Indirect search for dark matter with cosmic-ray antinuclei: the GAPS experiment

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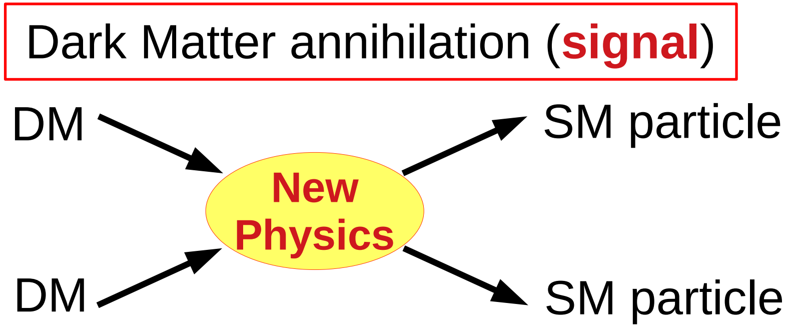
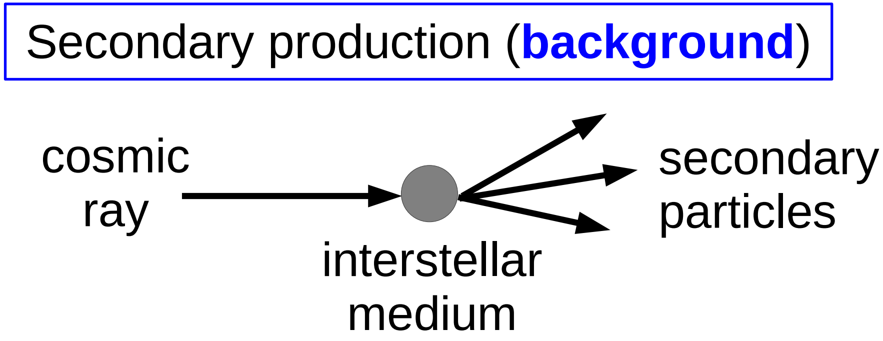
on behalf of the GAPS collaboration

13th CRIS-MAC 2024
Cosmic-Ray International Studies and Multi-messenger Astroparticle Conference
17-21 June 2024, Trapani, Italy

Dark matter indirect search

- Different kinematics between cosmic rays produced in **dark matter annihilation/decay** and standard astrophysical processes (**"secondary production"**)

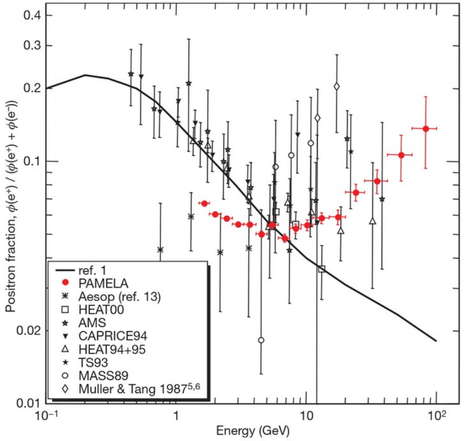




- **Indirect detection** of dark matter in cosmic rays: search for features (like peaks, bumps, …) in cosmic rays spectra due to a **dark matter annihilation** or **decay** component

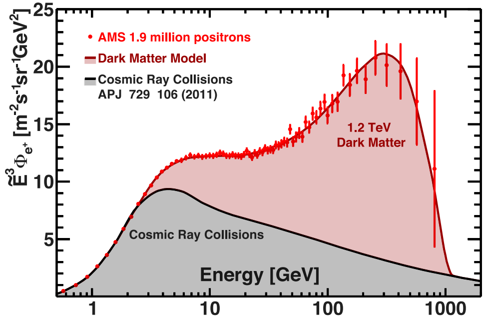
Hints of dark matter?

- Some unexplained features have been found in positrons, antiprotons, and gamma rays from the Galactic centre
- Could be produced by a dark matter contribution...



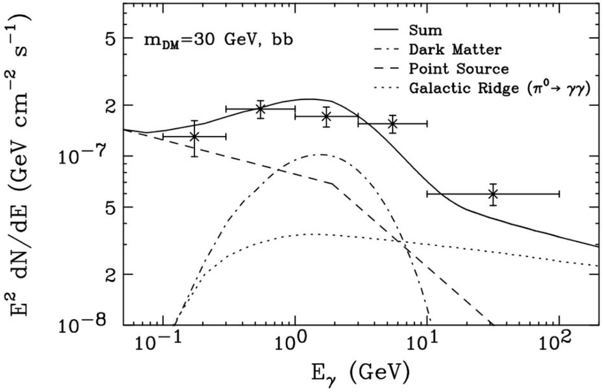
Nature 458, 607–609 (2009)

positrons



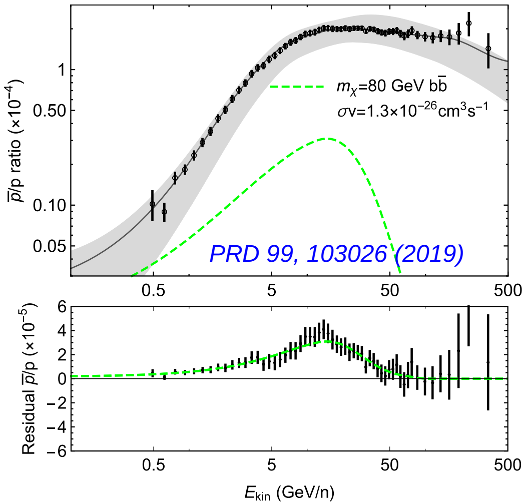
Physics Reports 894 (2021) 1–116

gamma rays



Phys. Rev. D 84, 123005 (2011)

antiprotons*

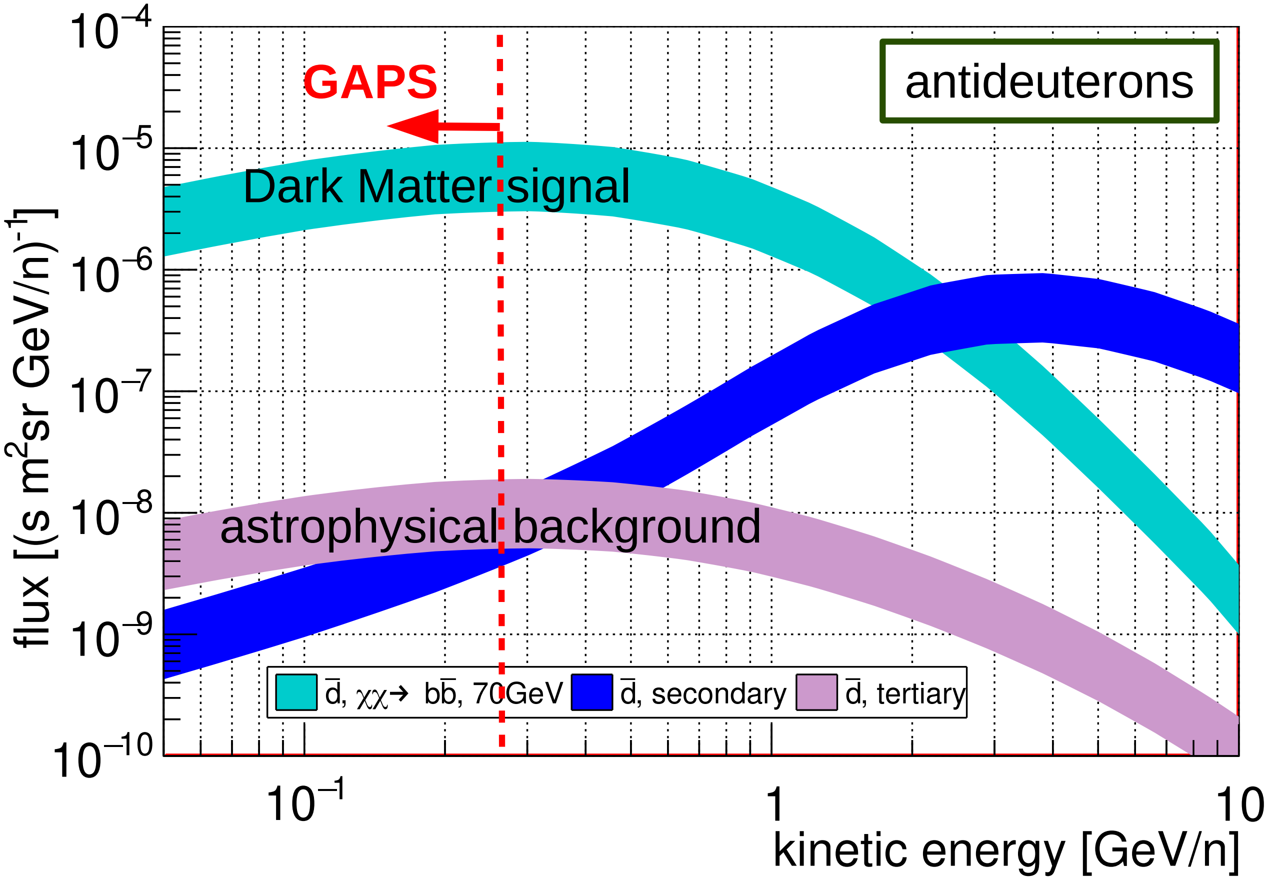


- ...but they can also be explained with astrophysical processes
- The understanding of the astrophysical background is crucial for the interpretation of the data

*much lower significance when considering correlation of systematic uncertainties
Phys. Rev. Research 2, 043017 (2020)

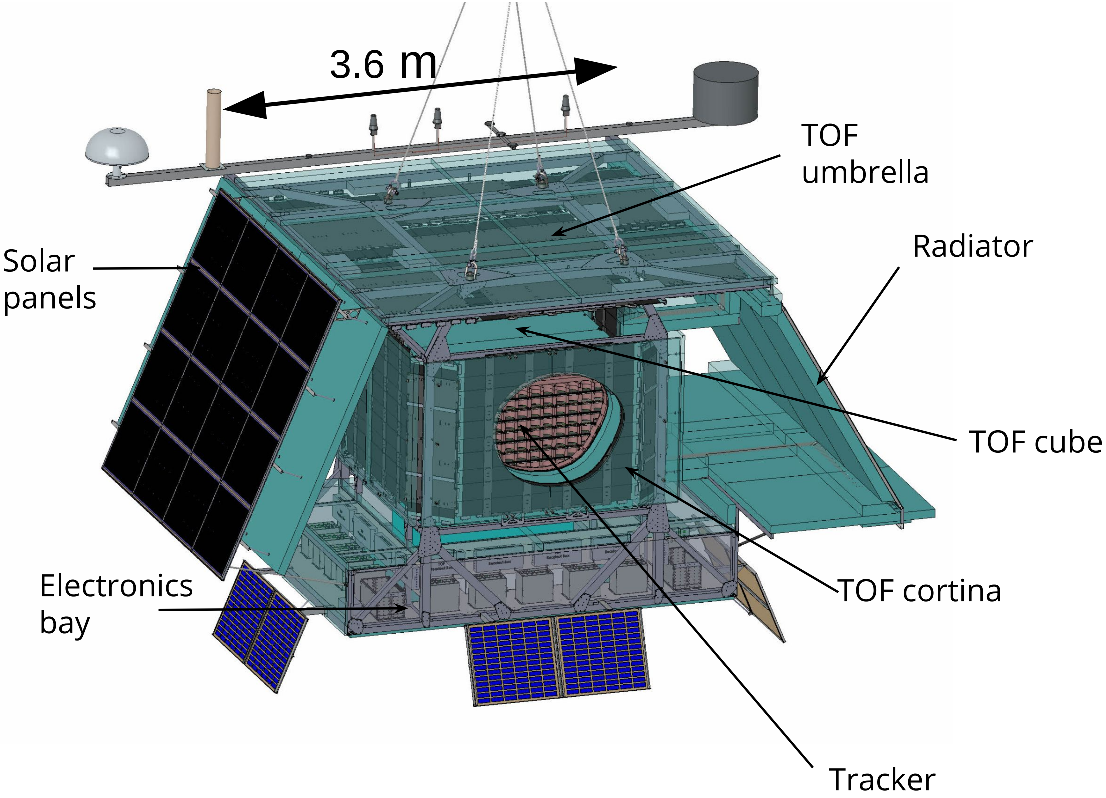
GAPS scientific goals

- **GAPS** is designed to detect **antideuteron** and **antihelium-3** below 250 MeV/n as evidence for **new physics**
- Possible antiparticle signal from DM is essentially **background free** at low kinetic energies
- GAPS will also perform a precise measurement of **antiproton** spectrum in an unexplored low-energy range
- Low-energy spectrum of **p**, **d**, and **He** will also be measured



