Cosmic-ray Antinuclei:
New Inputs on Dark Matter

Kerstin Perez

PASCOS 2018

June 5, 2018

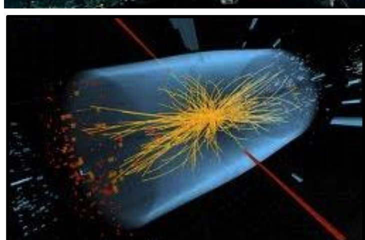
A Worldwide Hunt for Dark Matter

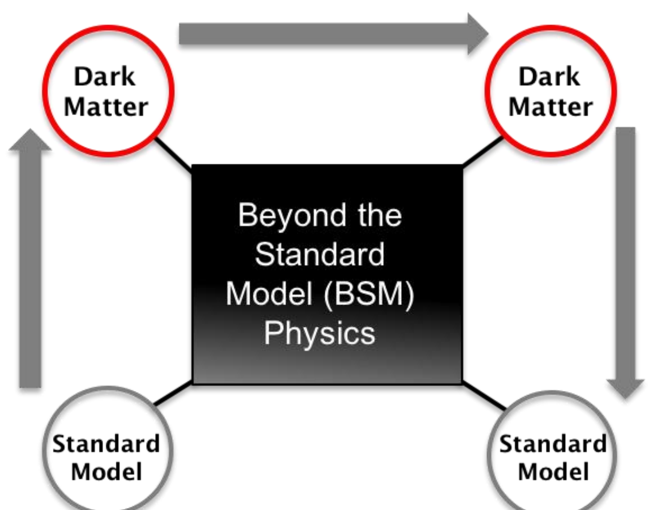
Focus on novel signatures of astrophysical dark matter processes…

Indirect Detection

Direct Detection

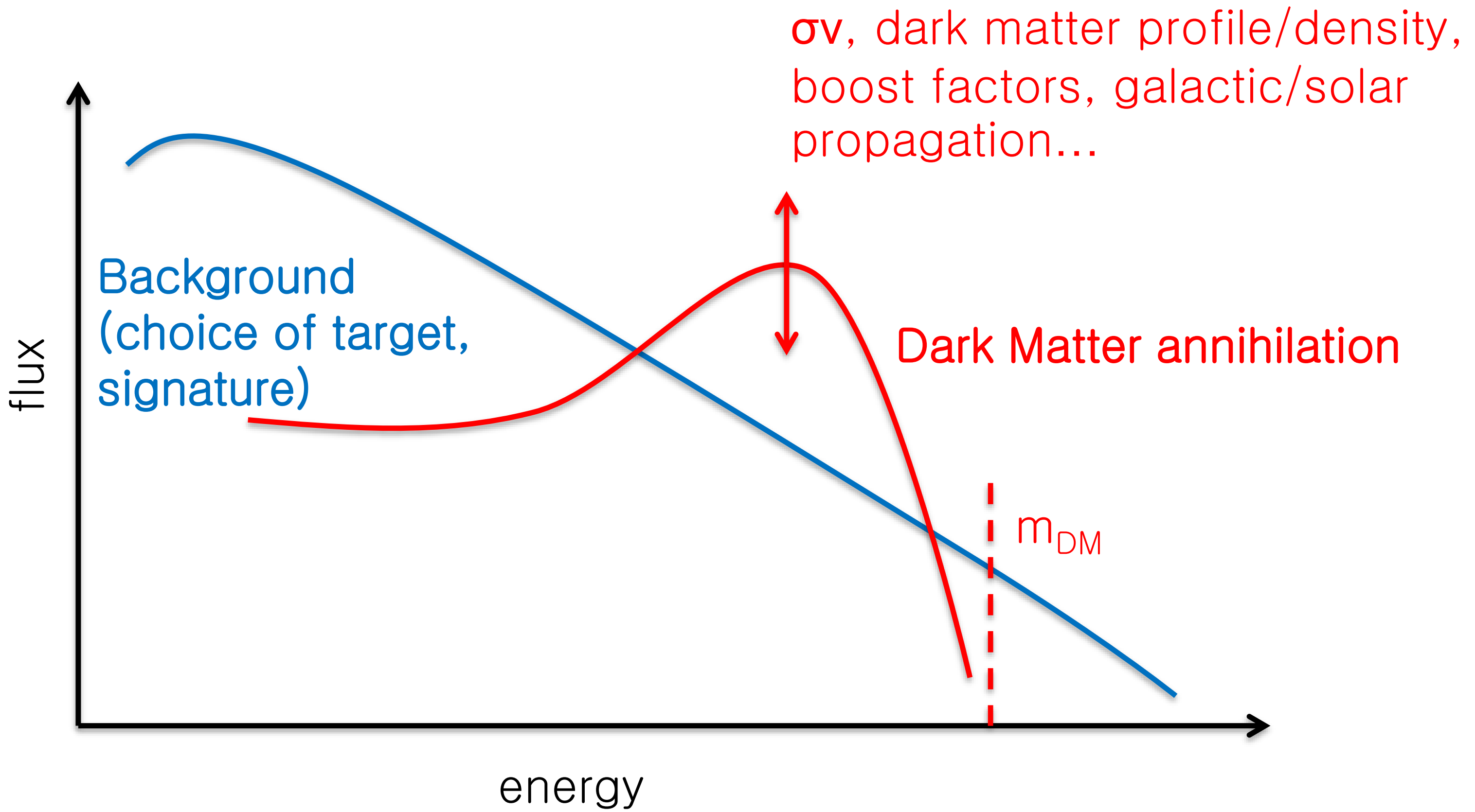
Particle Colliders





The challenge of astrophysical searches...

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



The challenge of astrophysical searches...

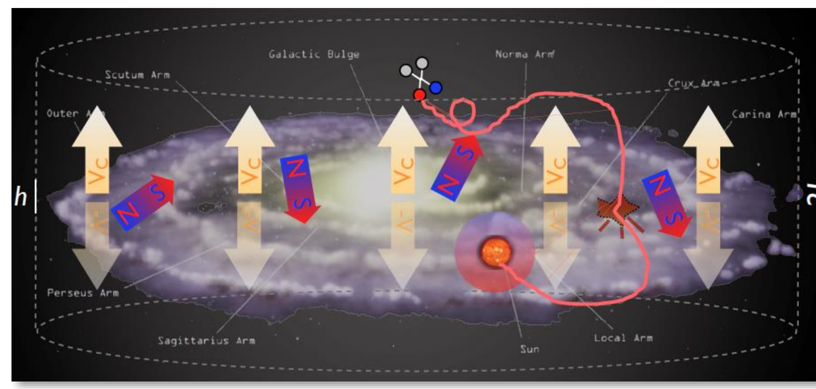
ɣ-rays, X-rays...

flux: $$\Phi_i \propto \frac{dN_i}{dE}\langle\sigma_{X\bar{X}}v\rangle\,\frac{1}{m_X}\,J(\Delta\Omega)\Delta\Omega$$

annihilation: $$J(\Delta\Omega) \propto \langle\int_{l.o.s.} dl\ \rho_X^2\rangle_\Omega$$

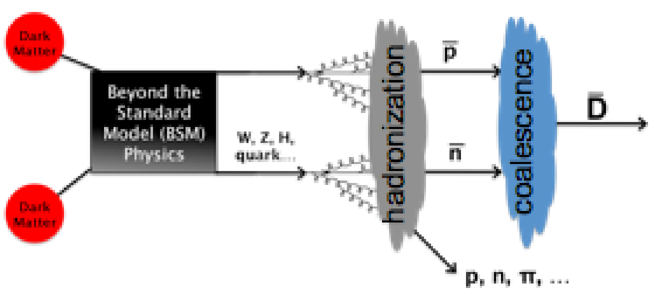
Choose high **J-factor** (GC, dwarf galaxies), low or well-constrained ***predicted*** astrophysical background

Credit: M. Cirelli (TAUP 2015)



Charged (anti)particles

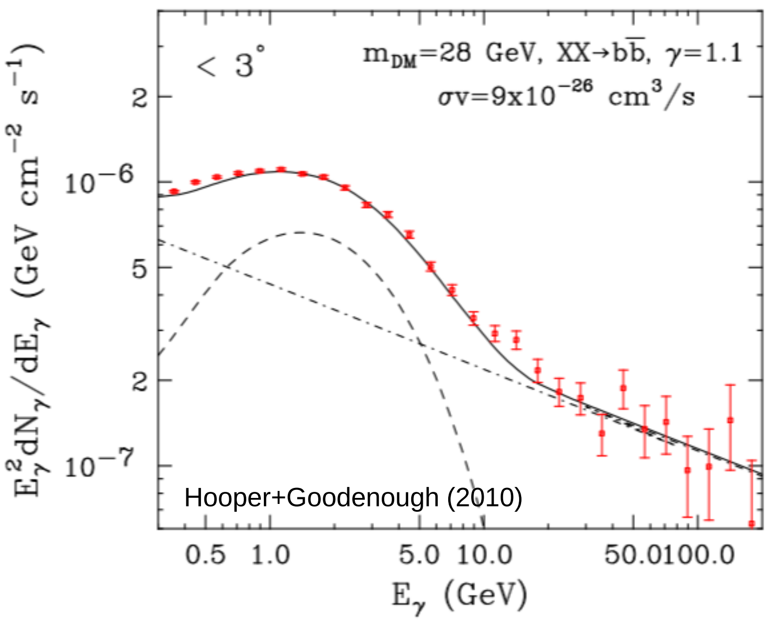
Choose low or well-constrained ***predicted*** background signature, need precise modelling of cosmic-ray **propagation**.

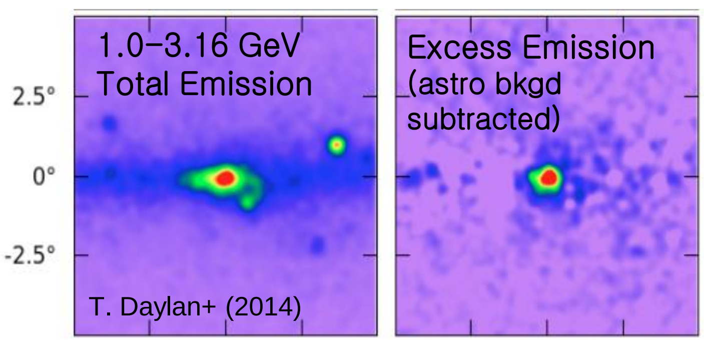


For $\bar{p}$, $\bar{D}$, $\overline{He}$... additional uncertainties from **hadronization, nuclear coalescence.**

There have been tantalizing possible detections!
But vulnerable to poorly-constrained astrophysical backgrounds

Current status: **The "GeV excess"**



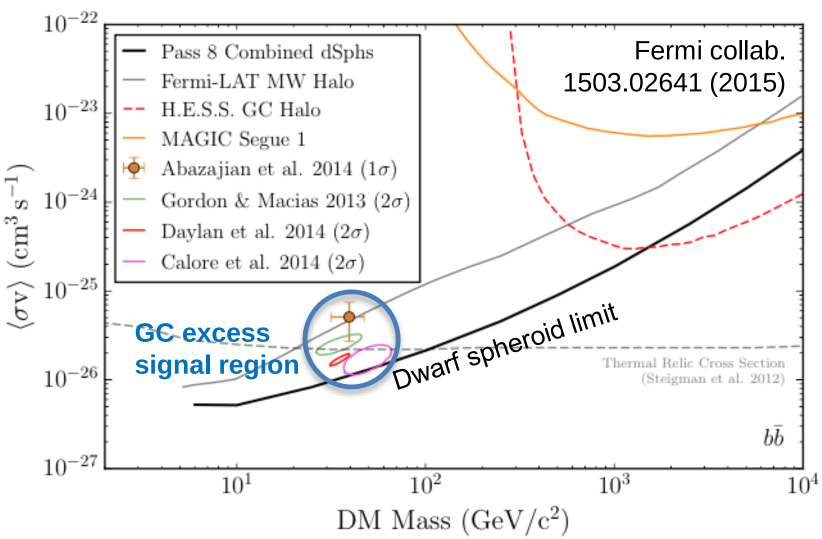


- An excess of gamma-rays at the Galactic Center, with spectrum, morphology, intensity consistent with annihilating dark matter

  e.g. Hooper, Linden (2011), Abazajian, Kaplinghat (2012), Gordon, Macias (2013), Daylan, et al. (2014), Calore, Cholis, Weniger (2014), Murgia, et al. (2015), Ackermann et al. (2017)

- Non-detection limits from dwarf galaxies weakened by Galactic and dwarf halo profiles, astrophysical background models – compatible with dark matter interpretation of Galactic Center excess

  e.g. Agrawal+ 1411.2592, Karwin+ 1612.05687, Hayashi+ 1603.08046, Klop+ 1609.03509, Abazajian+ 1510.06424, Benito+ 1612.02010



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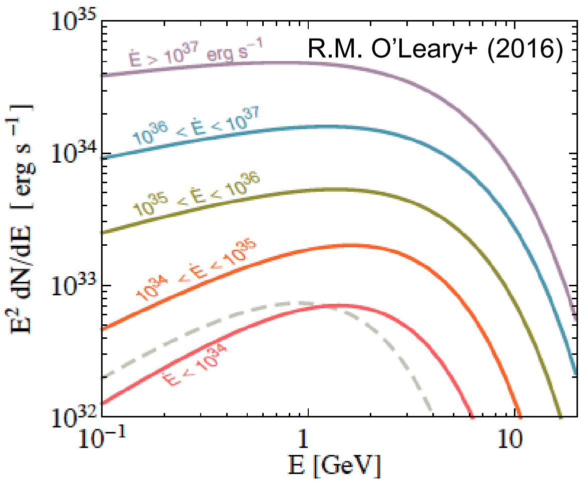
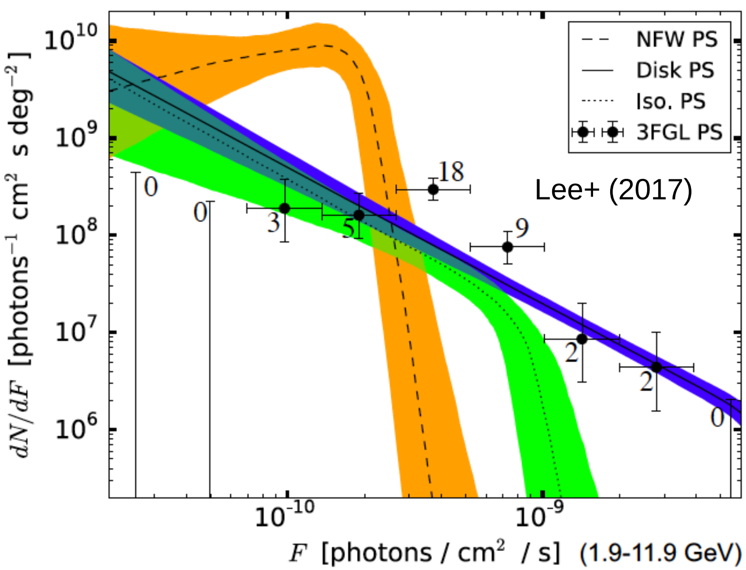
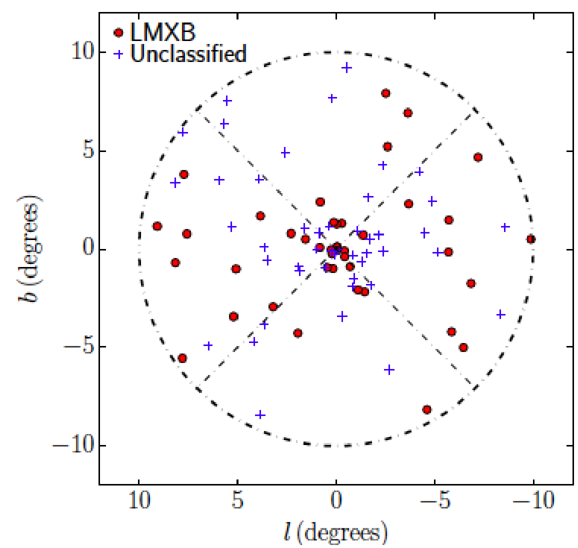


