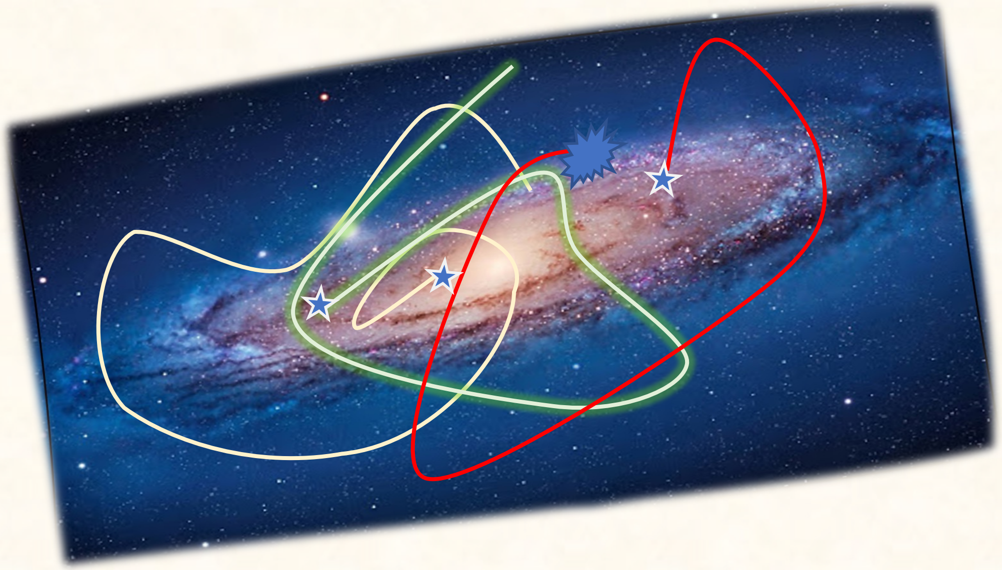
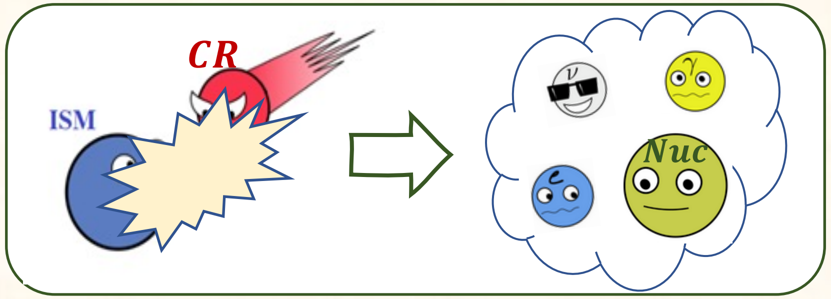
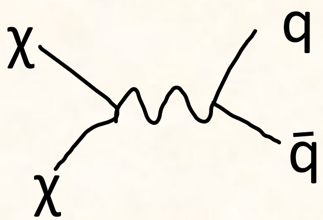
Pedro de la Torre Luque
pedro.delatorreluque@fysik.su.se

Scrutinizing current predictions for cosmic-ray antiparticles



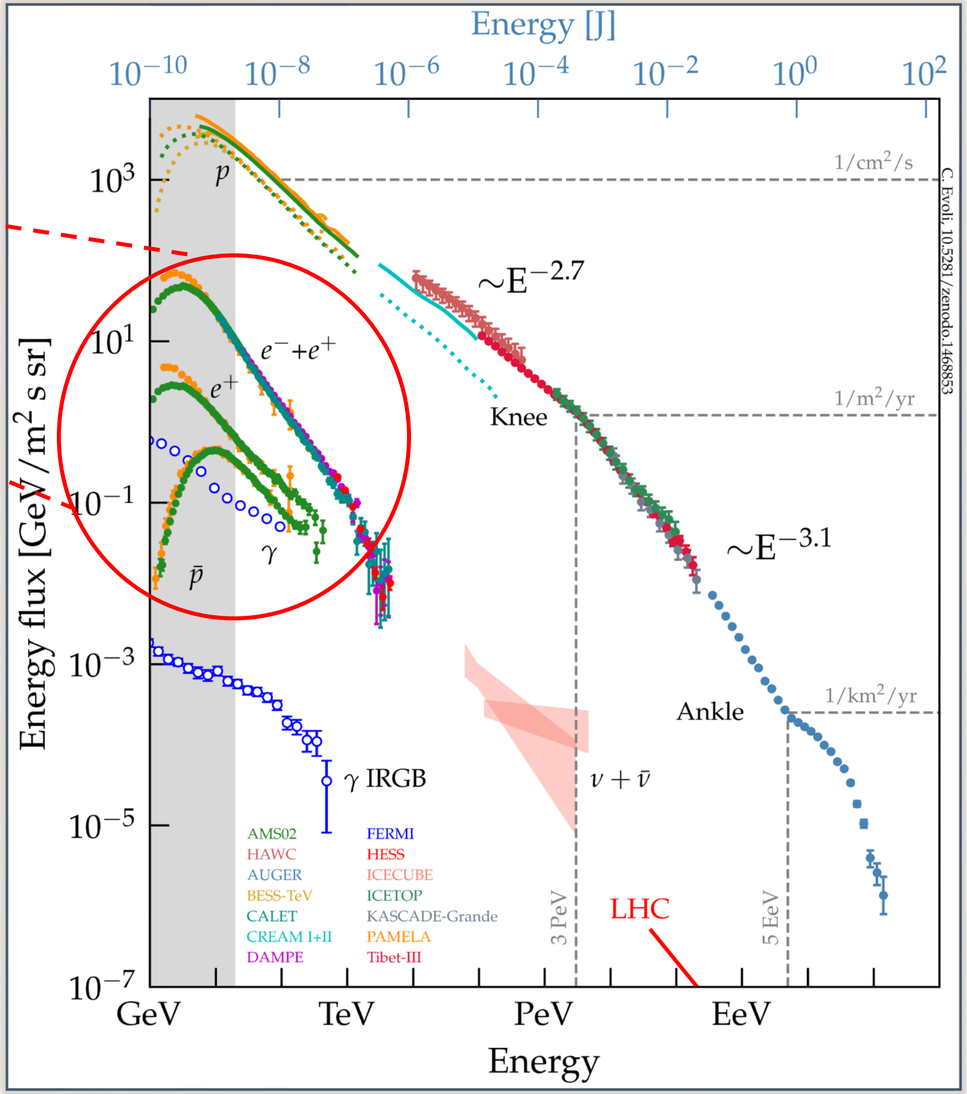




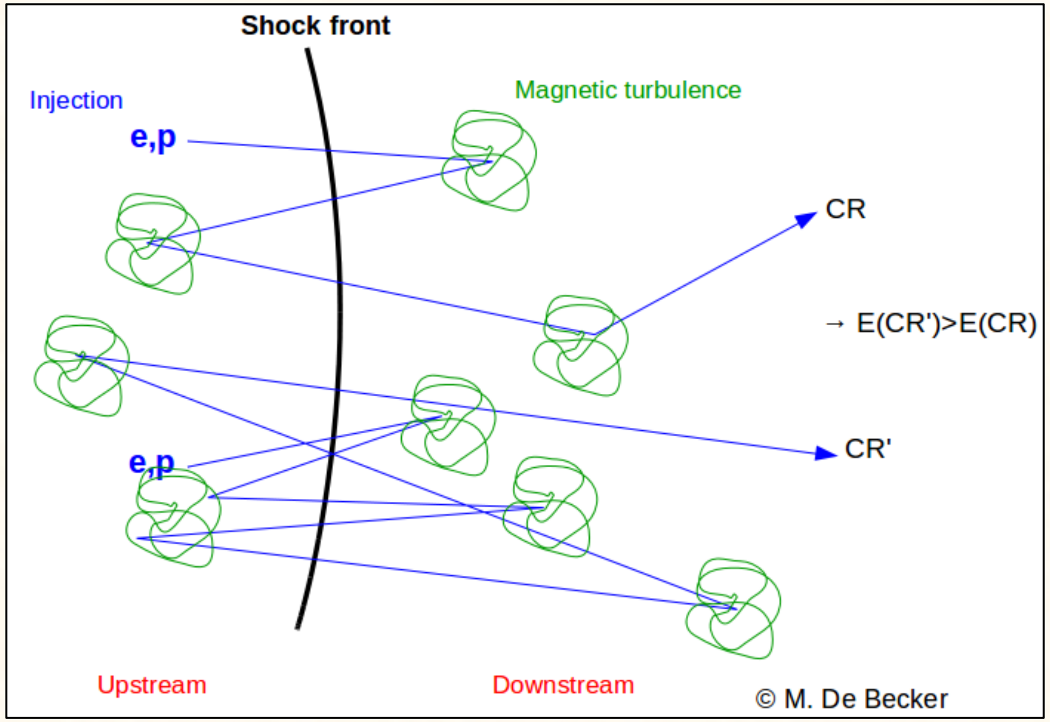
LPTHE particle physics seminar – 24/01/2023

The current generation of detectors provides accurate measurements on the spectra of Galactic cosmic rays **leaving many open questions**

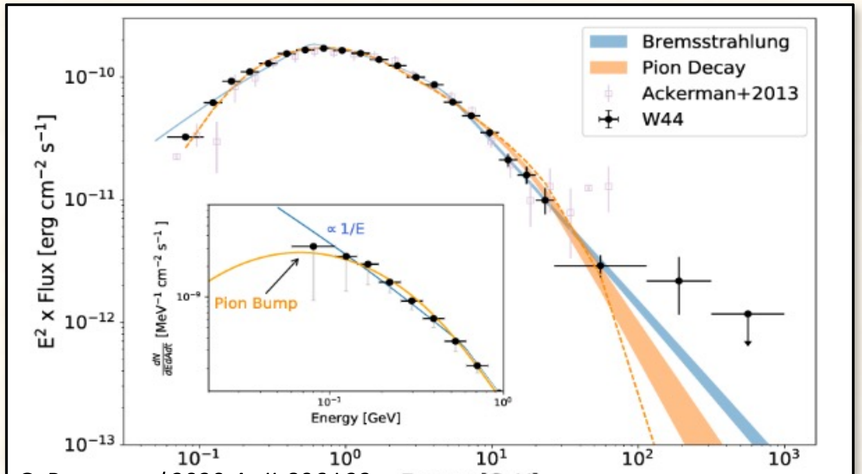
We focus in the GeV-TeV part, where diffusion dominates and WIMPs can leave imprints in CR antiparticles



Injection of CRs by sources



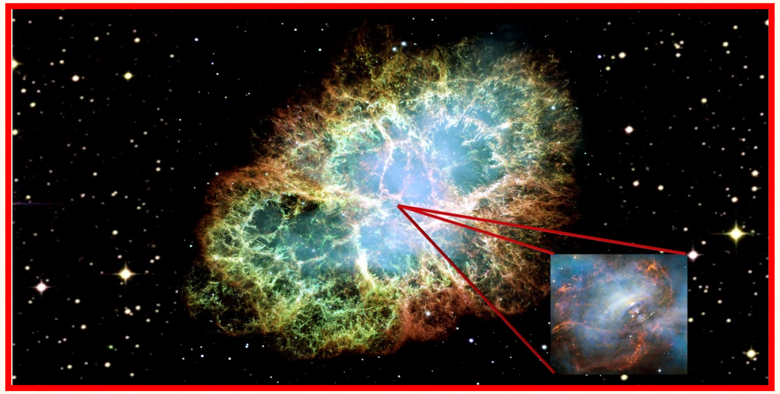
Diffusive shock acceleration (inspired in the Fermi mechanism) explains the power law distribution of CR particles



G. Peron *et al* 2020 *ApJL* 896 L23

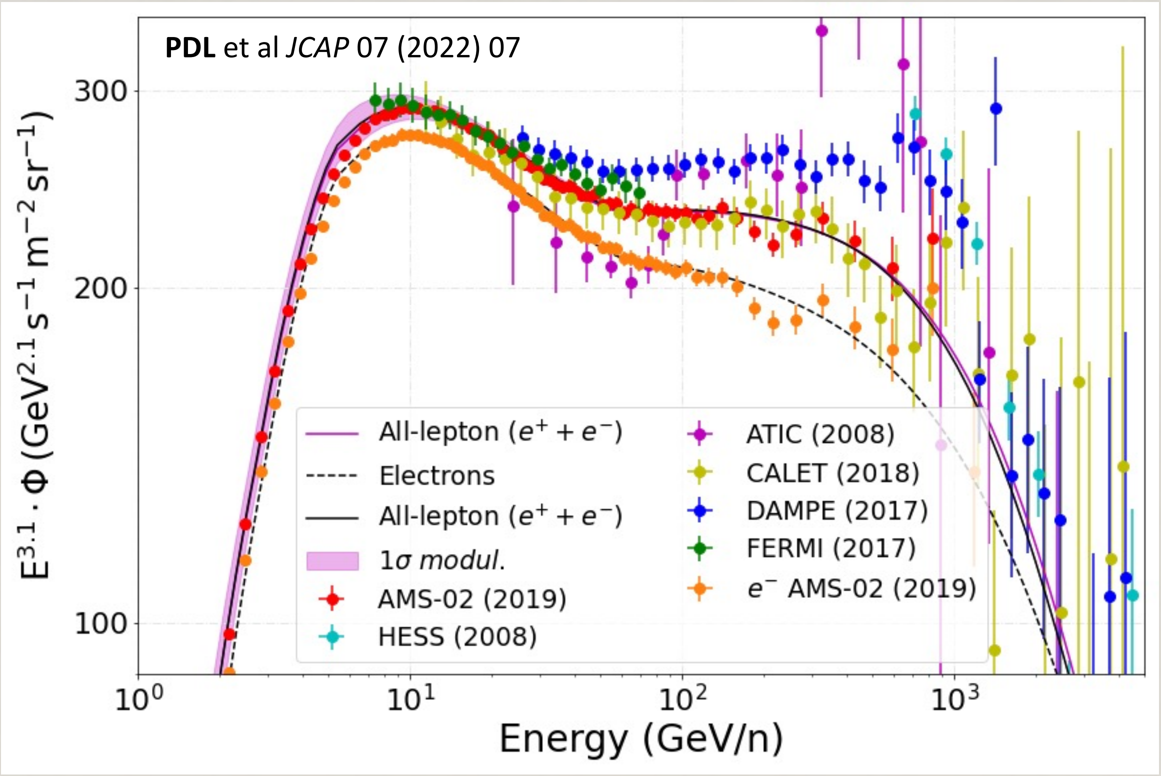
CRs are accelerated in shocks - Like those found in SNRs, star clusters or PWNe

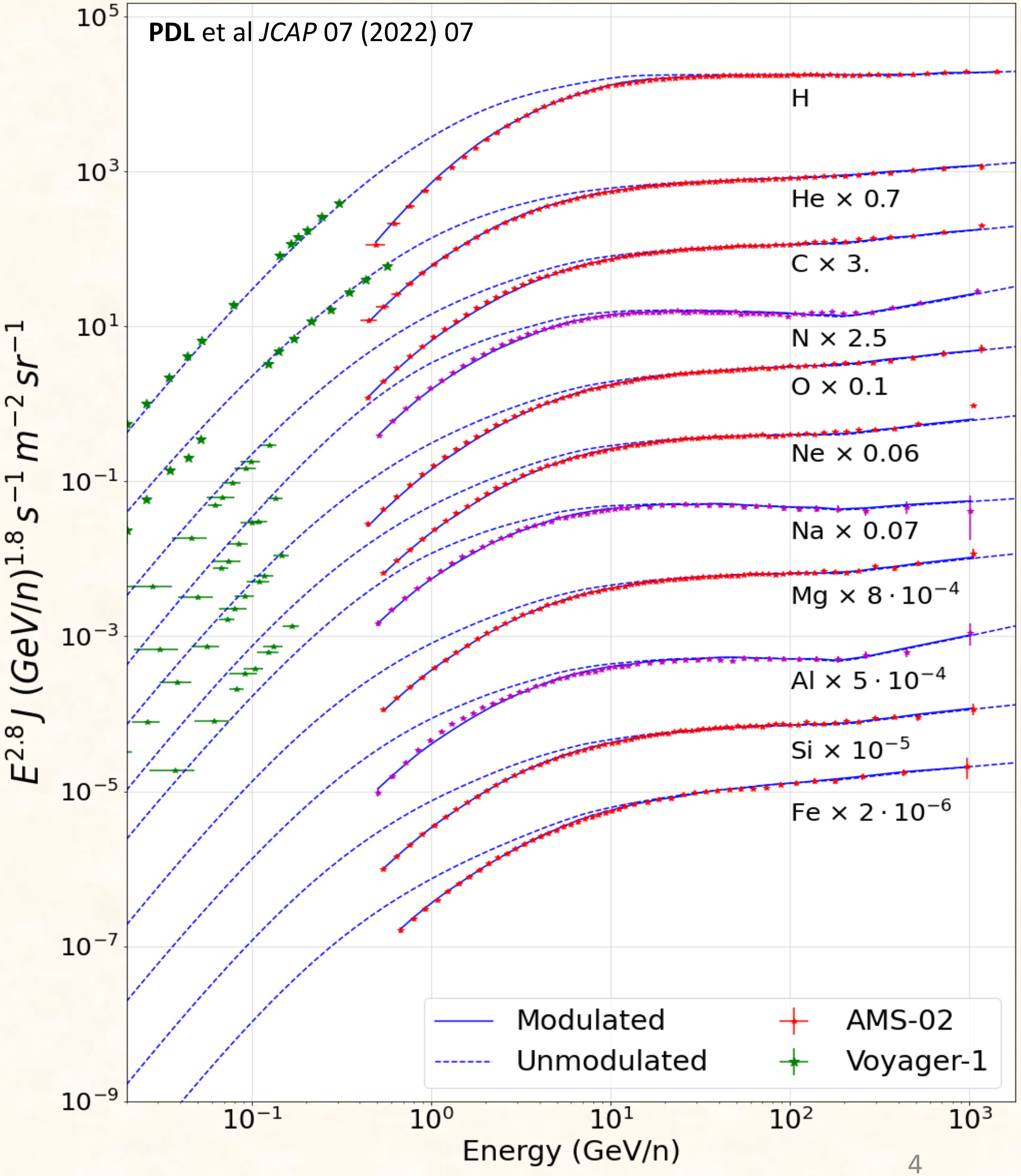
Then, they are injected to the interstellar medium where they can interact with gas and magnetic fields



Injection of CRs by sources

In Galactic CR studies, the injection spectrum is parametrized as a (broken) power-law and the distribution of sources follow SNR distrib.



