Development of the GAPS Experiment for Cosmic-ray Antinuclei Measurements

Fifth Joint Meeting of the DNP and the JPS
October 2018

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on behalf of the GAPS collaboration

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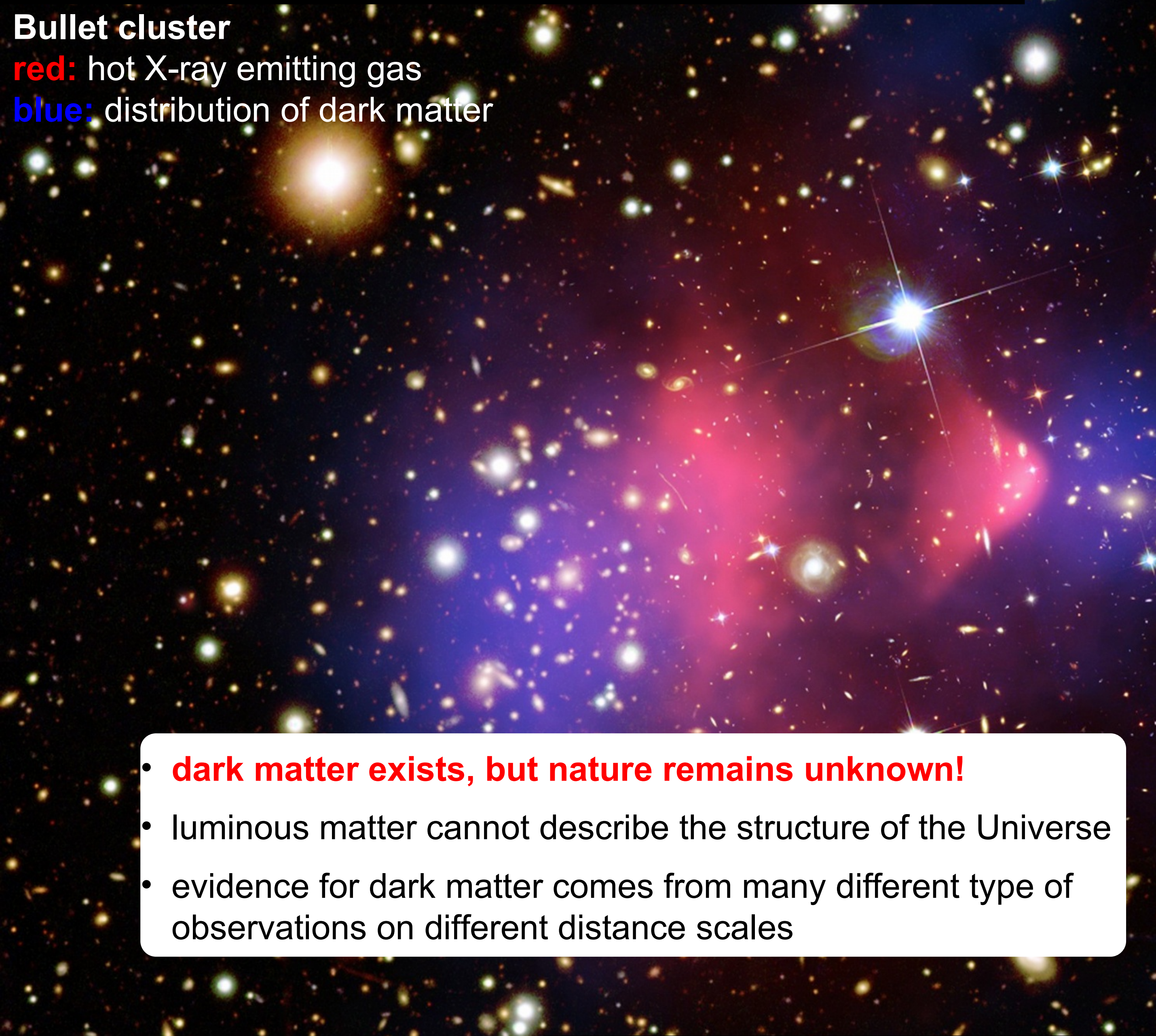
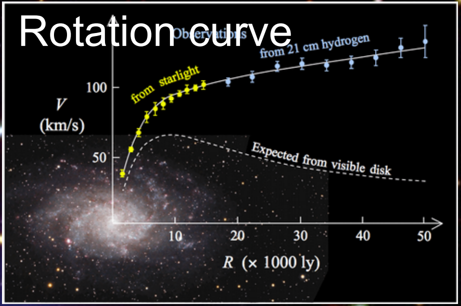
Evidence for dark matter

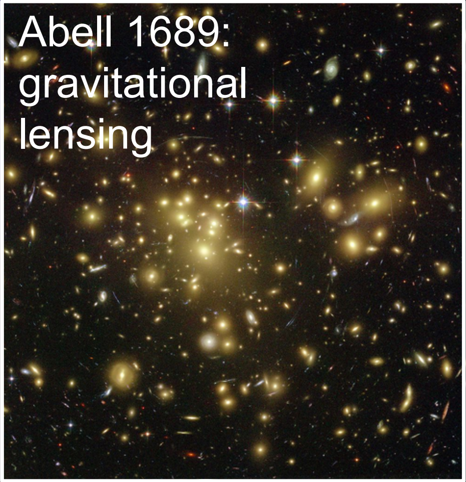
Bullet cluster
red: hot X-ray emitting gas
blue: distribution of dark matter

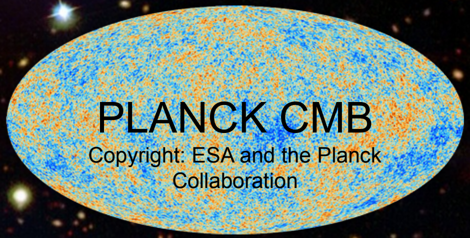


Rotation curve



Abell 1689:
gravitational
lensing



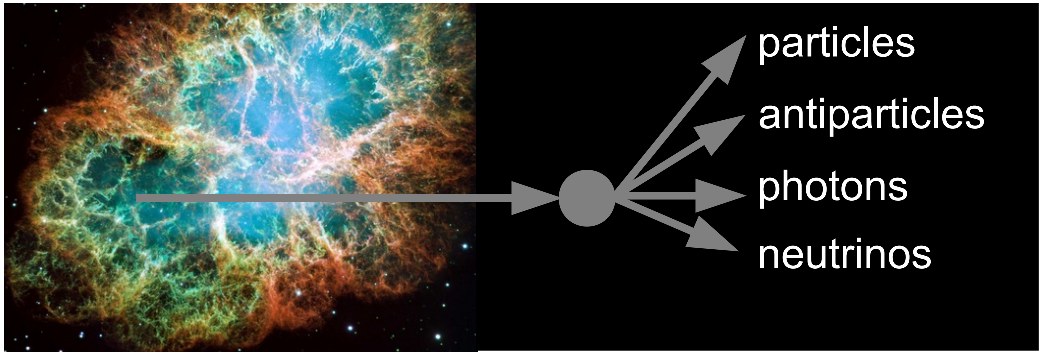


- **dark matter exists, but nature remains unknown!**
- luminous matter cannot describe the structure of the Universe
- evidence for dark matter comes from many different type of observations on different distance scales

Cosmic rays as dark matter messengers

background

conventional cosmic rays

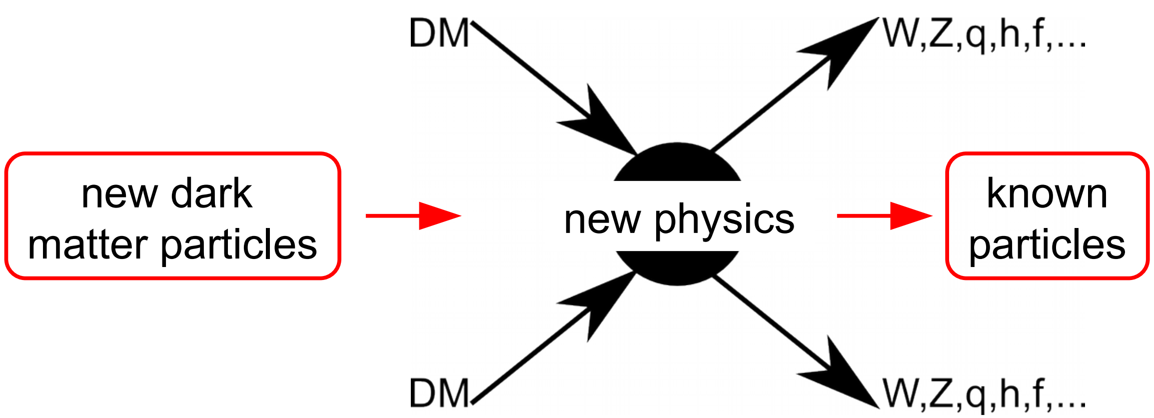


primary cosmic rays
from star explosions

interactions with
interstellar medium

signal

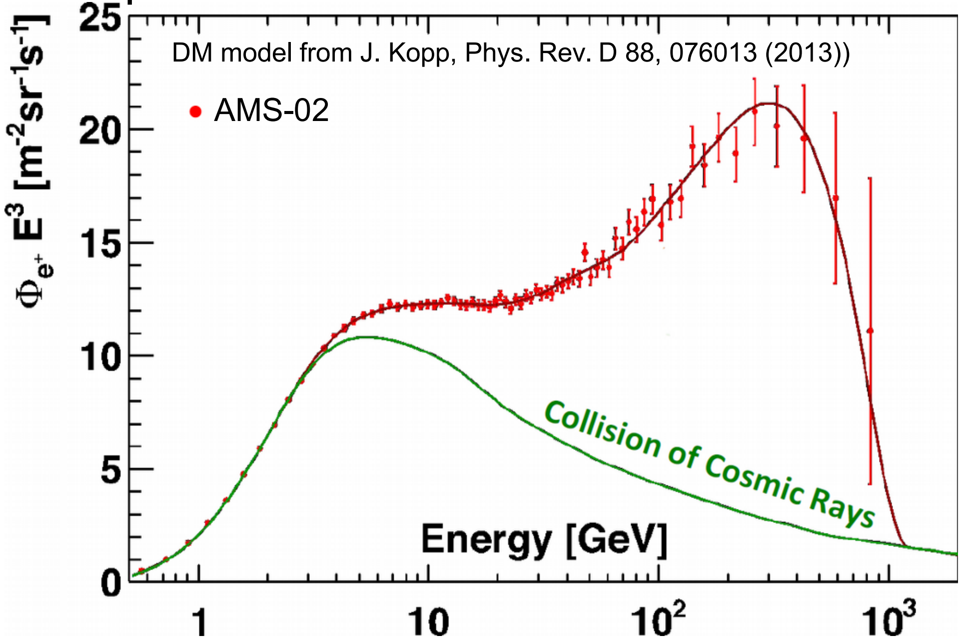
cosmic rays from the annihilation of dark matter



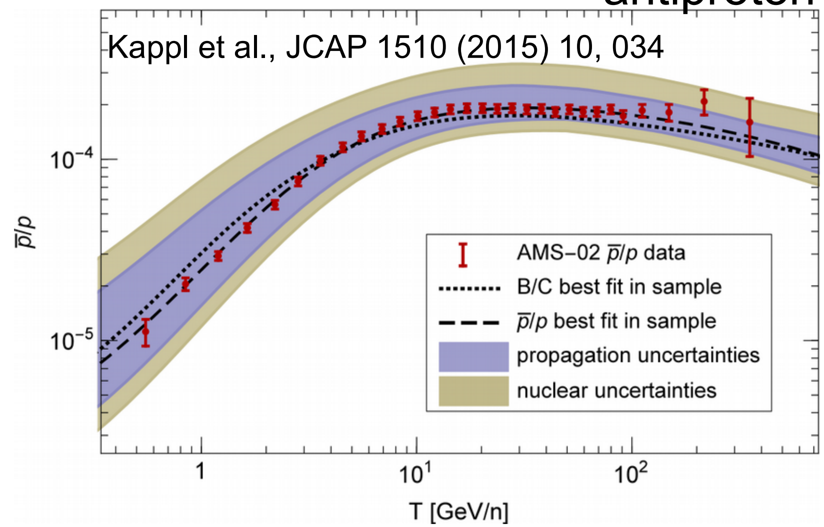
- **assumption:** cosmic-rays from dark matter annihilation follow different kinematics than conventional production
- peak/bump/shoulder on top of conventional spectrum
- use search channel without strong conventional production: e^{+}, γ, $\bar{p}$, ν

Dark matter signal in cosmic rays?

