The First Flight of the GAPS Antarctic Balloon Mission: Searching for Dark Matter with Cosmic Antinuclei

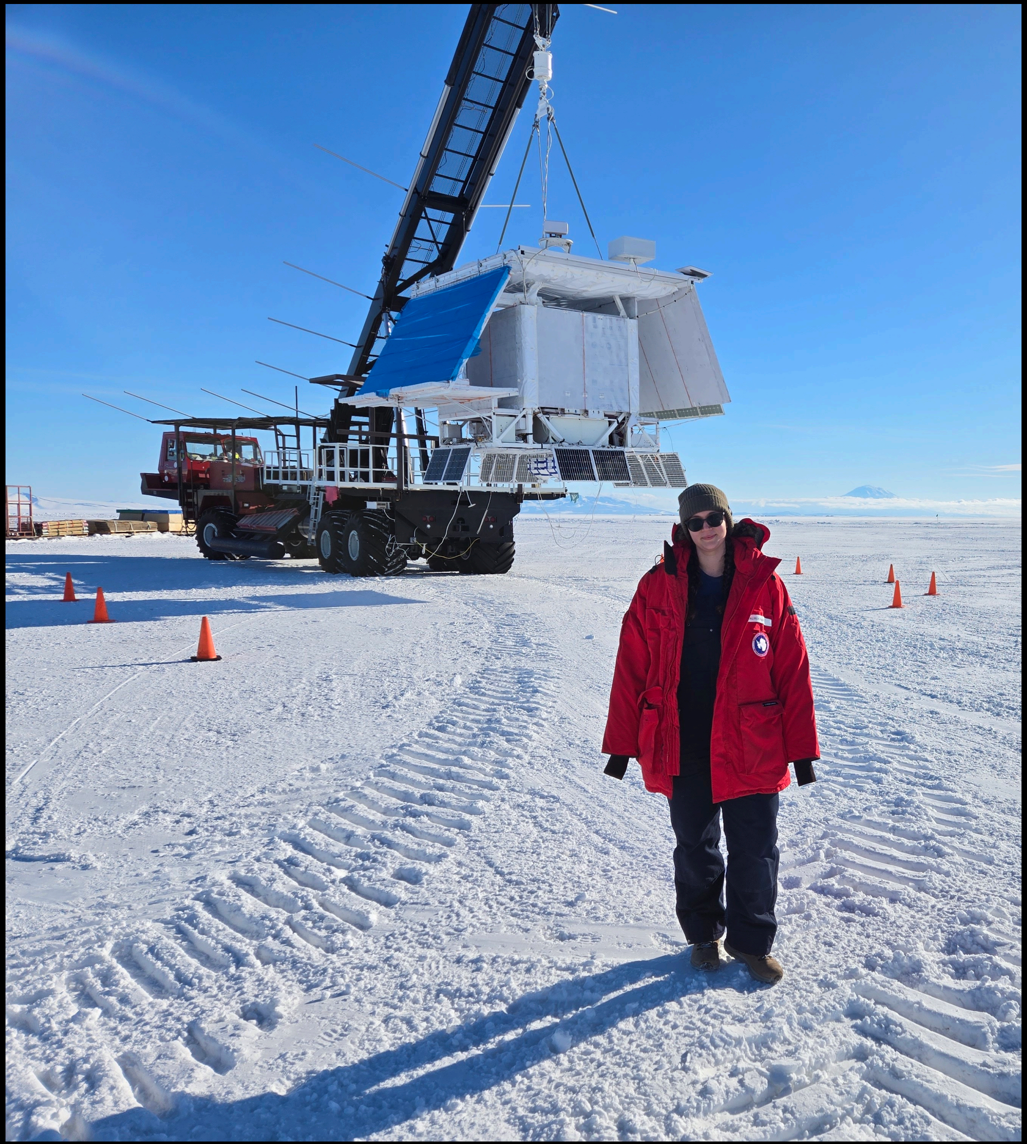
Identification of Dark Matter 2026

June 1, 2026

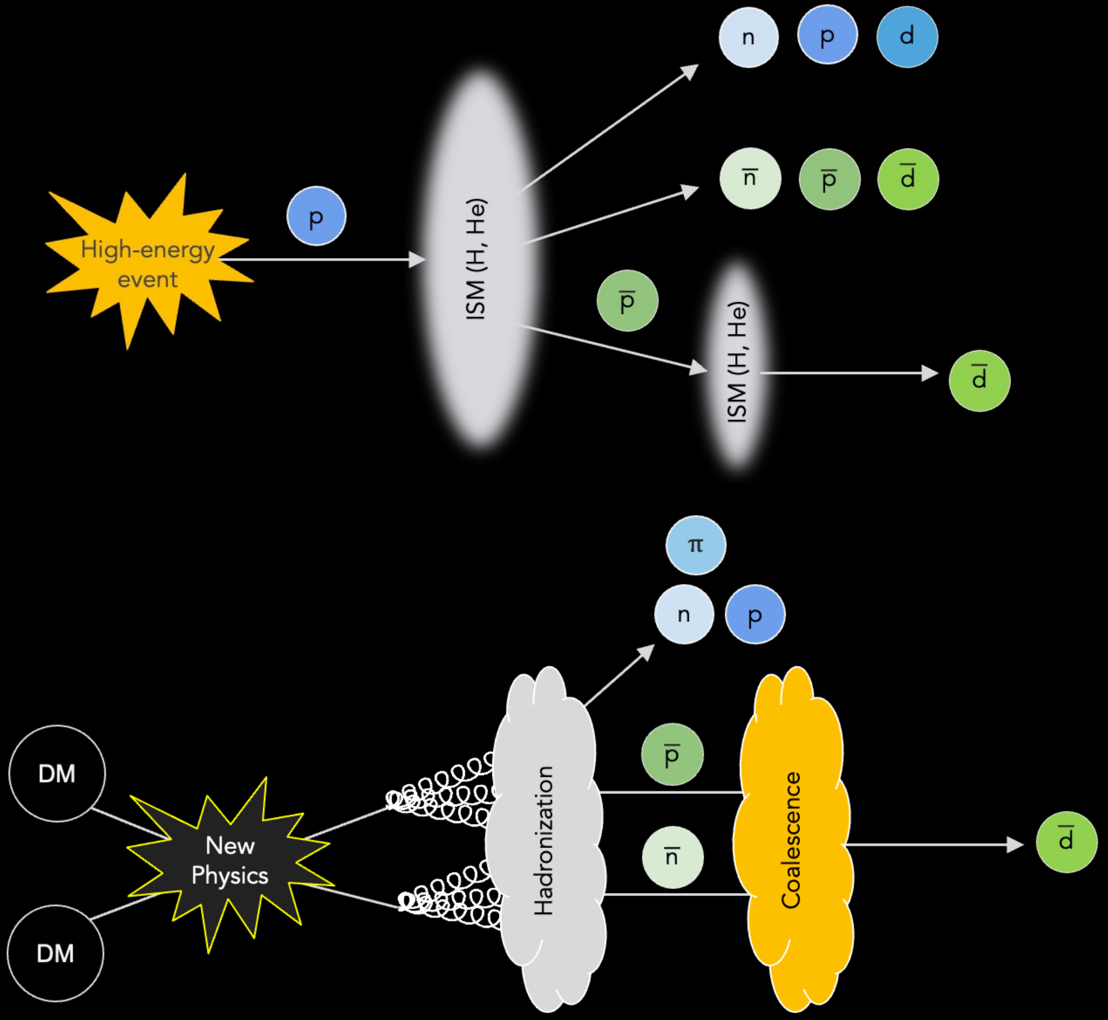
Kaliroë Pappas, Columbia University, on behalf of the GAPS collaboration

The General Antiparticle Spectrometer

- The GAPS Antarctic balloon program is the first experiment optimized specifically for low-energy (0.1-0.3 GeV/n) cosmic antinuclei
  - Low-energy antideuterons are uniquely low-background signatures of dark matter
- GAPS completed the first of three flights December 16, 2025 - January 10, 2026



How to produce a low-energy antideuteron?

