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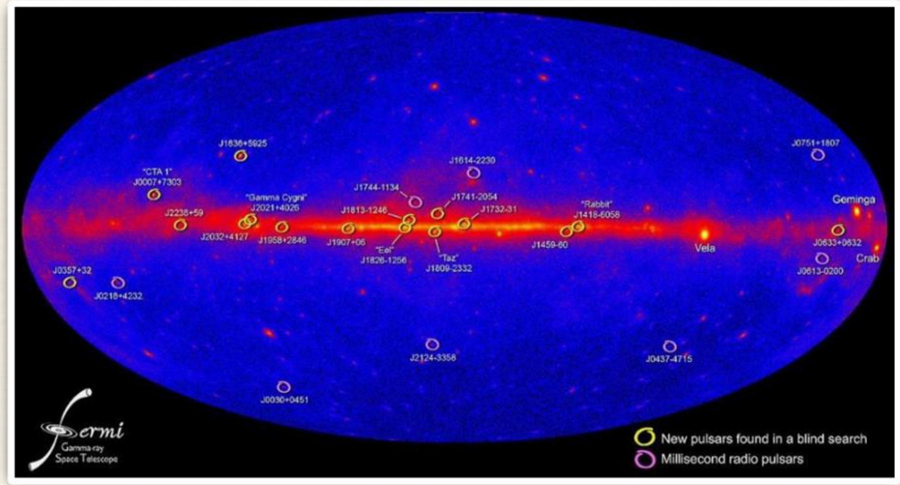
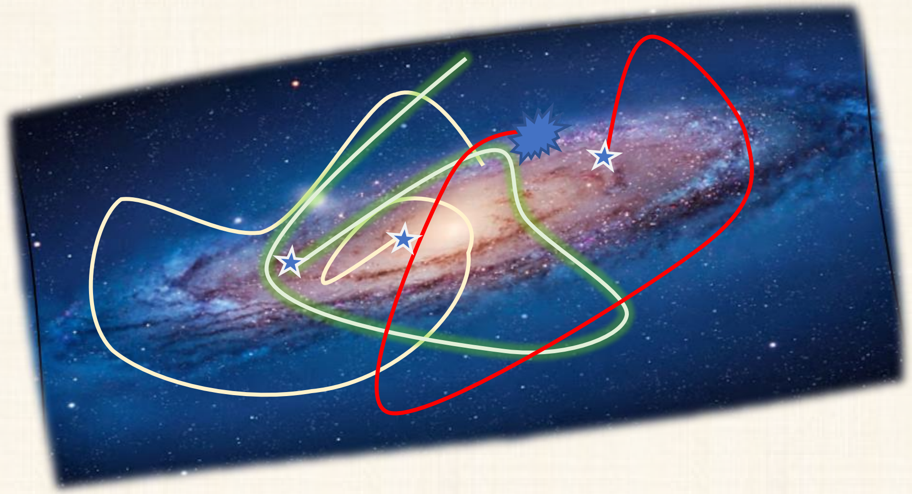
Gamma2022 04/07/2022

Galactic diffuse gamma rays meet the PeV frontier

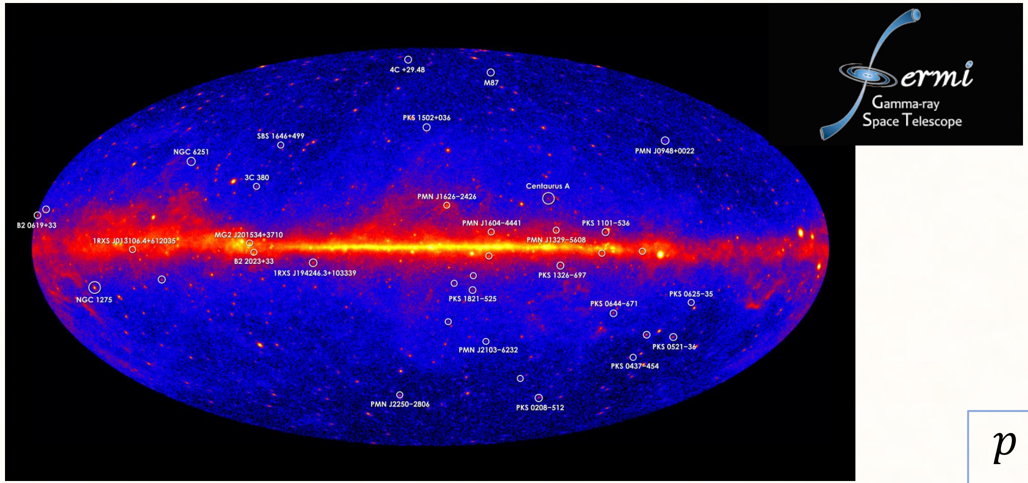
ArXiv: 2203.15759 In collaboration with D. Gaggero, D. Grasso, O. Fornieri, C. Evoli, K. Egberts, C. Steppa

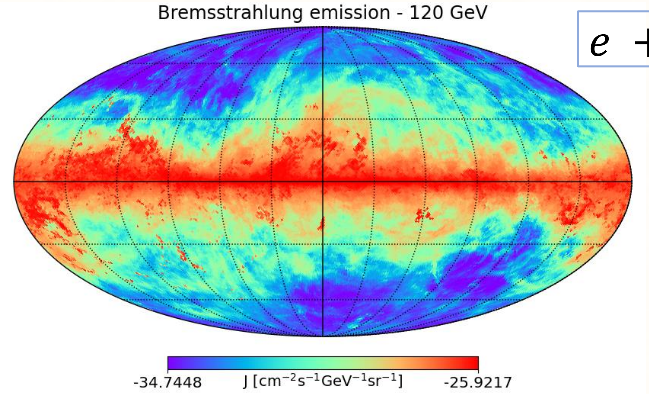




The Gamma-ray diffuse sky

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





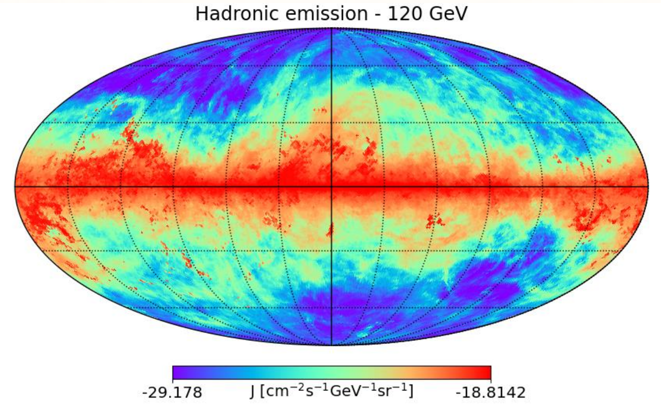
$e + N \rightarrow e' + \gamma' + N$

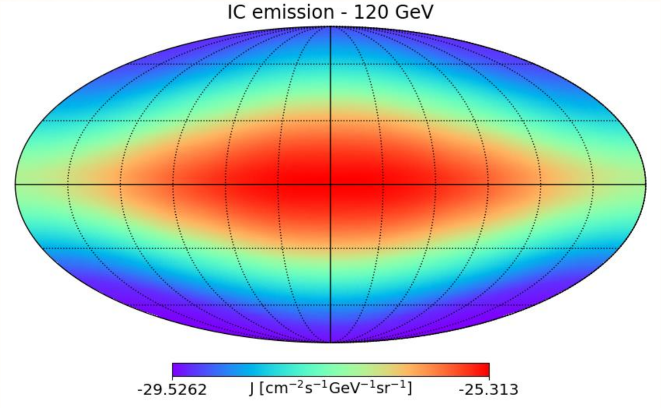
$p + p \rightarrow \pi^0$
$\pi^0 \rightarrow 2\,\gamma$

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

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

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



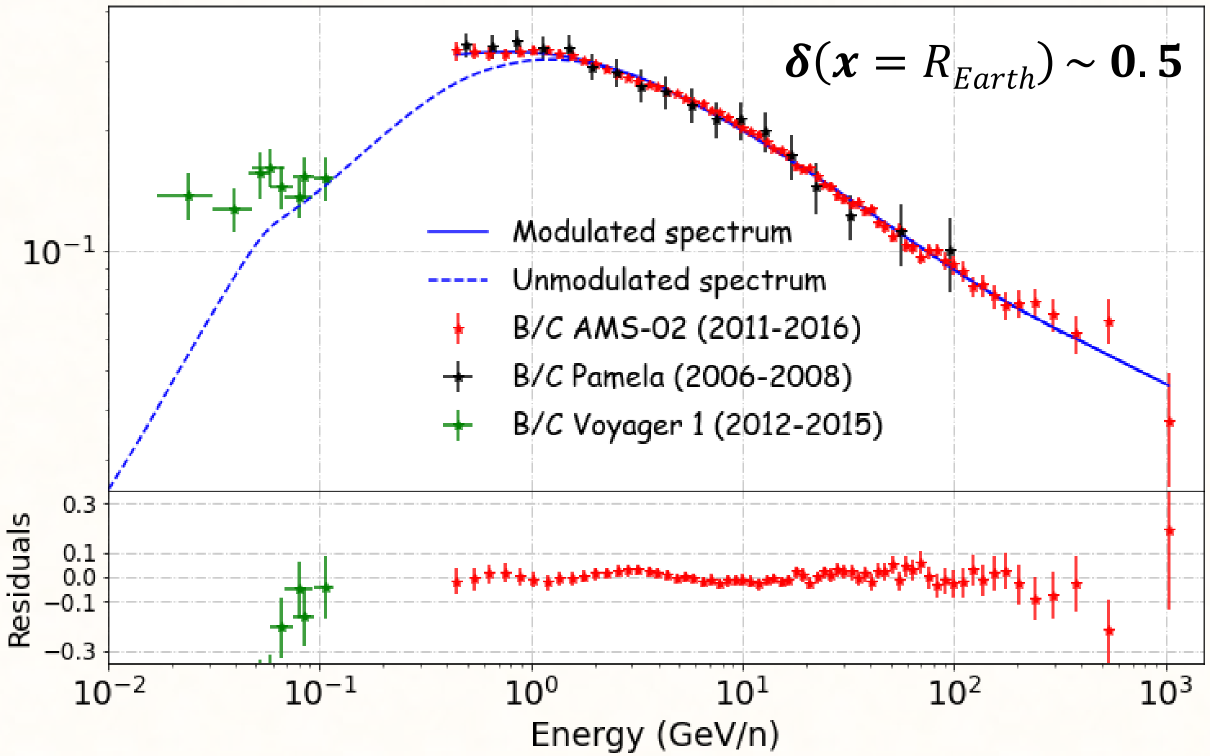


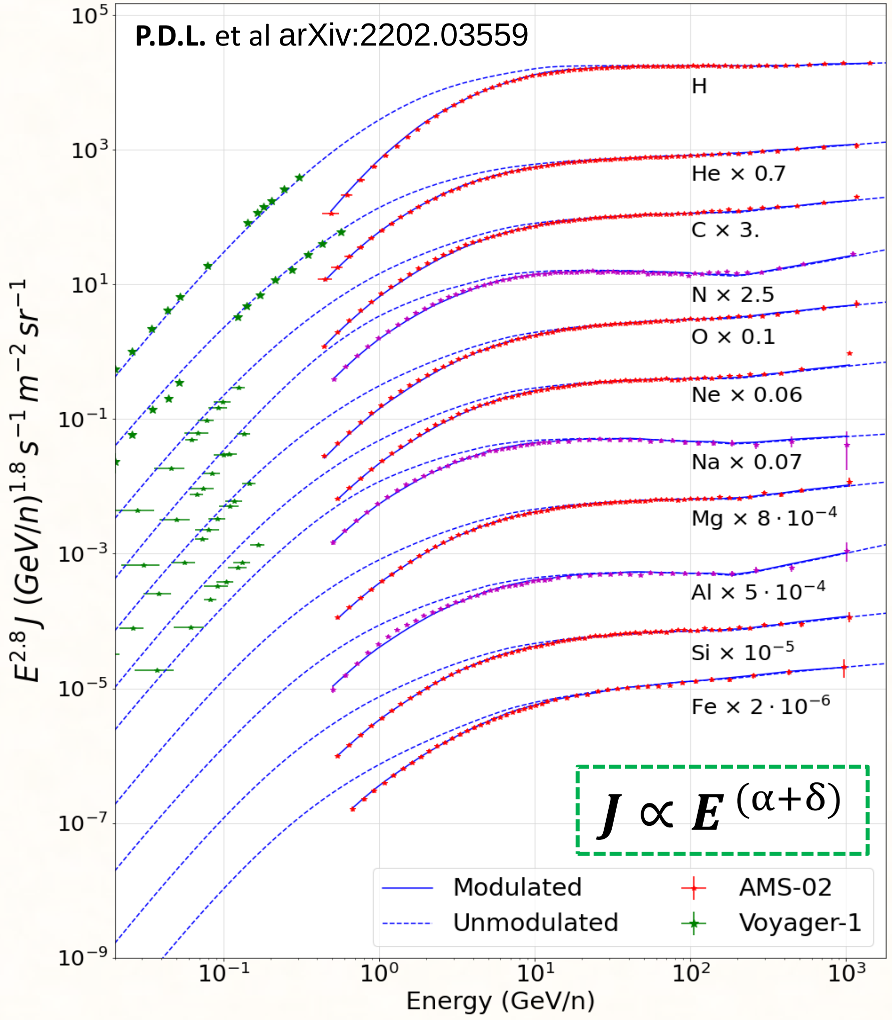
Galactic gamma-ray diffuse emission – Local cosmic rays

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

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

B/C spectrum





Galactic gamma-ray diffuse emission – Local cosmic rays

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

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

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

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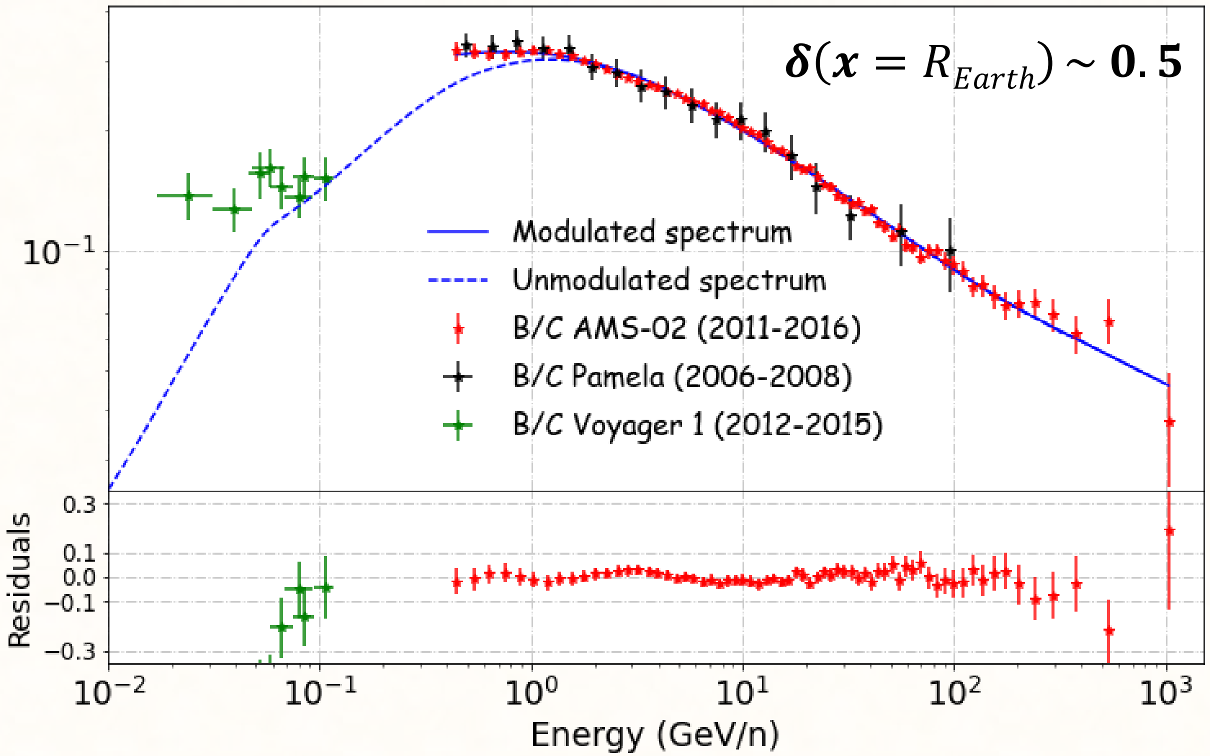

