

Low-energy Antinuclei Measurements

arXiv:2608.27787

Community Science (Ad ASTRA) Workshop

September 2026

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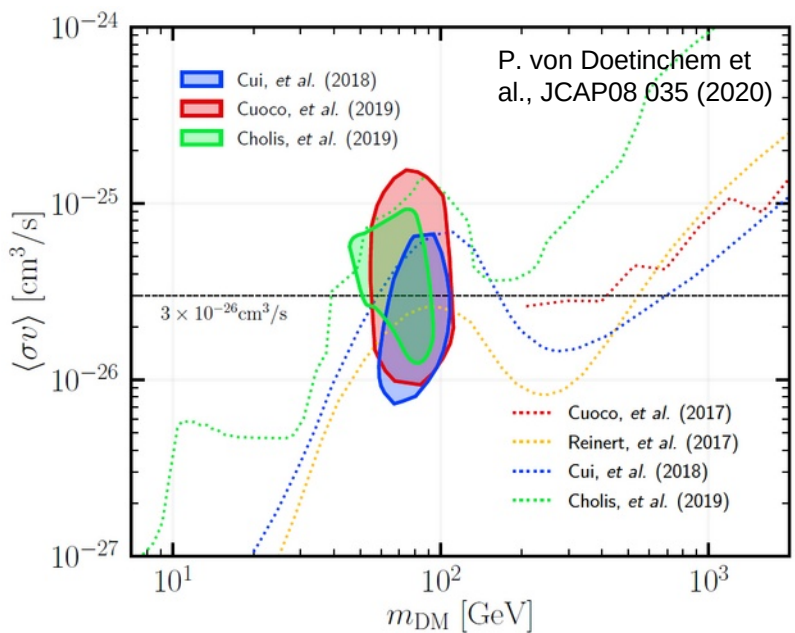
<https://www.phys.hawaii.edu/~philipvd>

Science Questions

The Nature of Dark Matter and New Physics:

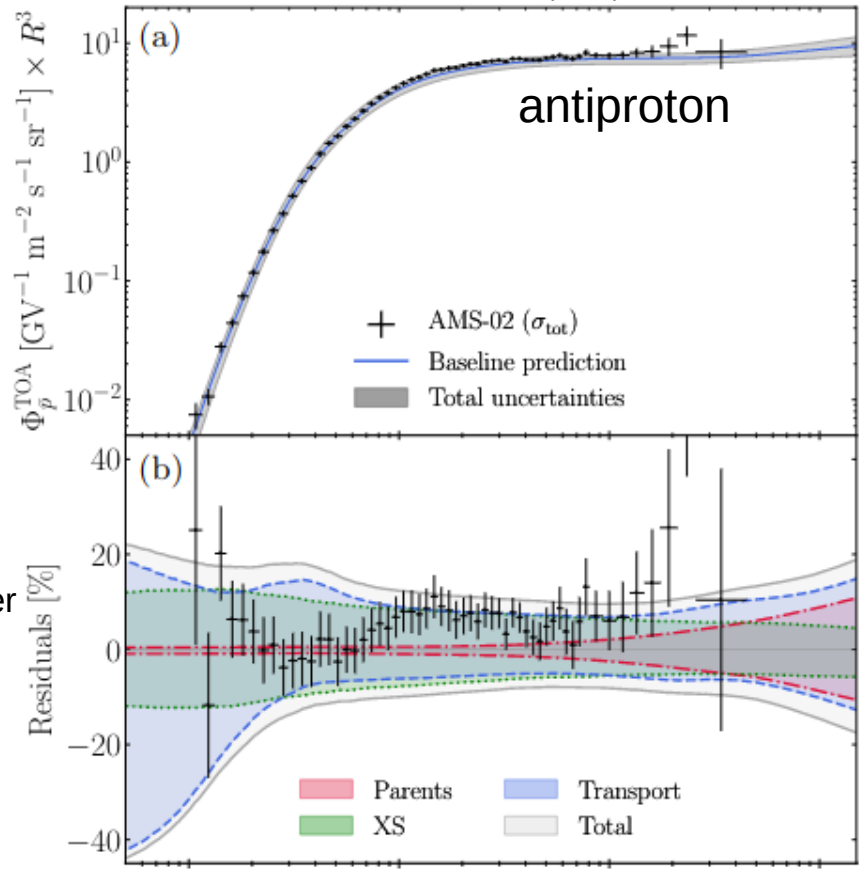
- What are the fundamental particle properties of dark matter?
- Do cosmic antinuclei exist at detectable levels, and what would they reveal about dark matter and the matter-antimatter asymmetry of the universe?
- Can we detect signatures from the evaporation of Primordial Black Holes?

