Beyond Standard Diffusion: The Impact of Inhomogeneous CR Propagation and Anisotropies

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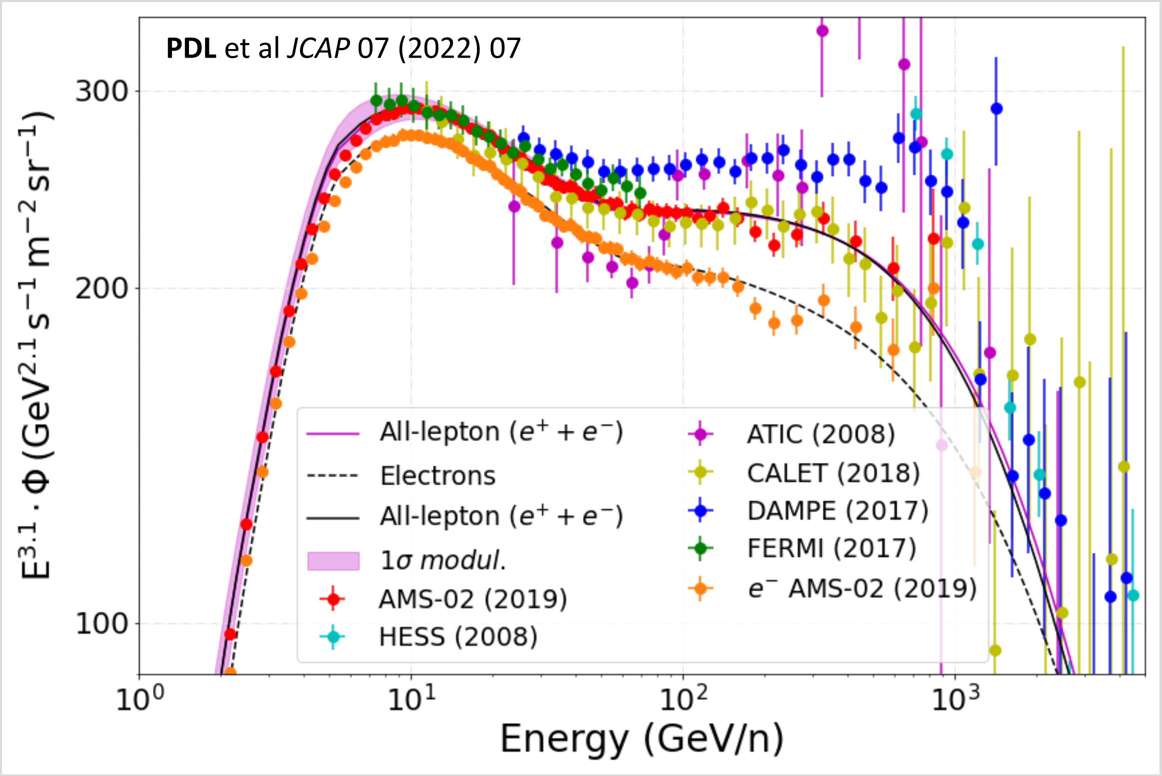
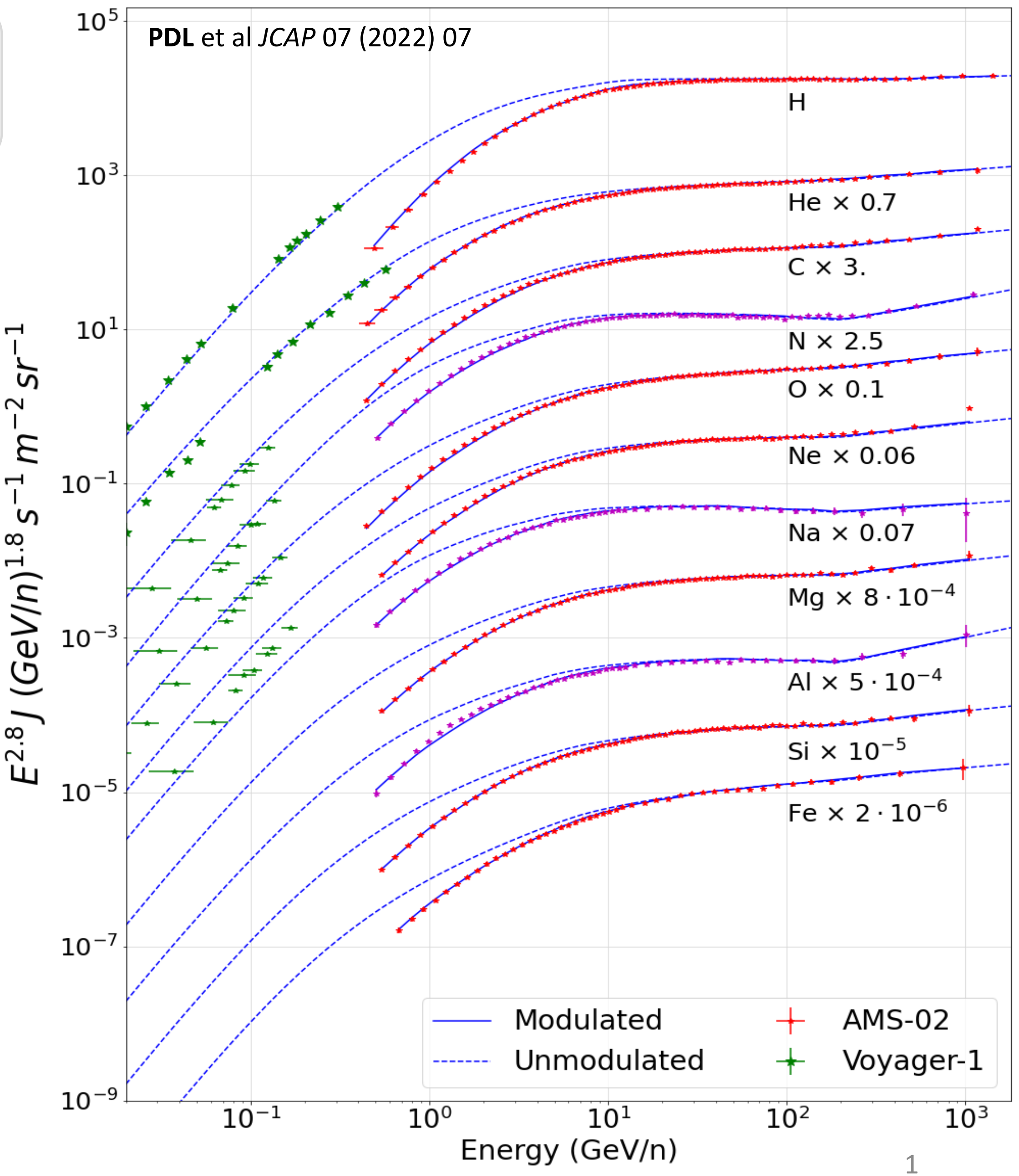
Standard picture of Gal. CRs

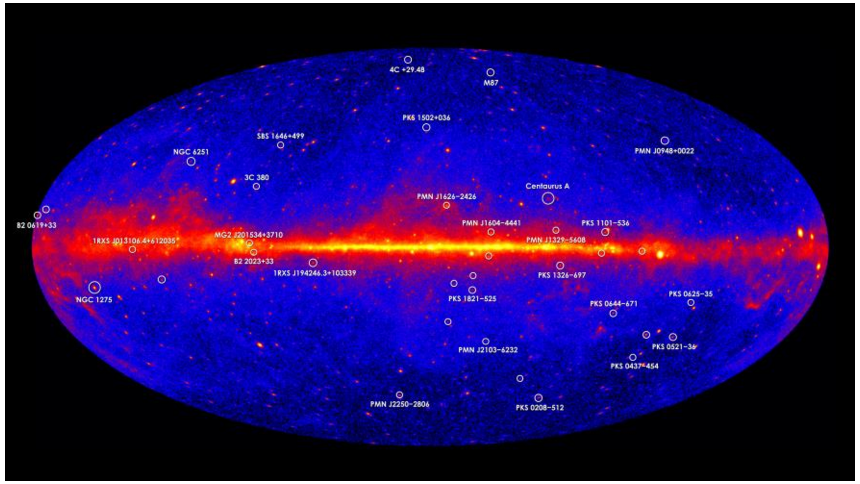
In the standard paradigm, Galactic CR sources are SNRs, which inject them following (broken) power-laws and which diffuse homogenously

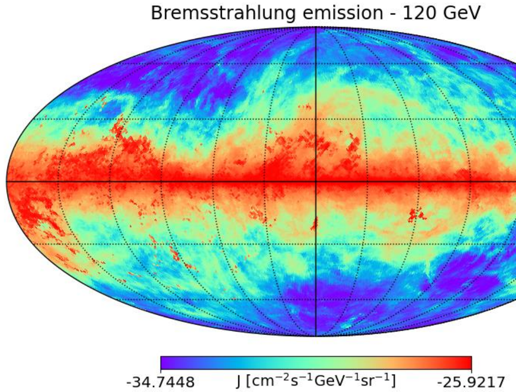




The gamma-ray diffuse sky

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

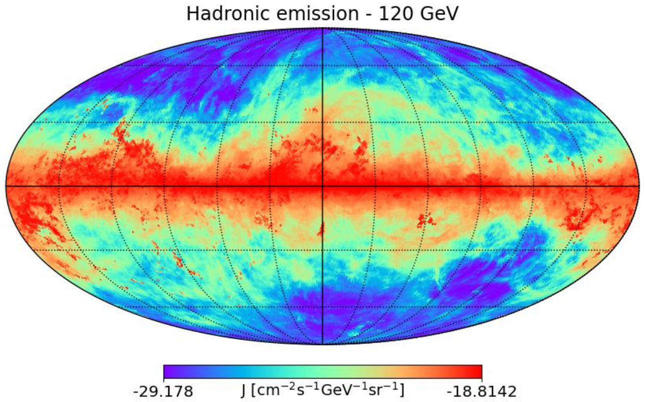


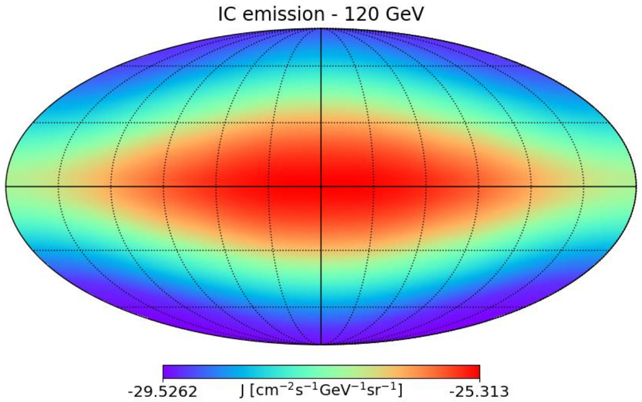


$e + N \rightarrow e' + \gamma' + \mathrm{N}$

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

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





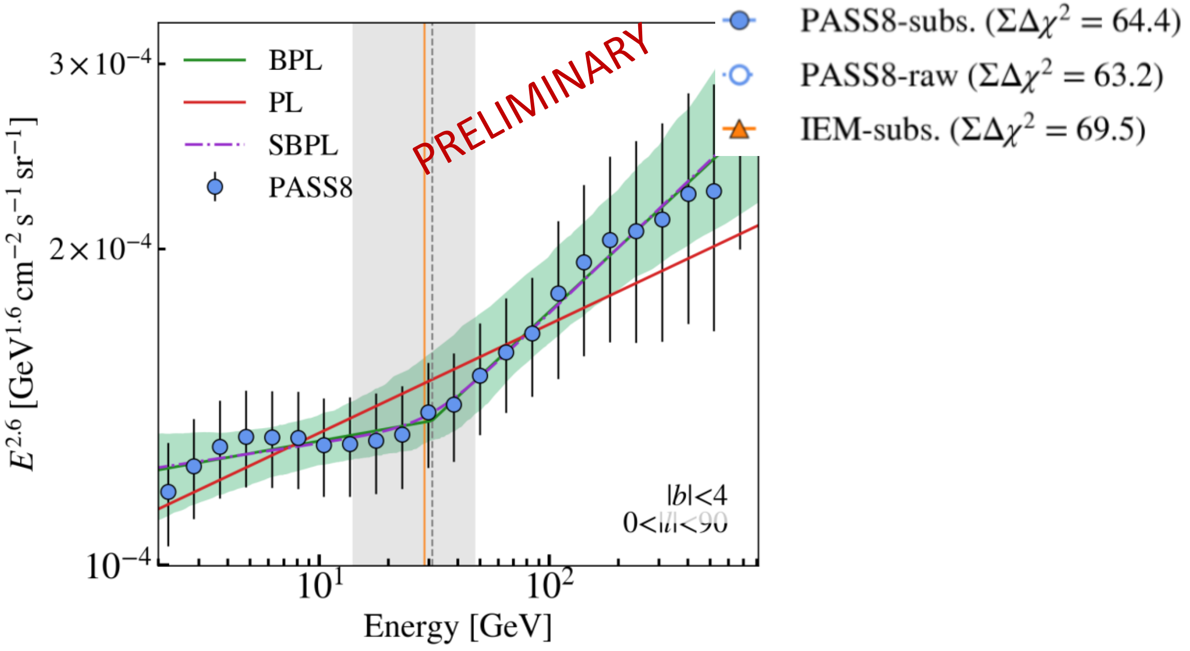
Hadronic (and **Bremss.**) emission follows the **ISM gas distribution**

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

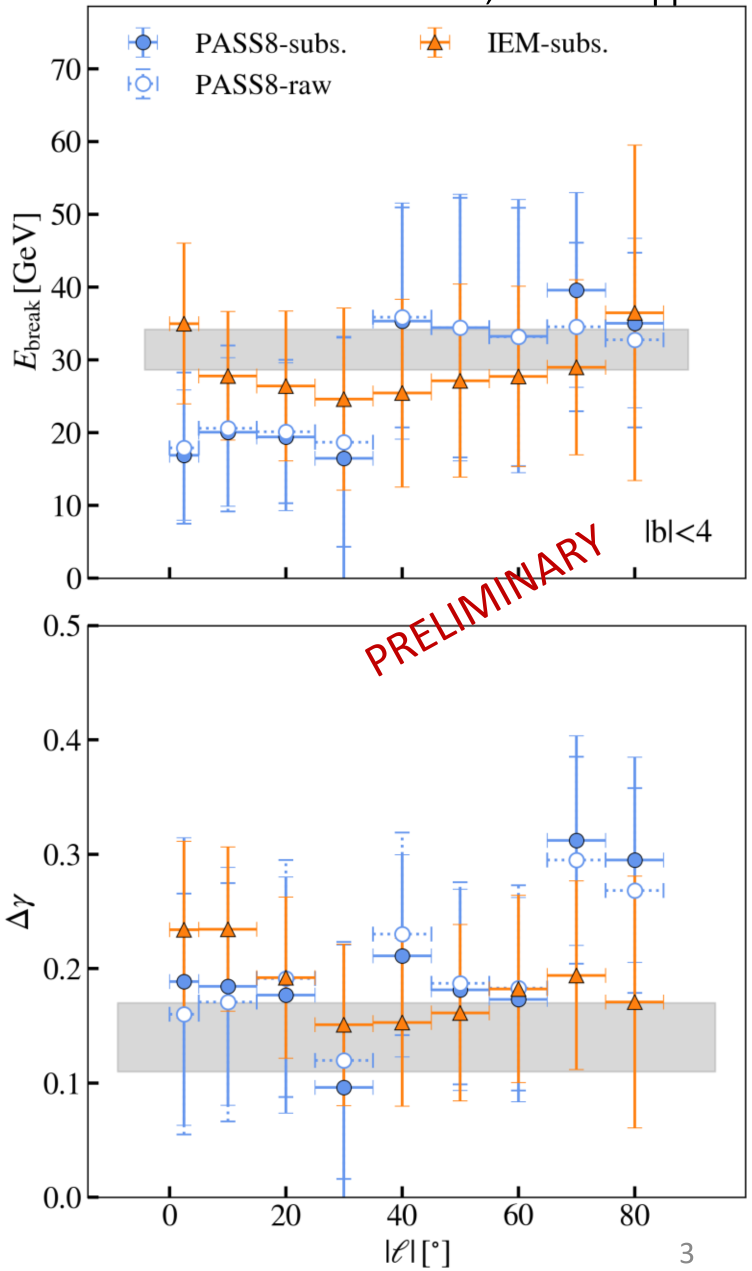
The CR "Hardening" at 300 GV

♦ Clear evidence of the local CR break in Fermi-LAT data
  - It provides evidence that the break at ~300 GV is a global feature (i.e. appears consistently in all windows)
  - The change in spectral slope roughly follows that from a transition from Kolmogorov to Kraichnan turbulence

♦ Searches with CTA will help unveil the origin of the ''DAMPE bump''



Valenciano, **PDL+** To appear

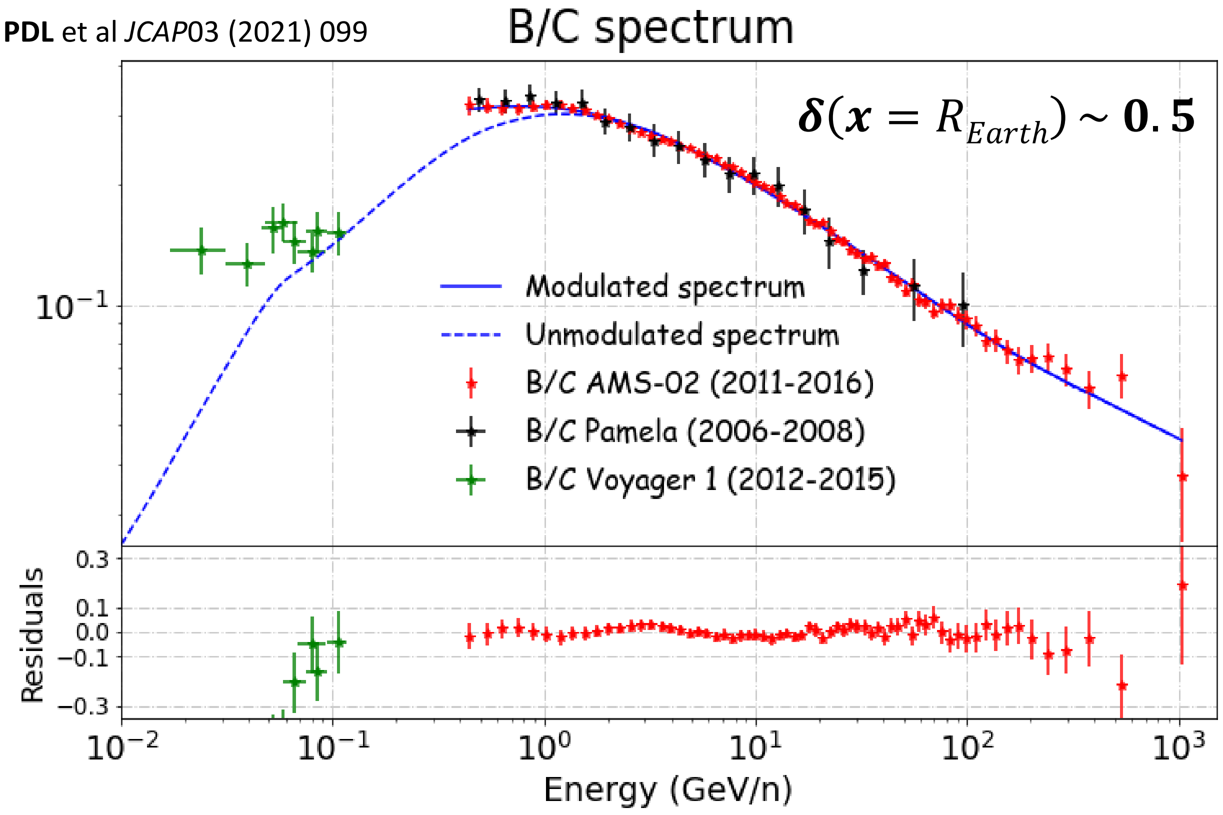


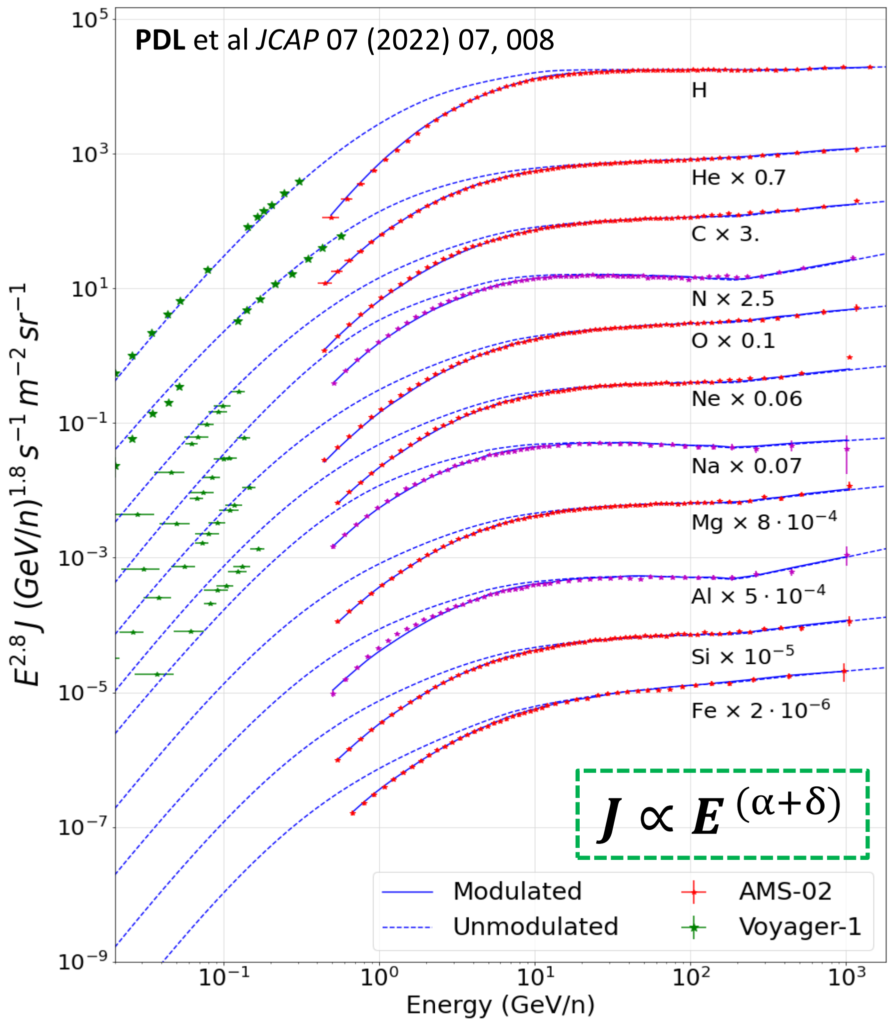
The Galactic gamma-ray diffuse sky – Local cosmic rays

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

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

PDL et al *JCAP*03 (2021) 099





The Galactic gamma-ray diffuse sky – Non-uniform transport?

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:

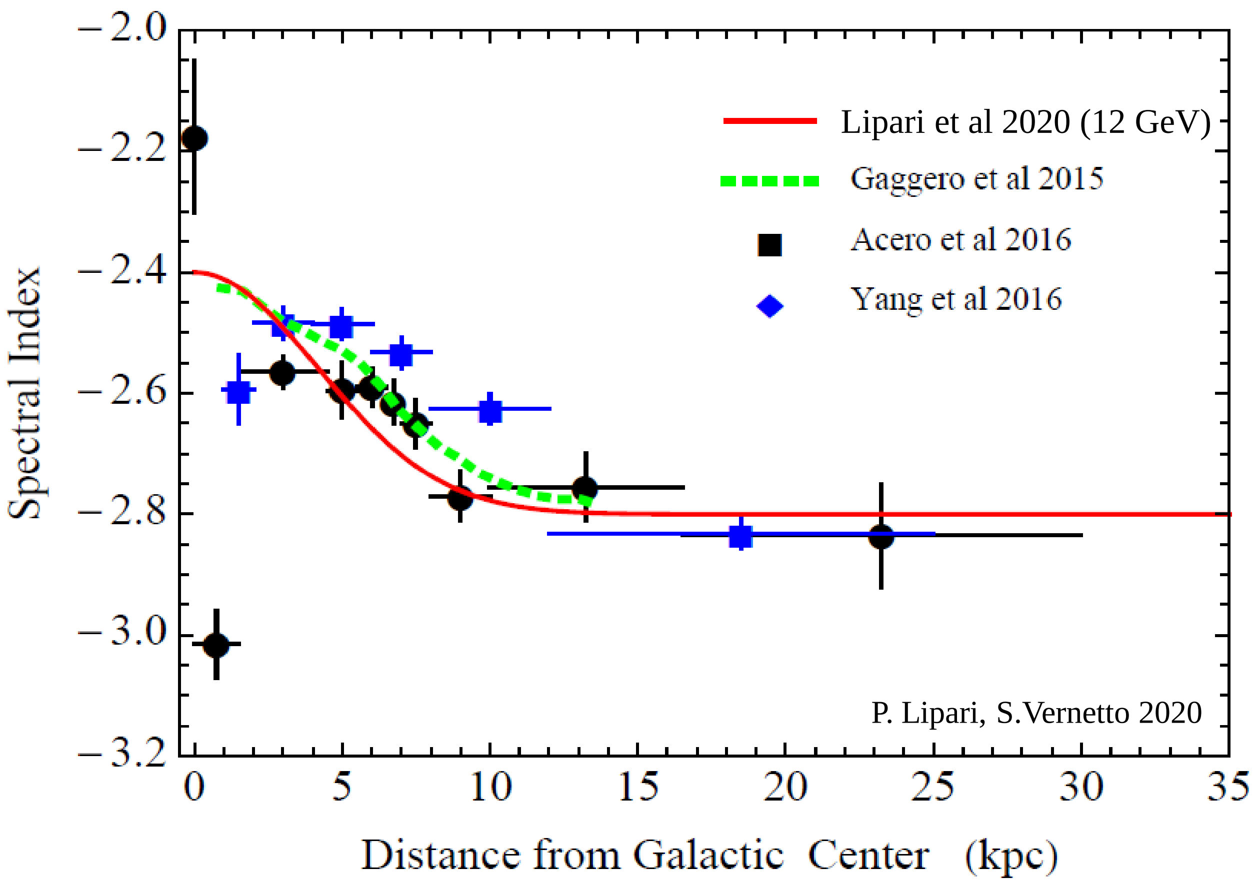
Diffusion effects?

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

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

Unresolved sources?

Source injection not isotropic?

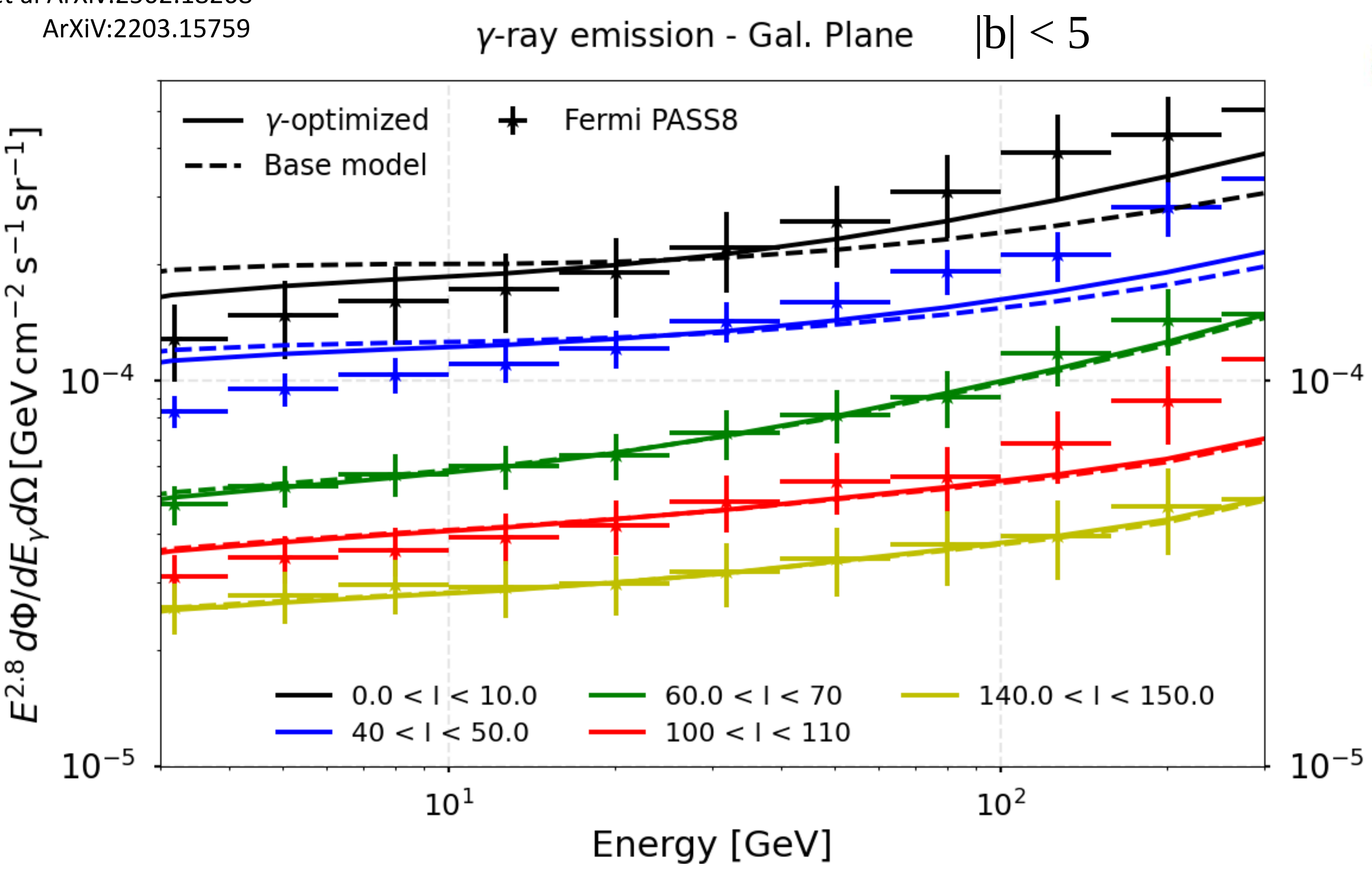


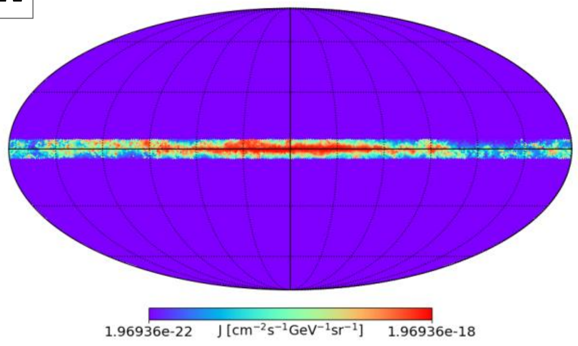
Inhomogeneous diffusion model

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

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

PDL et al ArXiv:2502.18268
ArXiV:2203.15759





DRAGON2

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

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

Comparing to Fermi-LAT

Source emission (4FGL-DR2 cat.), EGB and unresolved emissions added to compare with data

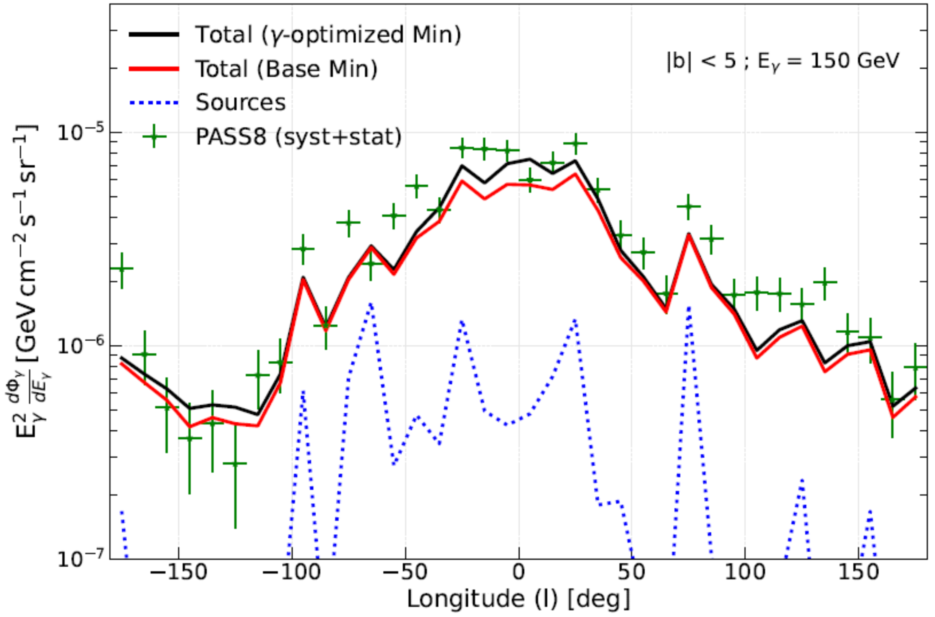
Only the XCO factor slightly tuned to improve normalization with respect to Fermi-LAT data

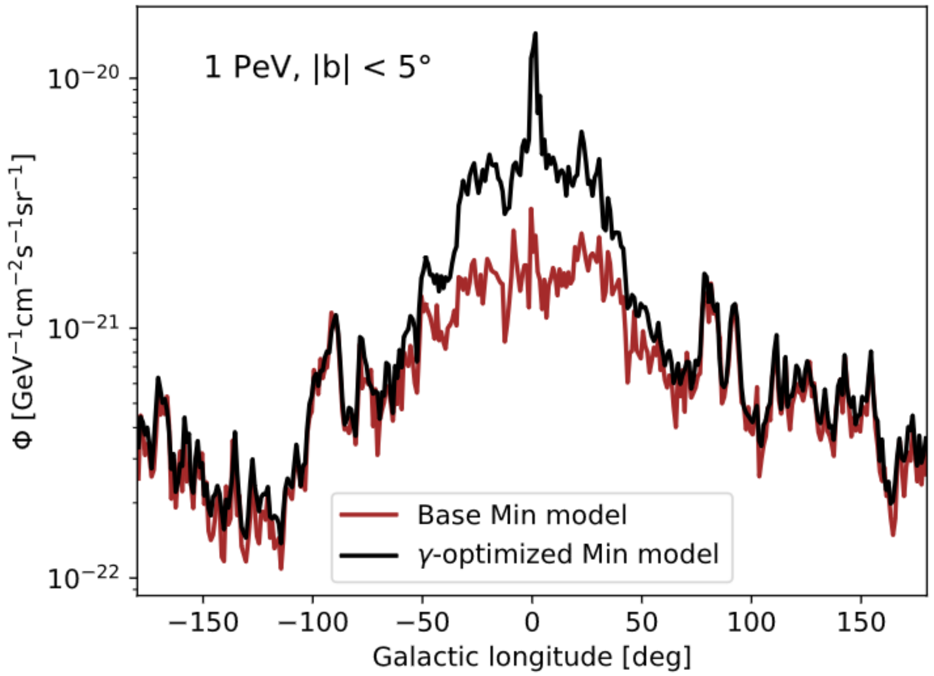
Good spectral and morphological agreement even though we do not carry out a dedicated fit

We expect a huge difference on the diffuse high-energy neutrino and gamma-ray flux around the Galactic Center!

