GAPS: General AntiParticle Spectrometer

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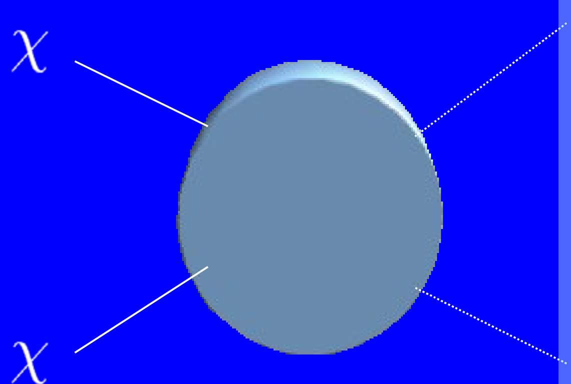
Consiglio di Sezione Pavia

4 Luglio 2016

DM annihilations

DM particles are stable. They can annihilate in pairs.



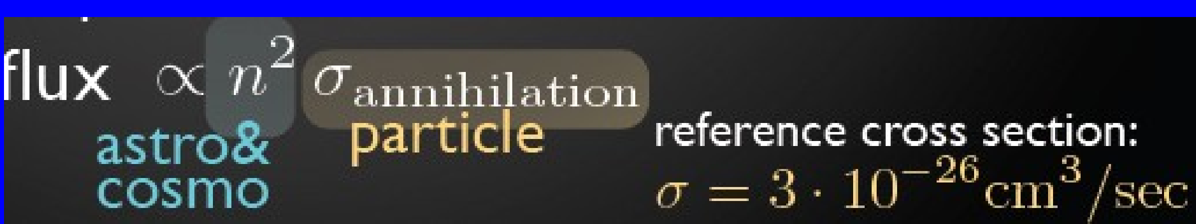
$W^-, Z^0, b, \tau^-, t, h^0, \ldots$ → $e^{\mp}, p^{(-)}, D^{(-)}, \ldots$

$W^+, Z^0, \bar{b}, \tau^+, \bar{t}, h^0, \ldots$ → $e^{\pm}, p^{(-)}, D^{(-)}, \ldots$

Primary annihilation channels

Decay

Final states



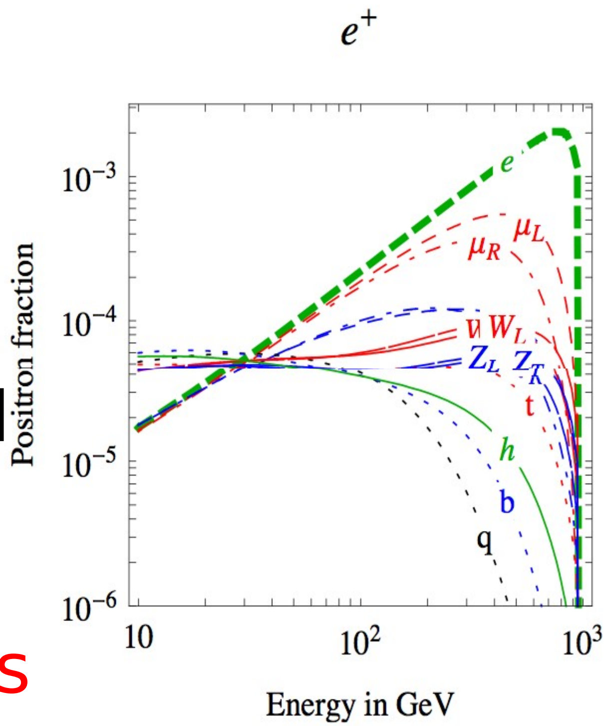
$\sigma_a = \langle \sigma v \rangle$

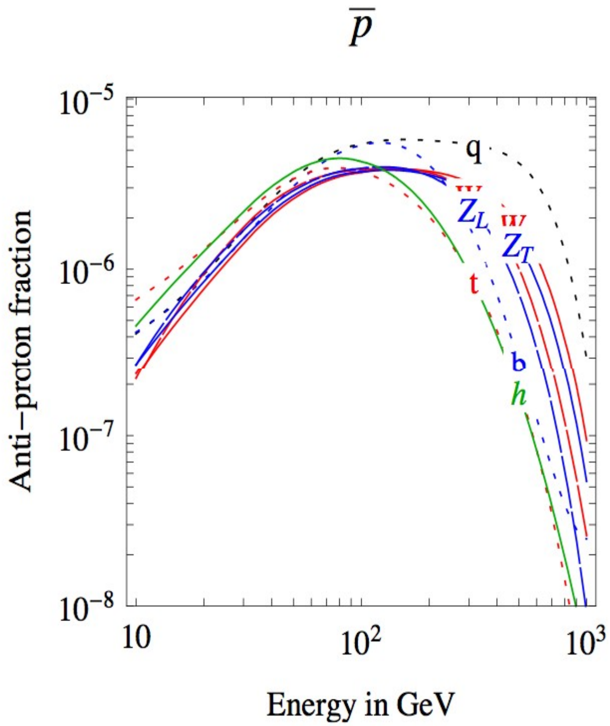
DM annihilations

Resulting spectrum for positrons and antiprotons
M_{WIMP}= 1 TeV

The flux shape is completely determined by:

1) WIMP mass
2) Annihilations channels





BESS-Polar Program

Status of the BESS-Polar I Flight

Observation Time: 8.5 days

Float Time: 8.5 days (12/13/2004-12/21/2004)

Events recorded: > 0.9×10^9

Data volume: ~ 2.1 terabytes
Data recovery: **completed** 2004
Payload recovery: **completed** 2004

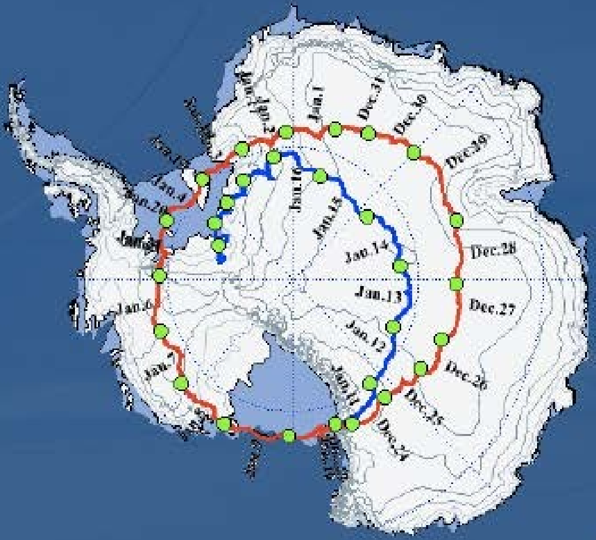
Status of the BESS-Polar II Flight

Observation Time: 24.5 days

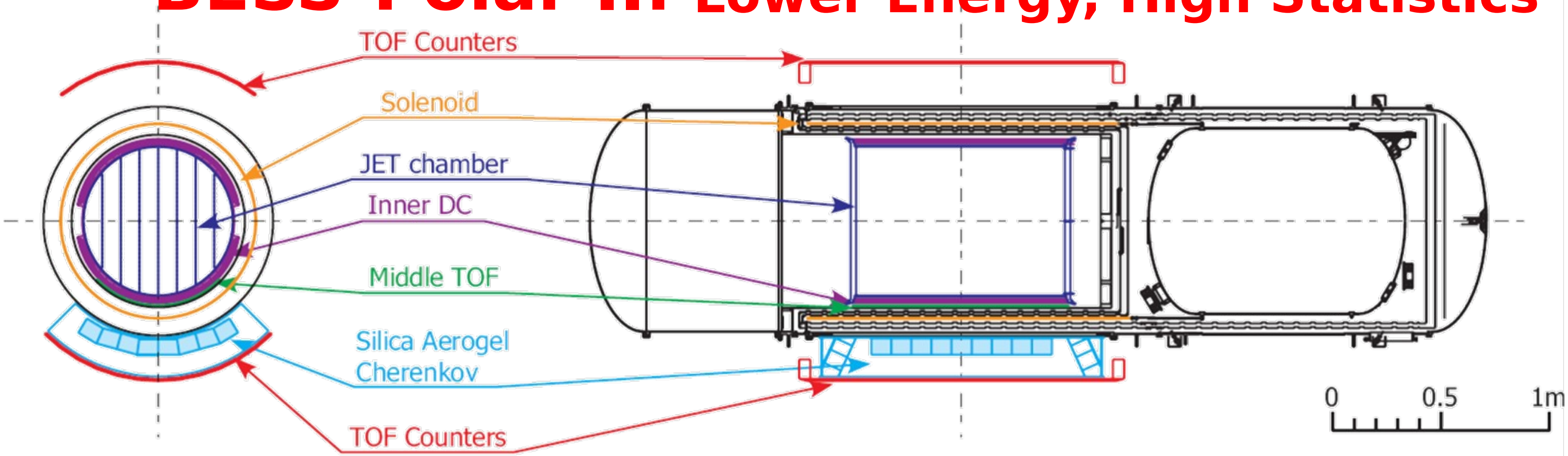
Float Time: 29.5 days (12/23/2007-01/21/2008)

Events recorded: > 4.7×10^9

Data volume: ~ 13.5 terabytes
Data recovery: **completed** Feb 3, 2008
Payload recovery: **completed** Jan 16, 2010



BESS-Polar II: Lower Energy, High Statistics



BESS-Polar II Antideuteron Search

Single Track Selection

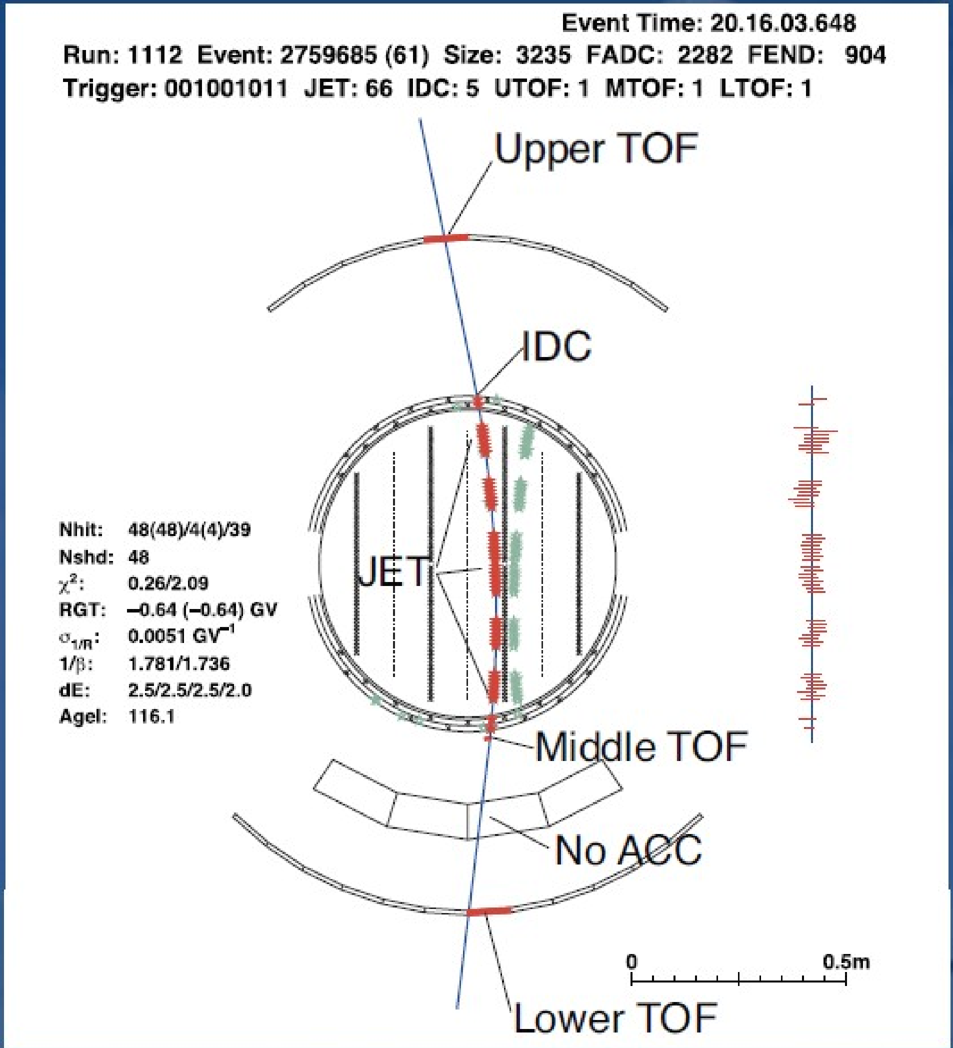
- Track Quality
  - No. of Hit, $\chi 2$ of fitting
  - Consistensy of Track and TOF

Extract (anti)deuterons

- dE/dX (UTOF, LTOF, MTOF, JET)
- Beta U-L
- Cherenkov

Optimize selection using positive curvature events

- wider energy range
- good rejection while keeping efficiency



Makoto Sasaki, Antideuteron2014, UCLA

BESS-Polar II Antideuteron Search

$\bar{d}$ (d) are clearly extracted in the band
$\bar{p}$ (p) contaminate the $\bar{d}$(d) region

