Tenth International Fermi Symposium

9th-15th October 2022

The Galactic diffuse gamma-ray emission meets the PeV frontier

Pedro de la Torre Luque*

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

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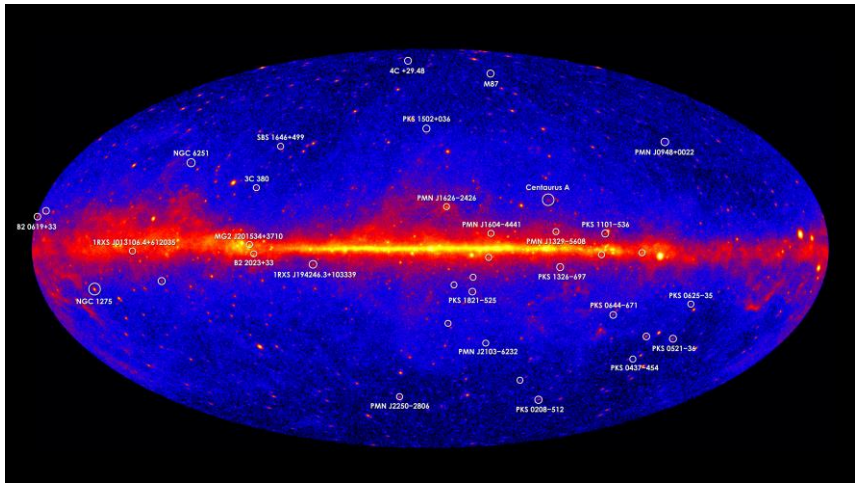
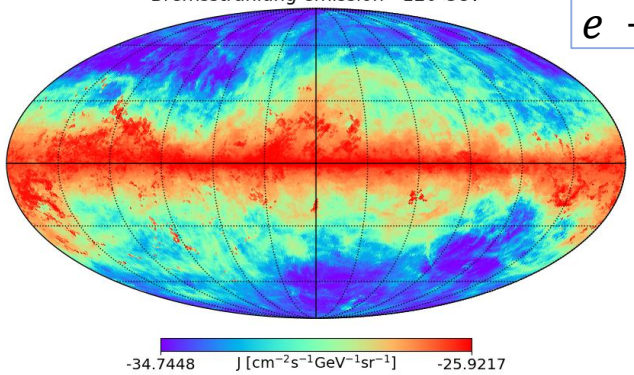
The Gamma-ray diffuse sky

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



Bremsstrahlung emission - 120 GeV



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

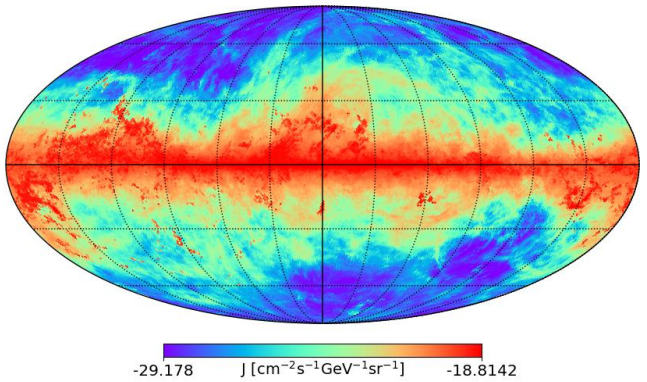
$p + p \rightarrow \pi^0$
$\pi^0 \rightarrow 2\,\gamma$

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

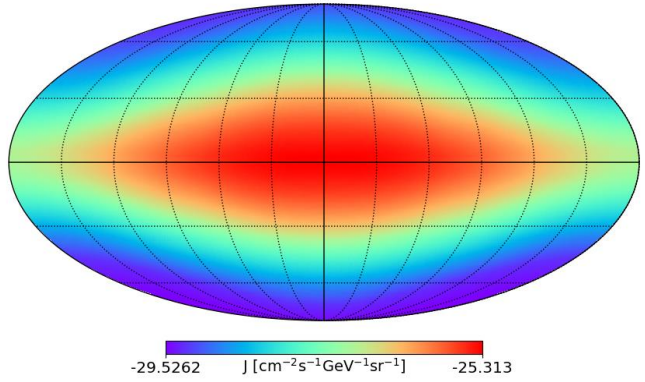
Hadronic (and **Bremss.**) emission follows the **ISM gas distribution**

