Future Cosmic Ray Experiments

Kerstin Perez
Columbia University

Latest Results in DM Searches
Stockholm, Sweden
May 14, 2014

Introduction

The Experiments: AMS and GAPS

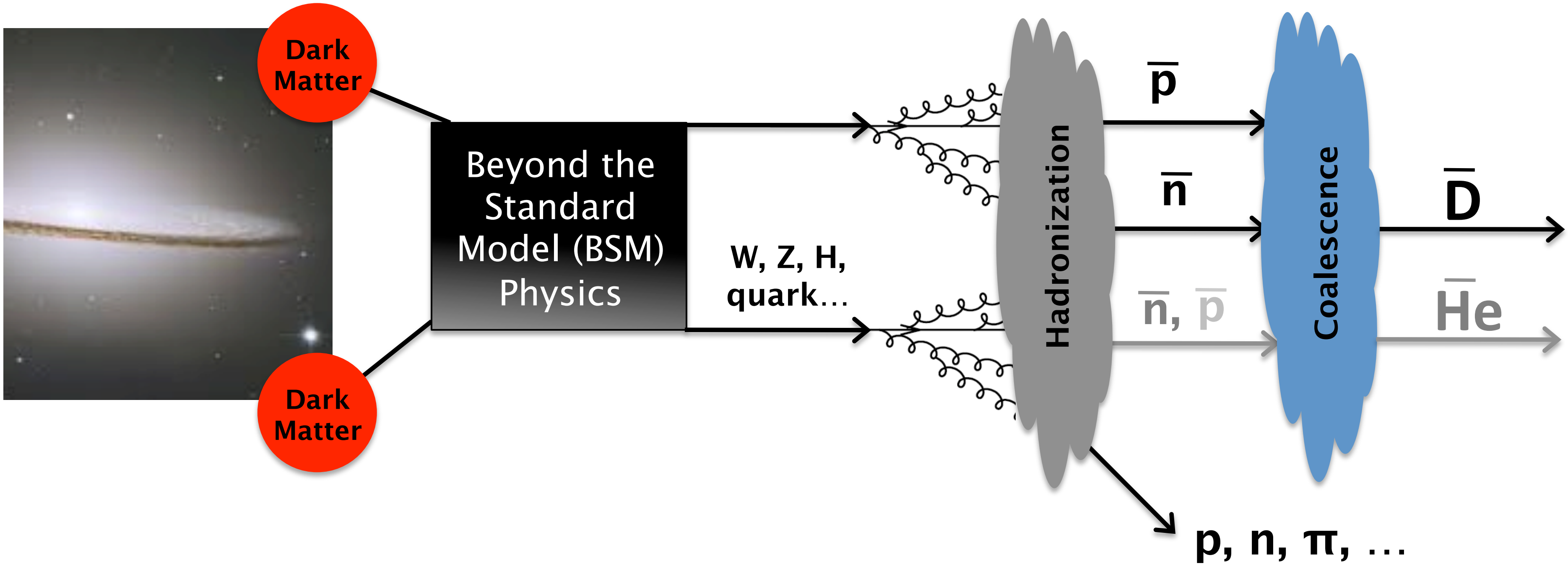
Antiprotons: Past limits and future prospects

Antideuterons: A “smoking gun” signature of dark matter?

Antihelium: Looking into the future

The Path Forward

$\bar{p}$, $\bar{D}$, $\overline{He}$ Signatures of Dark Matter

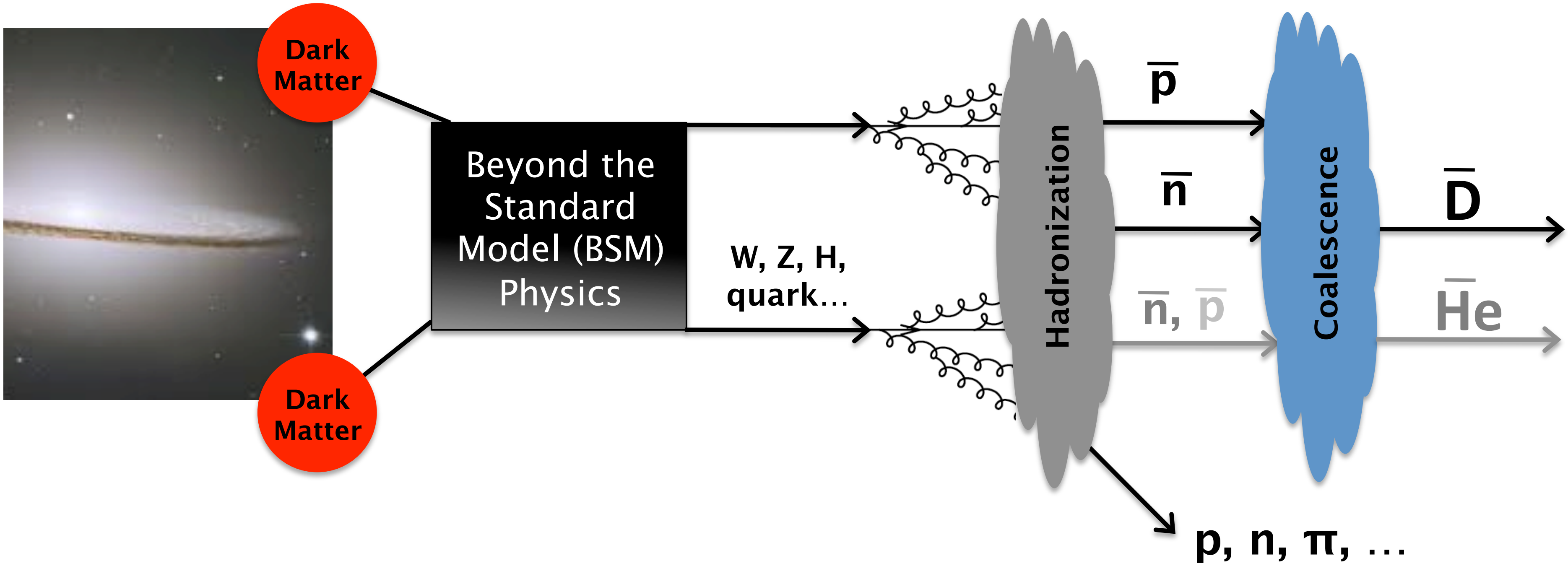


Dark matter particles annihilate…

…create jets of Standard Model particles…

…some of which can make an antideuteron, antihelium, etc…

$\bar{p}$, $\bar{D}$, $\overline{He}$ Signatures of Dark Matter



Dark matter particles annihilate…

…create jets of Standard Model particles…

…some of which can make an antideuteron, antihelium, etc…

- Interactions of cosmic rays on the interstellar medium ($p_{CR} + H_{ISM}/He_{ISM}$, $\bar{p}_{CR} + H_{ISM}/He_{ISM}$) create “secondary” anti-p, D, He
- Secondaries produced with typically higher total energy

Coalescence and Hadronization Models

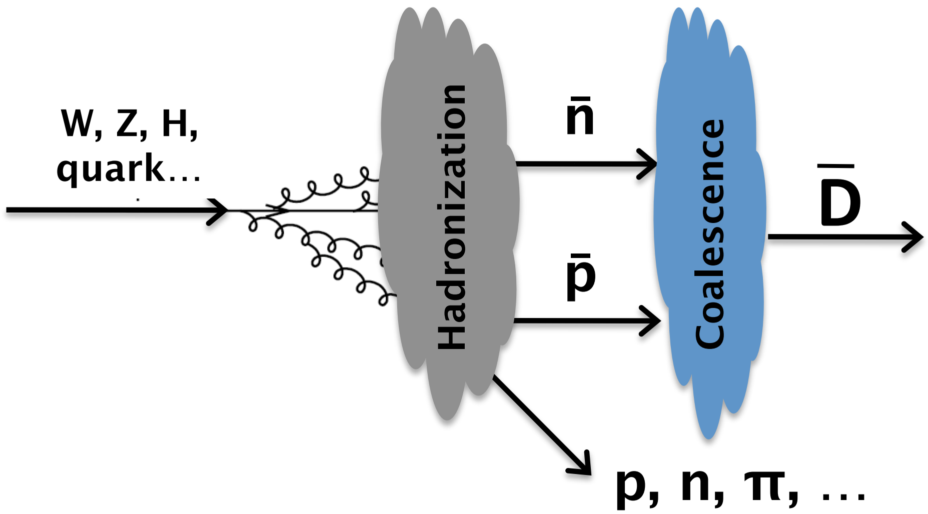
Coalescence:
n̄ and p̄, merge when relative momentum < $\mathbf{p_0}$

To determine p_0:

1. Assume uncorrelated, isotropic distribution of n̄ and p̄
2. MC method that accounts for correlations due to production channel or center-of-mass energy
3. MC method with additional Δr requirement

Then tune this to experimental data:
$e^+e^- \rightarrow \bar{d}$ data from LEP

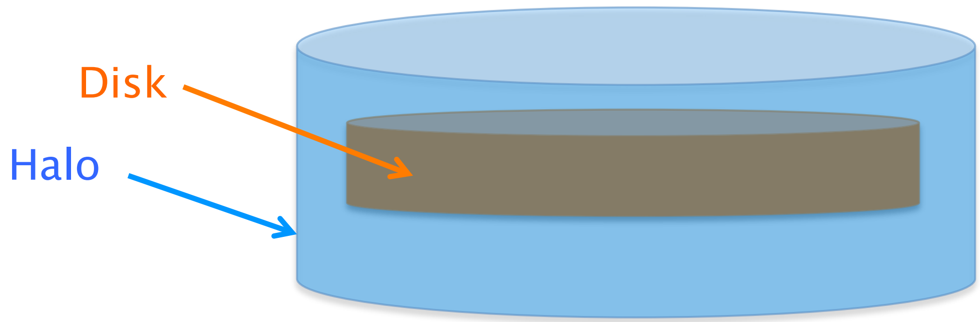
All depends on choice of hadronization model!
i.e. Pythia vs Herwig



Choice of coalescence and hadronization model affects d̄ sensitivity by factors of ~3-4

Propagation Model

Propagation in Galactic Environment:



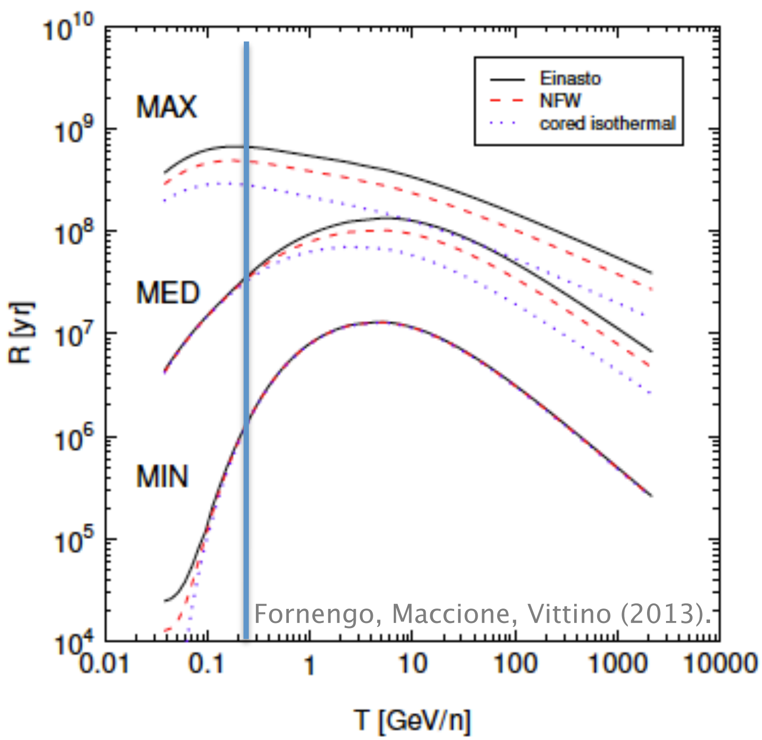
- diffusion
- convection
- annihilation
- size of halo
- size of disk

- Constrained by B/C data
  = secondary / primary

- But still largest source of uncertainty on đ flux!

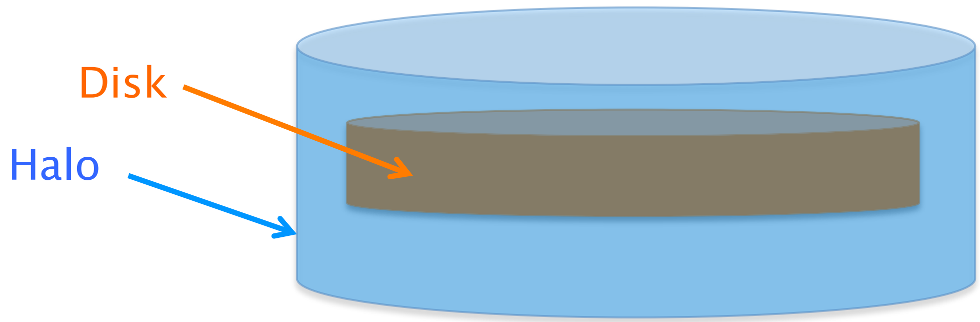
- Will be better constrained in the future by AMS-02 measurements

- Less sensitive to halo model, but affected by boost factor, *f*, from halo sub-structure



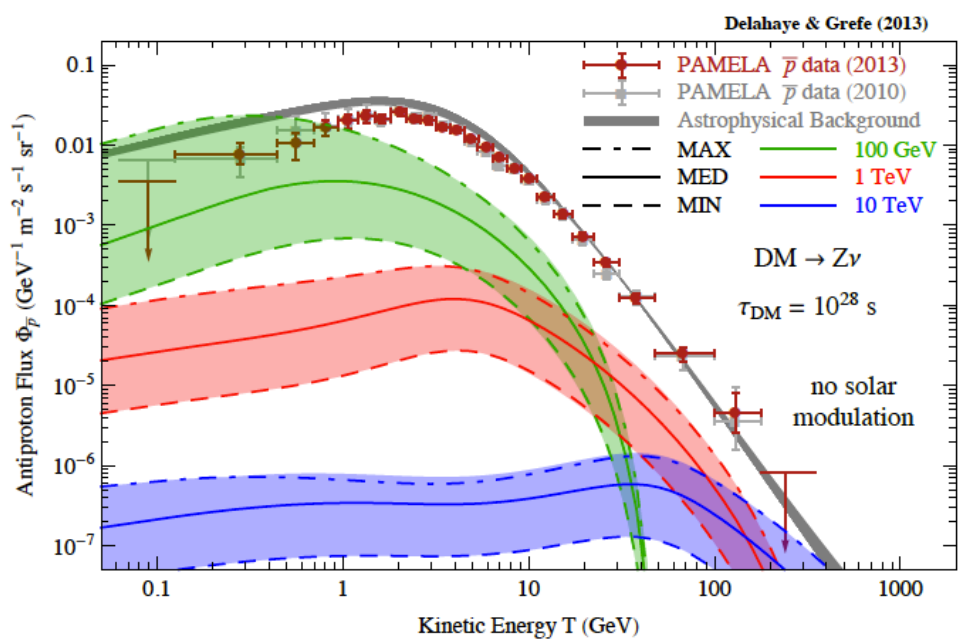
Propagation Model

Propagation in Galactic Environment:



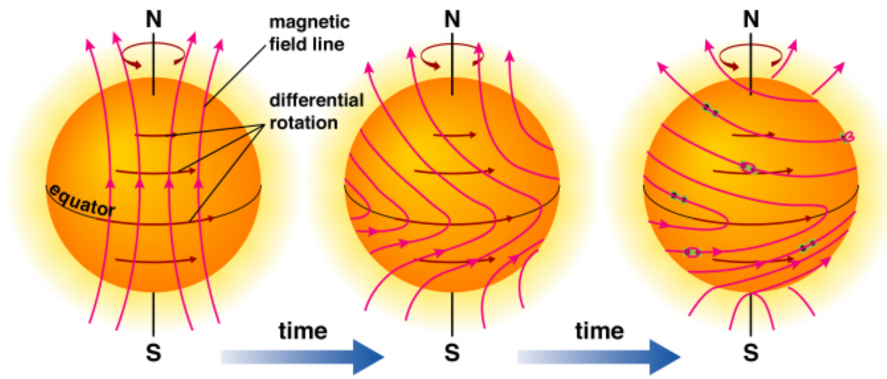
- diffusion
- convection
- annihilation
- size of halo
- size of disk

