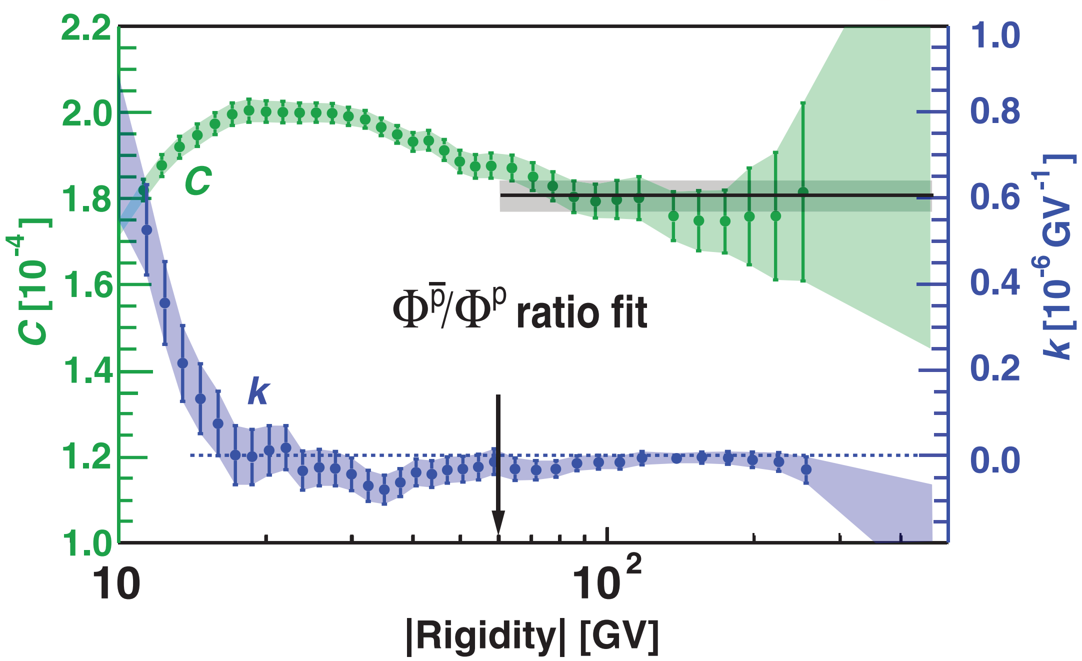
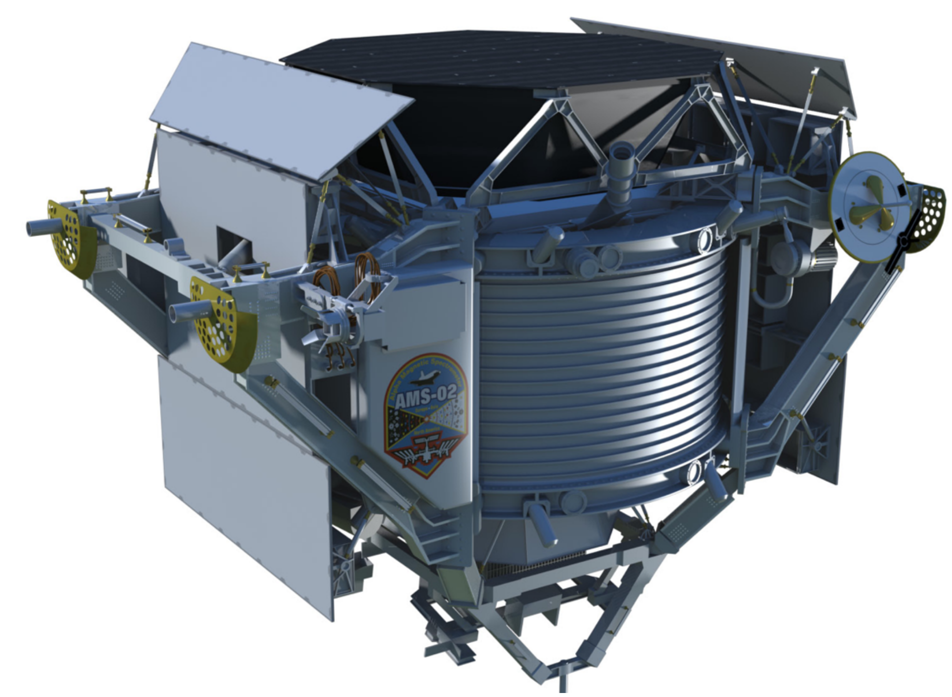
Antimatter Cosmic Ray Nuclei as a probe for Dark Matter





***IC**, Linden, Hooper, Phys. Rev. D 99, 103026 (2019)*

*Poulin, Salati, **IC**, Kamionkowski, Silk, Phys. Rev. D 99, 023016 (2019)*

***IC**, Linden, Hooper, Phys. Rev. D 102, 103019 (2020)*

***IC**, Hooper, Linden, JCAP 10, 51, (2022)*

***IC**, Rimal (in prep 2024)*

Ilias Cholis, 7/16/2024

The AMS-02 experiment on ISS

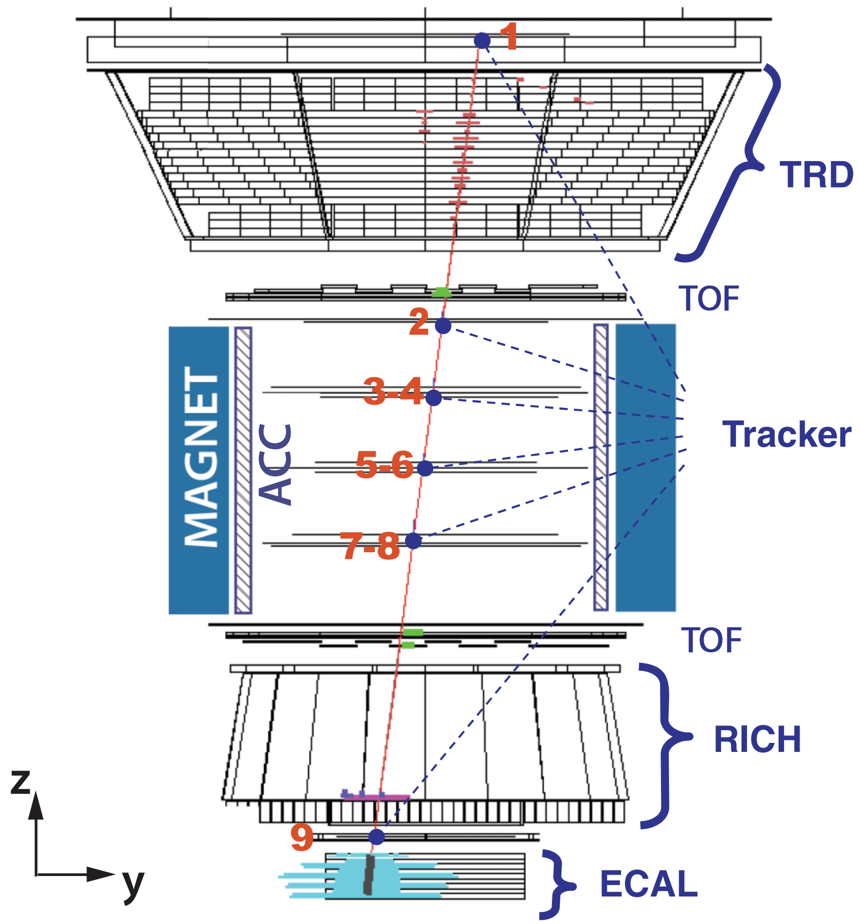
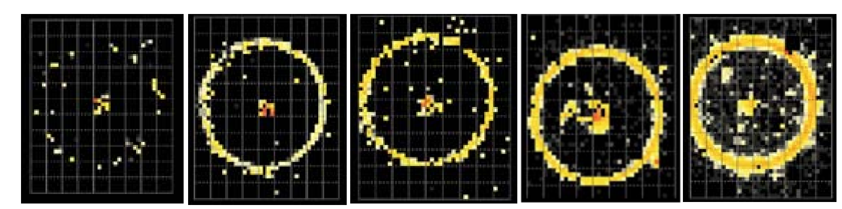
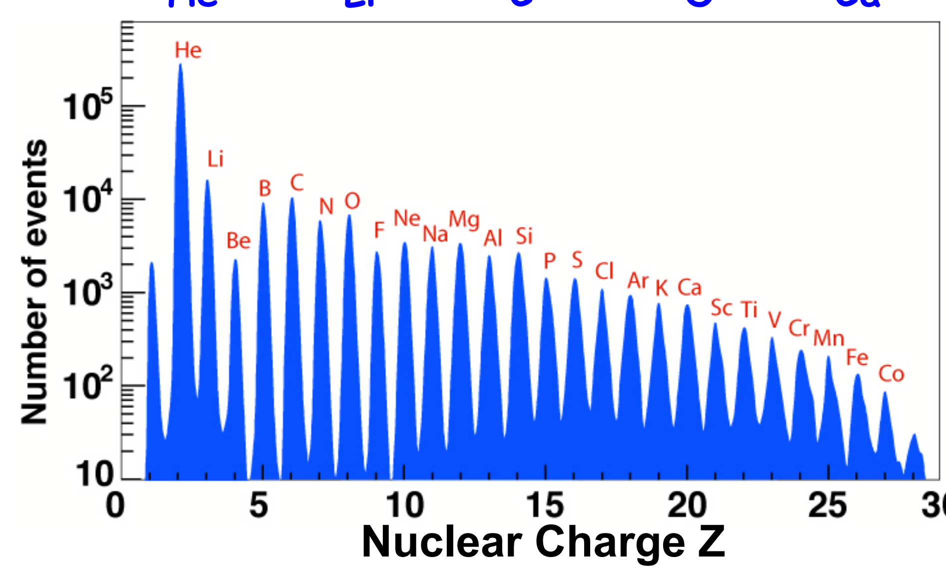


FIG. 1 (color). A 1.03 TeV electron event as measured by the AMS detector on the ISS in the bending (*y*-*z*) plane. Tracker planes 1–9 measure the particle charge and momentum. The TRD identifies the particle as an electron. The TOF measures the charge and ensures that the particle is downward-going. The RICH independently measures the charge and velocity. The ECAL measures the 3D shower profile, independently identifies the particle as an electron, and measures its energy. An electron is identified by (i) an electron signal in the TRD, (ii) an electron signal in the ECAL, and (iii) the matching of the ECAL shower energy and the momentum measured with the tracker and magnet.

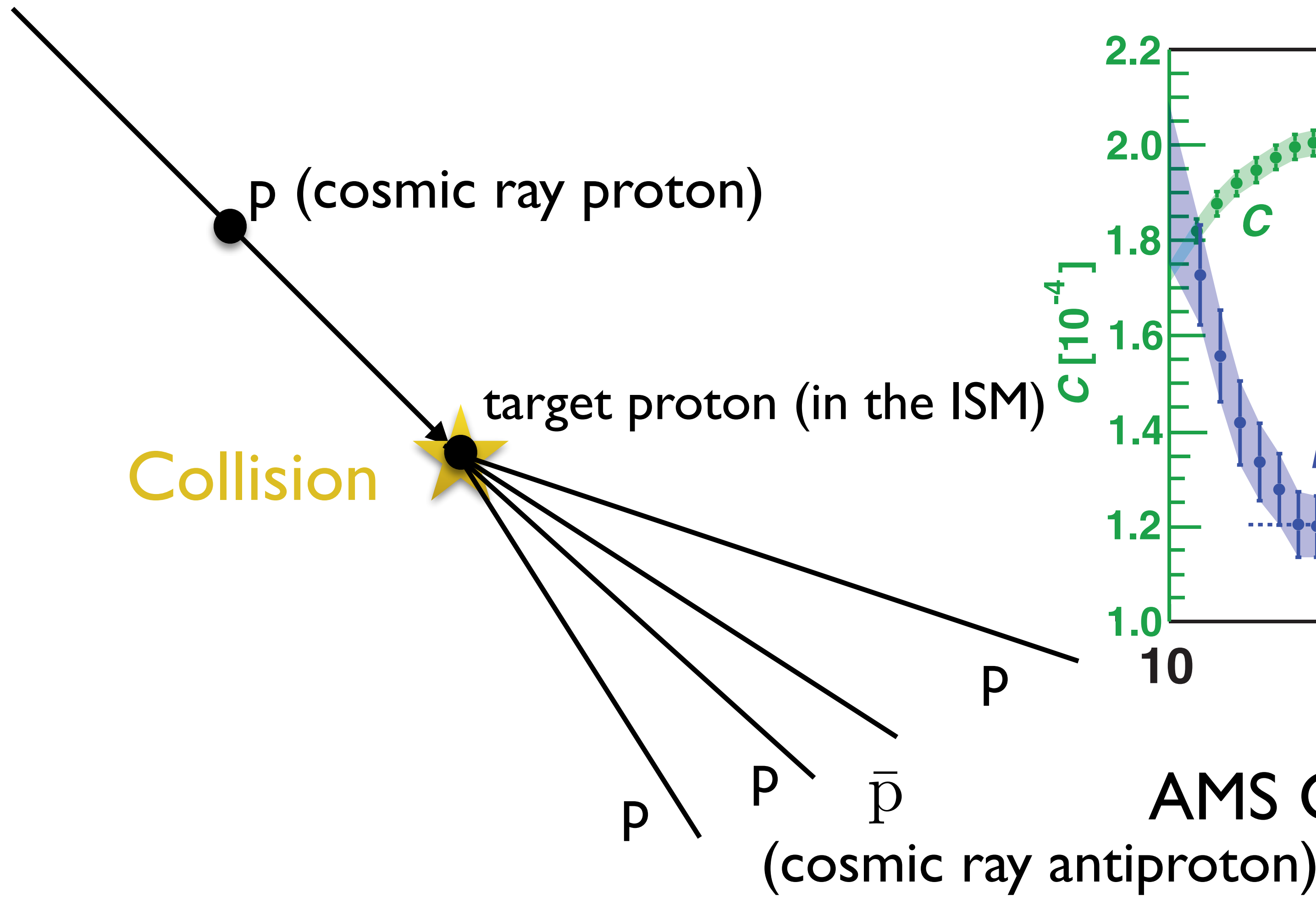
Lunched on May 2011, will collect data for 20 yrs.
Measuring all CR nuclei species up to Ni.