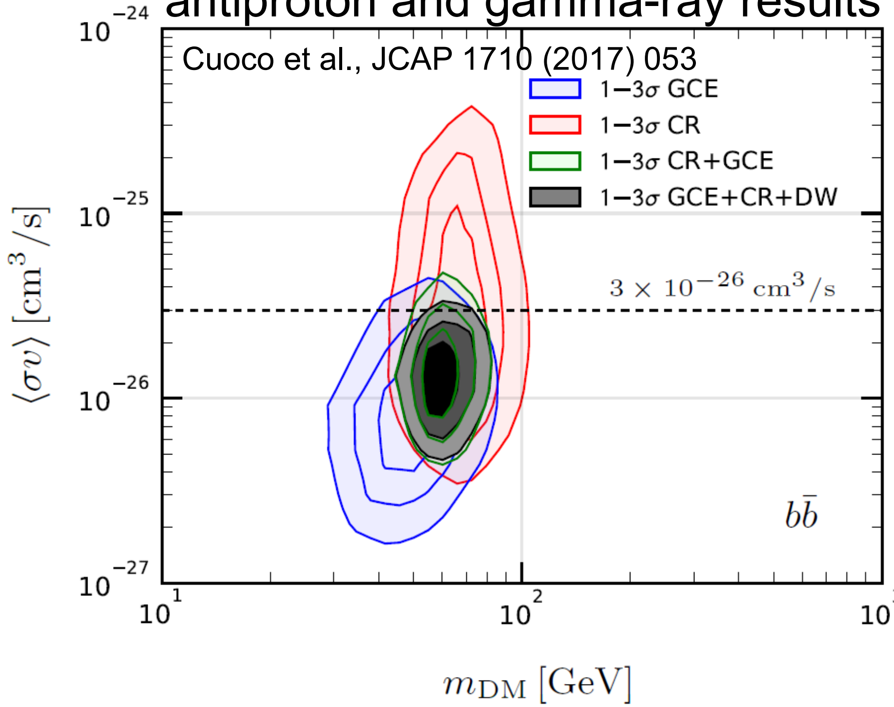
positron



antiproton

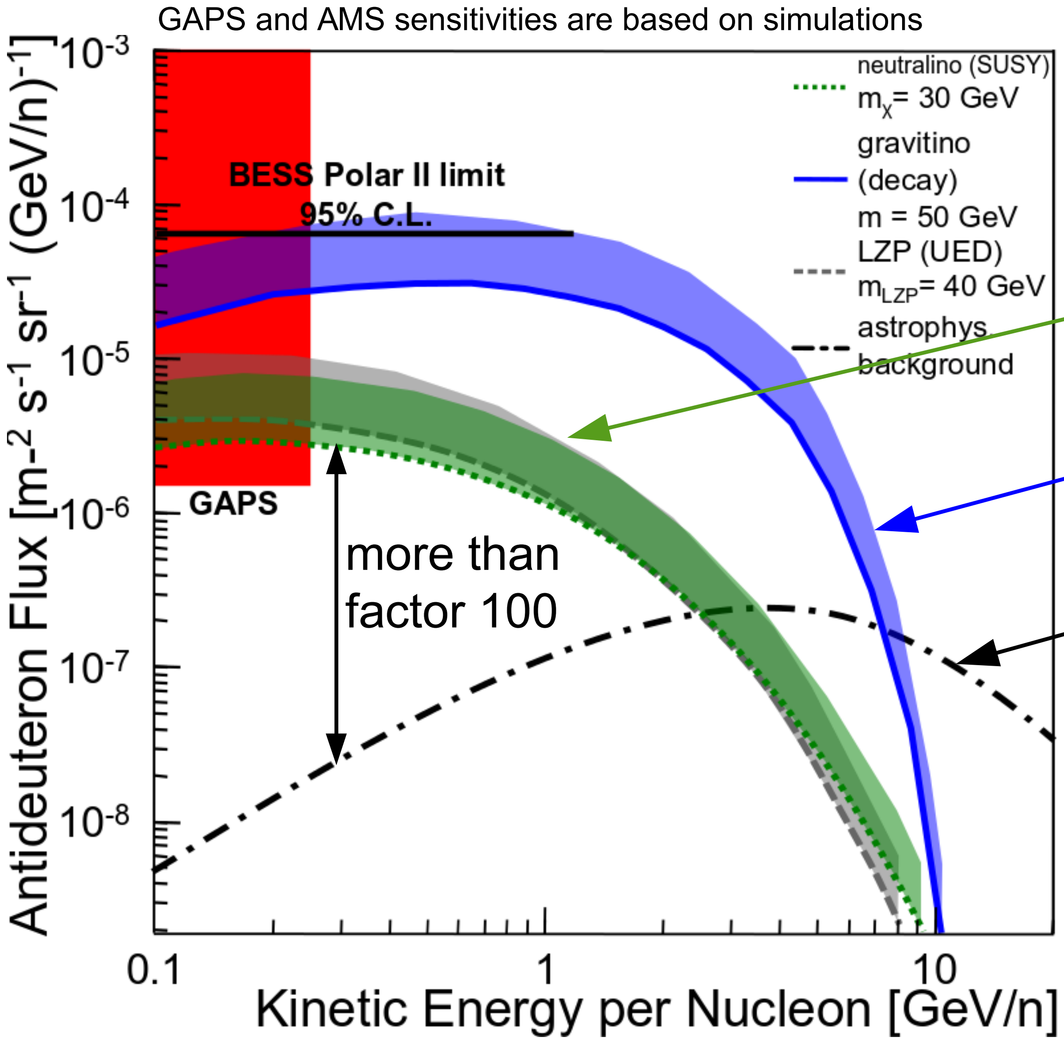


antiproton and gamma-ray results



- unexplained feature in positrons:
  - astrophysical origin → pulsars [HAWC excludes some local pulsars]
  - SNR acceleration
  - **dark matter annihilation**
- combined fit with antiproton and diffuse gamma-rays from the Galactic Center → 80GeV DM particle
- understanding astrophysical background is a challenge
- better constraints on cosmic-ray propagation and astrophysical production are needed

Antideuterons as a probe of dark matter



Examples for beyond-standard-model Physics (compatible with $\bar{p}$):

Neutralino:
SUSY lightest supersymmetric particle, decay into $b\bar{b}$
[Baer & Profumo, JCAP 0512, 008 (2005), Donato et al., Phys. Rev. D78, 043506 (2008)]

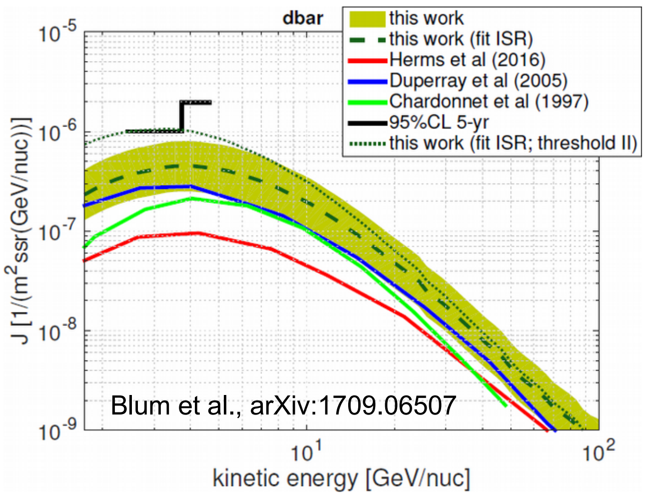
late decays of unstable gravitinos
[Dal & Raklev, Phys. Rev D89, 103504 (2014)]

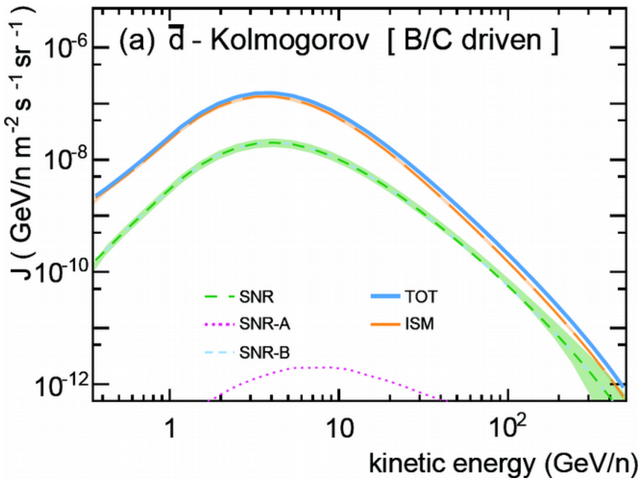
astrophysical background:
collisions of protons and antiprotons with interstellar medium
[Ibarra & Wild, Phys. Rev. D88, 023014 (2013)]

Antideuterons are an important unexplored indirect detection technique!

More antideuteron models

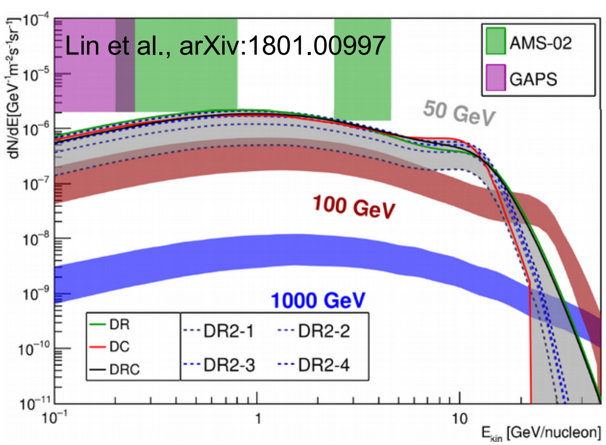
Astrophysical background only:

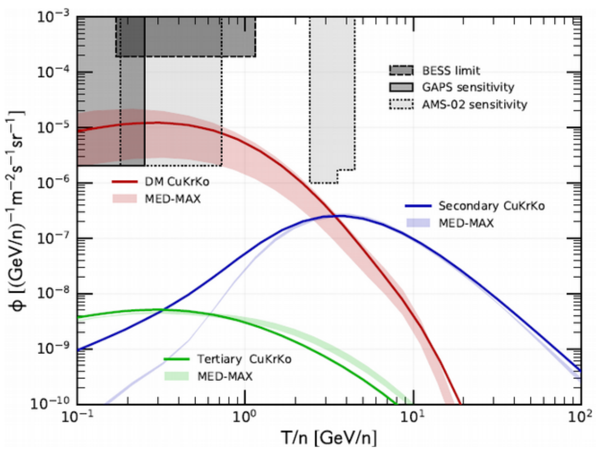




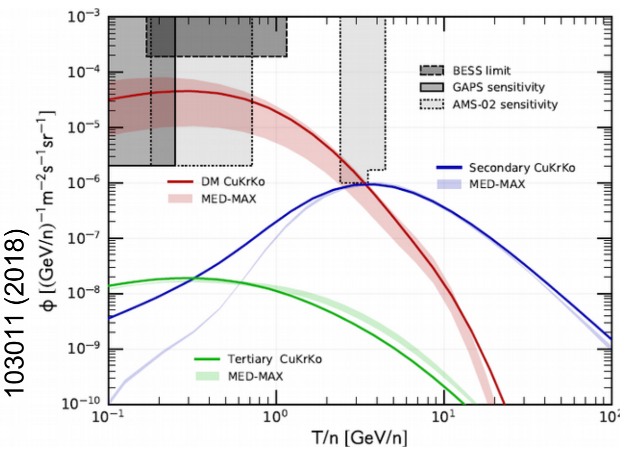
- All antinuclei species have to be explained together
- Report by AMS-02 of antihelium candidates triggered more theoretical work:
  - evaluate propagation effects
  - nuclear modeling

Dark matter annihilation:

