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Implications of unresolved sources for the interpretation of the total galactic gamma-ray diffuse emission.

Presented by: Vittoria Vecchiotti

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

Outline:

1. The total Galactic emission in gamma-ray;
2. The unresolved sources;
3. The total Galactic **diffuse** emission in gamma-ray;

4. **GeV energy range**: unresolved contribution and interpretation of the large scale diffuse emission observed by FermiLAT.

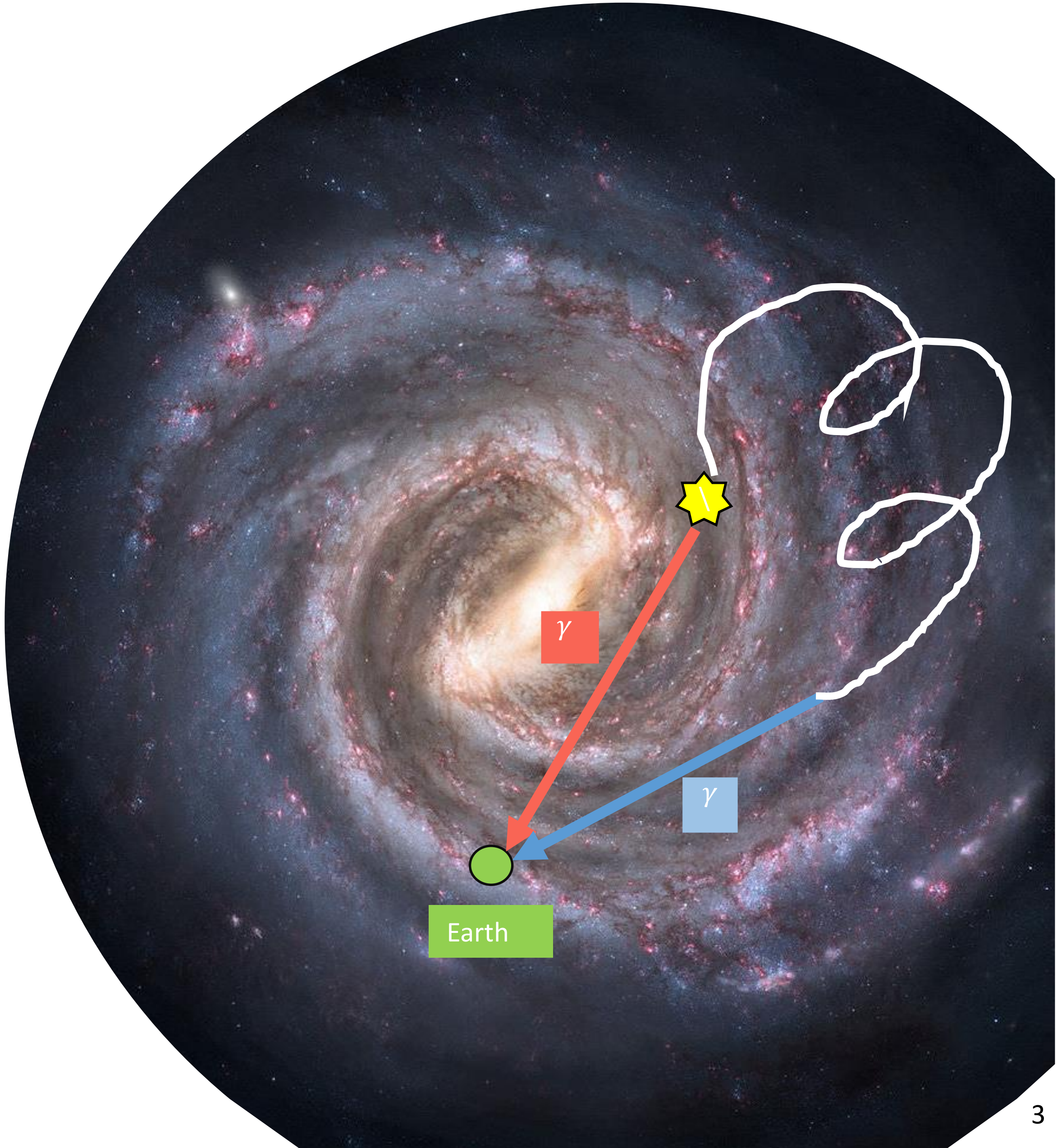
   Vecchiotti et al, ICRC 2021, Journal of Physics: Conference Series.

5. **Sub-PeV energy range**: unresolved contribution and interpretation of the large scale diffuse emission observed by Tibet.

   Vecchiotti et al., Astrophys.J. (2021)

Total Galactic emission GeV-PeV:

$$\phi_{\gamma,tot} = \boxed{\phi_{\gamma,S}} + \boxed{\phi_{\gamma,\mathrm{diff}}} + \phi_{\gamma,IC}$$



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

Diffuse component is due to the interaction of Cosmic Rsys (CRs) with the interstellar medium;

(Spectral features related to the one of CRs)

Inverse Compton: is due to the interaction of accelerated leptons with the CMB ;

Unresolved sources:

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

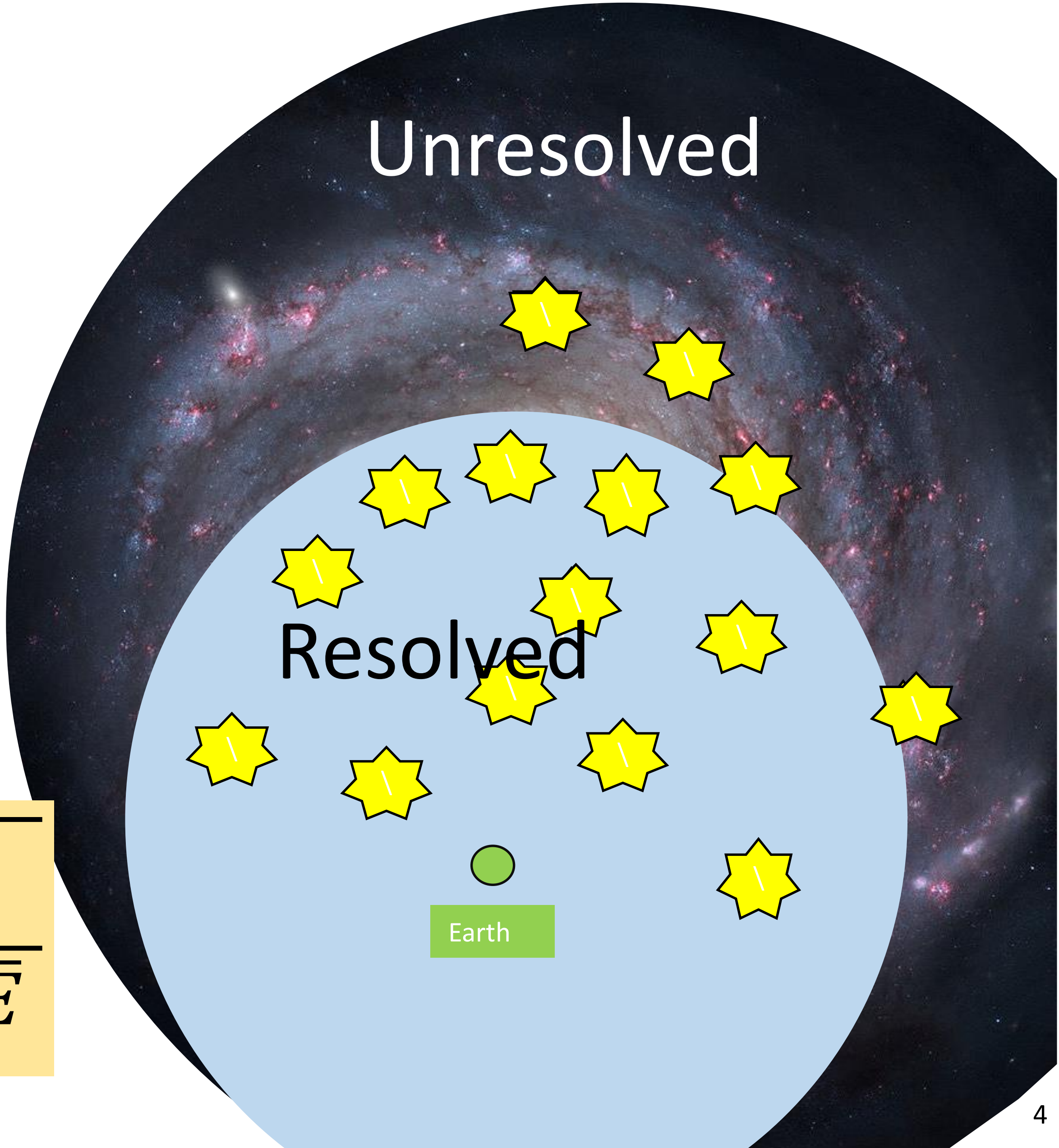
Measured

$$\phi_{\gamma,S} \rightarrow \phi_{\gamma,S}^{Res} \qquad \phi_{\gamma,S} \rightarrow \phi_{\gamma,S}^{UnRes}$$

Measured

The detectors have a limited sensitivity threshold and according to this they can resolve the sky up to a distance:

$$\bar{D} = \sqrt{\frac{L}{4\,\pi\phi_{th}\,\bar{E}}}$$



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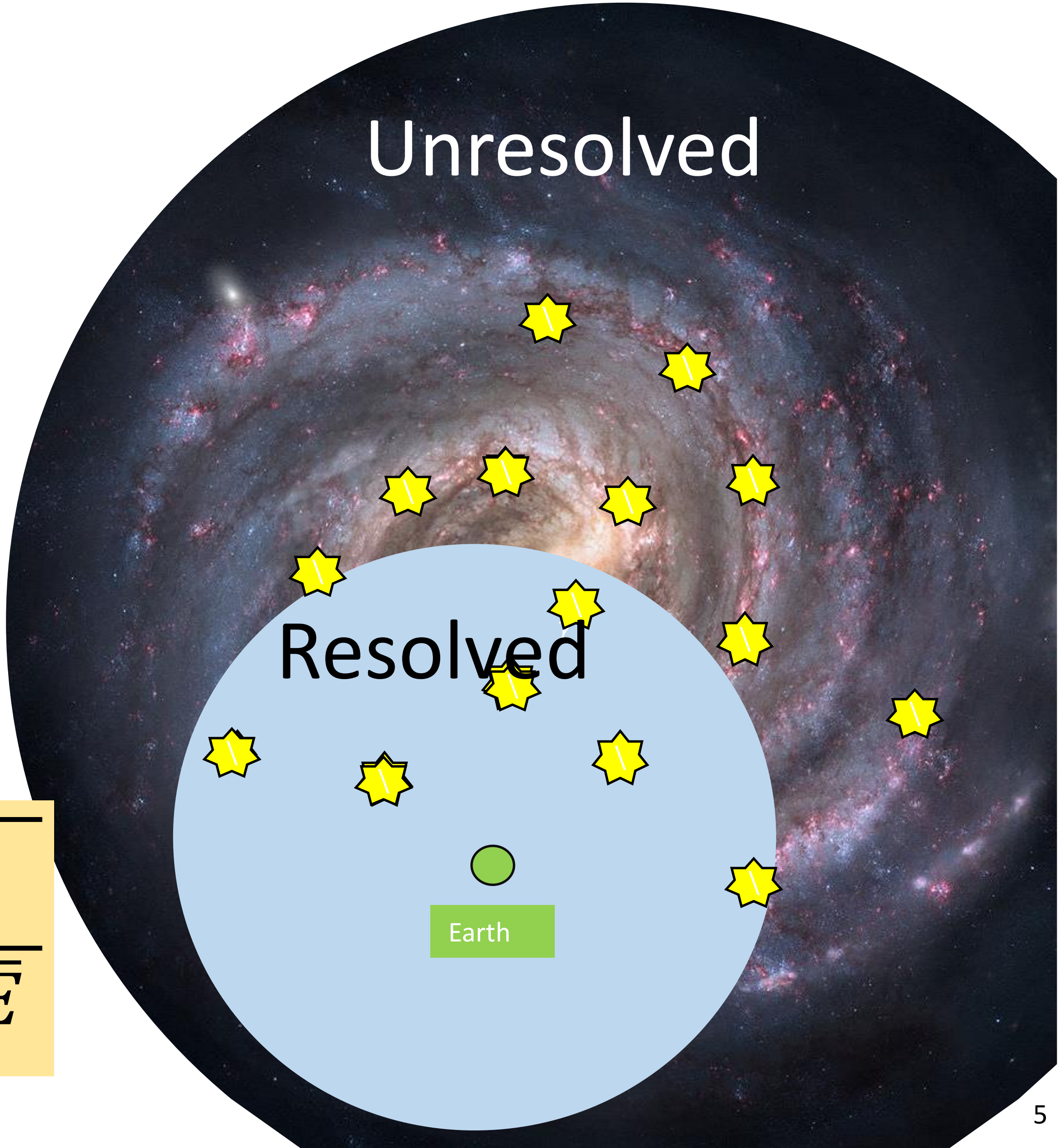

