The GAPS experiment: low-energy antinuclei measurements for dark matter searches

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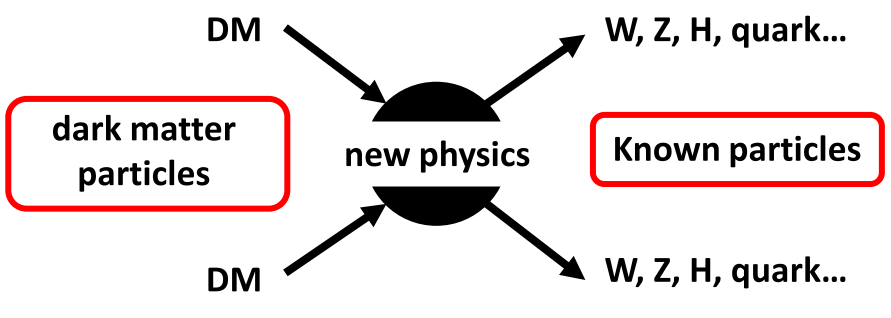
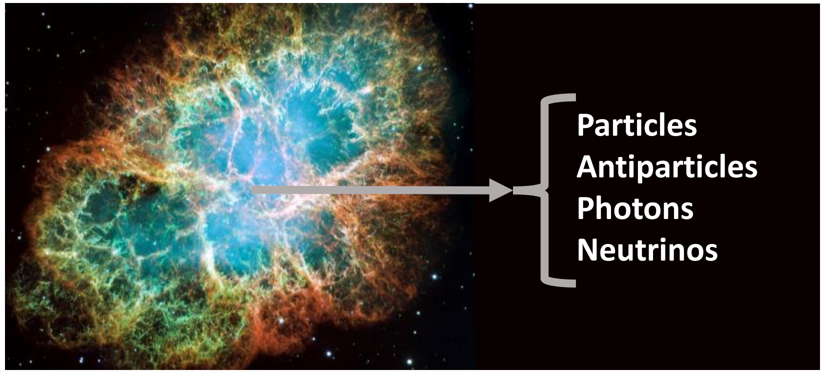
Cosmic Rays as DM Messengers

Signal



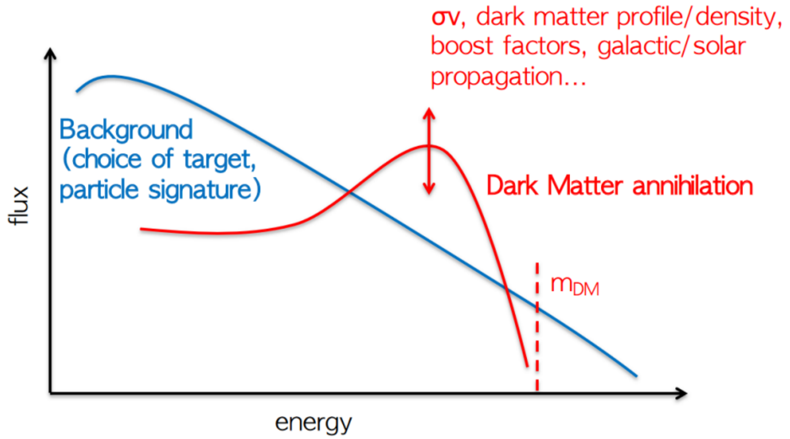
Cosmic rays from Dark Matter (DM) annihilation or decay

backgound



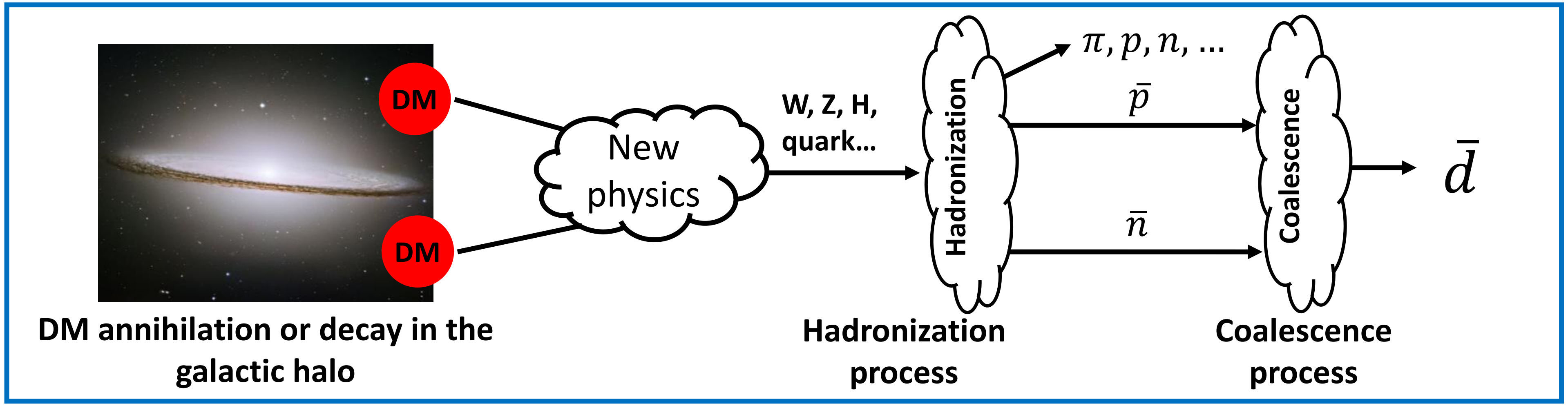
Primary cosmic rays (e.g., from SNR) interacts with the interstellar medium

- **Indirect DM searches:** DM signal as an excess with respect to the background
- **Low background channels:** Expected **antideuteron** and **antihelium-3** signal from DM annihilation/decay is orders of magnitude above the astrophysical background at low energies



Low-energy cosmic antideuteron

- **Primary flux:** particles from DM annihilation or decay



- **Secondary/tertiary flux:** Cosmic Ray (CR) interacting with the interstellar medium (ISM)

$$p(CR) + H(ISM) \rightarrow p + H + p + n + \bar{p} + \bar{n} \longrightarrow \bar{d}$$

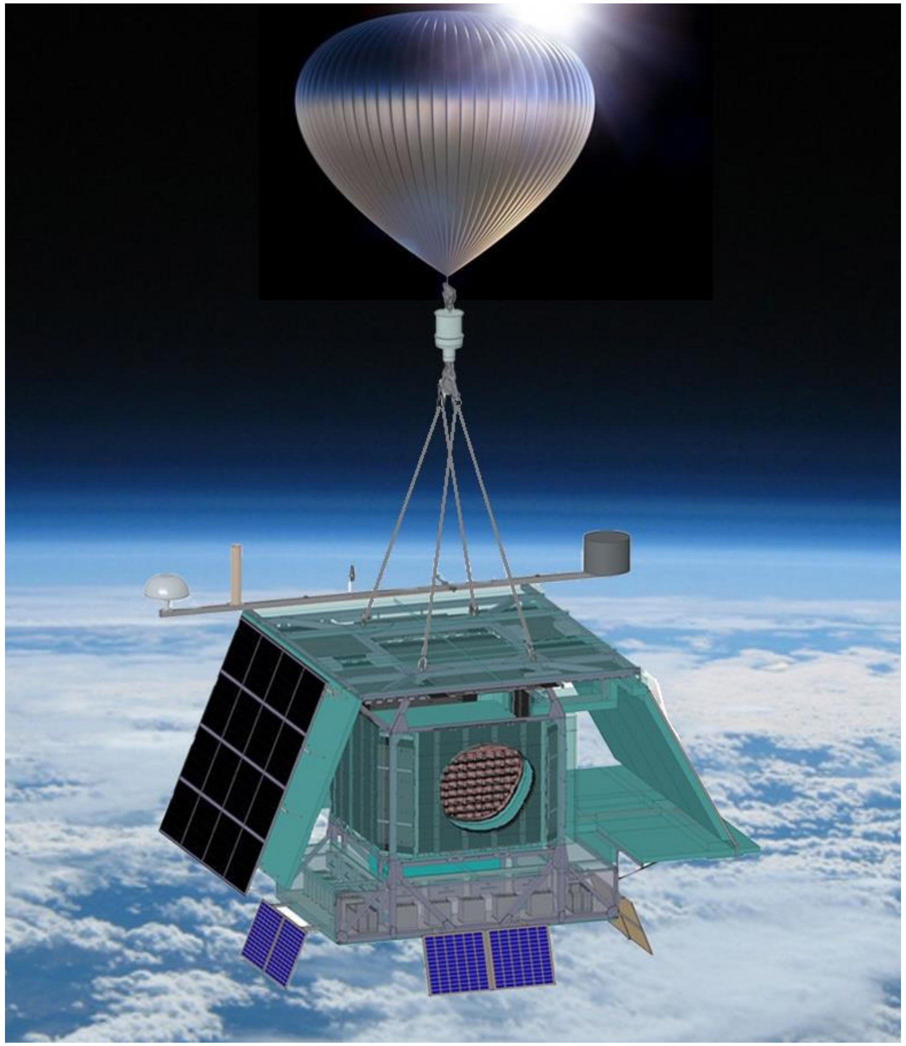
- For kinematical reasons, at energies below $\sim 250\ MeV/n$ the secondary flux is strongly suppressed
  $\rightarrow$ *more than 2 orders of magnitude with respect to the primary flux*

