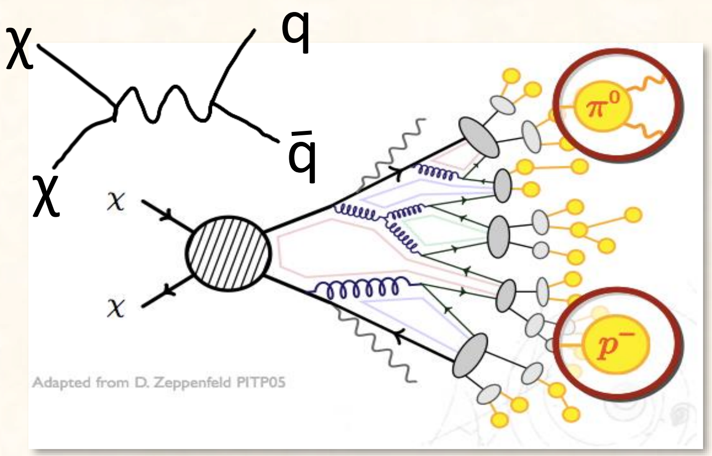
Universidad Autónoma de Madrid

Instituto de Física Teórica UAM-CSIC

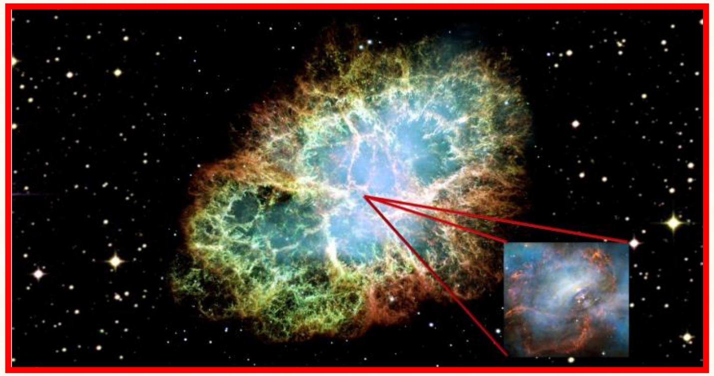
Dark matter searches with cosmic-ray antiprotons



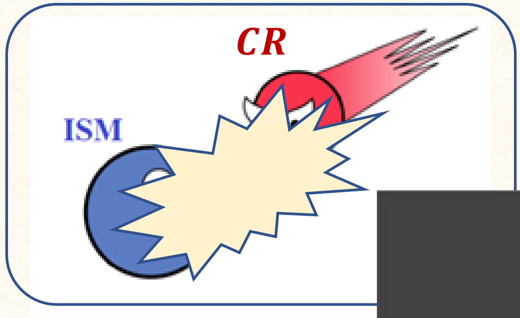
Pedro de la Torre Luque --- pedro.delatorre@uam.es
Juan de la Cierva fellowship (IFT/UAM - Madrid)

@ JENAA, CERN – 19/08/2024

CR Antiprotons in the Galaxy

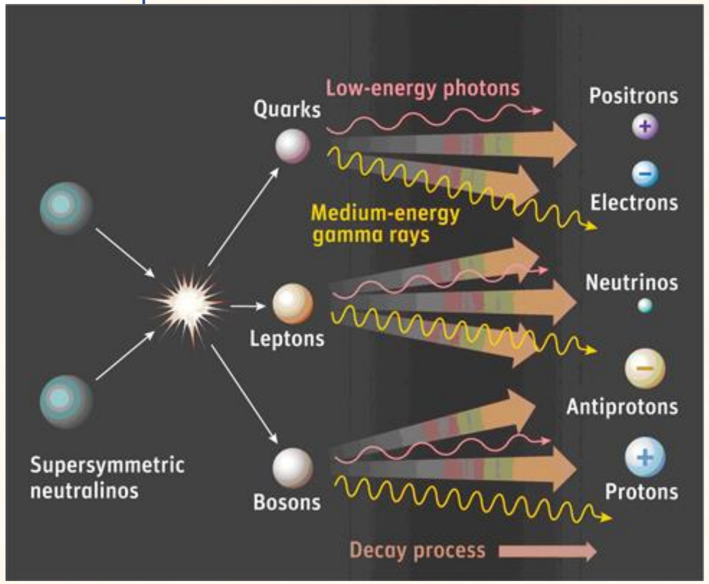


Cosmic rays (CRs) are ionized nuclei that are accelerated in astrophysical shocks (supernova remnants, pulsars, etc) and propagate in the Galaxy, interacting with gas and magnetic field



Antiprotons must be produced as secondary CRs that can be detected by our experiments

Antiprotons have long been considered critical channel for indirect DM searches: Many simple extensions of the SM lead to well-motivated dark matter candidates such as the bino, neutral wino or neutral Higgsinos expected to couple to quarks



Antiprotons as a tool to identify signals of BSM physics

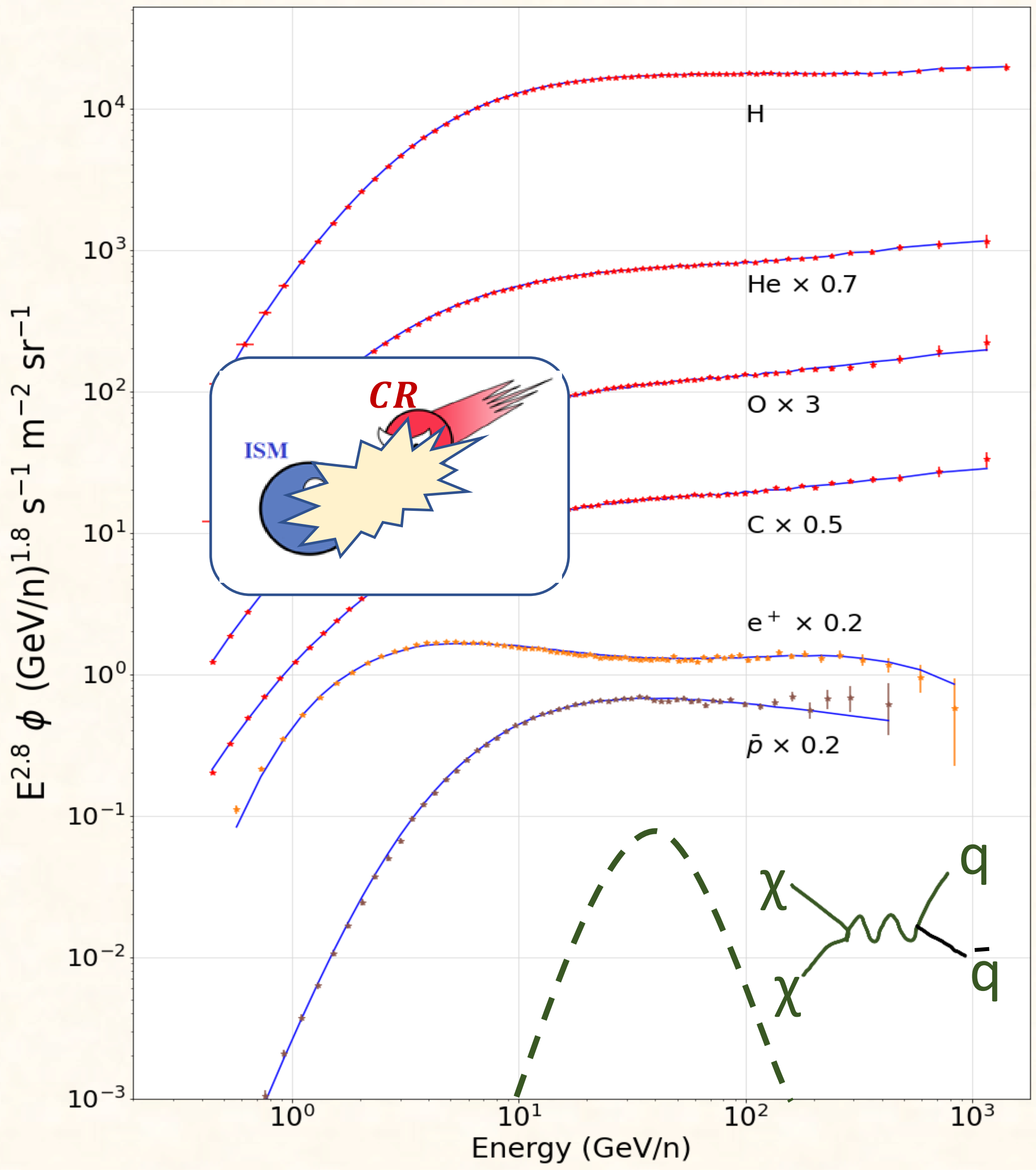
See talk by A. Oliva

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

The antiproton spectrum allows 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.

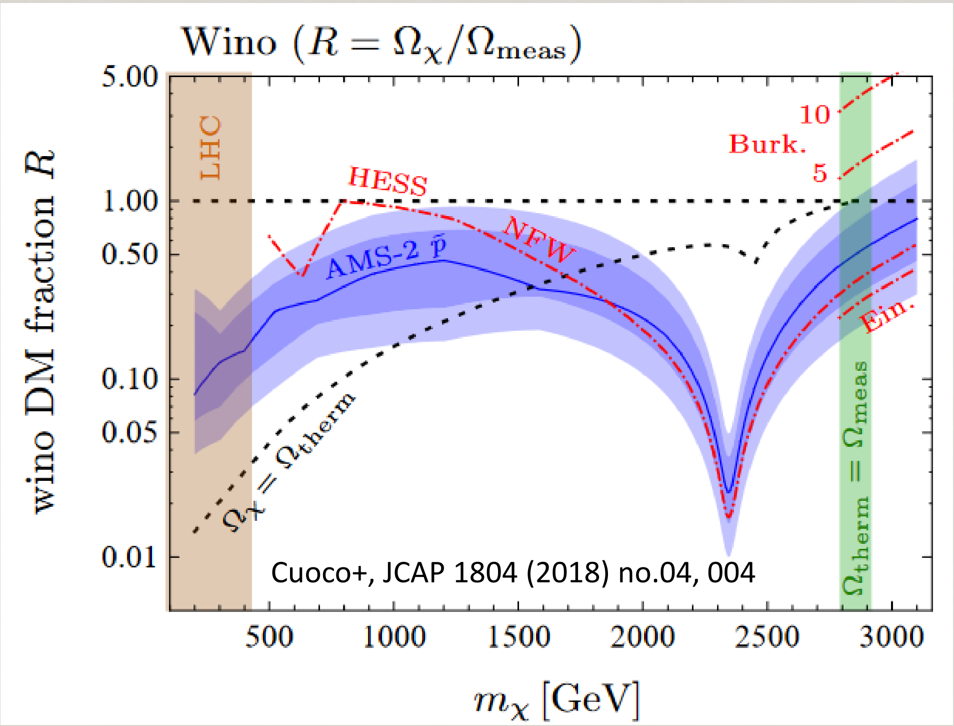
Flux of CR nuclei and antiparticles (data from AMS-02)

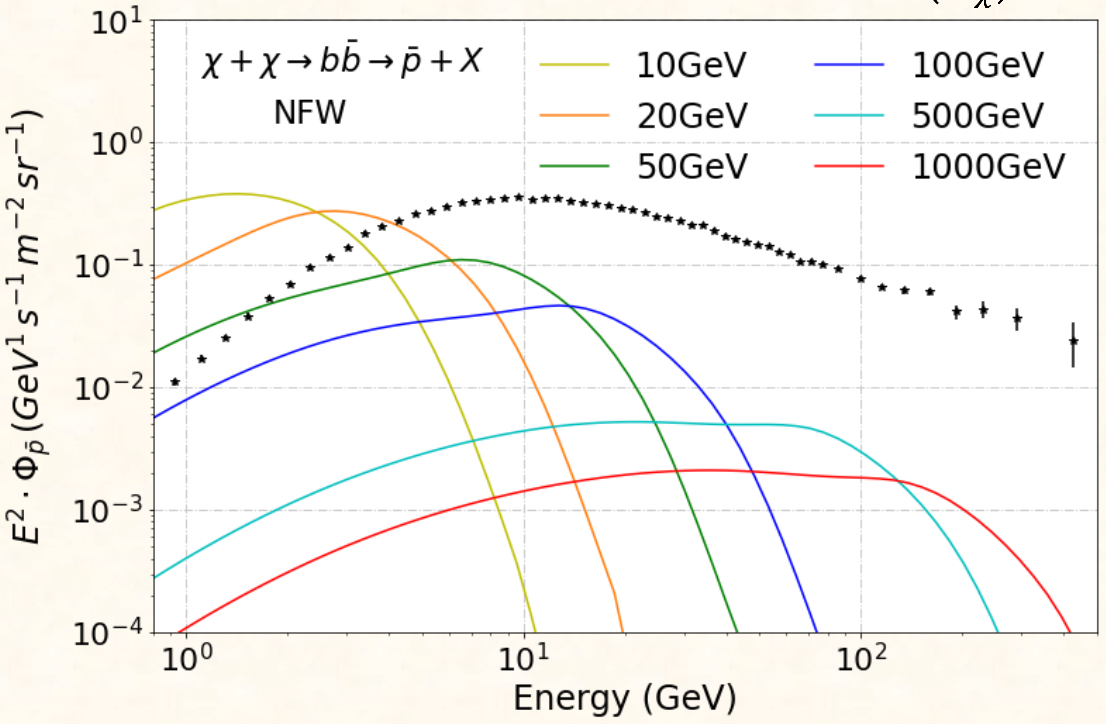


DM production - primary antiprotons

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)

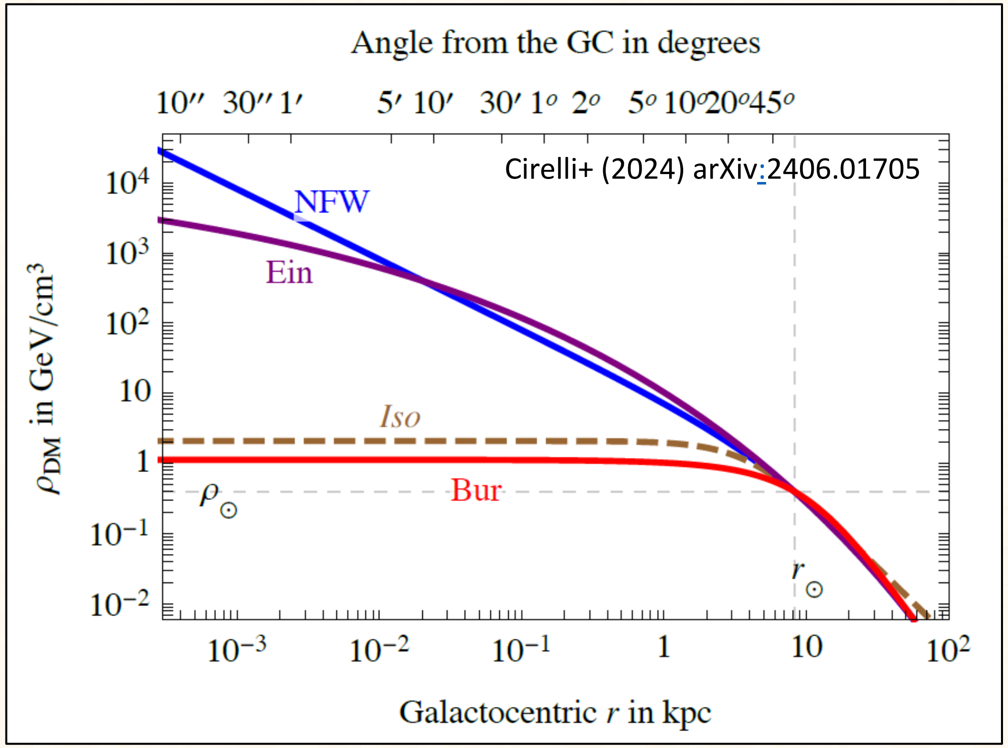
Intensity of the signal $\propto < \sigma v > \left(\frac{\rho_\chi}{m_\chi}\right)^2$

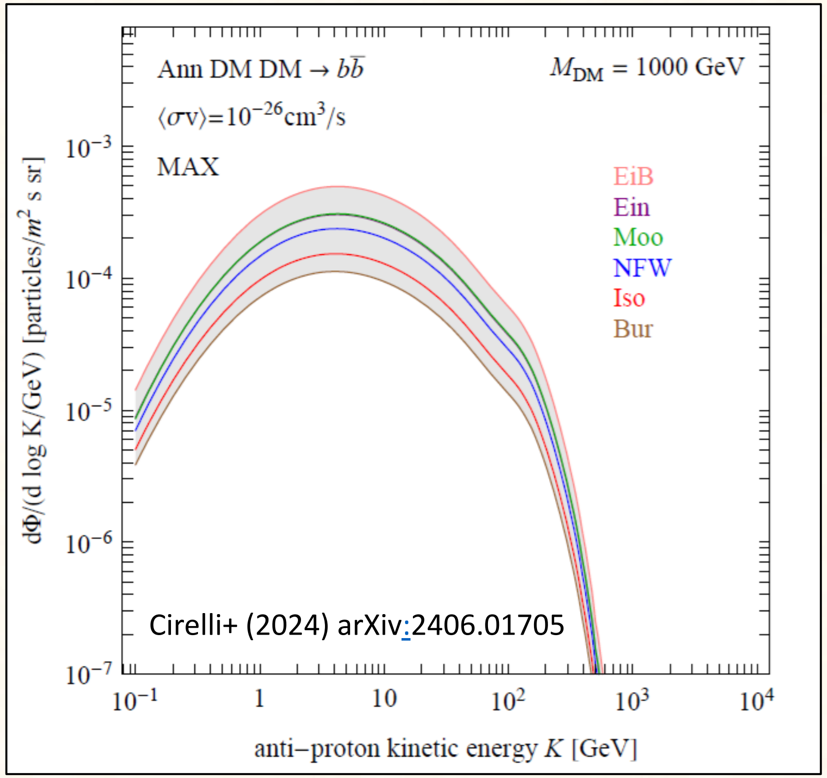




DM production - primary antiprotons

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.



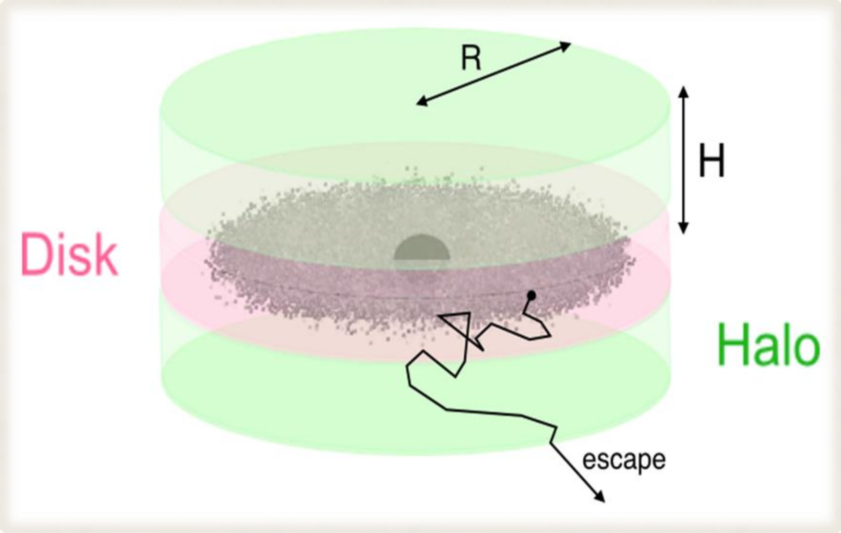


Antiprotons and propagation

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

See D. Maurin's talk

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



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

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

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

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

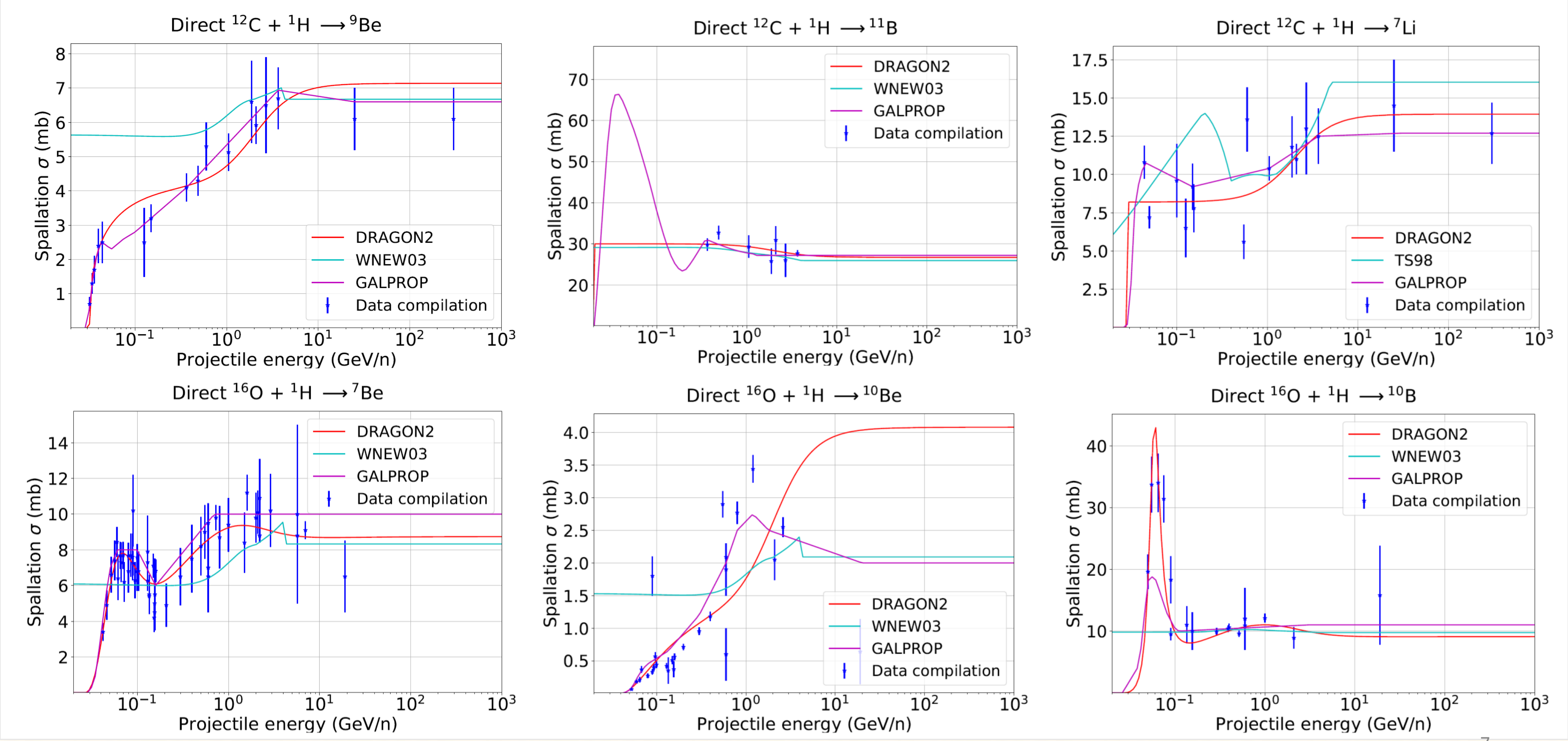
$$N_{sec} \propto Q_{sec}(E)/D(E)$$

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

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

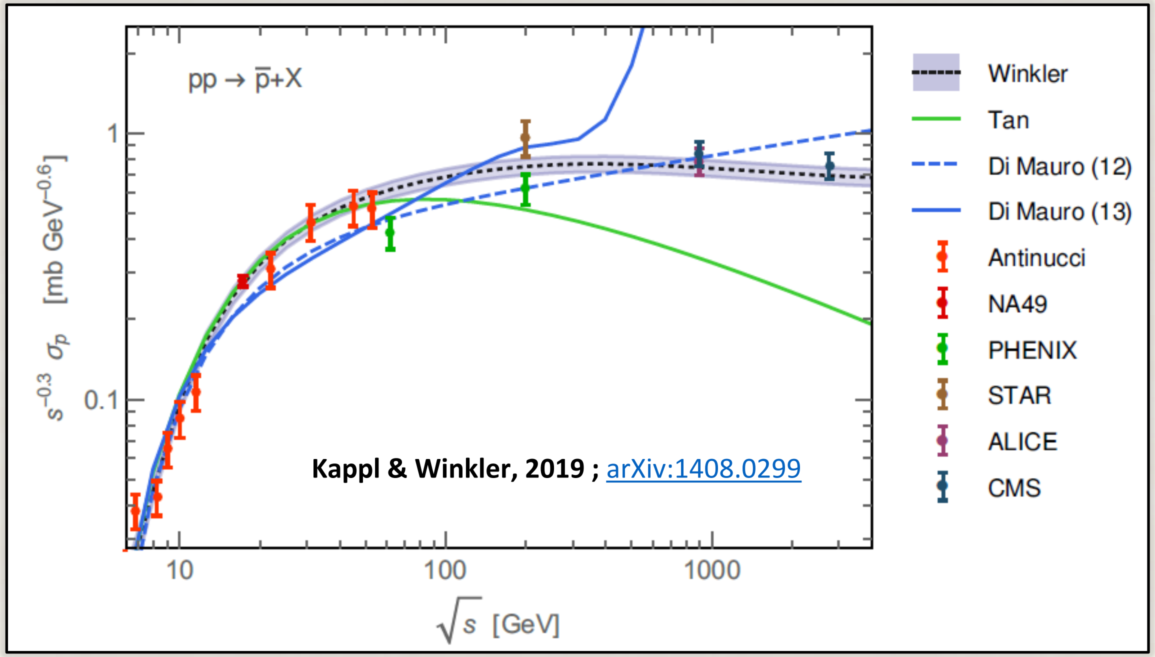
A precise estimation of the antiproton flux requires a careful analysis of several CR species and nuclear cross sections

Cross sections parameterizations for secondary CRs

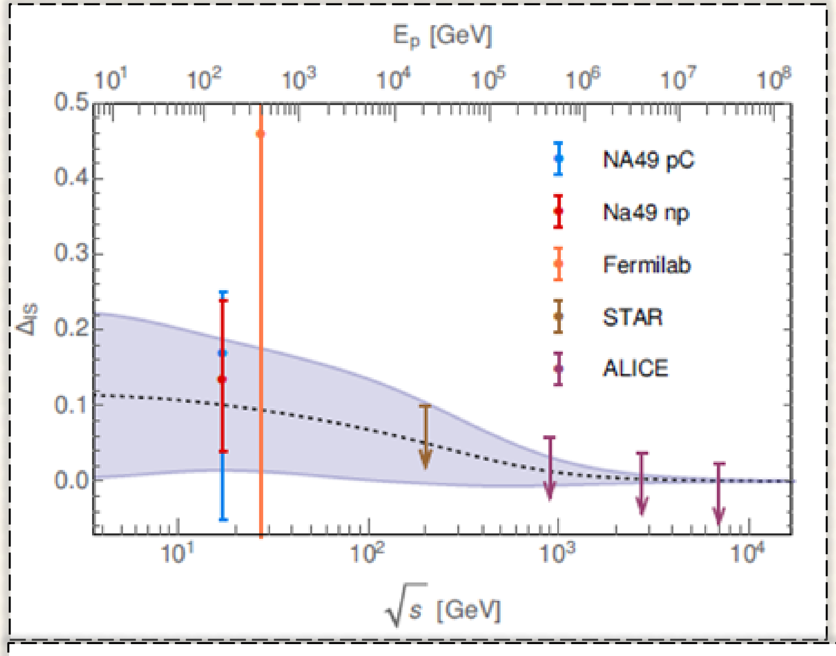


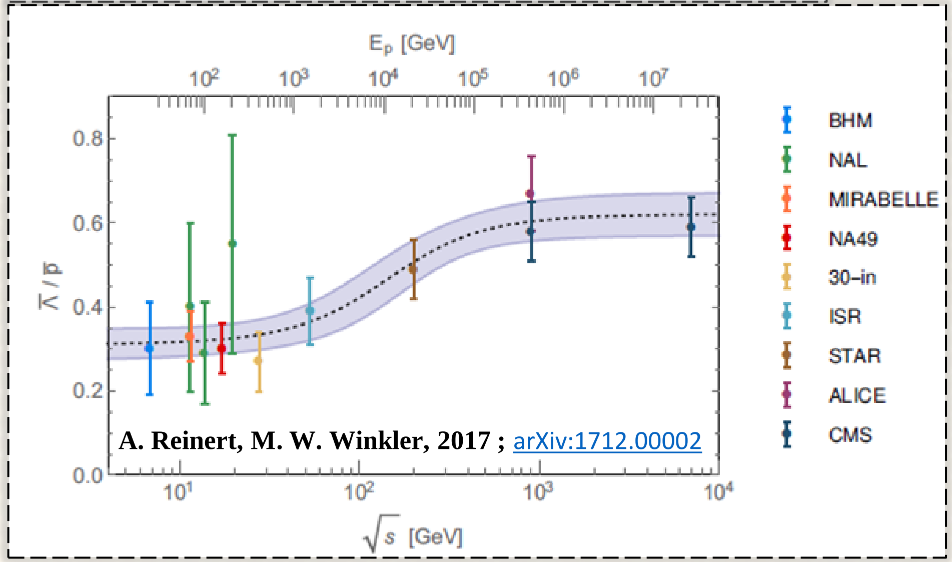
Antiproton cross sections

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



Kappl & Winkler, 2019 ; arXiv:1408.0299



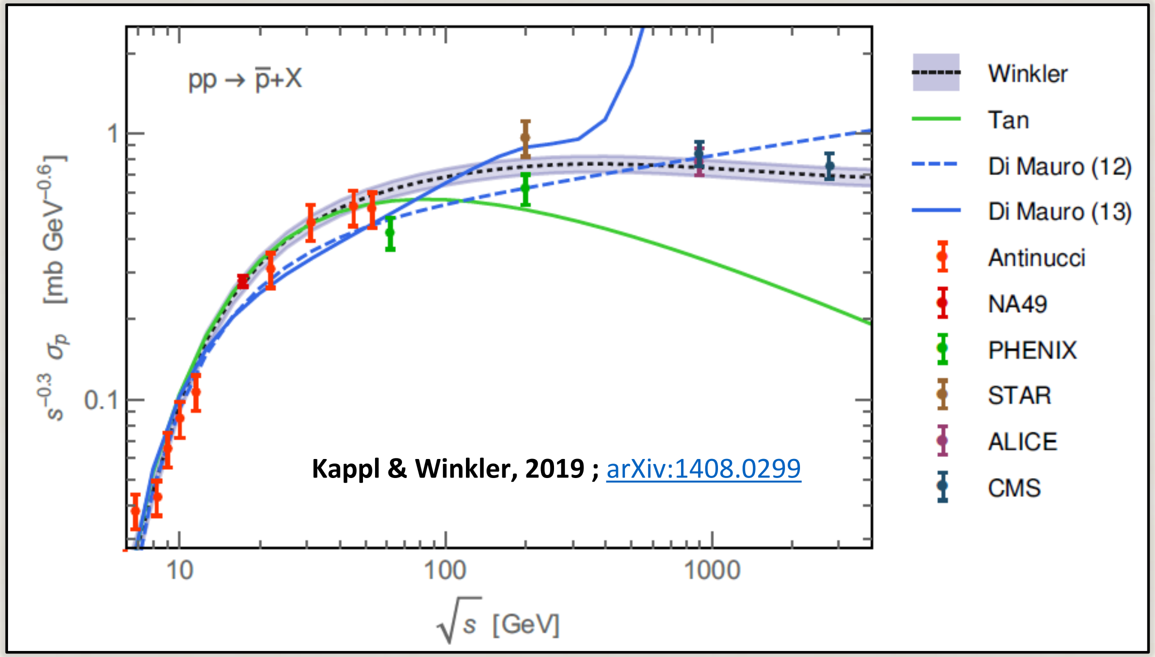


A. Reinert, M. W. Winkler, 2017 ; arXiv:1712.00002

8

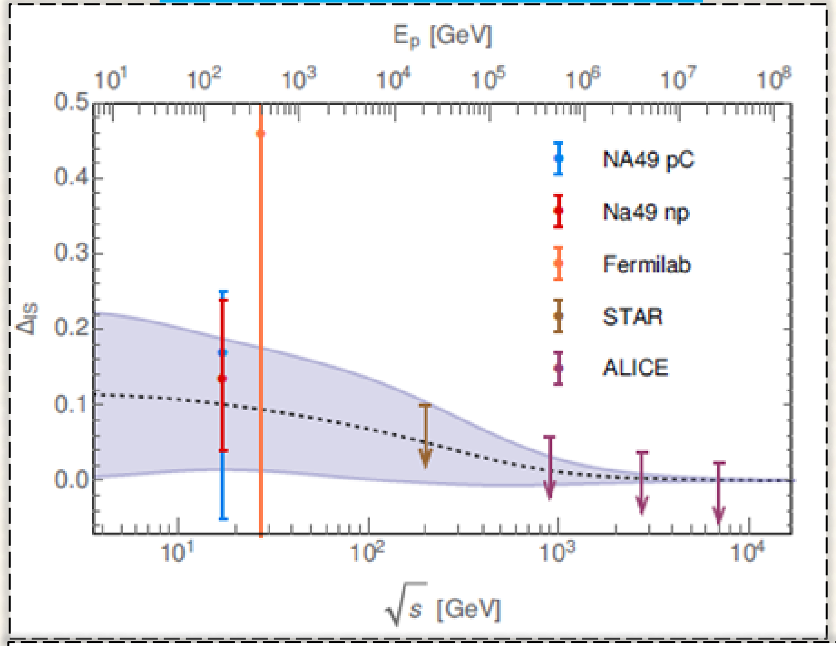
Antiproton cross sections

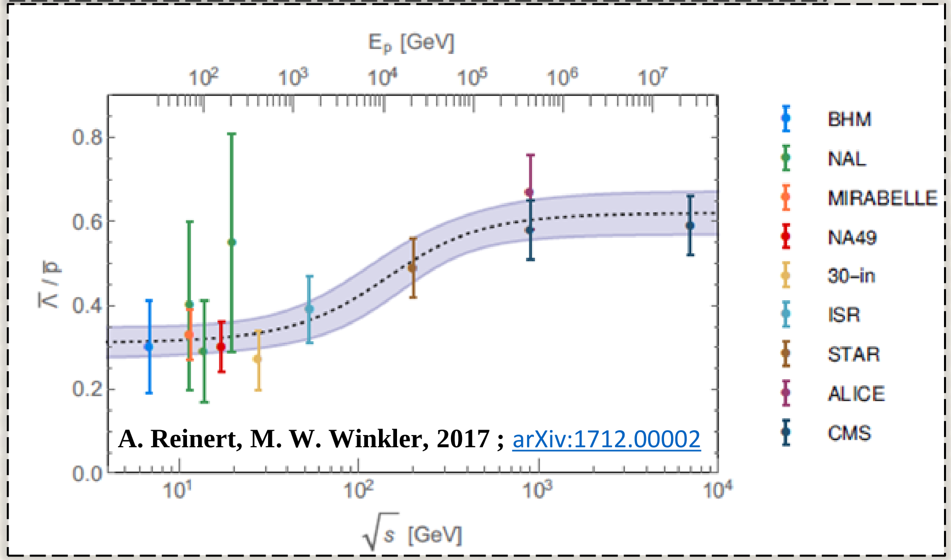
$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp\to\bar{p}} = \left(E\frac{d^3\sigma}{dp^3}\right)^{\text{prompt}}_{pp\to\bar{p}} \cdot (2 + \Delta_{IS} + 2\,\Delta_{\Lambda})$$