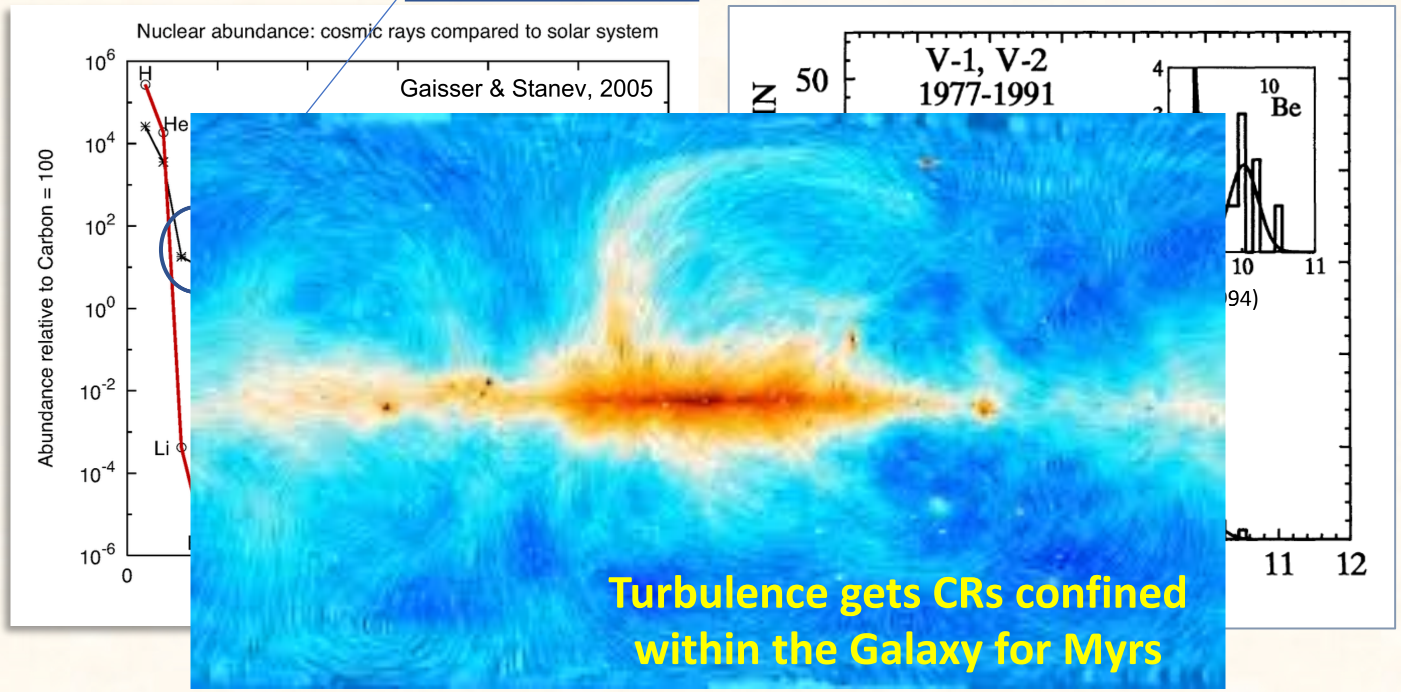


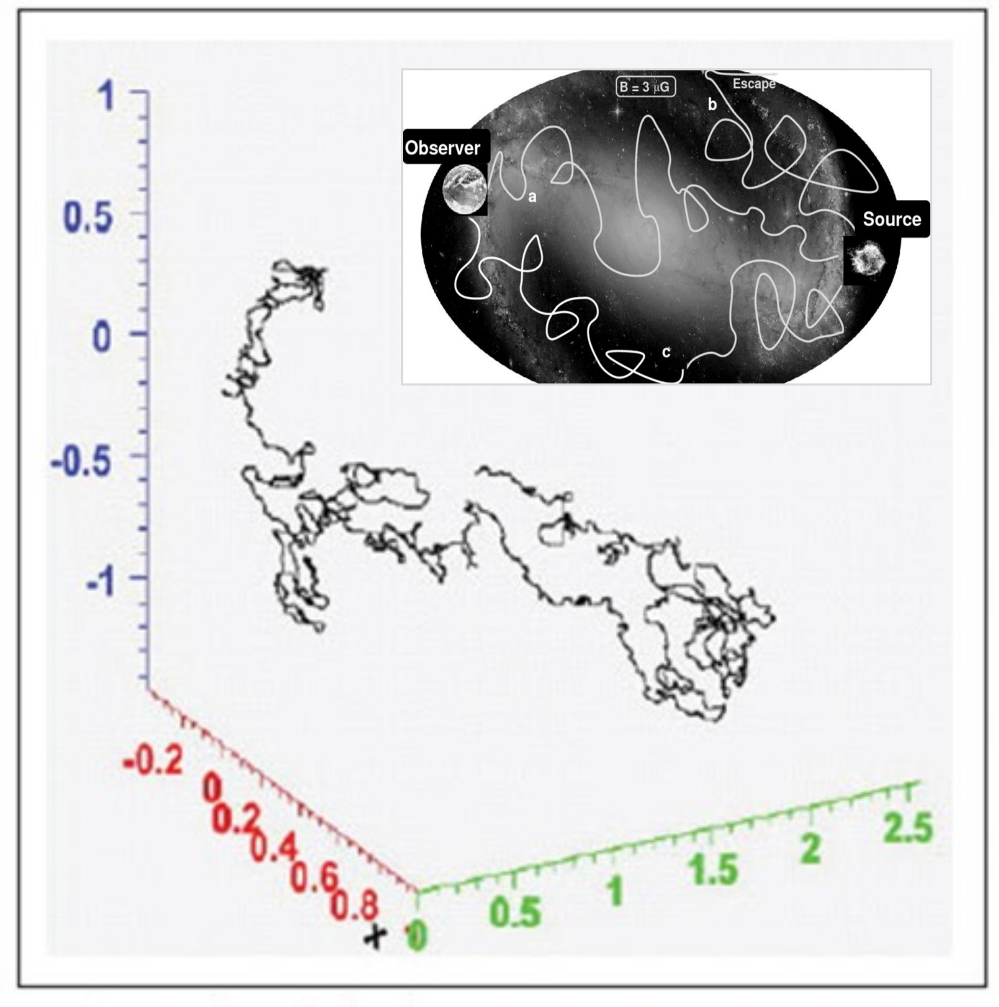
A few key observations show evidence that CRs propagate in the Galaxy for millions of years

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.

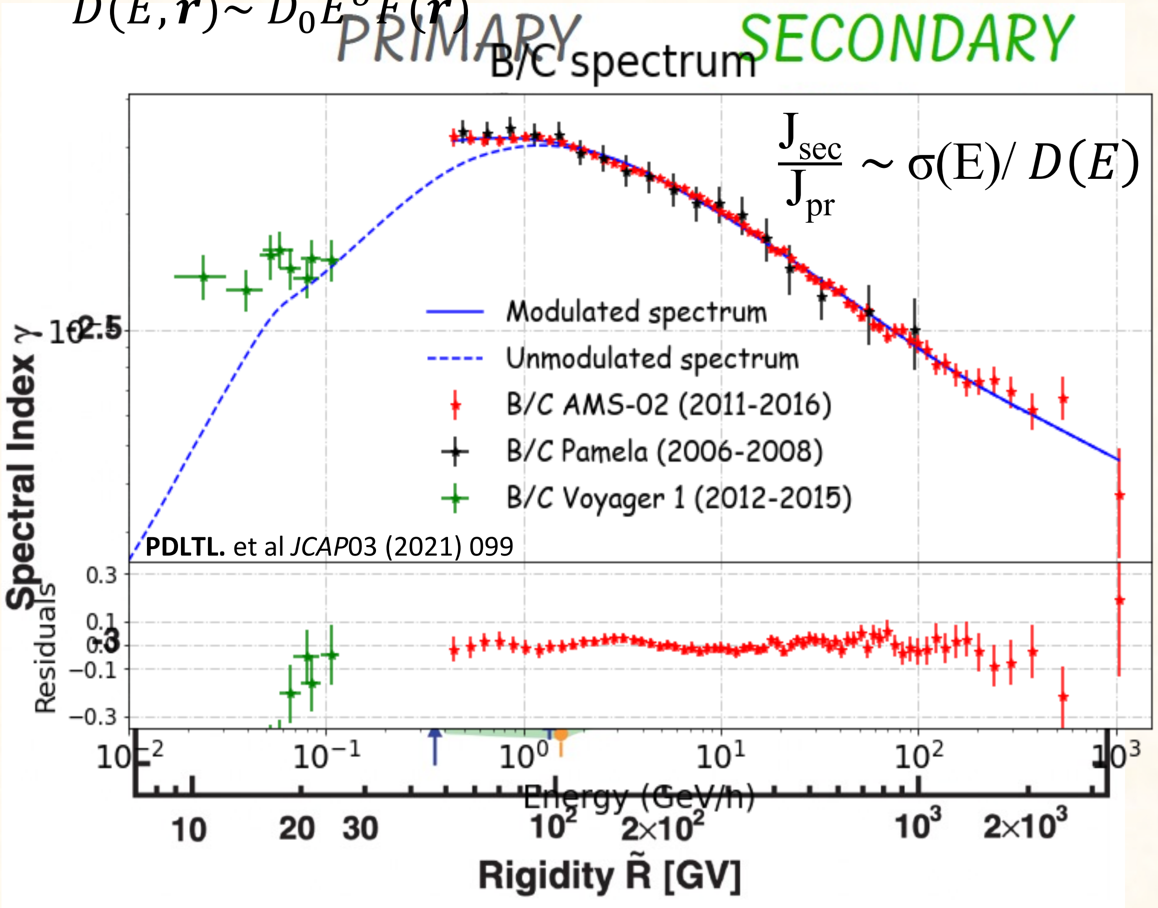
$$\tau^{esc}(E) \propto E^{-\delta}$$





Secondary-to-primary ratios – the diffusion coefficient

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



Simplest approximation to the diffusion equation:

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

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

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

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

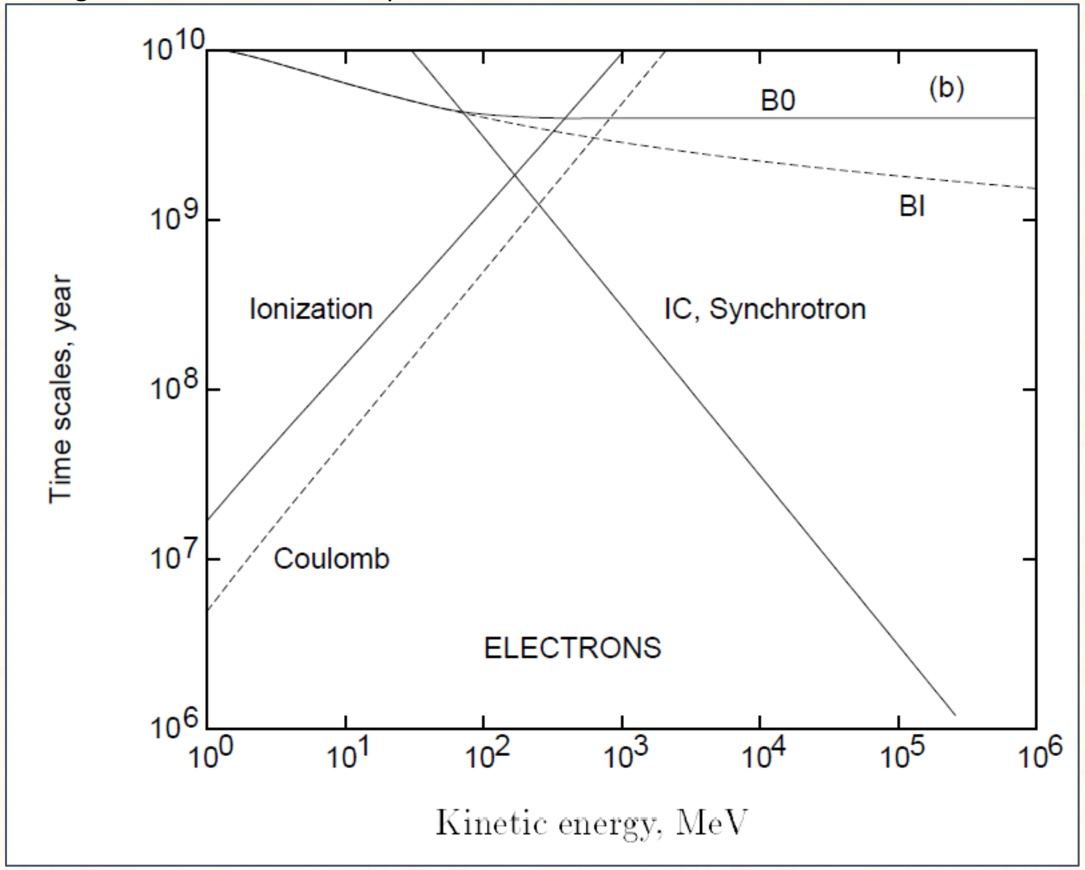
$$J_{sec}(E) \sim \frac{\sigma(E) J_{pr}(E)}{D(E)} \propto E^{-(\alpha_{inj}+2\delta)}$$

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

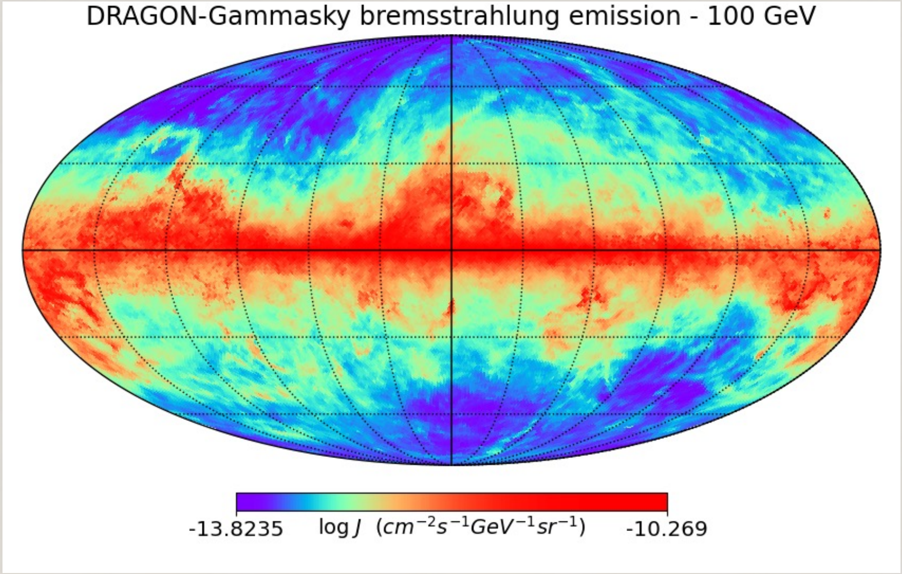
Lepton energy losses

$$\frac{\partial E}{\partial t} = \left(\frac{\partial E}{\partial t}\right)_{Coul,\ Ioniz} + \left(\frac{\partial E}{\partial t}\right)_{\mathrm{IC,\ Bremss,\ Sync}}$$

Strong & Moiskalenko 1998 *ApJ* **509** 212



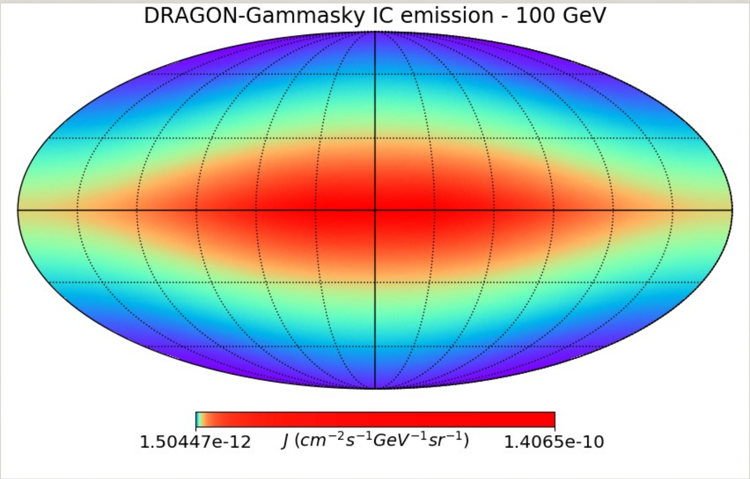
$e + N \rightarrow e' + \gamma' + \mathrm{N}$



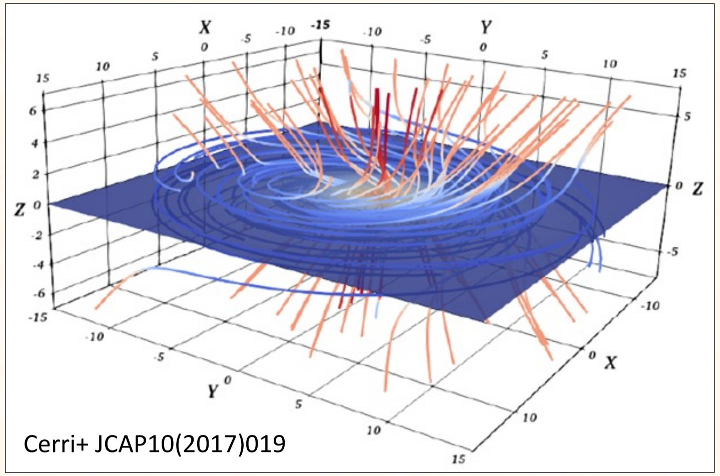
Ionization, Coulomb and bremsstrahlung energy losses depend on the gas distribution and are subdominant above the GeV

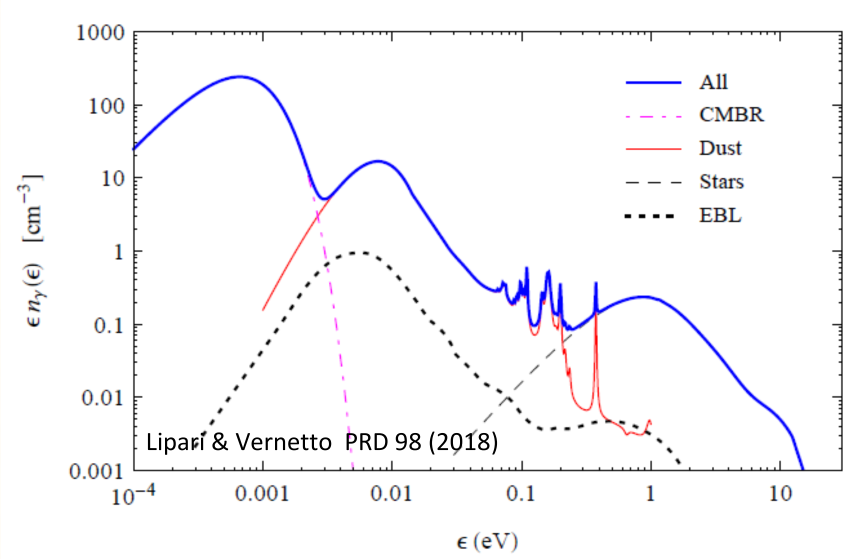
Lepton energy losses

IC and Synchrotron losses impede high energy electrons and positrons travel long distances!

