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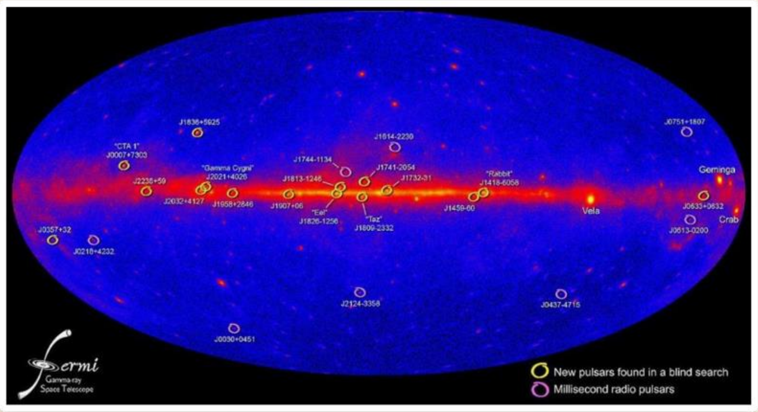
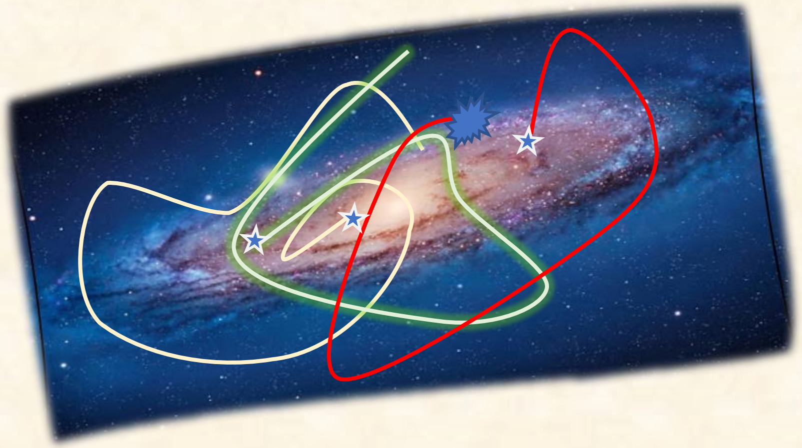
Oskar Klein centre

CRPropa Workshop 27/09/2023

The Galactic diffuse emission meets the PeV frontier

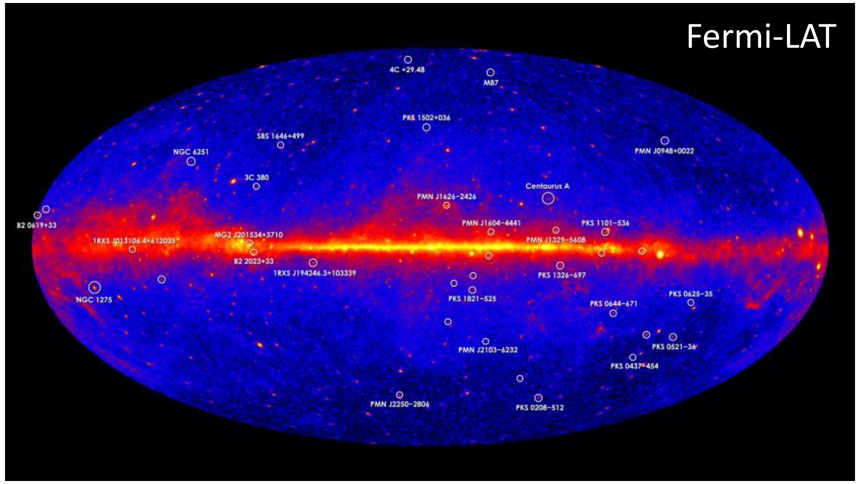
Based on **ArXiv: 2203.15759** and **ArXiv: 2209.10011** in collaboration with D. Grasso, D. Gaggero, C. Evoli, O. Fornieri, K. Egberts, C. Steppa, A. Marinelli

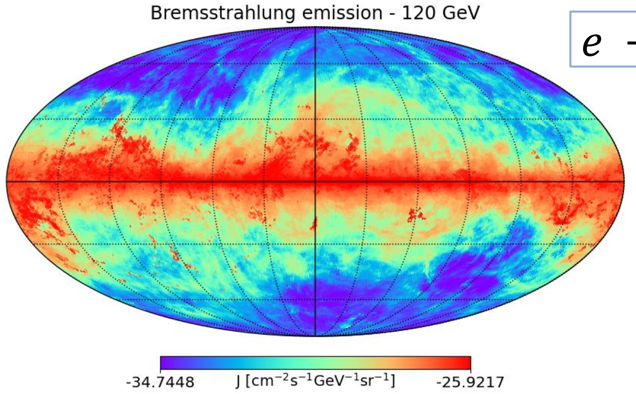




The Gamma-ray diffuse sky

Diffuse emission totally correlated with the propagation of cosmic rays
Dominated by protons, He (and e^-)

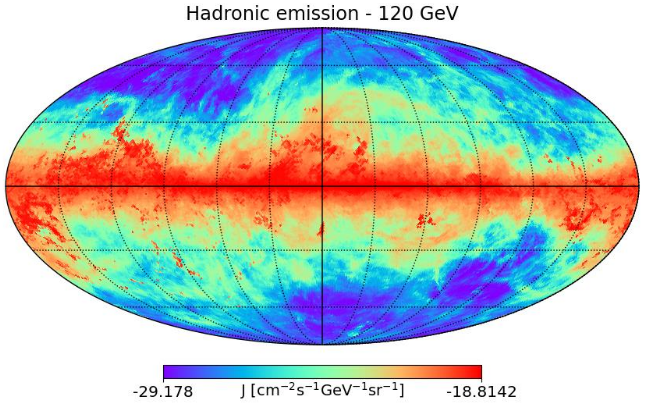


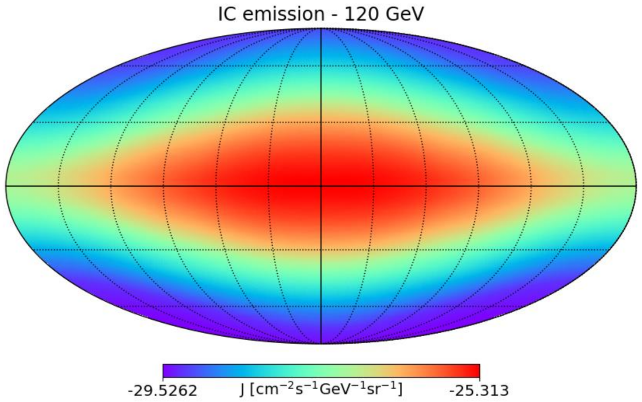


$e + N \rightarrow e' + \gamma' + \mathrm{N}$

$p + p \rightarrow \pi^0$
$\pi^0 \rightarrow 2\,\gamma$

$e + \gamma \rightarrow e' + \gamma'$





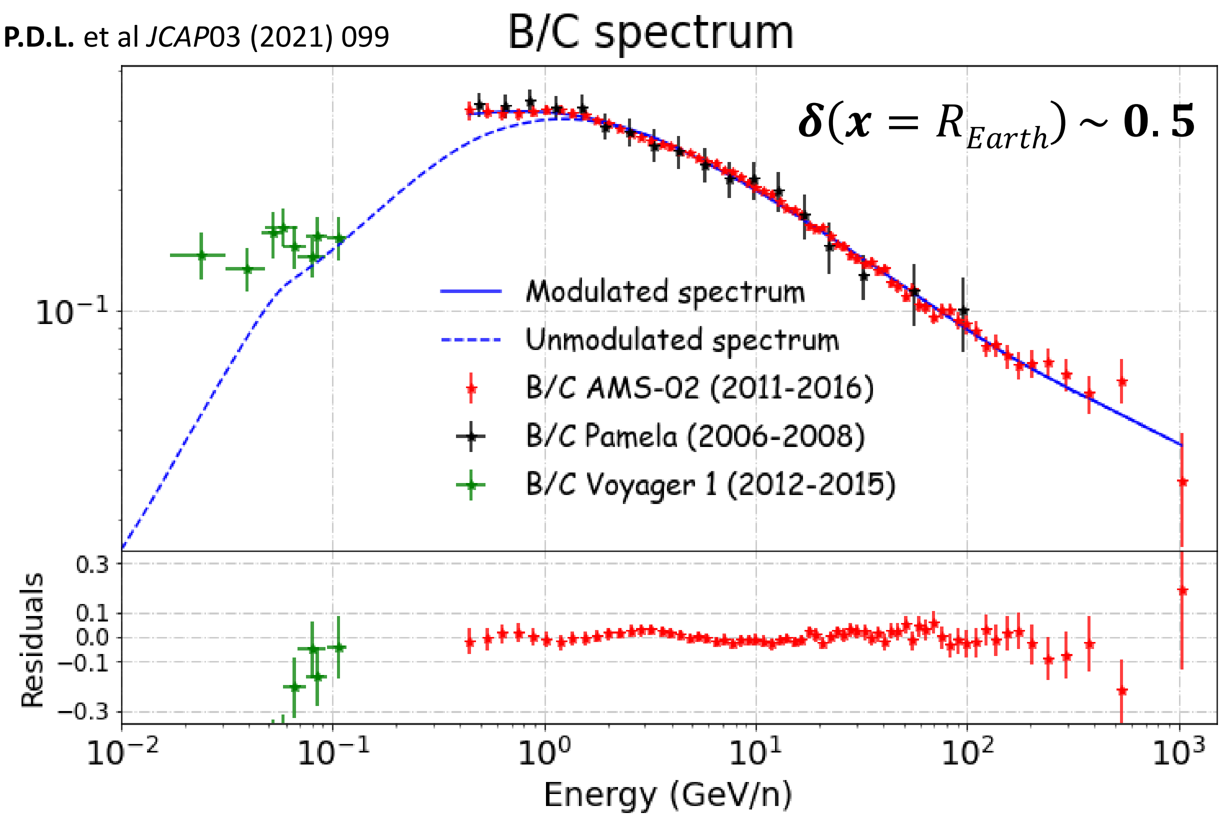
Hadronic (and **Bremss.**) emission follows the **ISM gas distribution**

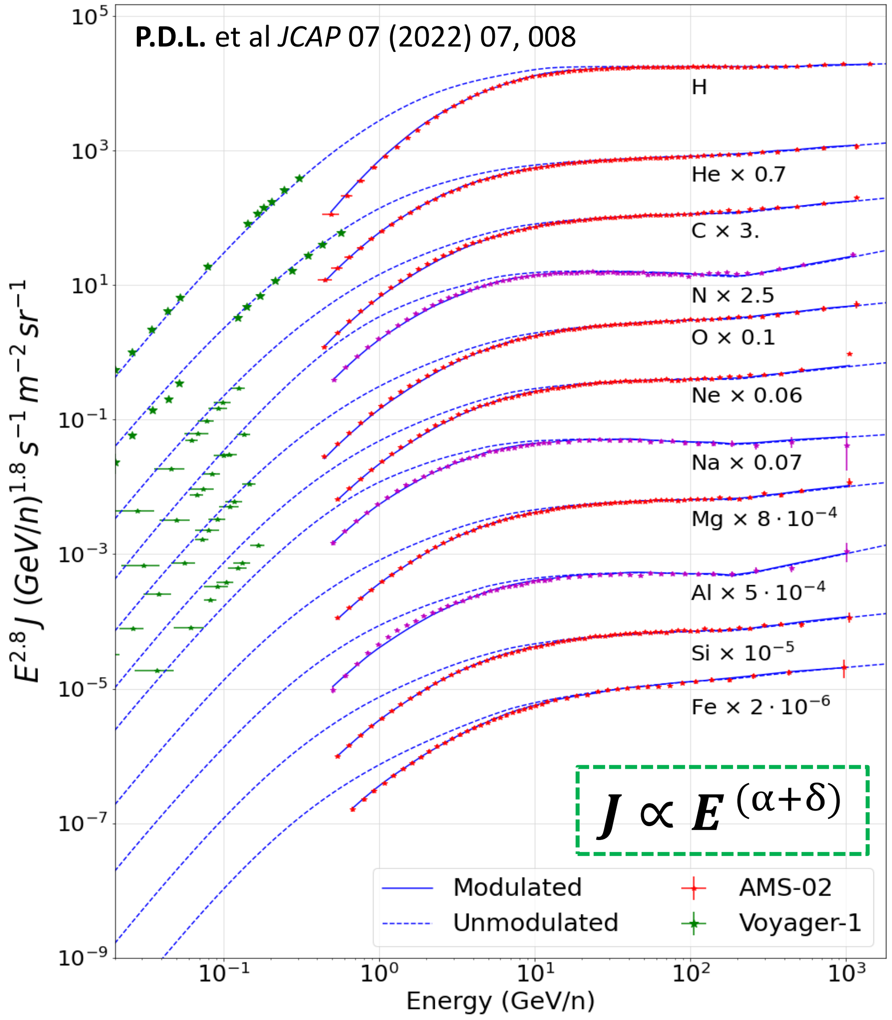
IC emission depends on the energy density of the **ISRFs**

Galactic gamma-ray diffuse emission – Local cosmic rays

Too limited information on Galactic CR propagation to build theoretical models beyond the Solar System

P.D.L. et al *JCAP*03 (2021) 099



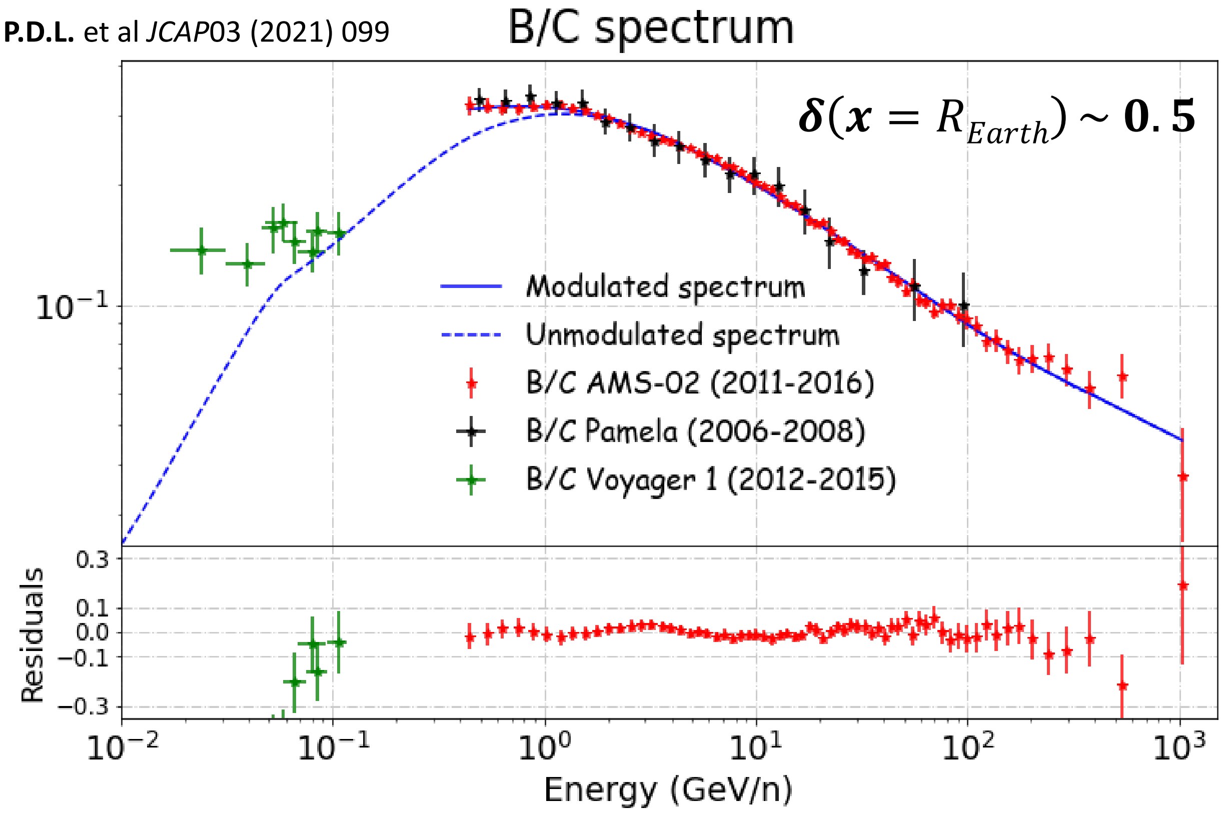


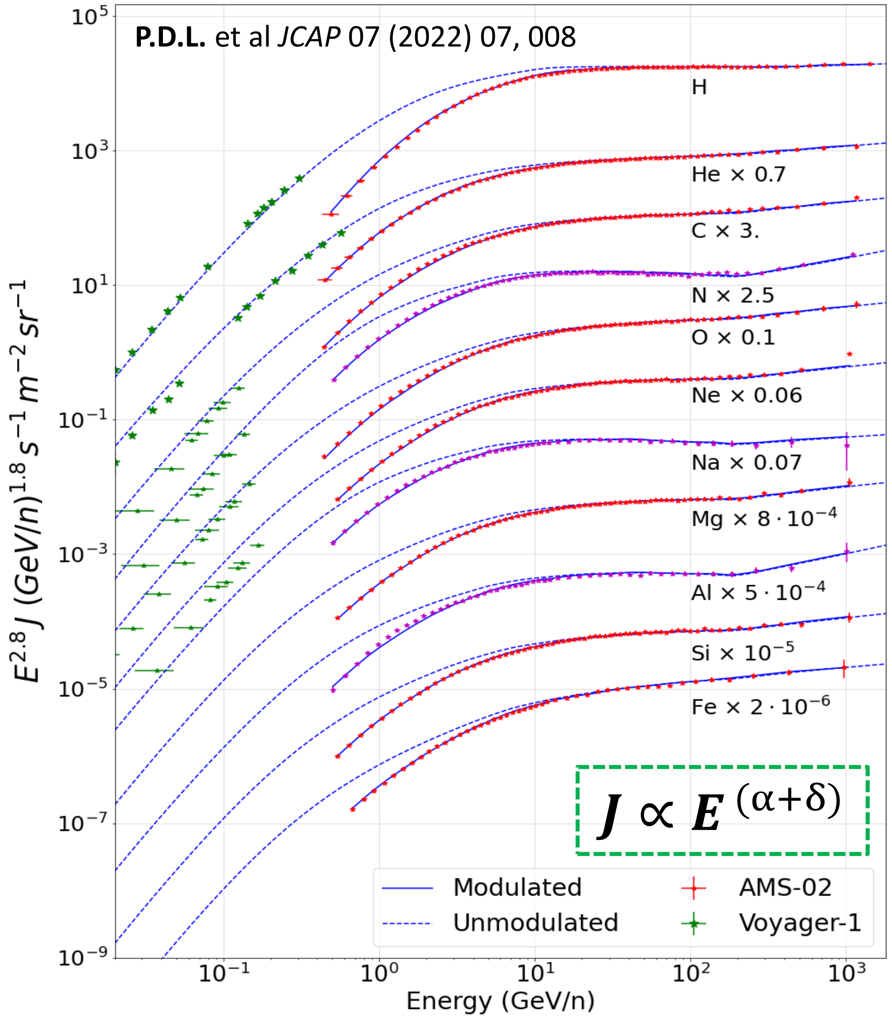
Galactic gamma-ray diffuse emission – Local cosmic rays

$$\frac{J_{sec}}{J_{pr}} \sim \sigma(E)/\, D(E)$$

$$D(E, \boldsymbol{x}) \sim D_0 \left(\frac{E}{E_0}\right)^{\delta(\boldsymbol{x})} F(\boldsymbol{x})$$