Kappl & Winkler, 2019 ; [arXiv:1408.0299](https://arxiv.org/abs/1408.0299)

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





A. Reinert, M. W. Winkler, 2017 ; [arXiv:1712.00002](https://arxiv.org/abs/1712.00002)

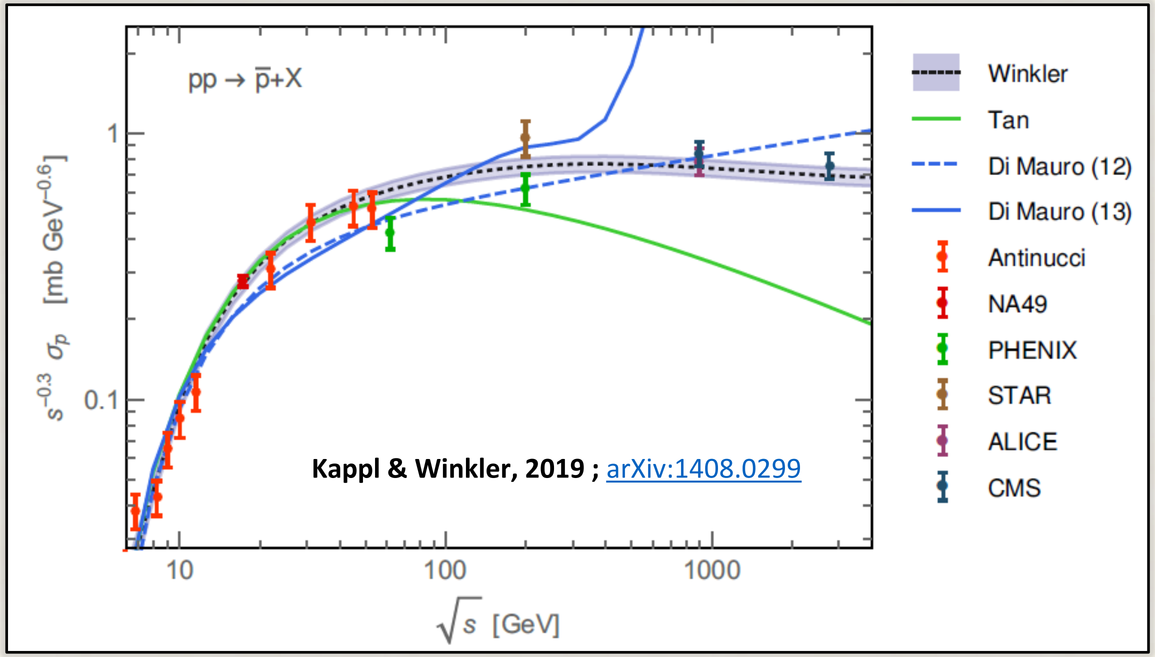
9

Antiproton cross sections

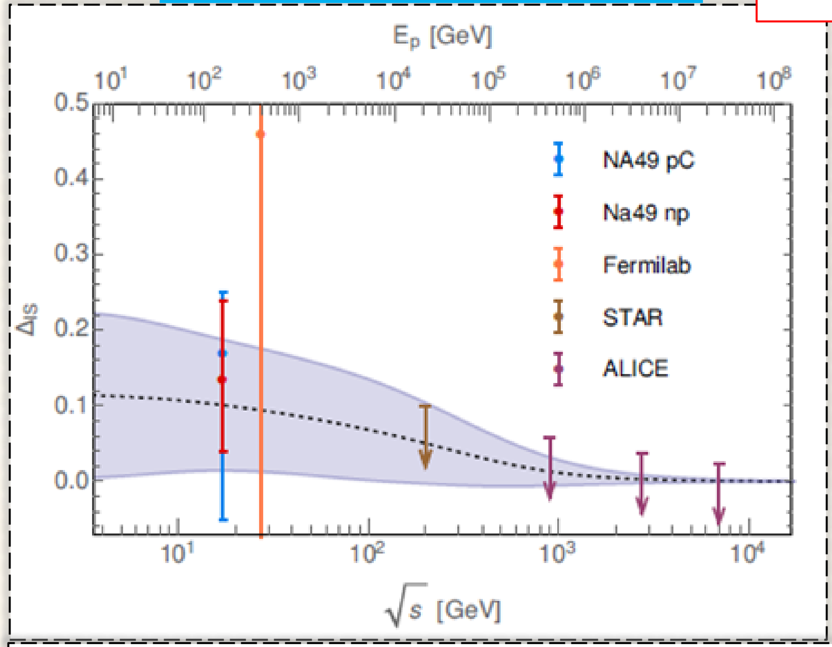
$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp\to\bar{p}} = \left(E\frac{d^3\sigma}{dp^3}\right)^{\text{prompt}}_{pp\to\bar{p}} \cdot (2 + \Delta_{IS} + 2\,\Delta_{\Lambda})$$

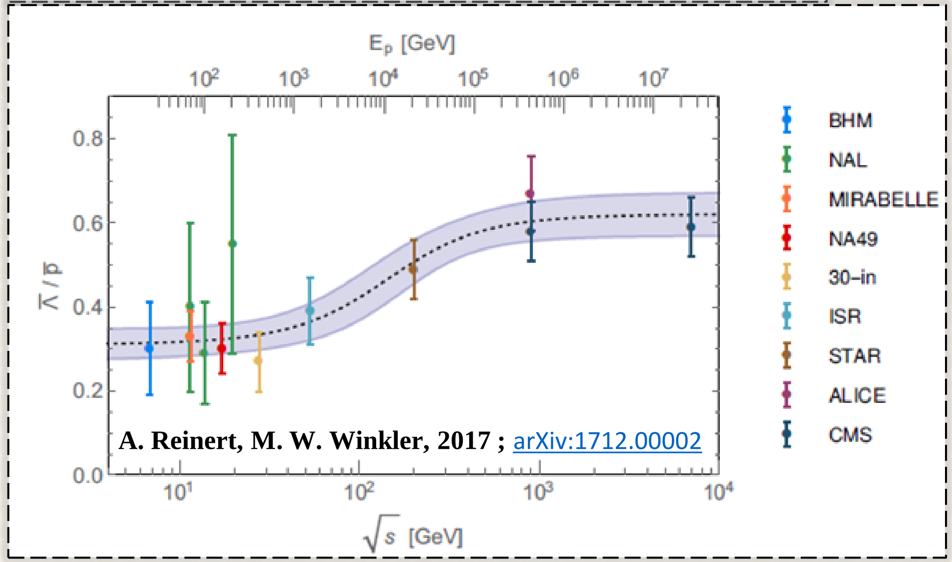
$$p + p \longrightarrow \{\bar{n} \longrightarrow \bar{p}\} + X$$

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



Kappl & Winkler, 2019 ; arXiv:1408.0299





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

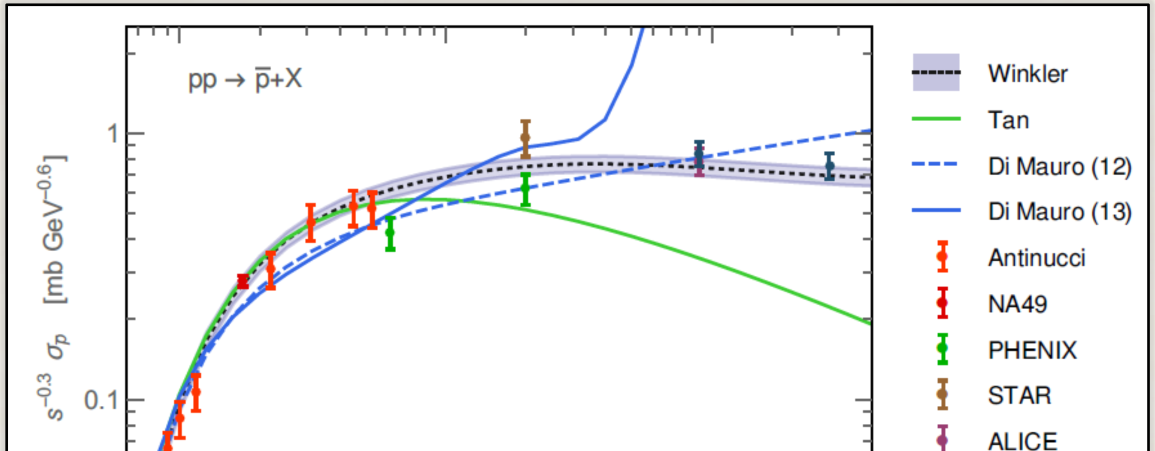
10

Antiproton cross sections

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

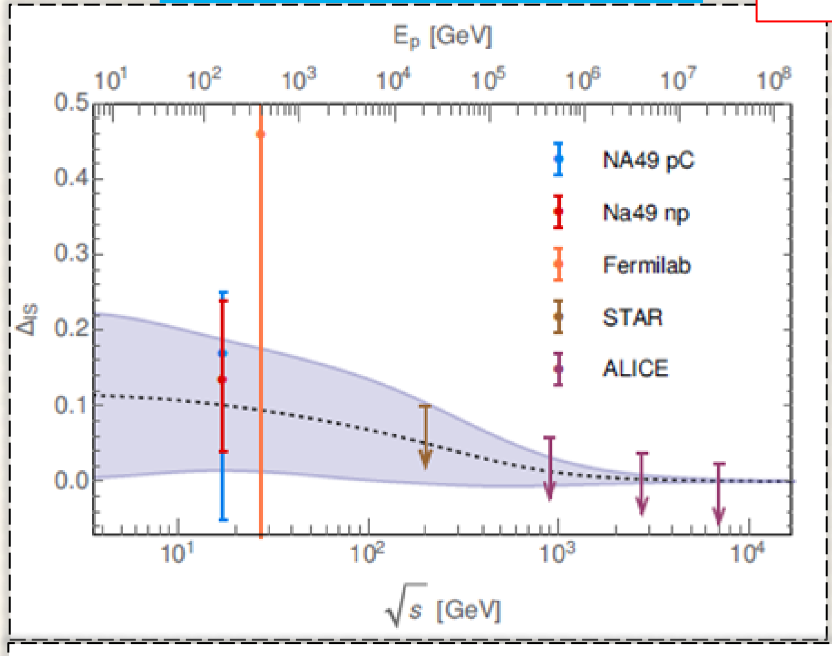
$$p + p \longrightarrow \{\bar{n} \longrightarrow \bar{p}\} + X$$

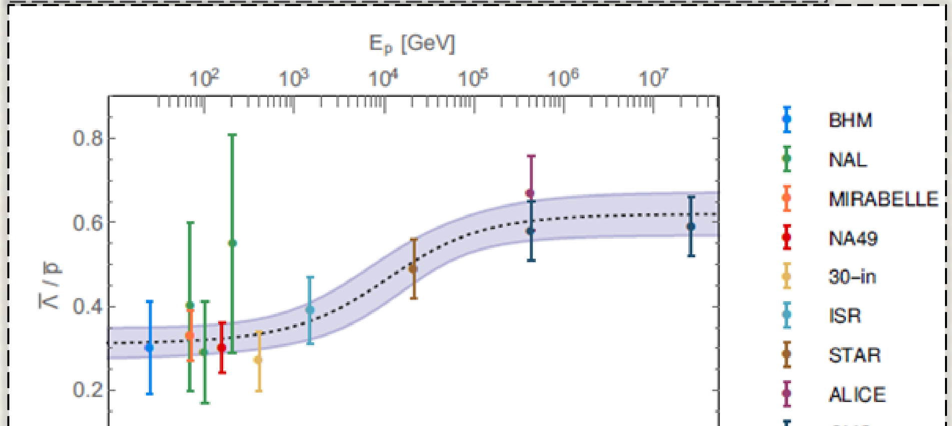
$$\Delta_{\rm IS} = \frac{\sigma_{pp\to\bar{n}}}{\sigma_{pp\to\bar{p}}} - 1$$



Kappl & Winkler, 2019 ; [arXiv:1408.0299](https://arxiv.org/abs/1408.0299)

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



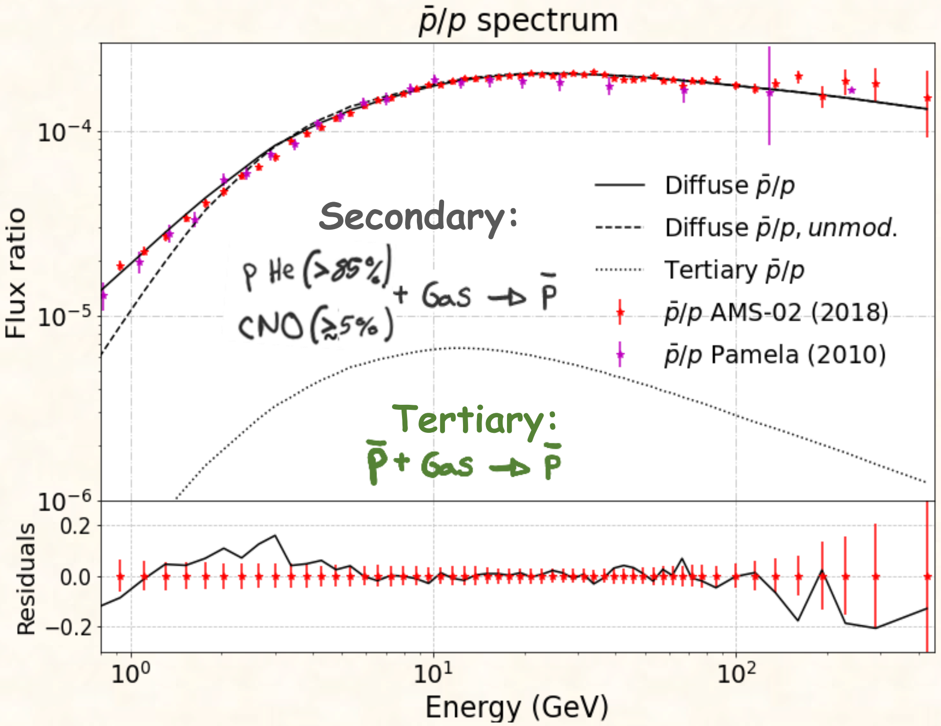


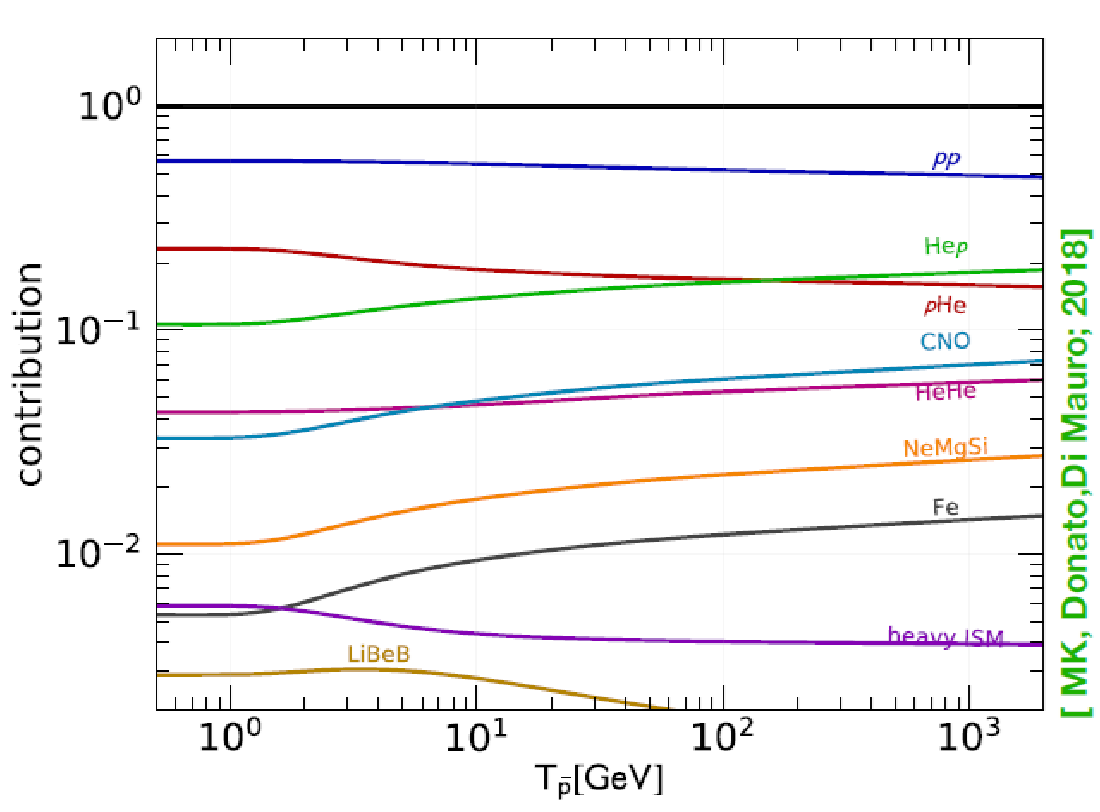
A. Reinert, M. W. Winkler, 2017 ; [arXiv:1712.00002](https://arxiv.org/abs/1712.00002)

11

Channels of secondary antiproton production

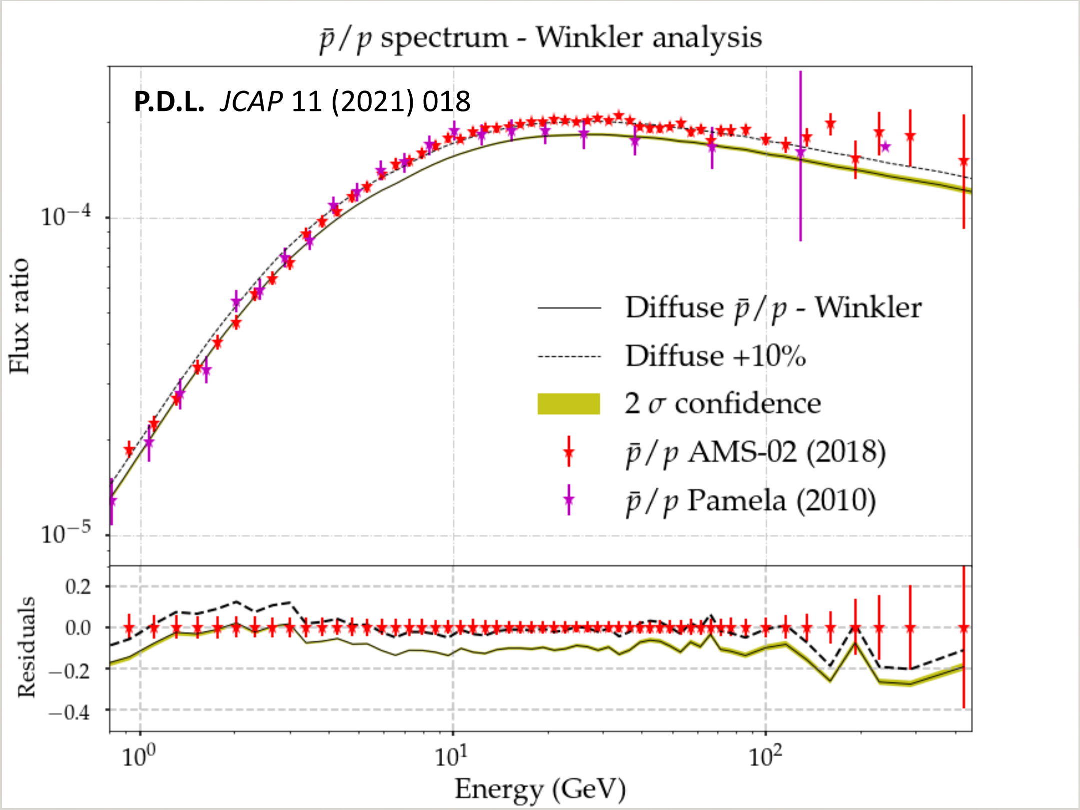
p + p → p + p + p + p̄ (High energy protons produce lower energy antiprotons)





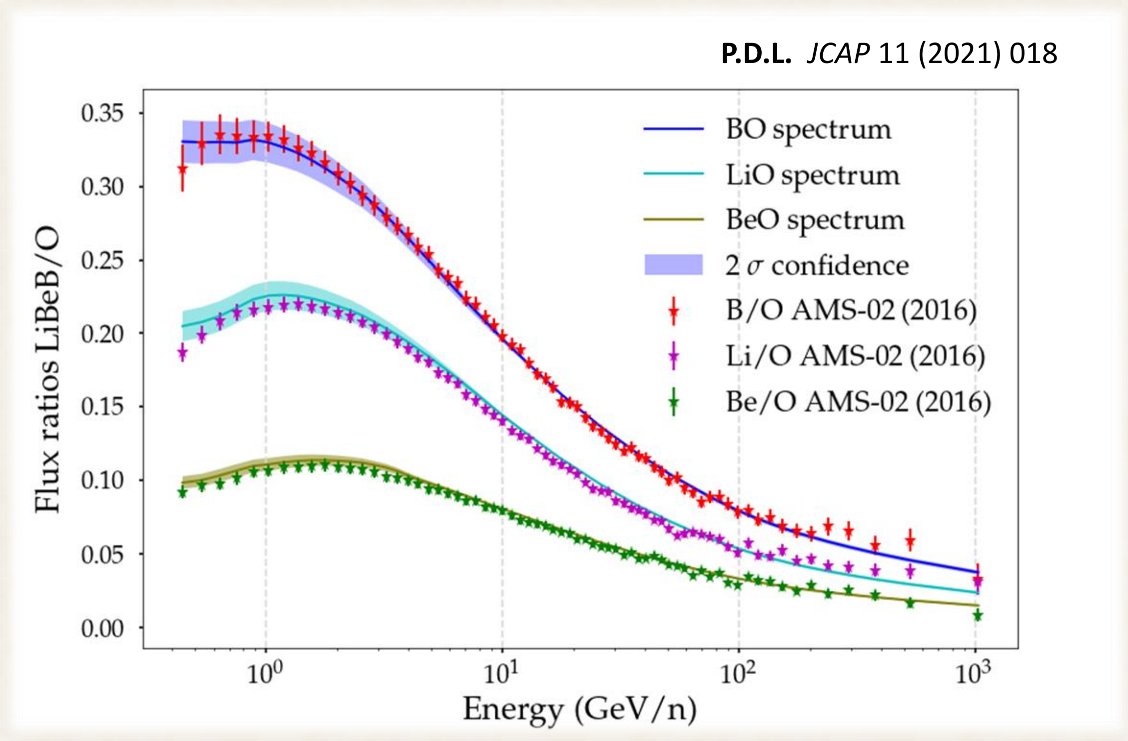
Different evaluations vary by tens of percent -- parameterizations seem more precise than current event generators, with **uncerts ~ 12%**
Heavy CRs may have a contribution > 7%

Secondary antiprotons – *The grammage excess*

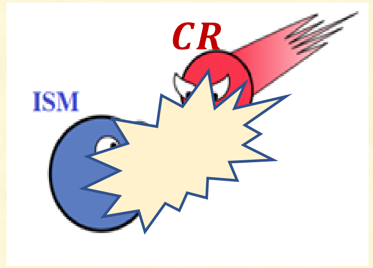


The spectrum of antiprotons is easily reproduced simultaneously with B, Be and Li allowing for a small (<10%) rescaling of cross sections

Diff. coeff. predicted by the flux-ratios of B, Be and Li underpredicts the antiproton flux by a 10-20%→ **Grammage tension**

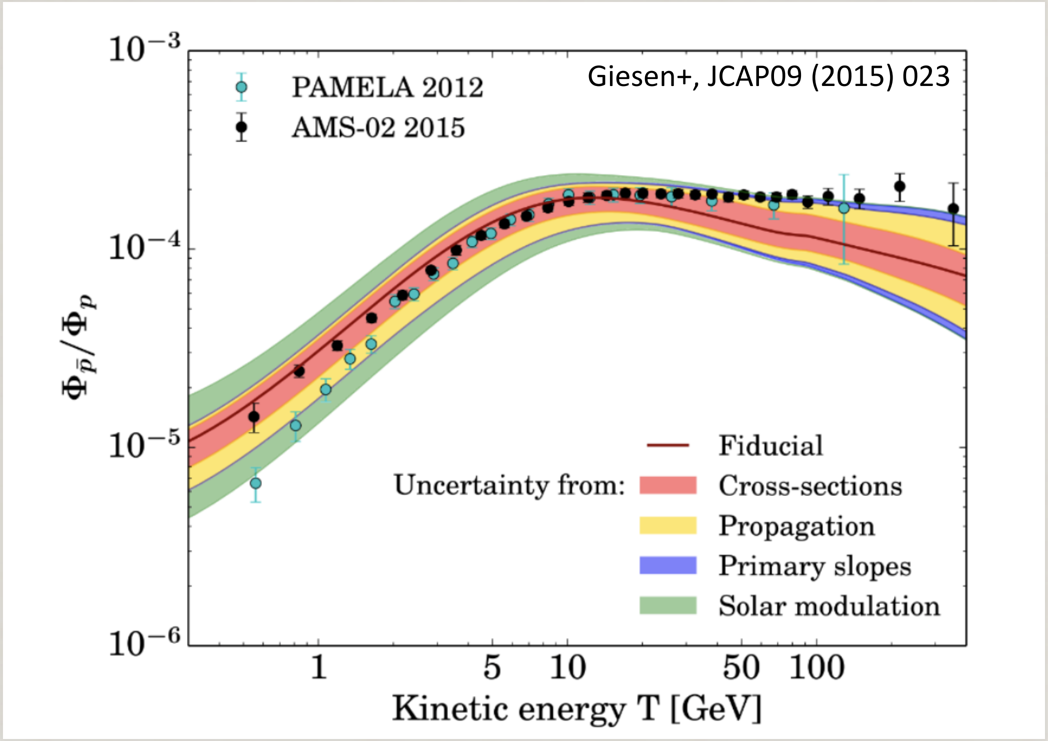


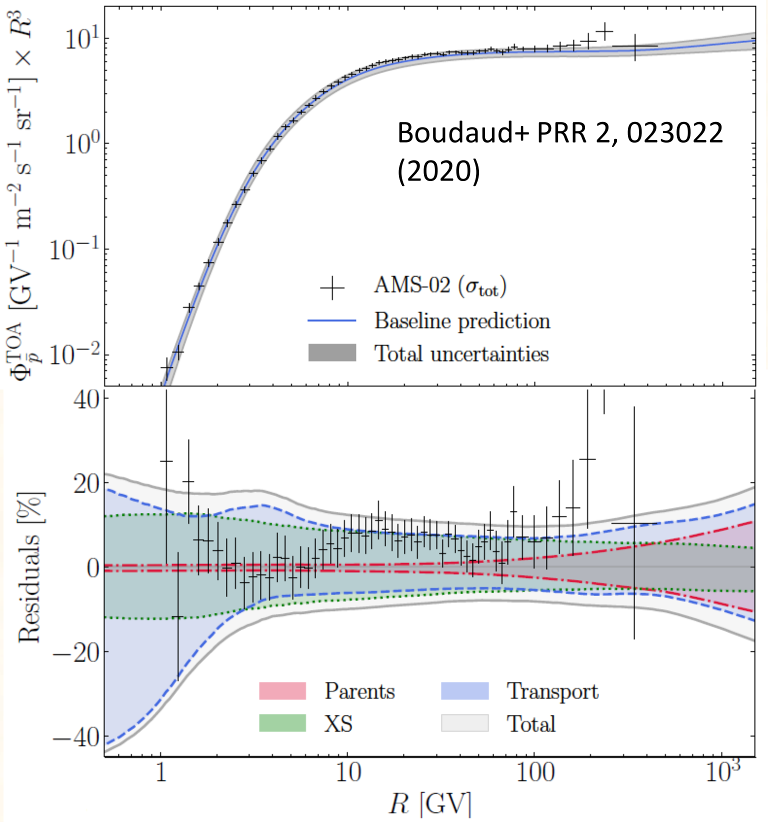
Secondary antiprotons



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

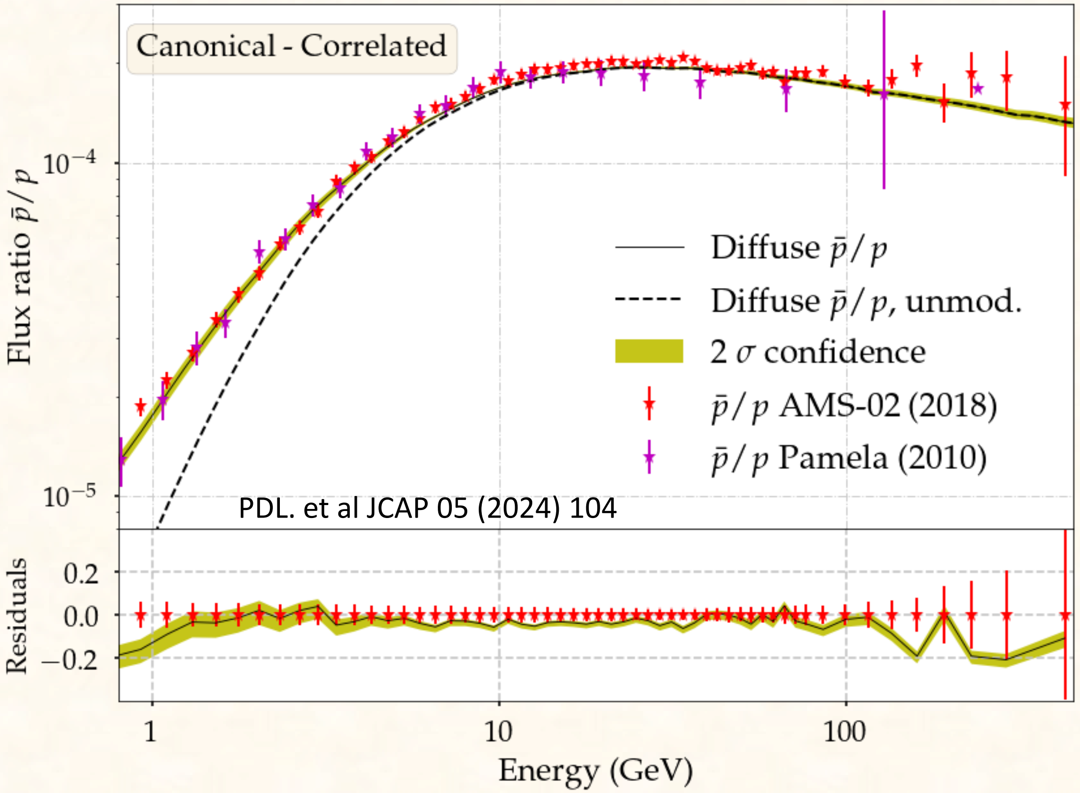
Recent analyses demonstrate that **antiproton observations are fully compatible with a secondary origin** and all secondary CRs can be well explained considering cross sections and propagation uncertainties



