Status of cosmic-ray antinuclei searches

UCLA Dark Matter
March 2025

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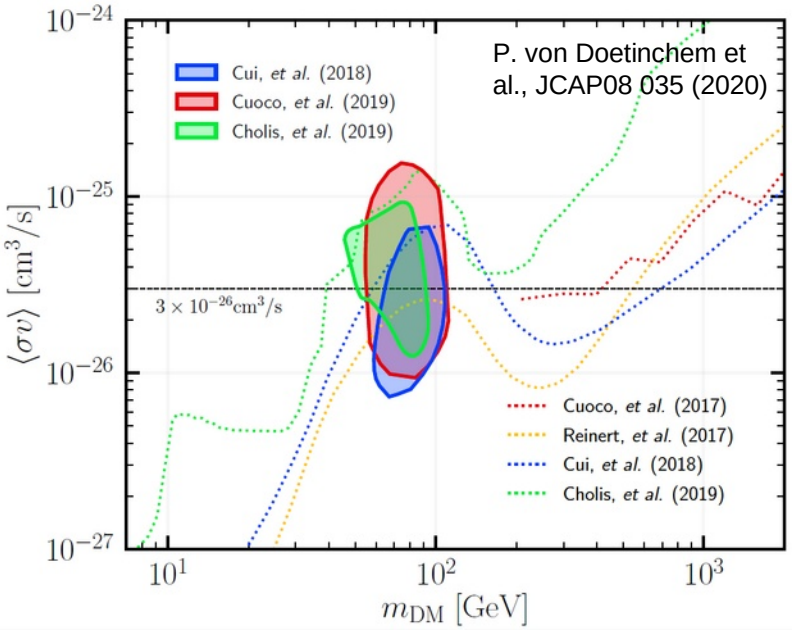
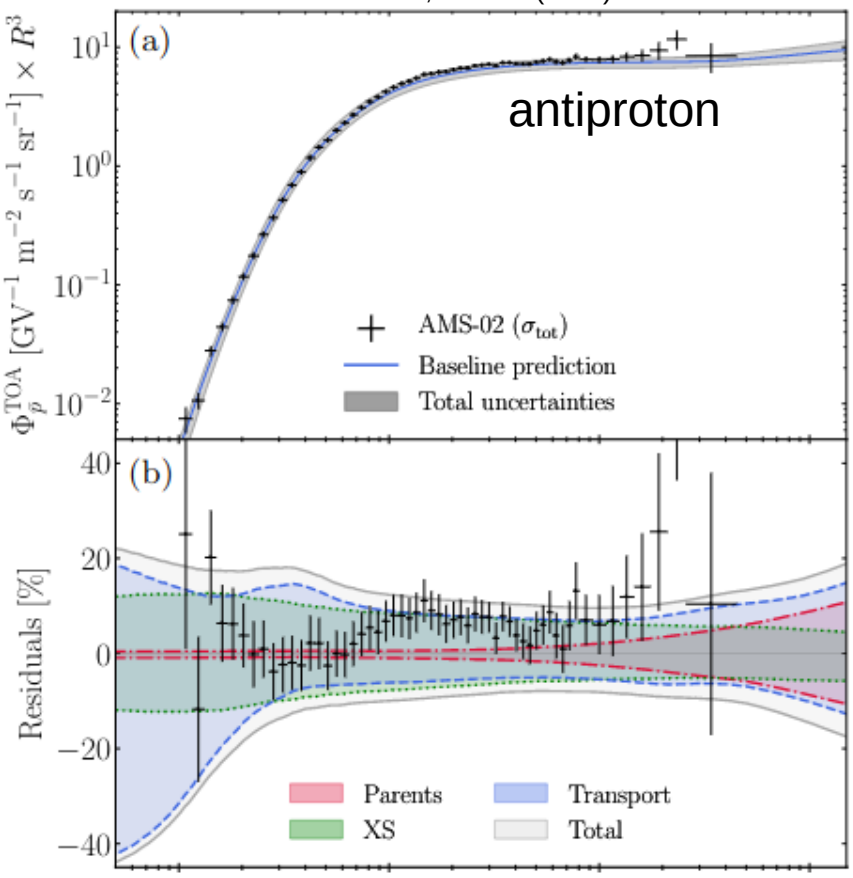
Unexplained features in cosmic antiparticles?



