Dark matter searches with cosmic-ray antideuteron and antihelium

Michael Korsmeier

UNIVERSITY of TURIN and INFN
Department of Physics

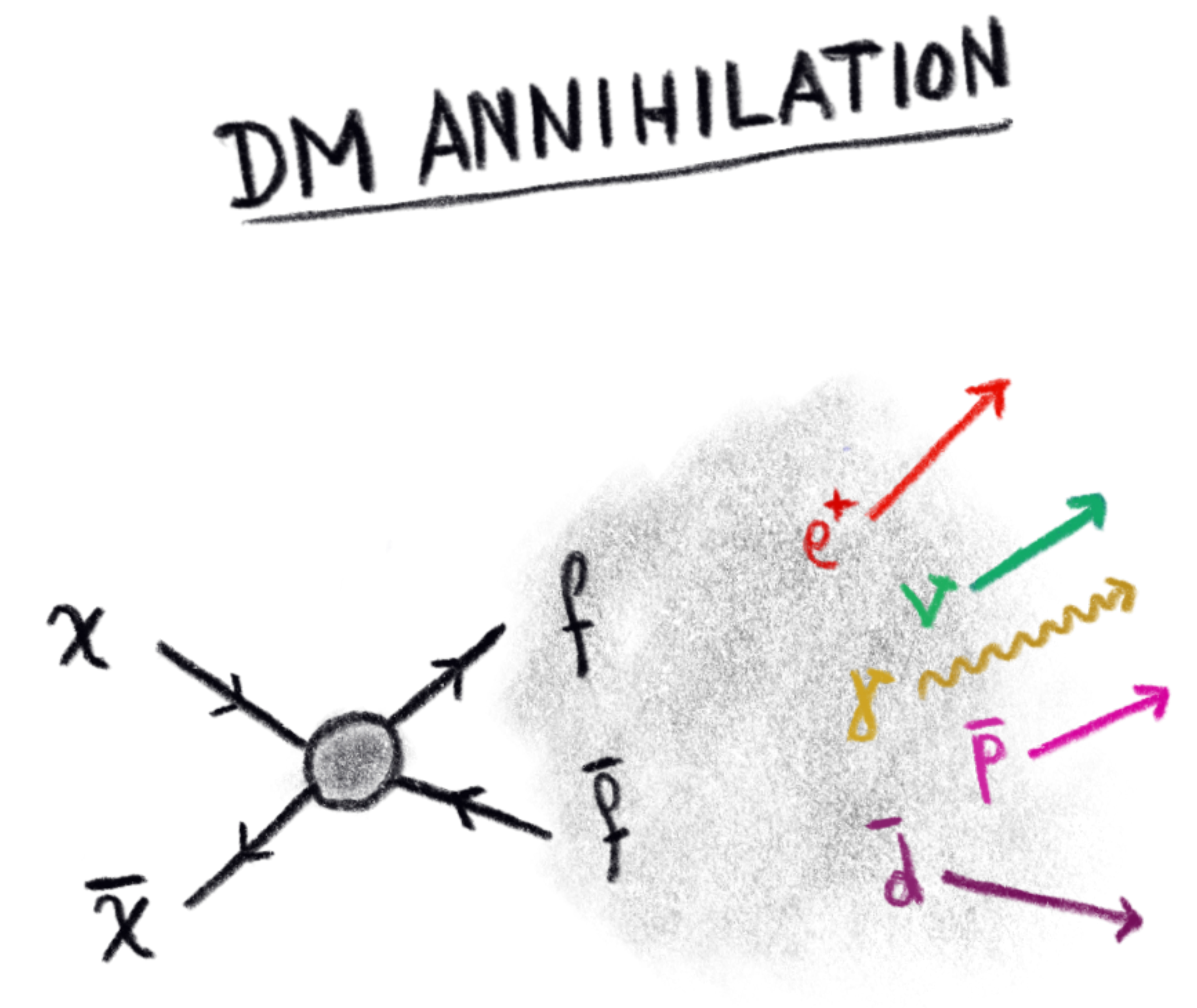
INFN Istituto Nazionale di Fisica Nucleare

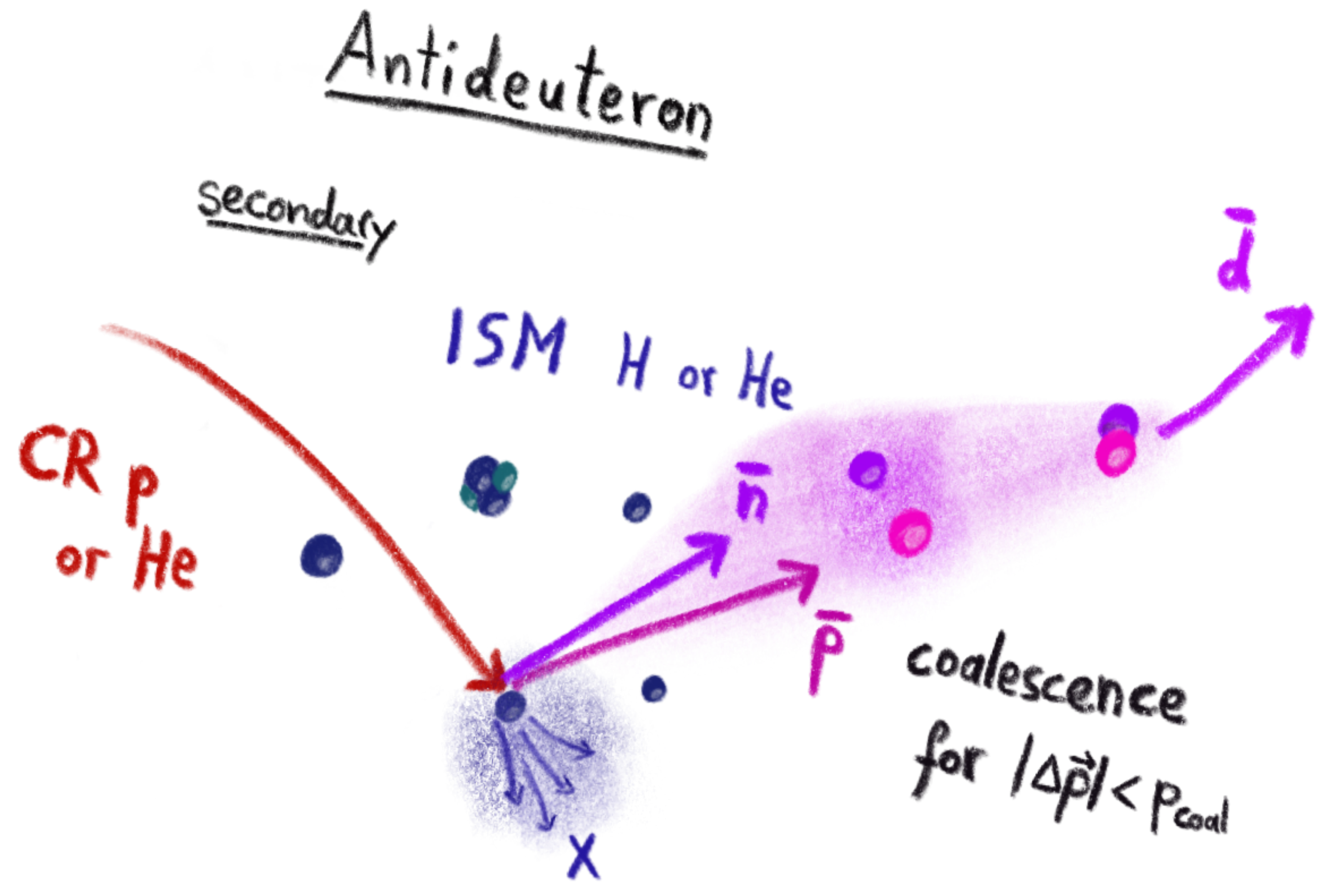
Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

Outline

- Introduction
- Cosmic rays
- Antiprotons
- Antideuteron
- Antihelium
- Conclusion





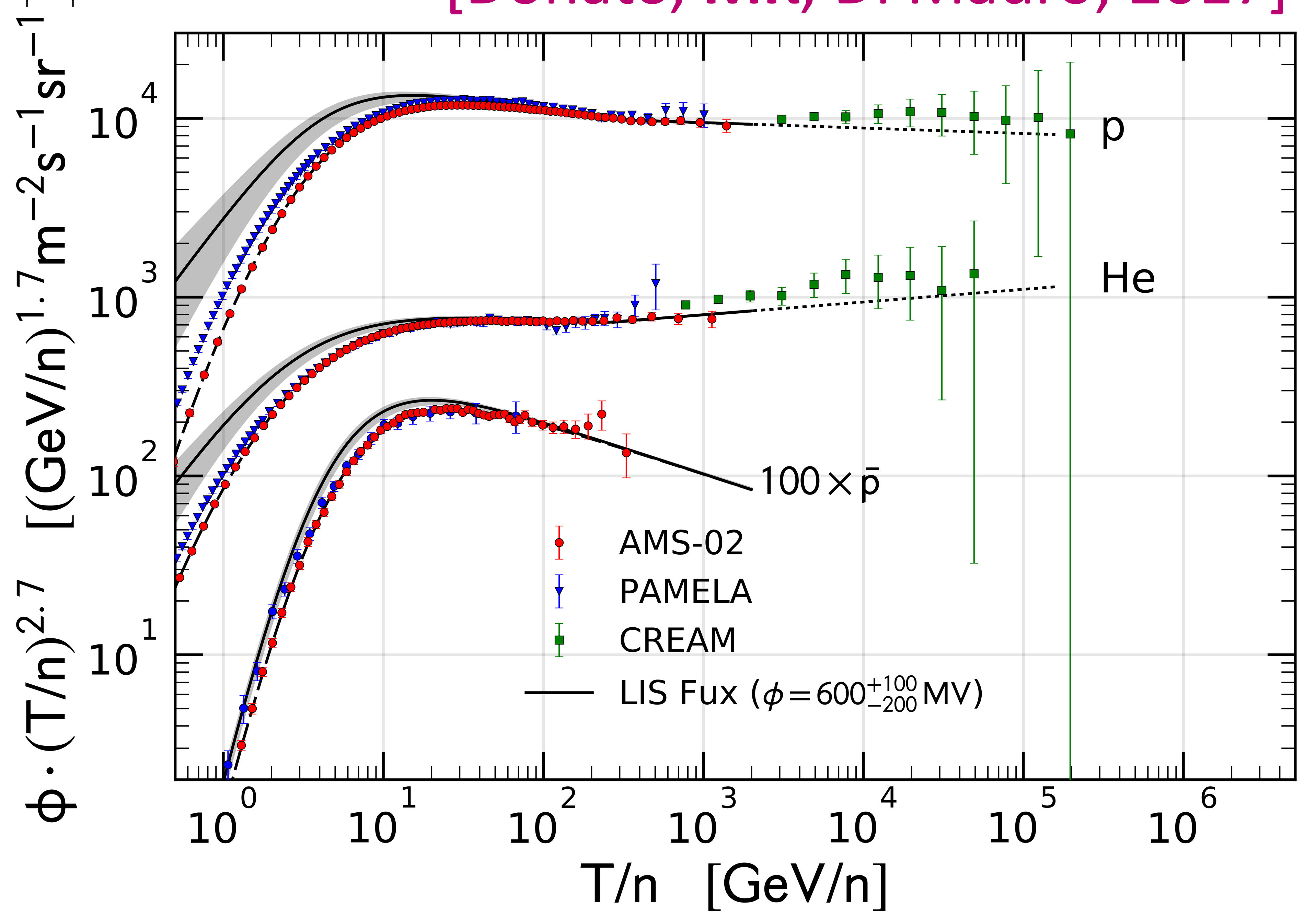
Cosmic rays in the precision era

- Space-based experiments PAMELA and AMS-02 determine cosmic-ray spectra with increasing precision