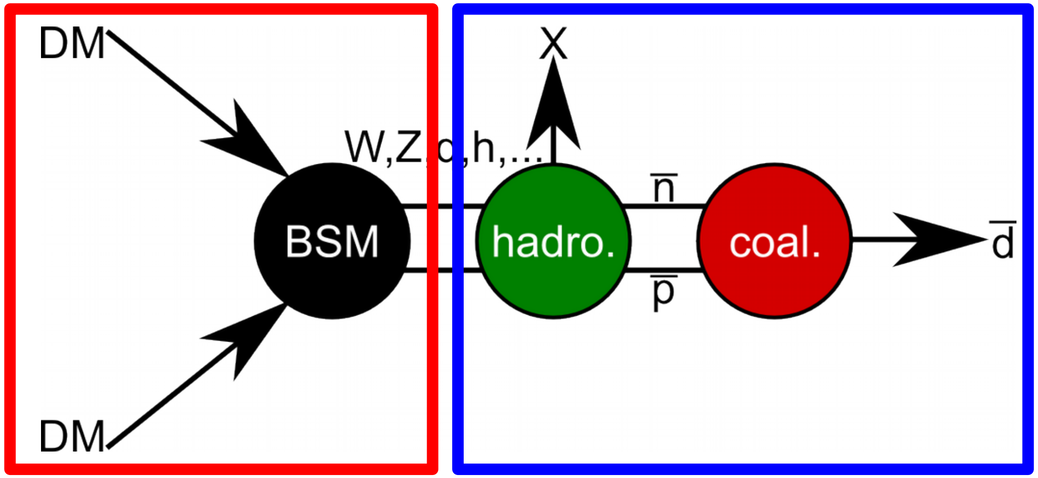




Korsmeier et al., Phys. Rev. D 97, 103011 (2018)

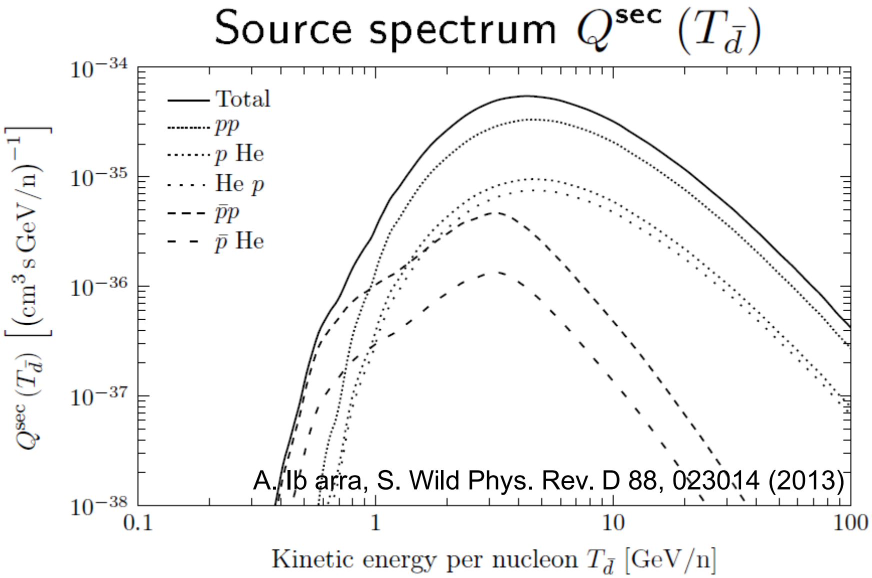


(Anti)deuteron formation



dark matter

conventional production (e.g., p+ISM) & dark matter



- d ($\bar{d}$) can be formed by an p-n ($\bar{p}$-$\bar{n}$) pair if coalescence momentum p_0 is small

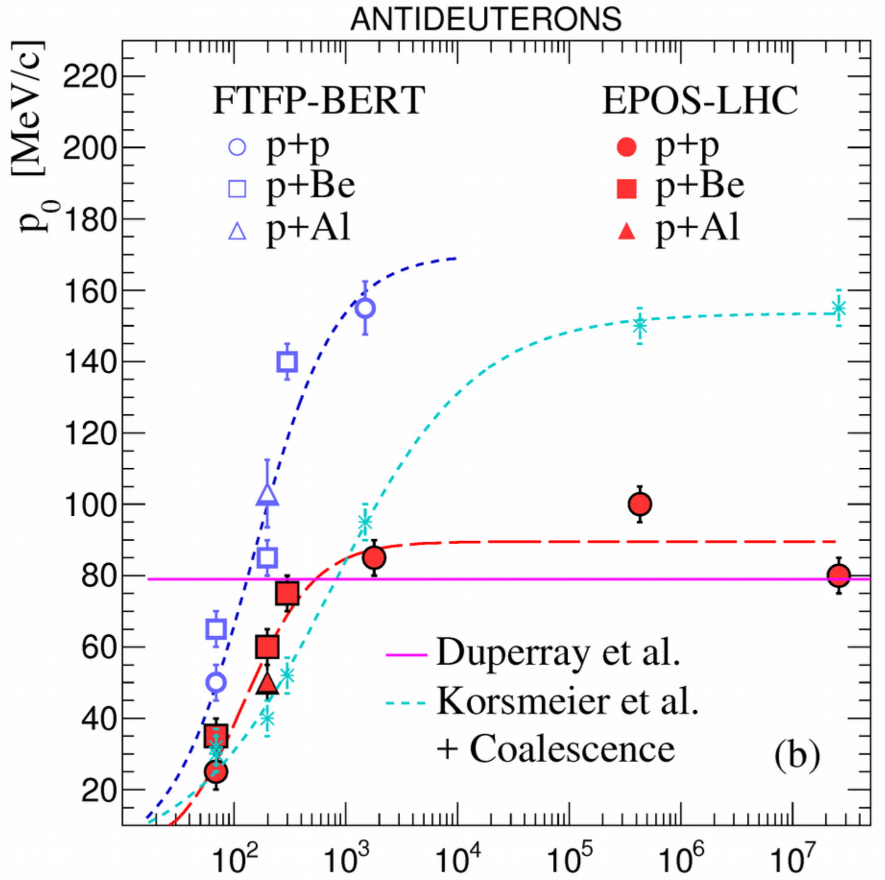
$$\gamma_d \frac{d^3 N_d}{dp_d^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_p \frac{d^3 N_p}{dp_p^3}\right) \left(\gamma_n \frac{d^3 N_n}{dp_n^3}\right)$$

- use an event-by-event coalescence approach with hadronic generators

Schwarzschild &Zupancic, Physical Review 129, 854 (1963)
Ibarra & Wild, Physical Review D88 020314 (2013)
Aramaki et al., Physics Reports 618, 1 (2016)

Issues of the coalescence model

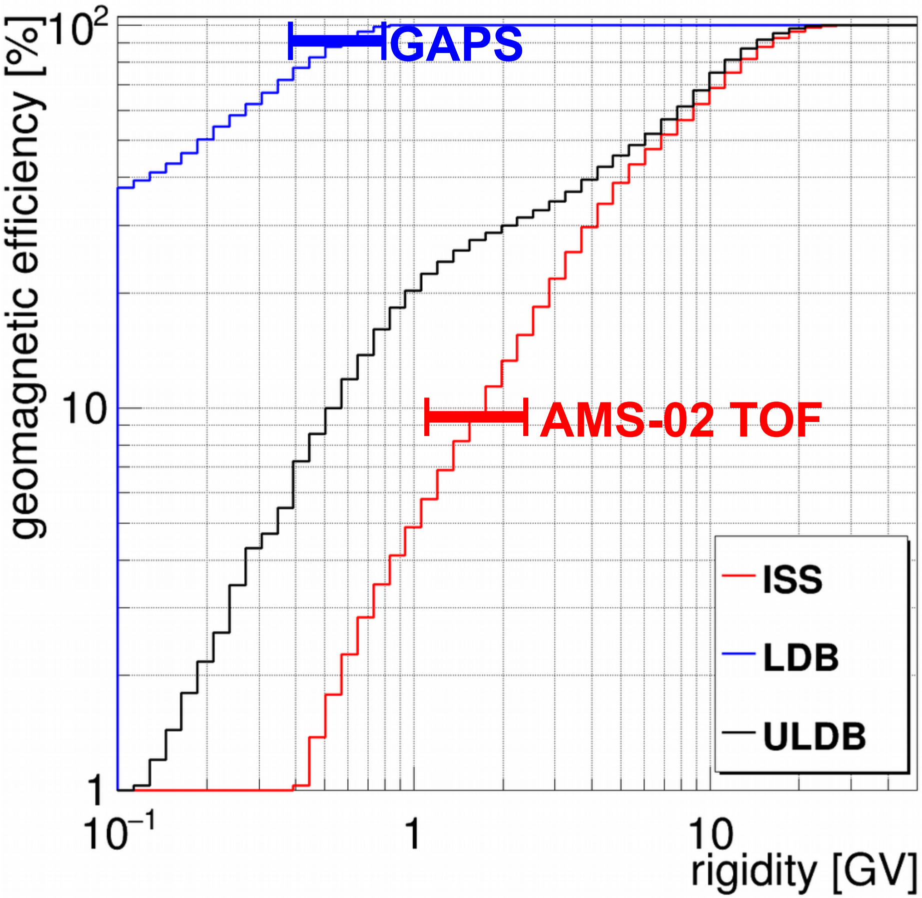
- coalescence uncertainties are about **a factor of 10** on the flux
- coalescence is highly sensitive to two-particle correlations between the participating (anti)nucleons (non-pertubative regime)
- generators not really tuned for antiparticle production
  → tune with antiproton, deuteron, and antideuteron data
  → test antiproton spectra first, antineutron data are hard to come by
- hadronic generators do not include coalescence formation
  → added ”afterburner“

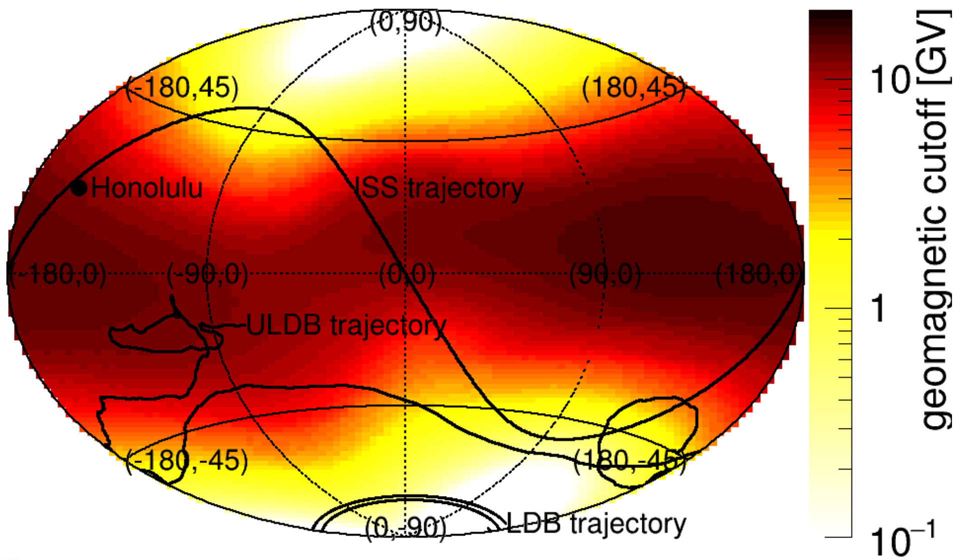


Gomez et al., Phys. Rev. D 98, 023012 (2018)

- compared simulation results to available data sets (p+p, p+A) → best-fit coalescence momentum per data set
- **more high statistics data needed to constrain (anti)deuteron coalescence model**

Geomagnetic efficiency





- Earth's magnetic field deflects charged particles depending on charge and momentum → not every position on orbit sees the same exposure to cosmic rays
- AMS-02 is installed on the ISS (latitude ±52°)

  → understanding of geomagnetic environment crucial for low rigidities

- GAPS is planned to fly from Antarctica (~-80°)
  → geomagnetic corrections are minimal

