Search for Dark Matter signatures from cosmic-ray antinuclei with the GAPS experiment

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on behalf of the GAPS collaboration

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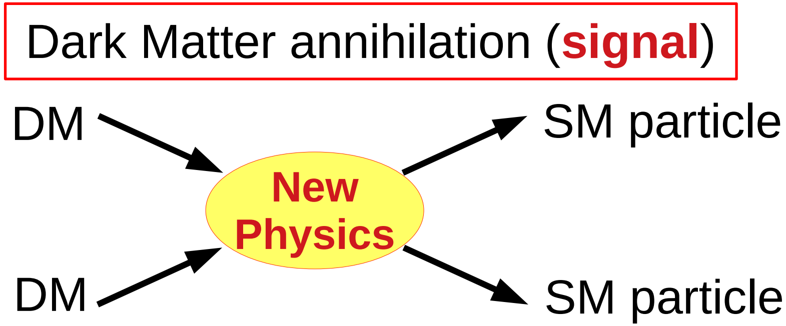
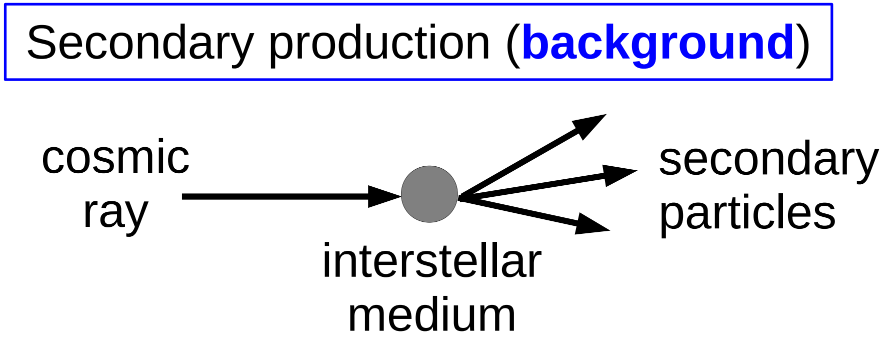
GAPS scientific goals

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

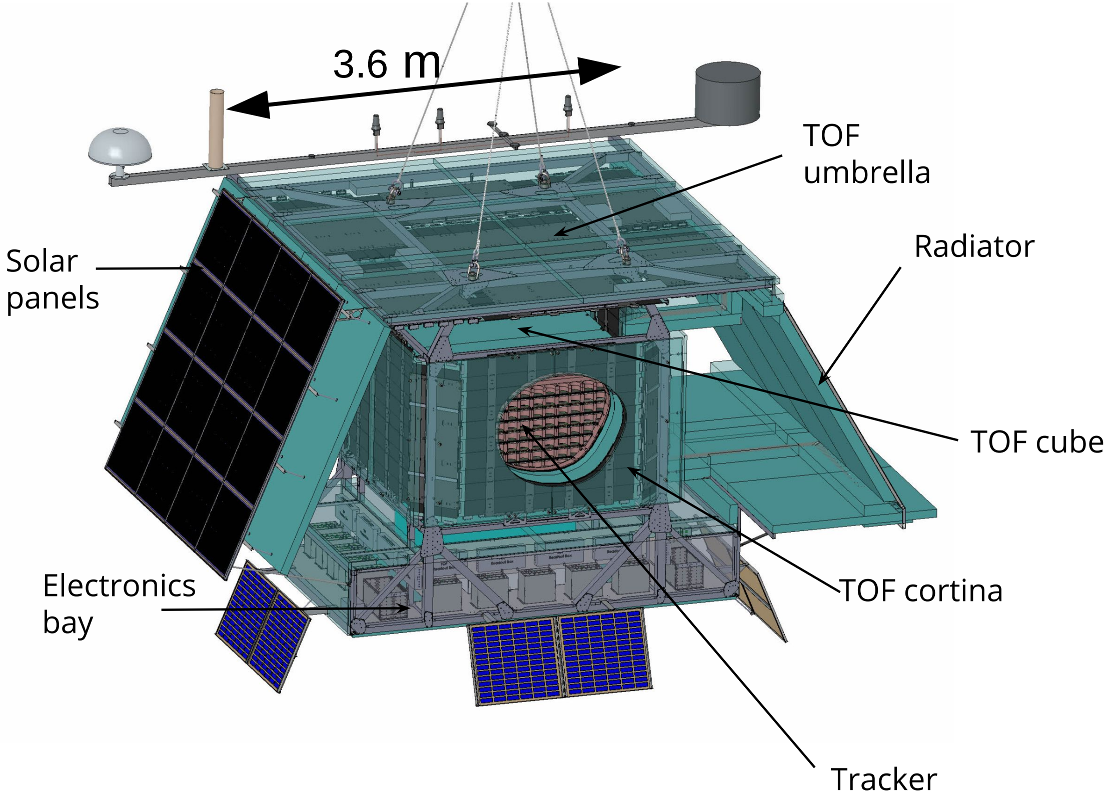




- Expected **antideuteron/antihelium** signal from DM annihilation/decay is orders of magnitude above the astrophysical background at low energies
- **GAPS** is designed to detect a possible DM signal from **antideuteron** and **antihelium** below **250 MeV/n**
- GAPS will also perform a precise measurement of **antiproton** spectrum in an unexplored low-energy range