The GAPS experiment is optimized for low-energy cosmic antideuteron searches
- The observation of a single antideuteron event would be sufficient to claim the discovery of new physics

The GAPS experiment

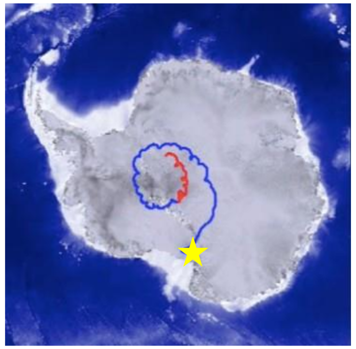
- **GAPS**: **G**eneral **A**nti-**P**article **S**pectrometer
  - Balloon-borne experiment
  - Flight from Antarctica (McMurdo Station)
  - Instrument size: $\sim 3.6\, m \times 3.6\, m \times 3.6\, m$
- Main objective: search for low-energy ($\lesssim 250 MeV/n$) cosmic anti-nuclei as signature of new physics.
  - Can probe various dark matter (DM) models.
- Anti-nuclei identification: uniquely characterized atomic X-rays from the decay of exotic atoms and charged particles from the annihilation of the antinucleus with nucleus of the exotic atom.
- High statistic measurements of low-energy antiprotons and leading sensitivity to antihelium.
- Precise measurements of low-energy nuclei as proton, deuteron, and alpha.

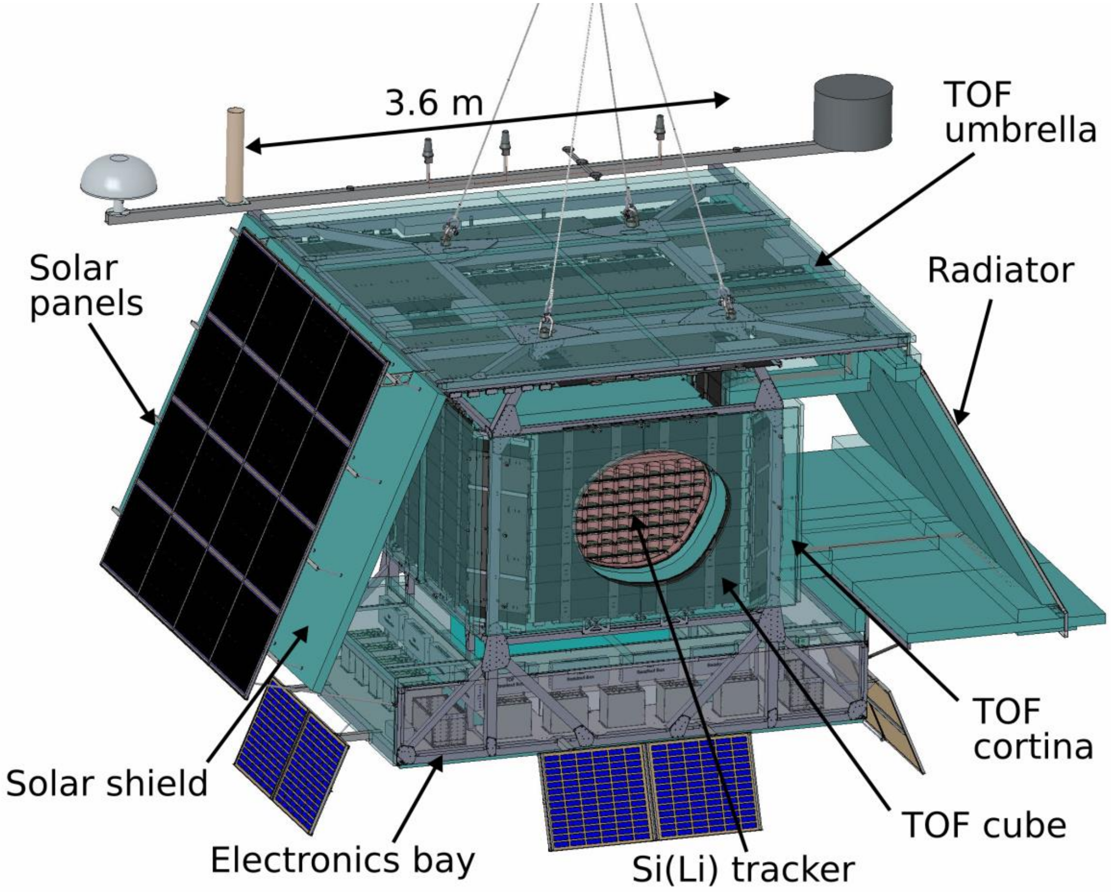
The first of a series of $\sim$35 days flights (at least 3) is planned for the austral summer of 2023-2024.



Instrument design

- **Time of Flight (TOF):**
  - High-speed trigger and veto
  - Velocity measurement $\beta = \frac{v}{c}$
  - dE/dx measurement
- **Si(Li) Tracker:**
  - Stopping depth, dE/dx
  - Charged particles multiplicity
  - X-ray identification
  - Annihilation vertex reconstruction
- **Thermal system:**
  - Cools Si(Li) detectors to ~ -40 °C

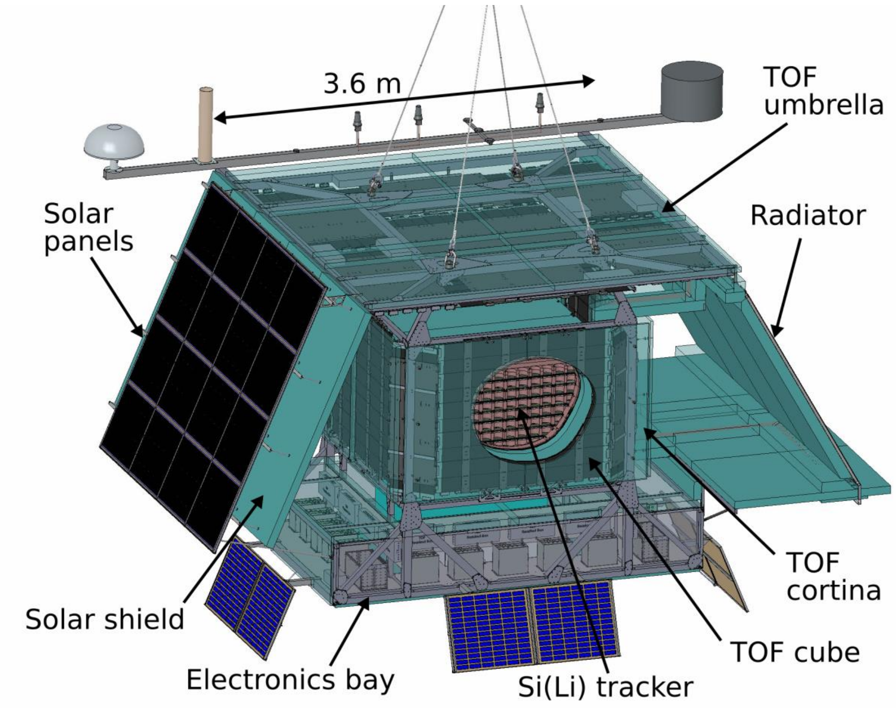


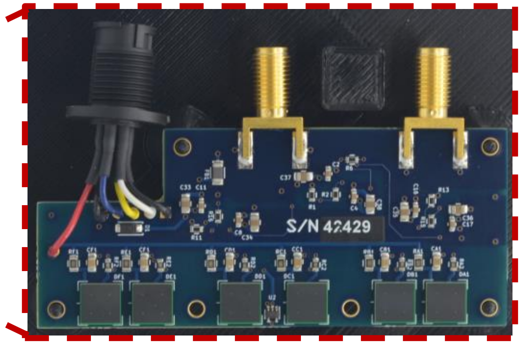


Total mass: $\sim 2500\ kg,$ **Power:** $1.3\ kW$

GAPS: Time of Flight system

- **3 components:**
  - Umbrella
  - Cortina
  - Cube
- **160 long, thin plastic scintillator paddles**
- **Preamp board on each paddle end, 6 SiPMs/board**
- **Fast sampling with DRS4 ASIC:**
  - < 400 ps timing resolution