P.D.L. et al *JCAP*03 (2021) 099





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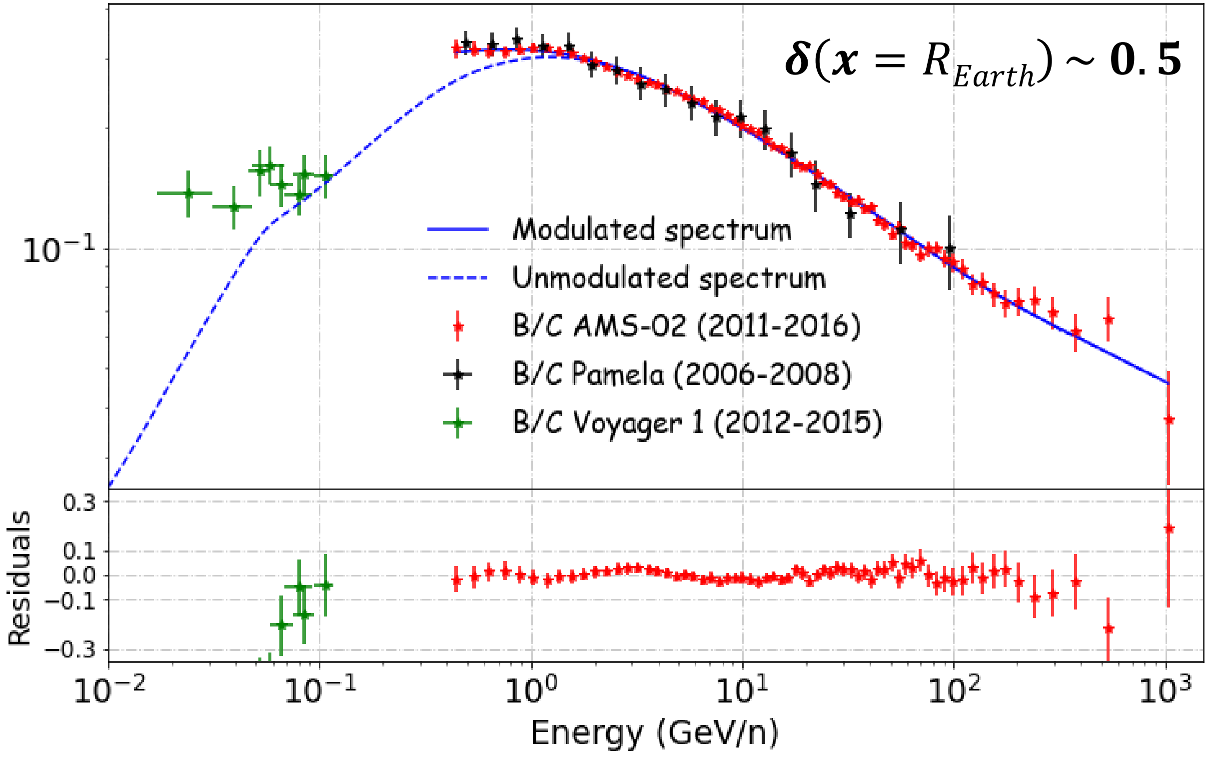
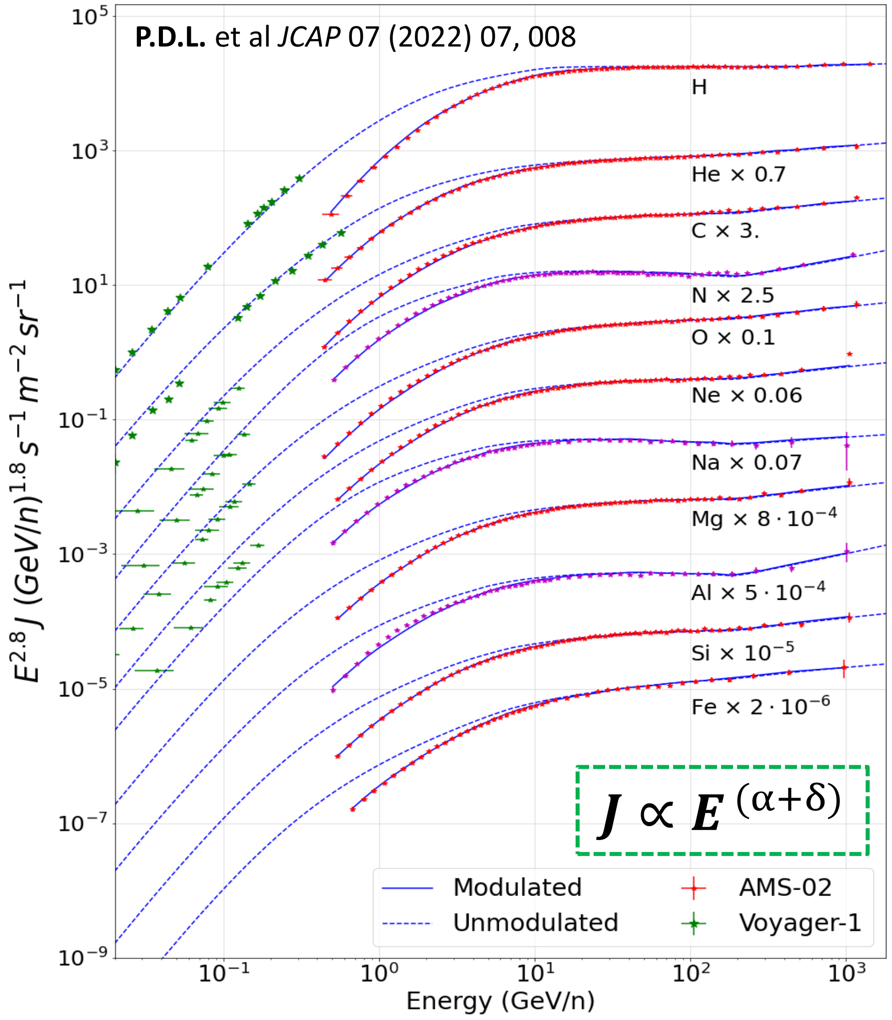
P.D.L. et al *JCAP*03 (2021) 099

B/C spectrum





Galactic gamma-ray diffuse emission – Hardening towards the centre

Progressive hardening of the gamma-ray diffuse spectrum towards the centre

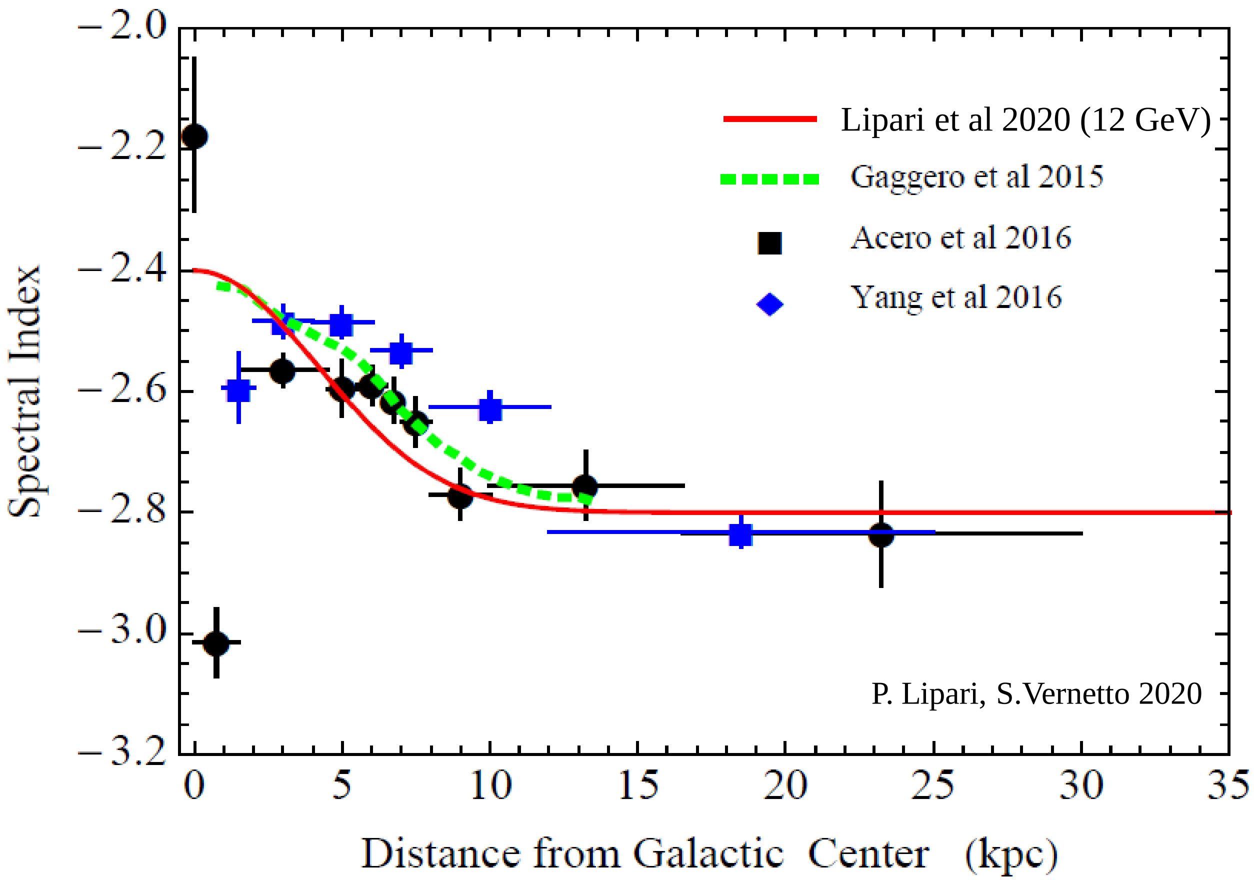
Diffuse gamma-ray spectrum essentially follows the spectrum of CR protons:

Purely diffusive – $\phi \propto E^{-(\alpha+\delta)}$

Advection dominated – $\phi \propto E^{-\alpha}$

Transient effects and source injection not isotropic (α(r, z))?

The conventional picture of **spatially-constant diffusion is not able to explain this** consistently

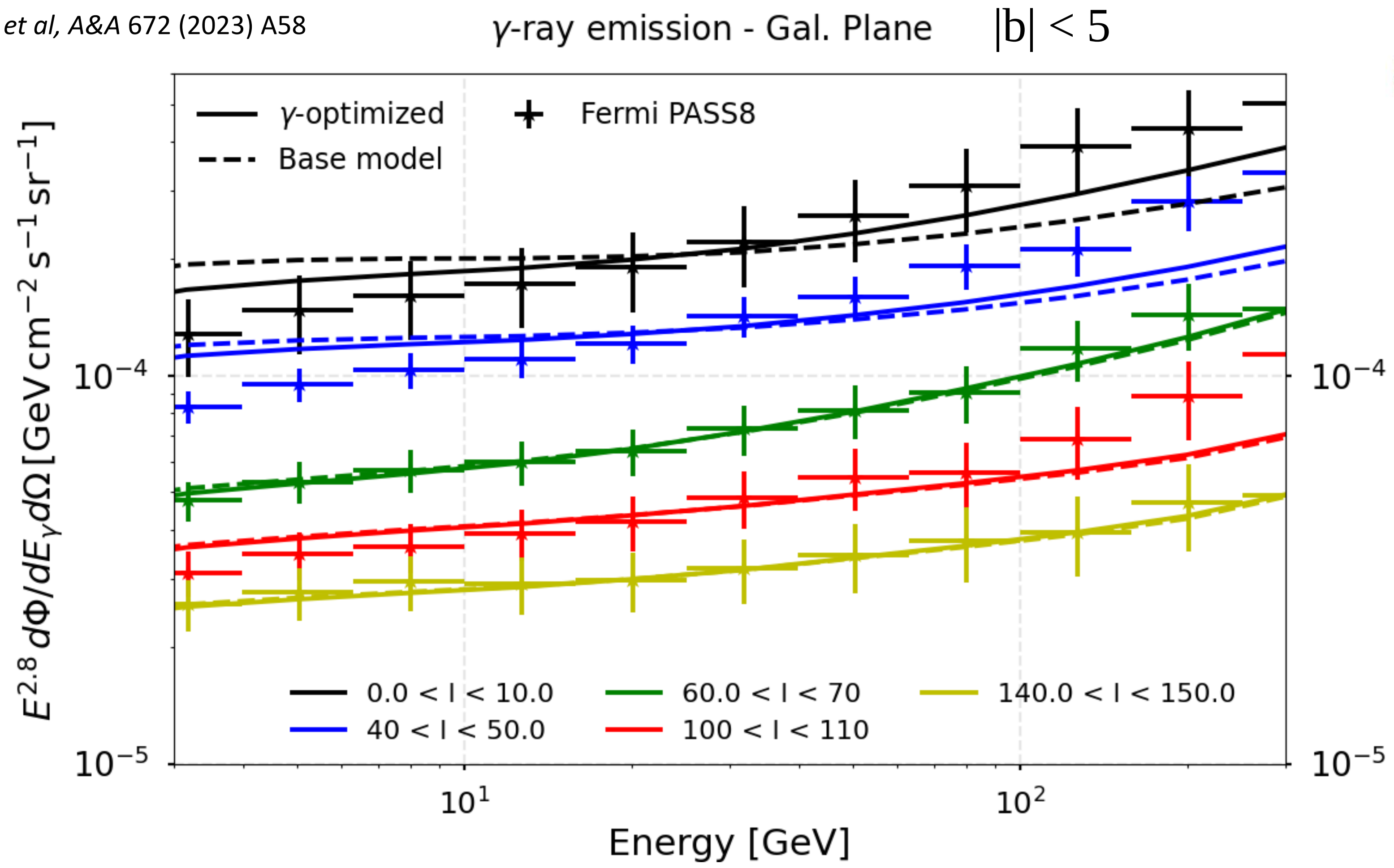


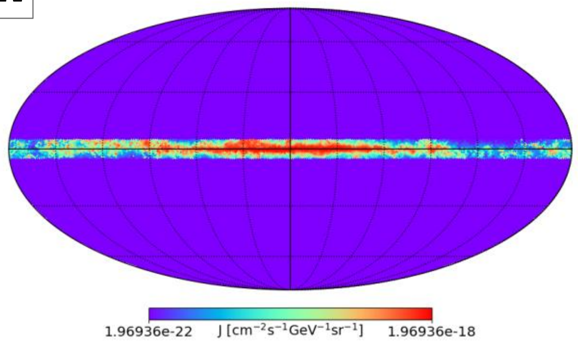
Inhomogeneous diffusion model

Diffusion coefficient changes towards the Galaxy centre $\boldsymbol{D} \propto \boldsymbol{E}^{\,\delta(\boldsymbol{R})}$

$$\delta(\boldsymbol{R}) = \delta_{\boldsymbol{0}} + \delta_{\boldsymbol{A}}\boldsymbol{R}$$

P.D.L. *et al, A&A* 672 (2023) A58





DRAGON2

$$D = D_0\beta\left(\frac{E}{E_0}\right)^{\delta(\boldsymbol{R})}$$

HERMES

Base model: Constant (δ_A = 0)
γ-optimized model: δ_A = 0.04
δ_0 = 0.17

Inhomogeneous diffusion model ($\delta \rightarrow \delta(R)$)

Two different interpretations (models) of the local proton and He data based on the "bump" at ~10 TeV found by DAMPE and the discrepancy from particle shower experiments.