The GAPS experiment

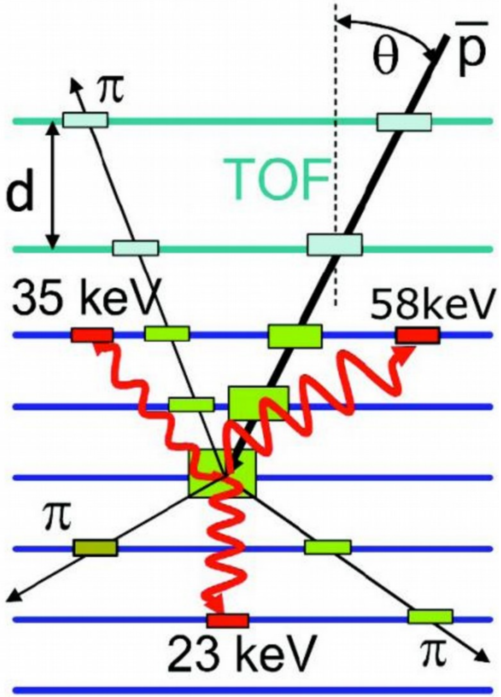
- **General Antiparticle Spectrometer**
- Balloon-borne experiment
  - three long duration balloon flights from Antarctica planned
  - First flight in 2022/2023 austral summer
- Experimental apparatus composed of a **time-of-flight (ToF)** system surrounding a **tracker**
- **ToF:** plastic scintillators (Eljen EJ-200) read with silicon photomultipliers (SiPM)
- **Tracker**: 10 planes of 12x12 Si(Li) detectors
- An **oscillating heat pipe** system is used to cool down Si(Li) detectors to -40°C



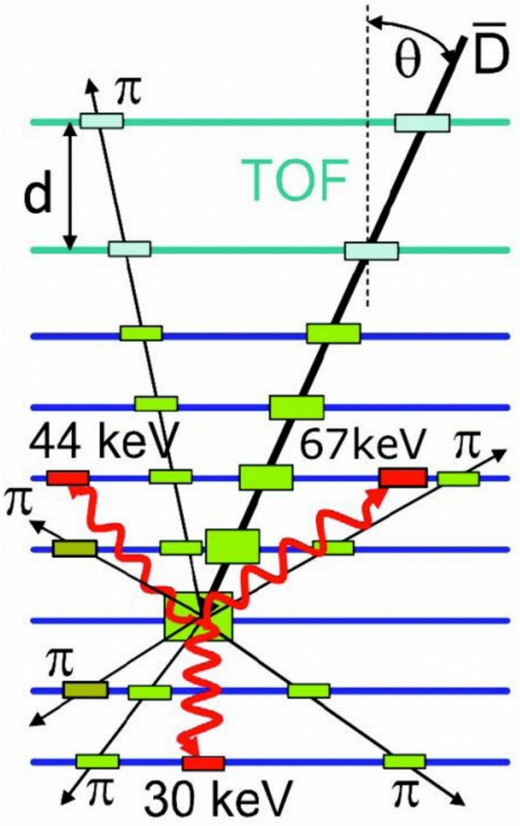
Detection principle

- 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**)
- **ToF:** velocity, direction, dE/dx, trigger and veto
- **Tracker:** stopping depth, dE/dx, charged particles multiplicity, X-ray identification, annihilation vertex reconstruction