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

Hadronic emission - 120 GeV



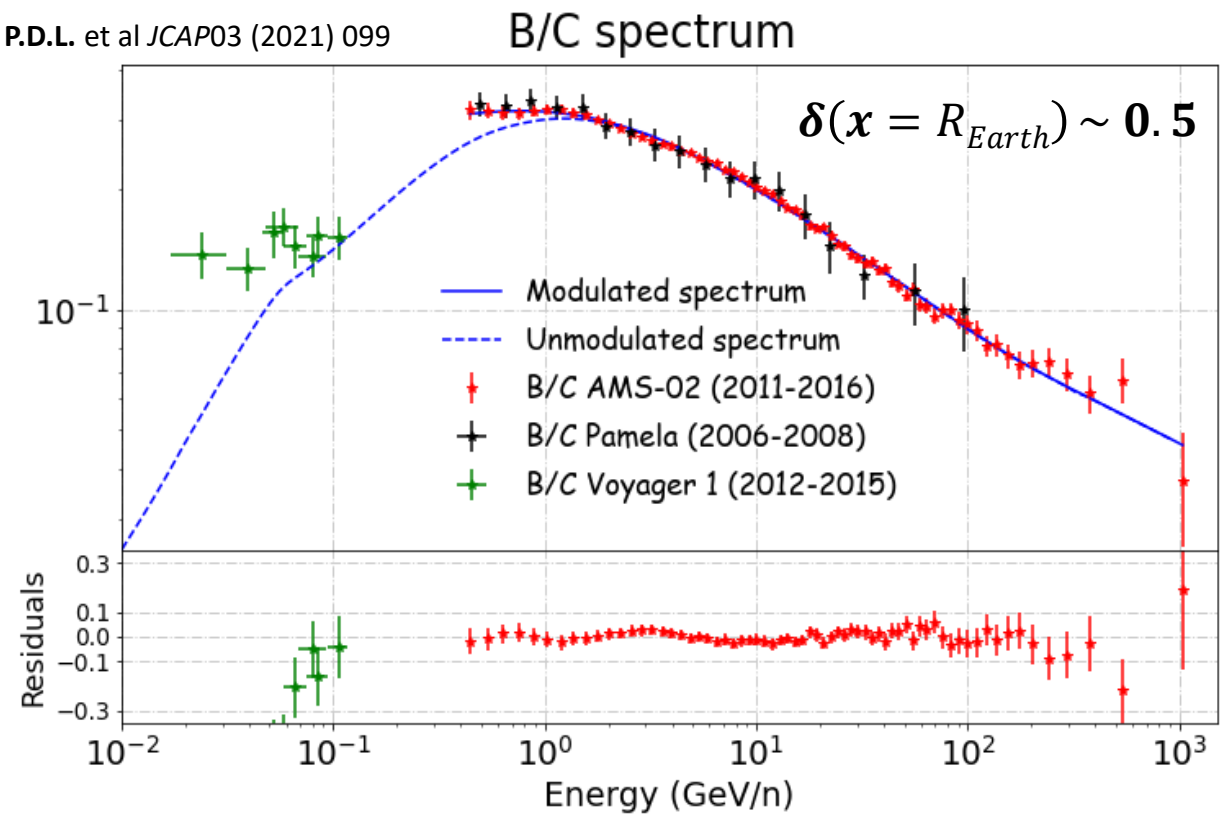
IC emission - 120 GeV

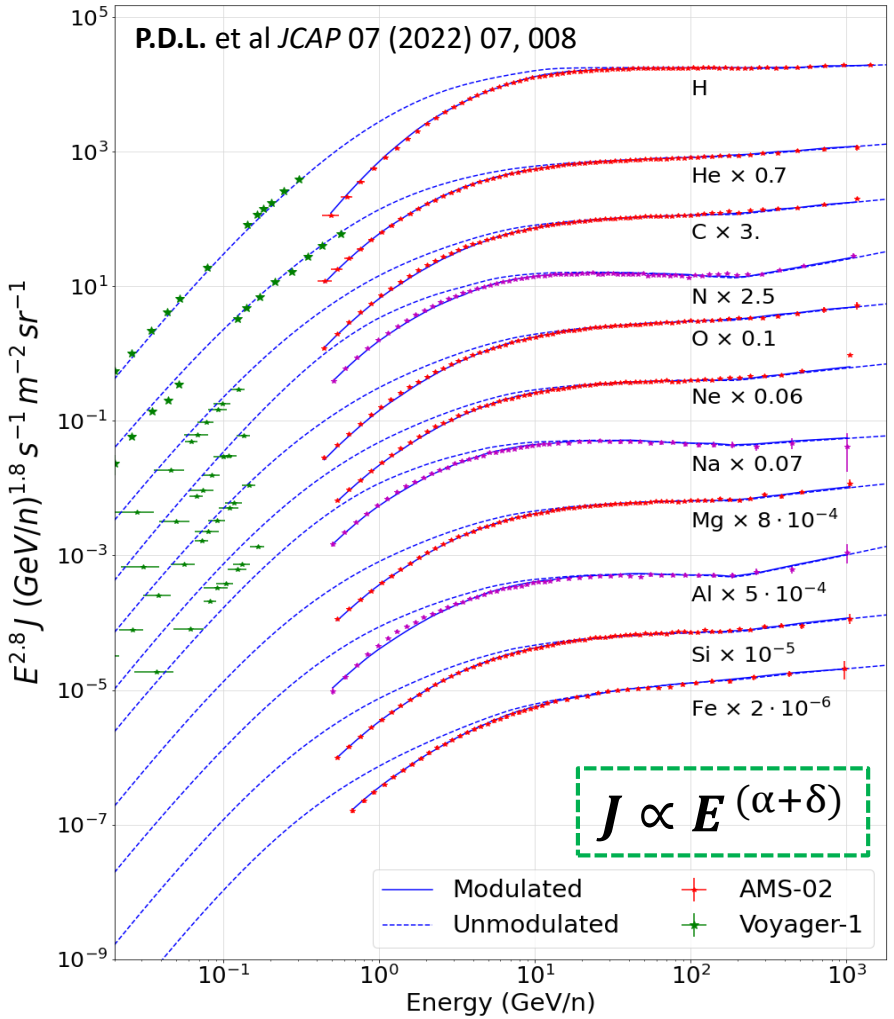


Galactic gamma-ray diffuse emission – Local cosmic rays

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

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



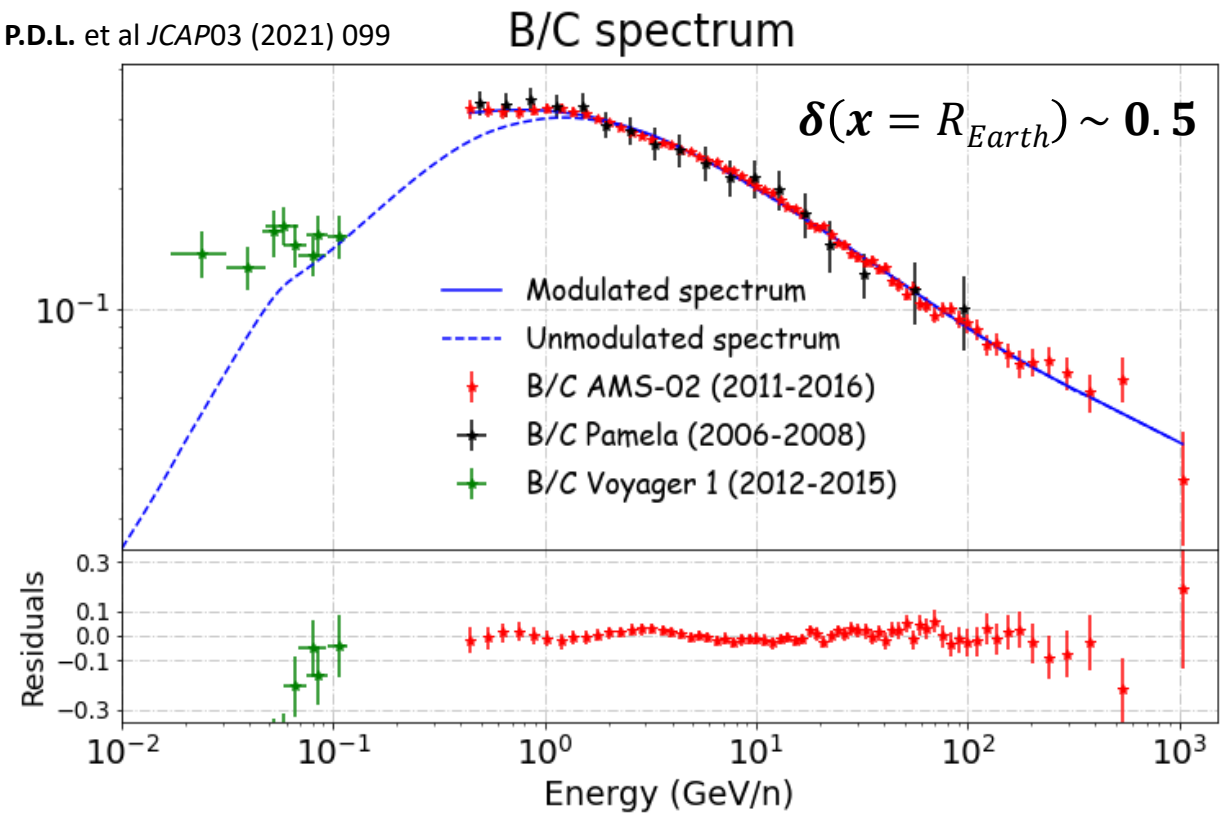


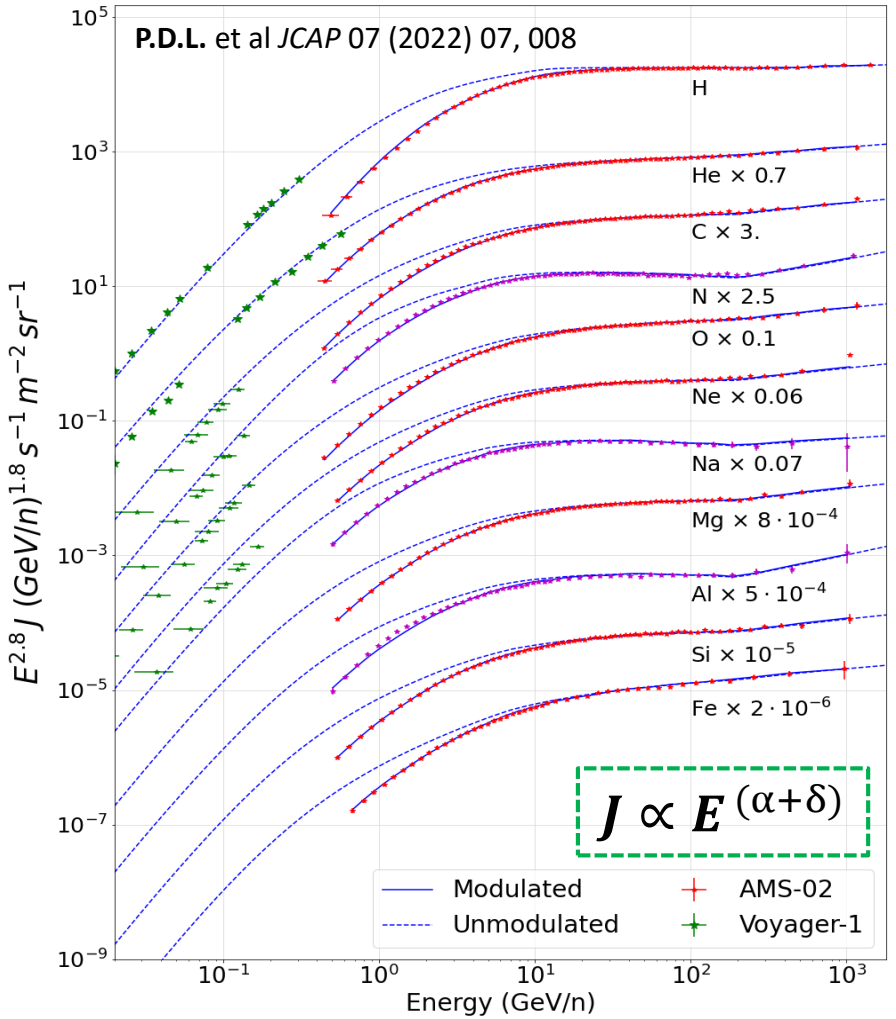
Galactic gamma-ray diffuse emission – Local cosmic rays

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

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

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





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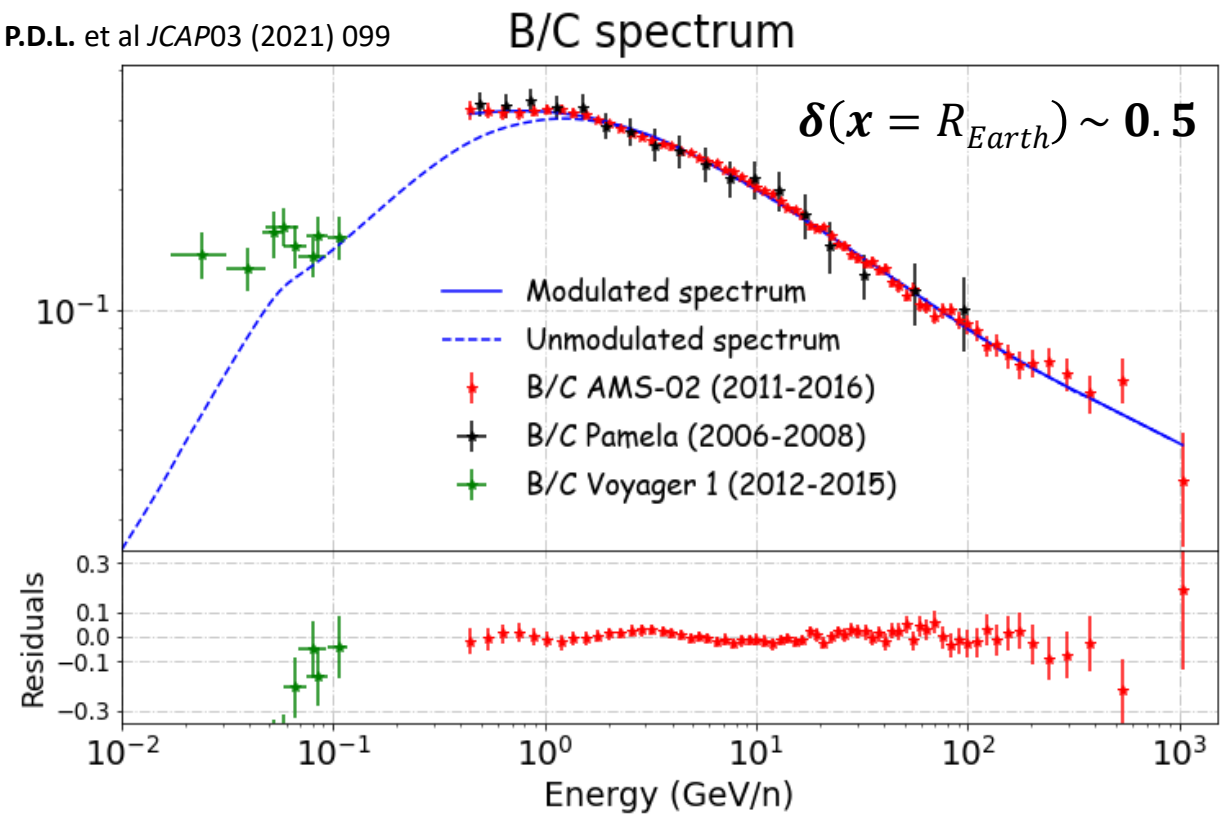
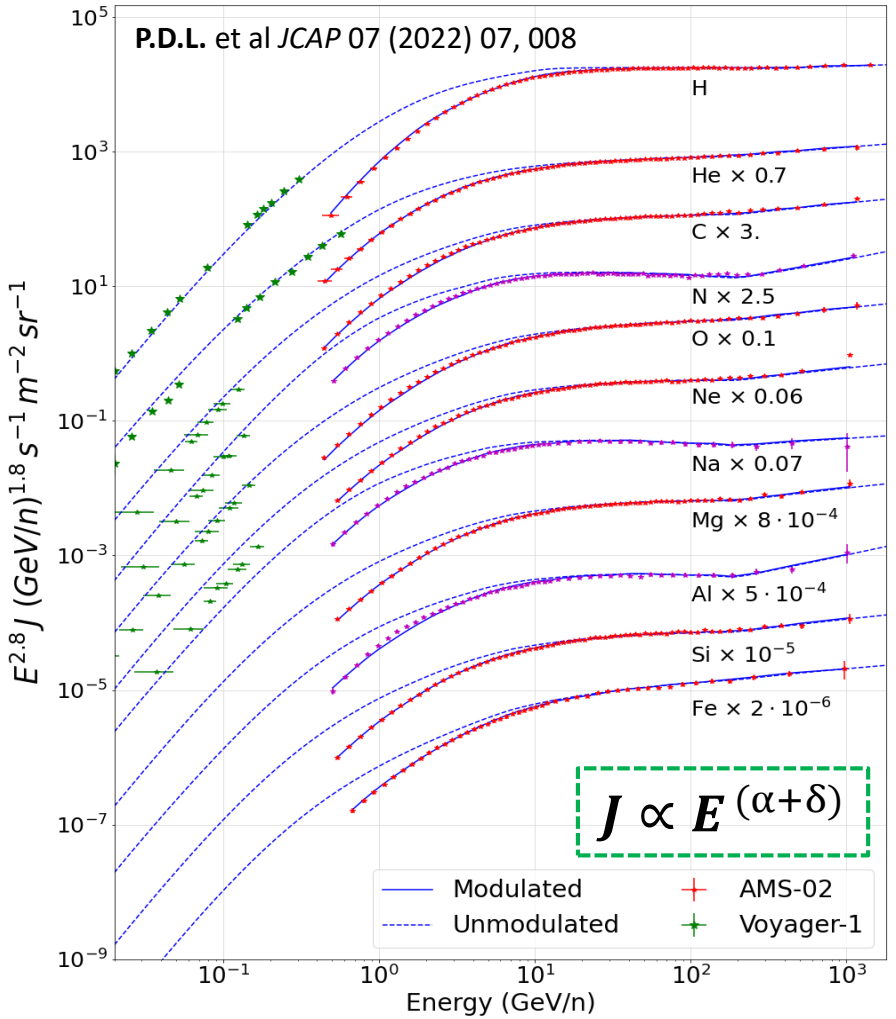