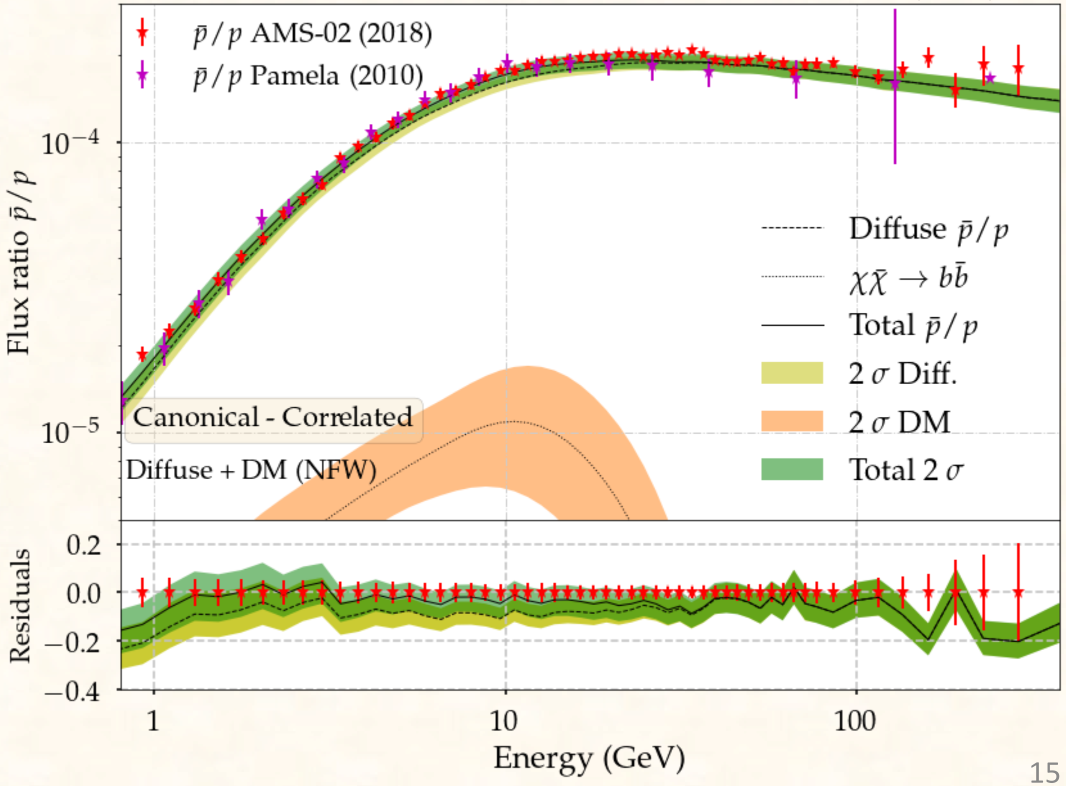


AMS-02 reveals the origin of antiprotons

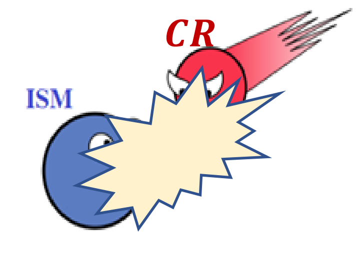
Recent analyses demonstrate that **antiproton observations are fully compatible with a secondary origin** and all secondary CRs can be well explained considering cross sections uncertainties – However, including also DM production is still preferred in the fit for a WIMP with mass around 70 GeV with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



PDL et al JCAP 05 (2024) 104



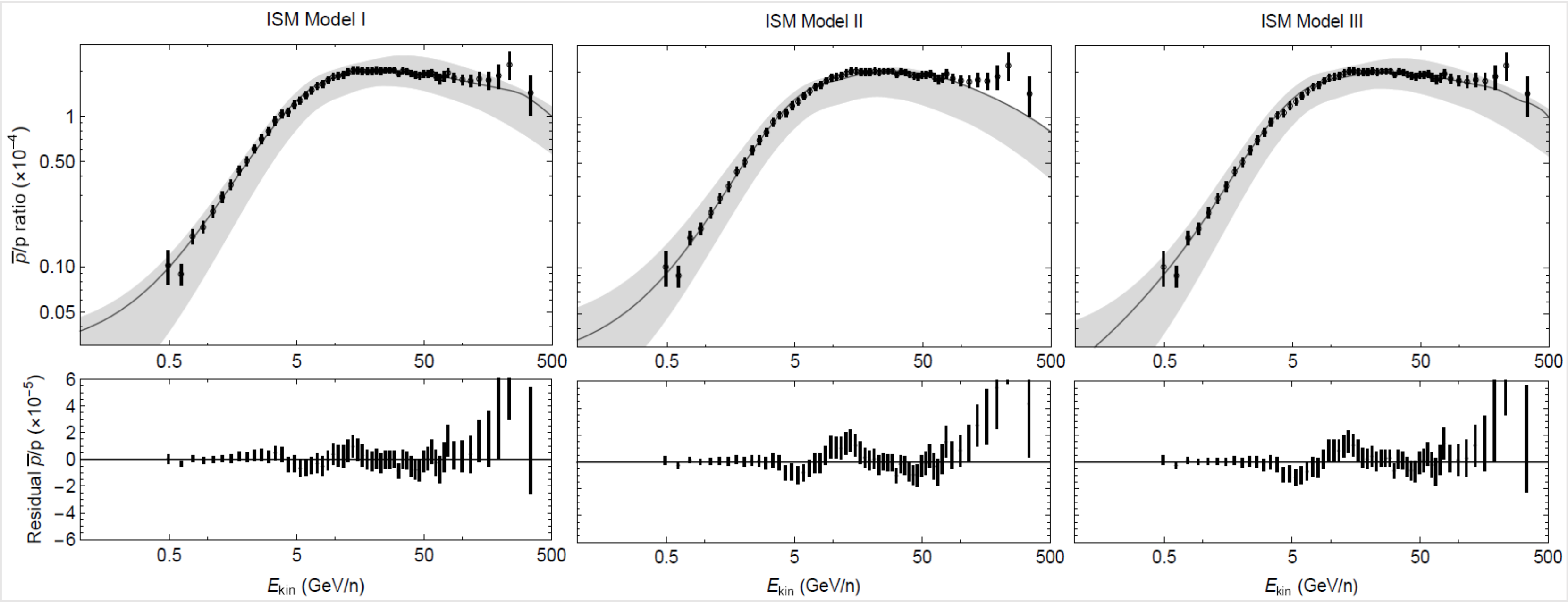
The Antiproton *excess*



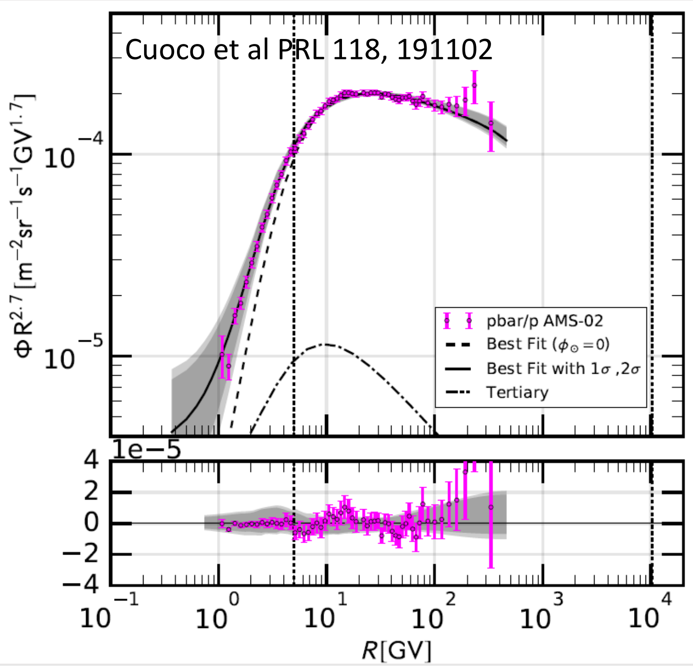
Recent studies have claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

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

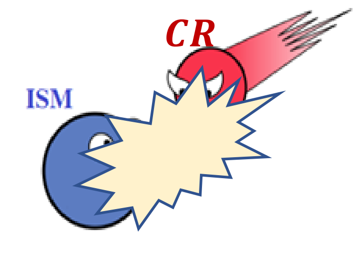
$$\chi + \chi \to \bar{p}$$



Cholis, Linden, Hooper PRD 99, 103026



The Antiproton *excess*

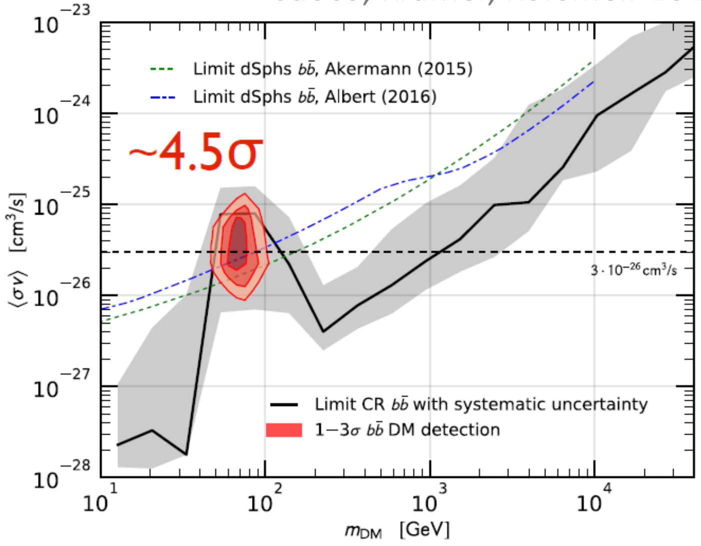


Recent studies have claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

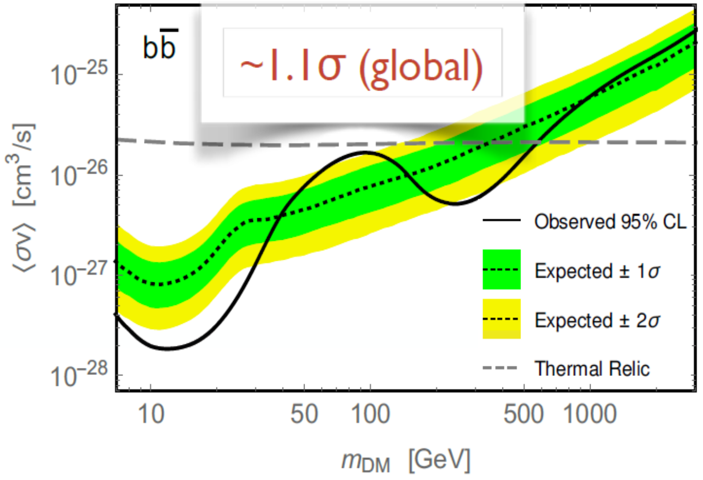
$$p_{CR} + p_{ISM} \to \bar{p}$$

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

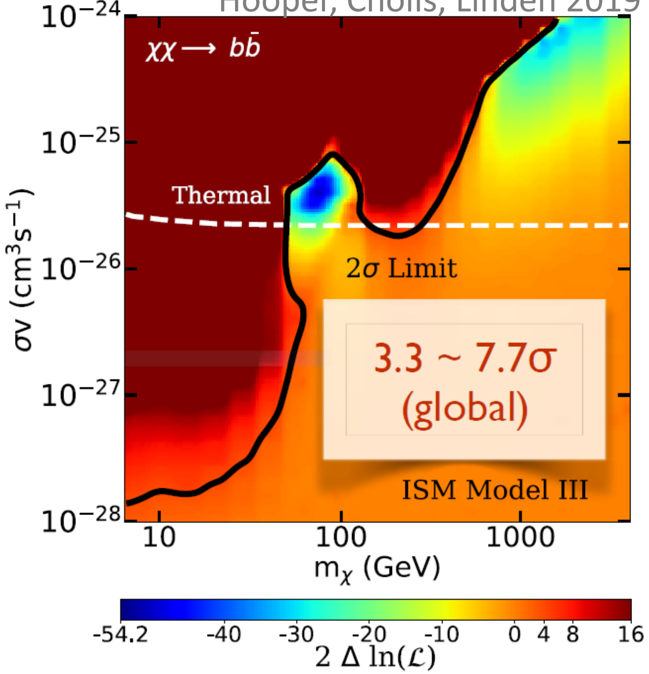
Cuoco, Kramer, Korsmeir 2017



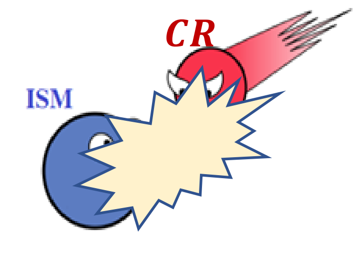
Reinert, Winkler 2018



Hooper, Cholis, Linden 2019



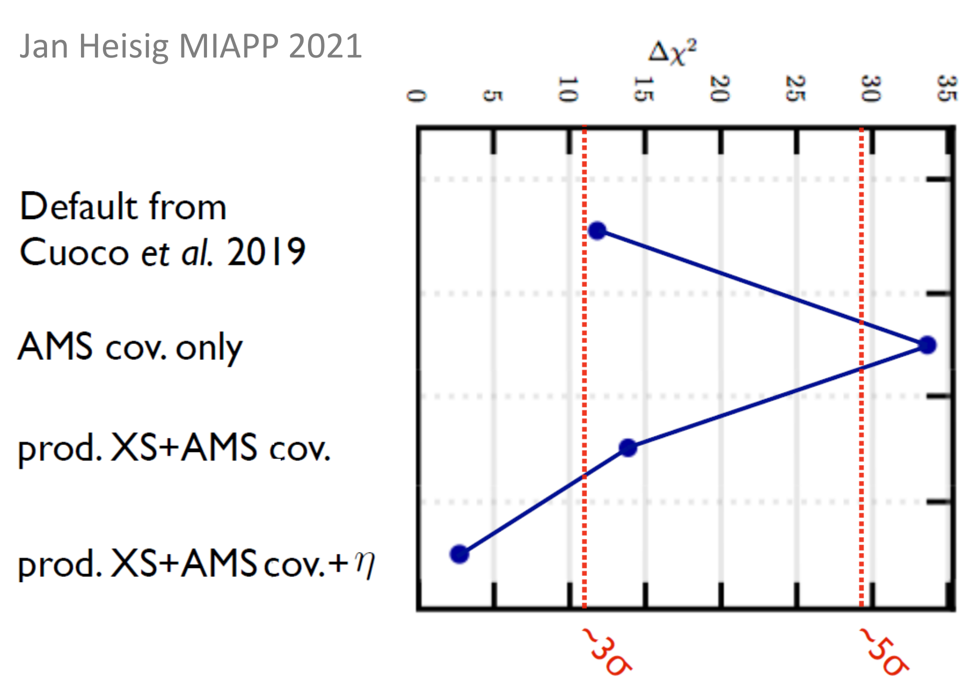
The Antiproton *excess*

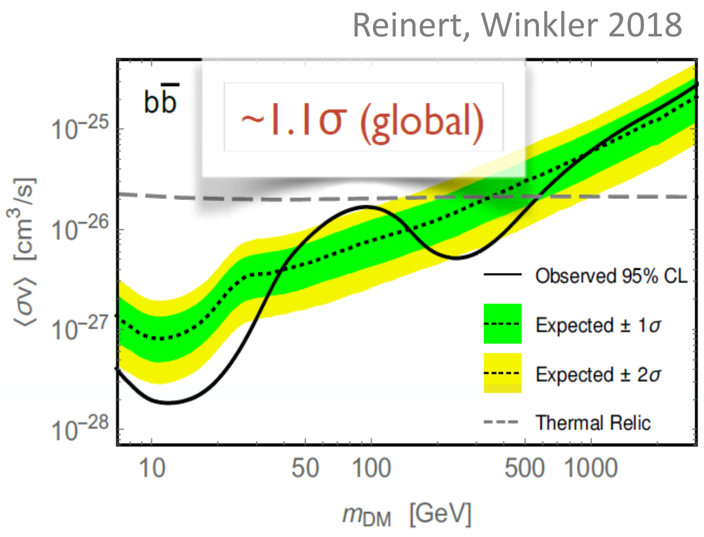


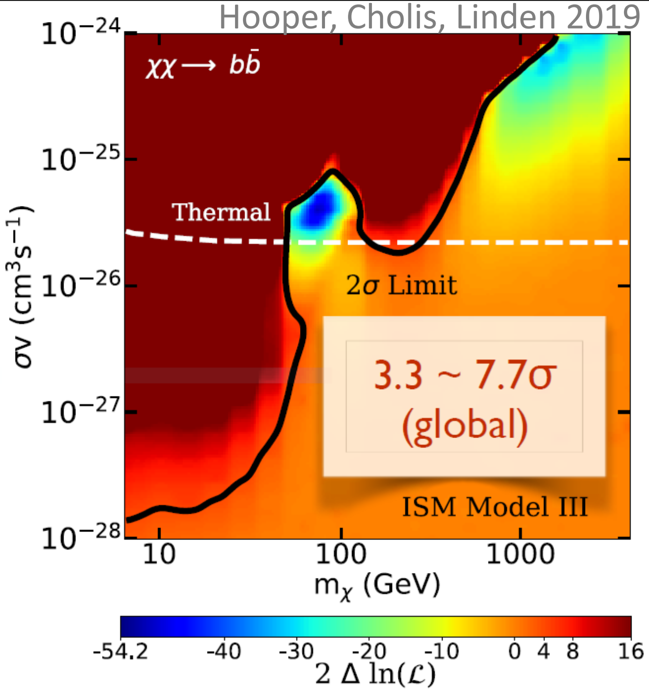
Recent studies have claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

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

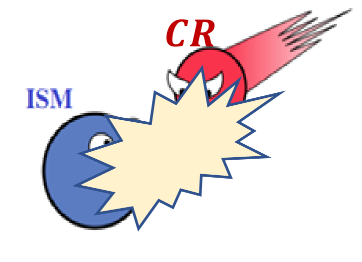
$\chi + \chi \to \bar{p}$







The Antiproton *excess*

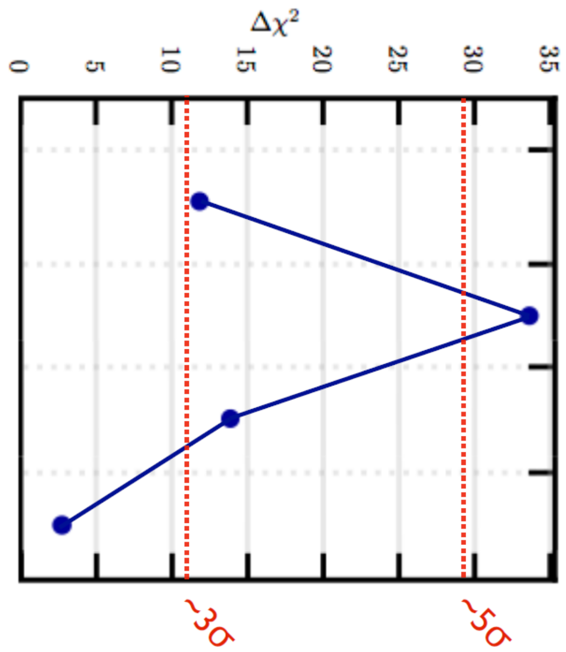


Recent studies have claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

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

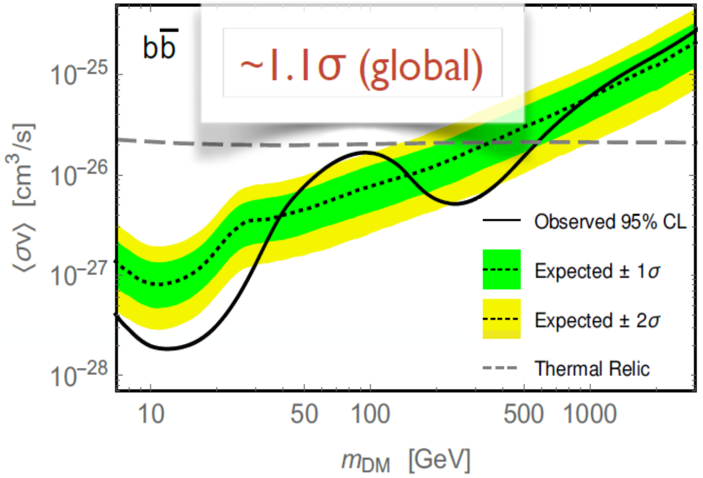
$\chi + \chi \rightarrow \bar{p}$

Jan Heisig MIAPP 2021

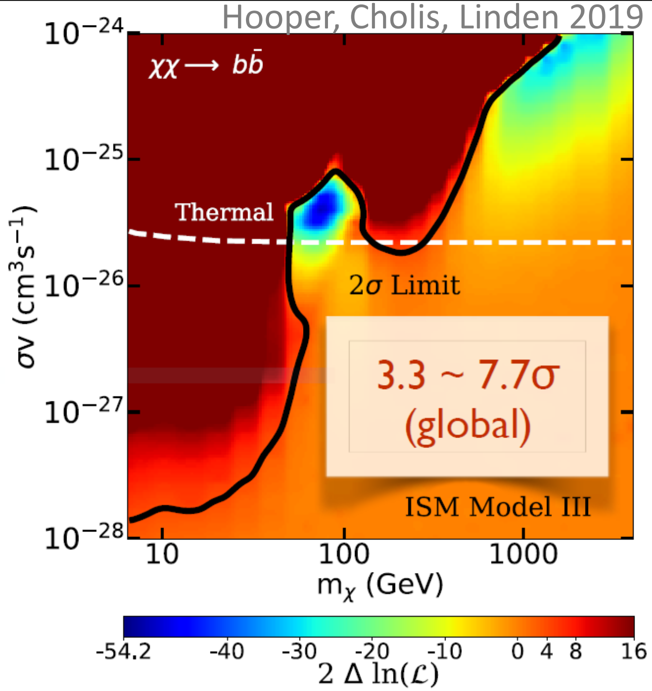


$D(E) \sim D_0\beta^{\eta}E^{\delta}$

Reinert, Winkler 2018

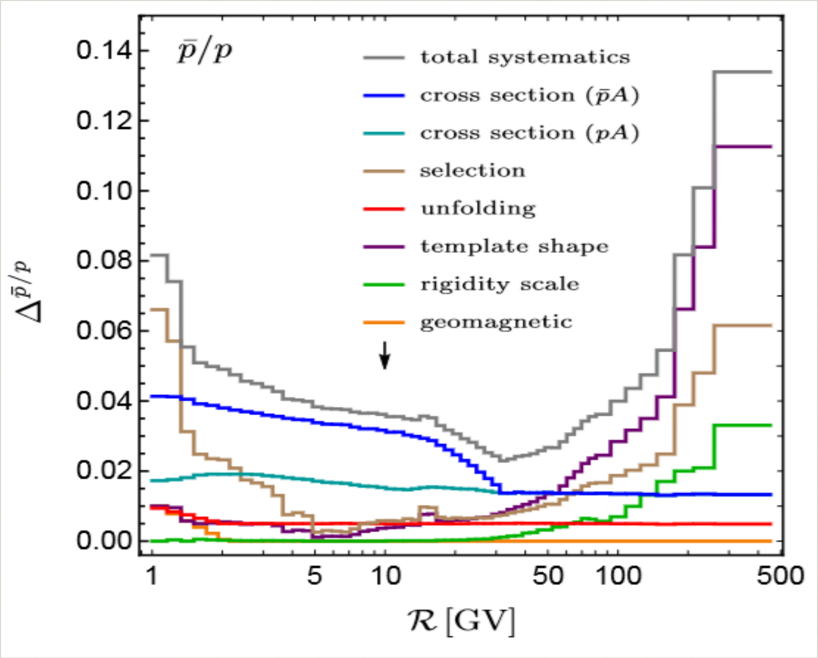


Hooper, Cholis, Linden 2019

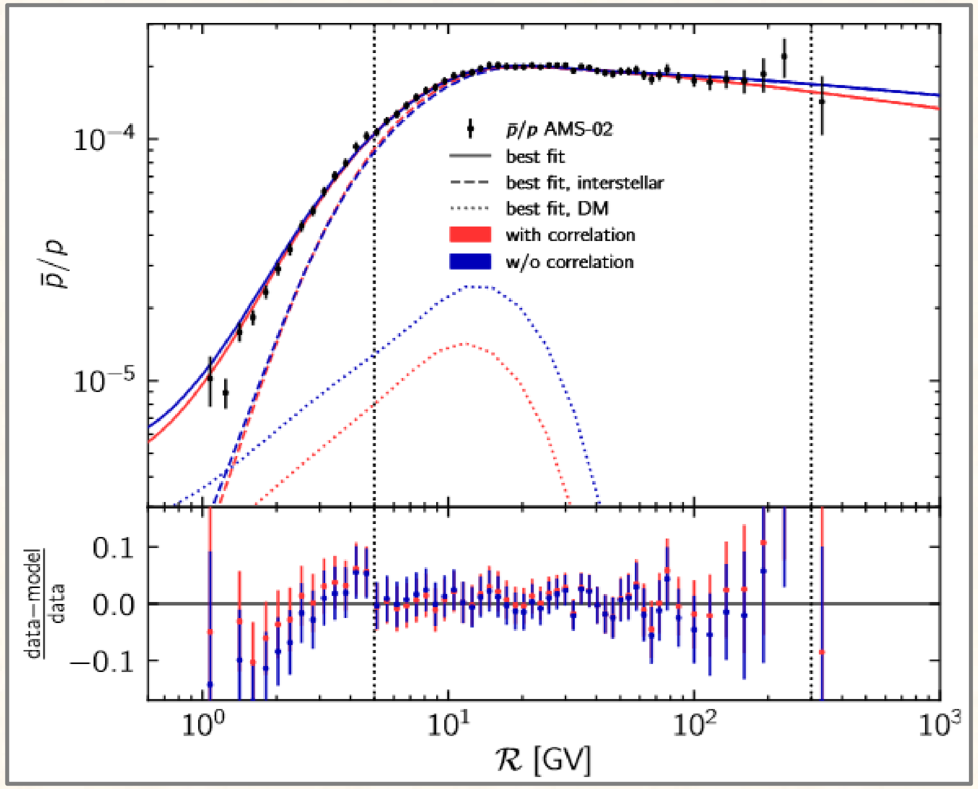


Systematics in AMS-02 data

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



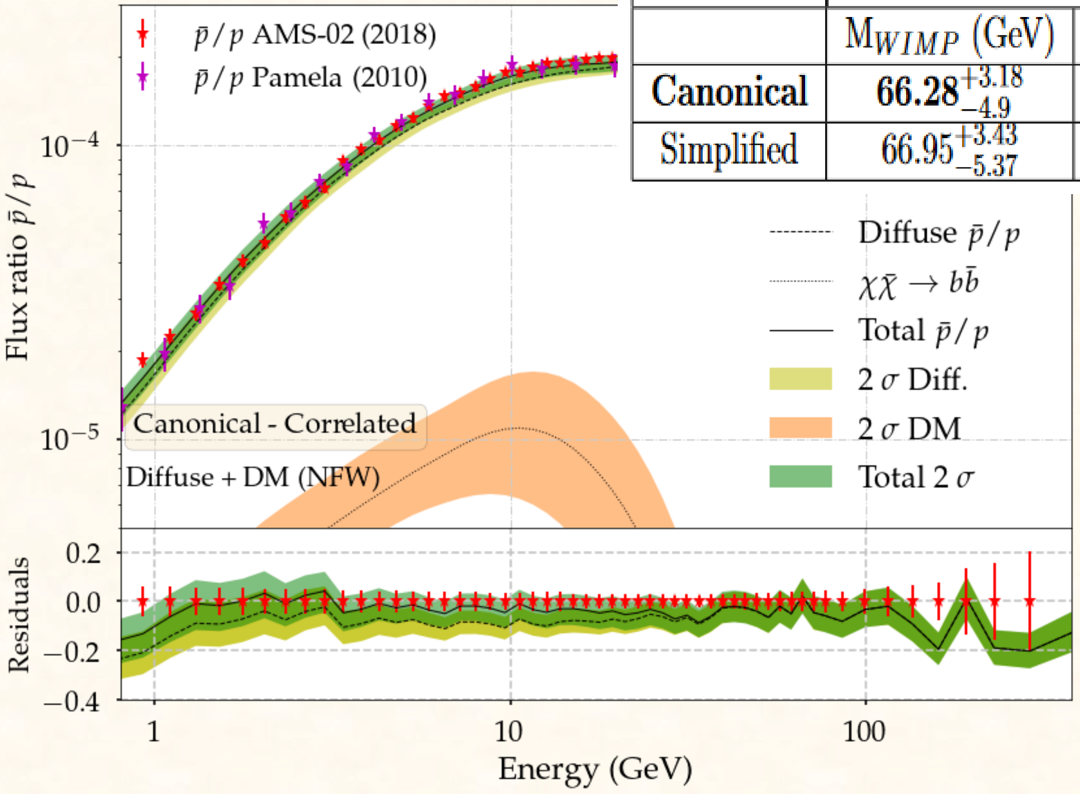
$$(C^{\alpha}_{\rm rel})_{ij} = \sigma^{\alpha}_i \sigma^{\alpha}_j \exp\left(-\frac{1}{2}\frac{(\log(R_i/R_j))^2}{(l^{\alpha}_{\rho})^2}\right)$$