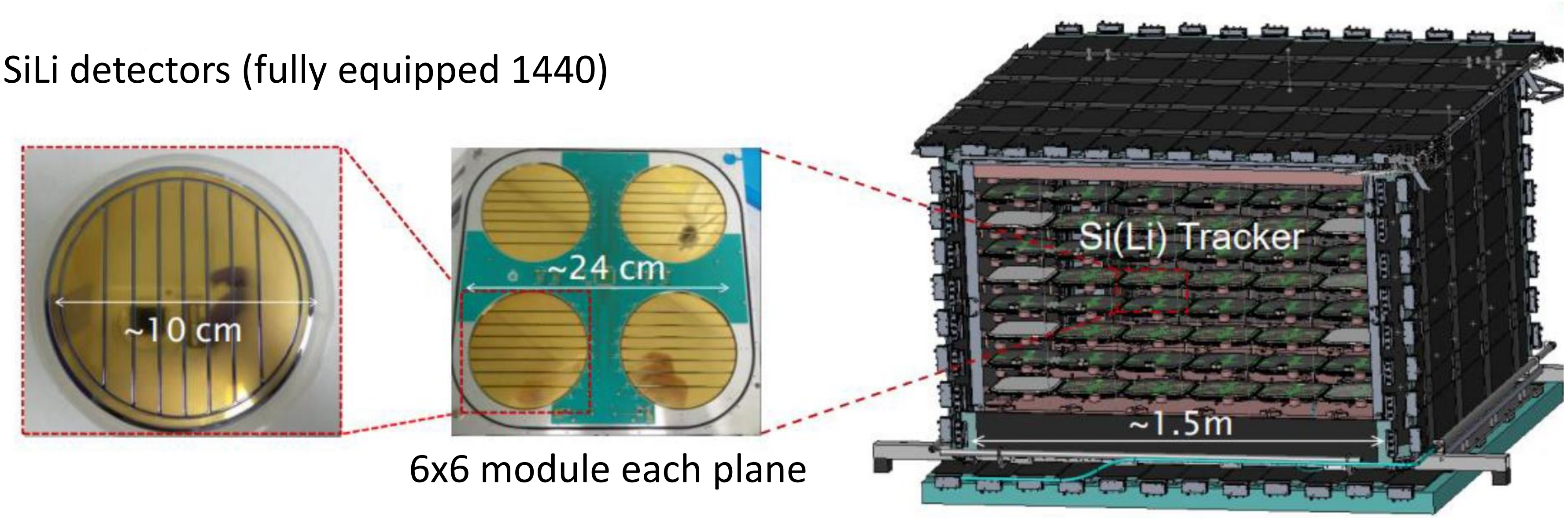




GAPS: Si(Li) Tracker

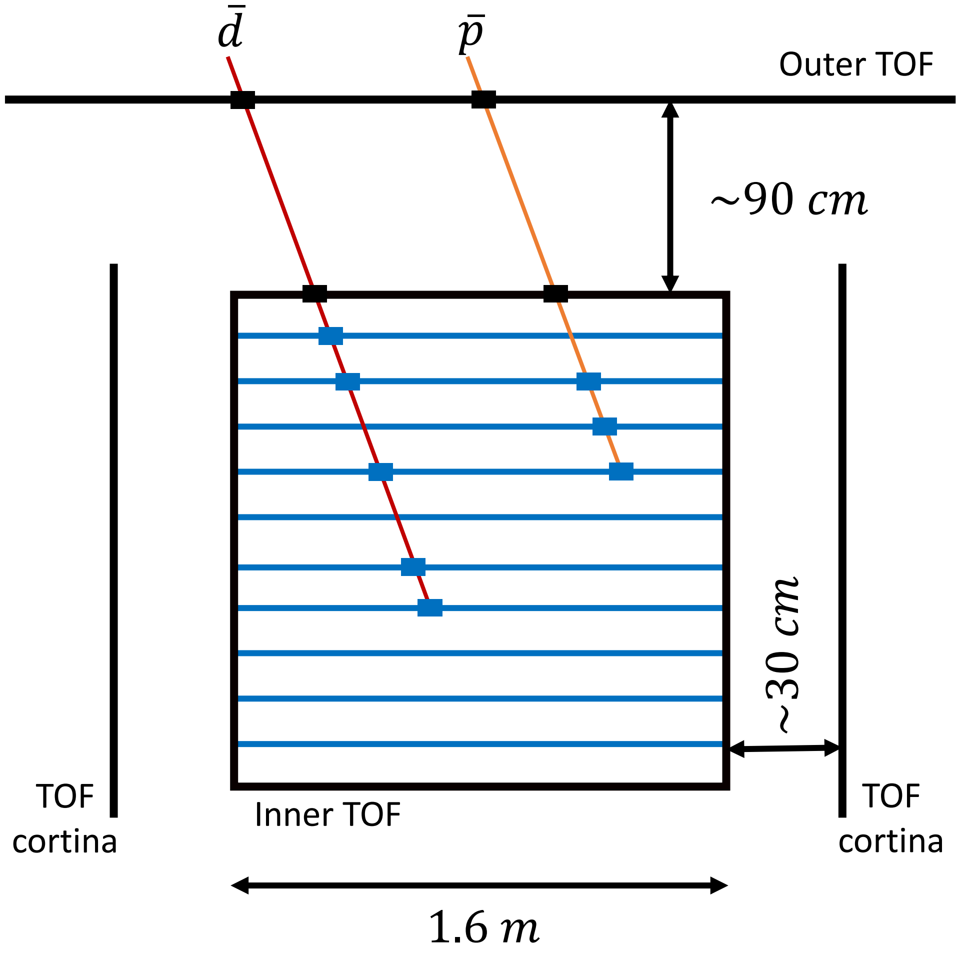
Lithium-drifted Silicon

- 10 planes of cylindrical Si(Li) detectors, 2.5 mm thickness and 10 cm in diameter
- Operation at relatively high temp of -35C to -45C
- 1100 SiLi detectors (fully equipped 1440)
- Large dynamical range (~10 keV→100 MeV)
- <4 keV FWHM (at ~60 keV) at -37°C



