Cosmic-Ray Antinuclei from Dark Matter and the GAPS Experiment

UCLA Dark Matter
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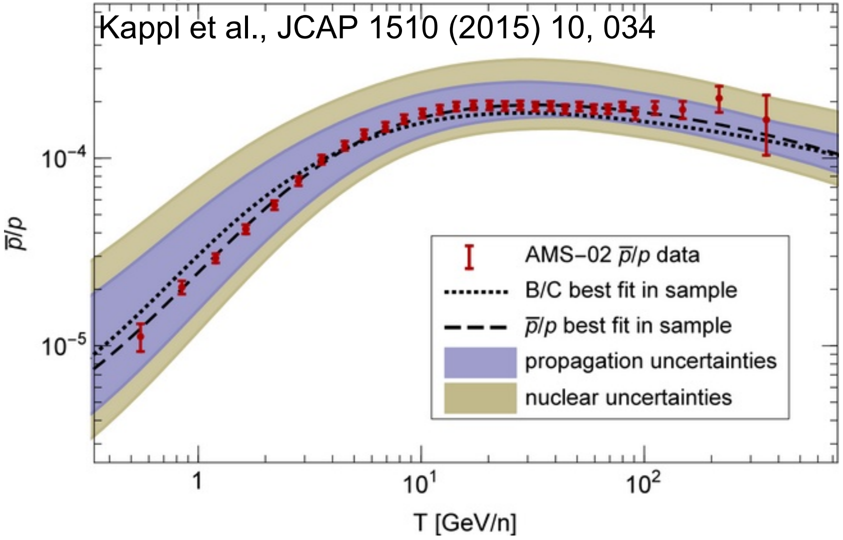
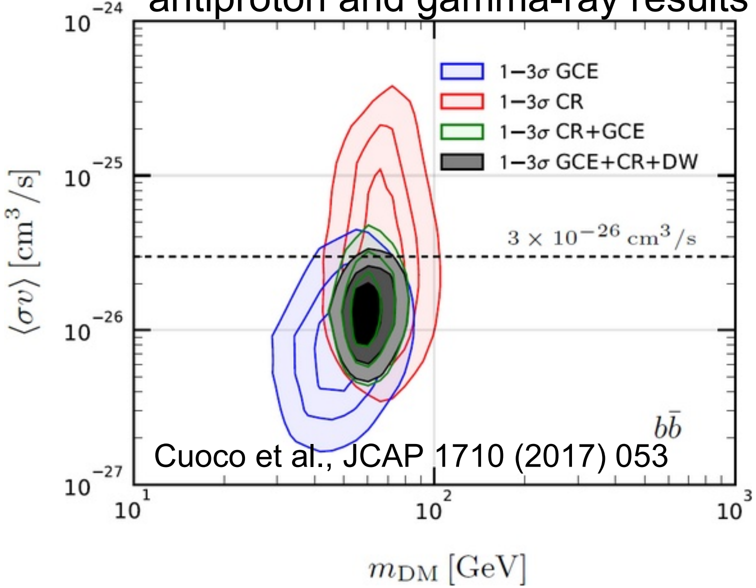
Unexplained features in cosmic rays

antiproton



Kappl et al., JCAP 1510 (2015) 10, 034

antiproton and gamma-ray results



Cuoco et al., JCAP 1710 (2017) 053

- combined fit with antiproton and diffuse gamma-rays from the Galactic Center → 80GeV DM particle (ongoing debate)

- unexplained feature in positrons:
  - astrophysical origin → pulsars
  - SNR acceleration
  - dark matter annihilation

- **understanding astrophysics background is a challenge** → better constraints on cosmic-ray propagation and astrophysical production are needed

Status Cosmic-ray Antinuclei Searches

- **Potential $\bar{p}$ excess** in AMS-02 data above secondary background predictions at *R*~10 GV was found in various studies
  → significance level unclear

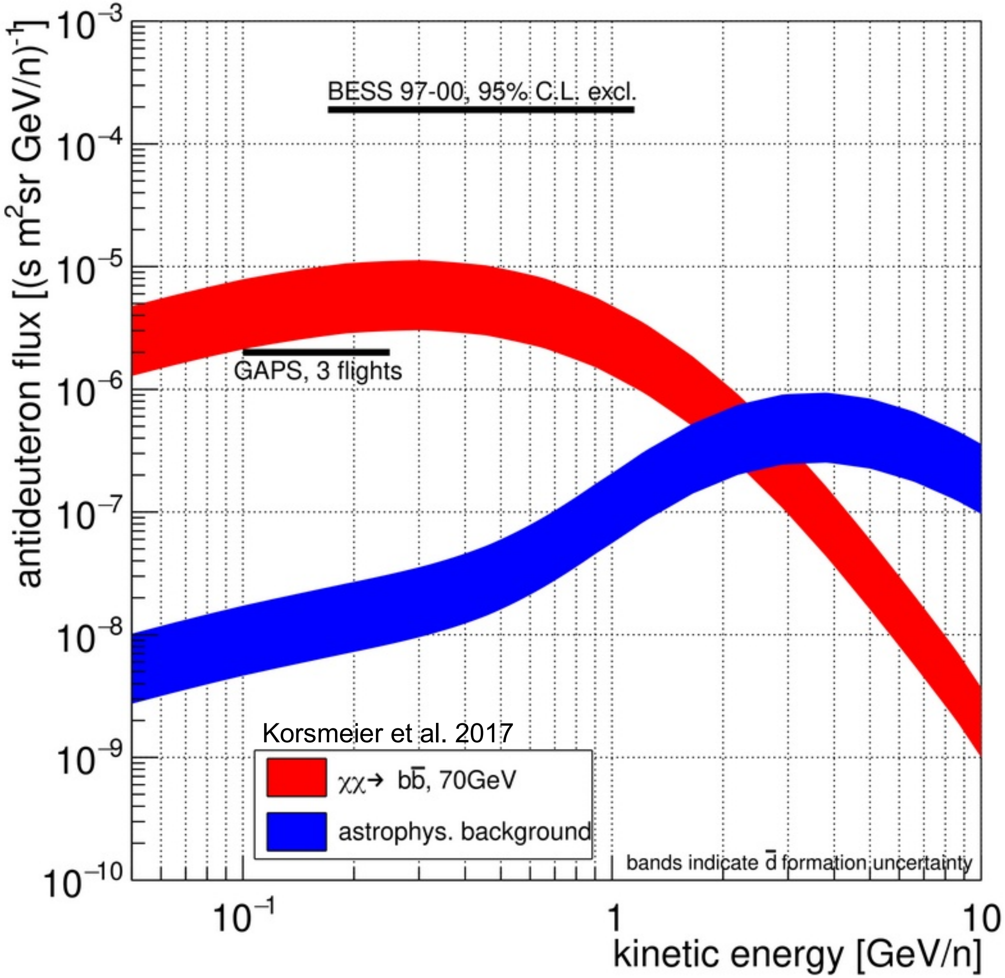
- AMS-02 reported at conferences the observation of **antihelium candidates (~1/year)**
  → interpretations are actively ongoing

- **Possible physics models that explain antihelium candidates include:**
  - Secondary astrophysical background
  - Dark matter annihilation or decay
  - Nearby antistar: at distance of ~1pc

- **No explanation of antiproton nor antihelium should overproduce antideuterons relative to existing limits**

- **Search for antinuclei with independent technique is critical**

- Review based on 2nd Cosmic-ray Antideuteron Workshop: “Cosmic-ray Antinuclei as Messengers of New Physics: Status and Outlook for the New Decade“ [JCAP08(2020)035, arXiv:2002.04163]