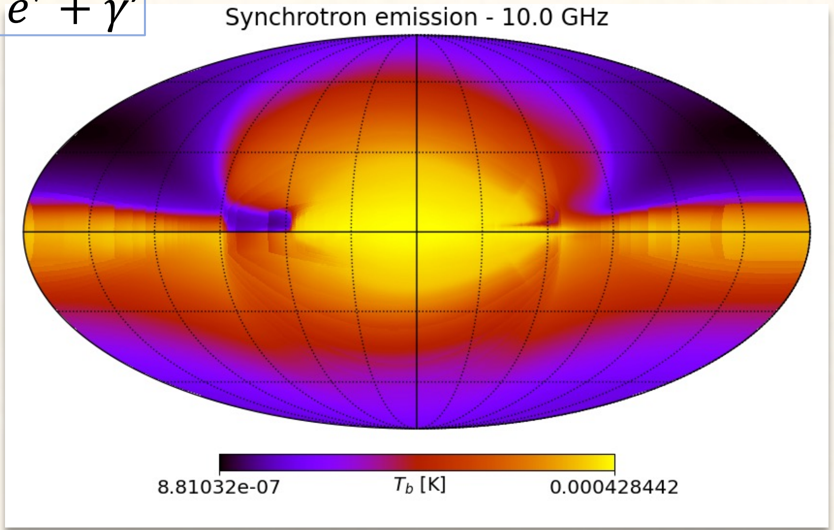


$e + \gamma \rightarrow e' + \gamma'$



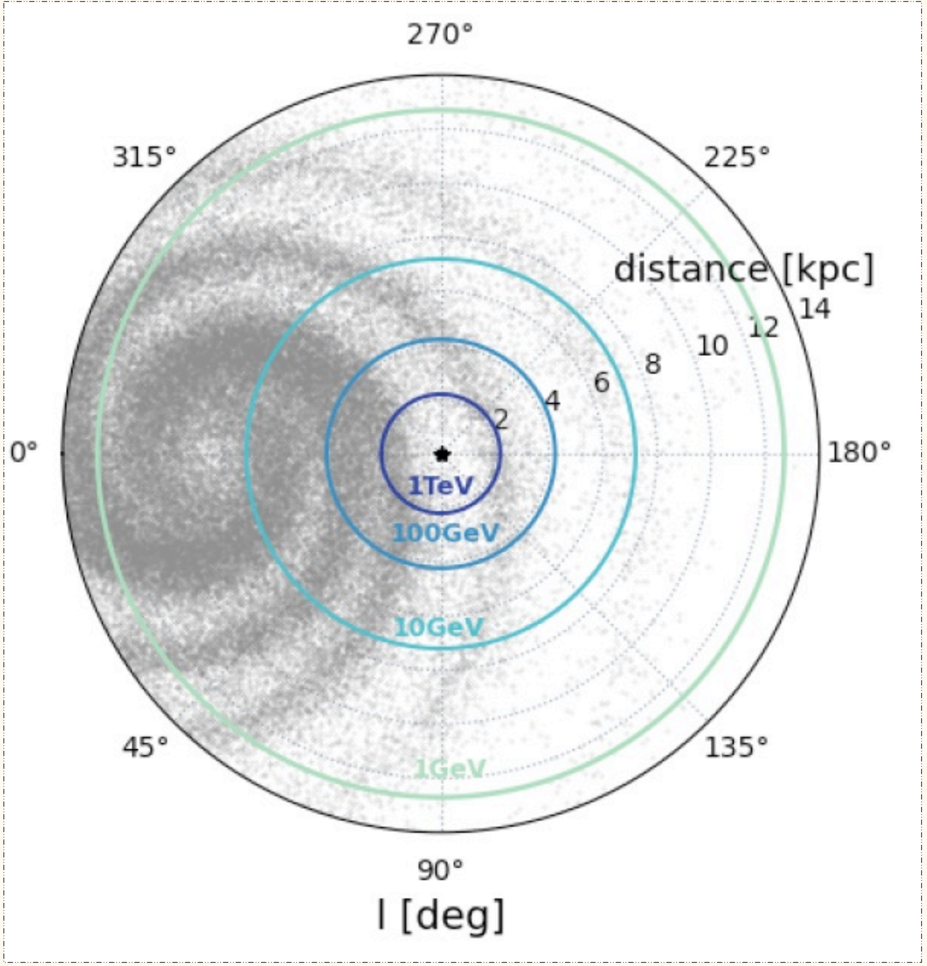


$e \rightarrow e' + \gamma'$

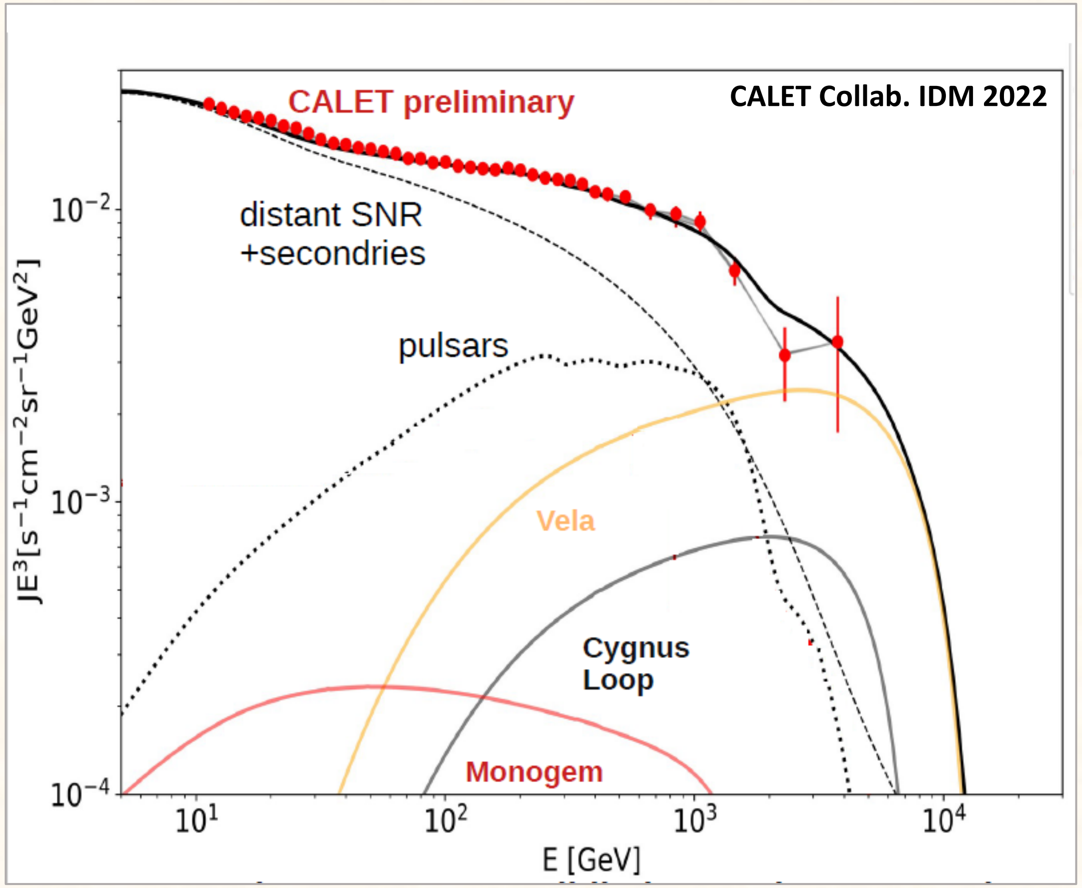


Positron propagation horizon

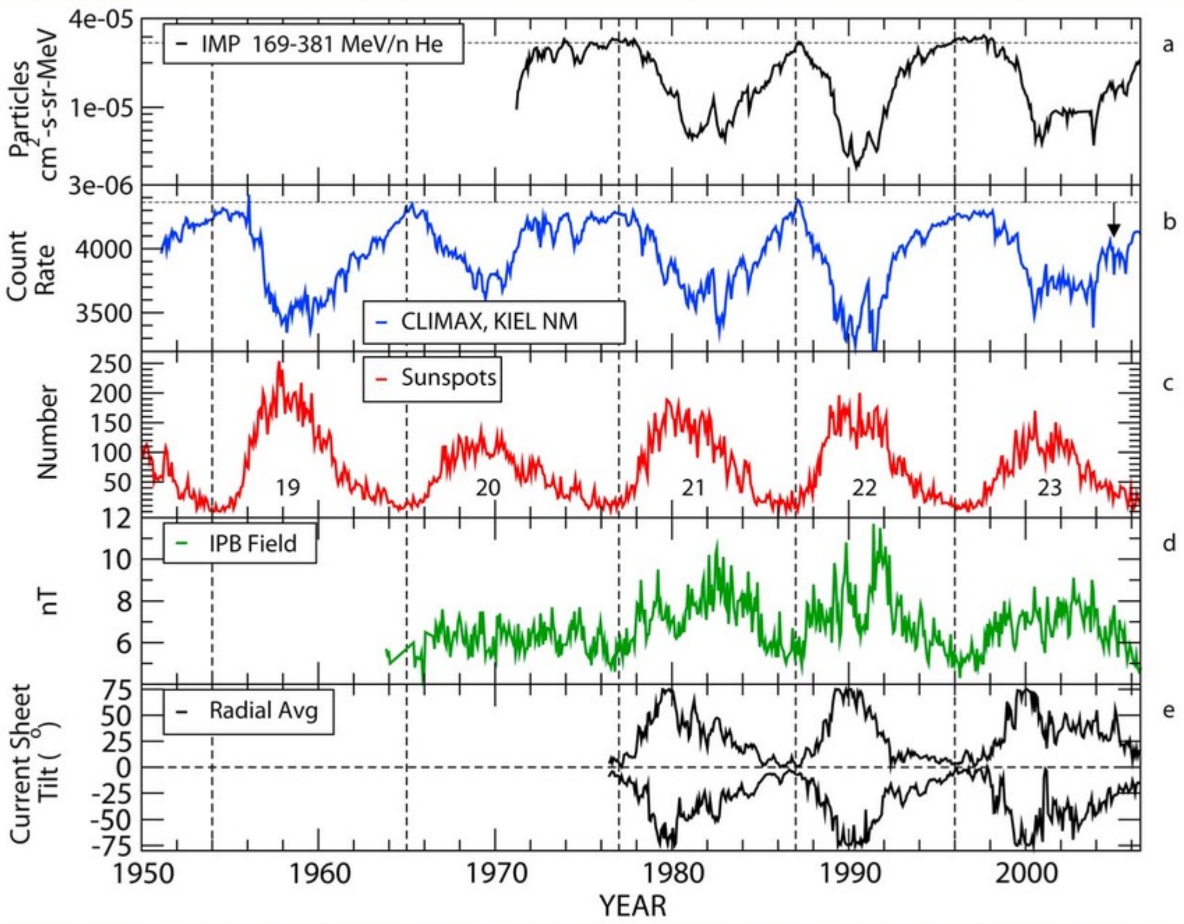
GeV-TeV e^- are dominated by the emission from local sources!



Manconi et al PRD 2020



Effect of the Heliosphere – Solar modulation



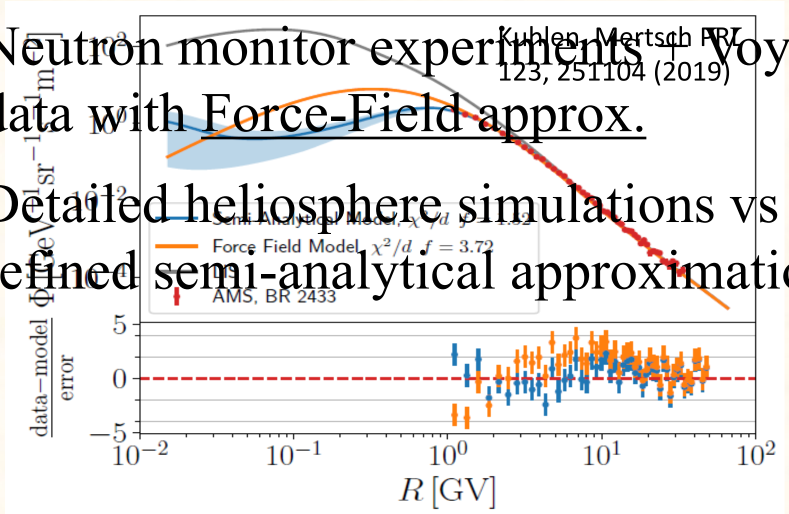
CRs experience a "firewall" when they enter the heliosphere from interstellar space

It significantly affects the propagation of low-energy CRs (below E~10 GeV/n)

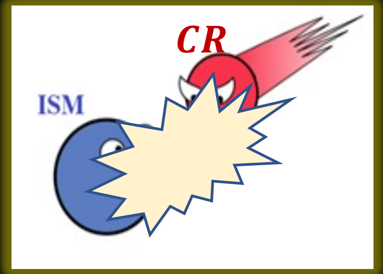
High uncertainty related with its treatment:

- ❖ Neutron monitor experiments + Voyager-1 data with Force-Field approx.
- ❖ Detailed heliosphere simulations vs refined semi-analytical approximations

Kuhlen, Mertsch PRL 123, 251104 (2019)



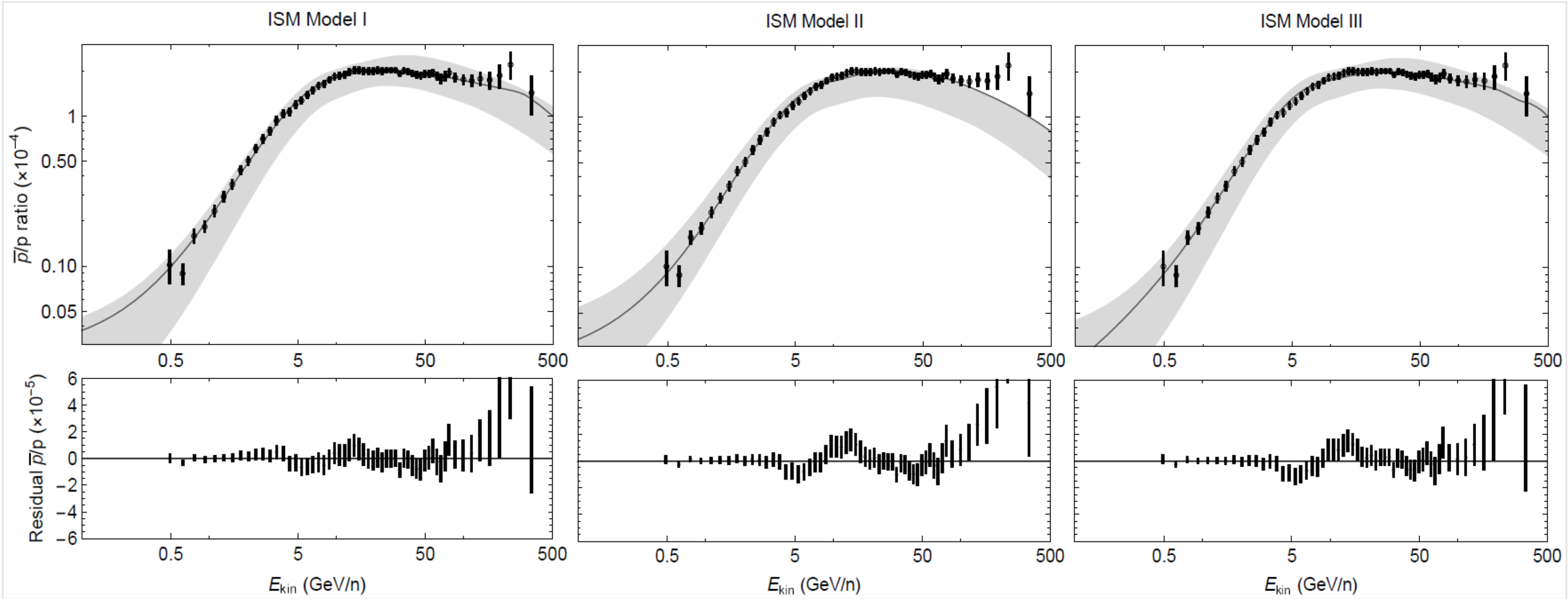
Antiproton *excesses* – *The spectral excess*



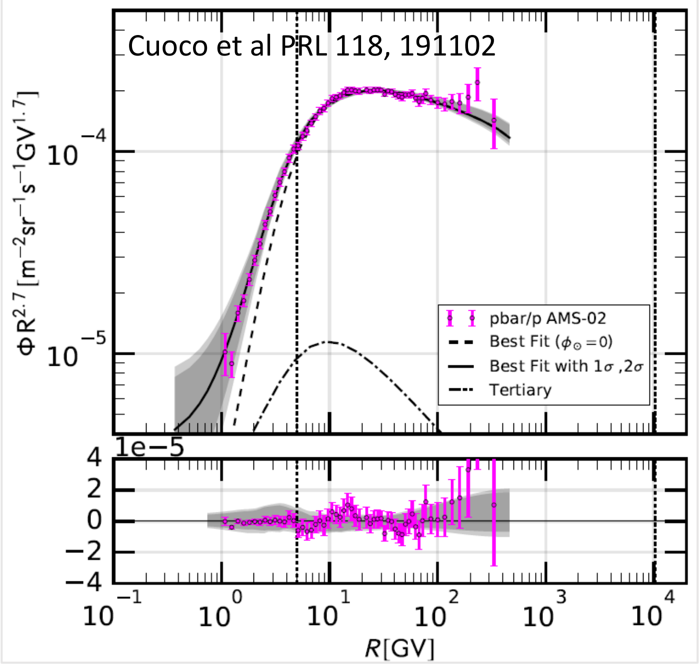
Several studies claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