Unresolved sources:

$$\phi_{\gamma,tot} = \boxed{\phi_{\gamma,s}} + \boxed{\phi_{\gamma,\mathrm{diff}}} + \cancel{\phi_{\gamma,IC}}$$

Measured

$$\phi_{\gamma,s} \rightarrow \phi_{\gamma,s}^{Res}, \quad \phi_{\gamma,s}^{UnRes}$$

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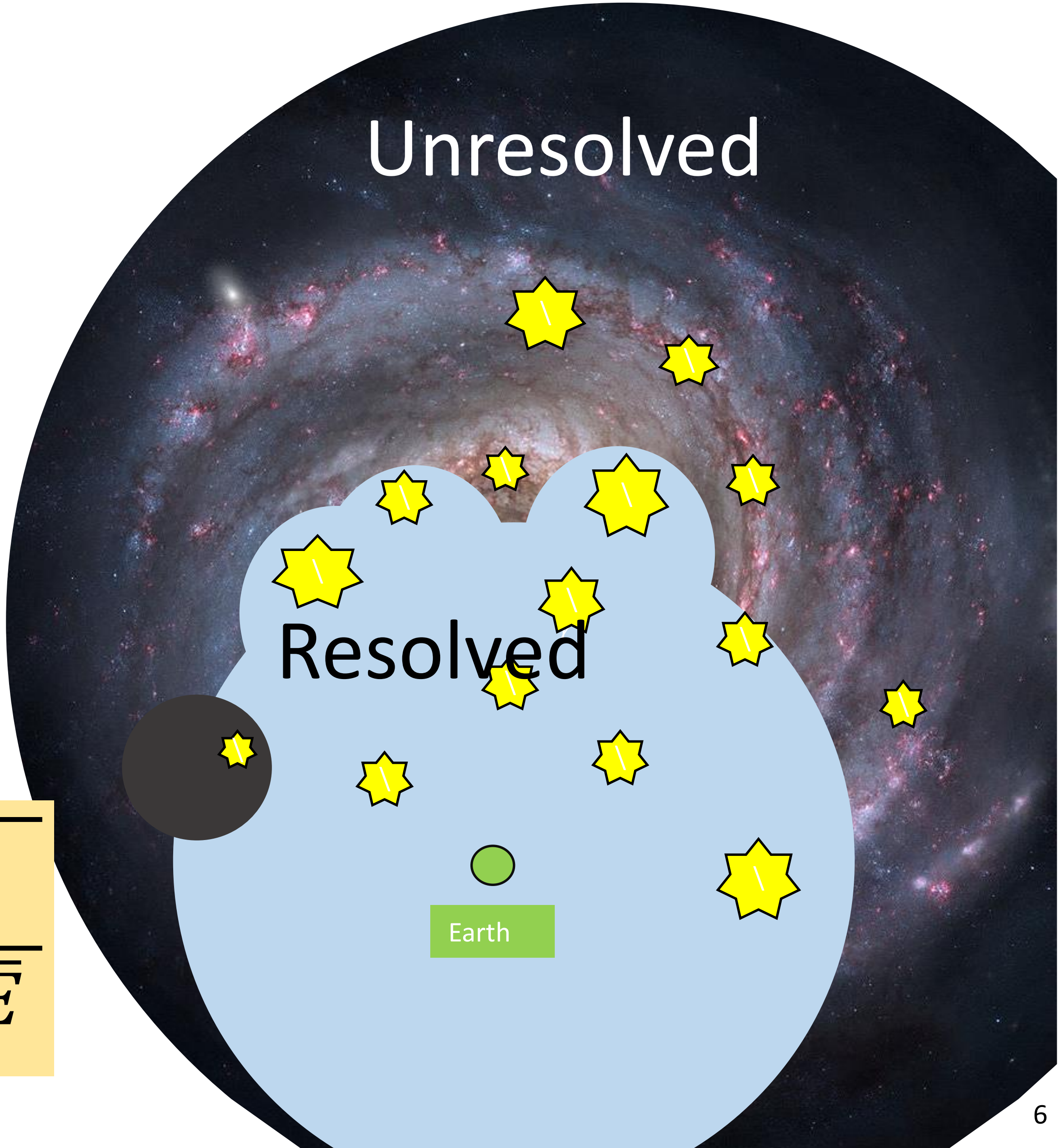


Total diffuse emission:

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

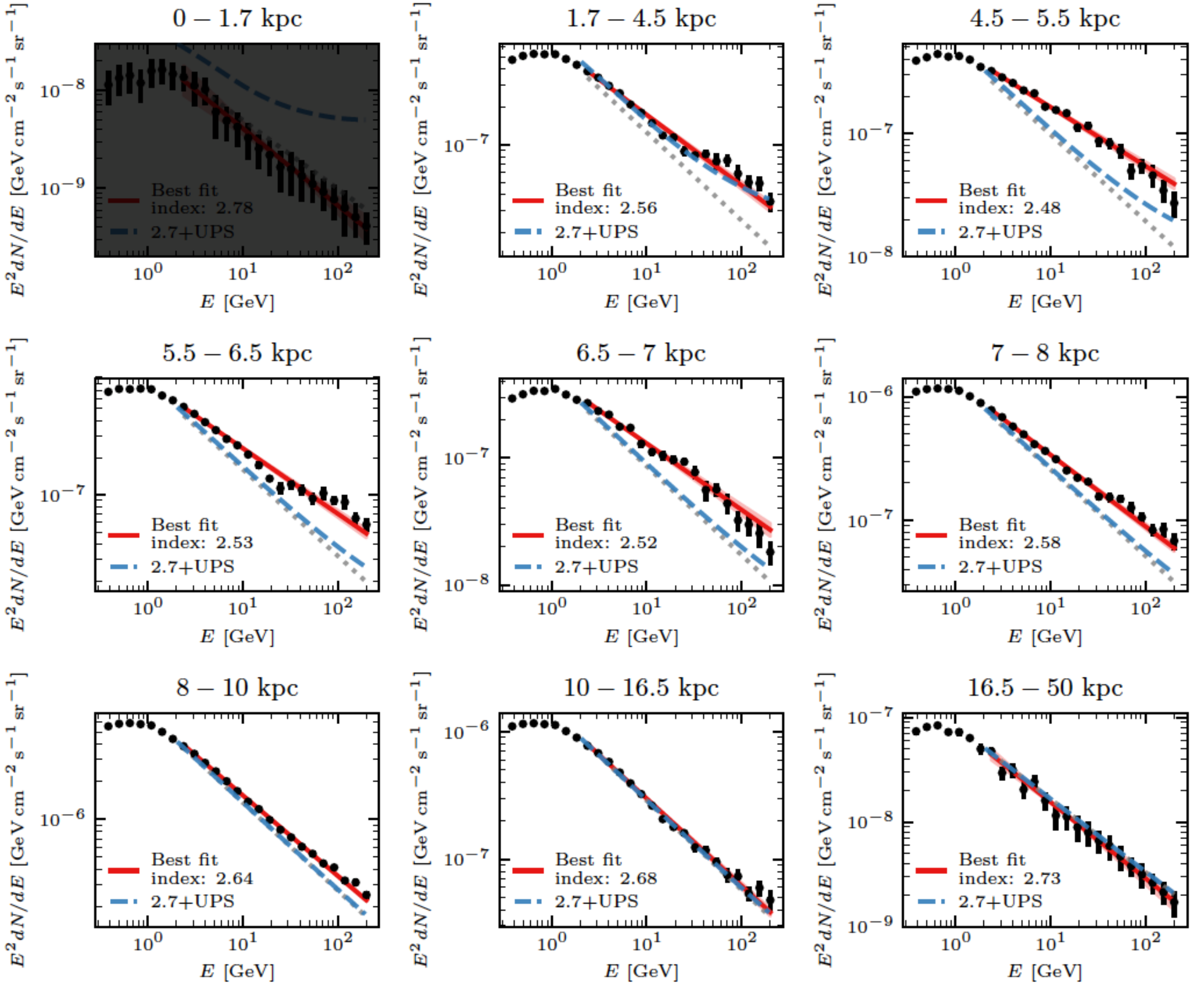
Measured

$$\phi_{\gamma,S}^{Res} \qquad \phi_{\gamma,S}^{UnRes}$$

Measured

Total diffuse emission

Total FERMI diffuse emission:



Total diffuse emission

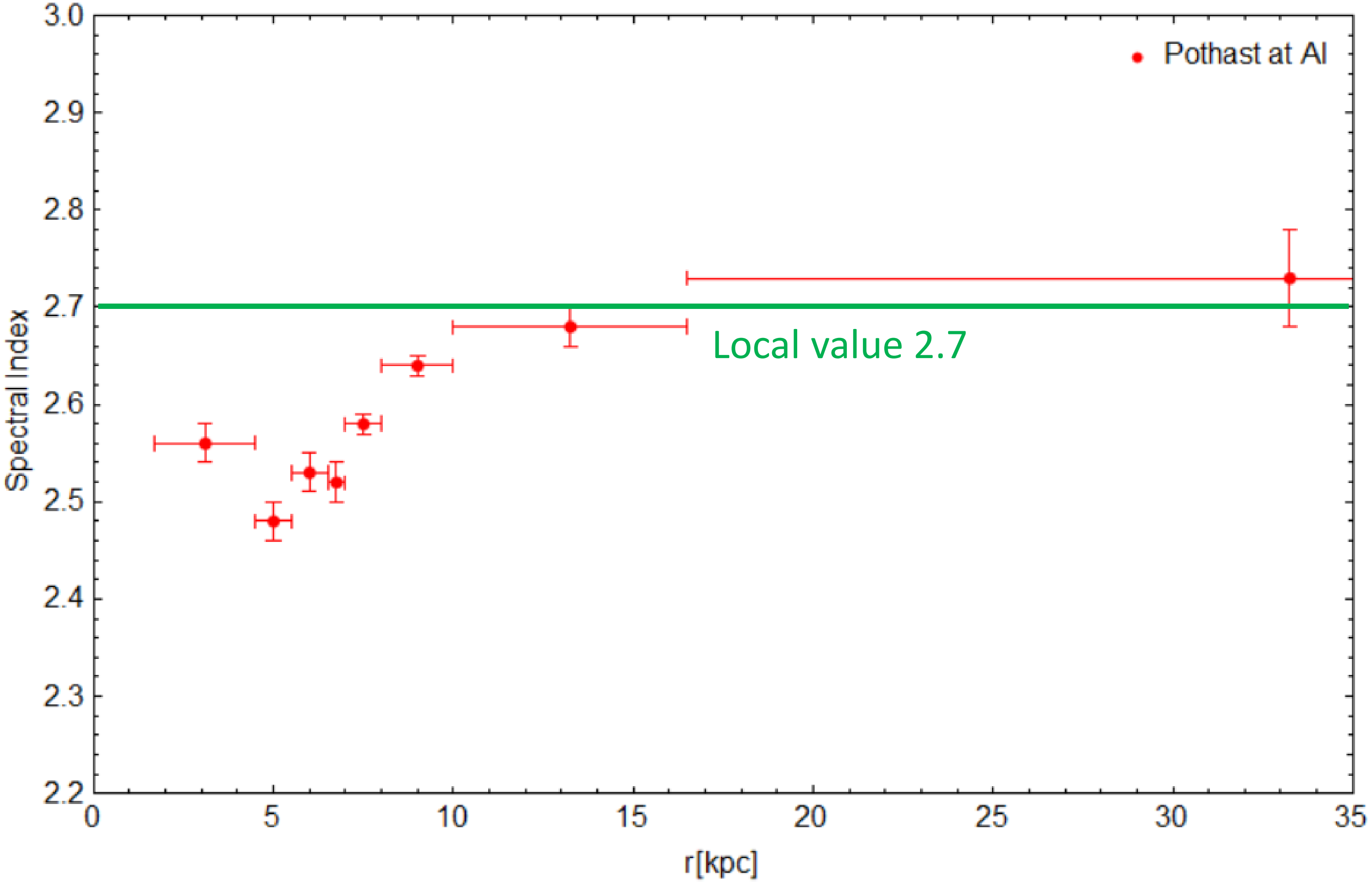
$$\phi_{\gamma,\mathrm{diff}} + \cancel{\phi_{\gamma,S}^{UnRes}}$$

$$\varphi_{\gamma}(E) = N E^{-\alpha_{\gamma}}$$

Total diffuse emission: 9.3 years of Fermi-LAT Pass 8 data (0.34−228.65) GeV and ($|l| < 180°$) and $|b| < 20.25°$