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

From “excesses” to just fluctuations

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 σ global)**



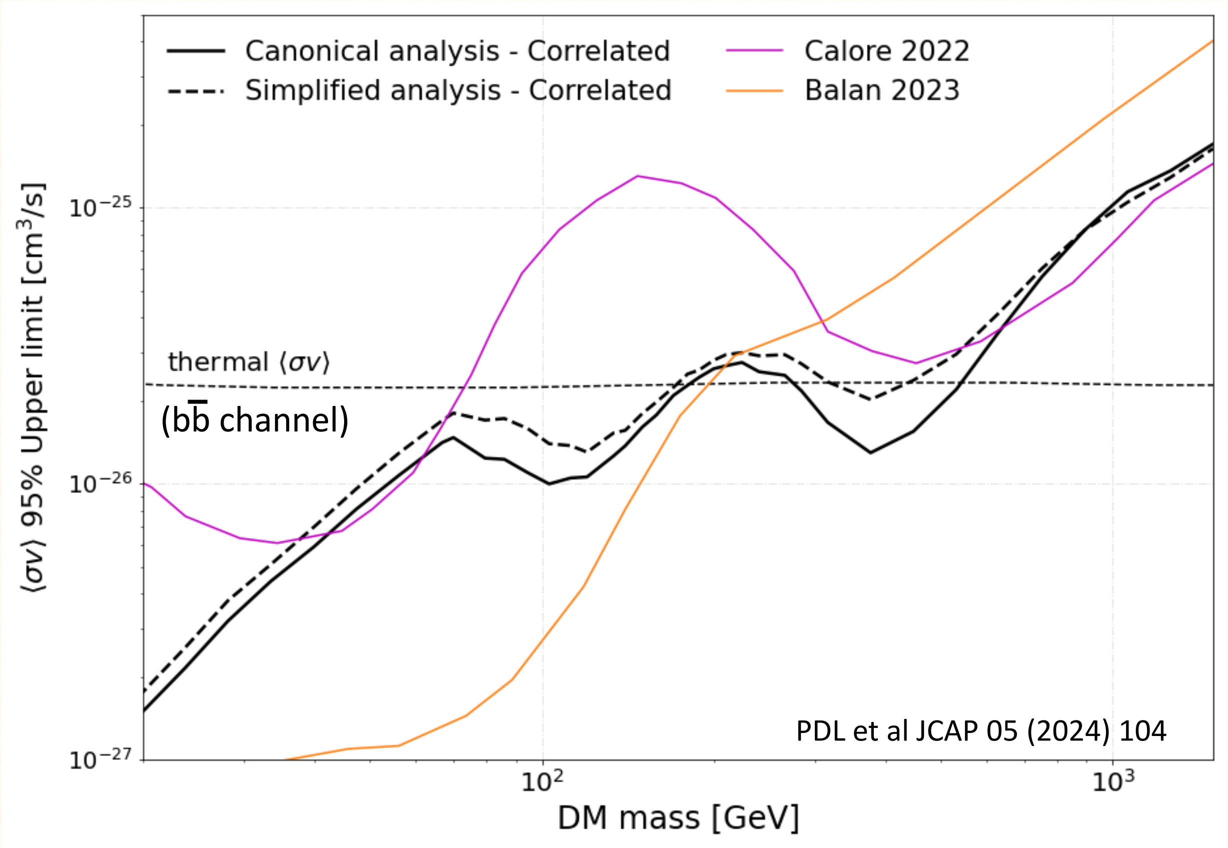
PDL+, JCAP 05 (2024) 104

	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

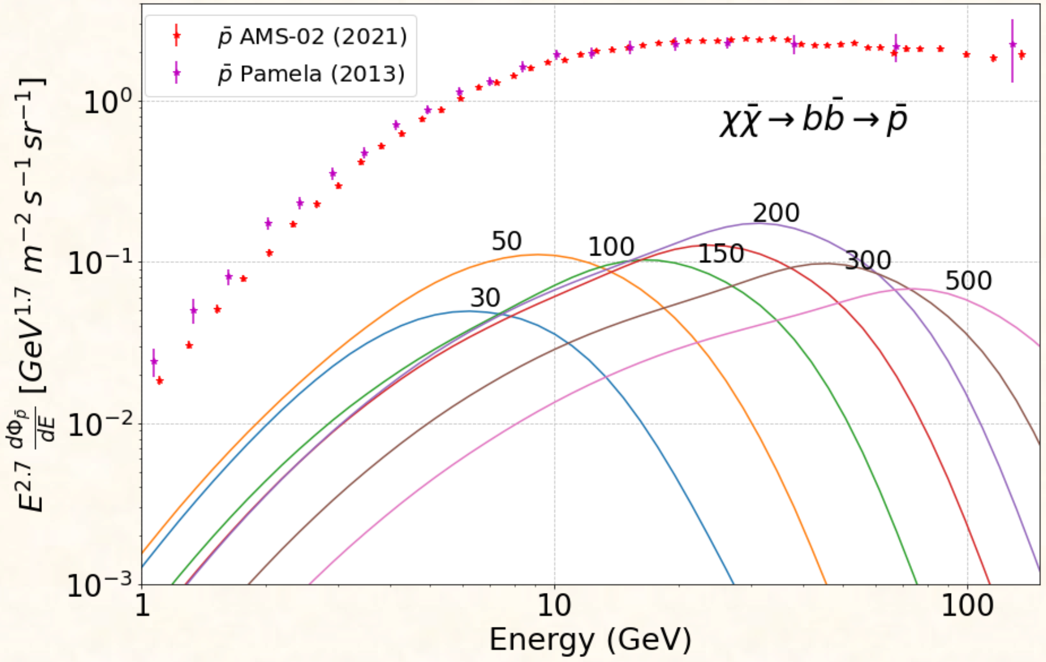
Calore+, SciPost Phys. 12, 163 (2022)

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
bb	SLIM	109.1	1.48e-26	1.7
bb	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



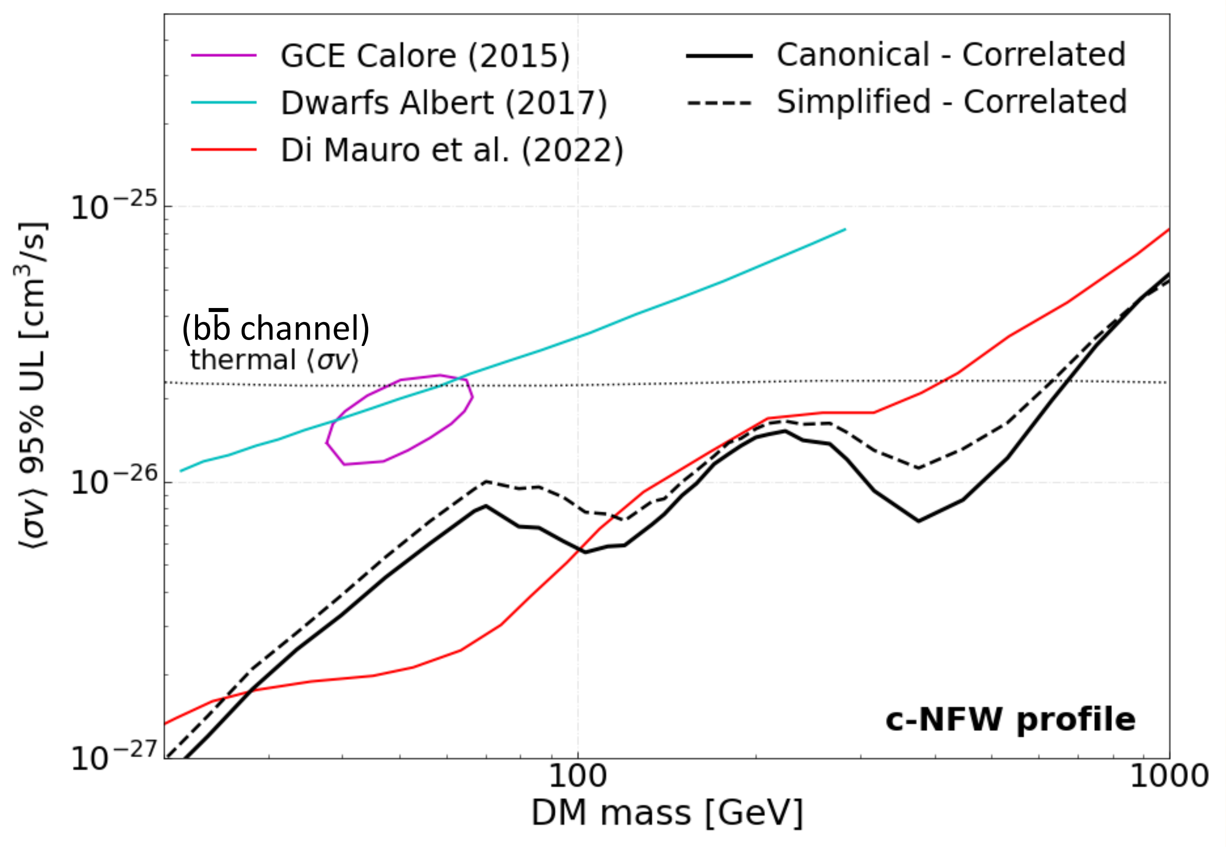
Maximal DM-induced signal (at 95% CL)



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

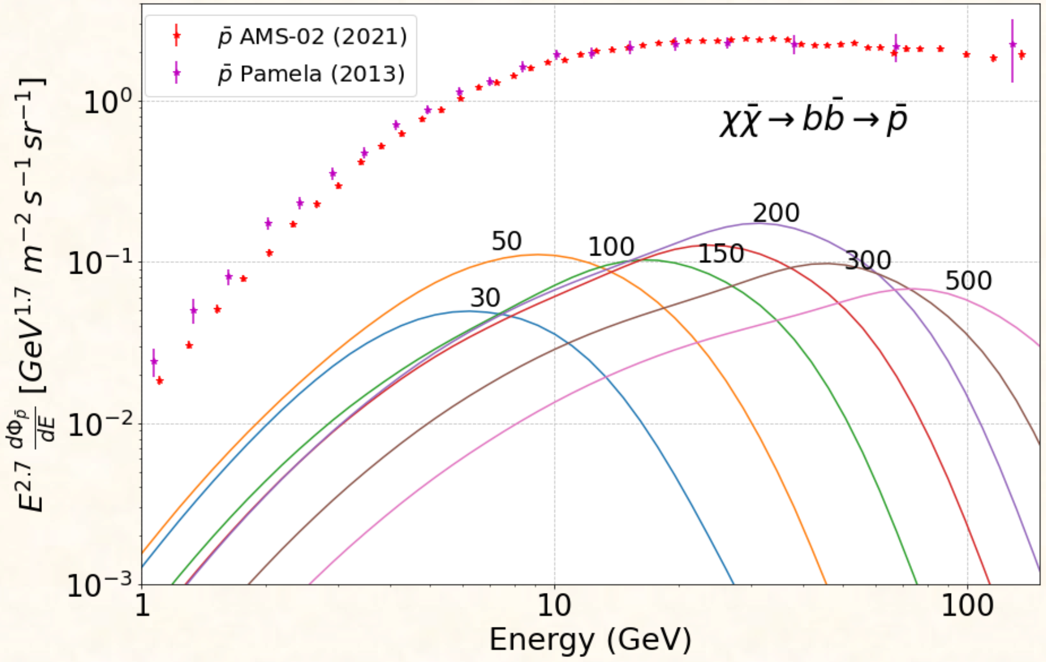
Leading constraints for WIMPs annihilating into hadronic final states, and able to rule out the thermal relic cross sections for masses below ~200 GeV

Dark matter bounds from antiproton analyses



PDL et al JCAP 05 (2024) 104

Maximal DM-induced signal (at 95% CL)

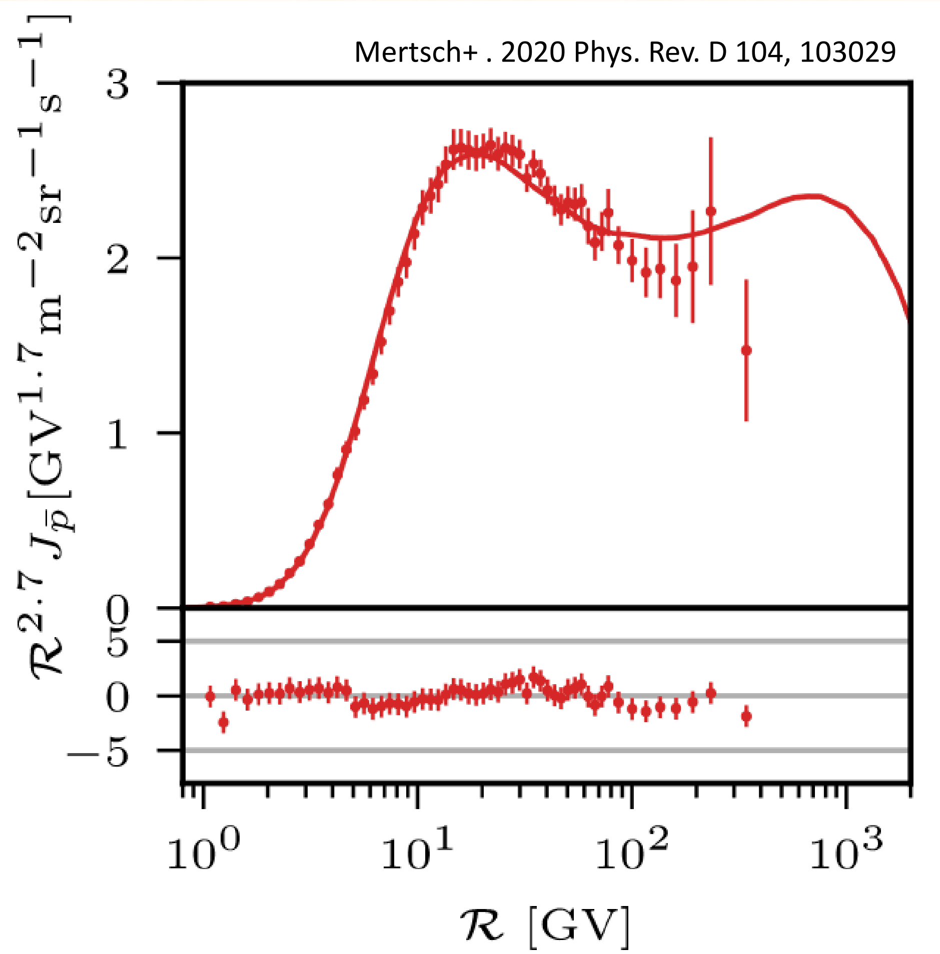


Leading constraints for WIMPs annihilating into hadronic final states,

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

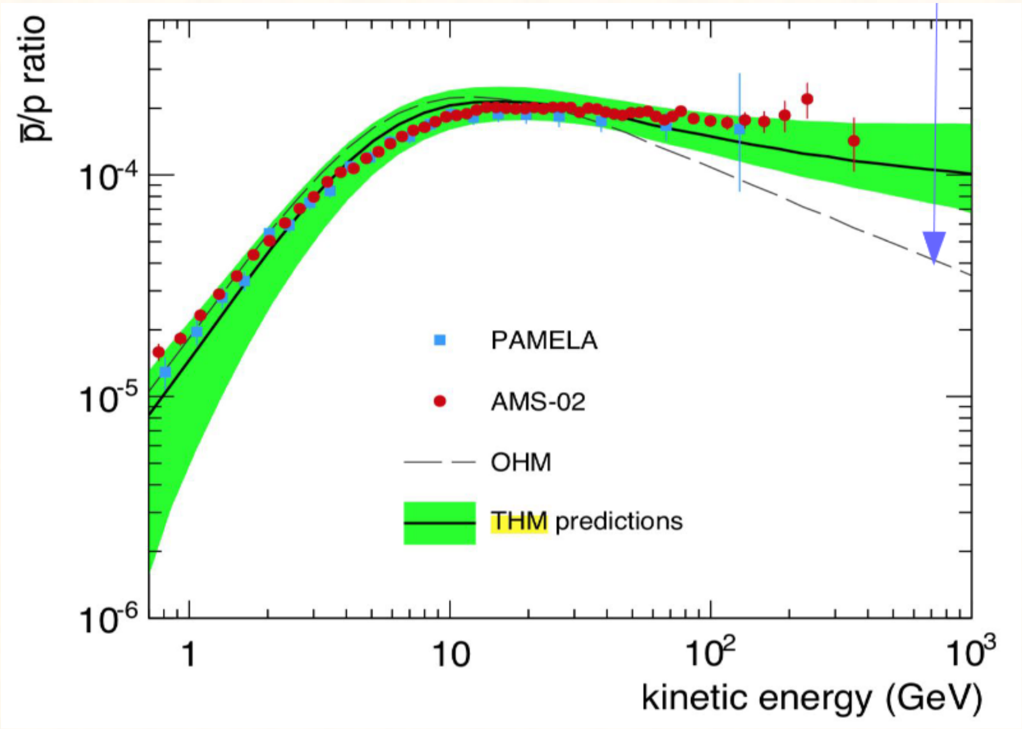
Antiprotons in the Galaxy *– More possibilities*

SNRs accelerating antiprotons



Mertsch+ . 2020 Phys. Rev. D 104, 103029

Inhomogeneous diffusion coefficient

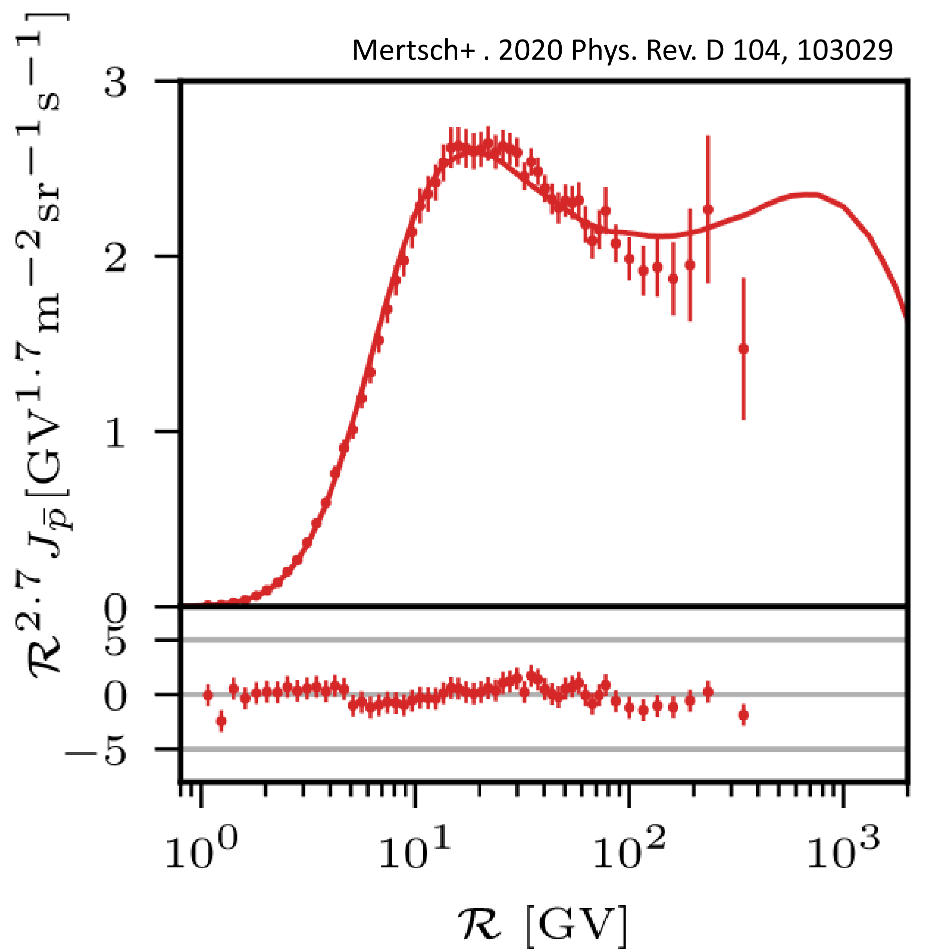


Feng+ PRD 94, 123007 (2016)
(Also: Zhao+ arXiv:2109.04112)

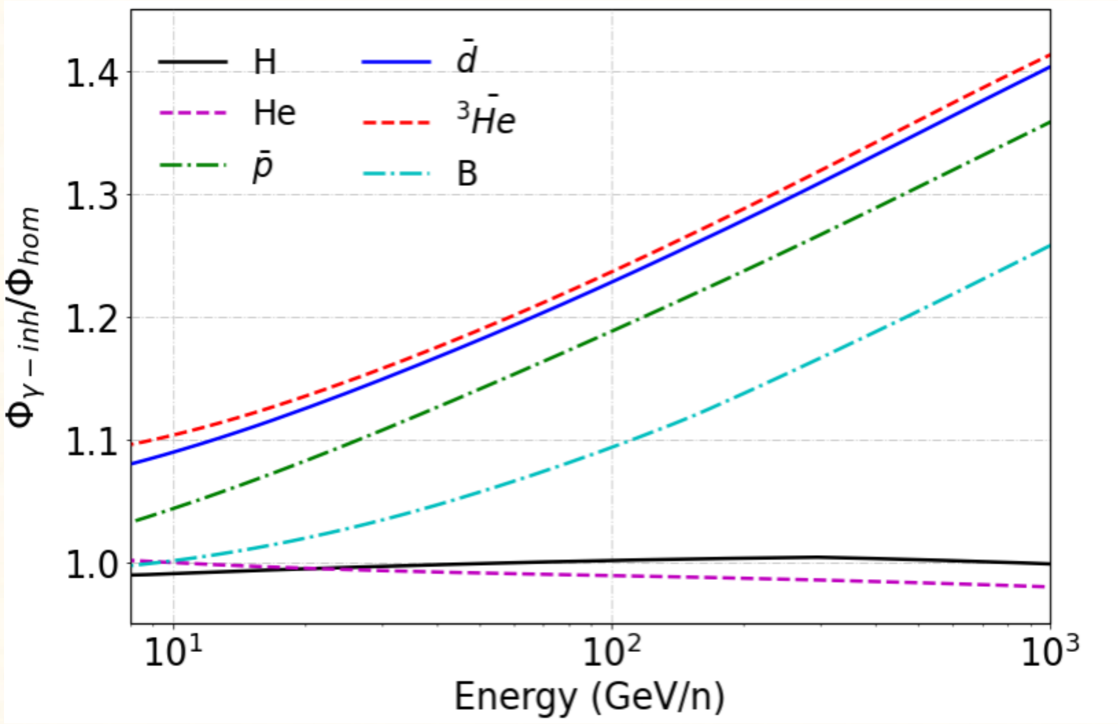
Antiprotons in the Galaxy – *More possibilities*

SNRs accelerating antiprotons

Mertsch+ . 2020 Phys. Rev. D 104, 103029



Inhomogeneous diffusion coefficient



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

Conclusions

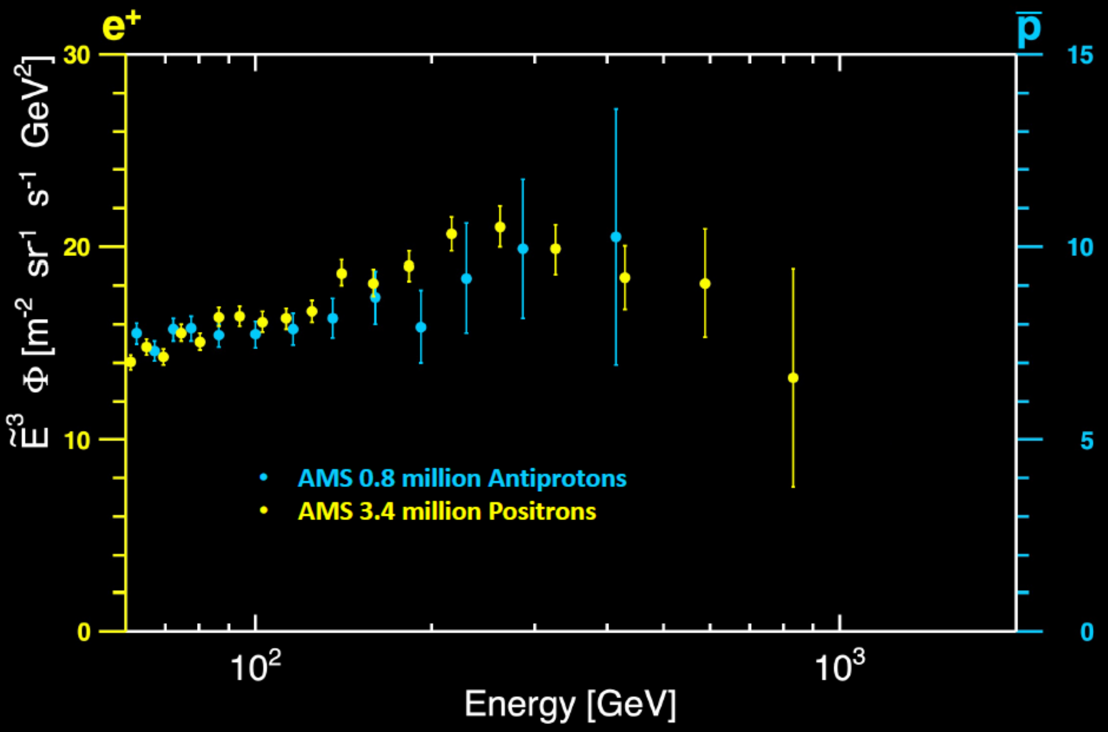
- **Antiproton observations seem to be in good agreement with the rest of CRs**
- **Uncertainties in the modelling of secondary antiprotons can be significantly reduced with better cross sections models**
- **No significant excess favouring a DM signal is found, with largest significance of around 1.8 σ – Publication of AMS-02 correlation matrix is needed!**
- **AMS-02 Antiproton measurements allow us to set strongest constraints at GeV masses for WIMPs coupling to quarks**
- A clear detection of a DM signal is not easy with antiprotons… **Anti-nuclei can offer a much cleaner window for their study**

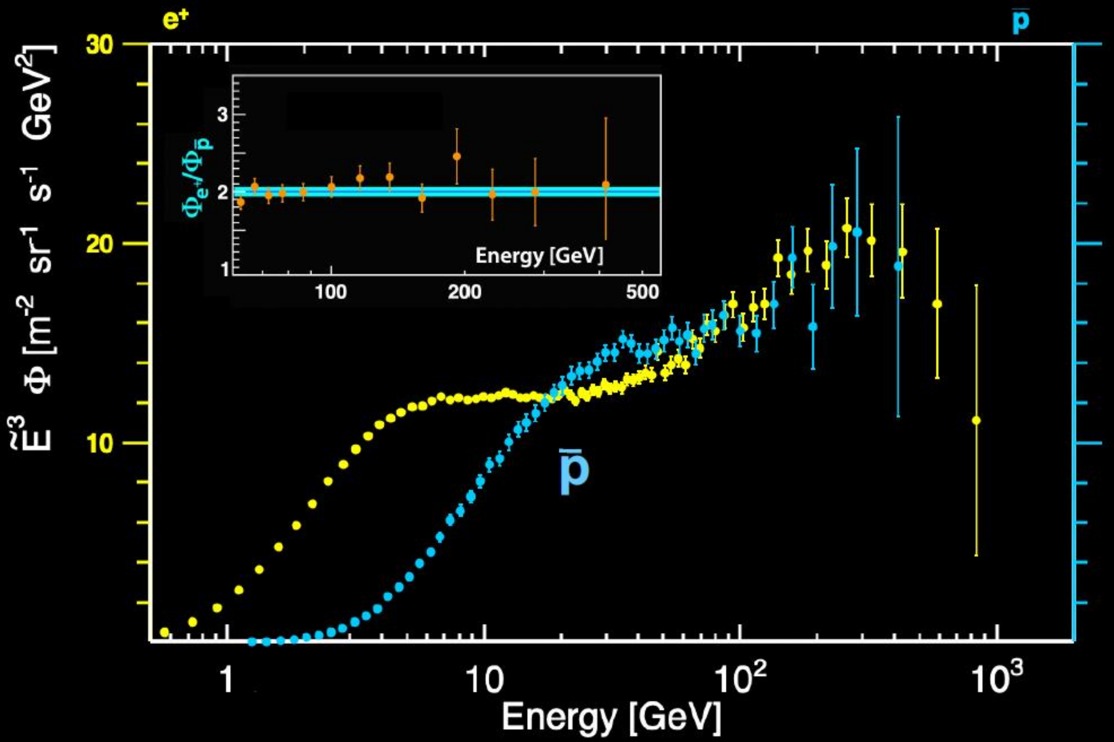
See talk by P. Salati

Pedro de la Torre Luque – 19/08/2024
pedro.delatorre@uam.es

BACK UP

An open question related to antiprotons





Paolo Zuccon MIAPP 2021

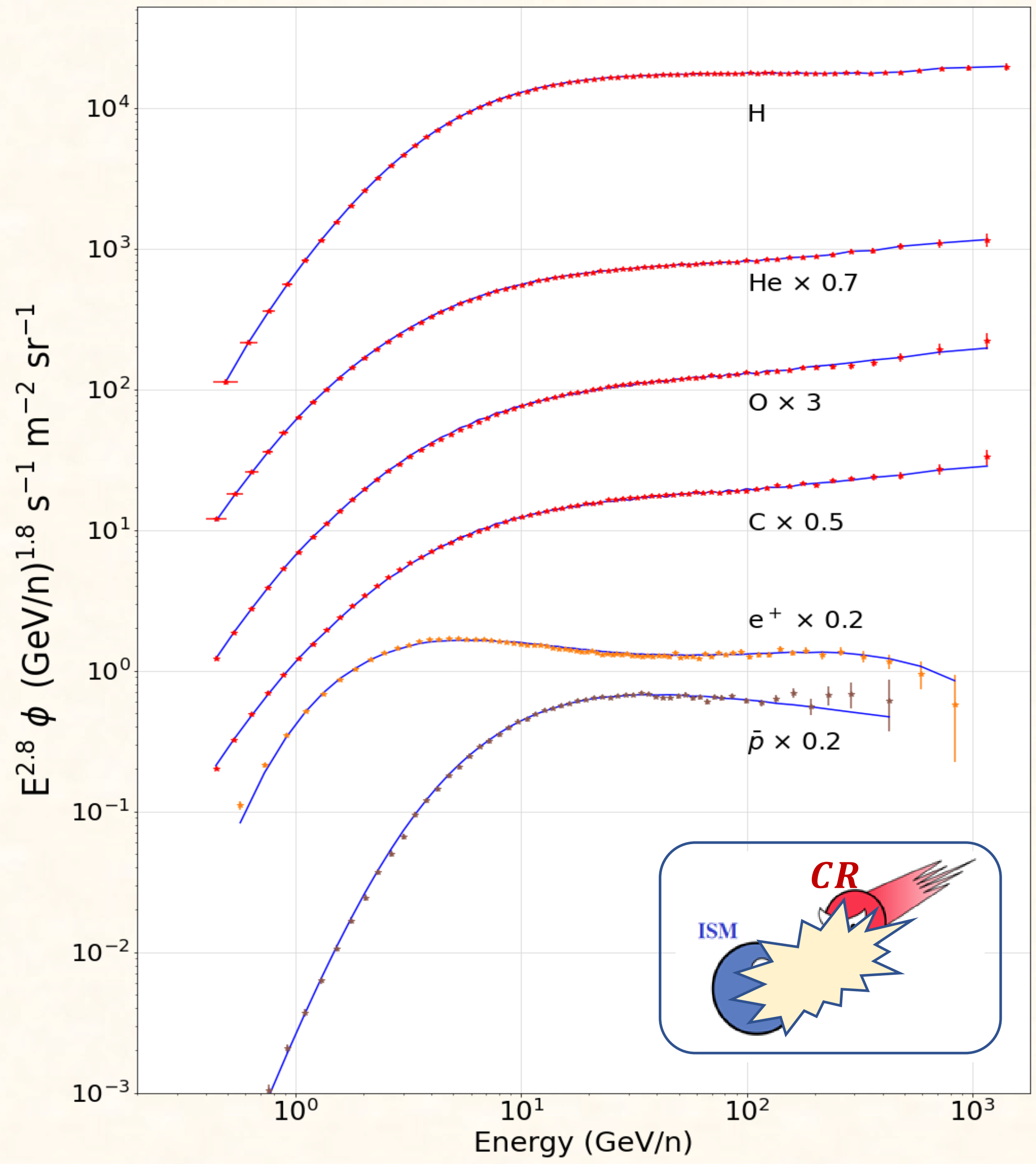
Antiprotons as a tool to identify signals of BSM physics

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

The antiproton spectrum allows us to strongly constrain the existence of BSM physics due to the expected low production and uncertainty in their modelling.

