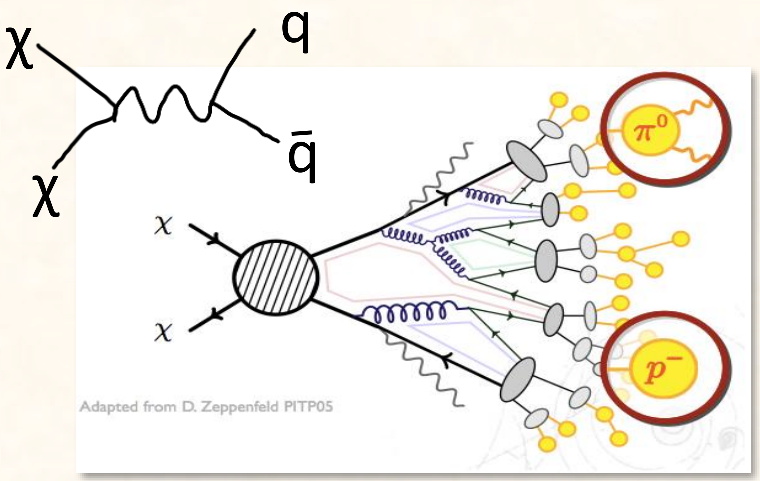
The challenge to understand Anti-nuclei observations

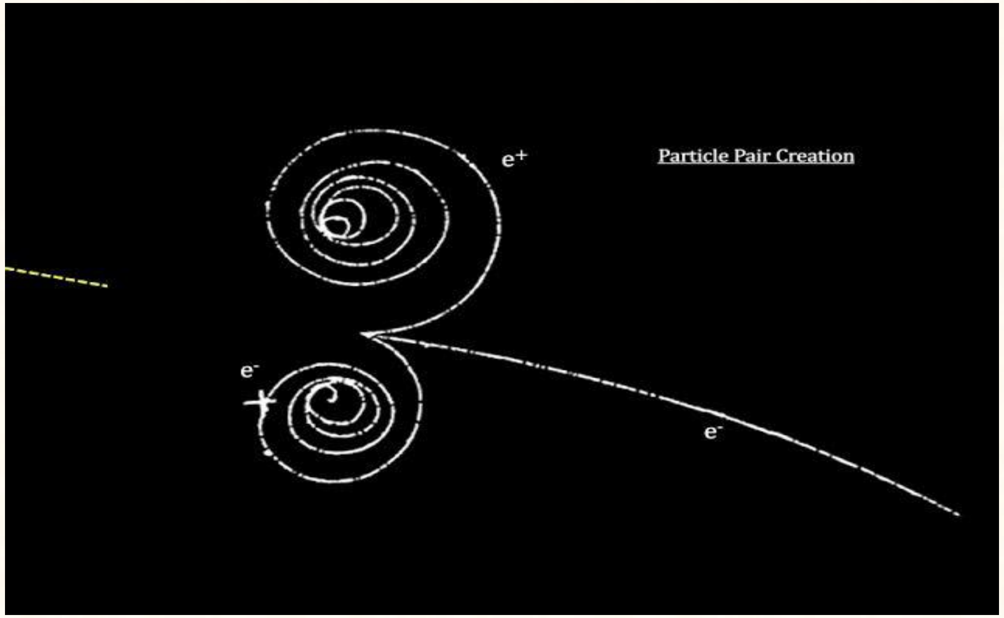


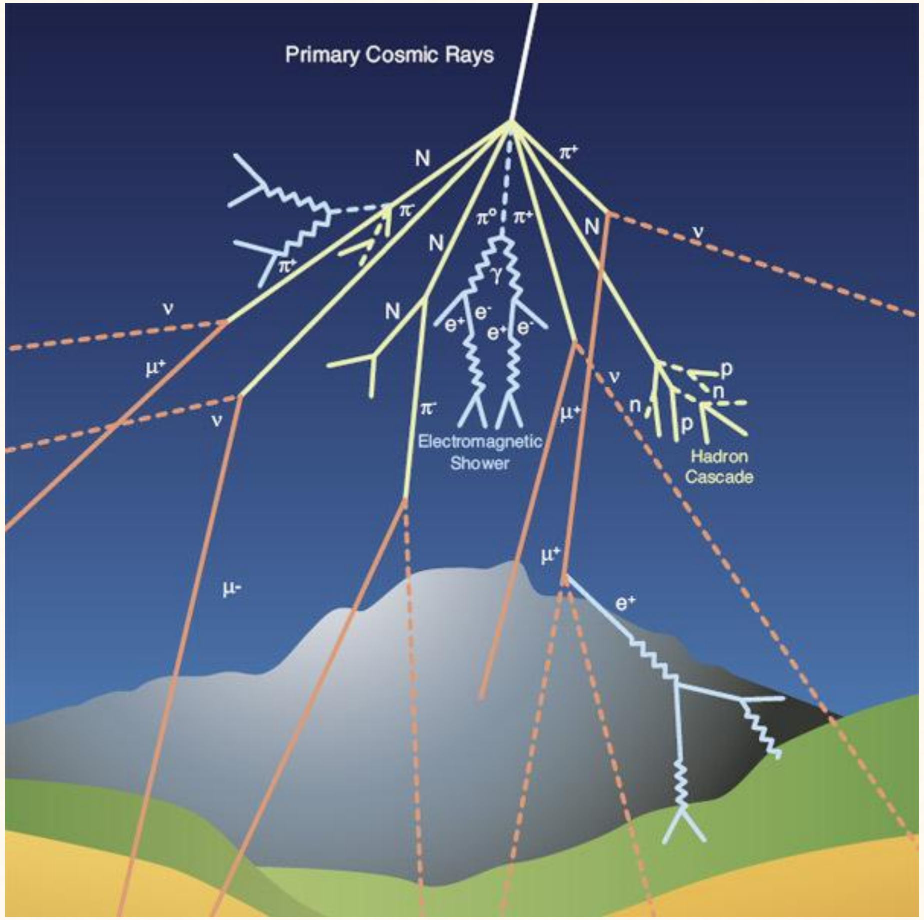
Pedro de la Torre Luque --- pedro.delatorre@uam.es
Juan de la Cierva fellowship (IFT/UAM - Madrid)

Cosmic rays open the window to the anti-world

Cosmic rays (CRs) revealed the existence of antimatter: **the positron was discovered by Anderson in 1932**

CR interactions with the atmosphere produce particle showers with high energy antiparticles



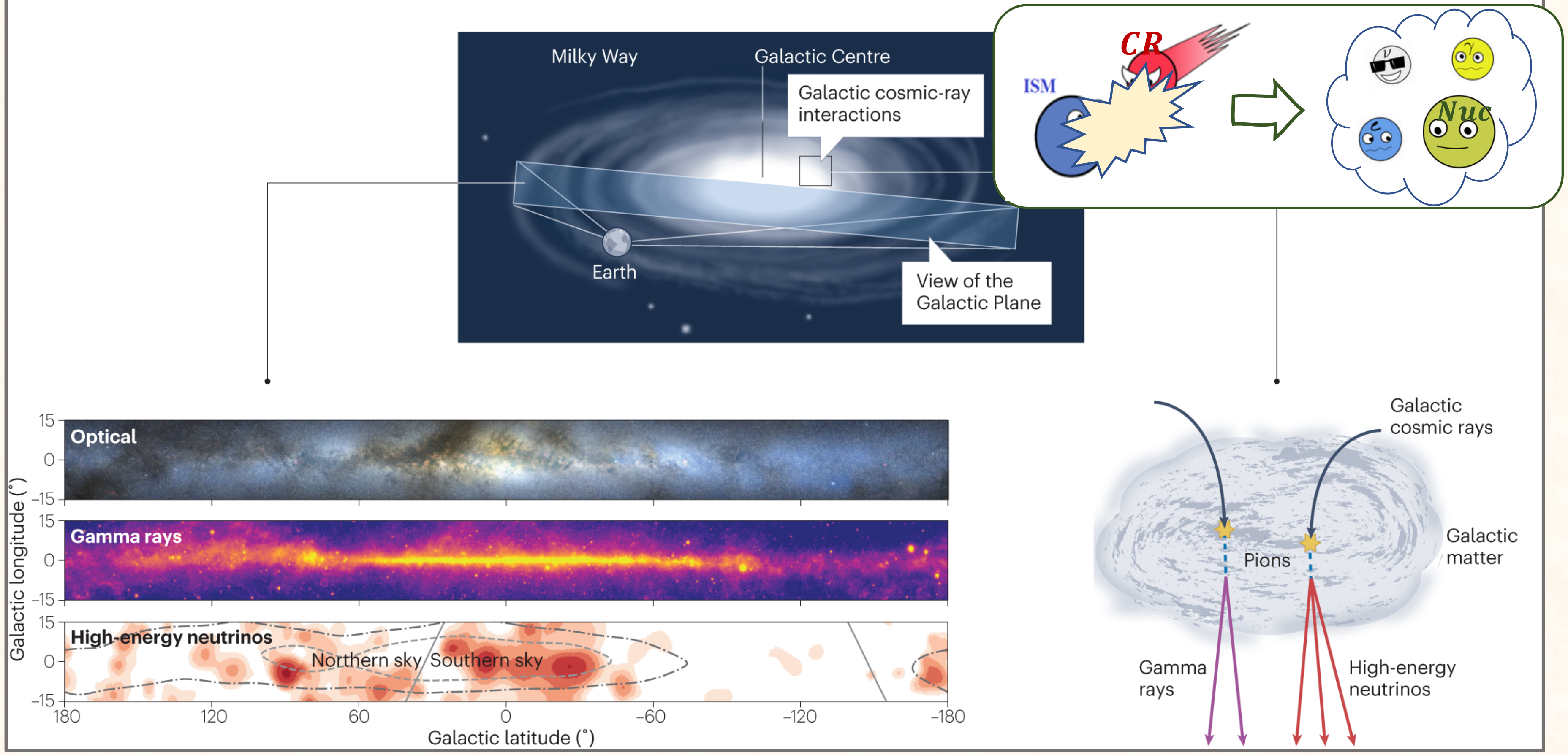


Cosmic rays open the window to the anti-world

These interactions are continuously happening in the disk of the Galaxy!

We can observe the disk of the Milky Way through gamma rays and neutrinos, evidencing that high-energy particle interactions are constantly going on

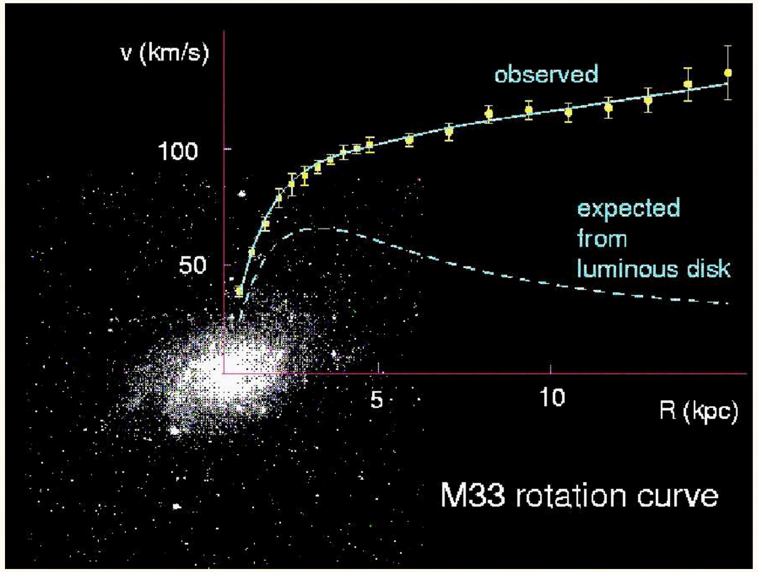
M. Bustamante Nature Reviews Physics, Vol 6 (2024)

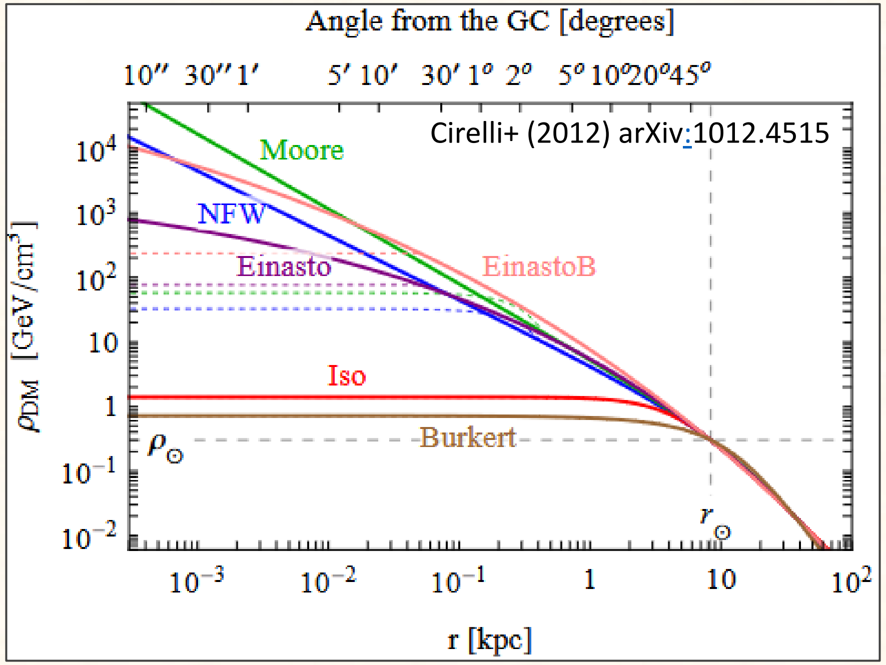


Dark matter in the Galaxy

Extensive evidence for the existence of a “substance” that determines, through its gravitational pull, the dynamics and structure of Galaxies and larger objects: **Dark matter**

Expected to be concentrated around the Galactic Center and to interact with conventional matter very feebly





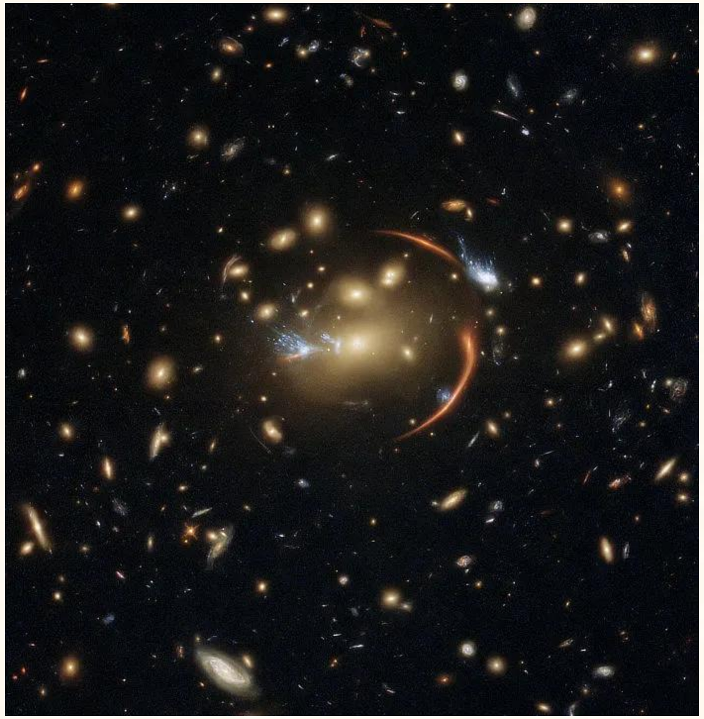
What’s dark matter?

A new particle? (best motivated is the WIMP)

Black holes?

MOND?

Many other possibilities…



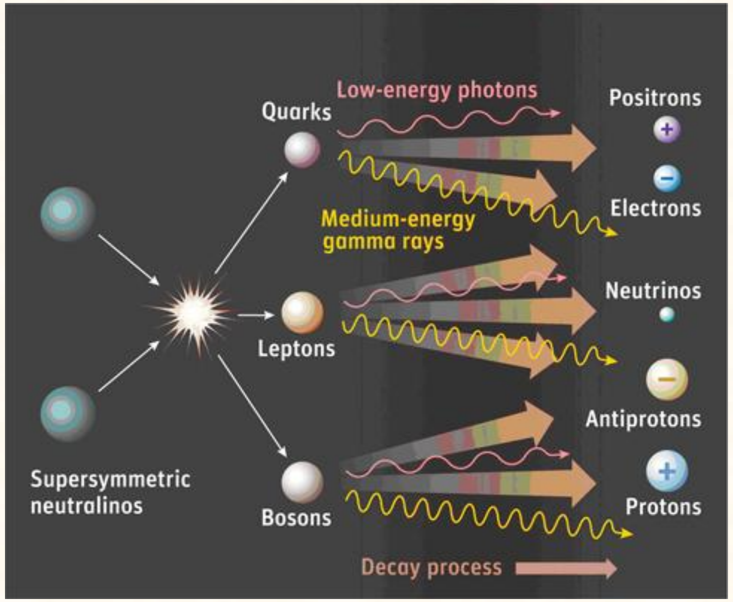
Anti-particles from Dark matter

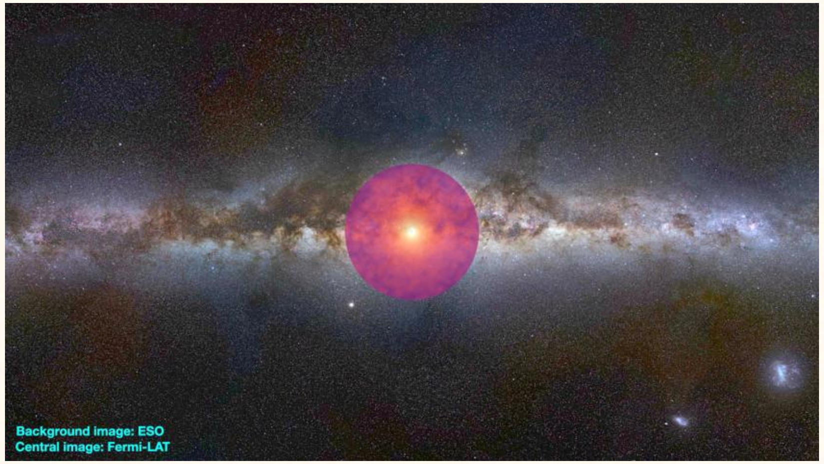
WIMPs must produce same number of particles and antiparticles in their decay/annihilation → Another potential source of antimatter

Observing the direct products of dark matter would reveal its nature and origin

Positrons and antiprotons have long been considered critical channels for dark matter searches: Many simple extensions of the SM lead to well-motivated dark matter candidates

$$Q_{\bar{N}}^{\mathrm{DM,ann}}(\vec{r},T) = \frac{1}{2}\left(\frac{\rho(\vec{r})}{m_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle_f \times \frac{dN_f^{\bar{N}}}{dT}$$





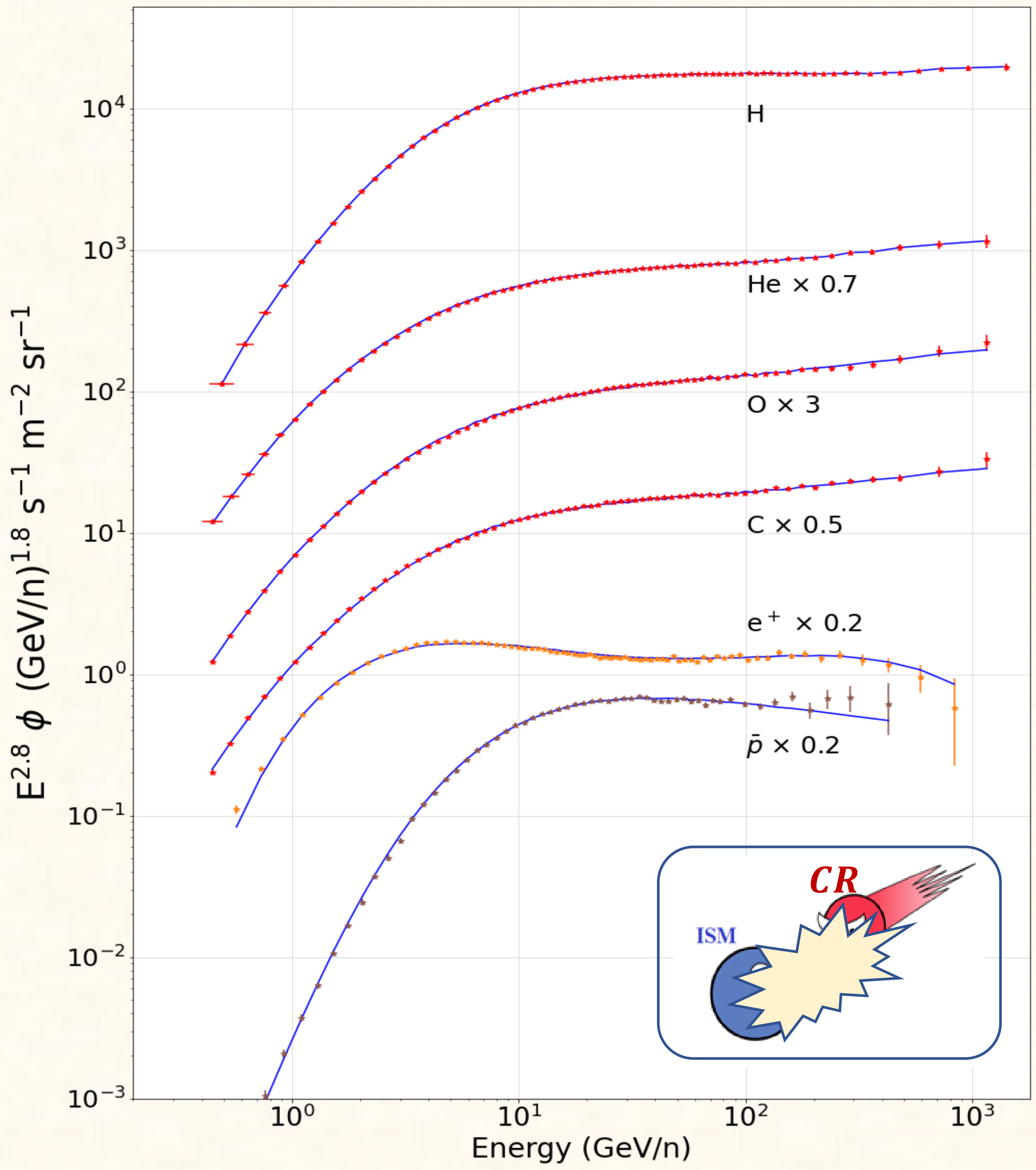
Potential of antiparticles to reveal the existence of BSM physics

High precision data for the fluxes of CR nuclei allow us to accurately model the production of CR antiparticles and uncertainties related.

Antiproton and positron observations provide strong constraints on the existence of BSM physics due to the expected low production and uncertainty in their modelling.

Specially, well-motivated **WIMPs** ($M_\chi \sim O(100\ GeV)$) are expected to leave imprints in the GeV energy region.

Flux of CR nuclei and antiparticles (data from AMS-02)



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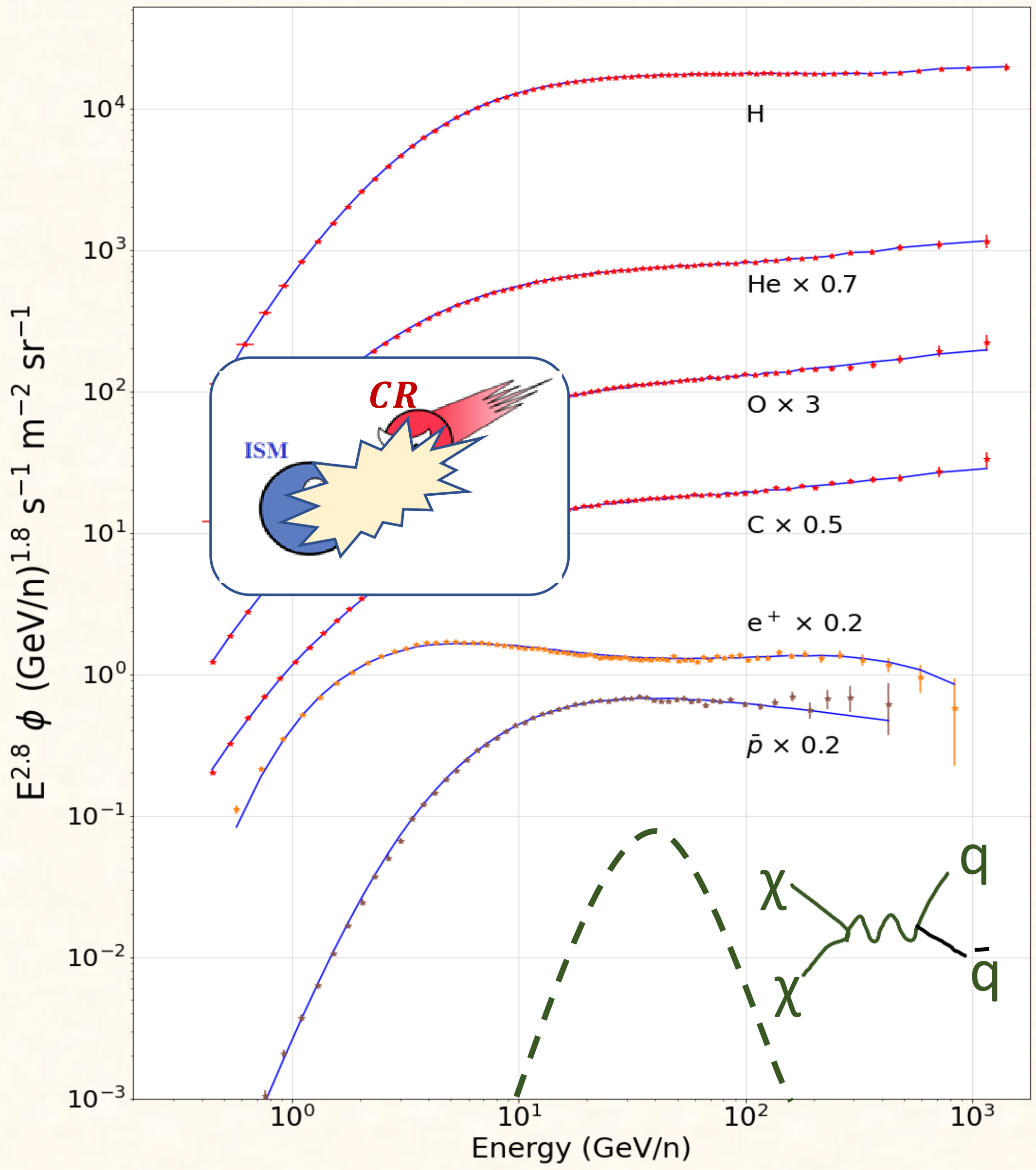
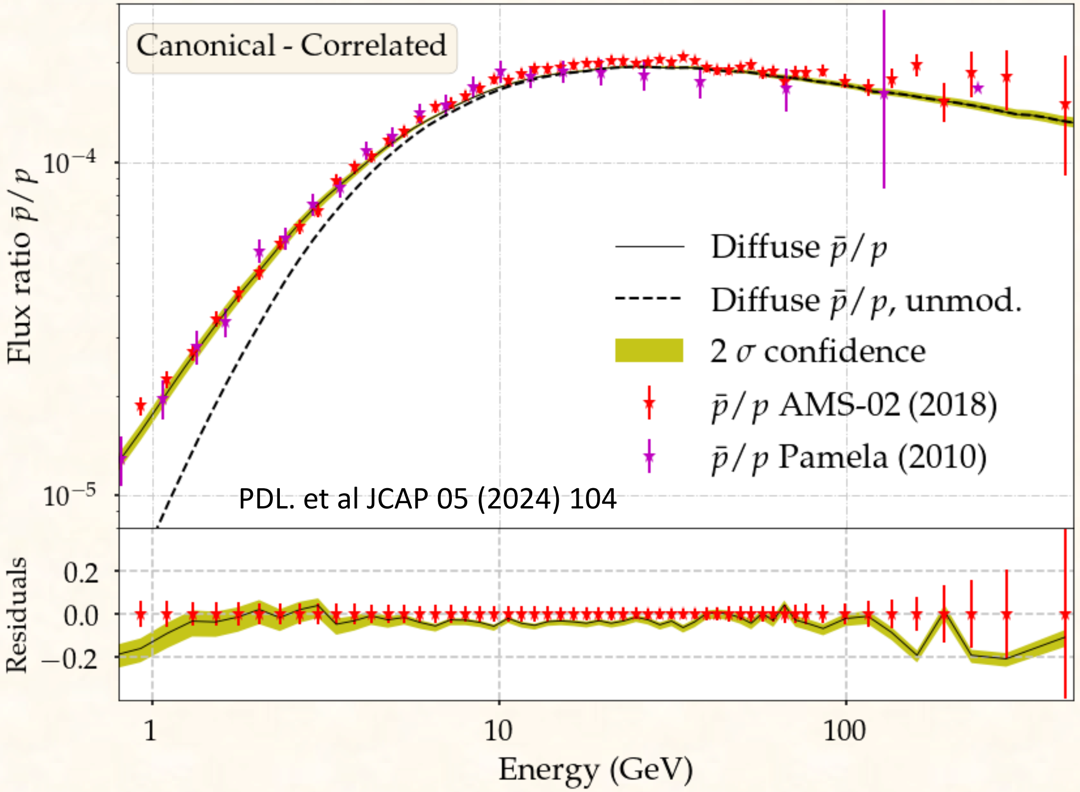
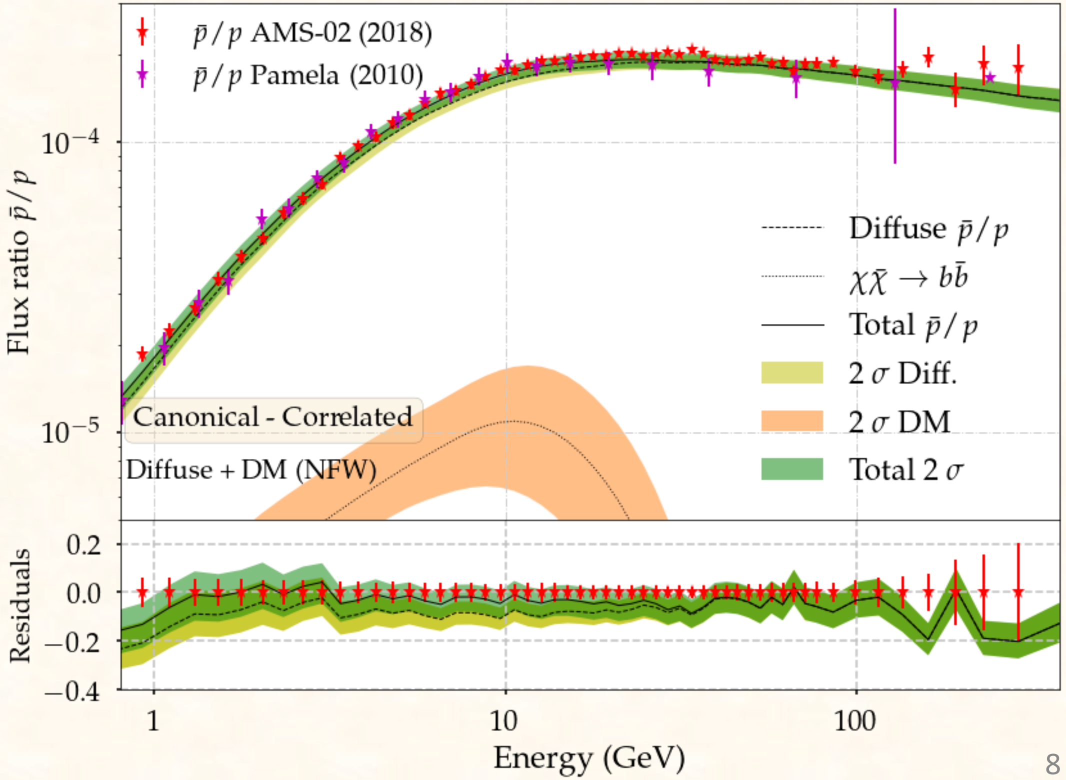