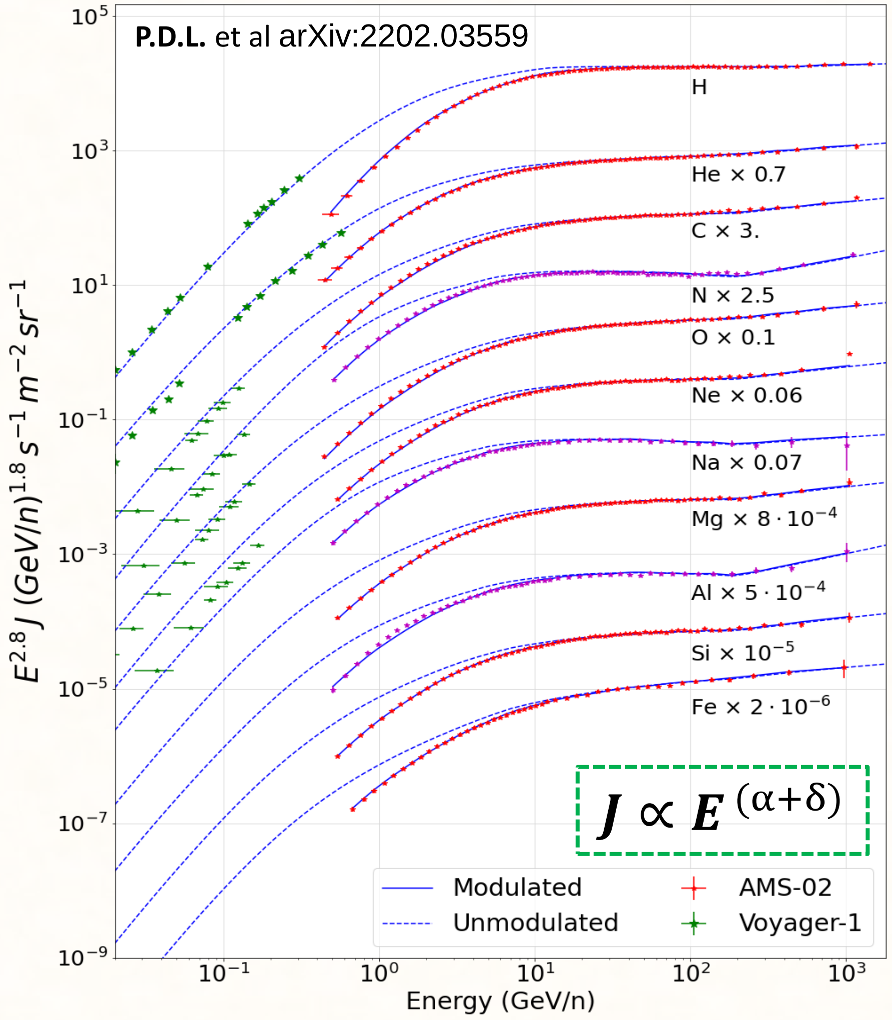

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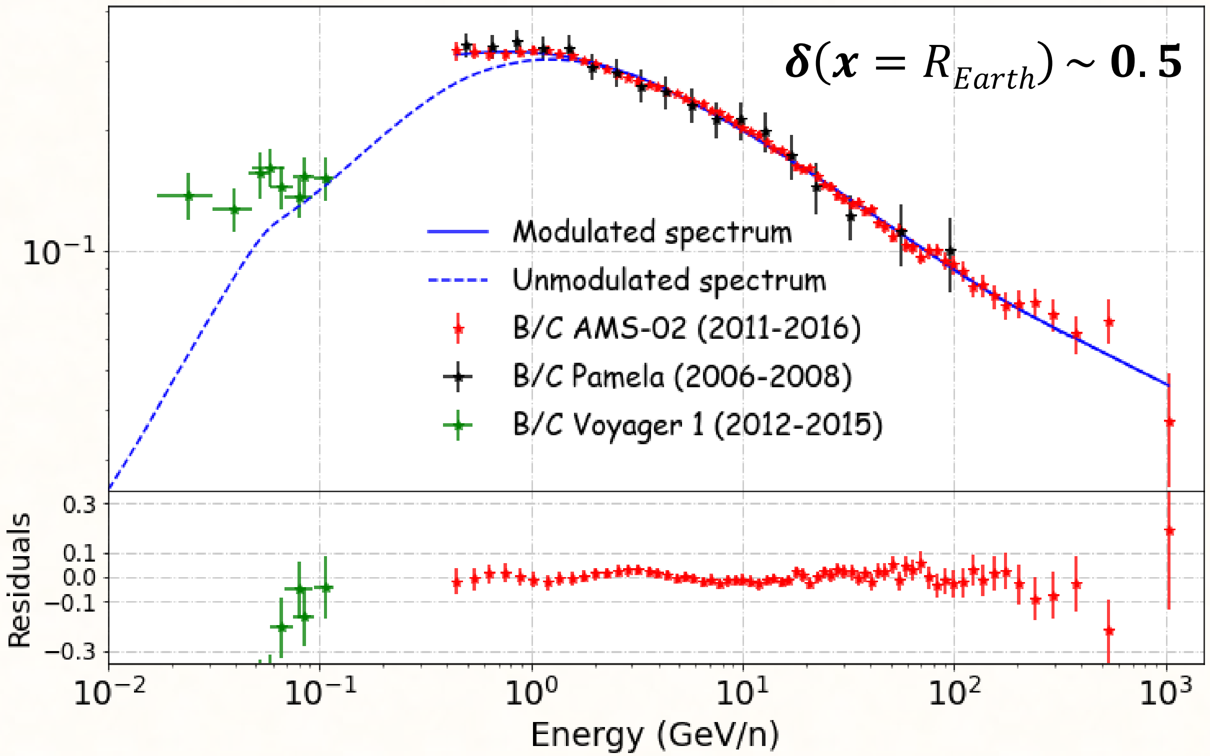
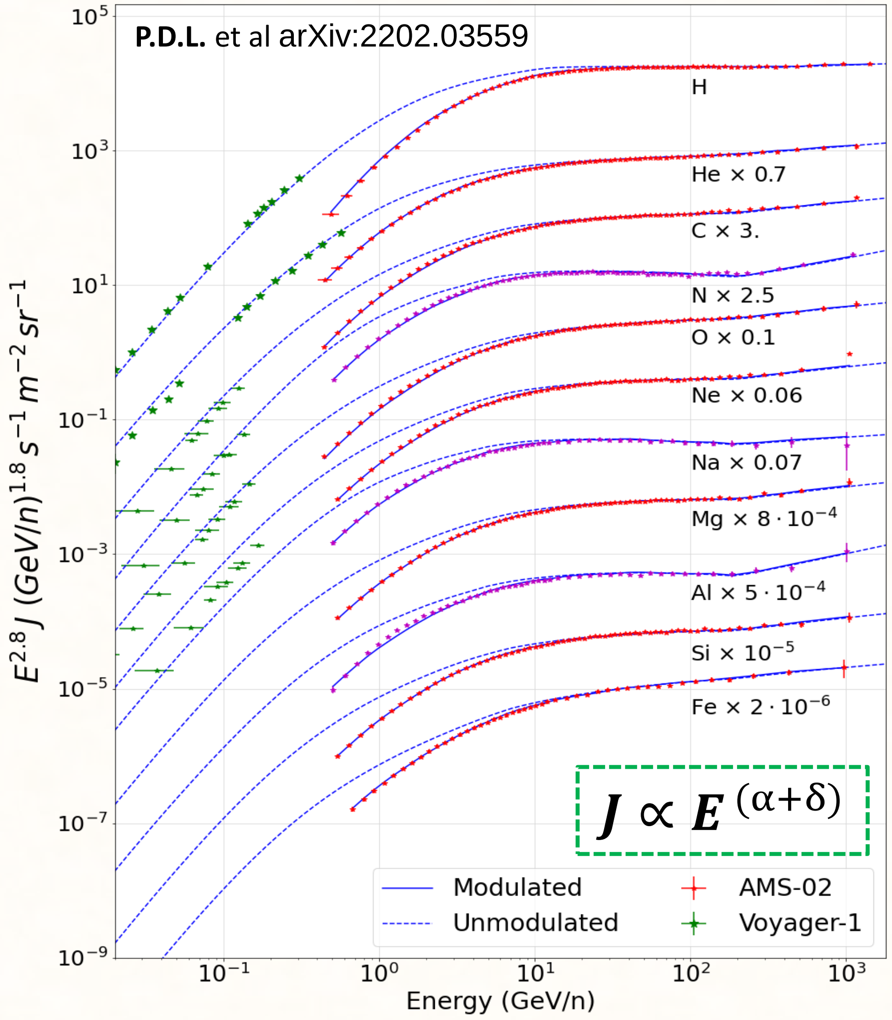




Galactic gamma-ray diffuse emission – Hardening towards the centre

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

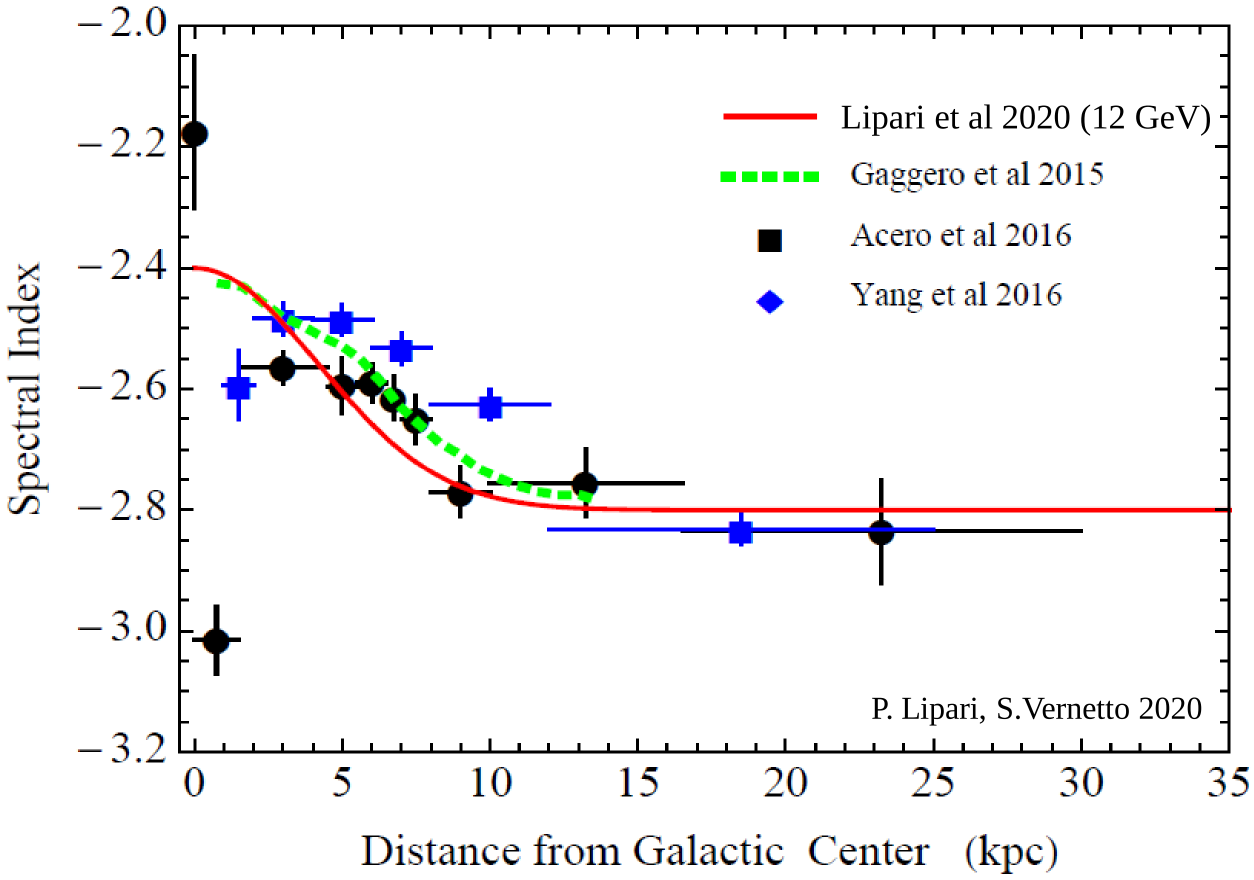
Progressive hardening of the gamma-ray diffuse spectrum towards the centre

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))

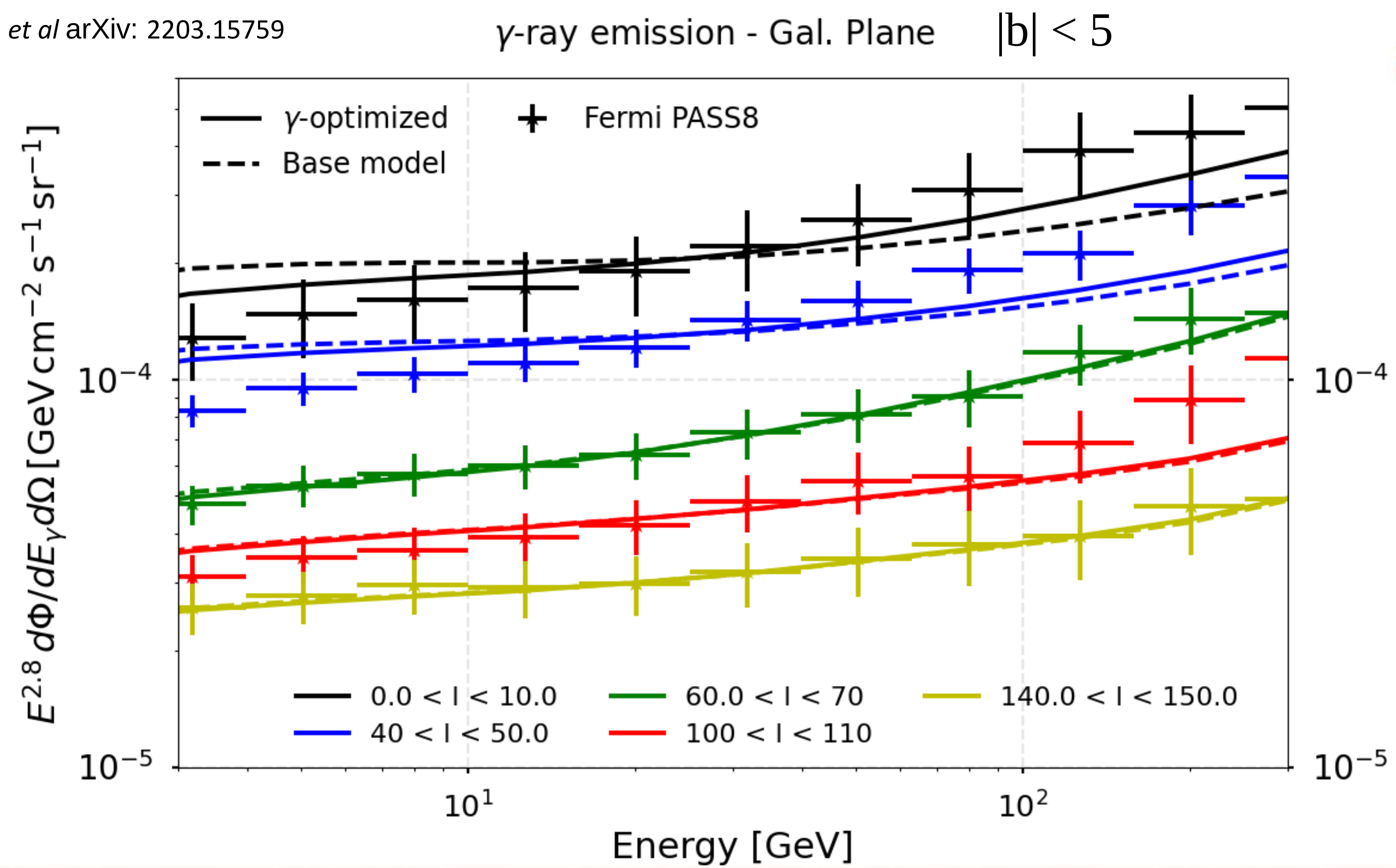


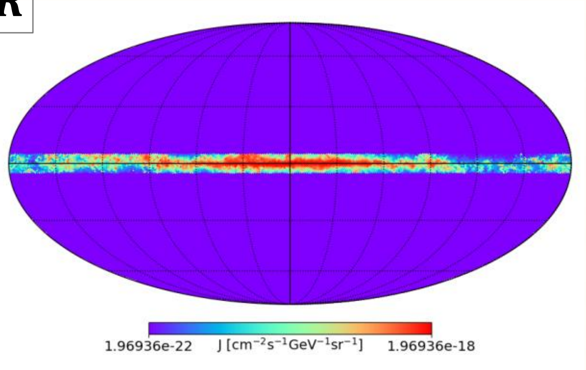
Inhomogeneous diffusion model

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.

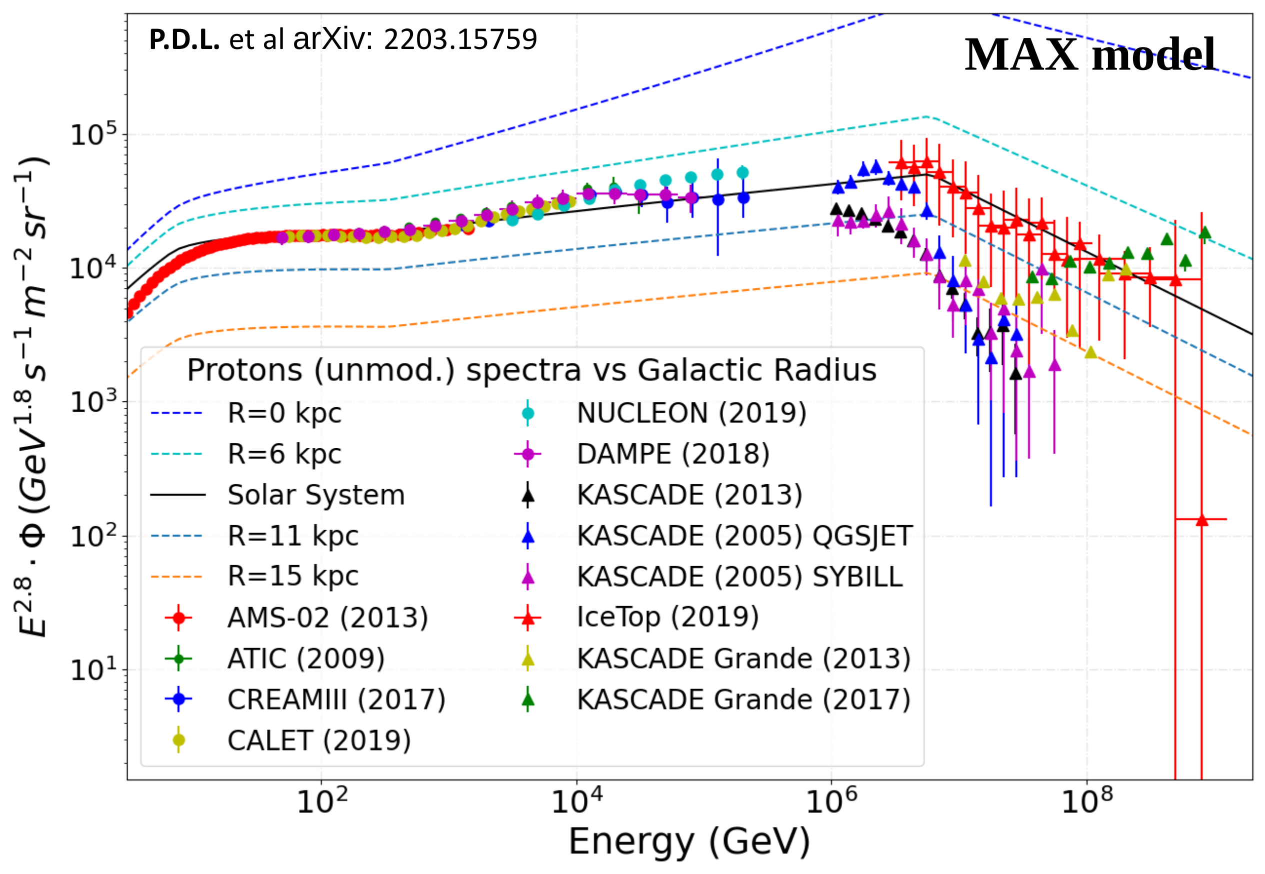
__MAX model__ adopted connects AMS-02 data with IceTop