PeV diffuse emission measurements could confirm such prediction.

Important implications for CTAO or SWGO, and for dedicated studies of the Galactic Centre





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.

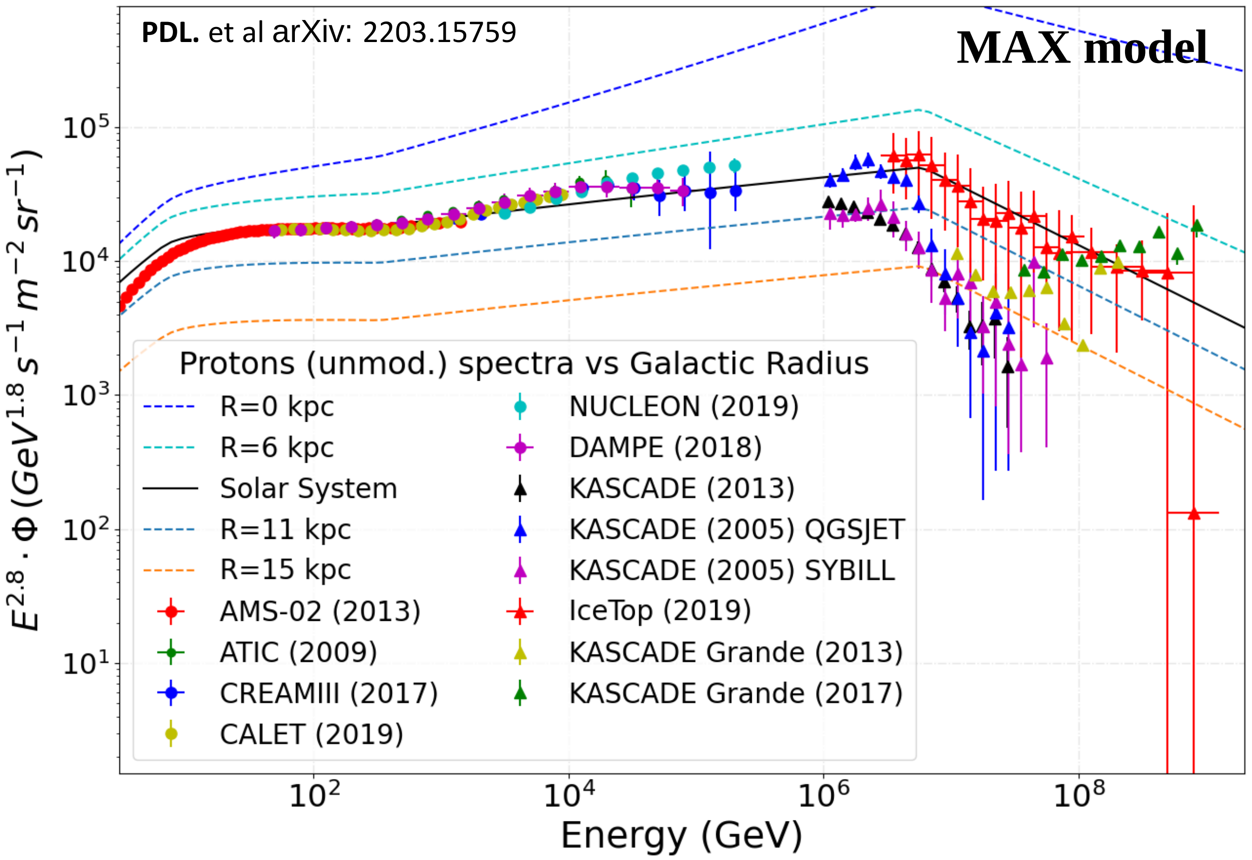
MAX model adopted connects AMS-02 data with IceTop

MIN model adopted connects the DAMPE "bump" with KASCADE

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

Different interpretations of local data

Local sources vs global features



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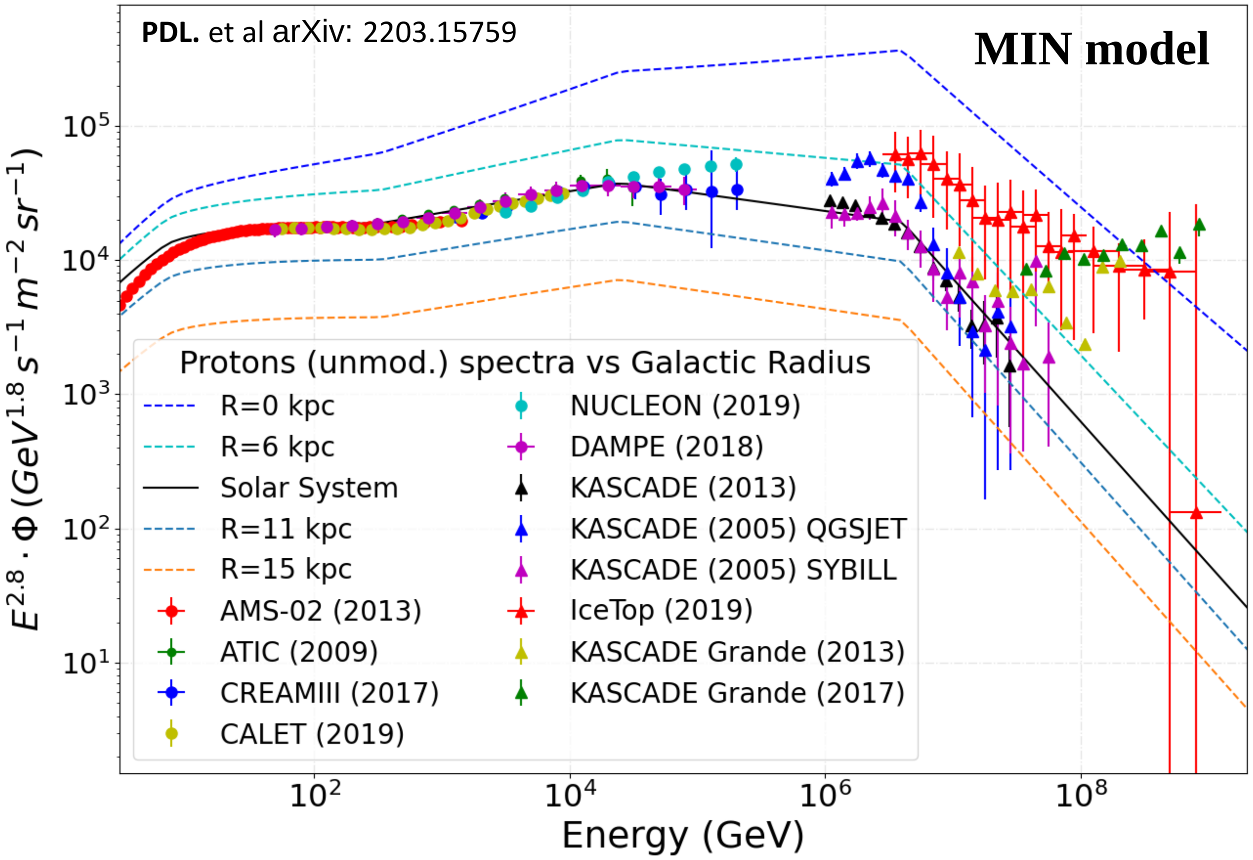
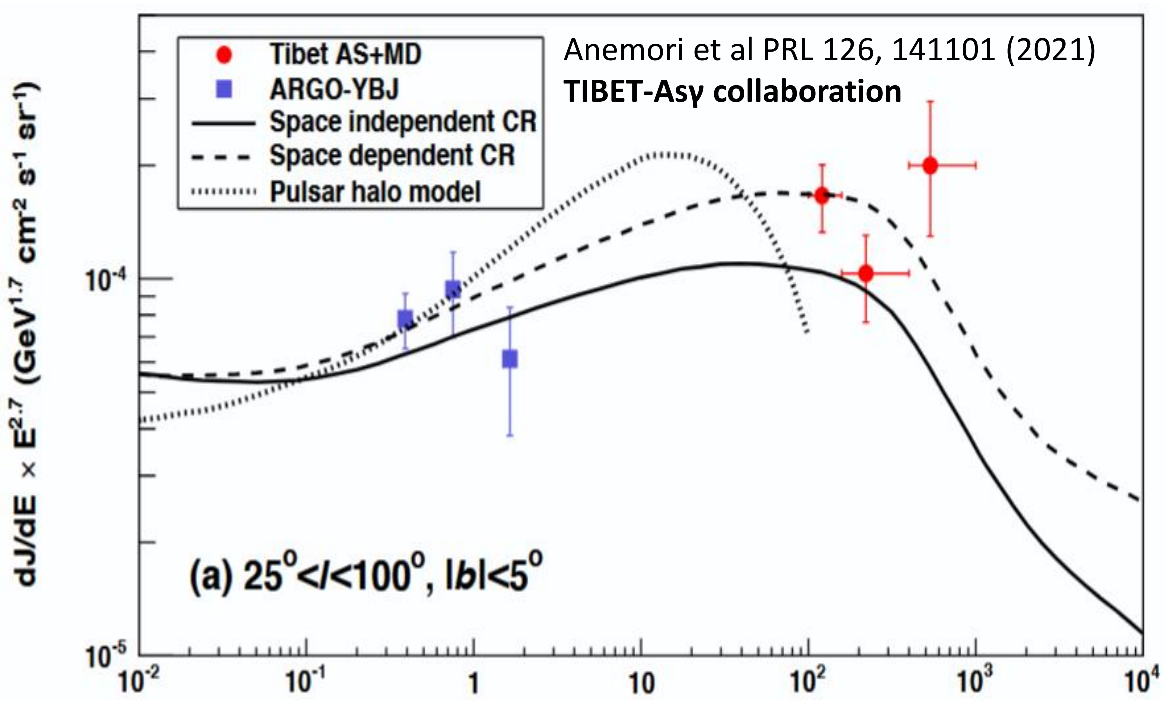
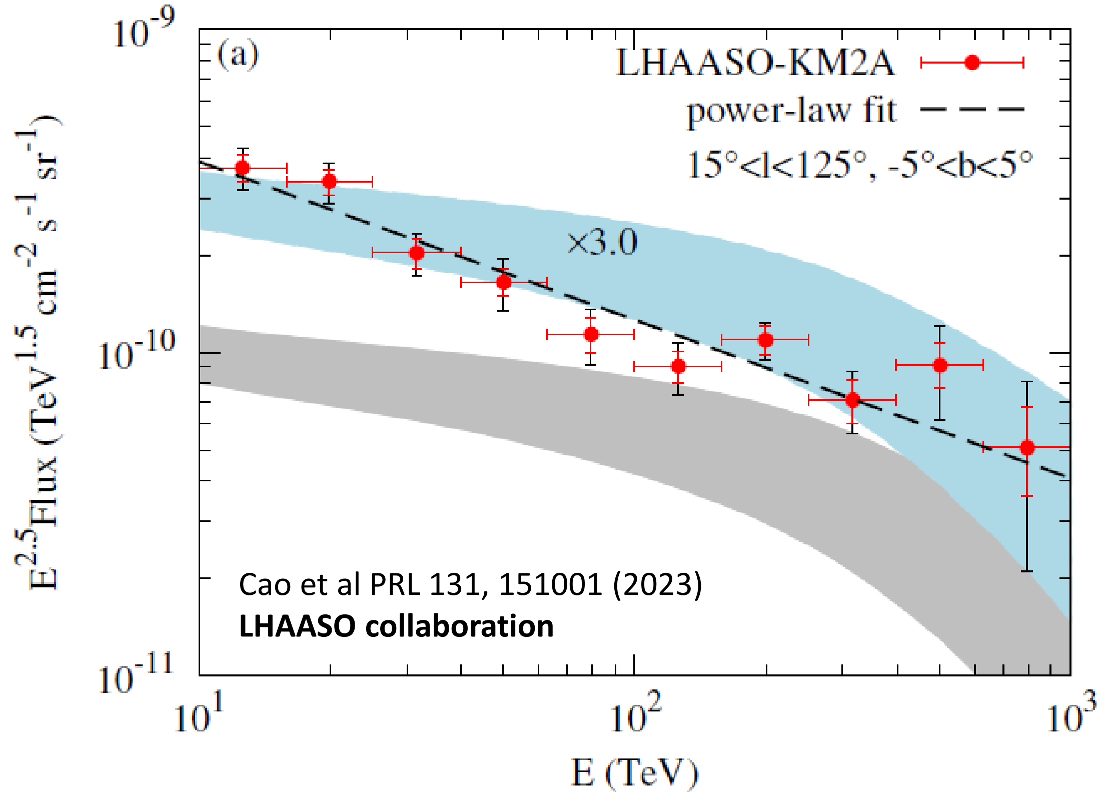


LHAASO and TIBET measurements:
A larger γ-ray diffuse flux than expected?

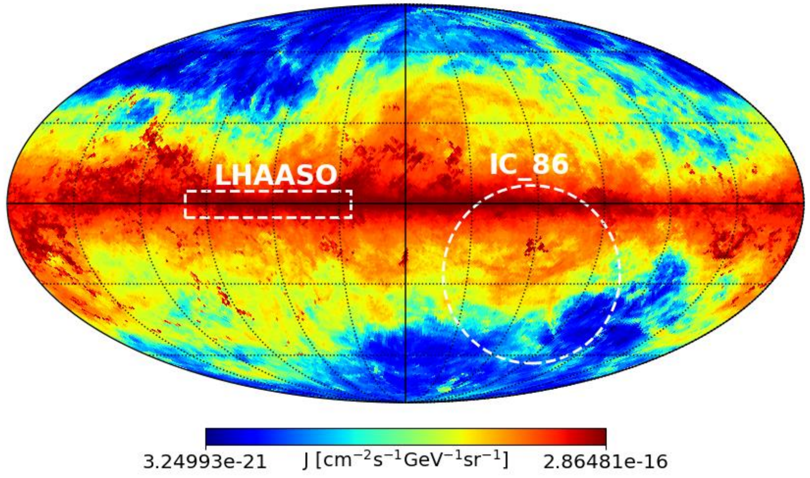
Does this hint for inhomogeneous diffusion? Unresolved sources?

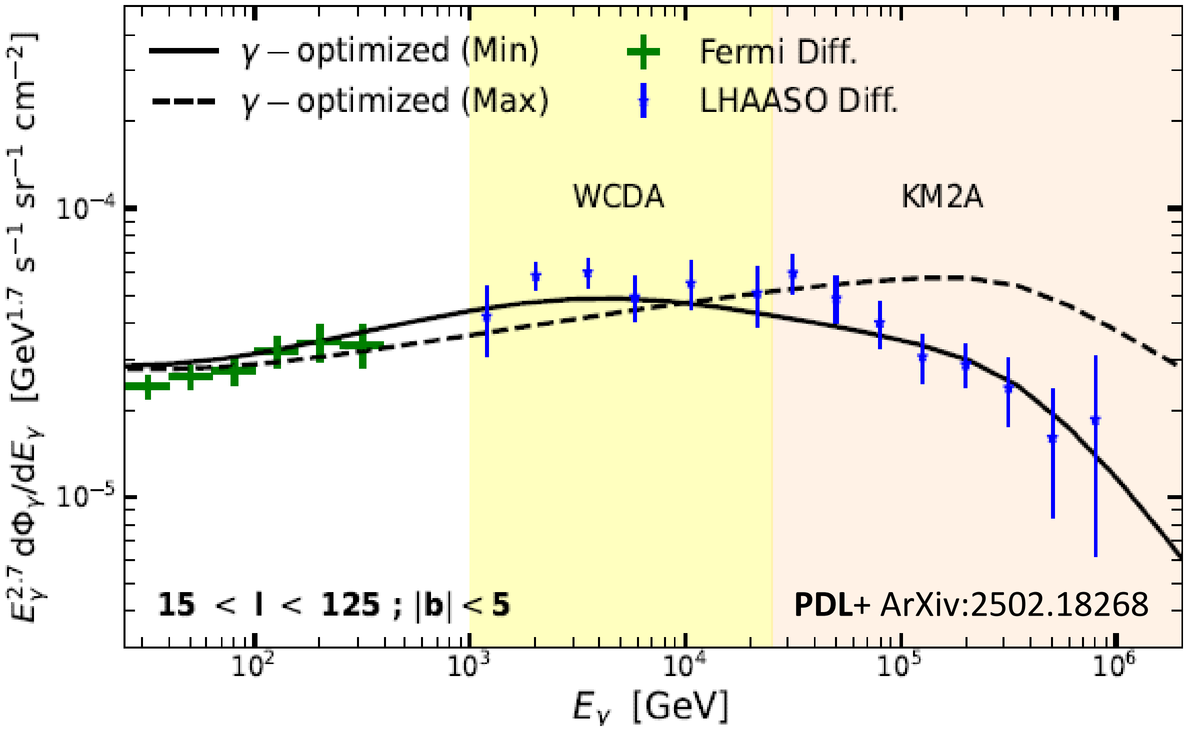


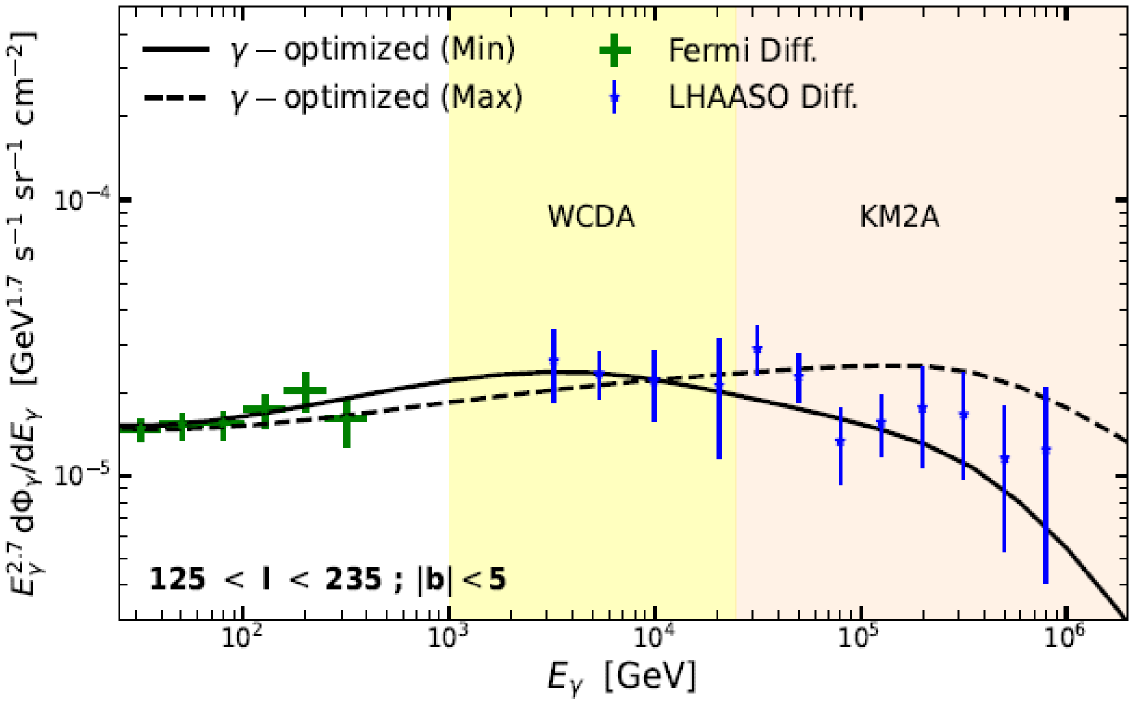


Inhomogeneous diffusion model

The diffuse emission meets PeV data



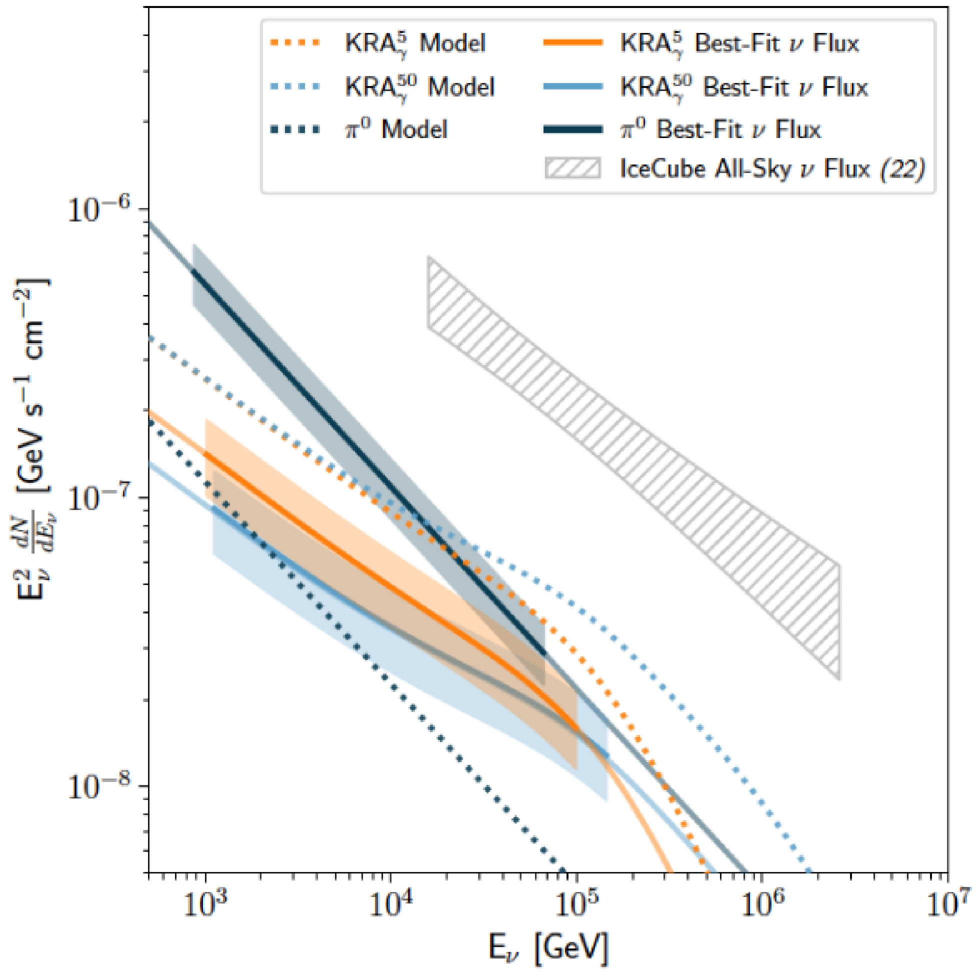




Region	ϕ_0 at 10 TeV (10^{-13} TeV^{-1} cm^{-2} s^{-1} sr^{-1})	α
$15° < l < 125°$ (inner)	$8.50 \pm 0.58_{stat}$	$-2.67 \pm 0.05_{stat}$
$125° < l < 235°$ (outer)	$3.49 \pm 0.55_{stat}$	$-2.83 \pm 0.19_{stat}$

(Table II of ArXiv:2411.16021)

IceCube measured the diffuse neutrino emission!



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

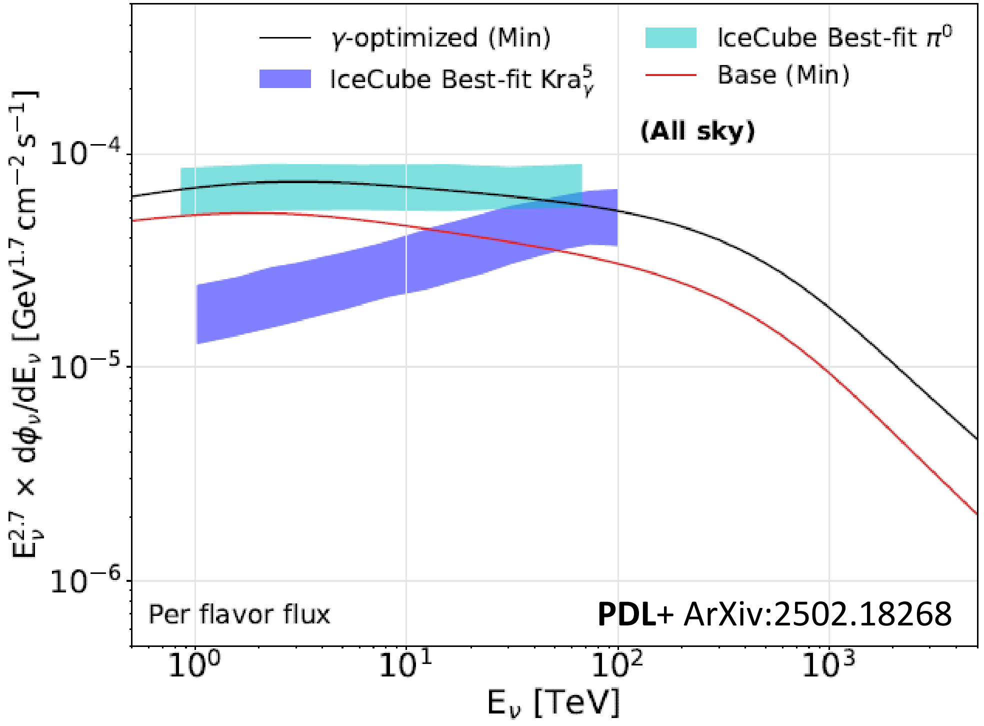
Indication that a Galactic diffuse component (10-20% of the total flux above 200 TeV) was clearly already identified by IceCube. **Confirmed by IceCube !!**

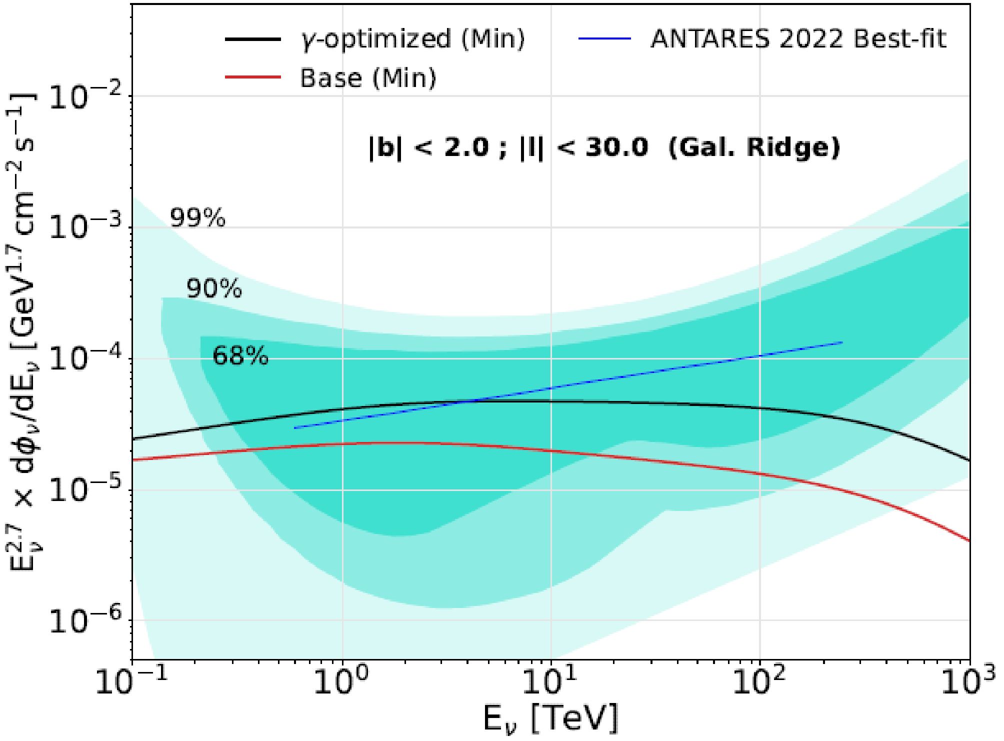
Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA_γ^{50}	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF

IceCube Coll. Nature 2023

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

This model predicts a neutrino flux in excellent agreement with the best-fit measurements of IceCube. Neutrino observations toward the GC are key to understand the different contributions involved and how diffusion operates in the Galaxy





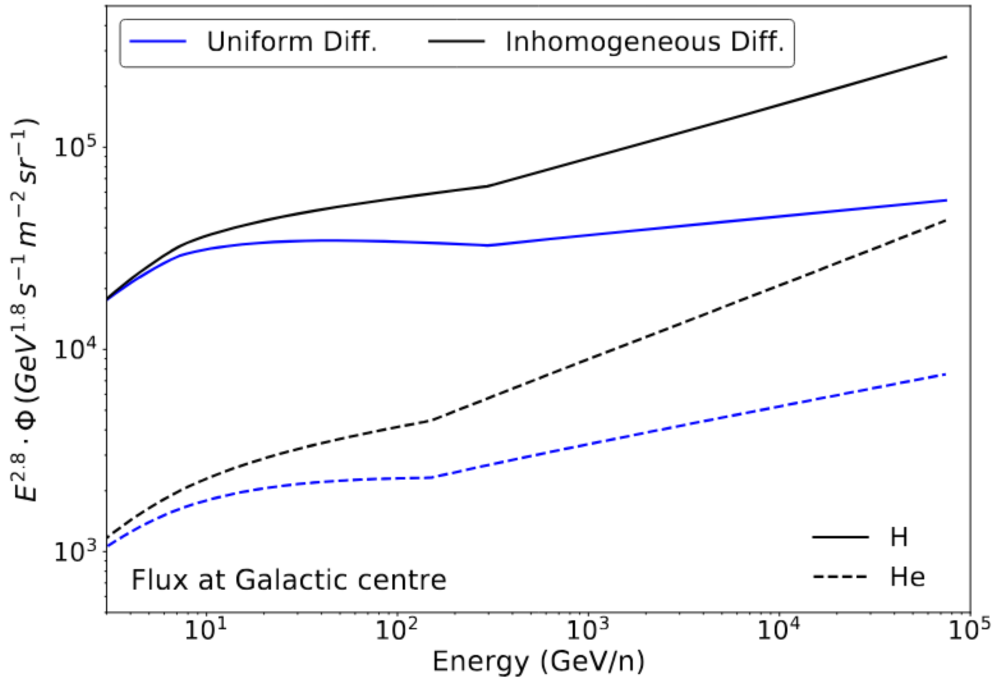
Consequences of such scenario?

