The GAPS Antarctic Balloon Mission:
A Dark Matter Search with Cosmic-ray Antinuclei

Field Rogers on behalf of the GAPS Collaboration

TeVPA ⬩ September 2023

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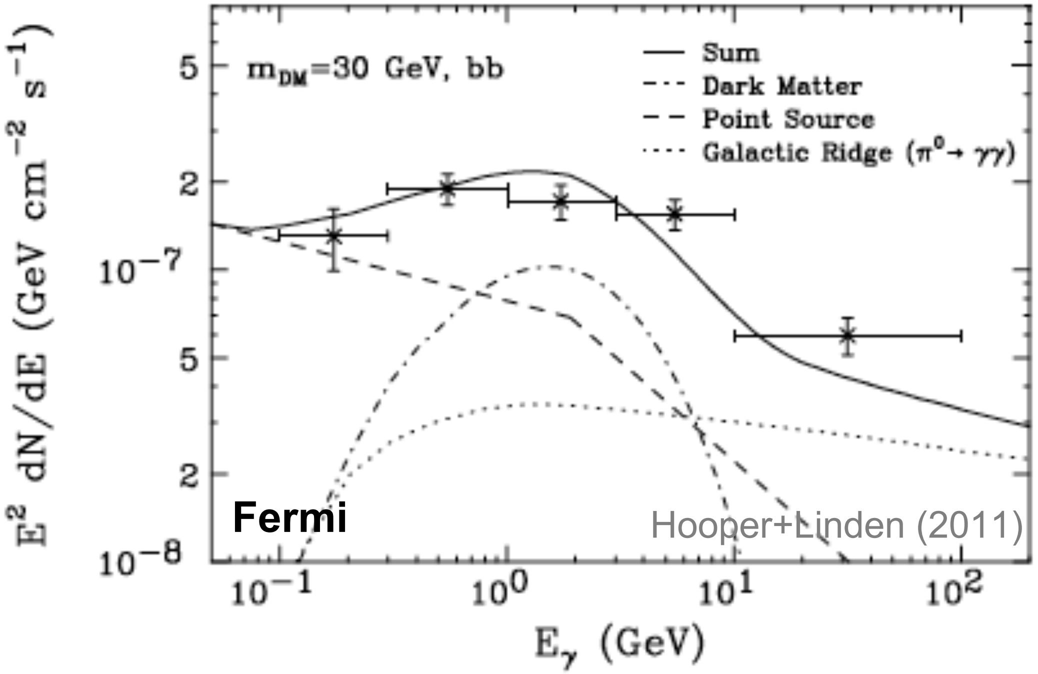
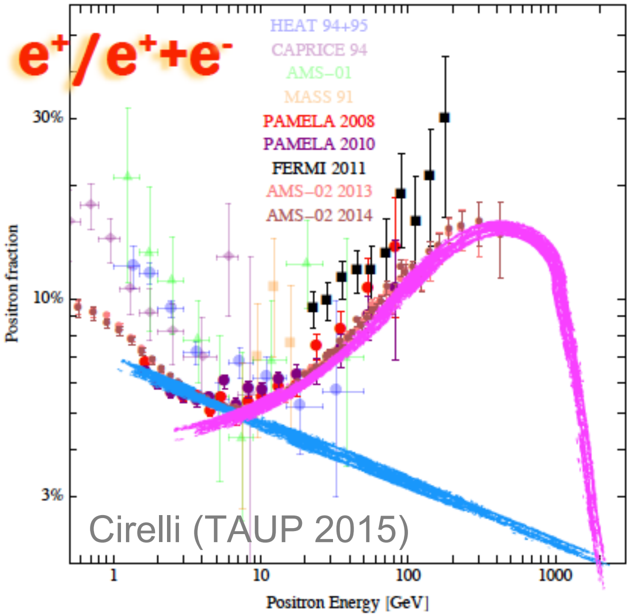
The Challenge of Cosmic-ray Dark Matter Searches

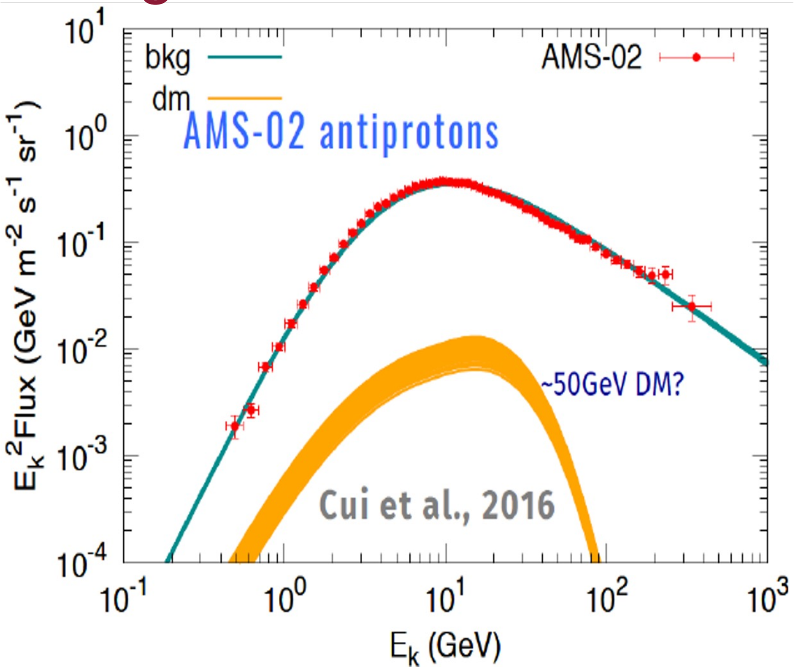
Cosmic rays are full of surprises!

There have been tantalizing hints of new physics…

But all are vulnerable to uncertain astrophysical background.







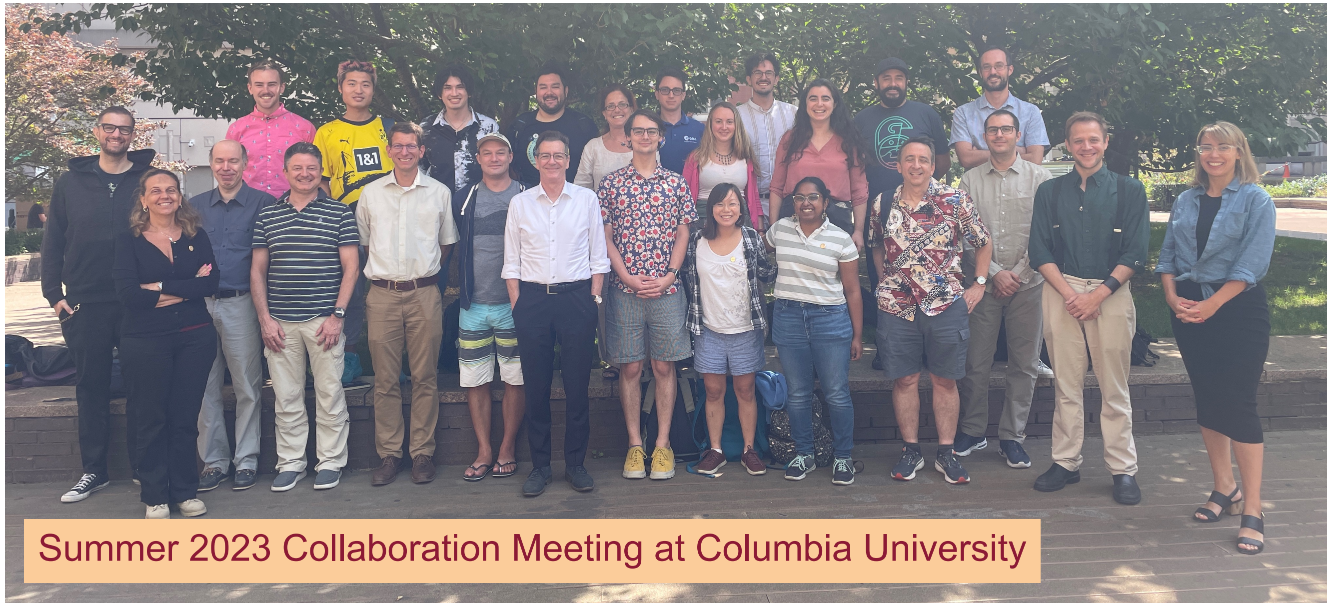
Low-energy antideuterons are a new physics signature essentially free of astrophysical background.

Donato, Fornengo, Salati, PRD 62 (2000)
Donato, Fornengo, Maurin, PRD 78 (2008)

The General Antiparticle Spectrometer (GAPS)

- **First experiment optimized for low-energy antideuterons**
- Novel particle identification strategy based on exotic atoms
  - Rejection power for positive nuclei
  - Antinucleus identification based on several orthogonal probes
  - Large sensitive area within the constraints of a high-altitude mission
- 3x 35-day Antarctic balloon flights
  - ~37 km anticipated float altitude
  - Low geomagnetic cut-off
  - Long exposure over land
- **First GAPS flight Dec 2024**

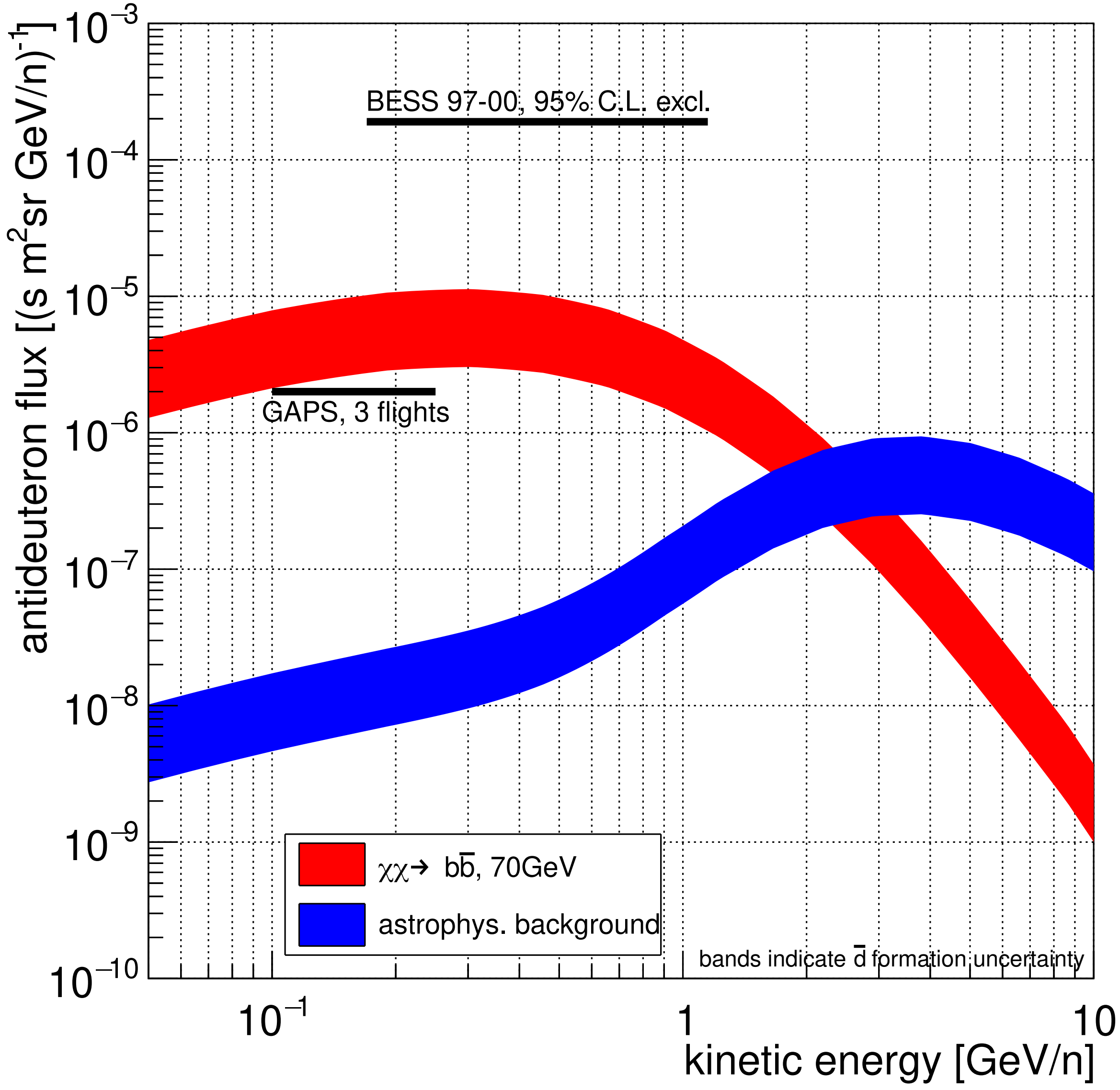
C Hailey, New J Phys. 11 (2009)



