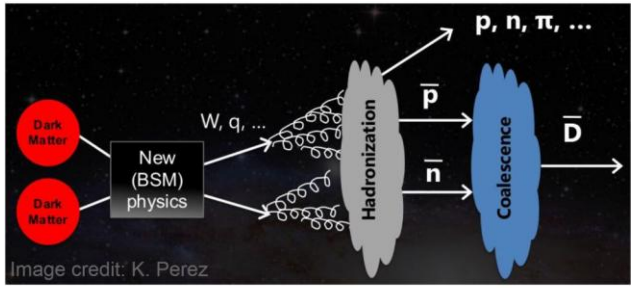
Searching for Dark Matter in Antarctica with the GAPS Experiment

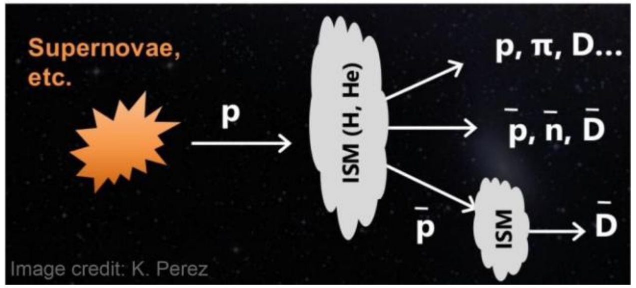
ELENA VANNUCCINI (INFN FLORENCE)

ON BEHALF OF THE GAPS COLLABORATION

Antideuterons as DM signatures

- DM decay/annihilation in the Galaxy produces $\bar{p}$, $\overline{D}$ and $\overline{He}$
- Low-energy cosmic $\overline{D}$ provides a potential **sizeable** **background-free** signature of DM

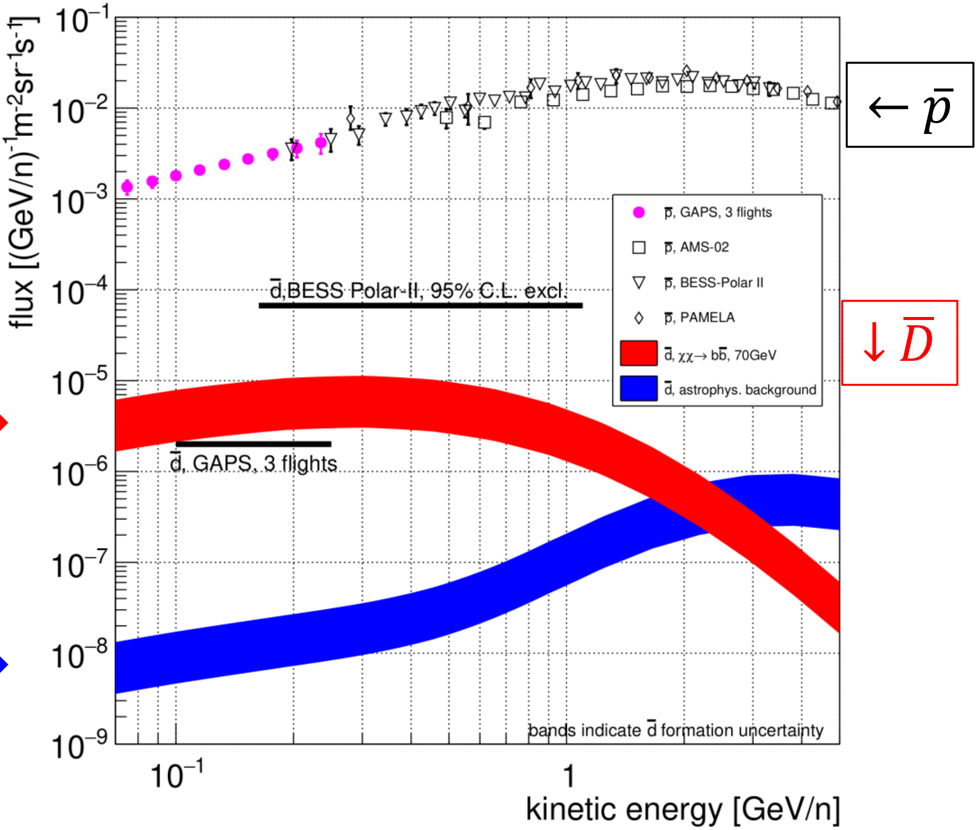




$\overline{D}$ from DM

secondary $\overline{D}$

(tertiary $\overline{D}$)

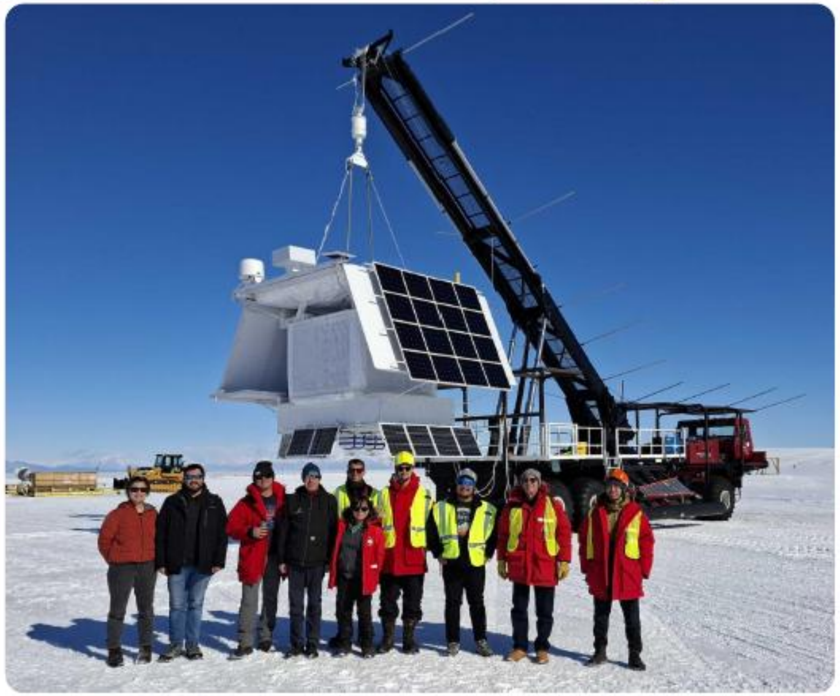


Models: Korsmeier, Donato, Fornengo Phys. Rev. D 97, 103011 (2018)

