The VHE neutrino (and gamma-ray) flux from the galactic plane

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Based on ***Astrophys.J.Lett.* 956 (2023) 2, L44** and ***JCAP* 09 (2023) 027**
in collaboration with: G. Pagliaroli and V. Vecchiotti

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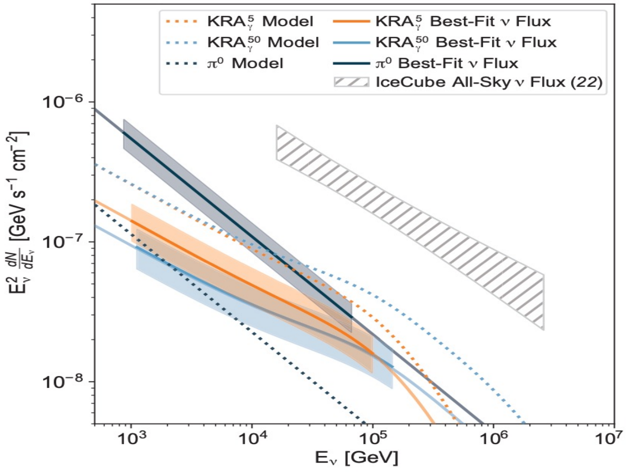
The VHE neutrino flux from the galactic plane - Observations

Relevant observational progress during 2023:

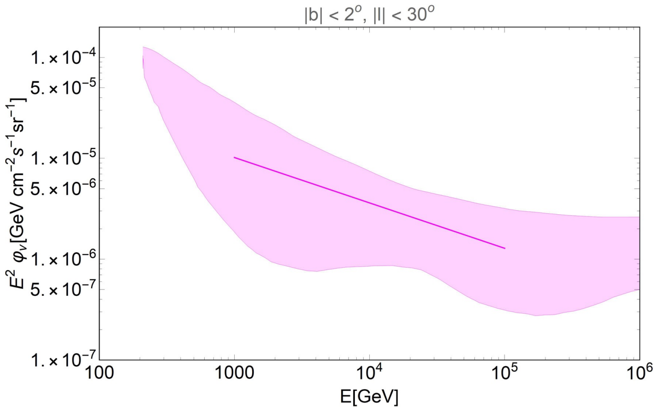
ICECUBE → Detection of Galactic diffuse neutrino emission (4.5σ evidence)
Templates for ν energy and arrival direction distributions are assumed

Abbasi, R, et al., 2023, Science 380, 1338



ANTARES → Hint of neutrino emission from the Galactic ridge (2.2σ evidence)
No templates assumed. Observation window |b|<2°; |l|< 30°

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



The VHE neutrino (and gamma-ray) flux from the galactic plane

$$\varphi^{\rm obs}_{\nu,{\rm diff}} = \varphi_{\nu,{\rm diff}} + \varphi_{\nu,{\rm S}}$$

The interaction of HE cosmic rays (CRs) with the gas contained in the galactic disk is a **guaranteed** source of **HE neutrinos (**and **gammas) → Diffuse emission**

HE neutrinos (and **gammas)** can be also produced by **freshly accelerated particles within or close to acceleration site → Source component**

The VHE neutrino (and gamma-ray) flux from the galactic plane

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

$$\varphi_{\gamma,\text{diff}}^{\text{obs}} = \varphi_{\gamma,\text{diff}} + \varphi_{\gamma,\text{S}}^{(nr)}$$

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Hadronic interactions imply a strict relation between neutrinos and gammas

However:
- bright sources are resolved by gamma-ray detectors while they cannot be resolved by neutrino telescopes
- gamma-rays can be absorbed either in source or in their path to Earth;
- gamma-rays can be also produced by leptonic interactions (both in sources and in interstellar medium)

The HE galactic diffuse gamma (and neutrino) fluxes

The diffuse **HE neutrinos** and **gammas** from the **Galactic plane** can be calculated as:

$$\varphi_{i,\mathrm{diff}}(E_i, \hat{n}_i) = A_i \left[\int_{E_i}^{\infty} dE \int_0^{\infty} dl \, \frac{d\sigma_i(E, E_i)}{dE} \times \varphi_{\mathrm{CR}}(E, \mathbf{r}_\odot + l\,\hat{n}_i) \times n_{\mathrm{H}}(\mathbf{r}_\odot + l\,\hat{n}_i) \right]$$

$i = \nu, \gamma$

where: $A_\gamma = 1$ $A_\nu = 1/3$ (ν_e: ν_μ: ν_τ) $\simeq$ (1:1:1) because of ν-flavour oscill.

$$\frac{d\sigma_i(E, E_i)}{dE} = \frac{\sigma(E)}{E} F_i\left(\frac{E_i}{E}, E\right)$$

nucleon-nucleon cross section
[Kelner & Aharonian, PRD 2008, 2010]

$n_{\mathrm{H}}(\mathbf{r})$ Gas density – same as Galprop
[http://galprop.stanford.edu]

$\varphi_{\mathrm{CR}}(E, \mathbf{r})$ Differential CR flux
- See next slides

N.B. At E_γ > 20 TeV, gamma-ray absorption should be also included (see back-up slides).

The CR flux in the Galaxy

The local determination has to be related to the CR flux in all the regions of the Galaxy where the gas density is not negligible.

$$\varphi_{\rm CR}(E,\mathbf{r}) = \varphi_{{\rm CR},\odot}(E)\, g(\mathbf{r})\, h(E,\mathbf{r})$$

where: $\varphi_{{\rm CR},\odot}(E)$ - CR flux at the Sun position

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Standard Case
e.g. Galprop

$$\begin{cases} g(\mathbf{r}) = \dfrac{1}{\mathcal{N}} \displaystyle\int d^3x\, f_{\rm S}(\mathbf{r}-\mathbf{x})\, \dfrac{\mathcal{F}(|\mathbf{x}|/R)}{|\mathbf{x}|} \\ \mathcal{F}(\nu) \equiv \displaystyle\int_\nu^\infty d\gamma\, \dfrac{1}{\sqrt{2\pi}} \exp\left(-\gamma^2/2\right) \end{cases}$$

Solution of 3D (isotropic) diffusion equation

- It takes into account the effect of sources distribution $f_S(r)$;
- R = Diffusion radius;
- Normalized to 1 at the Sun position

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Hardening Case
e.g. KRAγ, Dragon (+ Hermes), etc.