Looking for anomalies in CR antiprotons

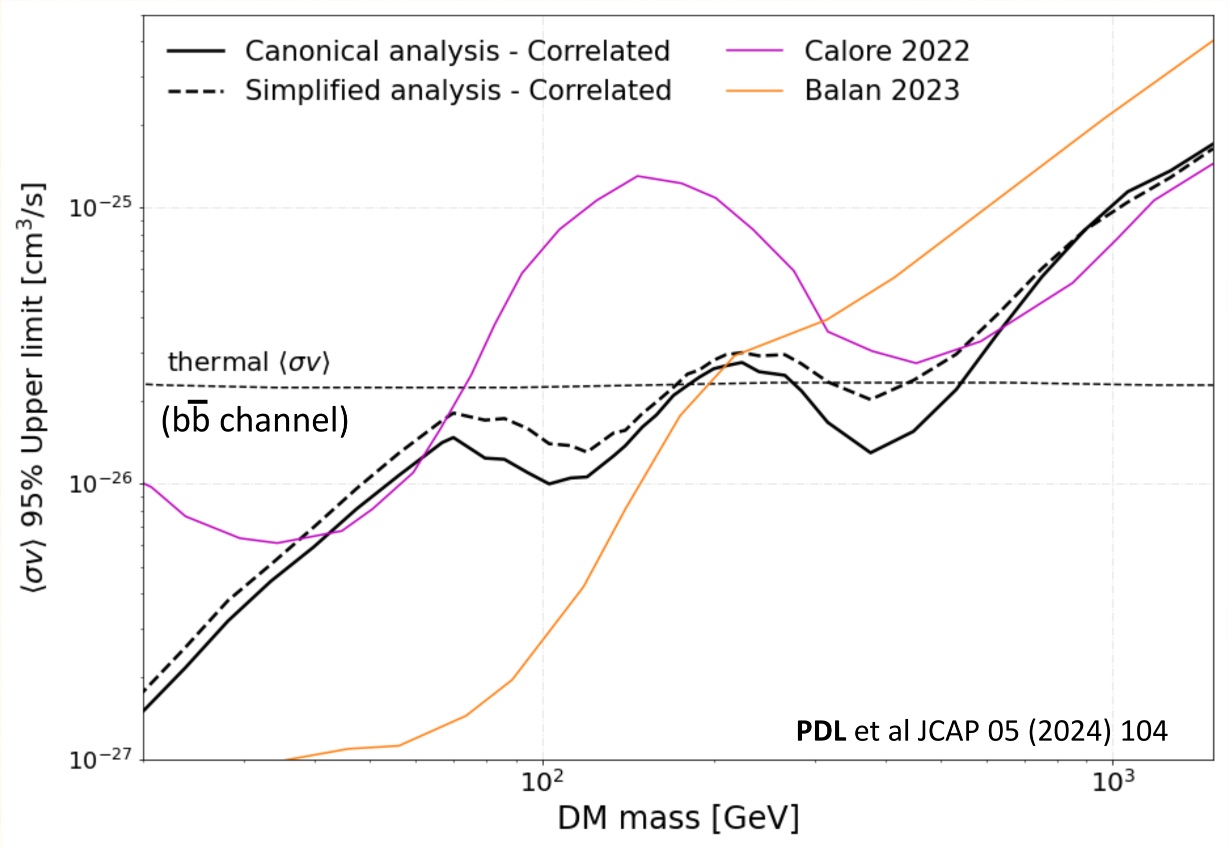
Antiproton observations are fully compatible with a secondary origin. Current DM searches found different sources of uncertainties difficult to avoid: Cross sections, correlated errors, propagation model, … **No significant excess is found (Max. 1.8 σ)**

PDL et al JCAP 05 (2024) 104

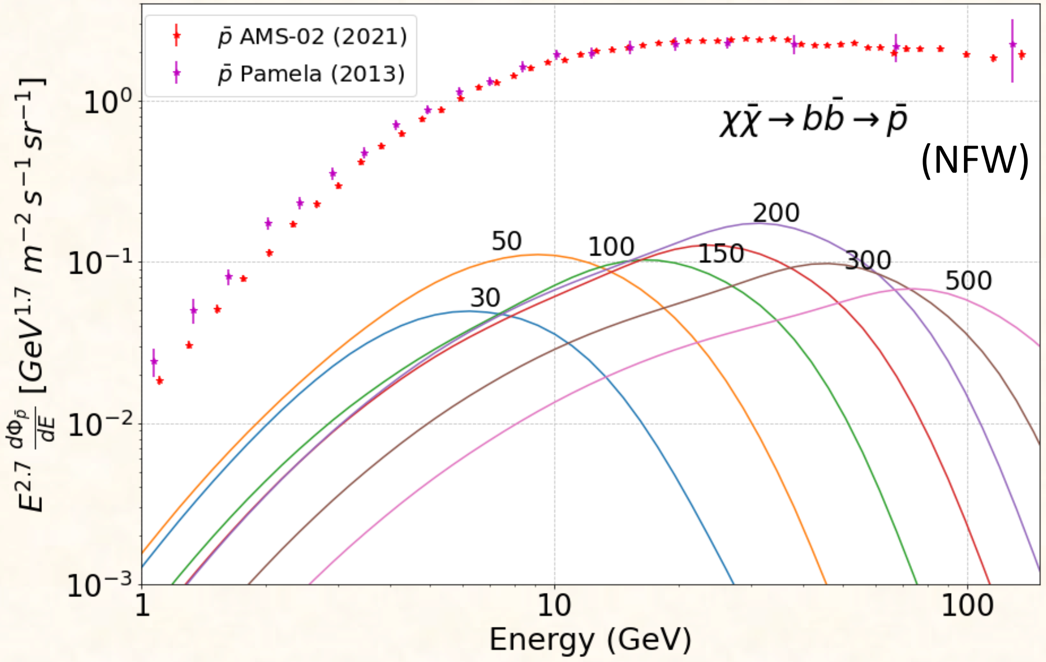




Dark matter bounds from antiproton analyses



Maximal DM-induced signal (at 95% CL)

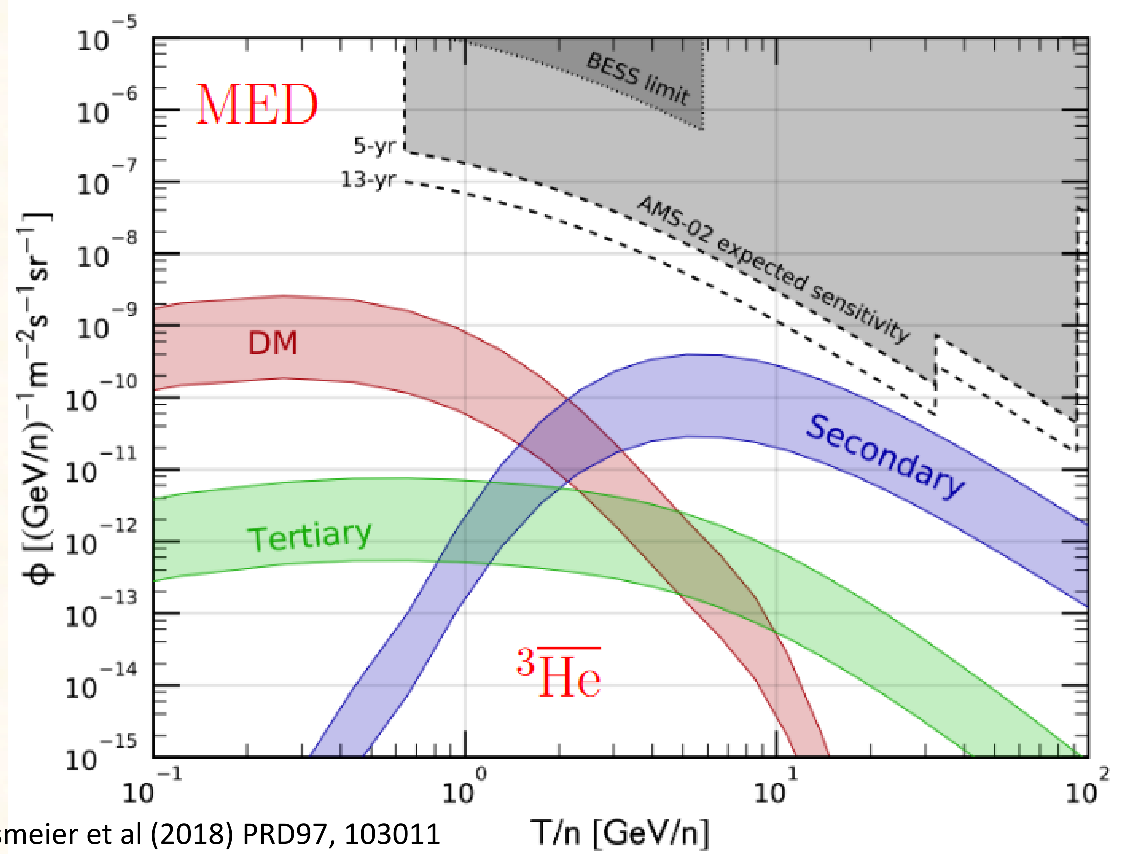


No excess found in the latest $\bar{p}$ analyses

Leading constraints for WIMPs annihilating into hadronic final states, and able to rule out the thermal relic cross sections for masses below ~200 GeV

Anti-nuclei as the dark matter smoking gun

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

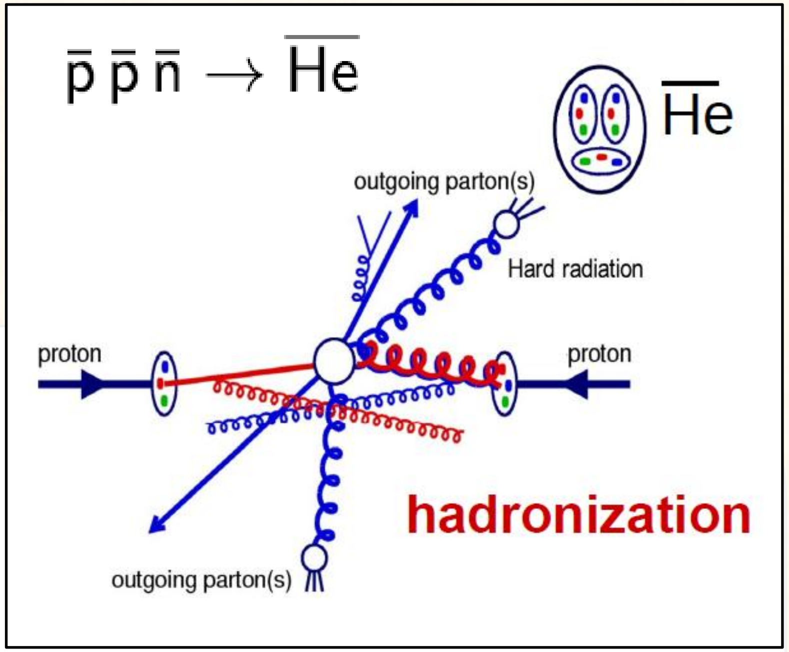


Korsmeier et al (2018) PRD97, 103011

Secondary antinuclei produced from homologous interactions as for $\overline{p}$, but highly suppressed (due to coalescence)!

The production of antinuclei from cosmic ray 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)

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

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

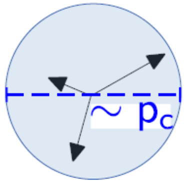
<u>Coalescence parameter</u> can be approximated from the coalescence momentum, $\boldsymbol{p_0}$

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

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

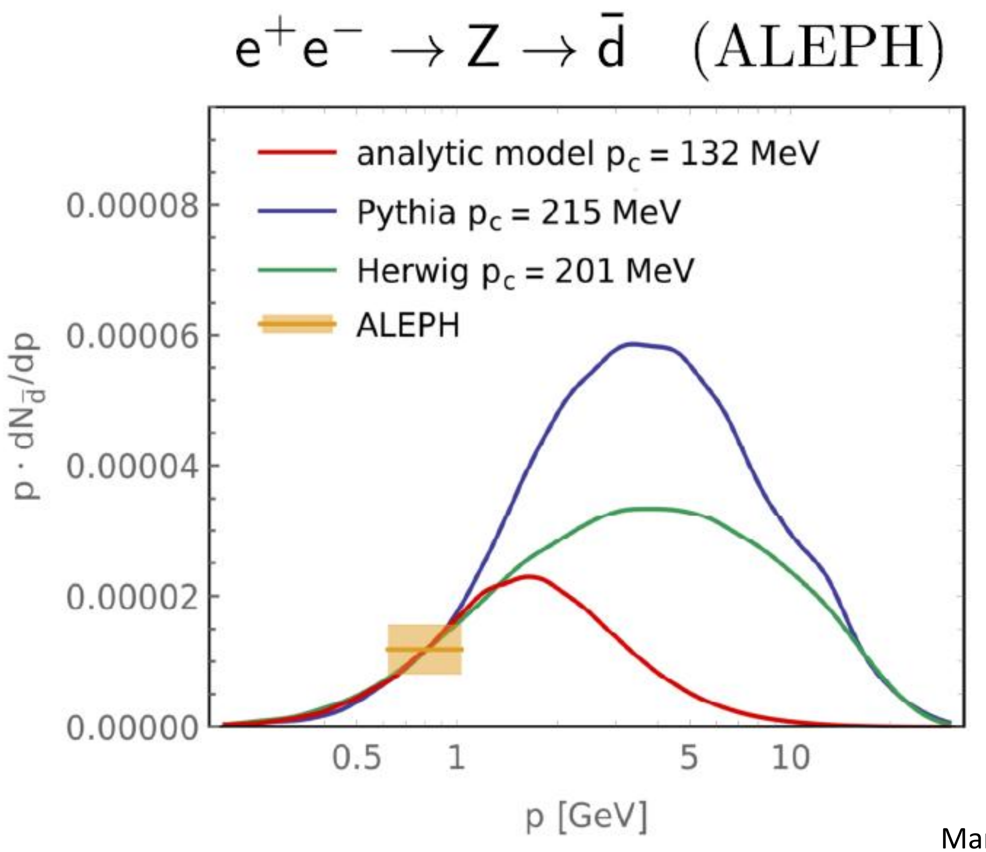
Anti-D $|\Delta p| < p_0$

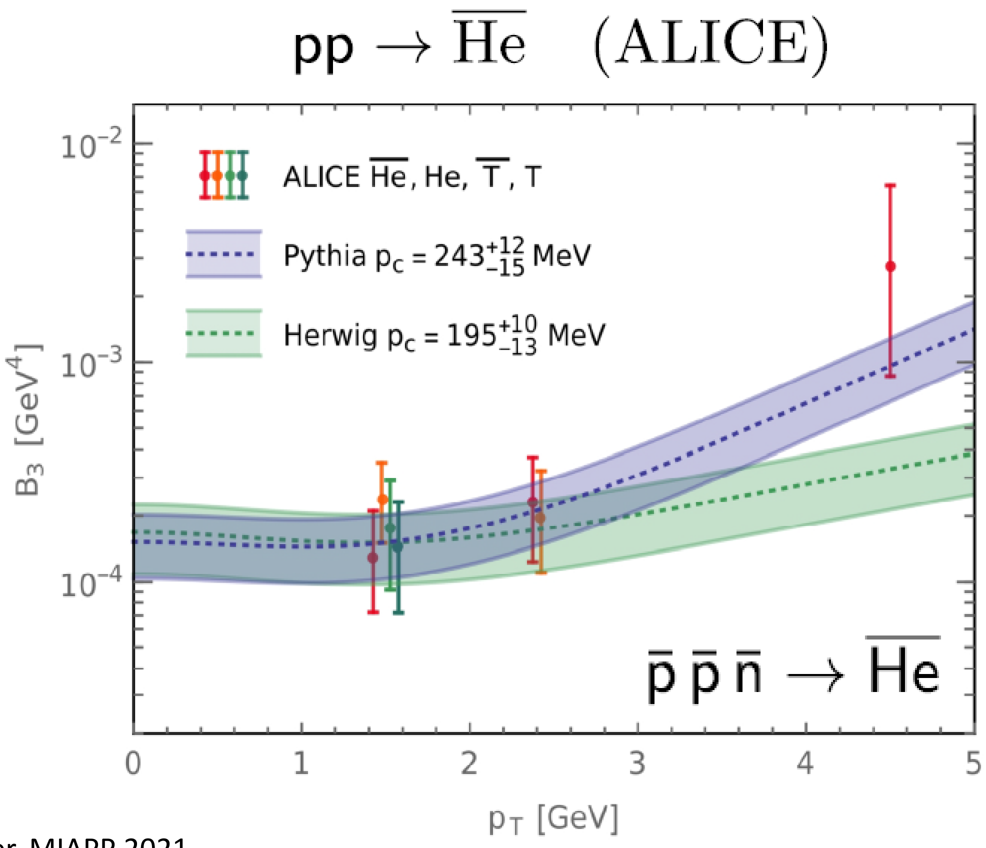
Anti-He



Formation of anti-nuclei

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





Martin Winkler, MIAPP 2021

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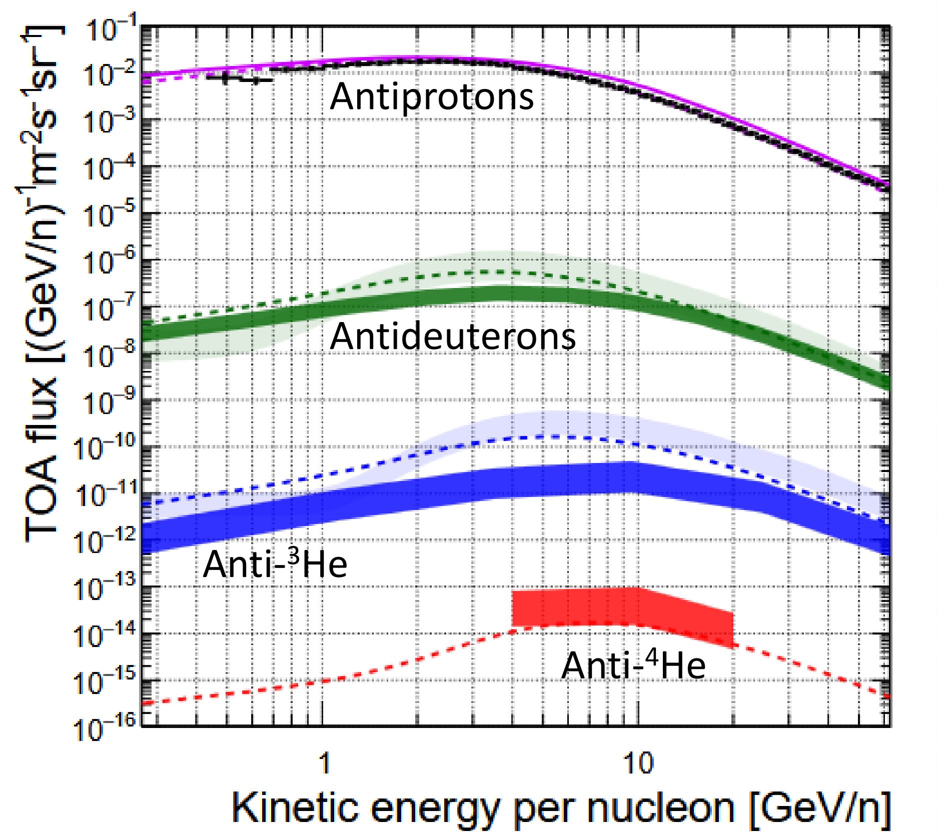

Shukla *PRD* 102, 063004 (2020)

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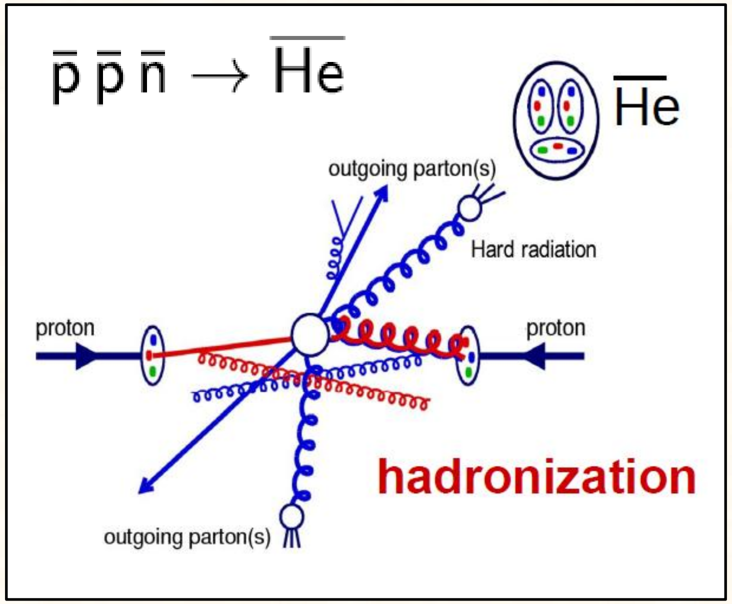
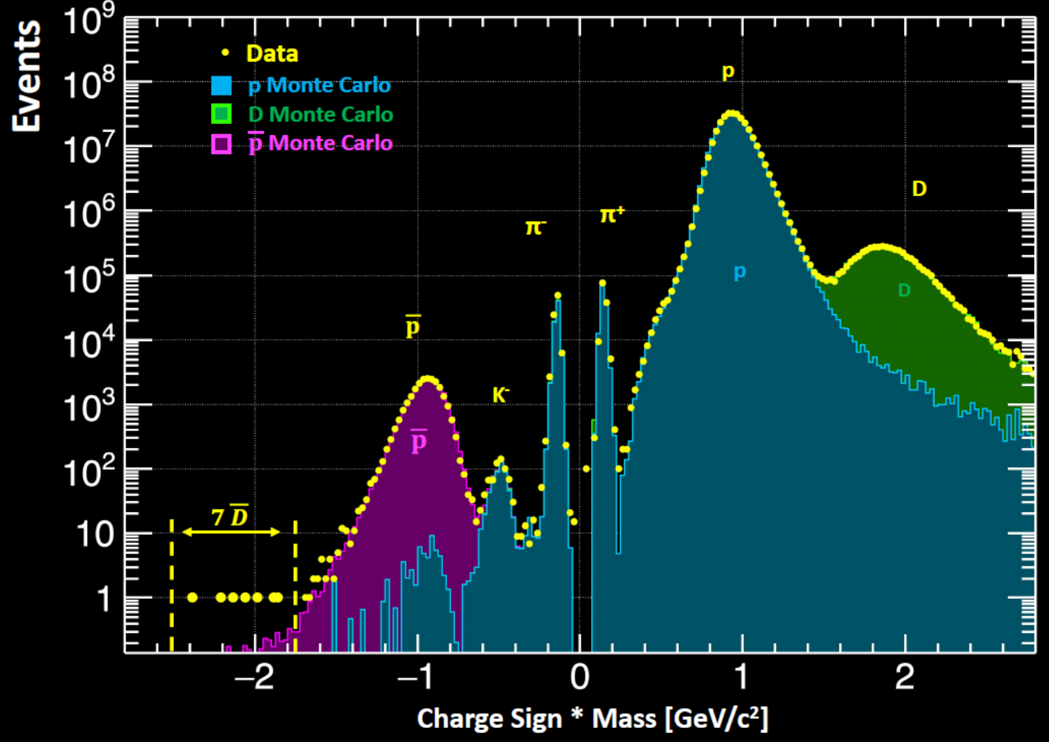
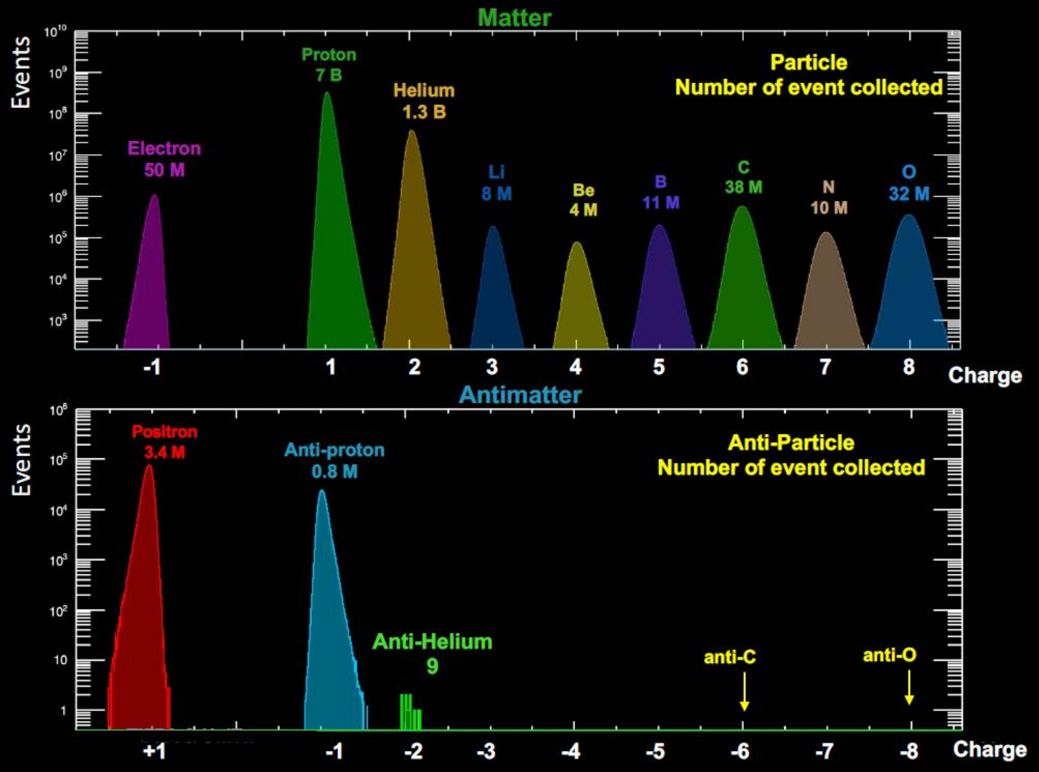


ANTI-NUCLEI: AMS-02 mass-charge spectra





Paolo Zuccon MIAPP 2021

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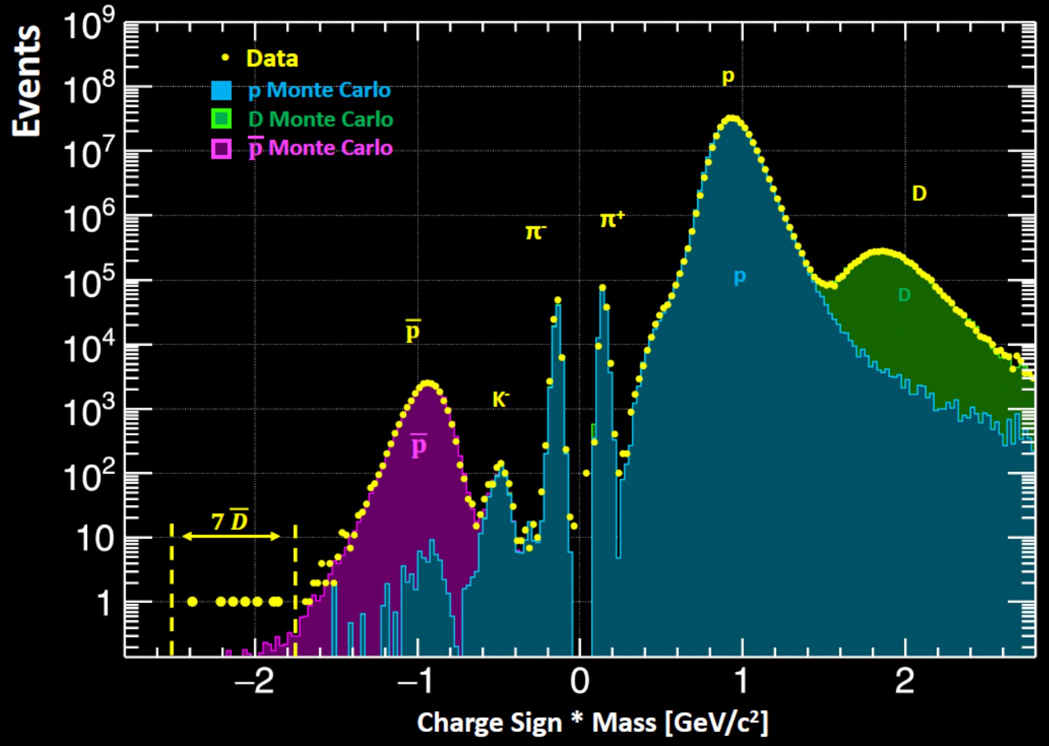

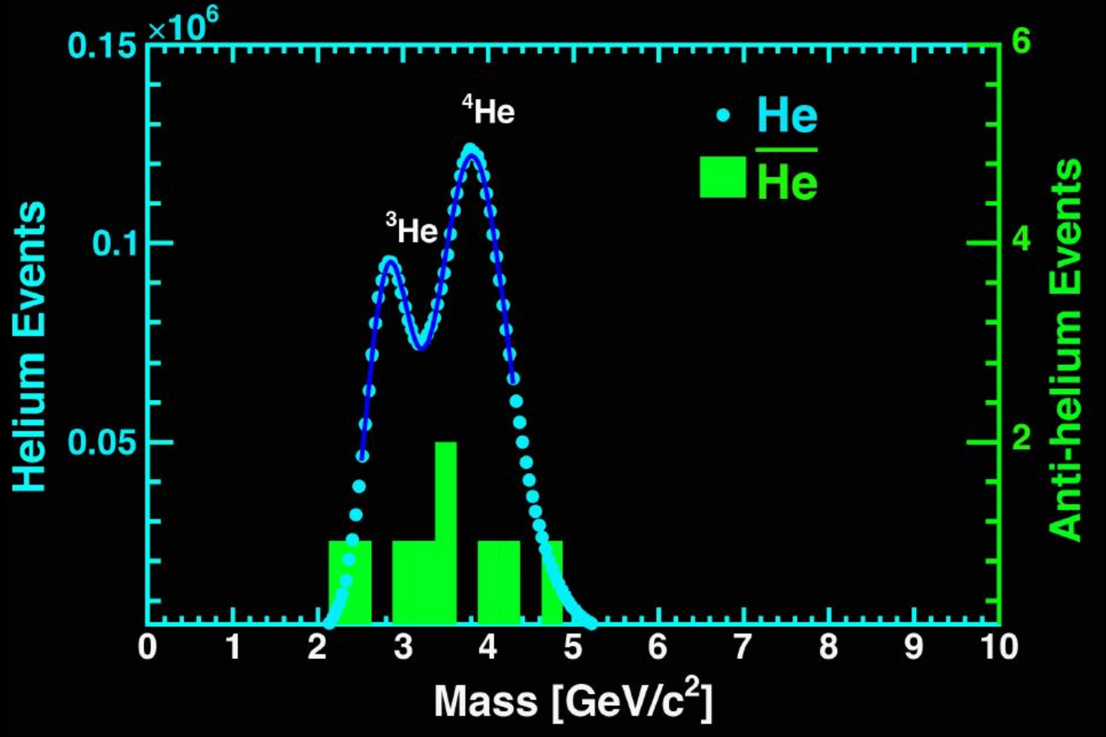

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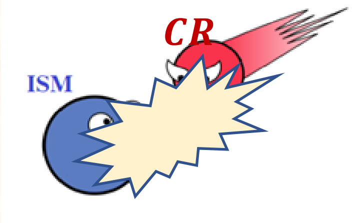
Astrophysical production