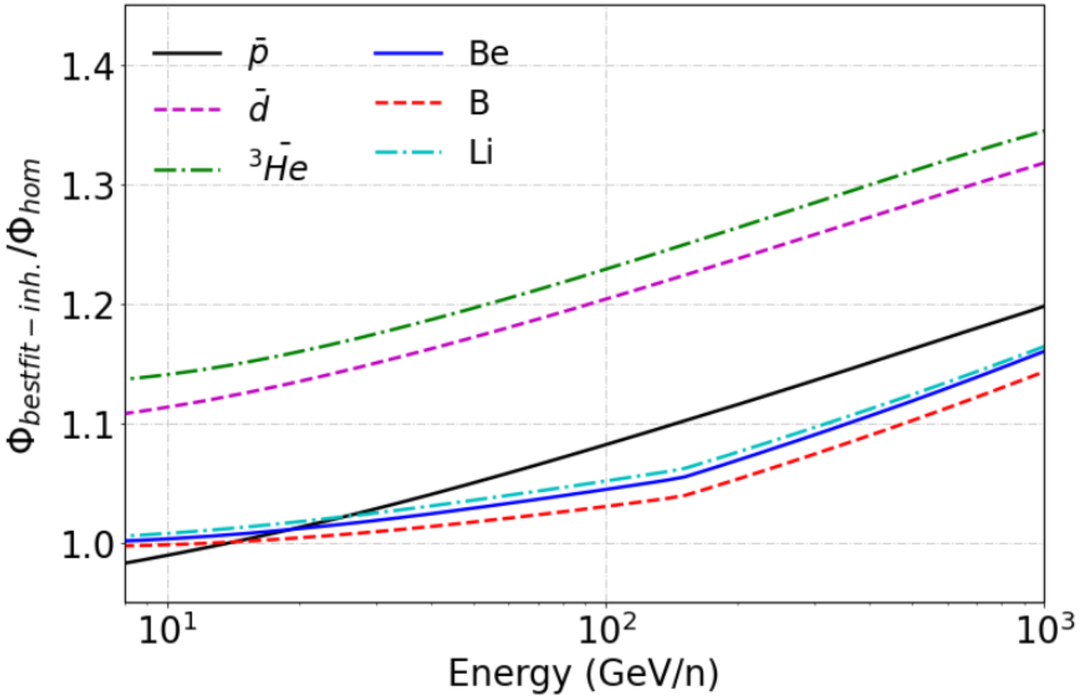
Primary and Secondary CRs are expected to get a **harder spectrum**

Secondary-to-primary ratios won't be very sensitive to it because of spallation interactions

But **antiproton-to-proton ratio might be!** Since antiprotons are produced with lower energy

Tovar-Pardo, **PDL** 2024 ArXiv:2405.12918





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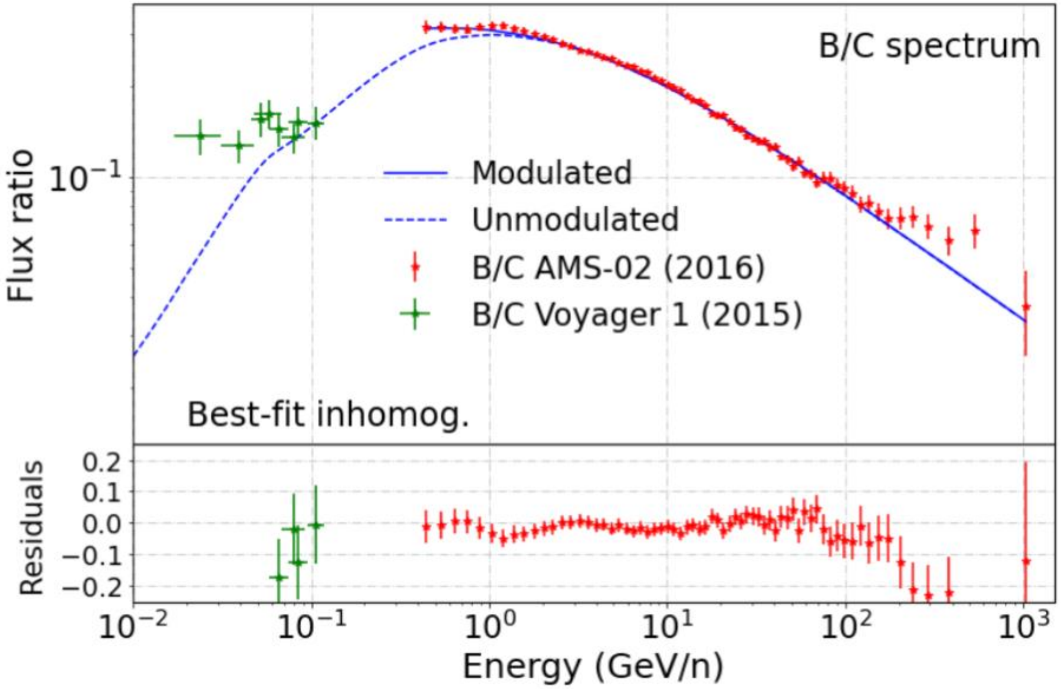
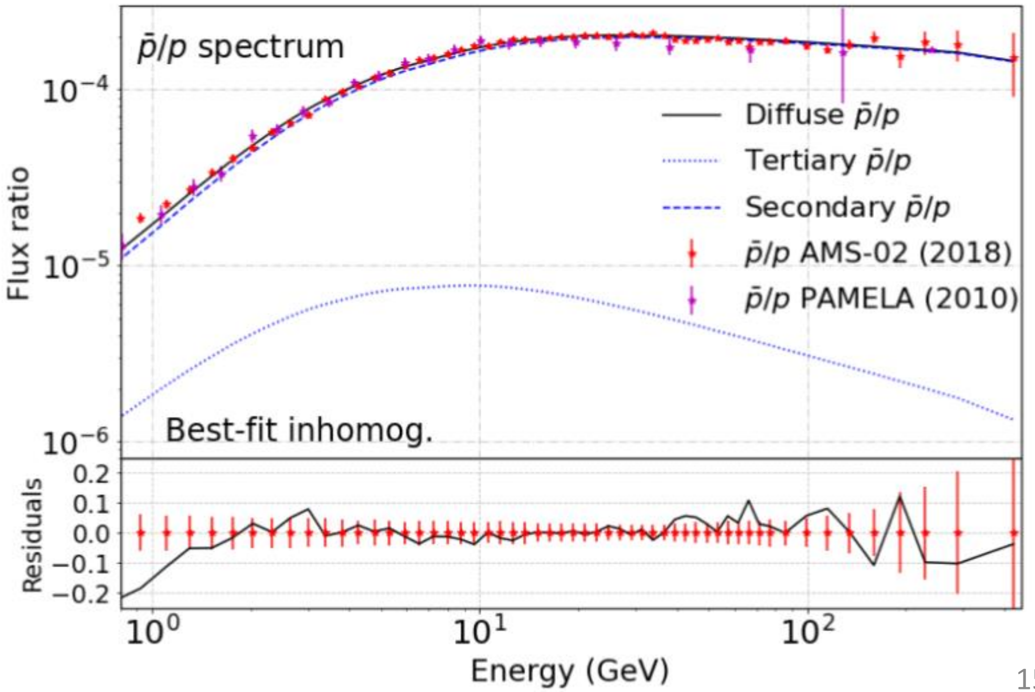
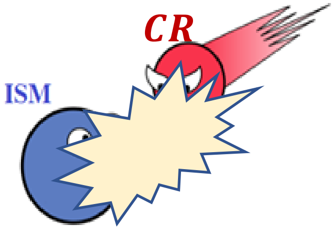




Hints for anomalies in antiproton data?

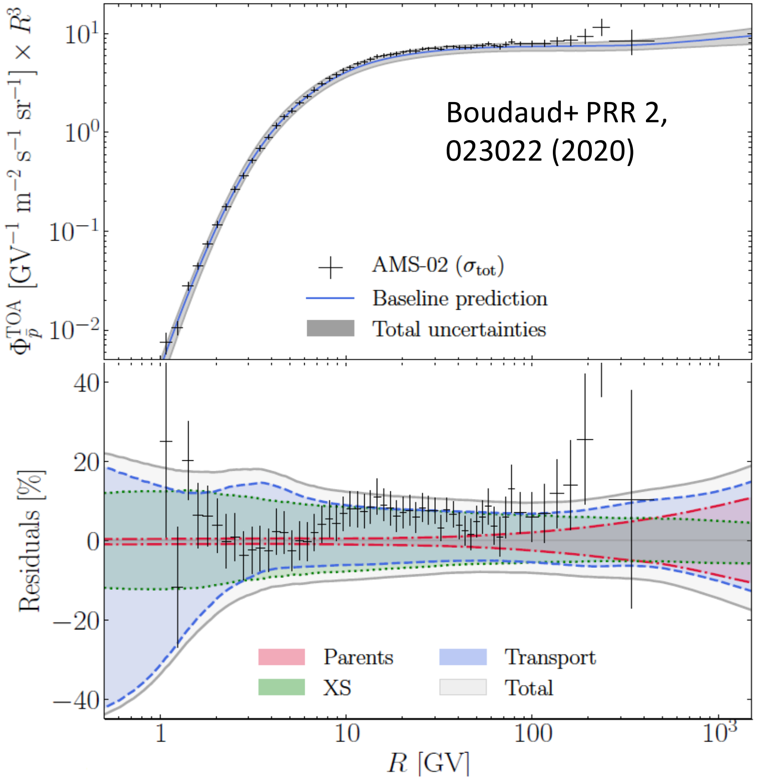


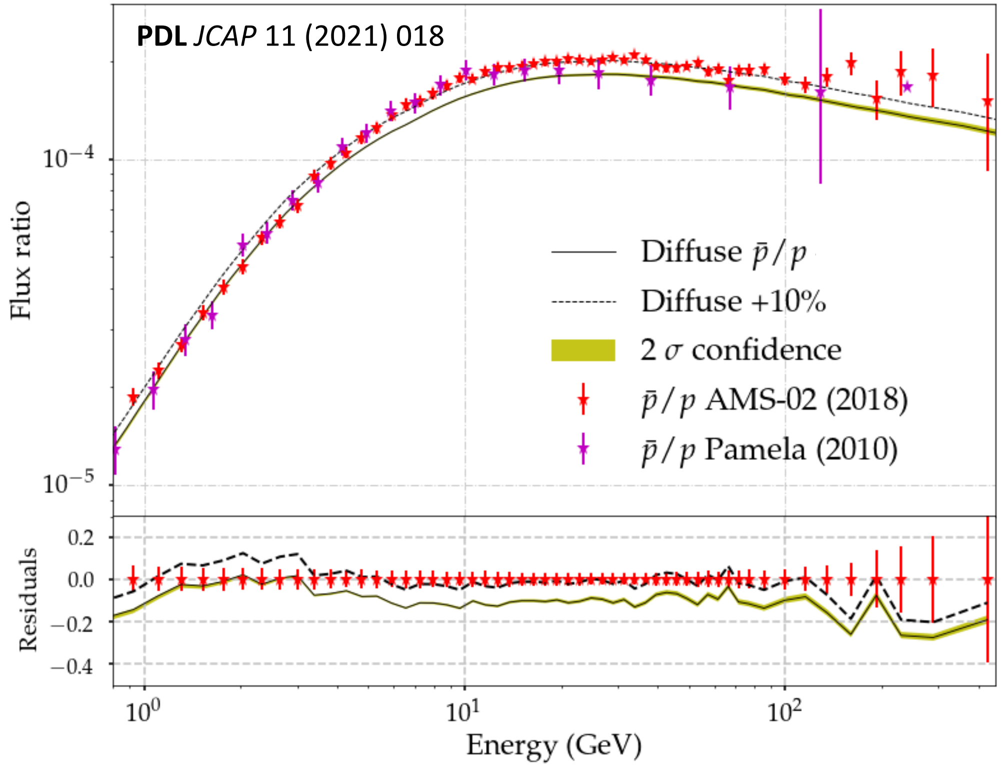
While antiproton data seem compatible with the rest of CRs, a preference for a **harder spectrum** has been reported several times

$p_{CR} + p_{ISM} \rightarrow \bar{p}$

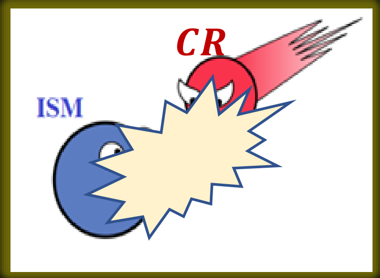
$\chi + \chi \rightarrow \bar{p}$

Acceleration of antiprotons and positrons around SNRs? P. Mertsch et al. 2020 PRD 104, 103029





Antiproton *excess* – A DM signal?

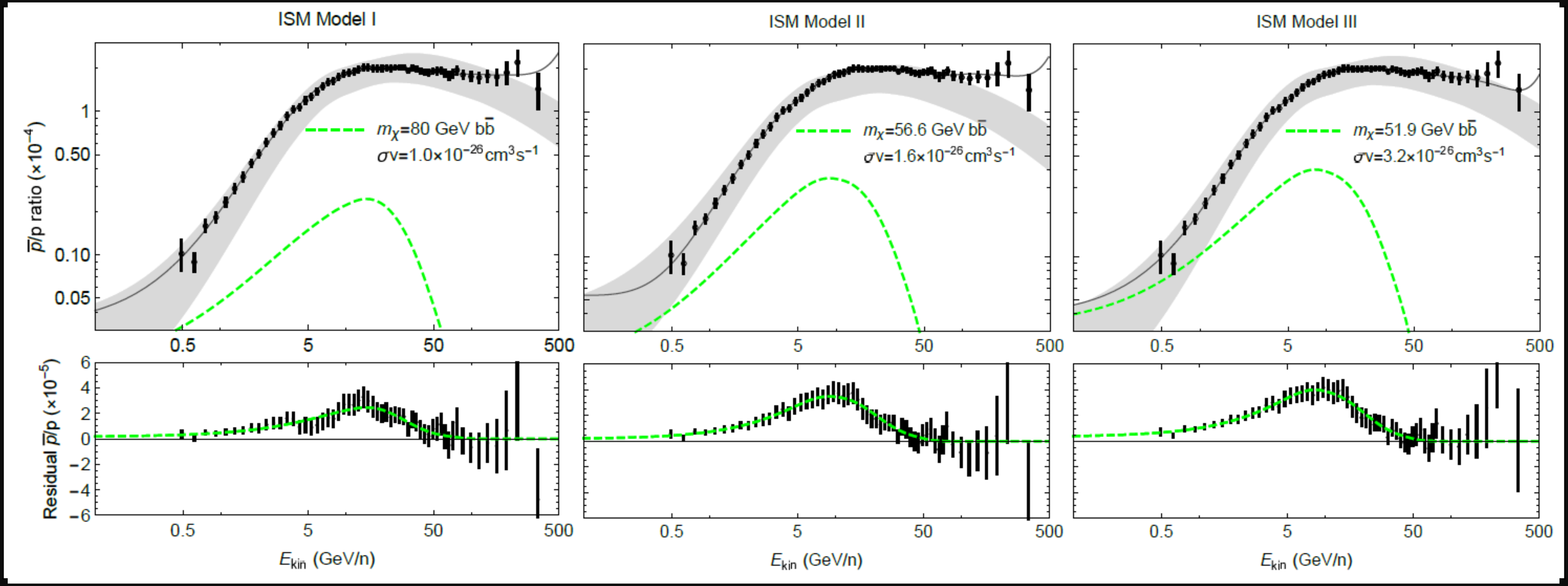


Several studies claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

$p_{CR} + p_{ISM} \rightarrow \bar{p}$

$\chi + \chi \rightarrow \bar{p}$

Cholis et al PRD 99, 103026



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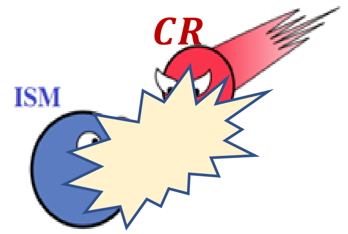
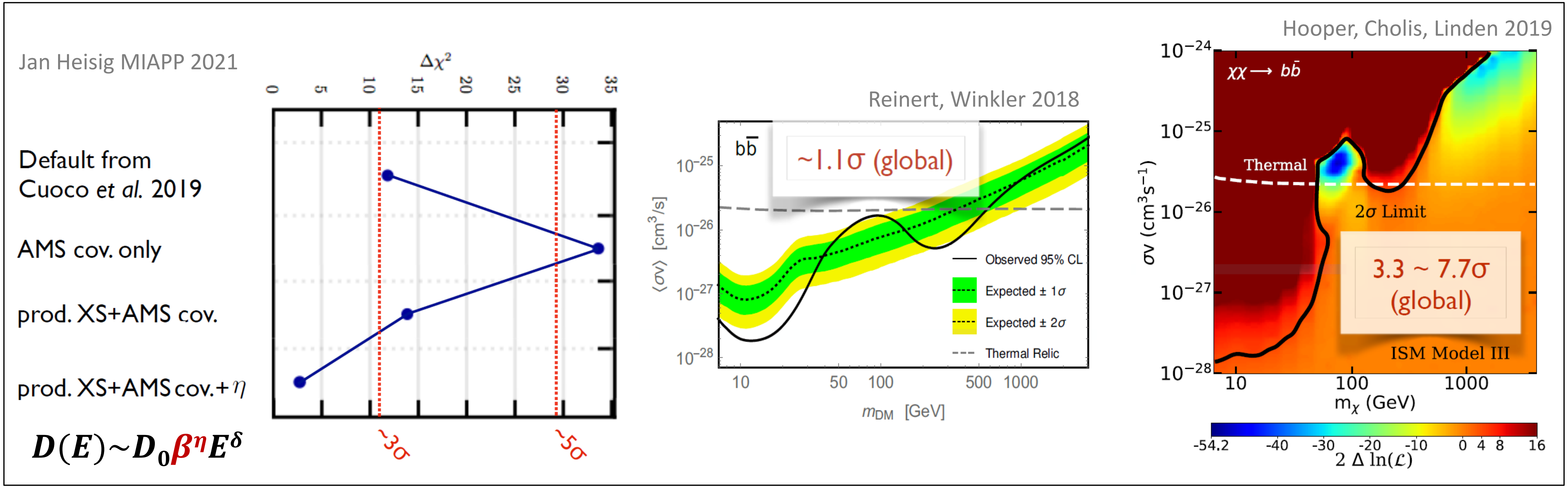


Many analyses coincided in the position of the excess, but not in its significance… Main ingredients affecting these analyses are: Correlations in AMS-02 errors, cross sections and propag. params

$$p_{CR} + p_{ISM} \rightarrow \bar{p}$$

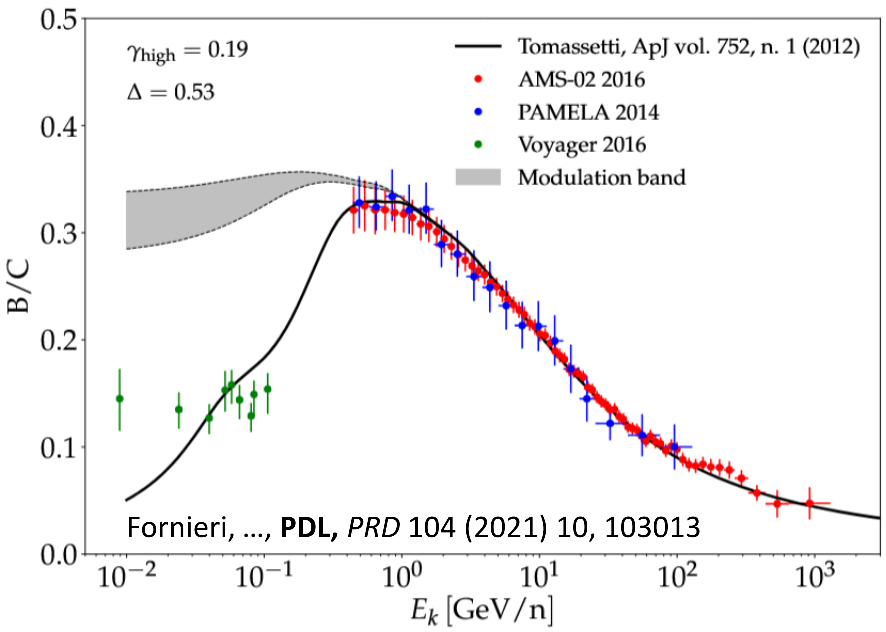
$$\chi + \chi \rightarrow \bar{p}$$



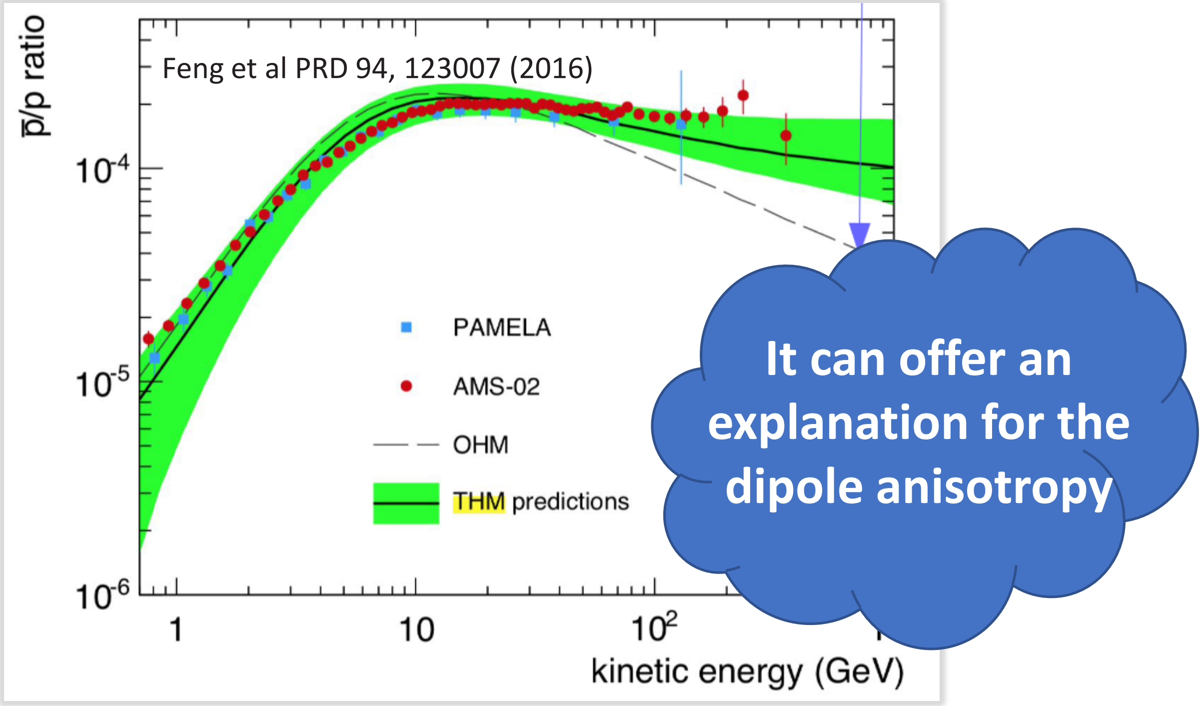
Tomassetti's two-zone model (Tomassetti APJ 762 - 2012)

It proposes a different diffusion based on plasma properties: Diffusion in the halo (as a hot plasma) vs diffusion in the disk (warm plasma)

Explains 300 GV break and hardens the antiproton-over-proton ratio. It leads to a lower significance for the DM signal



(See also: Zhao et al 2021 arXiv:2109.04112)

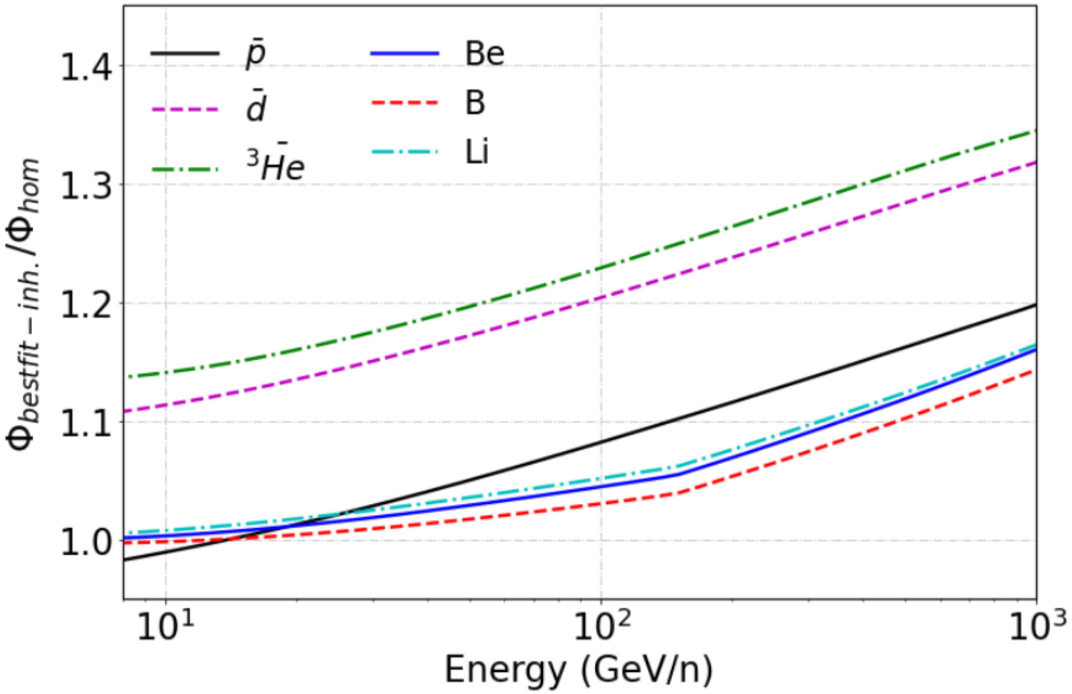


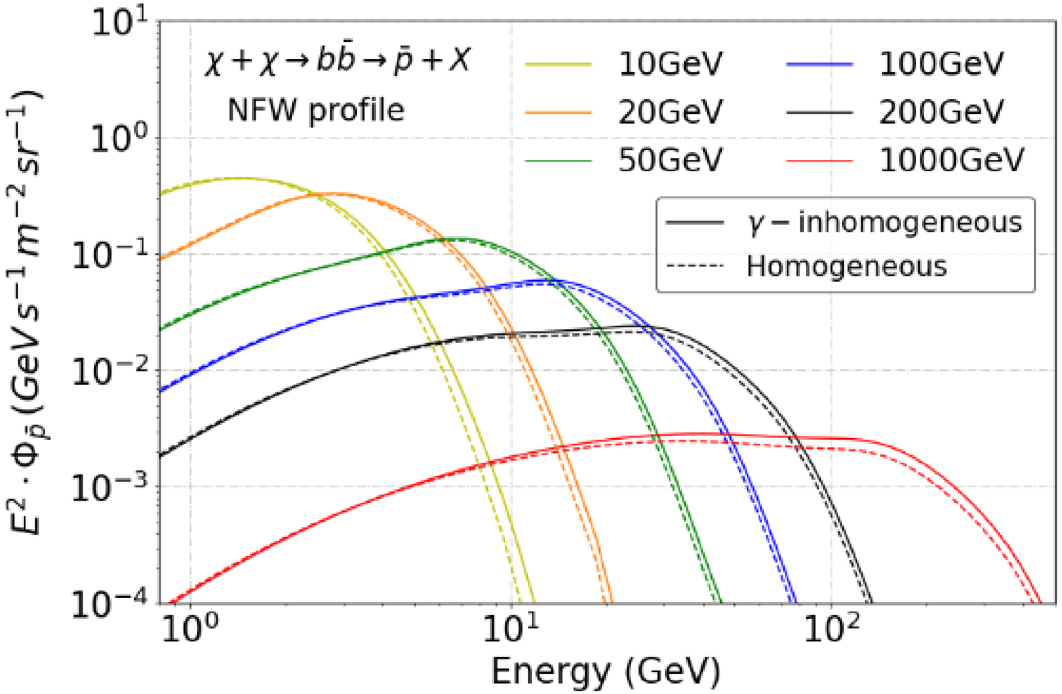
Gas Inhomogeneities and the non-uniformity of the CR transport are not explored in depth

Consequences of inh. diffusion for DM signals?