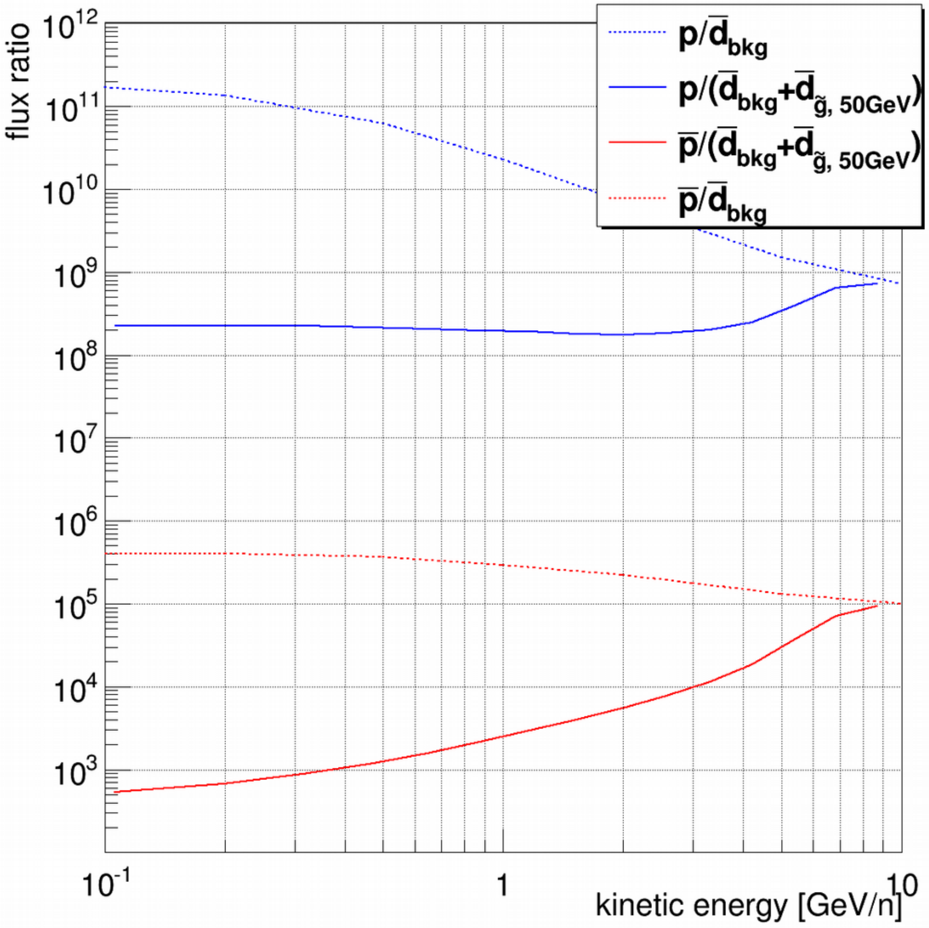
Identification challenge

Required rejections for antideuteron detection:

- **protons**: > 10^8 - 10^{10}
- **He-4**: > 10^7 - 10^9
- **electrons**: > 10^6 - 10^8
- **positrons**: > 10^5 - 10^7
- **antiprotons**: > 10^4 - 10^6

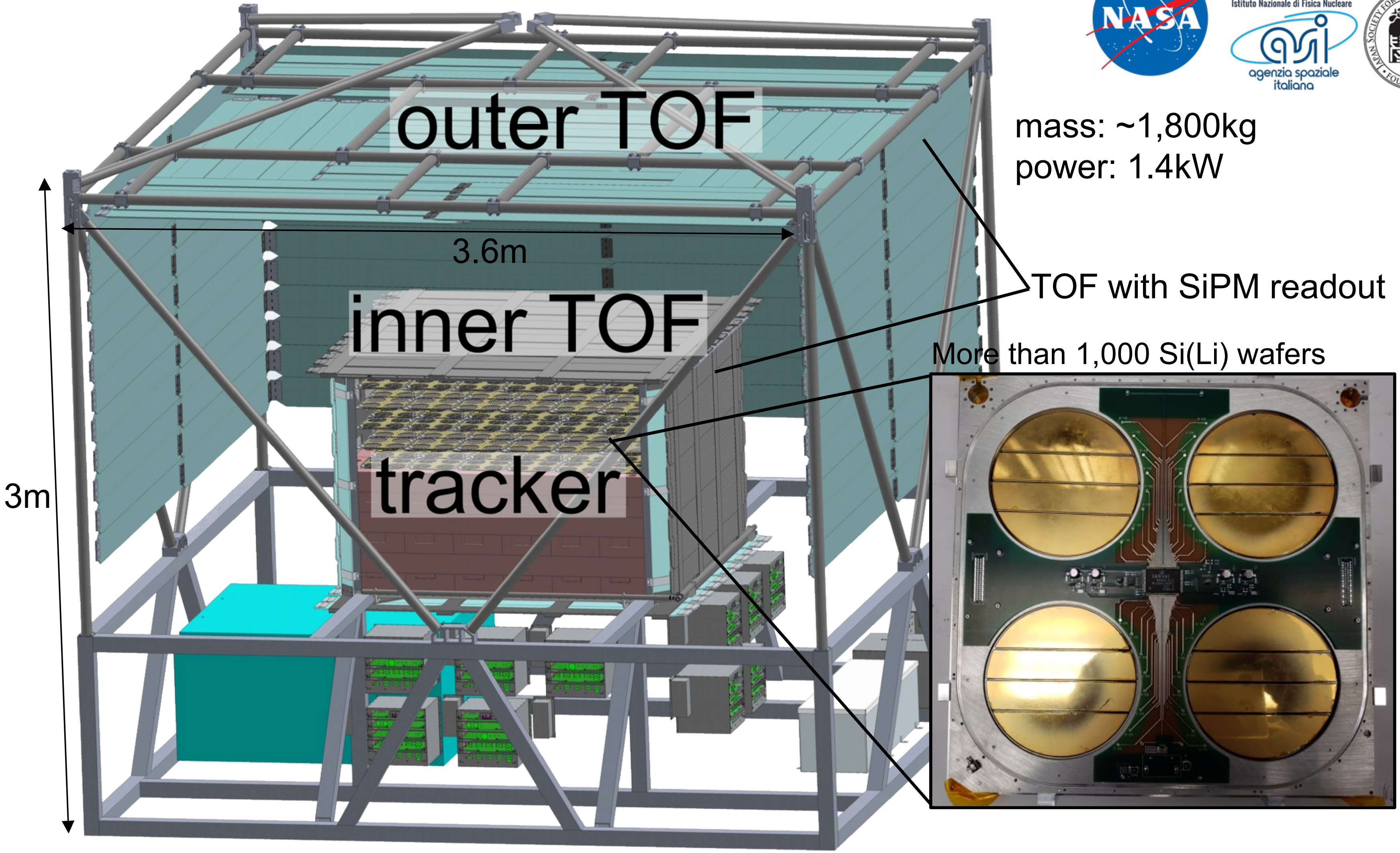
Antideuteron measurement with balloon and space experiments require:

- **strong background suppression**
- **long flight time and large acceptance**



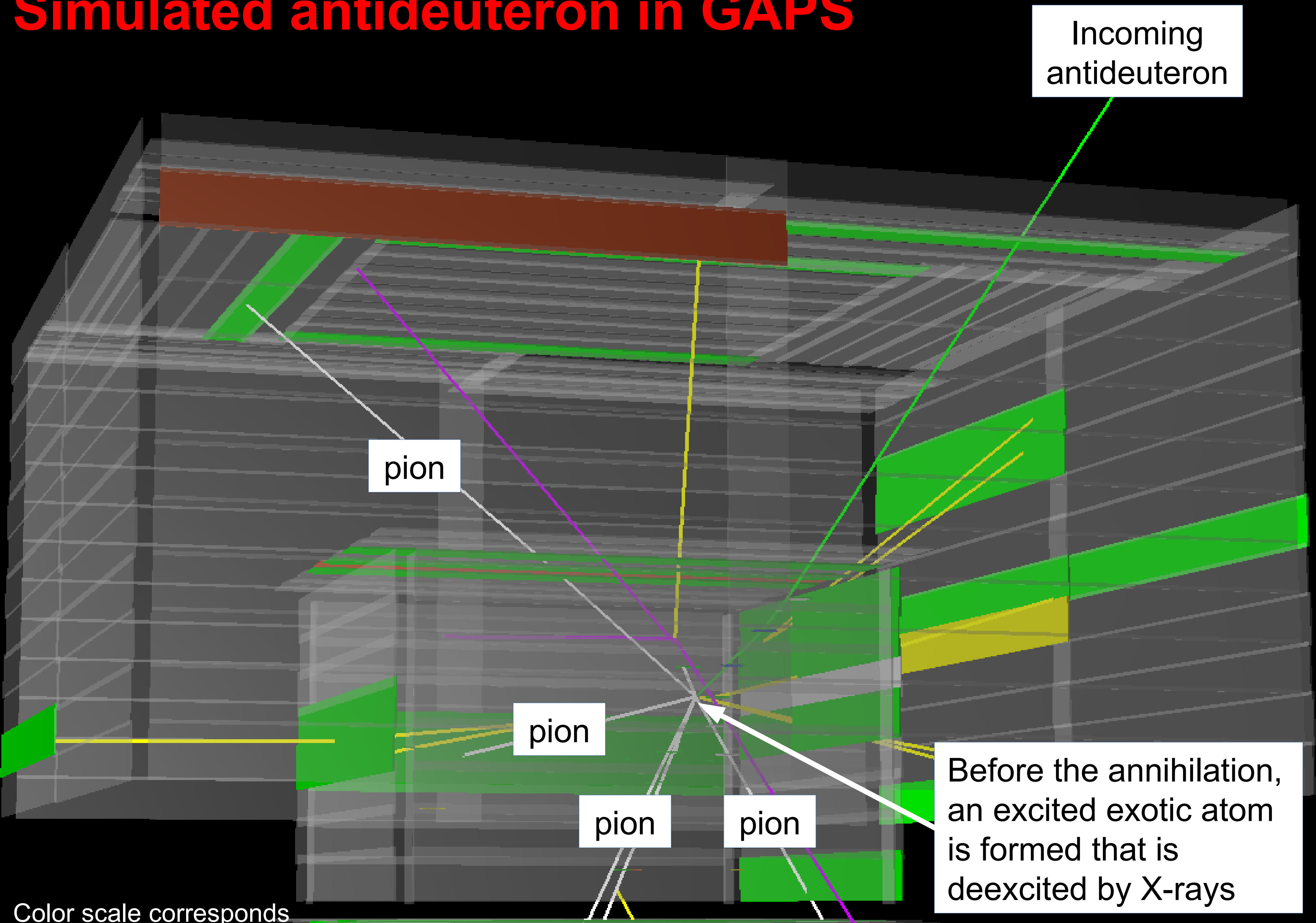
The GAPS experiment

Columbia U, UCSD
UCLA, UCB,
U Hawaii, MIT



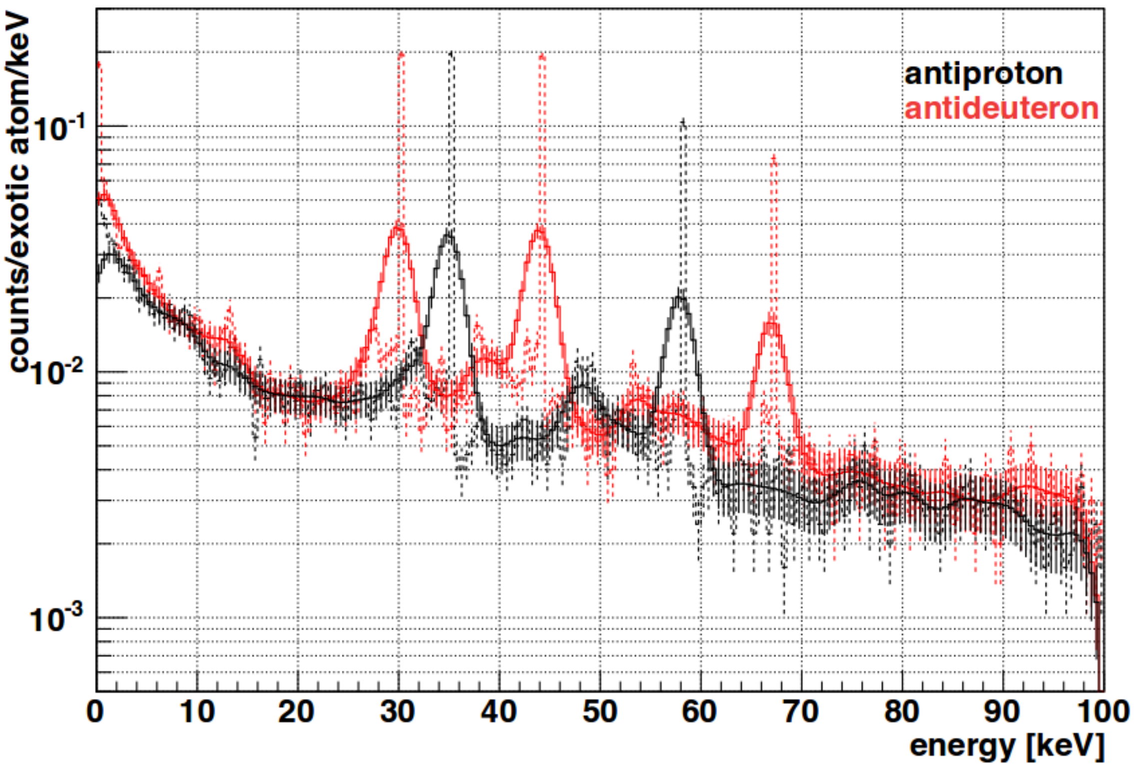
- the **G**eneral **A**nti**P**article **S**pectrometer is specifically designed for low-energy antideuterons, antiprotons and antihelium nuclei
- **GAPS is under construction → first Long Duration Balloon flights from Antarctica flight 2020**