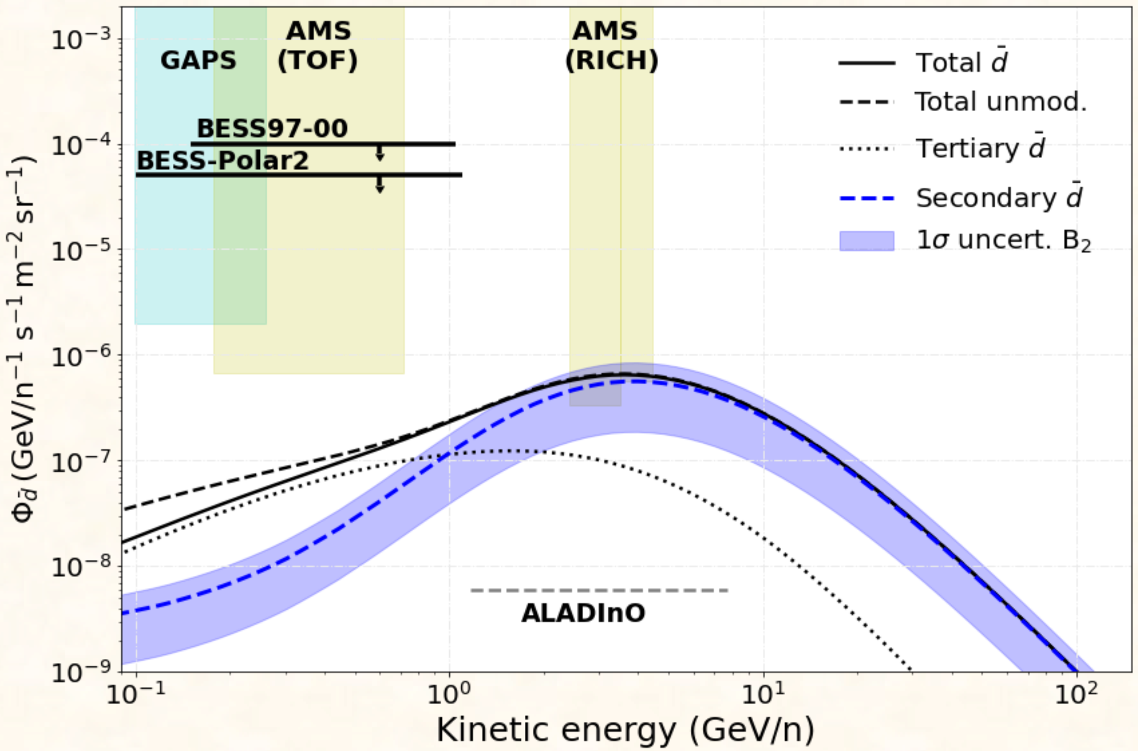
$CR + ISM \rightarrow \overline{He}, \overline{d}$

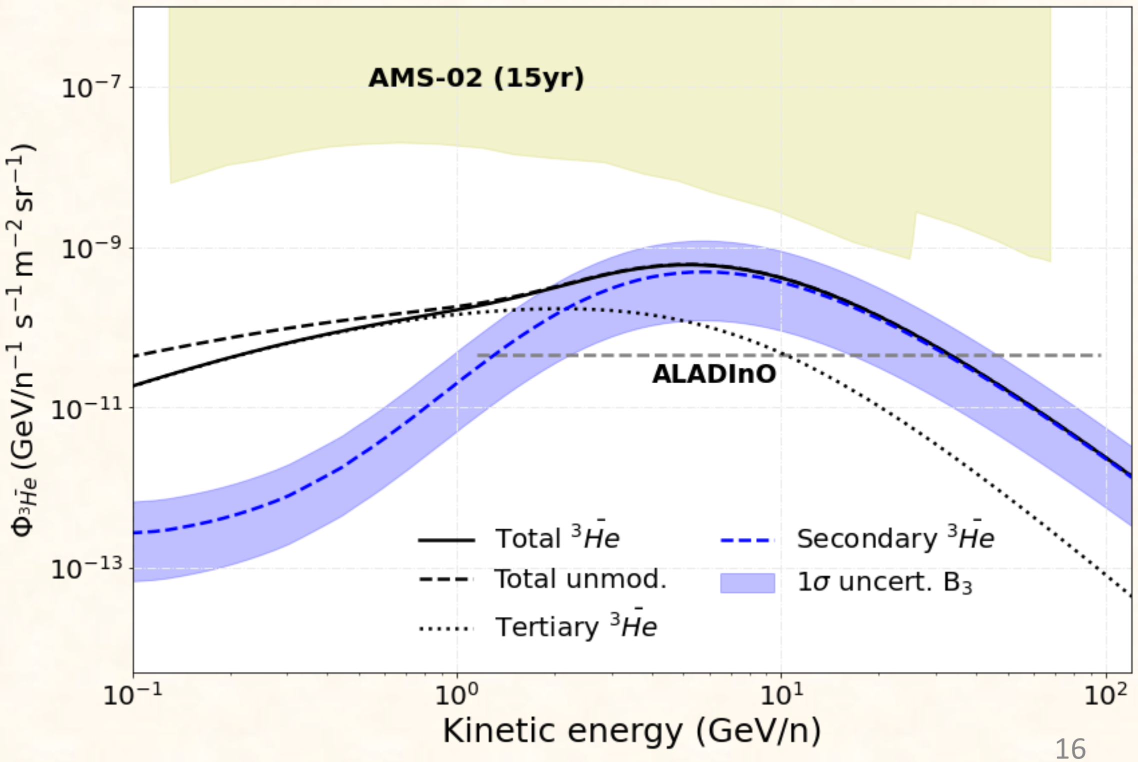


Can we explain the AMS-02 measurements without invoking any exotic source?

We expect to have measurements of the antideuteron flux in the next years!!
But no antihelium till future experiments: ALADInO or AMS-100 (foreseen to 2039)

PDL et al JCAP 10 (2024) 017

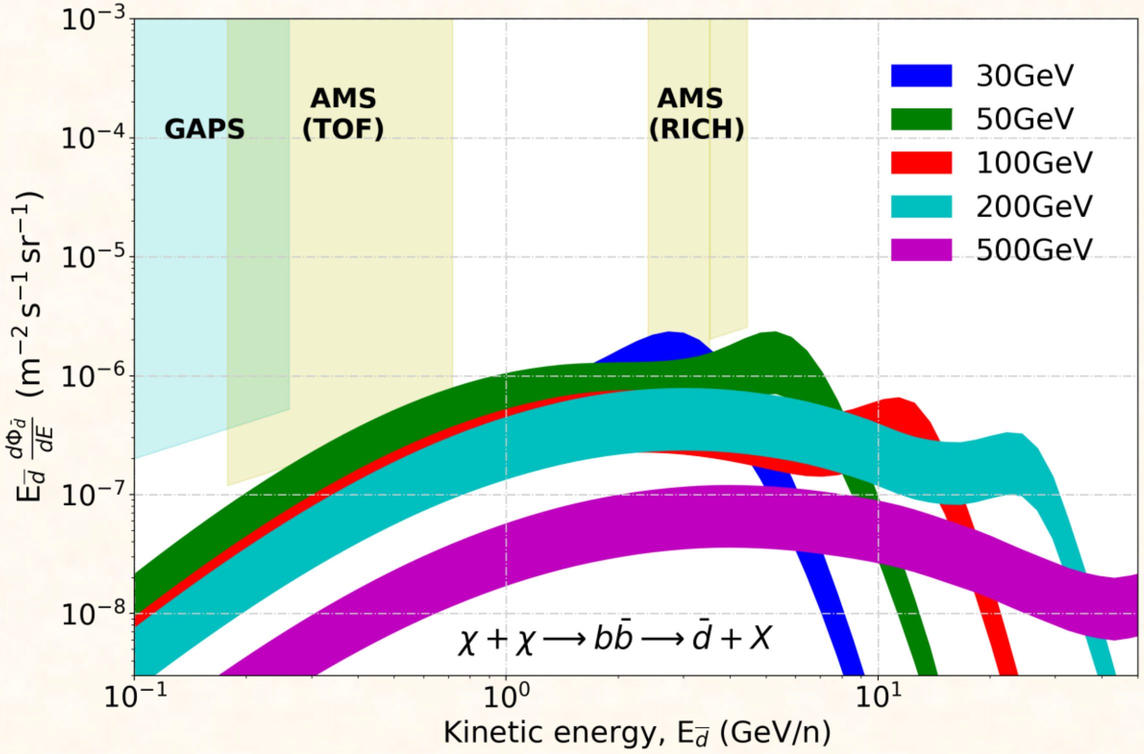


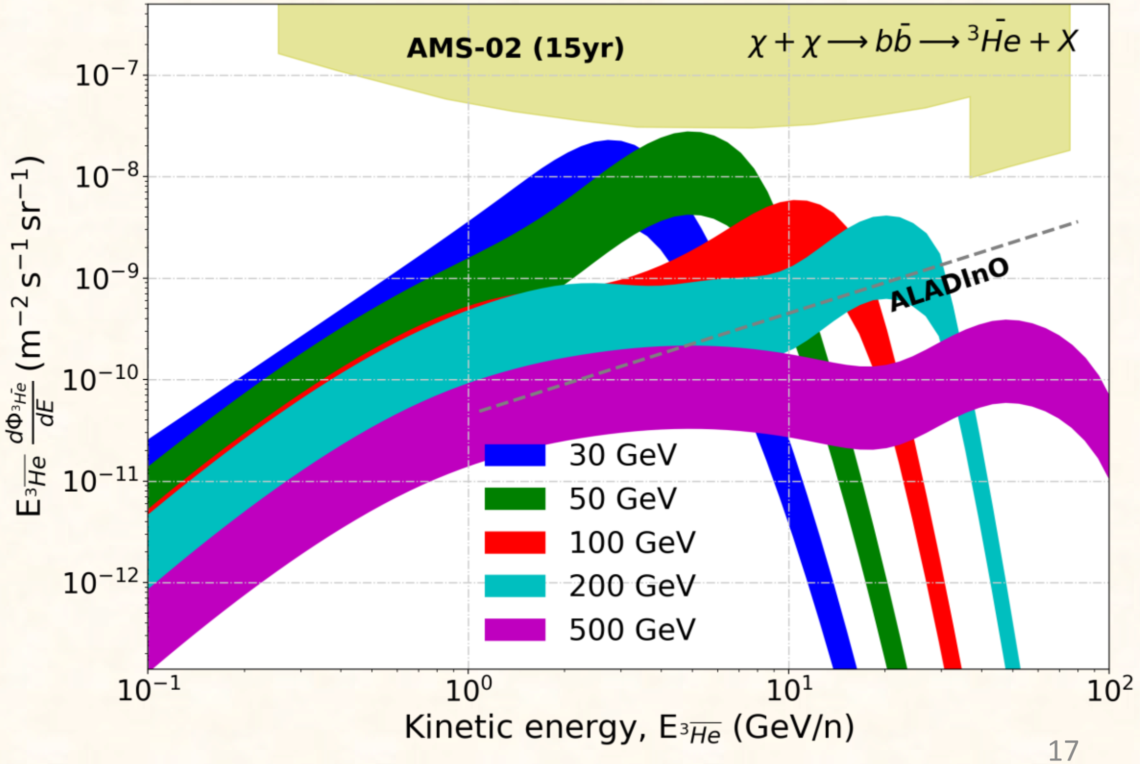


Dark matter production: Upper Limits

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

PDL et al JCAP 10 (2024) 017

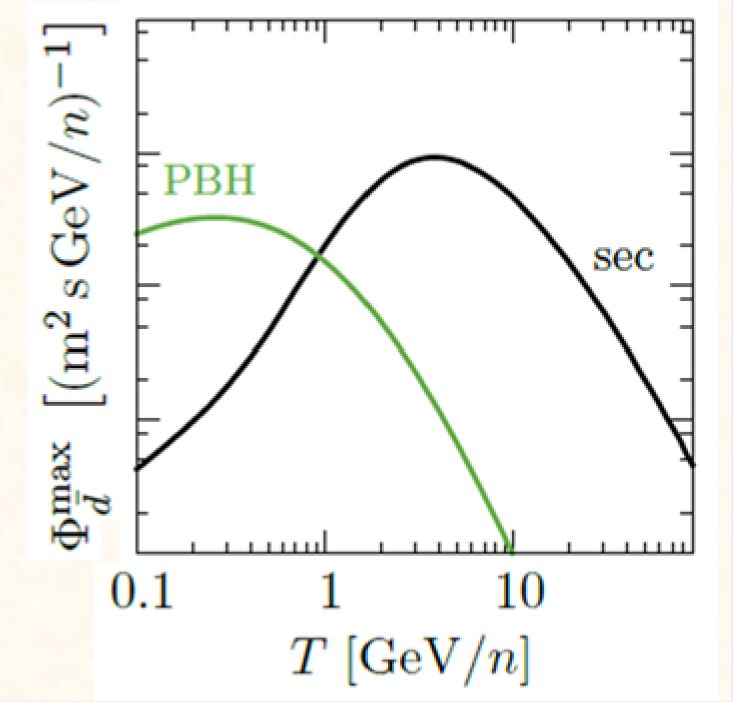


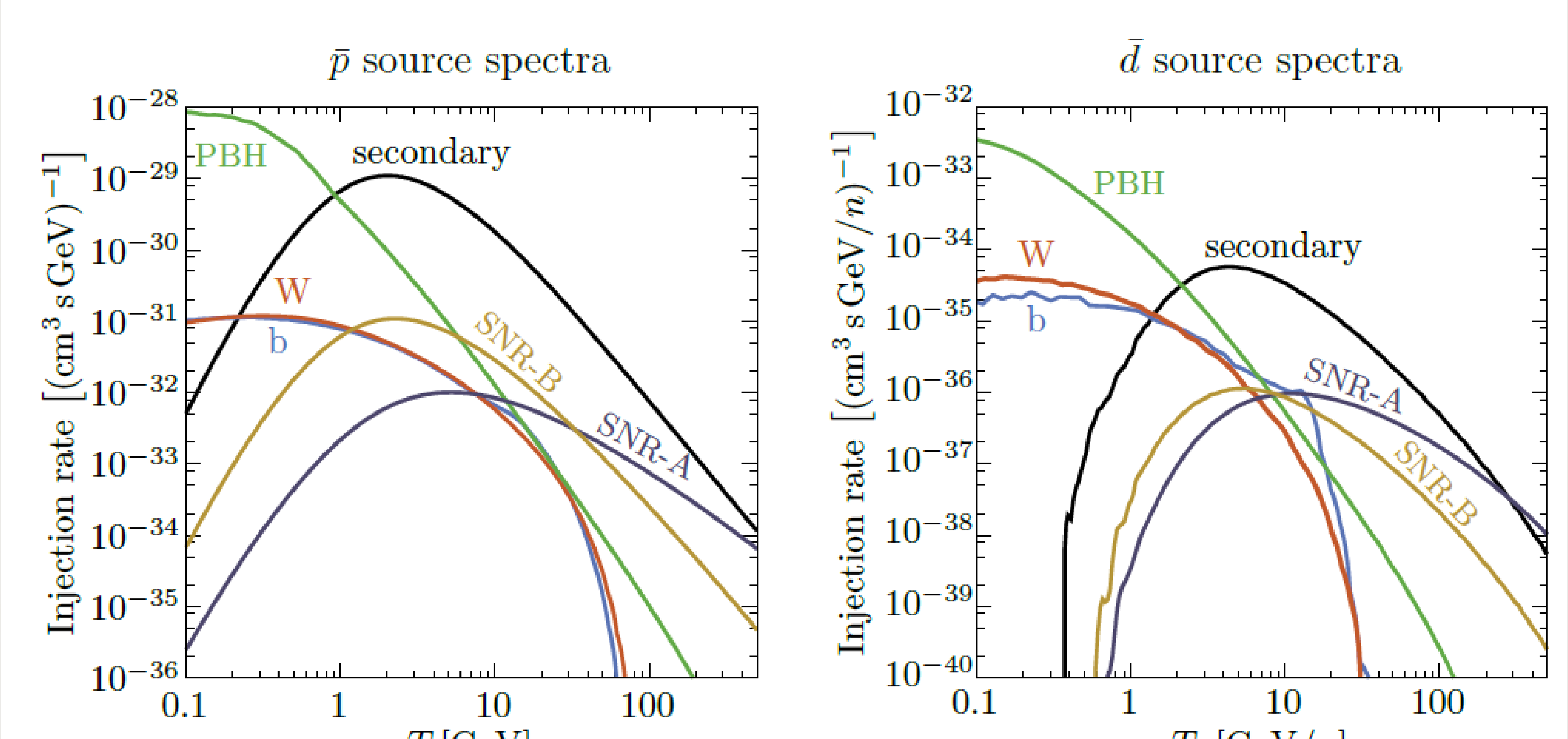


Light primordial black holes

Evaporation of light (asteroid-mass) PBHs could also produce antinuclei
Barrau et al. A&A 398, 403–410 (2003)

$$T = \frac{hc^3}{16\pi kGM} \approx \frac{10^{13}\mathrm{g}}{M}\,\mathrm{GeV}$$





Herms et al JCAP02(2017)018

PBH evaporation can produce large quantities of antinuclei, but also photons, electrons, …

Current limits make PBHs distributed as DM **unable to be observed**

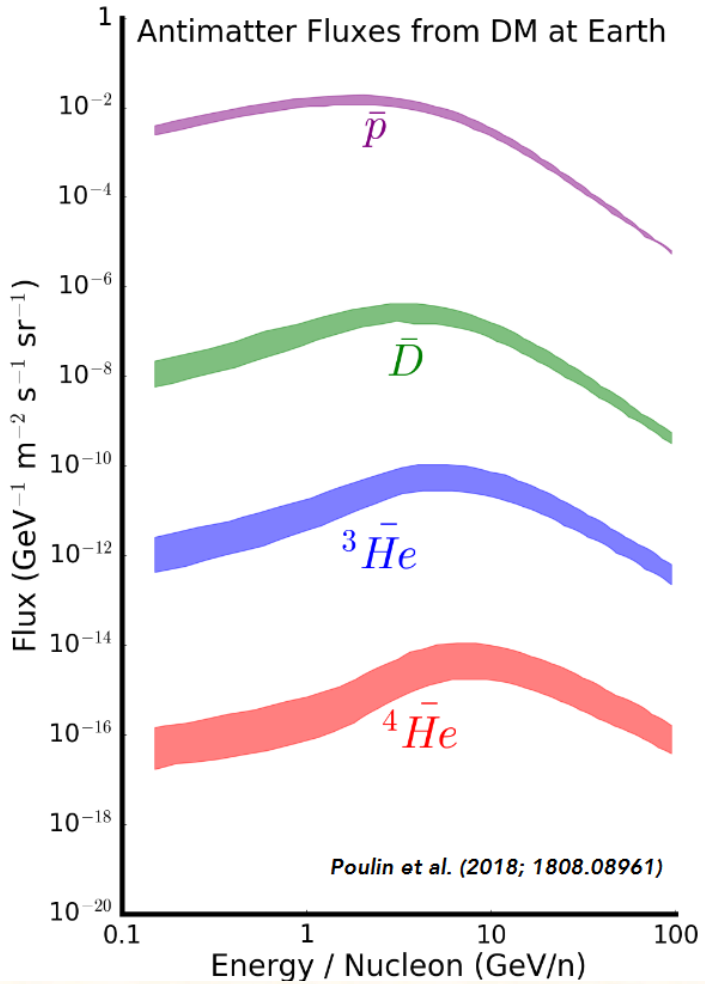
It also **needs too low PBH masses**

A few ways to boost the DM antihelium yield

Coalescence momentum is significantly larger that the one that we infer from current measurements?

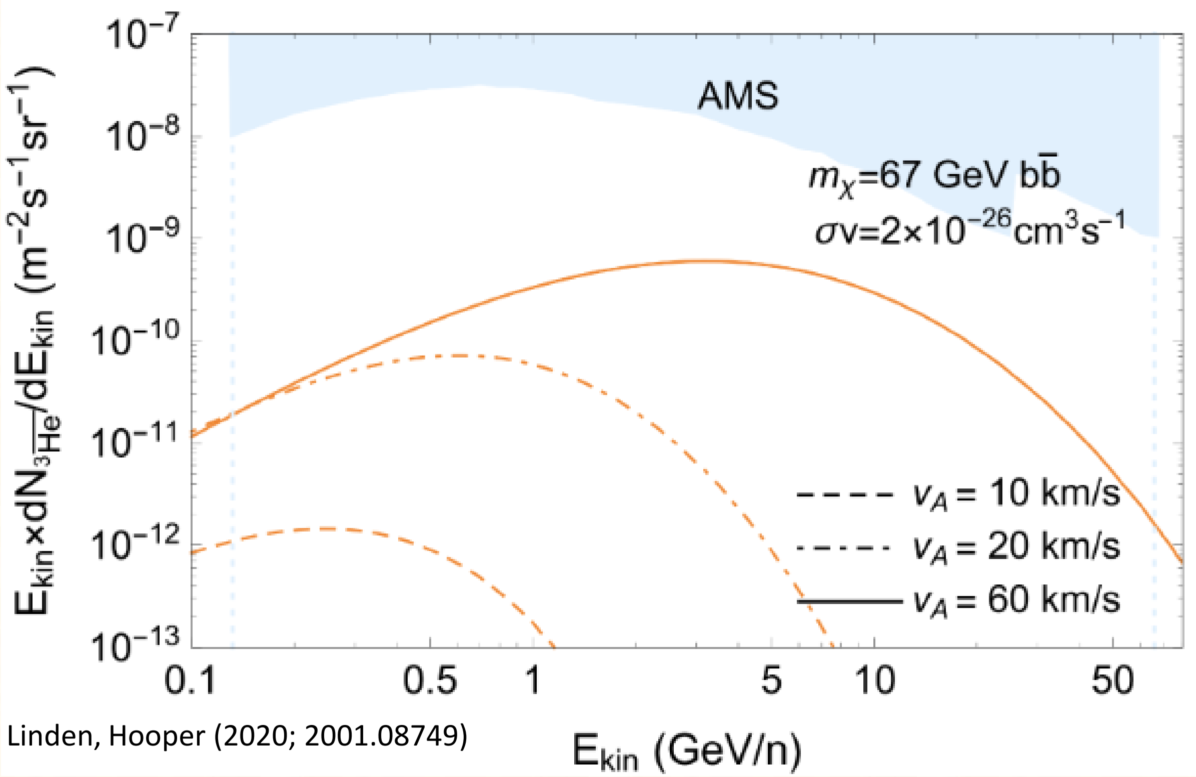
Given the scarcity of measurements, there have been different ways to compute the coalescence momentum

- Estimating the coalescence momentum from the deuteron-helium binding energies - Carlson et al. (2014; 1401.2461)
- Coalescence momentum dependent on energy - Diego Gomez et al. (2018; 1806.09303)
- Theory-based treatments, including particle correlations and size-dependent p_c - Kachelriess et al (2021; 2012.04352)

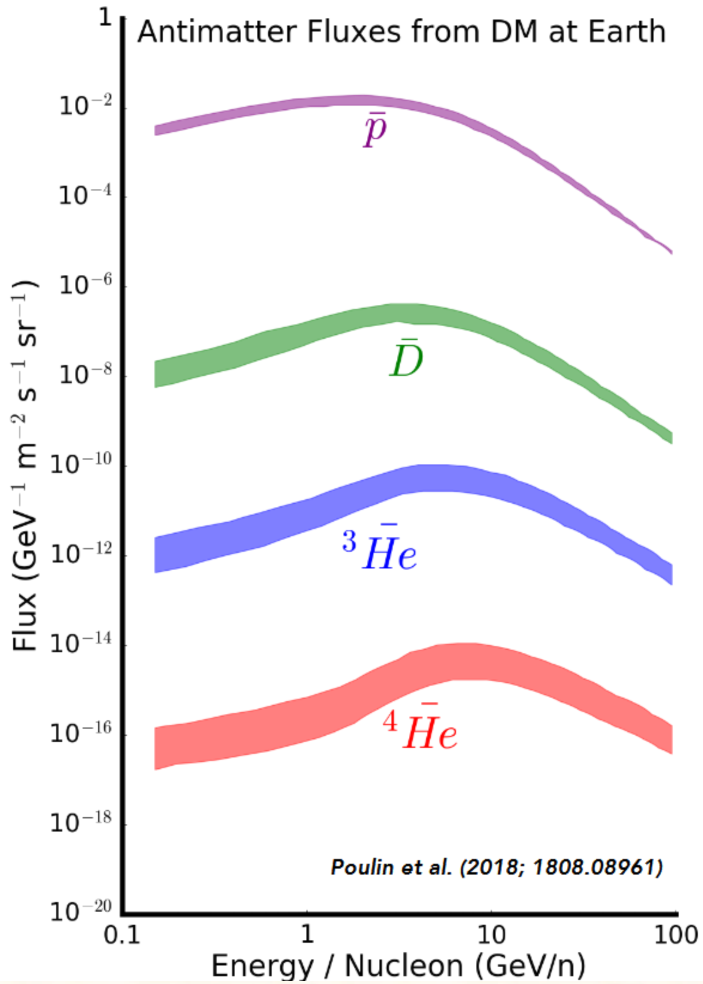


A few ways to boost the DM antihelium yield

Diffuse reacceleration boosts the signals? (with the plus of promoting low energy antinuclei to higher energies)

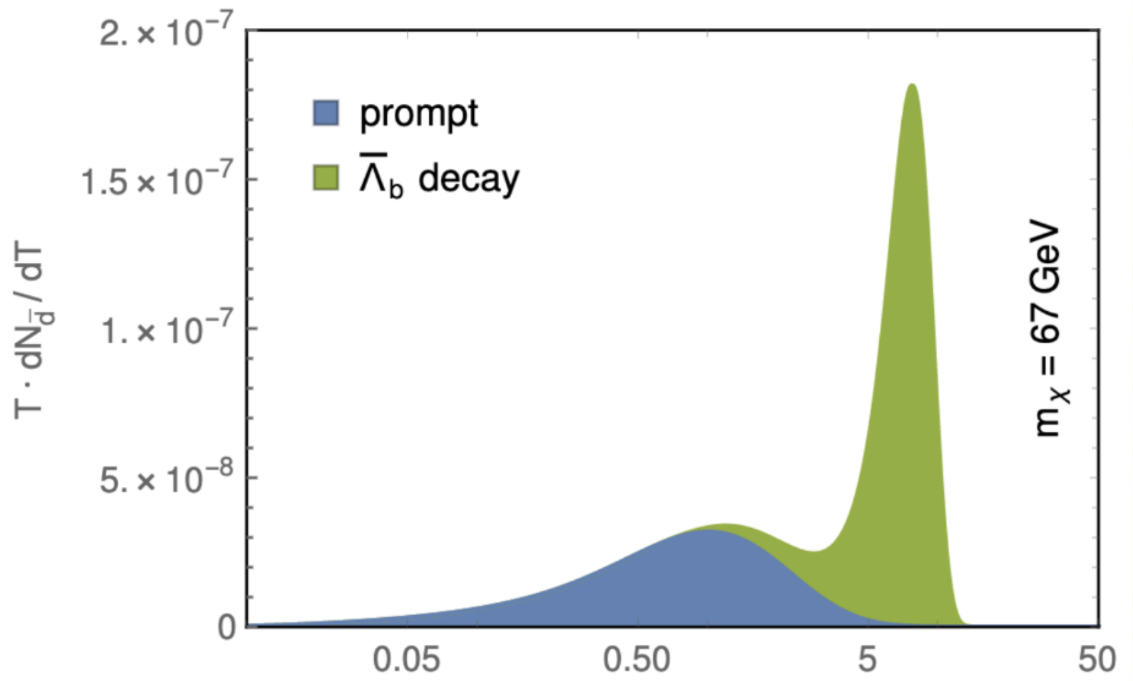


Cholis, Linden, Hooper (2020; 2001.08749)



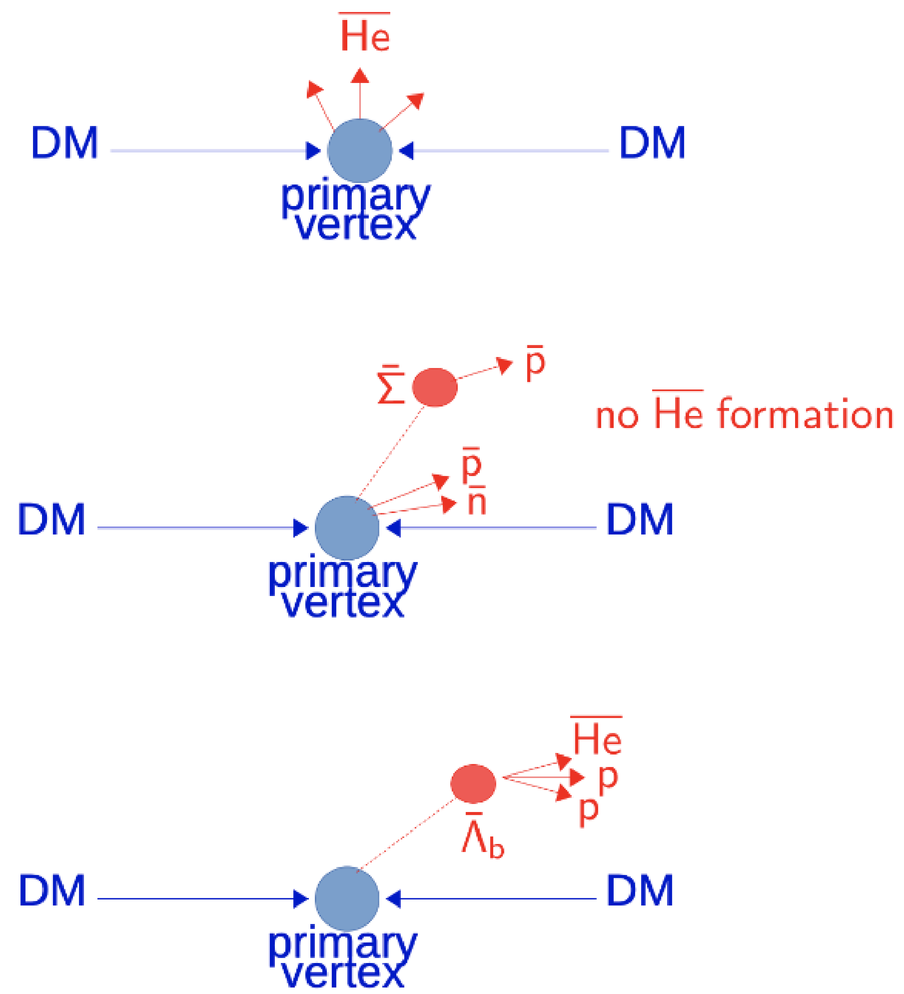
A few ways to boost the DM antihelium yield

Production of anti-lambda particles can be much higher than we thought? (not possible for $^4\overline{He}$!)



