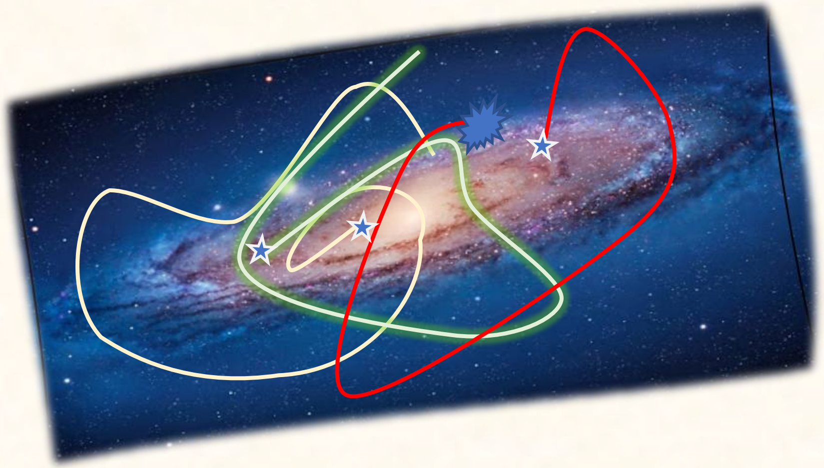
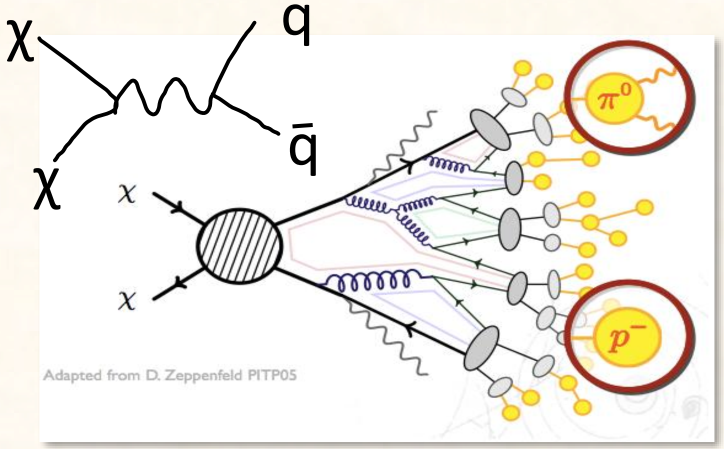
Cosmic Rays in the search for Dark Matter





Pedro de la Torre Luque --- pedro.delatorre@uam.es
Ramón y Cajal fellowship (UAM - Madrid)

IDM, Zaragoza – 2/6/2026

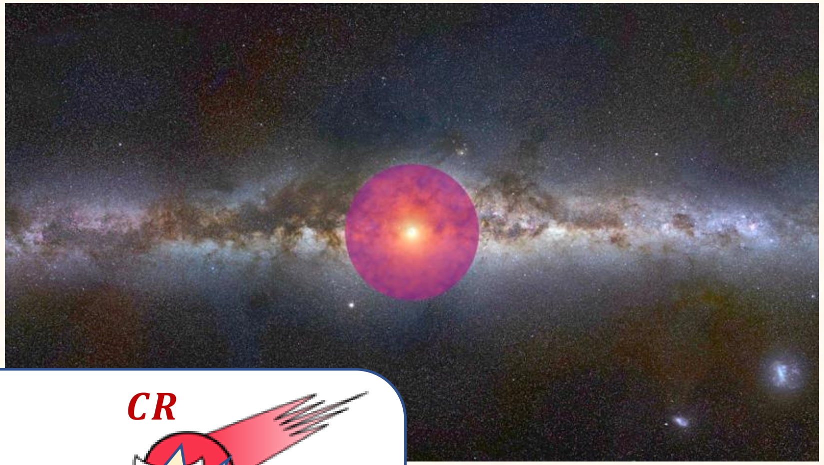
CR Antiparticles in the Galaxy

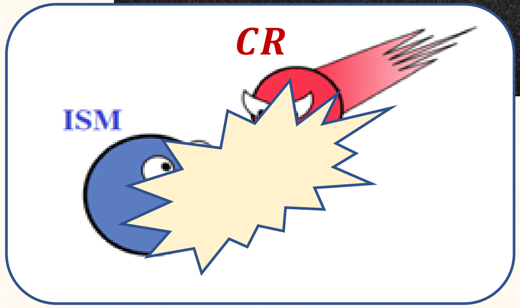
Common DM Candidates, such as WIMPs, must produce same number of particles and antiparticles in their decay/annihilation. **Observing the direct products of dark matter would reveal its nature and origin**

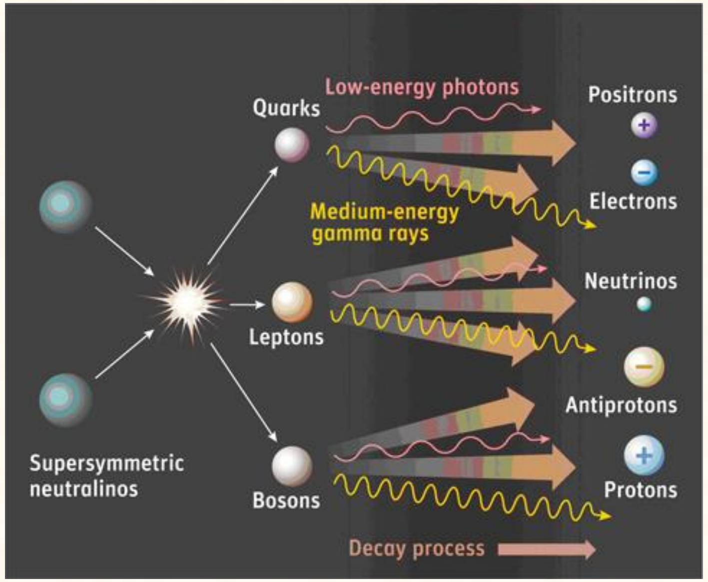
Positrons and antiprotons have long been considered critical channels for dark matter searches: Many simple extensions of the SM lead to well-motivated dark matter candidates

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

CRs are guaranteed sources of antiparticles, through **interactions with the ISM**. Production mainly depends on:
- Time that CRs stay in the Galaxy (diffusion coefficient)
- Probability of producing the antiparticle (cross sections)







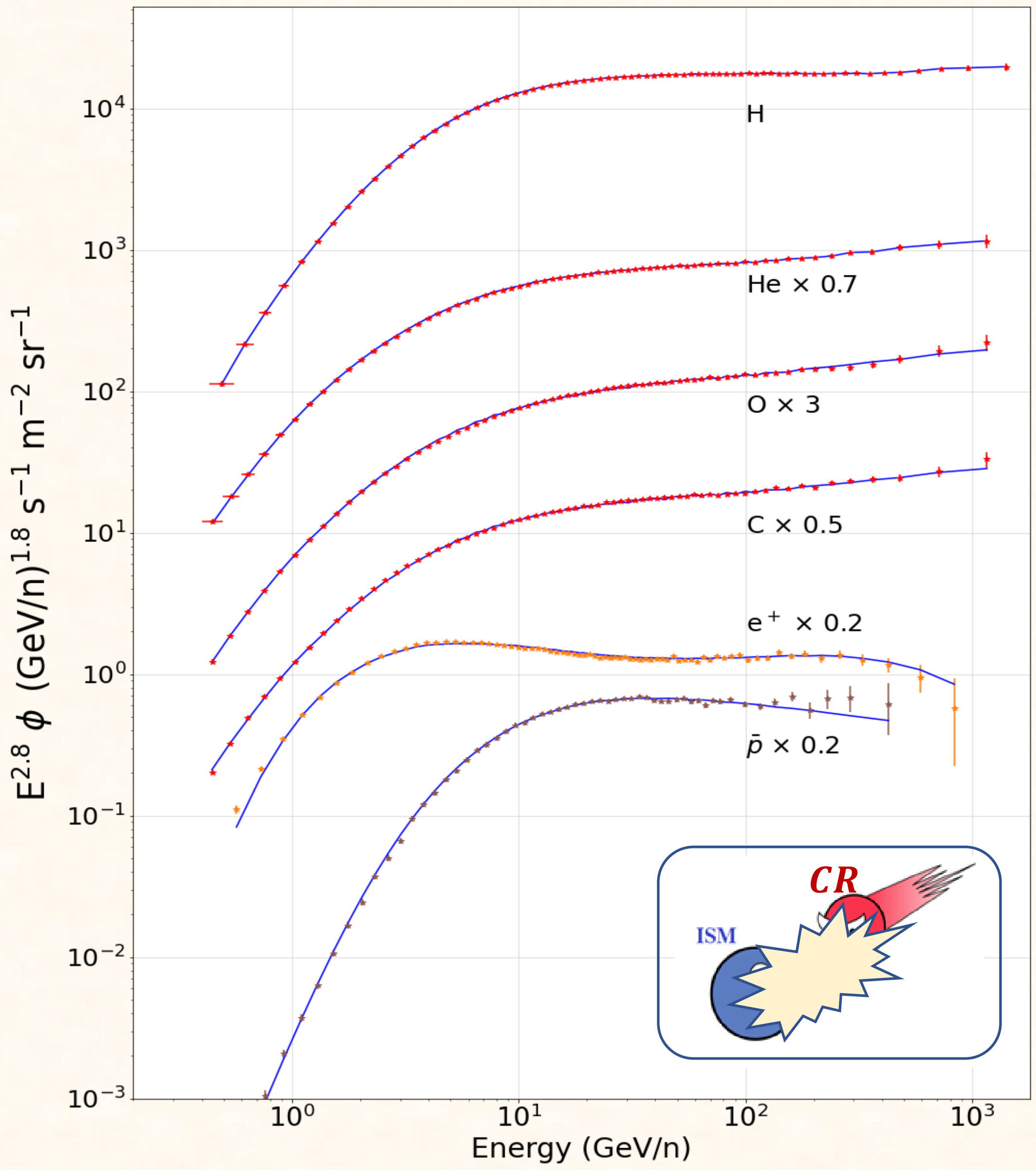
Antiparticles as a tool to identify signals of BSM physics

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

The antiproton and positron spectra allow us to strongly constrain 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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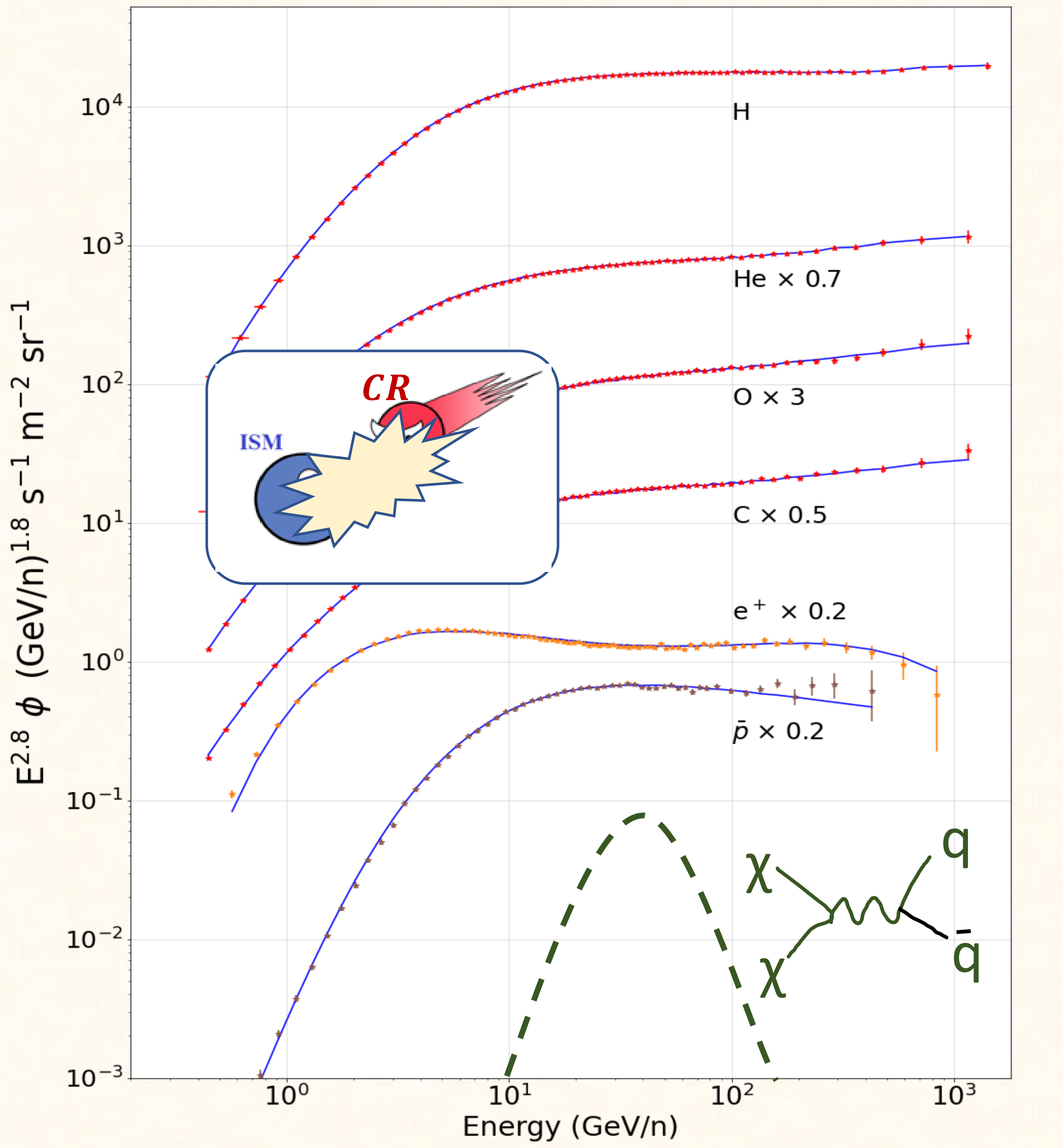
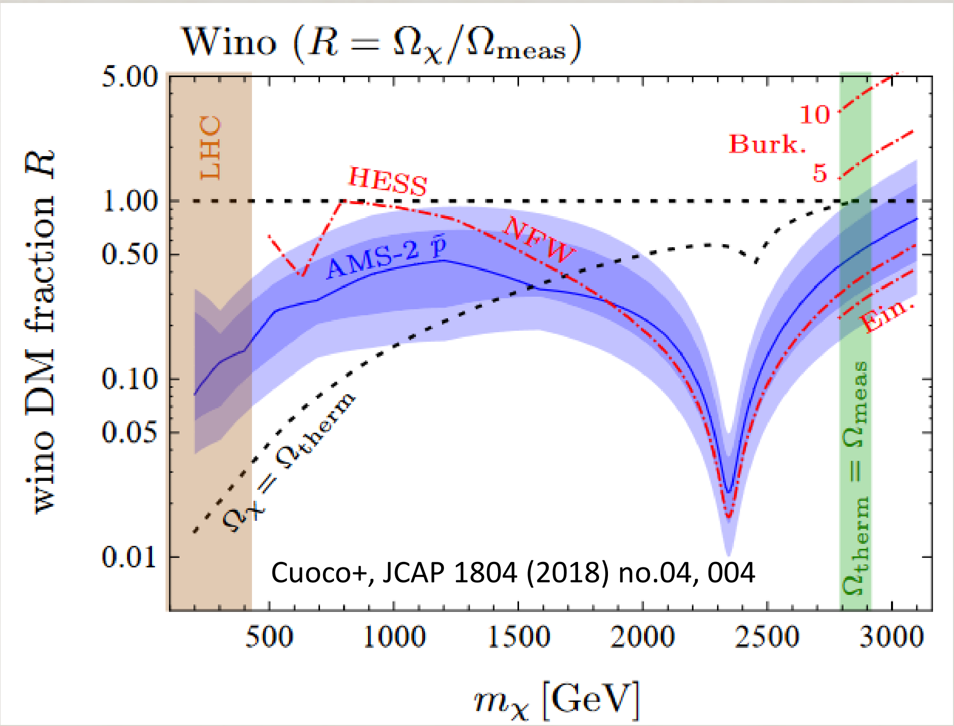
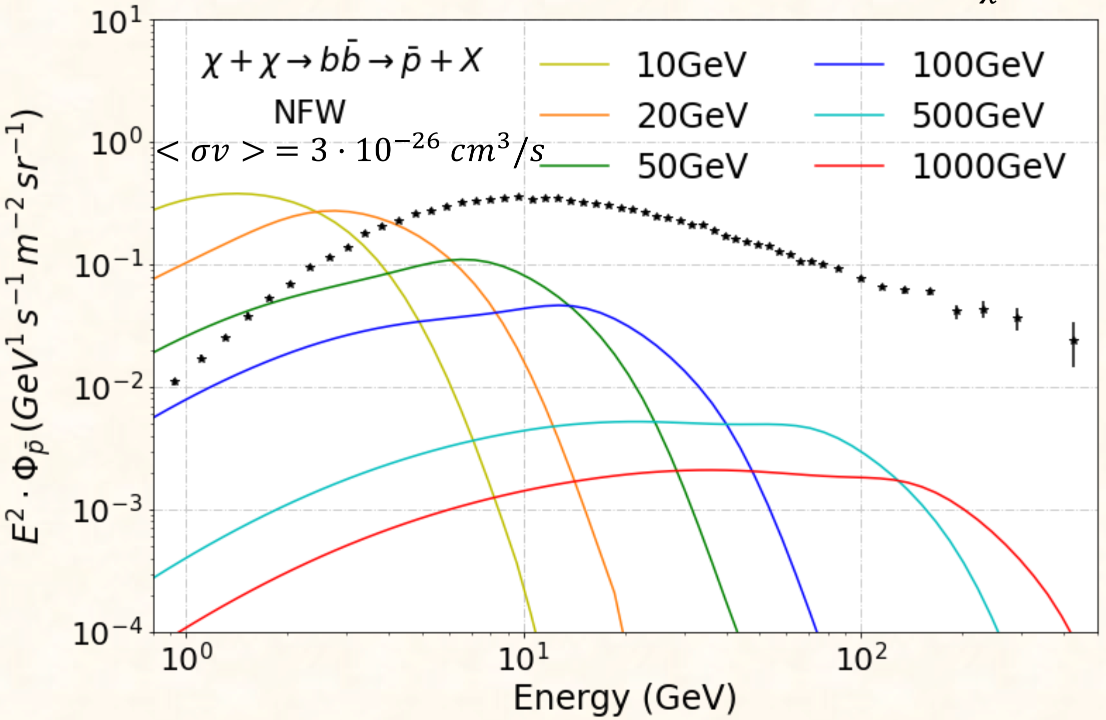


DM production - Primary antiprotons

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





Cosmic-ray production
Secondary antiprotons

Combined fits with other secondary CRs allows us to estimate the diffusion coefficient more accurately. The whole CR network must be accurately modelled

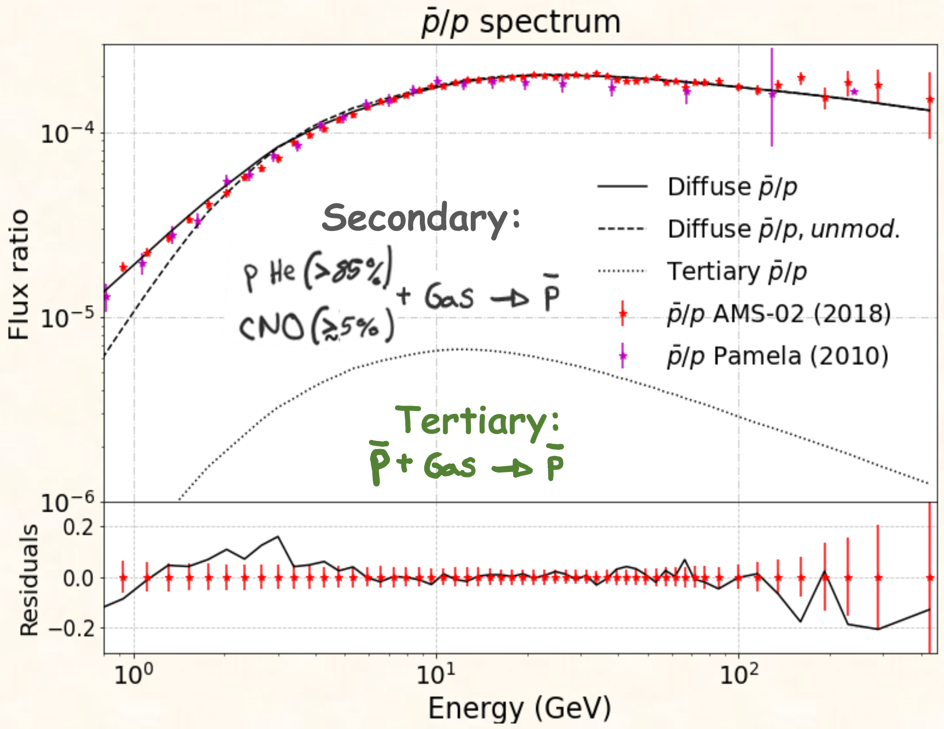
Main production channel: p + p → p + p + $\bar{\mathrm{p}}$ + p

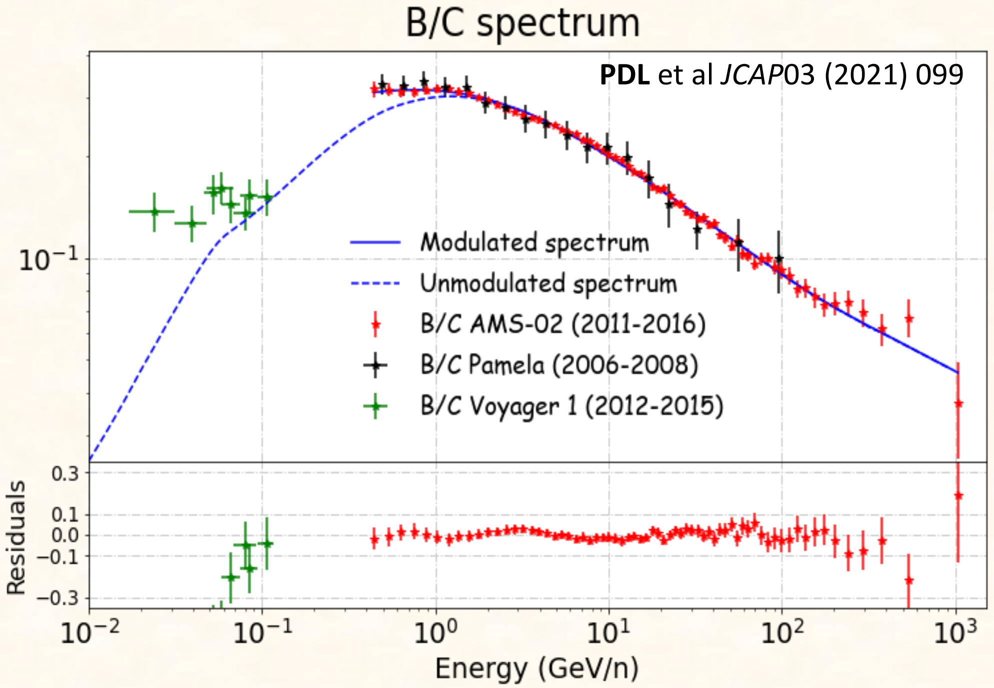
He still accounts for almost 30% of the production and heavier CRs must contribute to more than 10%

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

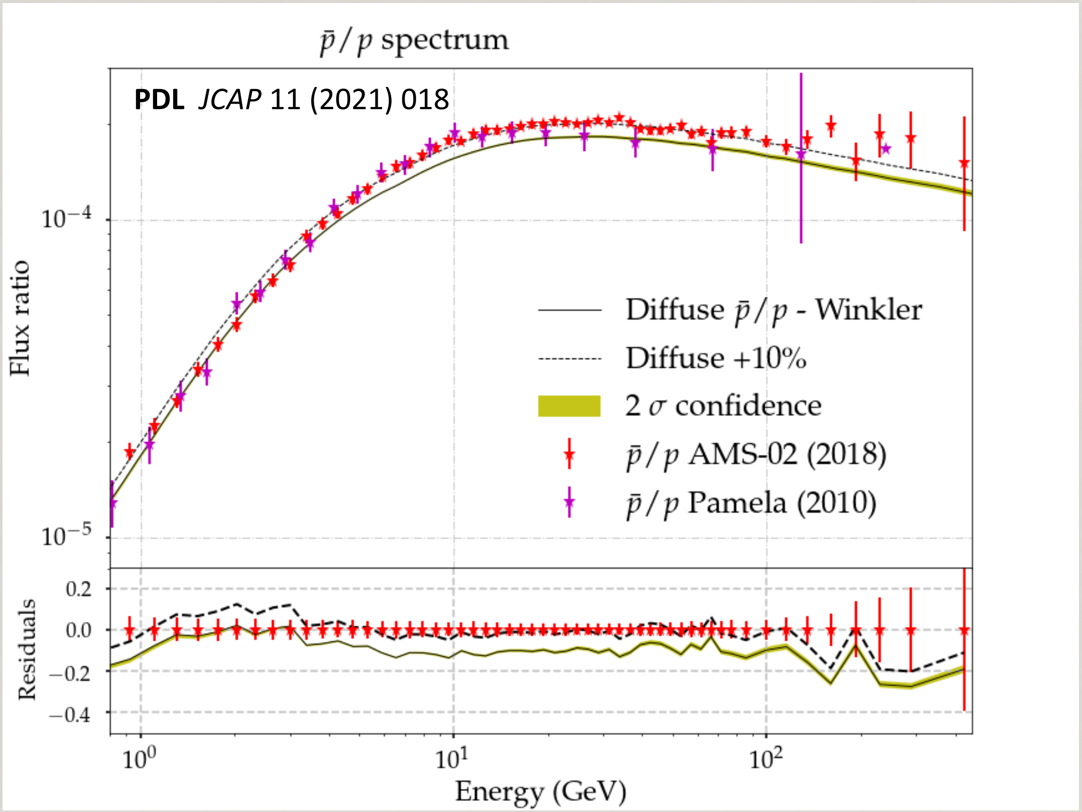
Diffusion coefficient

Production cross sections

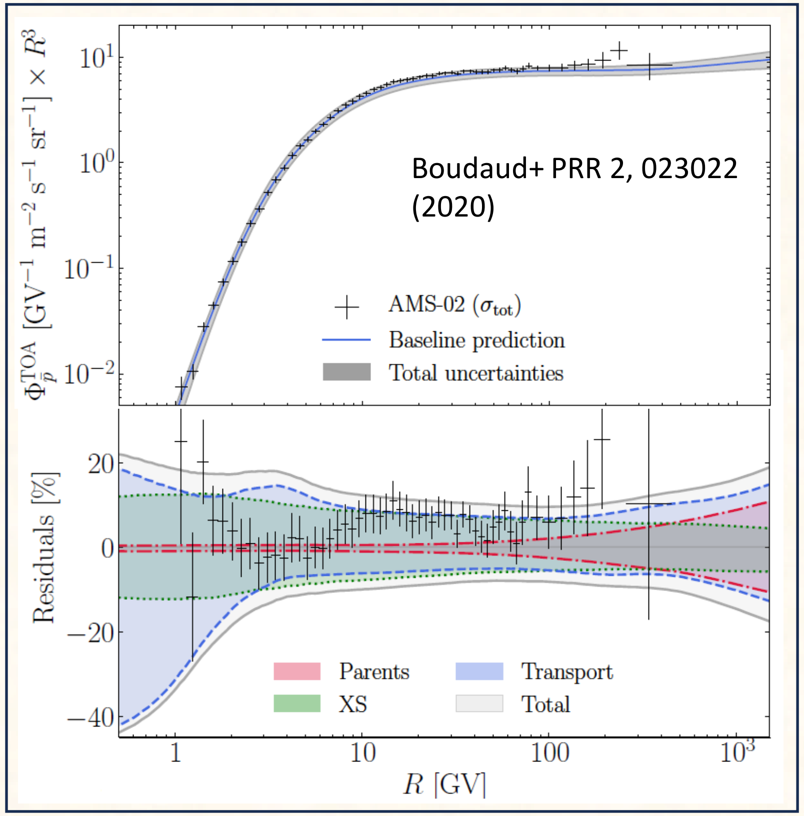




Cosmic-ray antiproton (secondary) production

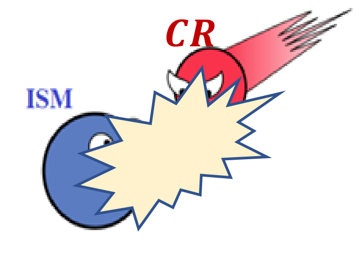


Antiproton observations are fully compatible with a secondary origin. All secondary CRs can be well explained after accounting for cross sections and propagation uncertainties



Cross sections are derived from parameterizations fitted to scarce data, which lead to **uncertainties ~ 10-20%**

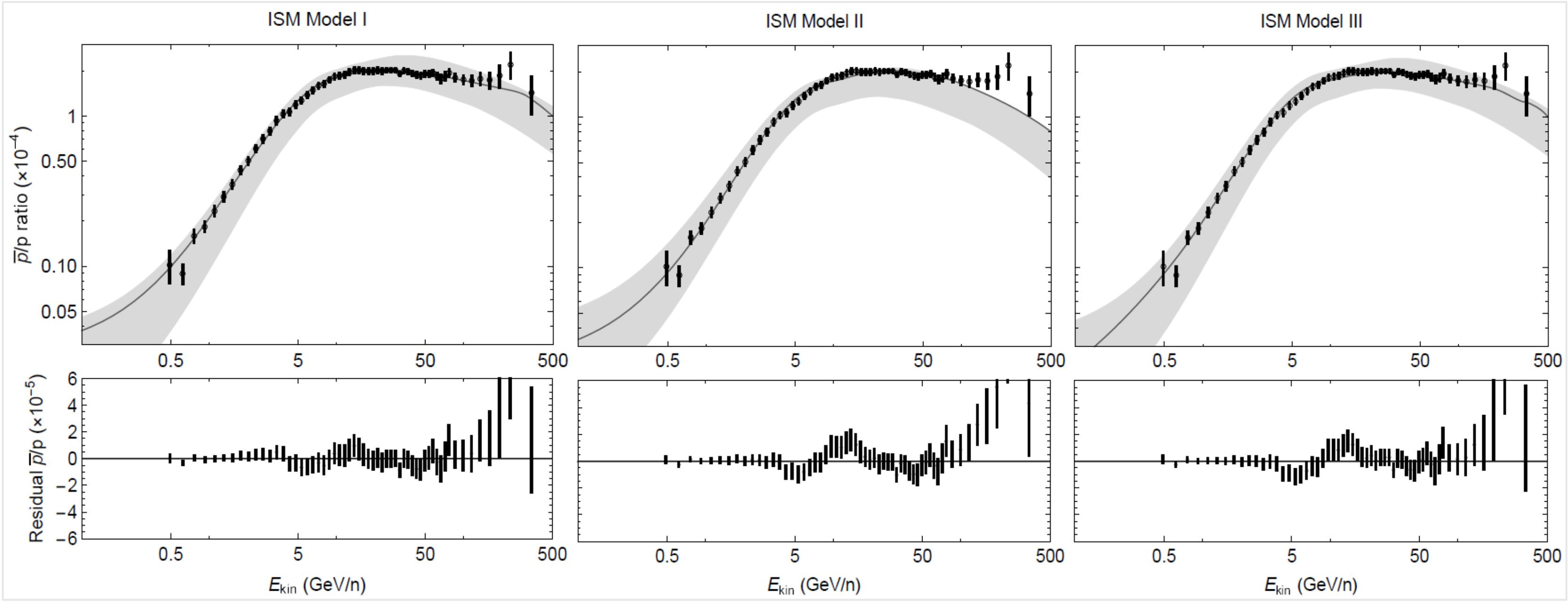
The Antiproton *excess*



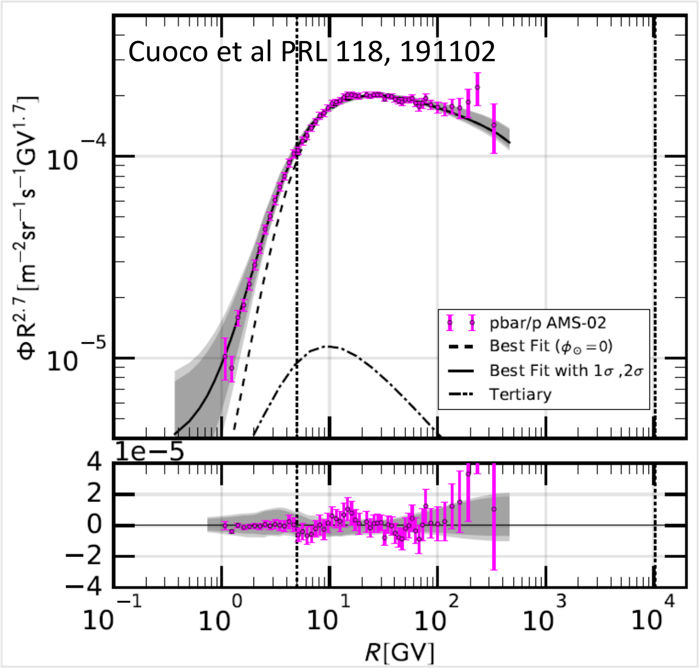
Recent studies have claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

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

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



Cholis, Linden, Hooper PRD 99, 103026



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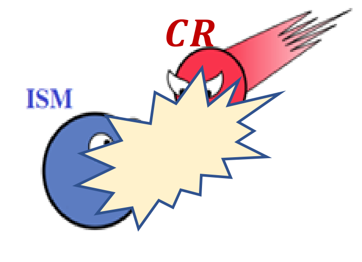

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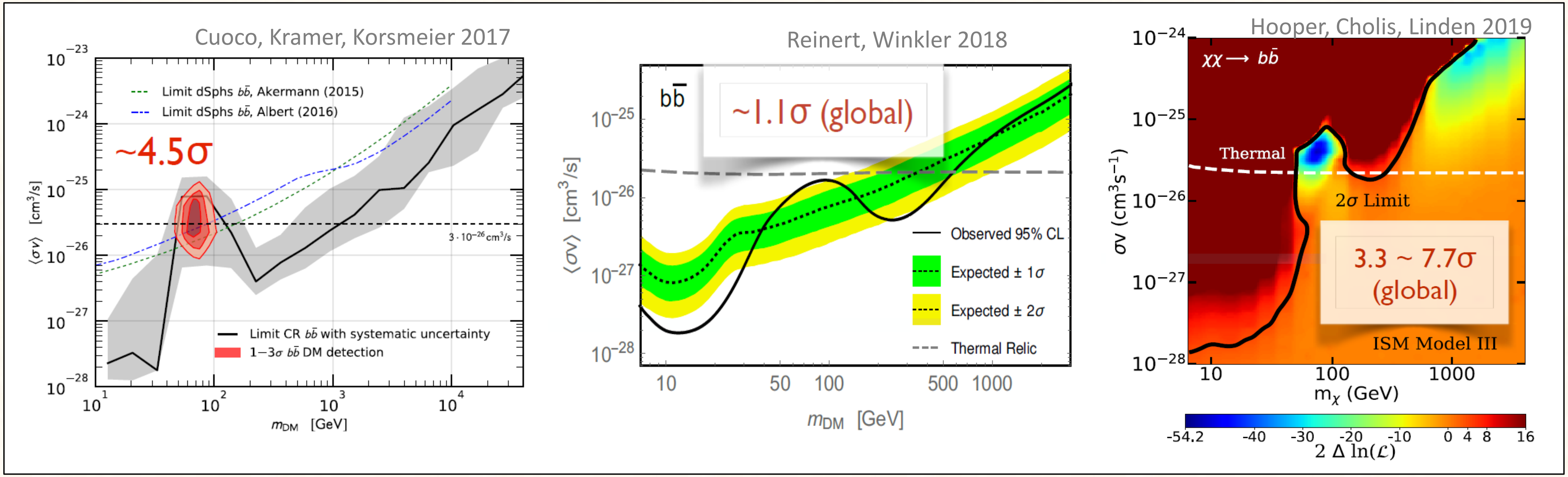
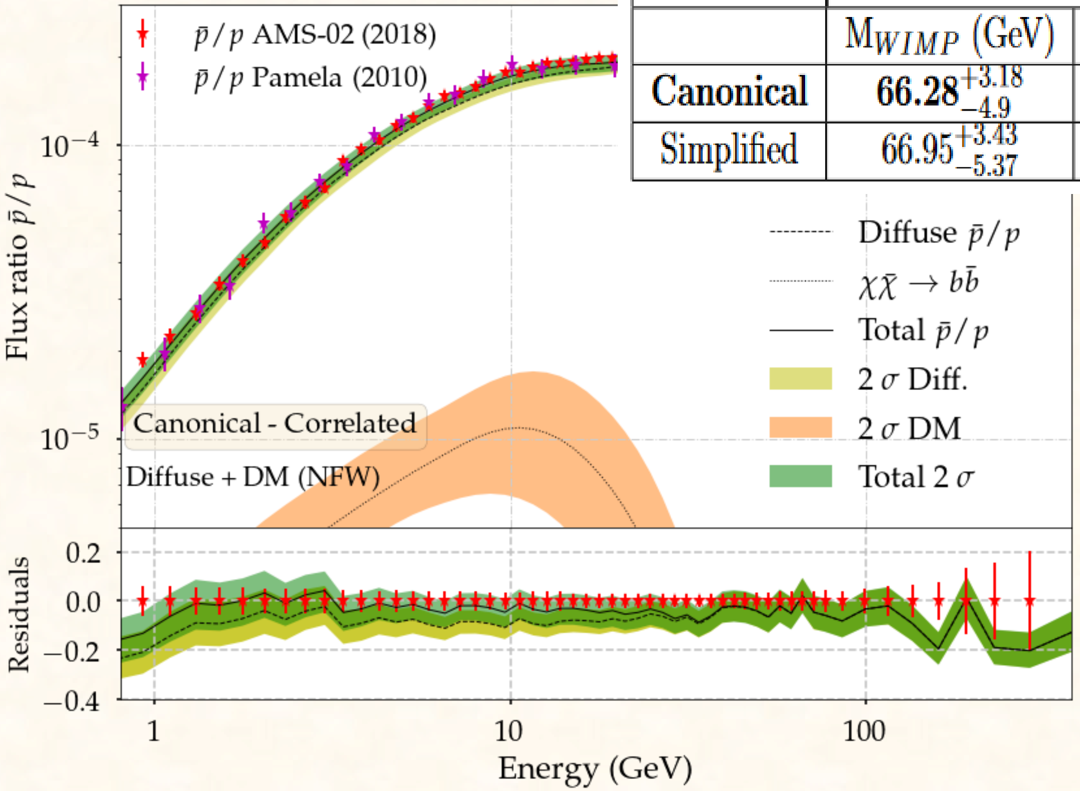