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

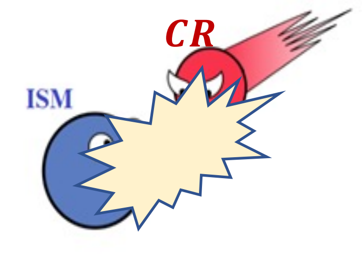
$\chi + \chi \to \bar{p}$



Cholis, Linden, Hooper PRD 99, 103026



Antiproton *excesses* – *The spectral excess*

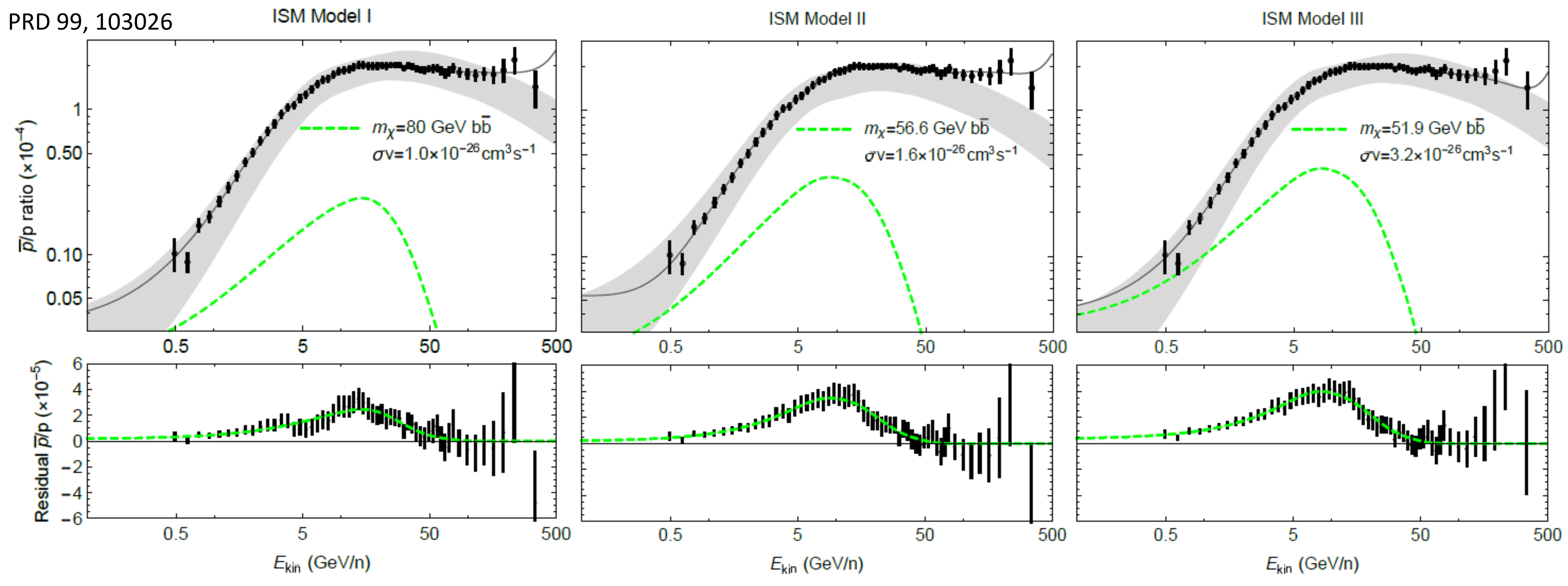


Recent studies have claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

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

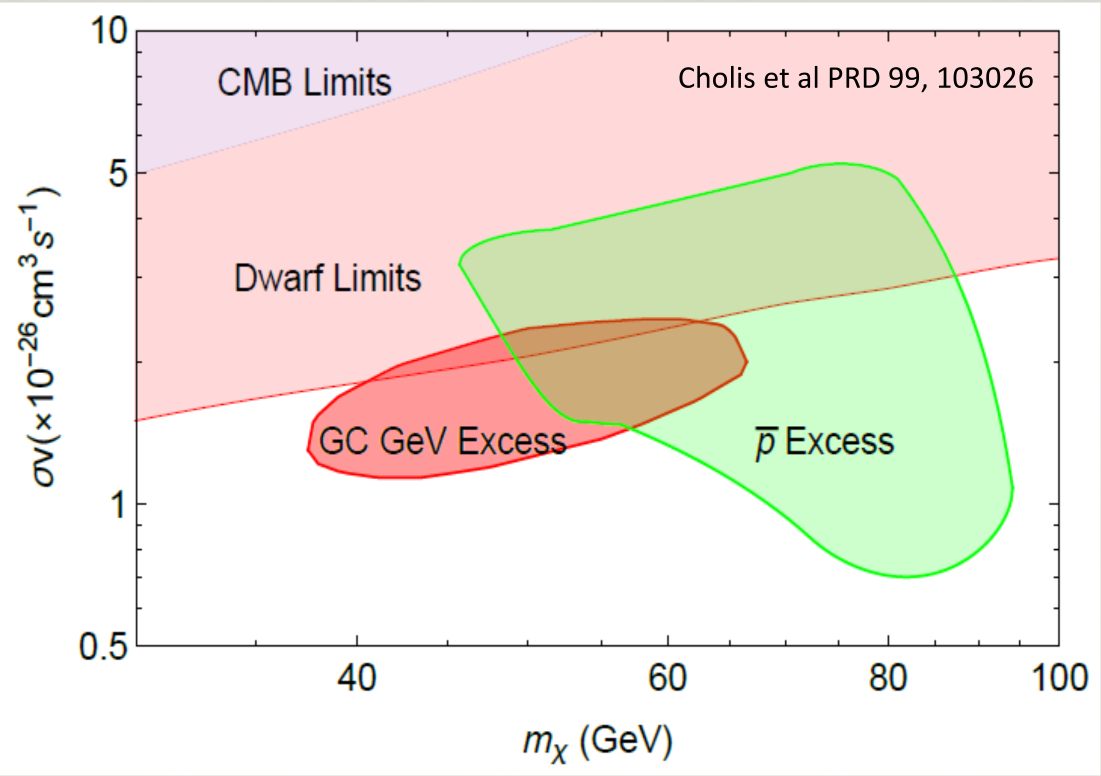
$\chi + \chi \rightarrow \bar{p}$

Cholis et al PRD 99, 103026

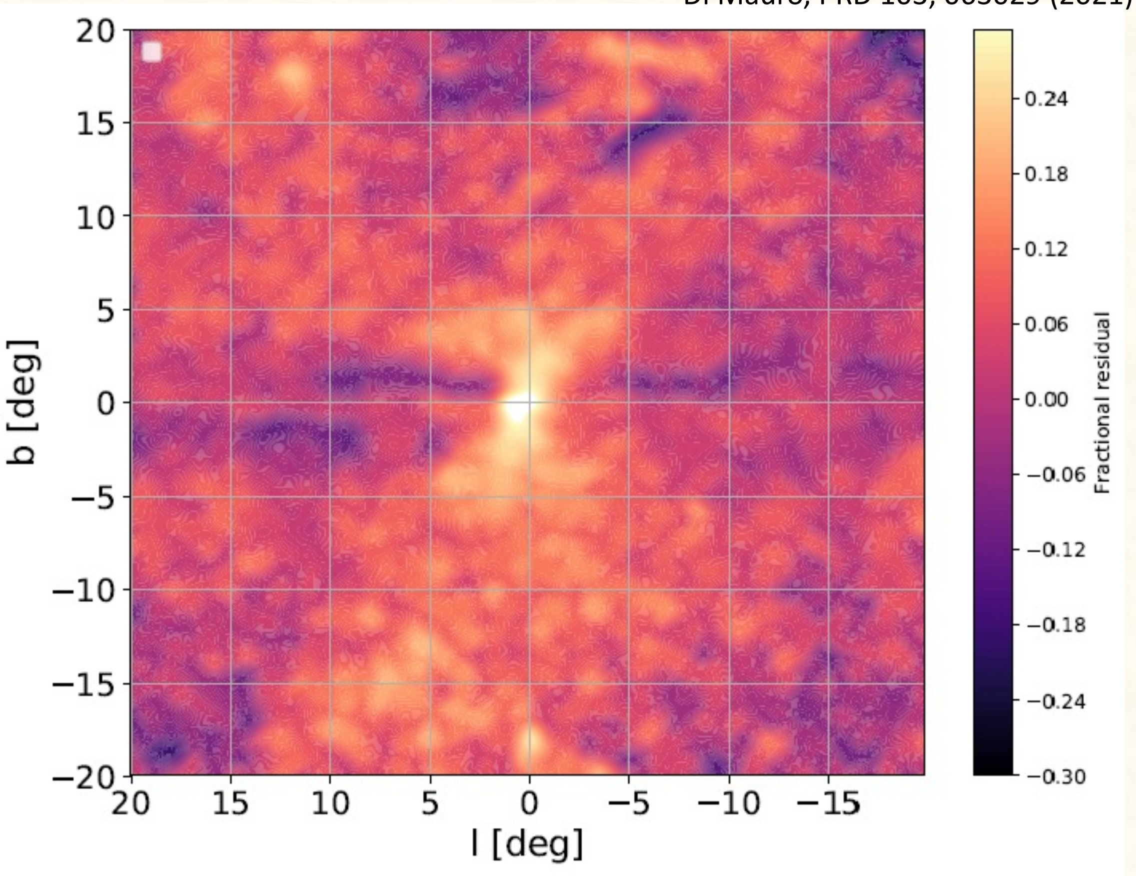


Antiproton excess and Galactic centre excess

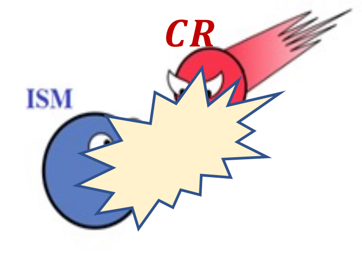
GC excess points to a WIMP of about 50 GeV
and $< \sigma v >$ close to thermal relic cross section



Di Mauro, PRD 103, 063029 (2021)



Antiproton ***excesses*** – *The spectral excess*



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

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

All analysis coincided in the position of the excess, but not in its significance… again, **the astrophysical uncertainties were not completely understood** (and they aren't yet!)

Jan Heisig MIAPP 2021

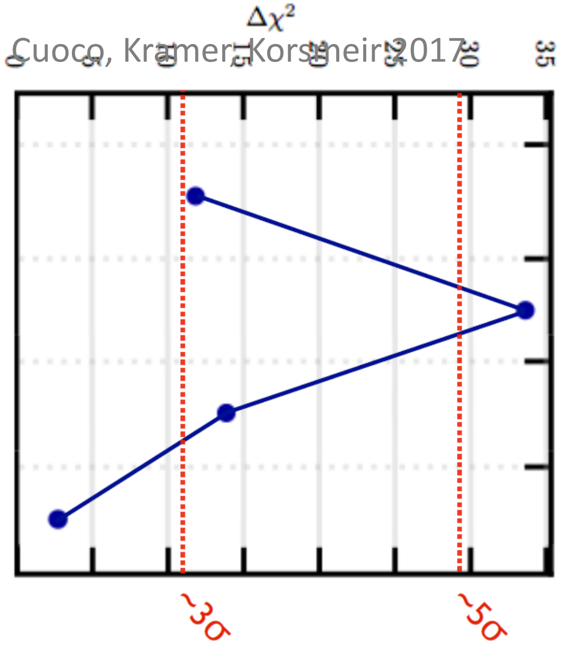
Default from Cuoco *et al.* 2019

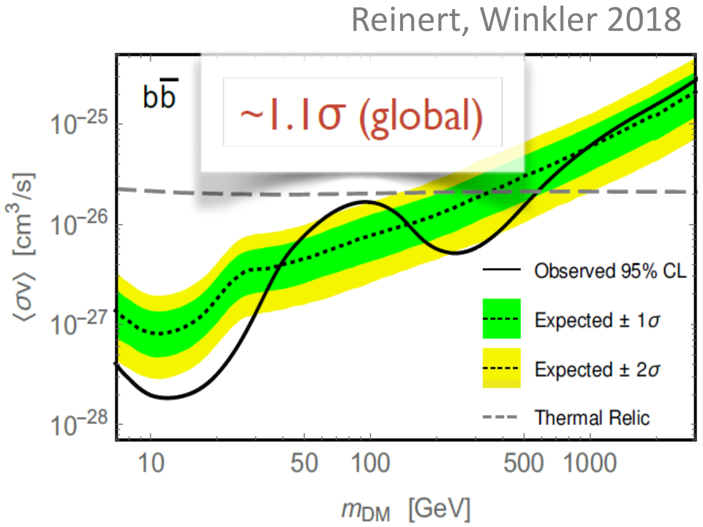
AMS cov. only

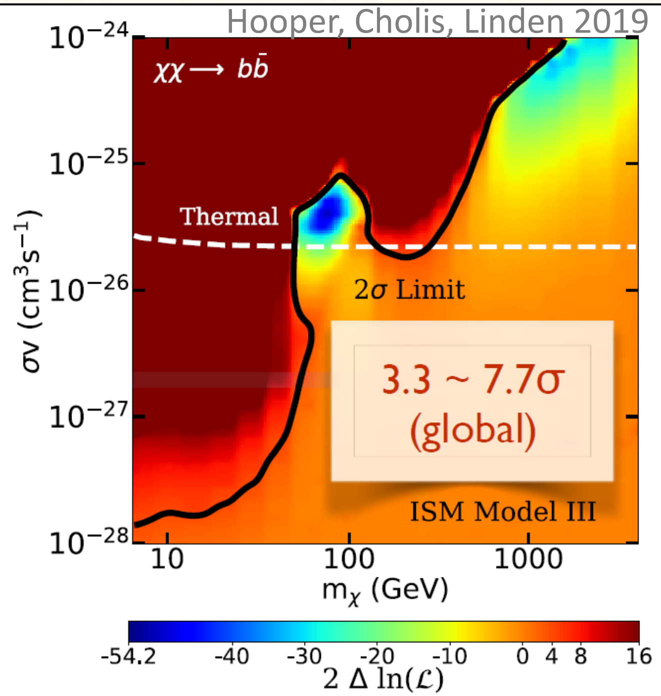
prod. XS+AMS cov.

prod. XS+AMS cov.+ η

$D(E) \sim D_0 \beta^\eta E^\delta$



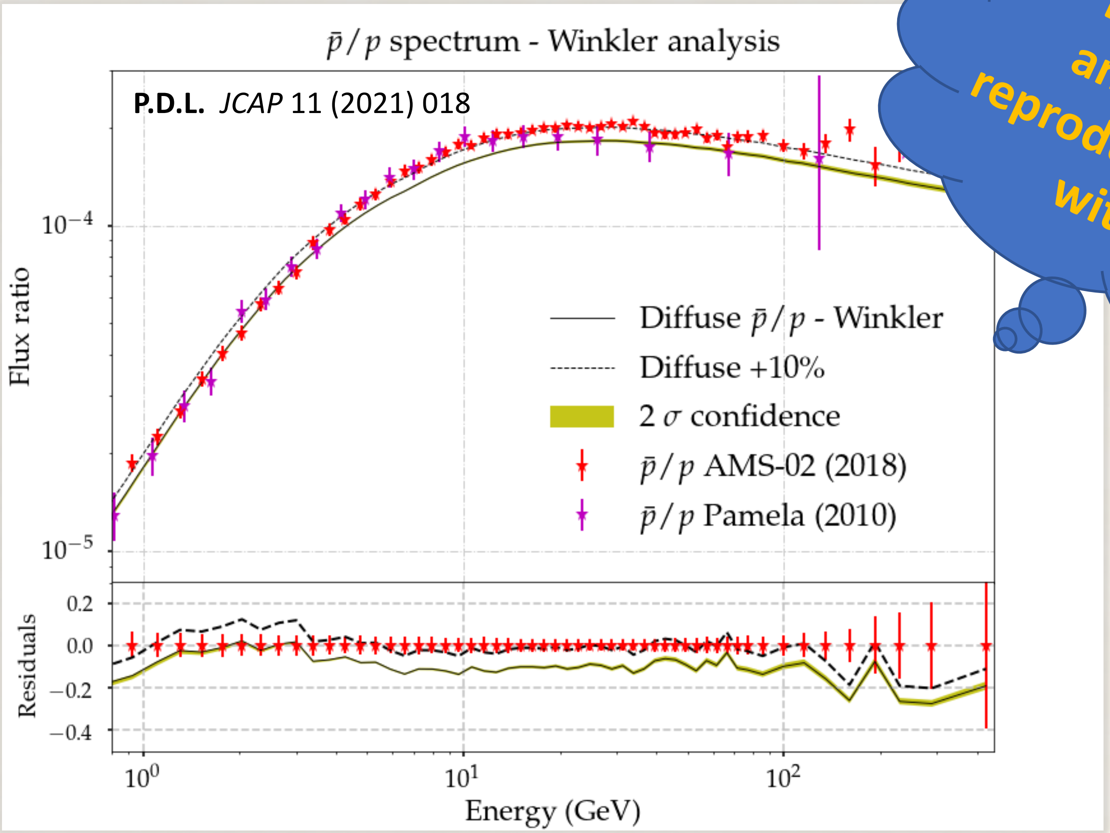


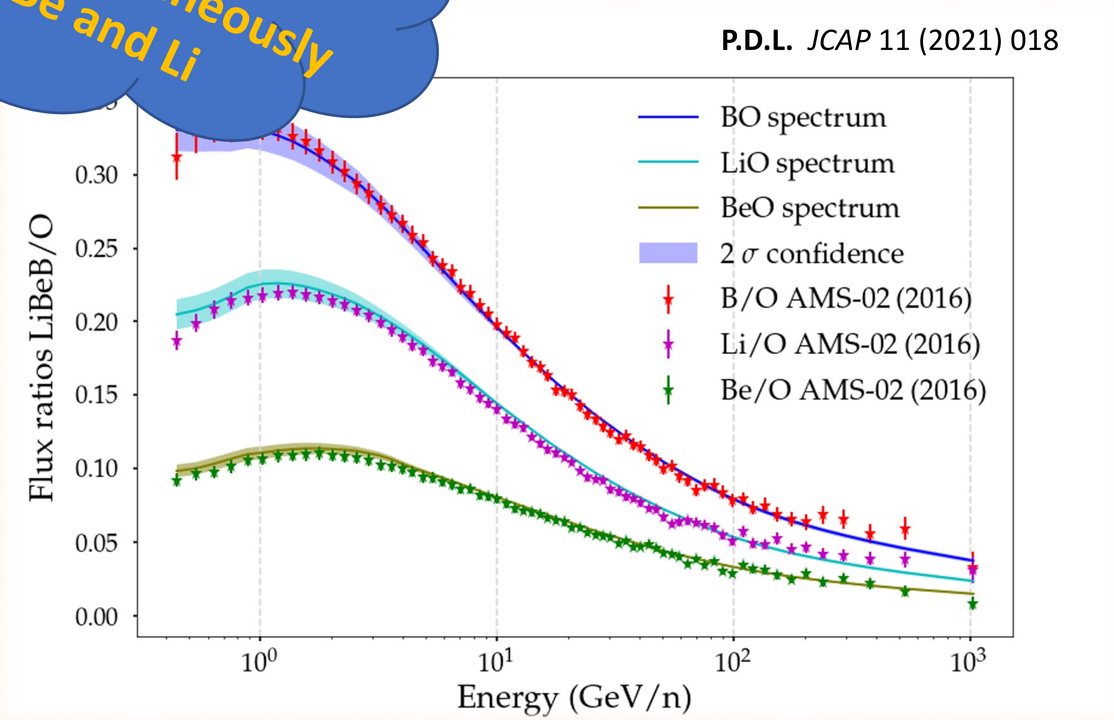


Antiproton *excesses* – *The grammage excess*

Energy spectrum of antiprotons is easily reproduced simultaneously with B, Be and Li