Winkler &Linden (2 020; 2020.16251)

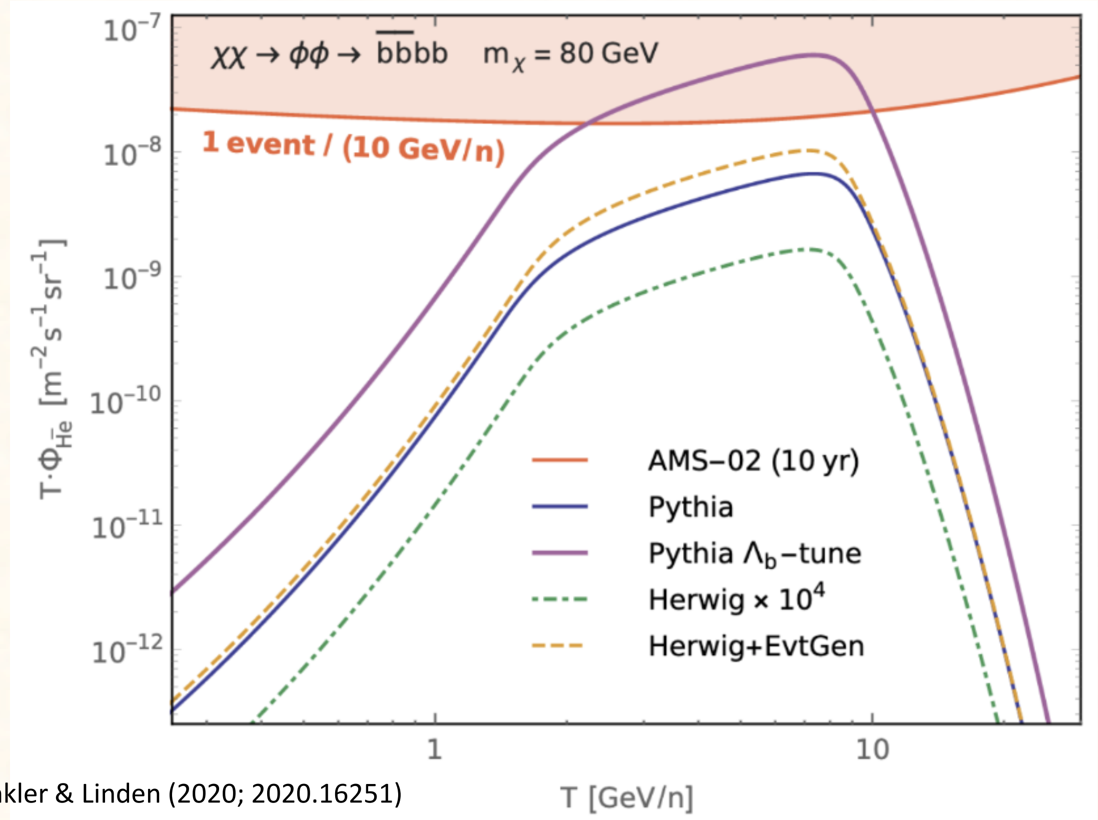
In tension with new LHCb measurements See ArXiv:2504.07172



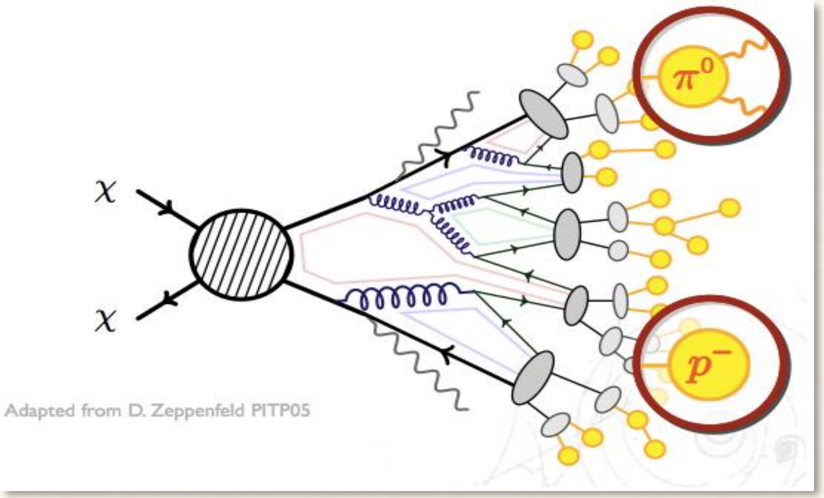
Credit: Martin Winkler

A few ways to boost the DM antihelium yield

Dark matter mediators can significantly boost the signal, depending on its mass



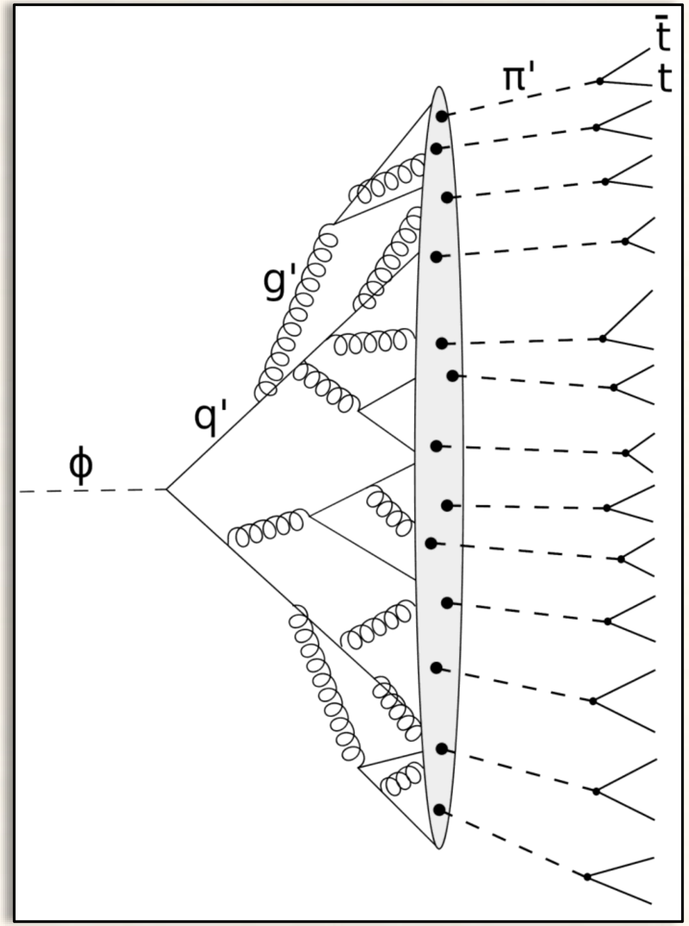
Winkler & Linden (2020; 2020.16251)



Playing with the decay channel and the mediators one can boost significantly the antihelium signal, enhancing more the $^4\overline{He}$ than $^3\overline{He}$. However, to reach the observed levels one needs something beyond WIMPs…

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

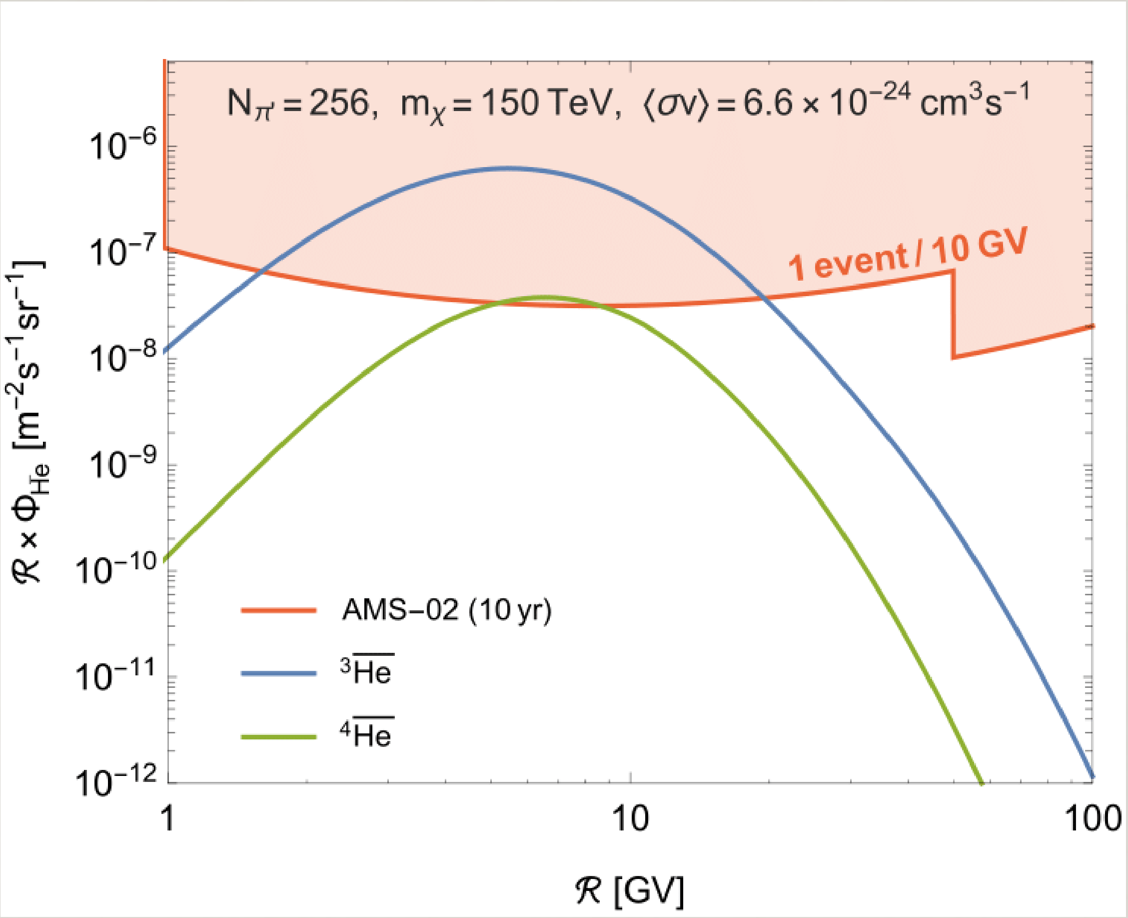
A **strongly coupled dark sector** can produce a “dark parton shower”, generating high multiplicity of “dark pions”. These would subsequently decay into SM quarks through, e.g., the Higgs or top portals, **triggering a hadronic shower.**

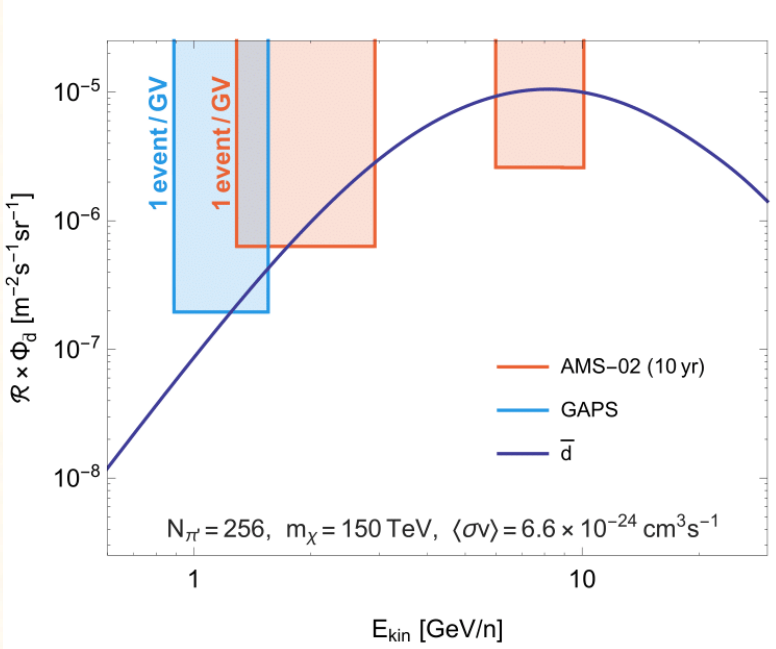
Simulated with Pythia as $\chi\chi \to \phi\phi \to 2\bar{q}'q' \to N_{\pi'}\,\pi' \to N_{\pi'}\,\bar{t}t$

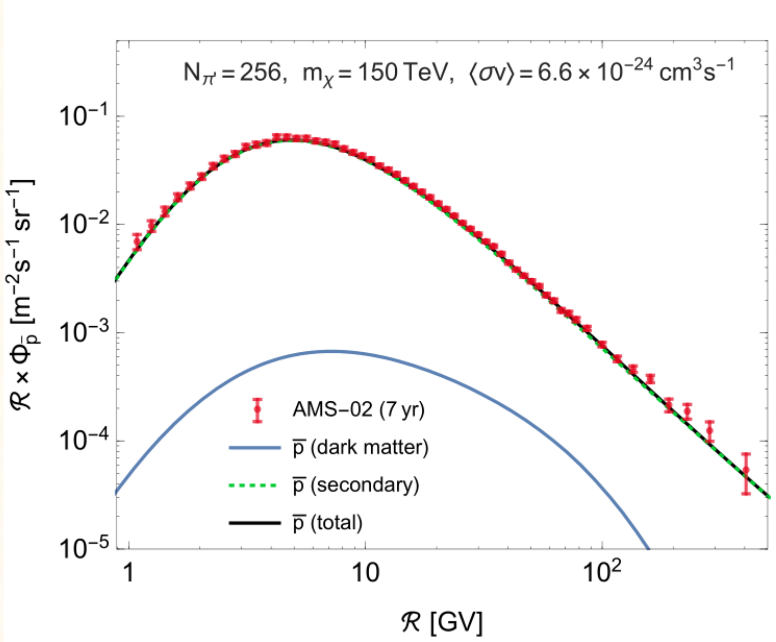
This could have escaped detection at LHC and it offers a pathway to look for excesses in the ditop channel

QCD-Like Dark sector

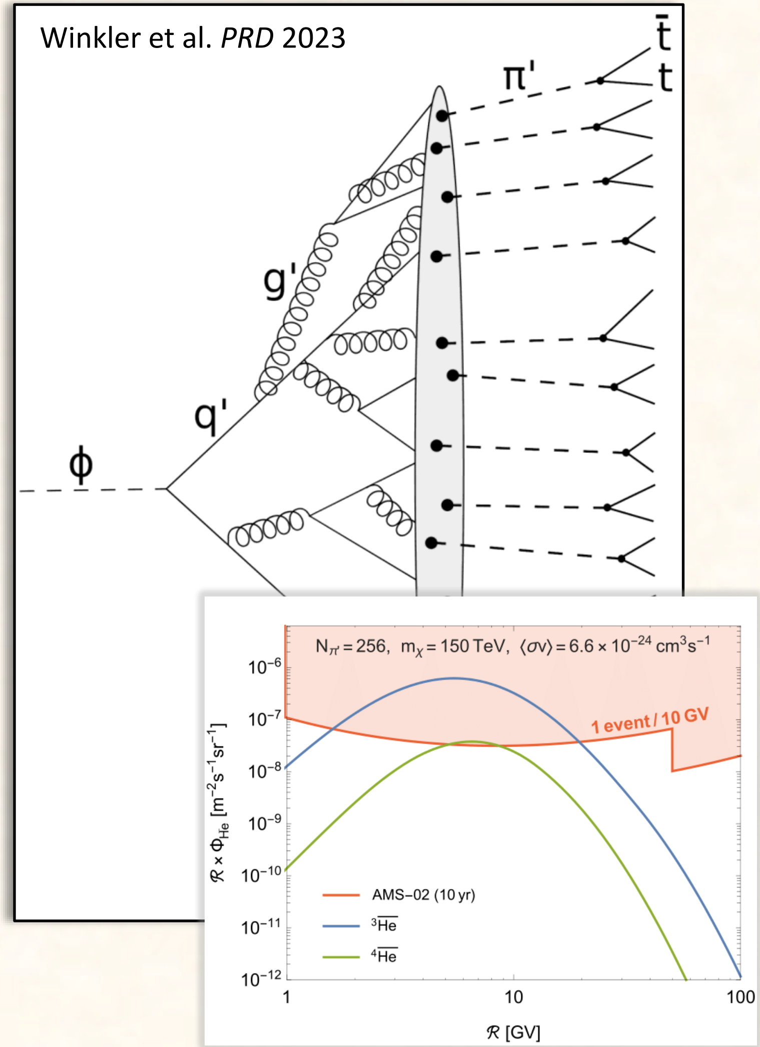
From factorized formula: $N_A \propto (N_p)^A$







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-stars (Poulin et al. *PRD* 99 (2019) 023016)

Stability and cosmological implications must be revised

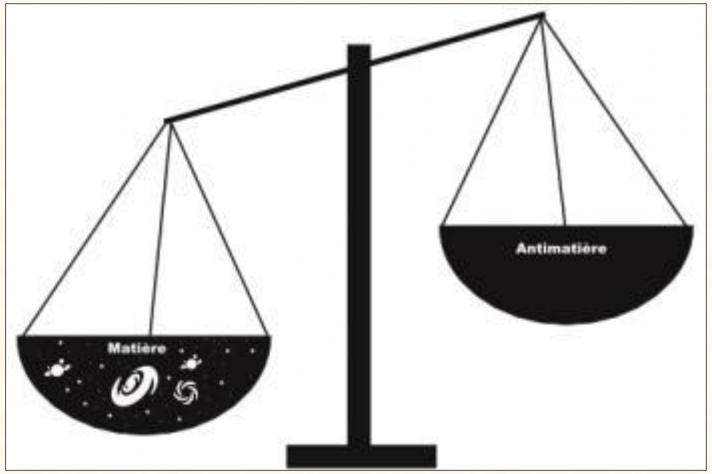
Fireball anti-nucleosynthesis (Fedderke et al. *PRD* 109 (2024) 12, 123028)

Fireballs must carry large net antibaryon number

QCD-Like Dark sector (Winkler, et al *PRD* 107 (2023) 12, 123035)

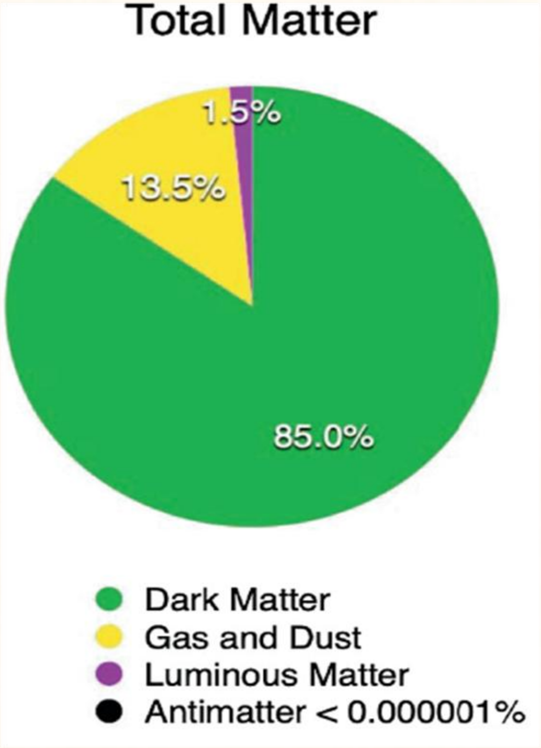
Can explain AMS-02 observations, but needs to be explored further

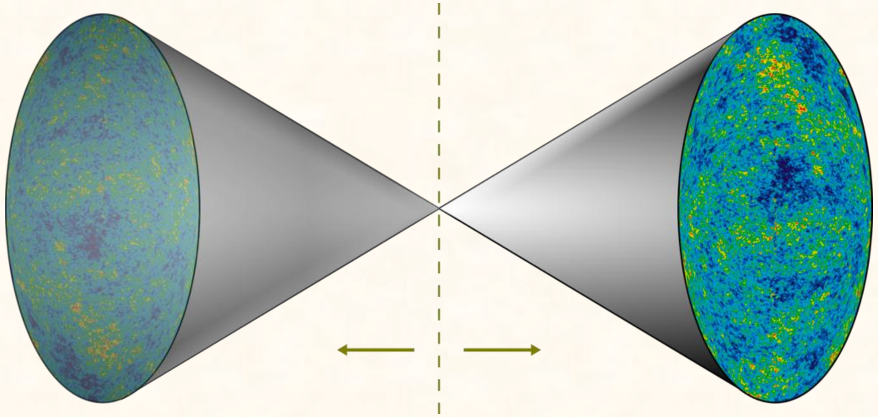
Matter-antimatter asymmetry



One of the most fundamental mysteries of modern physics is the asymmetry between the amount of matter and antimatter in the Universe.

"..We must regard it as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons.." **P. Dirac, Nobel Lecture 1933**





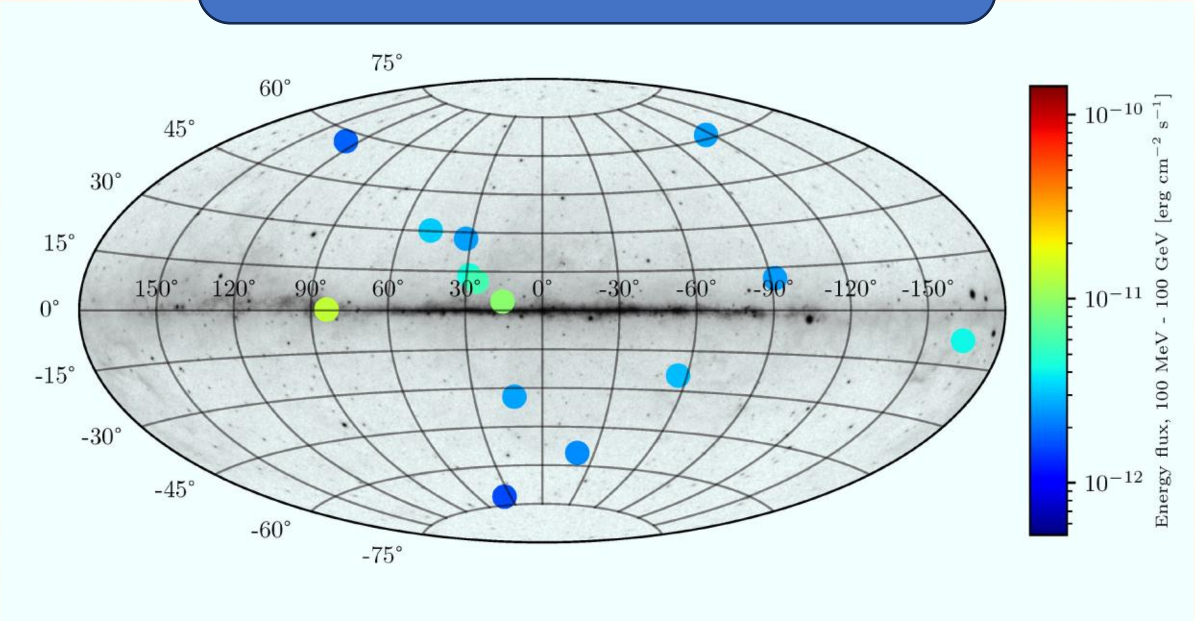
Matter-antimatter asymmetry

If these events come from anti-stars or similar systems, we could see them in gamma-rays…

This imposes limits on the amount of antistars systems. The authors of Poulin et al. *PRD* 99 (2019) 023016 show that within these limits, **there can be enough anti-stars to explain the observed total amount of antihelium events**

However, there are many open questions:
- How are these systems stable?
- How do they evolve to supernova?
- How can these systems explain the antihelium isotope ratios?

Map of possible anti-stars systems from gamma-ray observations



Dupourqué et al. *PRD* 103, 083016 2021

Conclusions

- **Antinuclei** are a very promising channel to study **signals from dark matter** and constrain our current **WIMP** models – **At reach in the next decade!**
- **The production of anti-deuteron from cosmic rays is already detectable by AMS-02** (And compatible with preliminary observations!)
- Exciting preliminary detection of anti-helium seems to challenge our models… WIMP production seems insufficient… **need of invoking exotic scenarios**
- A few possible (although speculative) explanations can be viable solutions and testable in accelerators – Although both the measurements and the models employed need to be refined

Pedro de la Torre Luque – 28/5/2025
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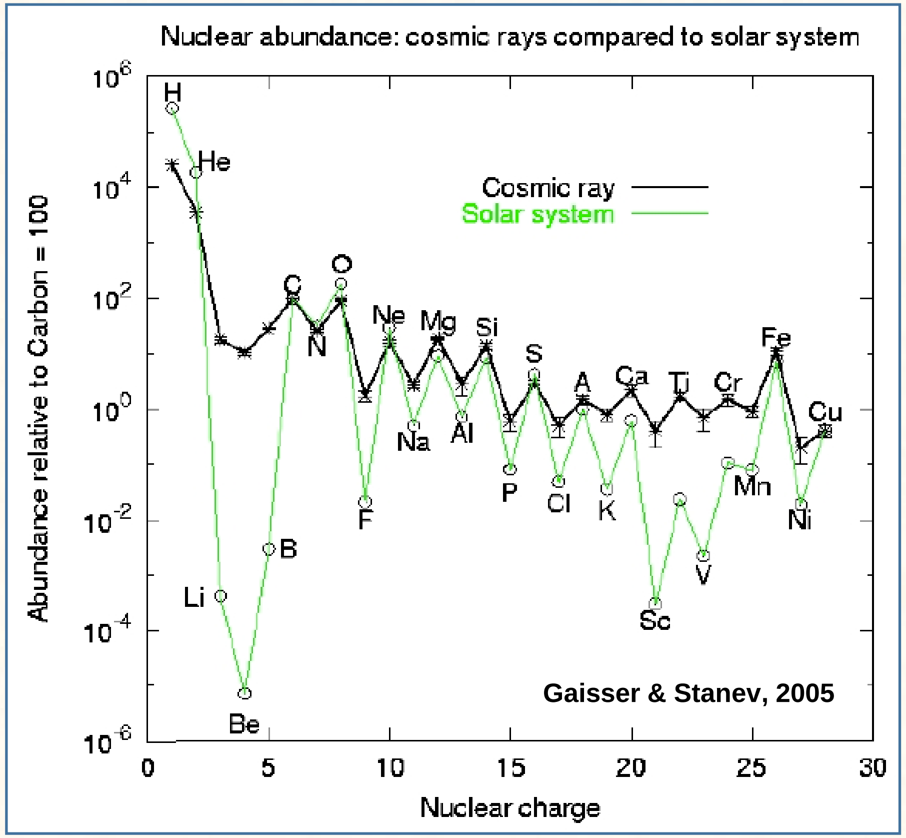
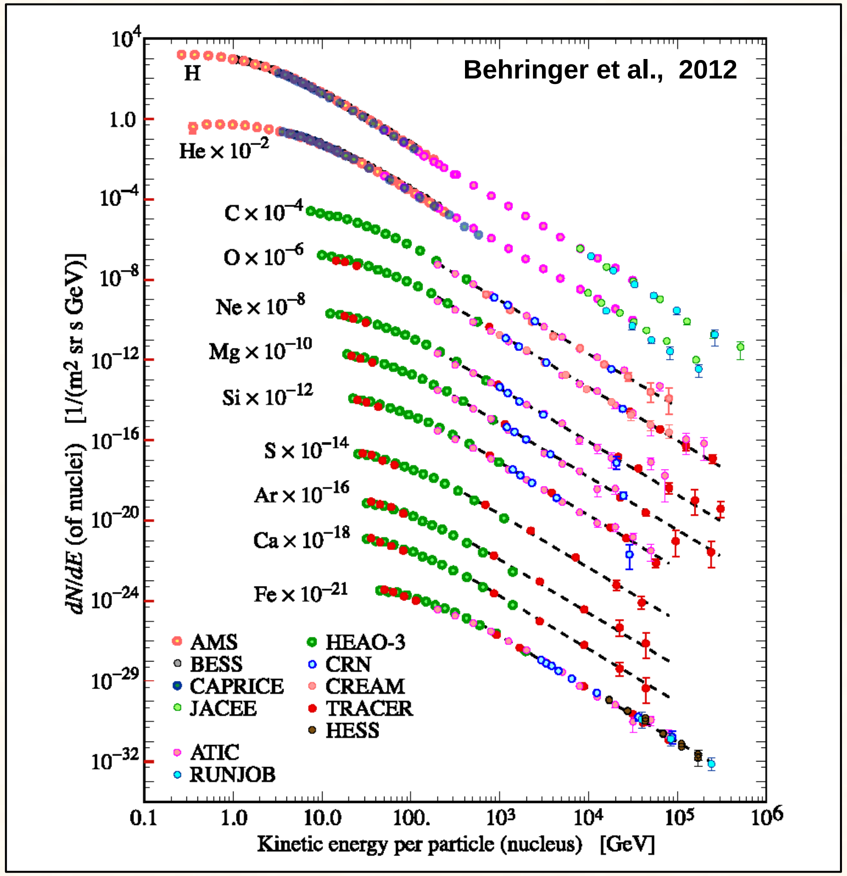
BACK UP

Cosmic rays: *Highly energetic charged particles constituting a steady, isotropic (to the Earth perspective) flow coming from the outer space*

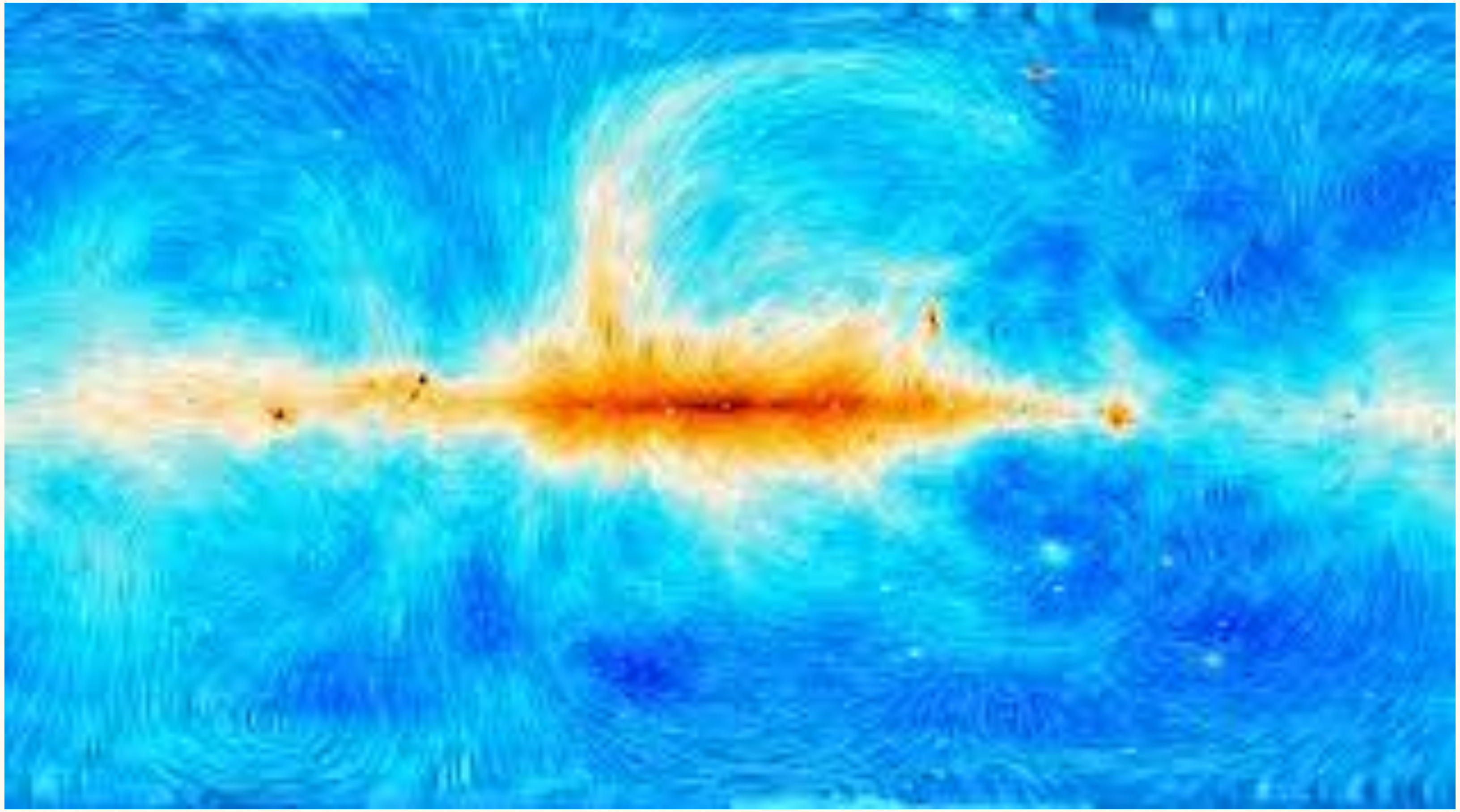
Unexpected abundance of secondary nuclei

