In Search of Cosmic-Ray Antinuclei from Dark Matter

Kerstin Perez MIT

On behalf of the many authors of:
Review of Cosmic Antinuclei Searches for Dark Matter
von Doetinchem, Perez+ JCAP (2020)
arXiv: 2002.04163

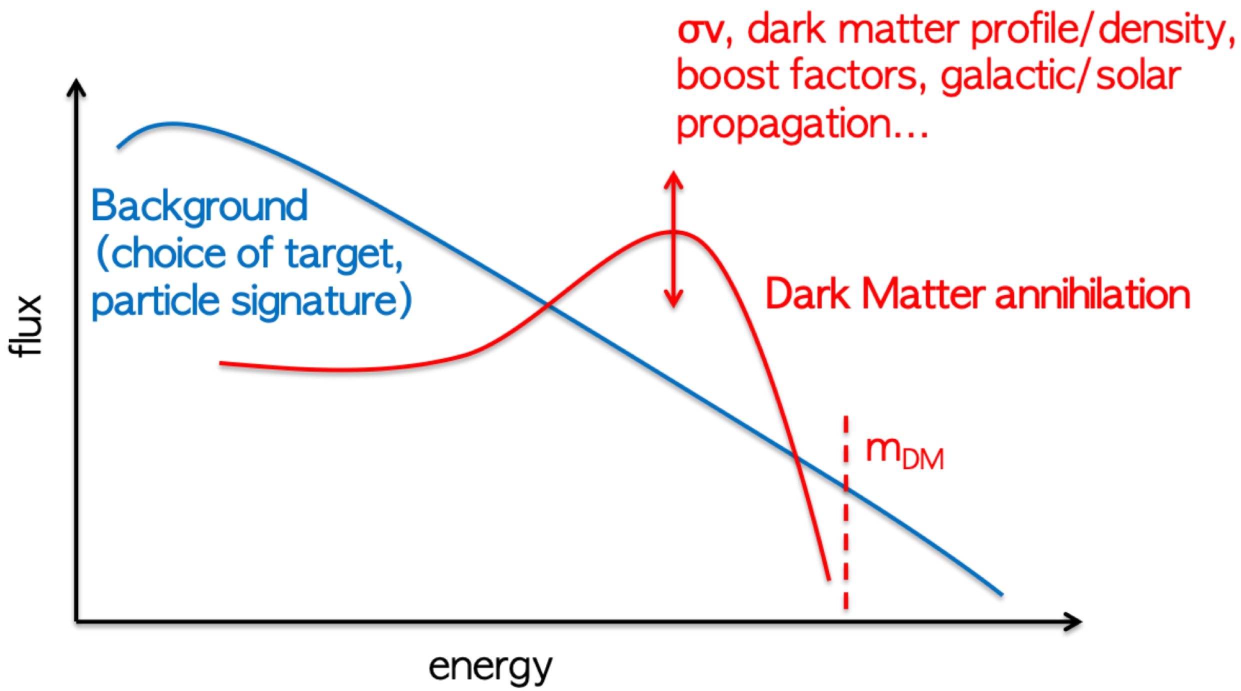
iDMEu Kickoff Meeting
May 11, 2021

* **Photo from 33 km up in the air!** Prototype GAPS balloon flight from Taiki, Japan in June 2012

Outline

- The (un)common challenges
- Current status of experimental searches:
  - Prospects for **antideuteron** signatures of dark matter
  - Antiproton constraints and **an excess?**
  - New physics in cosmic **antihelium?**
- Prospects for progress on modeling uncertainties:
  - Antiproton production cross sections
  - Antinuclei formation
  - Galactic and solar propagation

The challenge of astroparticle searches…

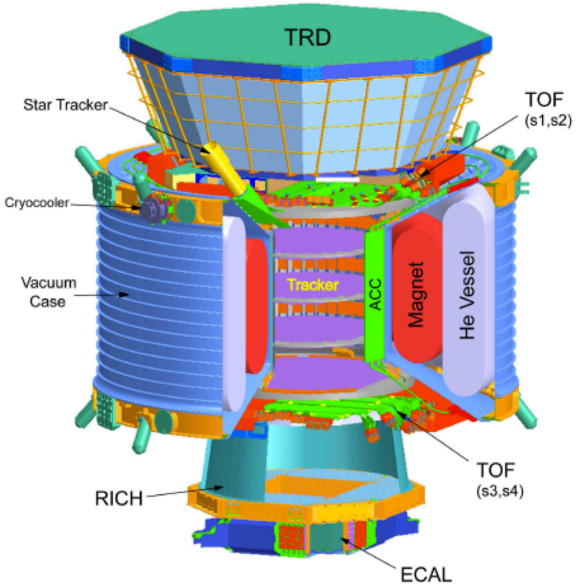


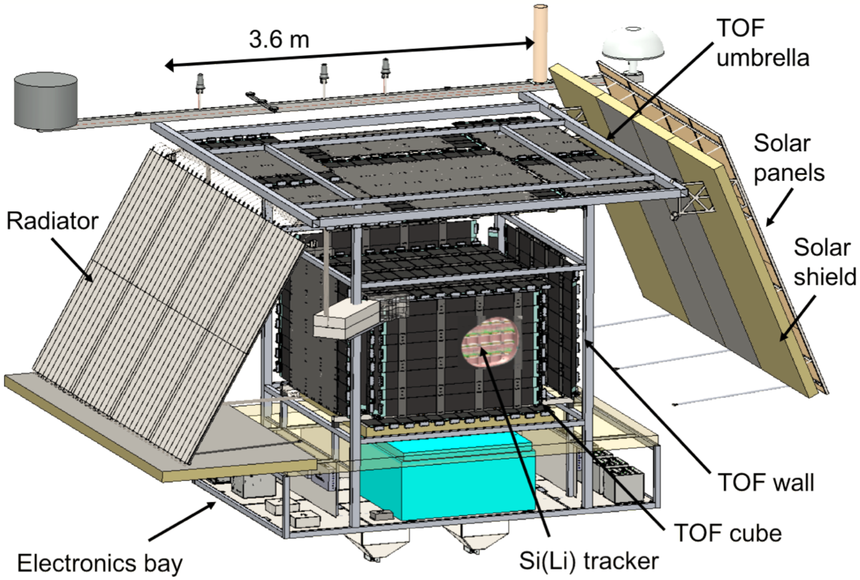
- Common challenge = minimize/constrain astrophysical background, maximize predicted dark matter signal

- Low-energy $\bar{d}$ give an essentially astrophysical background-free signature, i.e. *a rare-event search*
  - ***Un*****common challenge = large acceptance, particle mis-identification background (more similar to direct detection challenges)**

The Experiments: AMS and GAPS

Rare event search and first-time measurement!
Need multiple experiments with complementary experimental systematics

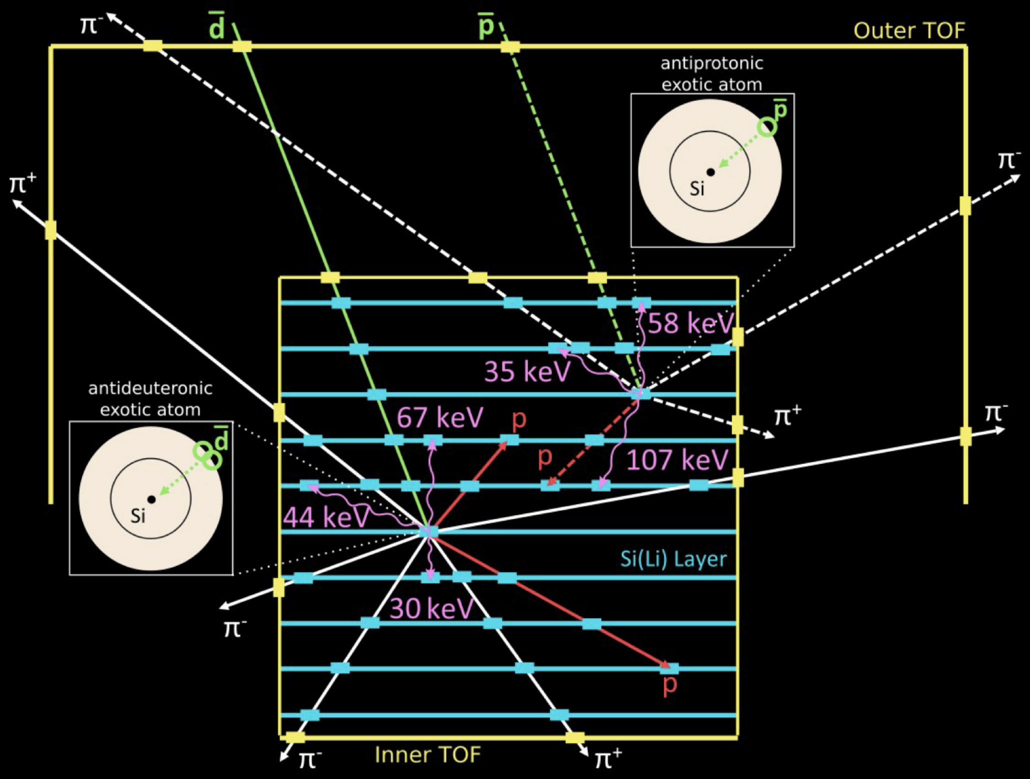




- AMS-02 has been in operation on the ISS since May 2011
- Magnetic spectrometer, combines signals from array of sub-detectors
- Advantages: high statistics spectra, comparison over solar cycle

- GAPS scheduled for initial Antarctic balloon flight late 2022
- Novel antiparticle detection method using exotic atom capture and decay
- Advantages: large acceptance, optimized for low-energy antiparticles

GAPS detection: exotic atom capture and decay



Time-of-flight system measures velocity and dE/dx, provides trigger

Si(Li) tracker acts as:

- ***target*** to slow and capture an incoming antiparticle into an exotic atom
- ***X-ray spectrometer*** to measure the decay X-rays
- ***particle tracker*** to measure the resulting dE/dX, stopping depth, and annihilation products

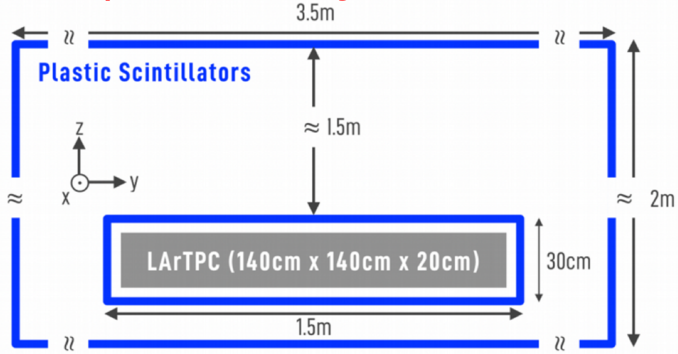
Extoic atom technique verified at KEK: Aramaki+ Astropart.Phys. 49, 52-62 (2013)
GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)
GAPS sensitivity to antiprotons: Aramaki+ Astropart.Phys. 59, 12-17 (2014)

Illustration credit:
A. Lowell (UCSD)

Large-area, low-cost Si(Li) detectors share challenges with nuclear experiments:
Perez+ 1807.07912 (2018), Kozai+ 1906.05577 (2019), Rogers+ 1912.06571 (2019), CPAD 1908.00194 (2019)

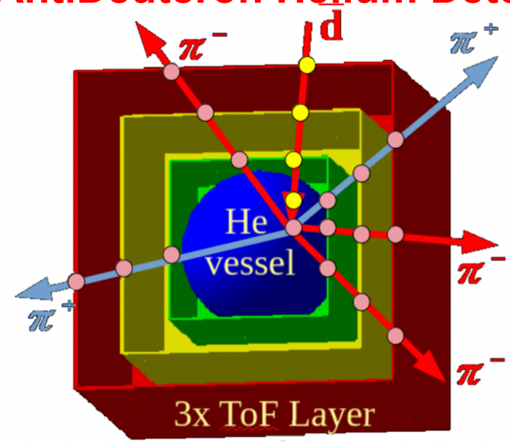
Beyond the current generation

GRAMS (Gamma-Ray and Antimatter Survey)



Balloon experiment for MeV gamma-rays via Compton scattering and antimatter via GAPS-like atomic atom signature Astropart. Phys. 114, 107 (2020)

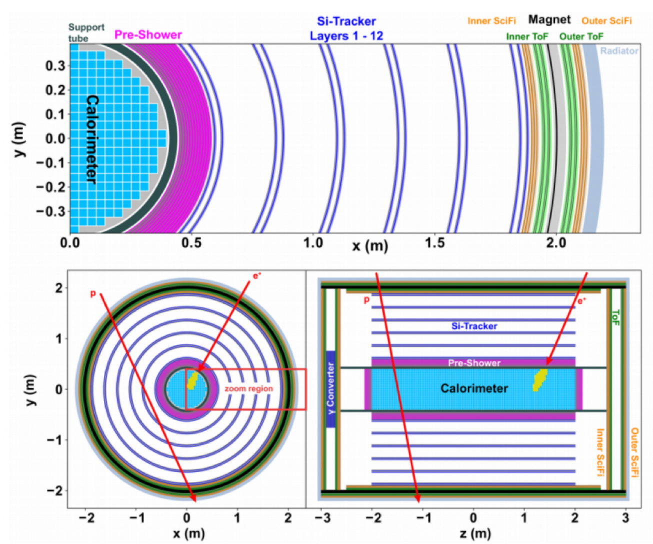
AntiDeuteron Helium Detector (ADHD)

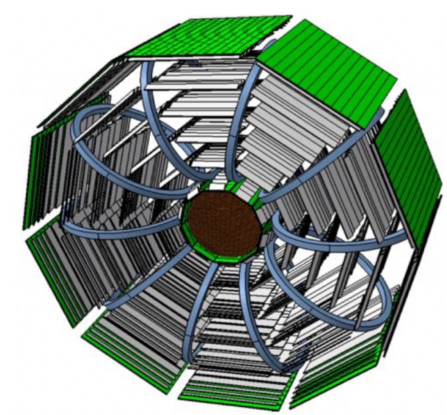


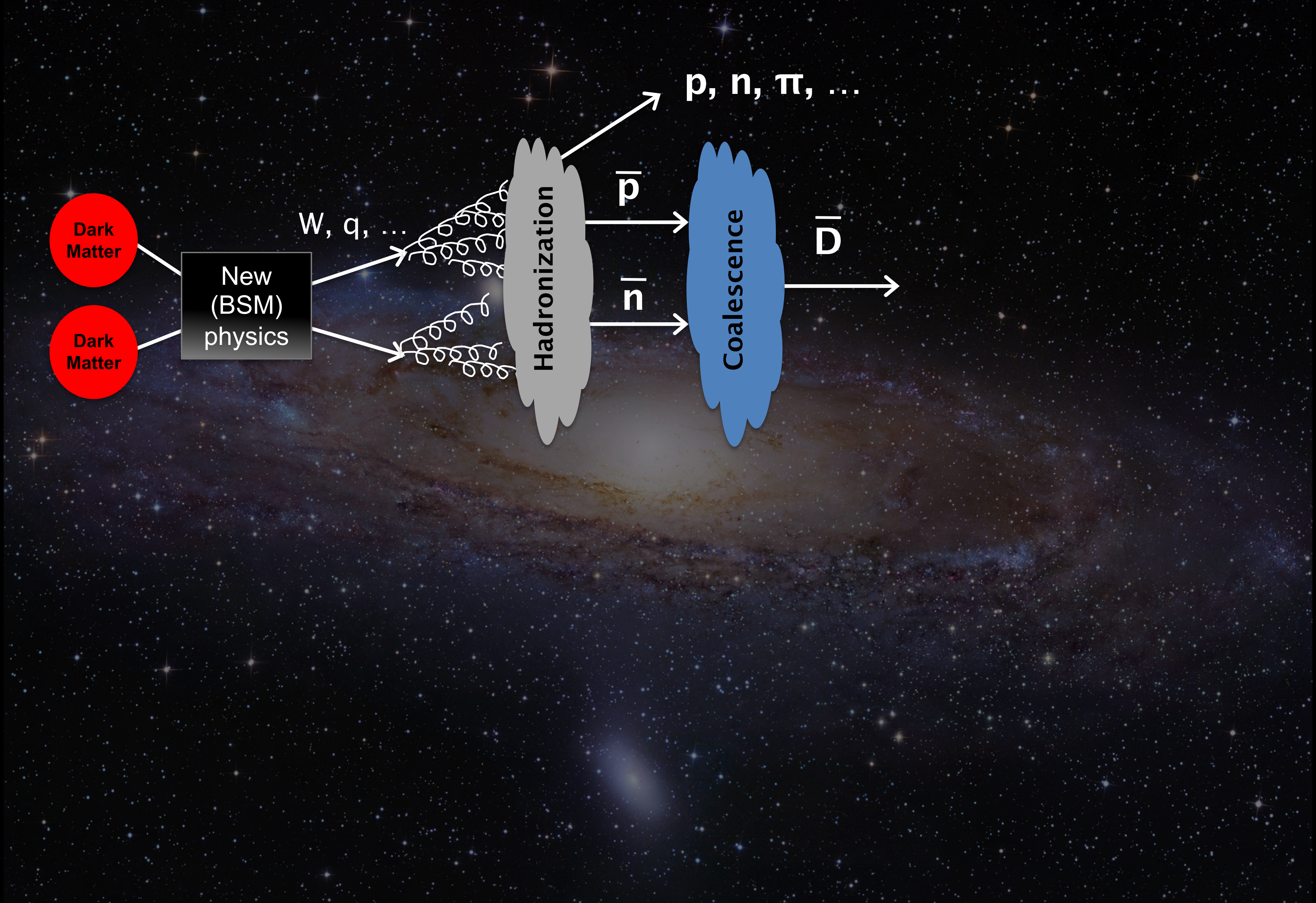
Use delayed annihilation of antinuclei in helium J. Phys. Conf. Ser. 1548 1, 012035 (2020)

AMS-100, ALADino

Space-based platforms at Lagrange Point 2 using a large-acceptance superconducting magnet NIM A 944 162561 (2019)