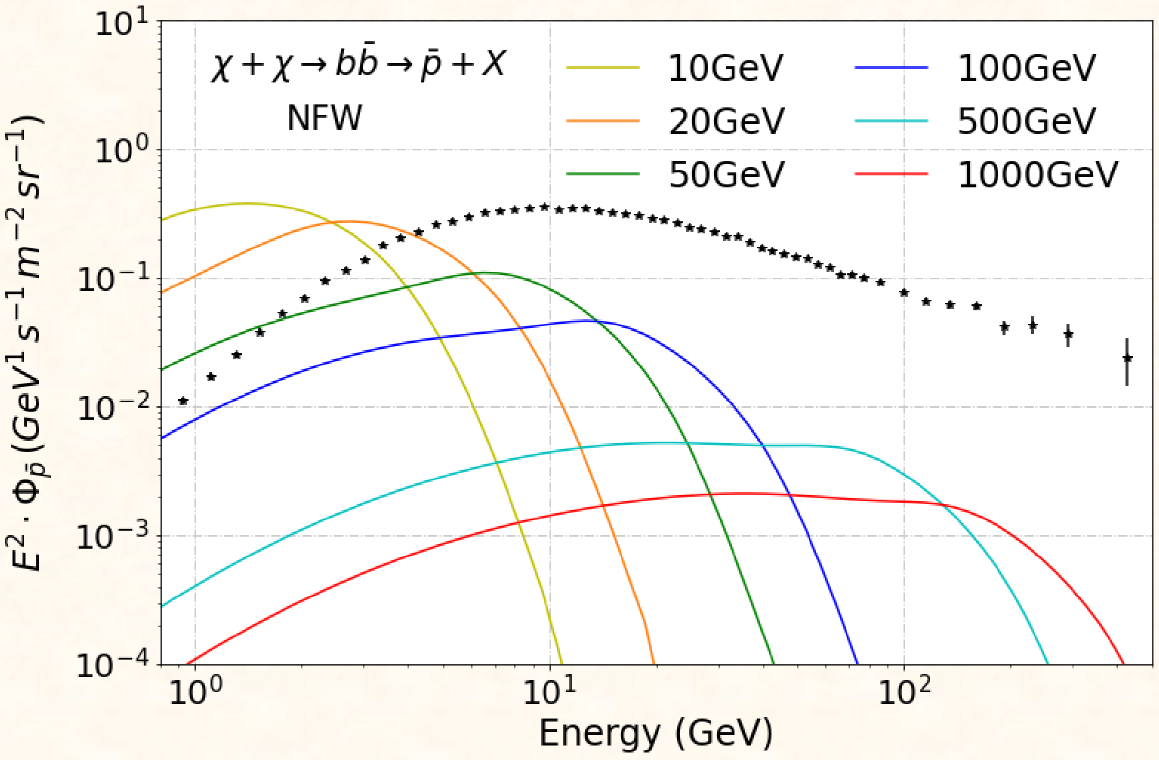
Specially, well-motivated **WIMPs** ($M_\chi \sim O(100\ GeV)$) are expected to leave imprints in the GeV energy region.

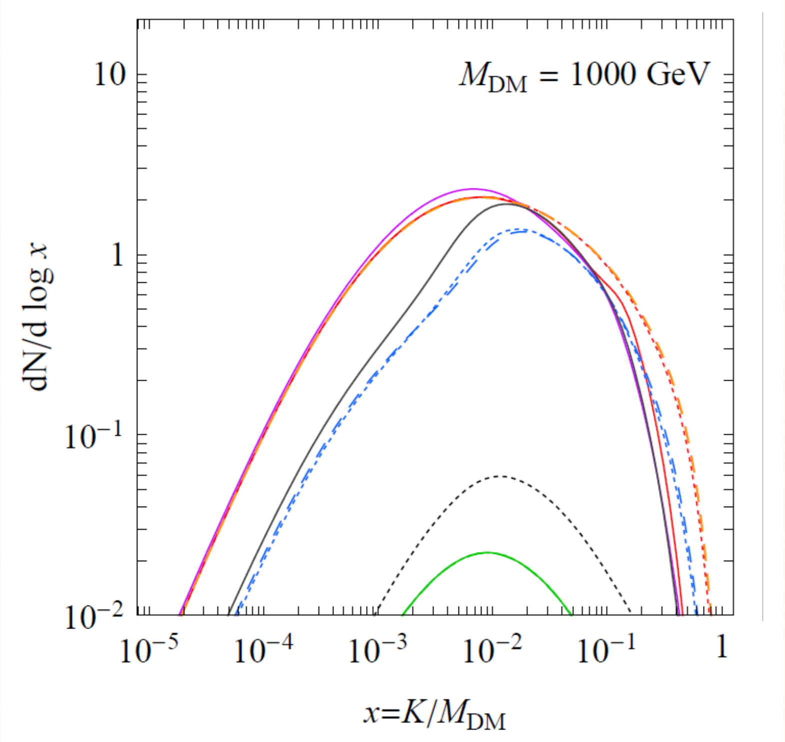
Flux of CR nuclei and antiparticles (data from AMS-02)



Primary antiprotons

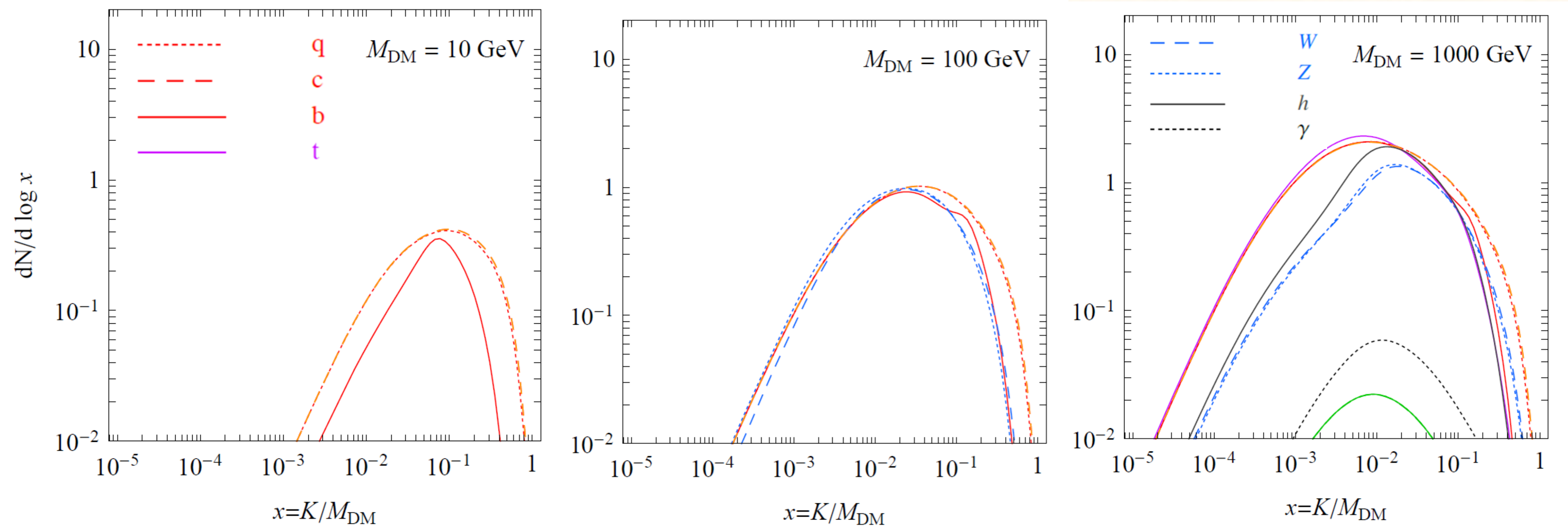
Indirect DM searches with antiprotons (similarly to what happens with other astroparticles) are either intended for specific particle models (wino, Higgsino, etc) or for a generic WIMP that is modelled as a neutral-colorless resonance that couples to the SM through specific channels (bb, tt, ττ, etc)





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)



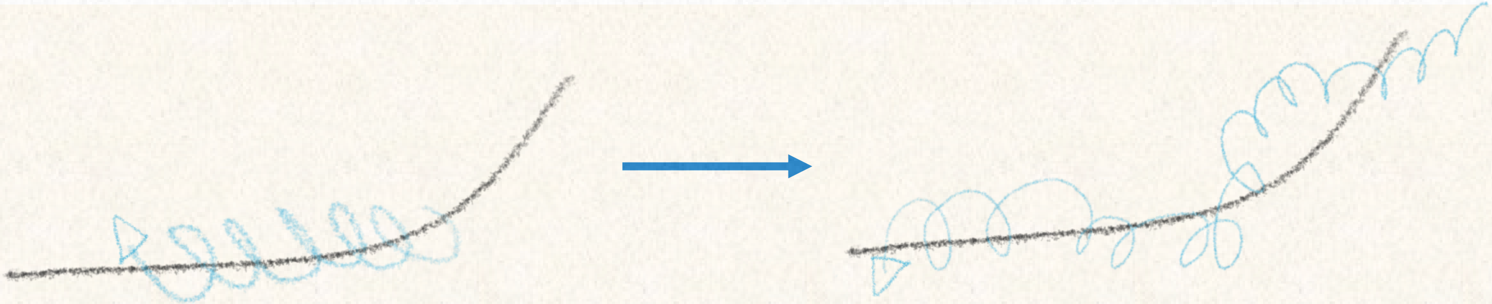
The *DRAGON2* code

- The basic idea is that primary particles are accelerated in astrophysical sources (namely SNRs) and propagate throughout the Galaxy during millions of years, due to scattering with plasma waves. Occasionally, they interact with gas and produce secondary nuclei through spallation.

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

$$D_{pp} \propto \frac{p^2\, VA^2}{D}$$

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



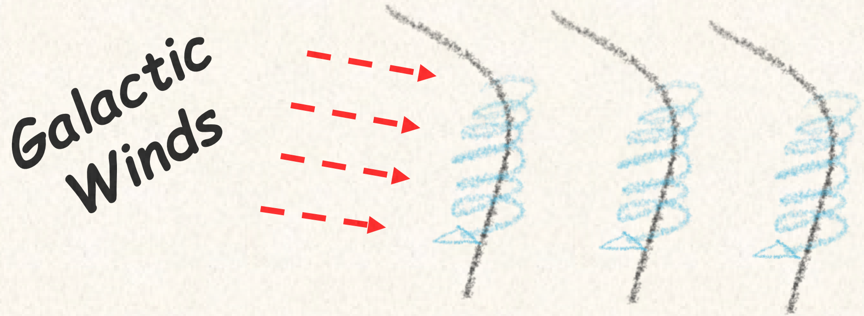
The *DRAGON2* code

- The basic idea is that primary particles are accelerated in astrophysical sources (namely SNRs) and propagate throughout the Galaxy during millions of years, due to scattering with plasma waves. Occasionally, they interact with gas and produce secondary nuclei through spallation.

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

$$D_{pp}\propto\frac{p^2\,VA^2}{D}$$

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



The *DRAGON2* code

- The basic idea is that primary particles are accelerated in astrophysical sources (namely SNRs) and propagate throughout the Galaxy during millions of years, due to scattering with plasma waves. Occasionally, they interact with gas and produce secondary nuclei through spallation.

$\frac{\partial N}{\partial R} q(x,y,z)$

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

$D_{pp} \propto \frac{p^2 VA^2}{D}$

***CROSEC* paramet.**

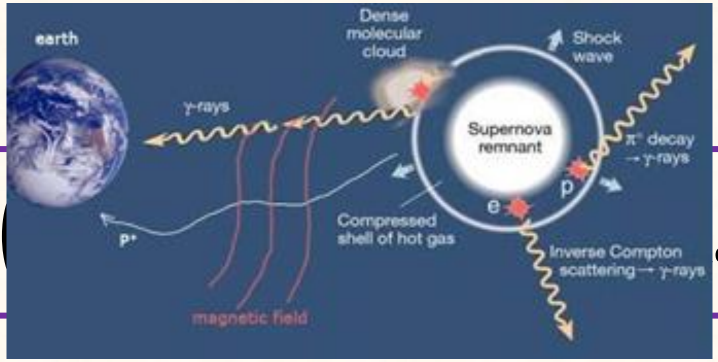
$$\frac{1}{\tau_i^f(T)} = c n_H \beta(T)\left[\sigma_{iP}(T) + f_{He}\,\sigma_{iHe}(T)\right]$$

$$\frac{1}{\tau_i^r(T)} = \frac{1}{\gamma(T)\tau_i^0}$$

***DRAGON2* paramet.**

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

$\frac{\partial p}{\partial t} = ($ … c

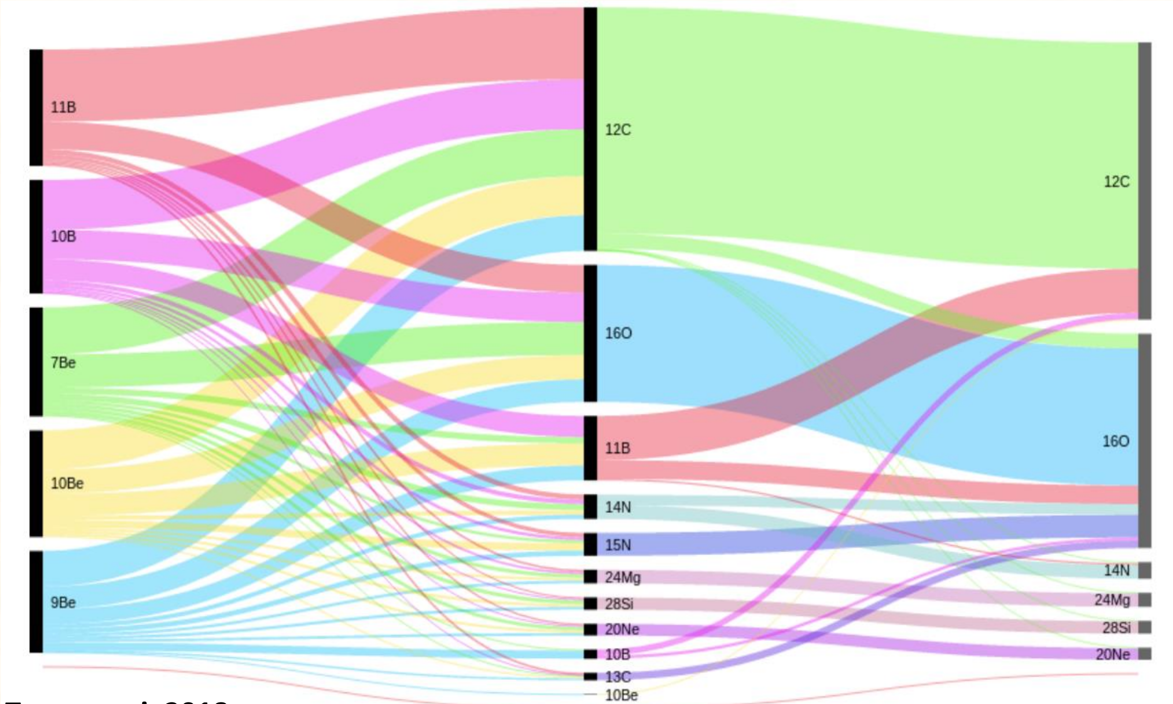


$$\Gamma^s_{j\to i} = \beta_j c n_t \sigma_{j\to i} N_j$$

Cross sections → Secondary CRs

$$Q_{sec}(E) \propto \sum^{pr} J_{pr}(E)\, \sigma_{pr \rightarrow sec}(E)$$

Complexity of the CS network



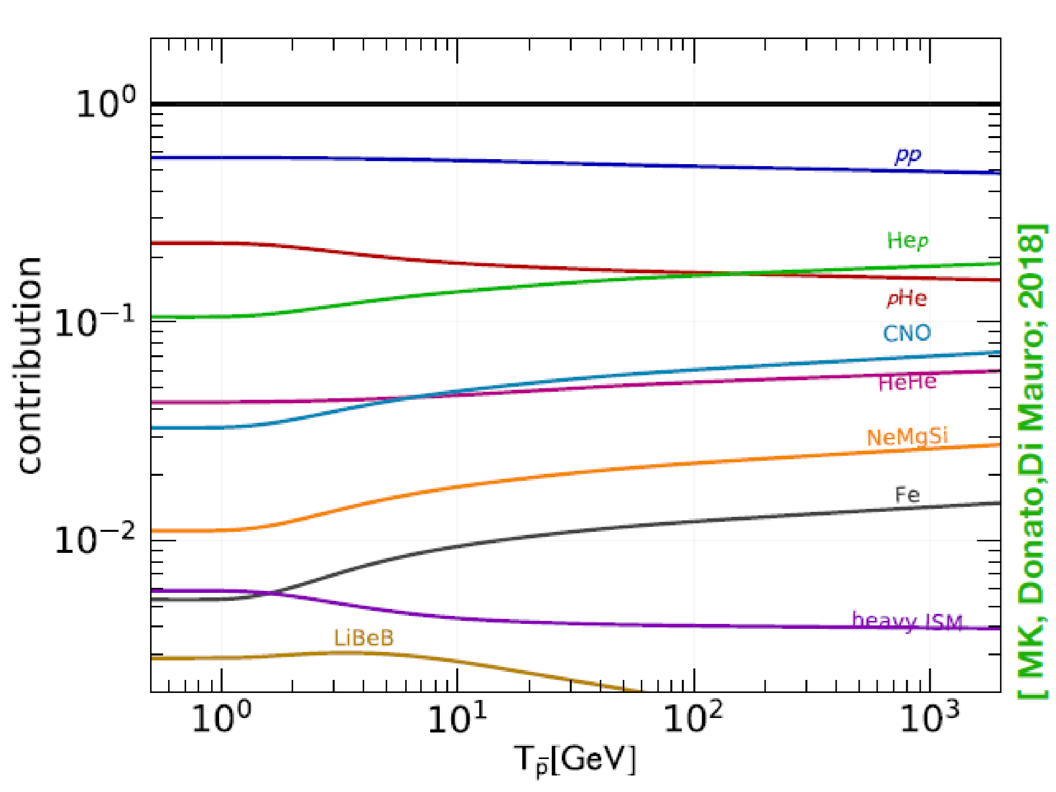
Tomassetti, 2018

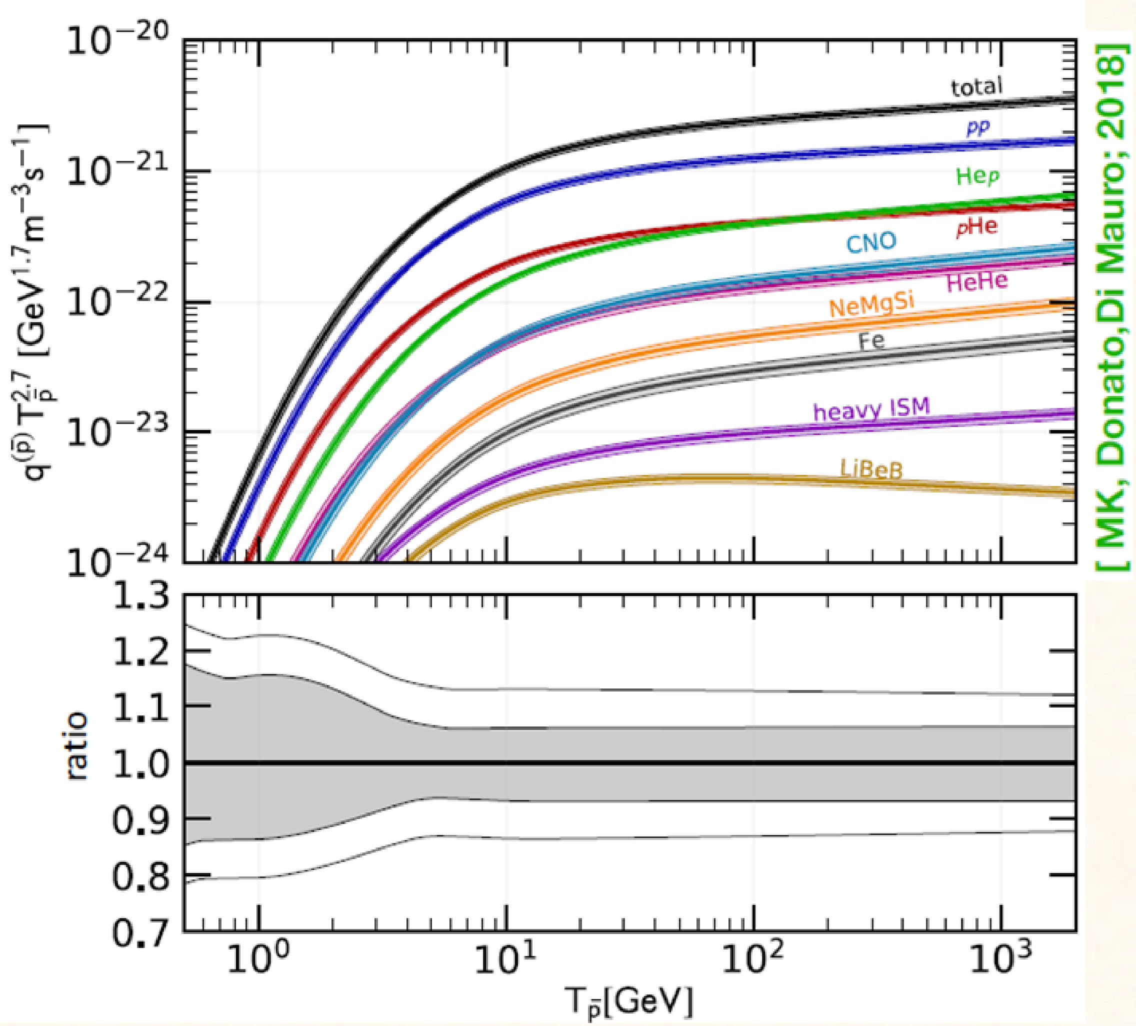
Production of secondary CRs

- Main spallation channels: O and C
- Secondary channels (N, Ne, Mg, Si & Fe) are very important for Li and Be (< 50%)
- Tertiary channels also matter:
  e.g. ^{11}B + gas → ^{10}B + X

Genolini et al. 2019 ; arXiv:1803.04686
Tomassetti, 2018 ; arXiv:1707.06917

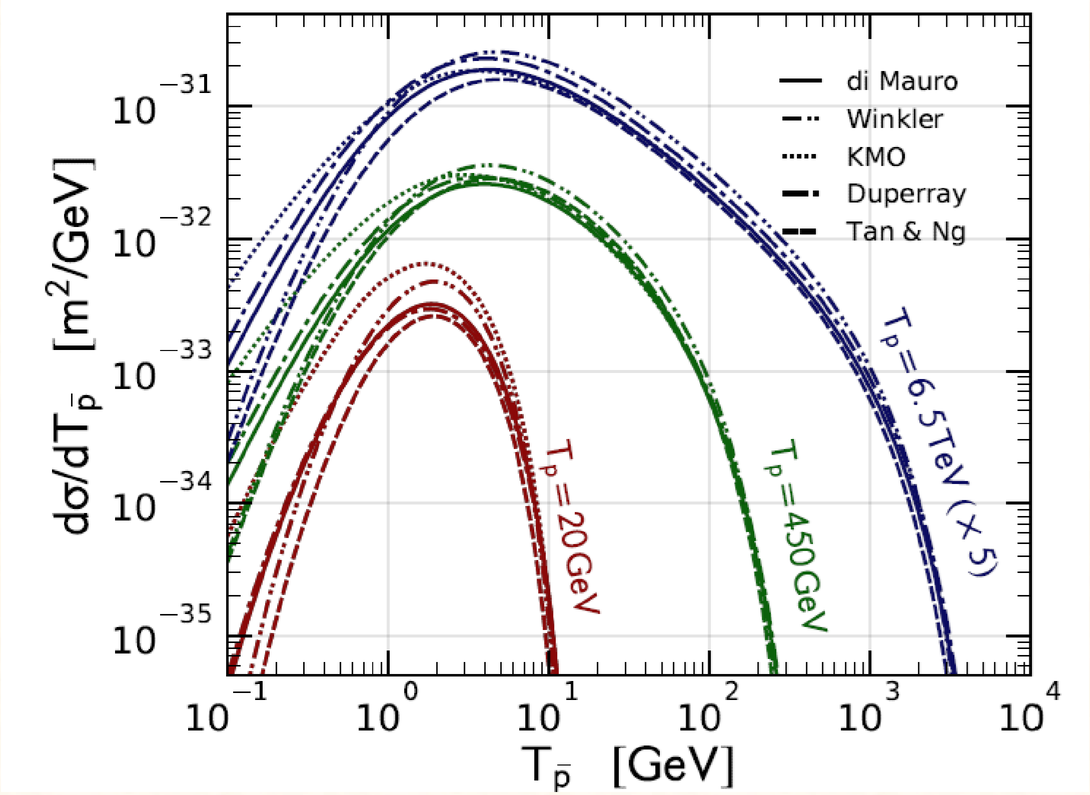
Channels of secondary antiproton production

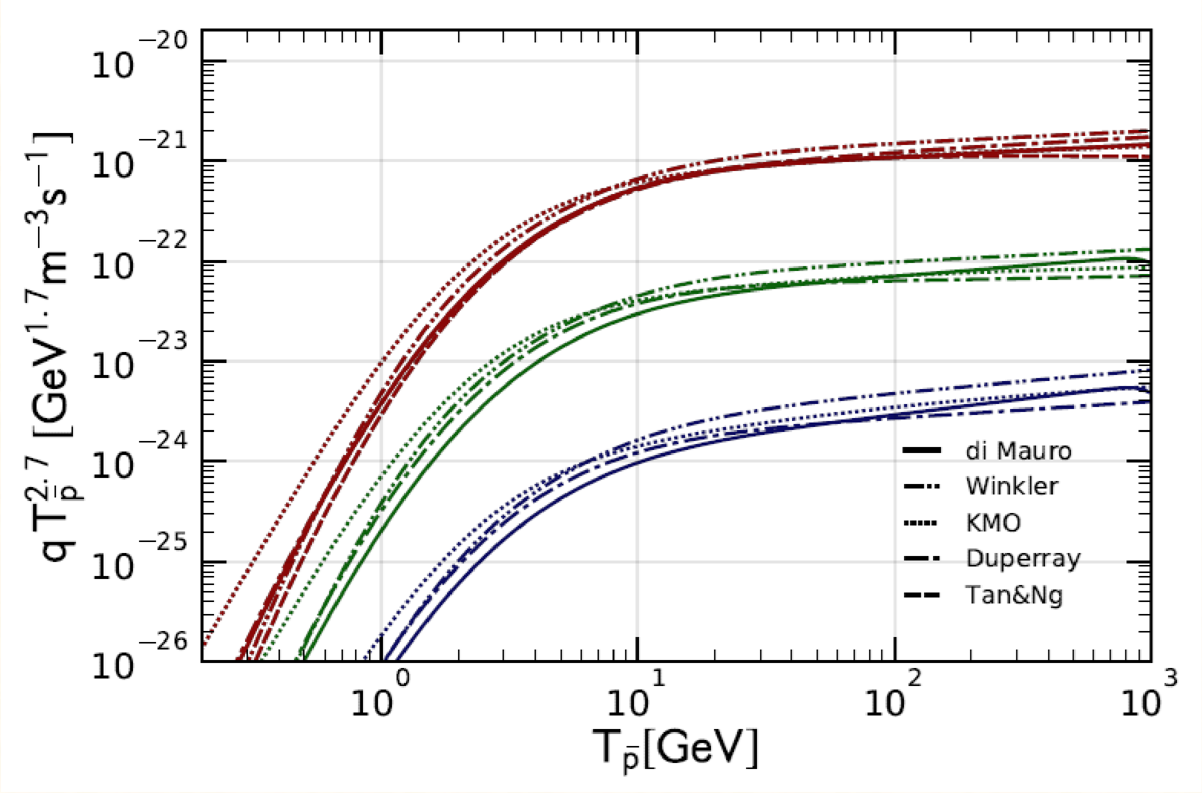




Antiproton parameterizations

Phys. Rev. D 96, 043007 (2017)