Summer 2023 Collaboration Meeting at Columbia University

Low-energy antideuterons: A clean signature of new physics

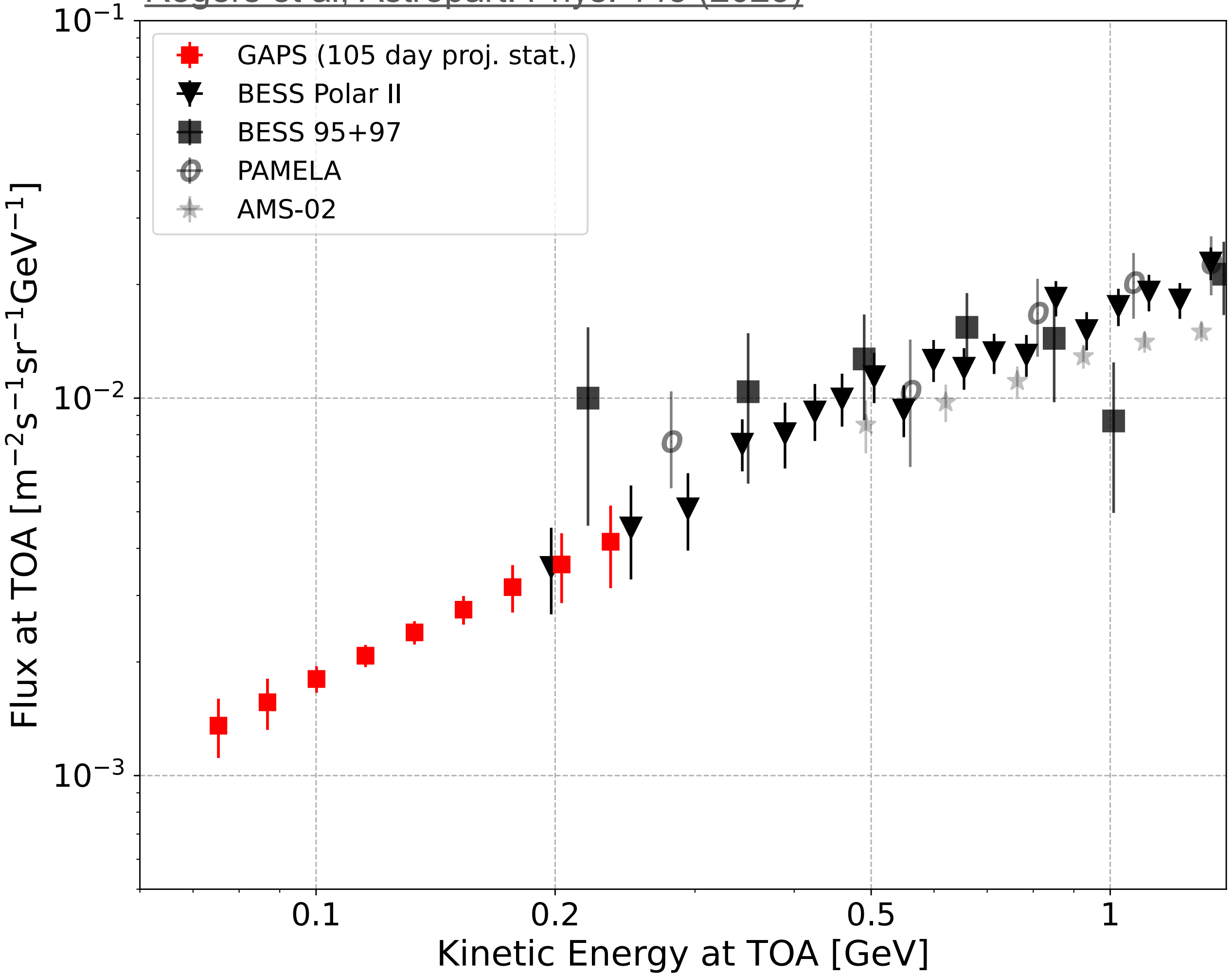
- Astrophysical production is kinematically suppressed at energies below a few GeV/*n.*
- Predicted flux from a variety of viable DM models exceeds background by several orders of magnitude for energies of order 100 MeV.
  - Includes models that evade direct detection and collider-based searches
- **GAPS is designed to detect $\bar{d}$ as a smoking-gun DM signature.**
  - A GAPS detection would mean new physics
  - 2 orders of magnitude improved sensitivity compared to current best limits



Low-energy antiprotons: Precision spectrum at unexplored energies

- GAPS will provide a precision $\bar{p}$ spectrum in a previously-unexplored energy range:
  - ~500 $\bar{p}$ per LDB flight
- Validate the GAPS technique using flight data
  - First cosmic-rays detected using exotic atoms for particle identification
  - Reconstruction of exotic atoms
  - X-rays from de-excitation
- Test models of atmospheric attenuation and production
- Probe light DM models and local primordial black hole evaporation

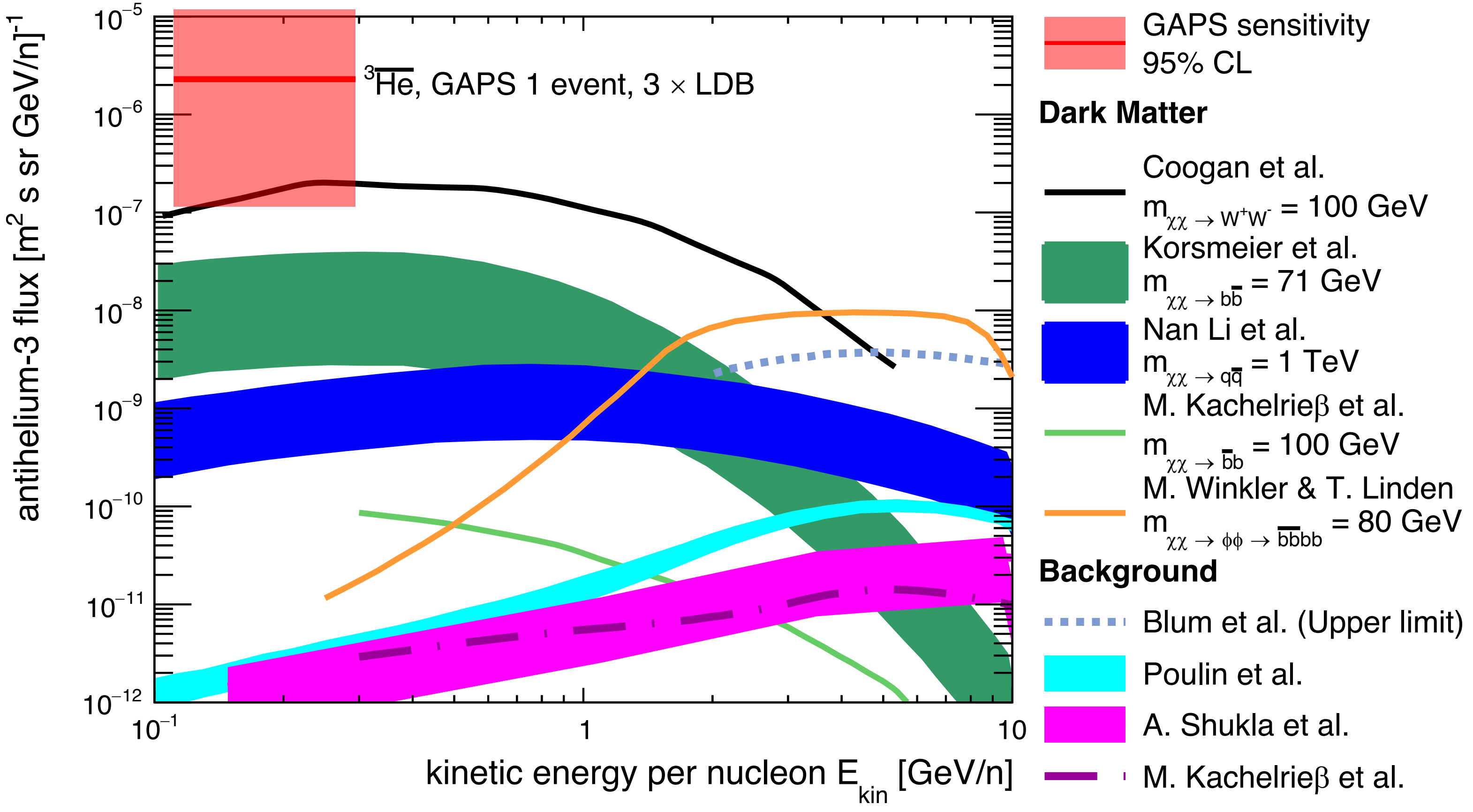
Rogers et al, Astropart. Phys. 145 (2023)



Low-energy antihelium-3: A new probe of hinted anomalies

- GAPS offers sensitivity to $^3\overline{\text{He}}$ with orthogonal instrument systematics compared to AMS.
- Low-energy sensitivity can help distinguish origin of AMS $^3\overline{\text{He}}$ candidates.
- Finding low-energy $^3\overline{\text{He}}$ would be revolutionary new physics.

Saffold et al., Astropart. Phys. 130 (2021)
Stoessl et al., POS ICRC (2021)



How it works:
Particle Identification using Exotic Atoms

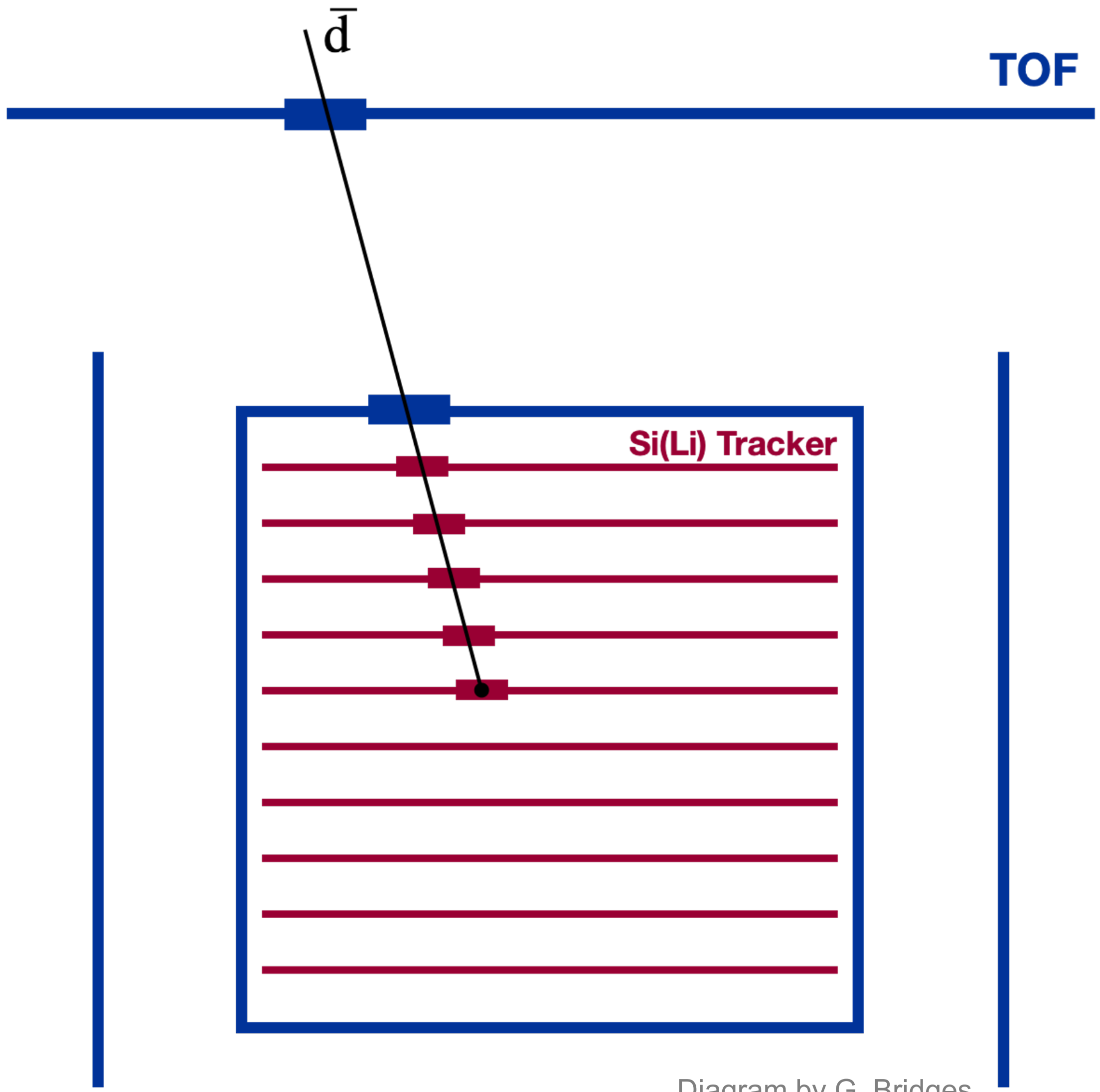


Diagram by G. Bridges

When an antinucleus encounters GAPS:

- Antinucleus traverses the TOF, which measures **velocity** and **d*E*/d*x* losses**
- It slows to stop in the tracker, where it is captured by a target nucleus to form an exotic atom in an excited state

Exotic atom technique verified at KEK:
Hailey+, JCAP 0601 (2006)
Aramaki+ Astropart.Phys. 49 (2013)

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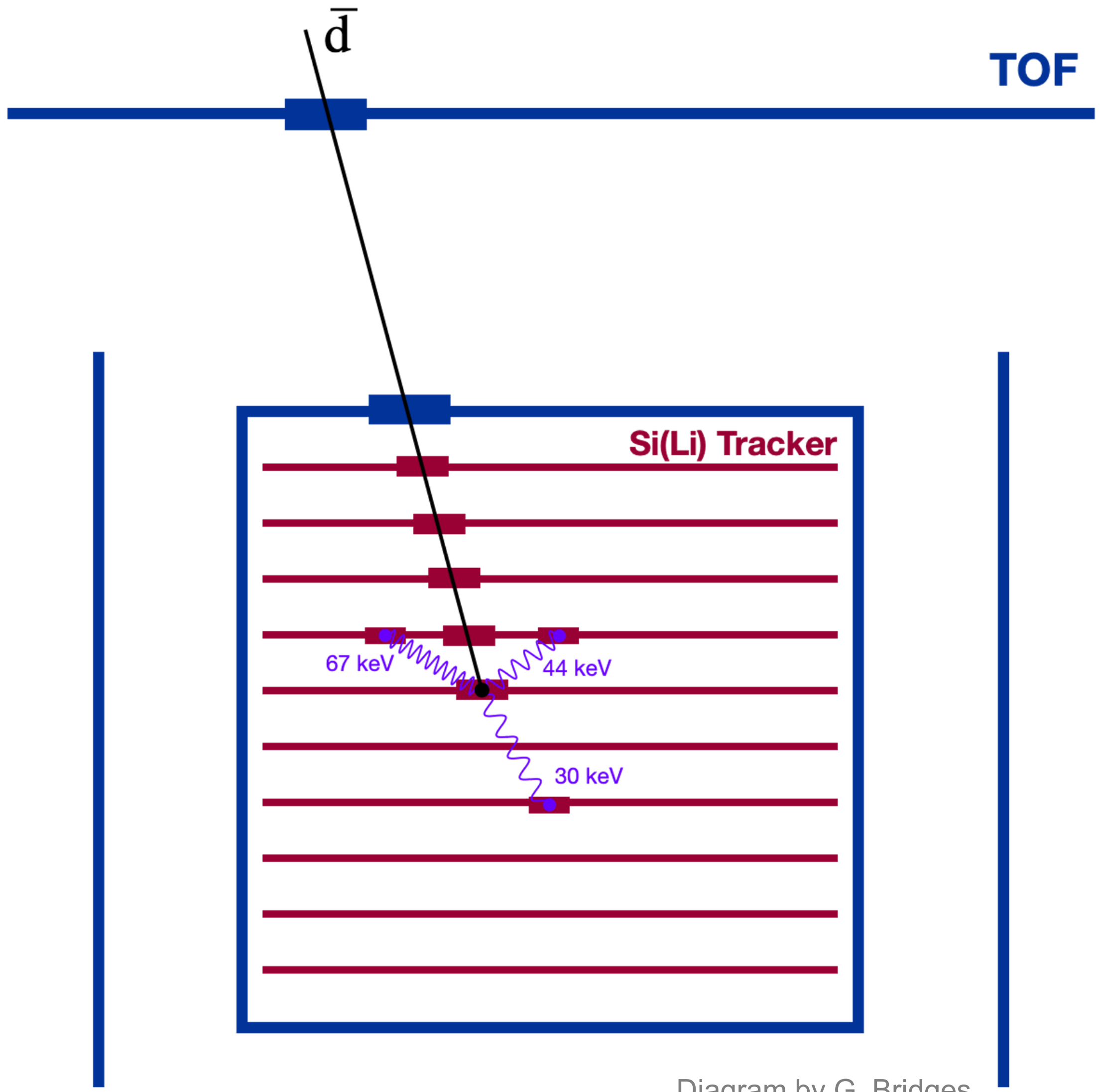

