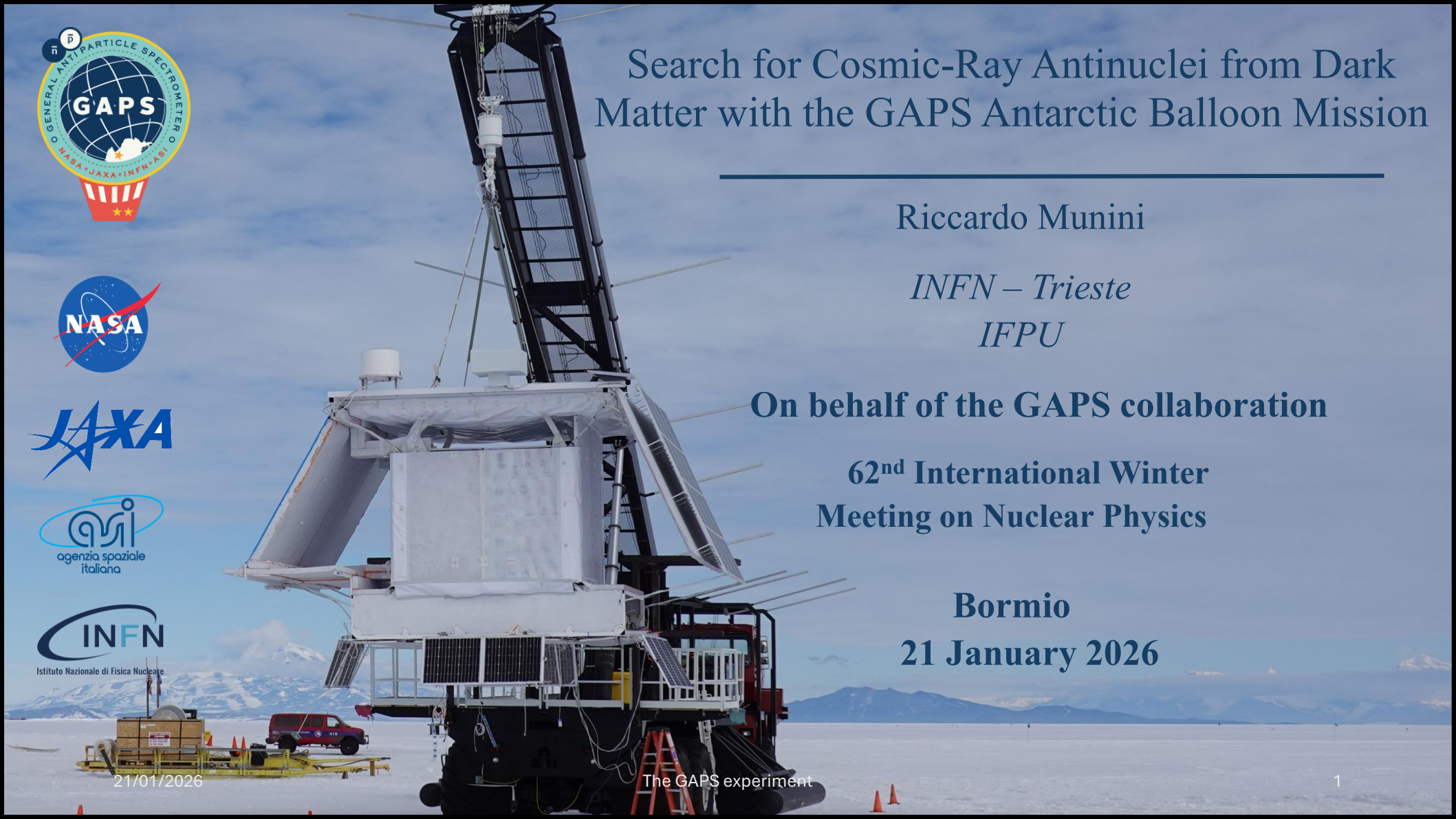


Search for Cosmic-Ray Antinuclei from Dark Matter with the GAPS Antarctic Balloon Mission

Riccardo Munini

INFN – Trieste

IFPU

On behalf of the GAPS collaboration

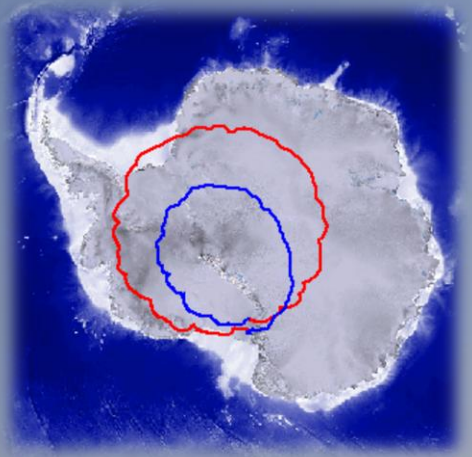
62nd International Winter Meeting on Nuclear Physics

Bormio

21 January 2026

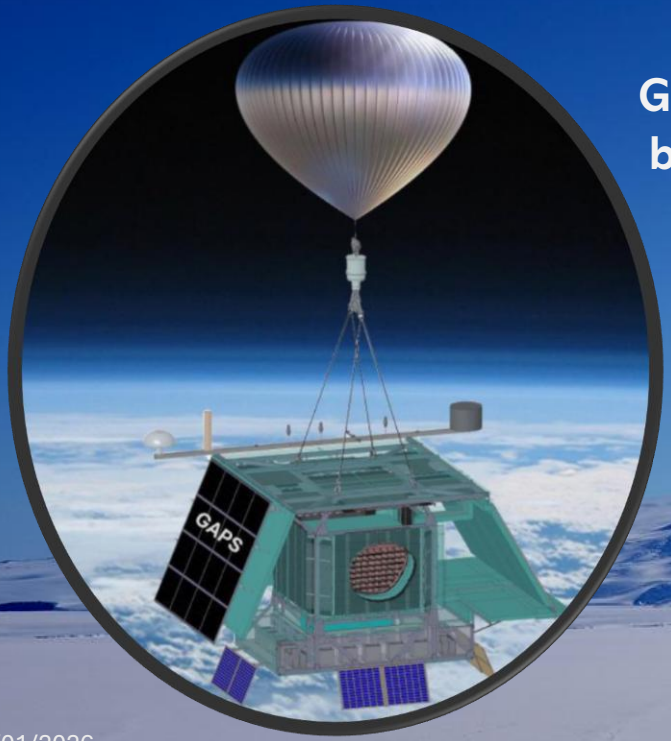
GAPS was successfully launched from McMurdo Station on December 16, 2025!

The flight lasted 25 days, until January 8, 2026.



GAPS experiment and collaboration

General AntiParticle Spectrometer: ballon born experiment for low energy antinucleus in cosmic rays

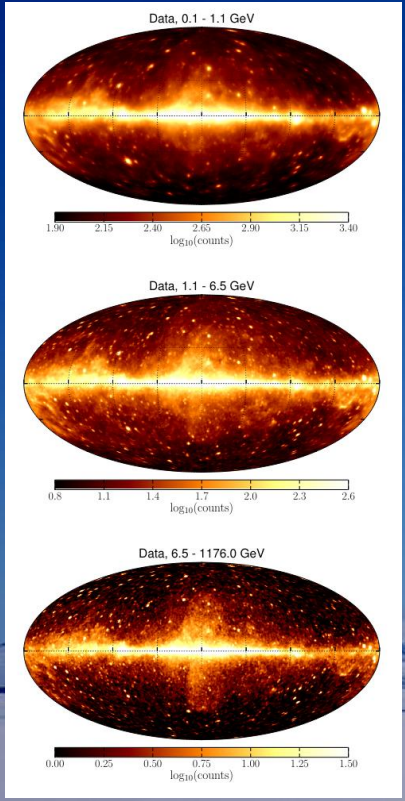


Goal: 3 long duration balloon flights (~ 30 days each) from Antarctica

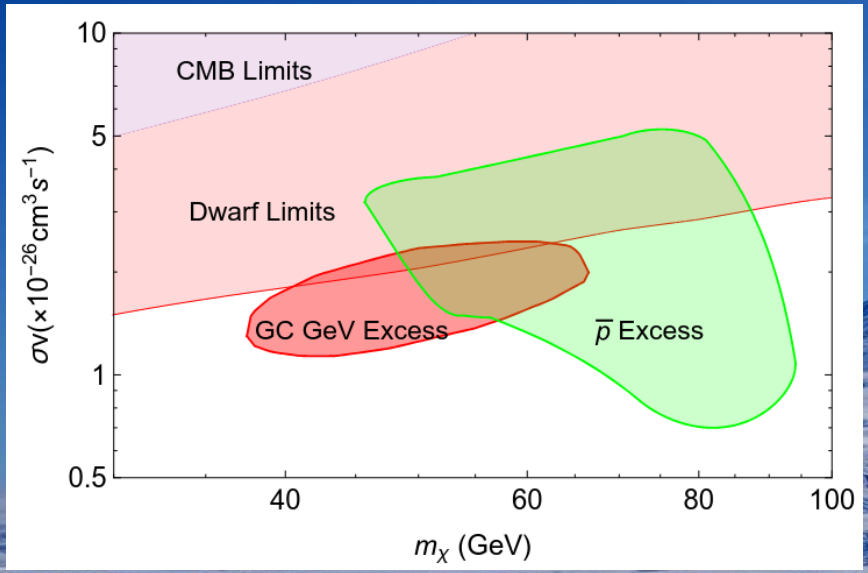
~ 50 people

Interesting but ambiguous excesses in Astrophysics

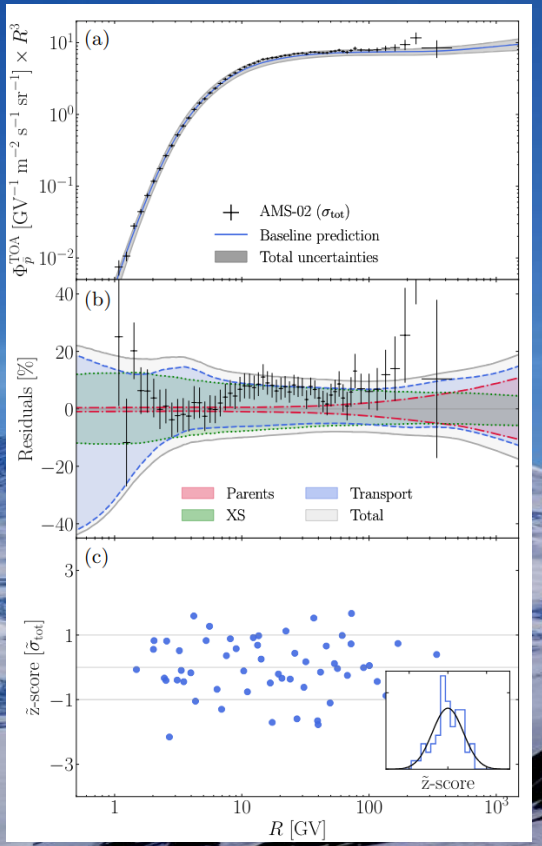
Fermi Galactic Center GeV Excess



Some Dark Matter Models Compatible with Both Excesses!