The GAPS experiment

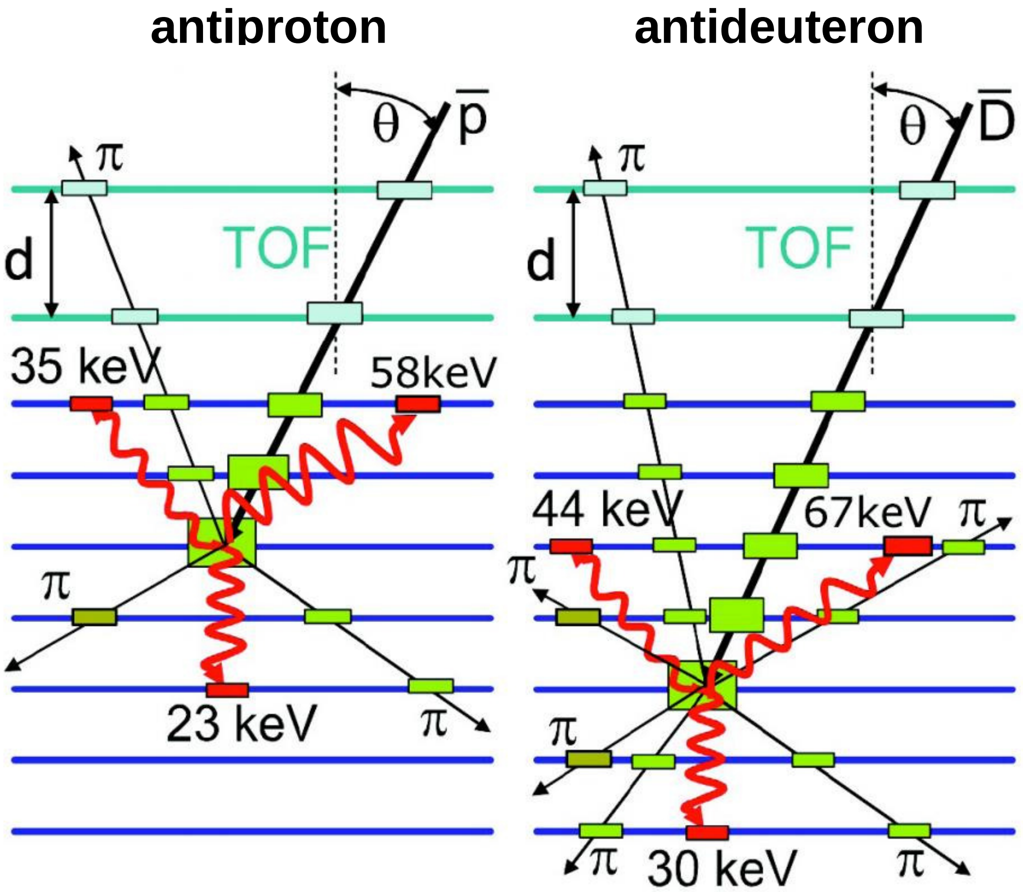
- **General Antiparticle Spectrometer**
- Balloon-borne experiment
  - three long duration balloon flights from Antarctica planned
  - First flight in 2024/2025 austral summer
- Experimental apparatus composed of a **time-of-flight (ToF)** system surrounding a **tracker**
- **ToF:** plastic scintillators (Eljen EJ-200) read with silicon photomultipliers (SiPM)
- **Tracker**: 7 planes of 12x12 Si(Li) detectors
- An **oscillating heat pipe** system is used to cool down Si(Li) detectors to -40°C



Detection principle

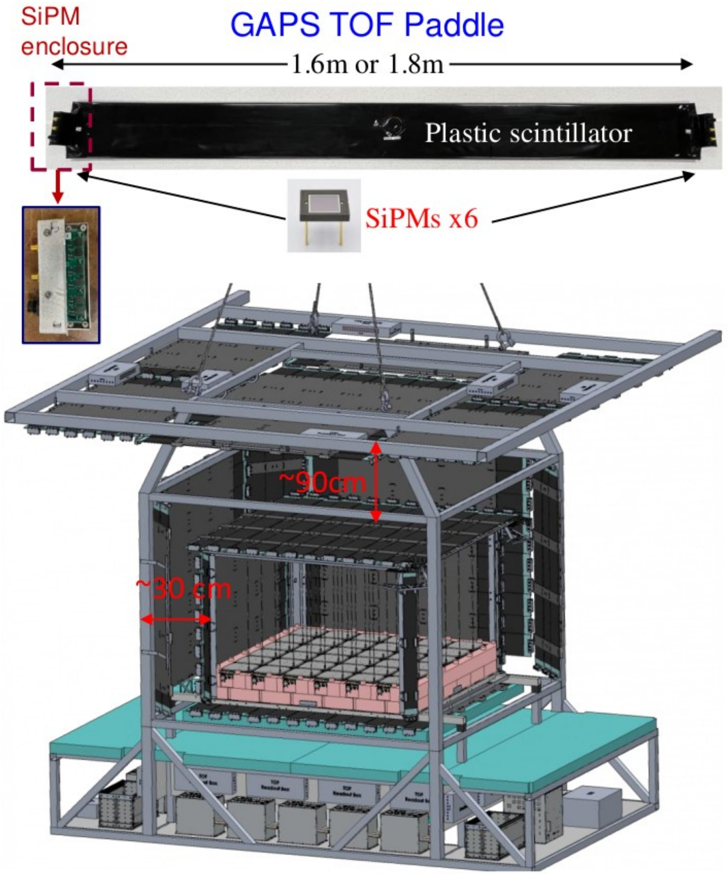
- The antinucleus slows-down and form an exotic atom in the tracker
- The exotic atom de-excites emitting characteristic **X-rays**
- The antinucleus annihilates with the nucleus of the exotic atom, emitting a "star" of secondary particles (**pions, protons**)
- Completely **different** and **complementary** technique with respect to other balloon and space experiments searching for antimatter

Astroparticle Physics 49 (2013) 52–62



Time of Flight

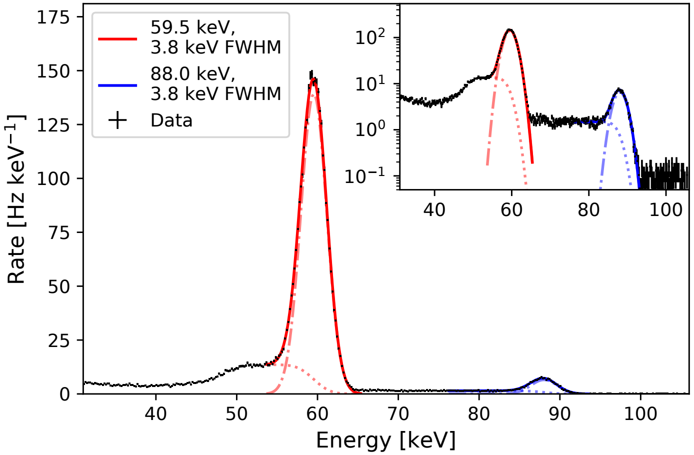
- Development led by **UCLA**
- Plastic scintillators: Eljen EJ-200
- Paddles dimensions: 1.5-1.8 m x 16 cm x 6.35 mm
- Each paddle read with **SiPMs** on both sides
  - Hamamatsu S13360-6050VE
  - provide position measurement
- **Timing** measurements with resolution <**400 ps**
- Antinuclei dedicated **trigger** (based on β, energy deposits and # of hits): rate <**500 Hz**
- Fast trigger sent to tracker
- Custom DAQ hardware developed
  - Waveform sampling by high-speed DRS4 ASIC

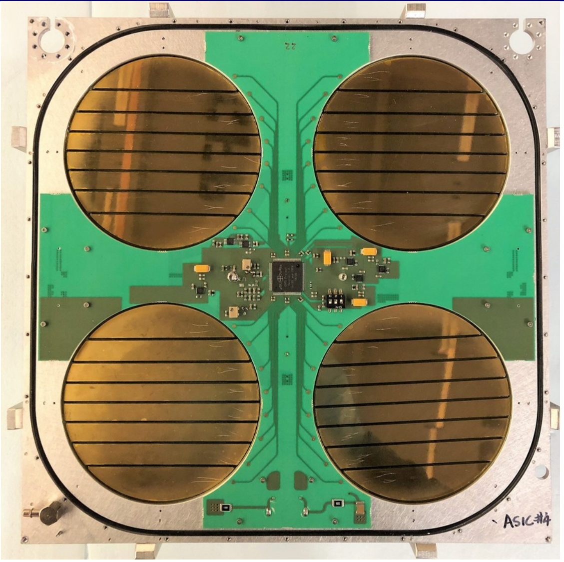


PoS (ICRC2019) 128   *PoS (ICRC2021) 079*   *PoS (ICRC2023) 120*

Tracker

- Large area **lithium-drifted silicon** detectors (**Si(Li)**)
  - developed by **Columbia**, **MIT**, **ISAS/JAXA**, produced by **Shimadzu** Corp.
- ~10 cm circular detectors, segmented in 8 strips with equal area and 2.5 mm thick
  - A module is made of 2x2 detectors
  - Modules are arranged in a 6x6 array in each plane
  - 7 planes vertically spaced by 10 cm
- Custom ASIC for energy deposit measurement
  - high dynamic range: ~10 keV → ~100 MeV
  - low power consumption
- Energy resolution <4 keV (for 60 keV X-rays)
  - needed to discriminate X-rays from different antinuclei and different target atoms

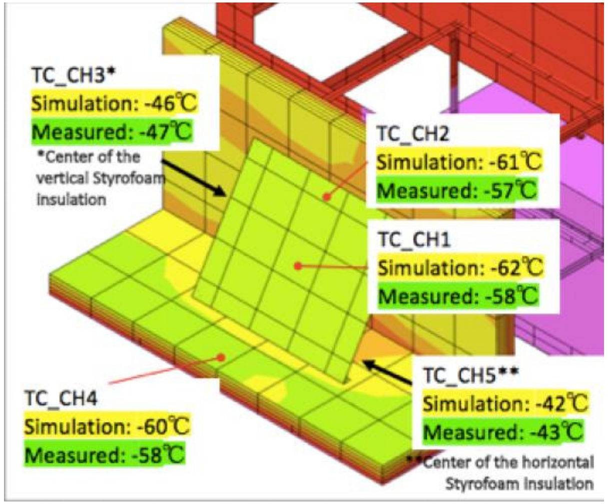


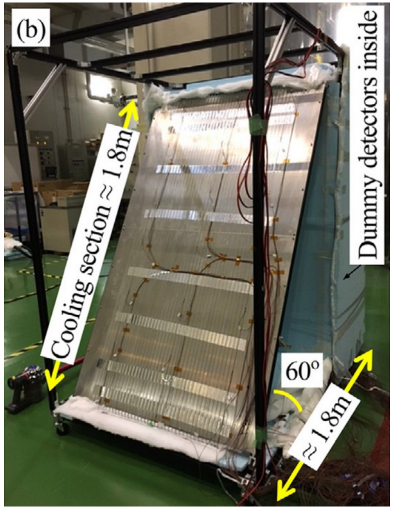


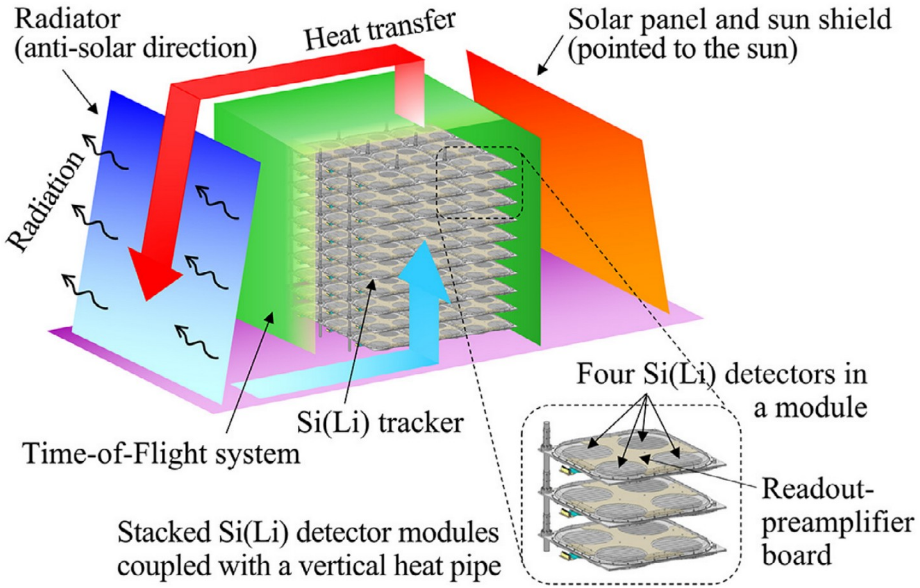
ASIC:
IEEE 68 (2021) 11, 2661-2669
NIM A 1045 (2023) 167617
IEEE 71 (2024) 1, 96-105

Si(Li):
NIM A 905 (2018) 12
NIM A 947 (2019) 162695
JINST 14 (2019) P10009
NIM A 997 (2021) 165015
NIM A 1034 (2022) 166820
IEEE Trans. Nuc. Sci. 70 (2023)

- Design led by **ISAS/JAXA**
- Passive cooling system → **low power** consumption
- Hybrid system between oscillating heat pipe (**OHP**) and thermosiphon
- OHP used for the first time in a balloon flight
- Scaled down prototype **successfully tested** in 2019