The difference from excess to fluctuation

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 ~2σ global)**

PDL+, JCAP 05 (2024) 104

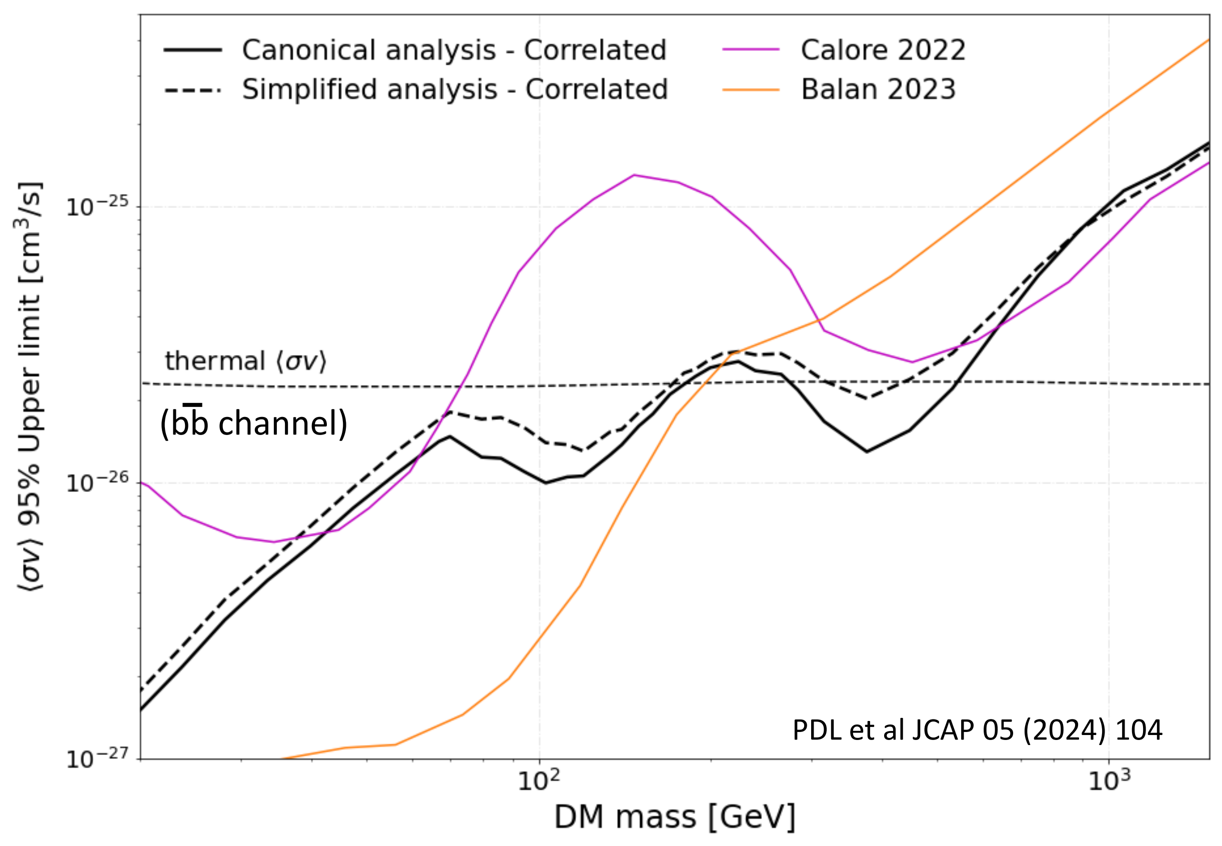
	Correlated AMS-02 errors			Uncorrelated AMS-02 errors		
	M_{WIMP} (GeV)	$\langle\sigma v\rangle$ (10^{-26} cm^3/s)	local σ	M_{WIMP} (GeV)	$\langle\sigma v\rangle$ (10^{-26} cm^3/s)	local σ
Canonical	$\mathbf{66.28^{+3.18}_{-4.9}}$	$\mathbf{0.99^{+0.2}_{-0.21}}$	**2.8**	$51.1^{+3.14}_{-3.89}$	$0.89^{+0.18}_{-0.18}$	3.5
Simplified	$66.95^{+3.43}_{-5.37}$	$1.18^{+0.26}_{-0.27}$	3.03	$100.64^{+9.4}_{-9.05}$	$2.01^{+0.40}_{-0.35}$	3.8



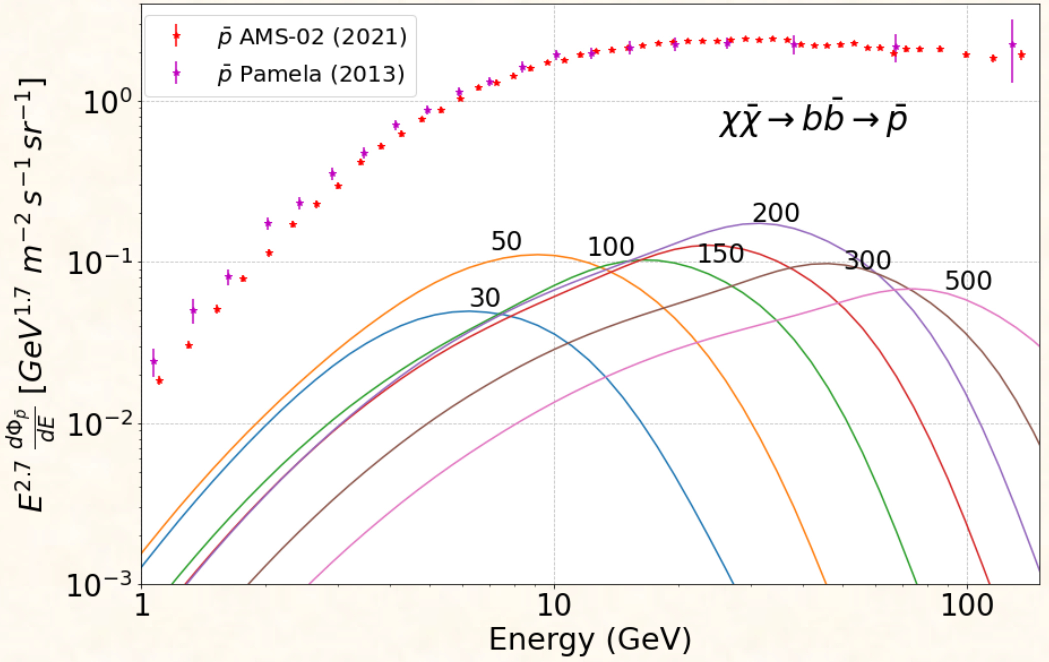
Calore+, SciPost Phys. 12, 163 (2022)

Final state	Model	m^* [GeV]	$\langle\sigma v\rangle^*$ [cm^3/s]	local signif. [σ]
$b\bar{b}$	BIG	109.3	1.71e-26	1.8
$b\bar{b}$	SLIM	109.1	1.48e-26	1.7
$b\bar{b}$	QUAINT	106.7	4.28e-27	0.5
$q\bar{q}$	BIG	88.5	4.41e-27	1.2
$\mu^+\mu^-$	BIG	155.7	2.65e-23	1.4
W^+W^-	BIG	106.8	2.20e-26	1.6
hh	BIG	166.7	3.62e-26	1.5

Dark matter bounds from antiproton analyses



Maximal DM-induced signal (at 95% CL)

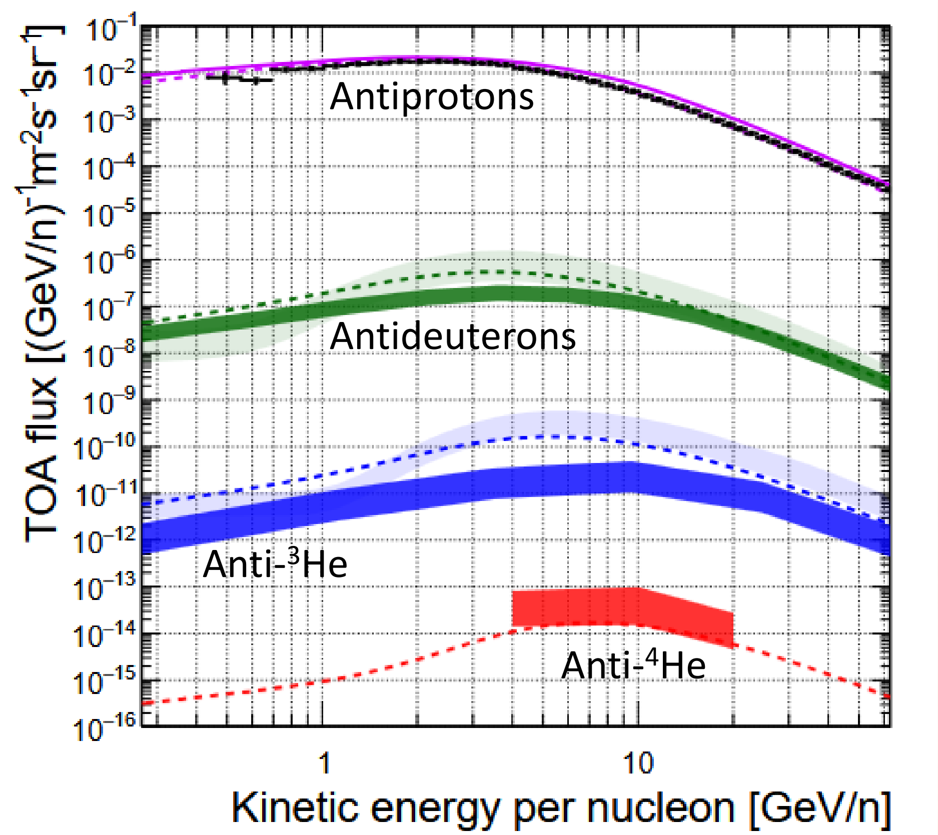


No excess found in the latest $\overline{\text{p}}$ analyses

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

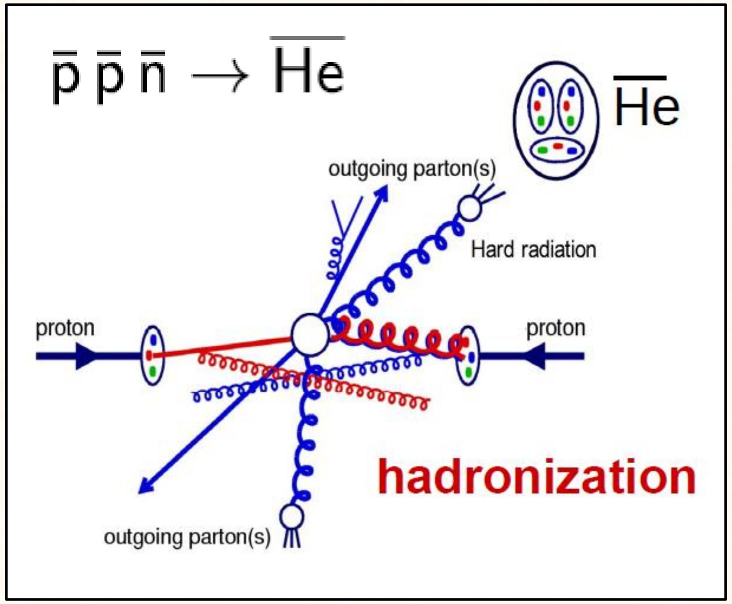
Anti-nuclei as the dark matter smoking gun

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

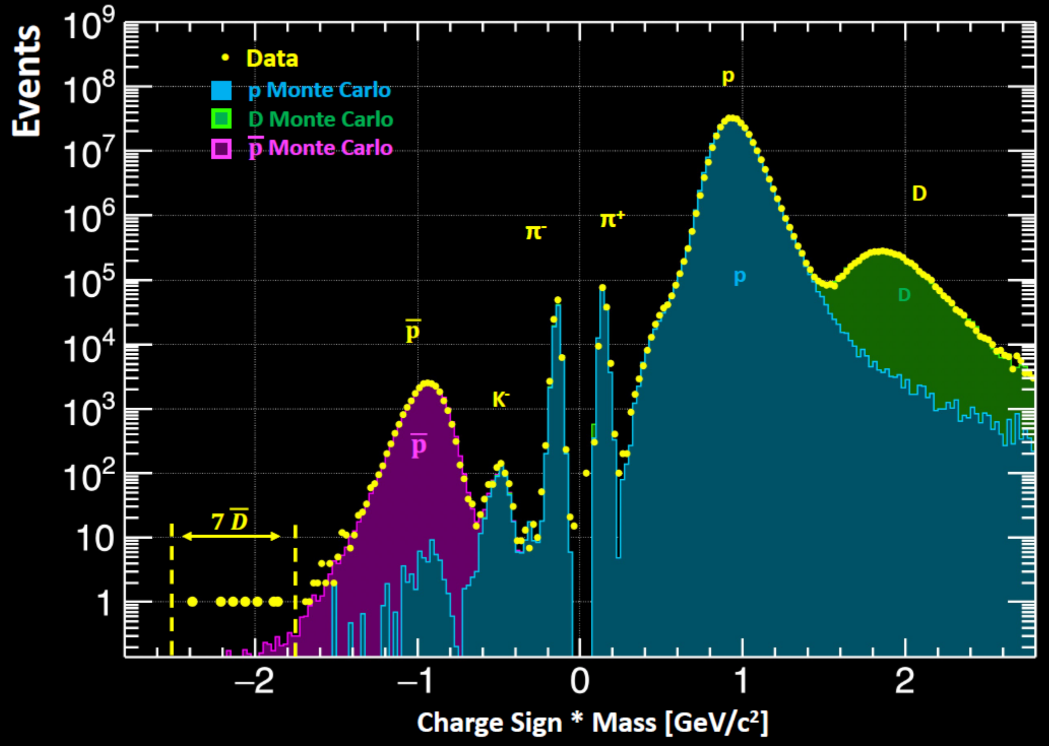


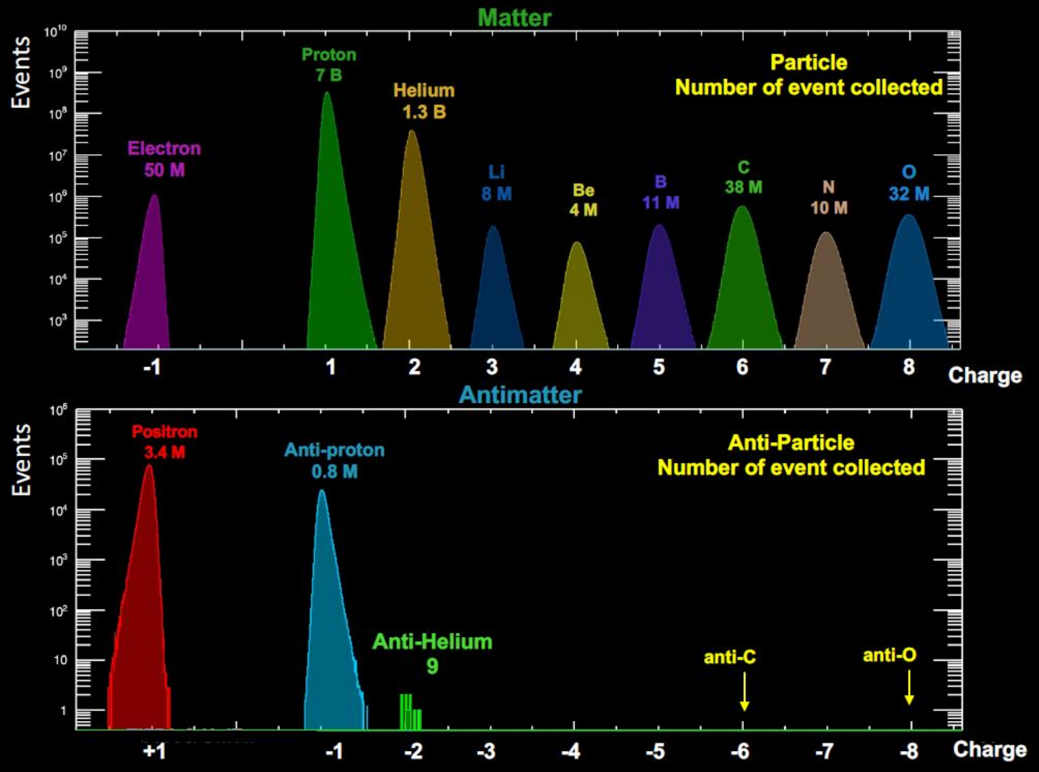
Shukla *PRD* 102, 063004 (2020)

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



ANTI-NUCLEI: AMS-02 mass-charge spectra





Paolo Zuccon MIAPP 2021

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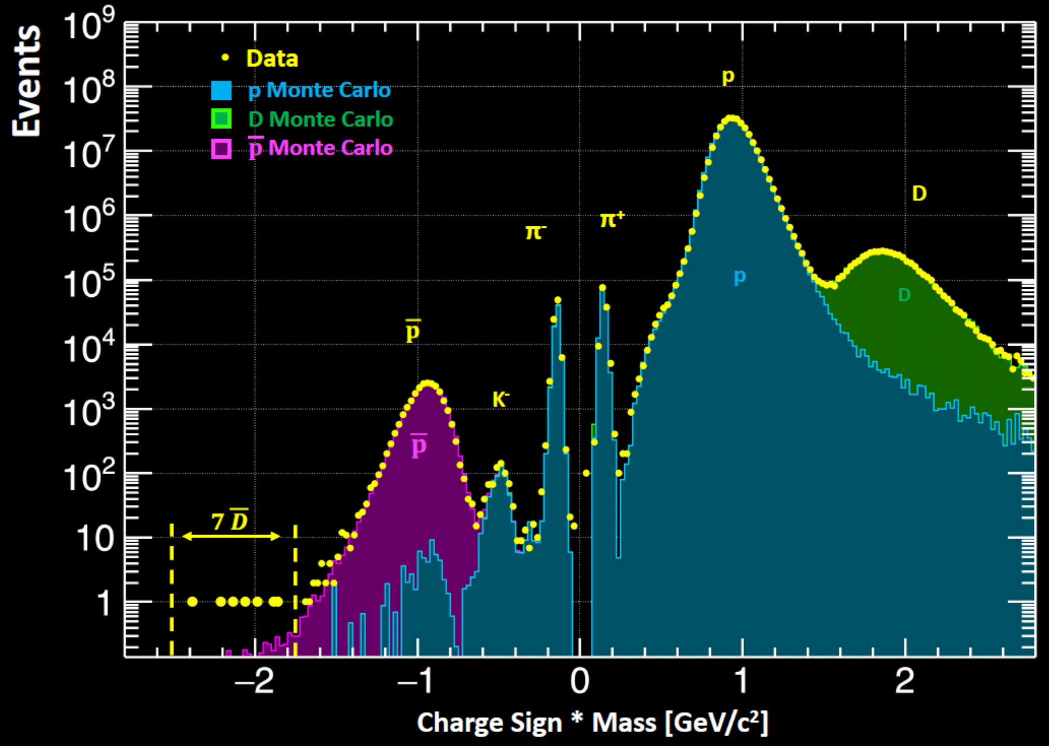

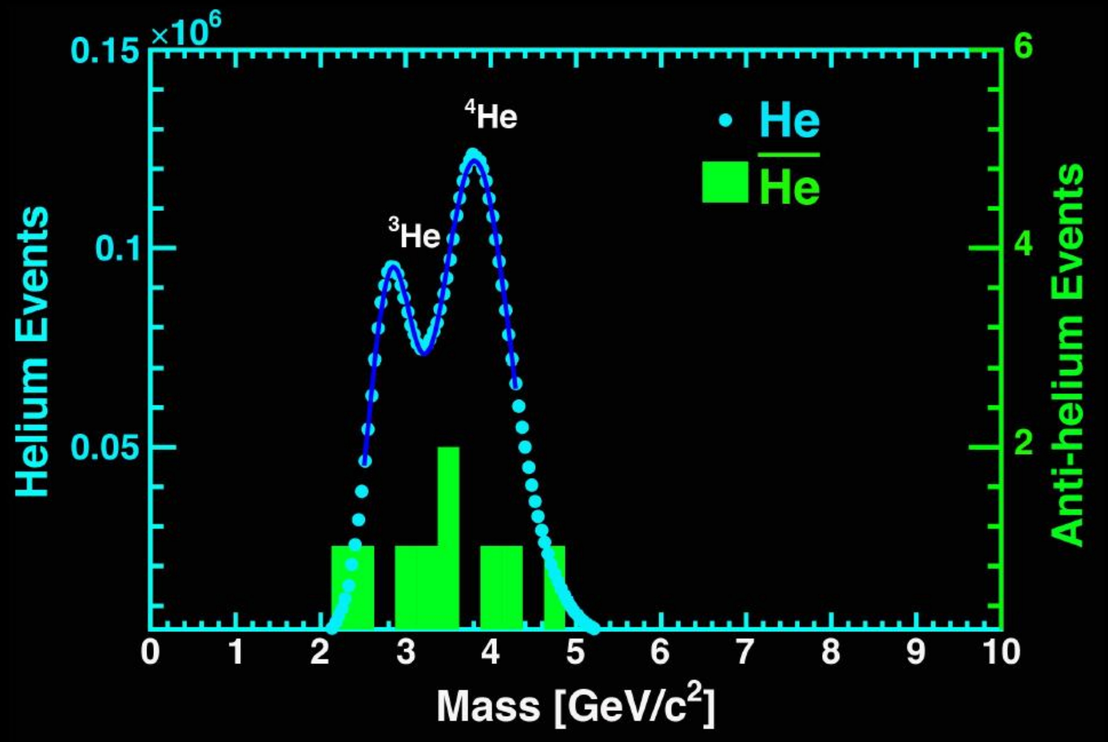

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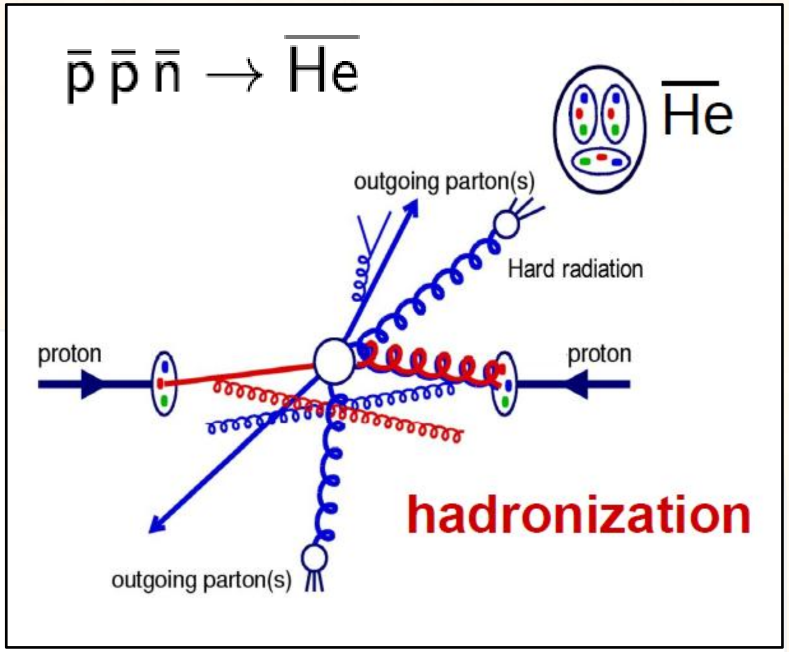
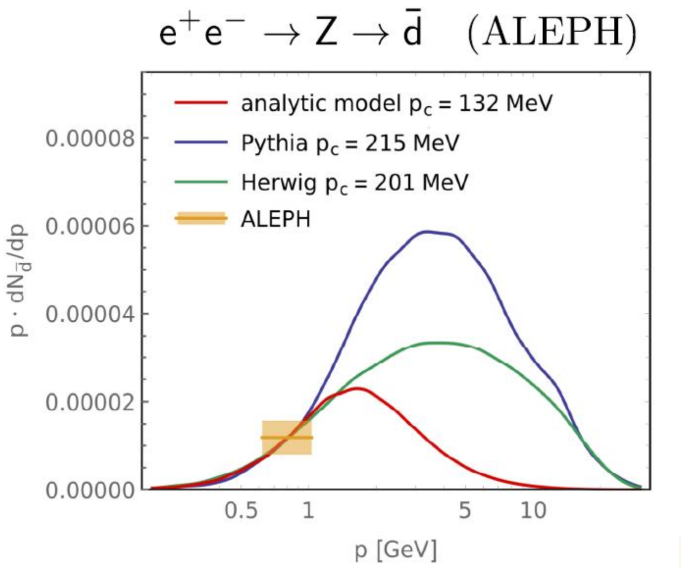
Formation of anti-nuclei



- Simplest coalescence model: *Factorised coalescence*

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

But antineutrons and antiprotons are produced uncorrelated! $E_{\bar{A}} \frac{d^3 N_{\bar{A}}}{dp^3_{\bar{A}}} \simeq B_A \left(E_{\bar{p}} \frac{d^3 N_{\bar{p}}}{dp^3_{\bar{p}}} \right)^A$



Other treatments, mostly based on Monte Carlo event generators, like Pythia, are used to account for correlations.

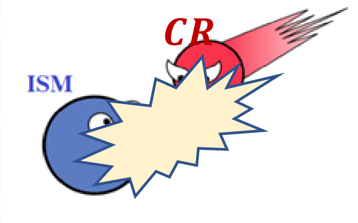
The main requirement is that the nucleons coalesce if they are close enough in space and momentum.

Other approaches have used the Wigner formalism, which allows to compute the coalescence probability in an event-by-event basis

2404.13114, 2006.16251, 2012.04352, 2411.04815

Astrophysical production

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

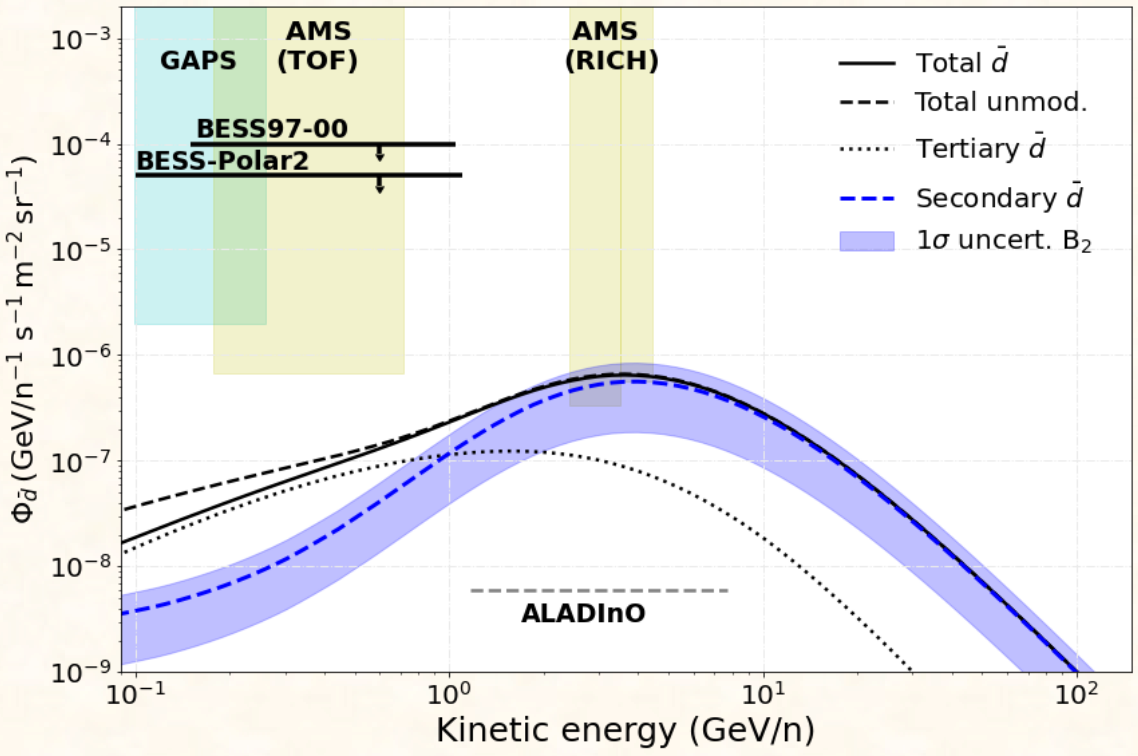


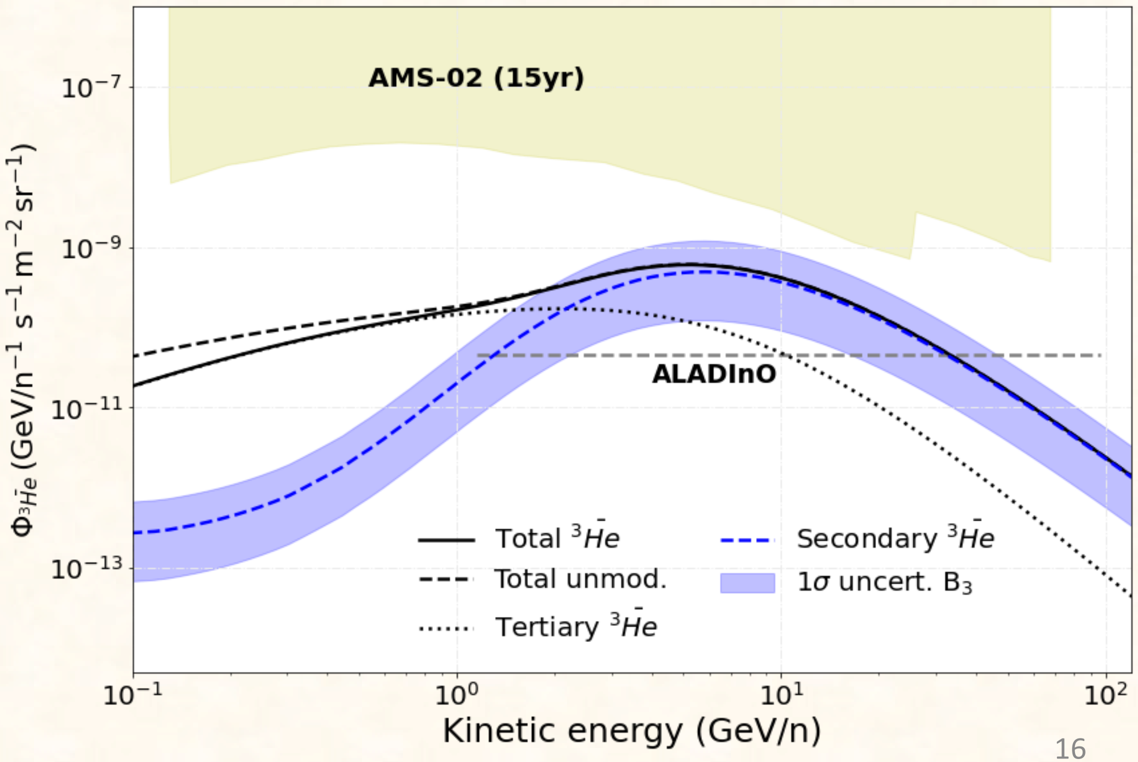
Can we explain the AMS-02 measurements without invoking any exotic source?

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

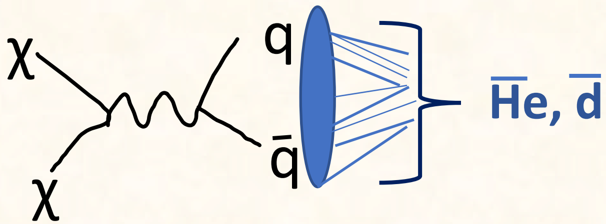
We expect to have measurements of the $\bar{\text{d}}$ flux in the next years!! But no $\overline{\text{He}}$ until ALADInO or AMS-100 (foreseen to 2039)

PDL et al, ArXiv: 2404.13114



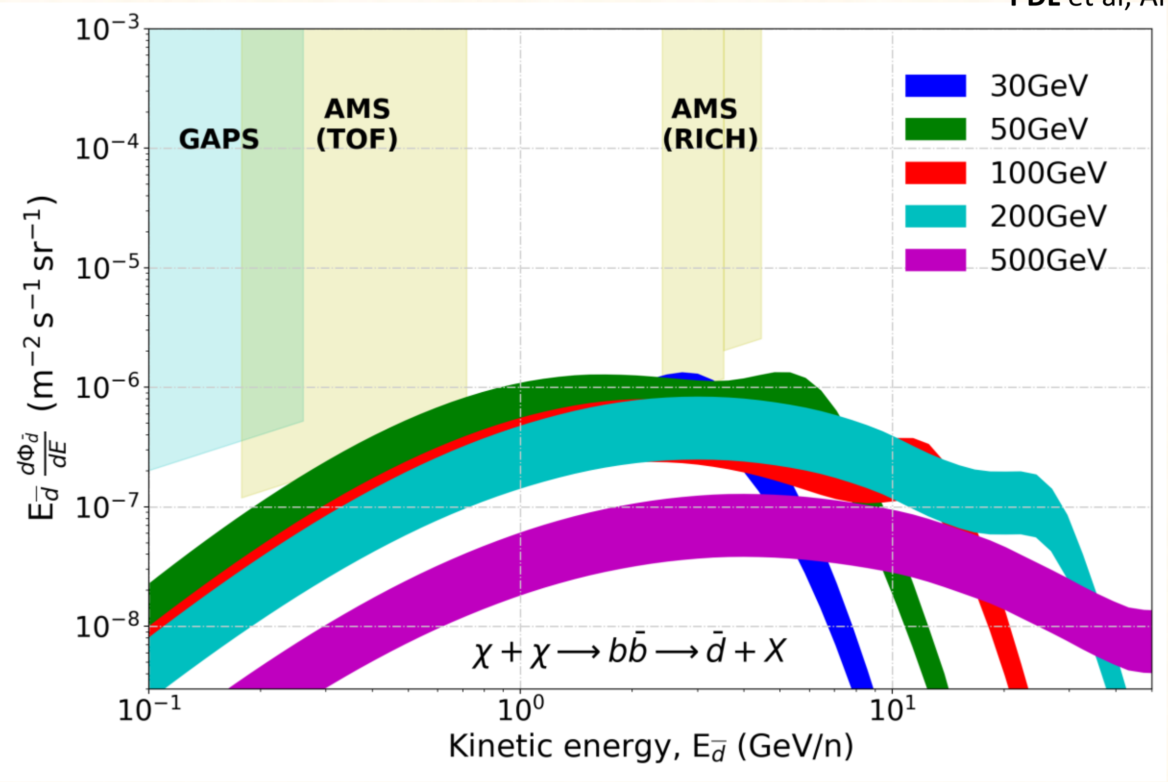


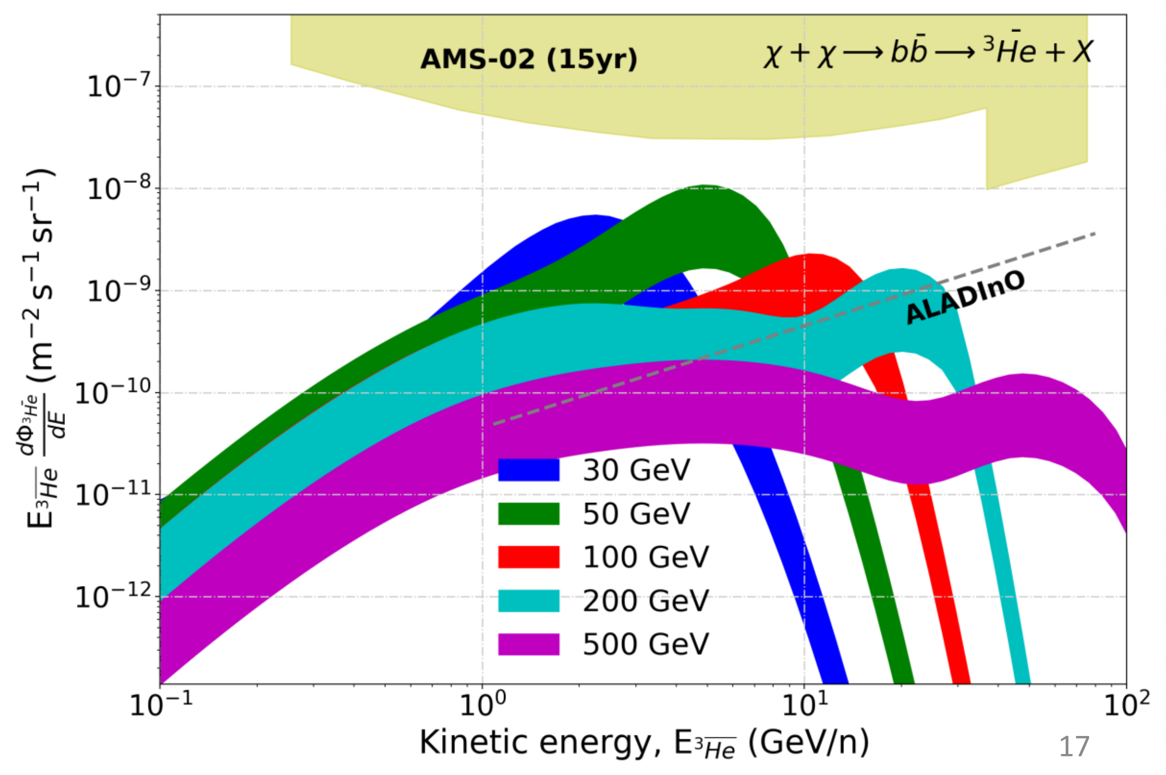
DM production: Upper Limits



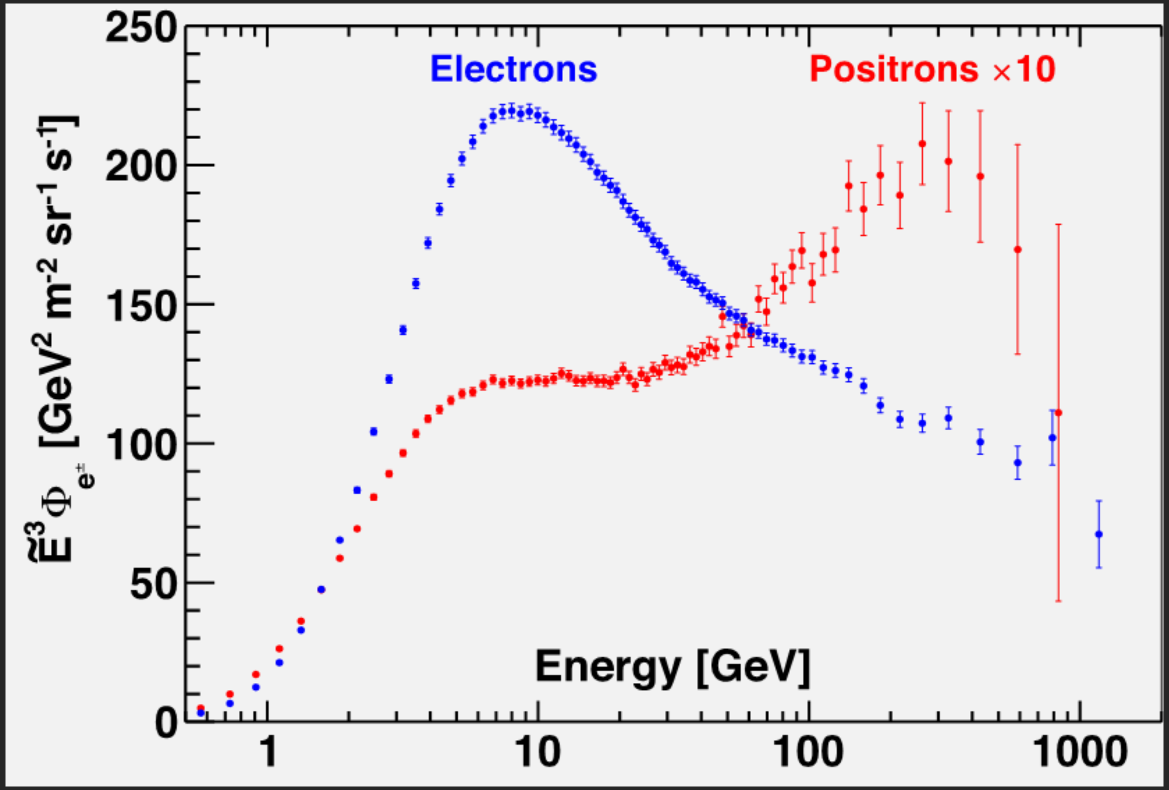
Maximal antinuclei flux allowed from our antiproton bounds. Even in optimistic cases, it seems we cannot explain the detection of a single antihelium-3 event by AMS-02, And clearly, we are **unable to explain any detection of antihelium-4 by AMS-02**…

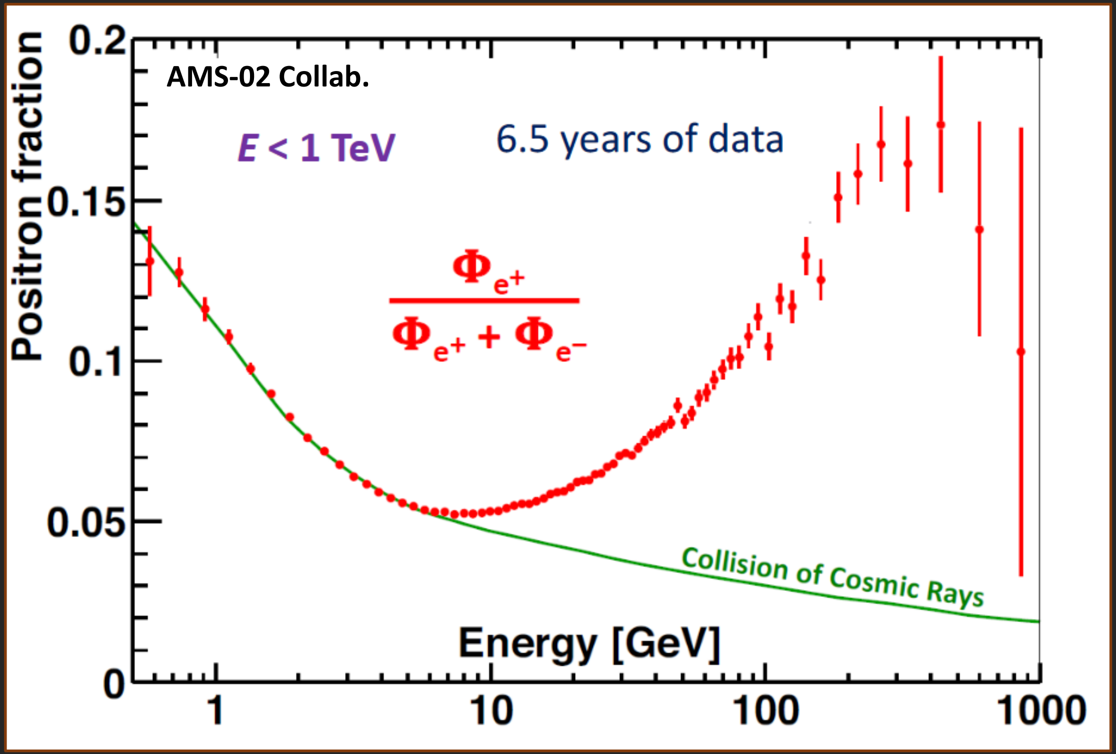
PDL et al, ArXiv: 2404.13114





The positron spectrum





The Pamela experiment showed a clear rise in the detected flux of positrons, which requires a new source of positrons.