AMS Antiproton Excess

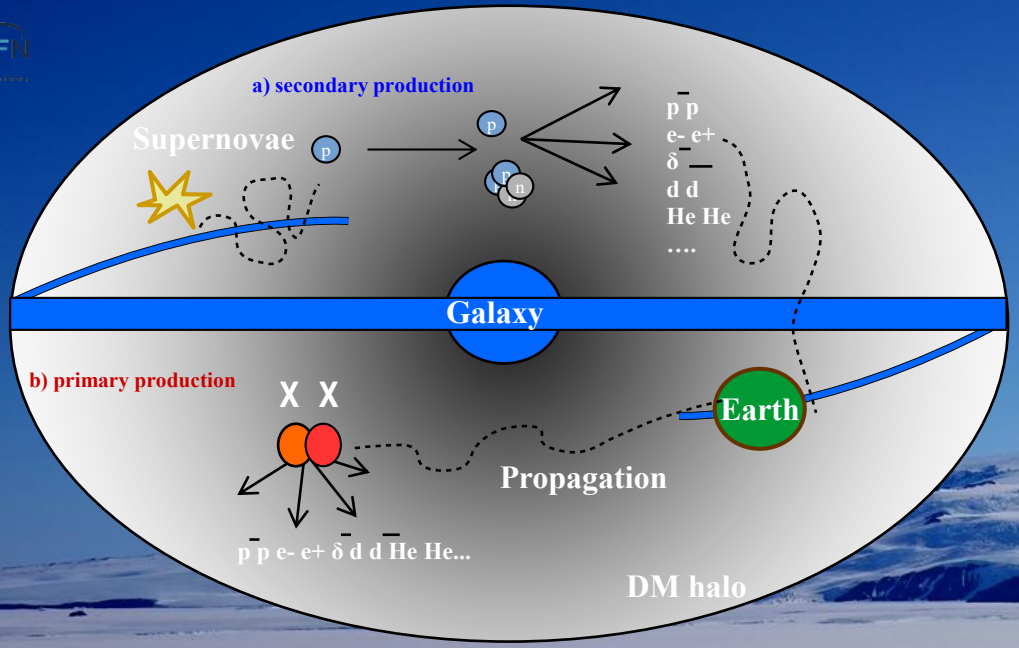


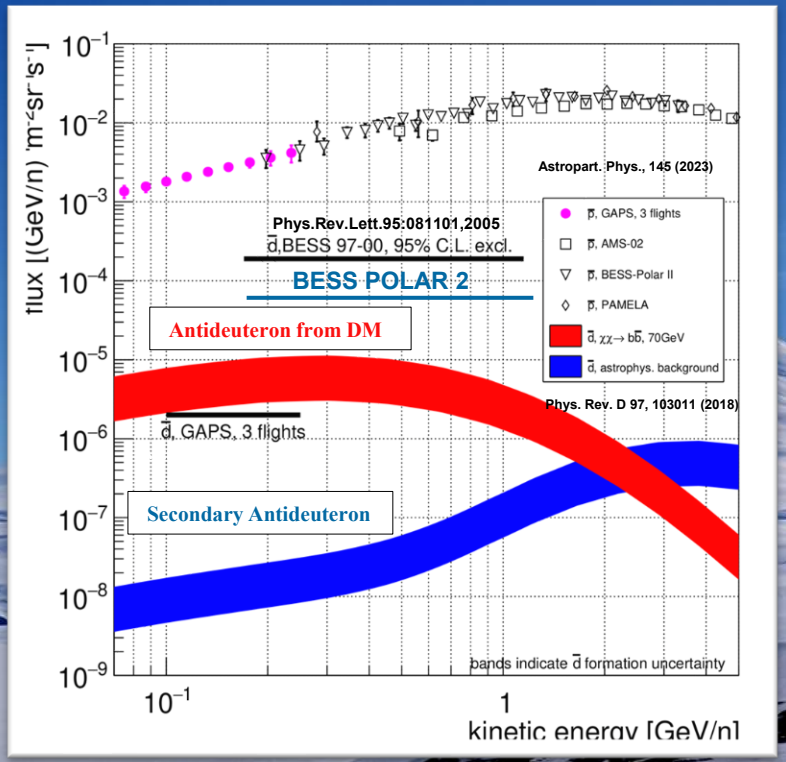
M. Ackermann+ The Astrophys. J. (2017)
D. Hooper+ Phys. Rev. D 99 (2019)
M. Boudaud+ Phys. Rev. Research 2 (2020)

GAPS: antinuclei and dark matter

Dark matter decay/annihilation in the Galaxy → antiprotons, antideuterons, antihelium nuclei

$\overline{D}$ and $\overline{He}$ nuclei < 250 MeV has an astrophysical background orders of magnitude < than signal expected from dark matter decay/annihilation

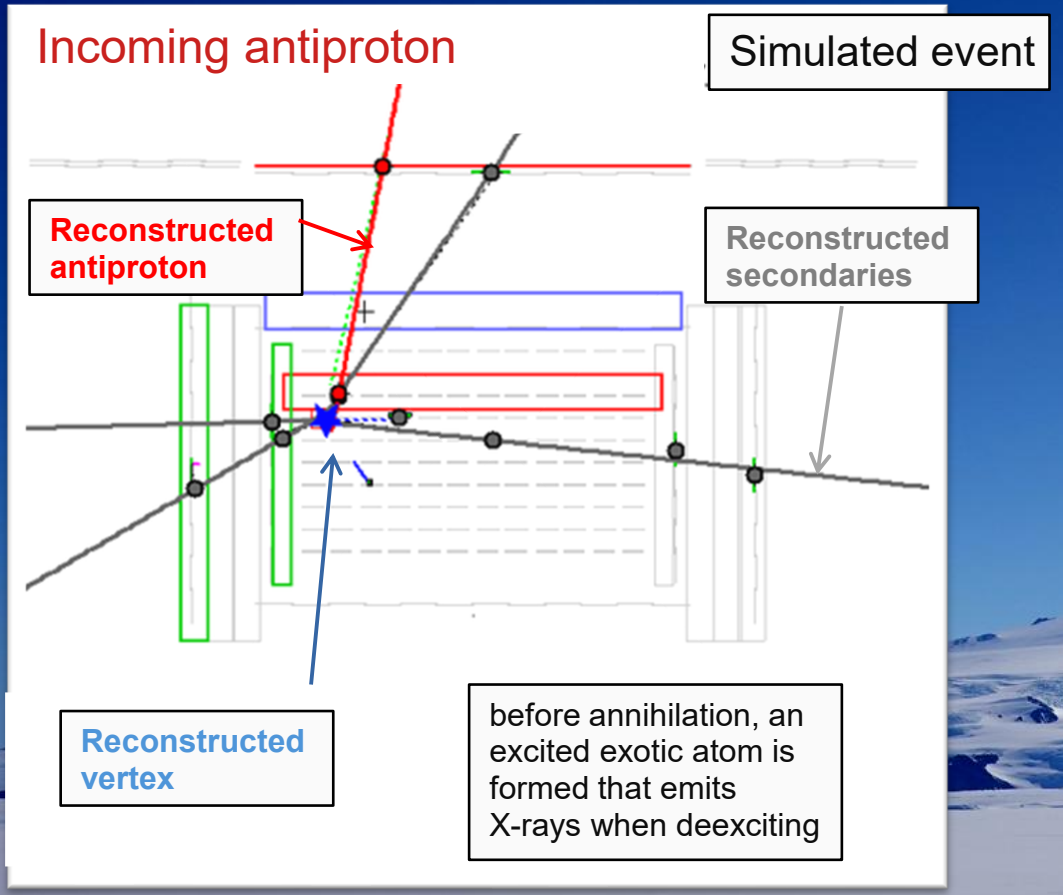




The GAPS detector

Mass: ~2.500 kg
Power: 1.3 kW

GAPS detection principle



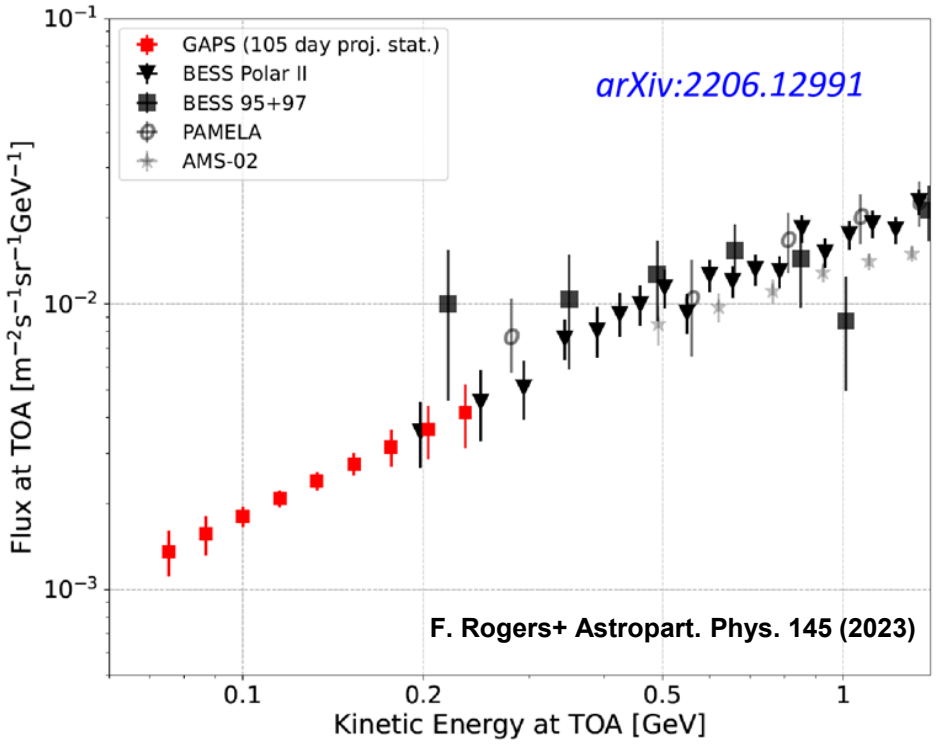
Detection technique

- Antiparticle **slows down,** stops and forms an **excited exotic atom**. **Complementary to magnetic spectrometer.**
- Hydrogen-like exotic atom **deexcites** via characteristic X-ray transitions depending on antiparticle mass
- **Nuclear annihilation** with characteristic number of annihilation products