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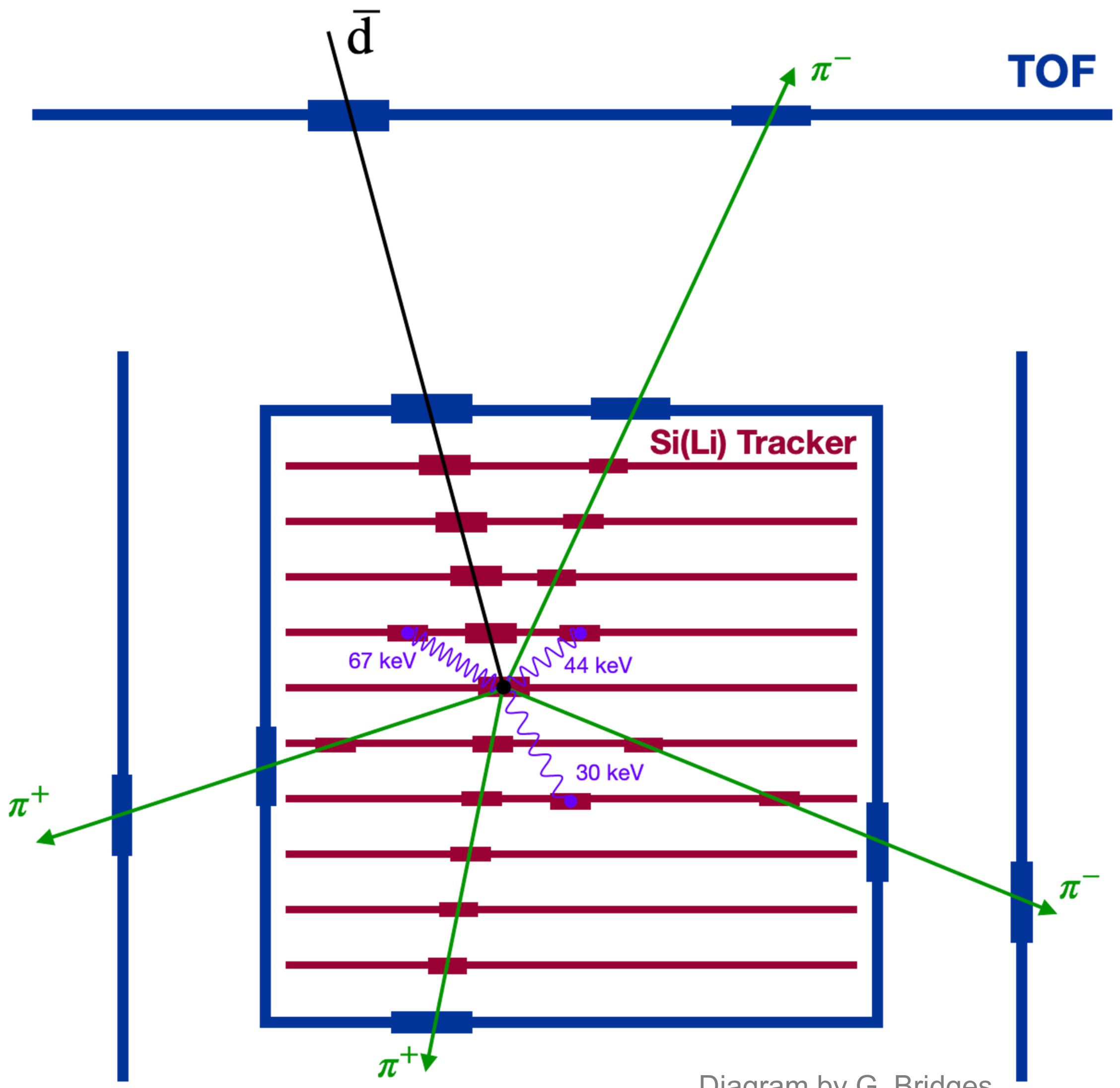

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- The exotic atom de-excites via X-rays (detected in the tracker)
- Then annihilates to secondary hadrons (tracked in the tracker and TOF)

Antinucleus discrimination based on:

- Stopping depth and d*E*/d*x* losses relative to incoming particle velocity
- Multiplicity of secondary hadrons
- X-ray energies

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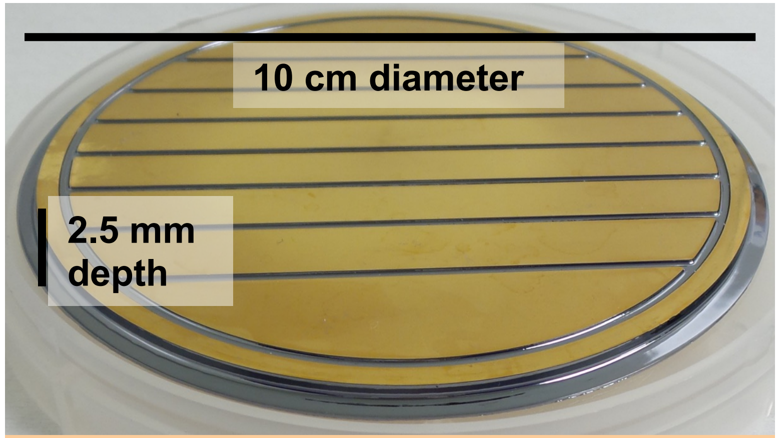
Hailey+, JCAP 0601 (2006)
Aramaki+ Astropart.Phys. 49 (2013)

Silicon Tracker System

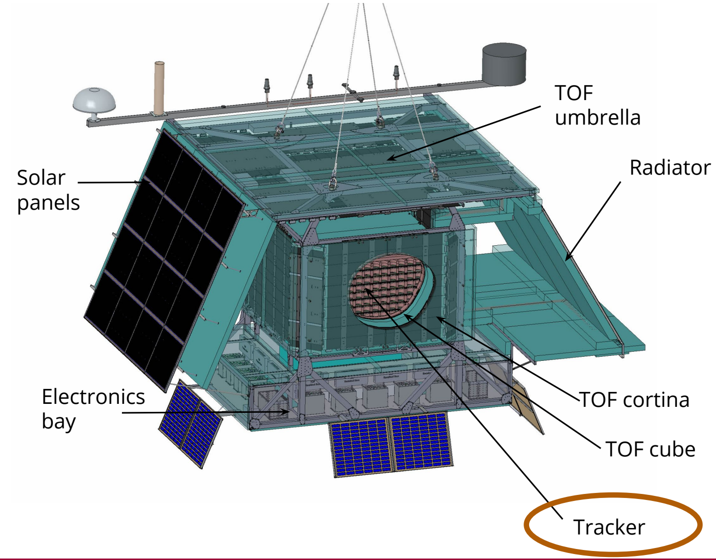
- 2.5m^3 tracker volume
  - 1060 custom silicon sensors
  - 10 layers (7 with active sensors)
- Individually-calibrated modules of 4 sensors with readout electronics
  - X-ray energy resolution <4 keV (FWHM)
  - <10% energy resolution up to 100 MeV
- Operates around –35°C
  - In-flight cooling based on integrated oscillating heat pipe (OHP) system

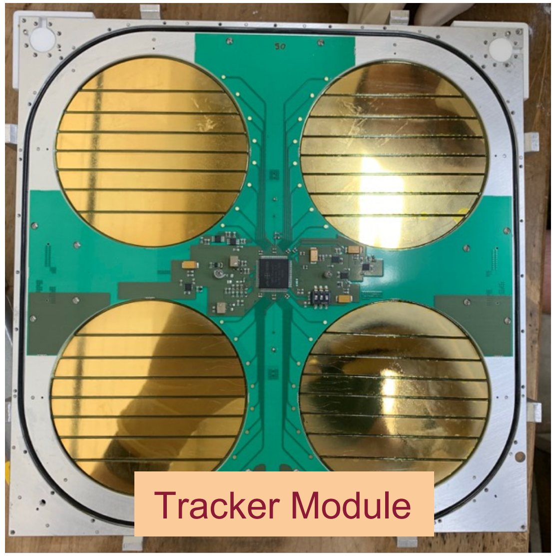


8-strip lithium-drifted silicon (Si(Li)) sensor

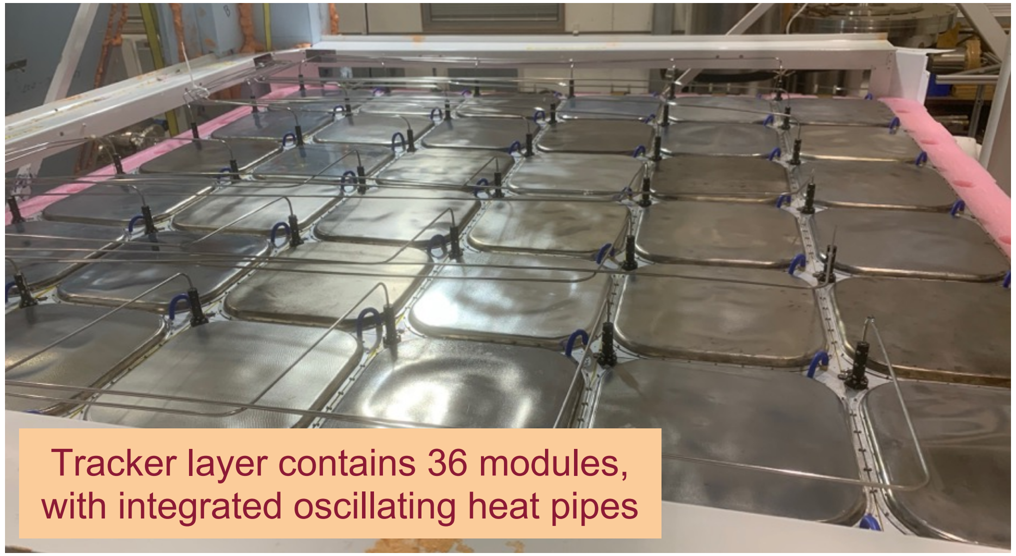
Si(Li):
Perez et al., NIM A 905 (2018)
Kozai et al., NIM A 947 (2019)
Rogers et al., JINST 14 (2019)
Saffold et al., NIM A 997 (2021)
Kozai et al., NIM A 1034 (2022)
Xiao et al., IEEE 70 (2023)

ASIC:
Manghisoni et al., IEEE 62 (2015)
Manghisoni et al., IEEE 68 (2021)





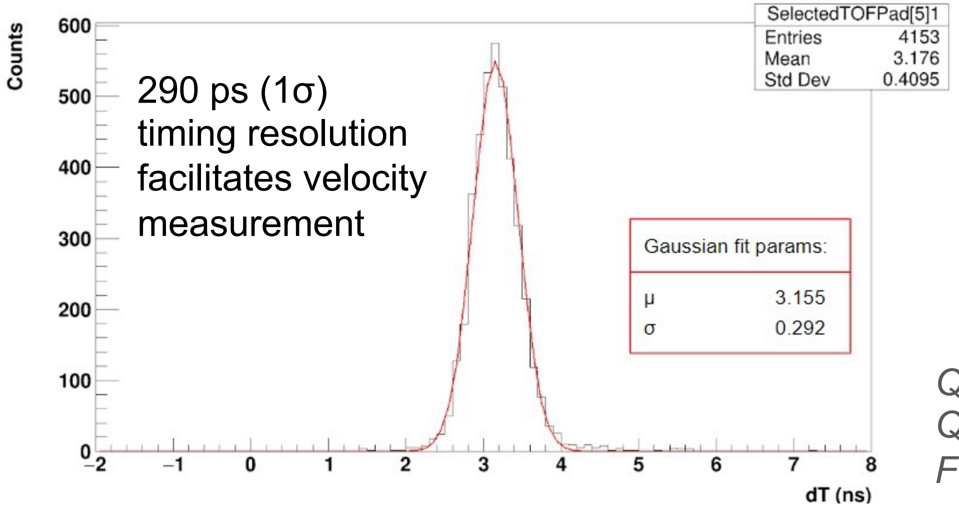
Tracker Module



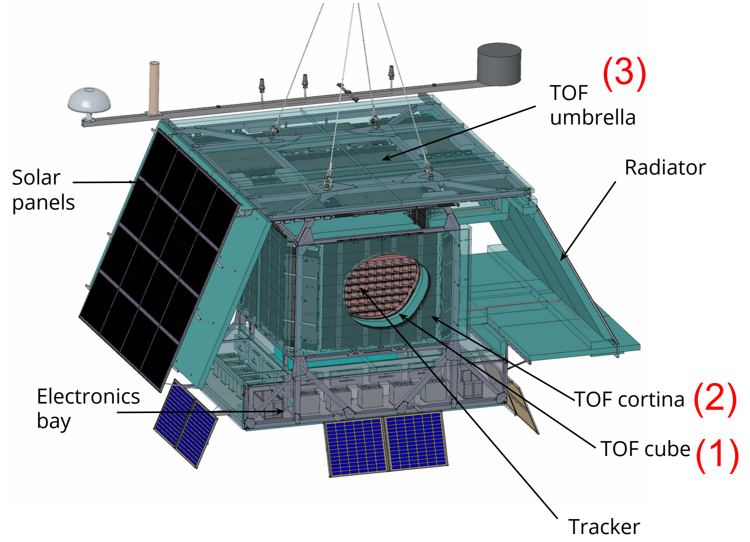
Tracker layer contains 36 modules, with integrated oscillating heat pipes