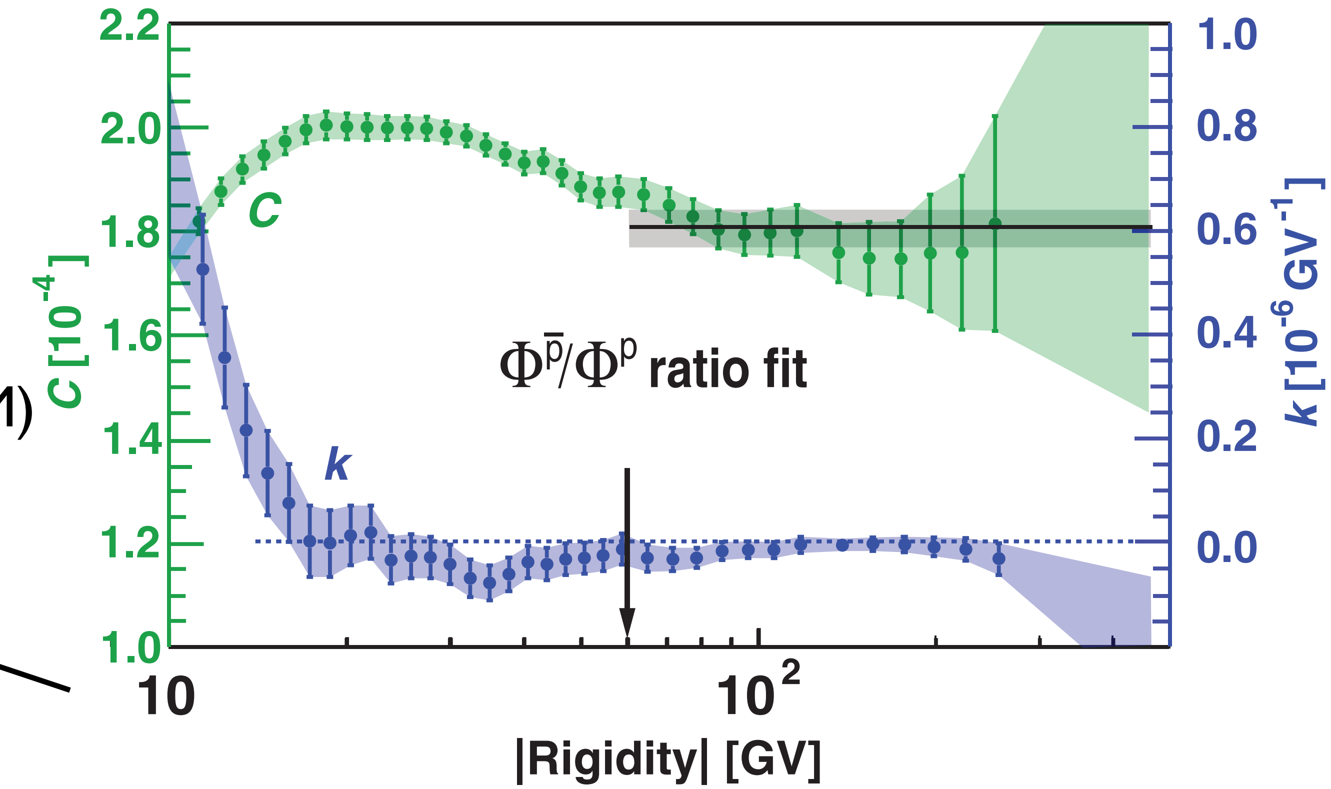
positron fraction,
positrons, electrons spectra,
antiproton/proton
anti-nuclei?
B/C, Be10/Be9



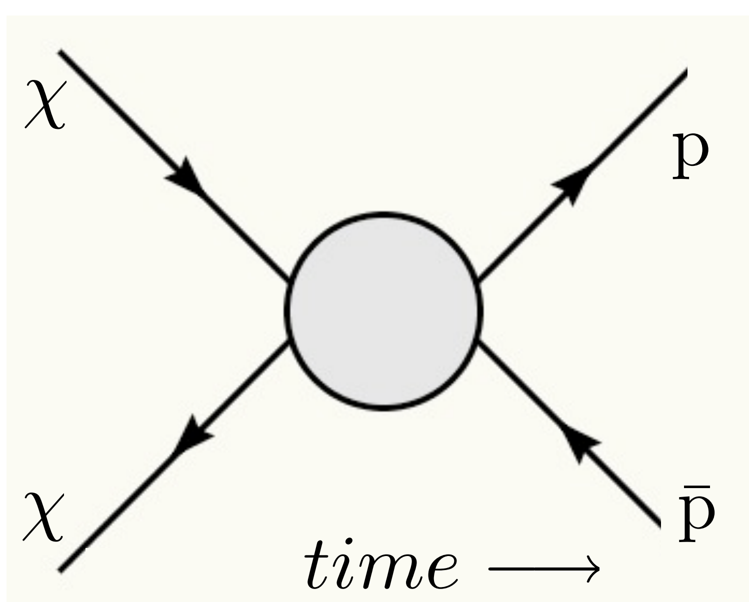


AMS-02 pbar/p ratio and Dark Matter





AMS Coll. PRL.117.091103 (2016)

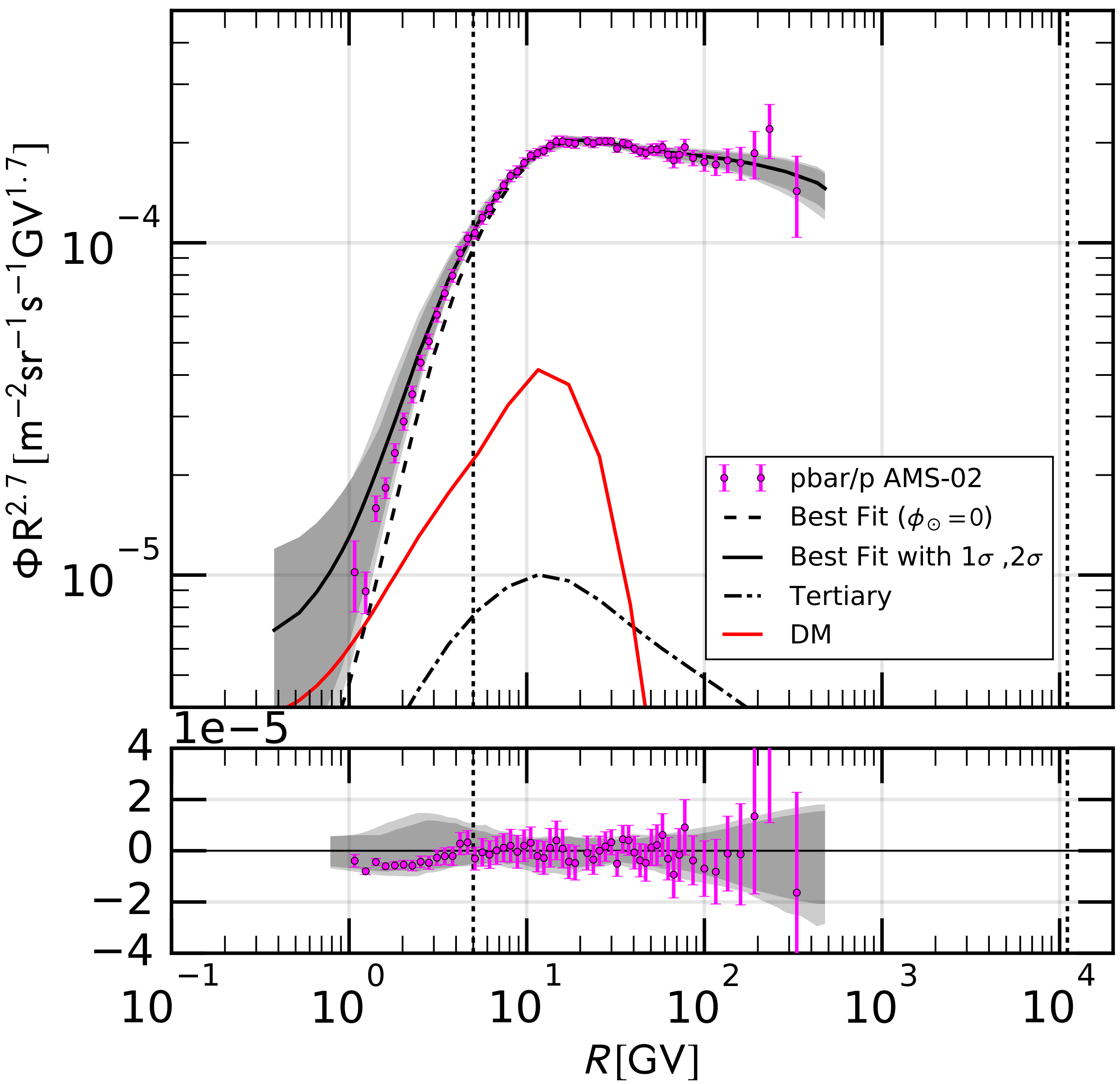


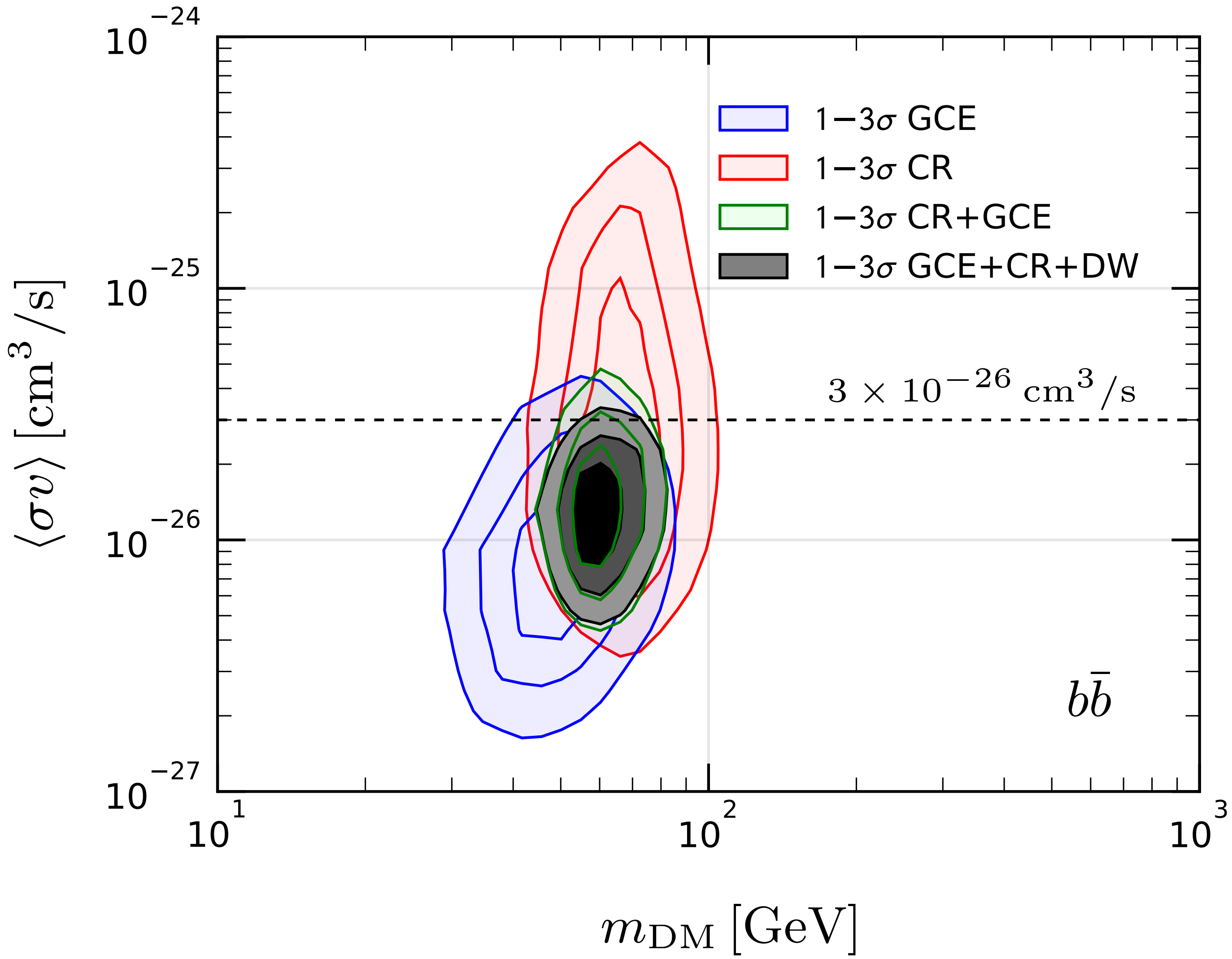
Could we have an additional contribution?

AMS-02 pbar/p ratio and Dark Matter (& Fermi Galactic Center excess?)

Early results/projections by :
Bringmann et al. 2014, Cirelli et al. 2014, Hooper, Linden, Mertsch JCAP 2015

Cuoco, Kramer, Korsmeier PRL 2017:





See also, Cui, Yang, Tsai & Fan, PRL 2017:

What about the Antiproton to Proton Ratio Uncertainties?

Antiprotons background uncertainties are significant.

They are associated with:

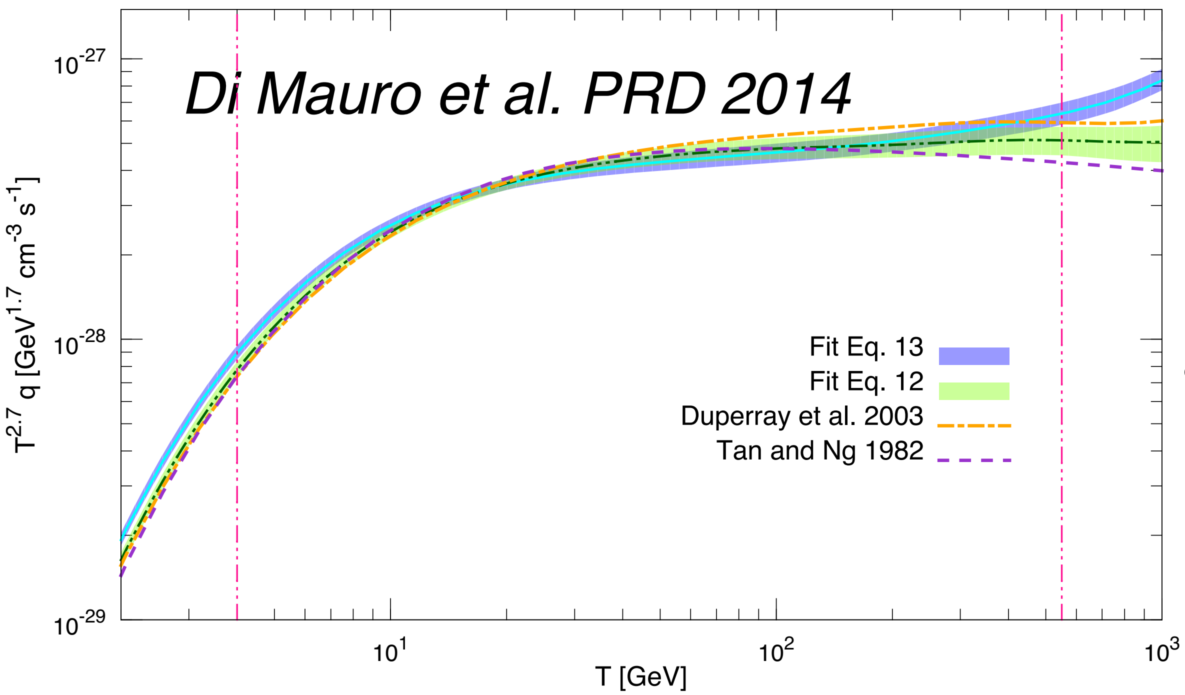
i) the antiproton production cross-section from CR protons and heavier nuclei collisions with the ISM gas

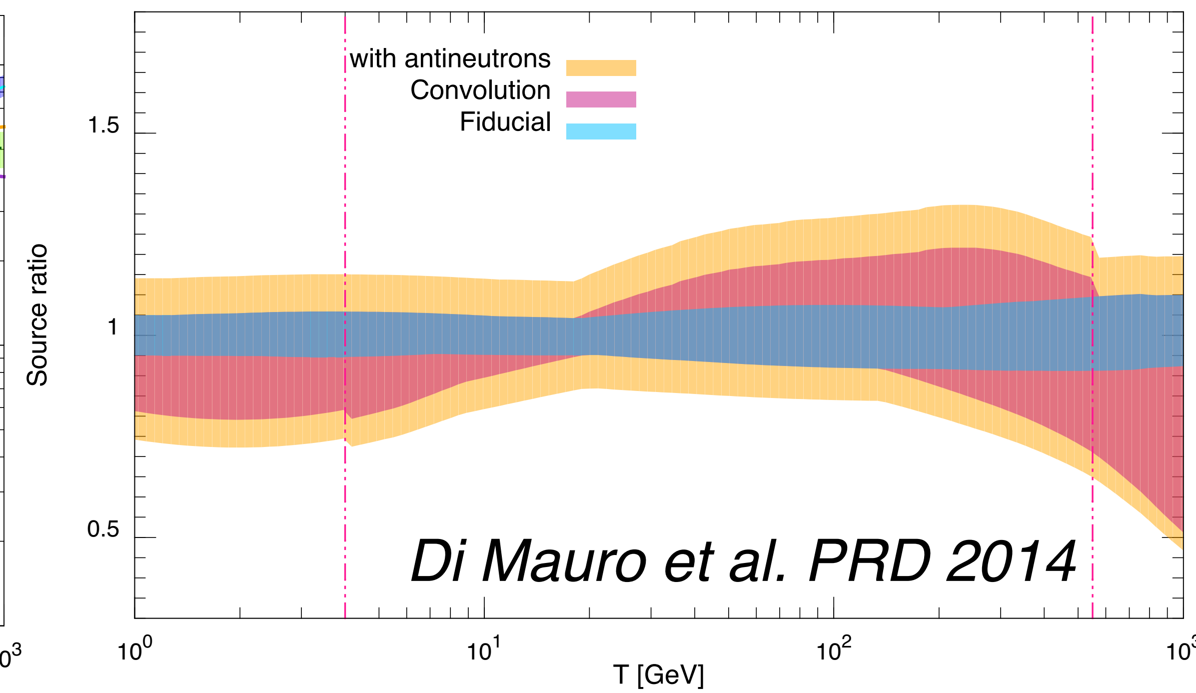
ii) the propagation of CRs through the ISM

iii) Solar Modulation (the propagation of CRs through the Heliosphere)

I) Antiproton production cross-section uncertainties

There are significant uncertainties on the antiproton production cross-section directly from p-p collisions. Most parametrizations have only used data from the 70s.