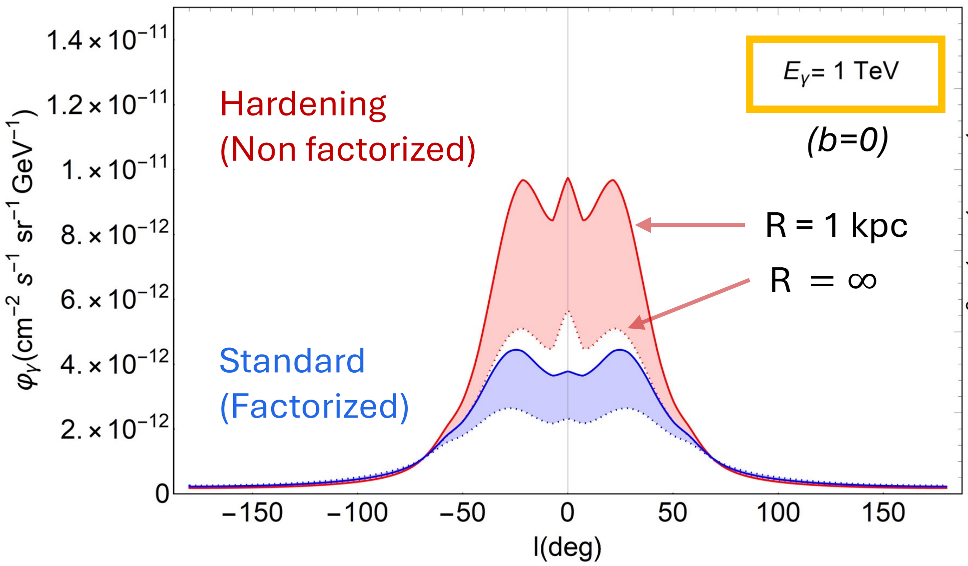
$$h(E,\mathbf{r}) = \left(\frac{E}{\overline{E}}\right)^{\Delta(\mathbf{r})}$$

$$\Delta(r,z) = \Delta_0\left(1 - \frac{r}{r_\odot}\right)$$

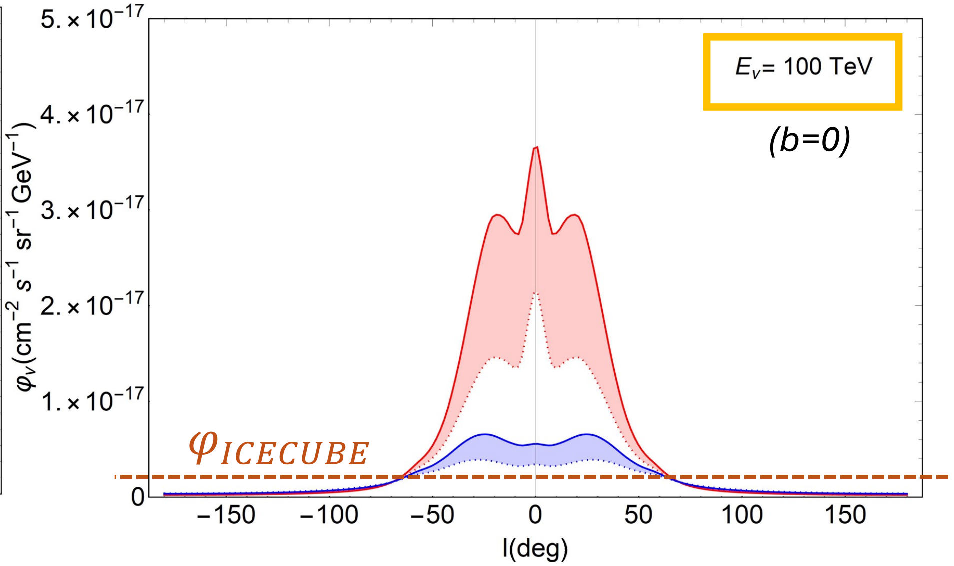
- It introduces a position-dependent variation $\Delta(r)$ of the CR spectral index (Gaggero et al. 2015, Acero et al. 2016, Yang et al, 2016, Pothast et al. 2018);
- $\Delta_0 = 0.3$ represents the difference between CR spectral index at the Sun position ($\alpha_\odot \simeq 2.7$ at $\overline{E} = 20\ GeV$) and its value close to the galactic center

The diffuse γ and ν fluxes in different scenarios

Gamma-ray flux



Neutrino flux



The gamma (neutrino) flux at E_γ=1 TeV (E_ν=100 TeV) is determined by CR flux at:

$$20\,E_\nu \simeq 2\,\mathrm{PeV}$$
$$10\,E_\gamma \simeq 10\,\mathrm{TeV}$$

No hardening (standard scenario):

$$\Phi_\gamma = (7.0 - 8.0) \times 10^{-13}\ \mathrm{cm^{-2}\ s^{-1}\ GeV^{-1}}$$

(Angle-integrated γ-ray flux a 1 TeV)

Hardening (non factorized):

- The angle integrated flux increase by a factor ~1.2
- More significant increase in the central region

(factor ~2 in the direction of the Galactic center)

- The angle integrated diffuse neutrino flux is globally ~ few % of the isotropic flux observed by IceCube
- it provides a dominant contribution in the central region ($-60° \leq l \leq 60°$)
- Small but not negligible. Potentially observable (with HESE in IceCube)

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

The source component

The source component includes the contribution of all the Galactic hadronic sources that can be either **resolved** or **unresolved** by gamma-ray detectors