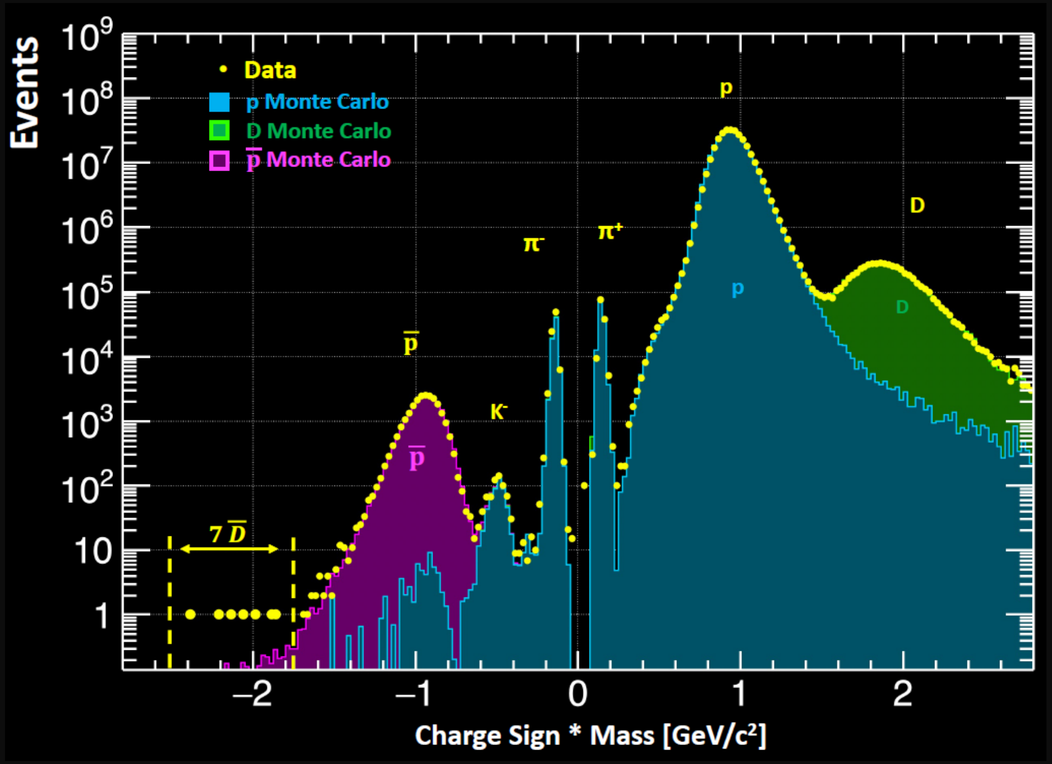
While we see that the secondary to primary ratios harden slightly, we do not find any significant difference in DM signals for masses below the TeV

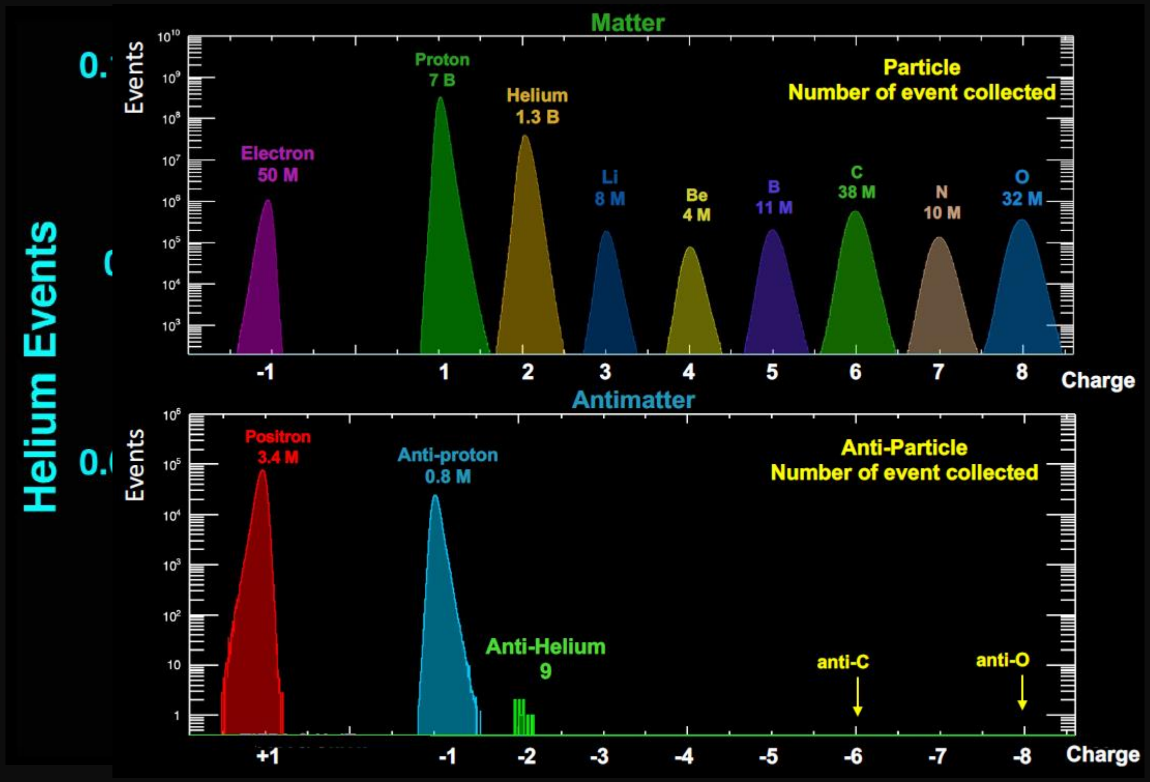
Tovar-Pardo, **PDL** 2024 ArXiv:2405.12918





ANTI-NUCLEI: AMS-02 mass-charge spectra

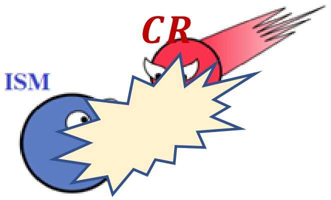




Paolo Zuccon MIAPP 2021

Astrophysical production

$\mathrm{CR} + \mathrm{ISM} \rightarrow \overline{\mathrm{He}}, \bar{\mathrm{d}}$

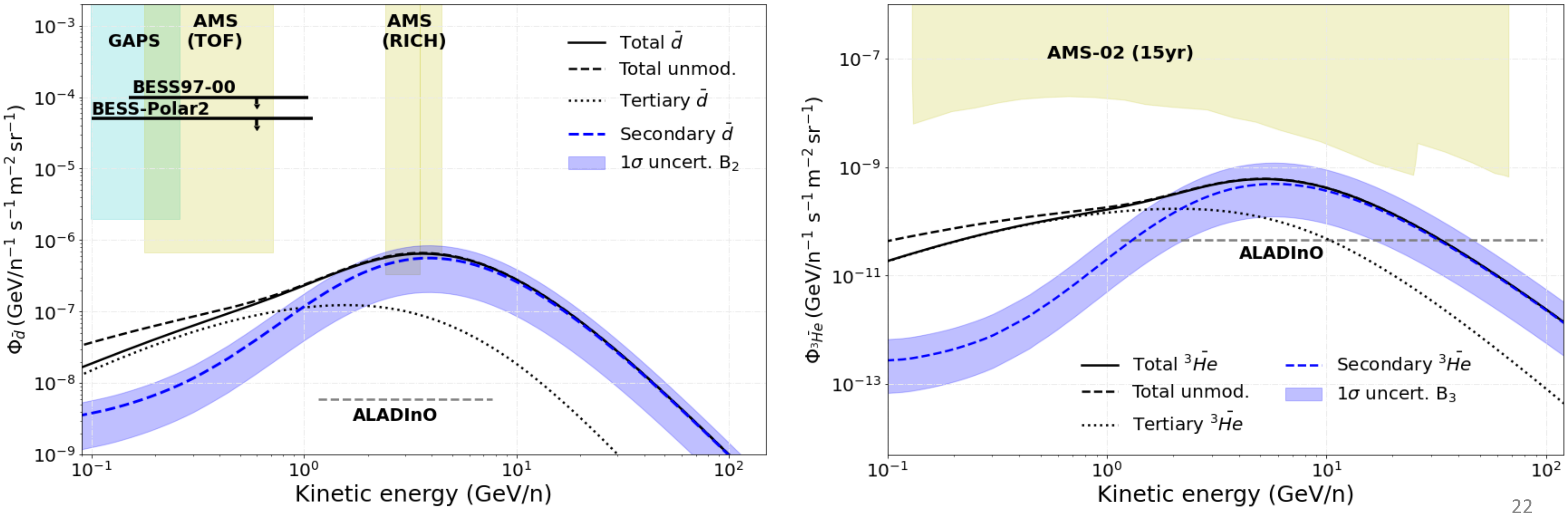


Can we explain the AMS-02 measurements without invoking any exotic source?

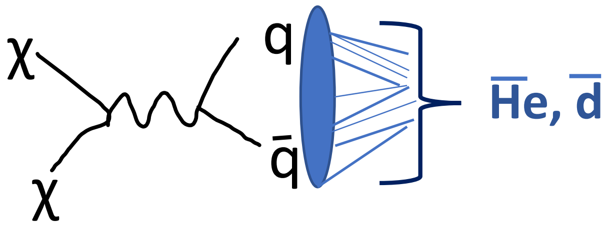
Main uncertainty is the coalescence parameter; the rest of uncertainties are under ~10%

We expect to have measurements of the $\bar{\mathrm{d}}$ flux in the next years!! But nothing about $\overline{\mathrm{He}}$ till ALADInO or AMS-100 (foreseen to 2039)

PDL et al, ArXiv: 2404.13114

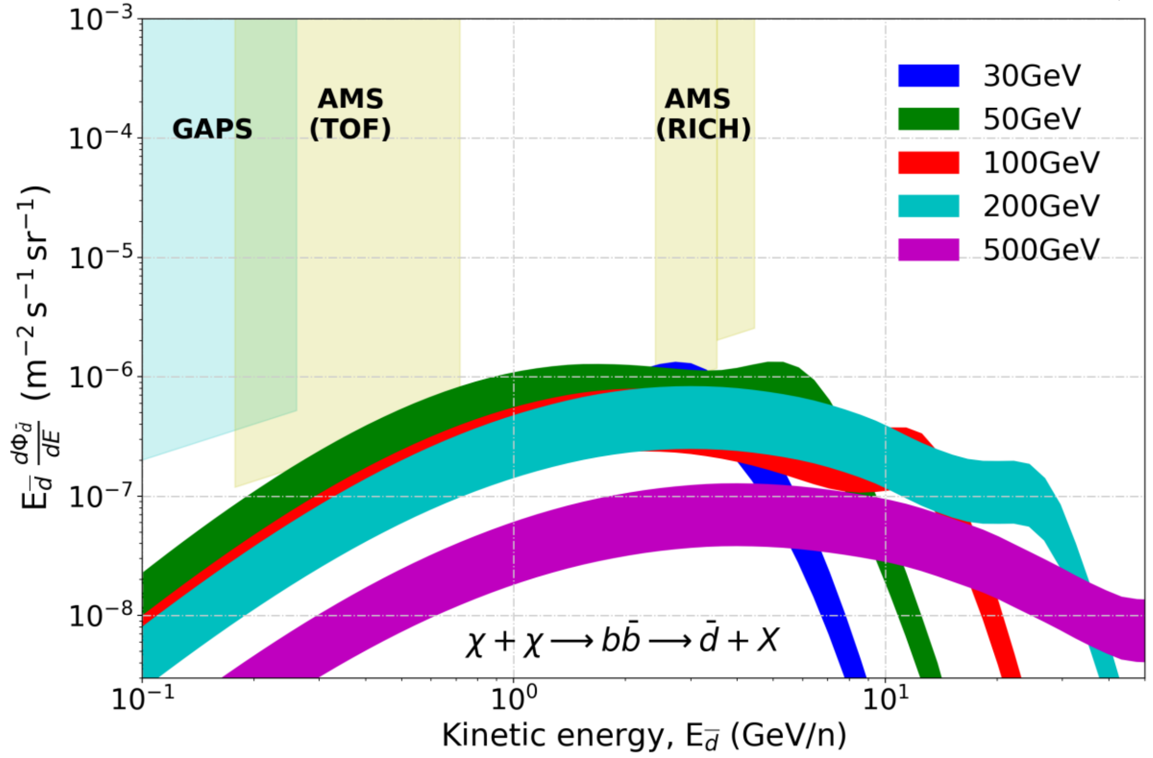


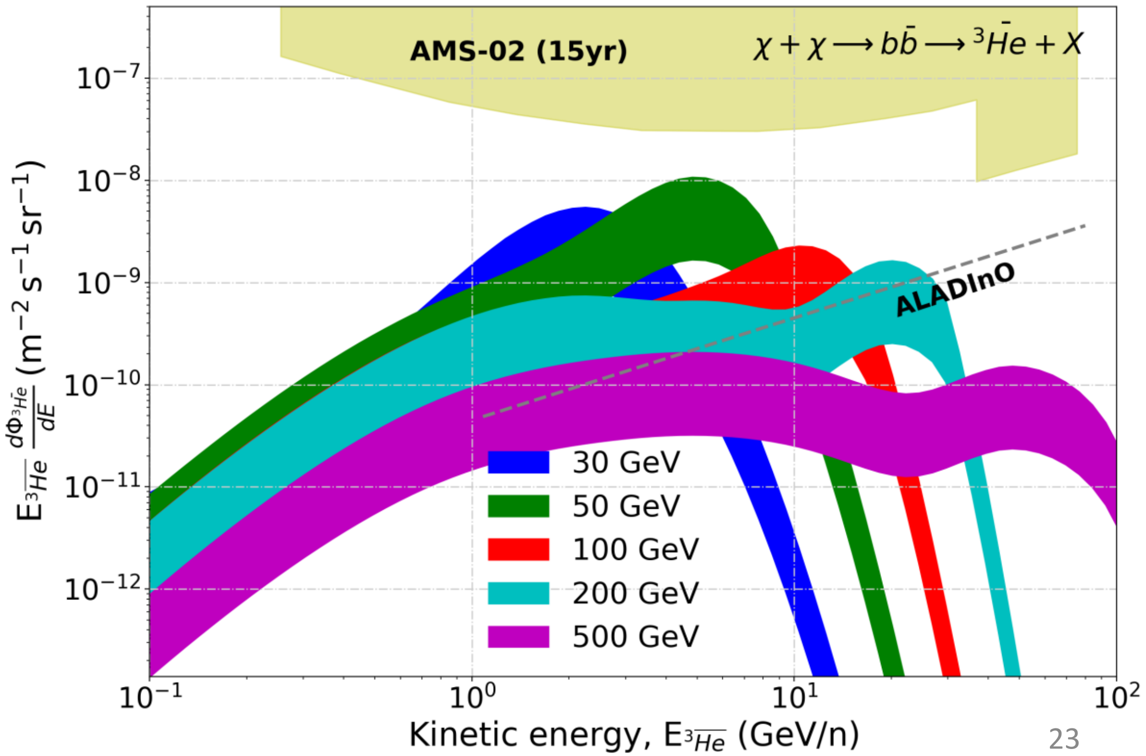
DM production: Upper Limits



Maximal antinuclei flux allowed from our antiproton bounds. Even in optimistic cases, it seems we cannot explain the detection of a single antihelium-3 event by AMS-02, And clearly, we are **unable to explain any detection of antihelium-4 by AMS-02**…

PDL et al, ArXiv: 2404.13114

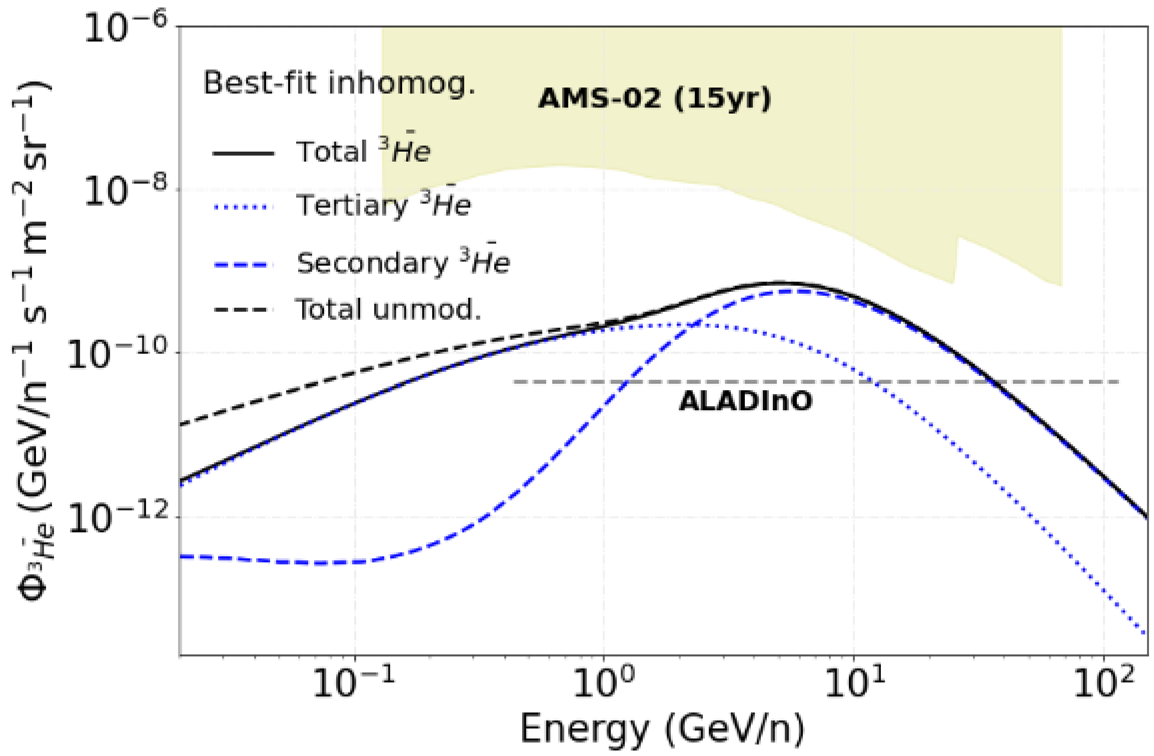


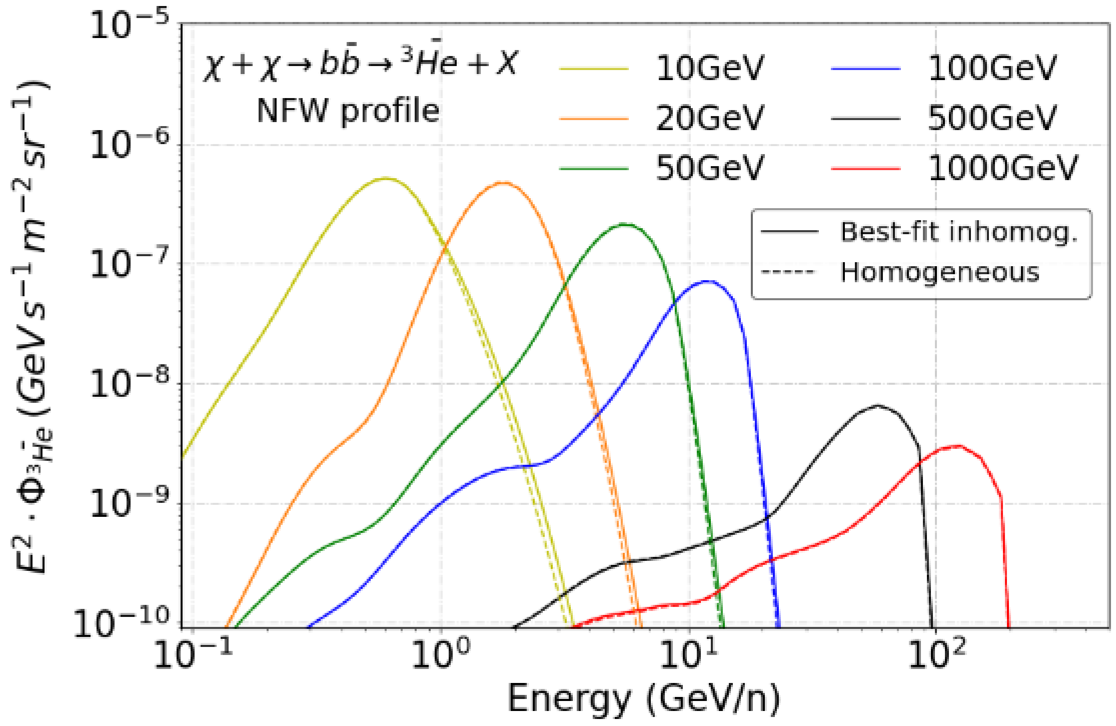


Consequences of inh. diffusion?

Antinuclei fluxes slightly increases (around 10% at 1 GeV) → Too small to explain any detection. DM signals are not different either

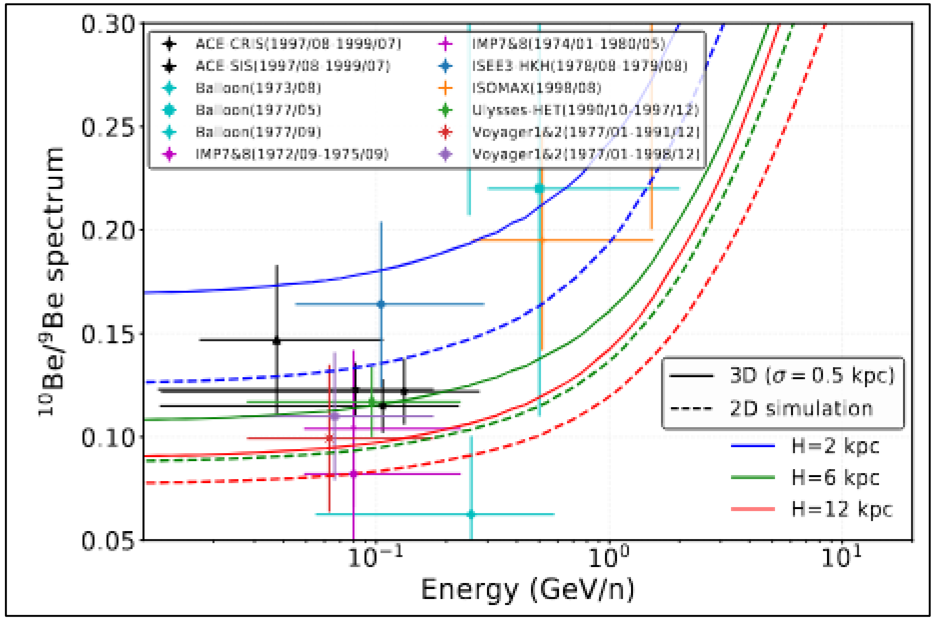
Tovar-Pardo, **PDL** 2024 ArXiv:2405.12918





Other anisotropies that depart from the standard paradigm also impact these studies…

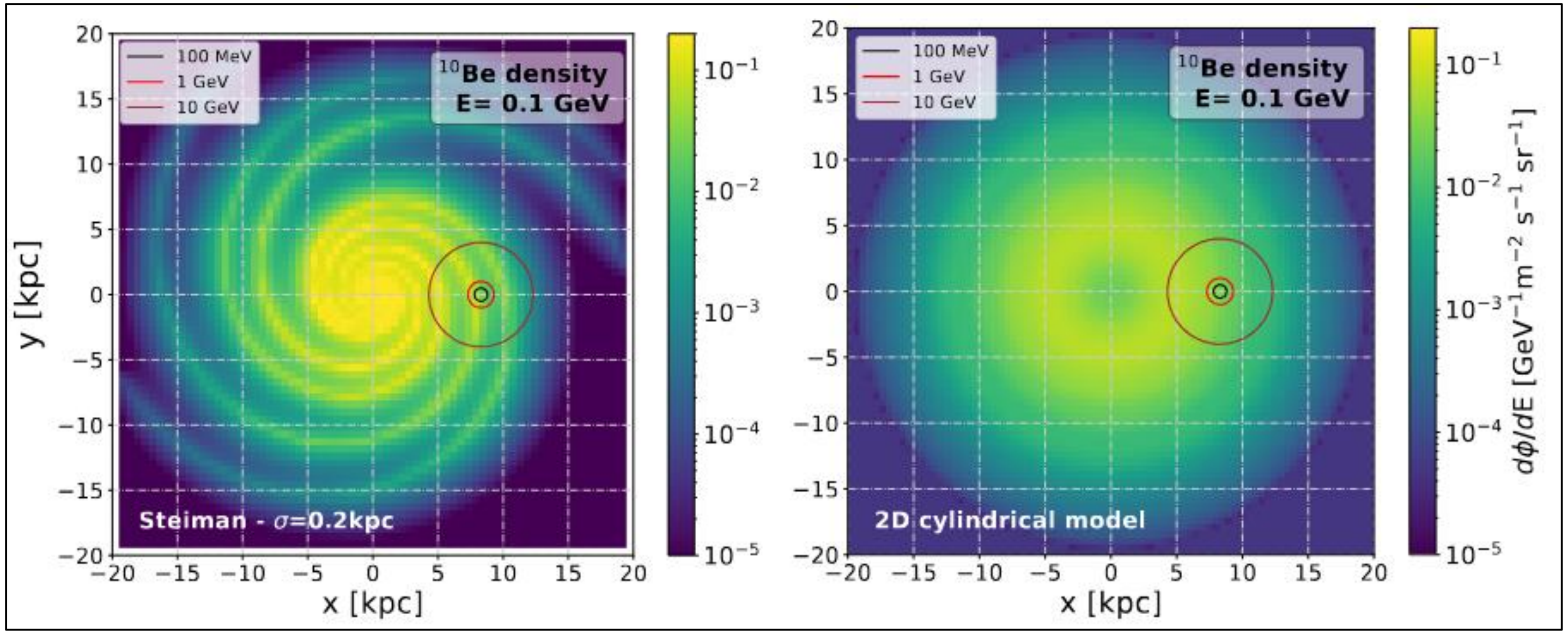
The halo height



The spatial distribution of the gas can have a large impact in the prediction of unstable isotopes

We may need a combination of different observables again

PDL, Linden *JCAP* 02 (2025) 062



Radio

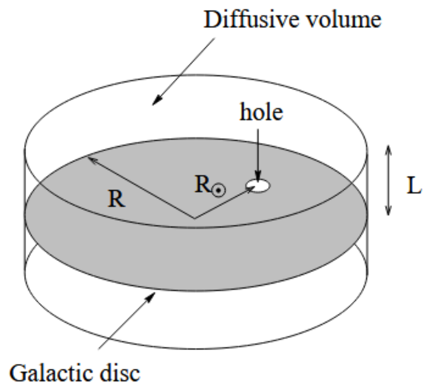
Di Bernardo+ ArXiv:1210.4546

Orlando+ ArXiv:1309.2947

Gamma rays

Zaharias+ ArXiv:1212.6755

The halo height… and the local bubble

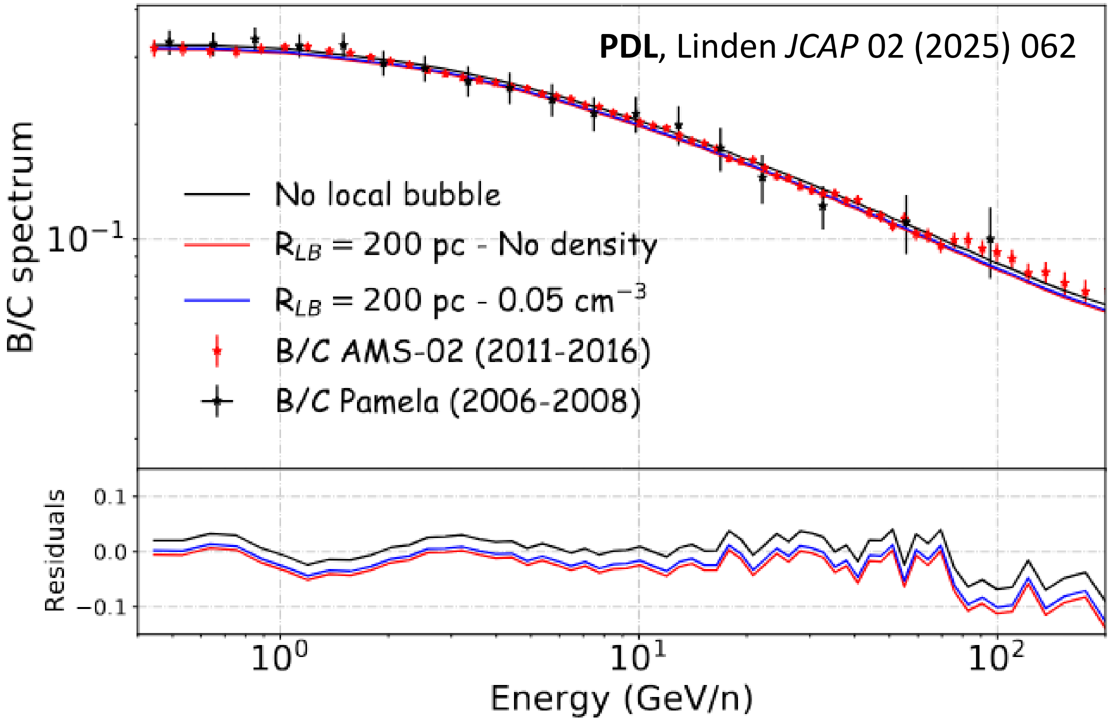


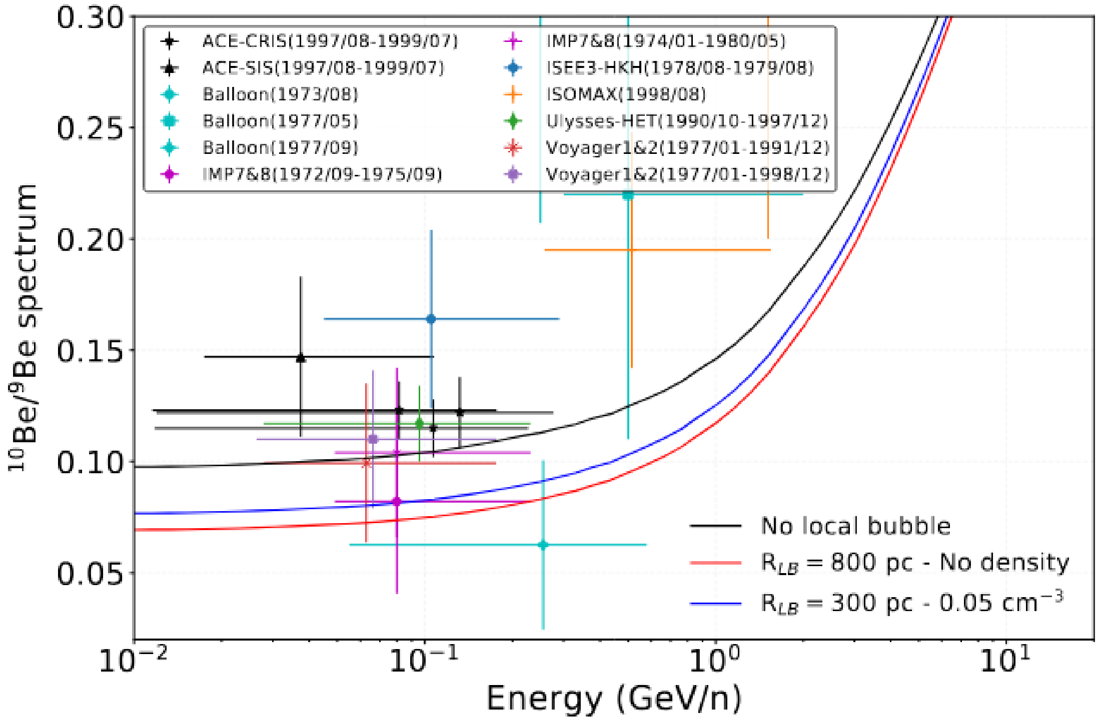
Donato et al A&A 381 (2002) 539

The spatial distribution of the gas can have a large impact in the prediction of unstable isotopes – Also electrons and heavy CRs

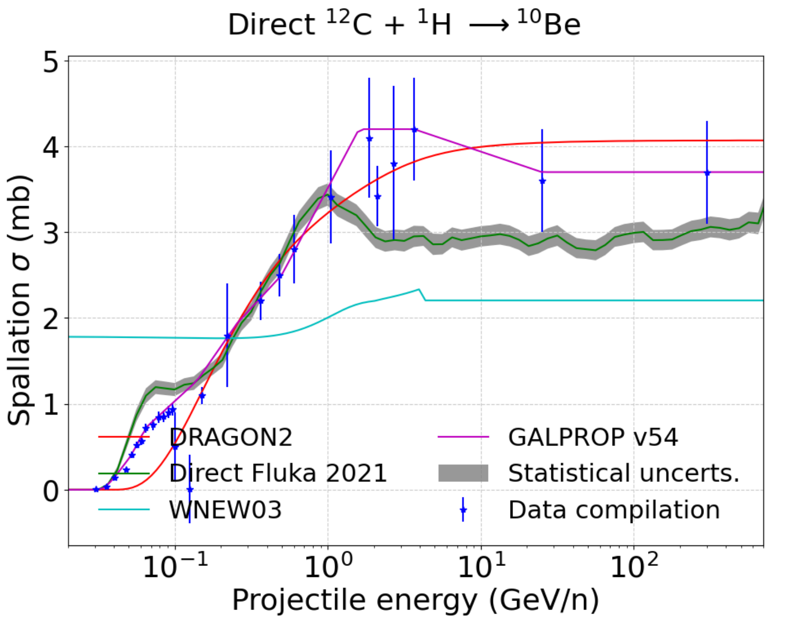
It is not clear whether diffusion must be different within this region either…

