Search for cosmic-ray antinuclei with the GAPS experiment

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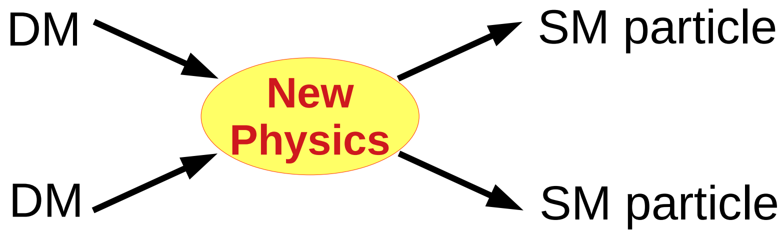
on behalf of the GAPS collaboration

4th EMMI workshop on Anti-matter, Hyper-matter and Exotica production at the LHC
13-17 February 2023, Bologna, Italy

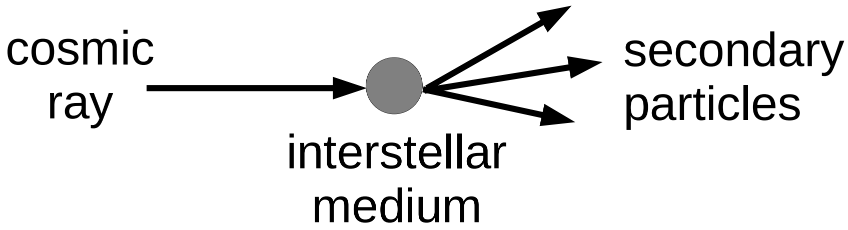
Dark matter indirect search

- **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

Dark Matter annihilation (**signal**)



Secondary production (**background**)

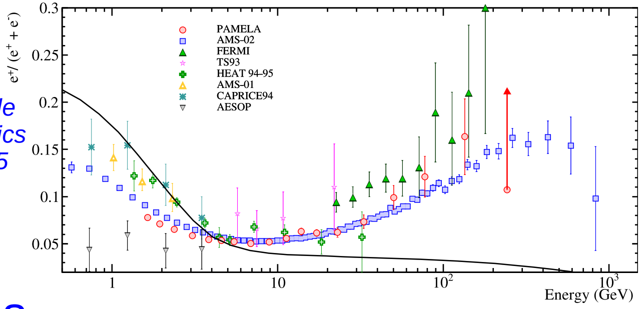


- Different kinematics between cosmic rays produced in dark matter annihilation/decay and standard astrophysical processes ("secondary production")

Hints of dark matter?

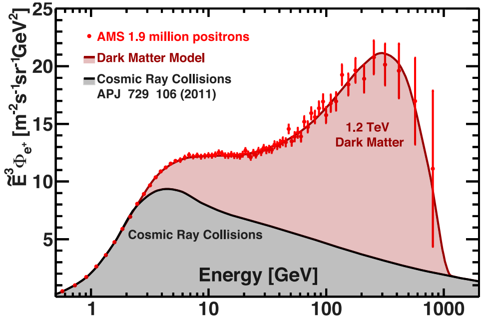
- Some unexplained features have been found in positrons, antiprotons, and gamma rays from the Galactic centre
- Could be explained with a dark matter contribution...

Progress in Particle and Nuclear Physics 112 (2020) 103765

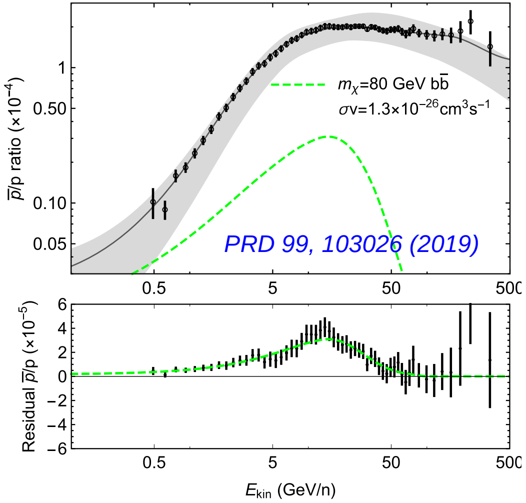


positrons

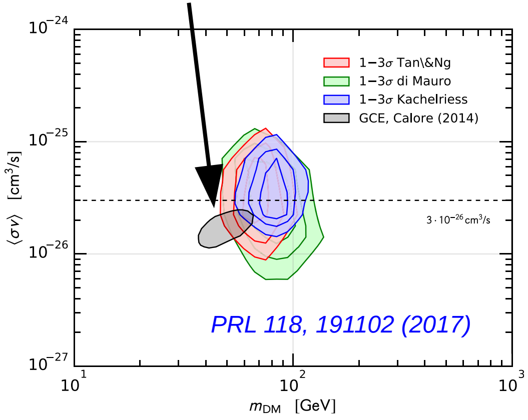
Physics Reports 894 (2021) 1–116



antiprotons



consistent with gamma ray excess from galactic center

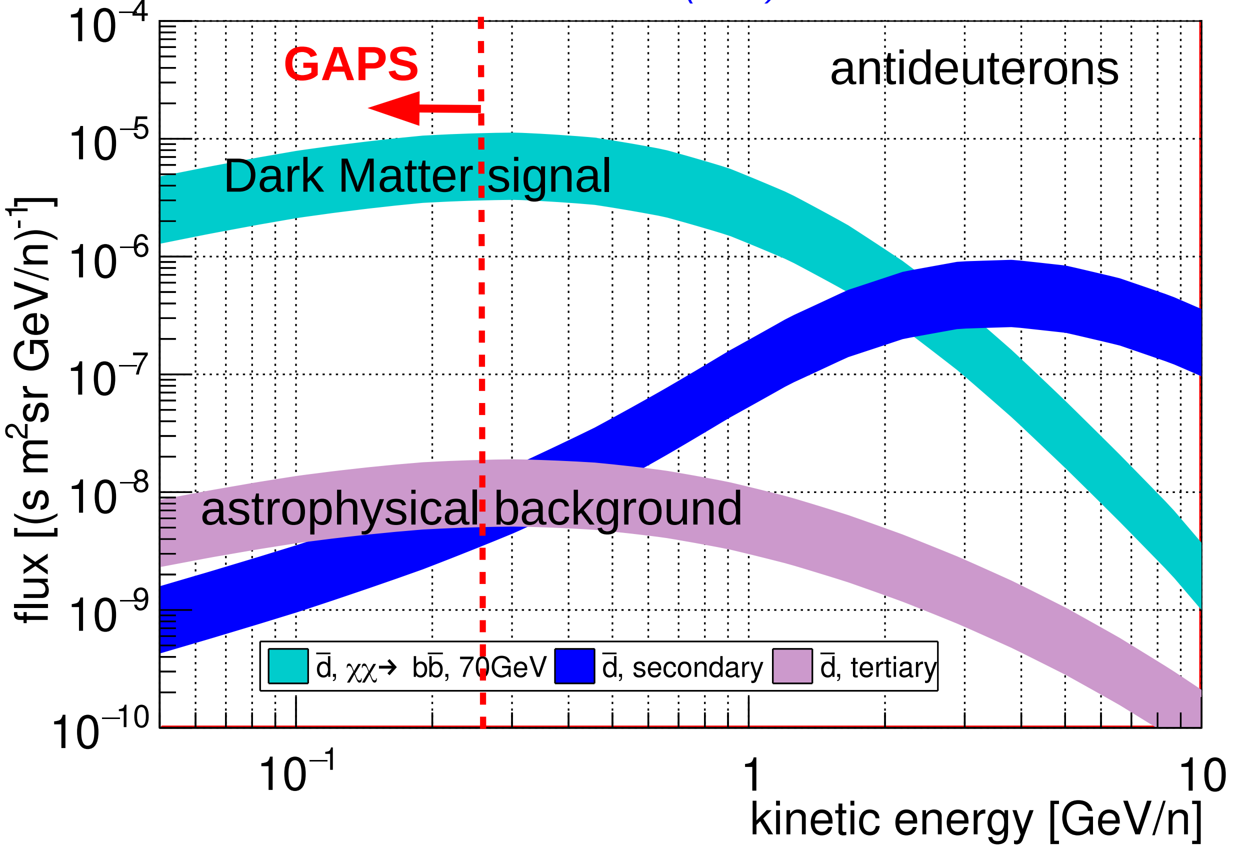


- ...but they can also be explained with astrophysical processes
- The understanding of the astrophysical background is crucial for the interpretation of the data

GAPS scientific goals

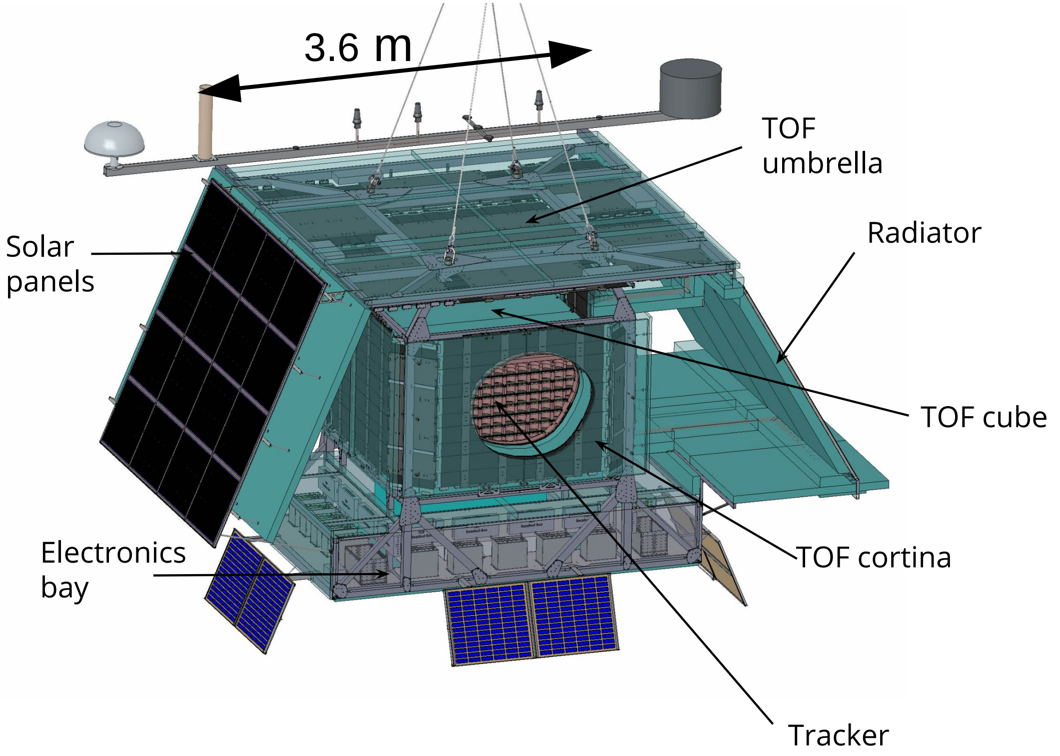
- Expected **antideuteron** and **antihelium-3** signal from DM annihilation/decay is orders of magnitude above the astrophysical background at low energies
- **GAPS** is designed to detect antideuteron and antihelium-3 below **250 MeV/n** as evidence for DM
- GAPS will also perform a precise measurement of **antiproton** spectrum in an unexplored low-energy range
- Low-energy spectrum of **p**, **d**, and **He** will also be measured