Galactic gamma-ray diffuse emission – Hardening towards the centre

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

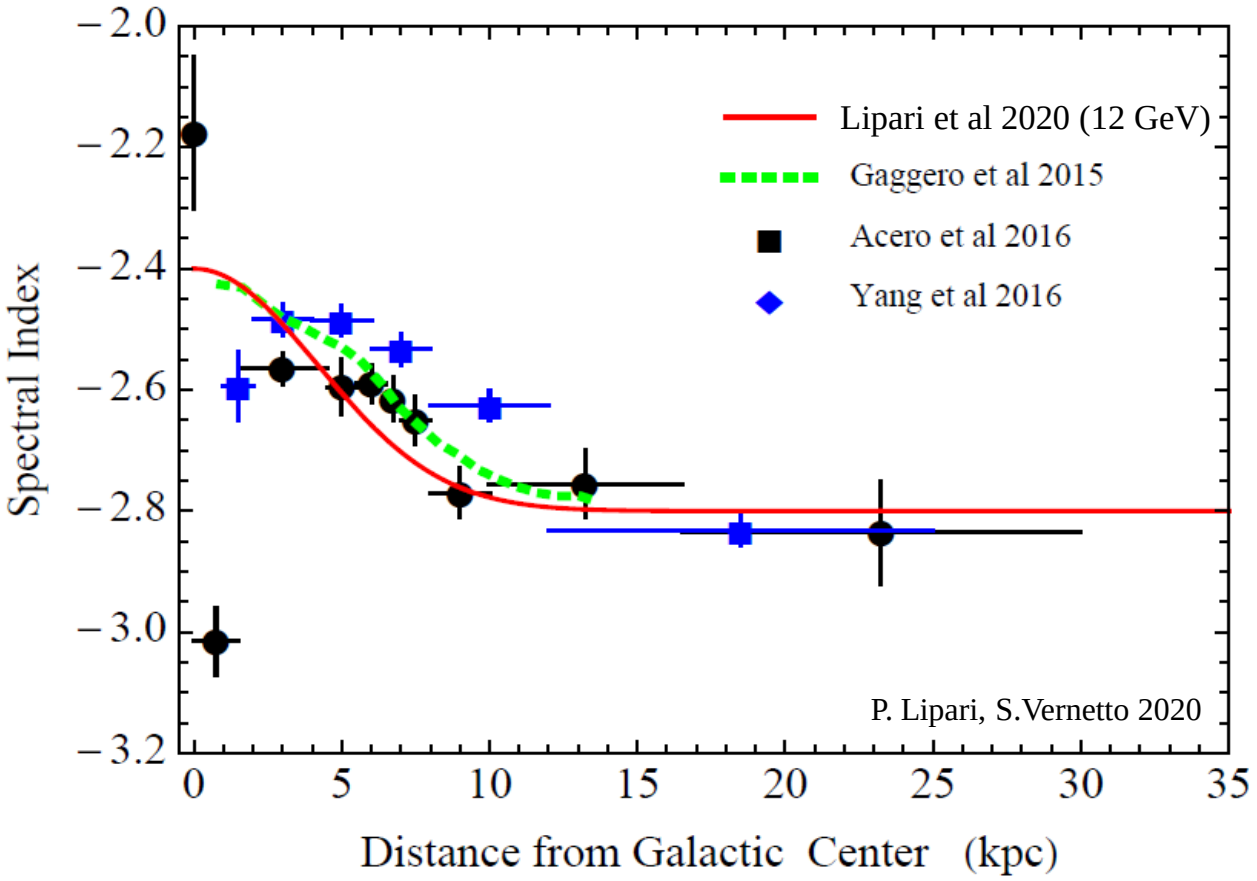
Diffuse gamma-ray spectrum essentially follows the spectrum of CR protons:

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

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

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

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

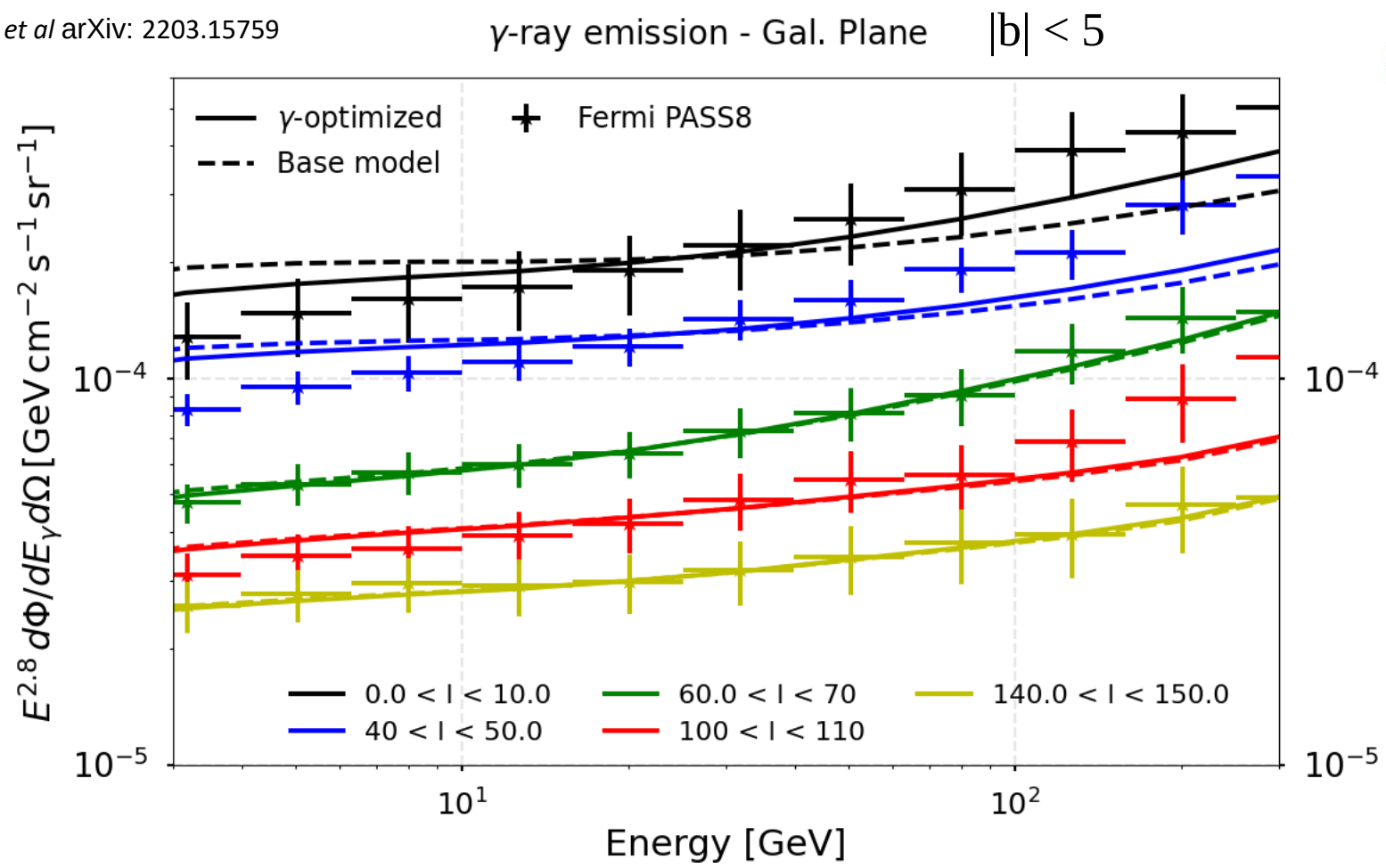


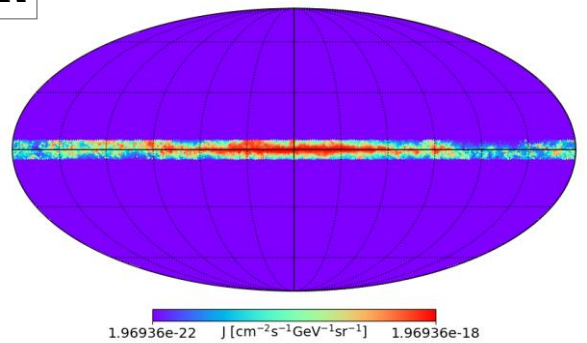
Inhomogeneous diffusion model

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

$$\delta(R) = \delta_0 + \delta_A R$$

P.D.L. *et al* arXiv: 2203.15759





DRAGON2

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

Base model: Constant ($\delta_A = 0$)
γ-optimized model: $\delta_A = 0.04$
$\delta_0 = 0.17$

Inhomogeneous diffusion model (δ → δ(R))