What is this source of e^+?

The positron excess

This component would require a ~TeV DM particle with annihilation rate of a few times $10^{-24}\ cm^2/s$ (in tension with other constraints and above the thermal!)

Main astrophysical explanation: **Pulsars**

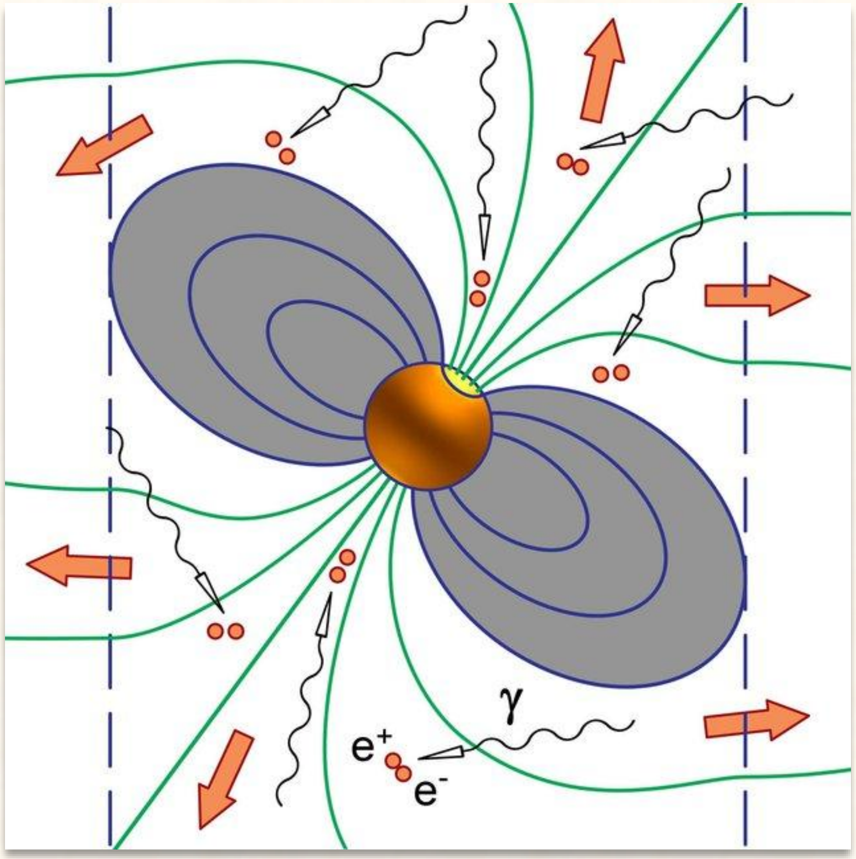
Cheng, Ho & Ruderman (1986–1990) — Predicted copious electron–positron pair production in magnetospheres

Stawarz, Aharonian & Malyshev (2003–2006) — Pulsar wind nebulae accelerate e^+e^- and escape into ISM

Hooper, Blasi & Serpico (2009) —Pulsars explaining the PAMELA excess

Consensus in the comunity that these signals must be dominant source of high-energy positrons

An astrophysical source of cosmic-ray positrons (and electrons) was not considered: **Nearby pulsars**



Production of positrons and DM identification

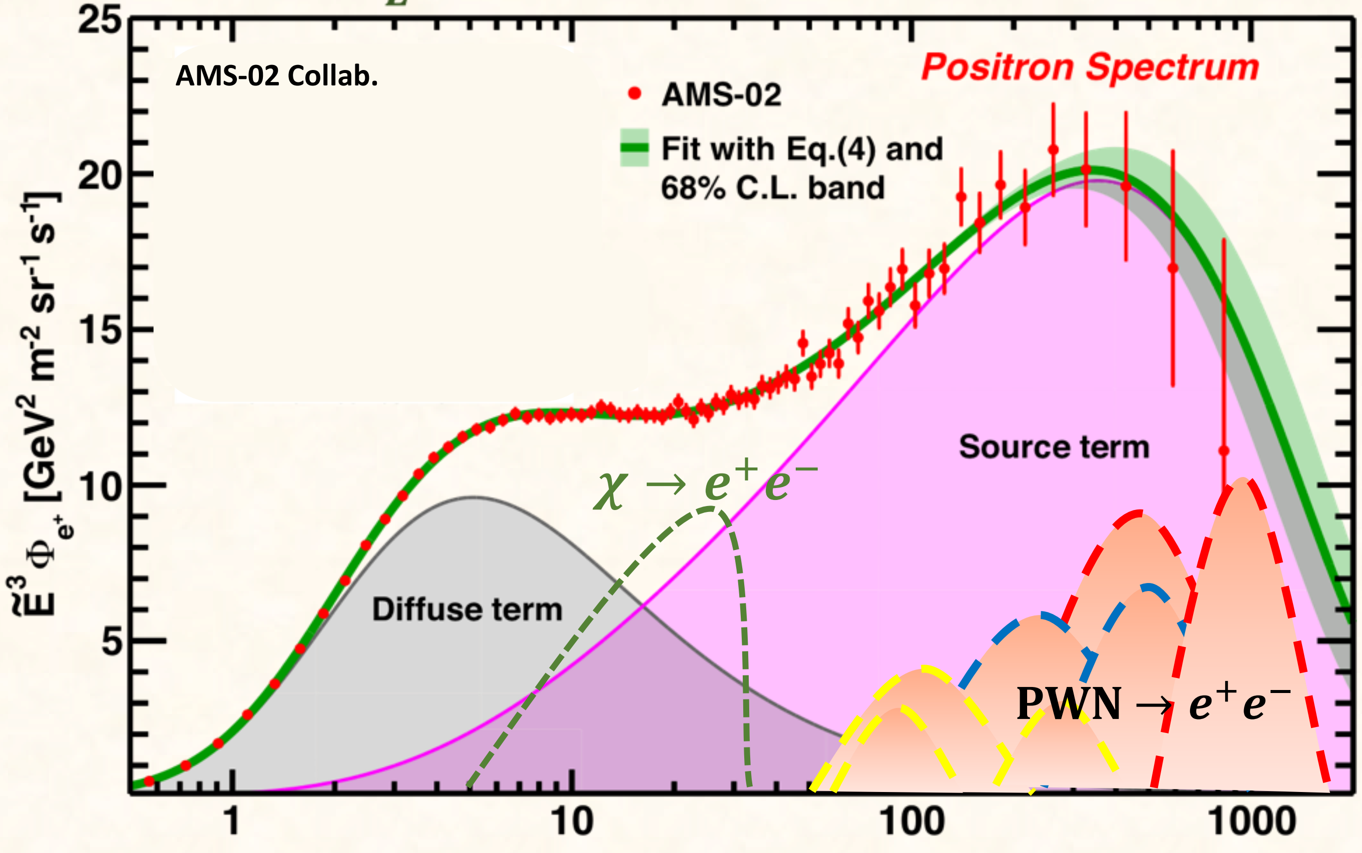
While conventional DM scenarios appear disfavoured, sub-dominant DM contributions may still be hidden.

But the stochastic nature of the PWN emission makes it difficult to find signatures of DM at high energies

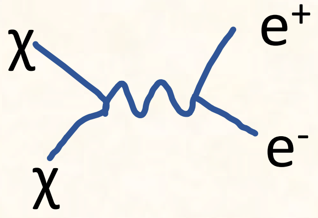
The low energy (diffuse) part might allow us to identify DM signals more easily, but it is uncertain by a factor of a few -- halo height, diffusion coefficient, Solar modulation, Cross sections (e.g. 2305.02958).

Diffuse term Source term

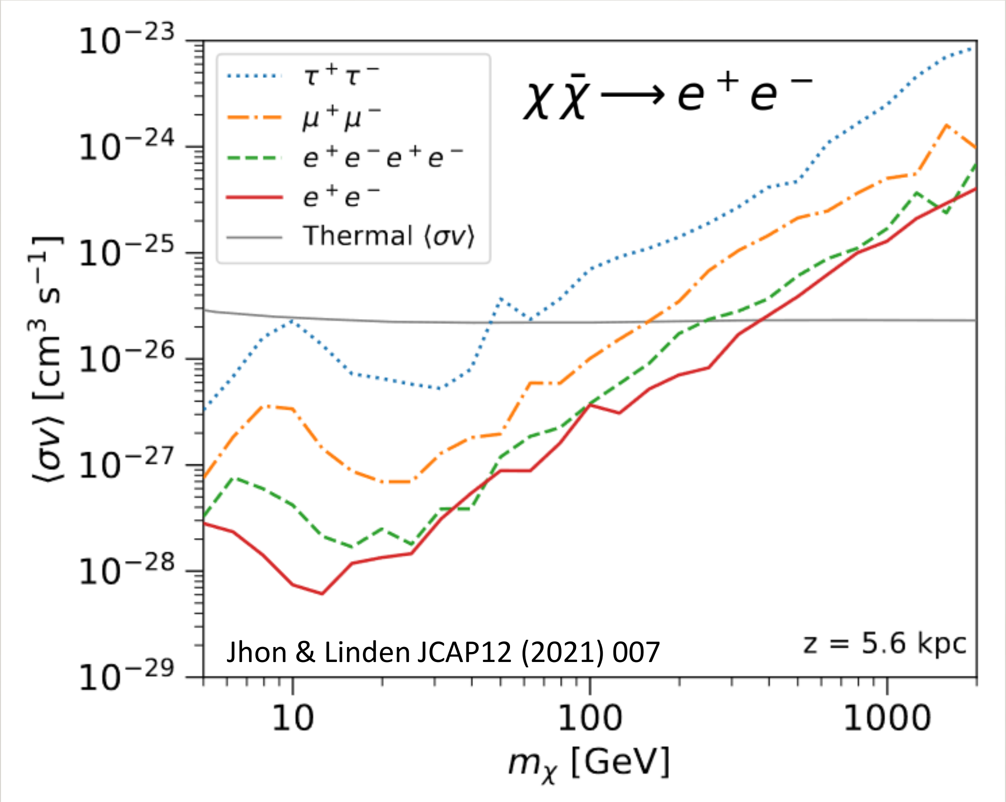
$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s\,(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

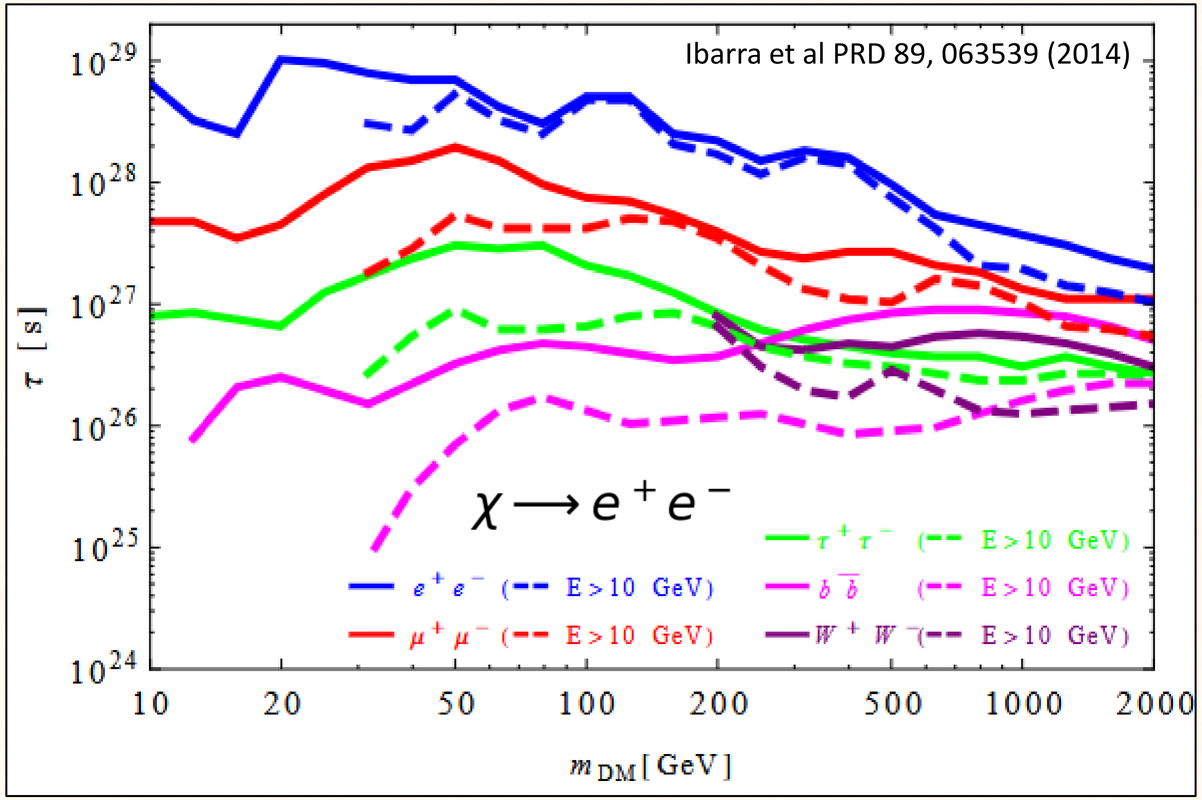


WIMP constraints from positron data



Leading constraints for leptonic channels, except for production of taus





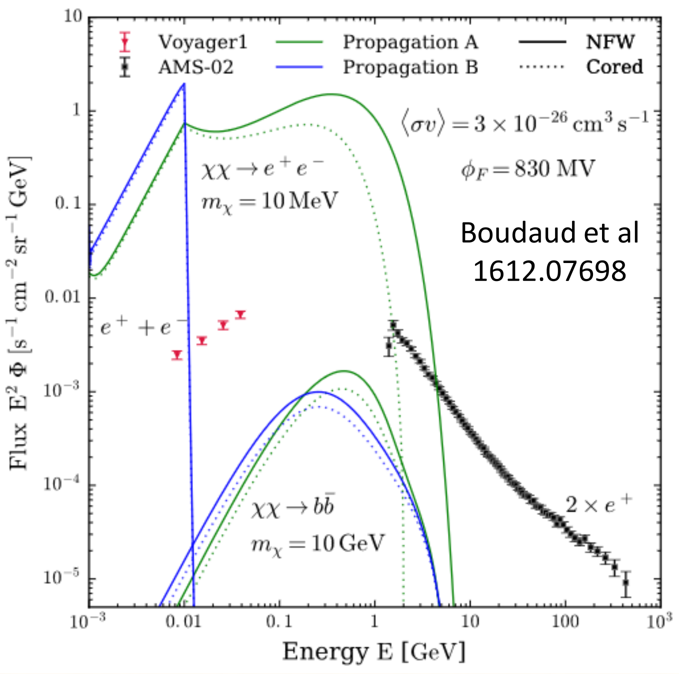
See also Krommydas & Cholis PRD 107,023003 for tests on DM identification with positron data

Beyond WIMPs: Sub-GeV DM

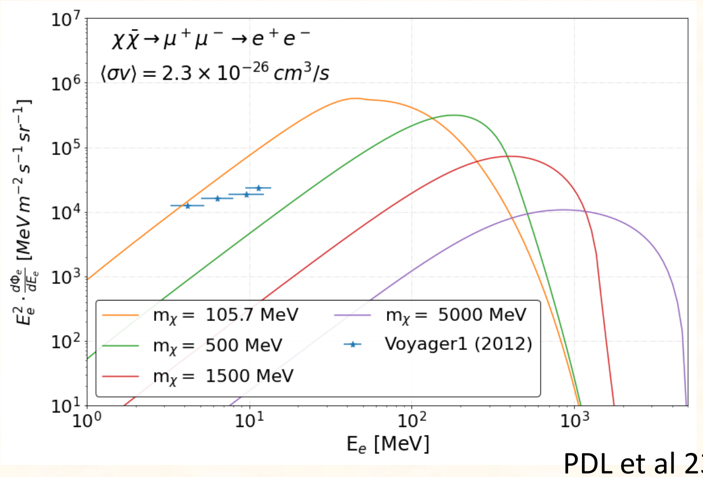
Voyager-1 provides the total e^+e^- data in the 2-50 MeV range, very valuable for probing the injection of MeV positrons in the Galaxy

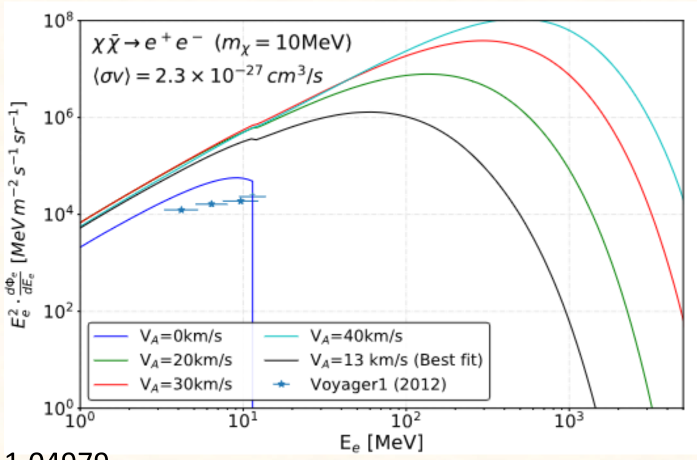
These measurements are unaffected by solar modulation, but propagation uncertainties are large (especially due to uncertainties in the level of reacceleration and the halo height)

AMS-02 can still constrain positrons reaching energies above a few hundred MeV, although this analysis requires a careful treatment of solar modulation

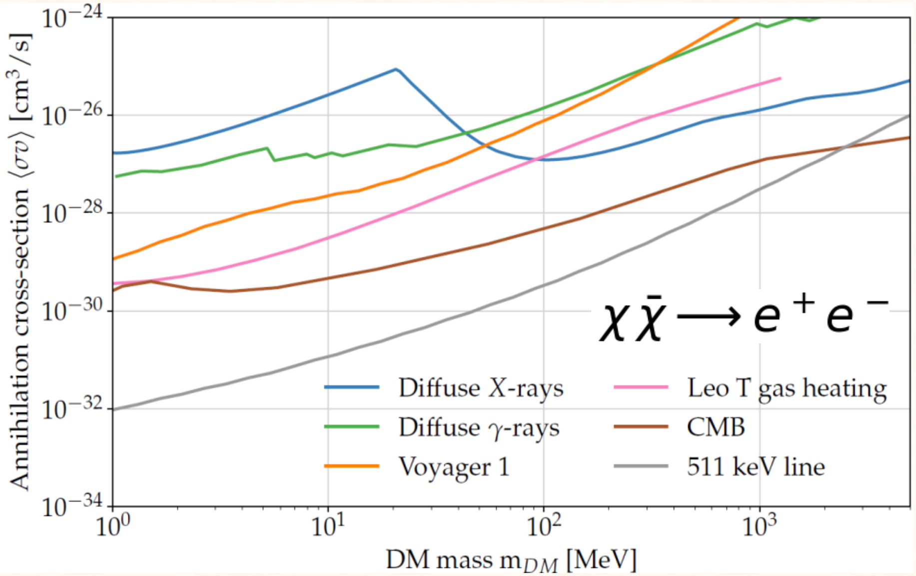


Boudaud et al 1612.07698





PDL et al 2311.04979

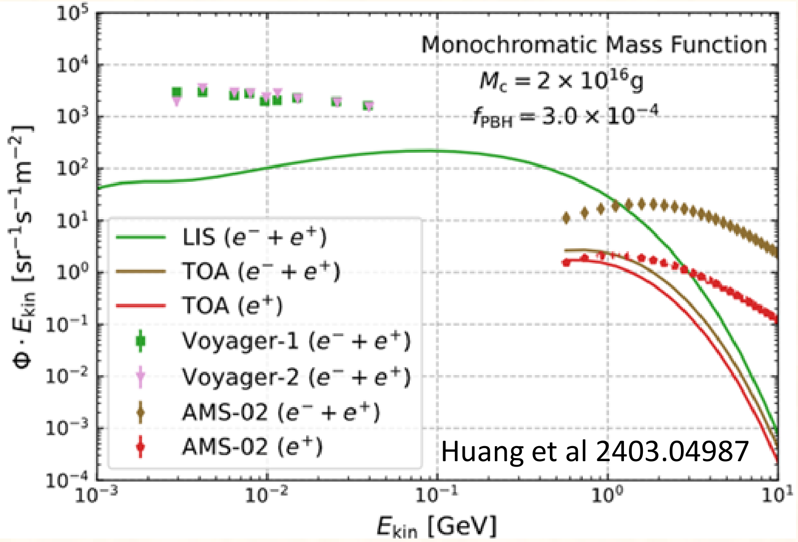


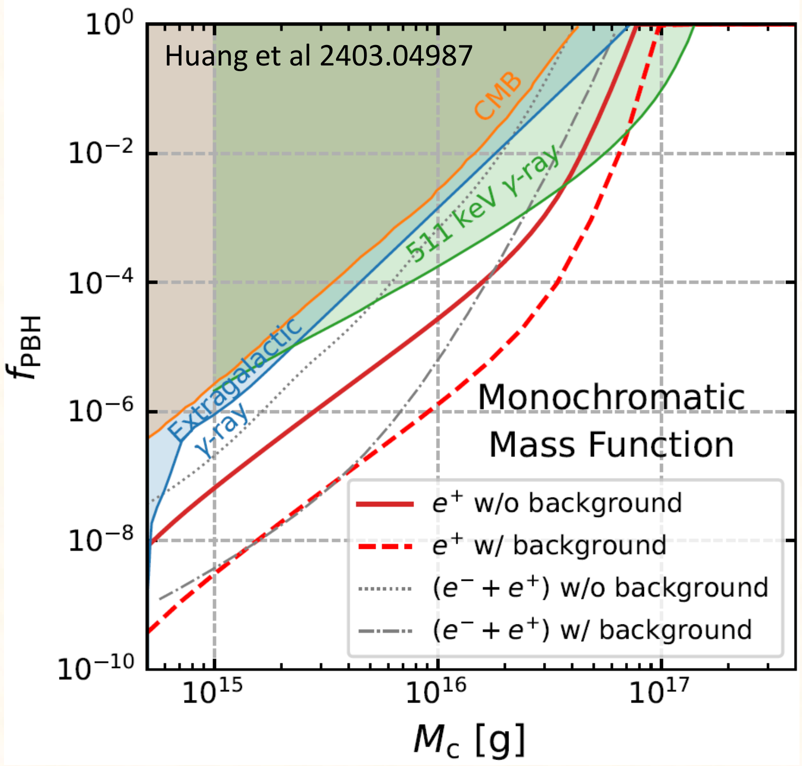
Beyond WIMPs: Light PBHs

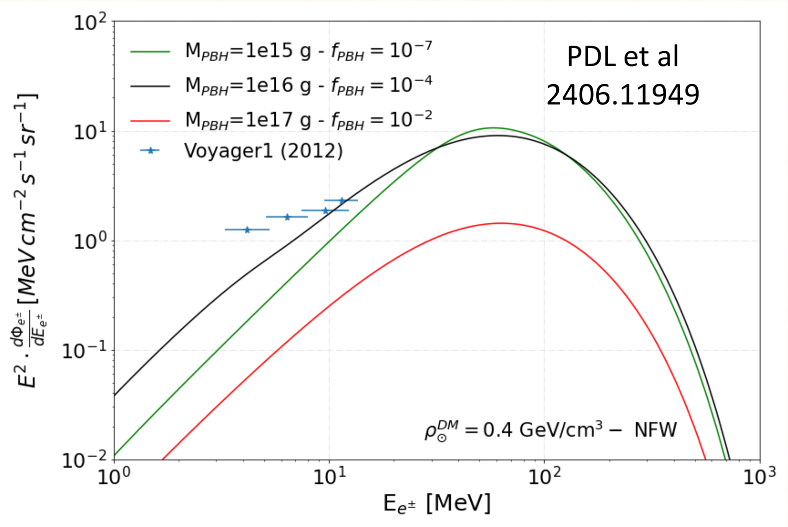
Light (asteroid-mass) **primordial black holes** evaporate via Hawking radiation**, injecting low-energy electrons and positrons into the ISM**, following a thermal grey-body spectrum

If PBHs constitute a fraction of the DM, Voyager-1 and AMS-02 can probe their emissions and constrain their abundance

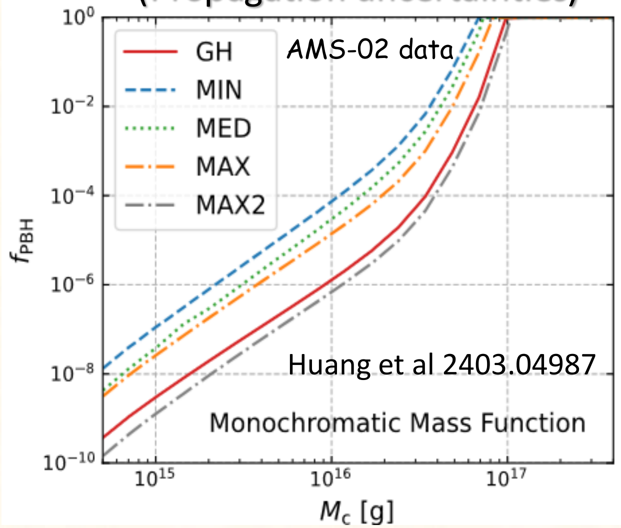
Under realistic propagation scenarios, these constraints are the strongest for PBHs with masses in the 10^{15}-10^{17} g range







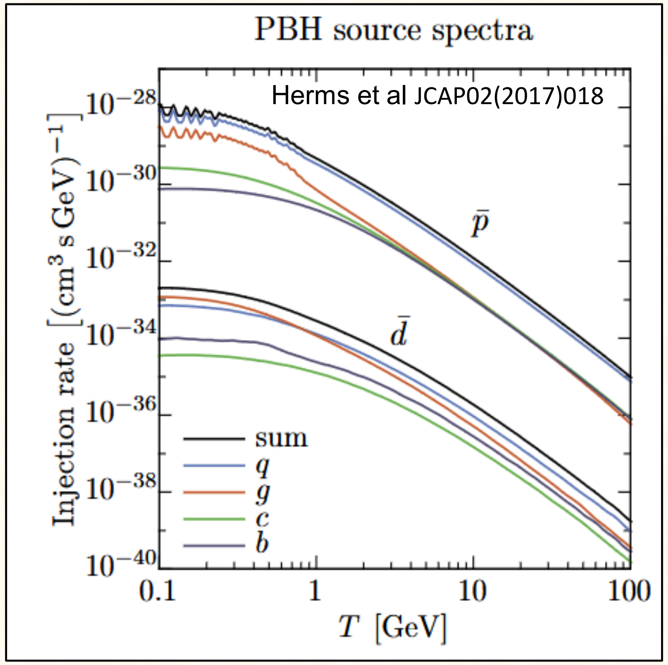
(Propagation uncertainties)

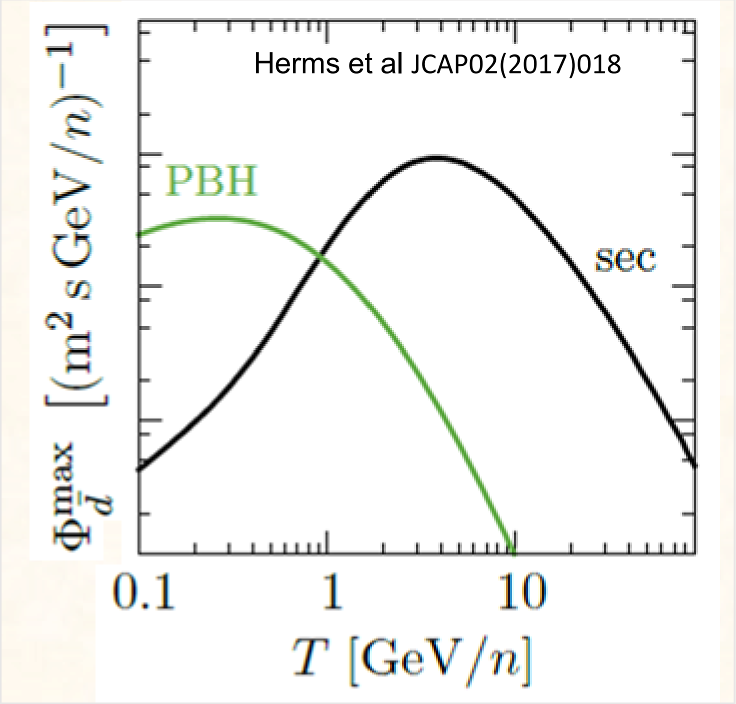


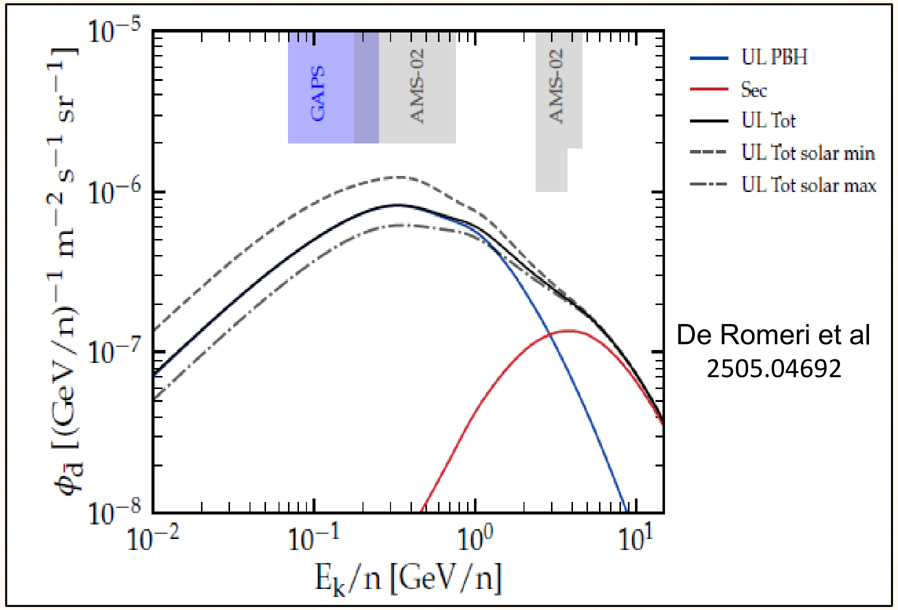
Beyond WIMPs: Light PBHs

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

$$T = \frac{hc^3}{16\pi k G M} \approx \frac{10^{13}\text{g}}{M}\ \text{GeV}$$





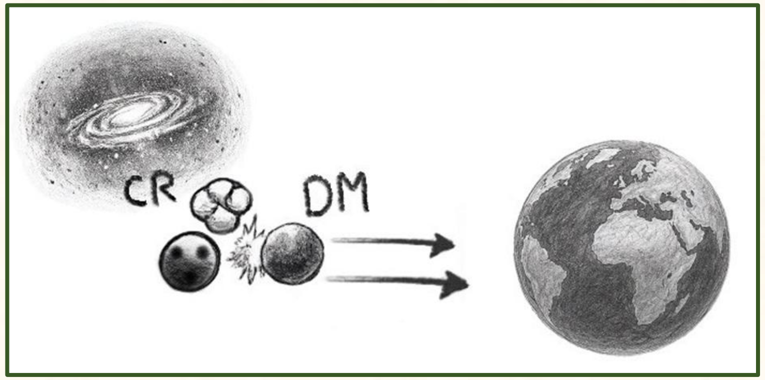


PBH evaporation can produce large quantities of antinuclei, along with photons, neutrinos, electrons, …

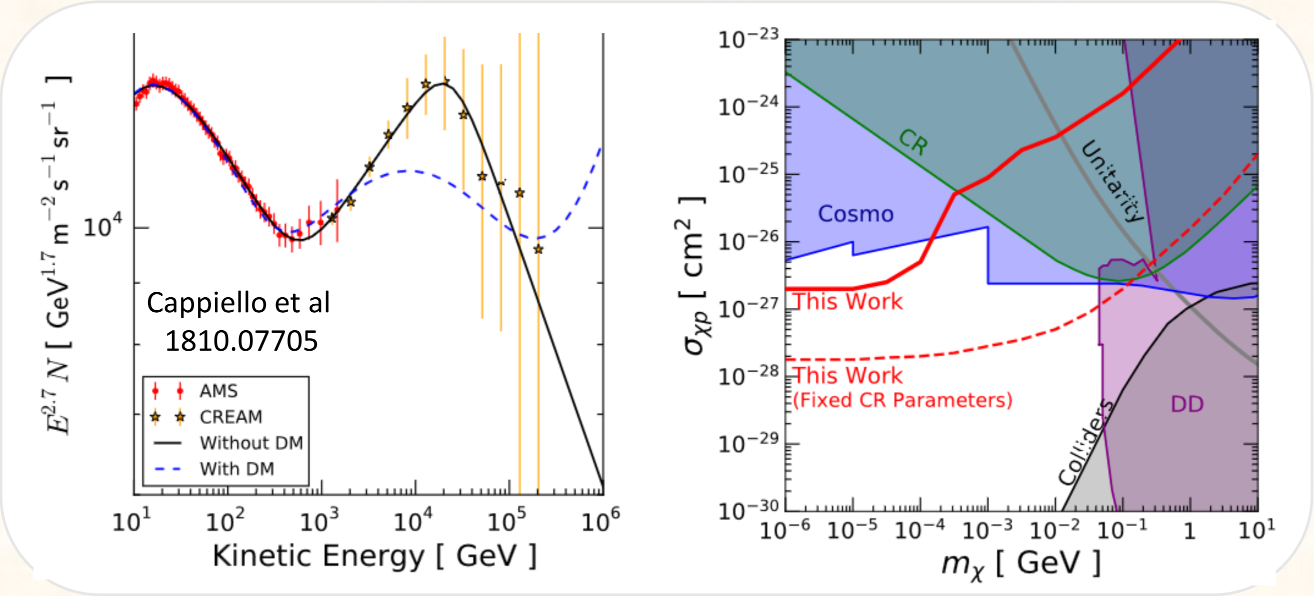
Current limits make antiproton emission from Hawking radiation **not observable by the current instruments,** since this requires **too low PBH masses**

CR-Boosted DM, BSM particles produced in the ISM, …

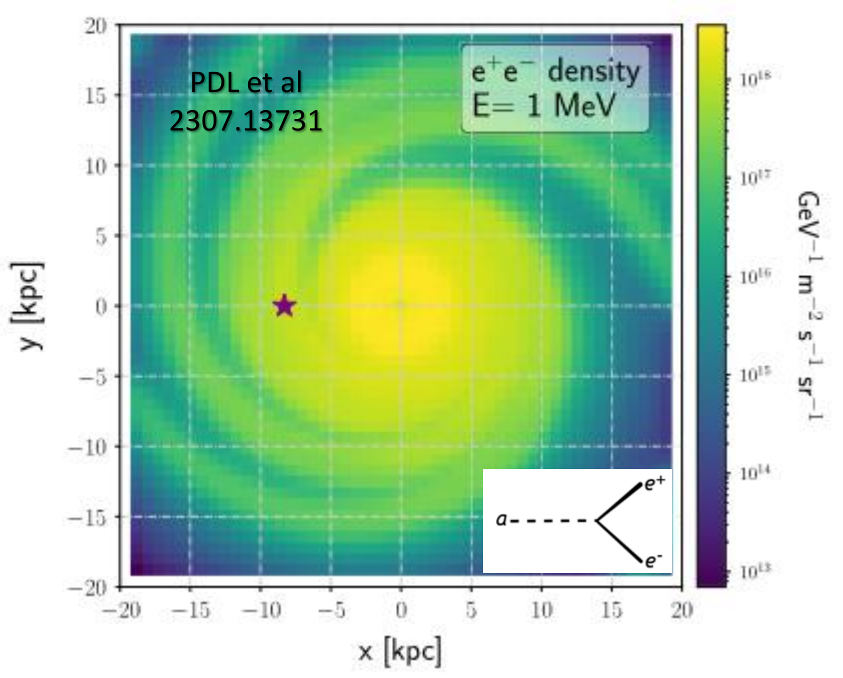
Low-mass DM can be up-scattered by CRs and detected by direct detection experiments: **Unique way to detect recoils thanks to CRs**. **Even CR interactions with the ISM and the atmosphere producing DM.**



Probing CR-DM direct scattering though features in the CR



Constraints on ALPs produced in SNe



Conclusions

Cosmic Rays in the search for Dark Matter

- Antiproton observations **seem to be in good agreement with the rest of CRs.** There is an interesting hint for an excess, but still, it isn't significant enough.
  Antiproton measurements lead to very strong constraints on WIMPs

- Antinuclei are a very promising channel to study **signals from dark matter** and constrain our current **WIMP** models – **At reach in the next decade!**
  Exciting preliminary detection of **anti-helium** seems to challenge our models… WIMP production seems insufficient… **need of invoking exotic scenarios**

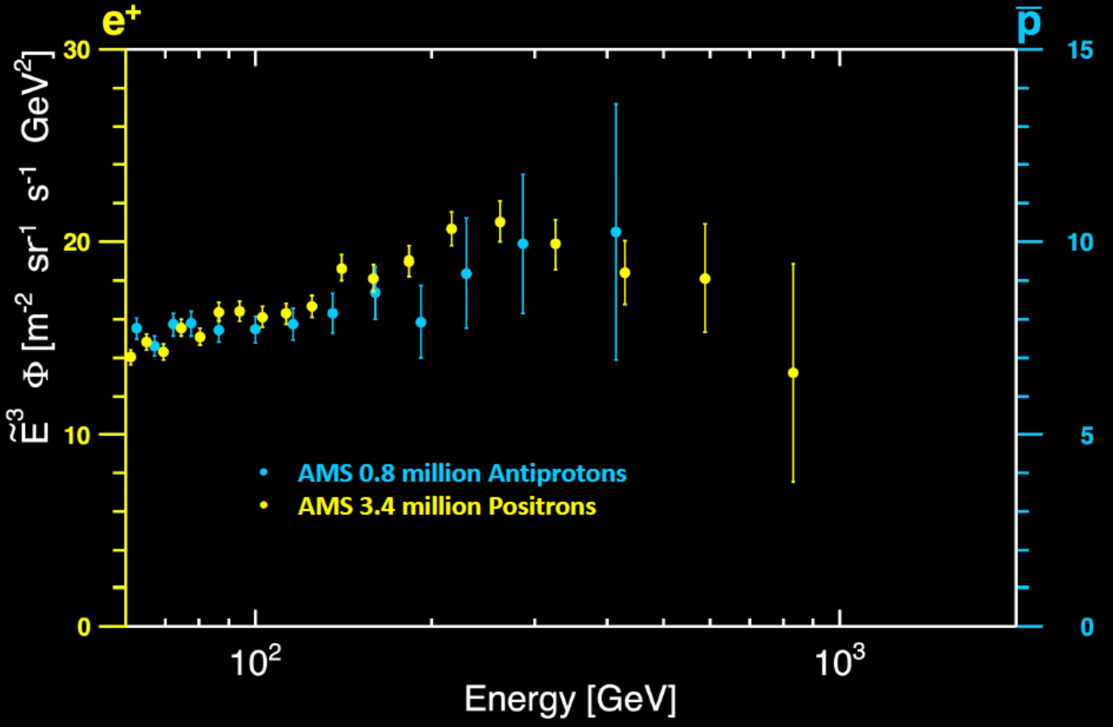
- Positron excess **compatible with pulsars**, which require a more complex modelling
  Very strong constraints on leptonic channels. Higher energy data will be very relevant