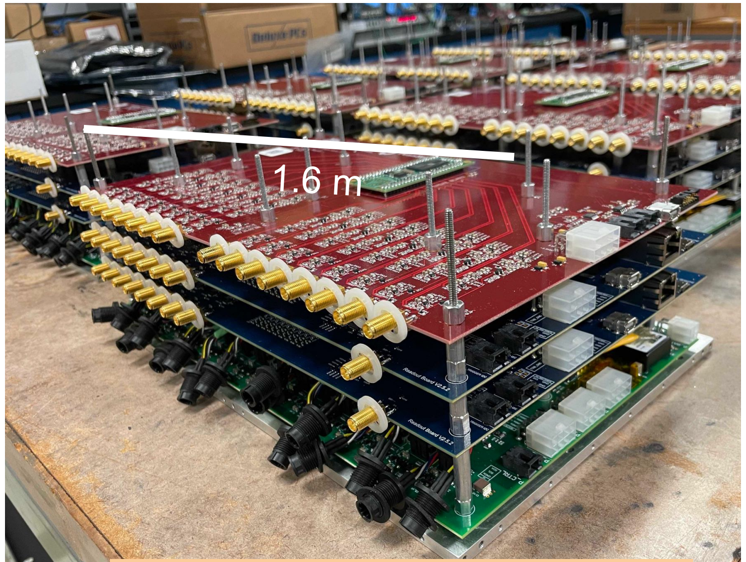
Time-of-flight (TOF) System

- 25 m^2 scintillator in 21 panels:
  - Cube encloses the tracker
  - Cortina ~30 cm from cube sides
  - Umbrella ~90 cm from cube top
- Velocity measurement is the basis of the GAPS energy scale
- System-level trigger generation
- Track reconstruction relies on >99% hermeticity of TOF cube

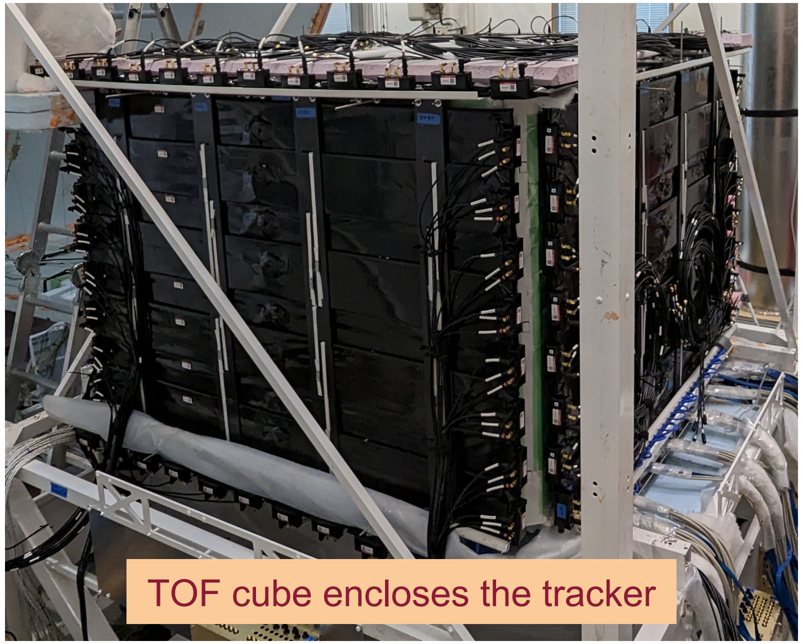


Quinn et al., POS ICRC 2019
Quinn et al., POS ICRC 2021
Feldman et al, POS ICRC 2023





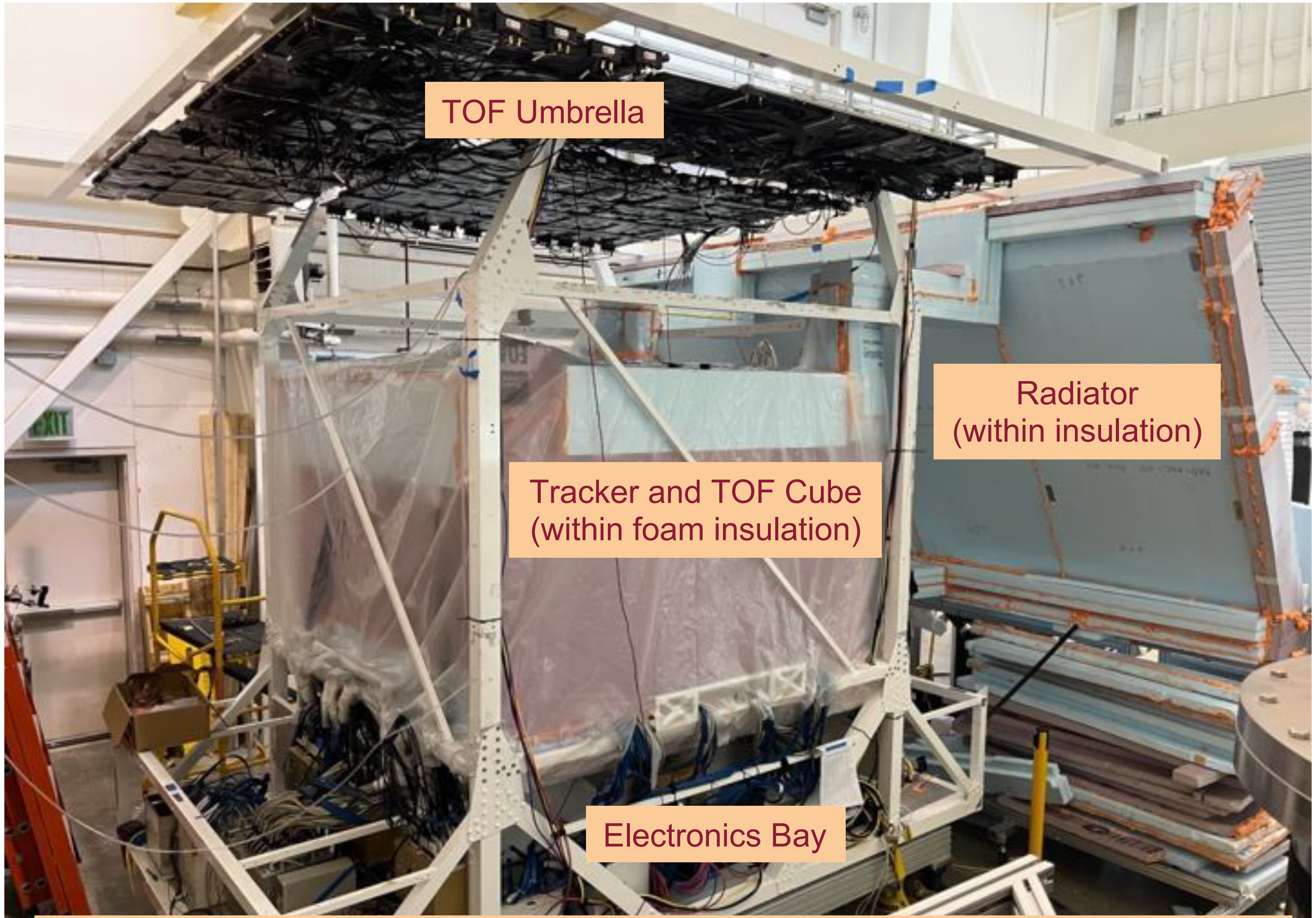
Readout and trigger electronics



TOF cube encloses the tracker

Payload Integration and Functional Testing

- GAPS payload integration March 2022 – May 2023
- GAPS has demonstrated:
  - Instrument readout based on ground (MIP) trigger
  - Data readout pipeline, from sensors to ground computers
  - Thermal control of tracker using OHP with ground cooling system
  - Control of payload using flight and ground software



Payload integration in progress in the high bay at UC Berkeley's Space Sciences Lab

Thermal-vacuum Test

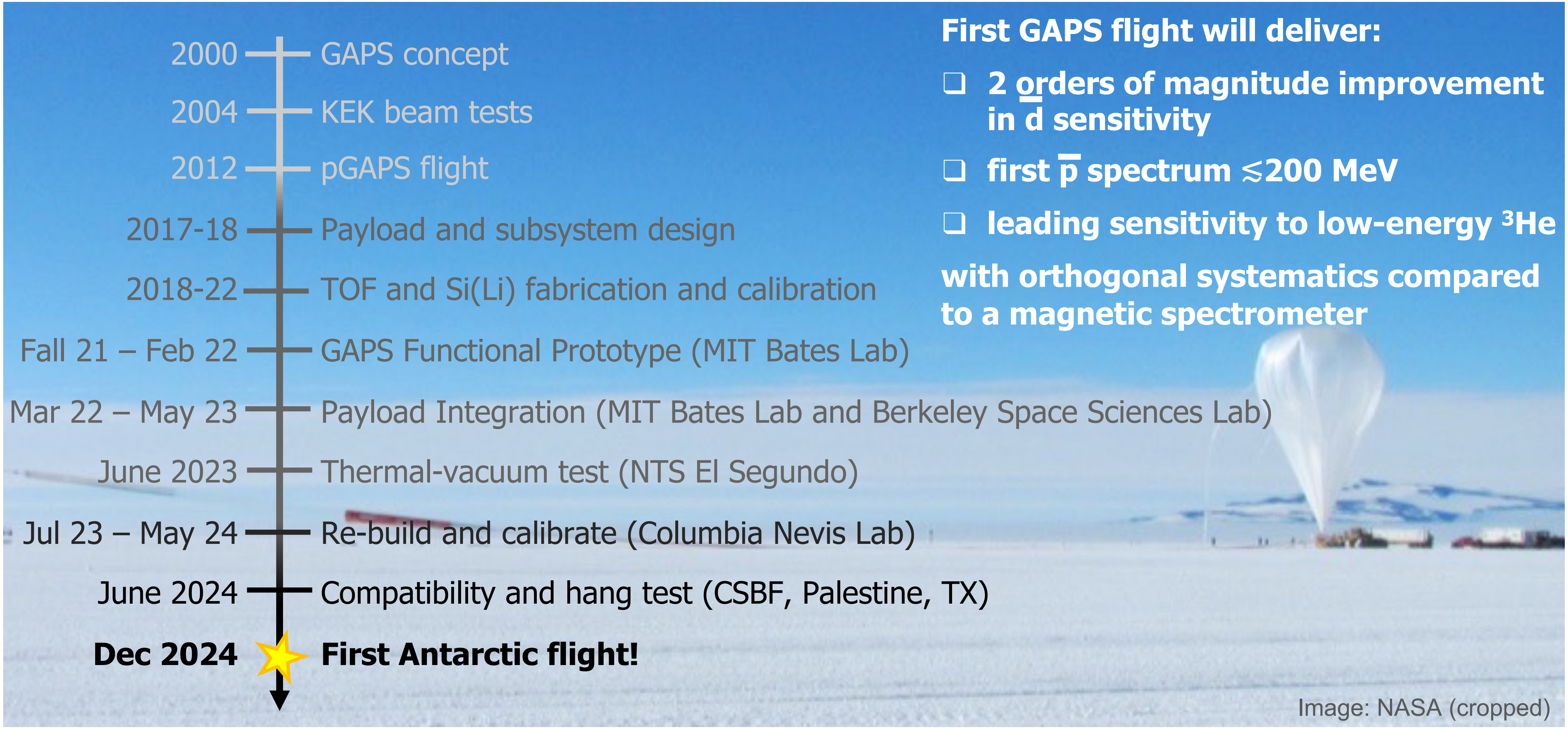
- June 2023 TVAC campaign @ National Technical Systems (NTS) El Segundo, CA
  - ~4 days total remote operation in vacuum

- Test 1 – Electronics, Mechanical
  - Validated functional and thermal performance of detector readout and system electronics
  - Validated payload thermal model

- Test 2 – Tracker Cold
  - Biased silicon detectors and operated at realistic flight pressures

GAPS payload enters the vacuum chamber at the NTS El Segundo facility, outfitted with heater panels to control the thermal environment in the chamber

On to Antarctica!



