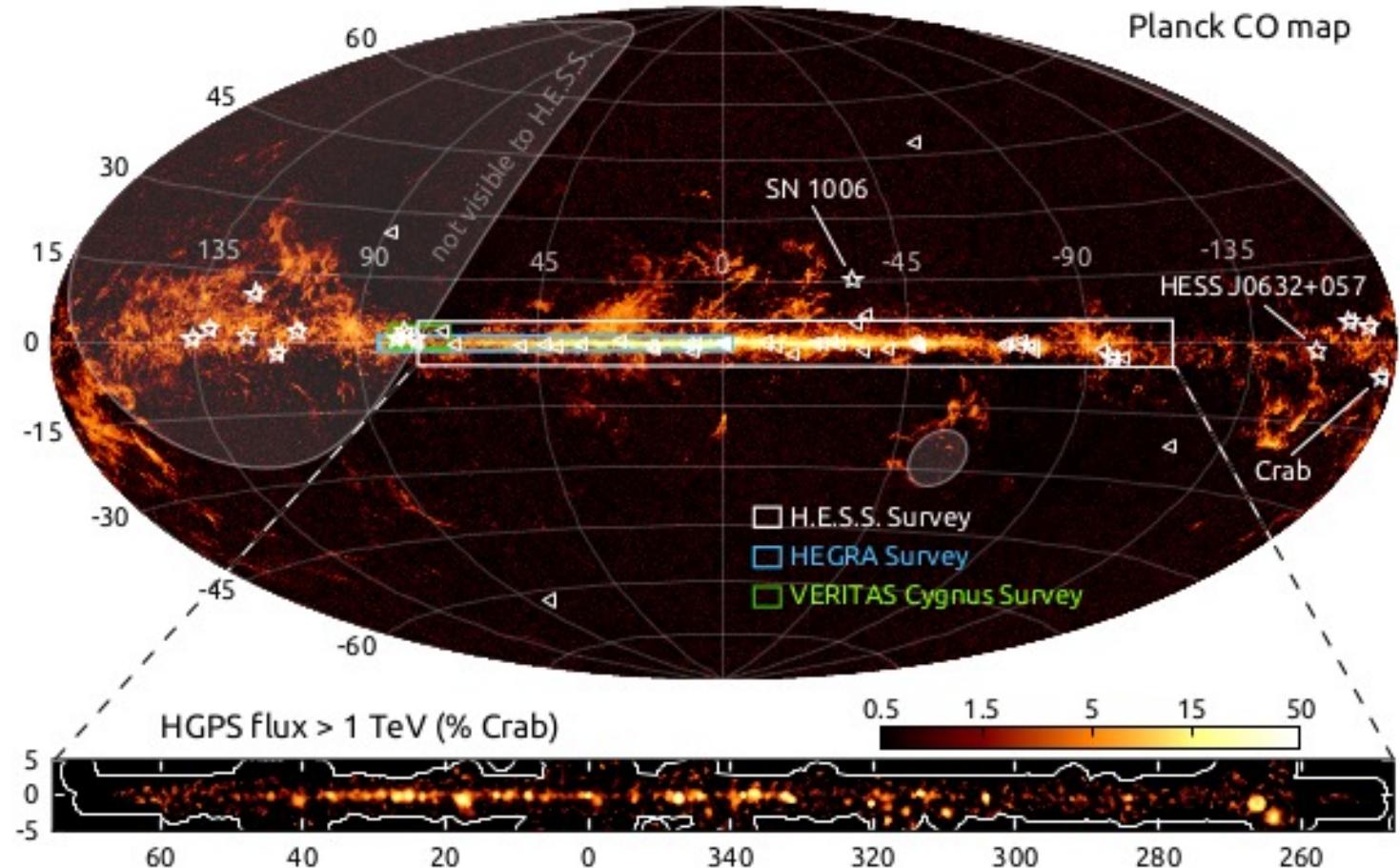


# Galactic Sources

Source component includes the contribution of all the Galactic hadronic gamma-ray sources **both resolved and unresolved** by gamma-ray detectors

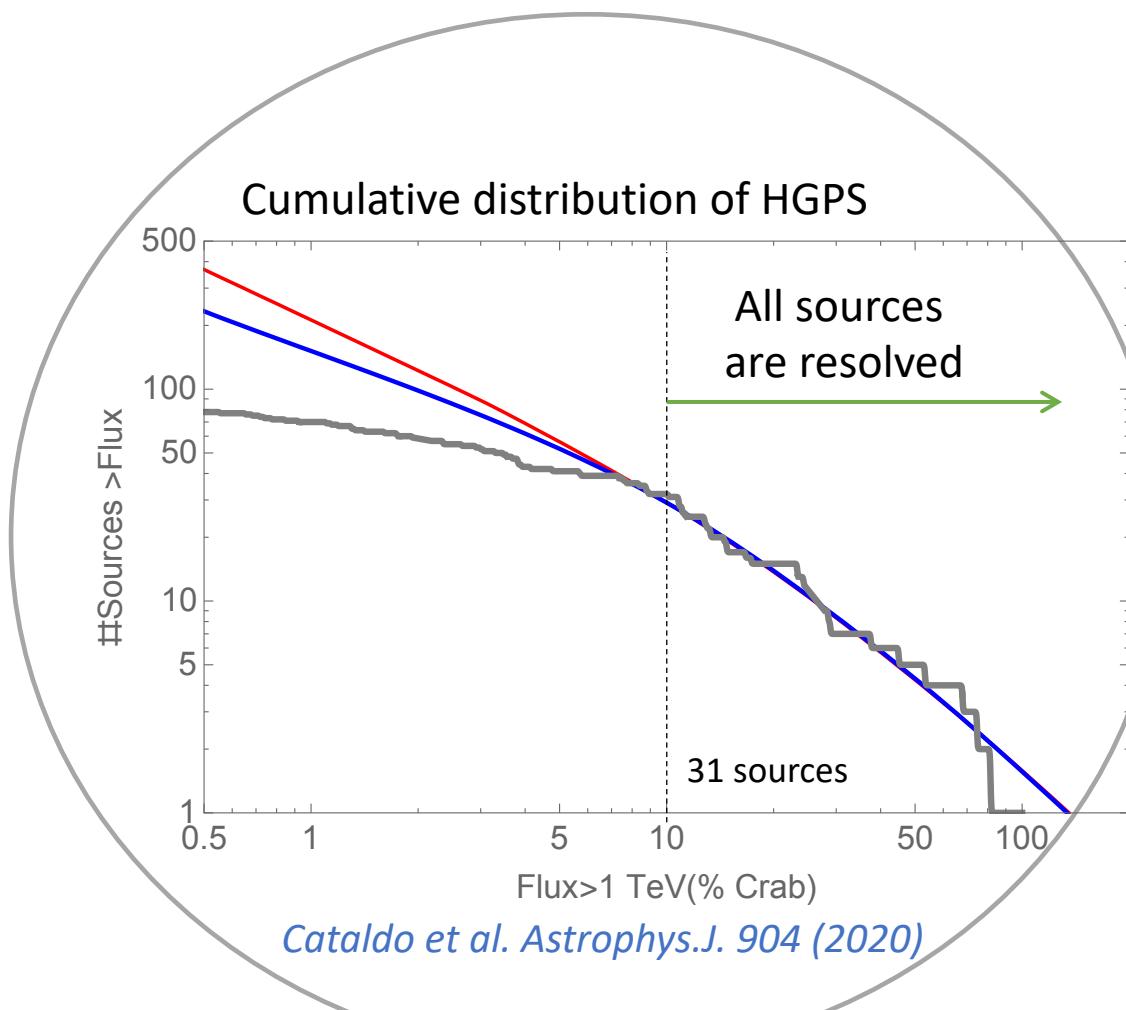
Sources catalogs

Sources Population study based on HGPS catalog of H.E.S.S.