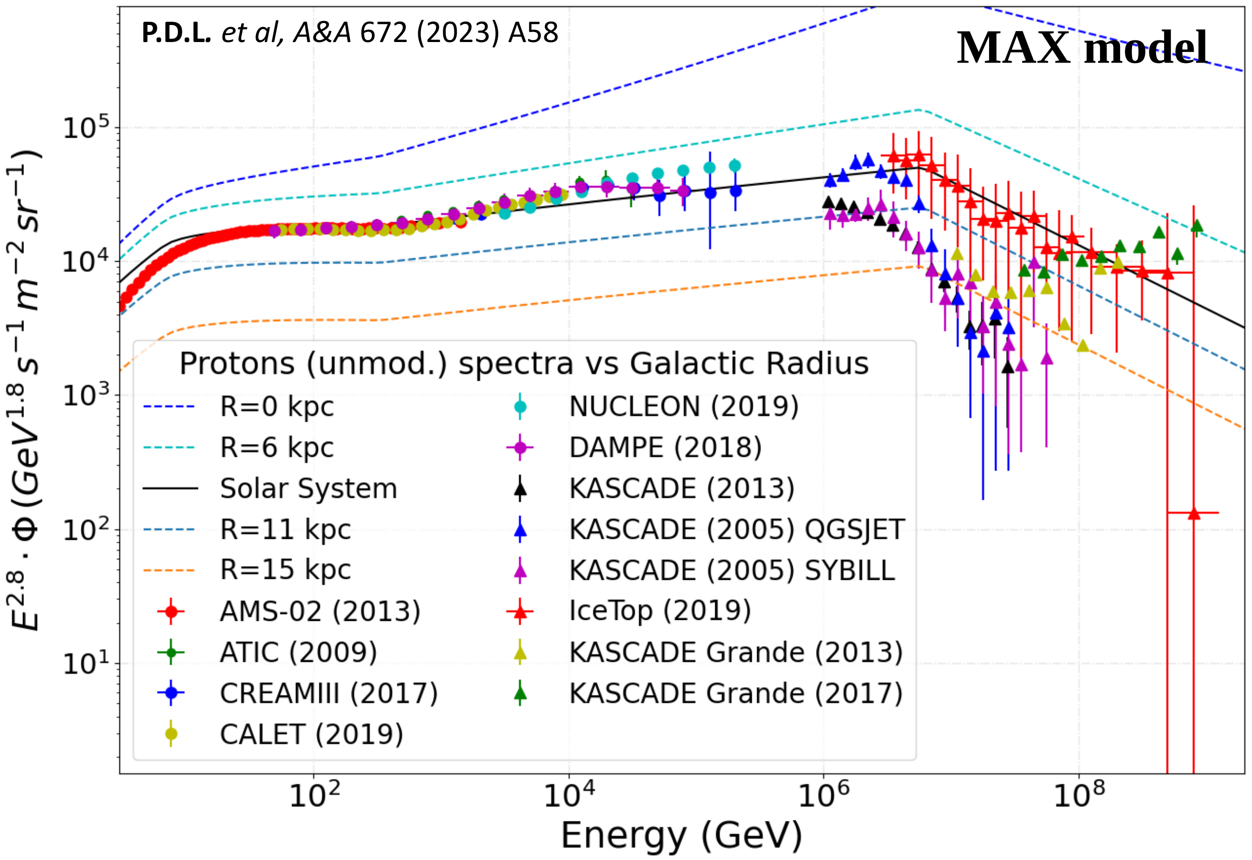
MAX model adopted connects AMS-02 data with IceTop

MIN model adopted connects the DAMPE "bump" with KASCADE

Both models incorporate a break at ~ 300 GeV and a strong softening at a few PeV

Different interpretations of local data

Local sources vs global features



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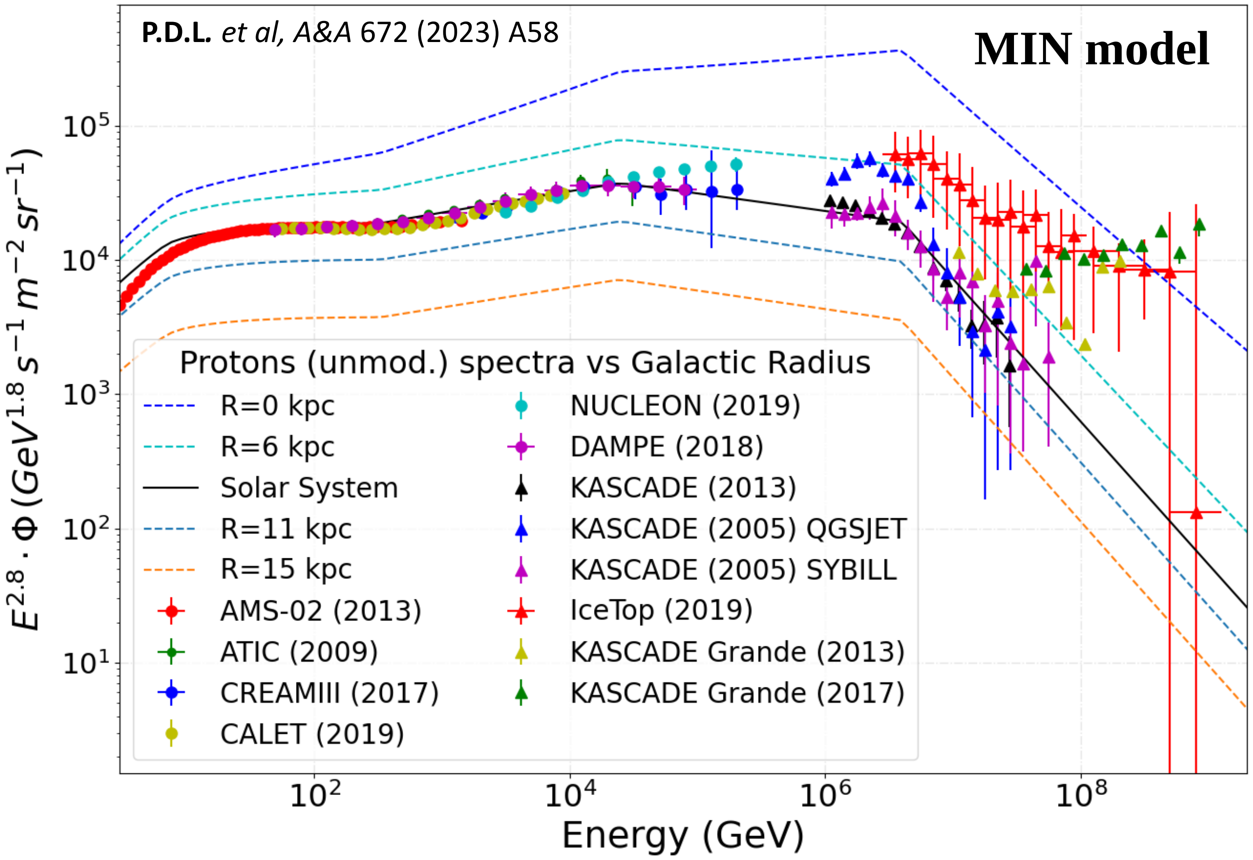
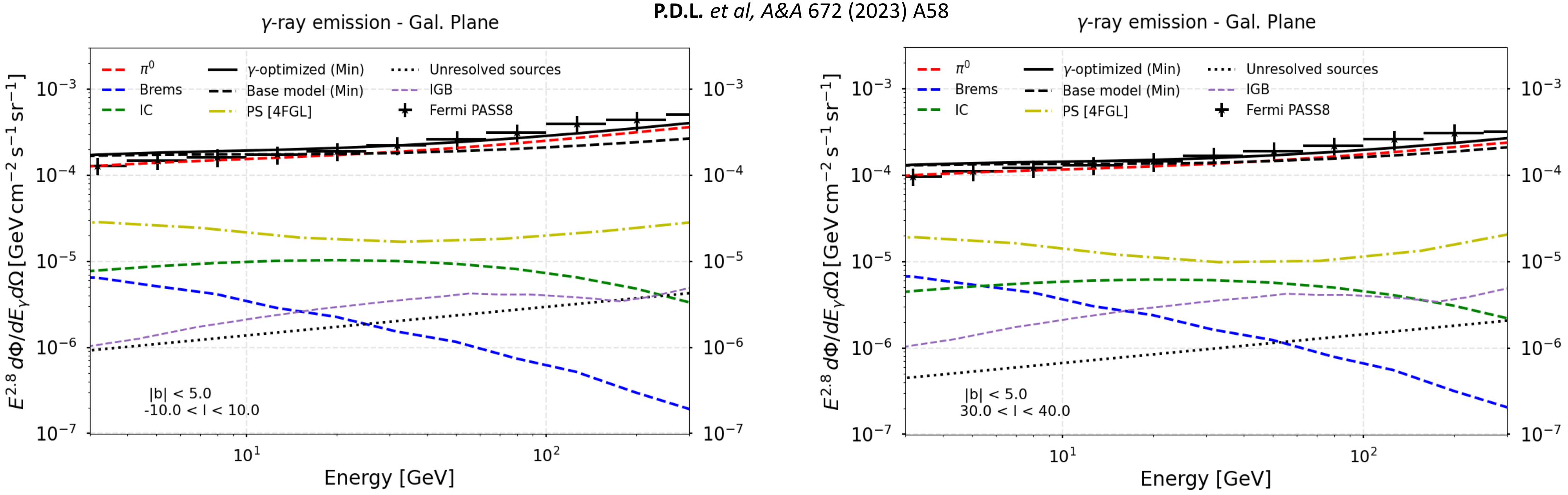


Inhomogeneous diffusion model

The different components

- The diffuse emission at GeV energies dominate over the emission sources emission (4FGL catalogue)
- Unresolved point sources (UPS) become more important at higher energies (Steppa+ A&A 643, A137 (2020))
- Isotropic gamma-ray background (IGB) contains Extra-galactic plus Fermi's instrumental background

P.D.L. *et al, A&A* 672 (2023) A58

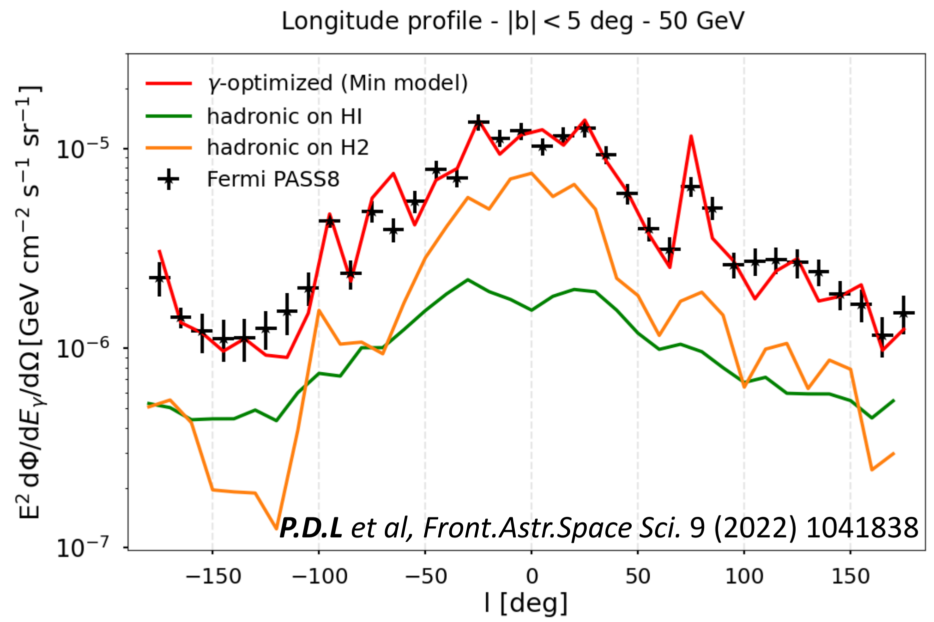


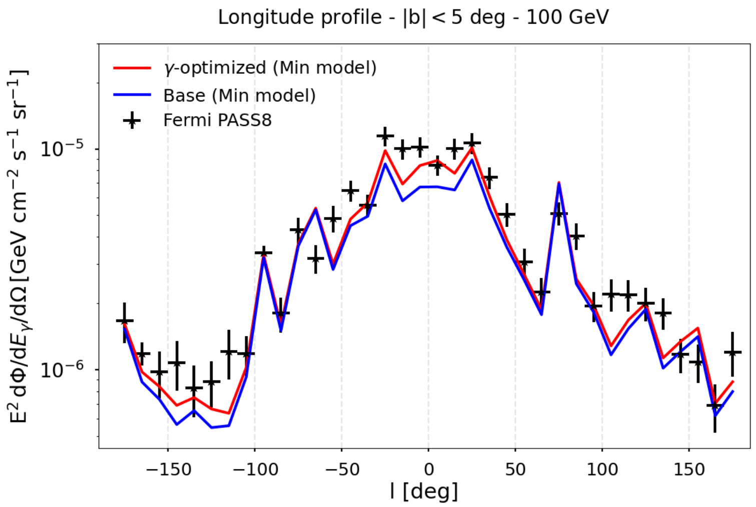
γ-optimized model vs Fermi

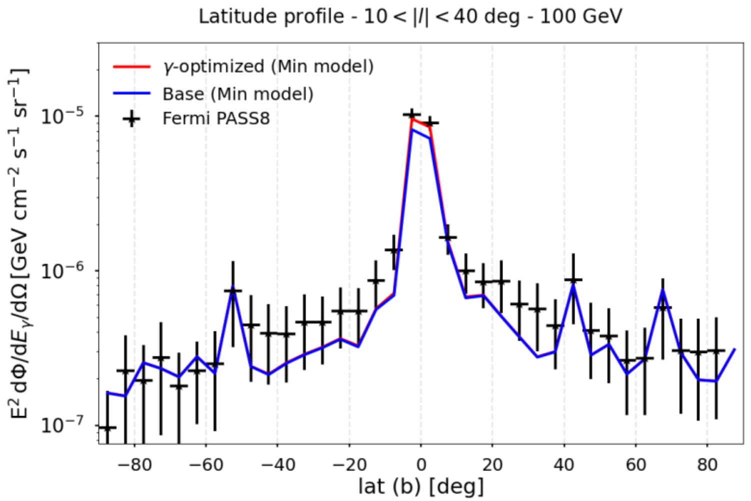
ISM gas distribution based on the ring gas model developed by Q. Remy

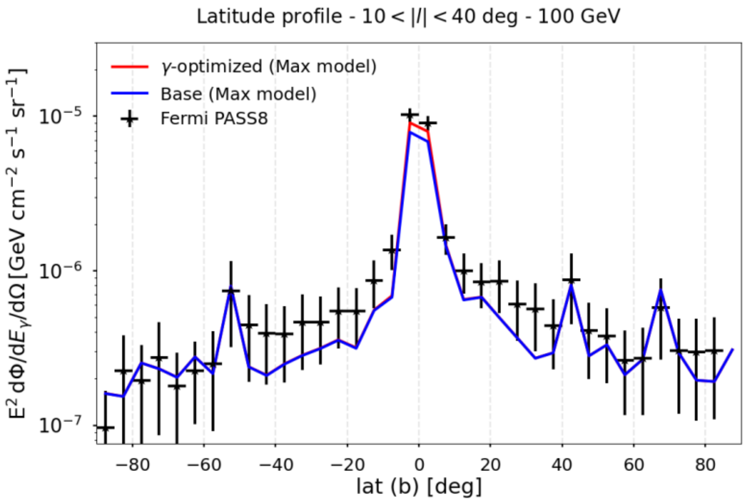
ISRF distribution (CMB + IR + Stellar) from Vernetto&Lipari Phys. Rev. D 94, 063009

XCO factor divided in rings to tune the normalization (**Different approaches can be used**)