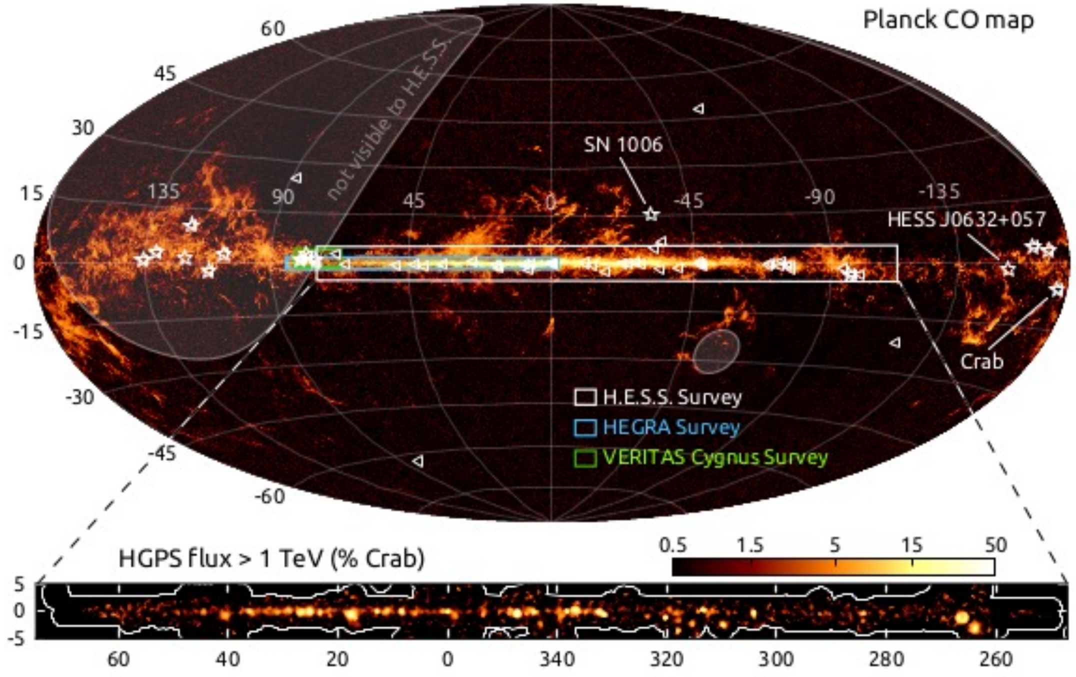
Sources catalogs

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

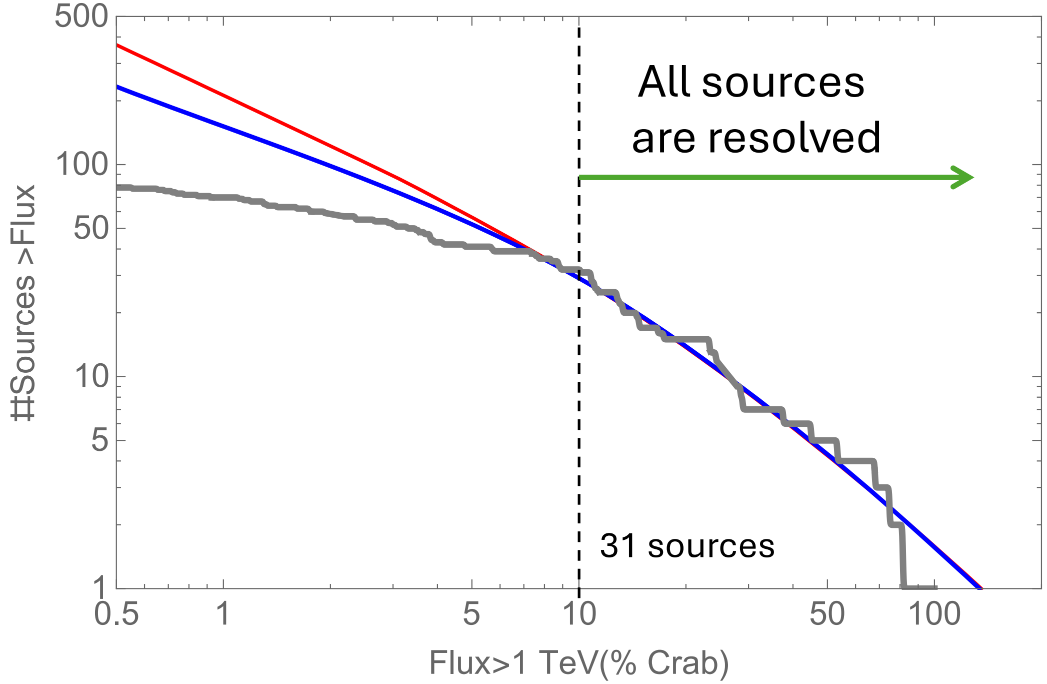
TeV gamma-ray source population study based on the **H.E.S.S. Galactic Plane Survey (HGPS)**

The luminosity function of the TeV gamma-ray source population is inferred by fitting the flux, longitude and latitude distribution of brightest sources in the HGPS catalog.

$\Phi_{\gamma,S}$ → cumulative gamma-ray flux produced by the entire population in the 1-100 TeV energy range



Cumulative distribution of HGPS sources



The ν-source component

The knowledge of the gamma-ray source population allow us to calculate:

$\Phi_{\nu,s}^{max}(E_{cut})$ = Maximal neutrino flux in the 1-100 TeV energy range
[Hp: the entire gamma-ray source population is powered by hadronic interactions]

By assuming that the average hadronic source spectrum is:

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

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

we predict the neutrino source component as a function of the energy according to:

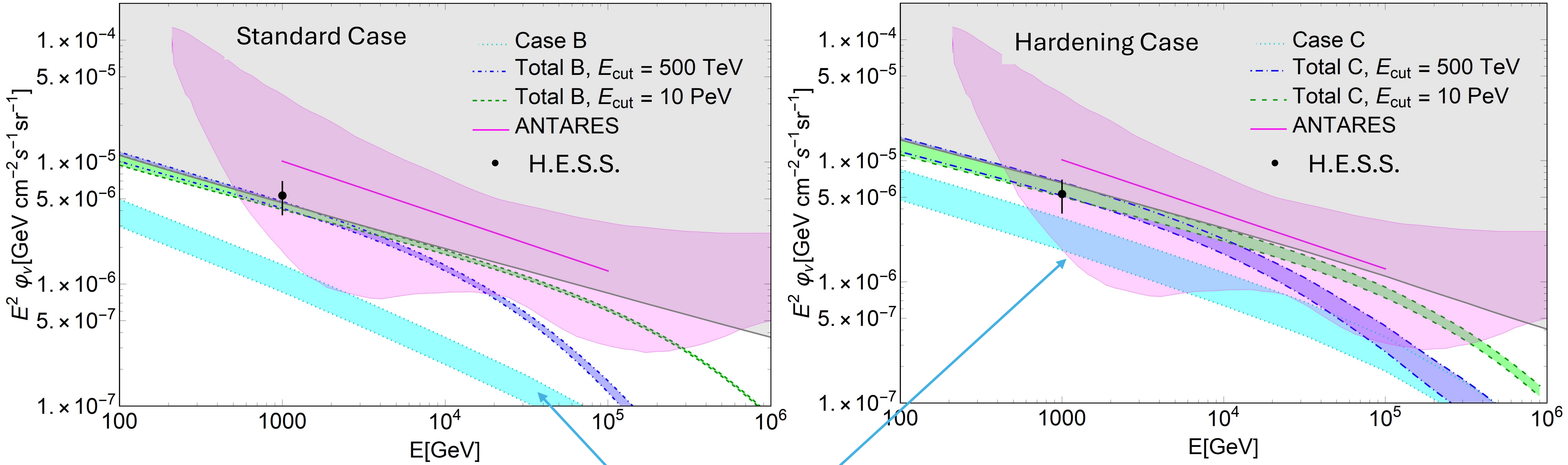
$$\varphi_{\nu,s}(E_\nu; E_{cut}, \xi) = \xi \Phi_{\nu,s}^{max}(E_{cut}) \phi_\nu(E_\nu; E_{cut})$$

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

Neutrino spectrum produced by $\phi_p(E; E_{cut})$ (normalized to 1 in the energy range 1-100 TeV)