__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__



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

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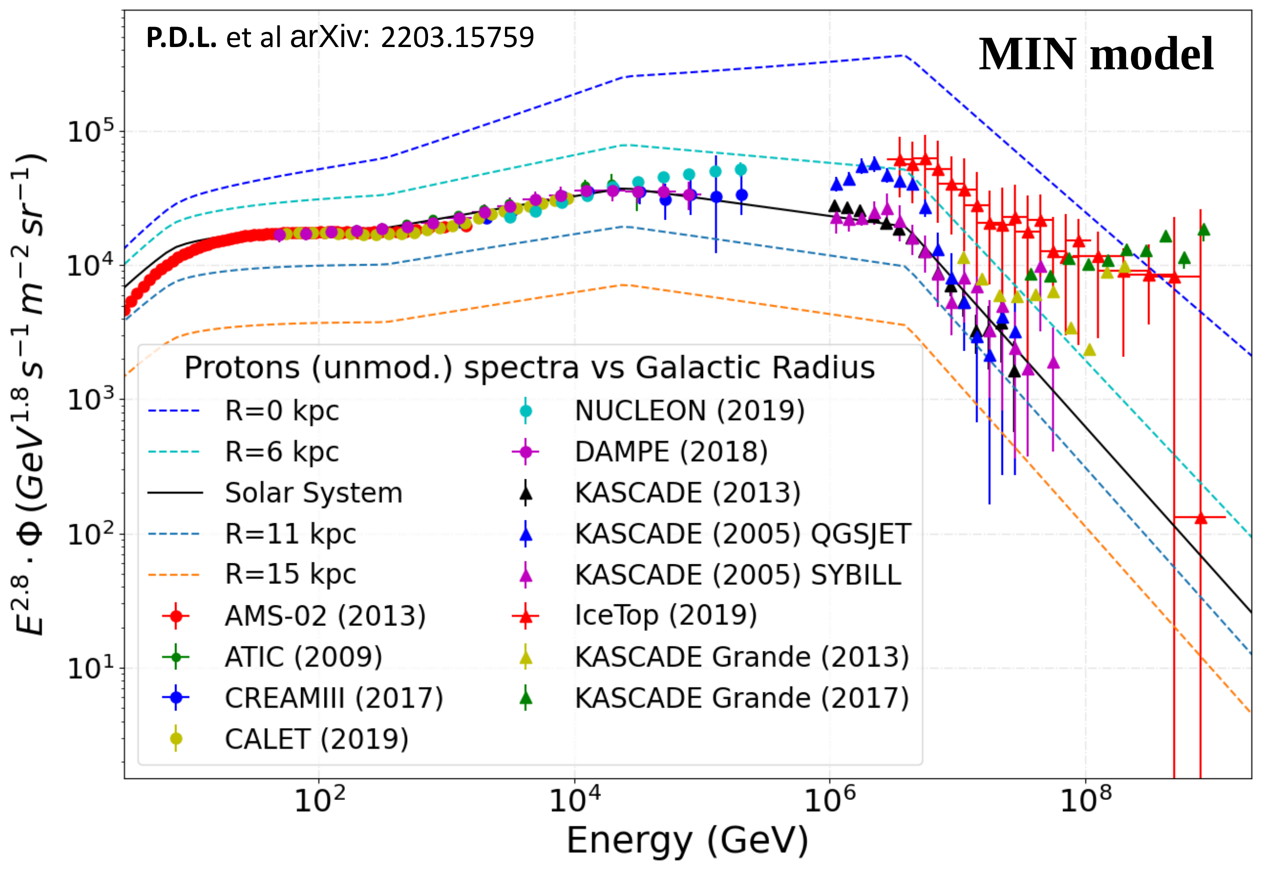
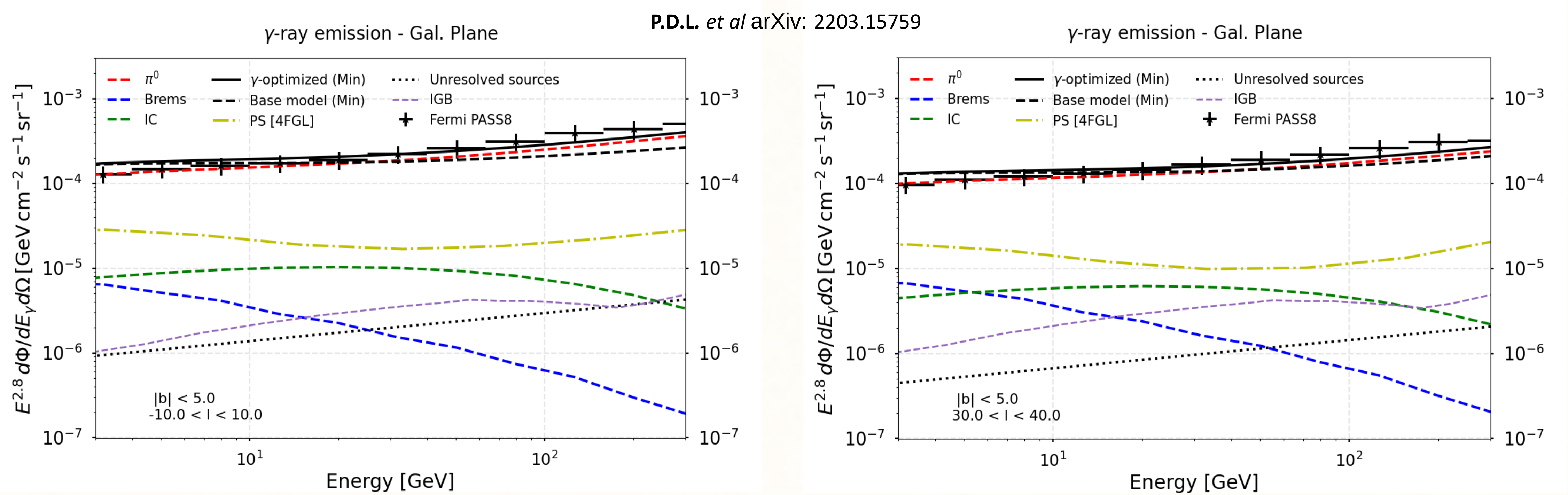


Inhomogeneous diffusion model – The different components

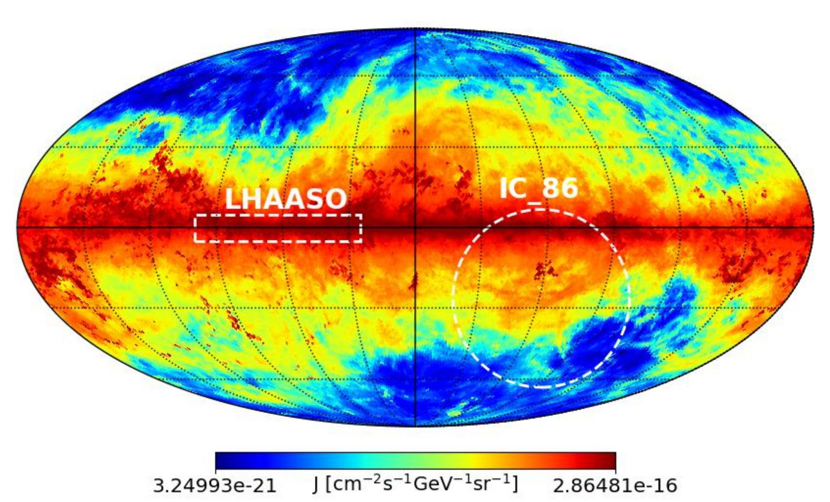
- The diffuse emission at GeV energies dominate over the emission sources emission (4FGL catalogue)
- Unresolved point sources (UPS) become more important at higher energies (Steppa+ A&A 643, A137 (2020))
- Isotropic gamma-ray background (IGB) contains Extra-galactic plus Fermi's instrumental background

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

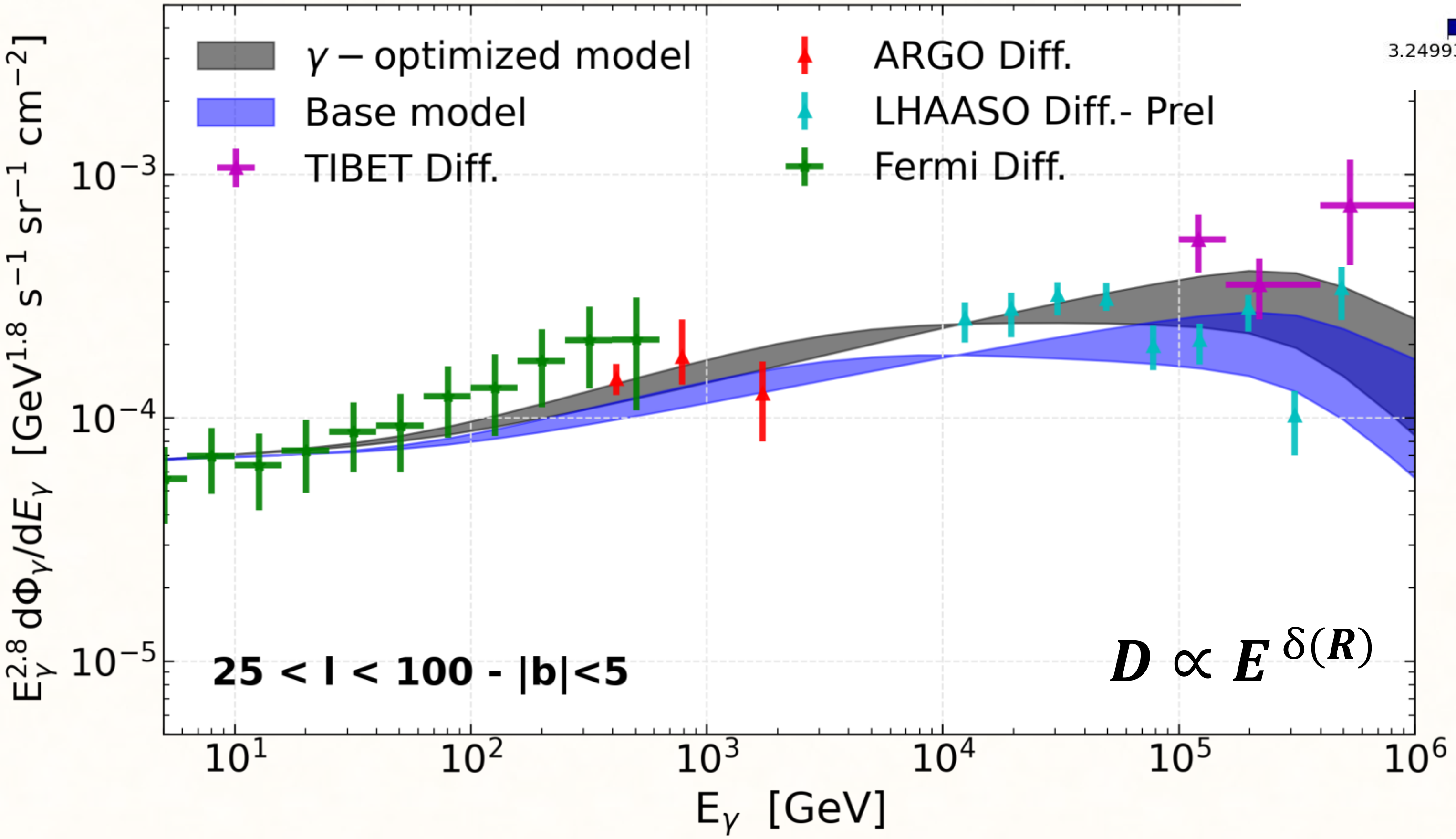


Inhomogeneous diffusion model

The diffuse emission meets TeV data



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



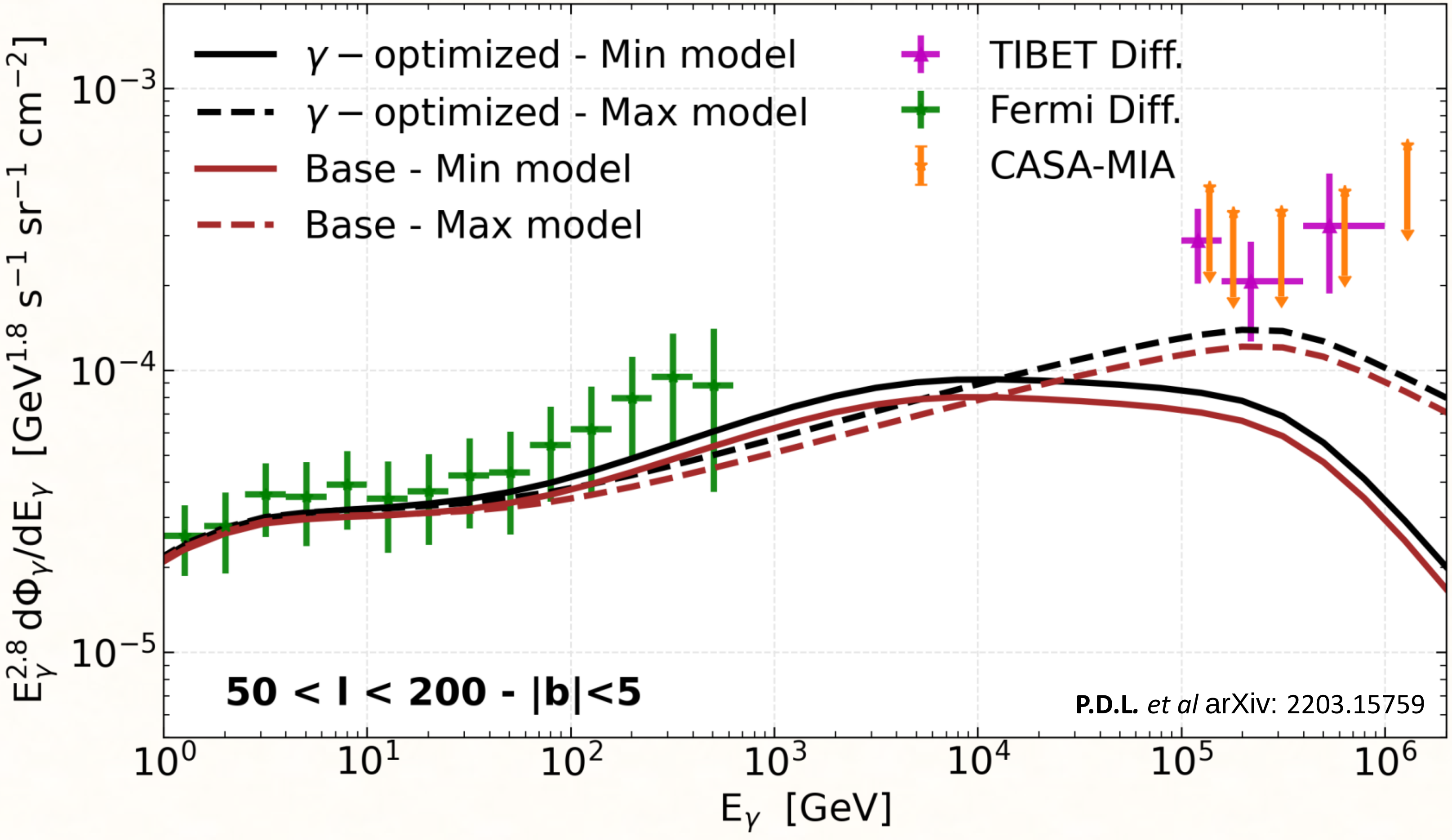
The spatially-dependent (**γ-optimized**) models, tuned on Fermi-LAT data are also **favoured by very high energy detectors** like LHAASO

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

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)

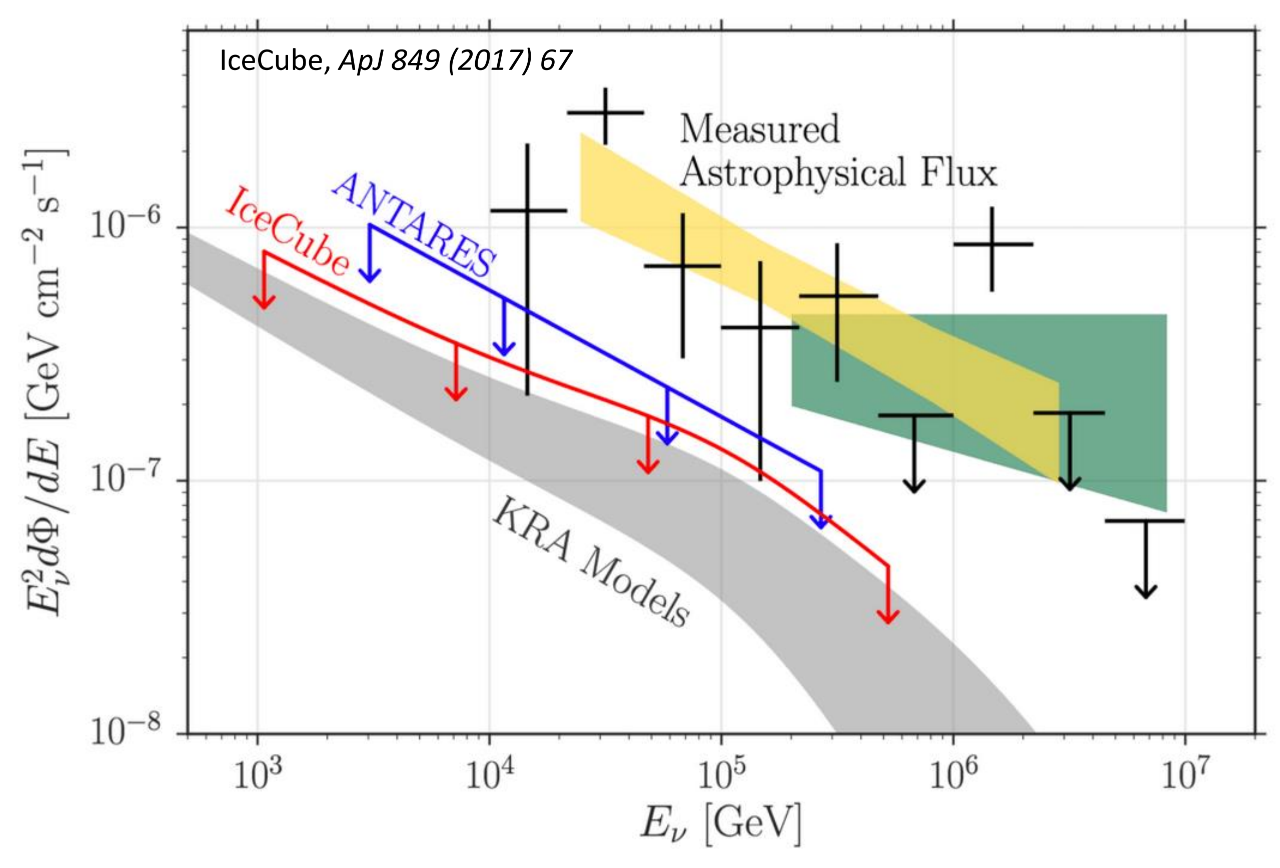


The effect of the inhomogeneous transport in such externals regions is small, therefore, **more data at these ROIs can help solving the degeneracy on the injection spectra (MAX/MIN)**

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). Observation of Galactic neutrinos could be very close

Work in progress for the evaluation of the Galactic neutrino flux from the γ-optimized model

TO CONCLUDE...

Galactic diffuse gamma rays meet the PeV frontier (ArXiv 2203.15759)

- **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. **Neutrinos could allow us to solve the puzzle**

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BACK UP

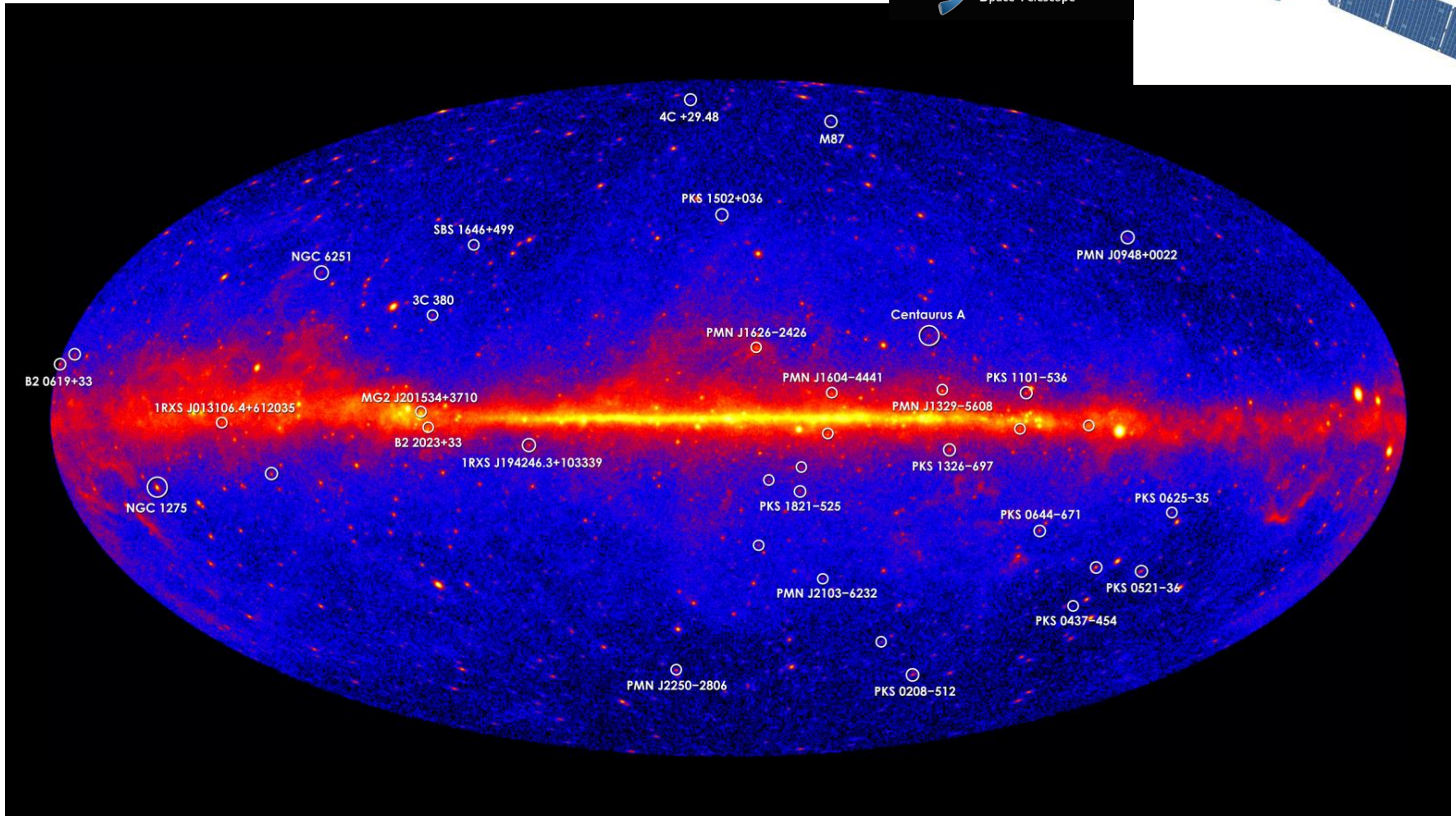
The Galactic Gamma ray emission - Components