- Constrained by B/C data
  = secondary / primary
- But still largest source of uncertainty on đ flux!
- Will be better constrained in the future by AMS-02 measurements
- Less sensitive to halo model, but affected by boost factor, *f*, from halo sub-structure



Propagation Model

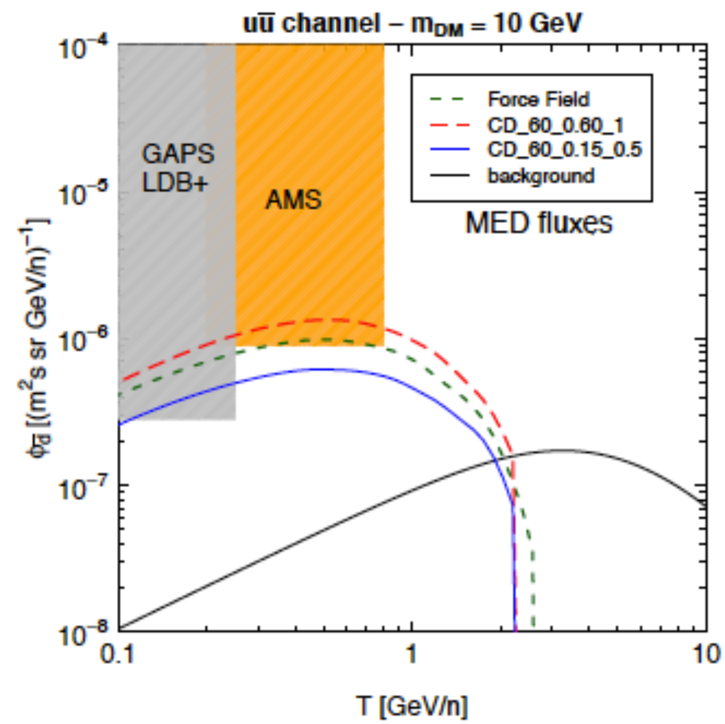
Propagation in Solar Environment:



- Cosmic rays drift and lose energy in the solar magnetic field

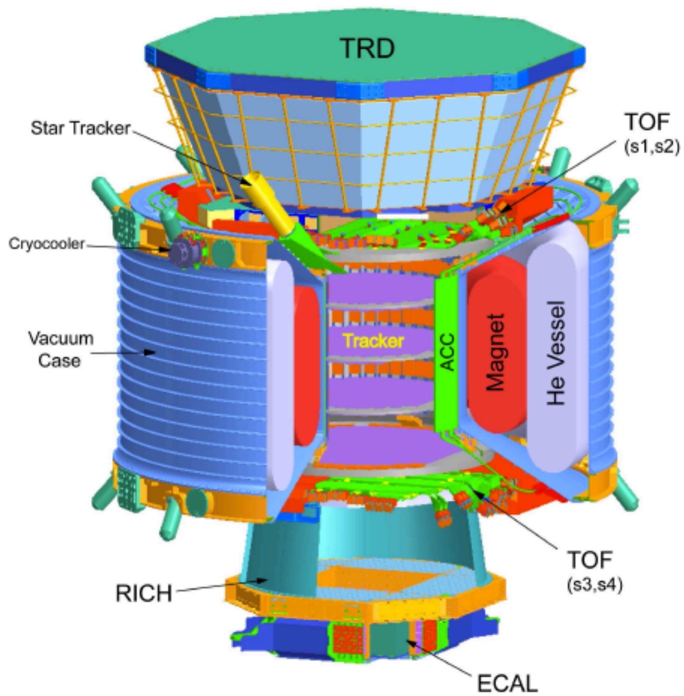
- Particularly important for *low-energy* cosmic rays

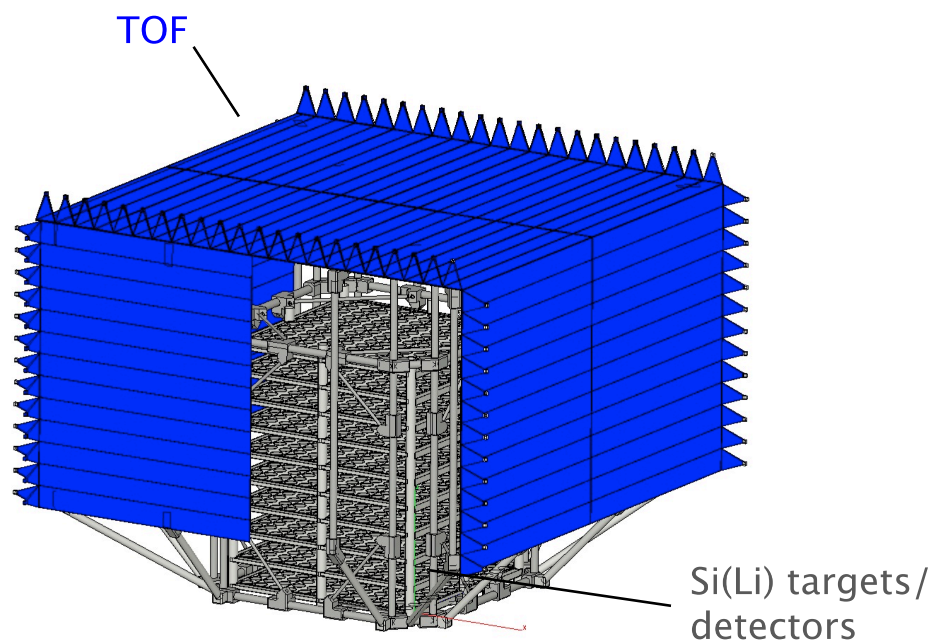
- Solar magnetic field changes on timescales of ~11 year



The Experiments

The Experiments: AMS and GAPS

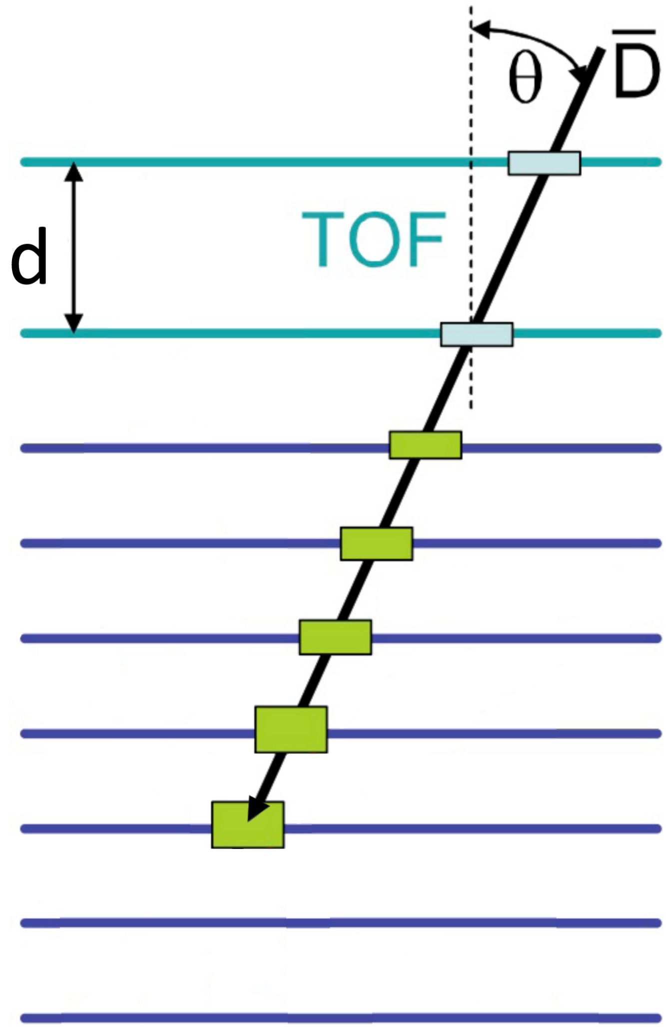




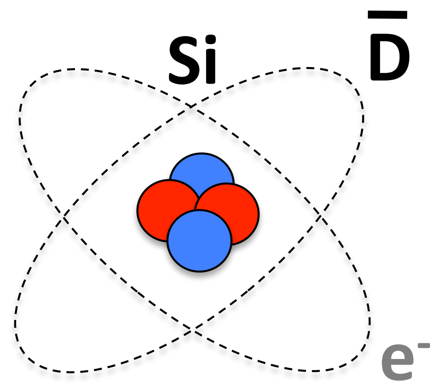
- AMS has been in operation on the ISS since May 2011
- Consists of TRD, TOF, tracker, permanent magnet, RICH, ECAL
- Uses primarily TRD and tracker for anti-p and anti-D detection

- GAPS proposed for initial Antarctic balloon flight late 2018
- Consists of TOF and Si(Li) targets/detectors
- Uses exotic atom capture and decay to detect anti-p and anti-D

GAPS Detection Concept

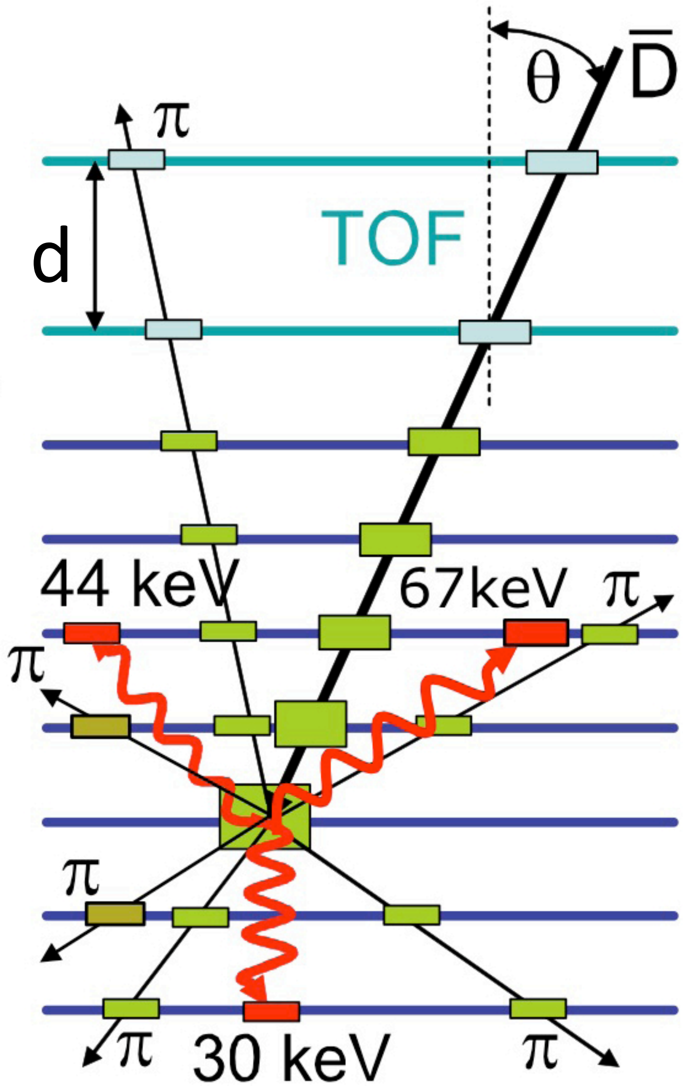


- **Time-of-flight** system measures velocity
- Loses energy in layers of semiconducting **Silicon targets/detectors**
- Stops, forming **exotic excited atom**
- Atom de-excites, emitting **x-rays**
- Remaining nucleus annihilates, emitting **pions and protons**

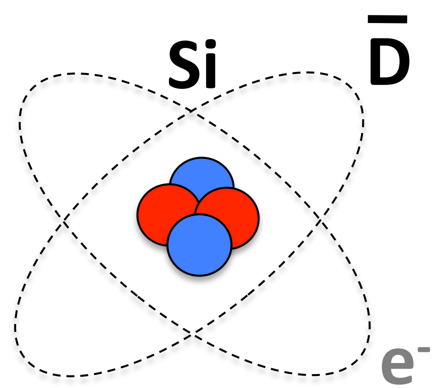


T. Aramaki et al., http://arxiv.org/abs/1303.3871

GAPS Detection Concept

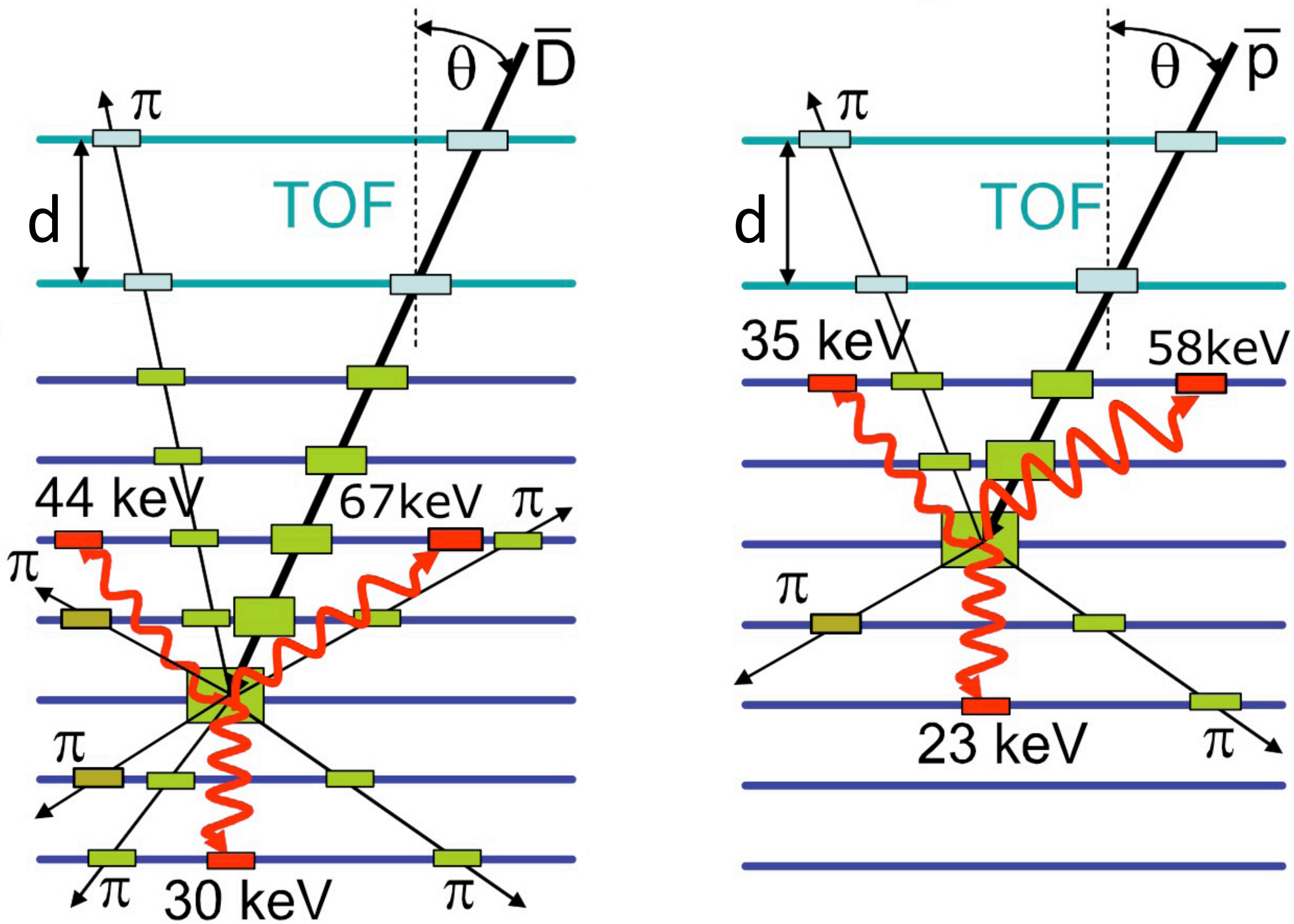


- Time-of-flight system measures velocity
- Loses energy in layers of semiconducting Silicon targets/detectors
- Stops, forming **exotic excited atom**
- Atom de-excites, emitting **x-rays**
- Remaining nucleus annihilates, emitting **pions and protons**