Single Track Selection

Track Quality

No. of Hit, $\chi 2$ of fitting

Consistensy of Track and TO

Extract (anti)deuterons

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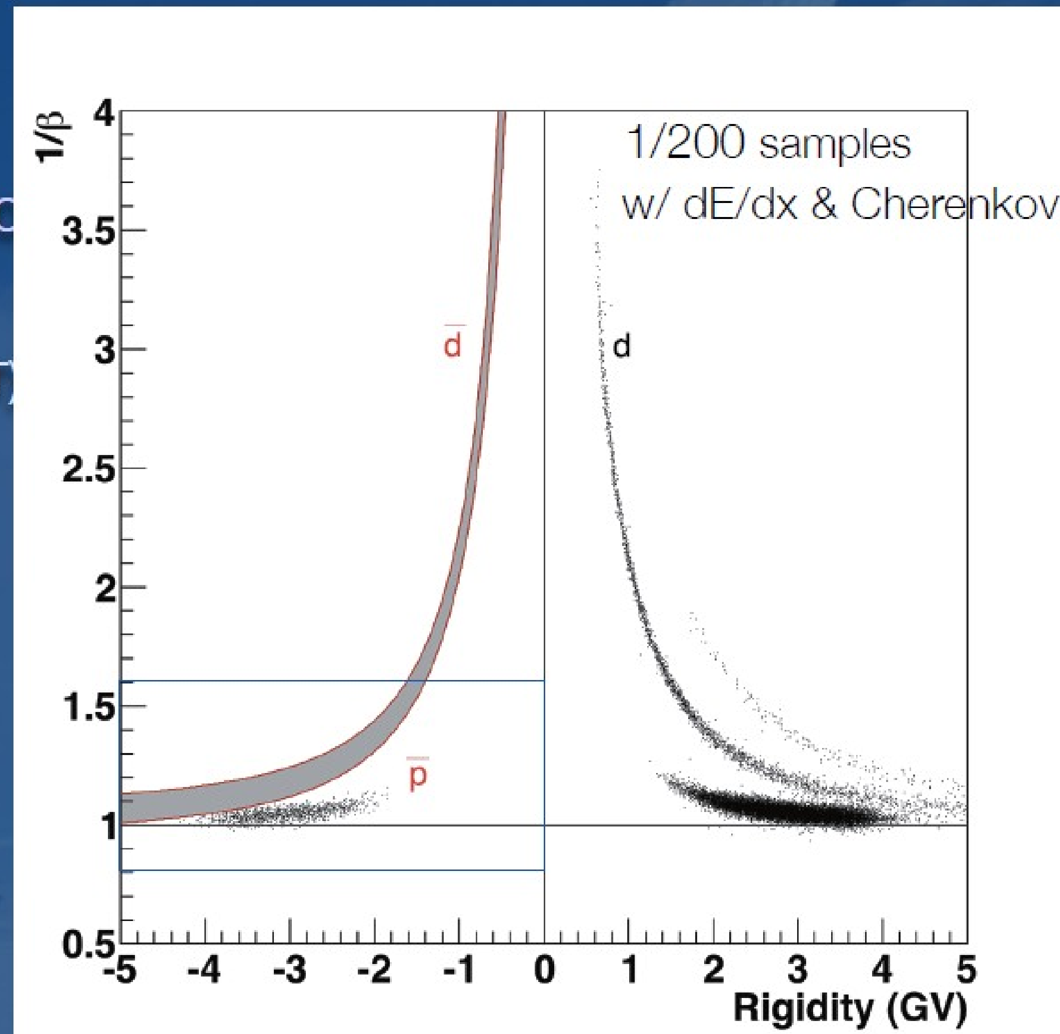
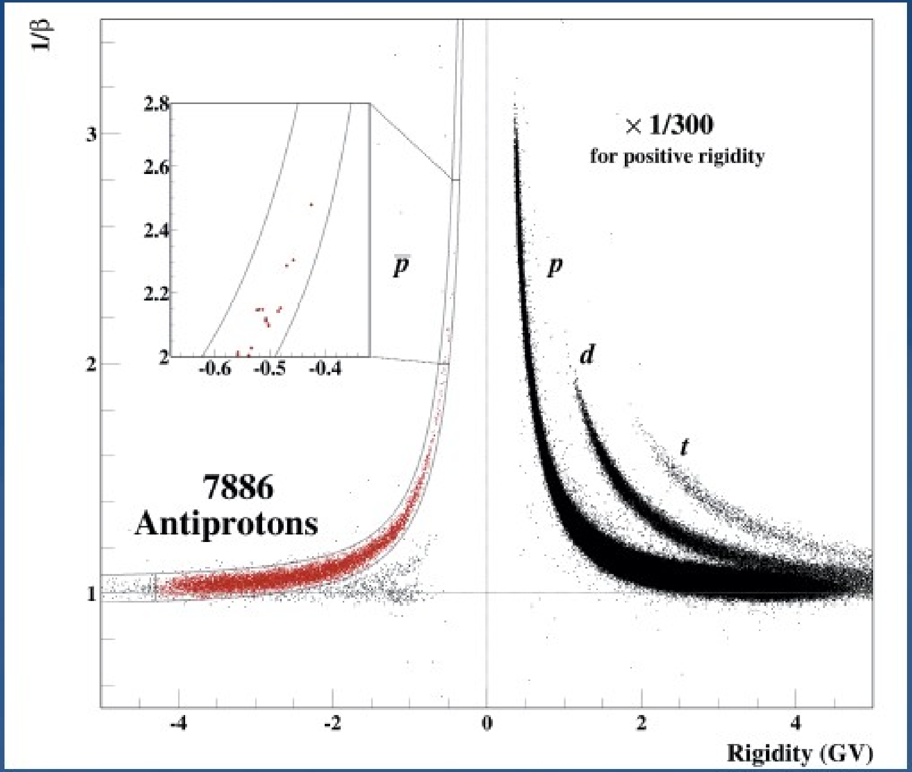
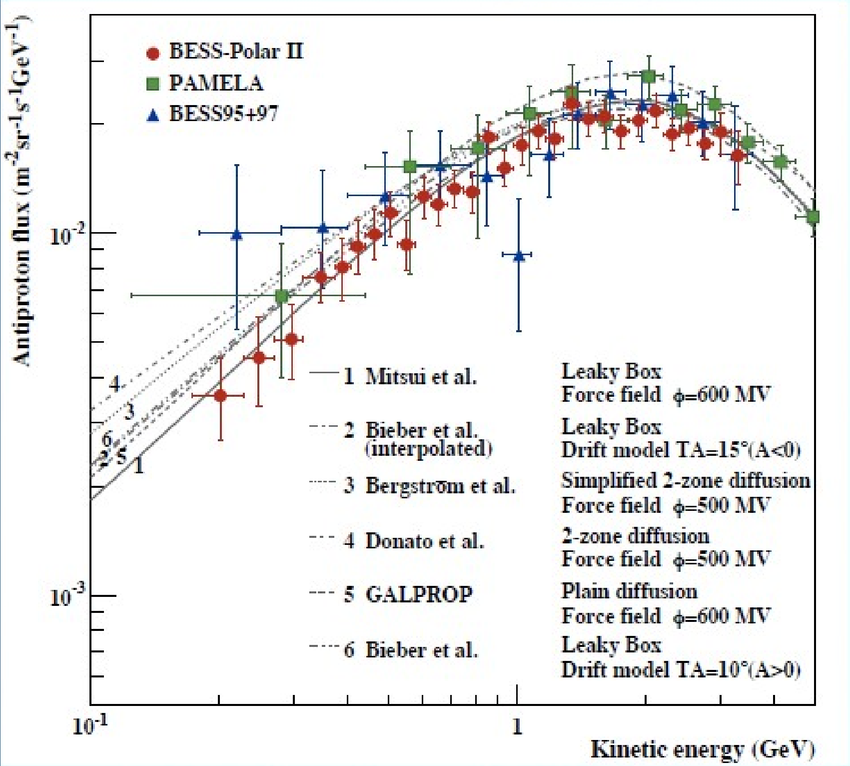


Antiproton Measurement

BESS-Polar II Z=1 Particle Id



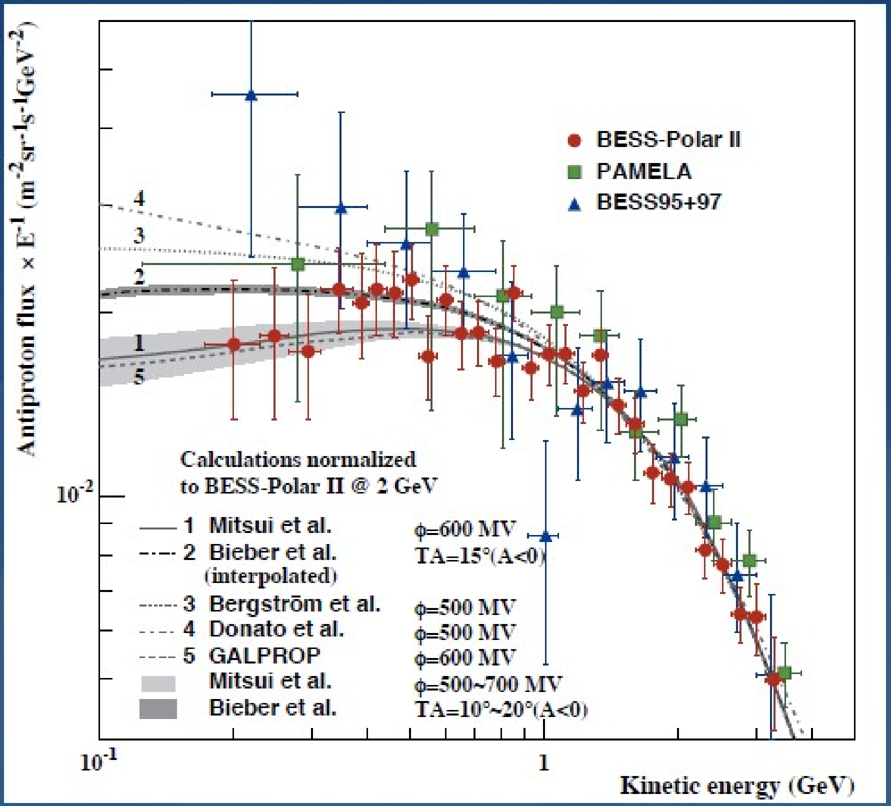
Antiproton Spectrum

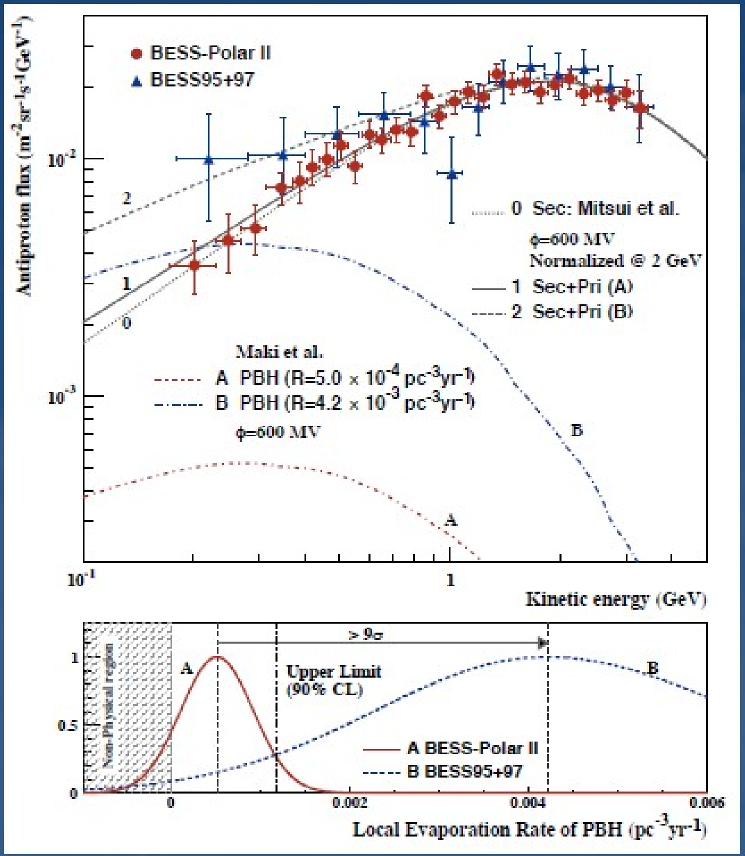


- MDR 240 GV, TOF 120 ps, ACC rejection 6100
- 7886 Antiprotons ~10-20 times previous Solar minimum dataset

- BESS-Polar II and PAMELA spectra agree in shape but differ ~14% in absolute flux
- Both agree in shape with secondary

Antiproton Measurement

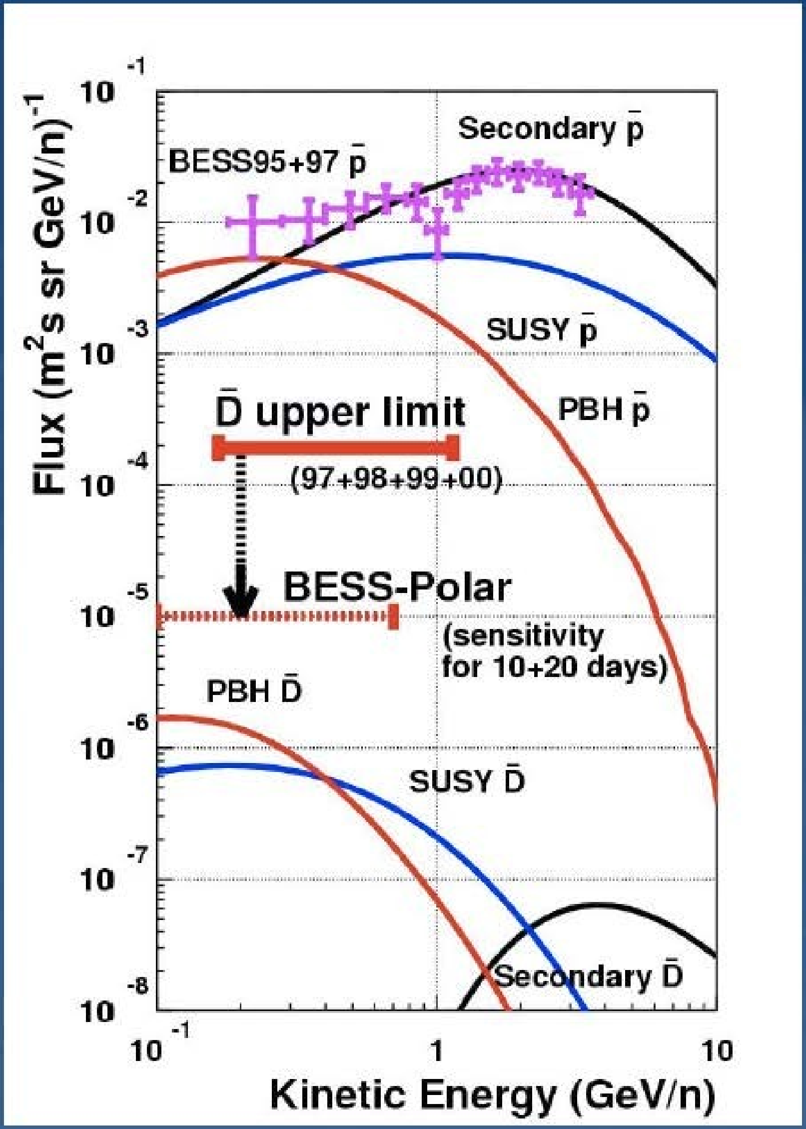




- Comparison of experimental data to calculations normalized to BESS-Polar II at 2 GeV
- Test if low energy antiprotons from PBH evaporation (Hawking radiation) are observed