Also one has to include the production of antiprotons from collisions with heavier nuclei (mainly He), which can contribute ~40% more antiprotons than the p-p collisions alone. In addition the contribution from antineutrons produced first at p-p collisions must be modeled.

FIG. 8. Estimate of the uncertainties in the antiproton source term from inelastic pp scattering. The blue band indicates the 3σ uncertainty band due to the global fit with Eq.(13), while the red band corresponds to the convolution of the uncertainties brought by fits to the data with Eq.(13), Eq.(12) and with the spline interpolation (see Fig.6.). The orange band takes into account the contribution from decays of antineutrons produced in the same reactions. Vertical bands as in Fig.6. See text for details.

See also results from Kappl & Winkler JCAP 2014

II) Accounting for ISM galactic propagation uncertainties for Cosmic Rays

sources · *diffusion*

$$\frac{\partial \psi(r,p,t)}{\partial t} = q(r,p,t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi)$$

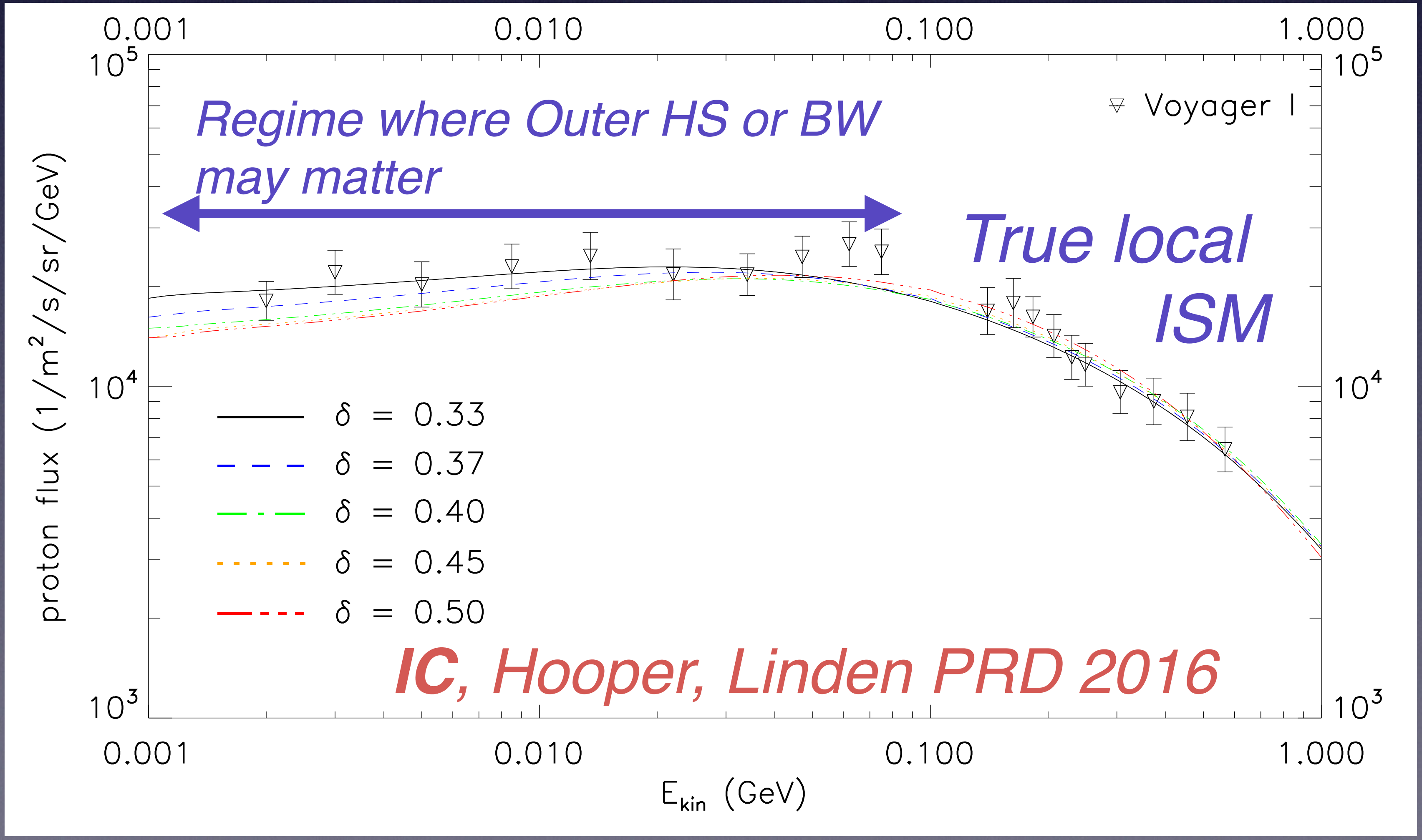
$$+ \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}(\frac{\psi}{p^2})\right] + \frac{\partial}{\partial p}\left[\frac{p}{3}(\vec{\nabla} \cdot \vec{V})\psi\right]$$

re-acceleration · *convection*

II) Accounting for ISM galactic propagation uncertainties for Cosmic Rays

$$\frac{\partial \psi(r,p,t)}{\partial t} = \underbrace{q(r,p,t)}_{\text{sources}} + \underbrace{\vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi)}_{\text{diffusion}} + \underbrace{\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{\psi}{p^2}\right)\right]}_{\text{re-acceleration}} + \underbrace{\frac{\partial}{\partial p}\left[\frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right]}_{\text{convection}}$$

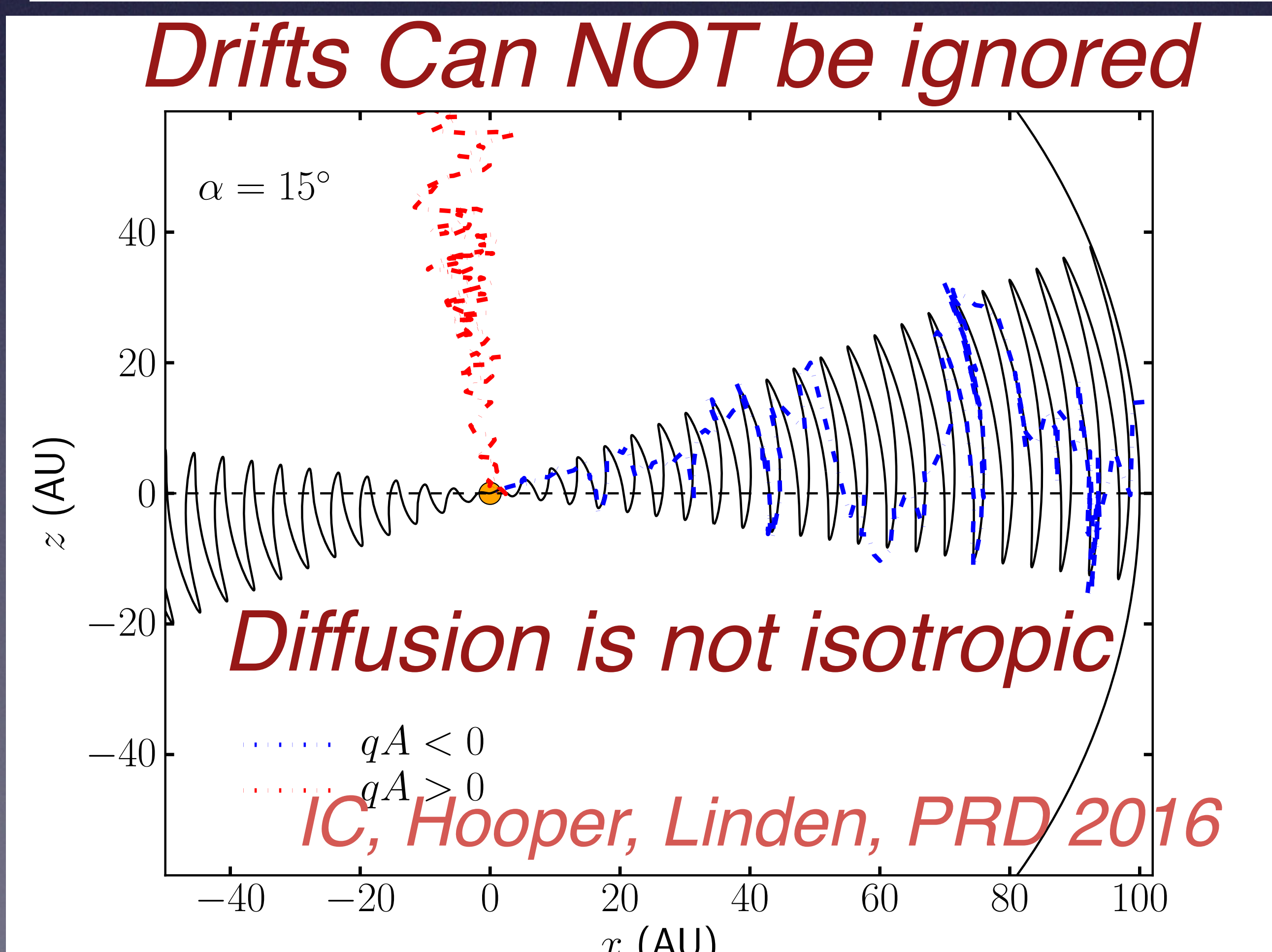
Voyager 1 (ISM) proton flux:

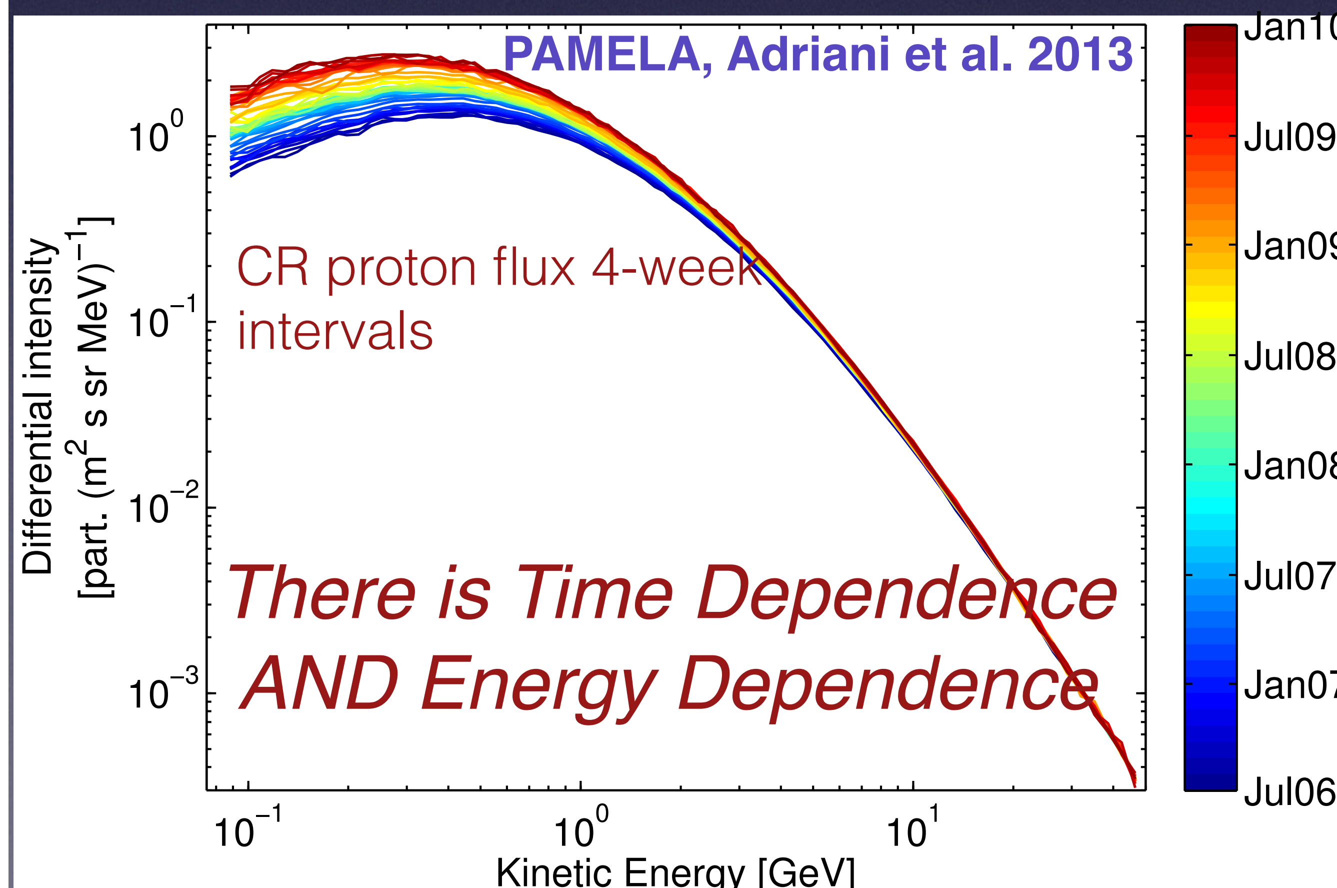


We use GALPROP a numerical solver build by Moskalenko, Strong et al. as a starting point and build several models that are in agreement with CR measurements

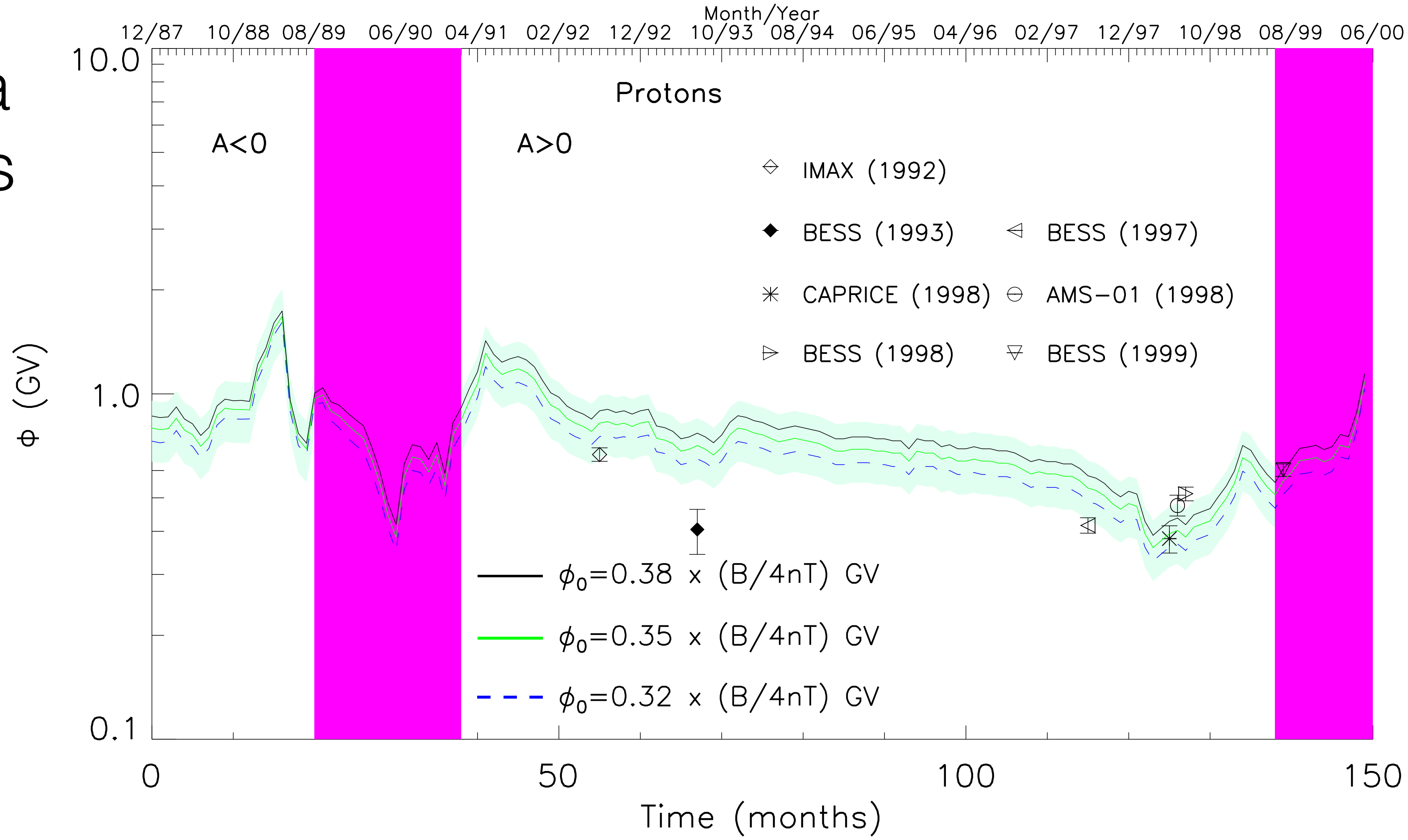
III) Dealing with Solar Modulation Uncertainties

Figure 7. Three-dimensional spatial representation of the particle trajectories shown in Figure 1. Two representative particle trajectories (black and gray lines) are shown for the $A > 0$ (left panel) and $A < 0$ (right panel) HMF polarity cycles. In the $A < 0$ cycle, the pseudo-particles (galactic electrons) are transported mainly toward higher latitudes, while in the $A > 0$ cycle, the particles remain confined to low latitudes and drift outward mainly along the HCS. This illustration is consistent with the results of galactic electrons shown in the previous figure.