JCAP08 (2020) 03511



The GAPS experiment

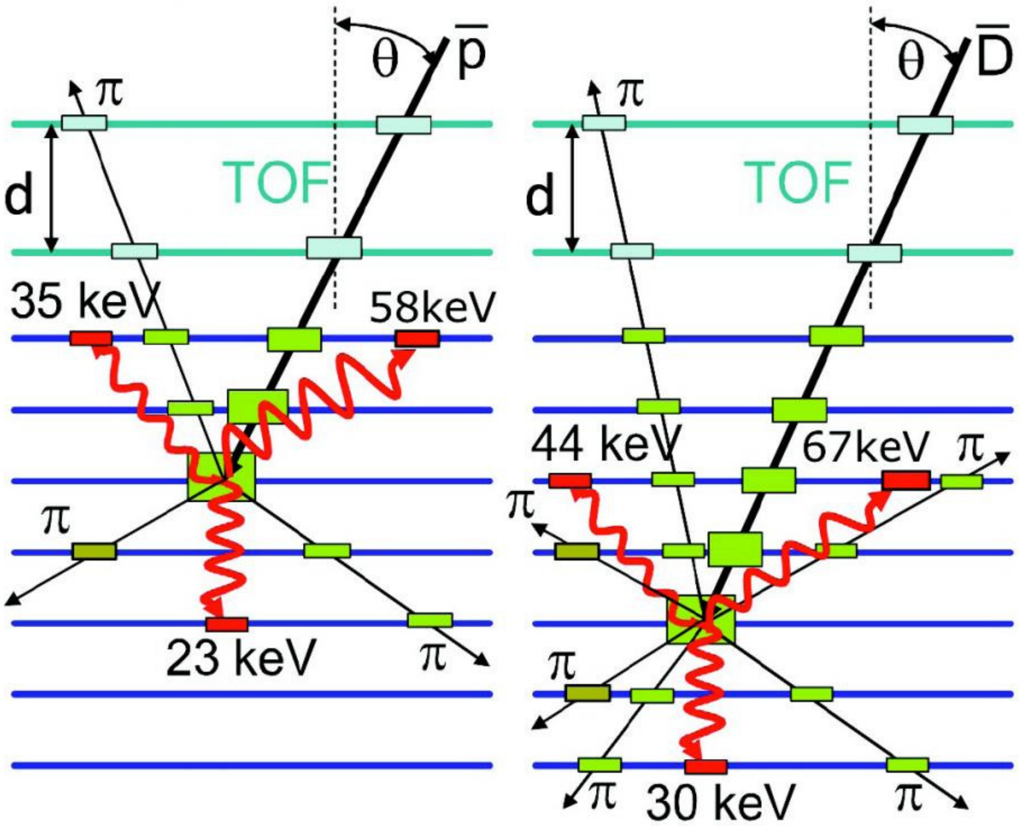
- **General Antiparticle Spectrometer**
- Balloon-borne experiment
  - three long duration balloon flights from Antarctica planned
  - First flight in 2023/2024 austral summer
- Experimental apparatus composed of a **time-of-flight (ToF)** system surrounding a **tracker**
- **ToF:** plastic scintillators (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

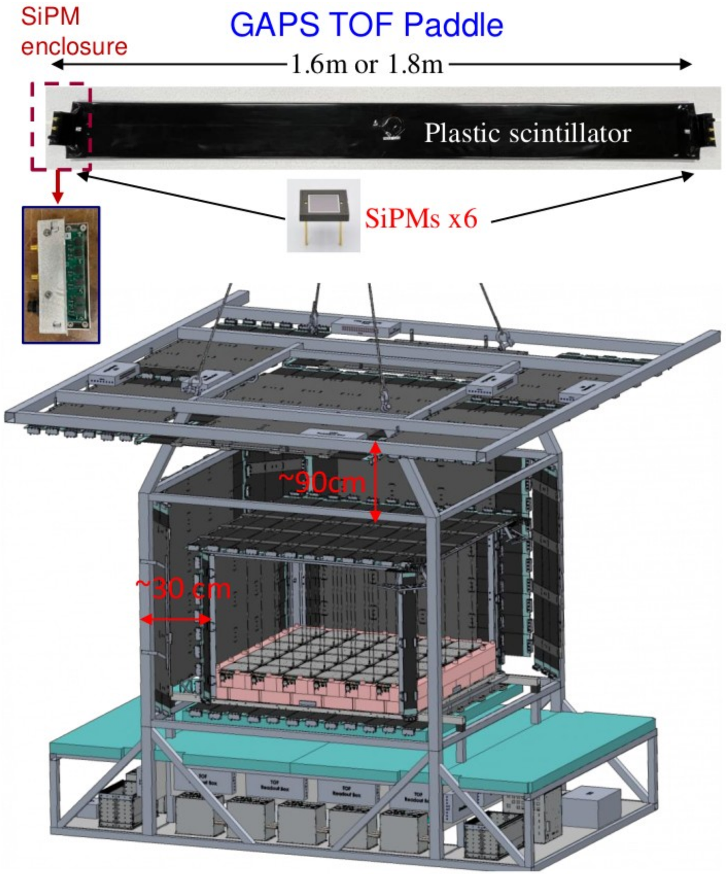
- The antinucleus slows-down and form an exotic atom in the tracker
- The exotic atom de-excites emitting characteristic **X-rays**
- The antinucleus annihilates with the nucleus of the exotic atom, emitting a “star” of secondary particles (**pions, protons**)
- Completely **different** and **complementary**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

antiproton **antideuteron**



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



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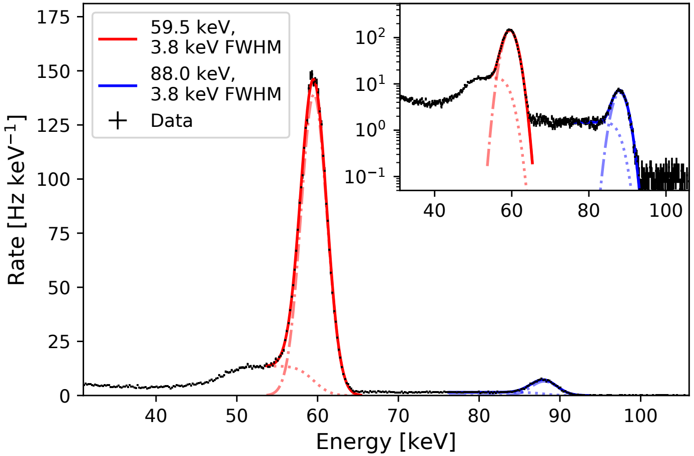
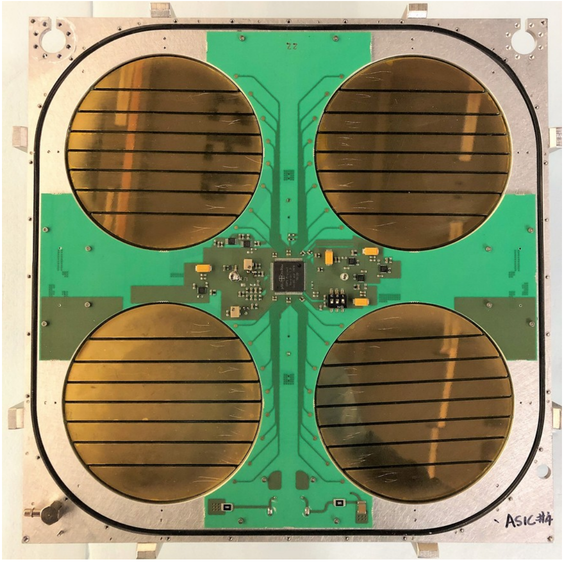
Tracker

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



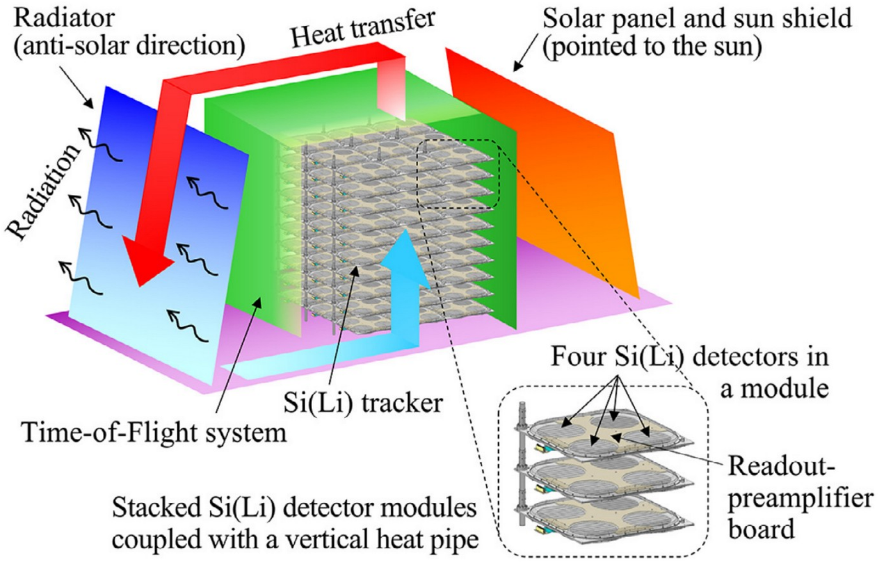


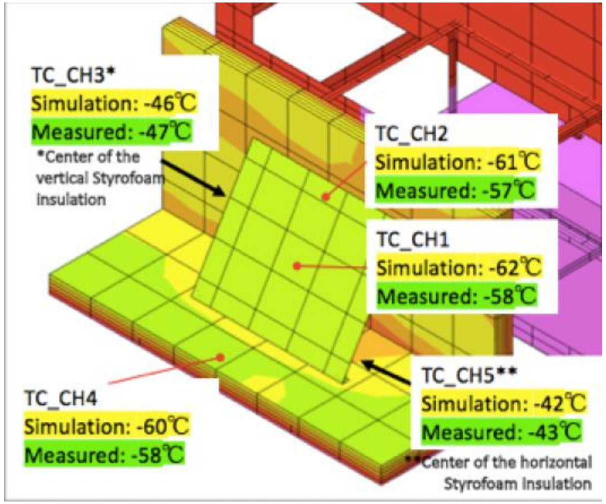
- Custom ASIC for energy deposit measurement
  - high dynamic range: **~10 keV → ~100 MeV**
  - low power consumption
- Energy resolution **<4 keV** (for 60 keV X-rays)
  - needed to discriminate X-rays from different antinuclei and different target atoms