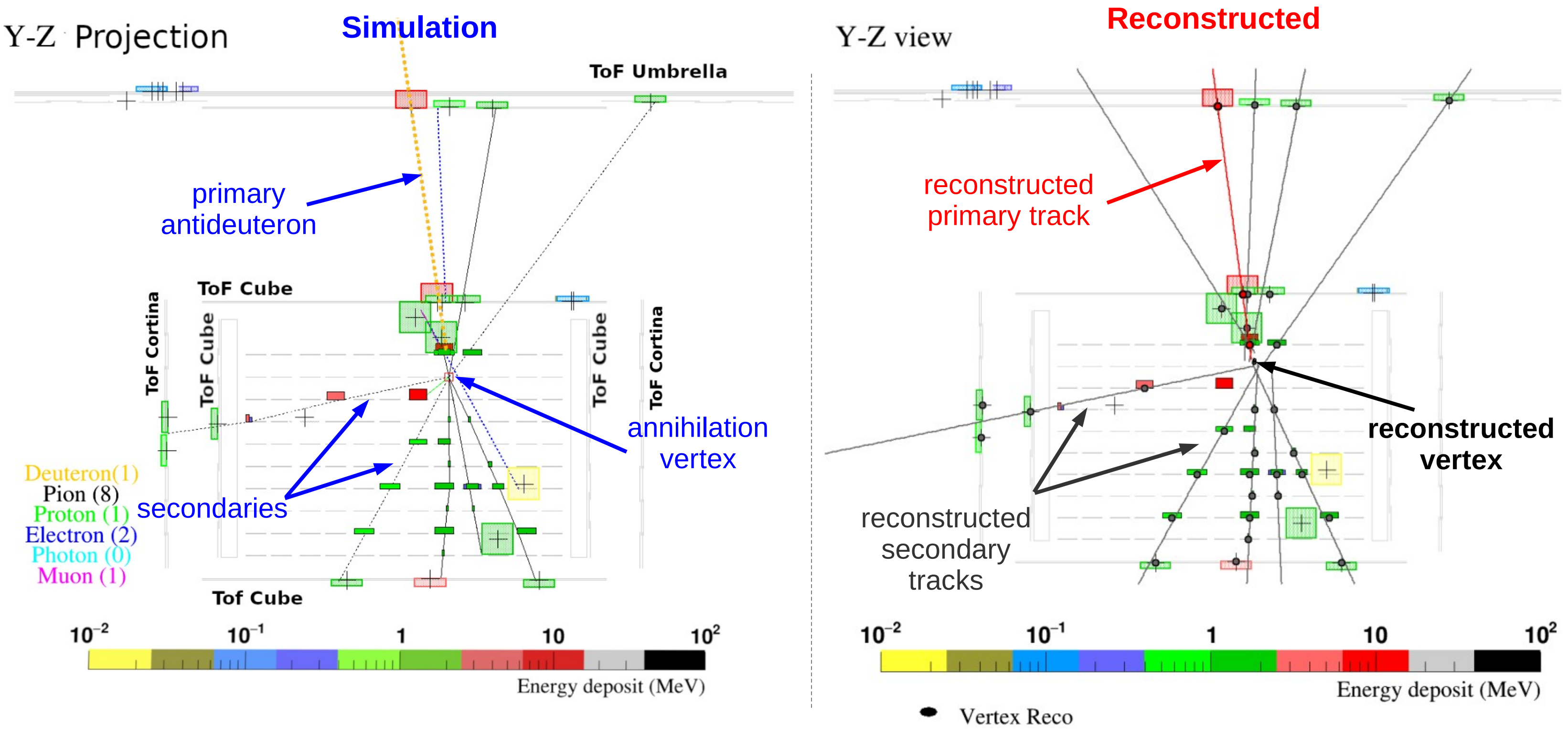




J. Astron. Inst. 3 (2014) 1440004
J. Astron. Inst. 06 (2017) 1740006
Applied Thermal Engineering 141 (2018) 20
NIM A 1049 (2023) 168102

Event reconstruction

- A custom algorithm has been developed to identify the **primary track**, the **annihilation vertex** and the **secondary tracks**
- Detailed Monte Carlo simulations confirm that the developed algorithm satisfies the required reconstruction performance



Astroparticle Physics 133 (2021) 102640

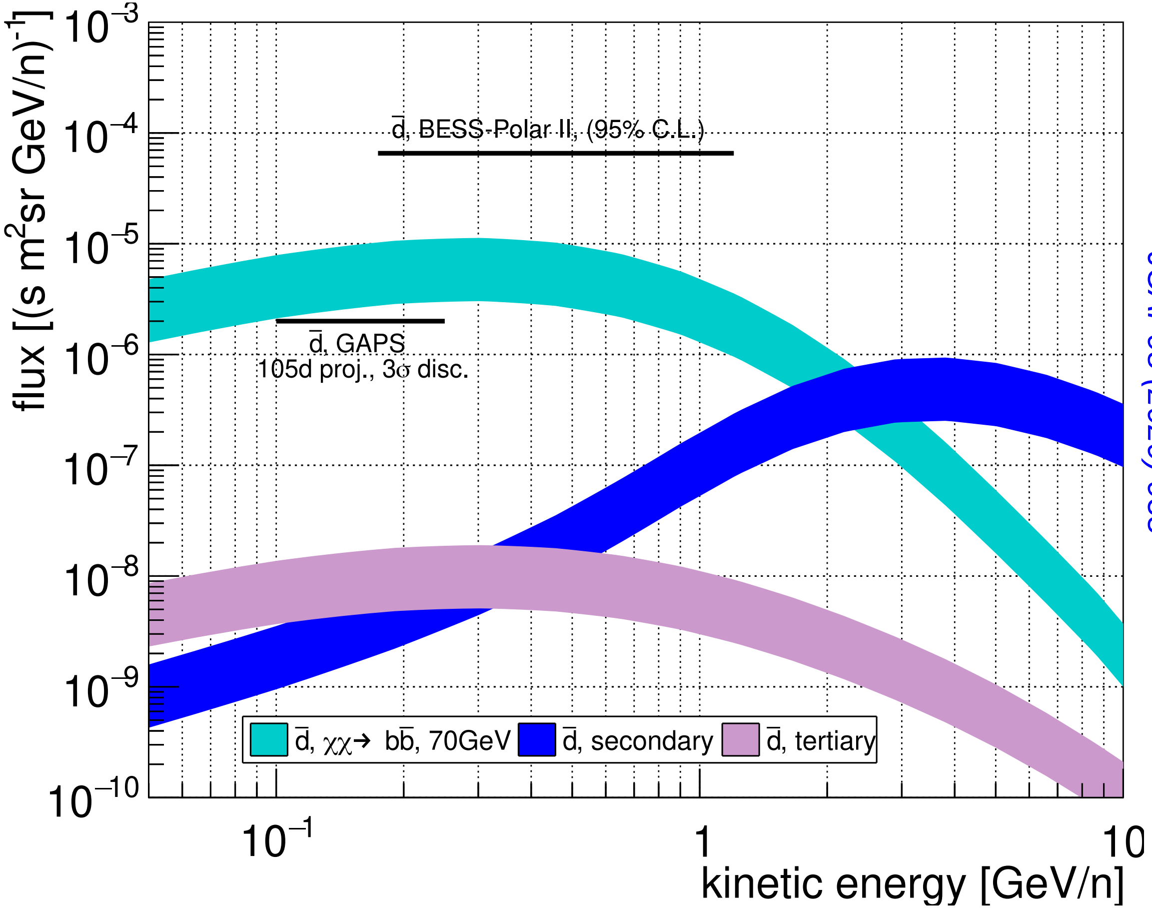
GAPS: antideuteron sensitivity

- Predicted **antideuteron** signal from dark matter decay or annihilation **~2 orders of magnitude** above astrophysical background below 250 MeV/n

- Even a single antideuteron would point to **new physics**

- GAPS **sensitivity** will greatly improve the existing BESS limit

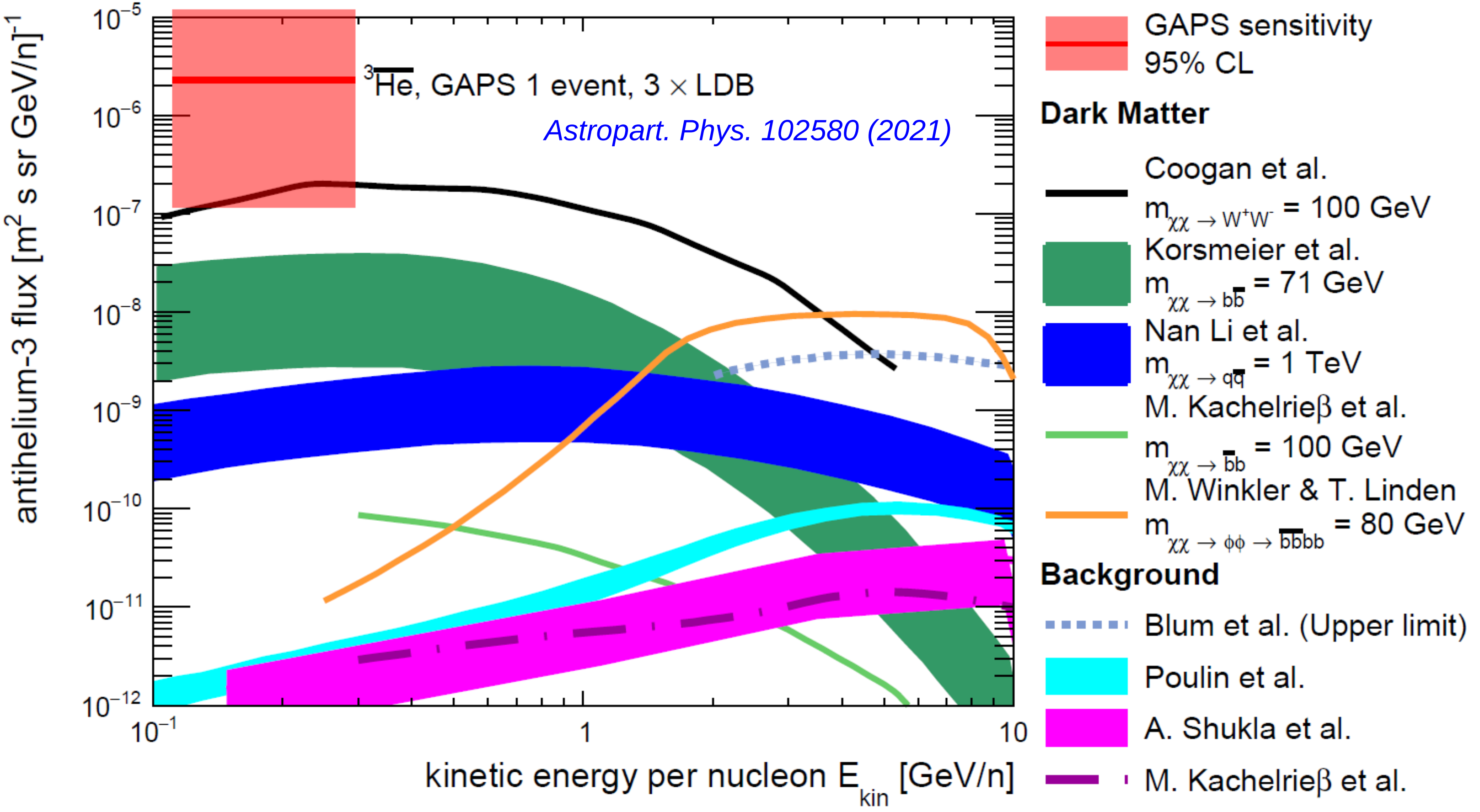
Astropart. Phys. 74 (2016) 6



JCAP08 (2020) 035

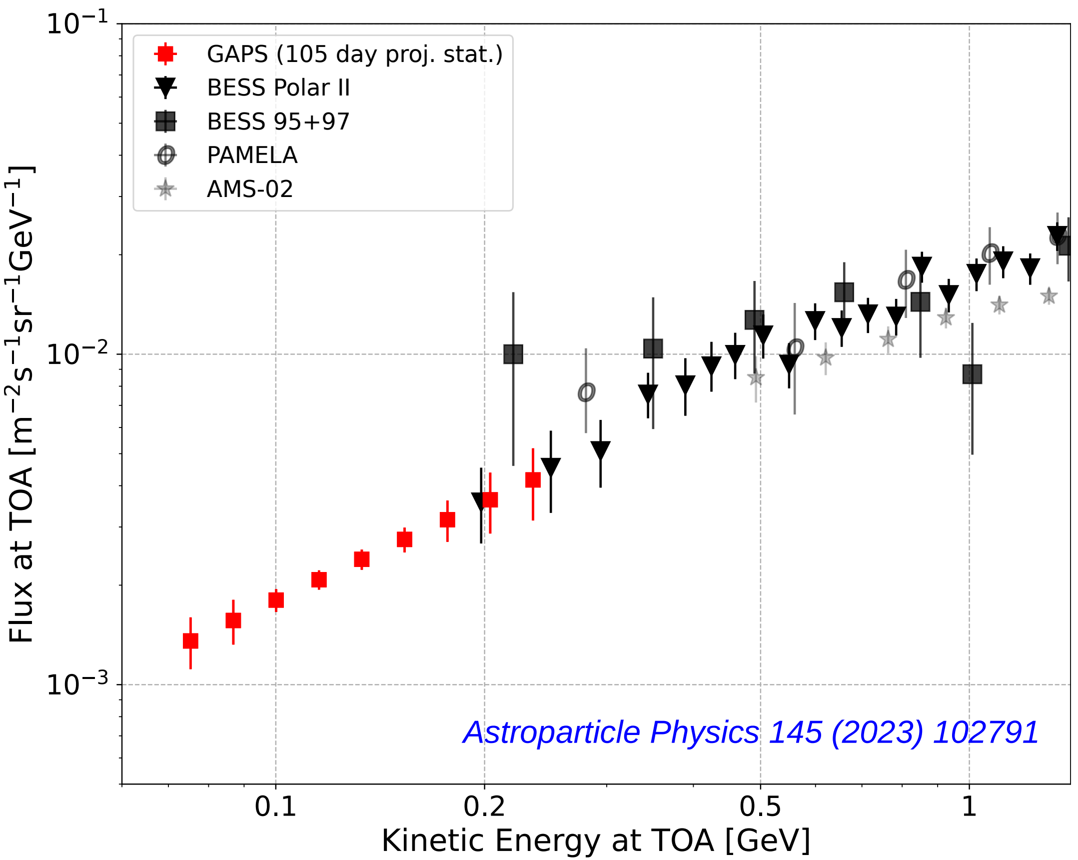
GAPS: antihelium-3 sensitivity

- GAPS will be sensitive to **antihelium-3**
- ...but antihelium-3 flux ~2-3 orders of magnitude below antideuteron flux
- An observation of antihelium-3 would be a clear indication of **new physics**
- Extend the energy coverage at low energies (**0.1-0.3 GeV/n**)