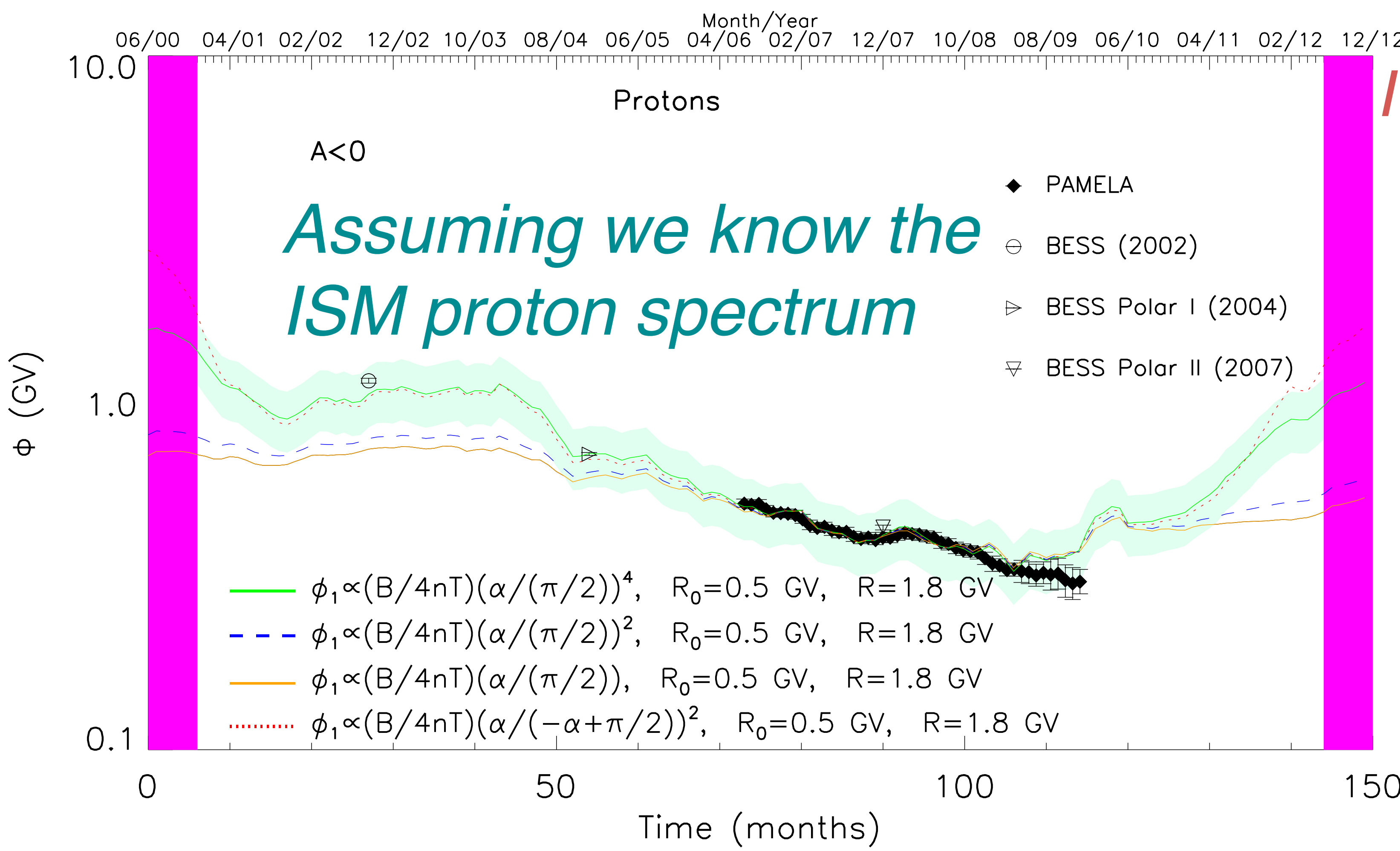


Let the CR archival Data tell us how the CR fluxes have been modulated:



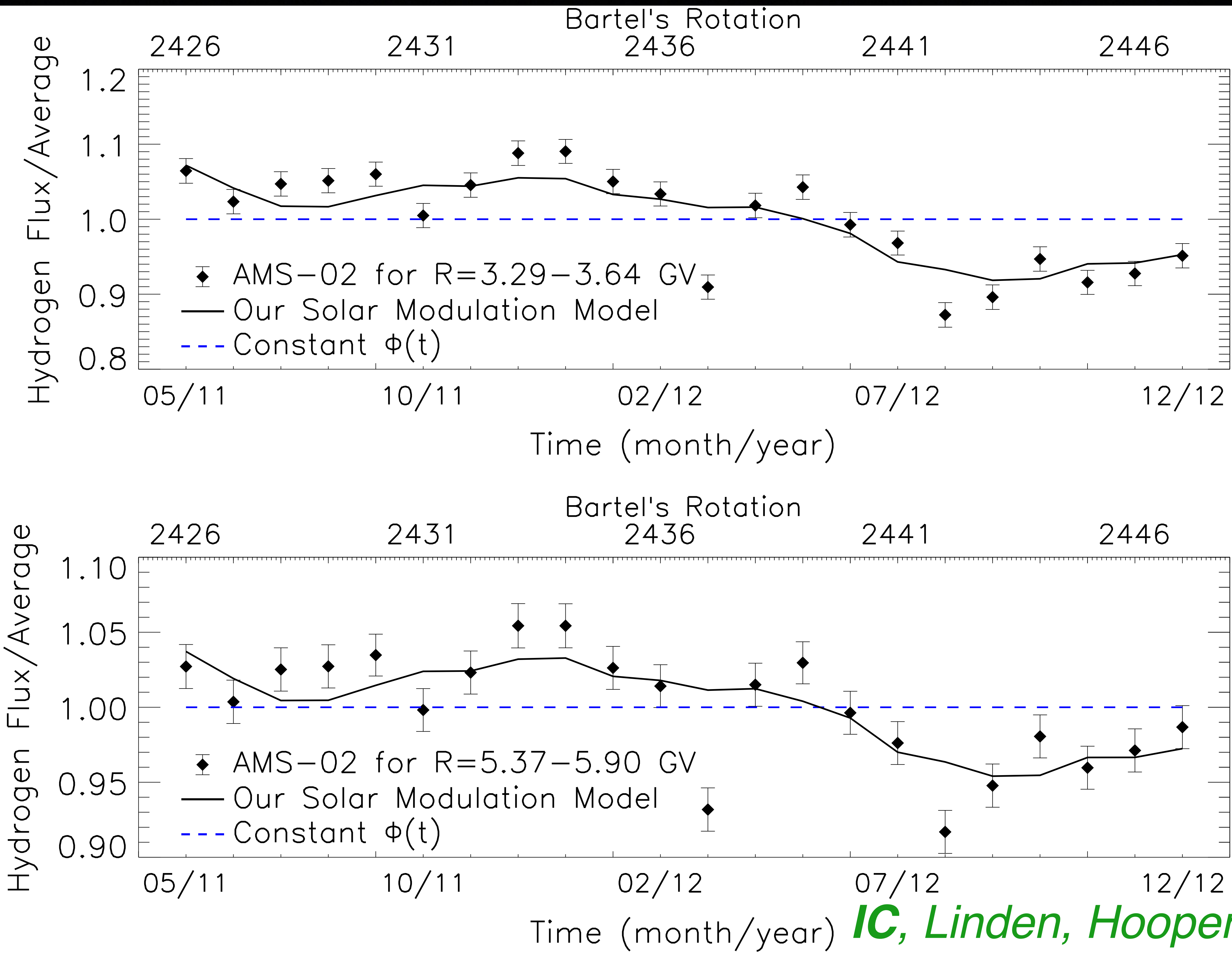
Constraining the qA>0 era:

Constraining the qA<0 era:



IC, Hooper, Linden, PRD 2016

Cross-checking with the PROTON data that account for the majority of observed cosmic rays; monthly AND total (i.e ISM & Solar Modulation):

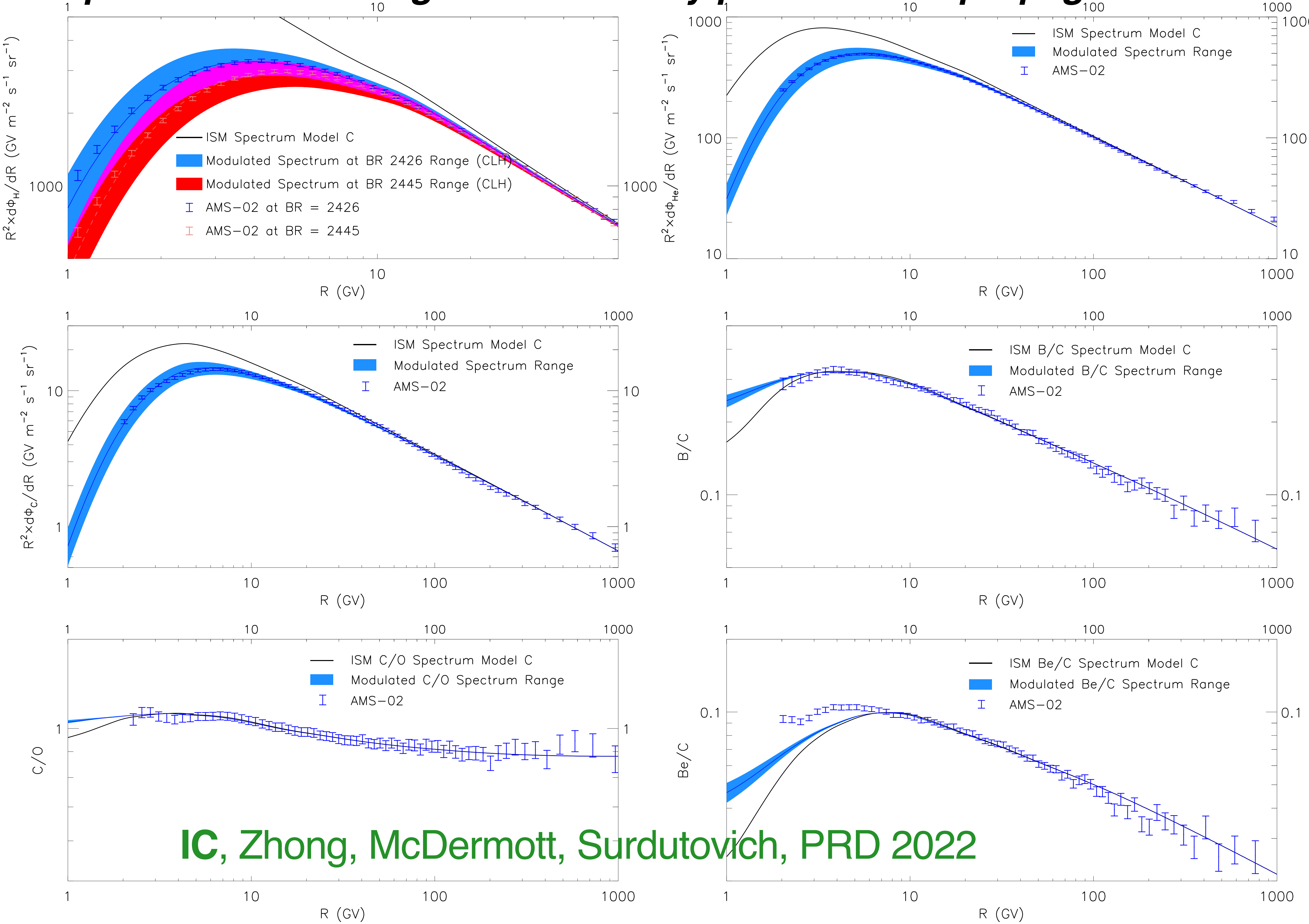


***IC**, Linden, Hooper JCAP 2022*

Constraining the form of the Modulation potential and the ISM p spectrum in a recursive manner.

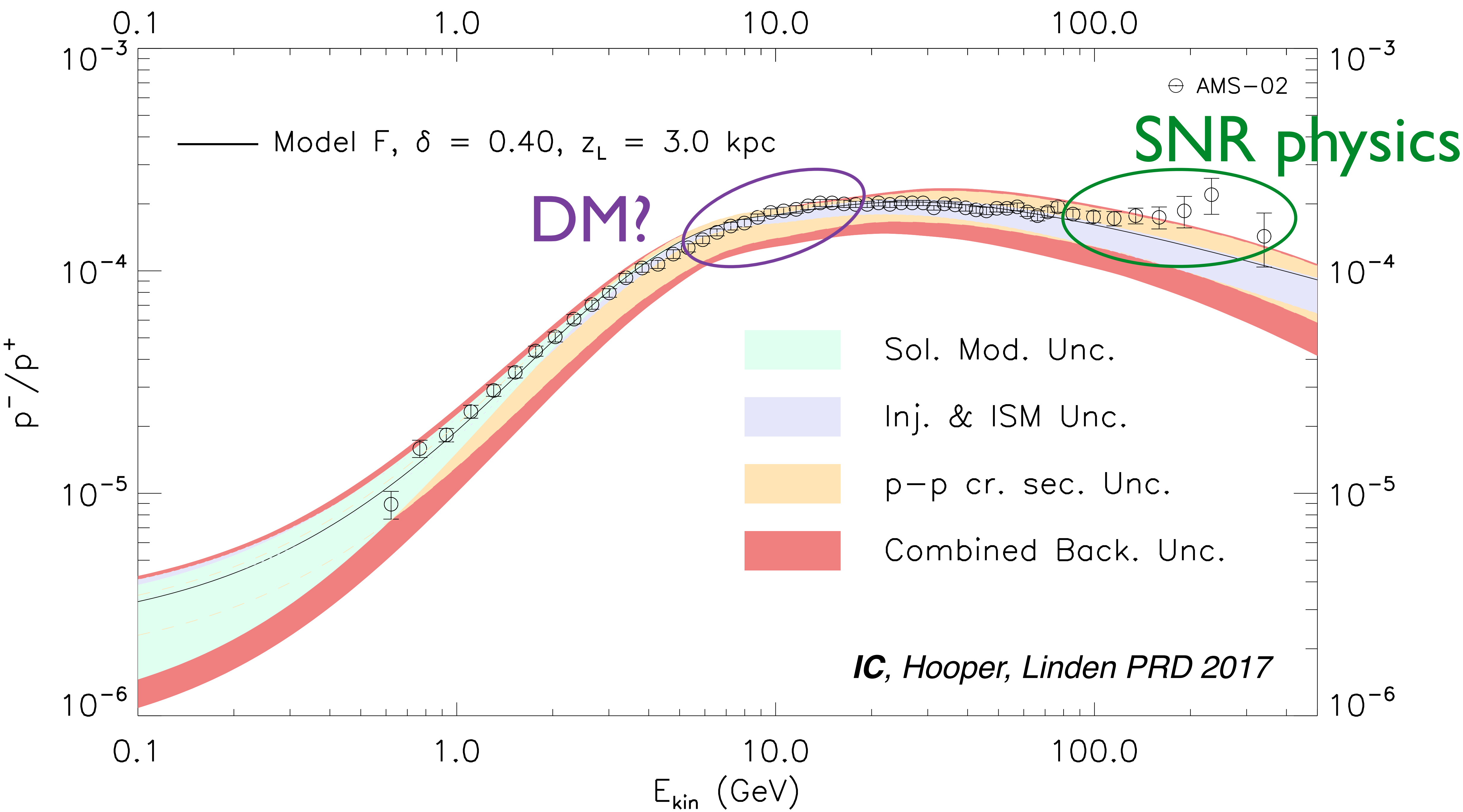
*Also **IC**, McKinnon PRD **106**, 063021 2022*