- 2000 — GAPS concept
- 2004 — KEK beam tests
- 2012 — pGAPS flight
- 2017-18 — Payload and subsystem design
- 2018-22 — TOF and Si(Li) fabrication and calibration
- Fall 21 – Feb 22 — GAPS Functional Prototype (MIT Bates Lab)
- Mar 22 – May 23 — Payload Integration (MIT Bates Lab and Berkeley Space Sciences Lab)
- June 2023 — Thermal-vacuum test (NTS El Segundo)
- Jul 23 – May 24 — Re-build and calibrate (Columbia Nevis Lab)
- June 2024 — Compatibility and hang test (CSBF, Palestine, TX)
- **Dec 2024 — First Antarctic flight!**

First GAPS flight will deliver:

- **2 orders of magnitude improvement in $\bar{d}$ sensitivity**
- **first $\bar{p}$ spectrum $\lesssim$200 MeV**
- **leading sensitivity to low-energy ^{3}He**

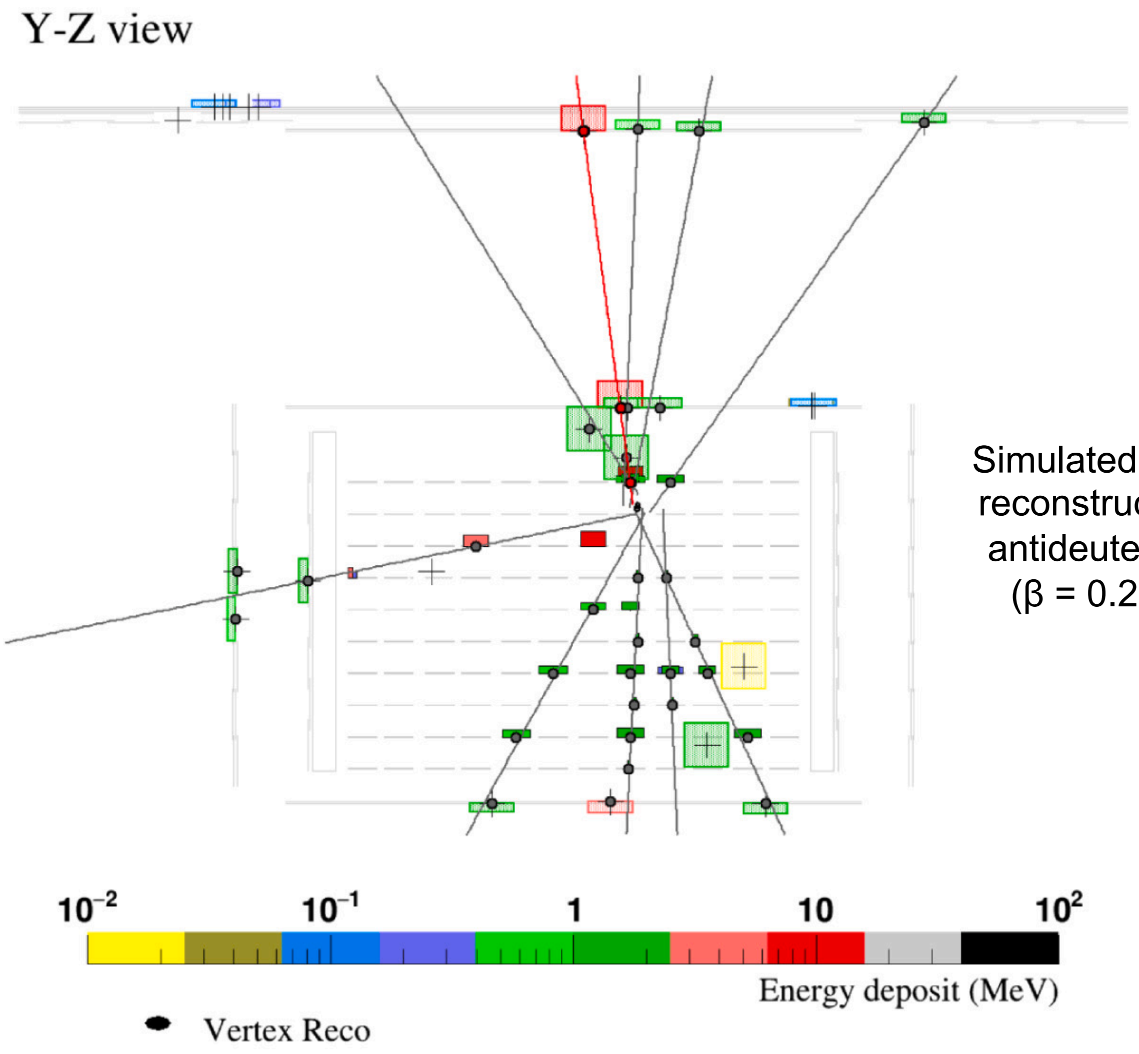
with orthogonal systematics compared to a magnetic spectrometer

Image: NASA (cropped)

Backup

Exotic Atom Event Reconstruction

- 4% velocity resolution for primary track
  - 400 ps TOF timing resolution
  - Primary track identification based on TOF timestamps and energy deposition
- Annihilation vertex reconstructed within 8 cm
  - Custom vertex-finding algorithm using iterative, adaptive, multi-step process
- Secondary track reconstruction based on TOF, tracker hits



Simulated and reconstructed antideuteron (β = 0.28)

Munini et al, Astroparticle Physics 133 (2021)

GAPS Detector Requirements for Particle Identification using Exotic Atoms

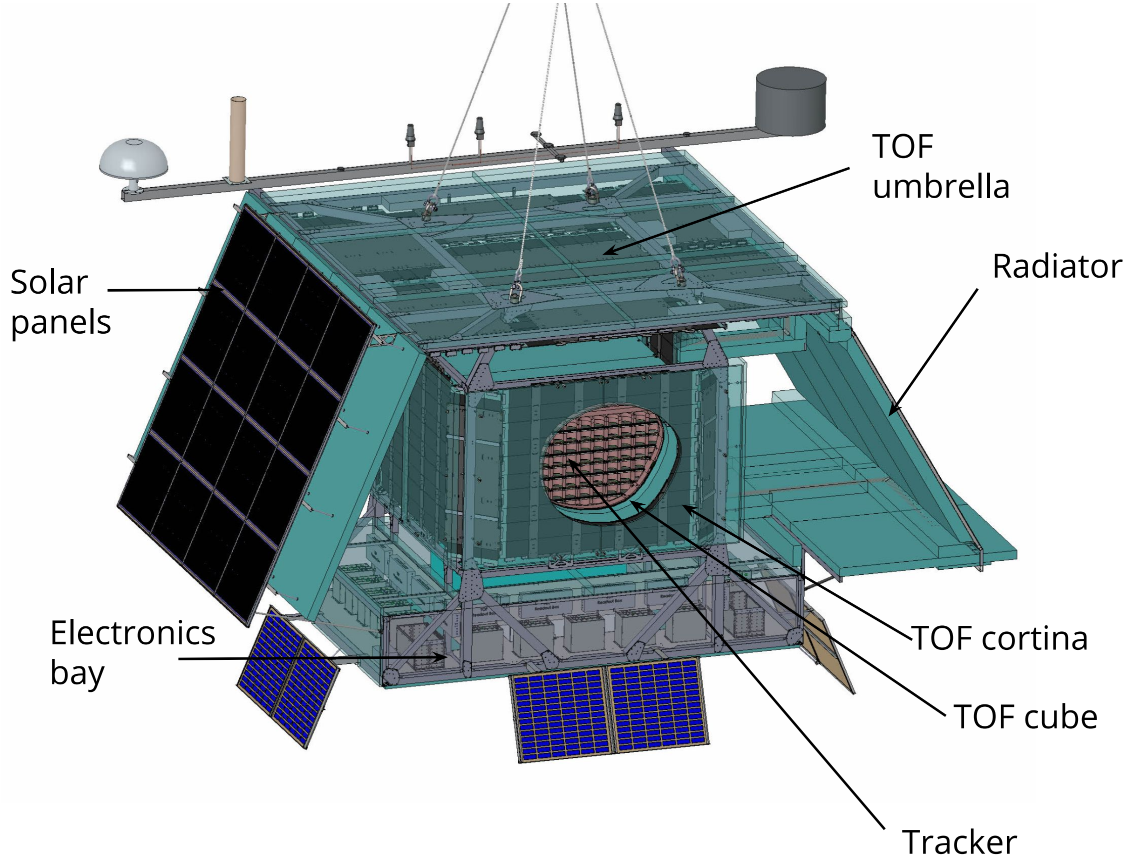


Diagram by G. Bridges

Time-of-Flight:

- ❑ Fast timing for primary velocity measurement
- ❑ Near-hermetic containment of tracker to provide at least 1 hit for >99% of secondaries
- ❑ Provide system trigger based on multiplicity, geometry, and energy of TOF hits

Tracker:

- ❑ Target to contain light nuclei $\lesssim 0.25$ GeV/*n*
- ❑ Tracker for primary and secondary hadrons
- ❑ Spectrometer for de-excitation X-rays

Both:

- ❑ Large sensitive area for rare events
- ❑ dE/dx for MIPs and slow particles with $|Z| = 2$
- ❑ Operate without cryostat or pressure vessel
- ❑ Low-power operation (solar powered!)

Powerful for GAPS: Particle Identification using Exotic Atoms

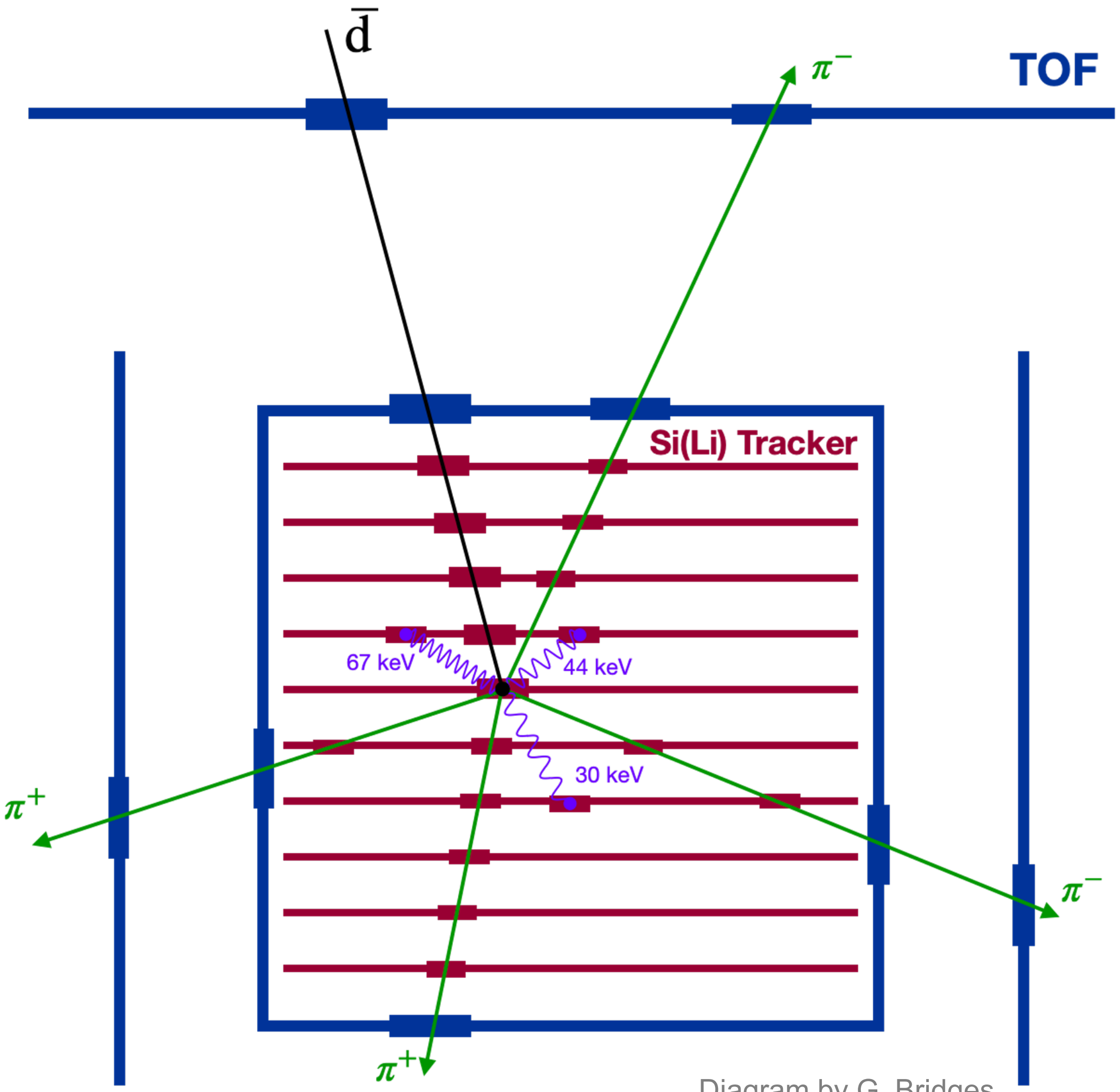


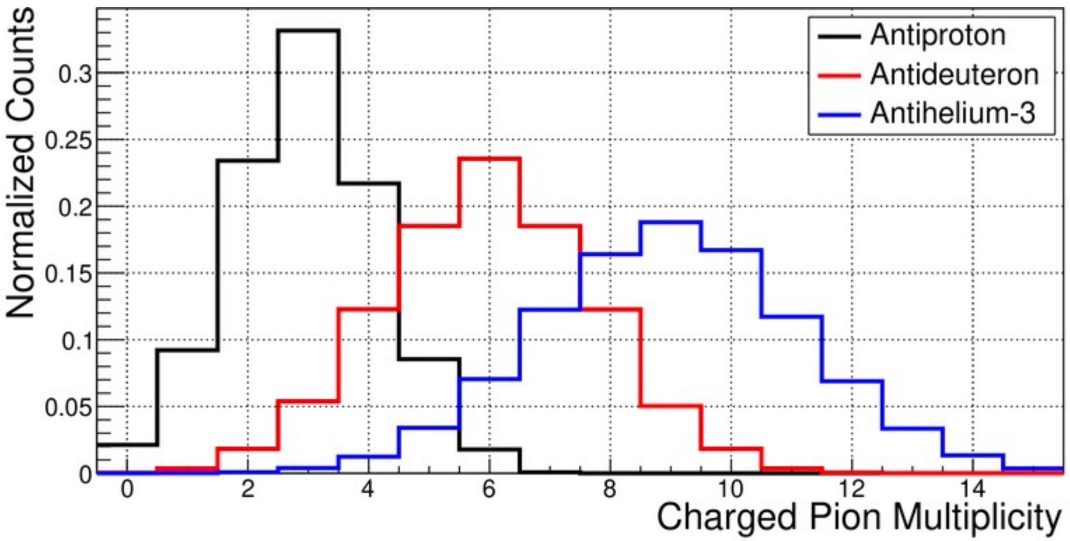
Diagram by G. Bridges

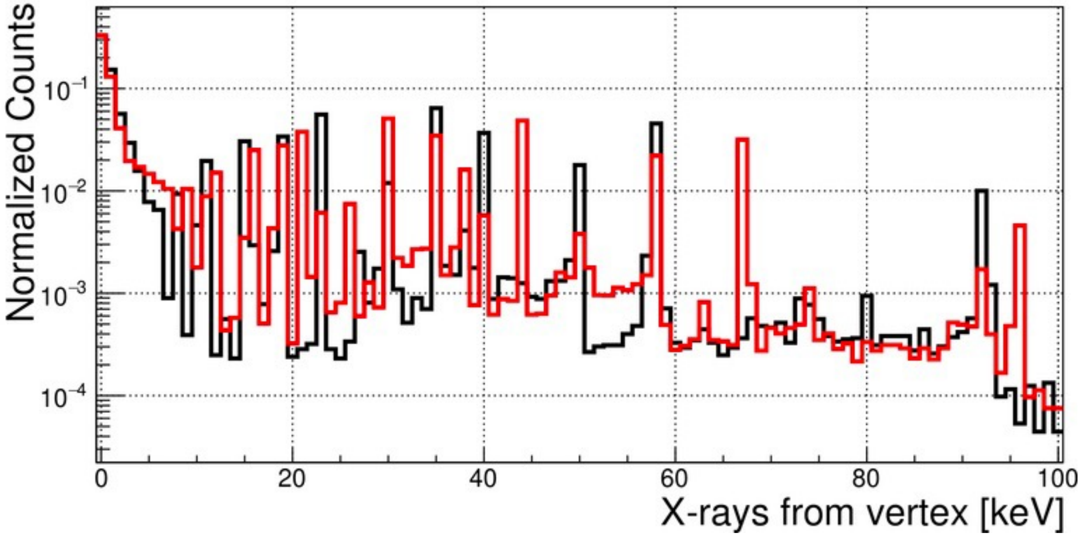
Compared to magnetic spectrometer, exotic atom-based particle ID is:

- Specific to negative particles which form exotic atoms with atomic nuclei
- Useful only at low energies where particles can be stopped in detector material, and velocity and/or calorimetry can form the energy scale
- Large sensitive area relative to payload size (no bulky magnet required!!)