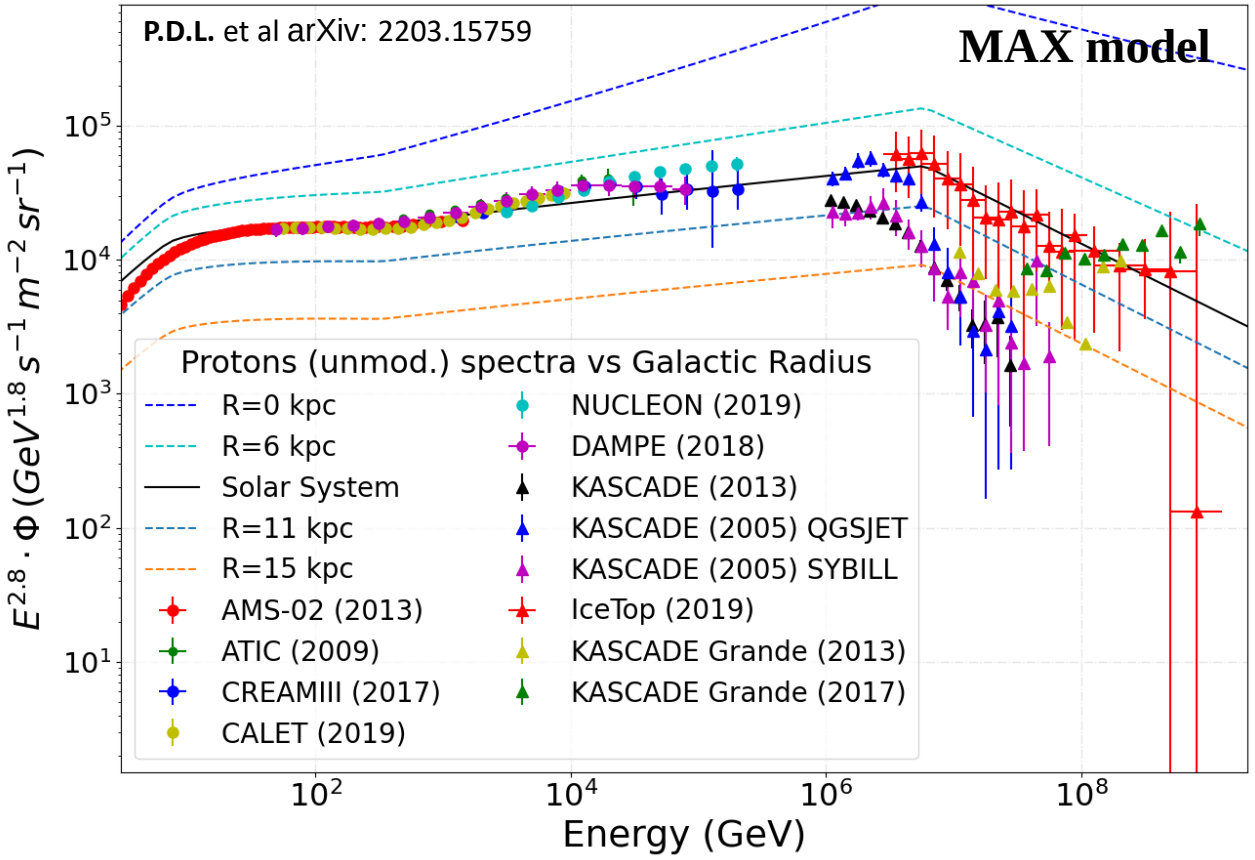
Two different interpretations (models) of the local proton and He data based on the "bump" at ~10 TeV found by DAMPE and the discrepancy from particle shower experiments.

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 (cut-off) at a few PeV

Different interpretations of local data
Local sources vs global features



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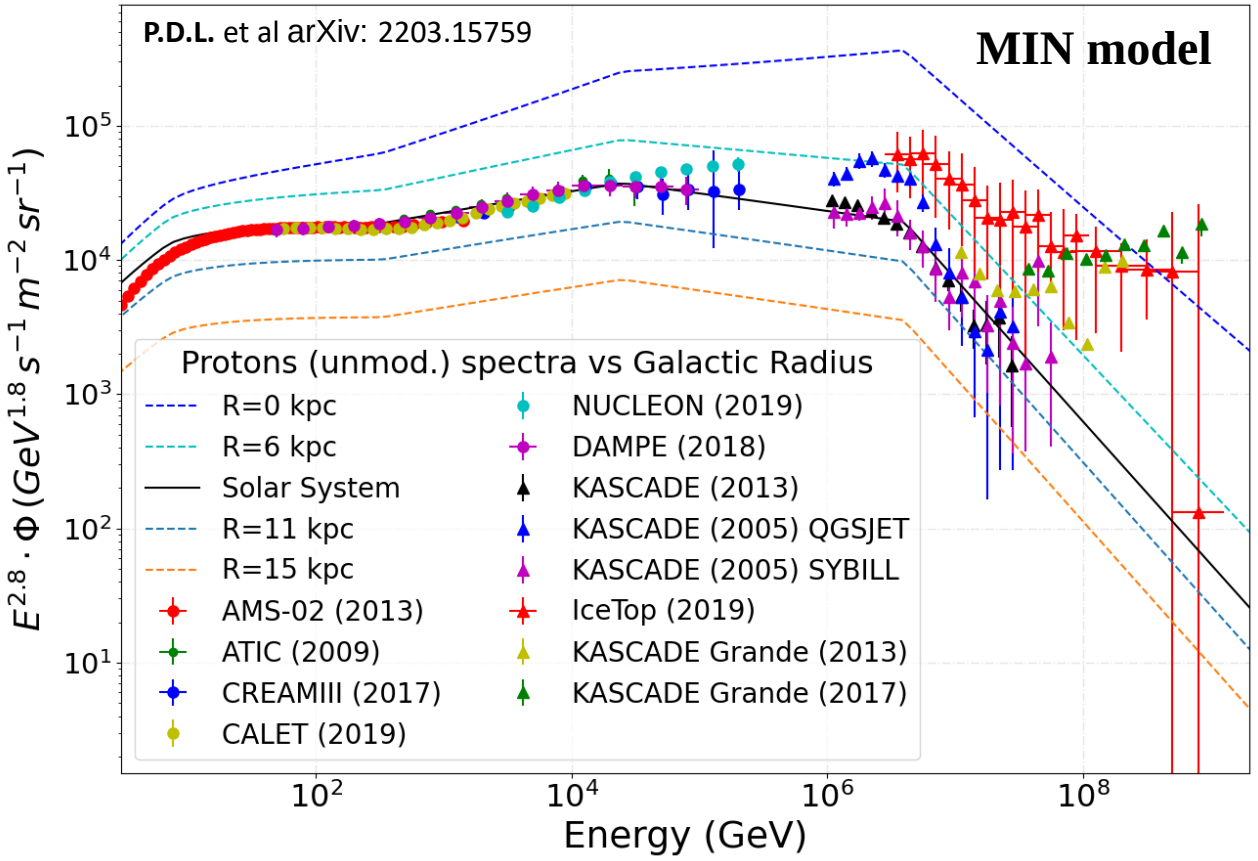
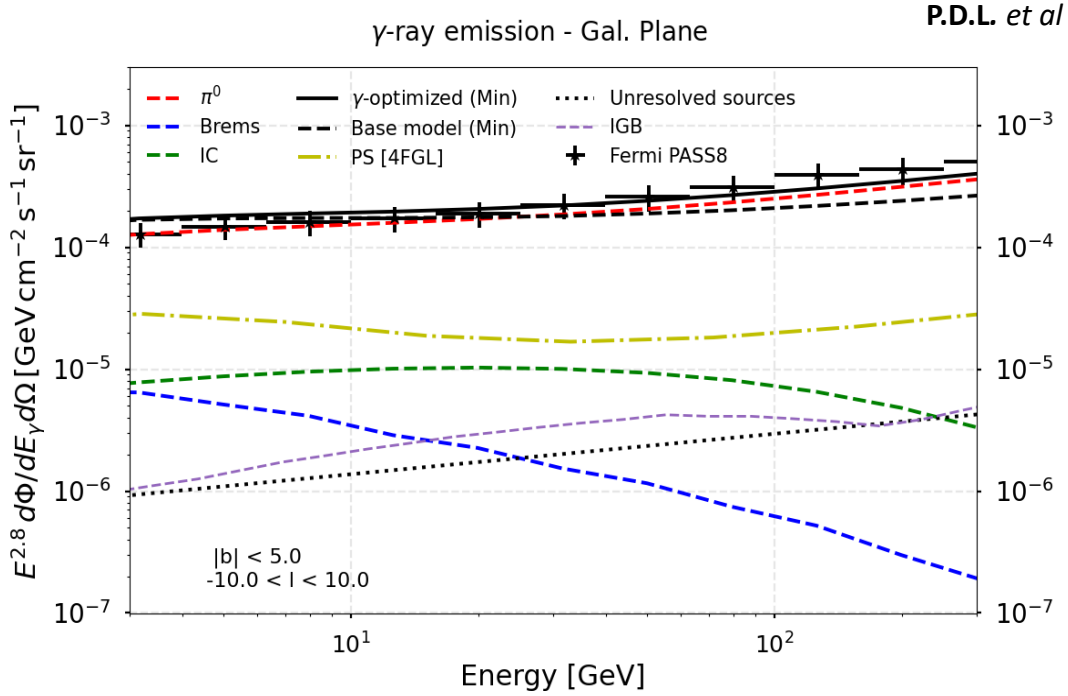
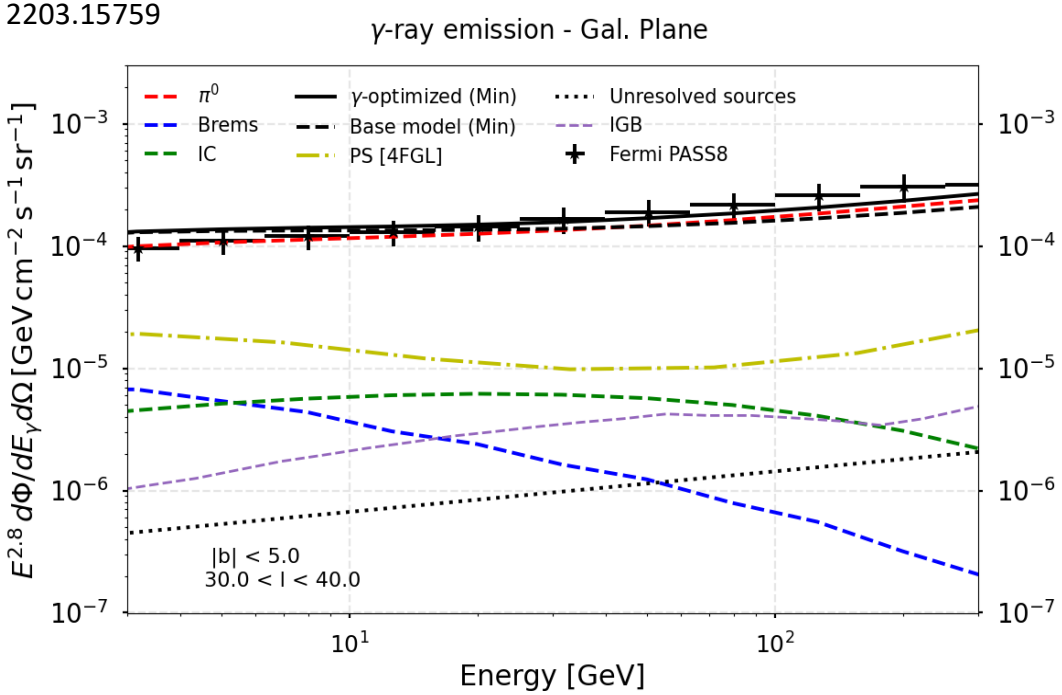