antiproton

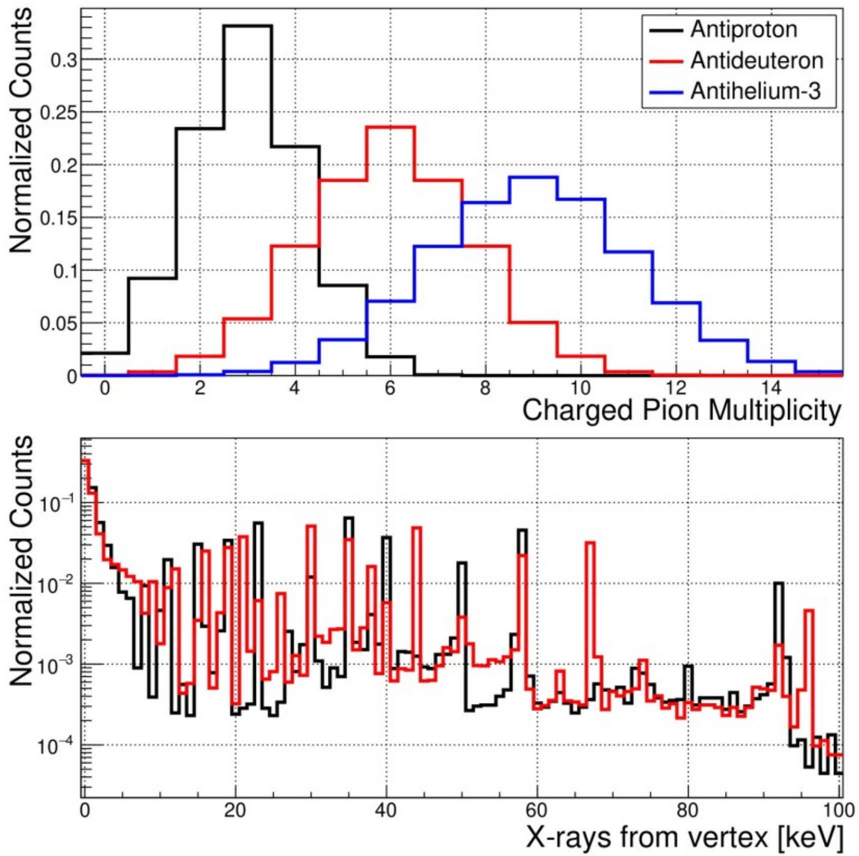


antideuteron



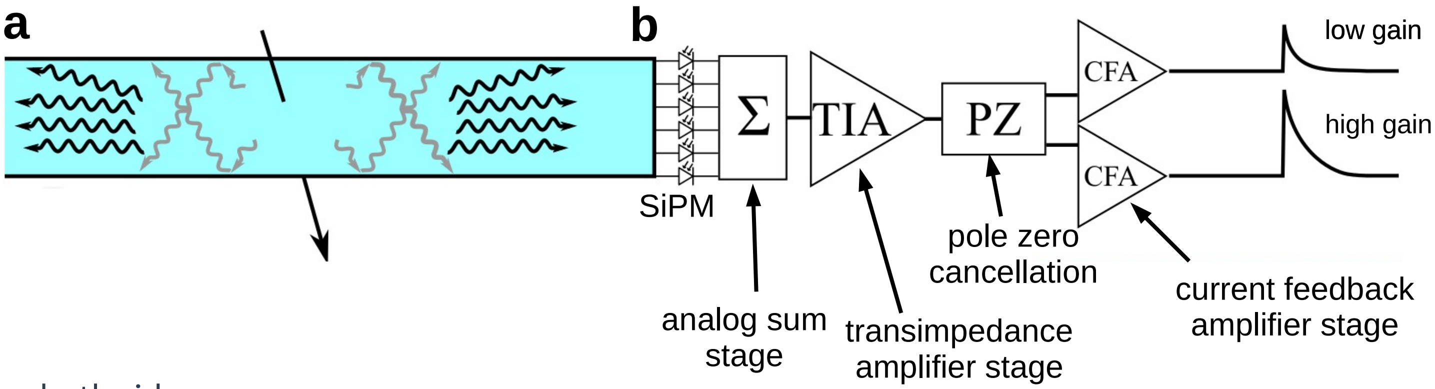
Antinucleus identification

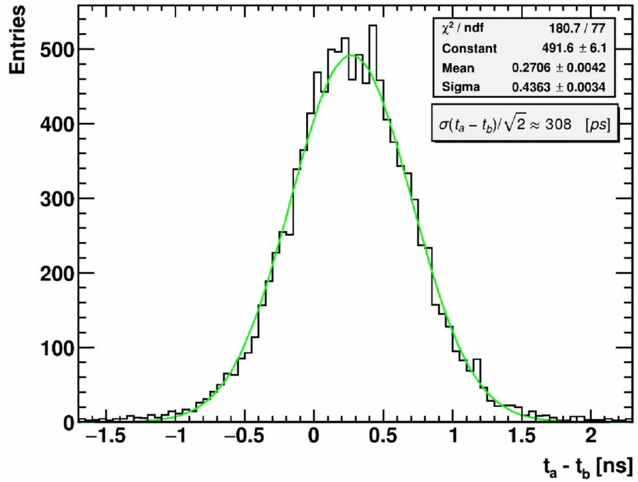
- The **identification** of the antinucleus is performed using:
  - velocity of the primary antinucleus
  - energy deposits of the primary antinucleus
  - depth in detector material crossed before annihilation
  - multiplicity of charged annihilation products
  - X-ray from exotic atom de-excitation



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
- Two gain channels
  - High gain: **timing** measurements
  - Low gain: **trigger** (based on β, energy deposits and # of hits)
- Custom DAQ hardware developed
  - Waveform sampling by high-speed DRS4 ASIC

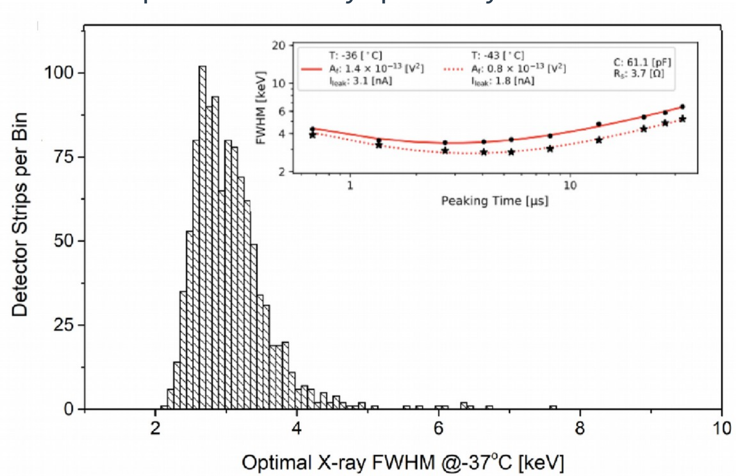


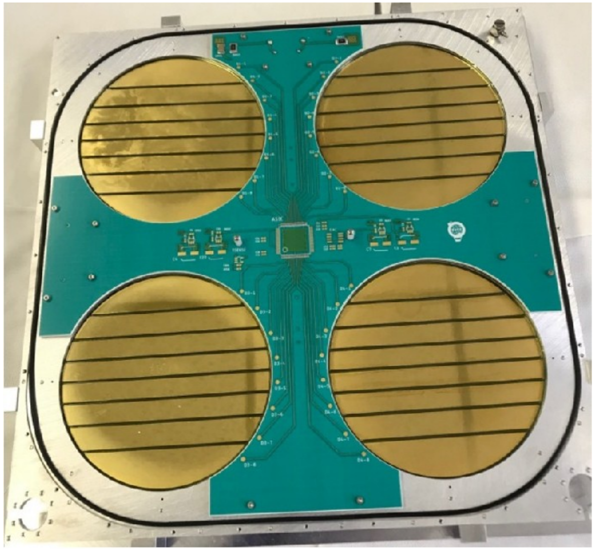


PoS (ICRC2019) 128

Si(Li) detectors

- Large area **Si(Li)** detectors
  - 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
  - 10 planes vertically spaced by 10 cm



