High energy γ from the galactic disk

F.L. Villante

Università dell’Aquila and INFN-LNGS

Based on work done in collaboration with:

G.Pagliaroli (LNGS), M. Cataldo (Univ. AQ), V. Vecchiotti (GSSI), F. Zuccarini (Univ. AQ), C. Evoli (GSSI)

The HE galactic diffuse gamma (and neutrino) fluxes

The interaction of HE cosmic rays (CRs) with the gas contained in the galactic disk is a **guaranteed** source of **HE neutrinos** and **gammas**. The flux at Earth can be written 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: $A_\gamma = 1$ $A_\nu = 1/3$ $(\nu_e : \nu_\mu : \nu_\tau) \simeq (1:1:1)$ 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 $E_\gamma > 20$ TeV, gamma-ray absorption should be also included (see back-up slides).

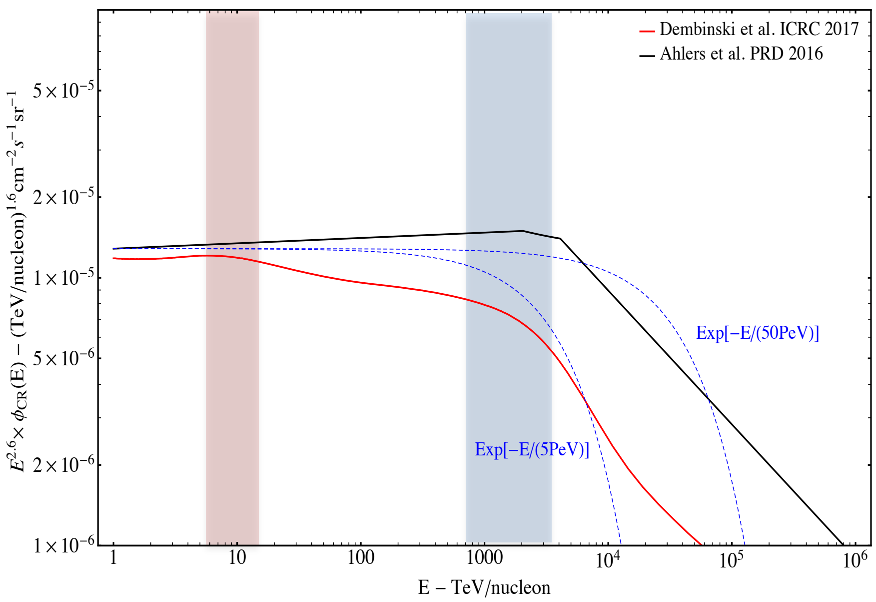
The CR flux: local determination

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



<u>Note that:</u>

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})

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:

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

$$\mathcal{F}(\nu) \equiv \int_\nu^\infty d\gamma\, \frac{1}{\sqrt{2\pi}} \exp\left(-\gamma^2/2\right)$$

<u>Solution of 3D (isotropic) diffusion equation</u>

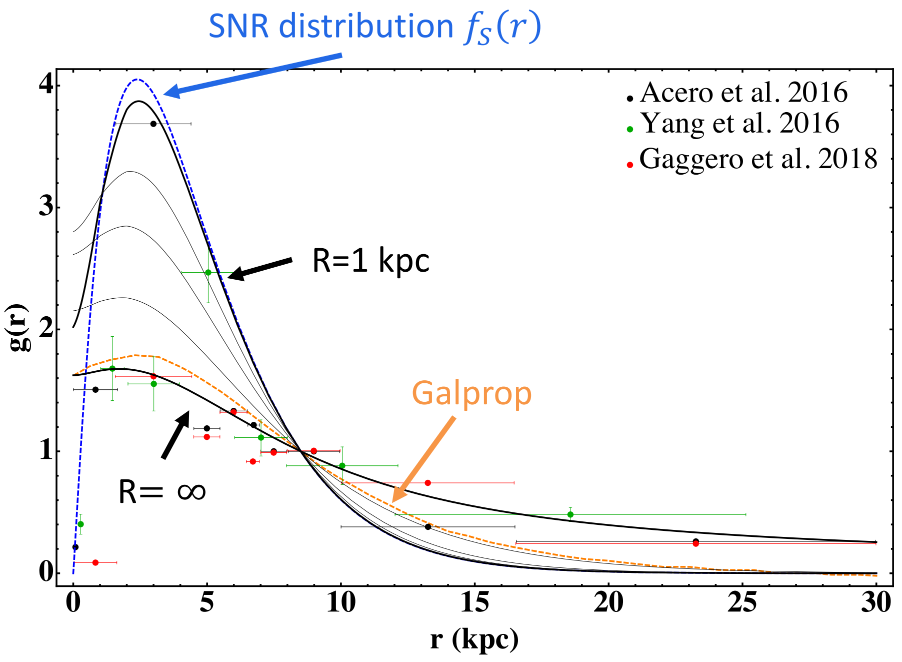
- It takes into account the effect of sources distribution $f_S(r)$;
- R = Diffusion radius;
- Normalized to 1 at the Sun position

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

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

- It introduces a position-dependent variation $\Delta(r)$ of the CR spectral index;
- $\Delta_0 = 0.3$ 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 CR flux in the Galaxy



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:

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

$$\mathcal{F}(\nu) \equiv \int_{\nu}^{\infty} d\gamma\, \frac{1}{\sqrt{2\pi}}\, \exp\left(-\gamma^2/2\right)$$

Solution of 3D (isotropic) diffusion equation

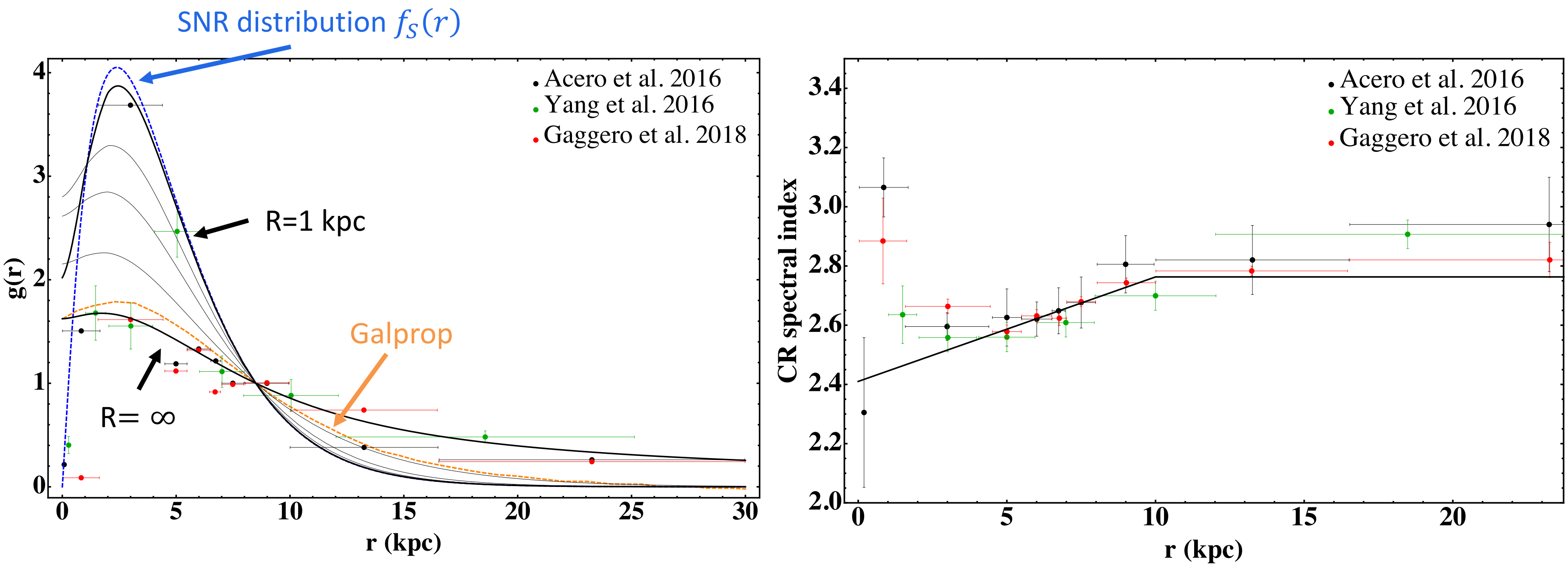
- It takes into account the effect of sources distribution $f_S(r)$;
- R = Diffusion radius;
- Normalized to 1 at the Sun position

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

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

- It introduces a position-dependent variation $\Delta(r)$ of the CR spectral index;
- $\Delta_0 = 0.3$ 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 CR flux in the Galaxy

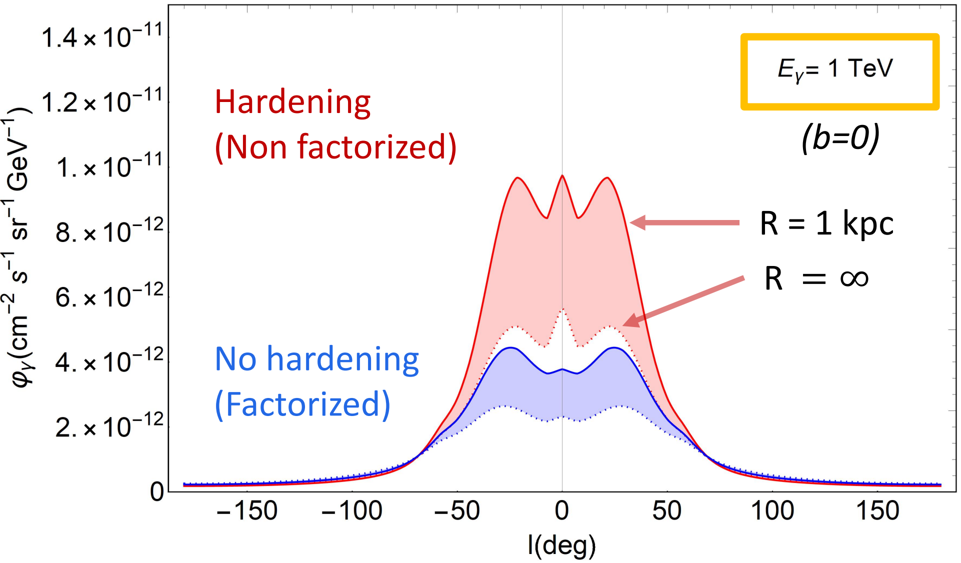


CR Spectral hardening in the inner Galaxy was suggested by Gaggero et al. 2015 and then reported by two different model-independent analyses of (Acero et al. 2016) and (Yang et al. 2016) of Fermi-LAT data.