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

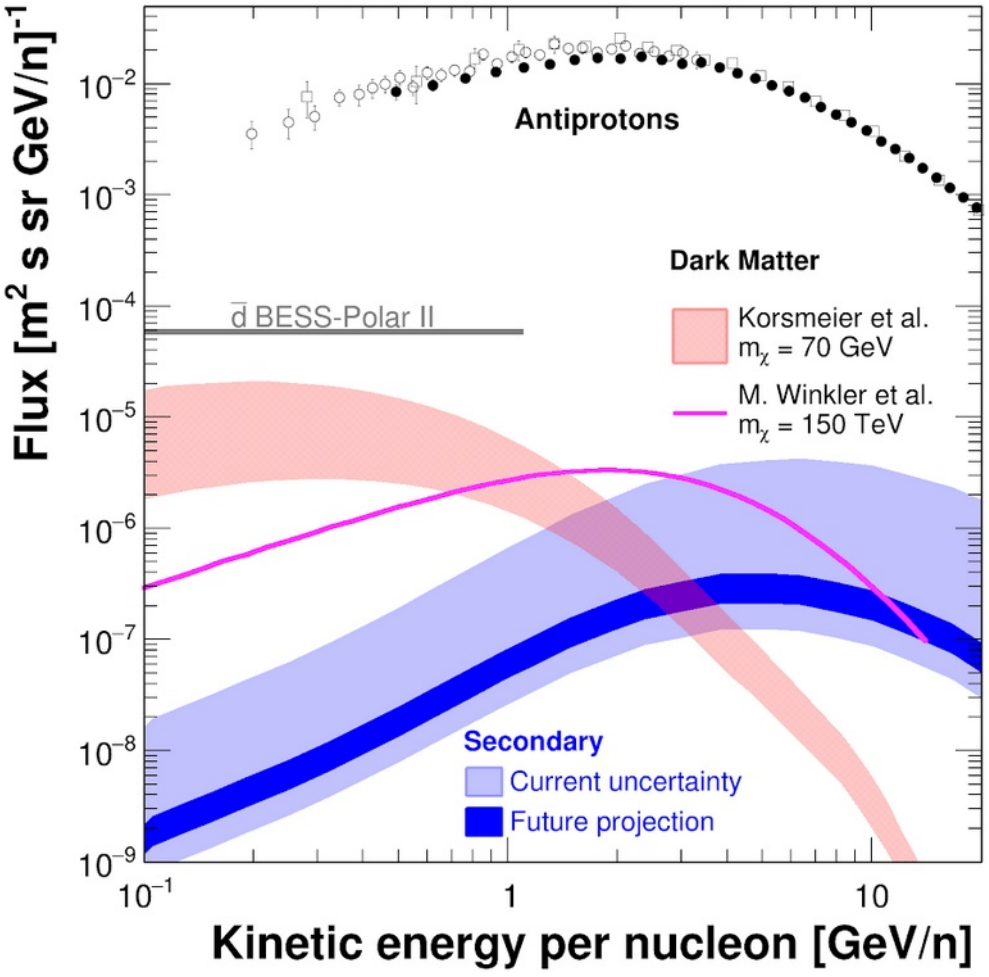


- combined fit with antiproton and diffuse gamma-rays from the Galactic Center → 70-80GeV DM particle? (ongoing debate)

- unexplained feature in positrons:
  - astrophysical origin → pulsars
  - SNR acceleration
  - dark matter annihilation

- **understanding astrophysics background is a challenge** → better constraints on cosmic-ray propagation and production needed