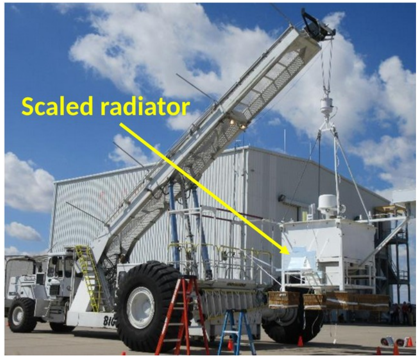


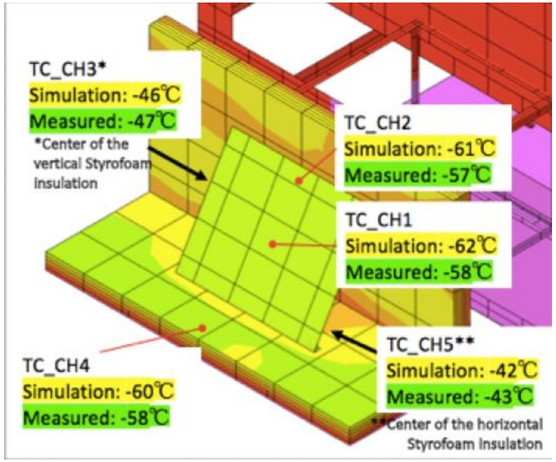
- Custom ASIC for energy deposit measurement
  - high dynamic range: **~10 keV → ~100 MeV**
- Energy resolution **<4 keV** (for 60 keV X-rays)
  - needed to discriminate X-rays from different antinucleui and different target atoms

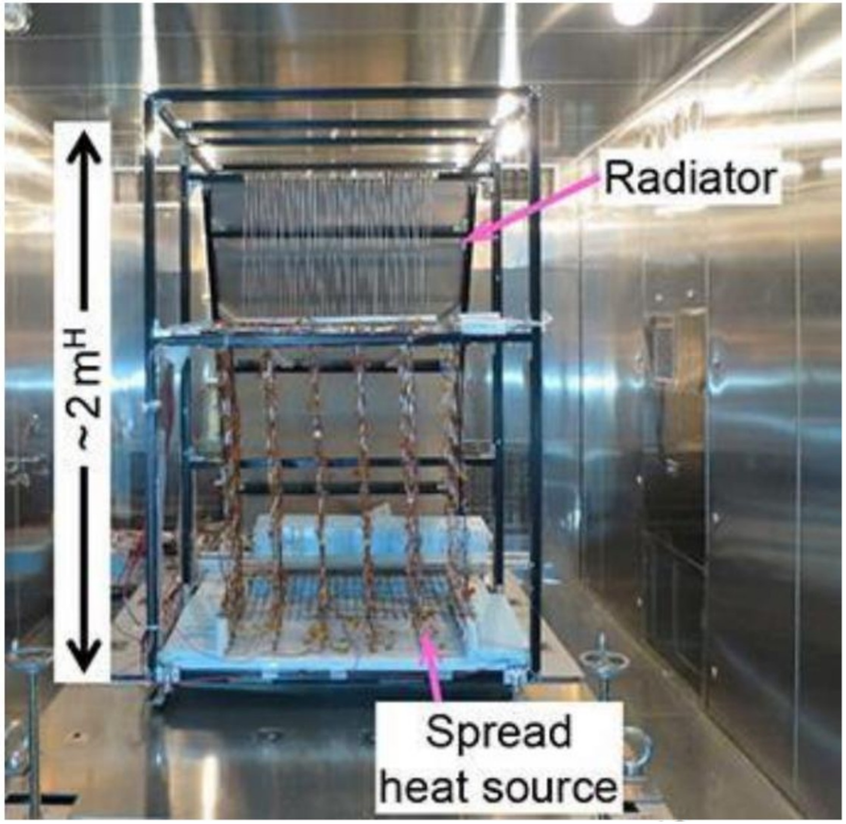
NIM A 905 (2018) 12 NIM A 947 (2019) 162695 JINST 14 (2019) P10009. NIM A 997 (2021) 165015

Tracker 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** at Ft. Sumner in 2019