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

The diffuse γ and ν fluxes in different scenarios

Gamma-ray flux



<u>No hardening (standard scenario):</u>

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

(Angle-integrated γ-ray flux a 1 TeV)

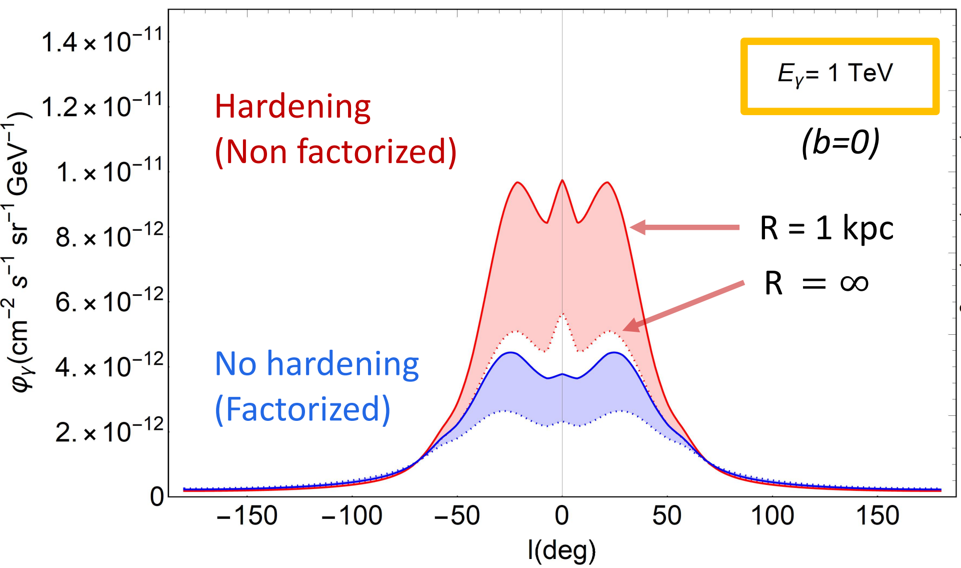
<u>Hardening (non factorized):</u>

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

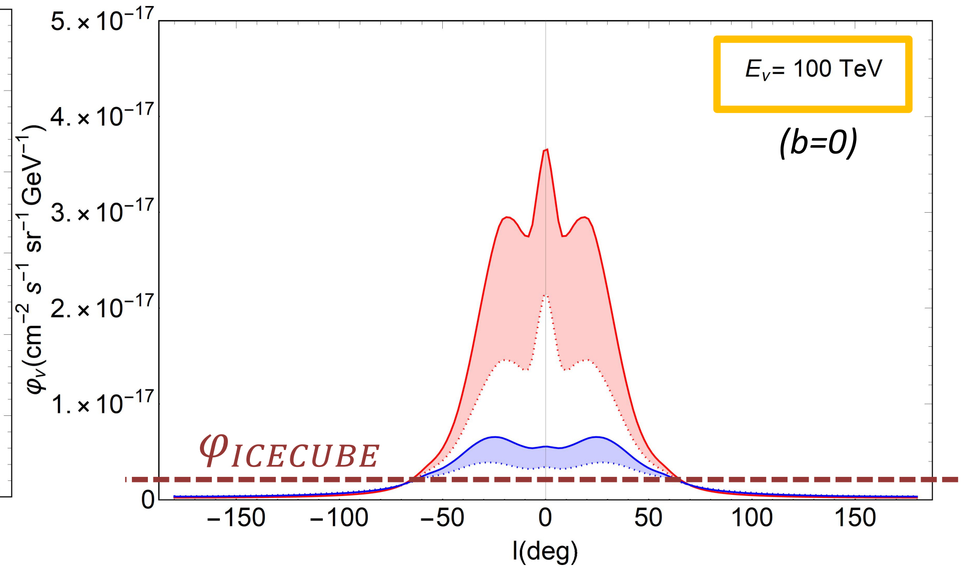
(factor ∼2 in the direction of the Galactic center)

The diffuse γ and ν fluxes in different scenarios

Gamma-ray flux



Neutrino flux



<u>No hardening (standard scenario):</u>

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

(Angle-integrated γ-ray flux a 1 TeV)

<u>Hardening (non factorized):</u>

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

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

Before comparing with observational data …

The results that I have presented for HE 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

A very recent calculation was presented few days ago (standard scenario, no CR spectral hardening; detailed comparison with local CR measurements) – Schwefer et al, arXiv 2211.15607

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

Comparison with observations

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

Observed — Predicted

- $\varphi_{\gamma,\mathrm{diff}}$ = CR diffuse emission
- $\varphi_{\gamma,\mathrm{S}}$ = flux produced by sources
- $\varphi_{\gamma,\mathrm{IC}}$ = inverse Compton emission by diffuse HE electrons.

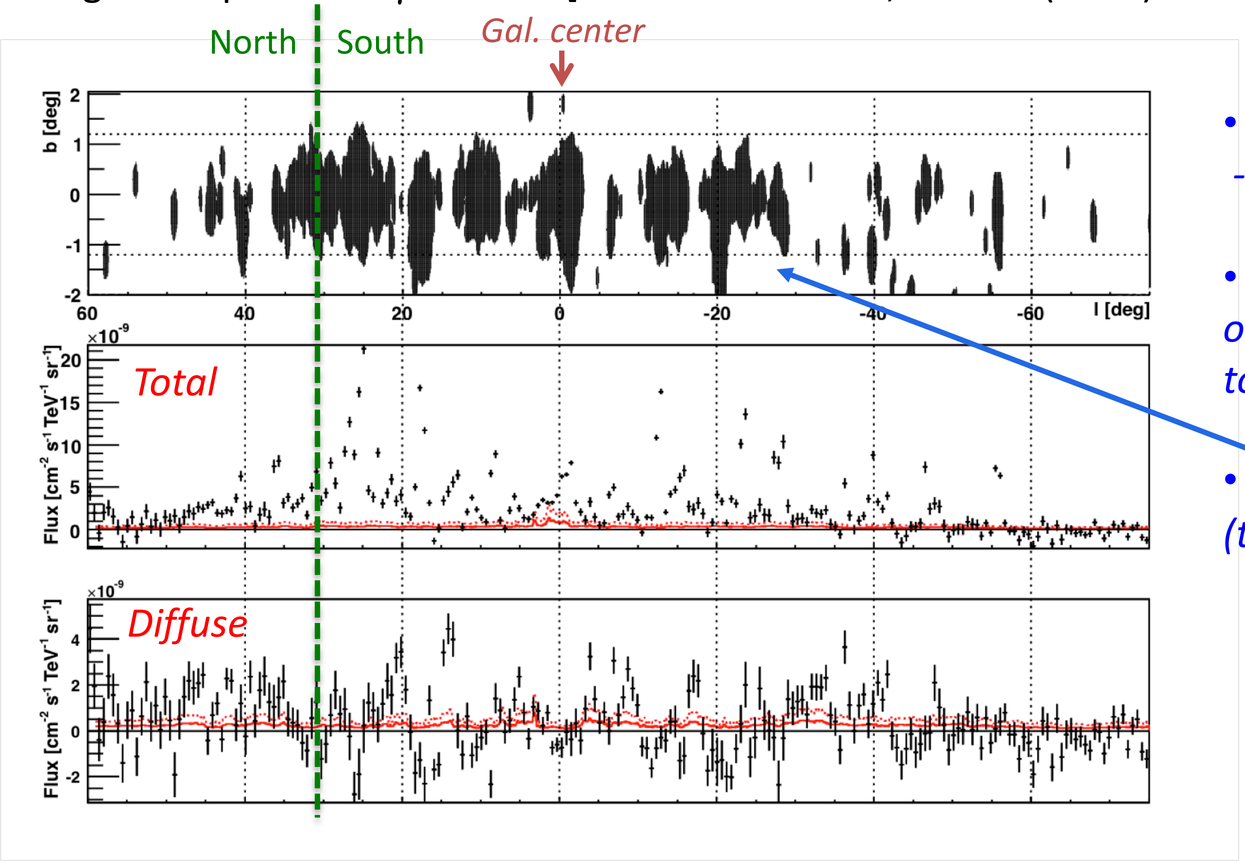
Several possible issues in comparing theoretical calculations with observations.

1. At $E_\gamma \geq 1$ TeV, sources are bright (wrt diffuse component) and extended. The cumulative source contribution and CR diffuse emission are comparable (and both arise from the galactic plane). Therefore, <u>it is difficult to separate the two components</u>.

2. The observational horizon is smaller than the size of the Galaxy. Therefore, we may expect a relevant contribution to observed diffuse emission from <u>unresolved sources</u>

The galactic plane in gammas

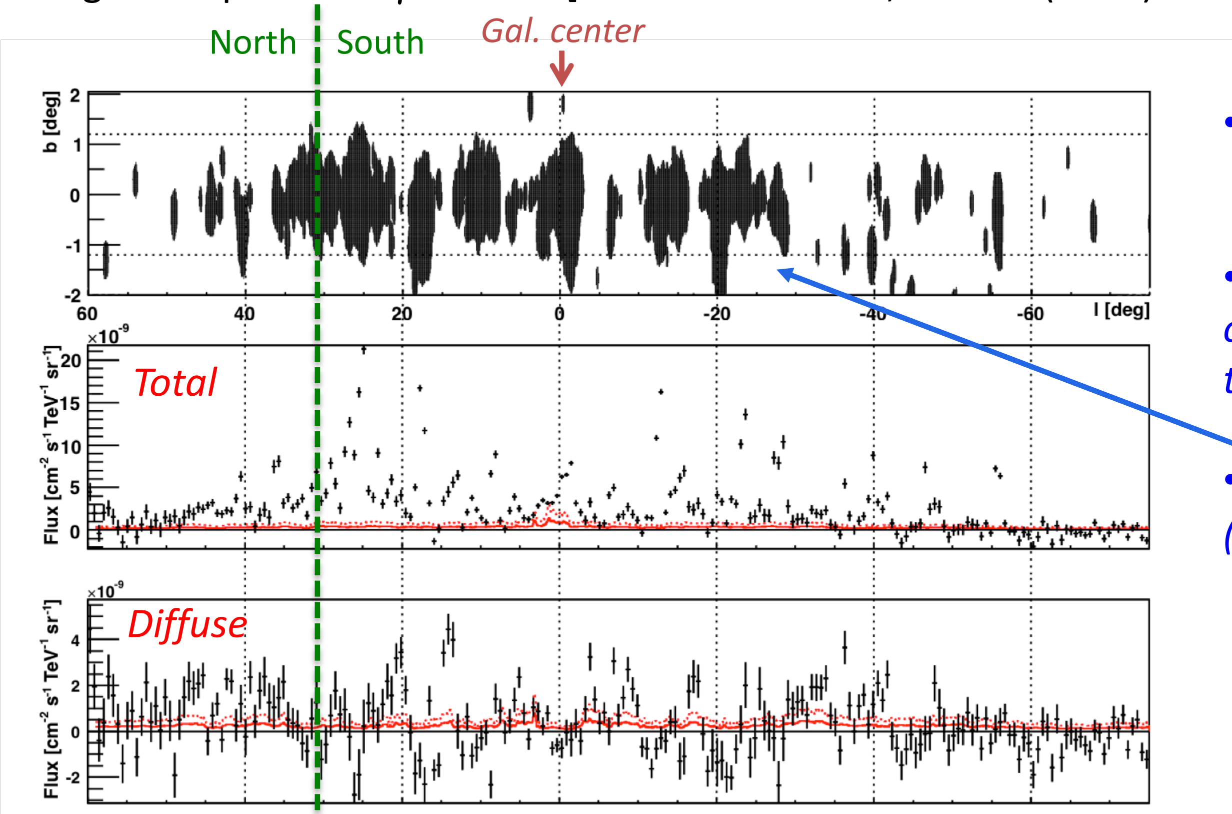
HESS provided in 2014 the first detailed observation of the large-scale γ-ray emission in the inner region of the galactic plane at $E\gamma \simeq 1$ TeV [Abramowski et al., PRD 90 (2014) 122007].



- *Observation window:* *-75° < l < 60° ; -2° < b < 2°*
- *Galactic signal:* *obtained as the excess relative to γ-ray emission at |b| ≥ 1.2°*
- *Vetoed regions* *(to mask resolved sources)*

The galactic plane in gammas

HESS provided in 2014 the first detailed observation of the large-scale γ-ray emission in the inner region of the galactic plane at $E\gamma \simeq 1$ TeV [Abramowski et al., PRD 90 (2014) 122007].