## Source component:

We analyse the brightest sources in the HGPS and we constrain the luminosity function of the entire population of TeV gamma sources:



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

- Total gamma-ray flux due to all the 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 to neutrino sources:

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

- CR injected spectrum:

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

$\beta = 2.4$  (to reproduce the average index of the HGPS);

$E_{cut} = 0.5 - 10 \text{ PeV}$

- 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.

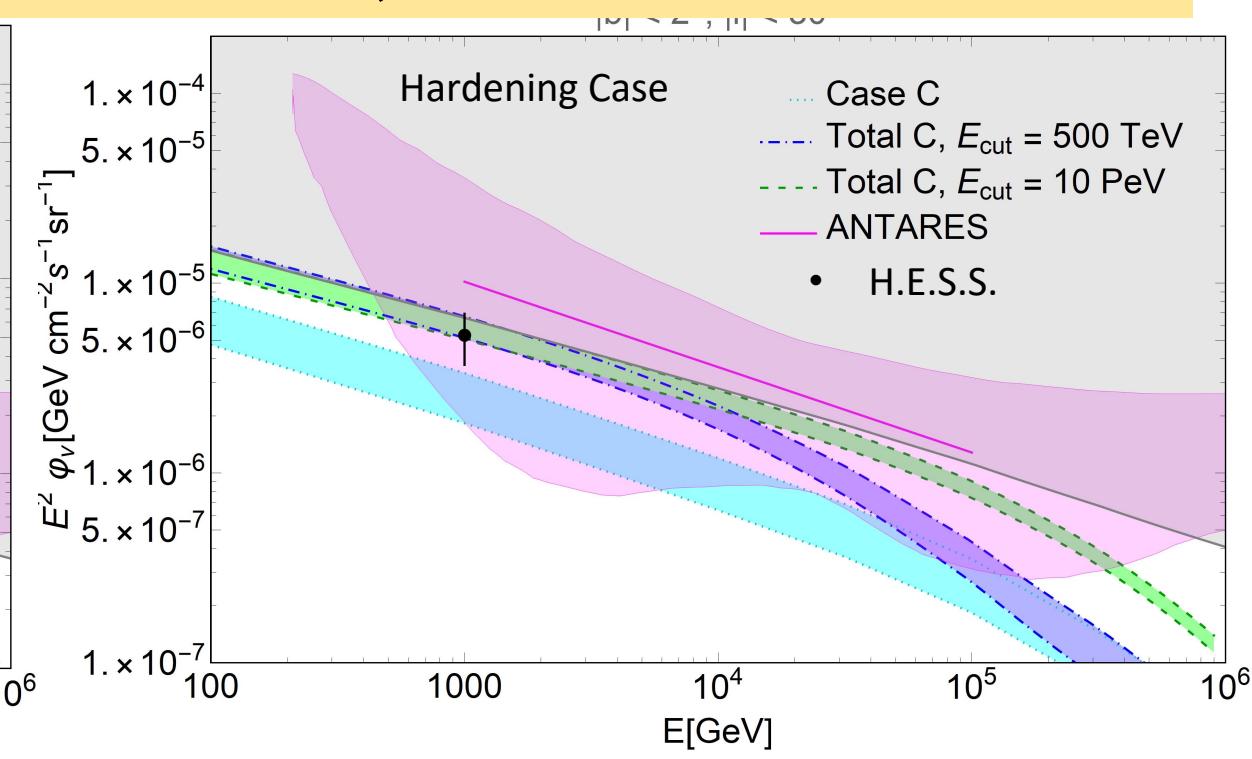
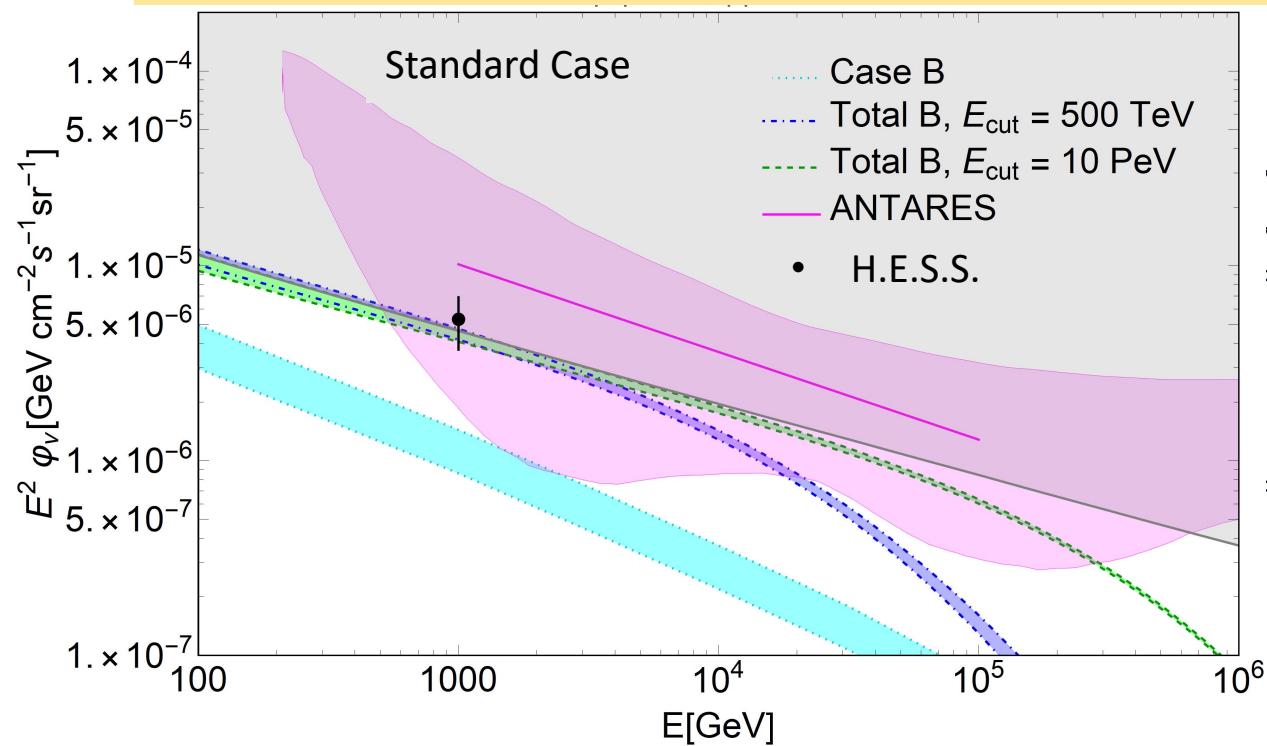
maximal neutrino flux from sources (1-100 TeV), the neutrino source contribution obtained by assuming that all the TeV gamma-ray sources are powered by hadronic processes