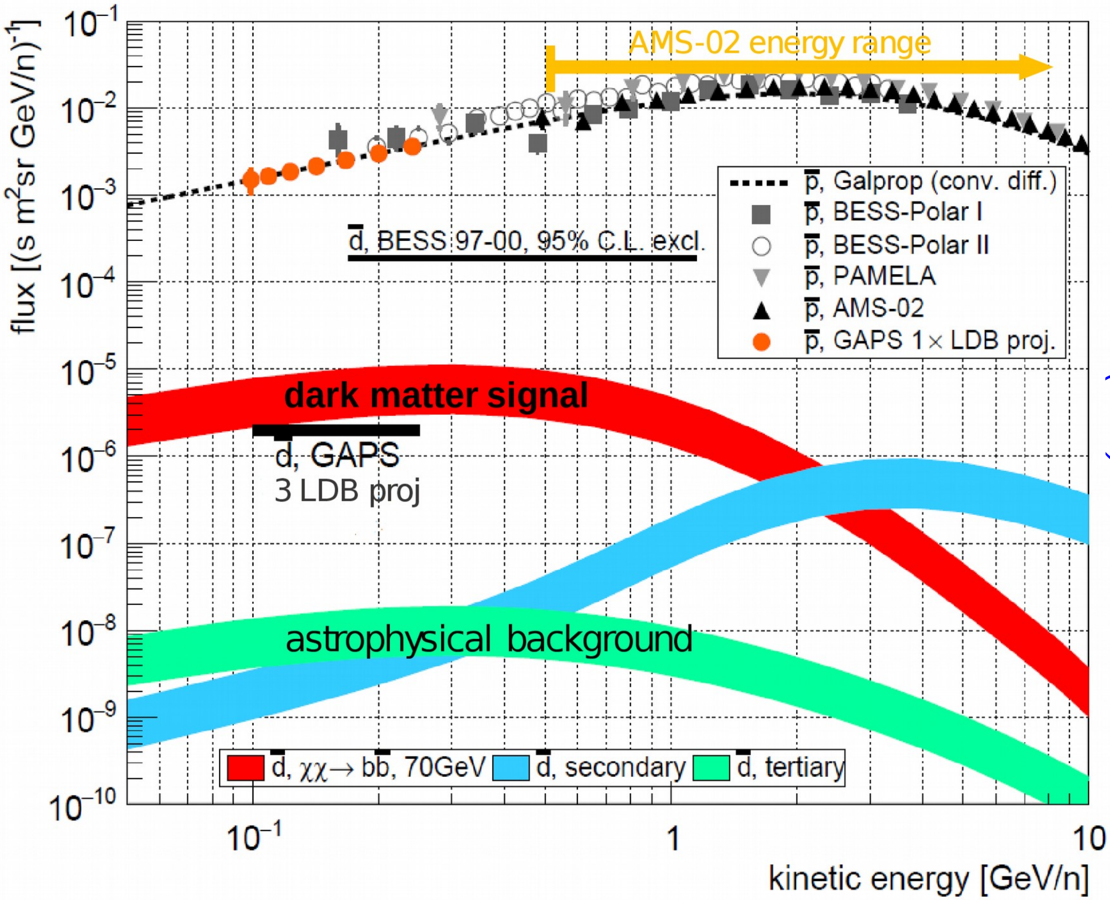
J. Astron. Inst. 06 (2017) 1740006

Applied Thermal Engineering 141 (2018) 20

Antideuteron sensitivity

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

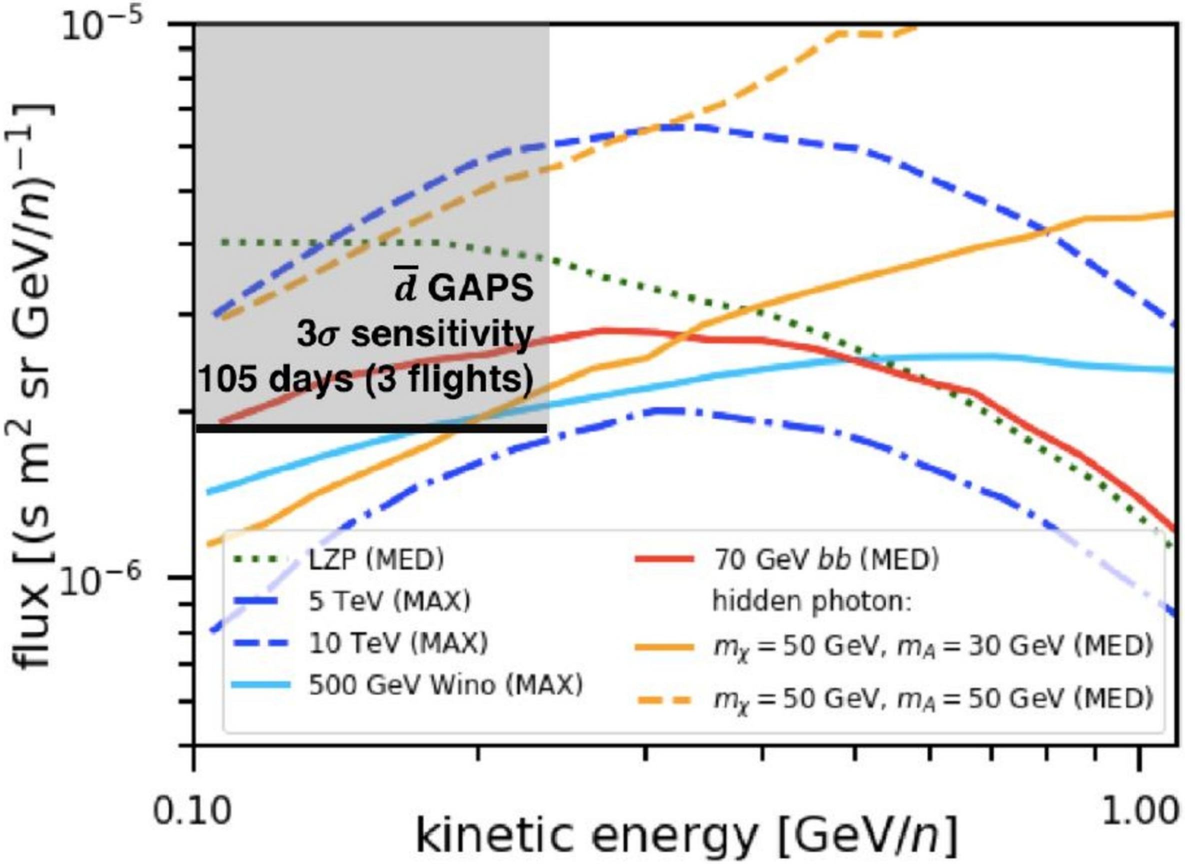
- Even a single antideuteron would point to **new physics**
- GAPS **sensitivity** will be **1-2 orders of magnitude** below existing BESS limit