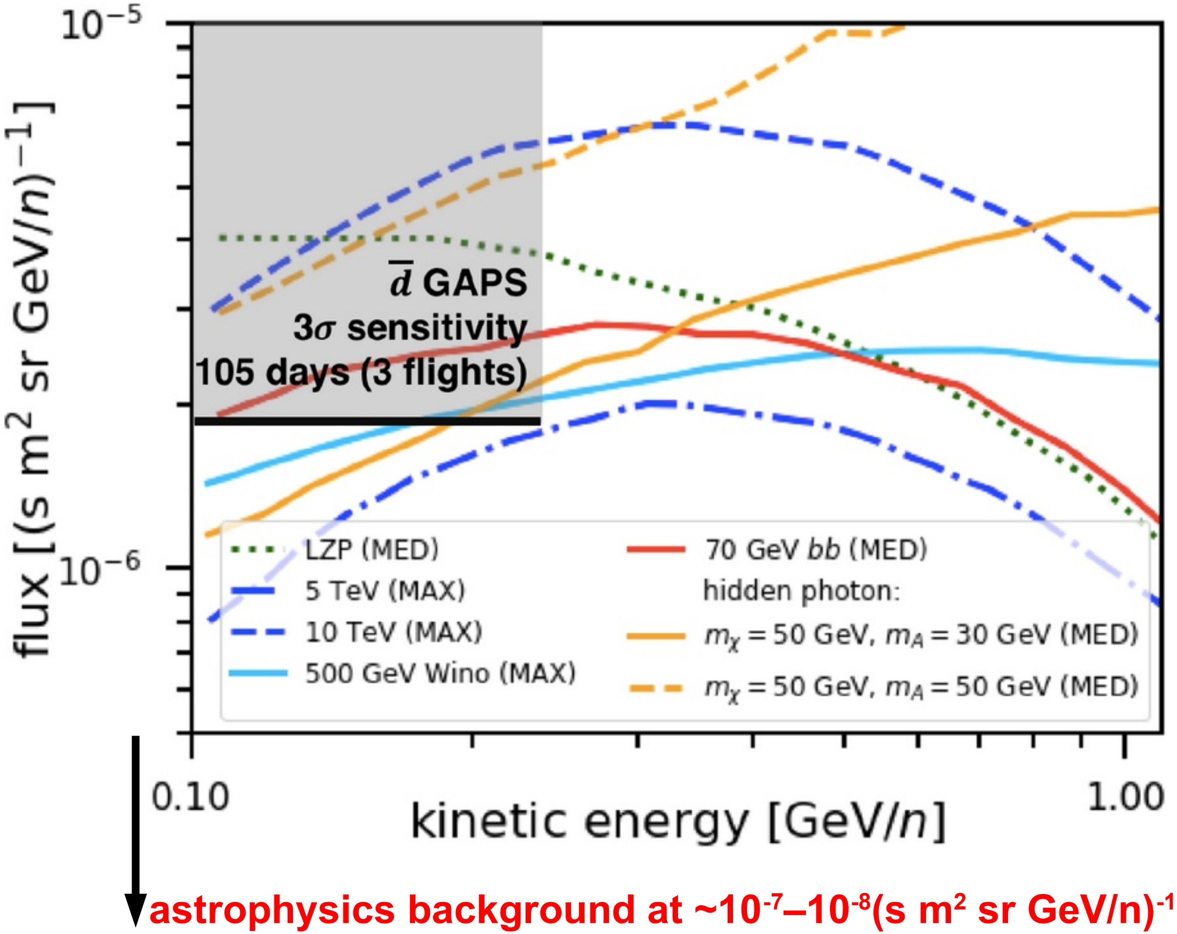


Antideuteron model sensitivity

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

- **Low-energy antideuterons are essentially free of astrophysics background**

- **Wide range of dark matter models**, e.g.:
  - Generic 70GeV WIMP annihilation model that explains antiproton excess and γ-rays from Galactic center
  - Dark matter gravitino decay
  - Extra dimensions
  - Heavy DM models with Sommerfeld enhancement
  - Dark photons (inaccessible to other techniques)
  - Selection of publications:
    Braeuninger et al. Physics Letters B 678, 20–31 (2009)
    Cui et al, JHEP 1011, 017 (2010)
    Hryczuk et al., JCAP 1407, 031 (2014).
    Korsmeier et al., Physical Review D 97, 103011 (2018)
    Randall & Xu, JHEP (2020)



astrophysics background at ~10^{-7}–10^{-8}(s m^2 sr GeV/n)$^{-1}$

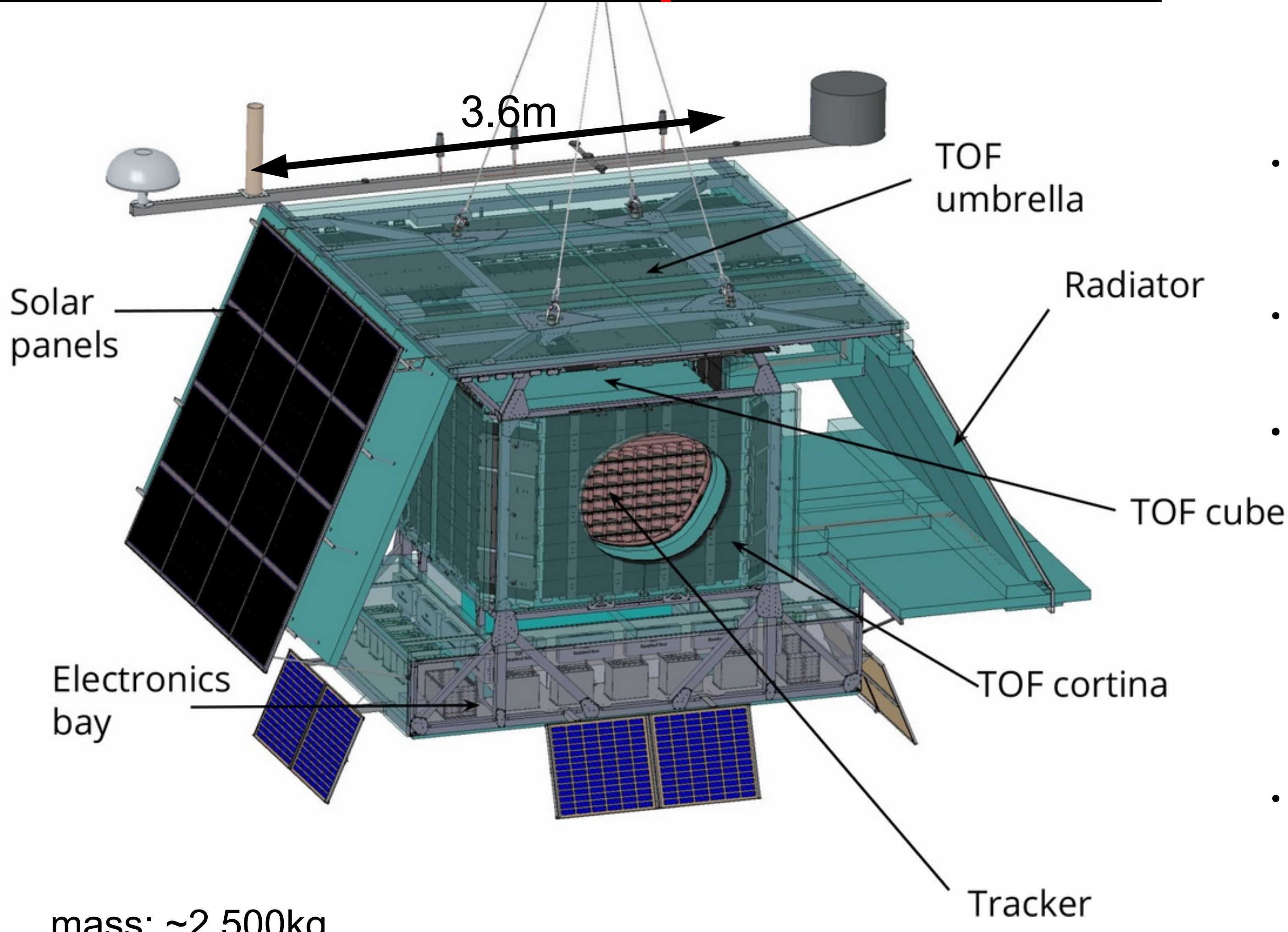
Antideuteron Workshops at UCLA

2014

2019

organized with Rene Ong

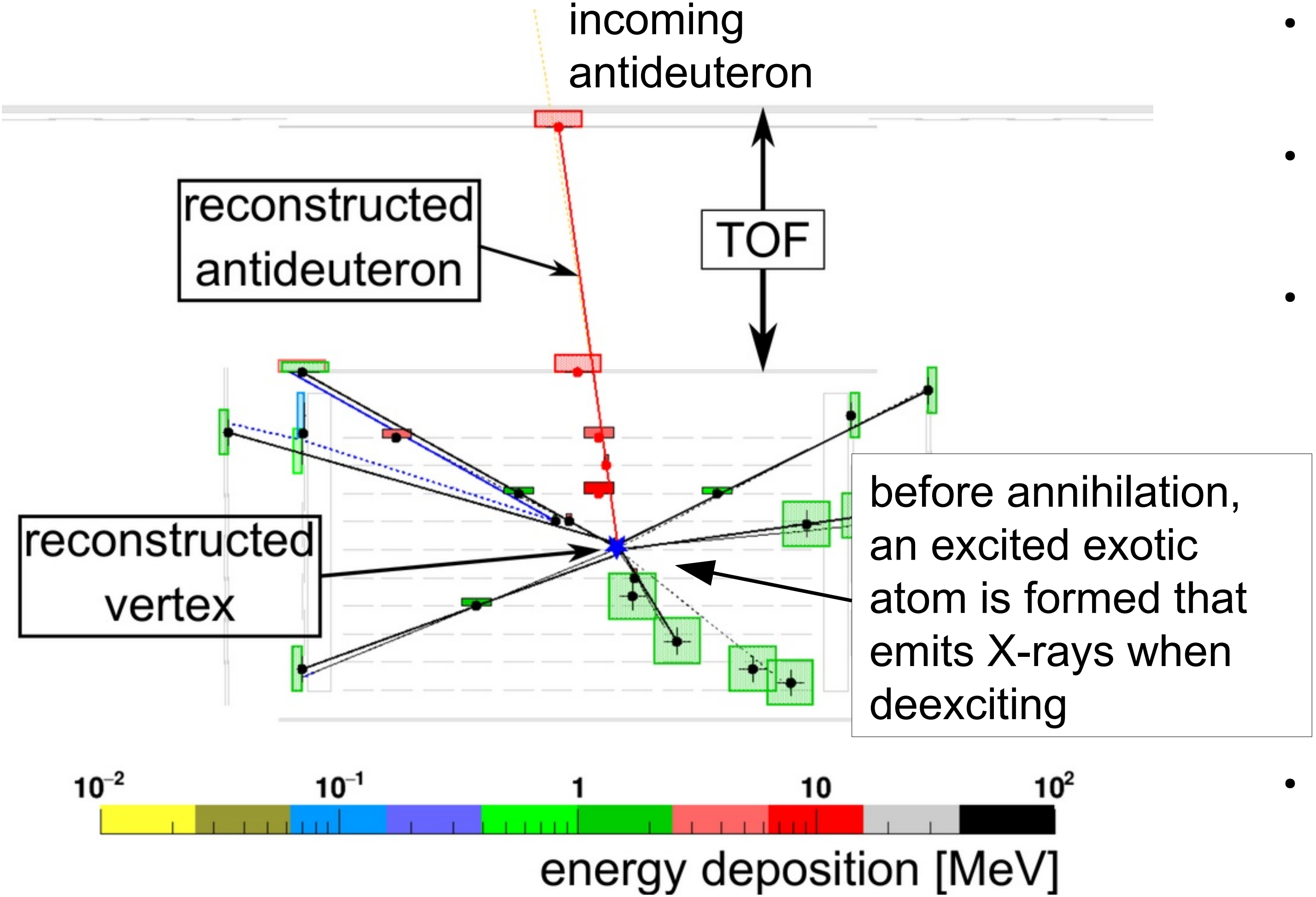
The GAPS experiment



mass: ~2,500kg
power: 1.3kW

- The **G**eneral **A**nti**P**article **S**pectrometer is the first experiment dedicated and optimized for low-energy cosmic-ray antinuclei search
- Requirements: long flight time, large acceptance, large identification power
- **GAPS will deliver:**
  - a precision antiproton measurement in an unexplored energy range <0.25 GeV/n
  - antideuteron sensitivity 2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range
  - leading sensitivity to low-energy cosmic antihelium nuclei
- **GAPS is under construction, preparing for first Antarctic Long Duration Balloon flight in December 2023**