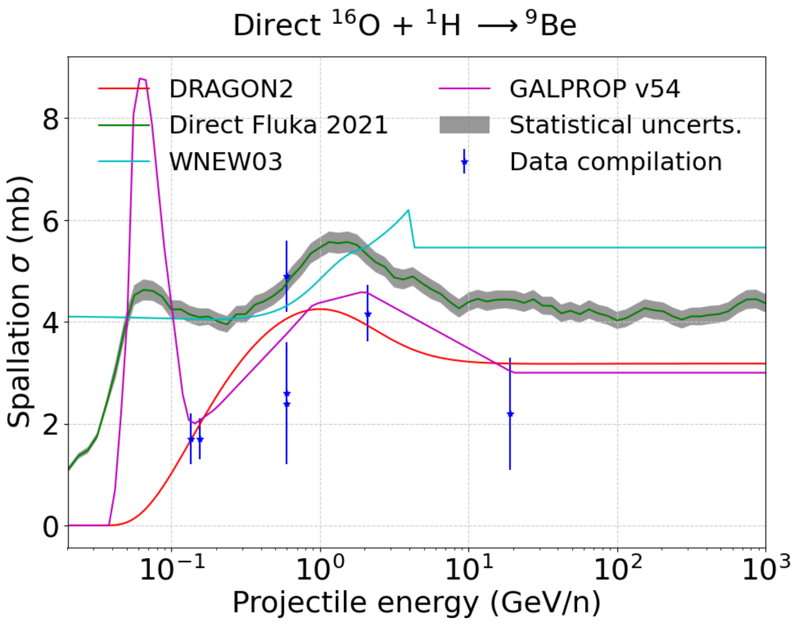
PDL, Linden *JCAP* 02 (2025) 062

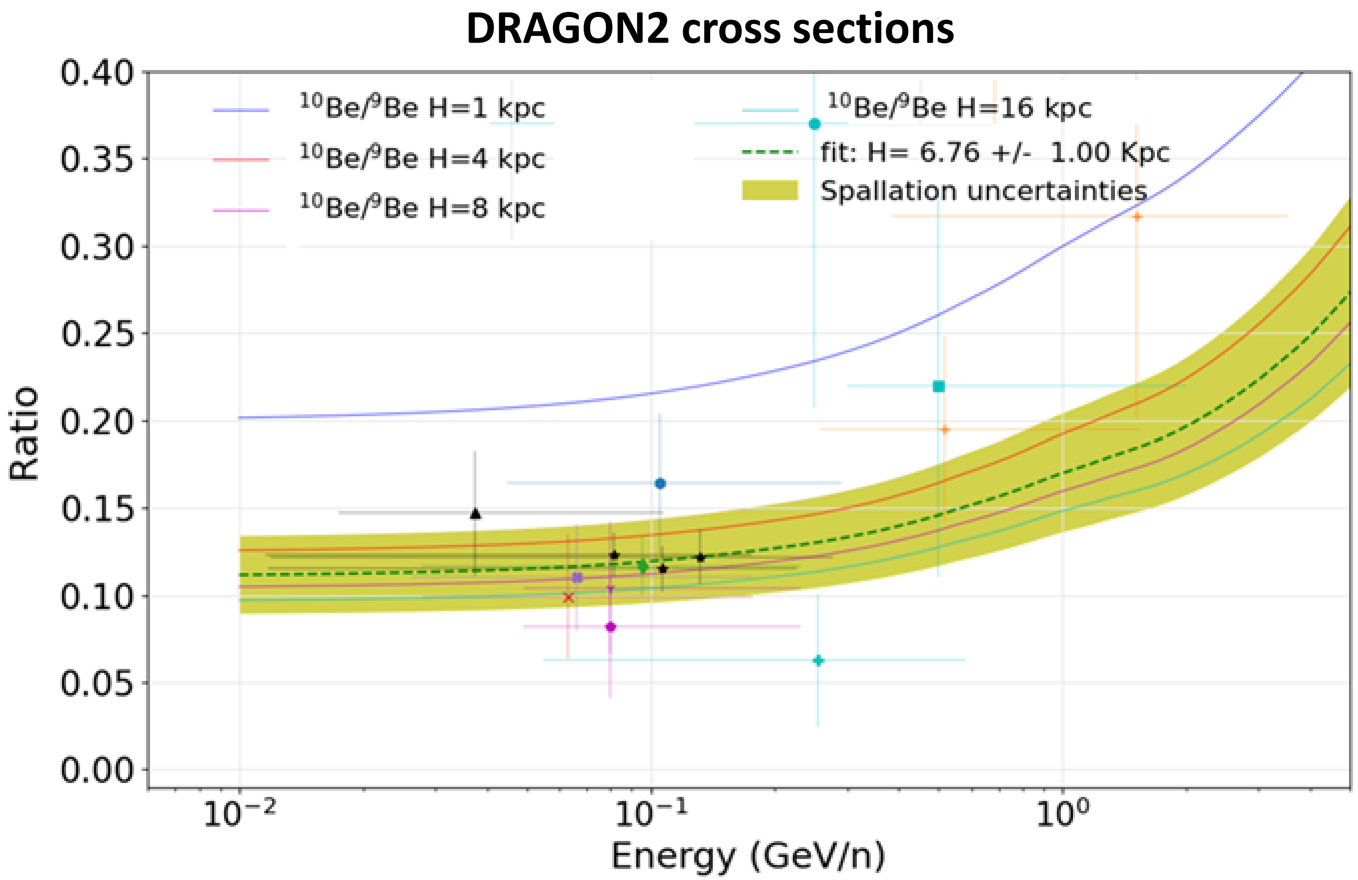




Determination of the halo size

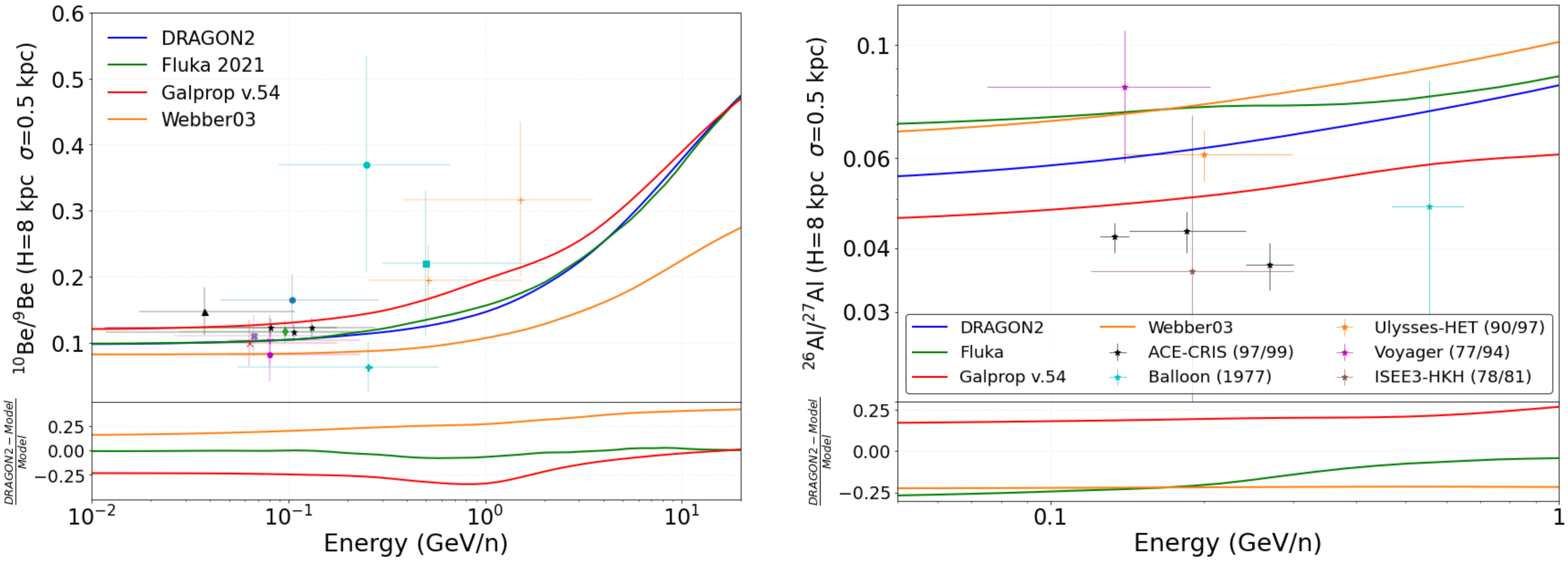






Determination of the halo size

Other cosmic-ray clocks can be used, but cross sections uncertainties can be even larger!



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FLUKA cross sections

http://www.fluka.org/fluka.php

FLUKA is a Monte Carlo event generator, dedicated to hadron and nuclei interactions and which is especially optimized for the study of cosmic rays. Computations with this code allows us to derive cross sections in a broad range of energies and species.

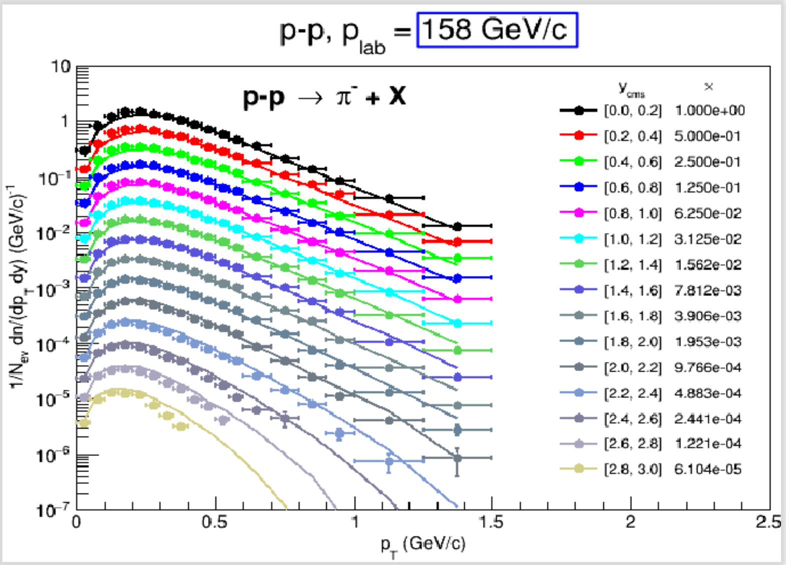
The result is a set a cross sections of secondary CRs that can be used in CR propagation codes. We have also computed cross sections for gamma-ray, secondary electrons and positrons, neutrinos and antiprotons.

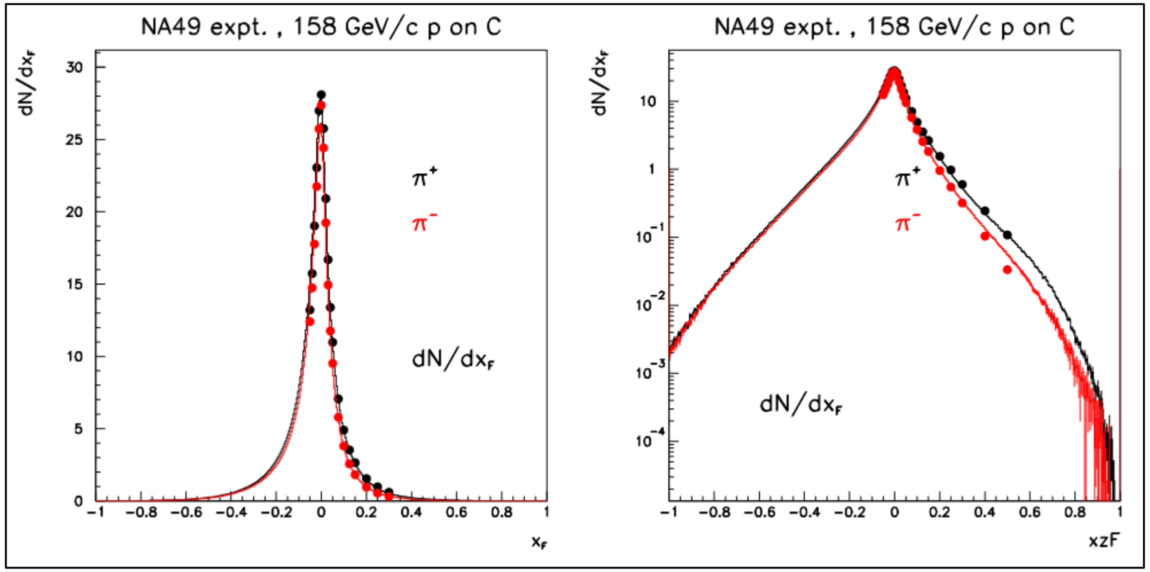
A few Refs:

G. Battistoni et al, Annals of Nuclear Energy, Vol. 82 (2015)

T. Böhlen Nuclear data sheets, Vol. 120 (2014)

F. Cerutti, “FLUKA: theoretical grounds and wished new data”, Talk at XSCR (2017)



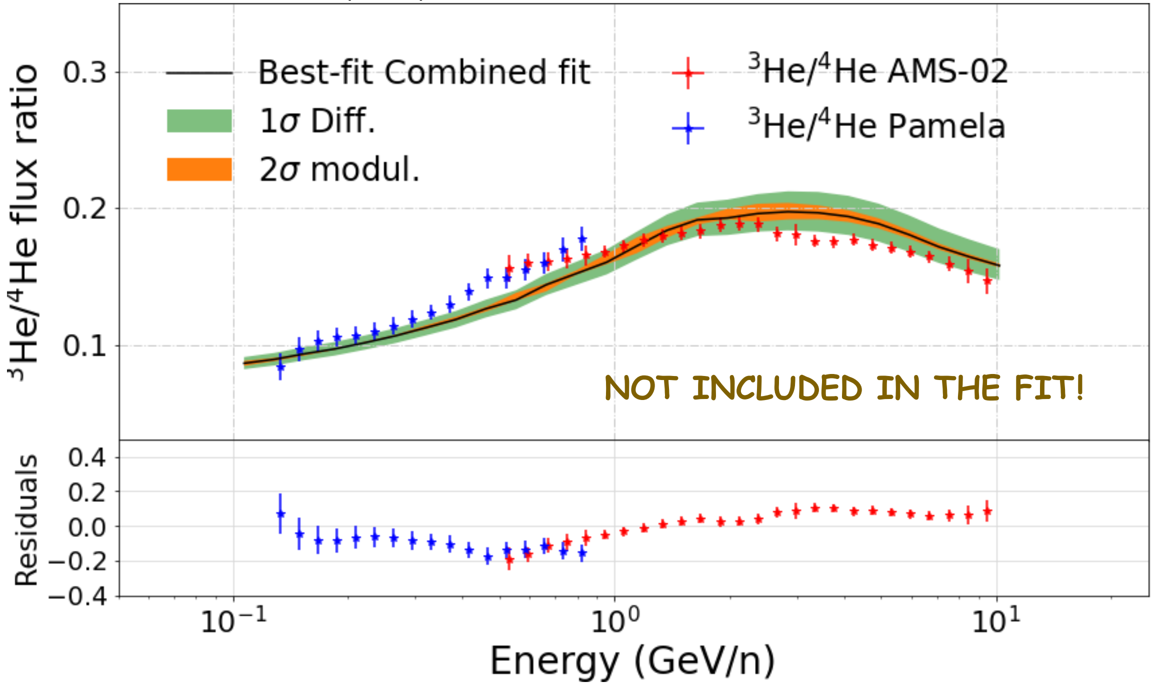


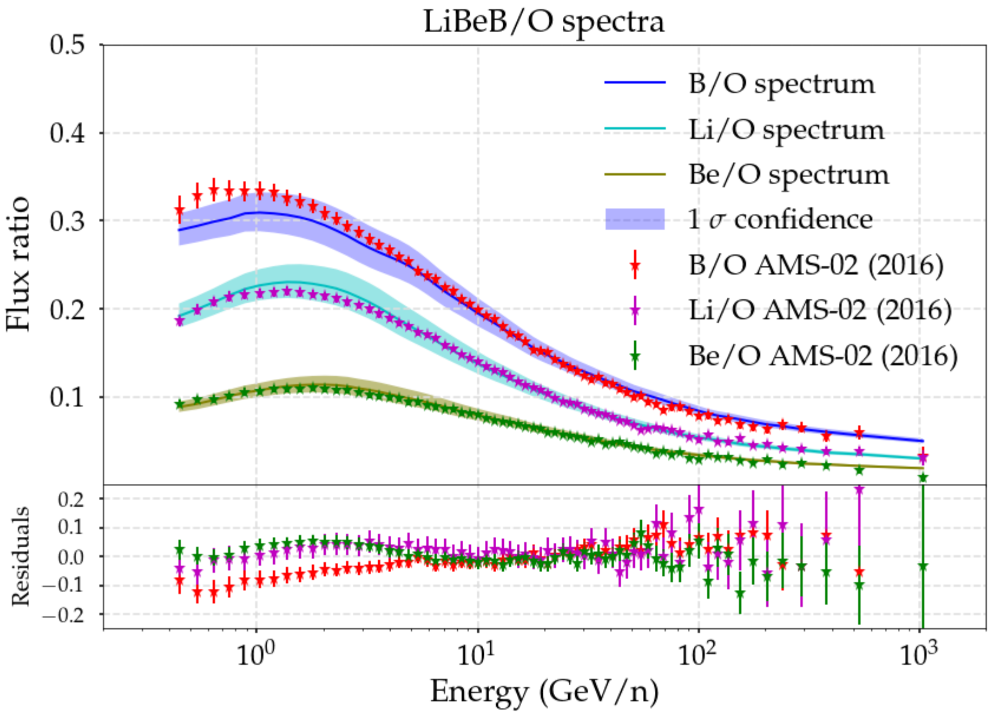
Combined fit of secondary CRs with FLUKA

MC Monte Carlo analysis: Combination of the ratios of secondary CRs **(PDL.** et al *JCAP*07, 2021, 010**)** including nuisance parameters (<u>Scale factors</u>) for renormalizing FLUKA cross sections.

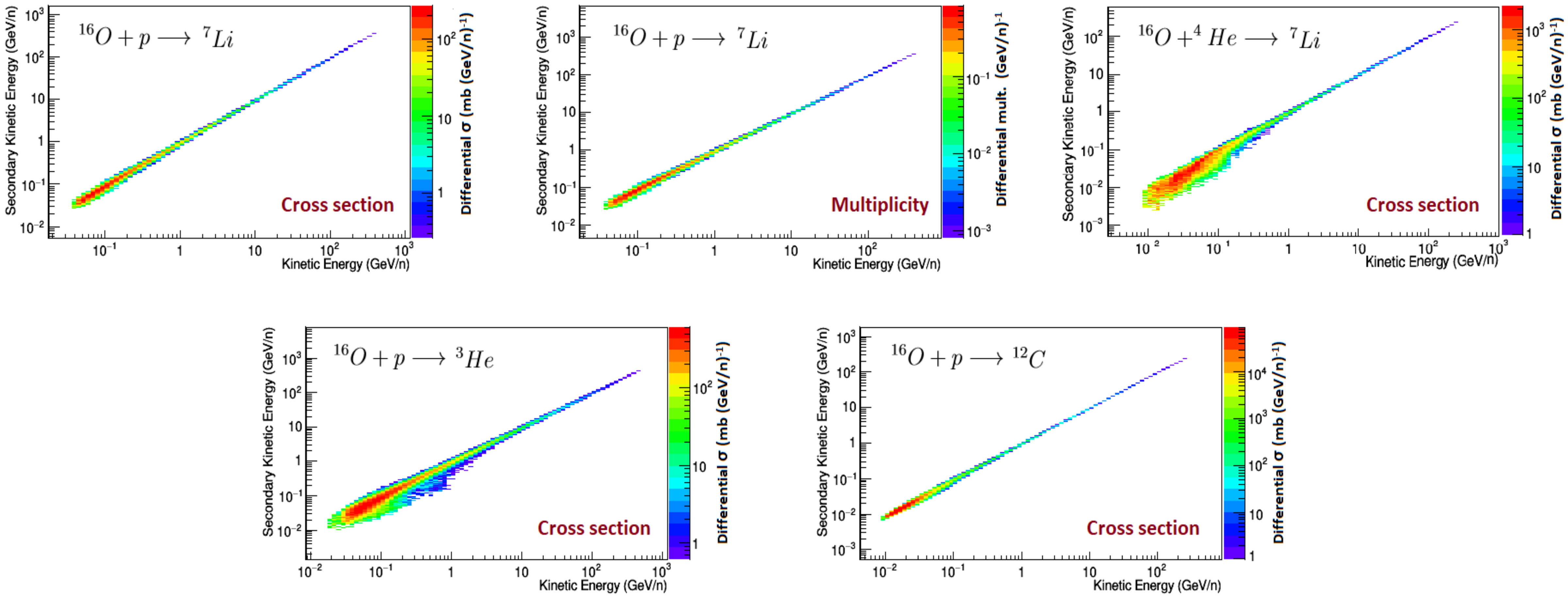
We can simultaneously reproduce all light secondary CRs with small scaling factors (~10%) !!

PDL et al *JCAP* 07 (2022) 07, 008



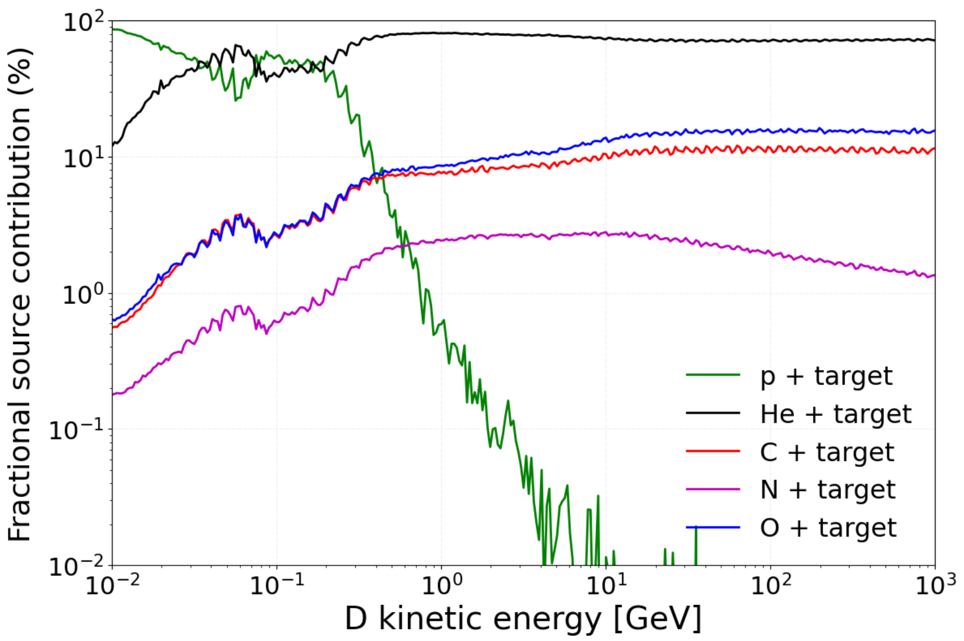


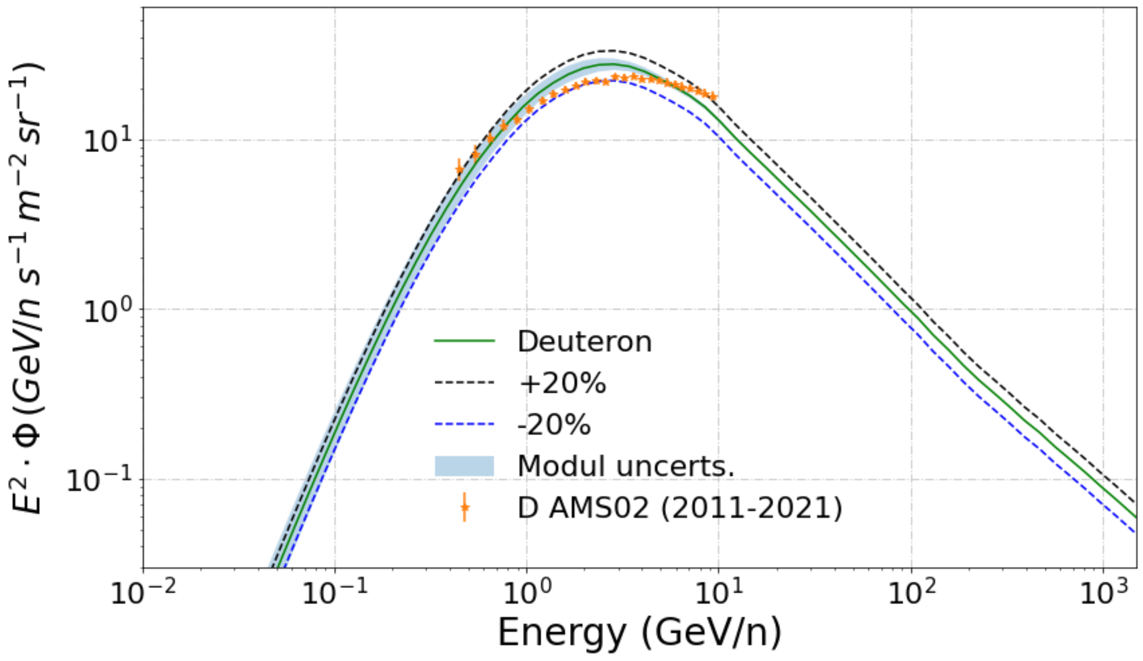
How valid is the head-on approximation below Li?

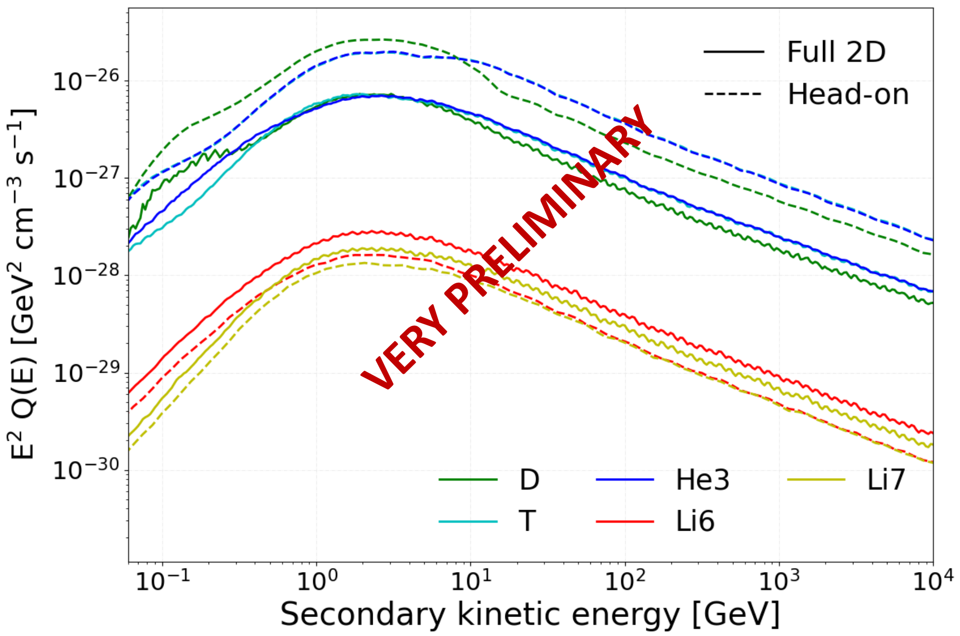


Deuteron seems incompatible with our expectations

Fluka provides a similar prediction as when using other cross sections params., all being steep compared to the data above a few GeV/n. The head-on approximation does not seem to be the problem… Correlated errors? Other contributions?