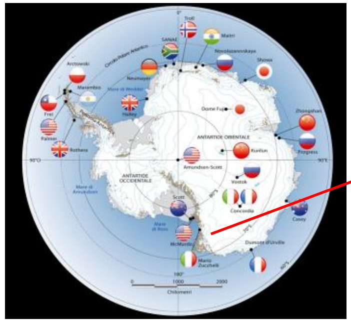
INFN

GAPS → General AntiParticle Spectrometer

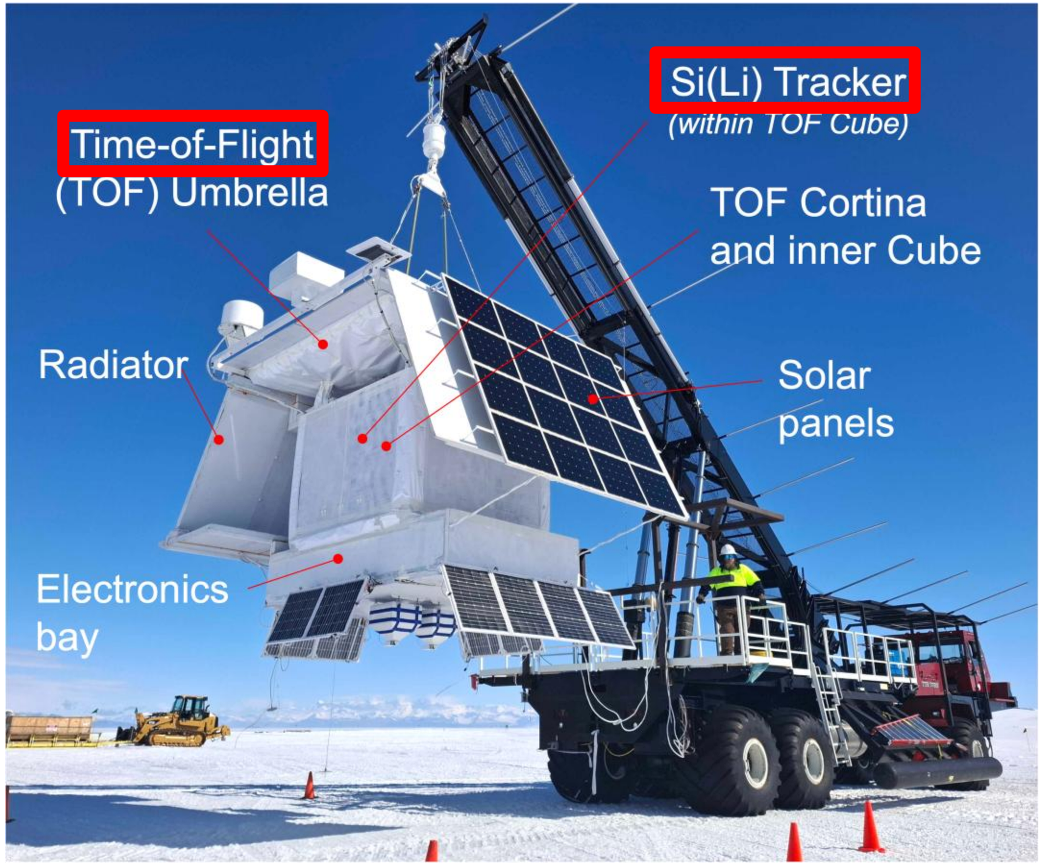
Columbia University
Massachusetts Institute of Technology
UCLA
Northeastern University
University of Hawai'i Mānoa
Oak Ridge National Laboratory
SSL UC Berkeley
NASA
Heising-Simons Foundation
NSF
INFN
agenzia spaziale italiana
JAXA
科研費 KAKENHI
Shinshu University
Università di Roma Tor Vergata
Kanagawa University
Università degli Studi di Napoli Federico II
Tokai
Università degli Studi di Trieste



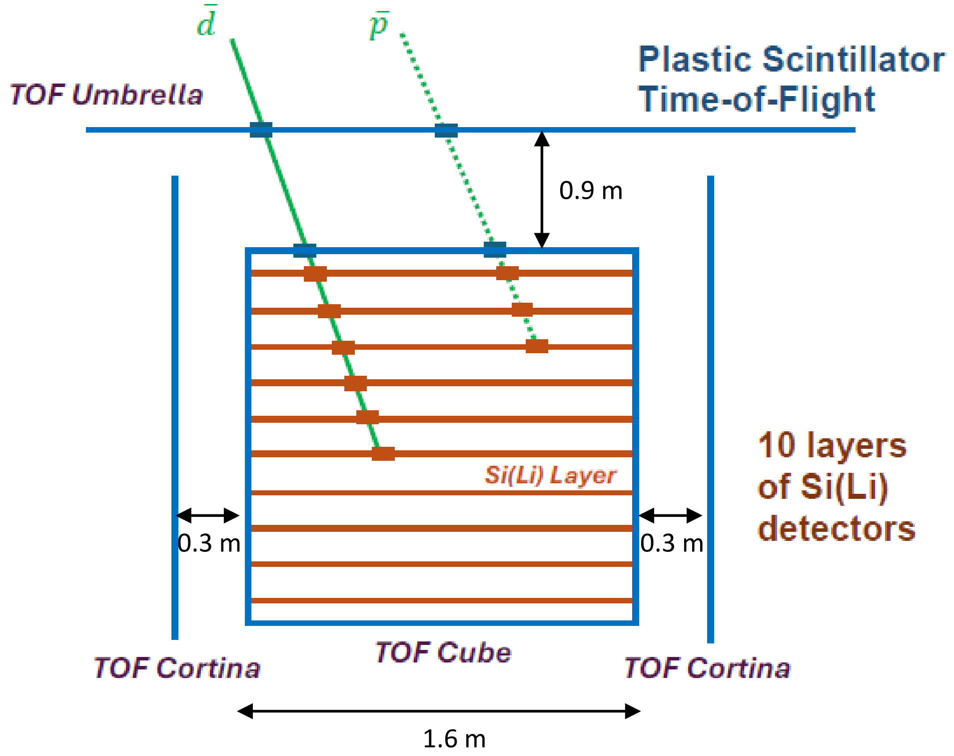
The GAPS mission



- **Antarctic balloon experiment**
  - **Long duration, low geomagnetic cutoff**
  - First flight attempt in summer 2024/2025, postponed due to weather conditions to 2025/2026
  - Two follow-up flights planned
- **Scientific Objectives**
  - Precision **antiproton** measurement in the energy range < 0.25 GeV/n (already with first flight)
  - **Antideuteron** search, with sensitivity 100 × below current best limits → probes wide range of DM models
  - Sensitivity to **antihelium** nuclei



GAPS detection principle



1. Antiparticle slows down and stops in the apparatus

Mass discrimination from range–velocity relation, via multiple dE/dx measurements in Si(Li) detectors and TOF plastic scintillators

Image credit: M.Xiao

GAPS detection principle

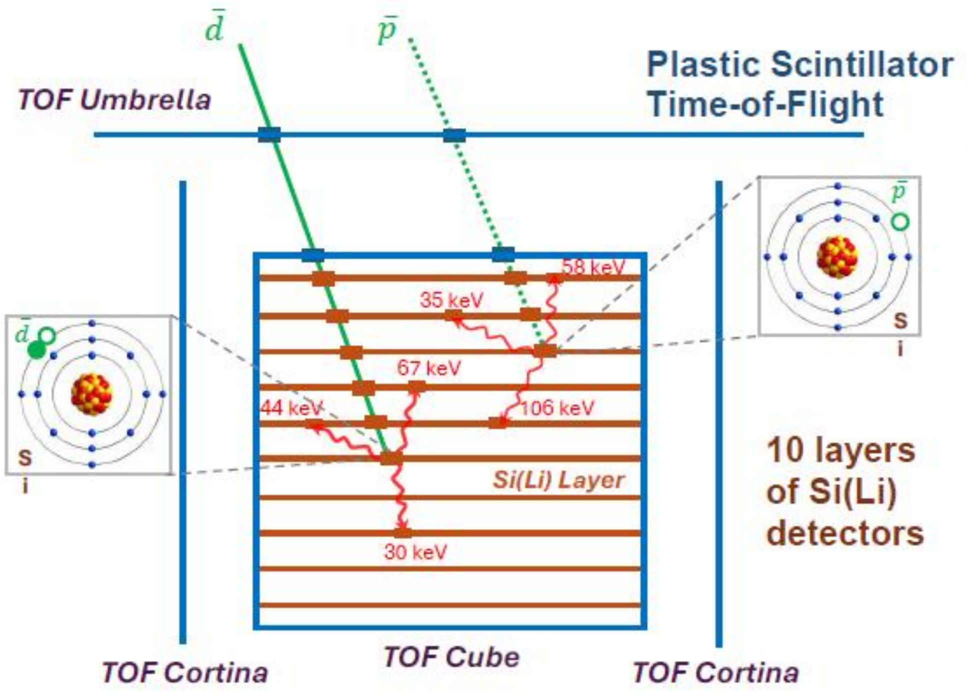
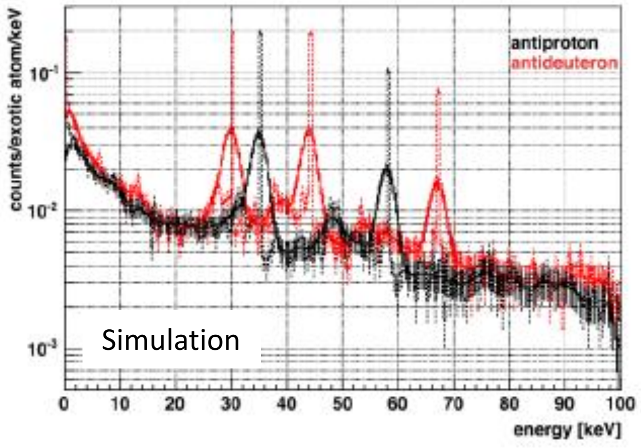