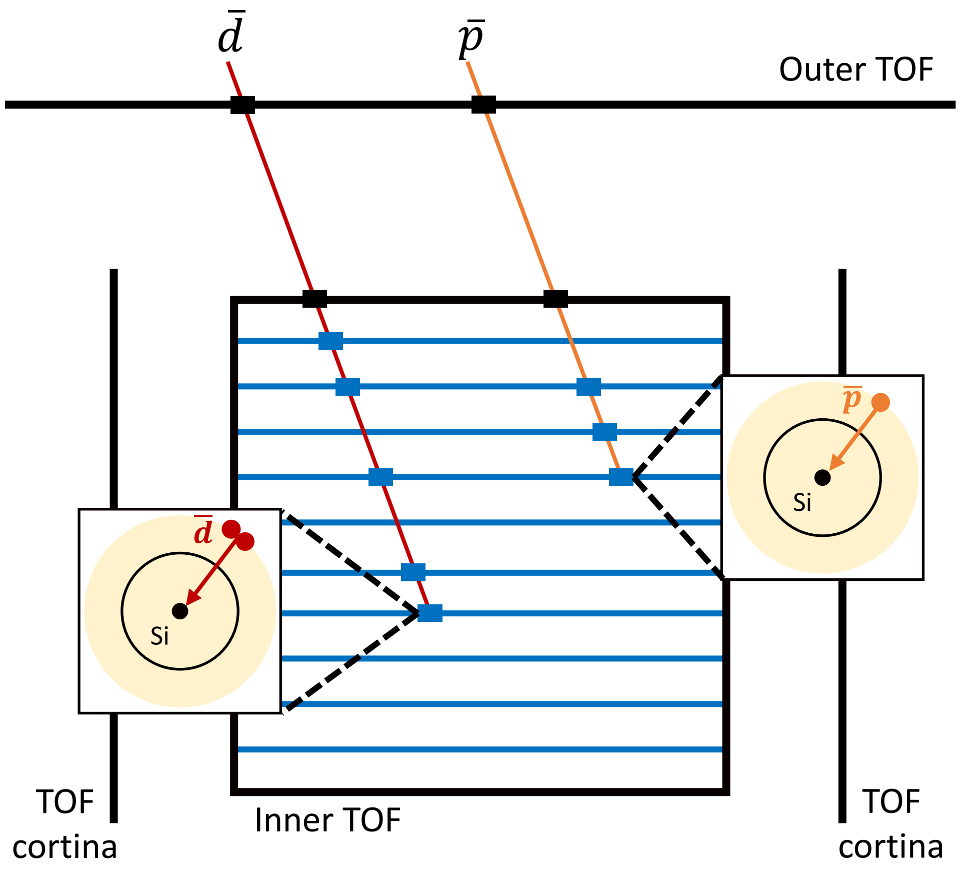
6x6 module each plane

Detection technique



Time-of-flight measures velocity, incident angle, and dE/dx

Detection technique

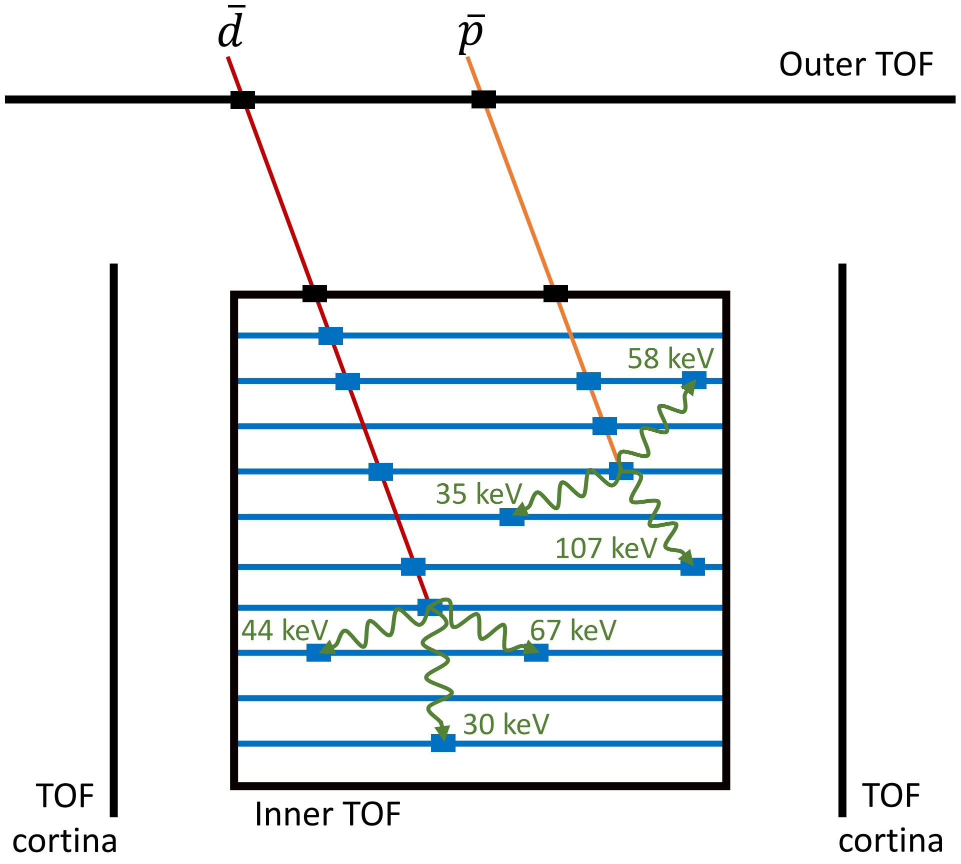


Time-of-flight measures velocity, incident angle, and dE/dx

Si(Li) Tracker (10 planes, 12x12 detectors each) act as:

- Target to slow and capture an incoming antiparticle forming an exotic atom in an exited state

Detection technique



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Si(Li) Tracker (10 planes, 12x12 detectors each) act as:

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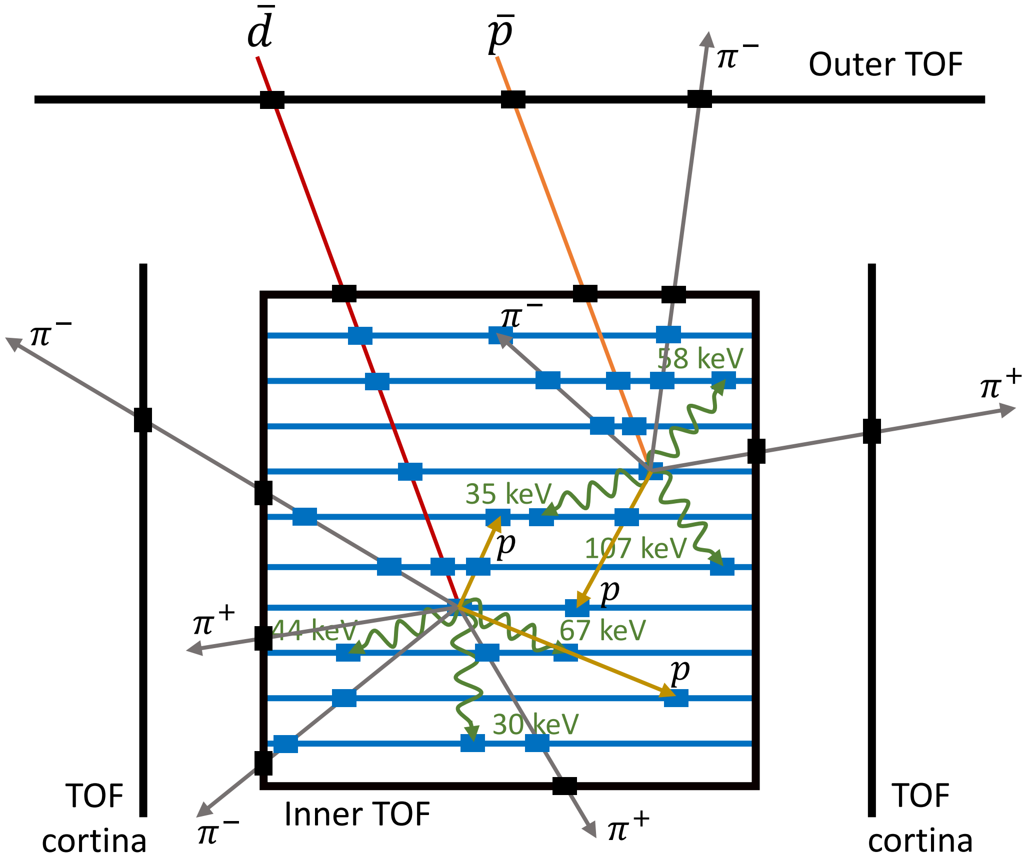
Detection technique