- *Observation window:*
  -75° < l < 60° ; -2° < b < 2°
- *Galactic signal:*
  obtained as the excess relative to γ-ray emission at |b| ≥ 1.2°
- *Vetoed regions*
  (to mask resolved sources)

✓ *By vetoing sources, a large fraction of the galactic plane is excluded.*
***Diffuse flux data** largely underestimate the real signal and **cannot** be directly compared to predictions*

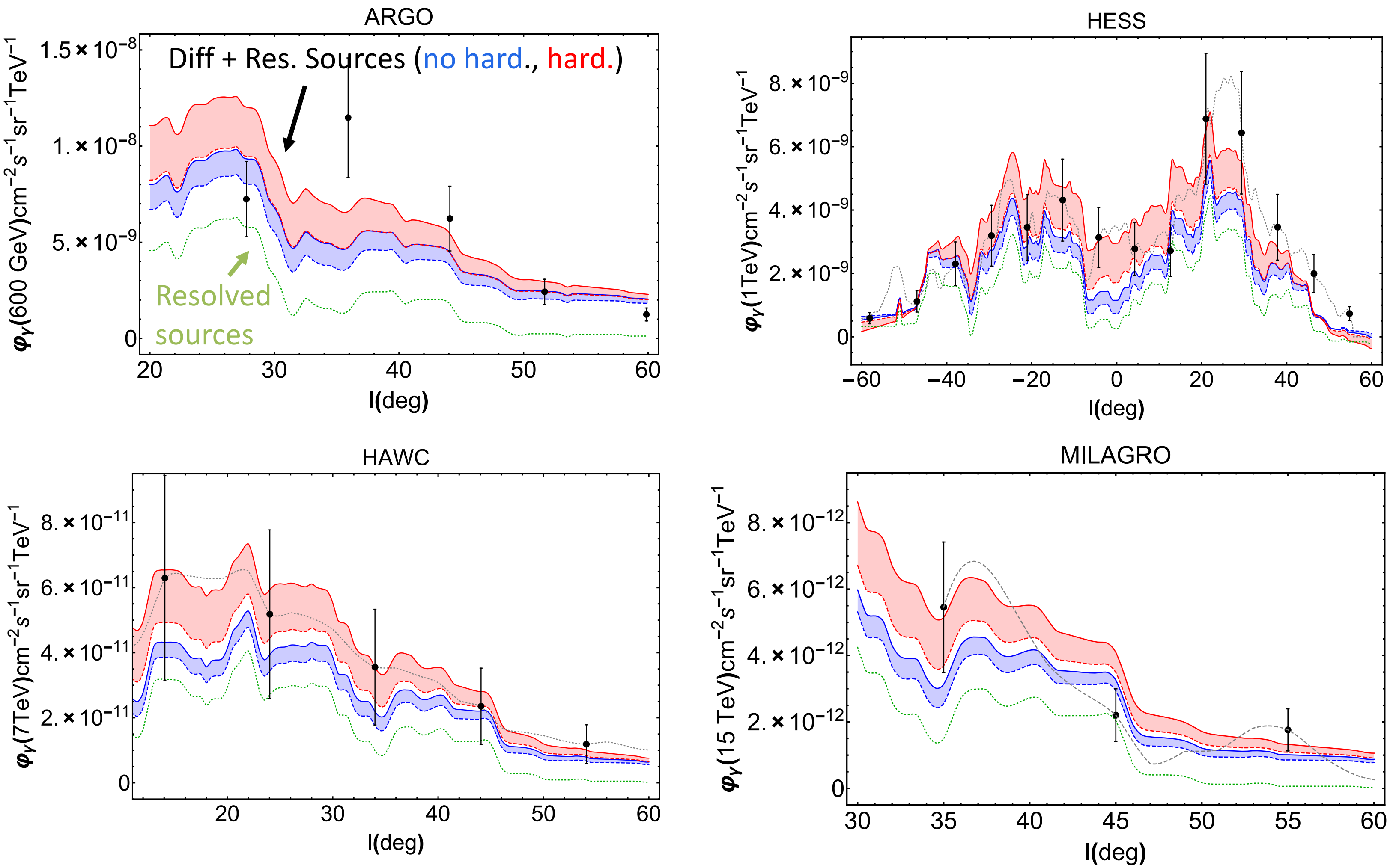
✓ *We construct a model that includes both contributions of **interstellar emission and sources** and we compare it with the **total flux** observed by the various gamma-ray experiments.*

Comparing with the total observed flux

[Cataldo et al, JCAP 2019]

$$\varphi_\gamma = \underbrace{\varphi_{\gamma,\mathrm{diff}} + \varphi^{(r)}_{\gamma,\mathrm{S}}} + \varphi_{\gamma,\mathrm{IC}}$$

We include the contribution of **78 resolved** sources included in HGPS catalog (HESS coll., A&A, 2018)

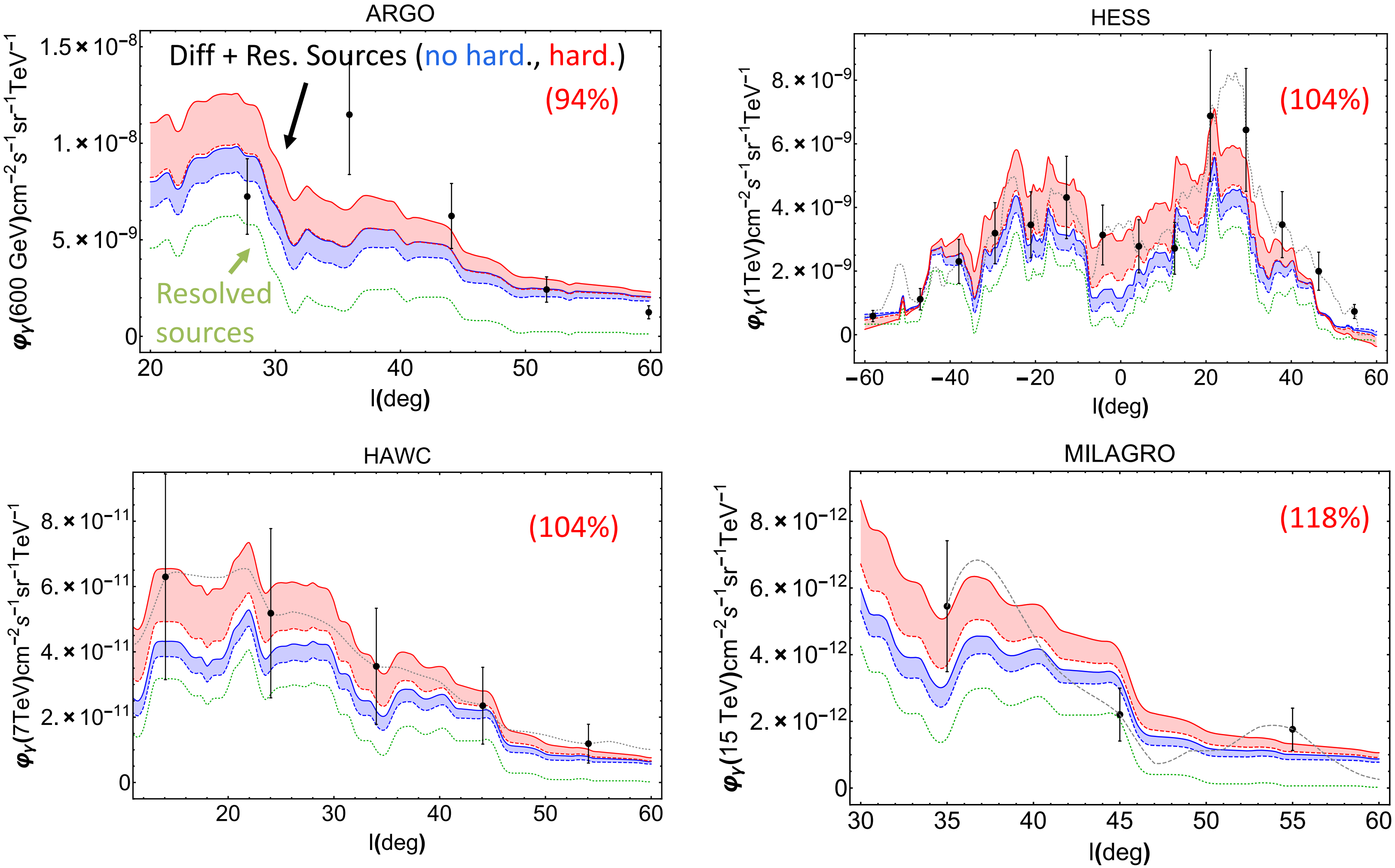


Comparing with the total observed flux

[Cataldo et al, JCAP 2019]

- If we assume CR hardening in the inner Galaxy →
resolved sources + CR diffuse emission saturate the total observed γ-ray flux

- This is a potential problem if unresolved source emission is not negligible



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

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

unresolved sources — resolved sources

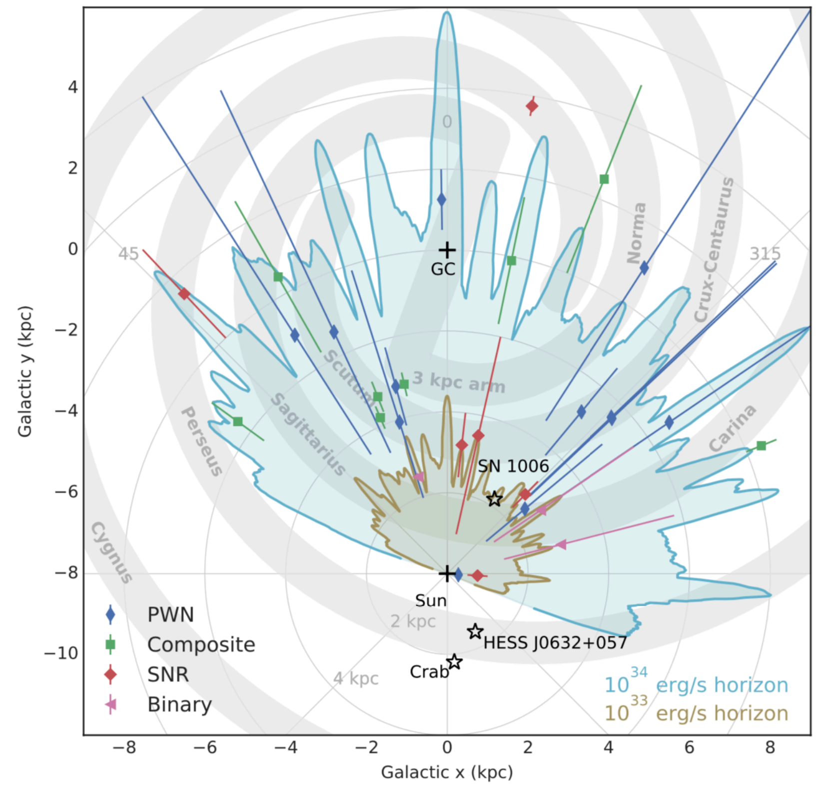
This contribution contaminates the diffuse large scale flux observed by different experiments, i.e.

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

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):

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

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

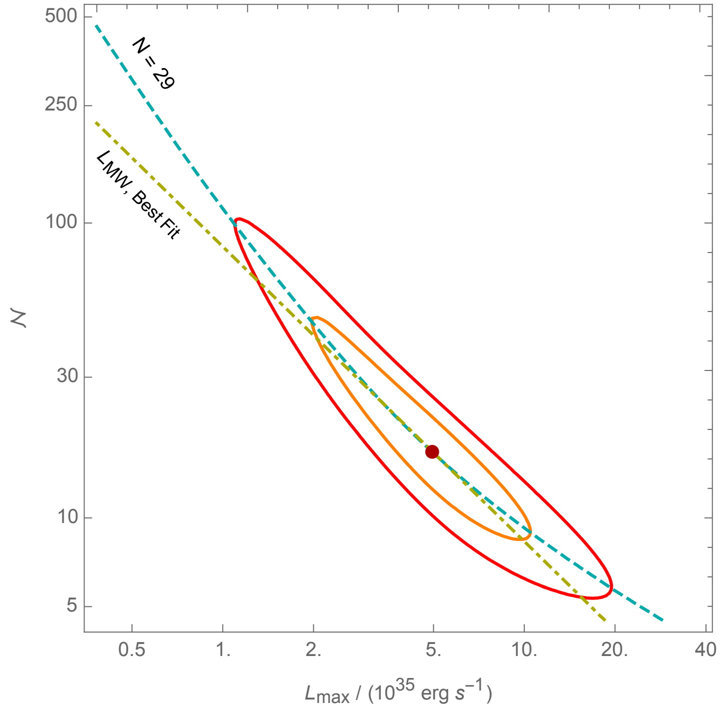
$$\mathcal{N} = R\,\tau\,(\alpha - 1)$$

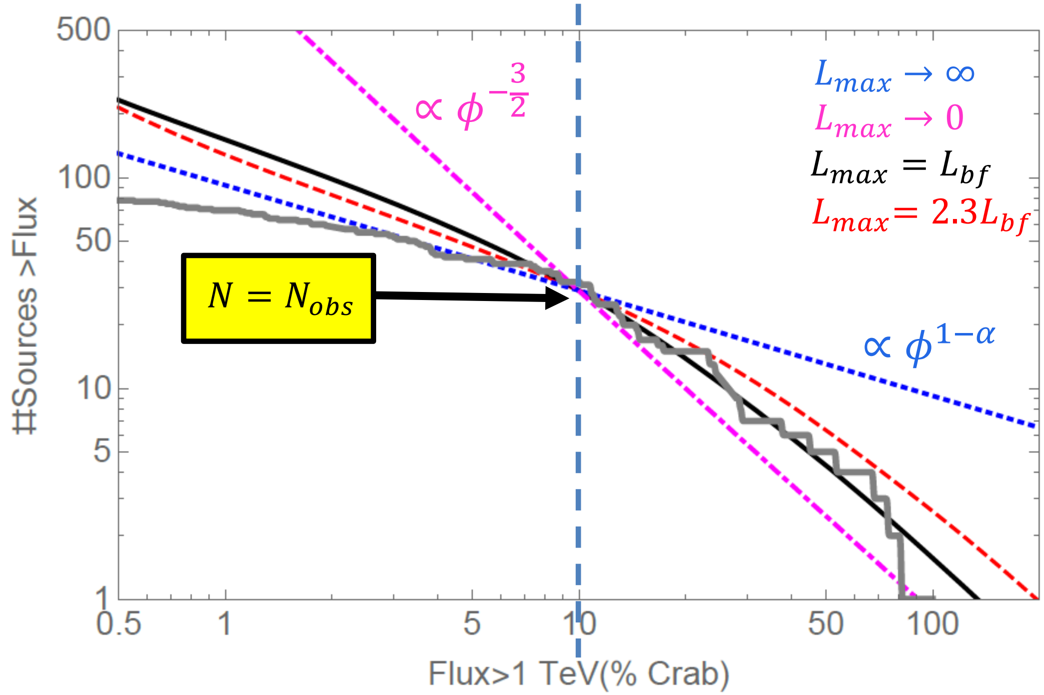
$R = 0.019\ yr^{-1}$
[SN Rate in the Galaxy]