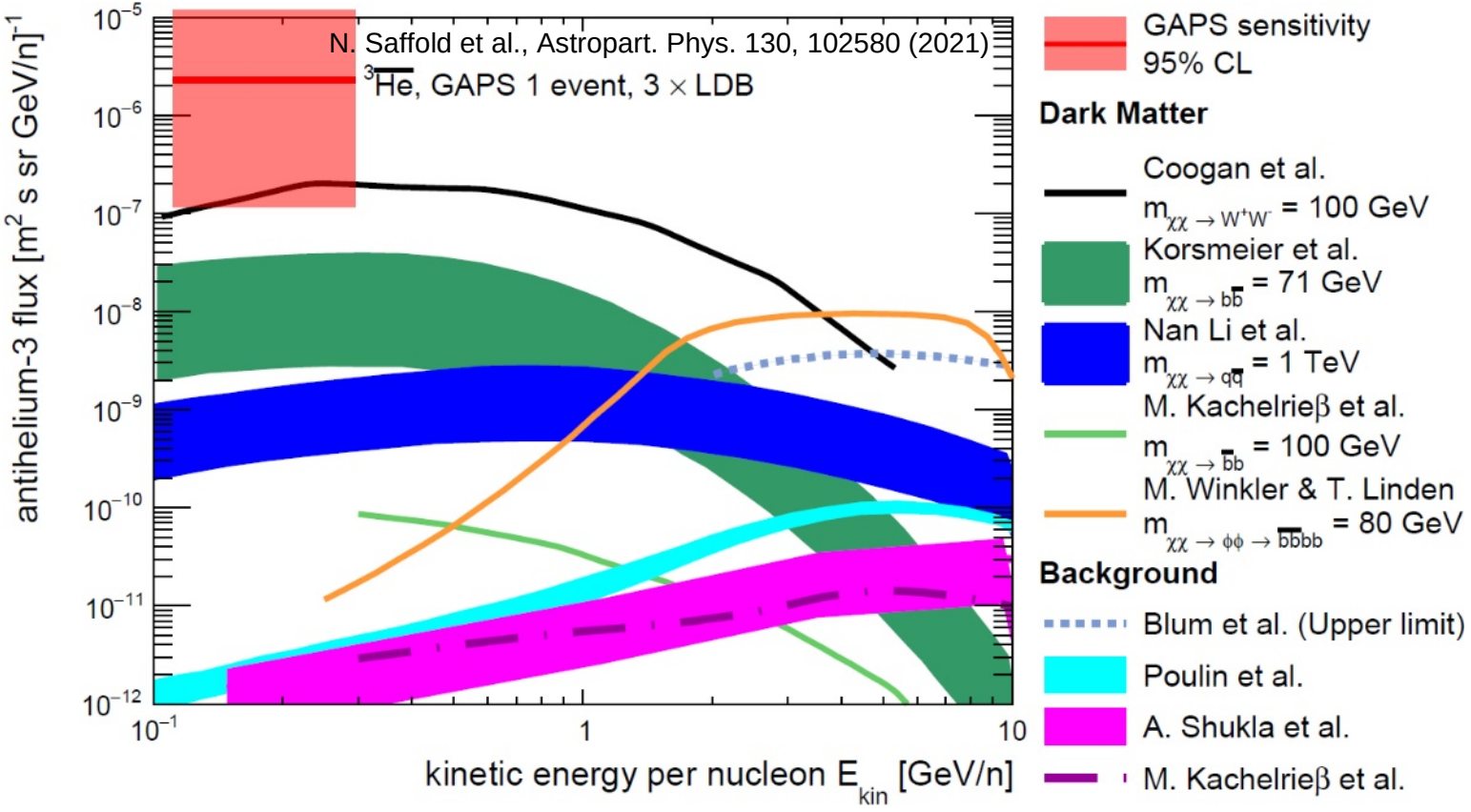
Antideuterons as a probe of dark matter



- Low-energy antideuterons from dark matter annihilation or decay can be orders of magnitude above the astrophysical background.
- Antideuterons are an important dark matter search technique that needs to be explored much more!