TO CONCLUDE

- **Gamma rays** offer crucial information about the **propagation of cosmic rays** in different zones of the Galaxy, despite the remaining high uncertainties… **No clear evidence in its favour is found, but several hints exist now**

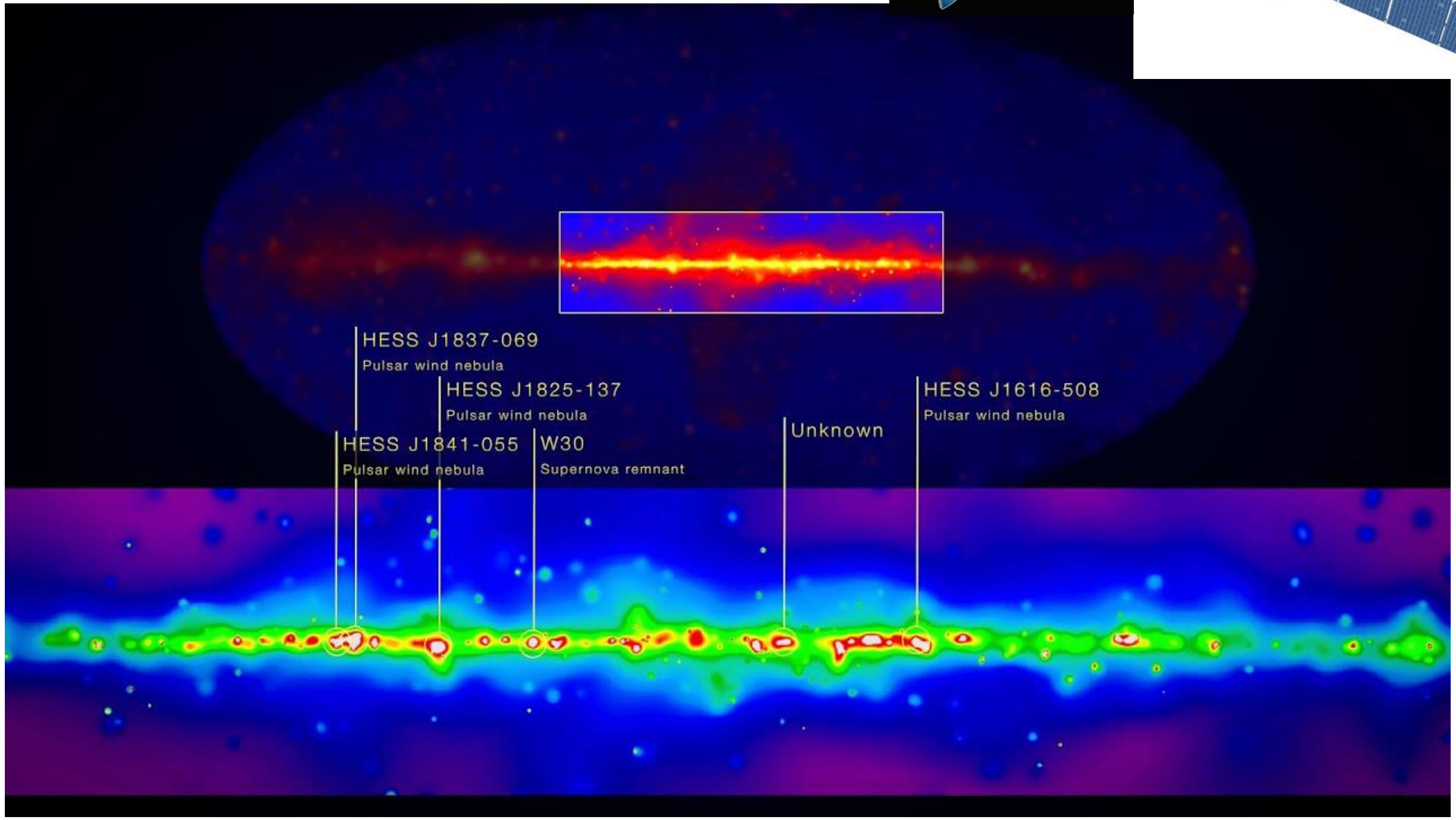
- **Heavy CRs could help find evidence for such inhomogeneities in diffusion.** Potential impact on heavy CRs not tested yet

- Adopting realistic gas density distributions might be necessary given the high accuracy of data

- **Fluka cross sections seem very promising and independent of the limited data** although much work is needed to characterize them and improve them further

The gamma-ray sky seen by Fermi-LAT

- > 7000 point-like sources have been observed by the Fermi satellite
- ~ 100 extended sources



Extragalactic and isotropic background (EBL)

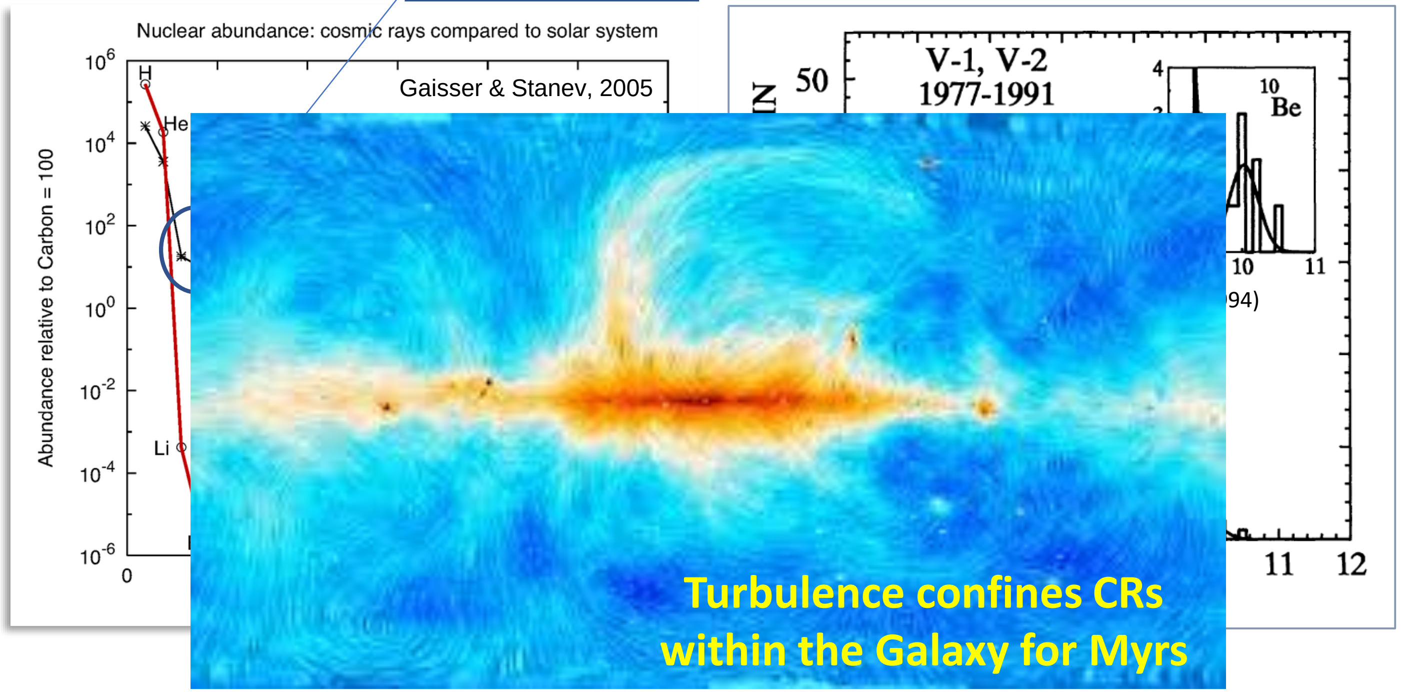
Galactic diffuse gamma-ray background

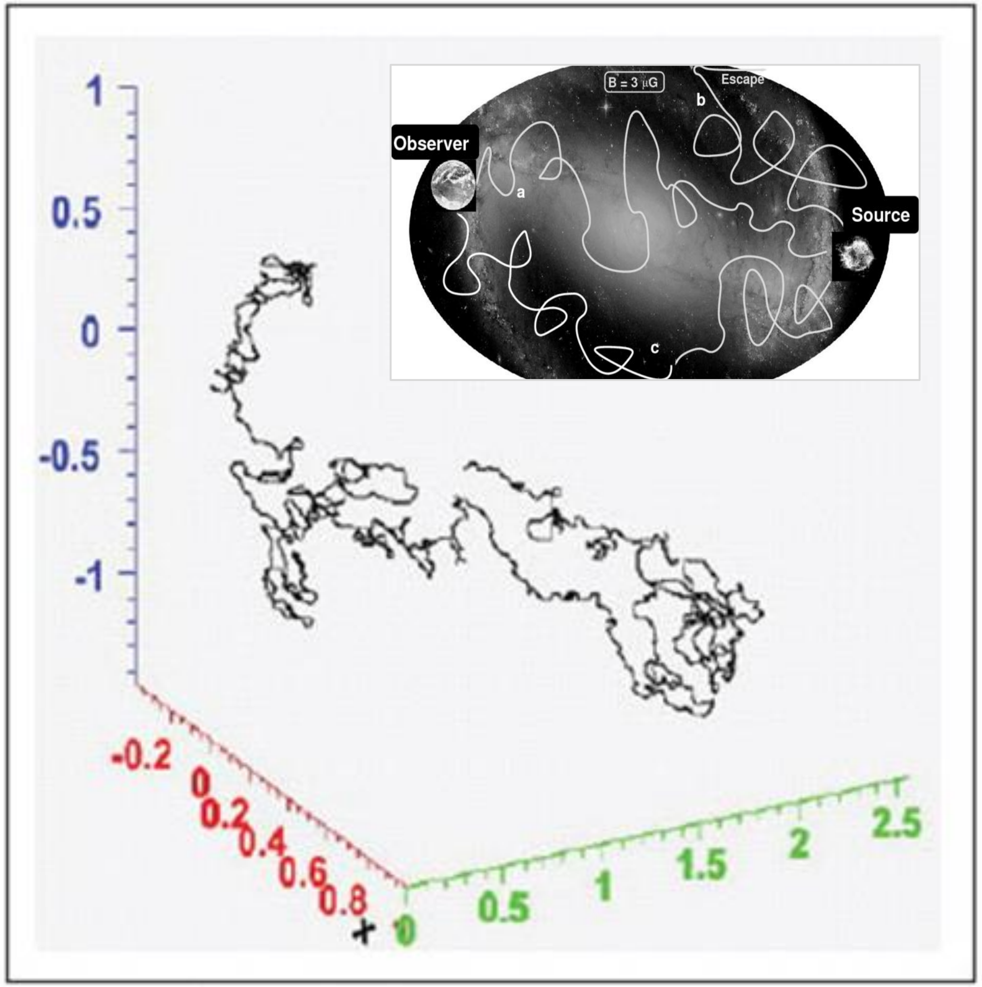
A few key observations show evidence that CRs propagate in the Galaxy for millions of years

Transport of CRs is described as a diffusive process!

Charged particles are accelerated by astrophysical sources and propagate throughout the Galaxy during millions of years, due to scattering with plasma waves.

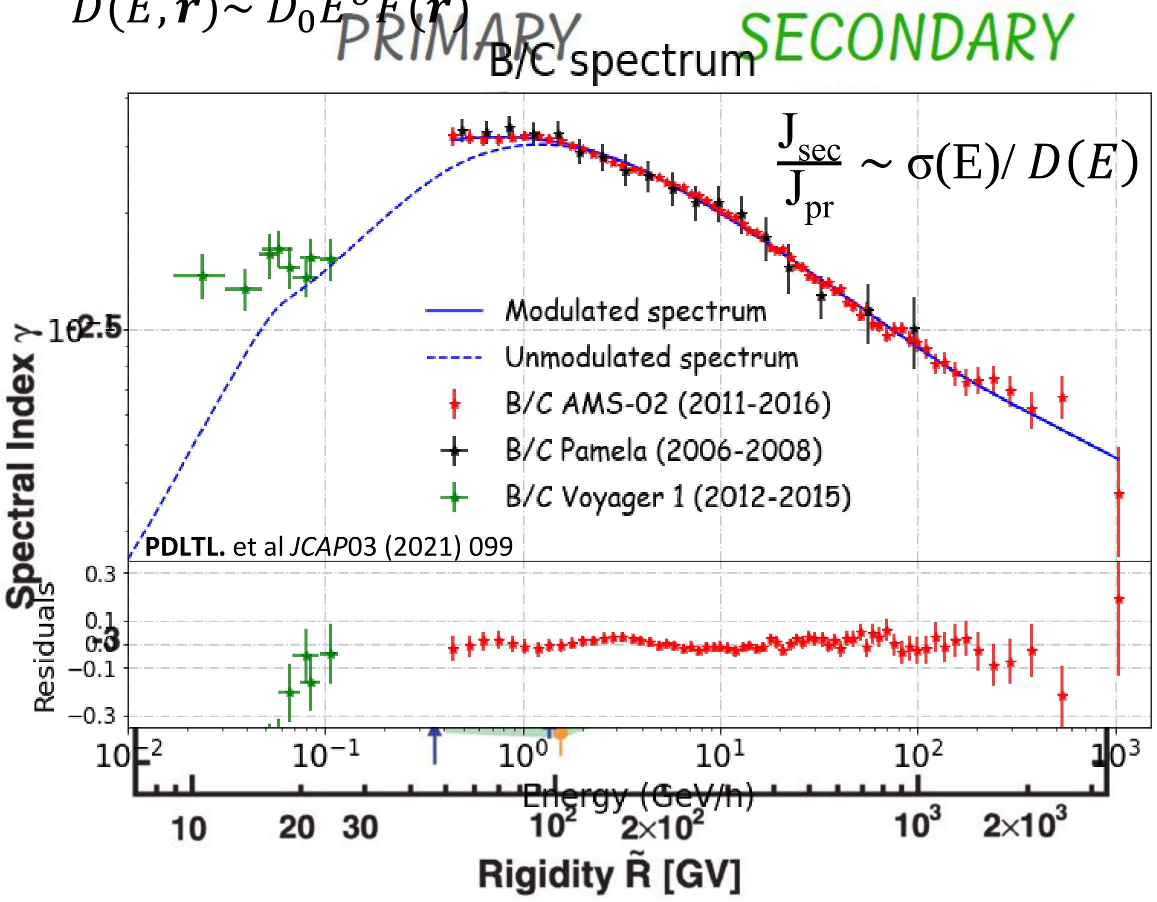
$\tau^{esc}(E) \propto E^{-\delta}$





Secondary-to-primary ratios – Diffusion coefficient

$D(E, \boldsymbol{r}) \sim D_0 E^{\delta} F(\boldsymbol{r})$



Simplest approximation to the diffusion equation:

$$\frac{\partial J_{pr}}{\partial t} = Q(E) - \frac{J_{pr}}{\tau^{esc}}$$

$$J_{pr}(E) \sim Q(E)\tau^{esc}(E) \sim \frac{Q(E)}{\mathbf{D}(\boldsymbol{E})}$$

The CR fluxes at E>tens of GeV/n are the convolution of diffusion and injection power-laws

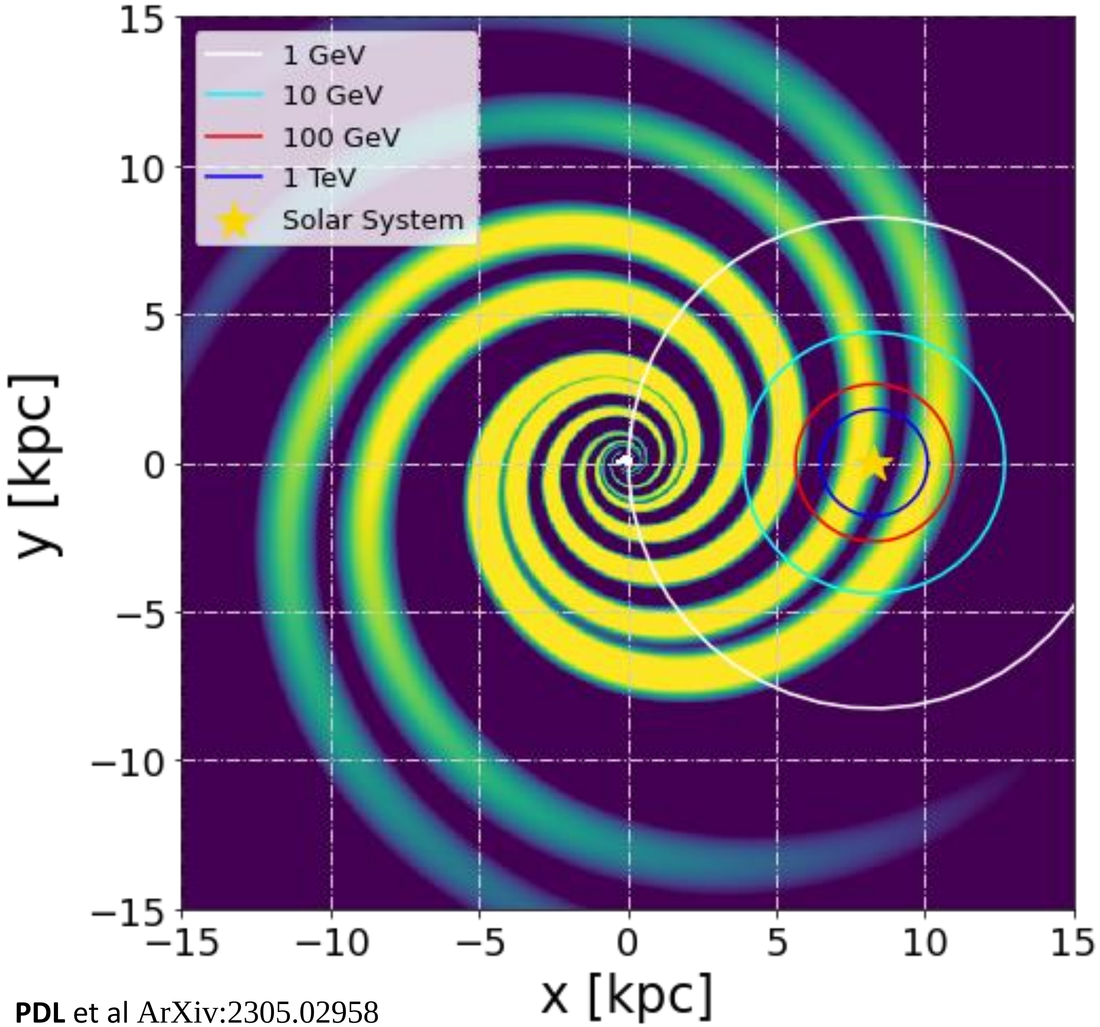
$$J_{pr}(E) \sim \frac{Q_{inj}(E)}{D(E)} \propto E^{-(\alpha_{inj} + \delta)}$$

$$J_{sec}(E) \sim \frac{\sigma(E) J_{pr}(E)}{D(E)} \propto E^{-(\alpha_{inj} + 2\delta)}$$

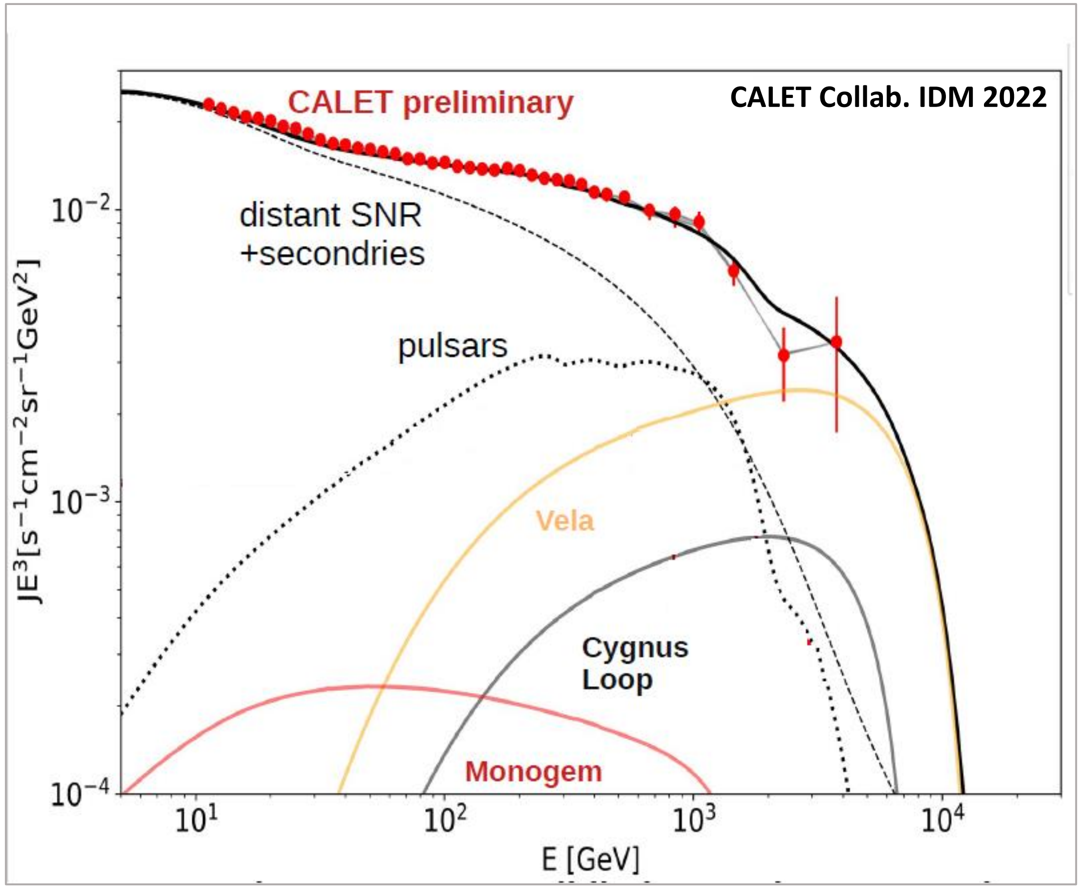
$$\frac{\mathbf{J_{sec}}}{\mathbf{J_{pr}}} \sim \boldsymbol{\sigma}(\mathbf{E})/\, \boldsymbol{D}(\boldsymbol{E})$$

e^+e^- propagation horizon

GeV-TeV e^- are dominated by the emission from local sources!



PDL et al ArXiv:2305.02958

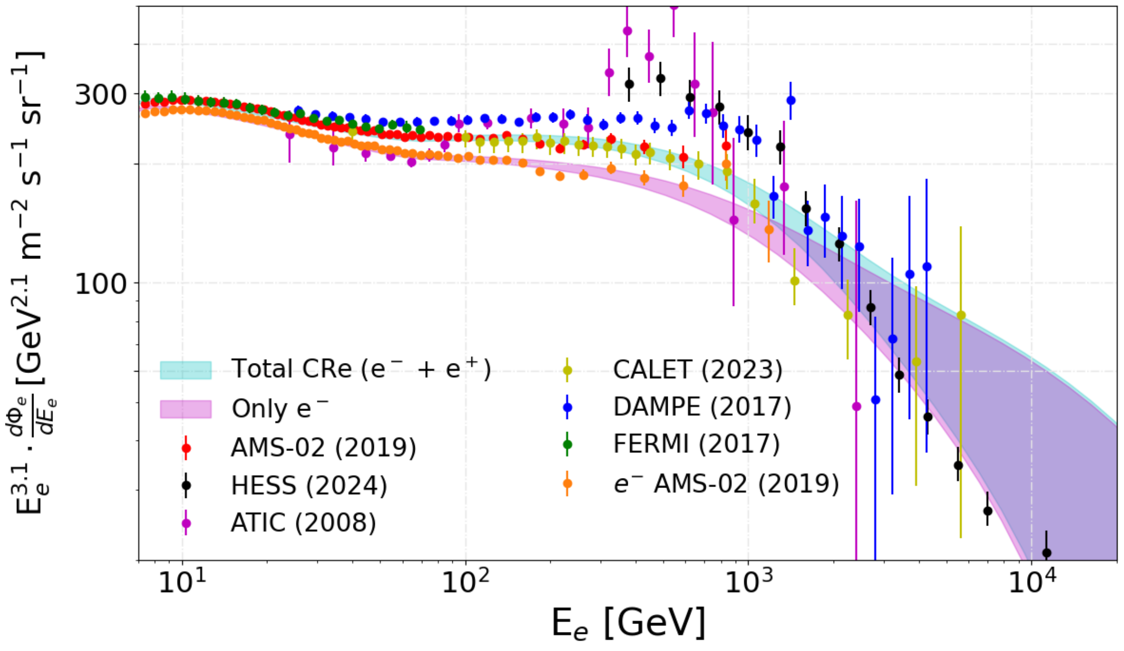


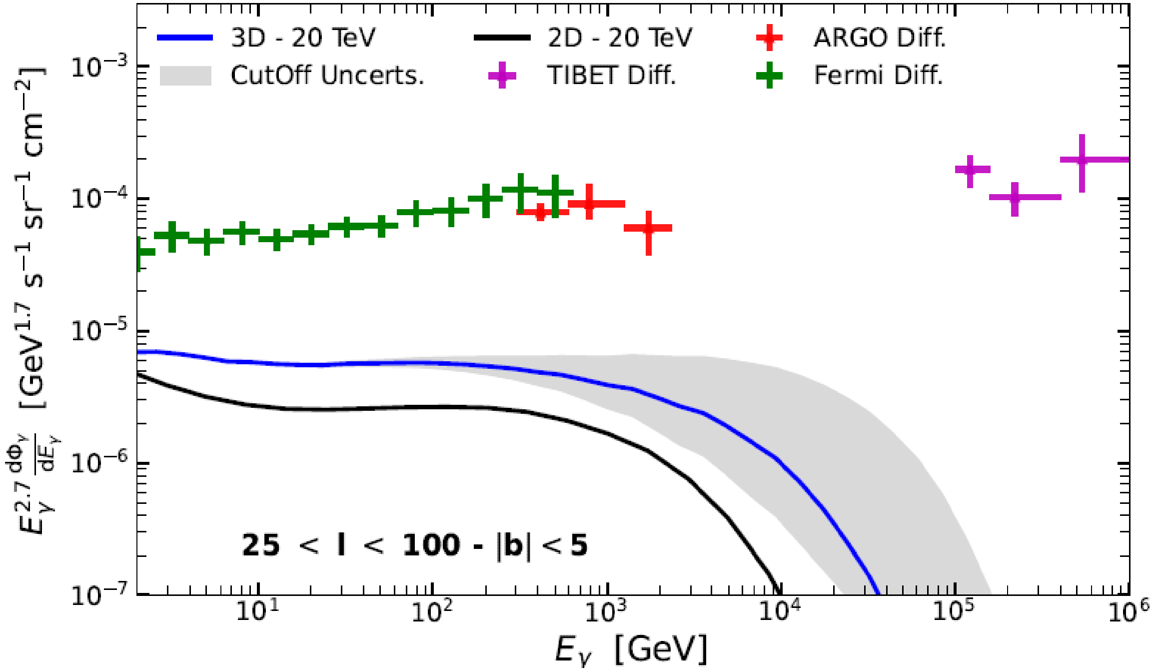
The Galactic gamma-ray diffuse sky – electrons contribution

Electrons lose energy very quickly due to their interaction with the magnetic field (leading to synchrotron emission) and ISRFs (inverse Compton emission)

Therefore, the electron spectrum measured at Earth is very influenced by the presence of local sources → Difficult to estimate with precision the IC emission in different parts of the Galaxy

PDL. et al arXiv:2502.18268

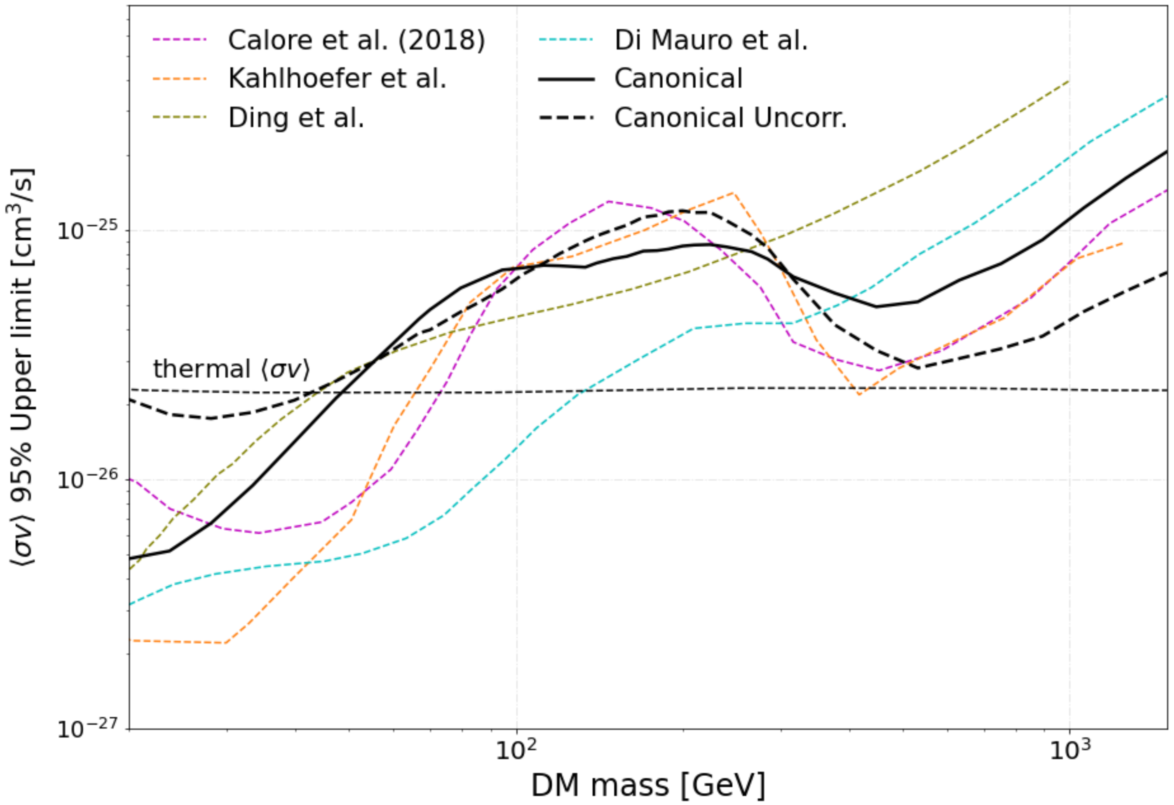


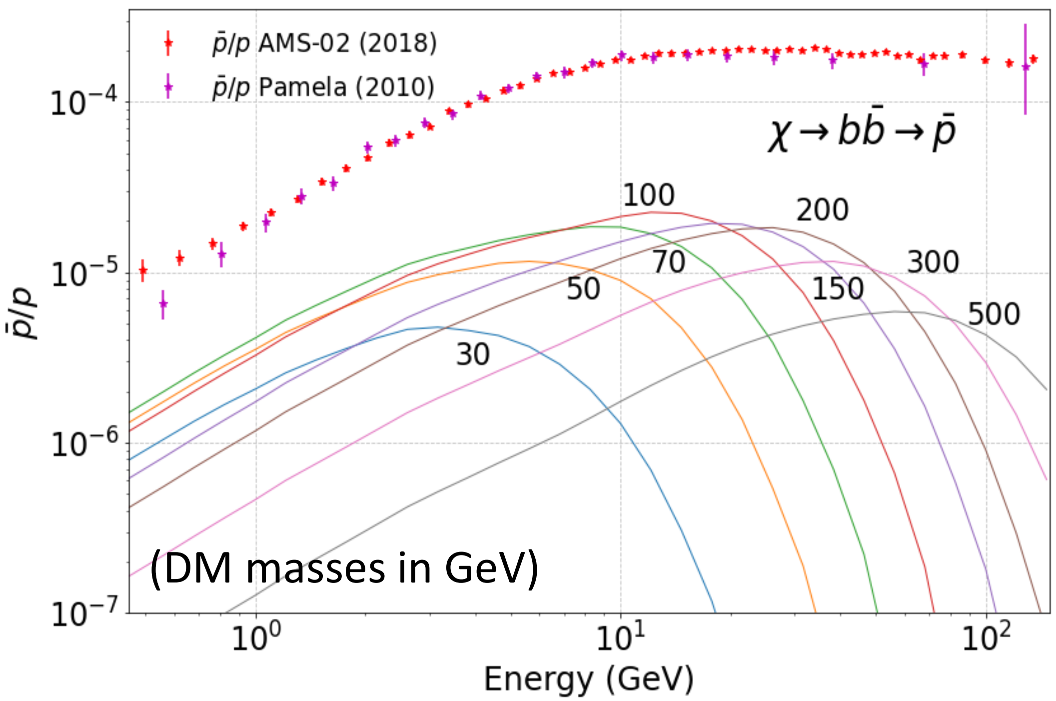


Dark matter bounds from antiproton combined analyses

Maximum significance found to be below 2σ (local)!

P.D.L. et al, **in preparation**





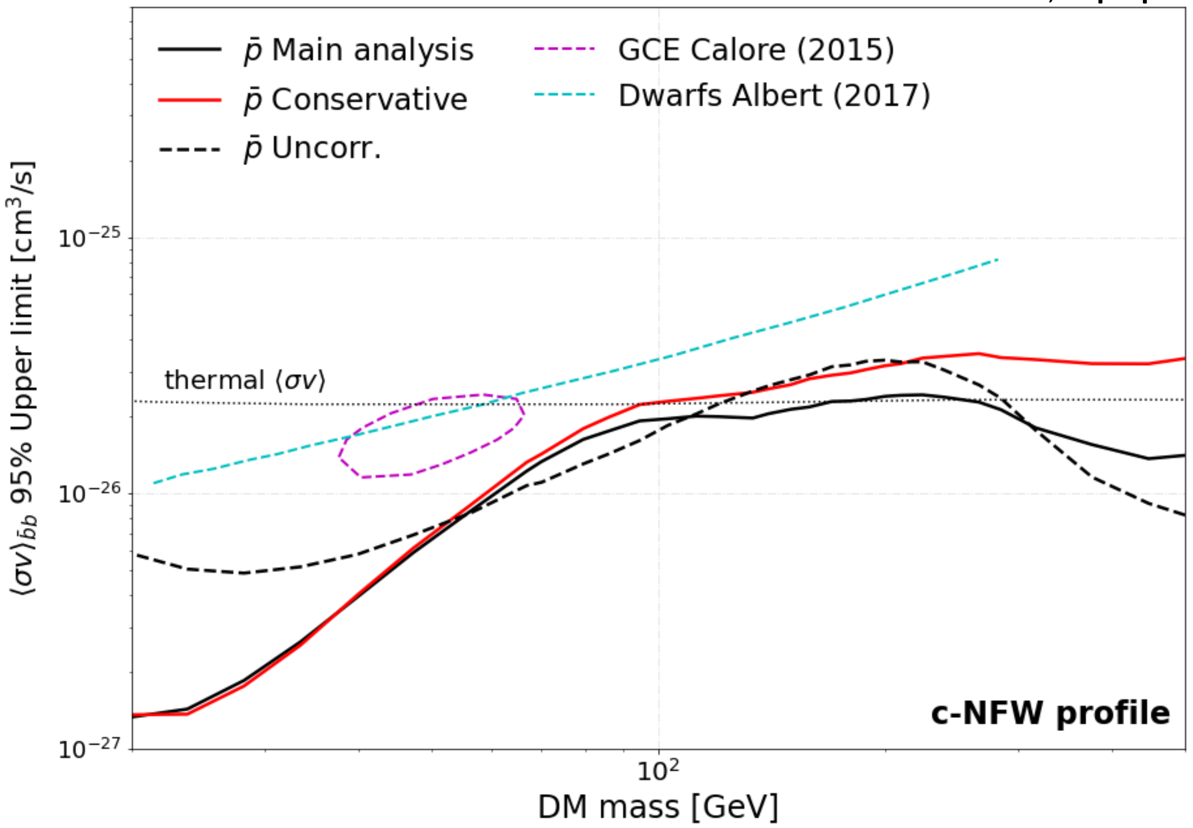
The DM signal is constrained to be, at most, a 10% of the total p̄ flux (for ~100 GeV DM) Moreover, there is some tension with the GCE!!