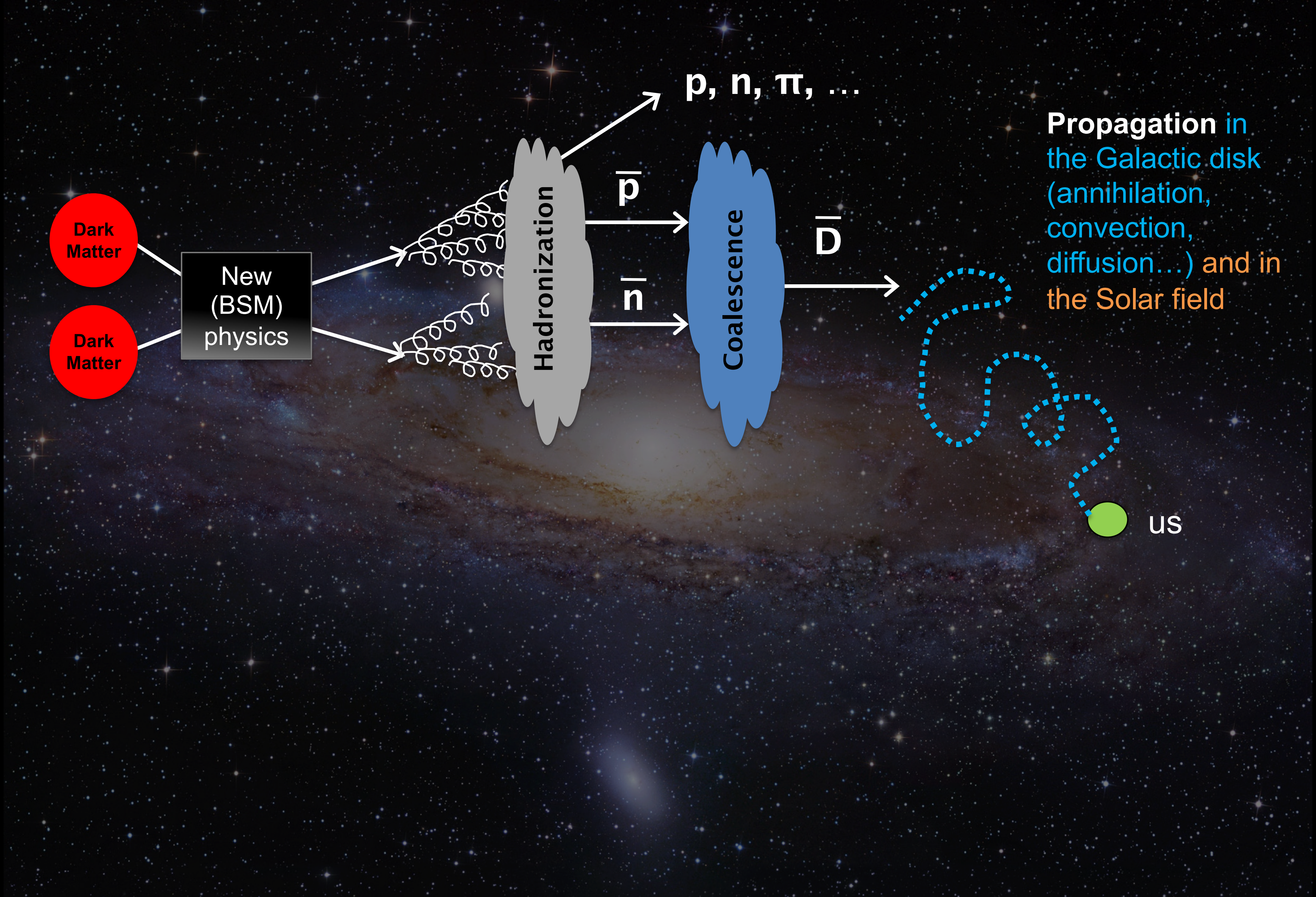






* Pretend this is our Galaxy

~~Andromeda Galaxy, Hubble telescope~~



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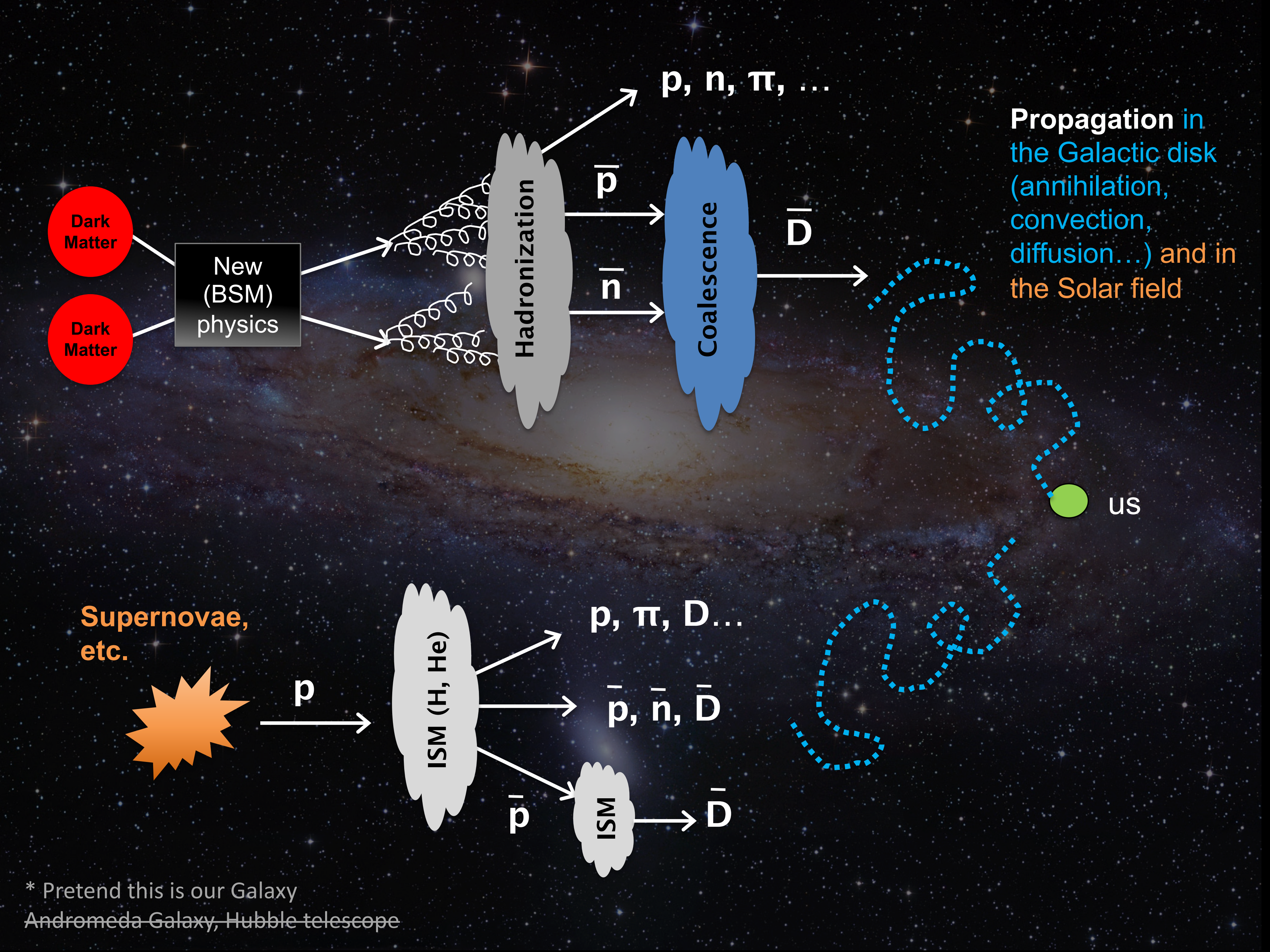
Dark Matter
Dark Matter
New (BSM) physics
Hadronization
p, n, π, …
$\bar{p}$
$\bar{n}$
Coalescence
$\bar{D}$
Propagation in the Galactic disk (annihilation, convection, diffusion…) and in the Solar field
us
Supernovae, etc.
p
ISM (H, He)
p, π, D…
$\bar{p}$, $\bar{n}$, $\bar{D}$
$\bar{p}$
ISM
$\bar{D}$
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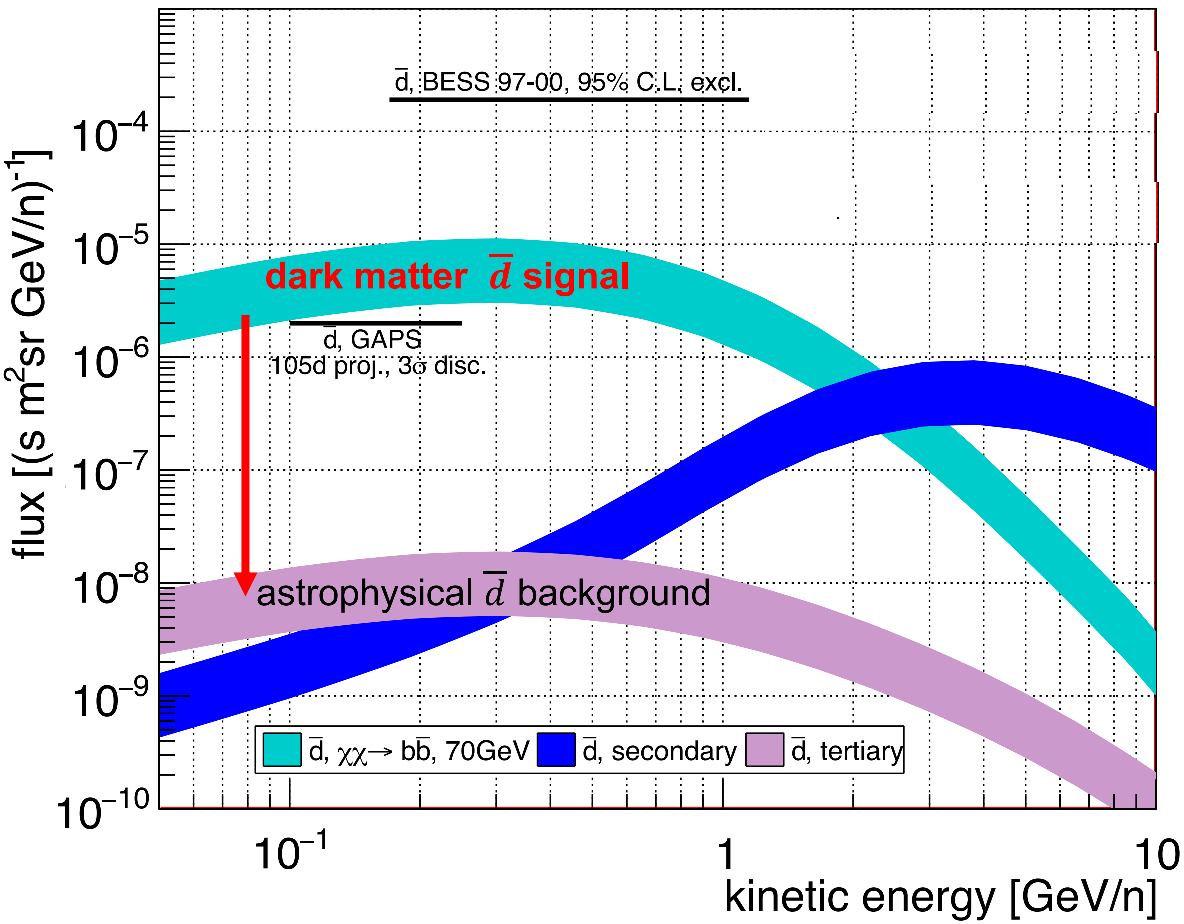
New physics in cosmic **antideuterons**