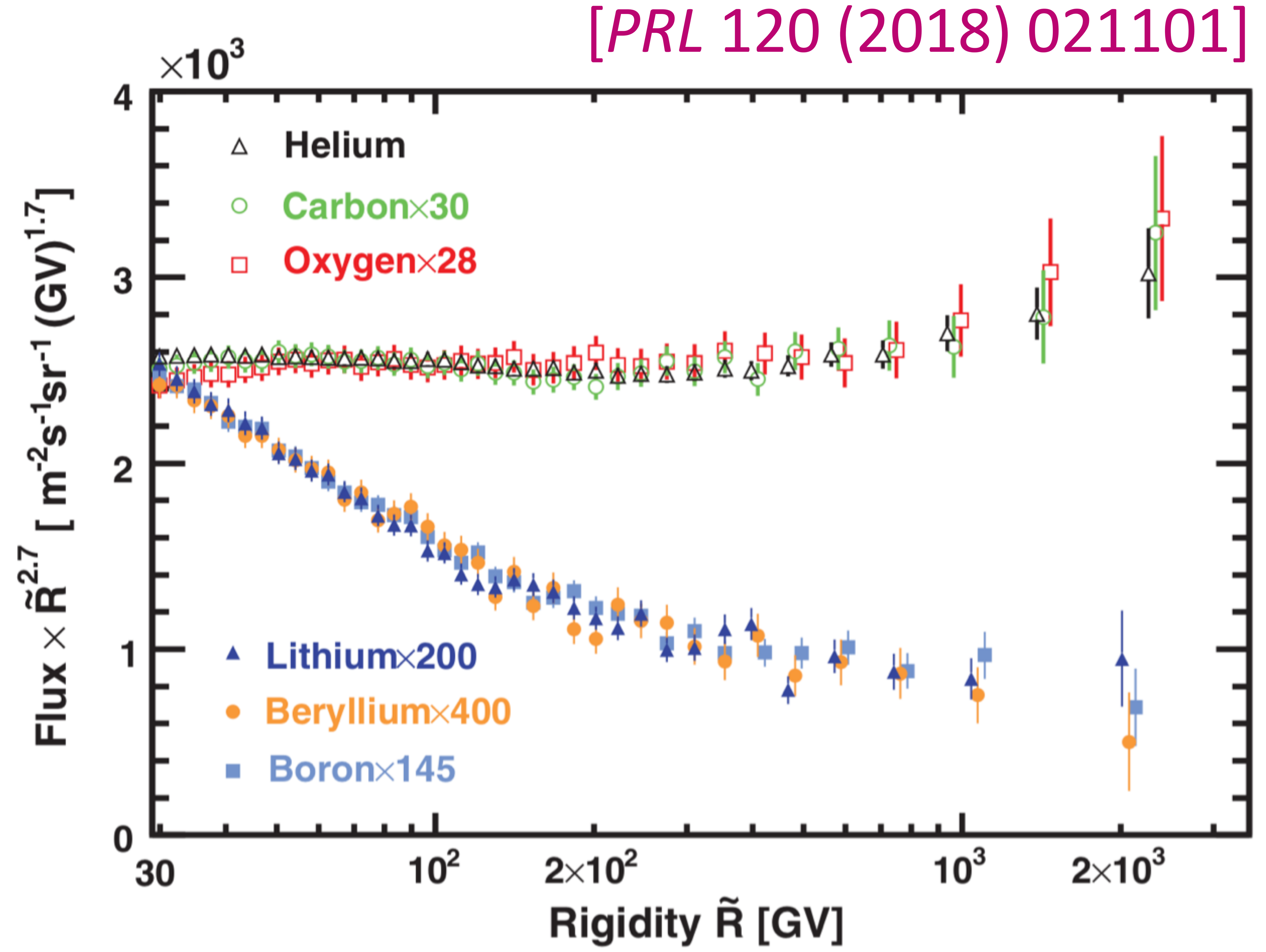
- Interpretation of the CR data requires understanding of:
    - Production
    - Propagation in the Galaxy
    - Solar modulation

- Future experiment GAPS aims to measure antideuteron

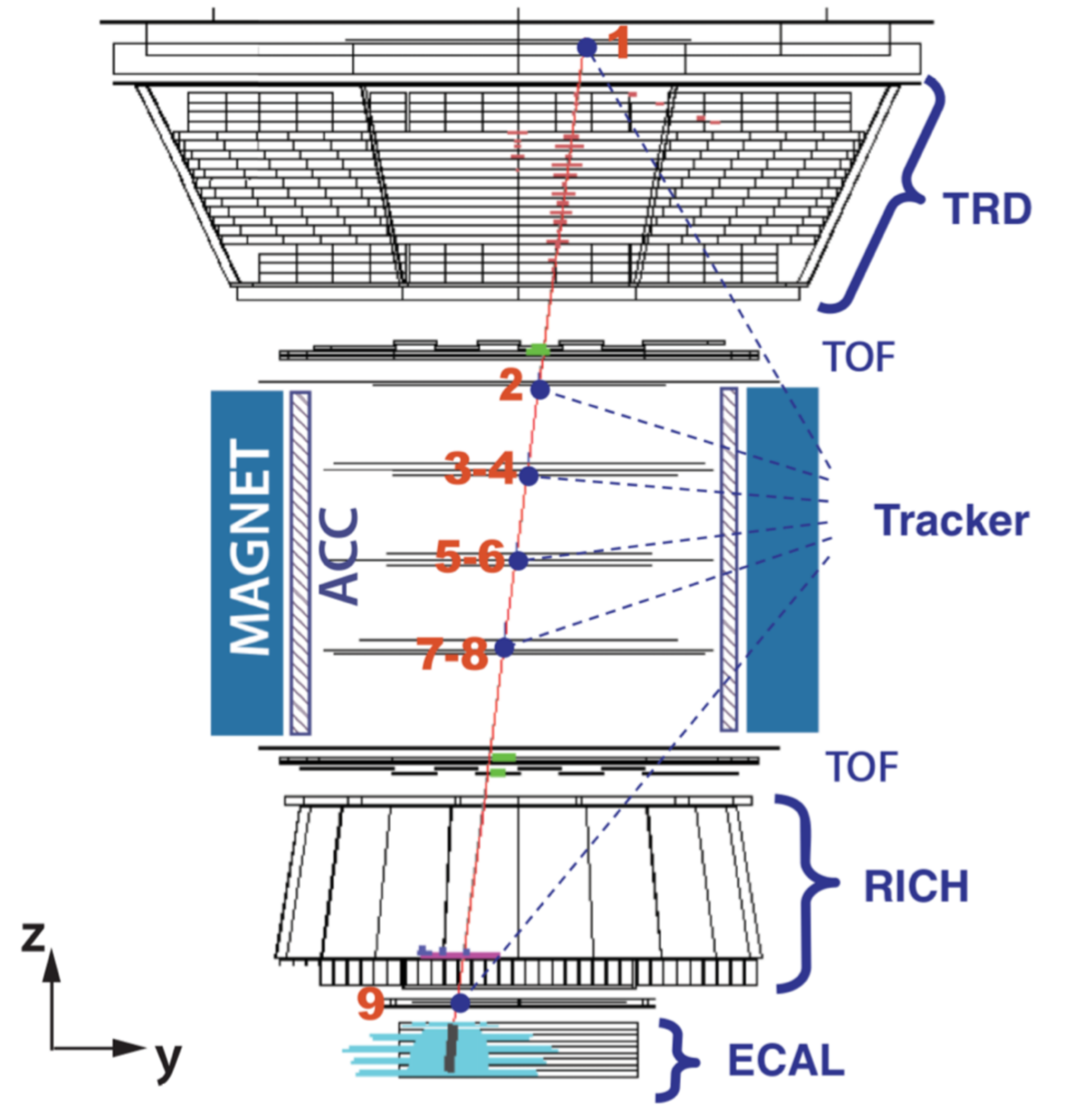
[Donato, **MK**, Di Mauro; 2017]



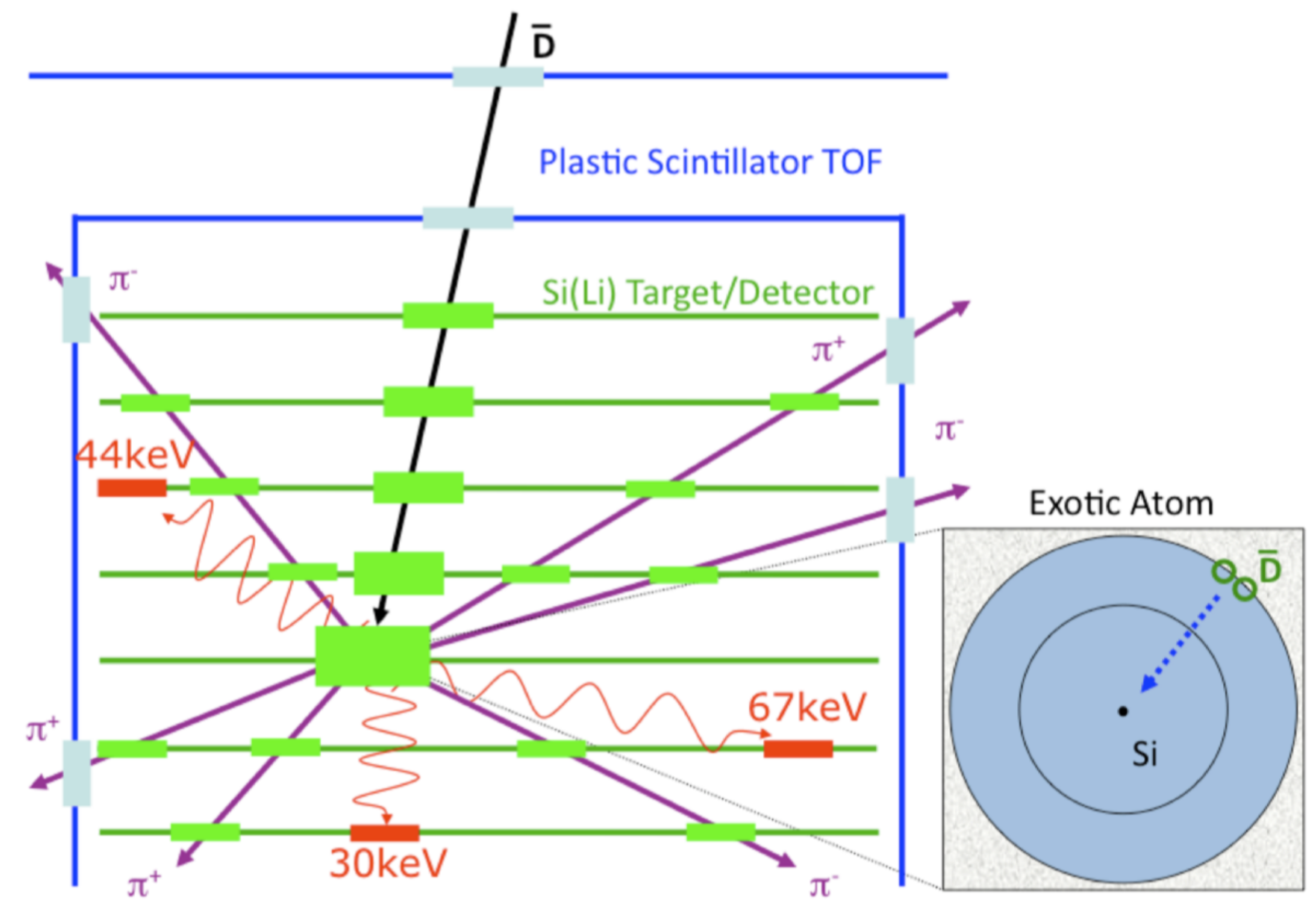
[*PRL* 120 (2018) 021101]



Experiments: AMS-02 and GAPS



[Aguilar, et al; PRL 110; 2013]