GAPS principle



before annihilation, an excited exotic atom is formed that emits X-rays when deexciting

- antiparticle slows down and stops in material
- near-unity 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
- Nuclear annihilation with characteristic number of annihilation products

Antiproton sensitivity

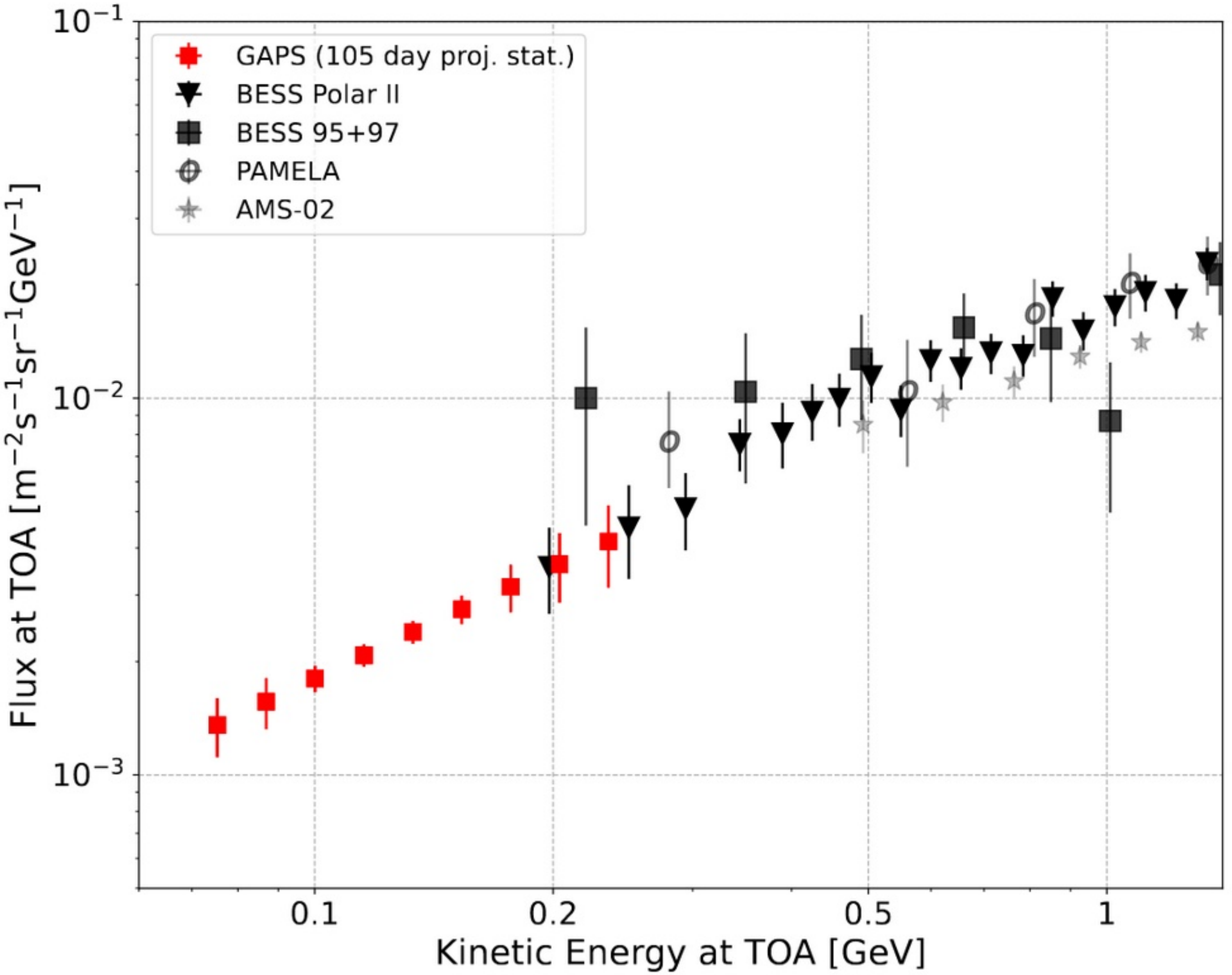
F. Rogers et al., Astropart. Phys. 145, 102791 (2022)

- Precision antiproton spectrum in unexplored low-energy range (<0.25 GeV/n): ~500 antiprotons for each long-duration balloon flight

- Validation of technique:
    - First cosmic rays detected with the exotic atom method
    - Reconstruction of annihilation signature
    - X-rays from exotic atom deexcitation
    - Test models for atmospheric effects

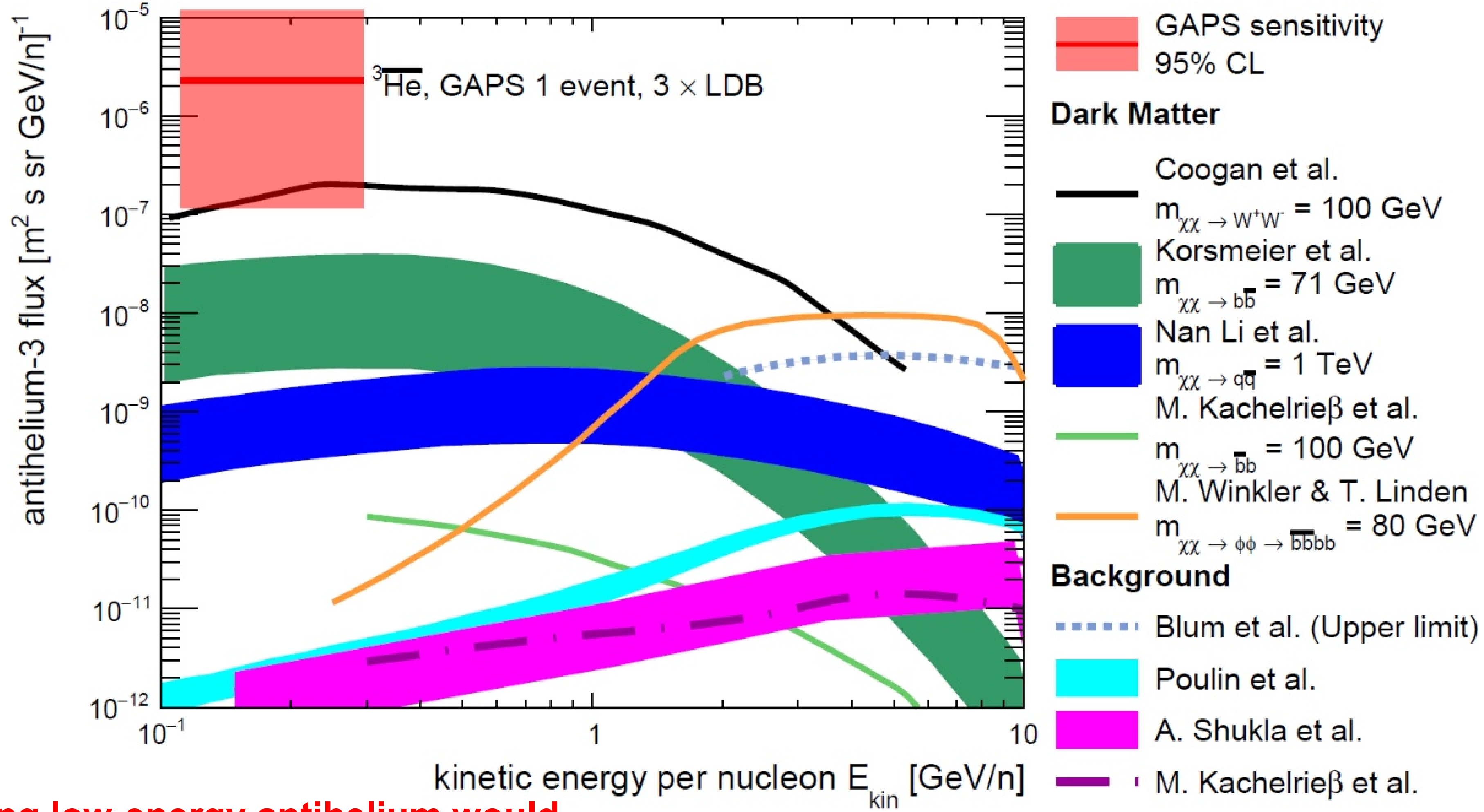
→ Reduces the systematic uncertainties for antideuteron search

