INFN
Istituto Nazionale di Fisica Nucleare

High-Energy Neutrinos from the Galactic Plane and the Galactic Hadronic sources

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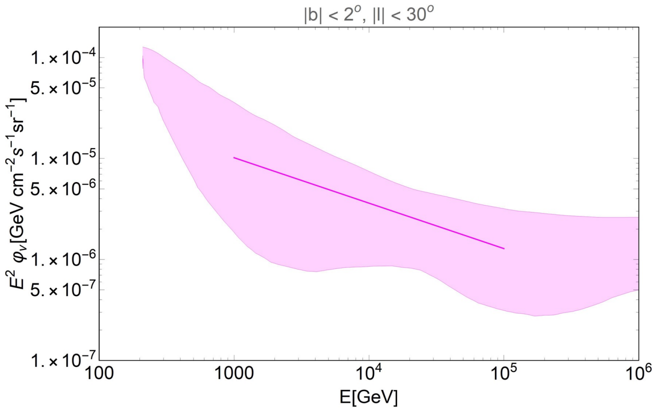
Based on
Vecchiotti *et al., Astrophys.J.Lett.* 956 (2023) 2, L44 and *JCAP* 09 (2023) 027
in collaboration with: F. L. Villante and V. Vecchiotti

RICAP 24

Large-scale neutrino diffuse emission

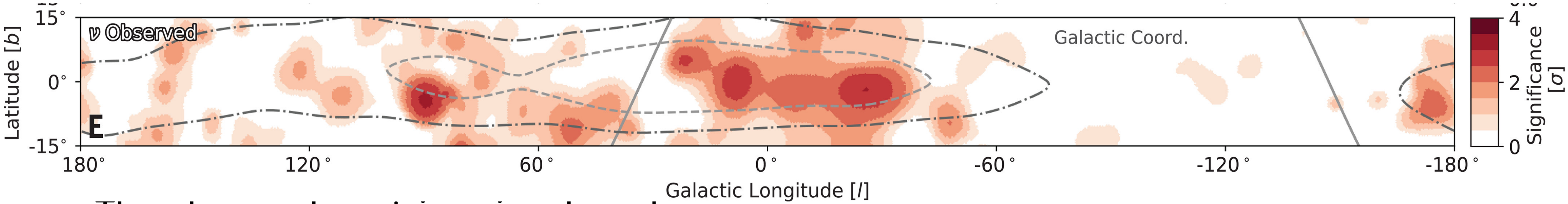
$\varphi_{\nu,\text{tot}}^{Antares}$ → First hint of neutrino emission from the Galactic ridge (2.2σ evidence)

Albert, A., et al. 2023, Phys. Lett. B, 841, 137951



$\varphi_{\nu,\text{tot}}^{IceCube}$ → Detection 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: $\varphi_{\nu,tot} = \varphi_{\nu,S} + \varphi_{\nu,diff}$

Large-scale neutrino diffuse emission

ν

$\varphi_{\nu,tot}^{Antares}$ → First hint of neutrino emission from the Ga

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

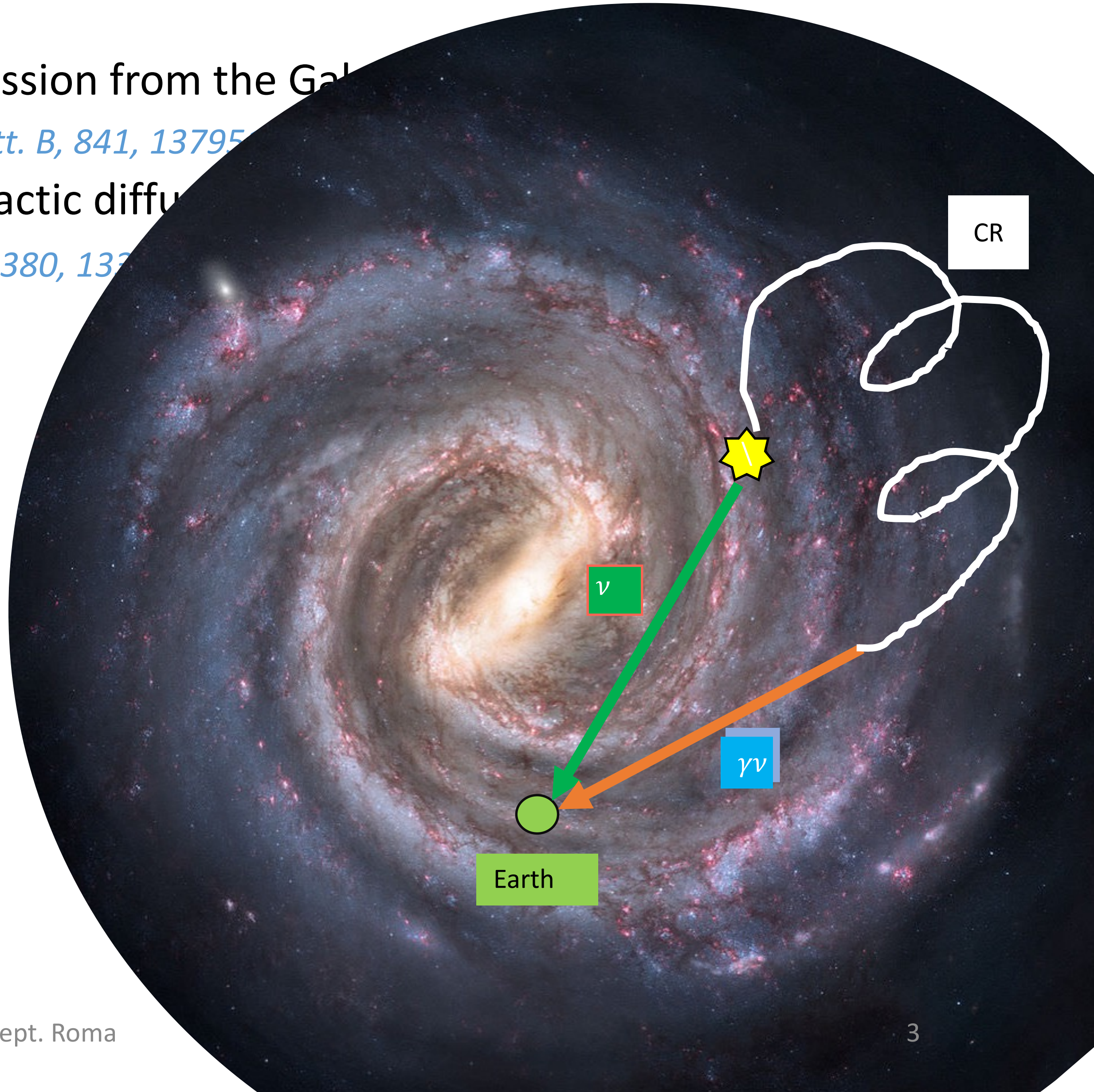
$\varphi_{\nu,tot}^{IceCube}$ → Measurement of the Galactic diffu

Abbasi, R, et al. 2023, Science, 380, 13

The observed neutrino signal can be interpreted as:

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

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



Truly 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,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.