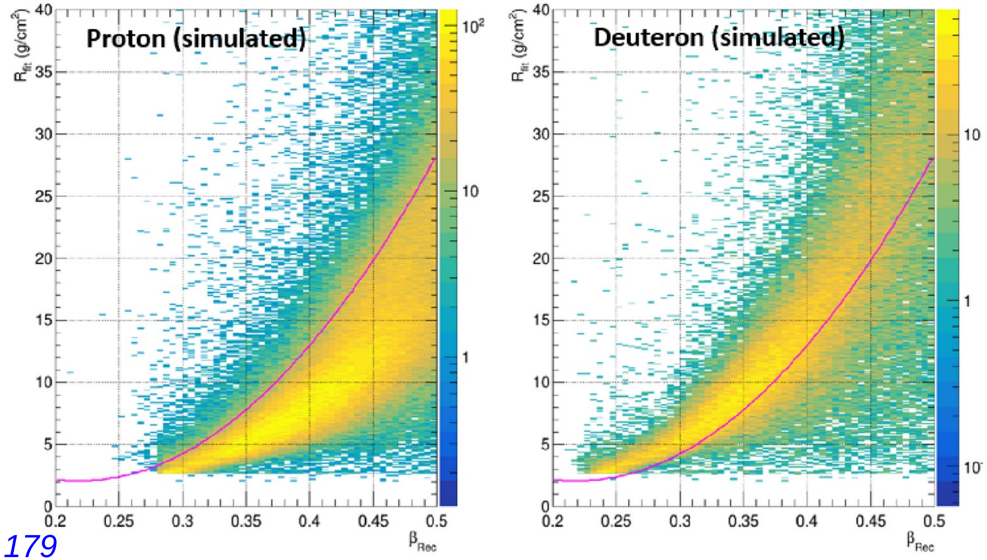
GAPS: antiproton spectrum

- Precision measurement of **antiproton** spectrum in an **unexplored low energy region**
- **~500** antiprotons expected for each balloon flight
  - other measurements:
    BESS: 29 @ ~0.2 GeV
    PAMELA: 7 @ 0.25 GeV)
    AMS: > ~0.3 GeV
- Provide constraints on **Galactic propagation** and **solar modulation**
- Observed antiproton excess also puts **constraints** on antideuteron flux predictions
- Sensitive to **light dark matter** and **primordial black hole evaporation**
- **Validation** of GAPS exotic atom identification technique

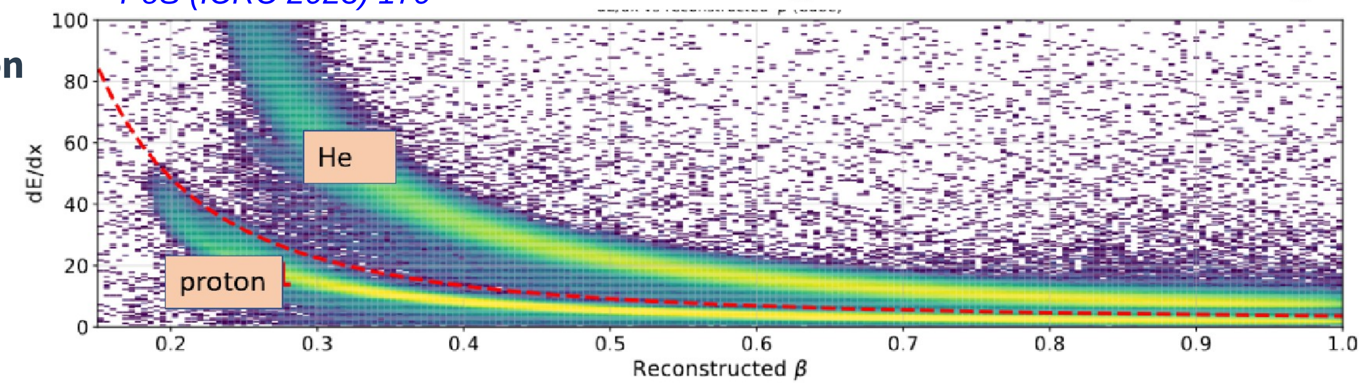


GAPS: deuteron and helium measurements

- Physics motivation:
  - Validate **solar modulation** models
  - Improve understanding of **atmospheric production**
  - **Calibrate** instruments and validate **reconstruction algorithm** with single-track events (no annihilation)
- Short runs with a **“minimum bias” trigger** instead of antinuclei-optimized trigger
- **Deuteron and helium identification** performed both with a classical cut analysis and machine learning techniques



PoS (ICRC 2023) 179

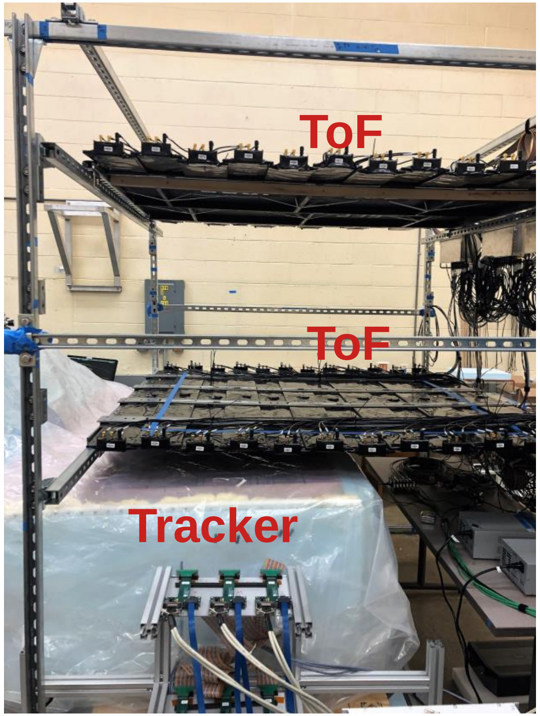


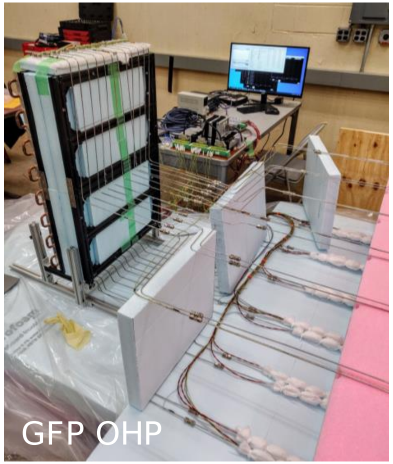
GAPS schedule

- **GAPS Functional Prototype** (GFP) @ MIT Bates Laboratory, *Fall 2021 → February 2022*
- **Payload integration** @ MIT Bates laboratory & Berkley Space Science Lab, *March 2022 → May 2023*
- **Thermal-vacuum test** @ NTS El Segundo, *June 2023*
- **Re-build and calibration** @ Columbia Nevis Laboratory, *July 2023 → May 2024*
- **Compatibility and hang tests** @ Columbia Scientific Balloon Facility, ***May-June 2024*** ***(now!)***
- **First flight** from Antarctica! ***December 2024***

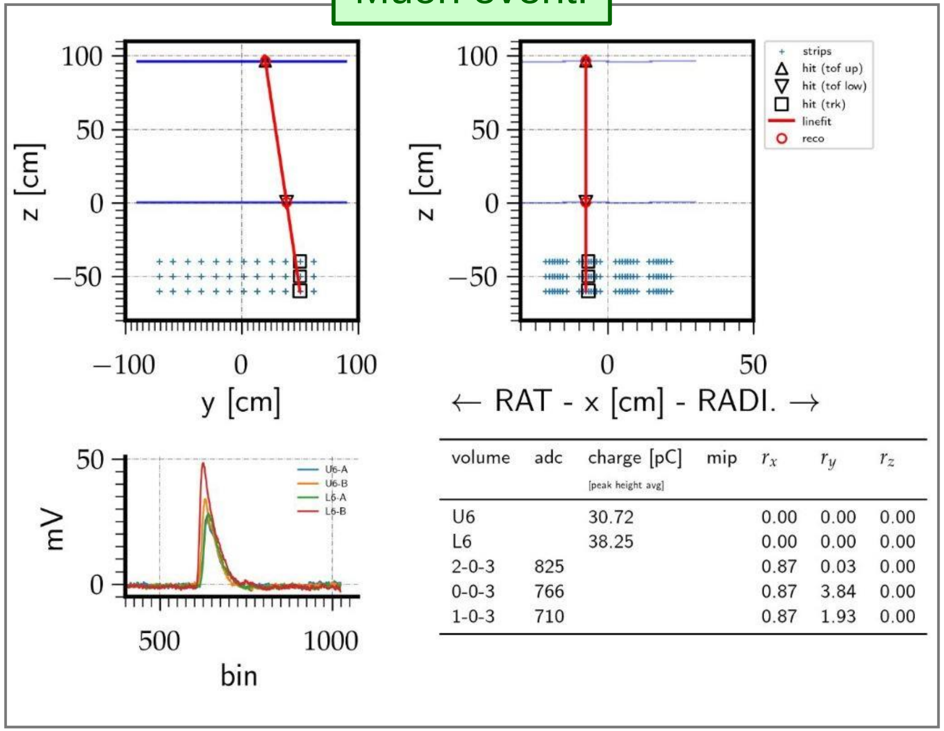
GAPS Functional Prototype

- GAPS functional prototype (**GFP**):
  - Tracker: 3 layer, 48 Si(Li) per layer
  - ToF: 2x12 paddles of plastic scintillators
  - Cooling: oscillating heat pipes for Si(Li)





Muon event!

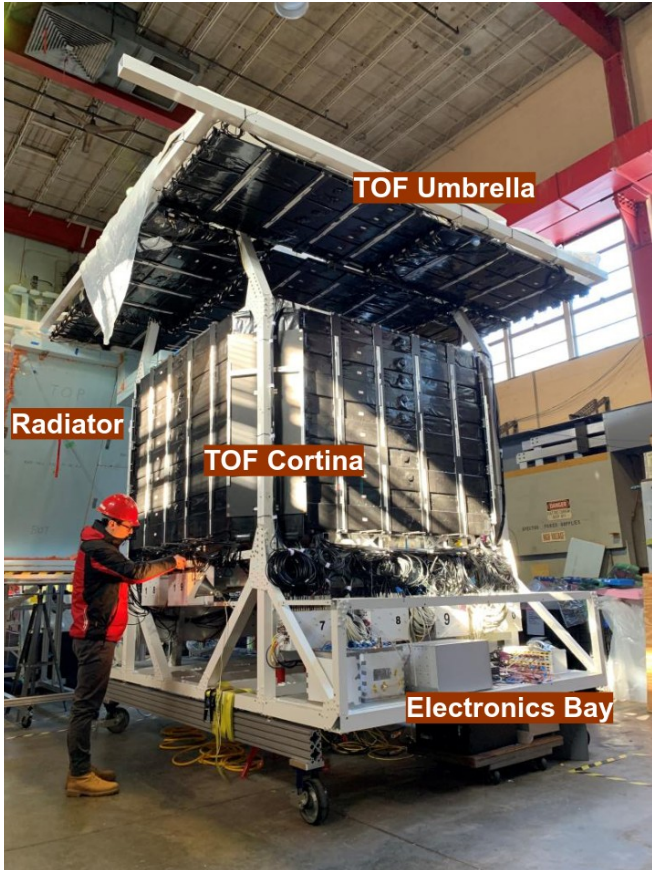


volume	adc	charge [pC] [peak height avg]	mip	r_x	r_y	r_z
U6		30.72		0.00	0.00	0.00
L6		38.25		0.00	0.00	0.00
2-0-3	825			0.87	0.03	0.00
0-0-3	766			0.87	3.84	0.00
1-0-3	710			0.87	1.93	0.00