- Probe light dark matter models and primordial black hole evaporation



Antihelium-3 sensitivity

N. Saffold et al., Astropart. Phys. 130, 102580 (2021)



Finding low-energy antihelium would be truly revolutionary new physics

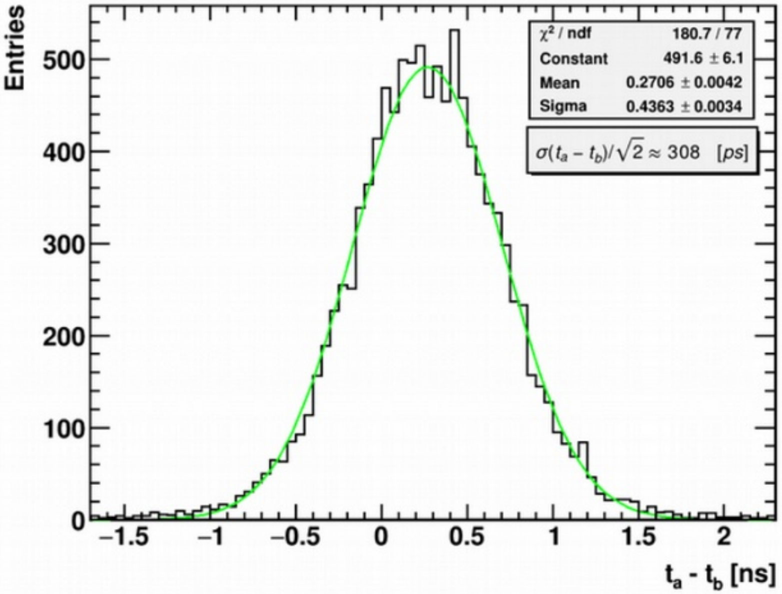
Time-of-Flight

- Tasks:
    - main trigger system, special antinuclei trigger achieves a manageable rate of ~500 Hz (down from 200 kHz individual TOF paddle rate)
    - Tracking of incoming (anti)particles and velocity measurement

- Plastic scintillator (Eljen EJ-200: 160-180cm long, 0.6 cm thick) with 6 SiPMs per end (Hamamatsu S13360-6050VE)

- fast sampling with custom-made readout board, based on the DRS-4 ASIC: <400ps timing resolution achieved in test paddles (end-to-end time difference) and in GAPS functional prototype (GFP).

Going on downstairs (photo from yesterday)



Tracker

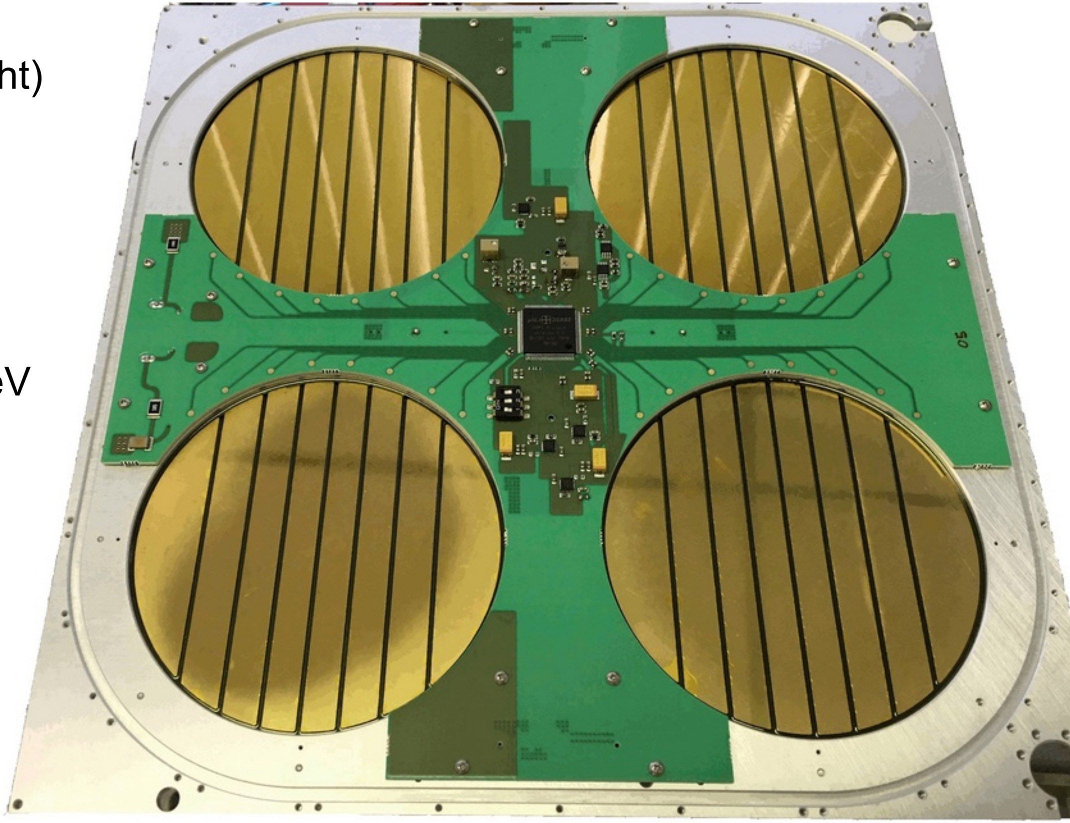
- Tracker acts as target and tracking device

- GAPS can accommodate 1,440 4” Si(Li) detectors, 2.5mm thickness (1109 detectors calibrated for first flight)

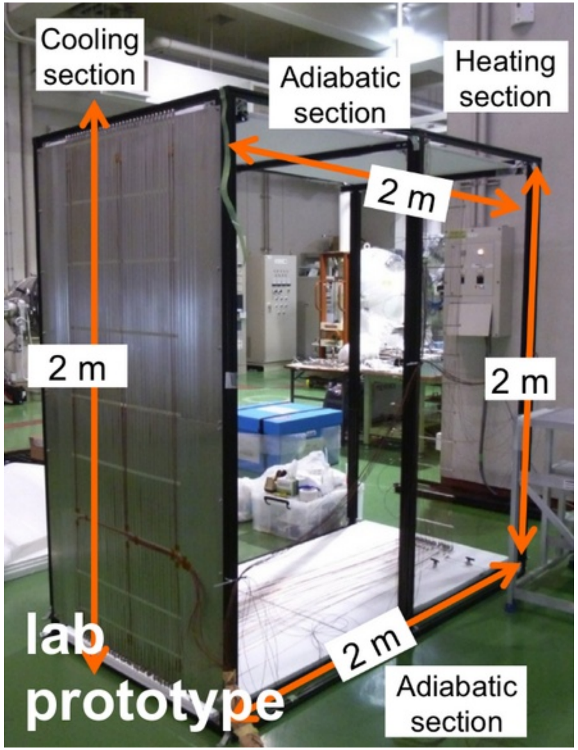
- Operation at temperature of –35C to –45C, cooling system will use novel OHP approach

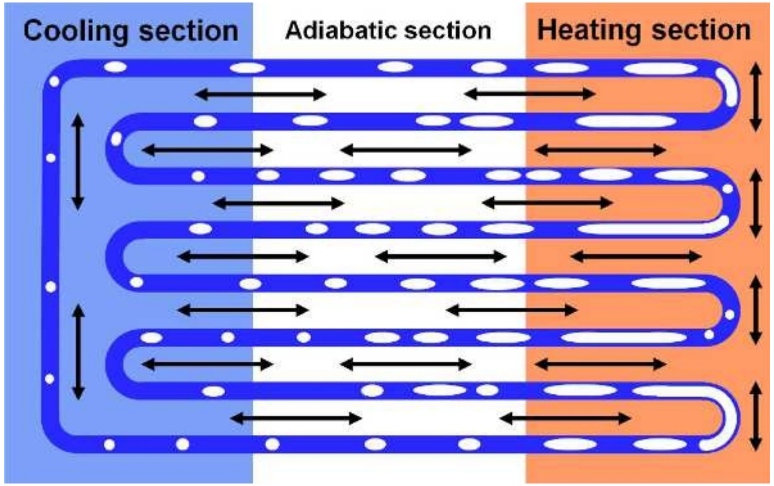
- Readout via custom ASIC: integrated low-noise preamplifier with large dynamic range: 10keV to 100MeV

- Publications:
  - Perez et al., NIM A 905, 12 (2018)
  - Kozai et al., NIM A 947, 162695 (2019)
  - Rogers et al., JINST 14, P10009 (2019)
  - Saffold et al., NIM A 997, 165015 (2021)
  - Manghisoni et al., IEEE 68 (11), 2661 (2021)
  - Kozai et al., NIM A 1034, 166820 (2022)
  - Xiao et al., in preparation (2023)
  - Roach et al., in preparation (2023)