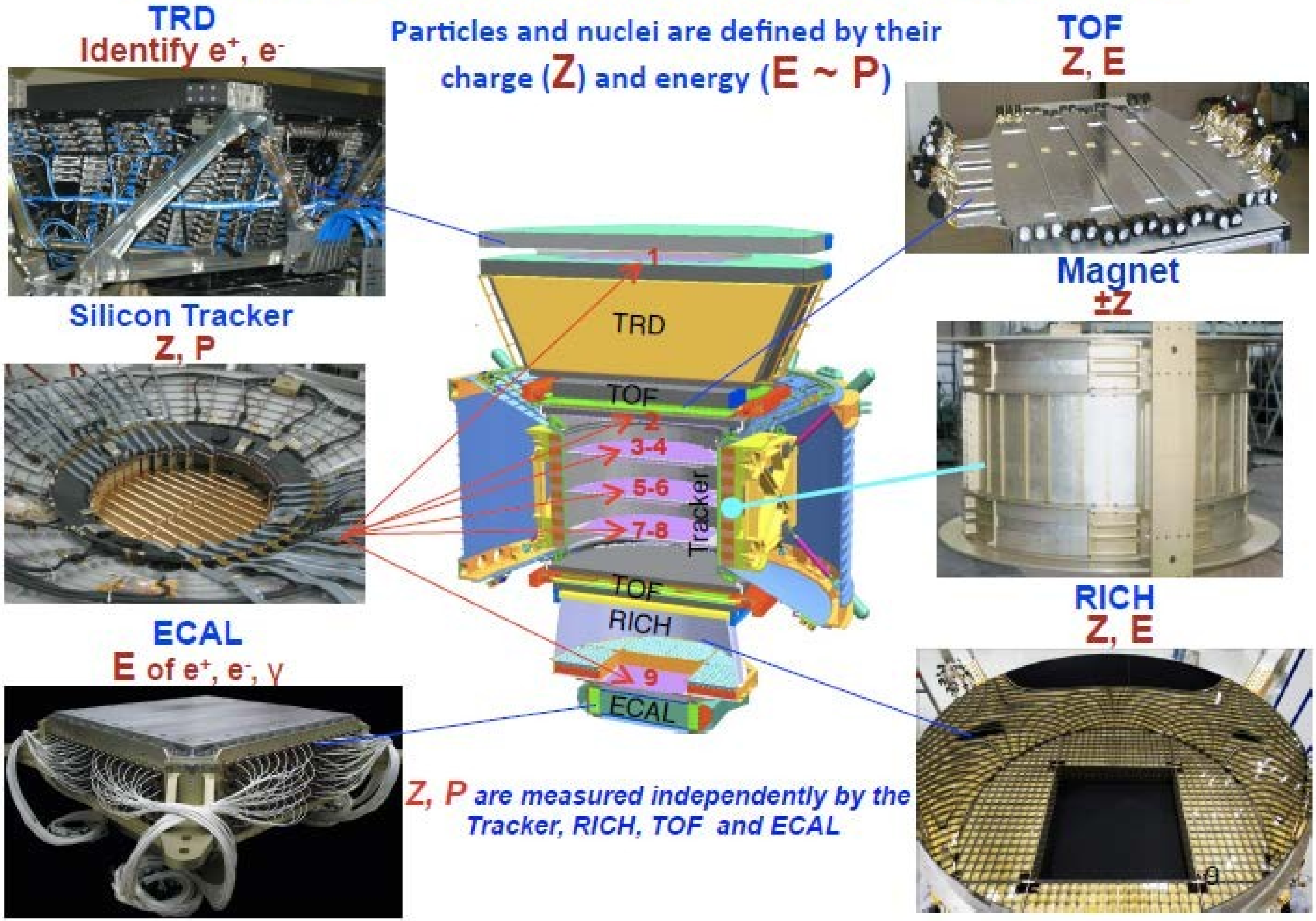
- Best fit evaporation rate: $R = \sim 5 \times 10^{-4}\ pc^{-3}yr^{-1}$
- 9 sigma below BESS-95+97 best fit
- No evidence of antiprotons from PBH evaporation

Antideuteron Search



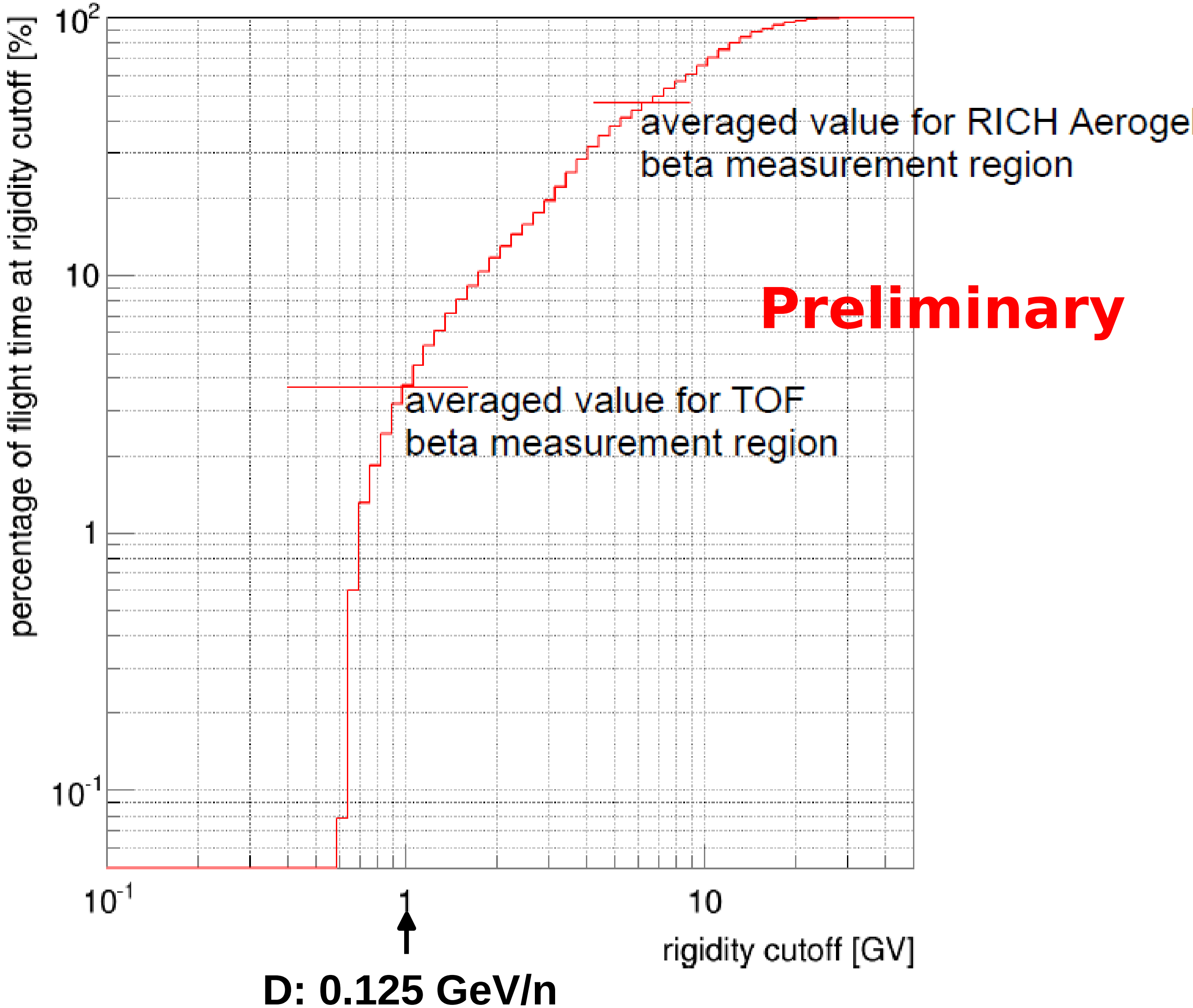
- Secondary $\bar{D}$ probability is negligible at low energies due to kinematics
- Any observed $\bar{D}$ almost certainly has a primary origin!
- $\bar{D}$ 95% C.L. upper limit (first reported) **1.92 x 10^{-4}** (m^2 s sr GeV/n)$^{-1}$ from BESS97+98+99+00.
- BESS-Polar II flight accumulated cosmic-ray data in near solar minimum conditions with more than 10~20 times the statistics of BESS97.

AMS: A TeV precision, multipurpose spectrometer



Average time spent at low rigidity cutoffs

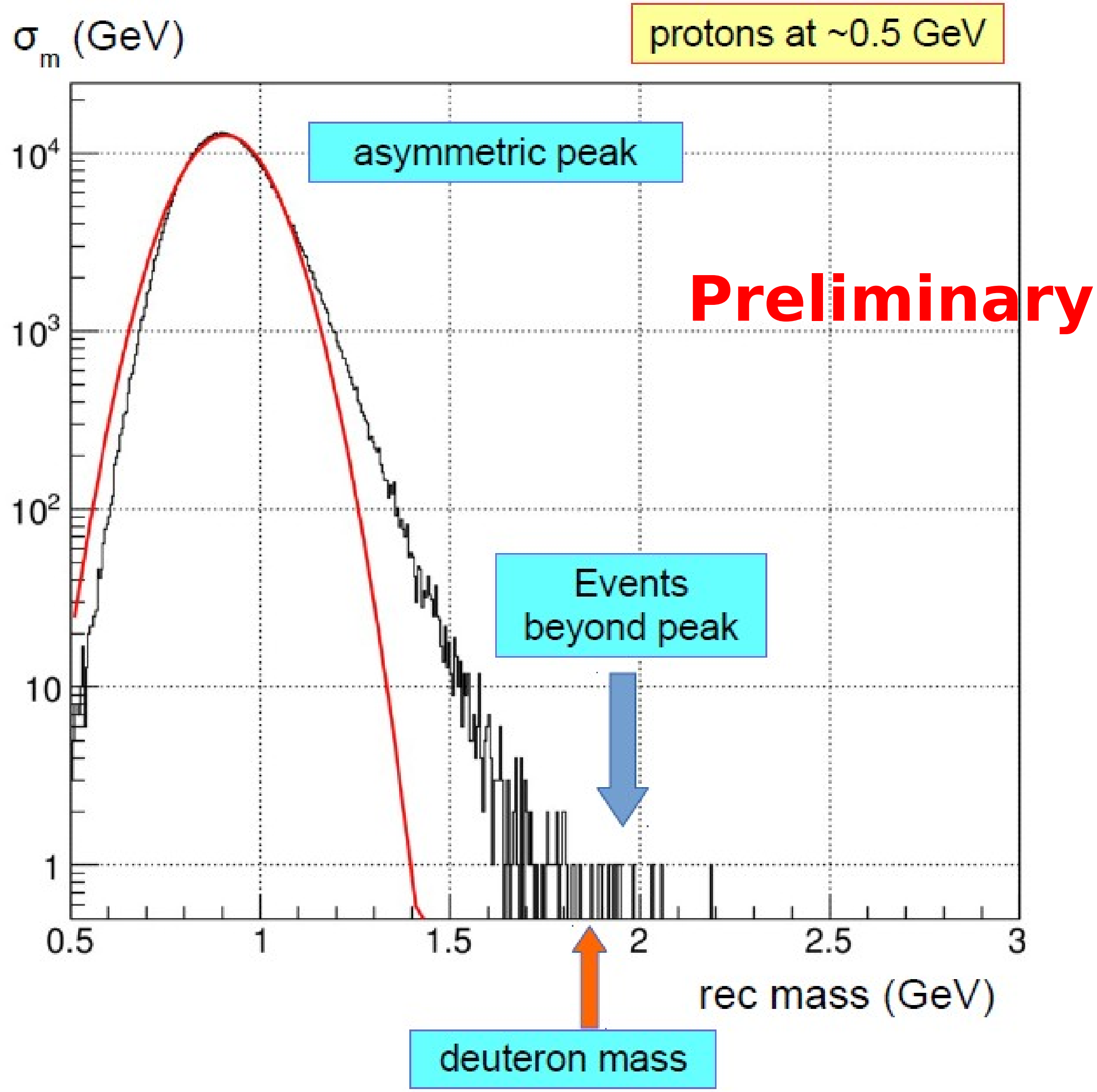
AMS-02



Mass resolution

AMS-02

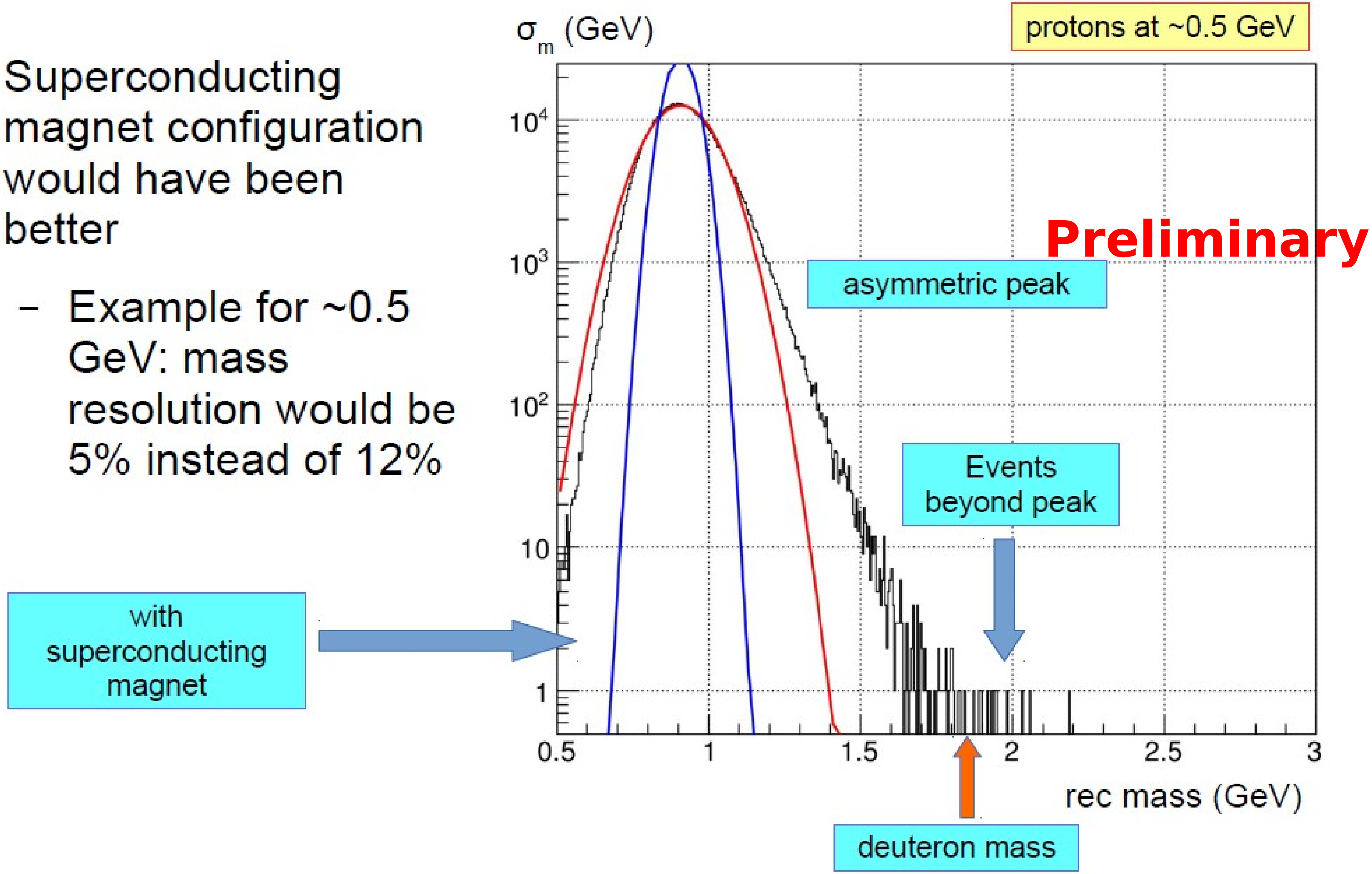
- Unfortunately, as expected, that is not exactly the case
  - Gaussian curve shown matches top of mass peak
  - Mass peak is slightly asymmetric, with larger tail on the right
  - A tiny, but non-zero fraction of events lies beyond the peak
- Ongoing work to improve reconstruction results