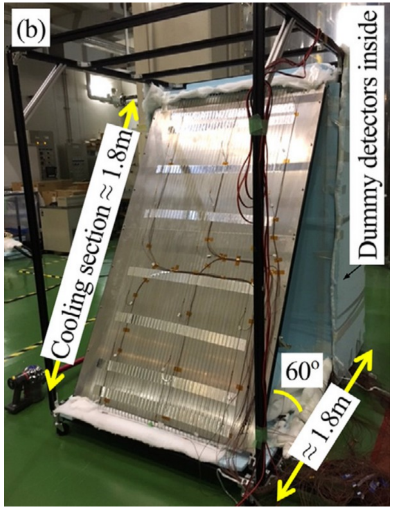
NIM A 905 (2018) 12   NIM A 947 (2019) 162695   JINST 14 (2019) P10009.   NIM A 997 (2021) 165015

Cooling system

- 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





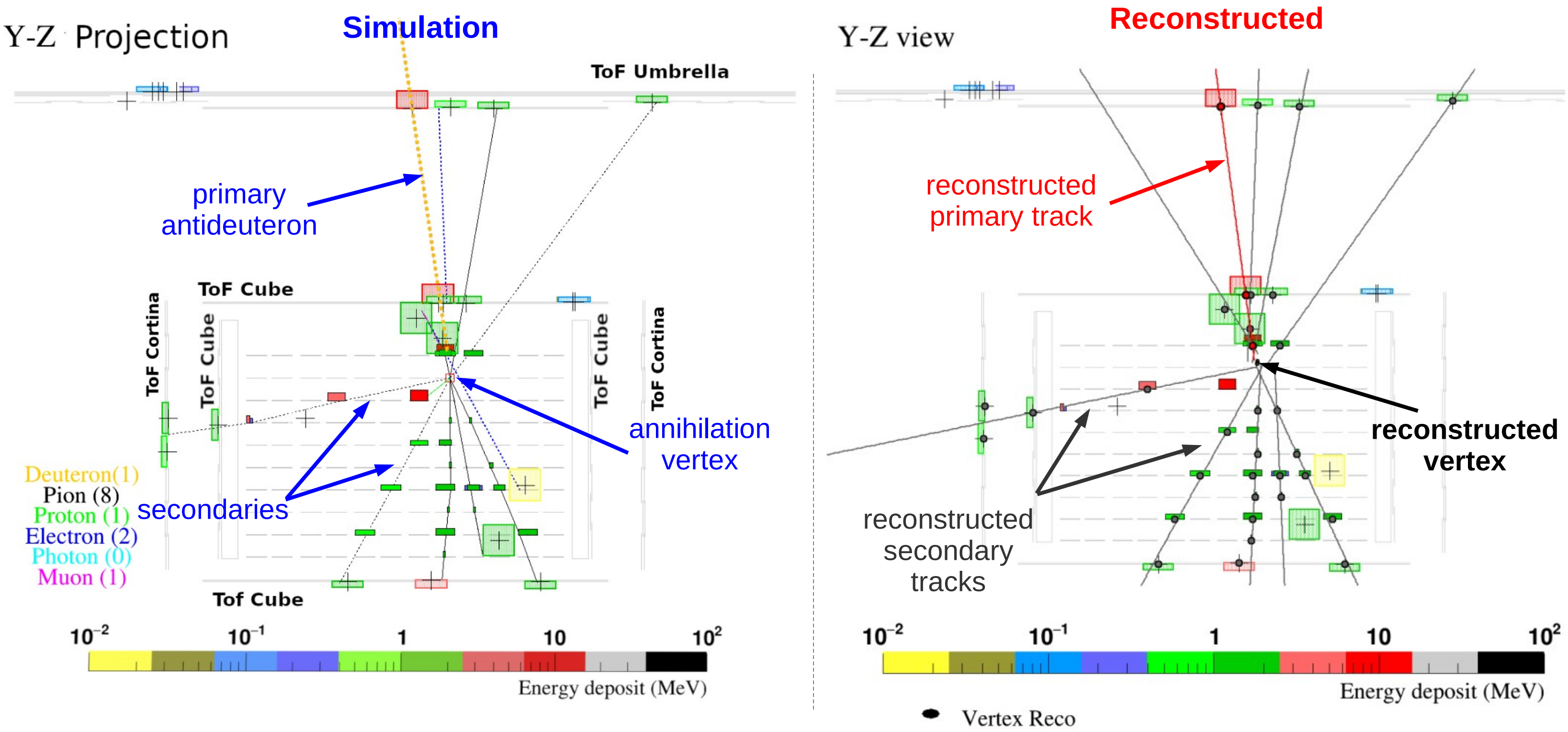


- Scaled down prototype **successfully tested** in 2019

J. Astron. Inst. 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

Reconstruction performance

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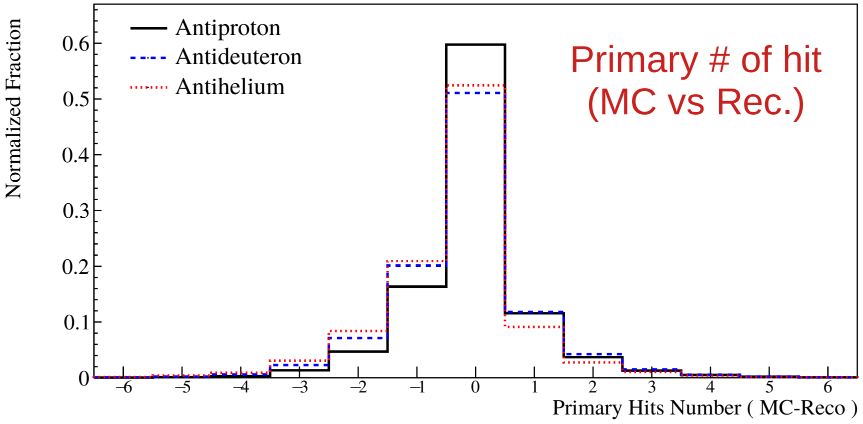
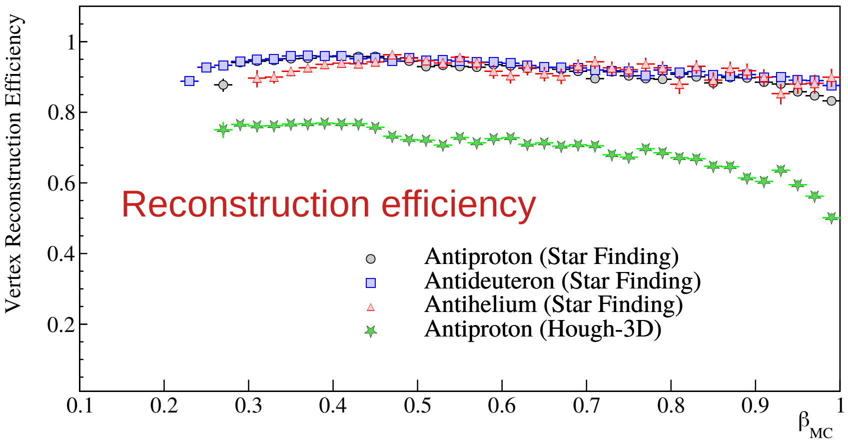
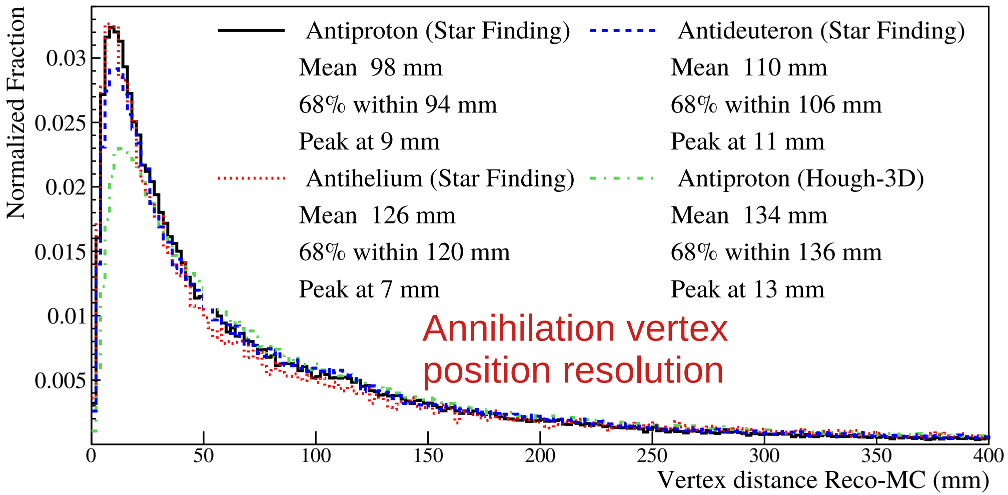


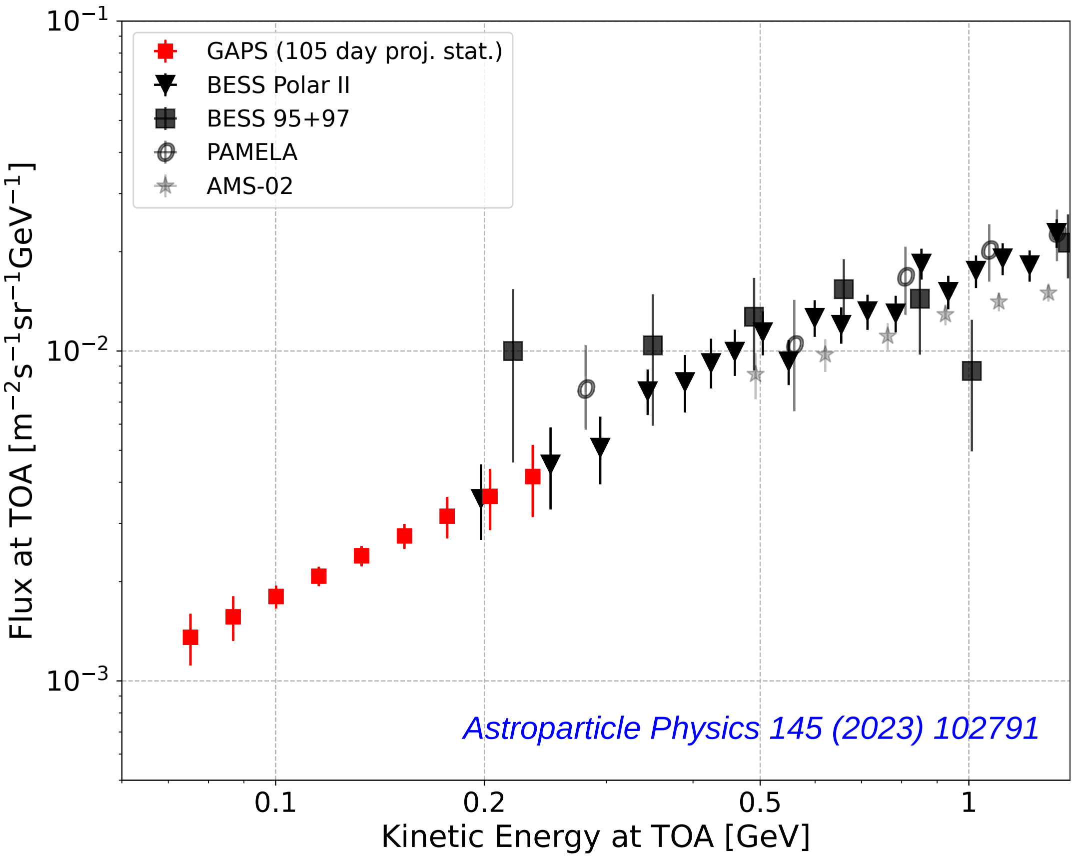




- Reconstruction efficiency: **~90%**
- Annihilation vertex resolution peaks at **~1 cm** for all antinuclei species of interest (68% containment within **~10 cm**)