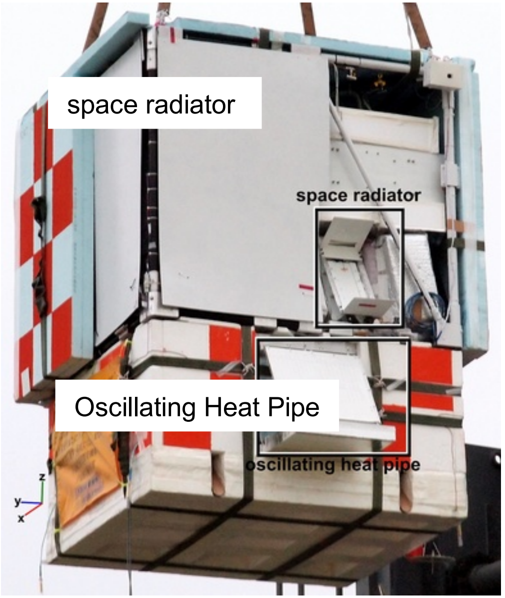


Oscillating heat pipe cooling system





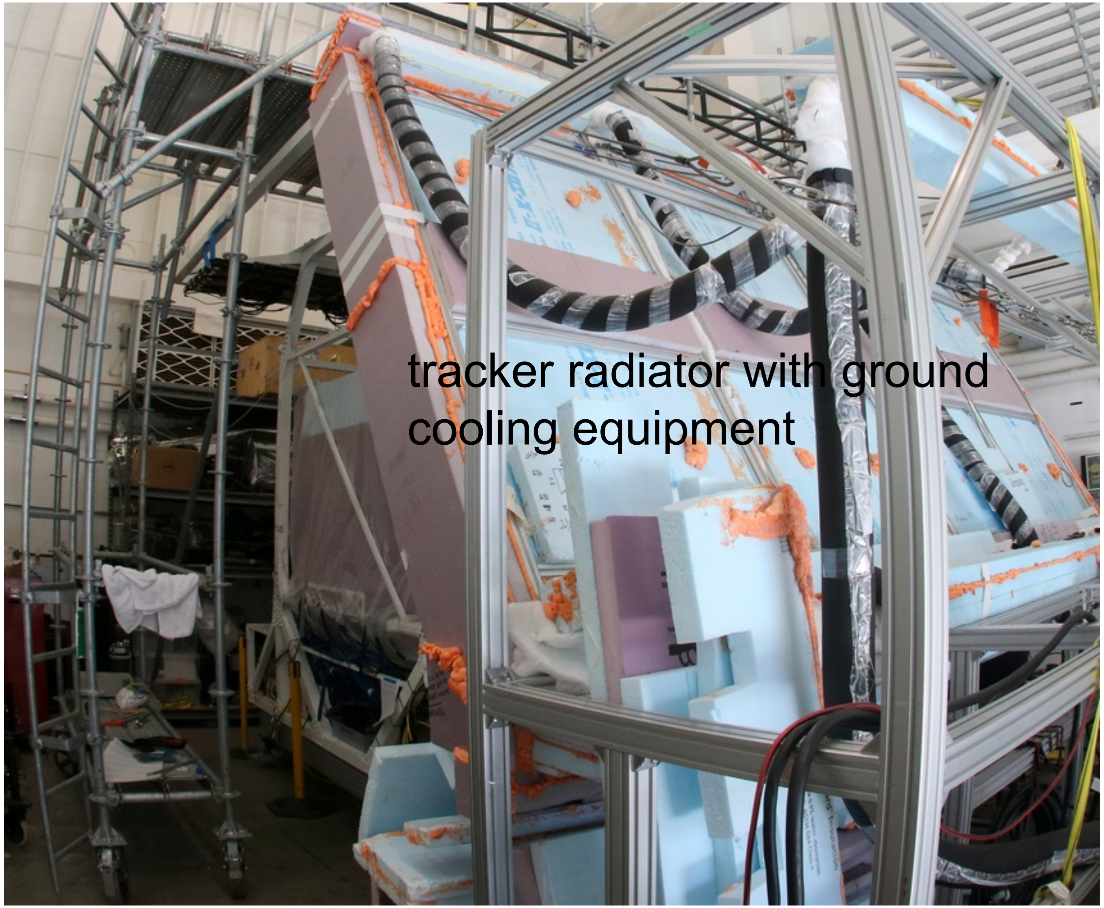
2012 prototype



- passive cooling approach developed at JAXA/ISAS:
- 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
- First prototype was flown in 2012 and another prototype was flown from Ft. Sumner in 2019

Okazaki et al., J. Astr.. Instr. 3 (2014)
Fuke et al., J. Astron. Instrum. (2017)
Okazaki et al., Appl. Therm. Eng. (2018)
Fuke et al., NIM A 1049, 168102 (2023)

Integration status 3/23



tracker radiator with ground cooling equipment

part of TOF umbrella

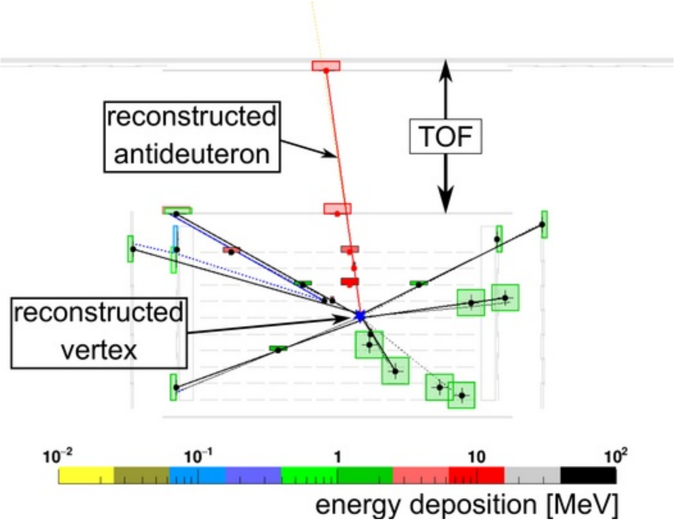
Timeline

- Integration and systems testing in spring 2023
- Thermal vacuum and compatibility testing summer 2023
- **First flight in Dec. 2023 from McMurdo, Antarctica**

Image credit: NASA (cropped)

GAPS path forward

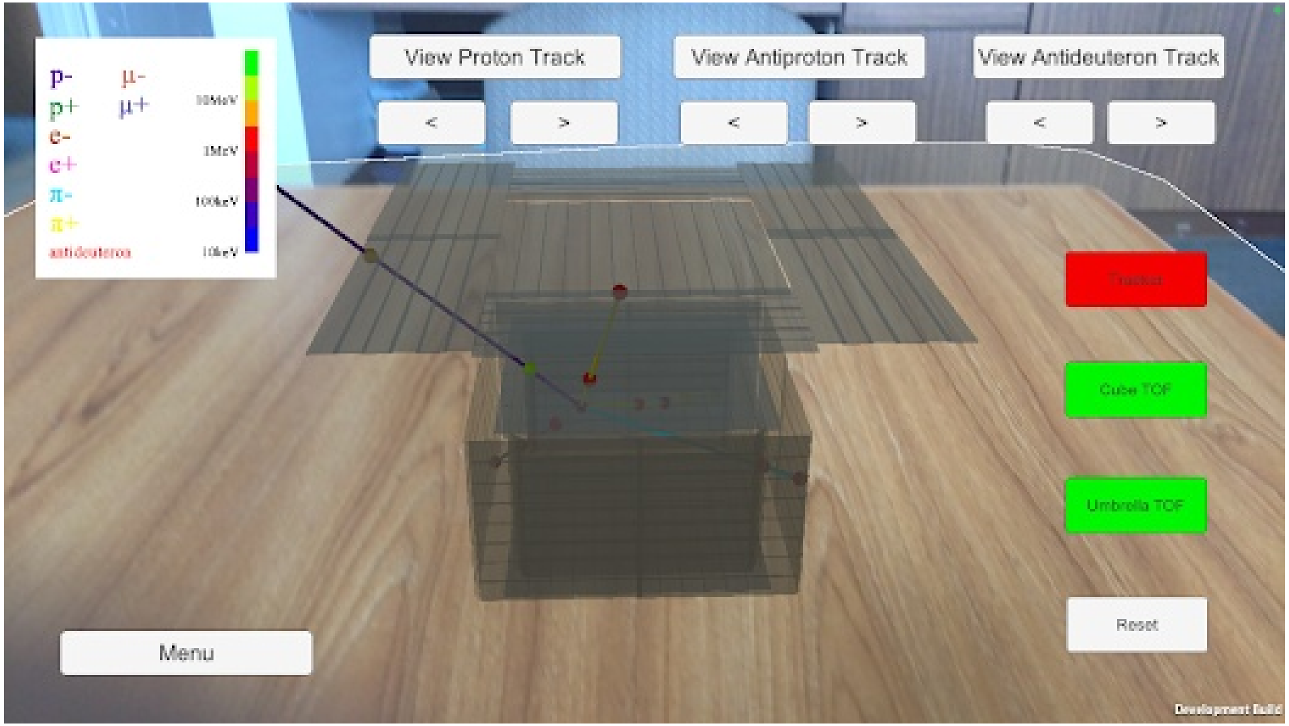

GAPS team - Oct 2019



- **GAPS will deliver:**
  - a precision antiproton measurement in an unexplored energy range <0.25 GeV/n
  - antideuteron sensitivity 2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range
  - the only complementary probe of the AMS-02 antinuclei signal

- GAPS instrument integration is ongoing → **first flight in austral summer 2023**