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

GAPS and Antiprotons

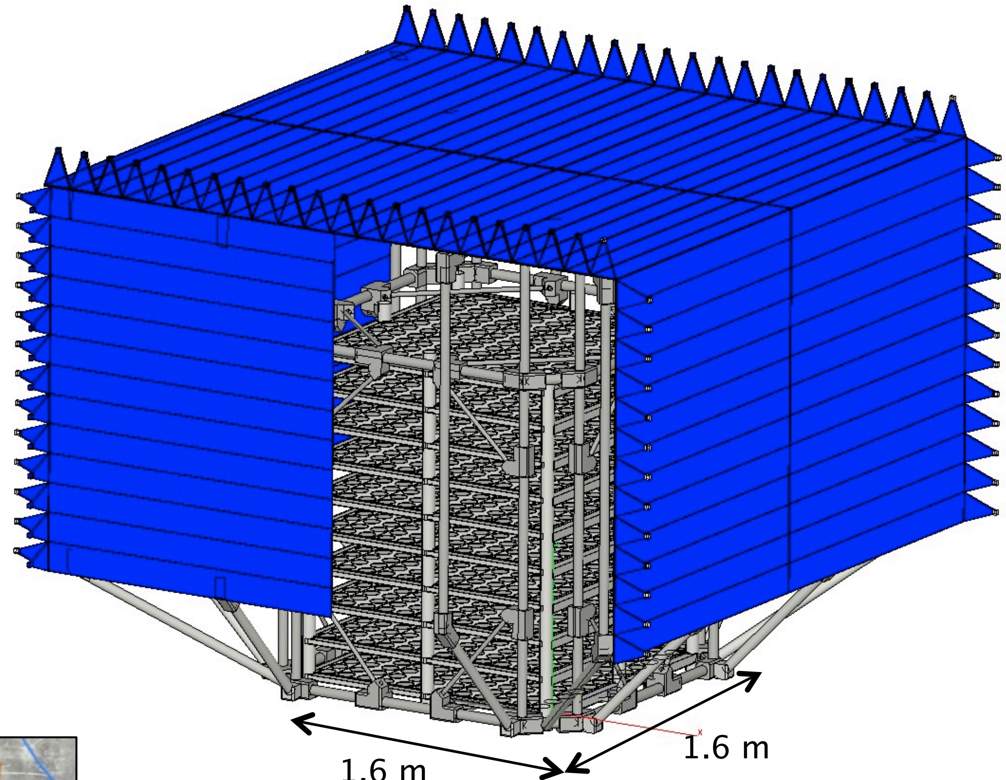


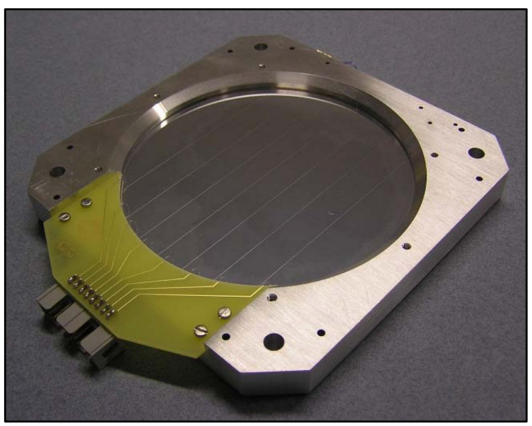
Combination of time-of-flight + depth-sensing, X-ray, and π detection can yield antiproton rejection >10^5

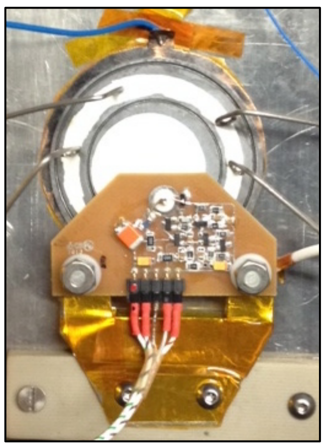
GAPS Detector Design

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” (or 2”) diameter
- 3 keV resolution for X-rays

Introduction

The Experiments: AMS and GAPS

Antiprotons: Past limits and future prospects ←

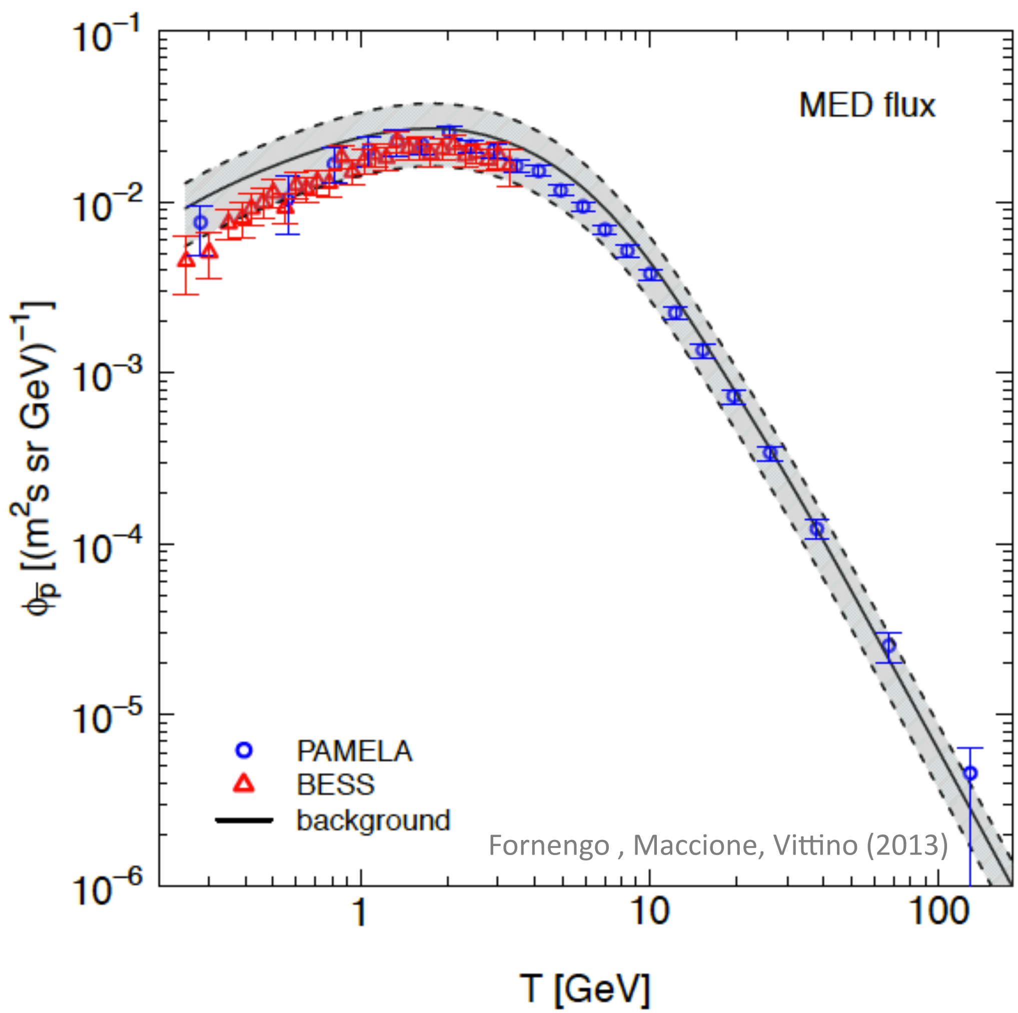
Antideuterons: A “smoking gun” signature of dark matter?

Antihelium: Looking into the future

The Path Forward

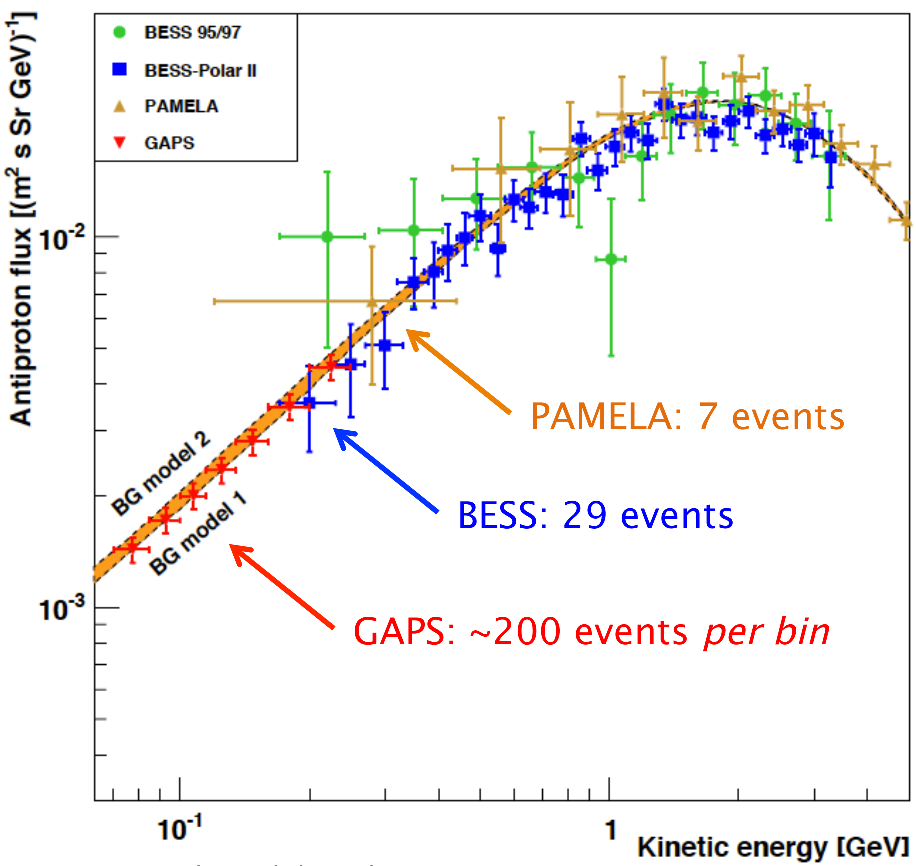
Antiprotons

Antiproton constraints



- Antiprotons thus far used to bound particle dark matter properties – PAMELA, BESS
- Thermal cross section excluded for m_{DM} < 90 (50) GeV for annihilation to light (heavy) quarks
- Very sensitive, *particulary at low energy/mass*, to variations of galactic and solar transport models
- For MIN case, exclusion decreased to m_{DM} < 4 GeV for light quarks, unconstrained for heavy quarks
- Variation of galactic propagation can vary bounds from few GeV up to 150 GeV
- Also poorest statistics for low energy bins

GAPS and antiprotons

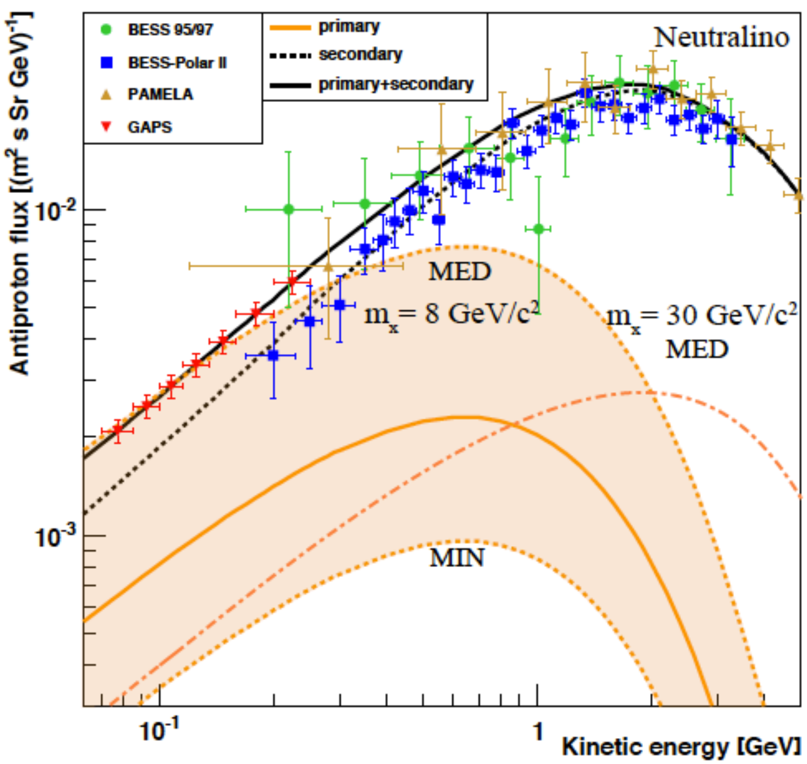


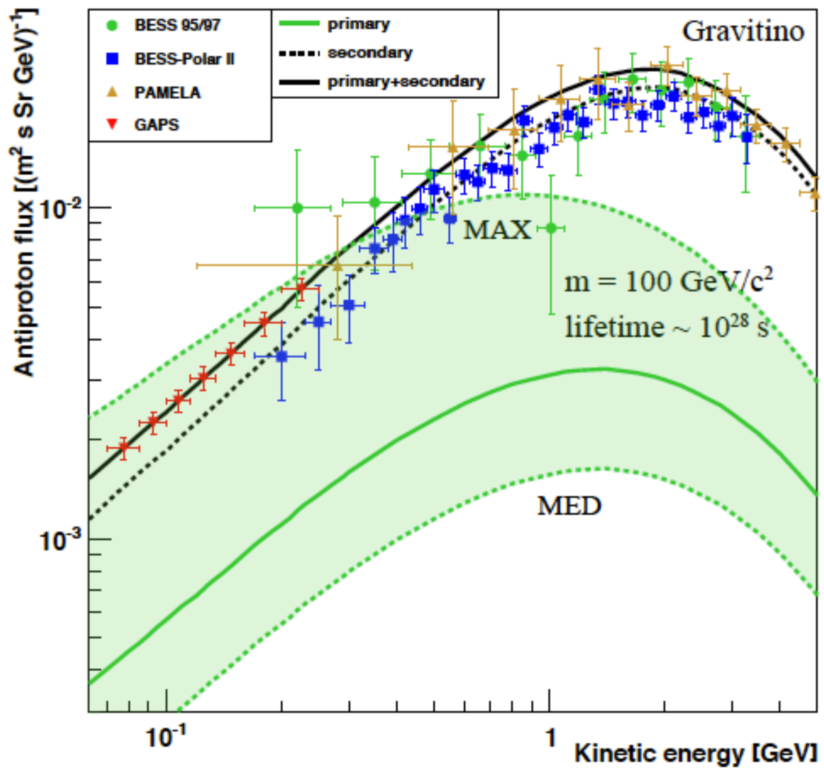
Aramaki et al. (2014)

- Bounds on light dark matter especially sensitive to low energy spectrum, where solar modulation most relevant
- GAPS will record ~1500 antiprotons per 35-day flight, with E < 0.25 GeV/n
- Can discover/constrain DM models in new parameter space
- Also probe cosmic-ray propagation and solar modulation

GAPS and antiprotons

GAPS able to detect realistic DM models that are missed by antiproton searches at higher energies

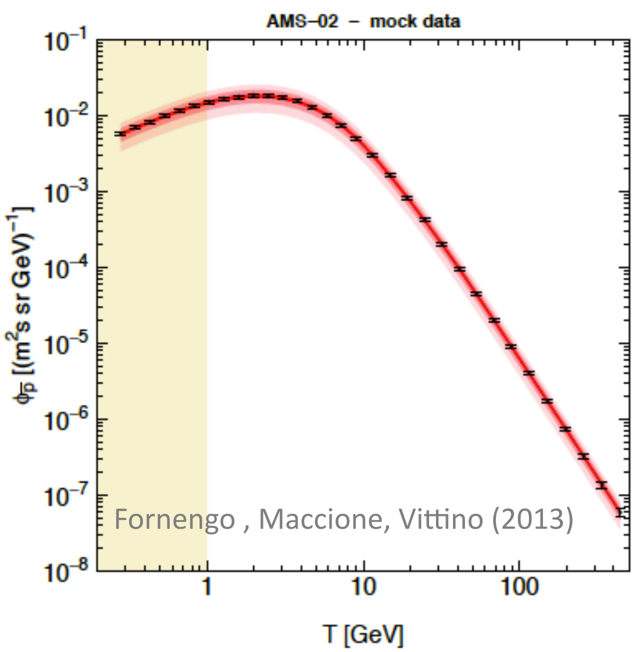




Aramaki et al. (2014)