GAPS will provide

- 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 1**antihelium** nuclei

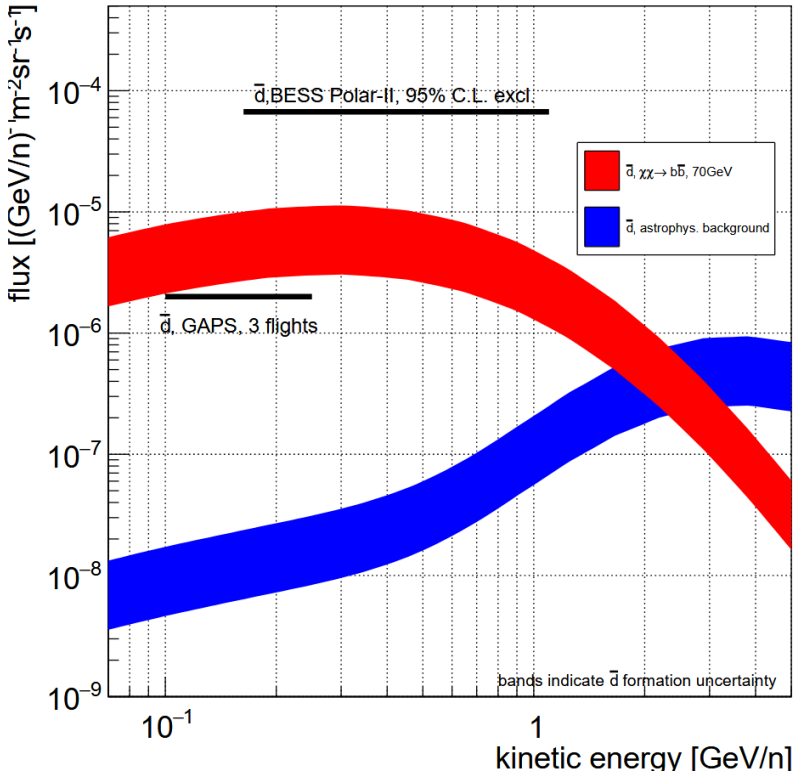
Antiprotons



$\bar{p}$

- Precision measurements of **antiproton** spectrum in an **unexplored energy range** (<250 MeV/n)
- ~**500** 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

Antideuterons



$\bar{d}$

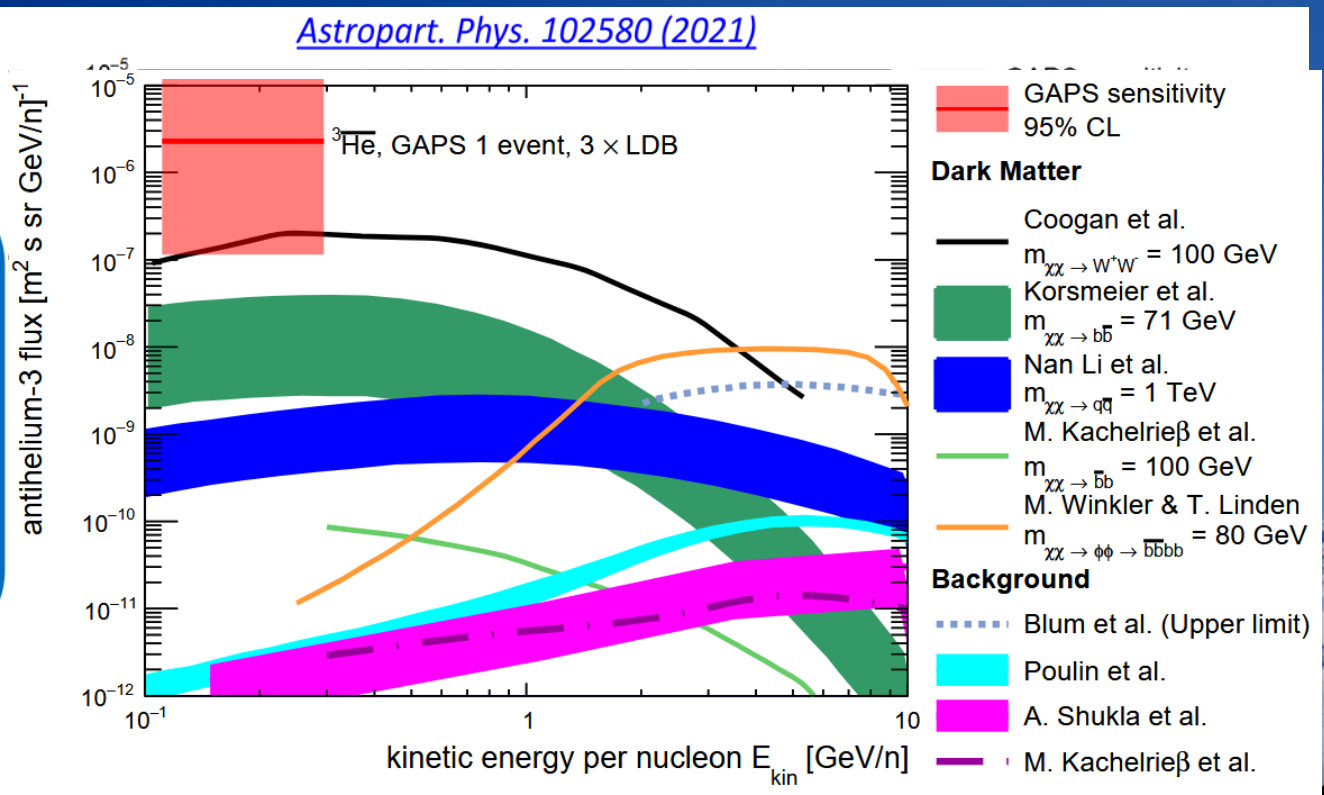
- Predicted **antideuteron** signal from DM annihilation or decay ~ 2 orders of magnitude above astrophysical background below 250 MeV/n
- An essentially **background-free** DM signature
- GAPS sensitivity will be up to 2 orders of magnitude below the BESS limit

P. von Doetinchem+ JCAP 08 (2020)
H. Baer and S. Profumo, JCAP 12 (2005)
Y. Cui+ JHEP 017 (2010)
N. Fornengo+ JCAP 09 (2013)
D. Cerdeño+ JCAP 08 (2014)
M. Korsmeier+ Phys. Rev. D 97 (2018)
L. Dal and A. Raklev, Phys. Rev. D 89 (2014)
L. Randall and W. Xu, JHEP 81 (2020)
M. Mauro+ arXiv:2504.07172 (2025)
V. Romeri+ Phys. Rev. D 112 (2025)
T. Aramaki+, Astropart. Phys. 74 (2016)

Antihelium

$^3\overline{He}$

- GAPS will be sensitive to $^3\overline{He}$
- $^3\overline{He}$ flux ~ 2-3 orders of magnitude below $\bar{d}$ 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)**

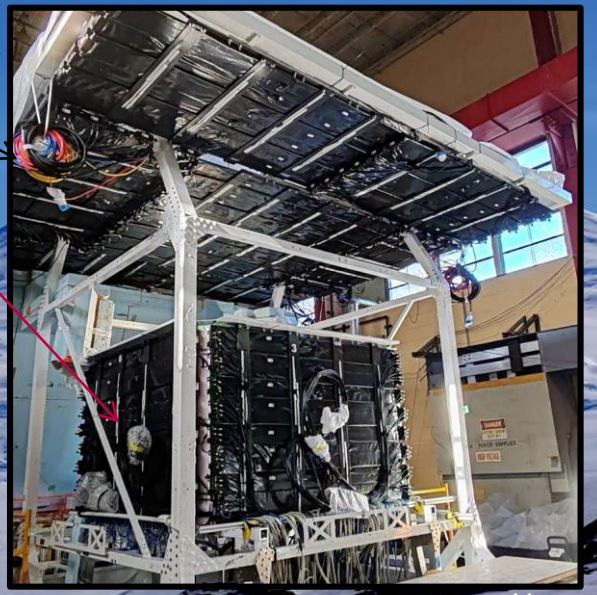


Time of Flight system

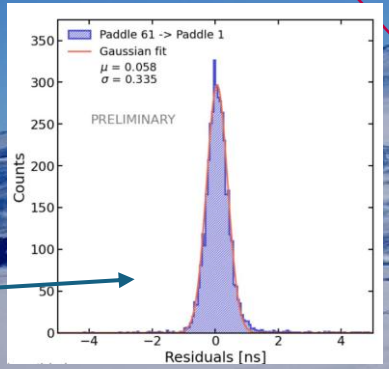
Plastic scintillator (x 160)

SiPms (6 at each end)

Umbrella



Inner Cube



Tasks:
Main trigger system, reduce data rate from few tens kHz → 500Hz. Velocity measurement, energy losses.

Plastic scintillator: Eljen EJ-200: 108-180 cm long, 0.635 cm thick.

SiPM: Hamamatsu S13360-6050VE

Fast sampling with DRS4 ASIC: < 350 ps **timing resolution** end-to-end/√2 timing has been demonstrated in the lab and in Antarctica.

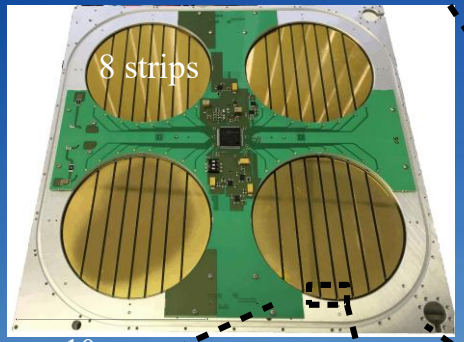
GAPS tracker

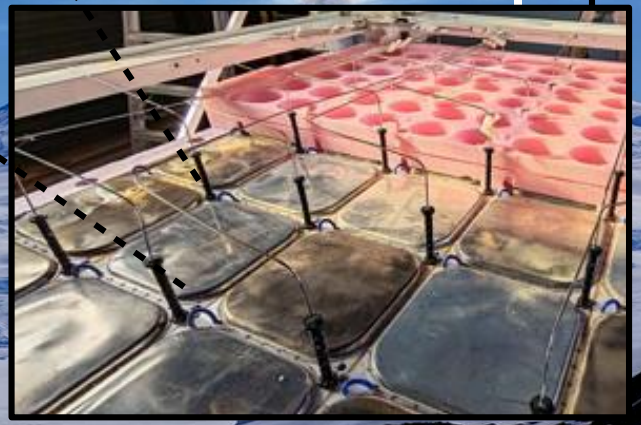
Tracker acts as target and tracking device

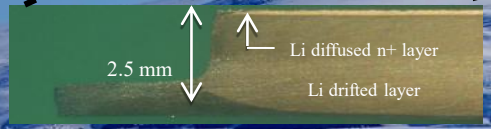
Lithium-drifted Silicon

- 7 planes of cylindrical Si(Li) detectors, 2.5 mm thickness and 10 cm in diameter
- Operation at relatively high temp of -35C to -45C, cooling system will use novel OHP approach
- 1009 SiLi detectors (fully equipped 1440)
- Large dynamical range (~20keV→100 MeV)
- <4 keV FWHM (at ~60 keV) at -37C