- > 5600 point-like sources have been observed by the Fermi satellite
- ~ 75 extended sources

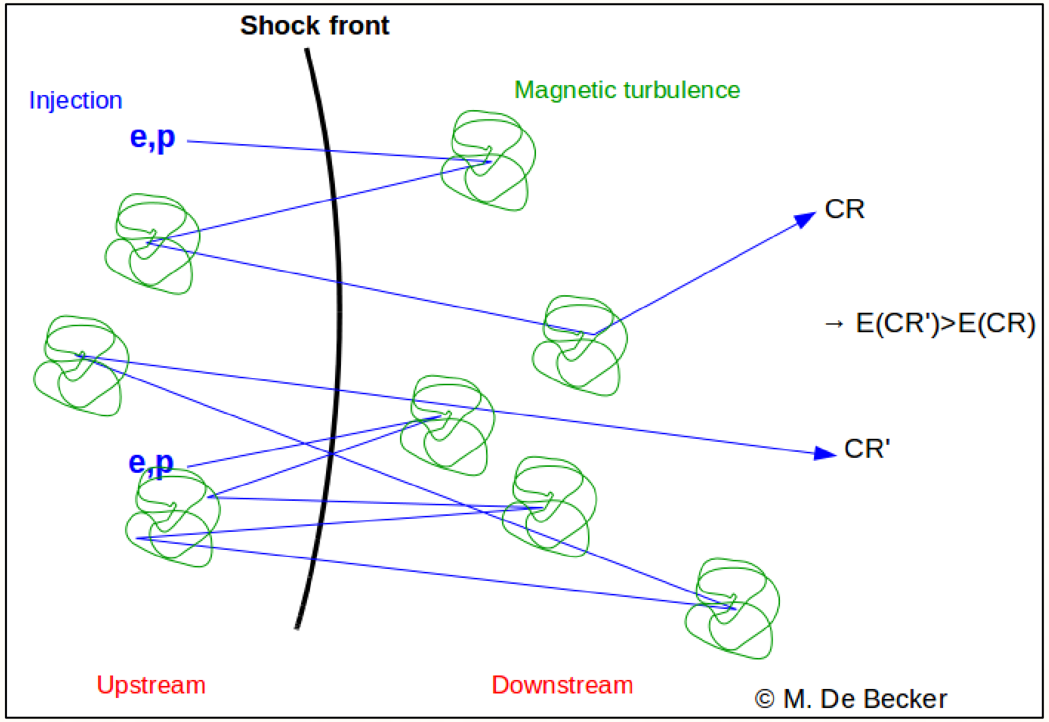
Extended structures (Fermi bubbles, Loop I, …)

Galactic diffuse gamma-ray background

Extragalactic background (EBL) is isotropic



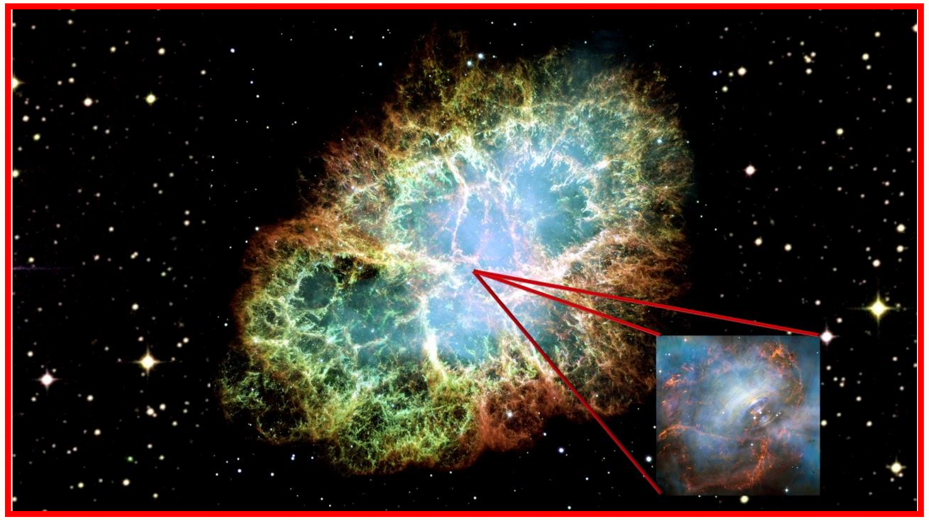
Acceleration of CRs in sources



Diffusive shock acceleration explains the power law distribution of CR particles

CRs are accelerated in shocks - Like those found in SNRs or PWNe

Then, these cosmic rays interact with their surroundings and generate gamma rays



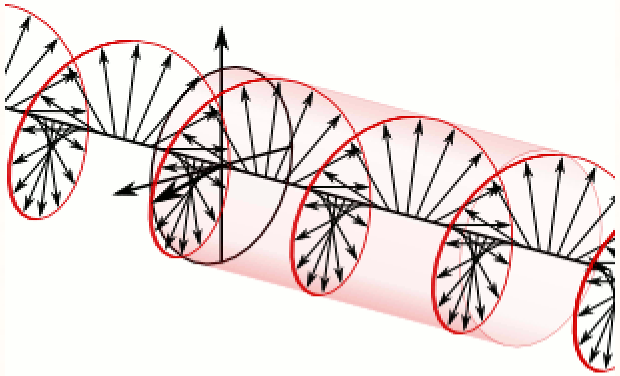
The **Milky Way** is described as *a magnetised plasma medium following the Magnetohydrodynamic equations*

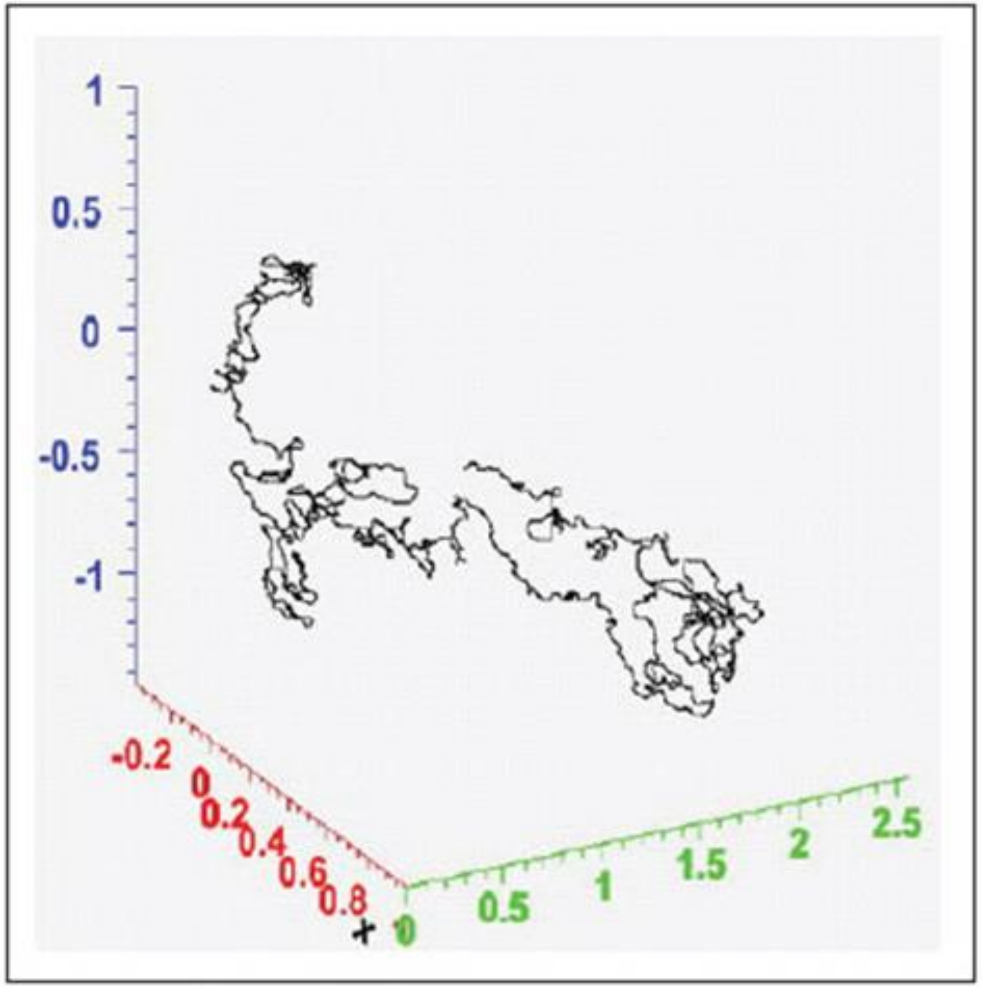
$$B = B_0 + \delta B \rightarrow \langle B \rangle = B_0$$

$$E = 0 + \delta E \rightarrow \langle E \rangle = 0$$

Longitudinal modes are compressional waves which are severely damped by the gas

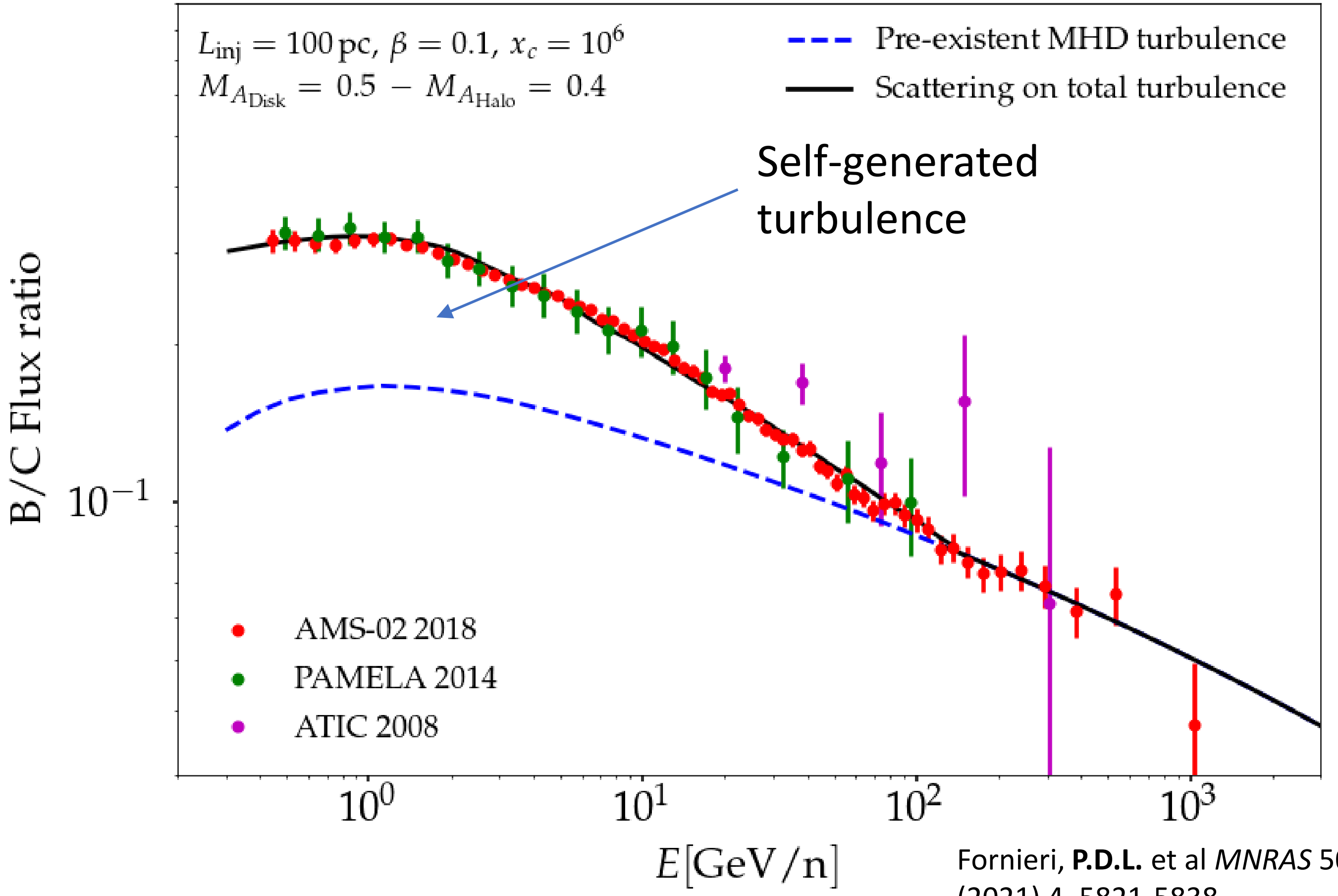
Alfven waves are circularly polarized whose resonant interaction governs the CR scattering





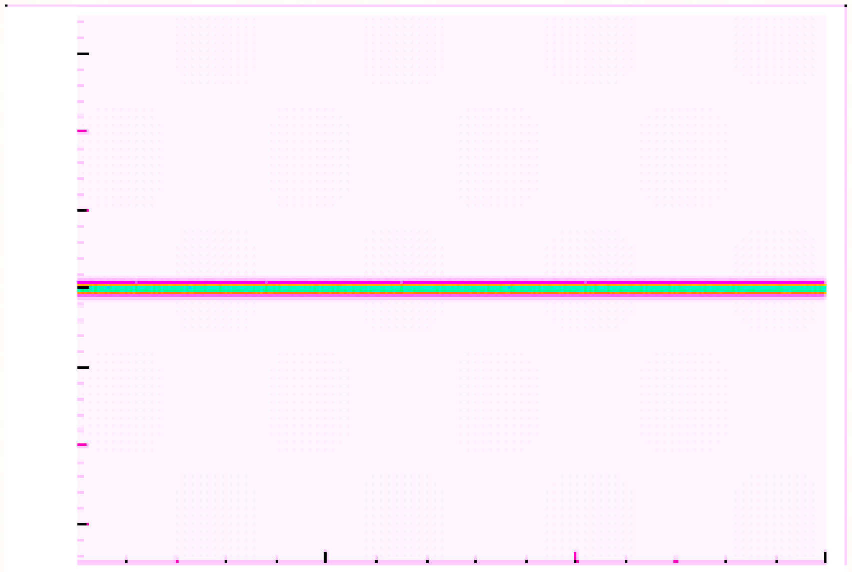
Secondary-to-primary CR flux ratios allow us to constrain the properties of the plasma where the turbulence is generated

CRs trigger instabilities in the plasma that lead to further confinement of cosmic rays in the Galaxy



Fornieri, **P.D.L.** et al *MNRAS* 502 (2021) 4, 5821-5838

$$\frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \Gamma_{\rm CR} W = q_W(k)$$



Diffusive transport of Galactic cosmic rays

Propagation equation is solved with the DRAGON2 code
https://github.com/cosmicrays/DRAGON2-Beta_version

$$\vec{\nabla}\cdot(-D\nabla N_i - \vec{v}_\omega N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] = Q_i + \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_\omega N_i\right)\right] - \frac{N_i}{\tau_i^f} + \sum \Gamma^s_{j\to i}(N_j) - \frac{N_i}{\tau_i^r} + \sum \frac{N_j}{\tau^r_{j\to i}}$$

$$D = D_0\beta^\eta\left(\frac{R}{R_0}\right)^\delta F(\vec{r},z)$$

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

$$\Gamma^s_{j\to i} = \beta_j c n_t \sigma_{j\to i} N_j$$

Confinement time → Diffusive transport

CR observed flux: $N \propto E^{-\gamma}$; $\gamma \sim 2.7$

DSA predicted flux: $Q \propto E^{-\alpha}$; $\alpha \sim 2\text{-}2.3$

$$\frac{dN_i}{dt} = Q_i(E) - \frac{N_i}{\tau^{esc}}$$ (Leaky box approx.)

Steady solution $N_i = Q_i \tau^{esc}$ → Confinement time must be: $\tau^{esc} \propto E^{-\delta}$; $\delta \sim 0.4$

Solving the equation $$\frac{d\vec{p}}{dt} = q\frac{\vec{v}\times(\vec{B}+\delta\vec{B})}{c}$$ leads to $\delta \propto (\delta B/B)^2 \propto k^{-\lambda}$

The power spectrum of MHD turbulence follow a power law in wavenumber (k) and is able to explain the propagation of CRs as a diffusive transport in the Galaxy with $0.3 < \delta < 0.6$

The Gamma-ray sky – Components: Diffuse

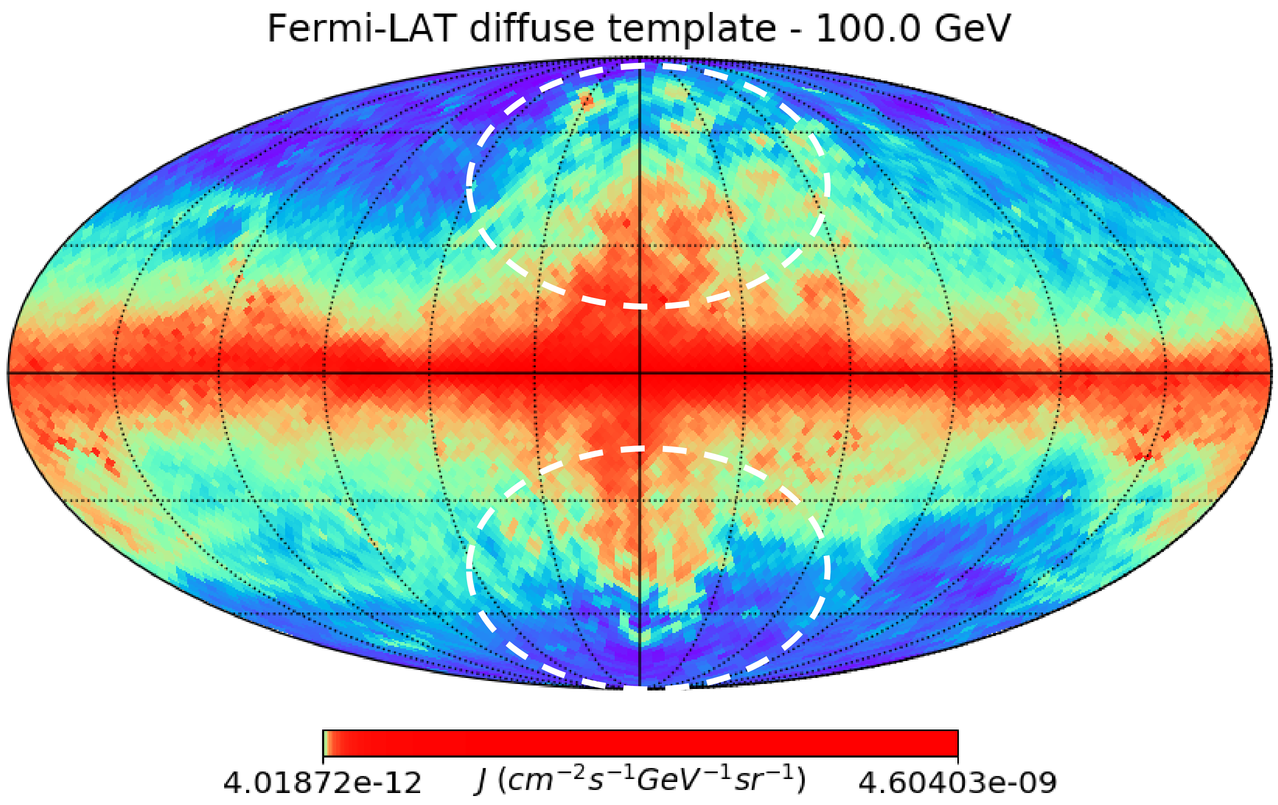
There are still extended (diffuse) emissions there:

Fermi bubbles

Loops and spurs

Below these foregrounds we find the diffuse gamma-ray sky!