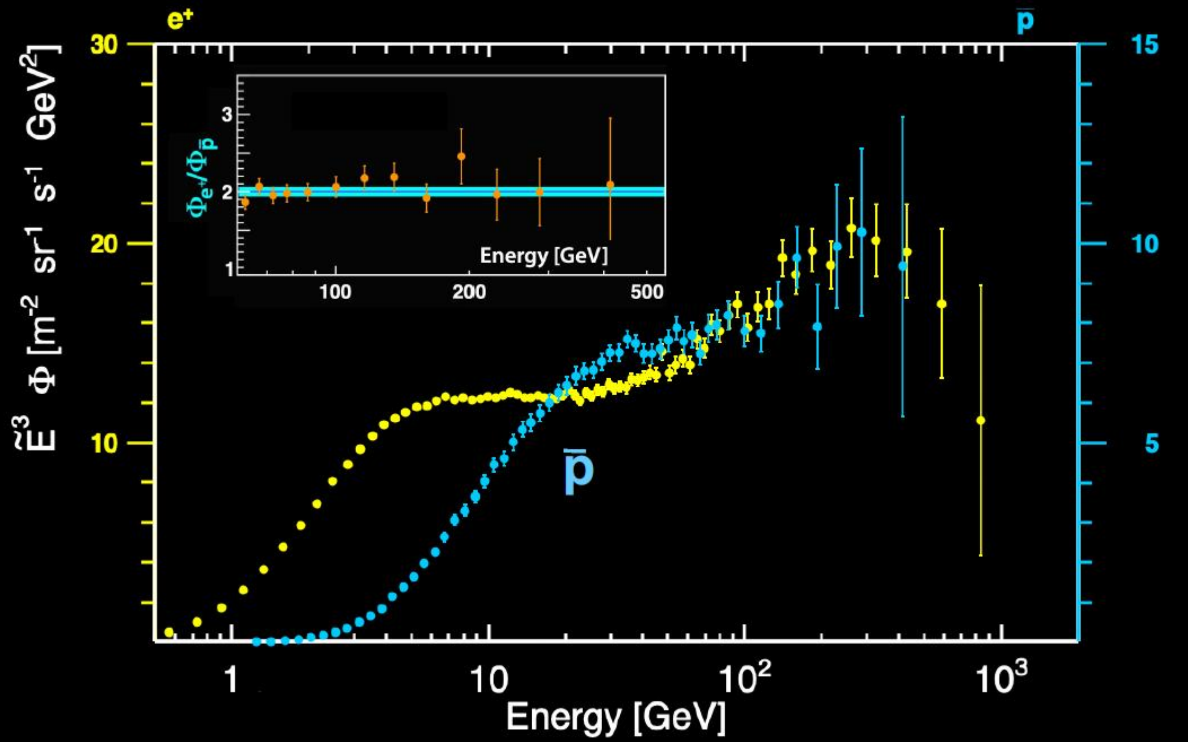
- **Asteroid mass PBHs or sub-GeV DM strongly constrained with** Voyager-1

- **A good modelling of the CR distribution allow us to study DM direct scattering and overcome problems with sub-GeV DM in direct detection experiments**

BACK UP

An open question related to antiprotons

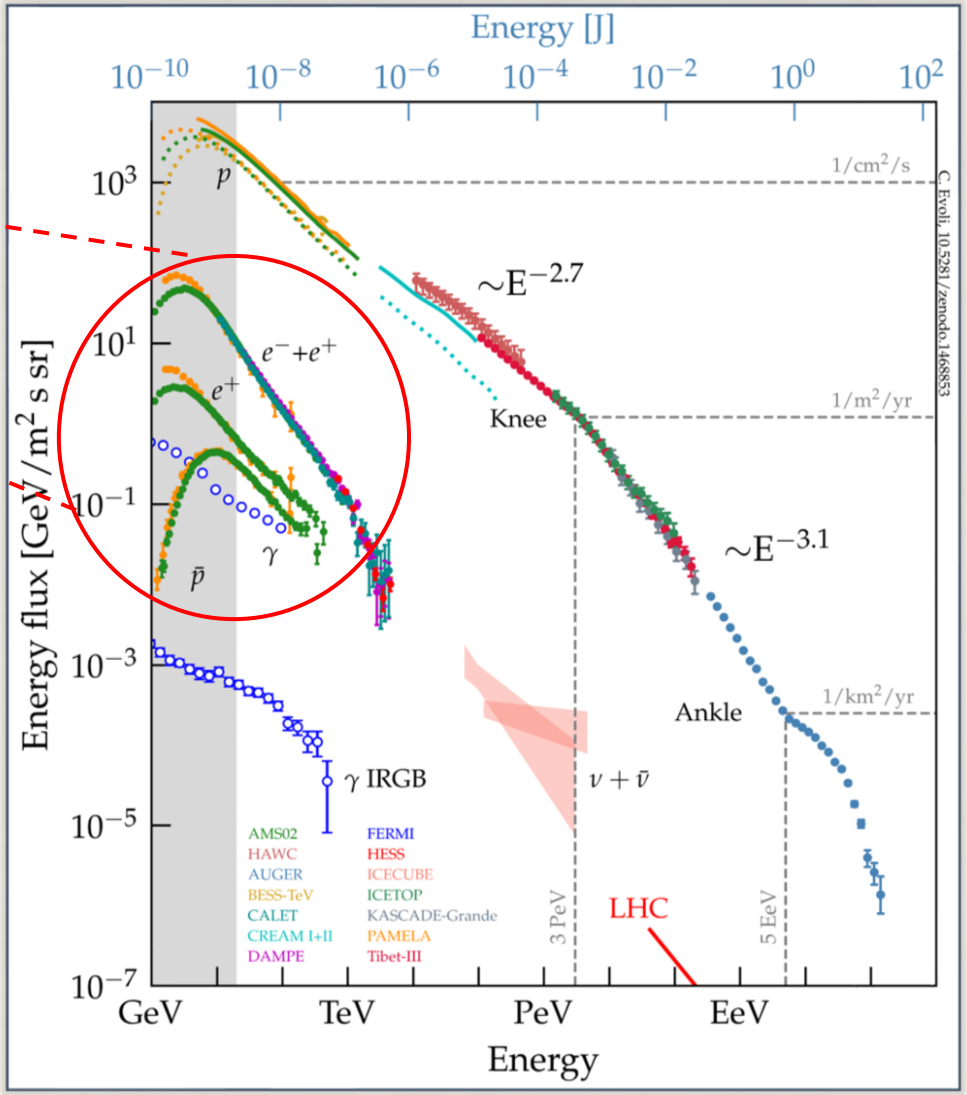




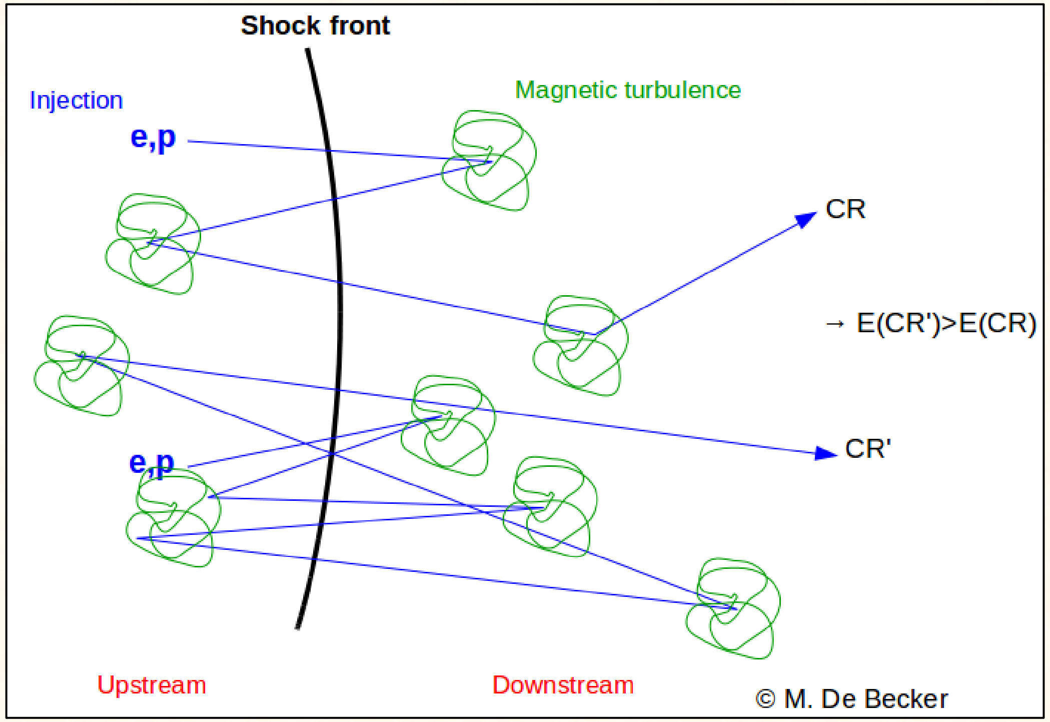
Paolo Zuccon MIAPP 2021

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

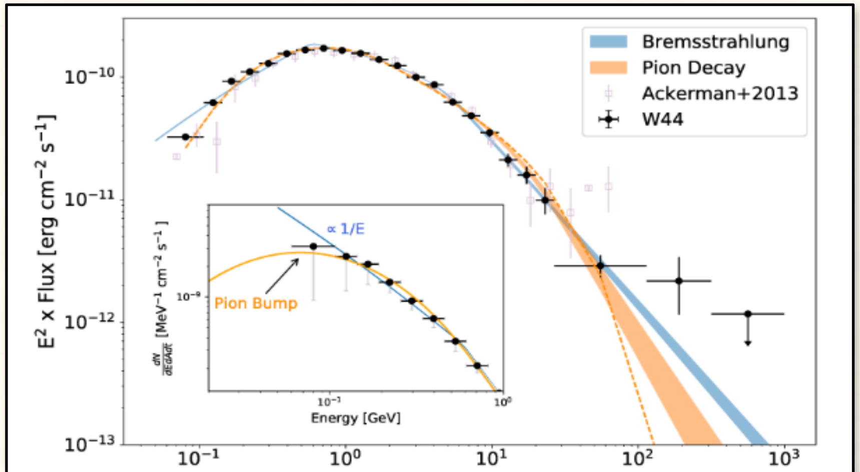
We focus in the GeV-TeV part, where diffusion dominates and WIMPs can leave imprints in CR antiparticles



Injection of CRs by sources



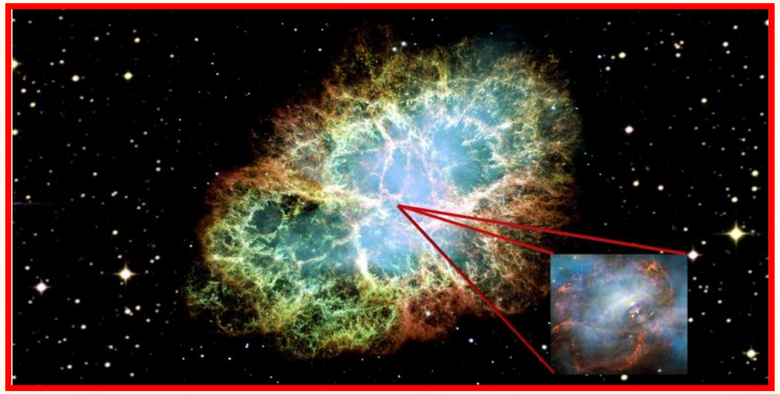
Diffusive shock acceleration (inspired in the Fermi mechanism) explains the power law distribution of CR particles



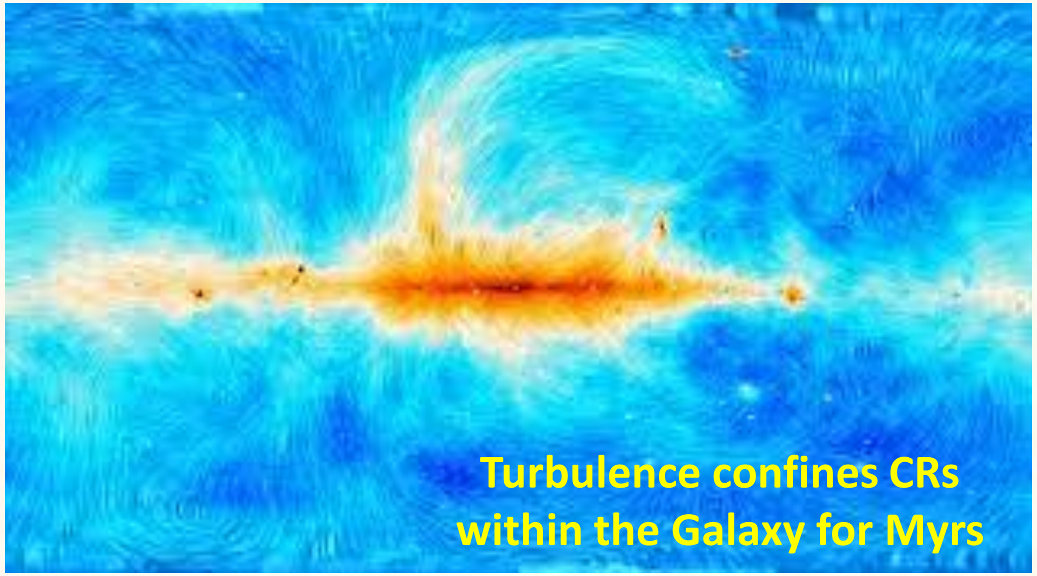
G. Peron *et al* 2020 *ApJL* 896 L23

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

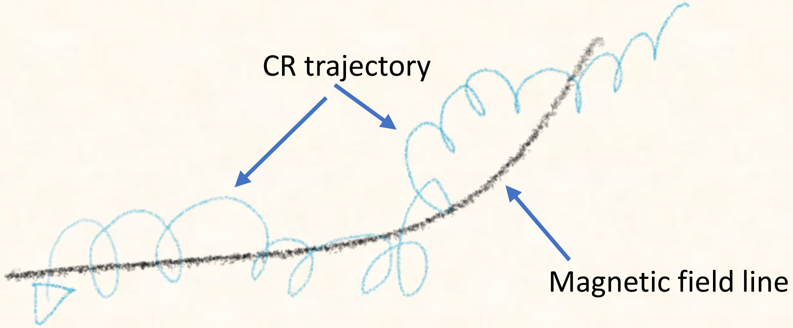
Then, they are injected to the interstellar medium where they can interact with gas and magnetic fields

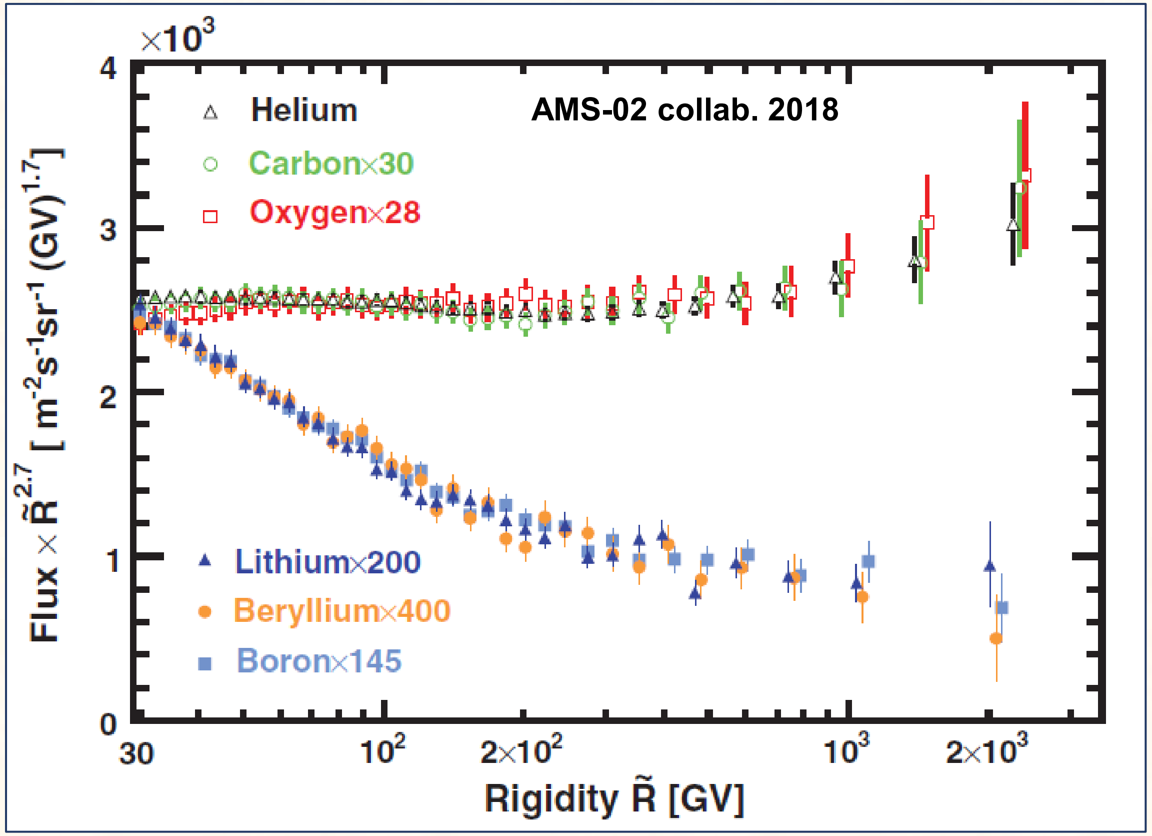


Galactic cosmic rays are accelerated in astrophysical sources (presumably SNRs) and propagate throughout the Galaxy for millions of years due to scattering with plasma waves. Occasionally they interact with ISM gas producing secondary nuclei through spallation.



Secondary CRs offer a sensitive tool to infer the <u>propagation properties</u> of CRs in the Galaxy

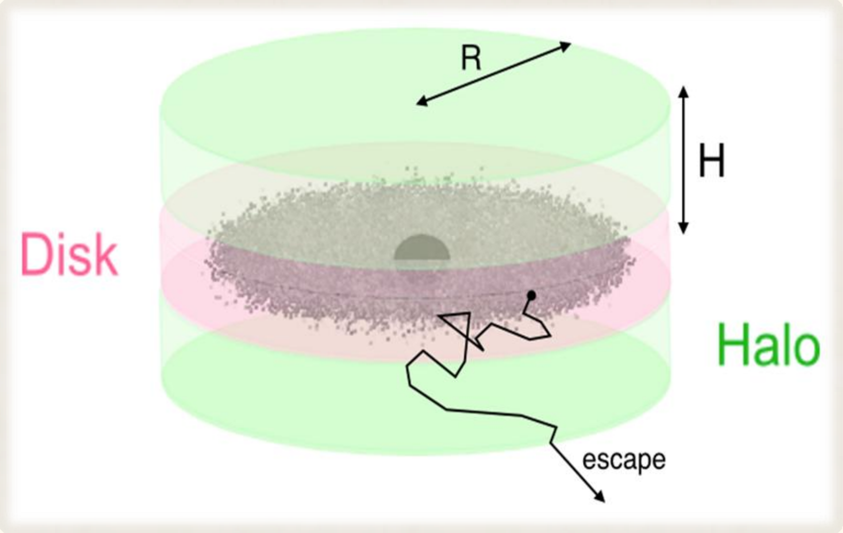




Antiprotons and propagation

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

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



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

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

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

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

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

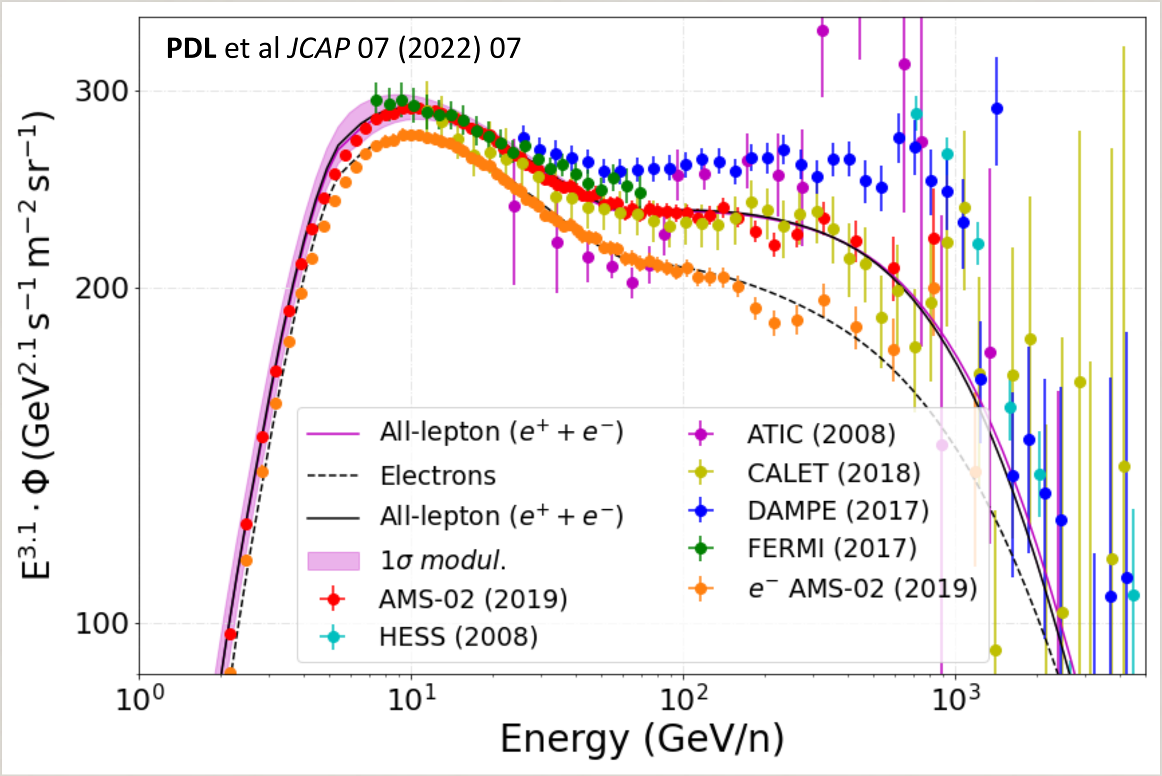
$$Q_{sec} = \Gamma \propto N_{pr}(E)\,\sigma(E)$$

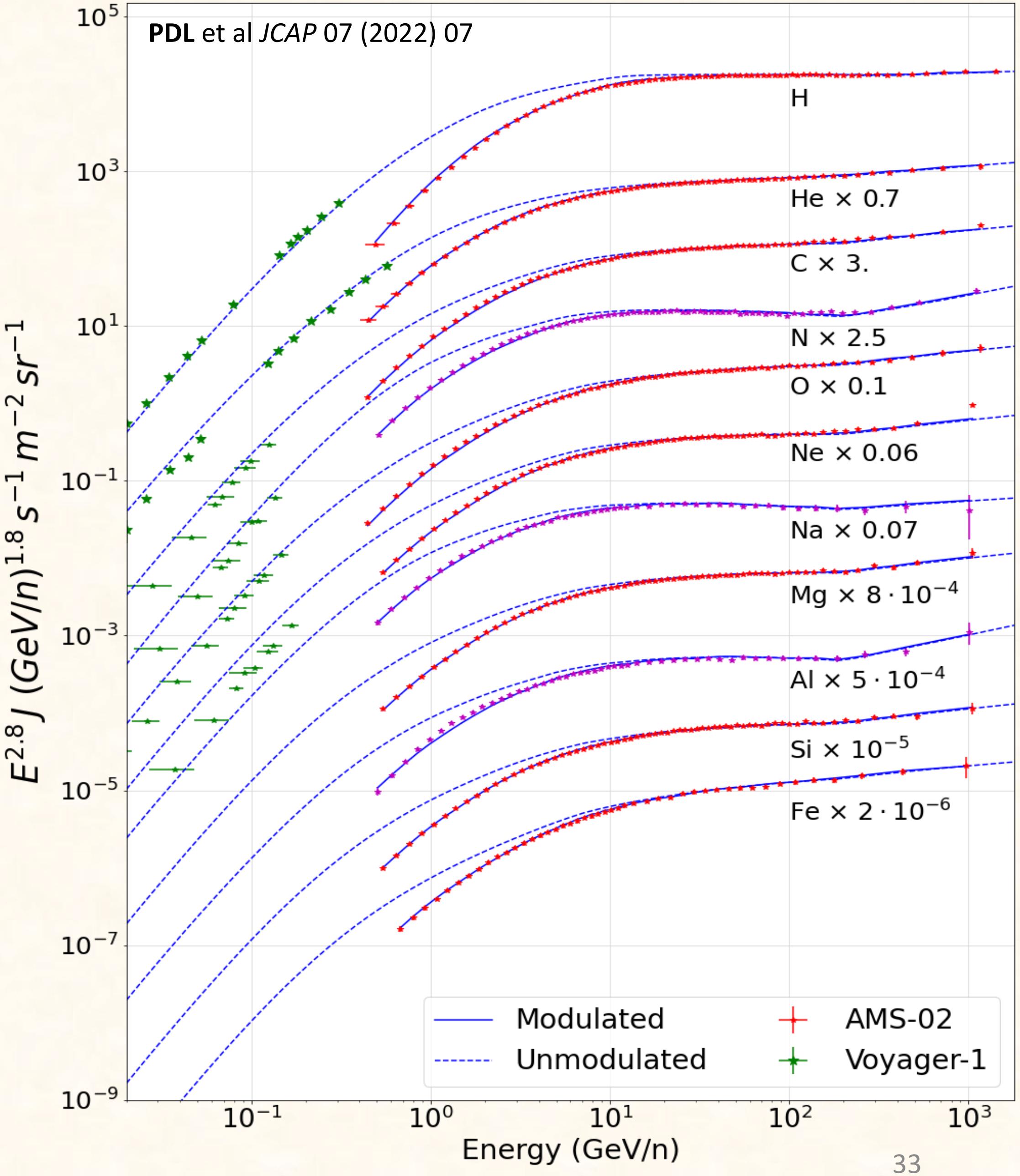
$$\frac{N_{sec}}{N_{pr}} = \frac{Q_{sec}}{Q_{pr}} \sim \sigma(E)/D(E)$$

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

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.

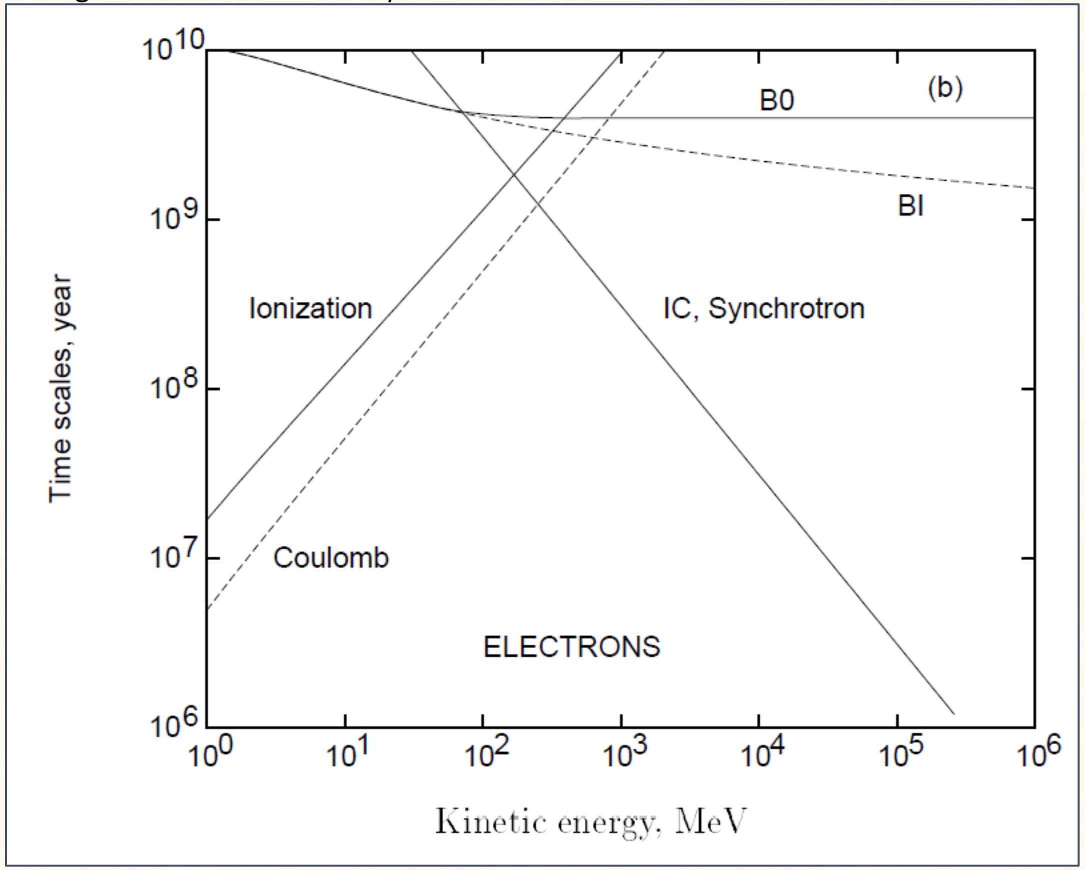




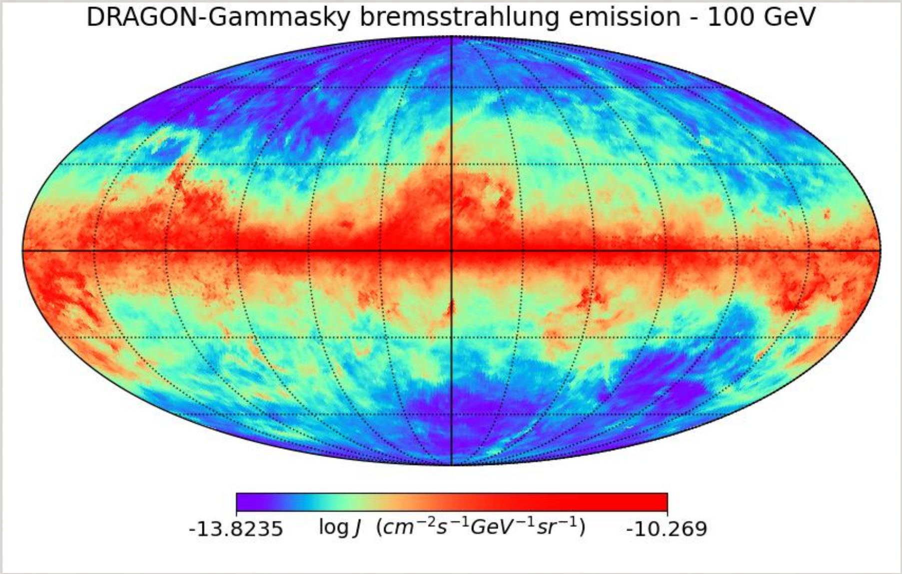
Lepton energy losses

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

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



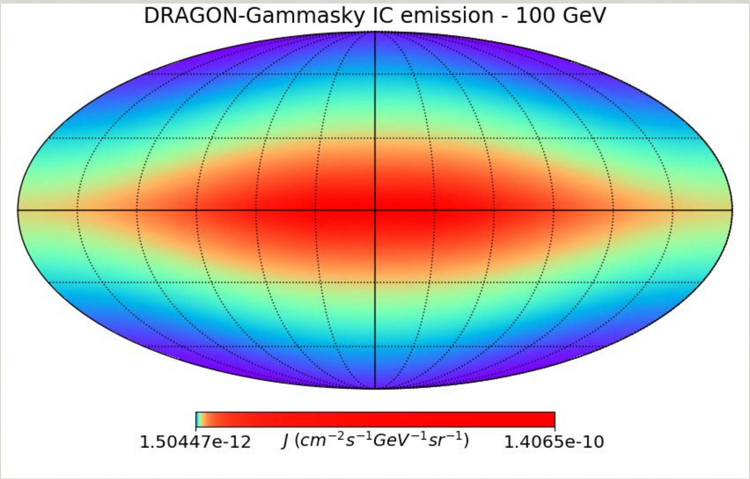
$$e + N \rightarrow e' + \gamma' + \mathrm{N}$$



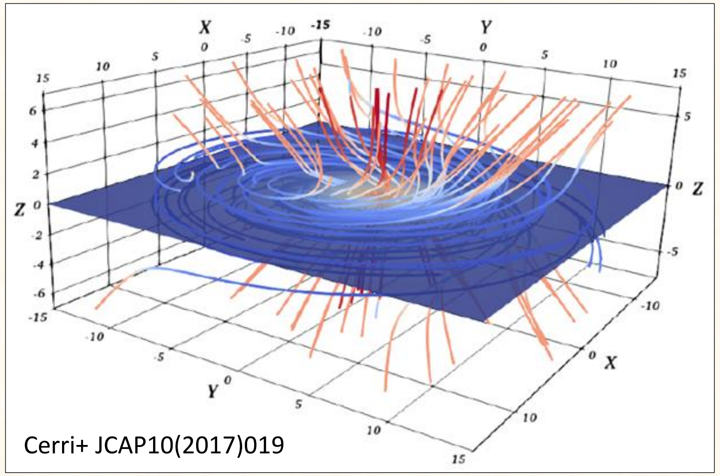
Ionization, Coulomb and bremsstrahlung energy losses depend on the gas distribution and are subdominant above the GeV

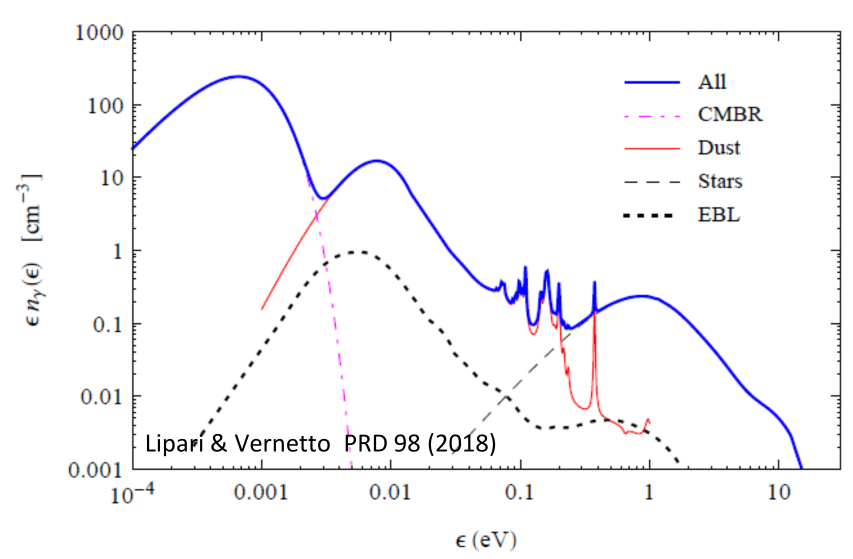
Lepton energy losses

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

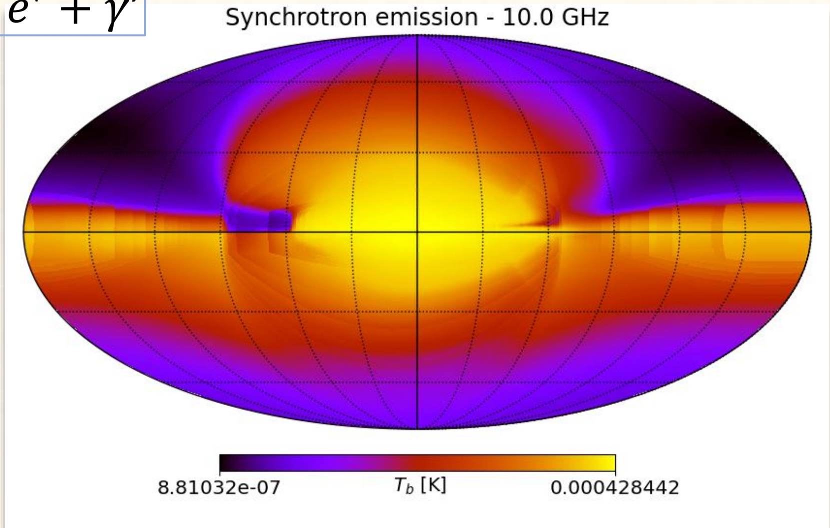


$e + \gamma \rightarrow e' + \gamma'$



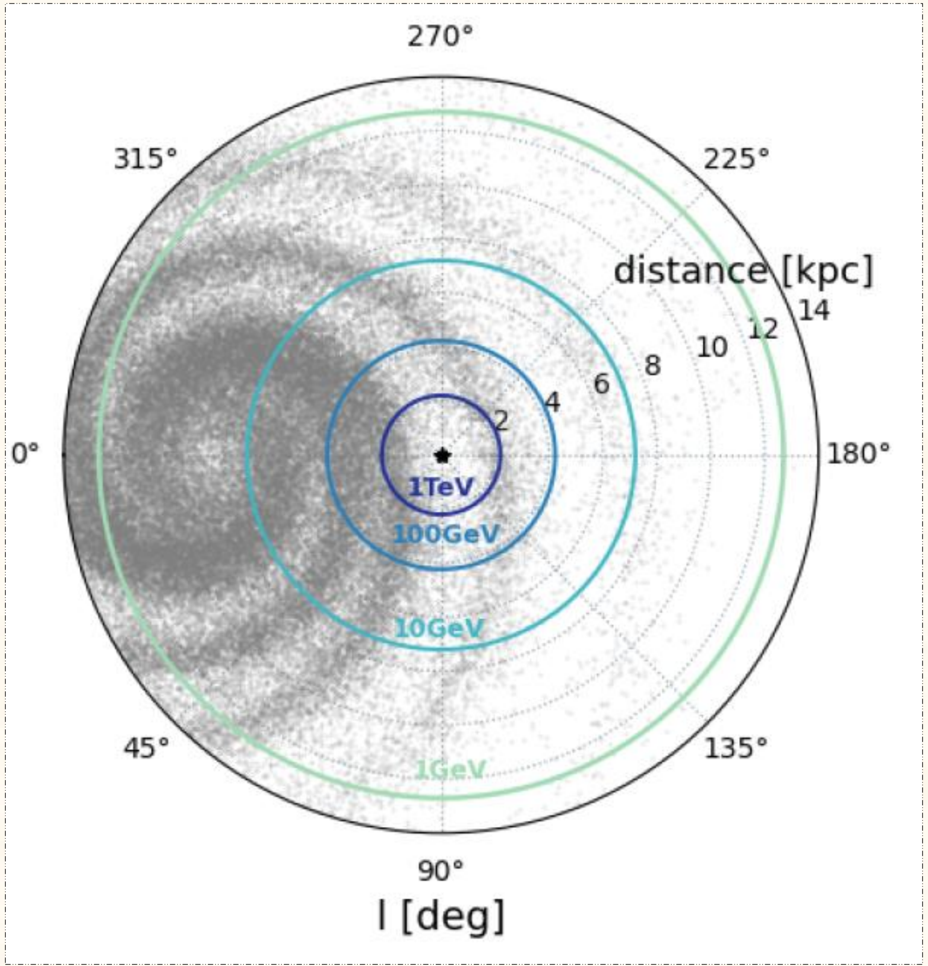


$e \rightarrow e' + \gamma'$

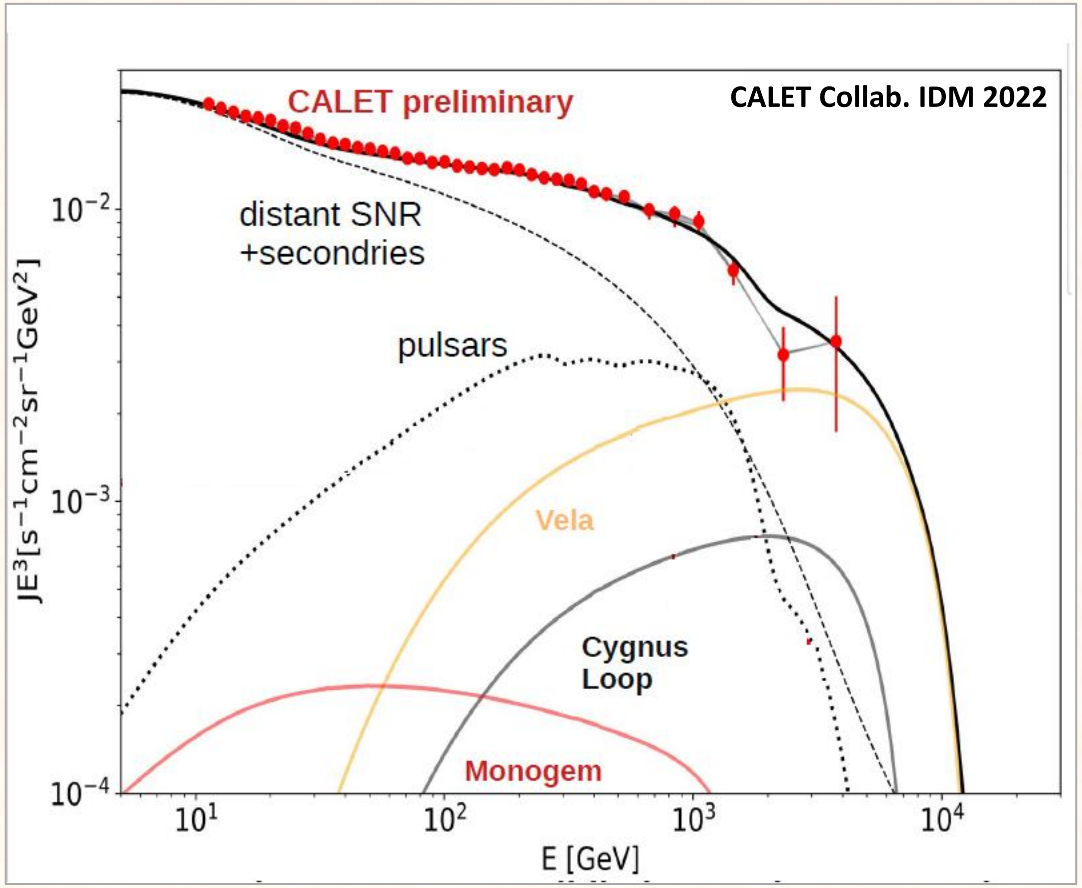


Positron propagation horizon

$\mathrm{GeV\text{-}TeV}\ e^{-}$ are dominated by the emission from local sources!