6x6 module each plane





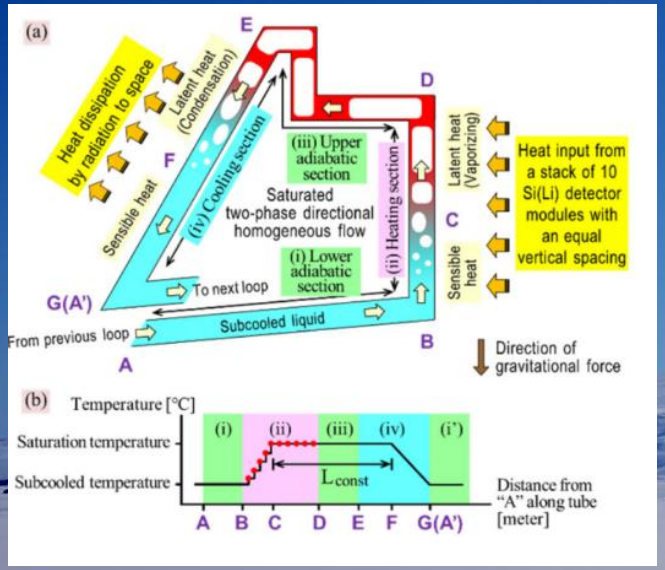


Li ions compensate impurities in boron-doped Si, creating extended thick depleted layer

Publications:
Perez et al., NIM A 905, 12 (2018)
Kozai et al., NIM A 947, 162695 (2019)
Rogers et al., JINST 14, P10009 (2019)
Saffold et al., NIM A 997, 165015 (2021)

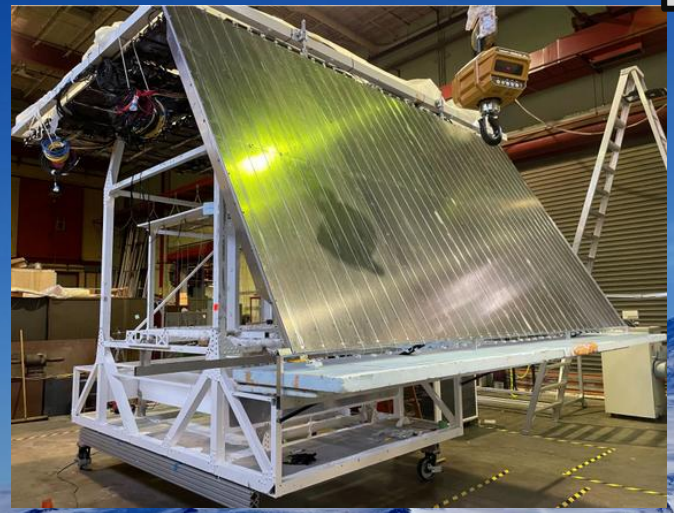
GAPS thermal subsistem

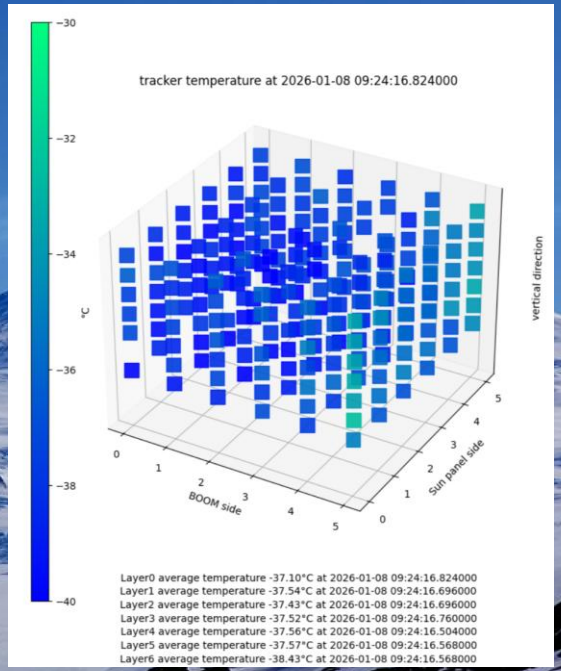
Small capillary metal tubes filled with a phase-changing refrigeration liquid
Vapor bubbles form in the fluid → expand in warm and contract in cool sections: no active pump system is required.



Passive cooling approach developed at JAXA/ISAS:

Achieved in-flight tracker cooling goal of ~-35 - -40 C!





S. Okazaki et al., J. Astr.. Instr. 3 (2014)

Shipment to Antartica

- ToF and electronics shipped to NZ by sea.
- Tracker shipped with airplane to NZ.
- From NZ all shipped with plane to McMurdo

Antarctic Campaigns

- ❑ Early November 2024 -> mid January 2025
- ❑ Early November 2025 -> now (recovery)
- ❑ 19 GAPS member in total
- ❑ Full instrument integration + instrument and electronics performance test + launch

GAPS integration building

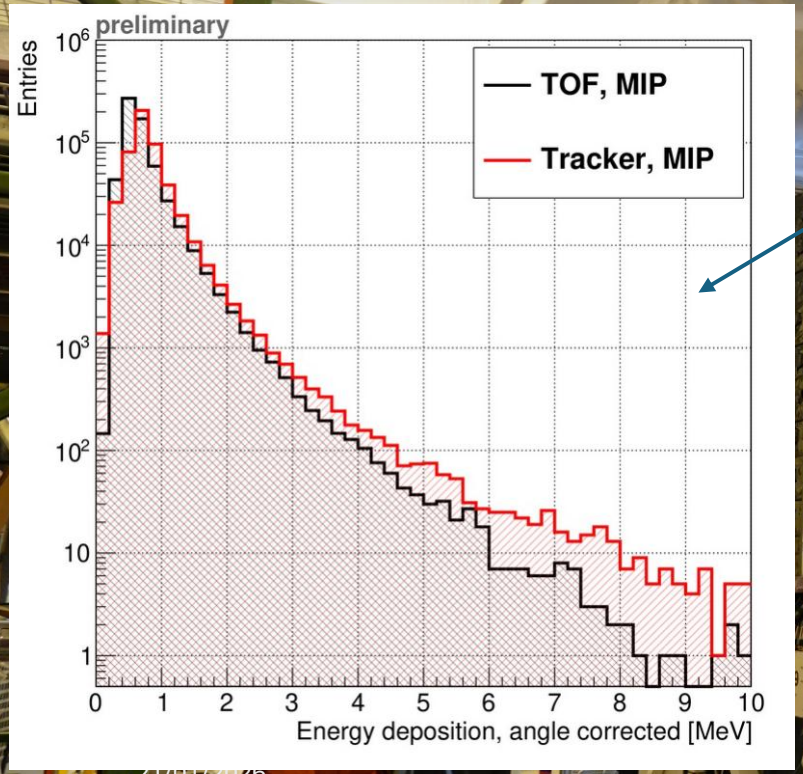
The Long Duration Ballone Facility ~ 10 Km from McMurdo

Fully integrated payload

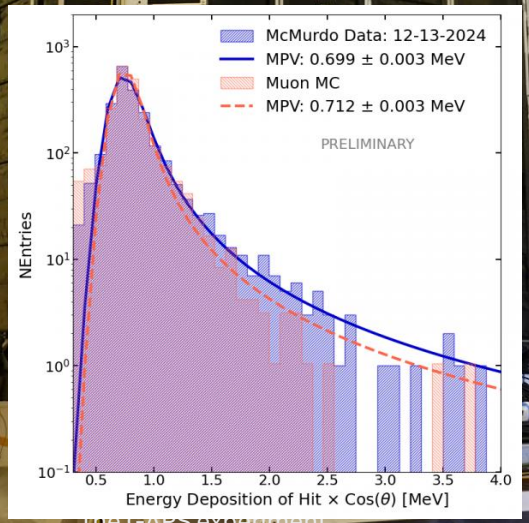
ToF - Tracker Energy Calibration

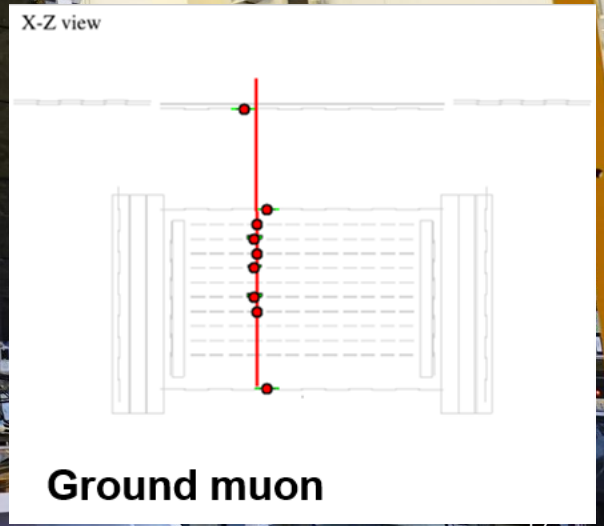
Several muon runs have been performed with the fully equipped detector.
4 days of muon runs with full instrument at ~ 400 Hz (similar to expected flight trigger rate).

Whole energy calibration chain checked and validated



Histograms show all single hits on single tracks in TOF and tracker with a reconstructed velocity beta between 0.9-1.1

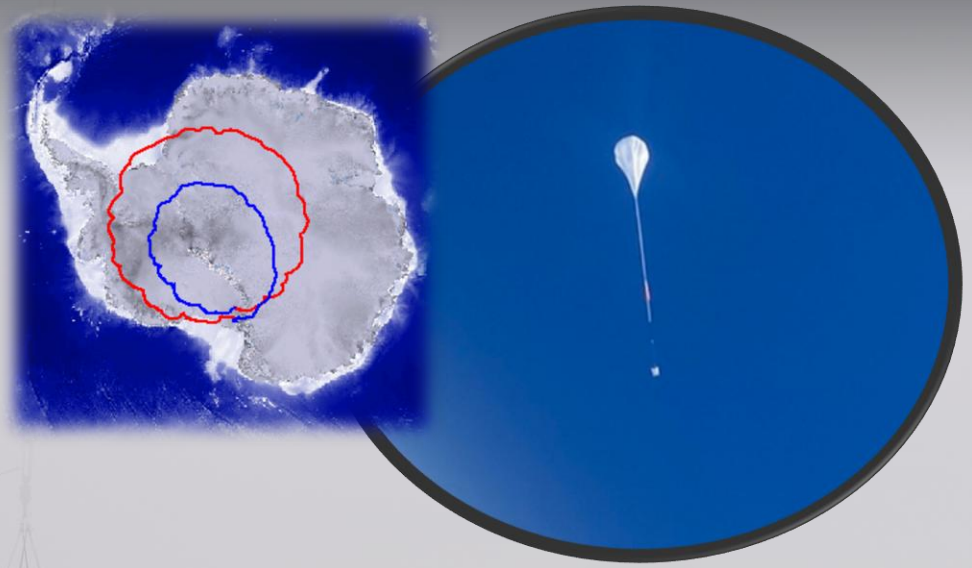




Launch 16 December 2025

Successful Launch on Attempt 5 (12/16/2025)!