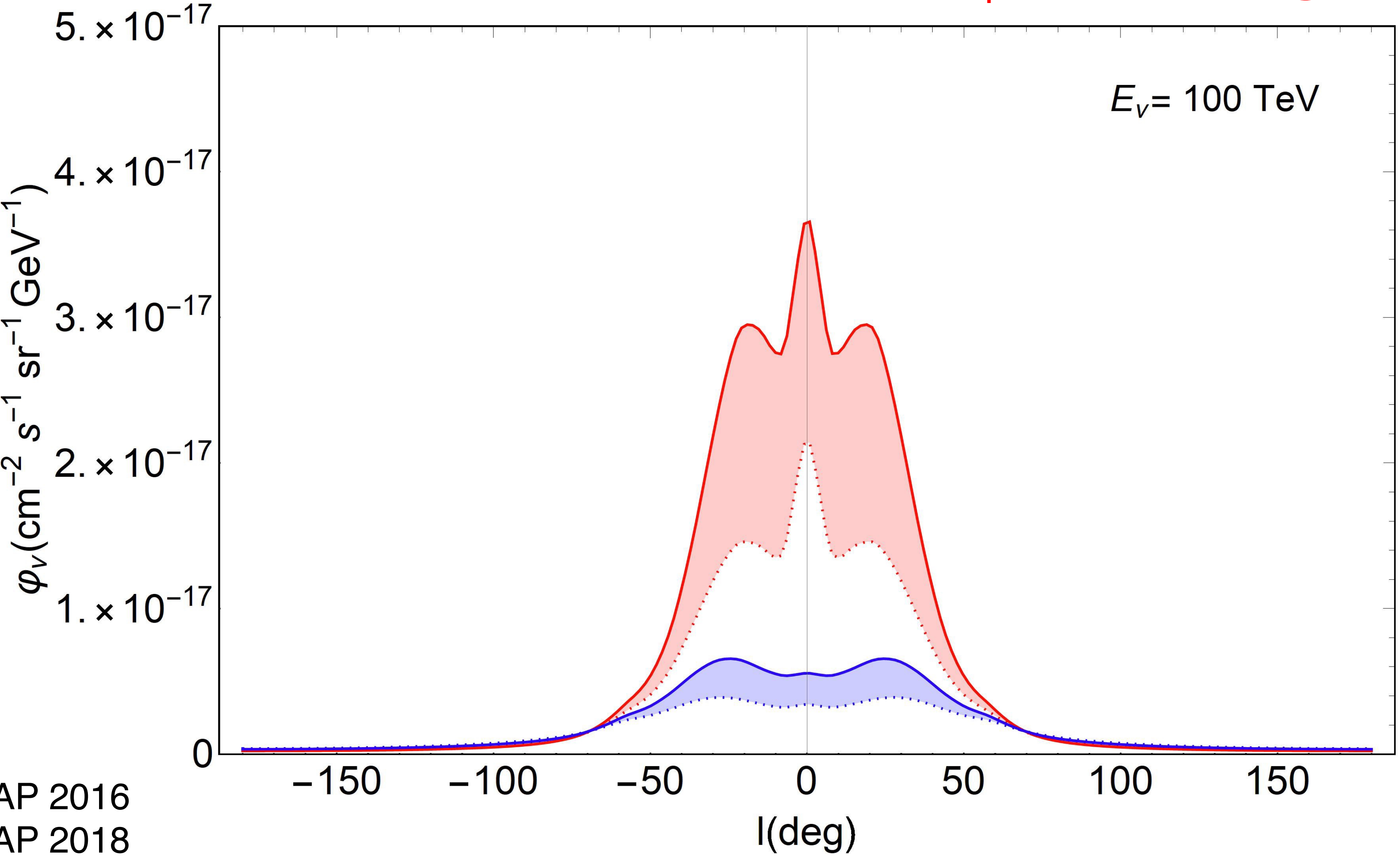
Standard Case B

Hardening Case C

Truly Diffuse Galactic ν 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

Pagliaroli et al, JCAP 2016
Pagliaroli et al, JCAP 2018

Large-scale neutrino diffuse emission

ν

$\varphi_{\nu,\text{tot}}^{Antares}$ ⇨ First hint of neutrino emission from the Ga

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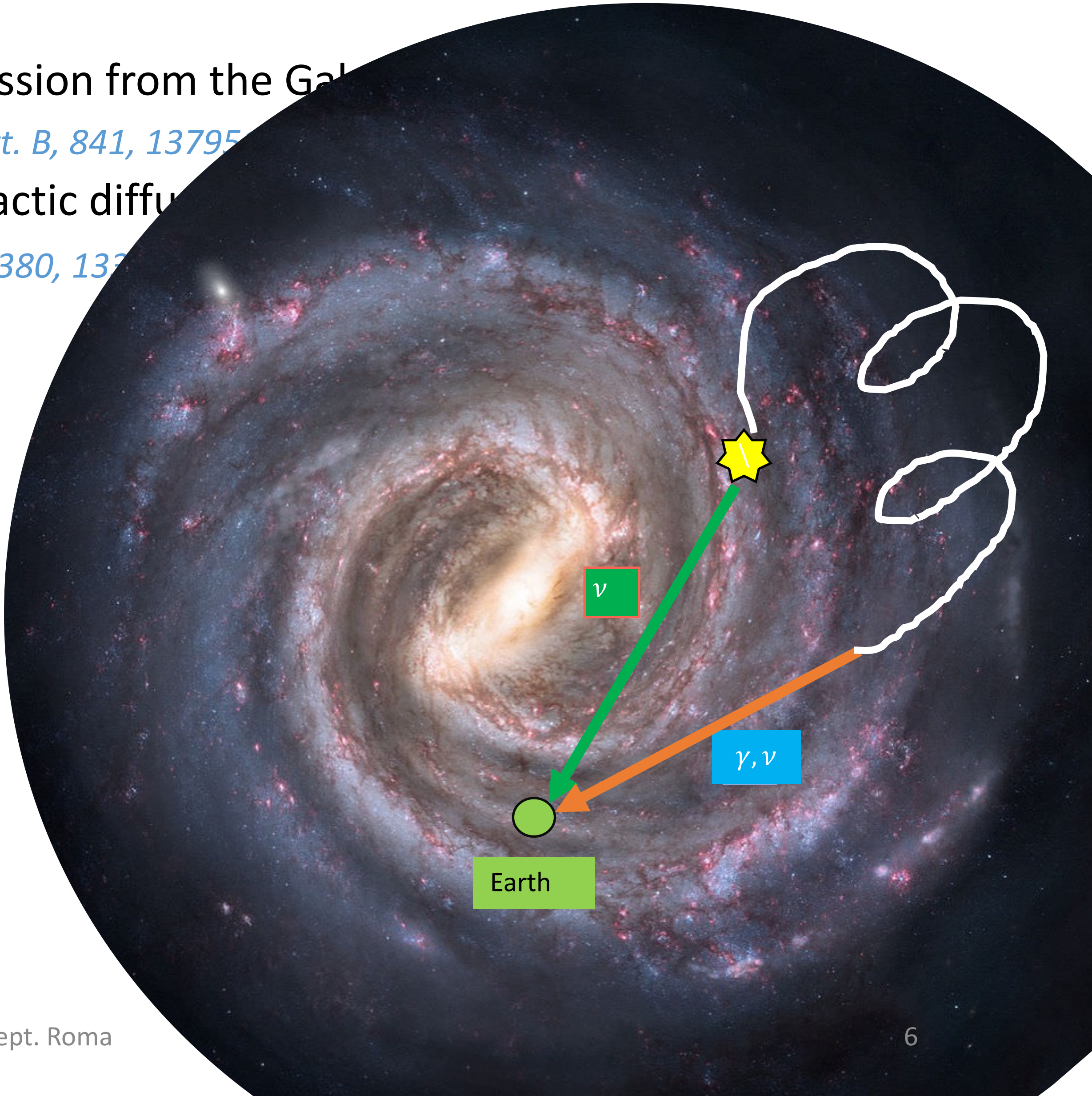
The observed neutrino signal can be interpreted as:

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

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).