- Test and operate all components together
- Test tracking with cosmic muons
- Built during fall 2021 and **successfully tested in early 2022**

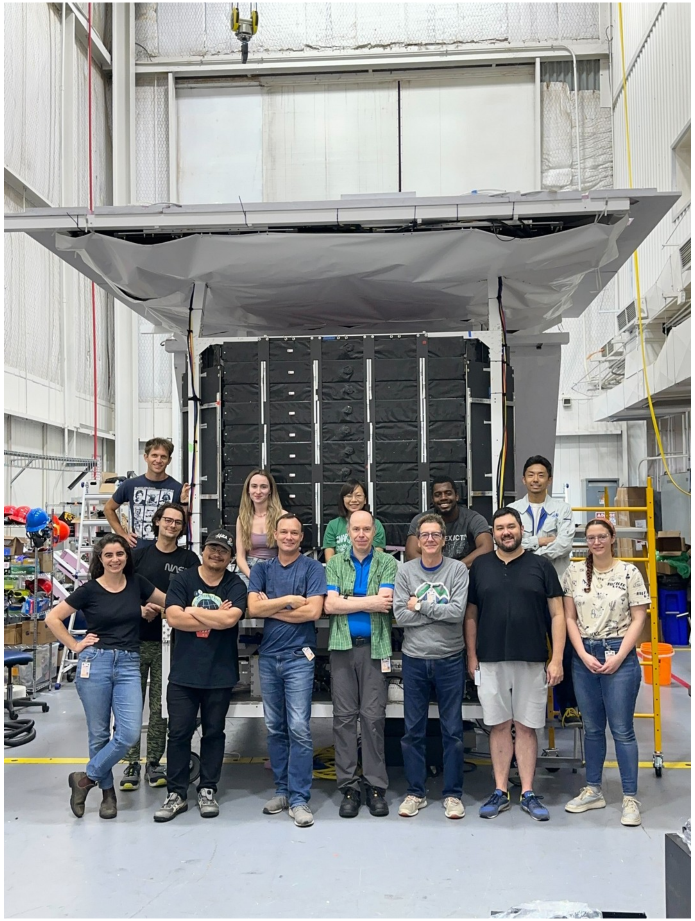
GAPS full payload integration (Columbia Nevis Lab)

- GAPS integration after TVAC done at Columbia Nevis Laboratory from July 2023 to May 2024
- Combined data taking (ToF + tracker) with cosmic muons (~10M tracks acquired)
- Detailed analysis of acquired data is ongoing



GAPS compatibility test (CSBF, Palestine, TX)

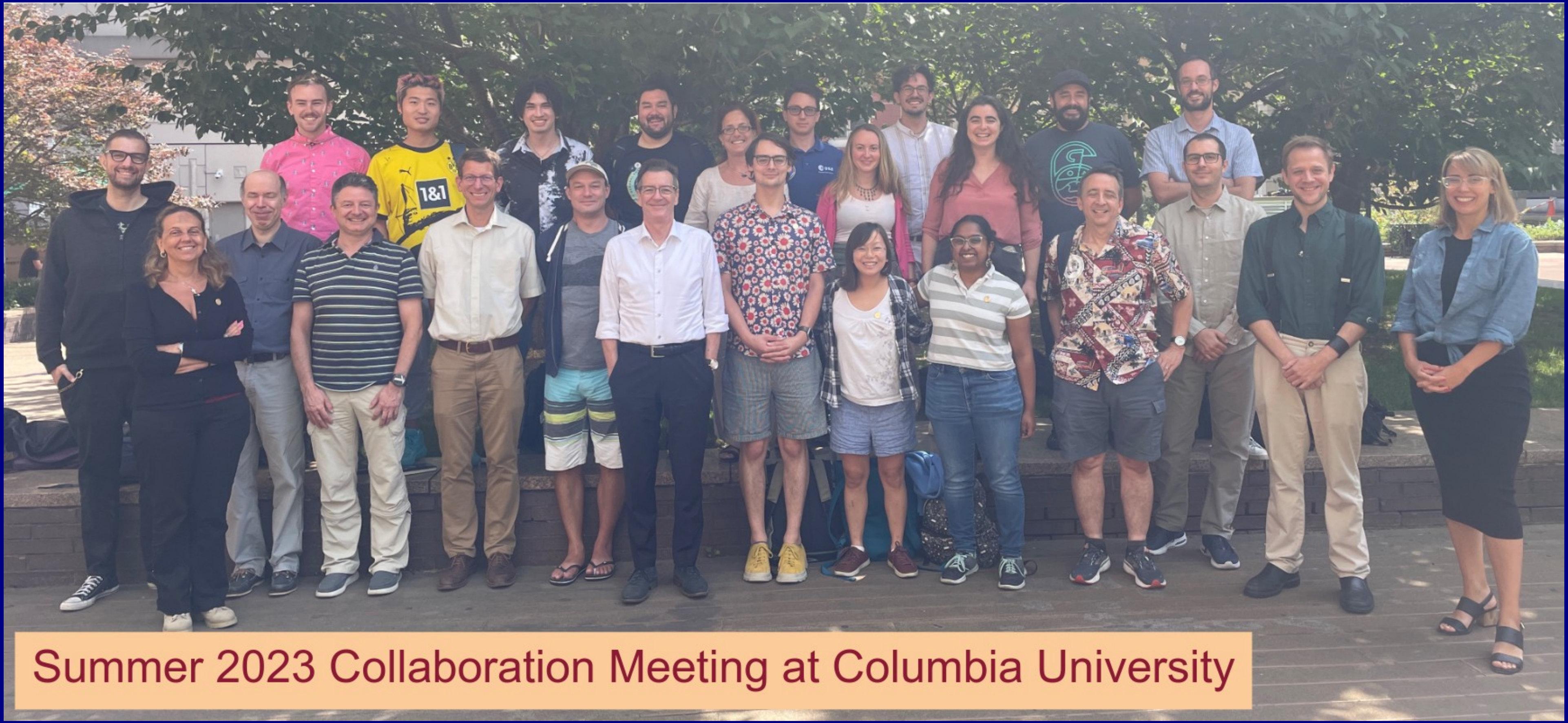
- GAPS ready for compatibility test!



Summary

- **GAPS** is the first experiment dedicated to the observation of cosmic **antiprotons**, **antideuterons**, and **antihelium-3** at energies below **250 MeV/n**
- The main scientific goals of the experiment are:
  - **First detection of cosmic antideuterons**, thanks to excellent sensitivity in a background-free region
  - **Precision measurement of the antiproton spectrum**, searching for dark matter signatures and to put constraints on dark matter and propagation models
  - **Detection of cosmic antihelium-3**, if present in the cosmic rays, using a complementary technique with respect to other experiments
- **Integration and testing** of the full payload has been completed, compatibility and hang test ongoing
- **First flight** is planned in **December 2024!**

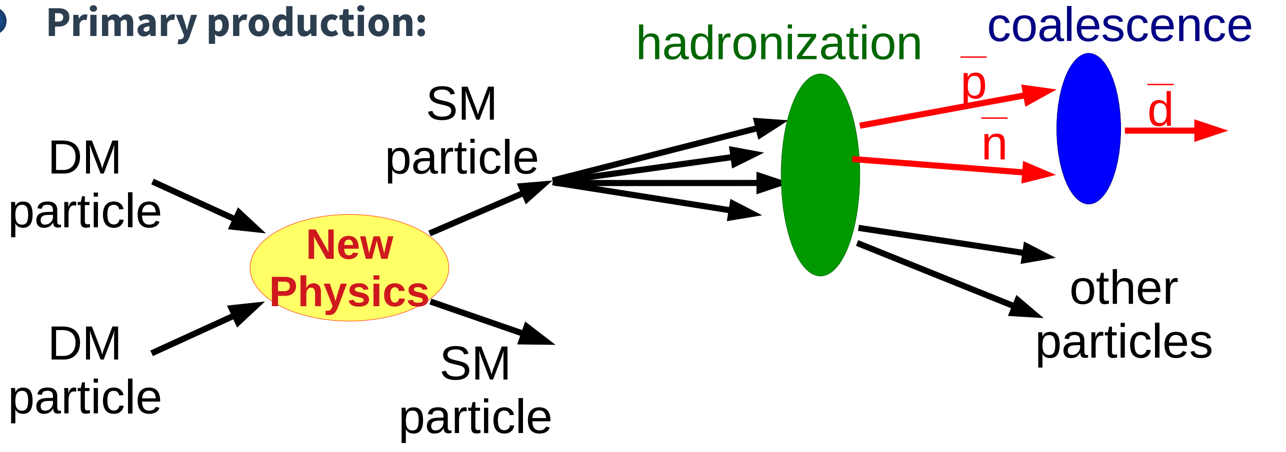
Thank you for your attention!

