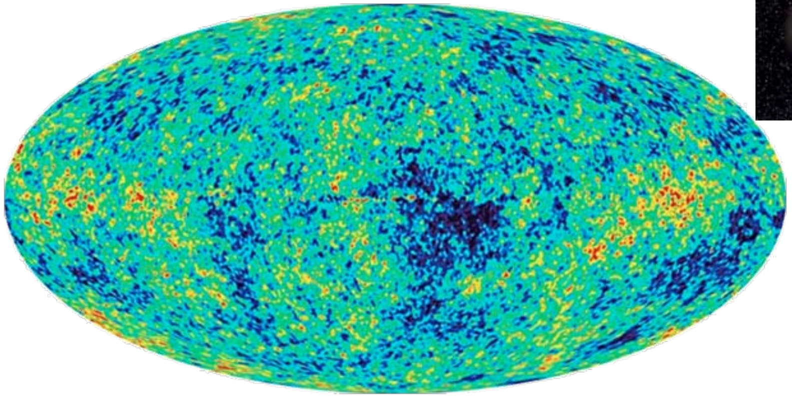
GAPS Antiproton and Antideuteron Measurement for Indirect Dark Matter Search

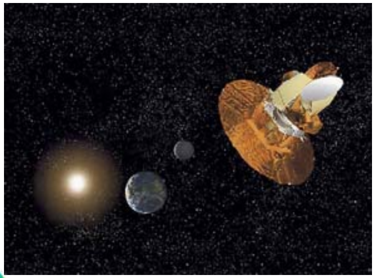
Charles J. Hailey
Columbia University

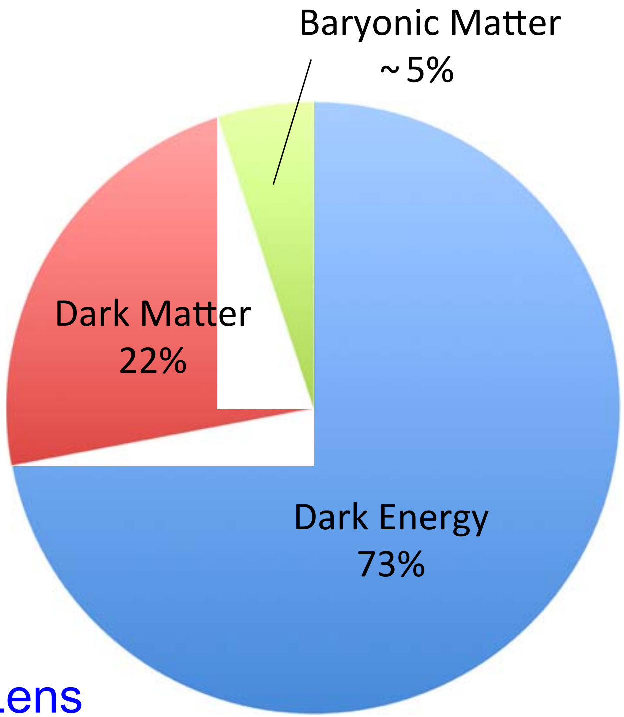
Dark Matter 2014 @ UCLA, Feb 26

Evidence for Dark Matter

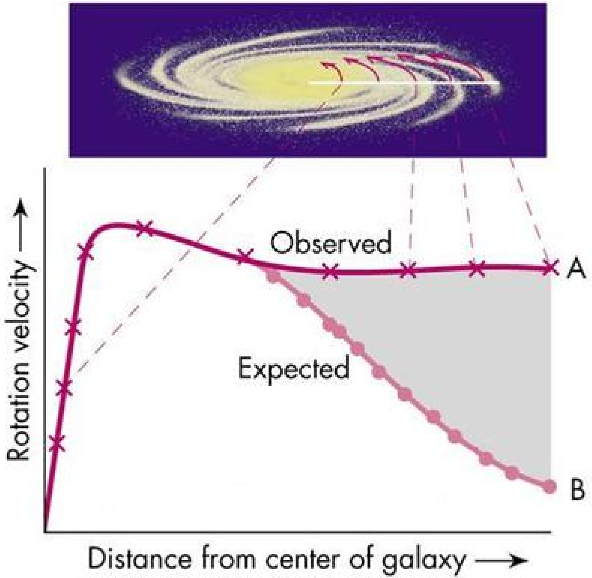
WMAP/Planck measured accurate cosmological information



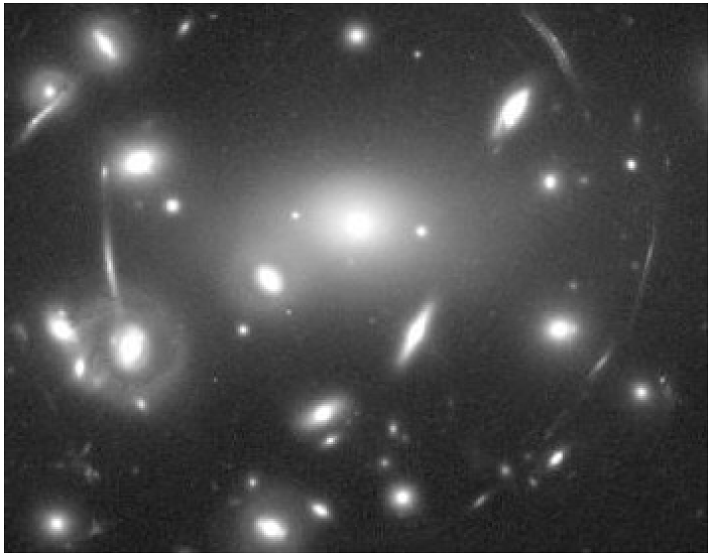




Galactic Rotation Curve



Gravitational Lens



What is Dark Matter?

DM theory has a previously unrecognized approximate symmetry

N(experiments) ≈ N(theories)

Lots of theories!

heavy neutrino
Axinos
Bino
Brane world DM
CHAMPS
Cryptons
D-matter
Gravitinos
Kaluza-Klein
Higgsino
Light scalars
Minimal DM
Mirror particles
Neutralinos
New symmetry little Higgs
Q-balls
Photino
Self-interacting DM
Simpzillas
SM neutrinos
Sneutrinos
Sterile neutrinos
SWIMPS
little Higgs
Wimpzillas
Wino

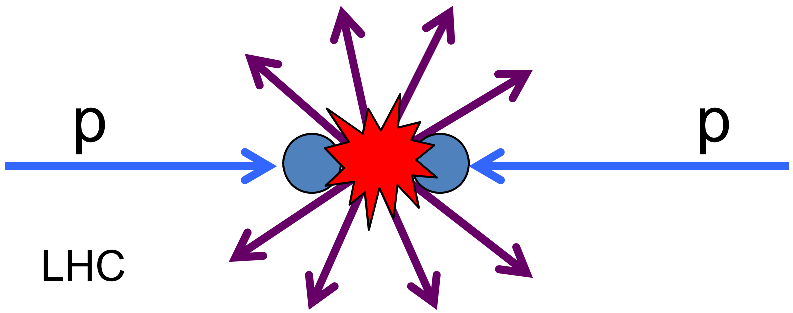
Lots of experiments!

AMS-2
AMANDA
ATIC
BESS
CDMSII
CDMSlite
SuperCDMS
CUORICINO
COSME
CoGeNT
CRESST-I II
DAMA/LIBRA
DAMA/NaI
DarkSide
ELEGANT V
EDELWEISS
Fermi-LAT
GAPS
GEDEON
Genius
Genino
HESS
IceCube
IGEX
LHC
LUX
PAMELA
PICASSO
PPB-BETS
SIMPLE
SNOLAB
NAIAD
XENON
10/100/1T
ZEPLIN
SuperK
Tevatron
VERITAS