Pothast et.al JCAP 2018

Cosmic Ray Spectral Hardening in the inner Galaxy:

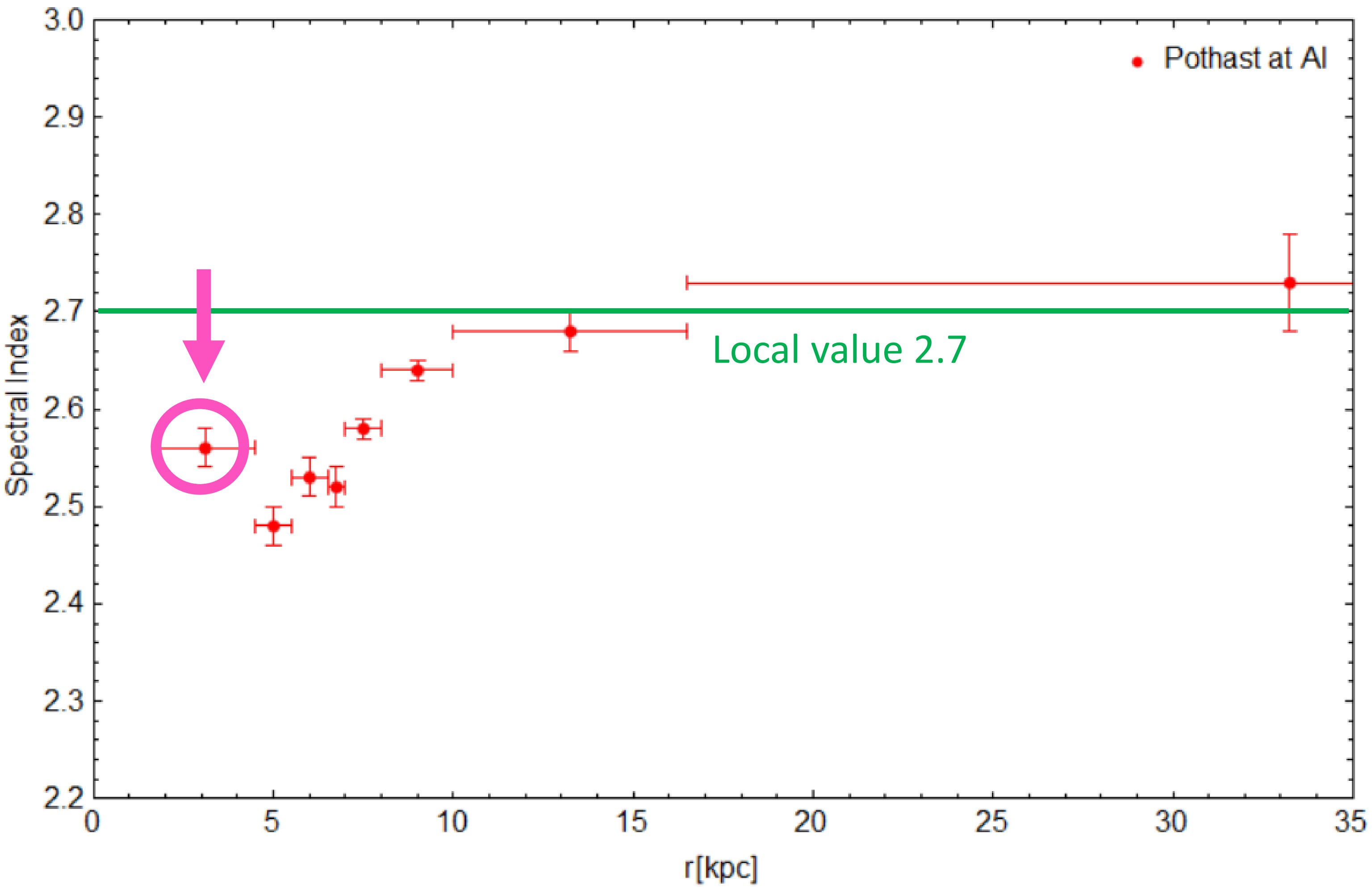


$$\phi_{\gamma,\mathrm{diff}} + \cancel{\phi_{\gamma,S}^{UnRes}}$$

π_0 decay: $\alpha_\gamma \simeq \alpha_p - 0.1$

Indirect evidence of a progressive hardening of the CRs spectrum in the inner Galaxy

Cosmic Ray Spectral Hardening in the inner Galaxy:



$$\phi_{\gamma,\mathrm{diff}} + \phi_{\gamma,S}^{UnRes}$$

π_0 decay: $\alpha_\gamma \simeq \alpha_p - 0.1$

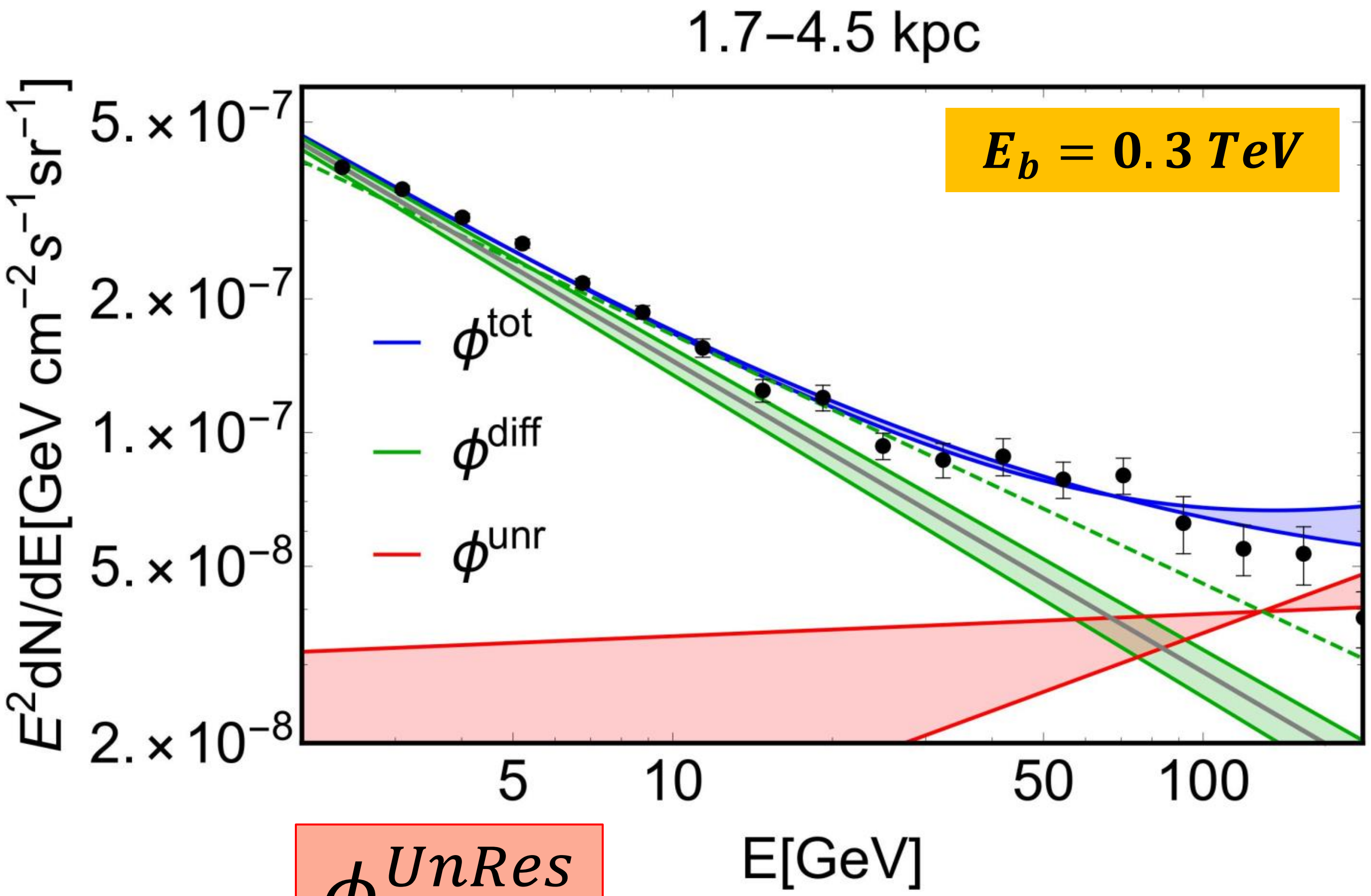
Indirect evidence of a progressive hardening of the CRs spectrum in the inner Galaxy

Reinterpreting the diffuse emission observed by Fermi:

The unresolved PWNe account up to the 36 % of the total diffuse emission in the ring 1.7-4.5 kpc.

$$\phi_{\gamma,\mathrm{diff}} + \cancel{\phi_{\gamma,S}^{UnRes}}$$

$$\alpha_\gamma = 2.56$$



$$\phi_{\gamma,S}^{UnRes}$$

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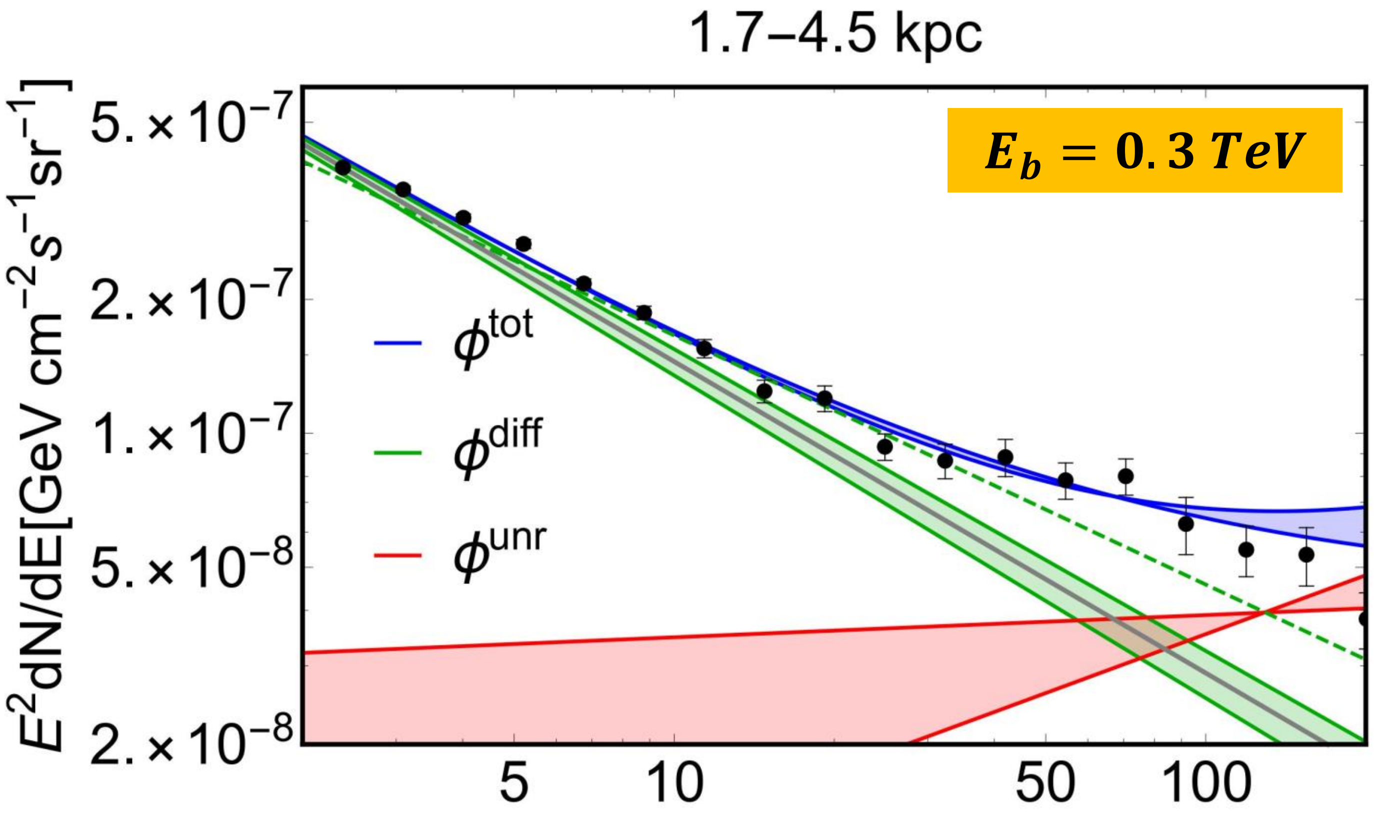
$$\alpha_\gamma = 2.56$$