A generic ***new physics*** signature with *essentially zero* conventional astrophysical background

von Doetinchem, Perez+ 2002.04163 (2020)



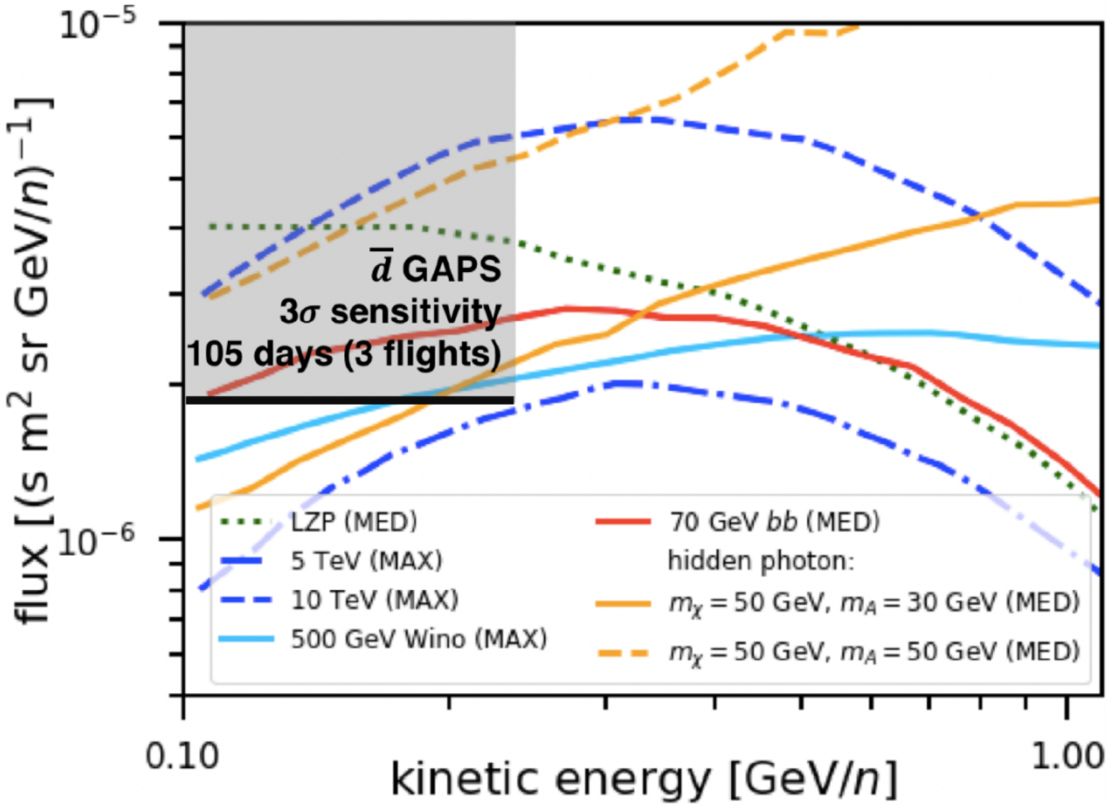
- Low-energy antideuteron background is kinematically suppressed:

  high energy threshold for antideuteron production
  + steeply falling incident cosmic ray spectra
  + low binding energy

- *Highly sensitive even considering modeling uncertainties (shaded bands)*

Complementary sensitivity to viable DM signatures

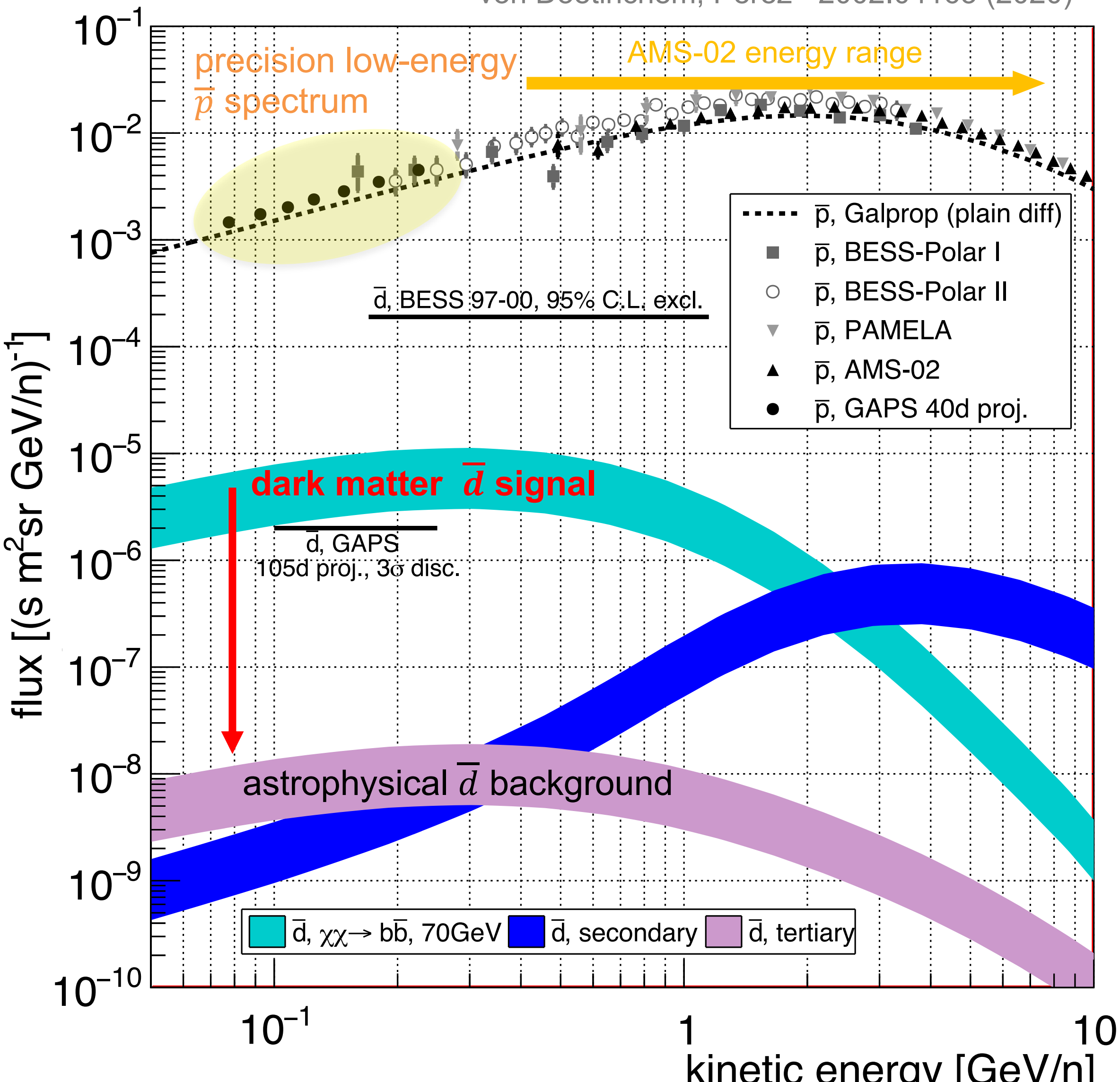
Korsmeier+ 1711.08465 (2018), Cui+ 1006.0983 (2010), Braeuninger+ 0904.1165 (2009), Hryczuk 1401.6212 (2014), Randall+ 1910.14669 (2020)



- Sensitive to ~10s of GeV mass dark matter models, ***as invoked to explain gamma-ray and antiproton observations***
- Sensitive to heavy dark matter models, ***as invoked to explain positron observations***
- Unique sensitivity to ***hidden sector models***

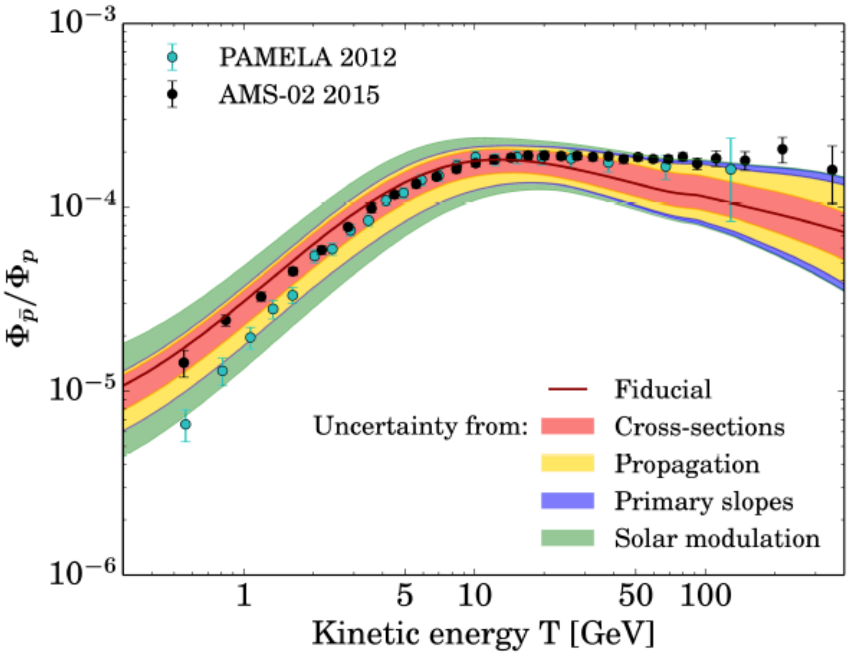
New physics in cosmic antideuterons & **antiprotons**

von Doetinchem, Perez+ 2002.04163 (2020)