GAPS: antiproton spectrum

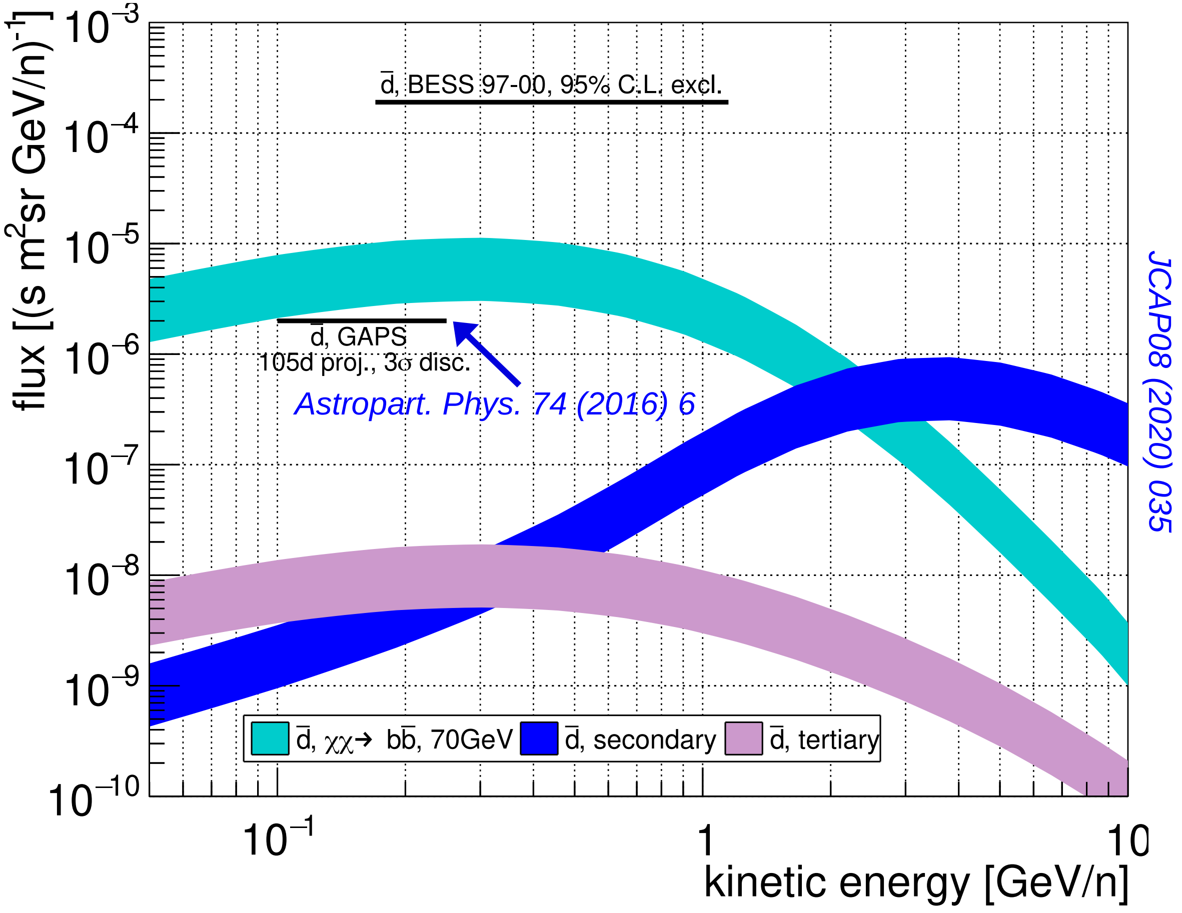
- Precision measurement of **antiproton** spectrum in an **unexplored low energy region**
- **~500** antiprotons expected for each balloon flight
  - other measurements:
    BESS: 29 @ ~0.2 GeV
    PAMELA: 7 @ 0.25 GeV)
    AMS: > ~0.3 GeV
- Provide constraints on **Galactic propagation** and **solar 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: antideuteron sensitivity

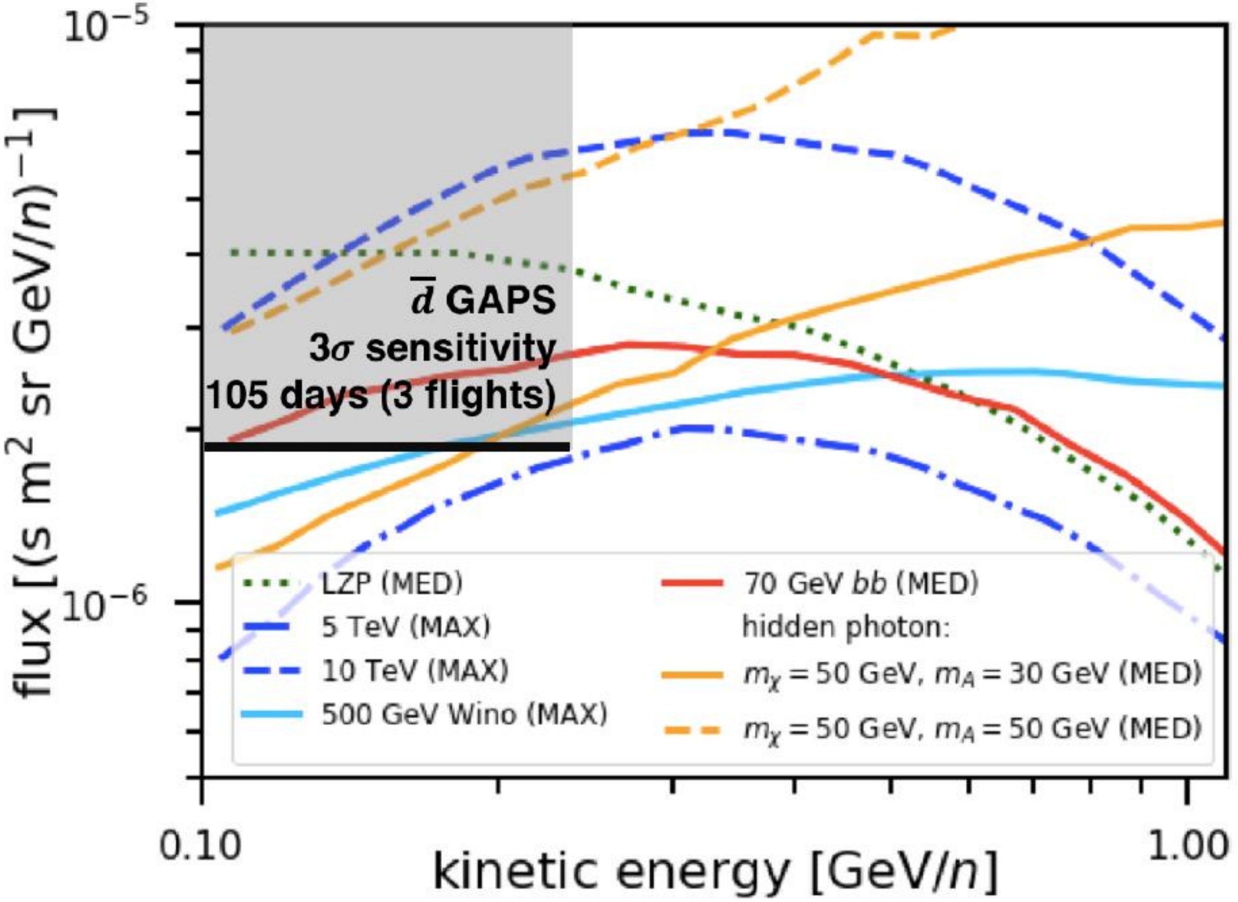
- Predicted **antideuteron** signal from dark matter decay or annihilation **~2 orders of magnitude** above astrophysical background below 250 MeV/n

- Even a single antideuteron would point to **new physics**
- GAPS **sensitivity** will be up to **two orders of magnitude** better than existing BESS limit