The population of TeV galactic γ-ray sources

[Cataldo et al., ApJ 2020]

L_{max} and $\mathcal{N}$ are determined by fitting (unbinned likelyhood) the longitude, latitude and flux distribution of observed sources with $\Phi \geq 0.1\ \Phi_{CRAB}$





<u>Message #1</u>

By assuming "standard" space and luminosity distribution, we obtain:

i. Observational constraints on the source luminosity function;

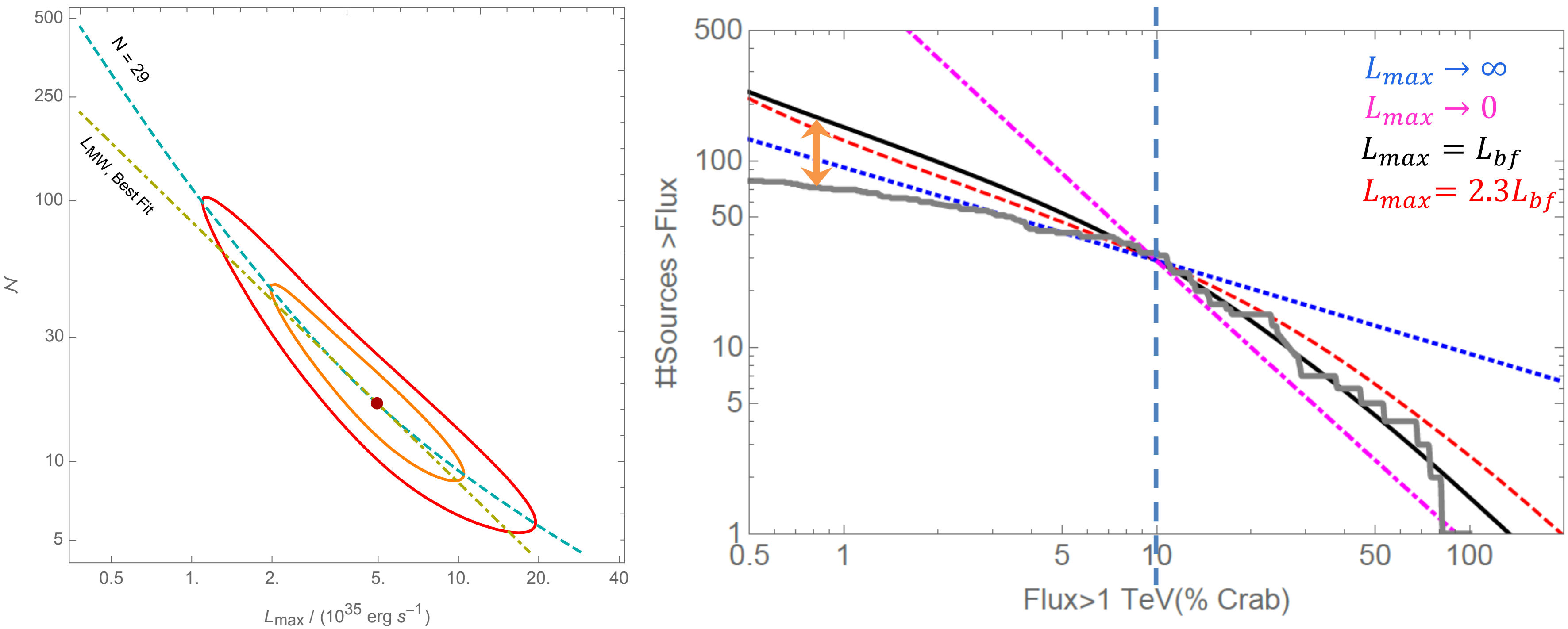
ii. Robust limits on the total TeV emission of the Milky Way;

iii. Estimates of the unresolved source contribution.

The population of TeV galactic γ-ray sources

[Cataldo et al., ApJ 2020]

L_{max} and $\mathcal{N}$ are determined by fitting (unbinned likelyhood) the longitude, latitude and flux distribution of observed sources with $\Phi \geq 0.1\ \Phi_{CRAB}$



<u>Message #1</u>

By assuming "standard" space and luminosity distribution, we obtain:

i. Observational constraints on the source luminosity function;

ii. Robust limits on the total TeV emission of the Milky Way;

iii. Estimates of the unresolved source contribution.

The population of TeV galactic γ-ray sources

[Cataldo et al., ApJ 2020]

If pulsar powered sources are responsible for bright TeV sources observed by HESS (N_{obs}=29)

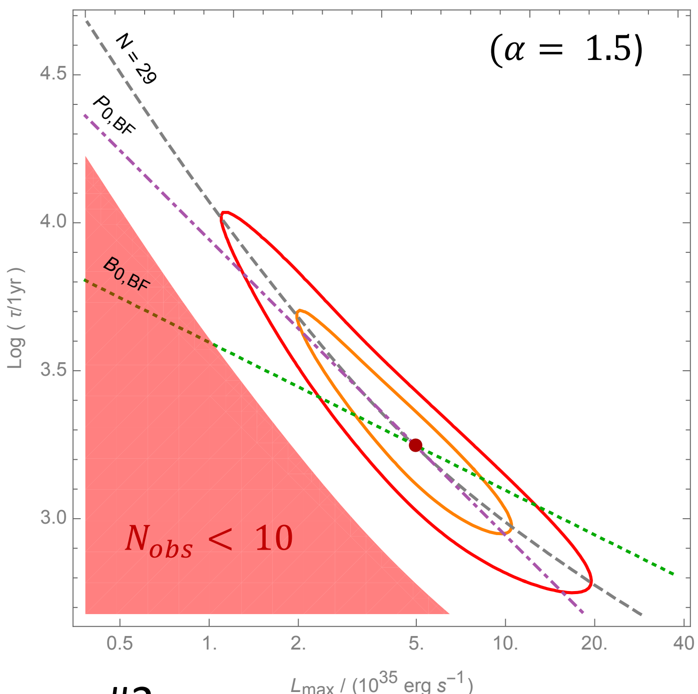
$$\begin{cases} \tau = \tau_{\rm sd}(B_0, P_0) \\ L_{\rm max} = \lambda \dot{E}_0(B_0, P_0) \end{cases} \longrightarrow \begin{cases} \dot{E}_0 = \dfrac{8\pi^4 B_0^2 R^6}{3c^3 P_0^4} \\ \tau_{\rm sd} = \dfrac{3Ic^3 P_0^2}{4\pi^2 B_0^2 R^6} \end{cases}$$

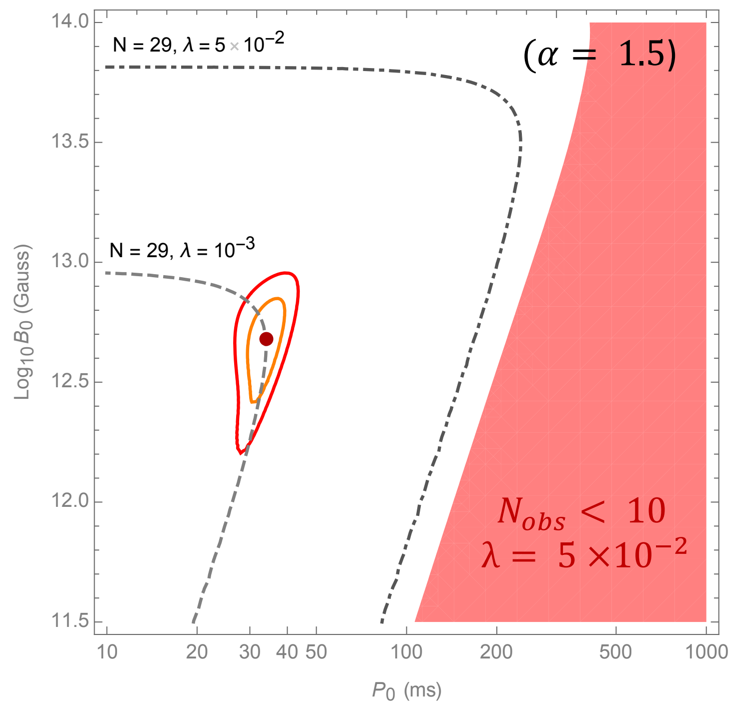
The population of TeV galactic γ-ray sources

[Cataldo et al., ApJ 2020]

If pulsar powered sources are responsible for bright TeV sources observed by HESS (N_{obs}=29)

$$\begin{cases} \tau = \tau_{\rm sd}(B_0, P_0) \\ L_{\rm max} = \lambda\, \dot{E}_0(B_0, P_0) \end{cases} \longrightarrow \begin{cases} \dot{E}_0 = \dfrac{8\pi^4 B_0^2 R^6}{3c^3 P_0^4} \\ \tau_{\rm sd} = \dfrac{3Ic^3 P_0^2}{4\pi^2 B_0^2 R^6} \end{cases}$$





<u>Message #2</u>

i. Reasonable value for τ

ii. Reasonable value for P_0 and B_0 (assuming $\lambda = 10^{-3}$)

iii. Upper limit on P_0 ($N_{obs} > 10$; $\lambda < 5 \times 10^{-2}$)

See Fiori et al, MNRAS 2022 – Modelling γ–ray PWNe population in our Galaxy

The population of TeV galactic γ-ray sources

[Cataldo et al., ApJ 2020]

	$\log_{10}\frac{L_{max}}{\mathrm{erg\,s^{-1}}}$	$\mathcal{N}$	$\log_{10}\frac{L_{MW}}{\mathrm{erg\ s^{-1}}}$	Φ_{tot}	τ	$\Delta\chi^2$
Ref. ($\alpha =$ 1.5)	$35.69^{+0.21}_{-0.28}$	17^{+14}_{-6}	$37.22^{+0.12}_{-0.13}$	$3.8^{+1.0}_{-1.0}$	$1.8^{+1.5}_{-0.6}$	–
SNR	$35.69^{+0.22}_{-0.25}$	18^{+15}_{-7}	$37.23^{+0.12}_{-0.13}$	$3.8^{+1.0}_{-1.0}$	$1.8^{+1.6}_{-0.7}$	1.4
$H = 0.1$ kpc	$35.65^{+0.22}_{-0.27}$	$15^{+14.5}_{-6}$	$37.13^{+0.12}_{-0.13}$	$5.0^{+0.4}_{-2.0}$	$1.6^{+1.5}_{-0.6}$	−7.3
$H = 0.05$ kpc	$35.34^{+0.26}_{-0.19}$	28^{+19}_{-13}	$37.08^{+0.12}_{-0.13}$	$4.4^{+1.3}_{-0.9}$	$2.9^{+2.0}_{-1.4}$	−10.5
$d = 20$ pc	$35.69^{+0.20}_{-0.26}$	17^{+16}_{-6}	$37.23^{+0.12}_{-0.13}$	$3.9^{+0.8}_{-1.0}$	$1.9^{+1.9}_{-0.7}$	−0.2
$d = 40$ pc	$35.67^{+0.20}_{-0.25}$	20^{+20}_{-8}	$37.28^{+0.12}_{-0.13}$	$4.4^{+1.2}_{-1.1}$	$2.2^{+2.0}_{-0.8}$	−1.8
$\alpha = 1.3$	$35.61^{+0.18}_{-0.27}$	$25^{+24}_{-8.5}$	$37.17^{+0.12}_{-0.13}$	$3.5^{+1.1}_{-0.9}$	$4.3^{+4.3}_{-1.5}$	0.0
$\alpha = 1.8$	$35.83^{+0.29}_{-0.24}$	7^{+6}_{-4}	$37.39^{+0.11}_{-0.13}$	$5.9^{+1.8}_{-0.1}$	$0.5^{+0.4}_{-0.2}$	0.5