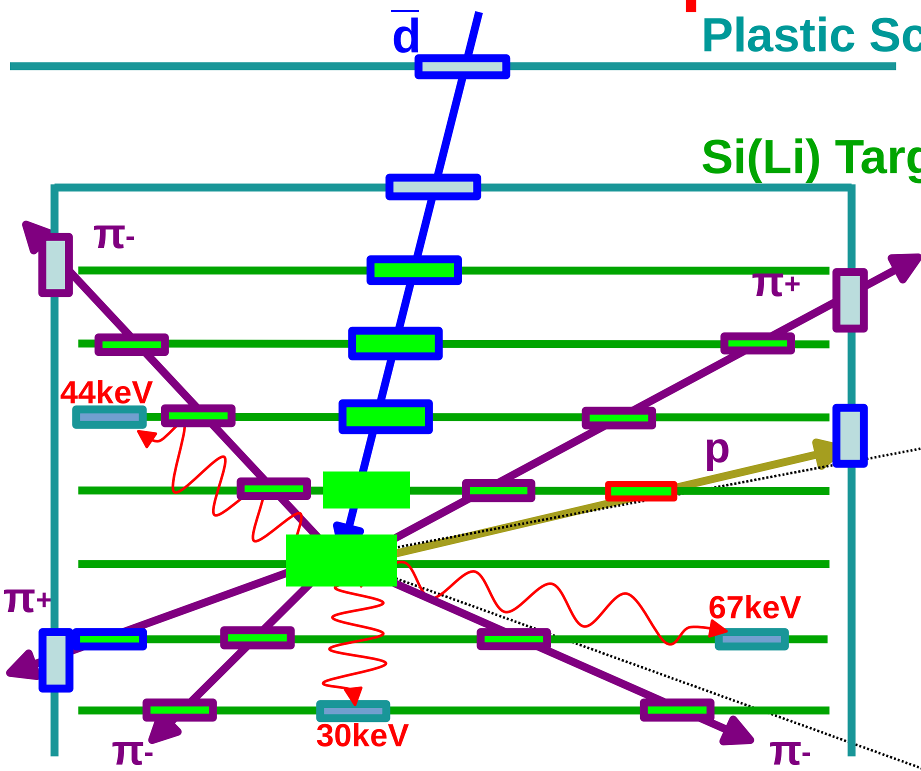
Mass resolution

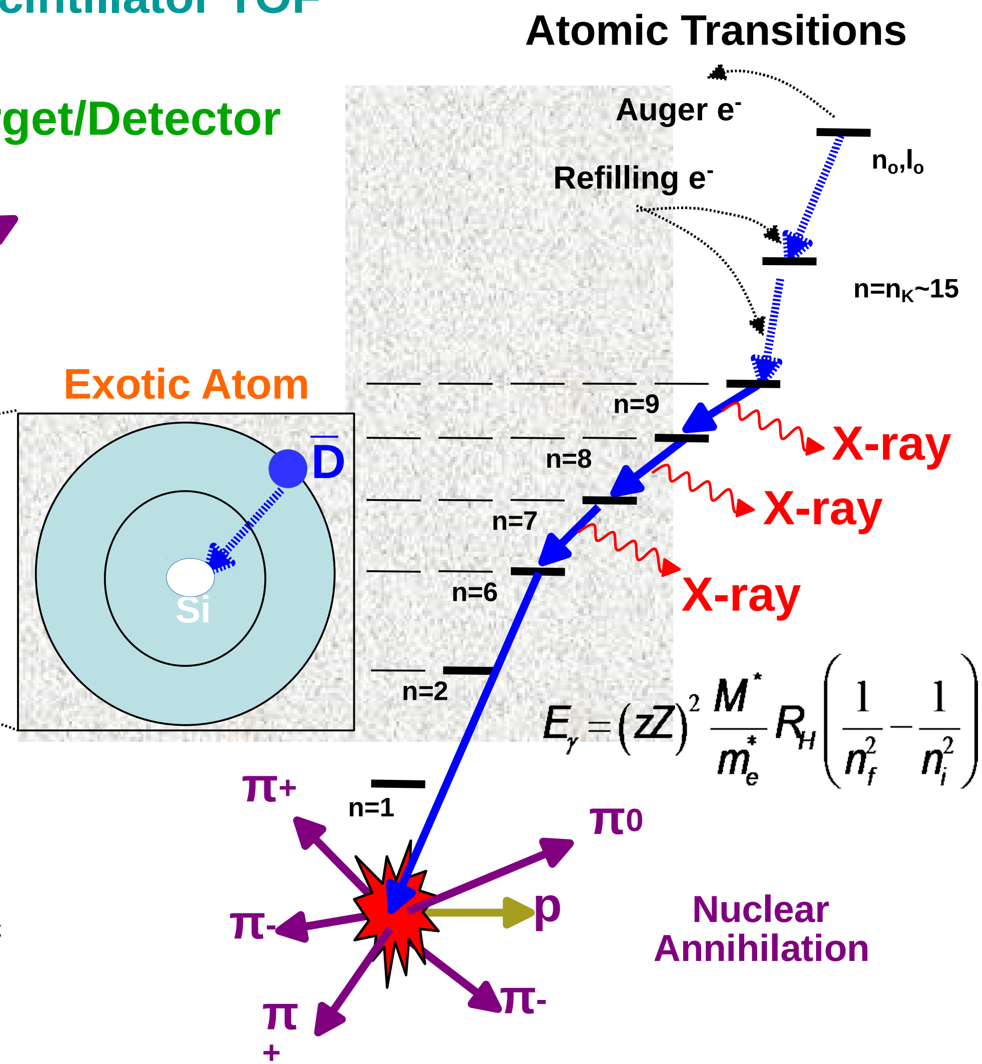
AMS-02

- Superconducting magnet configuration would have been better
  - Example for ~0.5 GeV: mass resolution would be 5% instead of 12%



GAPS detects atomic X-rays and annihilation products from exotic atoms





A time of flight (TOF) system tags candidate events and records velocity

The antiparticle slows down & stops in a target material, forming an excited exotic atom

Deexcitation X-rays provide signature

Annihilation products provide added background suppression

X-ray yields were measured at KEK in 2004 and 2005

GAPS project history

2002(original GAPS)
- Cubic detector
- 3 X-rays

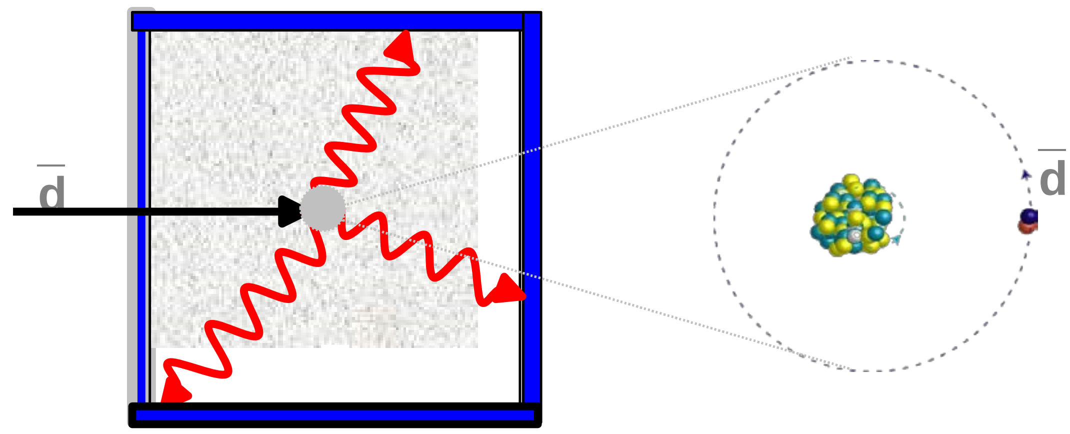
2004/2005
- KEK Beam Test

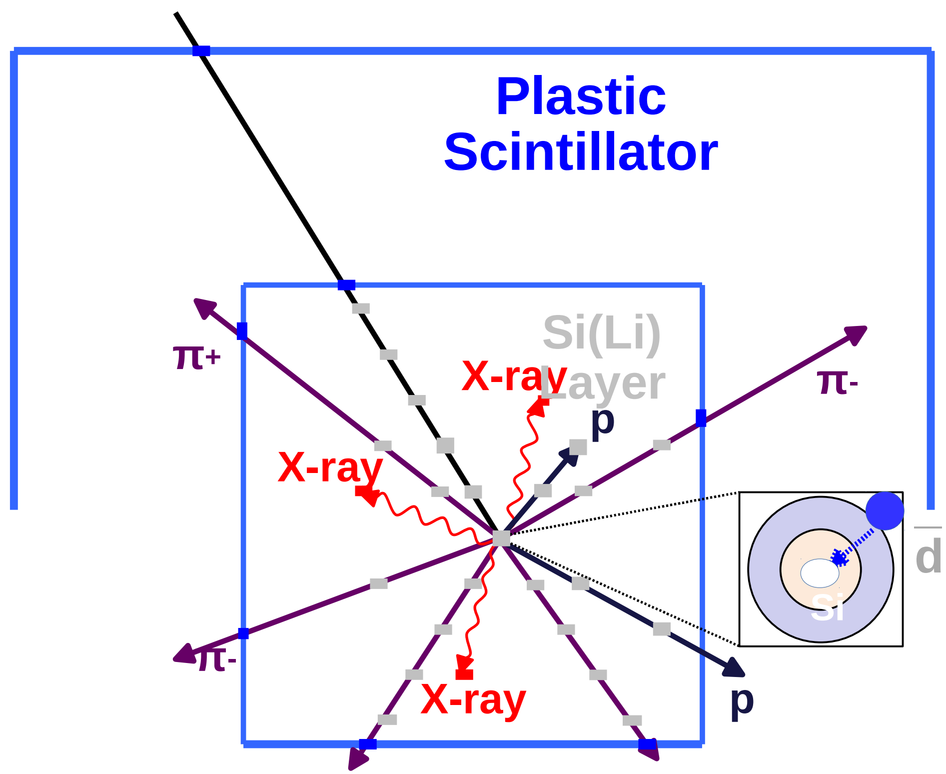
2006
- Multi-layer detector
- TOF stopping depth
- X-rays
- Pion multiplicity

2008
- Proton multiplicity

2009
- dE/dX

2012
- pGAPS flight
- Start Si(Li) fabrication





M. Hailey, Dark Matter 2014, UCLA

GAPS science summary

- *Antideuterons* **as DM signatures**
  - **no astrophysical background** at low energy
  - **complementary** to direct/indirect searches and collider experiments
  - search for: **light DM**, heavy DM, gravitinoDM,
    LZP in extra-dimensions theories, (evaporating PBH)
- *Antiprotons* **as DM and PBH signatures**
  - precision flux measurement at ultra-low energy (E < 0.25 GeV)
  - **complimentary** to direct/indirect searches and collider experiments
  - **~ 10 times more statistics** @ 0.2 GeV, compared to BESS/PAMELA
  - search for: **light DM** gravitinoDM,
    LZP in extra-dimensions theories, evaporating PBH
- *Expected to launch from Antarctica in 2020/2021*

- **1 LDB flight (~35 days) -> precision antiproton flux measurement**

  ~1500 antiprotons in GAPS E < 0.25 GeV, while 30 for BESS, 7 for PAMELA at E ~ 0.25 GeV
- **2 LDB flights (~70 days) -> improved antideuteron statistics**

  Antideuteron sensitivity: ~3.0 x 10^{-6} [$m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}$] at E < 0.25 GeV
- **3 LDB flights (~105 days) -> Antideuteron sensitivity: ~2.0 x 10^{-6} [$m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}$] at E < 0.25 GeV**

M. Hailey, Dark Matter 2014, UCLA

GAPS instrument summary

TOF plastic scintillators

-outer TOF: 3.6m x 3.6m, 2m height

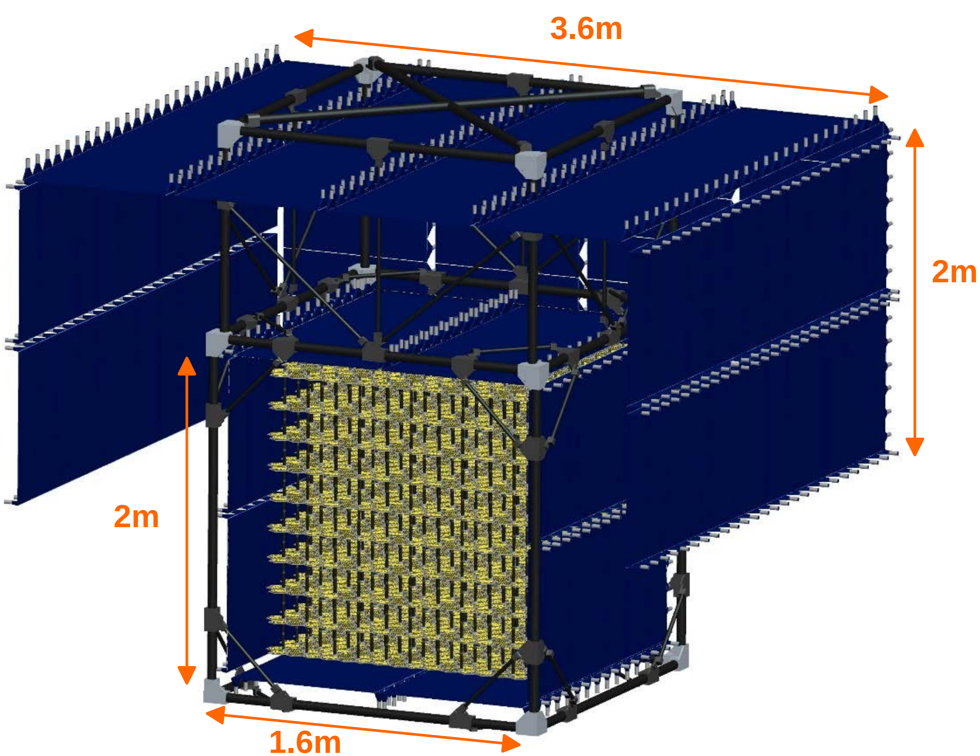
-inner TOF: 1.6m x 1.6m, 2m height

-1m b/w outer and inner TOFs

-500 pstiming resolution

-16.5 cm wide plastic paddles

-PMT on each end



Science weight: ~1700 kg, 34H balloon

Si(Li) detectors

-10 layers, 1.6m x 1.6m

-layer space: 20 cm

-Si(Li) wafer (~1500 wafers)