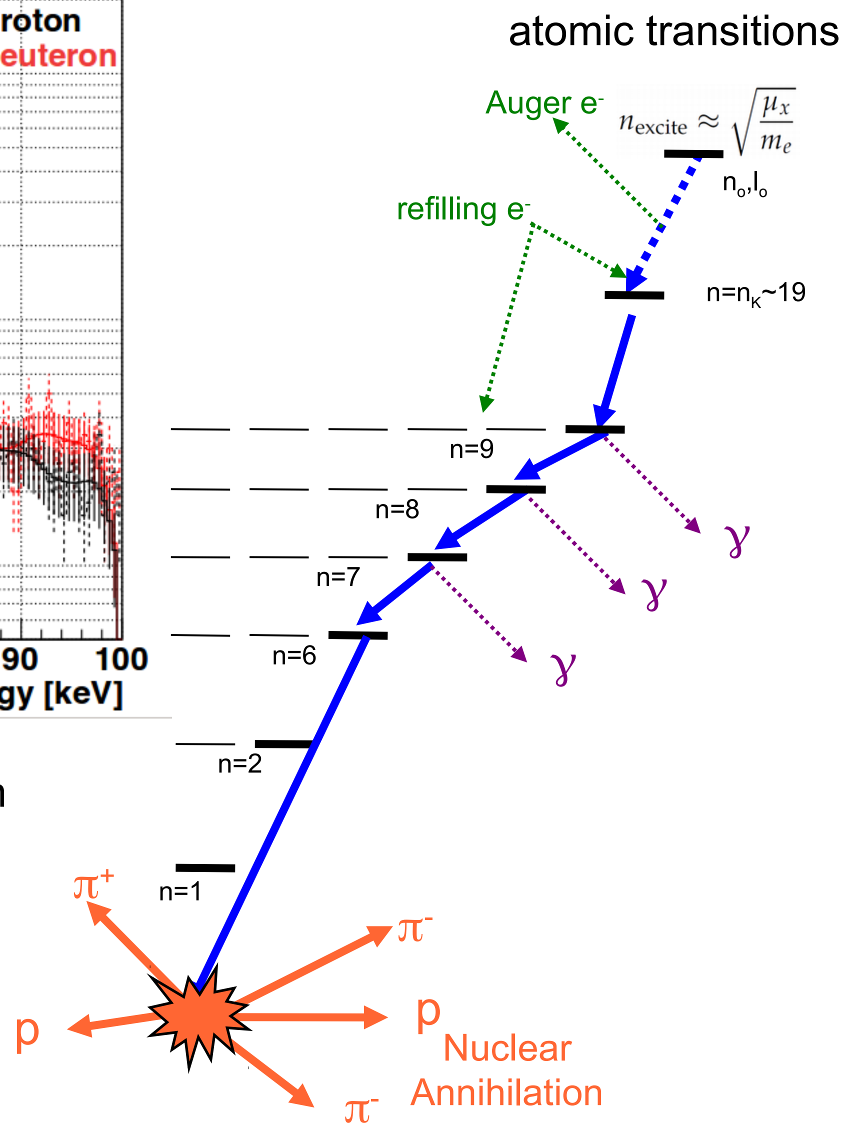
Simulated antideuteron in GAPS



Deexcitation X-rays

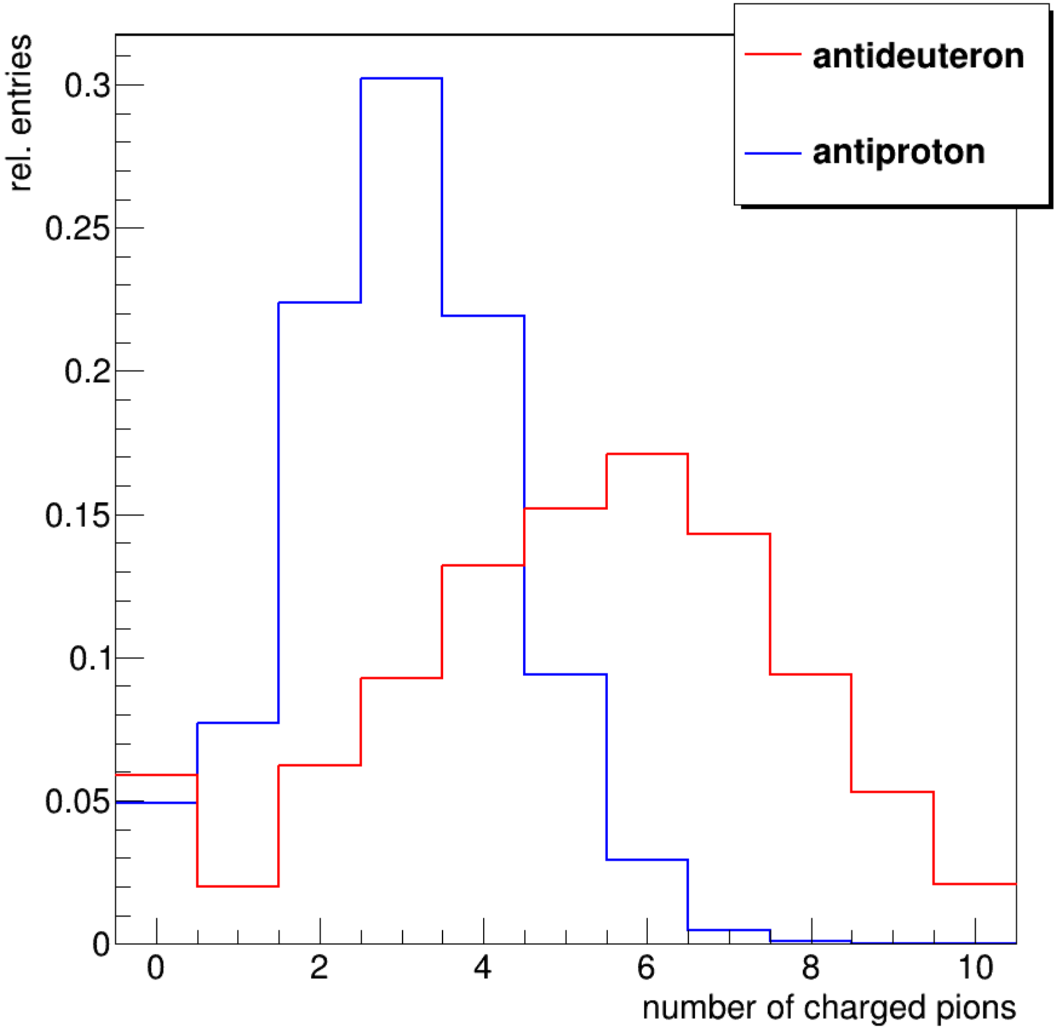
Aramaki et al., Astropart. Phys. 74, 6 (2016)





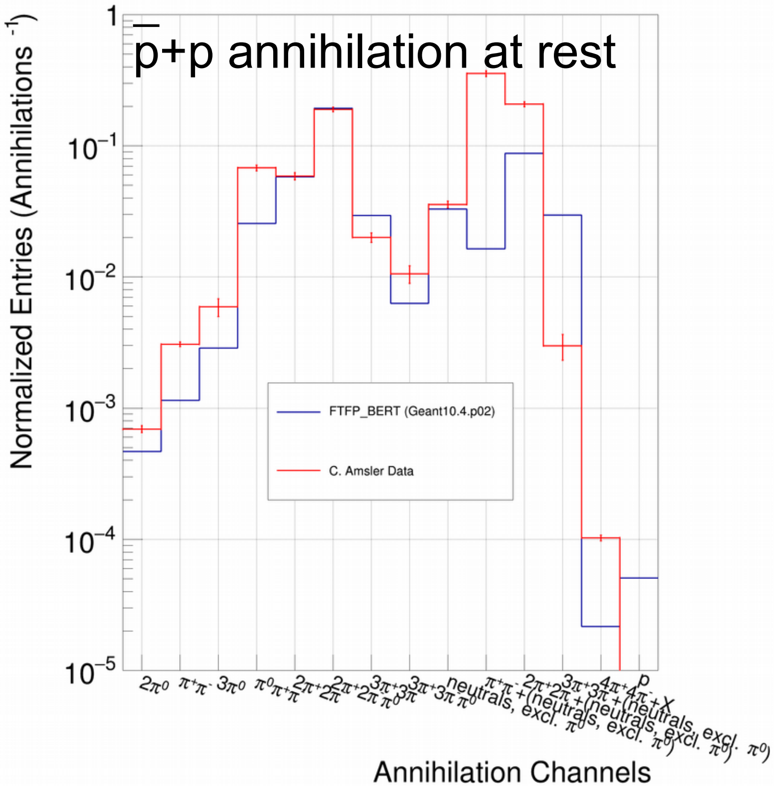
- **antiparticle slows down and stops in material**
- large chance for creation of an excited exotic atom (E_{kin}~E_I)
- deexcitation:
  - fast ionization of bound electrons (Auger) → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via **characteristic x-ray transitions depending on antiparticle mass**

Hadronic annihilation products



Number of charged pions for events that stop in the GAPS tracker material

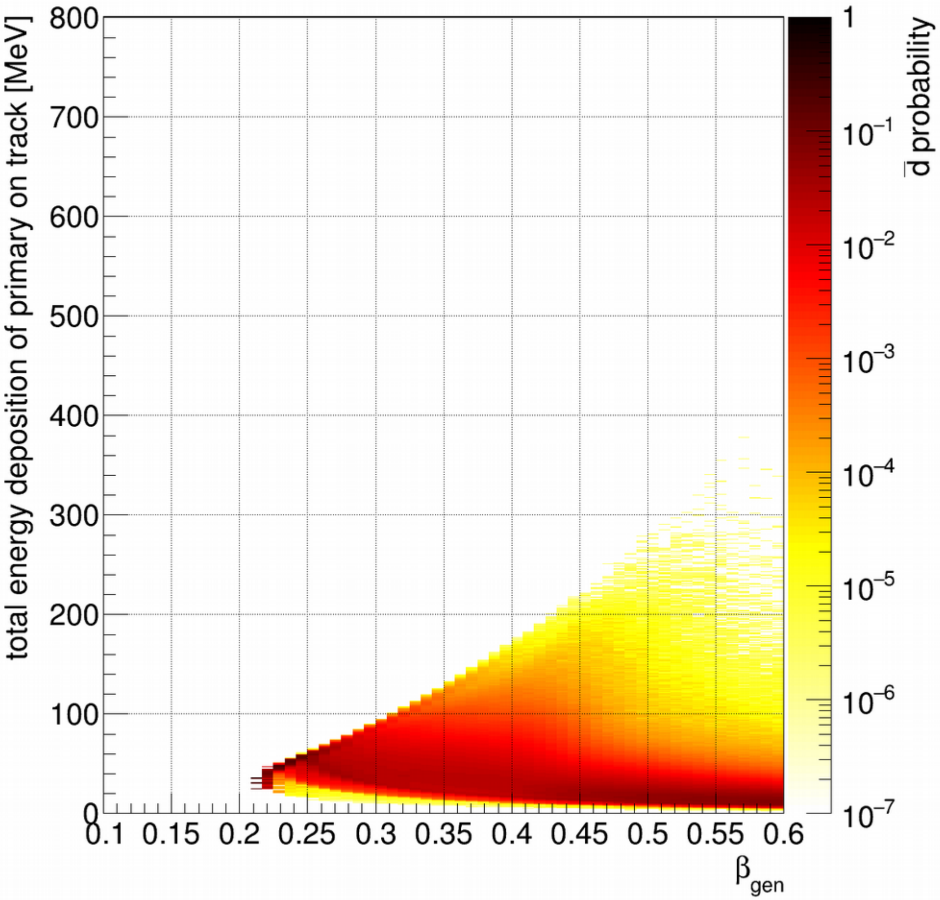
- Test of annihilation physics in Geant4 is currently ongoing
- Use antiproton data for validation
- Work with Geant4 developers