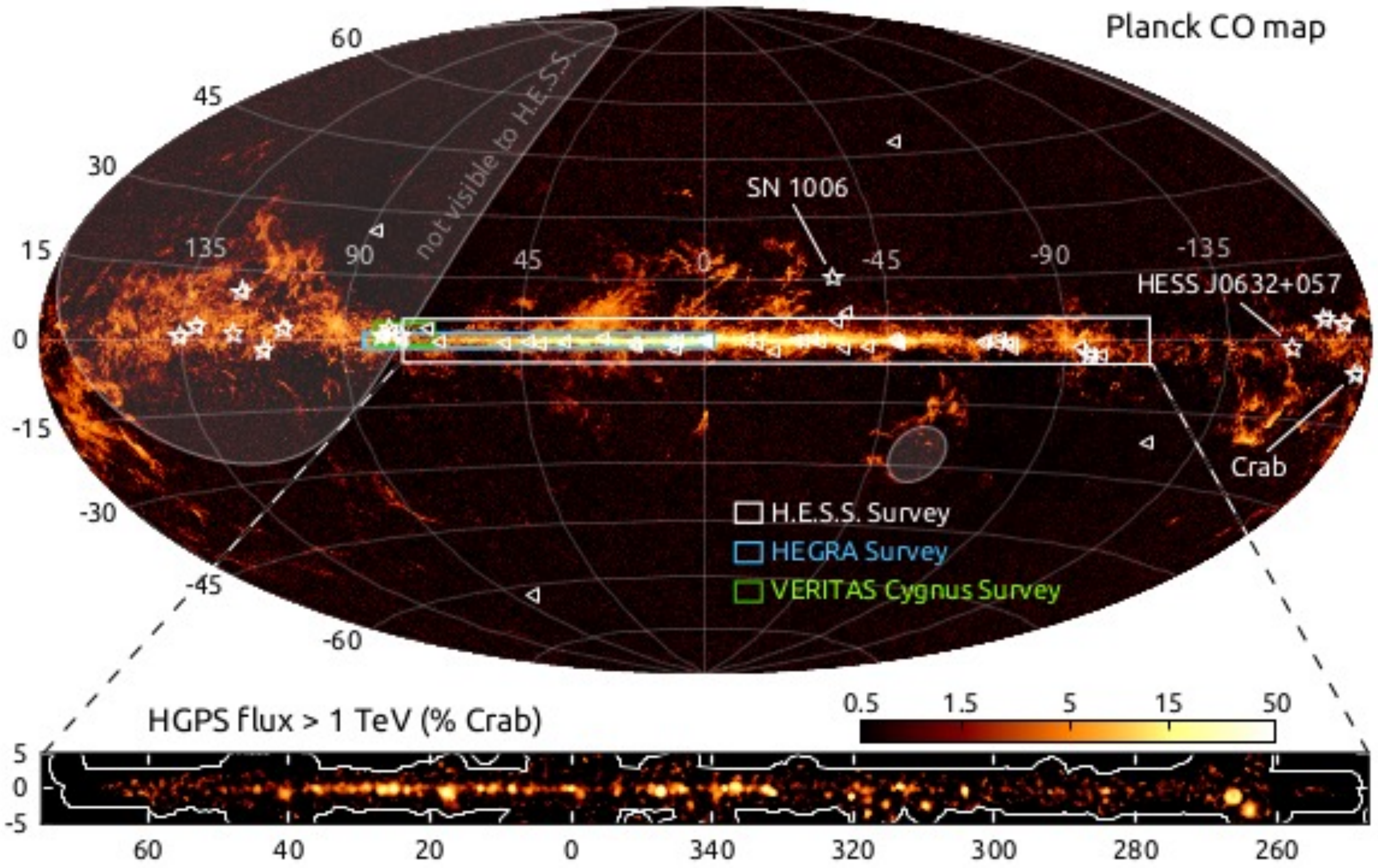


Galactic Sources

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

Sources catalogs

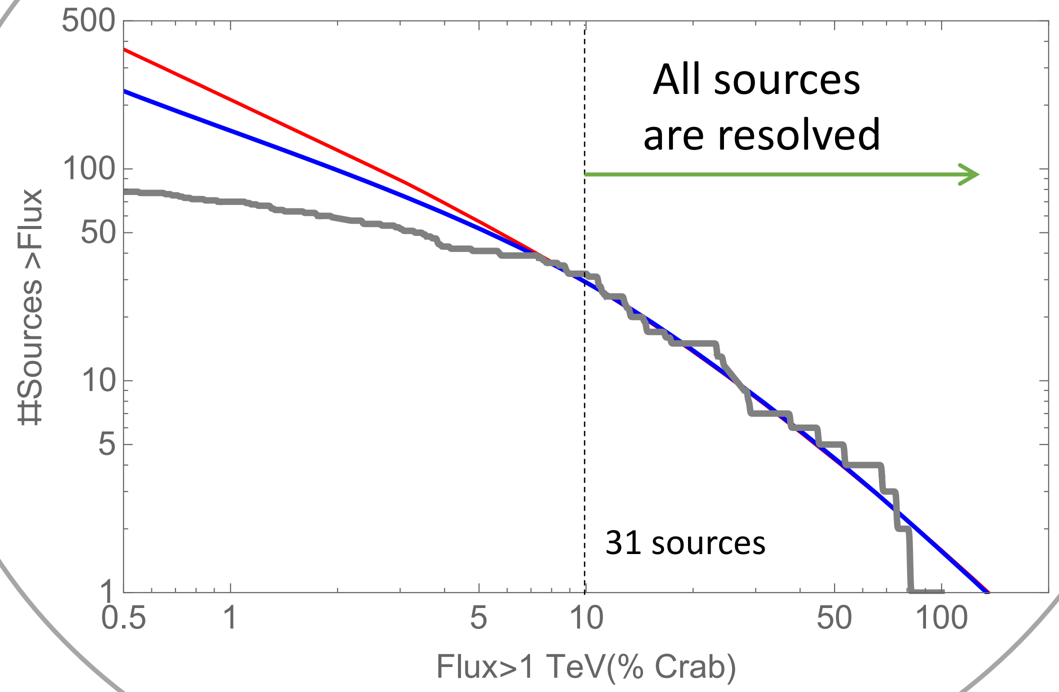
Sources Population study based on HGPS catalog of H.E.S.S.



Source component:

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

Cumulative distribution of HGPS



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

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

- 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 <u>unresolved</u> sources

Connection gamma-ray to neutrino sources:

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

- CR injected spectrum:

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

$\beta = 2.4$ *(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.

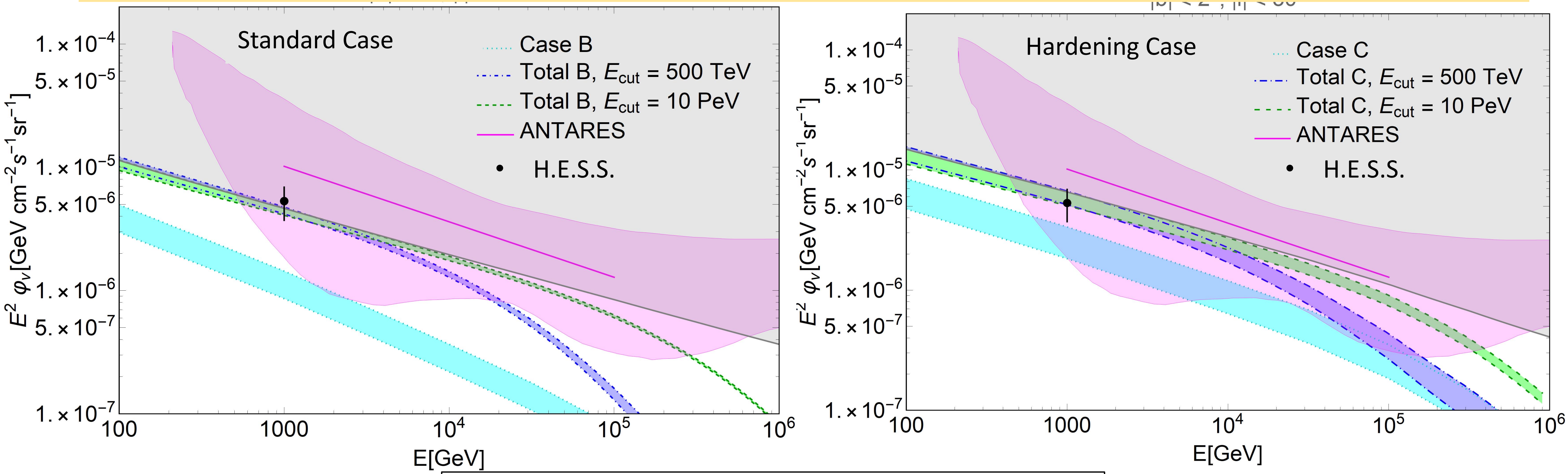
maximal neutrino flux from sources (1-100 TeV), the neutrino source contribution obtained by assuming that all the TeV gamma-ray sources are powered by hadronic processes