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

**ANTARES:** We add the source component to the diffuse emission in the Standard and the Hardening Cases.

arXiv:2306.16305

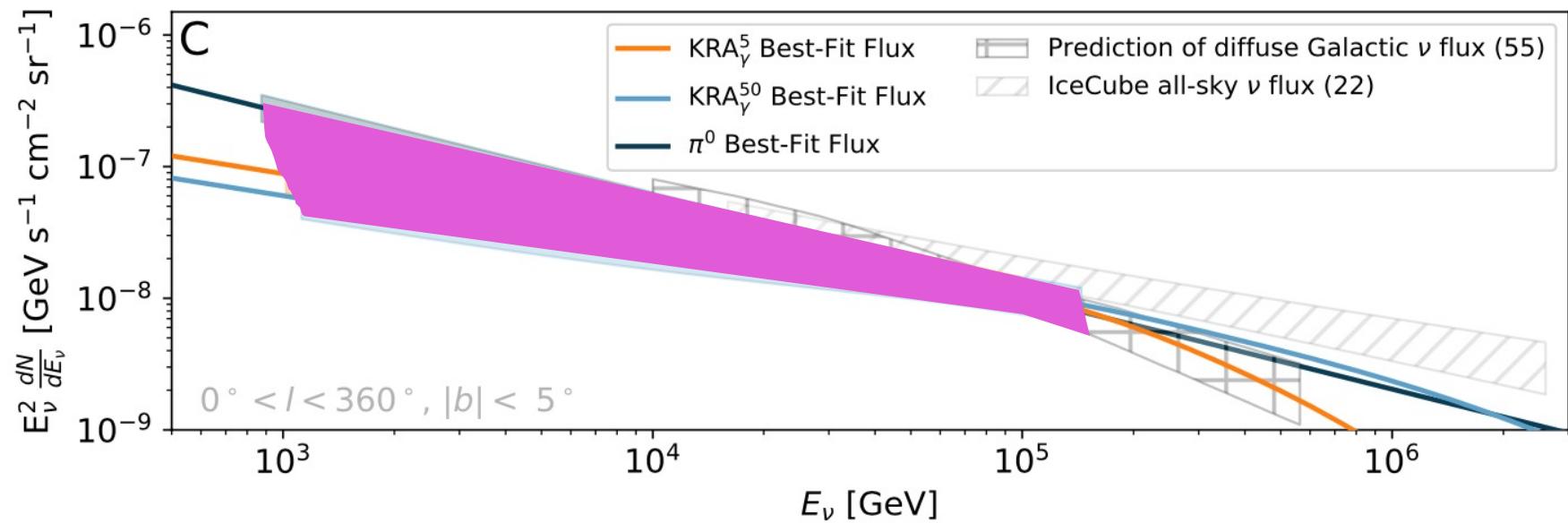
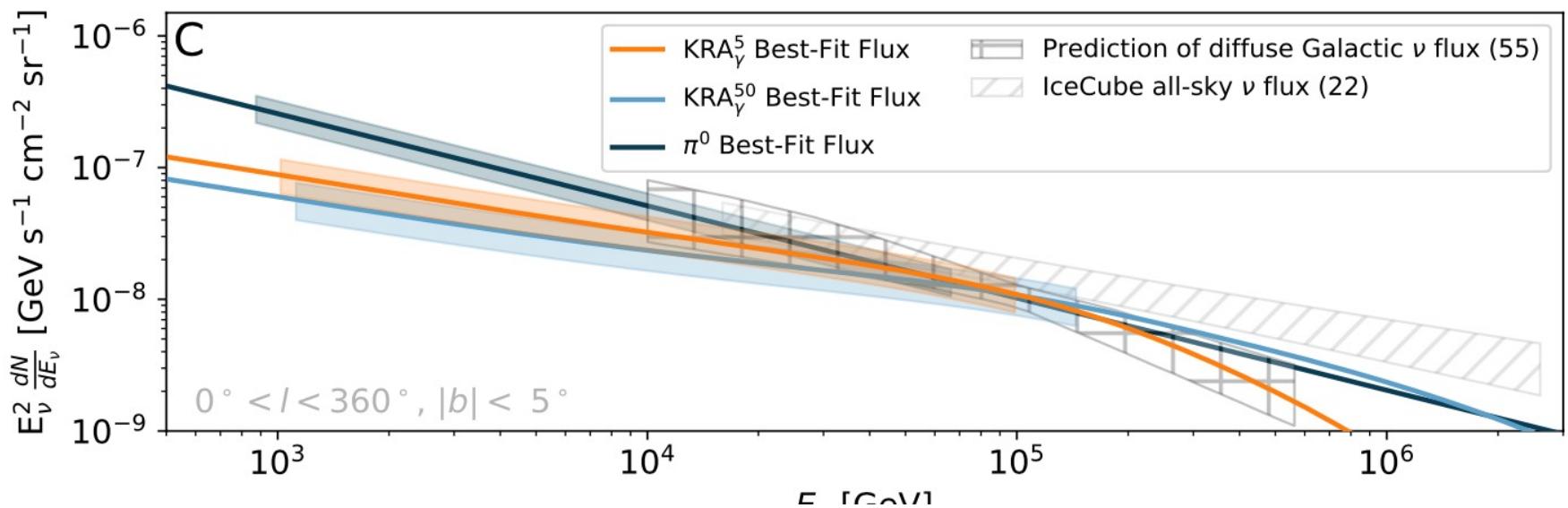
*All flavor,  $|l| < 30^\circ, |b| < 2^\circ, \xi = 1$*