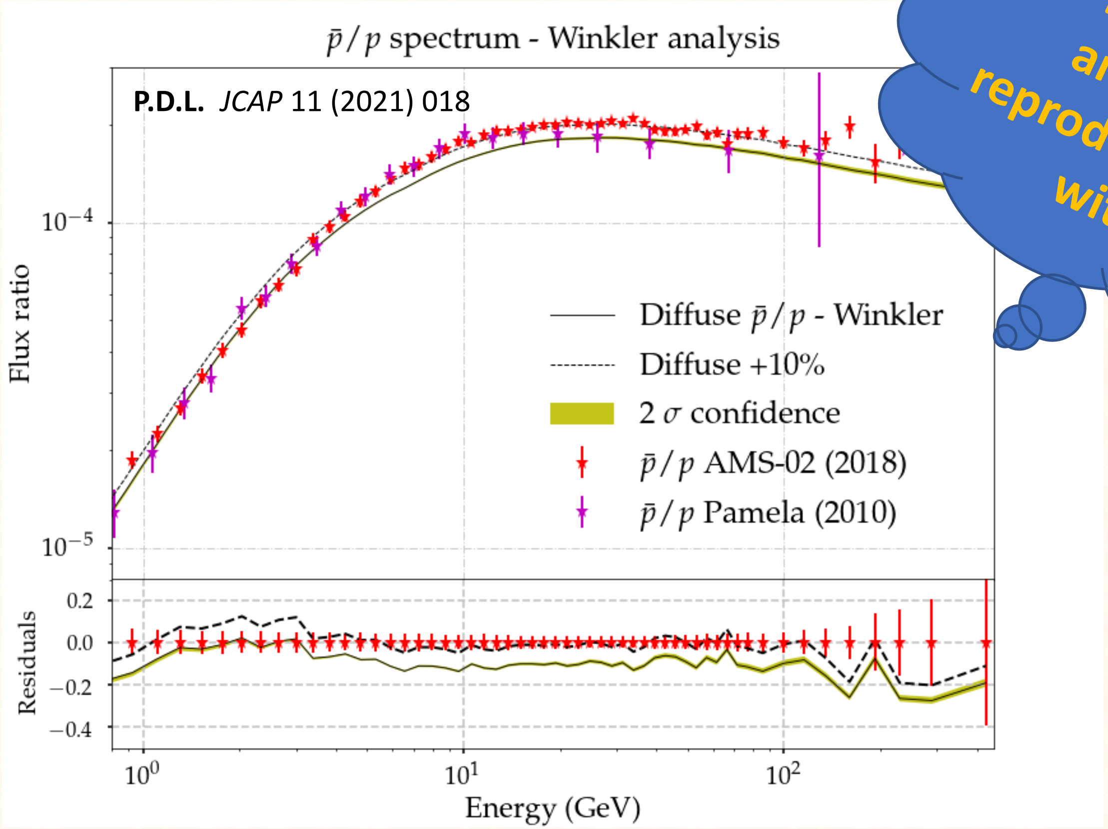


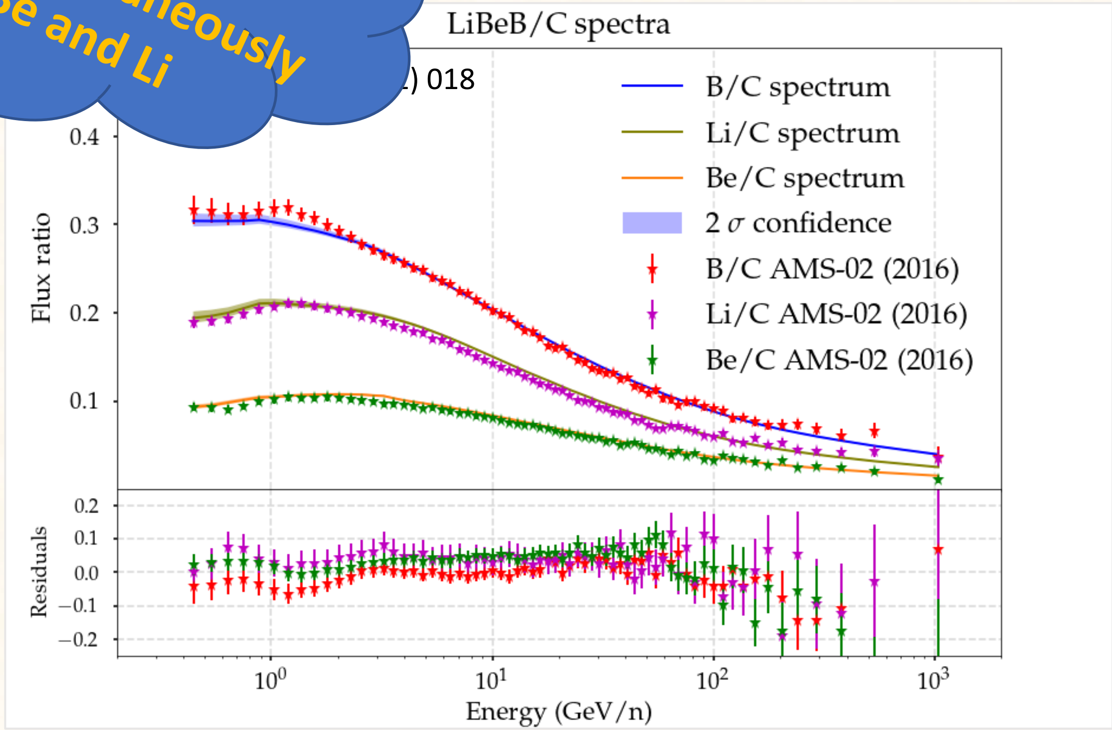


Antiproton *excesses* – *The grammage excess*

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**



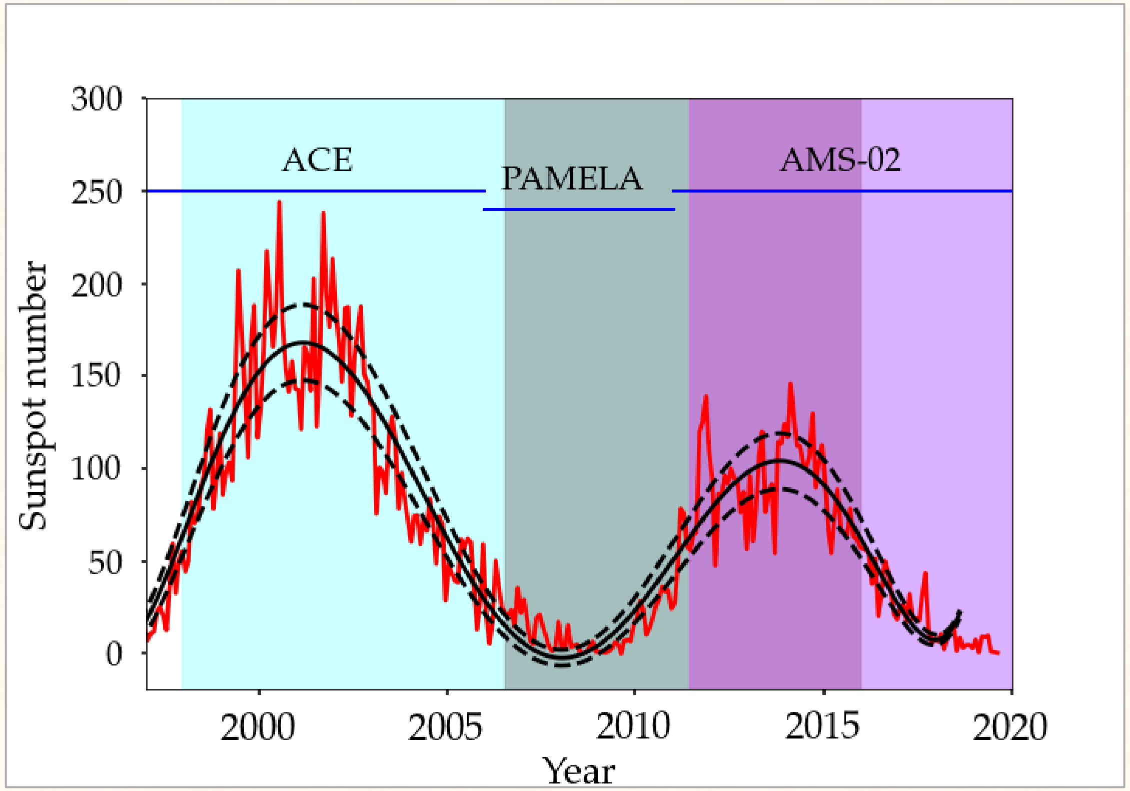


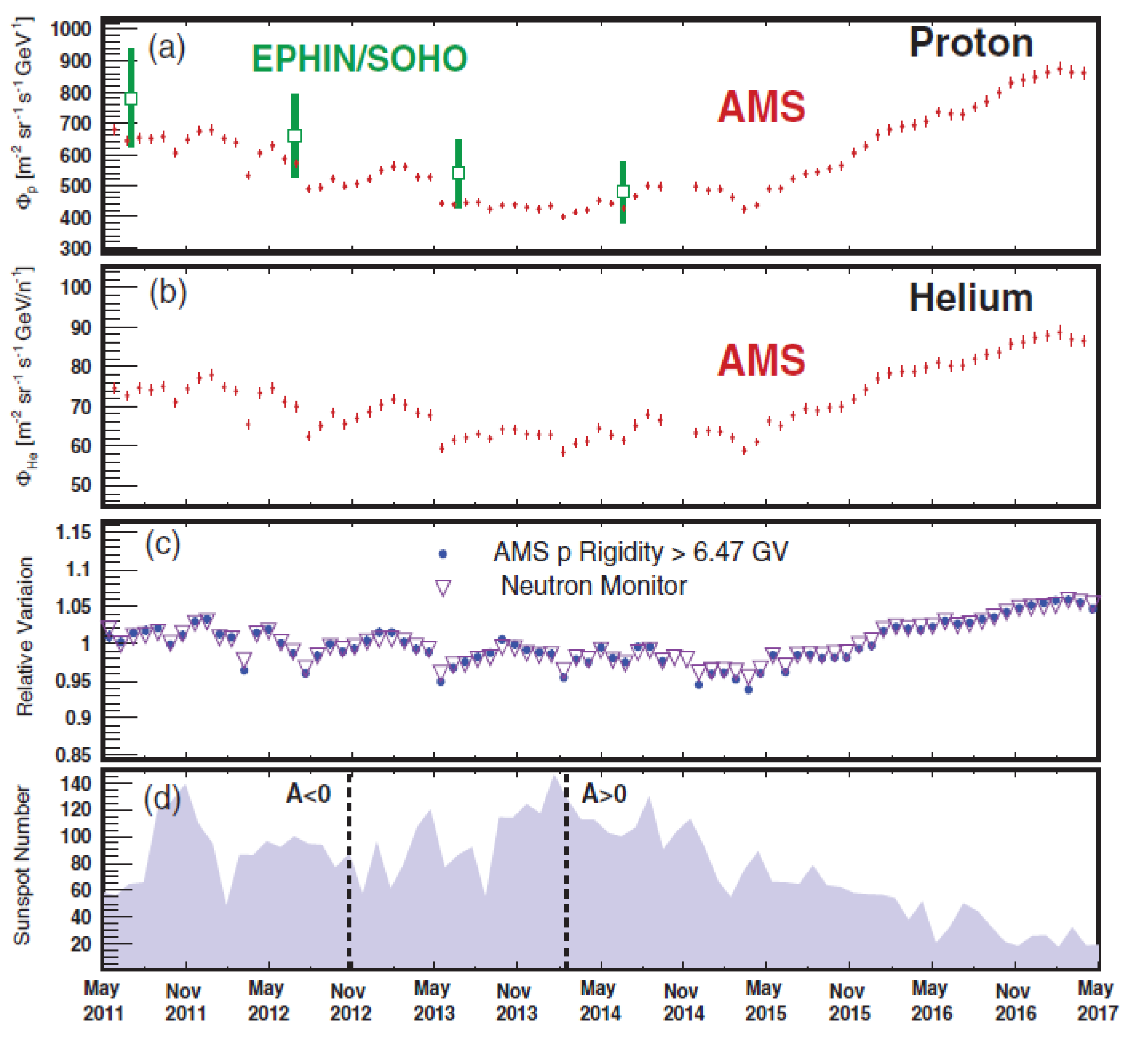
Diffusion coefficient

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

Production cross sections

Solar modulation

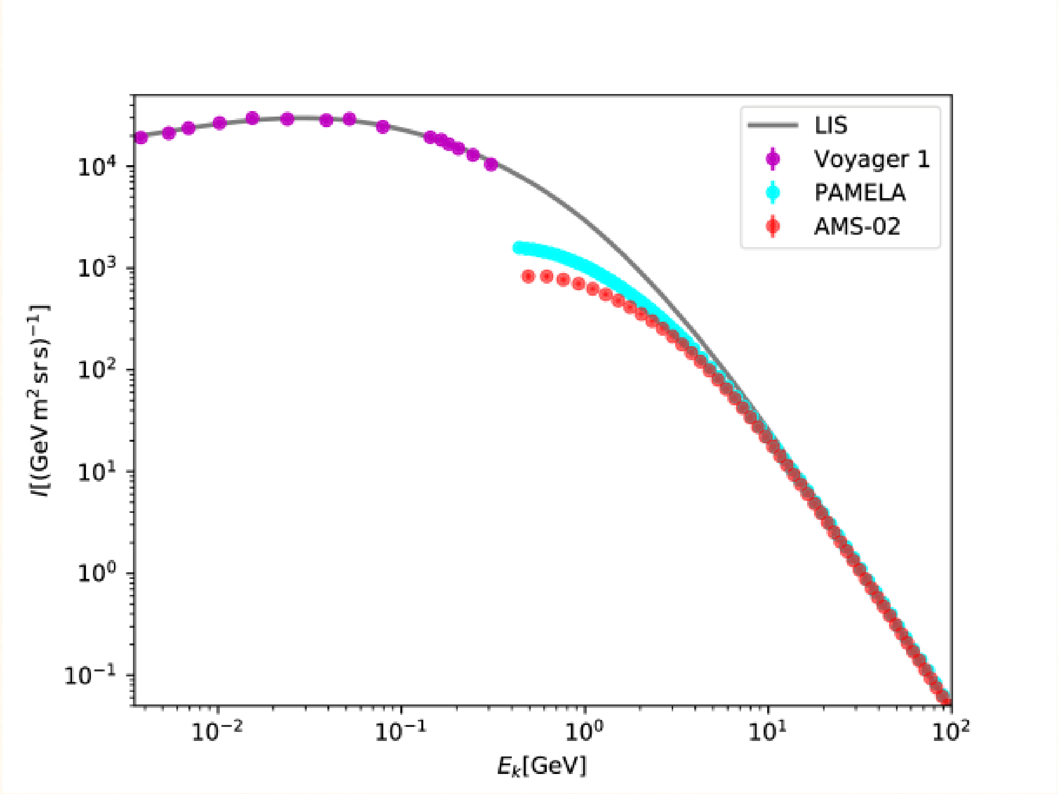


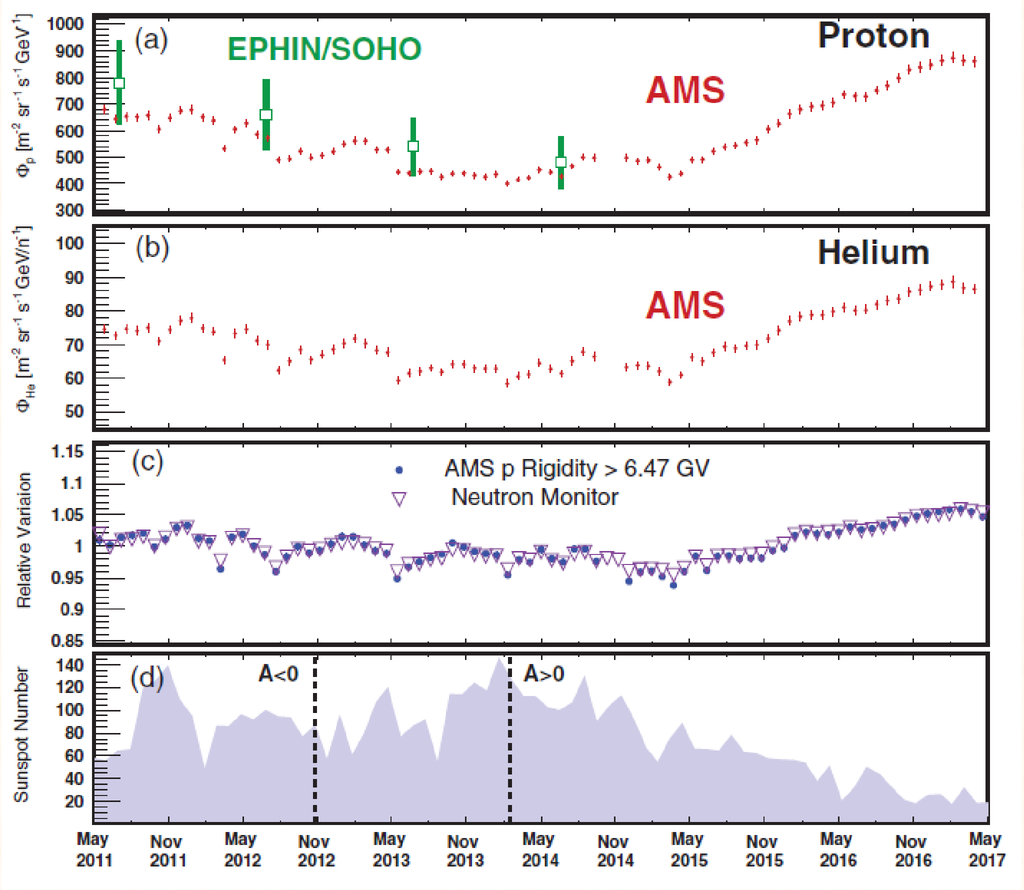


❖ Detailed heliospheric simulations or Force-Field approximation

❖ Neutron monitor experiments + Voyager-01 data

SOLAR MODULATION





- Force-Field approximation
- Neutron monitor data + Voyager-01 data
- Cholis-Hooper-Linden (arXiv:1511.01507) correction

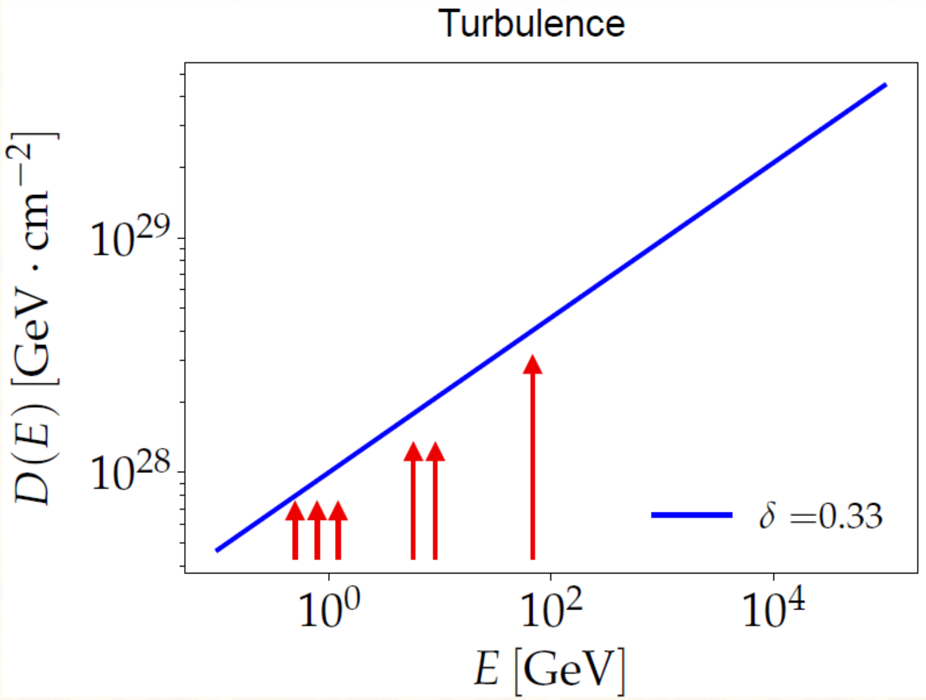
$$\Phi^{\mathrm{TOA}}(T) = \frac{2mT + T^2}{2m\,(T + \frac{Z}{A}\phi) + (T + \frac{Z}{A}\phi)^2}\,\Phi^{\mathrm{IS}}(T + \frac{Z}{A}\phi)$$

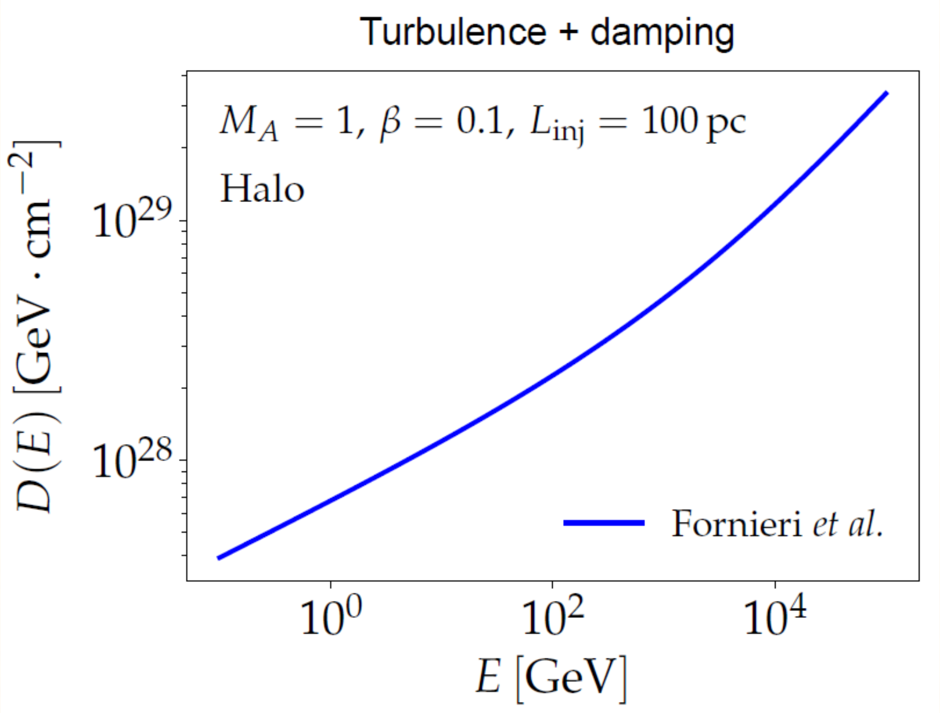
$$\phi^{\pm}(t, \mathcal{R}) = \phi_0(t) + \phi_1^{\pm}(t)\ \mathcal{F}\left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)$$

Non-uniform diffusion:
Inhomogeneous diffusion

Importance of the implementation of diffusion coefficients which are calculated in different ways, beyond standard parametrizations

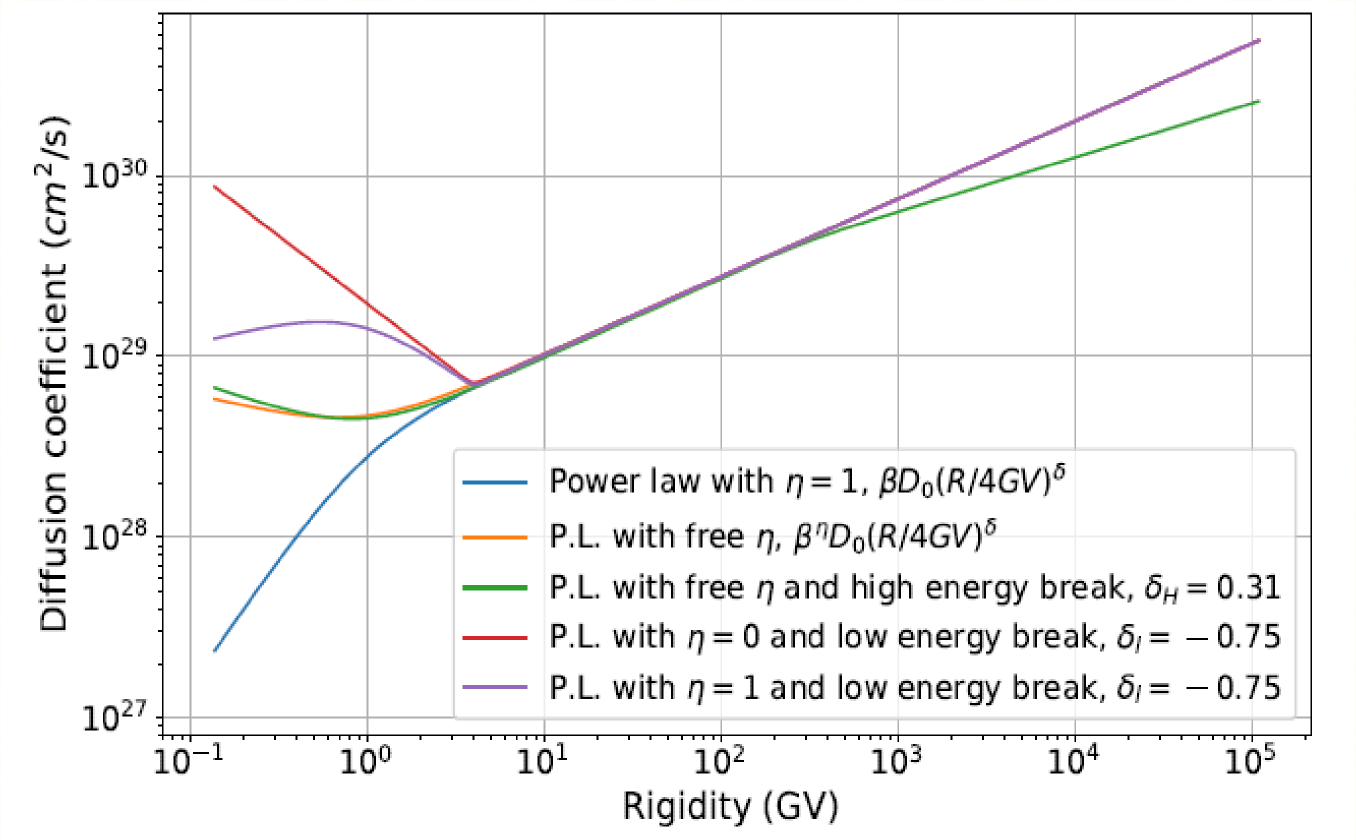
Change in the slope of D at low energies revealed by different analyses of AMS-02 data





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

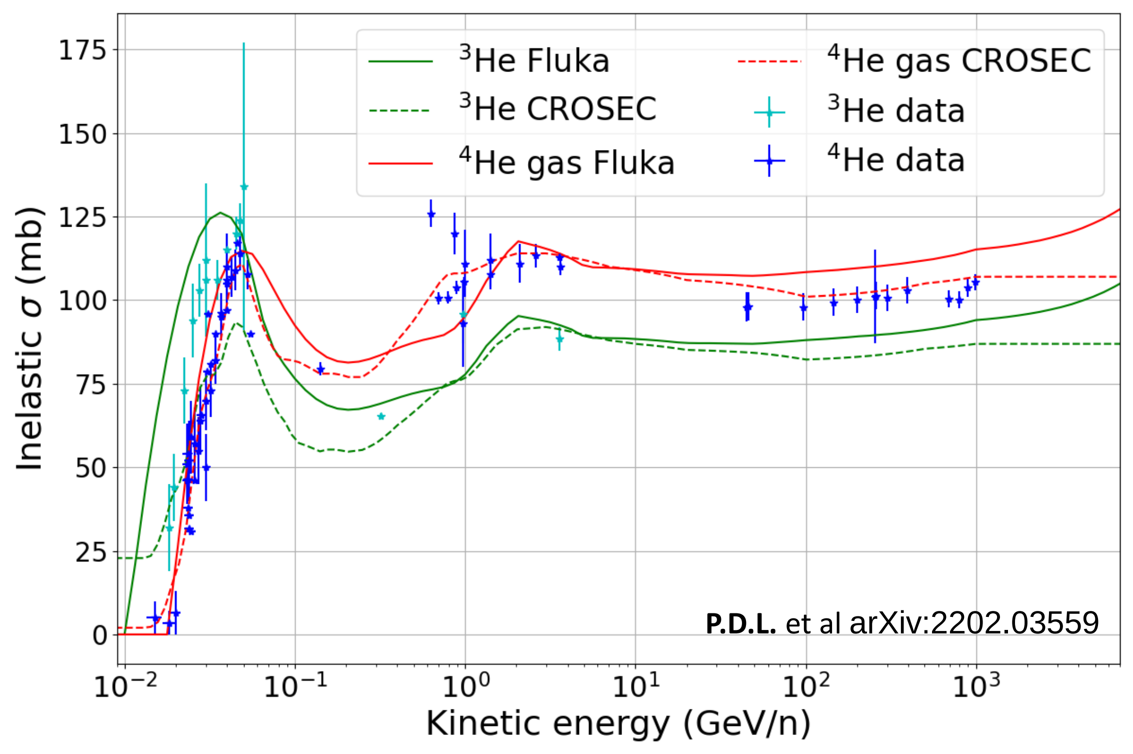
Diffusion coefficient parametrization

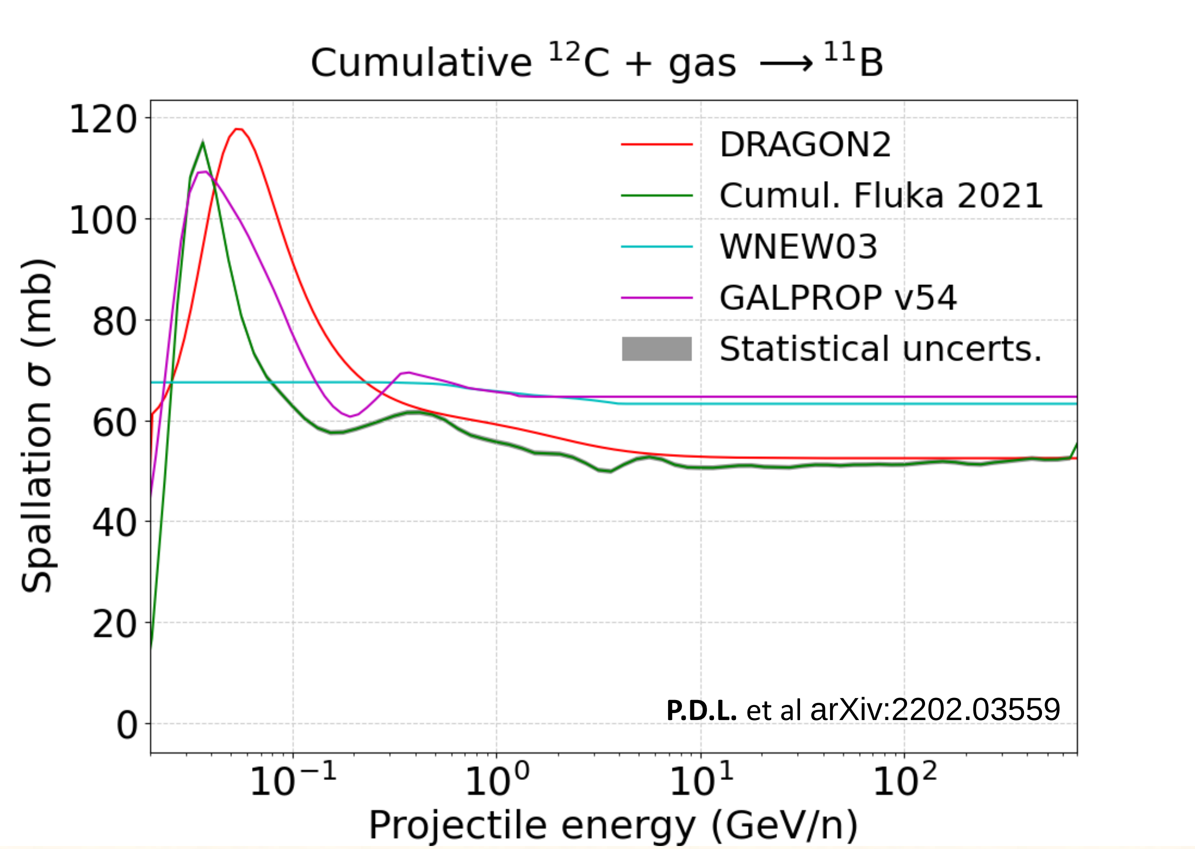


Precise studies of secondary CRs:
New set of Cross sections (FLUKA)

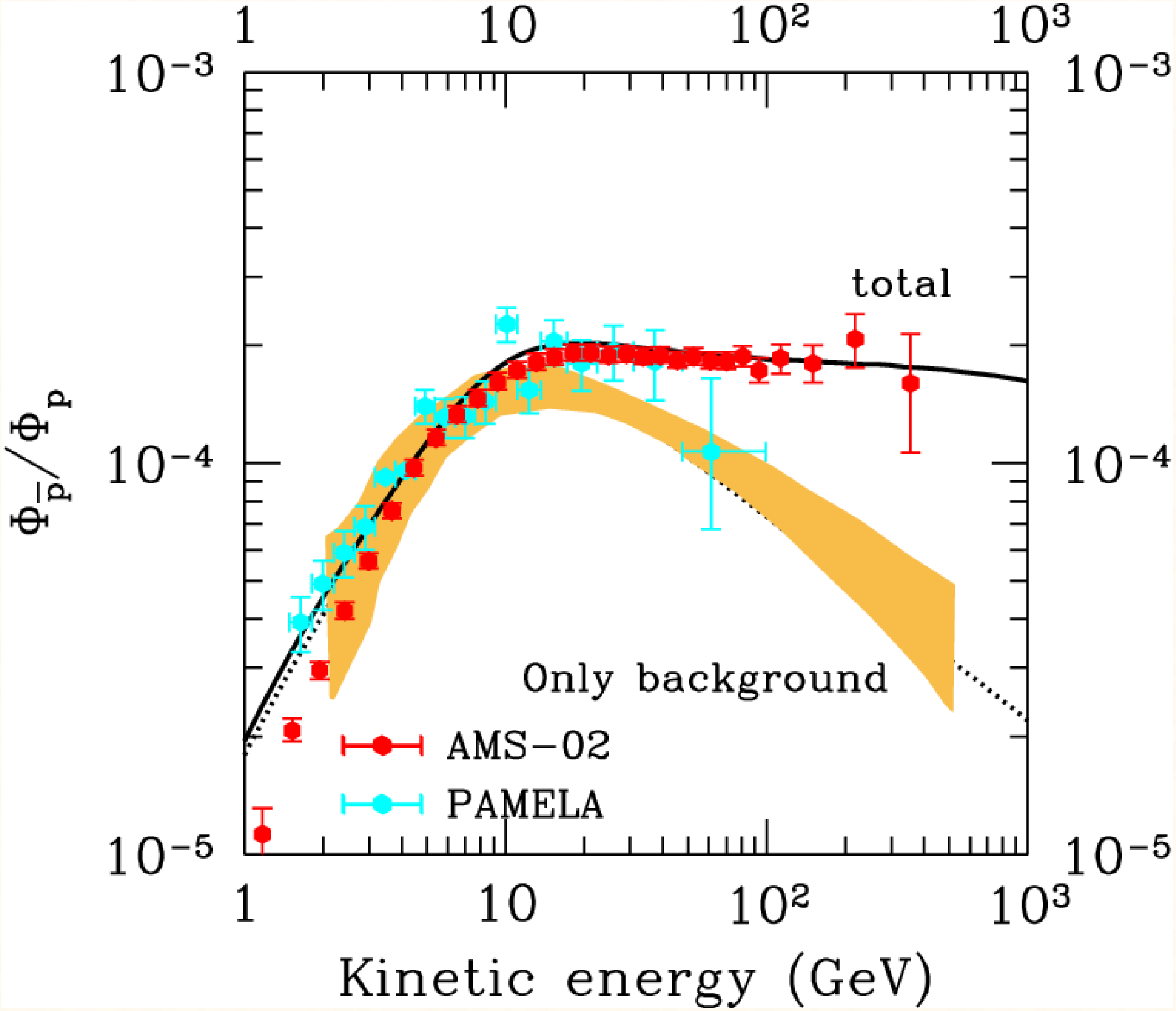
http://www.fluka.org/fluka.php

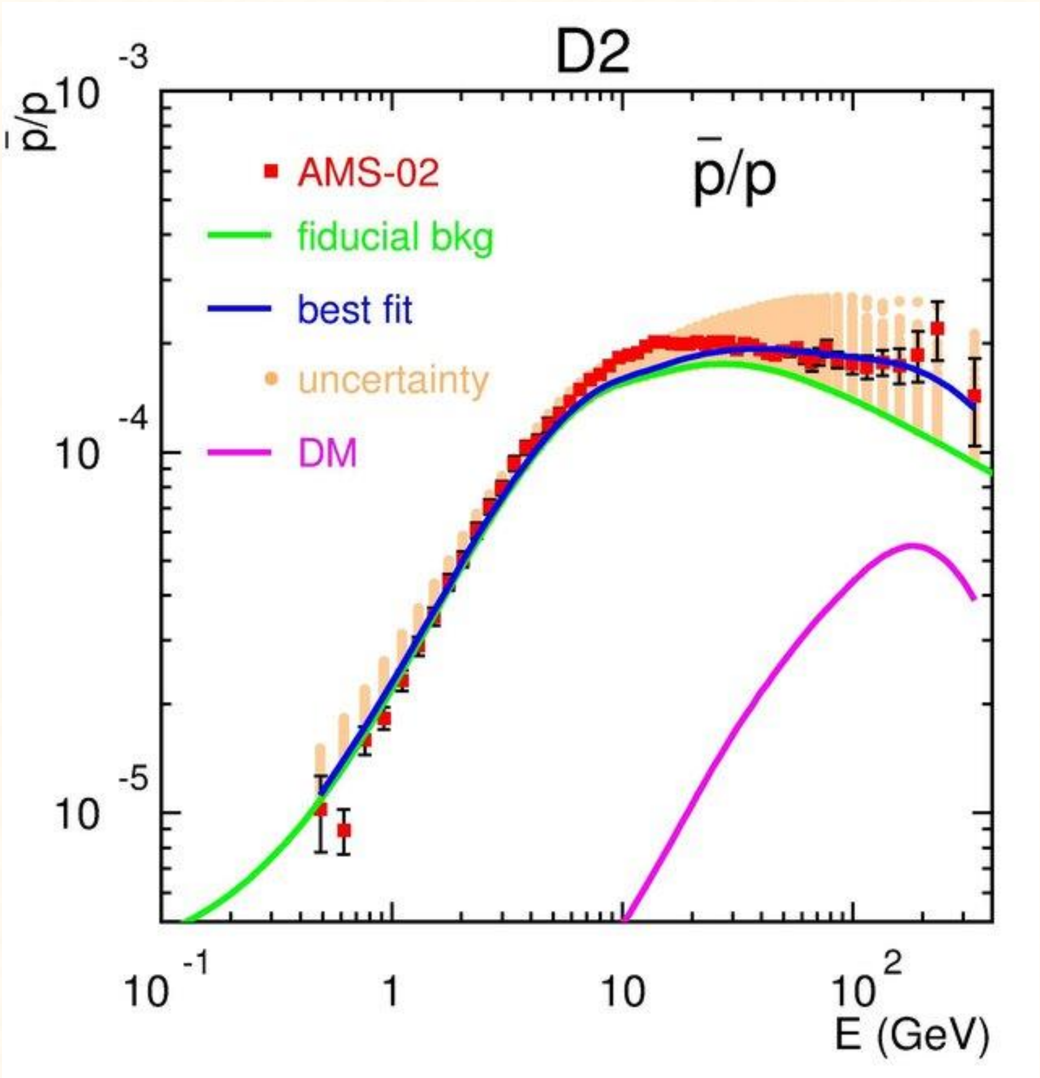
Inelastic and inclusive (spallation) cross sections computed from *FLUKA* for all nuclei until Z=28 (Fe). Agreement with dedicated parametrizations and experimental data at the level of 30%