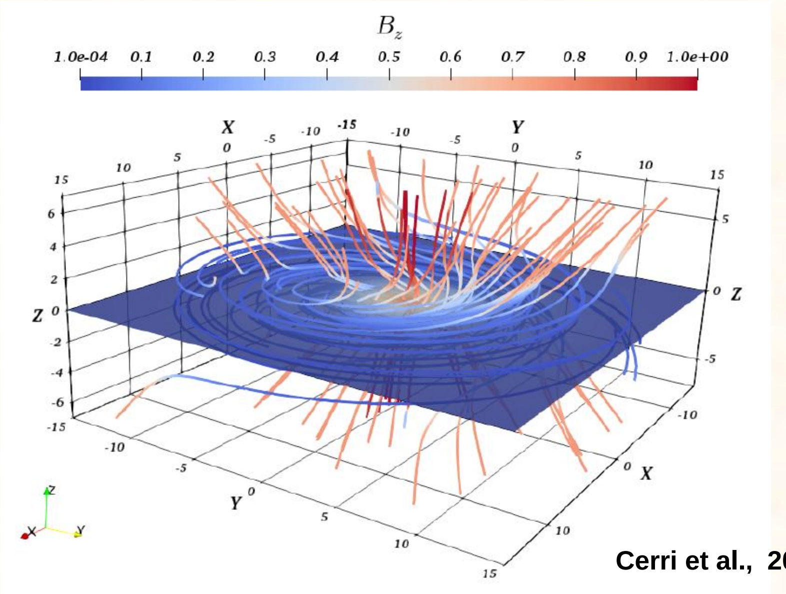


All cosmic rays seem to follow same power law behaviour: $J \propto E^{-\gamma}$; $\gamma \sim 2.7$

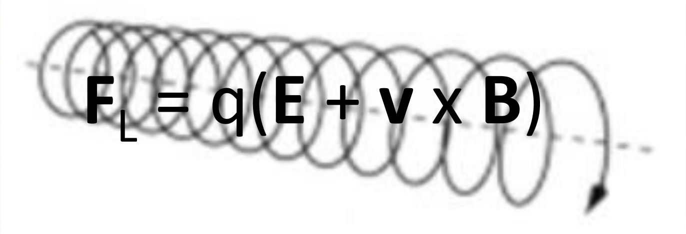


The **Milky Way** *is a magnetised plasma medium following the Magnetohydrodynamic equations*





Cerri et al., 2017



$$\mathbf{F}_L = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

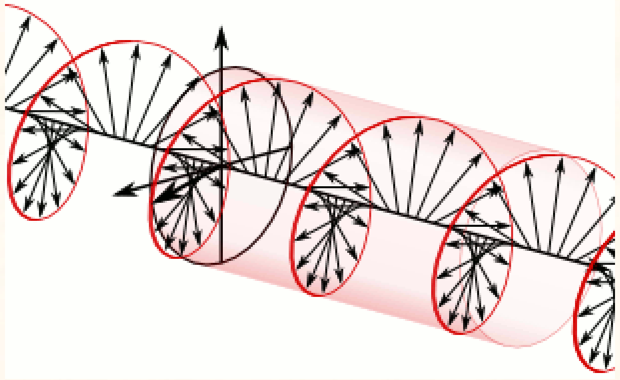
The **Milky Way** *is a magnetised plasma medium following the Magnetohydrodynamic equations*

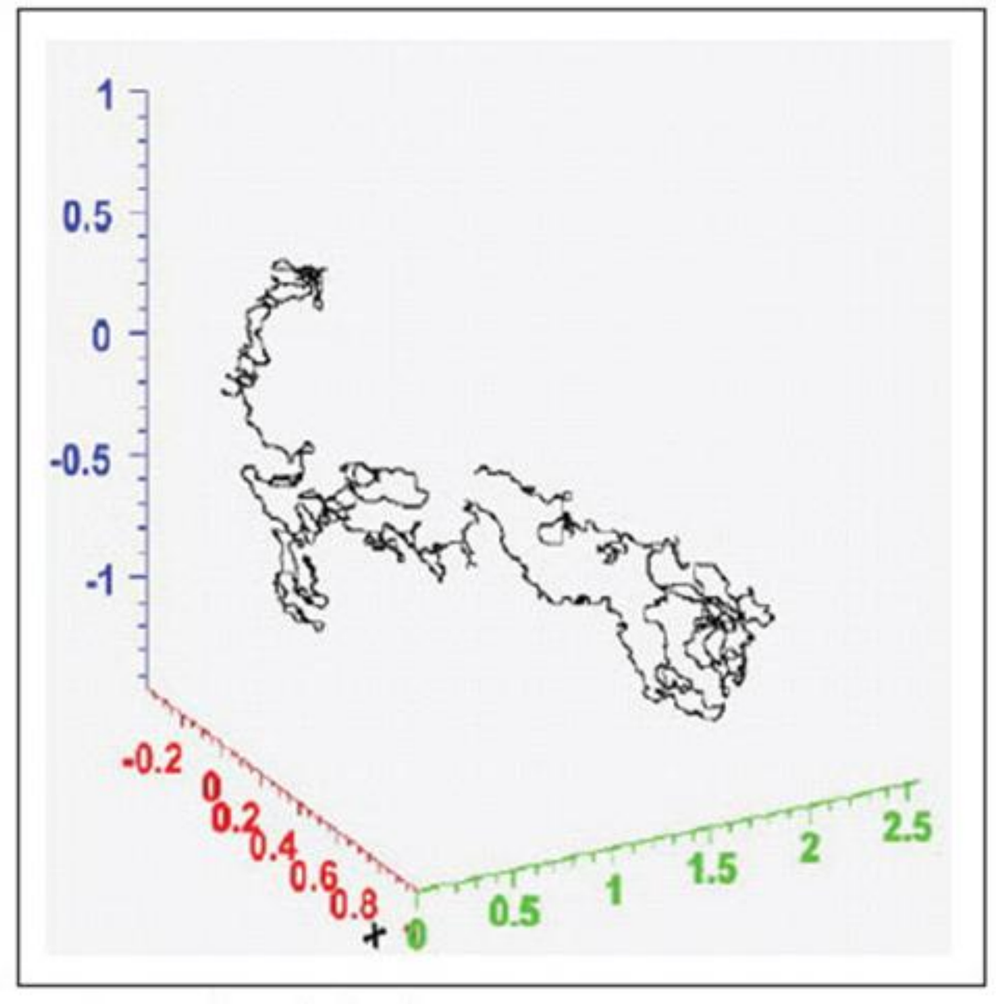
$$\mathbf{B = B_0 + \delta B \rightarrow \langle B \rangle = B_0}$$

$$\mathbf{E = 0 + \delta E \rightarrow \langle E \rangle = 0}$$

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

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

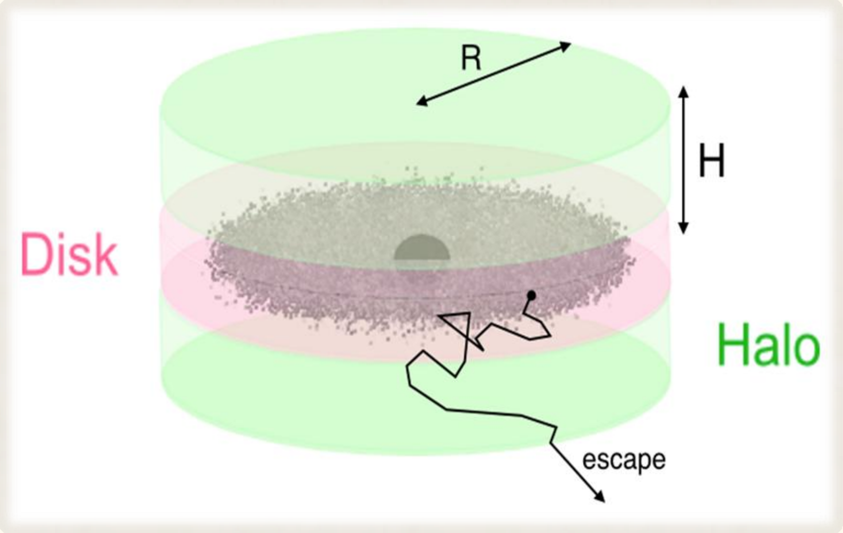




Antiprotons and propagation

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

Secondary-to-primary ratios (e.g. B/C) are key to evaluate the propagation parameters



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

$$Q = \frac{\partial N}{\partial E}q(x,y,z)$$

$$\Gamma \propto N_{pr}\, n_{gas}\, \sigma_{pr\to Ap}$$

$$N_{pr} \propto Q_{pr}(E)/D(E)$$

$$N_{sec} \propto Q_{sec}(E)/D(E)$$

$$Q_{sec} = \Gamma \propto N_{pr}(E)\,\sigma(E)$$

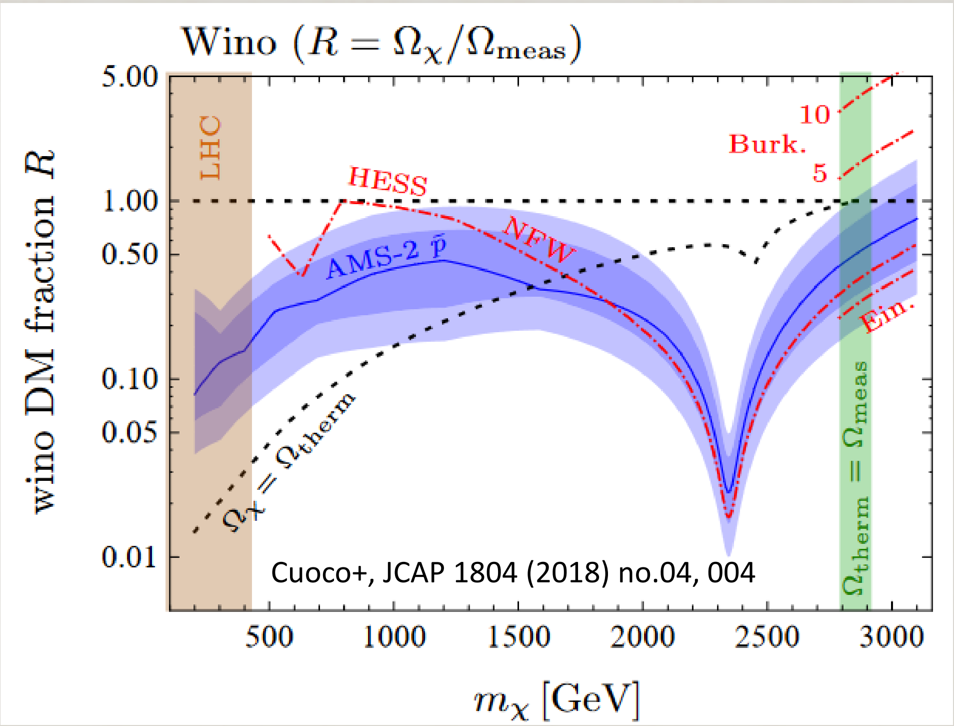
$$\frac{N_{sec}}{N_{pr}} = \frac{Q_{sec}}{Q_{pr}} \sim \sigma(E)/D(E)$$

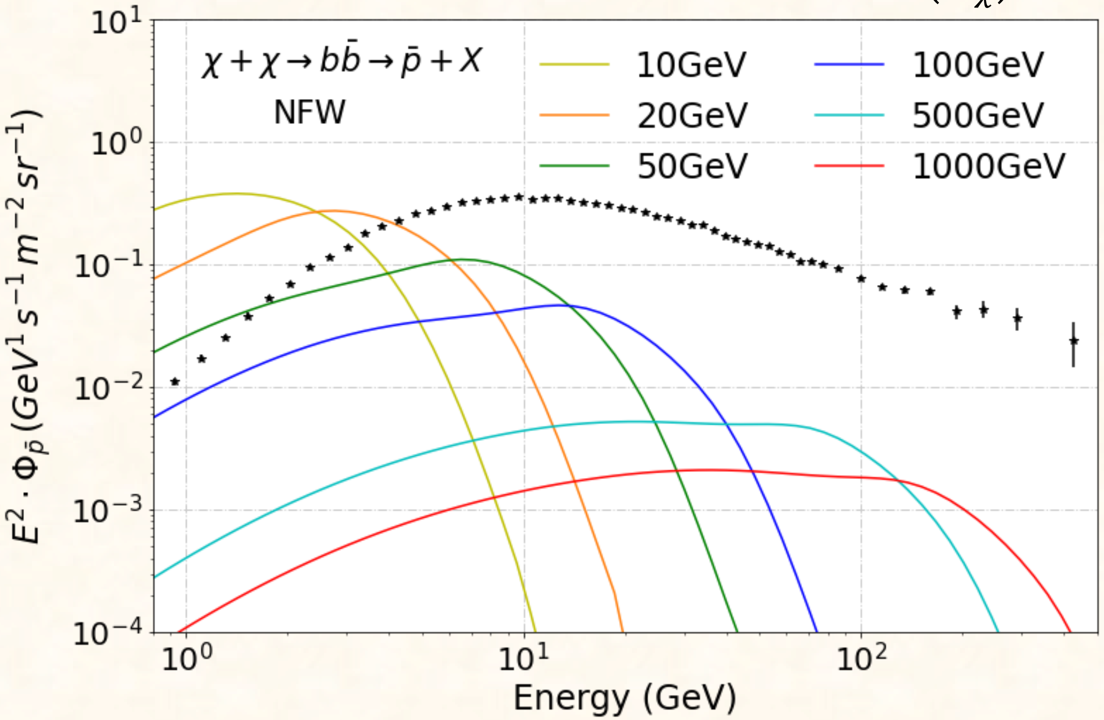
A precise estimation of the antiproton flux requires a careful analysis of several CR species and nuclear cross sections

DM production - primary antiprotons

Indirect DM searches with antiprotons (similarly to what happens with other astroparticles) are either intended for specific particle models (wino, Higgsino, etc) or for a generic WIMP that is modelled as a neutral-colorless resonance that couples to the SM through specific channels (bb, tt, ττ, etc)

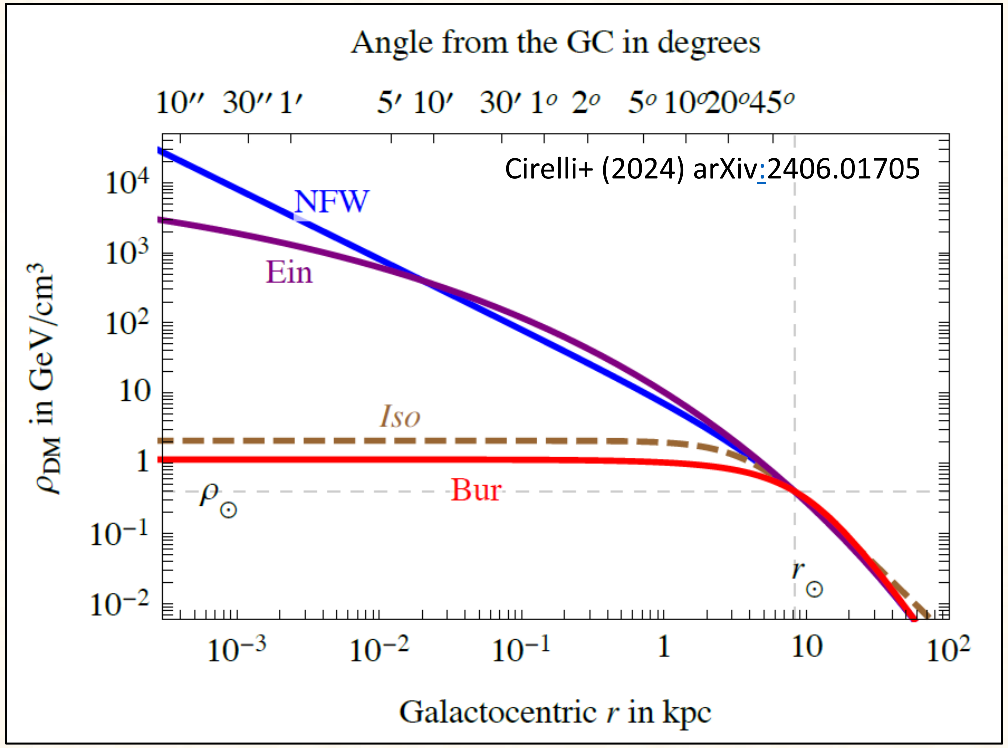
Intensity of the signal $\propto < \sigma v > \left(\frac{\rho_\chi}{m_\chi}\right)^2$

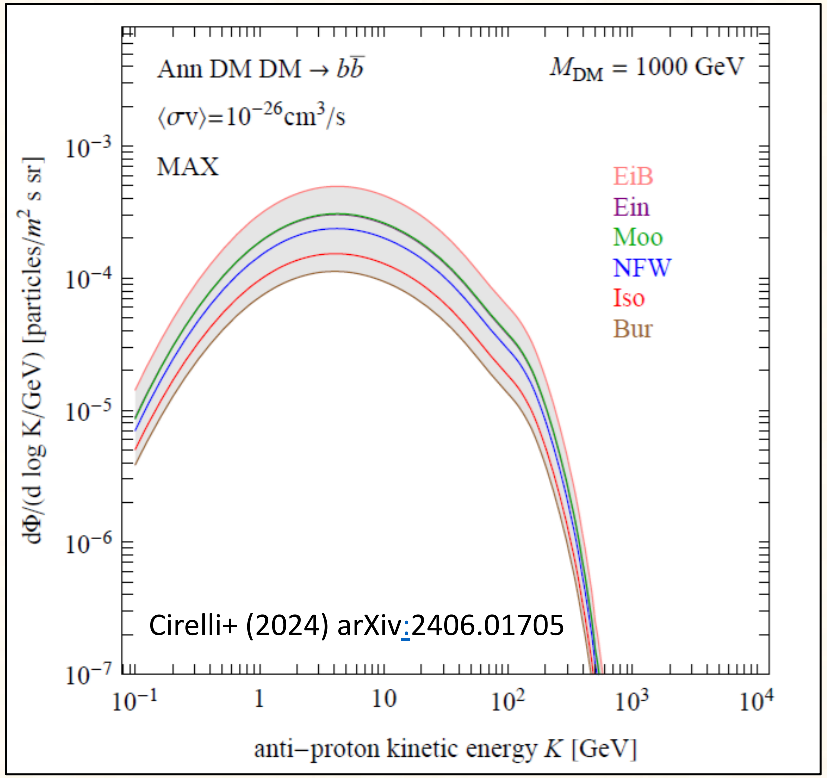




DM production - primary antiprotons

The uncertainty in the galactic DM distribution affects the predicted fluxes, roughly independently of energy. The difference between the flux for a cored and a peaked profile is ~ factor of a few for annihilating DM, and much smaller for decaying DM.





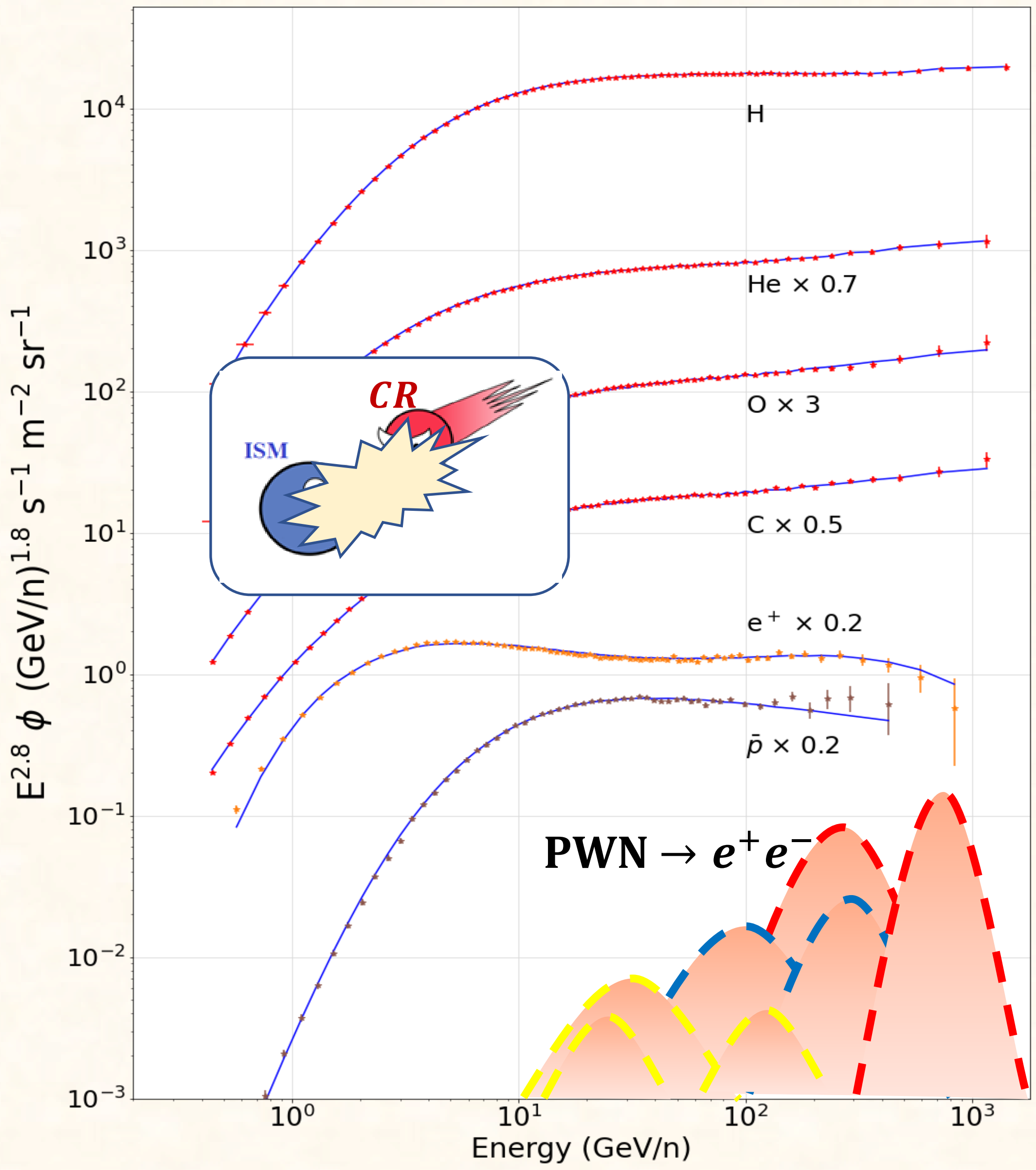
Current situation and the importance of CR positrons

High precision data for the fluxes of CR nuclei allow us to accurately model the production of CR antiparticles and uncertainties related.

The positron spectrum allows us to strongly constrain the existence of BSM physics and provides crucial information about the astrophysical environment.

Known sources of positron production are CR interactions with interstellar gas and PWNe. Other exotic and non exotic sources may also contribute.

Flux of CR nuclei and antiparticles (data from AMS-02)



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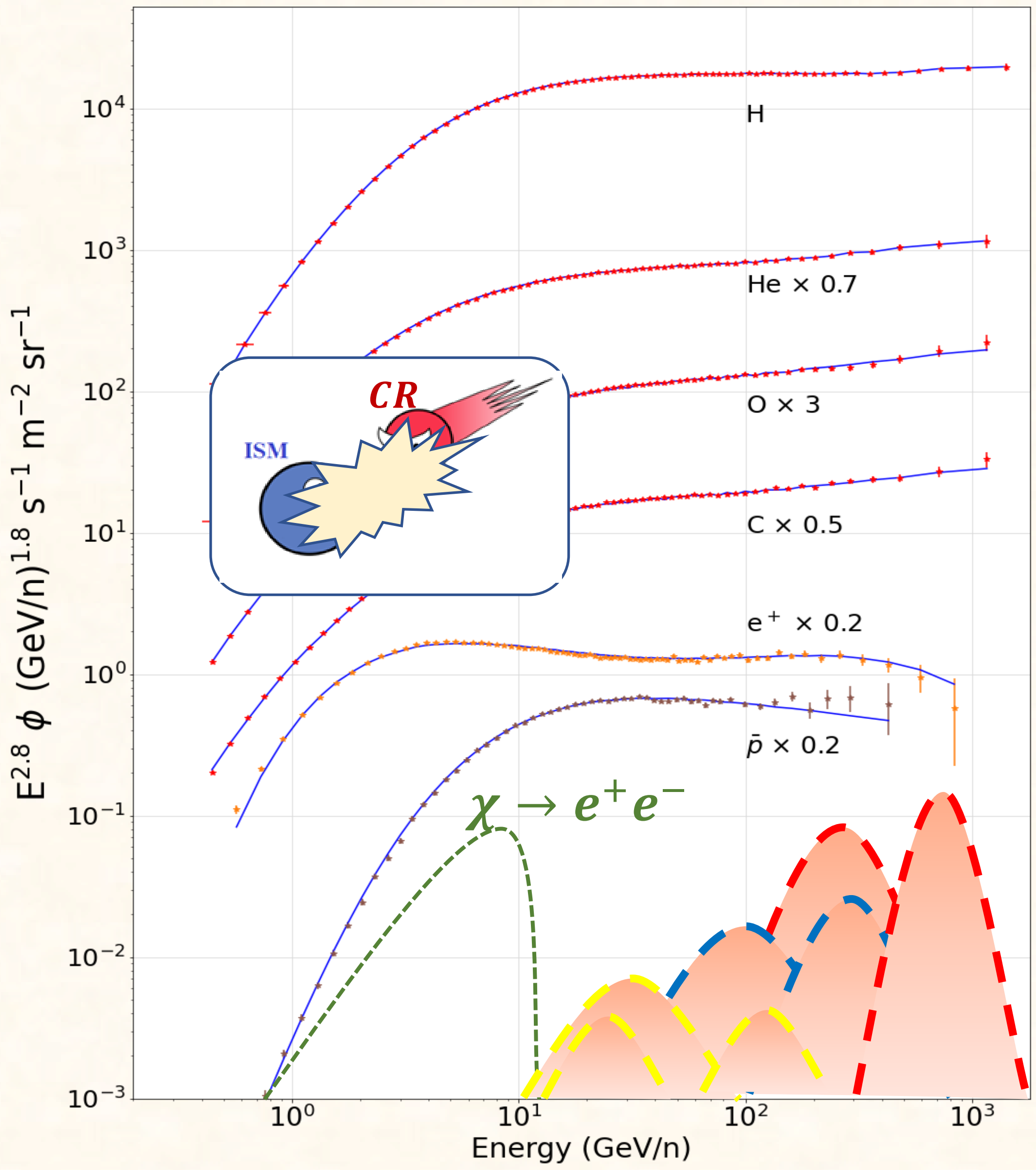
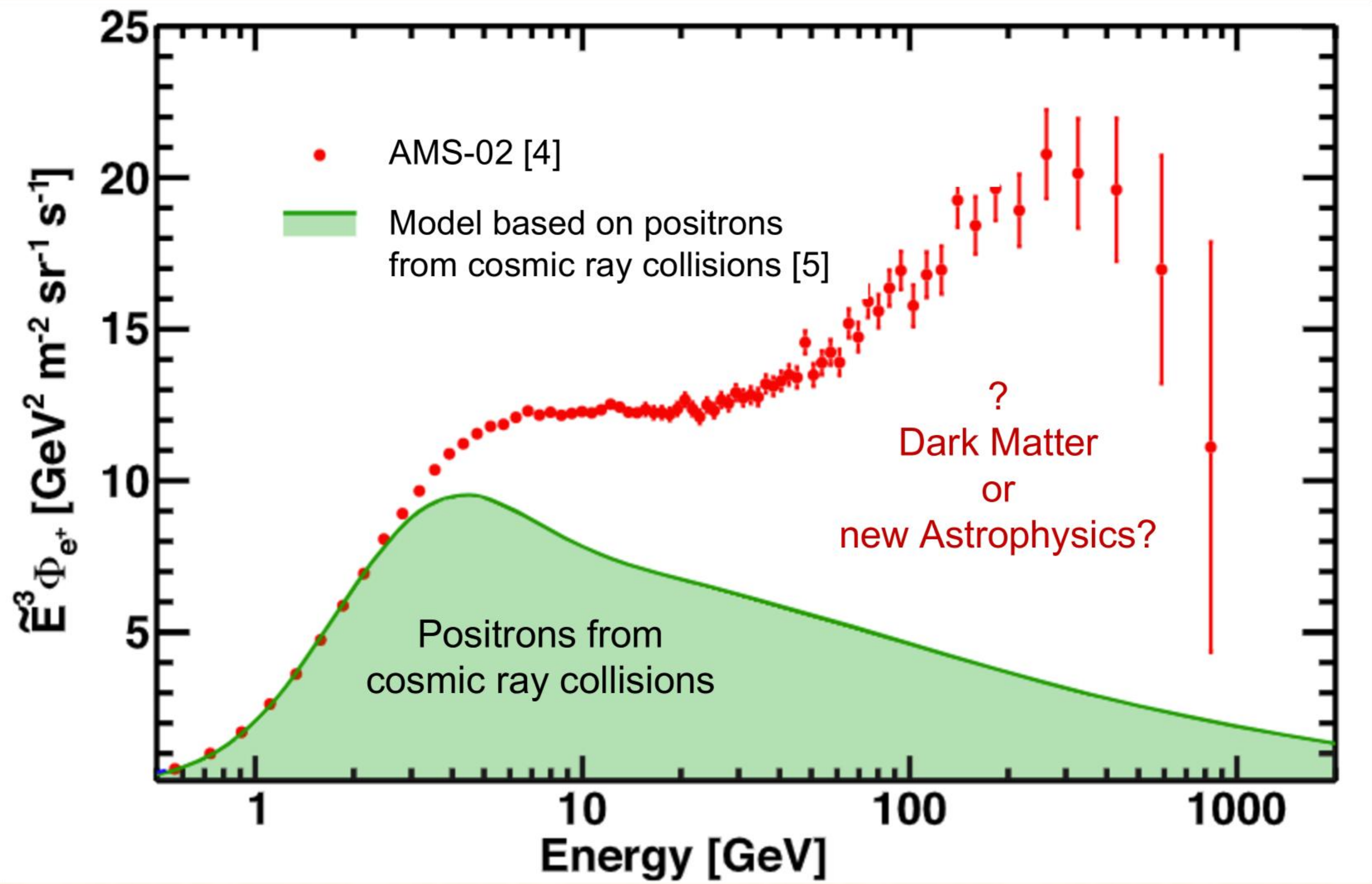


Looking for anomalies in CR positrons

Credit: AMS-02 Collaboration



Interestingly, **cosmic rays are not expected to create the observed amount of high energy positrons!**

Soon, we found evidence that high-energy positrons are copiously created at high energies in neutron stars (pulsars): A new source of positrons

The positron spectrum is compatible with the sum of the contribution from cosmic rays and pulsars

Identifying dark matter with positrons becomes a difficult task due to the high foregrounds!