Repeating for multiple Cosmic-Ray species we can constrain the physical processes affecting the cosmic-ray production & propagation

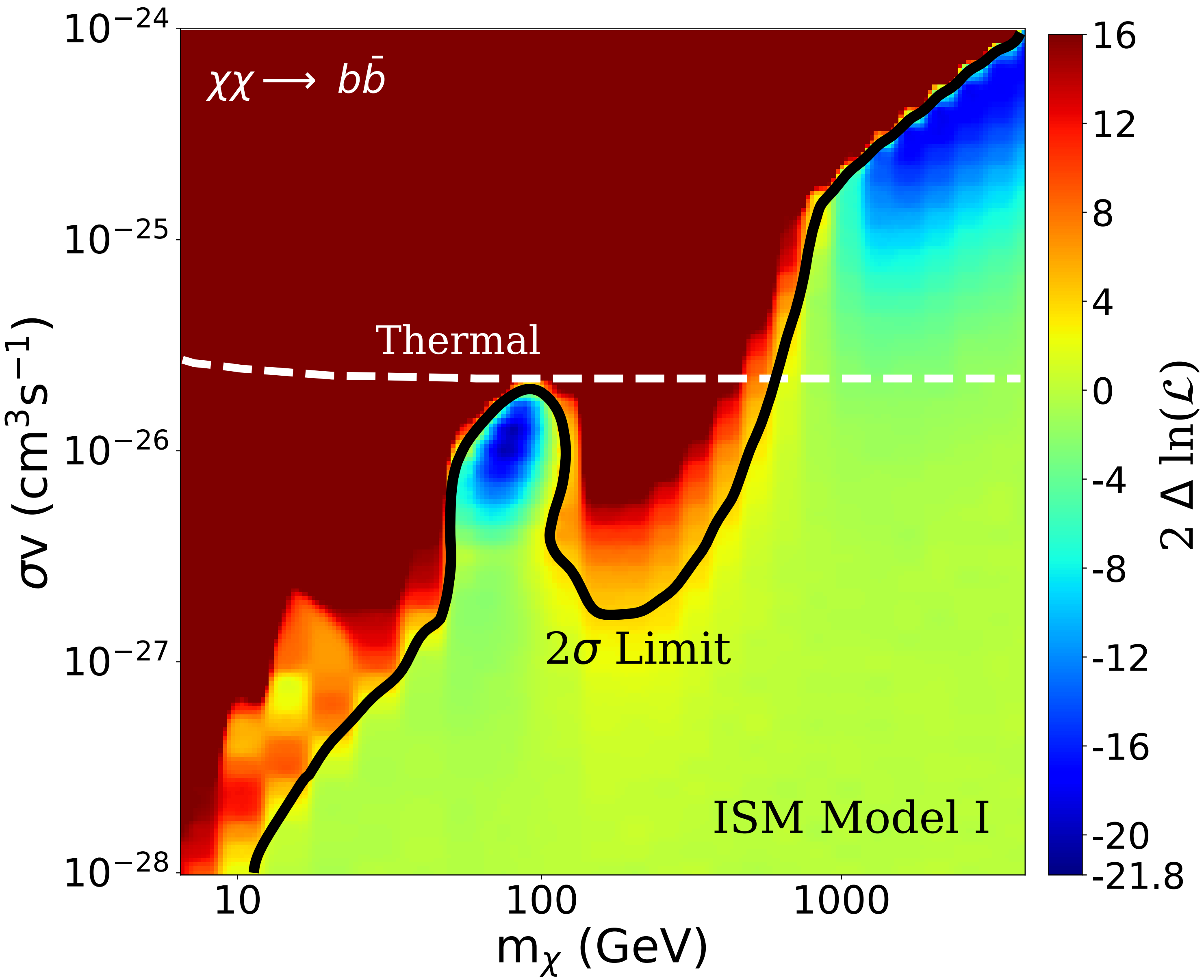


IC, Zhong, McDermott, Surdutovich, PRD 2022

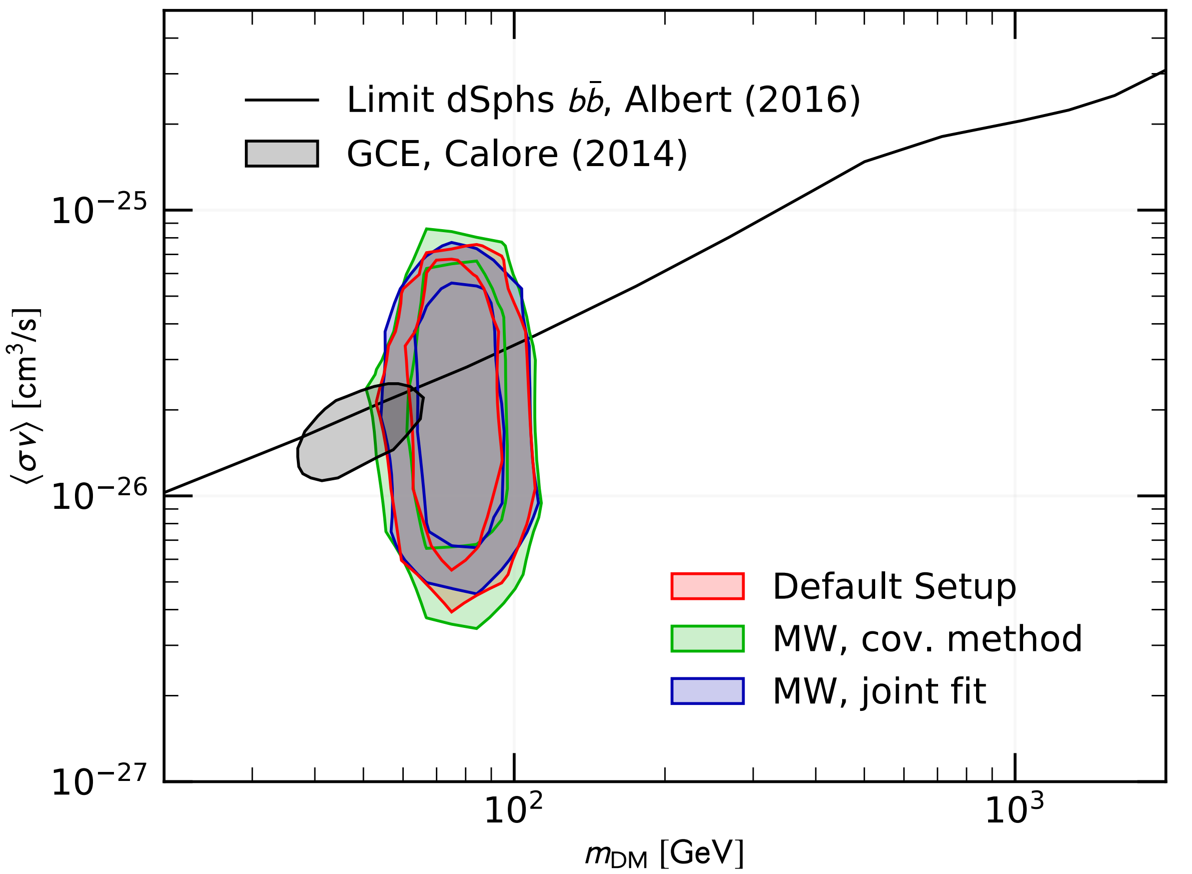
Combining all uncertainties together and marginalizing over them:



We find an the excess at~3+ sigma!