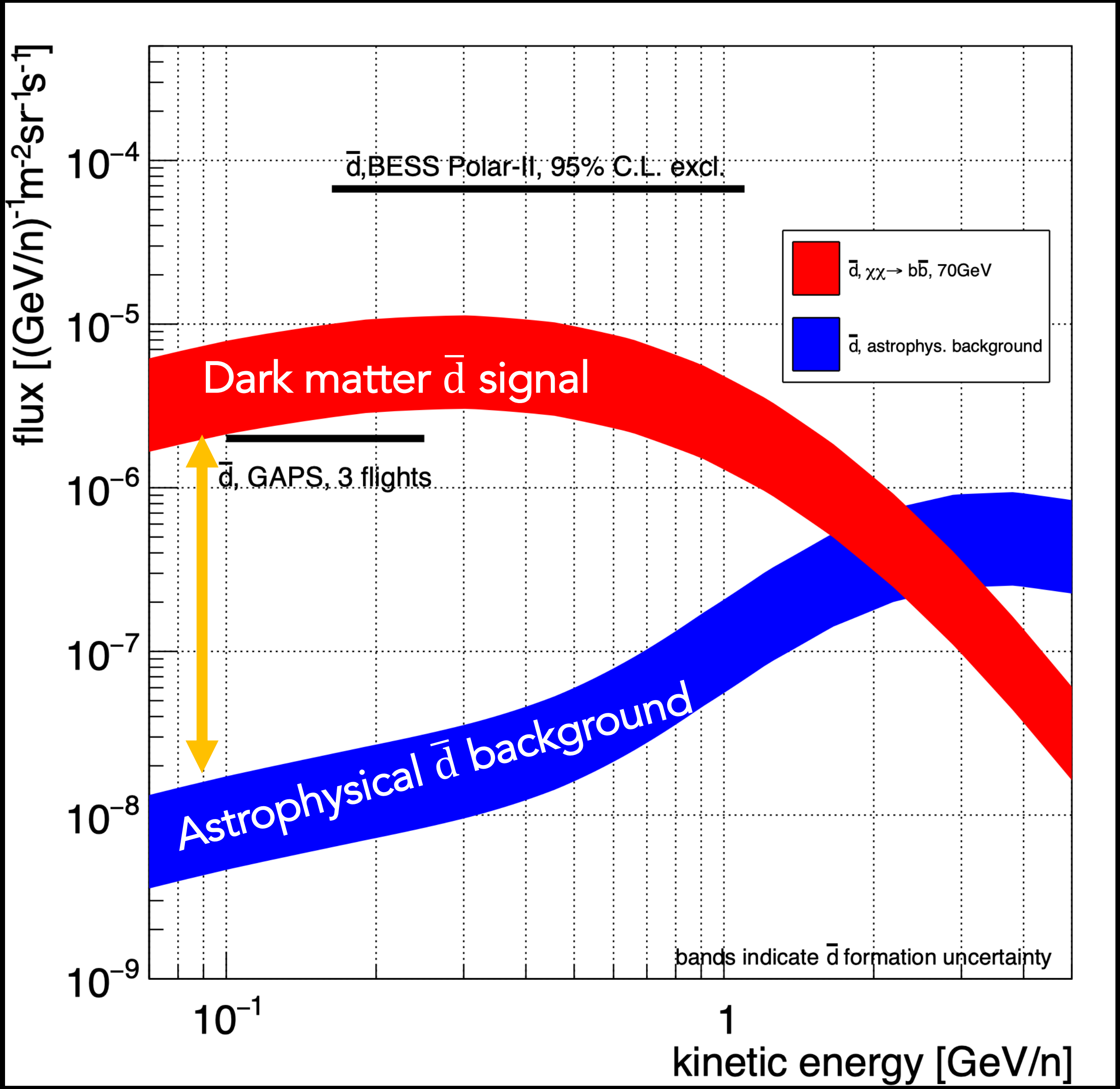


- Standard model productions of low-energy antideuterons:
  - Require high initial cosmic ray energy
  - Flux of cosmic rays decrease for higher energies
  - Kinematically suppressed
- Low-energy antideuterons produced from near at-rest DM particles are in a uniquely low-background energy range

Donato, Fornengo and Salati, PRD 62 (2000)

Low-energy antideuterons as signatures of new physics

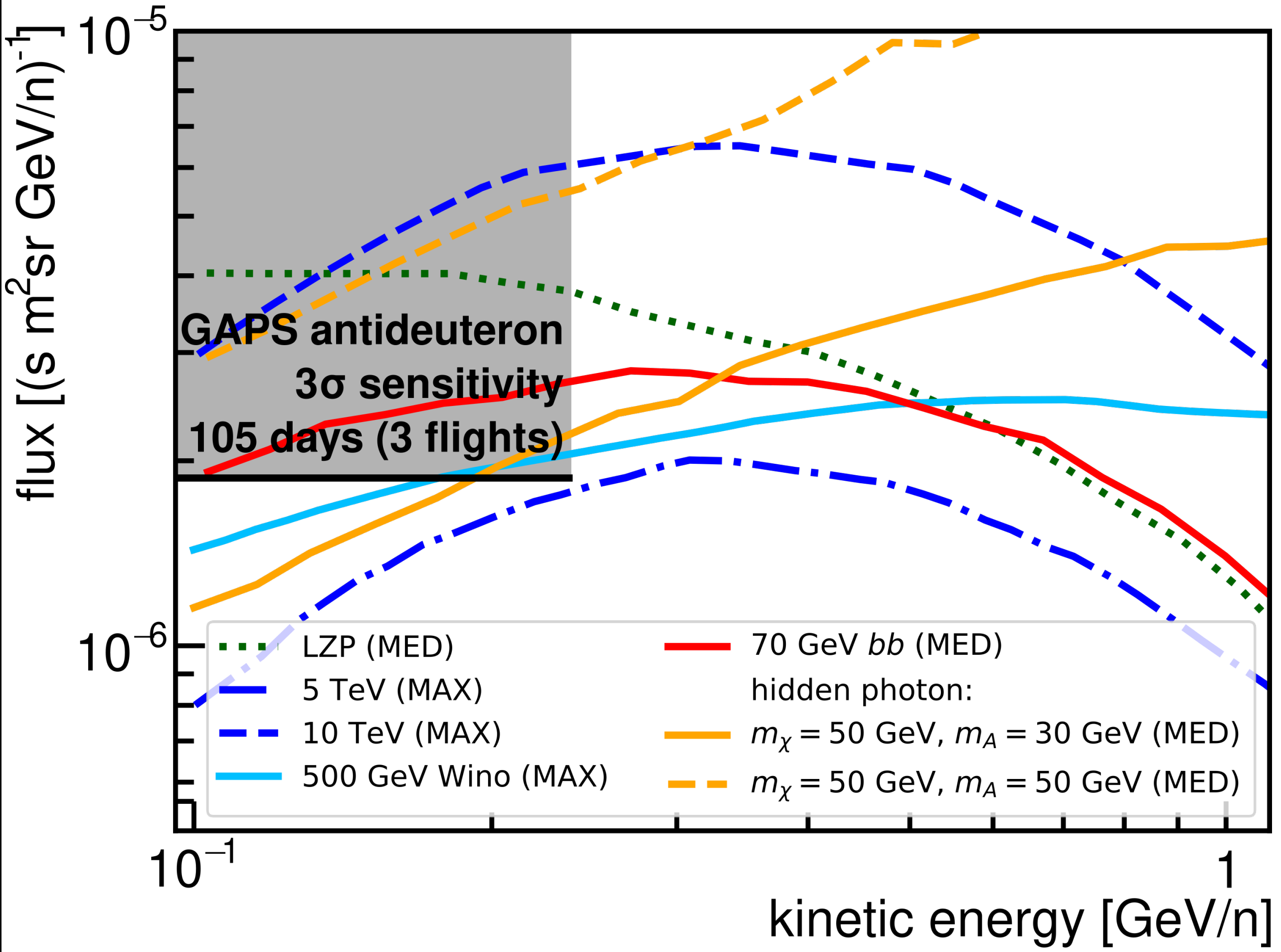
- Viable DM predictions of low-energy antideuterons ~3 orders of magnitude above astrophysical backgrounds
- GAPS is the first experiment optimized for low-energy antideuterons
- GAPS has sensitivity 1-2 orders of magnitude better than current limits, reaching expected DM signals



T. Aramaki+, Astropart. Phys. 74 (2016); K. Sakai+, Phys. Rev. D 132 (2024); R. Duperray+, Phys. Rev. D 71 (2005); P. Salati+, arXiv:1003.4124 (2010); A. Ibarra+, Phys. Rev. D 88 (2013)

Sensitivity to wide range of viable dark matter models

- ~10s of GeV mass DM models within GAPS sensitivity → predicted from gamma-ray and antiproton observations
- GAPS also has sensitivity to heavy dark matter models → predicted from positron observations
- Additionally GAPS is uniquely sensitivity to certain hidden sector models

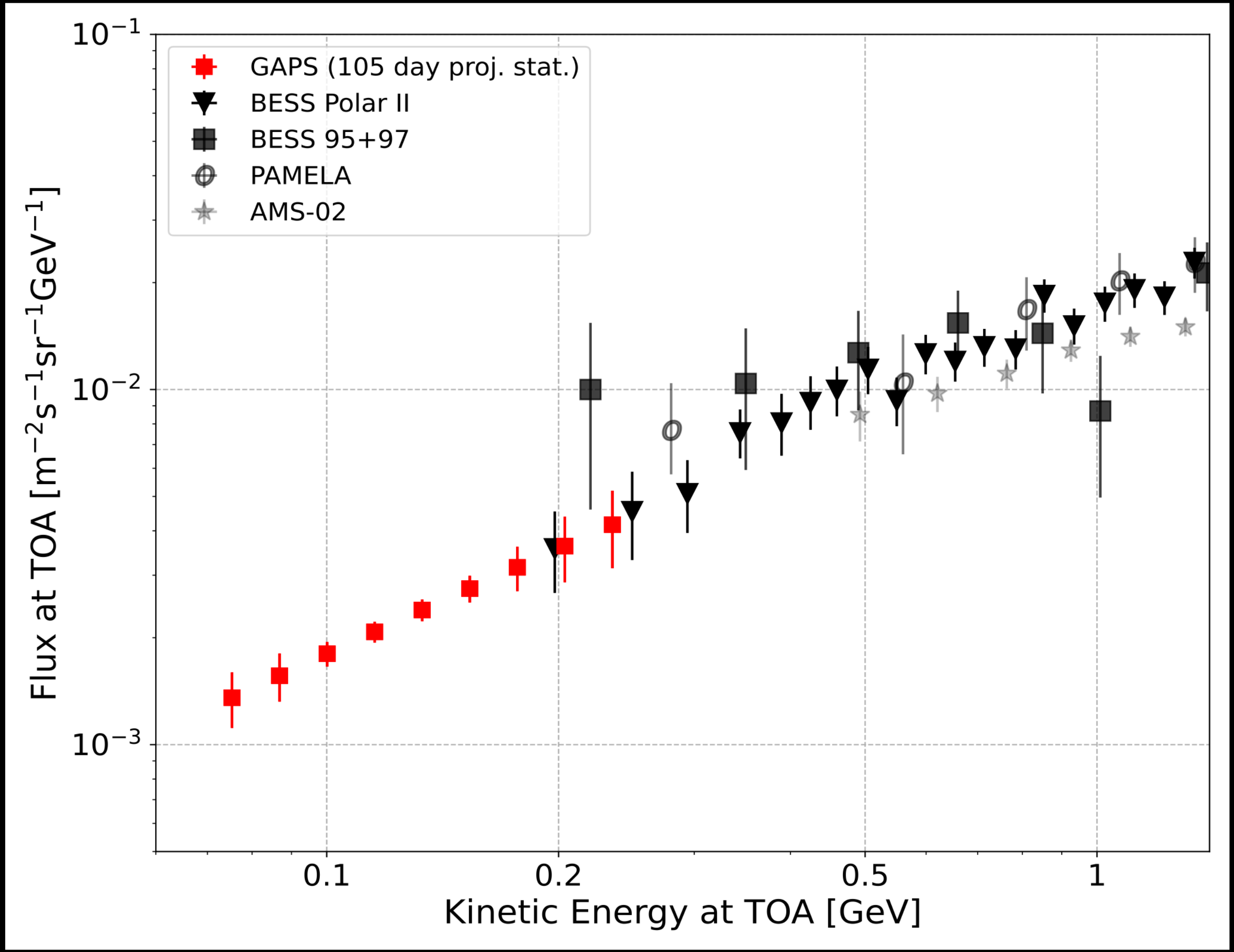


Korsmeier+ 1711.08465 (2018), Cui+ 1006.0983 (2010), Braeuninger+ 0904.1165 (2009), Hryczuk 1401.6212 (2014), Randall+ 1910.14669 (2020)