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

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

arXiv:2306.16305

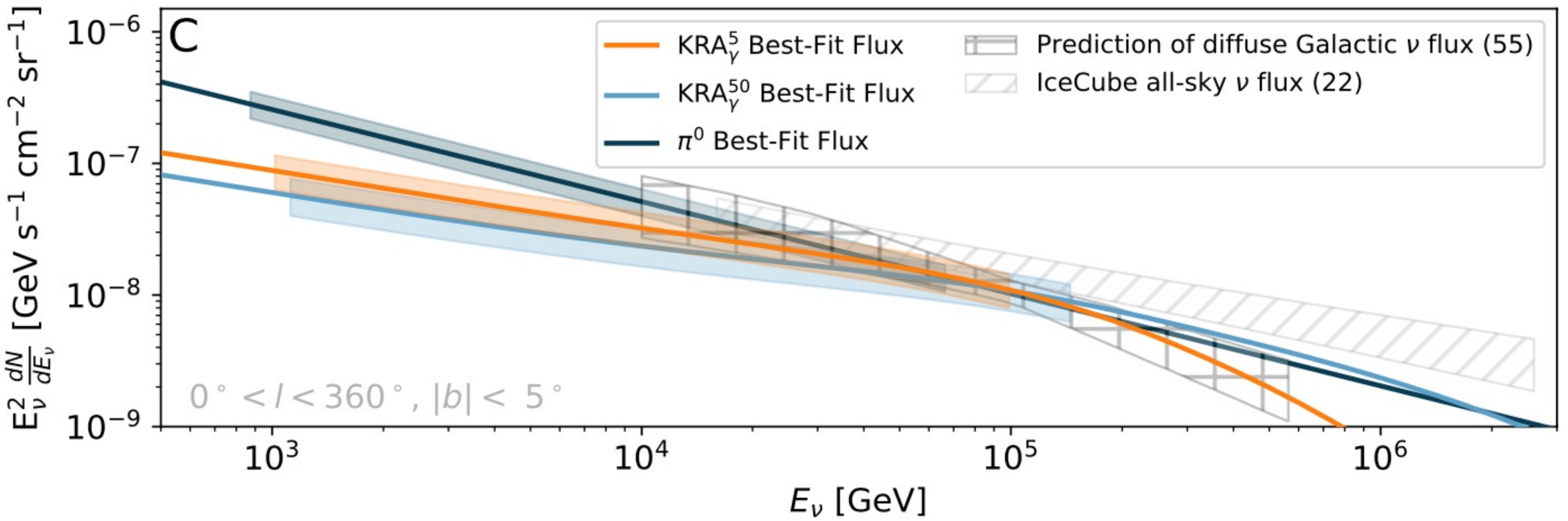
All flavor, $|l| < 30°, |b| < 2°, \ \xi = 1$

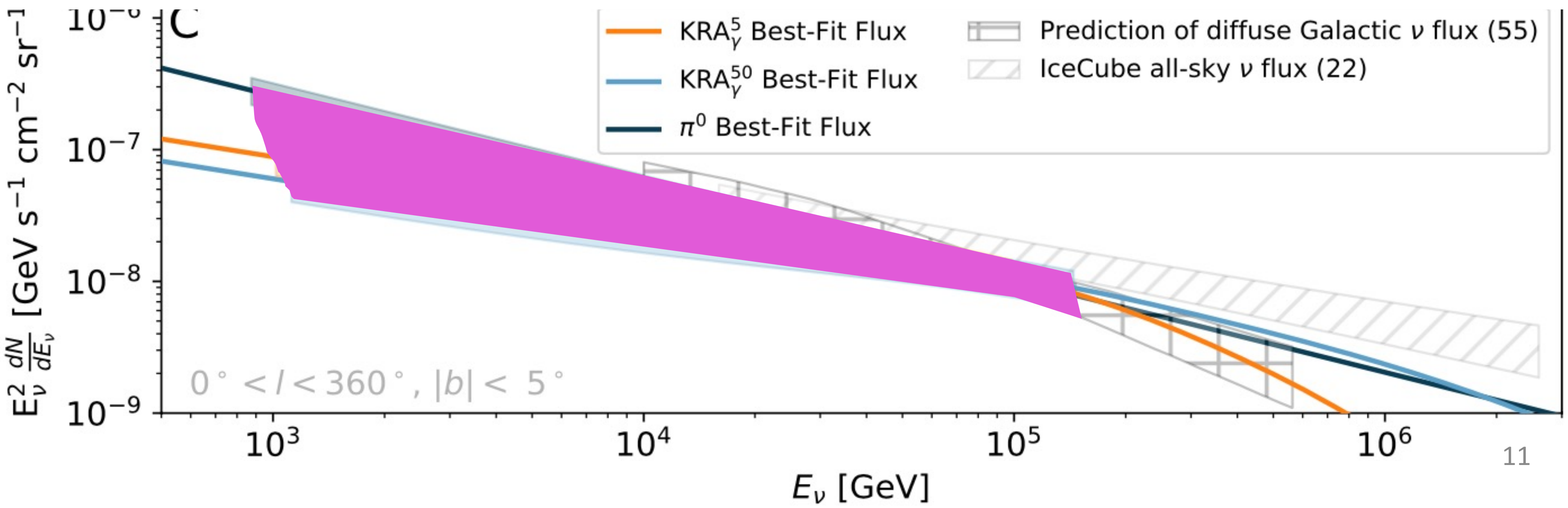


$$\varphi_{\nu,\mathrm{diff}}^{Antares} = \varphi_{\nu,S}(\xi, E_{\mathrm{cut}}) + \varphi_{\nu,\mathrm{diff}}$$

IceCube:

All flavor, $0° < l < 360°, |b| < 5°$



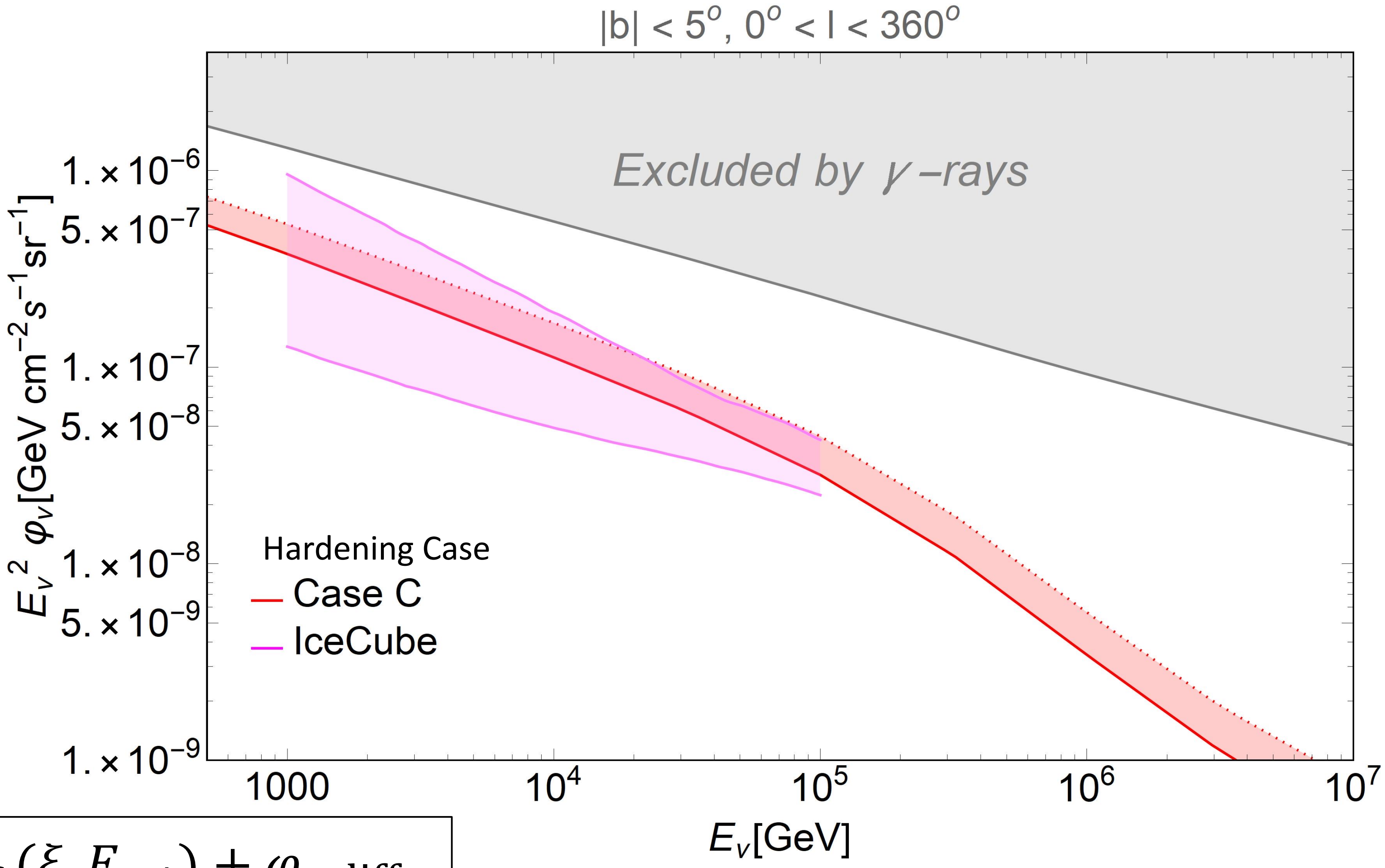


IceCube vs CR spectral hardening:

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!