…ff. coeff. predicted by the flux-ratios of … Li underpredicts the antiproton … 0%→ **Grammage tension**





<u>Conclusion</u>: Cross sections uncertainties affect very significantly our predictions and can explain the excess

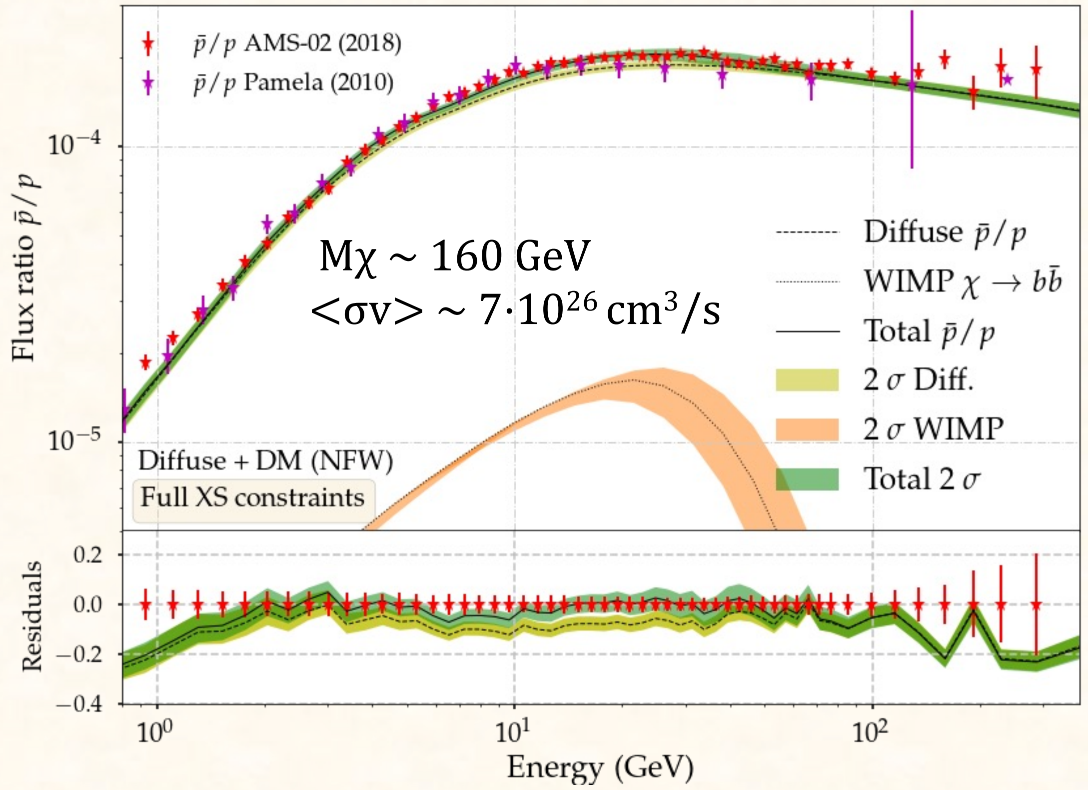
Search for DM features in the antiproton spectrum

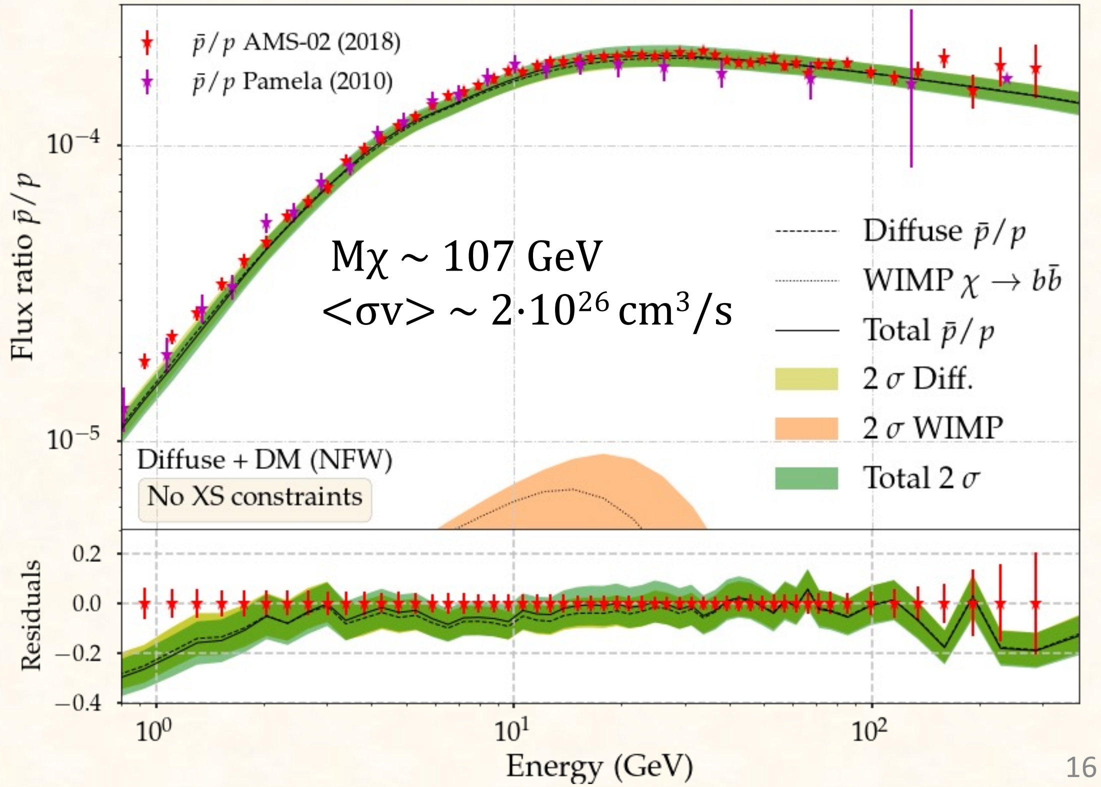
- Combination of B, Be and Li to determine prop. Params
- Cross-section (XS) normalizations as nuisance parameters
- Two modifications of XS prior constraints:
  - No constraints - Penalty factor same as for B (Full cons.)

B/C, B/O, Be/C, Be/O, Ap/p (Prop. parameters)
^{10}Be/^{9}Be, ^{10}Be/Be (H), **Li/B**

No statistical evidence in any analysis (0.6 < σ < 1.1)

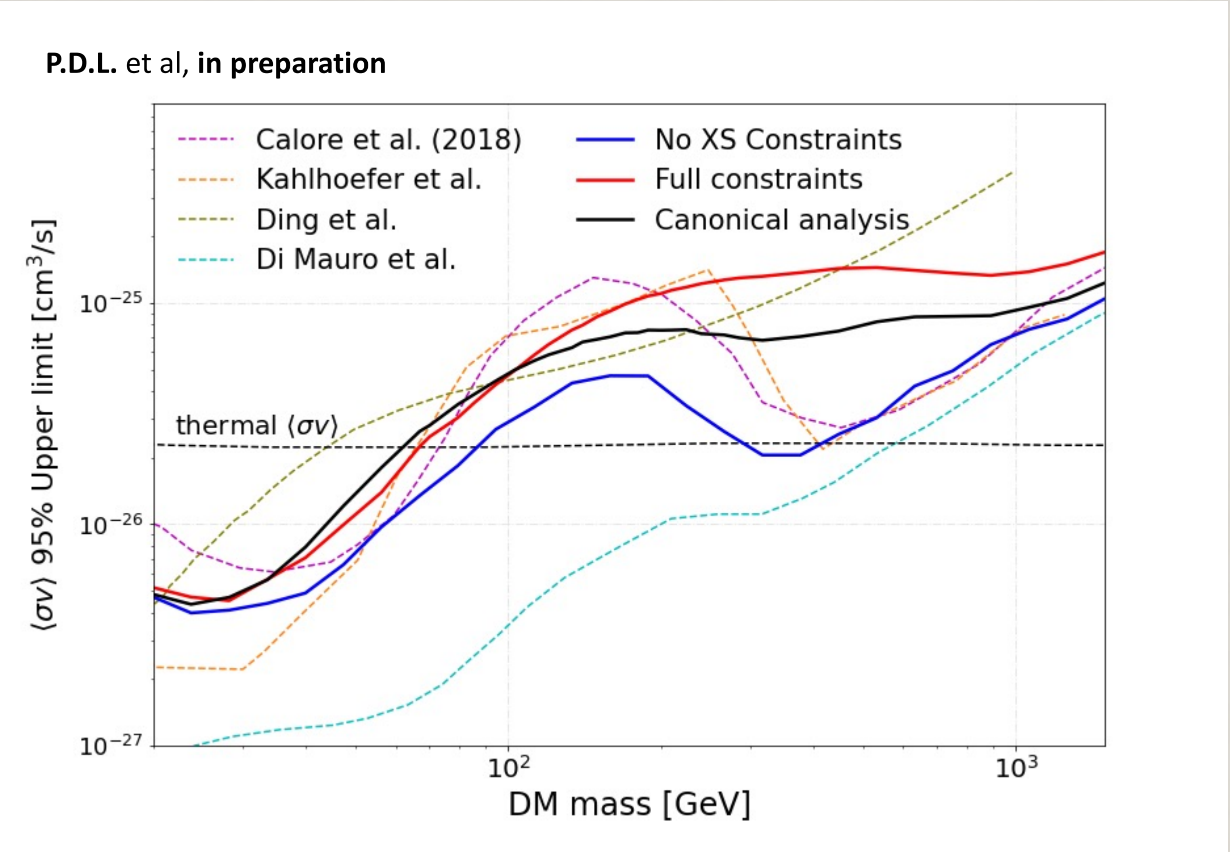
P.D.L. et al, **in preparation**

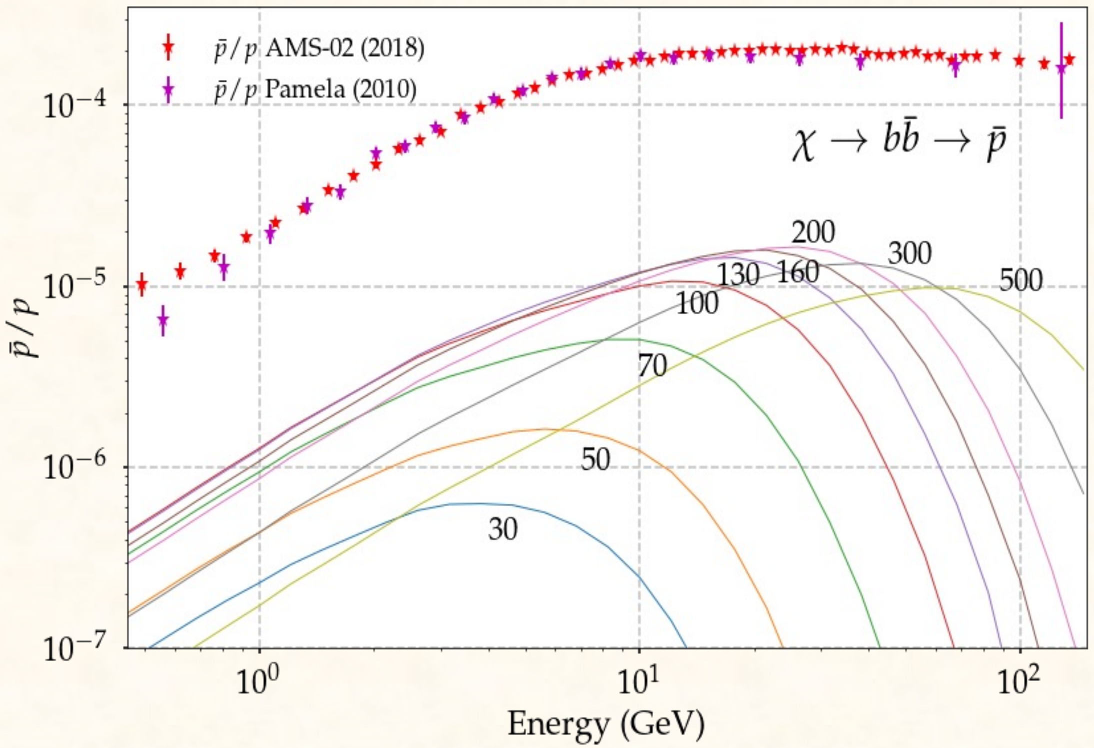




Dark matter bounds from antiproton combined analyses

No hints for WIMP signals in recent analyses…



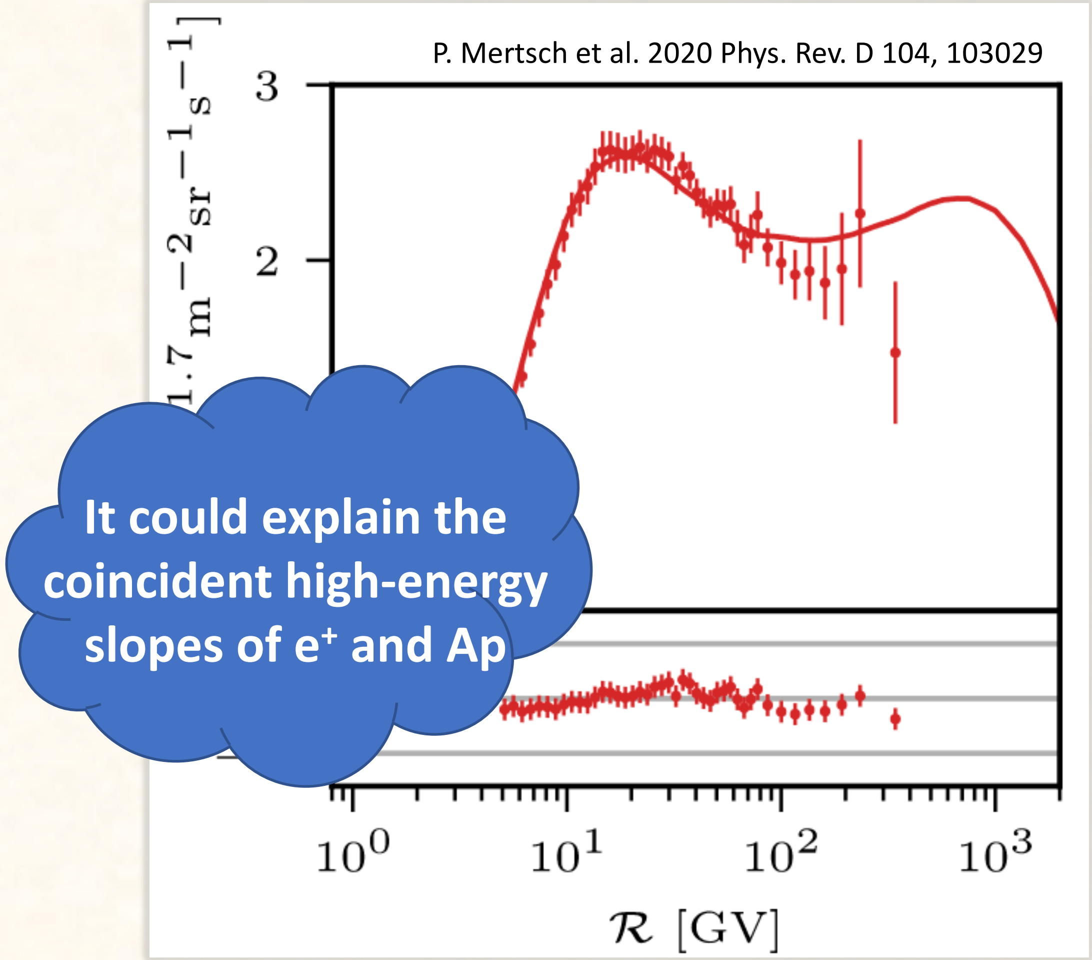


These analyses can rule out the thermal relic cross-section for WIMP masses below ~60 GeV
Tension with the GCE!