Comparing theoretical predictions with ANTARES 2.2σ hint

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

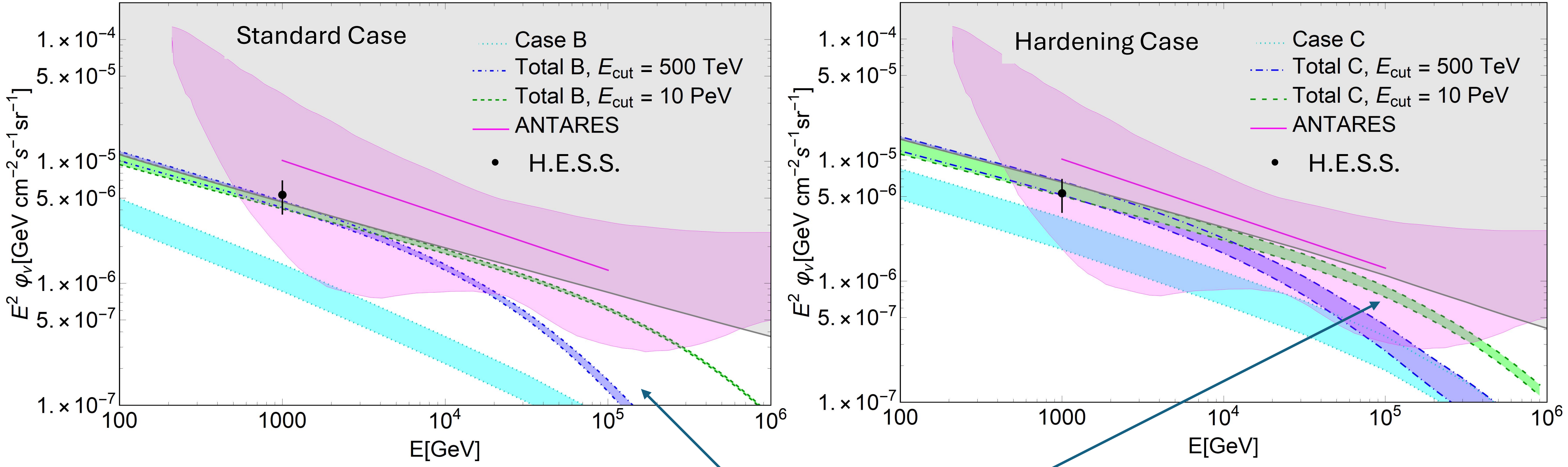


$$\varphi_{\nu,\mathrm{diff}}^{Obs} = \varphi_{\nu,\mathrm{diff}} + \varphi_{\nu,S}(\xi, E_{\mathrm{cut}})$$

Truly diffuse emission in the standard and hardening assumptions

Comparing theoretical predictions with ANTARES 2.2σ hint

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

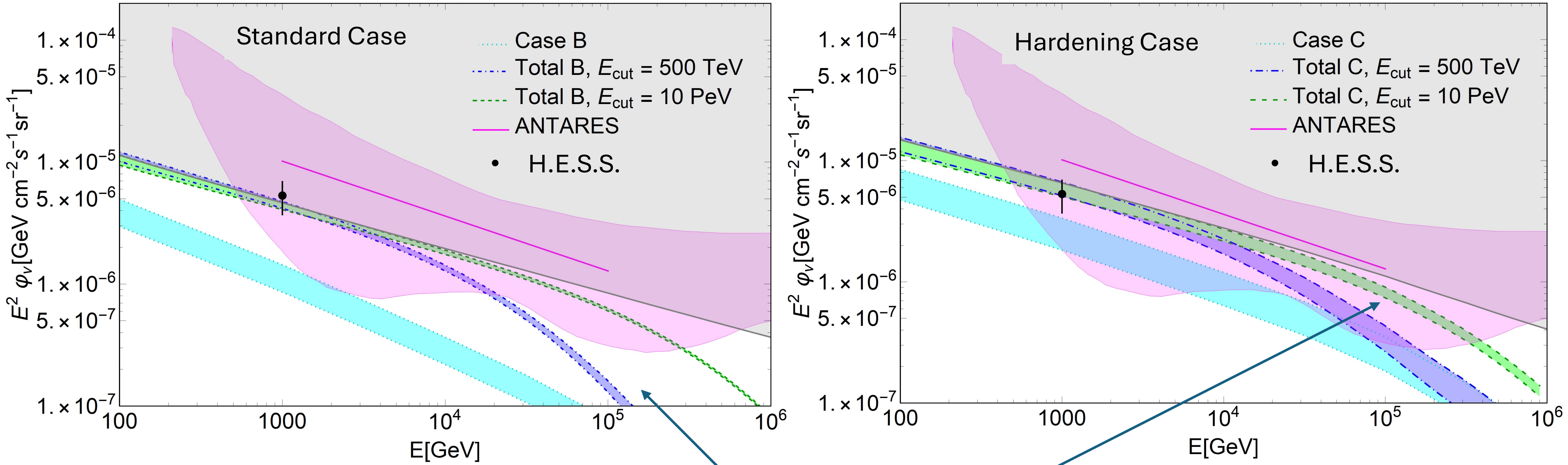


$$\varphi_{\nu,\rm diff}^{Obs} = \varphi_{\nu,\rm diff} + \varphi_{\nu,S}(\xi, E_{\rm cut})$$

Adding the souce component for different values of ξ and $E_{\rm cut}$

Comparing theoretical predictions with ANTARES 2.2σ hint

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



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

The **gray region** requires $\xi > 1$, i.e. neutrino "invisible" sources

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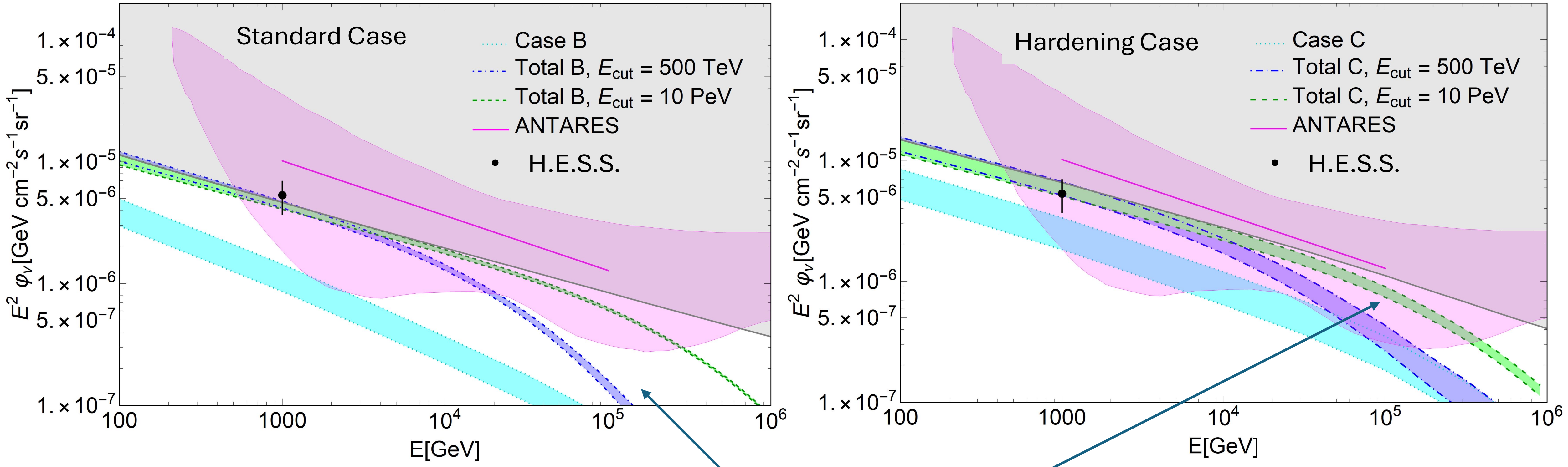


$$\varphi_{\nu,\text{diff}}^{Obs} = \varphi_{\nu,\text{diff}} + \varphi_{\nu,S}(\xi, E_{\text{cut}})$$