Identification variables

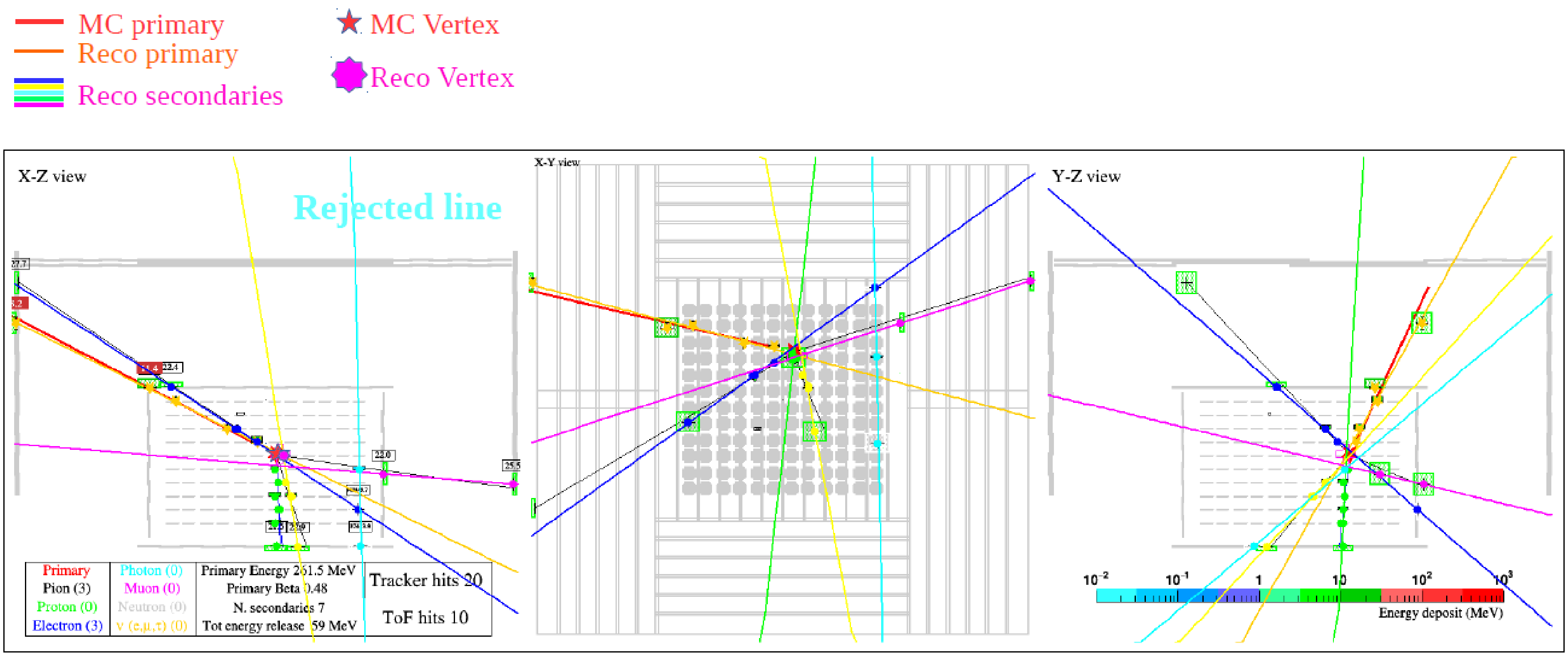
Identification is a task for multivariate identification techniques:

- Number of tracks from the annihilation vertex
- X-rays in association with nuclear annihilation products
- Total energy deposition of the primary particle
- Column density of material that the antiparticle traversed before stopping
- Total energy deposition from all tracks
- Number of hits in tracker
- Number of hits in TOF



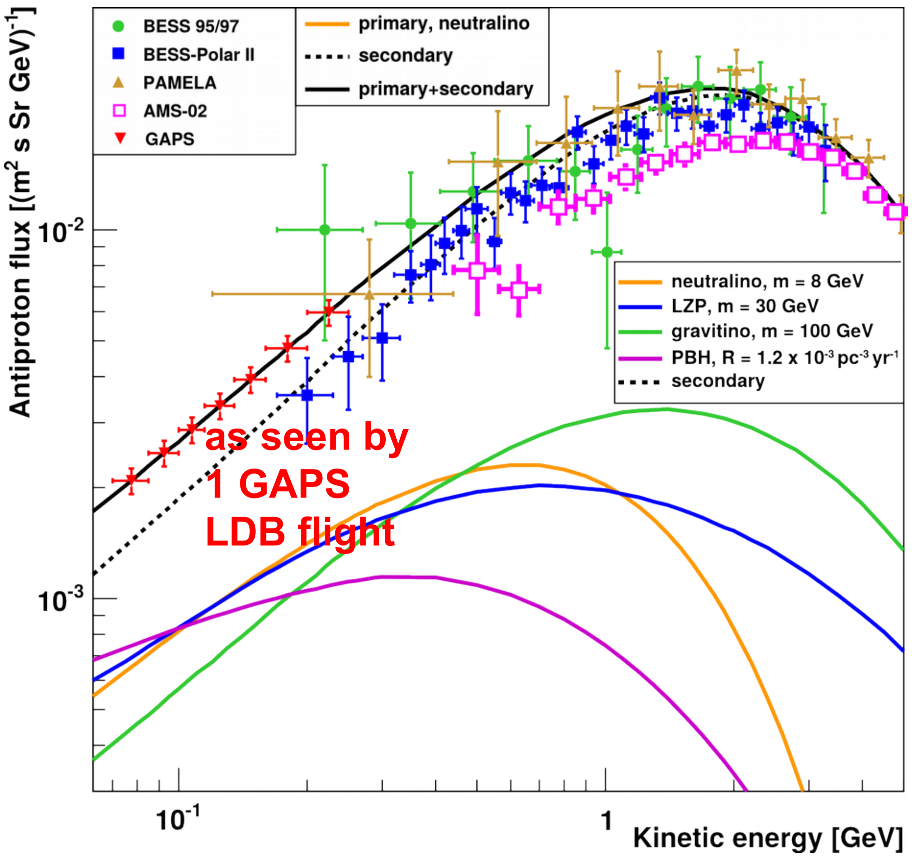
Total energy deposition on primary track in TOF and tracker

Event reconstruction



- For the event reconstruction it is critical to identify a well defined primary track → β measurement, energy deposition, column density
- The primary track is used as a seed for the determination of the stopping vertex with the corresponding secondary tracks

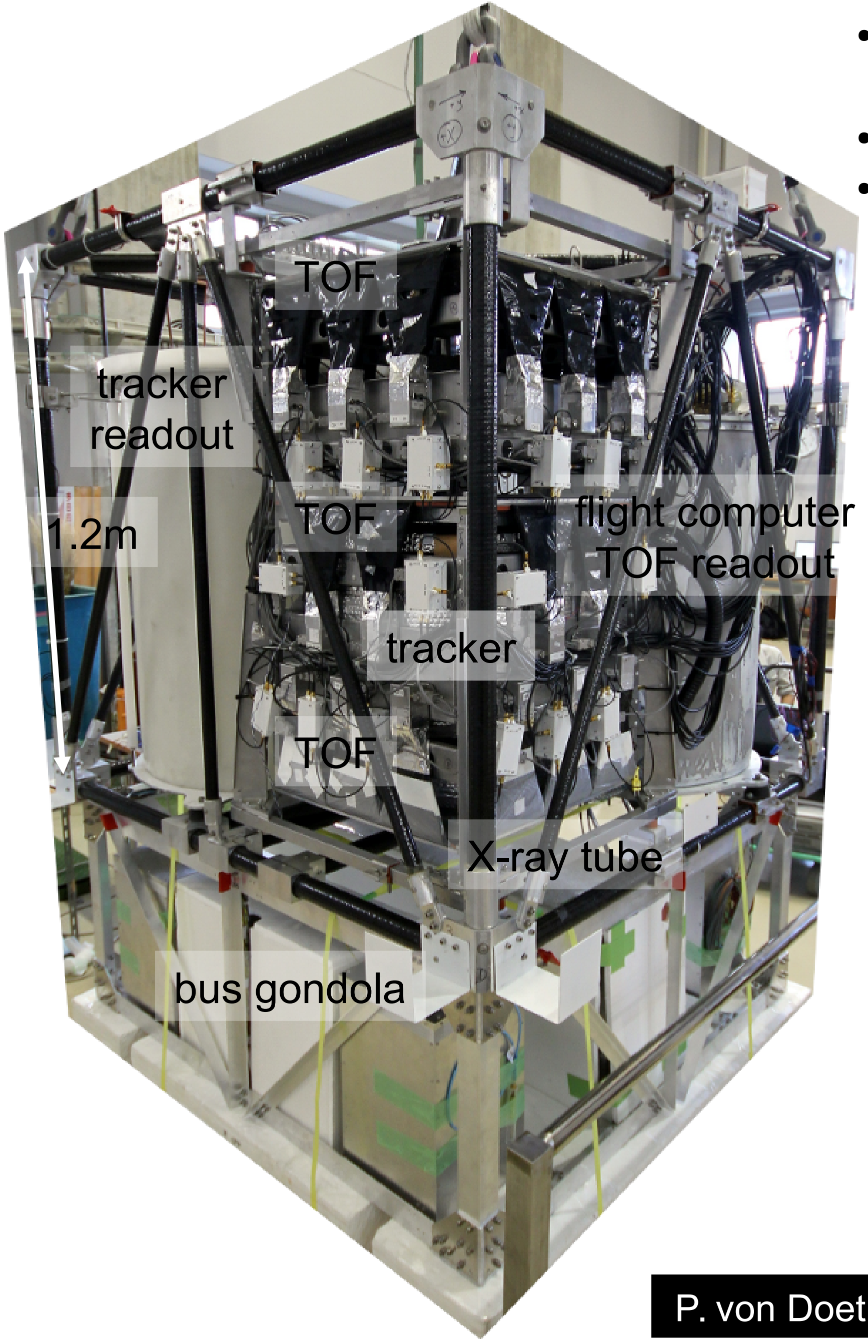
GAPS low-energy antiproton



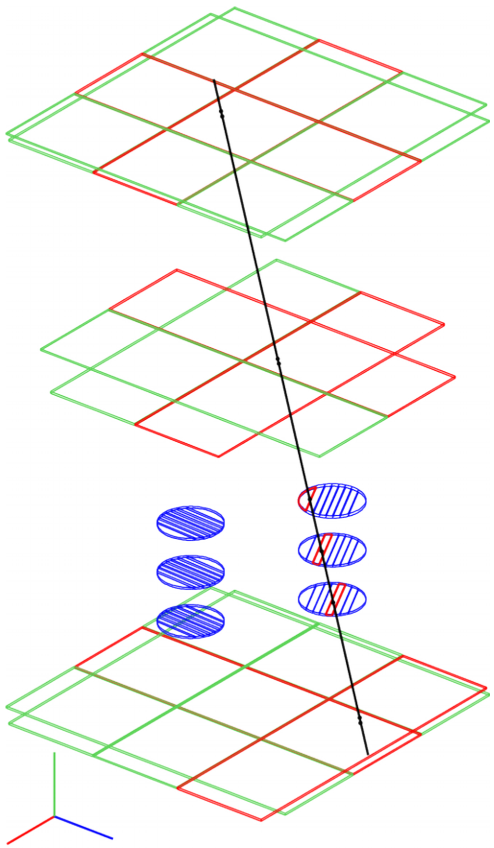
+ new BESS Polar II data points

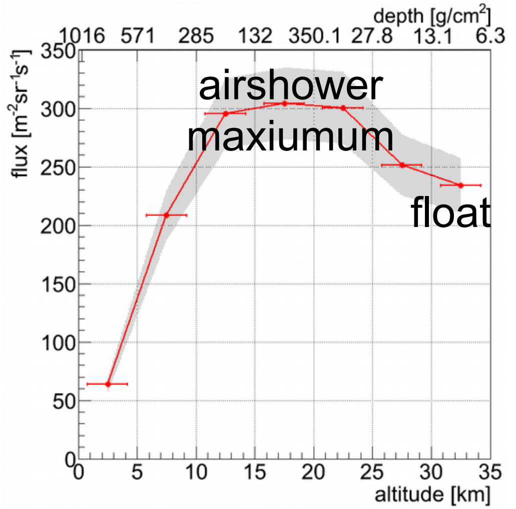
- GAPS will detect ~1000 antiprotons per 30day flight (order of magnitude more than BESS Polar II)
- Antiprotons are essential to:
  - Validate the identification technique
  - Compare with other experiments
  - Estimate antideuteron background
- Antiprotons are sensitive to various DM models: Neutralinos, LZP Gravitinos, primordial black holes