-4 inch diameter

-2.5mm thick wafer

-12 x 12 rectangular

-segmented into 4 strips

3D particle tracking

-timing resolution: ~ 100 ns

-energy resolution: 3 keV

-operation temperature: -35 C

-dual channel electronics

X-ray: 20 -80 keV

charged particles: 0.1 -100 MeV

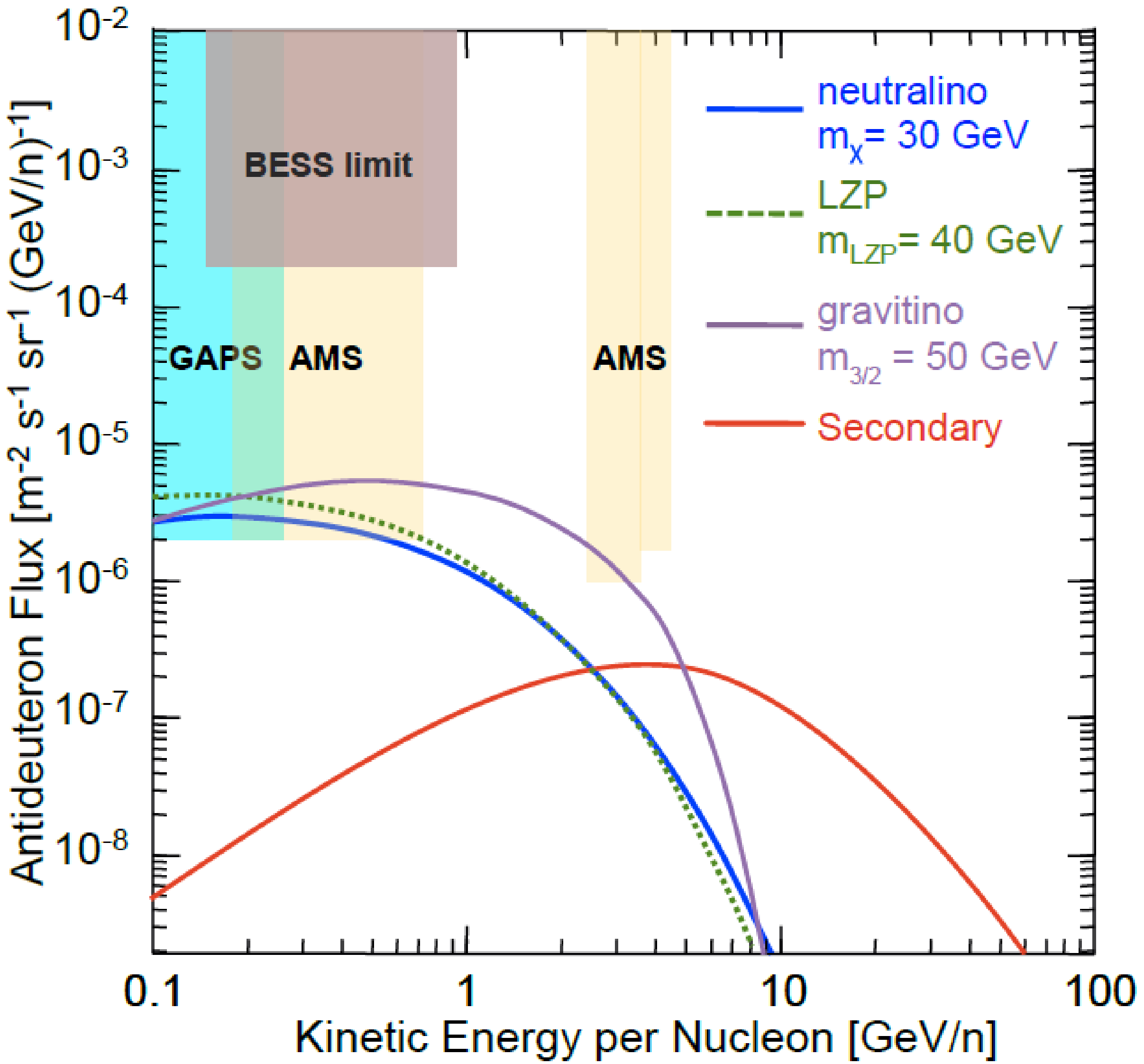
Cooling system

-oscillating heat pipe (OHP)

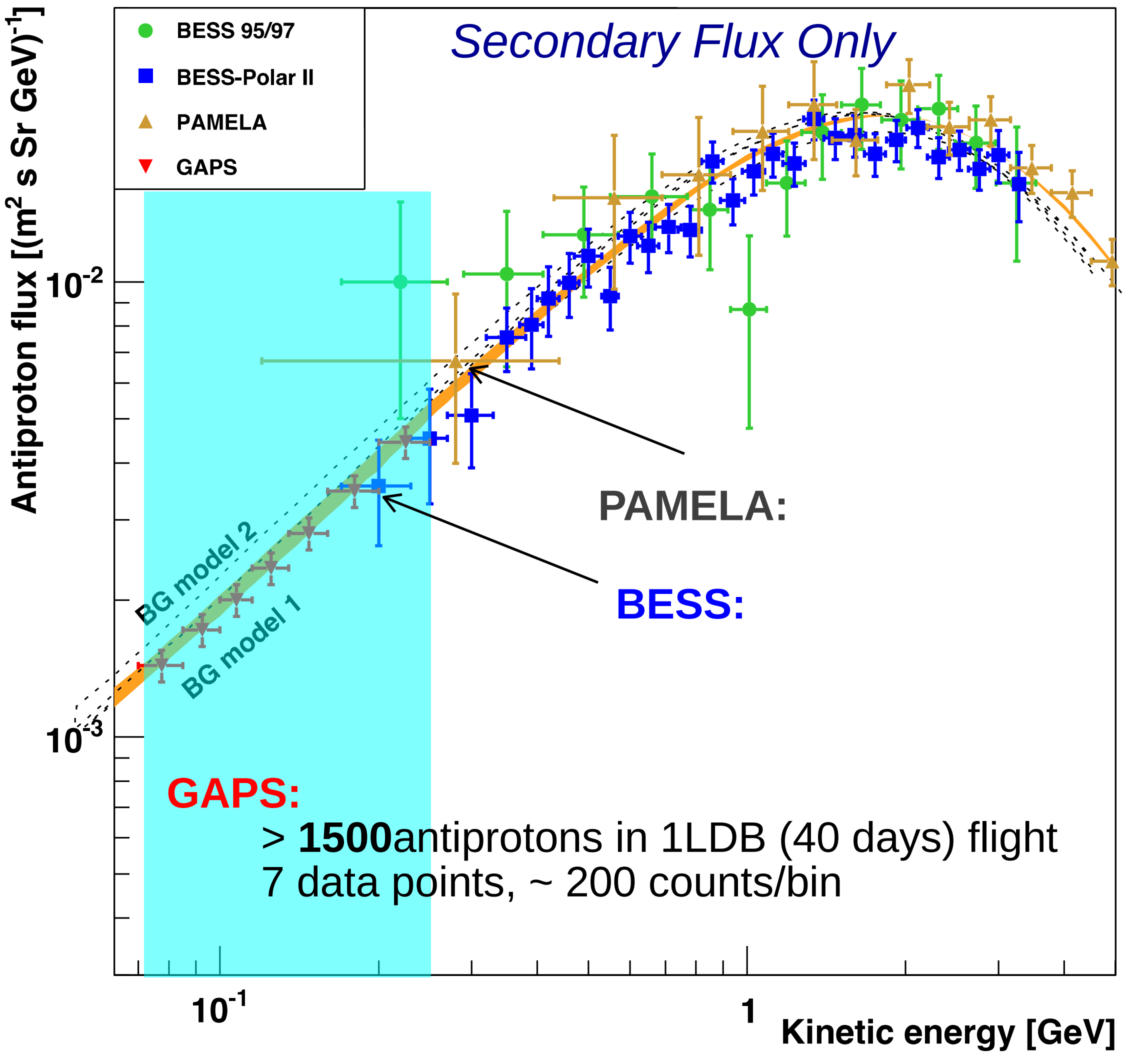
-demonstrated in pGAPS

Cosmic-ray Antideuterons

T. Aramakiet al.,
Astropart. Phys. 74 (2016) 6,
arXiv: 1506.02513



GAPS precision antiproton flux measurement provides strong constraints on DM and PBH models



Primary flux

$$\Phi_p \propto \langle \sigma v \rangle_{ann} \left(\frac{\rho_{DM}}{M_{DM}} \right)^2 \otimes \text{propagation}$$

x 10 for Max
x 0.1 for Min
due to Halo model

Secondary flux

-constrained by B/C ratio

M. Hailey, Dark Matter 2014, UCLA

Complementary to direct/indirect DM searches and collider experiments for light DM

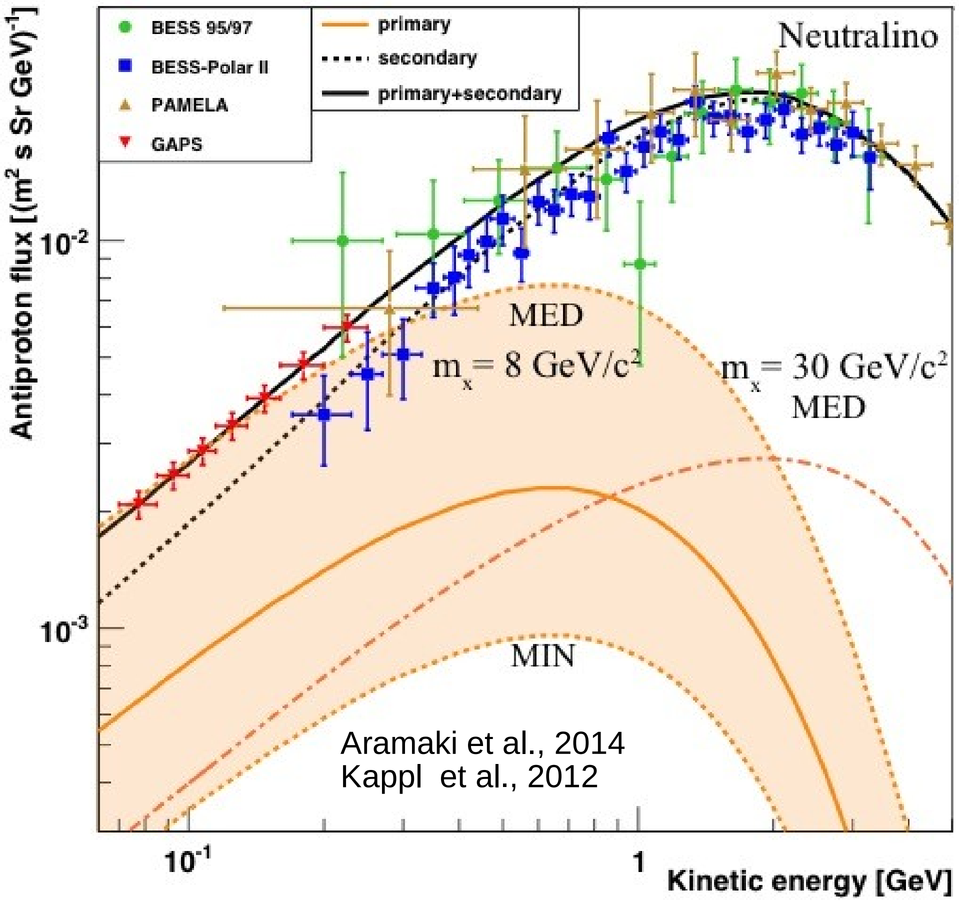
GAPS antiprotons probe light DM and gravitinoDM

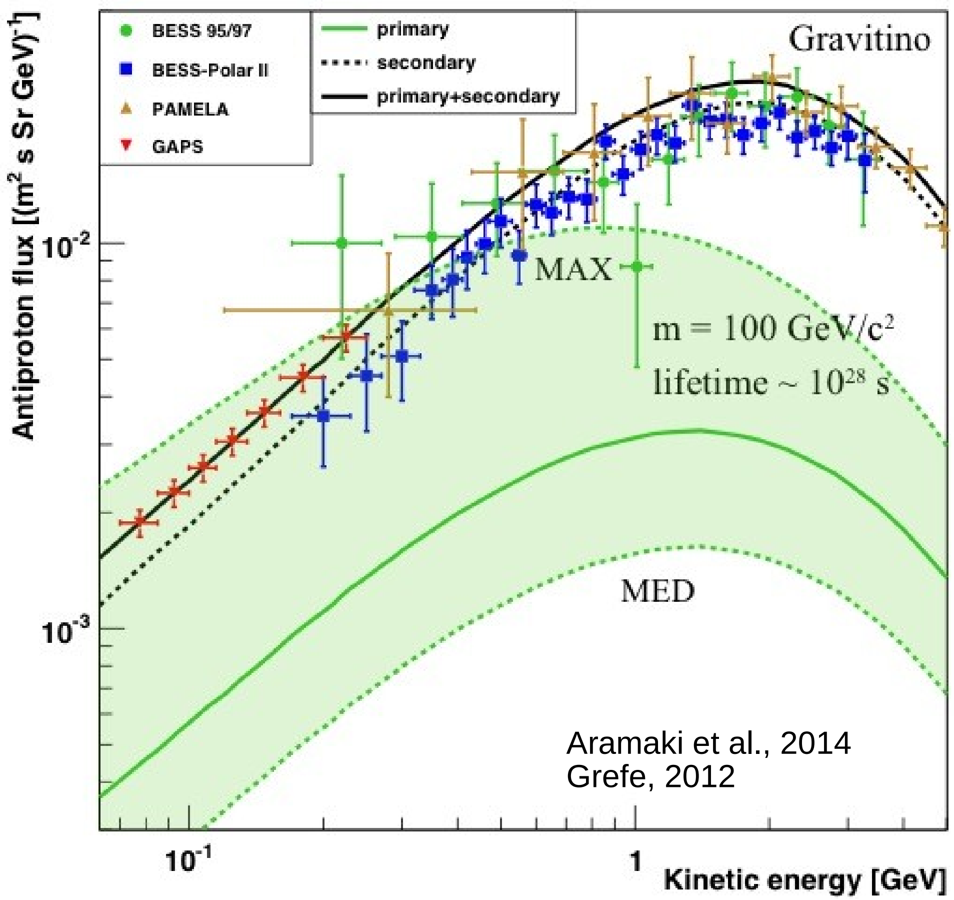
Light DM

- in non-universal gauginomodel
- good agreement with experimental data
  - uncertainty on propagation model
  - uncertainty on annihilation cross-section
  - different annihilation channels

gravitinoDM

- stable in galactic time scale
- small R-parity violation
  - avoid gravitinooverproduction