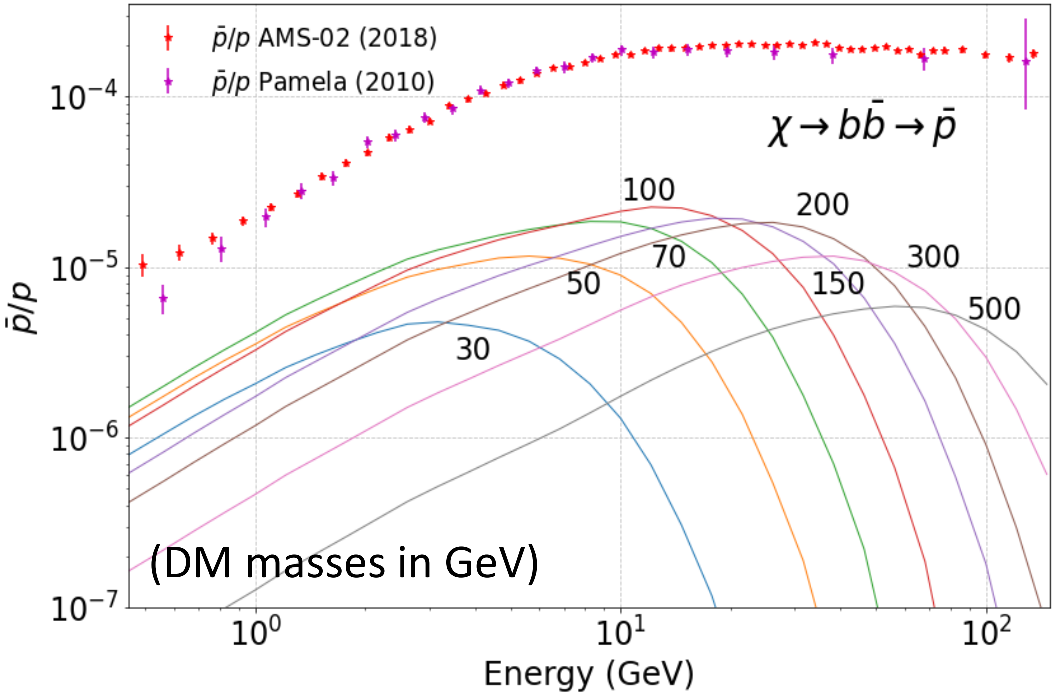
However, we are constrained to the classical model of production of antiprotons

Dark matter bounds from antiproton combined analyses

Maximum significance found to be below 2σ (local)!

P.D.L. et al, **in preparation**





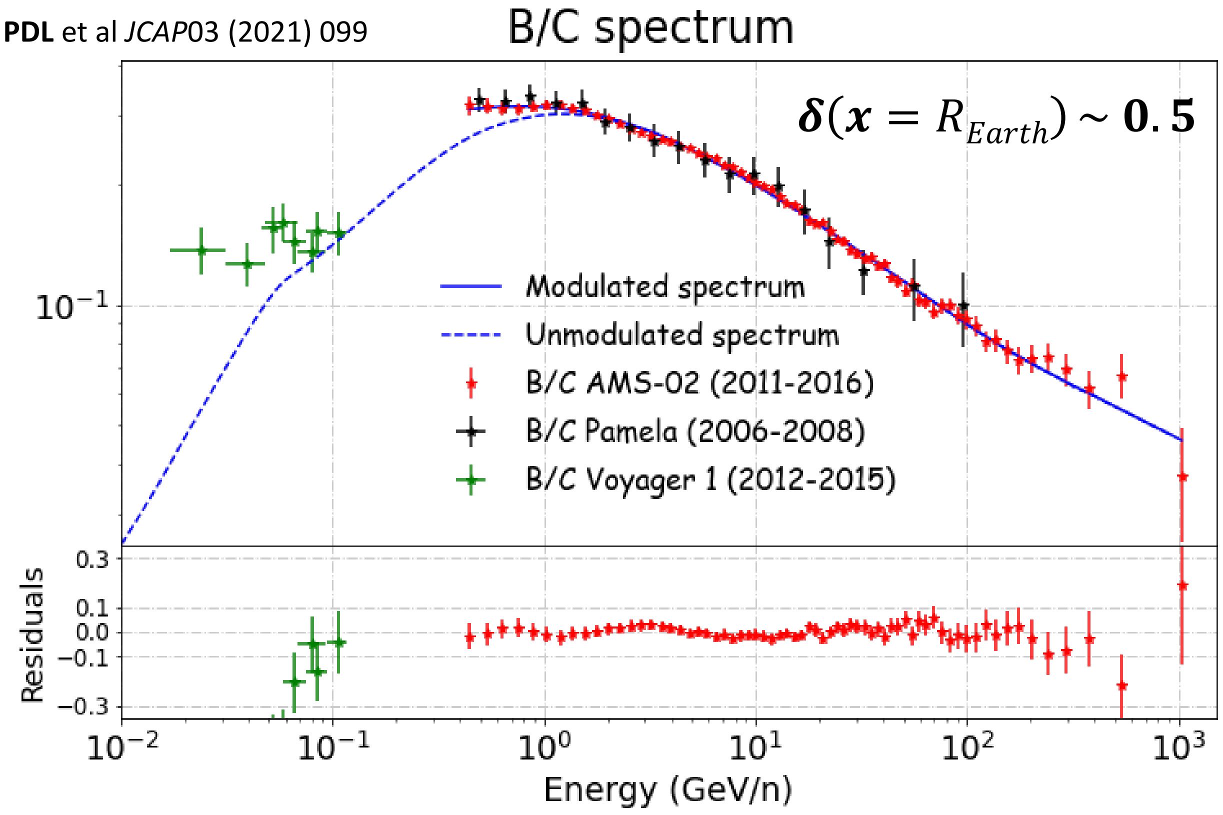
The DM signal is constrained to be, at most, a 10% of the total p̄ flux (for ~100 GeV DM) Moreover, there is some tension with the GCE!!

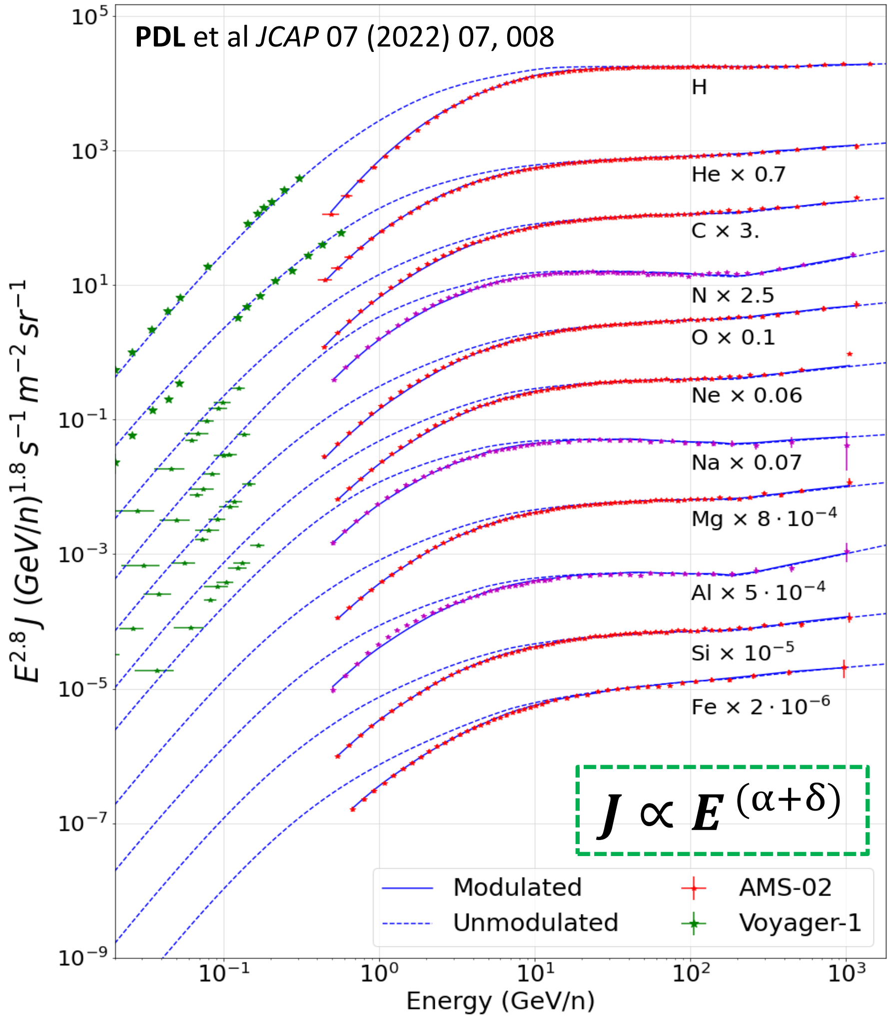
However, we are constrained to the classical model of production of antiprotons

The Galactic gamma-ray diffuse sky – Local cosmic rays

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

PDL et al *JCAP*03 (2021) 099





Non-uniform transport:
An Inhomogeneous diffusion model

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

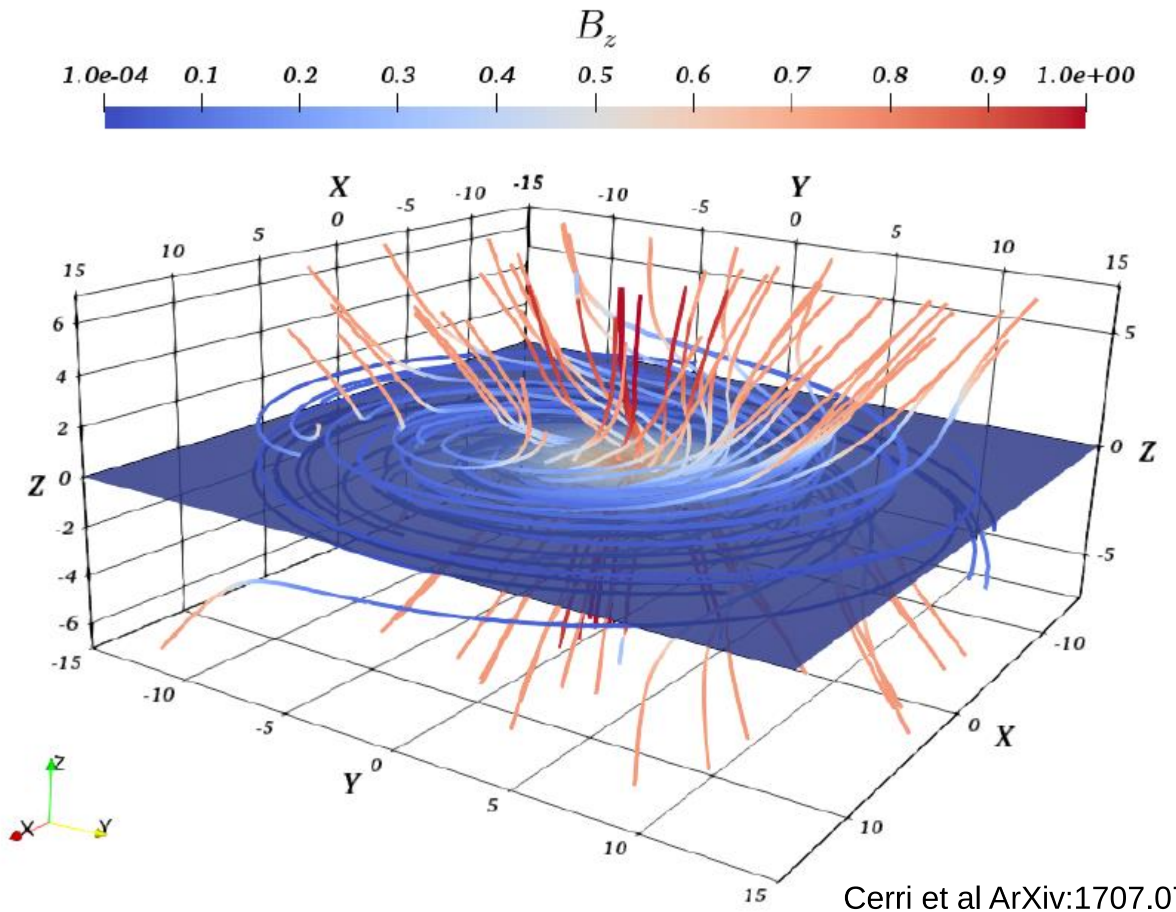
- Magnetic field intensity (and direction)

- Gas distribution (contributing to damping of MHD waves)

- Distribution of sources

- Anisotropy of turbulence cascade

- Non-steady particle distribution?

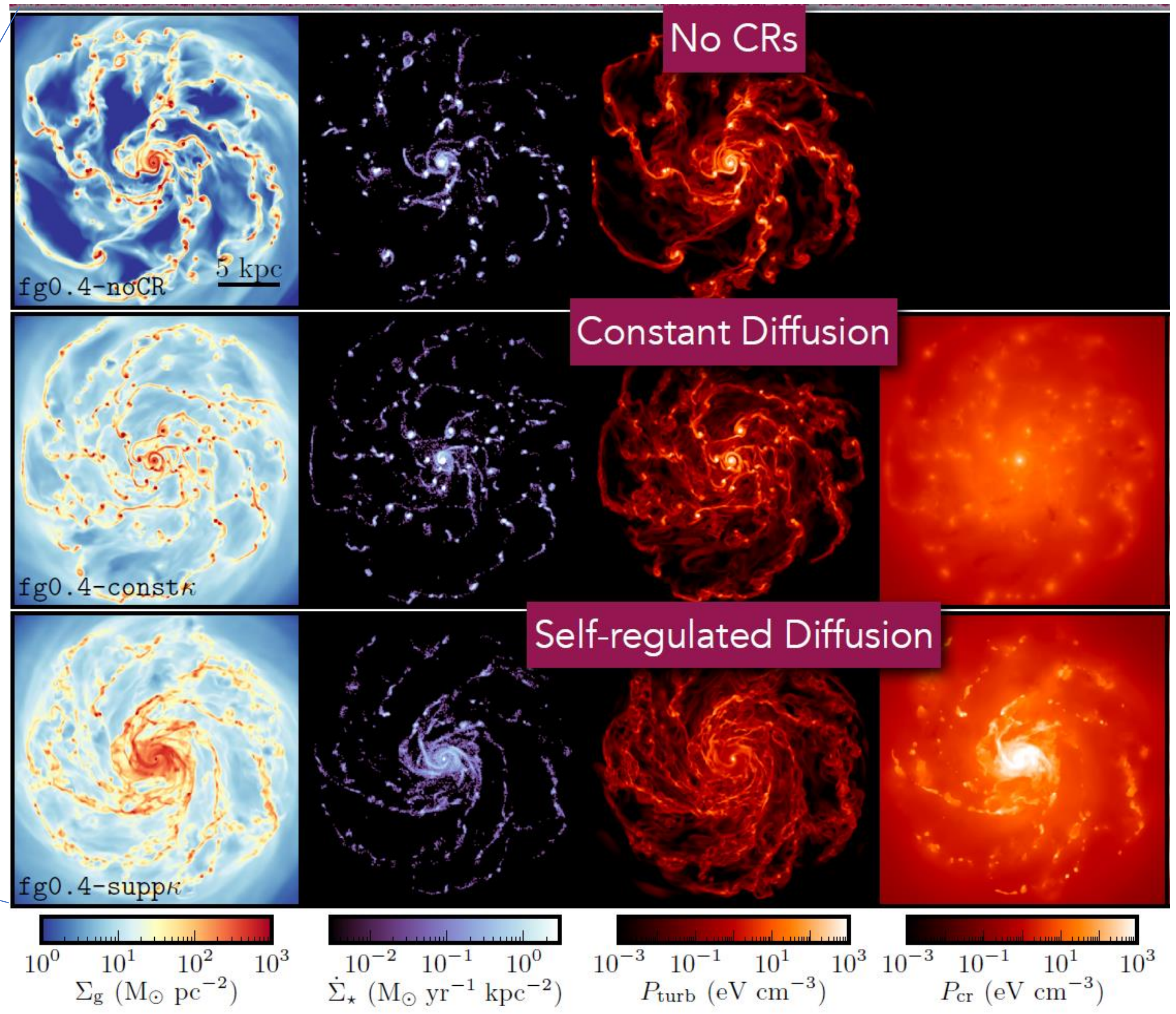


Cerri et al ArXiv:1707.07694

Impact of non-uniform transport

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?

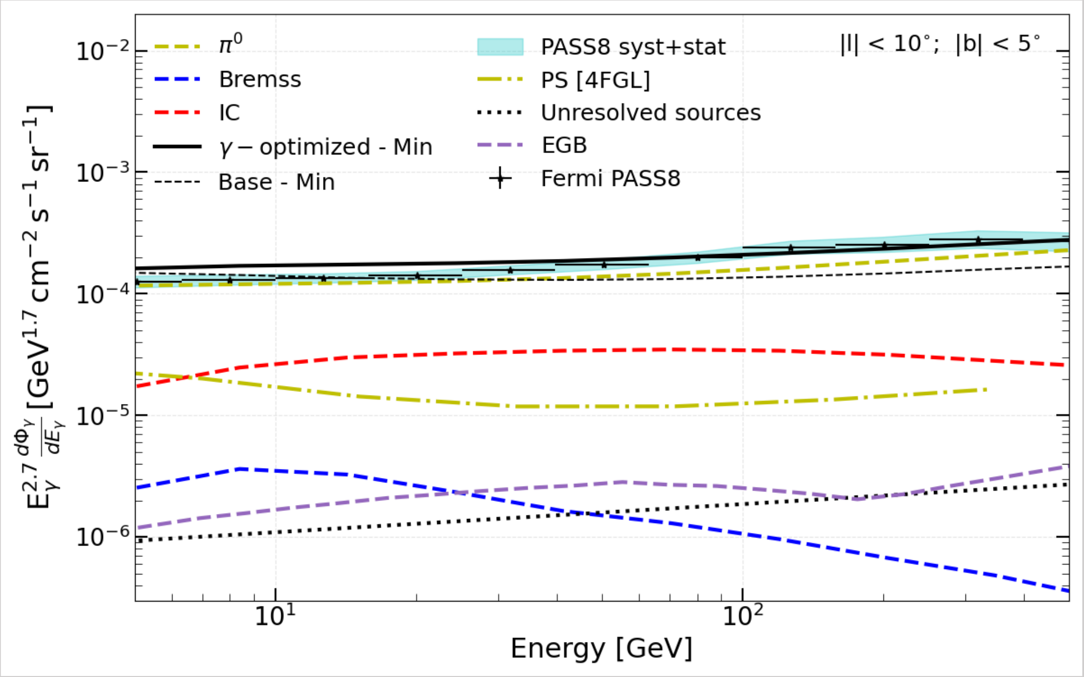


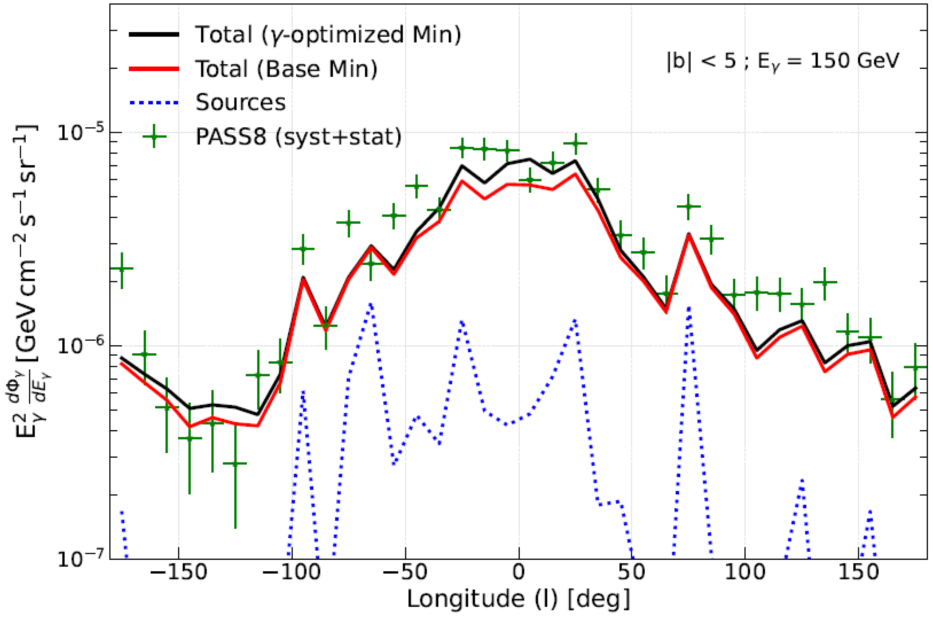
Comparing to Fermi-LAT

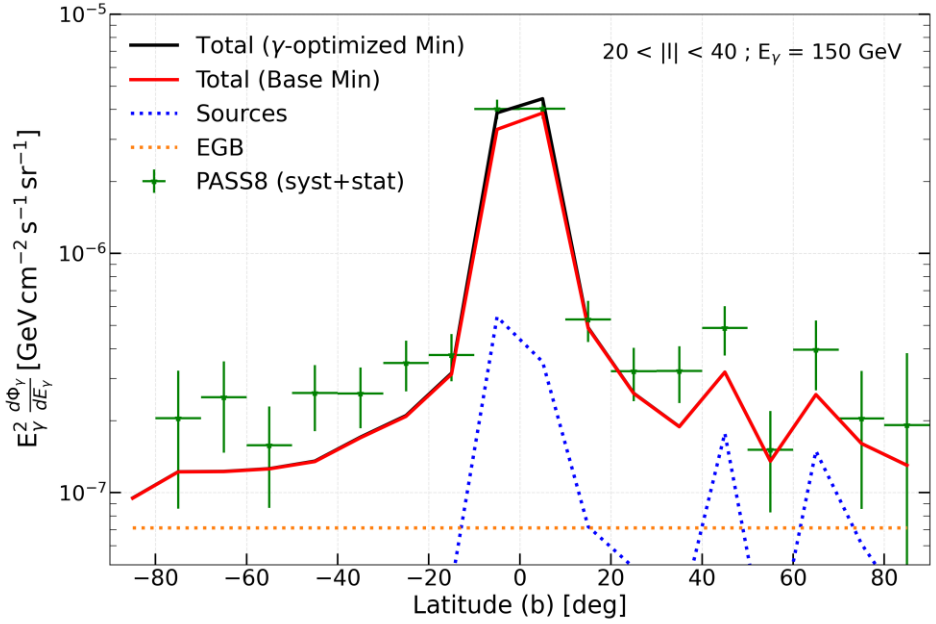
Source emission (4FGL-DR2 cat.), EGB and unresolved emissions added to compare with data

Only the XCO factor slightly tuned to improve normalization with respect to Fermi-LAT data

Good spectral and morphological agreement even though we do not carry out a dedicated fit





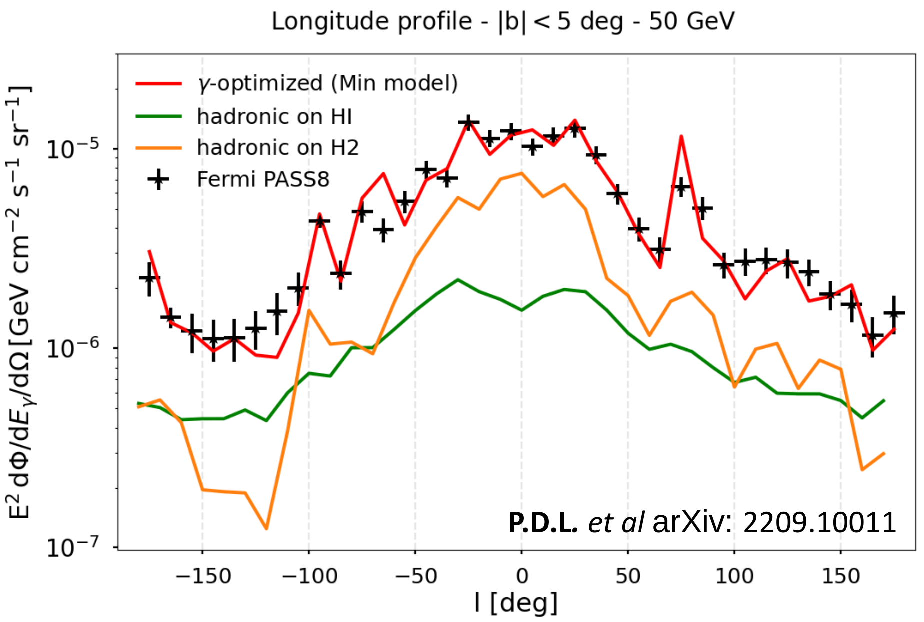


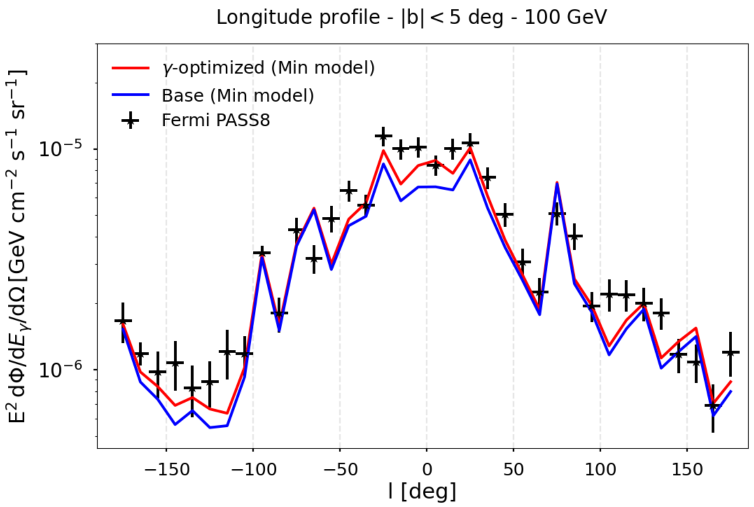
γ-optimized model vs Fermi

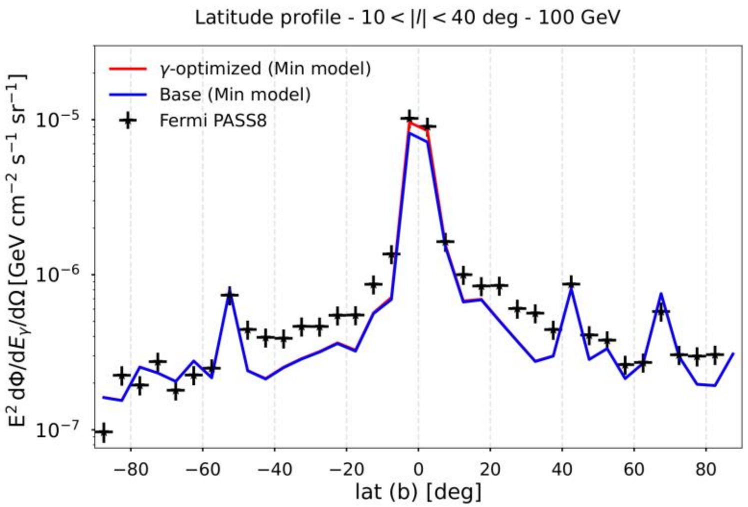
ISM gas distribution based on the ring gas model developed by Q. Remy

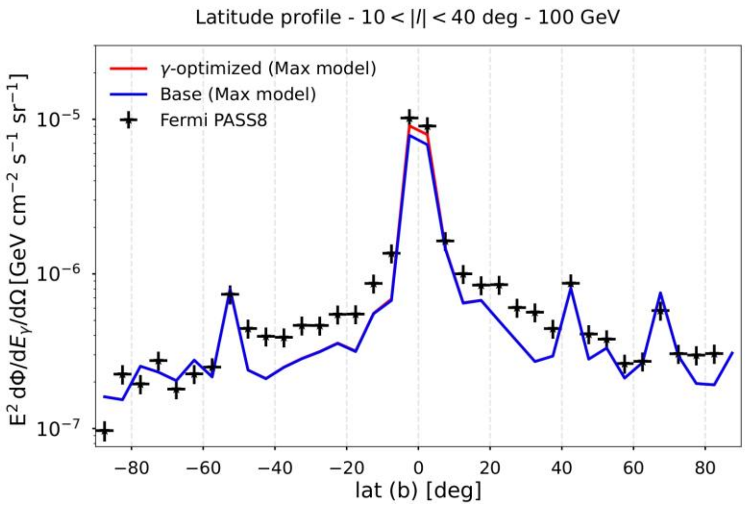
ISRF distribution (CMB + IR + Stellar) from Vernetto&Lipari Phys. Rev. D 94, 063009

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

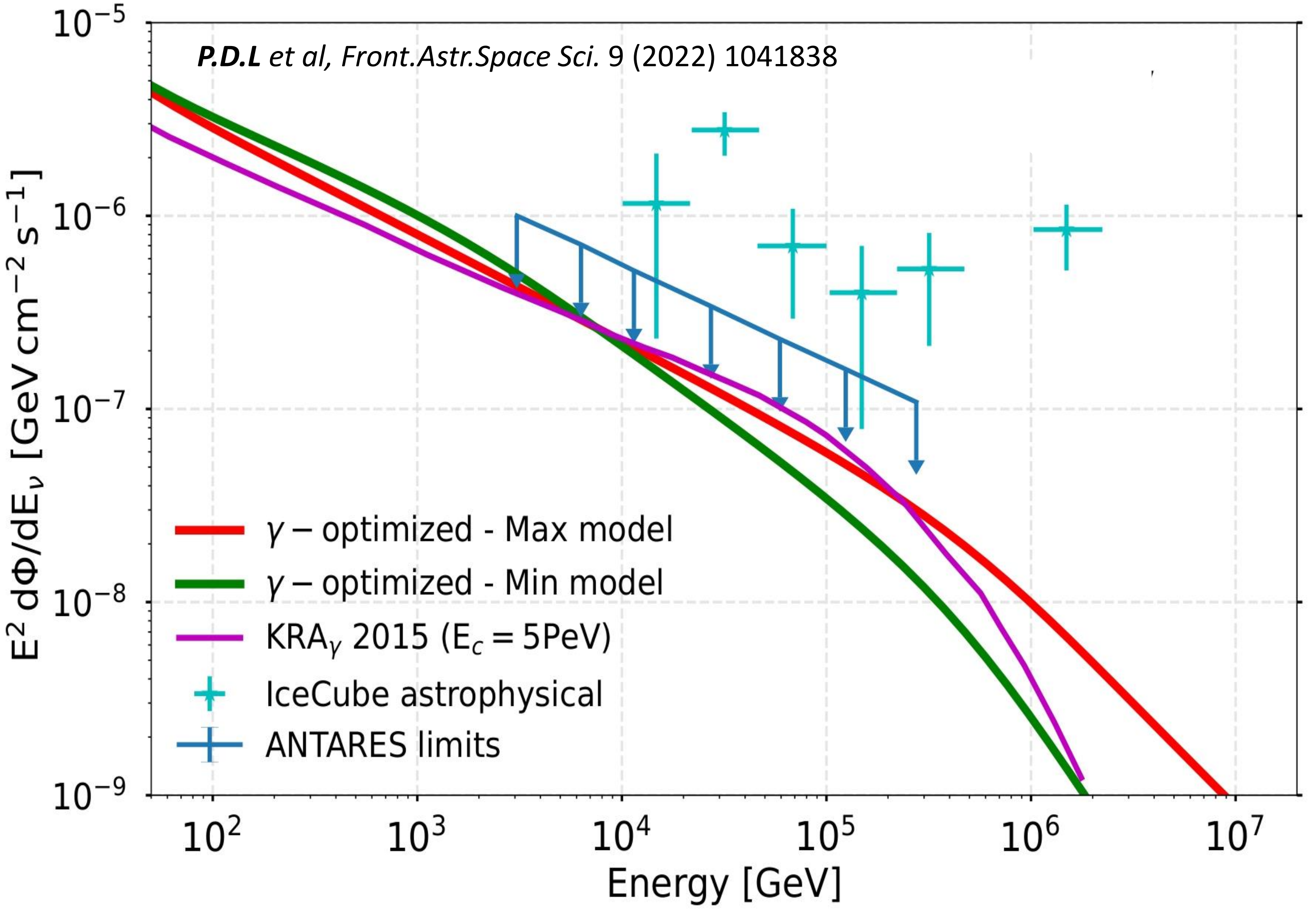








Diffuse gamma-ray production: detection of neutrinos as a smoking gun



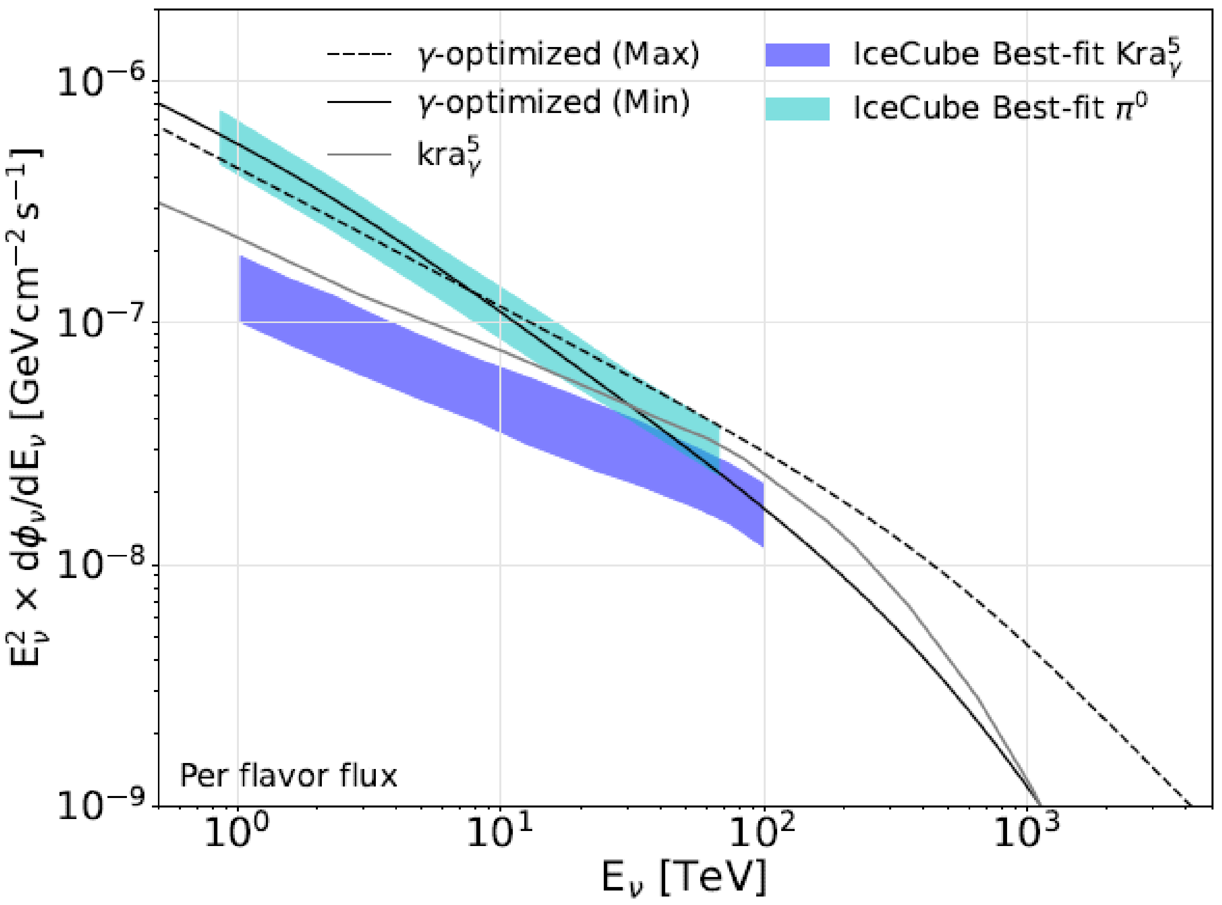
Neutrinos are also generated by CR collisions with ISM. This emission is similar in intensity and spectral shape to the gamma-ray emission

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) was clearly already identified by IceCube.