Inhomogeneous diffusion model – The different components

- 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* arXiv: 2203.15759



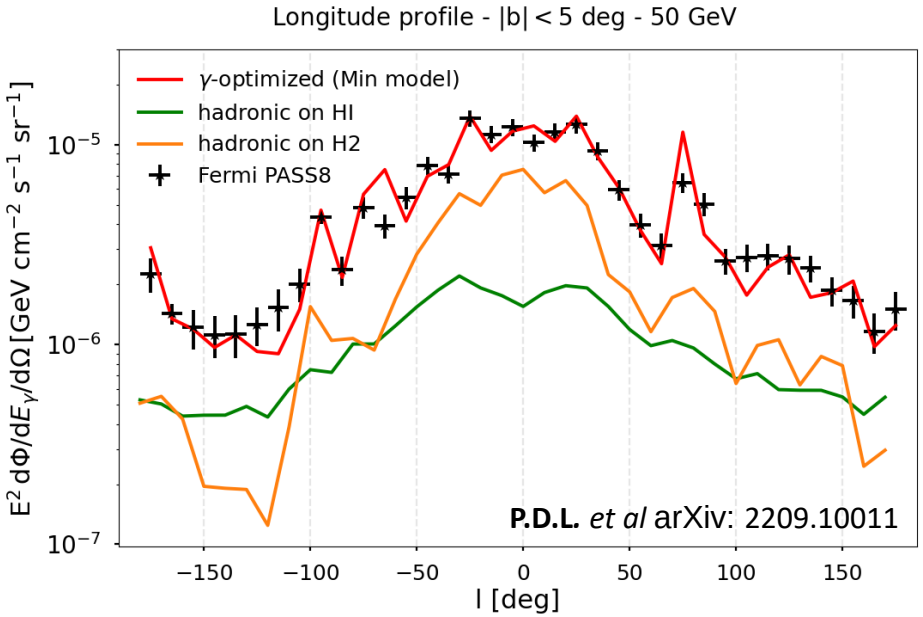


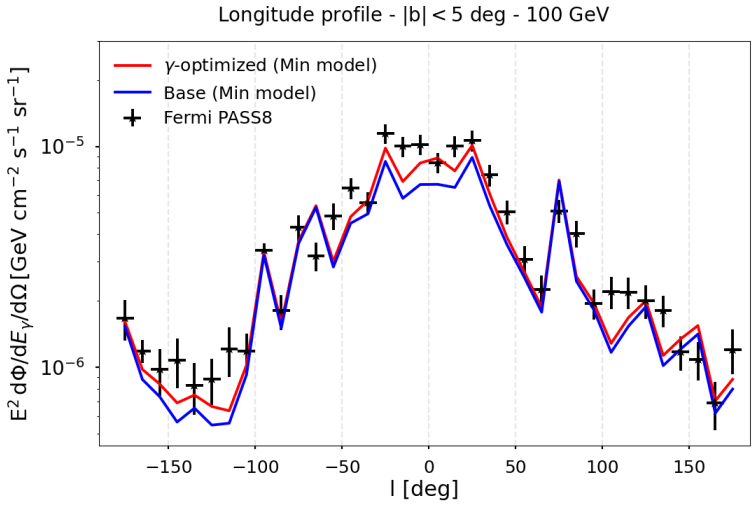
γ-optimized model vs Fermi

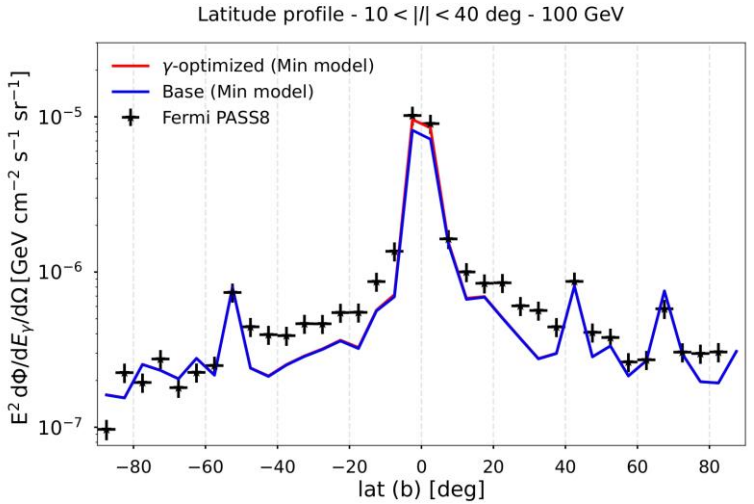
ISM gas distribution based on the ring gas model developed by Q. Remy

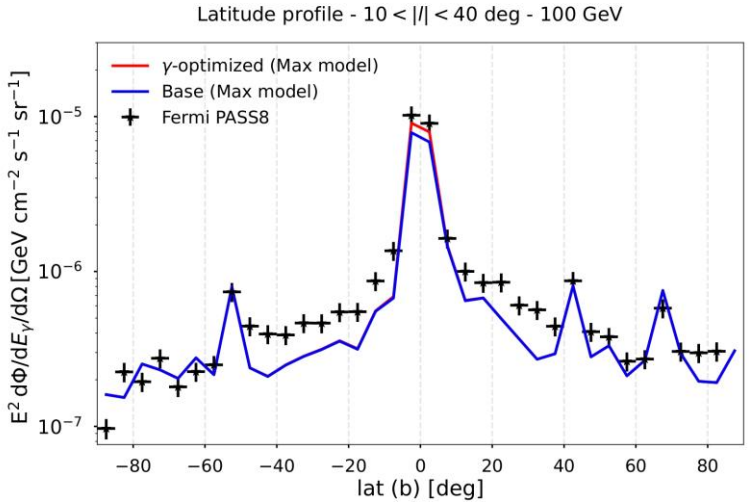
ISRF distribution (CMB + IR + Stellar) from Vernetto&Lipari Phys. Rev. D 94, 063009

XCO factor divided in rings to tune the normalization (**main caveat!!**)