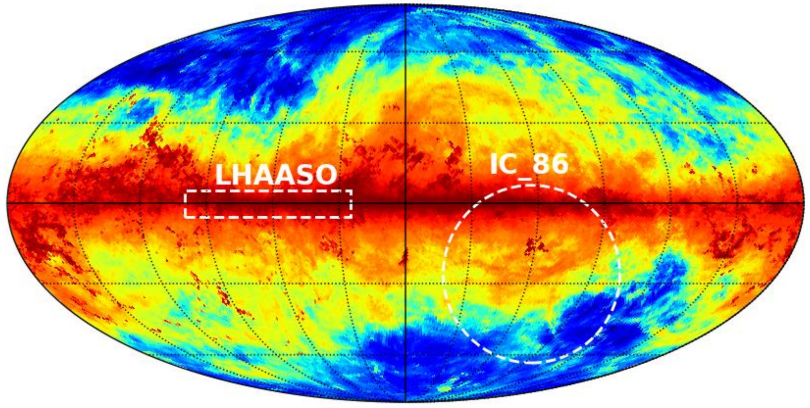




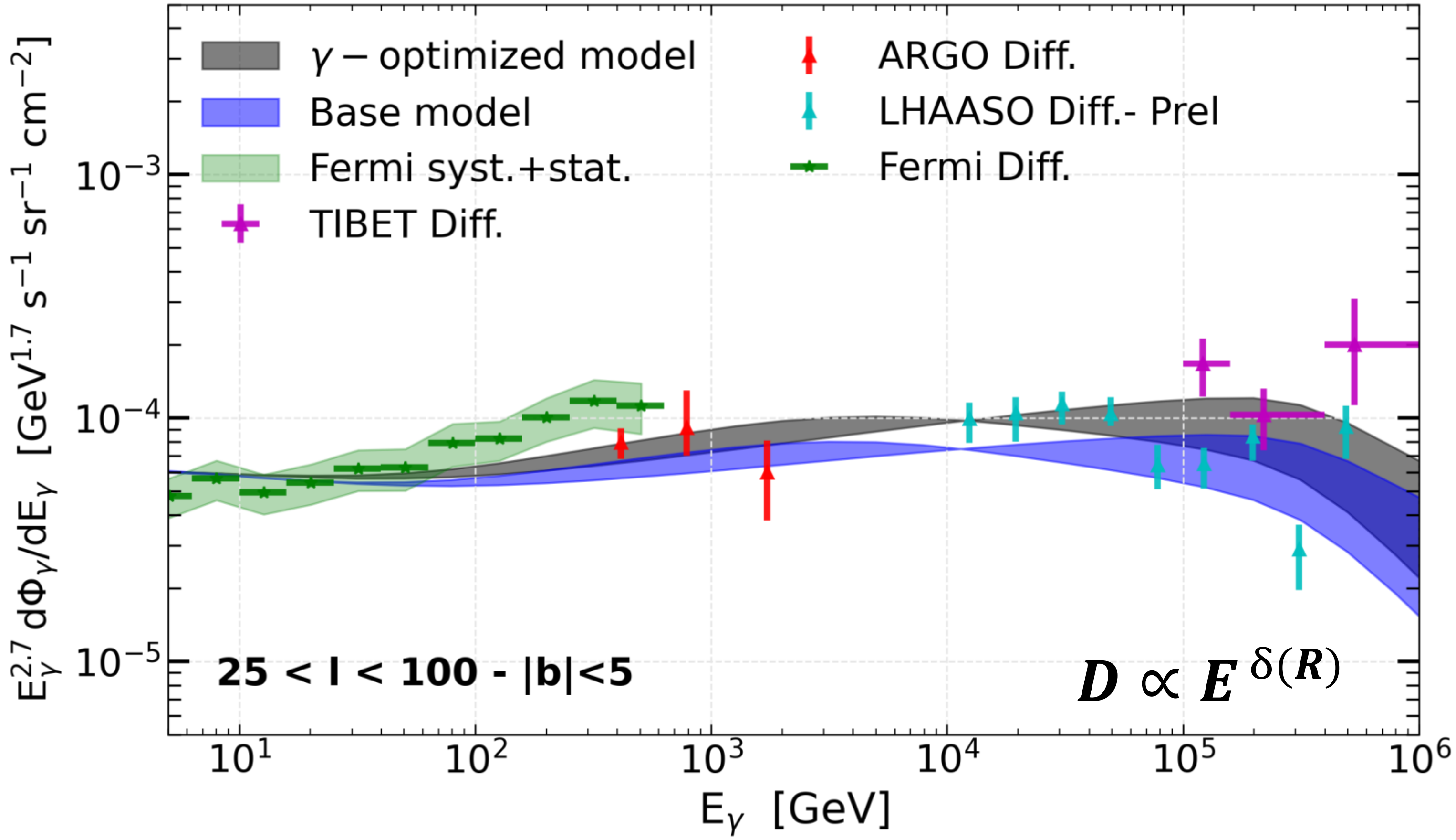


Inhomogeneous diffusion model

The diffuse emission meets TeV data



P.D.L. *et al, A&A* 672 (2023) A58

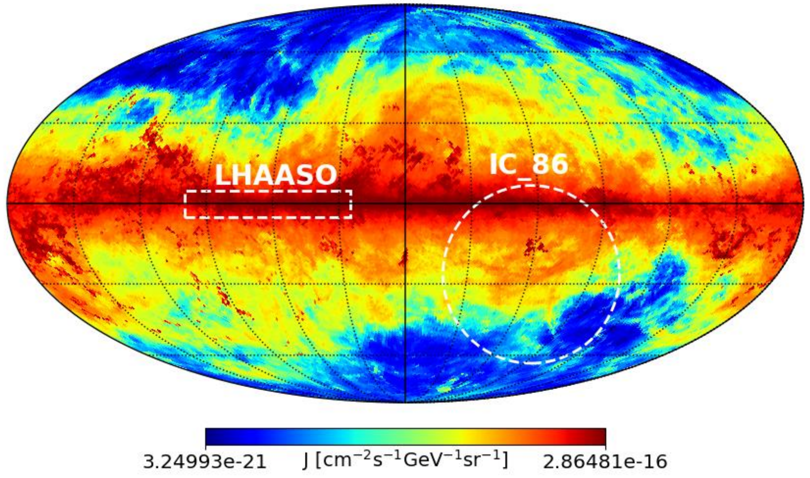


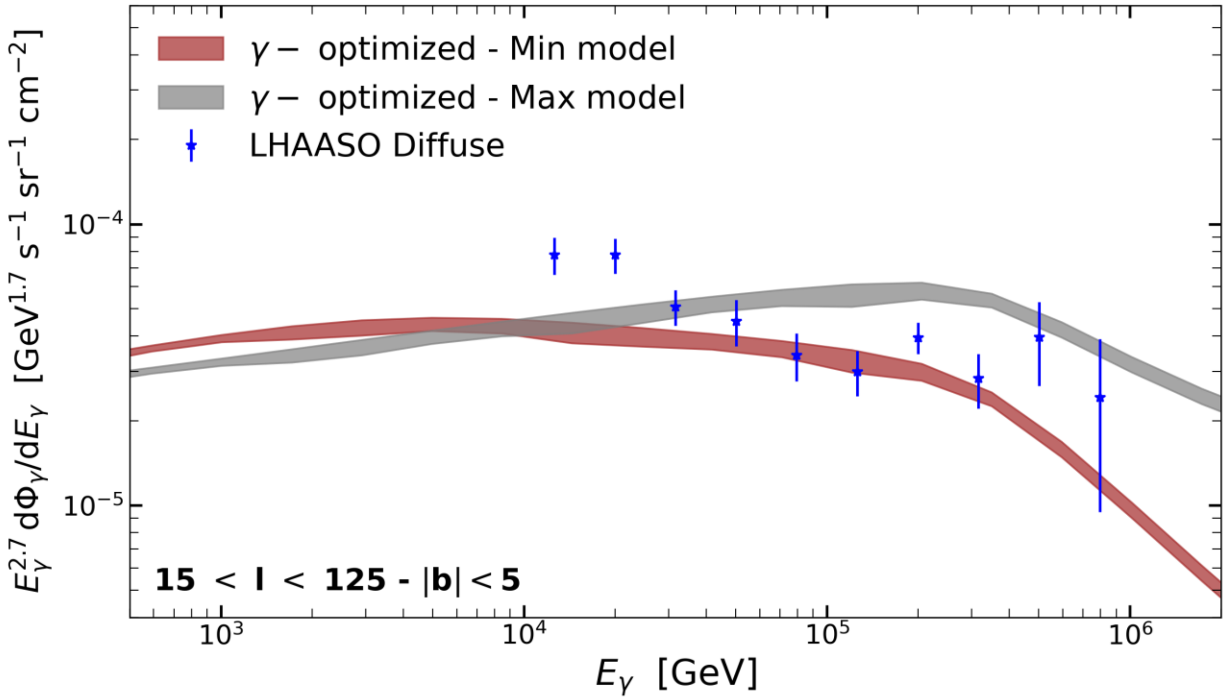
The spatially-dependent (**γ-optimized**) models, tuned on Fermi-LAT data are also **favoured by very high energy detectors** like LHAASO

Important implications for future experiments like CTA and for dedicated studies of the Galactic Centre (GeV excess)

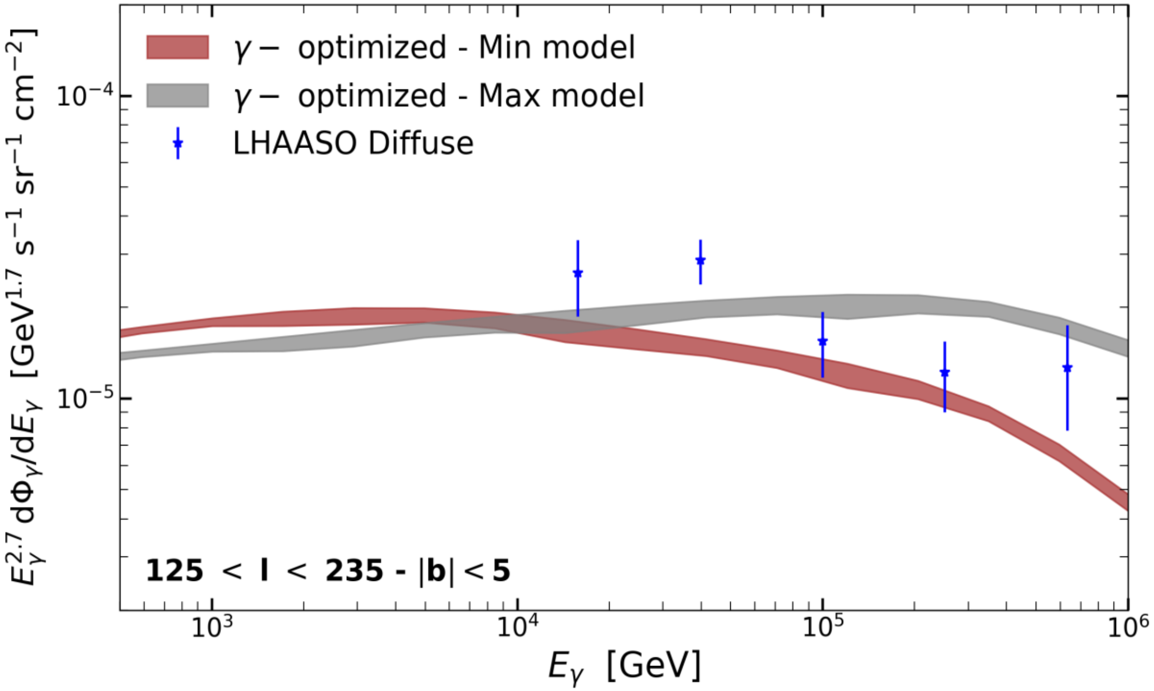
Inhomogeneous diffusion model

LHAASO diffuse emission



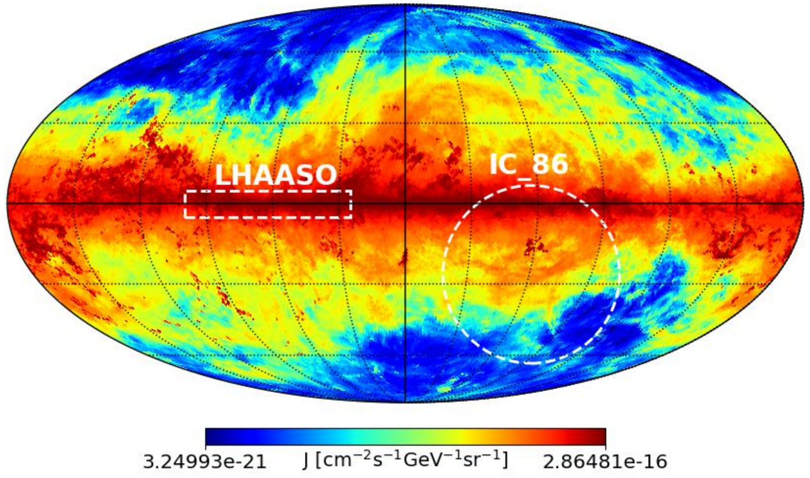


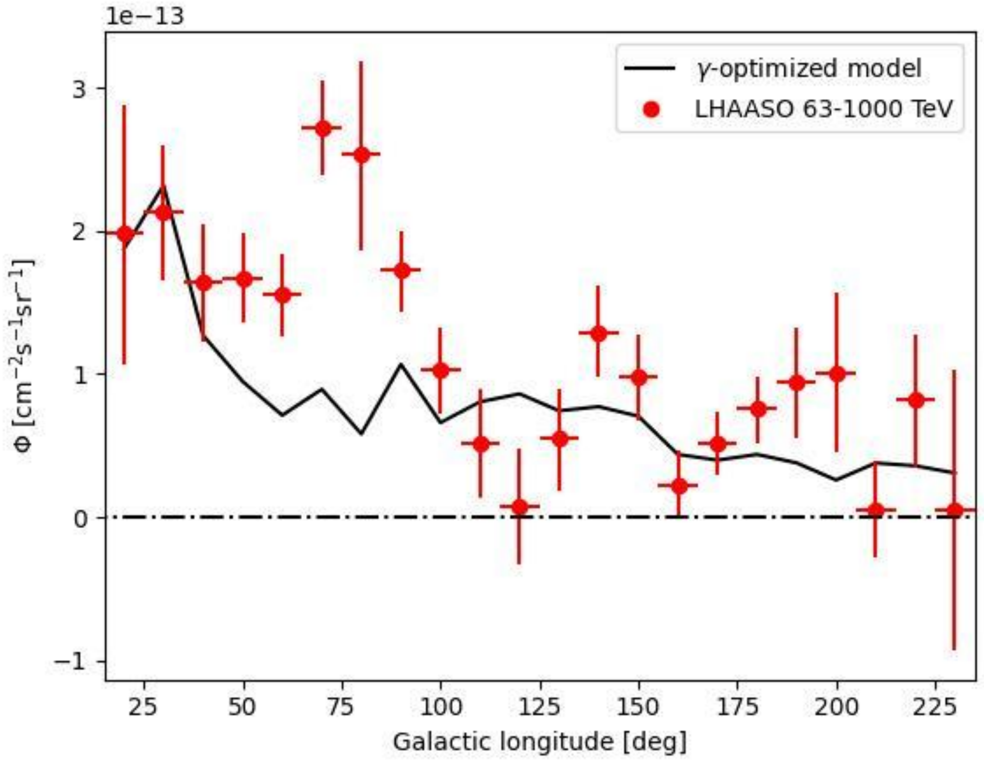
The spatially-dependent (**γ-optimized**) models, tuned on Fermi-LAT data are also **favoured by the very high energy observations of** LHAASO



Inhomogeneous diffusion model

Longitude profiles vs LHAASO





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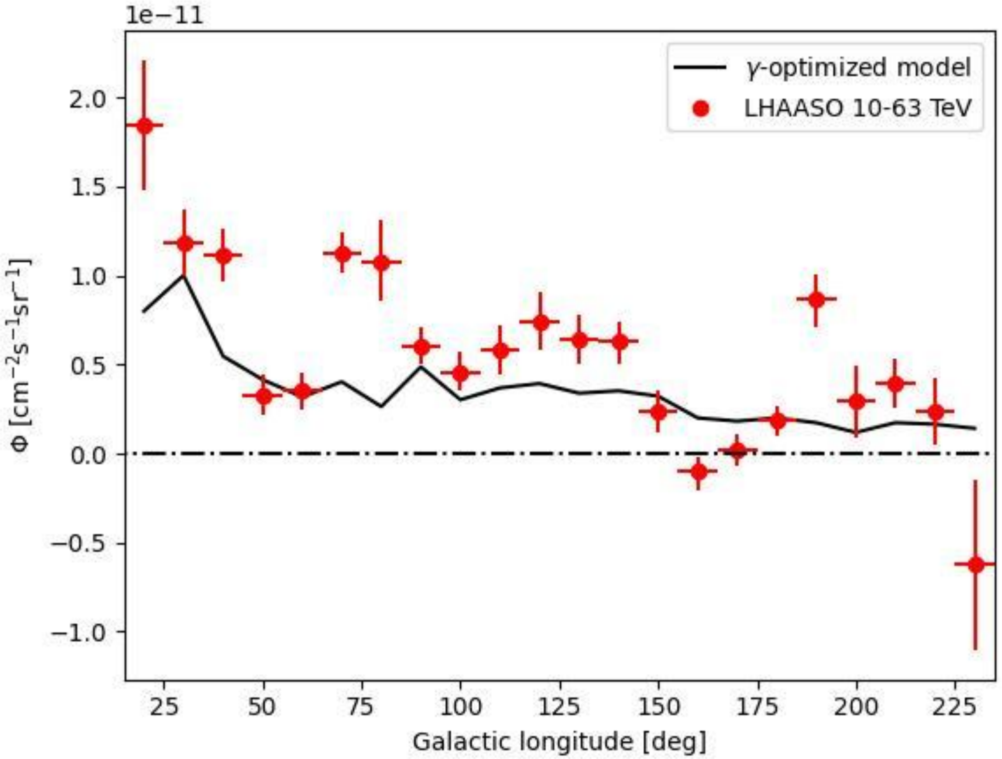
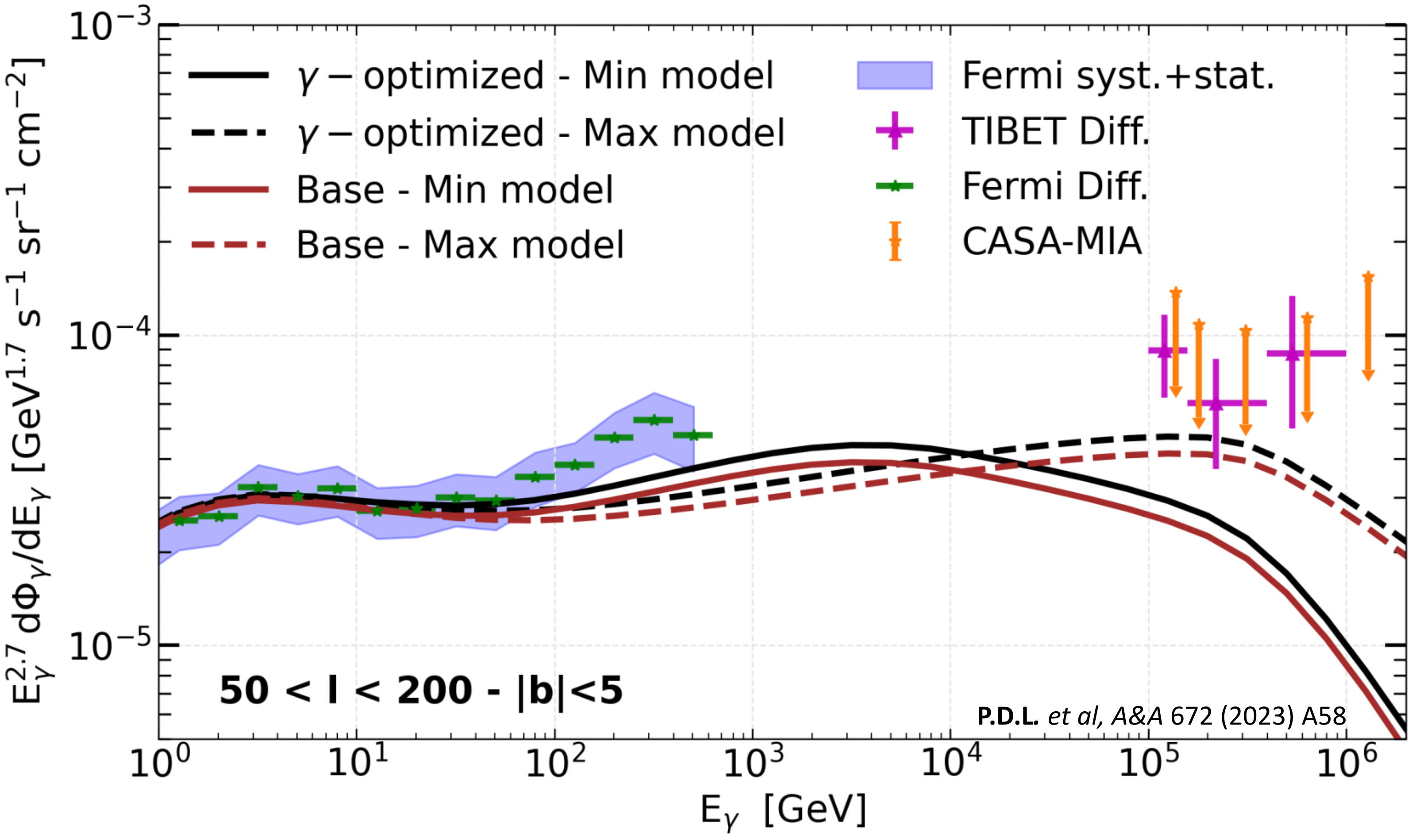


Inhomogeneous diffusion model

External Galactic regions

Both models under-produce TIBET data → **Region very affected by the emission of unresolved sources**! (dependent on the experiment)



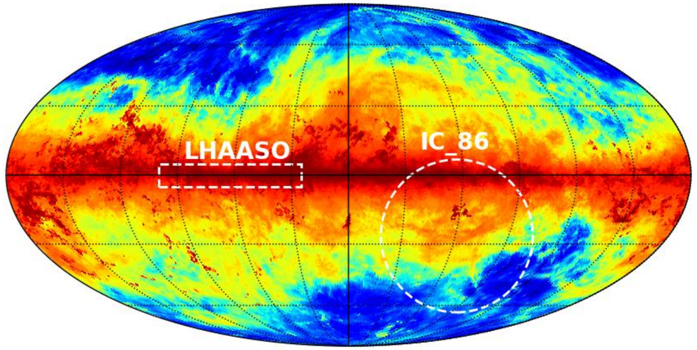
The effect of the inhomogeneous transport in such externals regions is small, therefore, **more data at these ROIs can help solving the degeneracy between emission from unresolved sources and the truly diffuse emission**