Message #3

1. Results are stable wrt assumptions *(H = thickness of the disk , d = physical dimension of sources; α = index of the luminosity function, etc.)*

2. The total luminosity and flux of the population at TeV are constrained within a factor ~2 ($L_{MW} = (1.2 - 2.5)\times 10^{37}\ erg\ s^{-1}$; $\phi_{tot} = (3.5 - 5.9) 10^{-10} cm^{-2} s^{-1}$)

3. The unresolved contribution is comparable to resolved emission ($\phi_{NR} = \phi_{tot}$ - $\phi_{HGPS} \cong 60\%\ \phi_{HGPS}$)

The population of TeV galactic γ-ray sources

[Cataldo et al., ApJ 2020]

	$\log_{10}\frac{L_{max}}{\mathrm{erg\,s^{-1}}}$	$\mathcal{N}$	$\log_{10}\frac{L_{MW}}{\mathrm{erg\ s^{-1}}}$	Φ_{tot}	τ	$\Delta\chi^2$
Ref. ($\alpha = 1.5$)	$35.69^{+0.21}_{-0.28}$	17^{+14}_{-6}	$37.22^{+0.12}_{-0.13}$	$3.8^{+1.0}_{-1.0}$	$1.8^{+1.5}_{-0.6}$	–
SNR	$35.69^{+0.22}_{-0.25}$	18^{+15}_{-7}	$37.23^{+0.12}_{-0.13}$	$3.8^{+1.0}_{-1.0}$	$1.8^{+1.6}_{-0.7}$	1.4
$H = 0.1$ kpc	$35.65^{+0.22}_{-0.27}$	$15^{+14.5}_{-6}$	$37.13^{+0.12}_{-0.13}$	$5.0^{+0.4}_{-2.0}$	$1.6^{+1.5}_{-0.6}$	-7.3
$H = 0.05$ kpc	$35.34^{+0.26}_{-0.19}$	28^{+19}_{-13}	$37.08^{+0.12}_{-0.13}$	$4.4^{+1.3}_{-0.9}$	$2.9^{+2.0}_{-1.4}$	-10.5
$d = 20$ pc	$35.69^{+0.20}_{-0.26}$	17^{+16}_{-6}	$37.23^{+0.12}_{-0.13}$	$3.9^{+0.8}_{-1.0}$	$1.9^{+1.9}_{-0.7}$	-0.2
$d = 40$ pc	$35.67^{+0.20}_{-0.25}$	20^{+20}_{-8}	$37.28^{+0.12}_{-0.13}$	$4.4^{+1.2}_{-1.1}$	$2.2^{+2.0}_{-0.8}$	-1.8
$\alpha = 1.3$	$35.61^{+0.18}_{-0.27}$	$25^{+24}_{-8.5}$	$37.17^{+0.12}_{-0.13}$	$3.5^{+1.1}_{-0.9}$	$4.3^{+4.3}_{-1.5}$	0.0
$\alpha = 1.8$	$35.83^{+0.29}_{-0.24}$	7^{+6}_{-4}	$37.39^{+0.11}_{-0.13}$	$5.9^{+1.8}_{-0.1}$	$0.5^{+0.4}_{-0.2}$	0.5

<u>Message #3</u>

1. Results are stable wrt assumptions *(H = thickness of the disk , d = physical dimension of sources; α = index of the luminosity function, etc.)*

2. The total luminosity and flux of the population at TeV are constrained within a factor ~2 ($L_{MW} = (1.2 - 2.5)\times 10^{37}\ erg\ s^{-1}$; $\phi_{tot} = (3.5 - 5.9) 10^{-10} cm^{-2} s^{-1}$)

3. The unresolved contribution is comparable to resolved emission ($\phi_{NR} = \phi_{tot}$ - $\phi_{HGPS} \cong 60\%\ \phi_{HGPS}$)

Implications of TeV galactic γ-ray sources at GeV energies

[Vecchiotti et al., Comm.Phys. 2022]

- TeV galactic γ–ray sources are expected to emit also at lower energies.
- They represent a subdominant population at GeV energies population wrt extragalactic objects (obscured at TeV due to γ–ray absoprtion) and/or pulsars (not relevant at TeV)

Not efficiently observed and constrained at GeV. They may easily escape detection.

- However, they are expected to have harder spectrum than other source classes (even harder than what observed at TeV, i.e. $\beta_{GeV} \leq \beta_{TeV} \simeq 2.3-2.4$) and to become dominant at TeV energies where they are bounded to produce $L_{MW} = (1.2-2.5)\times 10^{37}\, erg\, s^{-1}$; $\phi_{tot} = (3.5-5.9)10^{-10} cm^{-2} s^{-1}$ by HGPS observations.

Unresolved TeV-galactic sources may contaminate diffuse emission determinations at GeV partially explaining the observed γ–ray hardening in the inner Galaxy

Relevance of unresolved source emission for diffuse flux determination at GeV:

Pothast et al. 2018 – Population study based on Fermi 4FGL catalog only.

Pagliaroli et al. 2022 – Focus on TeV sources and implements the information provided by HGPS.

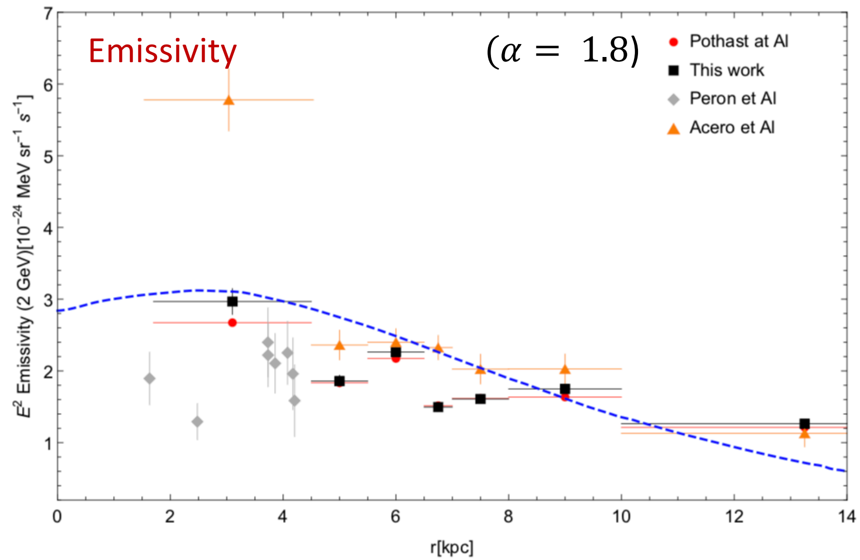
Implications of TeV galactic γ-ray sources at GeV energies

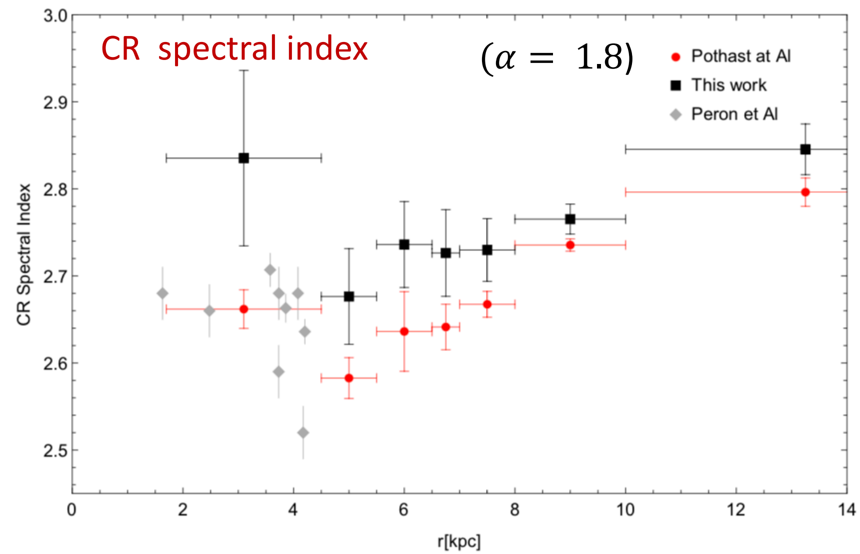
[Vecchiotti et al., Comm.Phys. 2022]

We model TeV-galactic sources - assumed to be PWNe (Abdalla et al. 2018a) or TeV halos (Linden & Buckman 2018; Sudoh et al. 2019; Giacinti et al. 2020) – by assuming **broken power-law** average emission spectrum:

$$\beta_{GeV} \neq \beta_{TeV} \simeq 2.3 - 2.4 \ (HGPS)$$
$$E_0 = \ 0.1 \ - 1.0 \ TeV;$$
$$R_\phi \equiv \Phi_{GeV}/\Phi_{TeV} = \ 250 - 1000$$

Validated by comparing Fermi-LAT 4FGL-D2R and HGPS catalogs





<u>Message #4:</u>

The emergence of a <u>TeV-PWNe unresolved component</u> could potentially account for the CR spectral index in the inner Galaxy.

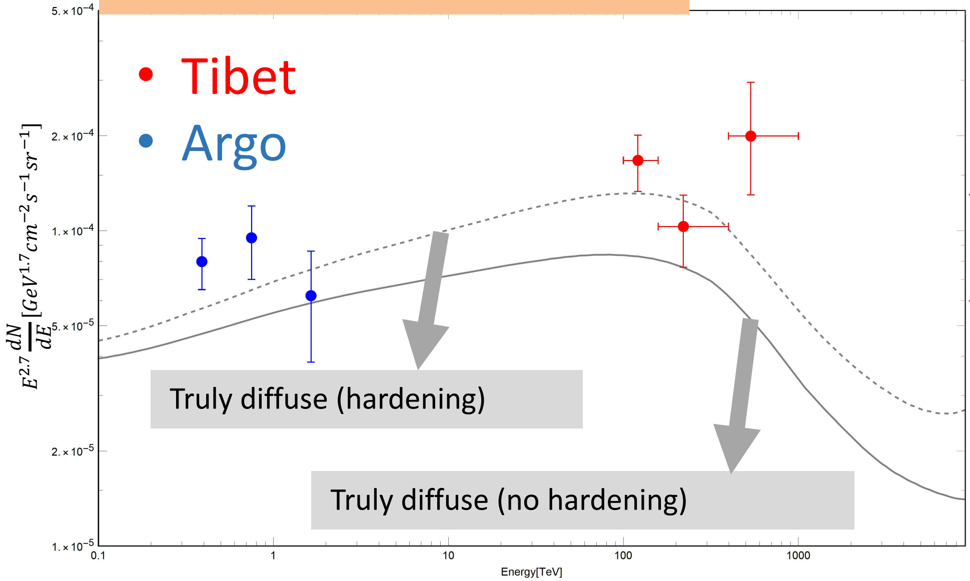
Diffuse fluxes at sub-PeV

Tibet ASγ

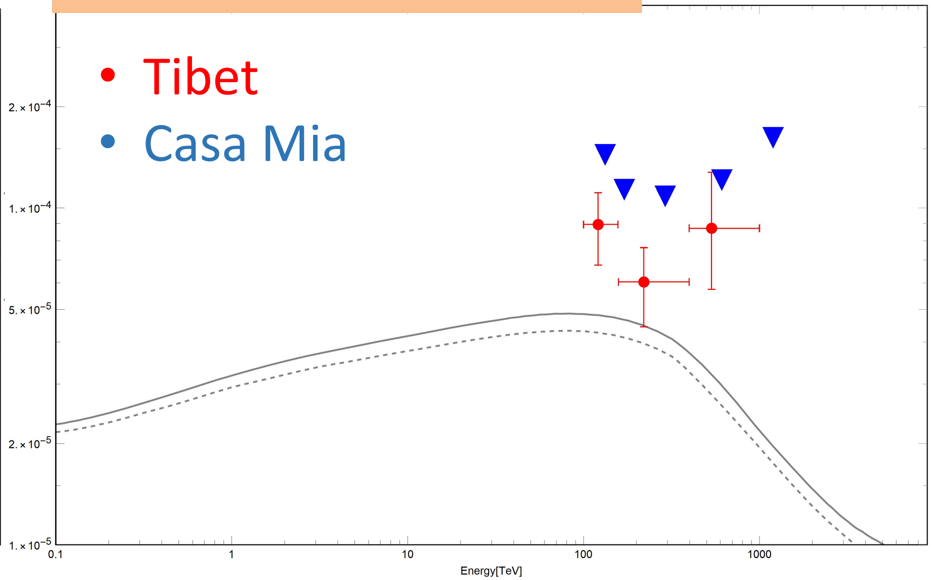
Amenomori, M., et al. 2021, Phys. Rev. Lett., 126, 141101,326