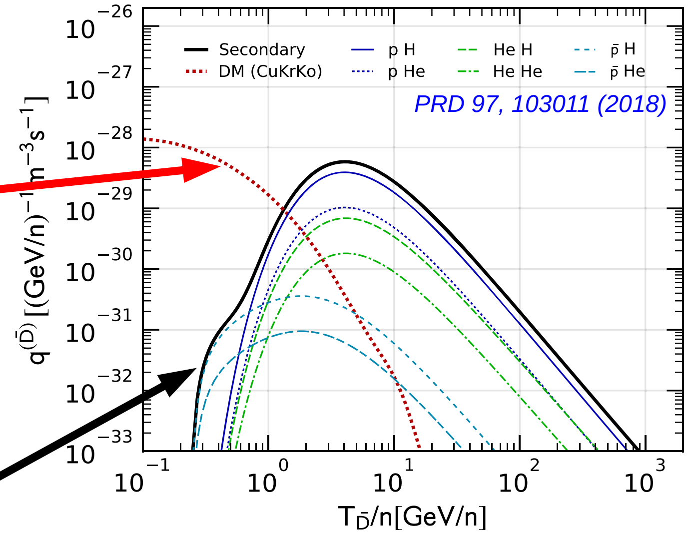


Summer 2023 Collaboration Meeting at Columbia University backup

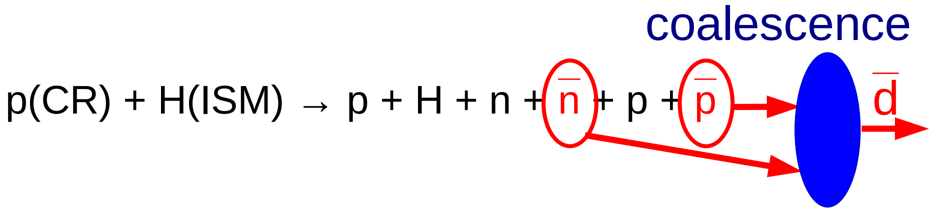
Antideuteron production

- **Primary production:**



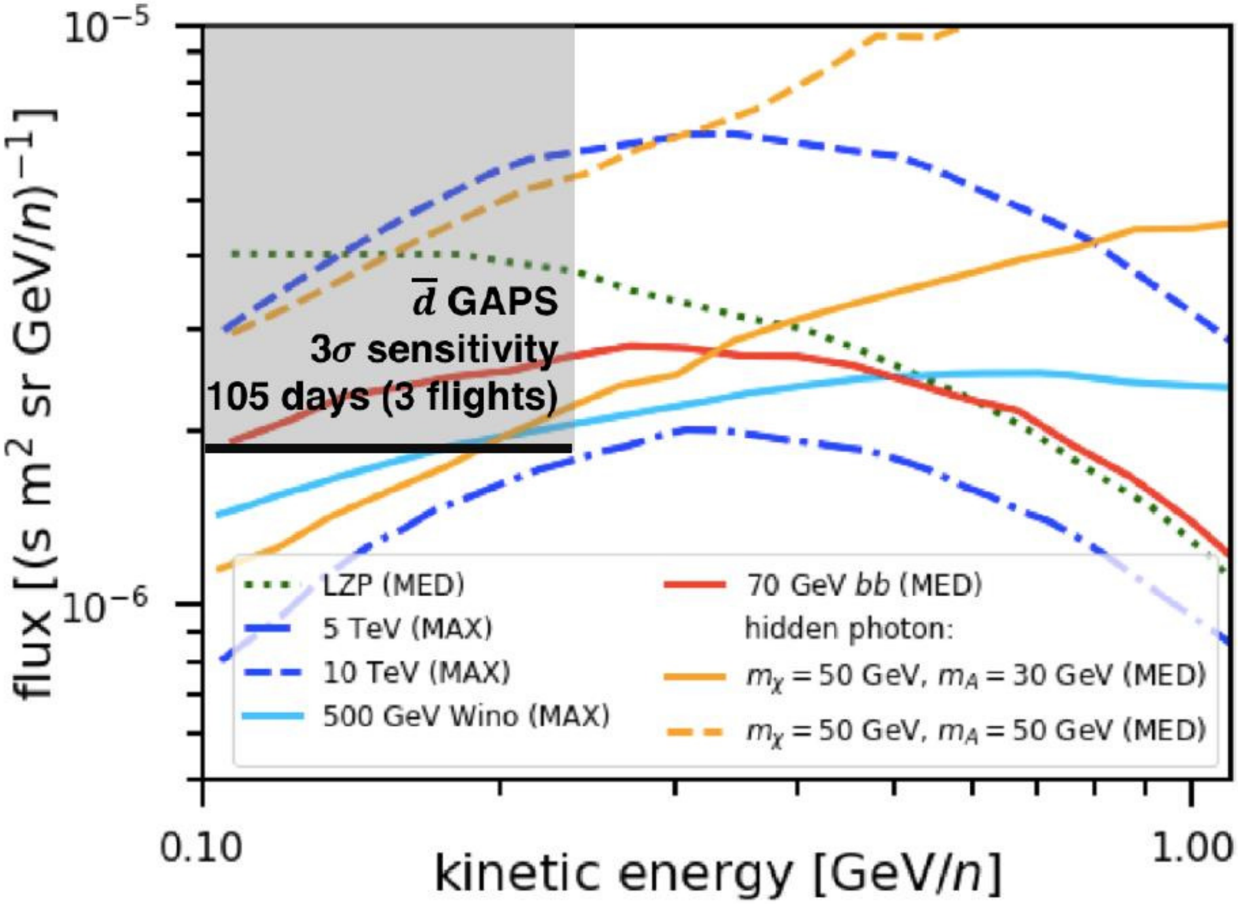


- **Secondary production:**



Antideuteron dark matter models

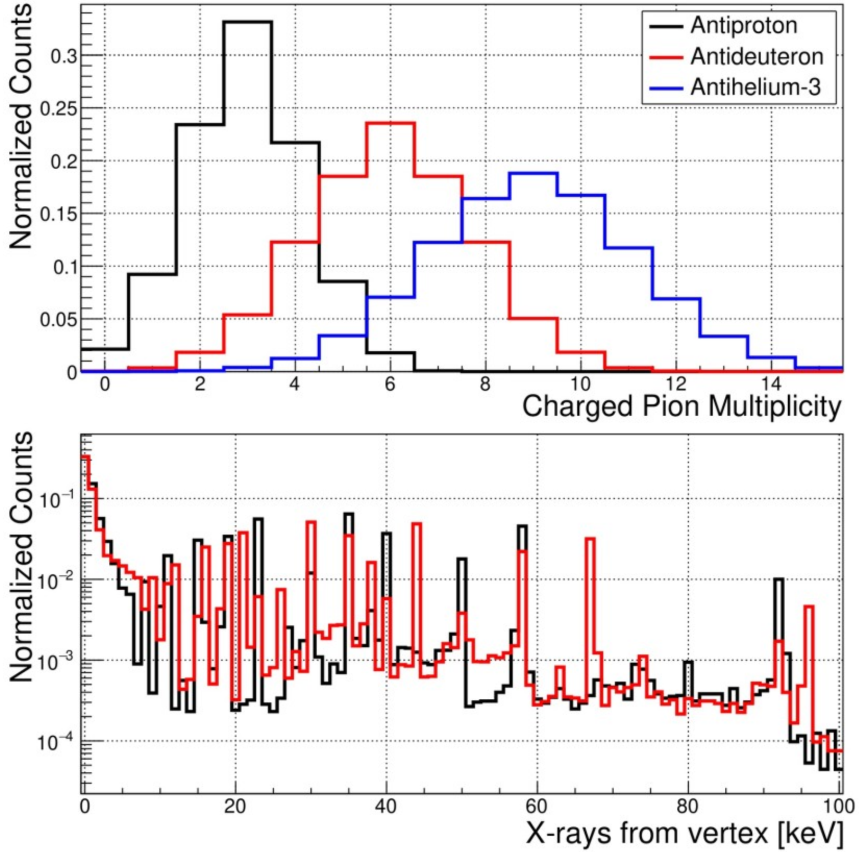
- GAPS will be sensitive to a wide range of **DM models**:
  - generic 70 GeV WIMP annihilation (consistent with antiproton excess and γ from Galactic centre)
  - dark matter gravitino decay
  - extra dimensions
  - dark photons
  - heavy DM models with Sommerfeld enhancement



PoS (ICRC2021) 494

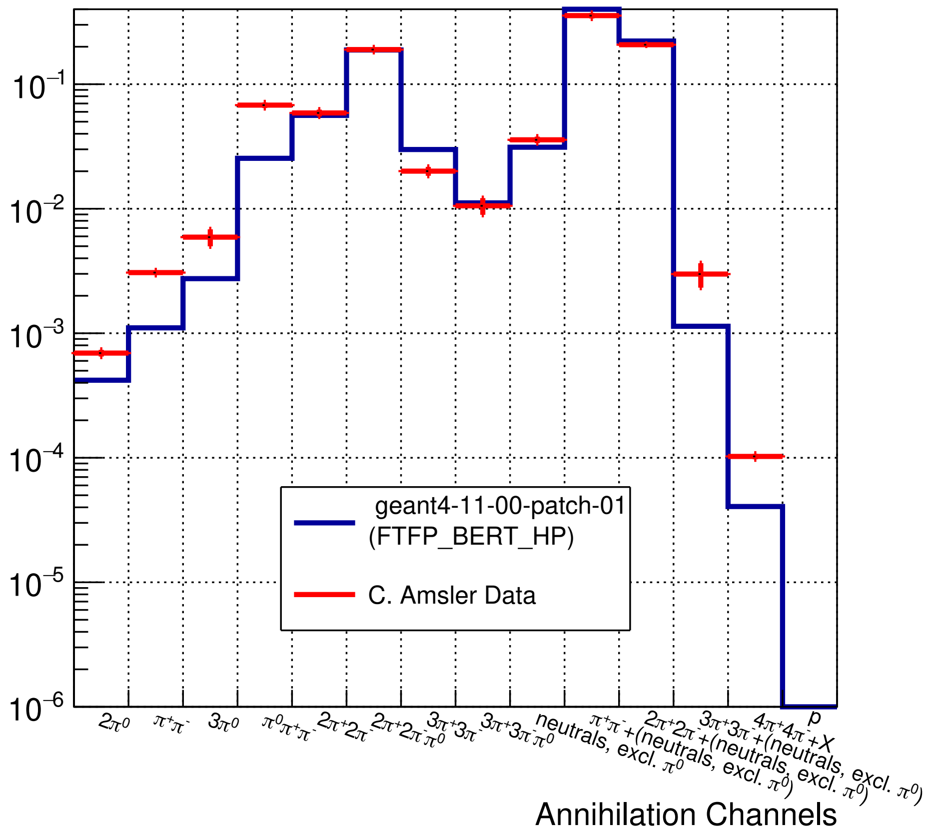
Antinucleus identification

- The **identification** of the antinucleus is performed using:
  - velocity of the primary antinucleus
  - energy deposits of the primary antinucleus
  - depth in detector material crossed before annihilation
  - multiplicity of charged annihilation products
  - X-ray from exotic atom de-excitation



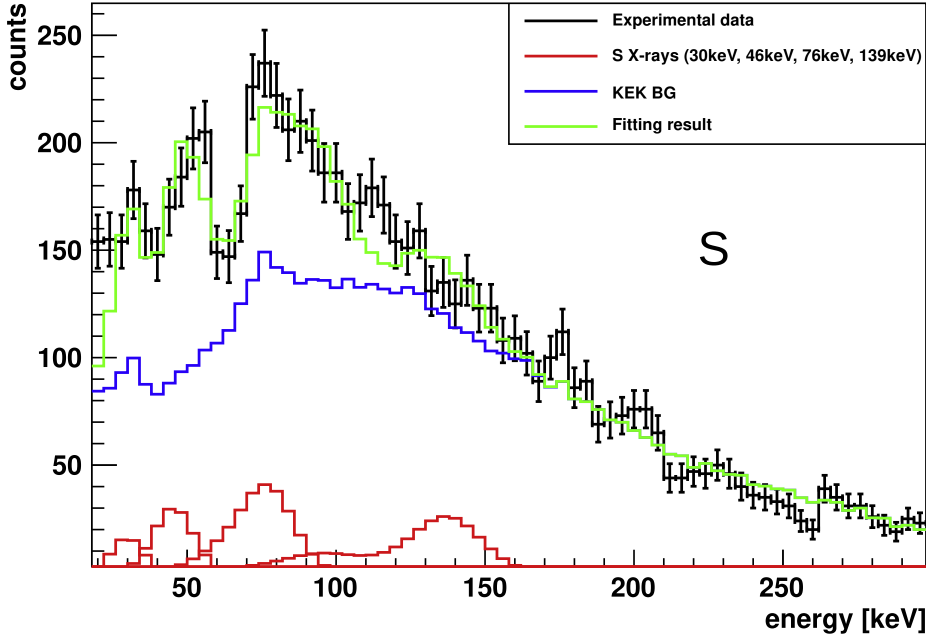
Antinucleus annihilation in Geant4

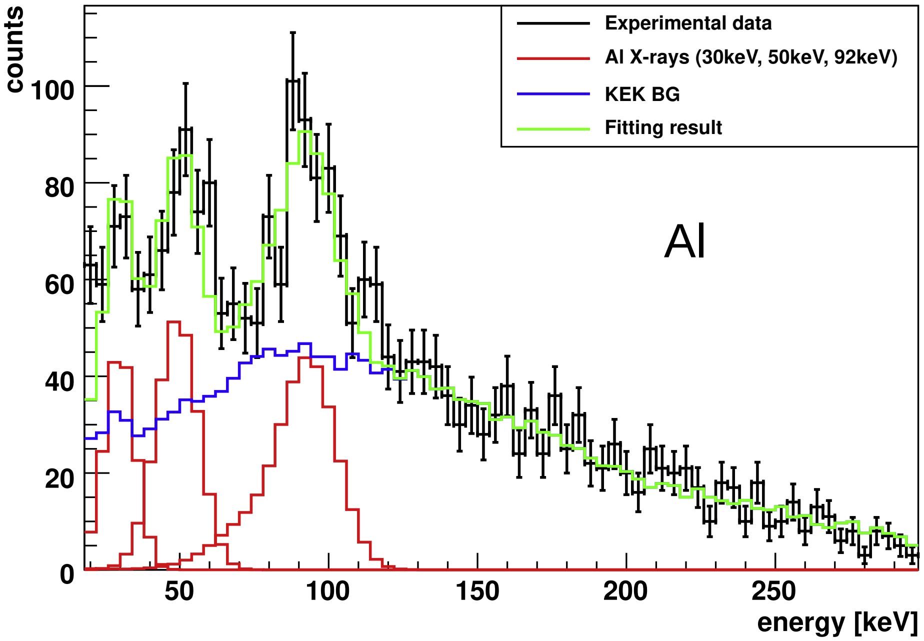
- Test of annihilation physics in Geant4
- Work with Geant4 developers
- Will be validated with antiproton data



Exotic atom technique validation

- Test at KEK accelerator in 2004/2005 with antiproton beam at 1 GeV/c
- X rays from antiprotonic exotic atom in Al, S, CBr_4, CCl_4 targets