Dark matter searches

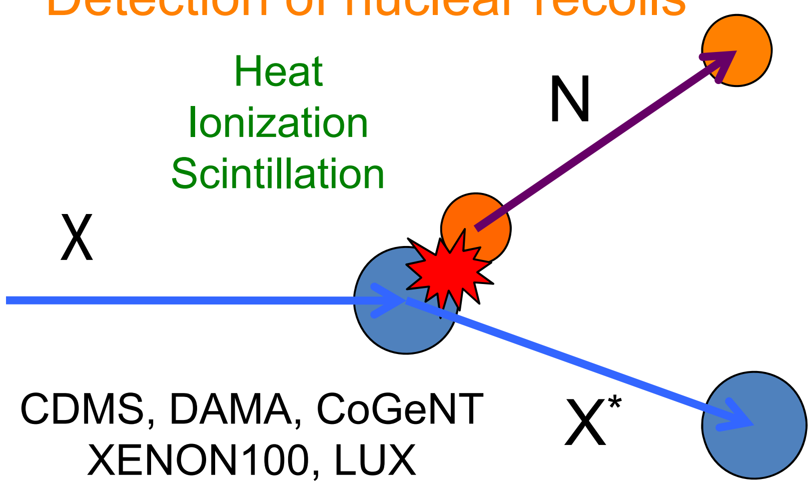
Collider Search

Missing energy and momentum for DM particle



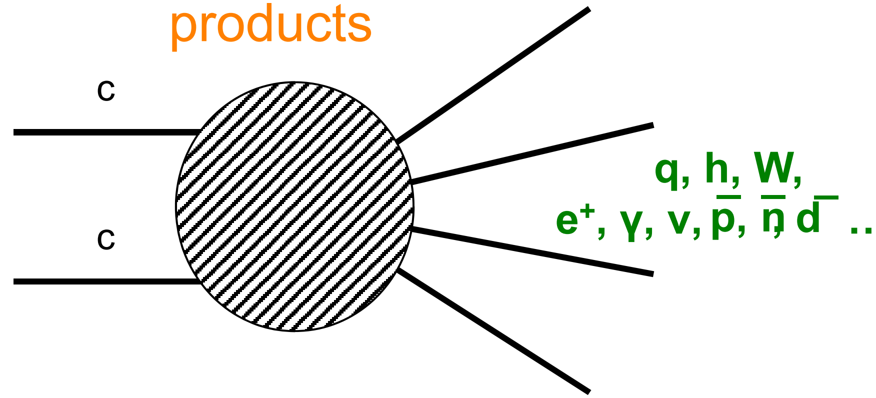
Direct Search

Detection of nuclear recoils



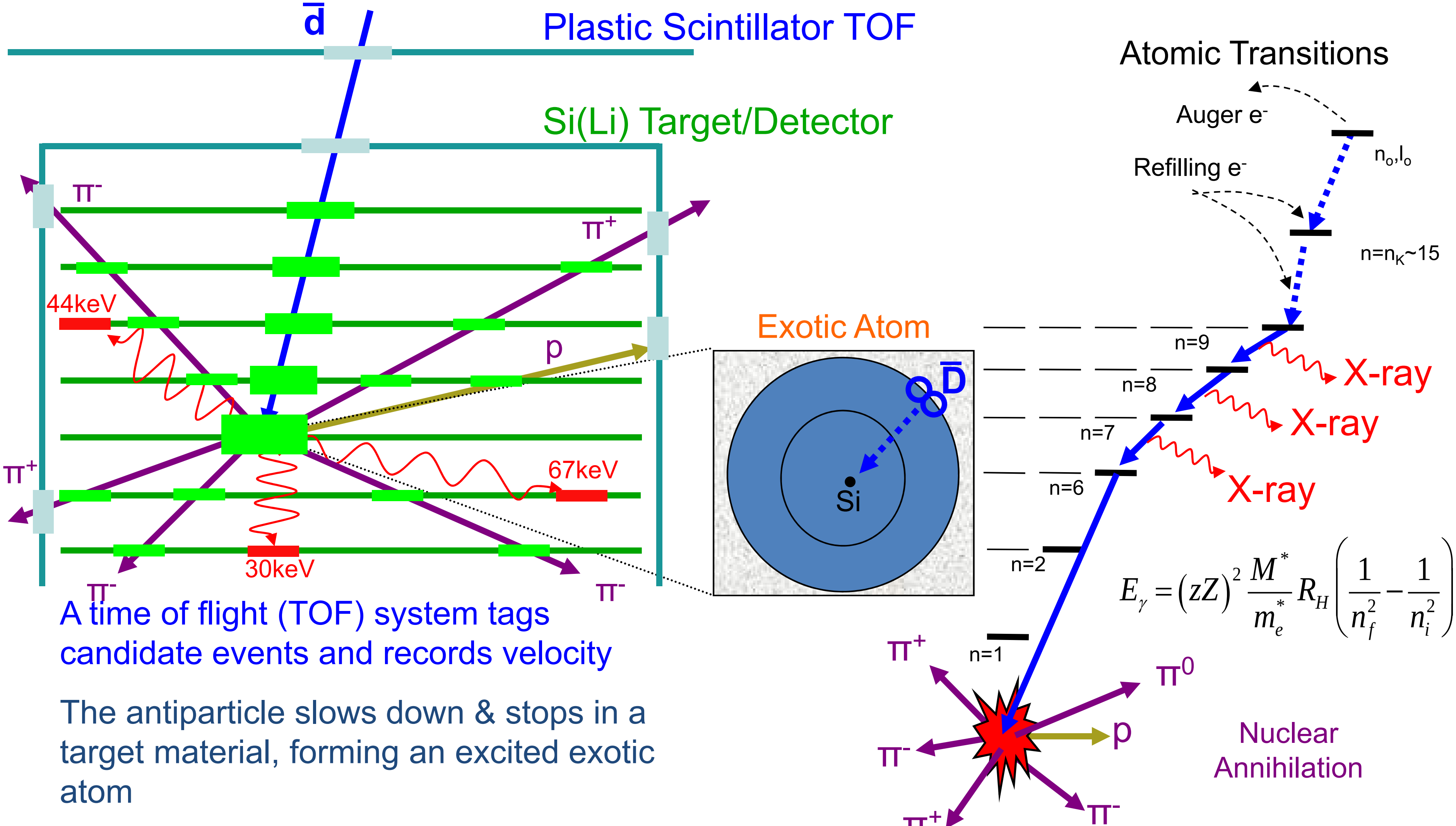
Indirect Search

Detect annihilation products



- Positron (e^+):
  PAMELA, Fermi-LAT, ATIC, AMS
- Photon (γ)
  Fermi-LAT, HESS…
- Neutrino (ν): AMANDA, IceCube…
- Antiproton ($\bar{p}$)
  BESS, AMS, PAMELA, GAPS
- Antideuteron ($\bar{d}$)
  GAPS, AMS

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



$$E_\gamma = (zZ)^2 \frac{M^*}{m_e^*} R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

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

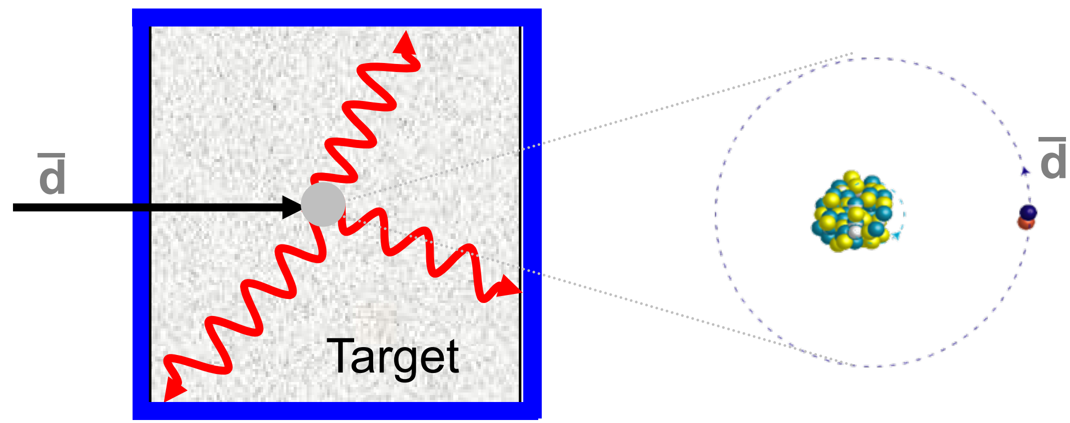
2006
- Multi-layer detector
- TOF stopping depth
- X-rays
- Pion multiplicity