Image credit: M.Xiao

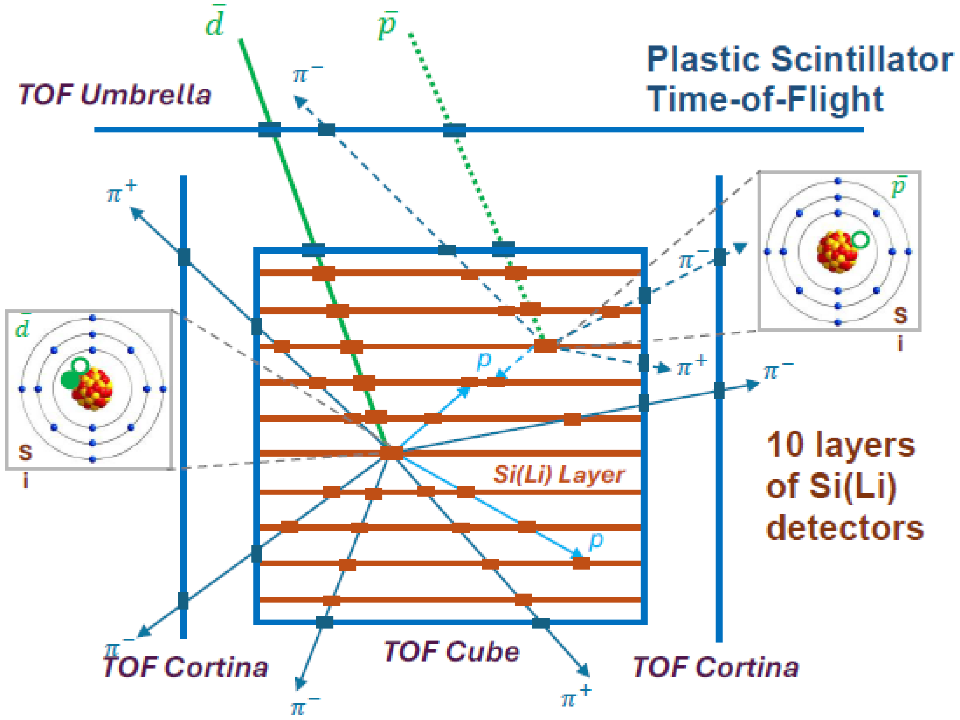
1. Antiparticle slows down and stops in the apparatus
2. Forms hydrogen-like exotic atom
   → emits characteristic X-rays (mass-dependent)



- Si(Li) detectors act as target and X-ray spectrometer

Exotic-atom technique verified at KEK → Aramaki+ Astropart.Phys. 49, 52-62 (2013)

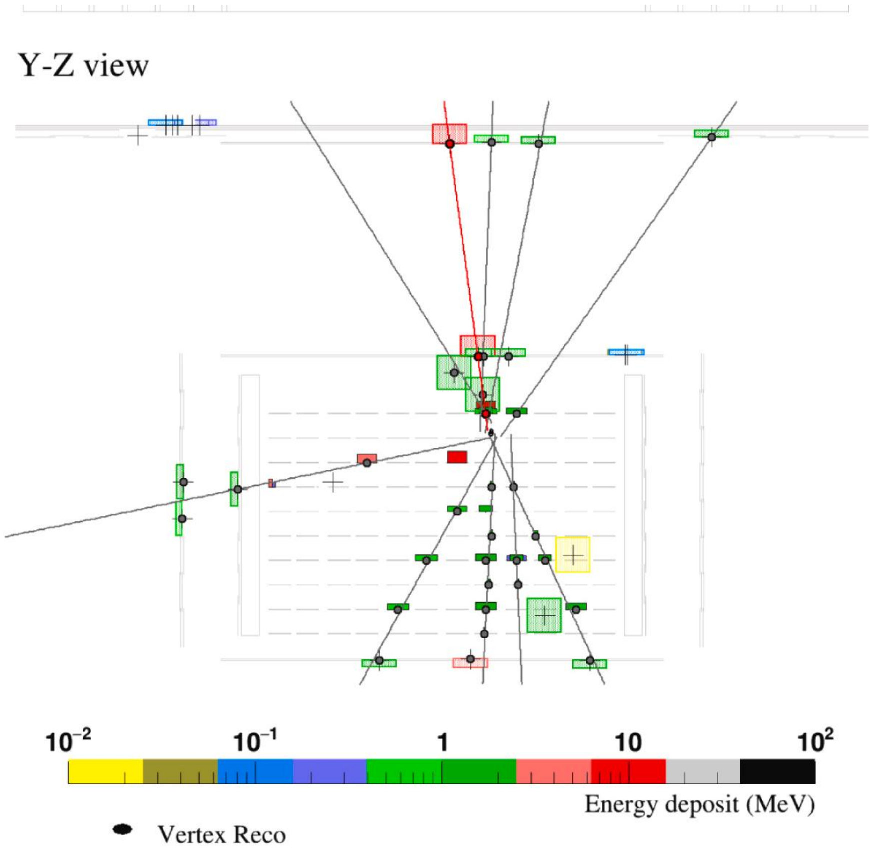
GAPS detection principle



1. Antiparticle slows down and stops in the apparatus
2. Forms hydrogen-like exotic atom → emits characteristic X-rays (mass-dependent)
3. Then undergoes nuclear annihilation → produces characteristic annihilation products (mass-dependent multiplicity)

Tracking of outgoing secondaries with Si(Li) and TOF layers, reconstruction of annihilation vertex

Image credit: M.Xiao



Reconstructed $\overline{D}$

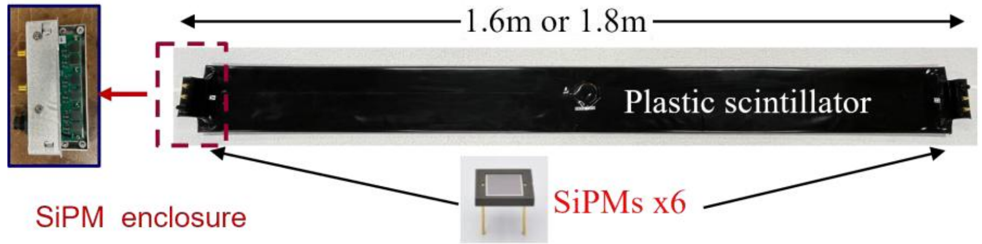
- **Primary track**
- **Secondary tracks**