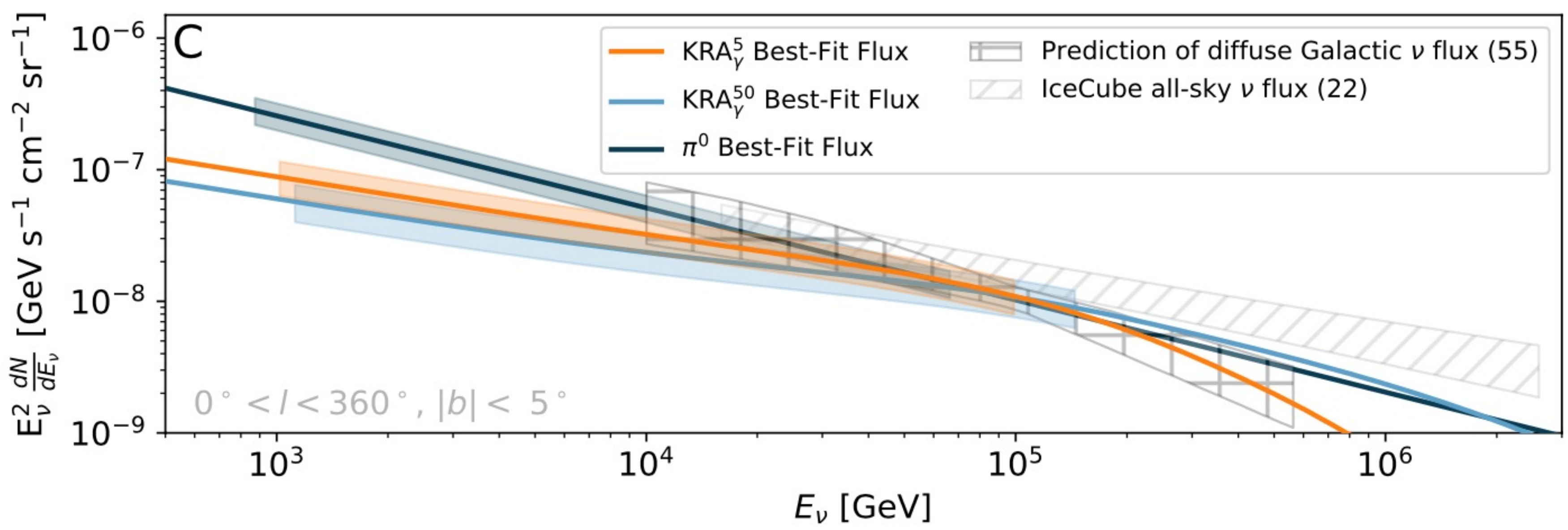
The ANTARES best−fit signal requires the existence of a large source component, close to or even larger than the most optimistic predictions obtained with our approach.

Comparing theoretical predictions with IceCube 4.5σ detection

Which sky and energy regions are really probed by IceCube? In order to be conservative:

a) We restrict to the angular region ($0° < l < 360°, |b| < 5°$) where different templates give almost the same constraints (above ~50 TeV).

All flavors, $0° < l < 360°, |b| < 5°$



Abbasi, R, et al., 2023, Science 380, 1338, Supplementary material

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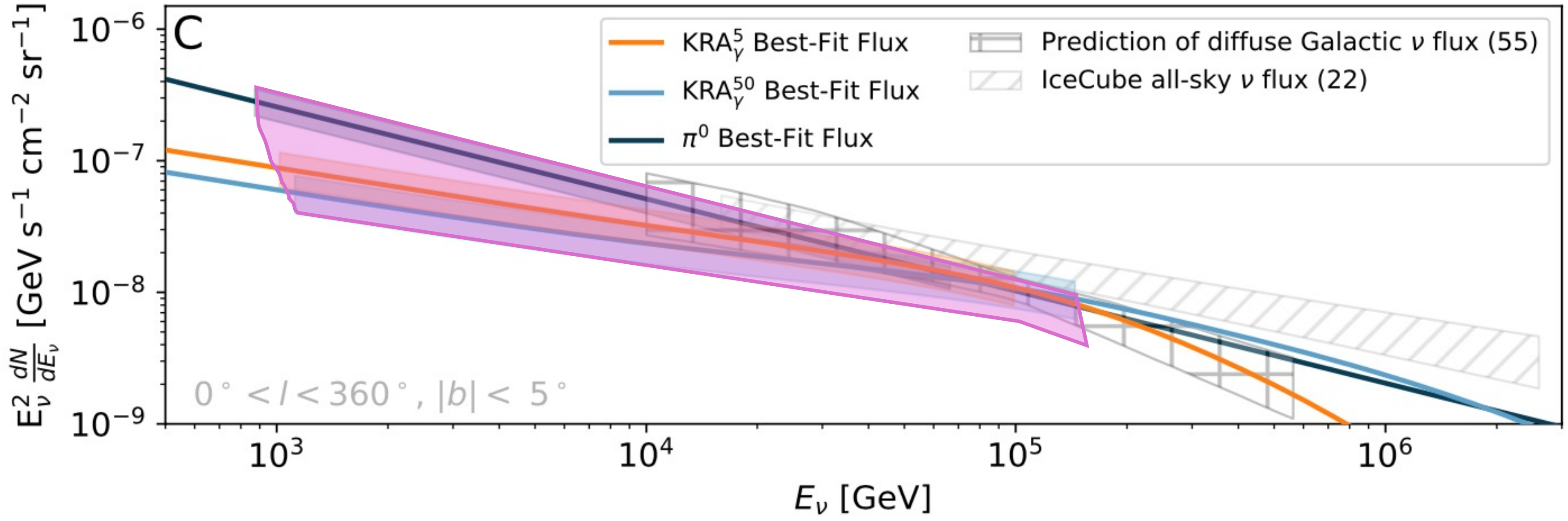
Which sky and energy regions are really probed by IceCube? In order to be conservative:

a) We restrict to the angular region ($0^\circ < l < 360^\circ, |b| < 5^\circ$) where different templates give almost the same constraints (above ~50 TeV).
b) We consider the superposition of the regions obtained by using different assumptions (including also 1σ uncertainties of the respective fits).

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



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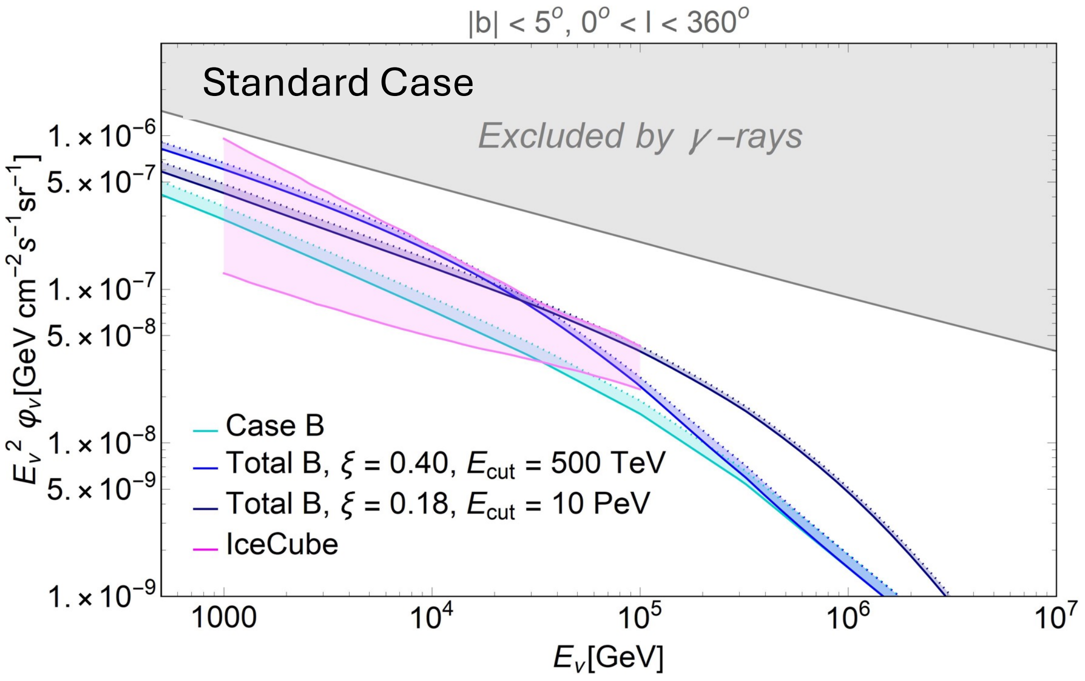

IceCube result are compatible with gamma-rays

Non-negligible source component allowed in the **Standard scenario**.