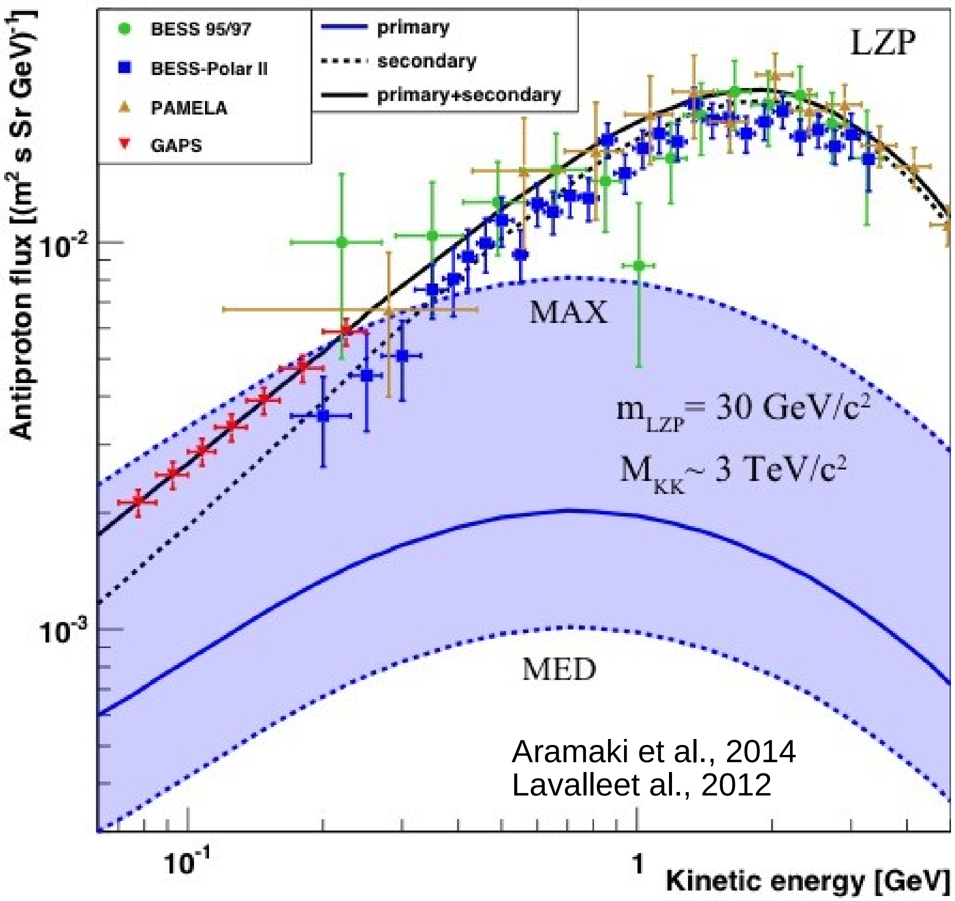
Unique probes for DM in extra-dimensions and evaporating PBHs

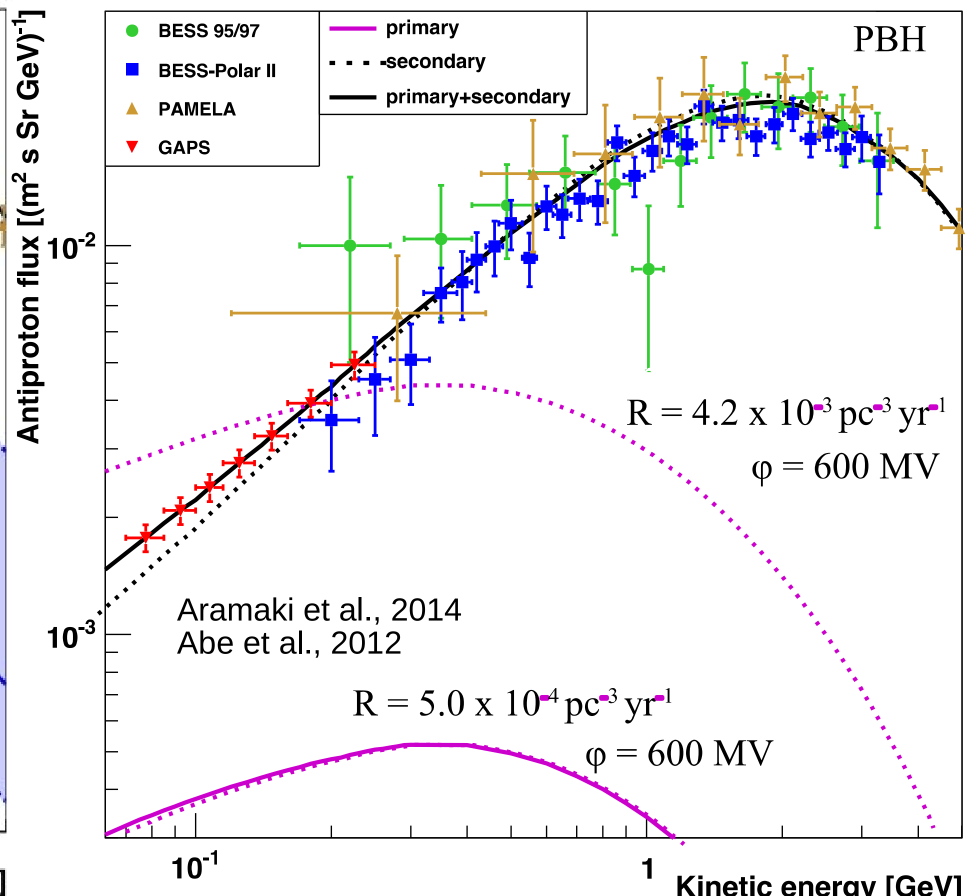
LZP

- Lightest Z_3 charged particle
- stable under Z_3 symmetry
- right-handed neutrino

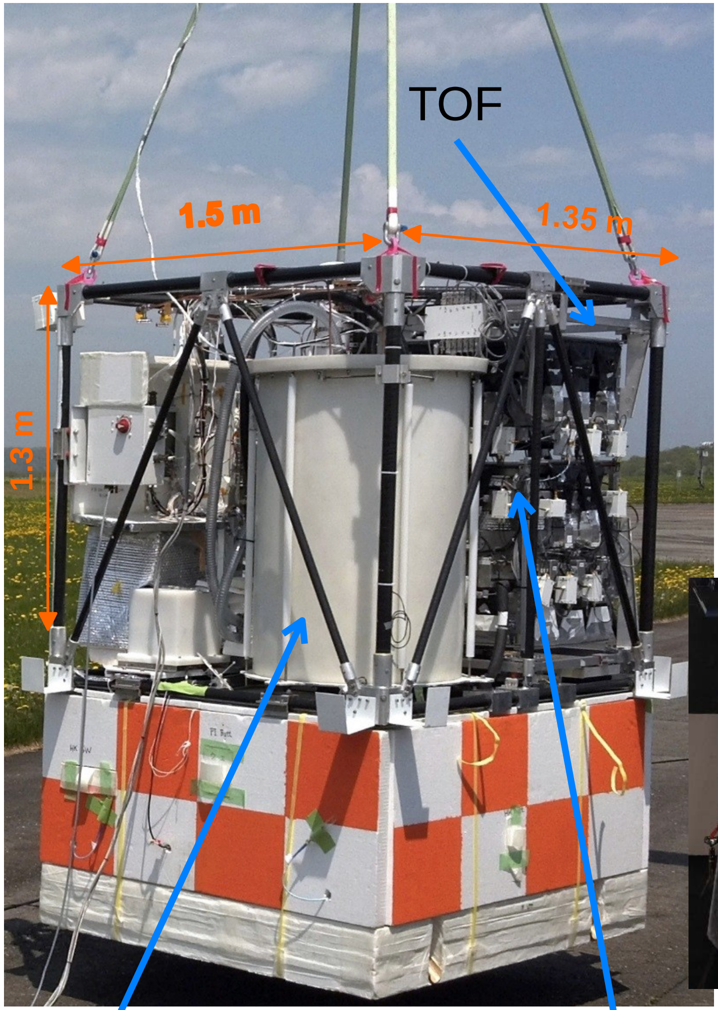
Primordial Black Hole Evaporation

- density fluctuations, phase transitions, collapse of cosmic strings in the early universe
- $R < 0.02\text{-}0.05\ pc^{-3}\ yr^{-1}$ (γ, Fermi, EGRET)
- $R < 0.0012\ pc^{-3}\ yr^{-1}$ (p, BESS-Polar II only)





Successful prototype (pGAPS) flight in 2002 @ Taiki, JAXA balloon facility in Japan

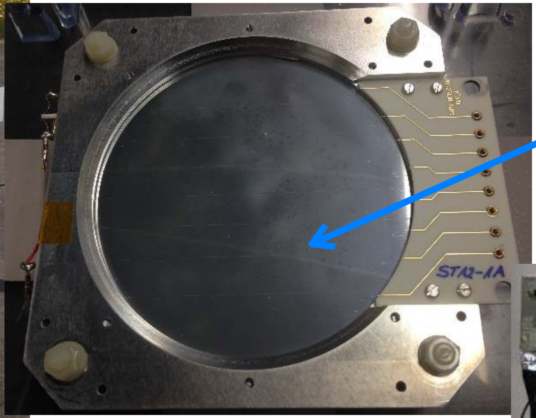


Vessel for DAQ

Si(Li) detector surrounded by TOF

- First balloon experiment with Si(Li) detectors
- TOF performance test and measure cosmic-ray proton count rate
- Demonstrate cooling system

M. Hailey, Dark Matter 2014, UCLA



Commercial SEMIKON Si(Li)
4 inch diameter, 2.5mm thick

The Flight

Instrument Paper

S. A. I. Mognet et al.
http://arxiv.org/abs/1303.1615

Flight Paper

P. von Doetinchem et al.
http://arxiv.org/abs/1307.3538v2

- Both TOF and Si(Li) systems worked very well.
- Rotator failed so no pointing (no active cooling available).
- Si(Li) operated for duration of flight from initial ground cooling (64% of strips still depleted at termination).
- OHP test very successful (first operation in a balloon flight).
- Thermal model fully validated (with pointing, active cooling would have worked).

The pGAPS flight was a great success!

Ready for Si(Li) mass production

M. Hailey, Dark Matter 2014, UCLA

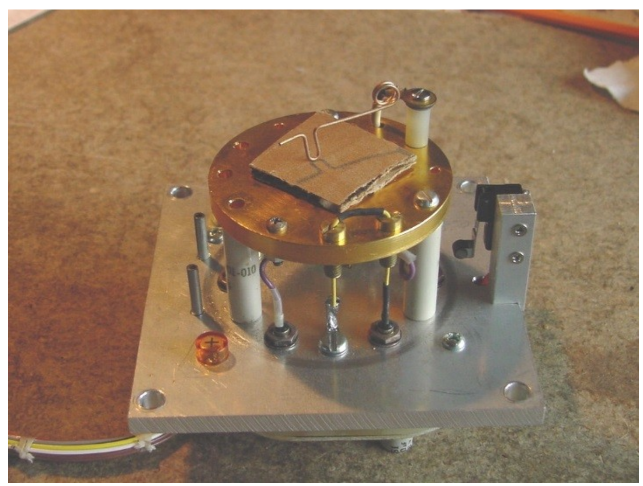
Si(Li) fabrication

-requires 1500 Si(Li) detectors
-Li evaporator, UI grinder in the lab
-HF etching in clean room
-computer controlled Li drifting system

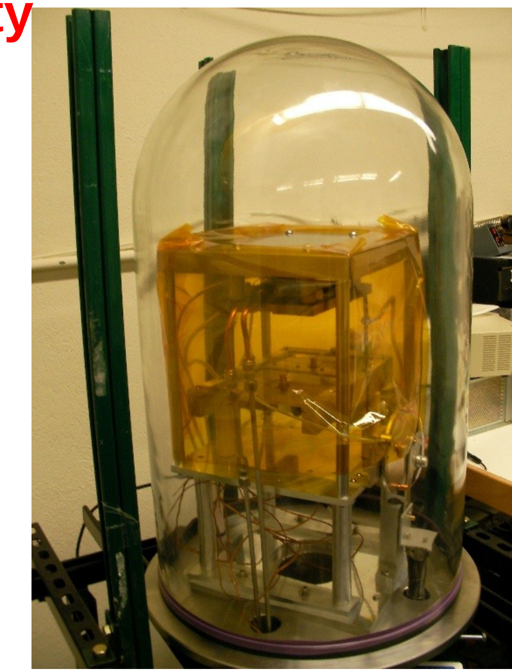
Fabrication facility has been set up at Columbia University