Antideuteron dark matter models

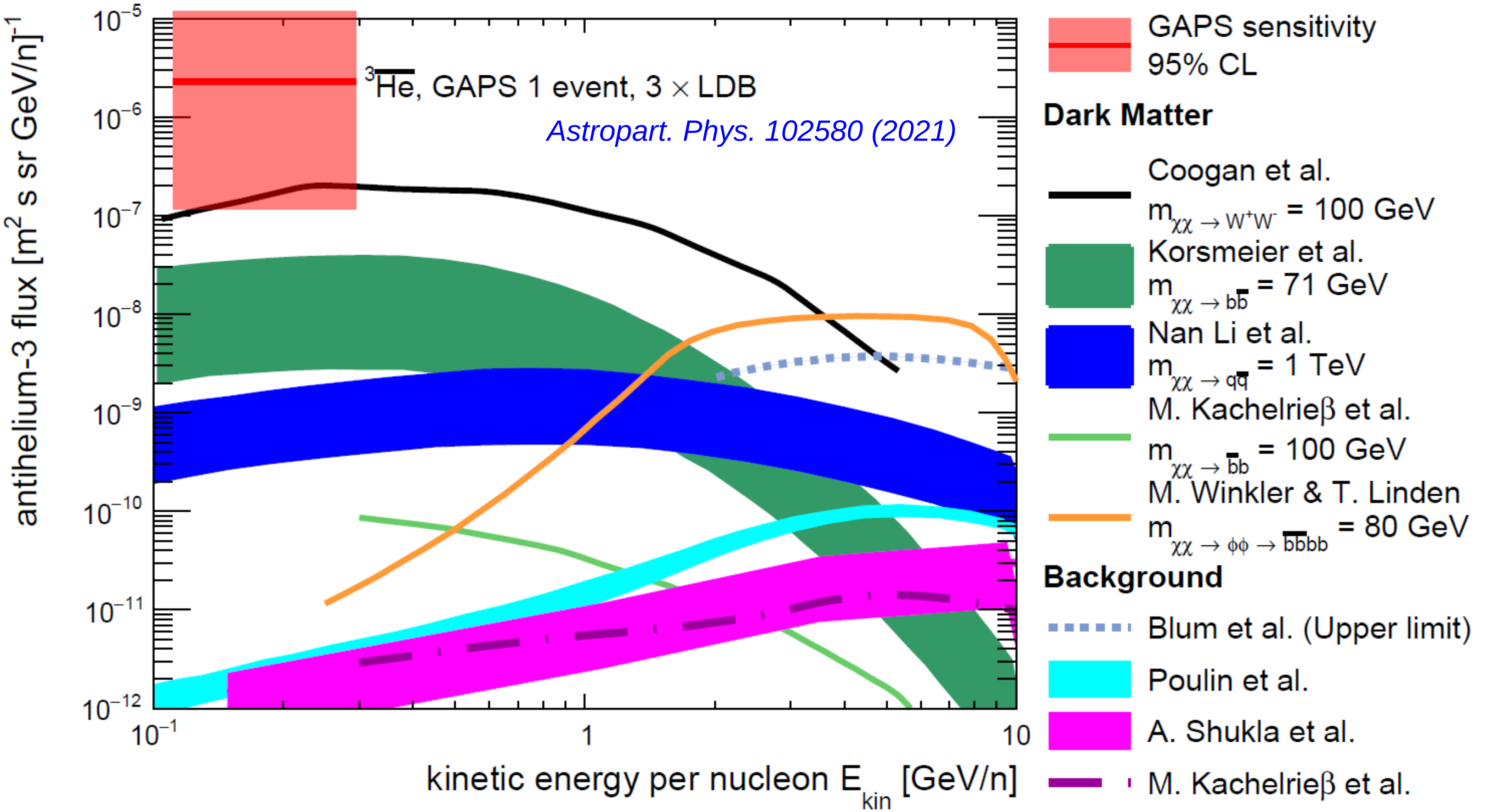
- GAPS will be sensitive to a wide range of **DM models**:
  - generic 70 GeV WIMP annihilation (consistent with antiproton excess and γ from Galactic centre)
  - dark matter gravitino decay
  - extra dimensions
  - dark photons
  - heavy DM models with Sommerfeld enhancement



PoS (ICRC2021) 494

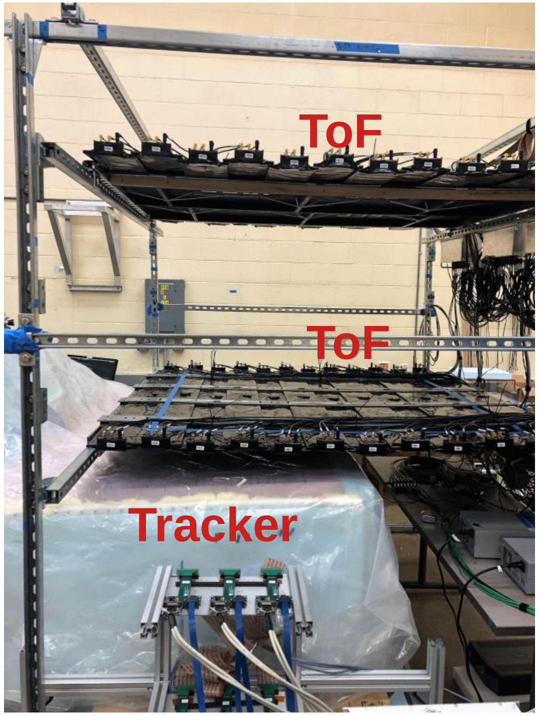
GAPS: antihelium-3 sensitivity

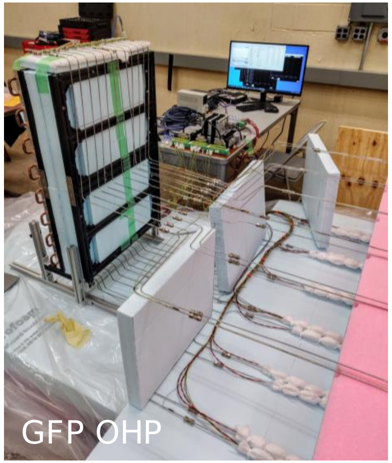
- GAPS will be sensitive to **antihelium-3**
- ...but antihelium-3 flux ~2-3 orders of magnitude below antideuteron flux
- An observation of antihelium-3 would be a clear indication of **new physics**
- Extend the energy coverage at low energies (**0.1-0.3 GeV/n**)



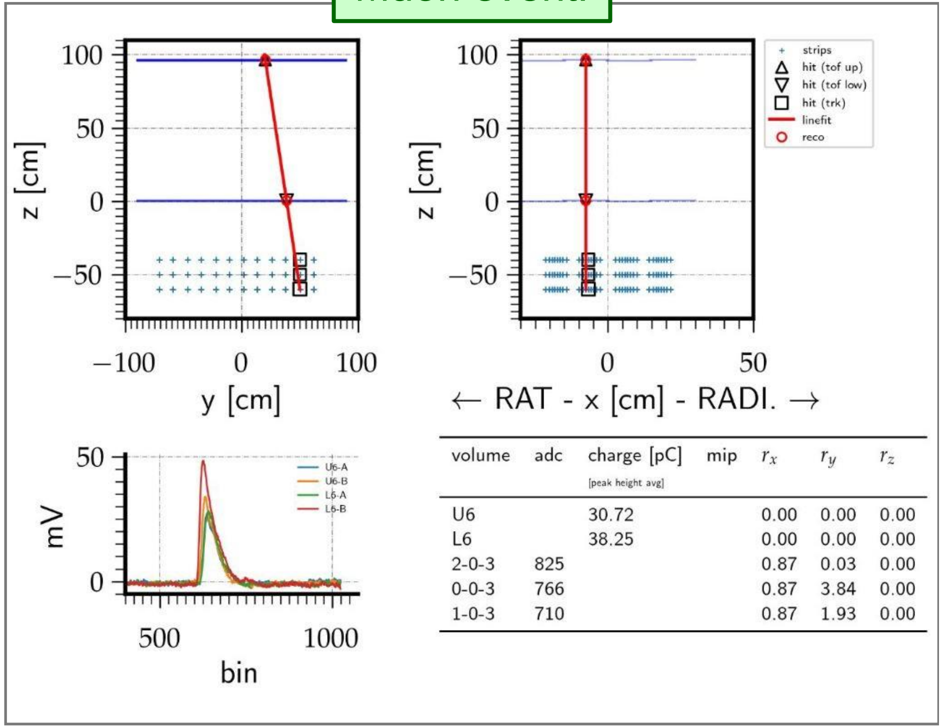
GAPS Functional Prototype

- 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!

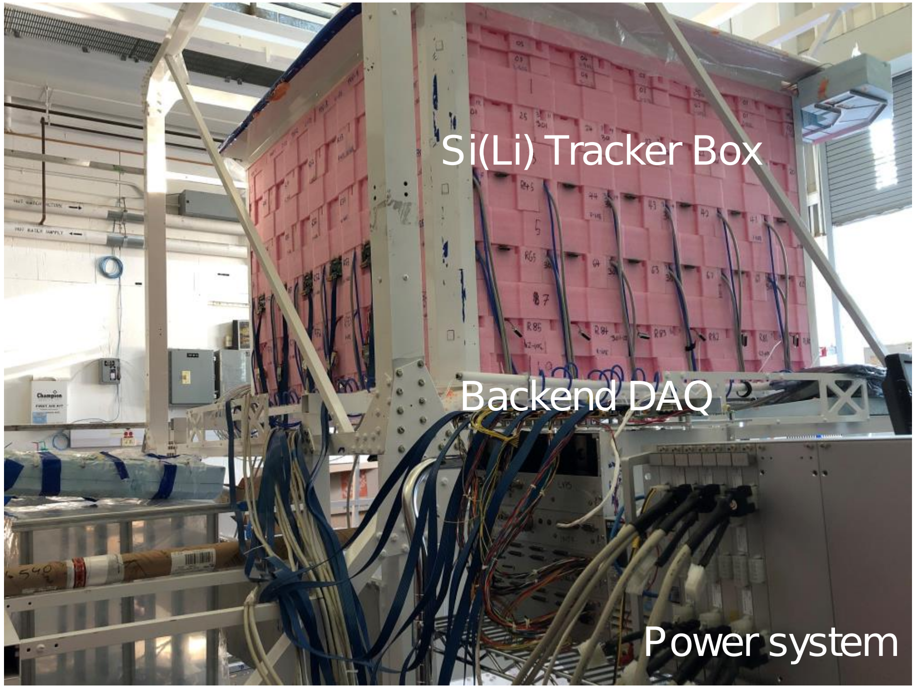


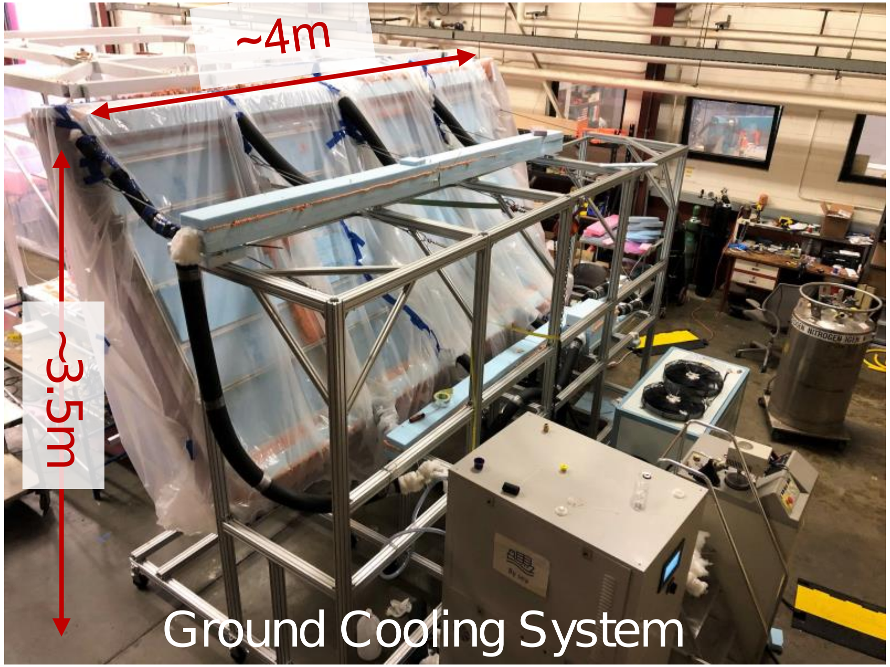
volume	adc	charge [pC] [peak height avg]	mip	r_x	r_y	r_z
U6		30.72		0.00	0.00	0.00
L6		38.25		0.00	0.00	0.00
2-0-3	825			0.87	0.03	0.00
0-0-3	766			0.87	3.84	0.00
1-0-3	710			0.87	1.93	0.00