GAPSimulator AR app

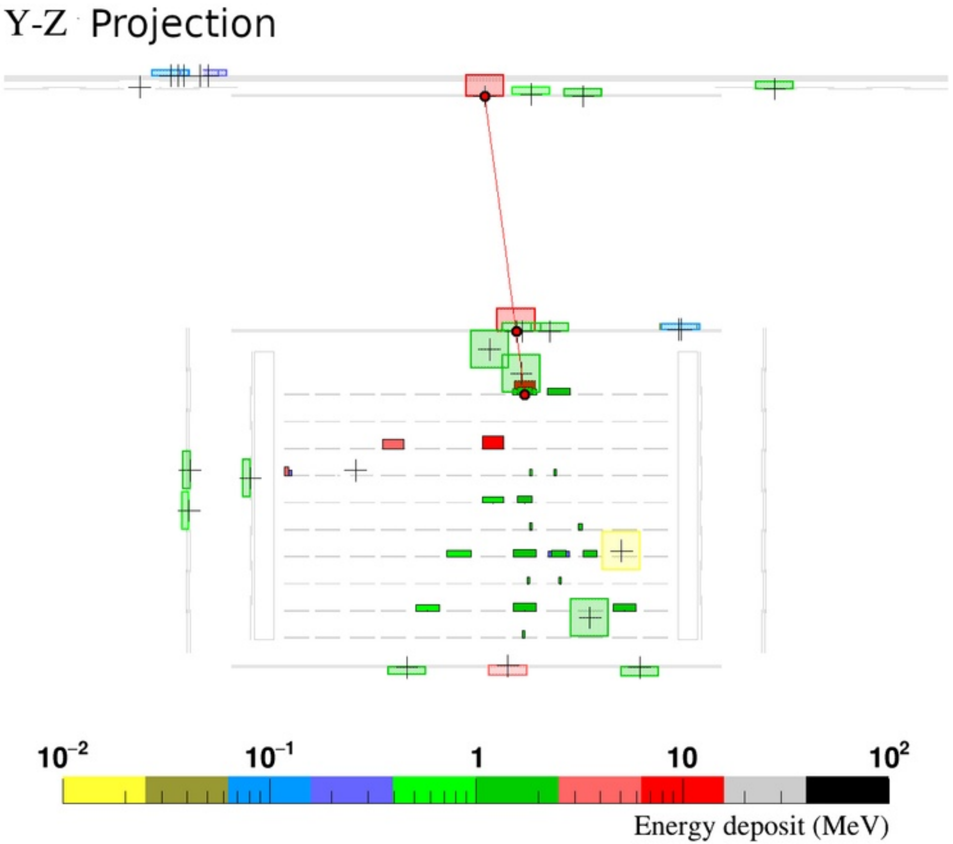


Get it on the PlayStore and App store → search for “GAPSimulator“
Developed by UH undergrads: Layne Fujioka, Ben Weiss, Zac Bailey

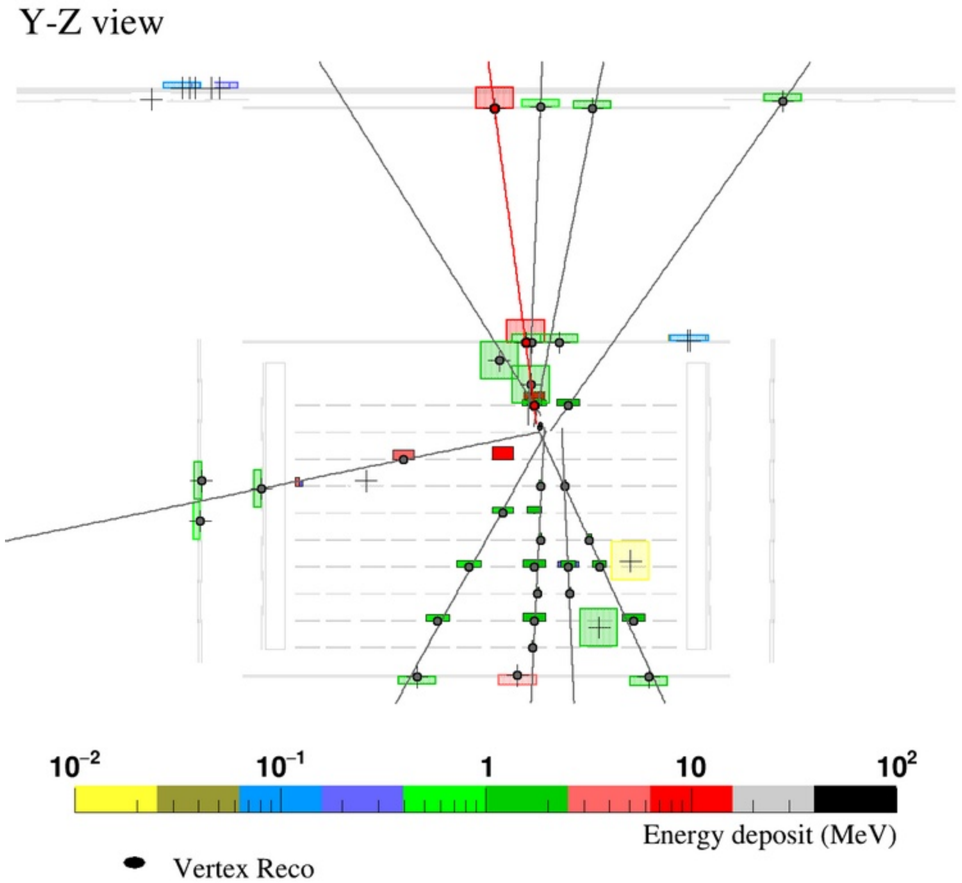
Event reconstruction

R. Munini et al., Astropart. Phys. 133, 102640 (2021)

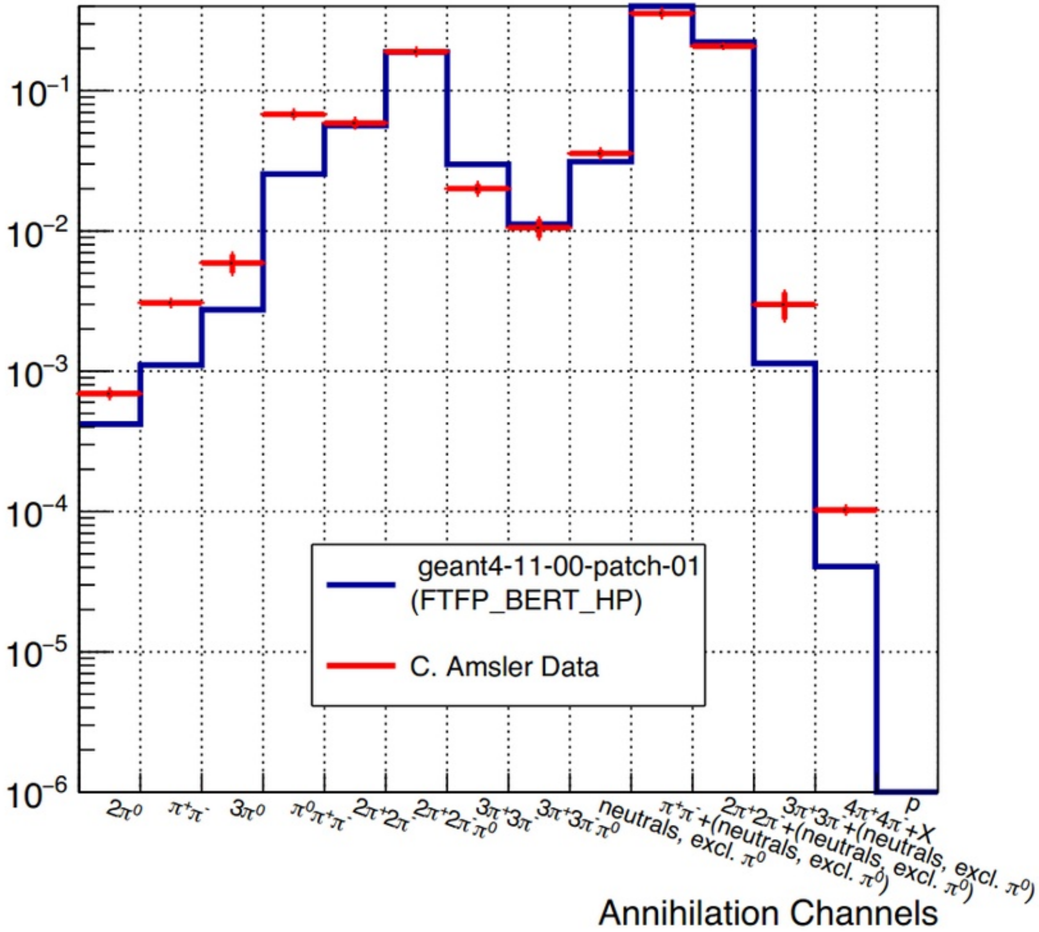
Primary track reconstruction



Annihilation track reconstruction

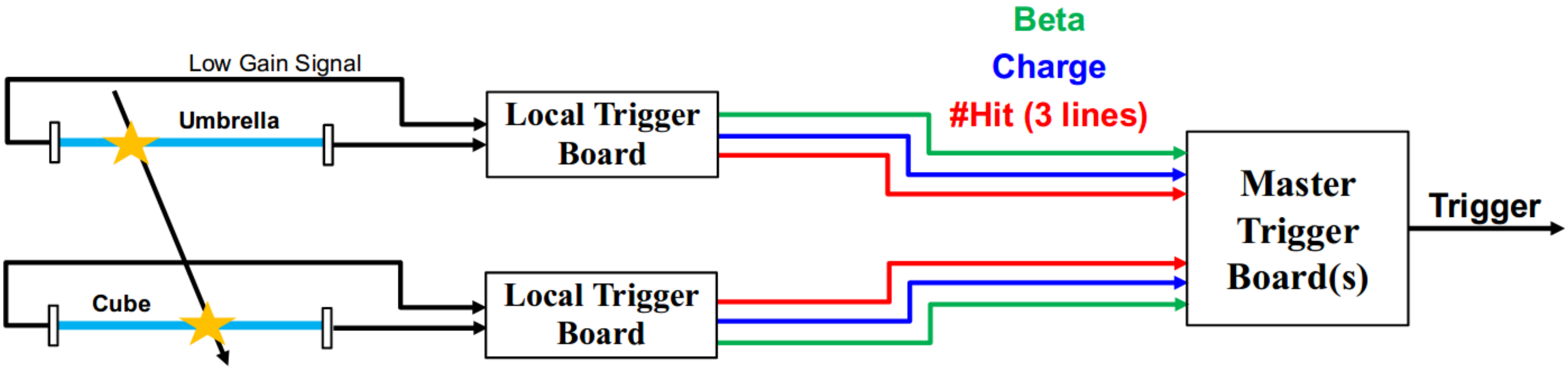


$\bar{p}$+p annihilation at rest



- test of annihilation physics in Geant4 is ongoing
- use antiproton data for validation
- work with Geant4 developers