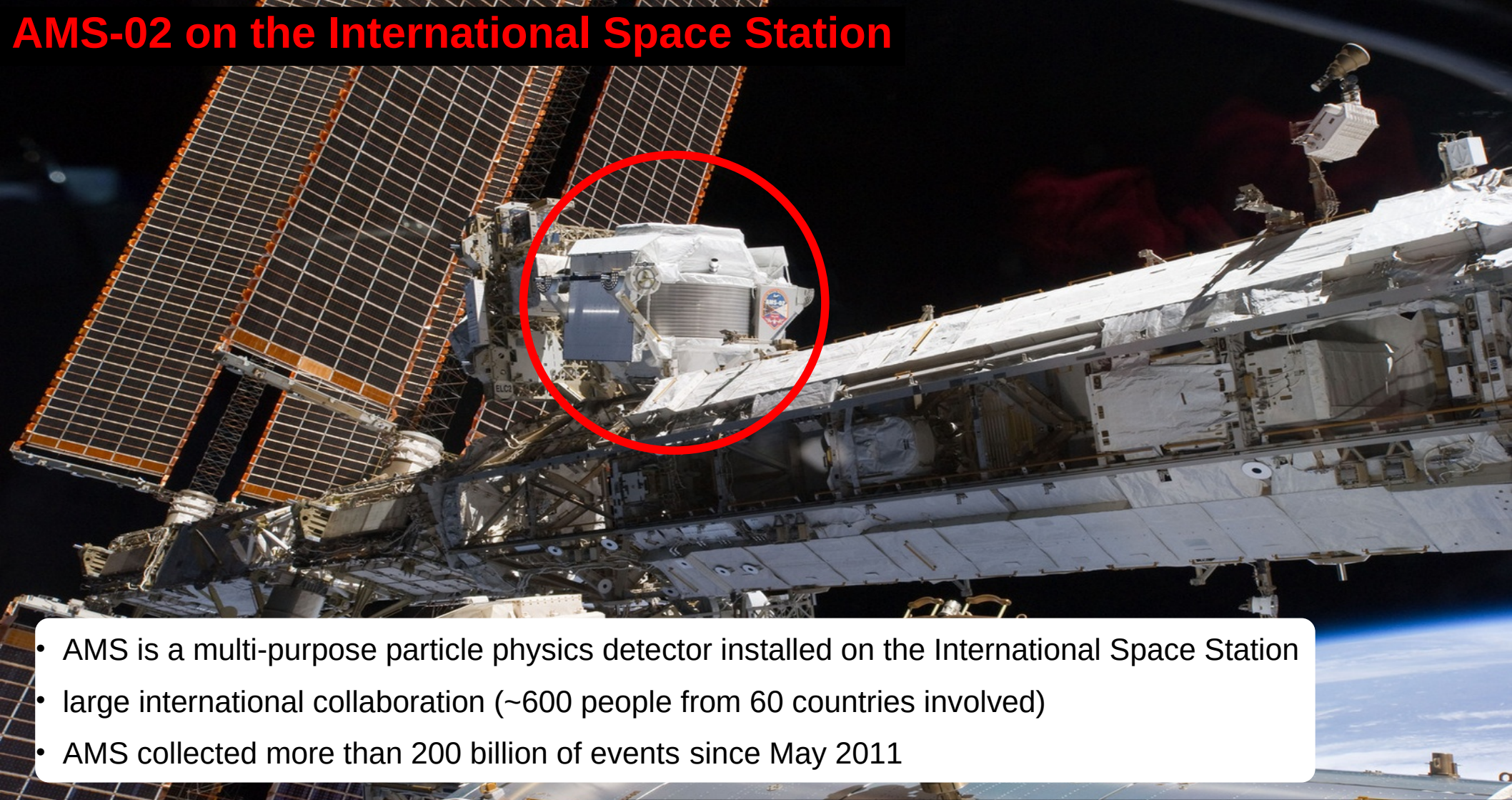
Cosmic antihelium-3

Finding low-energy antihelium would be truly revolutionary new physics



→ also see Tim Linden's talk

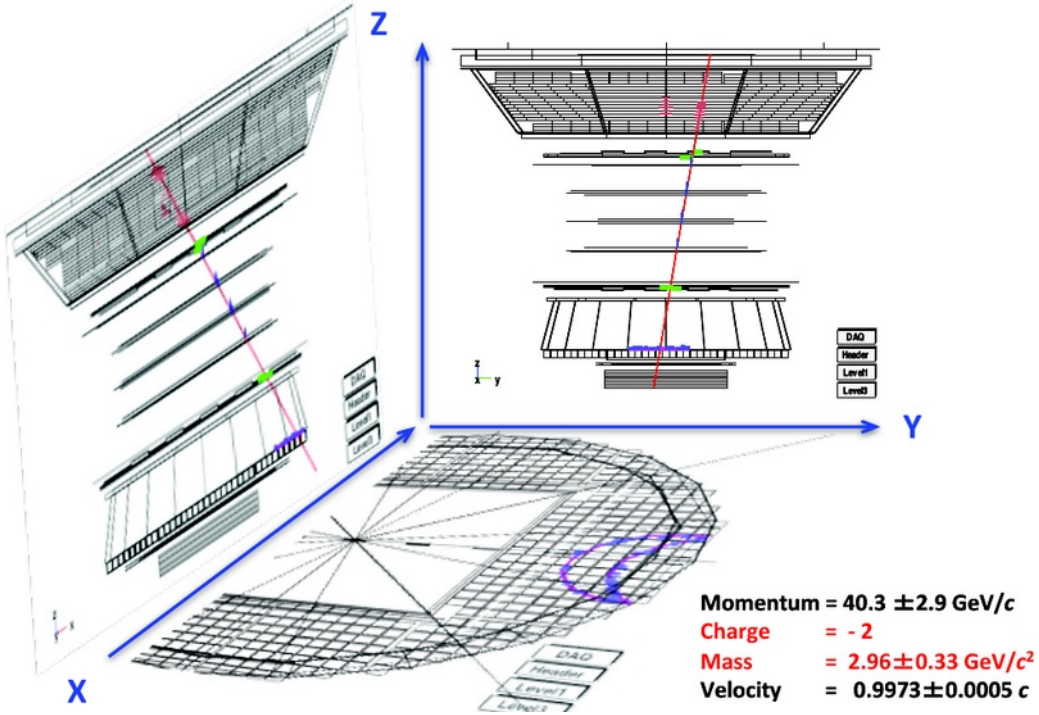
AMS-02 on the International Space Station