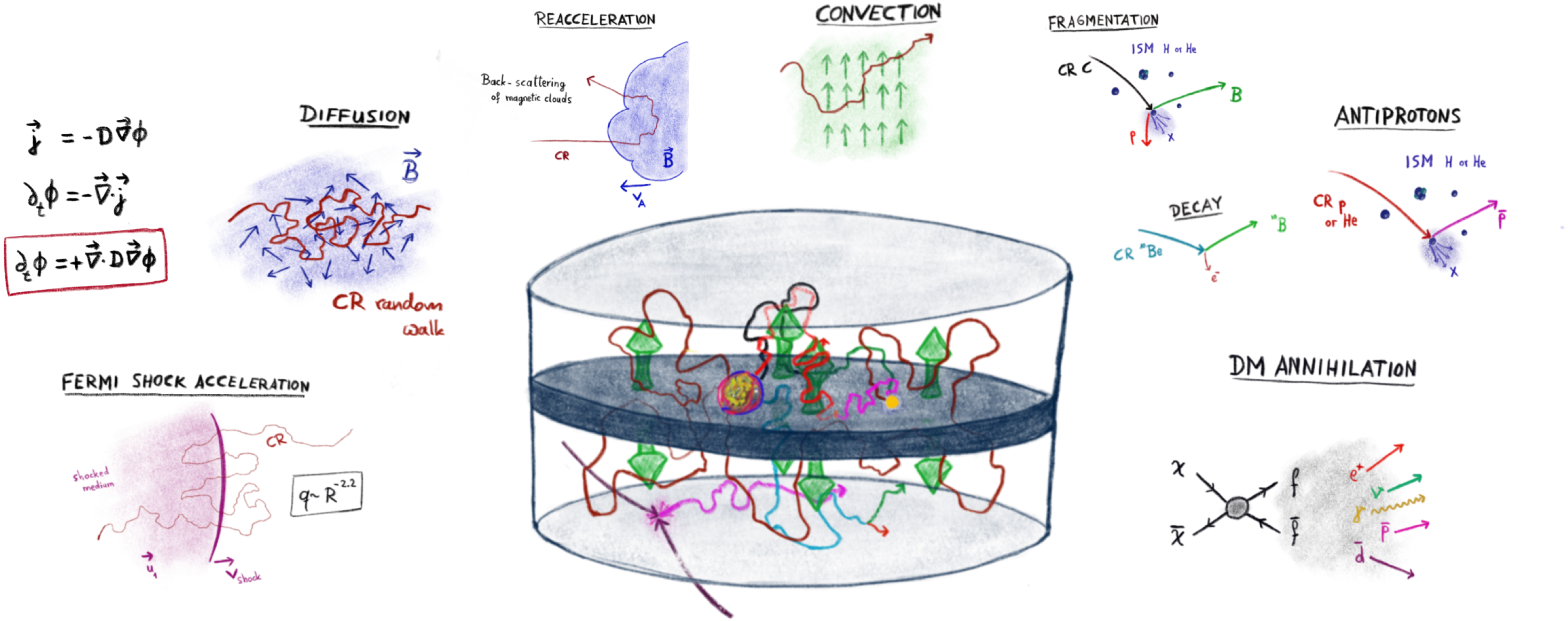


[Aramaki, et al; 2015]

- AMS-02 measures primary (p,He,C,N,O), secondary nuclei (Li,Be,B), and electrons/positrons between 1 GeV and a few TeV
- Antiprotons are determined with 5% precision between 1 and 400 GeV

- Approved balloon experiment dedicated to low-energy antiproton and antideuteron
- Unique identification due to capture of antiparticles in exotic atoms

Cosmic-ray propagation



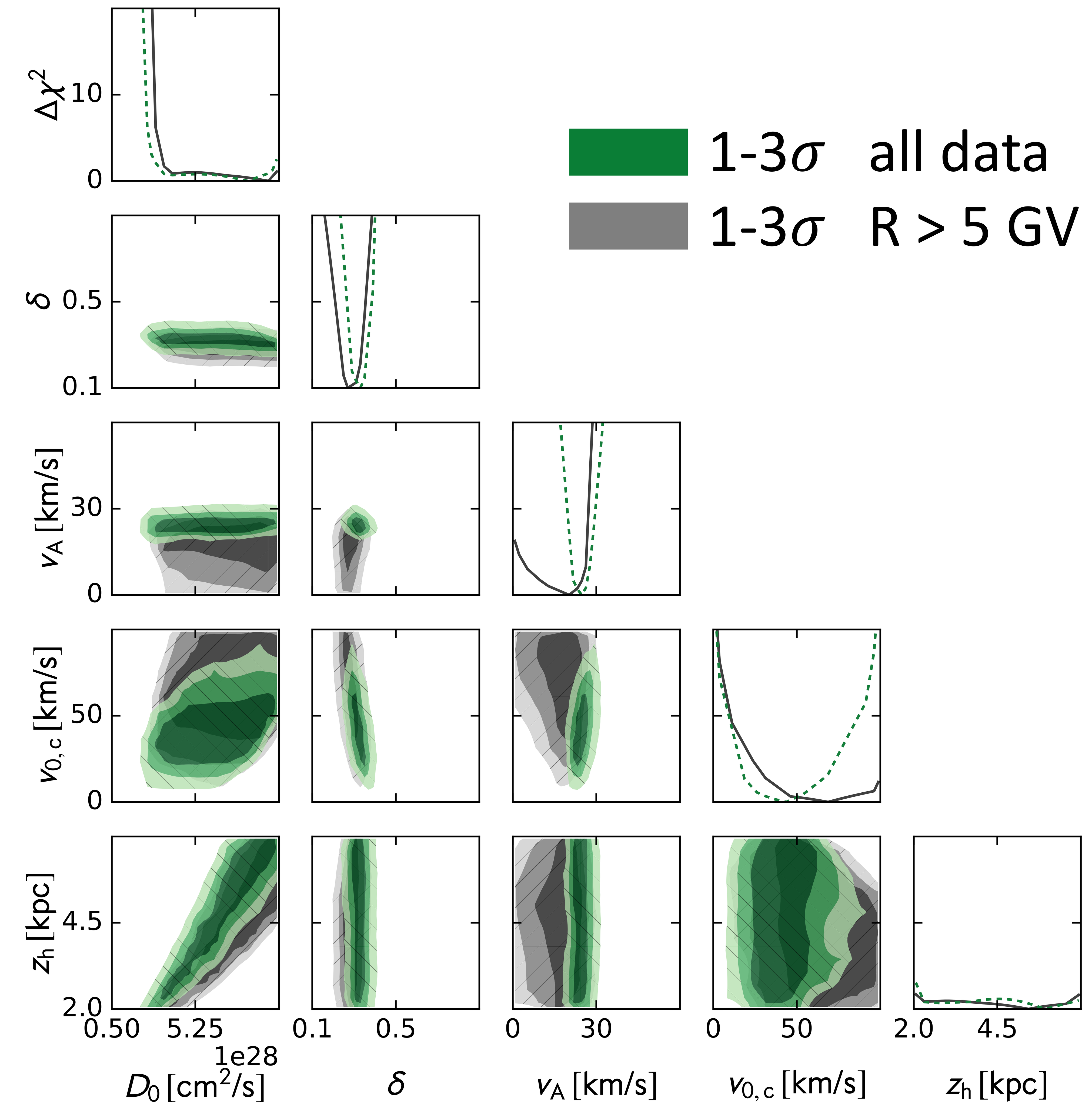
- Primaries (p, He, CNO, …) produced and accelerated in astrophysical sites
- Secondaries (Li, B, $\bar{p}$, $\bar{d}$, …) constrain propagation
- Description by a set of coupled diffusion equations:

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x}, p) + \boldsymbol{\nabla}\cdot(D_{xx}\boldsymbol{\nabla}\psi - \boldsymbol{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\psi - \frac{p}{3}\boldsymbol{\nabla}\cdot\boldsymbol{V}\psi\right) - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

Constrain cosmic-ray propagation

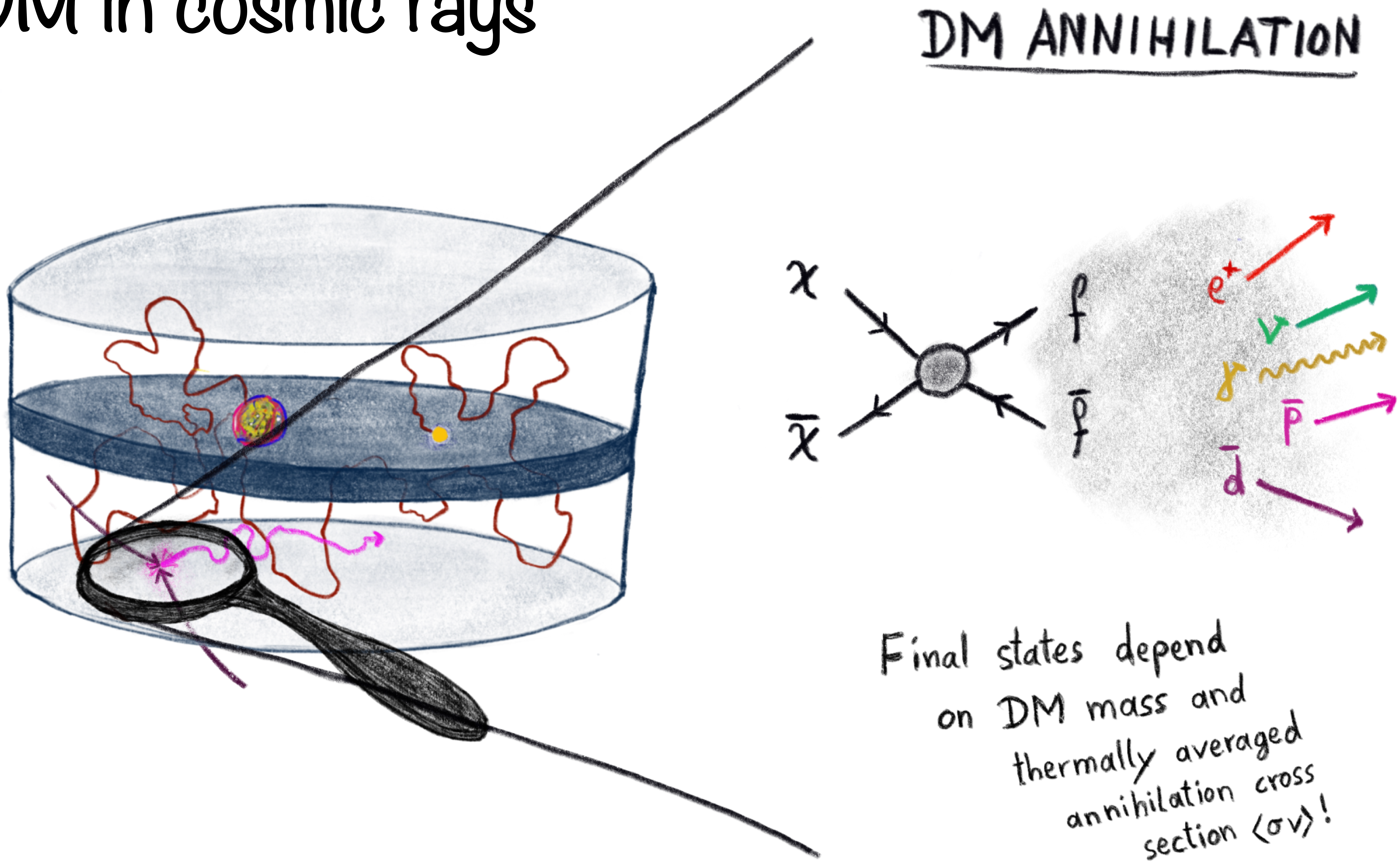
- Secondary-to-primary ratios constrain propagation since secondaries "undergo propagation twice"
- Standard rulers: B/C and $^{9}Be/^{10}Be$
  - [Donato, Fornengo, Maurin, Salati; 2004]
  - [Putze, Derome, Maurin; 2010]
  - [Kappel, Reinert, Winkler; 2014]
  - [Johannesson, et al.; APJ; 2016]
  - [Feng, Tomassetti, Oliva; 2016]
  - ...
- Light nuclei: D and $^{3}He/^{4}He$
  - [Coste, Derome, Maurin, Putze; 2010]
- Antiprotons
  - [Korsmeier, Cuoco; 2016]