- Spectrum also consistent with millisecond pulsars
- Evidence for sub-threshold point-source contribution
- Could indicates a population of MSPs with a luminosity function and low-mass X-ray binary progenitor population quite different from those in the Milky Way disk or globular clusters



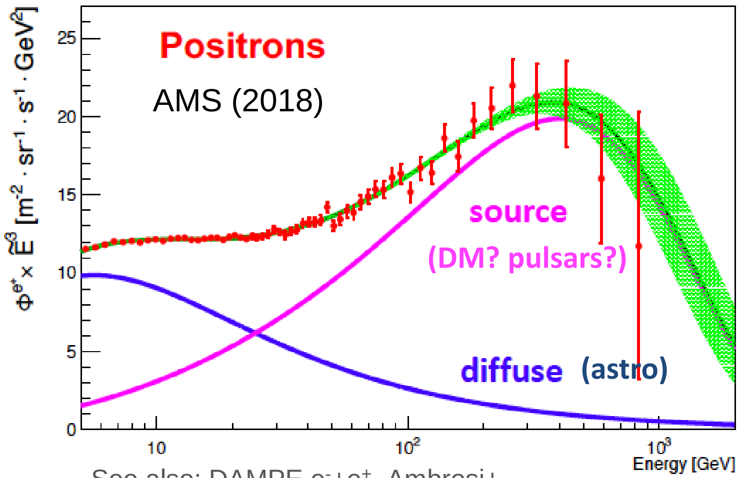
← Evidence for unresolved point sources
Lee, Lisanti, Safdi, Slatyer, Xue, 1506.05124; Bartels, Krishnamurthy, Weniger, 1506.05104

Comparison with LMXB distribution →
Haggard, Heinke, Hooper, Linden, JCAP, 1701.02726



Interpretation depends on poorly-understood Galactic source (MSP) population

Current status: The "positron excess"



See also: DAMPE e^-+e^+, Ambrosi+ 1711.10981 Nature (2017)

- Rising positron fraction observed since PAMELA 2008, confirmed to higher energies by AMS-02
- Implies heavy TeV-scale dark matter. Need enhanced annihilation cross section and leptophilic annihilation (to avoid antiproton bounds).
- Or local pulsars...

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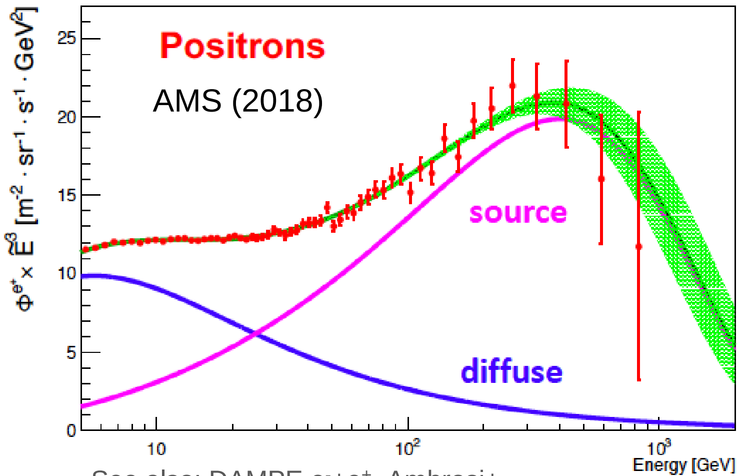

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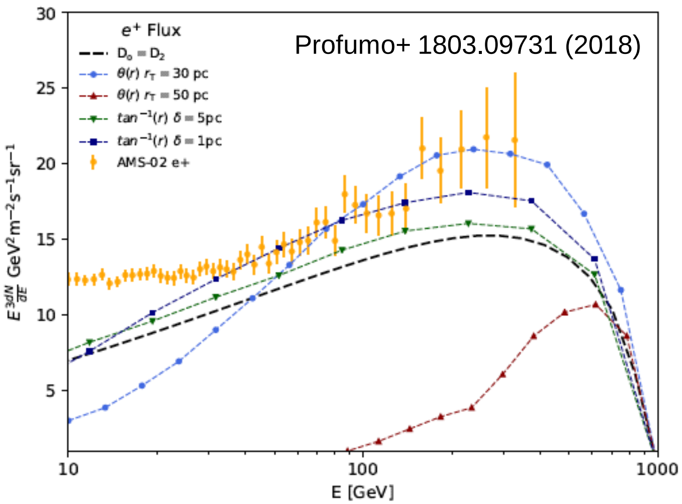
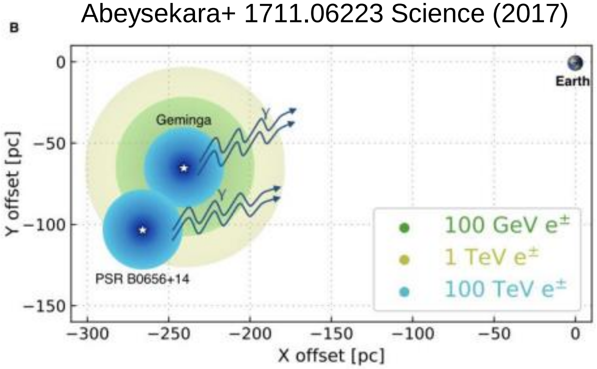
↓ HAWC – if Galactic diffusion similar to diffusion in regions of nearby pulsars, excess cannot be due to Geminga and PSR B0656+14



← Likely implies that diffusion not uniform throughout local interstellar medium

See also: Hooper+Linden 1711.07482 (2017)

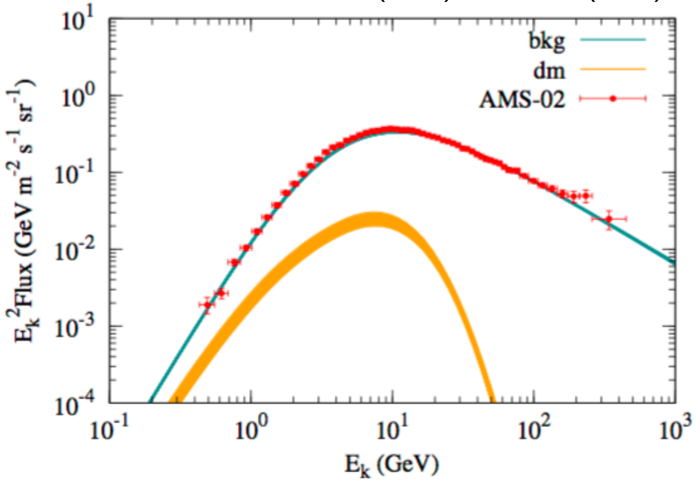
Abeysekara+ 1711.06223 Science (2017)



Interpretation depends on poorly-understood Galactic propagation (diffusion)

Current status: **an antiproton excess?**

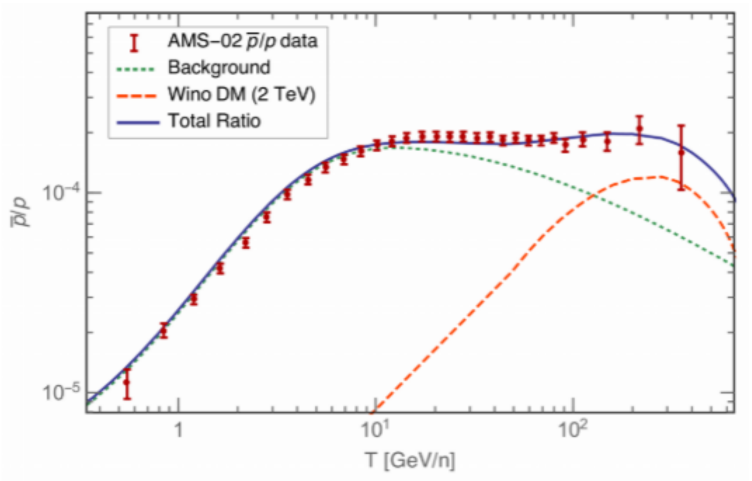
A. Cuoco+(2016), M-Y. Cui+(2016)



← ~10 GeV dark matter, consistent with GeV excess?

TeV-scale Wino dark matter? →

Ibe+(2015)



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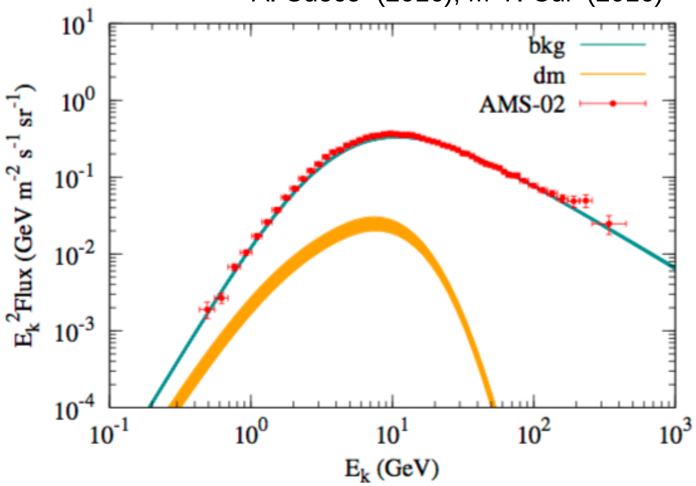

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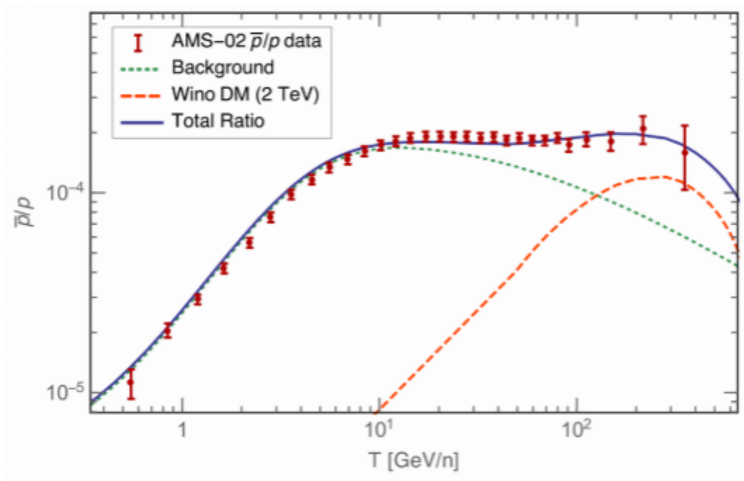
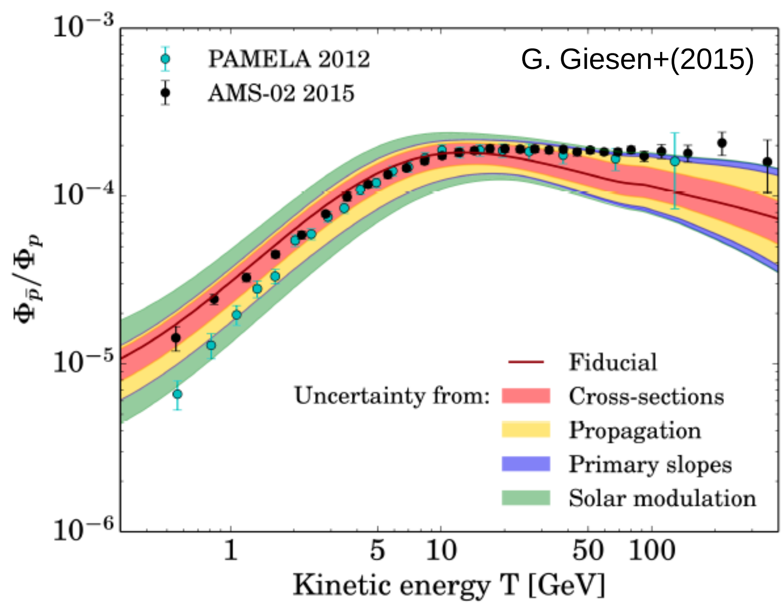
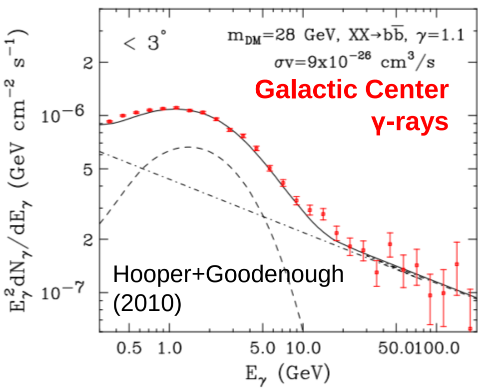
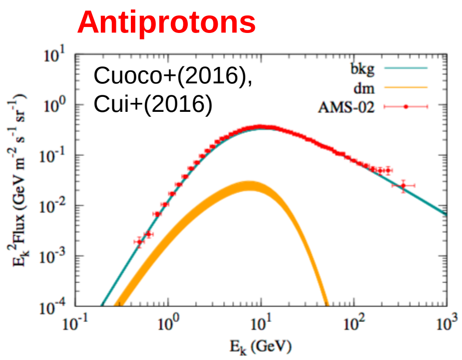


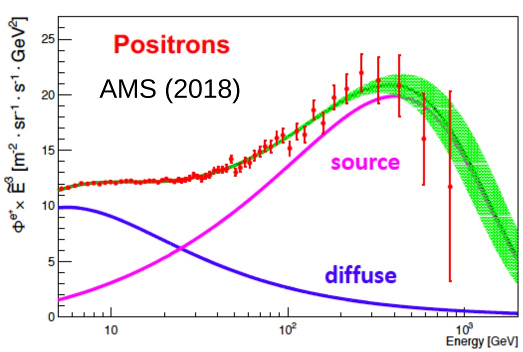
- Interpretation depends on poorly-understood Galactic and Solar propagation
- Can instead be used to constrain propagation models: favors MED-MAX scenario



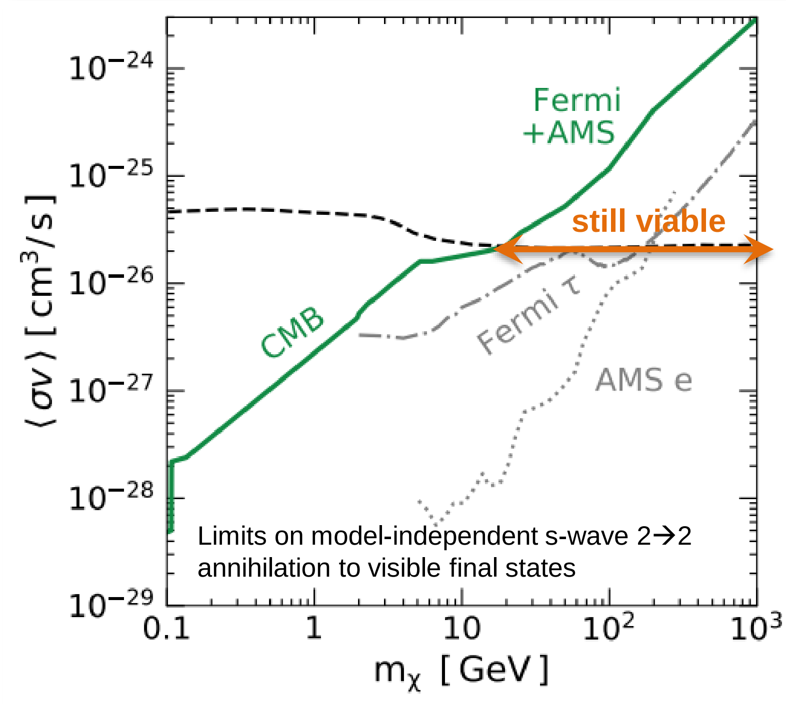
Current status: indirect searches for dark matter







Leane, Slatyer, Beacom, Ng (2018) 1805.10305.