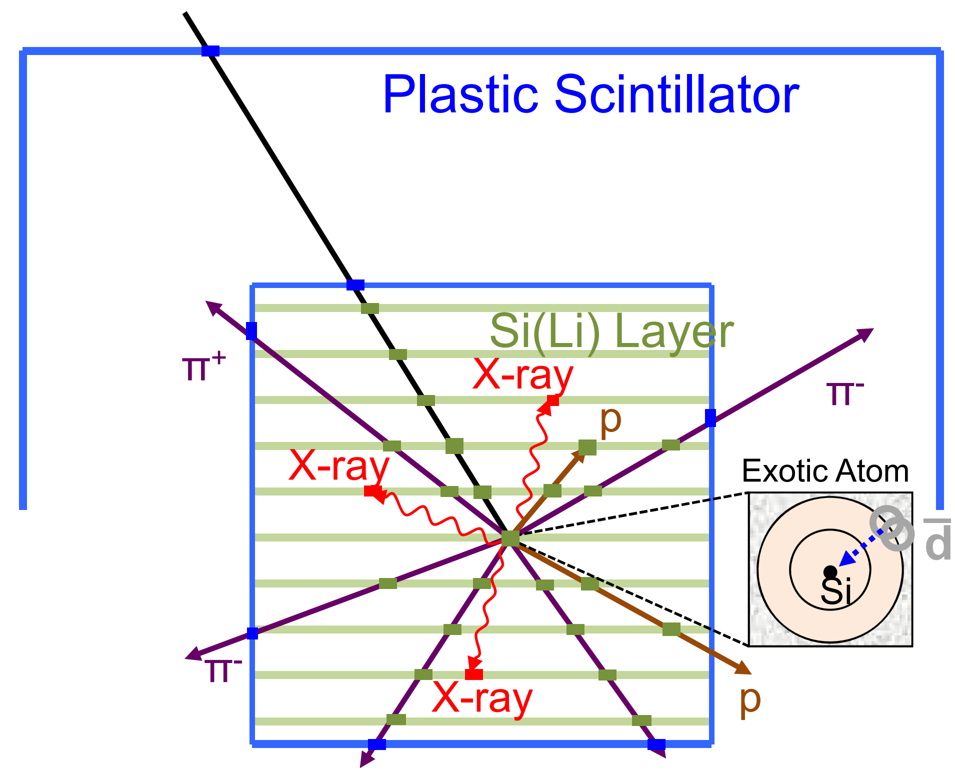
2008
- Proton multiplicity

2009
- dE/dX

2012
- pGAPS flight
- Start Si(Li) fabrication

2013
- **$\bar{p}$ for light DM search**





GAPS science summary

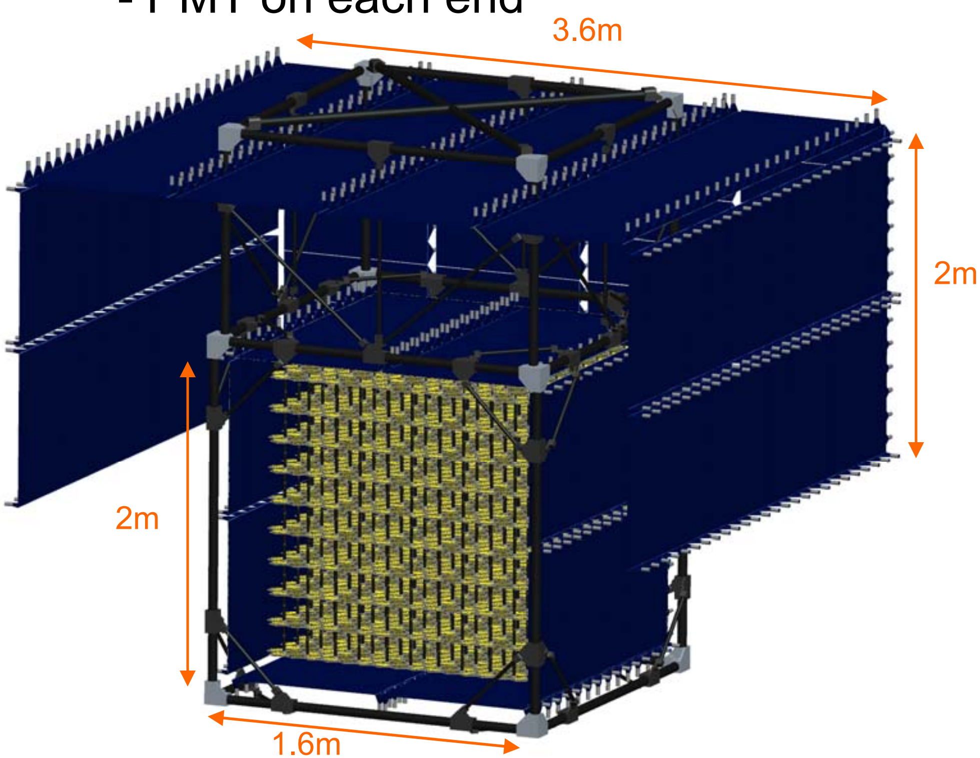
- ***Antideuterons*** as DM signatures
    - **no astrophysical background** at low energy
    - **complementary** to direct/indirect searches and collider experiments
    - search for: **light DM**, heavy DM, gravitino DM,
      LZP in extra-dimensions theories, (evaporating PBH)
- ***Antiprotons*** 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**, gravitino DM,
      LZP in extra-dimensions theories, evaporating PBH
- ***Expected to launch from Antarctica in 2018/2019***

> **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 $E \sim 0.25$ GeV
>
> **2 LDB flights** (~70 days) -> **improved antideuteron statistics**
>
> Antideuteron sensitivity: ~3.0×10^{-6} $[m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}]$ *at* $E < 0.25$ GeV
>
> **3 LDB flights** (~105 days) -> **comparable to AMS-02 (5 year)**
>
> Antideuteron sensitivity: ~2.0×10^{-6} $[m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/n)^{-1}]$ *at* $E < 0.25$ GeV

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 ps timing 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

GAPS can help elucidate light DM models

DAMA, CoGeNT, CDMS-II-Si vs. XENON100, LUX

- **Isospin-violating scenario**

  suppress DM-target interaction cross-section
- **Halo-independent analysis**

  mass-dependent v_{min} limit due to low energy threshold

➢ not completely ruled out by XENON100 and LUX

➢ GAPS offers an approach complementary to direct detection for constraining light DM models

isospin-conserving

halo-dependent

isospin-violating

halo-independent, m_{DM} = 7 GeV

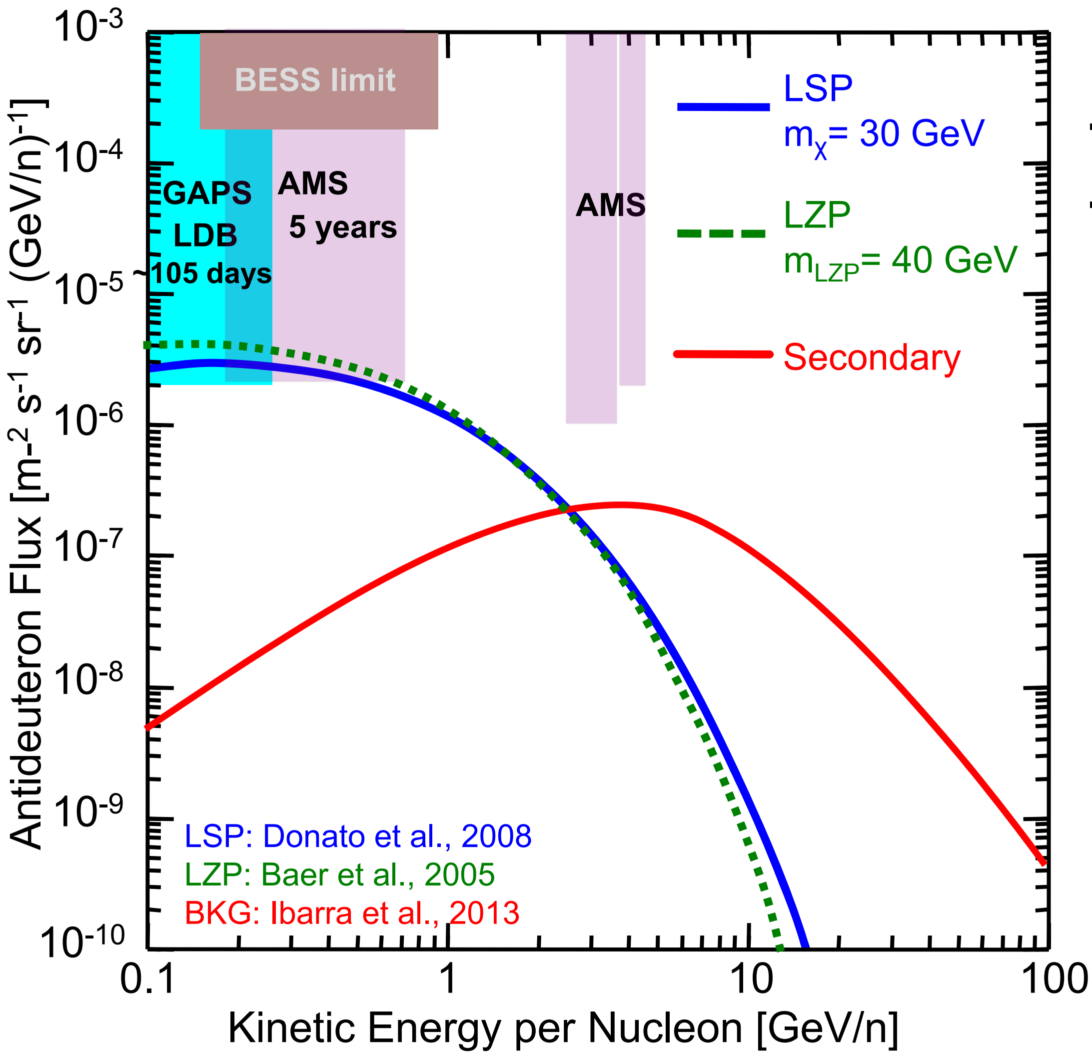
isospin-conserving

isospin-violating

Nobile et al., 2013

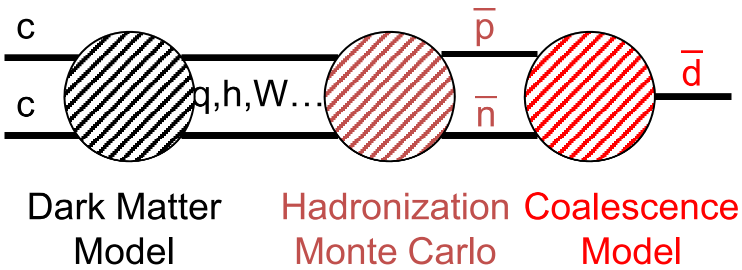
Antideuterons provide clean DM signatures

Background free at low energy!



Primary component

Neutralino annihilation



$$\Phi_{\bar{d}} \propto \langle \sigma v \rangle_{\text{ann}} \left(\frac{\rho_{DM}}{M_{DM}} \right)^2$$

$$\otimes (\text{coalescence } p_0)^3$$

$$\otimes \text{ propagation}$$

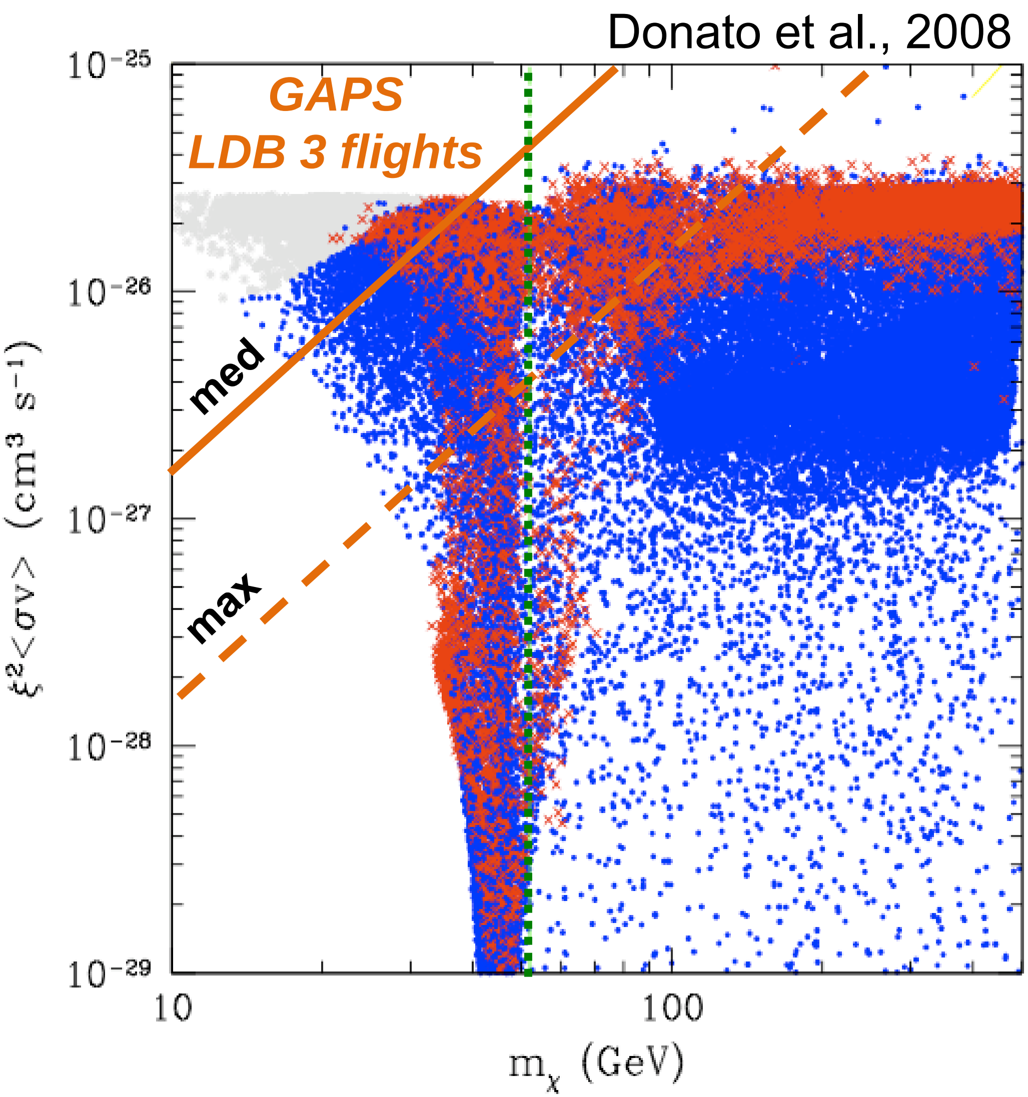
Secondary component

Cosmic ray interactions

p (CR) +H/He (ISM)
→ p + H/He + p + n + $\underbrace{\bar{p} + \bar{n}}_{\bar{d}}$