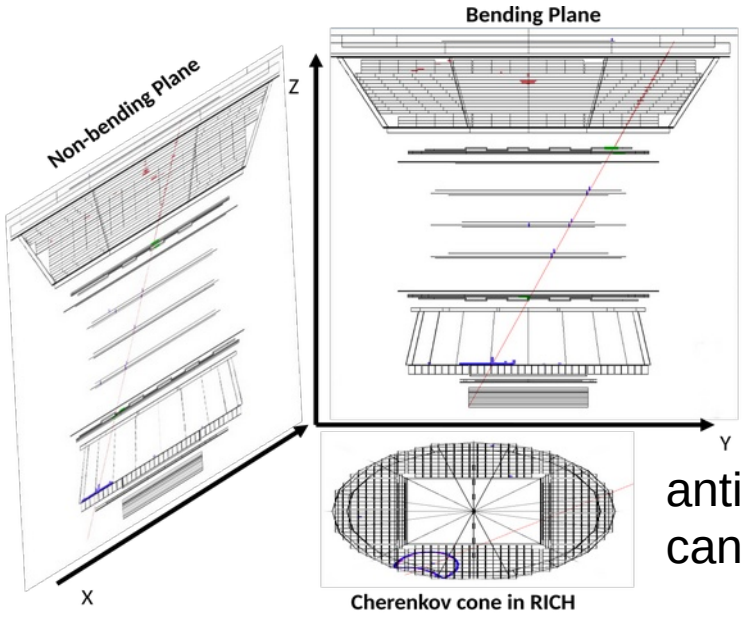
- AMS is a multi-purpose particle physics detector installed on the International Space Station
- large international collaboration (~600 people from 60 countries involved)
- AMS collected more than 200 billion of events since May 2011

AMS-02 antihelium and antideuteron candidates

- AMS-02 reported that **several $\overline{\text{He}}$ candidate events have been observed**
  → interpretations are actively ongoing
- **Possible antihelium candidate explanations include:**
  - Secondary astrophysical background
  - Dark matter annihilation or decay
  - Nearby antistar: at distance of ~1pc
- **New tracker layer on top of TRD to be installed soon**