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

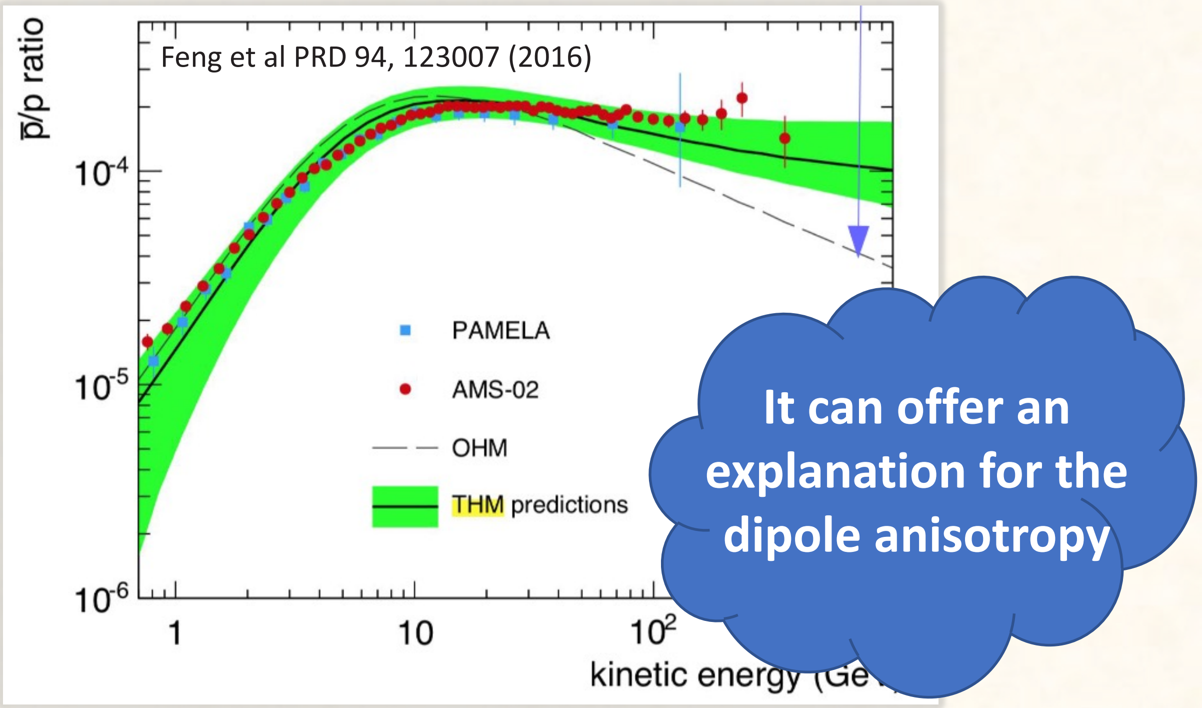
DM searches with antiprotons – *More possibilities*

SNRs accelerating antiprotons



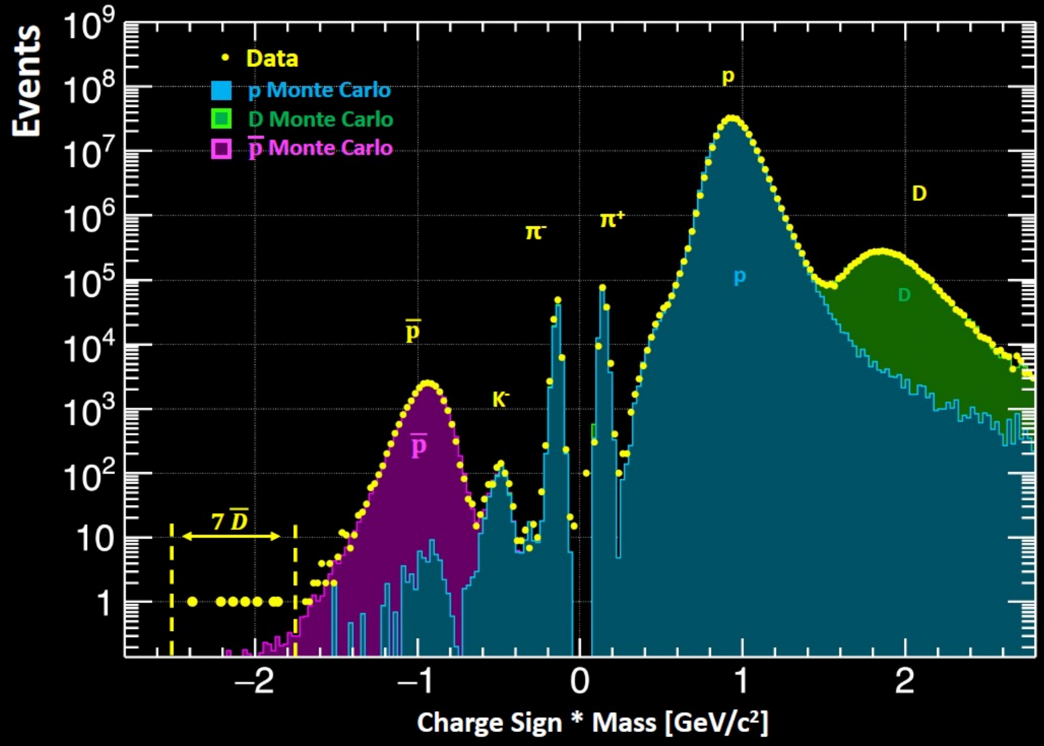
Inhomogeneous diffusion coefficient

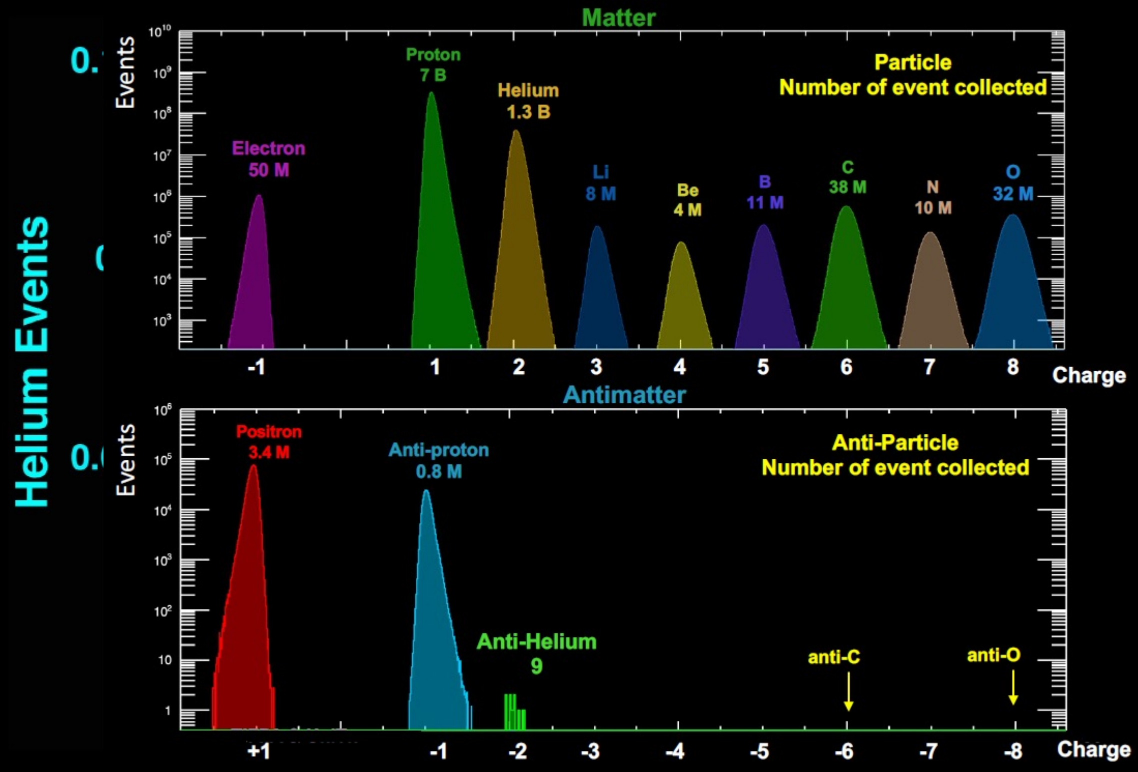
(See also: Zhao et al 2021 arXiv:2109.04112v1)



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

ANTI-NUCLEI: AMS-02 mass-charge spectra

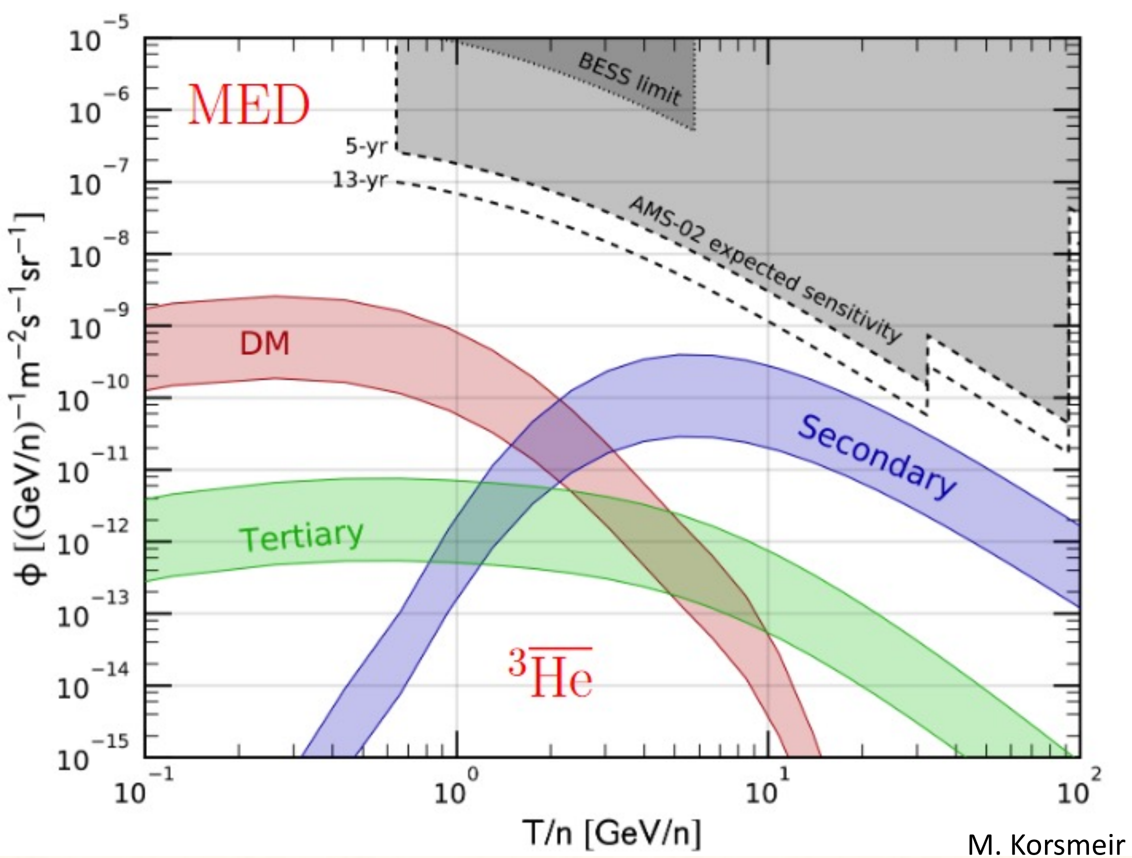




Paolo Zuccon MIAPP 2021

Anti-nuclei as the dark matter smoking gun

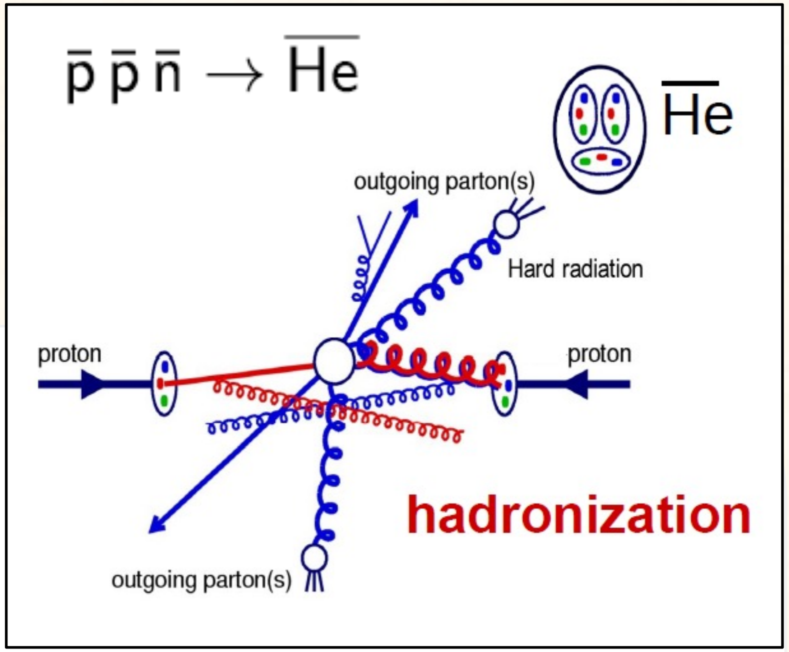
The window to prove (or disprove) many possible astrophysical excesses



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)

M. Korsmeir et al. (2018) Phys. Rev. D97, 103011

Formation of anti-nuclei



- Simplest coalescence model: *Factorised coalescence*

$$E_{\bar{d}}\frac{d^3N_{\bar{d}}}{dp^3_{\bar{d}}} \simeq B_2\left(E_{\bar{n}}\frac{d^3N_{\bar{n}}}{dp^3_{\bar{n}}}\right)\times\left(E_{\bar{p}}\frac{d^3N_{\bar{p}}}{dp^3_{\bar{p}}}\right) \simeq B_2\left(E_{\bar{p}}\frac{d^3N_{\bar{p}}}{dp^3_{\bar{p}}}\right)^2$$

Antineutrons and antiprotons are produced uncorrelated

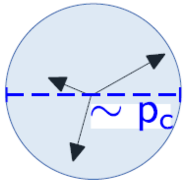
$$E_{\bar{A}}\frac{d^3N_{\bar{A}}}{dp^3_{\bar{A}}} \simeq B_A\left(E_{\bar{p}}\frac{d^3N_{\bar{p}}}{dp^3_{\bar{p}}}\right)^A$$

Coalescence parameter can be approximated from the coalescence momentum, p_0

(anti)nucleons with low relative momentum merge to form (anti)nuclei

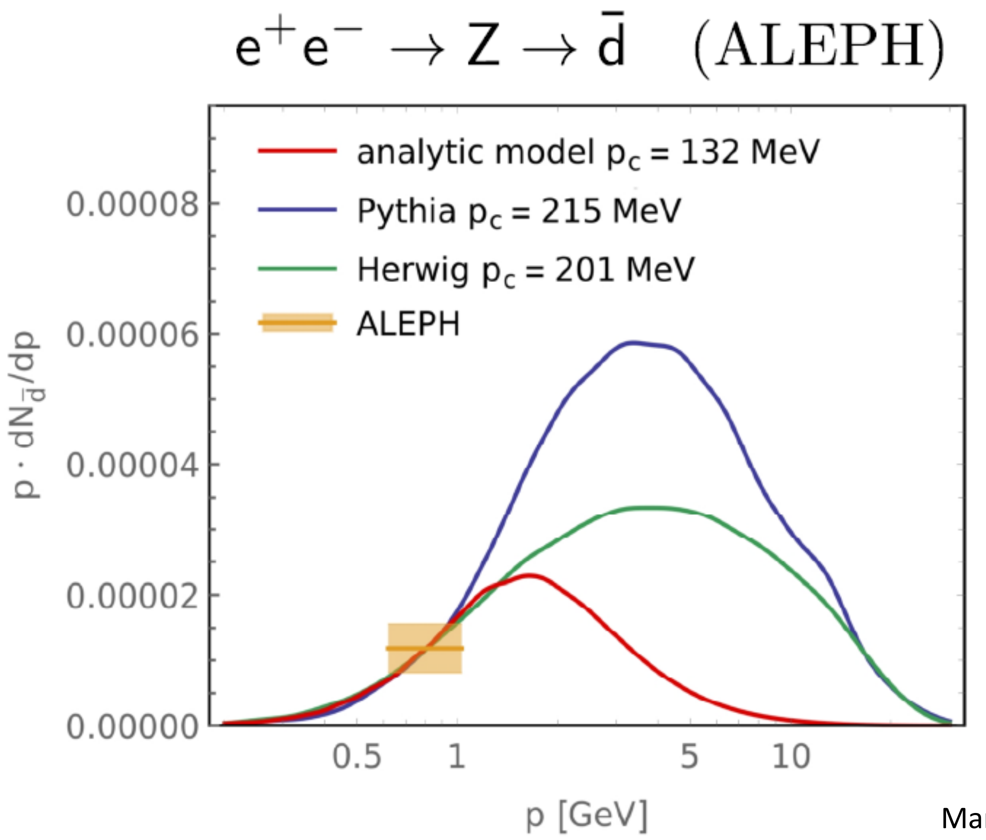
$$B_2 = \frac{1}{8}\frac{4\pi p_0^3}{3}\frac{m_{\bar{d}}}{m_{\bar{p}}^2}$$

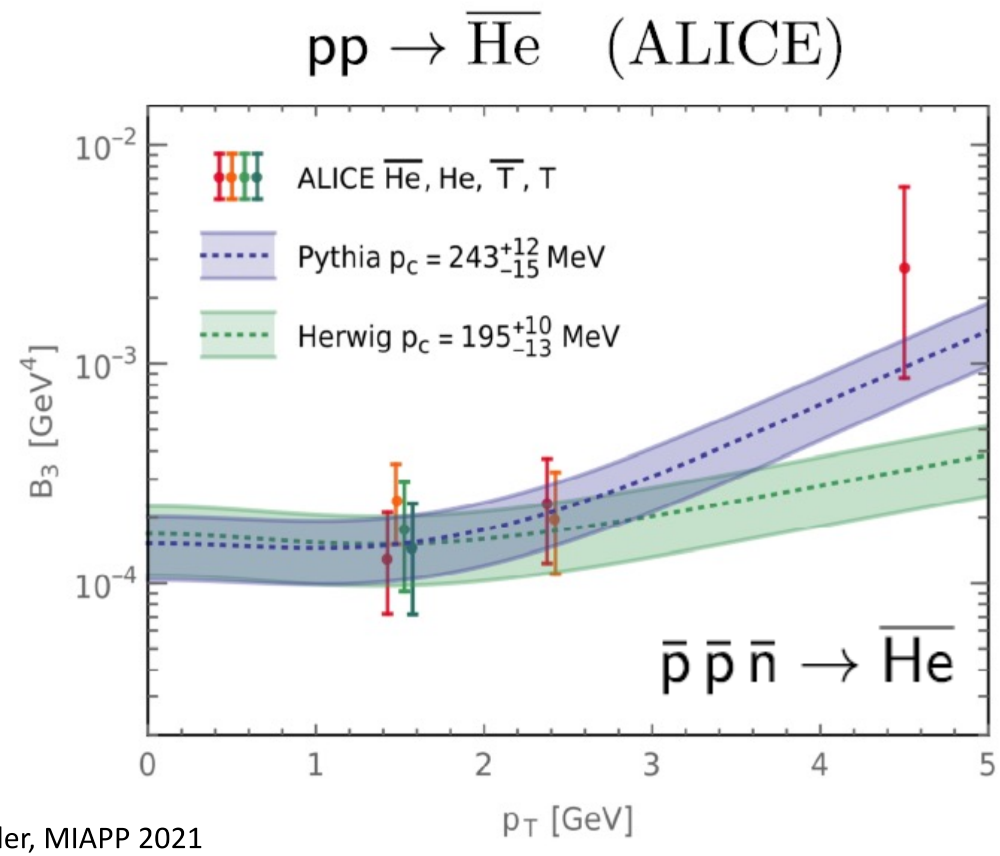
Anti-D $|\Delta p| < p_0$

Anti-He 

Formation of anti-nuclei

Coalescence parameter may depend on many kinematical parameters, including the size of the projectile and target