Exotic atom technique verified at KEK: Aramaki+ Astropart.Phys. 49 (2013)

Discrimination based on X-ray Energies and Particle multiplicity



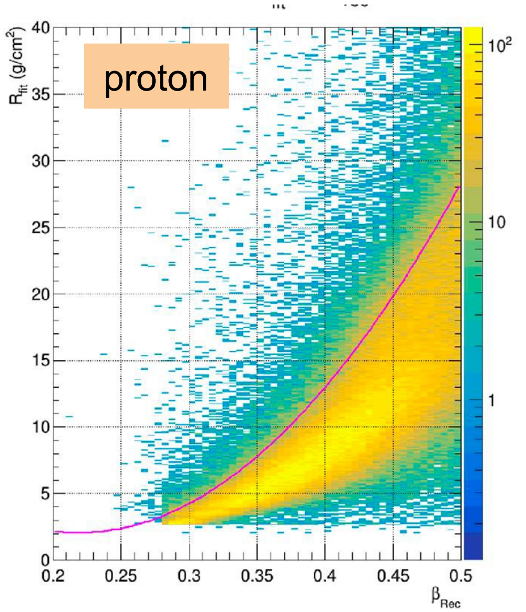


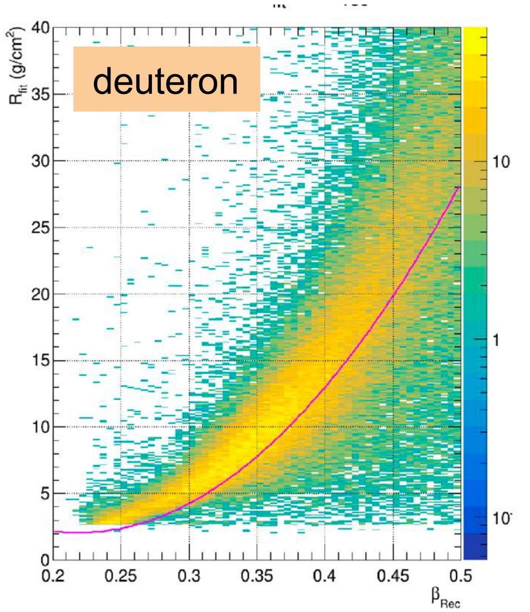
Exotic atom technique verified at KEK: Aramaki+ Astropart.Phys. 49 (2013)

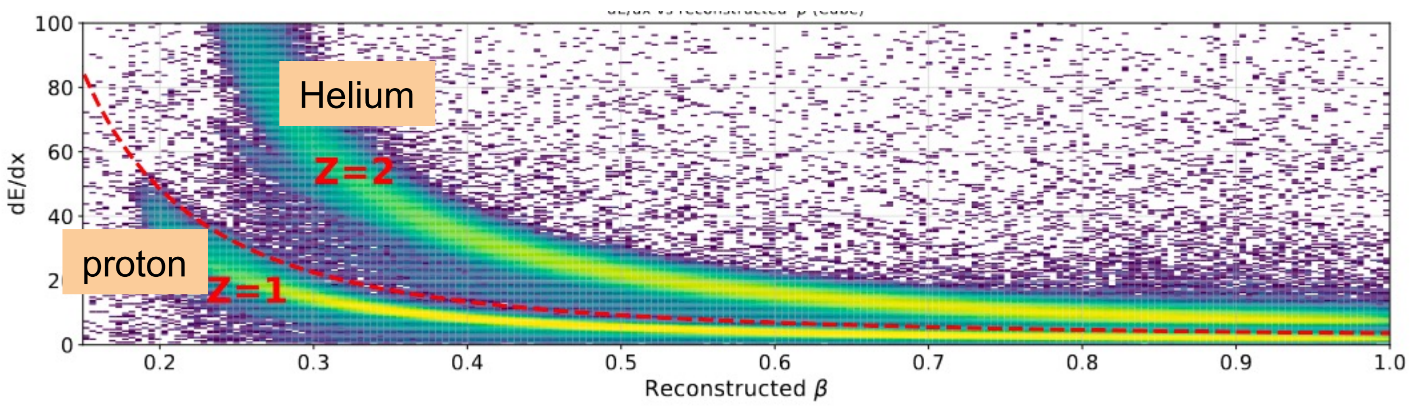
Sensitivity to Light Positive Nuclei

- Motivations:
  - Validate solar modulation models
  - Improve understanding of atmospheric production
  - Calibrate instrument using single track events

- Dedicated trigger mode
  - GAPS will primarily operate in an "antiparticle" trigger mode, optimized for events with slow primaries and secondary particle production
  - Some flight time in a minimal trigger mode dedicated to single track events





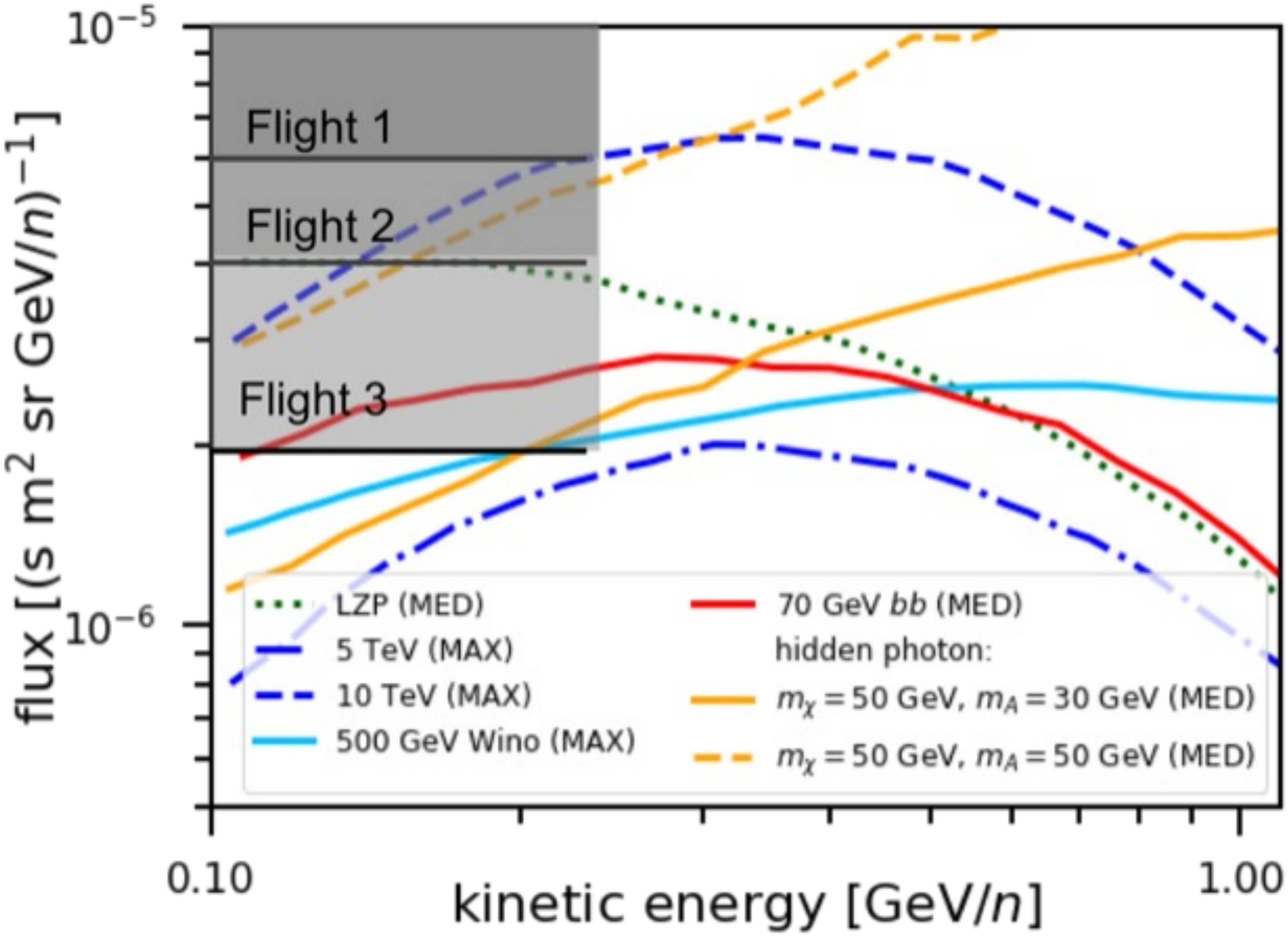


Details in: Munini et al, POS ICRC 2023

Antideuterons from diverse DM models

- Wide range of particle-like dark matter models, eg:
  - Generic 70 GeV WIMP annihilation that explains antiproton and galactic-center gamma-ray excesses
  - Dark photons (inaccessible to other techniques)
  - Gravitino decay
  - Extra dimensions
  - Heavy DM with Sommerfeld enhancement
- Select publications:

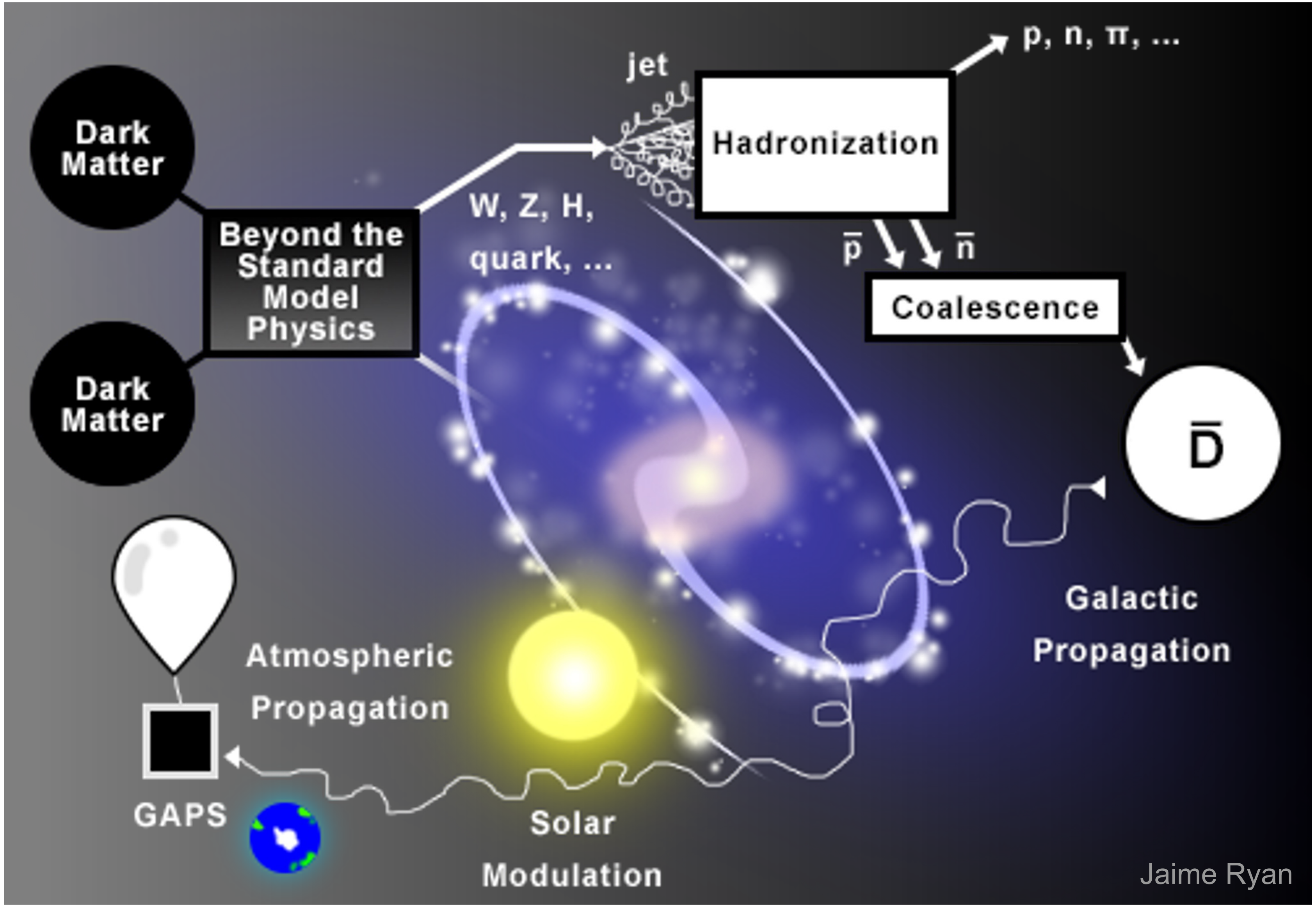
Braeuninger et al. Phys L B 678, 20–31 (2009)
Cui et al, JHEP 1011, 017 (2010)
Hryczuk et al., JCAP 1407, 031 (2014)
Korsmeier et al., PRD 97, 103011 (2018)
Randall & Xu, JHEP (2020)