$$\phi_{\gamma,\mathrm{diff}} + \phi_{\gamma,S}^{UnRes}$$

$$\alpha_{\gamma,BF} = 2.71$$



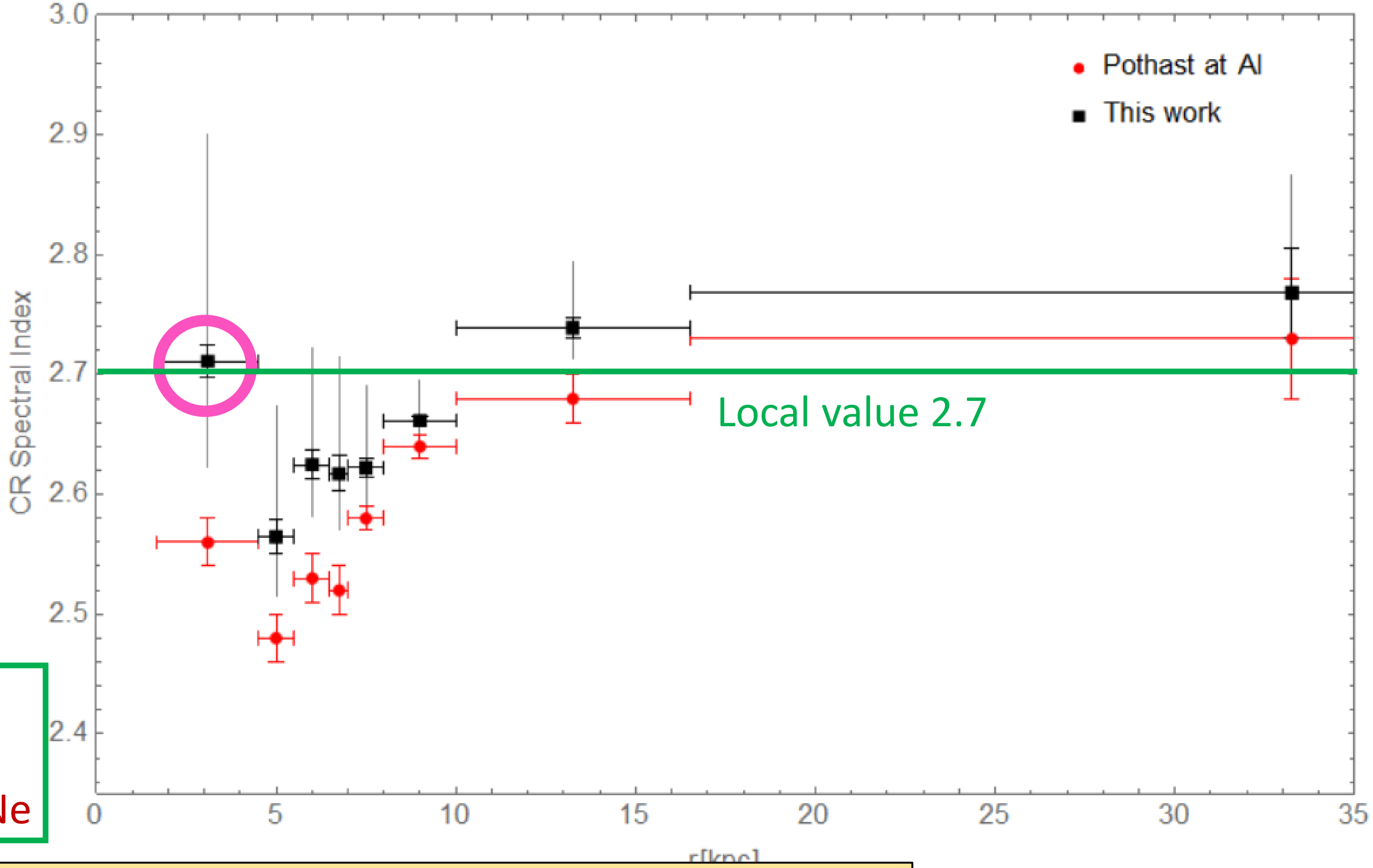
$$\phi_{\gamma,S}^{UnRes}$$

Spectral index of the truly diffuse emission (CR):

Ring (kpc)	α_γ	$\alpha_{\gamma,BF}$
1.7 – 4.5	2.56 ± 0.02	$2.71^{+0.19}_{-0.09} \pm 0.01$
4.5 – 5.5	2.48 ± 0.02	$2.56^{+0.11}_{-0.05} \pm 0.01$
5.5 – 6.5	2.53 ± 0.02	$2.62^{+0.10}_{-0.04} \pm 0.01$
6.5 – 7	2.52 ± 0.02	$2.62^{+0.10}_{-0.05} \pm 0.01$
7 – 8	2.58 ± 0.01	$2.62^{+0.07}_{-0.03} \pm 0.008$
8 – 10	2.64 ± 0.01	$2.66^{+0.03}_{-0.01} \pm 0.004$
10 – 16.5	2.68 ± 0.02	$2.74^{+0.05}_{-0.03} \pm 0.009$
16.5 – 50	2.73 ± 0.05	$2.77^{+0.10}_{-0.04} \pm 0.04$

Truly diffuse (Power-Law)

Truly diffuse (Power-Law) + Uresolved PWNe



PWNe contribution accounts for part of the spectral index variation observed by Fermi-LAT, weakening the evidence of CR spectral hardening in the inner Galaxy

Sub PeV energy range

The Tibet ASγ collaboration has recently obtained a measurement of the Galactic diffuse γ-ray emission.

Tibet Data

either spectral hardening or unresolved sources

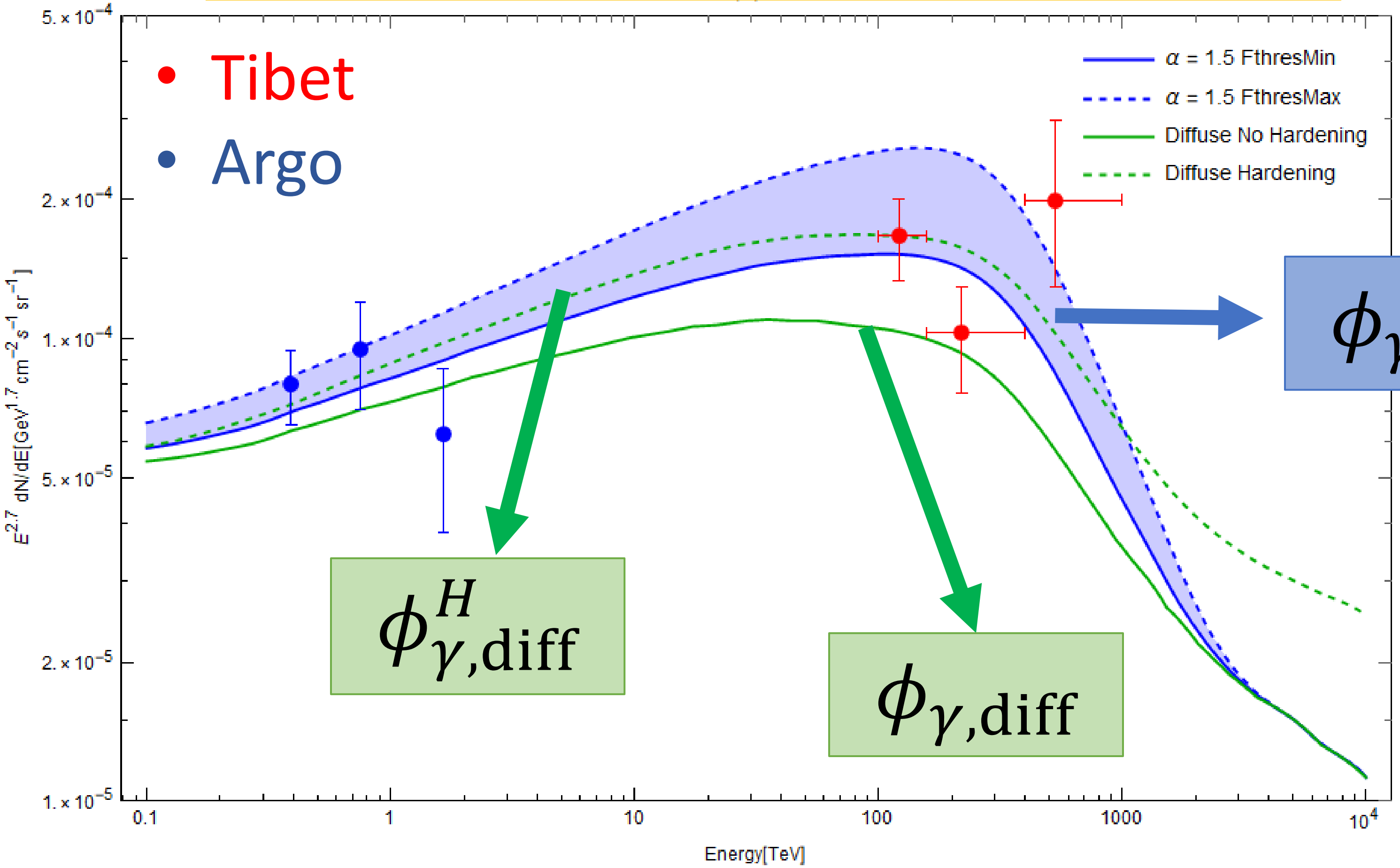
$\phi_{\gamma,\mathrm{diff}}^{H}$ Model **with** the hypothesis of CR spectral hardening.

$\phi_{\gamma,\mathrm{diff}}$ Model **without** the hypothesis of CR spectral hardening.

Tibet ASγ :

We add the contribution of unresolved sources to the truly diffuse emission without the hypothesis of CR spectral hardening (**P. Lipari and S. Vernetto, Phys. Rev. D 98, 043003 (2018)**) .

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



$E = 150\ TeV$:

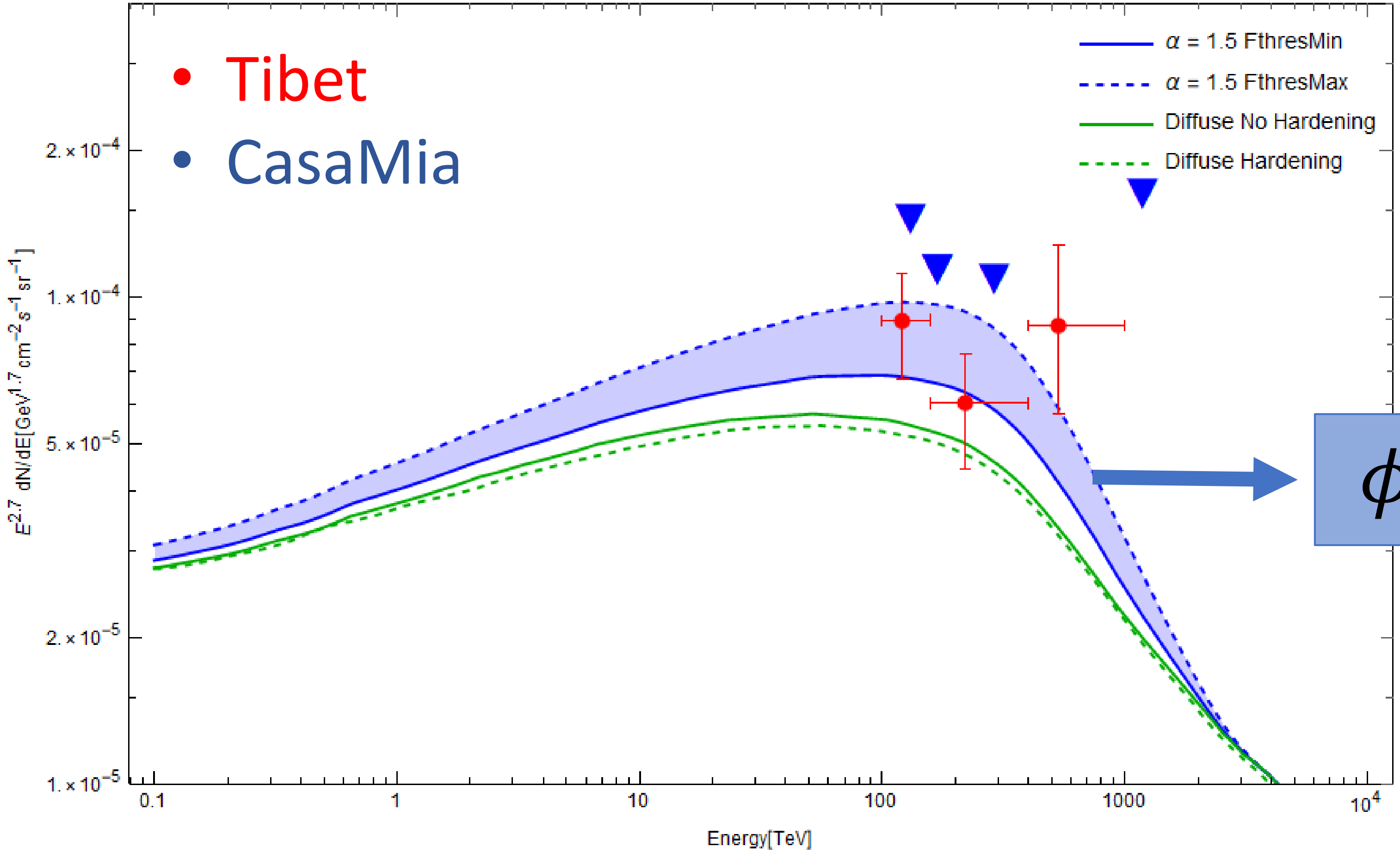
$$\frac{\phi_{NR}}{\phi_{tot\_diff}} = (49\ \% - 154\%)$$