1. Cosmic rays are full of surprises!
2. Surprises are difficult to interpret due to uncertain astrophysical backgrounds
3. Need cross-correlation with different signatures

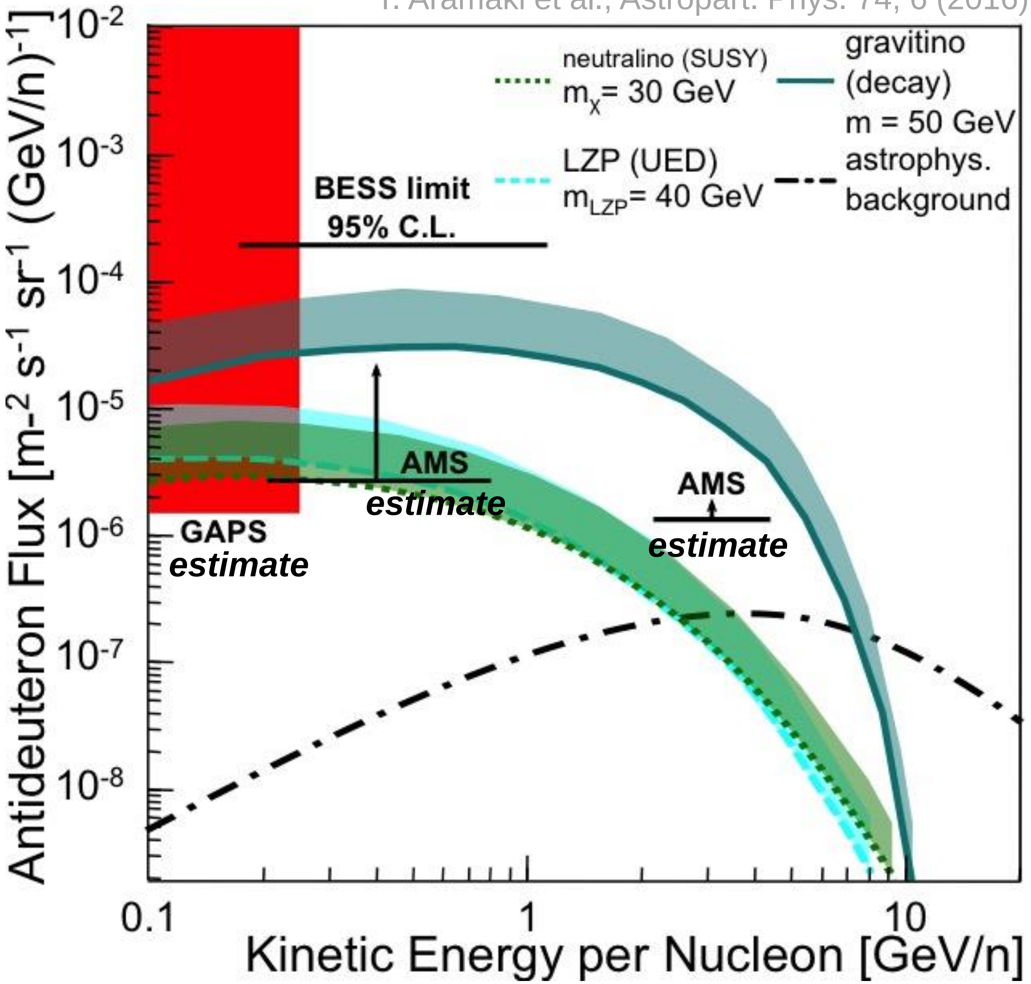
If interpreted conservatively, much parameter space remains for standard thermal WIMP dark matter

See parallel talk, R. Leane

New physics in cosmic-ray antideuterons

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

T. Aramaki et al., Astropart. Phys. 74, 6 (2016)



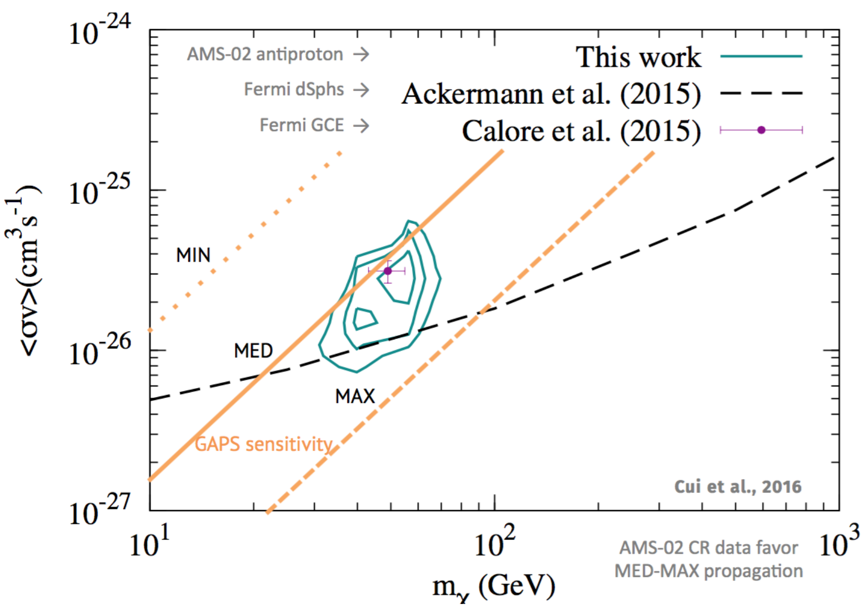
- Probes a variety of dark matter models that evade or complement collider, direct, or other cosmic-ray searches
- GAPS first experiment optimized specifically for low-energy antinuclei signatures
- **First GAPS Antarctic flight: late 2020**

Review of experiment and theory:
Phys. Rept. 618 (2016) 1-37

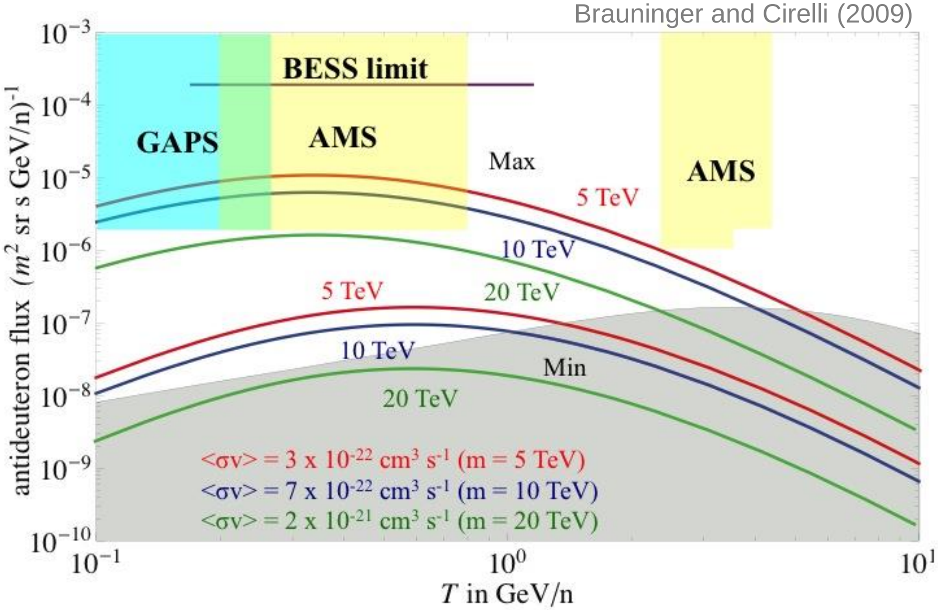
Complementary sensitivity to viable DM signatures

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

- Sensitive to ~10s of GeV mass DM models, ***as invoked to explain gamma-ray and antiproton observations***



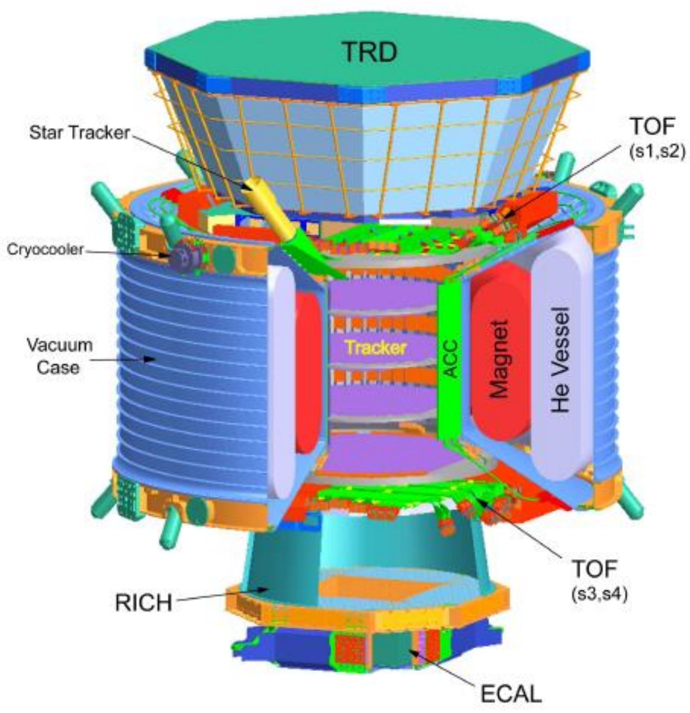
Brauninger and Cirelli (2009)

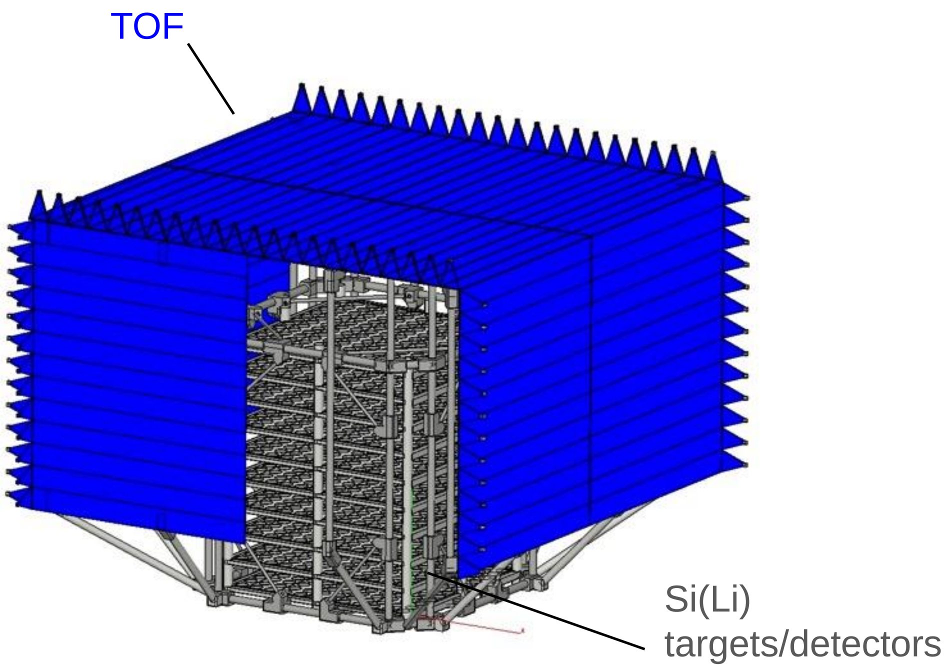


- Sensitive to heavy DM models, ***as invoked to explain positron observations***

The Experiments: AMS and GAPS

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





- AMS has been in operation on the ISS since May 2011
- Uses magnetic spectrometry for anti-p, anti-D, anti-He detection

- GAPS scheduled for initial Antarctic balloon flight late 2020
- Uses exotic atom capture and decay to identify antinuclei

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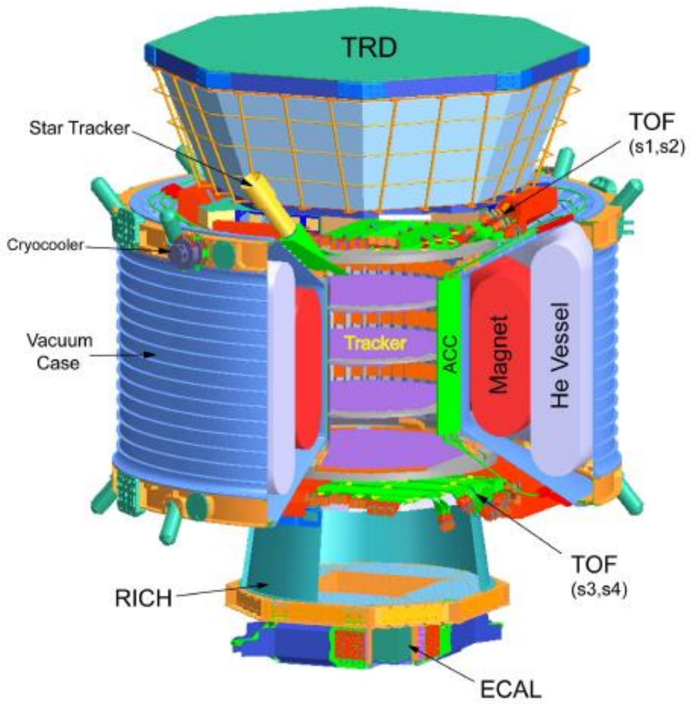
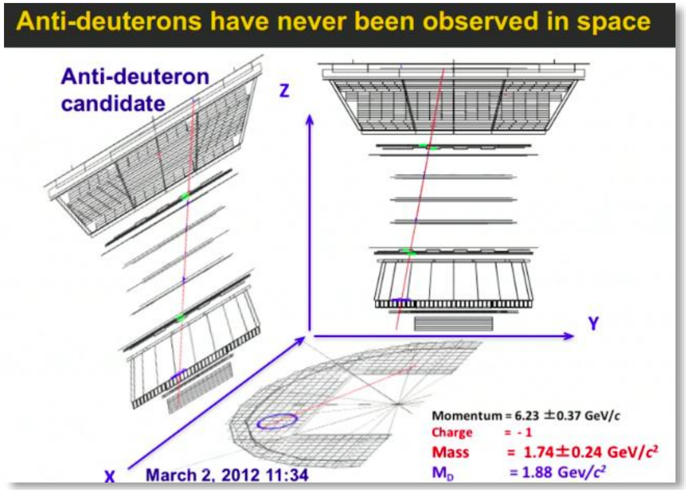
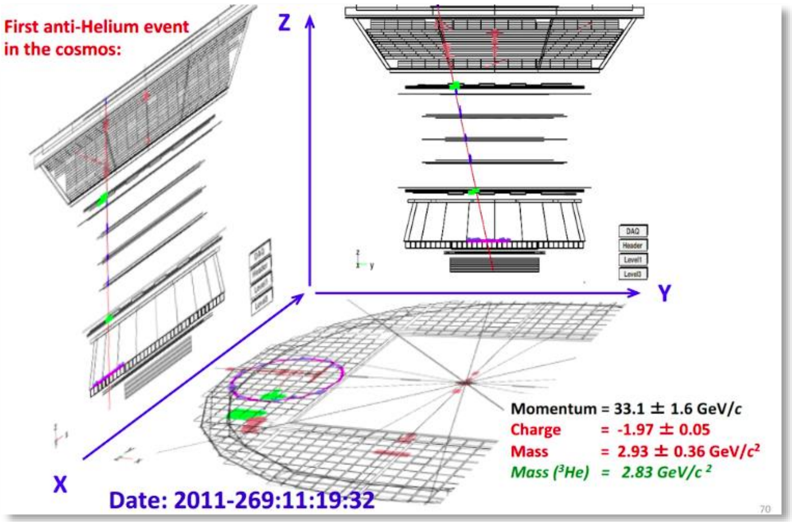