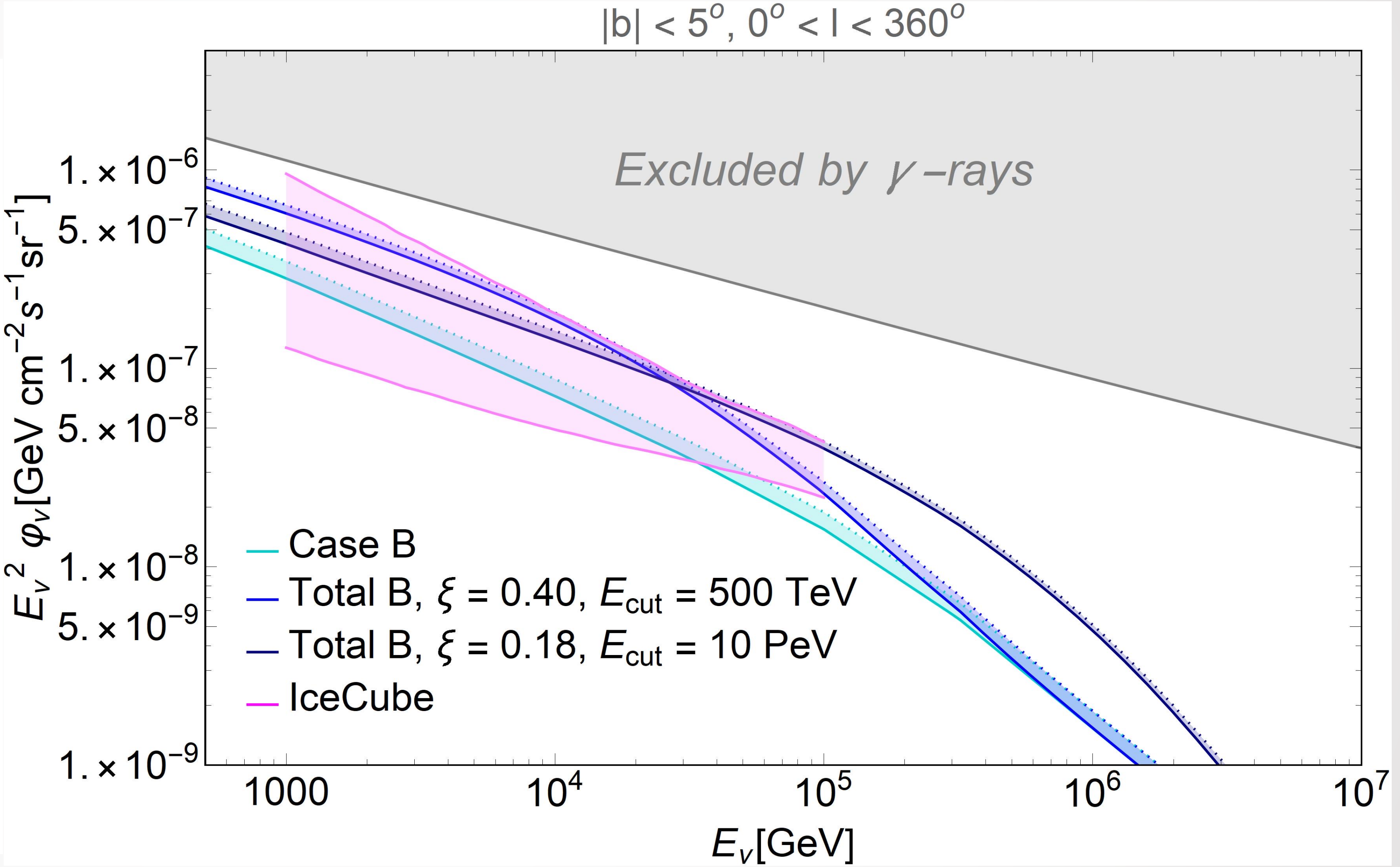


$$\varphi_{\nu,\mathrm{diff}}^{IceCube} = \varphi_{\nu,S}\,(\xi, E_{\mathrm{cut}}) + \varphi_{\nu,\mathrm{diff}}$$

IceCube:

arXiv:2307.07451

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



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

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 $|l| < 30°, |b| < 2°$ 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 $\xi \sim 0.20$;


Thank You

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

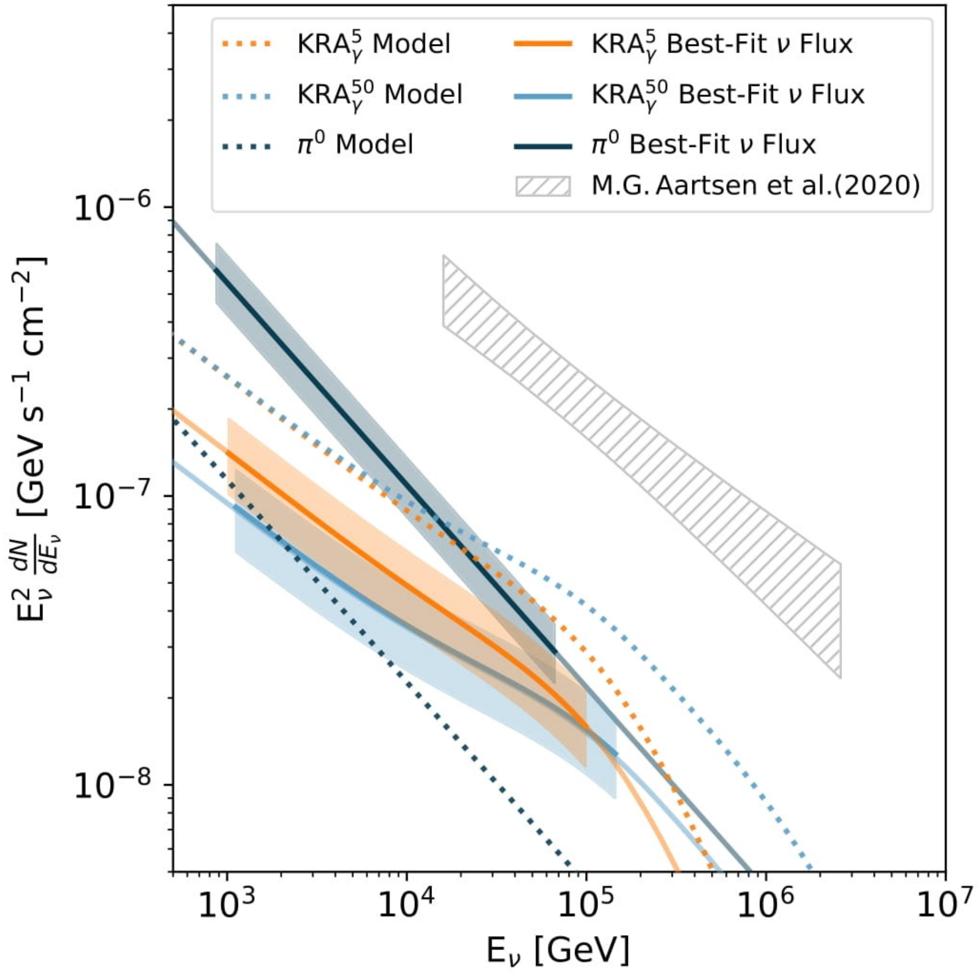
$$\Phi_{\nu,s} = 1.1 \cdot 10^{-10} cm^{-2} s^{-1}$$