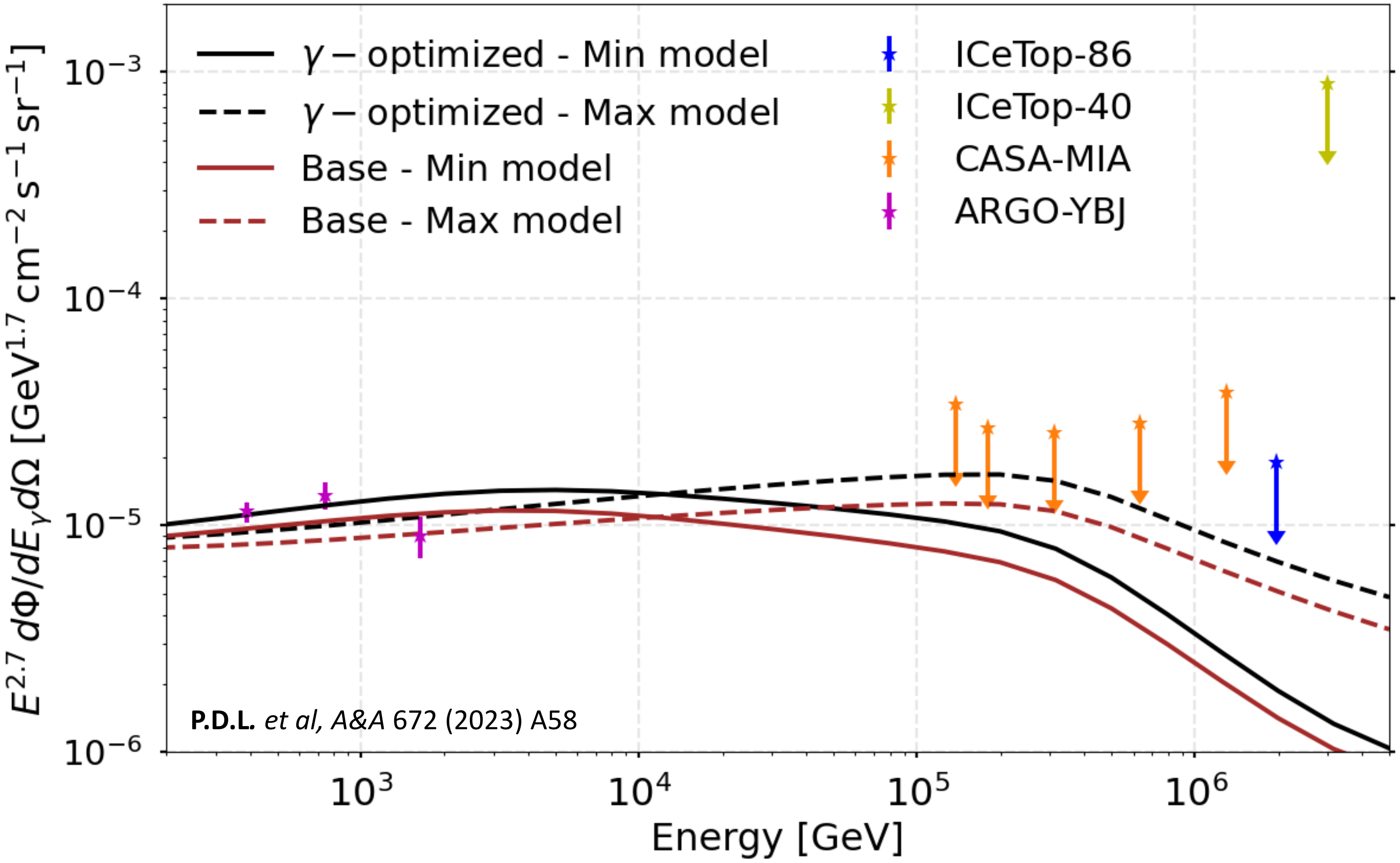
See also:
Vecchiotti et al *ArXiv*:2107.14584

Linden and Buckman *PRL* 120, 121101 (2018)

Inhomogeneous diffusion model

External Galactic regions



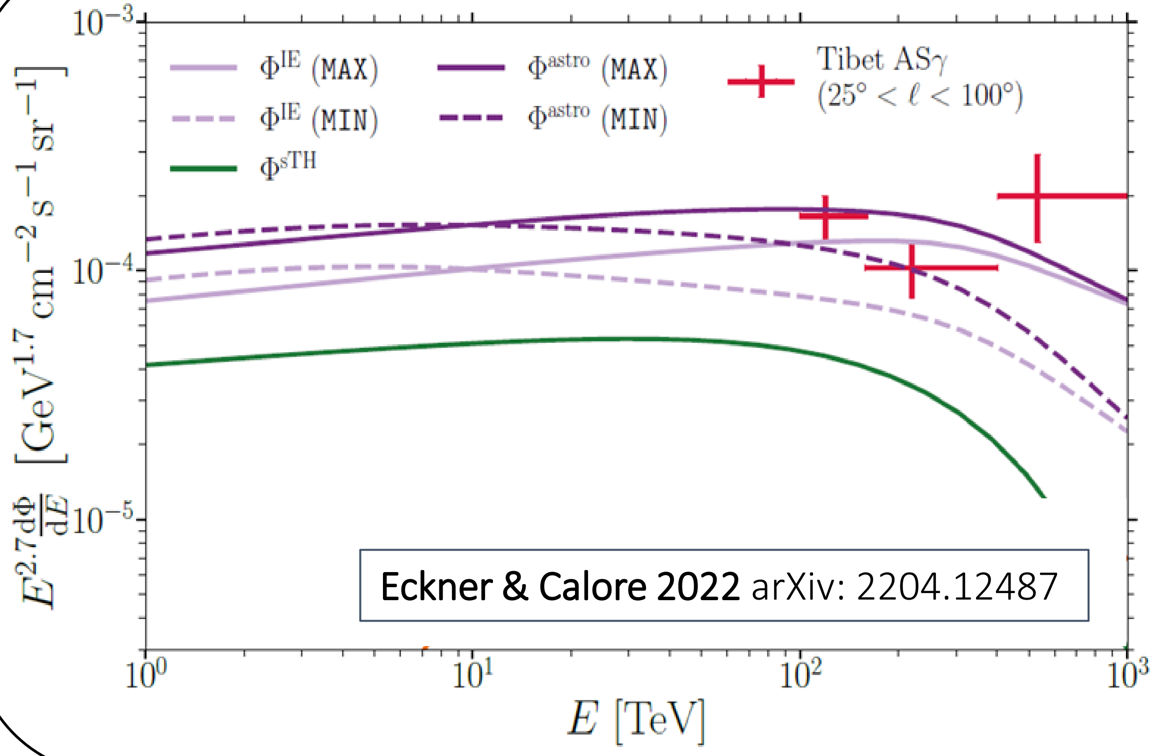


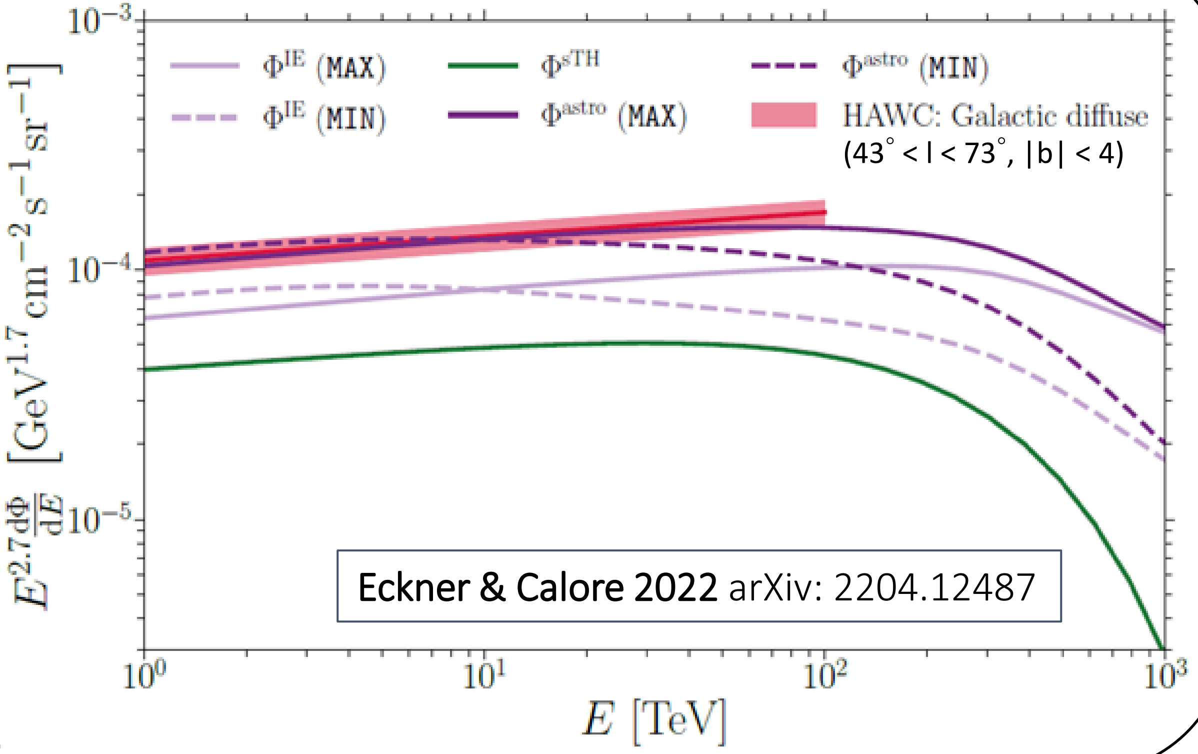
Within the **region of sensitivity of IceTop** there is little difference between models conventional diffusion and the gamma-optimized models

Observations in this region seem to be **around the corner**! In addition, unresolved sources may play a crucial role here

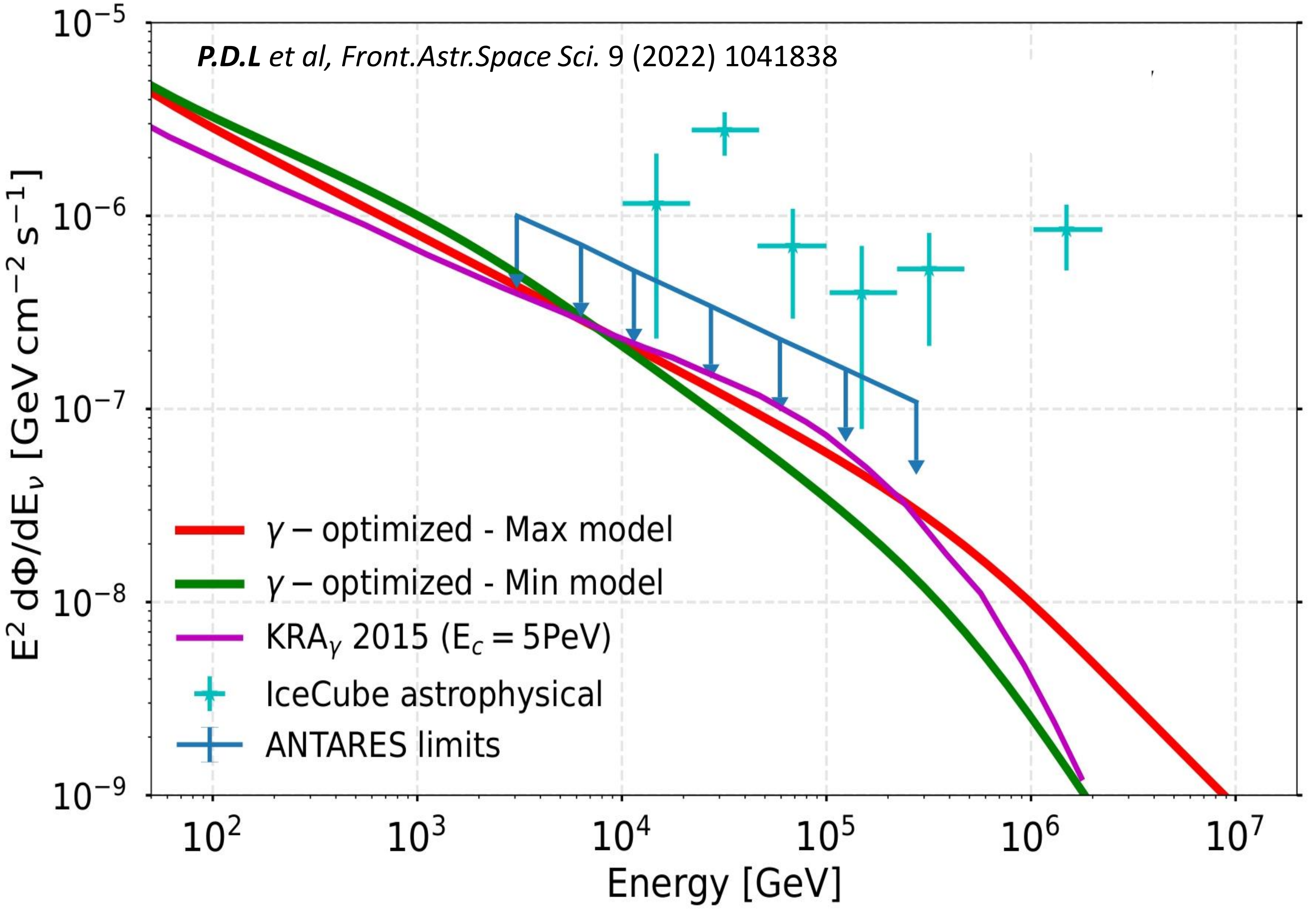
Total diffuse emission → MAX/MIN (truly diffuse) + Unresolved sources contribution

Compatibility with the total diffuse emission from the TeV (HAWC) to the PeV (TIBET)





Diffuse gamma-ray production: detection of neutrinos as a smoking gun



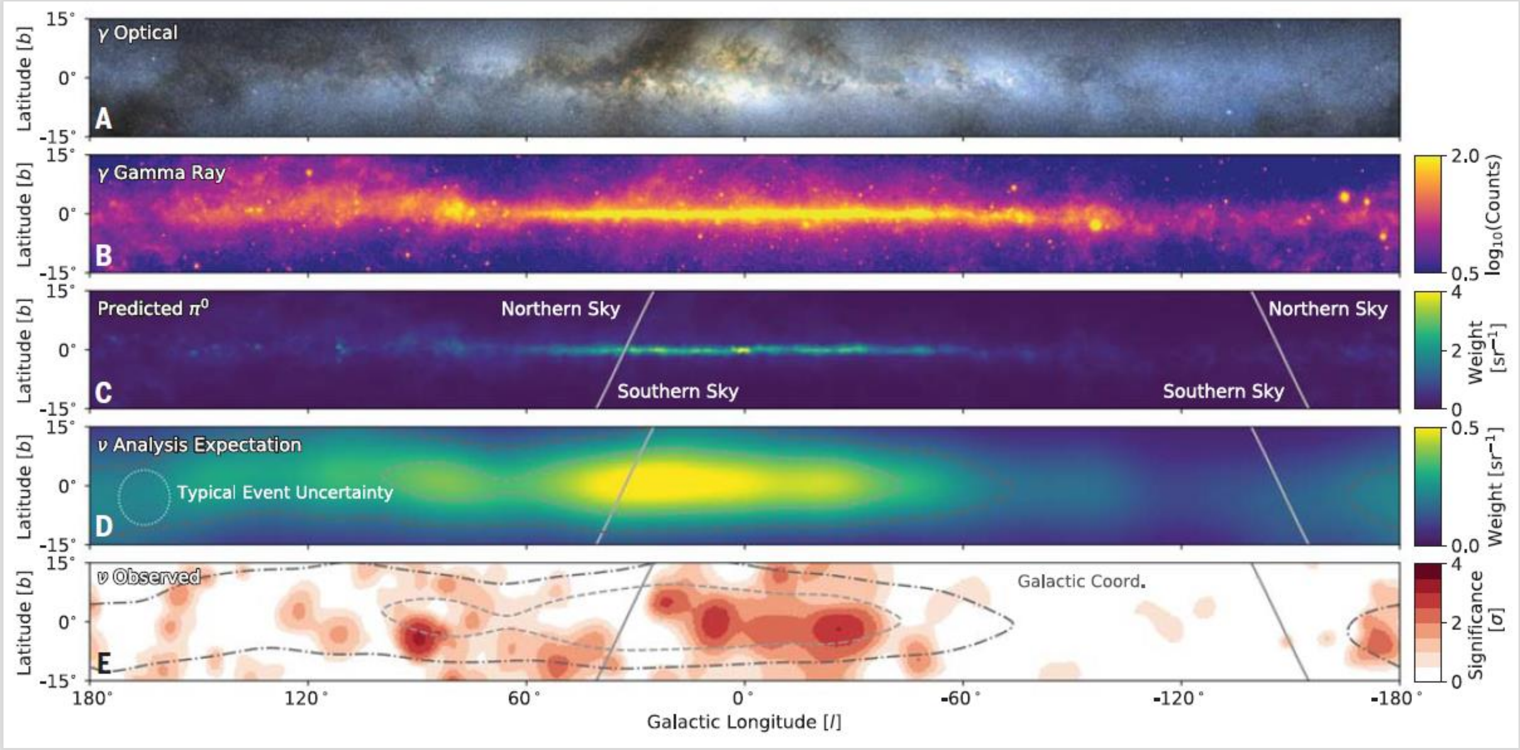
Neutrinos are also generated by CR collisions with ISM. This emission is similar in intensity and spectral shape to the gamma-ray emission

2σ hint observed by IceCube (Aartsen, et al. 2019, Astrop. J., 886, 12).

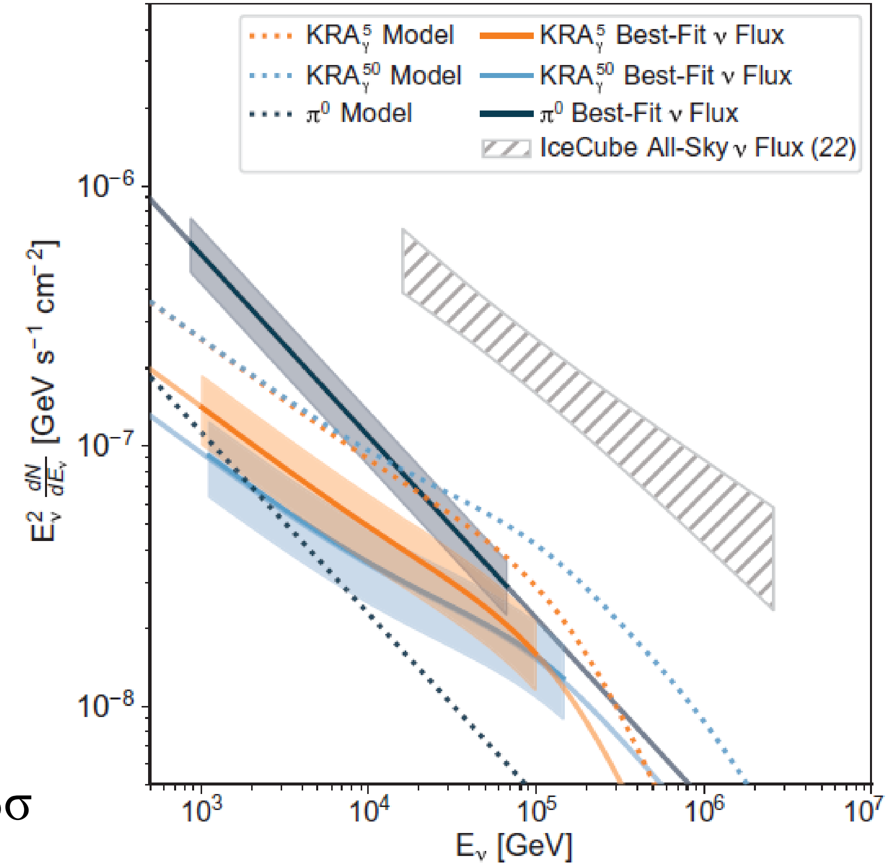
4.1σ observed in track-like IceCube events (arXiv: 2208.080423).