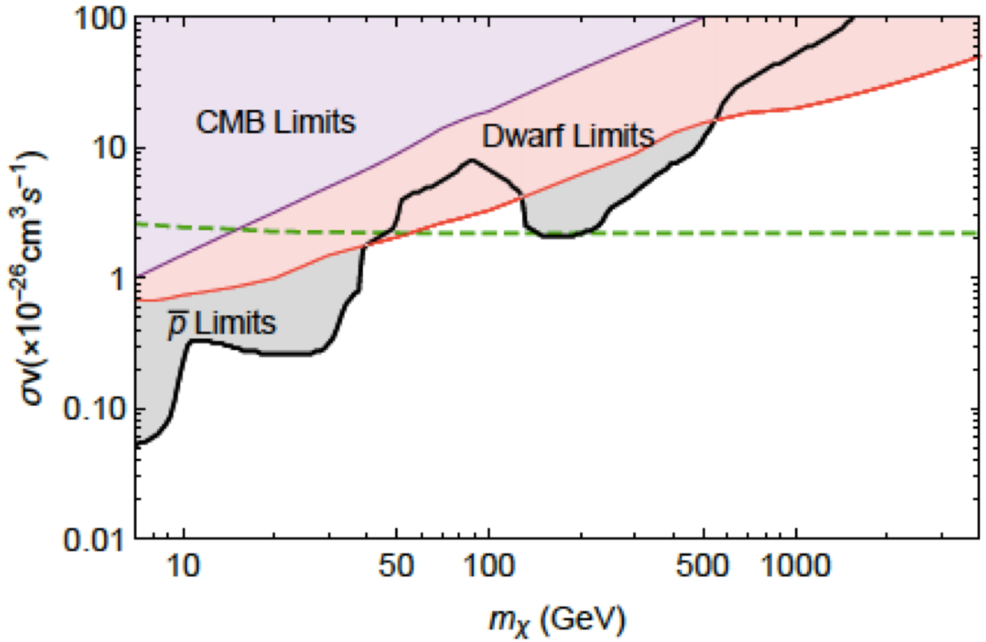


- Since the 1970s, antiproton experiments have developed from a first-time detection into a precision tool for dark matter studies and cosmic-ray physics
- AMS-02 providing high-statistics measurement as function of solar cycle
- GAPS will expand the precision antiproton spectrum into an unexplored low-energy range

Antiprotons: dark matter limits



G. Giesen+(2015)



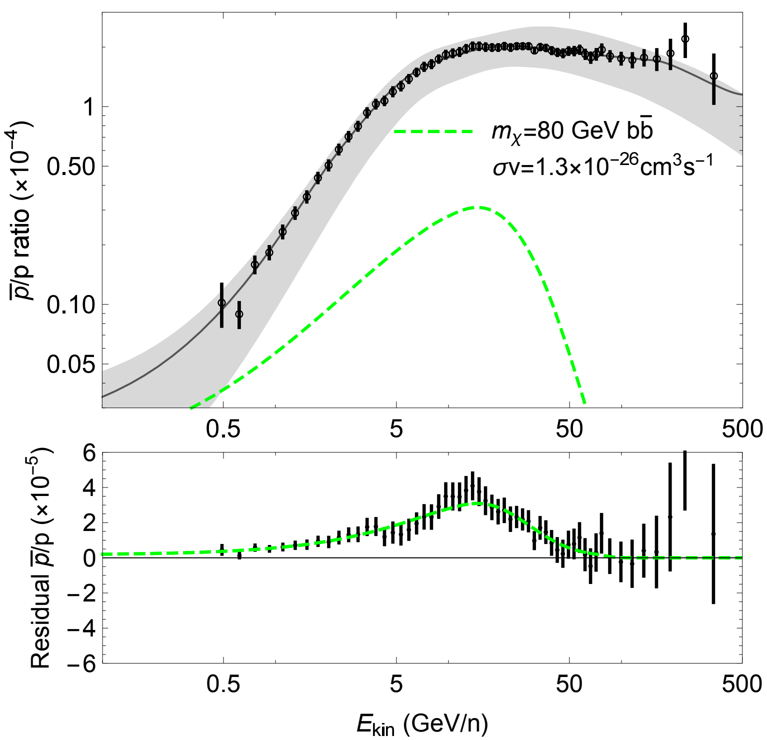
I. Cholis+(2019)

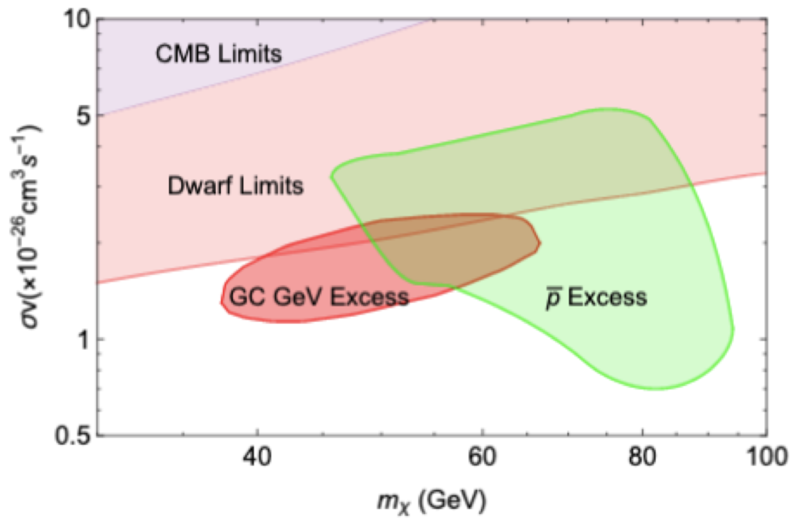
- High-precision AMS measurement prompts improved modeling of production cross-sections and propagation
- Strongest constraints on dark matter annihilation (to b-bbar) below 40 GeV

Current status: an antiproton excess?

↓ Possible excess in ~5-20 GeV antiprotons, at level of few % of total flux,
Signal from ~30-80 GeV dark matter?

Cuoco+(2016), Cui+(2016),
Cui+ (2018), A. Cuoco+ (2019), Cholis+ (2019)





↑ Antiproton signal consistent with Galactic center GeV excess

Interpretation depends on Galactic and Solar propagation, antiproton production uncertainties, *possible correlated systematic uncertainties from AMS*

New physics in cosmic **antihelium?**

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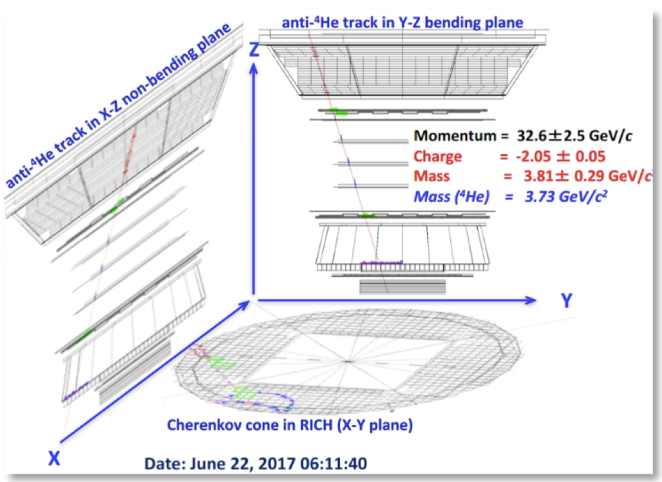
AMS Candidate Anti-He4 event (p = 32.6 GeV/c)