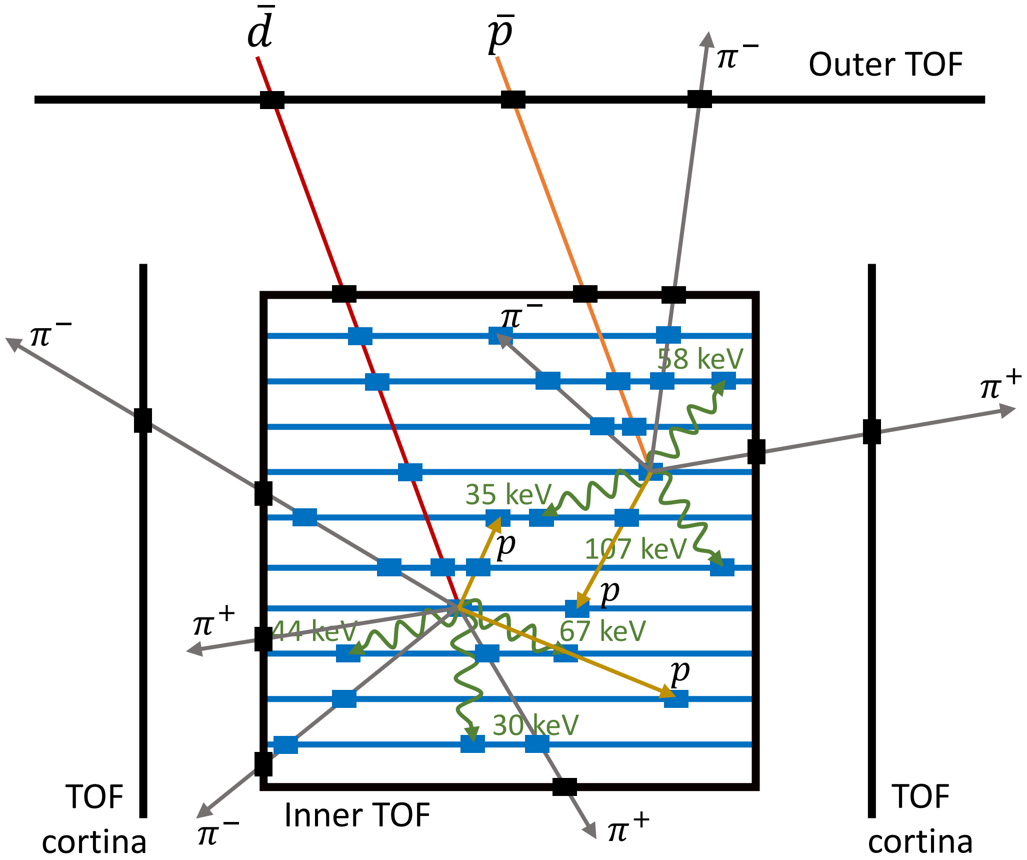


Time-of-flight measures velocity, incident angle, and dE/dx

Si(Li) Tracker (10 planes, 12x12 detectors each) act as:

- Target to slow and capture an incoming antiparticle forming an exotic atom in an exited state
- X-ray spectrometer to measure the decay X-rays
- Particle tracker to measure the resulting dE/dX, stopping depth and annihilation products

Detection technique



- The TOF together with the tracker help to select antinuclei ($\bar{d}$, $\bar{p}$, $\overline{He}$)
- Antinuclei identification ($\bar{p}/\bar{d}$) with:
  - Stopping range, dE/dx
  - Pion and protons multiplicity
  - Unique atomic X-rays

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Astropart. Phys. 74 (2016) 6-13

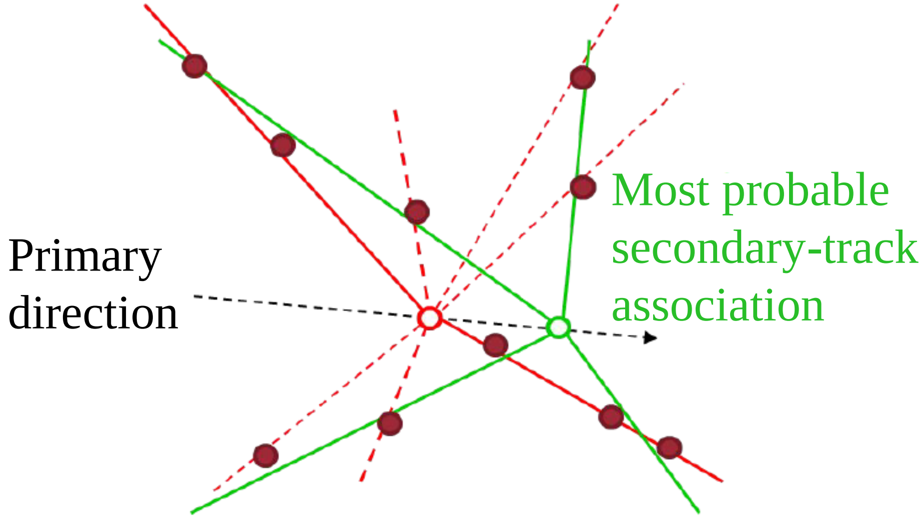
Reconstruction algorithm

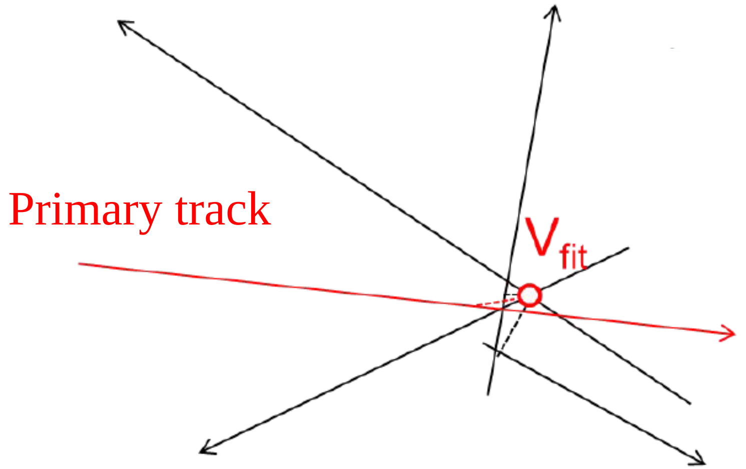
Custom algorithm developed to reconstruct the annihilation star, reconstruct the tracks of the **primary** and **secondary charged particles** and determine the annihilation **vertex** position.

1. **Primary track** search
   - ➢ Track following approach (initial direction from TOF timing)

2. **Secondary tracks** search
   - ➢ Search for star-like converging tracks along primary direction

3. **Annihilation vertex** position evaluation
   - ➢ Straight-line fitting of each track
   - ➢ Evaluation of point of minimum distance to all line associated to vertex