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)

Signs of dark matter from antiprotons

- GAPS will deliver a 10% precision antiproton spectrum
- GAPS will probe the unexplored low-energy range
- Antiprotons have leading sensitive to viable light DM and PBH models

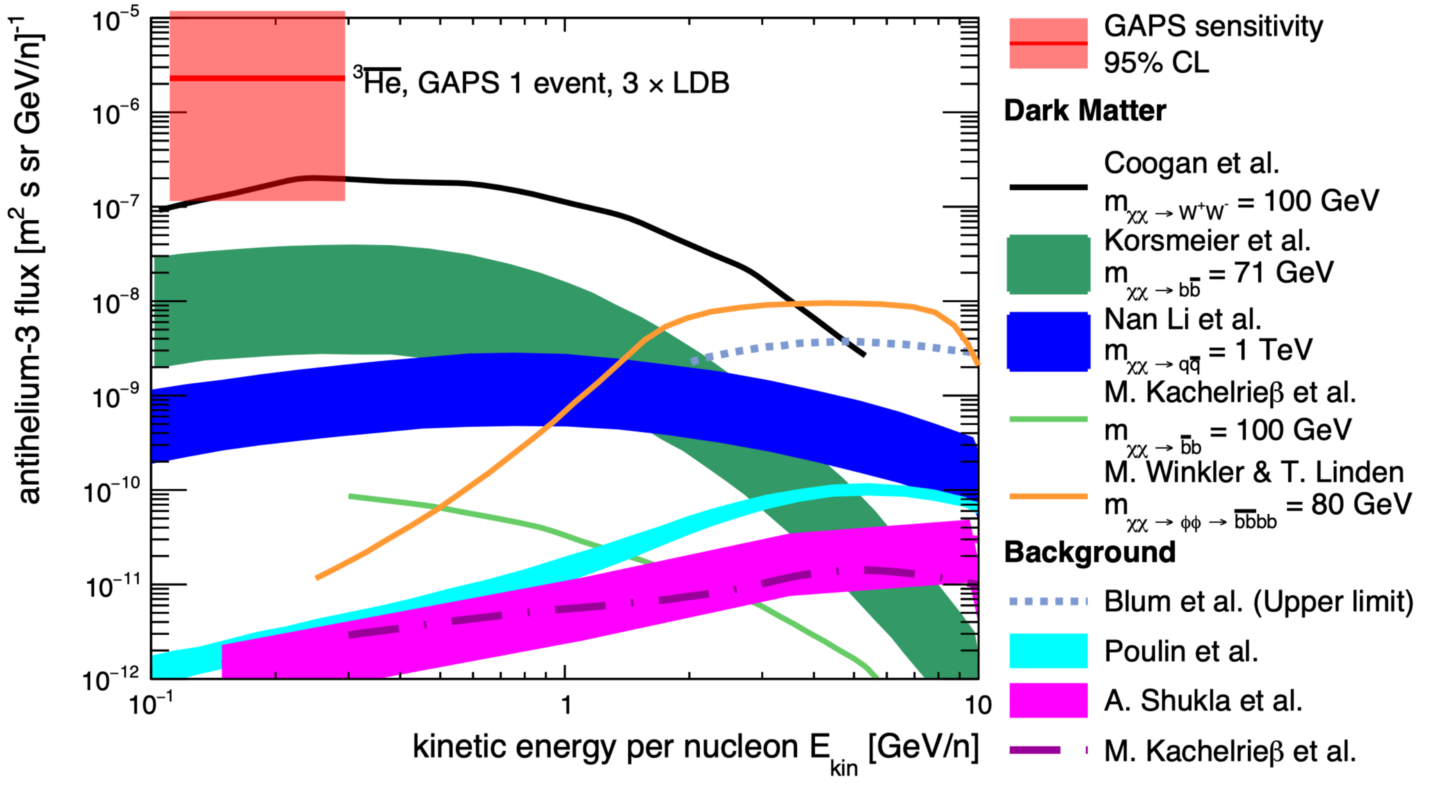


Rogers+ Astropart. Phys. 2022 2206.12991

D. Hooper+ JHEP 163 (2020)
P. Villanueva-Domingo+ Front. Astron. Space Sci. 8 (2021)
A. Barrau+ A&A 388 (2002)
A. Cuoco+ JCAP 04 (2018)
Romeri+ Phys. Rev. D 112 (2025)

Dark matter from antihelium?

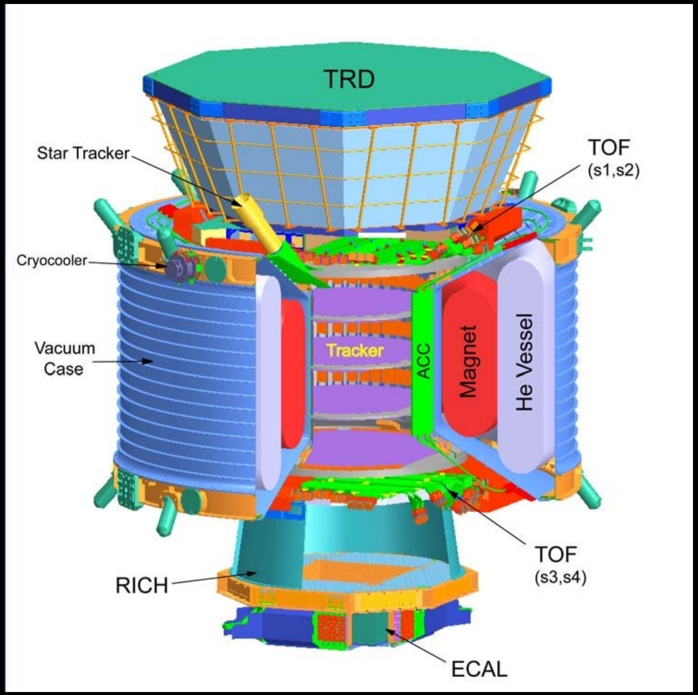
- AMS-02 has announced several candidate antihelium nucleus events
- Large array of theoretical models predicting broad antihelium flux and energy ranges
- GAPS is the only experiment outside of AMS-02 able to detect cosmic antihelium
  - Orthogonal detection technique



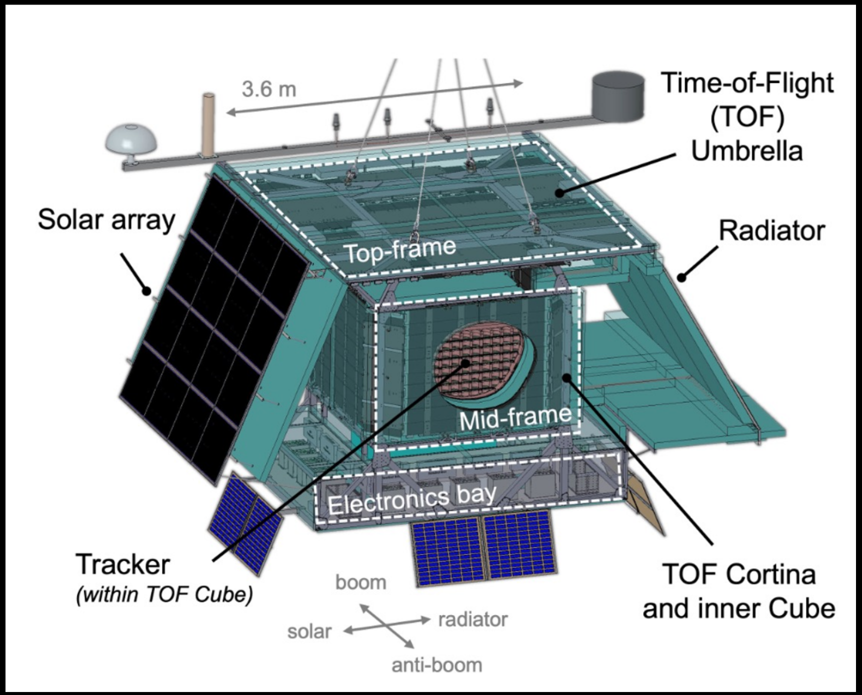
N. Saffold+ Astropart. Phys. 130 (2021)

K. Blum+ Phys. Rev. D 96 (2017)
A. Coogan and S. Profumo Phys. Rev. D 96 (2017)
M. Korsmeier+ Phys. Rev. D 97 (2018)
Y.-C. Ding+ JCAP 2019 (2019)
M. W. Winkler and T. Linden Phys. Rev. D 126 (2021)
M. W.+ Phys. Rev. D 107 (2023)
V. Poulin+ Phys. Rev. D 99 (2019)