JCAP08 (2020) 035

Dark Matter models

- GAPS will be sensitive to a wide range of **DM models**:
  - generic 70 GeV WIMP annihilation (explains antiproton excess and γ from Galactic center)
  - dark matter gravitino decay
  - extra dimensions
  - dark photons
  - heavy DM models with Sommerfeld enhancement
- Observed **antiproton** flux constraints **antideuteron** signal predictions



Antiproton spectrum

- Precision measurement of **antiproton** spectrum in an **unexplored low energy region**
- **~1000** antiprotons expected for each balloon flight
- Sensitive to light dark matter, evaporating primordial black holes, and Galactic and solar propagation models

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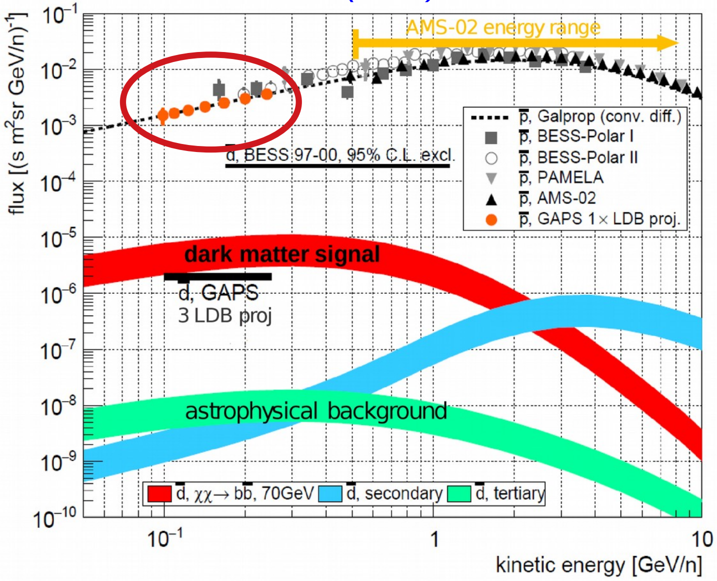
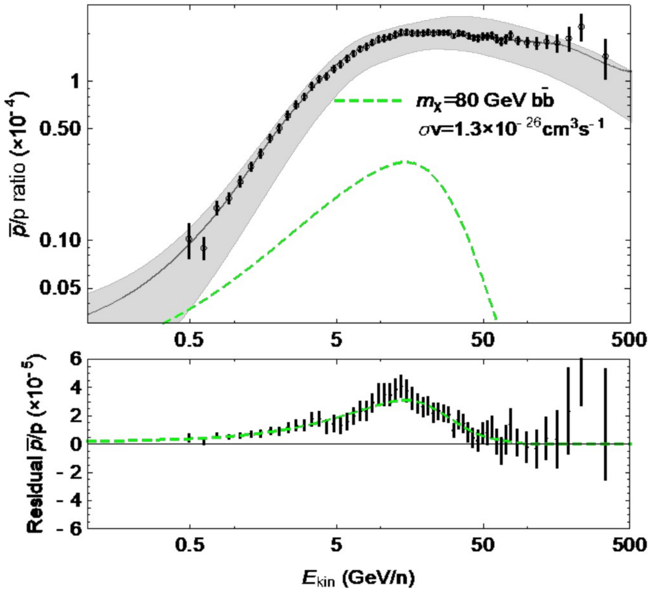


Cuoco+(2016), Cui+(2016), Cui+ (2018), Cuoco+ (2019), Cholis+ (2019)