Unexplained Features in Cosmic Rays and γ -rays?

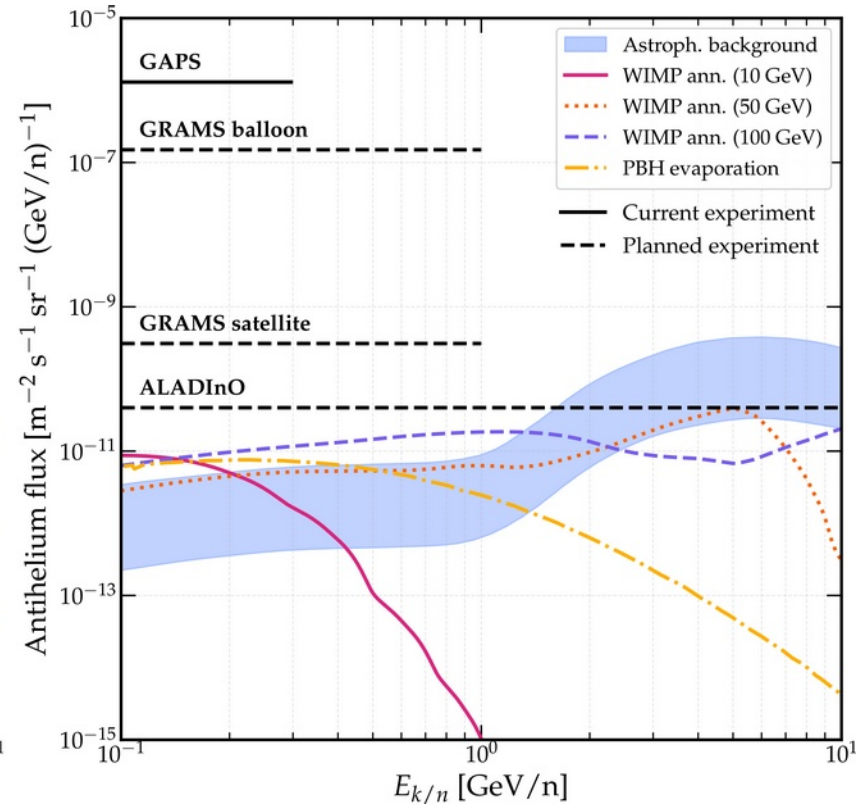
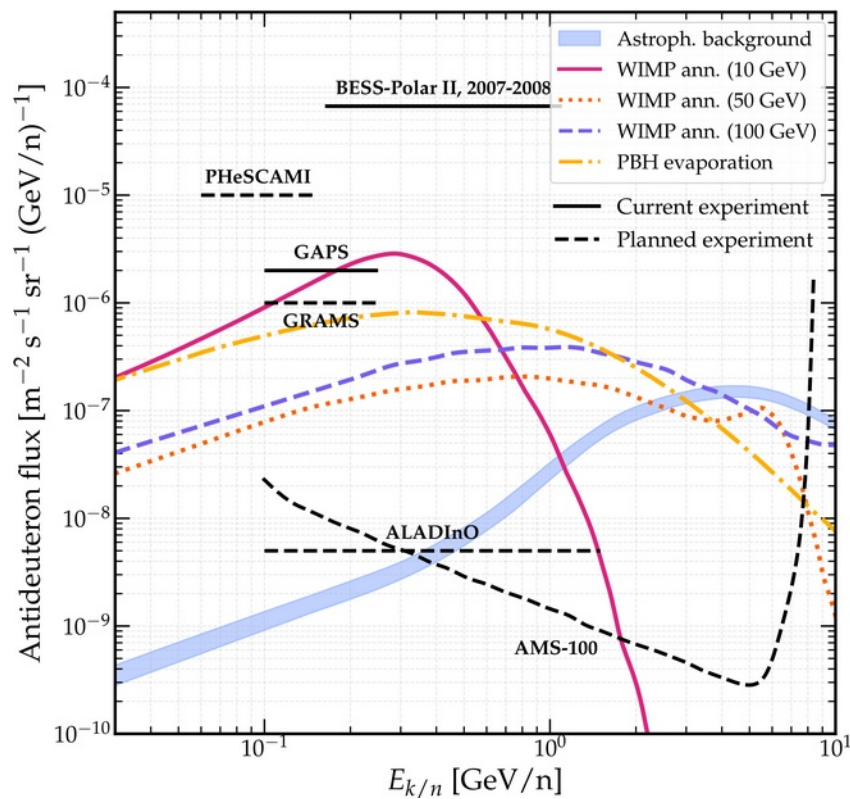