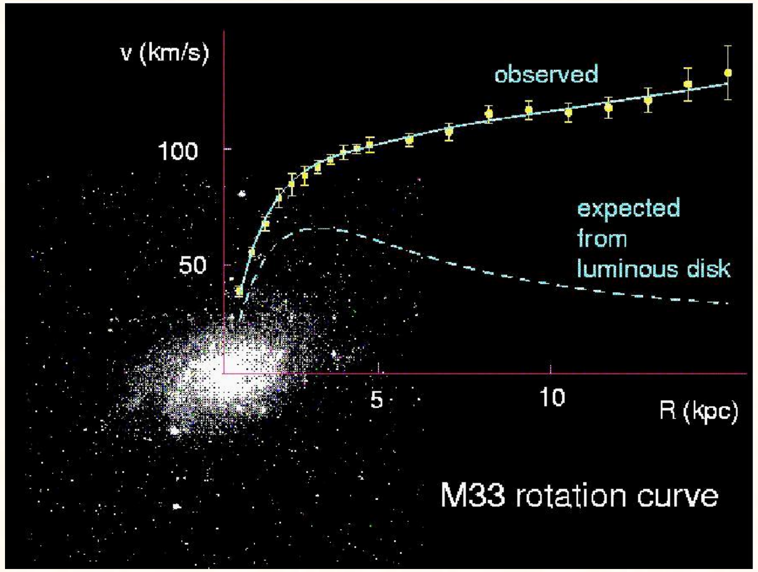
Manconi et al PRD 2020

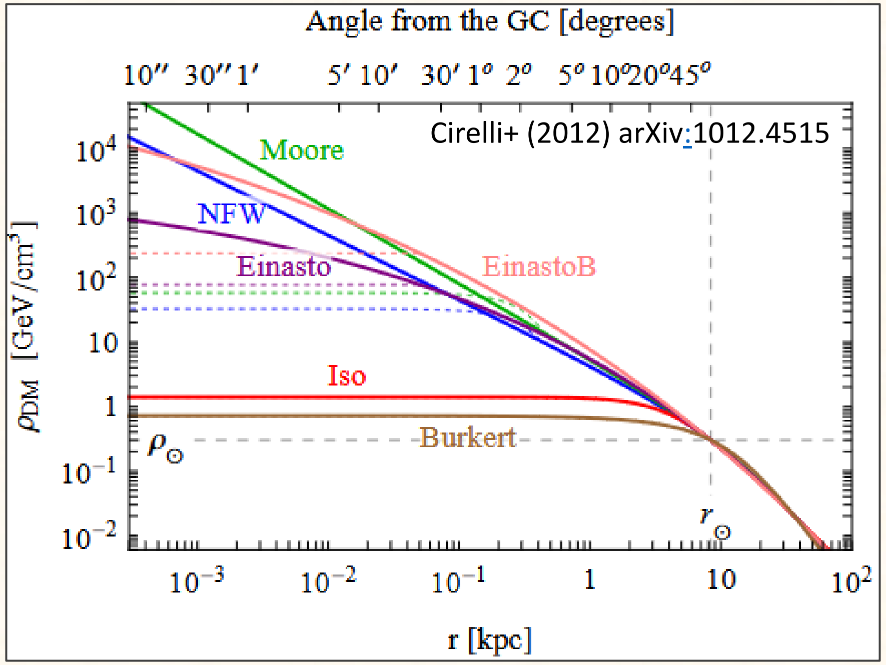


Dark matter in the Galaxy

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





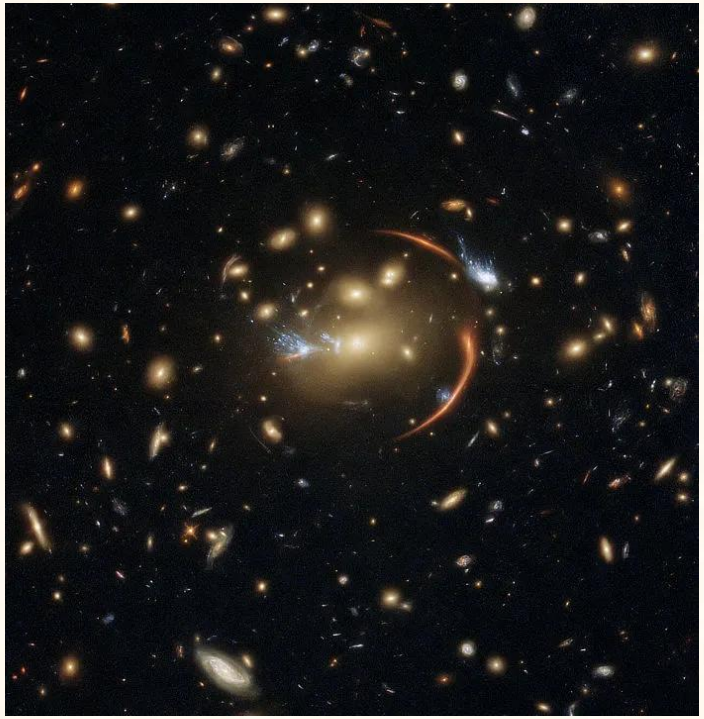
What’s dark matter?

A new particle? (best motivated is the WIMP)

Black holes?

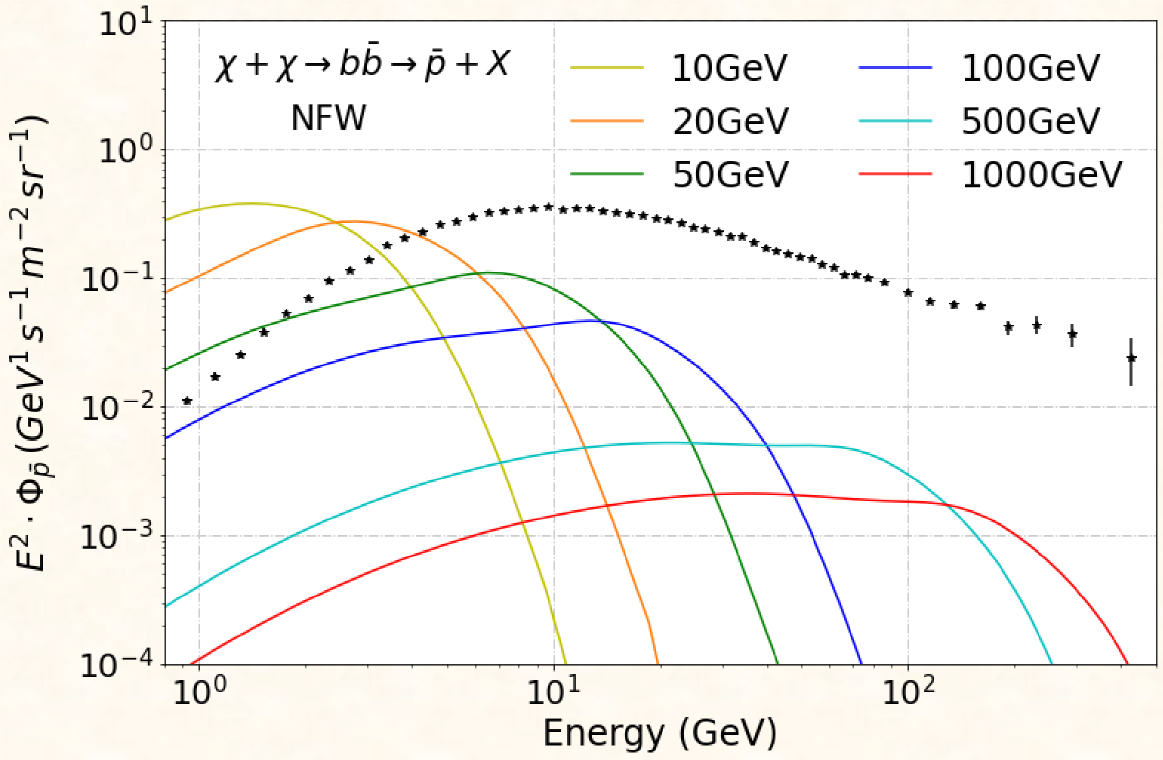
MOND?

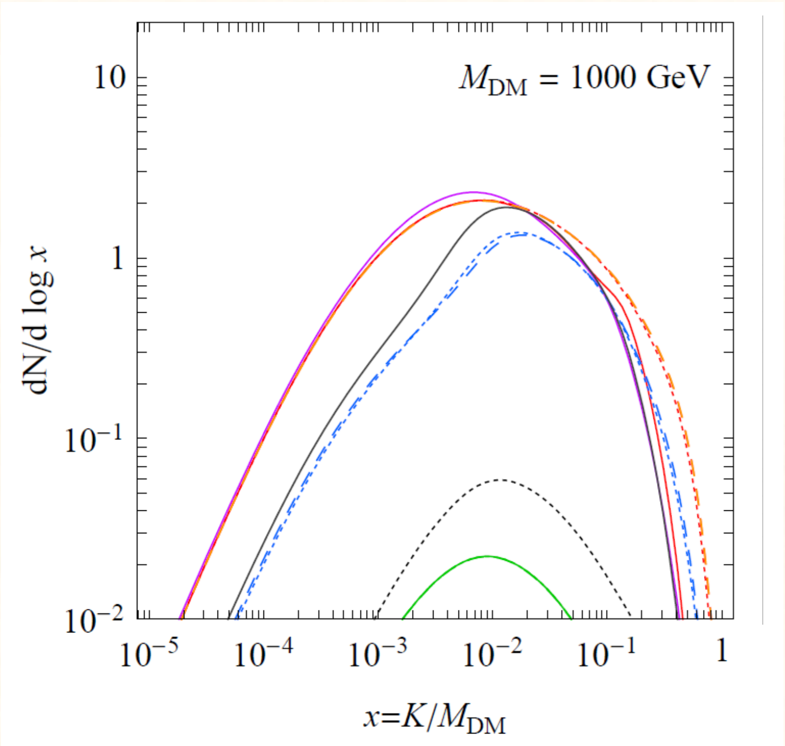
Many other possibilities…



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)





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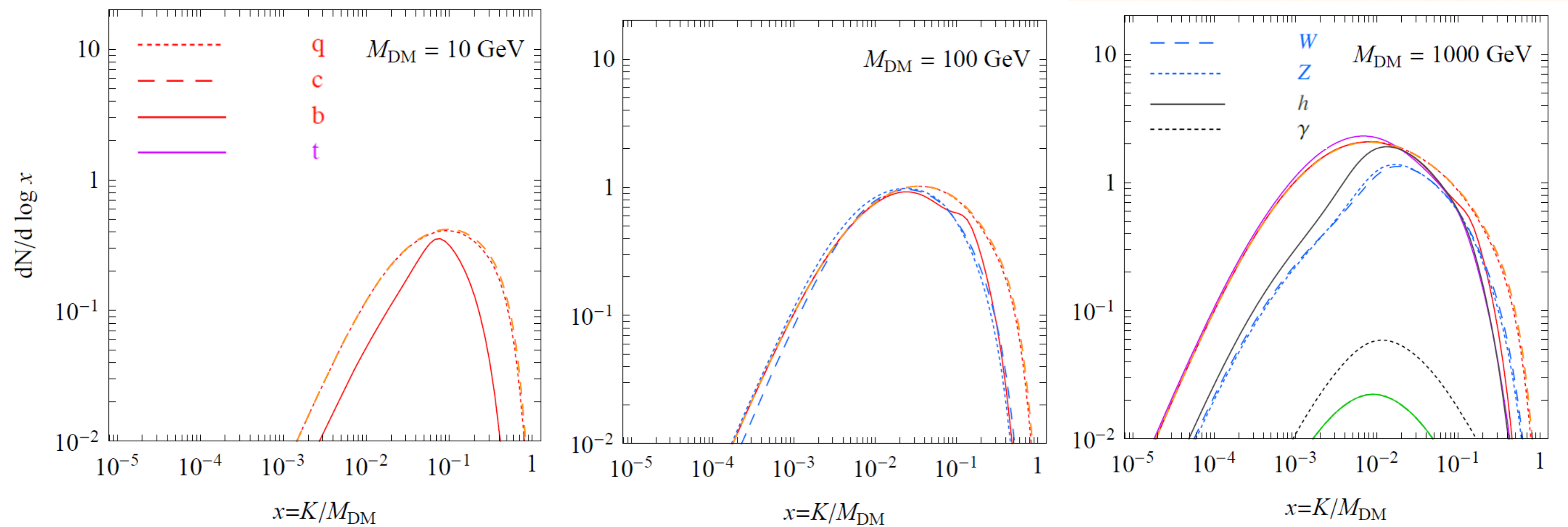
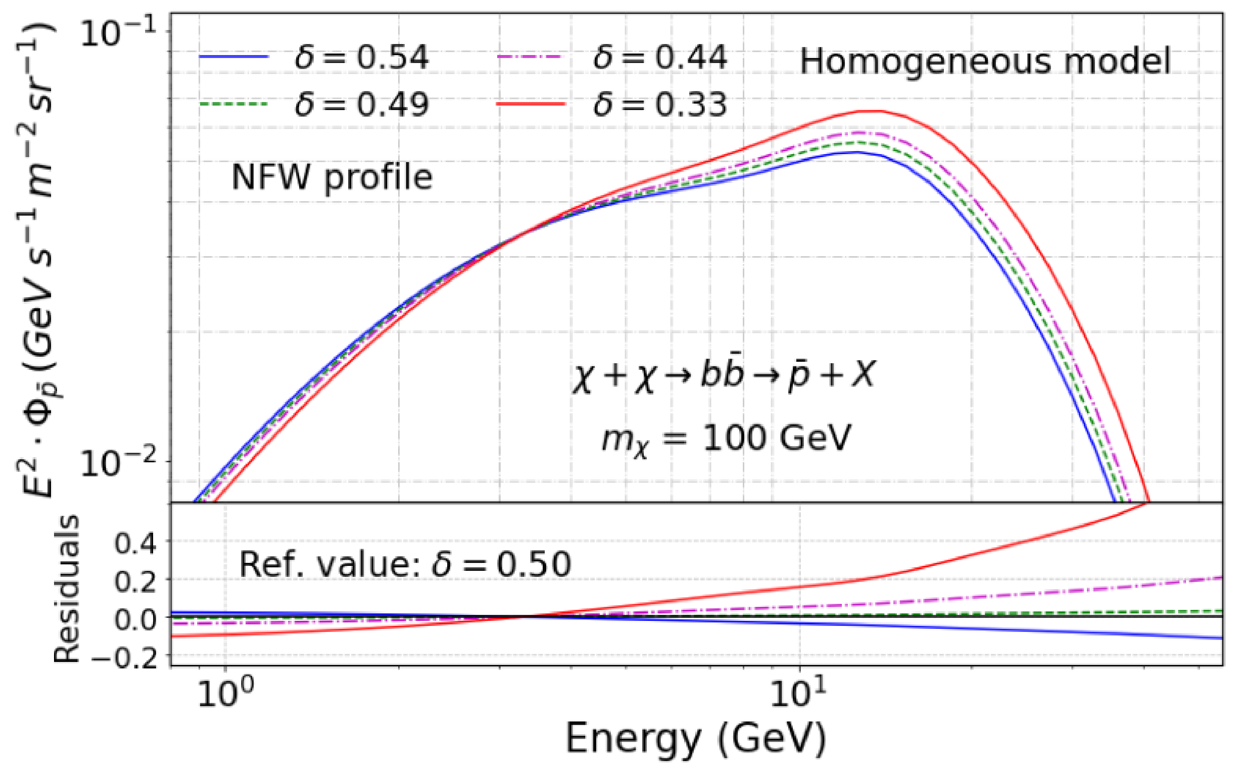
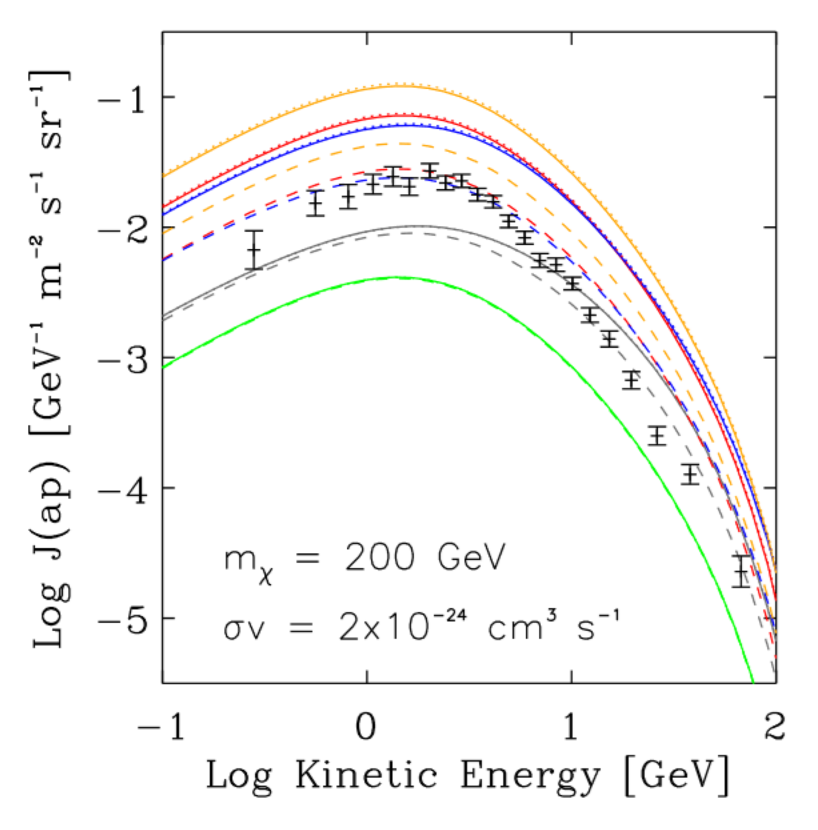


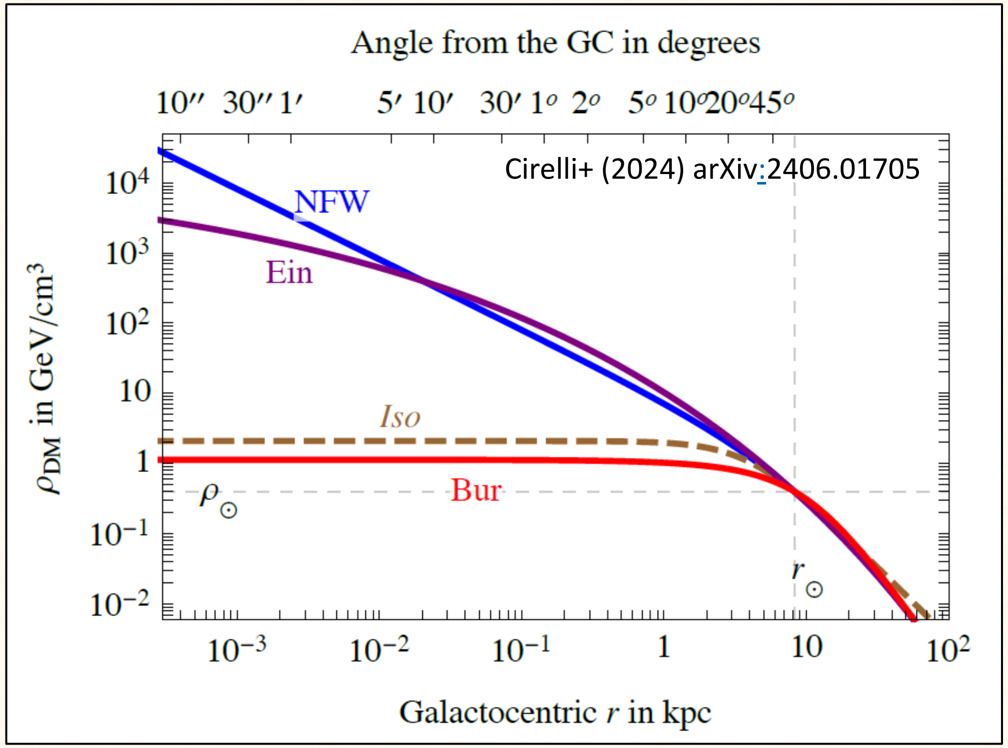
Primary antiprotons – The effect of diffusion

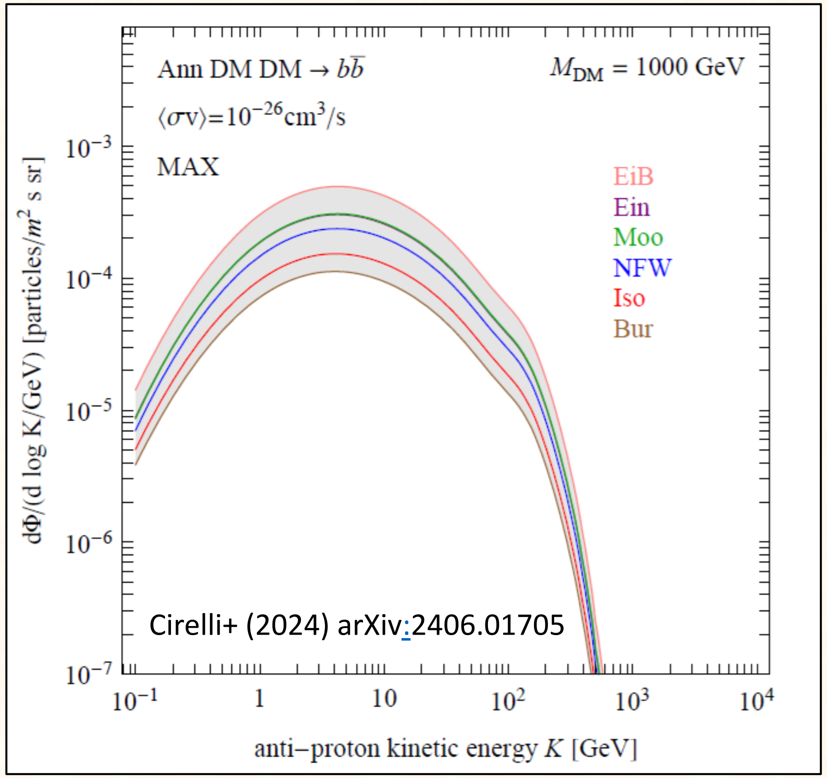




DM production - primary antiprotons

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.



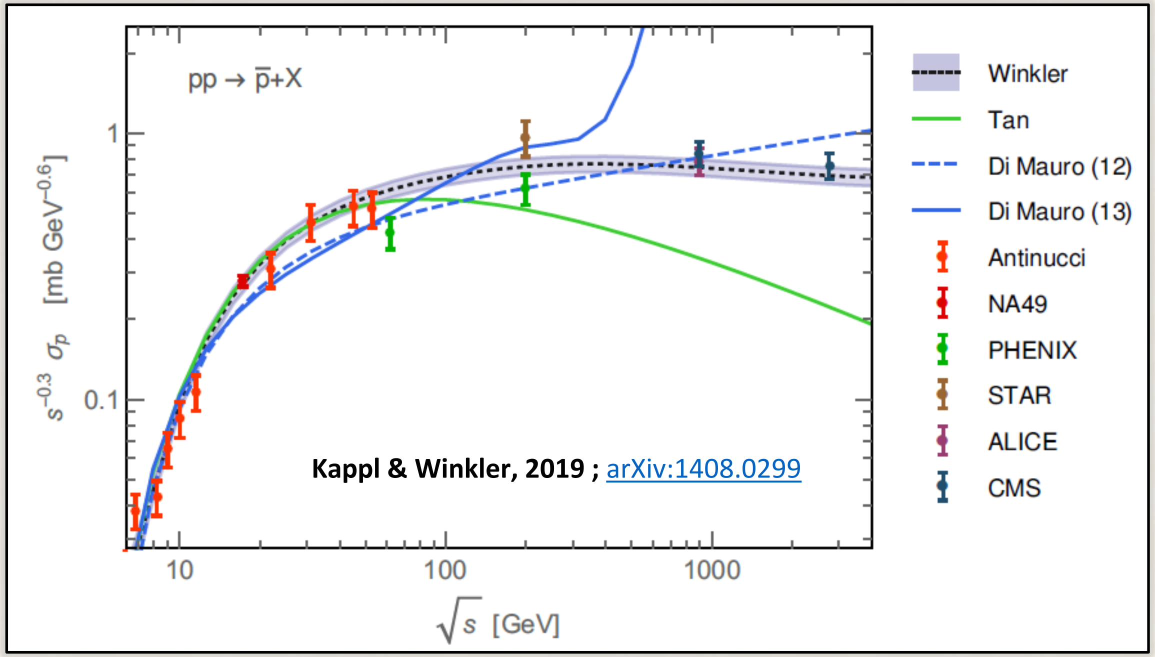


Antiproton cross sections

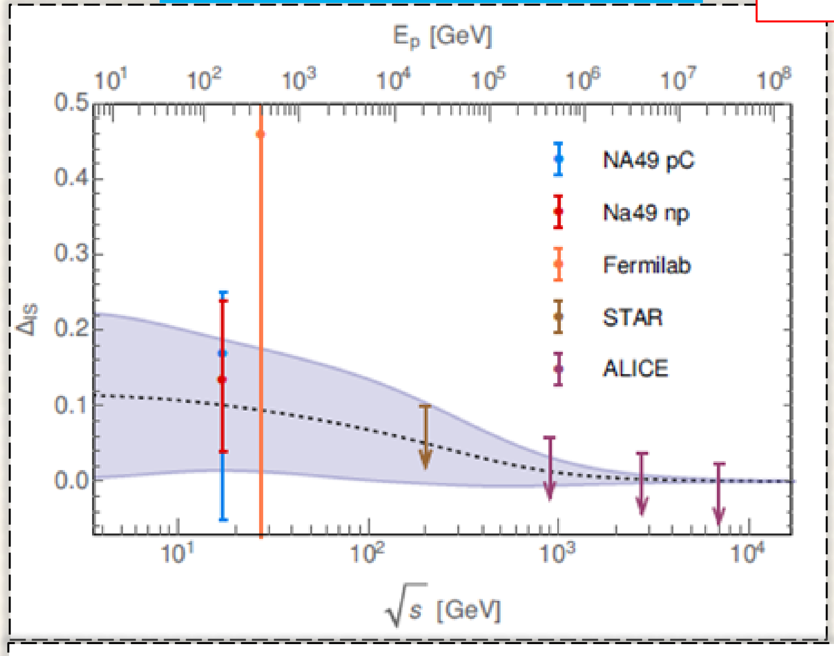
$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp\to\bar{p}} = \left(E\frac{d^3\sigma}{dp^3}\right)^{\text{prompt}}_{pp\to\bar{p}} \cdot (2 + \Delta_{IS} + 2\,\Delta_{\Lambda})$$

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

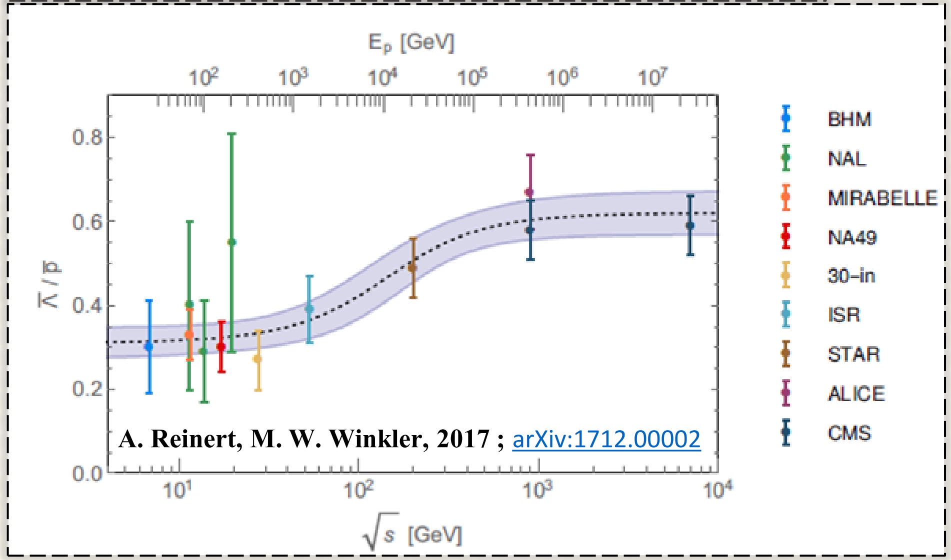
$$\Delta_{\rm IS} = \frac{\sigma_{pp\to\bar{n}}}{\sigma_{pp\to\bar{p}}} - 1$$



Kappl & Winkler, 2019 ; arXiv:1408.0299



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



A. Reinert, M. W. Winkler, 2017 ; arXiv:1712.00002

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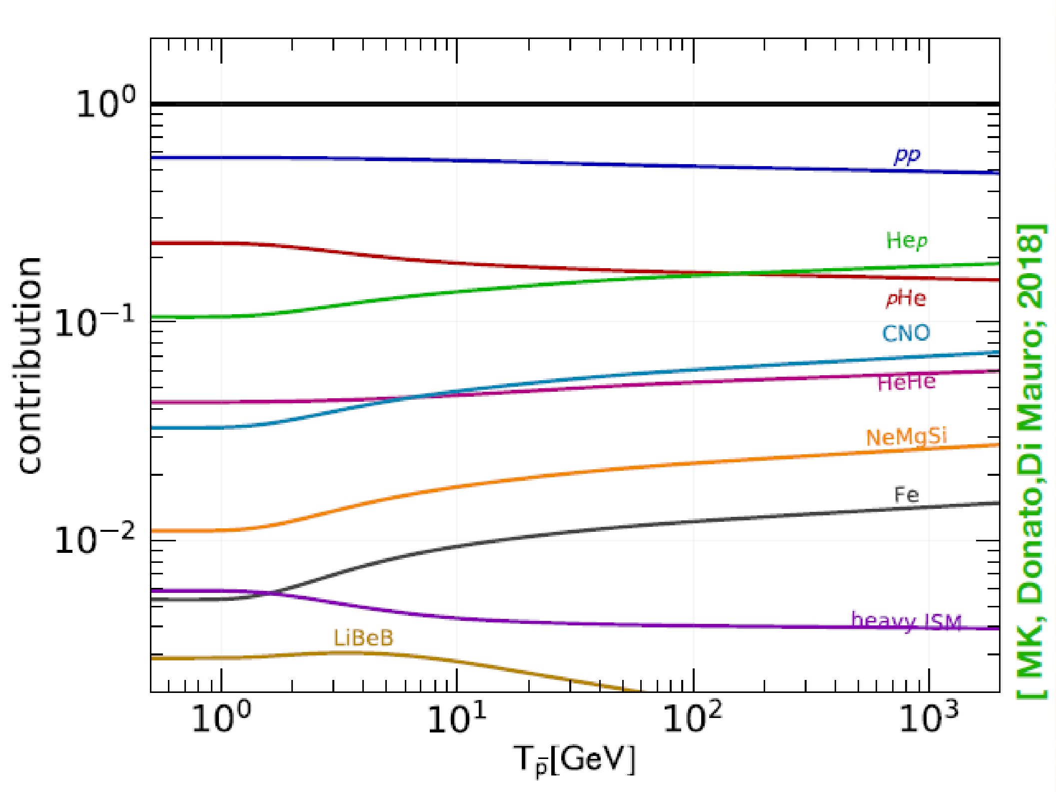
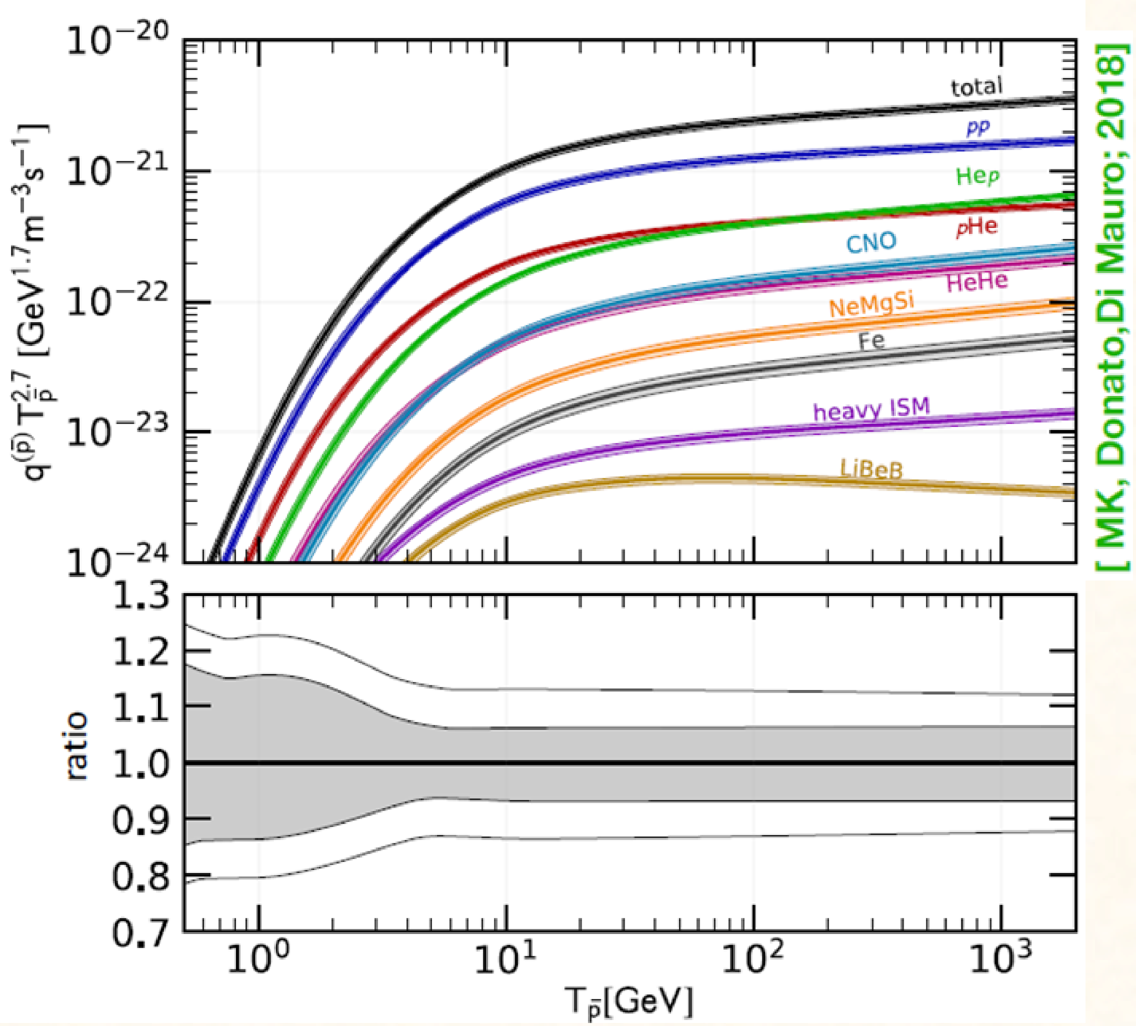
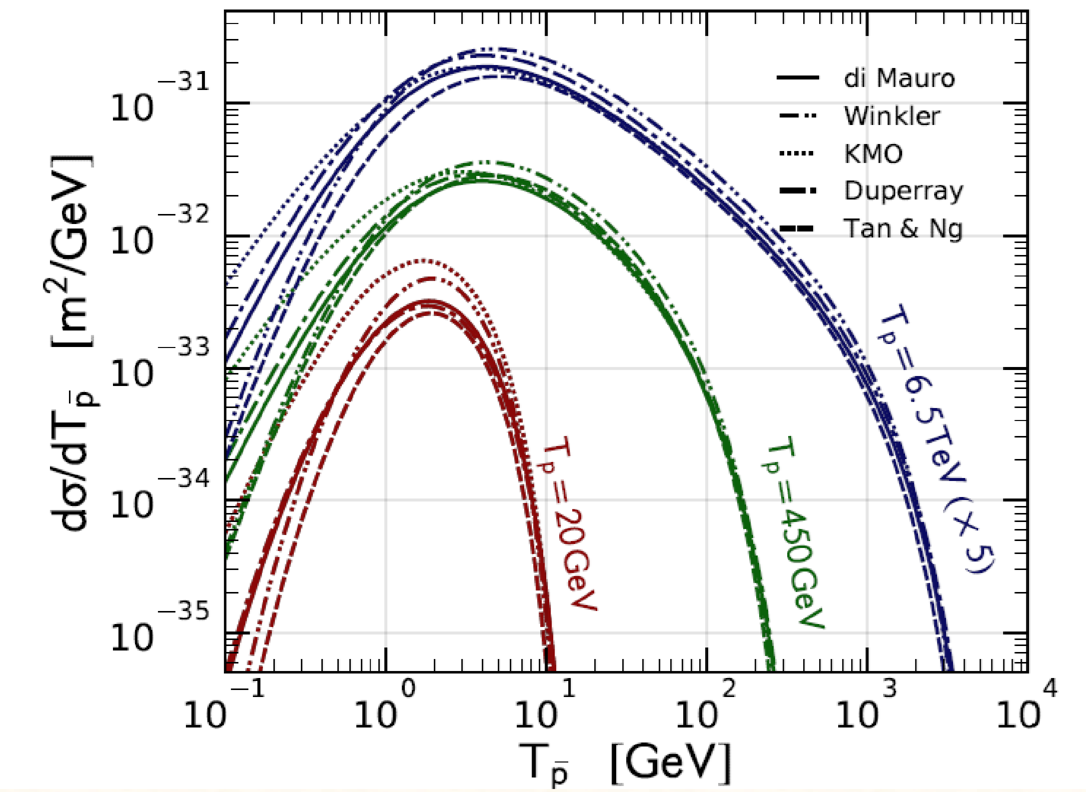
Channels of secondary antiproton production