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Reconstruction algorithm

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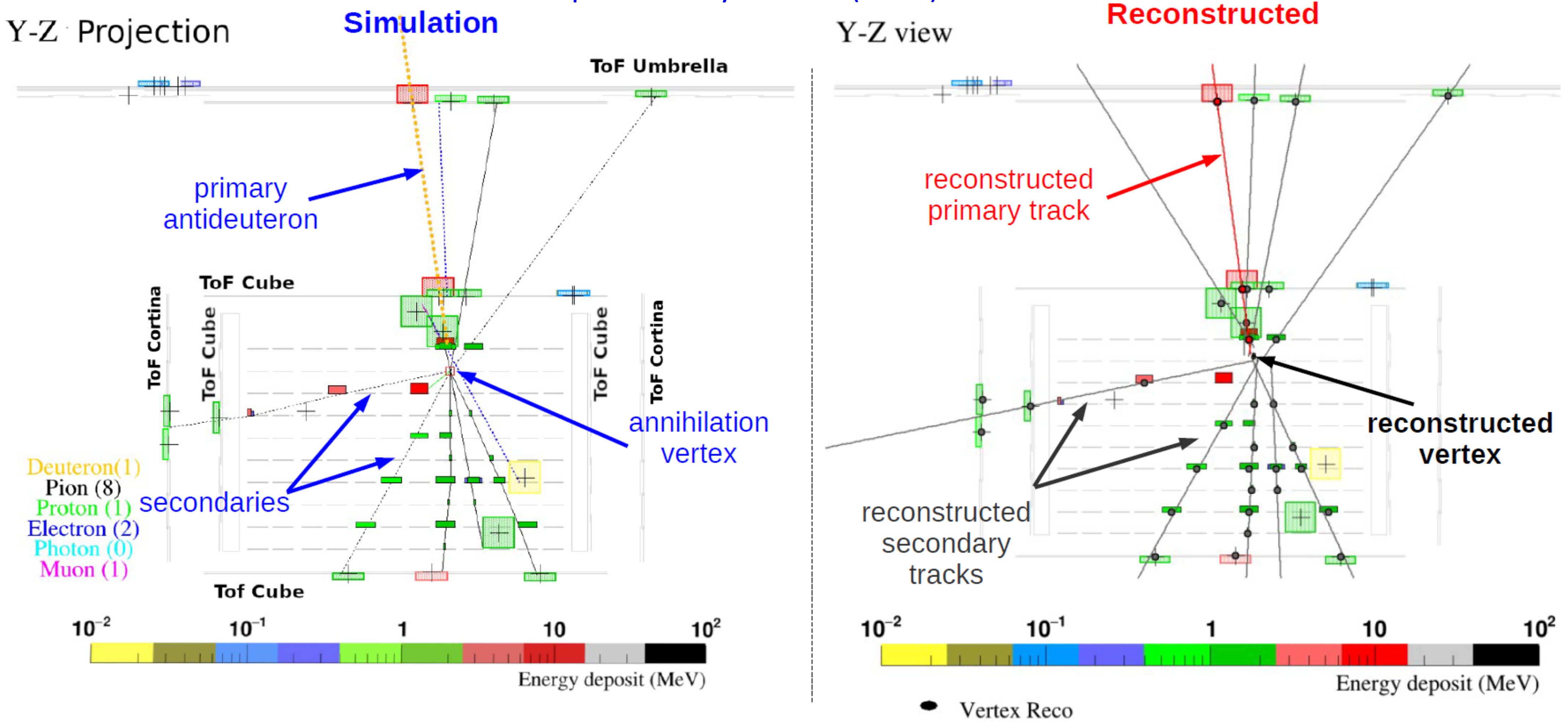
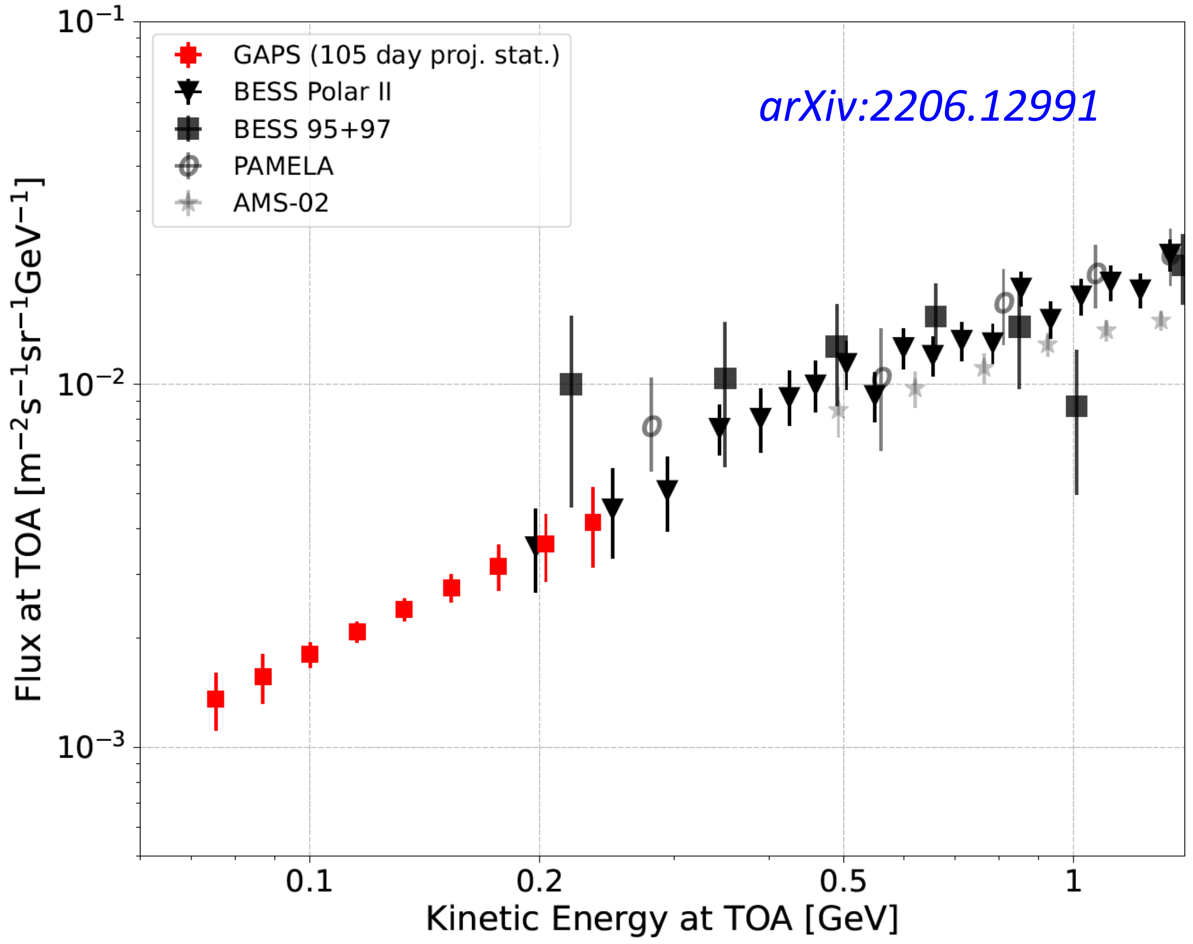


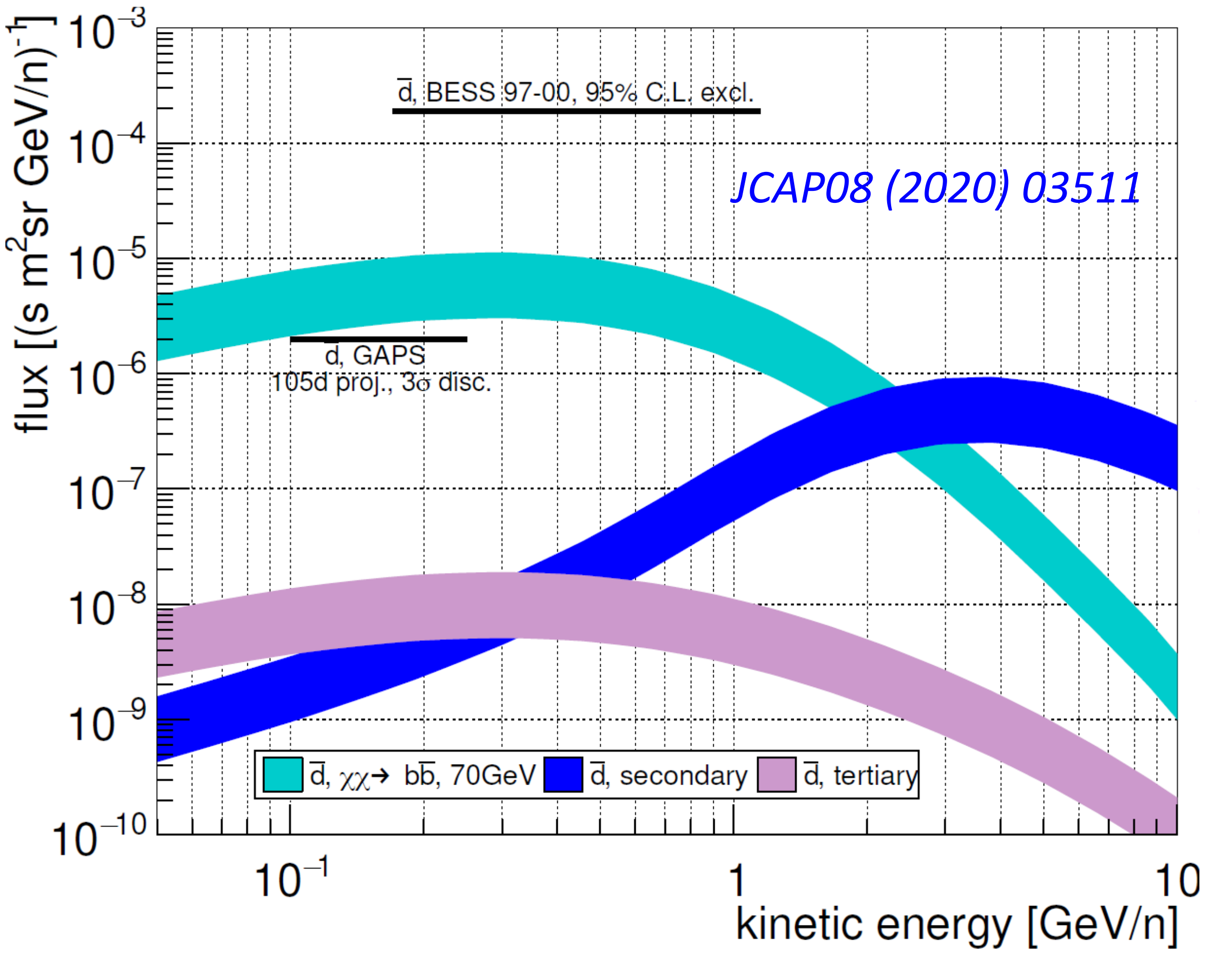
GAPS antiproton sensitivity



$\bar{p}$

- Precision measurements of **antiproton** spectrum in an **unexplored energy range** (<250 MeV/n)
- ~**500 GCR antiprotons** expected for each balloon flight:
  - BESS: 29 @ ~ 200 MeV/n
  - PAMELA: 7 @ ~ 250 MeV/n
- 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