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

# IceCube:

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

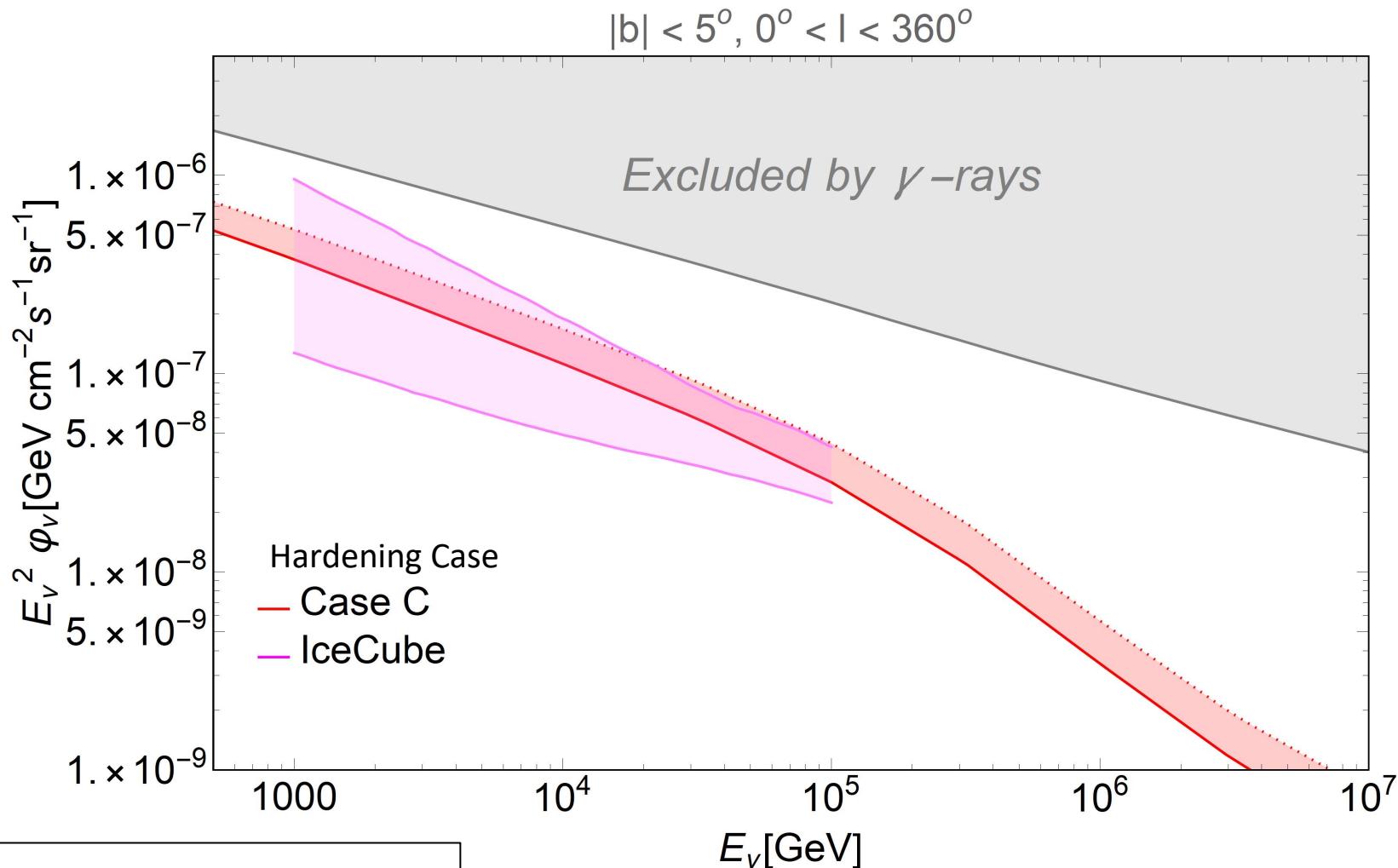


# IceCube vs CR spectral hardening:

arXiv:2307.07451

- In the scenario with a CR spectral hardening there is not space for the contribution of hadronic sources.

We expect PeVatrons in our Galaxy and the case C needs of hadronic sources to exists!

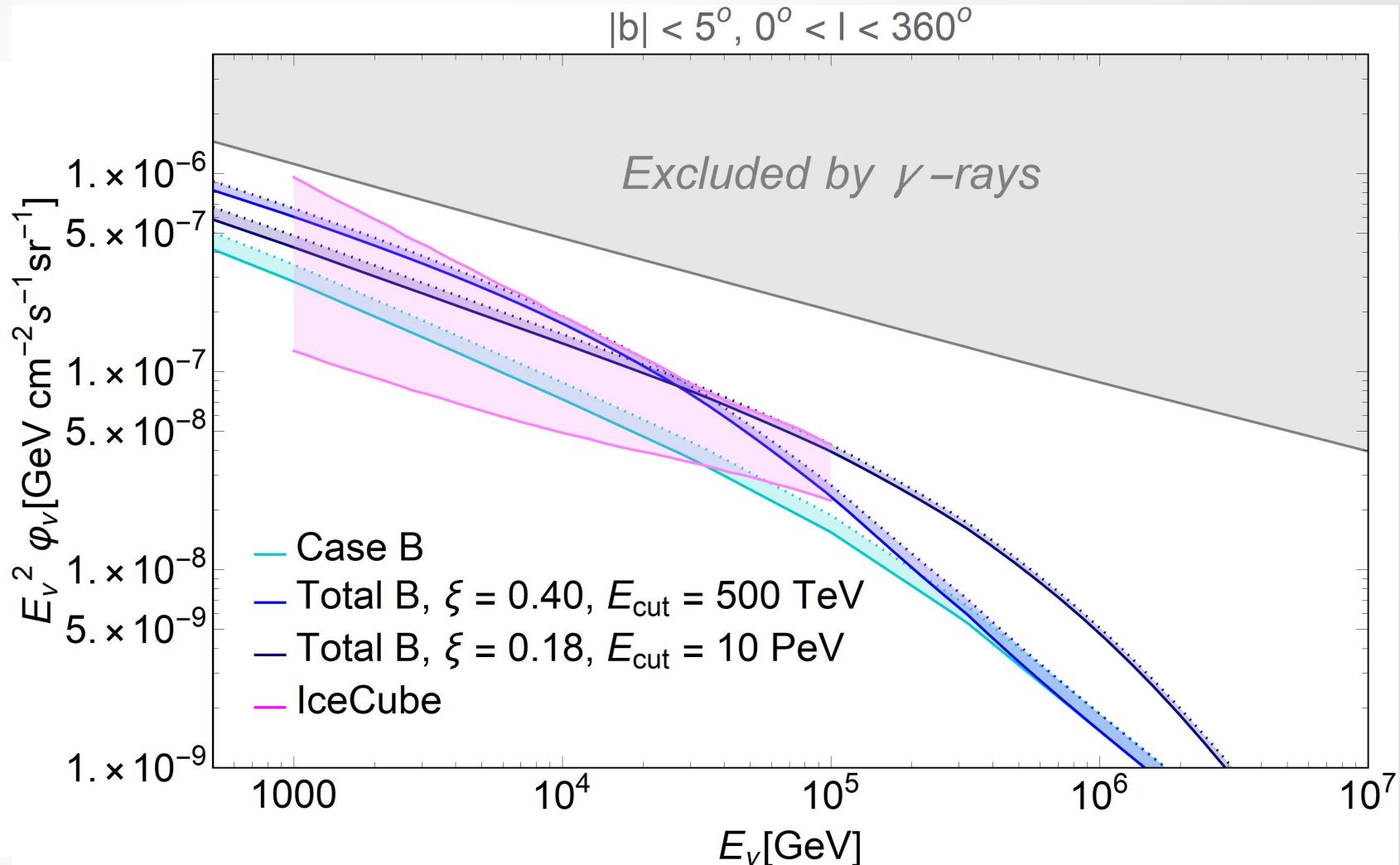


$$\varphi_{\nu, \text{diff}}^{\text{IceCube}} = \varphi_{\nu, S}(\xi, E_{\text{cut}}) + \varphi_{\nu, \text{diff}}$$

# IceCube:

arXiv:2307.07451

- In the scenario in which the CR spectrum is uniform within the Galaxy, the maximally allowed fraction is  $\xi < 0.40$  ( $E_{cut} = 500 \text{ TeV}$ ). If we require that Galactic sources should be able to accelerate particles up to the CR «knee» then the fraction reduces to  $\xi \sim 0.20$



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

# Conclusions:

We compared our prediction for the total neutrino galactic emission (including unresolved sources) with signal observed by ANTARES and IceCube;

The neutrino signal observed by ANTARES inside  $|l| < 30^\circ$ ,  $|b| < 2^\circ$  allows/requires a relevant hadronic source component;

The neutrino signal detected by IceCube requires 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 (strange!);
- 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