GAPS uses a novel antiparticle detection technique

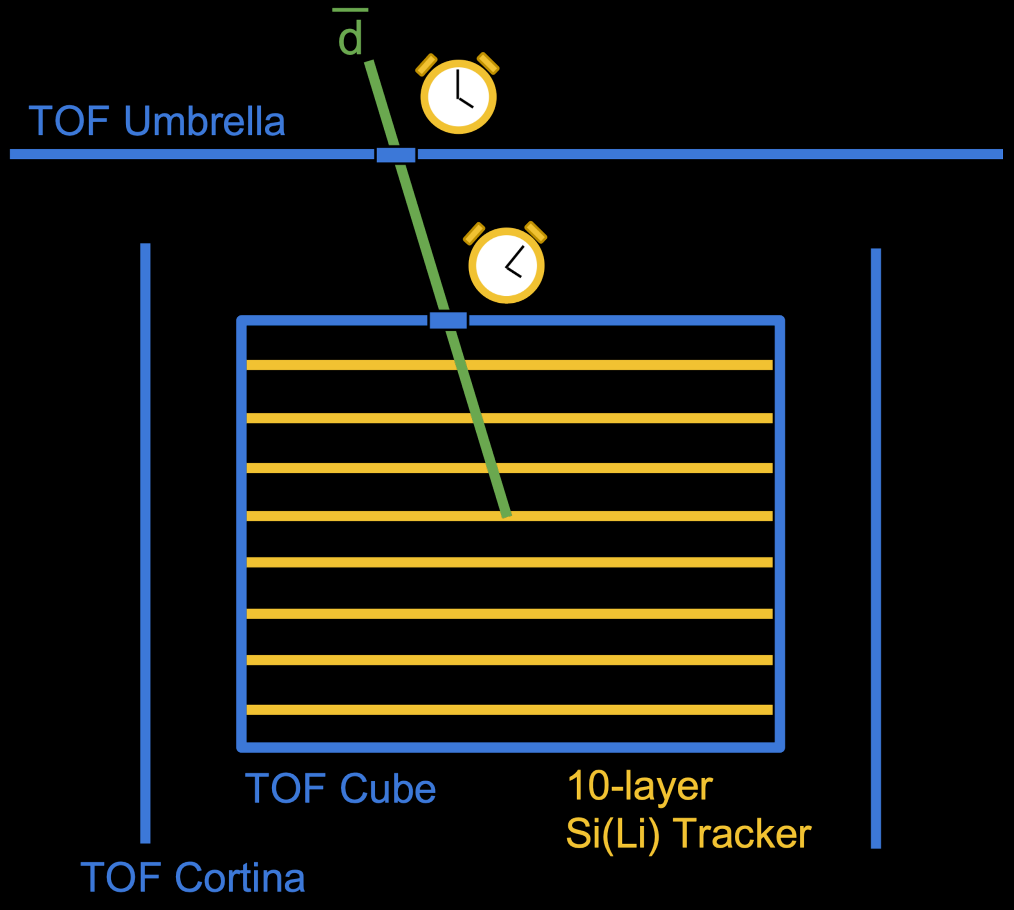


- AMS-02 has been in operation on the ISS since May 2011
- Magnetic spectrometer, combines signals from array of sub-detectors
- High statistics spectra, comparison over solar cycle



- GAPS had its first flight this past winter
- Novel exotic atom technique for antiparticle detection
- Large acceptance, optimized for low-energy antinuclei

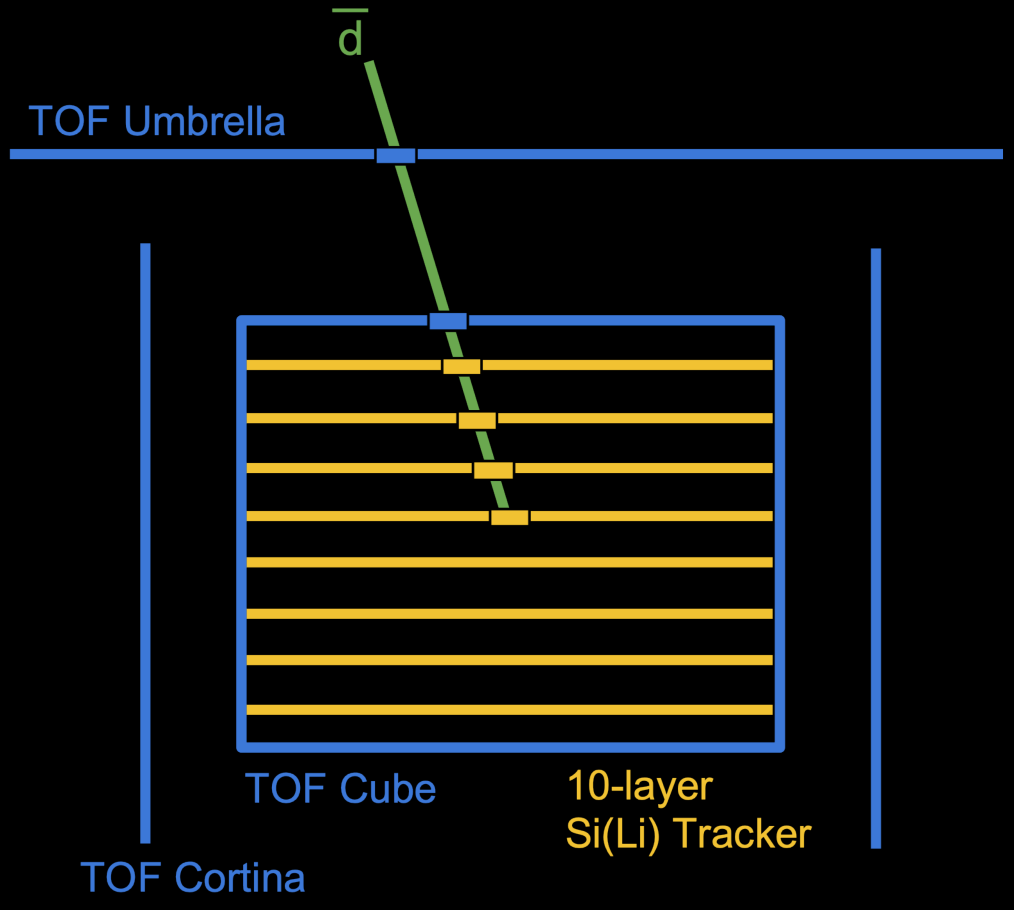
GAPS novel exotic atom detection technique



The incoming antinucleus first travels through the time of flight (TOF) system, which records the time, position and dE/dx of the particle hits

Image credit: Kelsey Yee

Depositing energy in the tracker



The antinucleus will slow in the tracker, which will measure the position and dE/dx of the particle

Image credit: Kelsey Yee

Forming an exotic atom

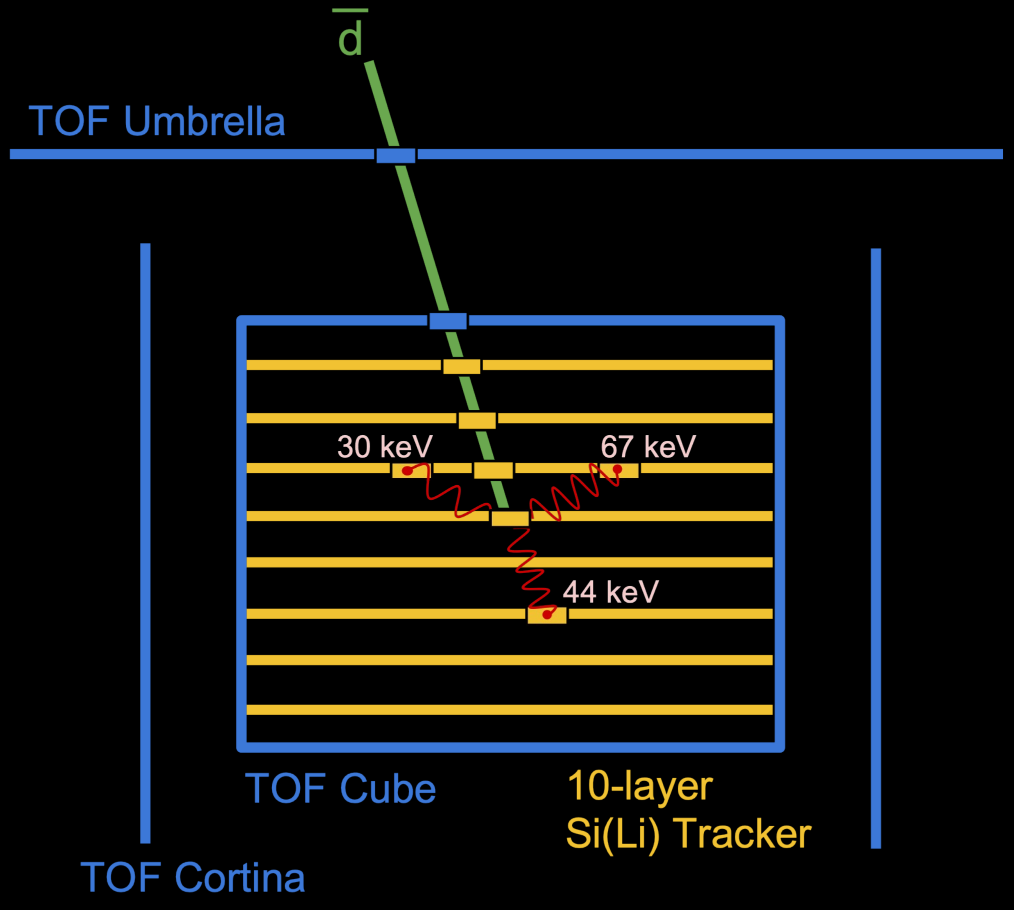
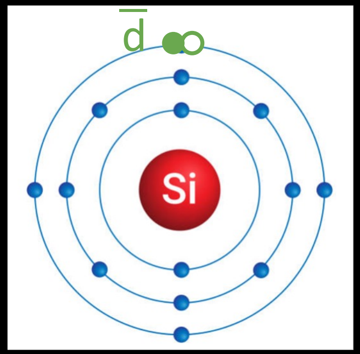


Image credit: Kelsey Yee

The antinucleus deposits energy in the tracker until it is captured to form an exotic atom



Exotic atom technique proposal: Mori et.al. ApJ 566 (2002); Hailey New J. Phys. 2009
Exotic atom technique verified at KEK: Hailey+, JCAP 0601 (2006); Aramaki+ Astropart.Phys. 49, 52-62 (2013)
GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)
GAPS sensitivity to antiprotons: Aramaki+ Astropart.Phys. 59, 12-17 (2014)