$\bar{d}$

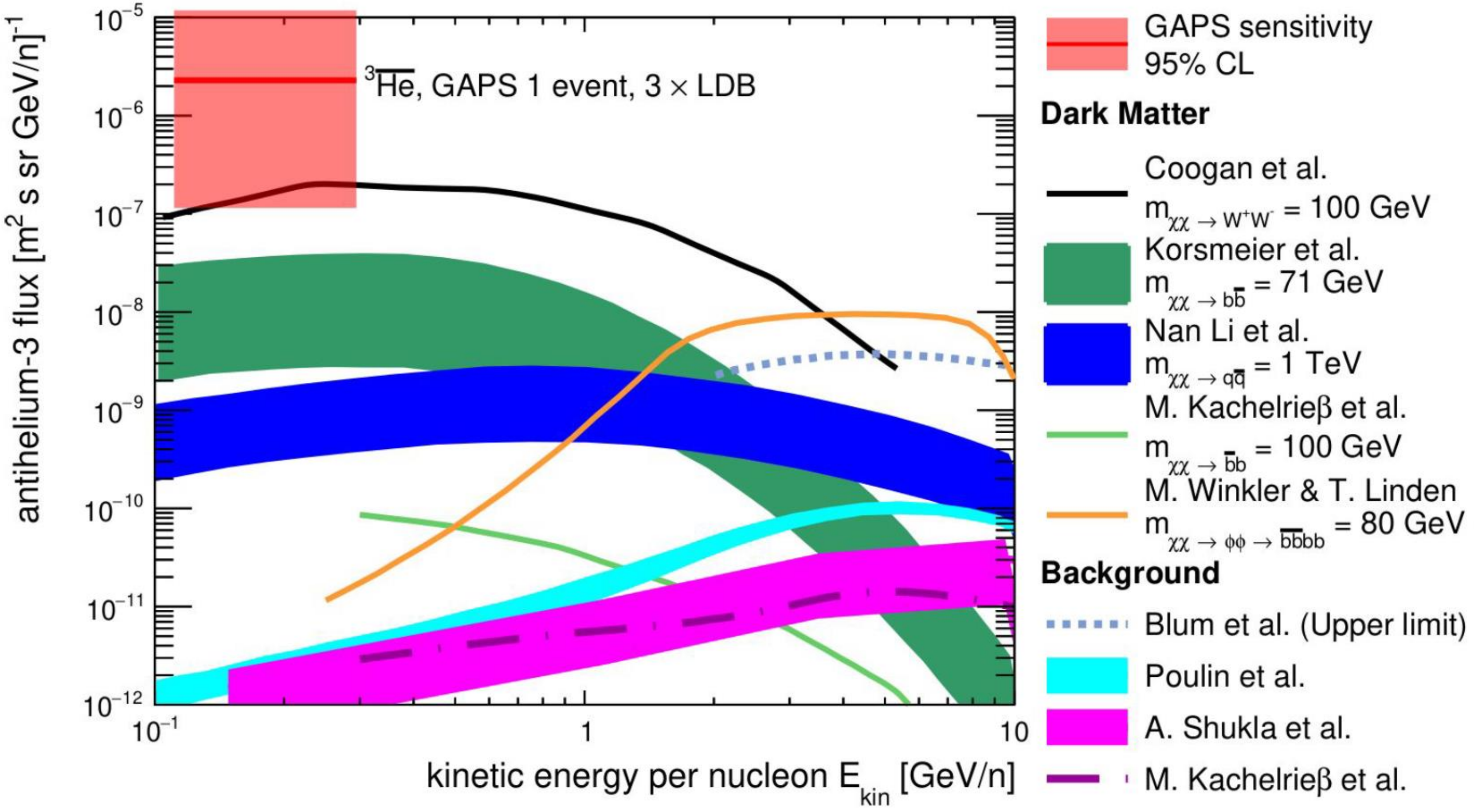
- Predicted **antideuteron** signal from DM annihilation or decay ~ 2 orders of magnitude above astrophysical background below 250 MeV/n
- An essentially **background-free** DM signature
- GAPS sensitivity will be up to 2 orders of magnitude below the BESS limit

GAPS antihelium-3 sensitivity

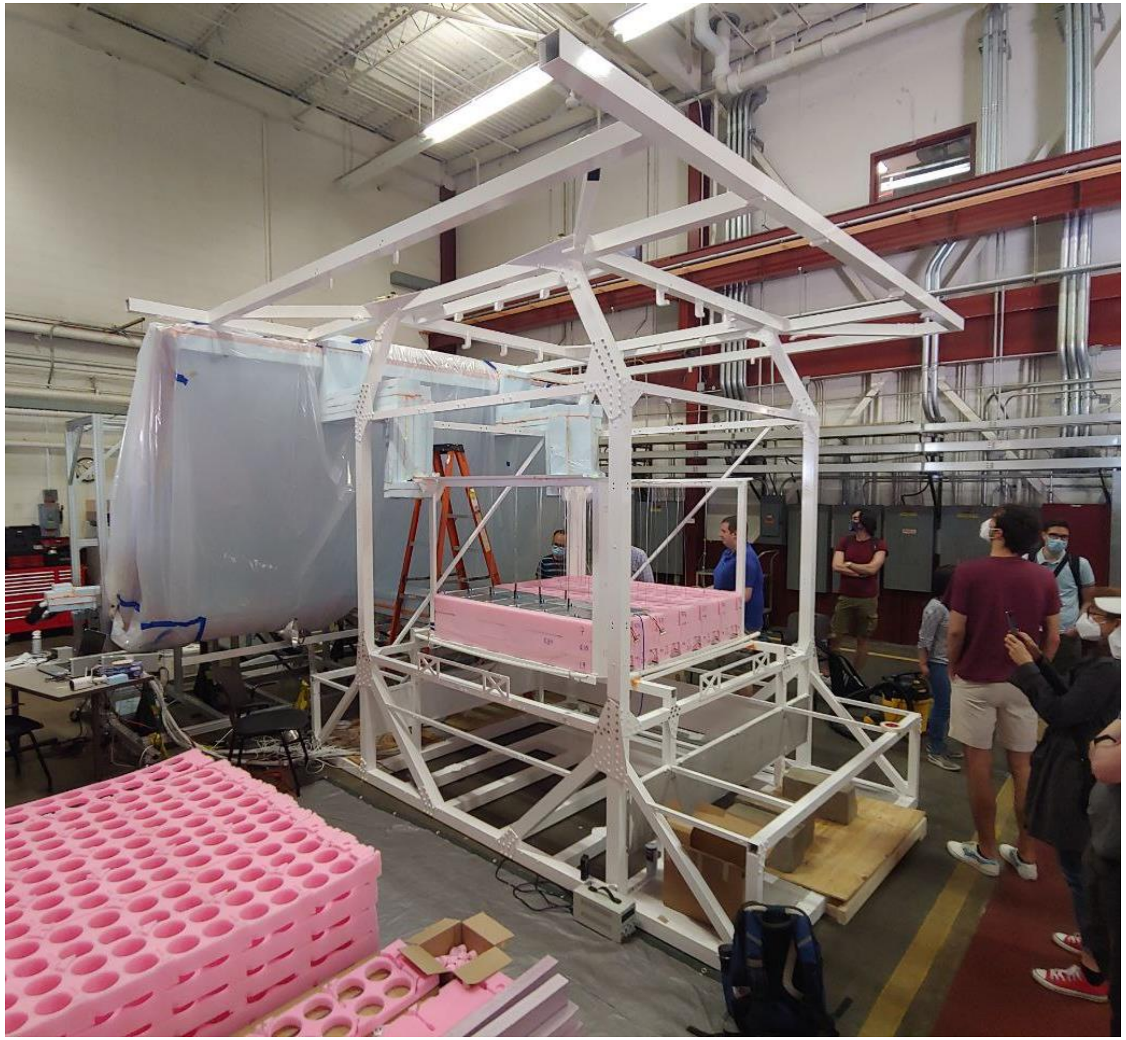
[Astropart. Phys. 102580 (2021)](#)