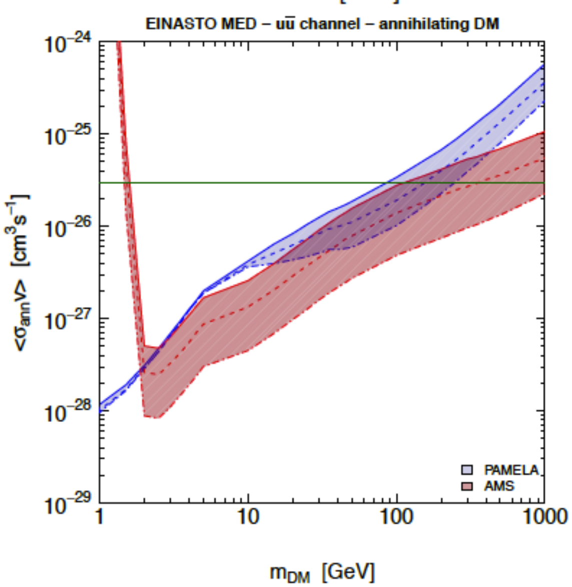
**Also LZP, primordial black holes, etc…

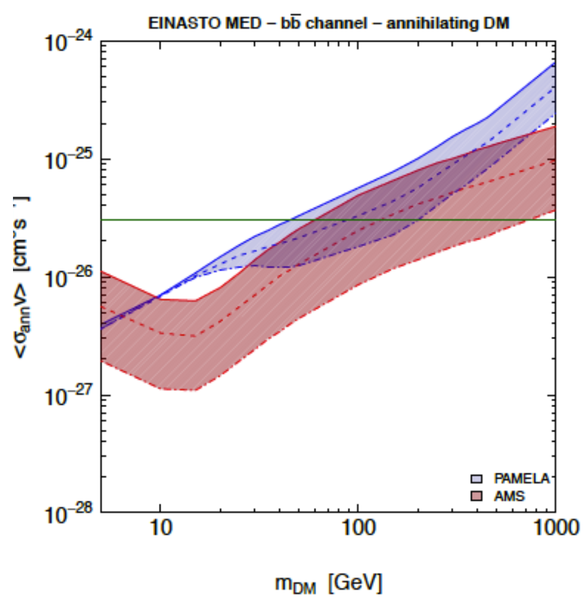
AMS and antiprotons

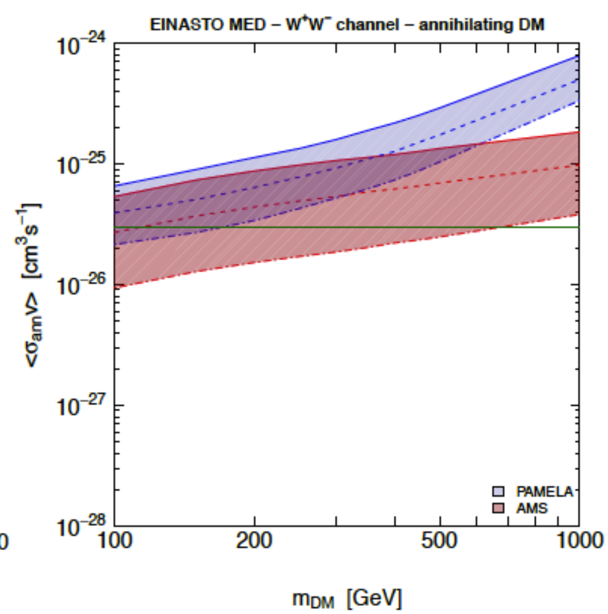


- AMS will extend the antiproton measurement beyond PAMELA and BESS

- AMS-02 will improve bounds for m_{DM} > 100 GeV







Introduction

The Experiments: AMS and GAPS

Antiprotons: Past limits and future prospects

Antideuterons: A “smoking gun” signature of dark matter? ←

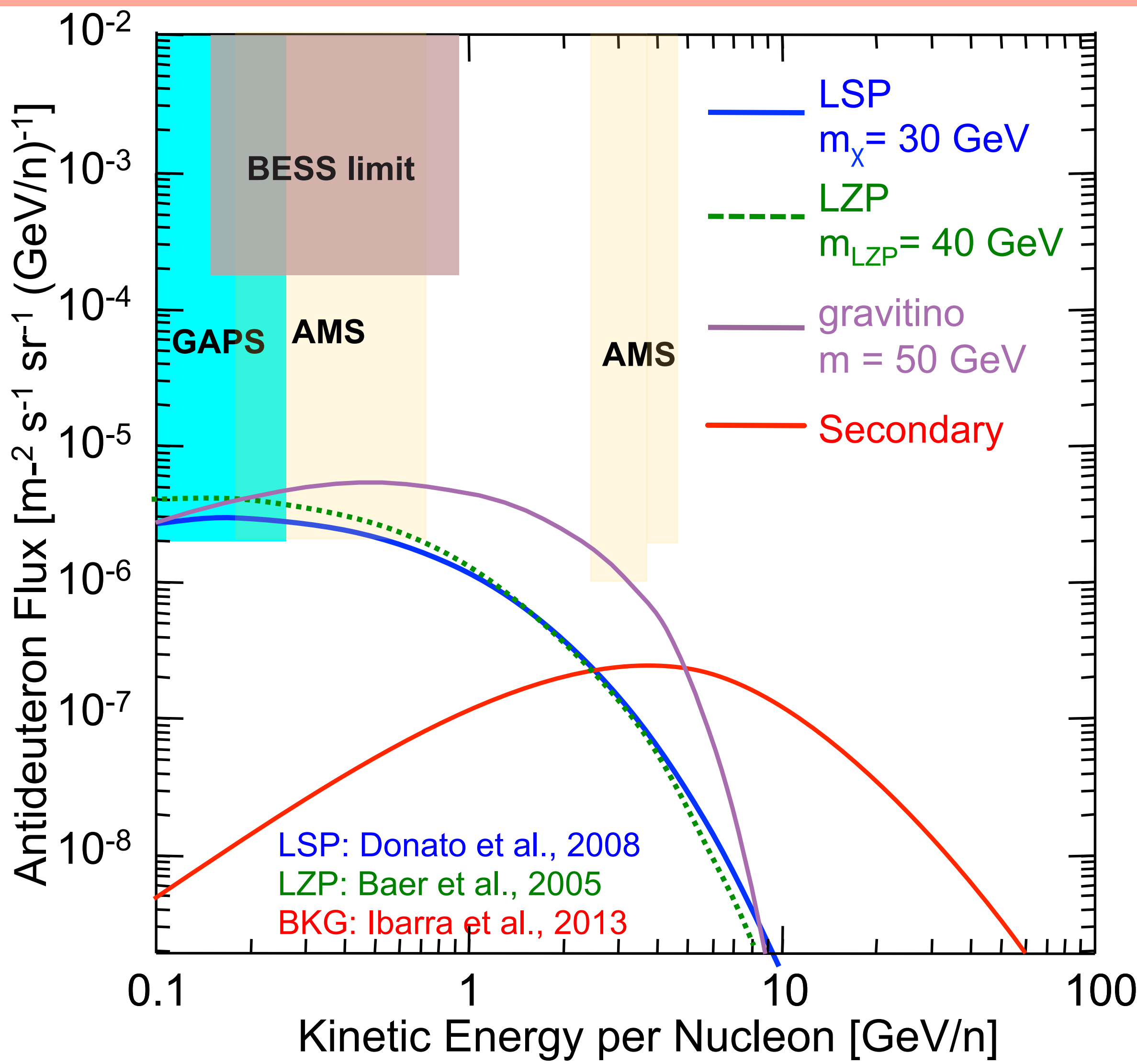
Antihelium: Looking into the future

The Path Forward

Antideuterons

GAPS, AMS, and Antideuterons

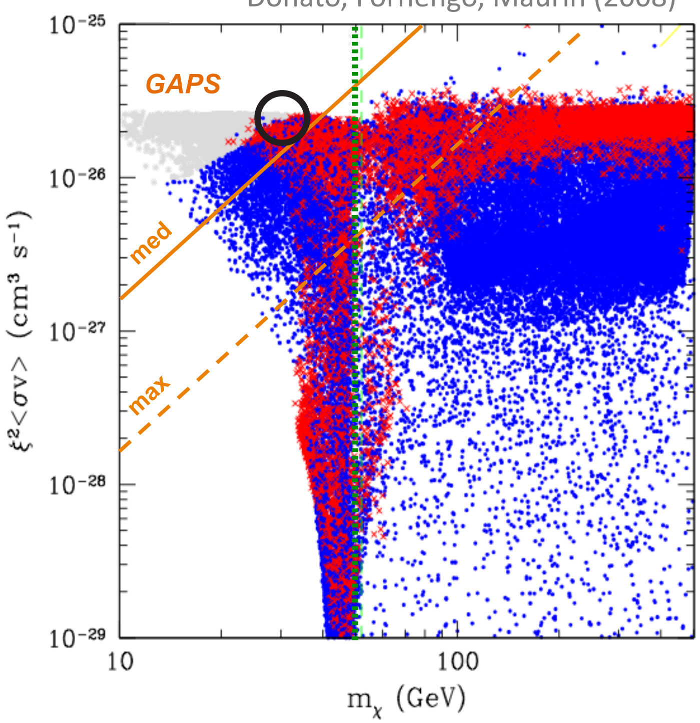
A generic dark matter signature with *essentially zero* conventional astrophysical background



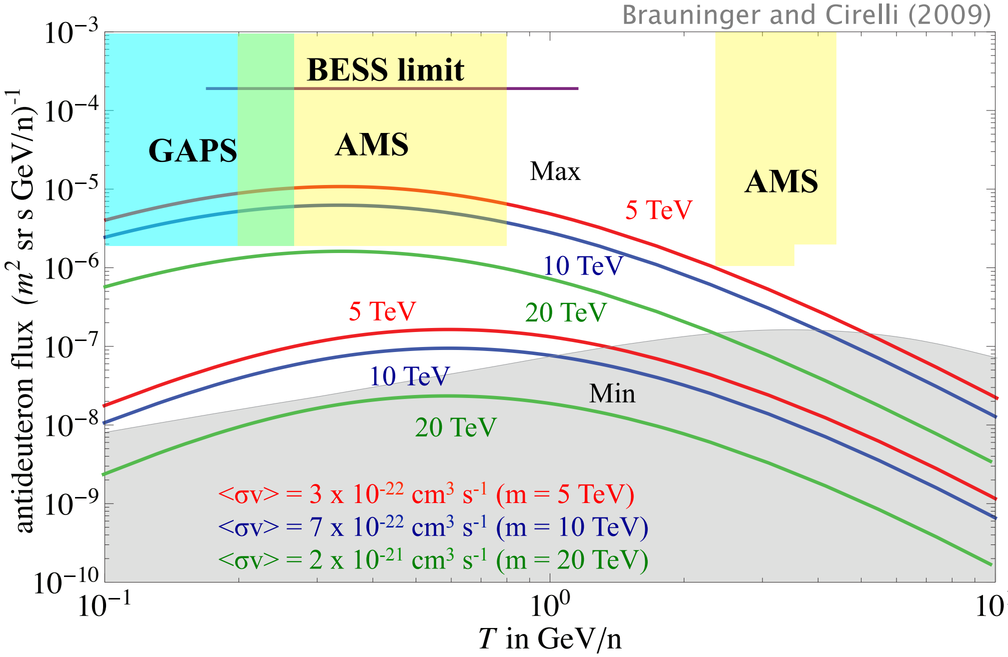
Sensitive to Viable Light and Heavy DM

- Sensitive to low-mass DM models, as invoked to explain CDMS-II Si, COGENT, Fermi observations

Donato, Fornengo, Maurin (2008)

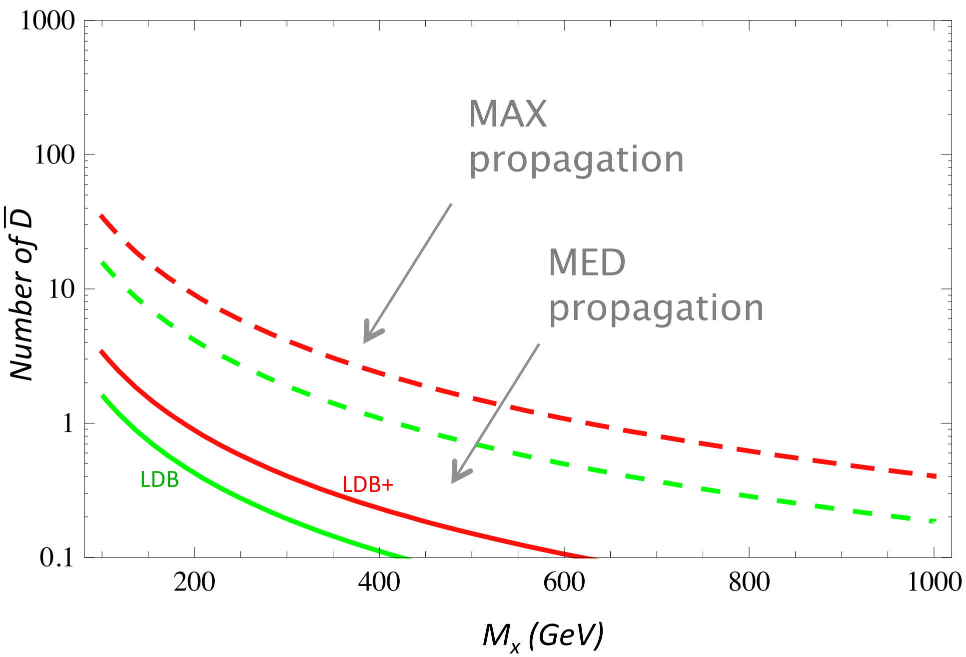


Brauninger and Cirelli (2009)



- Sensitive to heavy DM models, as invoked to explain PAMELA, AMS observations of positron excess

Rare Event Search



Neutralino fluxes from Cui, Mason, and Randall, J. High Energy Phys. 11, 017 (2010).

- Analogy to direct search experiments:
  - handful of signal events
  - instrument background dominated
  - long integration times
  - multiple technologies

Small expected signal flux and multiple uncertainties highlight need for many experiments, complementary sensitivities

Introduction

The Experiments: AMS and GAPS

Antiprotons: Past limits and future prospects

Antideuterons: A "smoking gun" signature of dark matter?

Antihelium: Looking into the future ←

The Path Forward

Antihelium

Coalescence and Hadronization Models

Coalescense:
$\bar{n}$ and $\bar{p}$, merge when relative momentum < $\mathbf{p_0}$

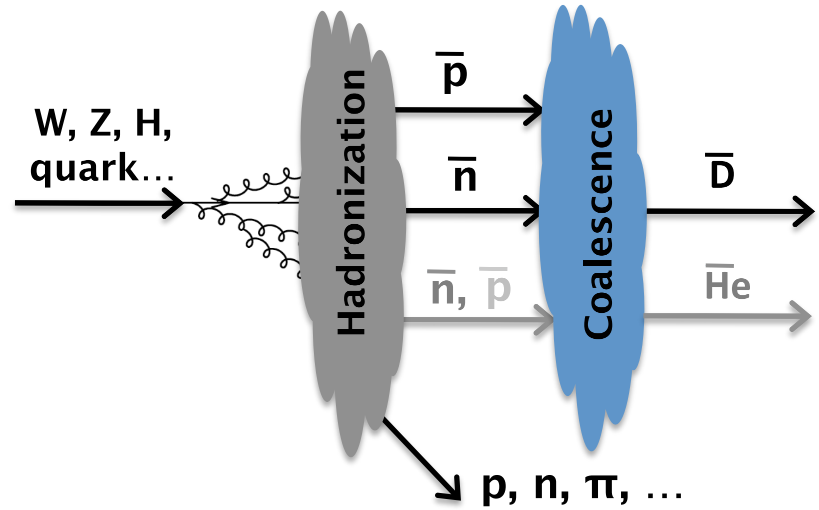
To determine p_0:

1. Assume uncorrelated, isotropic distribution of $\bar{n}$ and $\bar{p}$
2. MC method that accounts for correlations due to production channel or center-of-mass energy
3. MC method with additional Δr requirement

} *essential* for anti-He predictions

Then tune this to experimental data:
$e^+e^- \rightarrow \bar{d}$ data from LEP

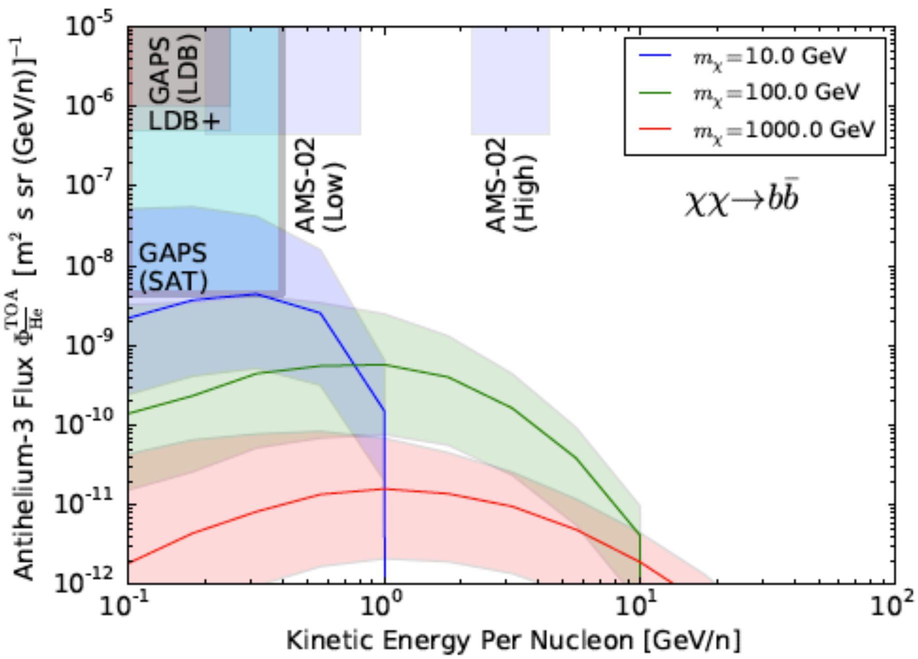
All depends on choice of hadronization model!