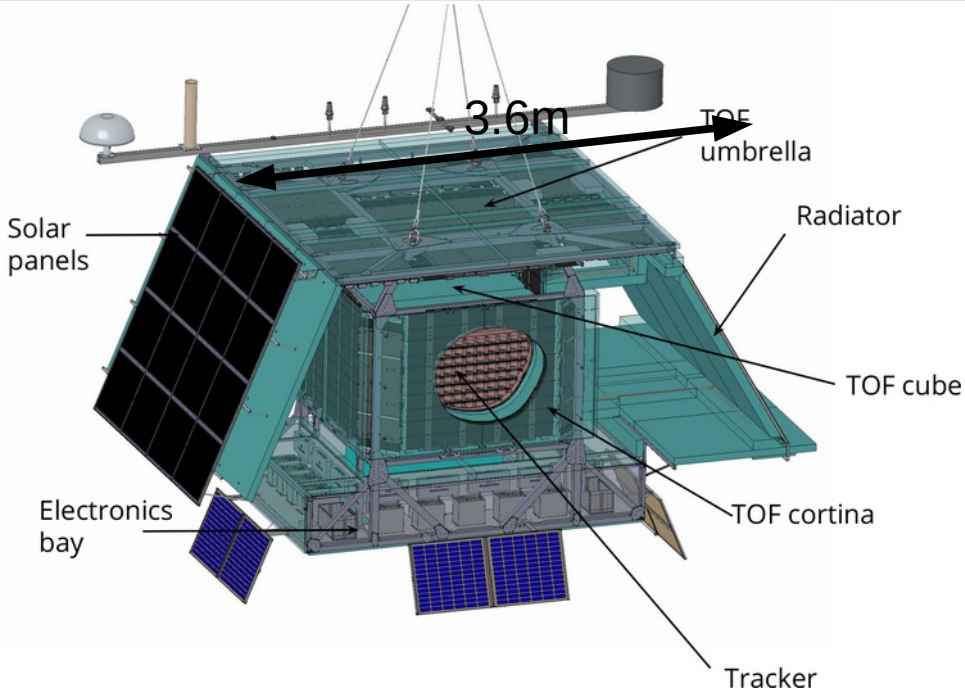
antihelium-3 candidate



antideuteron candidate

Magnetic spectrometer

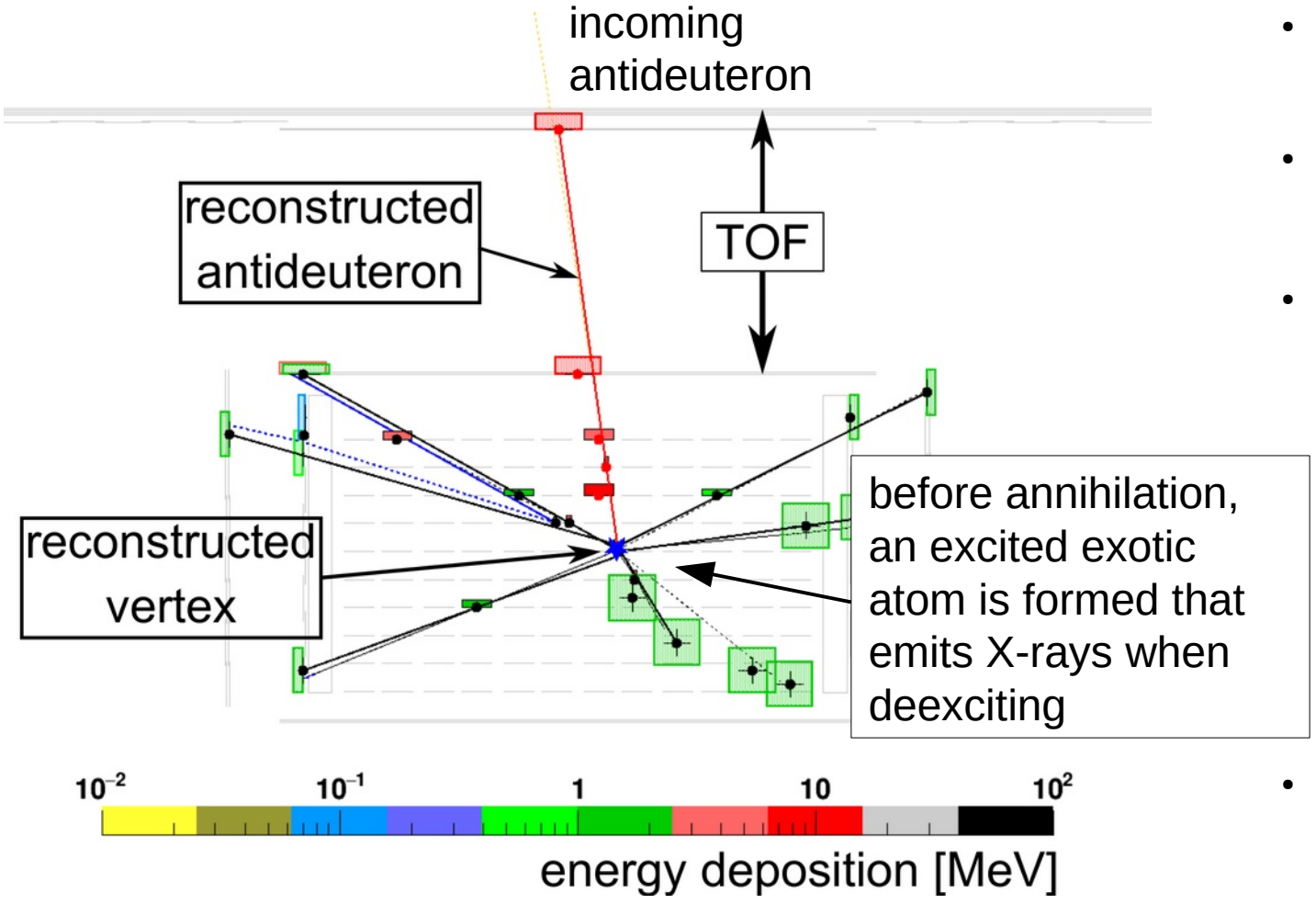
The GAPS experiment




GAPS team for 2024 launch attempt

- The **G**eneral **A**nti**P**article **S**pectrometer is optimized for low-energy cosmic-ray antinuclei search
- Requirements: long flight time, large acceptance, large identification power, low-geomagnetic cutoff
- **GAPS will deliver:**
  - a precision antiproton measurement in an unexplored energy range <0.25 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
- **GAPS is fully tested and already in Anarctica**