The fraction of hadronic sources depends on the assumed proton cutoff energy

- Up to »knee» (5 PeV) the maximal fraction is 20% corresponding to

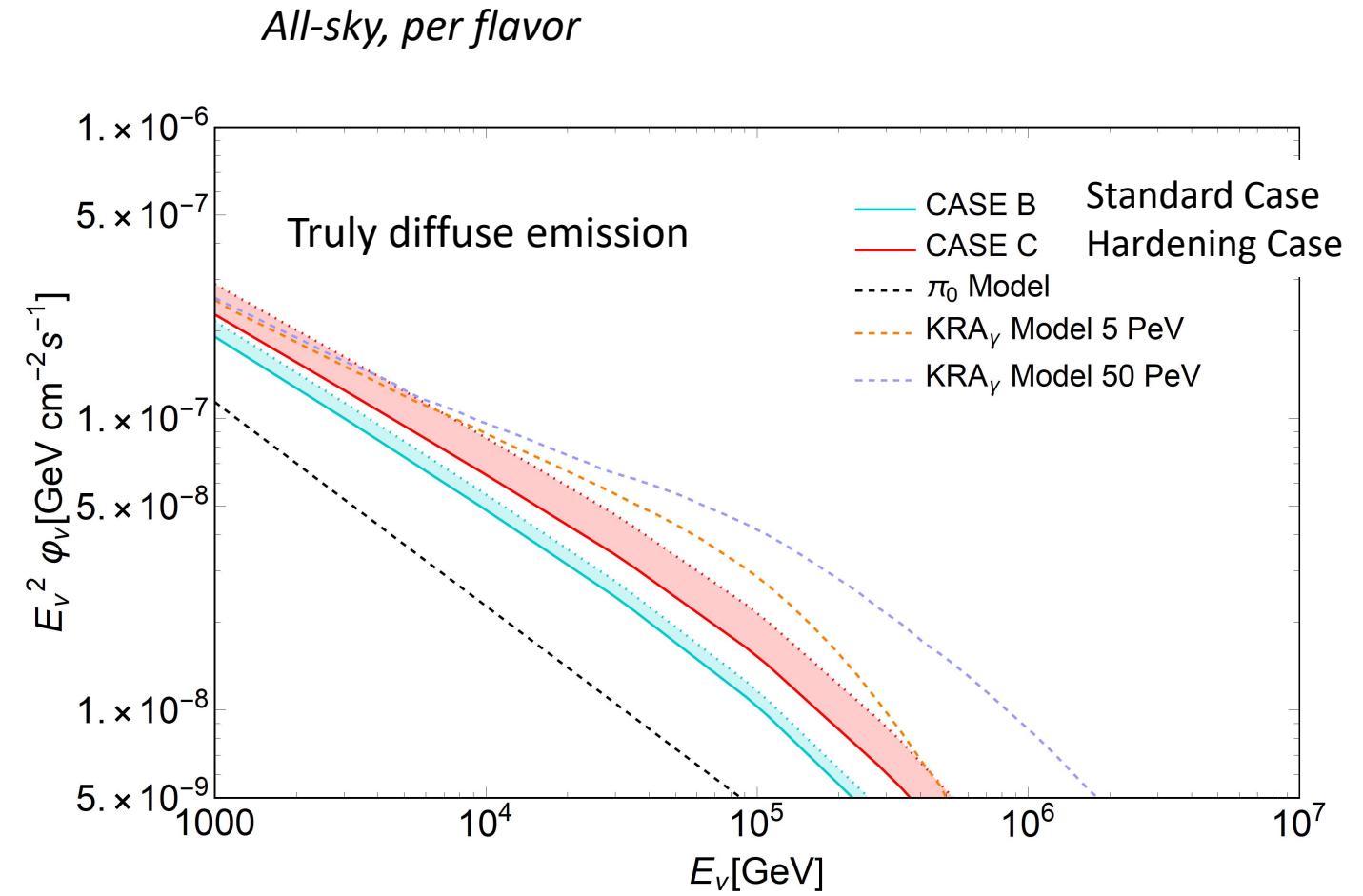
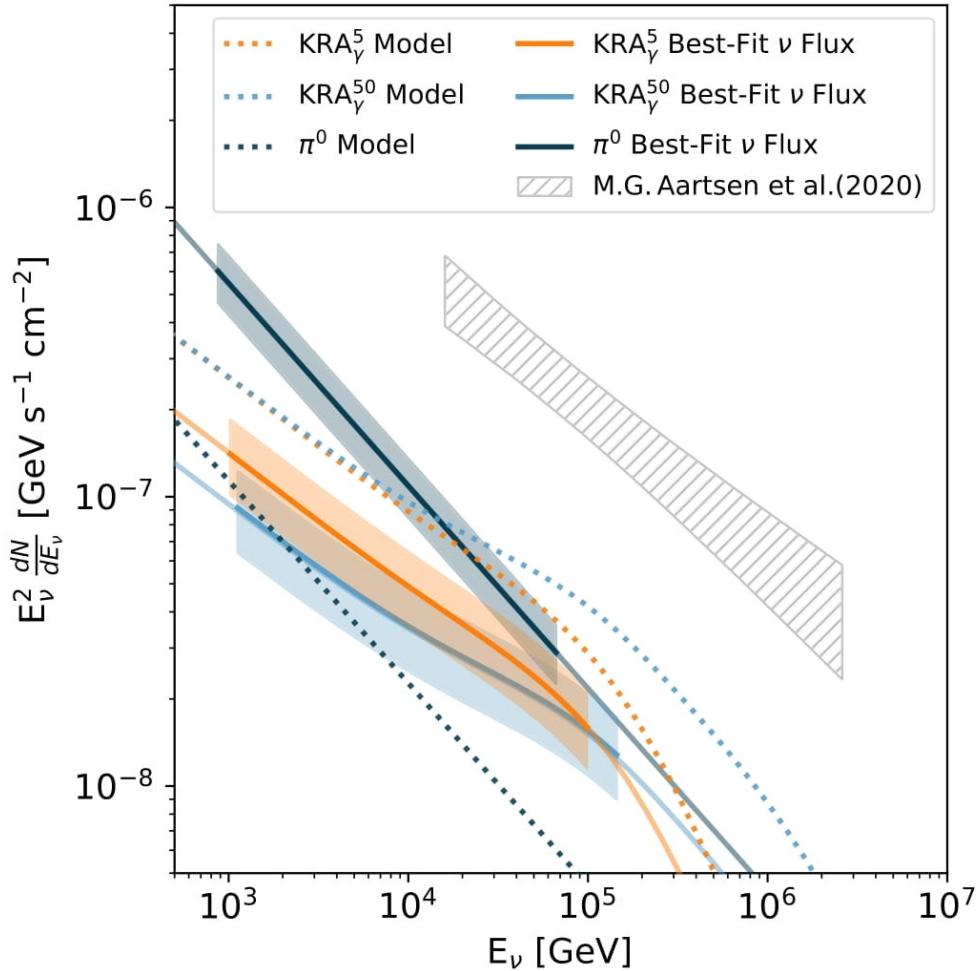
$$\Phi_{\nu,s} = 1.1 \cdot 10^{-10} \text{cm}^{-2}\text{s}^{-1}$$

In case B a comparable contribution to the IceCube signal is provided by sources and truly diffuse emission