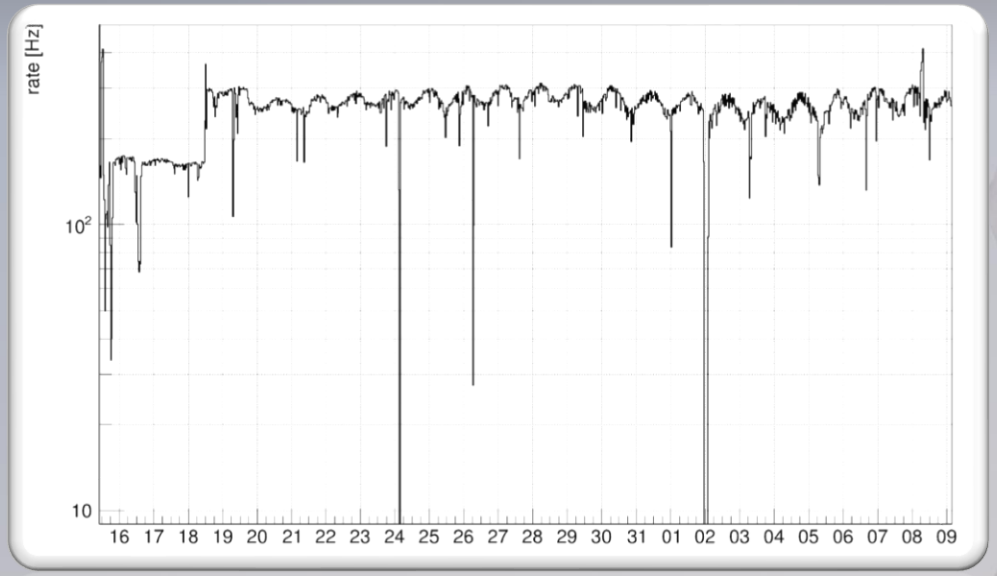
- Total number of triggers: 540 M
- Total amount of data:
  - 2 TB of reconstructed data from Starlink
  - 15 TB total data to be recovered



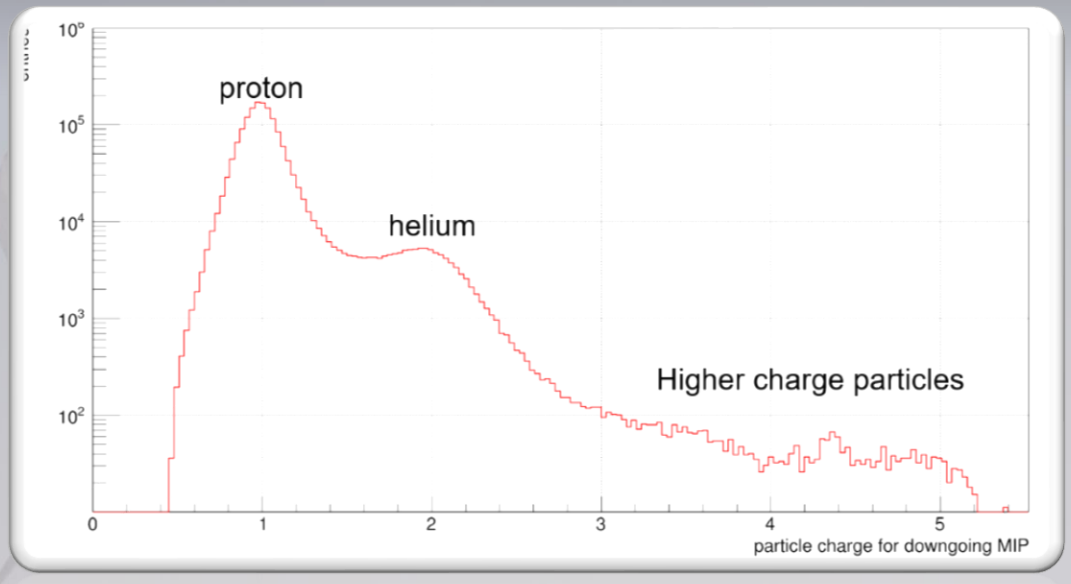
- **Total flight time: 25 days 2 Hours 53 Minutes**

Flight performances

Total Trigger Rate



Single-Track Minimum Ionizing Particles



Flight events will be shown by Chuck Hailey on Thursday 22 January at the **All that Antimatters in the Universe** conderence.
https://indico.cern.ch/event/1480110/

Conclusions

- Calibration and analysis for the next 2-3 years
- First publications in 2028: antiproton spectrum, proton and helium spectra
- Following publications 2029+: Antideuteron and antihelium spectra

- Refurbishments and upgrades for next flights 2028+
- We are confident that we will reach our published science goals in 3 flights.

Thanks to the LDB crew!
Thanks for your attention!

Backup slides

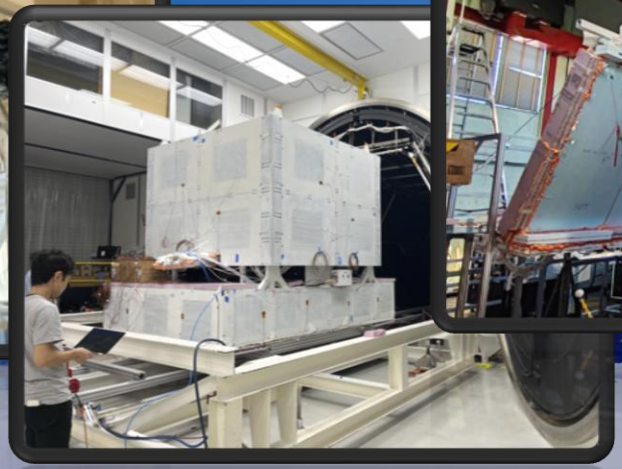
GAPS integration timeline

SSL - Berkeley — Half 2022 → May 2023

NTS – Los Angeles — June 2023

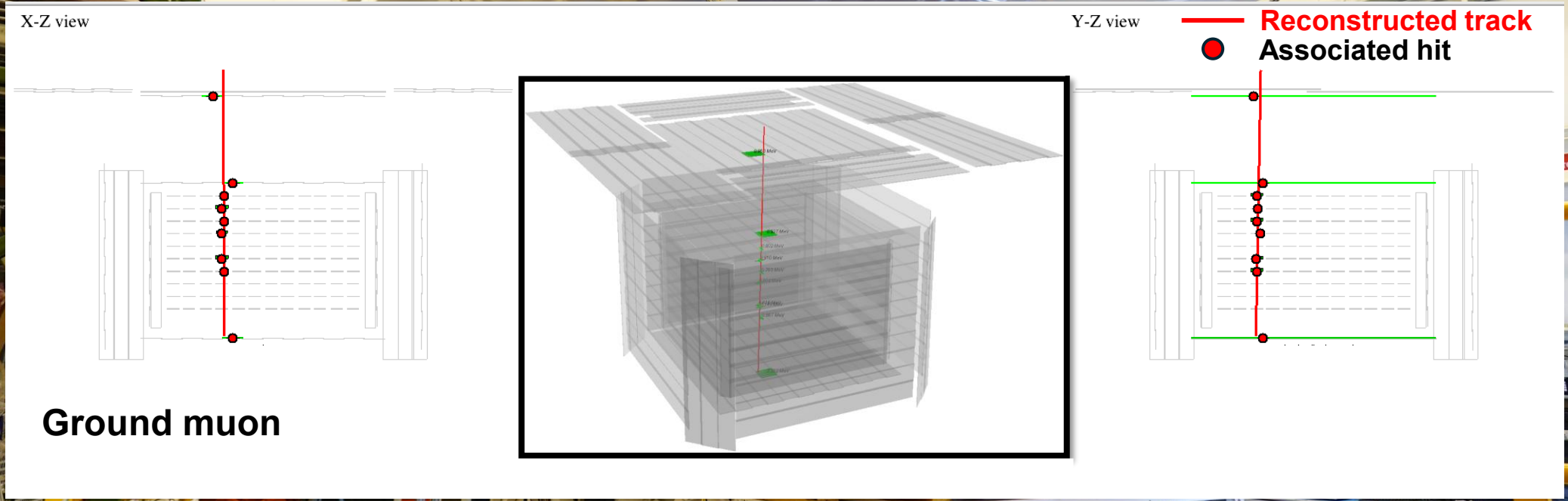
Nevis - Laboratories — July 2023 → May 2024

CSBF Palestine — May → August 2024



Ground Muon Data Taking

Several muon runs have been performed with the fully equipped detector.
4 days of muon runs with full instrument at ~ 400 Hz (similar to expected flight trigger rate).