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

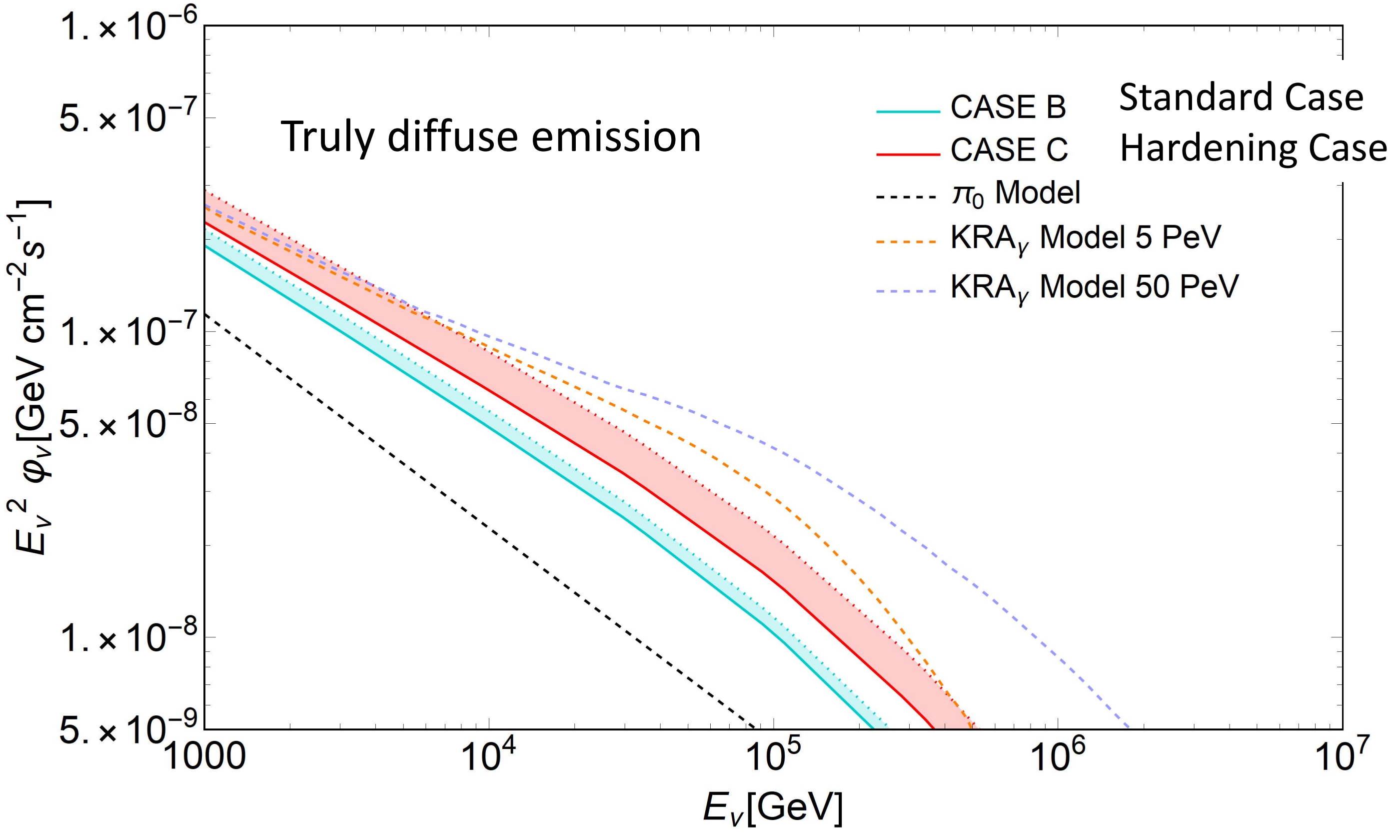
8 SNR +8 composite inside the HGPS catalog provide:

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

Comparison of different models for the neutrino diffuse emission:



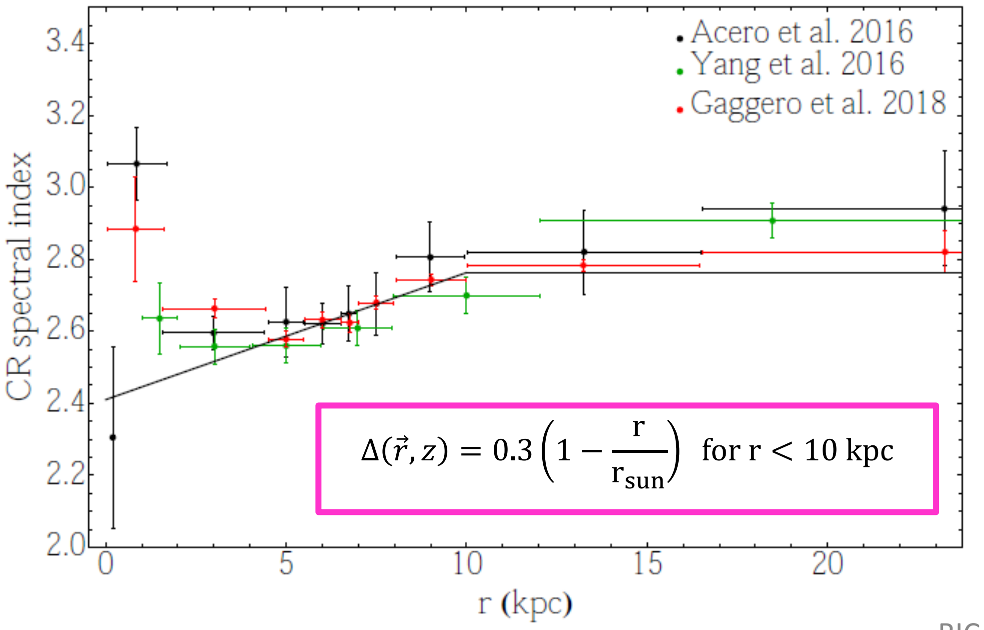
All-sky, per flavor

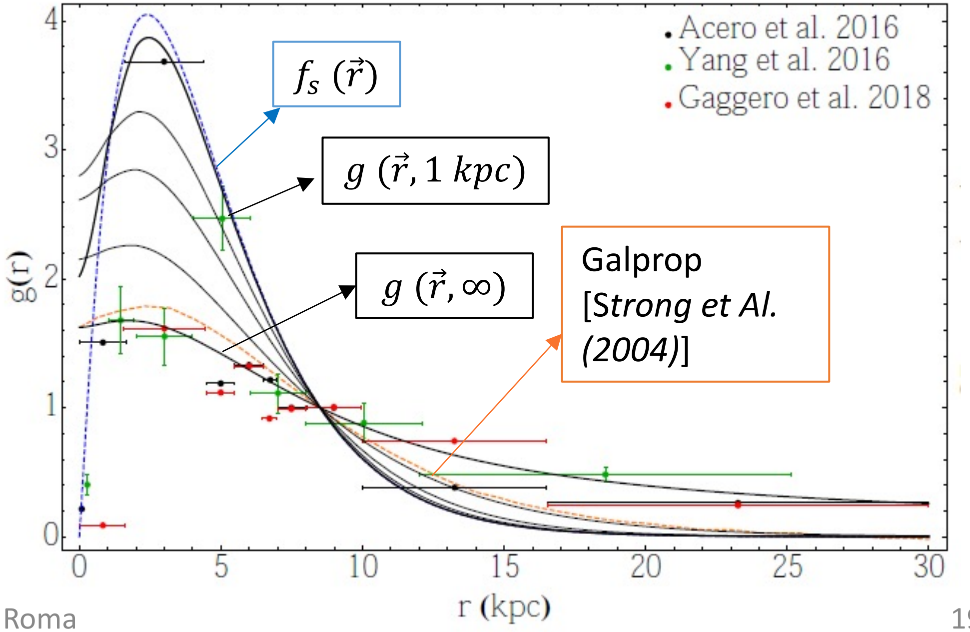


Cosmic ray distribution: $\varphi_{CR}(E,\vec{r}) = \varphi_{CR,Sun}(E)\, g(\vec{r},R)\, h(E,\vec{r})$

- 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)*])