  → Long Duration Balloon flight in December 2025

GAPS principle

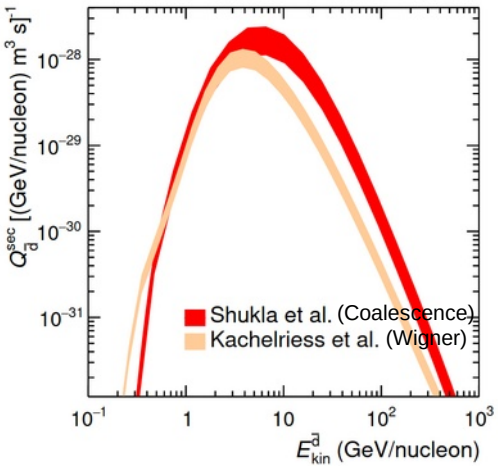


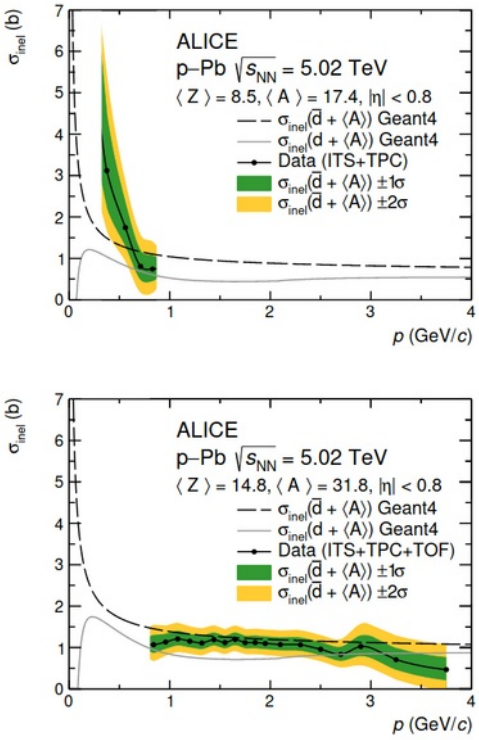
- antiparticle slows down and stops in material
- near-unity chance for creation of an excited exotic atom (E_{kin}~E_I)
- deexcitation:
  fast ionization of bound electrons (Auger)
  → complete depletion of bound electrons
  Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic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

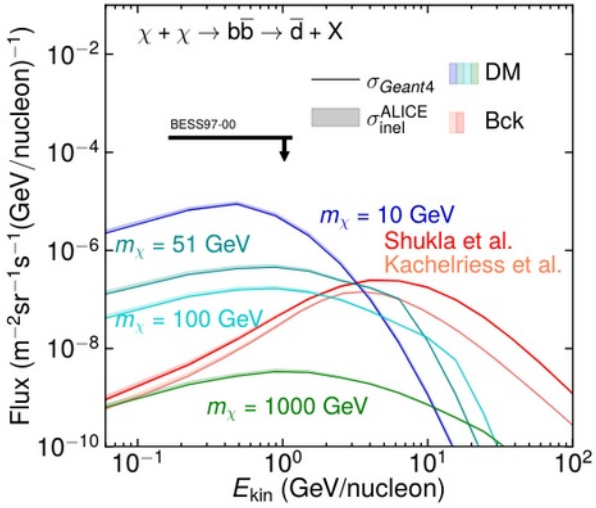
Astrophysical antideuteron background

Šerkšnytė et al., Phys. Rev. D 105, 083021 (2022)