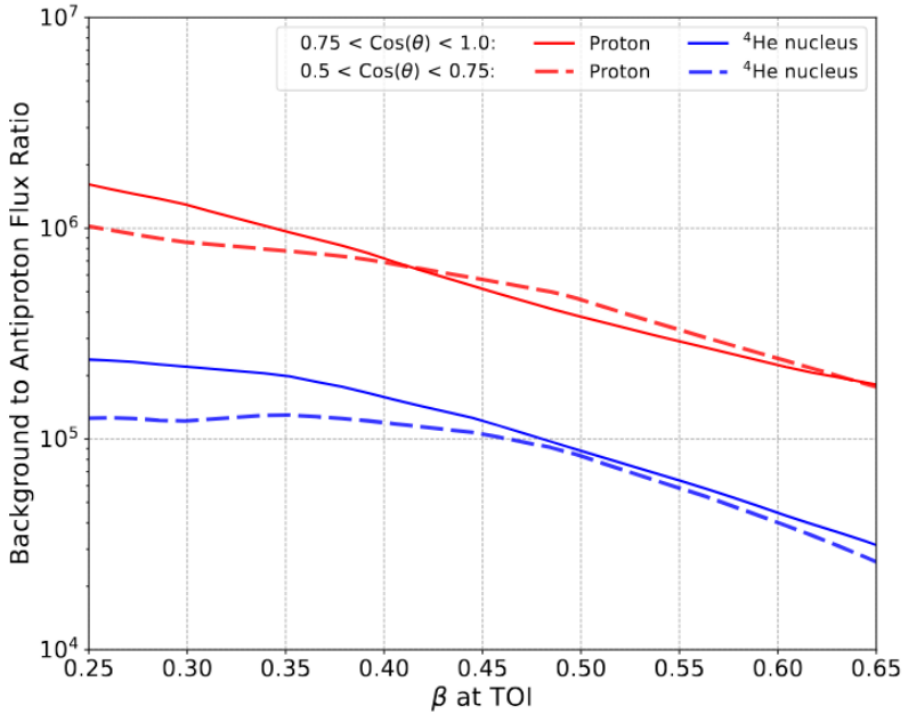


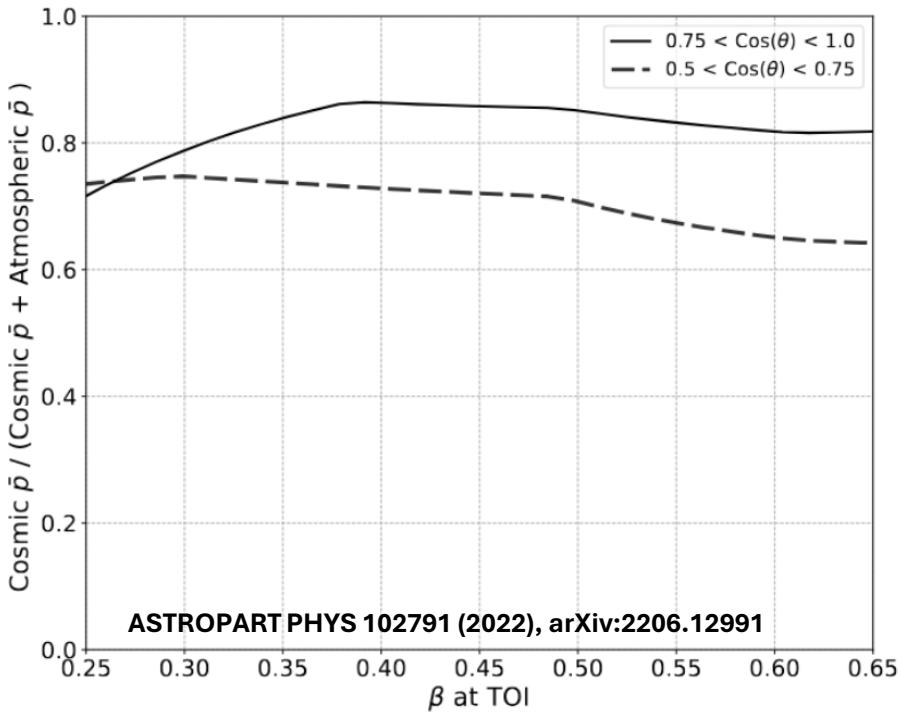
Launch attempts 2024/2025

GAPS was declared flight ready 7 times. 6 times the launch was stopped due to unfavorable winds conditions and one time due to a launch vehicle problem.

7 January

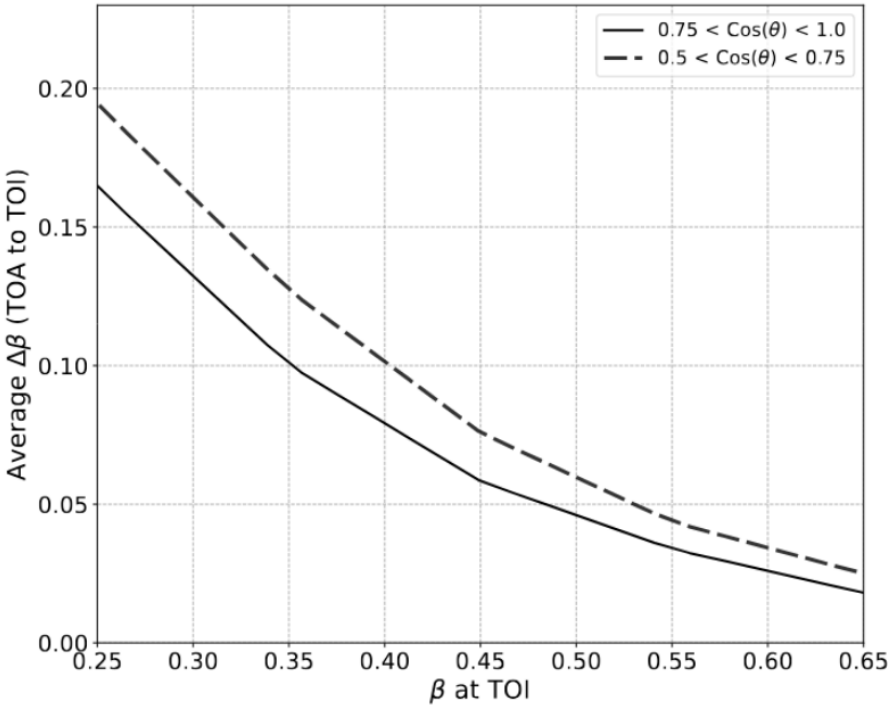
Antiproton background

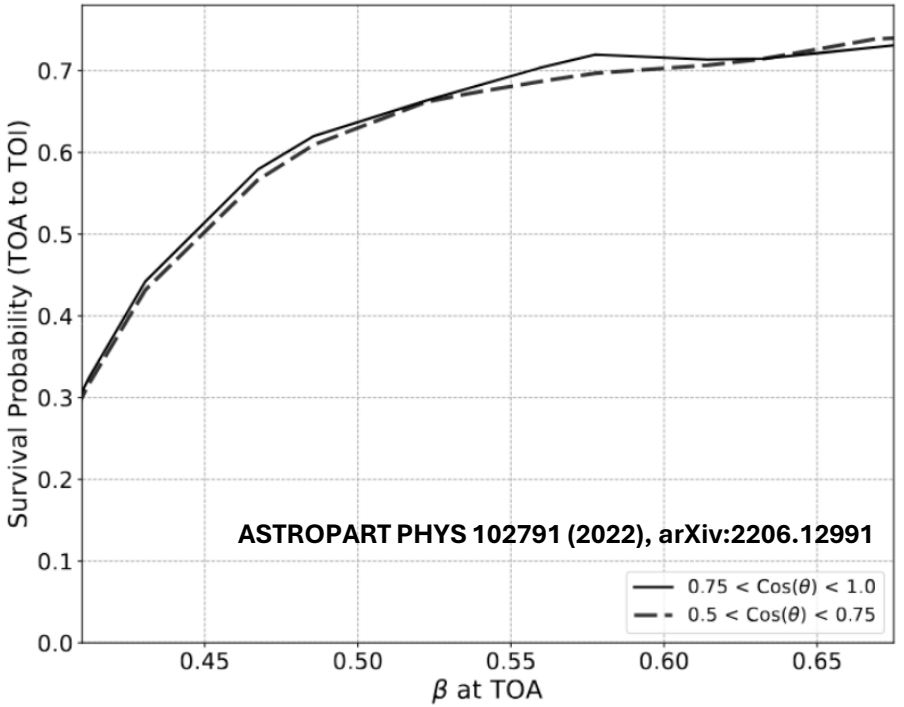




- The ratios of the proton (red) and 4He nucleus (blue) background fluxes to the total (cosmic and atmospheric) antiproton flux are shown as a function of β at TOI. The ratios for each species are binned by the zenith angle θ, where cos θ = 1 indicates a vertical trajectory, and are shown for 0.75 < cos θ < 1.0 (solid) and 0.5 < cos θ < 0.75 (dash).
- The ratio of the cosmic antiproton flux to the total antiproton flux at TOI is shown as a function of β in the same angular bins.

Atmospheric effects



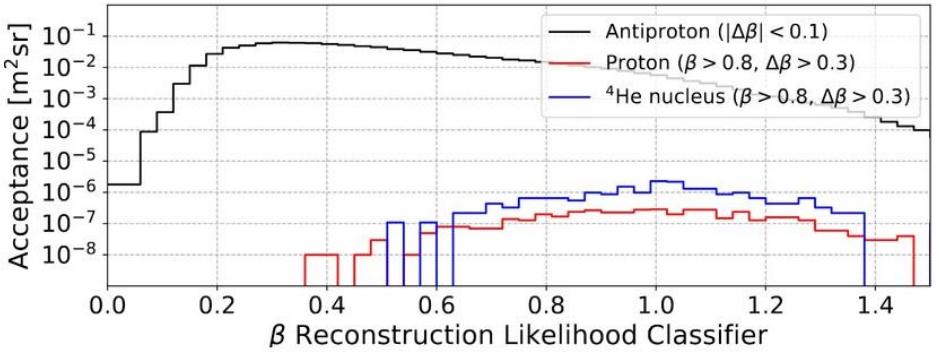


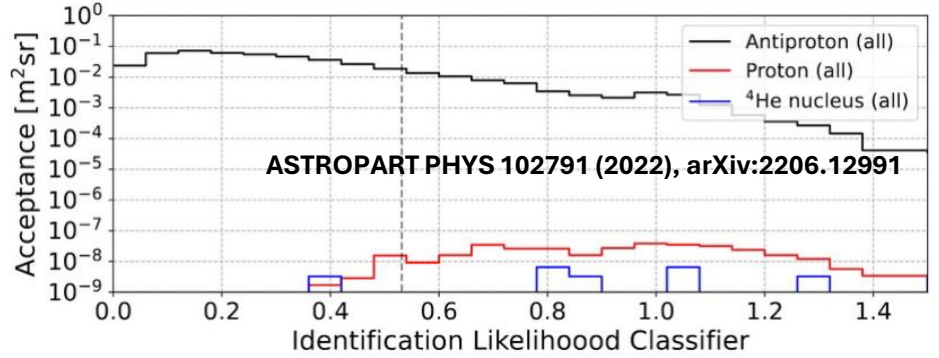
- The average velocity loss for antiprotons from the top of the atmosphere (TOA) to the top of instrument (TOI) is shown as a function of β at TOI. The decrease depends on the zenith angle θ, defined such that cos θ = 1 indicates a vertical trajectory, and is presented here in two bins relevant for the cosmic antiproton analysis: 0.75 < cos θ < 1.0 (solid) and 0.5 < cos θ < 0.75 (dash). The sensitive ange of 0.25 < β < 0.65 at TOI corresponds to 0.41 < β < 0.68 at TOA.
- The survival probability for antiprotons at TOA to reach TOI is given as a function of β at TOA and presented in the same angular bins.