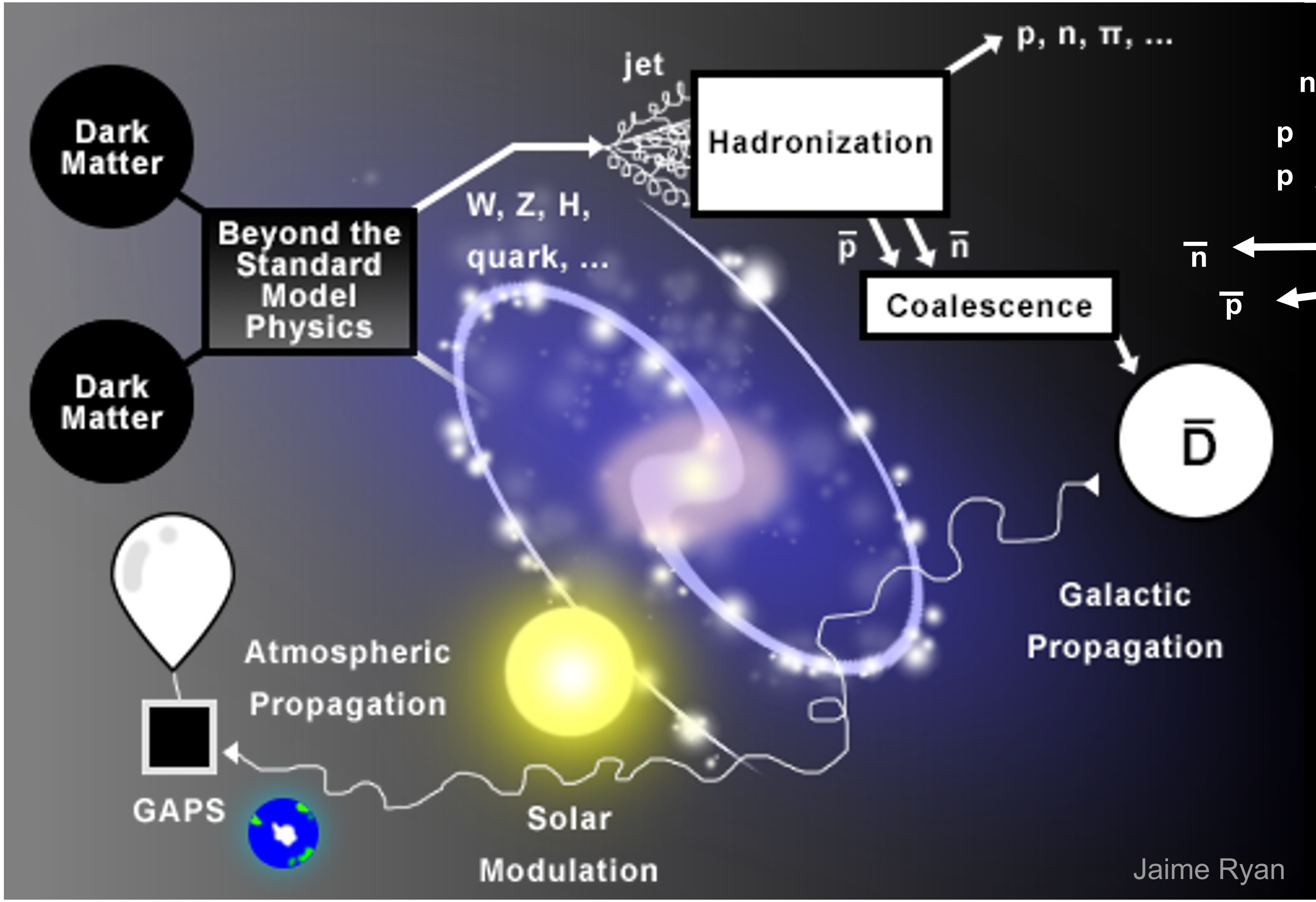
(Some) Proposed explanations of the AMS ^{3}He Candidates or of enhanced 3He fluxes

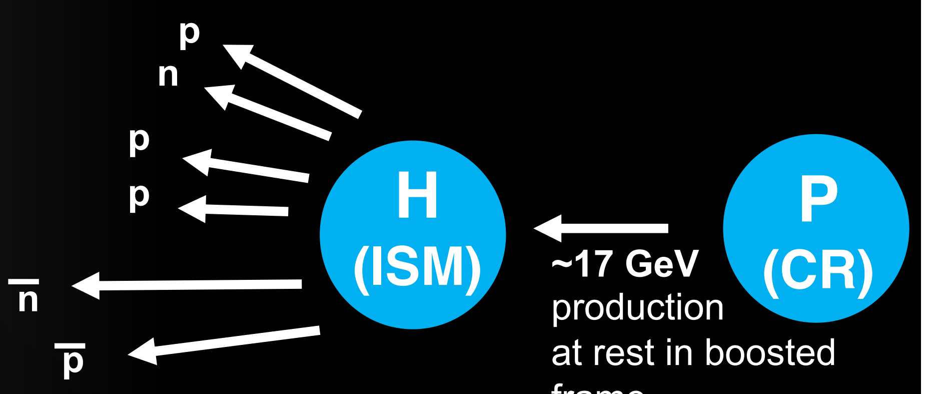
- Dark matter annihilation scenarios, eg
  - Light mediators near the ^{3}He production threshold [2212.02539]
  - Enhancement via Λ_b-baryon resonance [2012.05834]
  - Nonstandard coalescence models [2002.10481, 1808.03612]
- Galactic population of antistars [2303.04623]
- And more… origin of the AMS ^{3}He candidates remains an open question

How to Produce an Antideuteron from Dark Matter

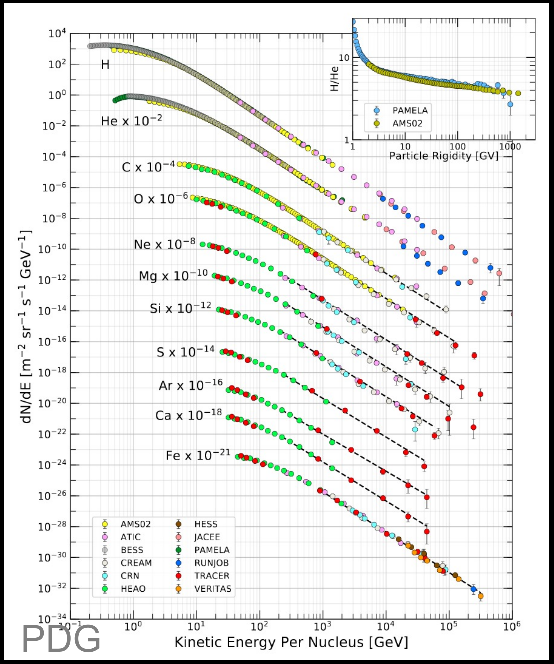


How to Produce an Antideuteron from Astrophysics



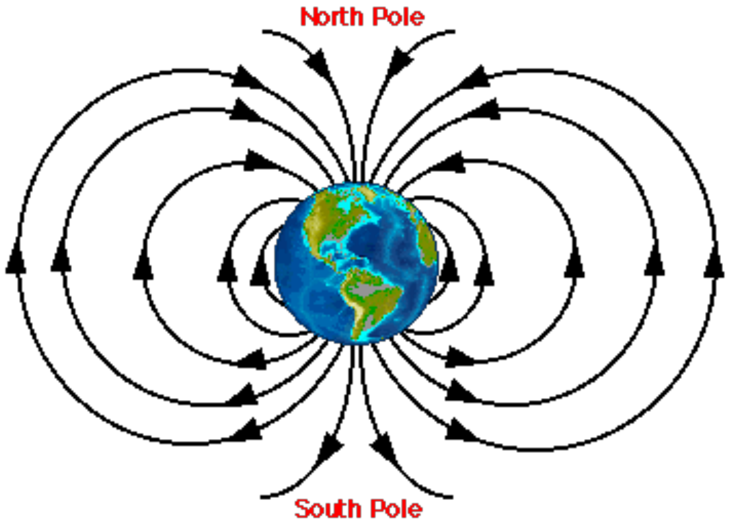


~17 GeV production at rest in boosted frame



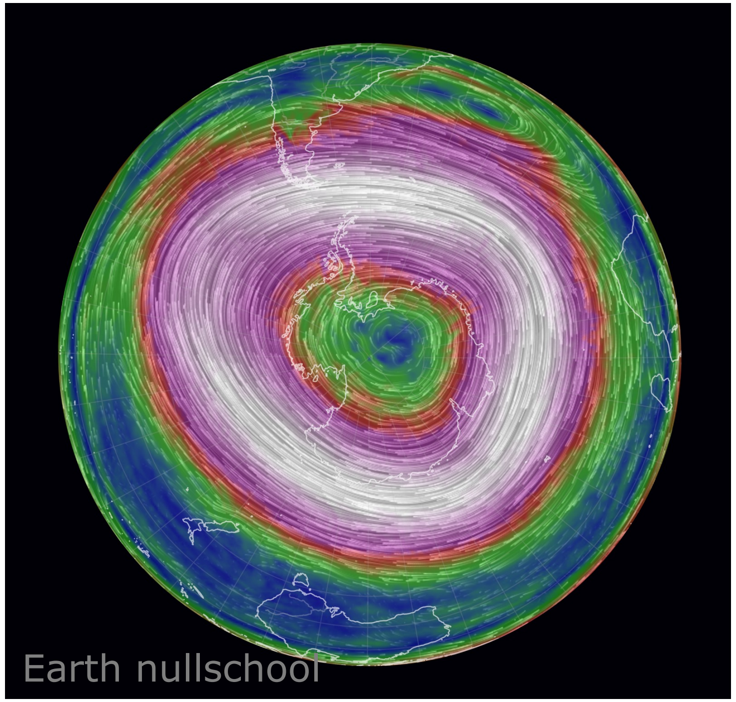
Why An Antarctic LDB Mission?

- ❑ Geomagnetic cutoff
  - Nuclei in the GAPS energy range are sensitive to geomagnetic deflection, which is minimized at the poles

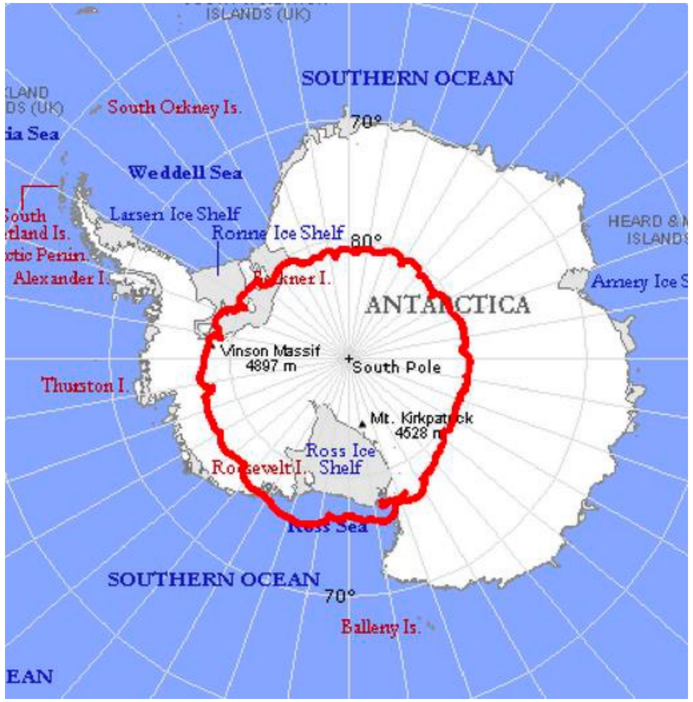


Oceanweb (UNC)

- ❑ Long flight-time over land
  - Circumpolar winds (interactive visualizer!)
  - International borders