- Combined fit with antiproton and diffuse gamma-rays from the Galactic Center
→ 50-90GeV DM particle? (ongoing debate)
- Unexplained feature in positrons:
 - astrophysical origin → pulsars
 - SNR acceleration
 - dark matter annihilation
- **Understanding astrophysics background is a challenge**

M. Boudaud et al., Phys. Rev. Research 2, 023022 (2020)

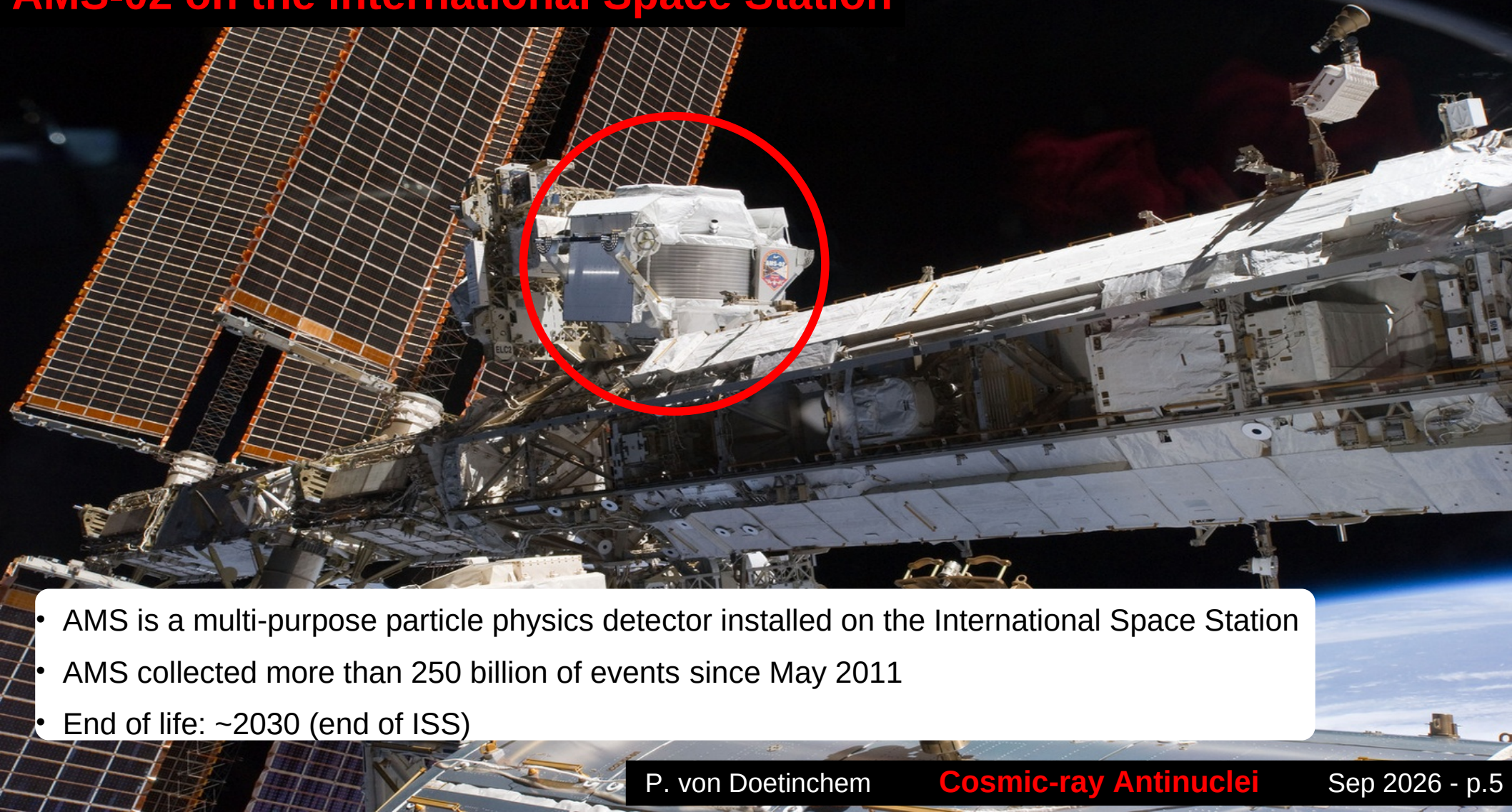


Antinuclei Fluxes