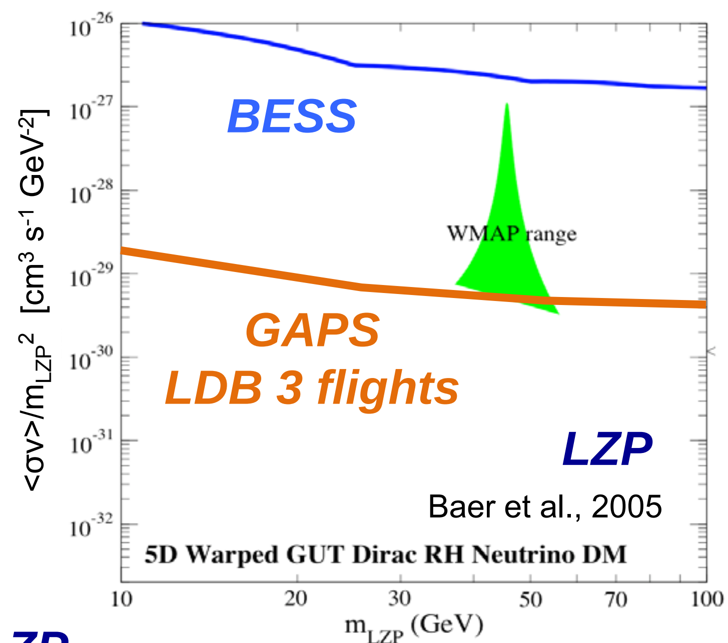
$\bar{p}$ (CR) +H/He (ISM)
→ H/He + n + $\underbrace{\bar{p} + \bar{n}}_{\bar{d}}$

GAPS can access the light DM parameter space



Light DM

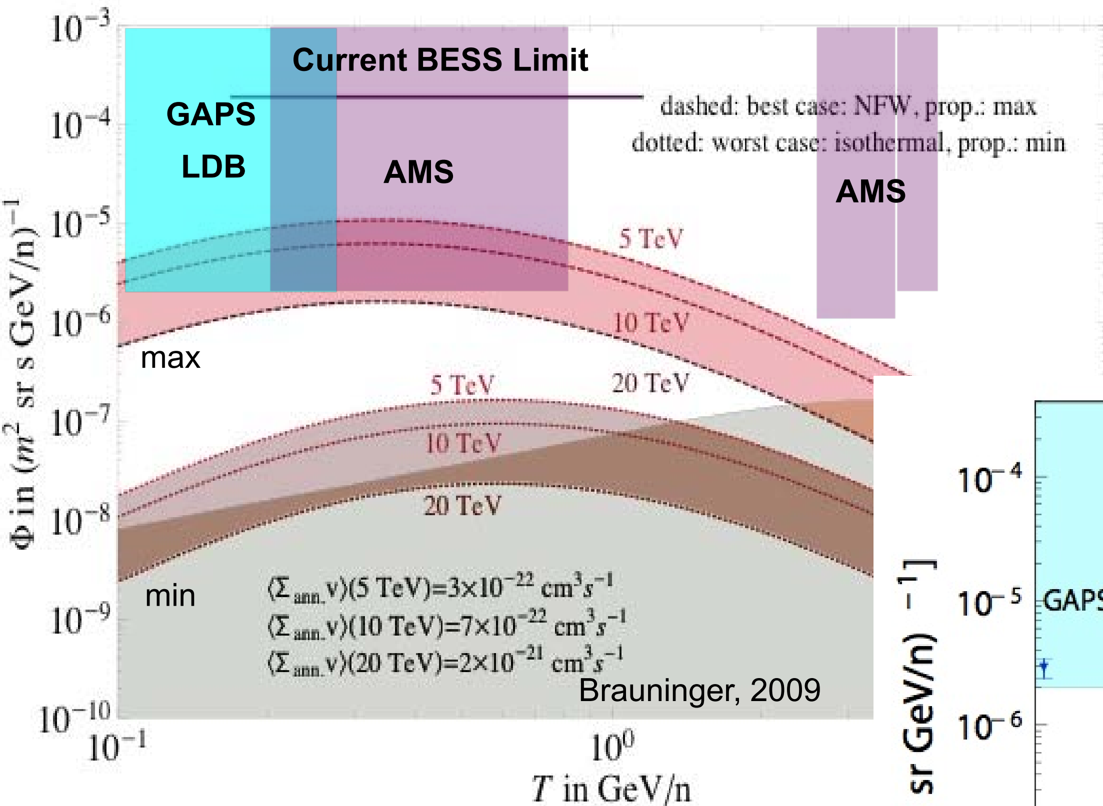
- non-universal gaugino model
- m_χ can be as low as 10 GeV/c^2
- Dominant/Sub-dominant DM