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

GAPS full payload integration (MIT Bates)

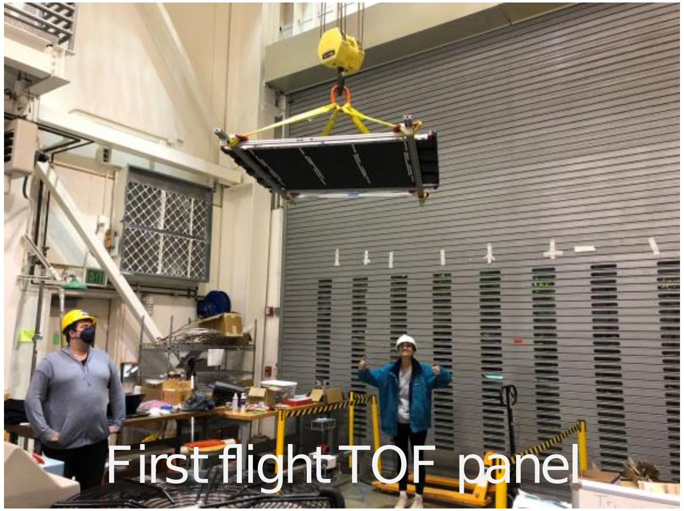
- GAPS integration of the full payload started at MIT Bates Laboratory (February-August 2022)
  - construction and testing of Si(Li) tracker (6 planes completed)
  - Integration of tracker with thermal system





GAPS full payload integration (UC Berkley)

- GAPS integration of the full payload now ongoing at the UC Berkley Space Science Laboratory (since September 2022)
  - Tracker integration completed in December 2022
  - Integration of tracker with ToF and readout electronics
  - Testing of the system
- Next: TVAC and compatibility testing



First flight TOF panel

GAPS @SSL, UC Berkeley

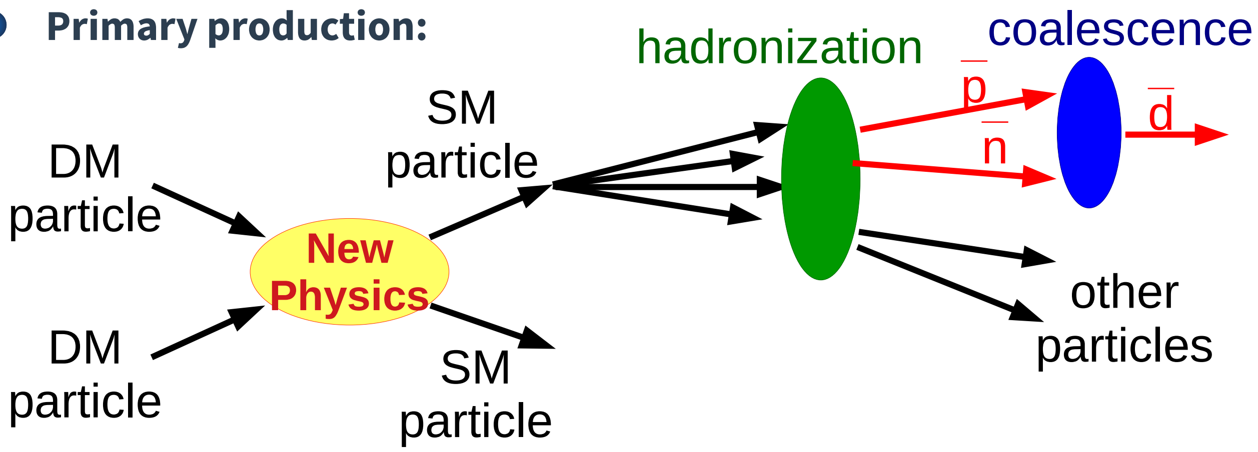
Summary

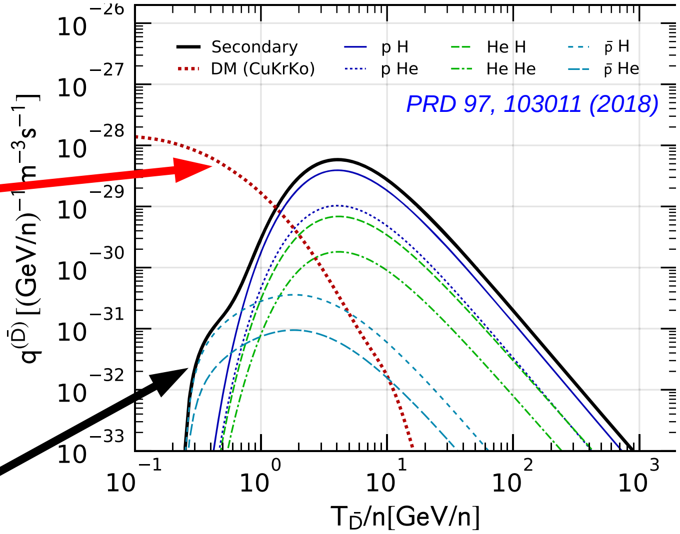
- **GAPS** is the first experiment dedicated to the observation of cosmic **antiprotons**, **antideuterons**, and **antihelium-3** at energies below **250 MeV/n**
- The main scientific goals of the experiment are:
  - **First detection of cosmic antideuterons**, thanks to excellent sensitivity in a background-free 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 is currently ongoing, a **functional prototype** has been assembled at the end of 2021 and successfully tested in 2022
- **First flight** is planned in late **2023**