First measurement of the Galactic diffuse γ-ray emission in the sub-PeV energy range. → $\phi_{\gamma,\mathrm{diff}}^{Tibet}$

$25° < l < 100°, |b| < 5°$



$50° < l < 200°, |b| < 5°$



Diffuse fluxes at sub-PeV

Tibet ASγ

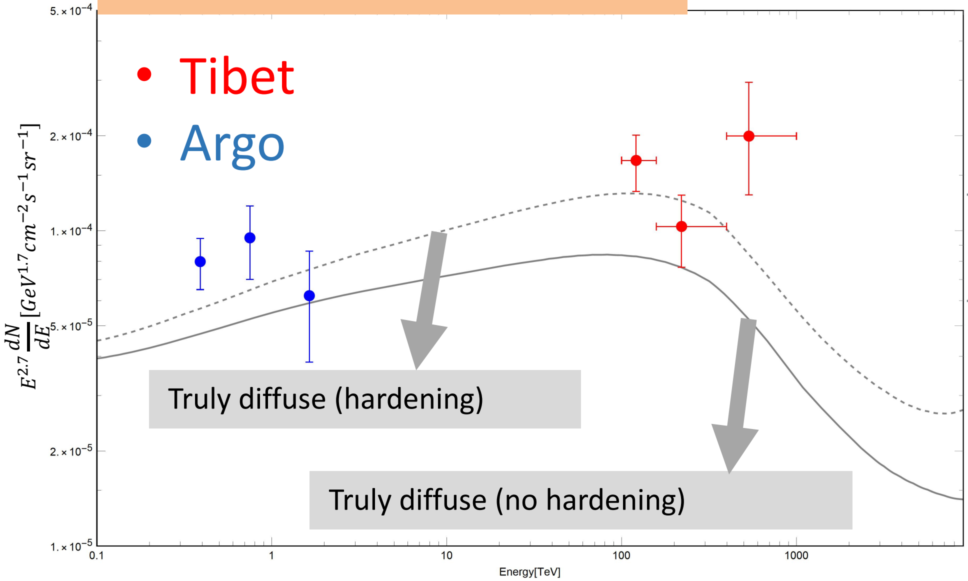
Amenomori, M., et al. 2021, Phys. Rev. Lett., 126, 141101,326

<u>Note that</u>: Tibet ASγ excludes the contribution from the known TeV sources (within 0.5 degrees) listed in the TeV source catalog.

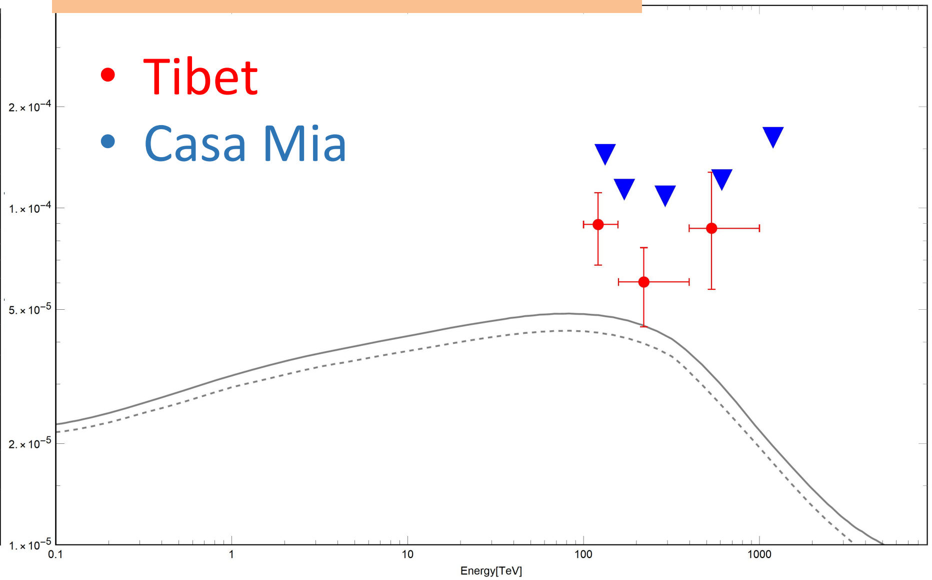
Diffuse measurements are contaminated by the presence of **TeV-unresolved sources**

$$\phi_{\gamma,\mathrm{diff}}^{Tibet} = \phi_{\gamma,S}^{NR} + \phi_{\gamma,\mathrm{diff}}$$

$25° < l < 100°, |b| < 5°$



$50° < l < 200°, |b| < 5°$



Unresolved source emission at sub-Pev

[Vecchiotti et al. ApJ 2022]

- We assume that the average source spectrum is a power-law with an exponential cut-off.

$$\varphi(E) = \left(\frac{E}{1\ TeV}\right)^{-\beta_{TeV}} Exp\left(-\frac{E}{E_{cut}}\right)$$

$\beta_{TeV} = 2.3$ from the HGPS catalogue [1-100 TeV];

$E_{cut} = 500\ TeV$ still not well constrained but motivated by recent observations of Tibet, HAWC and LHAASO;

Amenomori, M., Bao, Y. W., Bi, X. J., et al. 2019, Phys. Rev. Lett., 123

Abeysekara, A., Albert, A., Alfaro, R., et al. 2020, Phys. Review Letters, 124

Cao, Z., Aharonian, F. A., An, Q., et al. 2021, Nature, 594,33033

- We introduce a flux detection threshold based on the performance of H.E.S.S. detector

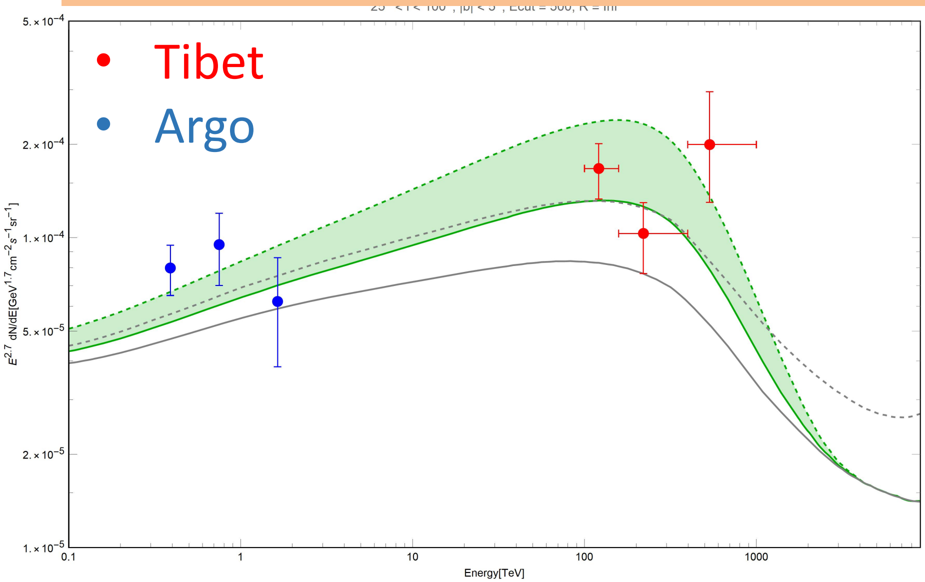
$$\phi_{th} = 0.01\phi_{CRAB} - 0.1\phi_{CRAB}$$

Unresolved source emission at sub-Pev

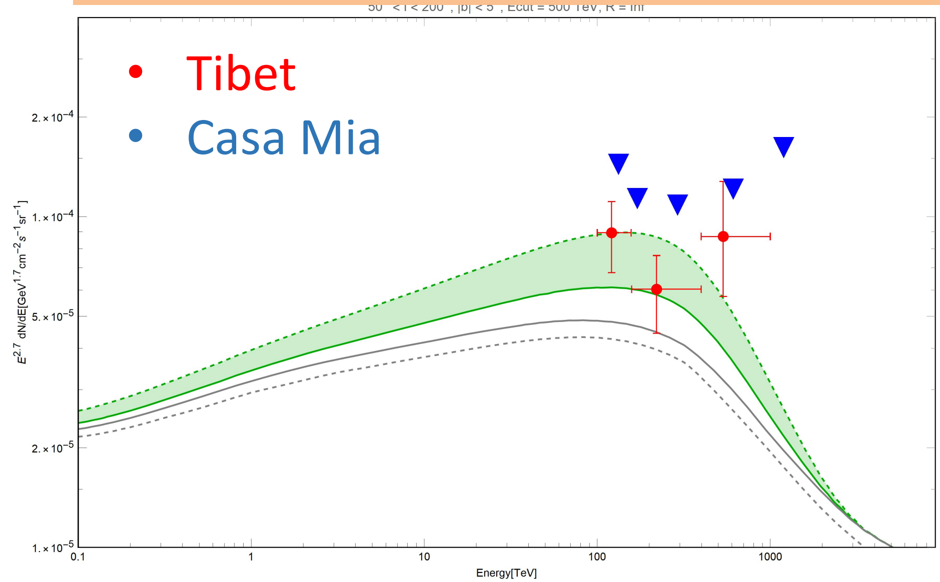
[Vecchiotti et al. ApJ 2022]

We add the contribution of unresolved sources to the CR diffuse emission calculated without assuming CR spectral hardening (green band in the figure).

$25^\circ < l < 100^\circ, |b| < 5^\circ, E_{cut} = 500\ TeV\ (\alpha = 1.5)$



$50^\circ < l < 200^\circ, |b| < 5^\circ, E_{cut} = 500\ TeV, (\alpha = 1.5)$

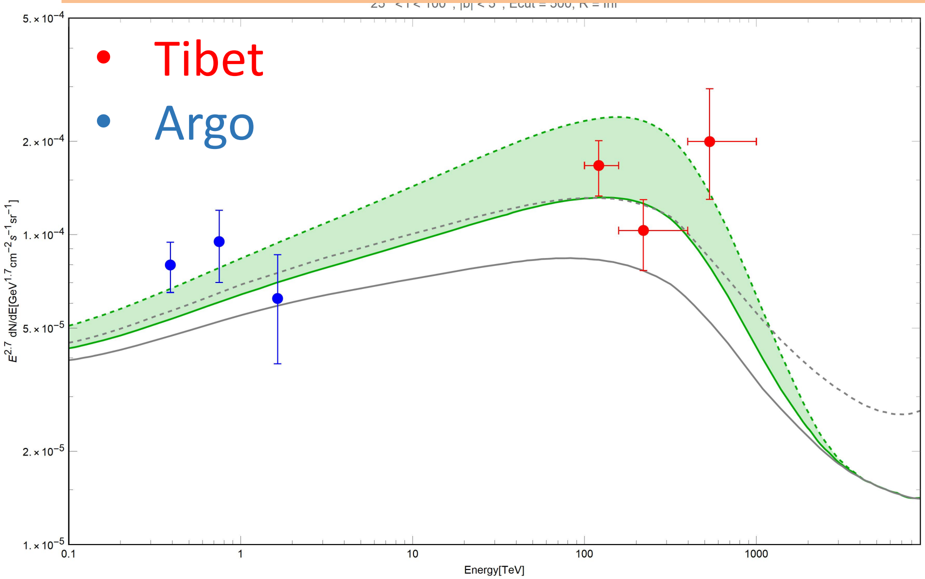


Unresolved source emission at sub-Pev

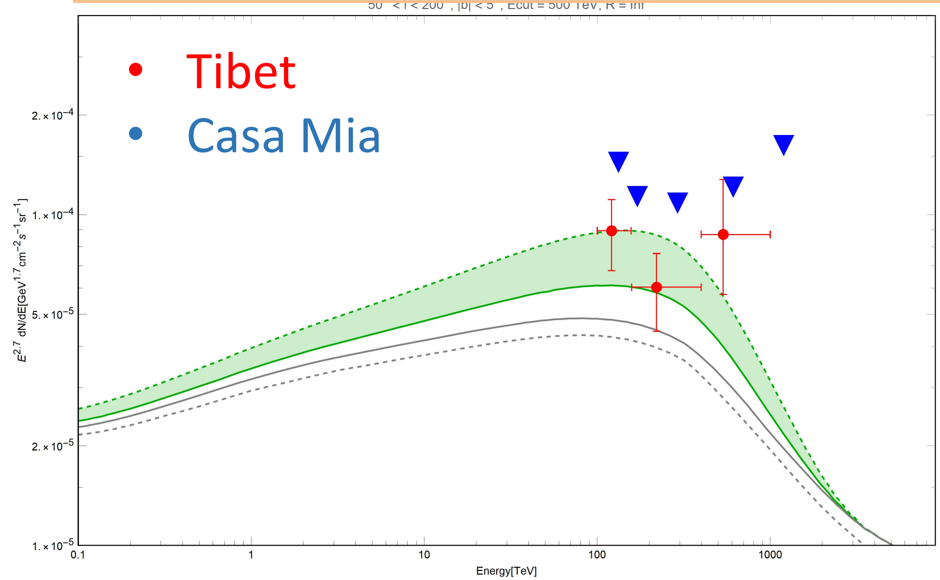
[Vecchiotti et al. ApJ 2022]

We add the contribution of unresolved sources to the CR diffuse emission calculated without assuming CR spectral hardening (green band in the figure).