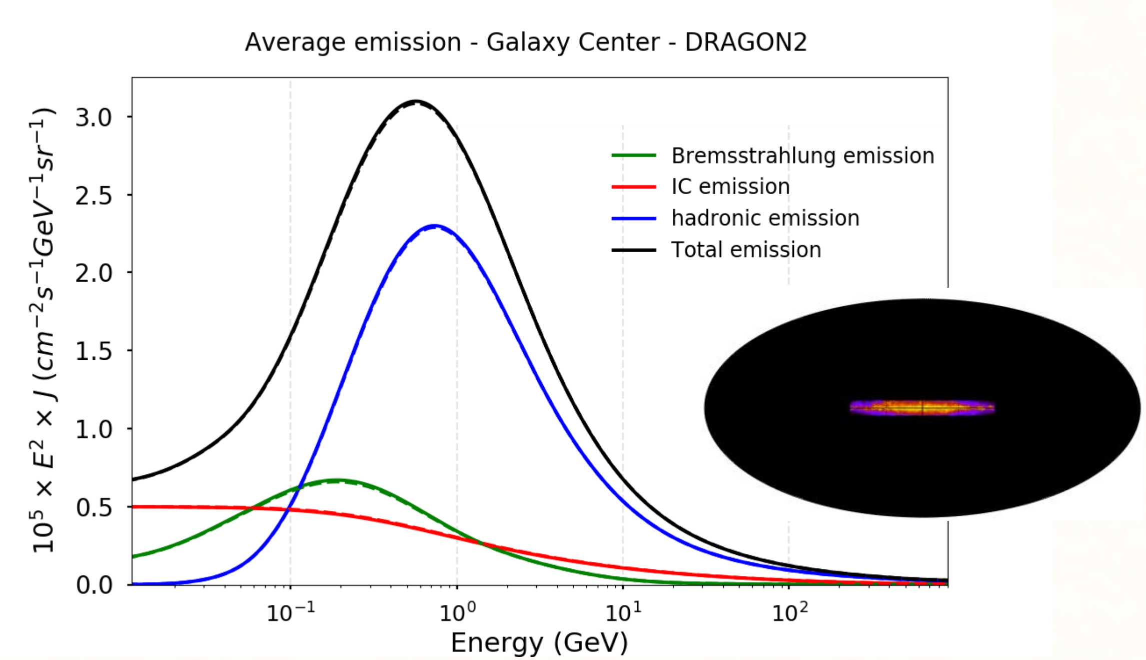
Extragalactic background (EBL) is isotropic!

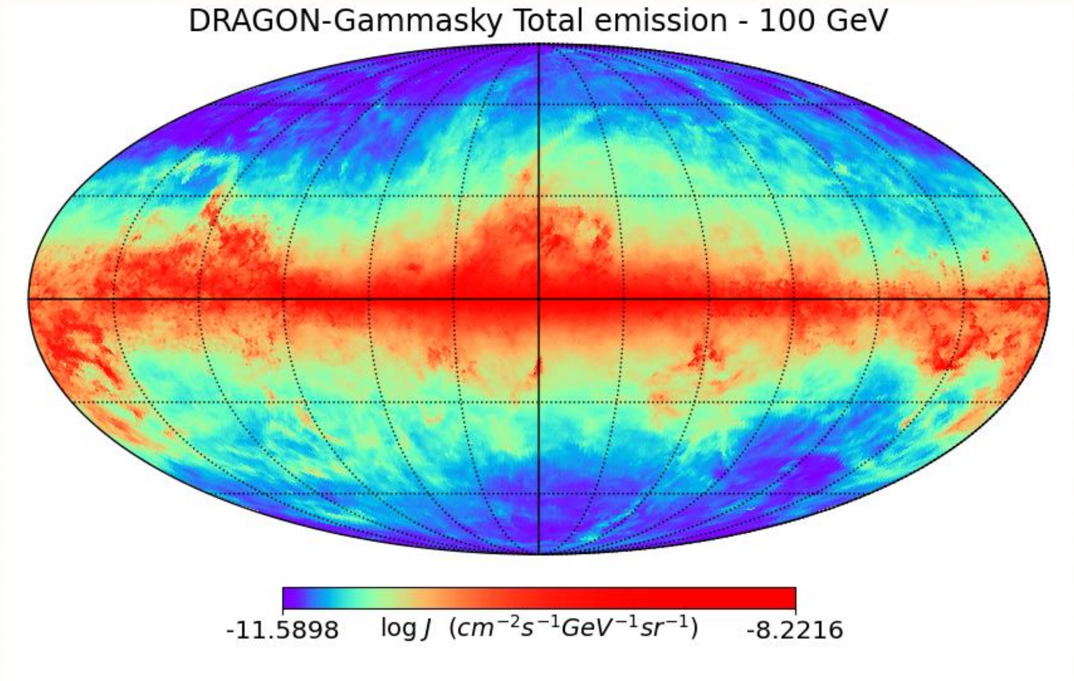


See https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

The Gamma-ray sky – Components: Diffuse

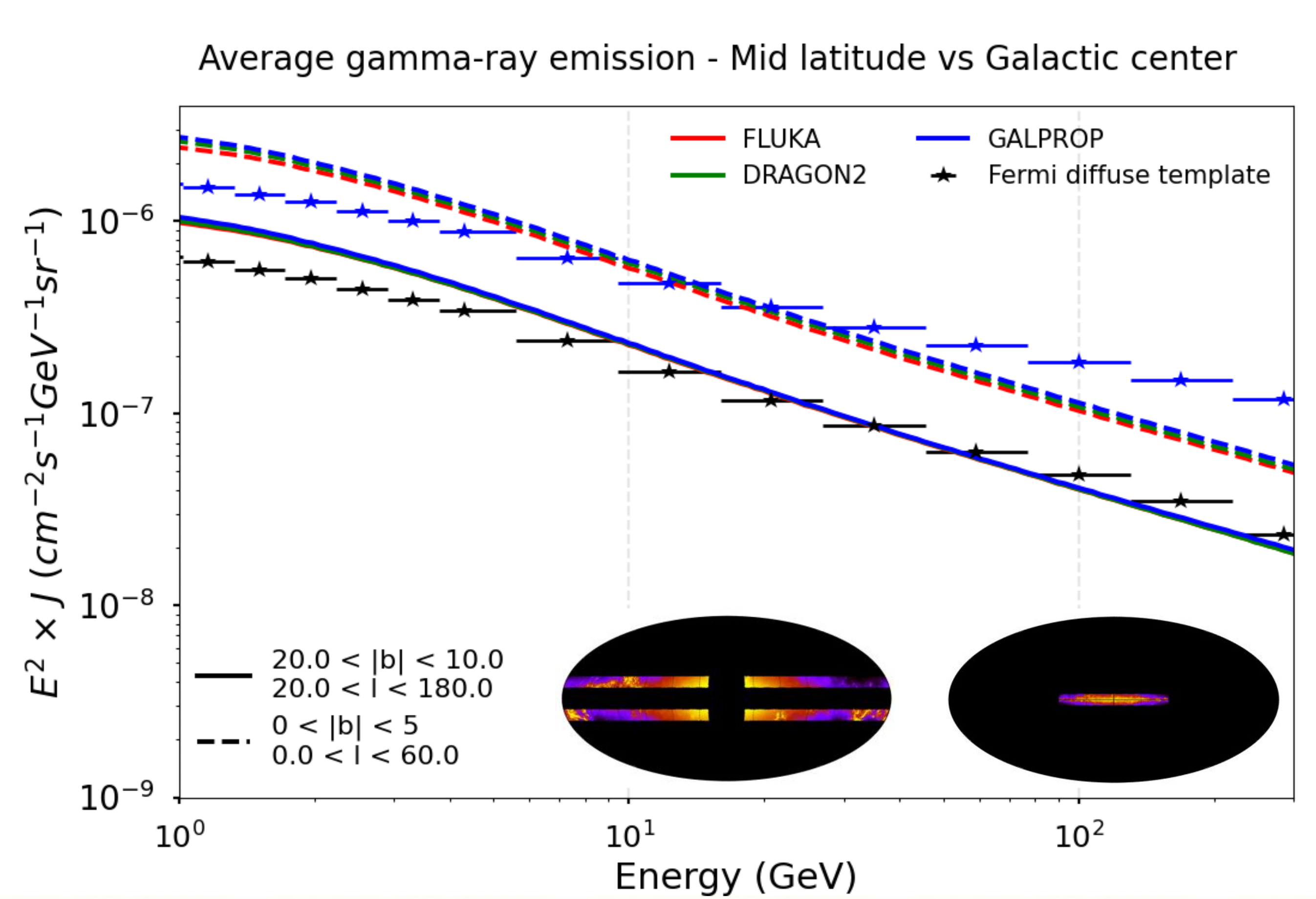
Diffuse gamma-ray sky has many components (different emission mechanisms) adding up on top of each other – Hadronic emission is the dominant one above ~ hundreds MeV





This diffuse emission is correlated with the propagation of cosmic rays in the galaxy! Dominated by protons, He (and e^-)

Galactic gamma-ray diffuse emissivity – From standard models



P.D.L. *PhD thesis (2021) ArXiv:*2202.07063

Main uncertainties in the IGRB

- CR propagation ingredients
- Gas distributions: XCO map factor
- Source distributions
- Unresolved sources
- Extra-galactic background is uncertain at the level of ~30%
- Fermi Bubbles
- Cosmic-ray gradient problem

Galactic gamma-ray diffuse emission – Hardening towards the centre

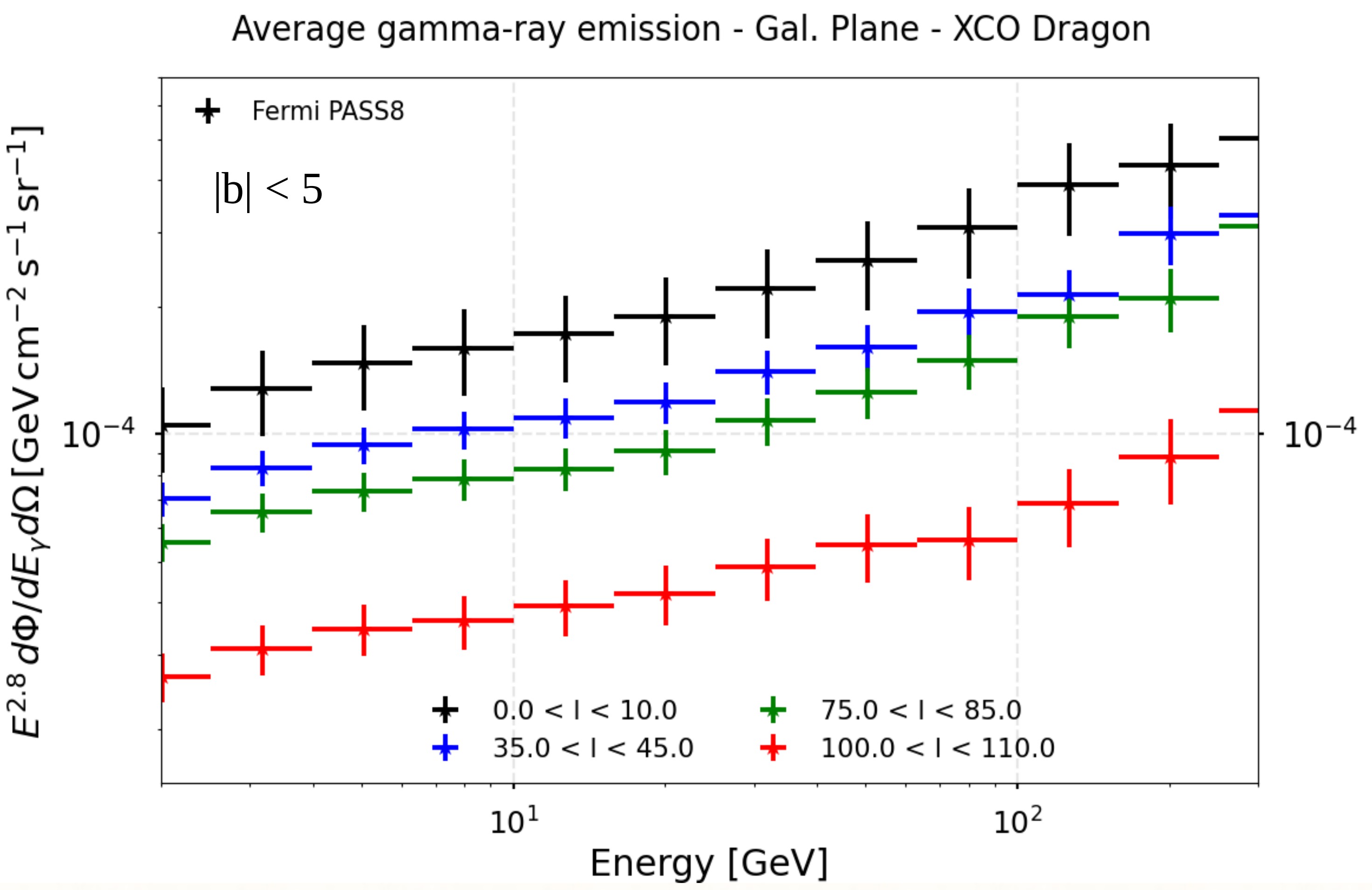
Progressive hardening of the gamma-ray diffuse spectrum towards the centre

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))



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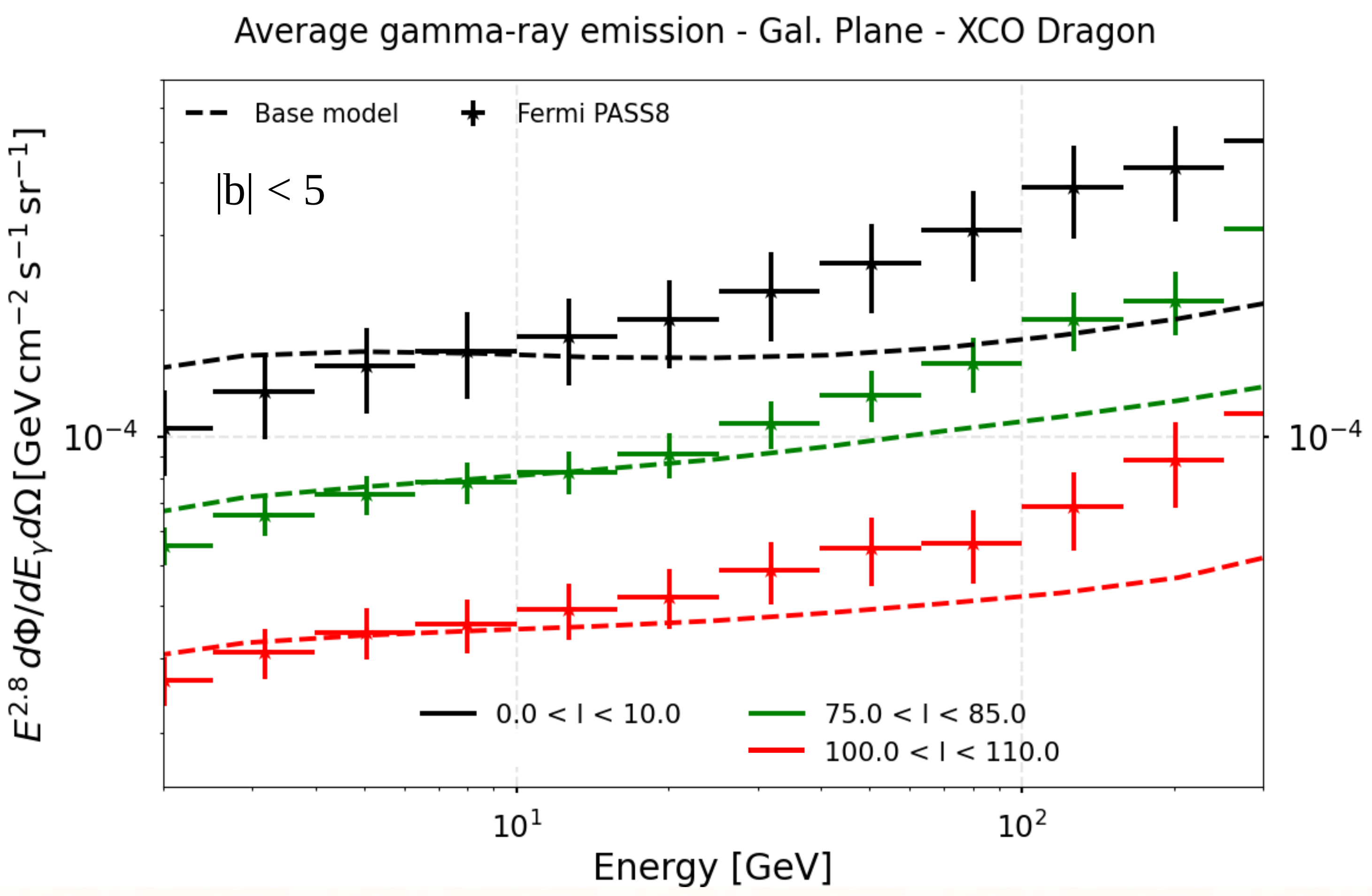

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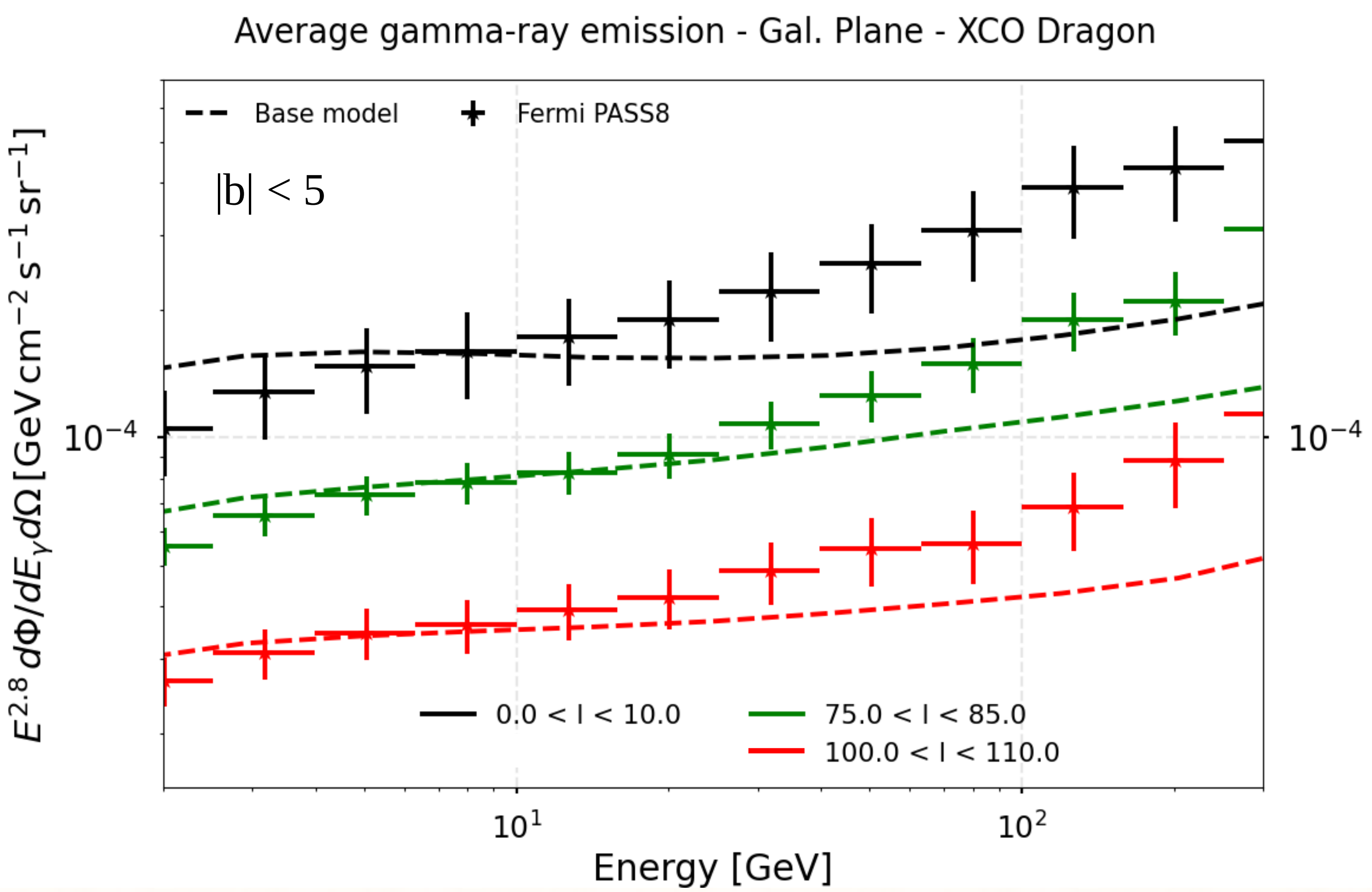
Role of unresolved sources?