8 SNR +8 composite inside the HGPS catalog provide:

$$\Phi_{\nu,s}^{HGPS} = 0.6 \cdot 10^{-10} \text{cm}^{-2}\text{s}^{-1}$$

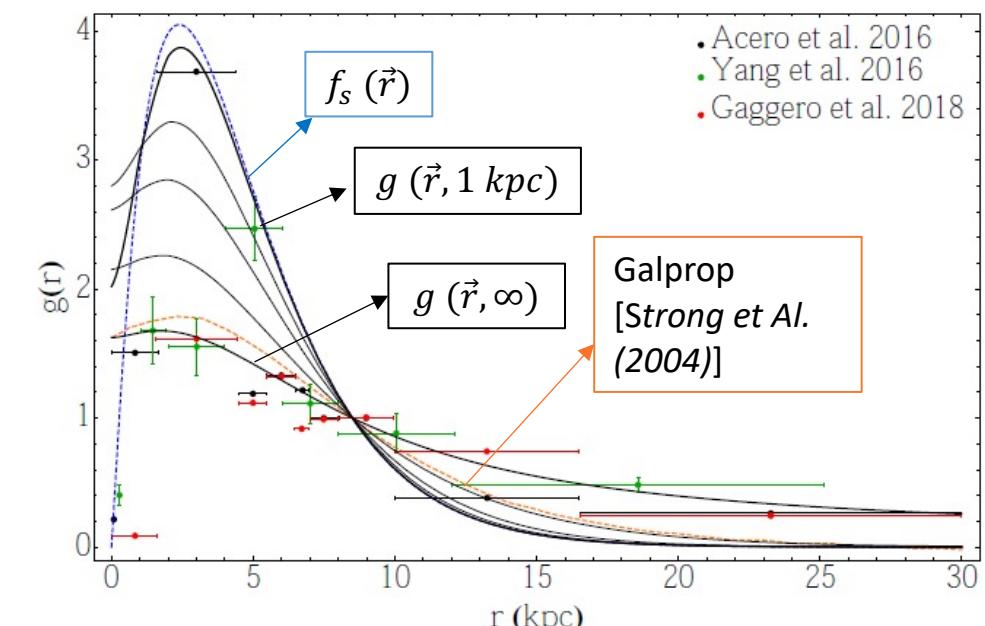
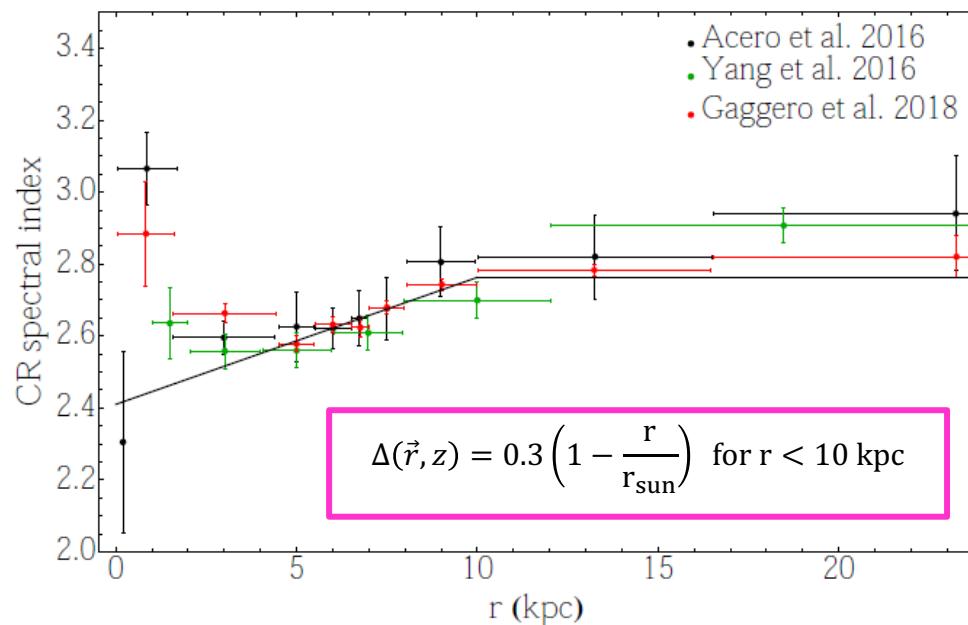
# Comparison of different models for the neutrino diffuse emission:



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

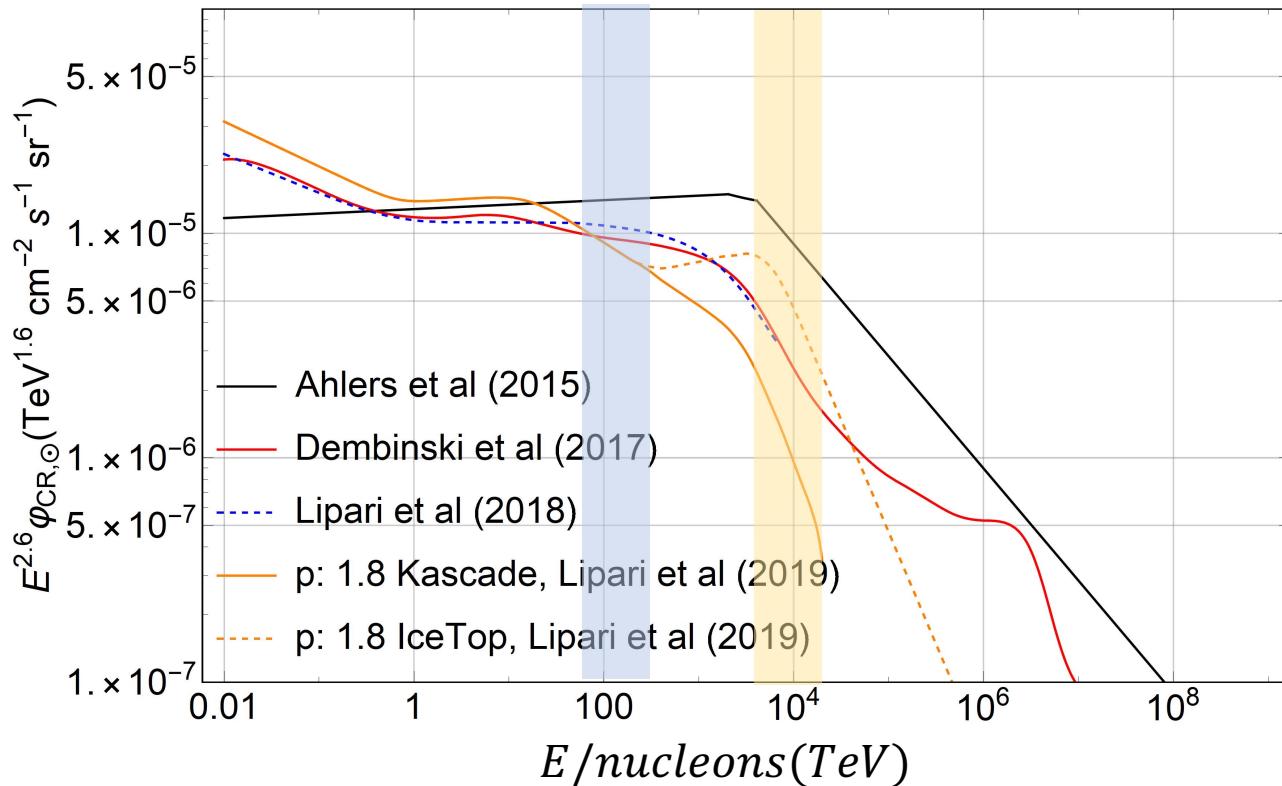
- ★ Data driven local CR spectrum [Dembinski, Engel, Fedynitch et al. (2018)]
- ★  $g(r)$  is determined by the distribution of the CR sources  $f_s(\vec{r})$  (proportional to the SNR number density by Green et al. (2015), and by the propagation of CR in the Galactic magnetic field.
- ★ **2 cases: with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