Ting, CERN May 2018: https://indico.cern.ch/event/729900/



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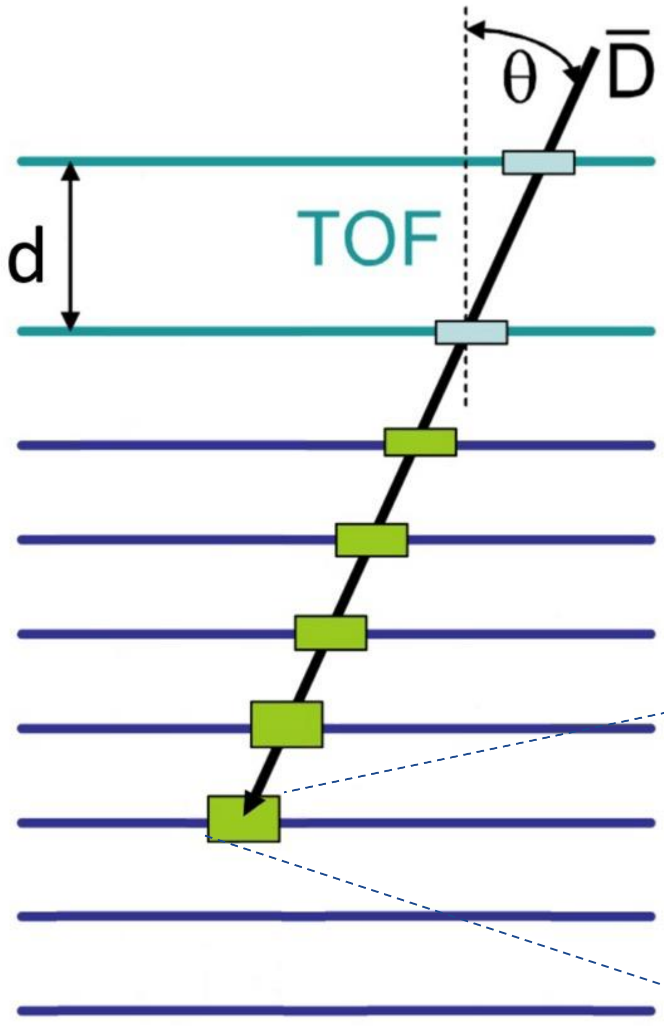
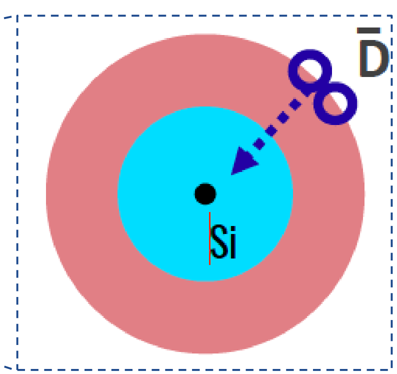
The GAPS Team

NASA
Columbia University
MIT Massachusetts Institute of Technology
UCLA
University of Hawai'i Mānoa
UC San Diego
SLAC
Oak Ridge National Laboratory
JAXA Japan Aerospace Exploration Agency
INFN Istituto Nazionale di Fisica Nucleare
科研費 KAKENHI
Heising-Simons Foundation
NSF

GAPS detection: exotic atom capture and decay



- **Time-of-flight** system measures velocity
- Loses energy in layers of semiconducting **Silicon targets/detectors**
- Stops, forming **exotic excited atom**



Aramaki et al., http://arxiv.org/abs/1303.3871

Aramaki et al., Astropart. Phys. 74, 6 (2016)

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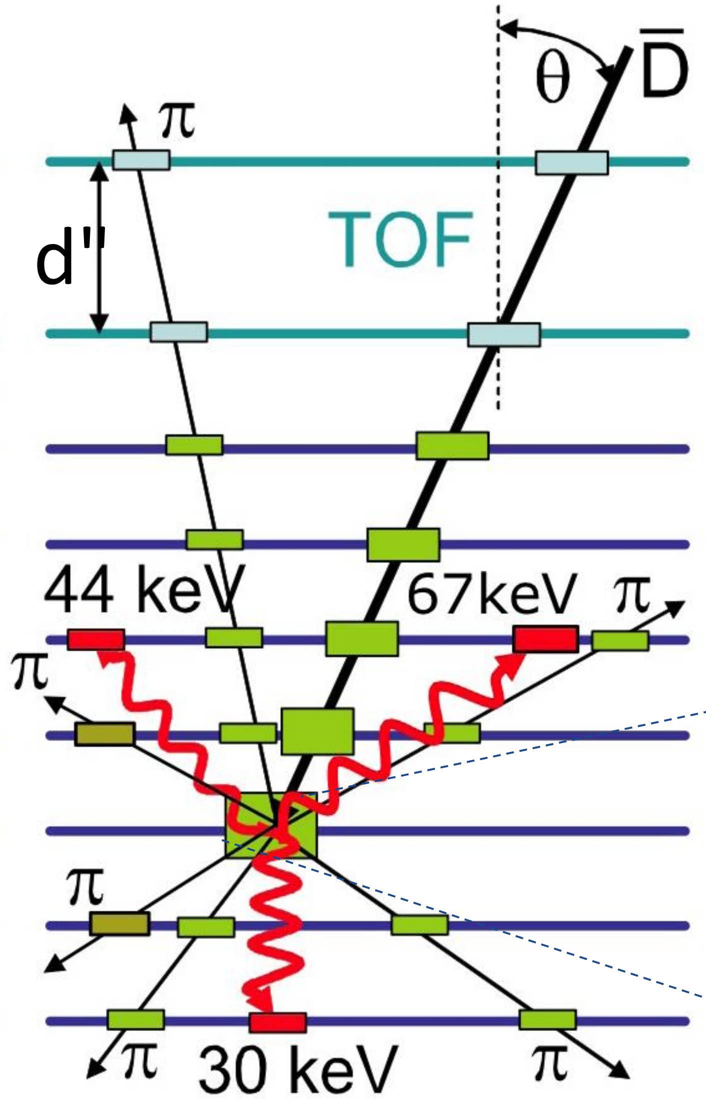

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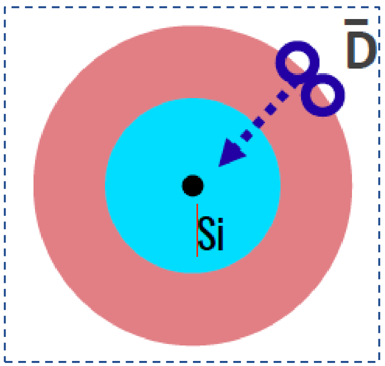
- Atom de-excites, emitting **X-rays**
- Remaining nucleus annihilates, emitting **pions and protons**



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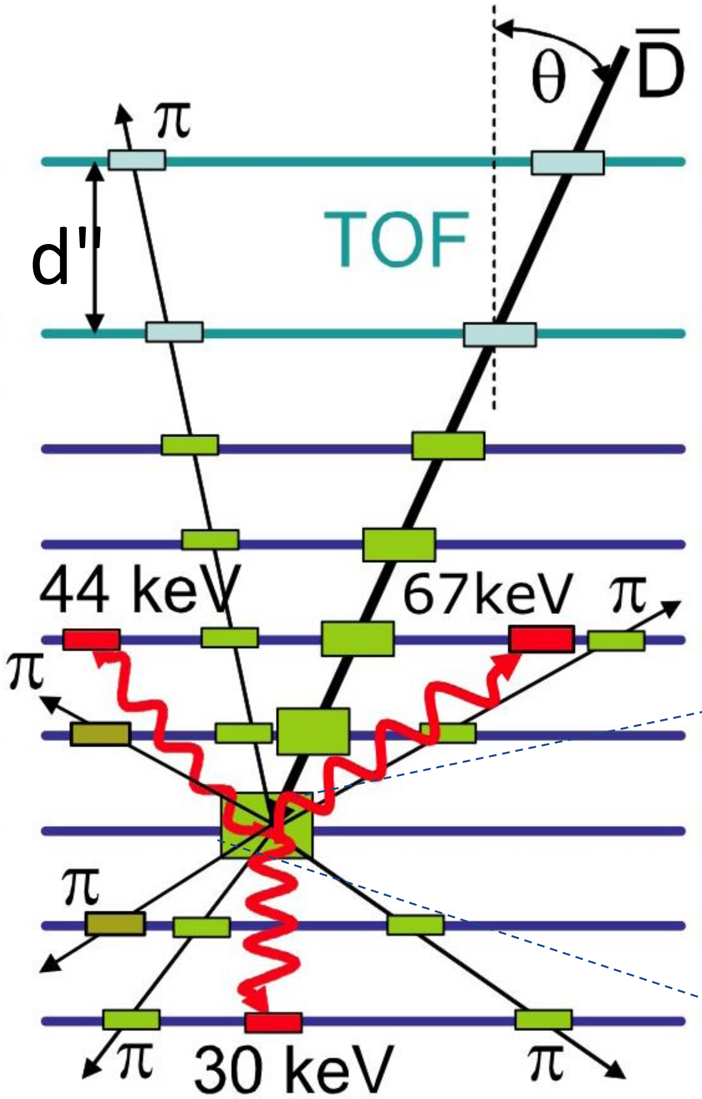

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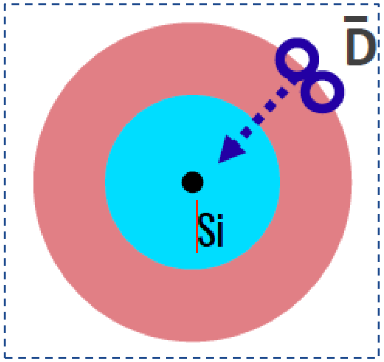

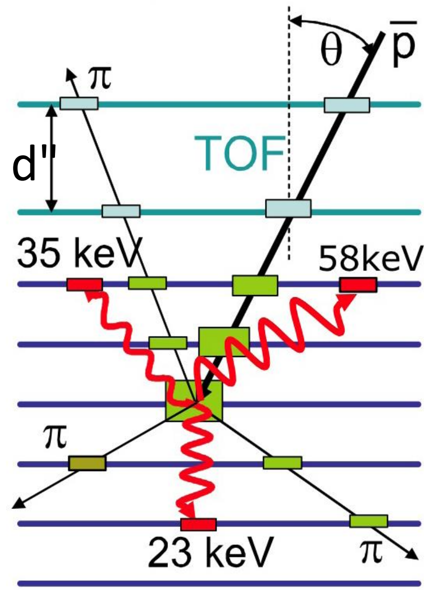

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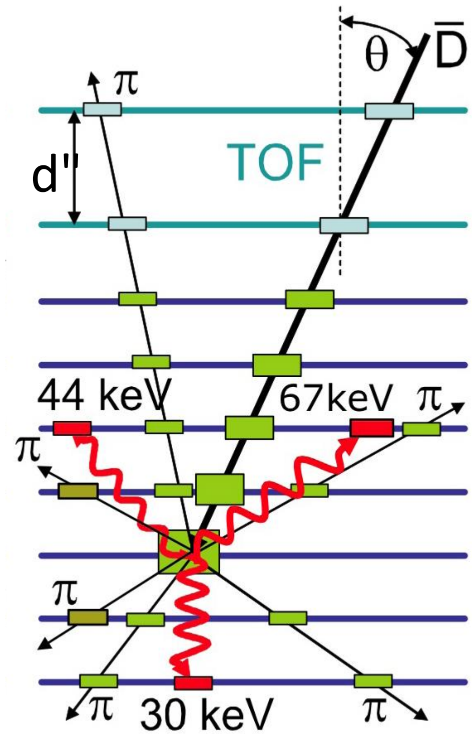
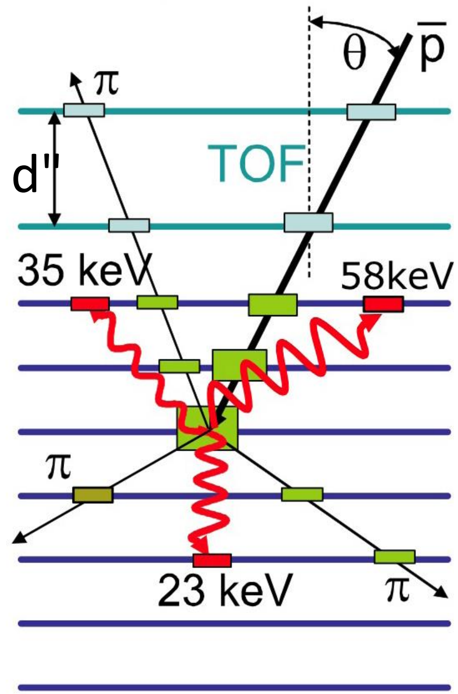
GAPS Background Rejection