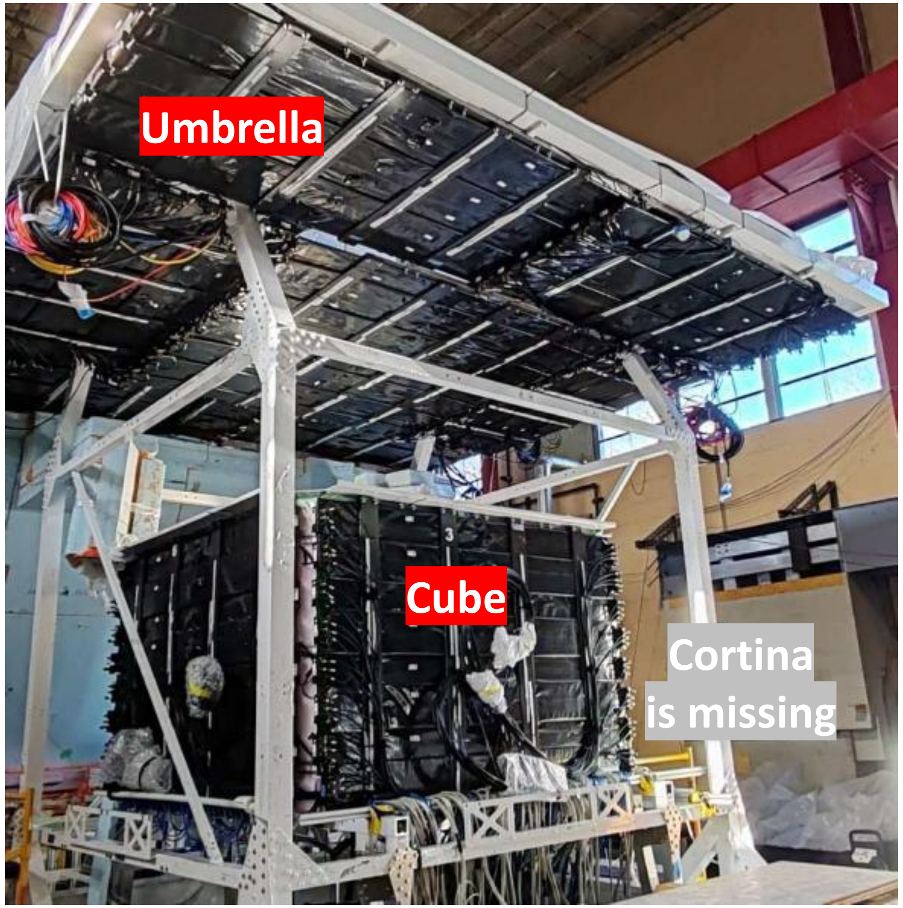
TOF system

Quinn+, PoS 358 (2019) 128

- Tasks
  - **Trigger system** → triggers single + multi-particle events, apply pre-scaling → reduce data rate from a few tens kHz to ~500Hz
  - **Velocity measurement** → < 500 ps timing resolution (end-to-end) required for p/D separation → < 350 ps measured on-ground
  - Measurement of energy deposits dE/dx

- **Plastic scintillators**: Eljen EJ-200: 108-180 cm long, 0.635 cm thick.
- **SiPMs**: Hamamatsu S13360-6050VE
- Fast sampling with DRS4 ASIC





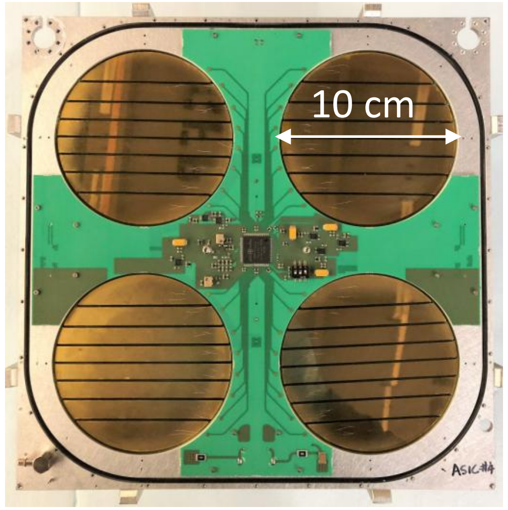
Si(Li) tracker

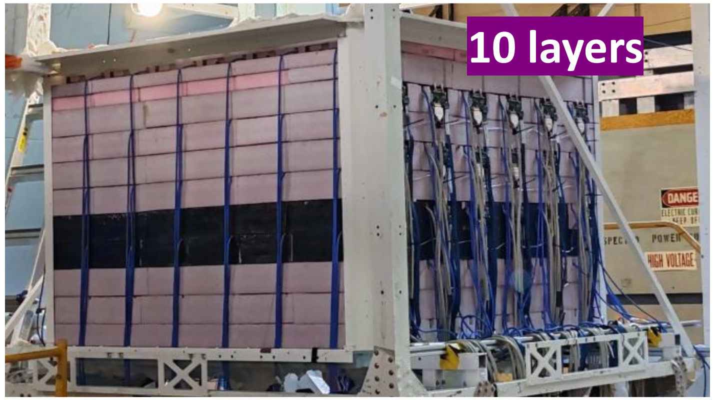
Rogers+ JINST 14 (2019) P10009

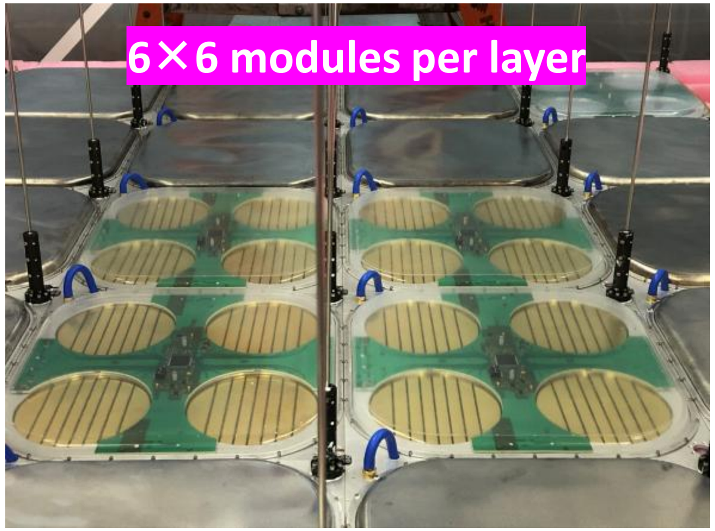
- Tasks
  - **Particle tracking** and multiple dE/dx measurements
  - Acts as target and **X-ray spectrometer**
    - → Large dynamical range (from ~20keV to 100 MeV)
    - → Energy resolution < 4keV

Li-drifted Si detectors

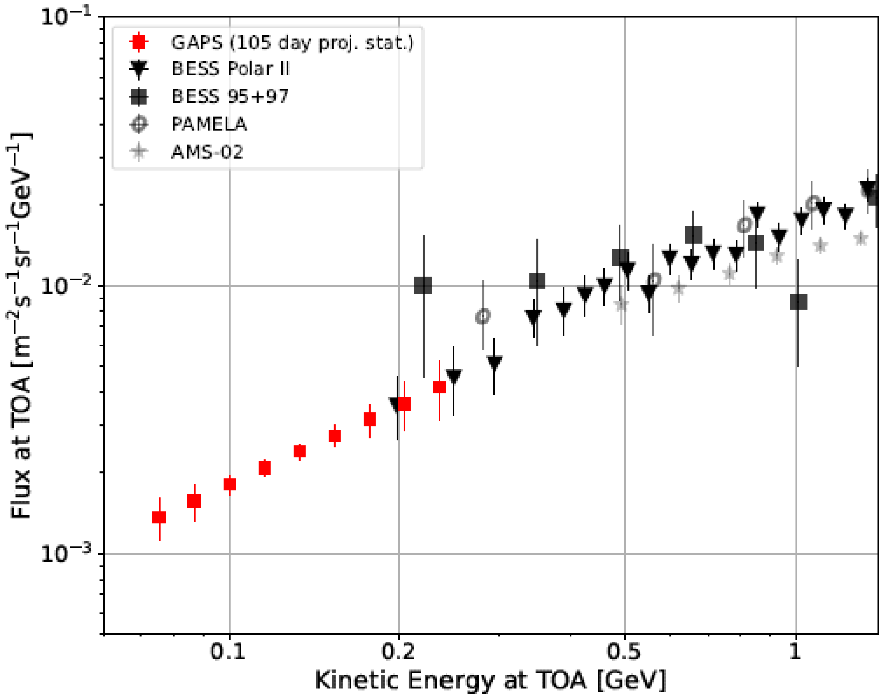
- 2.5 mm thickness, 10 cm in diameter, divided into 8 strips
- Operation temperature –(35÷45)^{o}C → cooling system will use novel OHP approach
- Fully instrumented: 10 layers, 1440 detectors
- First flight: 7 layers, 1008 SiLi detectors
- Custom low-noise readout ASIC with dynamic signal compression