Inhomogeneous diffusion model (δ → δ(R))

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

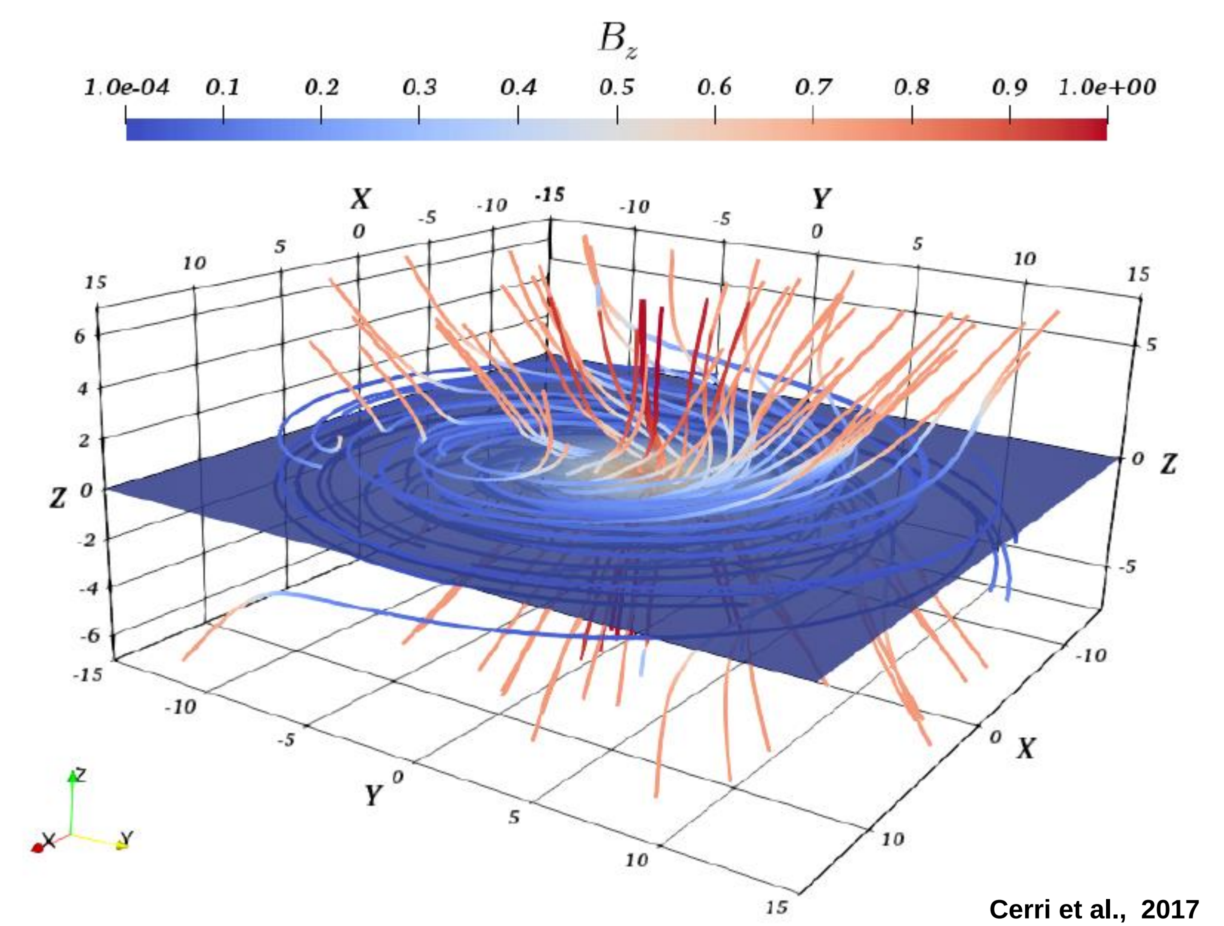
- Magnetic field intensity (and direction)

- 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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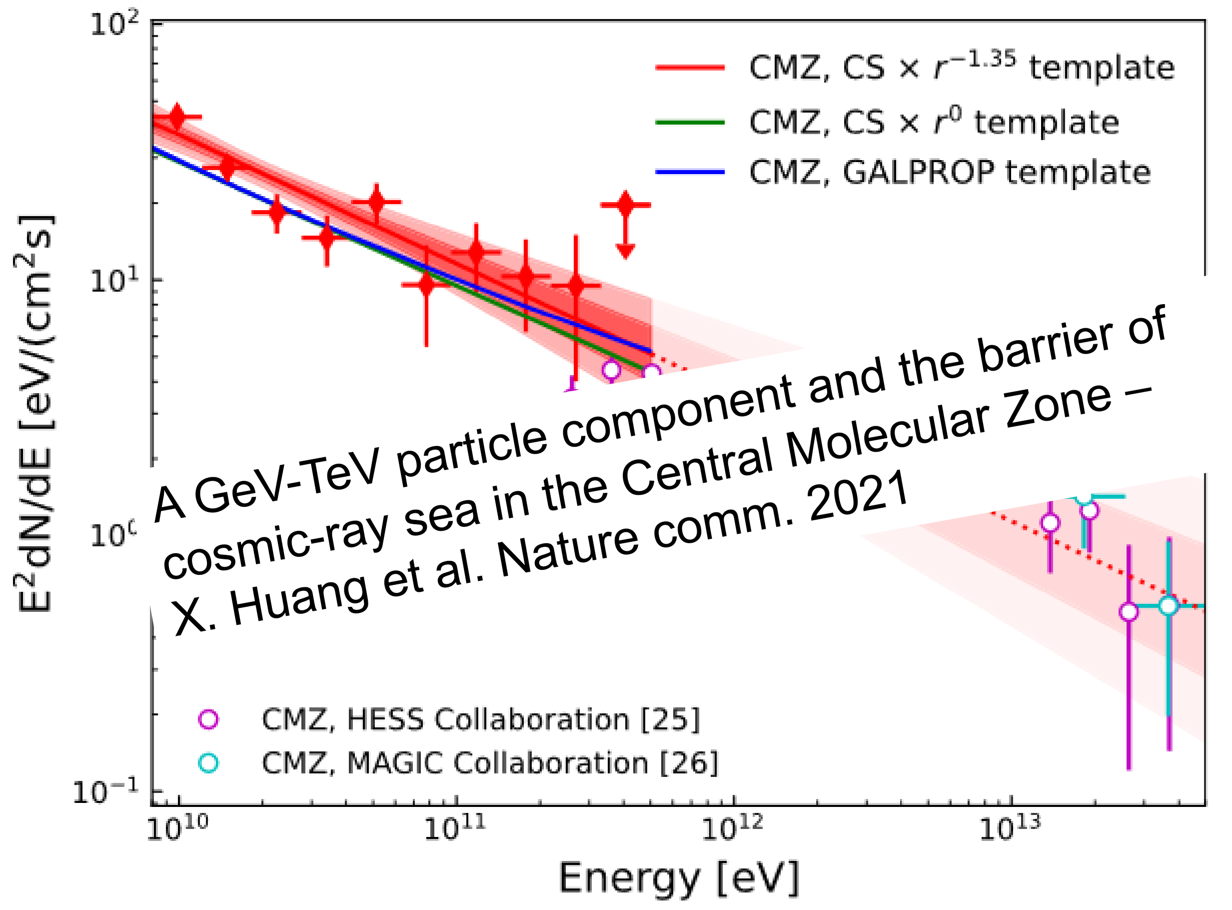
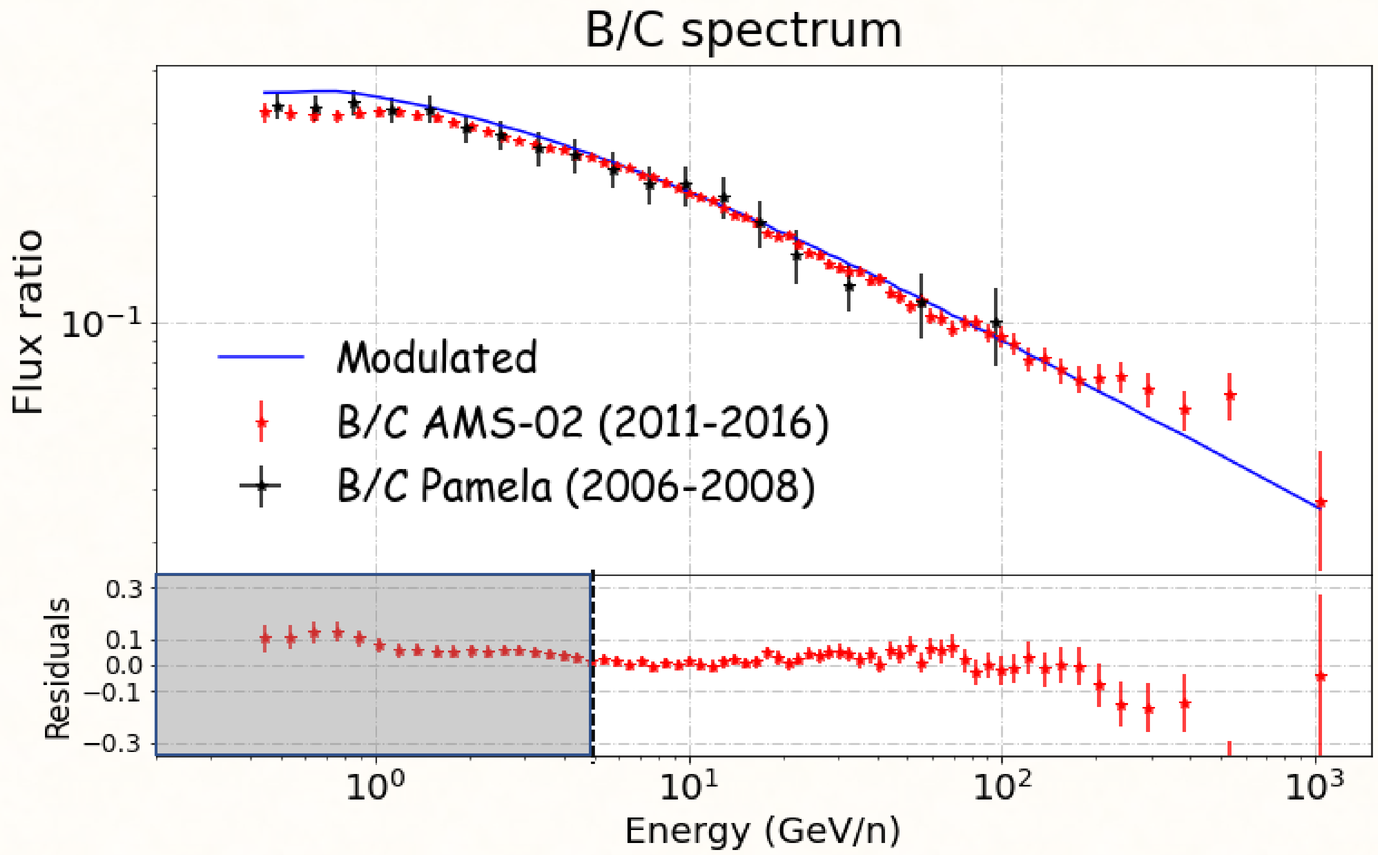


A GeV-TeV particle component and the barrier of cosmic-ray sea in the Central Molecular Zone – X. Huang et al. Nature comm. 2021

B/C spectrum from the *γ-optimized* model

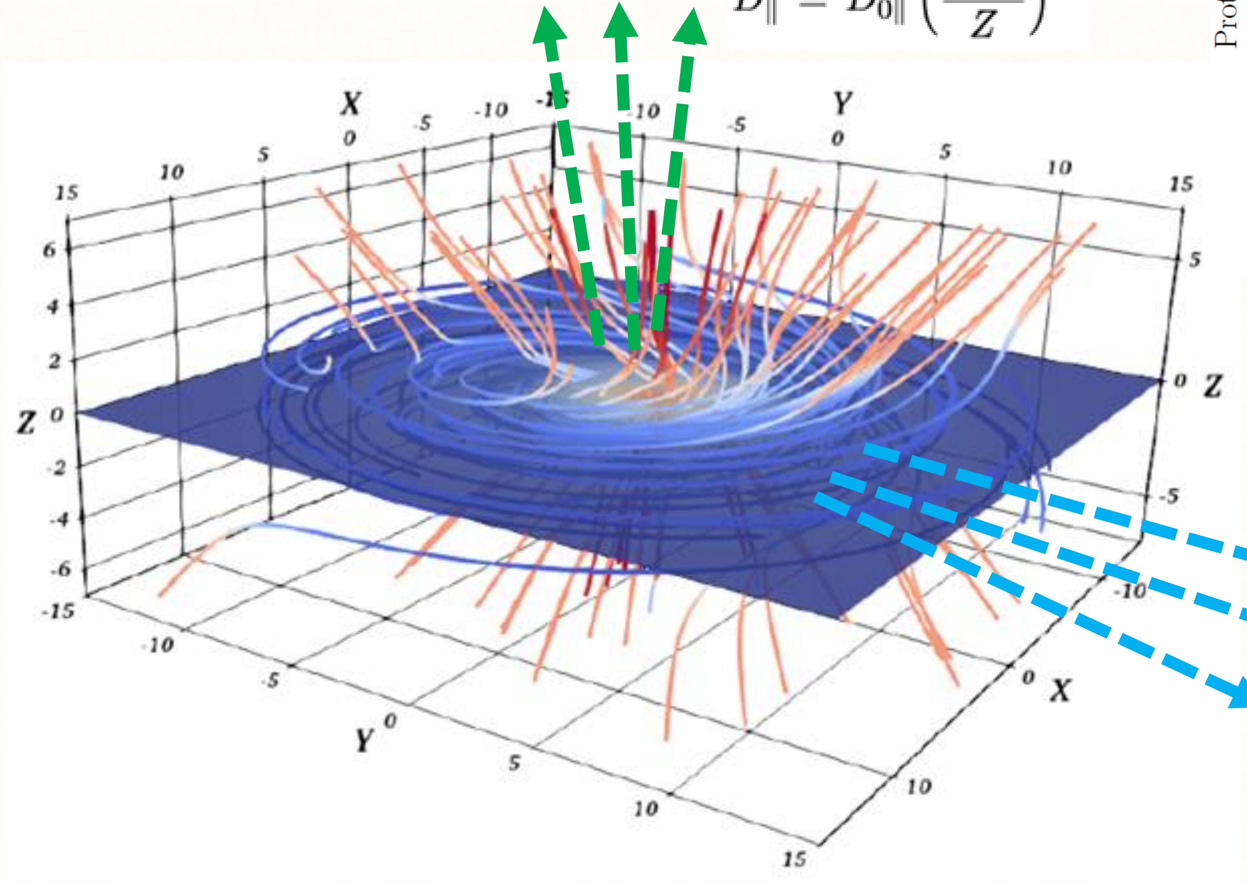


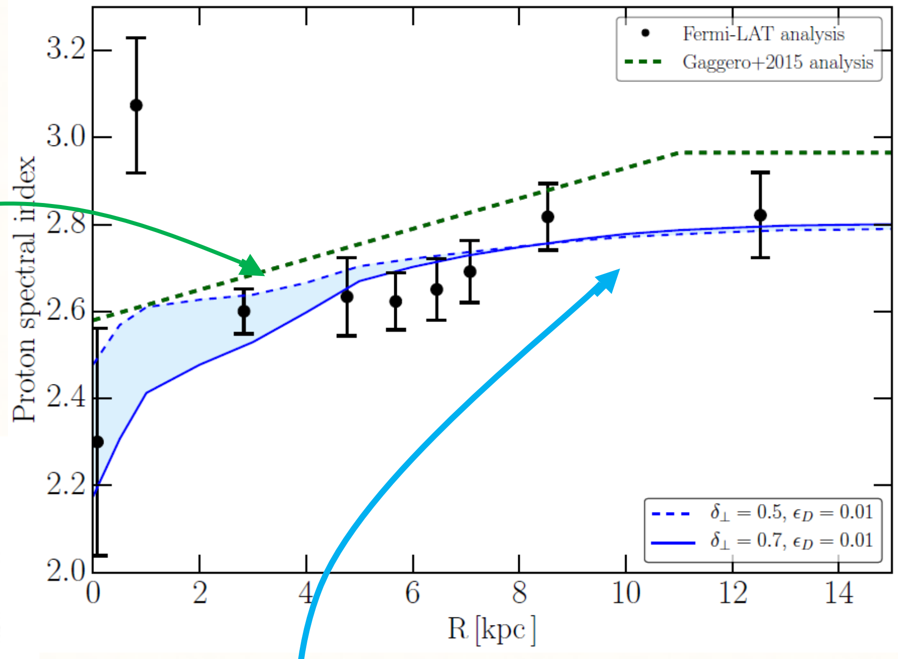
Non-uniform diffusion:

Anisotropic diffusion (Respect to the magnetic field)