Low-energy antideuterons or antihelium from dark matter annihilation or decay or primordial black hole evaporation can be orders of magnitude above the astrophysical background.

AMS-02 on the International Space Station

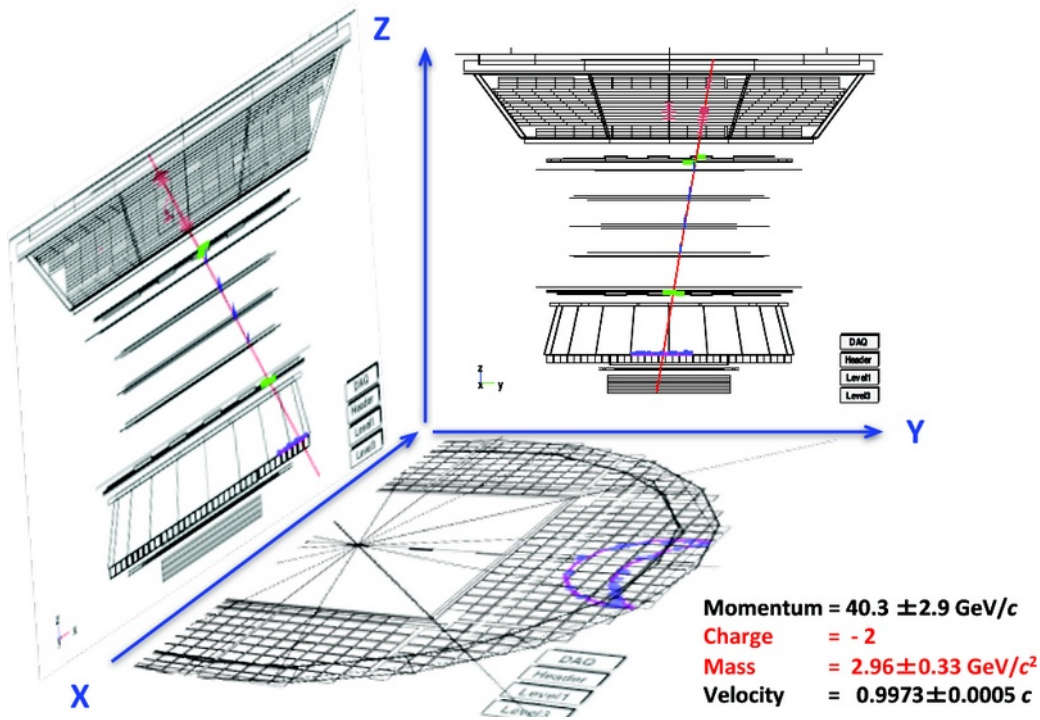


- AMS is a multi-purpose particle physics detector installed on the International Space Station
- AMS collected more than 250 billion of events since May 2011
- End of life: ~2030 (end of ISS)