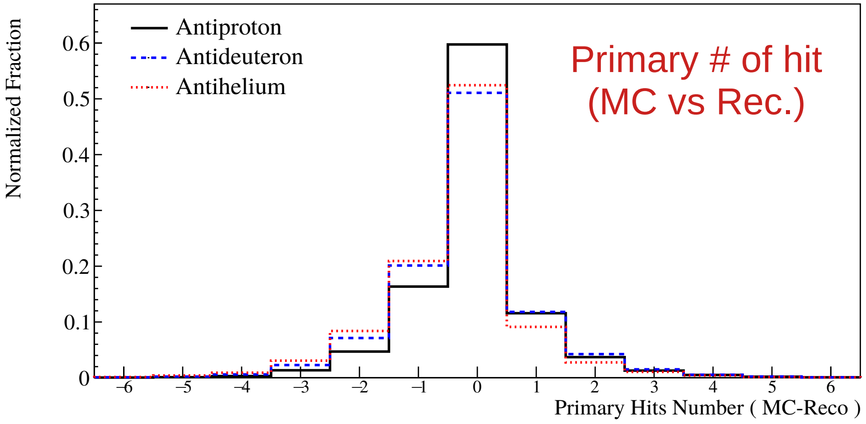


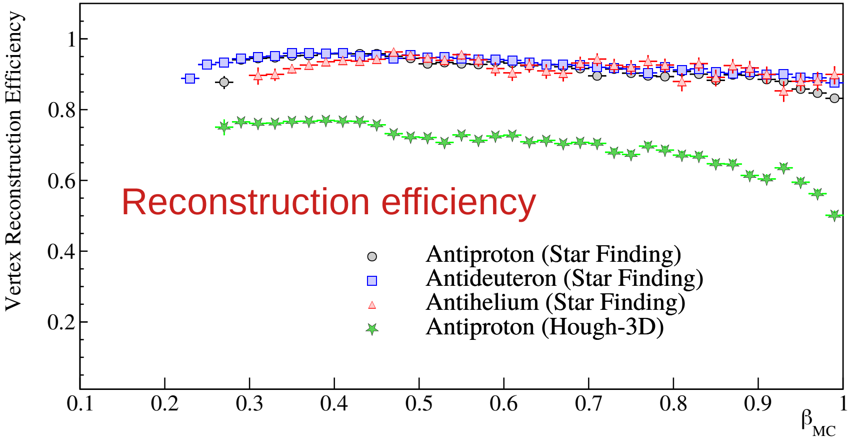


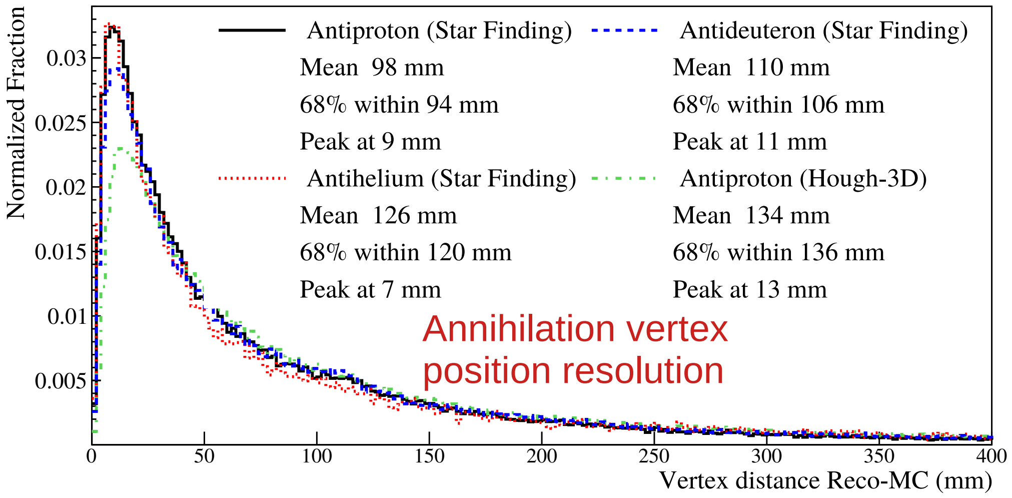
Astroparticle Physics 49 (2013) 52–62

Reconstruction performance

Astroparticle Physics 133 (2021) 102640



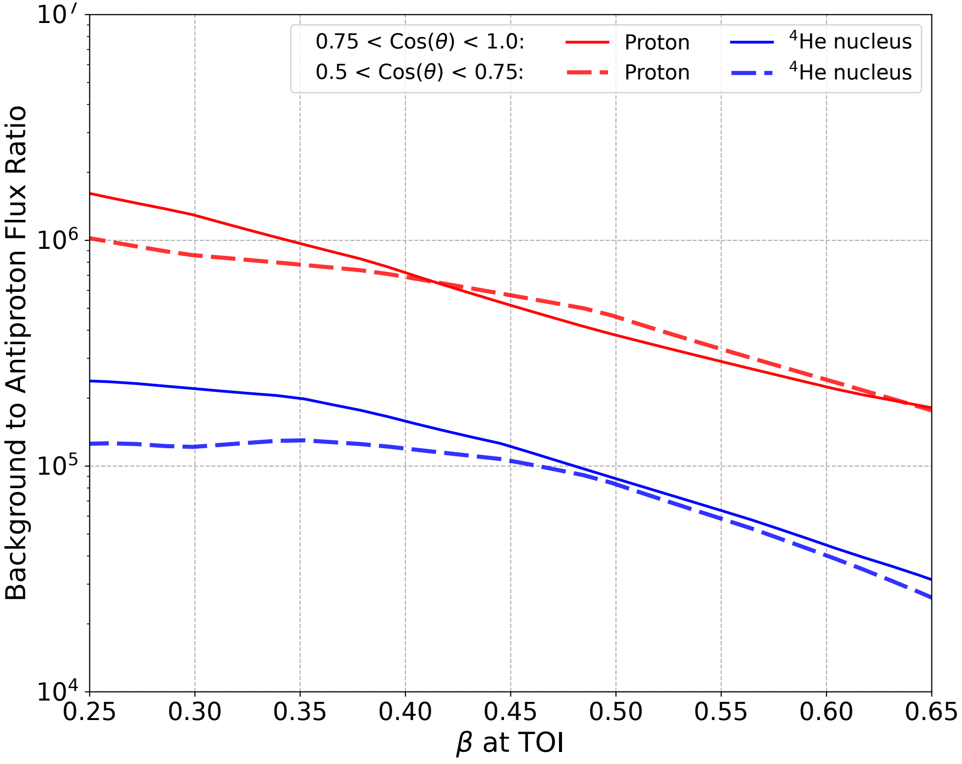


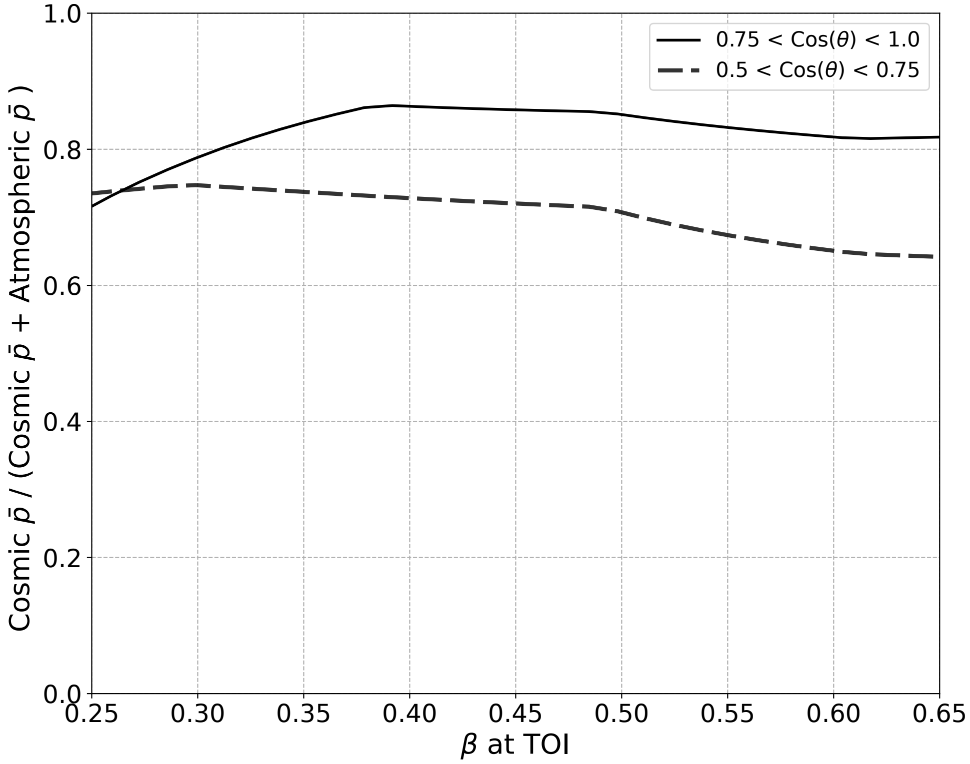


- Reconstruction efficiency: **~90%**
- Annihilation vertex resolution peaks at **~1 cm** for all antinuclei species of interest (68% containment within **~10 cm**)