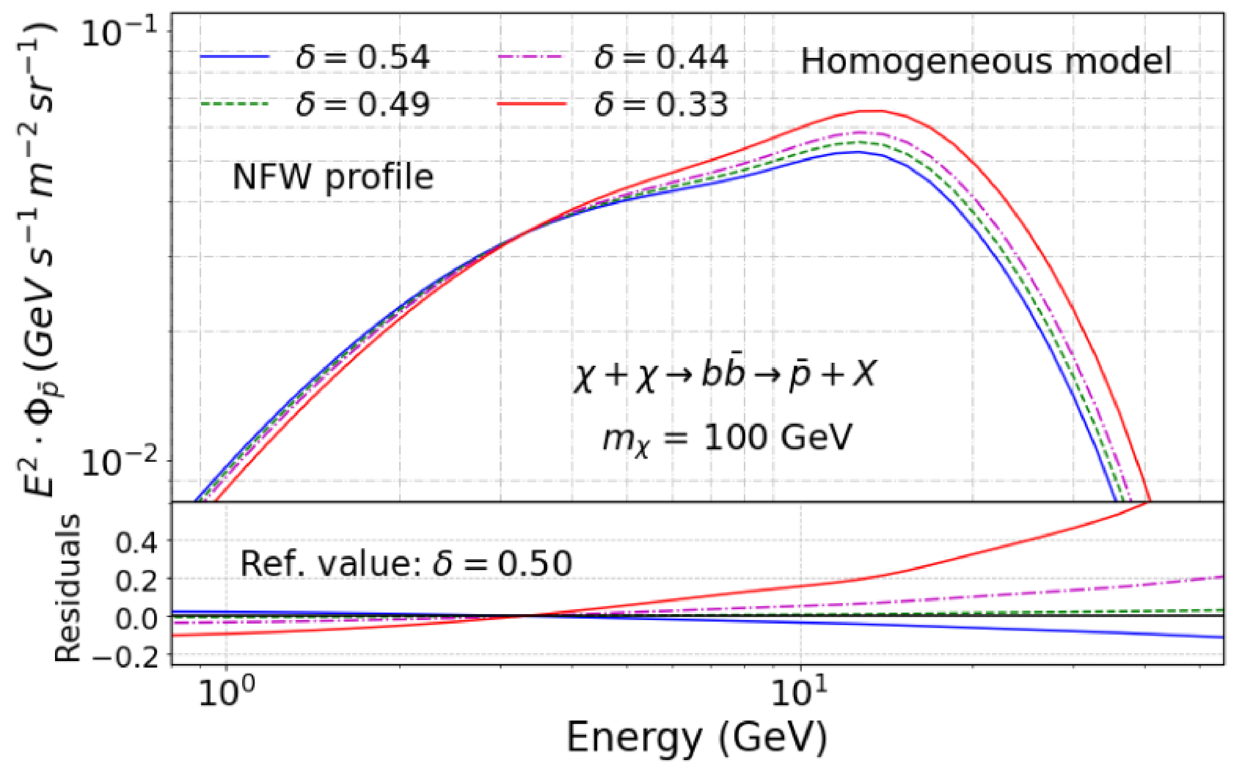


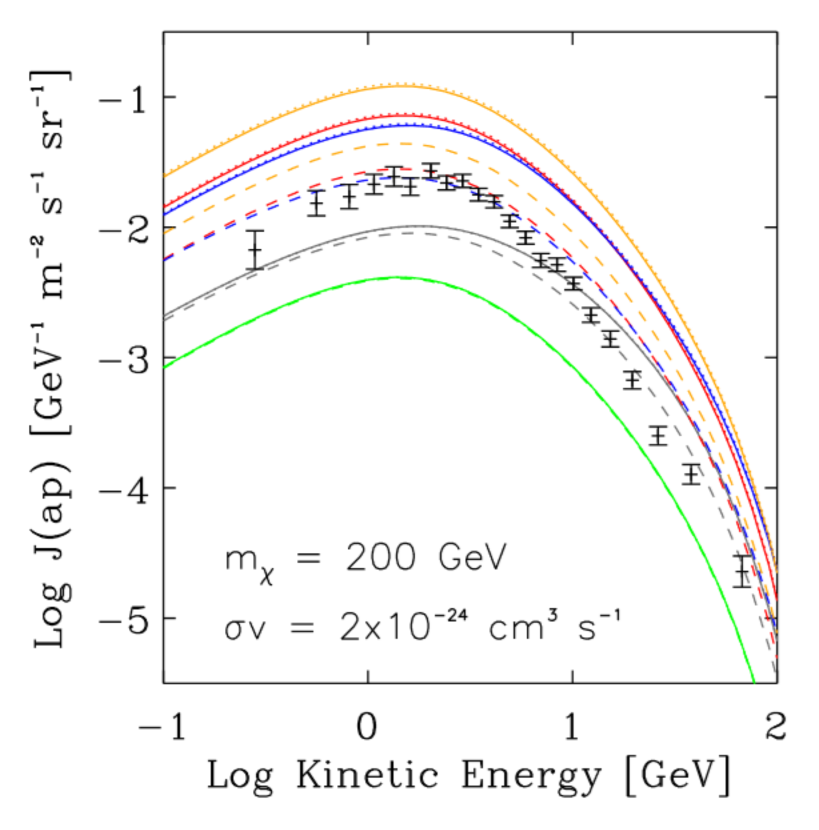
Li, T. *J. High Energ. Phys.* 2018, 151 (2018)





Primary antiprotons – The effect of diffusion

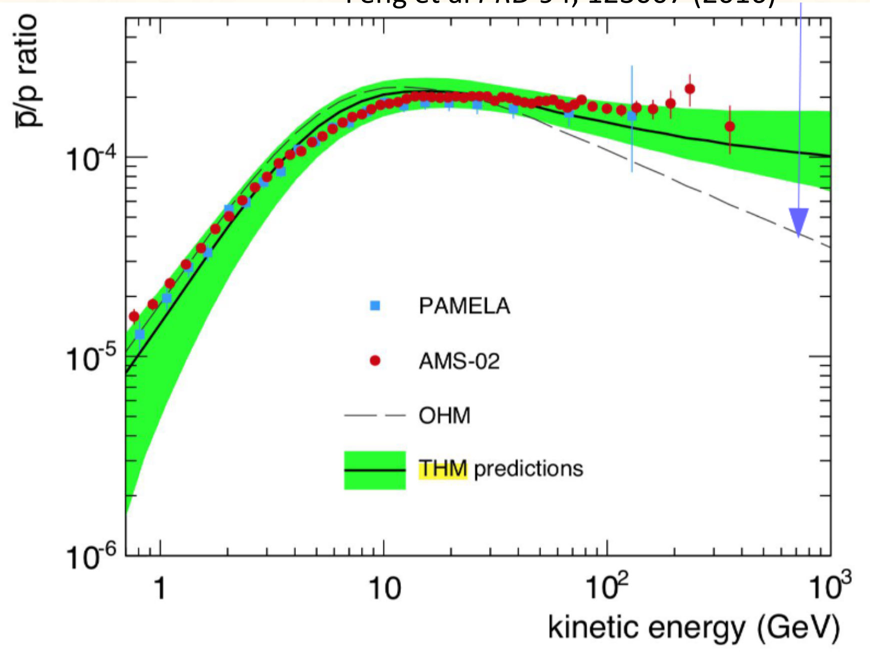


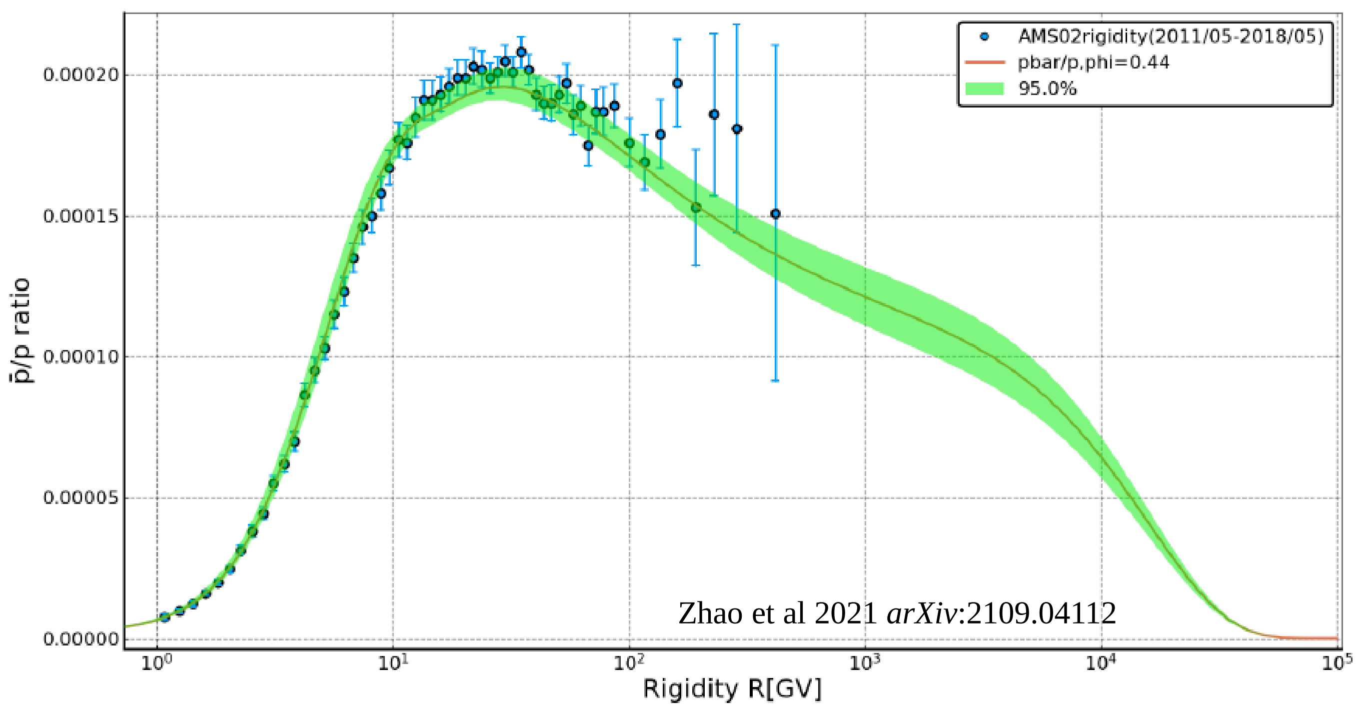


Non-uniform diffusion:
Inhomogeneous diffusion

Two-zone diffusion model (halo + disk) tuned from secondary to primary ratios is able to predict an antiproton flux in agreement with AMS-02 data without need of adding dark matter

Feng et al *PRD* 94, 123007 (2016)

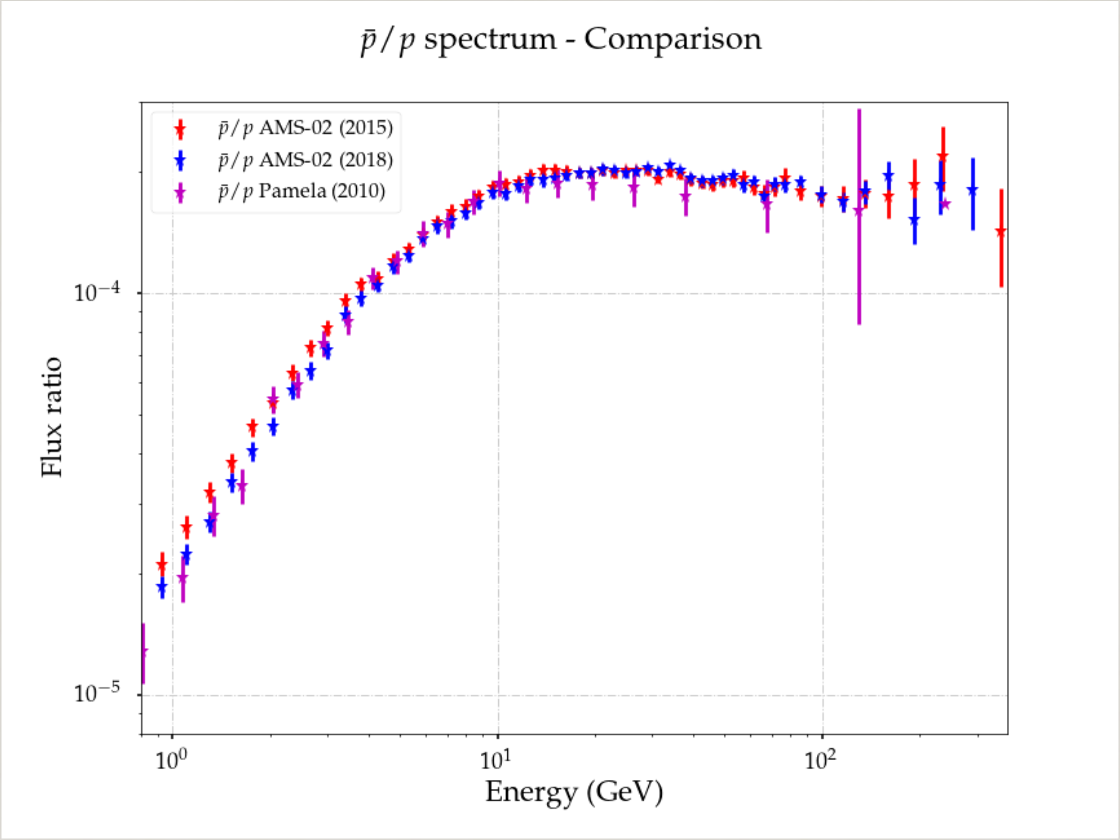


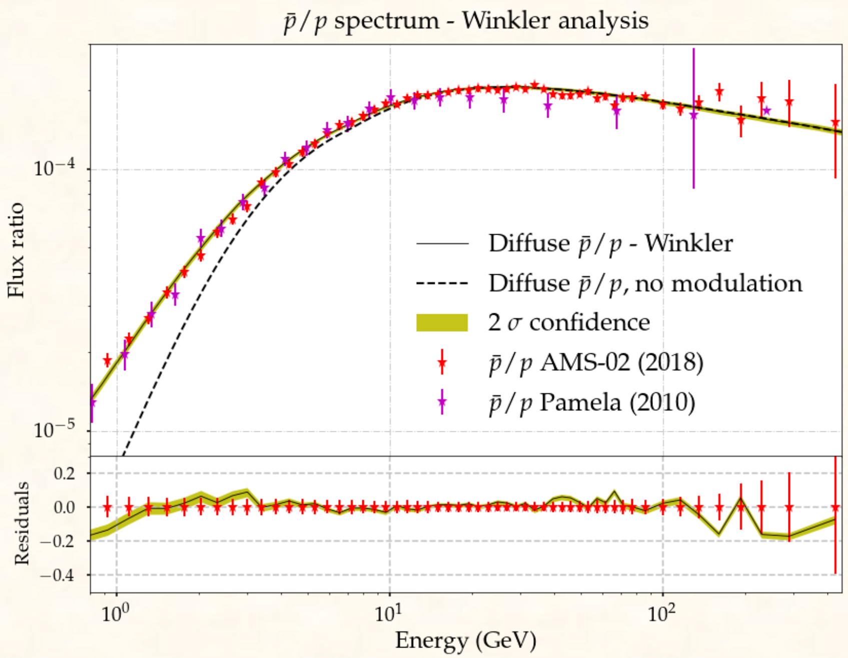


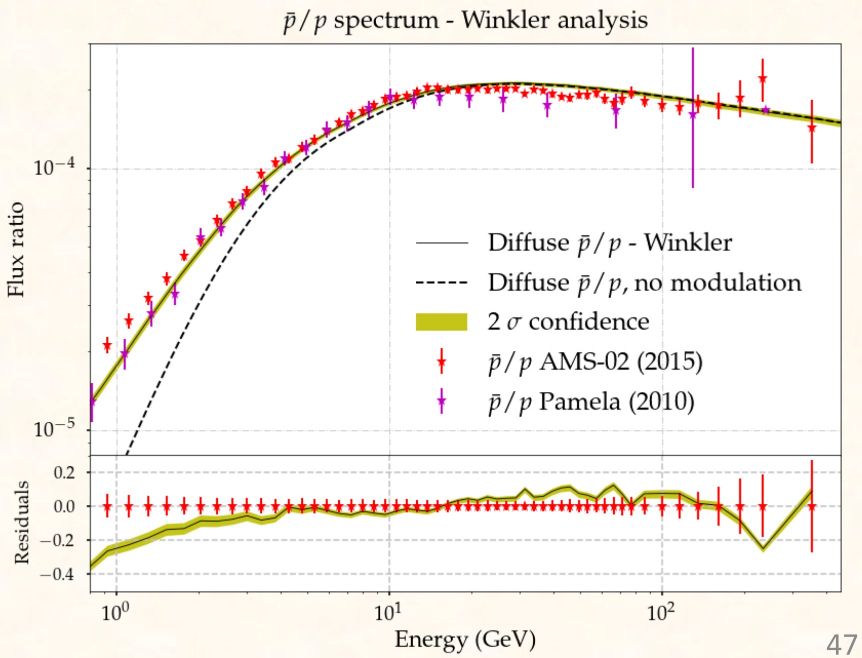
Zhao et al 2021 *arXiv*:2109.04112

It can offer an explanation for the dipole anisotropy

Systematics in AMS-02 data

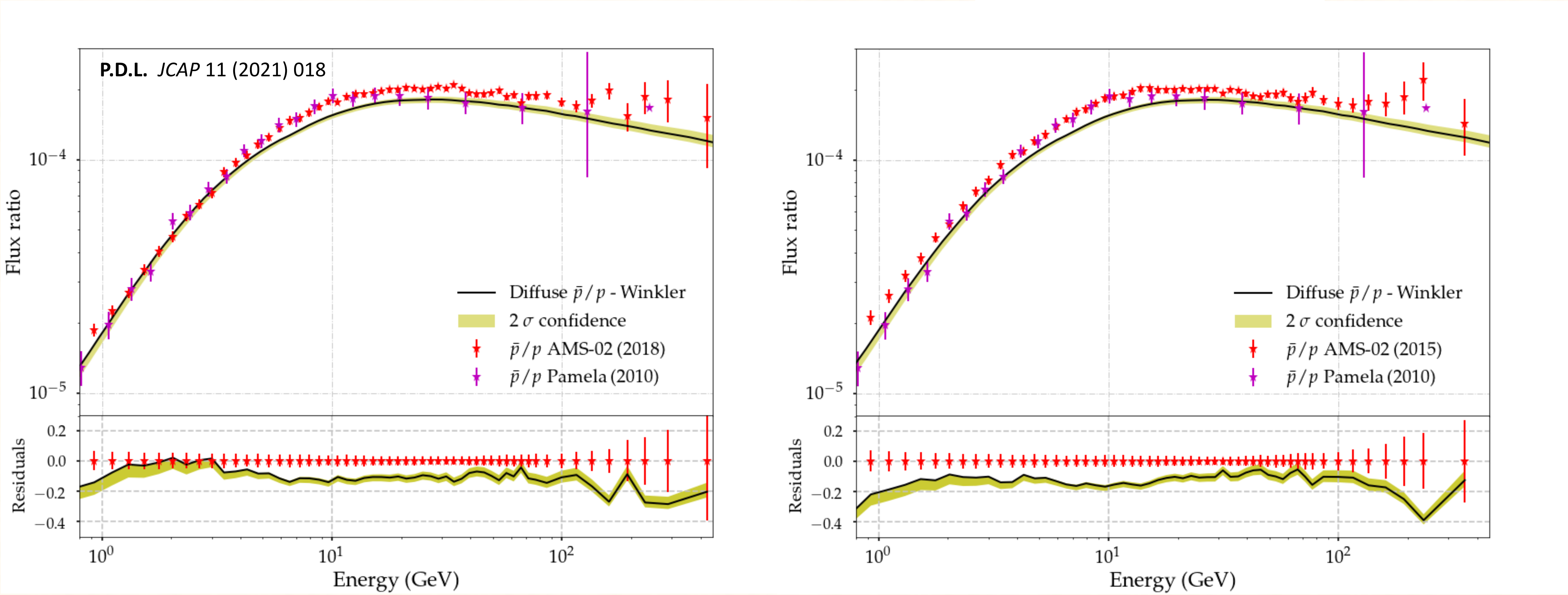






Systematics in AMS-02 data

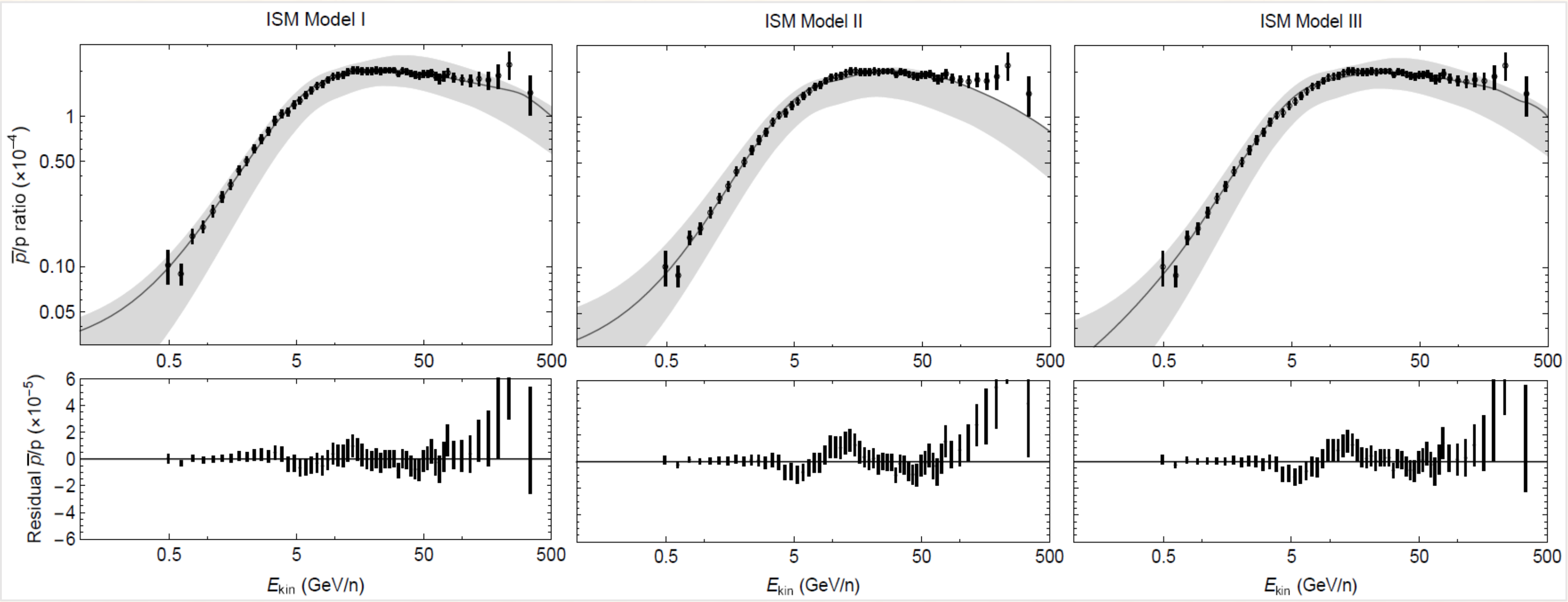
Including the correlation of AMS-02 systematic errors sizeably affects significance and properties of the DM signal → **Need of covariance matrices!**



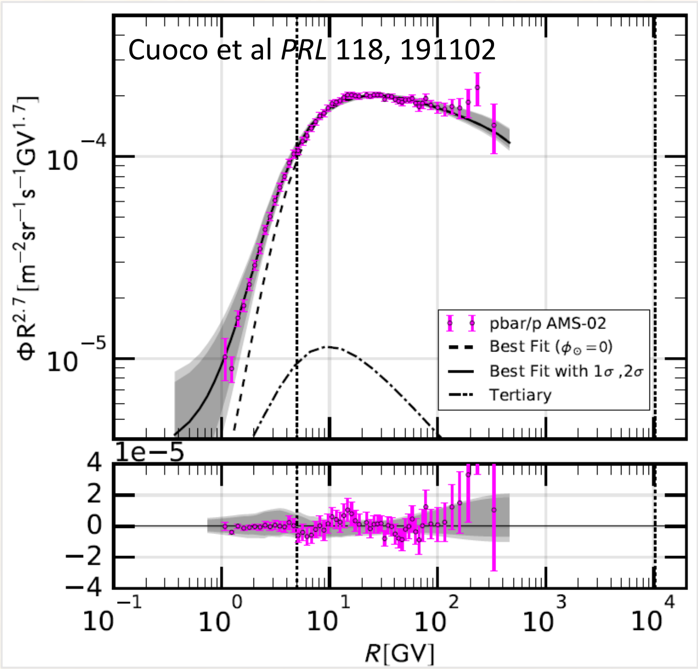
Precise studies of secondary CRs: ***The antiproton excesses***

I. Amount of grammage predicted by the flux-ratios of B, Be and Li underpredicts the antiproton flux by a 10-20%→ **Grammage tension**

II. 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



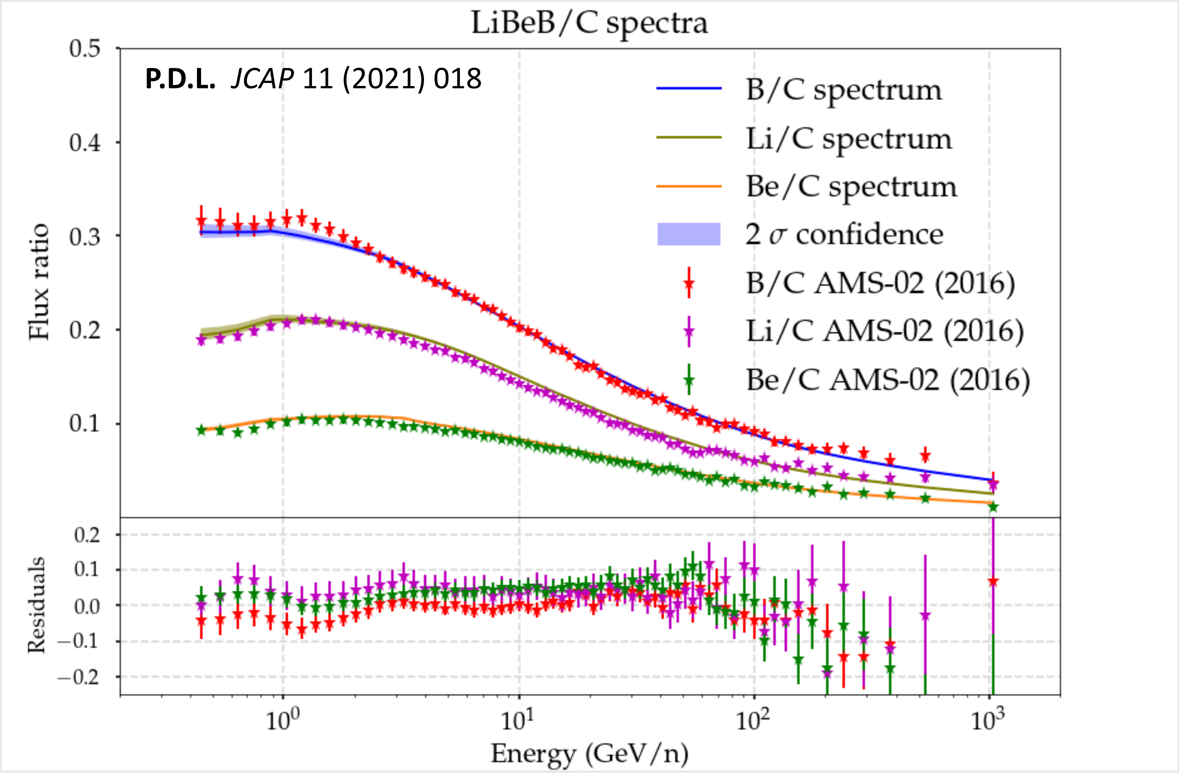
Cholis, Linden, Hooper *PRD* 99, 103026

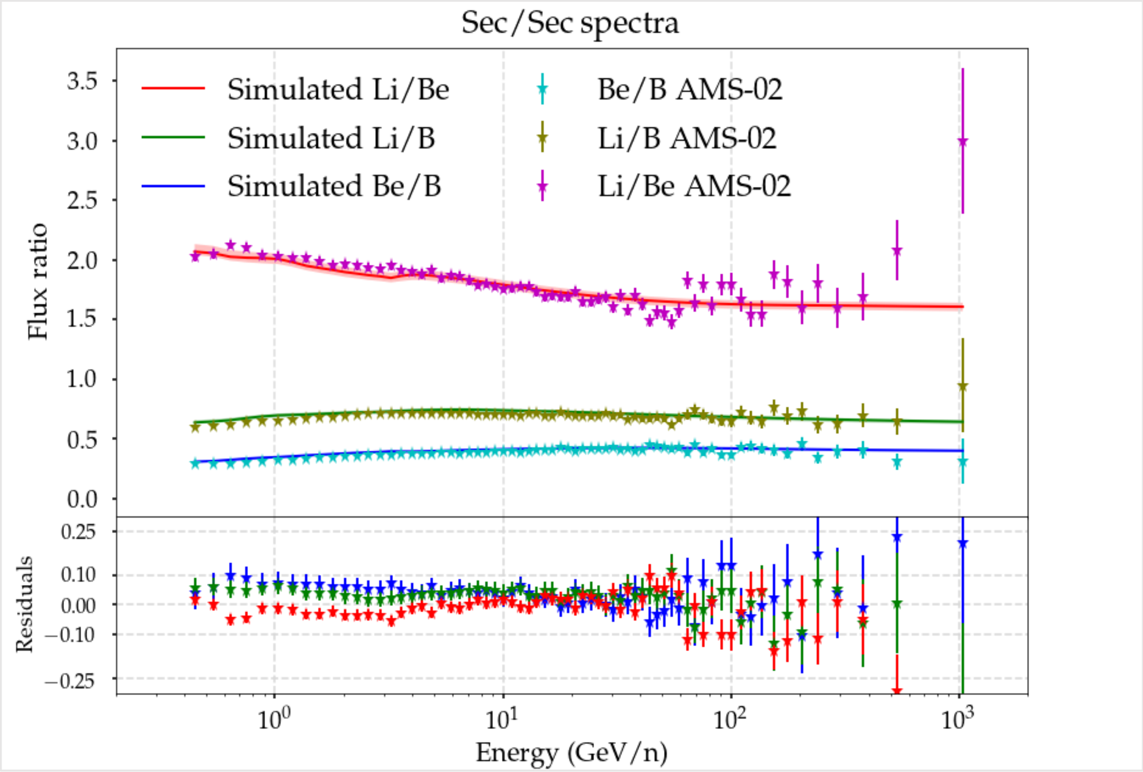


Precise studies of secondary CRs: *The antiproton excesses*

- *DRAGON2* cross sections for heavy secondary CRs
- *Winkler* (2017) cross sections for antiprotons