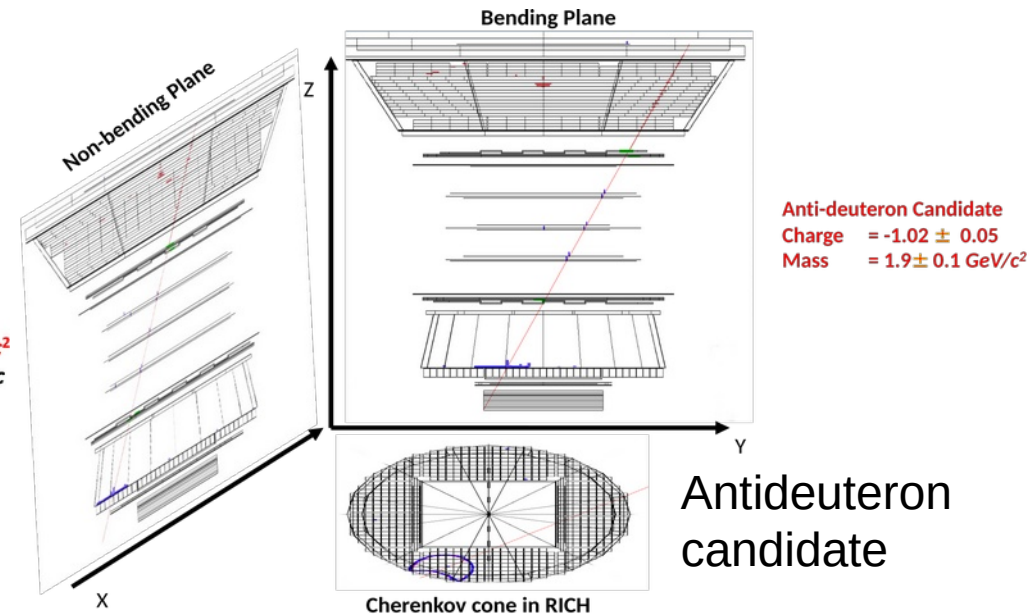
AMS-02 Antihelium and Antideuteron Candidates

AMS-02 reported at conferences that **several $\overline{\text{He}}$ candidate events have been observed**