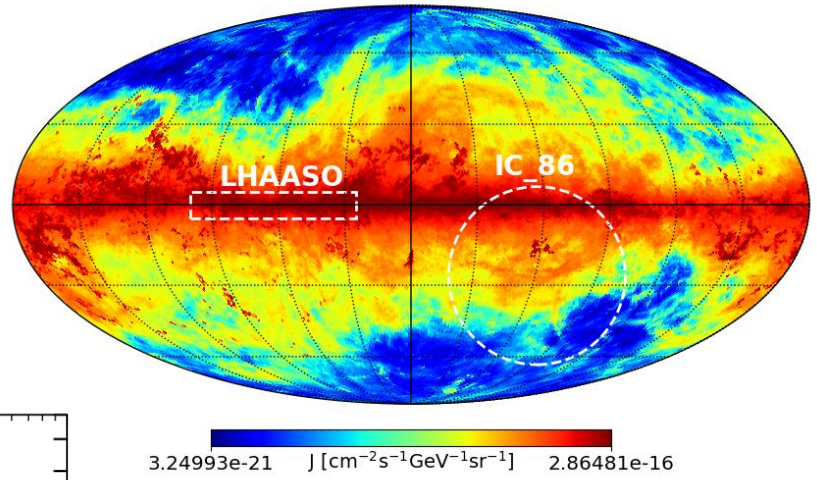




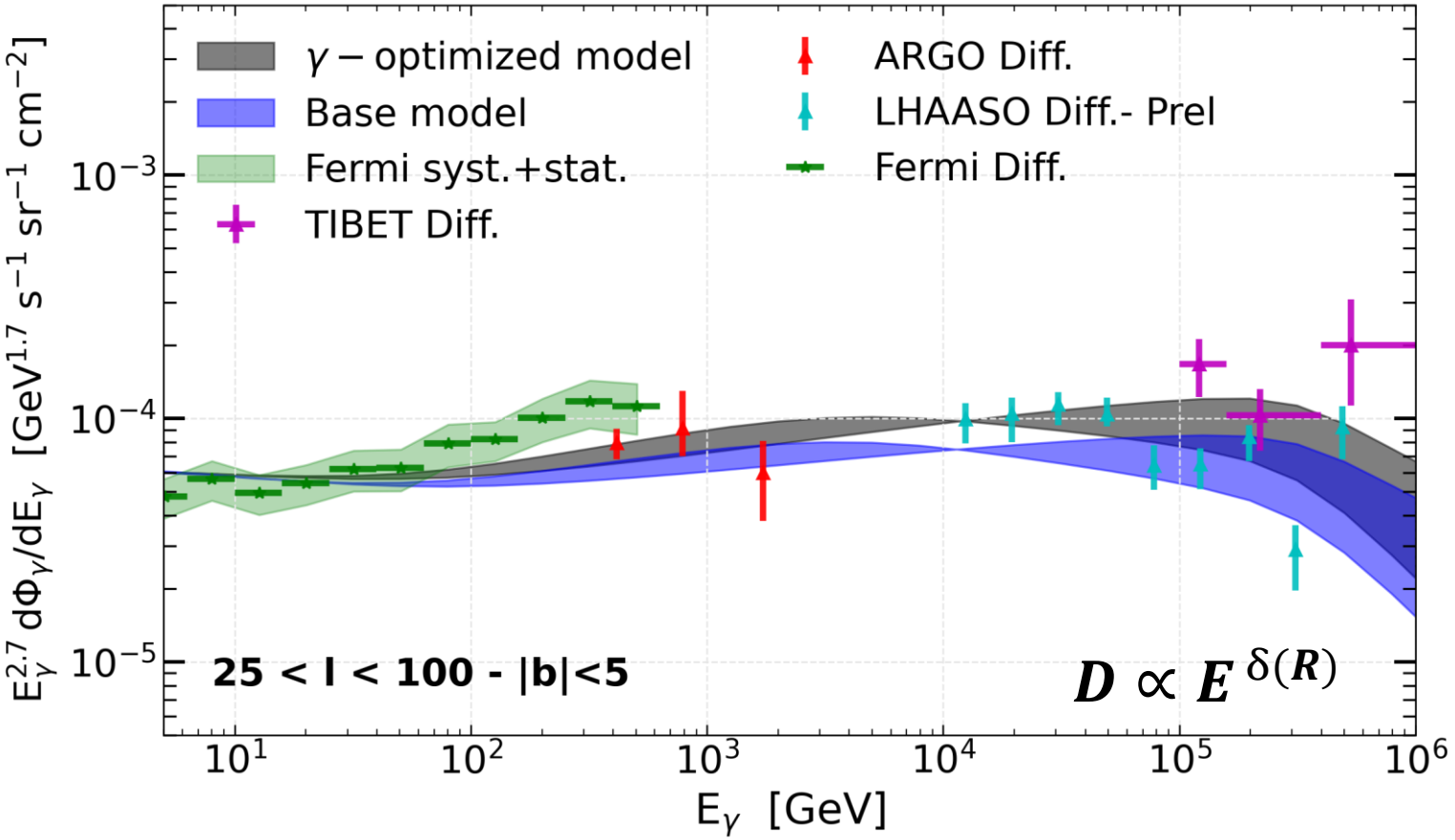


Inhomogeneous diffusion model

The diffuse emission meets TeV data



P.D.L. *et al* arXiv: 2203.15759

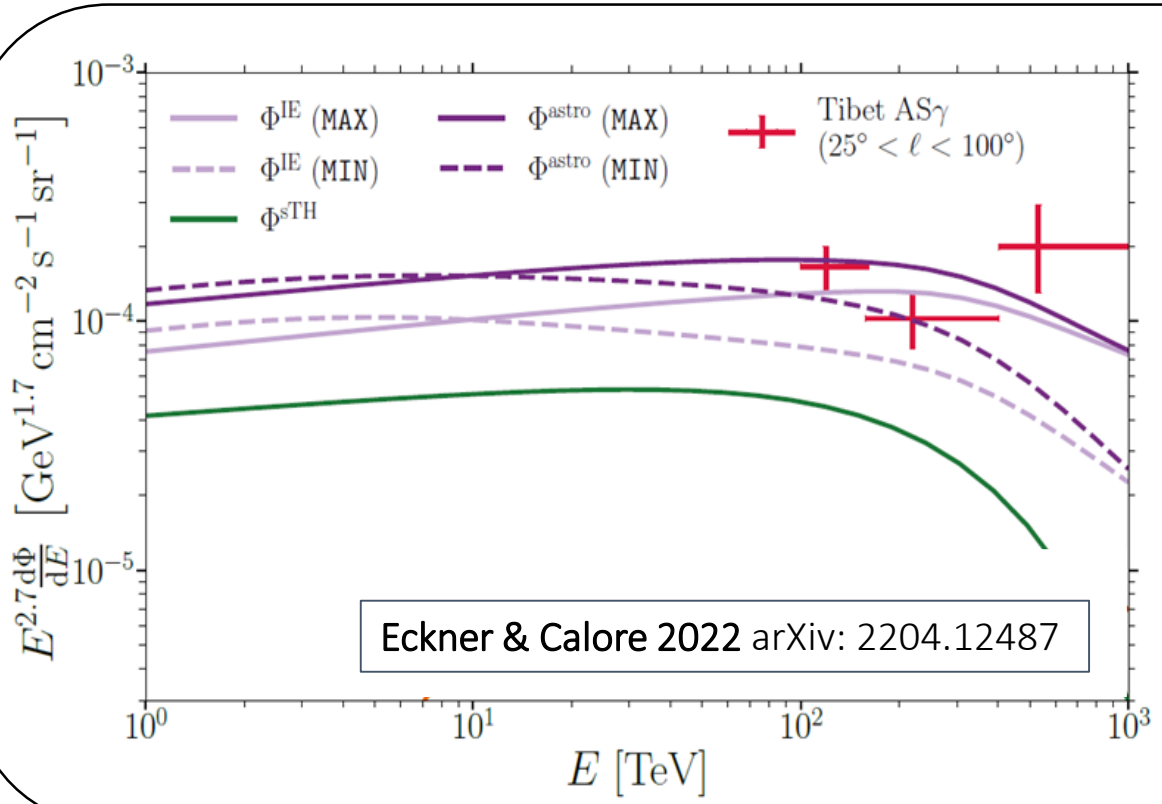


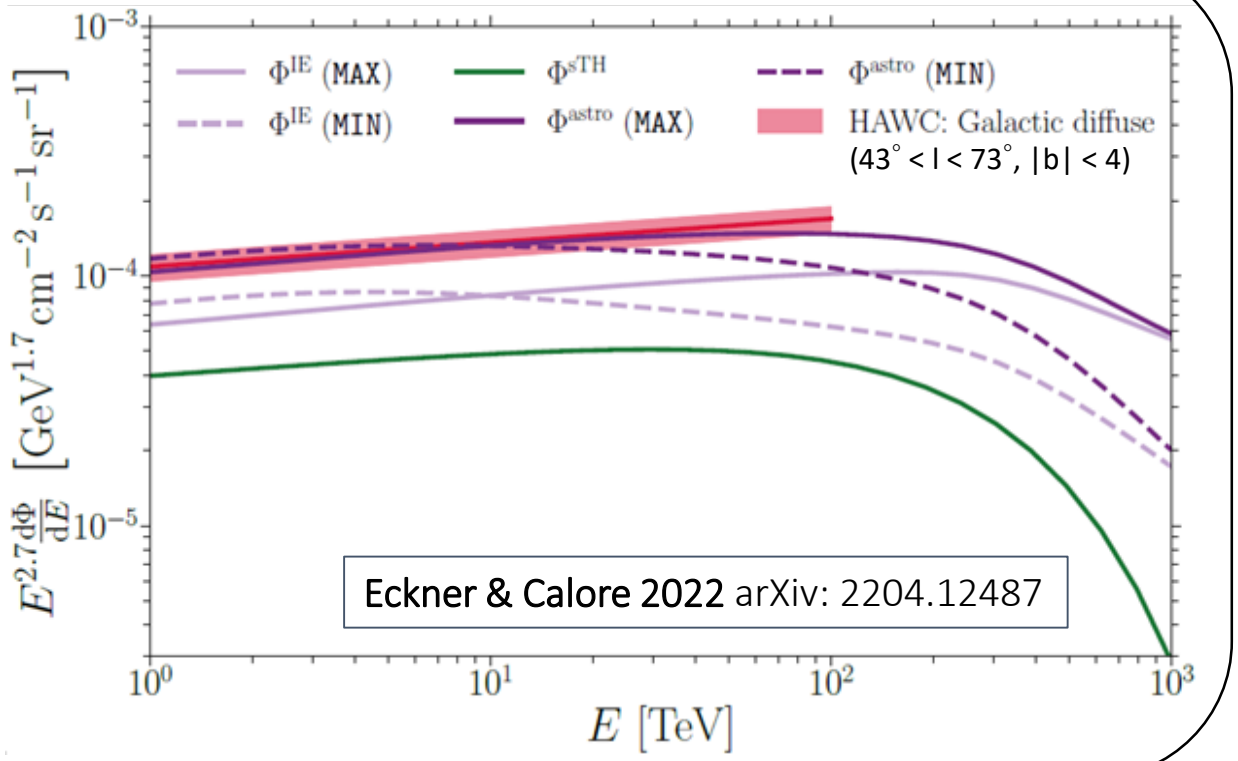
The spatially-dependent (**γ-optimized**) models, tuned on Fermi-LAT data are also **favoured by very high energy detectors** like LHAASO