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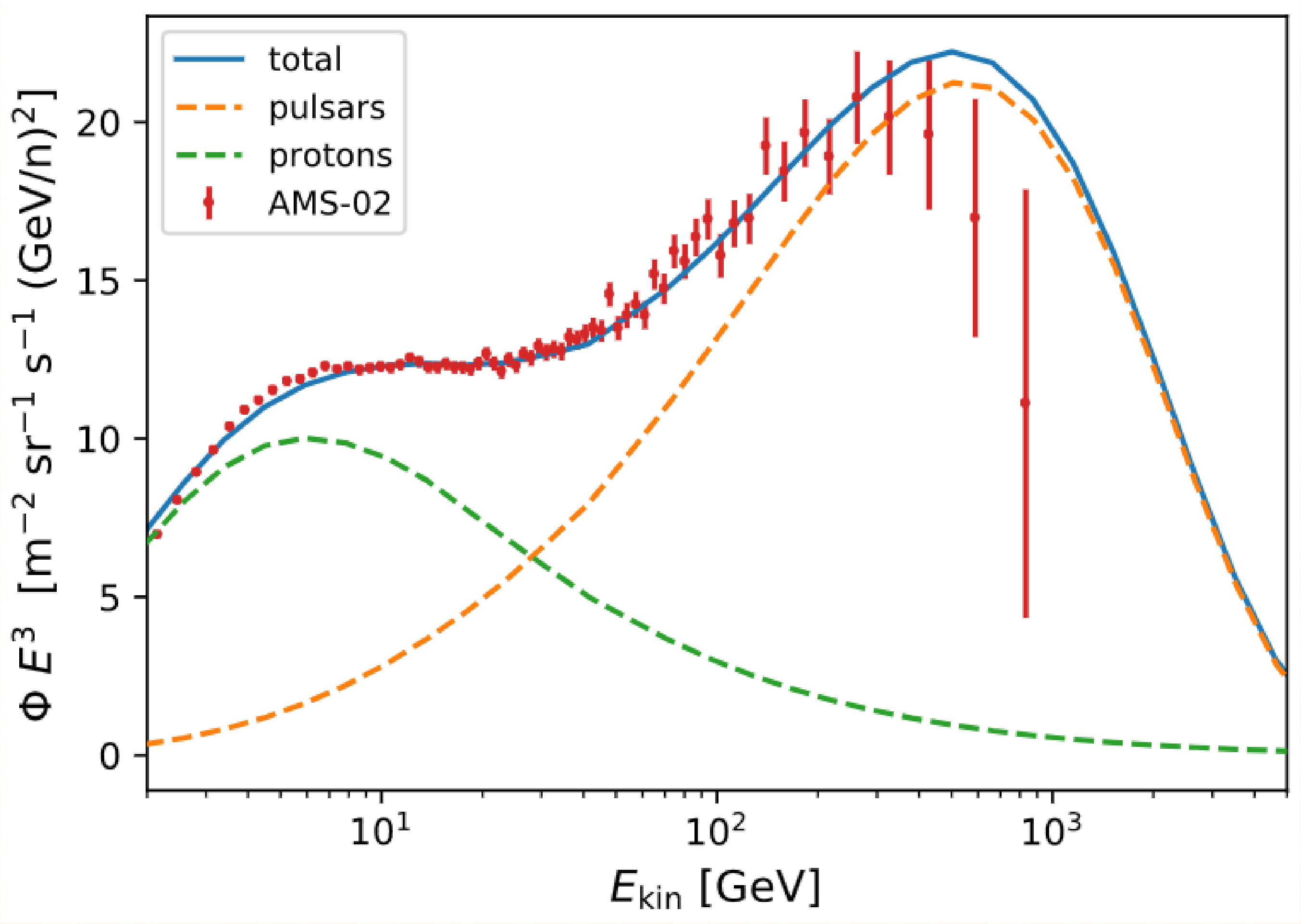
Credit: Isabelle John



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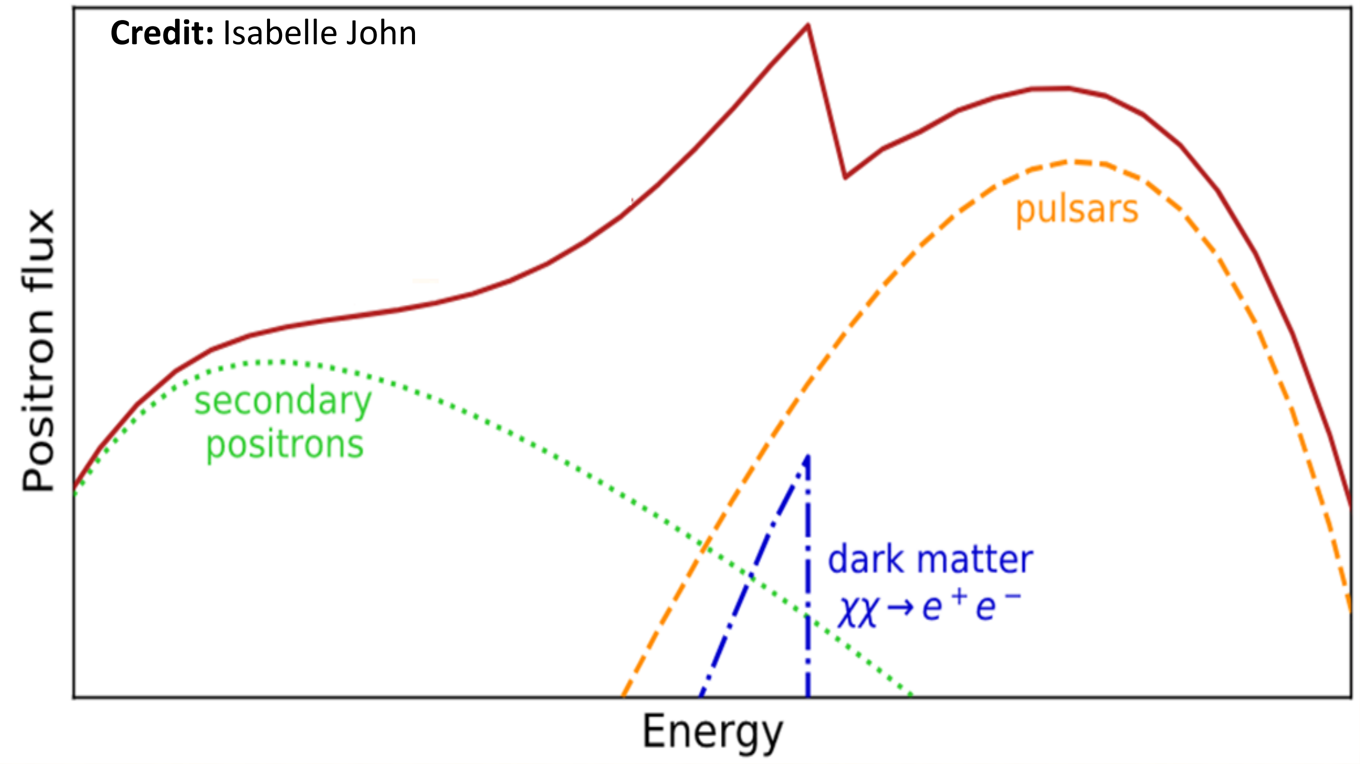


What about antiprotons?

Positron production and identification of exotic signals

The stochastic nature of the PWN emission makes it difficult to find signatures of exotic physics at high E:

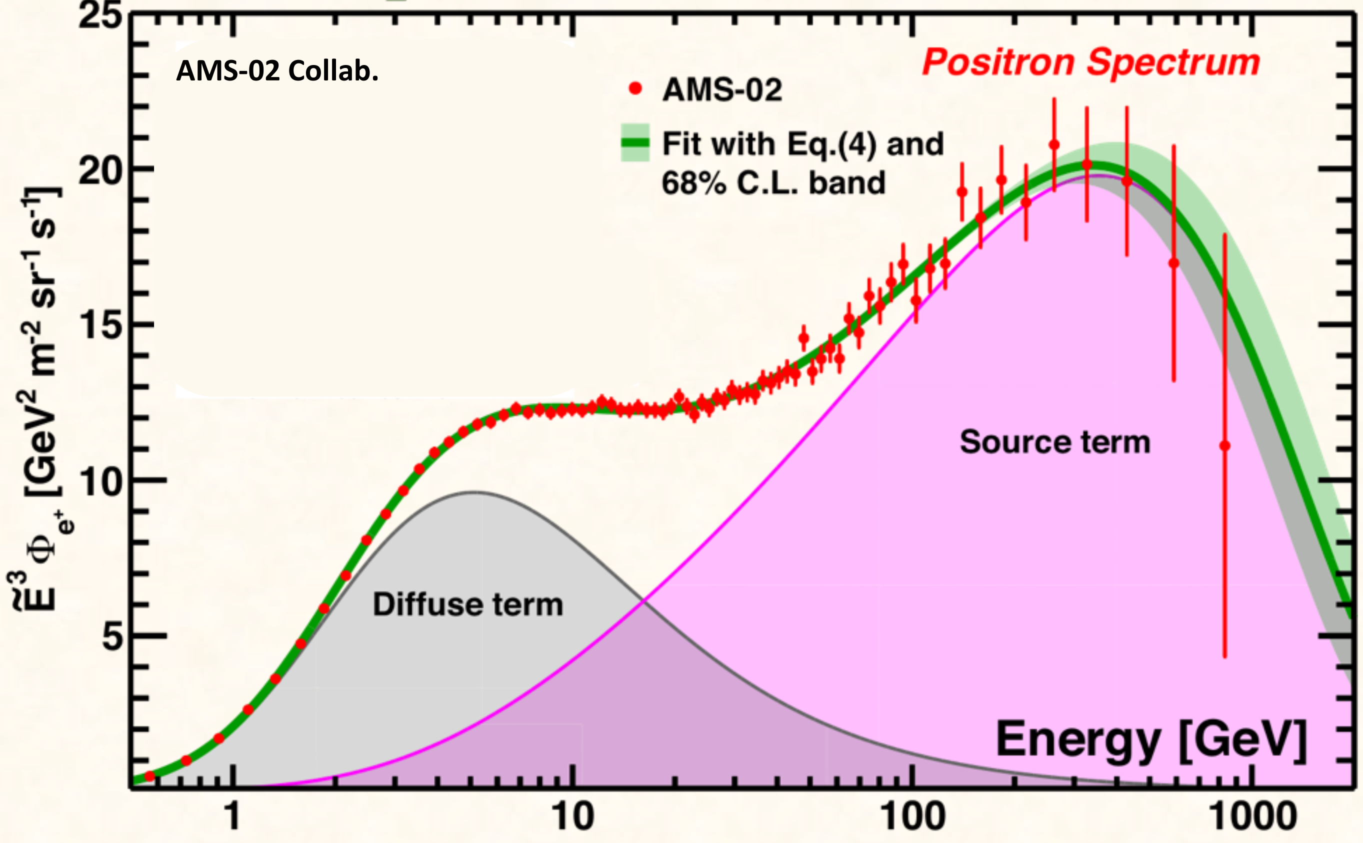
1. Sharp features can be easily masked by PWN contribution
2. High masses contributing to the e+ spectrum at those energies

Easier to spot these signals at low E

- Diffusion process
- Magnetised halo
- Nearby Galactic environment
- Solar modulation
- Cross sections

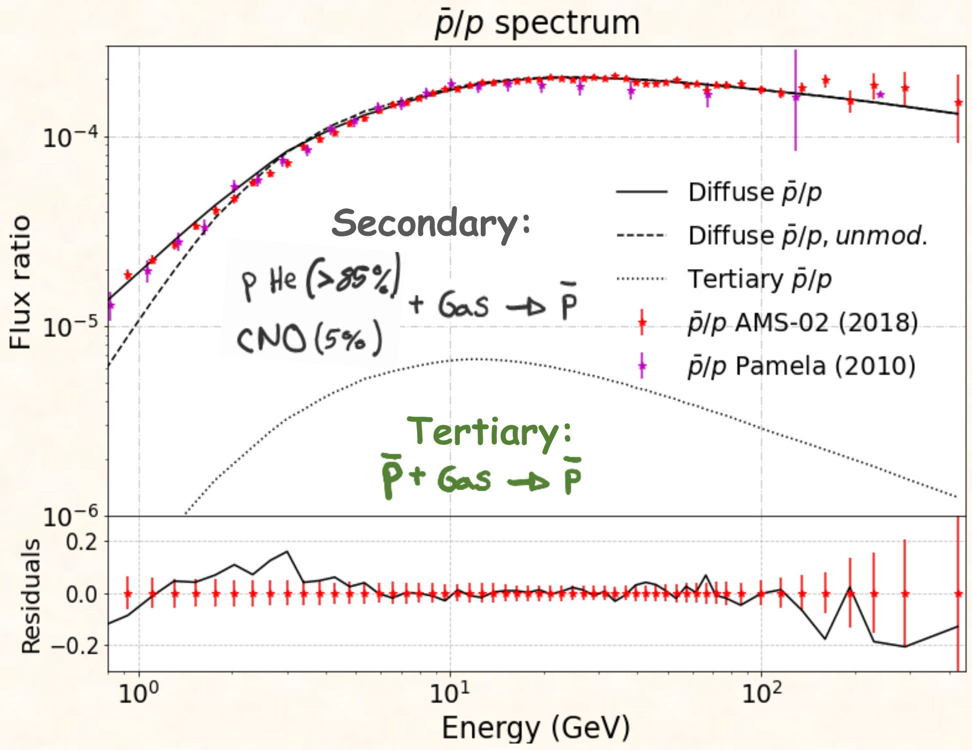
Diffuse term Source term

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s\,(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

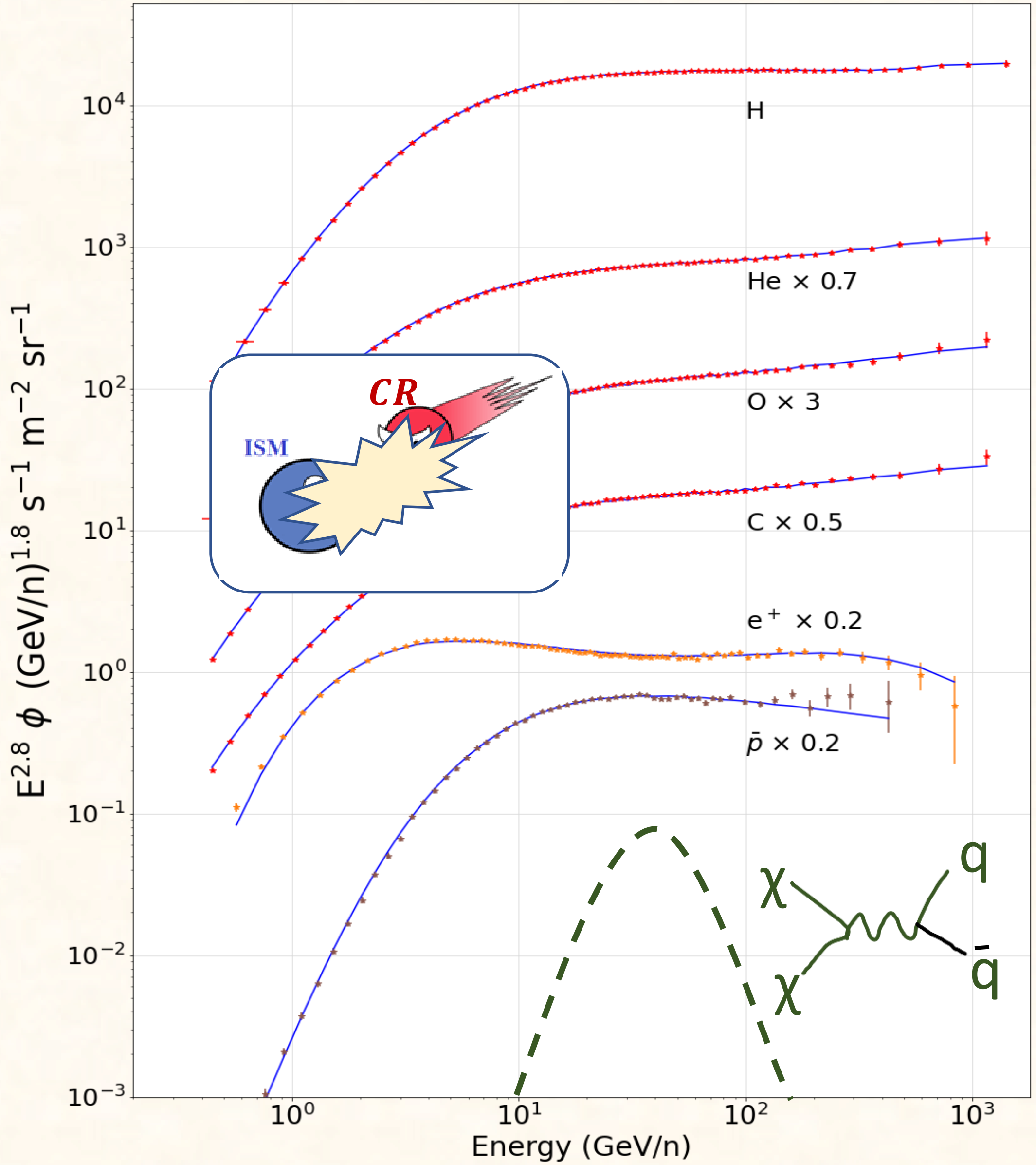


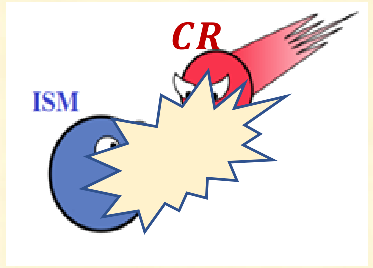
Potential of antiparticles to reveal the existence of BSM physics

p + p → p + p + p + $\bar{\text{p}}$ (High energy protons produce lower energy antiprotons)



Flux of CR nuclei and antiparticles (data from AMS-02)





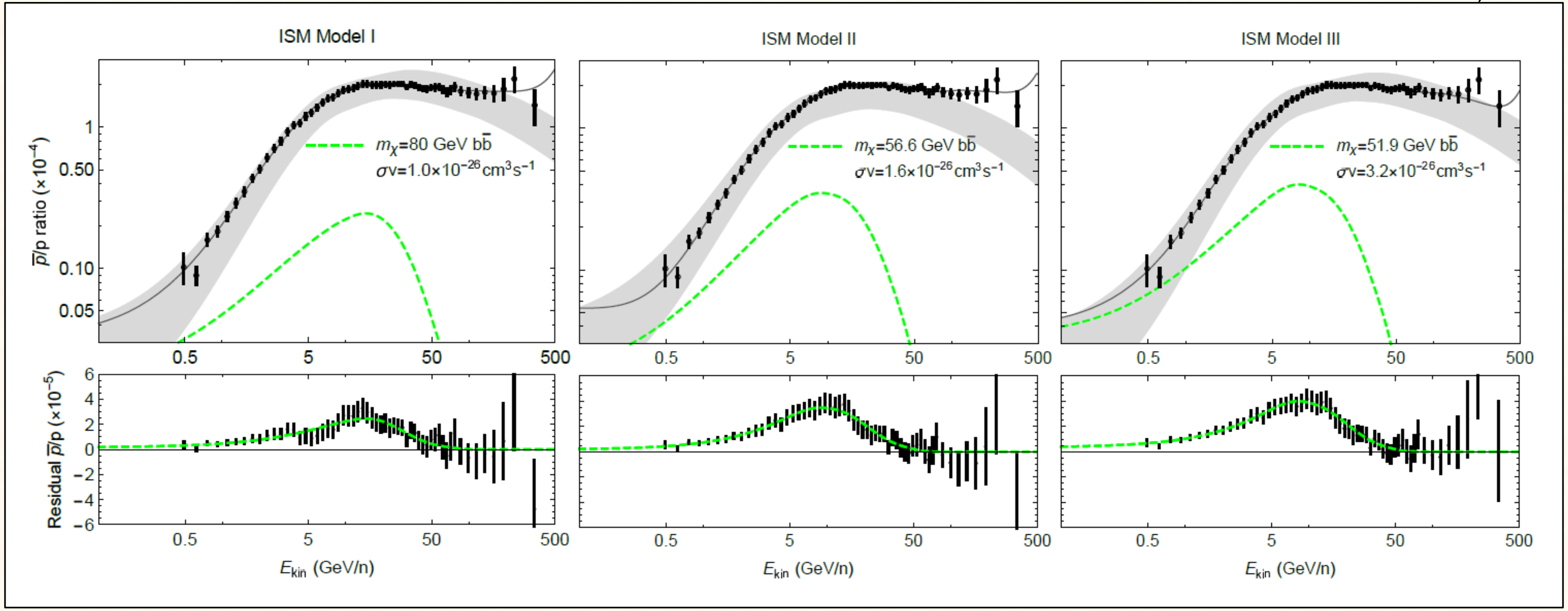
Antiproton *excess* – A DM signal?

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

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

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

Cholis et al PRD 99, 103026

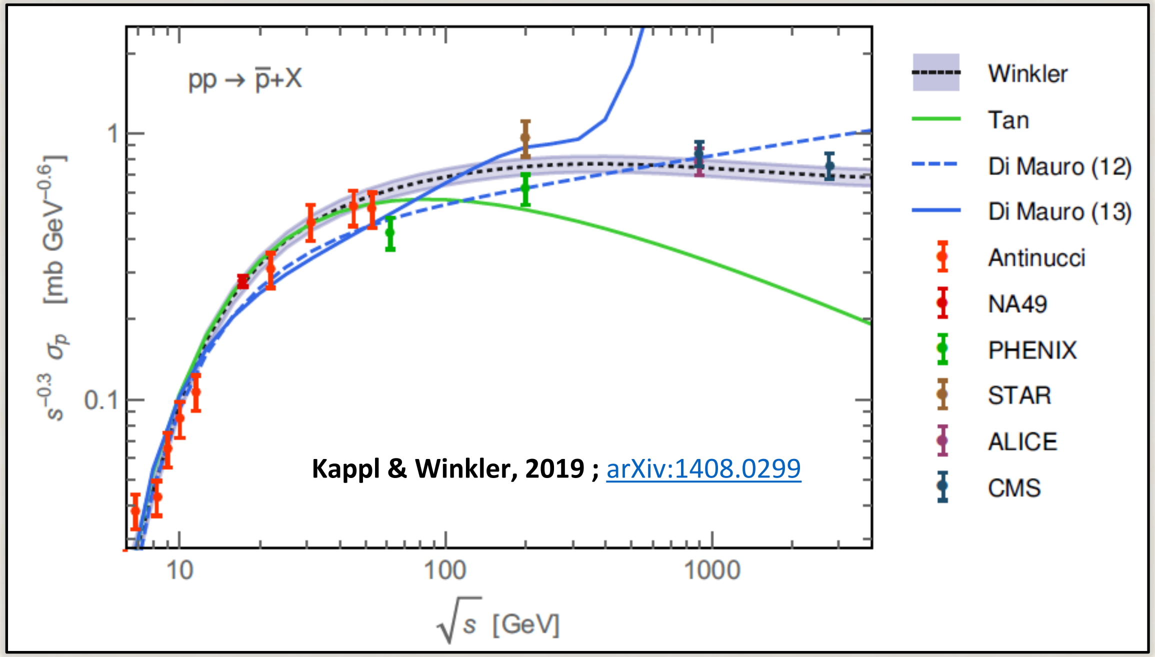


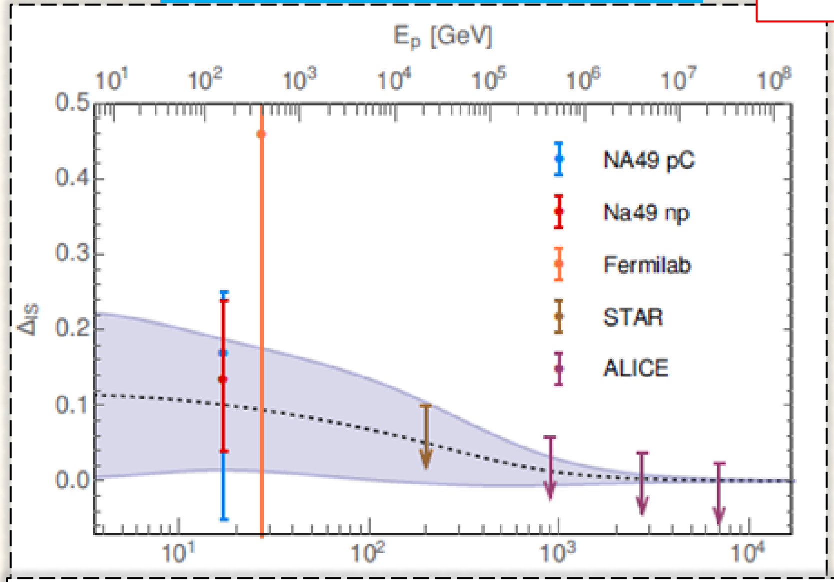
Antiproton cross sections

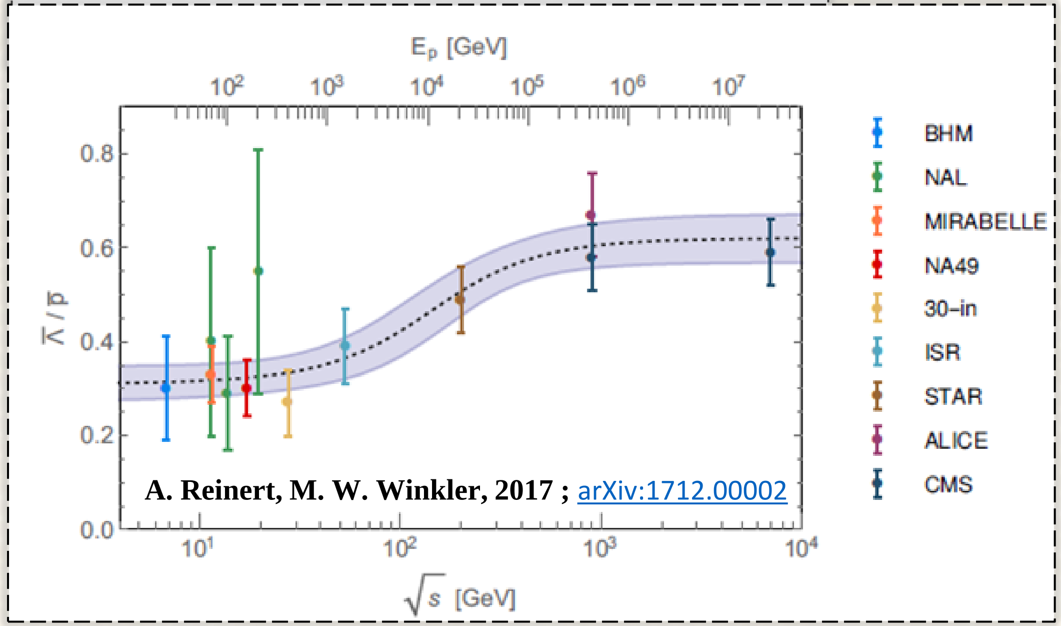
$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp\to\bar{p}} = \left(E\frac{d^3\sigma}{dp^3}\right)^{\text{prompt}}_{pp\to\bar{p}} \cdot (2+\Delta_{IS}+2\,\Delta_{\Lambda})$$

$$p+p\longrightarrow\{\bar{n}\longrightarrow\bar{p}\}+X$$

$$\Delta_{\text{IS}}=\frac{\sigma_{pp\to\bar{n}}}{\sigma_{pp\to\bar{p}}}-1$$



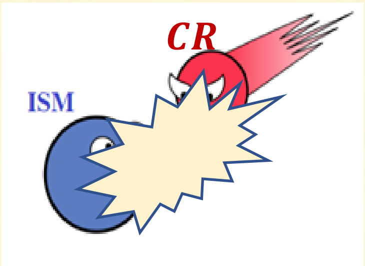




$$p+p\longrightarrow\{\bar{\Lambda},\bar{\Sigma}\longrightarrow\bar{p}\}+X$$

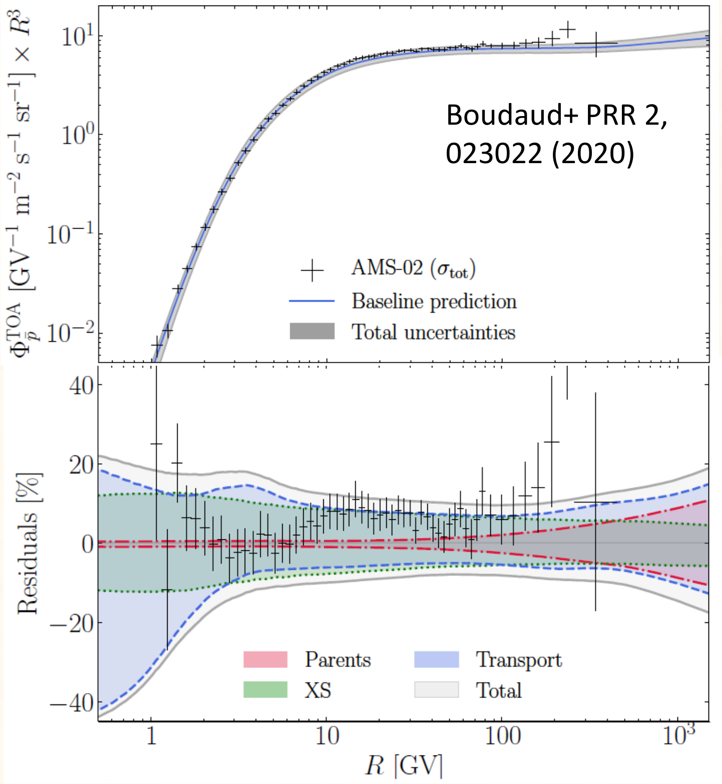
44

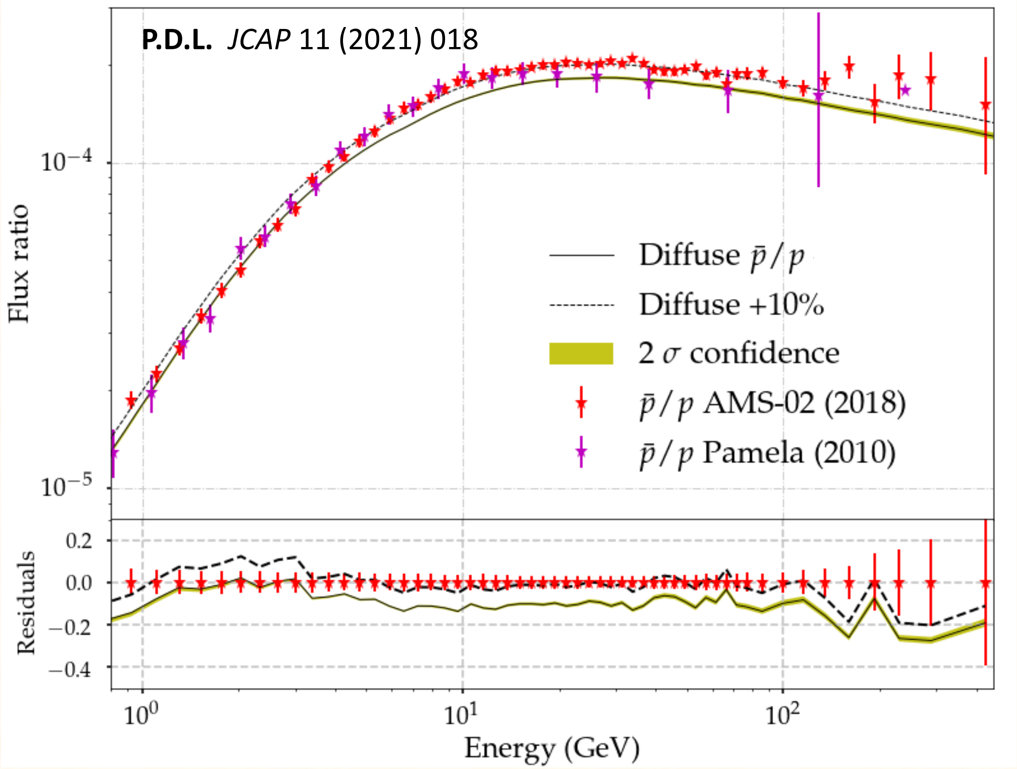
Antiproton *excess* – A DM signal?