Mainly parallel diffusion

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





Cerri et al JCAP10(2017)019

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

Mainly perpendicular diffusion

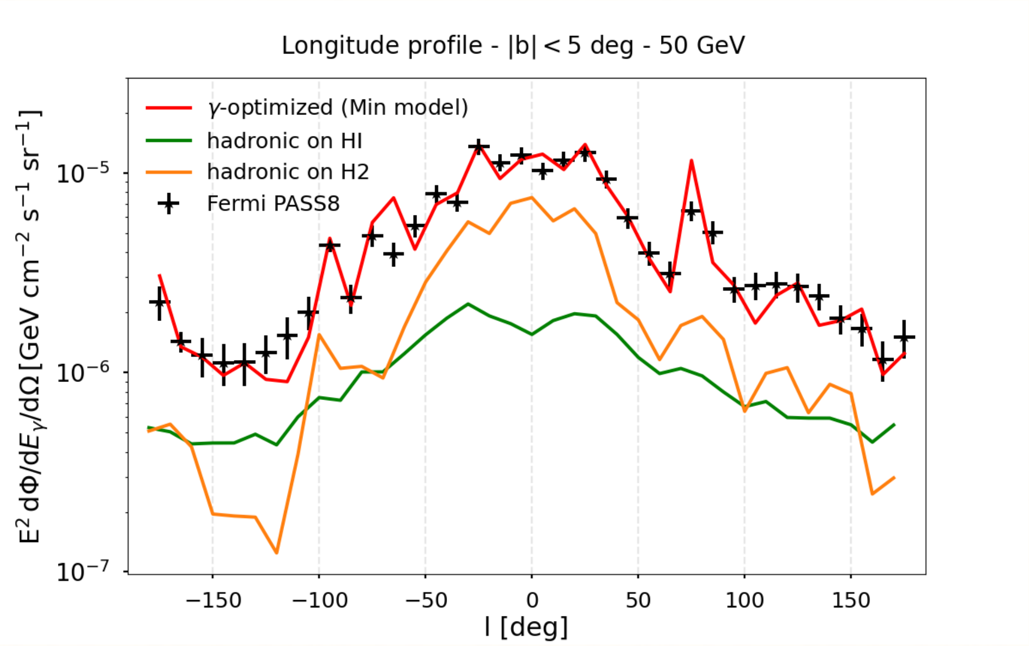
$$D_{\perp} = D_{0\perp} \left(\frac{p_{\rm GeV}}{Z}\right)^{\delta_{\perp}}$$

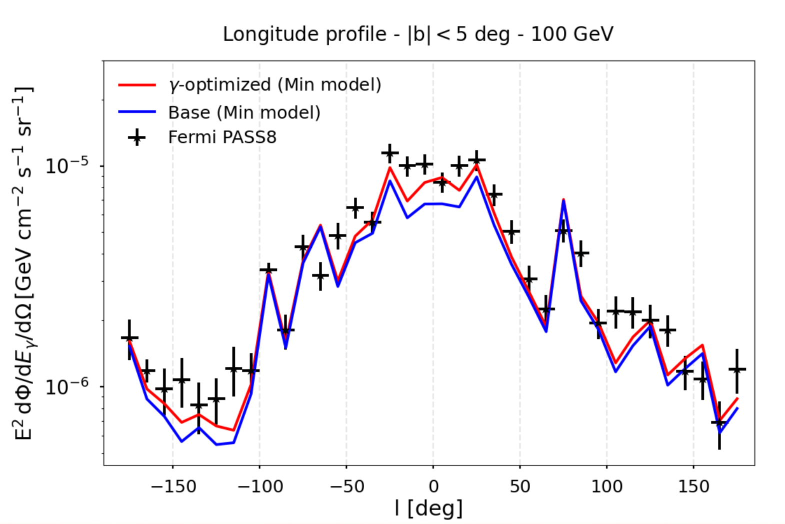
γ-optimized model vs Fermi

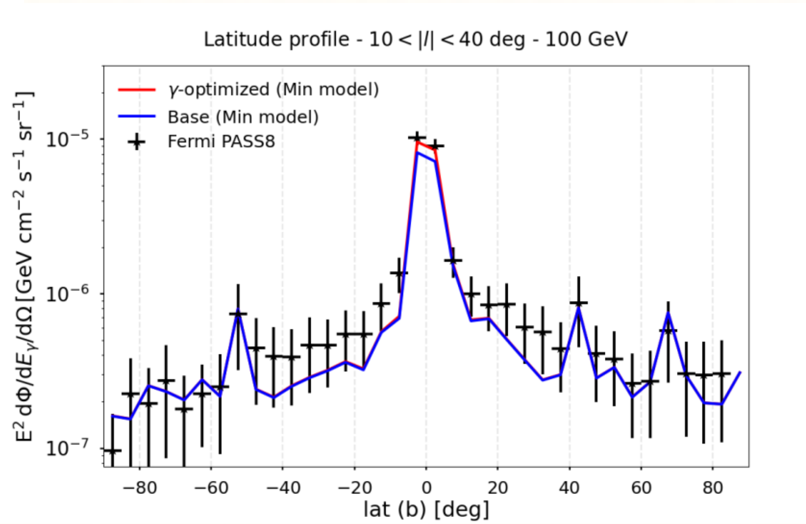
ISM gas distribution based on the ring gas model developed by Q. Remy

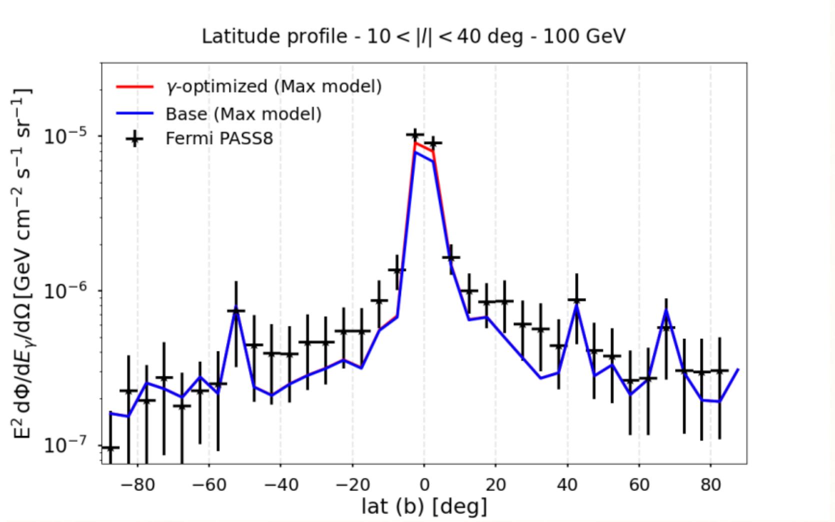
ISRF distribution (CMB + IR + Stellar) from Vernetto&Lipari Phys. Rev. D 94, 063009

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



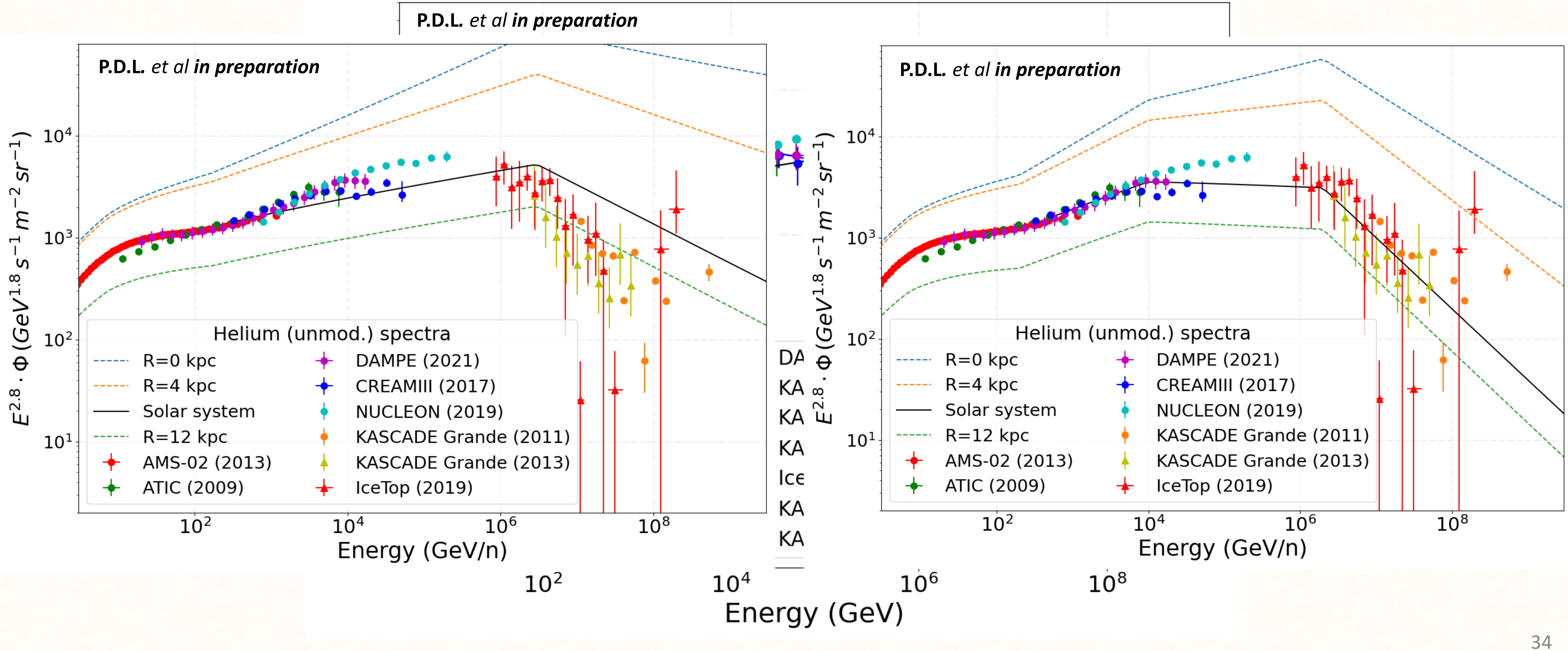






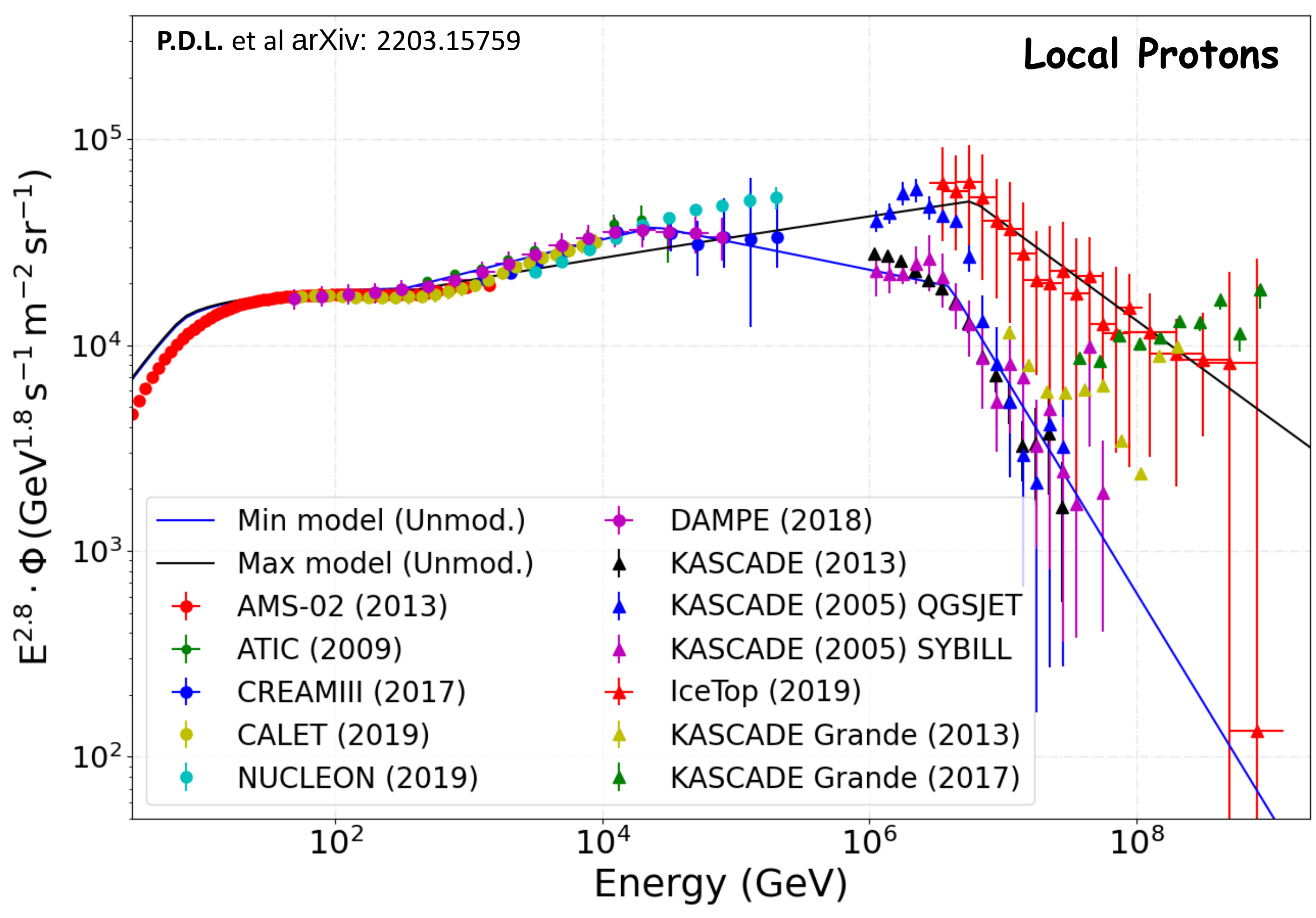
Inhomogeneous diffusion model (δ → δ(R))

Different interpretations of local data… <u>Local sources vs global features</u>



Inhomogeneous diffusion model (δ → δ(R))

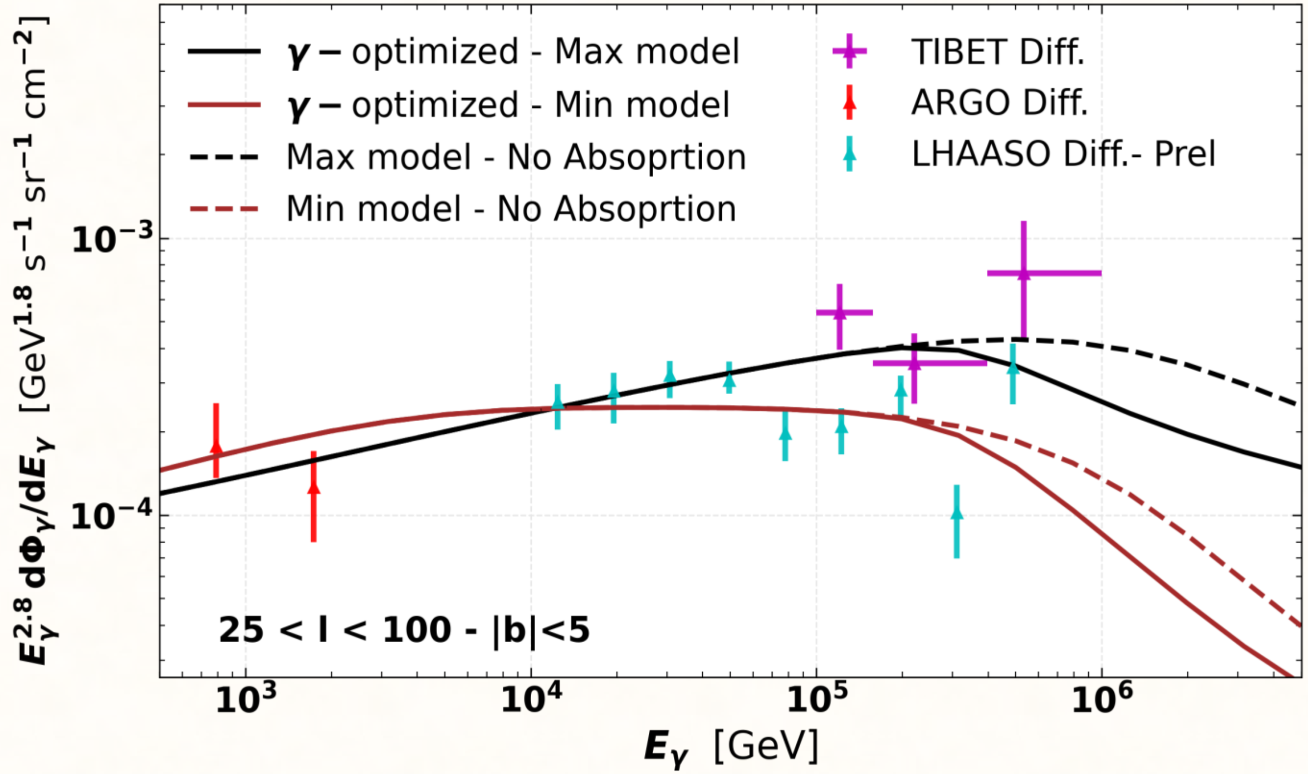
Different interpretations of local data… <u>Local sources vs global features</u>



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 <u>they do not represent the full uncertainty involved</u> !!

Inhomogeneous diffusion model

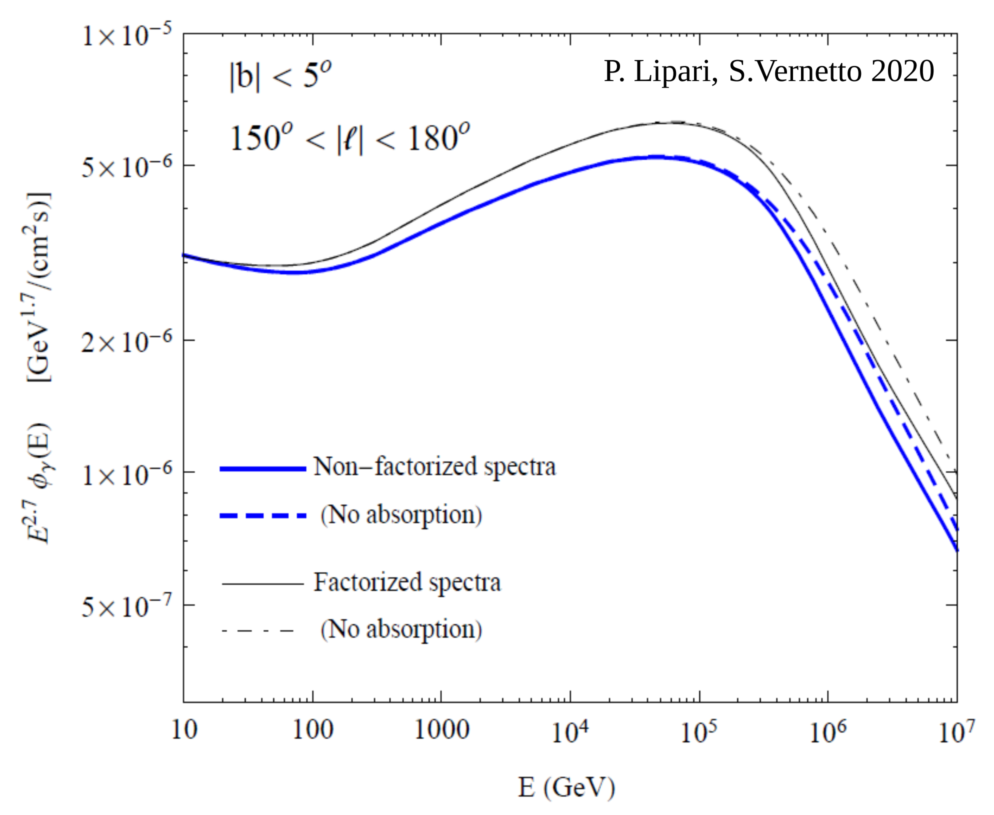
The diffuse emission meets TeV data



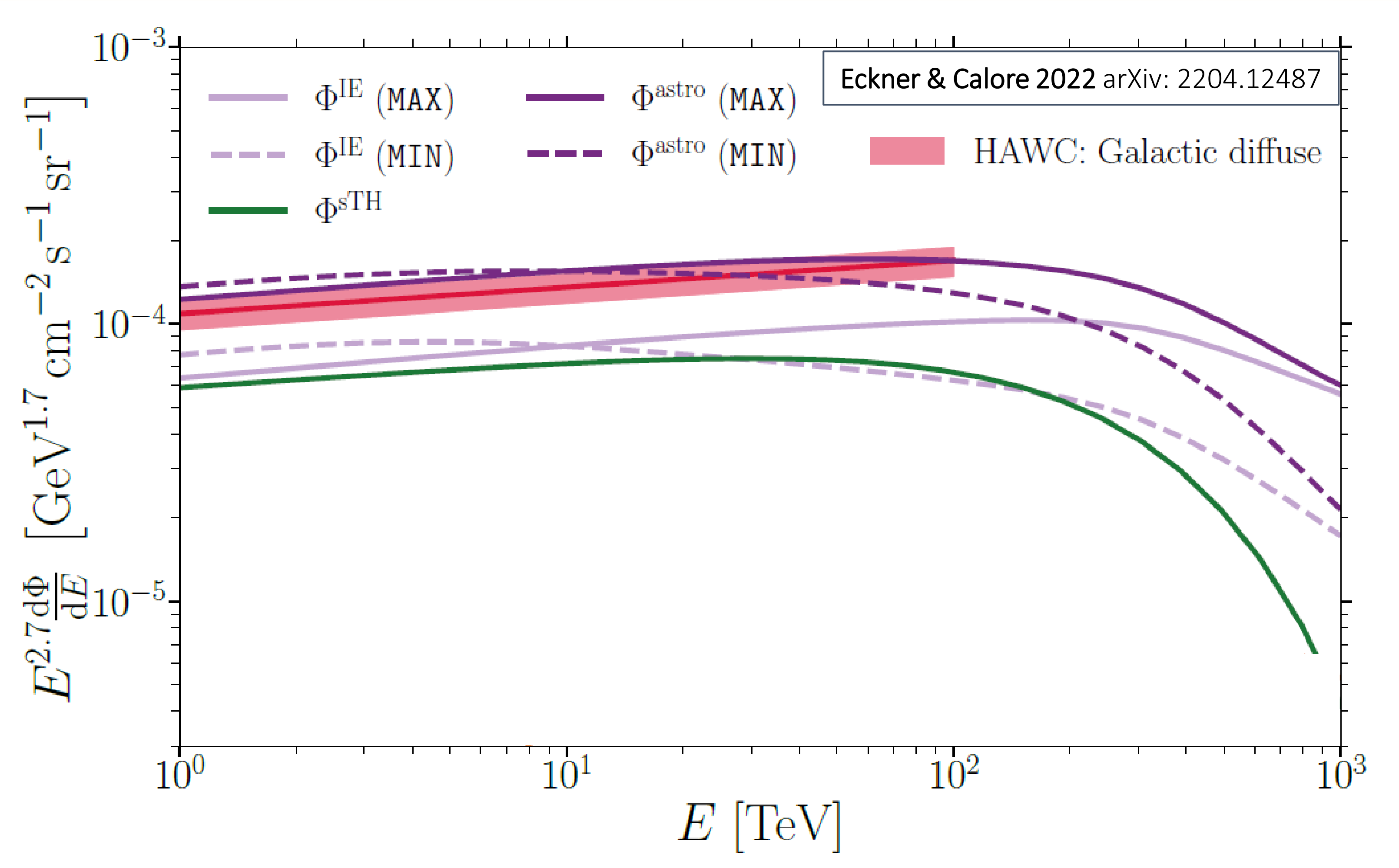
Absorption of very high energy gamma rays becomes important