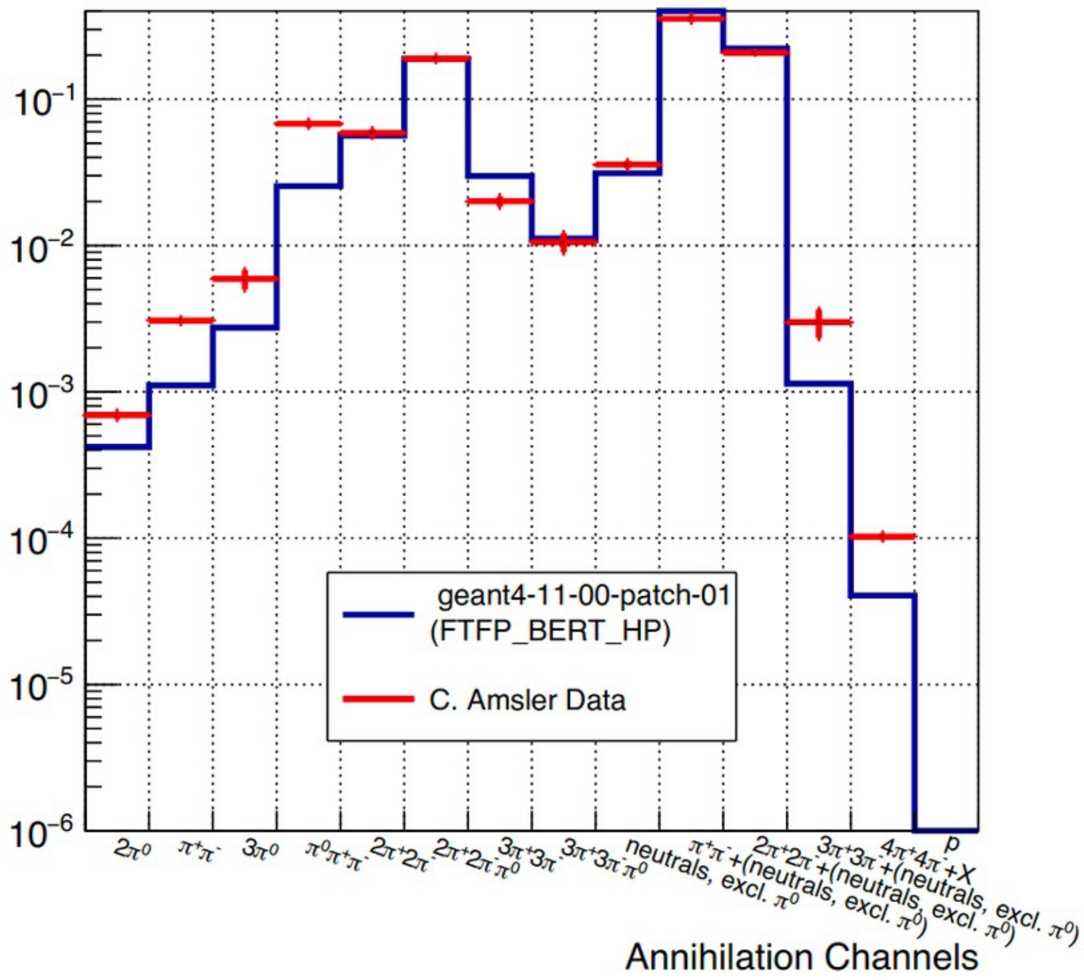


Earth nullschool



Simulating Annihilation Physics

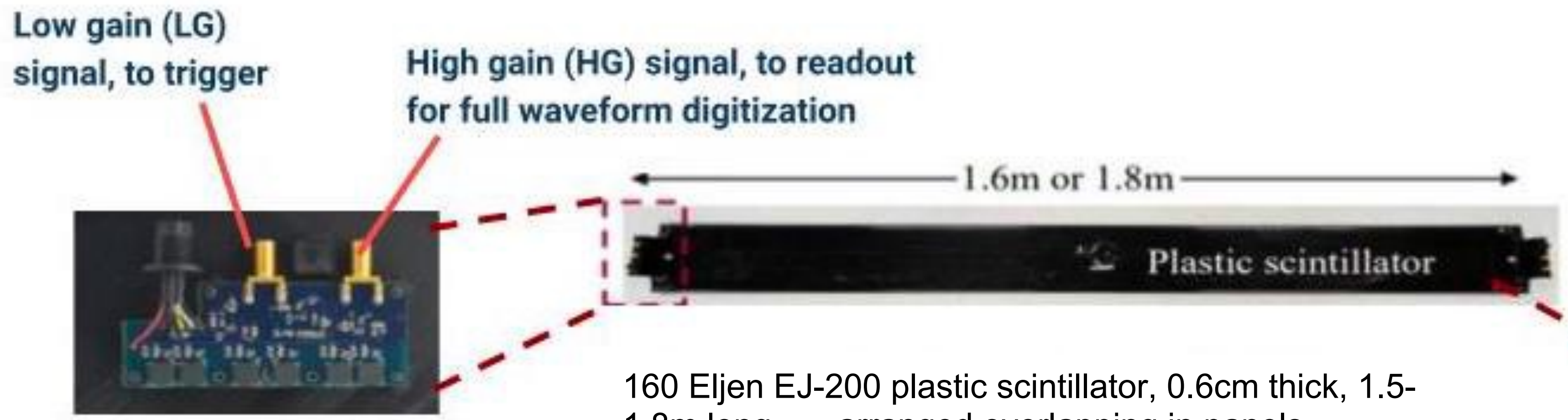
- Test of annihilation physics in Geant4 is ongoing
- Use antiproton data for benchmarking
- Work with Geant4 developers



Antinucleus Trigger

- Main backgrounds: proton, alpha, carbon
- High-speed trigger and veto
  - High energy deposition on two hits (first hits have energy deposition above MIP expectation)
  - Multiplicity of TOF hits (selects for annihilating events with production of secondaries)
  - Pattern of TOF hits (distributed between inner and outer paddles)
- In-flight trigger rate < 500 Hz

Time-of-flight (TOF) Panels



160 Eljen EJ-200 plastic scintillator, 0.6cm thick, 1.5-1.8m long, arranged overlapping in panels

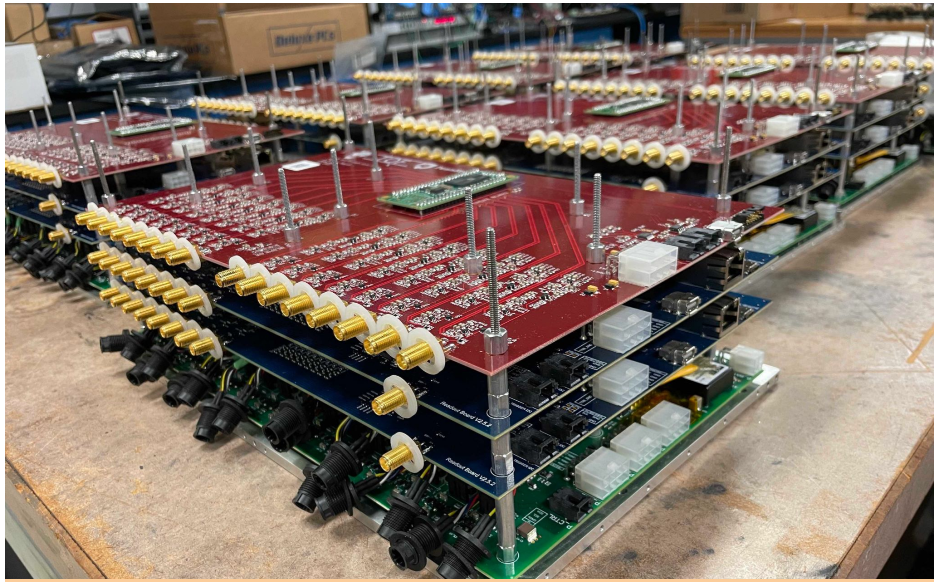
Hamamatsu S13360-6050VE SiPMs, 6 per paddle side, read out by custom preamp boards

21 TOF panels in GAPS, of various shapes and sizes

S Feldman et al, POS ICRC 2023

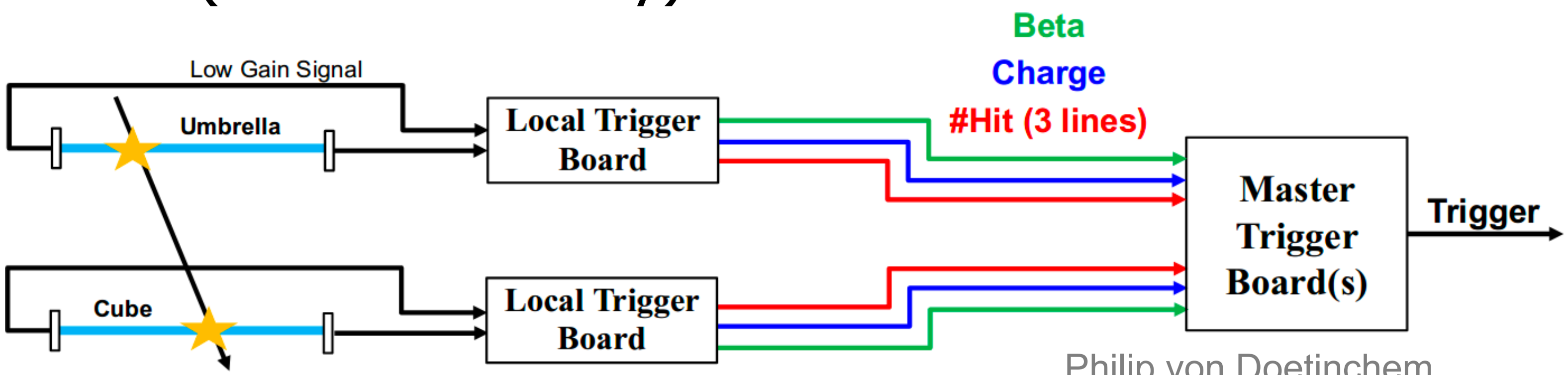
TOF Readout and Trigger Electronics

- Local trigger boards apply 3-level trigger to low-gain input
- Master trigger generates unique event ID based on all 20 local trigger boards
- Readout boards use 2 GHz DSR-4 chip to read out 512 ns high-gain data per channel
- Dedicated TOF CPU manages data, with preliminary calculation of event-level variables (such as velocity)



TOF readout-and-trigger electronics stack, contains 2 readout boards, local trigger board, and power board

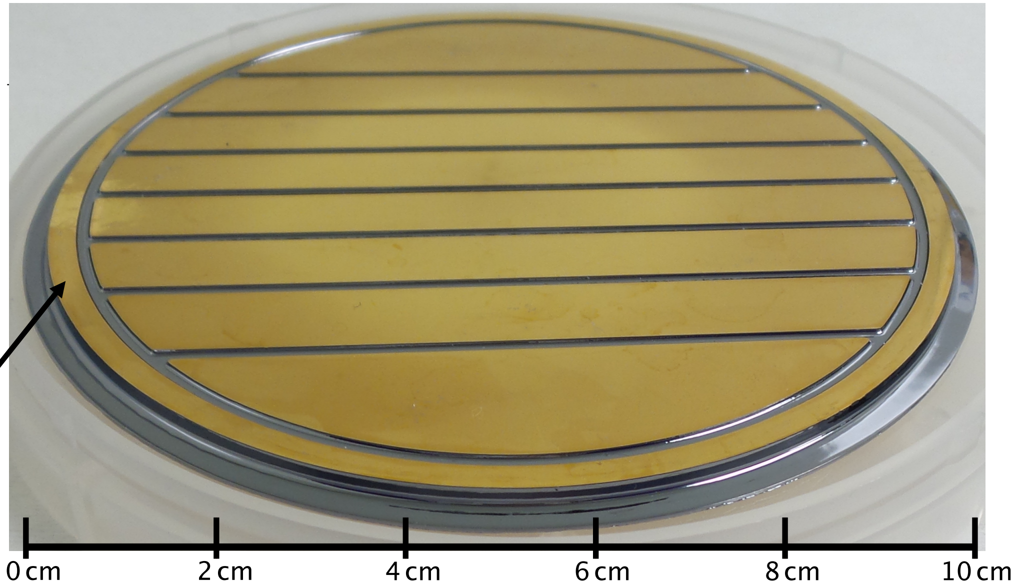
S Feldman et al, POS ICRC 2023

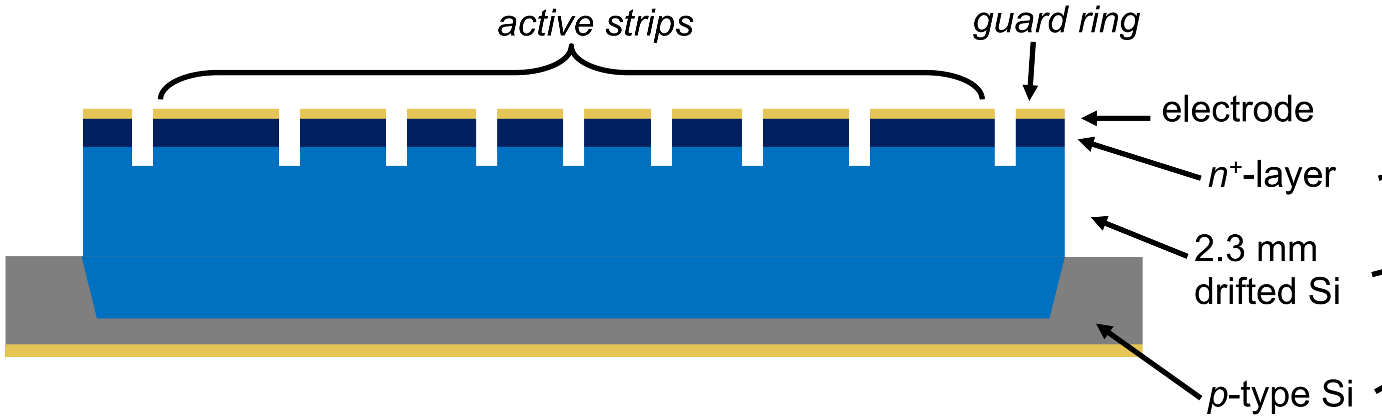


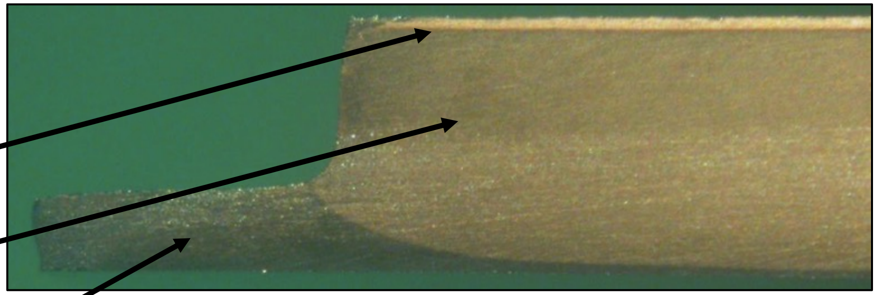
Philip von Doetinchem

Si(Li) Detector Fabrication

1. B-doped, *p*-type substrate wafers
2. Evaporate and diffuse Li for *n*⁺-layer
3. Form top-hat structure to control drift
4. Evaporate Ni + Au electrodes
5. Drift Li through wafer
6. Form guard ring + strips
7. Apply polyimide passivation





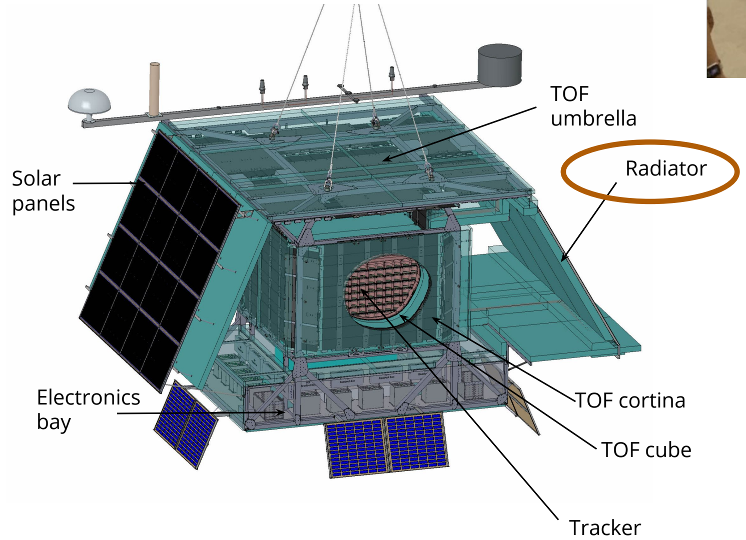


Cross-section (copper stained)

Kozai et al, NIM A 947 (2019)

Gondola Thermal System

- $8\ m^3$ radiator cools gondola during flight
- Methanol-cooled plate coupled to radiator for ground cooling
- Integrated oscillating heat pipes transport heat out of tracker to radiator
- No pump! No cryostat!




Radiator test mount


Ground cooling plate (with insulation)

Publications:
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)

Oscillating Heat Pipe Details

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 transport heat
- no active pump system required
- First prototype flown in 2012; another prototype flown from Ft. Sumner in 2019