Production → Propagation → Flux at detector







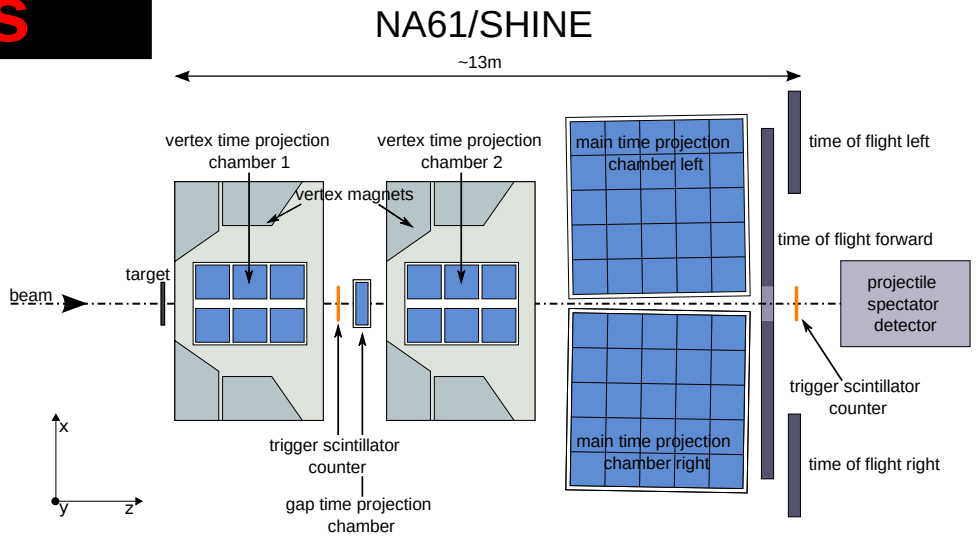
Antideuteron flux at the top of the atmosphere

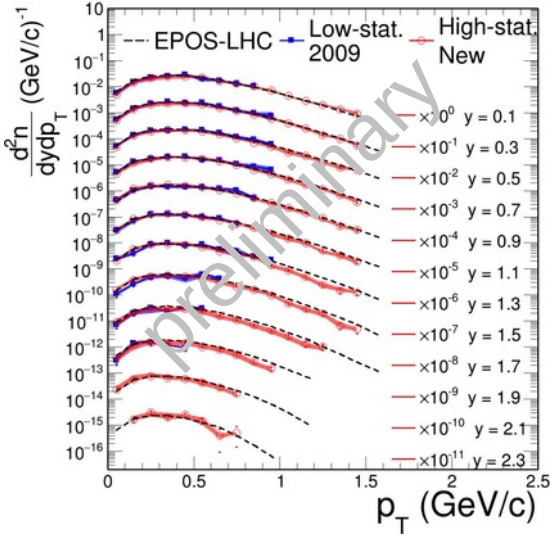
- Significant uncertainties for antinuclei production exist
- Significant uncertainties for propagation in Galaxy exist

→ Measurements of relevant primary cosmic ray and interstellar medium cross sections are important

Accelerator measurements

- NA61/SHINE at CERN SPS:
  - Fixed target experiment
  - High statistics $\bar{p}$ studies
  - C-p fragmentation cross section measurements
  - Deuteron production cross section, d/p ratio
  - Antiparticle correlation studies
  - **New very large pp data set coming up in 2025**
- LHCb at LHC:
  - Antideuteron production in heavy hadron decays and in fixed-target collisions
  - **New results from antihelium-3 from antilambda-b decays**
- ALICE at LHC
  - Antinuclei production
  - Antinuclei inelastic cross sections
- AMBER at CERN SPS (upgraded COMPASS):
  - Fixed target experiment
  - High-statistics antiproton production cross section measurements





Conclusion & Outlook

- Cosmic-ray antinuclei are important means to the study new physics
- Uncertainties need to be reduced:
  - Antideuteron and antihelium formation are not well understood
  - Cross section measurements need to be conducted for interpretation
- AMS-02 continues collecting data and will be upgraded
- GAPS will have first flight in 2025
- Accelerator experiment data are crucial for interpretation
- Recent community efforts:
  - XSCRC 2024: https://indico.cern.ch/event/1377509/
  - JENAA 2024: https://indico.cern.ch/event/1400721/overview
  - $\bar{d}$19: https://indico.phys.hawaii.edu/event/1449/
  - LAN19: https://indico.cern.ch/event/849055/
  - Reviews:
    - https://arxiv.org/abs/2503.16173
    - https://arxiv.org/abs/2002.04163