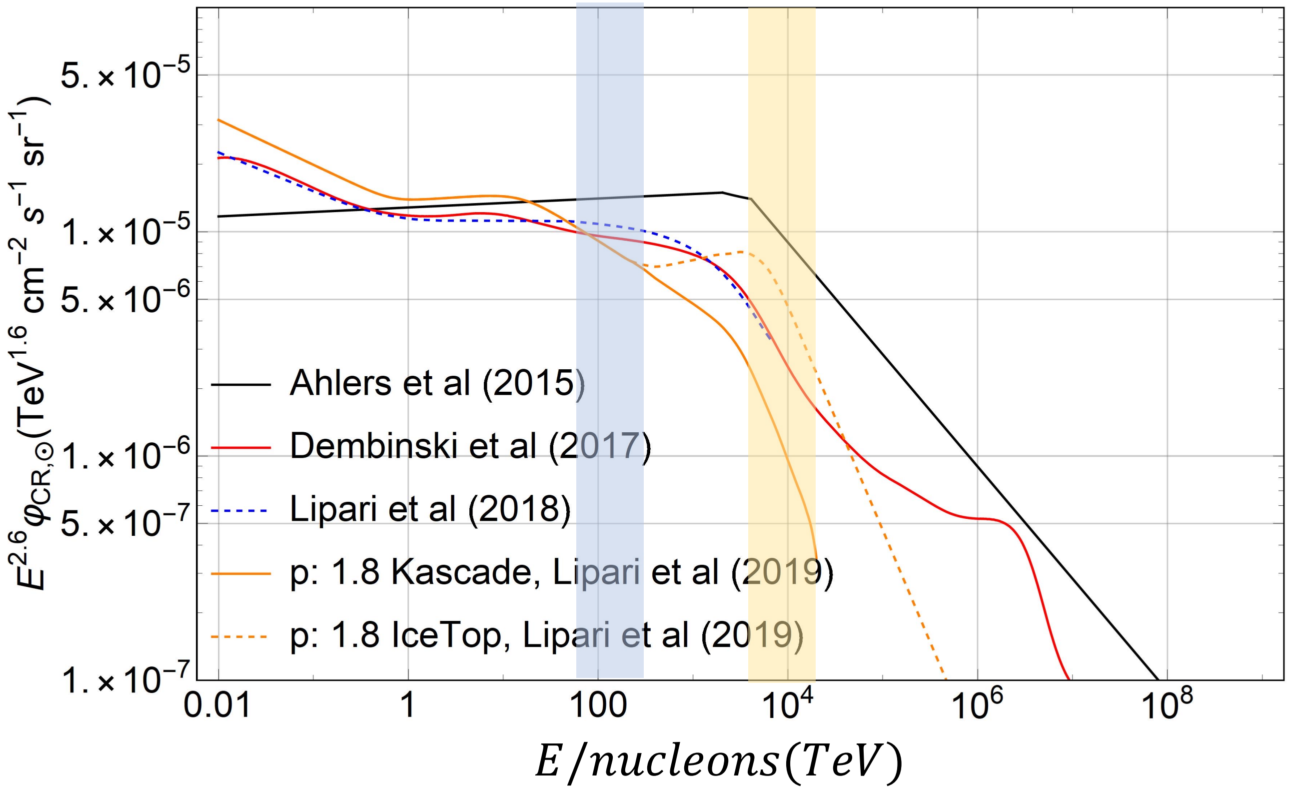
$$h(E,\vec{r}) = \left(\frac{E}{20\ GeV}\right)^{\Delta(\vec{r})}$$





Cosmic ray distribution:

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

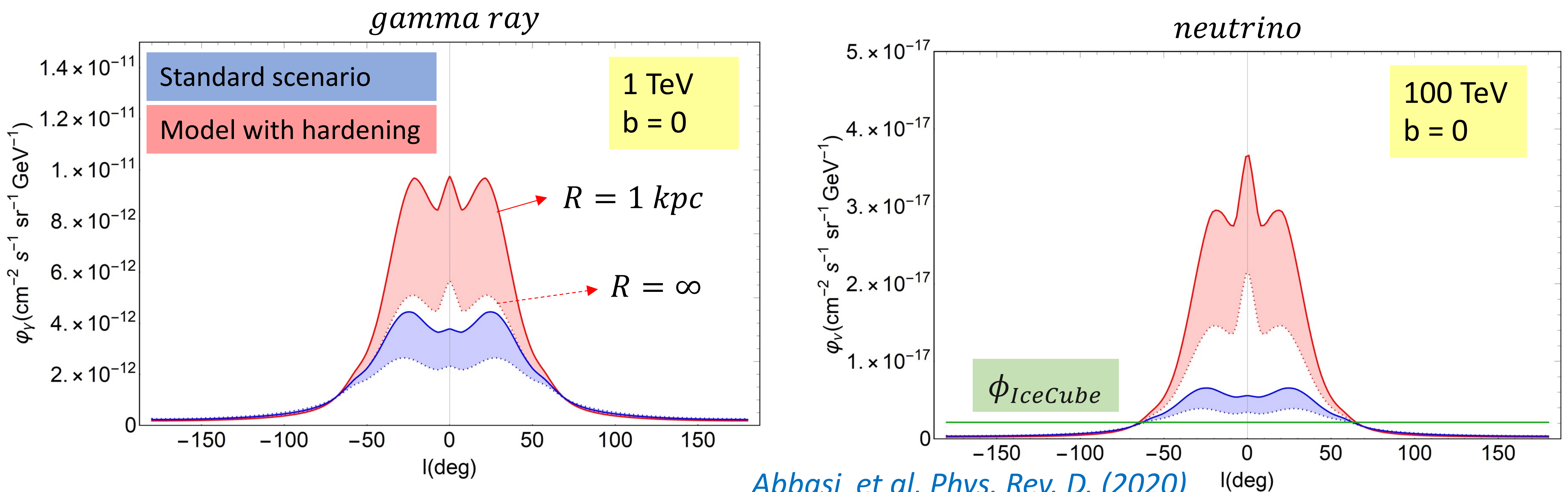


- Data driven local CR spectrum;

  Dembinski, Engel, Fedynitch et al. (2018)

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

Diffuse Galactic γ and ν emission:



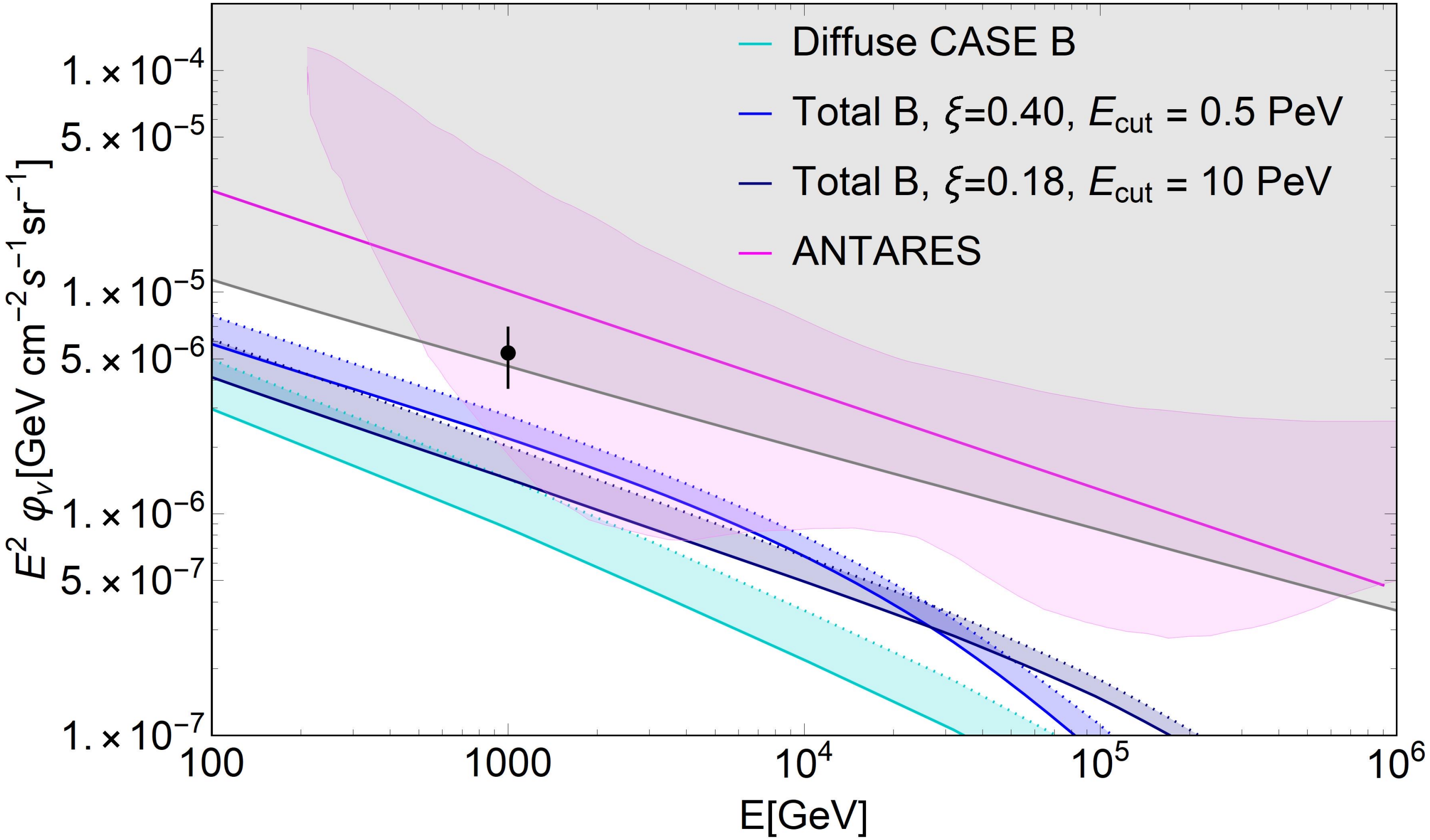
Abbasi et al, Phys. Rev. D. (2020)