Identification of antiproton

Variables that go into the β quality identifier and the reconstruction identifier

Variable	β	ID
Energy deposition on the primary track		✓
Average energy deposition on primary track	✓	
Max over mean energy deposition	✓	
Primary Truncated mean dE/dx	✓	
Primary TOF dE/dx		✓
TOF dE/dx over truncated mean dE/dx	✓	
Vertex energy over truncated mean dE/dx	✓	
Total energy deposition in the outer TOF	✓	
Energy deposition within 45 cm of the vertex	✓	
Average energy deposition per hit		✓
Number of secondary tracks from the vertex	✓	✓
Tracker number of hits		✓
Isotropy of secondary hits in the TOF cube	✓	✓
Isotropy of secondary hits in the tracker		✓
Average β of secondary tracks		✓



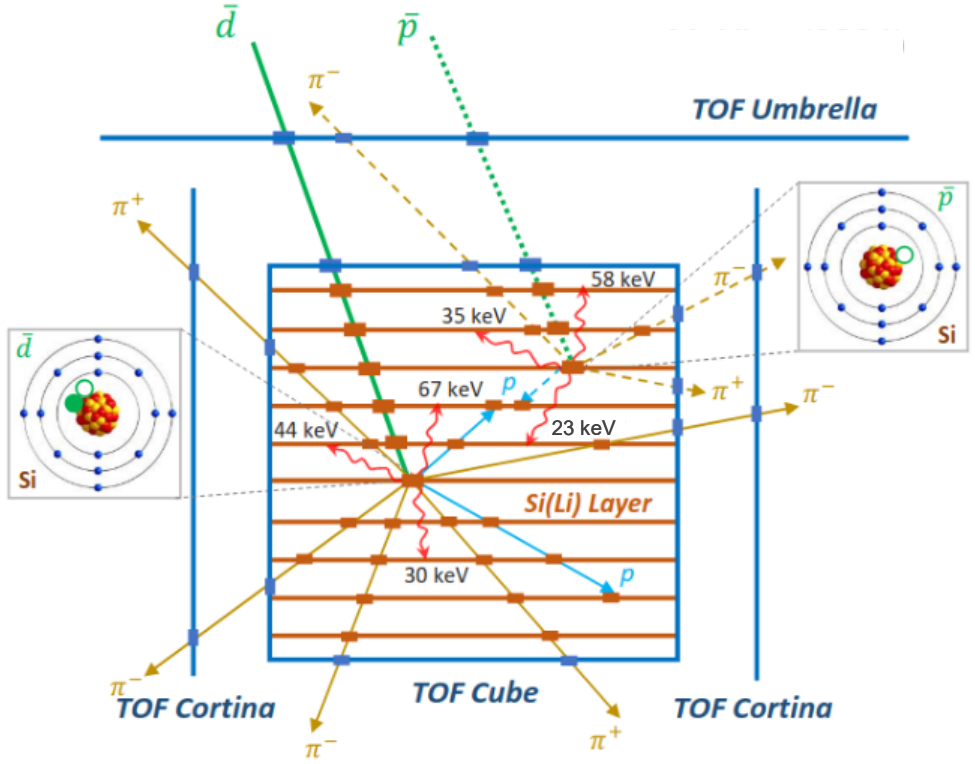


Example for events reconstructed with 0.34 ≤ β < 0.40 and cos(θ)>0.75 that have passed the trigger and preselection conditions.

GAPS Exotic Atom Capture and Decay

TOF measures Z, β, position, dE/dx of incident antinucleus and triggers readout

Si(Li) tracker measures position and dE/dx and acts as stopping target for antinucleus



On average, same β antiproton vs antideuteron has different stopping depth, decay X-rays, multiplicity of annihilation products

Antinucleus forms exotic atom

Si(Li) tracker measures decay X-rays

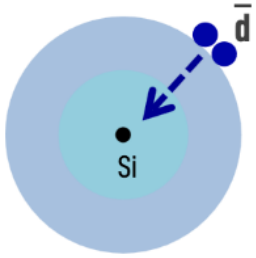
TOF and tracker measure properties of charged annihilation products

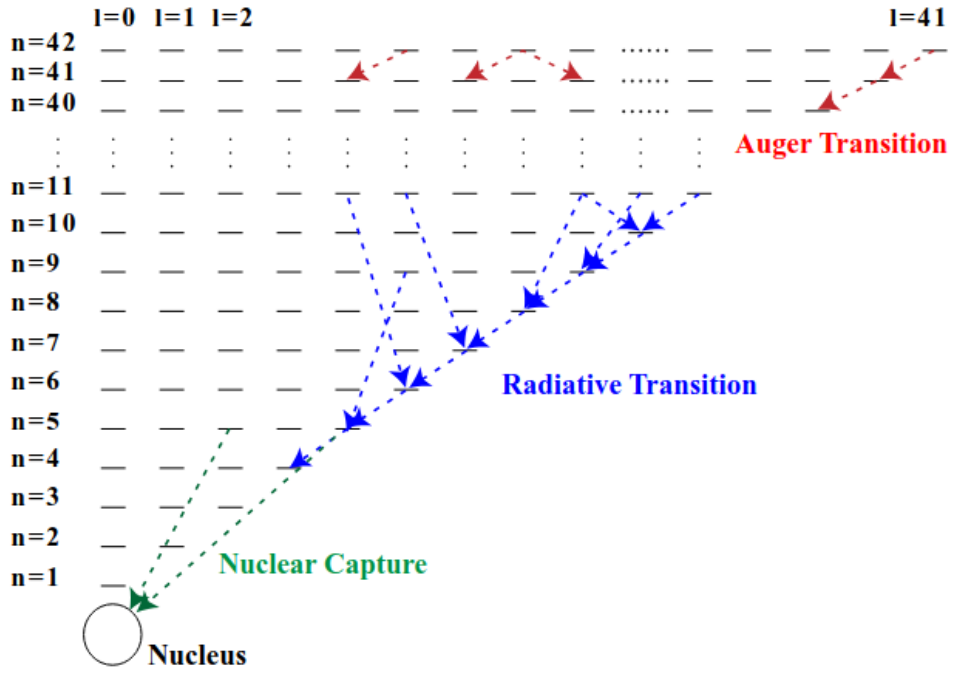
C. Hailey+ JCAP 01 (2006)

Image credit: M. Xiao

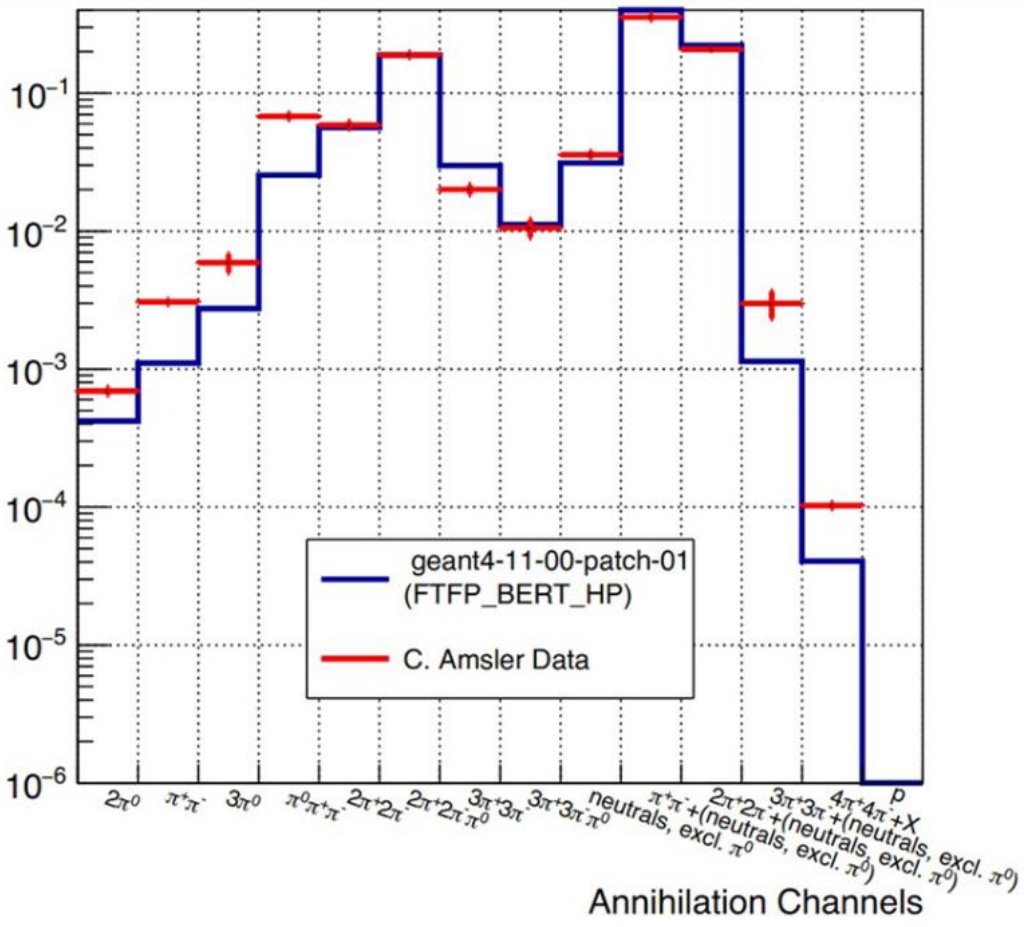
GAPS Utilizes Exotic Atom Technique

- An exotic atom is formed when low-energy antinuclei slows to have KE ~ e- binding energy
- Auger transitions followed by radiative transitions
- High yield of > 10 keV X-rays in low n radiative transitions
- Nuclear capture can happen at low n states; the annihilation is well approximated as an at-rest event





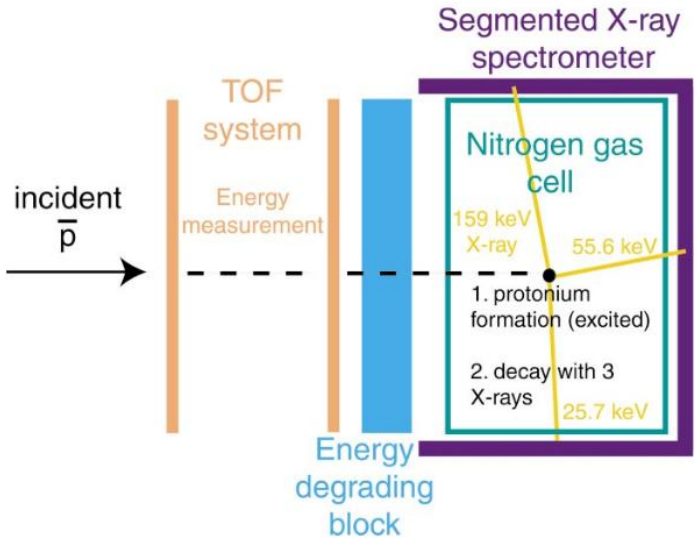
Antiproton Annihilation at Rest

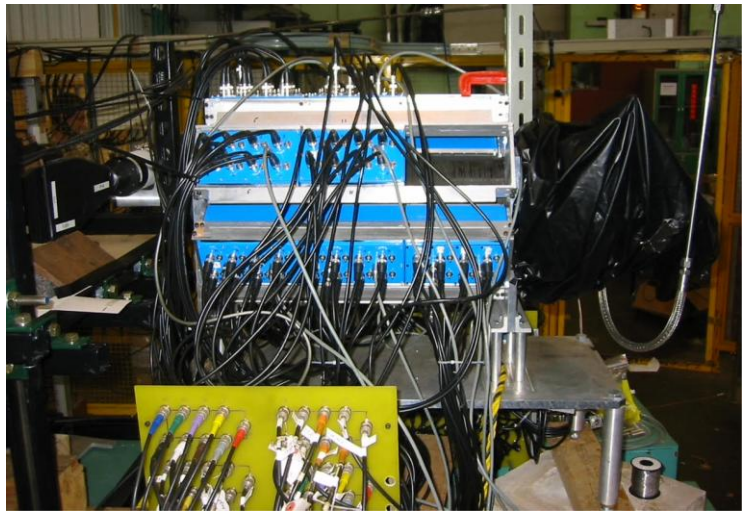


- Worked with Geant4 physics lists developers on improving annihilation at-rest physics (ongoing)
- GAPS antiproton data from Flight 1 will be used for validation

KEK 1 (2004): Proof of Concept

- High pressure nitrogen and liquid bromine were tested
- X-rays and pions were detected