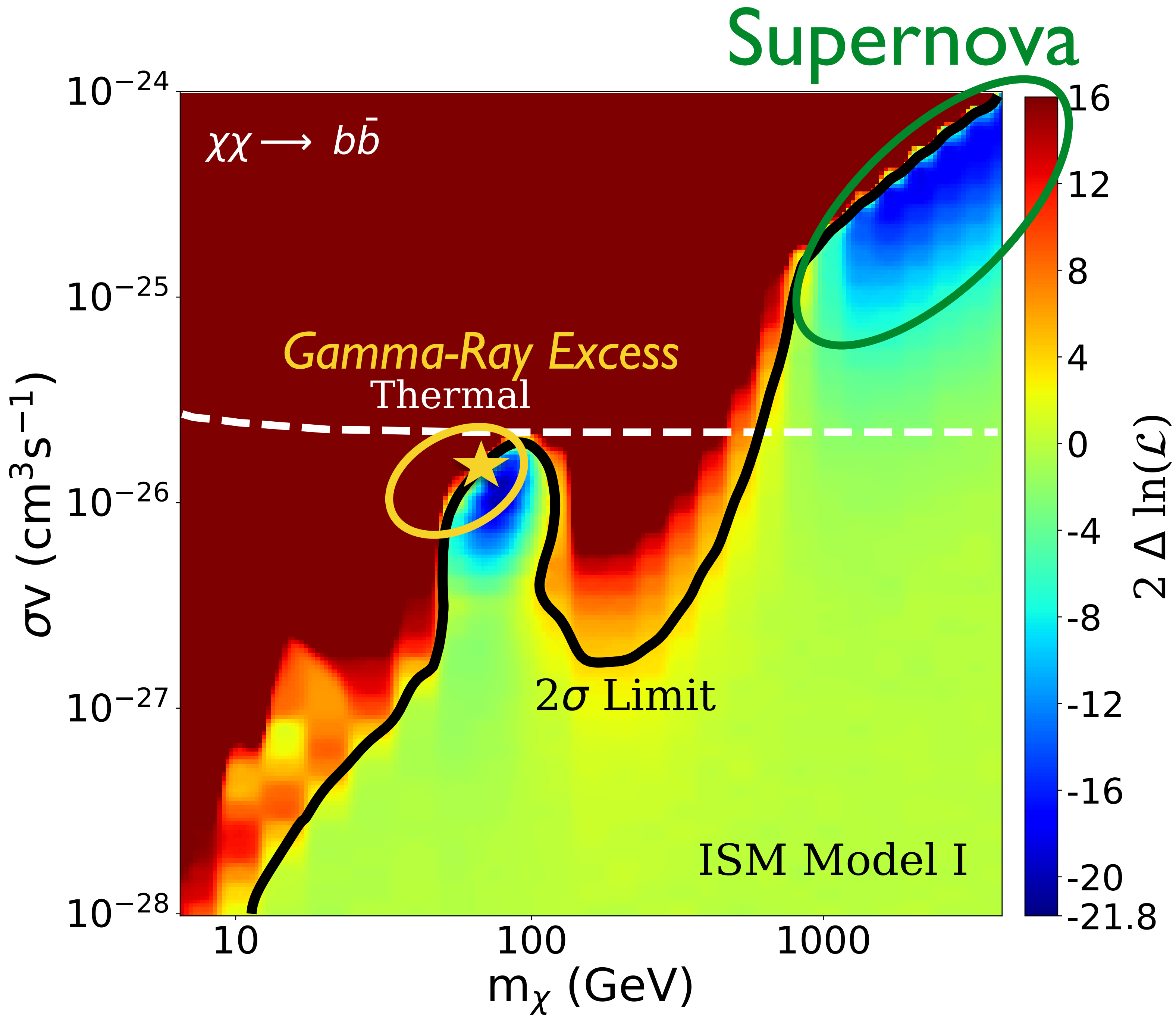


IC, Linden, Hooper PRD 2019



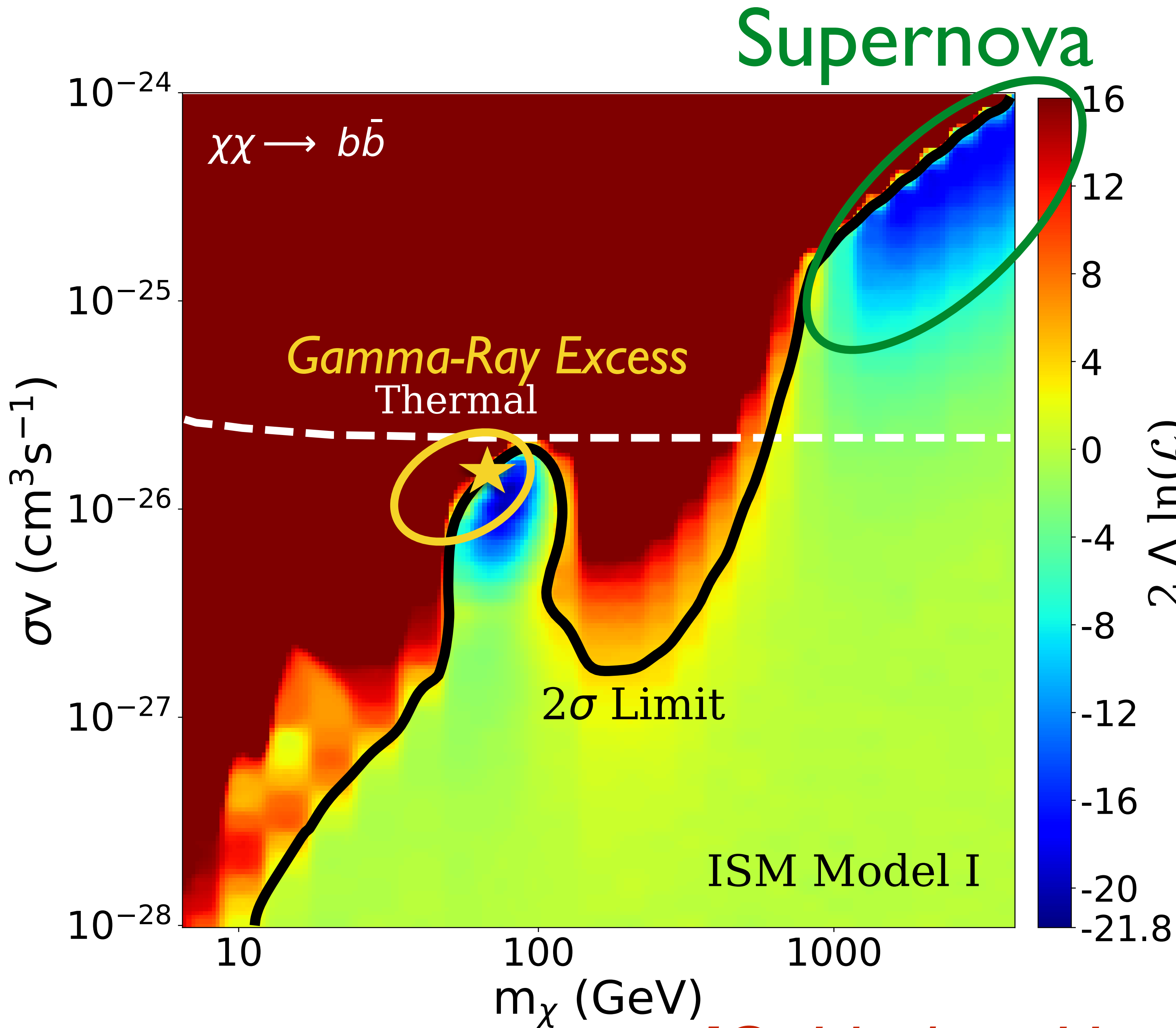
A. Cuoco et al. PRD 2019

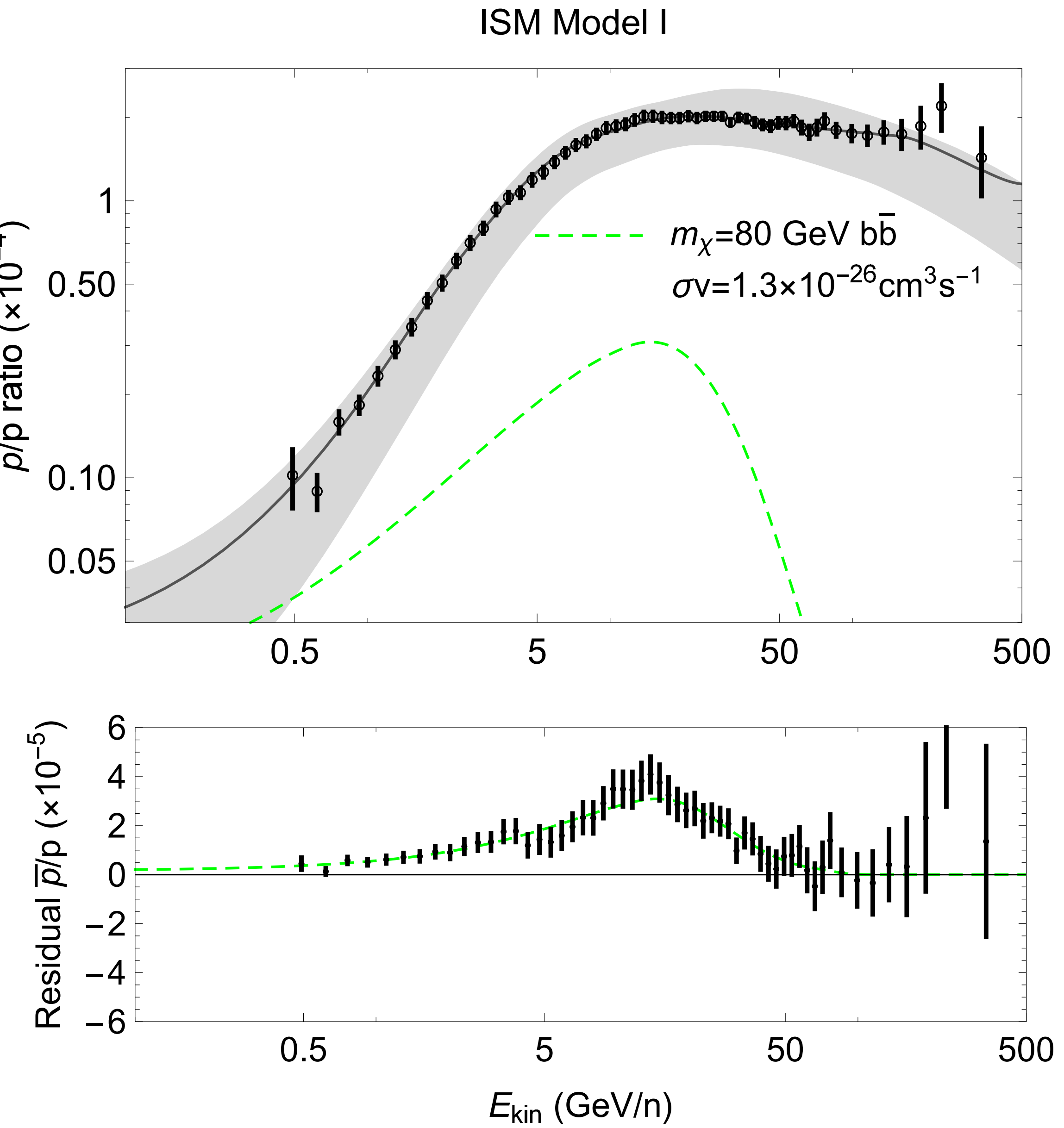
We find an the excess at~3+ sigma!



***IC**, Linden, Hooper PRD 2019*

Can we *fit away the excesses*? *NO (we find them at ~3+ sigma)*





***IC**, Linden, Hooper PRD 2019*

However, it is important to understand the AMS correlated errors. See : Boudaud et al. Phys. Rev. Res. 2020 and Heisig, Korsmeier & Winkler Phys. Rev Res. 2020.

After working on antiprotons

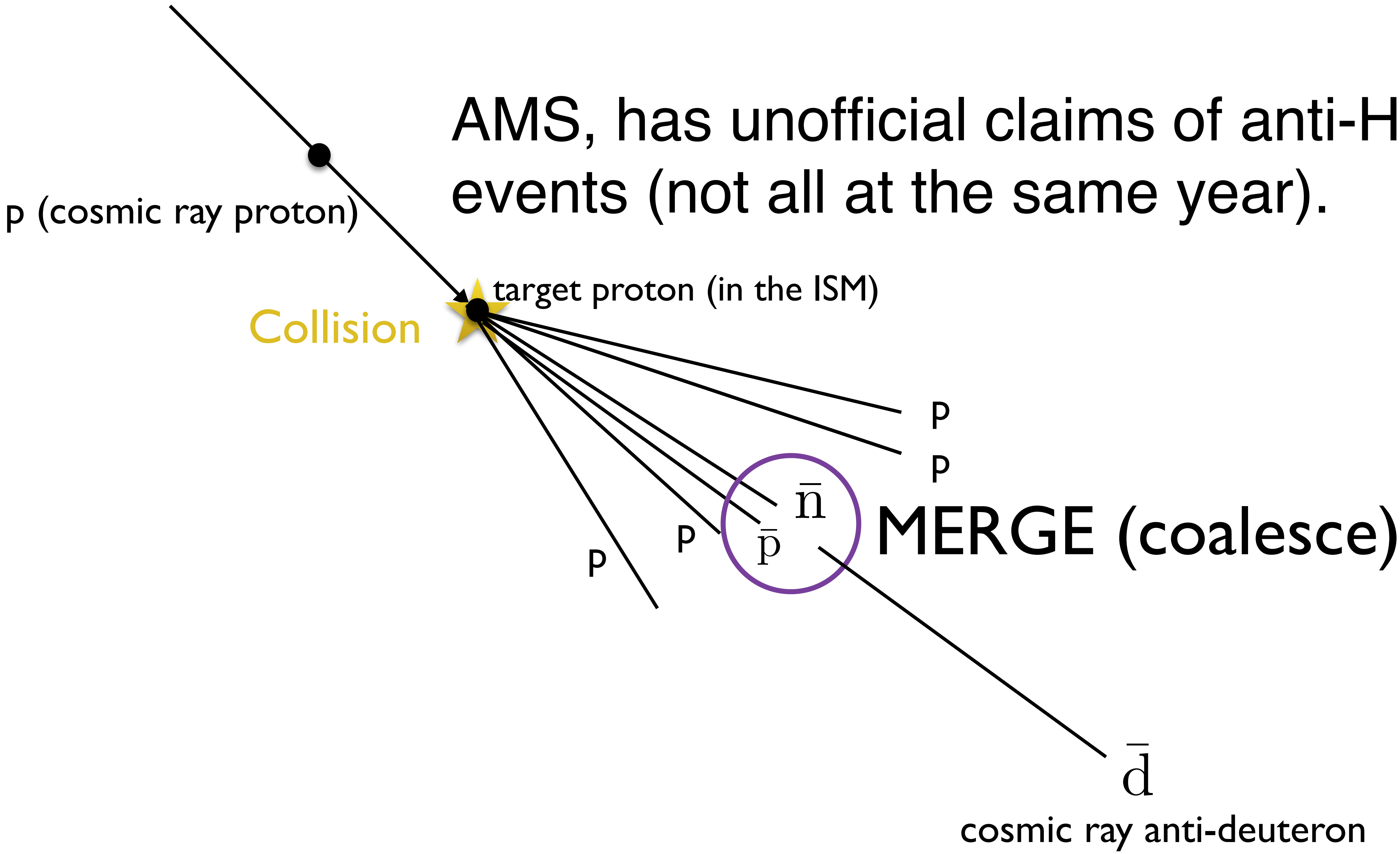
There are two antiproton excesses at ~3.7-6 sigma (each) of local significance.

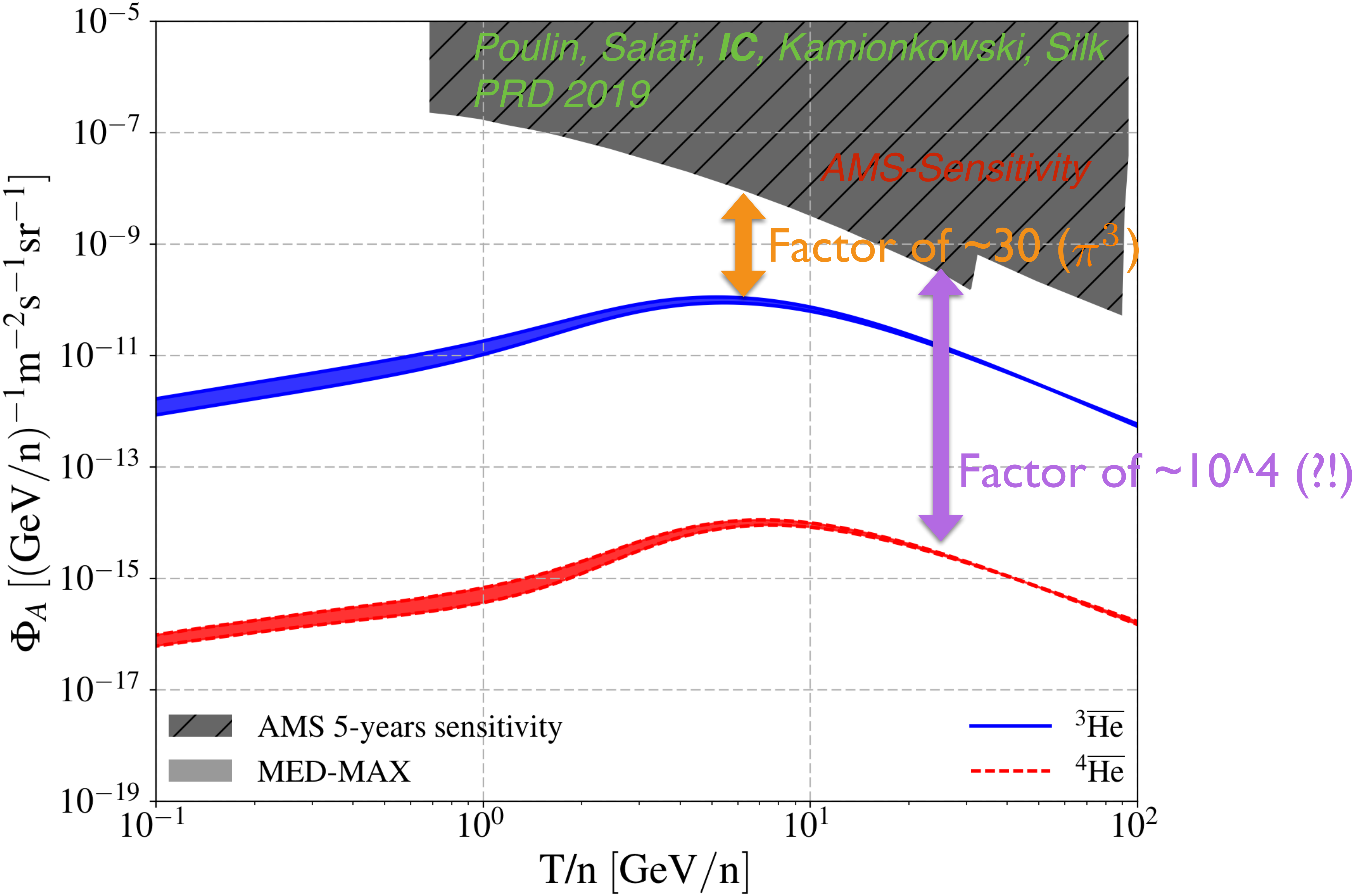
One is a "bump" at ~5-20 GeV in the anti-proton energies and the other is above ~80 GeV and is a hardening of the CR spectrum.

From this point on I will focus on the lower energy one.
I will work under the hypothesis that it is due to a DM particle of mass 50-90 GeV annihilating to b-bbar quarks with a cross-section of ~2x10^{-26} cm^3/s.
What else should we search for?

How about heavier nuclei?

AMS, has unofficial claims of anti-He CR events (not all at the same year).





There is an unexpected amplitude on the flux of anti-He

Roughly the ratio of production is

$$\bar{p} : \bar{d} : {}^3\bar{H}e \sim 10^{10} : 10^6 - 10^7 : 10^2 - 10^4$$

We run PYTHIA simulations to run p-p collisions in the ISM

We are testing CM energies from 40 GeV to 8 TeV.

Antinuclei ($\bar{A}$)	Coalescence momentum p_o (MeV)
$\bar{d}$	108±4
$\bar{t}$	133±11
$\overline{{}^3\mathrm{He}}$	133±11

TABLE I. Coalescence momentum of $\bar{d}, \bar{t}$, and $\overline{{}^3\mathrm{He}}$ with 2σ, obtained from [2]

ALICE Collaboration, ALICE-PUBLIC-2017-010

IC, Rimal (in prep)

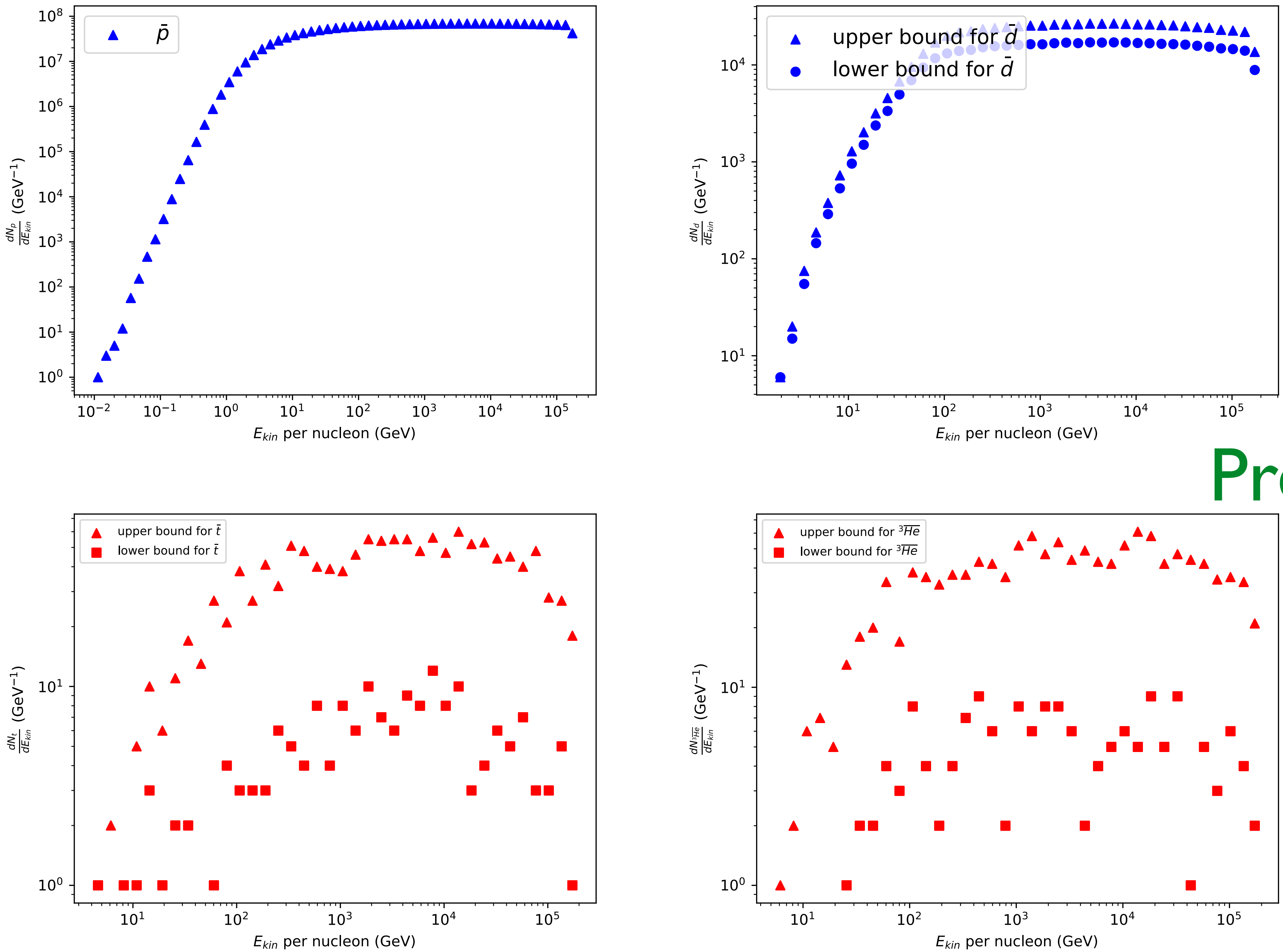
We get the total # of anti-nuclei from p-p collisions in the ISM with updated uncertainties.