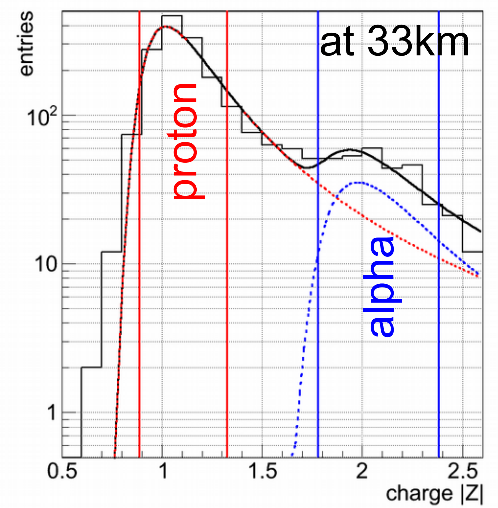
Prototype GAPS [2012]



- demonstrated stable operation of the detector components during flight
- studied Si(Li) cooling approach for thermal model
- measured background levels



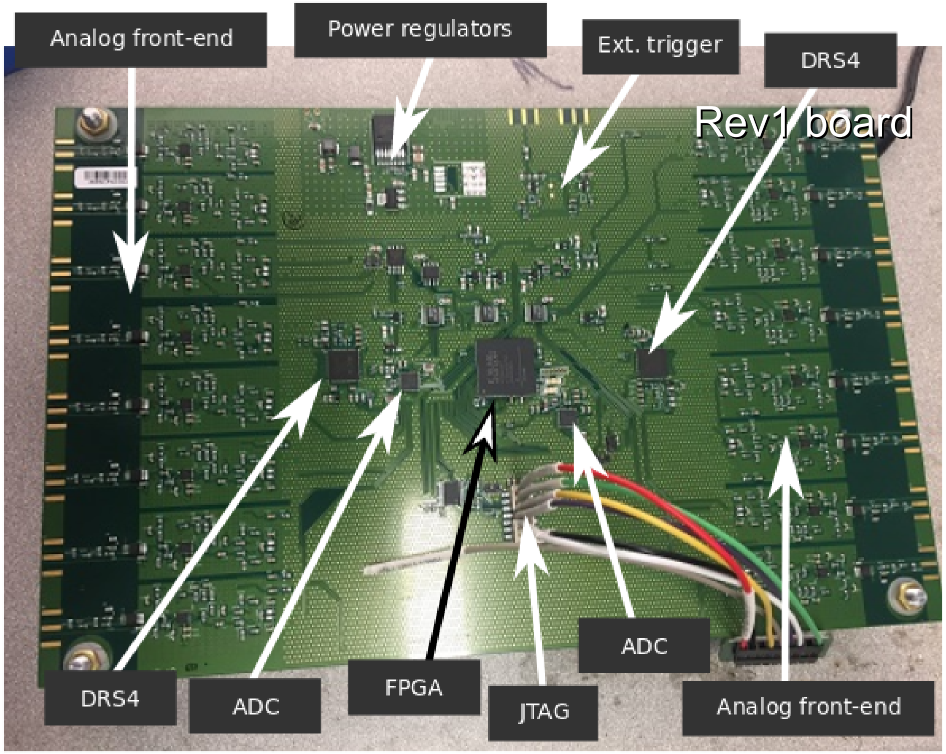




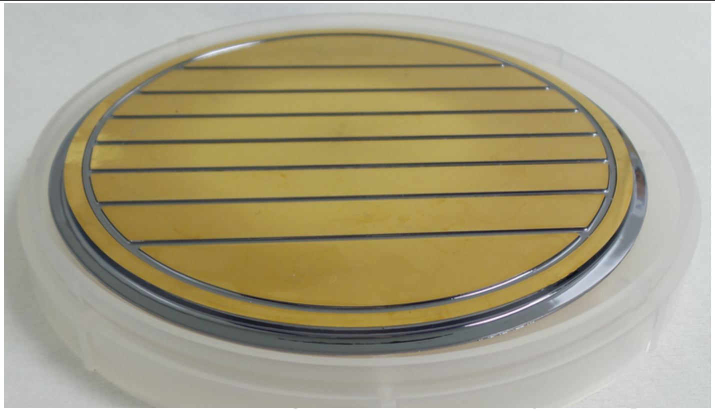
Time of flight

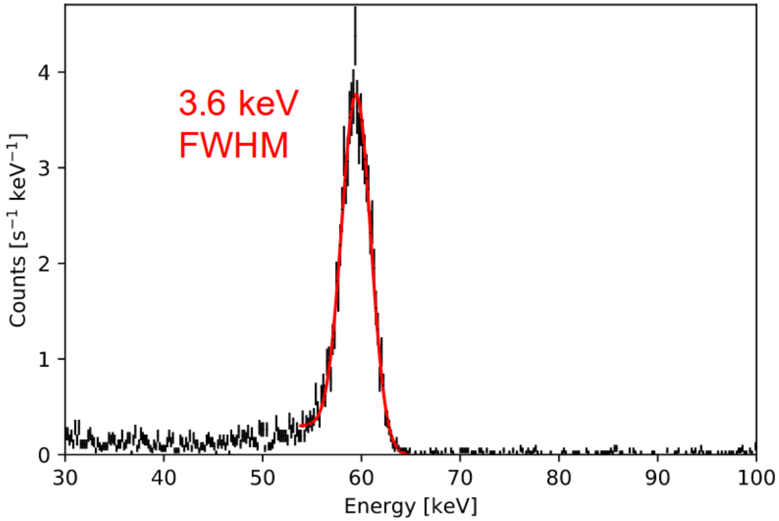
- High-speed trigger and veto

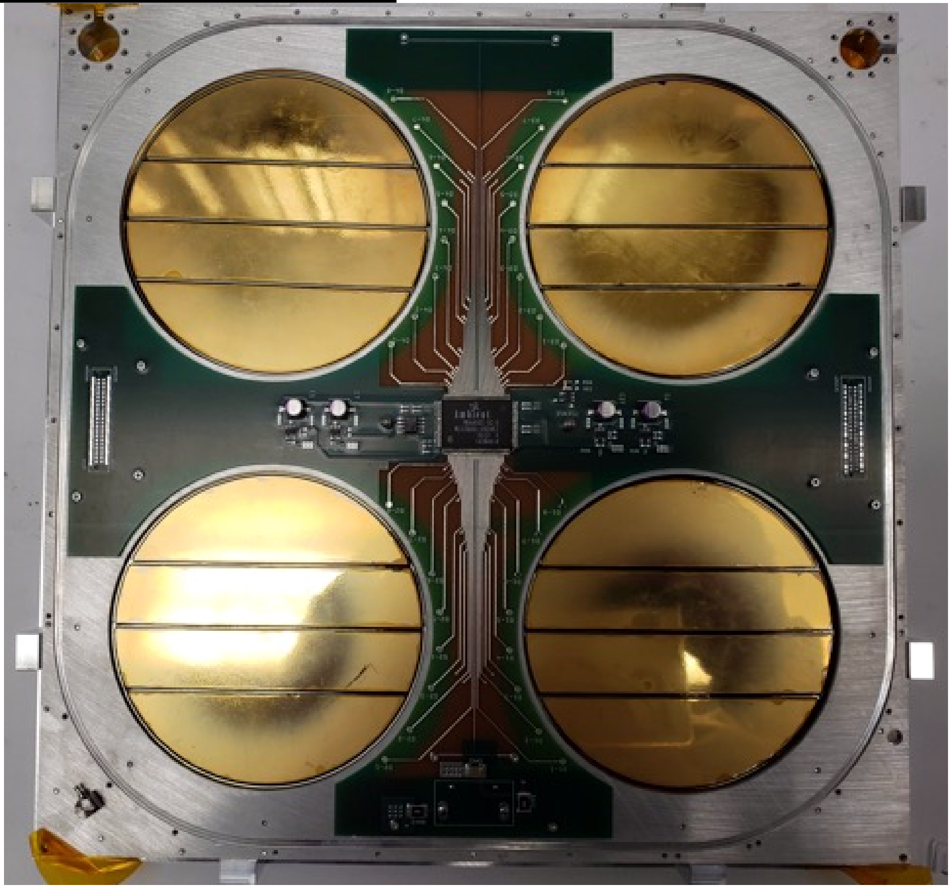
- 160-180cm long, 0.6 cm thick
- read out both ends with SiPM readout, fast sampling with DRS4 ASIC
  - < 500ps timing resolution end-to-end/√2 timing has been demonstrated in the lab
- Optimization of trigger is ongoing
  - accepts ~80% of antinuclei while reducing proton/alpha rate by 10^3-10^4
- TOF testing and development ongoing:
  - Rev1 testing completed, Rev2 read out board work has started



Tracker

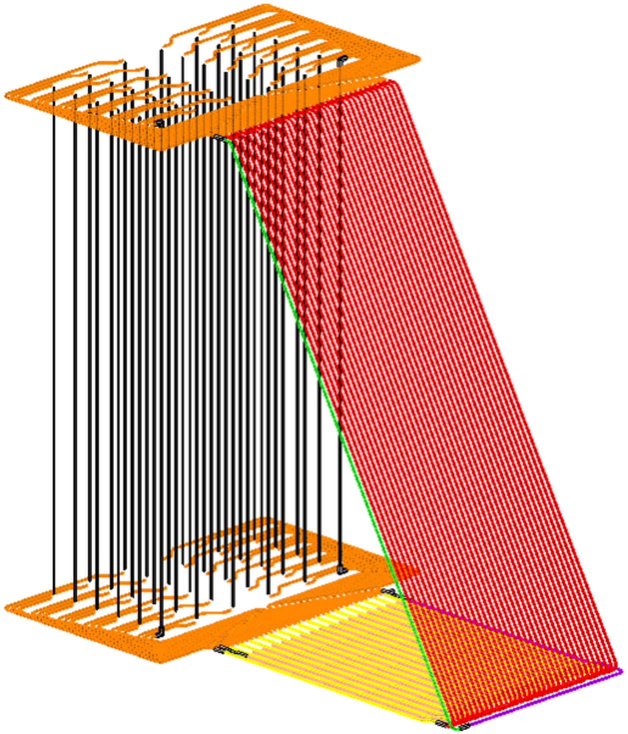


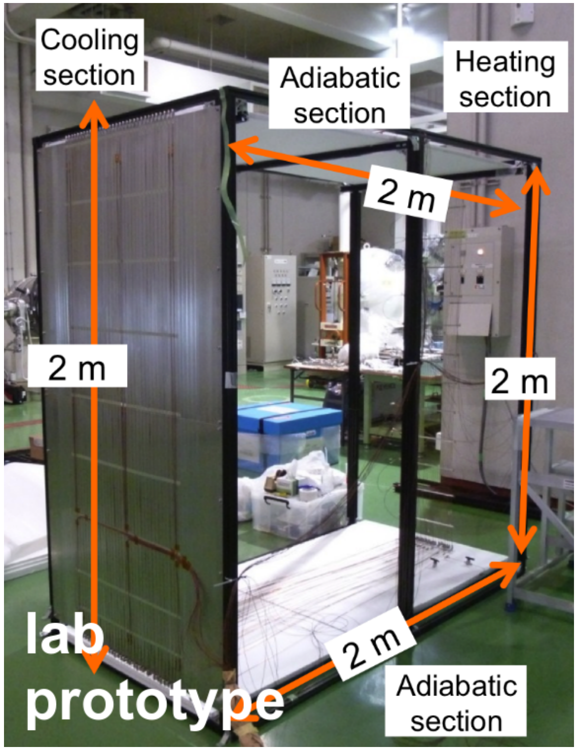


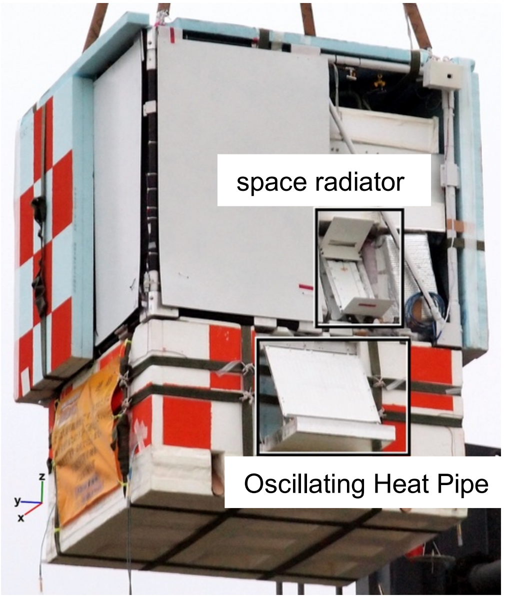


- GAPS will use ~1,000 4” Si(Li) detectors, 2.5mm thick
- Demonstrates required ~4keV energy resolution at relatively high temp of -35 to -45 C
- fabrication scheme developed at Columbia U and MIT, produced by private company Shimadzu, Japan
- confirmed performance with cosmic rays (MIPs) and Am-241 source (X-rays)
- Readout via custom ASIC: integrated low-noise preamplifier, dynamic range compression 20keV to ~100MeV