De-exciting an exotic atom

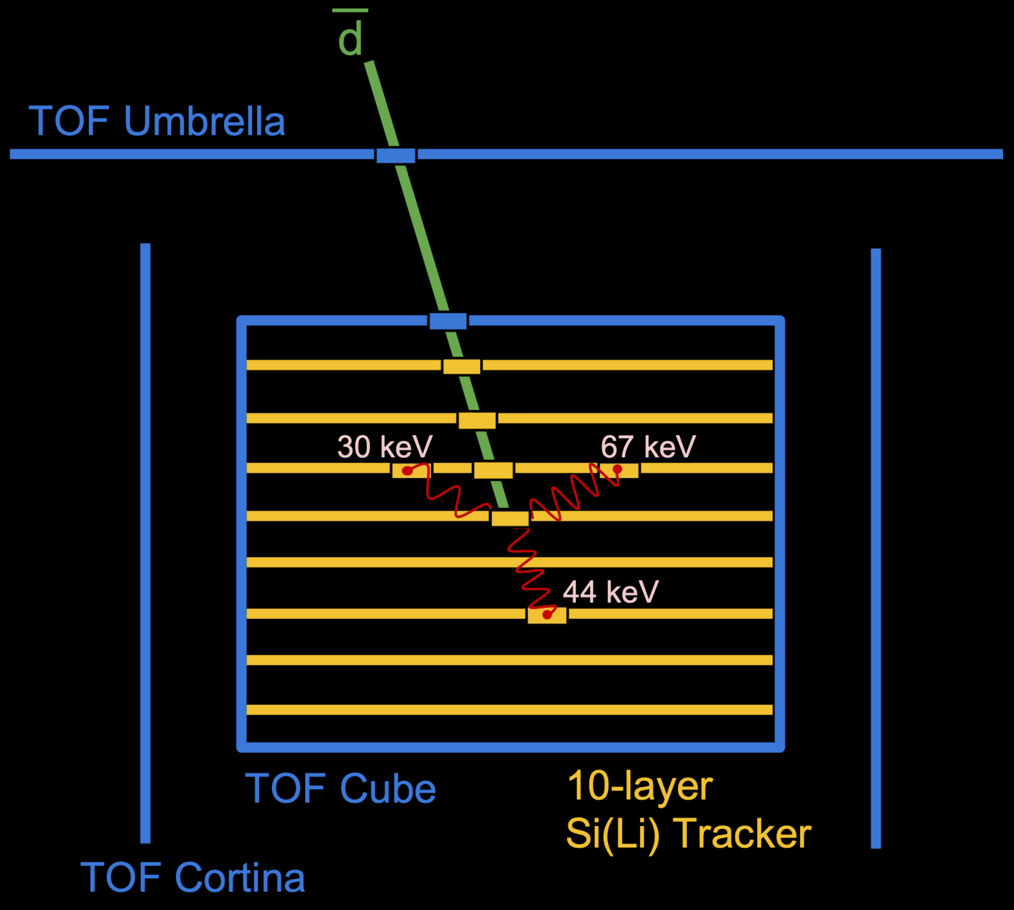
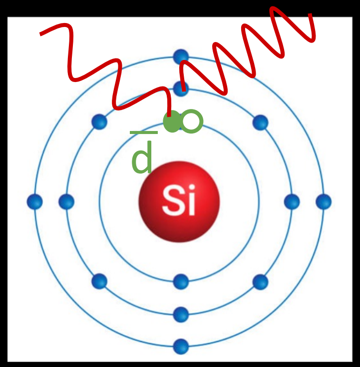


Image credit: Kelsey Yee

That exotic atom de-excites emitting x-rays at energies specific to the antinucleus in the exotic atom



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Nuclear annihilation

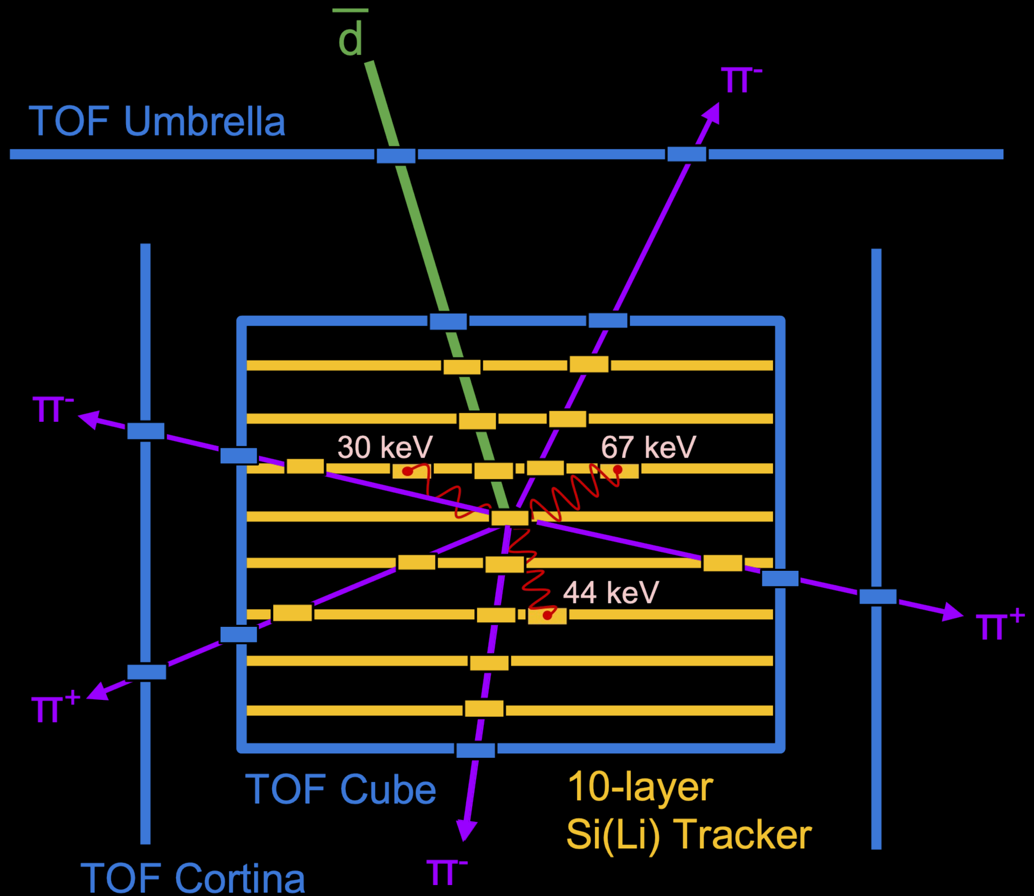
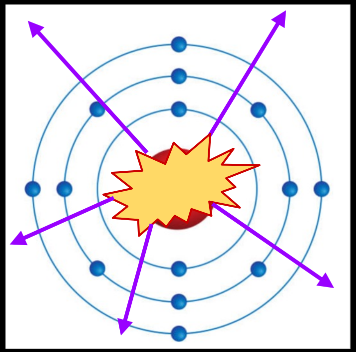


Image credit: Kelsey Yee

The antinucleus will then annihilate with the nucleus of the atom releasing products which deposit their own energy in the instrument



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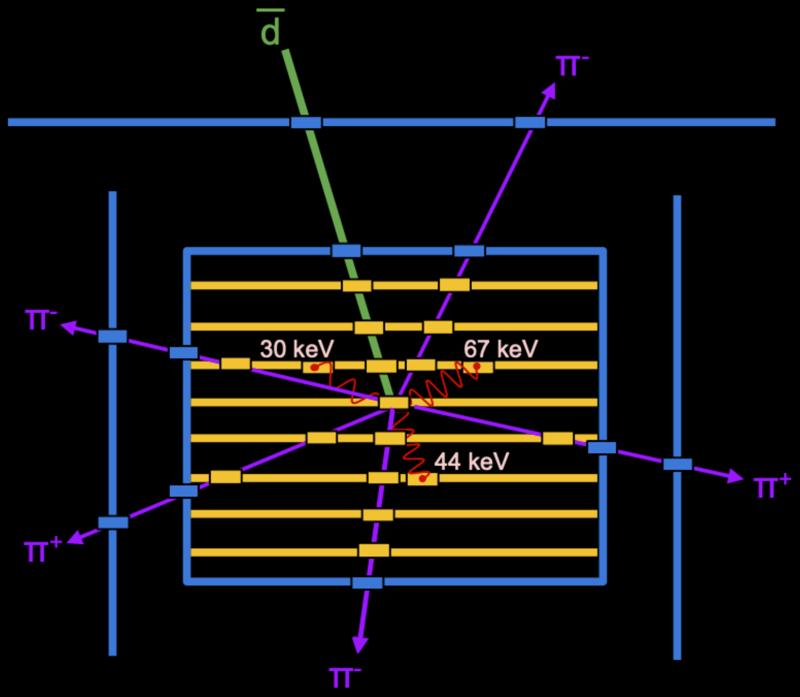
GAPS sensitivity to antiprotons: Aramaki+ Astropart.Phys. 59, 12-17 (2014)

GAPS can distinguish between different antinuclei and backgrounds

TOF + dE/dx + stopping depth + nuclear annihilation multiplicity + X-ray measurement
→ rejection factor >10^9 for positive nuclei, robust discrimination between antinuclei