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

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

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

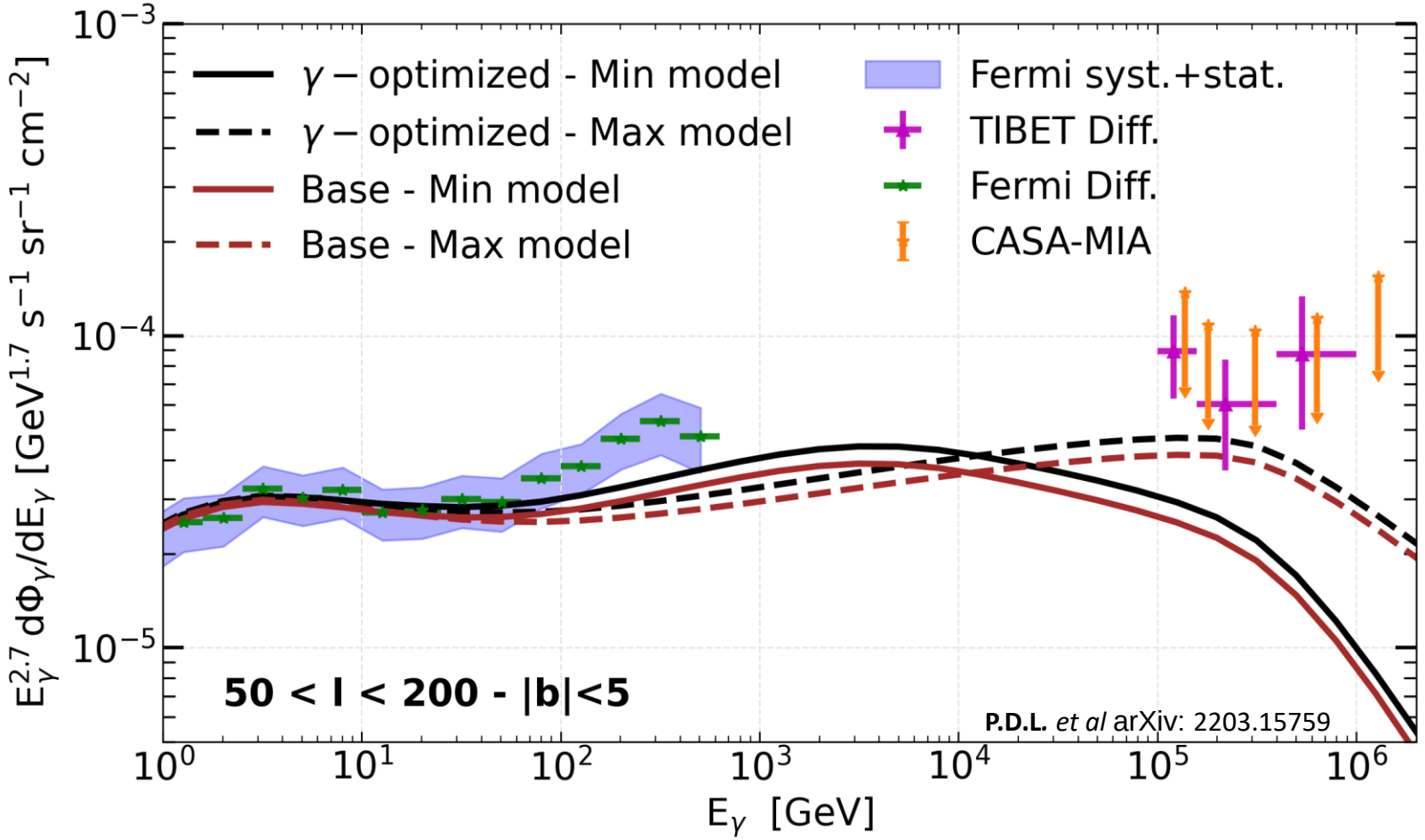




Inhomogeneous diffusion model

The diffuse emission meets TeV data

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

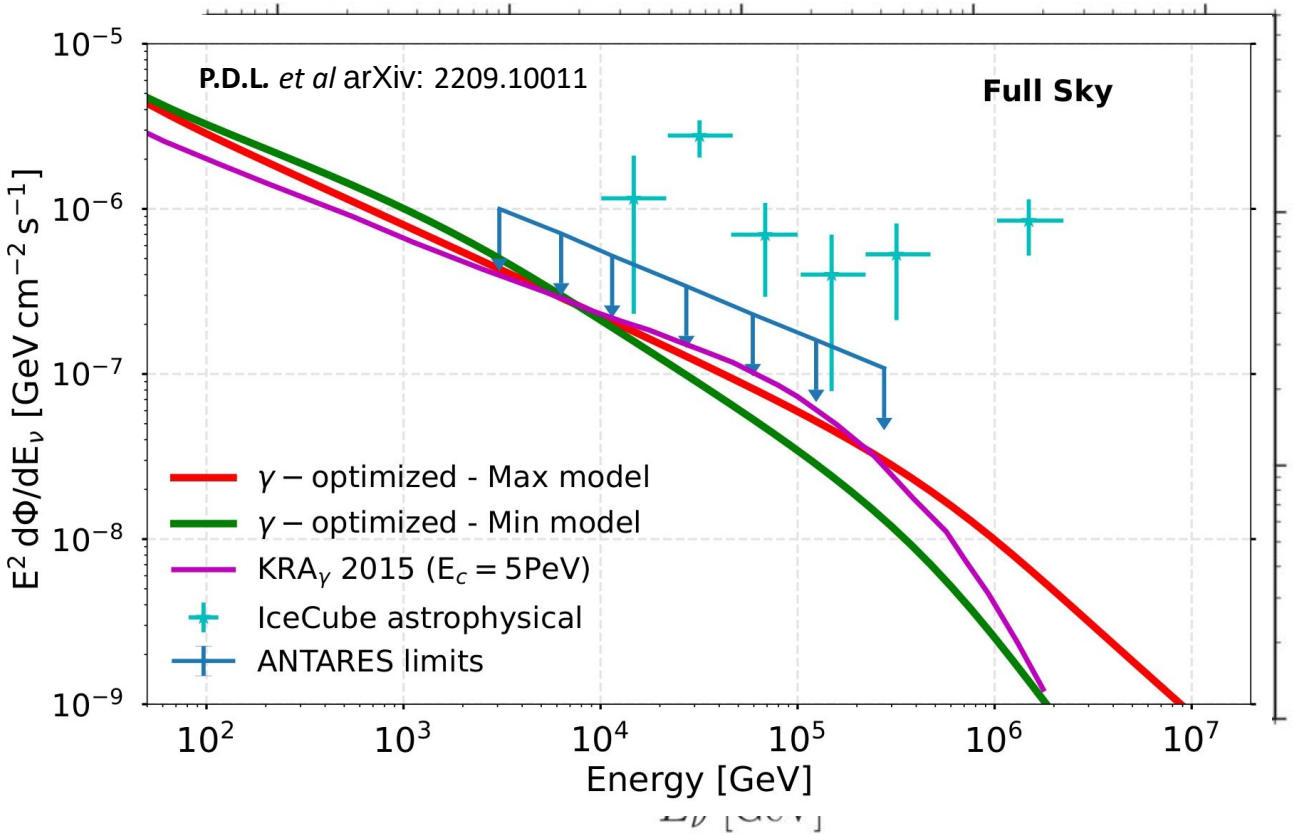


The effect of the inhomogeneous transport in such externals regions is small, therefore, **more data at these ROIs can help solving the degeneracy on the injection spectra (MAX/MIN)**

See also:
Vecchiotti et al
ArXiv:2107.14584

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

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).

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

TO CONCLUDE…

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- **Gamma rays** offer crucial information about the **propagation of cosmic rays** in different zones of the Galaxy, although many ingredients are involved…
- A formal study of the generation of turbulence (and its evolution) in different zones of the Galaxy is necessary
- **Precise predictions of unresolved sources** and **TeV halos** would help us improve our models. **The detection of Galactic neutrinos would support the scenario of inhomogeneous CR propagation**

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Thanks for your attention!

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Inhomogeneous diffusion model (δ → δ(R))

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

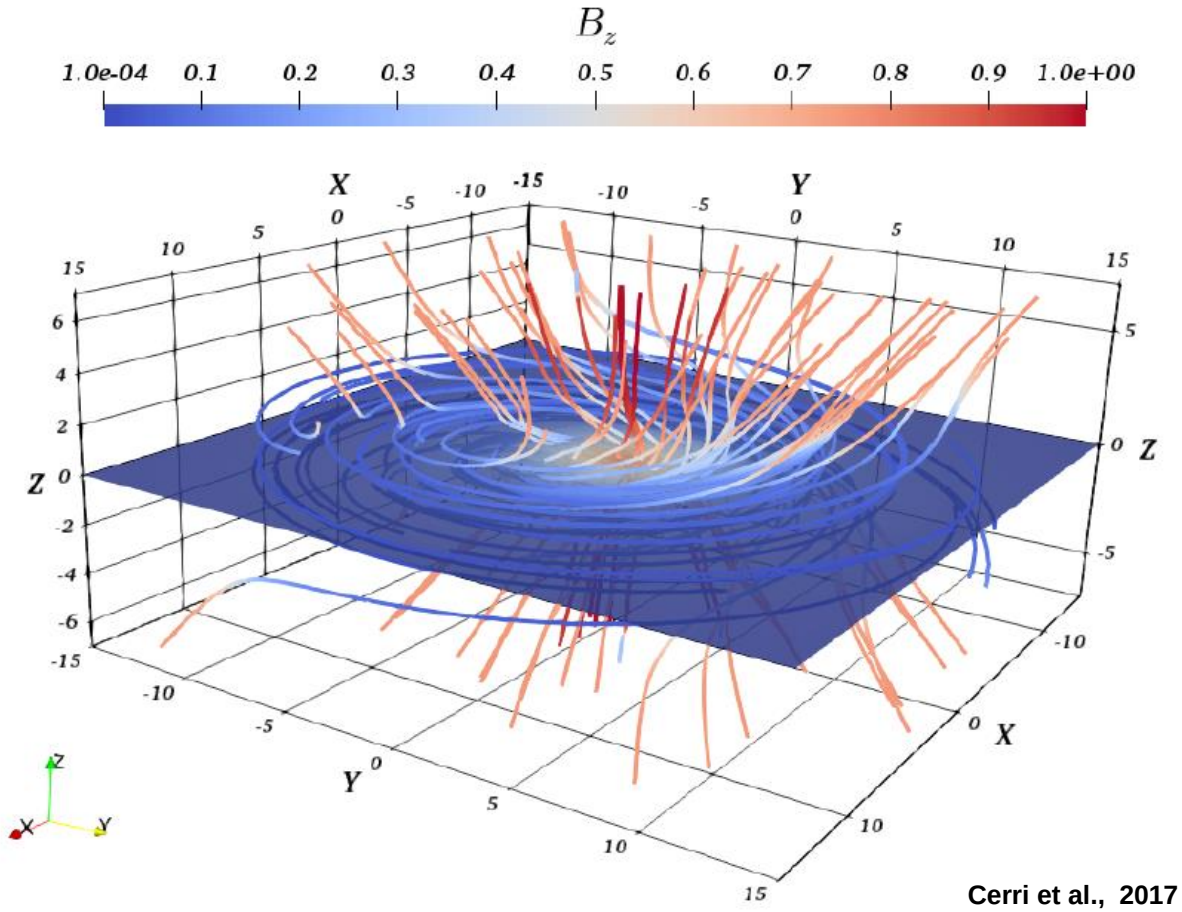
- Magnetic field intensity (and direction)

- Gas distribution (contributing to damping of MHD waves)

- Distribution of sources

- Anisotropy of turbulence cascade

- Non-steady particle distribution?



Cerri et al., 2017

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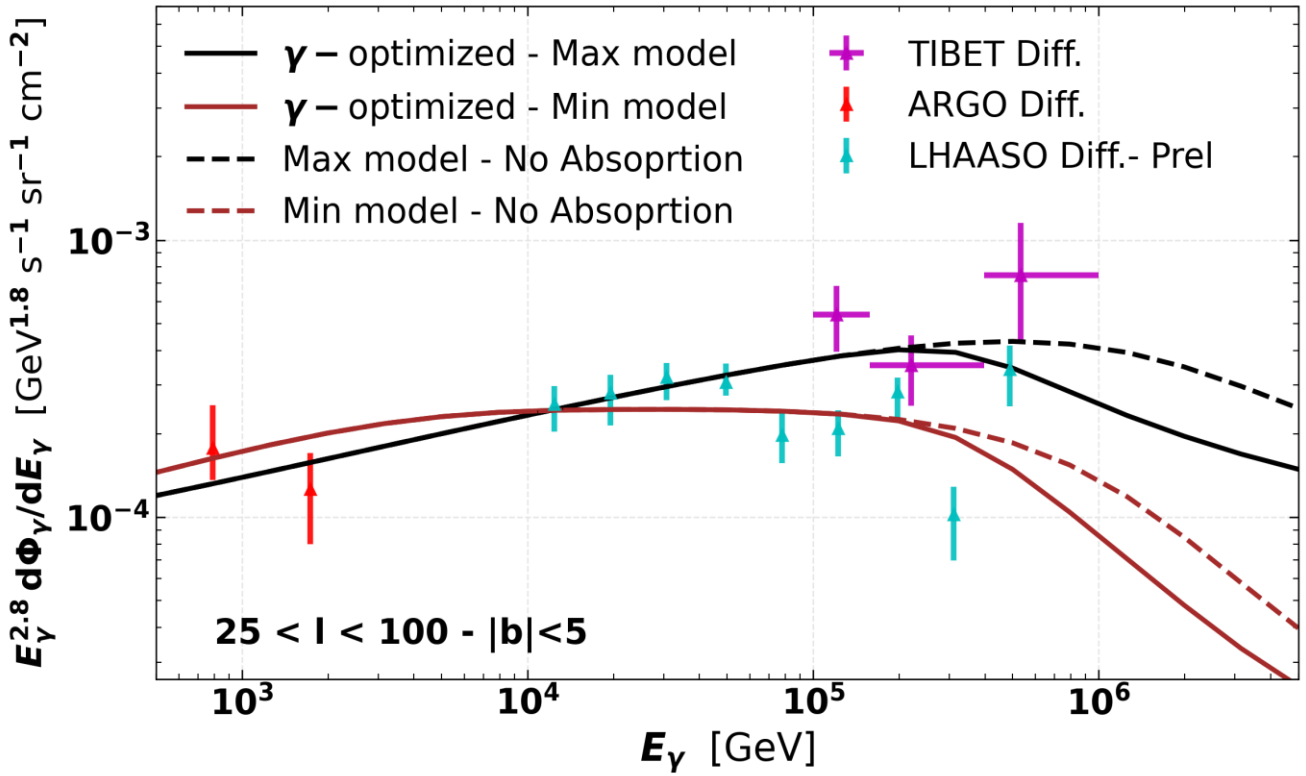
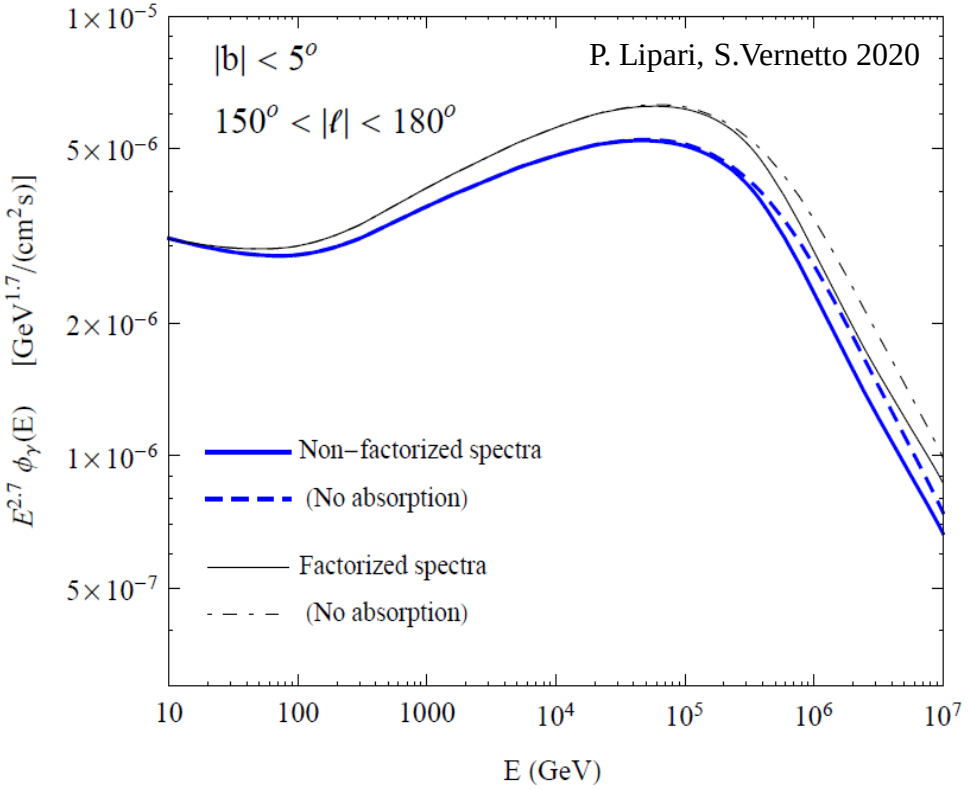