→ interpretations are actively ongoing

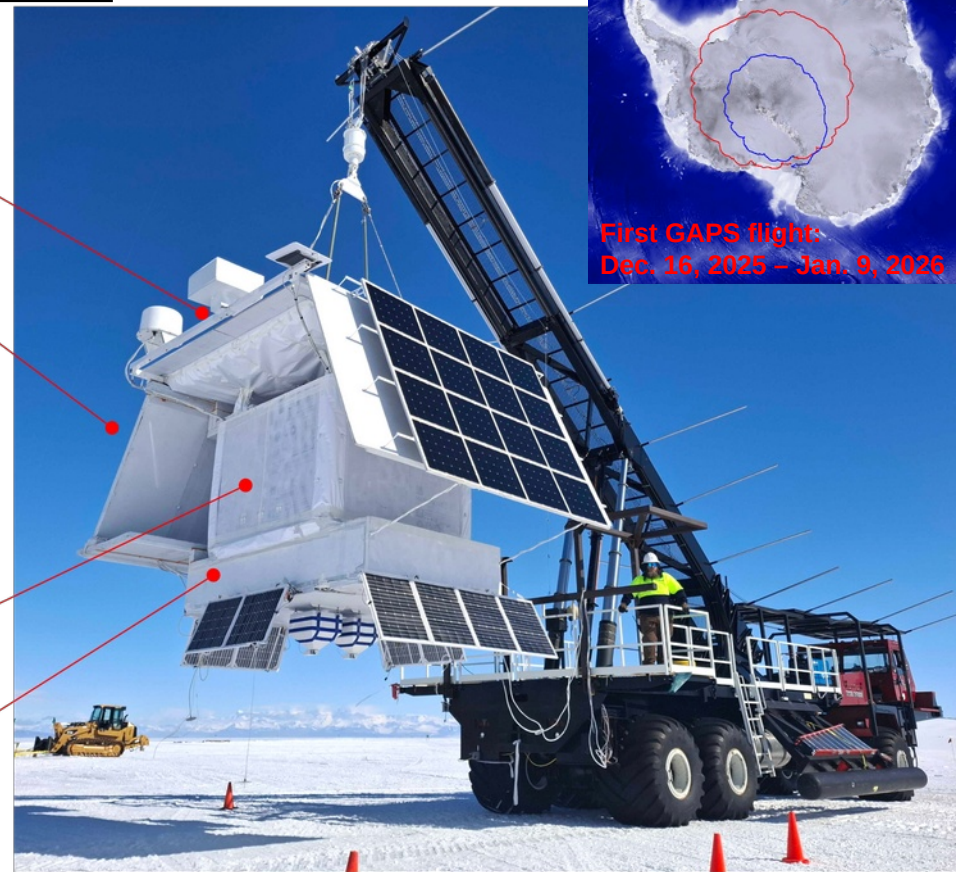
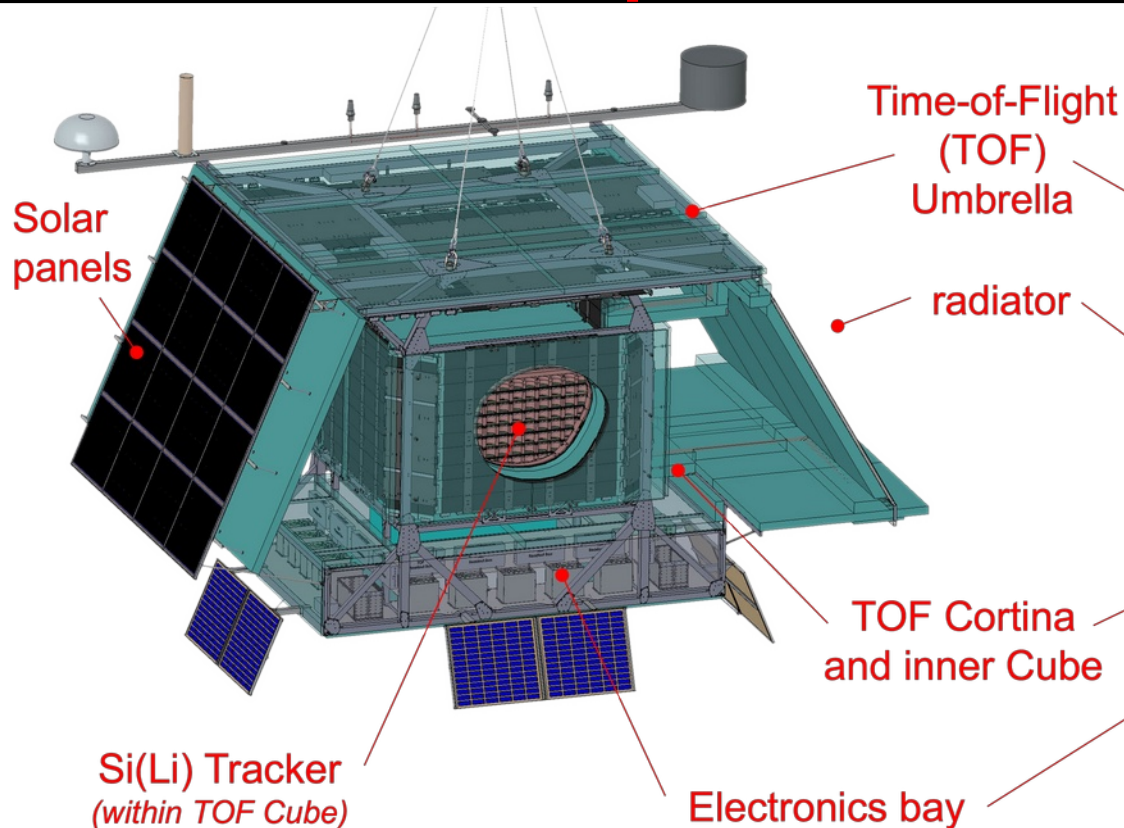