LZP

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

GAPS antideuteron search also probes gravitino DM and heavy DM models

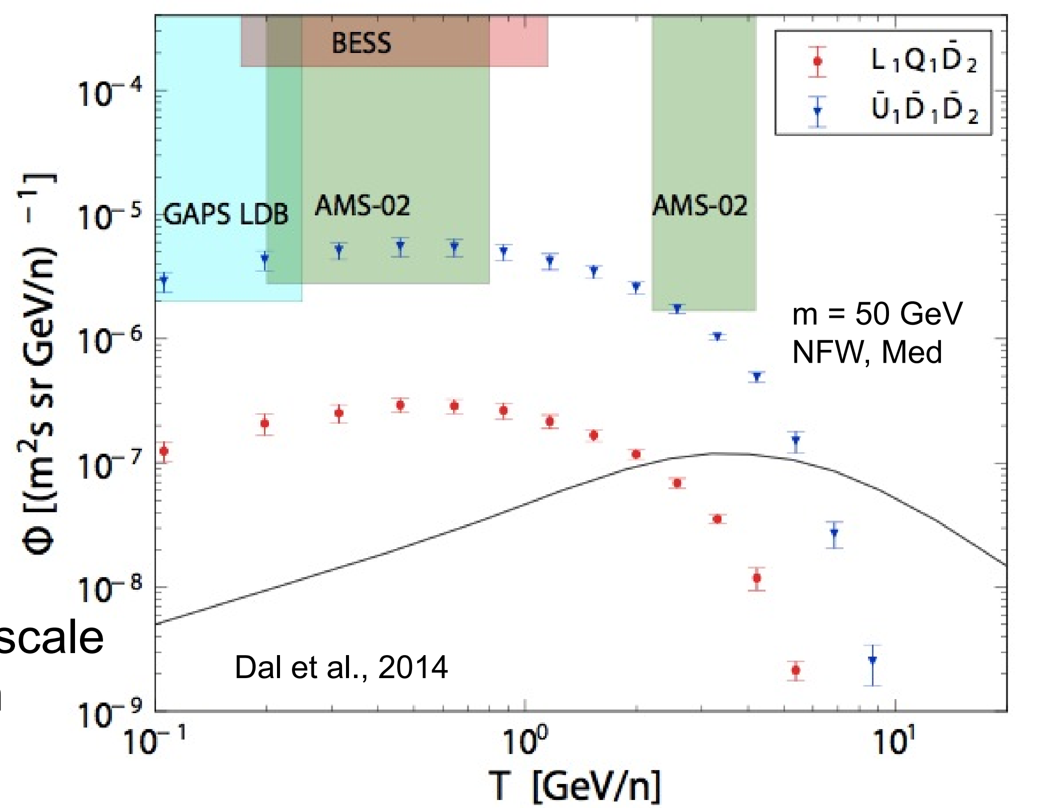


Heavy DM in Minimal DM Model

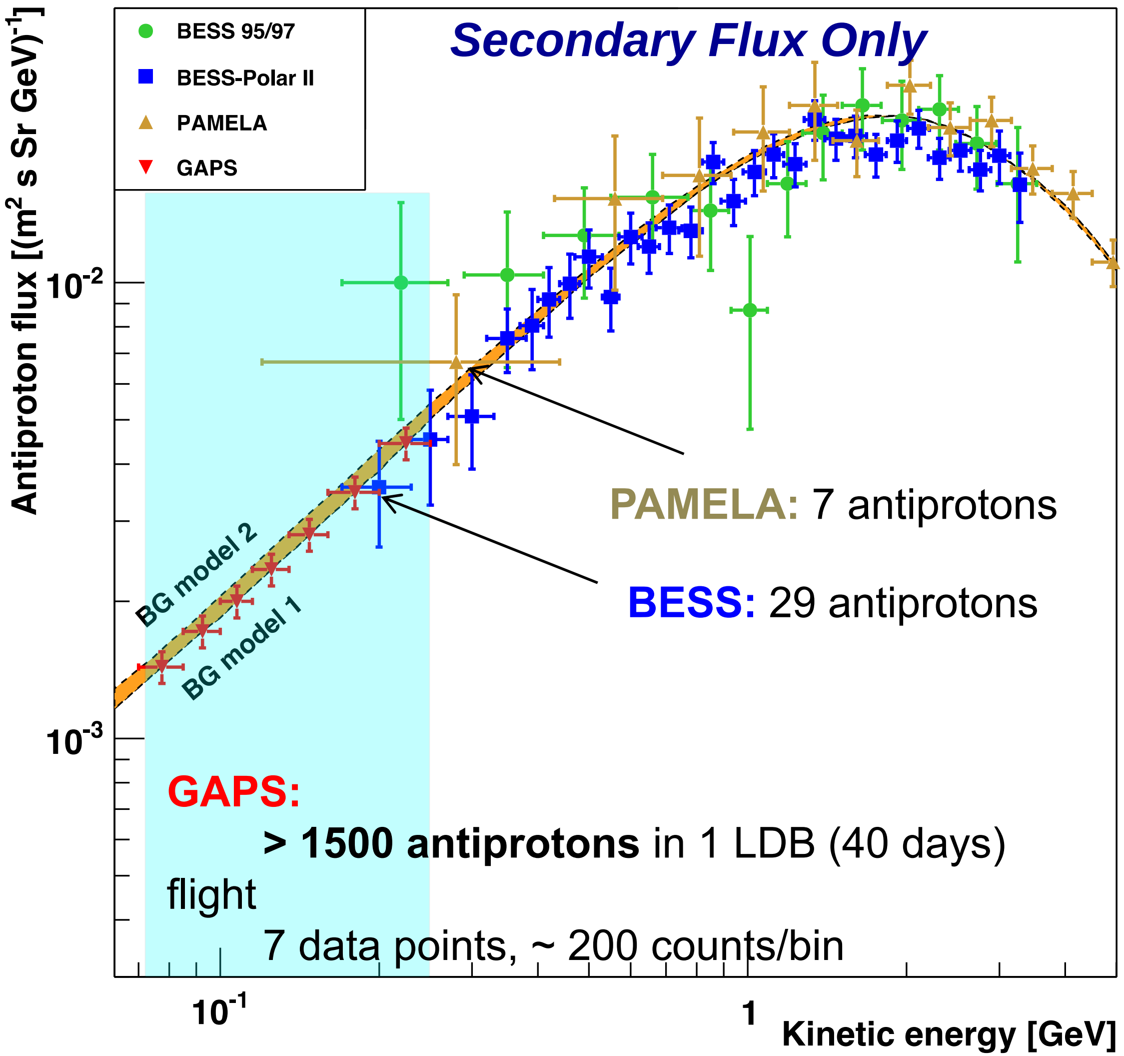
- large <σv> by Sommerfeld effect
- can explain PAMELA e^+ fraction

gravitino DM decay

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



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



Primary flux

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

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

Secondary flux

- constrained by B/C ratio

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

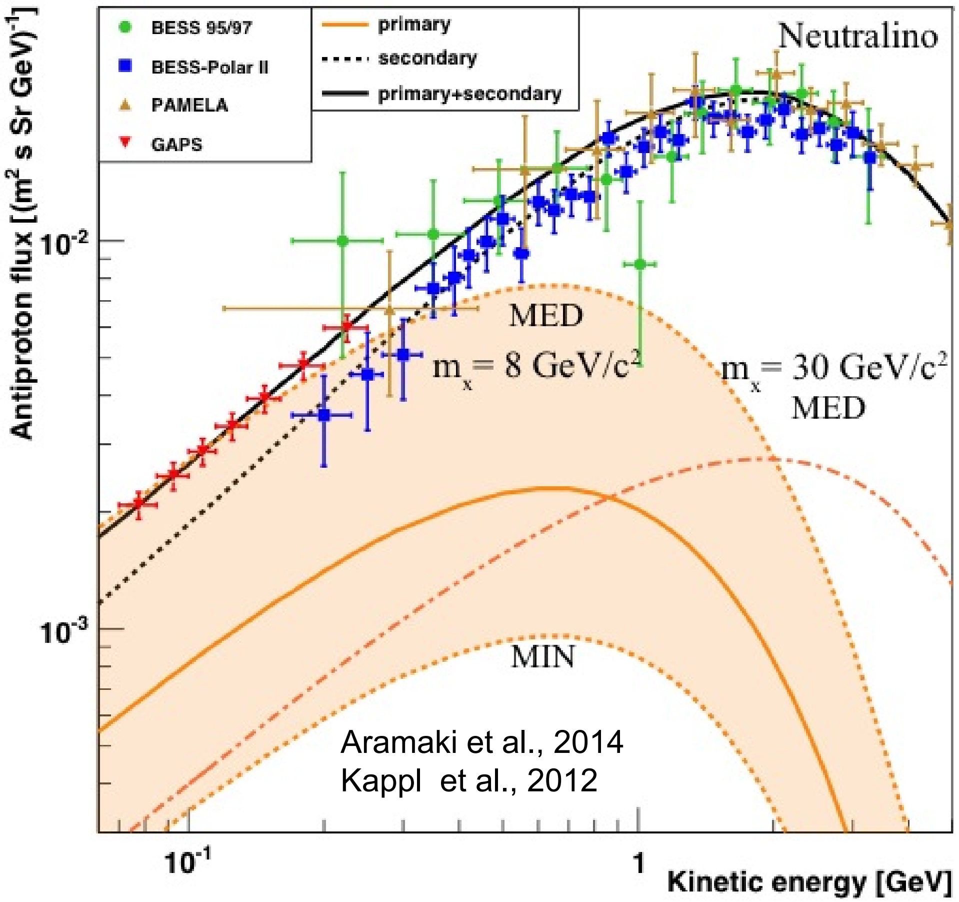
GAPS antiprotons probe light DM and gravitino DM

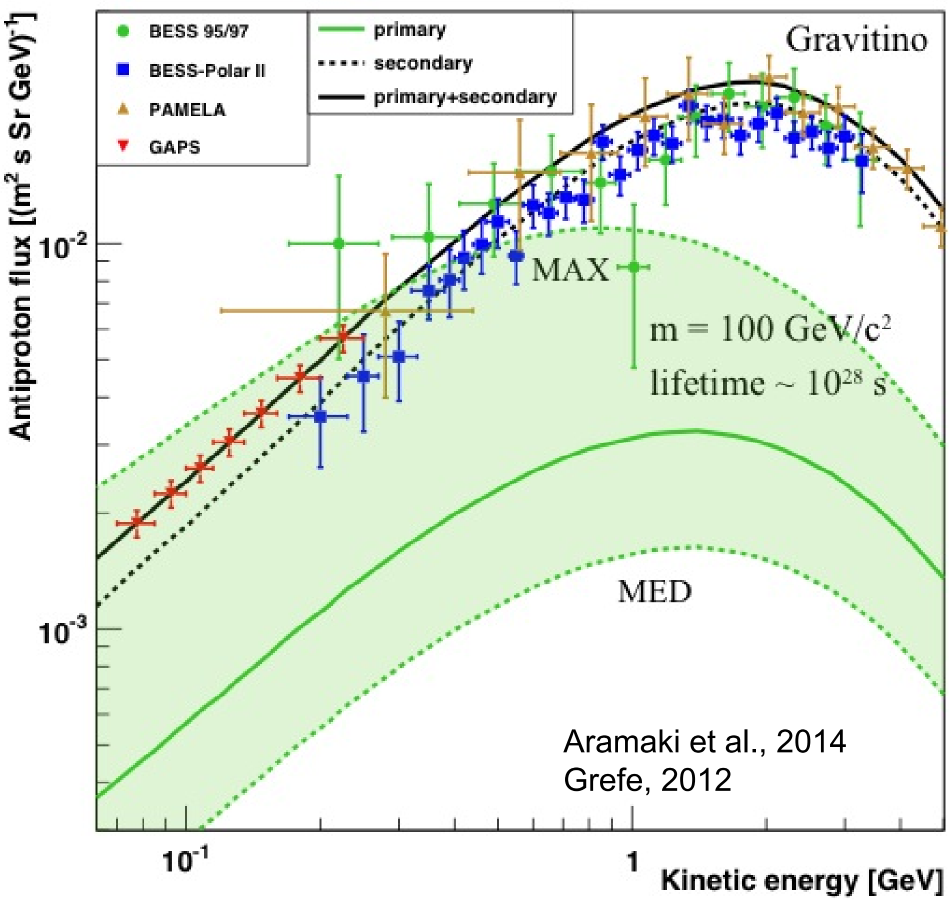
Light DM

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

gravitino DM

- stable in galactic time scale
- small R-parity violation
  - avoid gravitino overproduction