$$\phi_{\gamma,\mathrm{diff}} + \phi^{UnRes}_{\gamma,S}$$

Tibet ASγ :

We add the contribution of unresolved sources to the truly diffuse emission without the hypothesis of CR spectral hardening (**P. Lipari and S. Vernetto, Phys. Rev. D 98, 043003 (2018)**) .

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



$E = 150\ TeV$:

$$\frac{\phi_{NR}}{\phi_{tot\_diff}} = (25\ \% - 79\%)$$

$$\phi_{\gamma,\mathrm{diff}} + \phi_{\gamma,S}^{UnRes}$$

Summary:

- It is fundamental to estimate the **unresolved source** component in different detectors (and in different energy ranges) in order to interpret the data in a correct way.
- In particular can be used to constrain the truly diffuse emission and therefore the spectral features of the CRs that produce it.

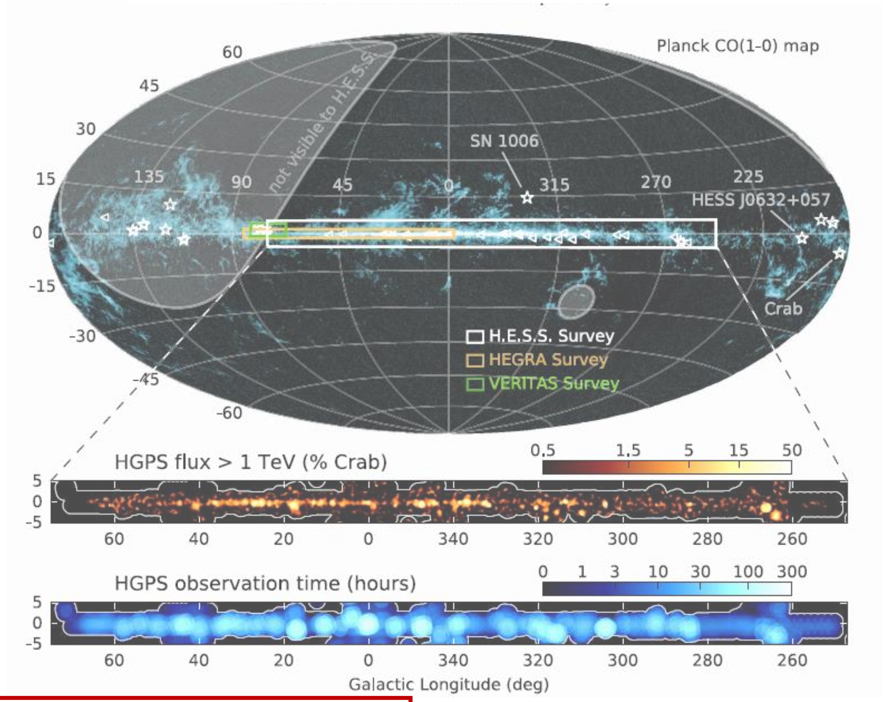
What's next?

- Prediction for future experiments.
- Disentangle the hardening from the unresolved source componet.

Thank you for the attention!

Backup slides

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



Study of the Pulsar wind nebulae population in the TeV range:

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

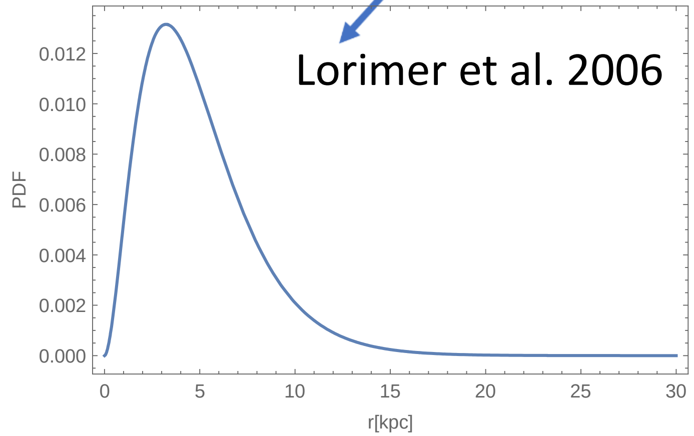
- The HGPS catalogue ($\phi > 0.1\phi_{Crab}$);
- Model for TeV source population:

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

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

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

Lorimer et al. 2006



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

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

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.

Study of the Pulsar wind nebulae population in the TeV range:

We fit the H.E.S.S. observational results with an unbinned likelihood

$$L_{max} = L^{BF}$$
$$\tau = \tau^{BF}$$

$\boxed{\Phi_{\rm PWN}}$

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

$\alpha = 1.8$

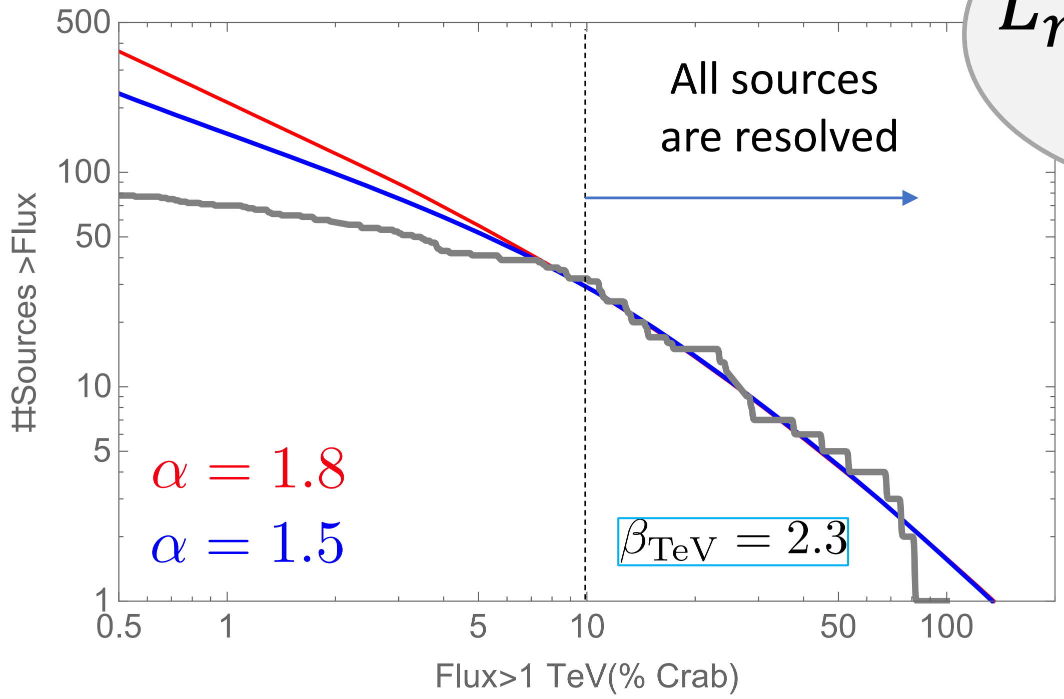
$L_{max} = 6.8 \times 10^{35}\ erg\ s^{-1}$

$\tau = 0.5\ kyr$

$\alpha = 1.5$

$L_{max} = 5.0 \times 10^{35}\ erg\ s^{-1}$

$\tau = 1.7\ kyr$



Total flux due to PWNe in the FERMI energy range (1-100 GeV)?

Extrapolate to GeV range:

We define the phenomenological parameter:

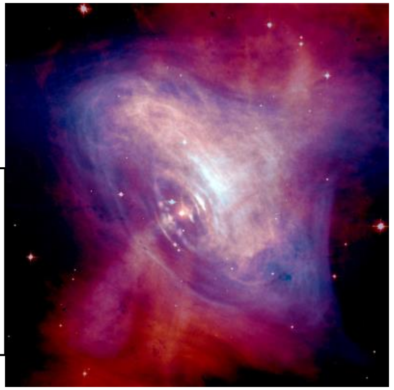
$$\boxed{R_\Phi = \frac{\Phi_{\mathrm{GeV}}}{\Phi_{\mathrm{TeV}}}}$$

That can be used to calculate the total source flux and the unresolved sources in the energy range 1-100 GeV using our knowledge of the 1-100 TeV energy range:

$$\phi_{GeV}^{tot} = R_\phi \phi_{TeV}^{tot}$$

$$\phi_{GeV}^{NR} = \int_0^{\phi_{GeV}^{th}} d\phi_{GeV} \phi_{GeV} \frac{dN}{d\phi_{GeV}}; \quad \frac{dN}{d\phi_{GeV}} = \frac{1}{R_\phi} \frac{dN}{d\phi_{TeV}} \left(\frac{\phi_{GeV}}{R_\phi}\right)$$

12 objects firmly identified as PWNe by both HGPS and 4FGL-DR2 give $\langle R_\phi \rangle \sim 1000 \rightarrow$ we assume $250 < R_\phi < 1500$ as a working hypothesis.