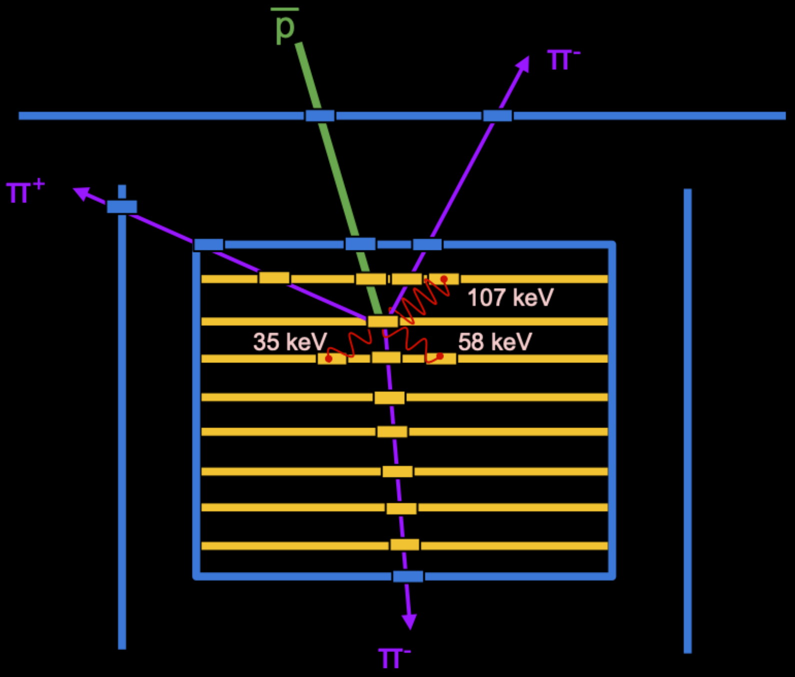


Image credit: Kelsey Yee

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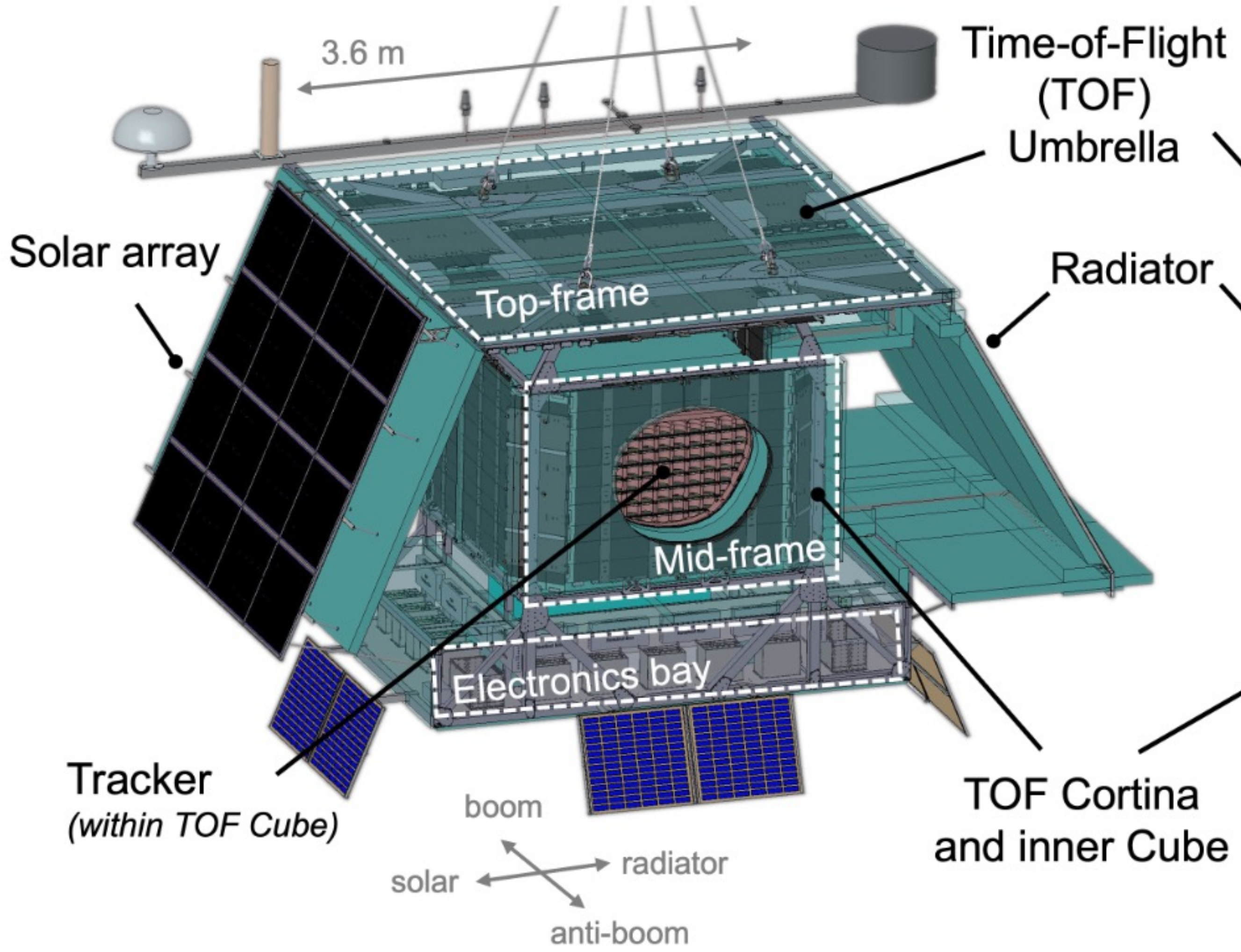
GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)
GAPS sensitivity to antiprotons: Aramaki+ Astropart.Phys. 59, 12-17 (2014)

The GAPS instrument

GAPS Collaboration: arXiv:2604.19830v1 (2026)

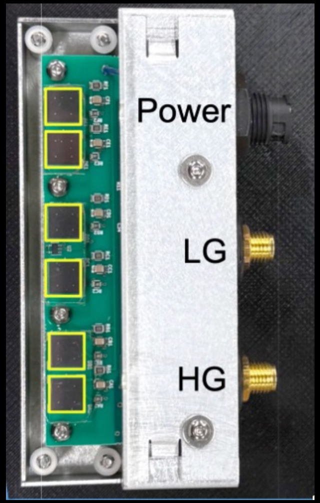


Time of flight system

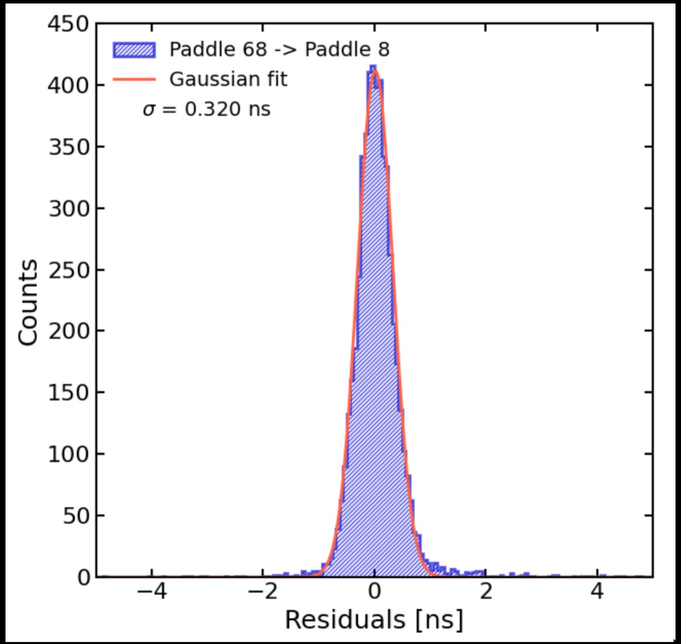
Bird et al., Proc. ICRC (2019); Quinn et al., Proc. ICRC (2019); Quinn et al., Proc. ICRC (2021); Feldman et al., Proc. ICRC (2023)

The TOF measures dE/dx, position and provides our trigger and velocity of the incident particle

- 160 plastic scintillating paddles surrounding the tracker
- <400 ps timing resolution
  - Cross-calibration between different paddle combinations



Preamp board for SiPM



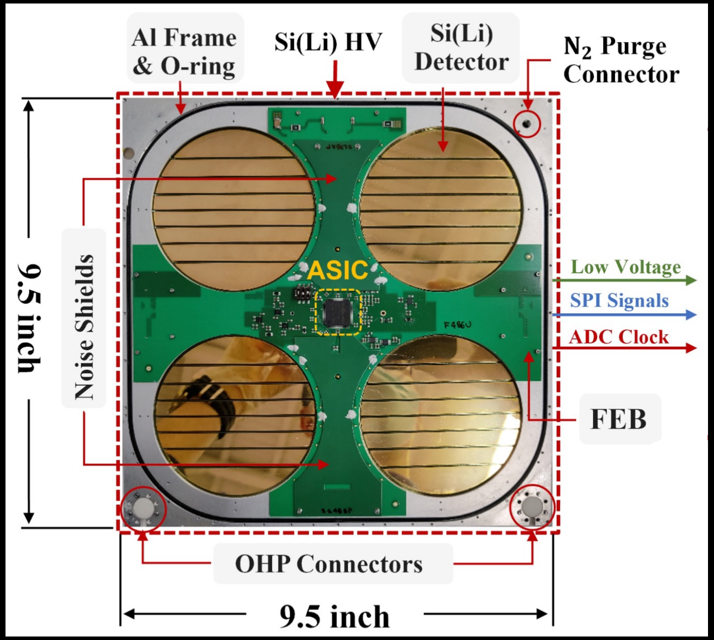
Timing resolution between paddles

Outer tof system

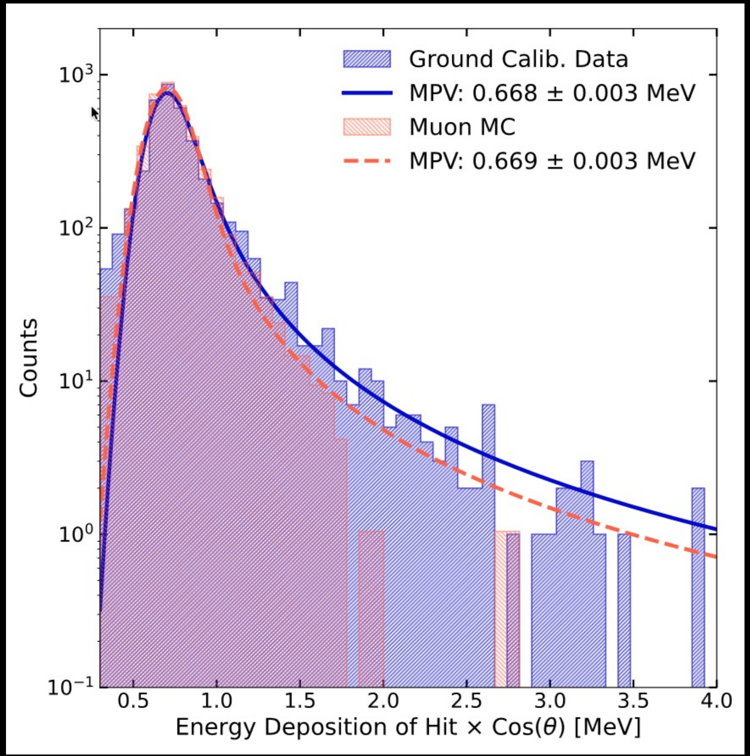

Inner TOF system, surrounding the tracker

Si(Li) tracker system

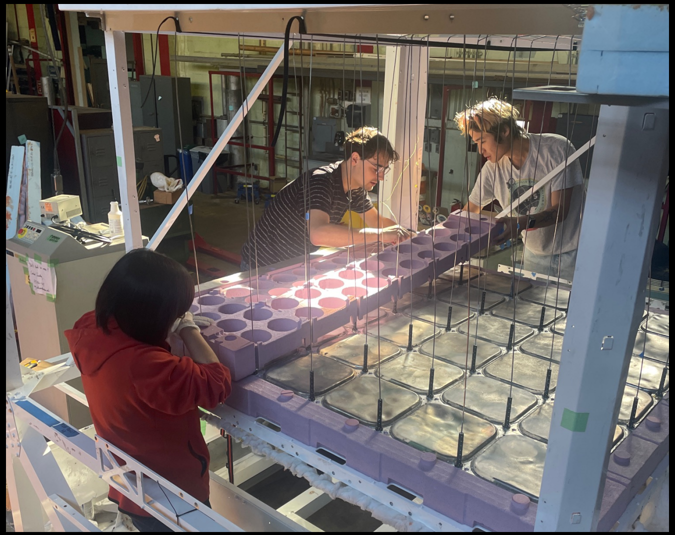
- 1009 Si(Li) detectors, 2.5 mm thick with 10 cm diameter
- Operates at temperatures $\lesssim -35°C$
- Energy resolution from 20 keV to 100 MeV
- <5 keV (FWHM) X-ray energy resolution below 100 keV and $\lesssim$ 10% in the MeV range