$25^\circ < l < 100^\circ, |b| < 5^\circ, E_{cut} = 500\ TeV\ (\alpha = 1.5)$



$50^\circ < l < 200^\circ, |b| < 5^\circ, E_{cut} = 500\ TeV, (\alpha = 1.5)$



<u>Message #5:</u>

I. The inclusion of the **unresolved sources** produces a similar effect to CR spectral hardening at small galactic longitudes ($|l| \leq 60^\circ$);

II. It better describes Tibet ASγ data at large galactic longitudes ($|l| \geq 60^\circ$);

III. The two effects can be distinguished by looking at different regions of the sky

Summary

1. The interaction of HE cosmic rays (CR) with the gas contained in the galactic disk is a guaranteed source of neutrinos and gammas at TeV.

2. Diffuse CR emission is being probed by gamma-ray and neutrino telescopes and can provide important information about CR space and energy distribution in the Galaxy (e.g. test CR spectral hardening in the inner Galaxy).

3. The interpretation of the observational results is complicated by the difficult separation of CR diffuse emission from (resolved and unresolved) sources. In particular, the "observed diffuse flux" is unavoidably contaminated by unresolved source component.

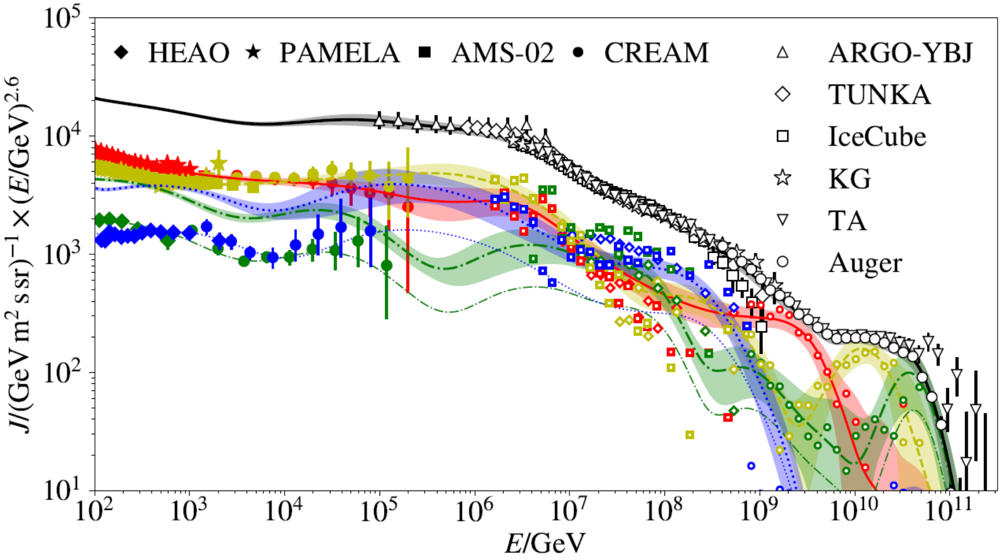
4. Population studies of HGPS catalog allow us to constrain the properties of TeV galactic sources (e.g. to determine their luminosity function and/or to test the assumption that they are dominated by pulsar powered sources) and to estimate unresolved source component.

5. The unresolved source component has a comparable magnitude to the CR diffuse emission at TeV and it appears to be relevant for the correct interpretation of observational gamma-ray results from GeV to PeV.

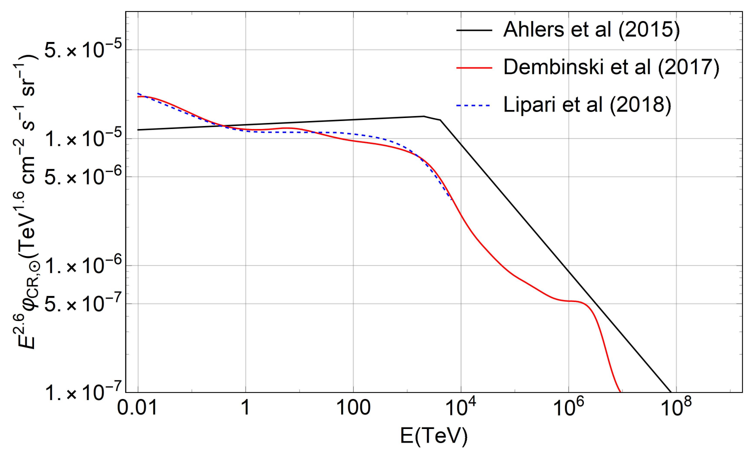
Thank you

Cosmic ray local spectrum:

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

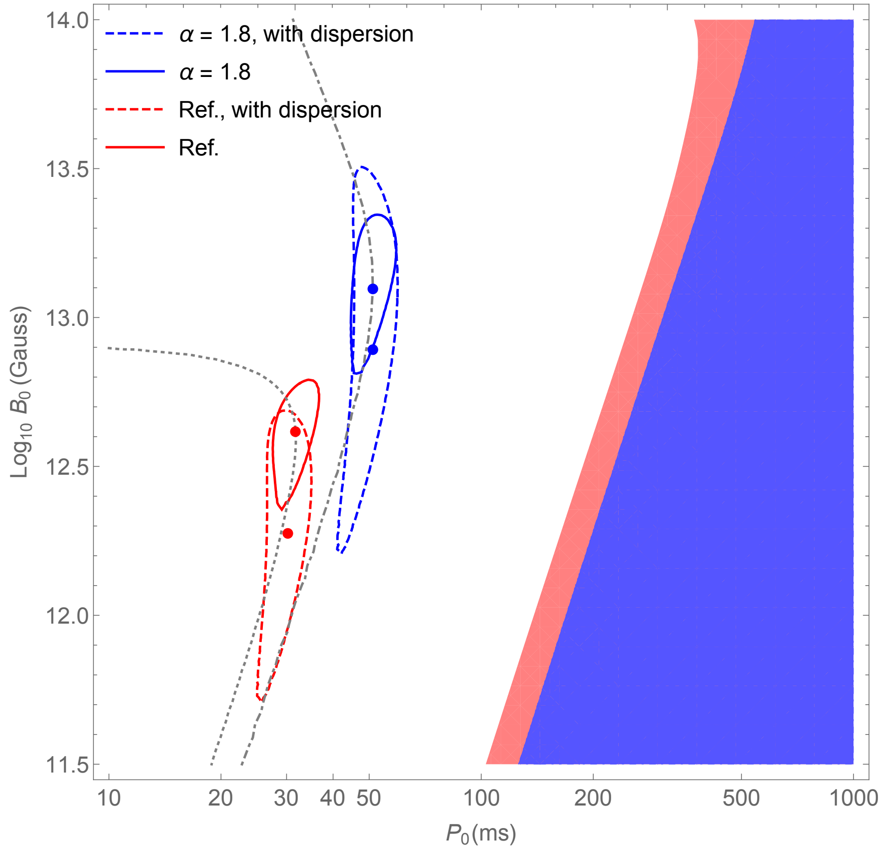


CR nucleons spectrum



The population of TeV galactic γ-ray sources

Effect of P_0 and B_0 dispersion:
- log-normal distribution for P_0 with $\sigma_{logP} = \log(\sqrt{2})$;
- log-normal distribution for B_0 with $\sigma_{logB} = \log(2)$;
- Bounds for the central values $\tilde{P}_0$ and $\tilde{B}_0$



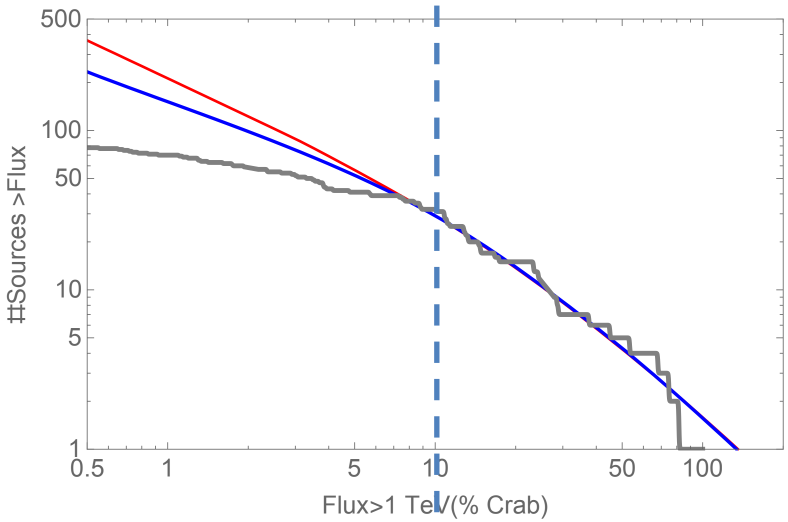
Implications of TeV galactic γ-ray sources at GeV energies

TeV-galactic sources, possibly **PWNe** (Abdalla et al. 2018a) or **TeV halos** (Linden & Buckman 2018; Sudoh et al. 2019; Giacinti et al. 2020), are expected to have harder spectrum at GeV energies than at TeV. We model the average emission spectrum as a borken power-law:

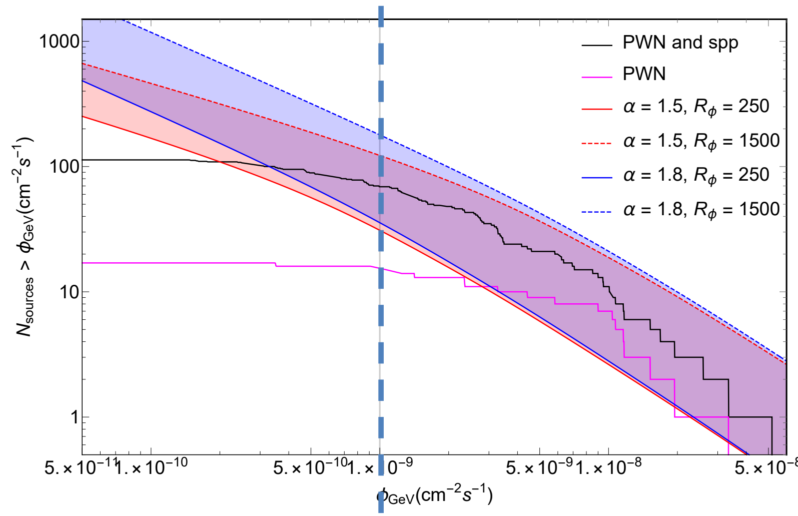
$$\varphi(E) = \begin{cases} \varphi_0(E/E_0)^{-\beta_{\rm GeV}} & E \leq E_0 \\ \varphi_0(E/E_0)^{-\beta_{\rm TeV}} & E \geq E_0 \end{cases}$$