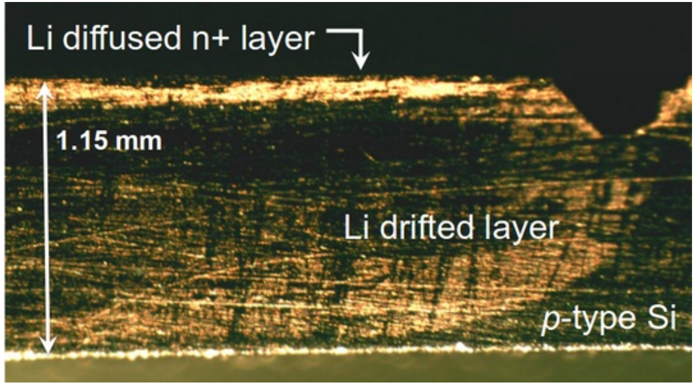
Trigger design

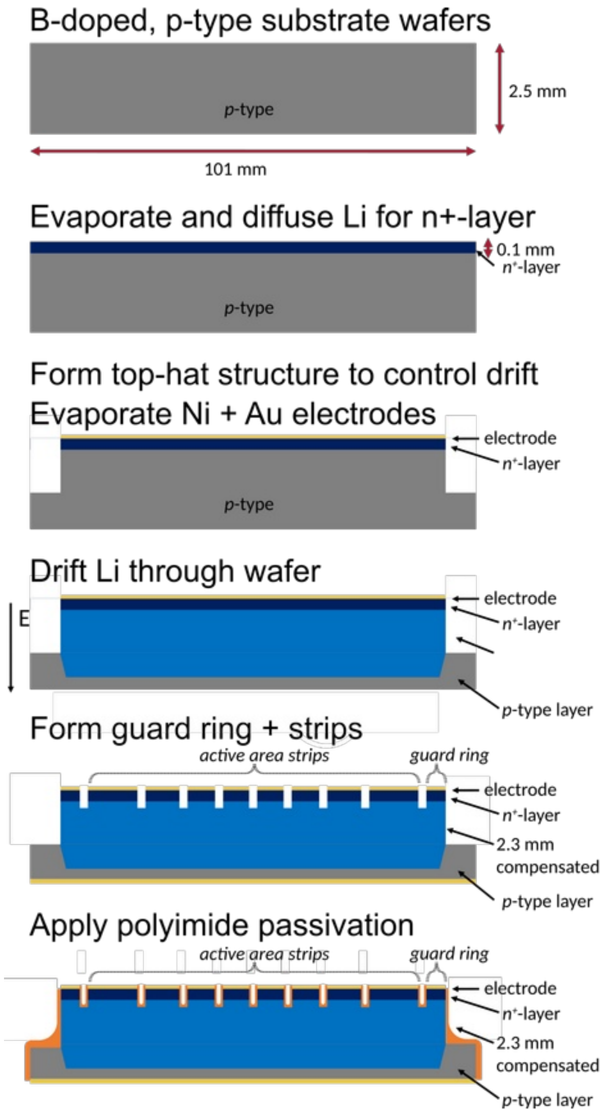


- main background: protons, alpha, carbon
- High-speed trigger and veto:
    - stopping events deposit more energy (lower beta)
    - annihilation events produce more TOF hits
    - paddle combinations can be used to constrain to zenith angle
- **smart combination reduces trigger rate to be below 500Hz**

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 (4.6days at 600V and 100C)
- ultrasonic machining on the n+(Li) contact → guard ring structure, reduces leakage current, much better energy resolution
- electrodes are thermal-evaporated ohmic/blocking contacts
- Passivation is applied




B-doped, p-type substrate wafers

Evaporate and diffuse Li for n+-layer

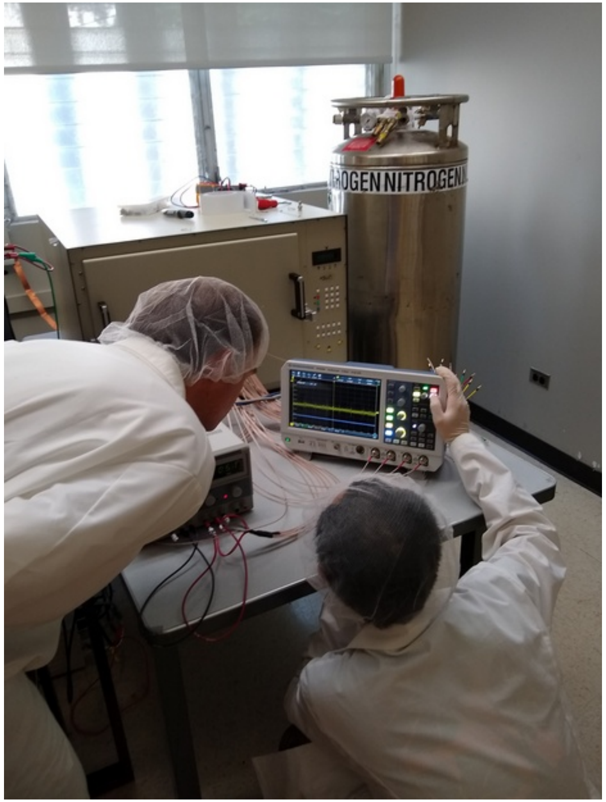
Form top-hat structure to control drift
Evaporate Ni + Au electrodes