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



# Cosmic ray distribution:

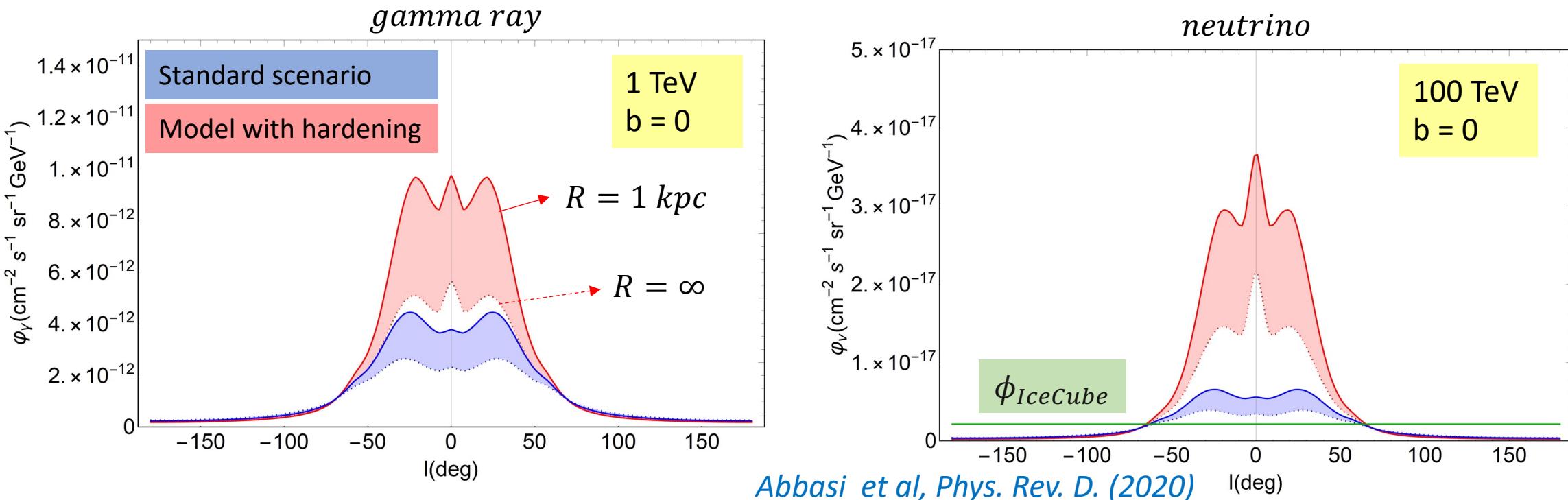
$$\varphi_{CR}(E, \vec{r}) = \varphi_{CR, Sun}(E) g(\vec{r}, R) h(E, \vec{r})$$



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

The gamma-ray (neutrino) flux at  $E_\gamma = 1 \text{ TeV}$  ( $E_\nu = 100 \text{ TeV}$ ) is determined by CRs with  $E_{CR} = 10 \text{ TeV}$  ( $E_{CR} = 2 \text{ PeV}$ );

# Diffuse Galactic $\gamma$ and $\nu$ emission:

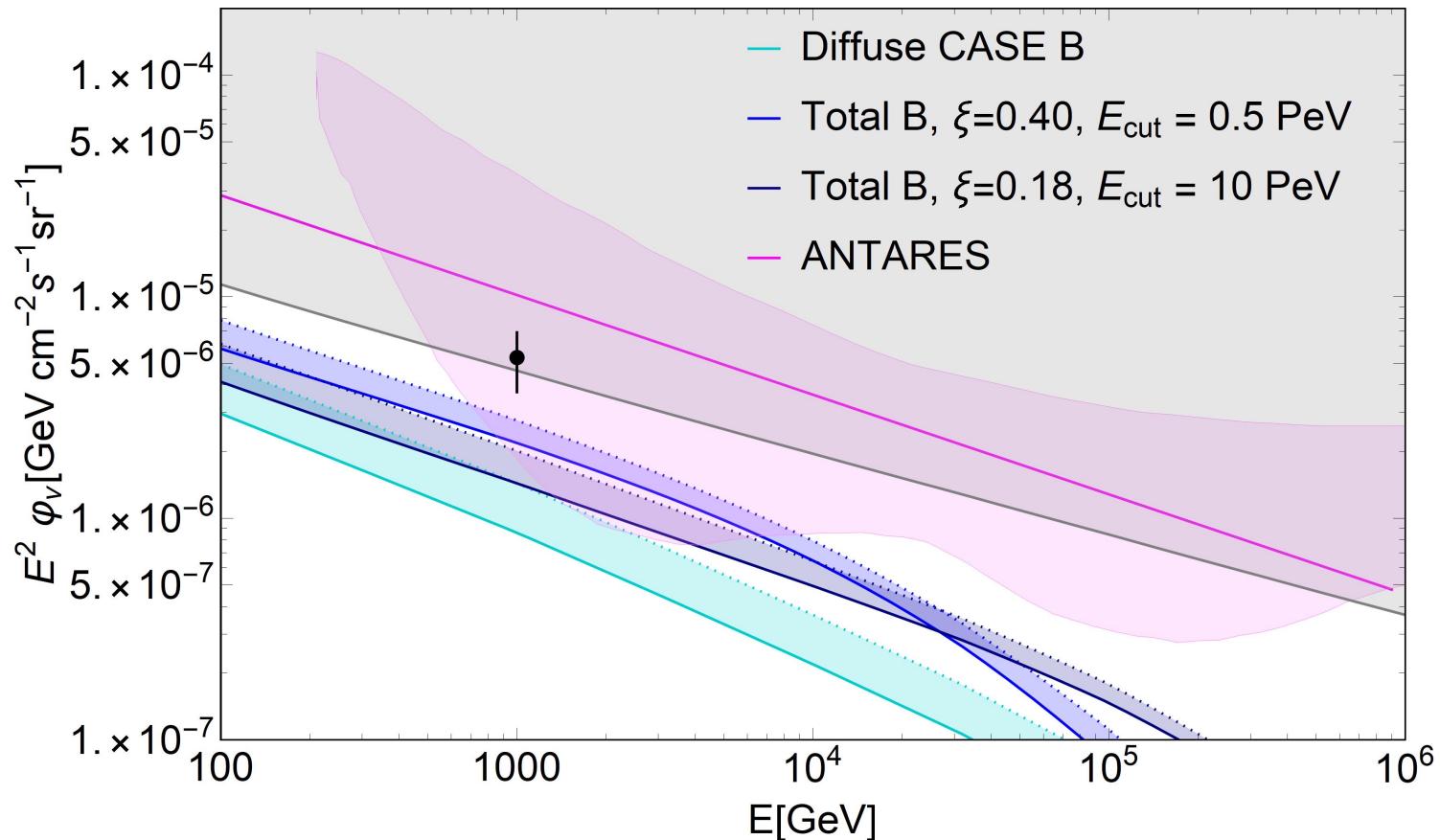


- The angle integrated  $\gamma$ -ray flux in the standard scenario is:  $\Phi_\gamma = (7.0 - 8.0) \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ GeV}^{-1}$ , and increases of a factor  $\sim 1.2$  in the hardening case.
- In the region  $|l| < 60^\circ$ ,  $|b| < 2^\circ$ , this factor becomes  $\sim 2(\sim 3)$  for  $\gamma$  ( $\nu$ ) respectively;
- The angle integrated neutrino flux is 3.9 % - 4.4 % (5.8 % - 8.2%) of the isotropic flux observed by IceCube (Abbasi et al, Phys. Rev. D. (2020)). Potentially observable in specific region of the sky.