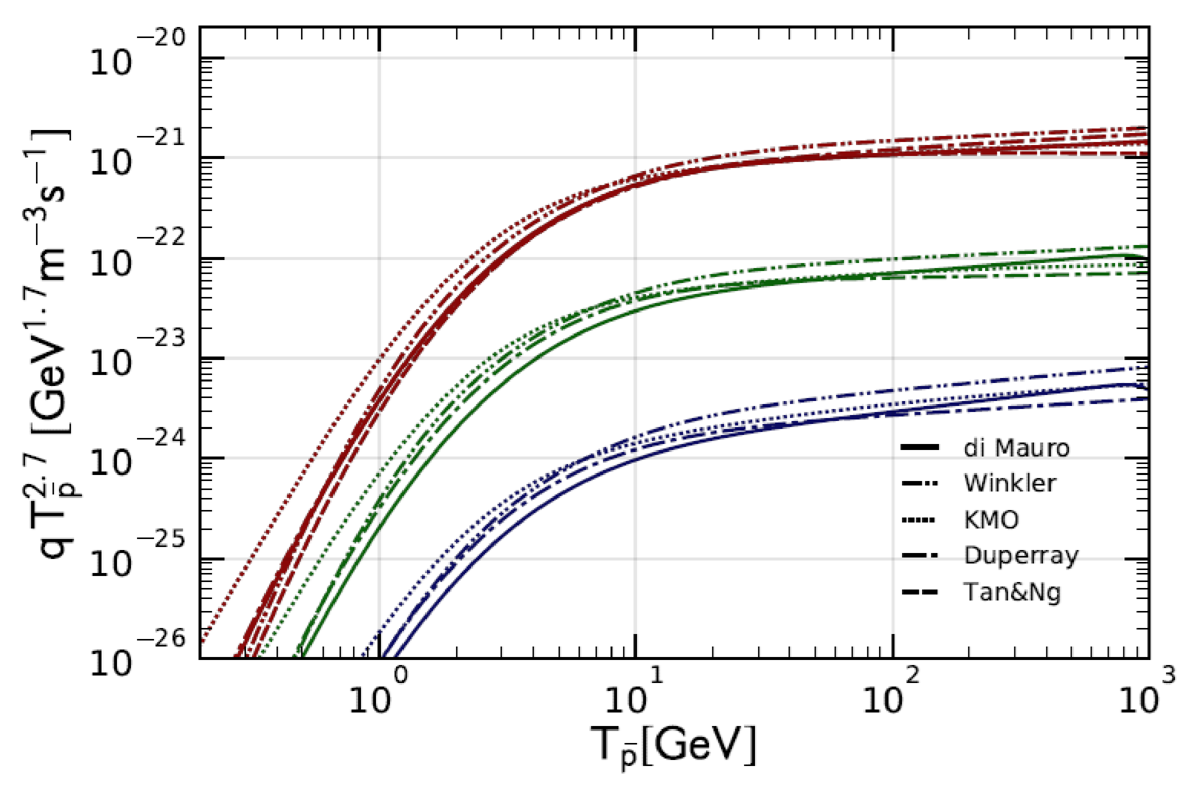




Antiproton parameterizations

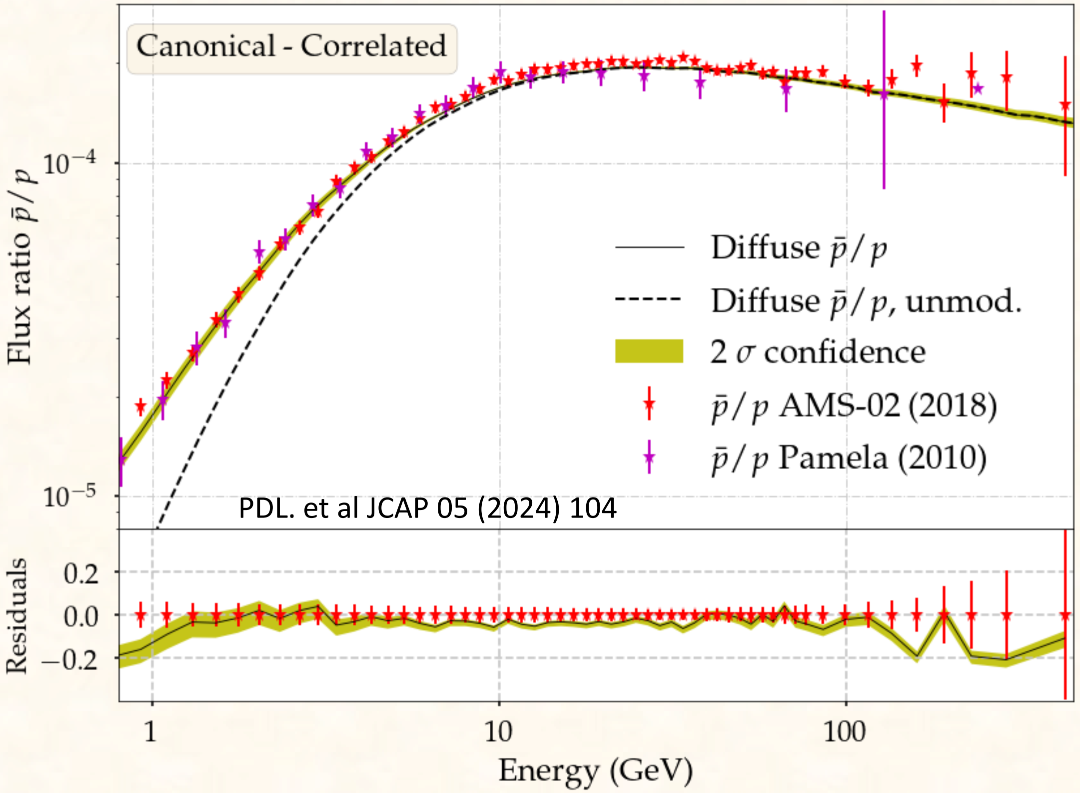
Phys. Rev. D 96, 043007 (2017)



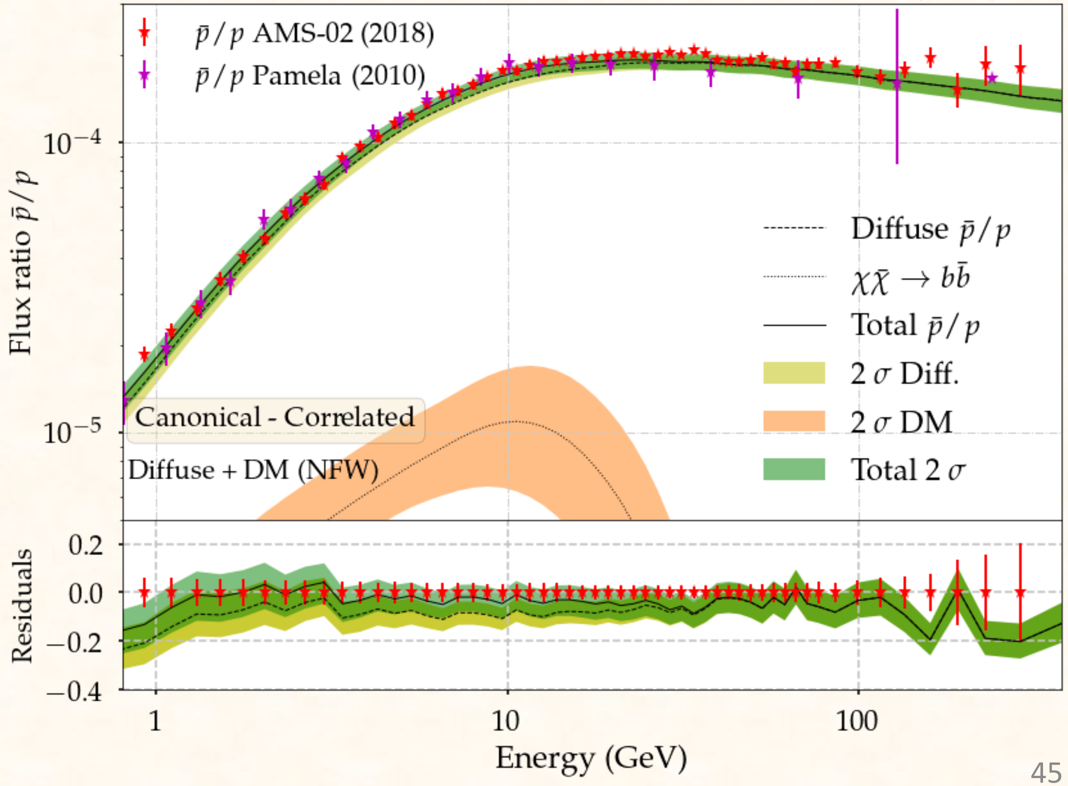


AMS-02 reveals the origin of antiprotons

Recent analyses demonstrate that **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…

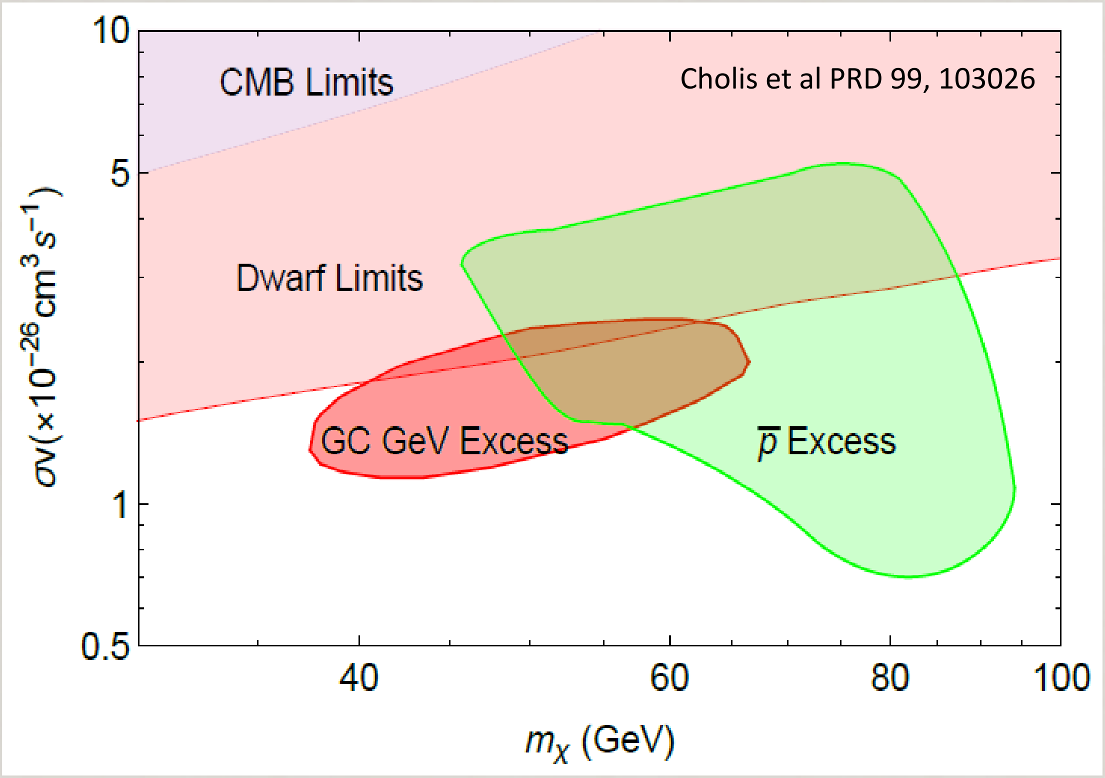


PDL et al JCAP 05 (2024) 104

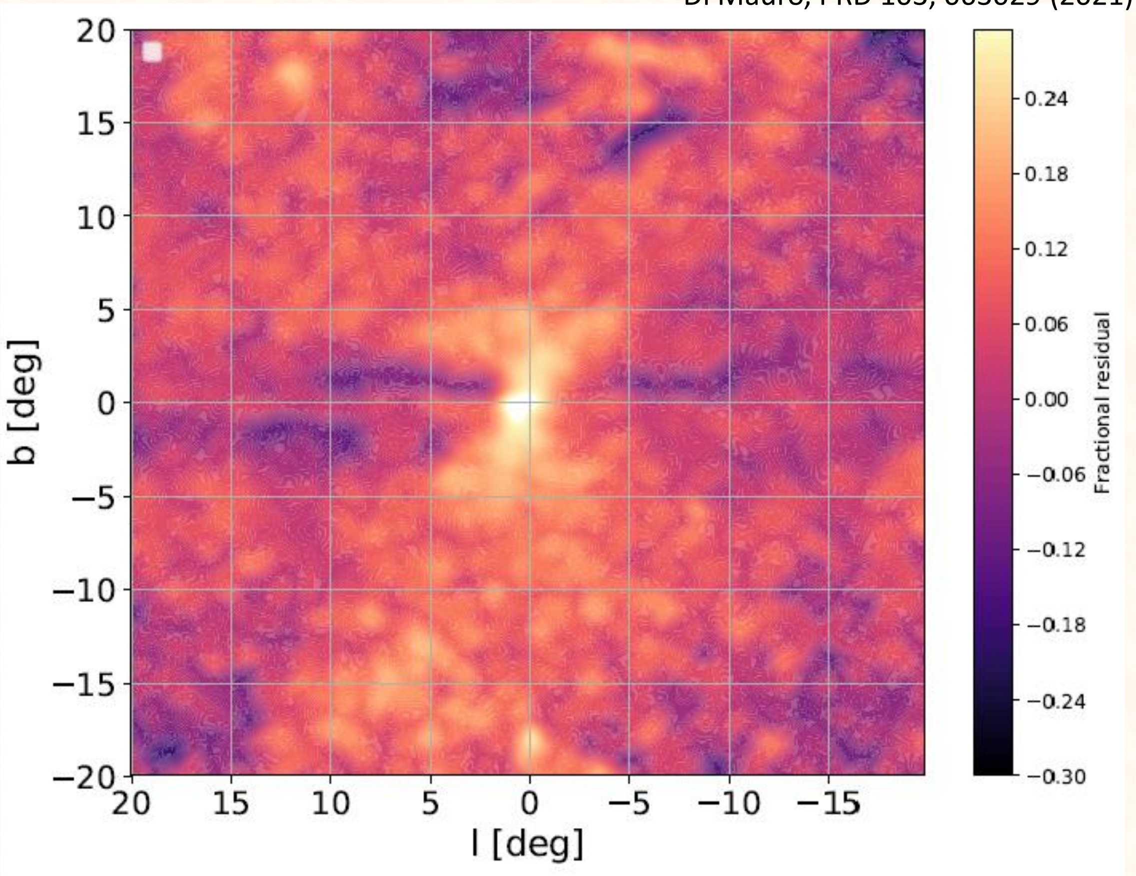


Antiproton excess and Galactic centre excess

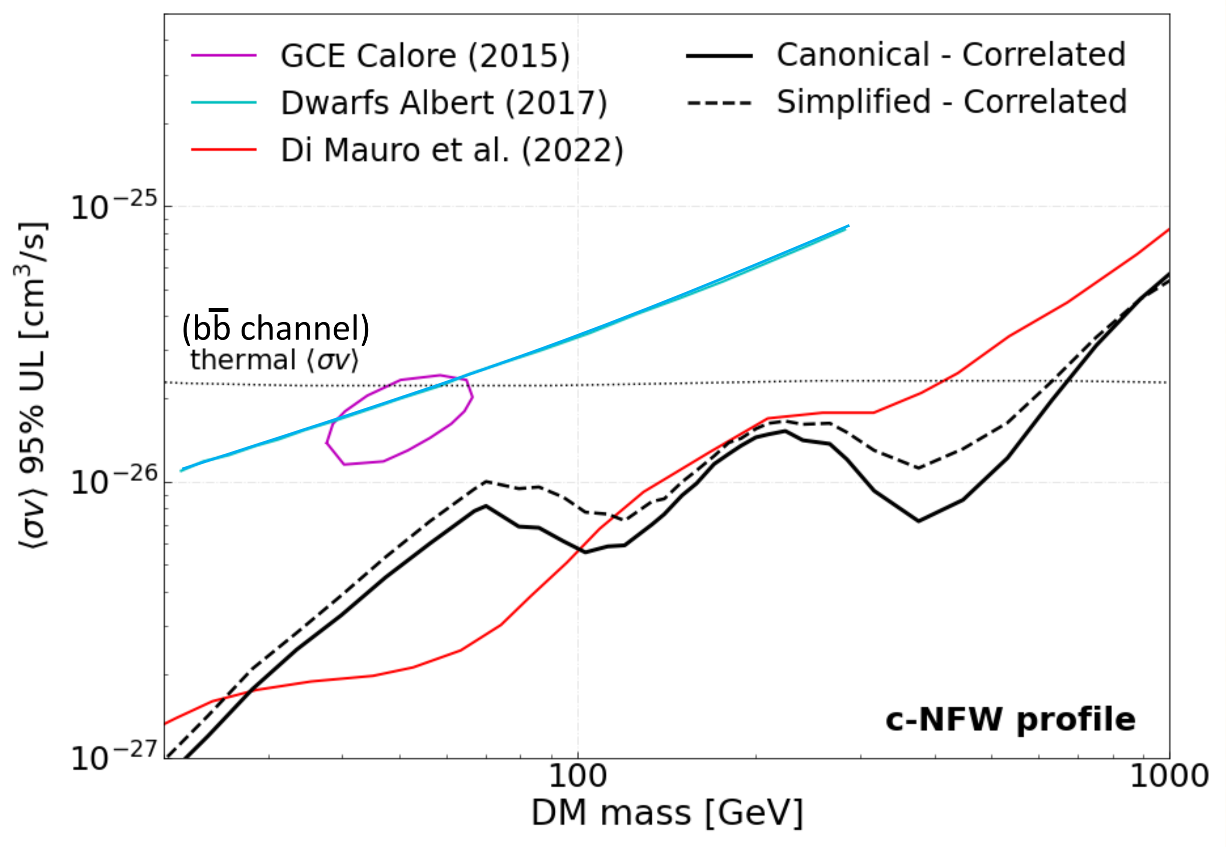
GC excess points to a WIMP of about 50 GeV and $< \sigma v >$ close to thermal relic cross section



Di Mauro, PRD 103, 063029 (2021)

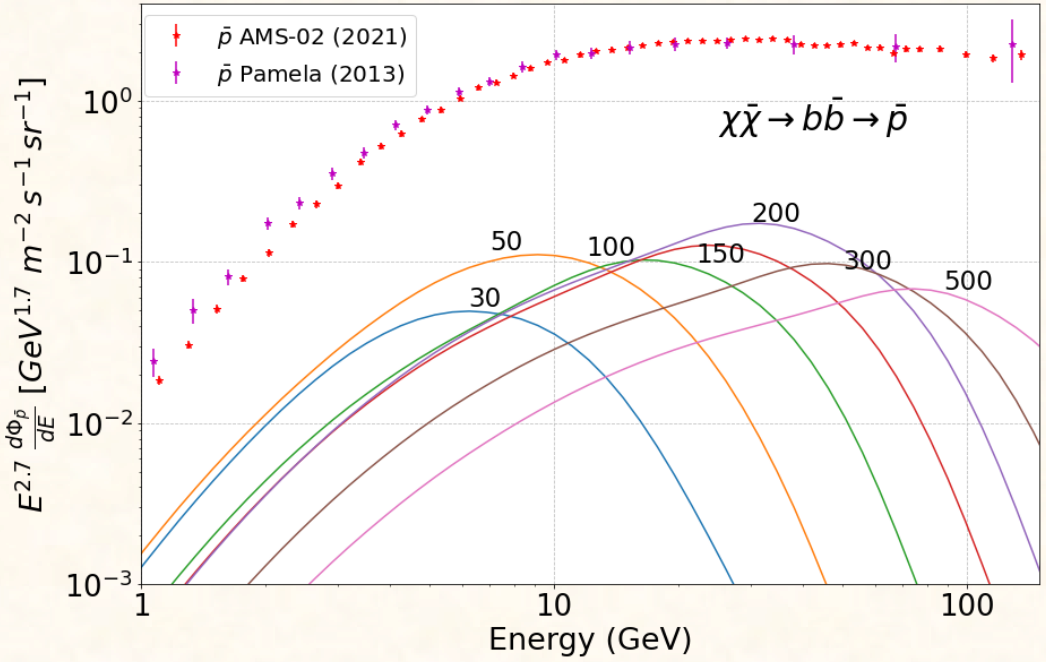


Dark matter bounds from antiproton analyses



PDL et al JCAP 05 (2024) 104

Maximal DM-induced signal (at 95% CL)

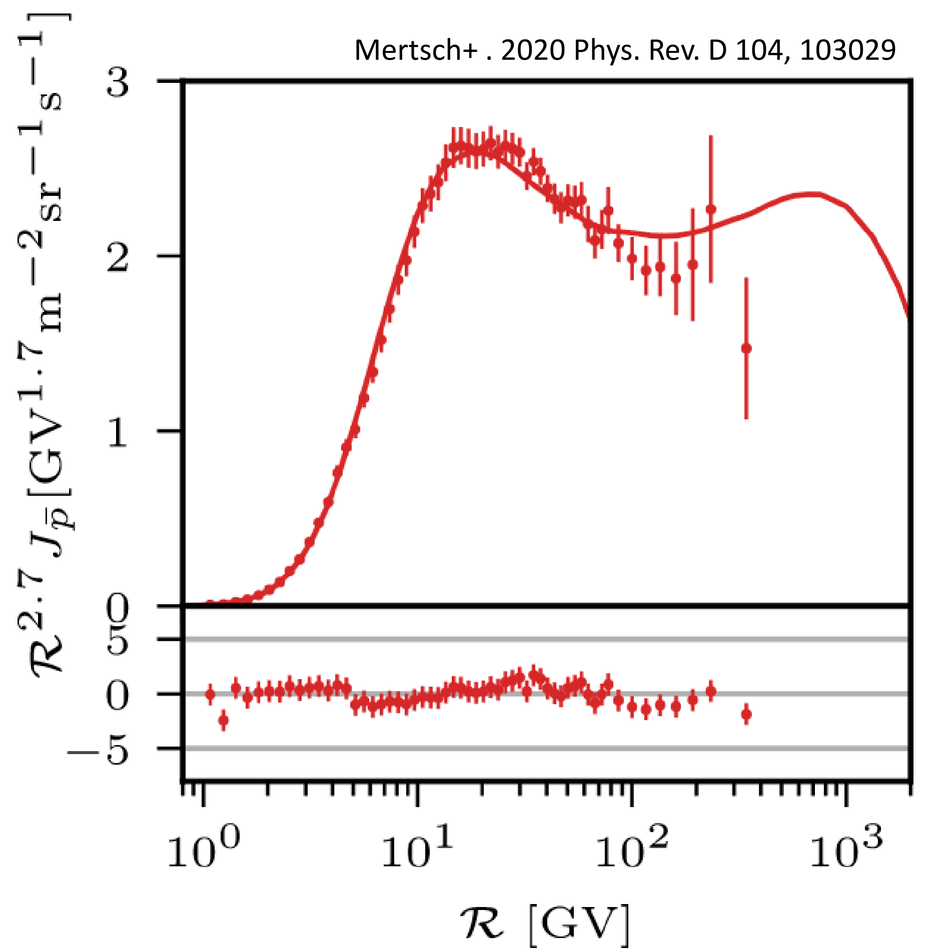


Leading constraints for WIMPs annihilating into hadronic final states,

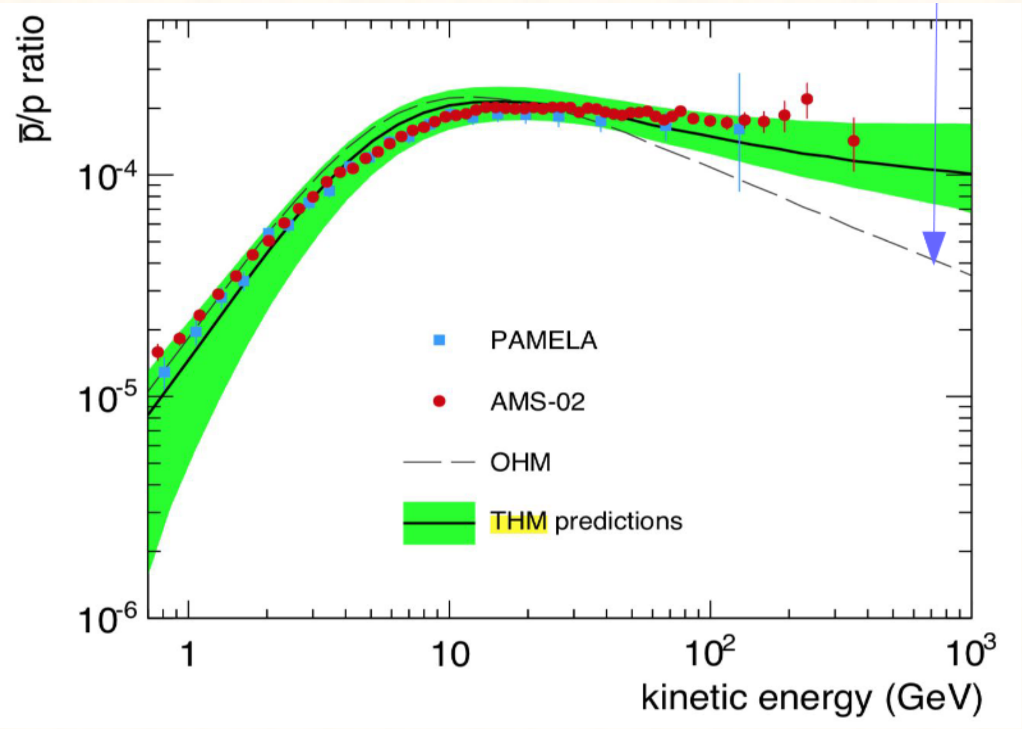
Compatible with GCE? See Di Mauro & Winkler PRD 103, 123005 (2021)

Antiprotons in the Galaxy – *More possibilities*

SNRs accelerating antiprotons



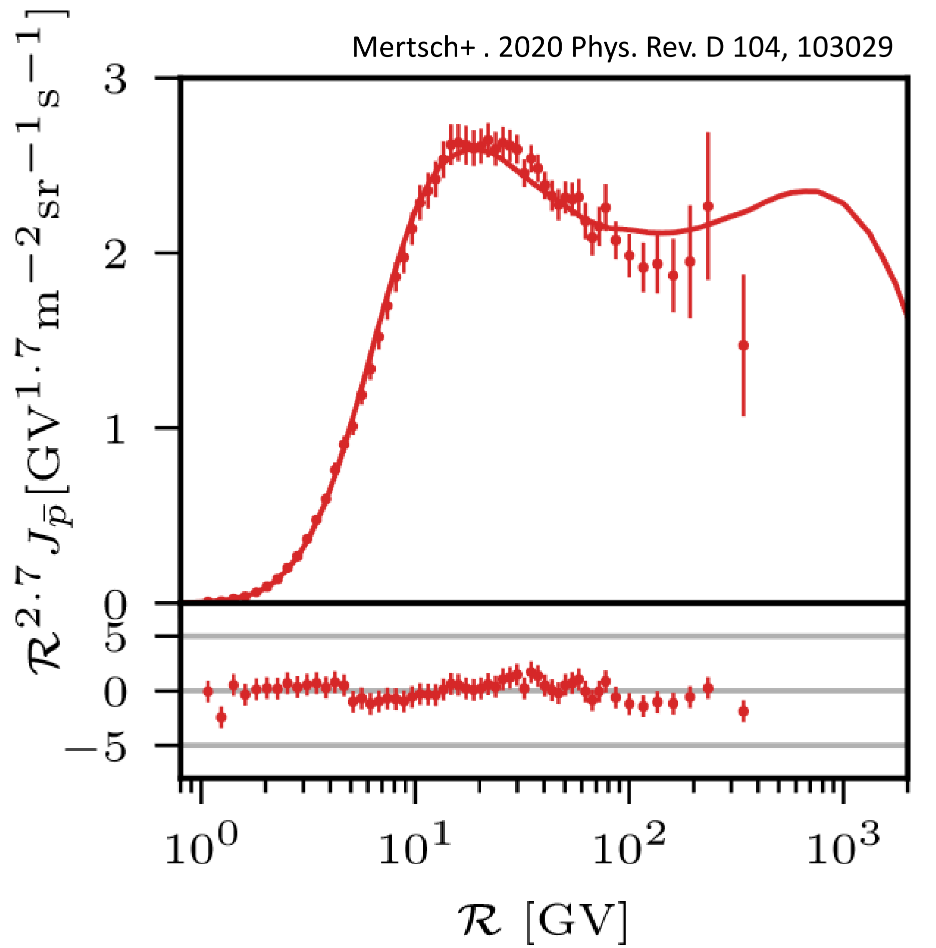
Inhomogeneous diffusion coefficient



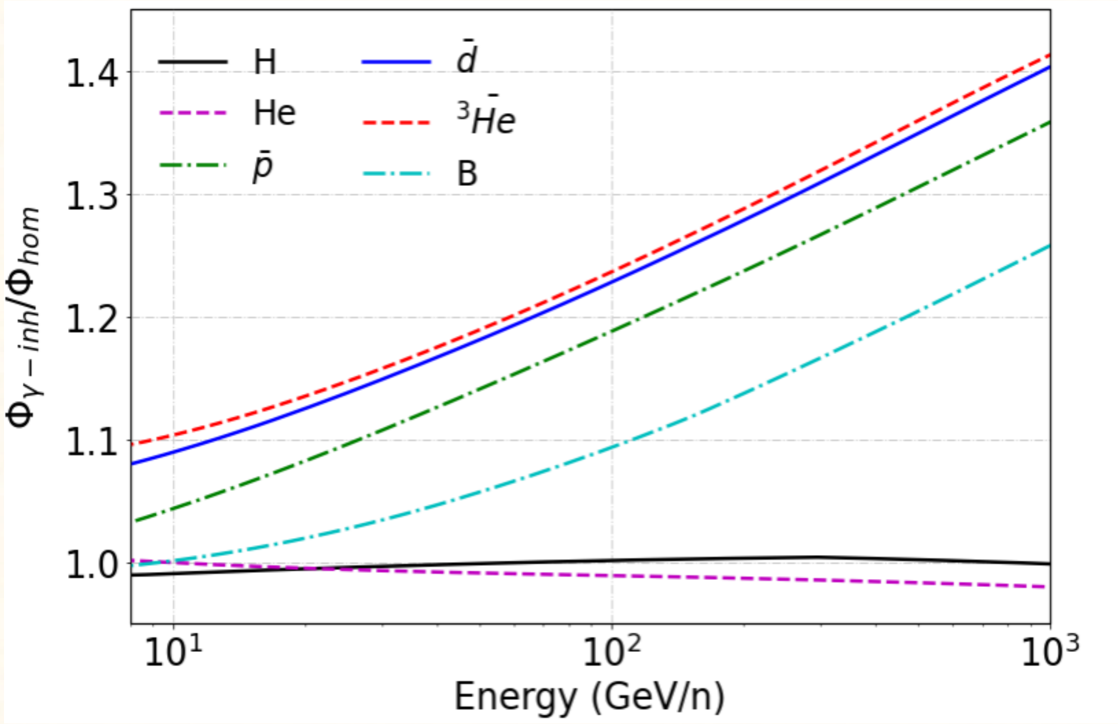
Feng+ PRD 94, 123007 (2016)
(Also: Zhao+ arXiv:2109.04112)

Antiprotons in the Galaxy – *More possibilities*

SNRs accelerating antiprotons



Inhomogeneous diffusion coefficient

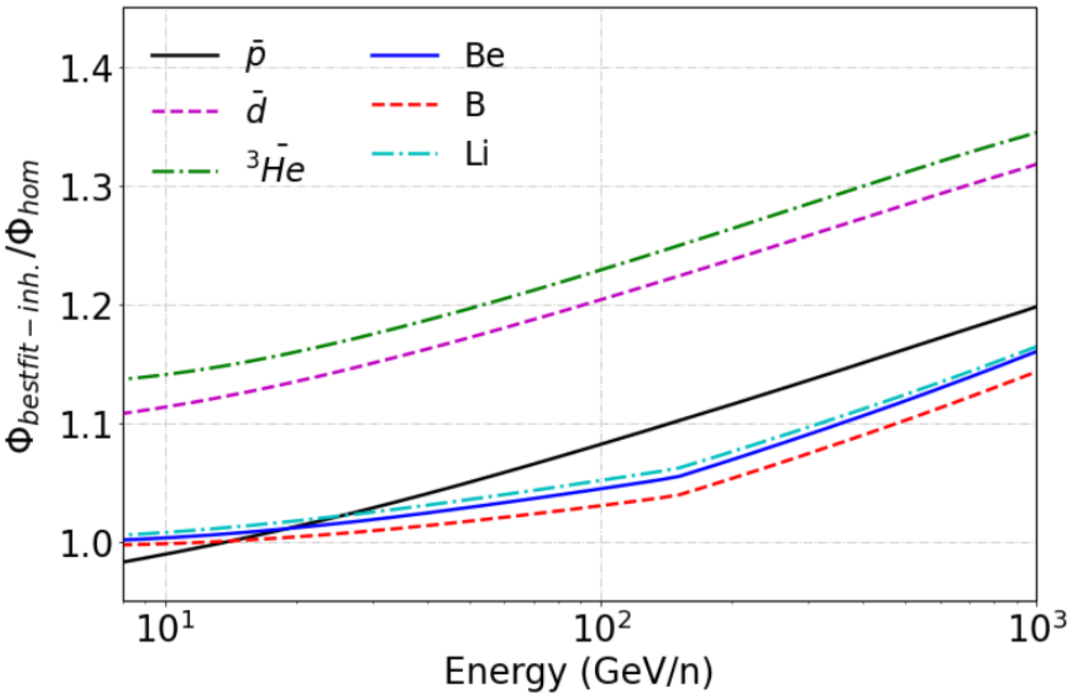


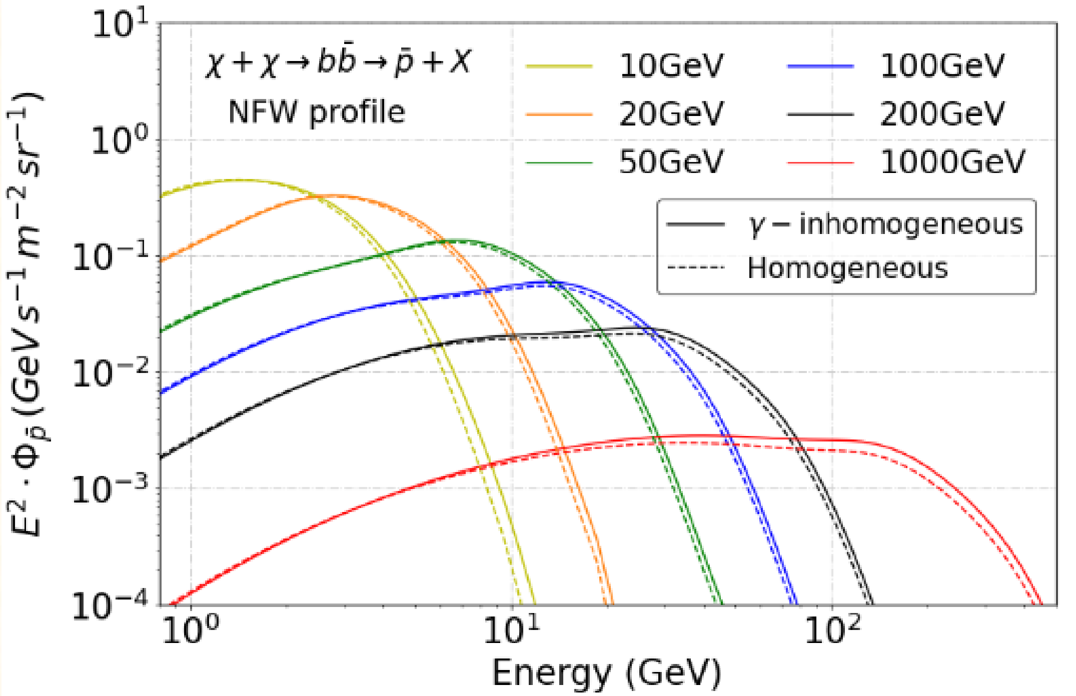
Tovar-Pardo, **PDL**, Sanchez-Conde arXiv:2405.12918

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

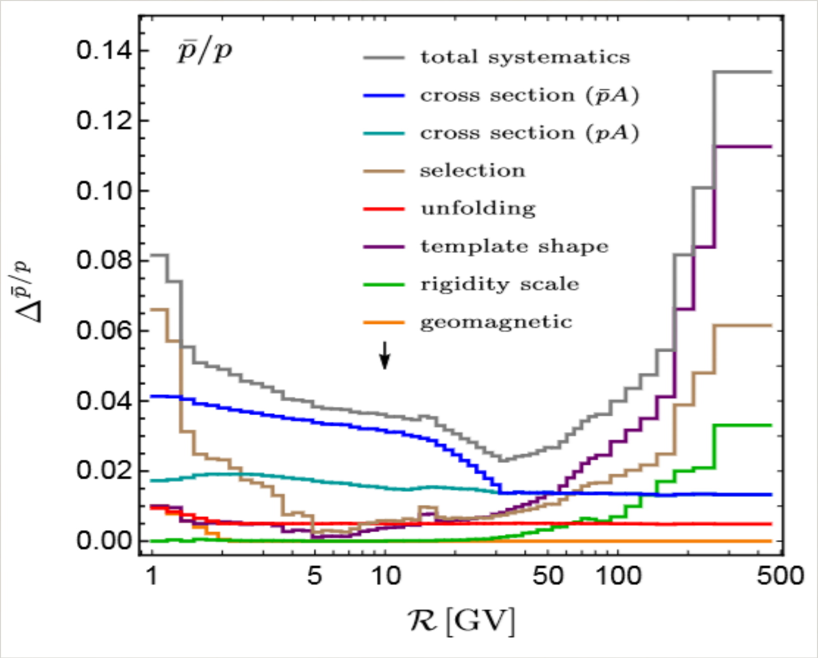
Tovar-Pardo, **PDL** 2024 ArXiv:2405.12918