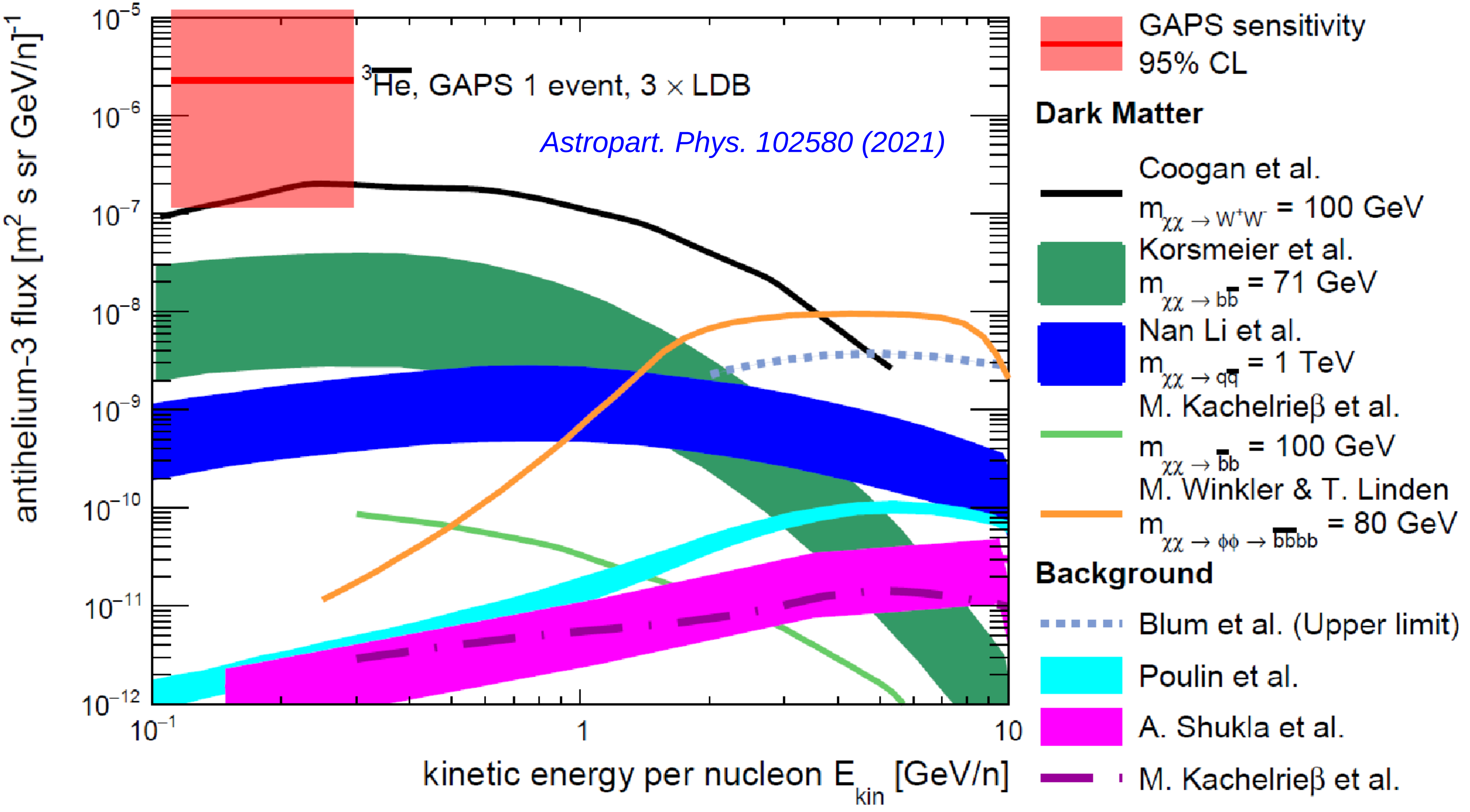


- Dark Matter antiproton signal: **~10-30%** of the secondary production
- Observed antiproton excess puts **constraints** to antideuteron flux predictions

Antihelium sensitivity

- GAPS will be sensitive to **antihelium-3**
- Extend the energy coverage at low energies (**0.1-0.3 GeV/n**)
- Orthogonal detection technique with respect to AMS-02

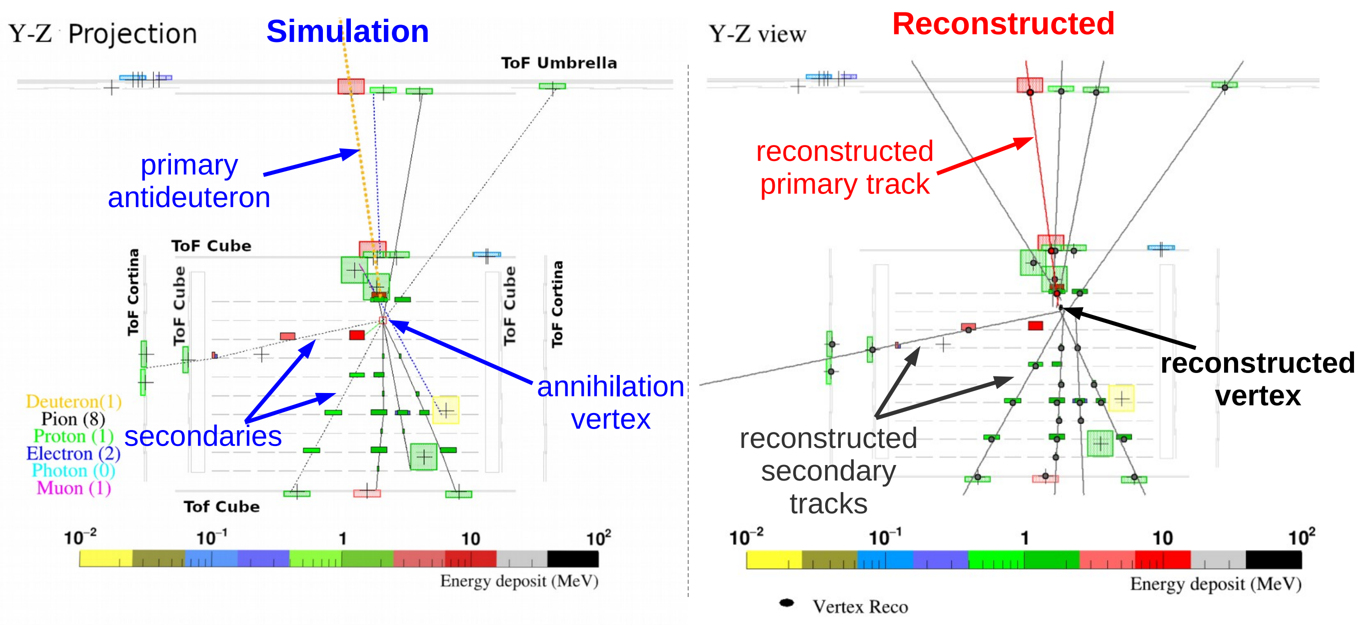
- Could confirm antihelium candidates observed by AMS-02