Scales as $p_0^{3(A-1)}$, so large uncertainty for anti-He

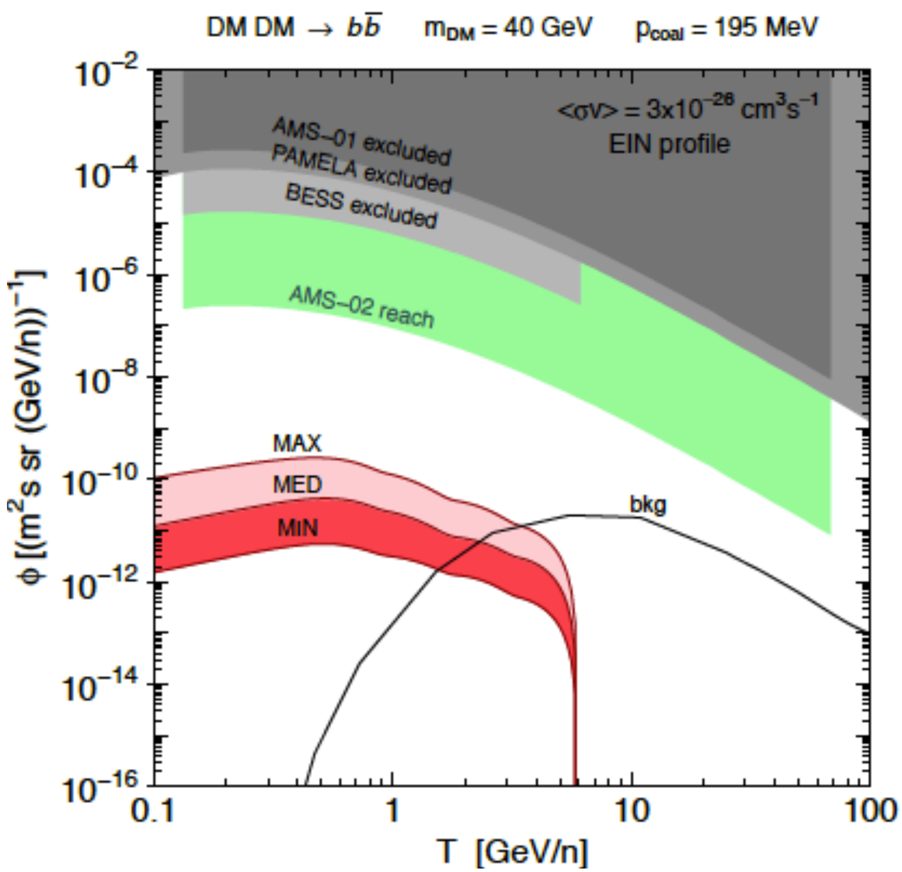
Need Future Experiments for $\overline{\text{He}}$

New work on $\overline{\text{He}}$ signatures is promising, but outside the scope of current experiments



Carlson et al. (2014)

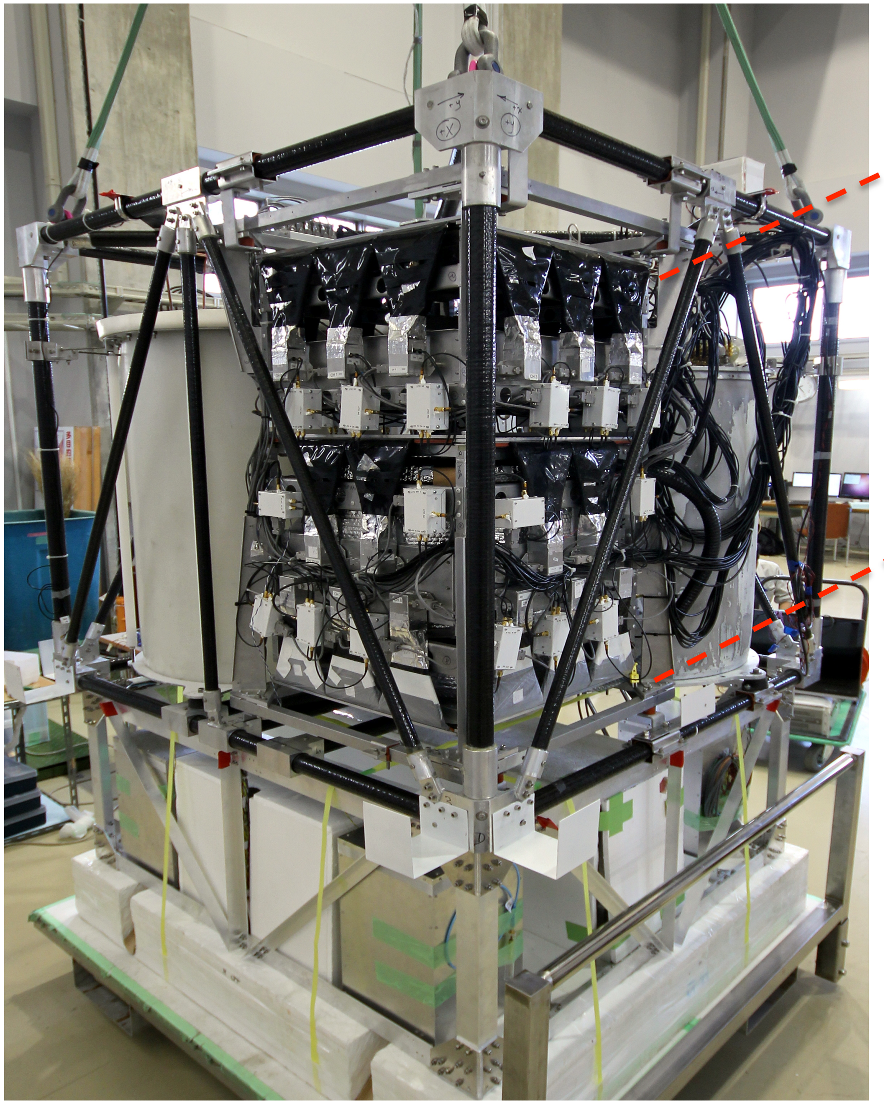
** ongoing work!



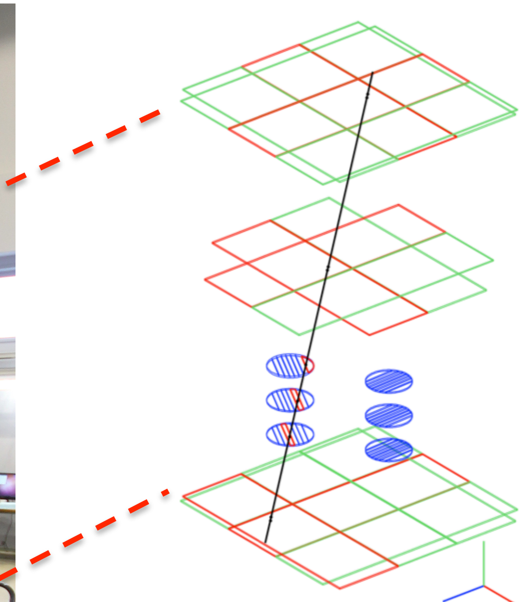
Cirelli et al. (2014)

The Path Forward

pGAPS: a Prototype GAPS Flight



S. A. I. Mognet, et al. (2013) arXiv:1303.1615

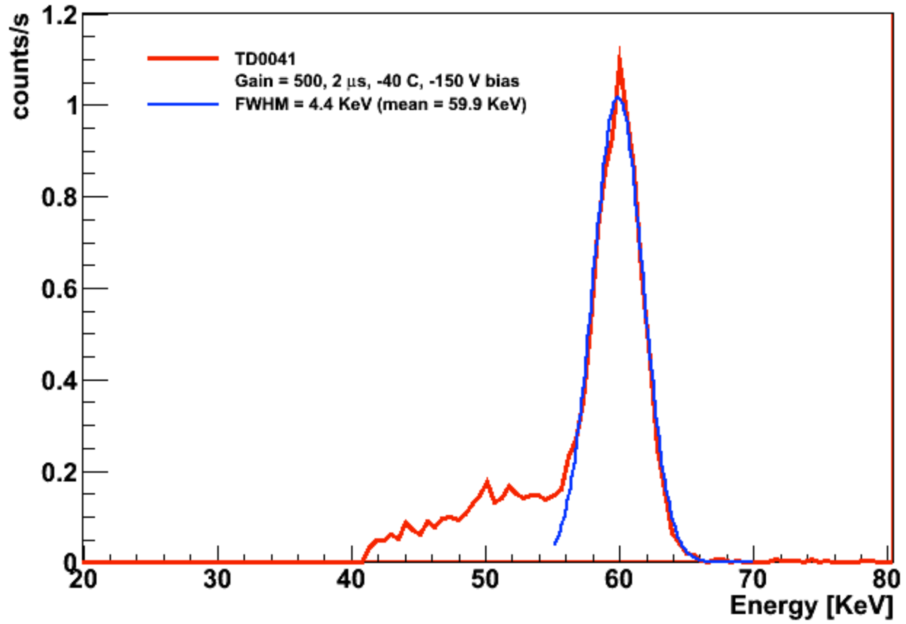


100% of flight goals met!

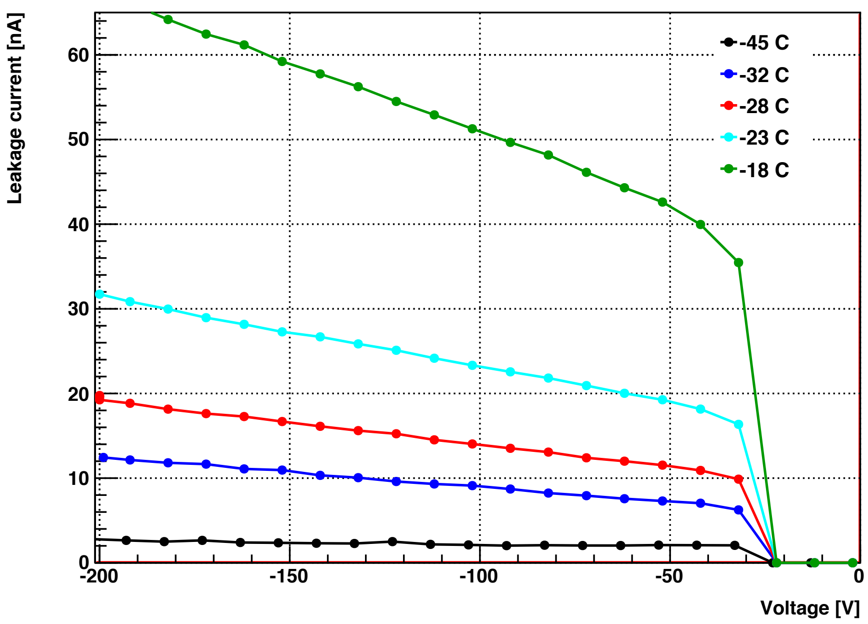
(1) verify stable, low-noise operation of Si(Li) detectors at ambient flight pressure
(2) validate the cooling system and thermal model for the Si(Li) system
(3) measure the background levels at flight altitude to validate simulation codes

Homemade Si(Li) Detector Performance

GAPS can use a cheap-and-dirty Si(Li) fabrication technique because of looser performance requirements



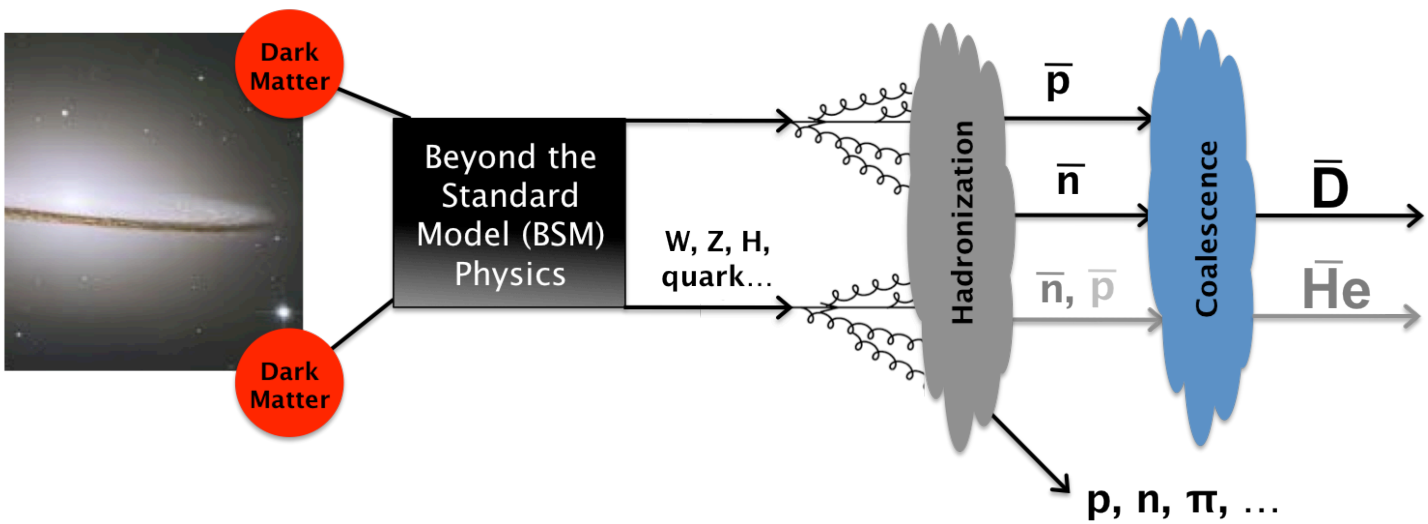
Resolution measured with an Am-241 X-ray source