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



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

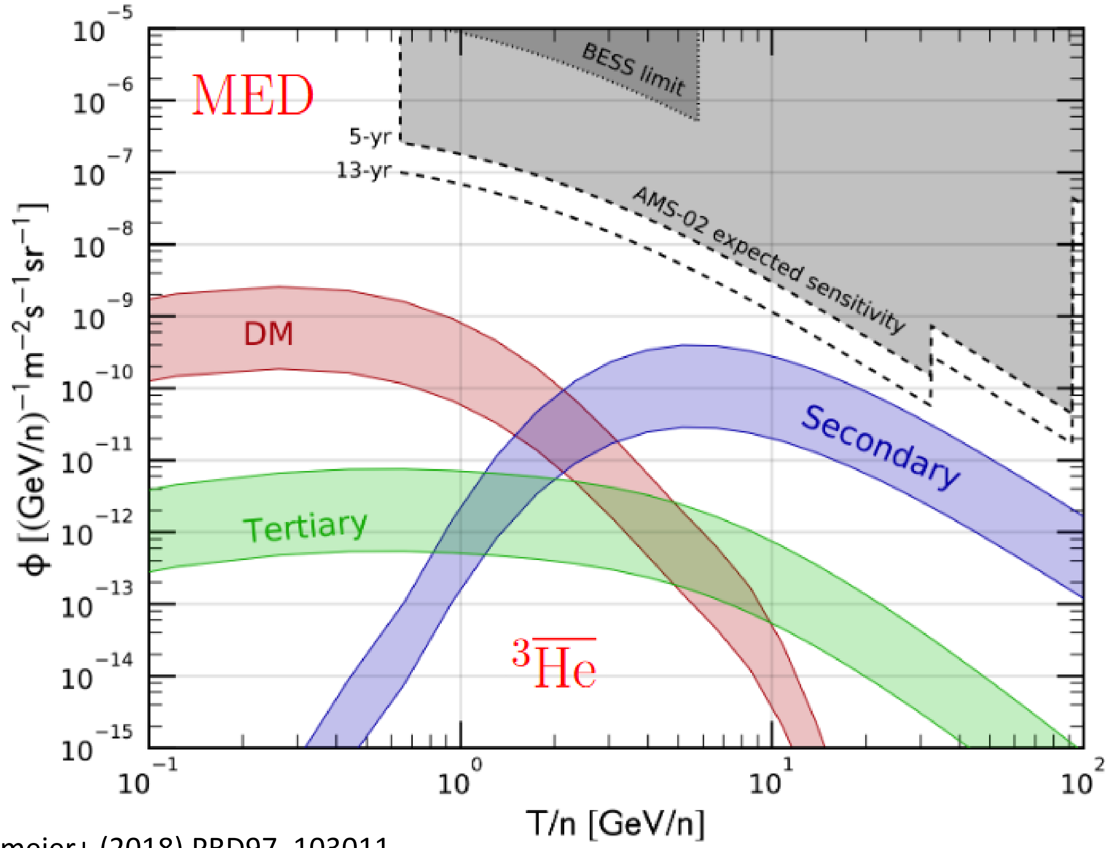
However, no much room for high-energy neutrino sources → Is that most of the γ-ray PeVatrons have a leptonic origin?

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

Anti-nuclei as the dark matter smoking gun

The window to prove (or disprove) many possible astrophysical excesses



Korsmeier+ (2018) PRD97, 103011

For kinematical reasons, the production of anti-nuclei from CR interactions is not important at energies below the GeV, offering a **clear way to spot the production of anti-nuclei from dark matter** (at least for masses below ~hundreds of GeV)

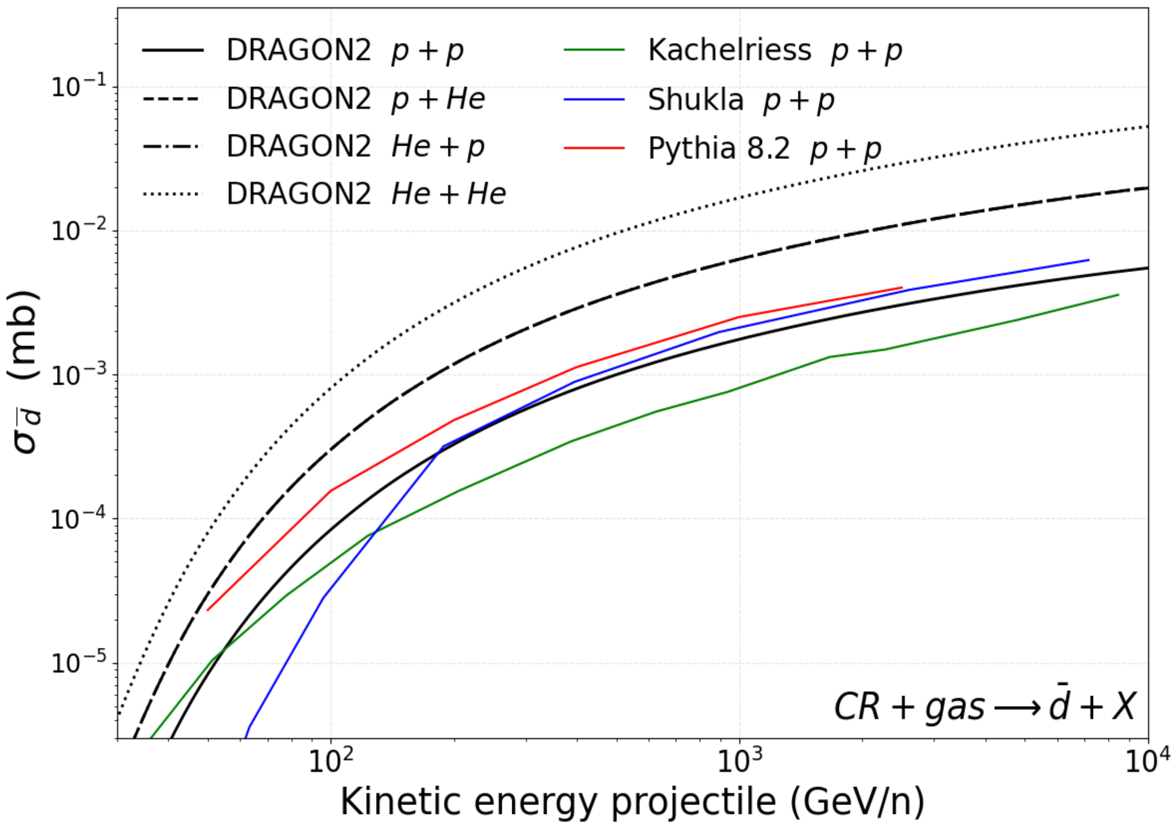
Secondary anti-nuclei produced from homologous interactions as for p, but highly suppressed (due to coalescence)!

Propagation setup

Propagation code: github.com/tospines/Customised-DRAGON-versions/Custom_DRAGON2_v2-Antinuclei/

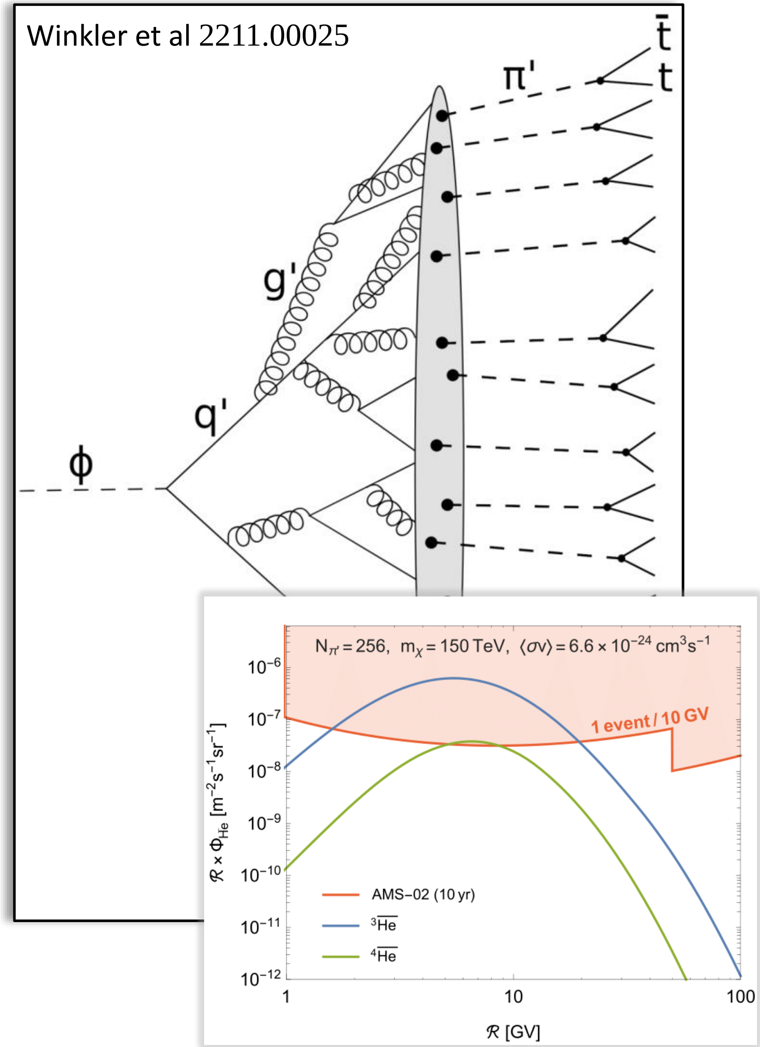
❖ Implementation of anti-nuclei dark matter and secondary production in DRAGON2

- Cross sections derived from analytical coalescence model. Using fits of antiproton (antineutron) production from *Winkler, JCAP 02, 048 (2017)*
- DM spectrum at production derived from *Pythia 8.2* simulating a neutral colourless resonance.
  Space and momentum (p_c) conditions for coalescence. Also including production from anti-hyperons
- Inelastic cross sections and tertiary production computed extrapolating antiproton parametrizations



PDL et al, ArXiv: 2404.13114

How to explain the AMS-02 $\overline{\text{He}}$ detection?



Our standard predictions do not explain total He events and foreseen a ratio $\overline{\text{He}}$-4/$\overline{\text{He}}$-3 of ~ 1/1000

Only a few ideas proposed so far:

Galactic anti-clouds (Poulin et al. 1808.08961) (see also 2304.04623)

Stability and cosmological implications must be revised

QCD-Like Dark sector (Winkler, **PDL**, Linden 2211.00025)

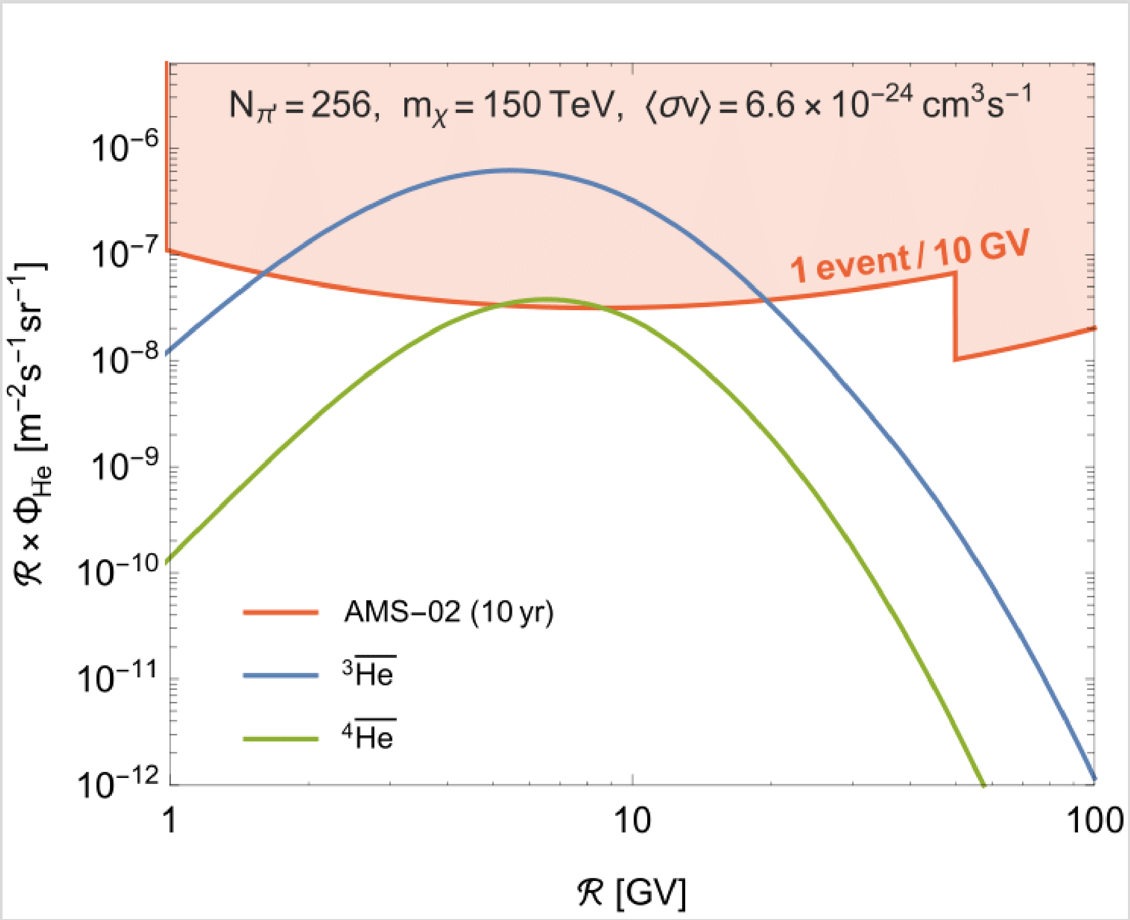
Can explain AMS-02 observations but need some tuning

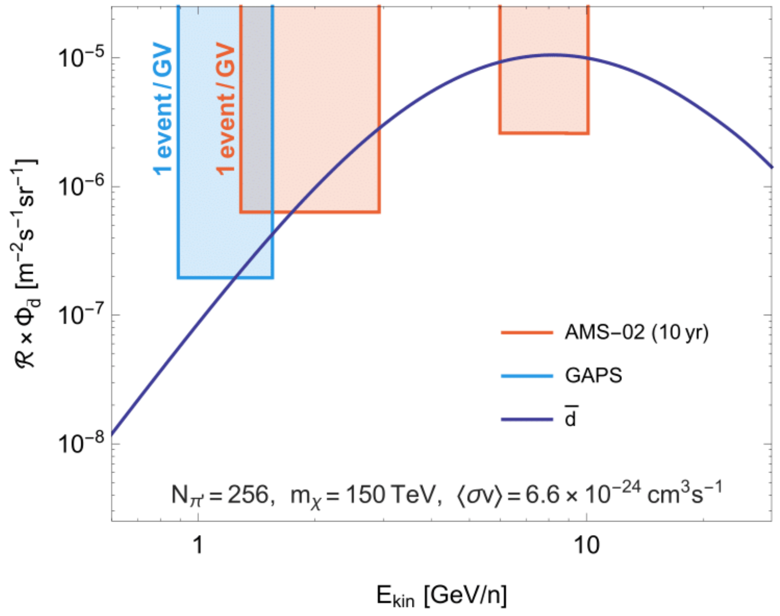
Fireball anti-nucleosynthesis (Fedderke et al. 2402.15581)

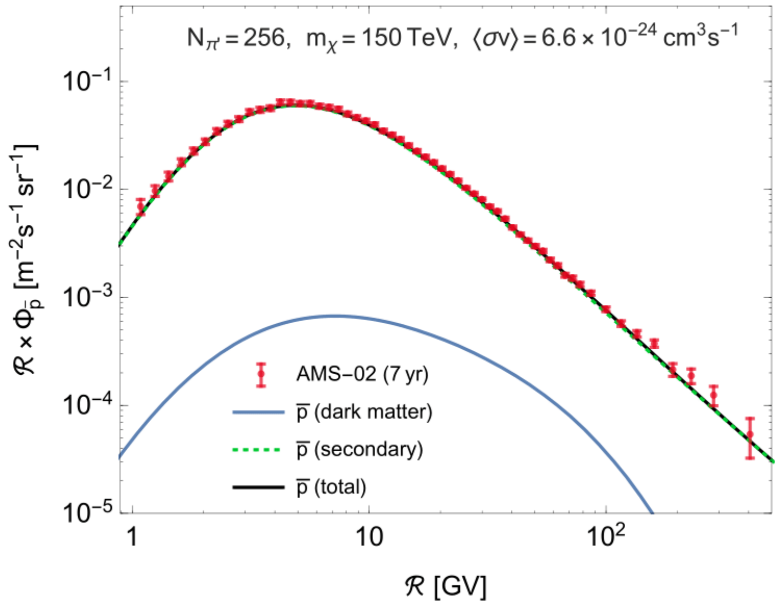
Fireballs must be very stable for long times and carry negative net antibaryon number

QCD-Like Dark sector

From factorized model: $N_A \propto (N_p)^A$







http://www.fluka.org/fluka.php

Evaluation of cross sections for CR interactions with the FLUKA code

FLUKA has been used in other CR studies as in Mazziotta, **P.D.L**. et al PRD 101(8):083011 (2020), as well as for other astrophysical applications as atmospheric neutrino studies (Astropart. Phys., 23:526–534, 2005) or gamma-ray flares from the Sun (Solar Phys., 294(8):103, 2019).

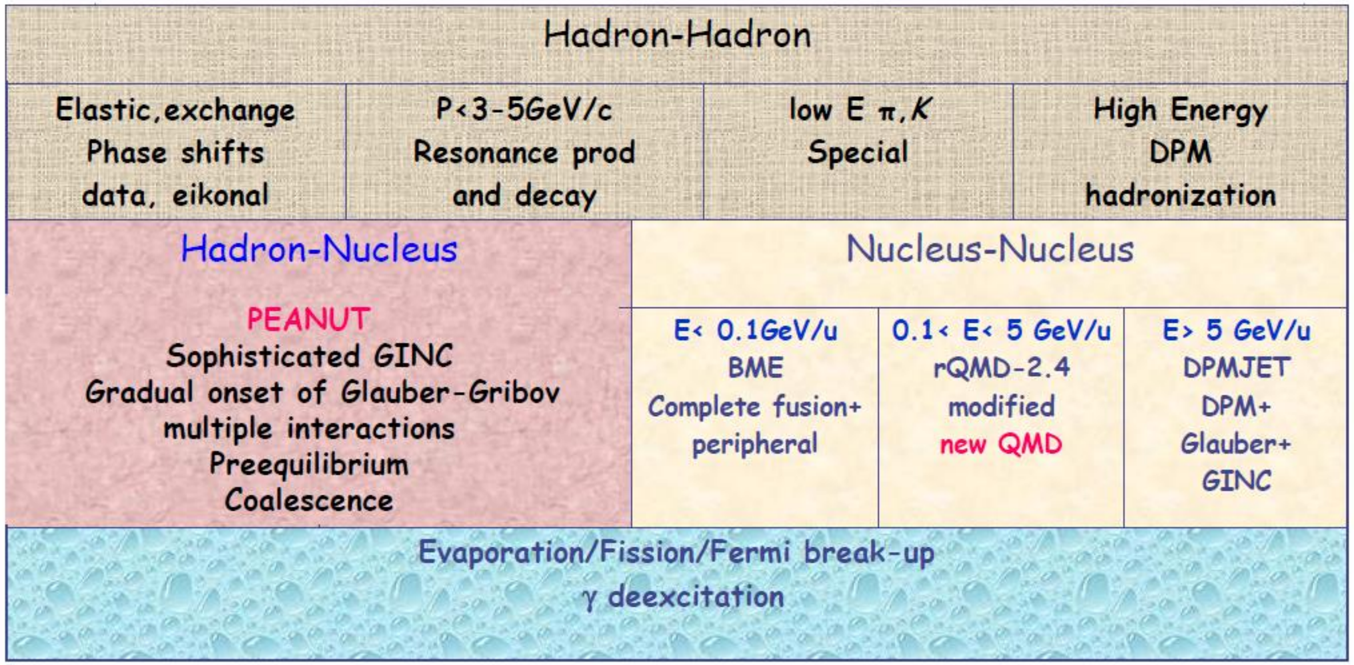
We have computed inelastic and inclusive cross sections of interactions of all isotopes of the CR nuclei up to Z=26 (Iron) with protons and helium, including a careful analysis of those short-living particles produced (ghost nuclei) from 1 MeV/n to 35 TeV/n.

The result is a set a cross sections of secondary CRs that can be used in CR propagation codes. We have also computed cross sections for gamma-ray, secondary electrons and positrons, neutrinos and antiprotons.

The FLUKA toolkit and the evaluation of cross sections for CR interactions

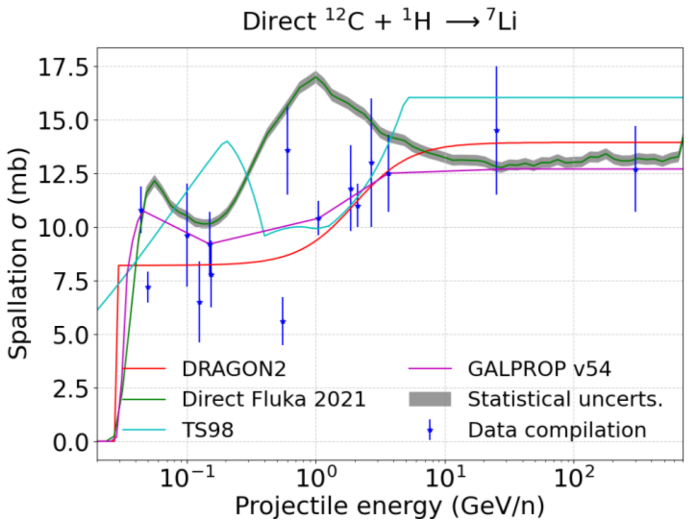
http://www.fluka.org/fluka.php

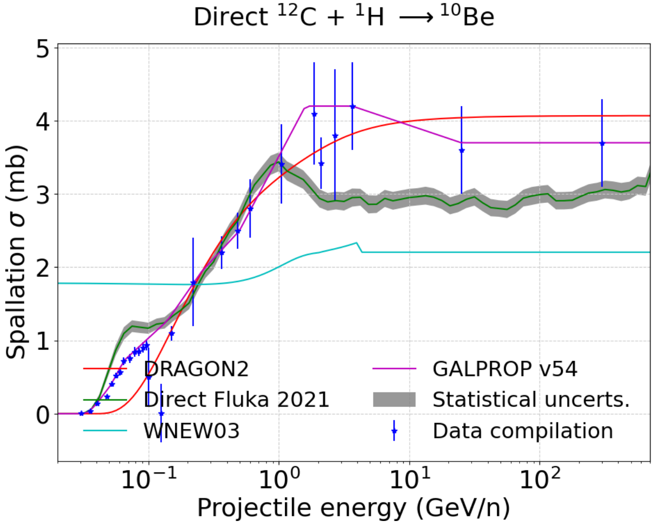
- **<u>Resonances</u>** produced in hadron-nucleon inelastic collisions dominate from the MeV up to 3-5 GeV
- Above 3-5 GeV hadronizations through <u>Dual Parton Model</u> (**DPMJET-3**) takes over
- Extension to <u>hadron-nucleus</u> collisions is achieved <u>through the **PEANUT** model</u> (GINC) + relaxation
- Nucleus-Nucleus use **Boltzmann thermal equation** at E<0.1GeV/u, **rQDM** model up to 5 GeV/u and **DPMJET** above

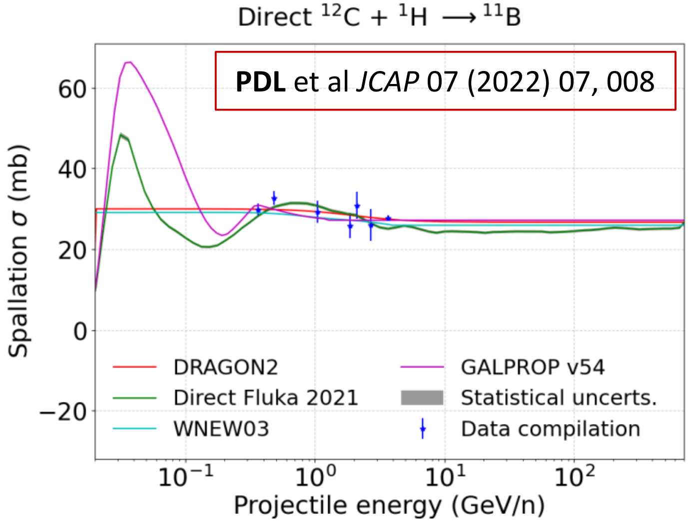


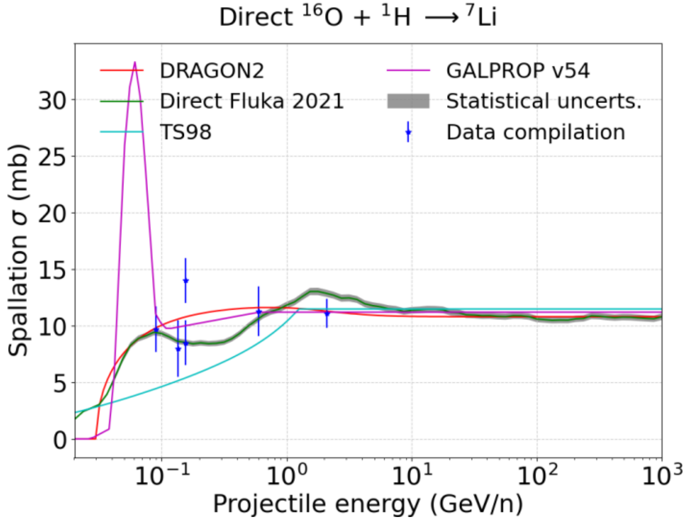
Credit: Paola sala

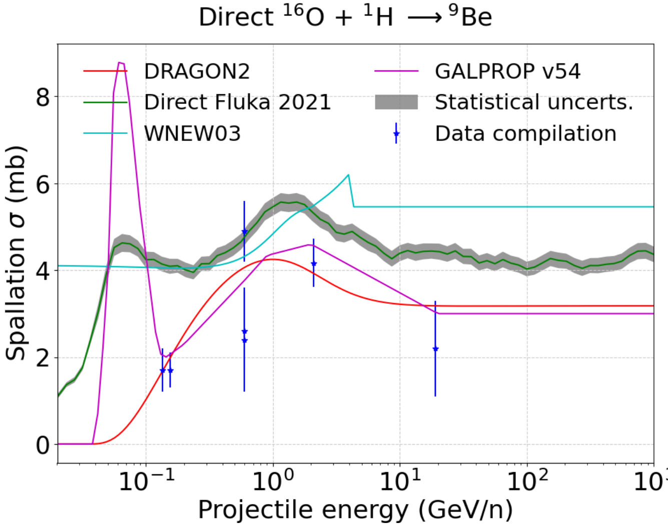
FLUKA (direct) inclusive cross sections

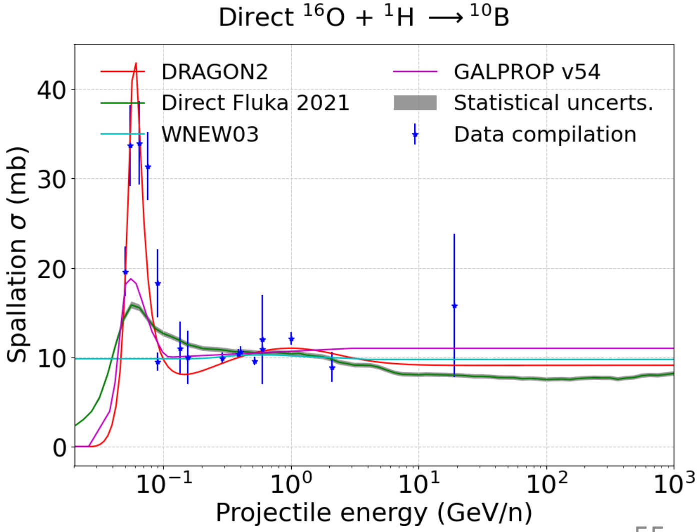












FLUKA inelastic cross sections

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