Event reconstruction

- The annihilation event is reconstructed using a custom algorithm
  - **primary track** is identified from the first ToF hits
  - a scan is done along the primary track to find the best annihilation vertex and **secondary tracks** candidates
  - the **annihilation vertex** is reconstructed as the point that minimizes its distance from the secondary tracks

Astroparticle Physics 133 (2021) 102640

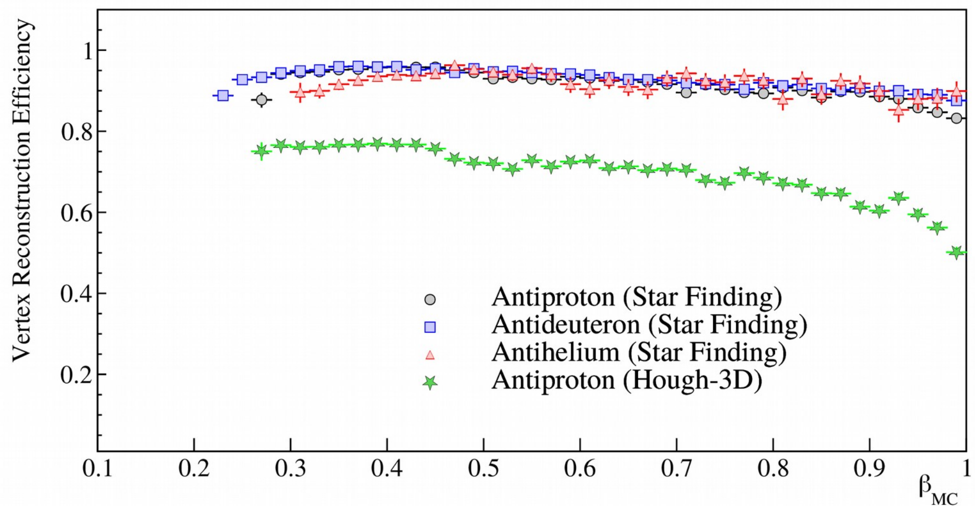


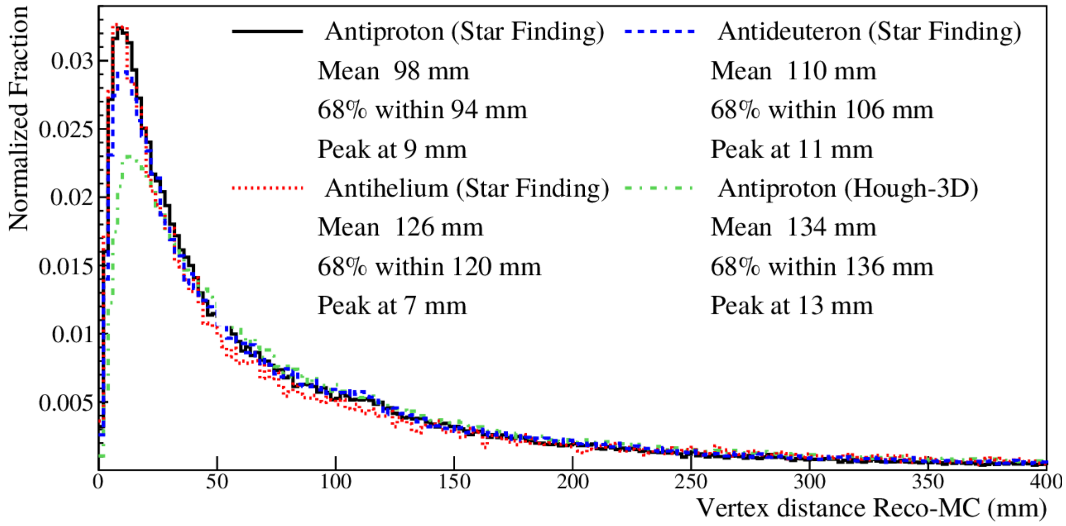
- Another algorithm based on Hough transform was also developed, but it exhibits worse performances

Reconstruction performance

Astroparticle Physics 133 (2021) 102640

- Custom algorithm: "Star Finding"
  Hough-based algorithm: "Hough-3D"
- Reconstruction efficiency **~90%** for Star Finding, **~75%** for Hough-3D





- Annihilation vertex resolution peaks at **~1 cm** for all antinuclei species of interest
- 68% containment within **9-12 cm**

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 a cosmic antideuteron**, thank to the GAPS sensitivity in an essentially backgroung-free region
  - **Precision measurement of the antiproton spectrum**, searching for dark matter signatures and to put constraints on DM and propagation models
  - **Detect cosmic antihelium-3**, in order to confirm AMS-02 candidates with a complementary measurement
- Hardware integration already started, a **functional prototype** is being assembled and will be tested at the end of 2021
- **First flight** is planned in late **2022**