- $\xi < 0.40$ ($E_{cut} = 500\ TeV$);
- $\xi \sim 0.20$, if we require that Galactic sources accelerate particles up to the CR «knee».

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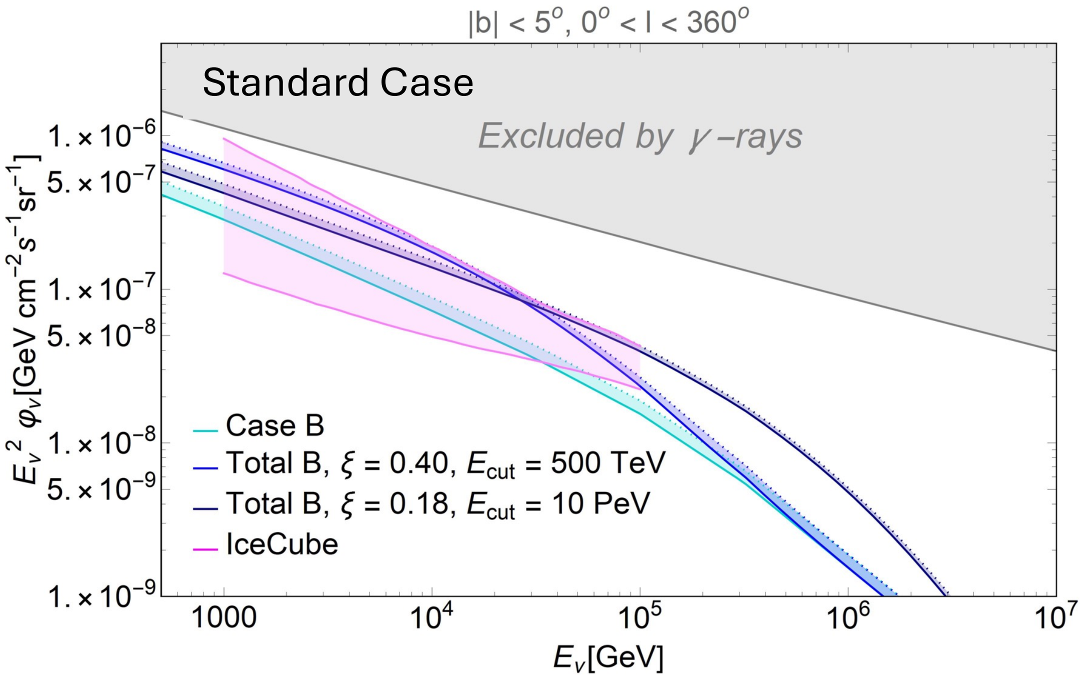

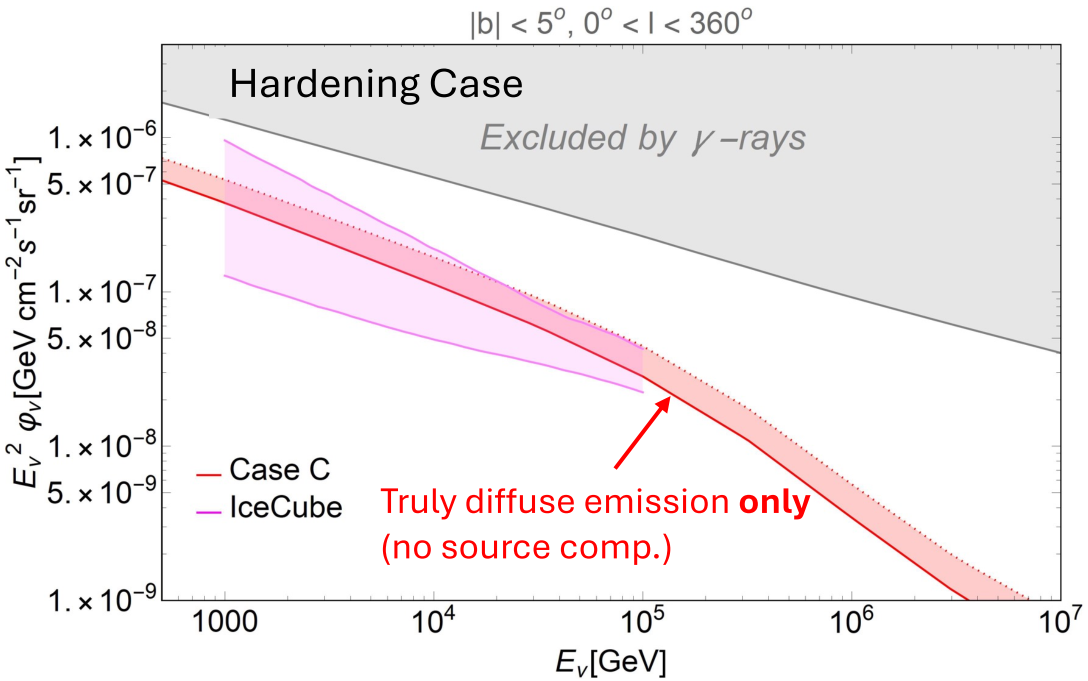

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No space for a relevant source component in the **Hardening case.**

Potentially problematic, because:
- we expect PeVatrons in our Galaxy;
- the Hardening case needs hadronic sources

Conclusions

We compared our predictions for the total neutrino galactic emission (including unresolved sources) with signals observed by ANTARES and IceCube.

Our analysis shows that constraints can be potentially obtained both for the truly diffuse emission and the source component.

The pictures that emerge from ANTARES and IceCube data do not seem completely consistent but differences may arise from limited statistics and/or assumptions in observational and theoretical analyses.

The considered window for the exploration for the Galaxy just opened. We may hope that future data and/or detectors (e.g. km3net) may clarify the picture.