Antihelium-3 candidate



Antideuteron candidate

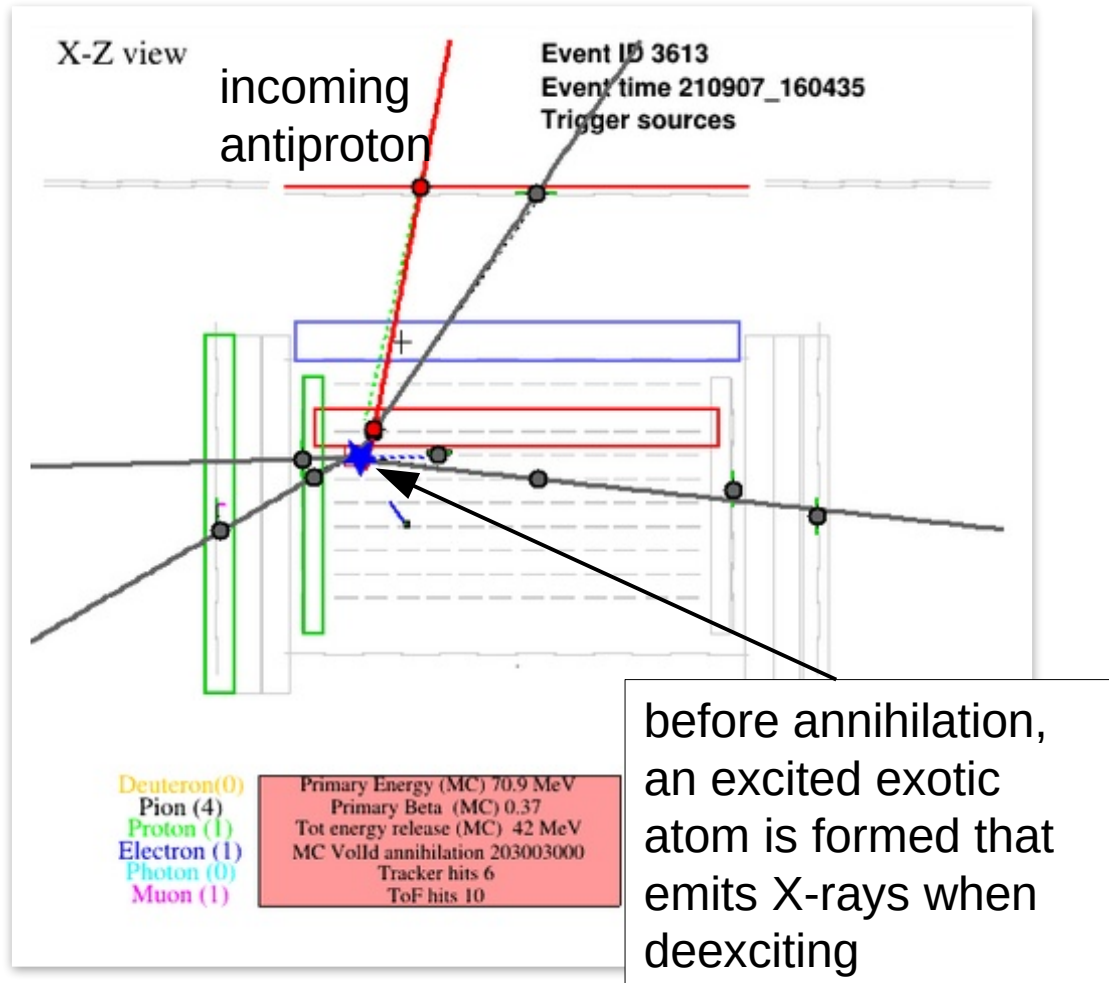
GAPS Experiment



- **General AntiParticle Spectrometer:**

- A precision antiproton measurement in an unexplored energy range $<0.25 \text{ GeV/n}$
- Antideuteron sensitivity 2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range
- Leading sensitivity to low-energy cosmic antihelium nuclei

Annihilation Identification Principle



- antiparticle slows down and stops in material
- near-unity chance for creation of an excited exotic atom ($E_{\text{kin}} \sim E_I$)
- deexcitation:
 - fast ionization of bound electrons (Auger)
 - complete depletion of bound electrons
 - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic X-ray transitions depending on antiparticle mass
- Nuclear annihilation with characteristic number of annihilation products