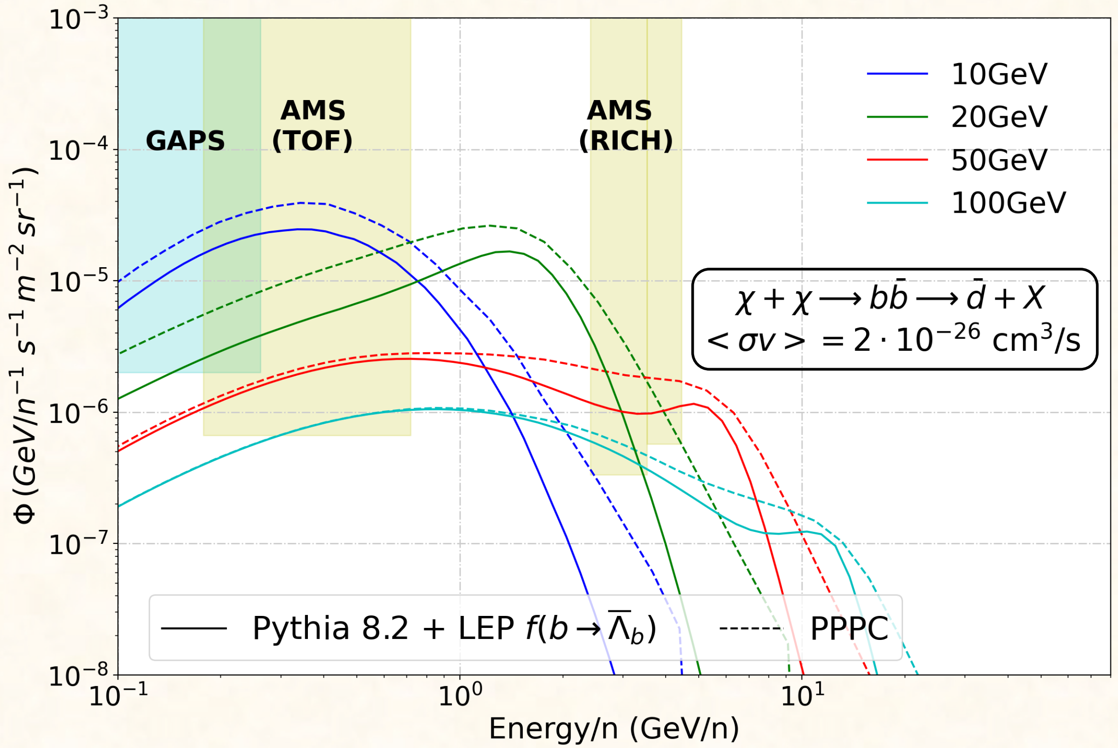


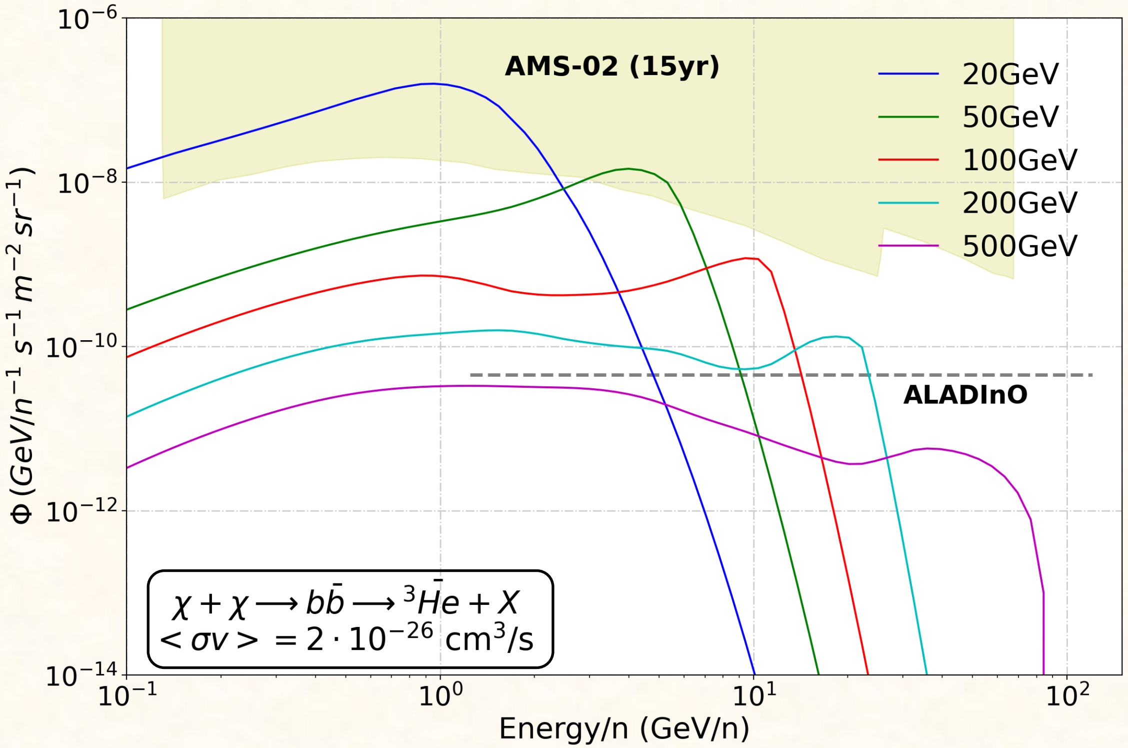


Martin Winkler, MIAPP 2021

Anti-nuclei as the dark matter smoking gun

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

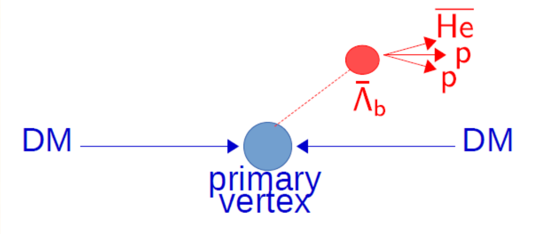




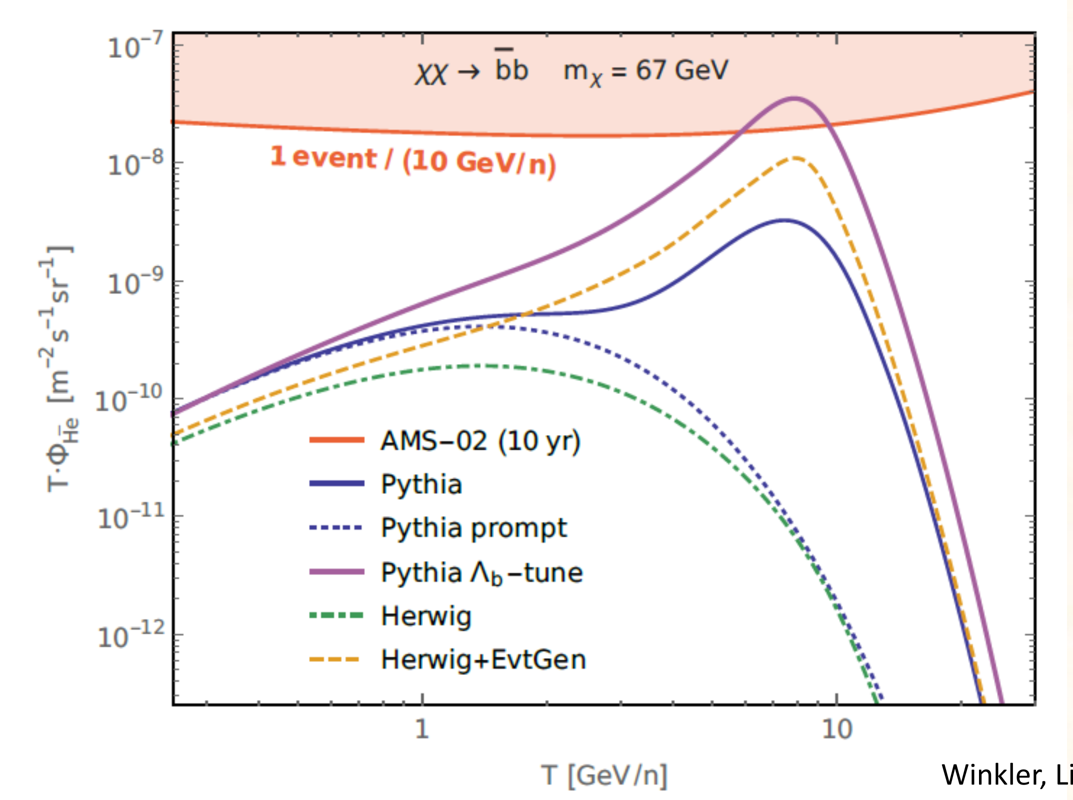
PPPC – M. Cirelli tables:
http://www.marcocirelli.net/PPPC4DMID.html

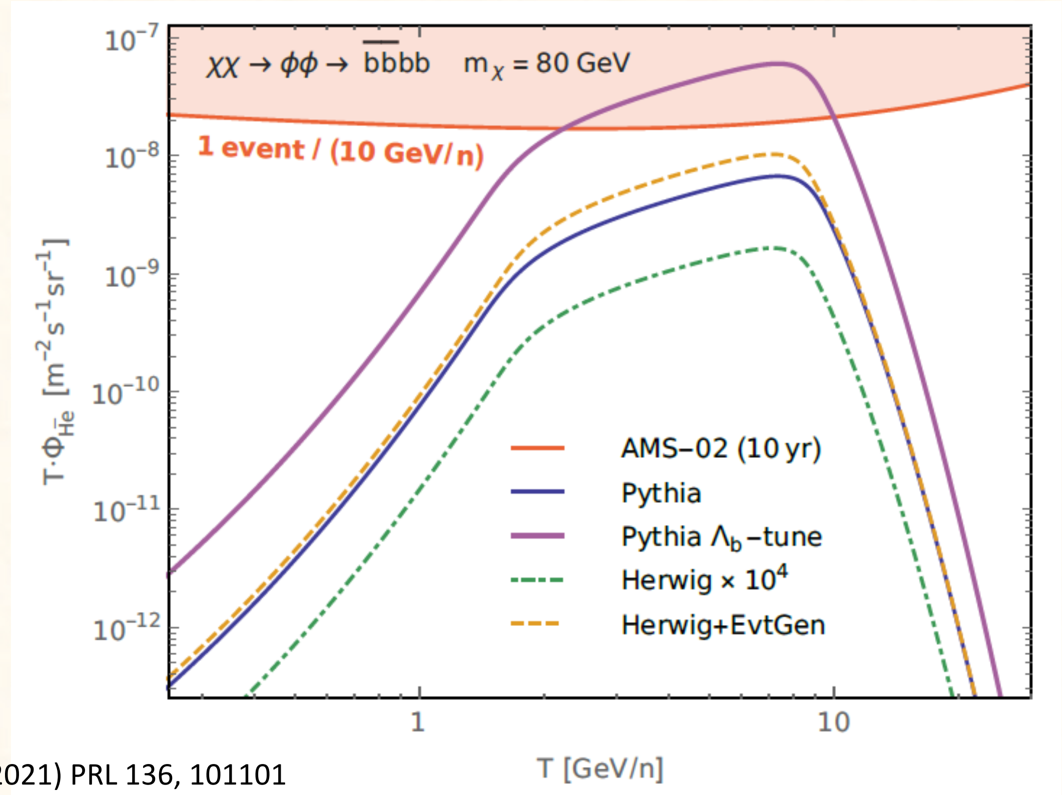
Propagation code: github.com/tospines/Customised-DRAGON-versions

Boosting the dark matter signal



- ✓ **Λ_b production** is a very important source of anti-helium, even able to explain the events reported by AMS-02, although not yet well constrained

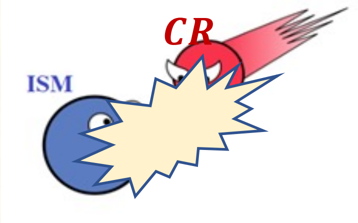




Winkler, Linden (2021) PRL 136, 101101

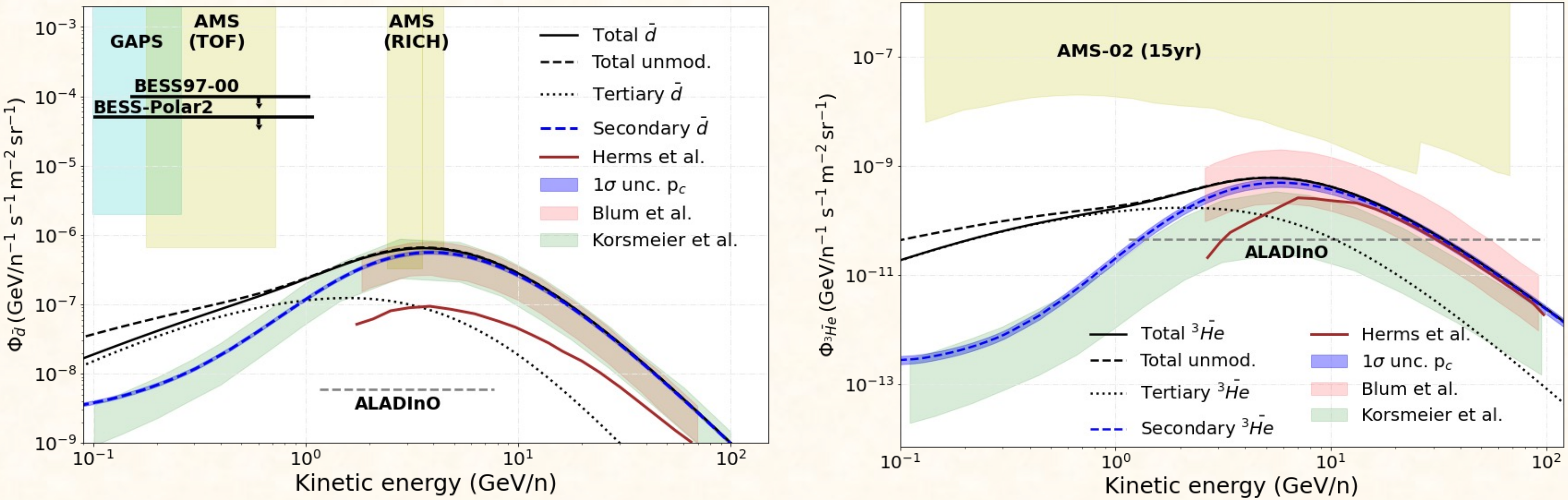
Astrophysical production

CR + ISM → $\overline{\text{He}}$, $\overline{\text{d}}$

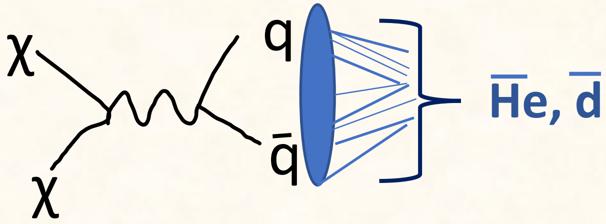


New cross sections: Derived analytically using the factorized coalescence model model from the Winkler (2017) cross sections for antiprotons. Coalescence momentum adjusted to reproduce ALICE p+p data. CR propagation simulated with DRAGON code (github.com/tospines/Customised-DRAGON-versions)

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



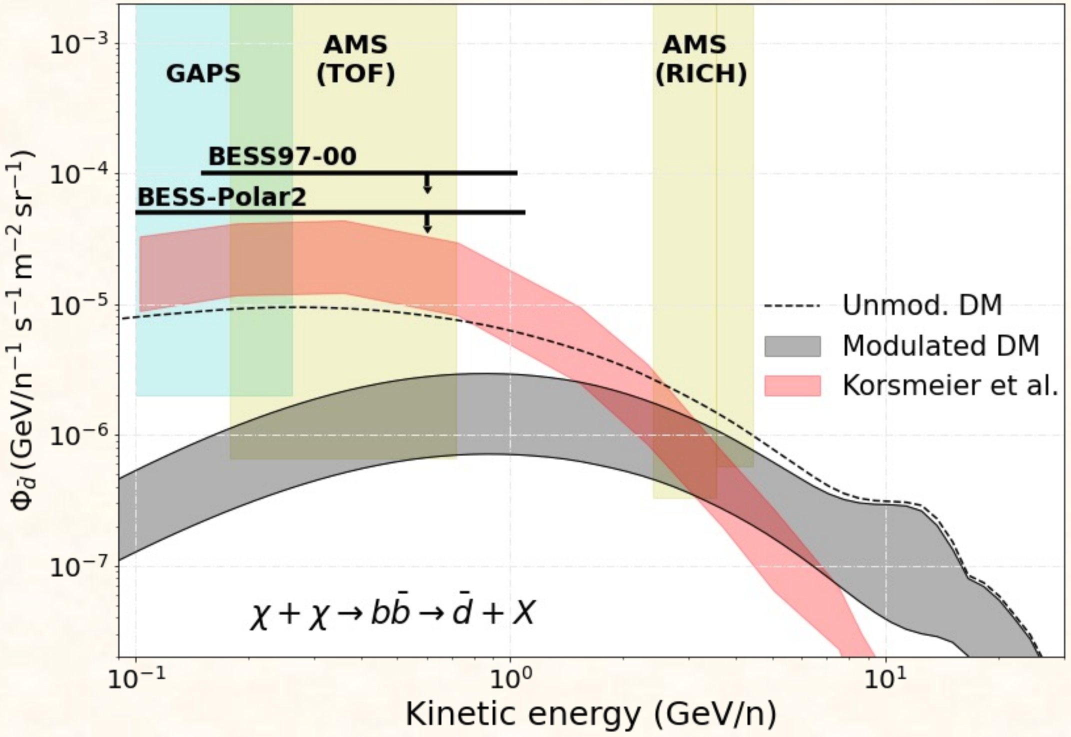
Dark matter production

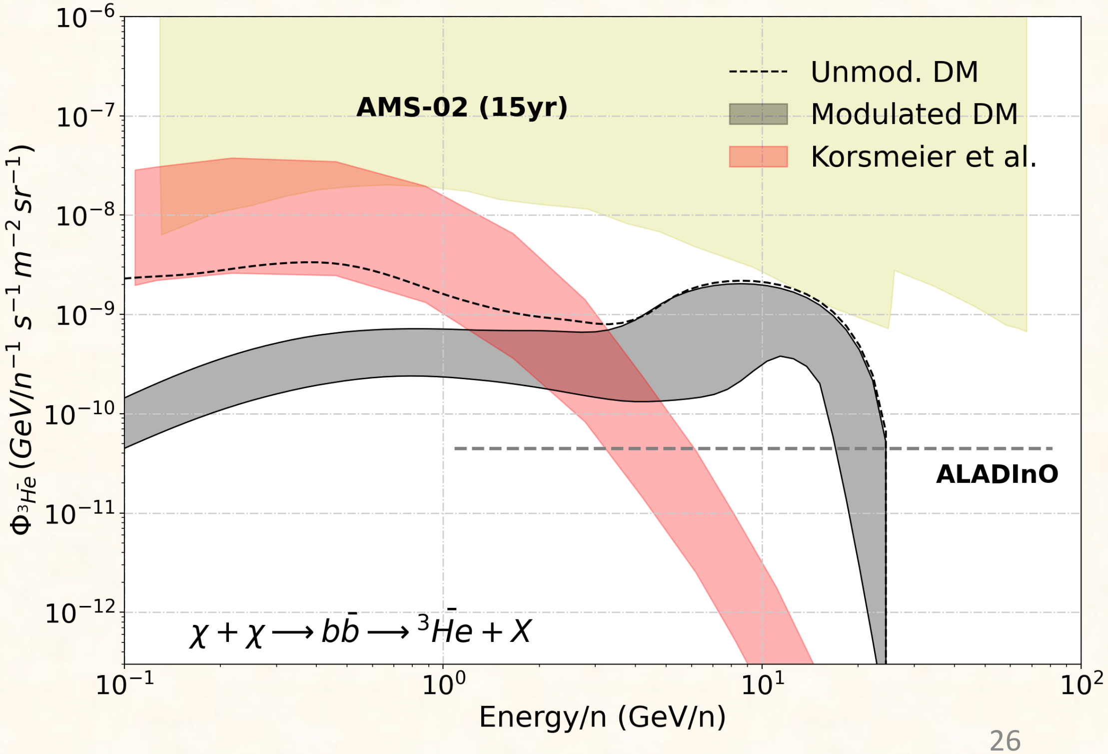


Dark matter yield derived with Pythia, simulating a electrically neutral and colourless resonance decaying, adjusting the coalescence momentum to reproduce ALEPH data.