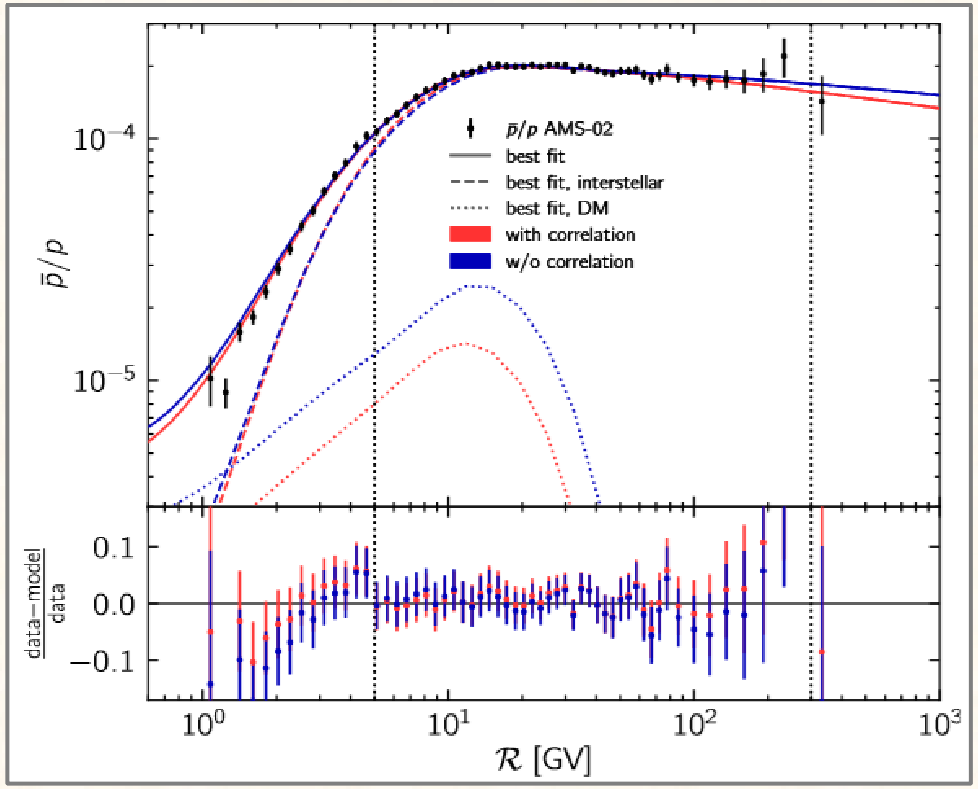


Systematics in AMS-02 data

Including the correlation of AMS-02 systematic errors sizeably affects significance and properties of the DM signal → Need of covariance matrices!



$$(C^{\alpha}_{\rm rel})_{ij} = \sigma^{\alpha}_i \sigma^{\alpha}_j \exp\left(-\frac{1}{2}\frac{(\log(R_i/R_j))^2}{(l^{\alpha}_{\rho})^2}\right)$$



Heisig+,Phys. Rev. Research 2, 043017 (2020)

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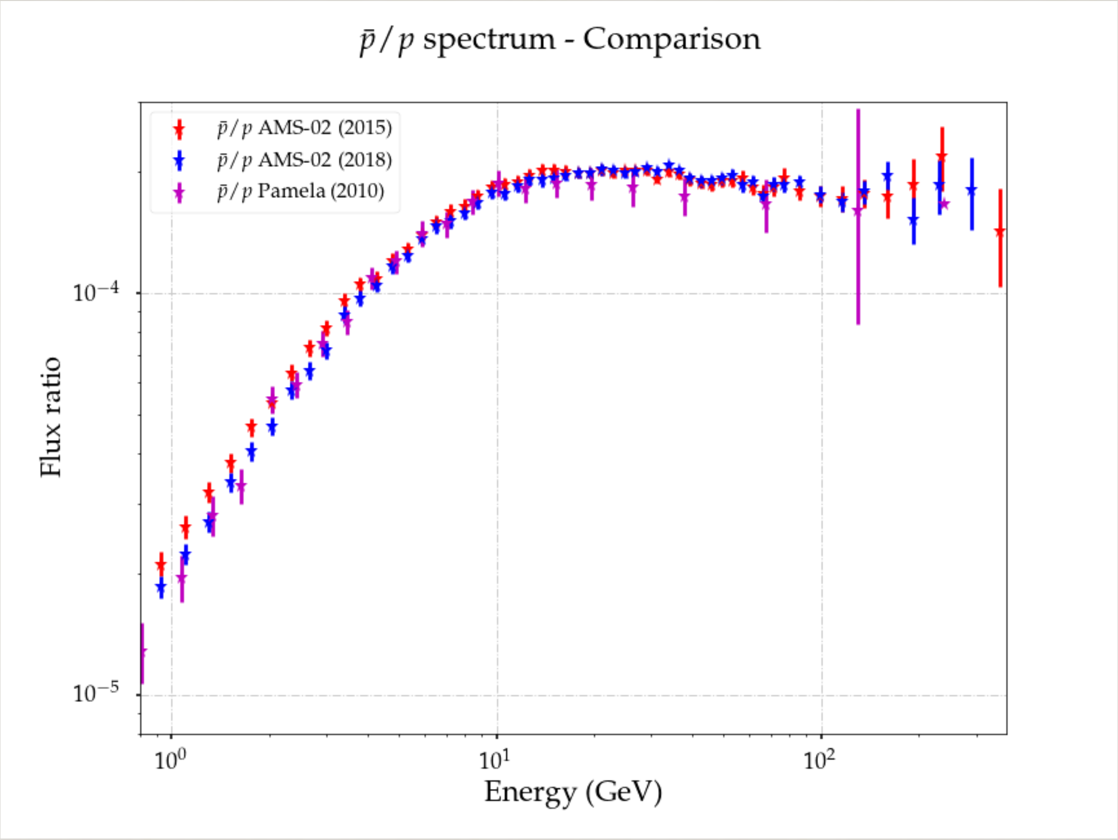

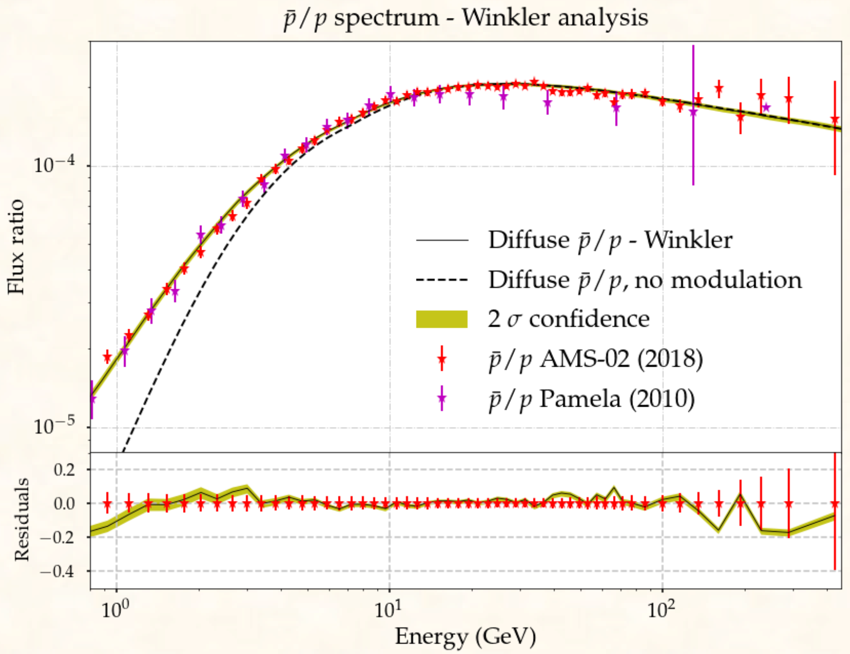

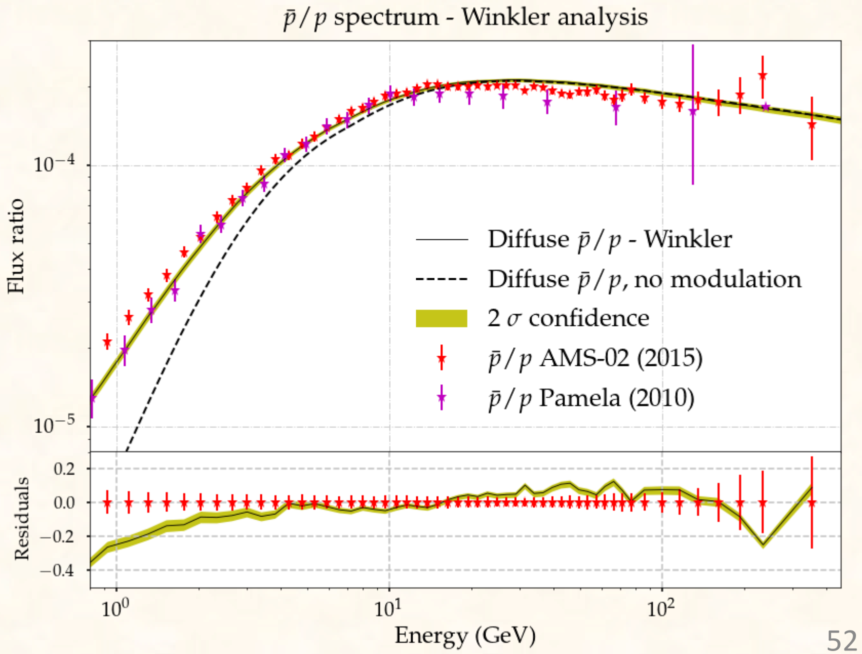

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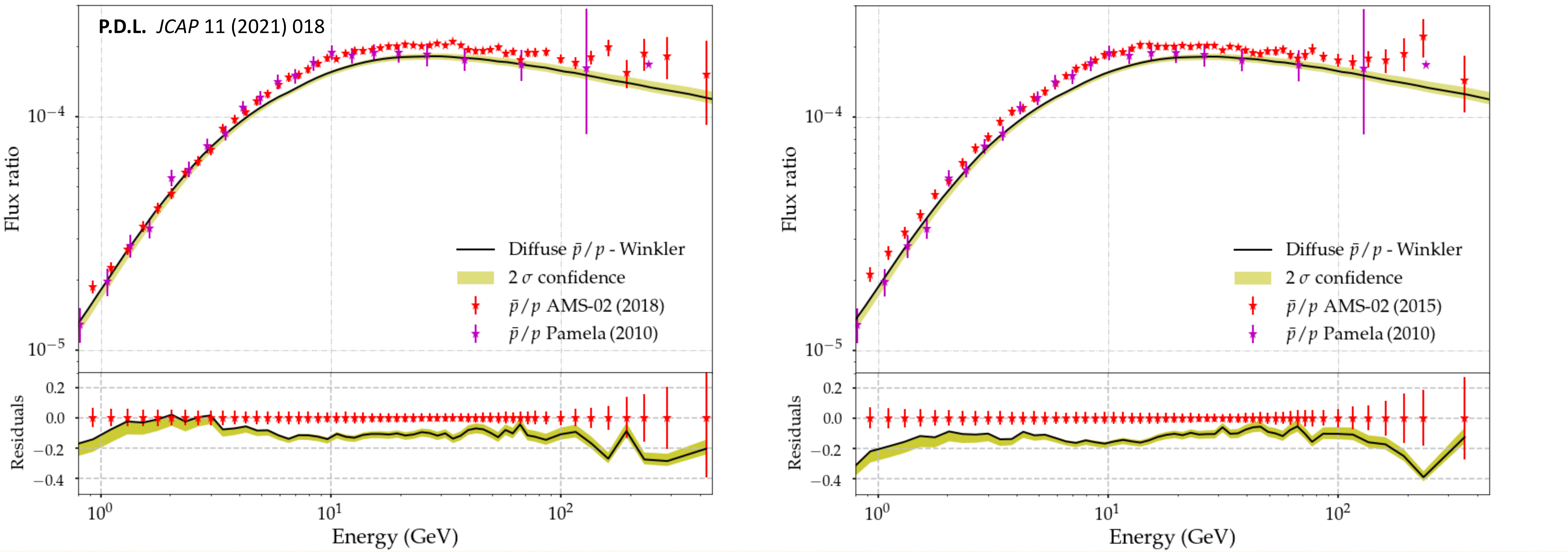
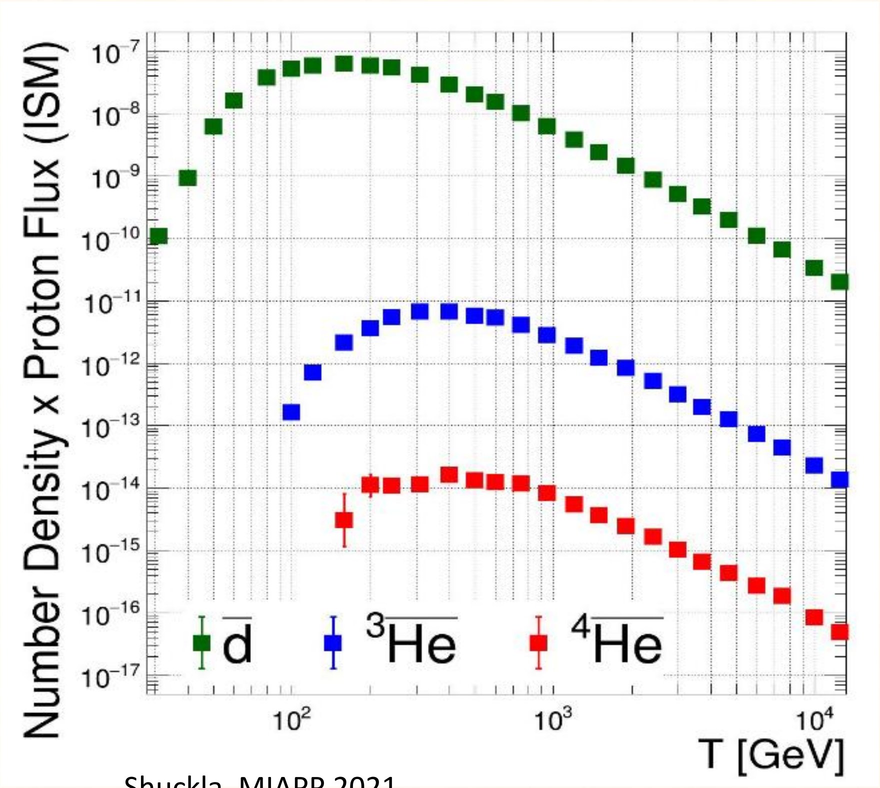


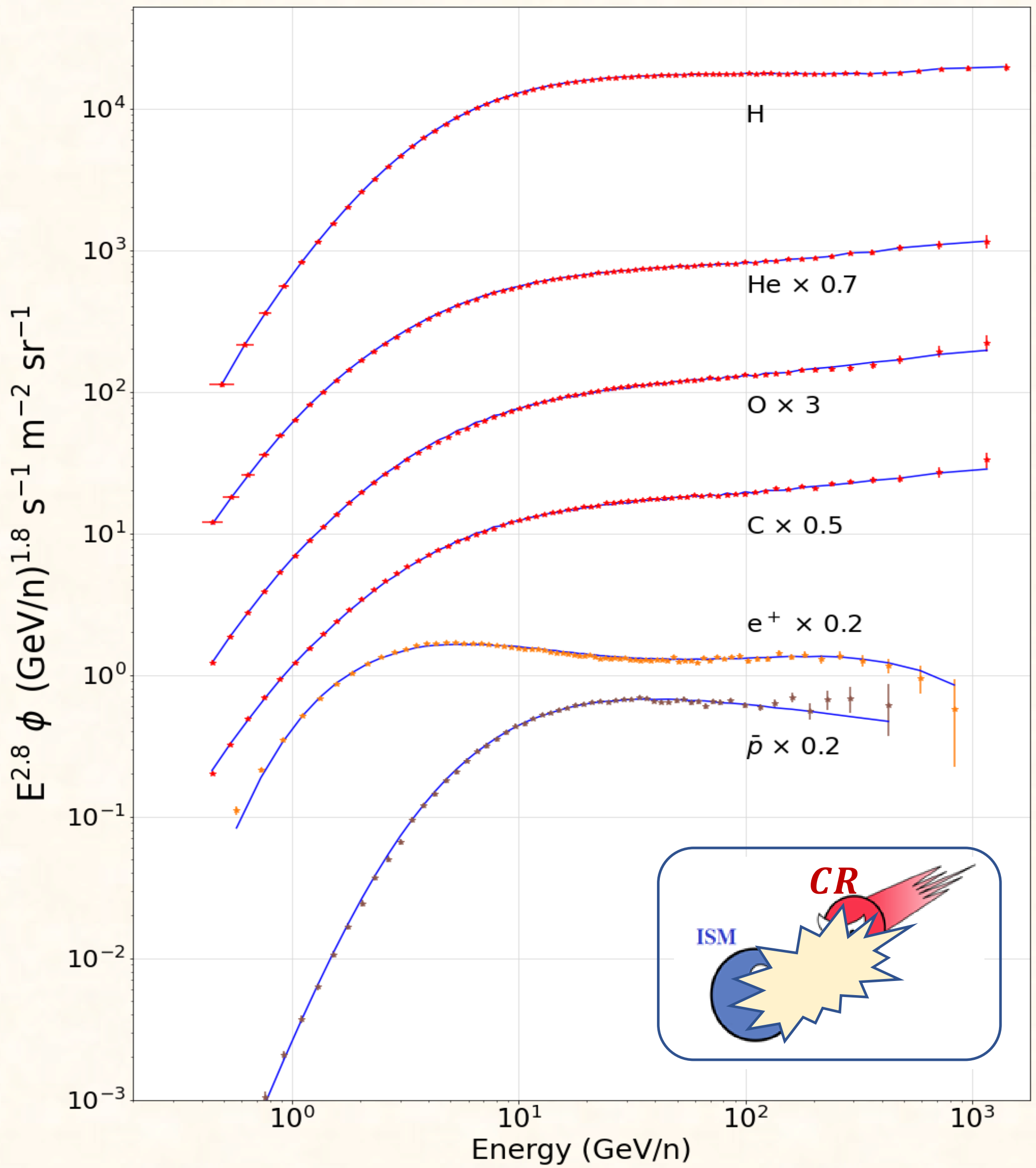
Potential of anti-nuclei to reveal the existence of BSM physics

p + p → p + p + p + ap + n + an

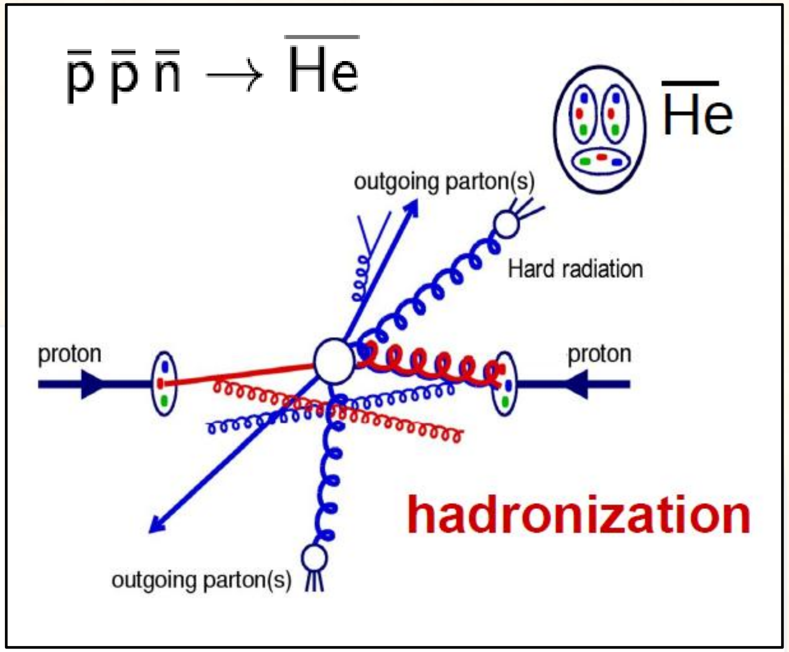


Shuckla, MIAPP 2021

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



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

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

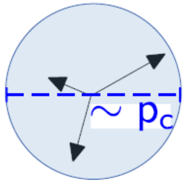
<u>Coalescence parameter</u> can be approximated from the coalescence momentum, $\boldsymbol{p_0}$

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

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

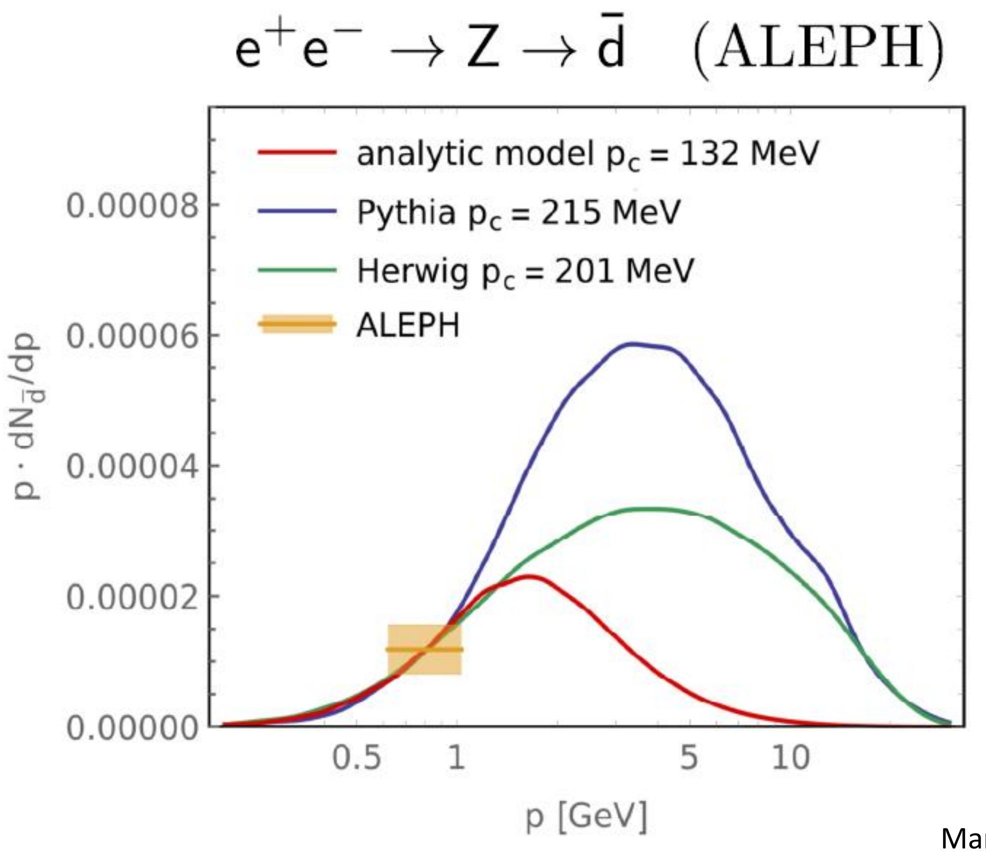
Anti-D $|\Delta p| < p_0$

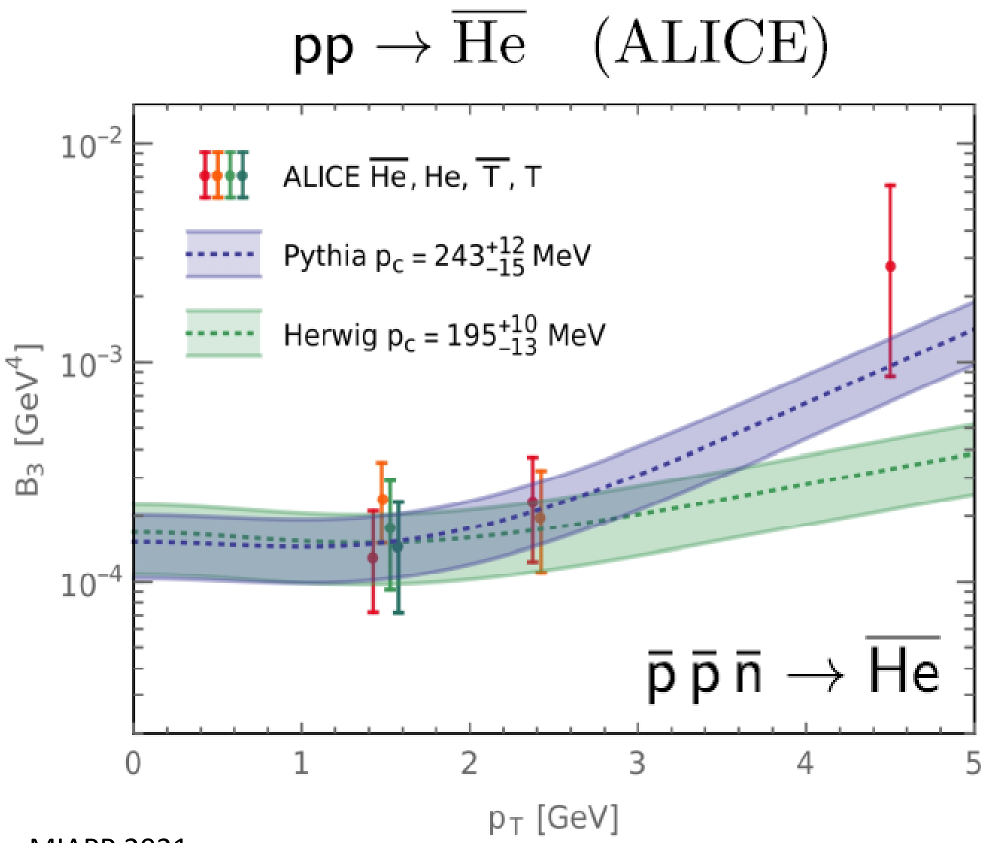
Anti-He



Formation of anti-nuclei

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





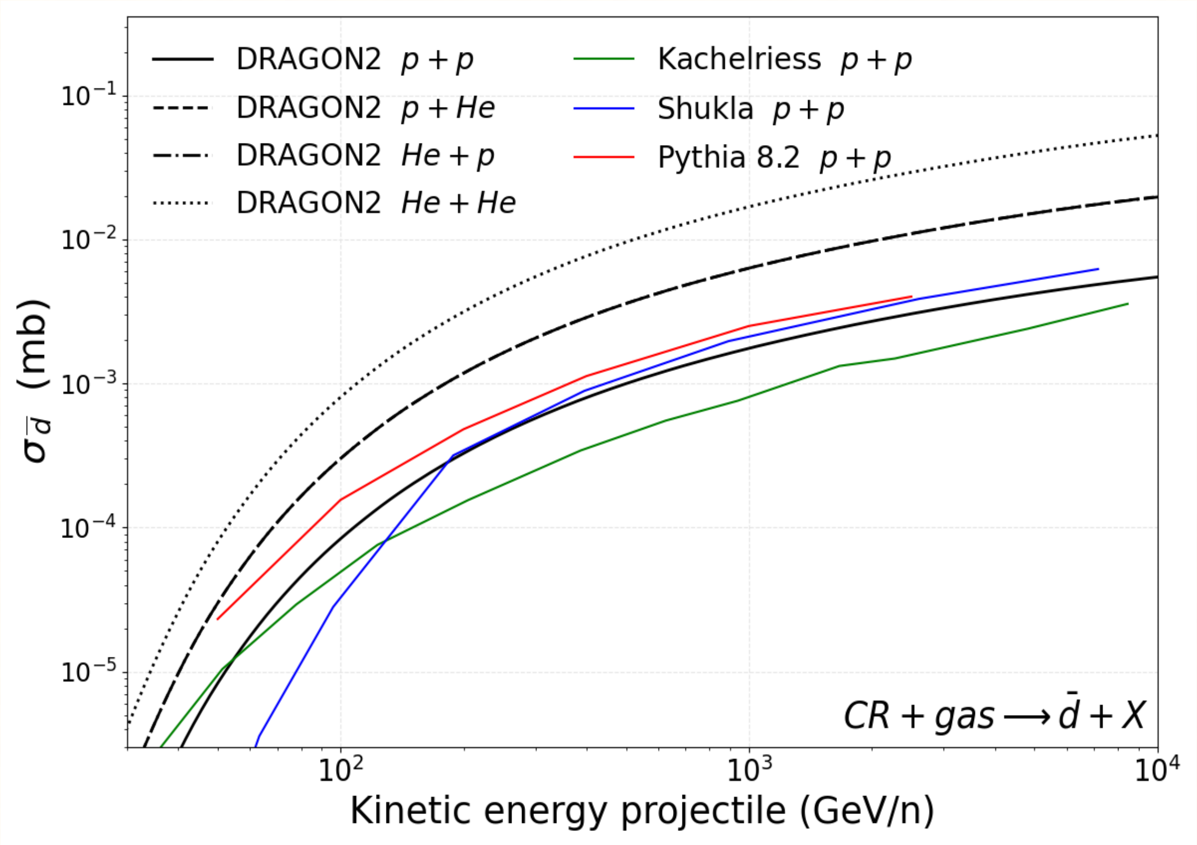
Martin Winkler, MIAPP 2021

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



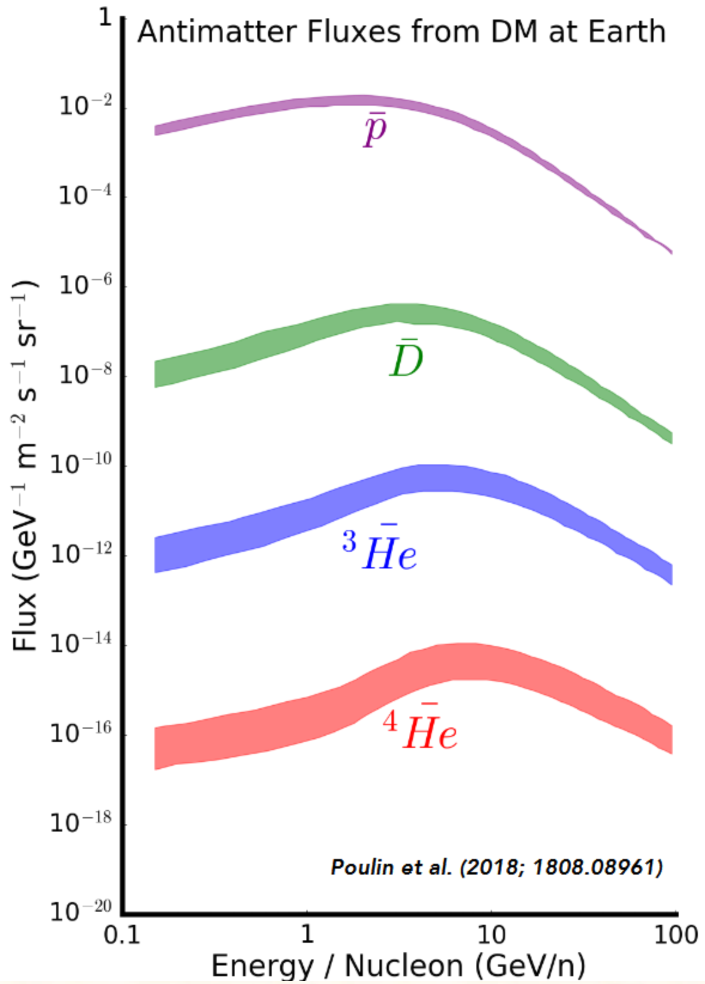
PDL et al, ArXiv: 2404.13114

A few ways to boost the DM antihelium yield

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

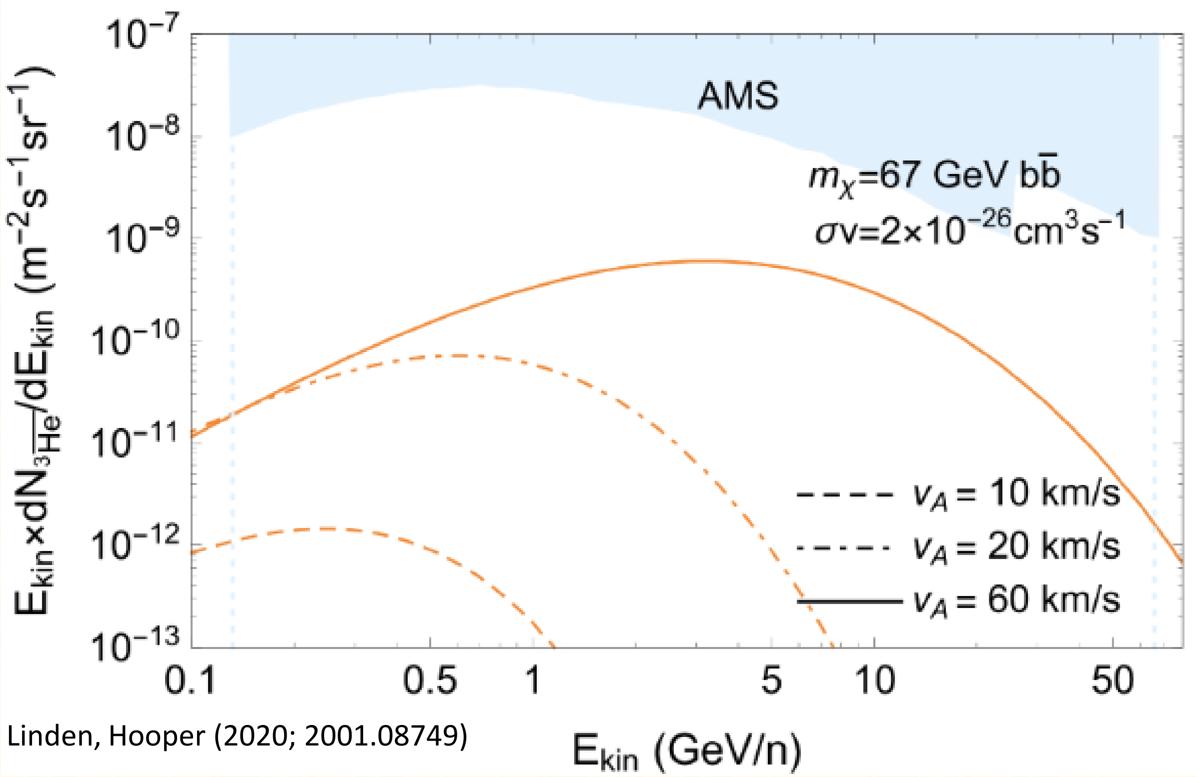
Given the scarcity of measurements, there have been different ways to compute the coalescence momentum

- 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)

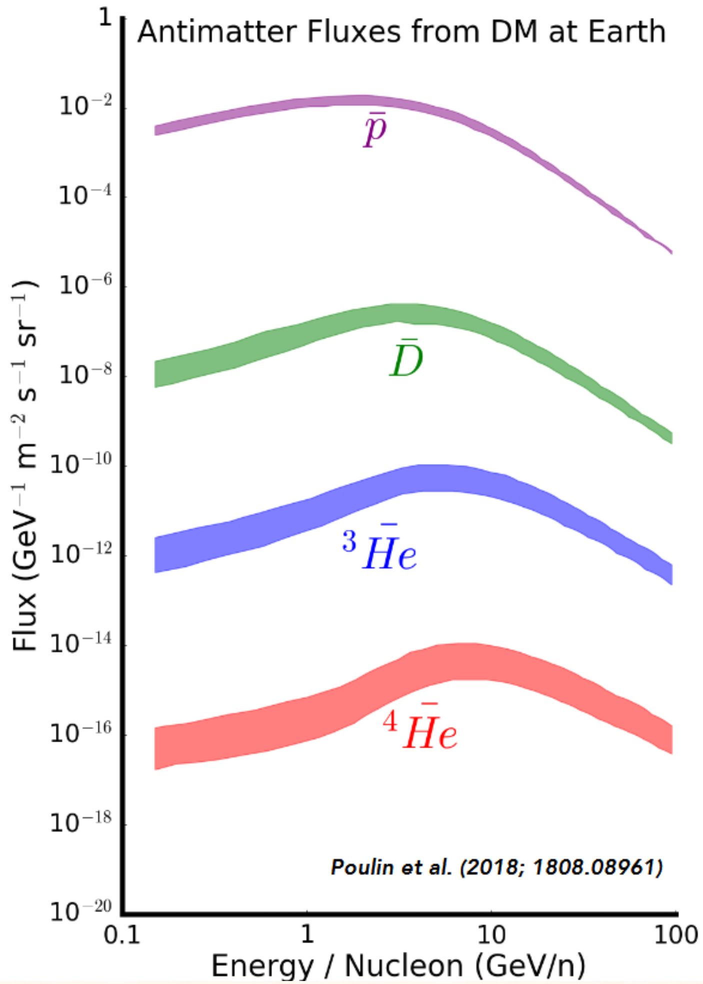


A few ways to boost the DM antihelium yield

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

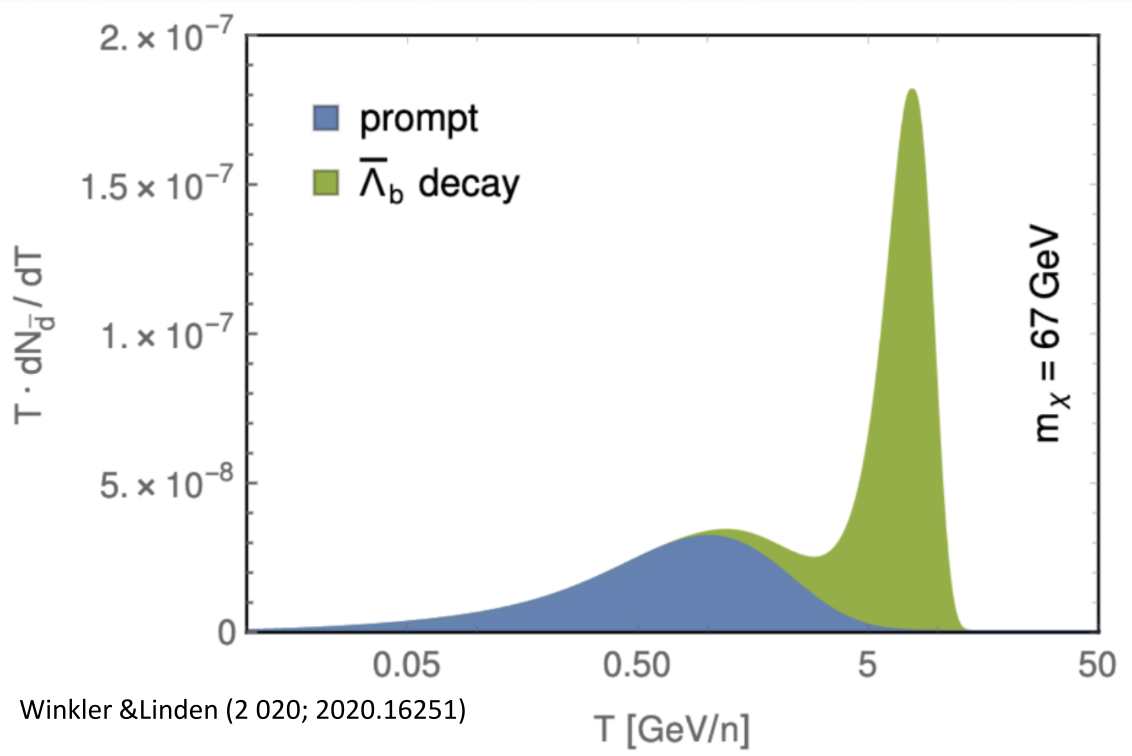


Cholis, Linden, Hooper (2020; 2001.08749)

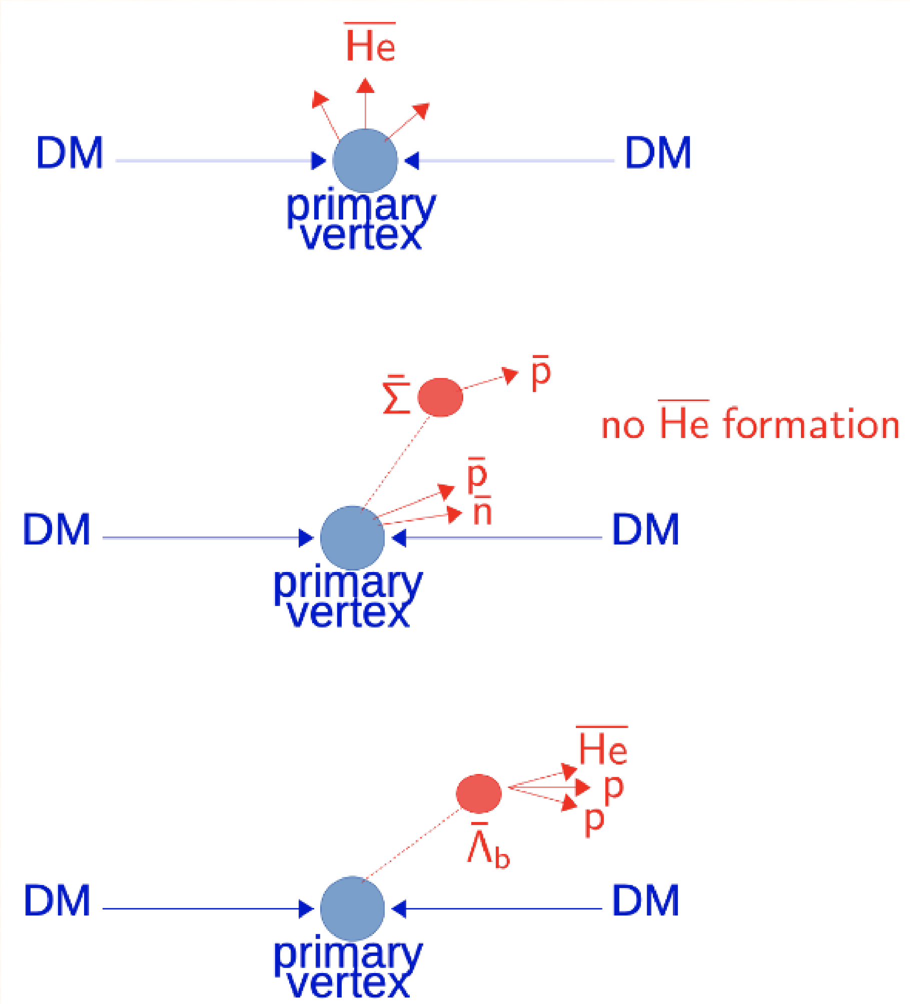


A few ways to boost the DM antihelium yield

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



Winkler &Linden (2 020; 2020.16251)