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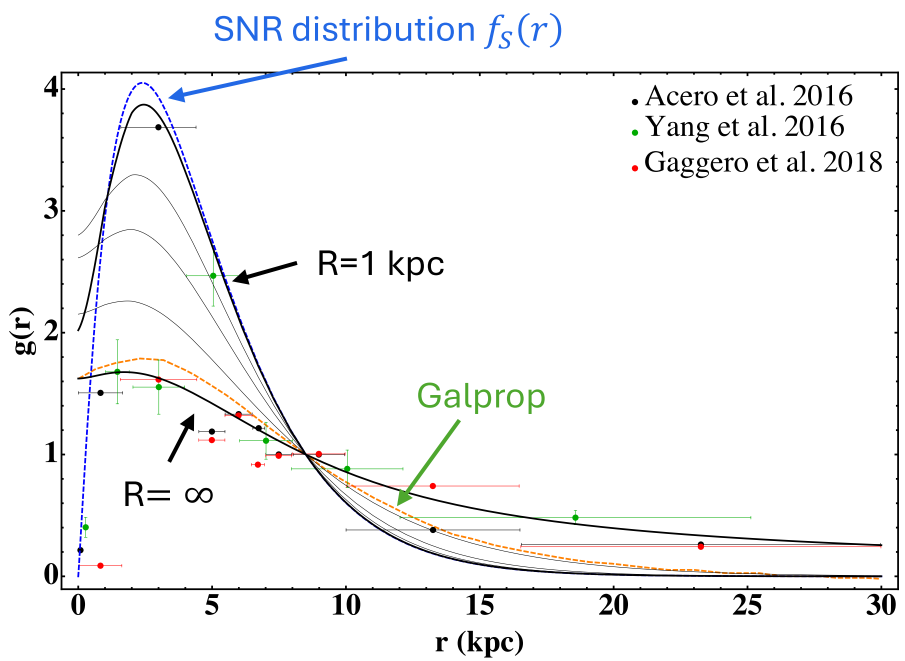
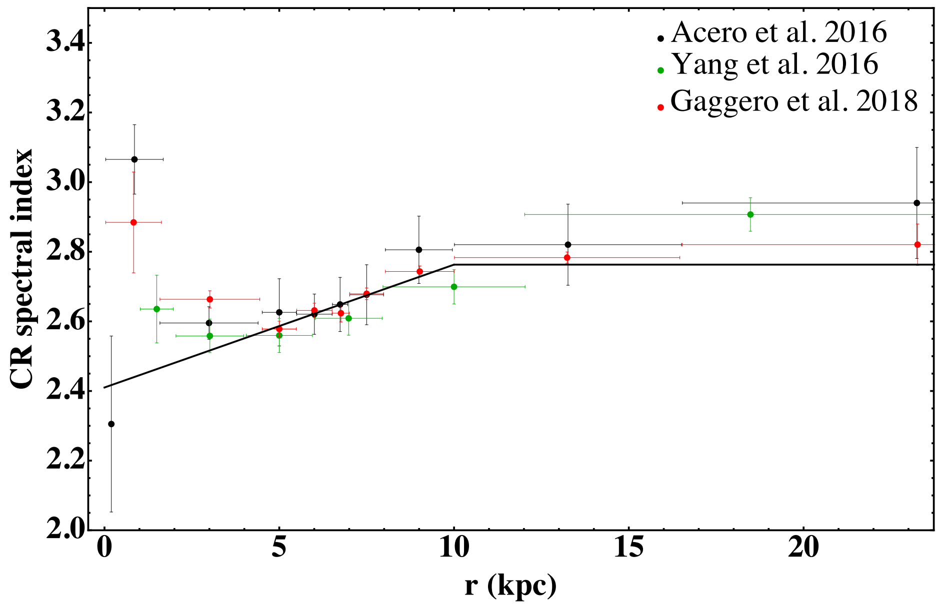
Thank you
for your attention

Additional slides

The CR flux in the Galaxy





<u>CR Spectral hardening in the inner Galaxy</u> was suggested by Gaggero et al. 2015 and then reported by two different model-independent analyses of (Acero et al. 2016) and (Yang et al. 2016) of Fermi-LAT data.

More recent analysis (Pothast et al. 2018) reports the same behavior. → The spectral hardening is observed in different energy ranges and resilient wrt different prescriptions in the analysis

Credits and comparisons ...

The results that I have presented for HE diffuse photon and neutrino fluxes are from:

- Pagliaroli et al, JCAP 1611 (2016), 004
- Pagliaroli et al, JCAP 1808 (2018), 035
- Cataldo et al, JCAP 12 (2019) 050

A similar (bottom-up) approach to ours was used by Lipari and Vernetto, PRD 2018 with different prescriptions for CR space and energy distribution.

- Factorized flux → No hardening
- Non-factorized flux → Hardening

KRAγ, Dragon (+ Hermes), etc. - CR Propagation model with radially dependent transport properties, see e.g. Gaggero et al., APJ 2015, De la Torre Luque et al, 2022

See also Schwefer et al, arXiv 2211.15607 - recent calculation
(standard scenario, no CR spectral hardening; detailed comparison with local CR measurements) –

→ There is generically a good agreement between different calculations (when performed with similar assumptions)

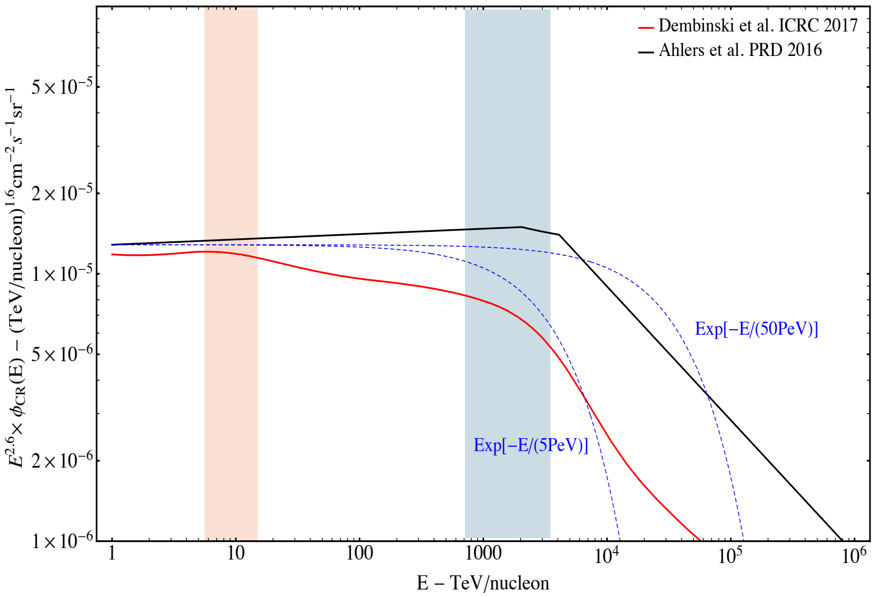
The CR flux: local determination

At the Sun position the CR flux is constrained by observational data

The gamma (neutrino) flux at E_γ=1 TeV (E_ν=100 TeV) is determined by CR flux at:

$$\begin{aligned} 20\,E_\nu &\simeq 2\,\mathrm{PeV} \\ 10\,E_\gamma &\simeq 10\,\mathrm{TeV} \end{aligned}$$