<u>Indication that a Galactic diffuse component (10-20% of the total flux above 200 TeV) is already identified by IceCube.</u>

Diffuse gamma-ray production: detection of neutrinos as a smoking gun



IceCube Coll. Nature 2023



IceCube confirmed the detection of neutrinos from the disk at almost 5σ using cascade events. New analysis using track events also ongoing

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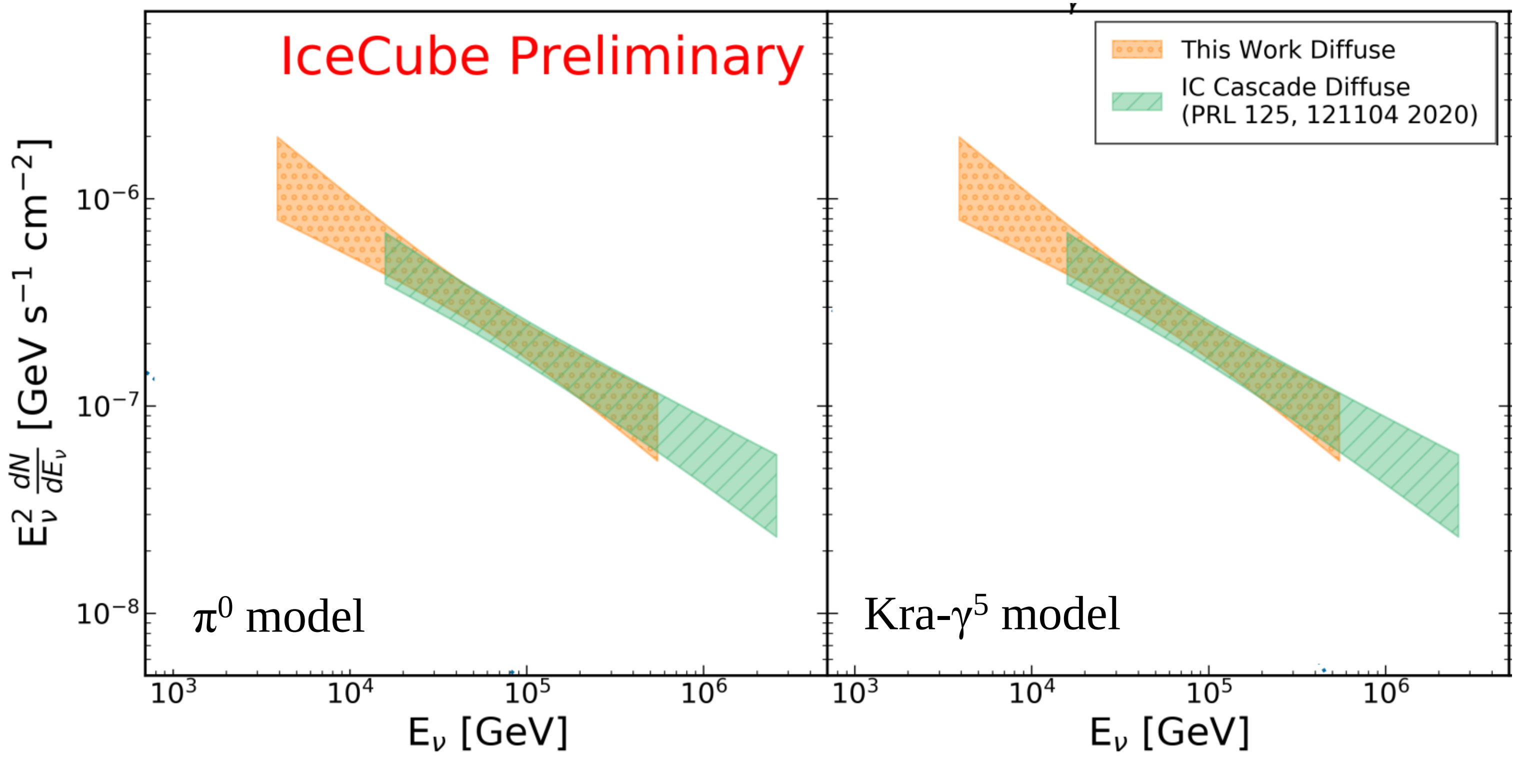

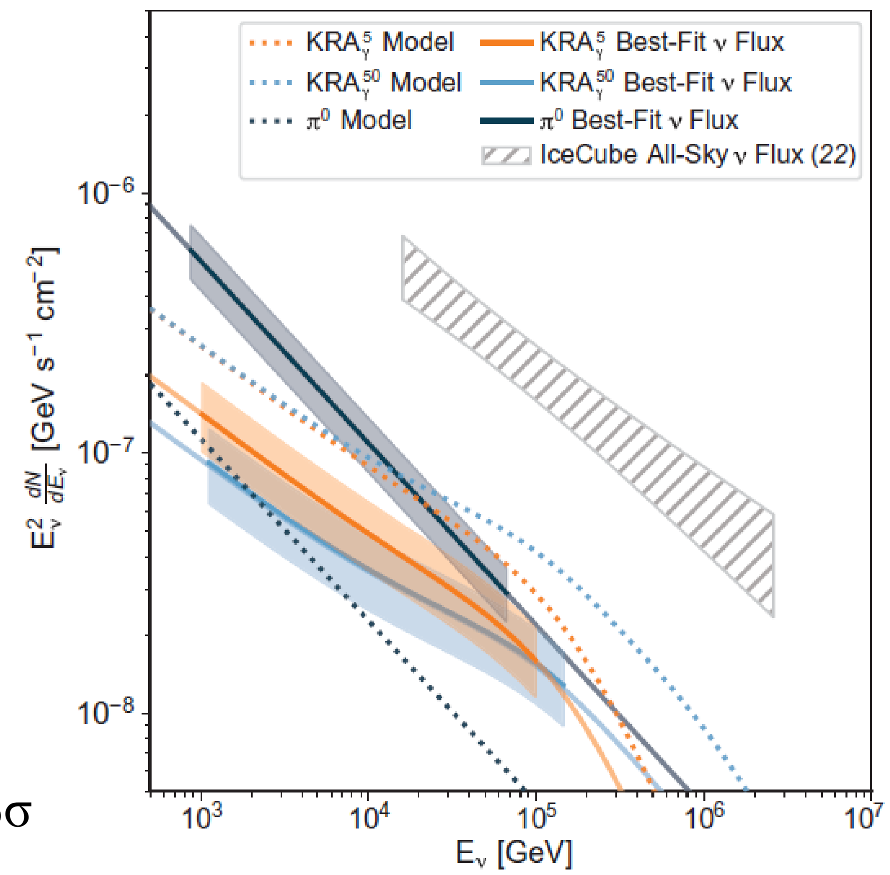

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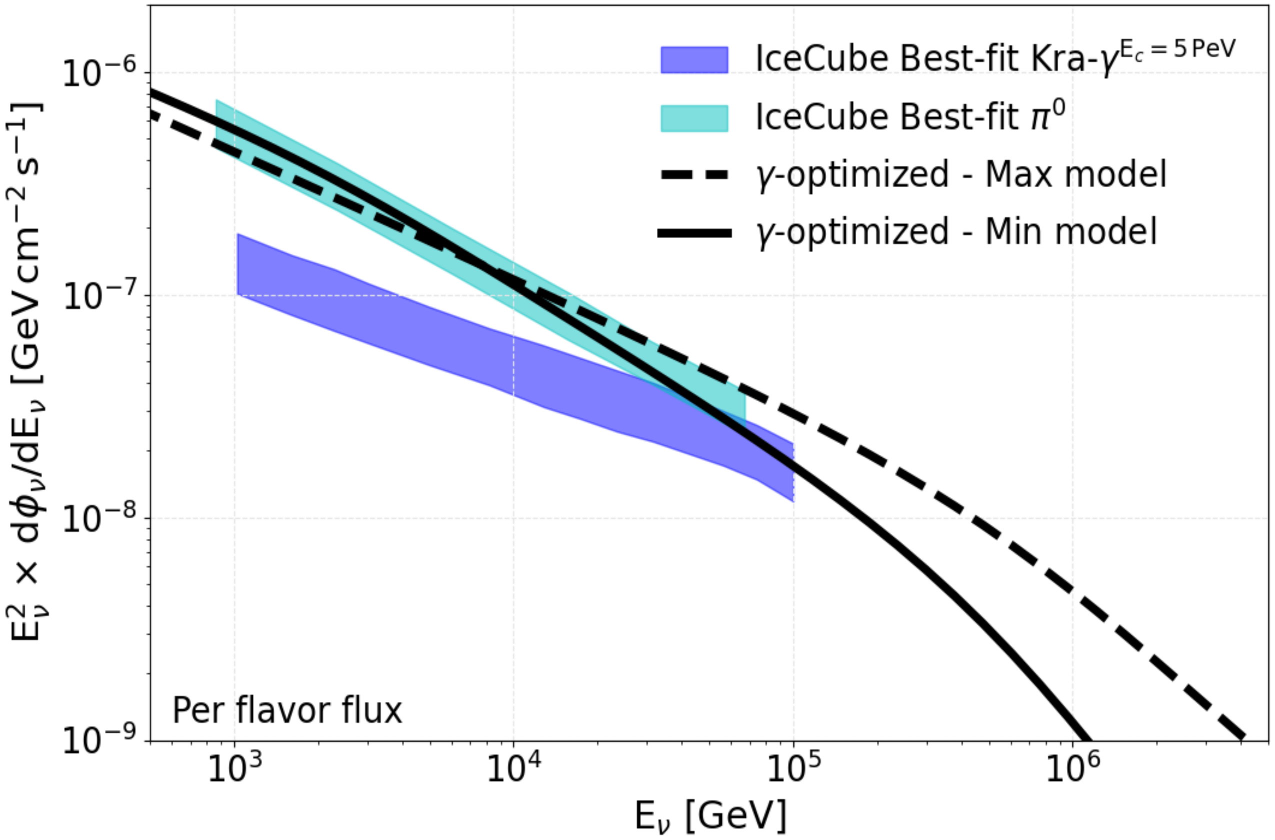


This model predicts a neutrino flux in excellent agreement with the best-fit measurements of IceCube

However, no much room for high-energy neutrino sources → Most PeVatrons observed in γ rays have a leptonic origin

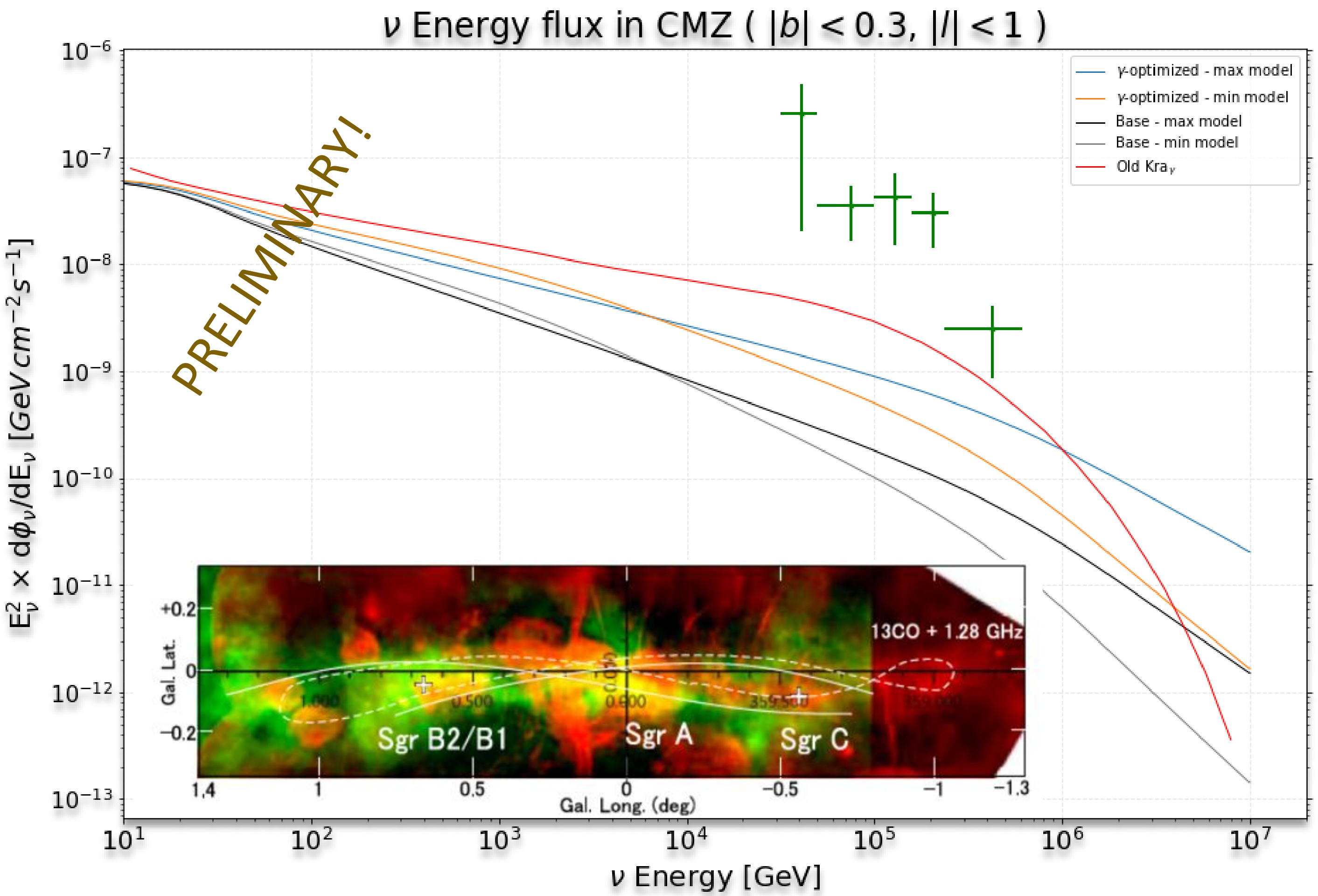
IceCube observation slightly favour the scenario of a Galactic flux correlated with the CR distribution, although uncertainties are enormous

γ-optimized model predicts both the observed high-energy neutrino and high-energy γ-ray emissions perfectly

The CMZ offers a wonderful test!

The CMZ is the region where more gas is concentrated and where the spectral assumptions of different models can have very large discrepancy.

Obtained from the last release of track-like events collected by IceCube between 2008 and 2018, through-going tracks, that reach the detector from all directions, as well as track events that start within the instrumented volume



TO CONCLUDE

- **Gamma rays** offer crucial information about the **propagation of cosmic rays** in different zones of the Galaxy, although many ingredients are involved and uncertainties are very high…

- The predictions from the γ-optimized model (modelled from GeV Fermi data) explain perfectly both, LHAASO and IceCube observations

- **Precise predictions (not only fits to data!) of unresolved sources** and **extended sources** are needed to improve our models

Inhomogeneous diffusion model (δ → δ(R))

Many reasons to believe that the turbulence is progressively different towards the Galactic centre:

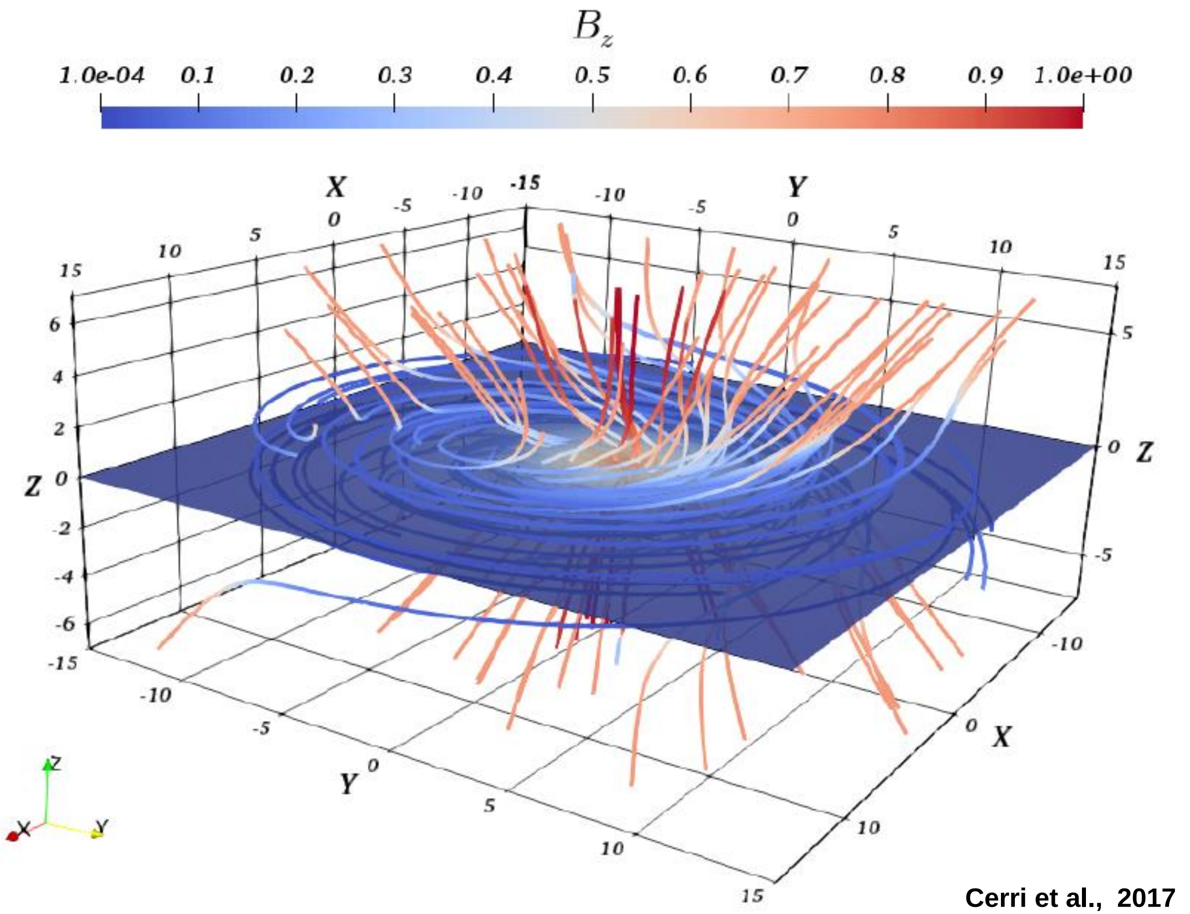
- Magnetic field intensity (and direction)

- Gas distribution (contributing to damping of MHD waves)

- Distribution of sources

- Anisotropy of turbulence cascade

- Non-steady particle distribution?