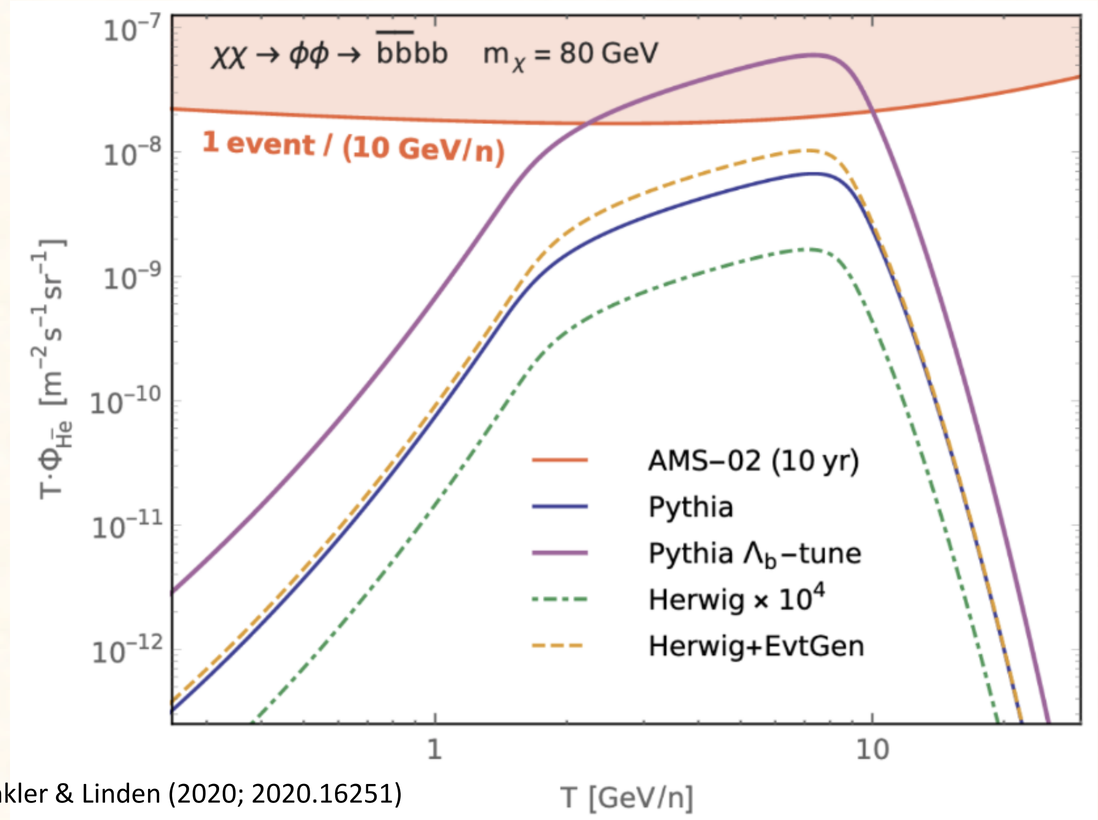


Credit: Martin Winkler

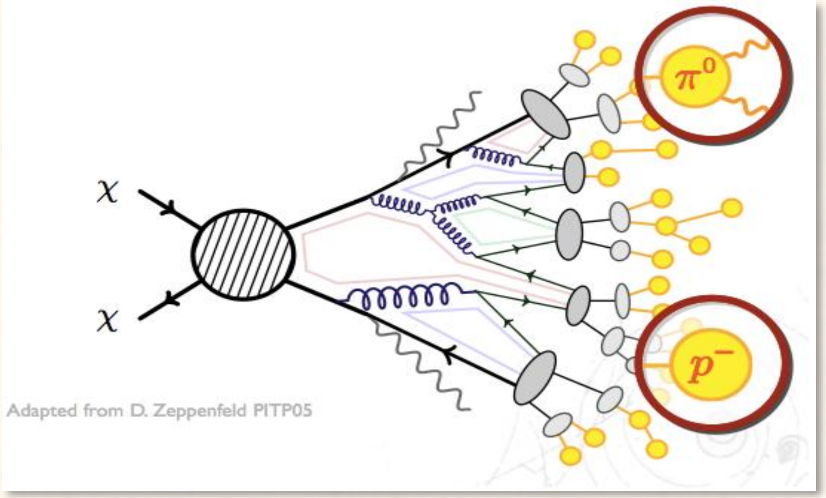
In tension with new LHCb measurements See ArXiv:2504.07172

A few ways to boost the DM antihelium yield

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

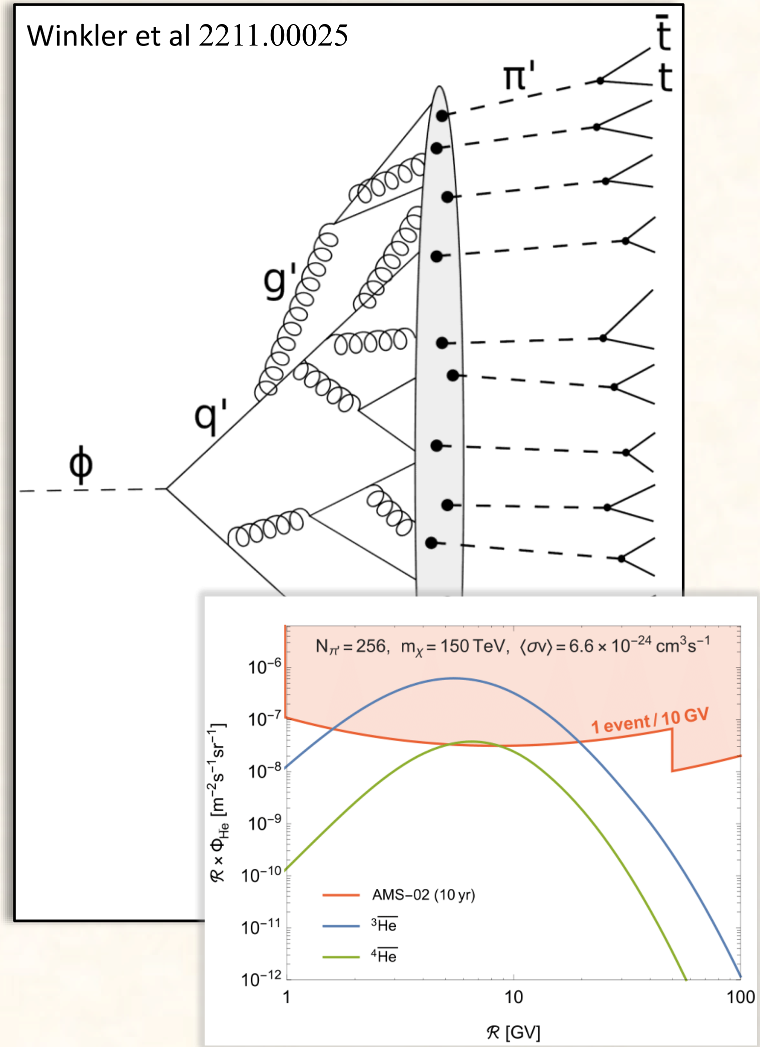


Winkler & Linden (2020; 2020.16251)



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…

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



Our standard predictions do not explain total $\overline{\mathrm{He}}$ events and foresee a ratio $\overline{\mathrm{He}}$-4/$\overline{\mathrm{He}}$-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)

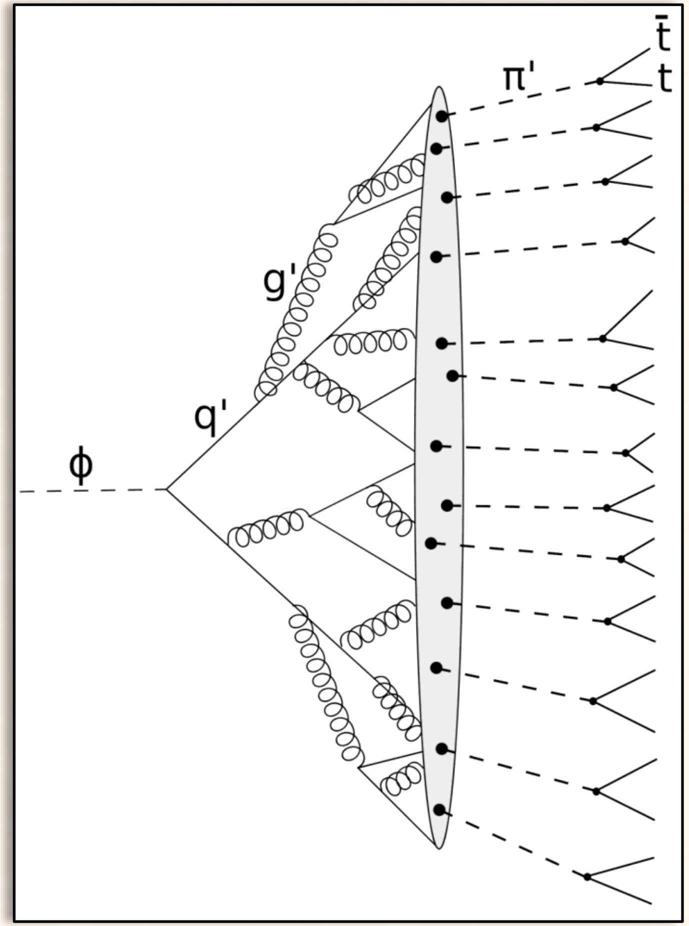
Can explain AMS-02 observations but need some tuning

Fireball anti-nucleosynthesis (Fedderke et al. 2402.15581)

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

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

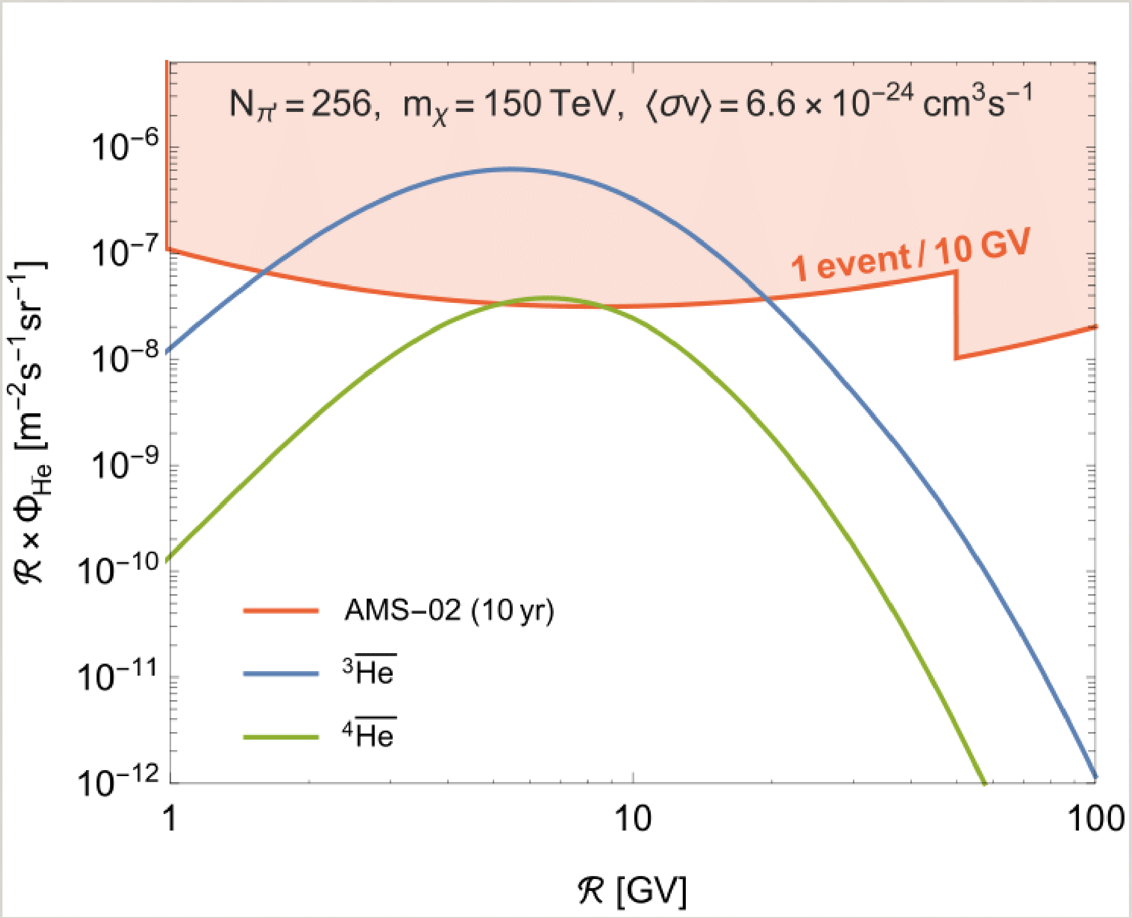
A **strongly coupled dark sector** can produce a “dark parton shower”, generating high multiplicity of “dark pions”. These would subsequently decay into SM quarks through, e.g., the Higgs or top portals, **triggering a hadronic shower.**

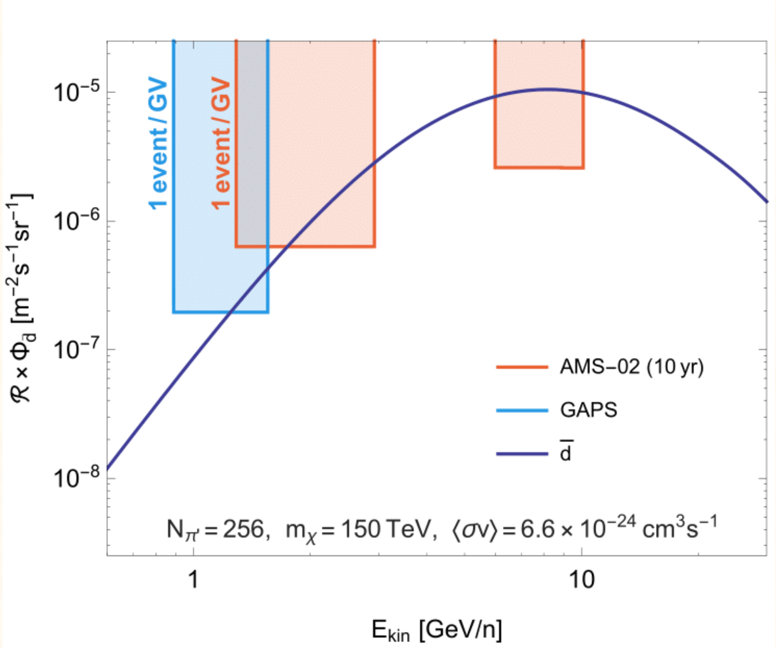
Simulated with Pythia as $\chi\chi \to \phi\phi \to 2\bar{q}'q' \to N_{\pi'}\,\pi' \to N_{\pi'}\,\bar{t}t$

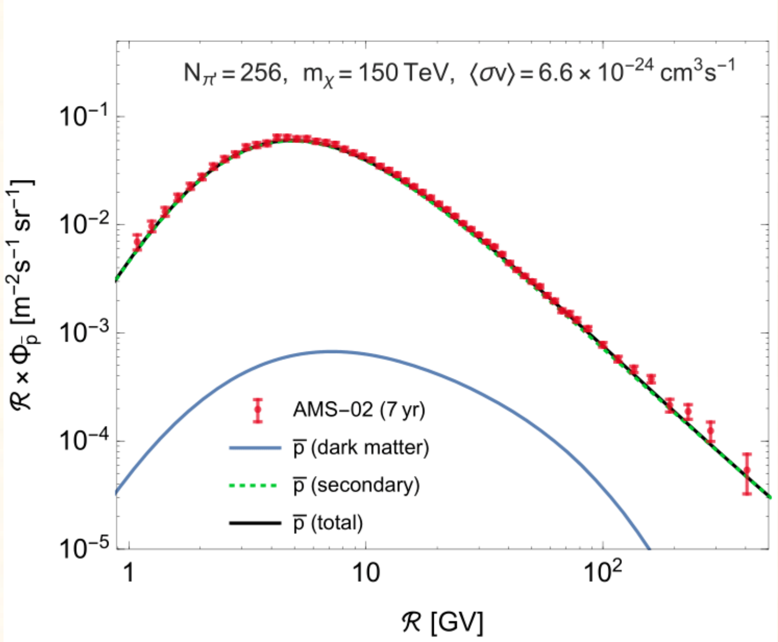
This could have escaped detection at LHC and it offers a pathway to look for excesses in the ditop channel

QCD-Like Dark sector

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

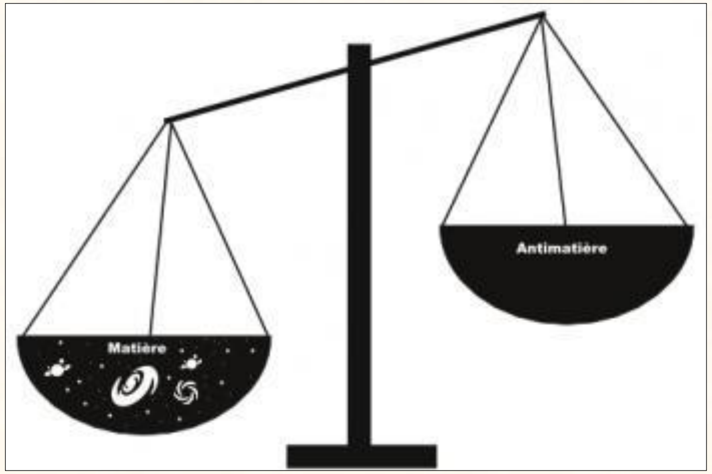




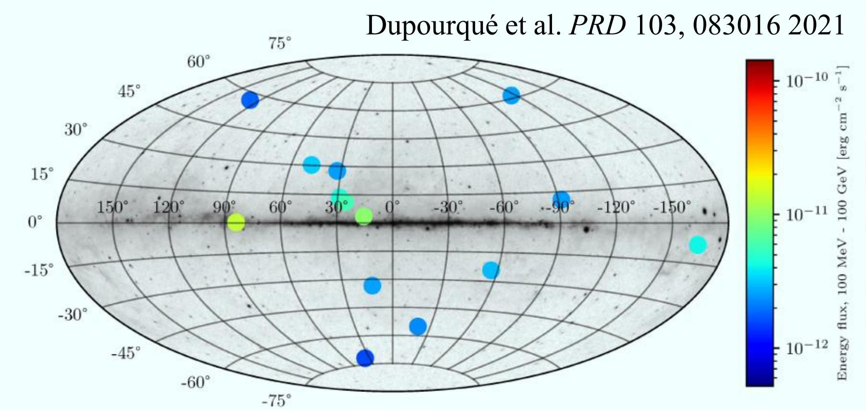


Matter-antimatter asymmetry

"..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**

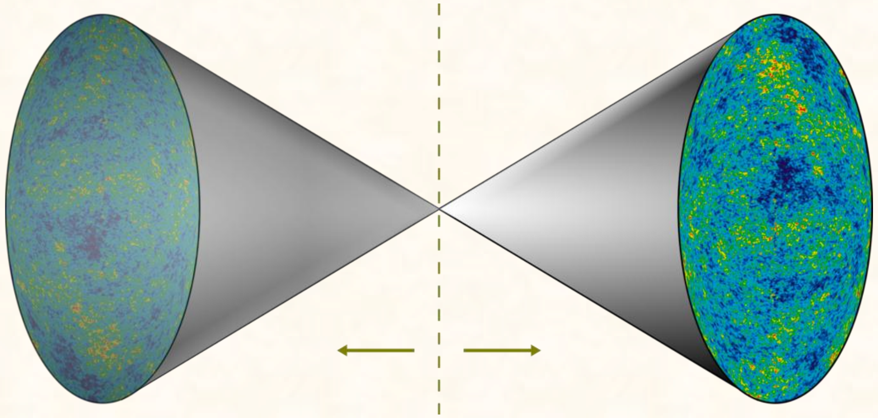


If these events come from anti-stars or similar systems, we could see them in gamma-rays… Poulin et al. *PRD* 99 (2019) 023016 show that within these limits, **there can be enough anti-stars to explain the observed total amount of antihelium events**



Dupourqué et al. *PRD* 103, 083016 2021

Possible anti-stars systems



The positron excess

This component would require a ~TeV DM particle with annihilation rate of a few times $10^{-24}\ cm^2/s$ (in tension with other constraints and above the thermal!)

<u>Main astrophysical explanation:</u> **Pulsars**

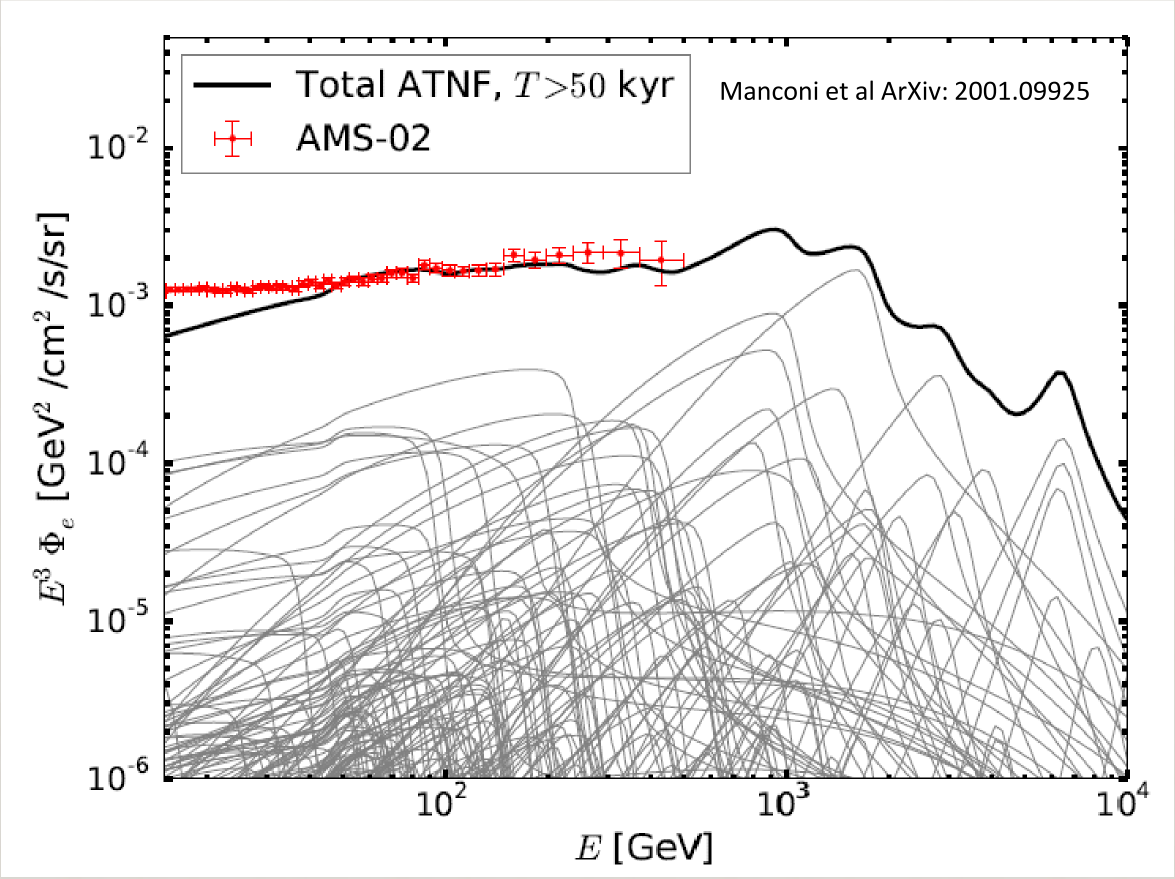
Cheng, Ho & Ruderman (1986–1990 series) — Predicted copious electron–positron pair production in magnetospheres

Stawarz, Aharonian & Malyshev (2003–2006) — Pulsar wind nebulae can accelerate electrons/positrons and escape into ISM

Hooper, Blasi & Serpico (2009) — first widely cited on pulsars explaining the PAMELA excess

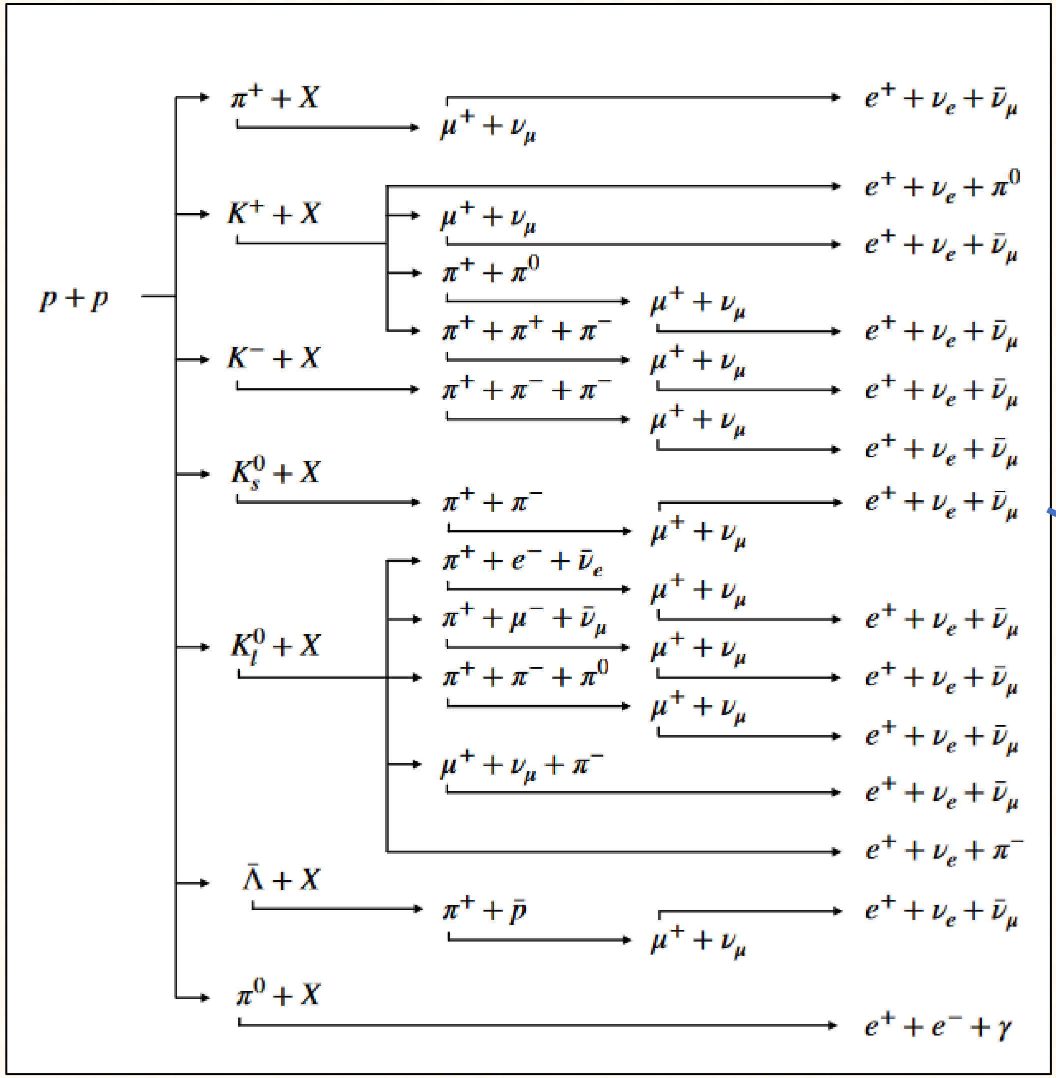
Consensus in the comunity that these signals must be dominant source of high-energy positrons

An astrophysical source of cosmic-ray positrons (and electrons) was not considered: **Nearby pulsars**

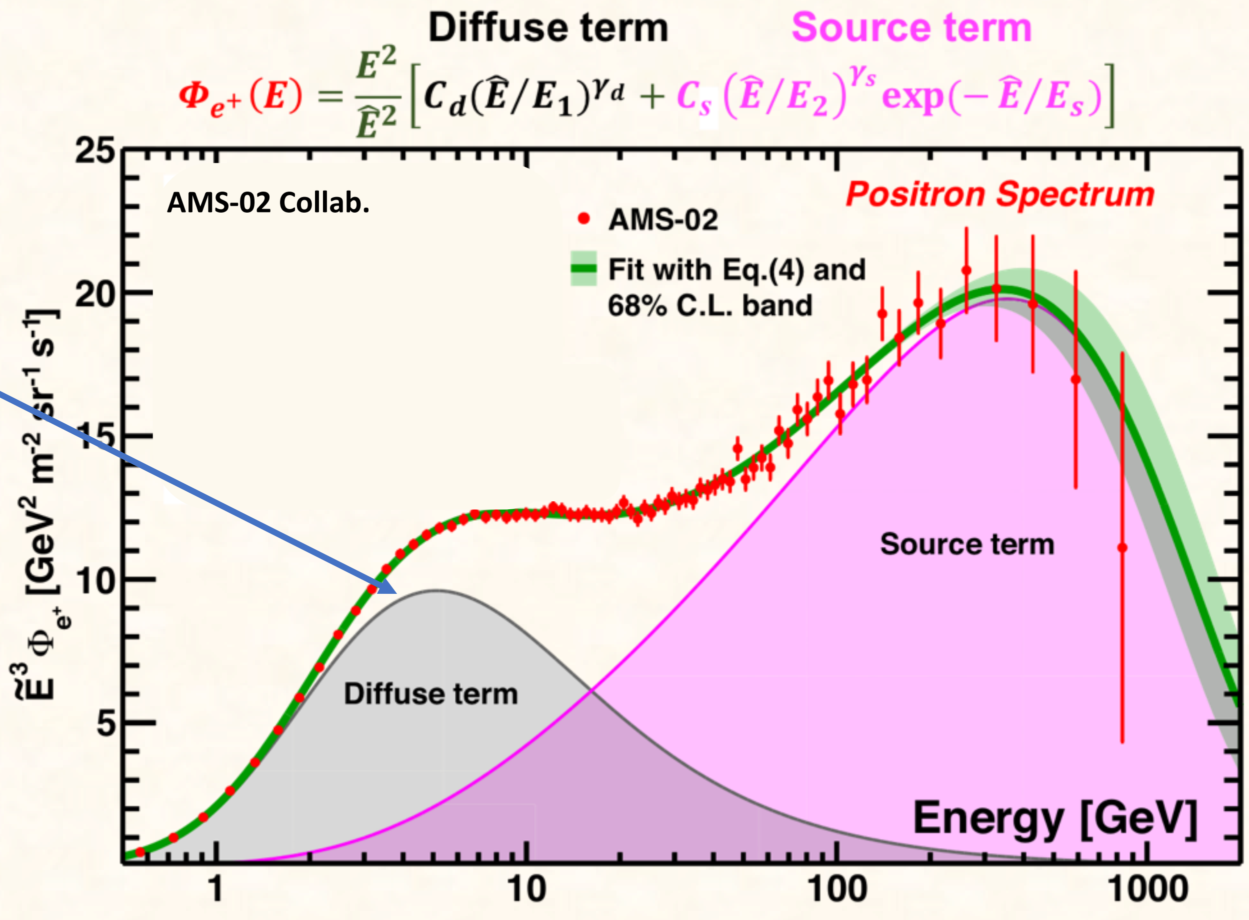


The cross section problem

Orusa et al PRD 105 (2022) 12



Positrons mainly produced from p+p interactions, but also He and heavier CRs are also involved and produce positrons!



Production of positrons and DM identification

The stochastic nature of the PWN emission makes it difficult to find signatures of DM at high energies:

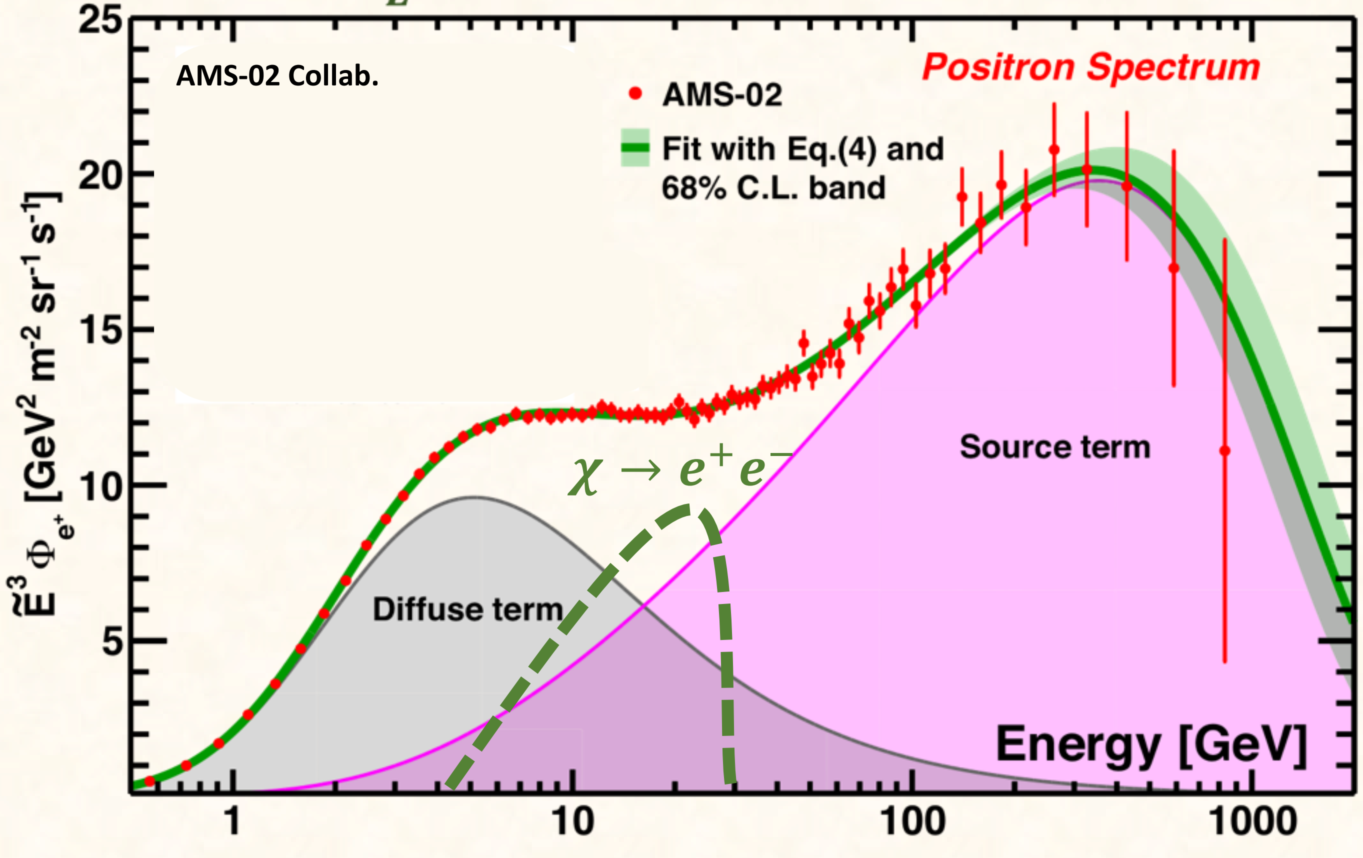
1. Sharp features can be easily masked by PWN contribution
2. High masses contributing to the e+ spectrum at those energies

Easier to spot DM signals at low E

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

Diffuse term Source term

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



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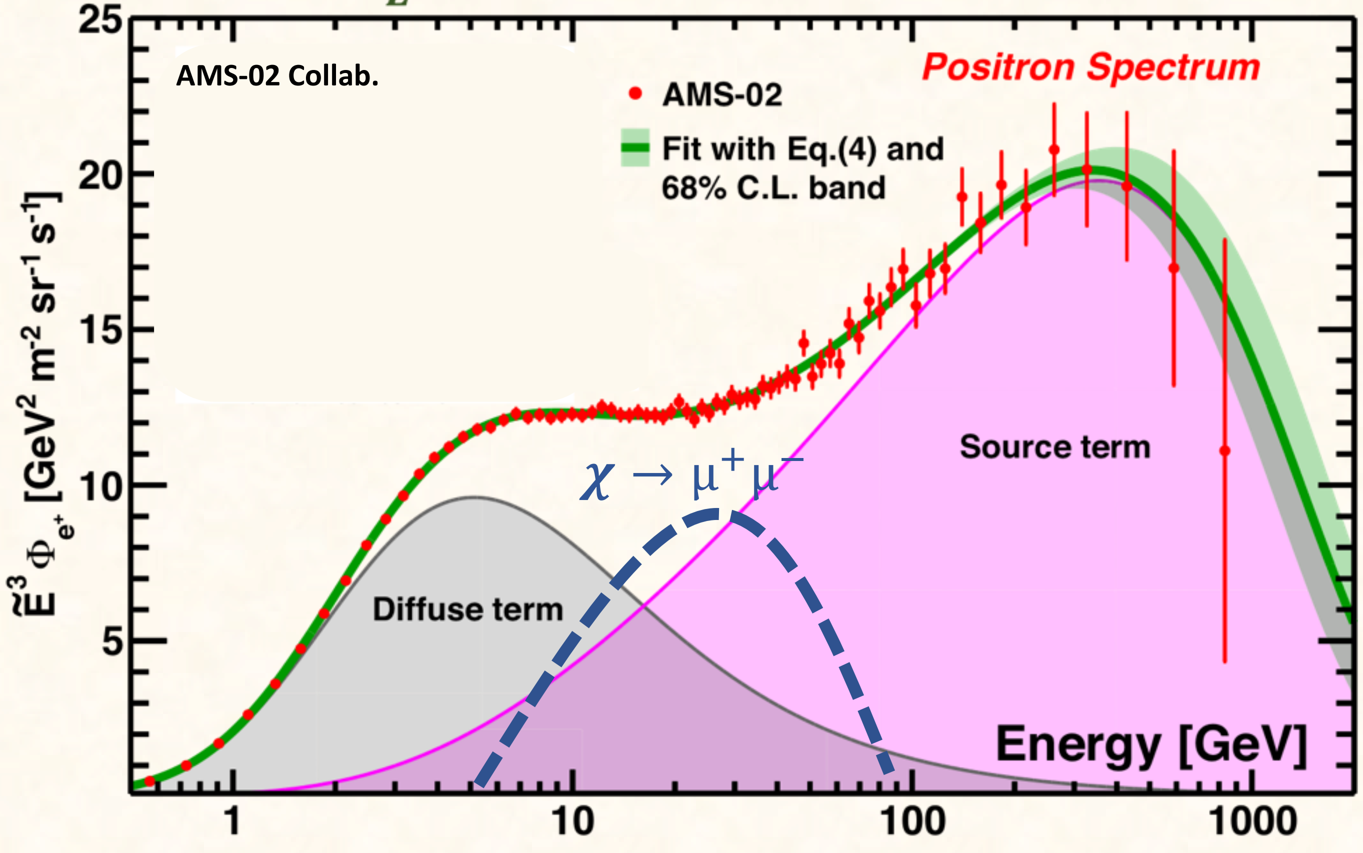

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