GAPS science → antiproton

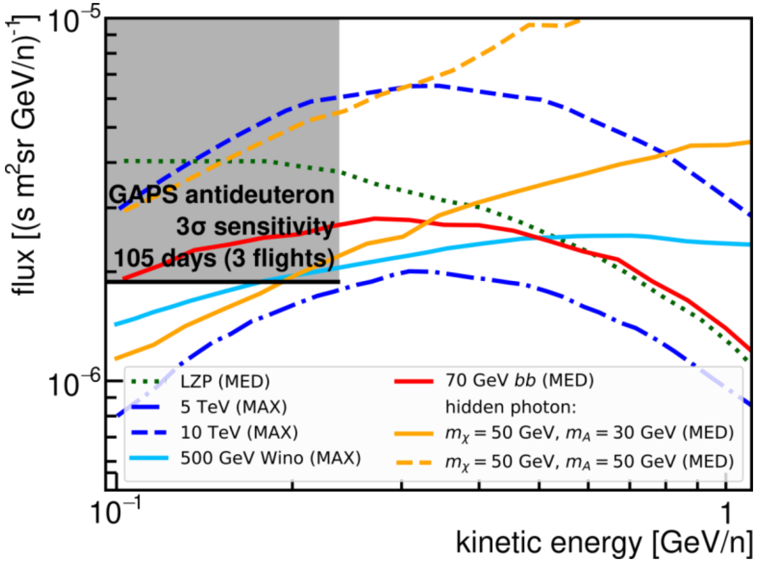


Sensitivity of the GAPS Experiment to Low-energy Cosmic-ray Antiprotons: Rogers+ Astropart.Phys. 145 (2023) 102791

- Will perform precision measurement in the unexplored energy range < 0.25 GeV/n
  - ~ 500 antiprotons expected with the first flight
  - BESS → 29 at ~ 0.2 GeV | PAMELA → 7 at ~ 0.25 GeV | AMS-02 → E > 0.25 GeV
- Science
  - Constrain Galactic cosmic ray propagation and solar modulation
  - Sensitivity to light dark matter and primordial black hole evaporation
  - Constrain antideuteron flux predictions
- Validate anti-nuclei identification technique

GAPS science → antideuteron

- Leading antideuteron sensitivity (3 flights):
  - 100× above expected astrophysical bkg → essentially bkg-free DM signature
  - 100× below current best limits
- Probes wide range of DM models
  - *Consistent with antiproton and γ-ray constraints!*



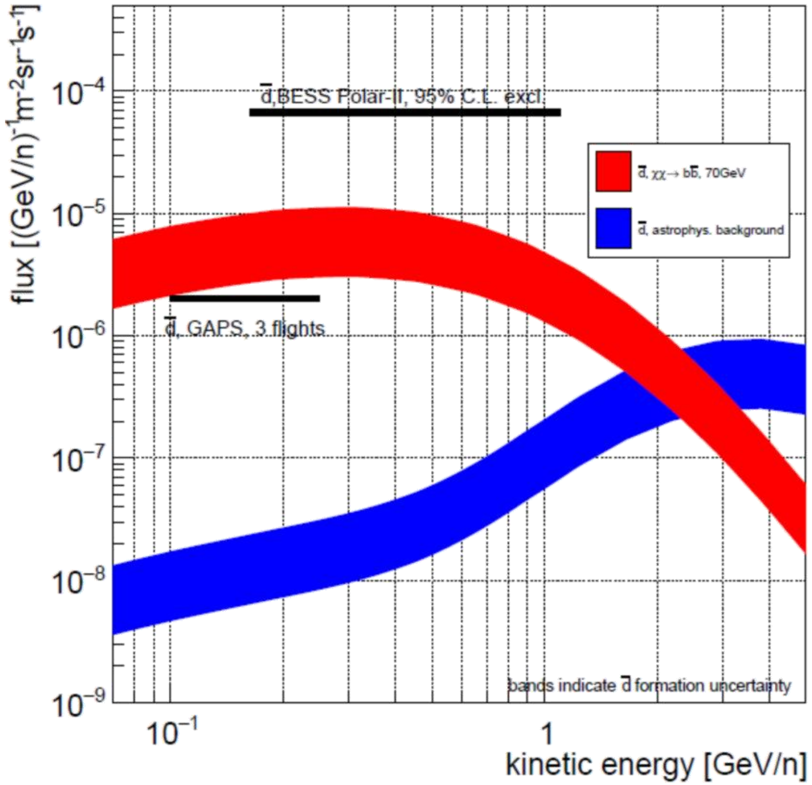
Generic WIMP Korsmeier, Donato, & Fornengo, *Phys. Rev. D* 97 (2018) 103011

LZP Cui, Mason & Randall, *JHEP* 017 (2010) 1011.

Heavy WIMP Brauninger, & Cirelli, *Phys. Lett. B* 678 (2009) 20–31.

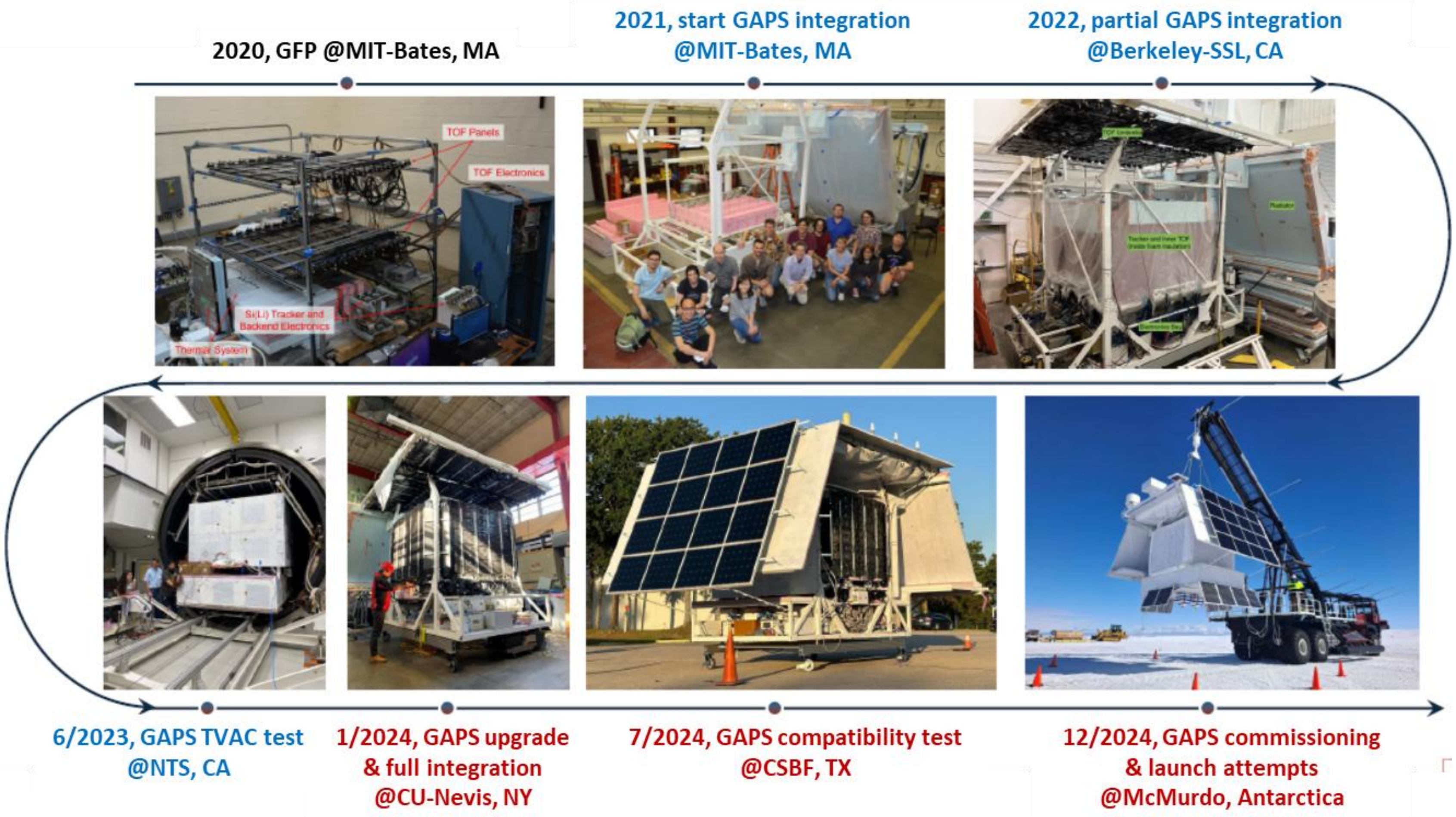
Wino Hryczuk, Cholis, Iengo, Tavakoli and Ullio, *JCAP* 1407 (2014) 031.