CM Energy $\sqrt{s}$ (GeV)	# of Events (billion)	$\bar{d}$		$\overline{^3\mathrm{He}}$	
		min	max	min	max
8000	2	463741	713658	329	2585
6664	2	473791	729309	350	2475
4624	2.54	638216	980897	496	3347
3852	2.56	641678	987292	489	3173

There is still a significant (but reduced) range of uncertainty on the anti-nuclei.

IC, Rimal (in prep)

We also derive spectra of the anti-nuclei at production:

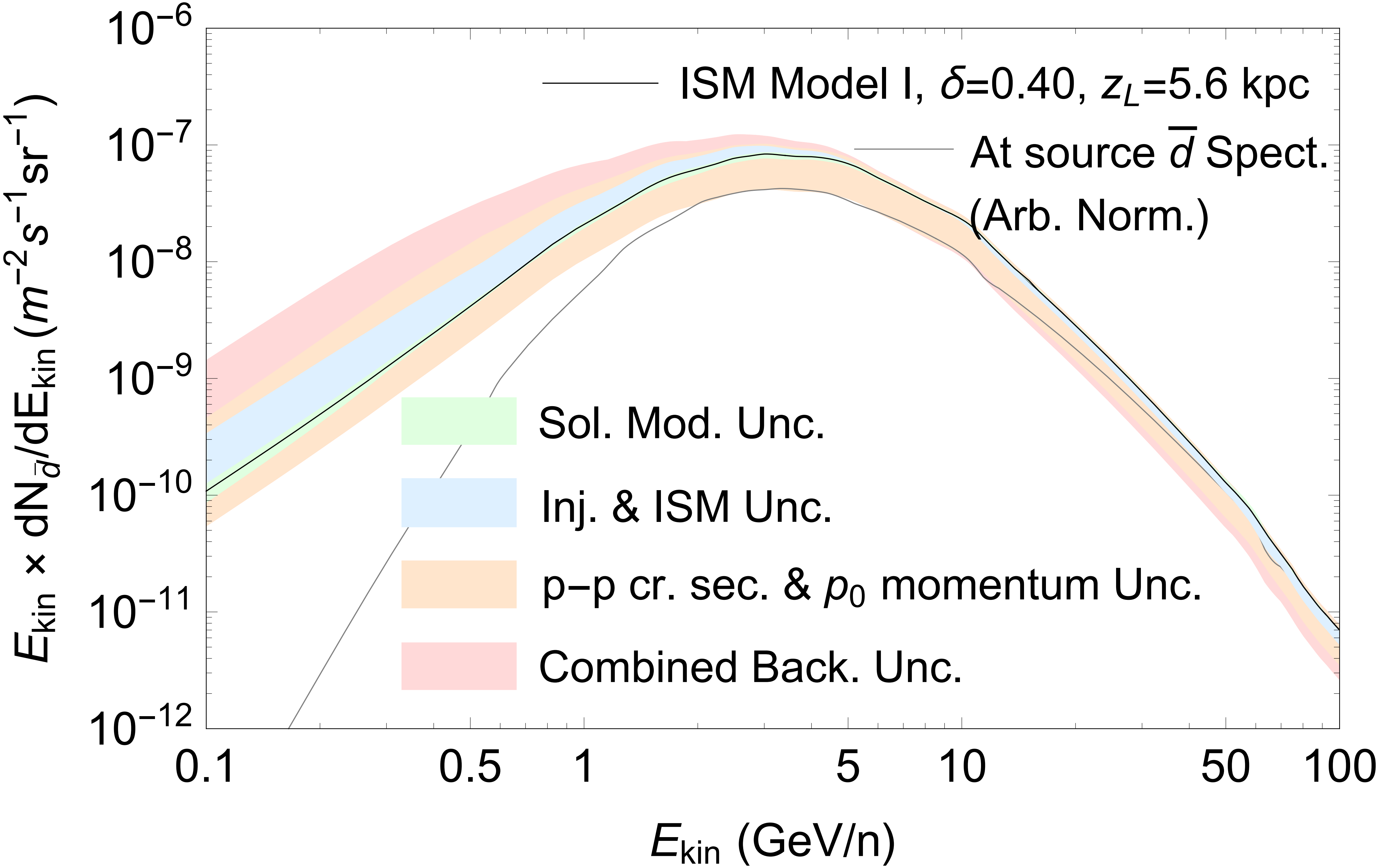


Preliminary

FIG. 1. Spectrum of $\bar{p}$ (top-left), $\bar{d}$ (top-right), $\bar{t}$ (bottom-left), and $^3\overline{He}$ (botton-right) after 2 billion collision with $\sqrt{s} = 8$ TeV

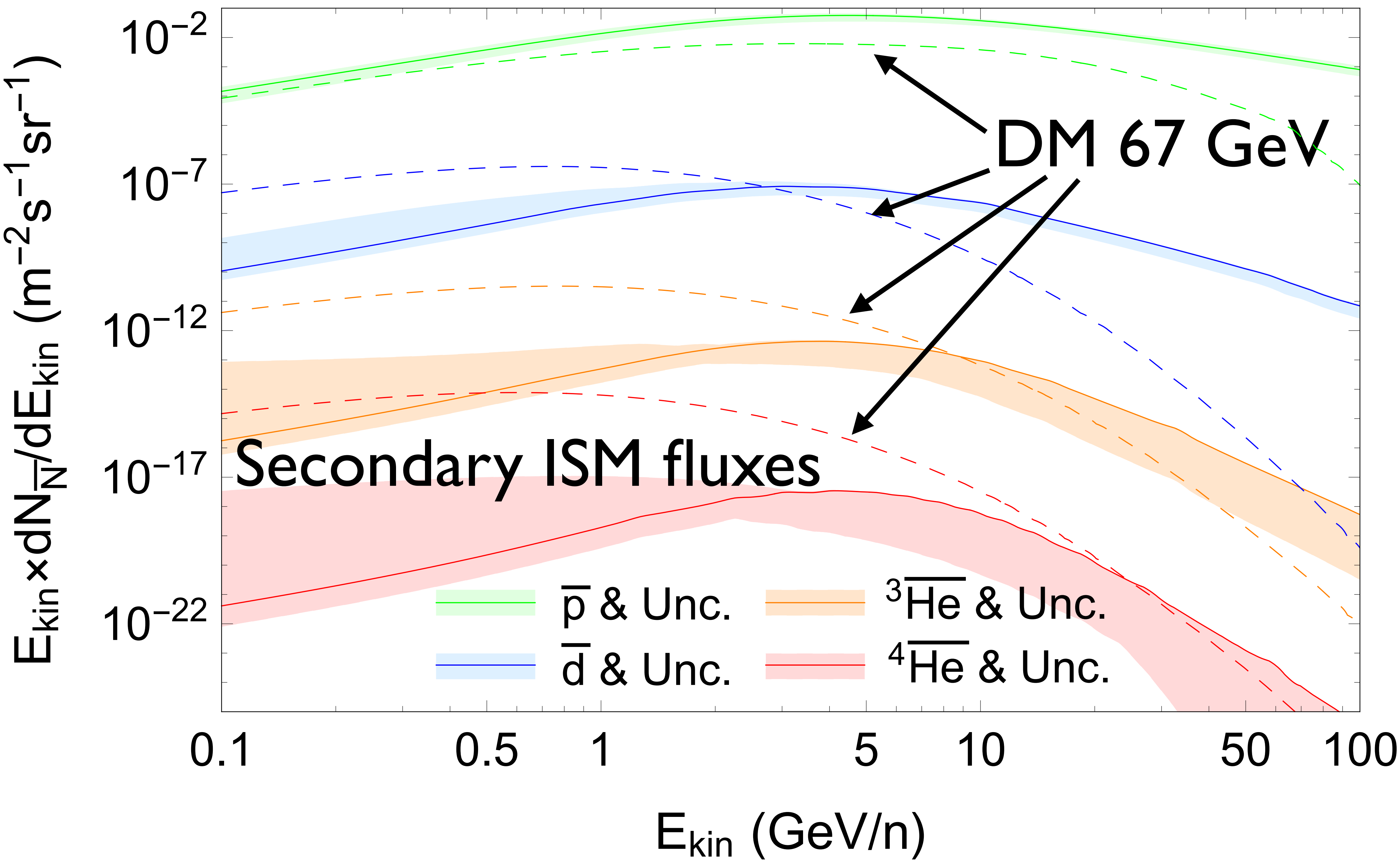
Which can be combined with the information on the ISM cosmic-ray flux of protons, He etc.