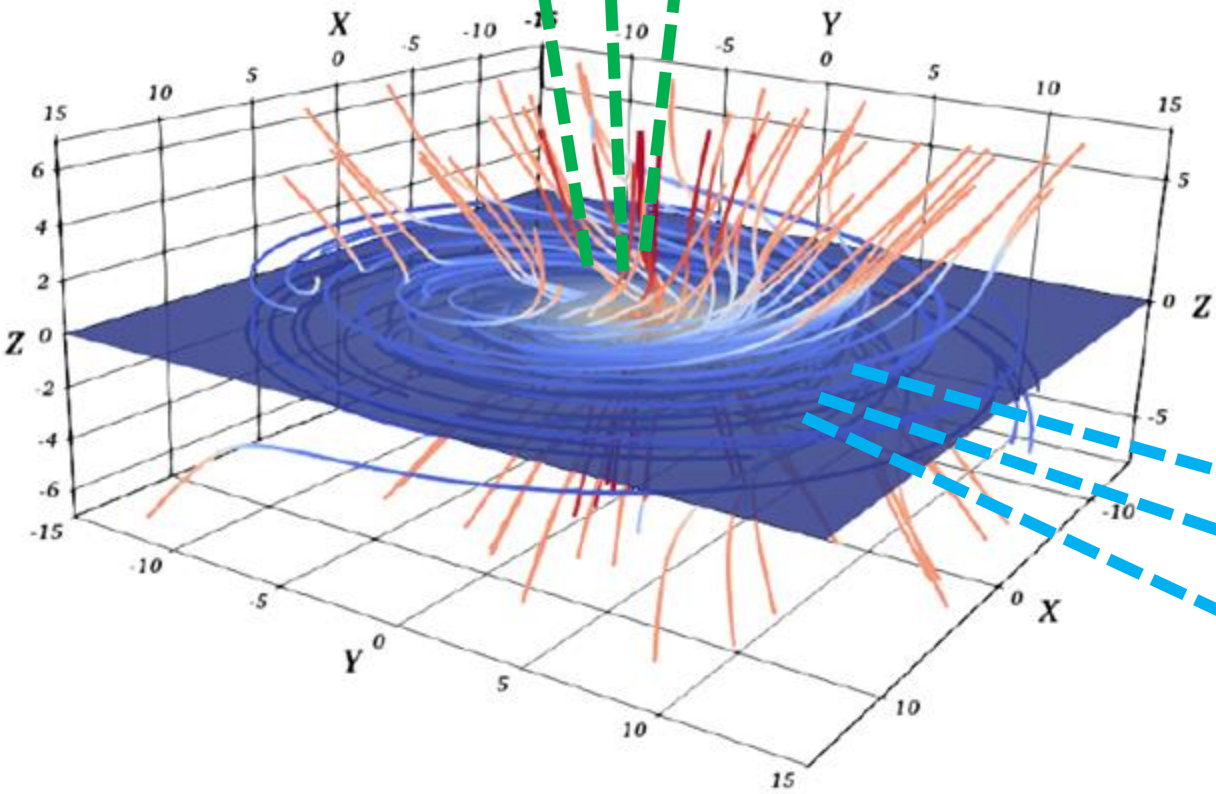
Cerri et al., 2017

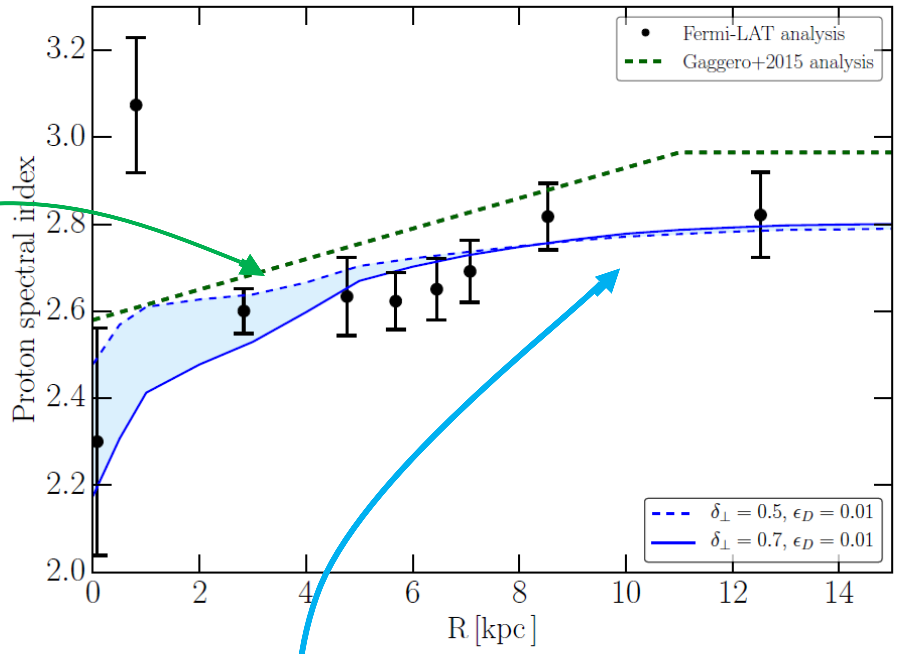
Non-uniform diffusion:

Anisotropic diffusion (Respect to the magnetic field)

Mainly parallel diffusion

$$D_{\|} = D_{0\|}\left(\frac{p_{\rm GeV}}{Z}\right)^{\delta_{\|}}$$





Cerri et al JCAP10(2017)019

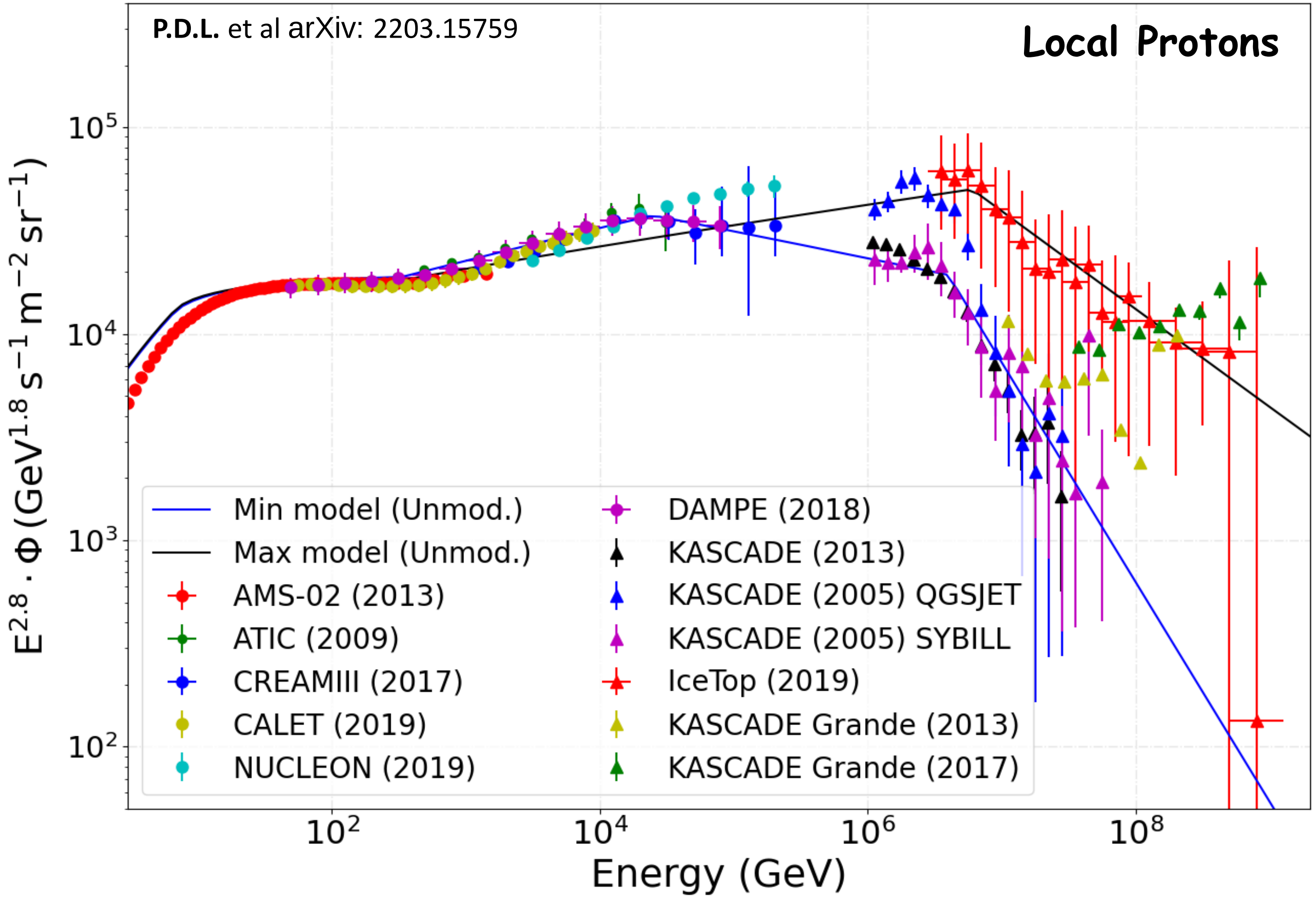
Light version of *DRAGON* (**fully anisotropic**):
https://github.com/sscerr/DRAGONCELLO

Mainly perpendicular diffusion

$$D_{\perp} = D_{0\perp}\left(\frac{p_{\rm GeV}}{Z}\right)^{\delta_{\perp}}$$

Inhomogeneous diffusion model (δ → δ(R))

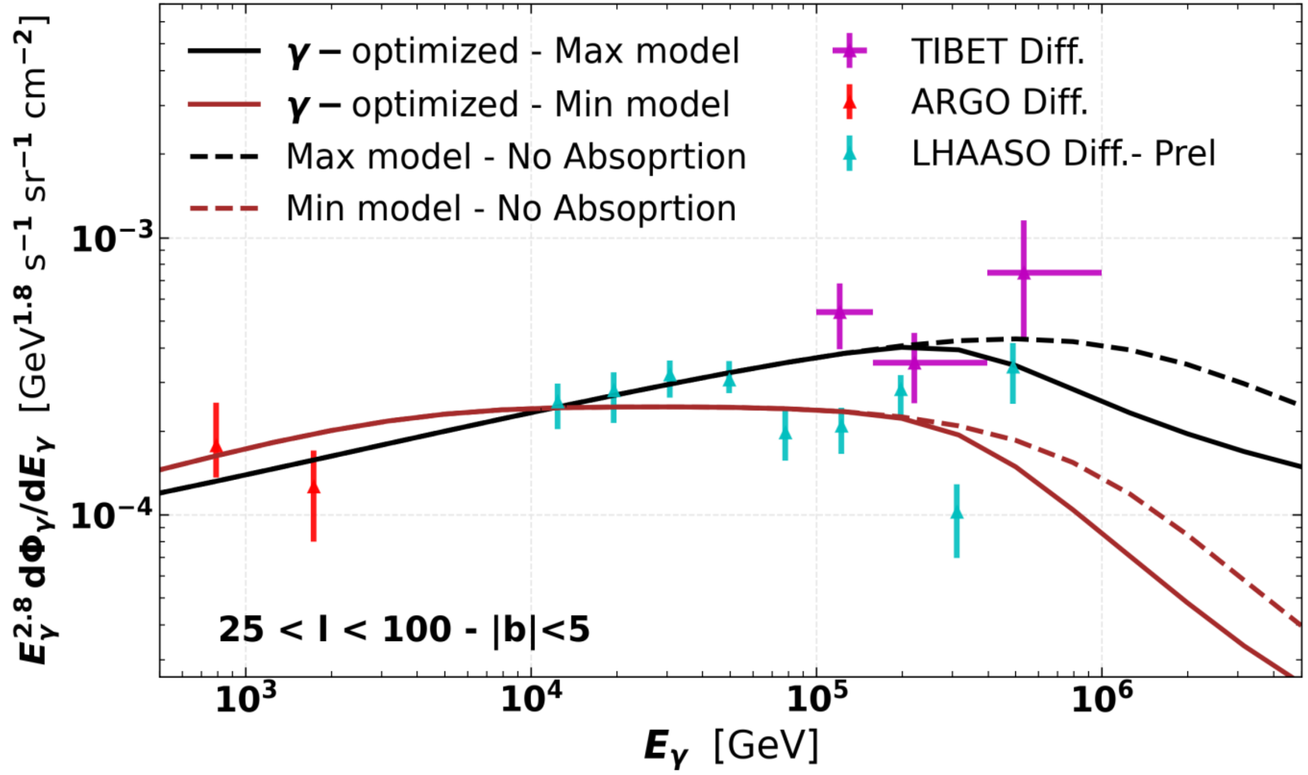
Different interpretations of local data… Local sources vs global features



MAX and MIN models allow us to have an idea of the uncertainties on the local CR spectra of protons and helium at different energies, but they do not represent the full uncertainty involved !!

Inhomogeneous diffusion model

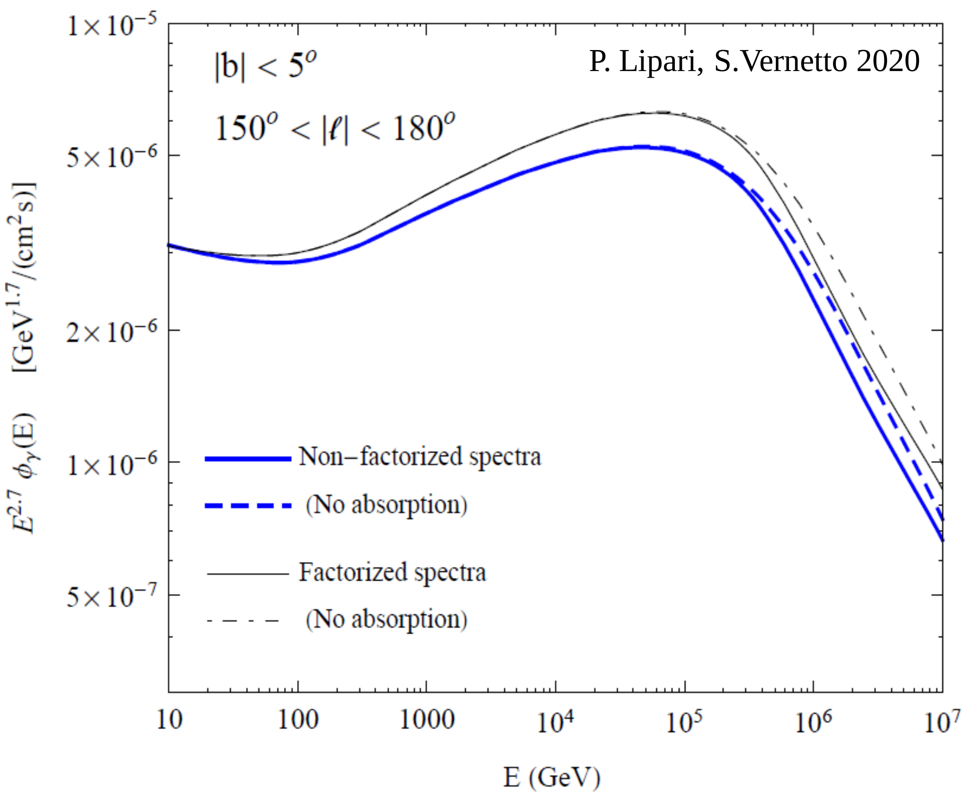
The diffuse emission meets TeV data

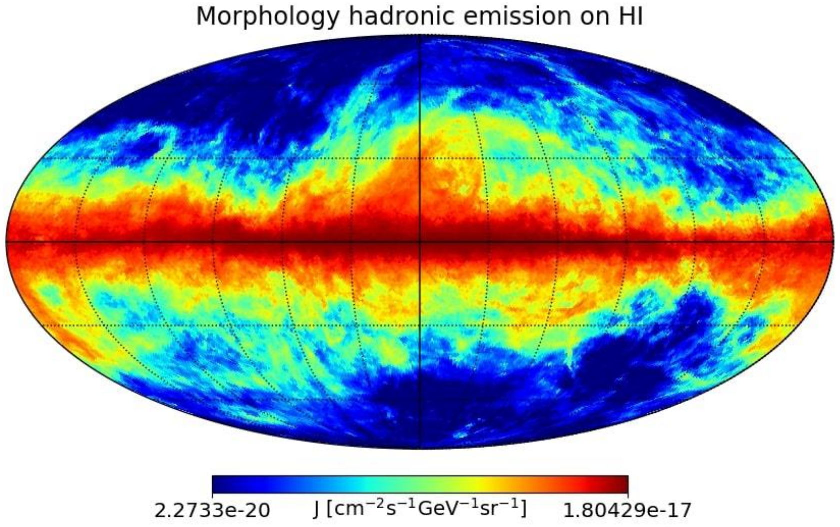


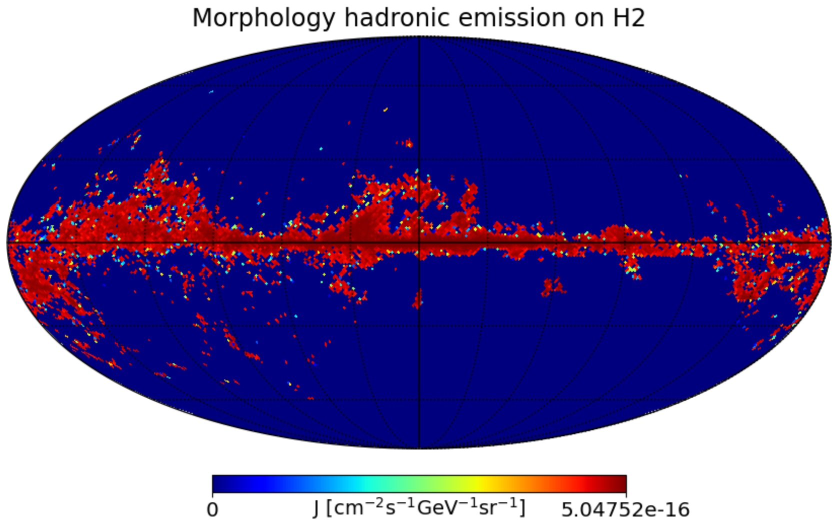
Absorption of very high energy gamma rays becomes important

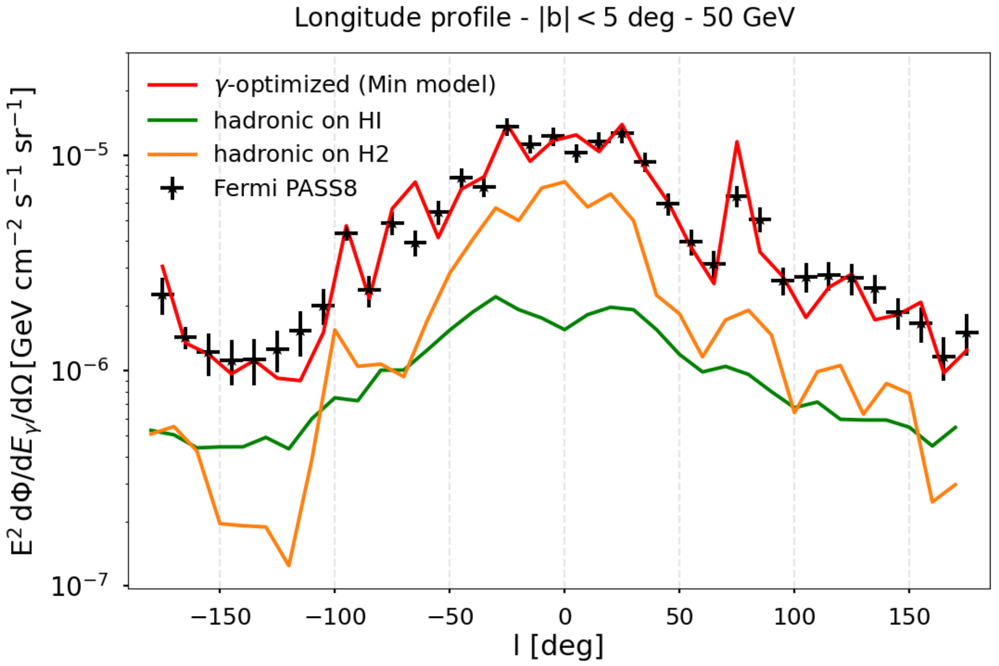
$$\gamma + \gamma_{ISRF} \rightarrow e^+ e^-$$