Fit to AMS-02 data p, He, $\bar{p}$



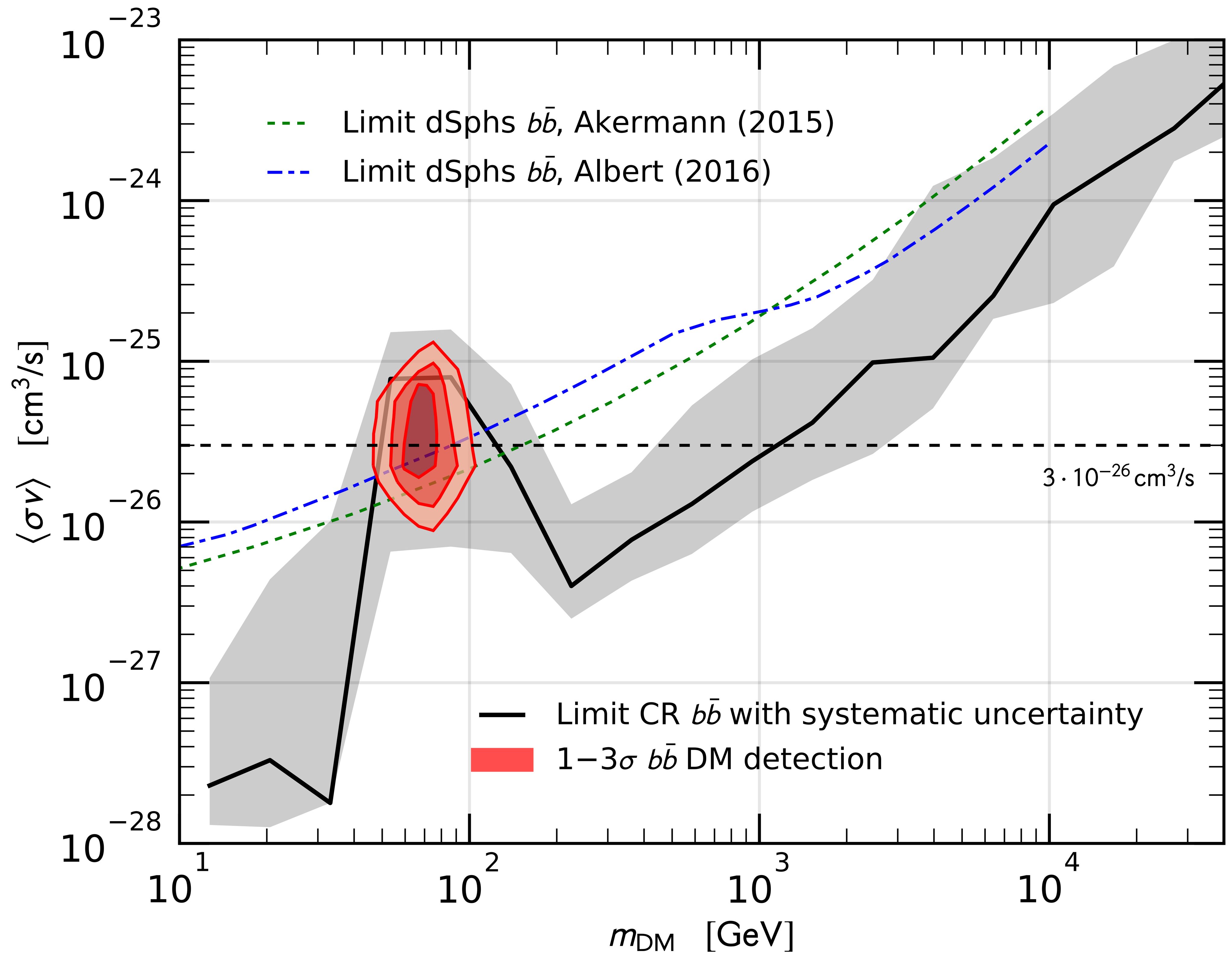
[MK, Cuoco; 2016]

DM in cosmic rays

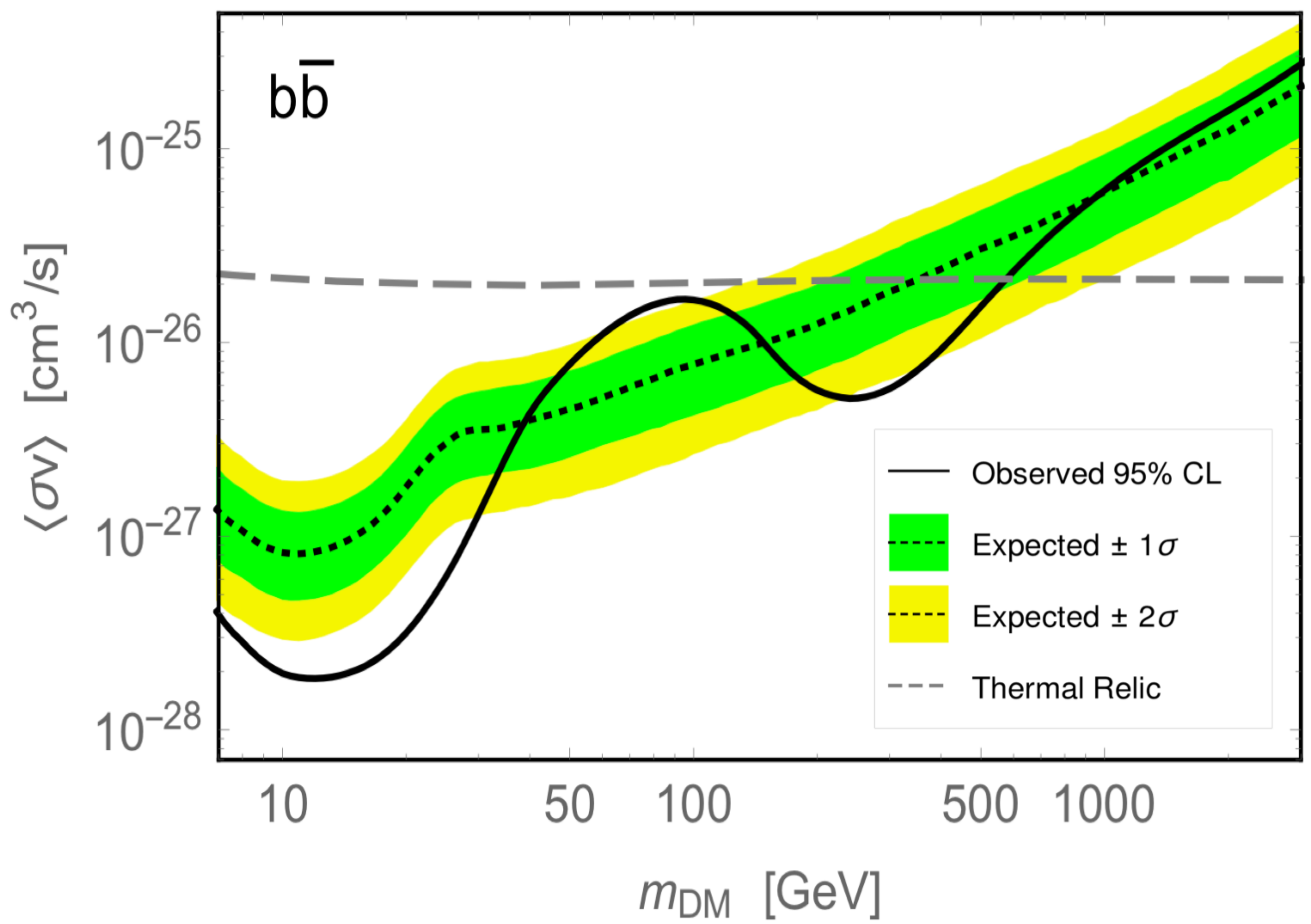


DM and cosmic-ray antiprotons

[Cuoco , Krämer, **MK**; 2017]



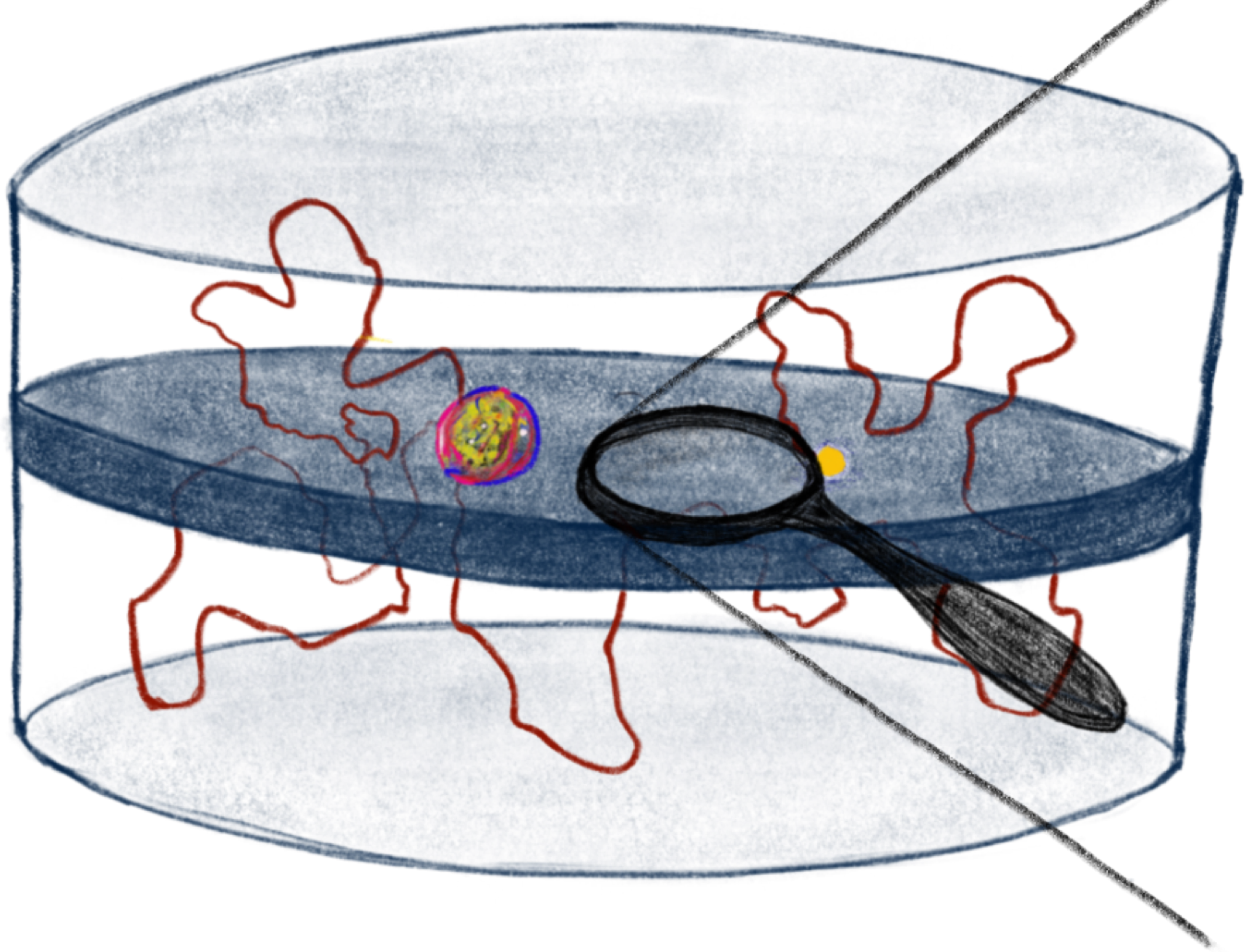
[Reinert, Winkler; 2018]



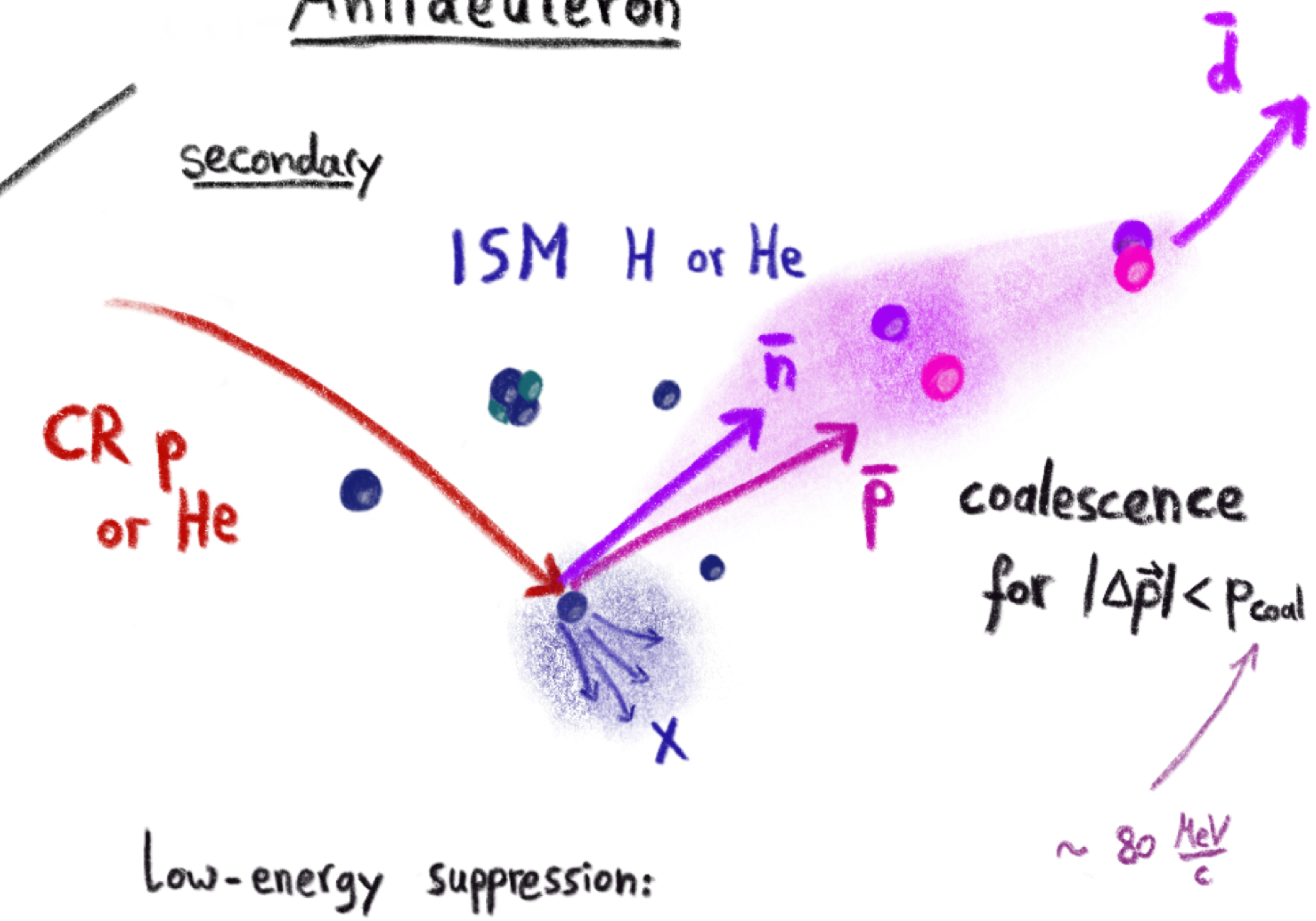
- CR antiprotons constrain WIMP DM [see talk by Jan Heisig, Tue]
- Potential DM signal in CR antiproton at m_{DM} ~ 70 GeV
- **But:** the estimation of systematic uncertainties is non-trivial

Is there an <u>complementary</u> way to investigate the potential signal?