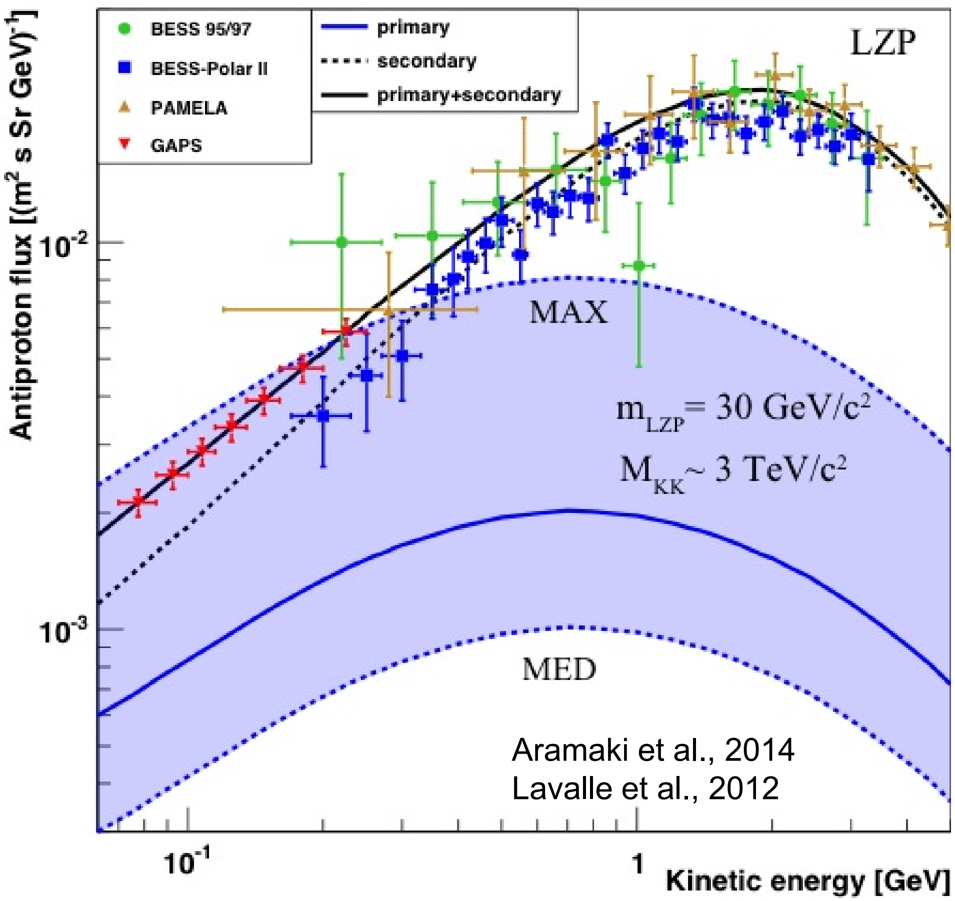
Unique probes for DM in extra-dimensions and evaporating PBHs

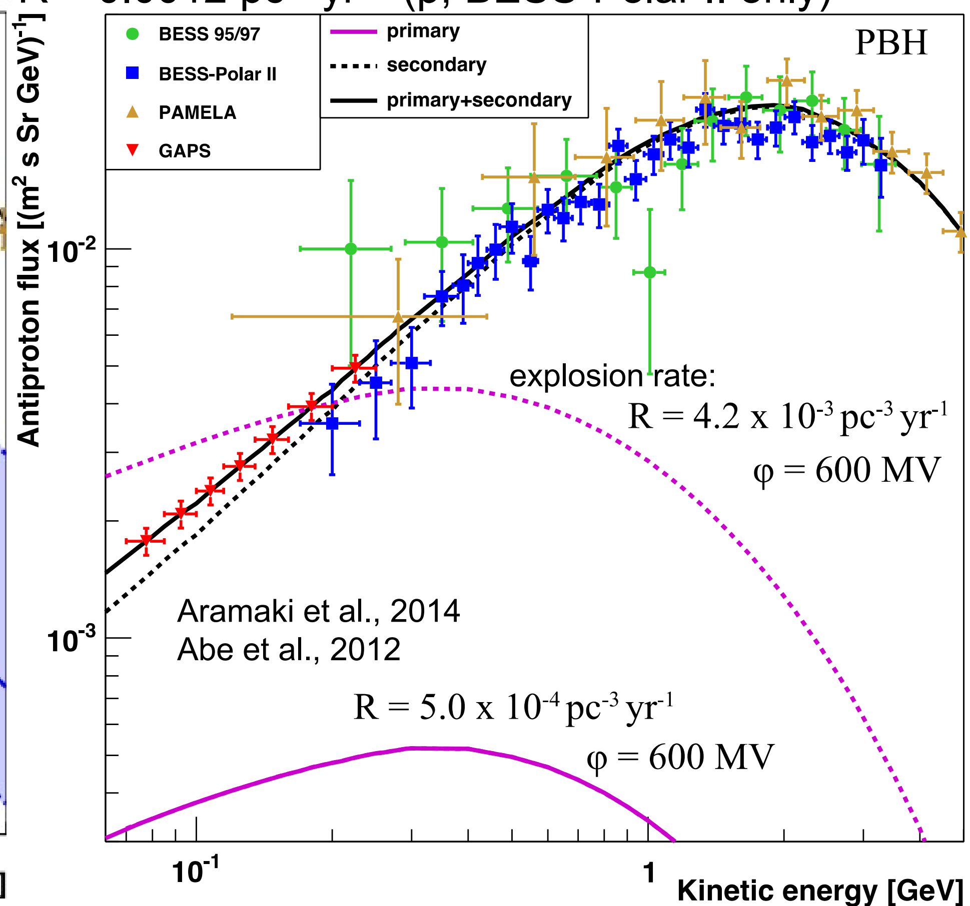
LZP

- 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 < 0.02-0.05 $pc^{-3}\ yr^{-1}$ (γ, Fermi, EGRET)
- R < 0.0012 $pc^{-3}\ yr^{-1}$ (p, BESS-Polar II only)

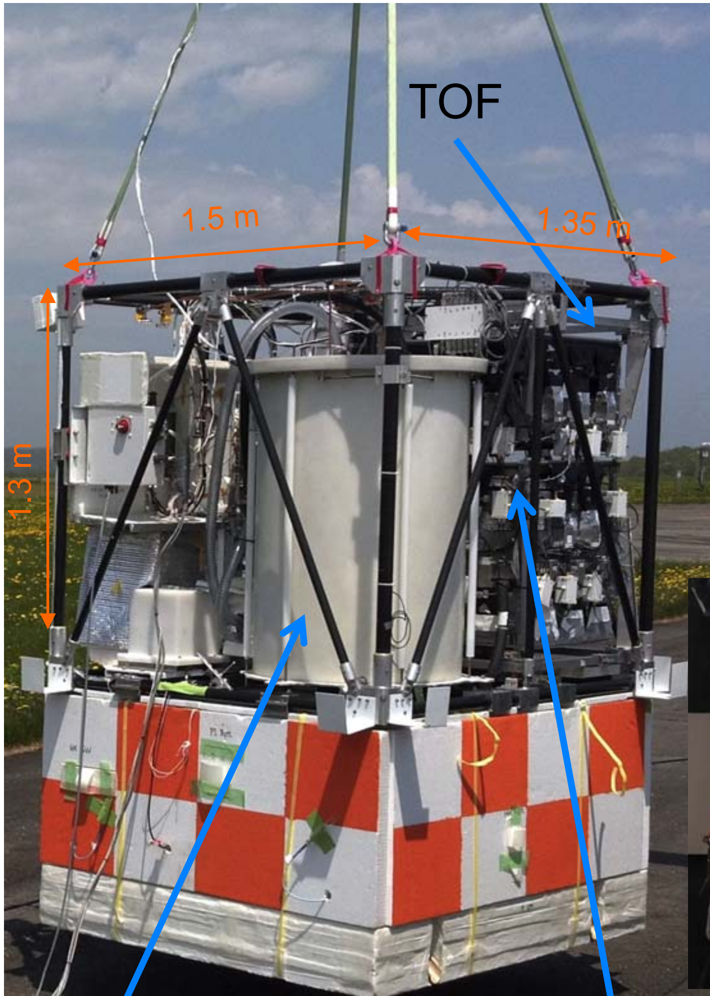




Successful prototype (pGAPS) flight in 2002 @ Taiki, JAXA balloon facility in Japan

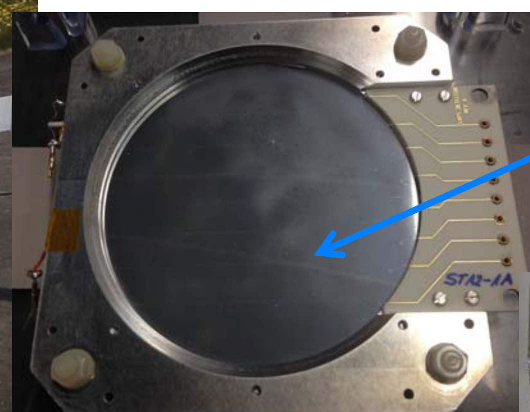
- ✓ First balloon experiment with Si(Li) detectors
- ✓ TOF performance test and measure cosmic-ray proton count rate
- ✓ Demonstrate cooling system