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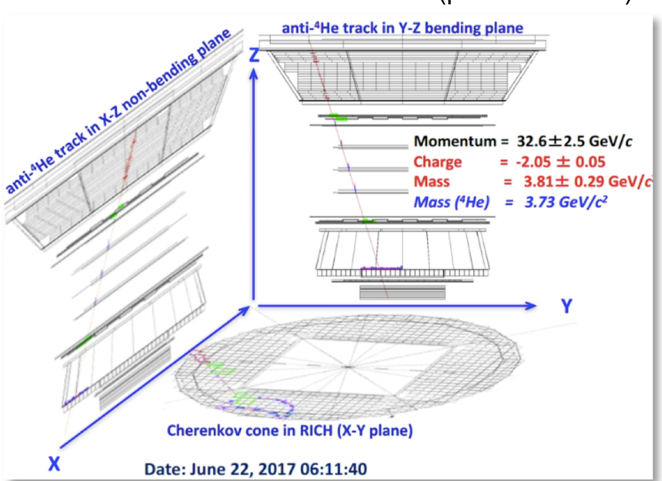
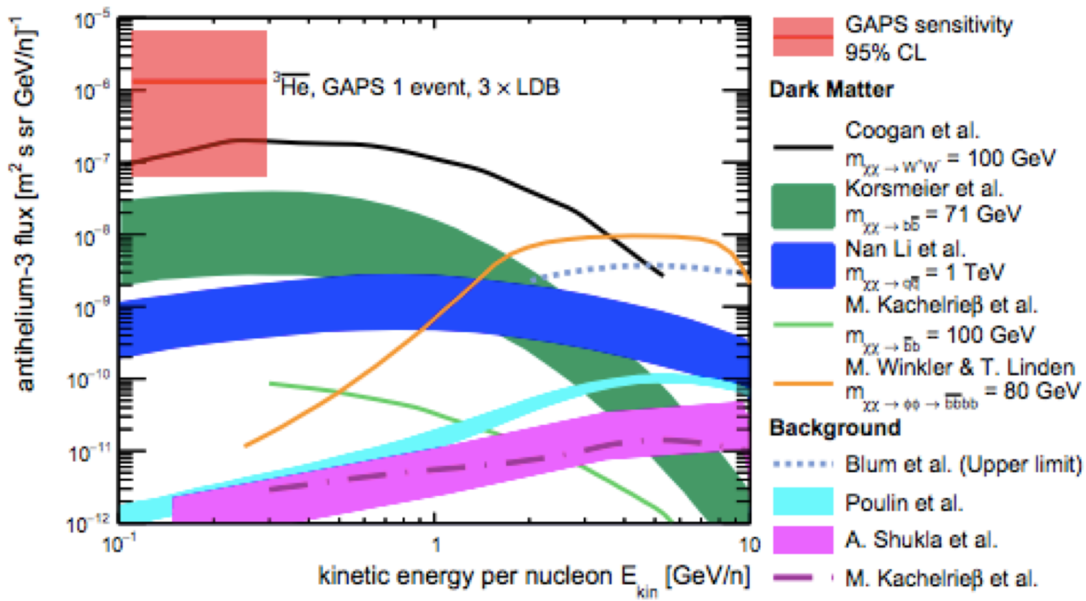
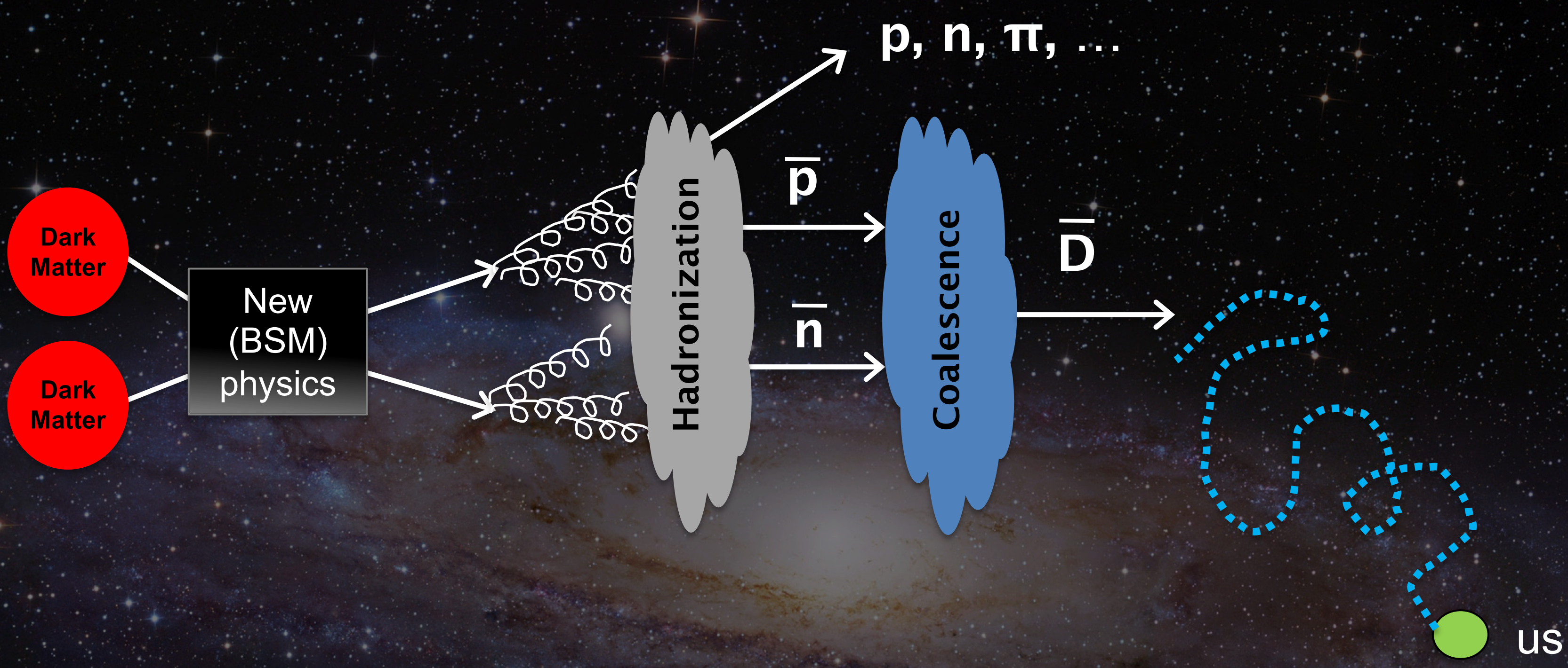


Saffold+ (GAPS collab.) arXiv:2012.05834 (2020)



- GAPS only experiment capable of confirming signal
- Orthogonal detection technique
- Uniquely low-background energy range



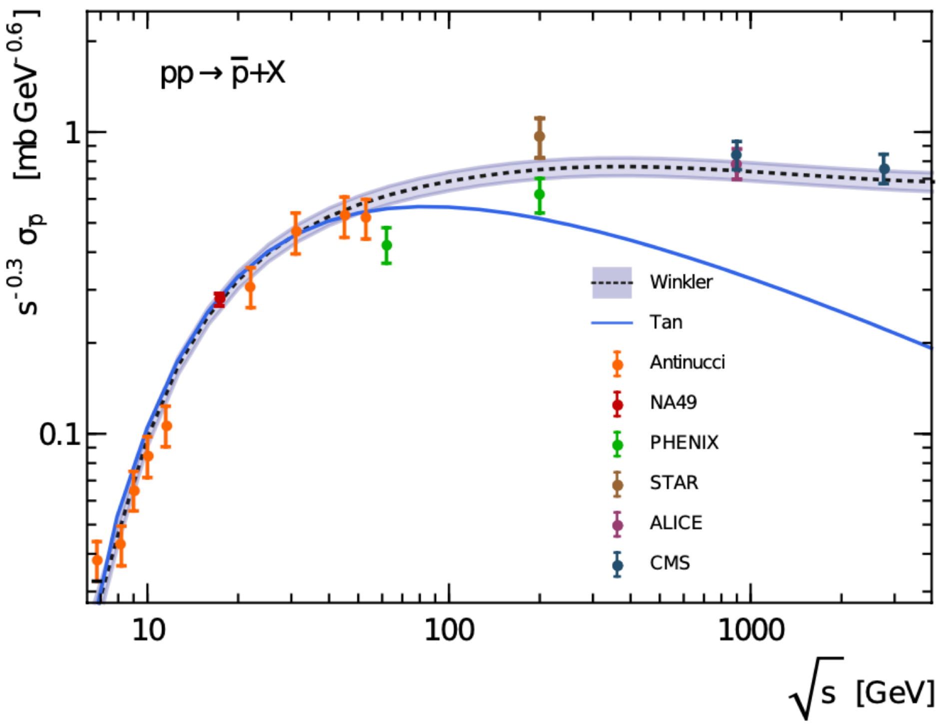
Challenges for comparing antinuclei results with other methods:

1. Antiproton production cross sections
2. Antinuclei formation
3. Propagation in the Galactic disk and Solar field

* Pretend this is our Galaxy
~~Andromeda Galaxy, Hubble telescope~~

Antiproton production

Winkler+ arXiv:1610.03071 (2017)



← At high energies, AMS-02 antiproton spectrum showed excess over predictions

New parameterization at √s > 100 GeV from PHENIX, STAR, CMS, ALICE (along with updated B/C ratio) relieved this tension

↑ At √s < 20 GeV, NA61/SHINE has provided new cross section measurements

- Uncertainties remain ~10-20% at AMS-02 energies
- Larger uncertainties at lower energies, for p+N processes
- Future measurements at lower energies of p+N processes (e.g. LHCb) could improve

Antinculei Formation: Coalescence Model

Coalescence: n̄ and p̄, merge when relative momentum < $\mathbf{p_0}$ (Yield ~ p_0^3)

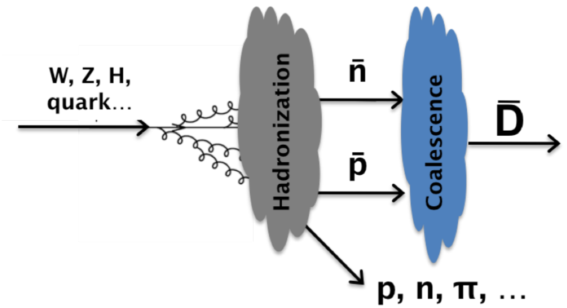
To determine p_0:

- MC generator with antideuteron "afterburner" accounts for correlations due to production channel or center-of-mass energy
- All depends on choice of **hadronization** model (and antiproton cross sections)
- Then tune this to experimental data

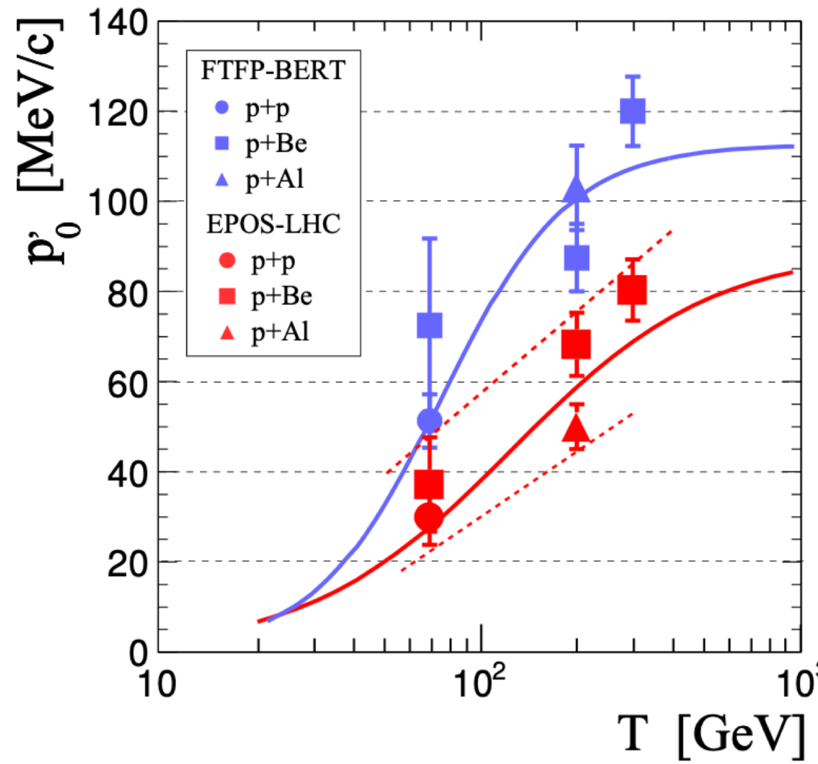
Current status: a dominant uncertainty of ~10x on low-E antideuteron production