Operational temperature range for 1 mm thick prototype detector

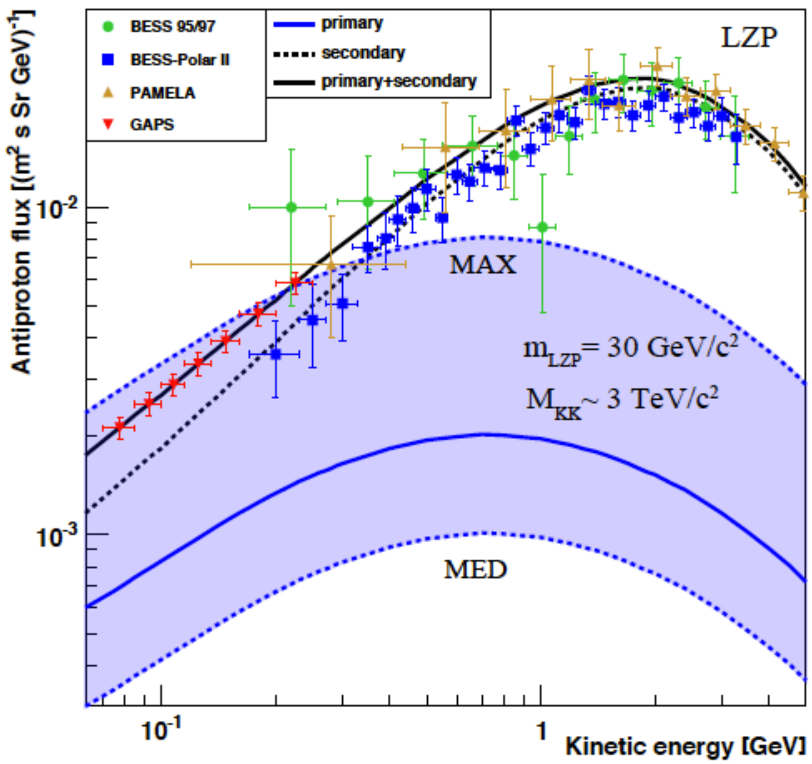
Conclusions

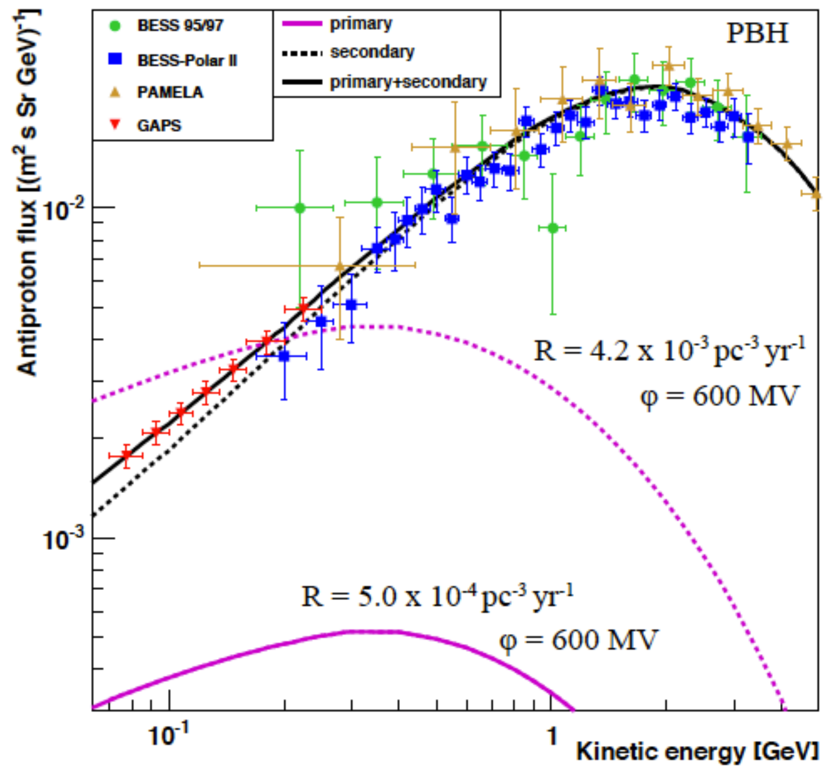
- Antiprotons have been a valuable tool in constraining DM models. In the next decade, AMS and GAPS can extend this reach to higher/lower DM masses
- Antideuterons are a very attractive, ultra-low background search channel, which has currently been *unexplored*
- Antihelium could provide motivation for next-generation experiments



Backup

GAPS and antiprotons





Background sources of $\bar{p}$, $\bar{D}$, $\bar{He}$

• Interactions of cosmic rays on the interstellar medium create "secondary" anti-p, D, He
• Differences in spectral shape allow discrimination

$$p_{CR} + H_{ISM}$$

$$p_{CR} + He_{ISM}$$

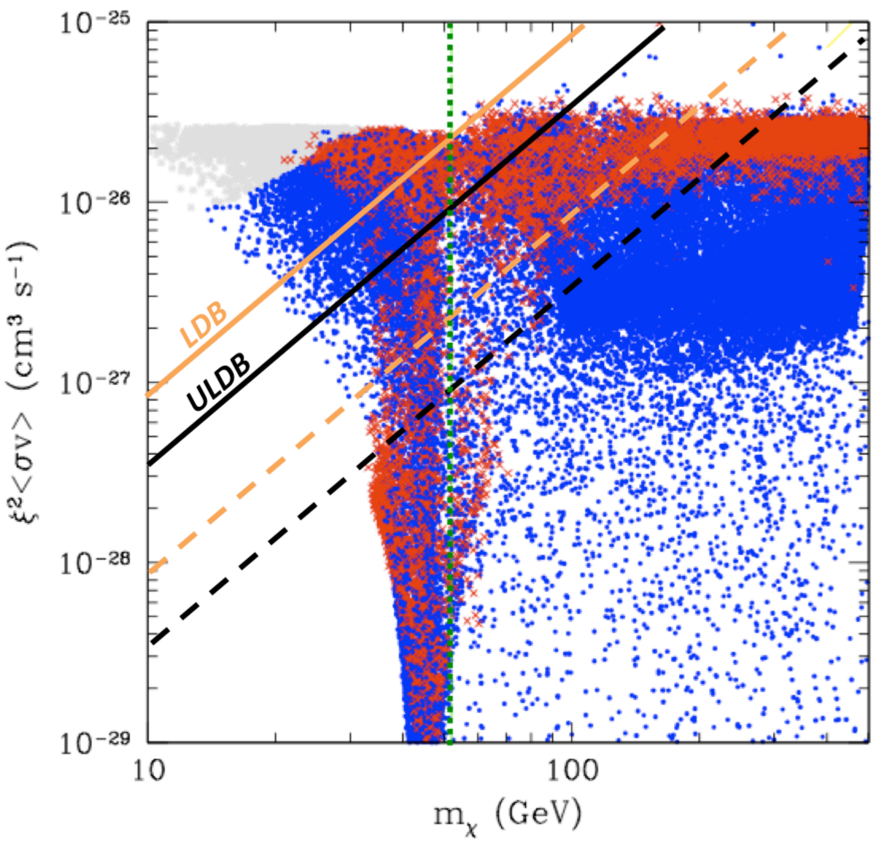
$$\bar{p}_{CR} + H_{ISM}$$

$$\bar{p}_{CR} + He_{ISM}$$

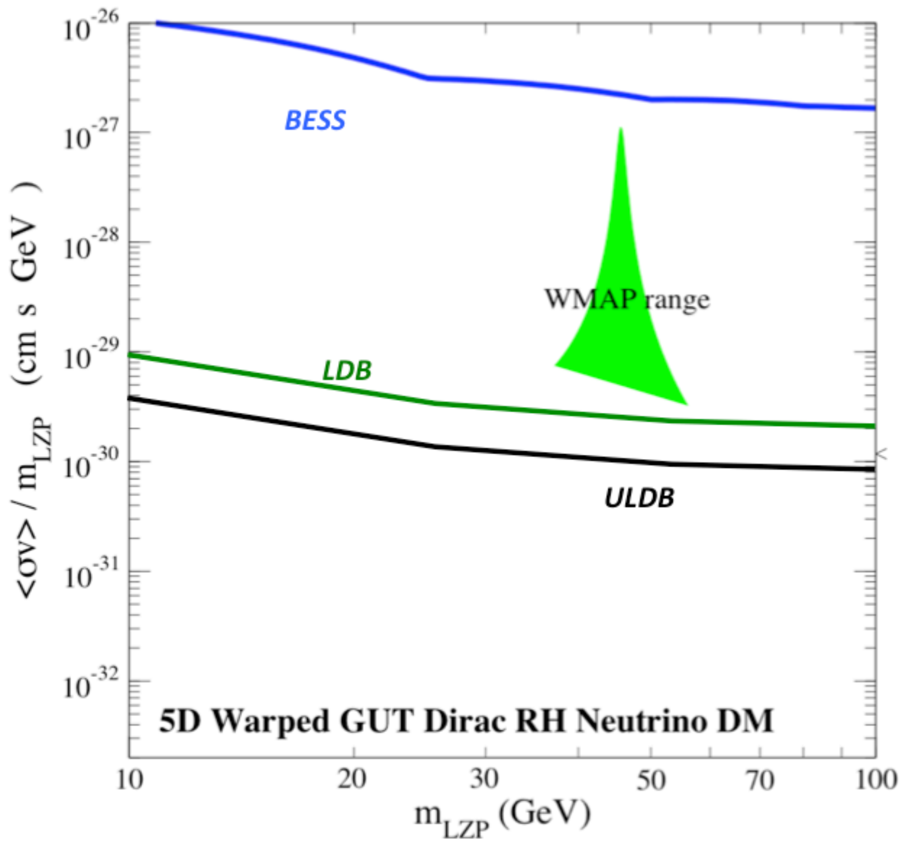
$$\rightarrow \quad \bar{p} + X, \quad \bar{D} + X, \quad \bar{He} + X$$

information on anit-He production only from p-nucleus or heavy-ion collisions → very different kinematics than DM annihilation at rest → large uncertainties on coalescence momentum

Antideuteron Model Sensitivity

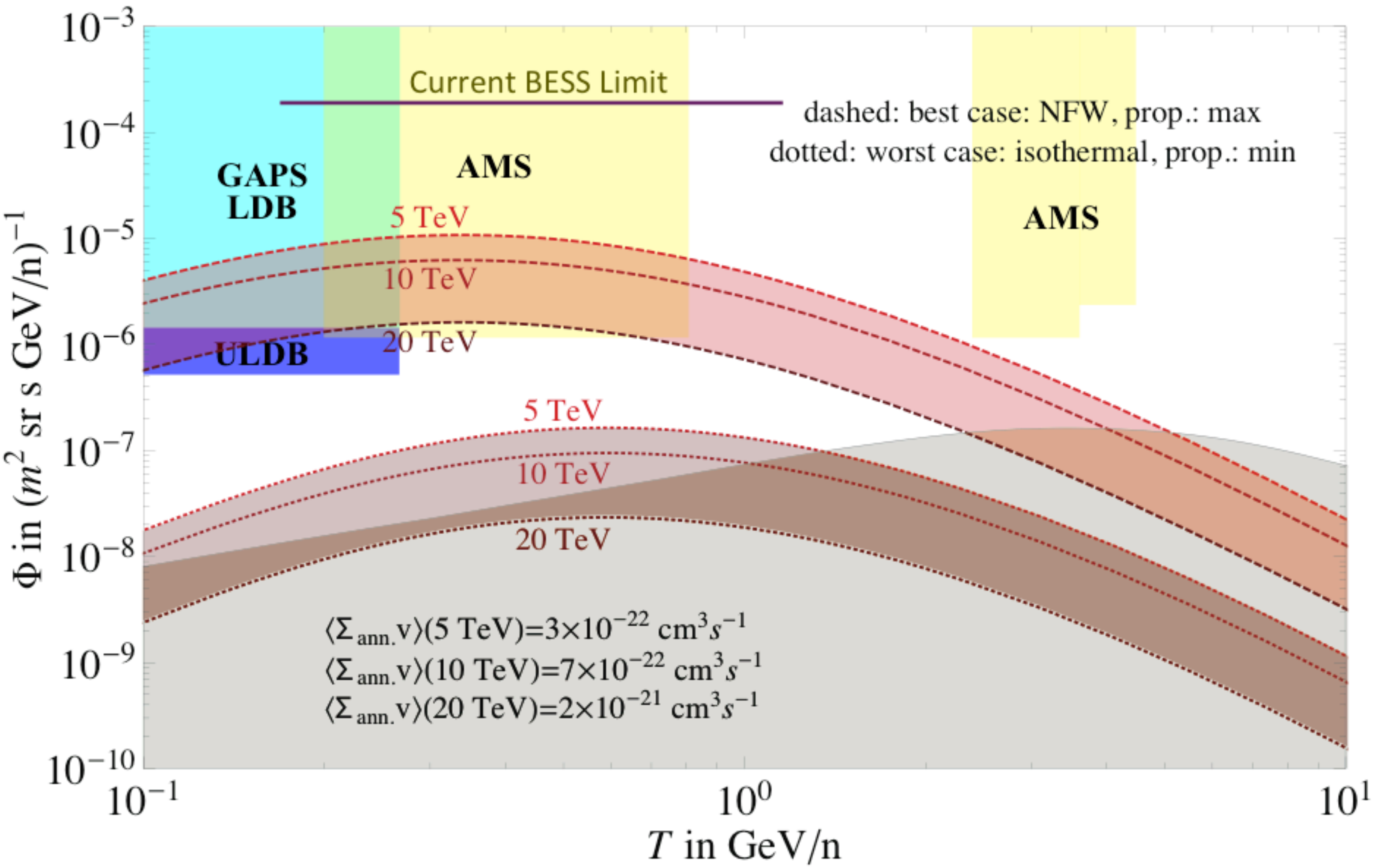


* Donato, F, Fornengo, N. and Maurin, D., "Antideuteron fluxes from dark matter annihilation in diffusion models," Phys. Rev. D 78, 043506, 2008.



* Baer, H. and Profumo, S., "Low energy antideuterons: shedding light on dark matter," JCAP 12, 008, 2005.

Sensitivity to Heavy Dark Matter



* Bräuninger, C.B. and Cirelli, M., "Anti-deuterons from heavy Dark Matter," Phys. Lett. B 678, 20-31, 2009.

Coalescence Model

Coalescence is the process by which n̄ and p̄ form a d̄

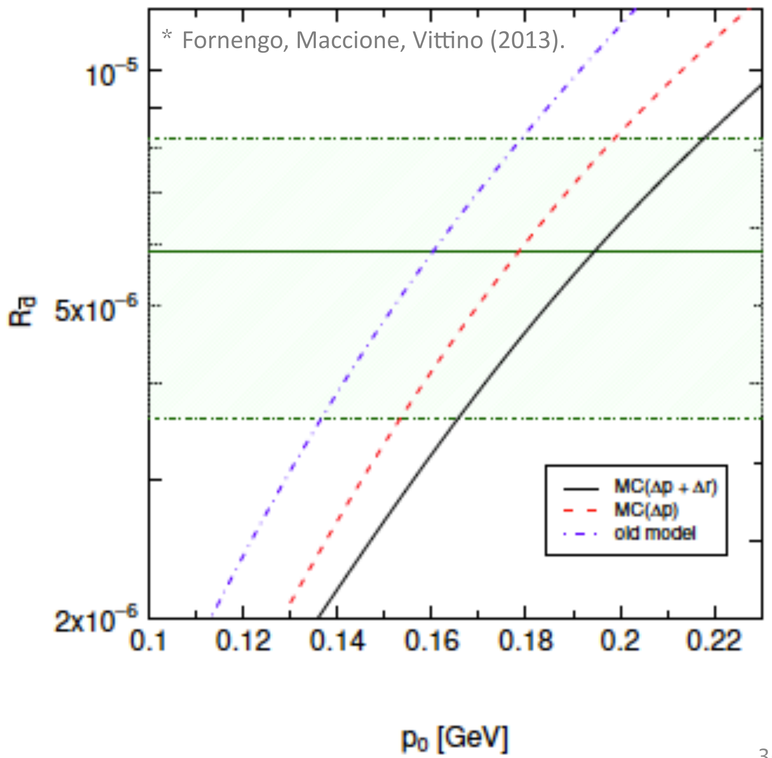
$$\int d^3\vec{\Delta}C(\vec{\Delta}) \equiv V_{coal} = \frac{4\pi p_0^3}{3}$$

← **p_0** defined by the volume of phase-space in which n̄ and p̄ will merge

To determine p_0:

1. Assume uncorrelated, isotropic distribution of n̄ and p̄, merge when relative momentum < p_0
2. MC method that accounts for correlations due to production channel or center-of-mass energy
3. MC method with additional Δr requirement