- 6 commercial Si(Li) detectors
- 3 TOF layers, 50cm x 50cm, ~ 50cm separation



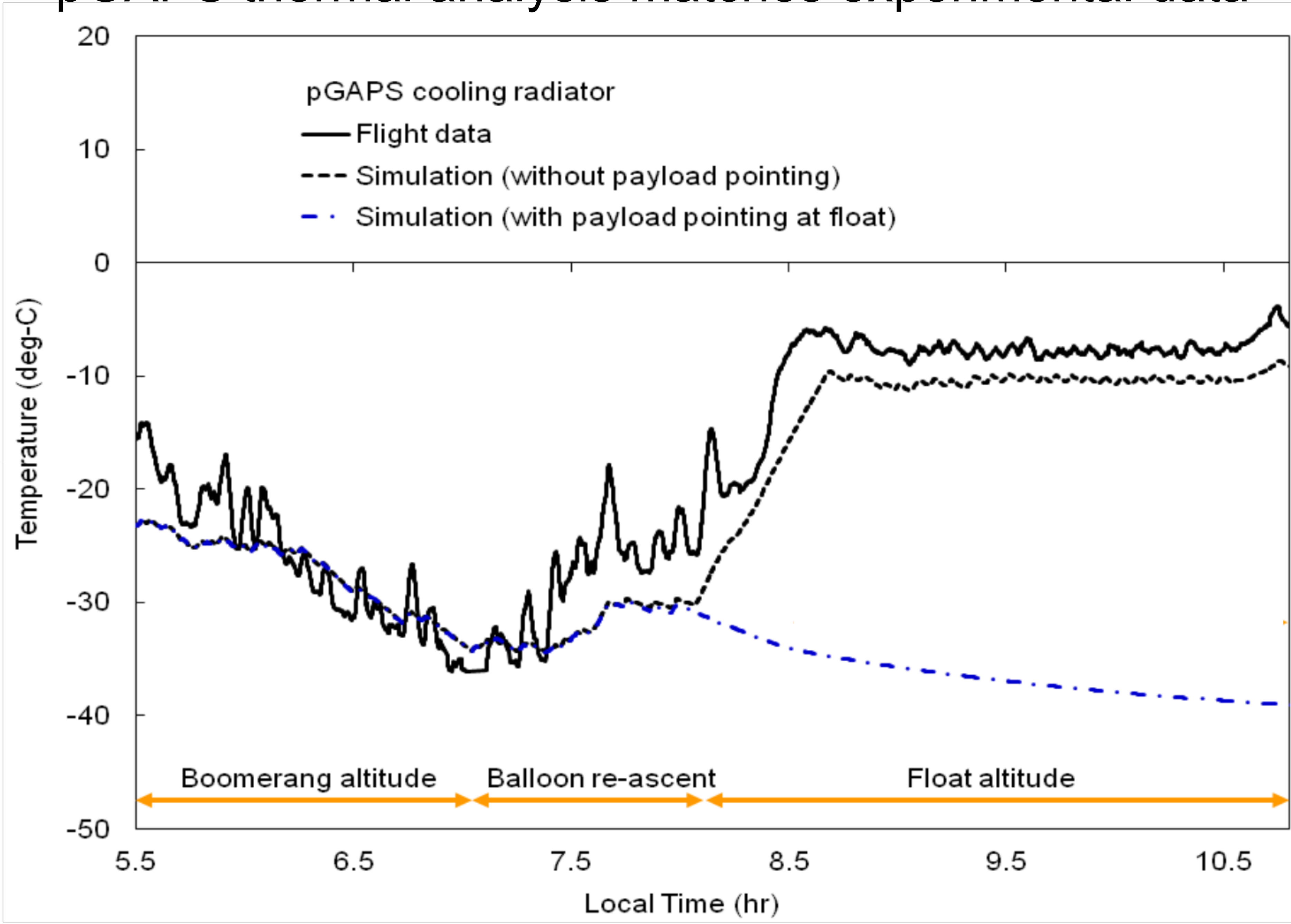
Vessel for DAQ

Si(Li) detector surrounded by TOF

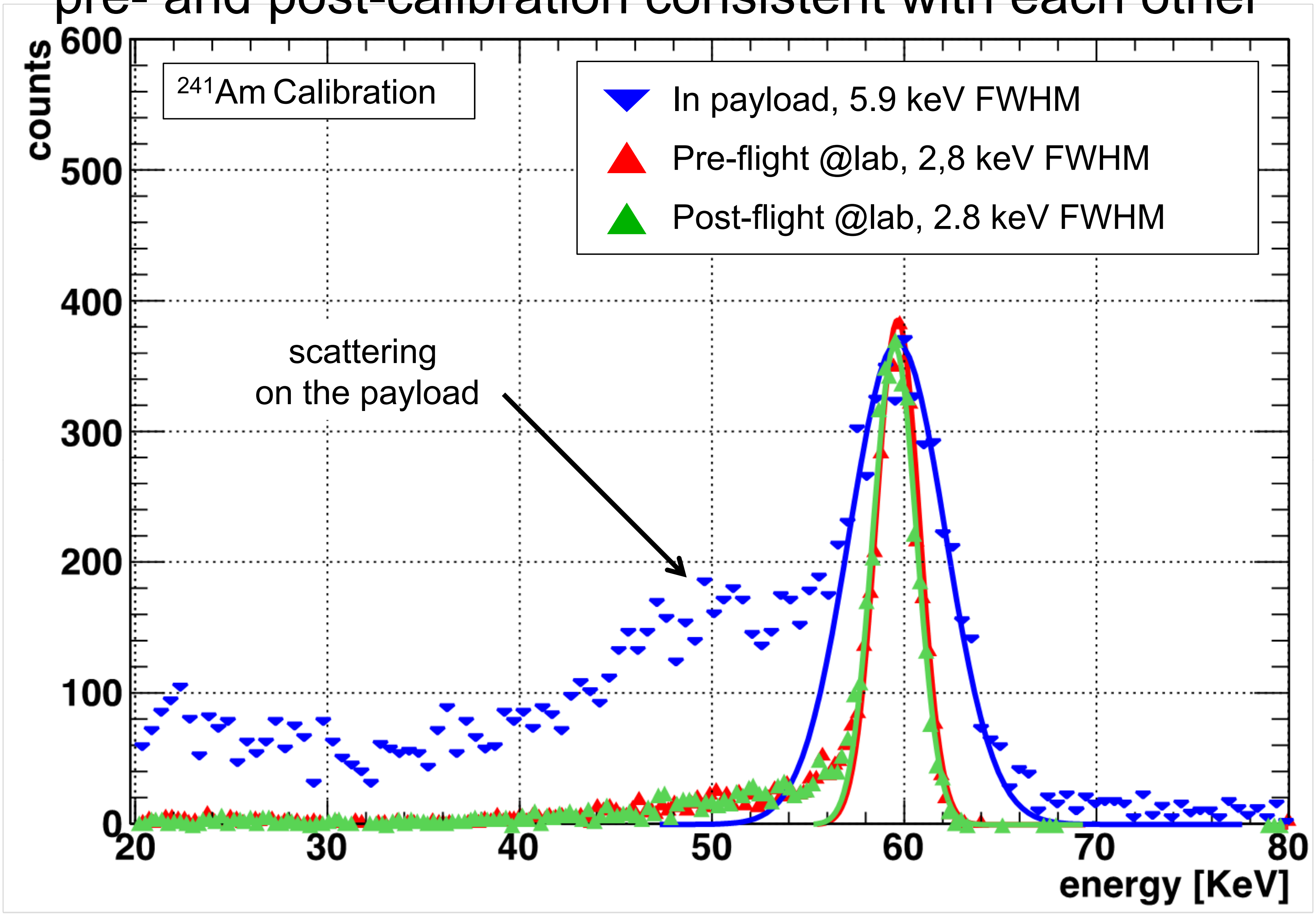


Commercial SEMIKON Si(Li)
4 inch diameter, 2.5mm thick

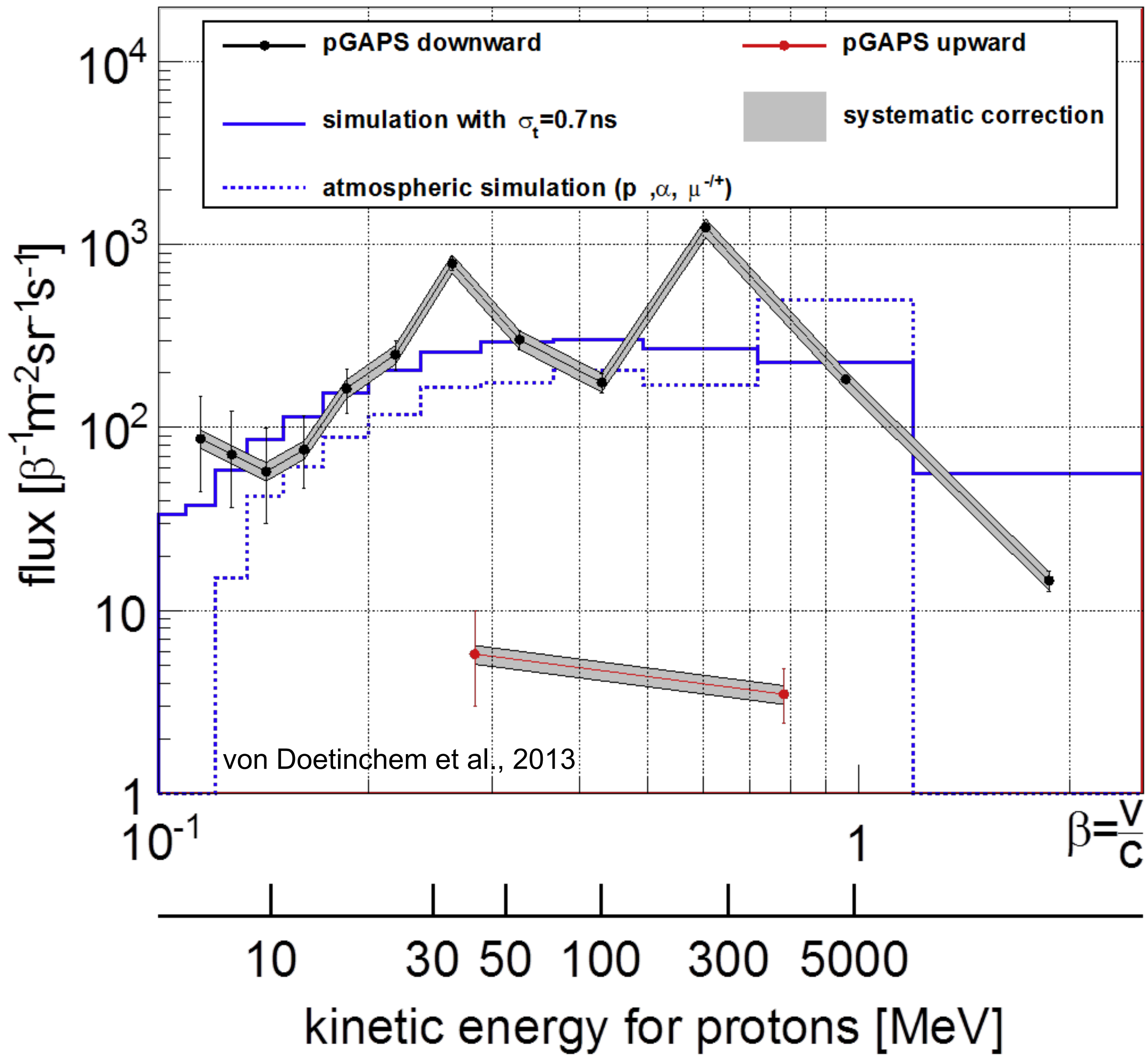
pGAPS thermal analysis matches experimental data