Prospects for improvement (soon!): measurements at NA61/SHINE, COMPASS, LHCb, ALICE

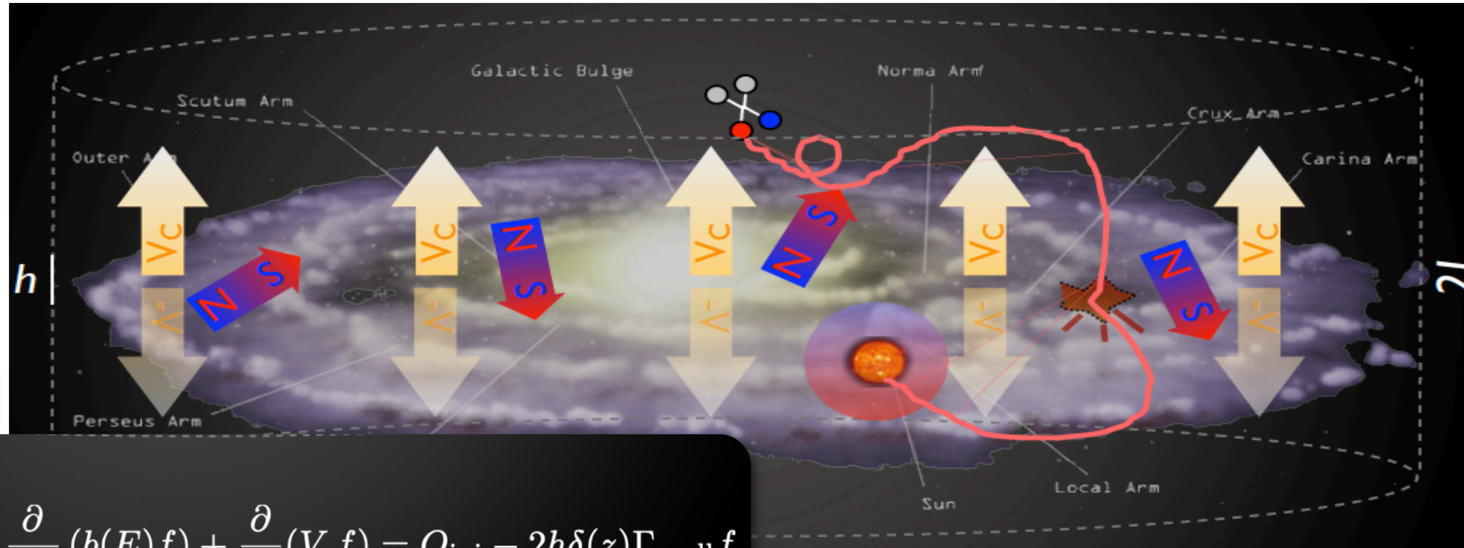
See also: freeze-out from a quark-gluon plasma aka "**statistical thermal model**", e.g. Floris 1408.6403 (2014), Bellini+Kalweit 1807.05894 (2019)



D.-M. Gomez-Coral+ arXiv:1806.09303 (2018)



Propagation of Charged Cosmic Rays



M. Cirelli (TAUP 2015)

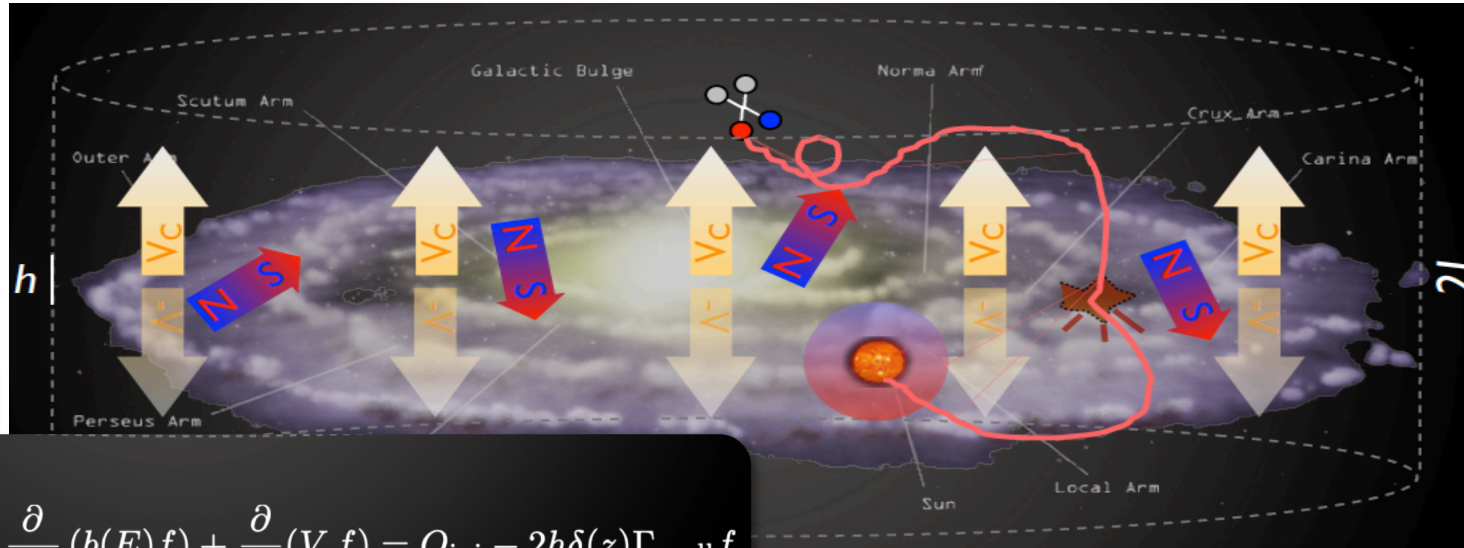
spectrum

$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion | energy loss | convective wind | source | spallations

- Diffusion, convection, annihilation parameterized in MAX, MED, MIN Galactic transport models

Propagation of Charged Cosmic Rays



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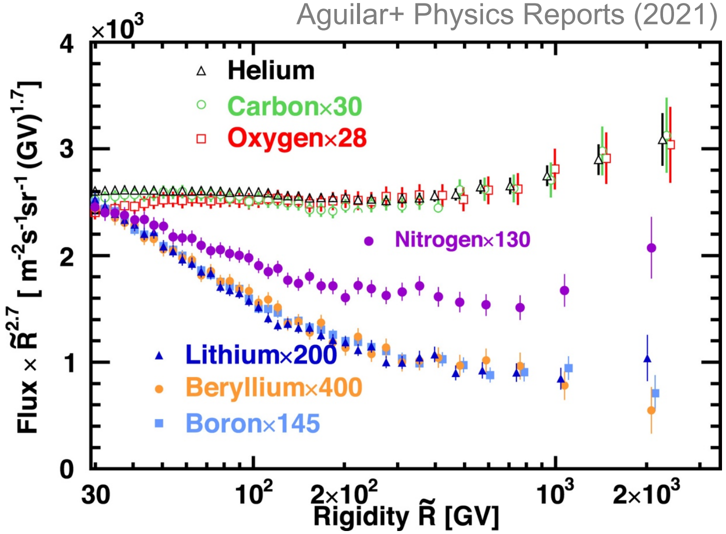
diffusion | energy loss | convective wind | source | spallations

- Diffusion, convection, annihilation parameterized in MAX, MED, MIN Galactic transport models
- Constrained by e.g. B/C = secondary / primary
- Radioactive secondaries, e.g. Be-10, break degeneracy between diffusion, halo size
- Current status:
  - MIN disfavored by positrons, antiprotons → *good news for low-energy searches!*
    (Lavalle+ 2014, DiMauro+ 2014, Giesen+ 2015)

Aguilar+ Physics Reports (2021)