*Pagliaroli et al, JCAP (2016), Pagliaroli et al, JCAP (2018)*

# ANTARES:

$$|l| < 30^\circ, |b| < 2^\circ$$

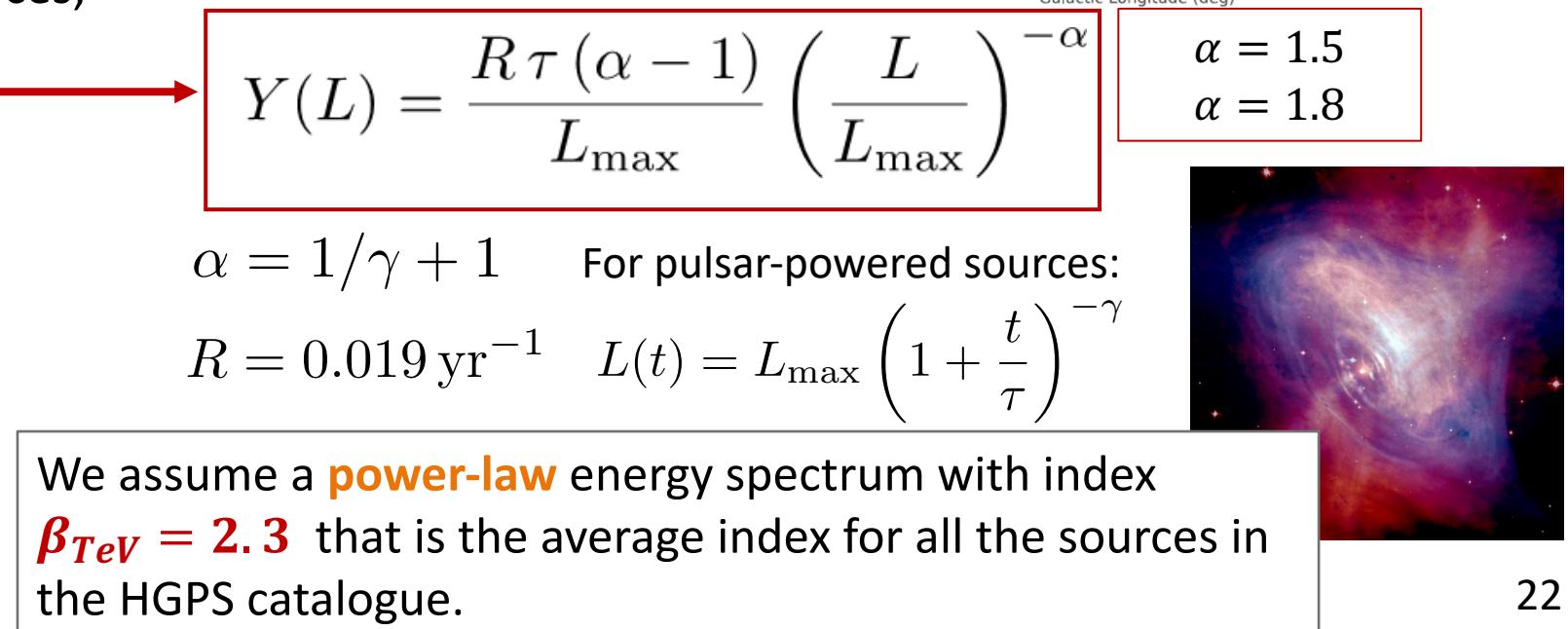
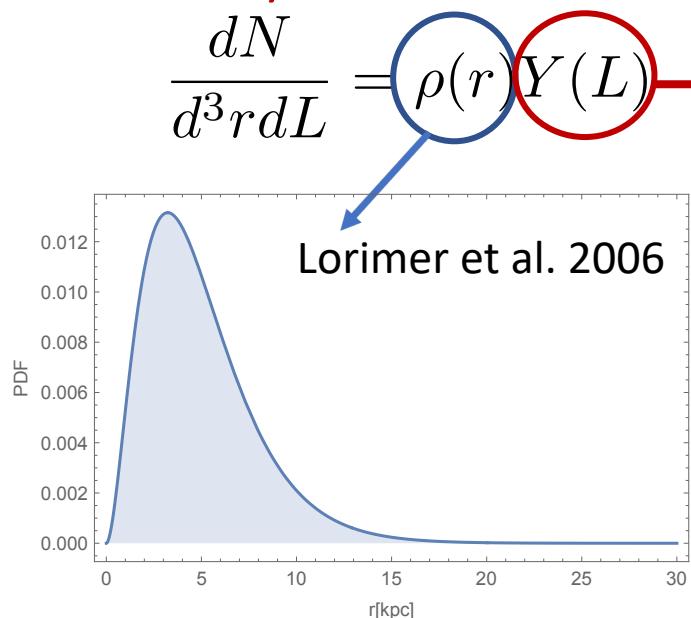


$$\varphi_{\nu, \text{diff}}^{\text{Antares}} = \varphi_{\nu, S}(\xi, E_{\text{cut}}) + \varphi_{\nu, \text{diff}}$$

# Study of the sources population in the TeV range:

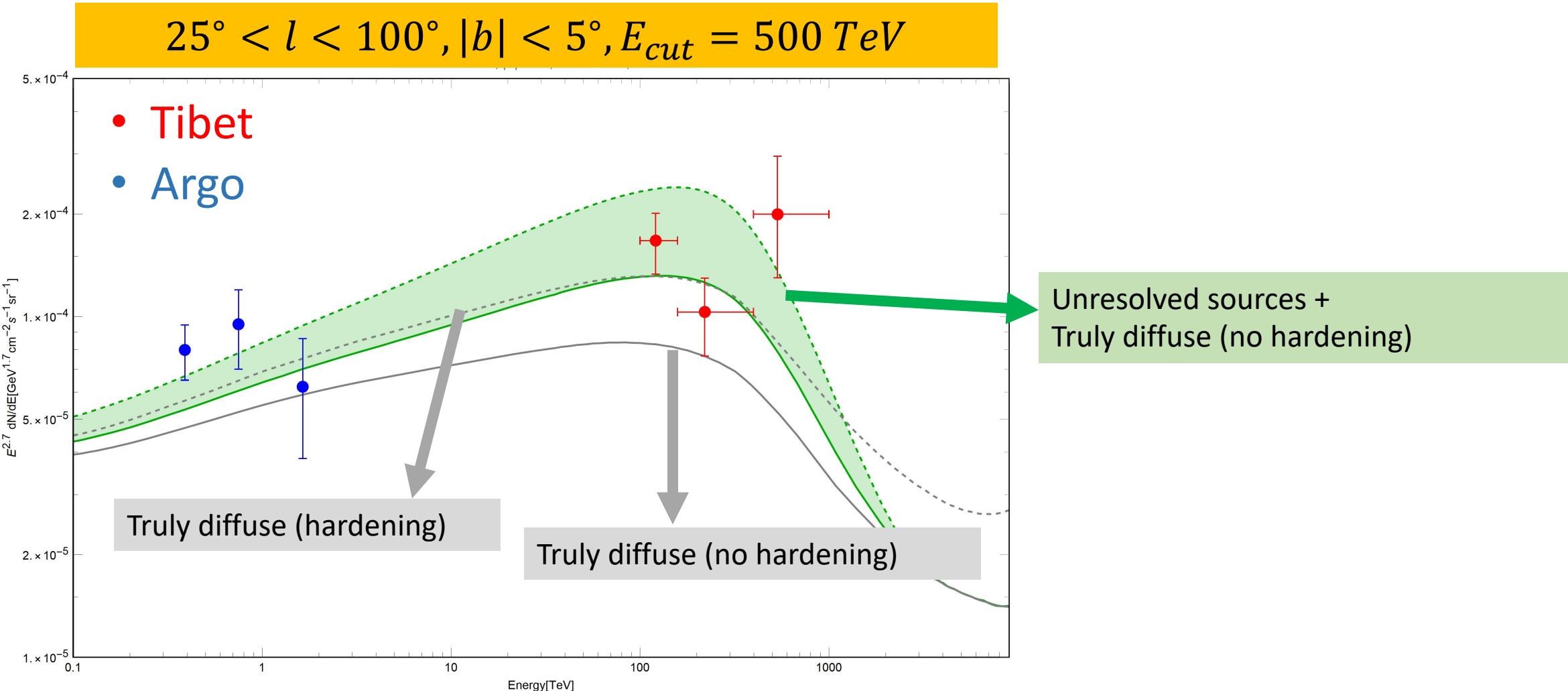
Cataldo et al. *Astrophys.J.* 904 (2020)

- 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;



**Tibet AS $\gamma$**  : We add the contribution of unresolved sources to the truly diffuse emission without the hypothesis of CR spectral hardening.

*Definition: Hardening  $\equiv$  spatially dependent CR spectral index*



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