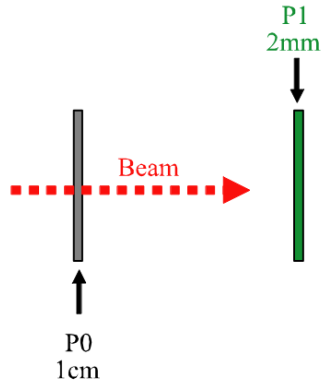


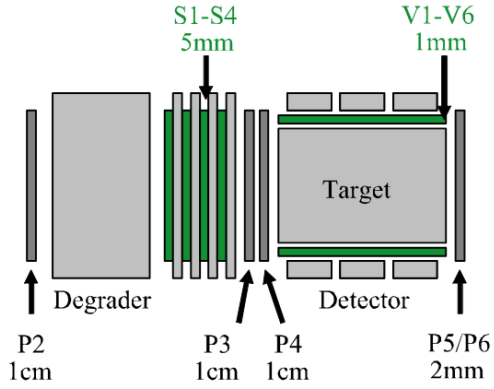


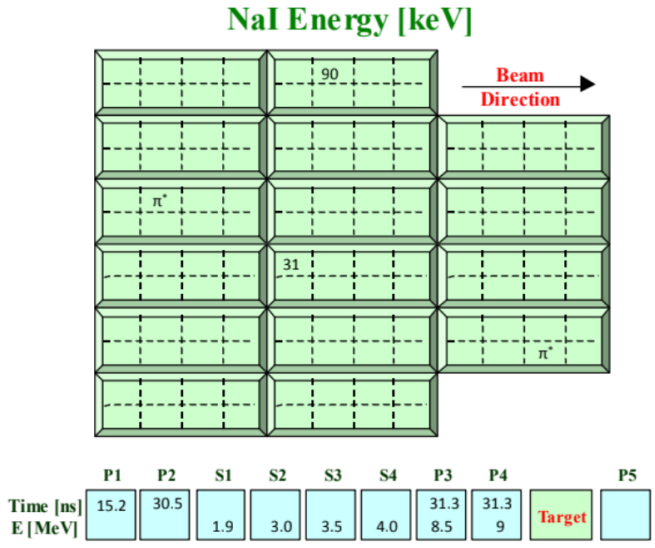
C. Hailey+ JCAP 01 (2006)
K. Mori+ ApJ 566 604 (2002)

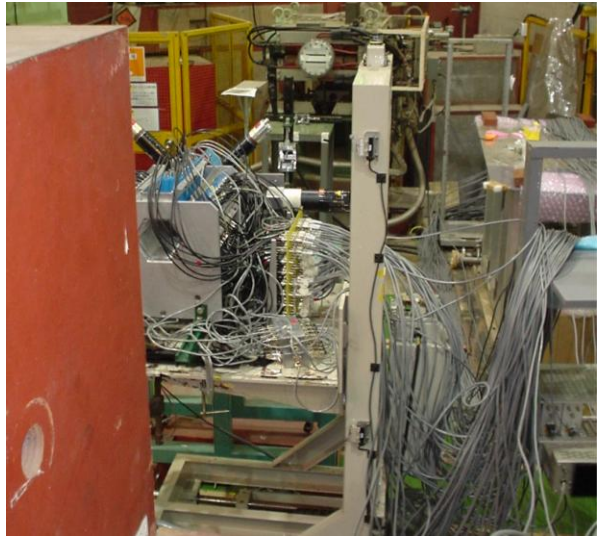
KEK 2 (2005): Developing Exotic Atomic Model

- Demonstrated viability of liquid and solid targets
- Determined absolute X-ray yields in liquid and solid targets
- Validated absolute X-ray yields against complete atomic physics models
- Model is extrapolatable to any Z atom





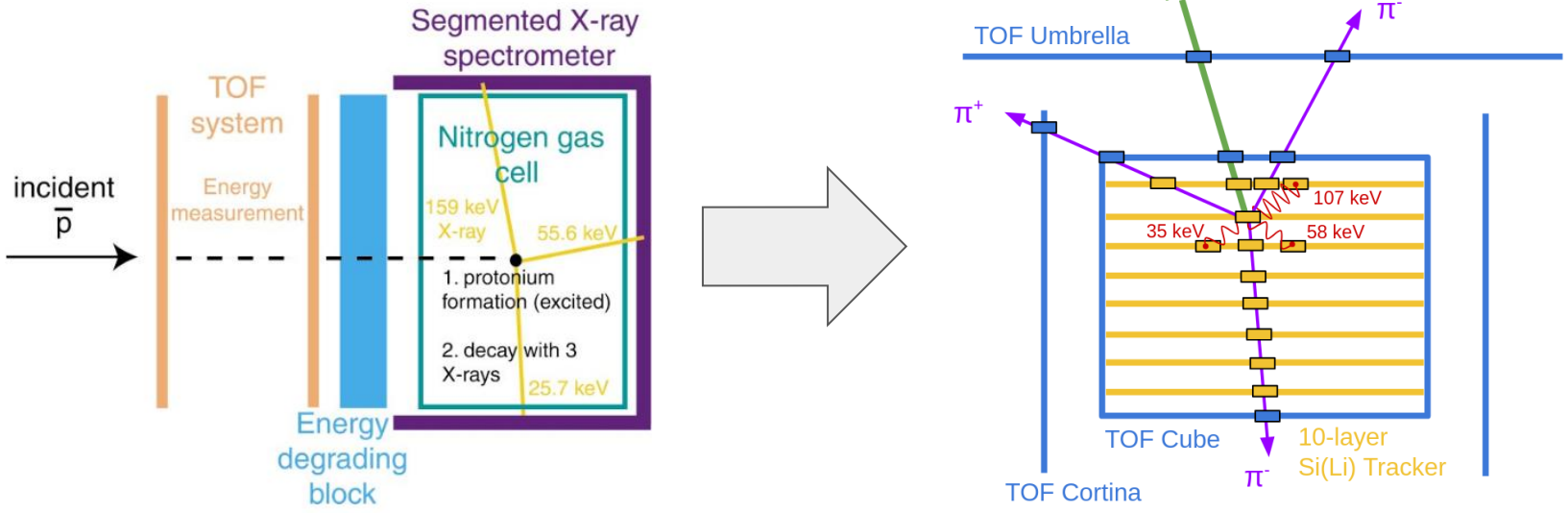




C. Hailey+ JCAP 01 (2006)
ADD: Aramaki (2011)

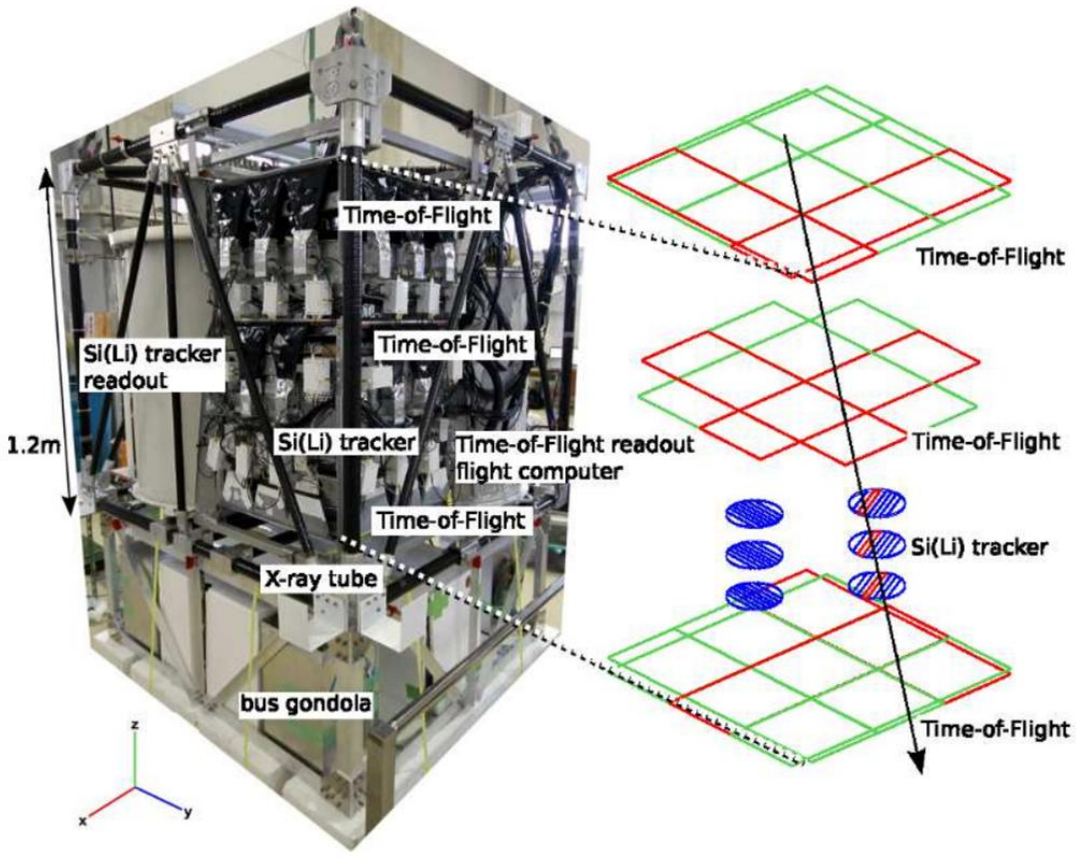
Evolution to the Tracker Geometry (2007)

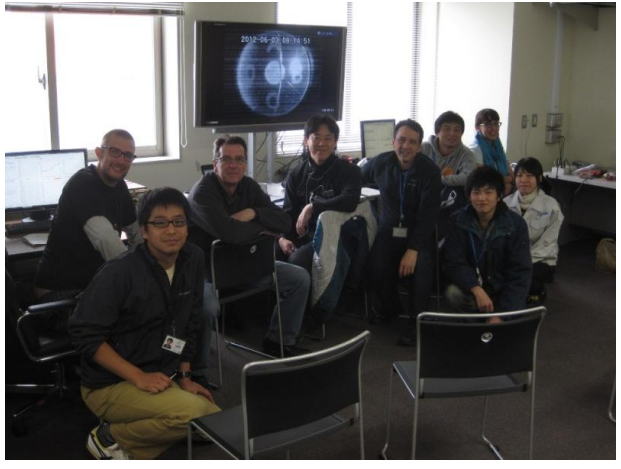
- Simulations show that a tracker geometry is extremely constraining without the X-rays.
- Time of flight B, dE/dx, secondaries, beta of secondaries, can be used to identify particles in silicon detector-based tracker



K. Mori+ Astrophys. J. 566 (2002)
C. Hailey New J. Phys. 11 (2009)
F. Rogers+ Astropart. Phys. 145 (2023)

pGAPS (2012) Testing the New Concept





S.A.I. Mognet+ NIM A 735 (2014)
P. von Doetinchem+ Astropart. Phys. 54 (2014)

GAPS Landed in the Field

- GAPS has landed close to McMurdo base for an in-season recovery but landed with the TB drives facing the ground!