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

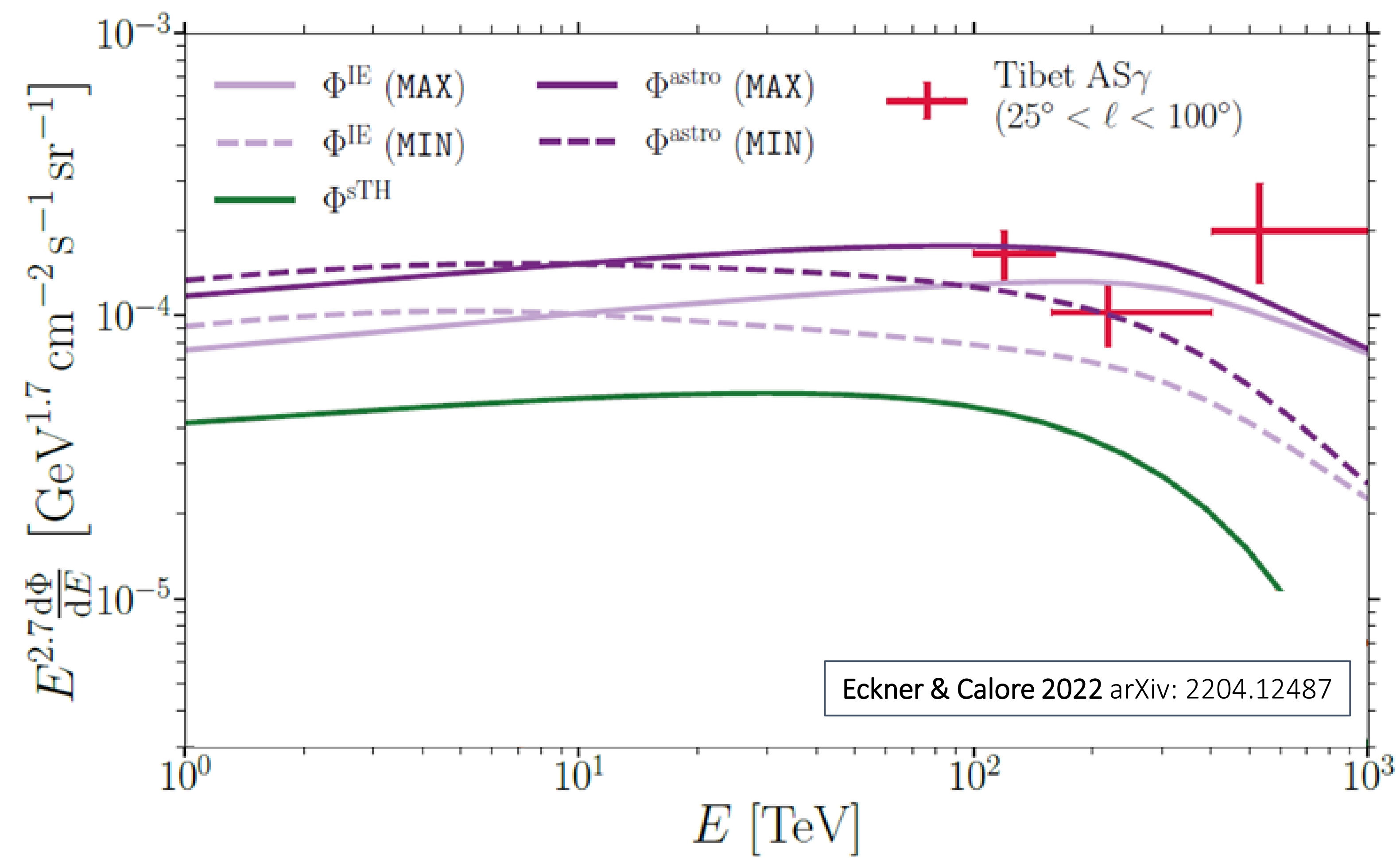
Absorption from the CMB dominates over the other ISRFs (IR from dust, Optic and UV from stars and extra-galactic background light)



MAX/MIN + Unresolved emission vs HAWC data

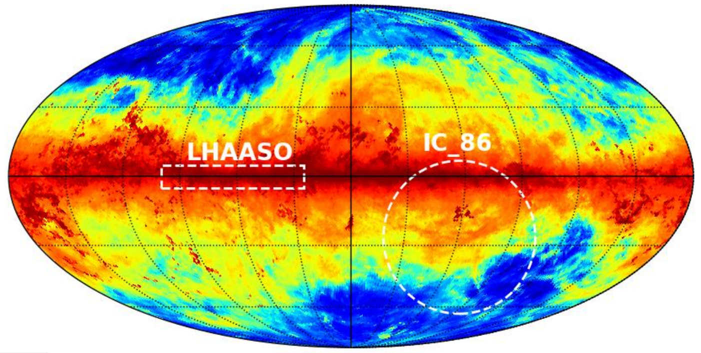


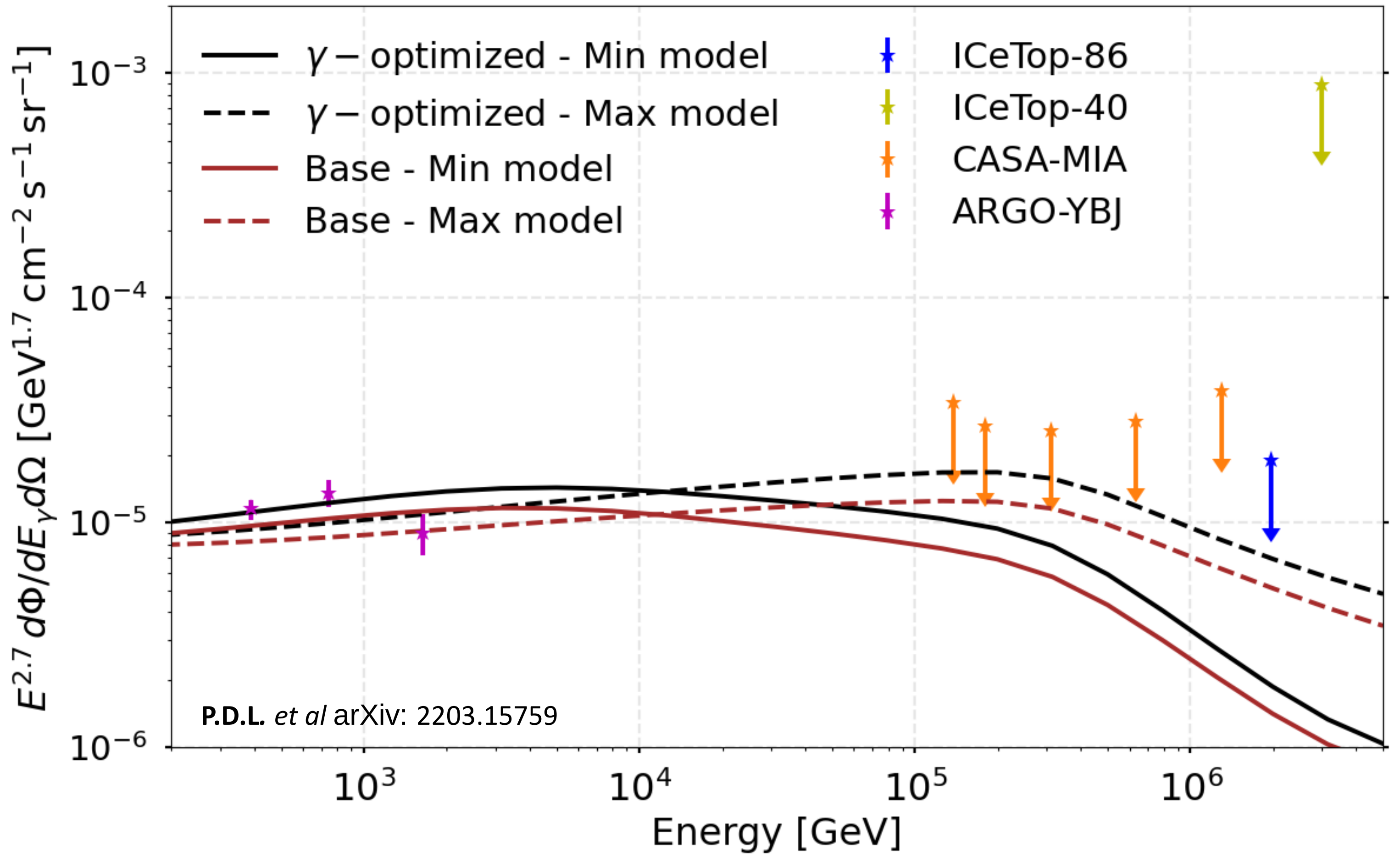
MAX/MIN + Unresolved emission vs TIBET data



Inhomogeneous diffusion model

The diffuse emission meets TeV data



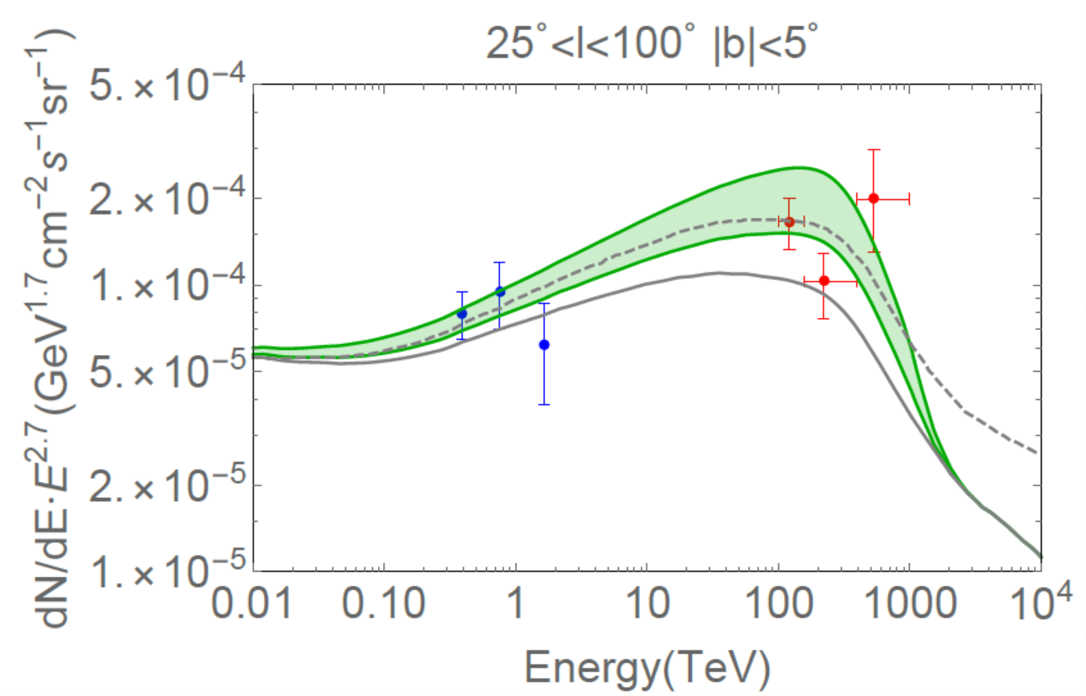


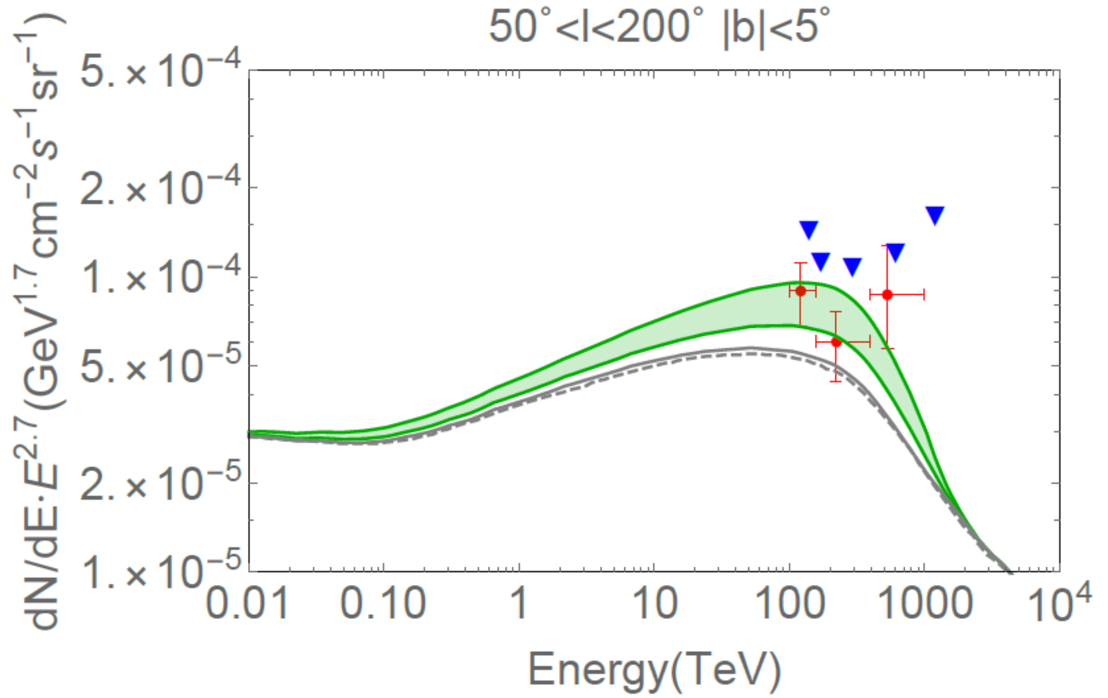
Within the **region of sensitivity of IceTop** there is little difference between models conventional diffusion and the gamma-optimized models

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

The role of unresolved sources

Vecchiotti et al (2021), *ArXiv:*2107.14584v1



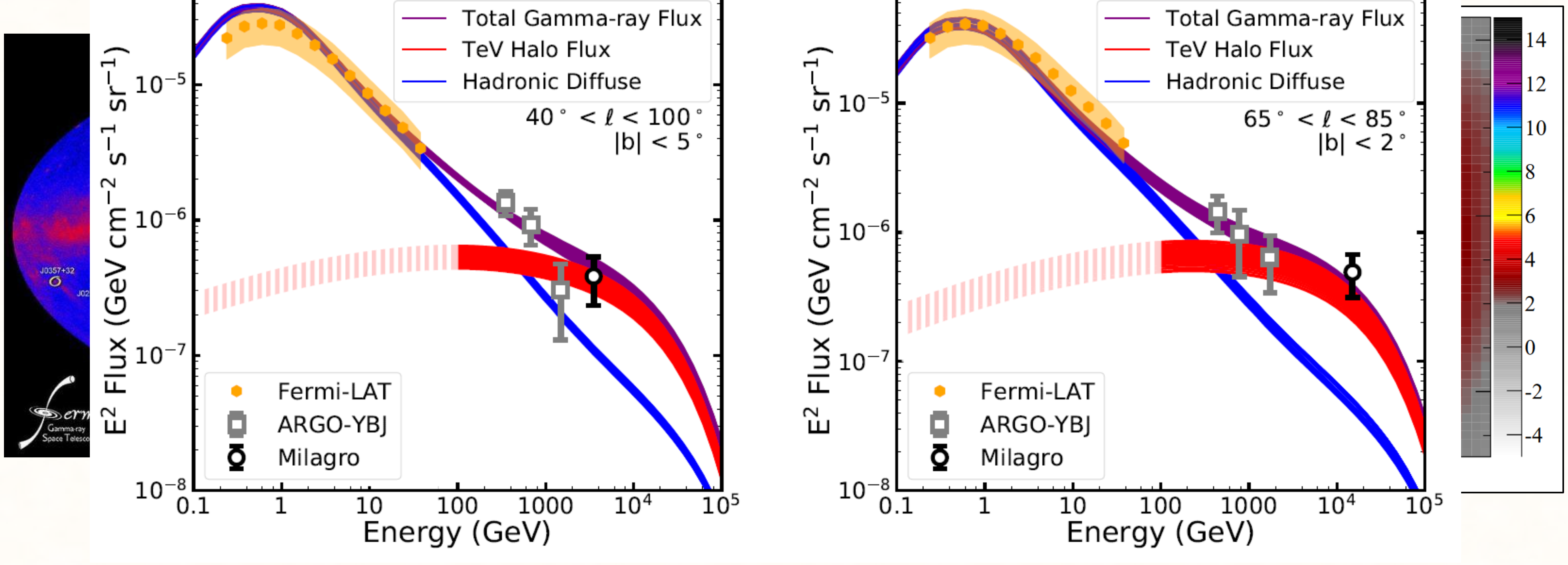


"Unresolved source contribution is not negligible for E > 1 TeV and becomes progressively more relevant as energy increases. This is a natural consequence of the fact that sources are expected to have, on average, harder spectrum than CR diffuse emission."

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

Probably similar inhibited diffusion is present around every source injecting CRs …

T. Linden, B. Buckman 2017



Is this really important?

- 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?

Semenov, Krtavsov, Caprioli 2021