Cosmic-ray antideuteron



Antideuteron



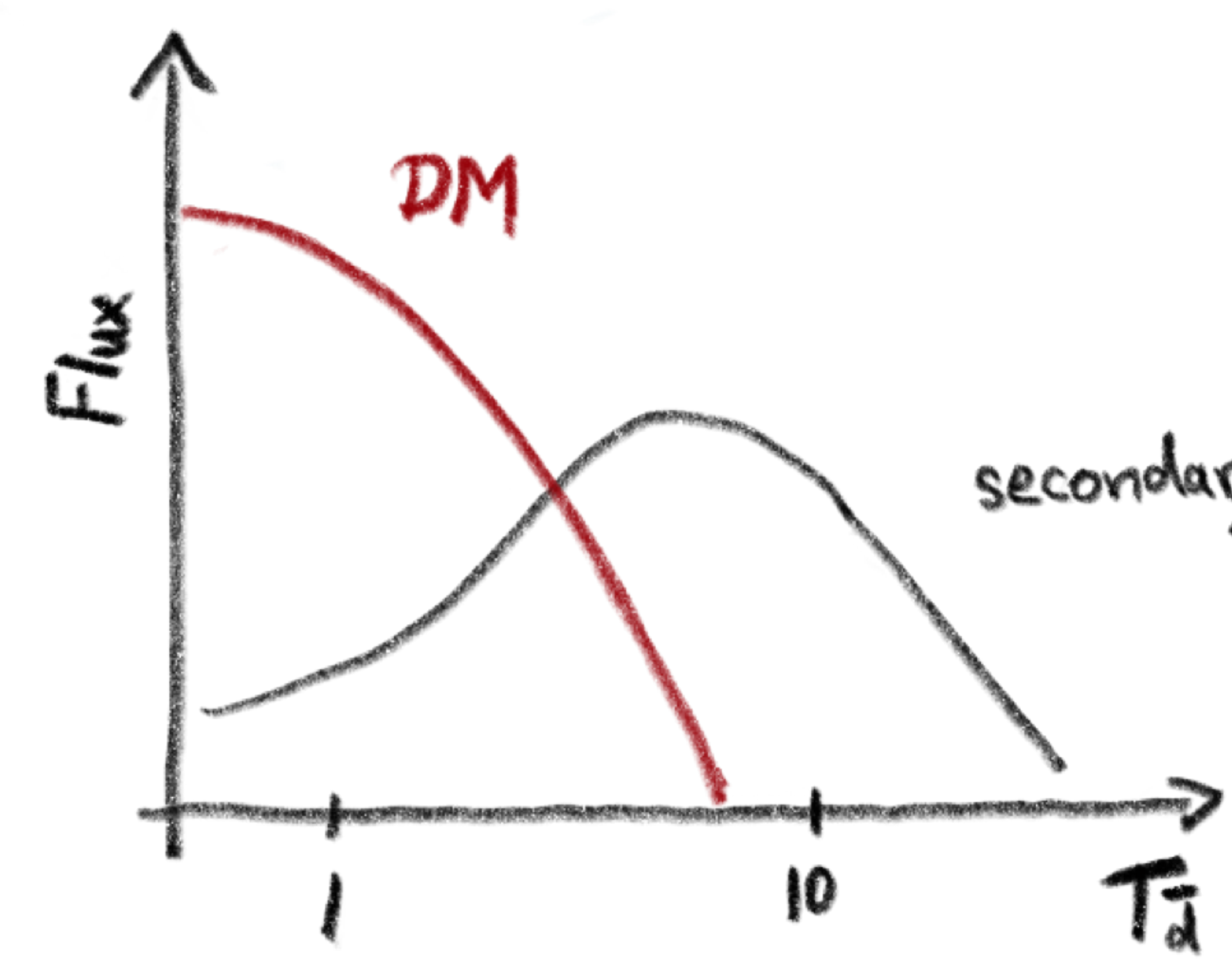
Low-energy suppression:

$$2E_p m_p + 2m_p^2 = \left[\begin{pmatrix}E_p\\ \vec{p}_p\end{pmatrix} + \begin{pmatrix}m_p\\ 0\end{pmatrix}\right]^2 = M_{sys}^2 \geq (4m_p + 2m_n)^2$$

$$\Leftrightarrow \boxed{E_p \geq 17 m_p}$$

DM

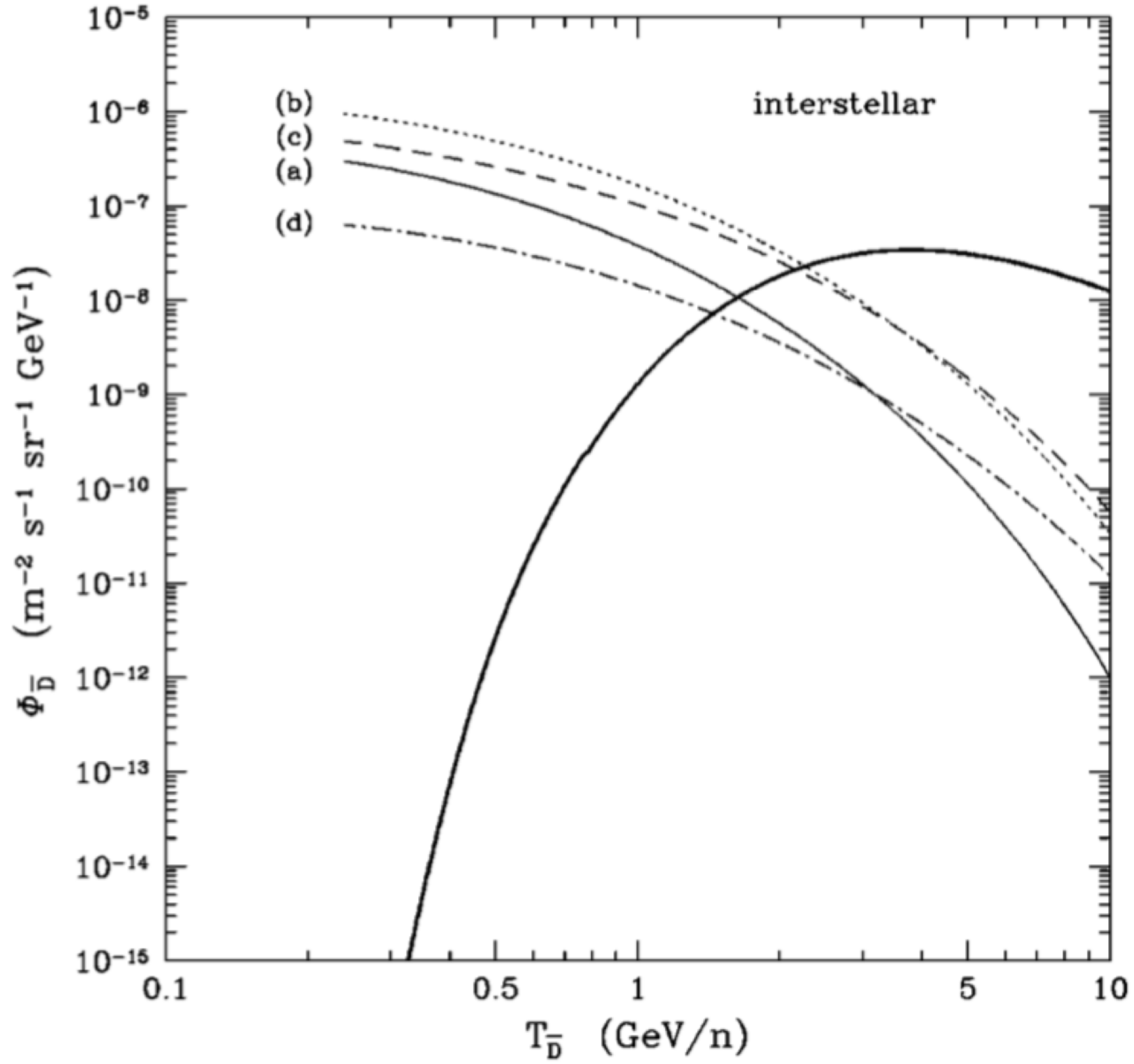
- Production by coalescence
- No low-energy suppression (annihilation at rest)



Antideuteron in CRs

- Secondary antideuteron
  - [Chardonnet, Orloff, Salati; 1997]
  - [Duperry, et al.; 2005]
  - [Blum, Ng, Sato, Takimoto; 2012]
  - …
- DM antideuteron
  - [Donato, Fornengo, Salati; 2000]
  - [Duperray, Protasov, Voronin; 2003]
  - [Ibarra, Tran; 2009]
  - [Brauninger, Cirelli; 2009]
  - …
- Mote Carlo based coalescence
  - [Kadastik, Raidal, Strumia; 2010] (PYTHIA)
  - [Ibarra, Wild; 2013] (PYTHIA)
  - [Fornengo, Maccione, Vittino; 2013] (PYTHIA)
  - [Herms, Ibarra, Vittino, Wild; 2017] (PYTHIA)
  - [Dal, Kachelriess; 2012] (HERWIG vs. PYTHIA)
  - [Dal, Raklev; 2014] (HERWIG)
  - …
- Antideuteron propagation
  - [Donato, Fornengo, Maurin, Slati; 2004]

[Donato, Fornengo, Salati; 2000]



Secondary:

$$E_{\bar{D}} \frac{d^3\sigma_{\bar{D}}}{dk^3_{\bar{D}}} = \frac{1}{\sigma_{\rm tot}} \frac{m_D}{m_p m_n} \frac{4\pi}{3} \frac{p^3_{\mathcal{C}}}{8} E_{\bar{p}} \frac{d^3\sigma_{\bar{p}}}{dk^3_{\bar{p}}} E_{\bar{n}} \frac{d^3\sigma_{\bar{n}}}{dk^3_{\bar{n}}}$$

DM:

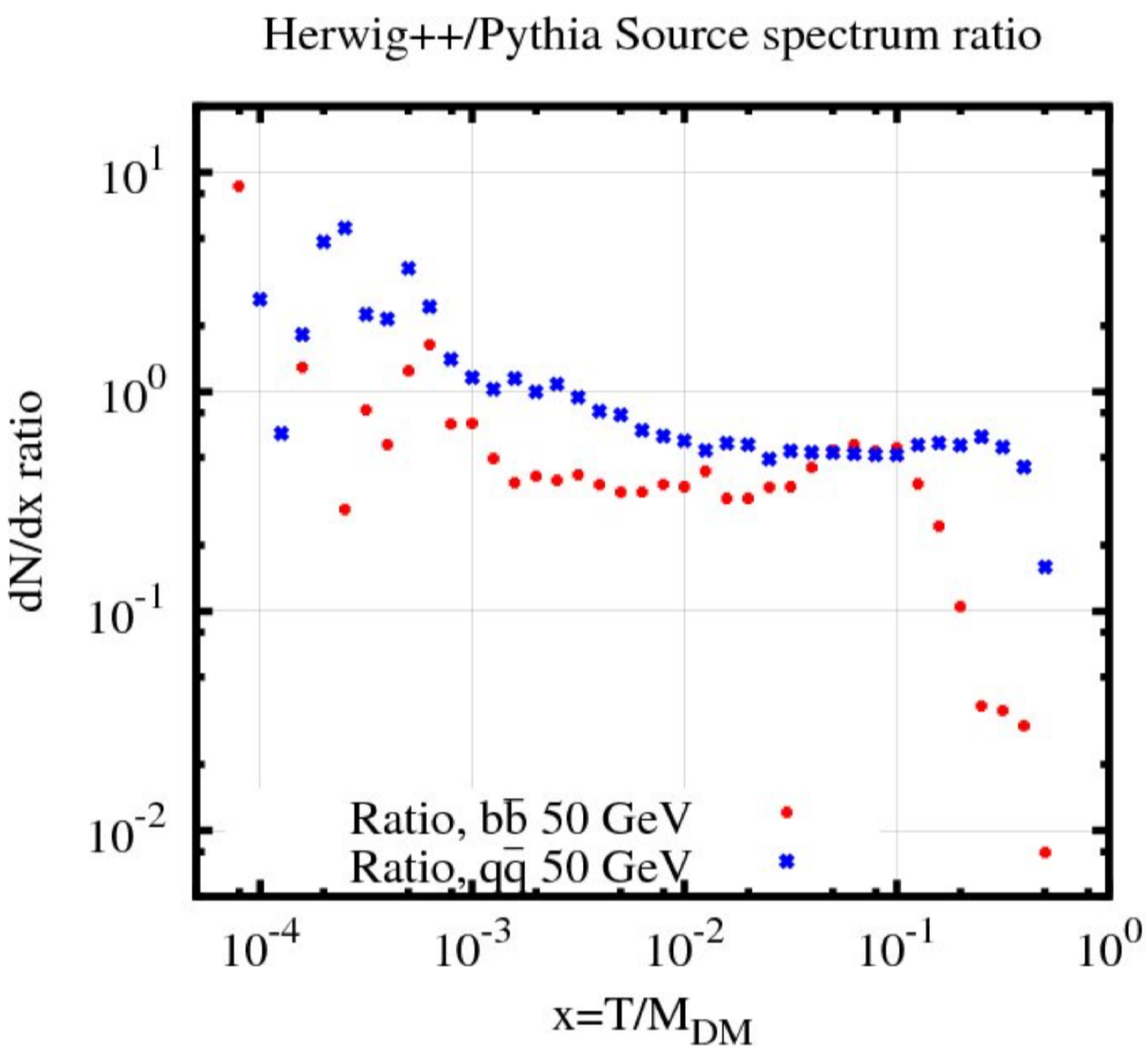
$$\frac{dN_{\bar{D}}}{dE_{\bar{D}}} = \frac{m_D}{m_p m_n} \frac{4}{3} \frac{p^3_{\mathcal{C}}}{8k_{\bar{D}}} \frac{dN_{\bar{p}}}{dE_{\bar{p}}} \frac{dN_{\bar{n}}}{dE_{\bar{n}}}$$

Antideuteron coalescence

- Historical approach: Analytic coalescence, assumes uncorrelated production of $p\bar{p}$ and $n\bar{n}$ pairs

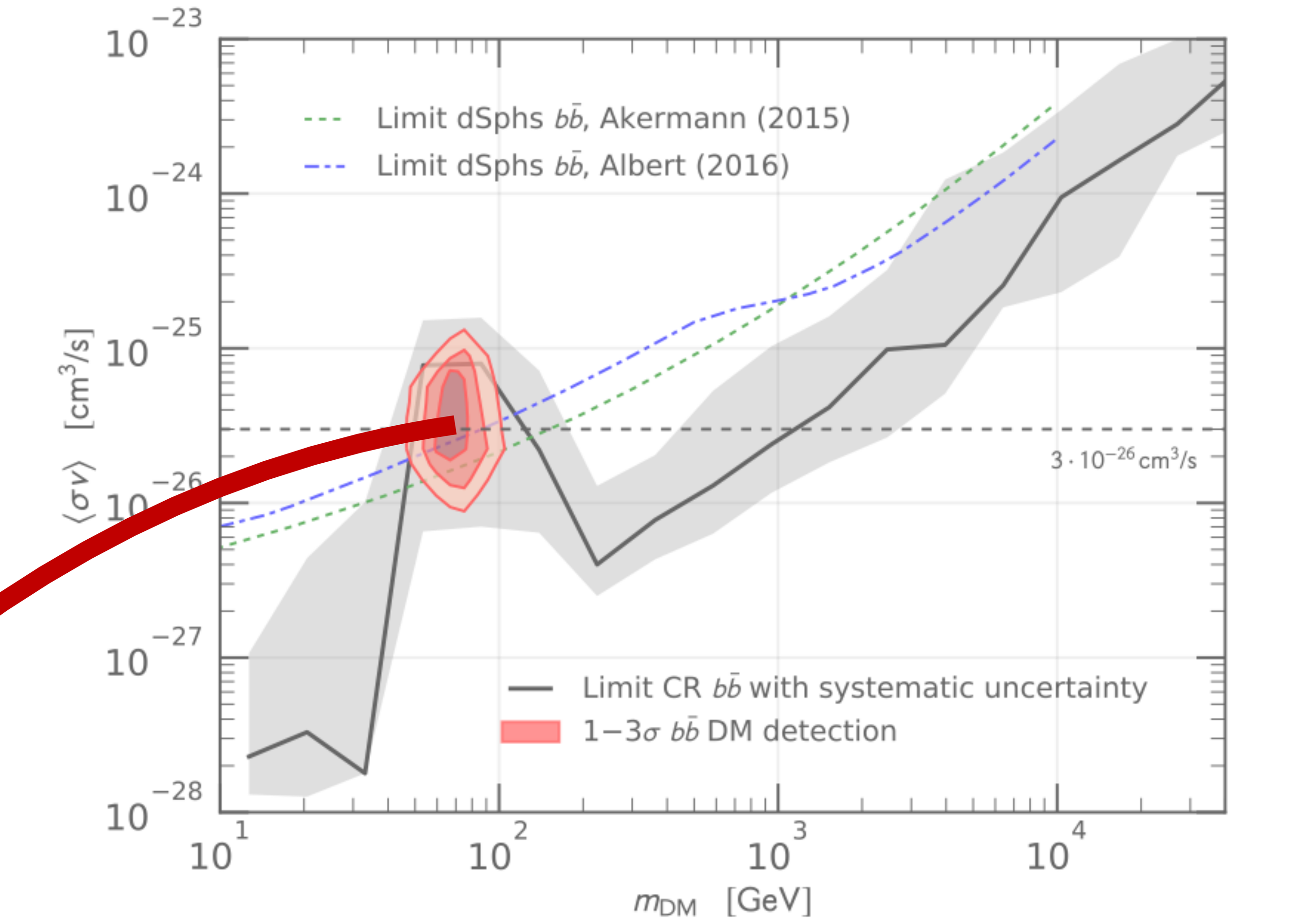
- Nowadays: Monte Carlo approach, coalescence criterium is checked on single event basis, **but** there are significant differences between generators

- Coalescence (might) depend on:
  - Final state
  - Initial state
  - Energy



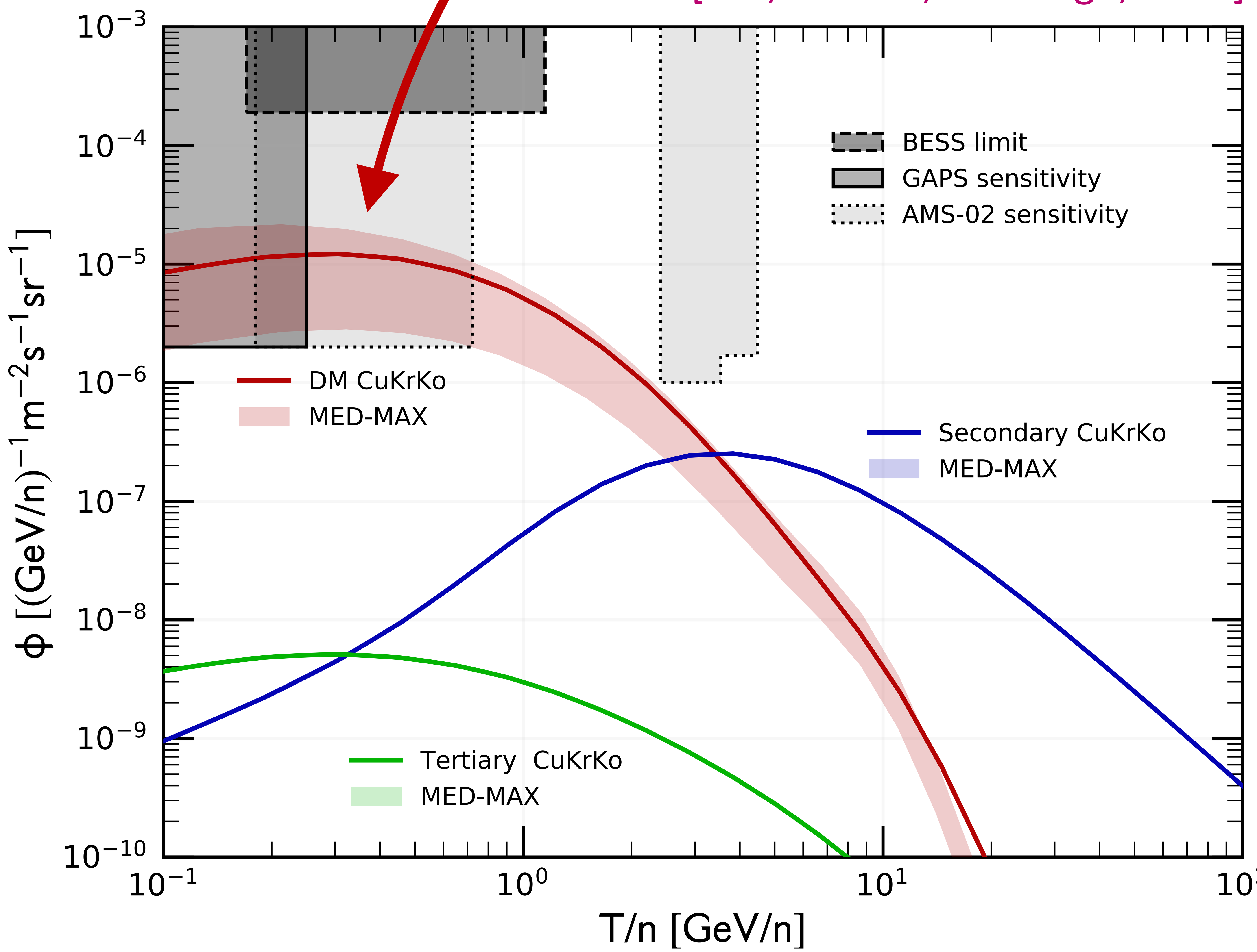
[Dal, Kachelriess; 2012]

Expected antideuteron flux



- We compute the antideuteron flux corresponding to the DM hint in CR antiprotons
- Our standard scenario:
  - Analytic coalescence
  - Coalescence momentum from ALEPH (Z decay)
  - Flux propagation with GALPROP
  - DM energy spectra from PPPC4DM (M. Cirelli)

[**MK**, Donato, Fornengo; 2018]



The DM hint from CR antiprotons is well within the antideuteron sensitivity of GAPS and AMS-02!