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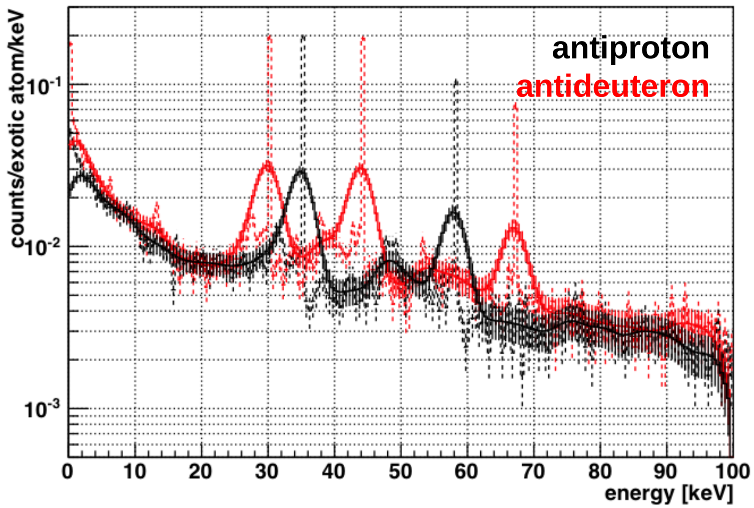
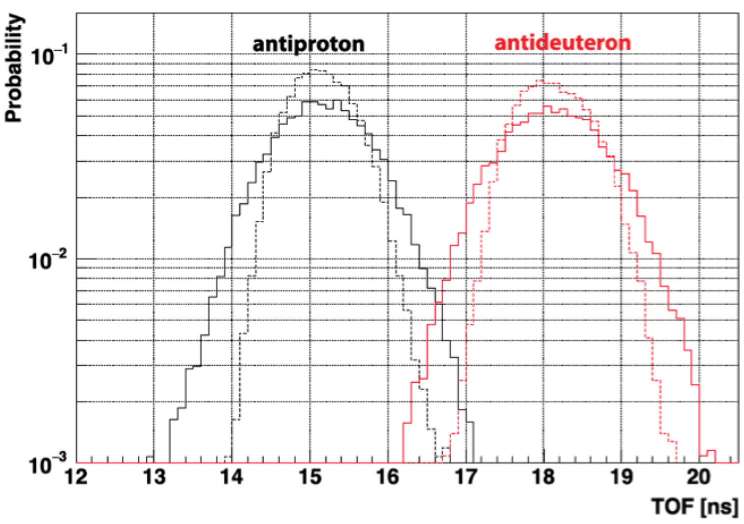
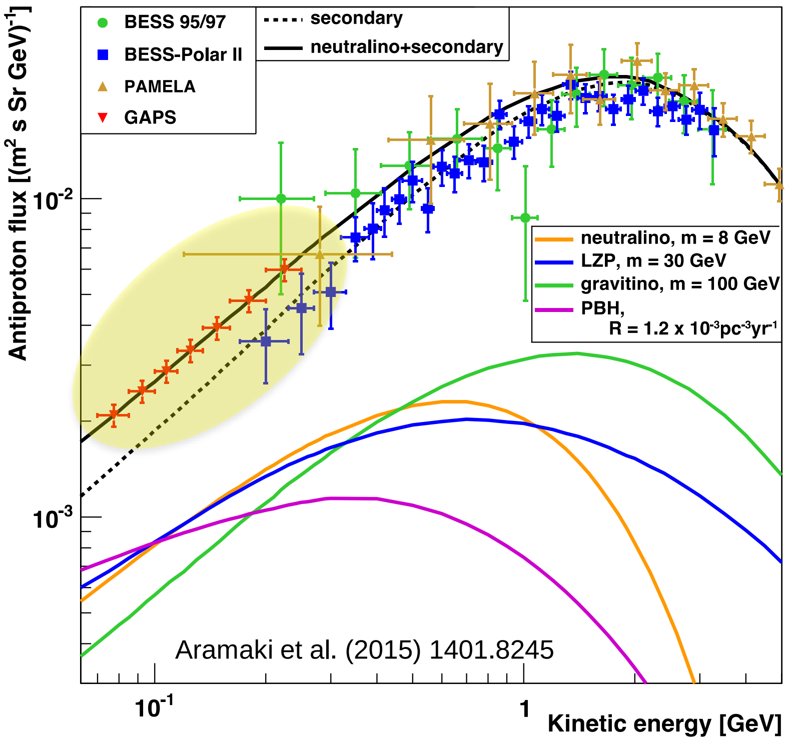


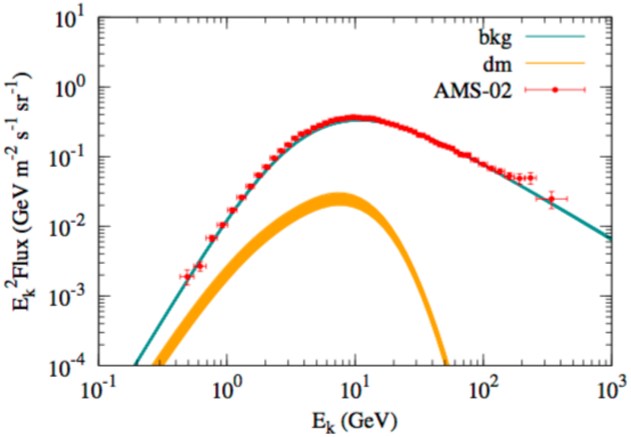


Combination of time-of-flight + depth-sensing, X-ray, and π detection yield necessary rejection of >10^6

Precision antiproton spectrum

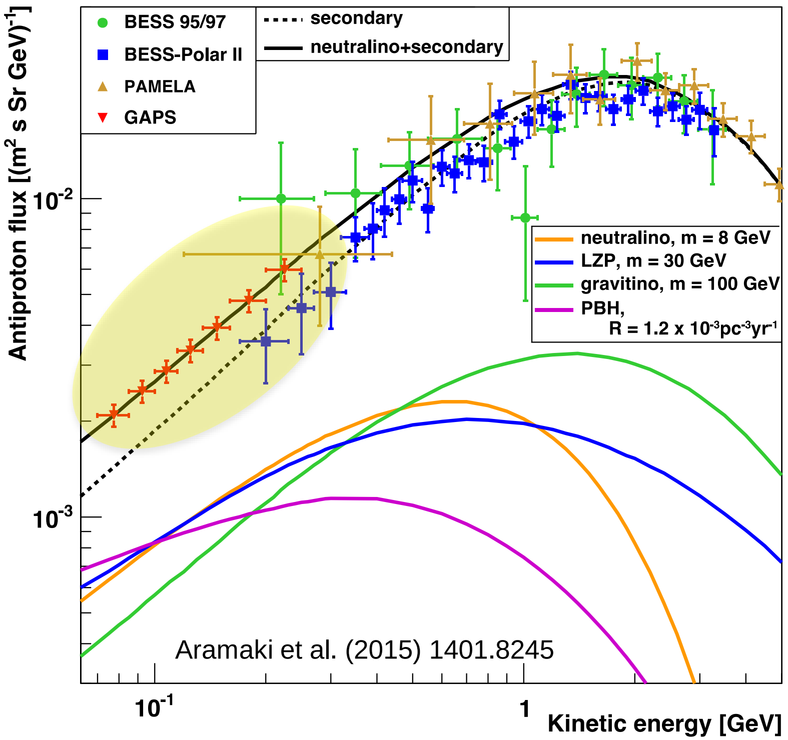


- GAPS will measure >1000 antiprotons per flight, in ***unprecedented low energy range***
- Reduces systematic and theoretical uncertainties for antideuteron search



Sensitive to light DM

Precision antiproton spectrum *and anti-He searc*



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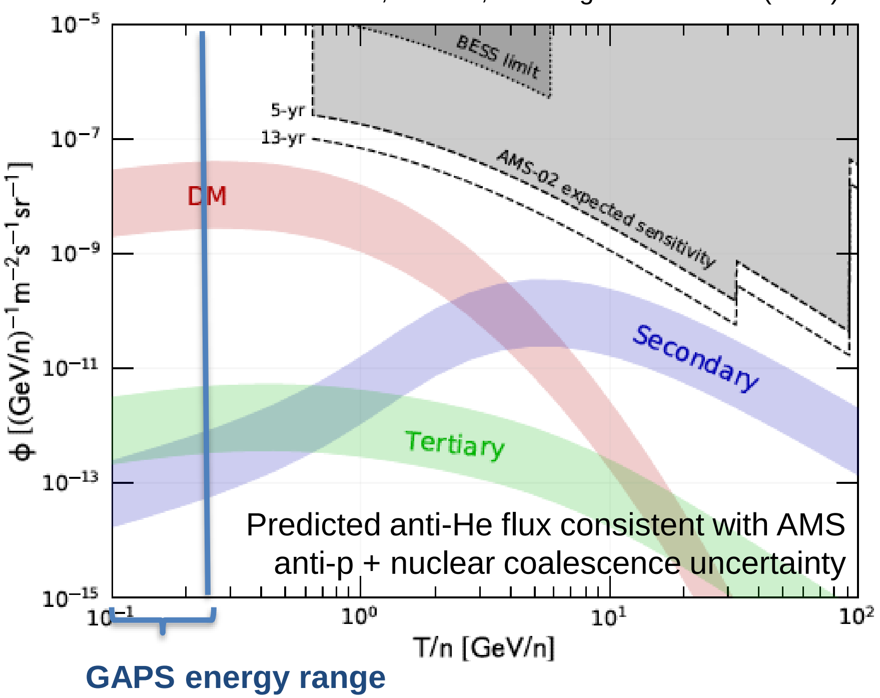
Korsmeier, Donato, Fornengo 1711.08465 (2018)



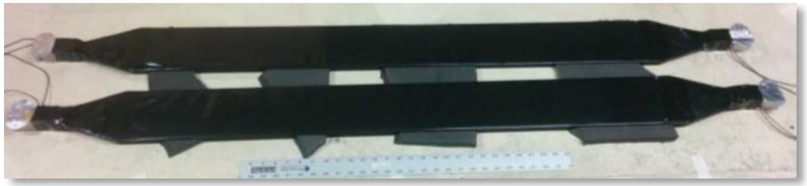
GAPS also sensitive to anti-He, in complementary energy range to where AMS has reported candidate events. Ongoing work to estimate and optimize sensitivity.

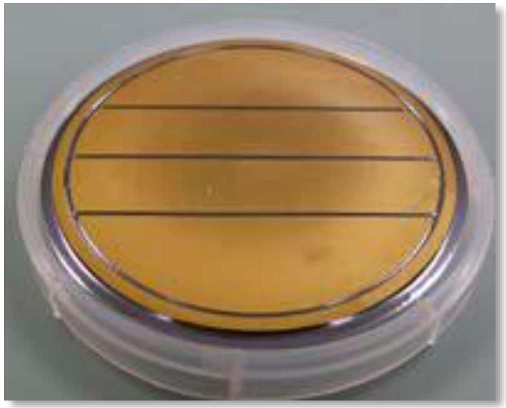
See also: Googan+Profumo 1705.09664, Blum+ 1704.05431

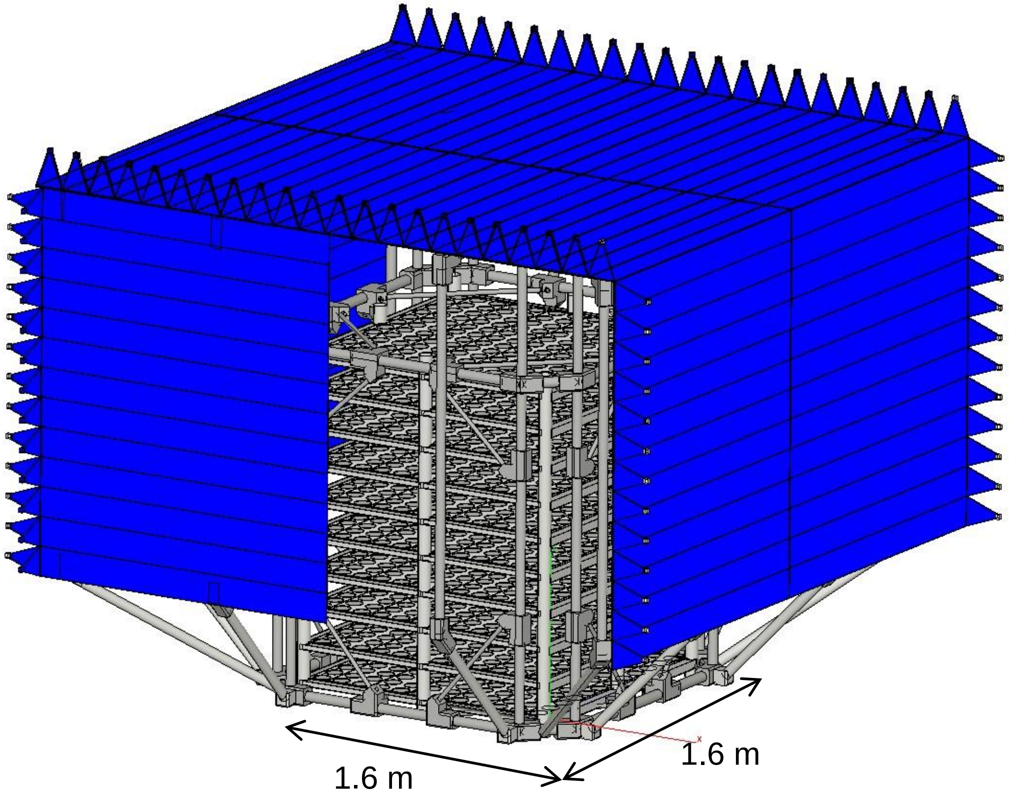
GAPS Detector Design

Plastic scintillator TOF

- high-speed trigger and veto
- 160-180 cm long, 0.5 cm thick
- read out both ends
- ~500 ps timing resolution







Si(Li) targets/detectors

- X-ray identification, dE/dx, stopping depth, and shower particle multiplicity
- 2.5 mm thick, 4” diameter
- 4 keV resolution for X-rays

Prototype flight (pGAPS)

Taiki, Japan
2012

6 TOF planes
+ 6 Si(Li)
detectors

100% of flight goals met!

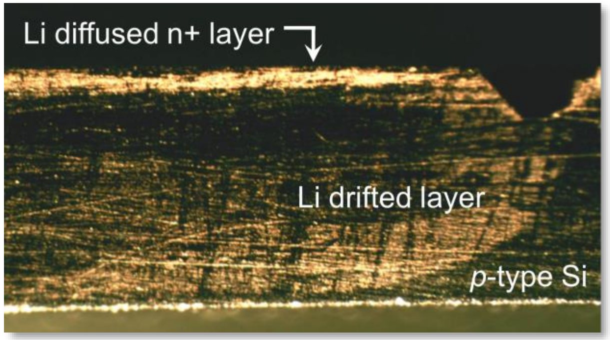
- ✓ verify stable, low-noise Si(Li) operation at ambient flight pressure
- ✓ validate the cooling system and thermal model
- ✓ measure the background levels to validate simulation codes

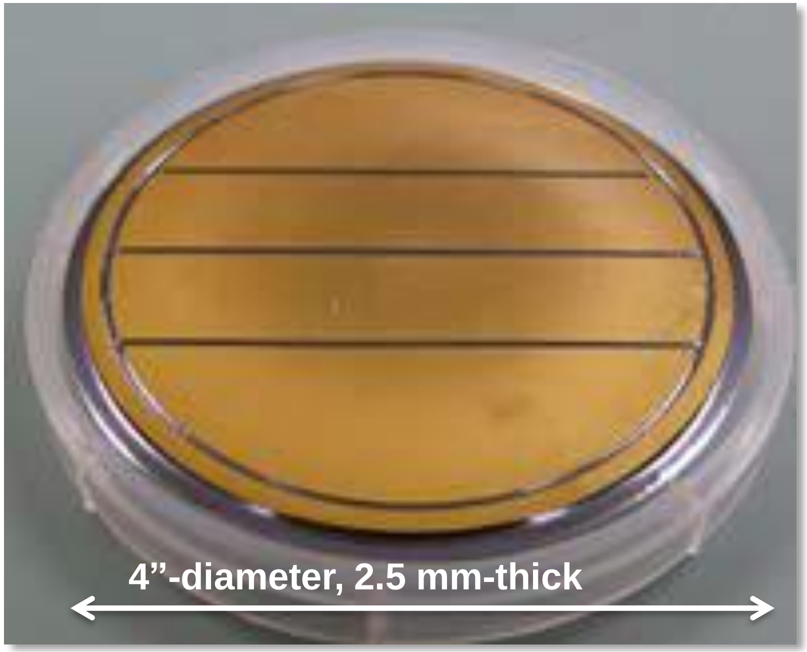
Mognet et al., Nucl. Instrum. Meth. A735 (2014) 24
von Doetinchem et al., Astropart. Phys. 54 (2014) 93

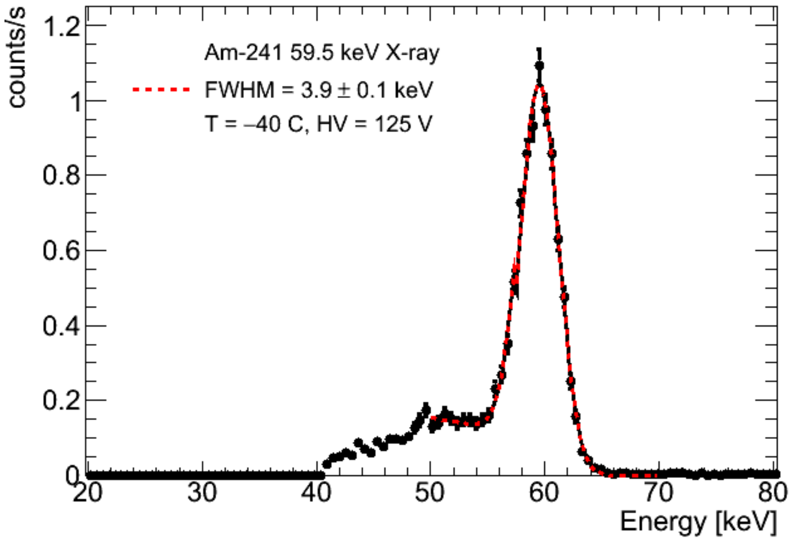
Development and construction: Si(Li) detectors

GAPS will need ~1000 Si(Li) detectors!