Hidden photon Randall & Xu, *JHEP* 81 (2020) 2020.



Antideuteron Sensitivity for the GAPS Experiment
Aramaki+ Astropart.Phys. 74 (2016) 6-13

GAPS integration timeline

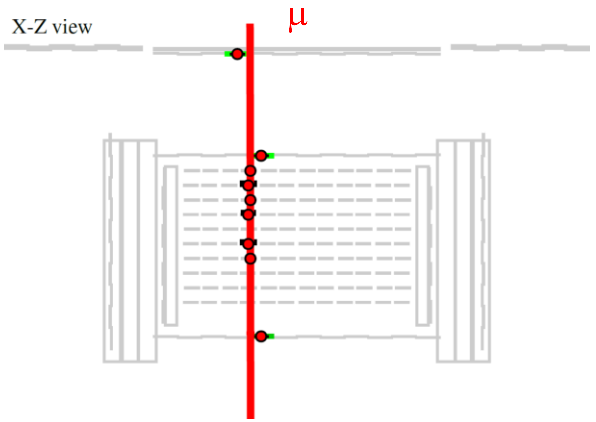


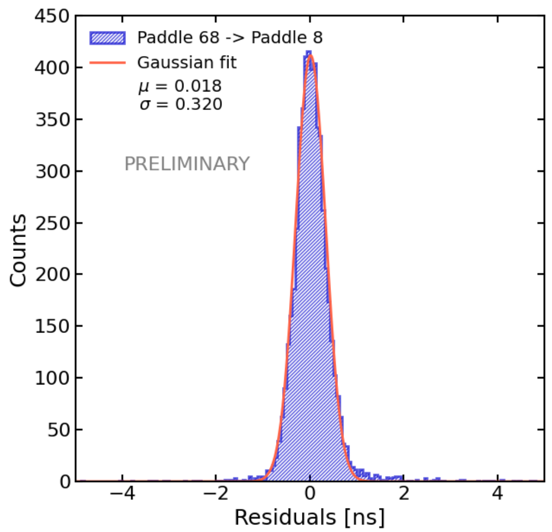
GFP = GAPS Functional Prototype

Courtesy of: M.Xiao

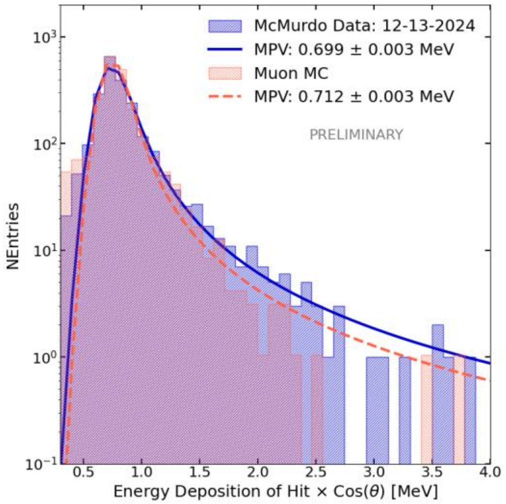
Ground data taking

- ~10M events (mostly muons) collected during on-ground test
  - Stable operations with tuned trigger at 450-500 Hz (single + multi track triggers, pre-scaled)
  - Clean sample of single straight tracks to test/validate detector performance and energy calibration





- TOF timing resolution

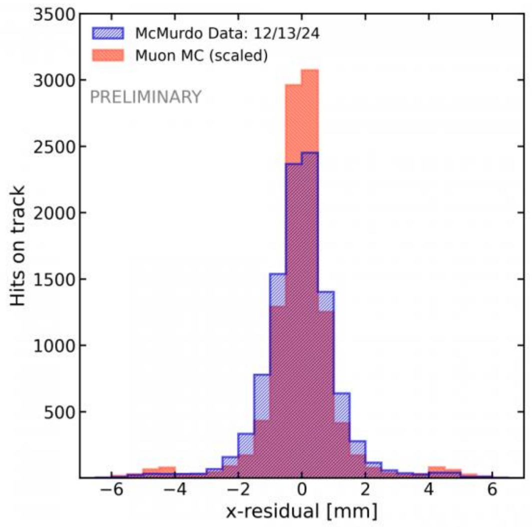


- Energy depositions in Si(Li) strips along the track

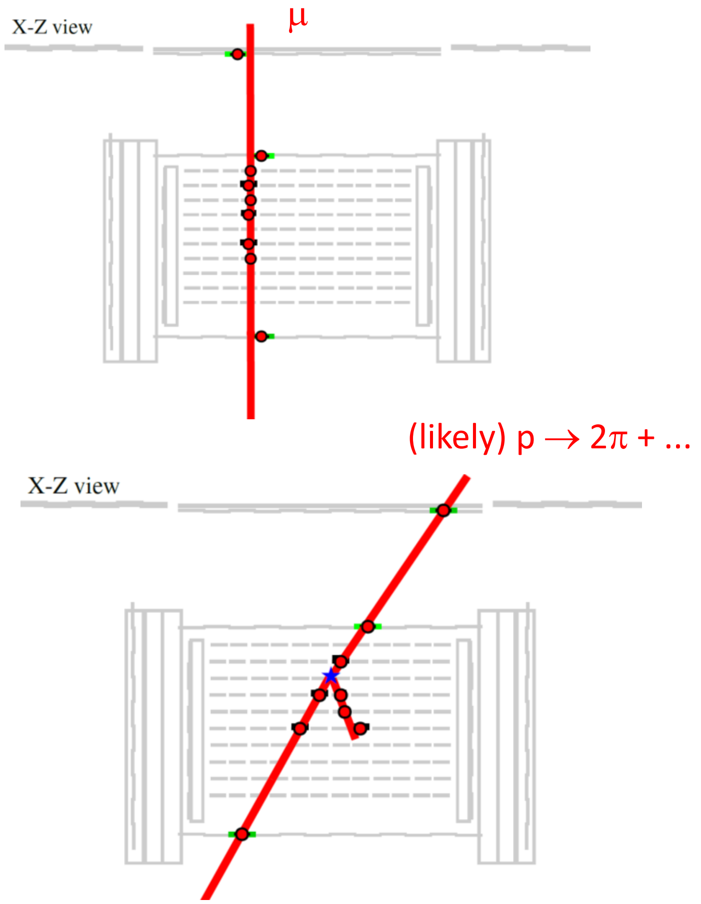
Ground data taking

- ~10M events (mostly muons) collected during on-ground test
  - Stable operations with tuned trigger at 450-500 Hz (single + multi track triggers, pre-scaled)
  - Clean sample of single straight tracks to test/validate detector performance and energy calibration
  - Test track reconstruction with single and multi-track event
    - detector alignment
    - tracking efficiency
    - vertex reconstruction