- The angle integrated γ-ray flux in the standard scenario is: $\Phi_\gamma = (7.0 - 8.0)\times 10^{-13} cm^{-2} s^{-1} GeV^{-1}$, and increases of a factor ~ 1.2 in the hardening case.
- In the region $\mathrm{l} < |60°|, \mathrm{b} < |2°|$, this factor becomes $\sim 2(\sim 3)$ for γ (ν) 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:

$|l| < 30°, |b| < 2°$

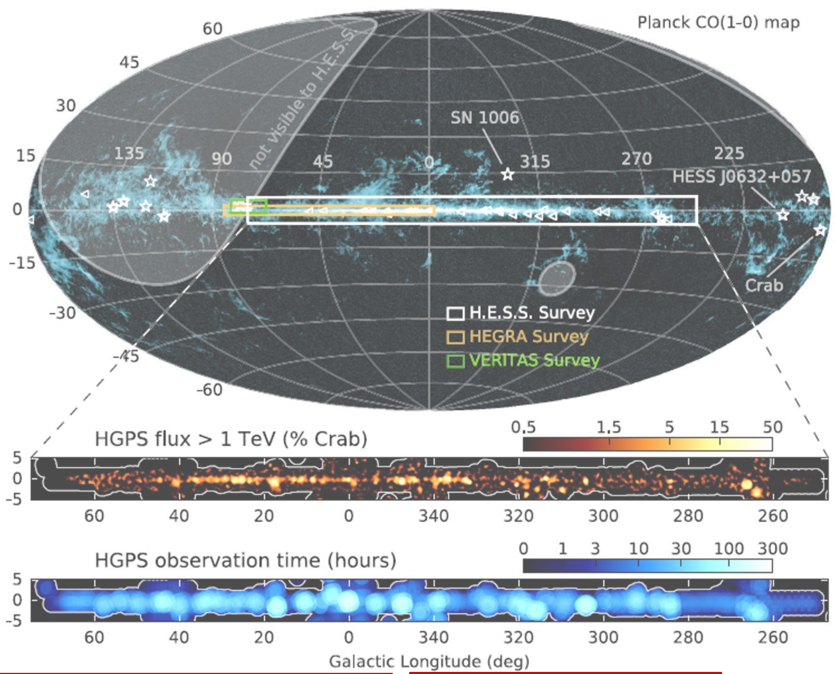


$$\varphi_{\nu,\text{diff}}^{Antares} = \varphi_{\nu,S}(\xi, E_{\text{cut}}) + \varphi_{\nu,\text{diff}}$$

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

Study of the sources population in the TeV range:

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



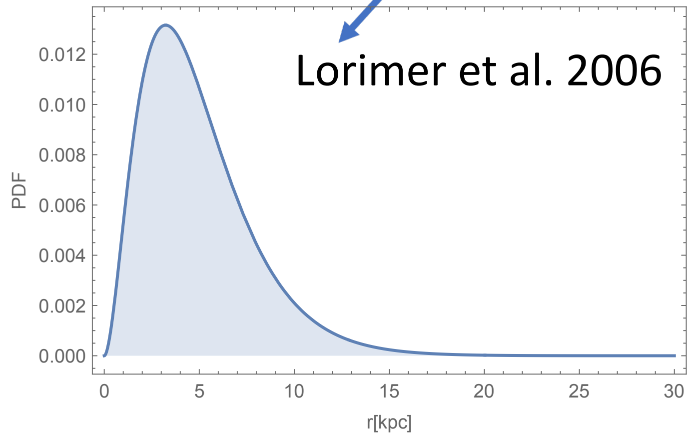
- The HGPS catalogue ($\phi > 0.1\phi_{Crab}$);
- Model for TeV source population:

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

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

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

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



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

$$R = 0.019\,\mathrm{yr}^{-1}$$

For pulsar-powered sources:

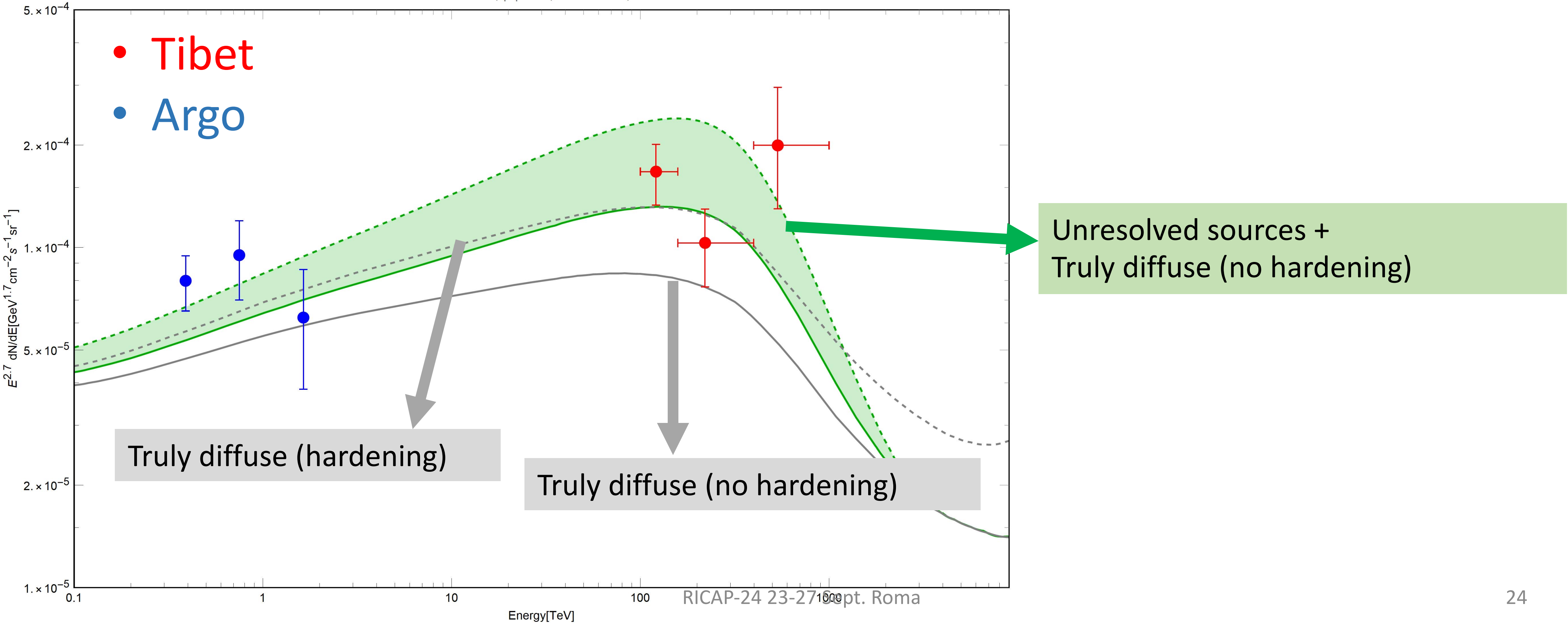
$$L(t) = L_{\max}\left(1 + \frac{t}{\tau}\right)^{-\gamma}$$

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.

Tibet ASγ : We add the contribution of unresolved sources to the truly diffuse emission without the hypothesis of CR spectral hardening.

Definition: Hardening ≡ spatially dependent CR spectral index

$$25° < l < 100°, |b| < 5°, E_{cut} = 500\ TeV$$



Tibet ASγ : We add the contribution of unresolved sources to the truly diffuse emission without the hypothesis of CR spectral hardening.

Definition: Hardening ≡ spatially dependent CR spectral index

$$50° < l < 200°, |b| < 5°, E_{cut} = 500\ TeV$$