Then tune this to experimental data:
e^+e^- → d̄ data from LEP



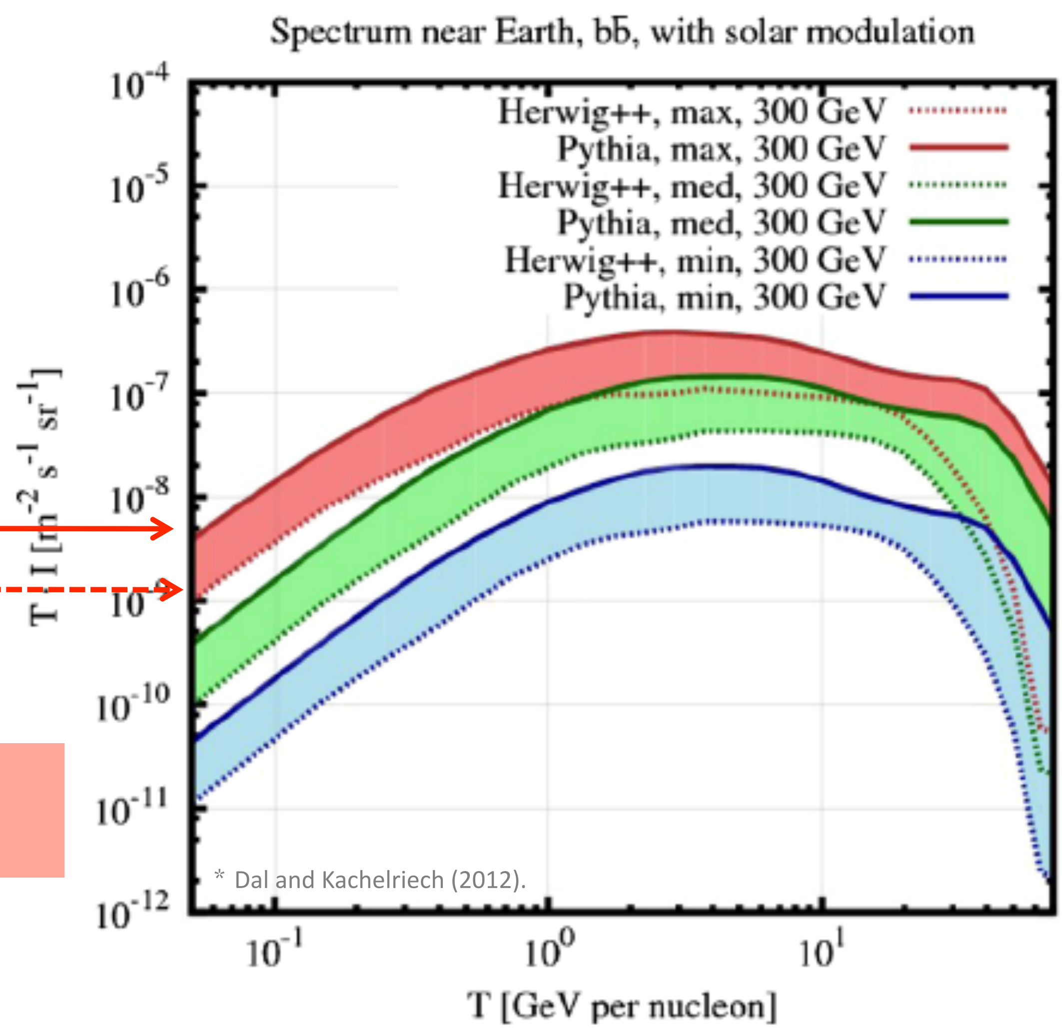
Hadronization Model

Choice of hadronization model affects correlations between n̄ and p̄

PYTHIA (string model)

Herwig (cluster model)

Affects d̄ sensitivity by factors of ~few



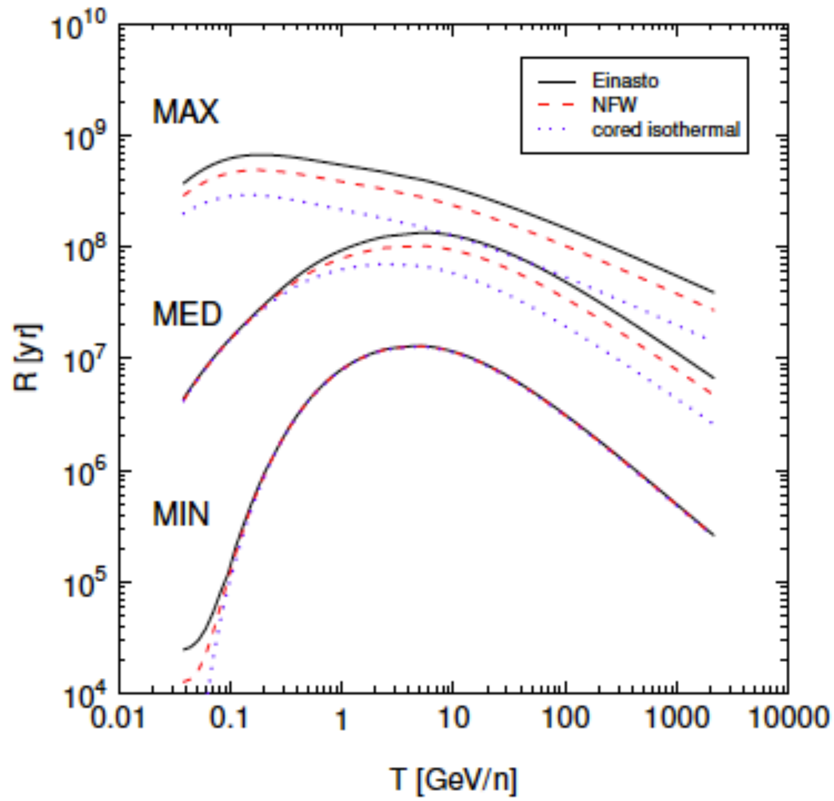
Propagation Model

Propagation in Galactic Environment:

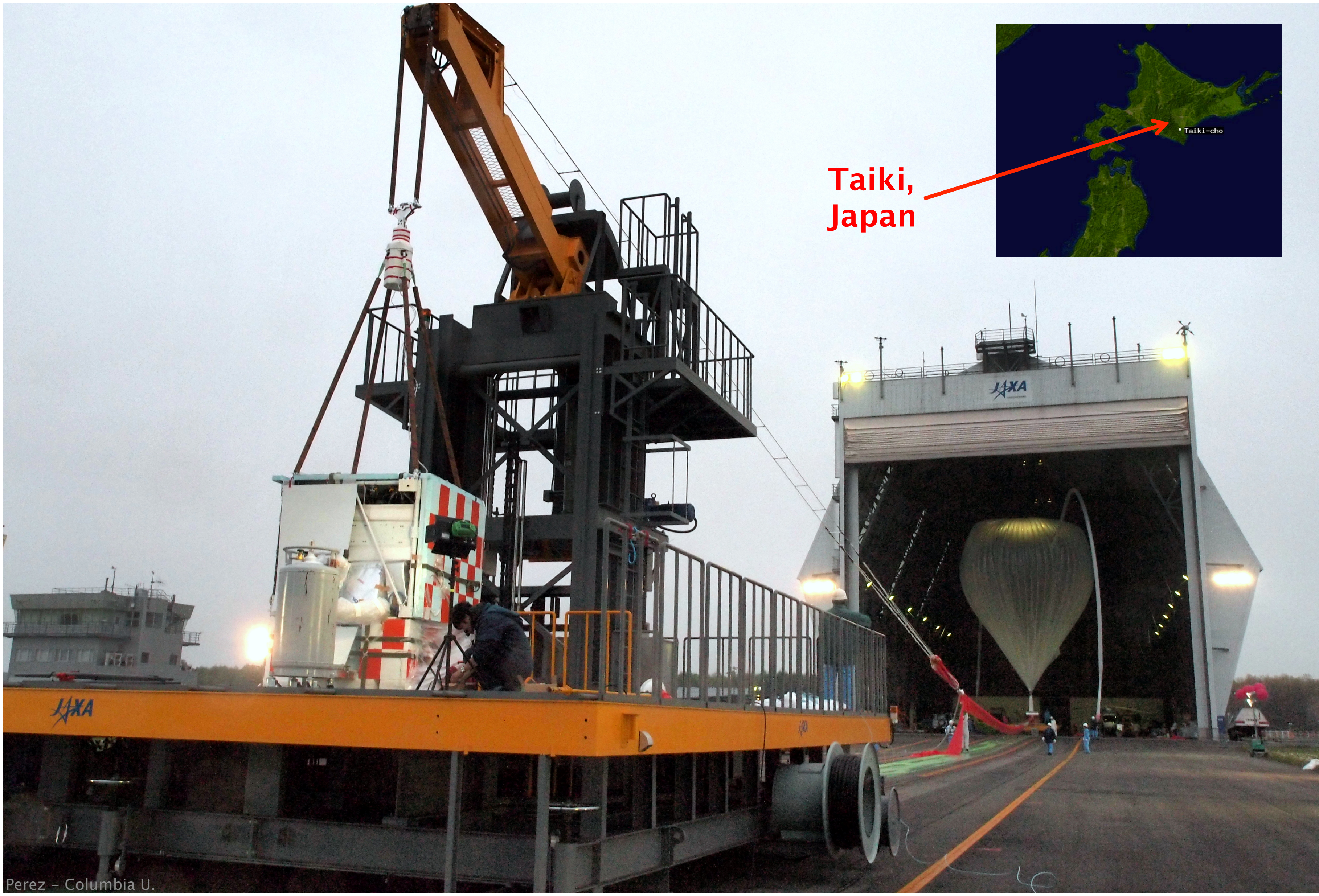
$$-\nabla[K(r,z,E)\nabla n_{\bar{d}}(r,z,E)] + V_c\frac{\partial}{\partial z}n_{\bar{d}}(r,z,E) + 2h\delta(z)\Gamma^{\bar{d}}_{\rm ann}n_{\bar{d}}(r,z,E) = q_{\bar{d}}(r,z,E)$$

diffusion — convection — annihilation with ISM — source

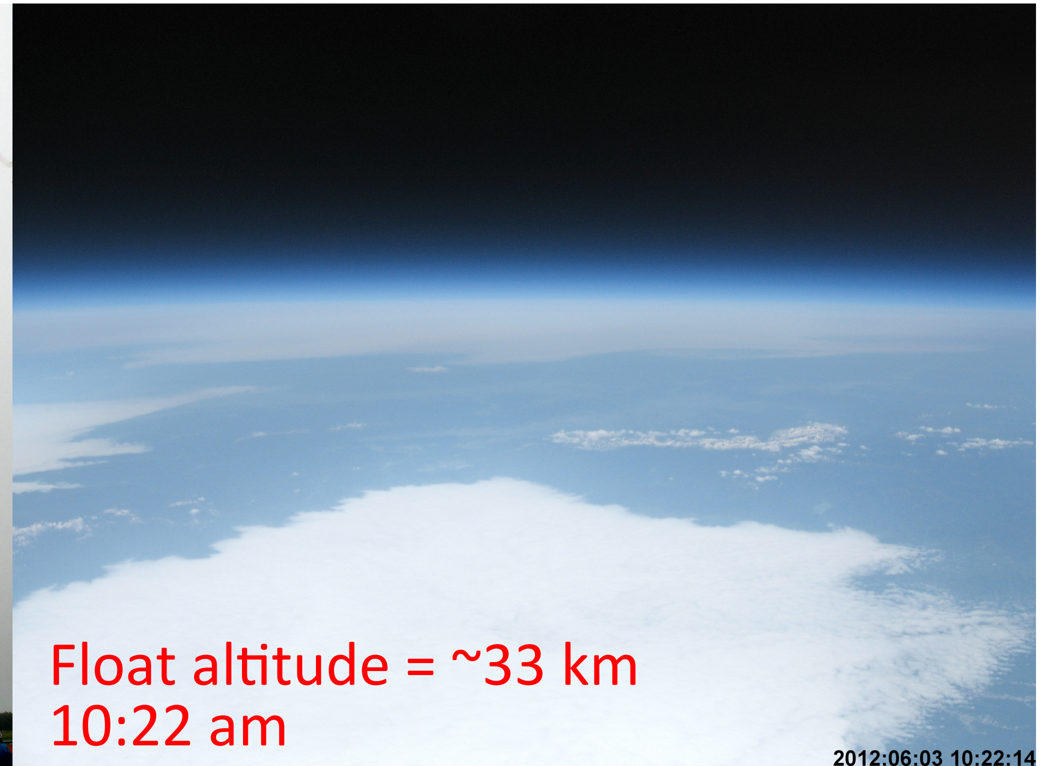
- Constrained by B/C data = secondary / primary
- But still largest source of uncertainty on anti-D flux!
- Will be better constrained in the future by AMS-02 measurements
- Less sensitive to halo model, but affected by boost factor, *f*, from halo sub-structure