→ on-going analysis



- Tracker spatial residuals

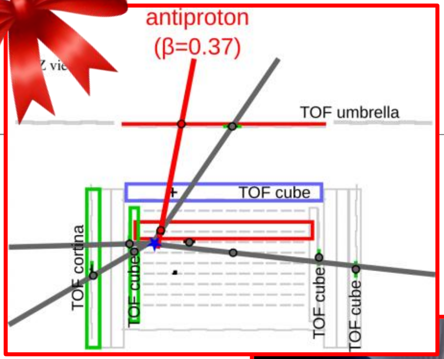


Conclusions

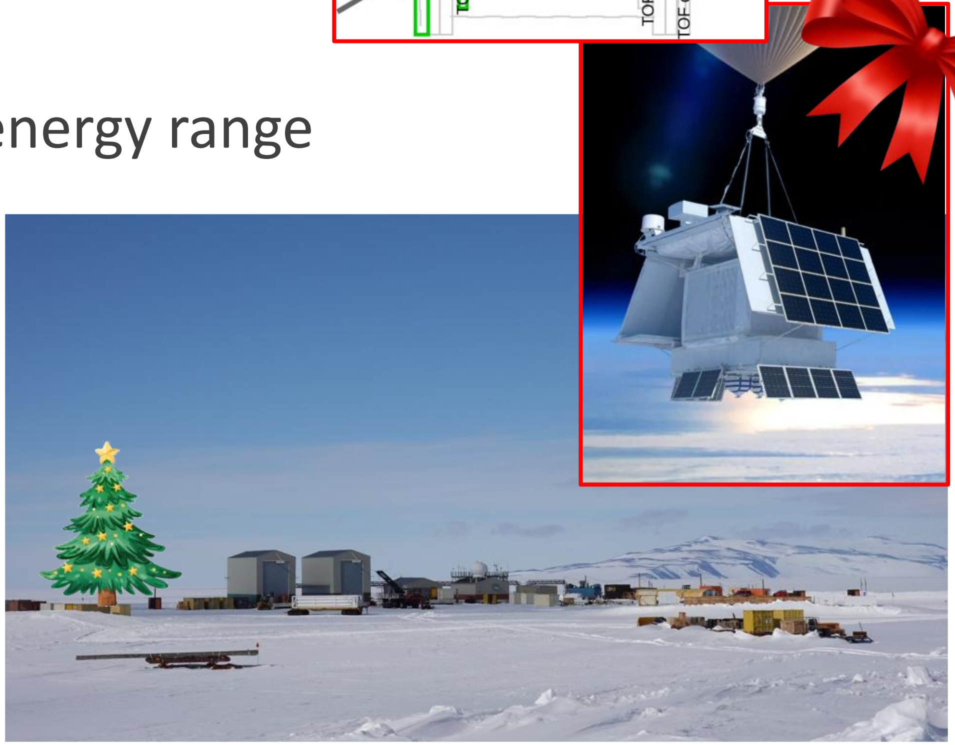
- Low-energy cosmic antinuclei are unexplored and unique for new physics searches (e.g. DM)
- GAPS aims to achieve:
  - precision $\bar{p}$ measurement in an unexplored energy range
  - unprecedented $\bar{D}$ sensitivity
  - leading sensitivity to low-energy $\overline{He}$
- Ready for next Antarctic campaign!!
  - start mid November 2025
  - flight readiness in early December 2025
  - launch within the first half of December

Conclusions

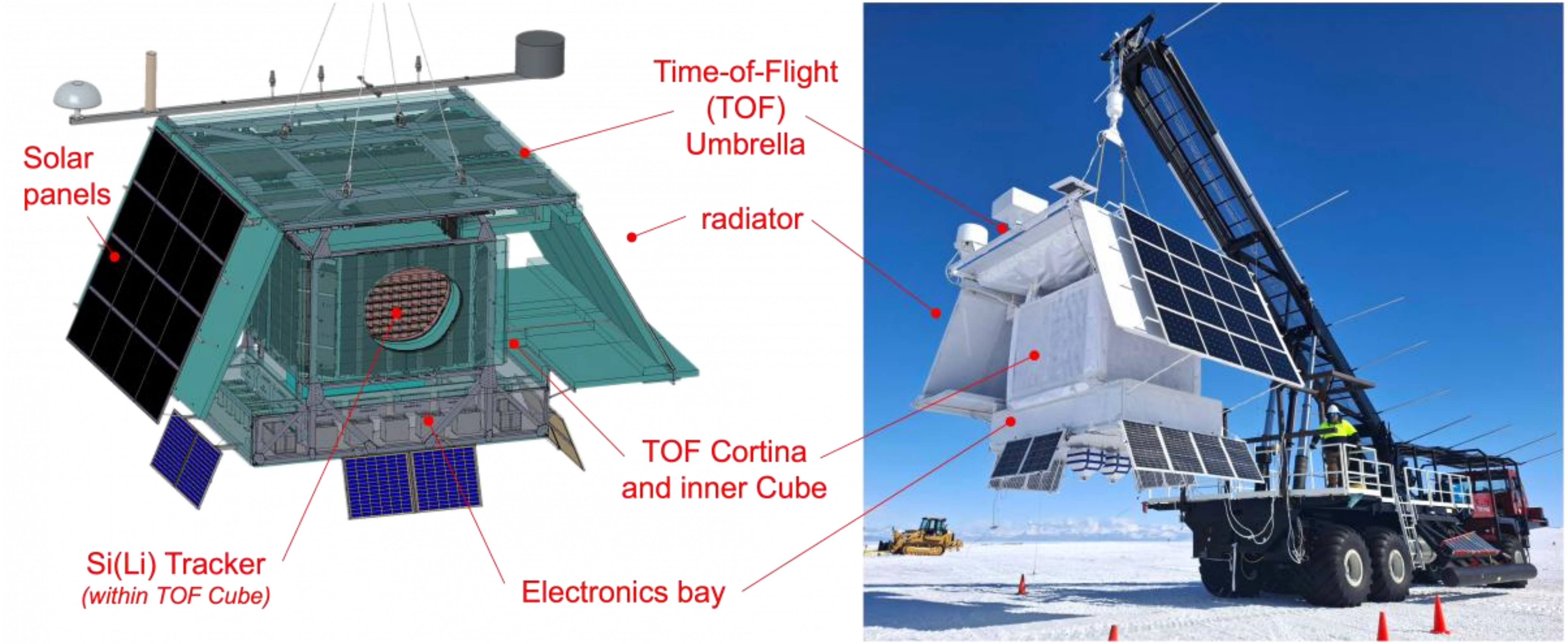
- Low-energy cosmic antinuclei are unexplored and unique for new physics searches (e.g. DM)
- GAPS aims to achieve:
  - precision $\bar{p}$ measurement in an unexplored energy range
  - unprecedented $\overline{D}$ sensitivity
  - leading sensitivity to low-energy $\overline{He}$