- ✓ Low-cost fabrication scheme developed in partnership with Shimadzu Corp.
- ✓ Demonstrates required ~4 keV energy resolution at relatively high temp of -35 to -45 C
- ✓ Readout via custom ASIC

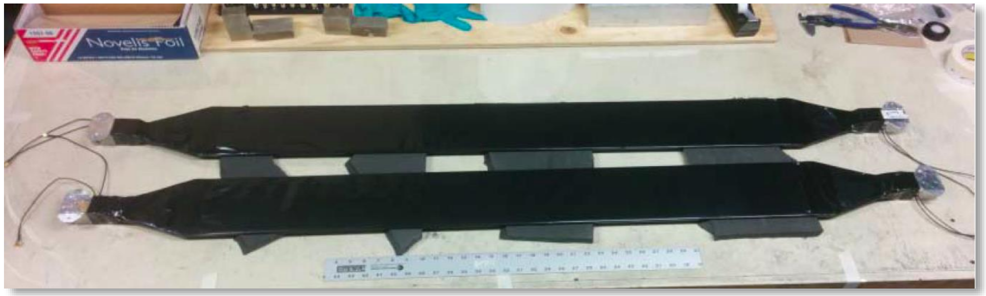






Perez+ submitted to NIM A (2018),
Perez+ Proc. IEEE (2013),

Development and construction: TOF and cooling

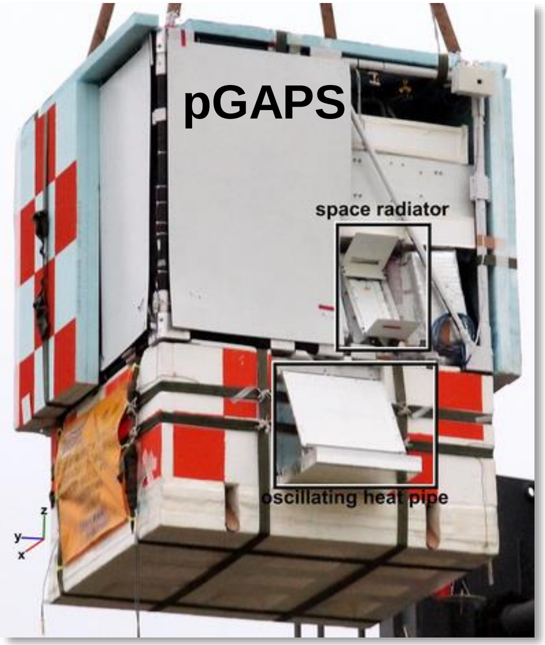


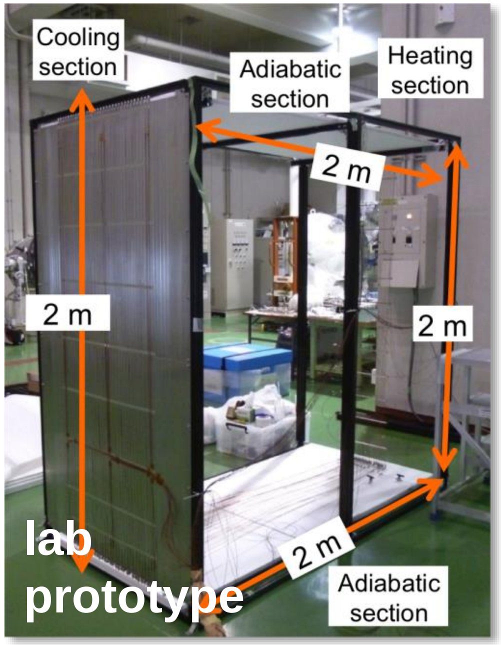
TOF will use 225 scintillation counters, read out on both ends

- evaluating PMT vs SiPM
- custom DRS-4 ASIC @ 2GSps
- optimizing trigger algorithm

Oscillating heat pipe (OHP) validated on pGAPS, developed for GAPS

- small capillary tubes filled with a phase-changing refrigeration liquid
- rapid expansion and contraction of bubbles in liquid create thermo-contraction hydrodynamic waves that transport heat





Okazaki+ Conference, 2014 IEEE, 1–9 (2014).
Fuke+ vol. 39 of COSPAR Meeting, 568 (2012)
Okazaki+ Journal of Astronomical Instrumentation 3 (2014).

Exciting coming decade of anti-nuclei searches!

- Indirect astrophysical dark matter searches continue to uncover surprises

- The GAPS design, dedicated to anti-nuclei signatures, is timely, following candidate events from AMS-02

- Low-energy antideuterons offer a new window on dark matter parameter space, providing complementary coverage with direct detection, collider, and other indirect searches

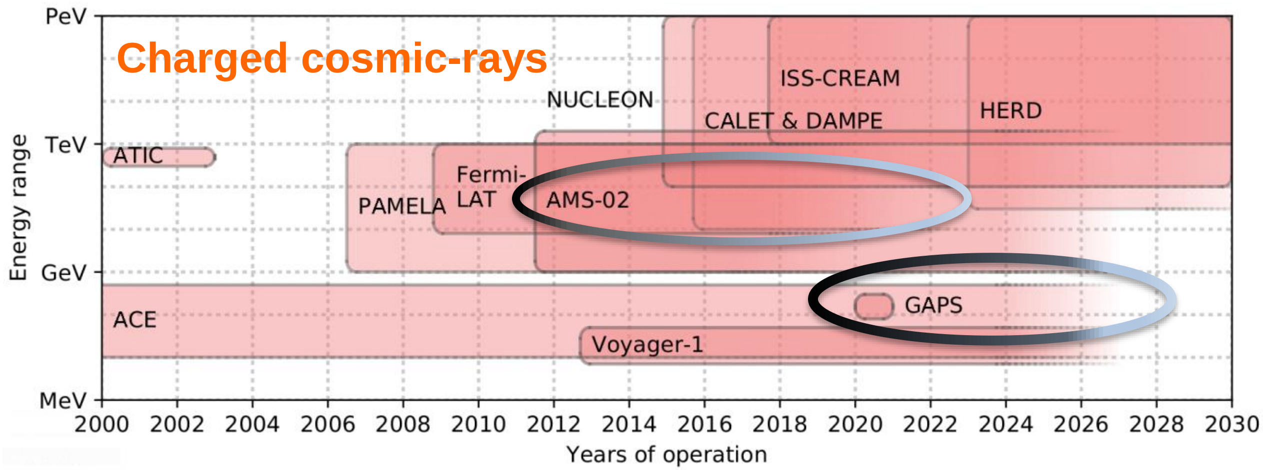
- First GAPS flight will ***improve current antideuteron limit by ~1.5 orders of magnitude***, deliver ***first precision antiproton flux below 0.25 GeV/n***, and provide sensitvity to anti-He with orthogonal detection technique to AMS

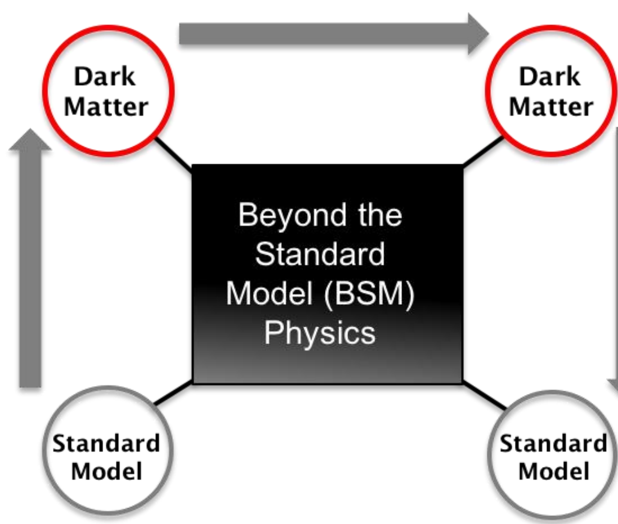
- ***First GAPS flight in late 2020***
- Subsequent Antarctic flights planned to optimize sensitivity

Backup

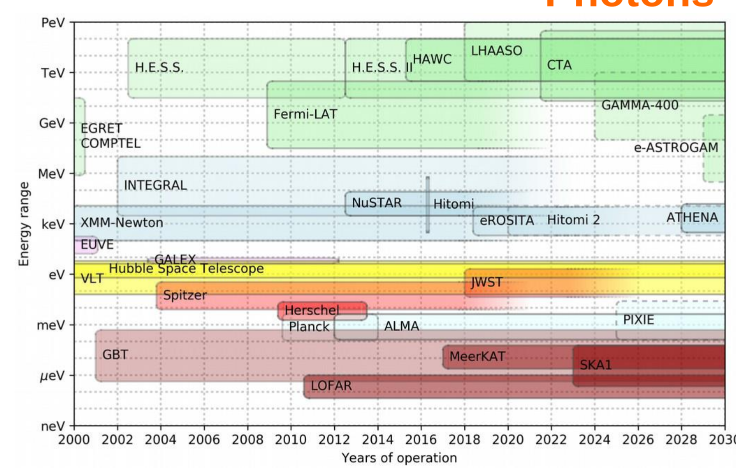
A Worldwide Hunt for Dark Matter

Focus on novel signatures of astrophysical dark matter processes…

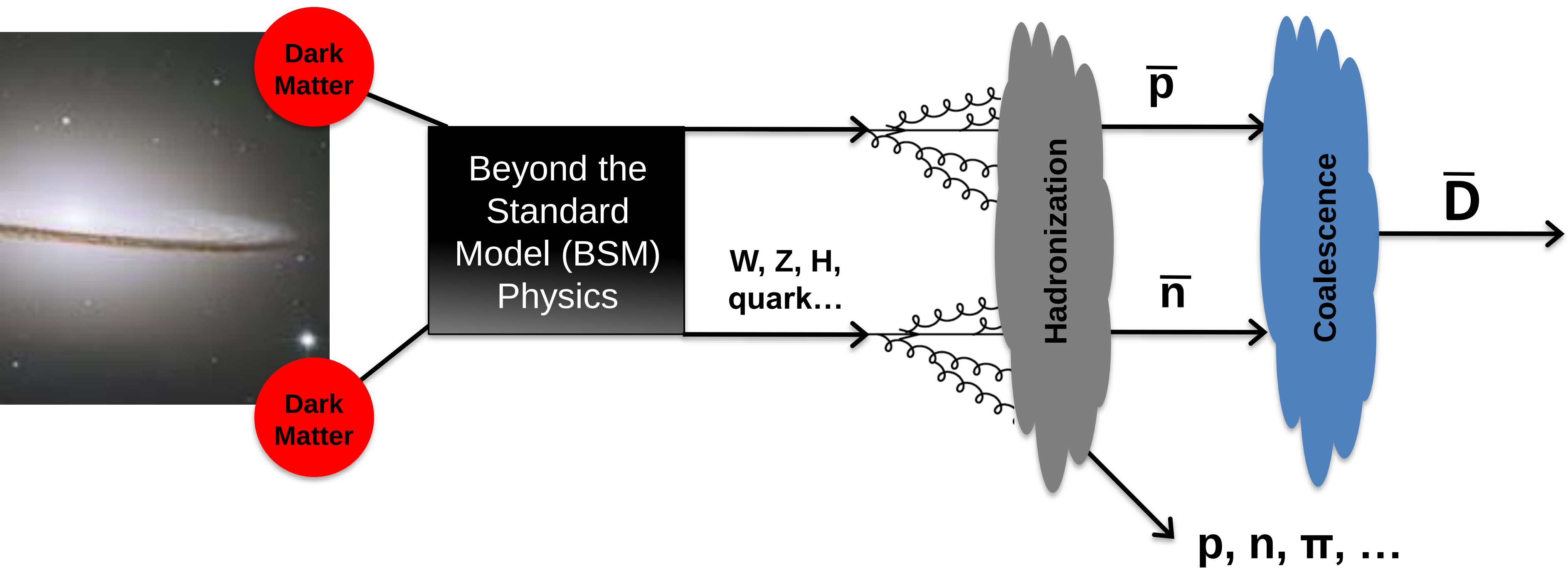




Photons



Antideuteron Signal of Dark Matter



Dark matter particles annihilate…

…create jets of Standard Model particles…

…some of which can make an antideuteron…

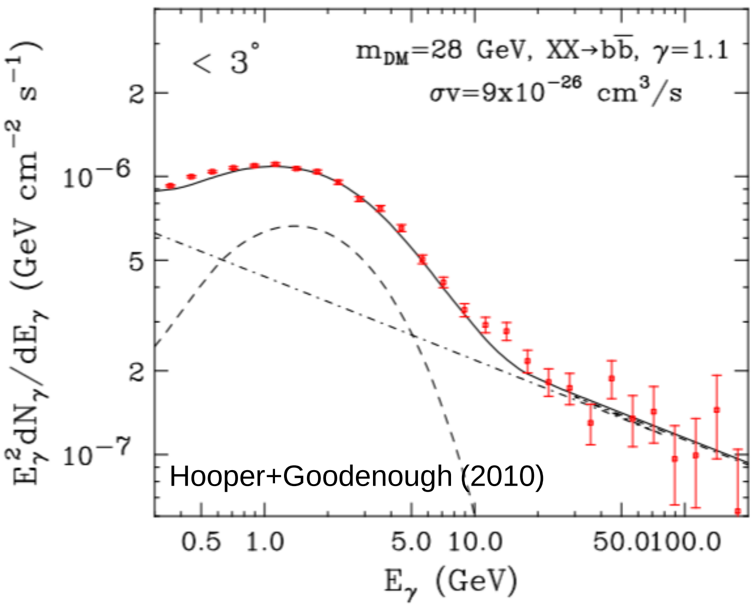
Indirect searches: **The "GeV excess"**

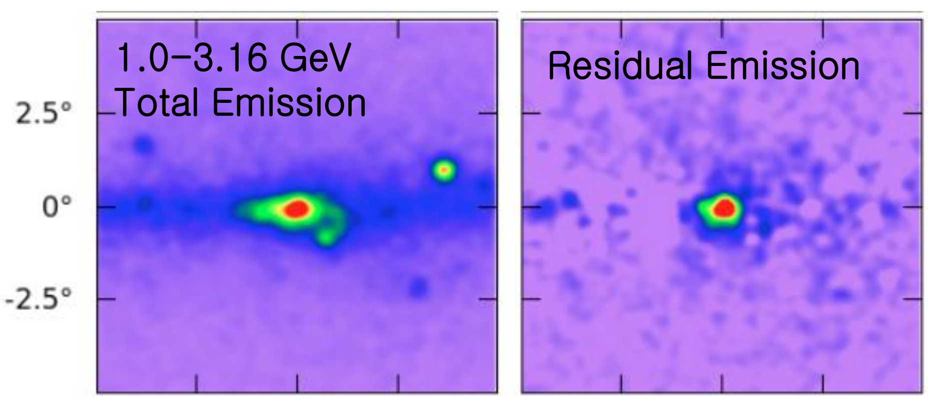
- An excess of gamma-rays at the Galactic Center, with spectrum, morphology, intensity consistent with annihilating dark matter

  e.g. Hopper, Linden (2011), Abazajian, Kaplinghat (2012), Gordon, Macias (2013), Daylan, et al. (2014), Calore, Cholis, Weniger (2014), Murgia, et al. (2015), Ackermann et al. (2017)