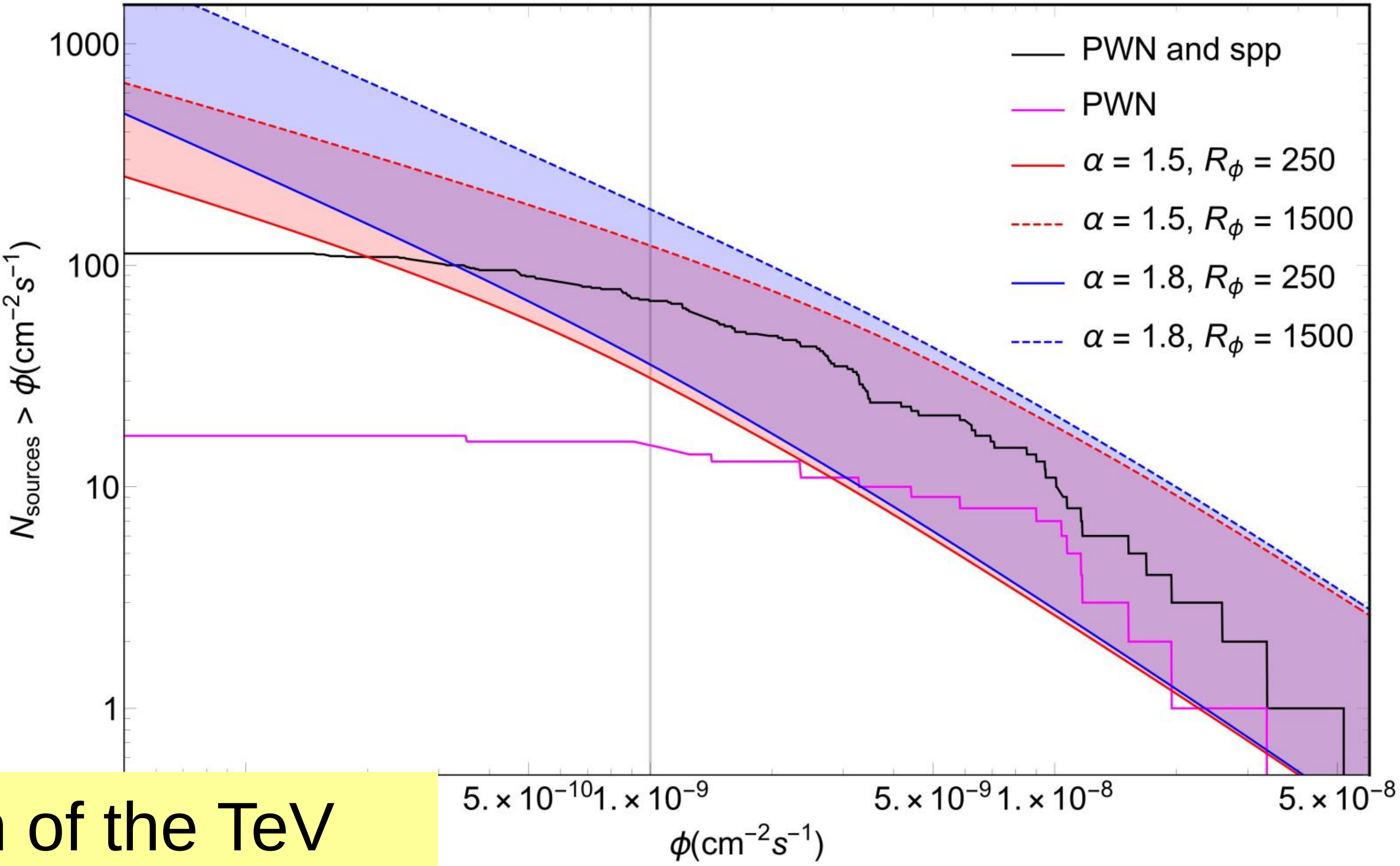
Unresolved PWNe by FermiLAT:

$\alpha = 1.8$

$$\frac{\phi_{NR}}{\phi_{PWN}} = (32\ \% - 46\ \%)$$

$\alpha = 1.5$

$$\frac{\phi_{NR}}{\phi_{PWN}} = (10\ \% - 25\ \%)$$



A non-negligible fraction of the TeV PWNe population cannot be resolved by Fermi-LAT

$= 10^{-9}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ Acero et.al. 2015

Source contribution to Sub-PeV energy range:

- Spectral assumption: 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;

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

Amenomori, M., Bao, Y. W., Bi, X. J., et al. 2019, Phys.323Rev. Lett., 123, 051101

Abeysekara, A., Albert, A., Alfaro, R., et al. 2020, Physical316Review Letters, 124

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

- Absorption from CMB.

We introduce a flux detection threshold based on the performance of H.E.S.S.
$\phi_{th} = 0.01\phi_{crab} - 0.1\phi_{crab}$

We calculate the unresolved source contribution.

Model:

The power-law for the luminosity distribution can be automatically obtained assuming a fading source population (like PWNe, TeV Halos) create at a constant rate $\bar{r}$.

The spin-down power is described by: $\dot{E}\,(t) = \dot{E}_0 \left(1 + \frac{t}{\tau}\right)^{-2}$

Considering that a fraction $\boldsymbol{\lambda(t)}$ of the spin-down power is converted into gamma-rays then the intrinsic luminosity decreases according to:

$$L(t) = \lambda(t)\dot{E}(t) = \underbrace{\lambda\dot{E}_0}_{L_{max}}\left(1 + \frac{t}{\tau}\right)^{-\gamma} \text{ where } \gamma = 2(\delta + 1);$$

$$\lambda(t) = \lambda\left(\frac{\dot{E}(t)}{\dot{E}_0}\right)^{\delta}$$

Abdalla et al, *A&A*, 612, A2 (2018)

Then:

$$\boxed{Y(L) = \frac{\bar{r}\,\tau\,(\alpha - 1)}{L_{\max}}\left(\frac{L}{L_{\max}}\right)^{-\alpha}}$$

Where $\bar{r} = 0.019\ yr^{-1}$ is the SN's rate and $\alpha = \left(\frac{1}{\gamma} + 1\right)$ therefore for $\gamma = 2$ we have $\alpha = 1.5$.

And instead of the parameter $\mathcal{N}$ we have the spin-down timescale of the Pulsar τ.

GSSI

Table of the 12 sources observed by both Fermi and HESS:

Table 1: *In the table are shown the 12 PWNe observed by both FermiLAT (4FGL-DR2) and H.E.S.S. (HGPS). In addition we show also the Crab although is it is not observed by H.E.S.S.. In the first columns is reported the calculated value of R_ϕ. In the second one the power-law spectral index (it is specified when the spectral form is different than a simple power-law) in the GeV energy range taken from the 4FGL-DR2 catalogue. In the last column is reported the power-law spectral index (it is specified when the spectral form is different than a simple power-law) in the TeV energy range taken from the HGPS catalogue.*

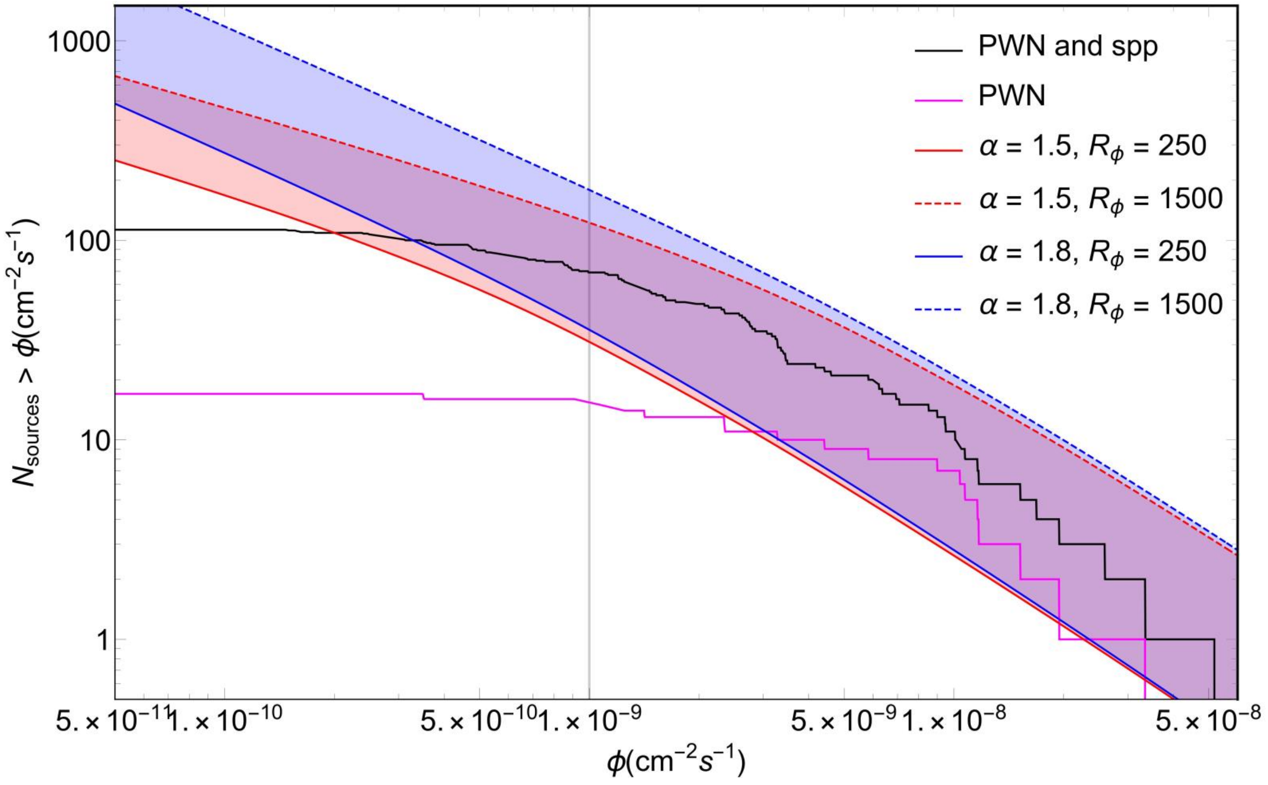
H.E.S.S.-association	R_ϕ	β_{GeV}	β_{TeV}	D(kpc)	τ_c(kyr)
Crab	1481.24	1.38 (1 GeV) (log-par)	2.30	2.0	0.94
HESS J0835-455	754.938	2.18	1.89	0.29	11.3
HESS J1303-631	447.05	1.81	2.33	6.7	11.0
HESS J1356-645	63.47	1.41	2.20	2.4	7.31
HESS J1420-607	999.354	1.99	2.20	5.6	13.0
HESS J1616-508	1223.36	2.05	2.32	6.8	8.13
HESS J1632-478	799.56	1.76	2.51	-	-
HESS J1746-285	98950.	0.96 (1 GeV) (log-par)	2.17	-	-
HESS J1825-137	582.721	1.73	2.38	3.9	21.4
HESS J1837-069	1612.13 (483.598)	2.04 (1.84)	2.54	6.6	22.7
HESS J1841-055	1149.91	1.98	2.47	-	-
HESS J1857+026	2390.84	2.12	2.57	-	20.6
HESS J1514-591	686.30	1.83	2.05	5.2	1.56

Extrapolate to GeV range:

Spectral assumption: broken power-law:

Different arguments supporting it:

- Consistency among HGPS and 4FGL;



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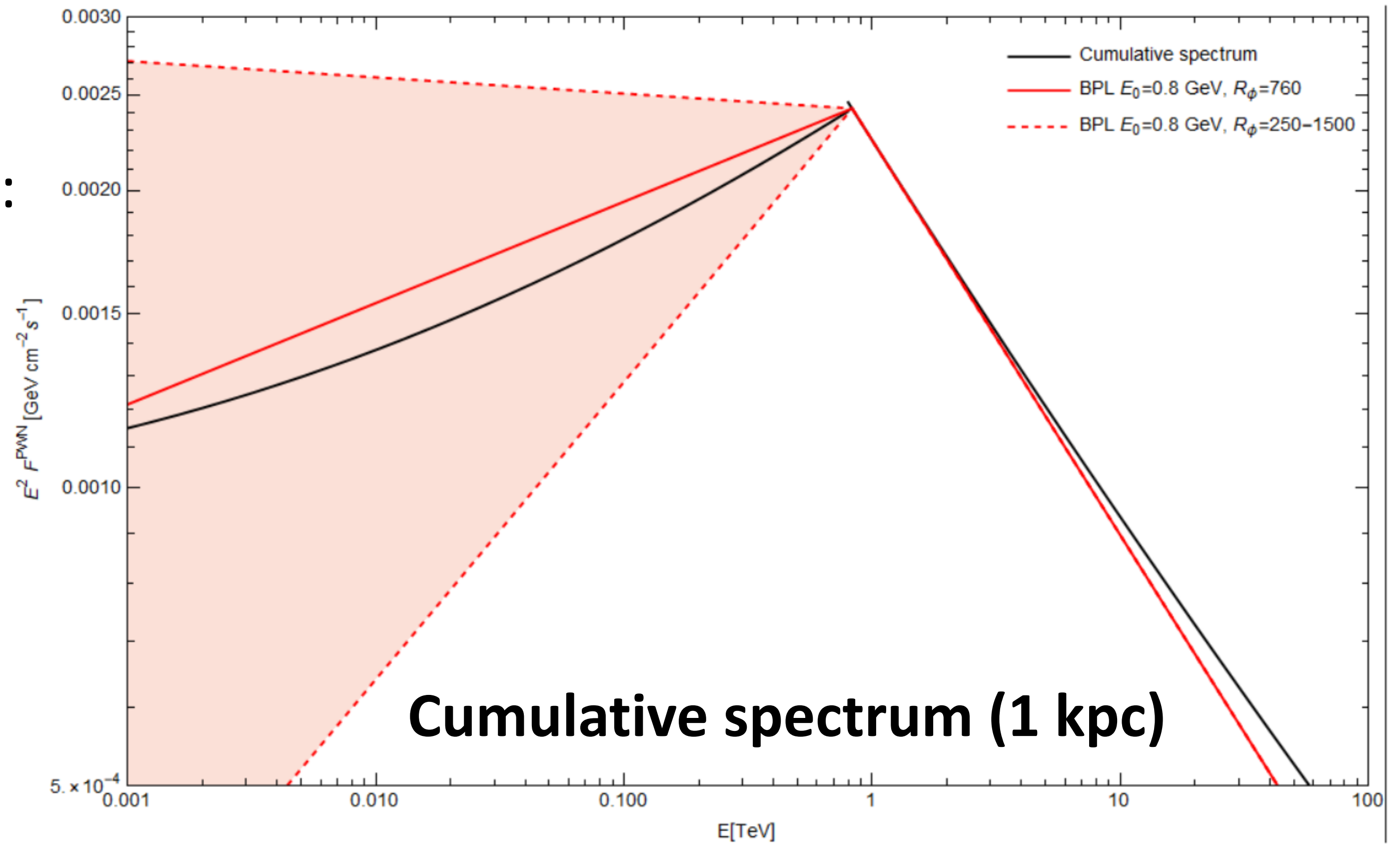
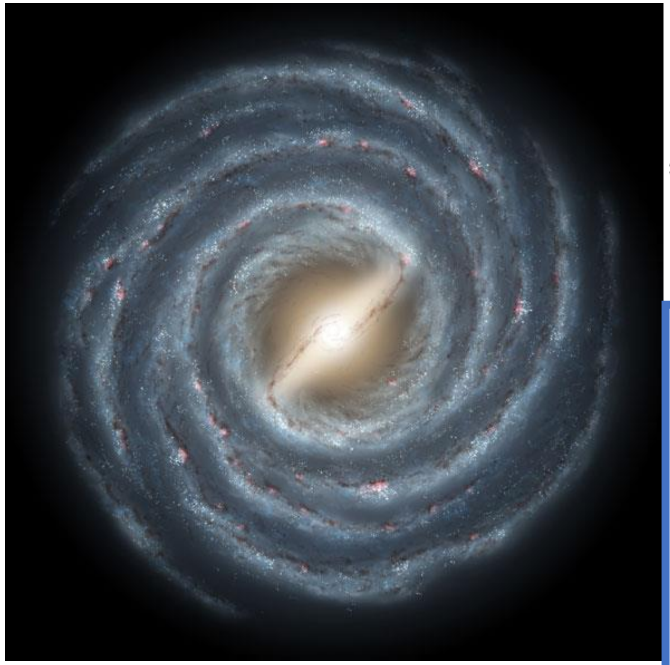