Systematic uncertainties

Coalescence momentum

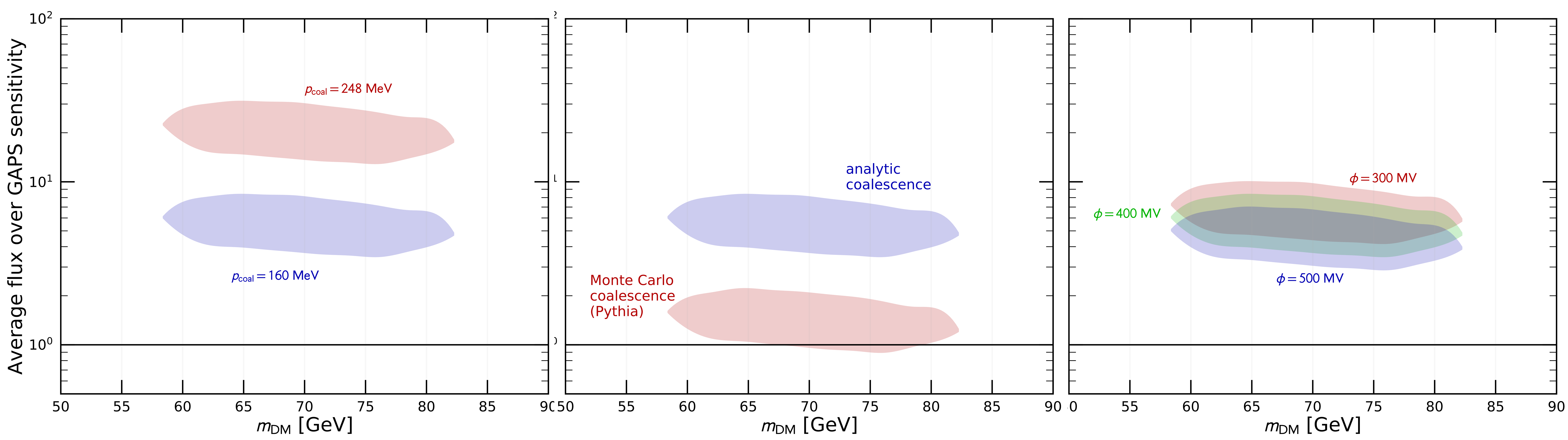
- p_c suggested by recent ALICE measurements would increases signal by a factor of 4

Coalescence approach

- Monte Carlo based coalescence might decrease GAPS signal by a factor of 4

Solar modulation

- Has only a small impact

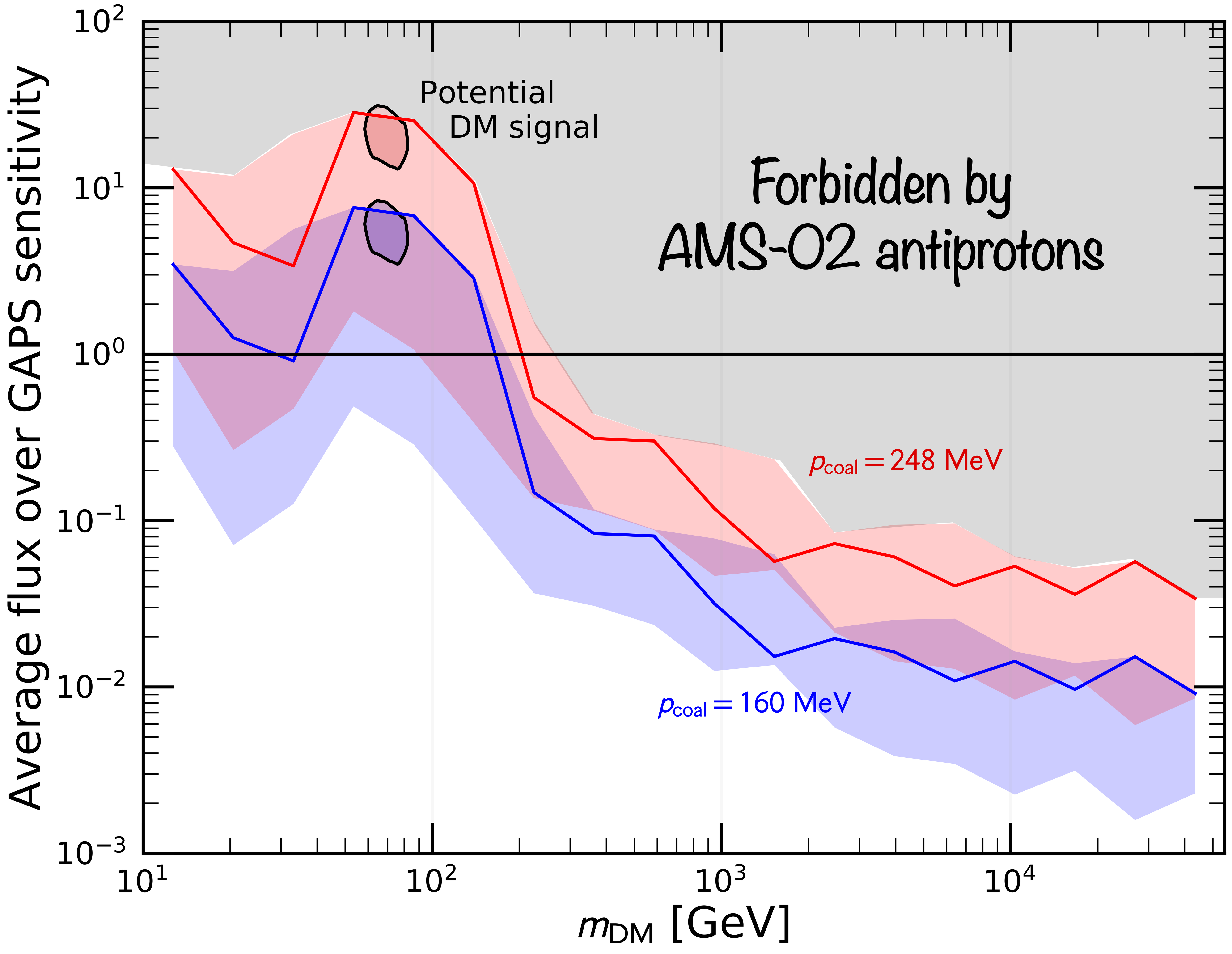


[MK, Donato, Fornengo; 2018]

Conservative approach: DM limits

- We calculate maximal antideuteron flux which does not violate limits derived from the AMS-02 antiproton flux measurements

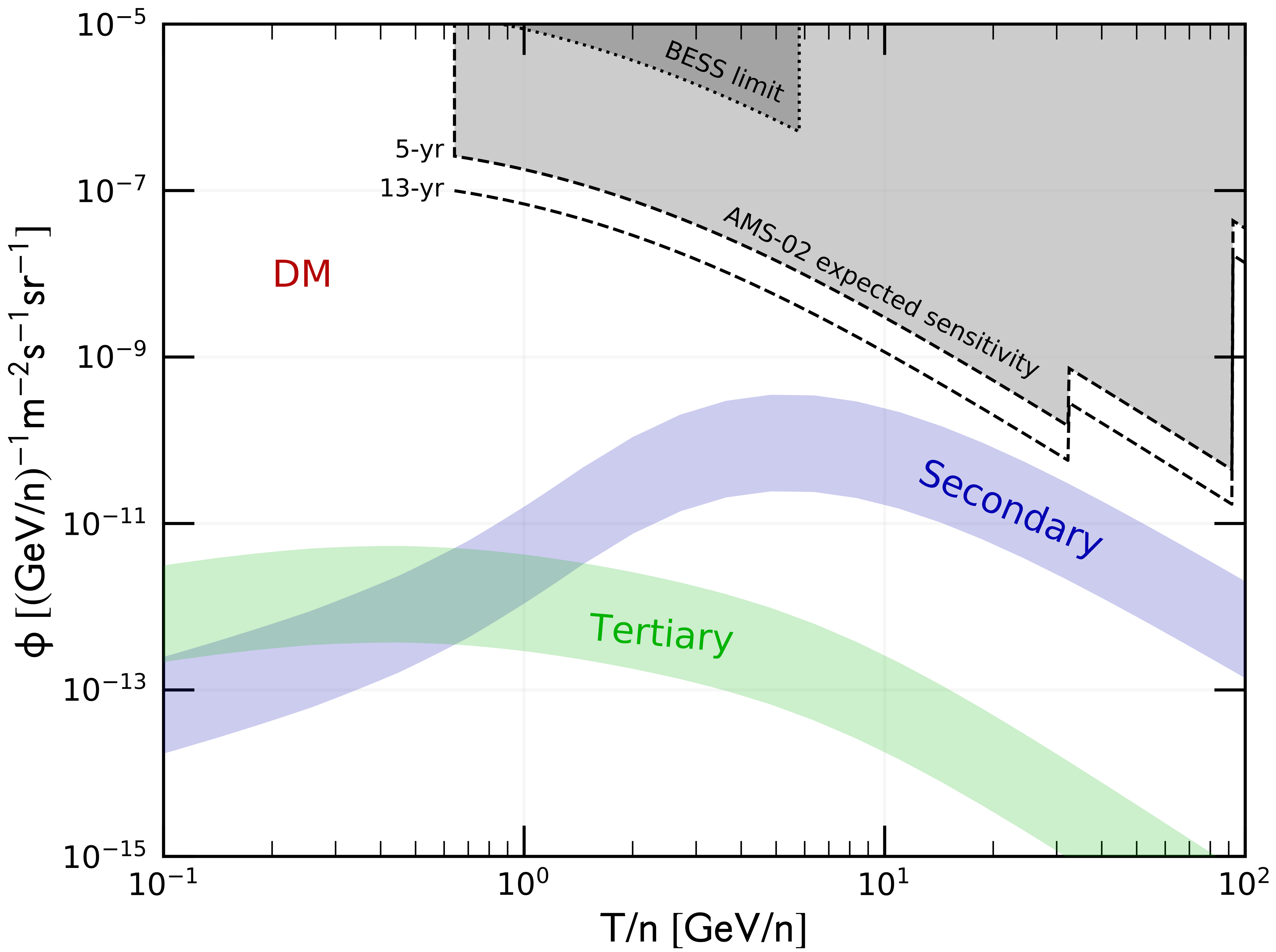
- GAPS may find anti-deuterons from DM with m_{DM} < 200 GeV (in the $b\bar{b}$ channel)



What about antihelium?

- In the standard scenario all the expected antihelium ($\overline{^3He}$) fluxes are at least one order of magnitude below the expected sensitivity of AMS-02
- With optimistic assumptions on the coalescence momentum secondaries are a factor 2 below the final AMS-02 sensitivity

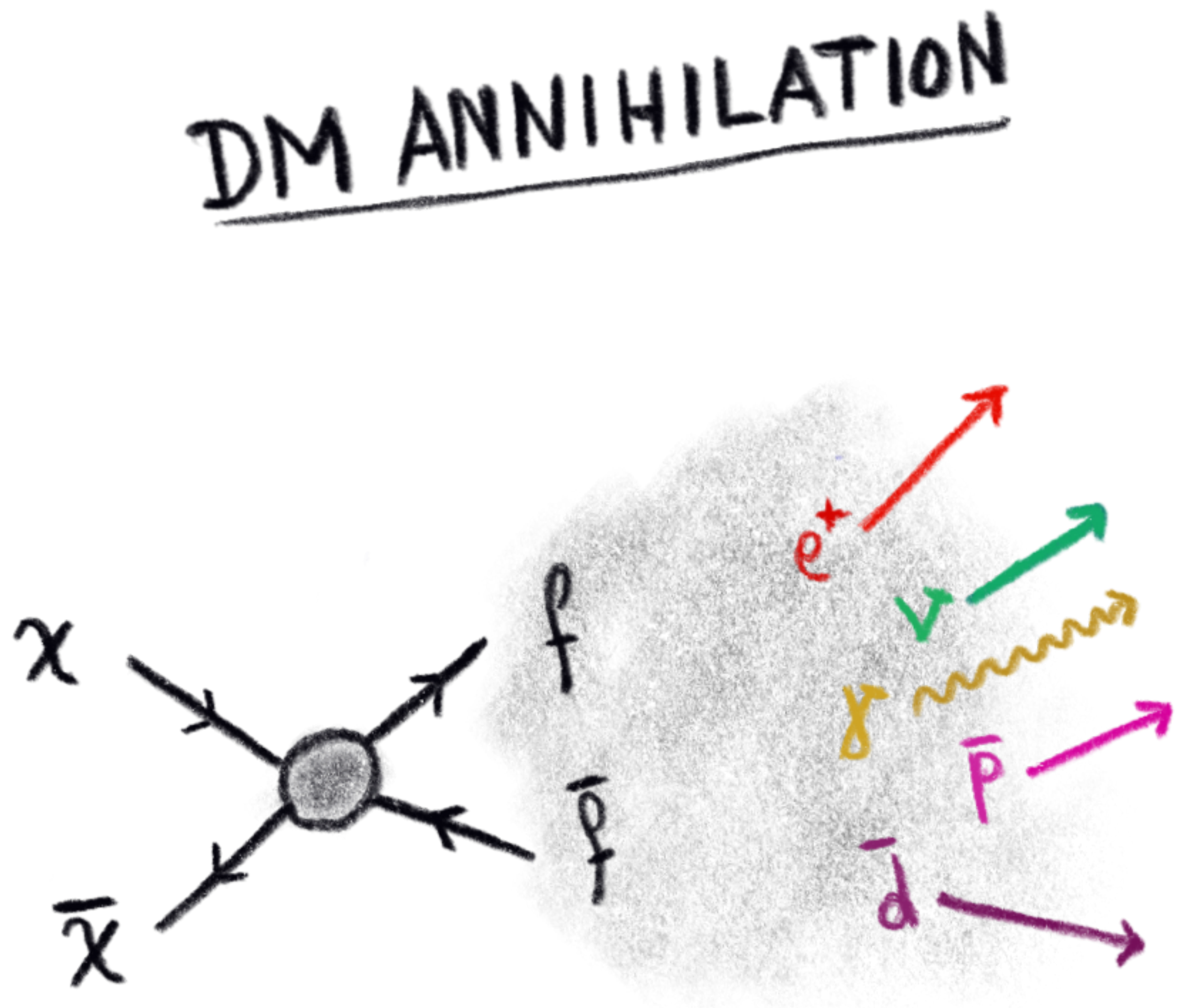
[**MK**, Donato, Fornengo; 2018]