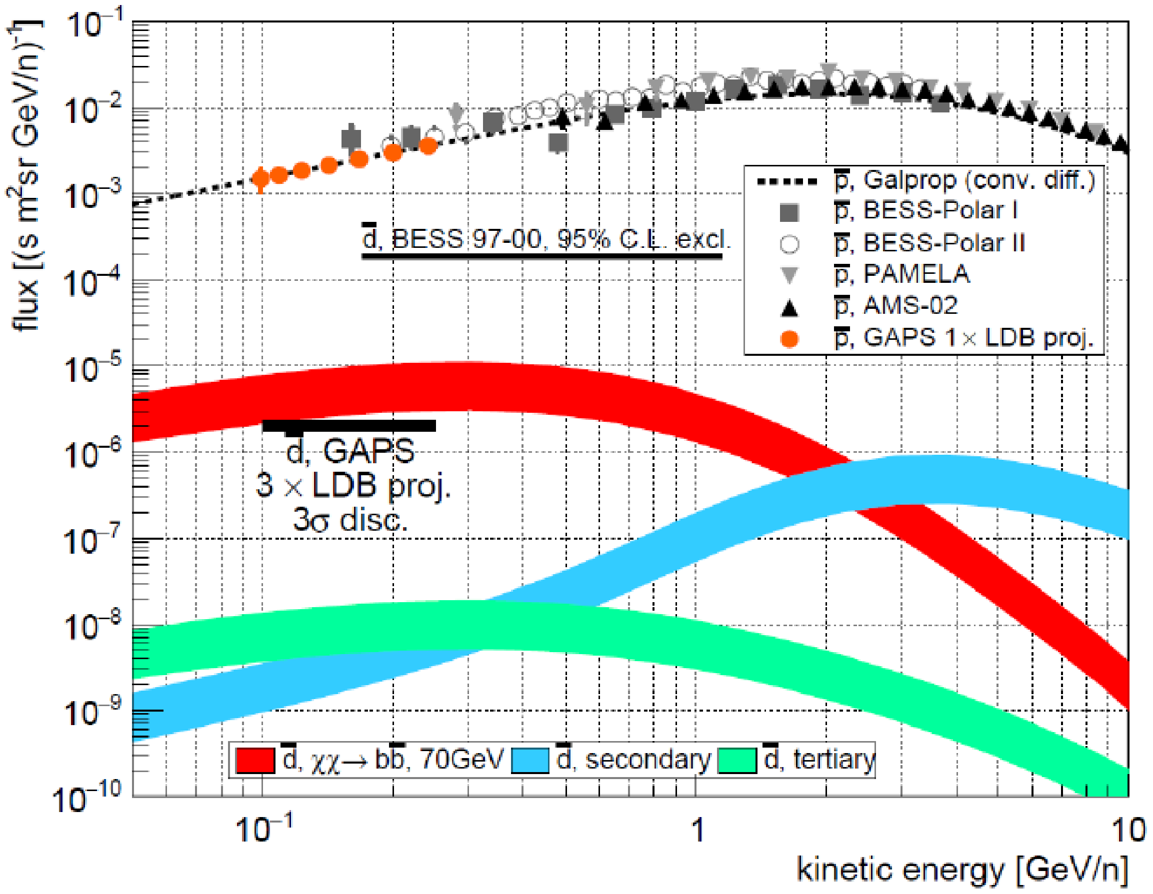


- Ready for next Antarctic campaign!!
  - start mid November 2025
  - flight readiness in early December 2025
  - launch within the first half of December

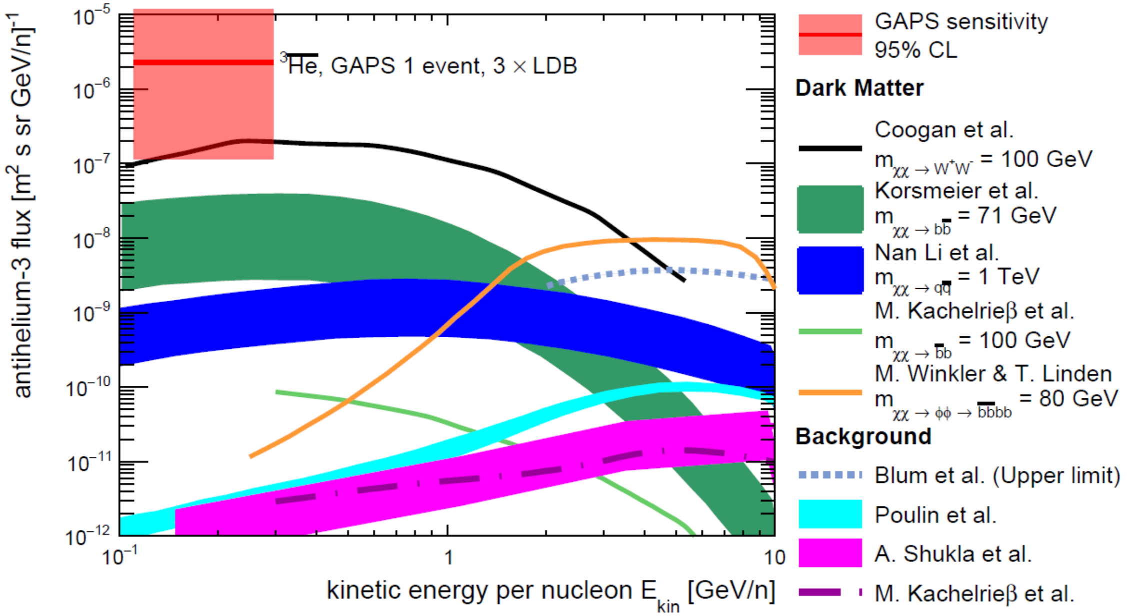


Spares


Time-of-Flight
(TOF)
Umbrella
Solar
panels
radiator
TOF Cortina
and inner Cube
Si(Li) Tracker
(within TOF Cube)
Electronics bay


flux [(s m^{2}sr GeV/n)$^{-1}$]
kinetic energy [GeV/n]
$\bar{p}$, Galprop (conv. diff.)
$\bar{p}$, BESS-Polar I
$\bar{p}$, BESS-Polar II
$\bar{p}$, PAMELA
$\bar{p}$, AMS-02
$\bar{p}$, GAPS 1 × LDB proj.
$\bar{d}$, BESS 97-00, 95% C.L. excl.
$\bar{d}$, GAPS
3 × LDB proj.
3σ disc.
$\bar{d}$, $\chi\chi \rightarrow b\bar{b}$, 70GeV
$\bar{d}$, secondary
$\bar{d}$, tertiary

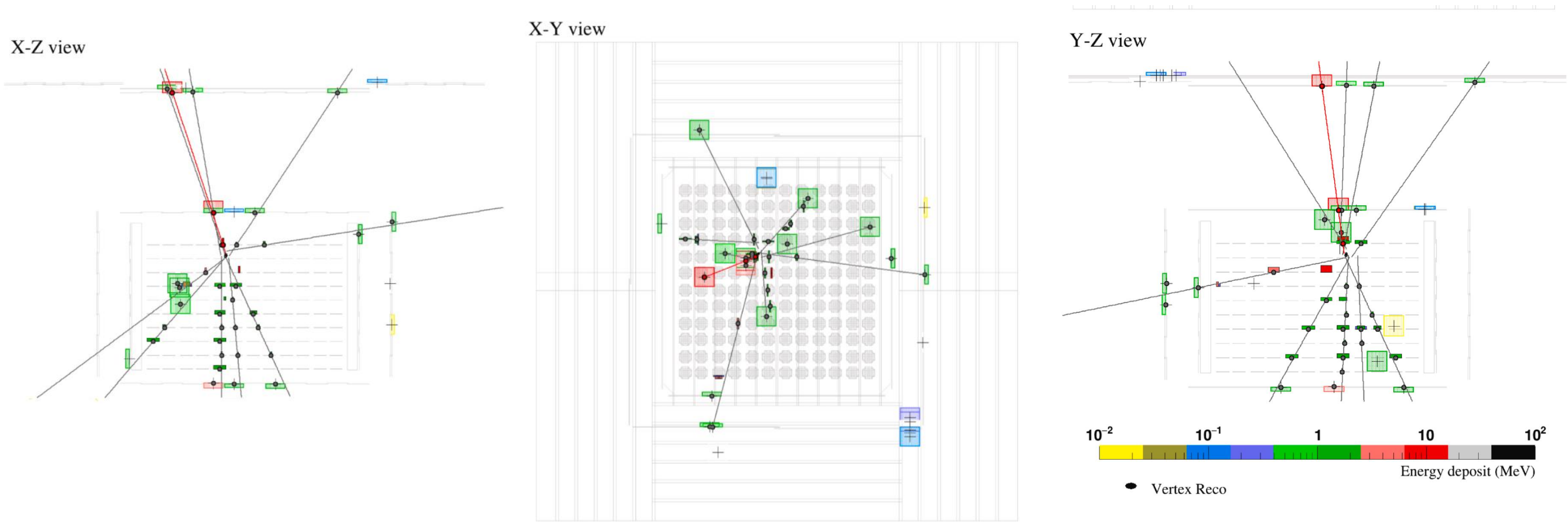
GAPS science → antihelium



Cosmic antihelium-3 nuclei sensitivity of the GAPS experiment: Saffold+ Astropart.Phys. 130 (2021) 102580 Stoessl+ ICRC2021

- Sensitivity to low-energy $\overline{^3He}$
  - $\overline{^3He}$ flux $\sim 100 \div 1000 \times$ below $\overline{D}$ flux
  - An observation of $\overline{^3He}$ would be a clear indication of new physics

- GAPS search
  - complementary to AMS-02
  - extends to lower energies (0.11÷0.3 GeV/n)
    → capable of confirming possible signal
  - Orthogonal detection technique → uniquely low bkg



X-Z view
X-Y view
Y-Z view
10^{-2}
10^{-1}
1
10
10^{2}
Energy deposit (MeV)
Vertex Reco

Muon data taking