Ultrasonic Impact Grinder

Etching in cleanroom

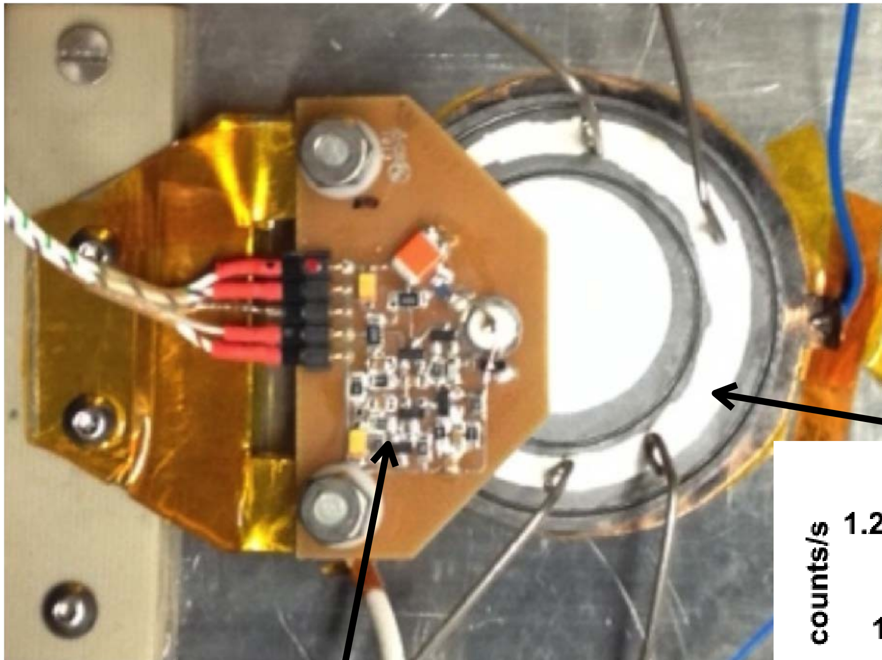


Li drifting station



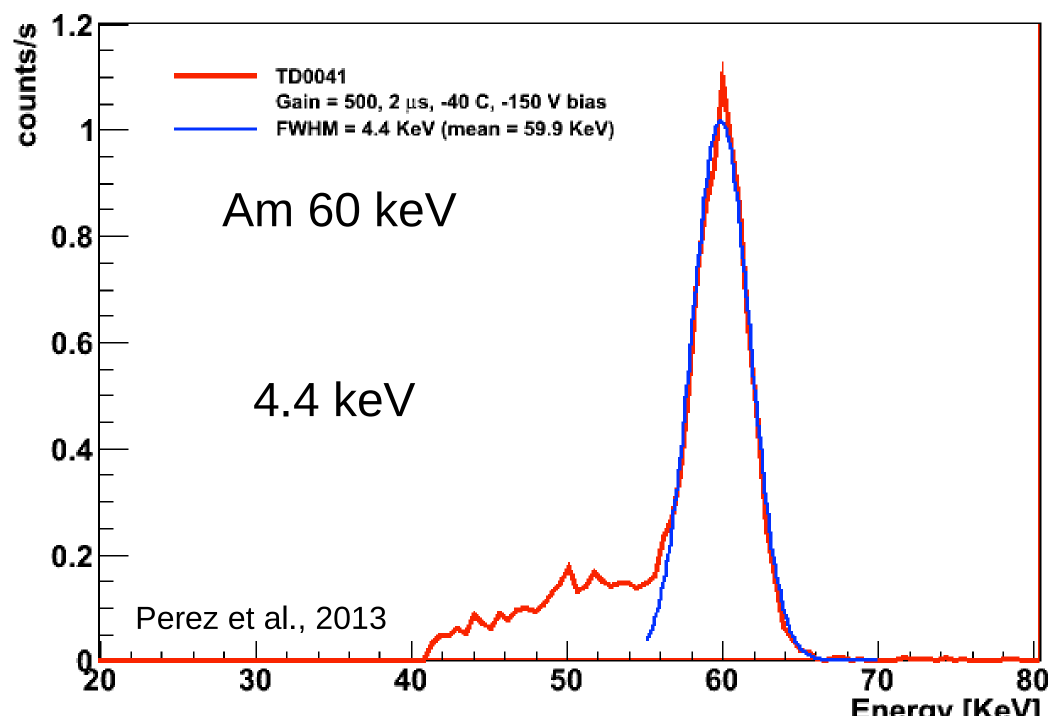
Li evaporator

Homemade Si(Li) performance test



2 inch diameter homemade Si(Li)
-in vacuum chamber
-reproduce flight environment
-cooled down by LN2
-with flight candidate preamp

preamp



Upgrade with
better electric contacts
more uniform Li-drifting

-> 3 **keV**energy resolution

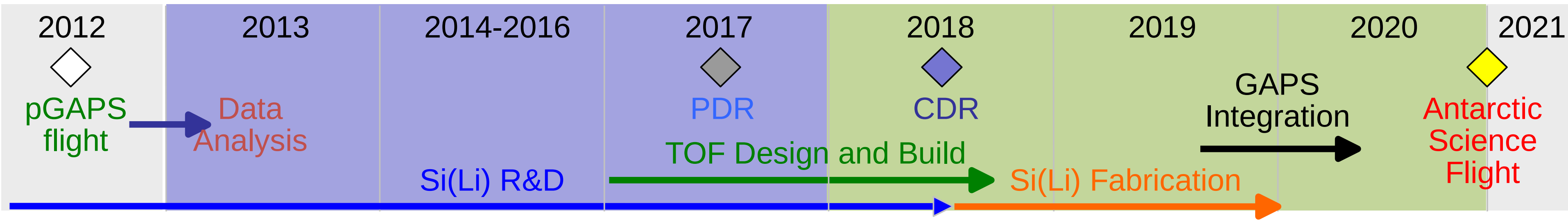
M. Hailey, Dark Matter 2014, UCLA

GAPS: Detector Development

Plastic scintillator based time-of-flight system.

- Read out at both ends with very compact, fast Hamamatsu (R7600-200) Ultra-Bialkali PMTs.
- Each PMT base has dedicated internal HV supply (total power consumption <0.5W per PMT in prototype).
- 0.5 m prototype version counters already flight tested, will extend to 1.6-2 m for GAPS.

Development Plan



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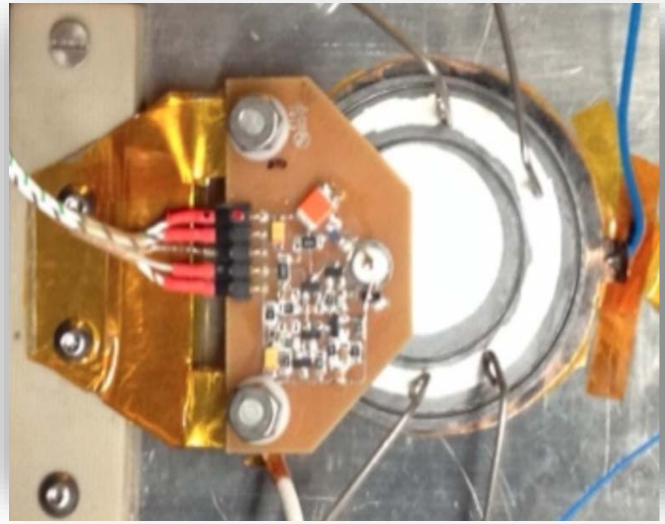
GAPS ASIC design



Objective

read out 2.5 mm thick, 1” diameter Si(Li) detectors [$C_D \approx$ 75 pF, I_{LEAK} = O(1 nA)]

Requirements

- dynamic range of 50 MeV
  minimum signal ≈20 keV
- energy resolution of 4 keV FWHM
  at the lower end (goal of 3 keV FWHM)
- interface to already available discrete preamplifier

Available design choices and optimization opportunities

- Selection of the CMOS technology (at present electronics is discrete)
- Investigate the possibility to integrate the preamplifier
- ASIC architecture (shaper, peak detector vs S/H, multiplexing, internal digitization?)

PossibilePartecipazioneINFN

- Collaborazione GAPS desidera una partecipazione INFN in quanto ritiene che aumenti sia la credibilità scientifica (impatto internazionale dell'INFN ed il nostro successo con PAMELA) che finanziaria (nel loro budget manpower specializzato, come ingegneri elettronici, conta molto).

- L'INFN potrebbe contribuire alla realizzazione degli ASIC per il DAQ dei rivelatori al silicio.

  A questa attività parteciperebbe INFN TS e INFN PV/Università Bergamo:

- **INFN Trieste: Valter Bonvicini (I Ric.); Benigno Gobbo (I Ric.); Gianlugi Zampa (Tecnologo) ed i laboratori di elettronica di INFN Trie (con l'approvazione del direttore di Sezione);**
- **Università Bergamo (INFN Pavia): Valerio Re (PO); MassimoManghisoni(Ric.Univ.),**

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  A questa attività parteciperebbe INFN TS e INFN PV/Università Bergamo:

- **Partecipazione allo sviluppo del software di Simulazione e analisi dei dati: INFN TS, FI, Pavia Università/INFN di Torino e di Tor Vergata:**
  - **INFN TS: Mirko Boezio (I. Ric.), post. Doc.;**
  - **INFN FI: Elena Vannuccini(Ric.);**
  - **INFN PV: P.W. Cattaneo(I. Ric.), Andrea Rappoldi (I Tec.);**
  - **Università Torino: Nicolao Fornengo(PA); Fiorenza Donato (PA);**
  - **Università Roma Tor Vergata: Roberta Sparvoli(PA).**

Sviluppo temporale

- Dead line per la sottomissione del proposal alla NASA è verso la metà marzo. Se partecipazione INFN, necessaria una lettera indicante il contributo italiano (se progetto approvato da NASA) entro fine febbraio.
- Verso inizio autunno 2016 vi sarà la risposta NASA.
- Se positiva avvio ufficiale attività gennaio-marzo 2017.
- Se approvato il progetto si svilupperà su un periodo di 5 anni nei quali si dovrà fare un volo in pallone e produrre i primi risultati scientifici.
- Volo previsto inverno 2020-2021. Si tratterà di un “long duration” da McMurdo (Antartide).
- Èabbastanza probabile che la NASA supporti e finanzi voli successivi.

Richieste finanziarie

- Costi sviluppo e produzione prototipo ASIC: ~35 keuro.
- Se si volesse contribuire al run di produzione finale la stima costi è di 200 ke, altrimenti inserita nelle richieste gruppi americani alla NASA.
- Trasferte (da perfezionare con resto collaborazione):
  - Italia: Trieste-Bergamo per sviluppo ASIC:
    - 2017: 5 keuro
    - 2018: 5 keuro
  - Italia: Riunioni componente italiana: 4 persone x 1ke per anno
  - USA: riunioni per sviluppo sottorivelatori:
    - 2017: 2 m.u.: 12 keuro
    - 2018: 2 m.u.: 12 keuro
  - USA: Integrazione
    - 2019: 3 m.u.: 18 keuro
    - 2020: 3 m.u.: 18 keuro
  - McMurdo: 1 o 2 persone per preparazione lancio ed operazioni di volo (Nov. 2020-Feb 2021). Costi permanenza base dovrebbero essere a carico NASA. Da verificare se questo vale anche per collaboratori stranieri. Se sì solo costi di viaggio: 5 keuro
  - Meeting collaborazionenegli USA (2 all'anno): 4 persone x 4 ke per anno

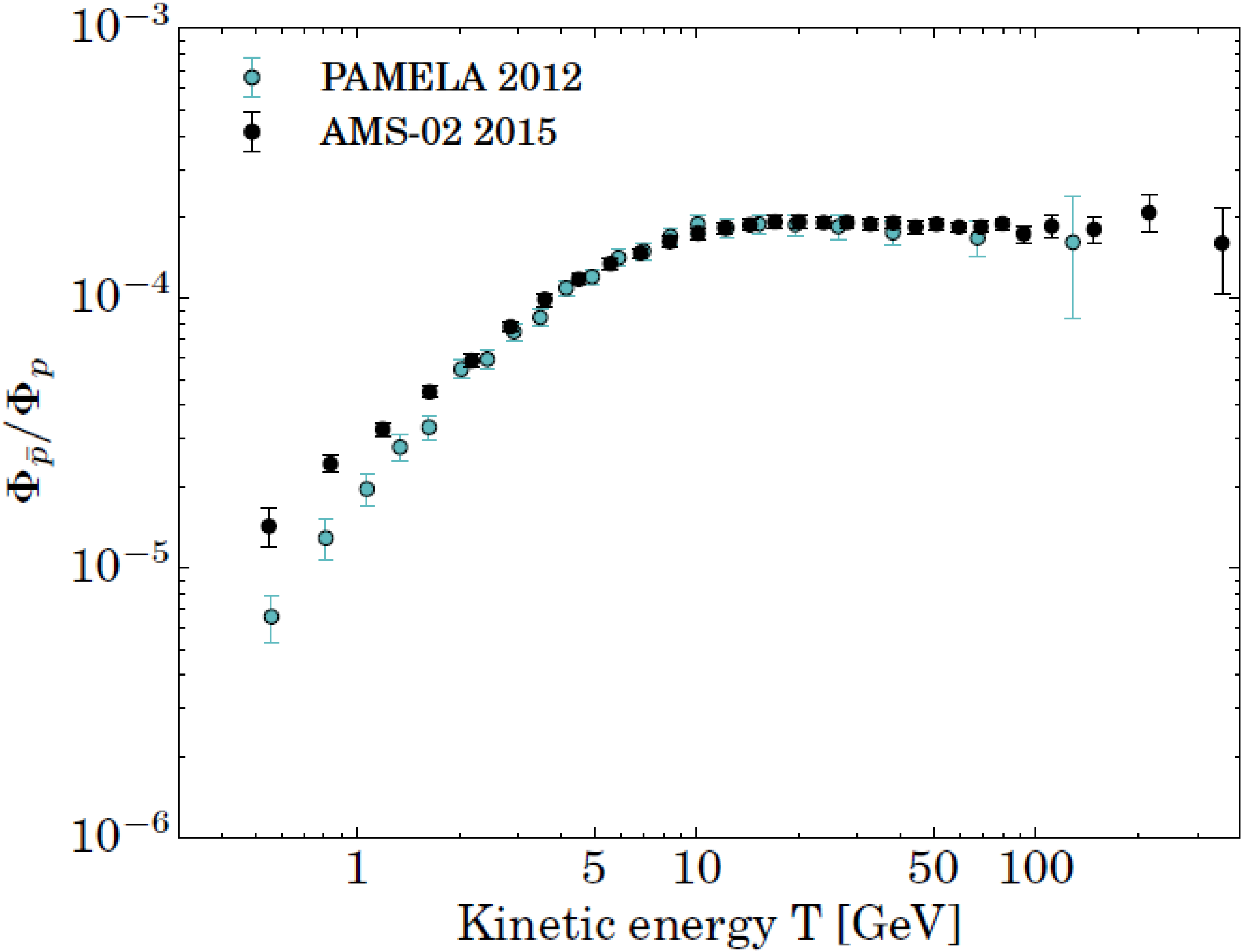
Previsione richieste complessive

(in ke)

Anno	Costruzione+ Cons.& Inv.	Missioni	Totale
2017	30	37	67
2018	10	37	47
2019	10	38	48
2020	10	38	48
2021	5	25	30
2022	5	20	25
2017-2022	70	195	265