Spectral assumption: broken power-law:

Different arguments supporting it:

- Consistency among HGPS and 4FGL;
- Cumulative spectrum from the sources observed by both Fermi-LAT and HESS with known distance;

Cumulative spectrum: $E_b \sim 0.8\,TeV,\;\; R_\phi \sim 760 \;\rightarrow \beta_{GeV} \sim 1.9$;
Red Band: $E_b \sim 0.8\,TeV$, $250 < R_\phi < 1500 \;\rightarrow 1.7 < \beta_{GeV} < 2.0$.



PWNe contribution in galactocentric rings

	$\Phi^{\rm diff}_{\rm GeV}$ $(cm^{-2}\ s^{-1})$	$\Phi^{\rm NR}_{\rm GeV}$ $(cm^{-2}\ s^{-1})$		$\Phi^{\rm R}_{\rm GeV}$ $(cm^{-2}\ s^{-1})$	
		$R_\Phi = 250$	$R_\Phi = 1500$	$R_\Phi = 250$	$R_\Phi = 1500$
1.7 – 4.5 kpc	3.86×10^{-7}	3.35×10^{-8} (8.6%)	1.40×10^{-7} (36%)	1.32×10^{-8}	1.39×10^{-7}
4.5 – 5.5 kpc	3.11×10^{-7}	1.91×10^{-8} (6.1%)	8.00×10^{-8} (26%)	1.01×10^{-8}	9.56×10^{-8}
5.5 – 6.5 kpc	5.09×10^{-7}	2.13×10^{-8} (4.2%)	8.93×10^{-8} (17%)	1.46×10^{-8}	1.26×10^{-7}
6.5 – 7.0 kpc	2.57×10^{-7}	1.15×10^{-8} (4.5%)	4.81×10^{-8} (19%)	1.01×10^{-8}	8.17×10^{-8}
7.0 – 8.0 kpc	7.7×10^{-7}	2.67×10^{-8} (3.5%)	1.12×10^{-7} (14%)	3.44×10^{-8}	2.54×10^{-7}
8.0 – 10.0 kpc	3.84×10^{-6}	4.89×10^{-8} (1.3%)	2.05×10^{-7} (5.3%)	1.10×10^{-7}	7.50×10^{-7}
10.0 – 16.5 kpc	7.68×10^{-7}	1.51×10^{-8} (1.9%)	6.37×10^{-8} (8.3%)	9.19×10^{-9}	8.21×10^{-8}
16.5 – 50.0 kpc	4.44×10^{-8}	3.87×10^{-10} (0.8%)	2.07×10^{-9} (4.7%)	4.15×10^{-11}	5.03×10^{-10}
0.0 – 50.0 kpc	6.89×10^{-6}	1.79×10^{-7}(2.6%)	7.53×10^{-7} (11%)	2.03×10^{-7}	1.54×10^{-6}

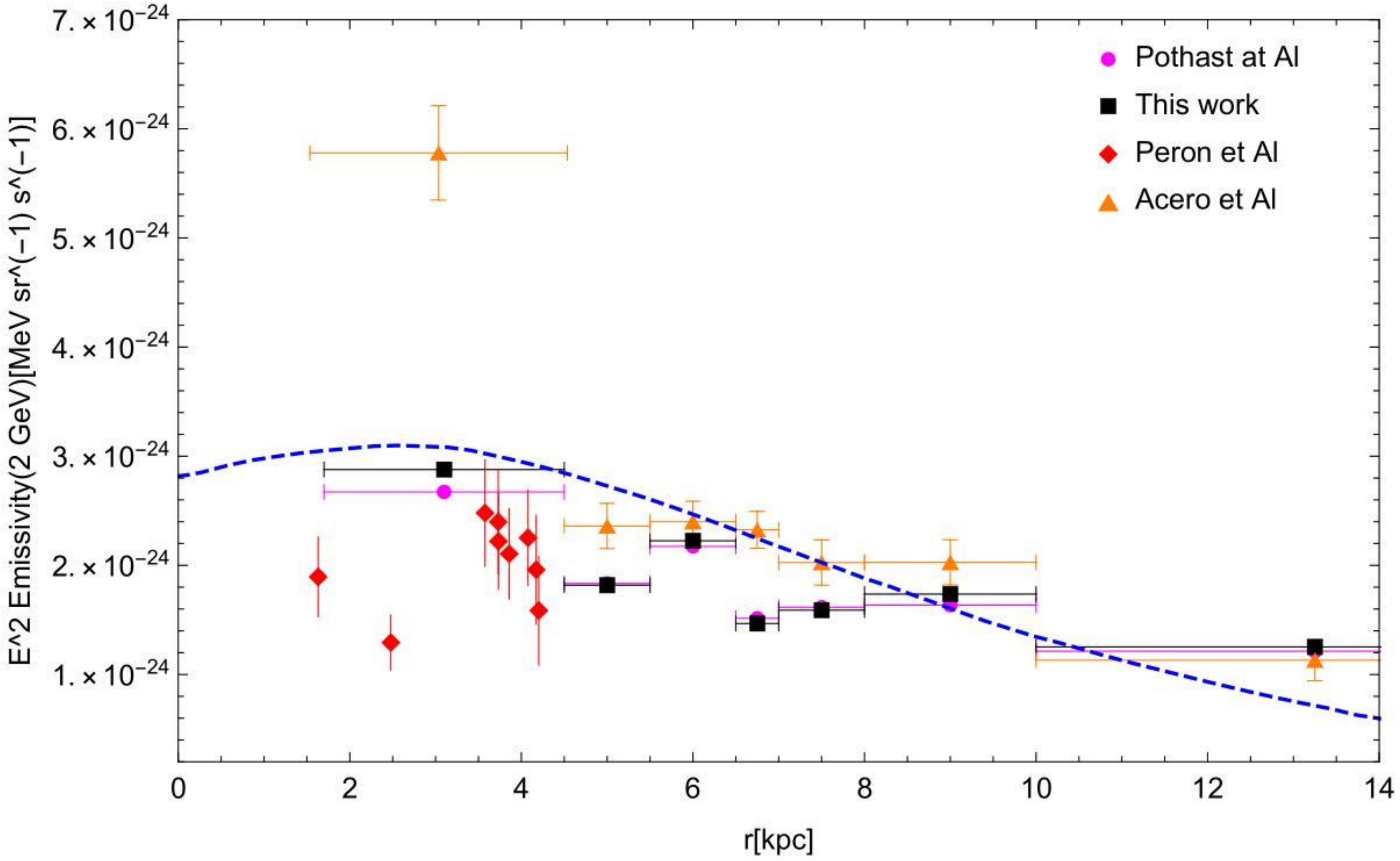
9 Galactocentric rings

Total diffuse emission: 9.3 years of Fermi-LAT Pass 8 data (0.34−228.65) GeV and (|l|<180◦) and |b|<20.25◦

Diffuse emission due to unresolved PWNe (1-100) GeV

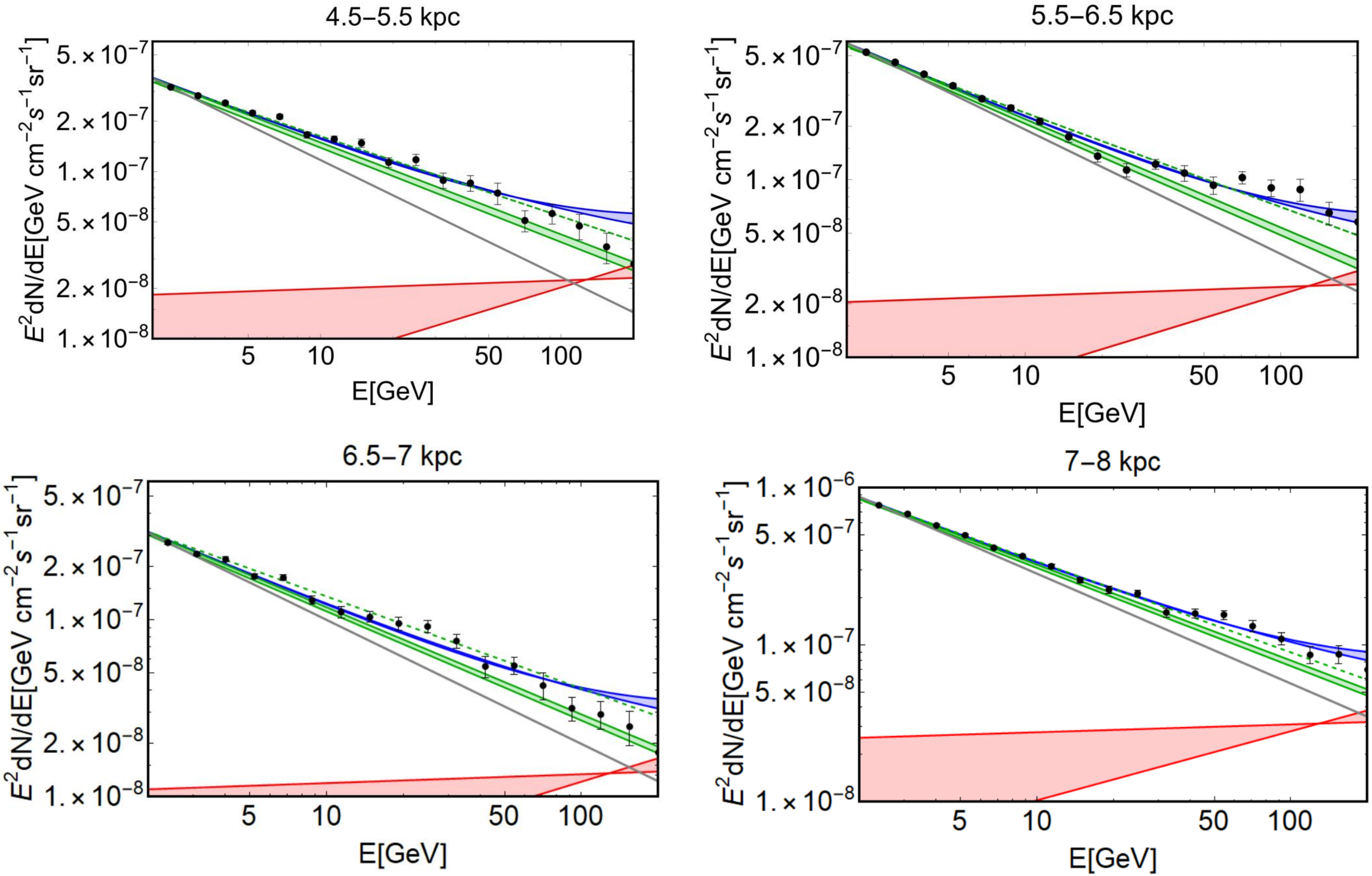
Resolved flux due to PWNe

Gamma-ray emissivity:

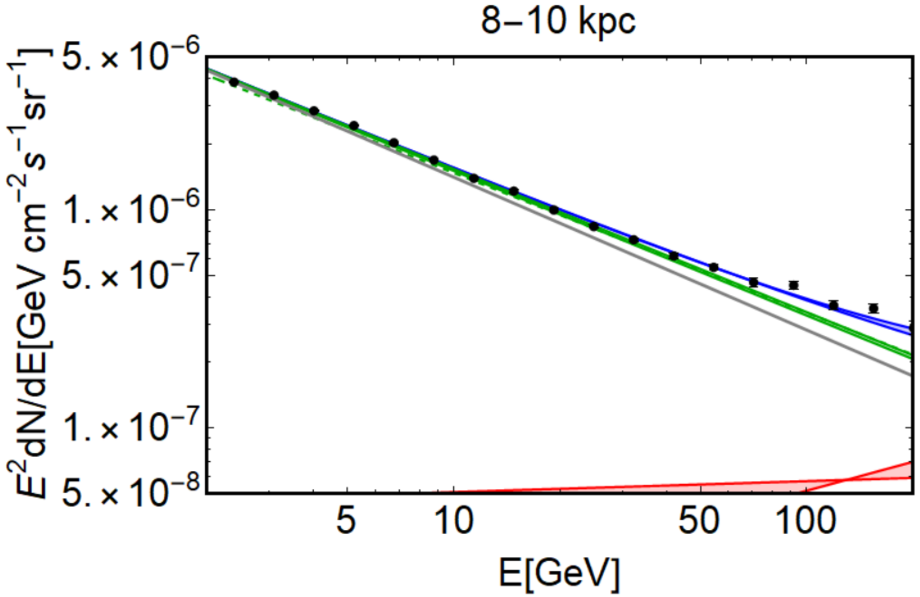


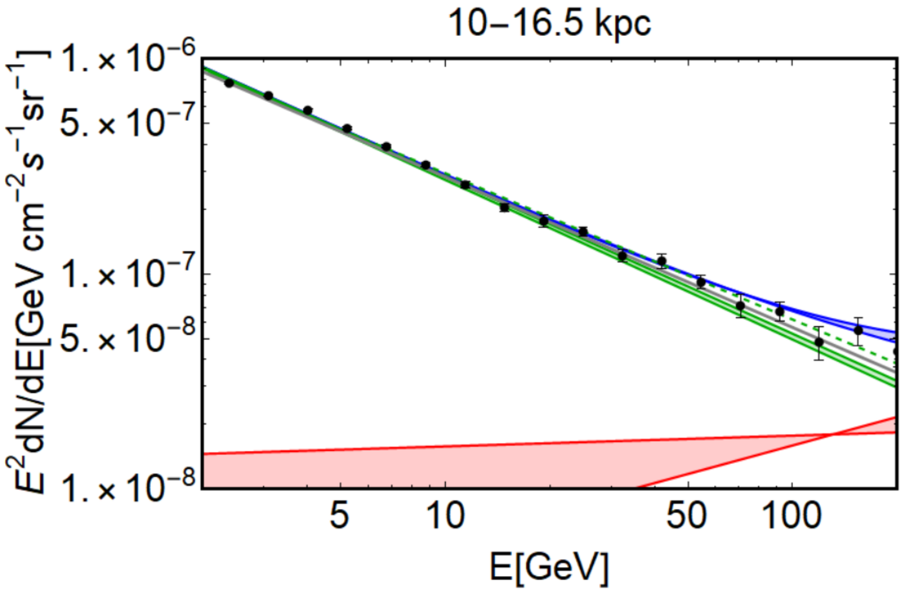
Results for $\alpha = 1.8$

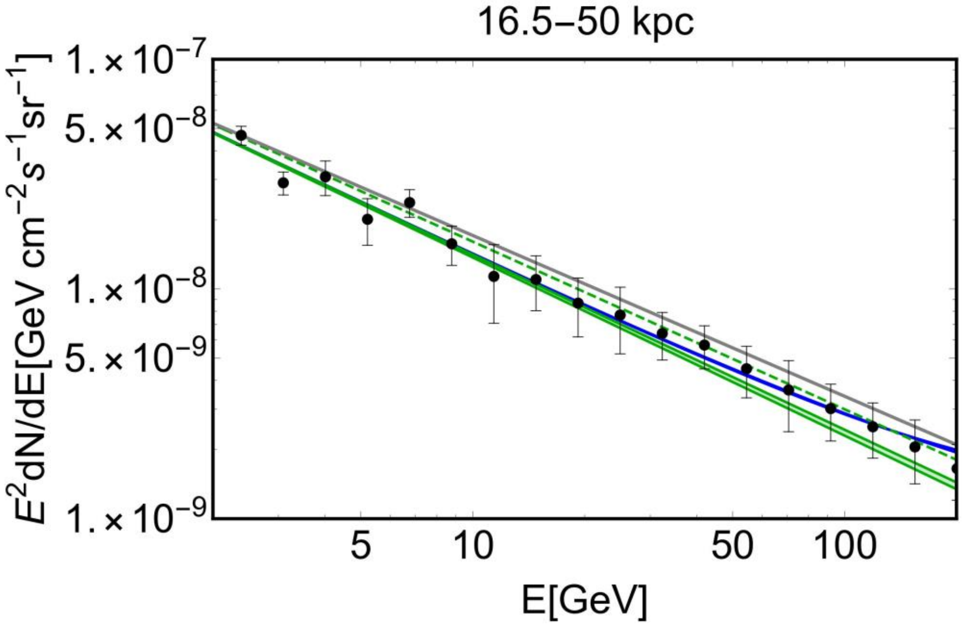
Gray line: speculative diffuse component with spectral index fixed to 2.7 normalized in order to interpolate the data at ~ 2 GeV.



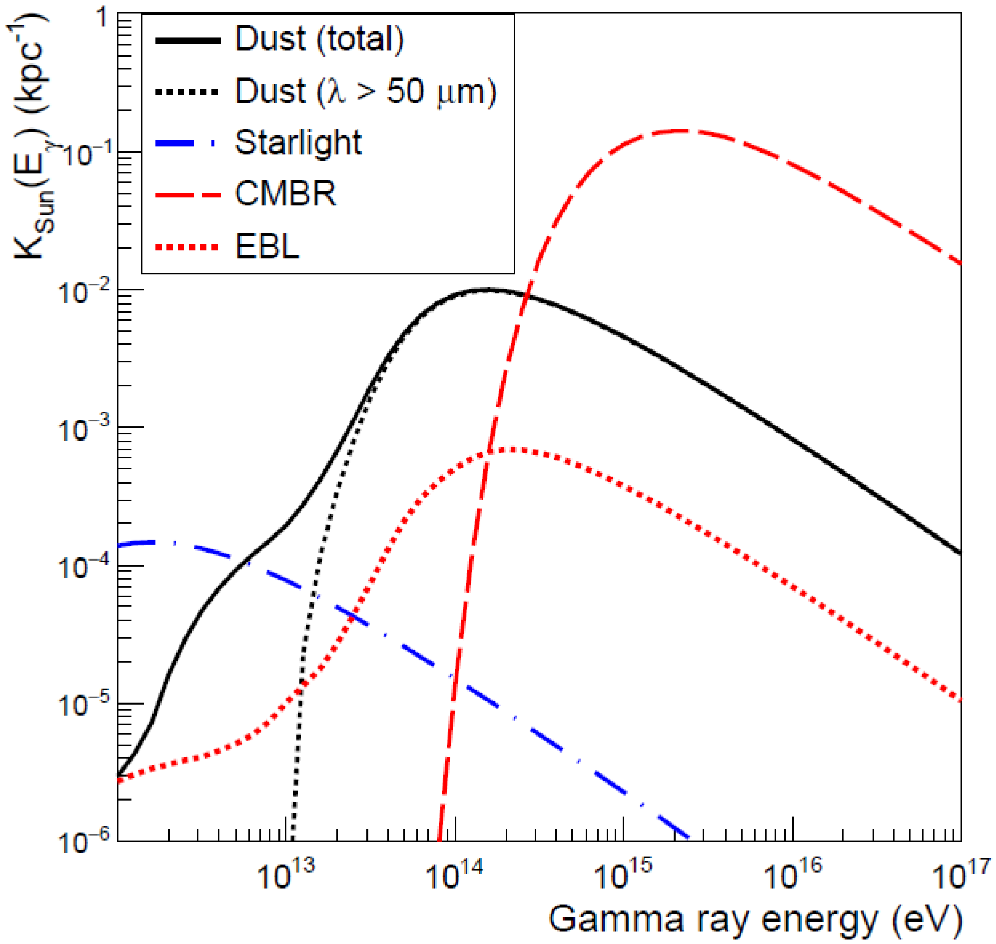
Results for $\alpha = 1.8$

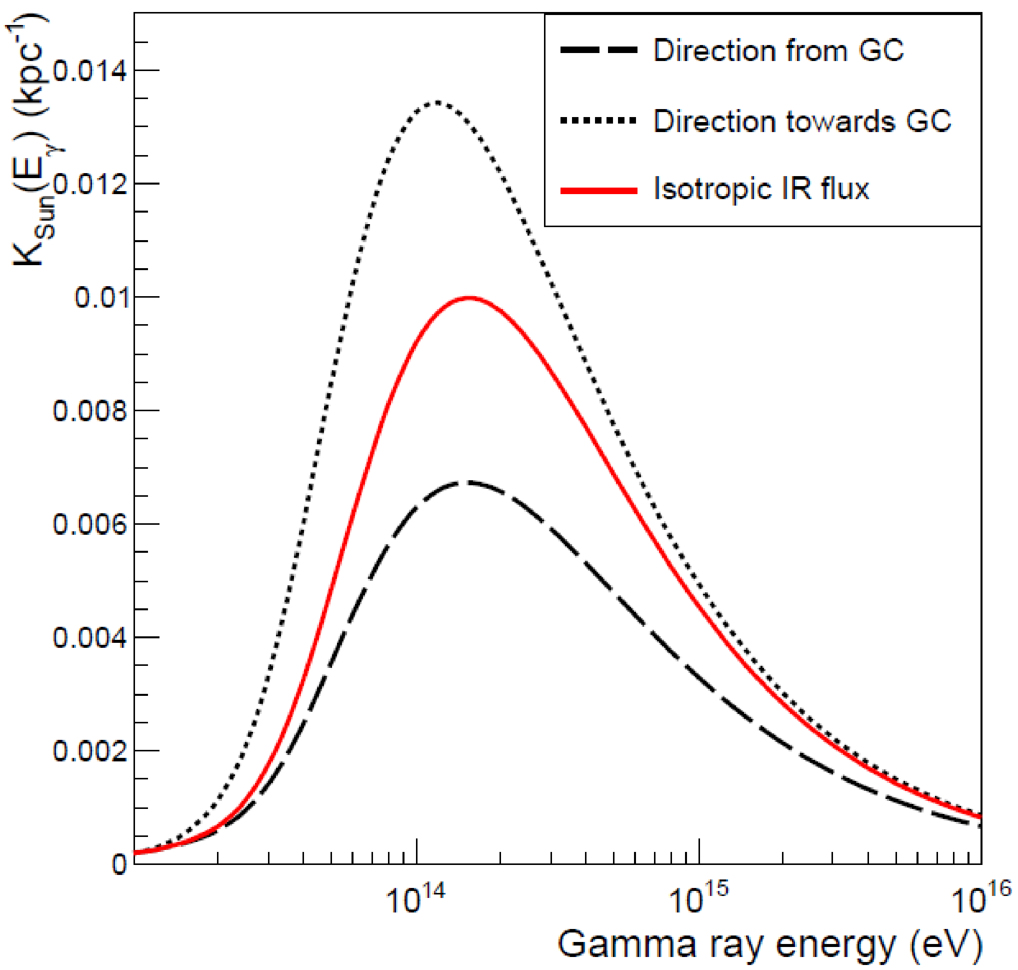






Absorption in the Sub PeV energy range:





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