Oscillating heat pipe cooling system

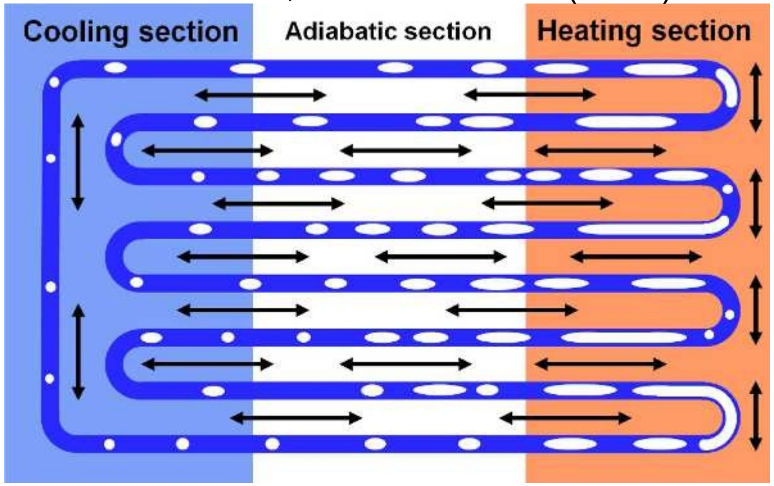






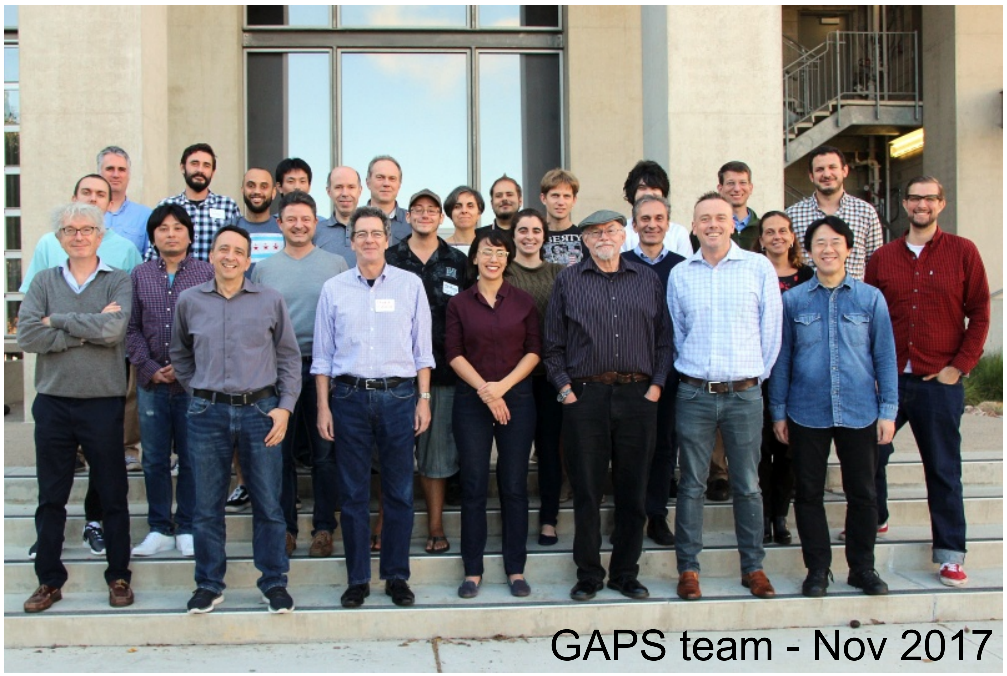
2012 prototype

S. Okazaki et al., J. Astr.. Instr. 3 (2014)



- alternative cooling approach:
  - small capillary metal tubes filled with a phase-changing refrigeration liquid
  - small vapor bubbles form in the fluid → expand in warm sections/contract in cool sections
  - rapid expansion and contraction of these bubbles create thermo-contraction hydrodynamic waves that transport heat.
  - no active pump system is required
- development at JAXA/ISAS

GAPS path forward


GAPS team - Nov 2017

- GAPS is specifically designed for low-energetic antideuterons
- all goals for prototype GAPS were met
- currently in finalizing-design phase
- **first GAPS science flight from Antarctica 2020**

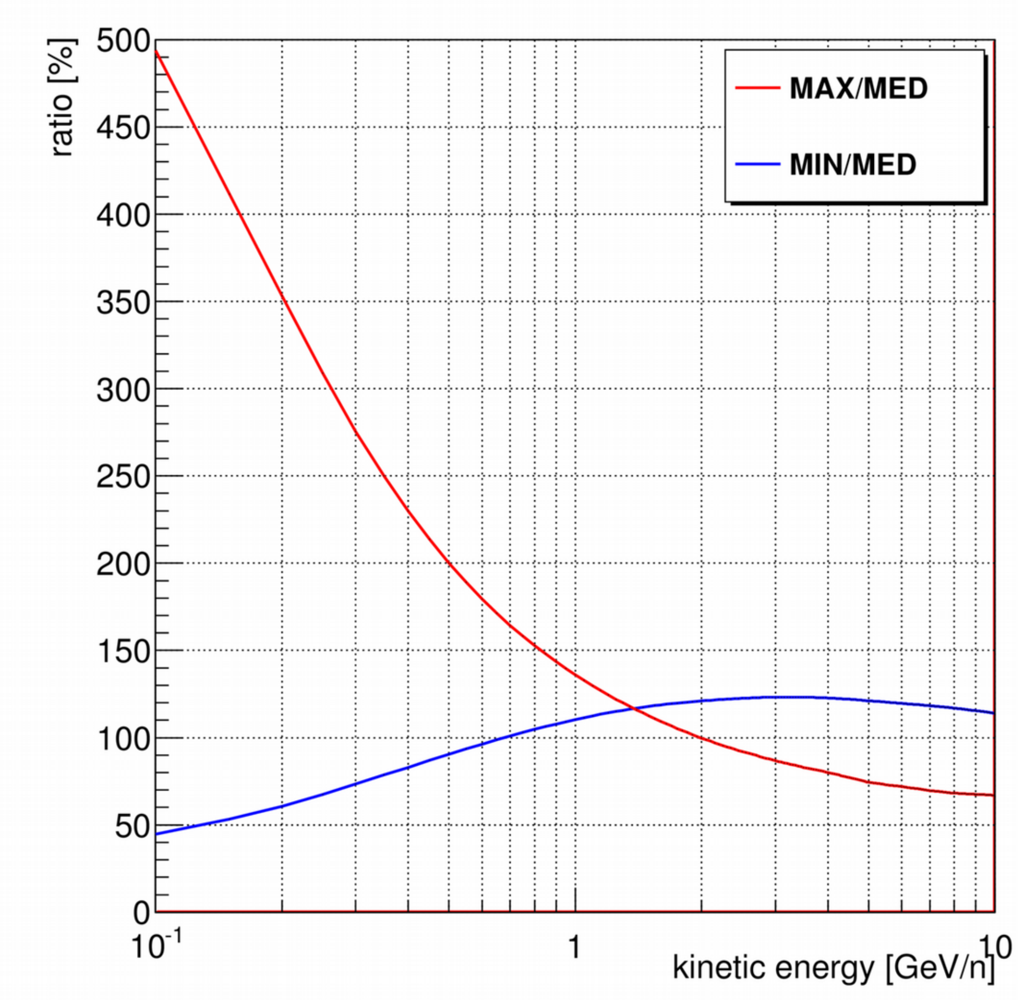
d19 2nd cosmic-ray antideuteron workshop

UCLA, March 27-29, 2019

https://indico.phys.hawaii.edu/e/dbar19

Backup

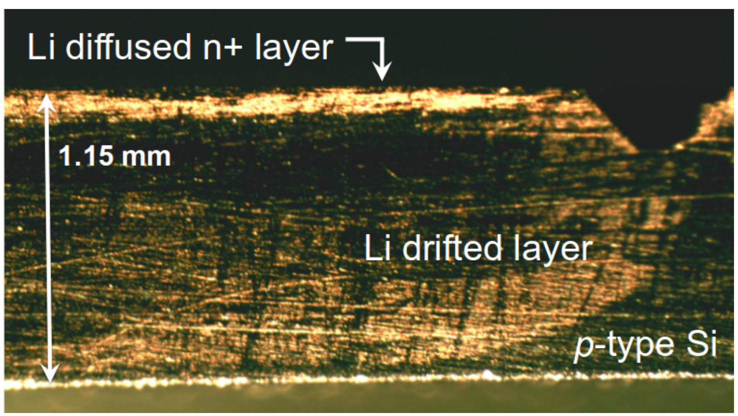
Propagation uncertainty



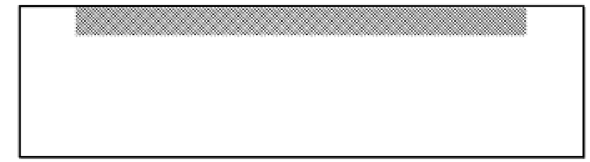
- propagation is a large uncertainty source for low-energy antideuterons: **halo size for diffusion calculation is poorly constrained**
- **antiproton and positron results tend to exclude MIN halo models and favor larger halo sizes**

Si(Li) detector development

- Lithium is applied to the front surface of B-doped p-type Si and diffused through short depth
- Li atoms donate electrons, resulting in an n-type Si lattice layer and leftover free positive Li ions
- under reverse bias, positive Li ions move away from the n-type region
  → compensate acceptor atoms in the p-type bulk
  → compensate impurities in the Si
- drifting procedure creates a thick compensated region (<1.5 days at 500V and 130C)
- ultrasonic machining on the n+(Li) contact → guard ring structure, reduces leakage current, much better energy resolution
- electrodes are thermal-evaporated ohmic/blocking contacts

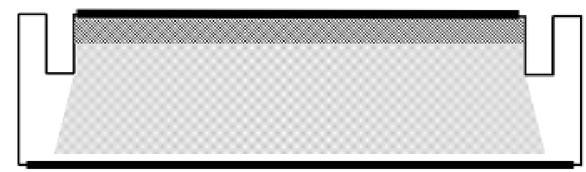


Perez et al., NIM A 905, 12 (2018)

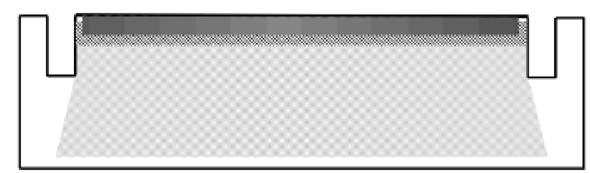


(a) Evaporate and diffuse initial Li layer

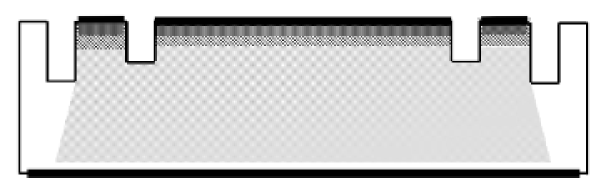
(b) Cut circular groove and apply contact



(c) Drift Li through wafer



(d) Remove contacts and diffuse second, shallower Li layer



(e) Cut guard ring groove and re-apply contacts