backup

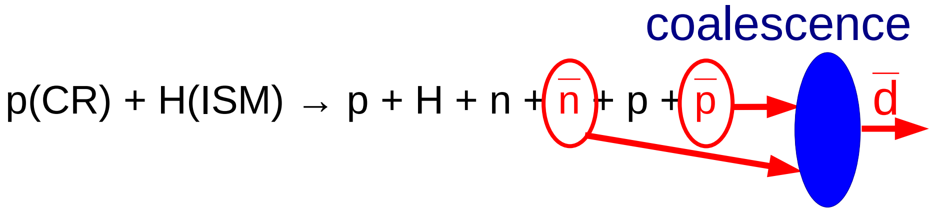
Antideuteron production

- **Primary production:**



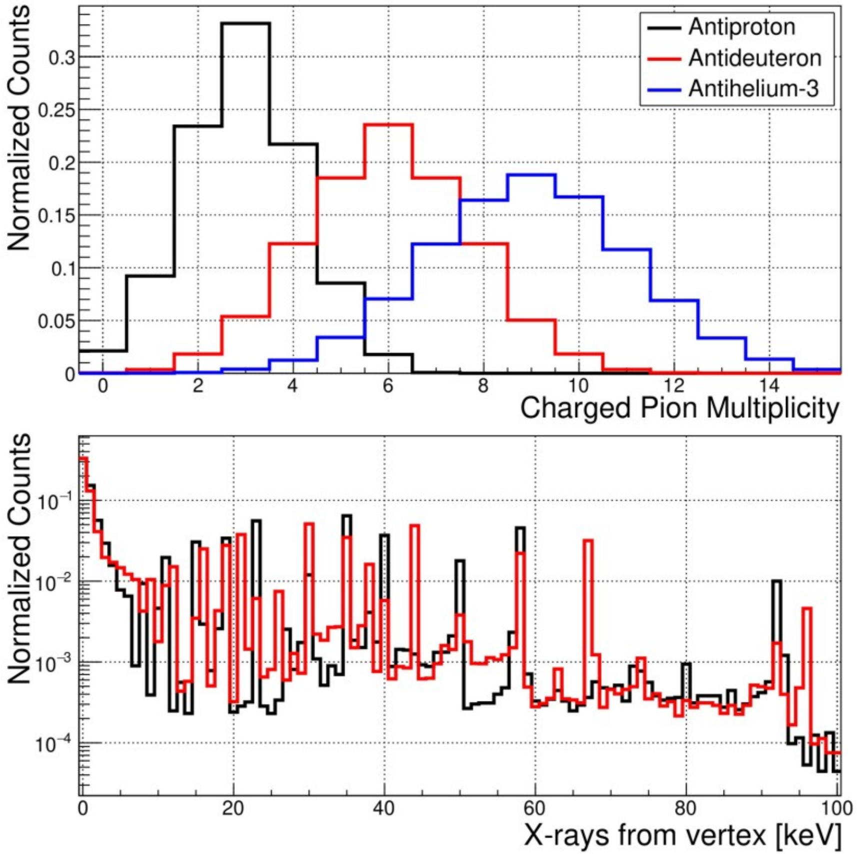


- **Secondary production:**



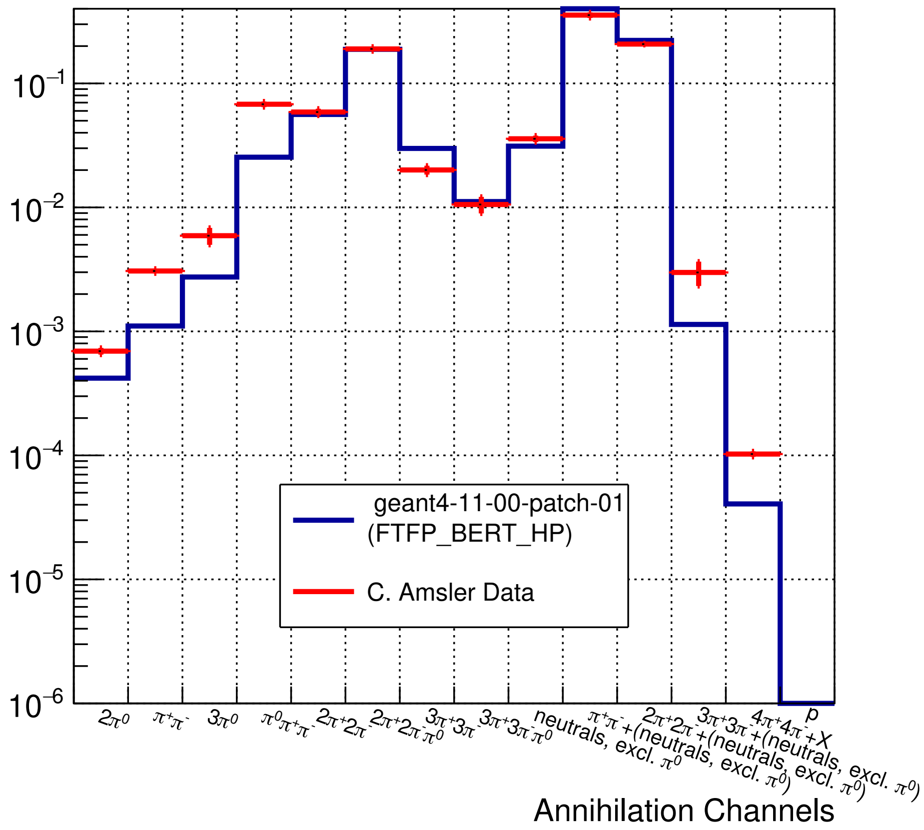
Antinucleus identification

- 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



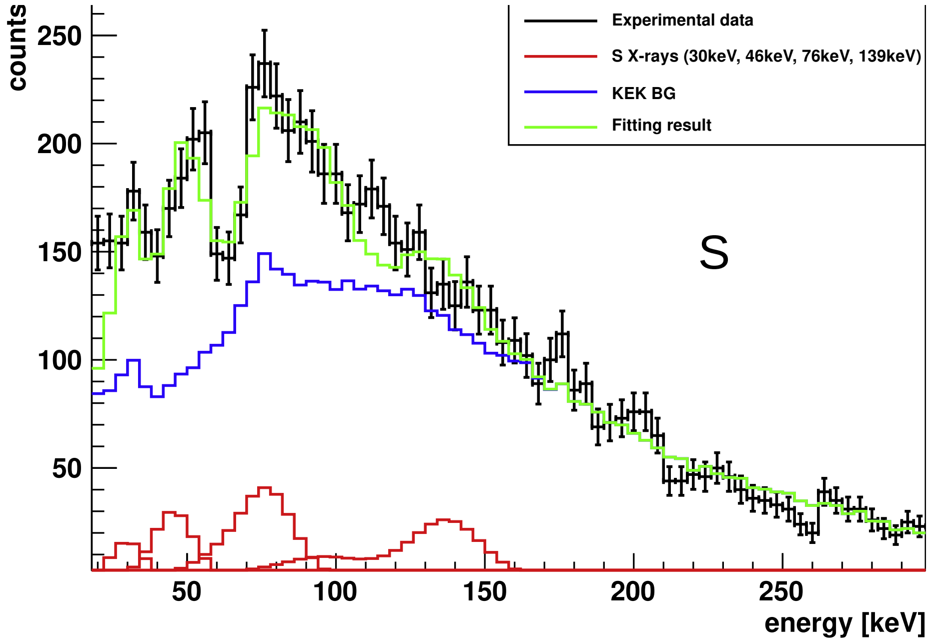
Antinucleus annihilation in Geant4

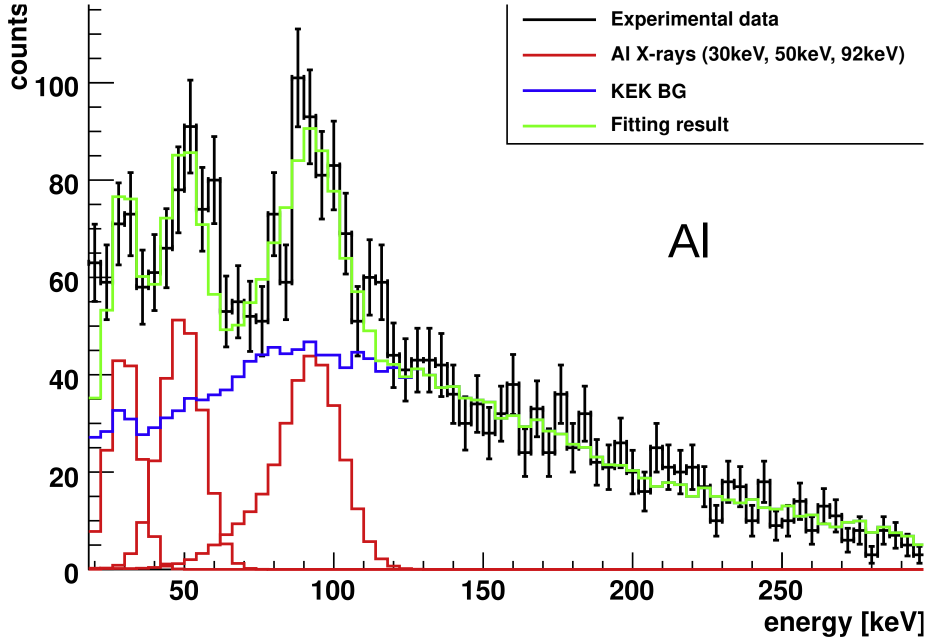
- Test of annihilation physics in Geant4
- Work with Geant4 developers
- Will be validated with antiproton data