Anti-deuterons Uncertainties

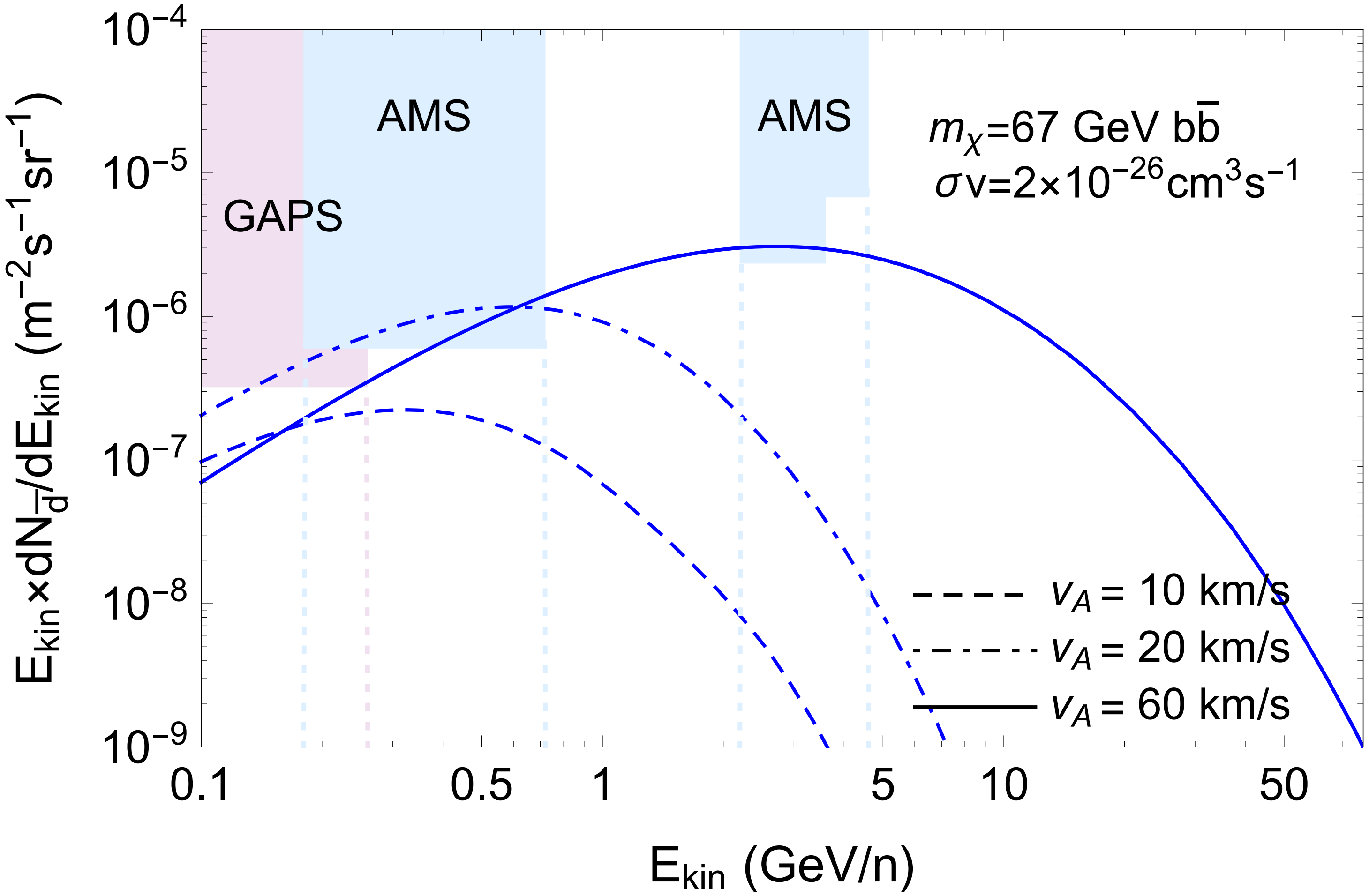


***IC**, Linden, Hooper PRD 2020*

Anti-matter flux Uncertainties

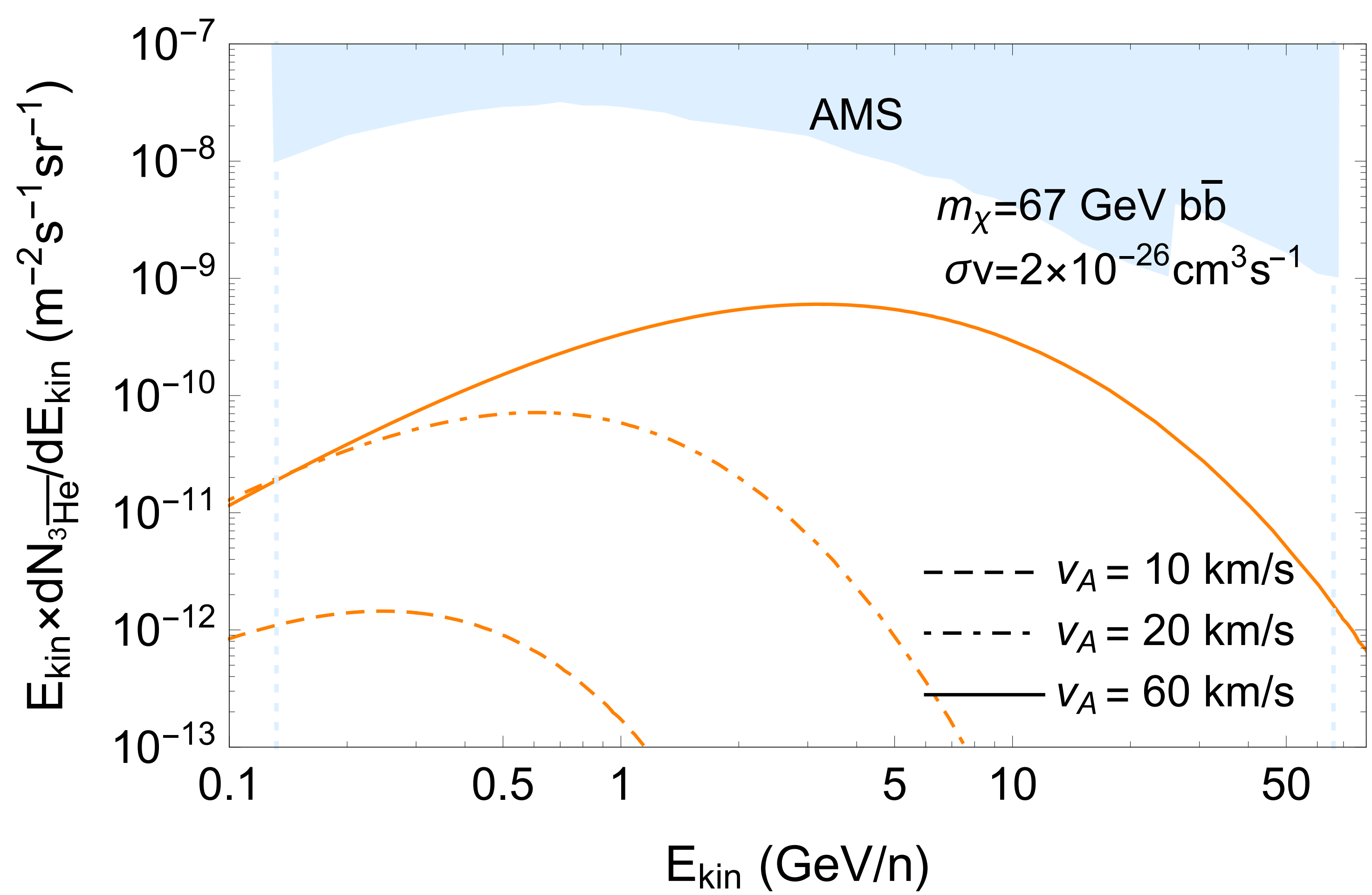


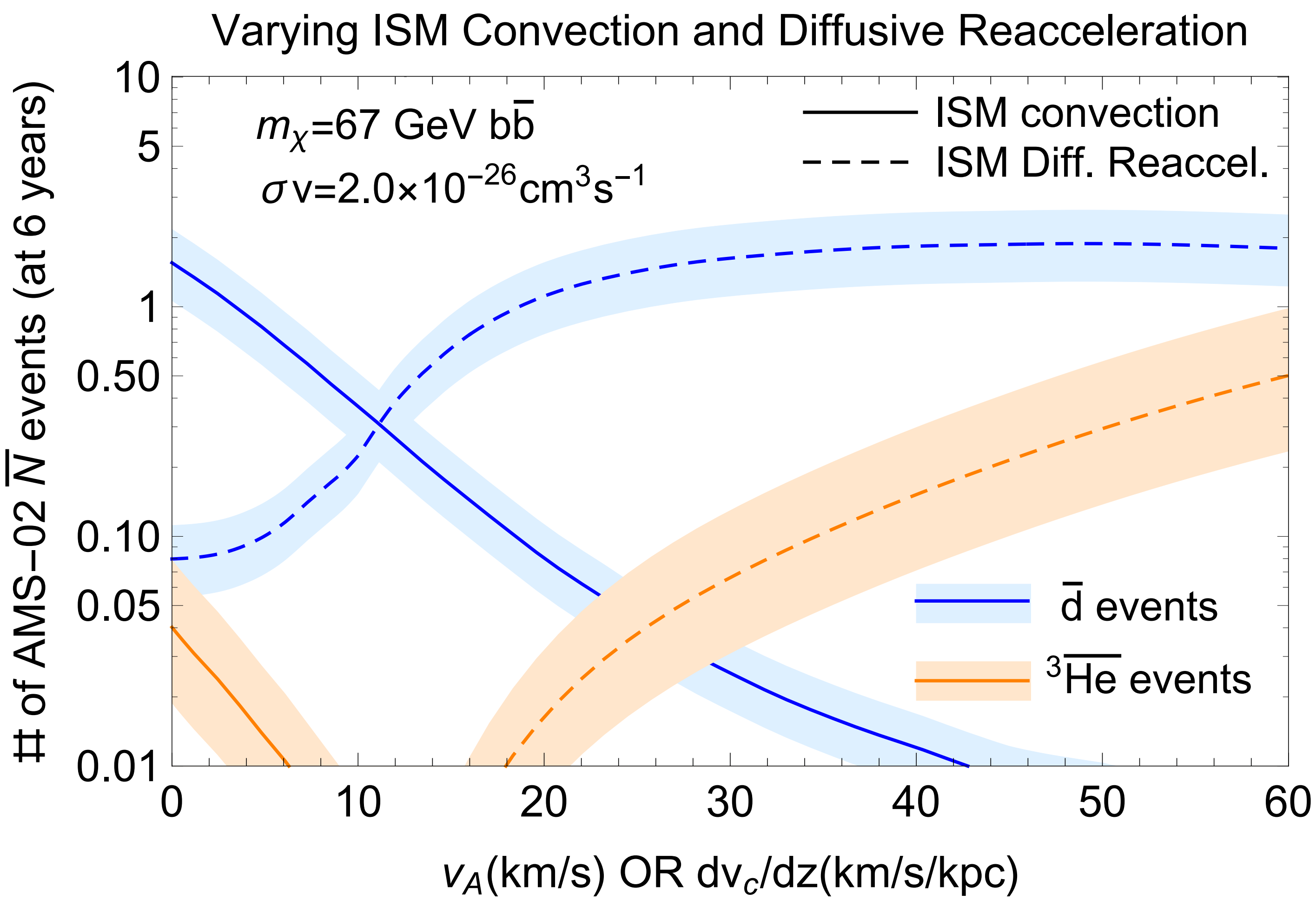
***IC**, Linden, Hooper PRD 2020*



Diffusive re-acceleration in regions of high turbulence can reshape antimatter cosmic-ray spectra from energies where instruments can not detect them to energies where AMS02 and future GAPS can.

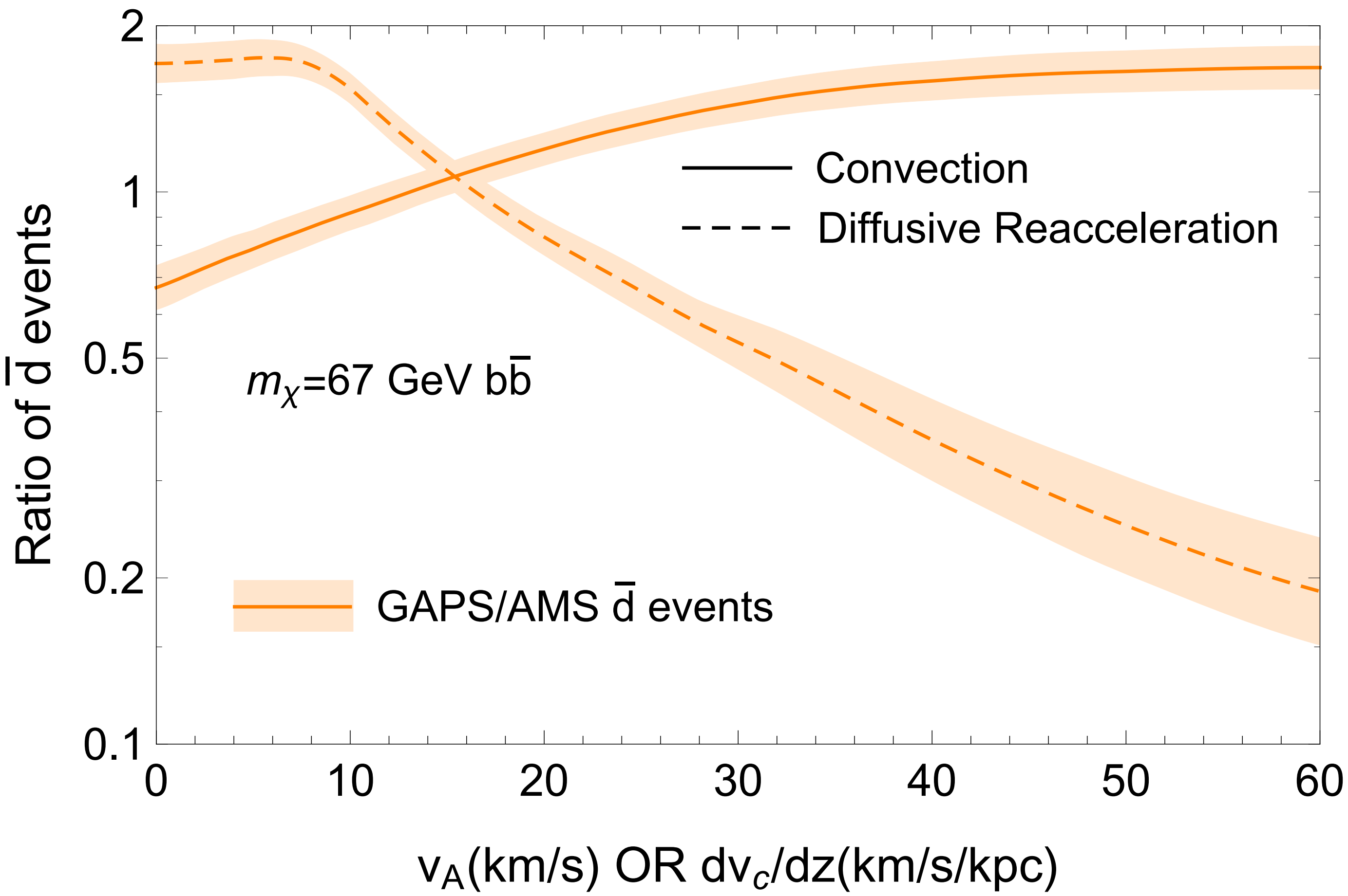
IC, Linden, Hooper
PRD 2020



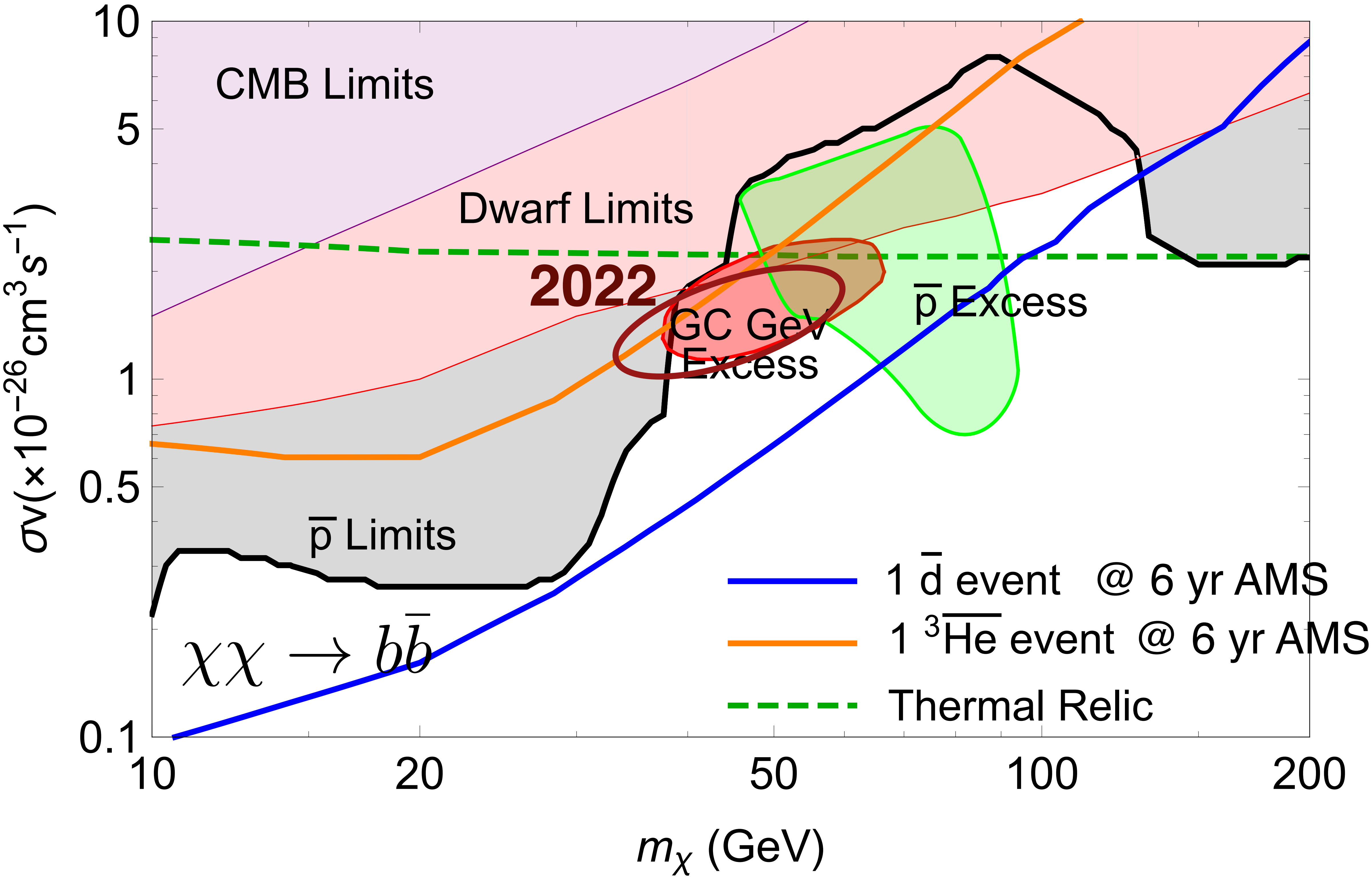


Propagation conditions in the ISM do matter. Cosmic-rays can gain energy as they propagate in the ISM (diffusive re-acceleration). Also we have to account for convective winds and regular diffusion.

There is complementarity between AMS-02 and GAPS. By comparing their measured anti-deuteron numbers of detected events we can learn about DM and ISM properties.

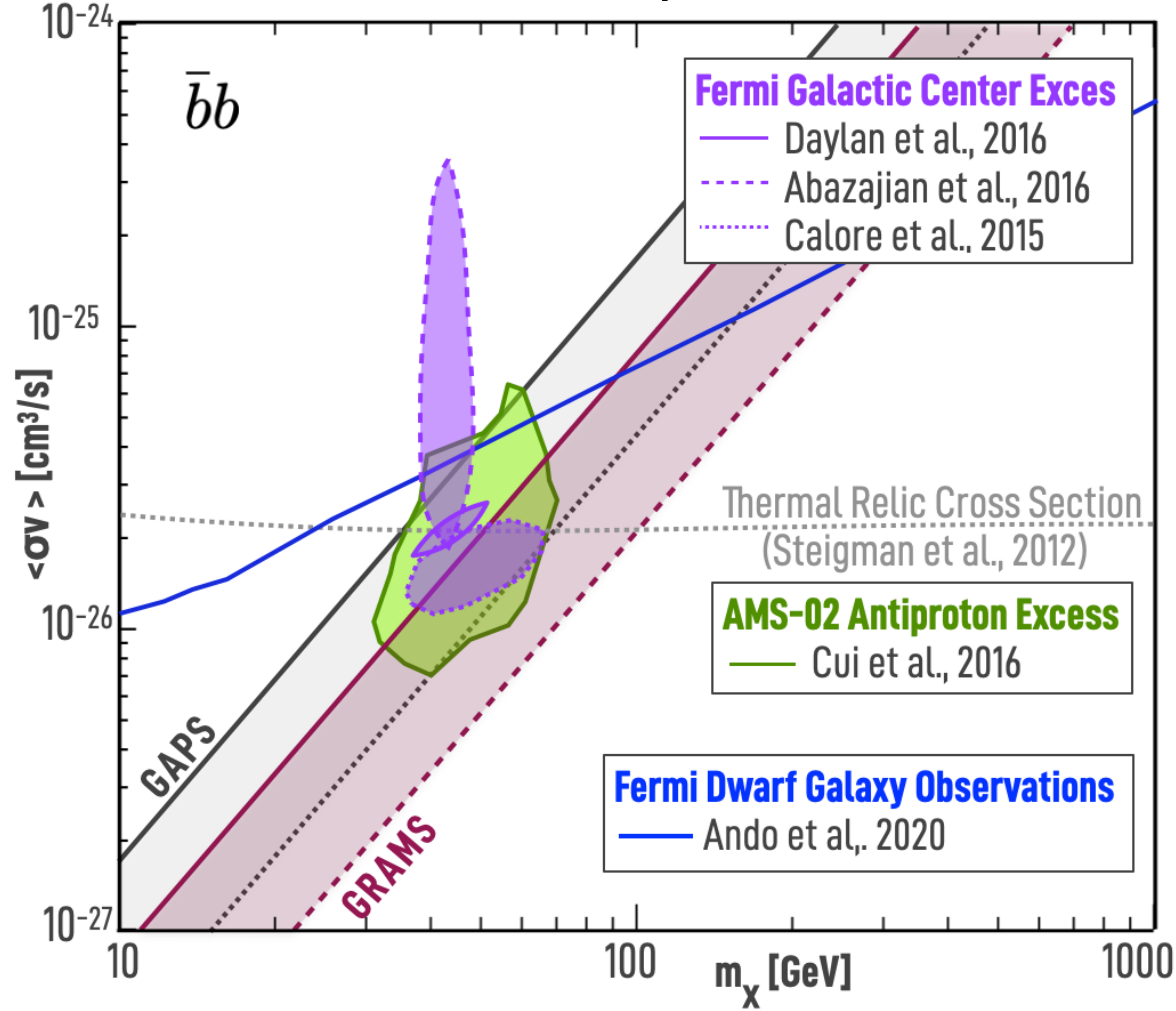


Combining all Indirect DM searches



IC, Linden, Hooper PRD 2020

Future Projections



Aramaki et al. Astrop. Phys.2020

Conclusions

- *There is an additional component in the AMS antiproton data BOTH at ~GeV energies AND above ~80 GeV.*

- *To study the pbar/p ratio we have taken into account all basic uncertainties (injection and propagation through the ISM, antiprotons production cross-sections).*

- *May possibly be an indication of a dark matter signal in agreement with the GeV excess at gamma-rays.*

- *Heavier anti-nuclei may have been claimed by AMS. These would be very challenging to interpret given the **KNOWN** coalescence uncertainties.*

- *We are using **ALICE data** to better probe the production uncertainties.*

- *Anti-He3 and anti-deuterons events may be in agreement with the GeV excesses in gamma-rays and antiprotons.*

- *Signal of DM in the Milky Way!?*

Thank you