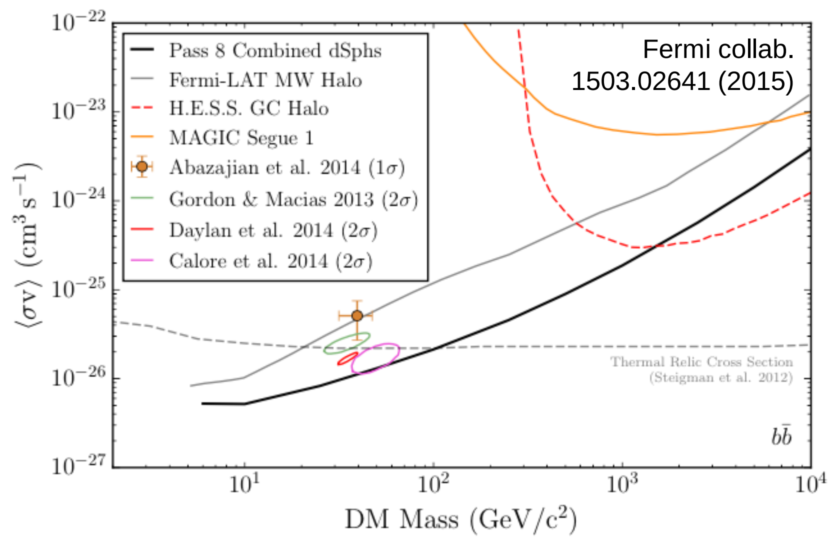
- Non-detection limits from dwarf galaxies weakened by GC and dwarf halo profiles, astrophysical background models

  e.g. Agrawal+ 1411.2592, Karwin+ 1612.05687, Hayashi+ 1603.08046, Klop+ 1609.03509, Abazajian+ 1510.06424, Benito+ 1612.02010



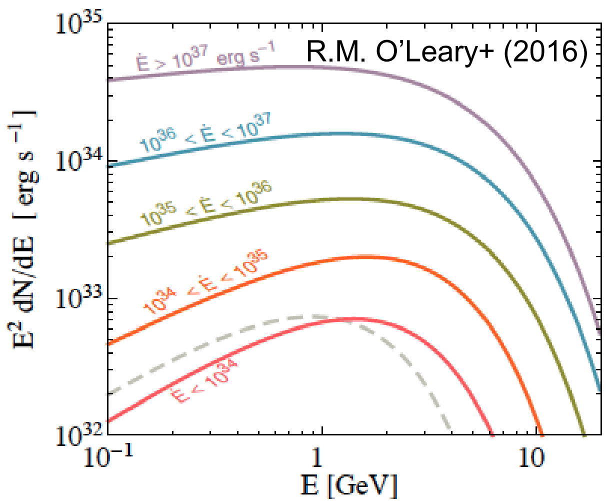


T. Daylan+ (2014)

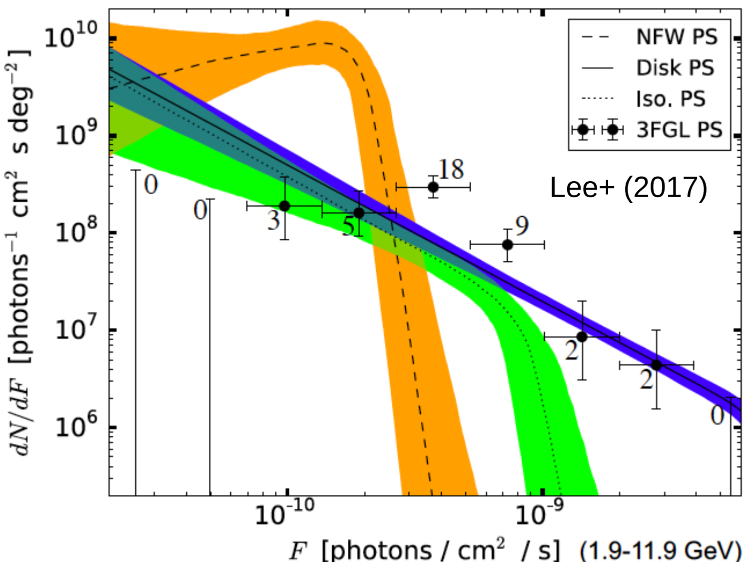


Indirect searches: **The "GeV excess"**

Interpretation depends on poorly-understood Galactic source (MSP) population

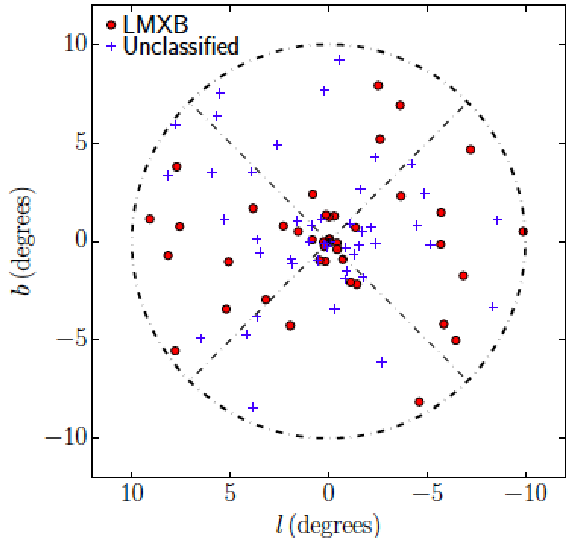


- Spectrum also consistent with millisecond pulsars
- Evidence for sub-threshold point-source contribution
- Indicates a population of MSPs would have a luminosity function and low-mass X-ray binary progenitor population quite different from those in the Milky Way disk or globular clusters

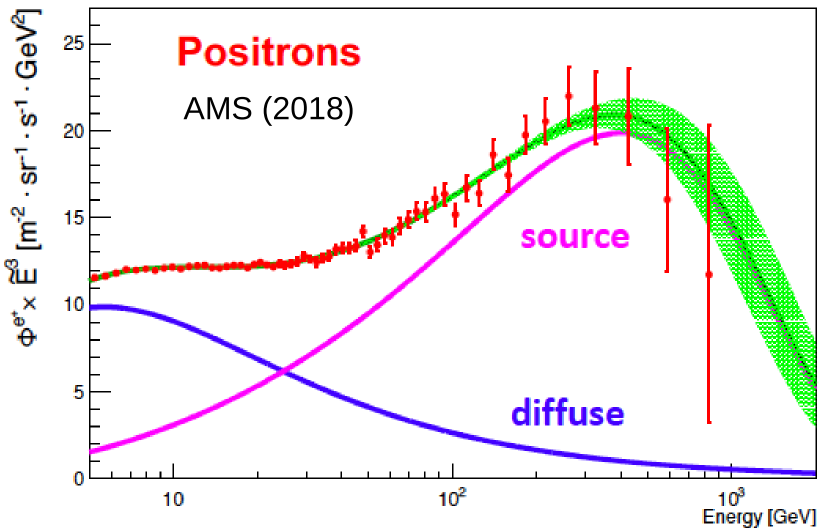


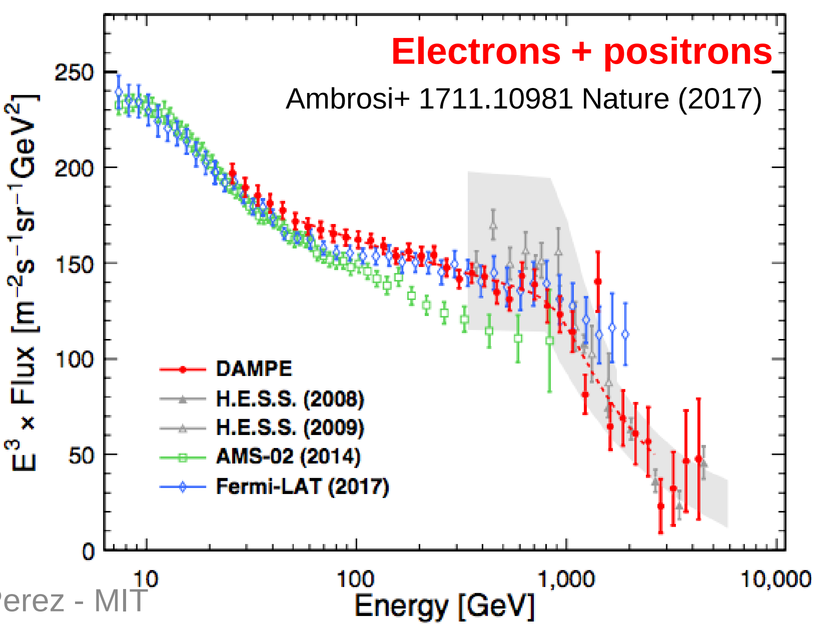
← Evidence for unresolved point sources
Lee, Lisanti, Safdi, Slatyer, Xue, 1506.05124
Bartels, Krishnamurthy, Weniger, 1506.05104

Comparison with LMXB distribution →
Haggard, Heinke, DH, Linden, JCAP, 1701.02726

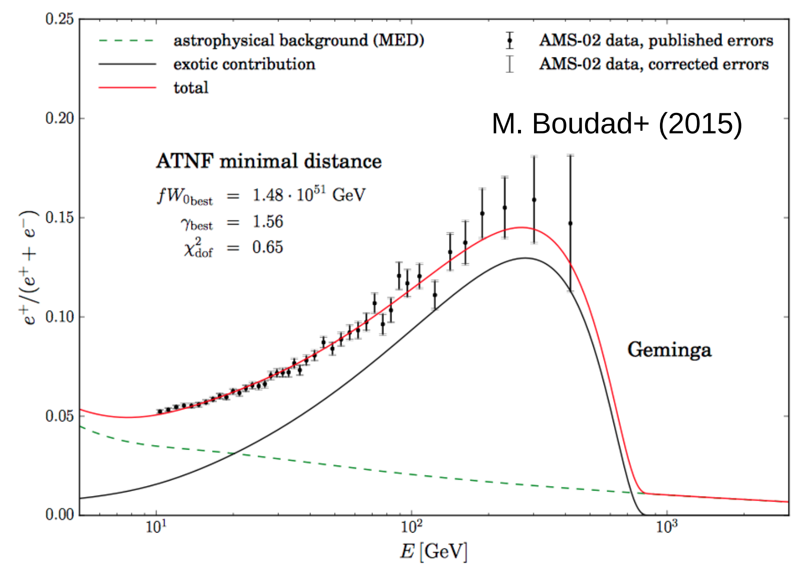


Indirect searches: **The “positron excess”**



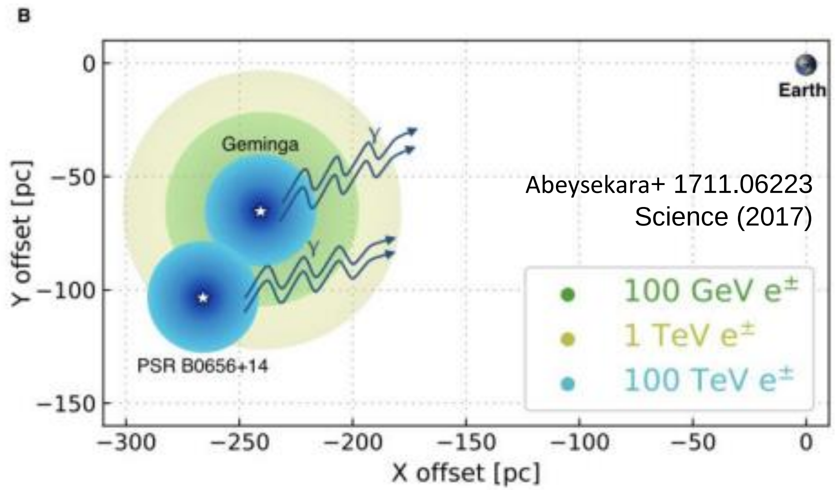


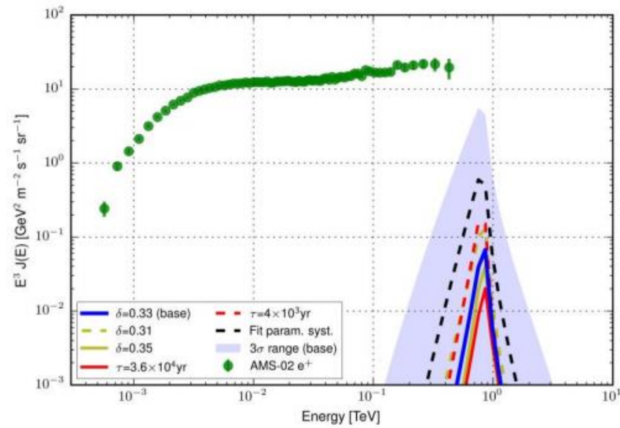
- Rising positron fraction observed since PAMELA 2008, confirmed to higher energies by AMS-02
- Implies heavy TeV-scale dark matter. Need enhanced annihilation cross section and leptophilic annihilation (to avoid antiproton bounds).
- …or could be pulsars:

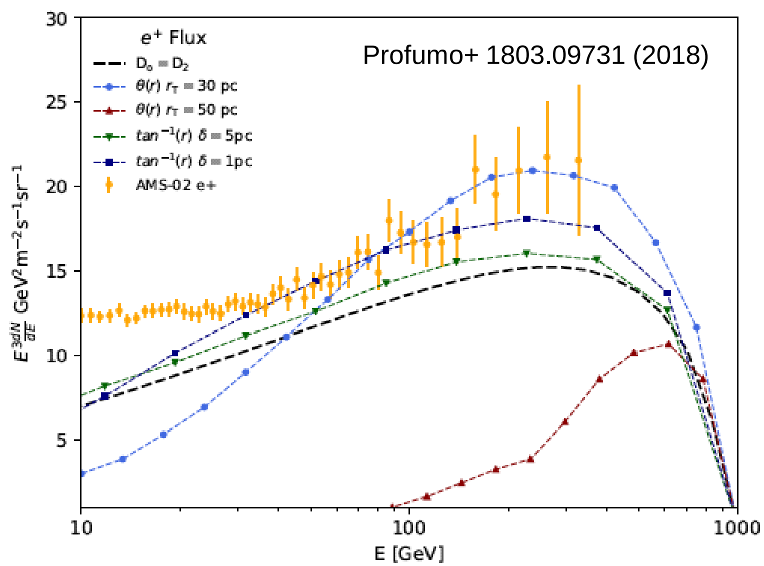


Indirect searches: **The "positron excess"**

Interpretation depends on poorly-understood Galactic propagation (diffusion)