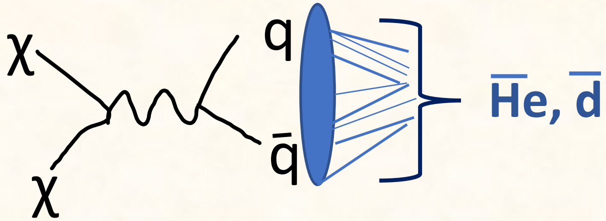
Uncertainty band comes from the uncertainty of the determination dark matter properties.

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



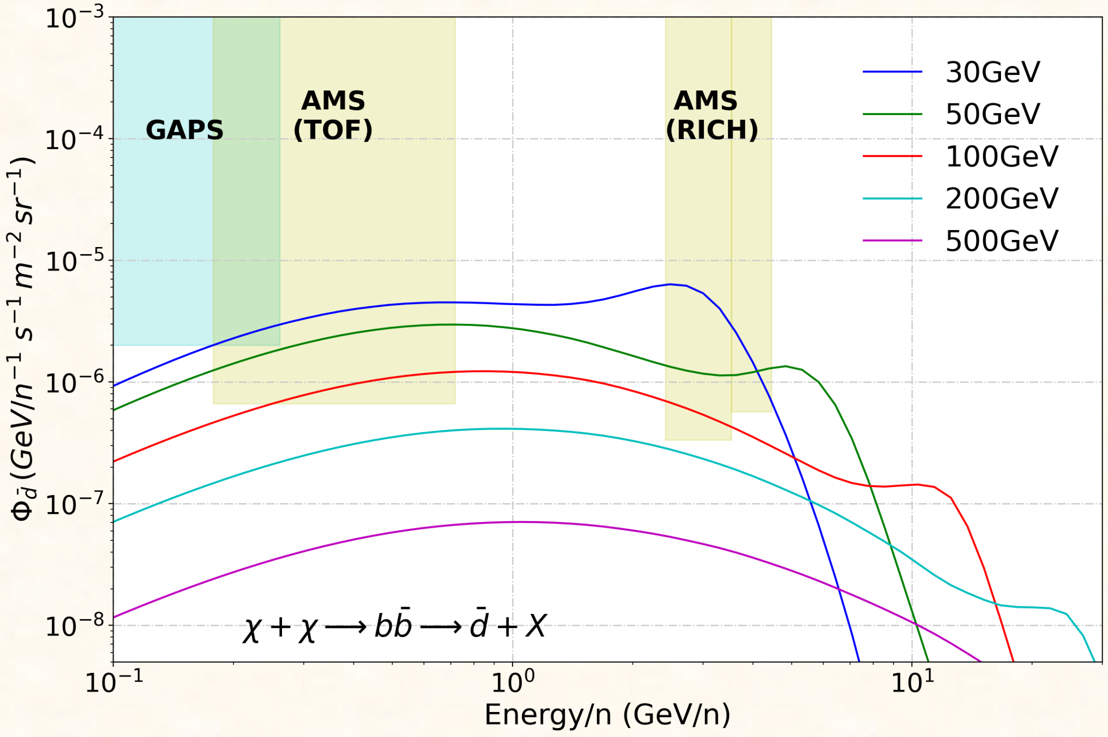


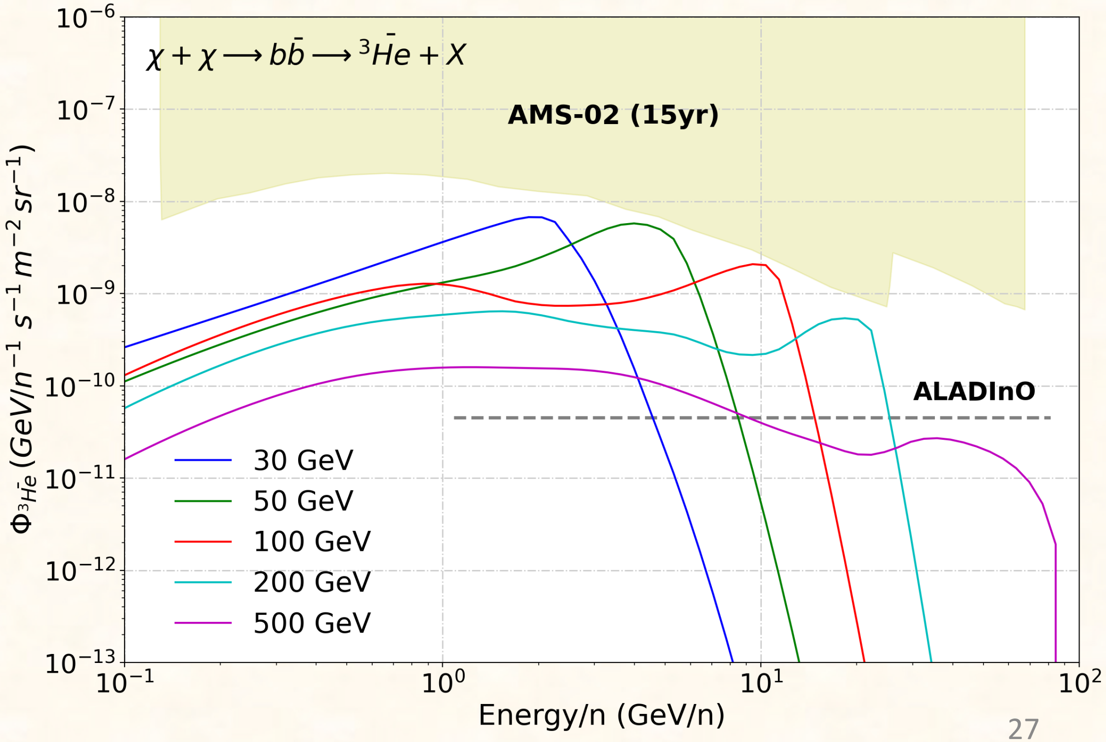
DM production: Upper Limits



Maximal antinuclei flux allowed from our antiproton bounds. Uncertainties in the coalescence momentum can hardly explain the detection of $O(1)$ antihelium-3 event by AMS-02, but are unable to explain any detection of antihelium-4...

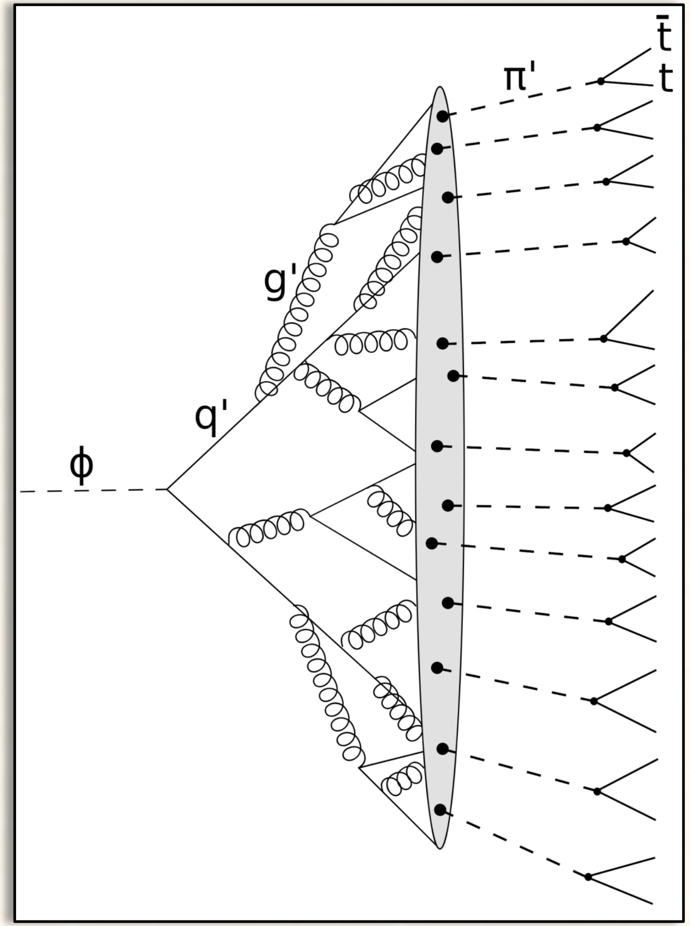
P.D.L. et al, **in preparation**





A solution: QCD-Like Dark sector

Winkler, **PDL**, Linden
ArXiv:2211.00025



The observation of antihelium-4 is much harder to explain because standard models predict a production ratio ~ 1/1000

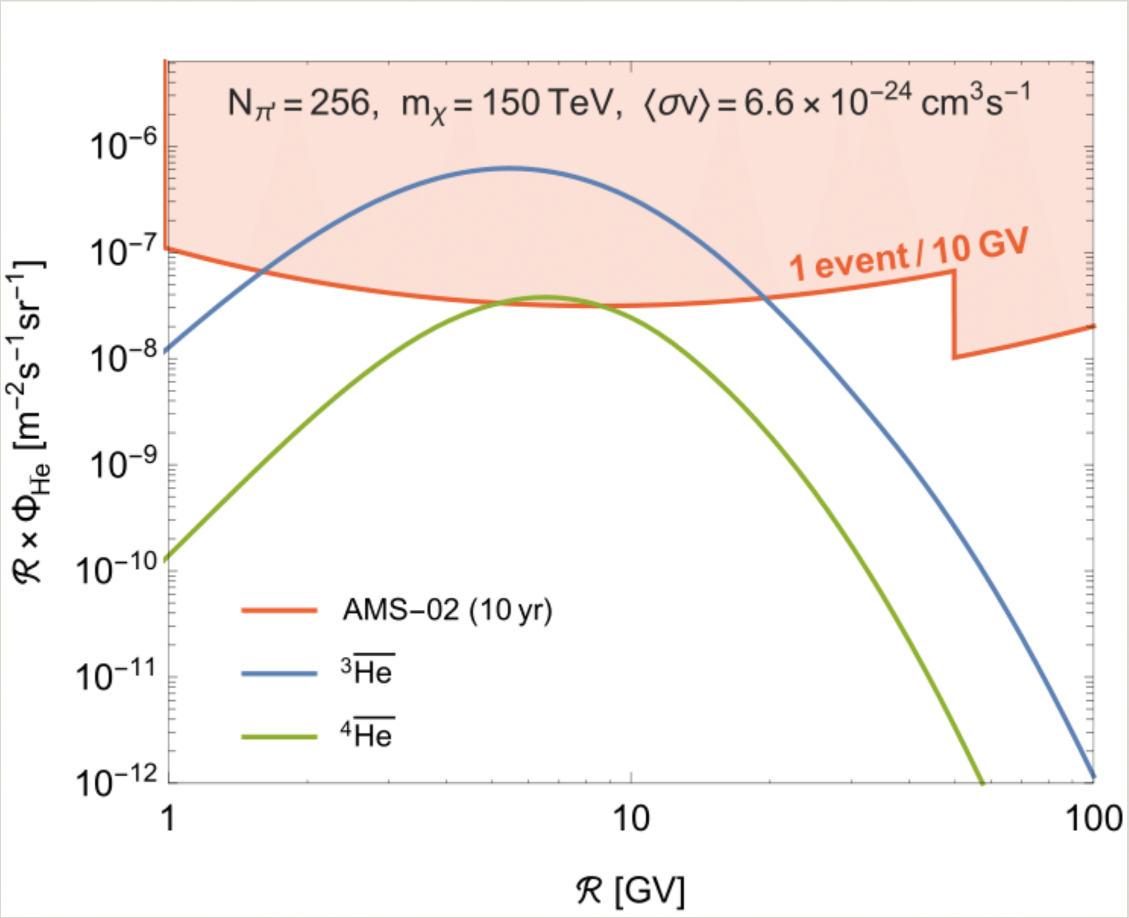
A **strongly coupled dark sector** can produce a “dark parton shower”, generating high multiplicity of “dark pions”. These would subsequently decay into SM quarks through, e.g., the Higgs or top portals, **triggering a hadronic shower.**

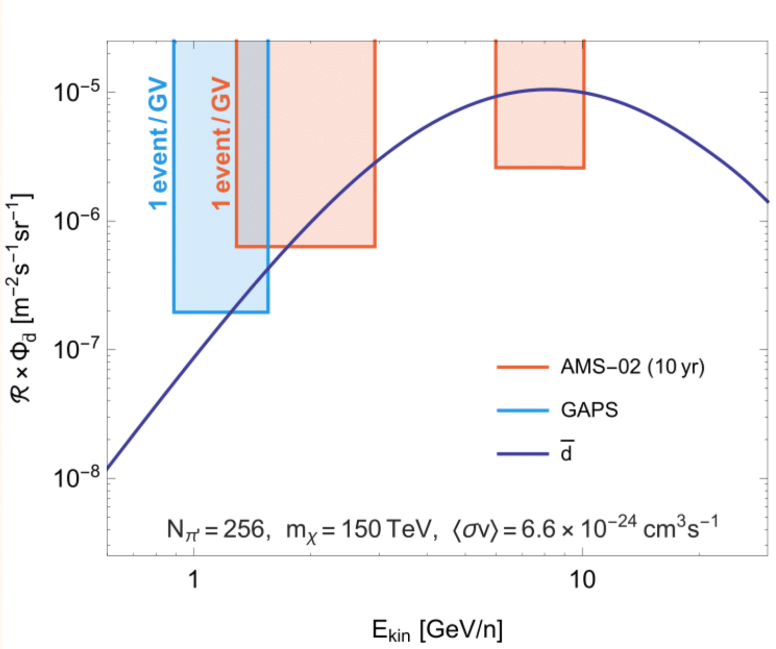
Simulated with Pythia as $\chi\chi \to \phi\phi \to 2\bar{q}'q' \to N_{\pi'}\,\pi' \to N_{\pi'}\,\bar{t}t$

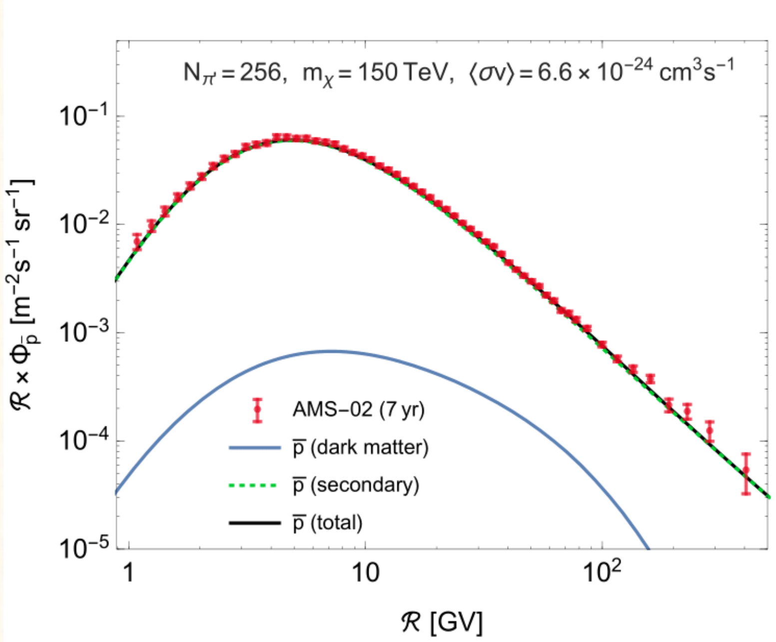
This could have escaped detection at LHC and it offers a pathway to look for excesses in the ditop channel

QCD-Like Dark sector

From factorized formula: $N_A \propto \left(N_p\right)^A$







Conclusions

Scrutinizing current predictions for cosmic-ray antiparticles

- **Uncertainty associated to the different CR antiparticles prevents us from constraining transport parameters, environment properties, …**
- Exciting period when experimental data is allowing us to go beyond standard paradigm of Galactic CR propagation – **Multimessenger studies**
- A formal study of the **generation and interaction of turbulence** in the **heliosphere** and in different zones of the **Galaxy** is necessary
- **Antinuclei** seem a very promising channel to study **signals from dark matter** and constrain our current **WIMP** models – **At reach in the next decade!**

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