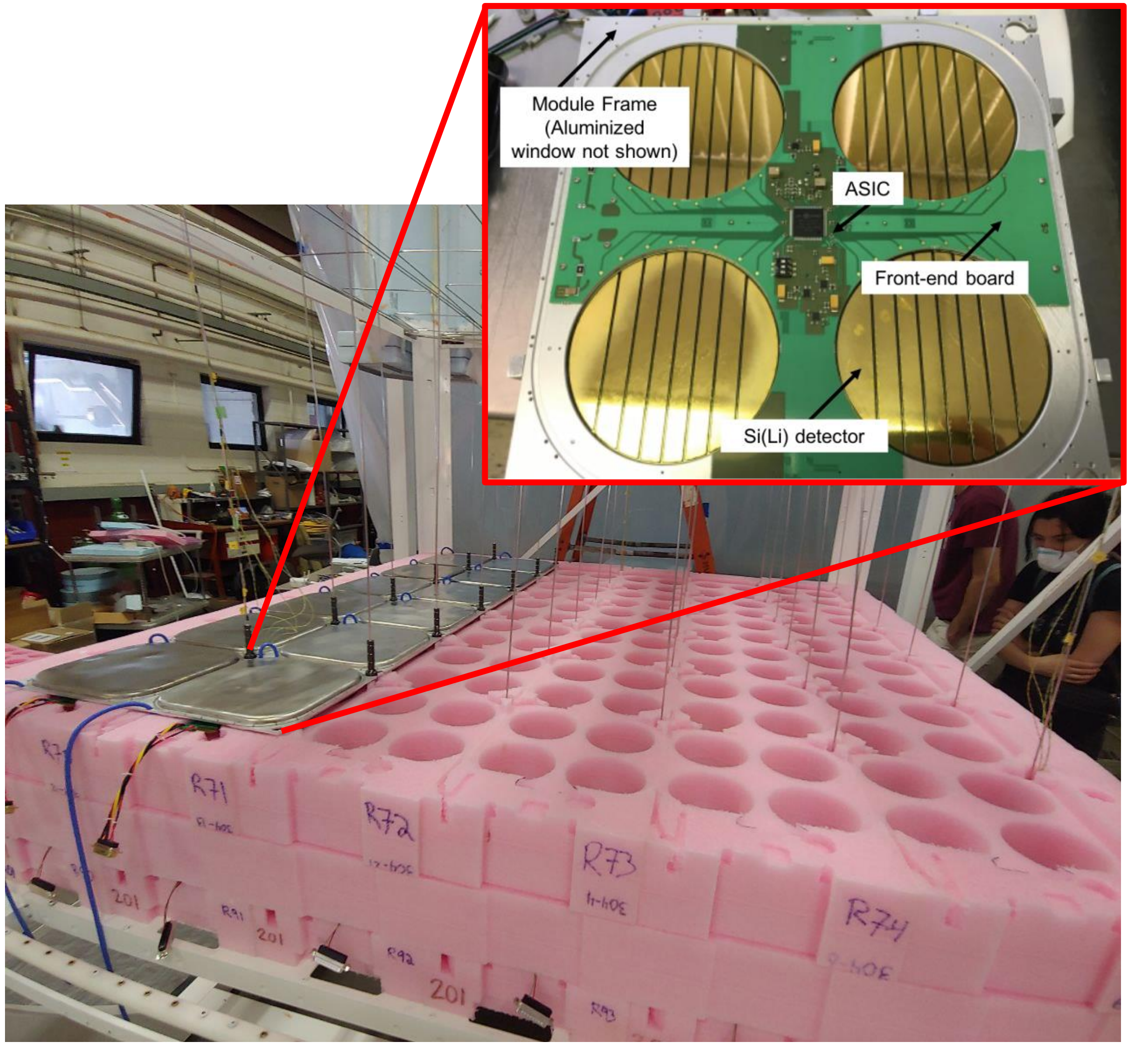
$^{3}\overline{He}$

- GAPS will be sensitive to $^{3}\overline{He}$
- $^{3}\overline{He}$ flux ~ 2-3 orders of magnitude below $\overline{d}$ flux
- An observation of $^{3}\overline{He}$ would be a clear indication of **new physics**
- Extend the energy coverage at low energies **(0.1-0.3 GeV/n)**



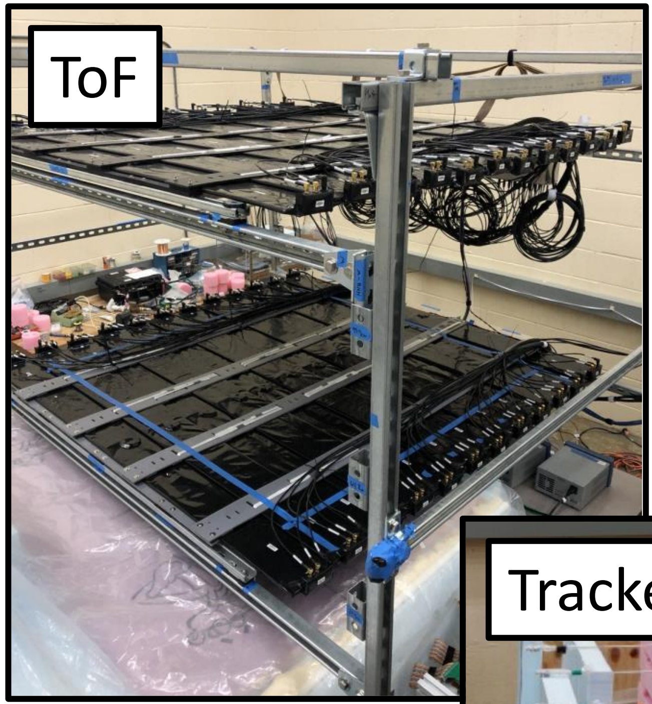
GAPS hardware integration

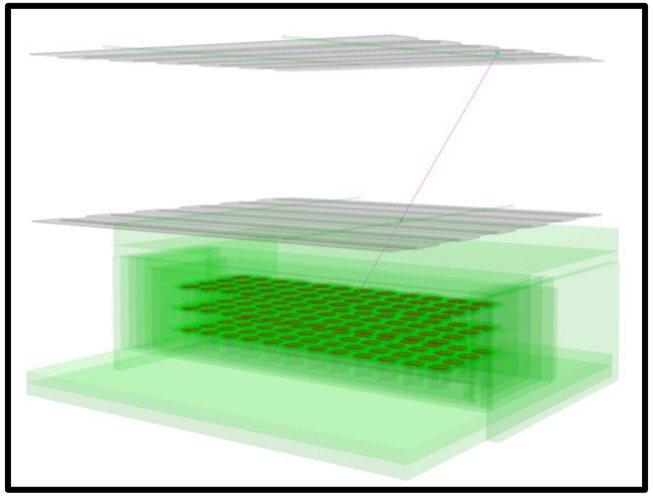


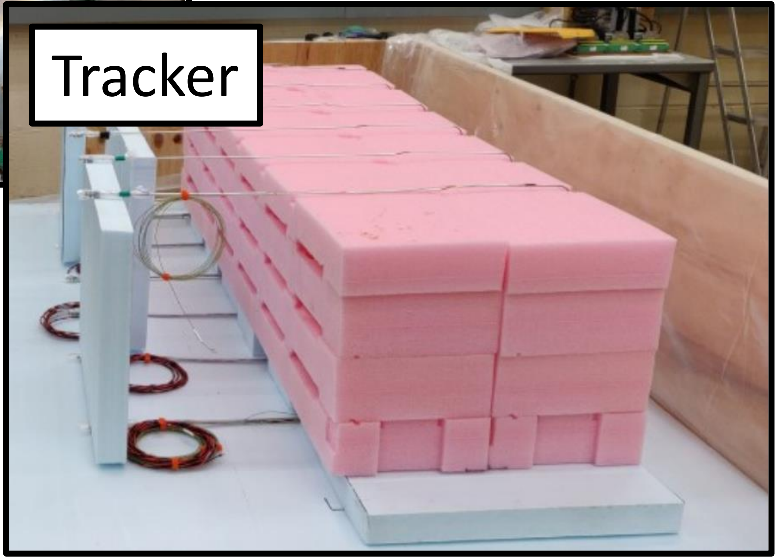


GAPS hardware integration

GAPS Functional Prototype (GFP)







Goals:

- test and operate all components together
- test readout chain
- collect X-ray data
- collect muon data

Results:

- The GFP demonstrated for the first time that all key system interfaces successfully
- Reconstruction of cosmic muon tracks demonstrates compliance with the key performance requirements
- Trigger, event building, and track reconstruction algorithms verified

Merging data from Si(Li) and TOF to get a complete picture of muon data → **Done. Analysis ongoing.**

Conclusions

- **GAPS** is the first experiment dedicated to the observation of cosmic **antiprotons**, **antideuterons**, and **antihelium-3** at energies **below 250 MeV/n**

- **GAPS** main scientific goals:

  - **First detection of cosmic antideuterons**, thanks to excellent sensitivity in a backgroundfree 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

- Hardware integration already started, a **functional prototype** has been assembled at the end of 2021 and successfully tested in 2022
- **First flight** is planned in late **2023**

GAPS collaboration meeting at MIT, 8-9 June 2022