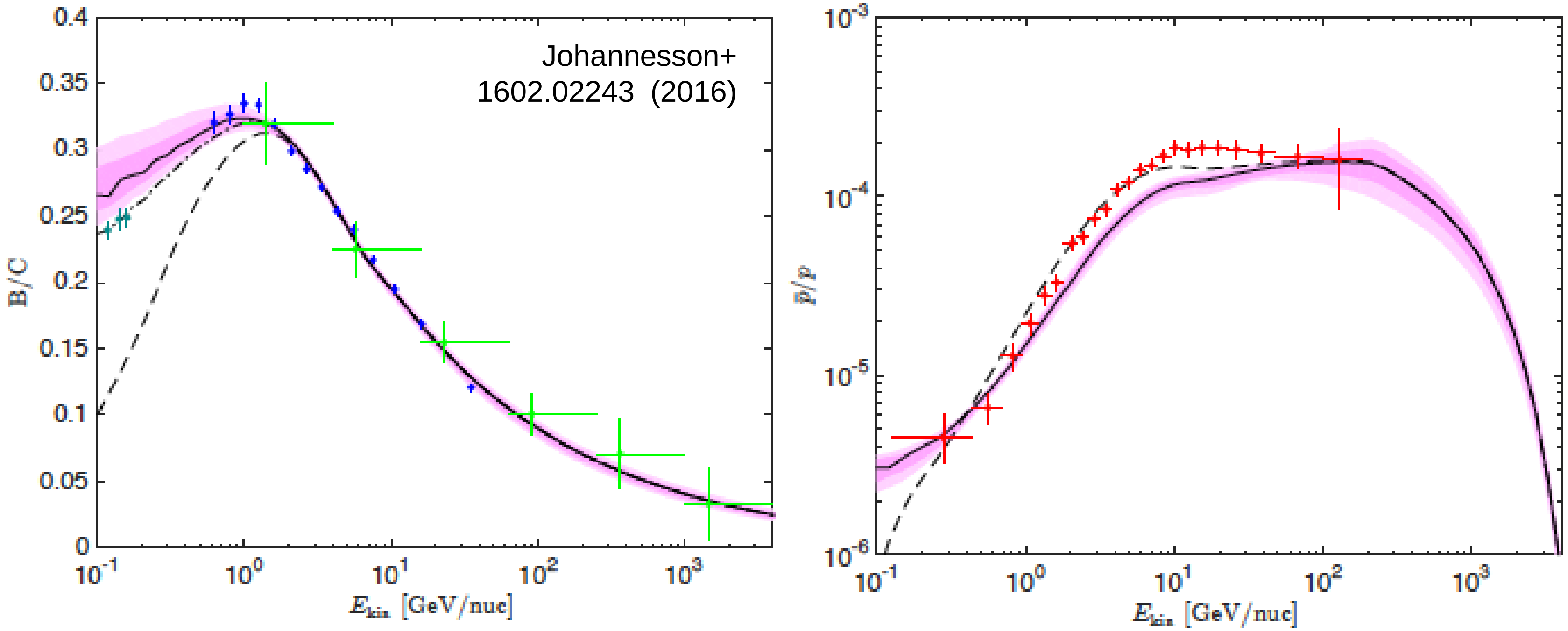




↑ HAWC – if Galactic diffusion similar to diffusion in regions of nearby pulsars, excess cannot be due to pulsars

← Likley implies that diffusion not uniform throughout local interstellar medium

Propagation parameters



Secondary-to-primary ratio 68% and 95% posterior bands from light element (Be–Si) scan (left) The pbar/p ratio (right) indicates that using the same propagation parameters for hydrogen yields a very bad fit to the data.

Korsmeier, Donato, Fornengo (2018)

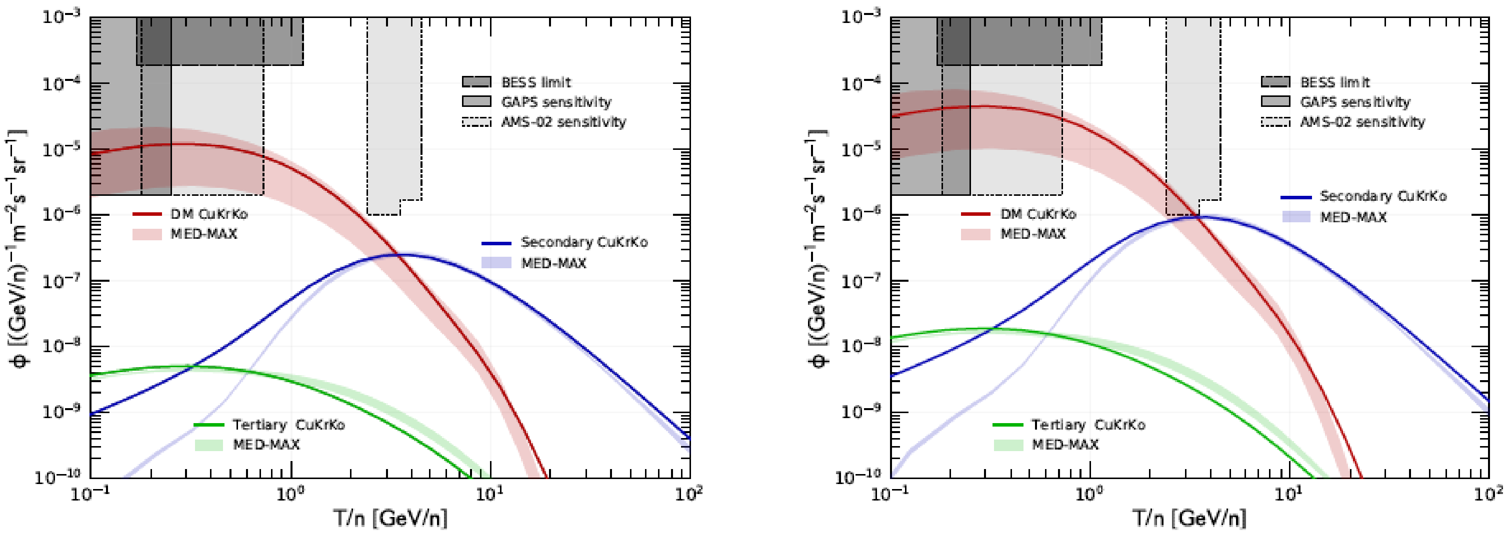
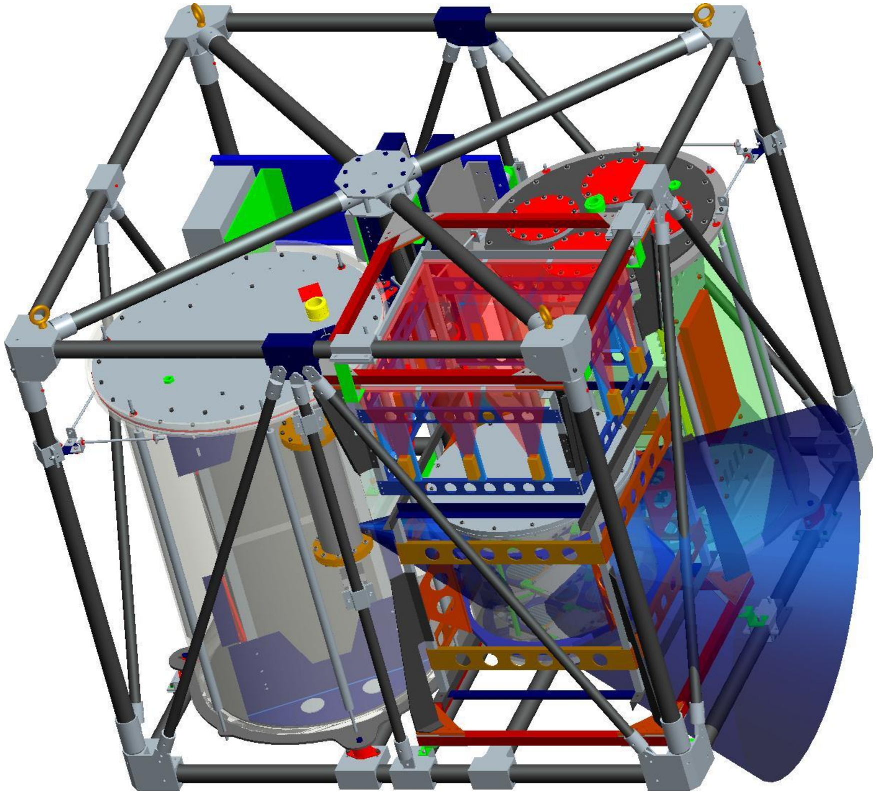
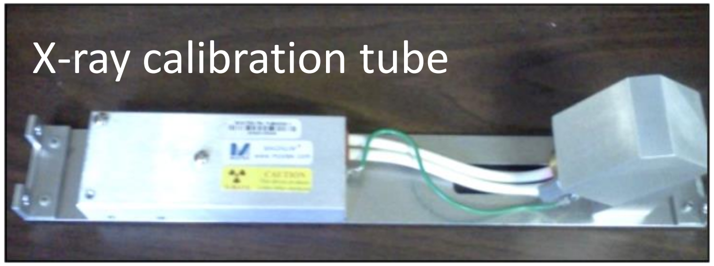
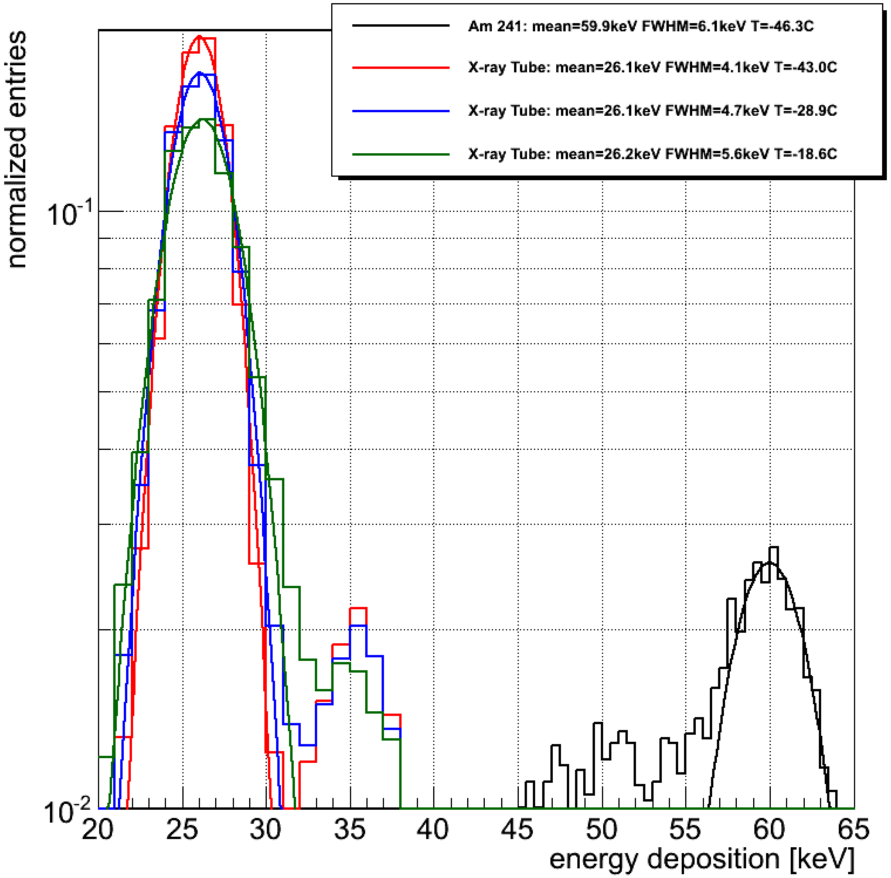


FIG. 2. Antideuteron flux for secondaries in the ISM and the potential DM signal, corresponding to generic $b\bar{b}$ annihilation from the excess in CuKrKo. We show the different propagation models MED and MAX, which are constrained to fit B/C data in Ref. [41]. CuKrKo corresponds to the propagation parameters obtained from the best fit of $b\bar{b}$ DM in [14]. All fluxes are derived in the analytic coalescence model with $p_C = 160$ GeV (left panel) and $p_C = 248$ GeV (right panel). Solar modulation is treated in the force-field approximation with a potential of $\phi = 400$ MV. Additionally, the current limit by the BESS experiment (95% CL) [55], the AMS-02 sensitivity of [21], and the expected sensitivity for GAPS (99% CL) [20] are displayed.

pGAPS Detector Results



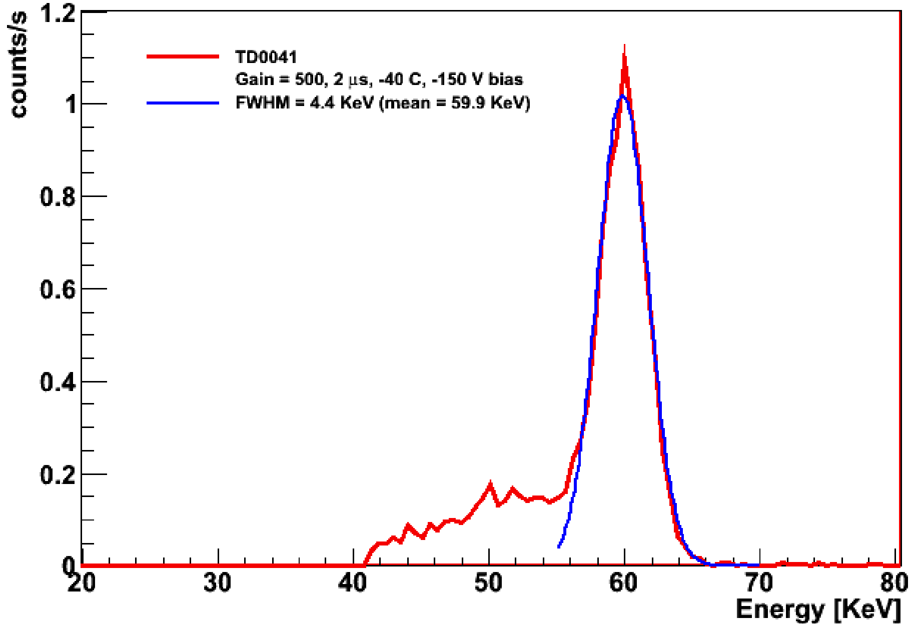




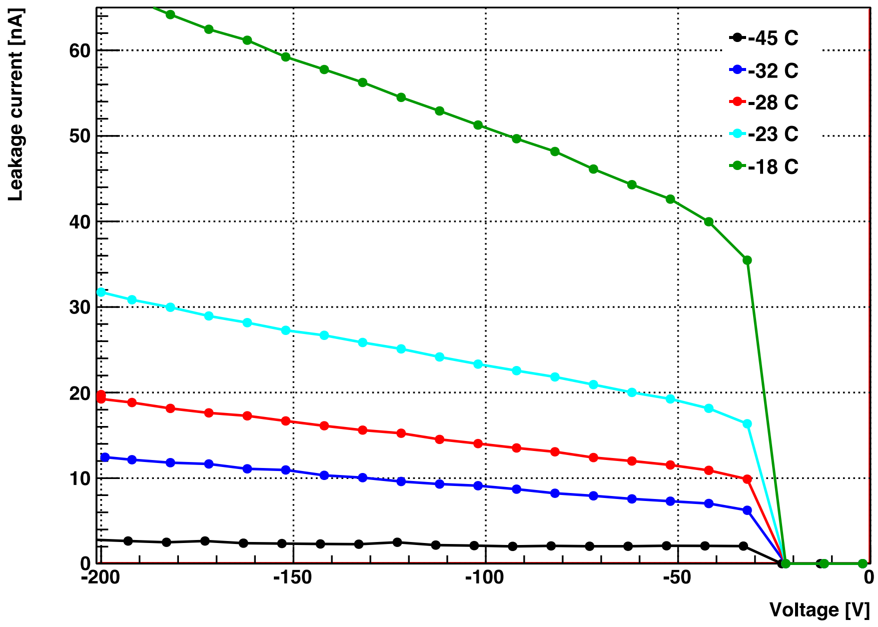
Si(Li) resolution consistent with temperature-dependent predictions

Si(Li) Detector Performance

2"-diameter, 1 mm thick prototype detectors have been produced with the required performance!



Resolution measured with an Am-241 X-ray source



Operational temperature range for 1 mm thick prototype detector