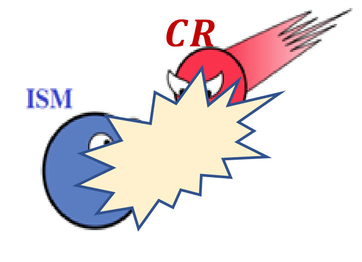
Further investigations revealed that the $\bar{p}$ spectrum is **totally compatible with the rest of CRs**, without any need of dark matter. Cross sections uncertainties and AMS-02 correlated errors are crucial

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





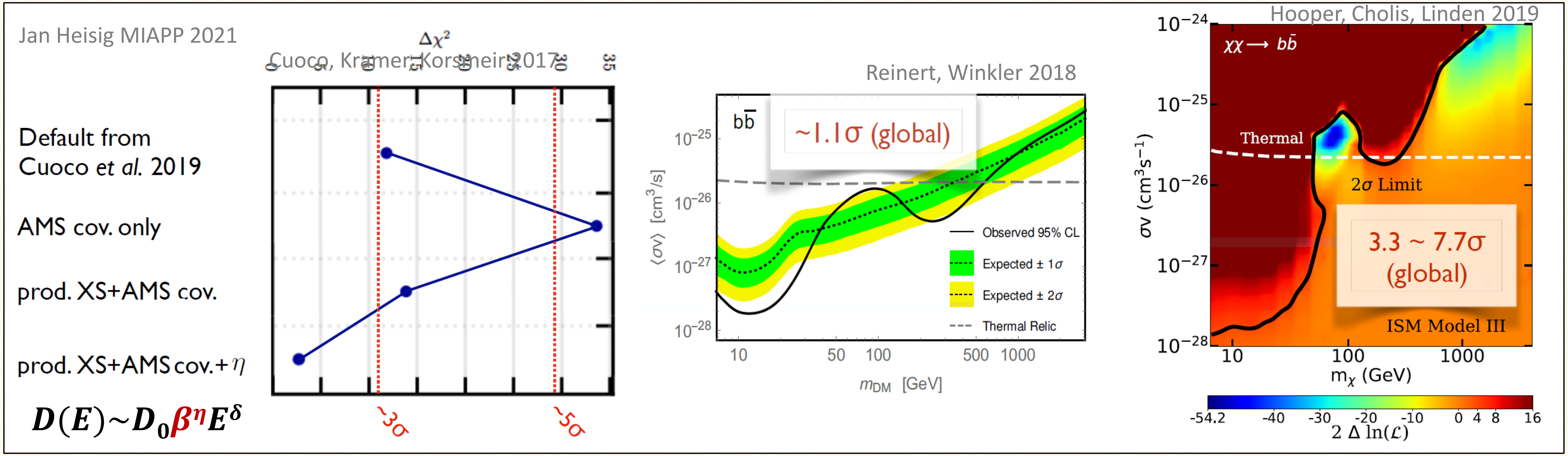
Antiproton excesses – *The spectral excess*



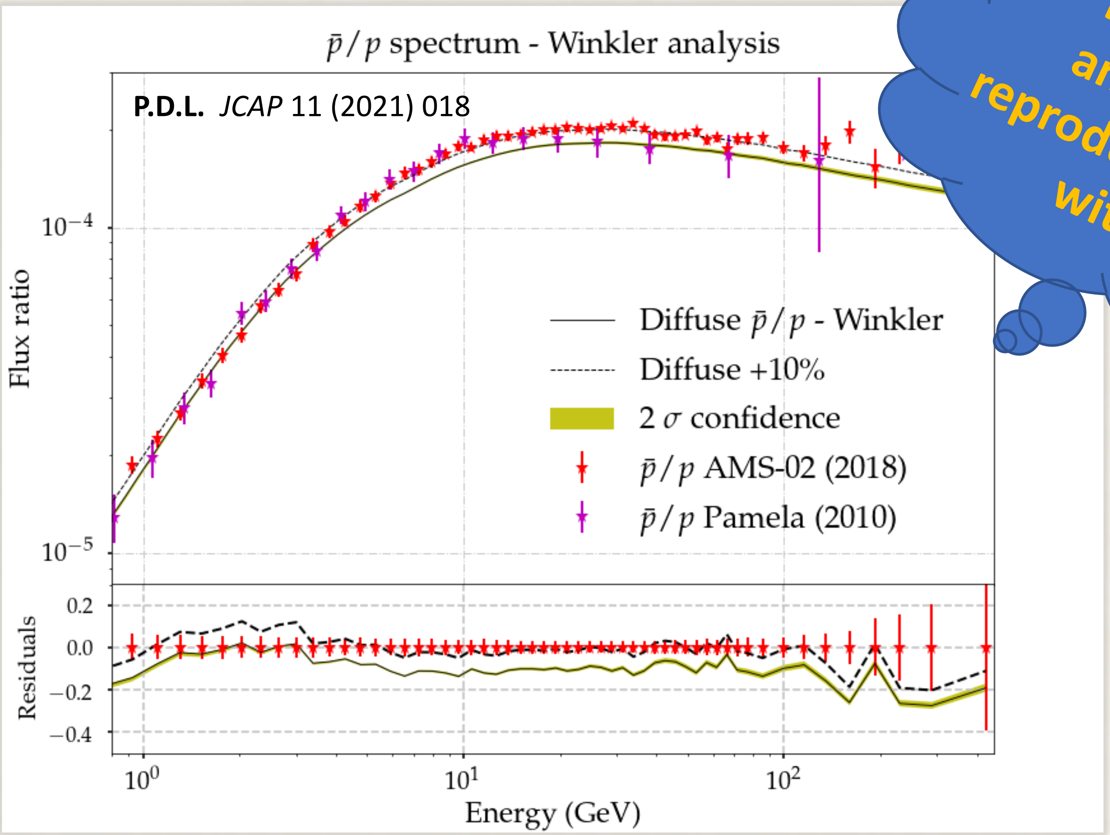
$p_{CR} + p_{ISM} \rightarrow \bar{p}$

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

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!)

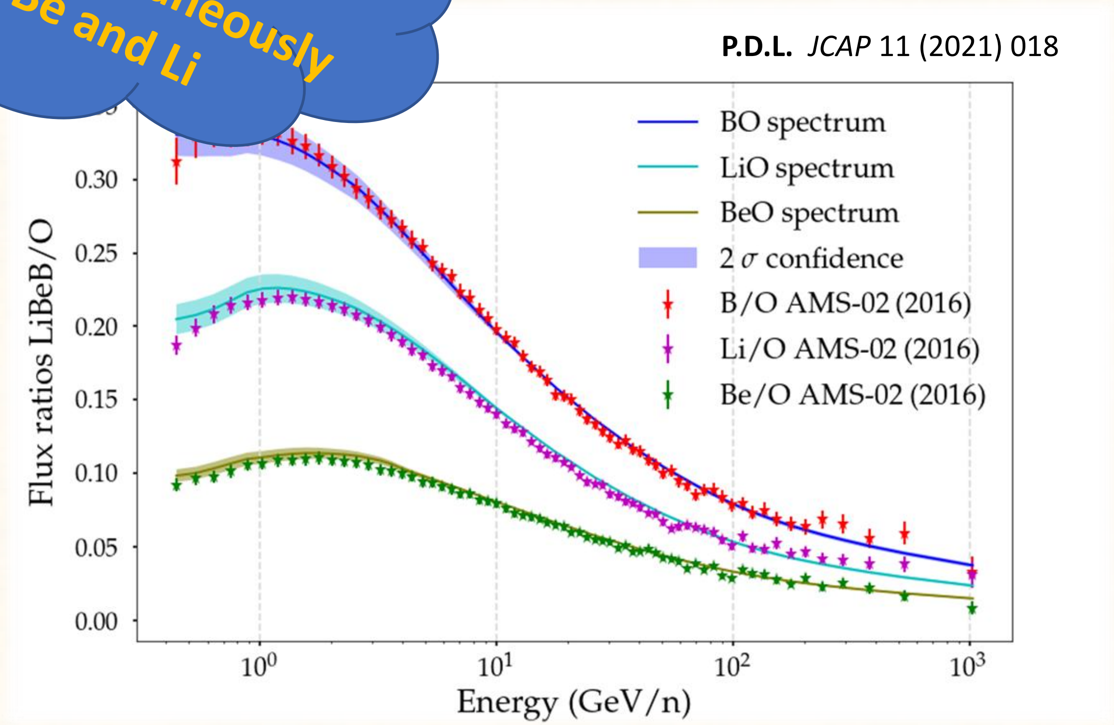


Antiproton excesses – *The grammage excess*



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**

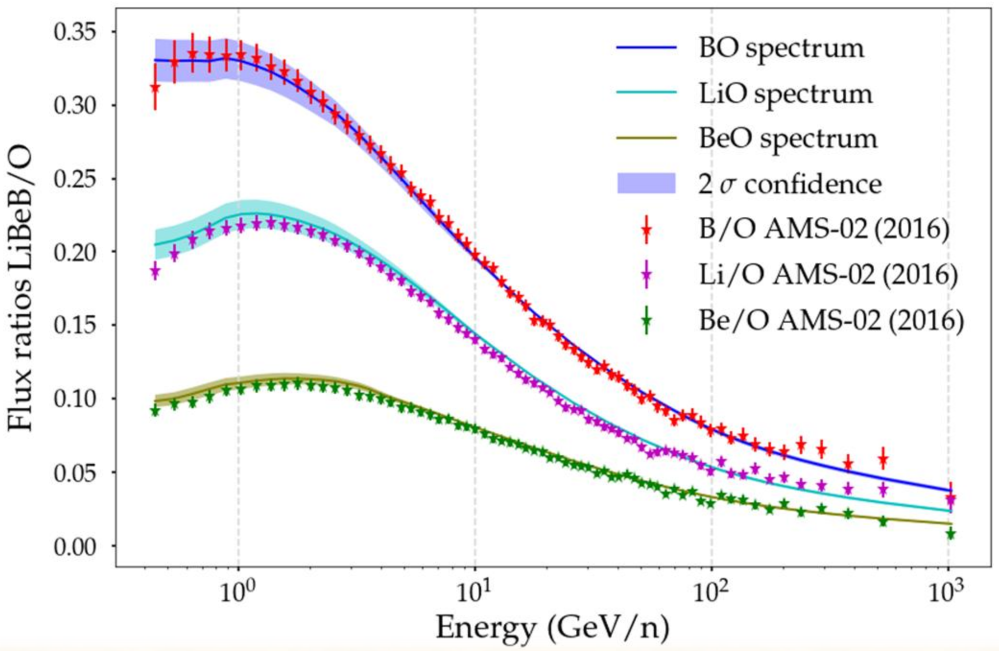


<u>Conclusion</u>: Cross sections uncertainties affect very significantly our predictions and can explain the excess

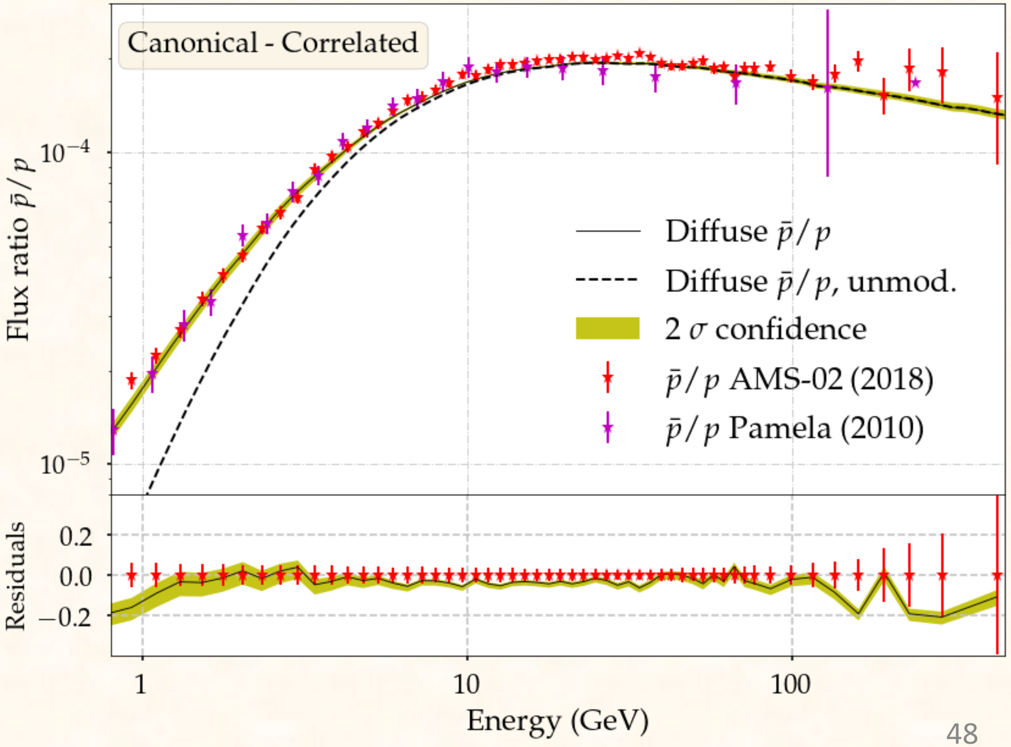
Looking for anomalies in CR antiprotons

Antiproton observations are fully compatible with a secondary origin and all secondary CRs can be well explained considering cross sections uncertainties – However, including also DM production is still preferred in the fit for a WIMP with mass around 70 GeV with annihilation rate close to the thermal relic one…

P.D.L. *JCAP* 11 (2021) 018



PDL et al JCAP 05 (2024) 104



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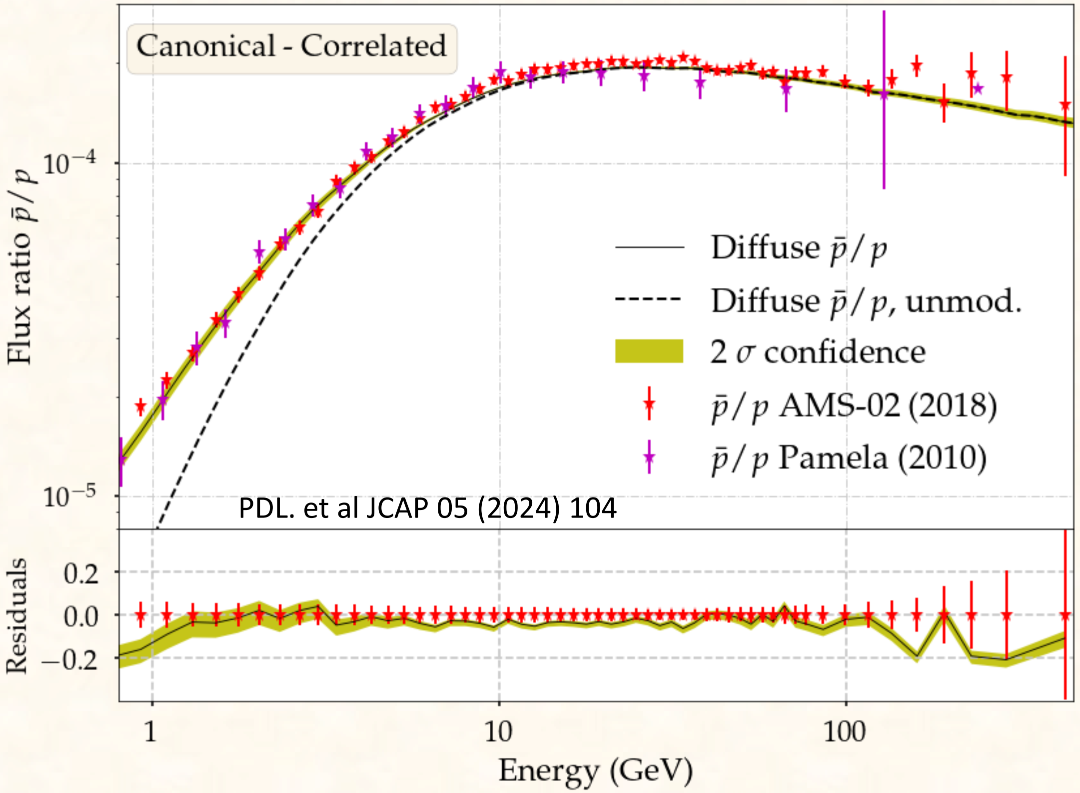
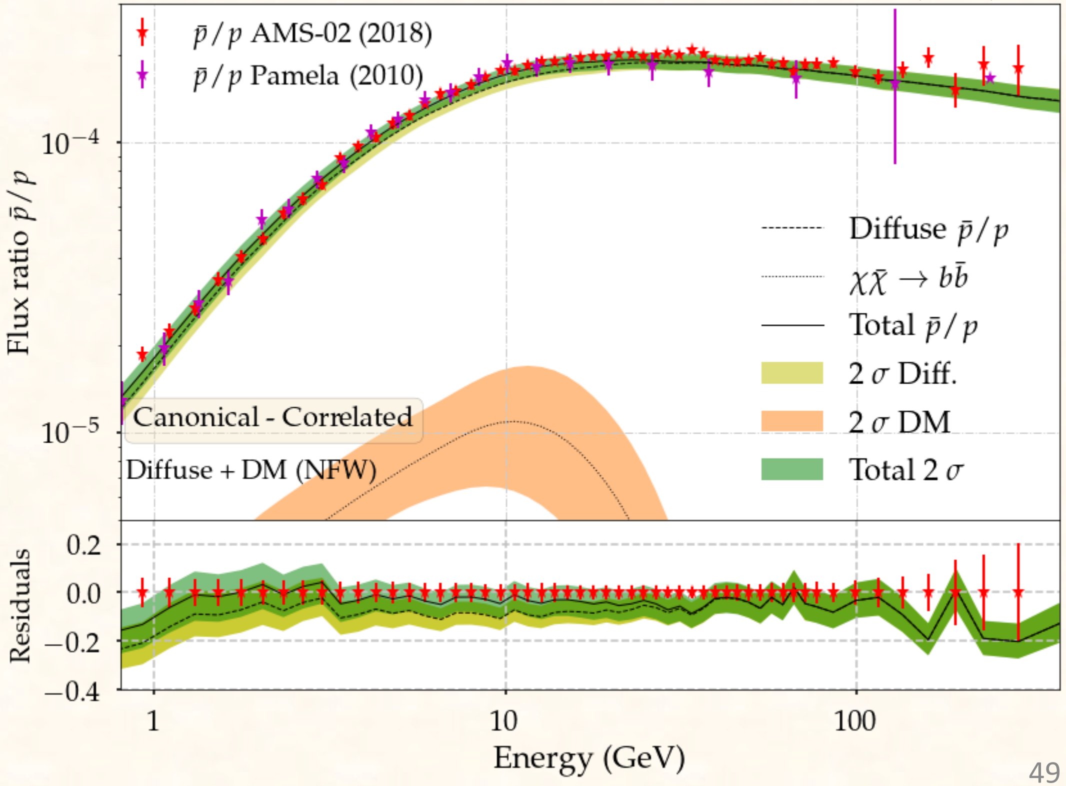
PDL et al JCAP 05 (2024) 104

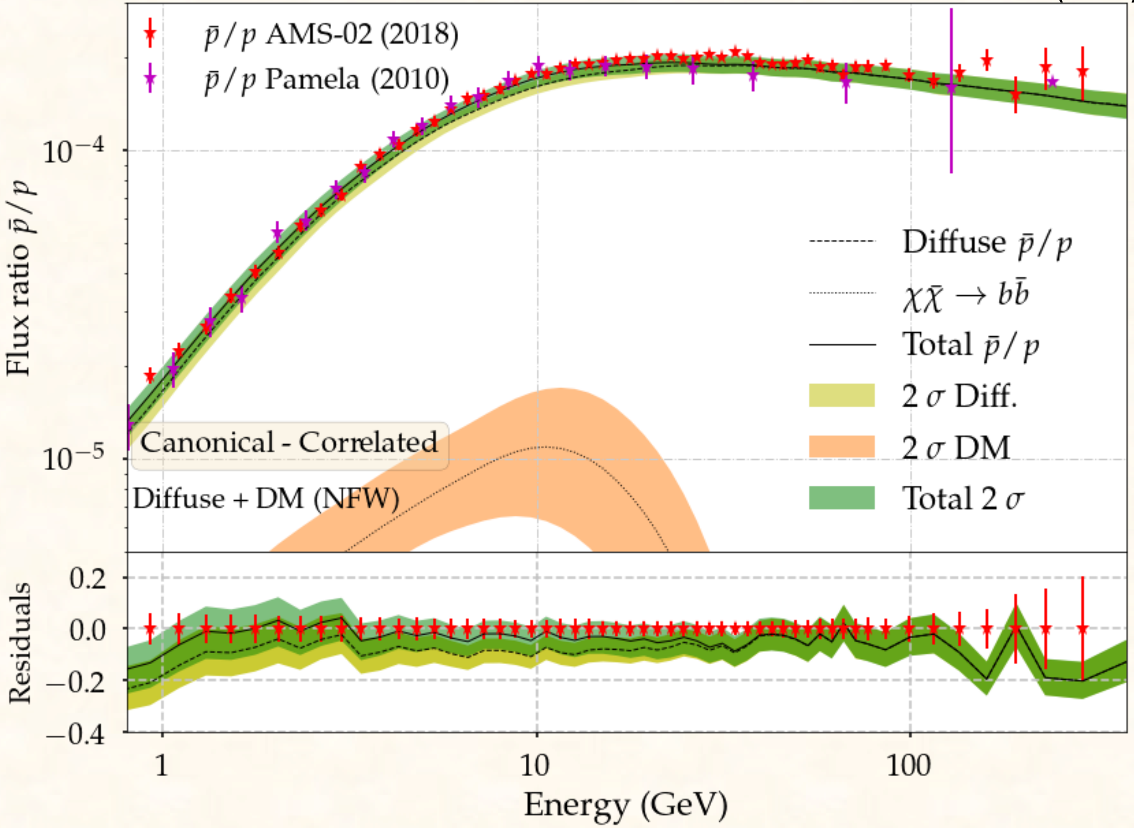




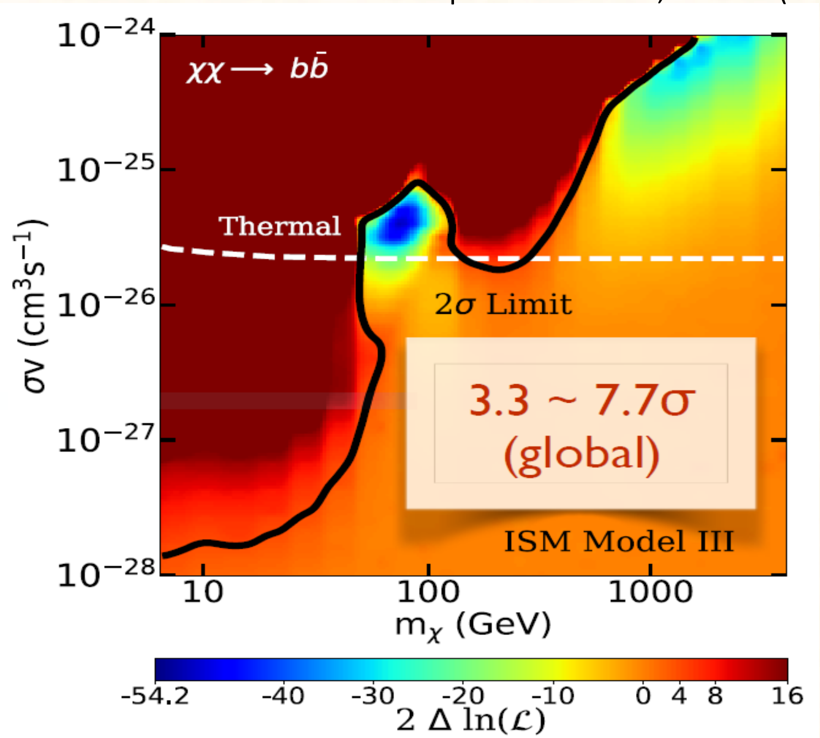
Looking for anomalies in CR antiprotons

Detailed DM searches found different sources of uncertainties difficult to avoid in current studies: Cross sections, correlated errors, diffusion model … A statistical evaluation of the signal shows that **there is no significant excess in the data (maximum of 1.8 sigma)**

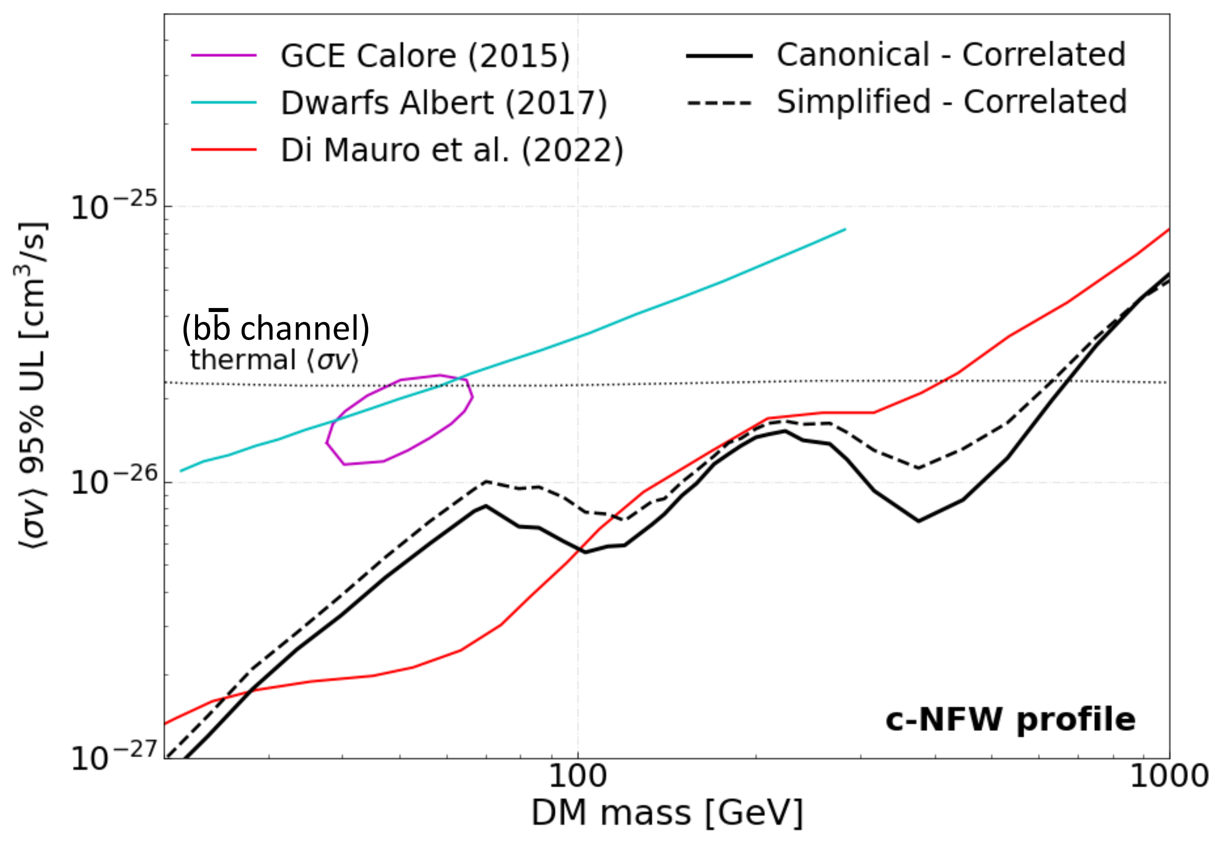
PDL et al JCAP 05 (2024) 104



Hooper et al PRD 99, 103026 (2019)

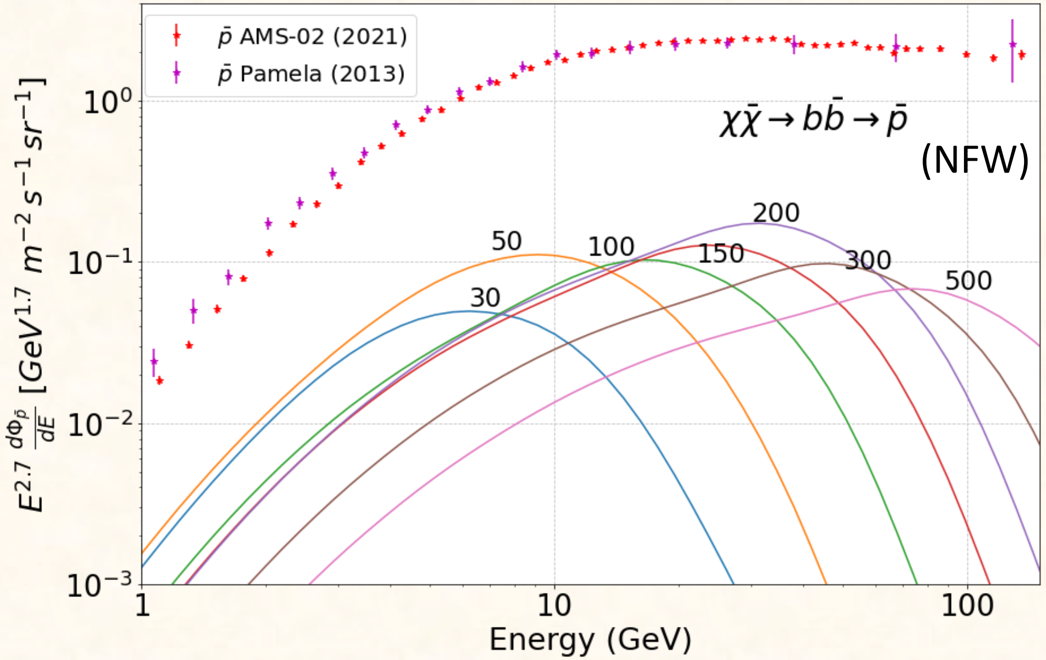


Dark matter bounds from antiproton analyses



PDL et al JCAP 05 (2024) 104

Maximal DM-induced signal (at 95% CL)