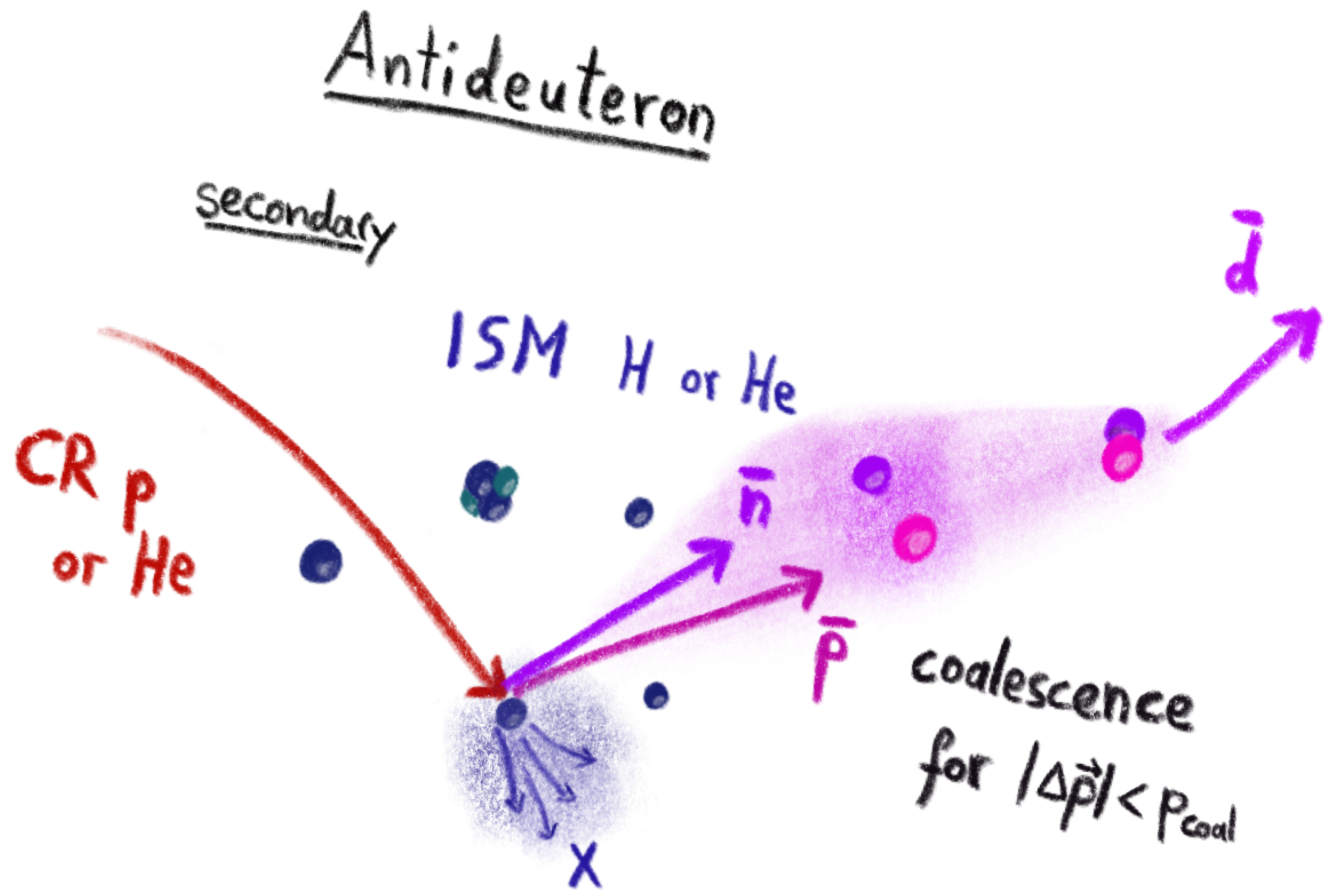


The band shows the range of coalescence momenta from ALEPH (Z-decay, p_c = 160 MeV) to recent ALICE measurements (pp collision at 7 TeV CM energy, p_c = 248 MeV)

Conclusion

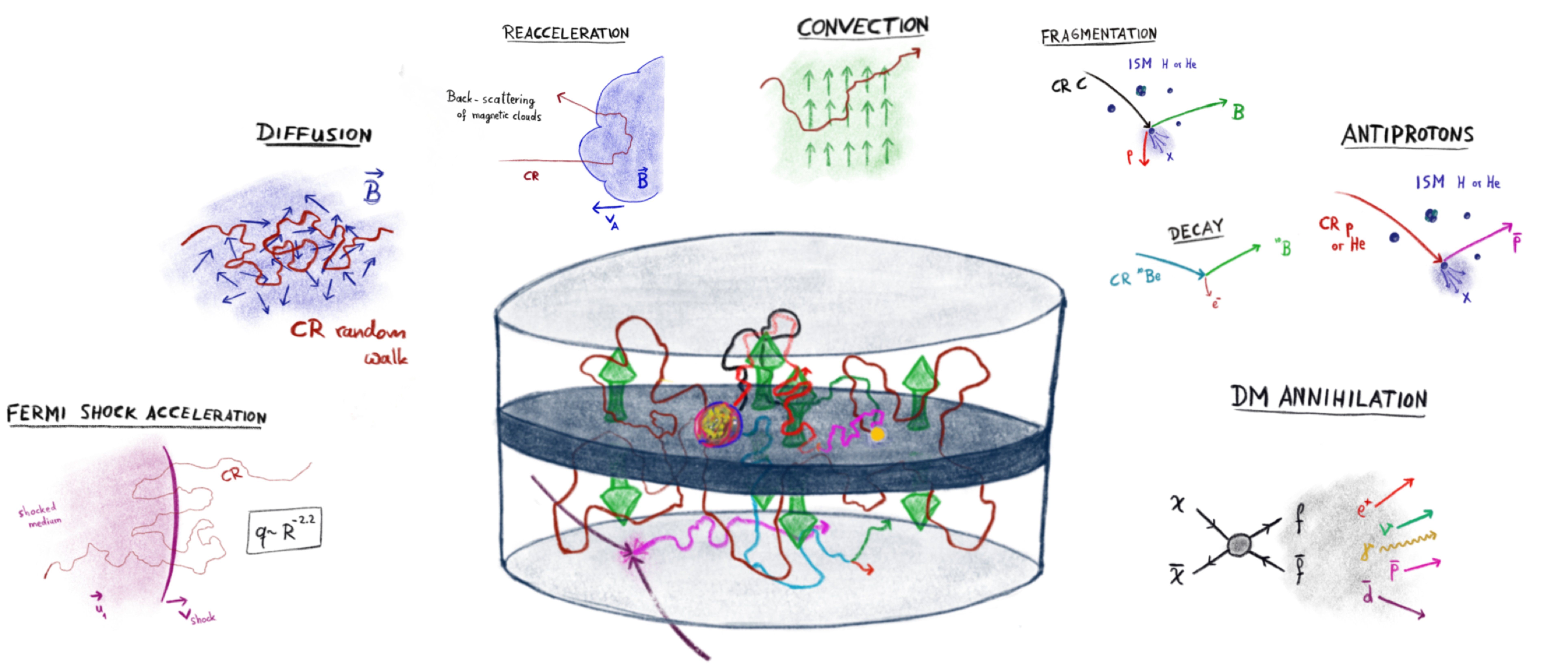
- GAPS will resolve whether the DM interpretation of the AMS-02 antiproton flux is correct
- Conservative interpretation: AMS-02 antiproton limits allow antideuteron observation by GAPS for m_{DM} < 200 GeV
- Antihelium predictions are below AMS-02 sensitivity



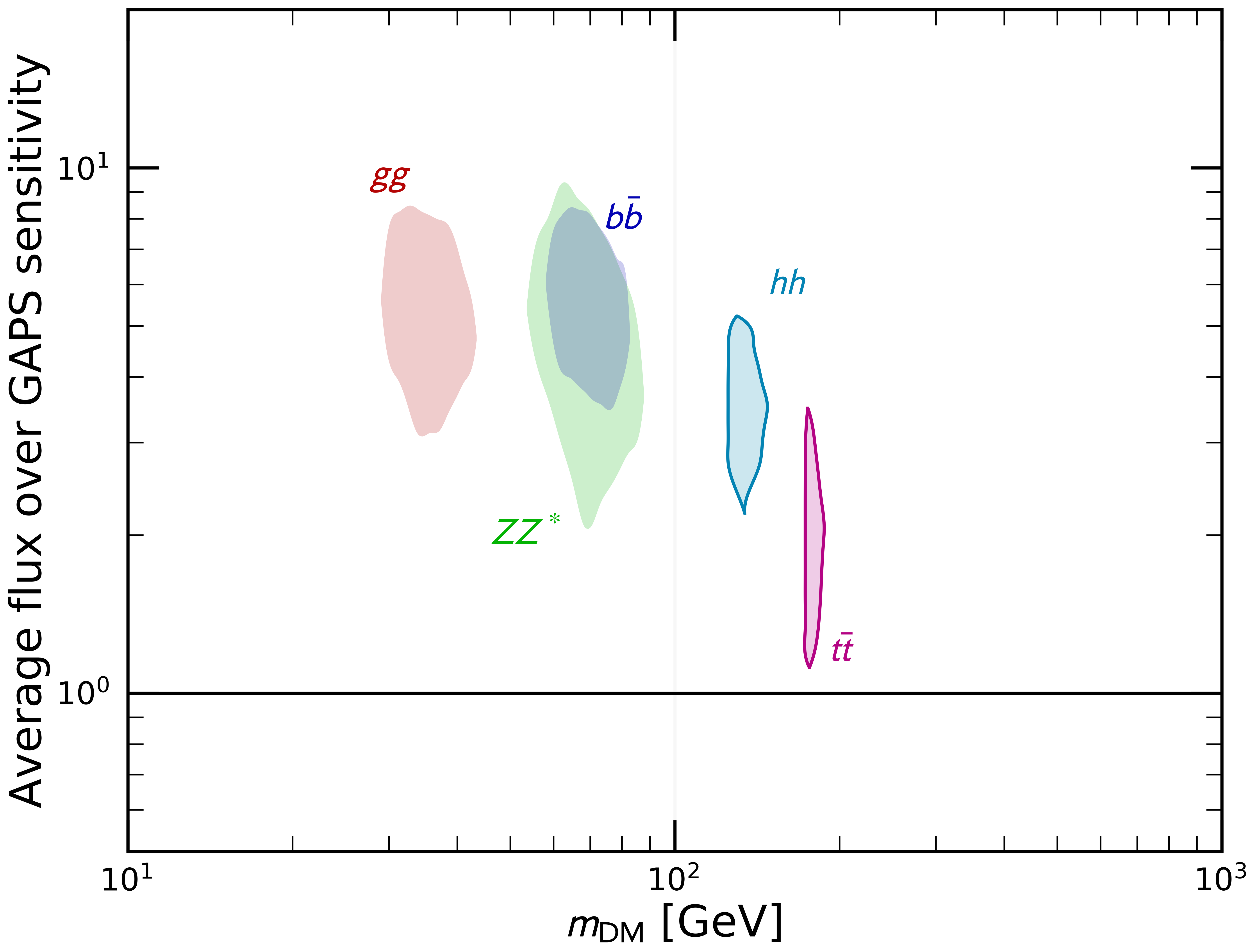


Thank you for your attention!

Backup


REACCELERATION
Back-scattering of magnetic clouds
CR
$\vec{B}$
v_A
CONVECTION
FRAGMENTATION
ISM H or He
CR C
B
p
x
DIFFUSION
$\vec{B}$
CR random walk
ANTIPROTONS
ISM H or He
CR p or He
$\bar{p}$
x
DECAY
CR ^{10}Be
^{10}B
e^-
FERMI SHOCK ACCELERATION
shocked medium
CR
$q \sim R^{-2.2}$
u_1
v_{shock}
DM ANNIHILATION
χ
$\bar{\chi}$
f
$\bar{f}$
e^+
ν
γ
$\bar{p}$
$\bar{d}$

[**MK**, Donato, Fornengo; 2018]



[Aramaki, et al; Phys.Rept. 618; 2016]