Absorption from the CMB dominates over the other ISRFs (IR from dust, Optic and UV from stars and extra-galactic background light)



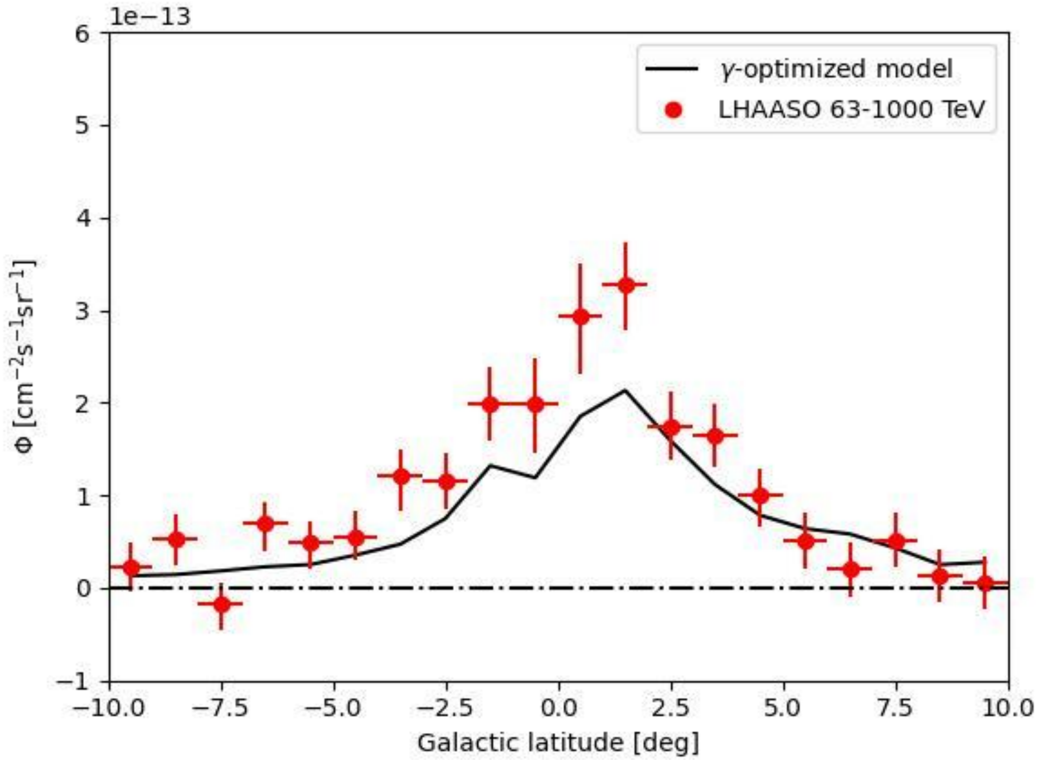

Morphology hadronic emission on HI
2.2733e-20
J [cm^{-2}s^{-1}GeV^{-1}sr^{-1}]
1.80429e-17

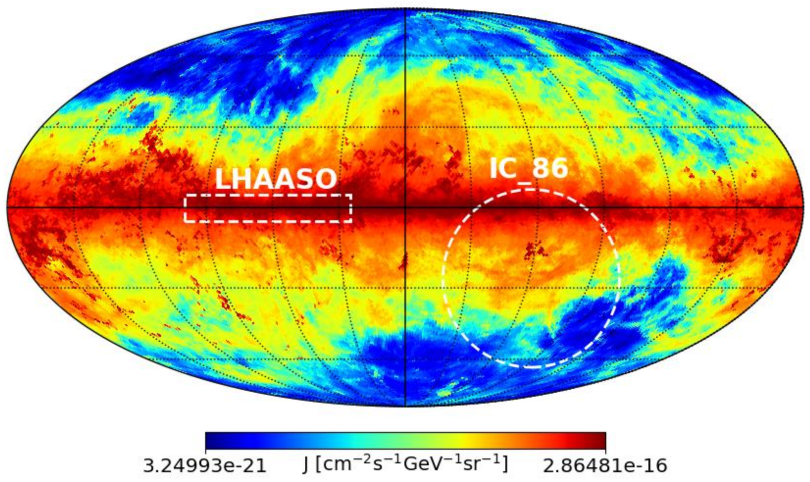

Morphology hadronic emission on H2
0
J [cm^{-2}s^{-1}GeV^{-1}sr^{-1}]
5.04752e-16

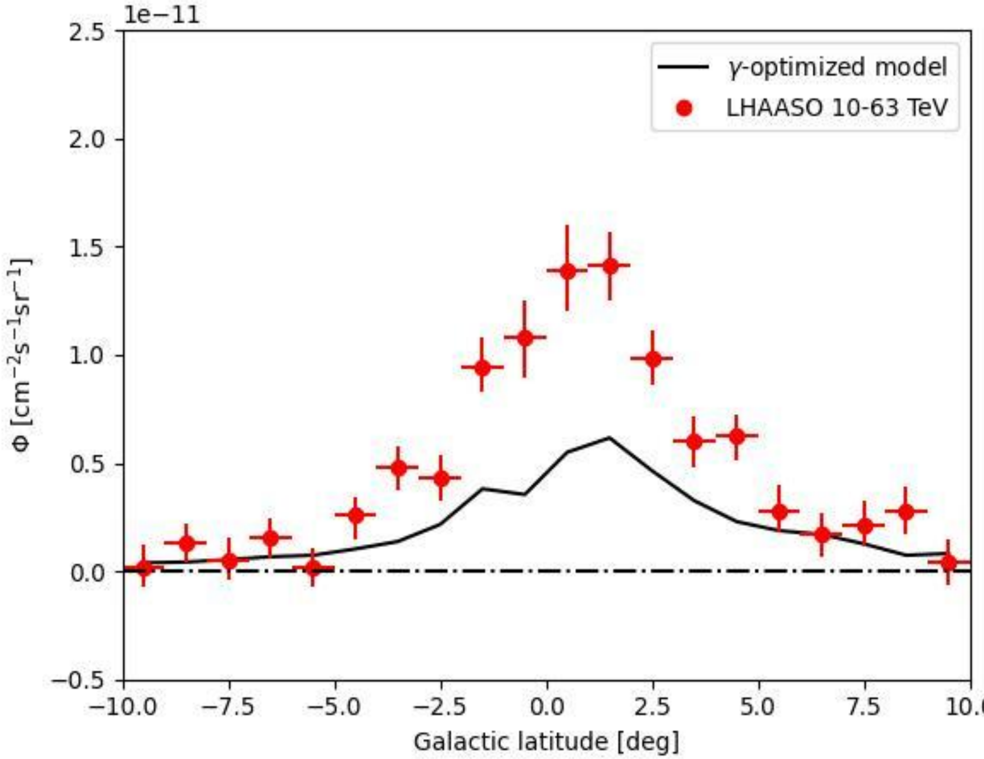

Longitude profile - |b| < 5 deg - 50 GeV
γ-optimized (Min model)
hadronic on HI
hadronic on H2
Fermi PASS8
$E^2\, d\Phi/dE_\gamma/d\Omega$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-5}
10^{-6}
10^{-7}
−150
−100
−50
0
50
100
150
l [deg]

Inhomogeneous diffusion model

Latitude profiles vs LHAASO



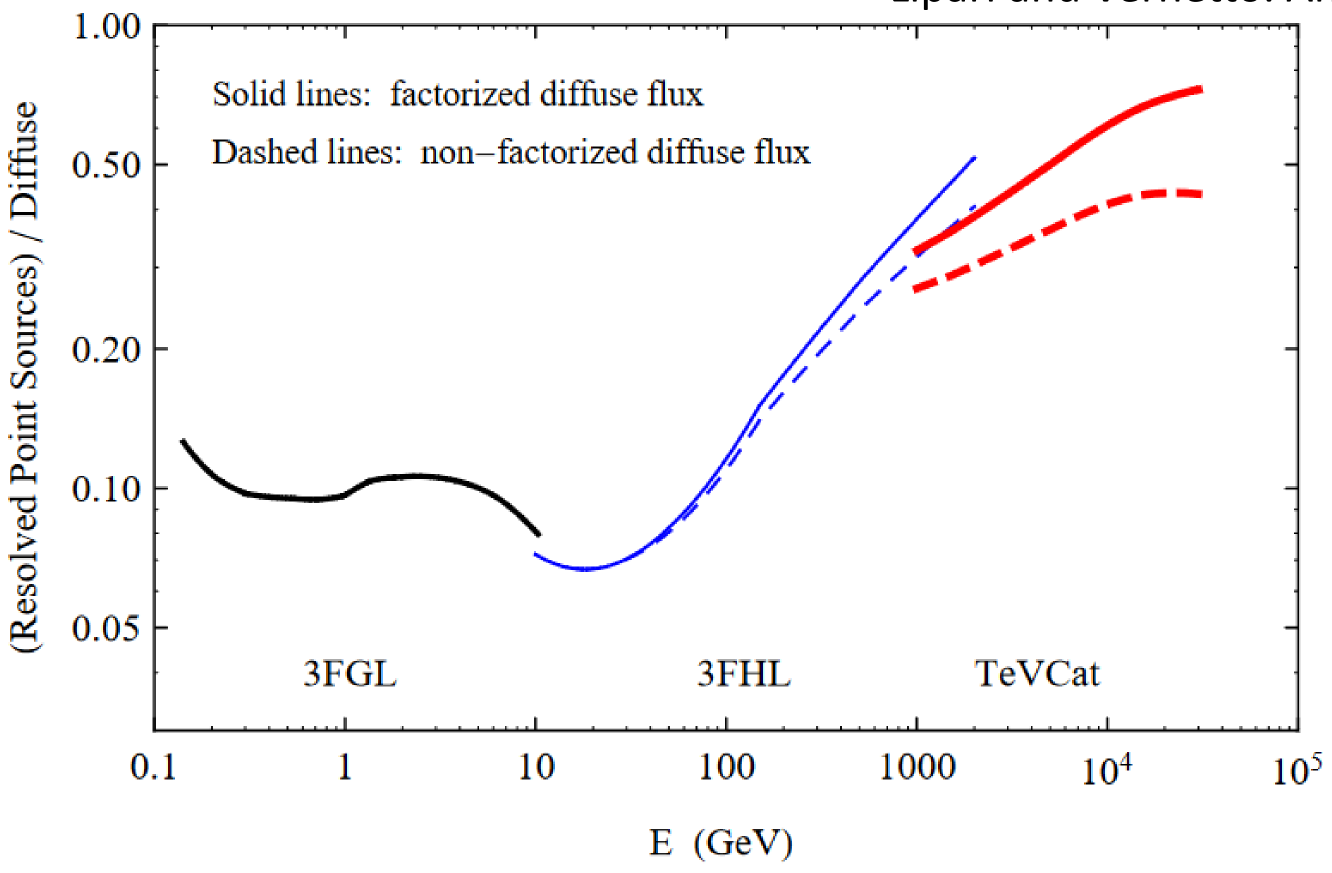




The spatially-dependent (**γ-optimized**) models, tuned on Fermi-LAT data are also **favoured by the very high energy observations of** LHAASO

Should the galactic neutrino emission be dominated by sources?

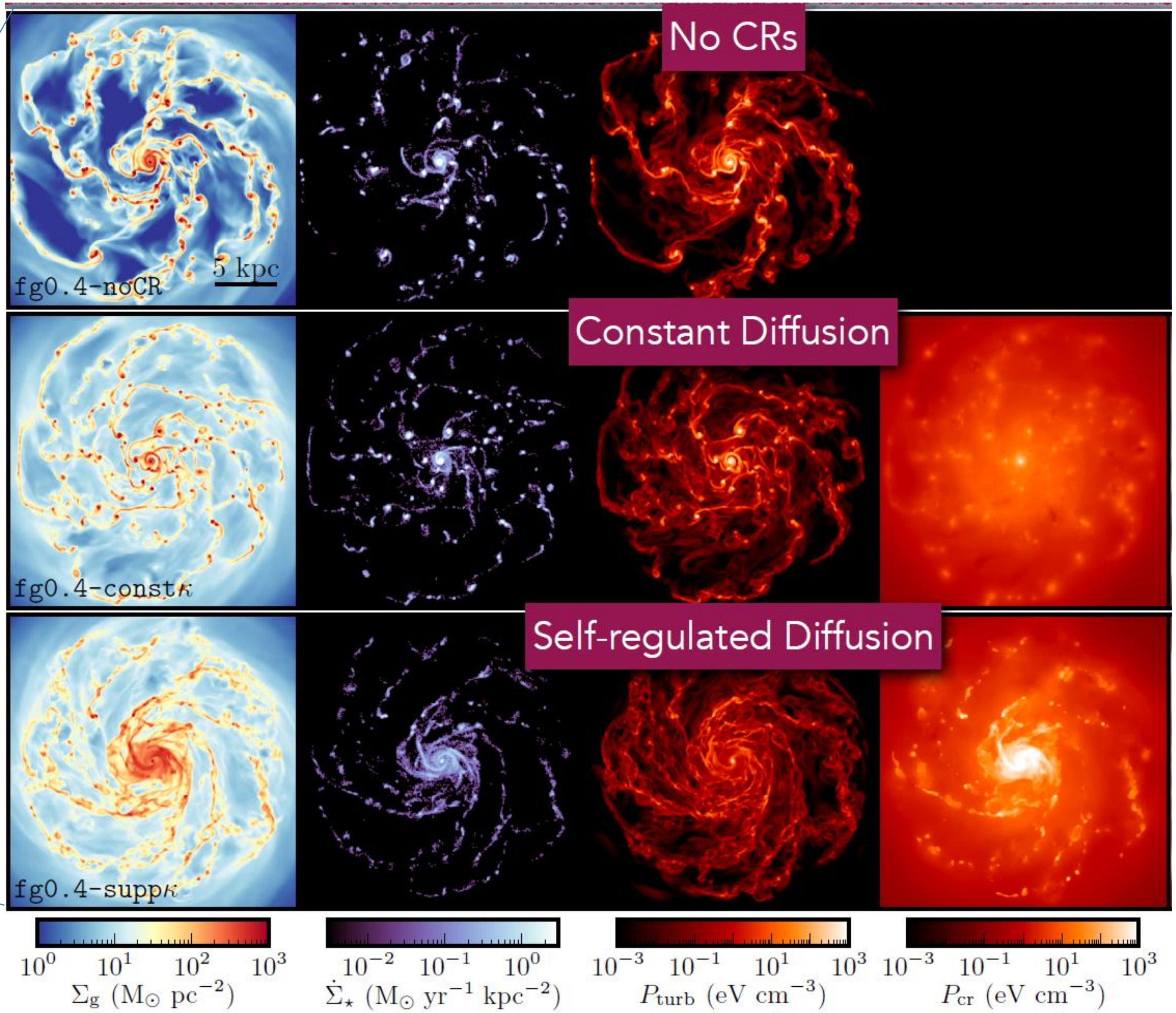
Lipari and Vernetto. ArXiv:1804.10116



A few implications …

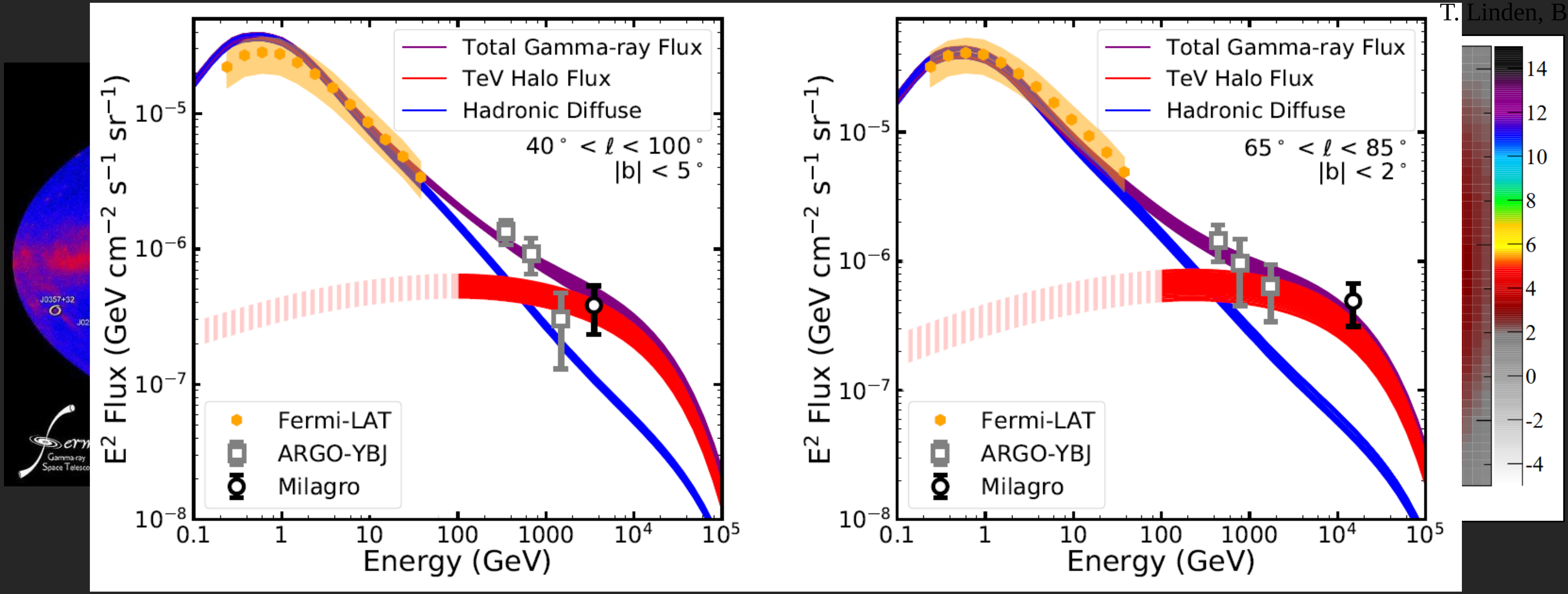
Semenov, Krtavsov, Caprioli 2021

- Injection mechanism and acceleration of CRs (PeVatrons?)
- Environments of PWNe and SNRs as well as the mechanism of turbulence generation and propagation, …
- Astrophysical plasmas, magnetic fields, ionization rates in MCs, …
- Galaxy formation
- GeV excess?



TeV halos and inhibited diffusion of leptons around Pulsar Wind Nebulae (PWNe)

Probably similar phenomena is present around every source injecting CRs …



T. Linden, B. Buckman 2017