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

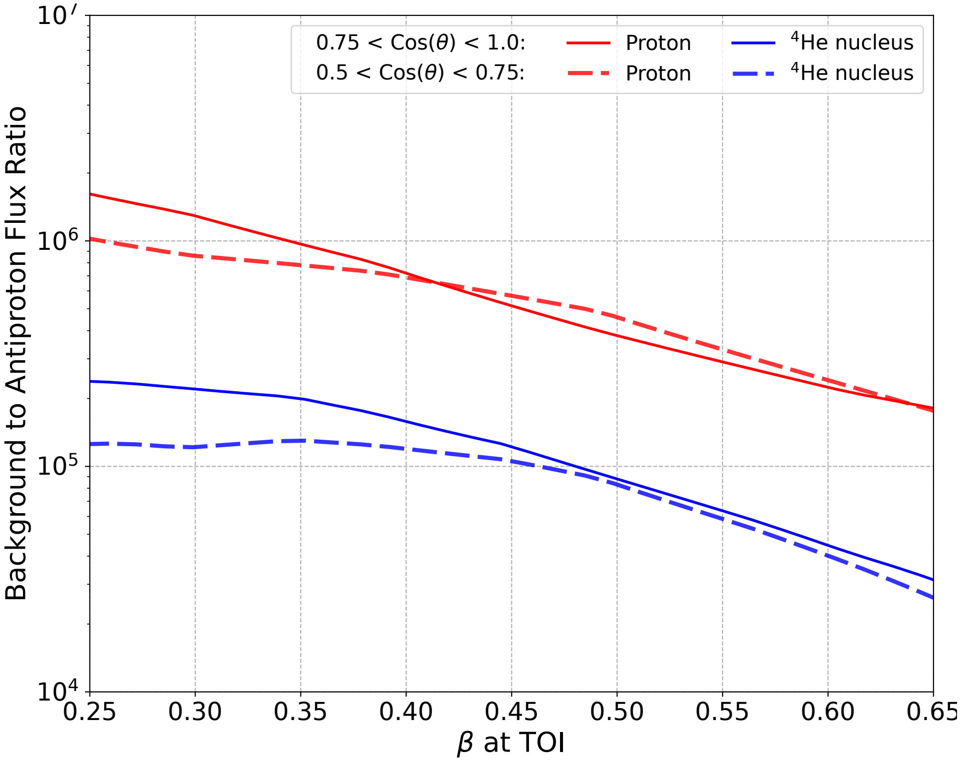


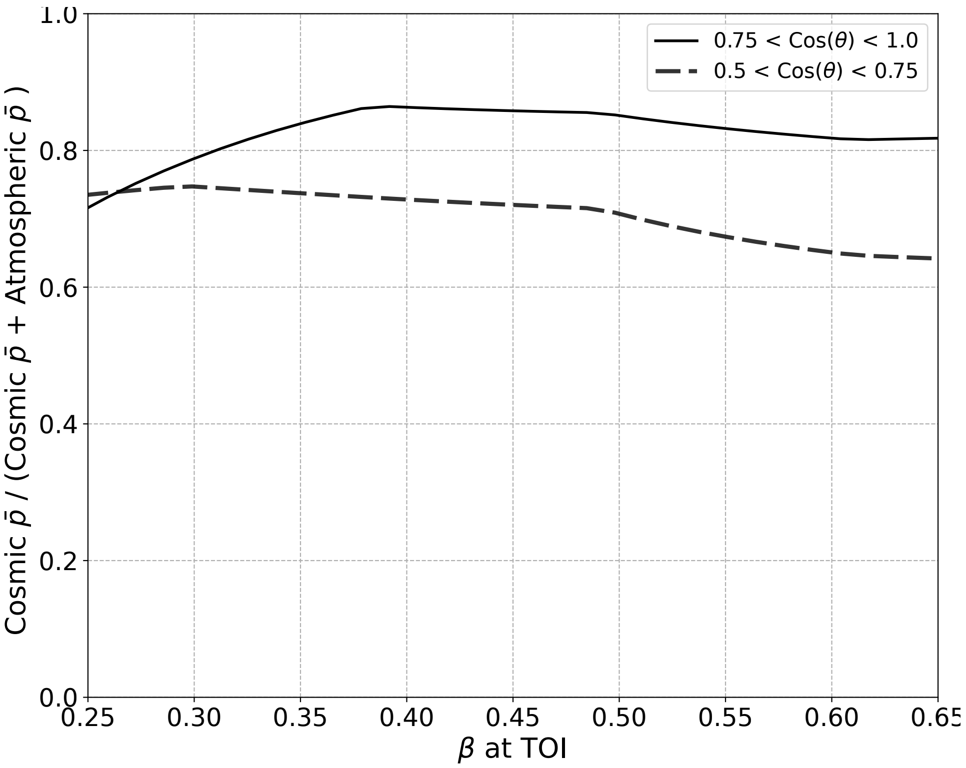


Astroparticle Physics 49 (2013) 52–62

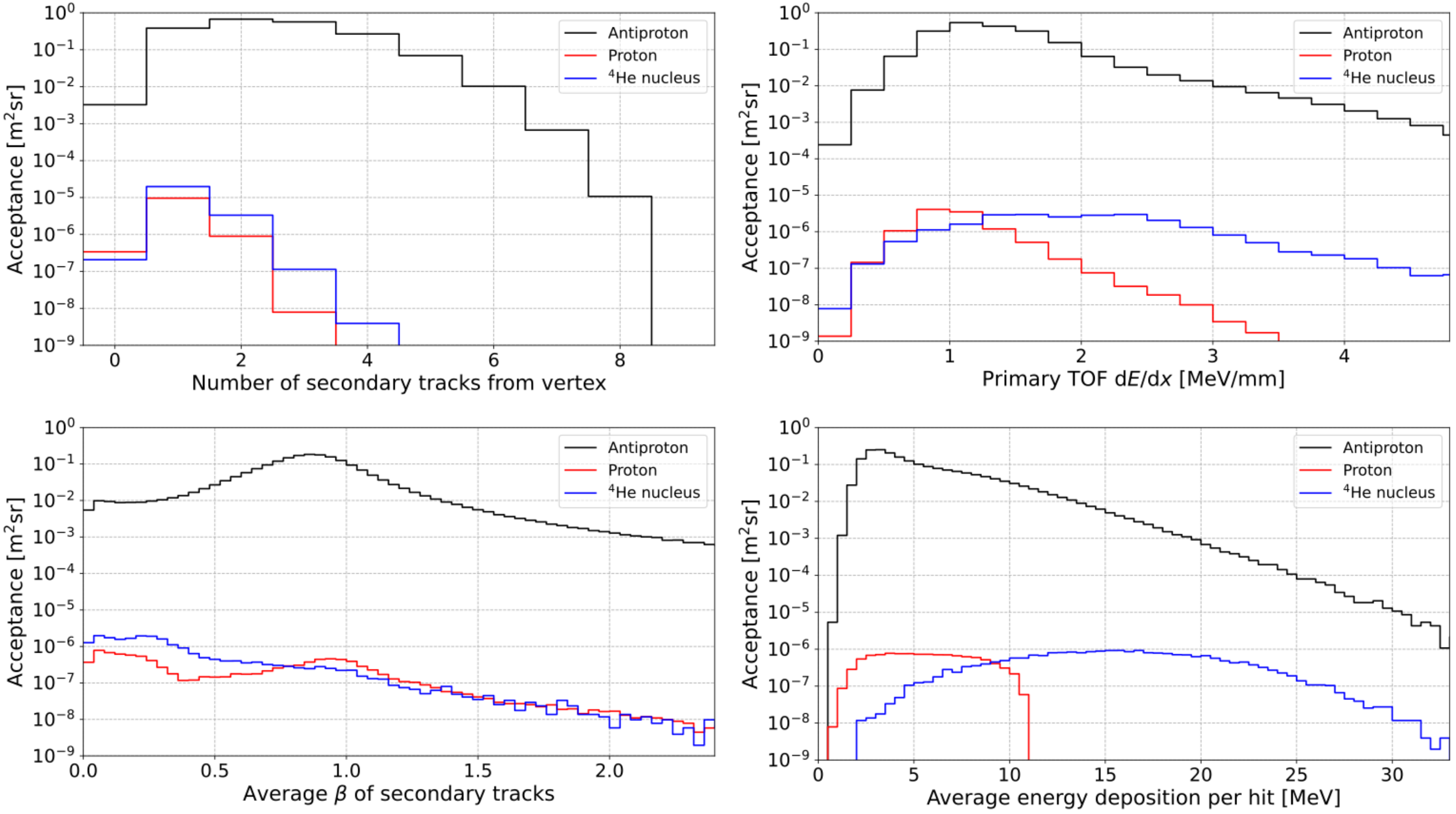
Antiproton background

Astroparticle Physics 145 (2023) 102791





Antiproton identification



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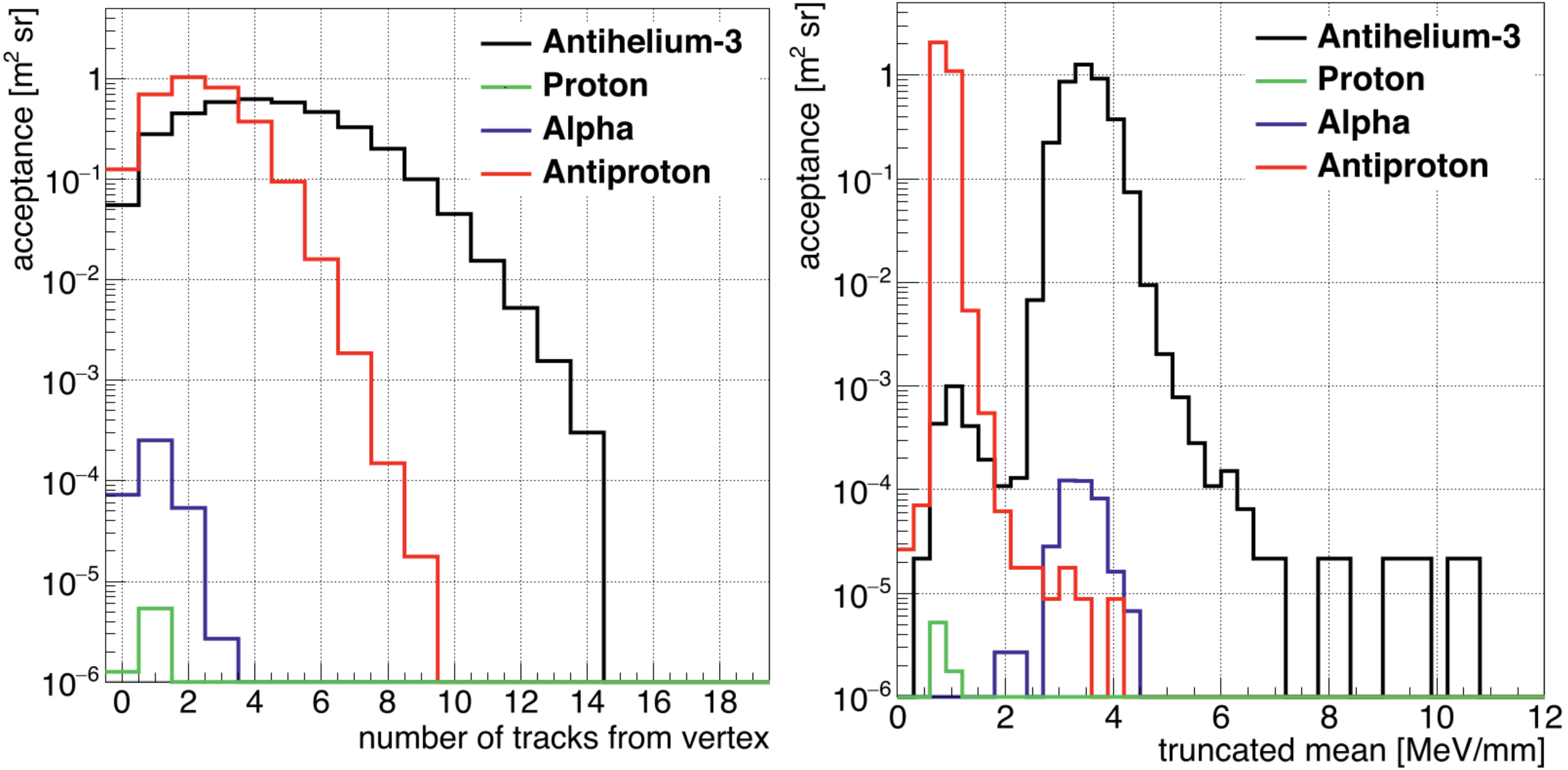
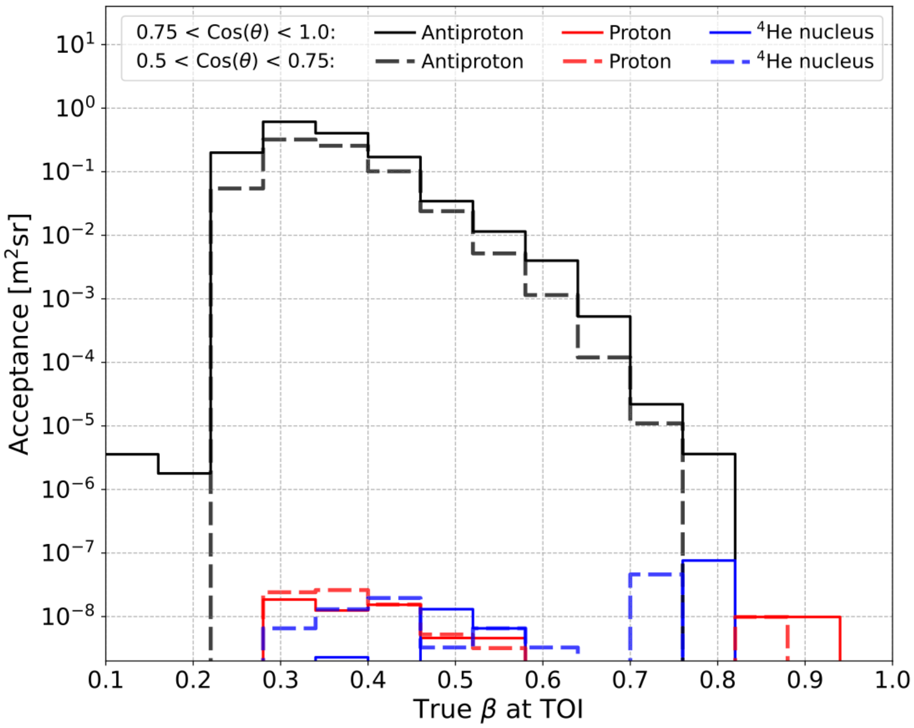
Antihelium-3 identification



Astropart. Phys. 102580 (2021)

Acceptance

antiproton



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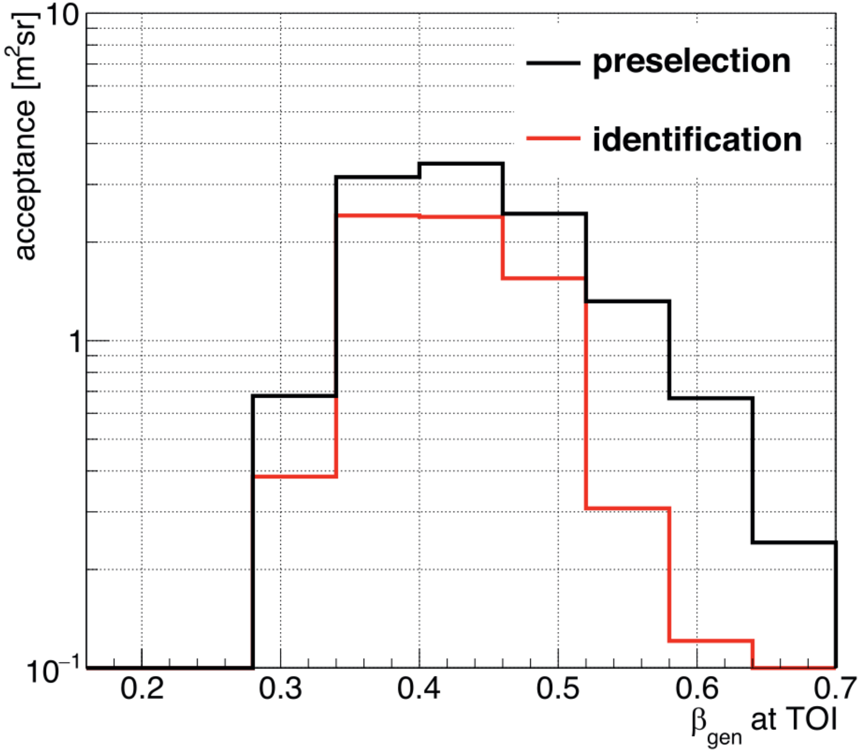
antihelium-3



Astropart. Phys. 102580 (2021)