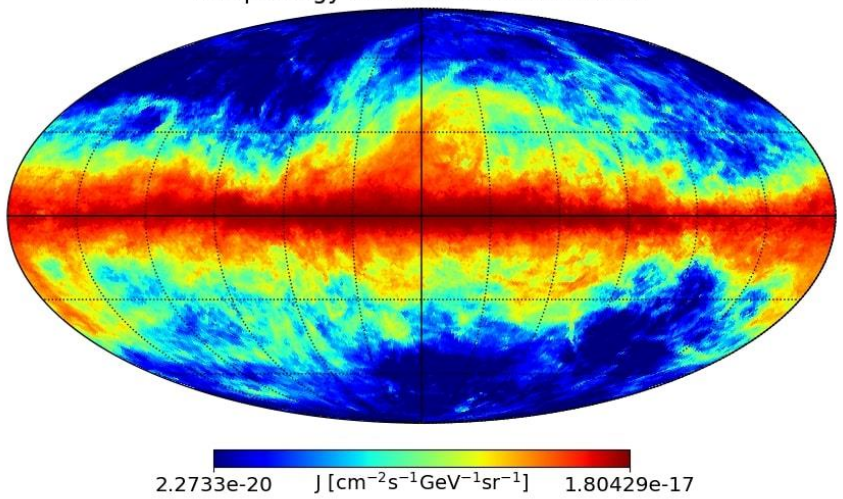
Absorption of very high energy gamma rays becomes important

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

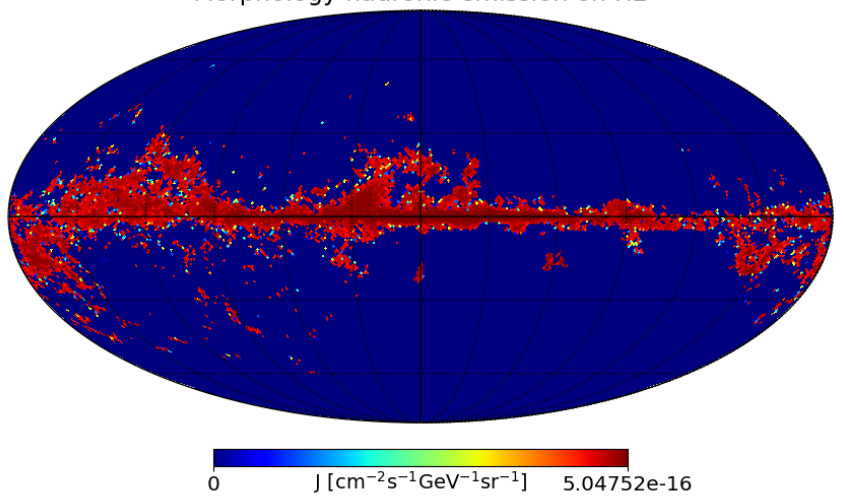
Absorption from the CMB dominates over the other ISRFs (IR from dust, Optic and UV from stars and extra-galactic background light)



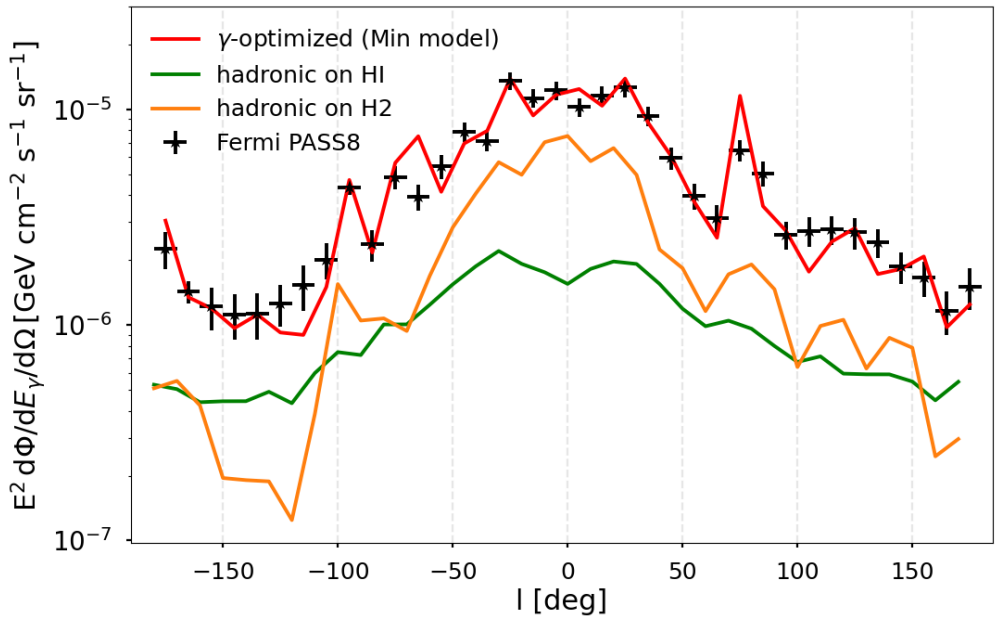
Morphology hadronic emission on HI



Morphology hadronic emission on H2



Longitude profile - |b| < 5 deg - 50 GeV



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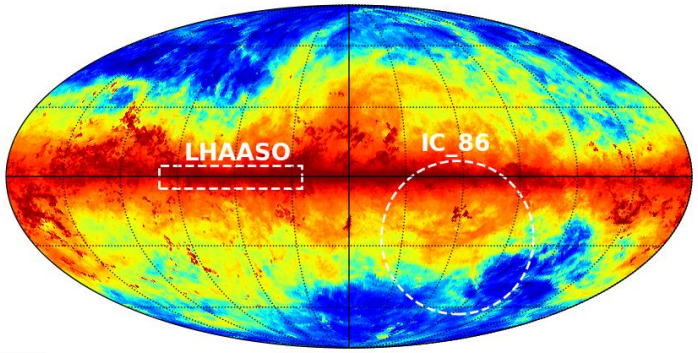

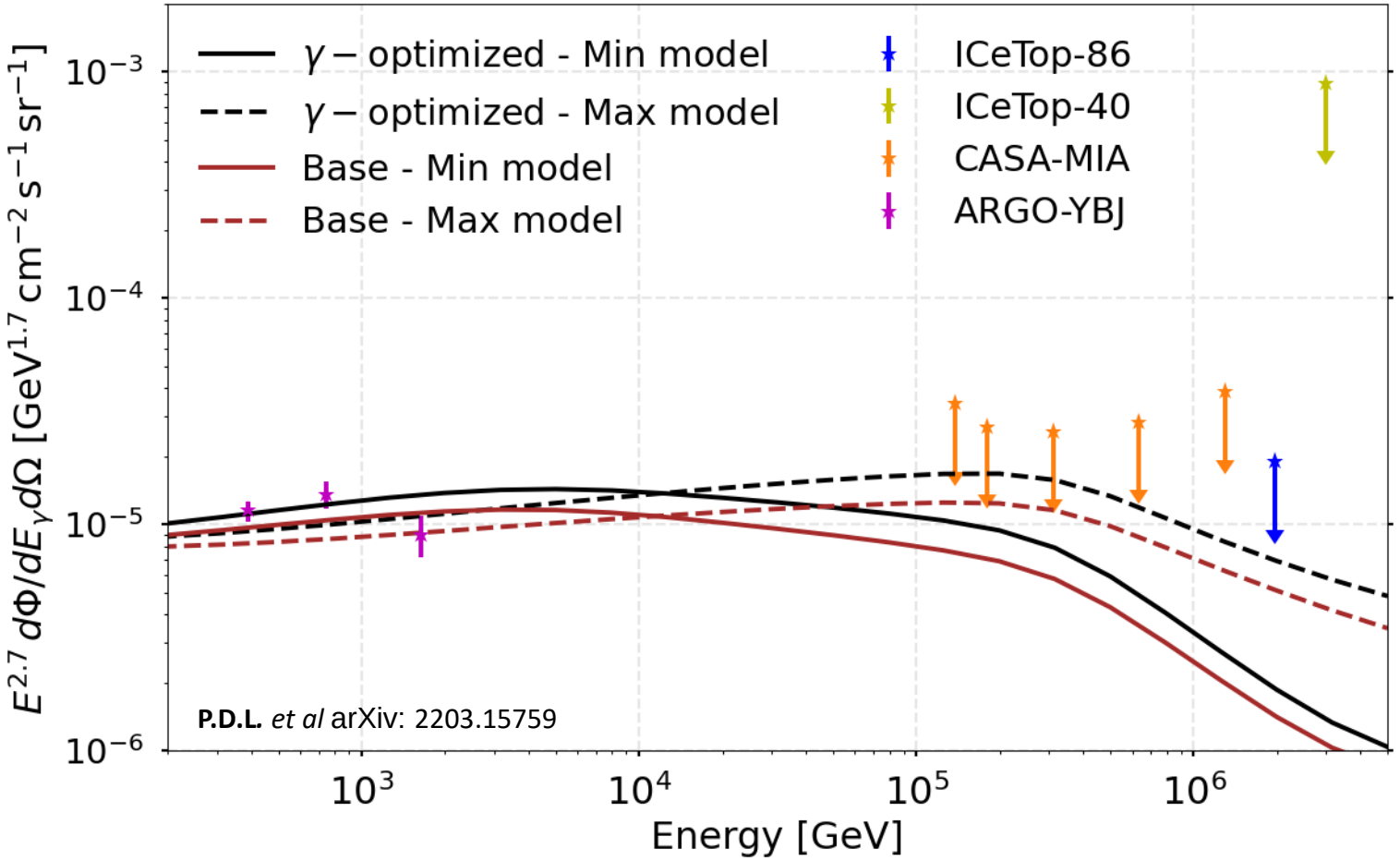

Within the **region of sensitivity of IceTop** there is little difference between models conventional diffusion and the gamma-optimized models

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