- $E_0 = [0.1 - 1.0]\ TeV$
- $\beta_{TeV} = 2.3 - 2.4$ (fixed by HGPS)
- β_{GeV} = obt. by requiring realistic values of $R_\phi \equiv \frac{\phi_{GeV}}{\phi_{TeV}}$

HGPS – 1-100 TeV



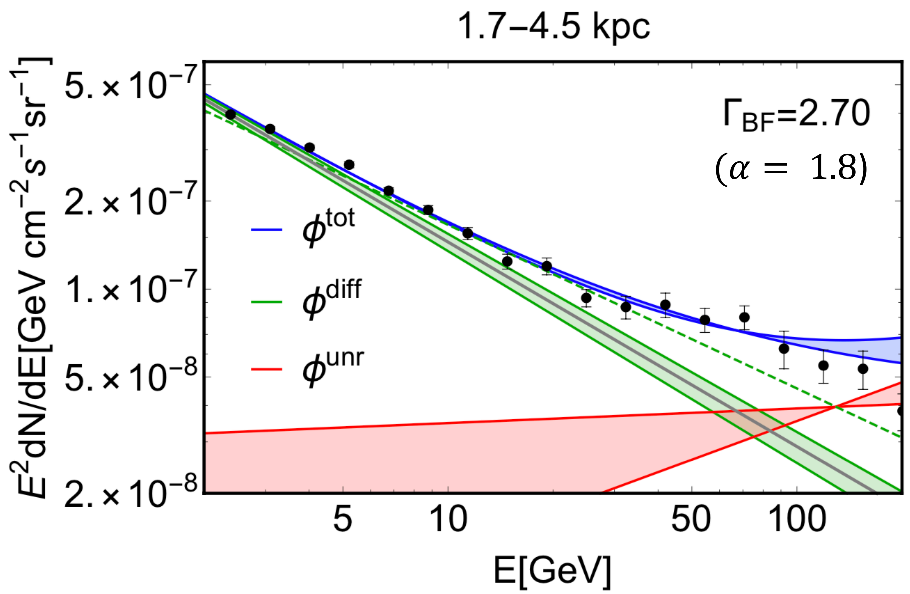
Fermi-LAT 4FGL-DR2 – 1-100 GeV



Fermi-Lat detection threshold for objects in the galactic plane (see e.g. Pothast et al. 2018)

Implications of TeV galactic γ-ray sources at GeV energies

	$\Phi_{\rm GeV}^{\rm diff}$ $(cm^{-2}\ s^{-1})$	$\Phi_{\rm GeV}^{\rm NR}$ $(cm^{-2}\ s^{-1})$	$(\alpha = 1.8)$
		$R_\Phi = 250$	$R_\Phi = 1500$
1.7 – 4.5 kpc	3.86×10^{-7}	3.35×10^{-8} (8.6%)	1.40×10^{-7} (36%)
4.5 – 5.5 kpc	3.11×10^{-7}	1.91×10^{-8} (6.1%)	8.00×10^{-8} (26%)
5.5 – 6.5 kpc	5.09×10^{-7}	2.13×10^{-8} (4.2%)	8.93×10^{-8} (17%)
6.5 – 7.0 kpc	2.57×10^{-7}	1.15×10^{-8} (4.5%)	4.81×10^{-8} (19%)
7.0 – 8.0 kpc	7.7×10^{-7}	2.67×10^{-8} (3.5%)	1.12×10^{-7} (14%)
8.0 – 10.0 kpc	3.84×10^{-6}	4.89×10^{-8} (1.3%)	2.05×10^{-7} (5.3%)
10.0 – 16.5 kpc	7.68×10^{-7}	1.51×10^{-8} (1.9%)	6.37×10^{-8} (8.3%)
16.5 – 50.0 kpc	4.44×10^{-8}	3.87×10^{-10} (0.8%)	2.07×10^{-9} (4.7%)
0.0 – 50.0 kpc	6.89×10^{-6}	1.79×10^{-7}(2.6%)	7.53×10^{-7} (11%)



ABSORPTION IN THE SUB PEV ENERGY RANGE:

Vernetto and Lipari, Phys. Rev. D 94, 063009 – Published 19 September 2016

The pair production cross section:

$$\sigma_{\gamma\gamma} = \sigma_T \left(\frac{3}{16}\right)(1-\beta^2)\left[2\beta(\beta^2-2)+(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

Where: $\beta = \sqrt{1-\frac{1}{x}}$ and $x = \frac{2E_\gamma\epsilon(1-\cos\theta)}{4\,m_e^2}$, $x > 1$

For a fixed values of ϵ the energy threshold is:

$$E_\gamma^{th} = \frac{2\,m_e^2}{\epsilon(1-cos\theta)} \simeq \frac{0.52}{\epsilon_{eV}(1-cos\theta)}\,TeV$$

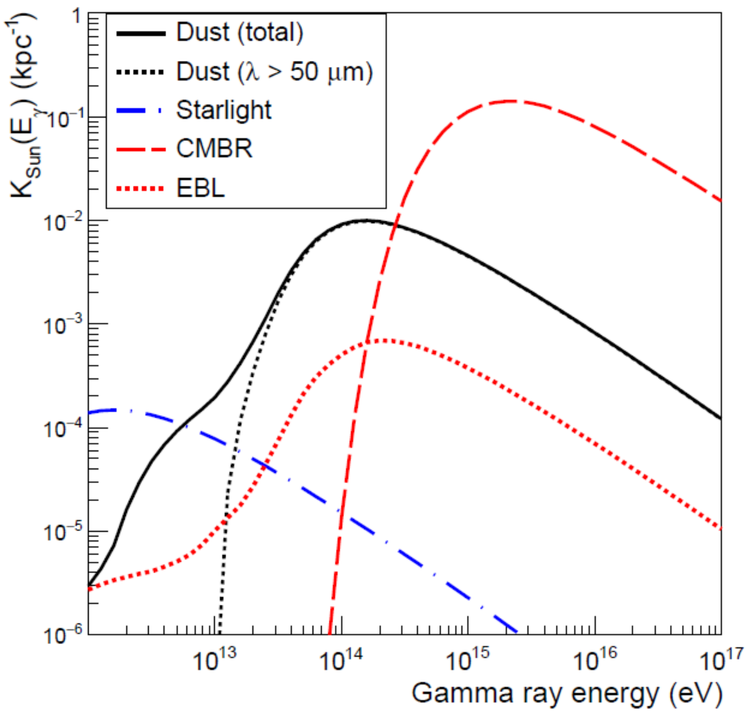
The absorption probability per unit path length (for CMB) is:

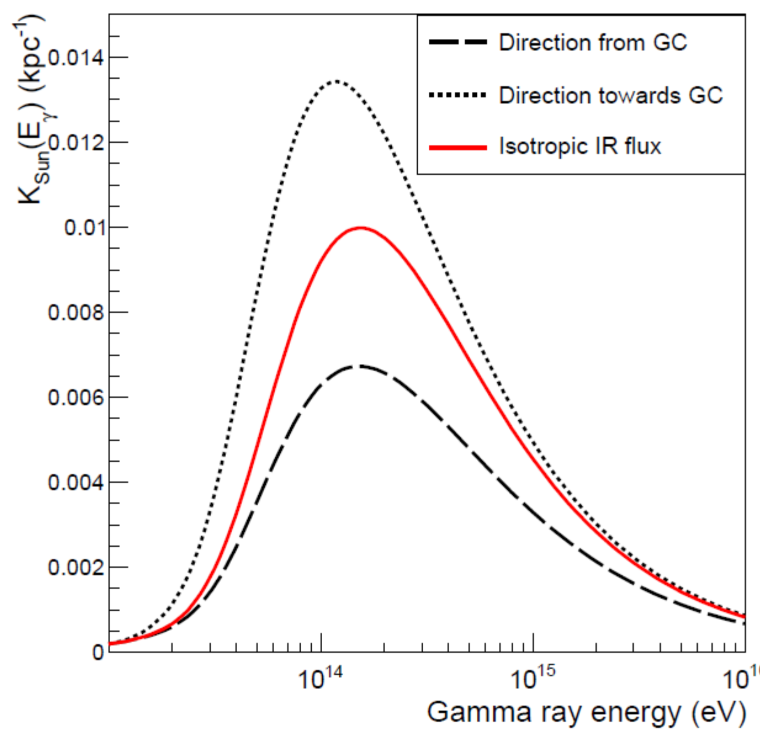
$$K(E_\gamma) = \int \epsilon \int d\Omega(1-\cos(\theta))n_{\gamma,CMB}(\epsilon)\sigma_{\gamma\gamma}(x(E_\gamma,\epsilon,\theta))$$

The optical depth is:

$$\tau(E_\gamma, r) = \int_0^r \mathrm{dr}'\ K(E_\gamma)$$

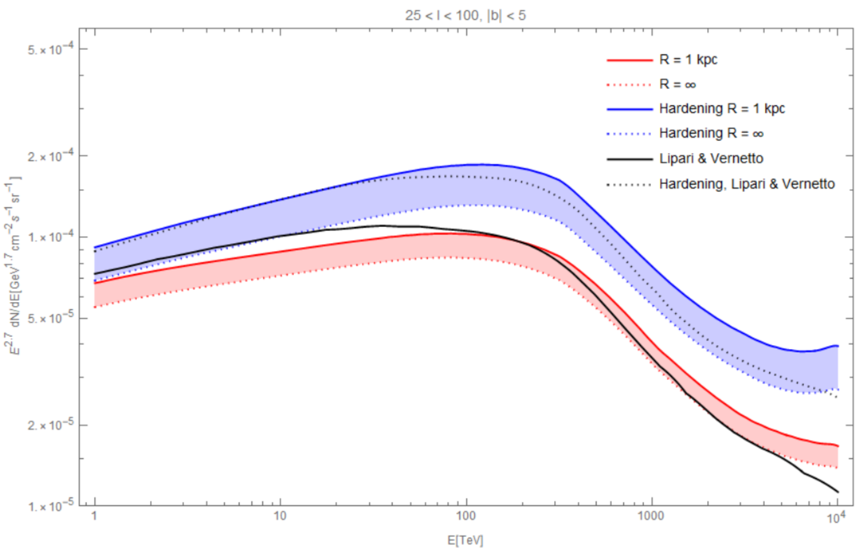
ABSORPTION IN THE SUB PEV ENERGY RANGE:

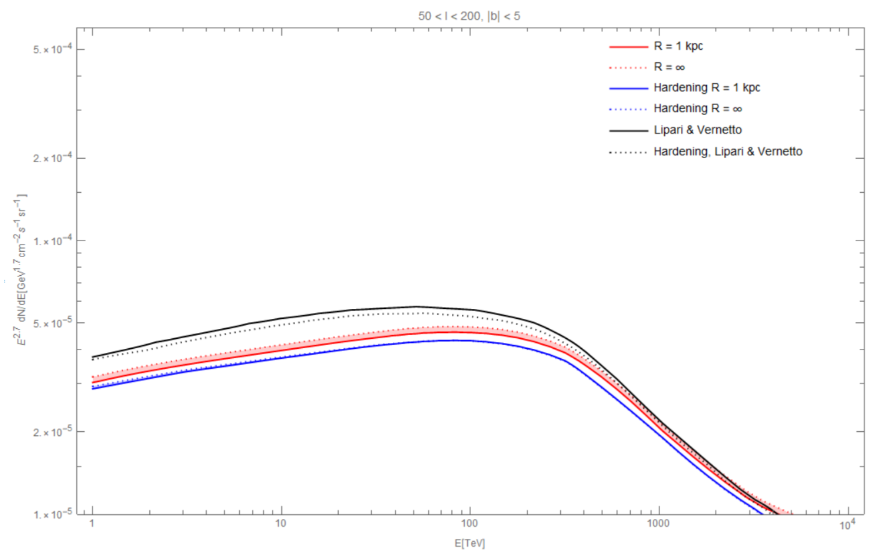




Vernetto and Lipari, Phys. Rev. D 94, 063009 – Published 19 September 2016

Comparison between different diffuse γ–ray calculations:





Why not LHAASO?

Extraction of Resolved Sources

Region:
Inner Galactic Plane
(25°<l<100°)

Masked radius $R < 2\sqrt{\mathrm{p.s.f}^2 + \sigma_{ext}^2} \sim 1^\circ$

LHAASO Collaboration– ICRC 2021