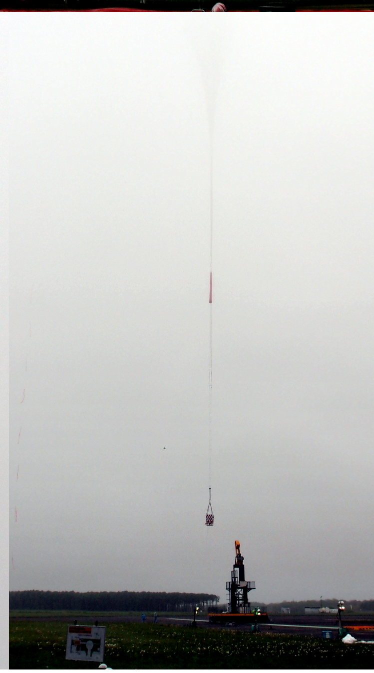


The pGAPS Flight



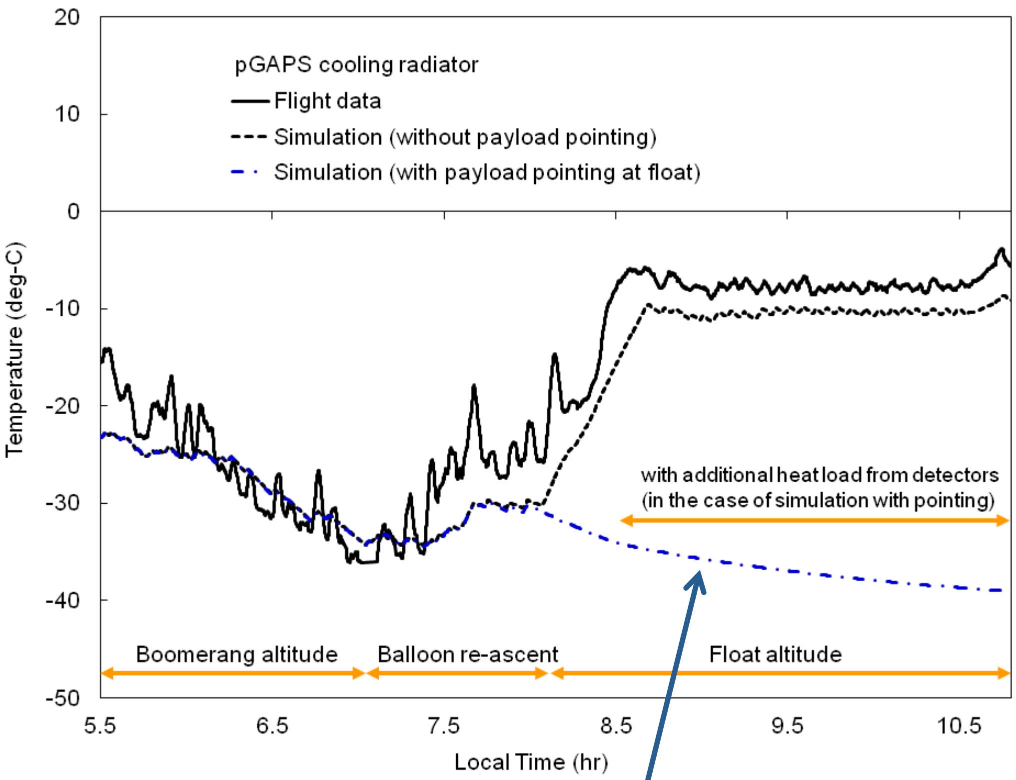

Liftoff!
4:55 am


Float altitude = ~33 km
10:22 am
2012:06:03 10:22:14




Recovery
11:45 am

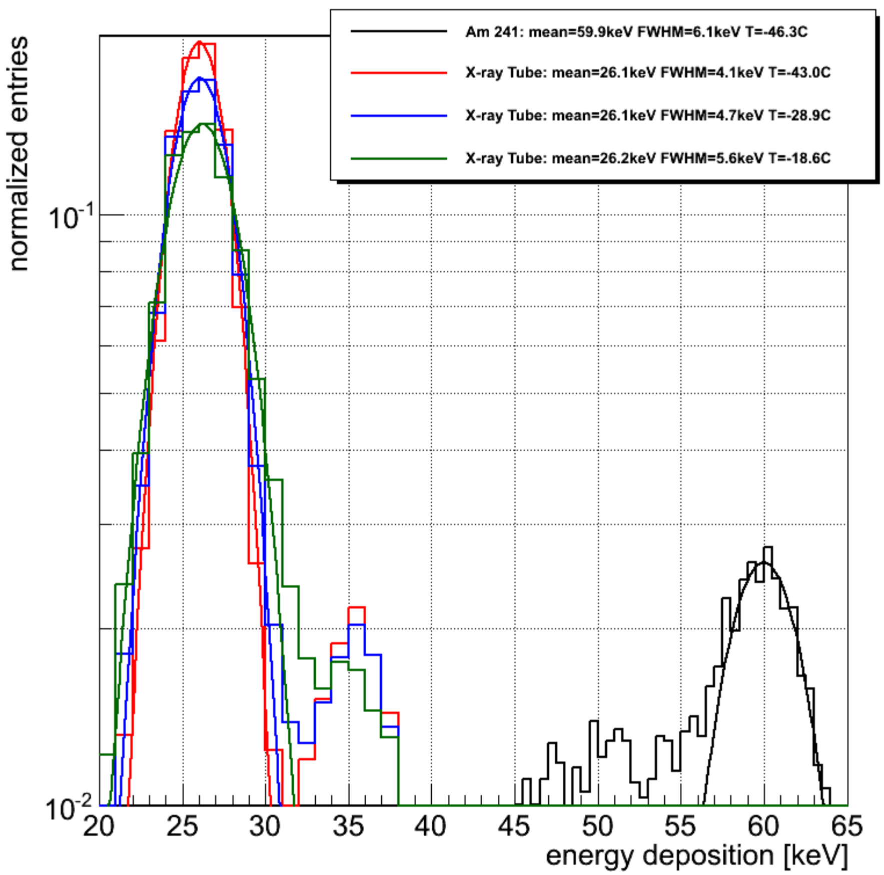
pGAPS Cooling Results



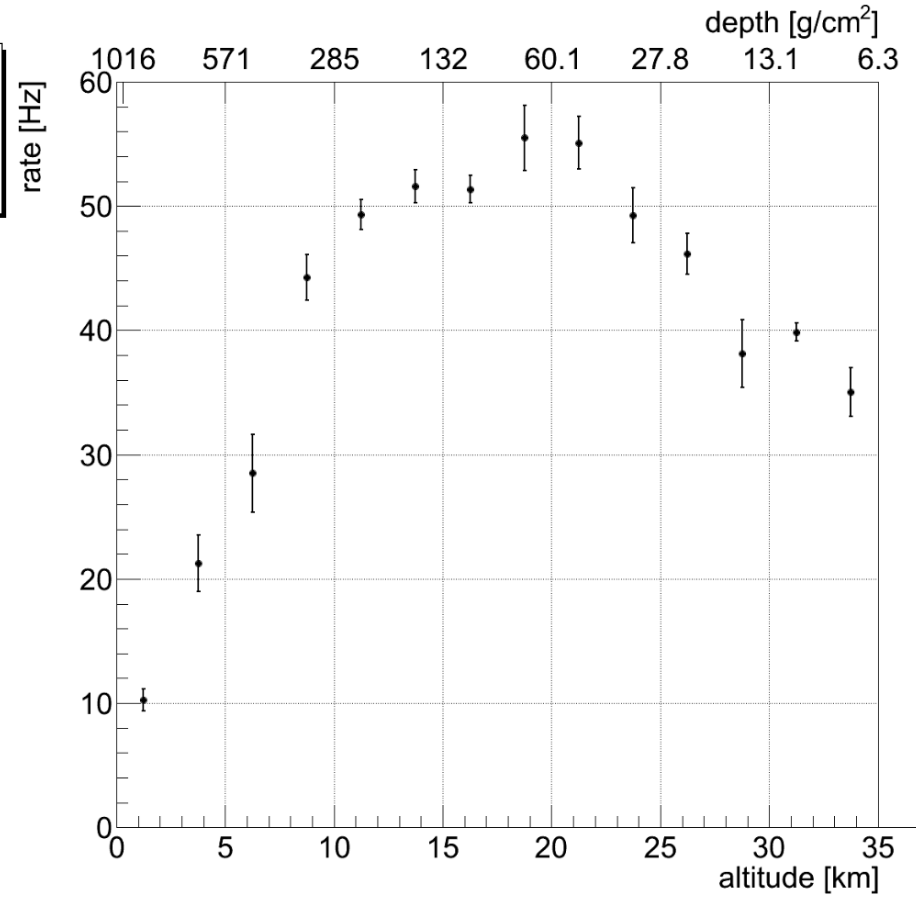
Cooling performance confirms thermal model

- With proper pointing, cooling system allows optimal Si(Li) operation
- Oscillating heat pipe (OHP) system also validated with thermal simulation

pGAPS Detector Results

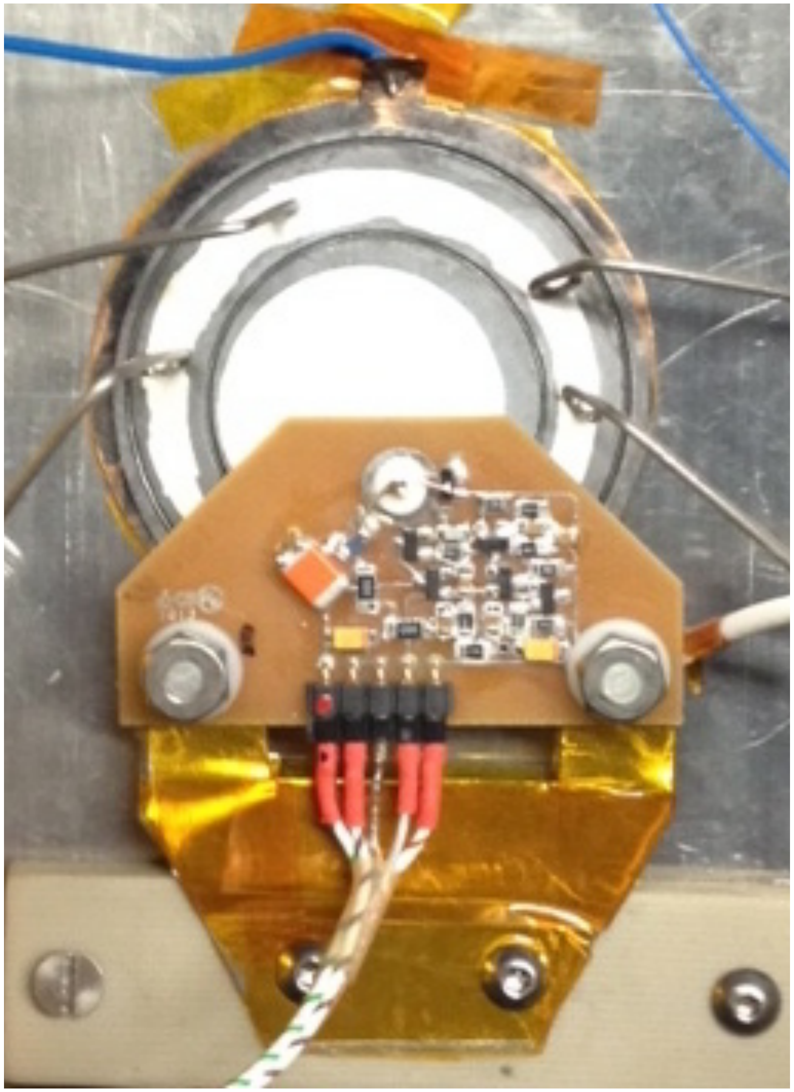


Si(Li) resolution consistent with temperature-dependent predictions

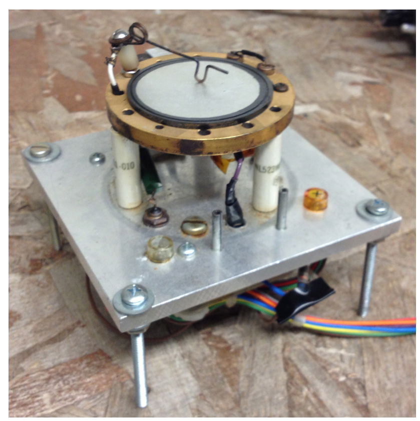


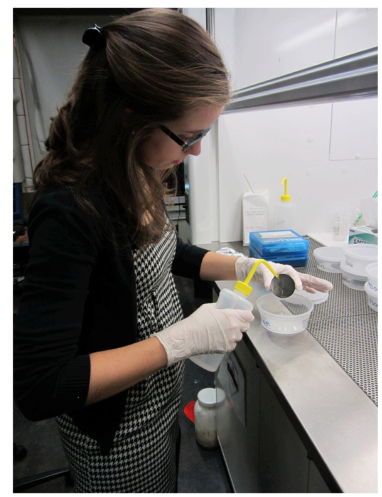
TOF trigger rates in good agreement with other measurements and air shower simulations

Homemade Si(Li) Detectors



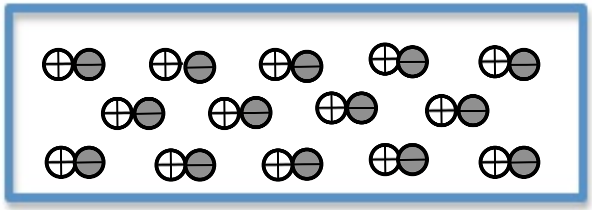
GAPS will need ~1300 Si detectors!



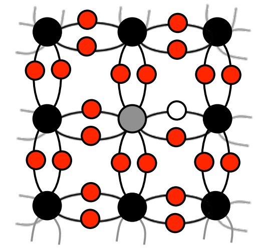


Lithium-drifted Si Detectors

"p-type" doped wafer

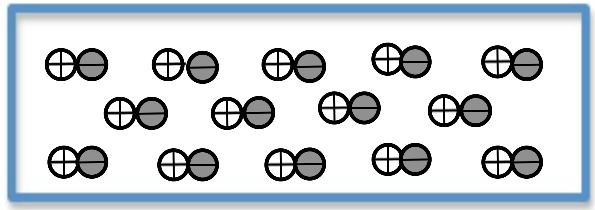


- free positive hole
- fixed negative ion

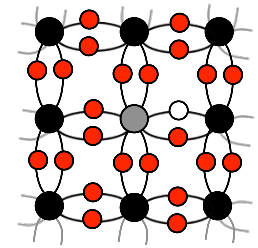


Lithium-drifted Si Detectors

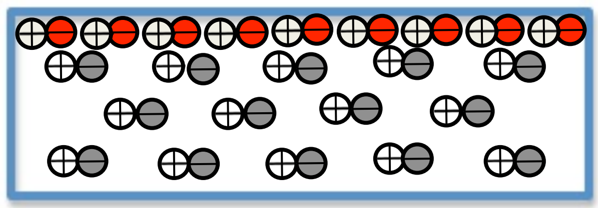
“p-type” doped wafer



• free positive hole
• fixed negative ion



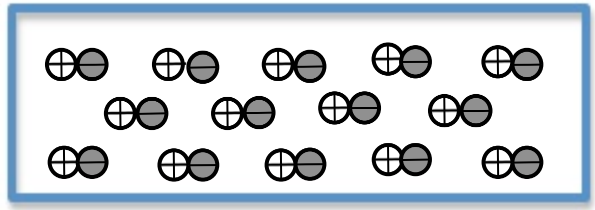
Li “n-type” layer



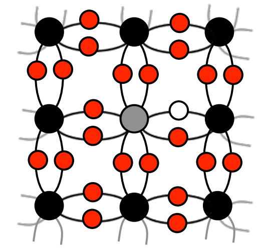
• free electron
• mobile positive ion

Lithium-drifted Si Detectors

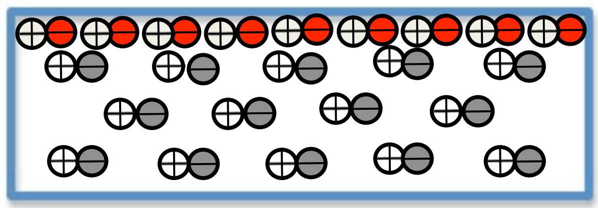
"p-type" doped wafer



- free positive hole
- fixed negative ion

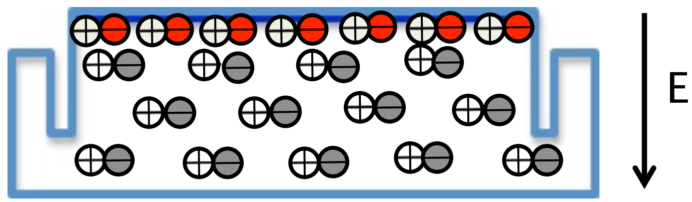


Li "n-type" layer



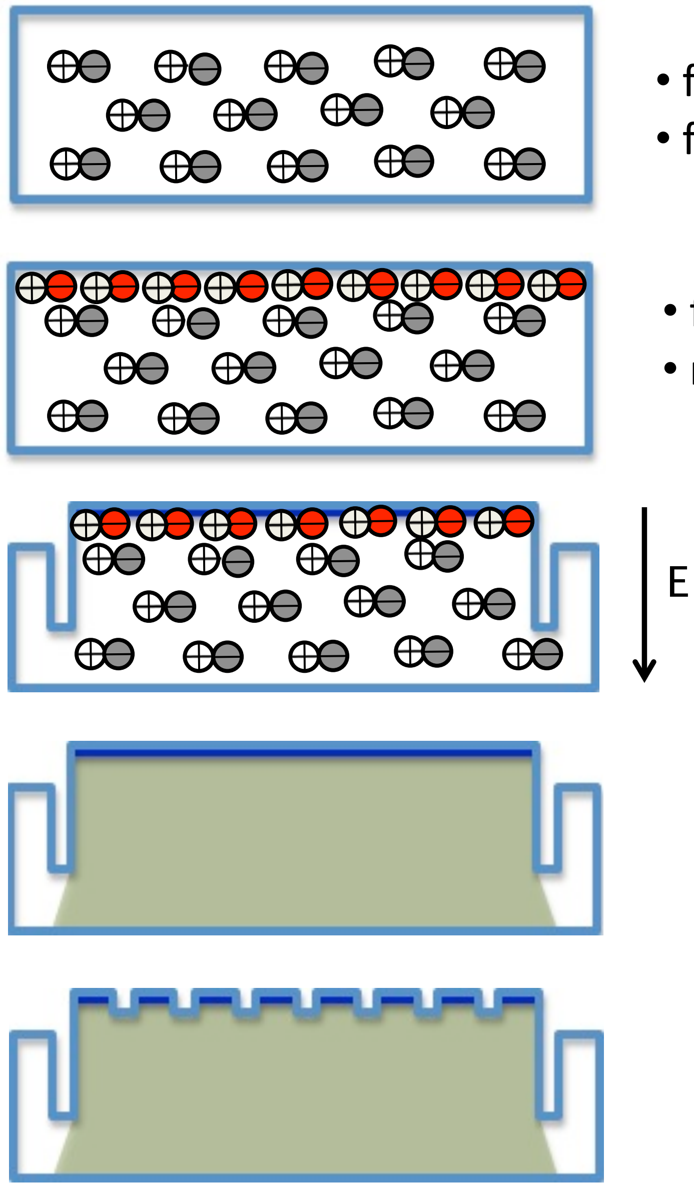
- free electron
- mobile positive ion

Li drift



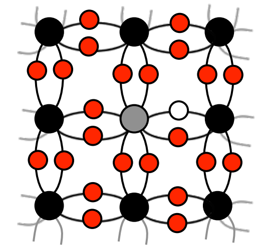
- high temperature, ~110 C
- constant voltage, ~500 V
- long time, ~90 hrs for 2.5 mm

Lithium–drifted Si Detectors



“p-type” doped wafer

- free positive hole
- fixed negative ion



Li “n-type” layer

- free electron
- mobile positive ion

Li drift

- high temperature, ~110 C
- constant voltage, ~500 V
- long time, ~90 hrs for 2.5 mm

Extended charge-free region!

Guard ring and channels

The pGAPS Flight