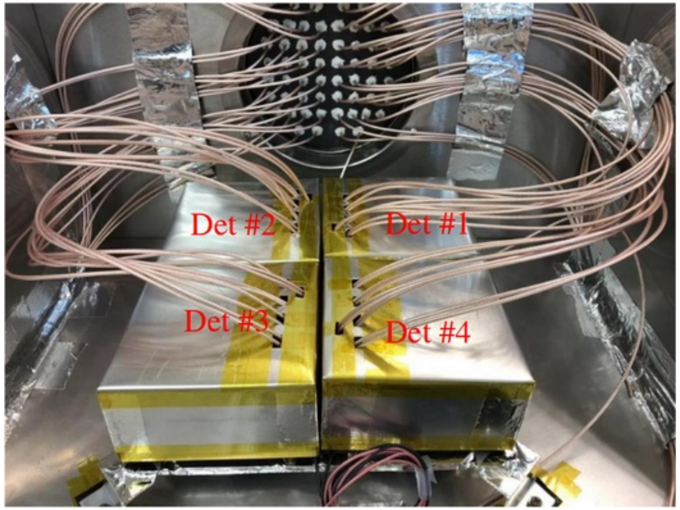
Drift Li through wafer

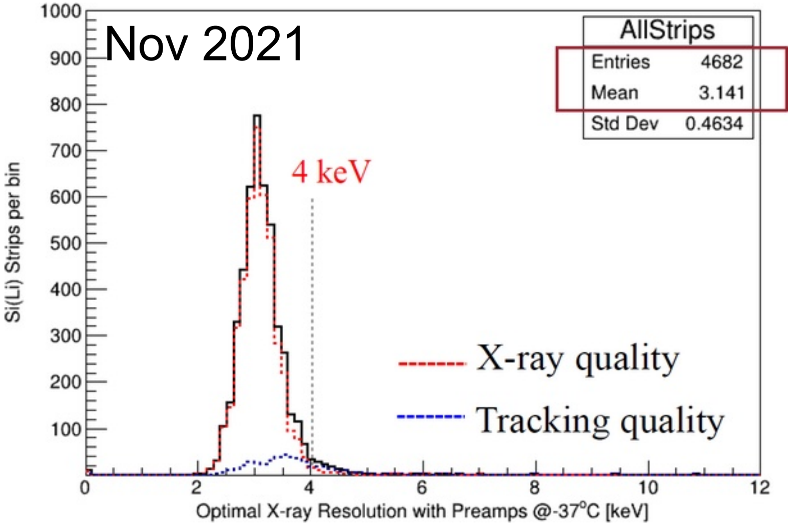
Form guard ring + strips

Apply polyimide passivation

Tracker qualification

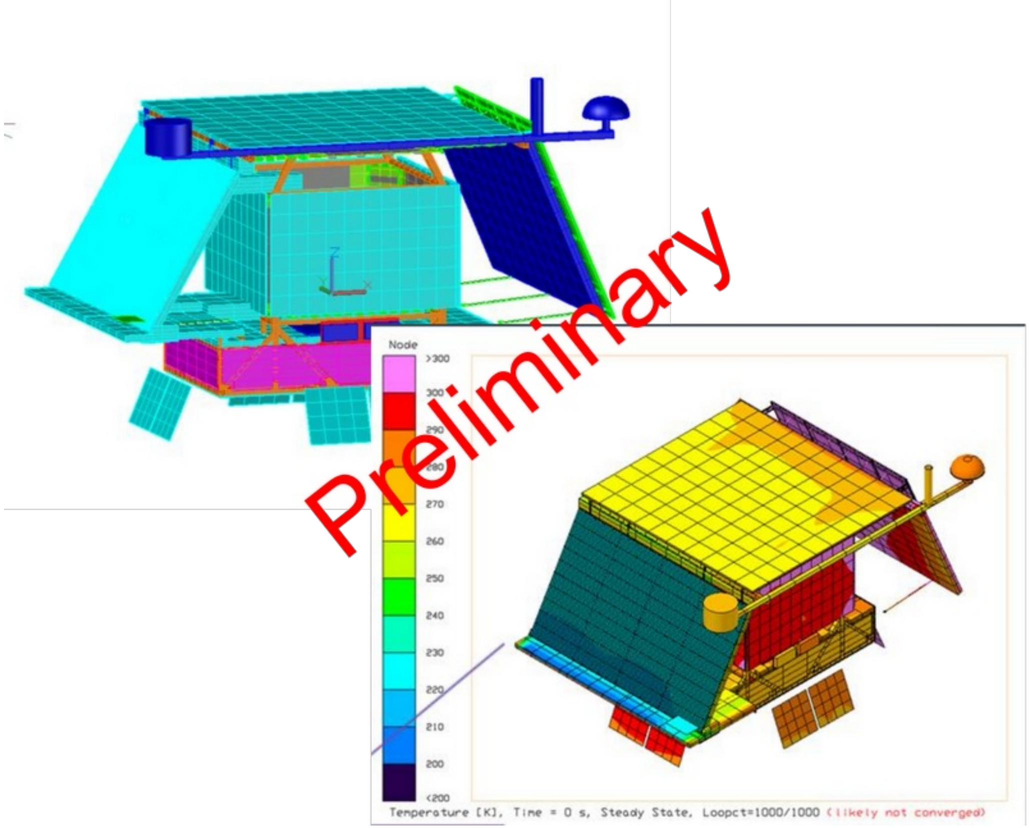


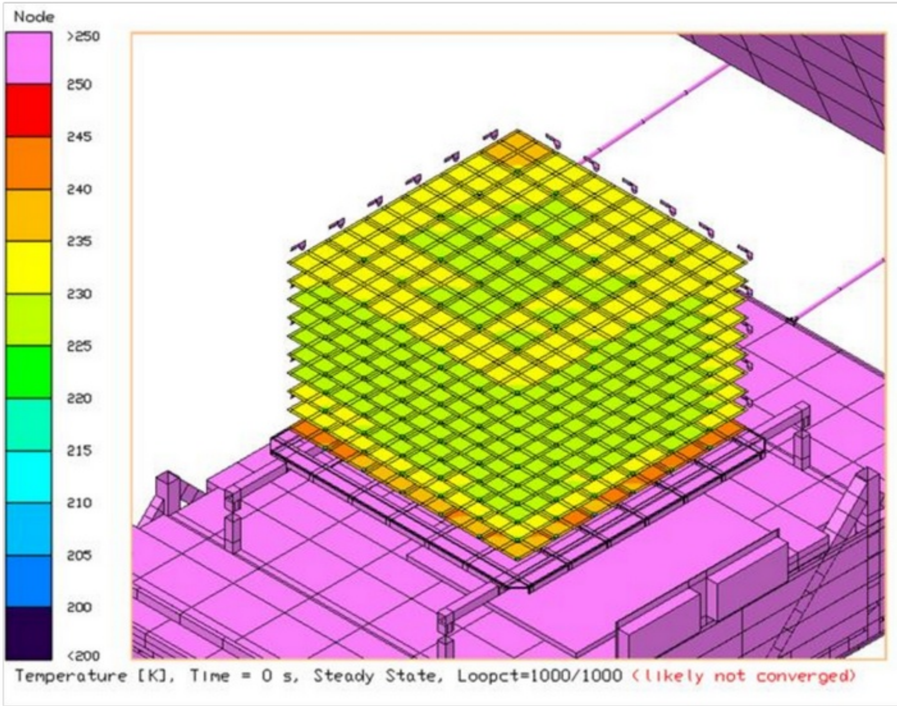




- Single detector test shows the required resolution of the detectors
- Detector module calibration facilities are set up at MIT and UHM
- All modules calibrated

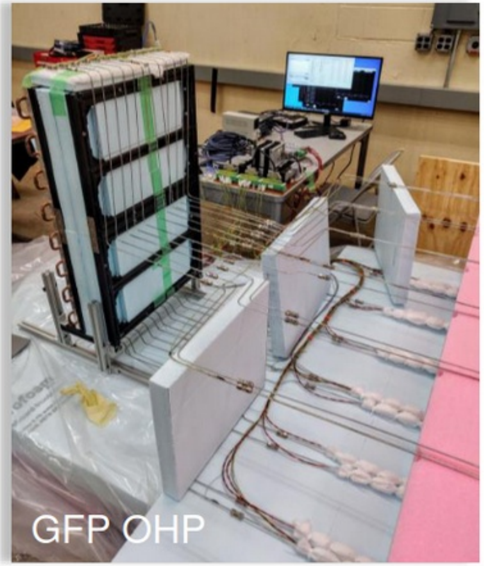
Oscillating heat pipe cooling system

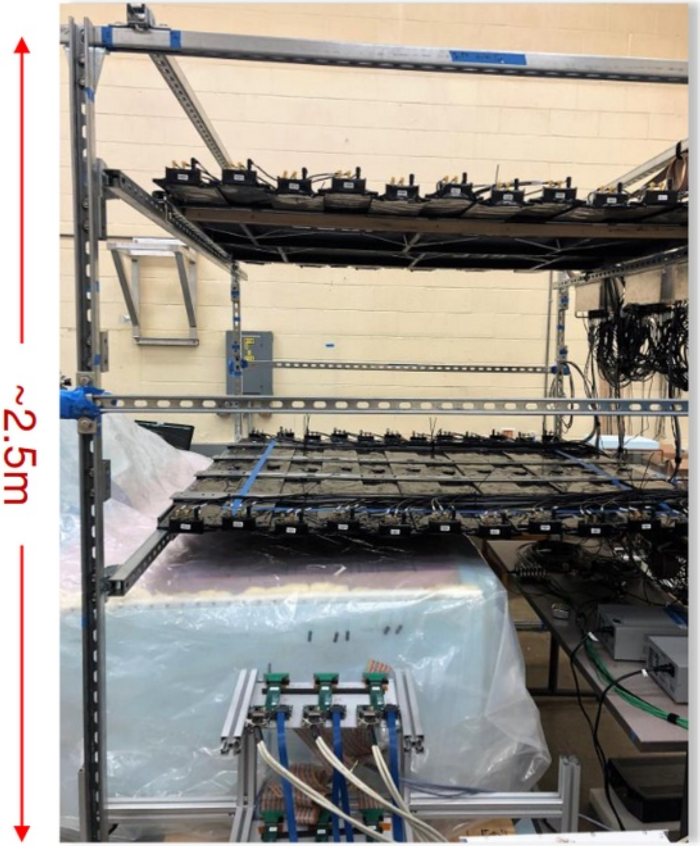


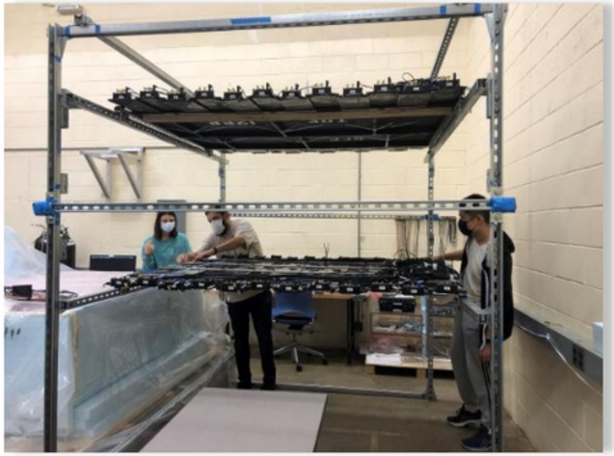


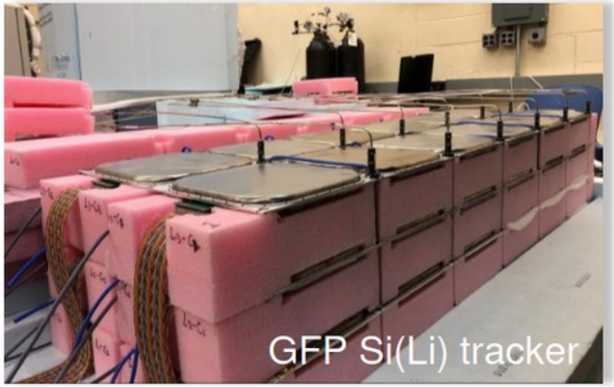
- Most of the Si(Li) detectors are cooled down to lower than -40C. Thermal design will be further optimized to satisfy all detector temperature requirements

GAPS Functional Prototype (GFP)









- Protoype: 3 layers of Si(Li) tracker (36 modules): readout with flight ASIC, 2 layers of TOF above
- **Goals:** test and operate all components together, test readout chain, collect X-ray data, collect muon data