Science Table

Physical Parameters	Science Objectives	Observables	Potential Challenges
Primary antideuteron detection	Potential DM and PBH discovery	Sensitivity at $< 10^{-5} [\text{m}^2\text{sr}(\text{GeV}/n\text{s})]^{-1}$	Need to reject antiproton events
Secondary antideuteron detection	Provide constraints on antideuteron production models (cross section and coalescence model) and DM/PBH contribution	Sensitivity at $< 10^{-8} [\text{m}^2\text{sr}(\text{GeV}/n\text{s})]^{-1}$	Large acceptance area and long measurement times are required.
Primary antihelium detection	New, unknown sources; Potential DM and PBH discovery	New, unknown sources: Sensitivity at $< 10^{-9} [\text{m}^2\text{sr}(\text{GeV}/n\text{s})]^{-1}$ Potential DM and PBH discovery: Sensitivity at $< 10^{-11} [\text{m}^2\text{sr}(\text{GeV}/n\text{s})]^{-1}$	Large acceptance area and long measurement times are required.
Secondary antihelium detection	Provide constraints on antihelium production models (cross section and coalescence model) and DM/PBH contribution	Sensitivity at $< 10^{-12} [\text{m}^2\text{sr}(\text{GeV}/n\text{s})]^{-1}$	Large acceptance area and long measurement times are required.

New Mission Design

Goal: **Factor of 1,000 improvement in antinuclei sensitivity**

- **Magnetic Spectrometer:**

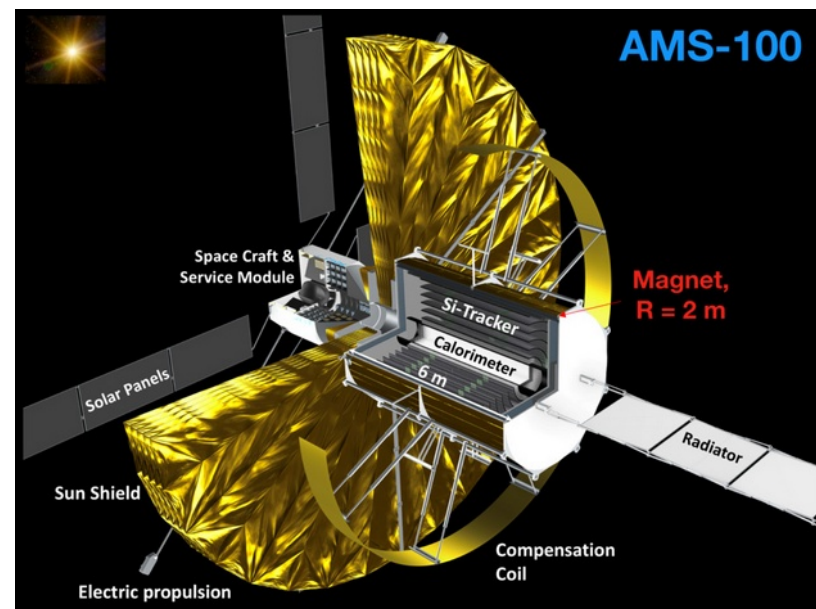
- Lightweight High-Temperature Superconducting (HTS) magnet system. HTS magnets operate cryogen-free (e.g., cooled passively or mechanically to around 55 K)
- Strength: ~ 0.5 T
- Enable precision determination of momentum, charge, charge sign

- **Annihilation Identification:**

- GAPS uses lithium-drifted silicon tracker for stopping and annihilation
- GRAMS uses a Liquid Argon Time Projection Chamber (LArTPC) detector surrounded by a plastic scintillator shield → *talk by Tsuguo Aramaki*

- **Requirement:** low geomagnetic cutoff, long measurement times

- **Location trade space:** Sun-Earth Lagrange Points (L1 & L2), Lunar Surface



Conclusion & Outlook

- *Cosmic-ray antinuclei are important means to the study new physics*
 - All antinuclei species need to be explained together
 - AMS-02 continues collecting data, and will be upgraded
 - GAPS had its first successful flight during the 2025/26 season
- A lot of related community efforts, e.g.:
 - XSCRC 2024, JENAA 2024, $\bar{d}19$, LAN19
 - Review: JCAP08(2020)035, <https://arxiv.org/abs/2002.04163>
 - CRN-SIG webinars:
 - <https://science.nasa.gov/astrophysics/programs/physics-of-the-cosmos/community/cosmic-ray-and-neutrino-sig-seminar-16-april-2025/>
 - <https://science.nasa.gov/astrophysics/programs/physics-of-the-cosmos/community/crn-sig-seminar-17-june-2026/>
 - Start of a new CRN Science Analysis Group for low-energy antinuclei measurements
- Planning for next-generation experiment has to start now
 - **Goal: factor 1,000 improvement in sensitivity**