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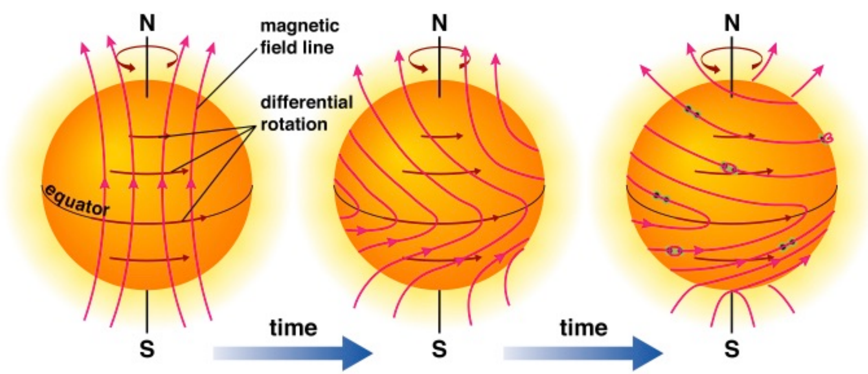
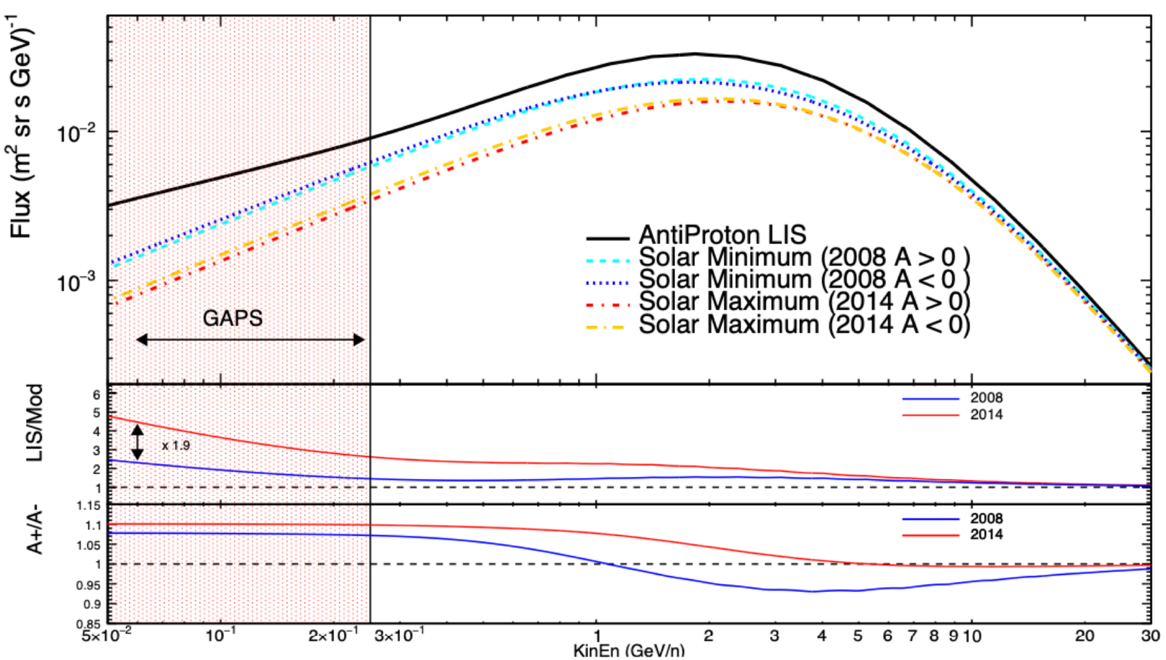


- Solar activity varies on ~11 year timescales
- Valuable constraints from Voyager, ACE, PAMELA, AMS-02, and concurrent antiproton measurements



- Factor x2 modulation between solar minimum and maximum
- ~10% systematic uncertainty due to charge sign affects
- Important constraints for antideuterons and anti-He from simultaneous measurements of antiprotons

A rapidly evolving field…

Antideuteron 2019 - University of California, Los Angeles

27-29 March 2019

Organizing committee:
Philip von Doetinchem, Rene Ong, Mirko Boezio, Kerstin Perez

Lots of updates!
https://indico.phys.hawaii.edu/event/1449/
Google: "**antideuteron workshop 2019**"

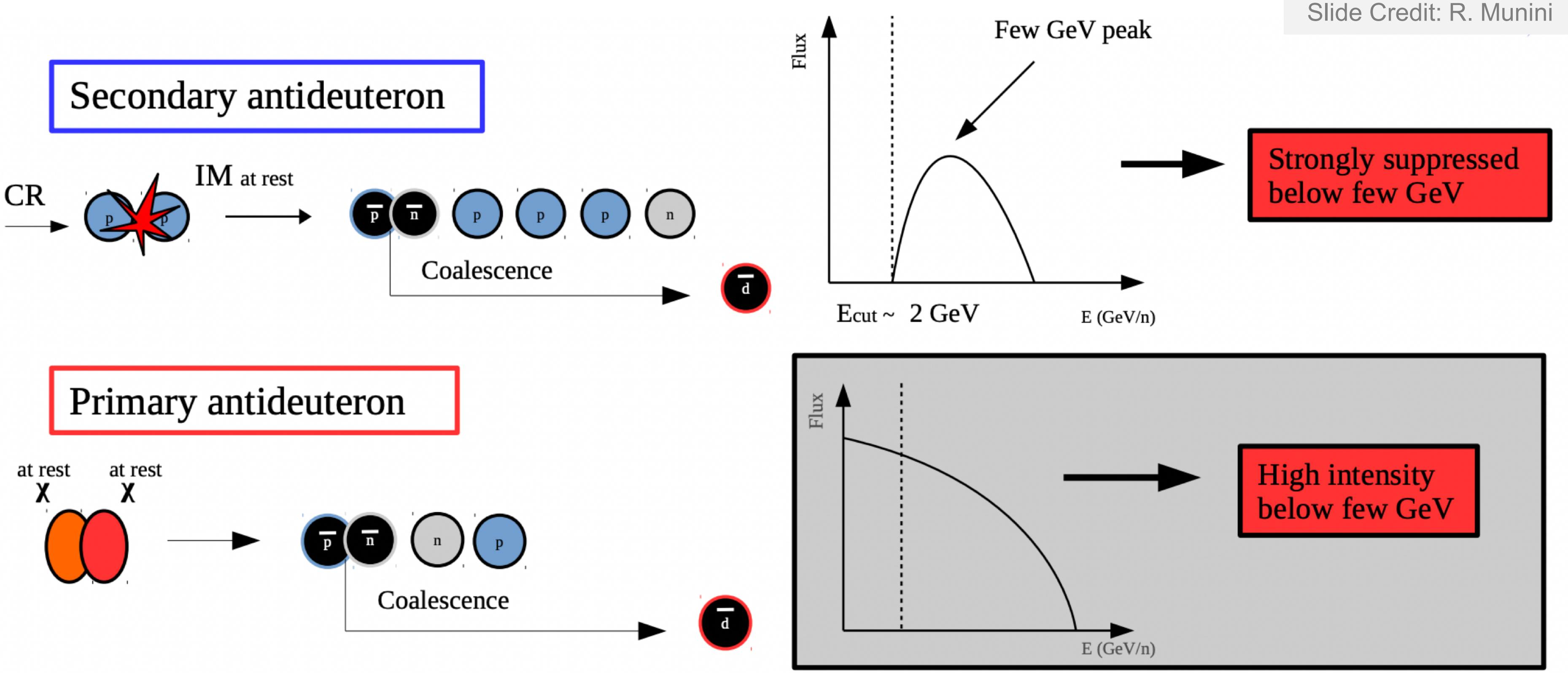
Stay tuned for GAPS first flight in late 2022

Thank you!

Backup

Antideuteron production

Slide Credit: R. Munini



Complementary sensitivity to viable DM signatures

See also: Korsmeier, Donato, Fornengo 1711.08465 (2018), Aramaki+ 1505.07785 (2016)

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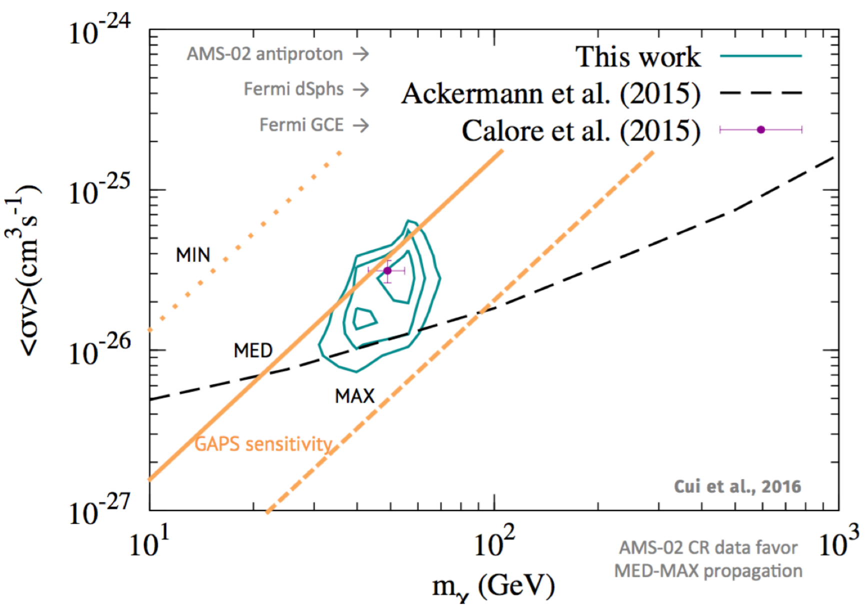
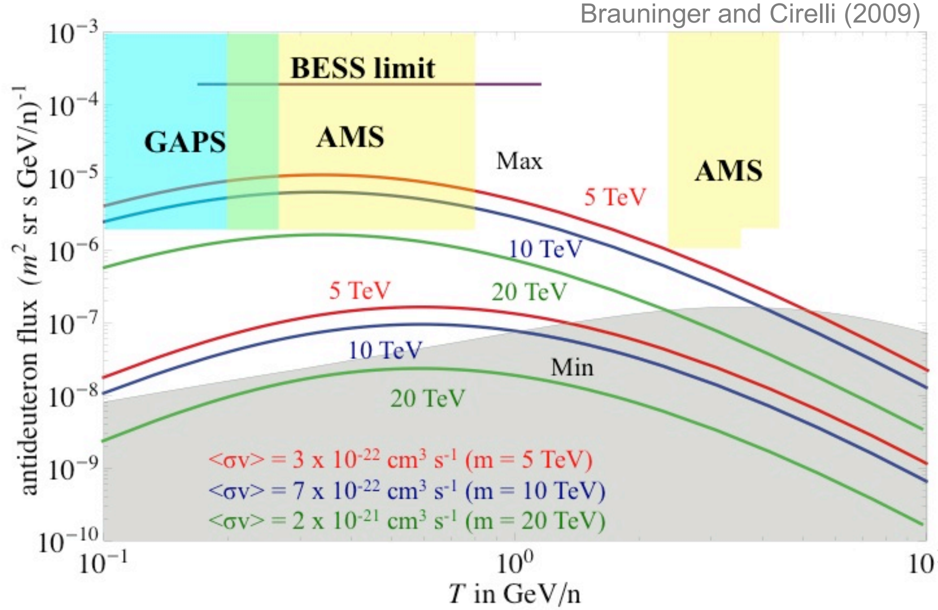


Brauninger and Cirelli (2009)



- Sensitive to heavy DM models, ***as invoked to explain positron observations***