The local CR flux between 1 Tev and 1 EeV



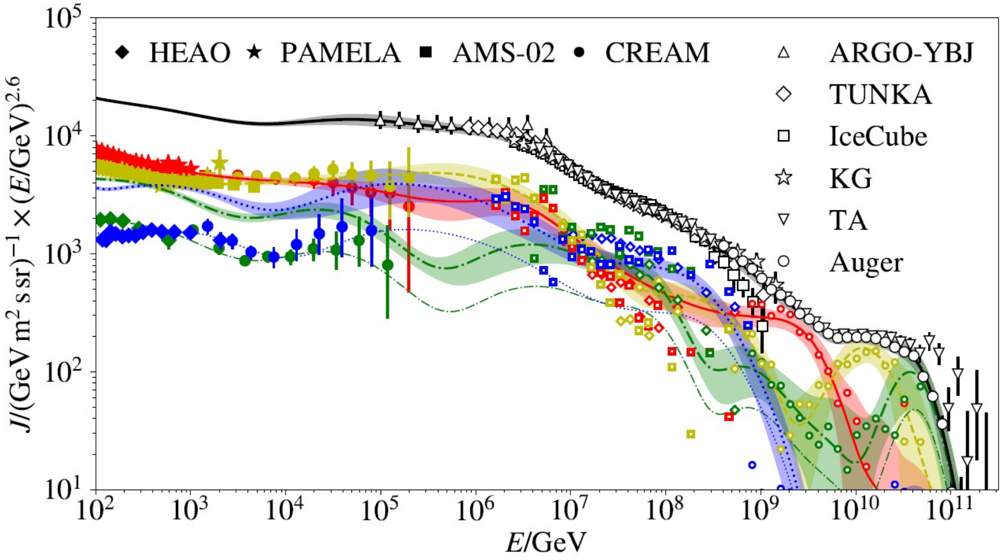
Note that:
Diffuse gamma and neutrino fluxes are determined by the total nucleon flux (that may depend on the assumed CR composition)

$$\varphi_{\mathrm{CR},\odot}(E) \equiv \sum_A A^2 \frac{d\phi_A}{dE_A d\Omega_A}(AE)$$

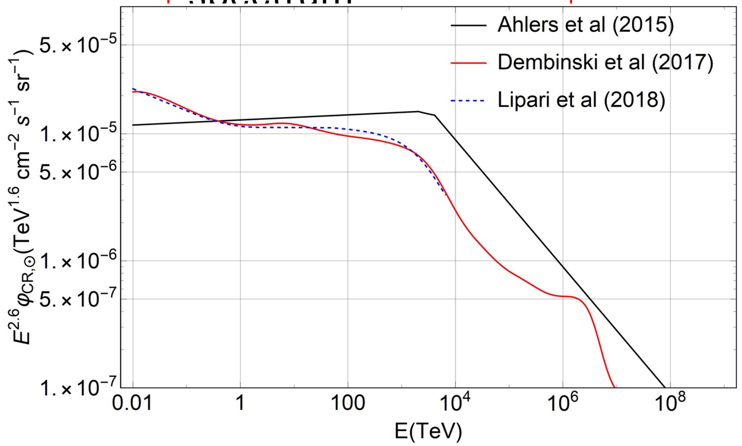
If we increase heavy element contribution at expenses of hydrogen, we obtain a smaller CR flux (since the flux decrease faster than E^{-2})

Cosmic ray local spectrum:

[*Dembinski, Engel, Fedynitch et al. (2018)*]



CR nucleons spectrum



The role of unresolved sources

A relatively small region of the Galaxy is resolved by γ–ray telescopes (even if sources are assumed to be very luminous).

Therefore, unresolved sources plausibly give a substantial contributions to the cumulative source emission

$$\varphi_{\gamma,S} = \varphi_{\gamma,S}^{(nr)} + \varphi_{\gamma,S}^{(r)}$$

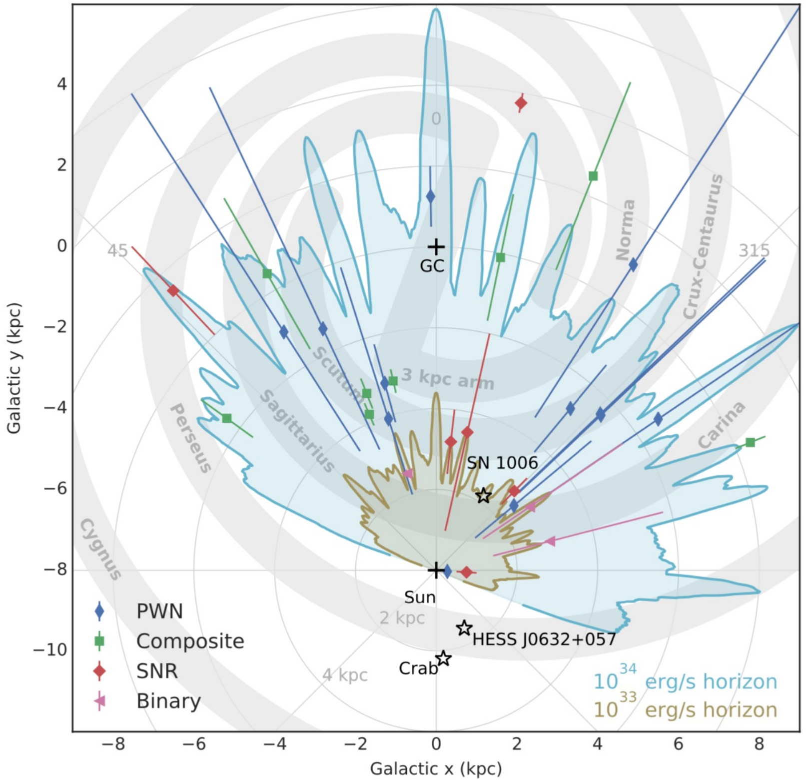
unresolved sources — resolved sources

This contribution contaminates the diffuse large scale flux observed by different experiments, i.e.

$$\varphi_{\gamma,\mathrm{diff}}^{\mathrm{obs}} = \varphi_{\gamma,\mathrm{diff}} + \varphi_{\gamma,S}^{(nr)}$$

observed "diffuse" γ-ray flux
i.e. residual flux after subtraction of resolved sources

HESS observational horizon



The population of TeV galactic γ-ray sources

[Cataldo et al., ApJ 2020]

We perform a population study of the **Hess Galactic Plane Survey (HGPS)**
[78 VHE sources in the ranges $-110^\circ \leq l \leq 60^\circ$ and $|b| < 3^\circ$;
angular resolution 0.08°, sensitivity $\simeq 1.5$ % Crab flux for point-like objects.]

N.B. The catalog is considered **complete** for sources emitting a flux $\Phi \geq 0.1\,\Phi_{CRAB}$ in the range $E_\gamma = 1 - 100\ TeV$

The **source space and intrinsic luminosity distribution** is assumed to be:

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

$\rho(r)$ = proportional to pulsar distribution (normalized to 1) – Lorimer et al. 2006

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

$$\Phi = \frac{L}{4\pi r^2 \langle E \rangle} \quad \rightarrow \quad \langle E \rangle = 3.25\ \mathrm{TeV}$$

We assume that sources have a power-law spectrum with $\beta_{TeV} = 2.3$

Note that: the adopted luminosity function is naturally obtained for a population of fading sources (such as PWNe):

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

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

$$\mathcal{N} = R\,\tau\,(\alpha - 1)$$

$R = 0.019\ yr^{-1}$
[SN Rate in the Galaxy]