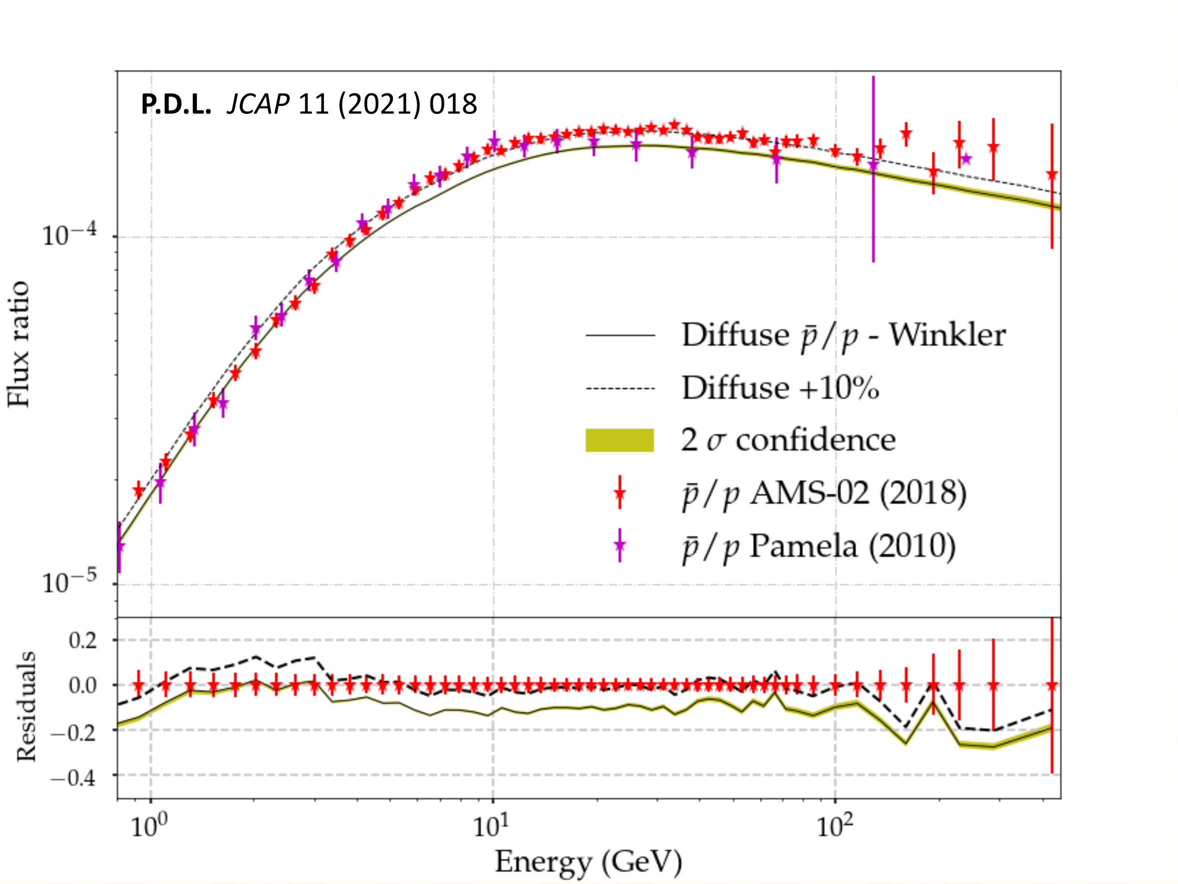
B/C, B/O, Be/C, Be/O, Ap/p (Propagation parameters)
^{10}Be/^{9}Be, ^{10}Be/Be (H), **Be/B, Li/B, Li/Be** (Scale factors, S_X)

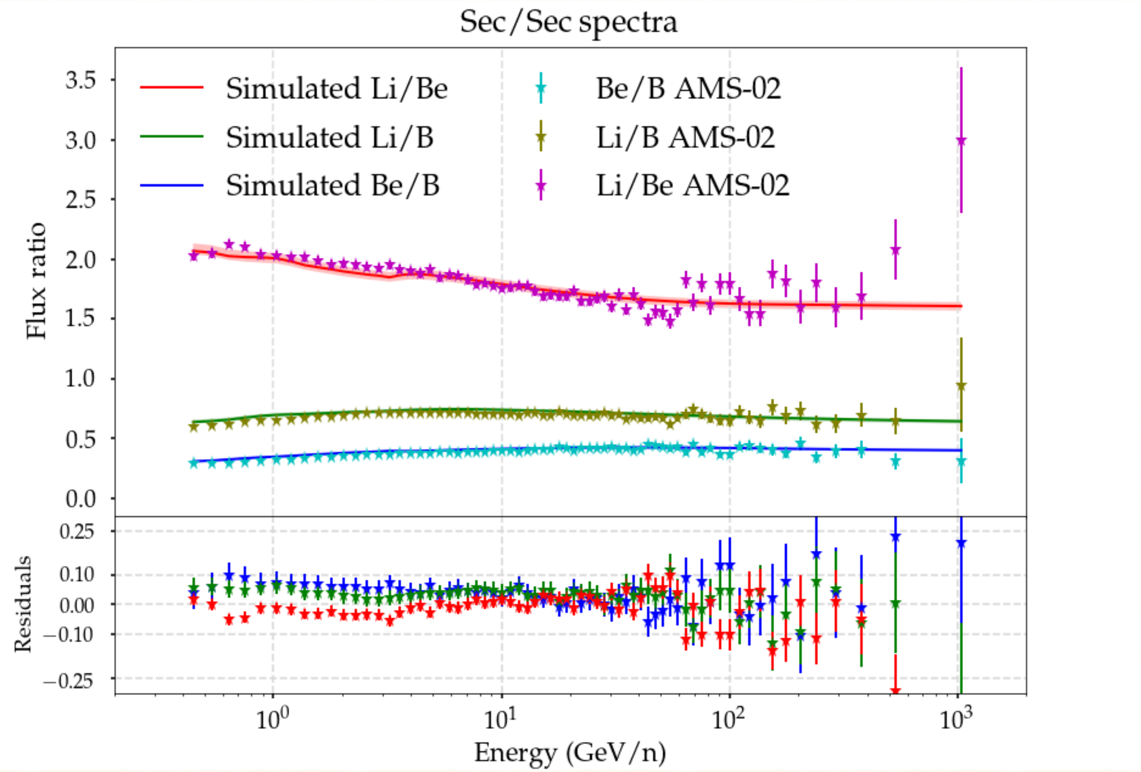




Precise studies of secondary CRs: The antiproton excesses

There is a set of propagation parameters that reproduce the energy dependence of the antiproton and the other secondary CRs (B, Be and Li) !!



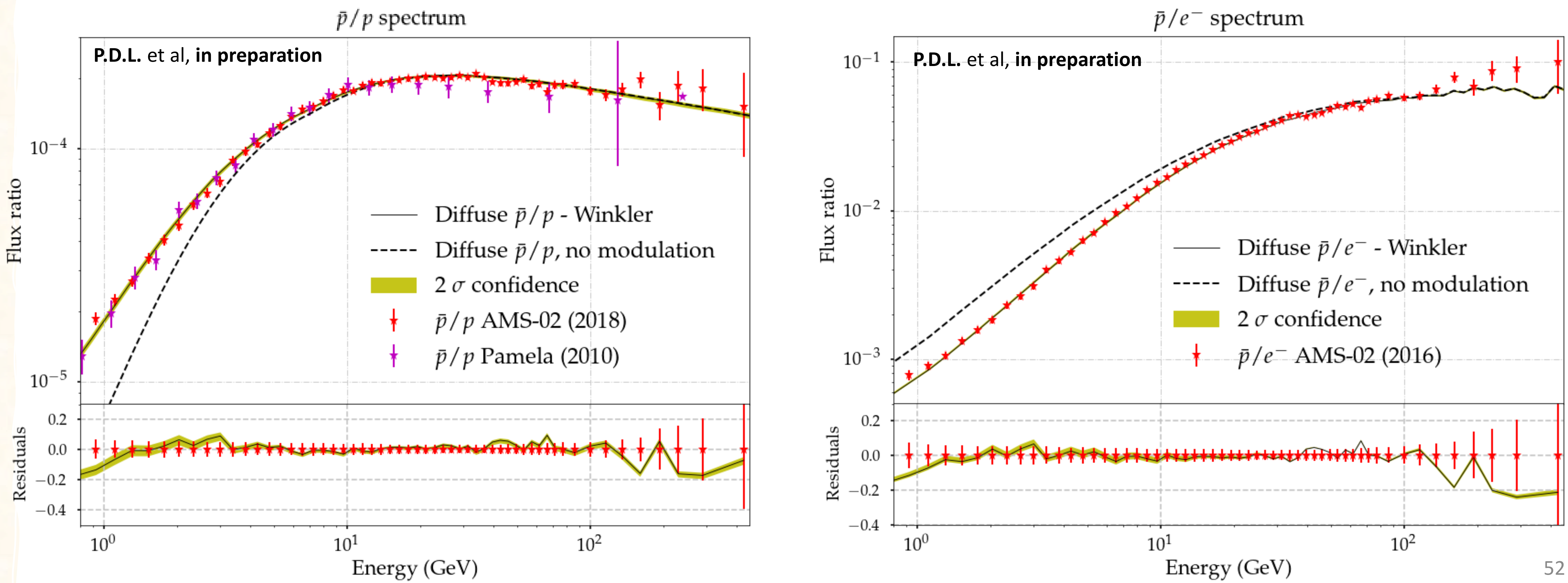


See also Heisig, Korsmeier, Winkler *PRD* 2, 043017 (2020)

Precise studies of secondary CRs: ***The antiproton excesses***

Prior constraints on antiproton cross sections are included in different ways: Dark matter component is still statistically preferred

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

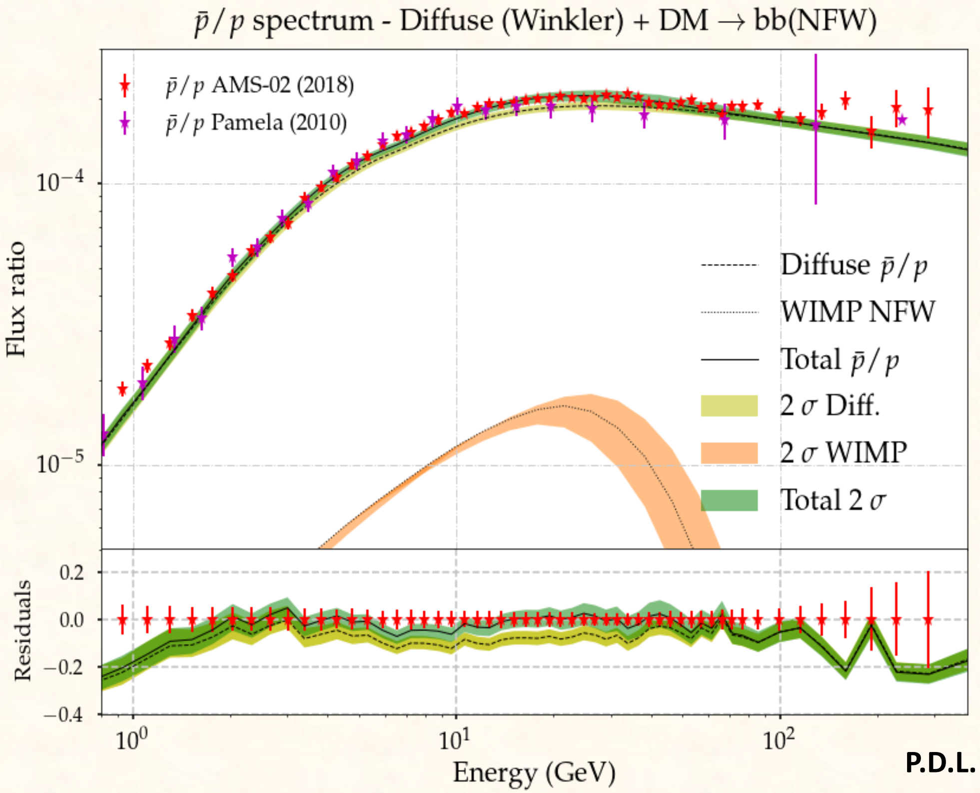


Precise studies of secondary CRs:* *The antiproton excesses

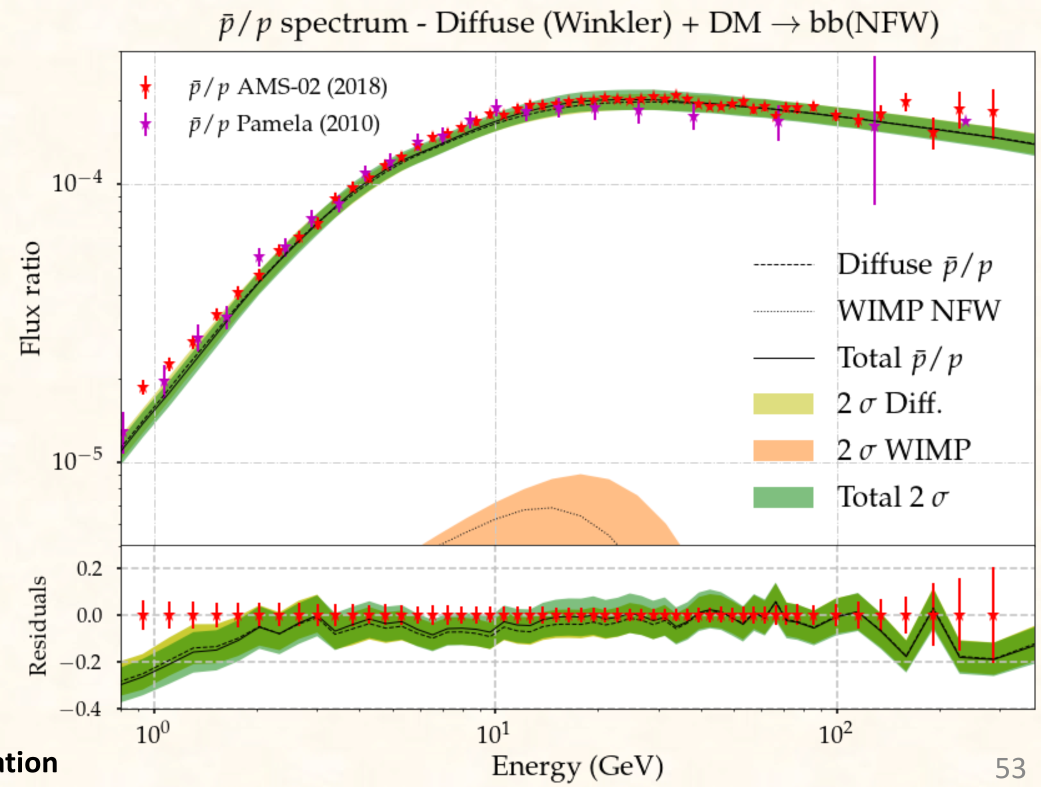
Two extreme cases:

Full XS constraints (Antiproton prior constraints ~ B prior constraints) **vs No prior constraints**

Full XS prior constrains Mχ ~ 160 GeV
<σv> ~ $7{\cdot}10^{26}$ cm^3/s



No XS prior constrains Mχ ~ 100 GeV
<σv> ~ $2{\cdot}10^{26}$ cm^3/s

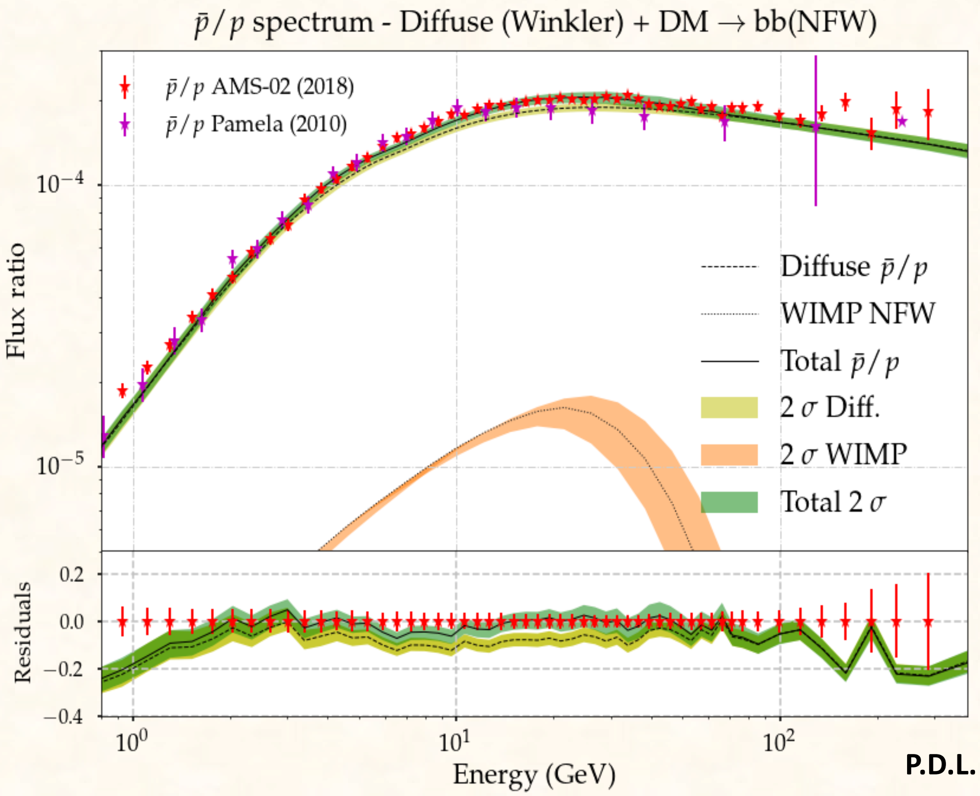


P.D.L. et al, **in preparation**

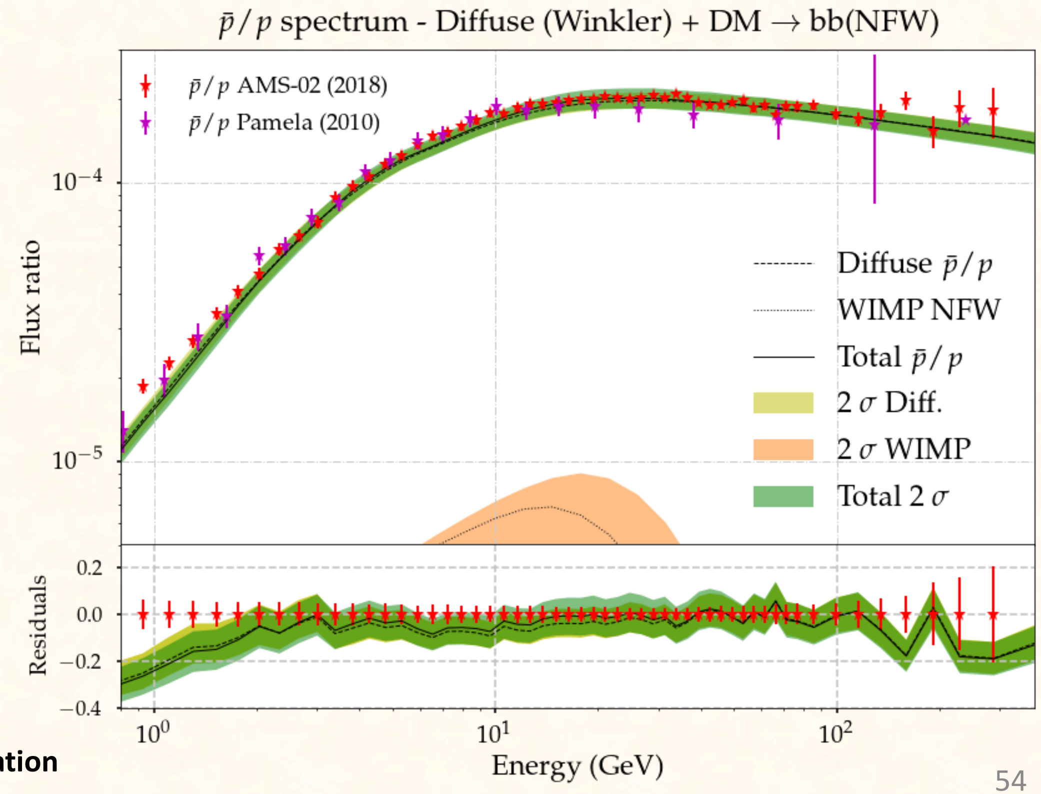
Antiproton *excess*

DM globally favoured. The way to asses the antiproton uncertainties affect the properties of the DM candidate reproducing the signal. Significance below 2σ

Full XS prior constrains $M\chi \sim 160$ GeV, $\langle \sigma v \rangle \sim 7 \cdot 10^{26}\ cm^3/s$



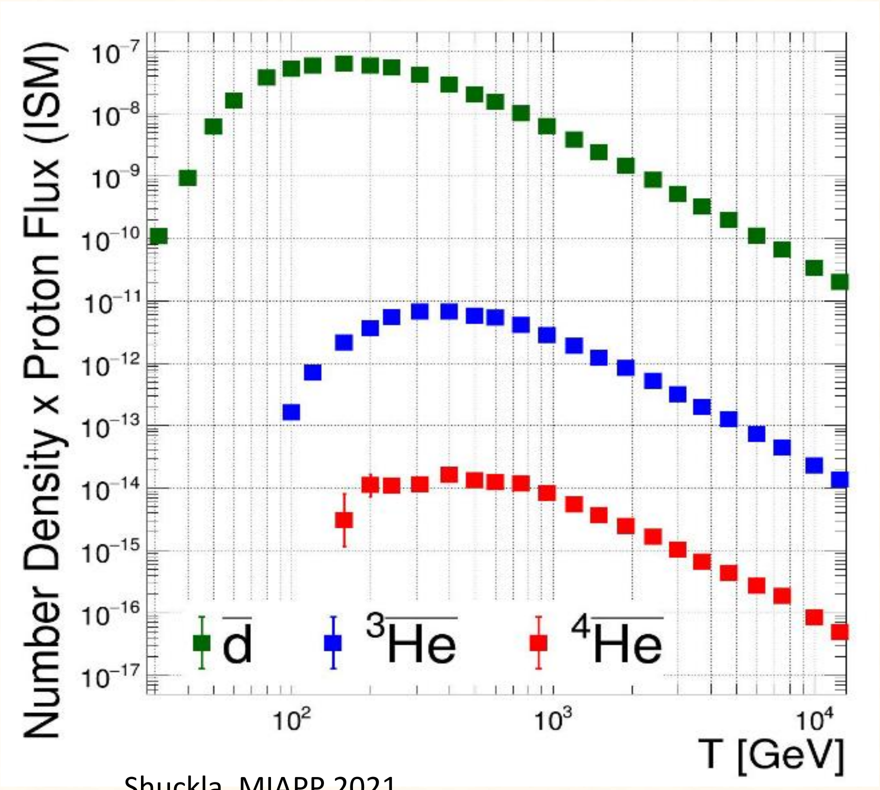
No XS prior constrains $M\chi \sim 100$ GeV, $\langle \sigma v \rangle \sim 2 \cdot 10^{26}\ cm^3/s$



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

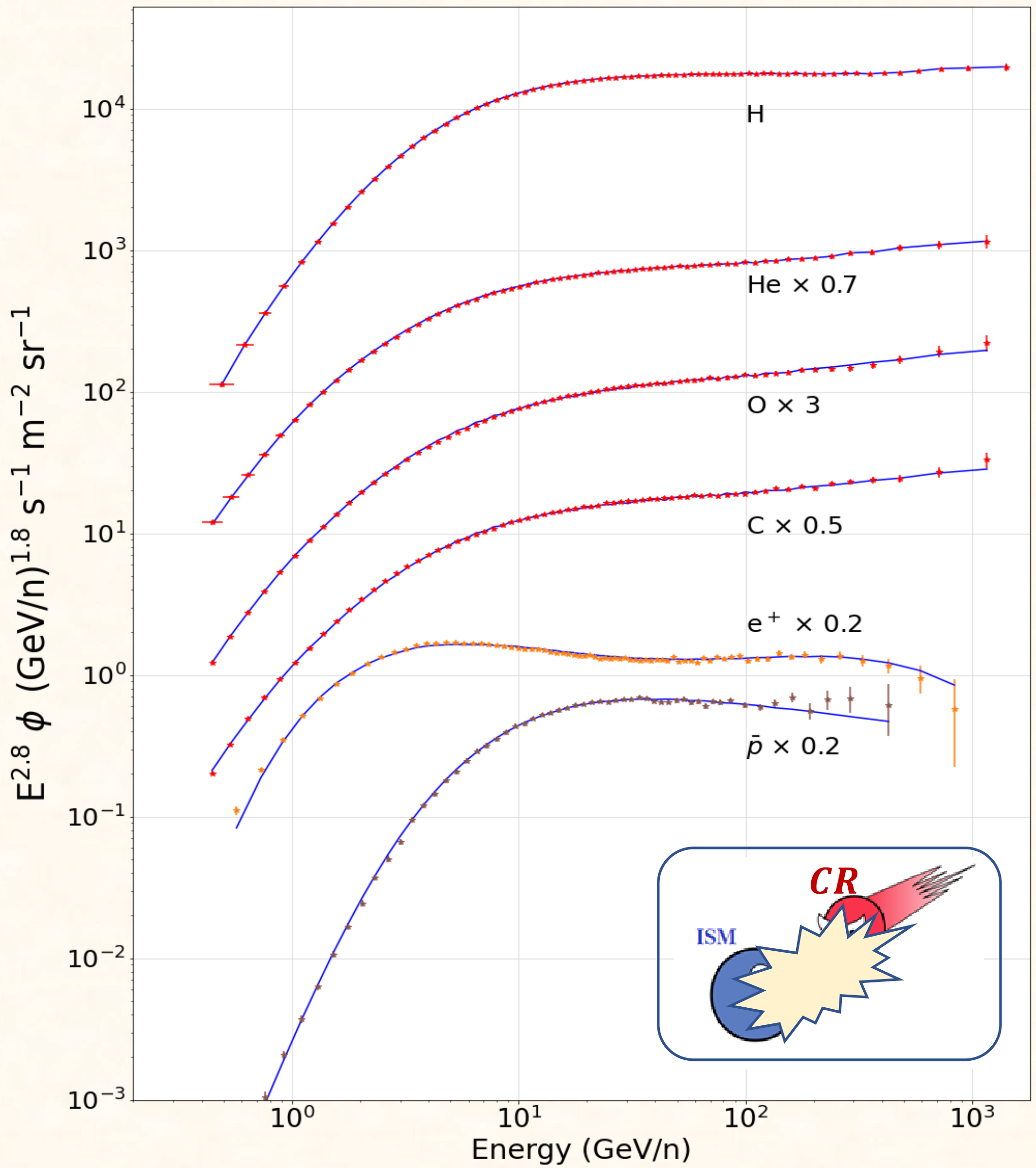
Potential of anti-nuclei to reveal the existence of BSM physics

P + p → p + p + p + ap + ap + an



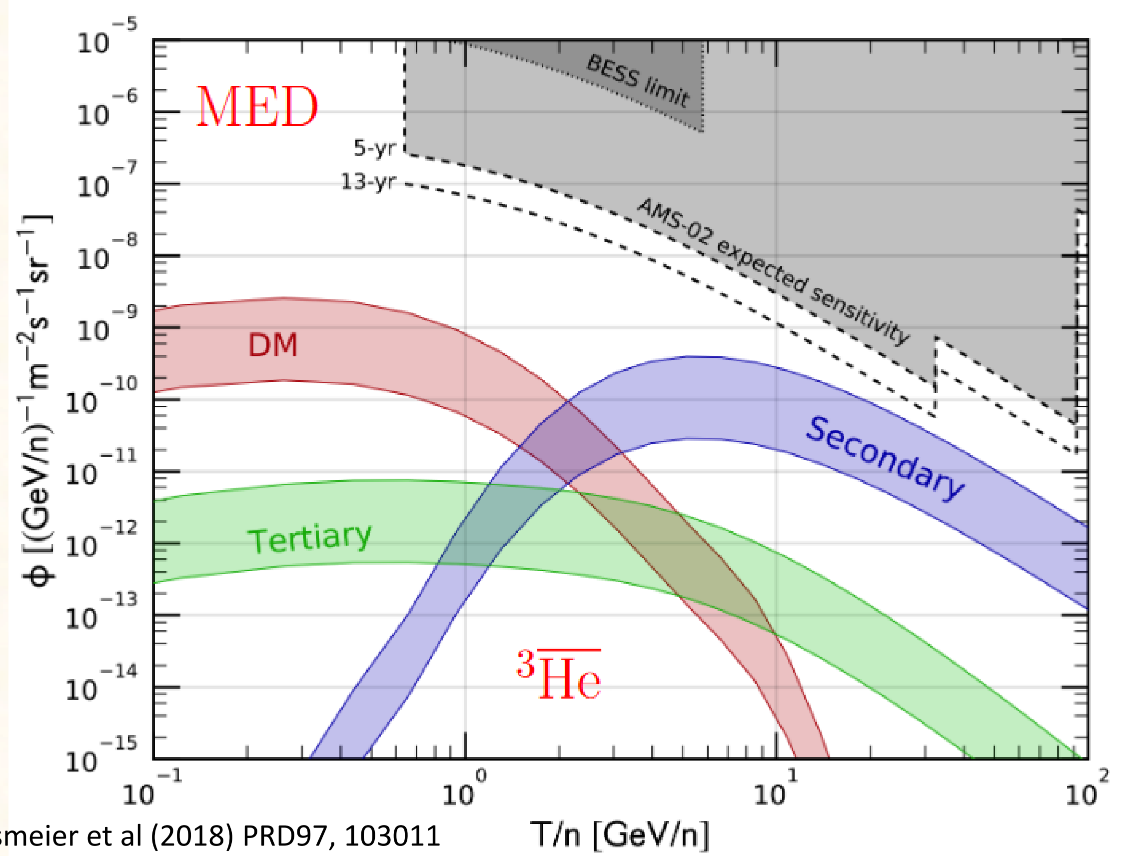
Shuckla, MIAPP 2021

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



Anti-nuclei as the dark matter smoking gun

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



Korsmeier et al (2018) PRD97, 103011

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

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