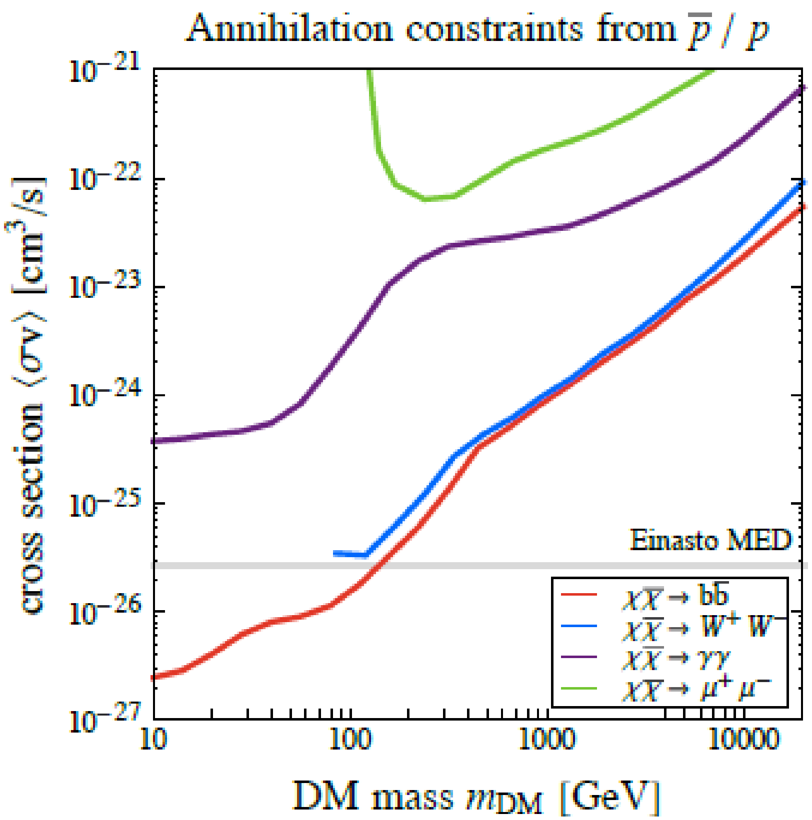
SPARE SLIDES

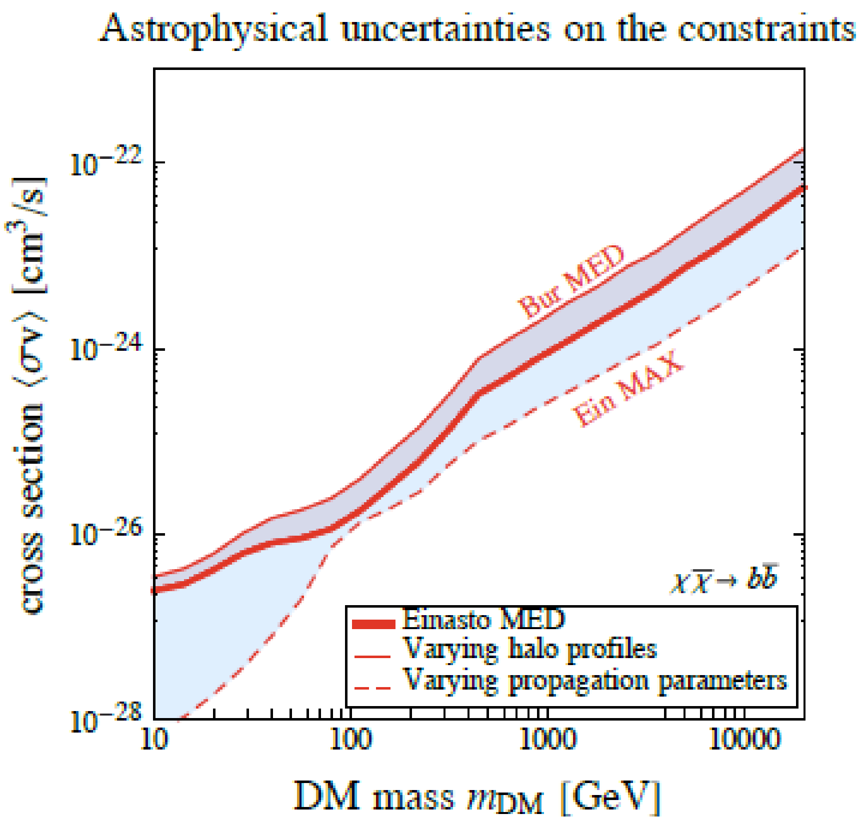
High energypbardata: PAMELA & AMS-02 pbar/p ratio



M. Cirelli,
Rapporteur talk
ICRC 2015

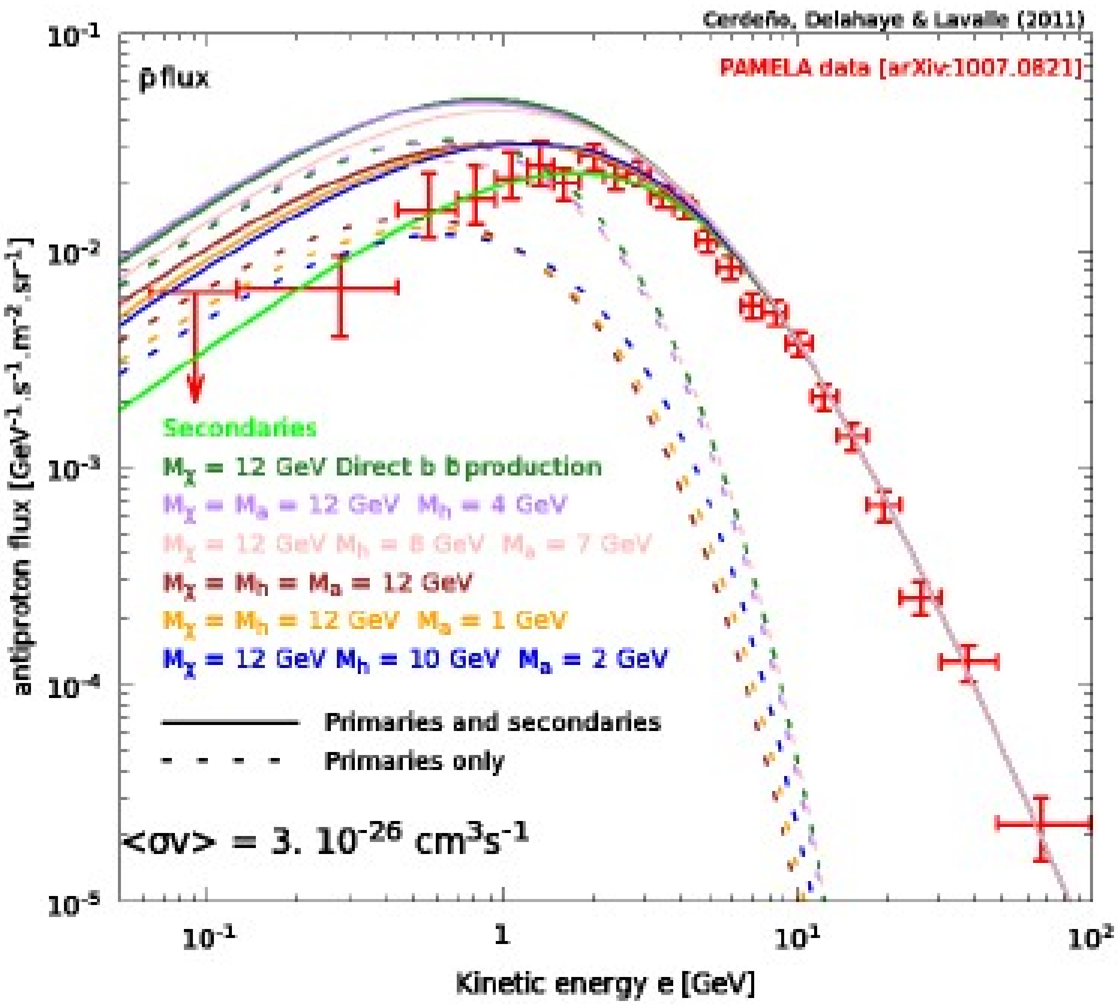
Cosmic-Ray Antiprotons and DM limits





G. Giesen et al., JCAP 1509 (2015) 023, arXiv: 1504:04276
Constrains from preliminary AMS-02 antiproton data

Cosmic-Ray Antiprotons and DM limi

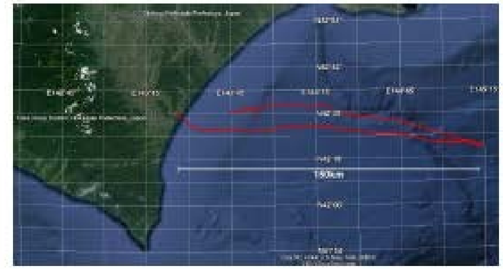


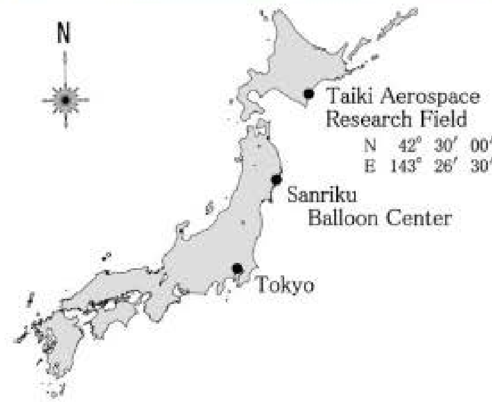
D. G. Cerdeno, T. Delahaye& J. Lavalle,
Nucl. Phys. B 854 (2012) 738
Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.

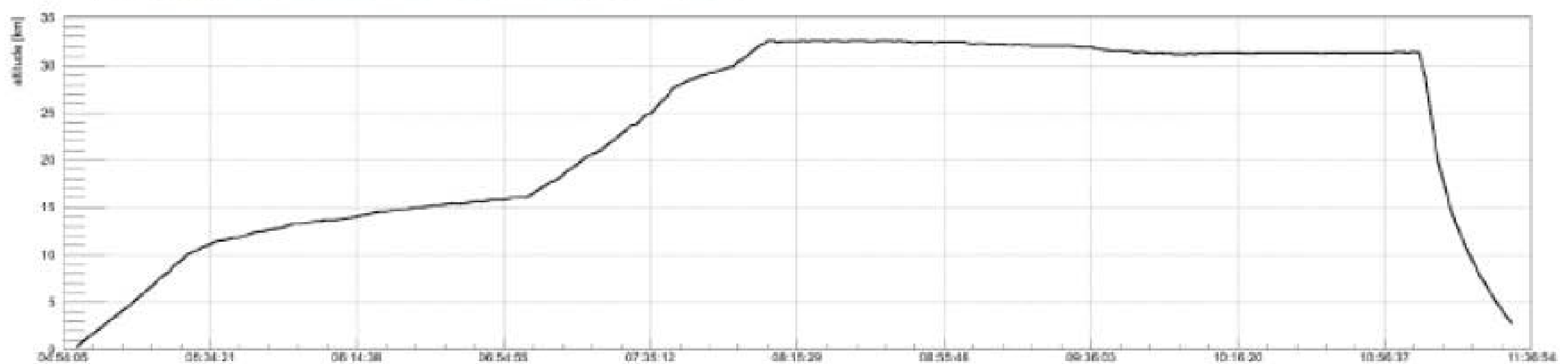
See also:

• M. Asano, T. Bringmann& C. Weniger, Phys. Lett. B 709 (2012) 128.
• M. Garny, A. Ibarra & S. Vogl, JCAP 1204 (2012) 033
• R. Kappl & M. W. Winkler, PRD 85 (2012) 123522

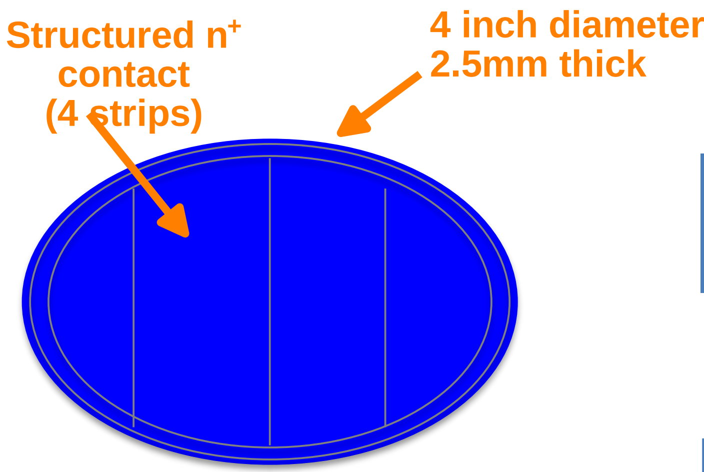
pGAPS Balloon Flight, June 3, 2012





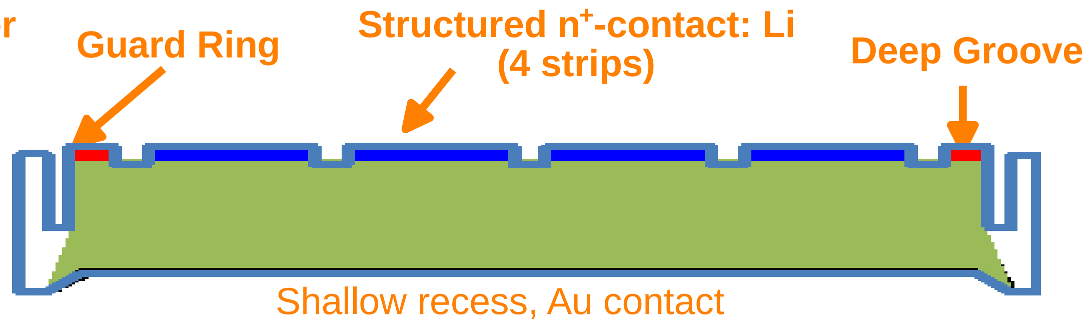


Si(Li) fabrication procedure (well-studied since 1960's)

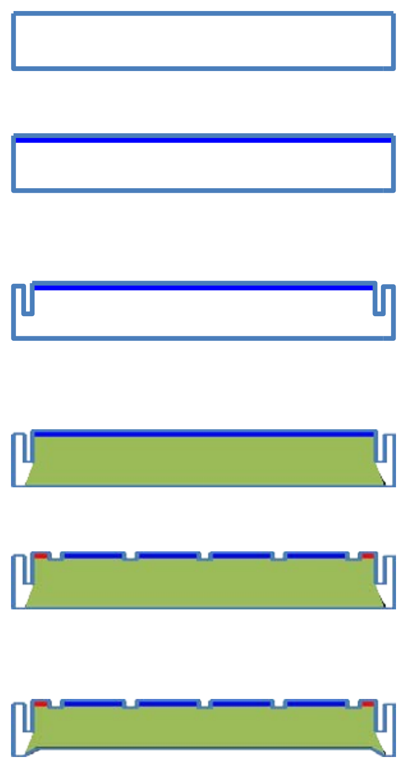


4 inch diameter, 2.5mm thick

- n^+ contact: Lithium
  - Al coating
  - 4 strips
  - Guard Ring
- p^+ contact:
  - Au contact
  - HV
  - Shallow recess to protect HV contact



Proven, easy process



Cut from the ingot

Evaporate Lithium

Produce the deep groove and mesa (optional)

Drift the Li into the silicon

Make strips and guard ring

Etch the back (shallow recess) and evaporate Au