pGAPS Si(Li) Performance
pre- and post-calibration consistent with each other



pGAPS cosmic-ray count rate in good agreement with simulation results



Ready for Si(Li) mass production

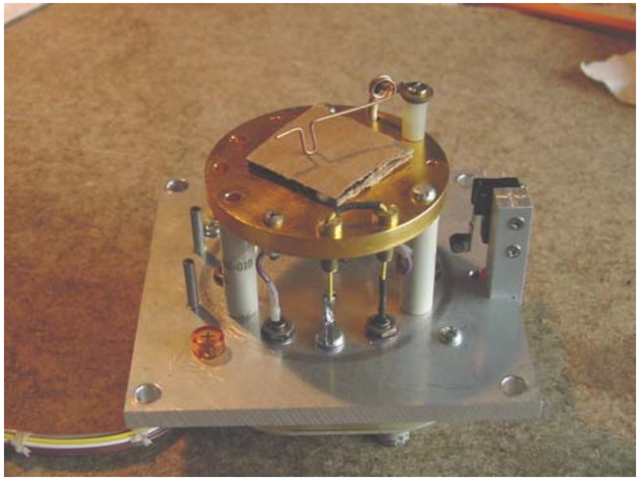
Si(Li) fabrication

- 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



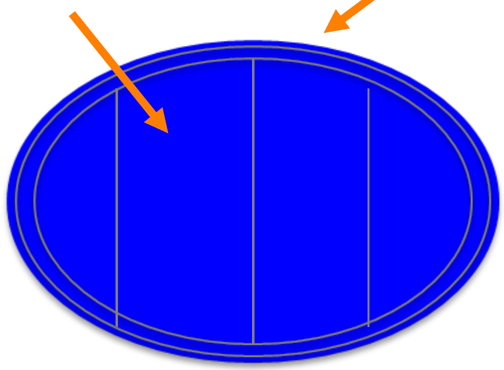
Li drifting station

Li evaporator

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

Structured n^+ contact (4 strips)

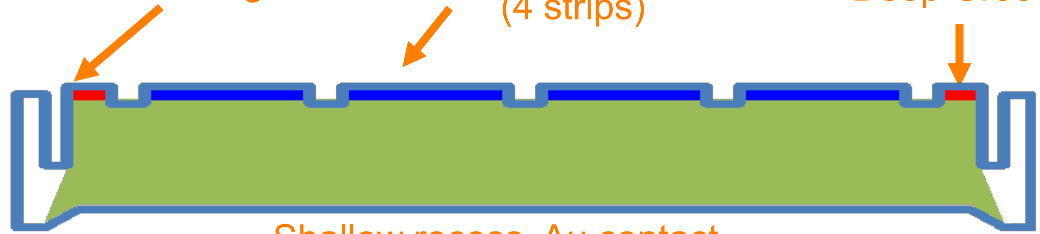
4 inch diameter 2.5mm thick



Guard Ring

Structured n^+-contact: Li (4 strips)

Deep Groove

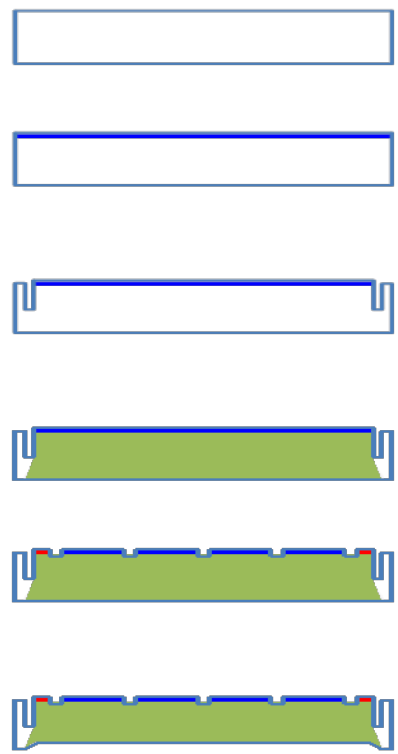


Shallow recess, Au contact

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

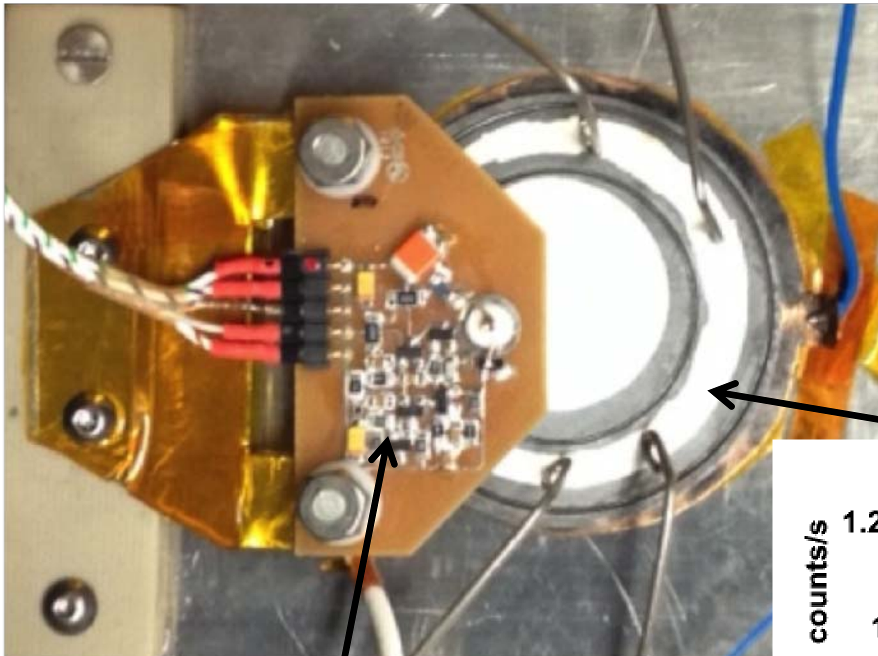
Produce the deep groove and mesa (optional)

Drift the Li into the silicon

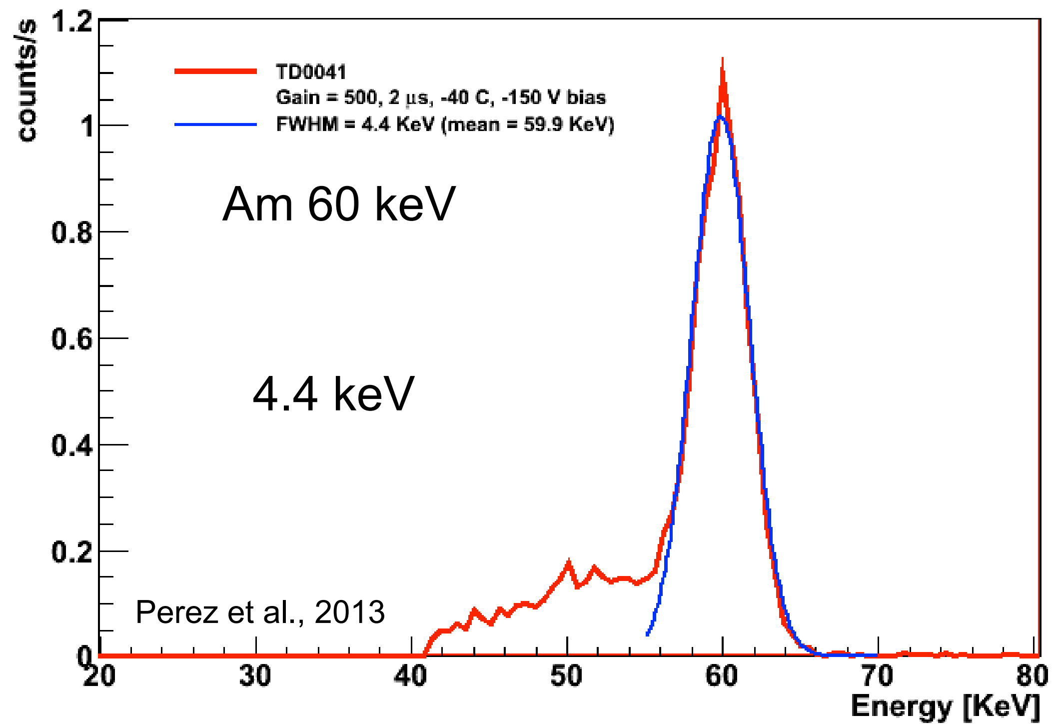
Make strips and guard ring

Etch the back (shallow recess) and evaporate Au

Homemade Si(Li) performance test



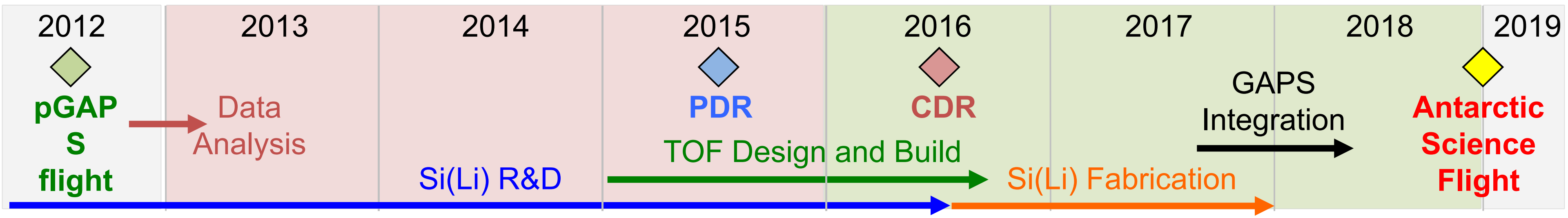
2 inch diameter homemade Si(Li)
- in vacuum chamber
  - reproduce flight environment
  - cooled down by LN2
- with flight candidate preamp



Upgrade with
better electric contacts
more uniform Li-drifting

-> **3 keV** energy resolution

Development Plan



C.J. Hailey (PI), T. Aramaki, N. Madden, K. Mori, K. Perez

Columbia University

R.A. Ong, S.A.I Mognet, J. Zweerink

University of California, Los Angeles

S.E. Boggs

University of California, Berkeley

P. von Doetinchem

University of Hawaii, Honolulu

H. Fuke, S. Okazaki, T. Yoshida

Institute of Space & Astronautical Science, Japan Aerospace Exploration Agency

ORNL

L. Fabris, K.P. Ziock

Oak Ridge National Laboratory

F. Gahbauer

University of Latvia