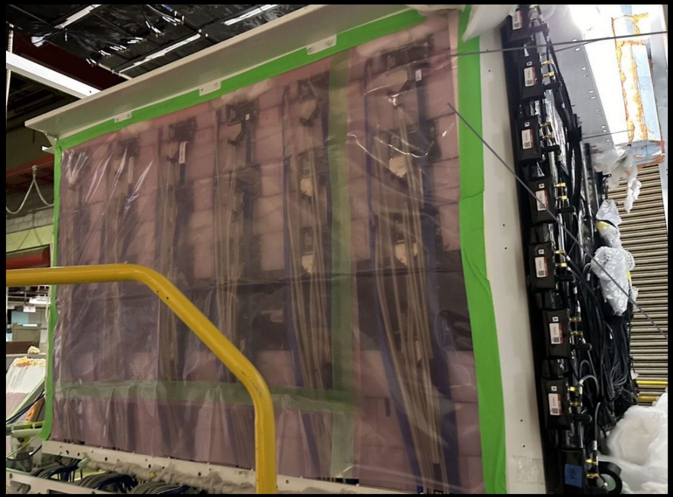


Tracker module



Energy depositions on track

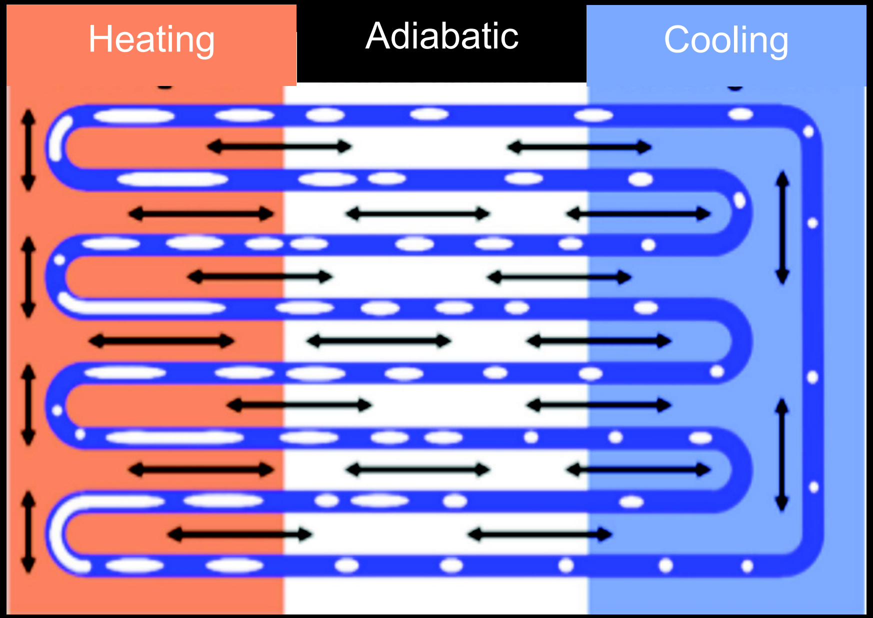

Integration of the tracker

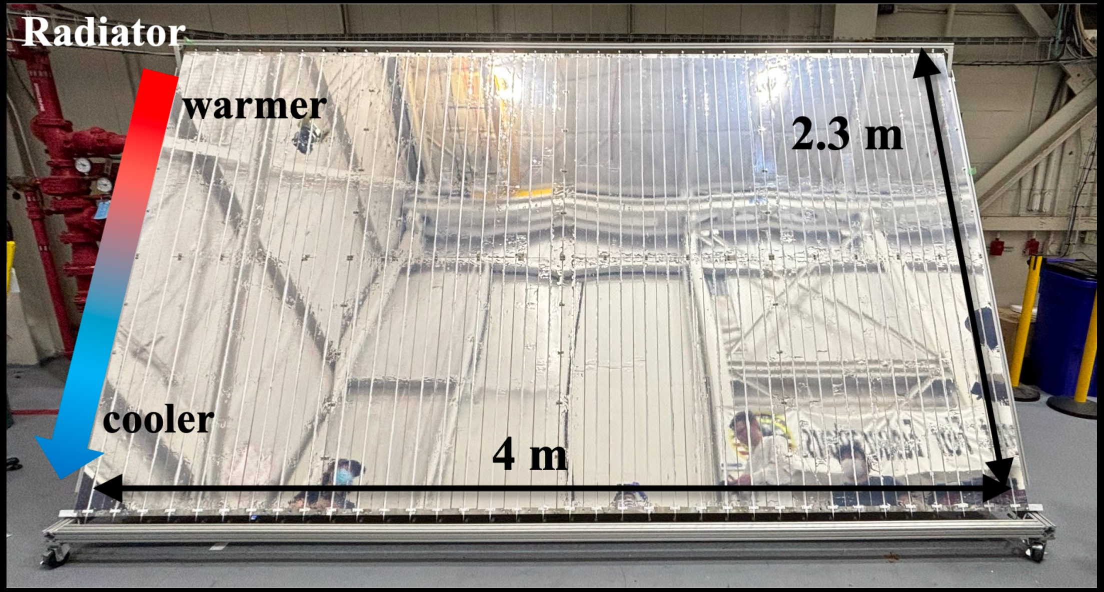

Integrated tracker

ASIC: Manghisoni et al., IEEE 62 (2015); Manghisoni et al., IEEE 68 (2021); Manghisoni et al., IEEE 71 (2023);
Si(Li): Perez et al., NIM A 905 (2018); Kozai et al., NIM A 947 (2019); Rogers et al., JINST 14 (2019); Saffold et al., NIM A 997 (2021); Kozai et al., NIM A 1034 (2022); Xiao et al., IEEE 70 (2023)

Thermal system

- First multi-meter-scale multi-loop capillary heat pipe system operated in space
- Passive cooling circulation developed at JAXA/ISAS:
  - Small capillary tubes filled with a phase-changing refrigeration liquid → Bubble expansion and contraction create thermo-contraction hydrodynamic waves that transport heat
- Can transport up to 300 W of heat
- Minimal power requirements

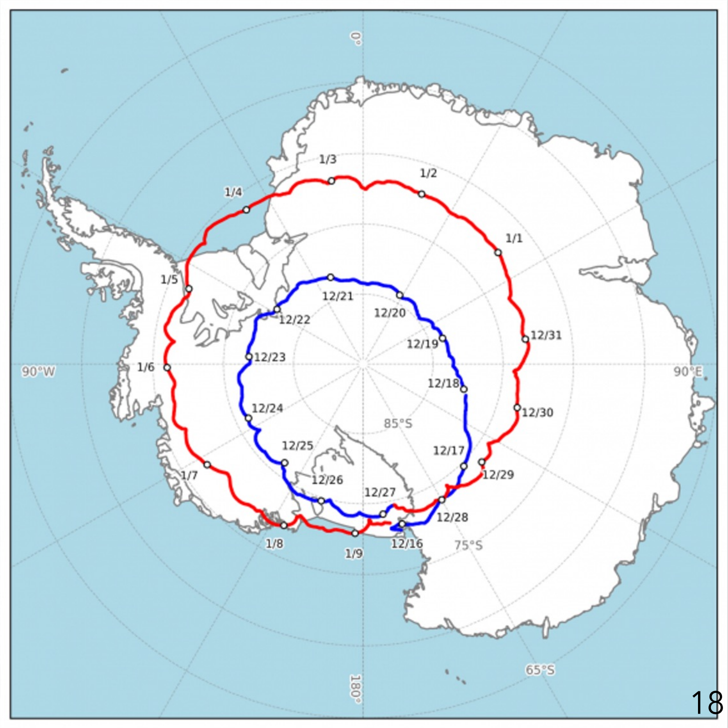




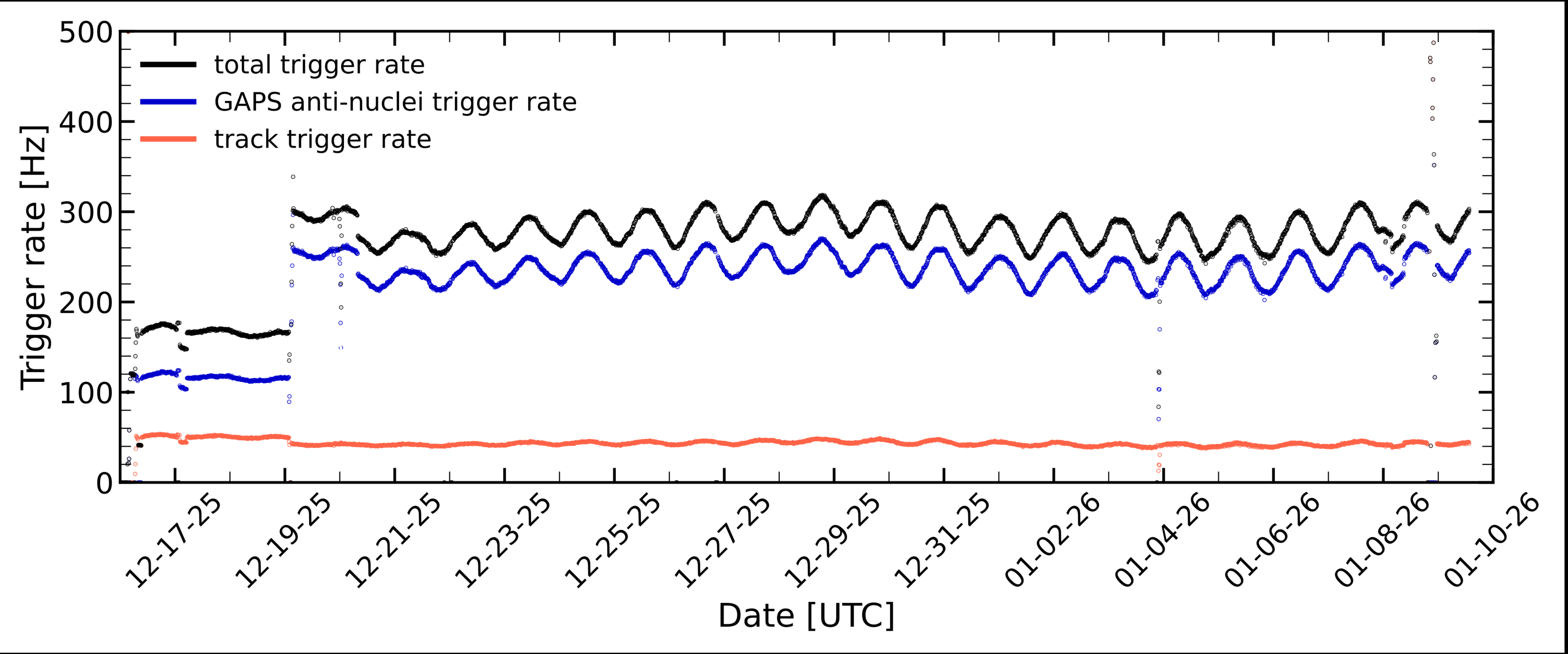
The GAPS MCHP system

Fuke+ Transactions JSASS Aerospace Technology (2016)
Fuke+ Journal of Astronomical Instrumentation (2017)
Okazai+_Journal of Evolving Space Activities (2024)
Fuke+ Journal of Evolving Space Activities (2023, 2024)