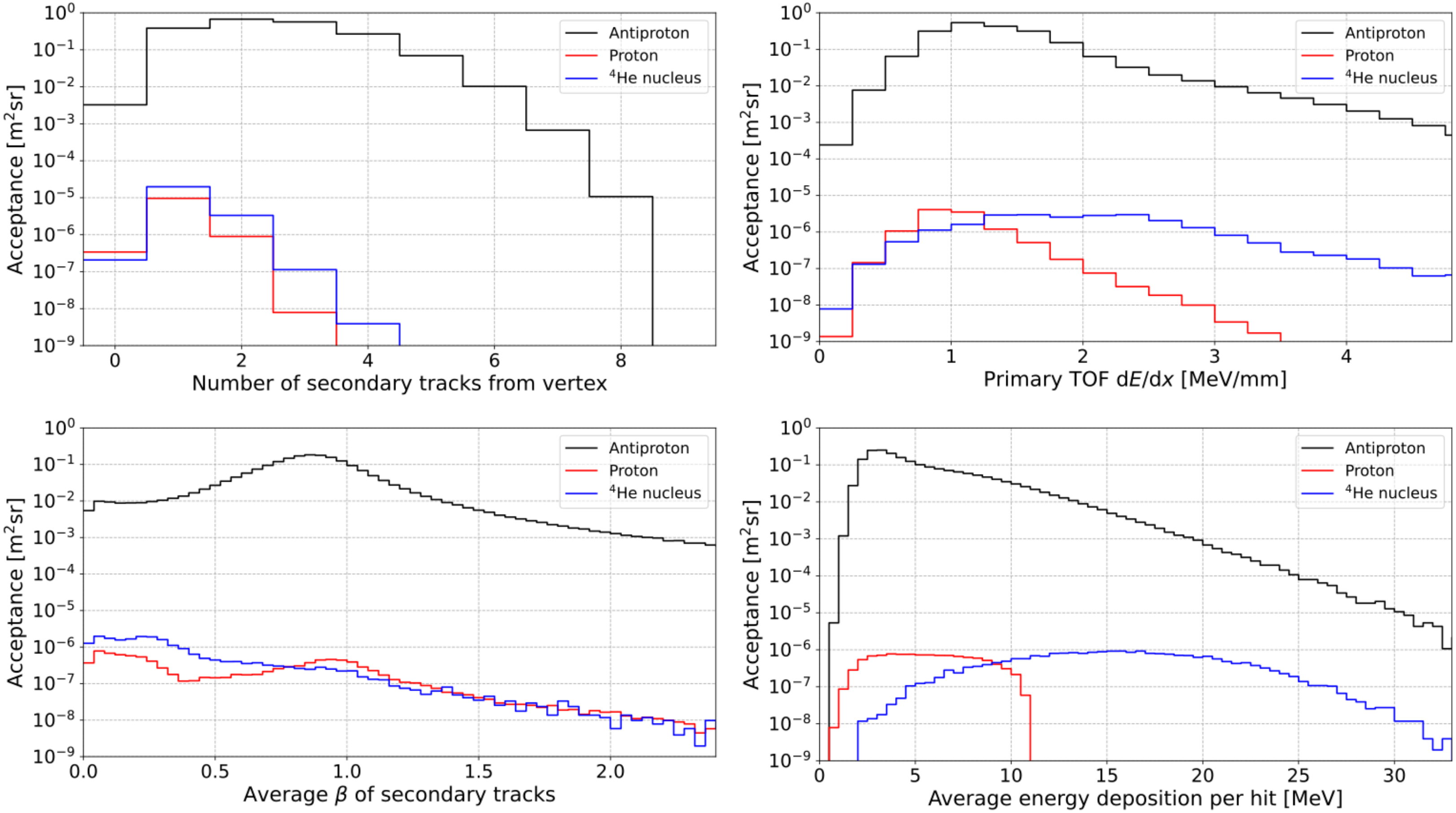
Antiproton background

Astroparticle Physics 145 (2023) 102791



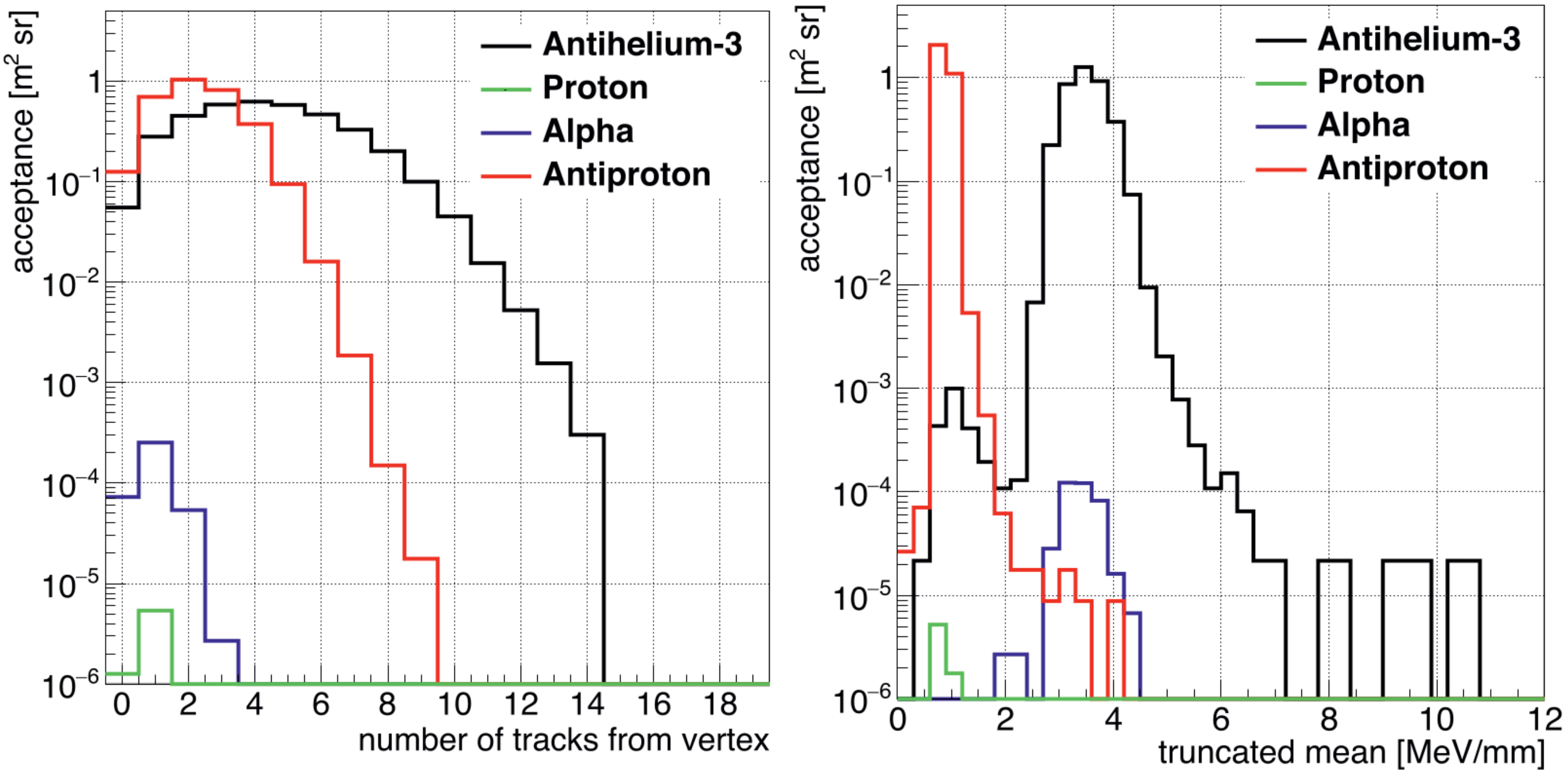


Antiproton identification



Astroparticle Physics 145 (2023) 102791

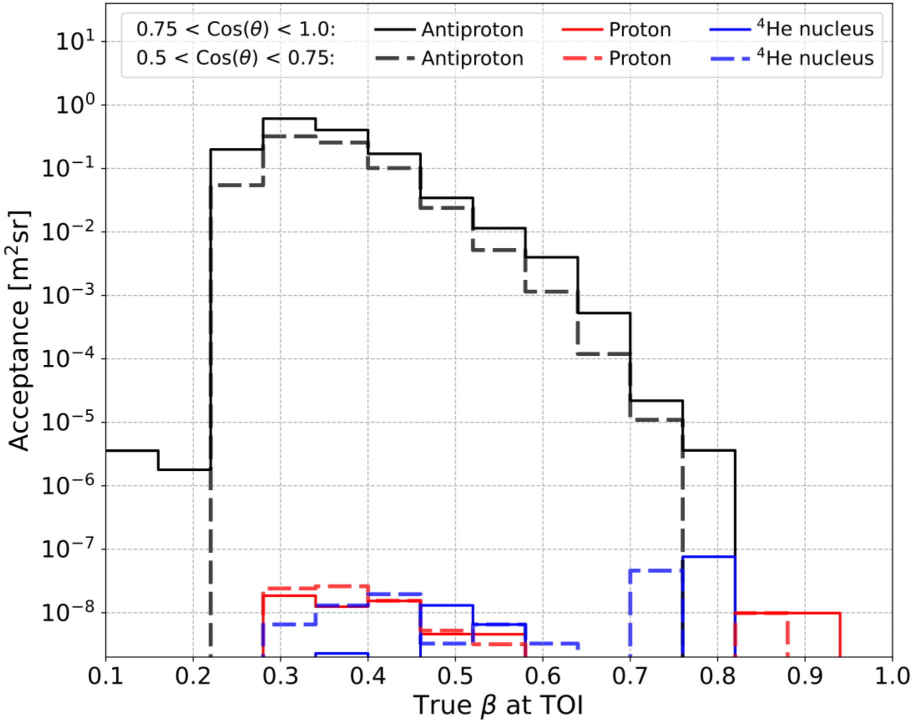
Antihelium-3 identification



Astropart. Phys. 102580 (2021)

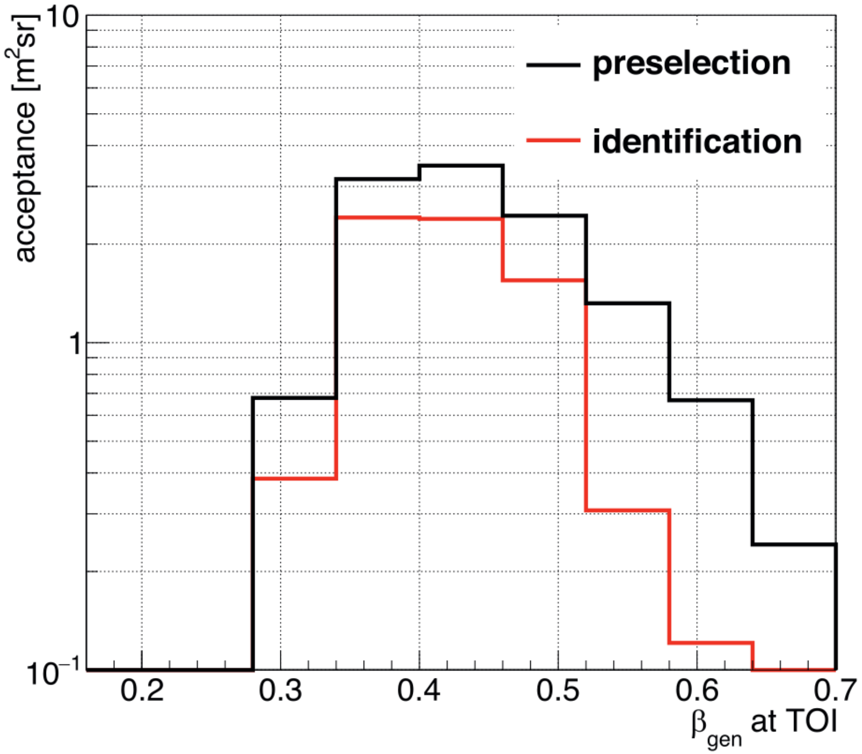
Acceptance

antiproton



Astroparticle Physics 145 (2023) 102791

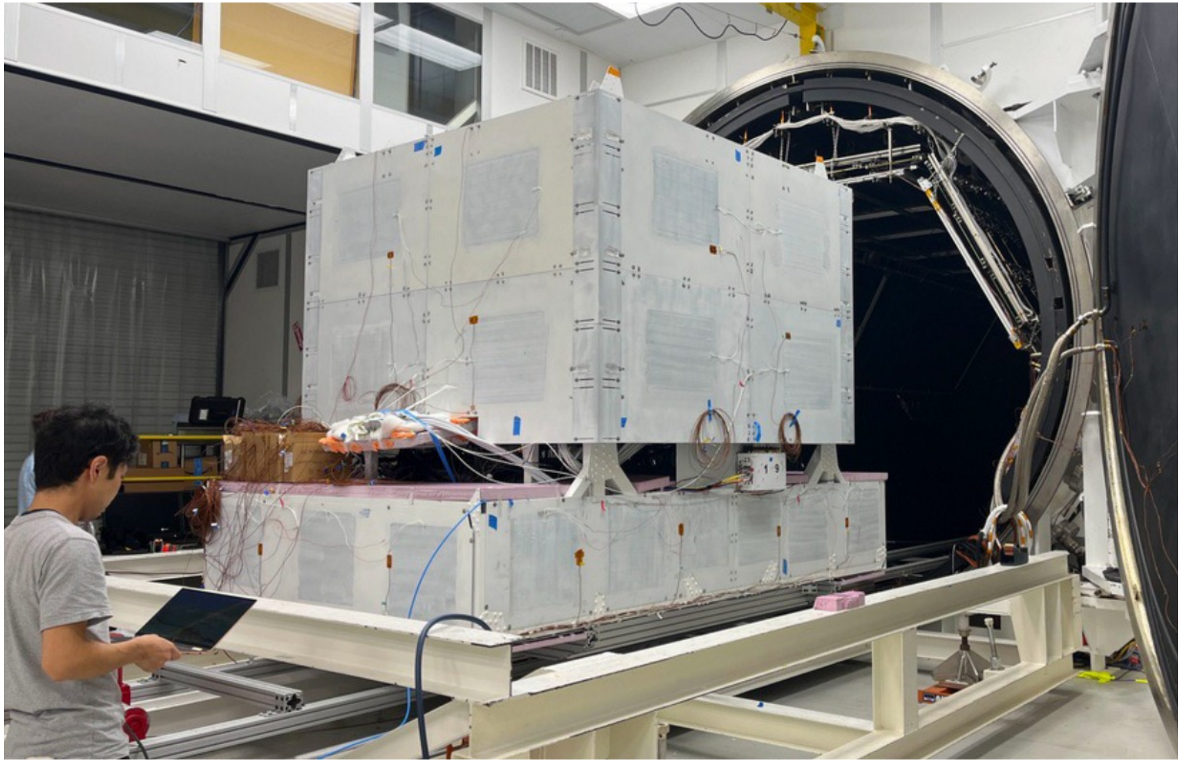
antihelium-3



Astropart. Phys. 102580 (2021)

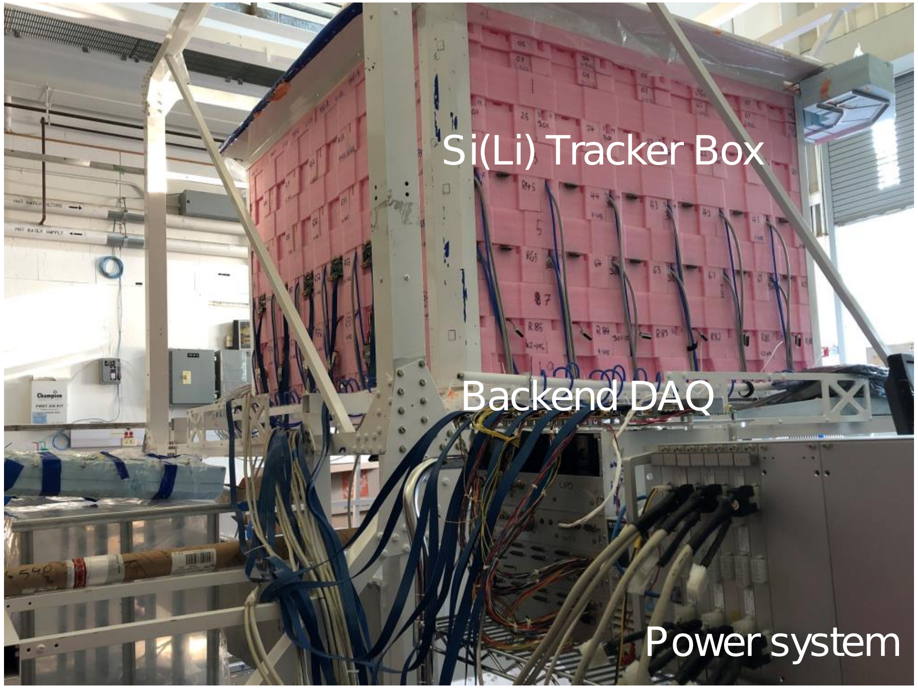
Thermal-vacuum test (TVAC)

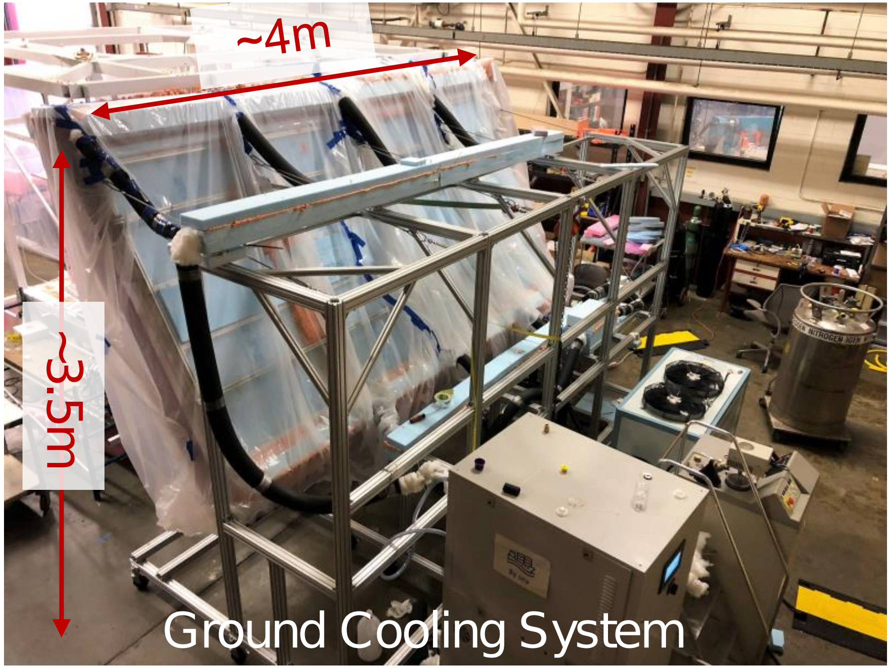
- TVAC at National Technical Systems (NTS), El Segundo, CA
  - validate thermal model
  - demonstrate functionality of electronics and detector systems
  - test of operation with cooled down and biased silicon detectors
- 4 days of test during June 2023



GAPS payload integration (MIT Bates Lab)

- GAPS integration of the payload at MIT Bates Laboratory (March 2022 → August 2022)
    - construction and testing of Si(Li) tracker (6 planes)
    - Integration of tracker with thermal system





GAPS payload integration (UC Berkley SSL)

- GAPS integration of the payload at the UC Berkley Space Science Laboratory (September 2022 → May 2023)
  - Complete tracker integration
  - Integration of tracker with ToF and readout electronics
  - Testing of the system