Leading constraints for WIMPs annihilating into hadronic final states,

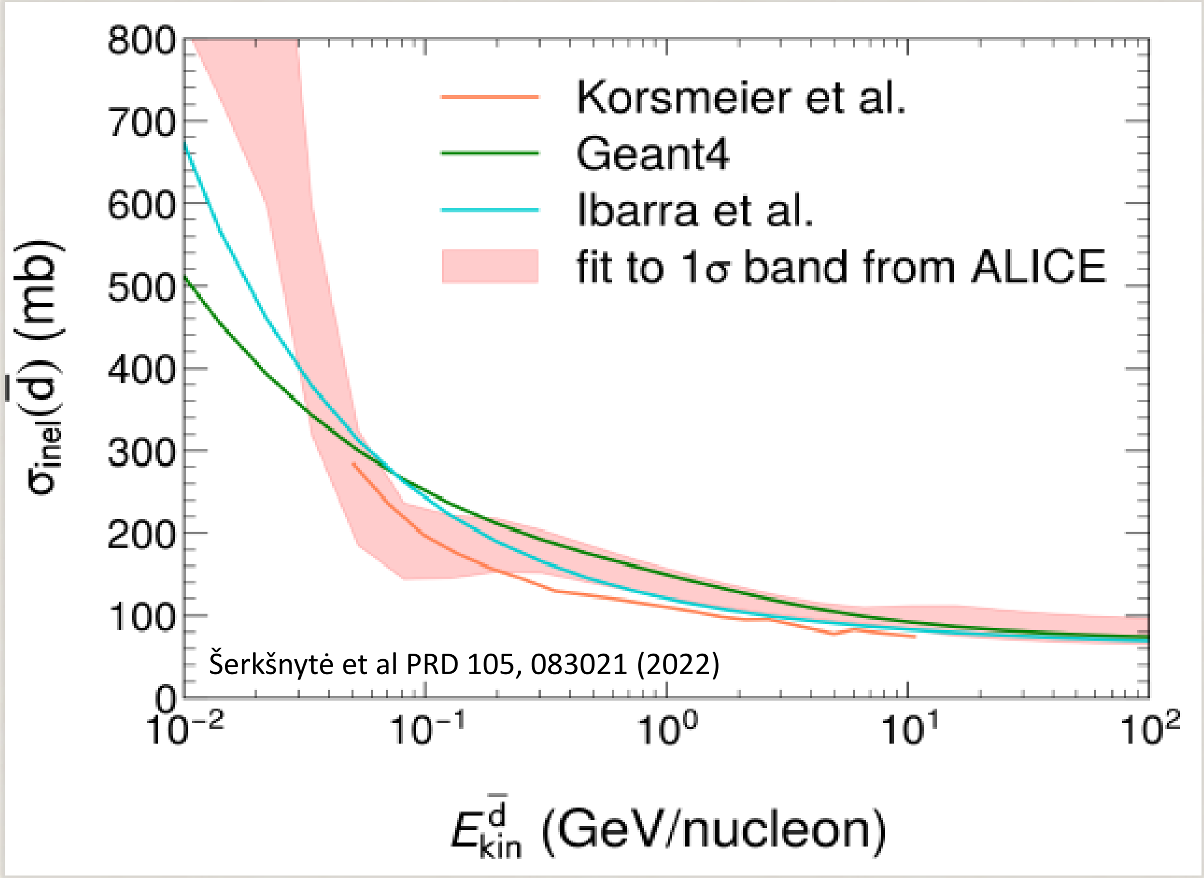
Compatible with GCE? See Di Mauro, Winkler PRD 103, 123005 (2021)

Propagation setup

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

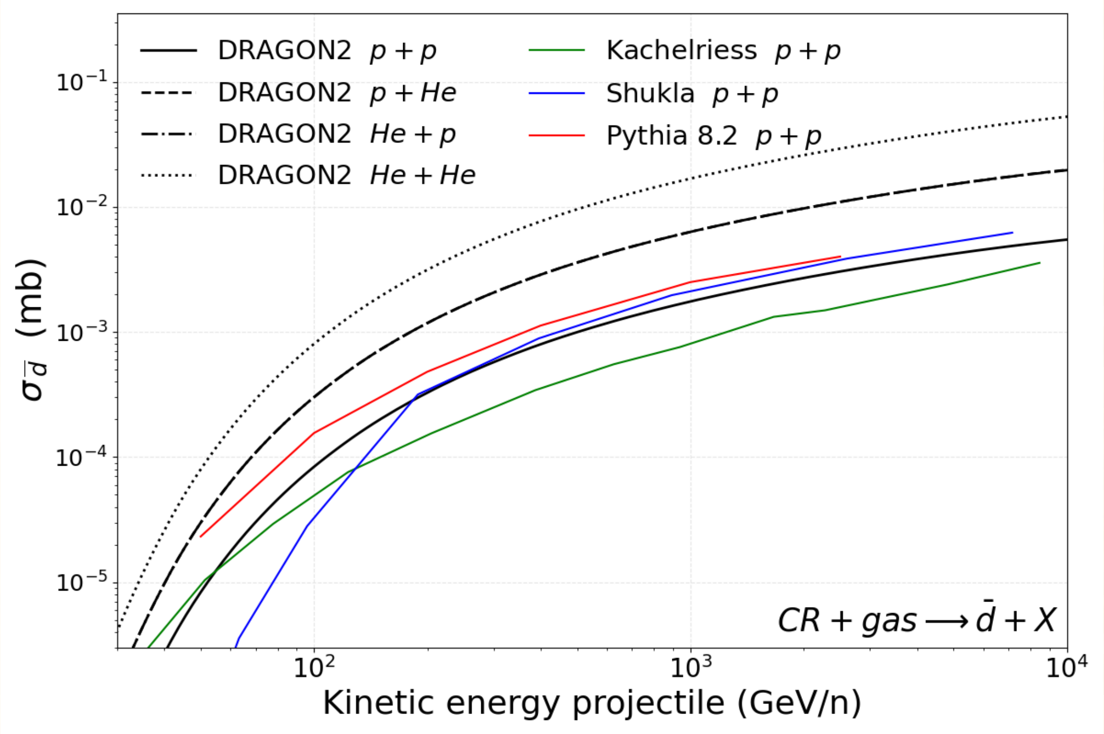
❖ Implementation of anti-nuclei dark matter and secondary production in DRAGON2

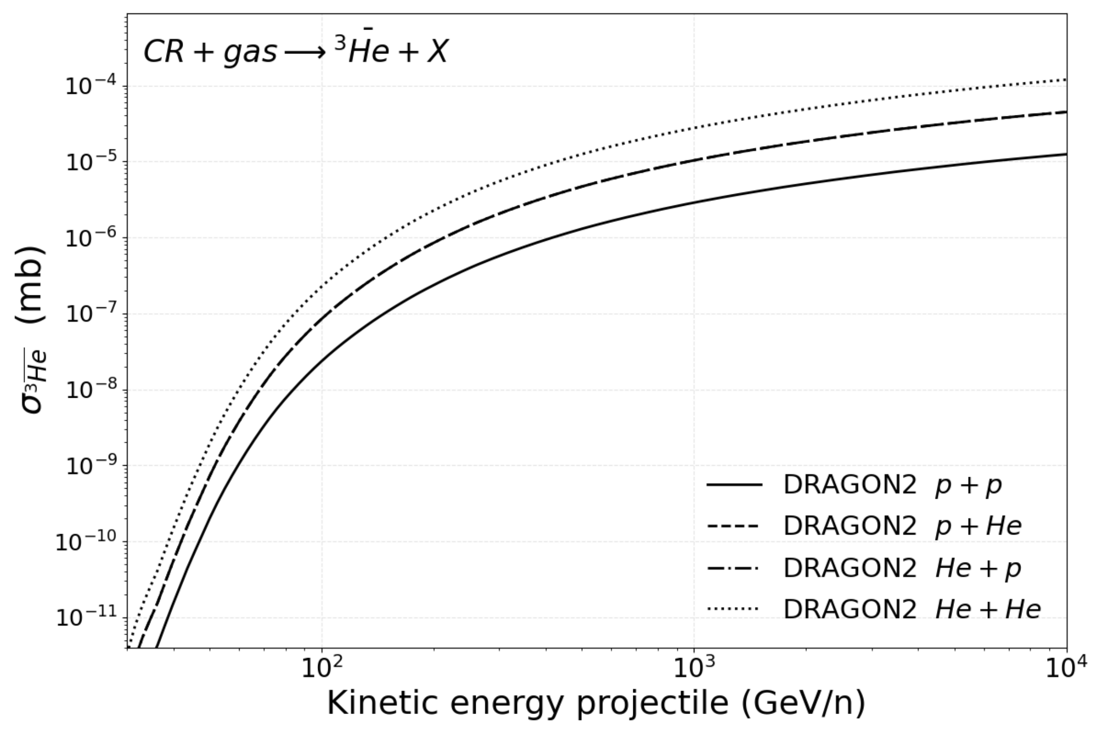
- Cross sections derived from analytical coalescence model. Using fits of antiproton (antineutron) production from Winkler, JCAP 02, 048 (2017)
- DM spectrum at production derived from Pythia 8.2 simulating a neutral colorless resonance.
  Space and momentum (p_c) conditions for coalescence. Also including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



New antinuclei cross sections!

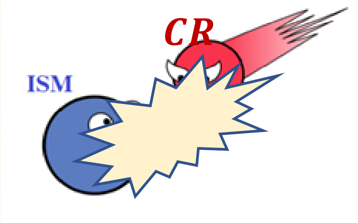
Derived analytically using the factorized coalescence model model from the Winkler (2017) cross sections for antiprotons. Coalescence momentum adjusted to reproduce ALICE p+p data!





Astrophysical production

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

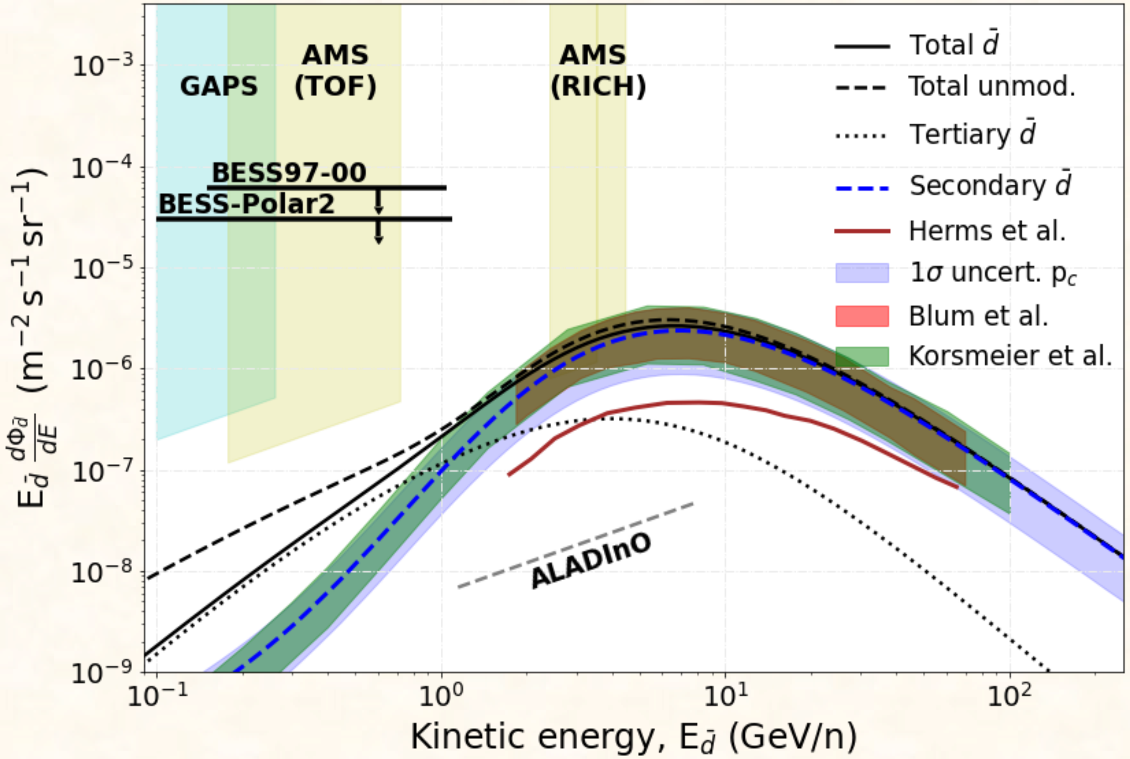


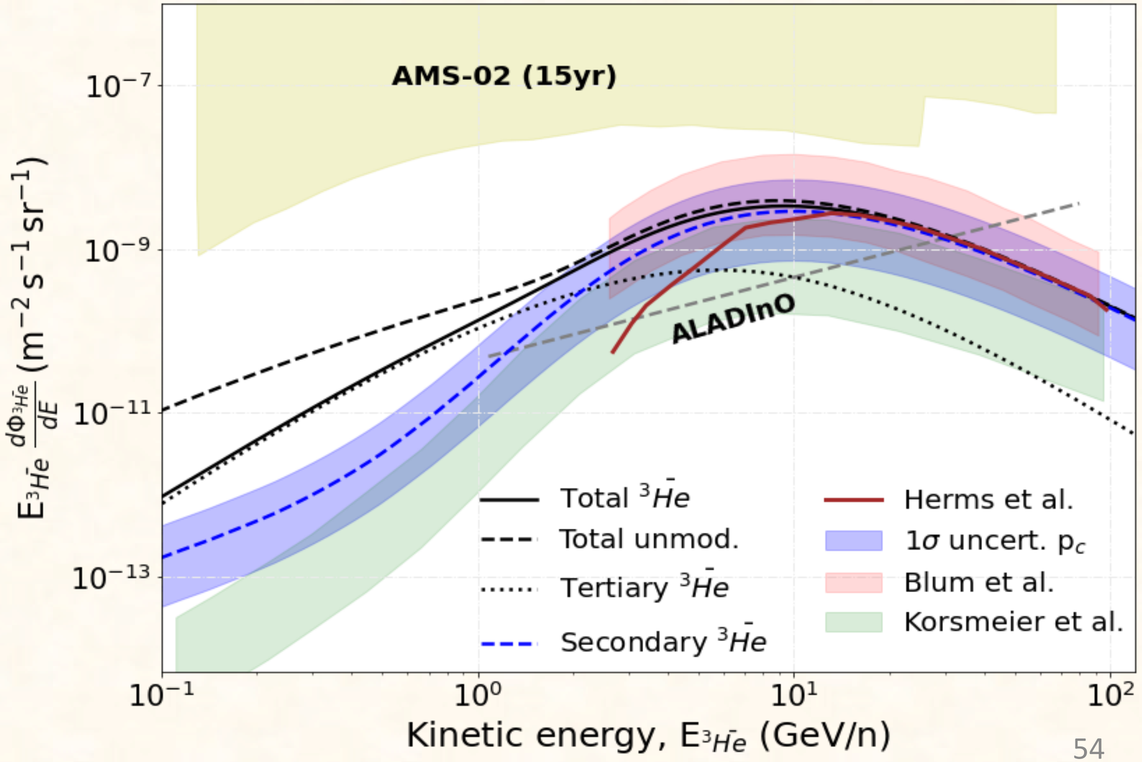
Can we explain the AMS-02 measurements without invoking any exotic source?

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

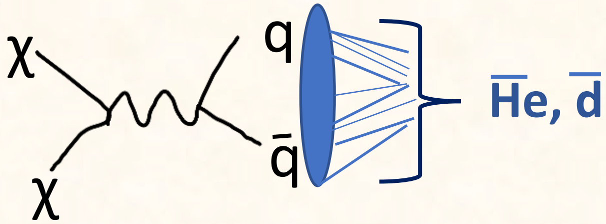
We expect to have measurements of the $\bar{d}$ flux in the next years!! But nothing about $\overline{He}$ till ALADInO or AMS-100 (foreseen to 2039)

P.D.L. et al, ArXiv: 2404.13114



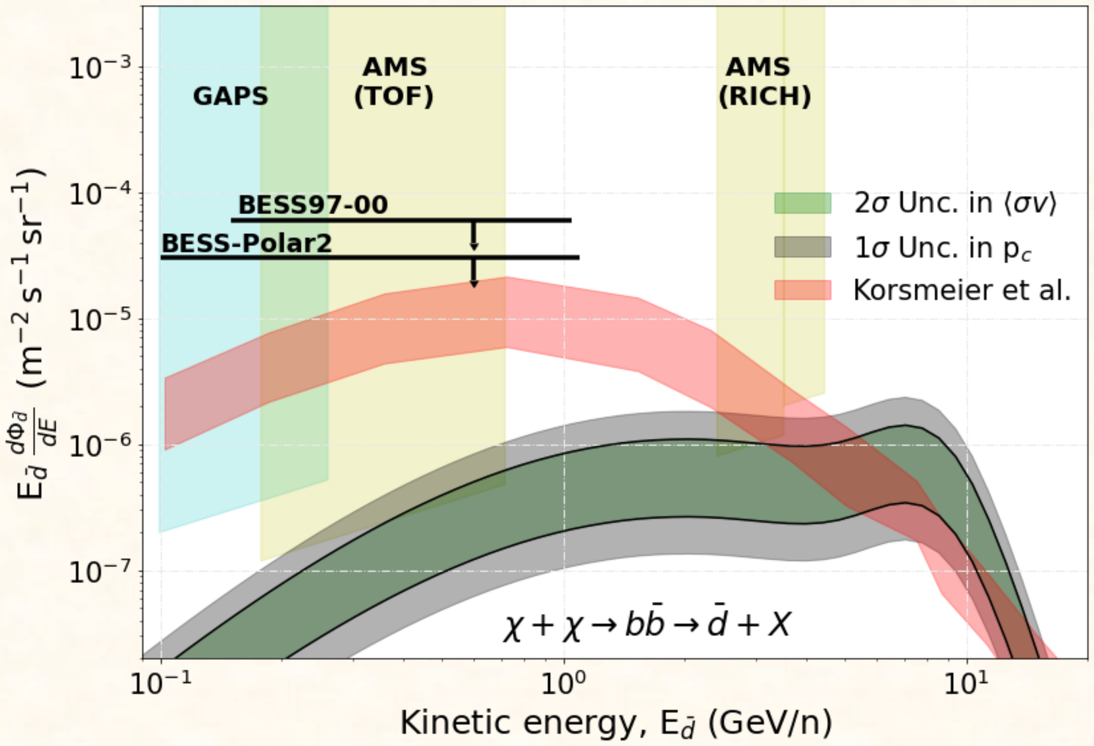


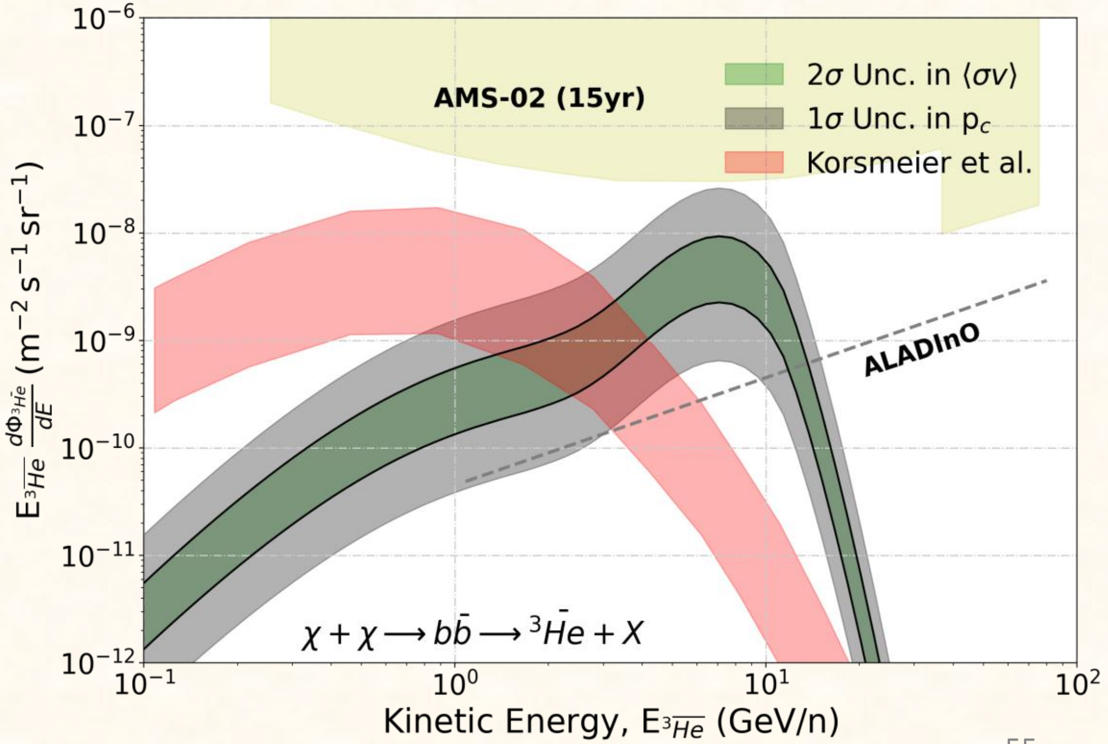
Dark matter production



Estimations of the expected flux from DM hints have changed significantly over the last years. **The measurement of anti-deuteron events by GAPS or the TOF (AMS-02) will certainly evidence exotic mechanisms of production of these particles**

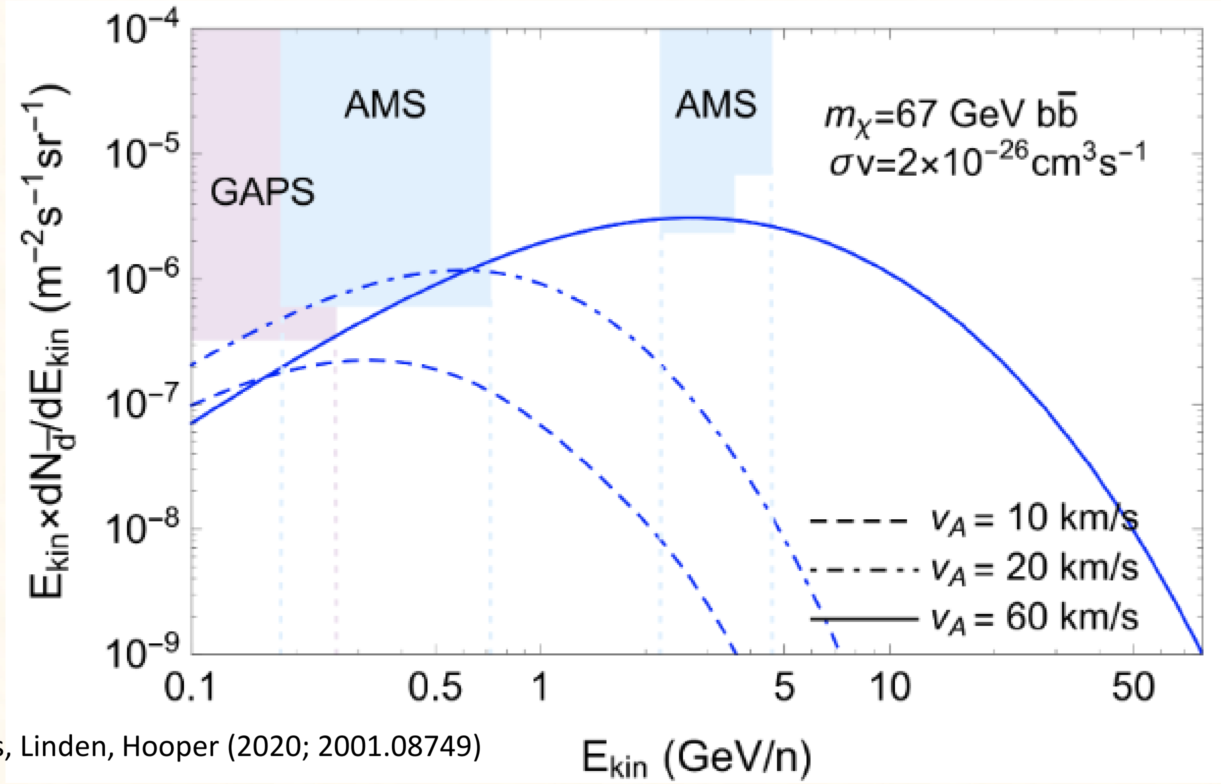
PDL et al JCAP 10 (2024) 017



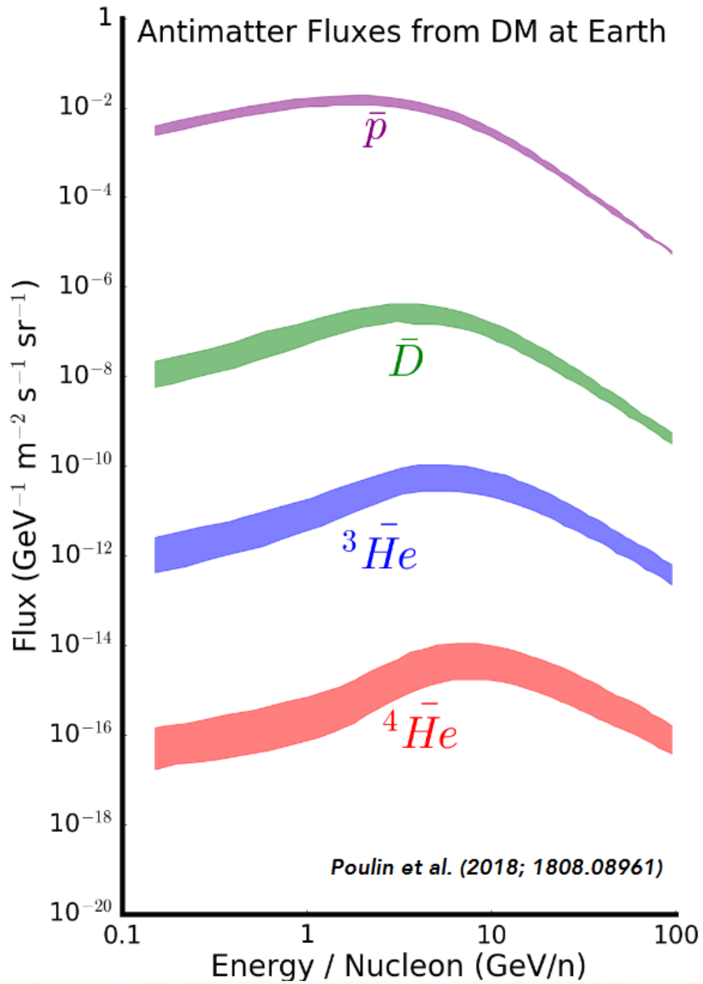


A few ways to boost the DM antihelium yield

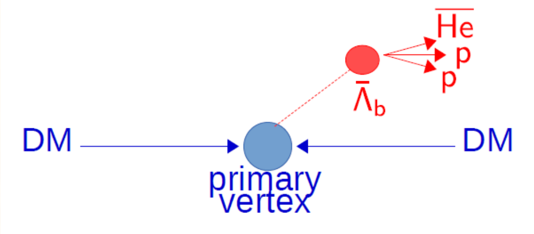
Diffuse reacceleration boosts the signals? (with the plus of promoting low energy antinuclei to higher energies)



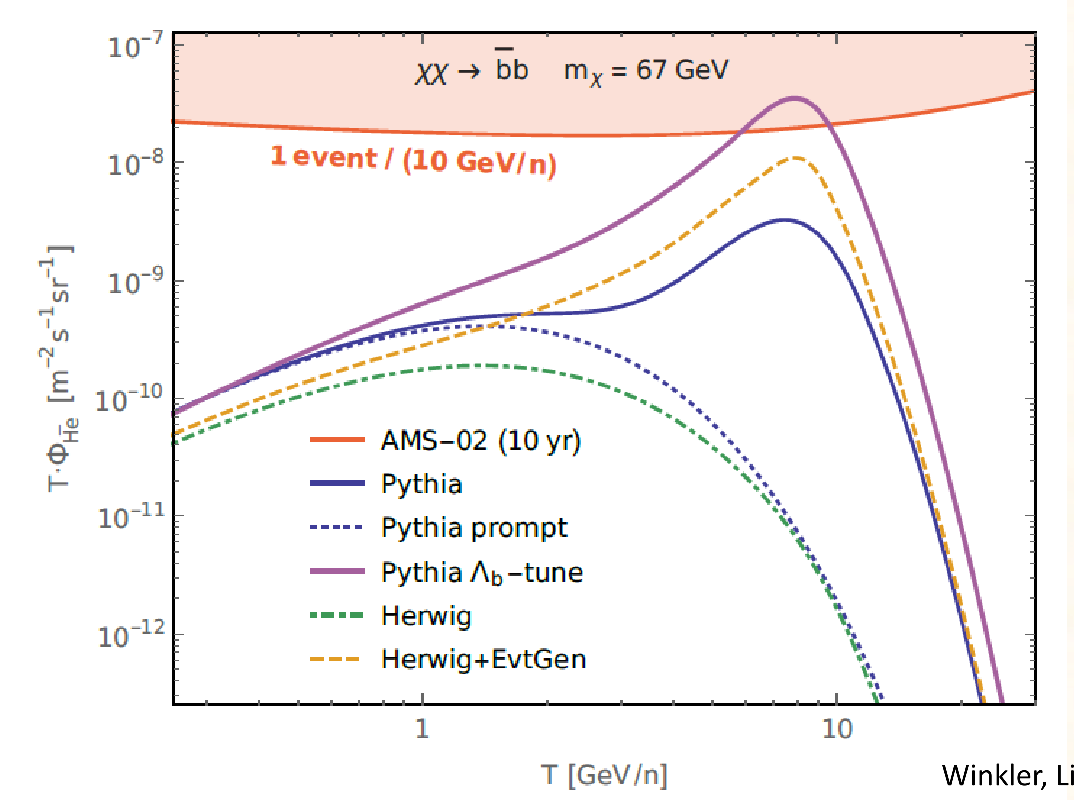
Cholis, Linden, Hooper (2020; 2001.08749)

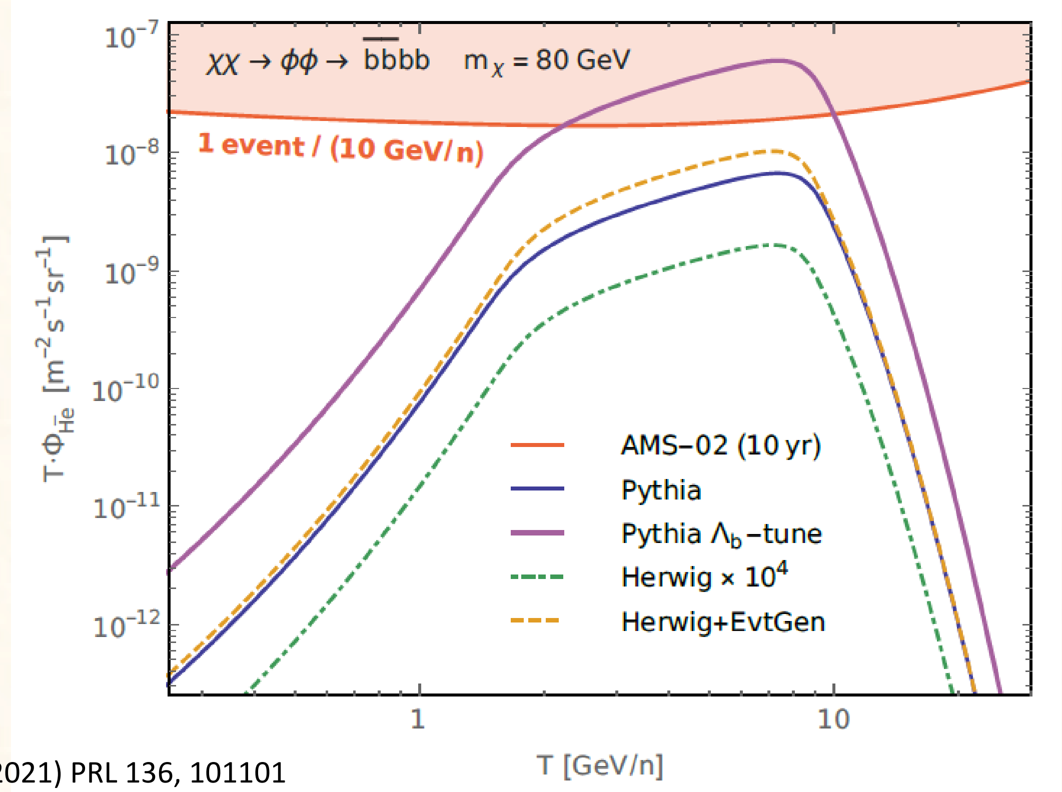


Boosting the dark matter signal



✓ **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