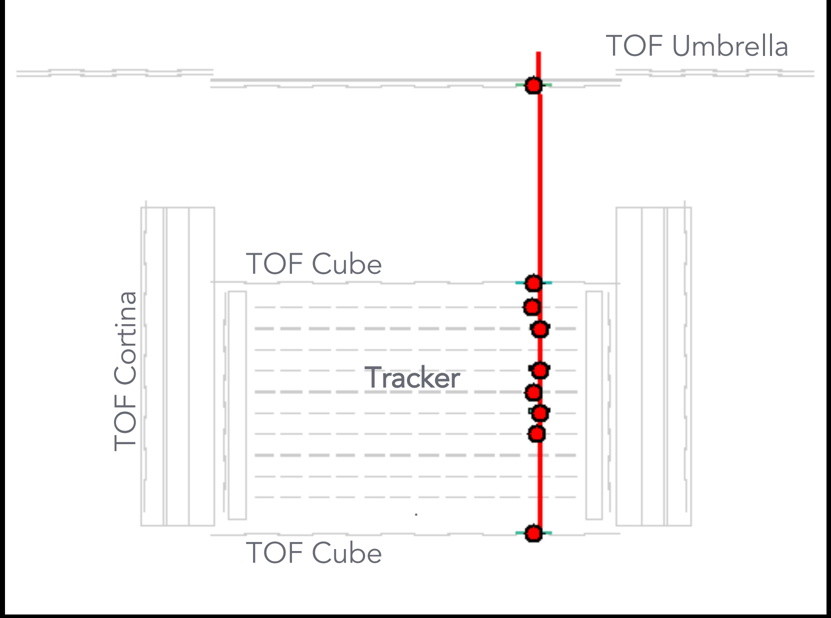
GAPS Flight 1: December 16, 2025 to January 10, 2026



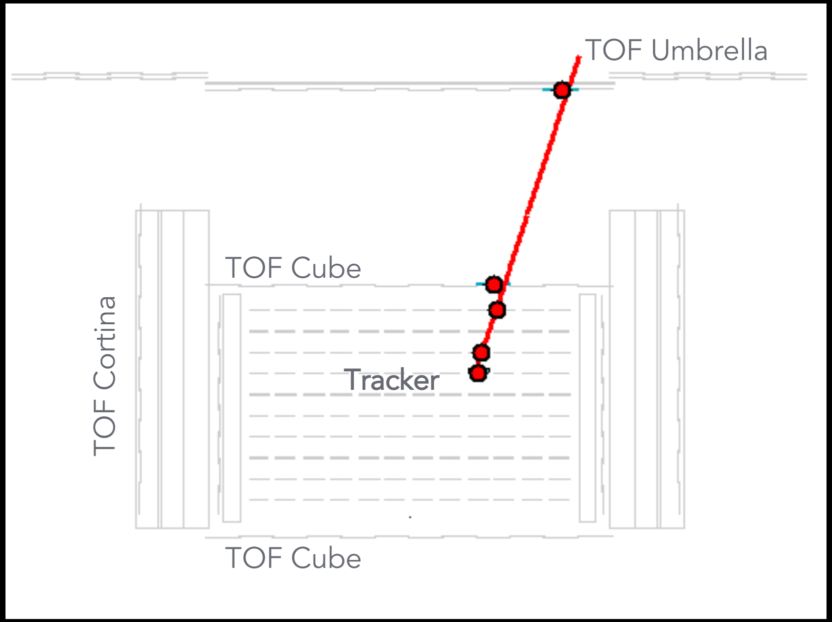
Flight time: 25 days, 2 hours, 53 mins = 540M triggers



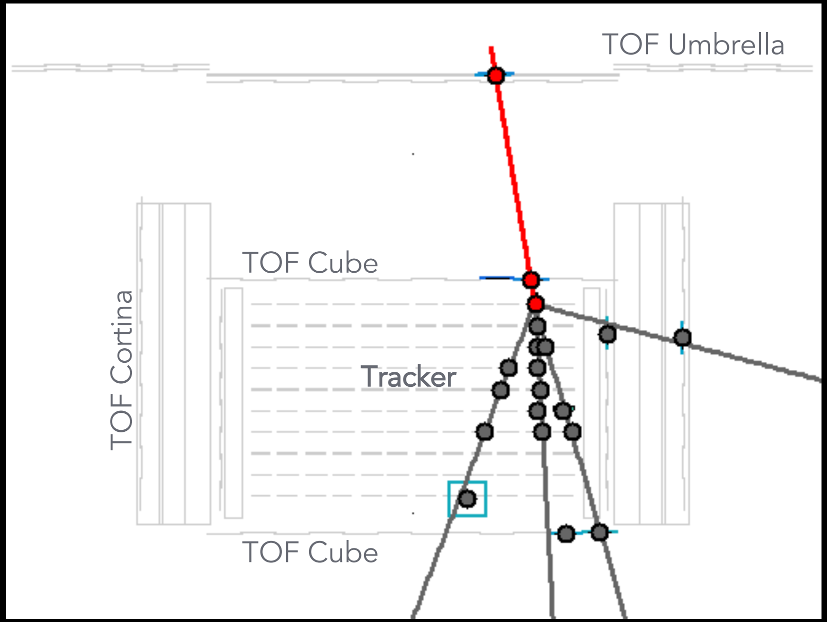
Single and multitrack events from ground and flight data



Fast muon from ground calibrations

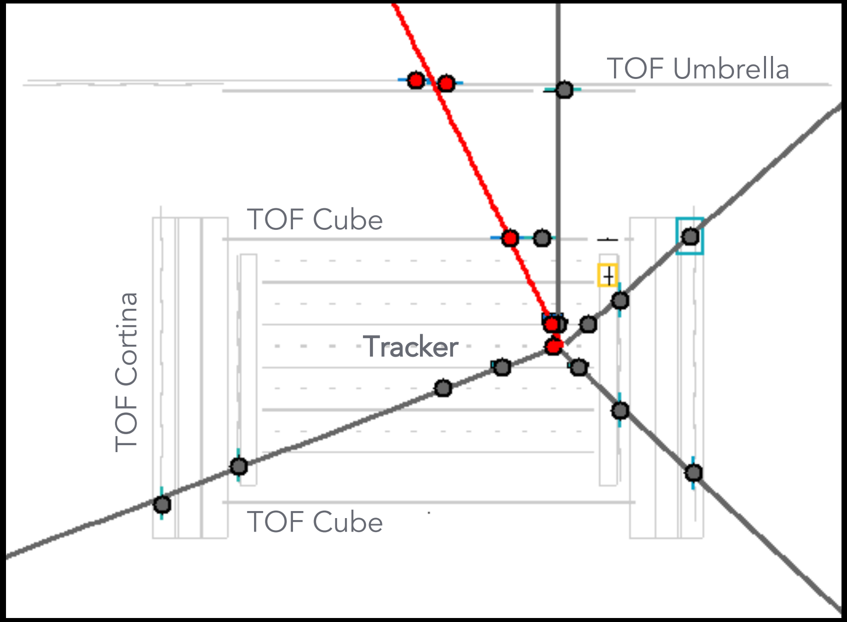


Slow single-track event during flight

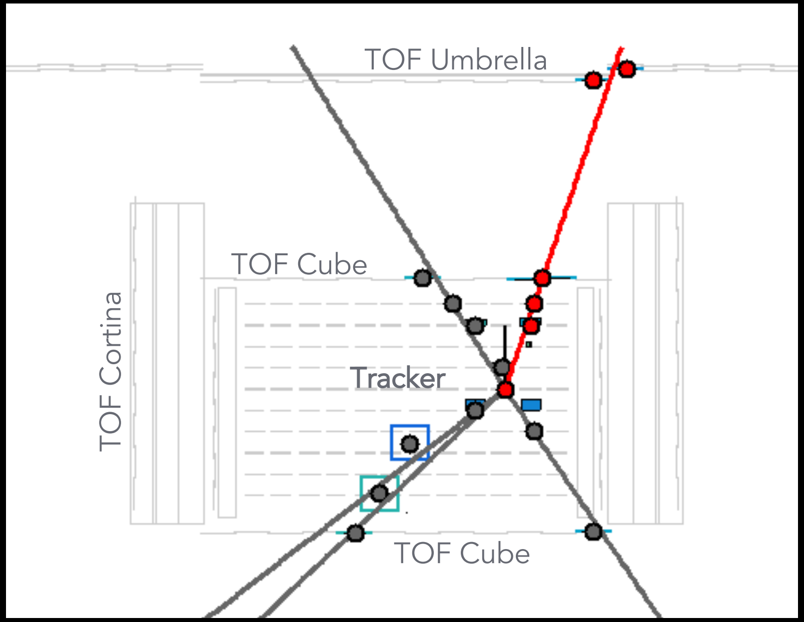


Forward-shower during flight

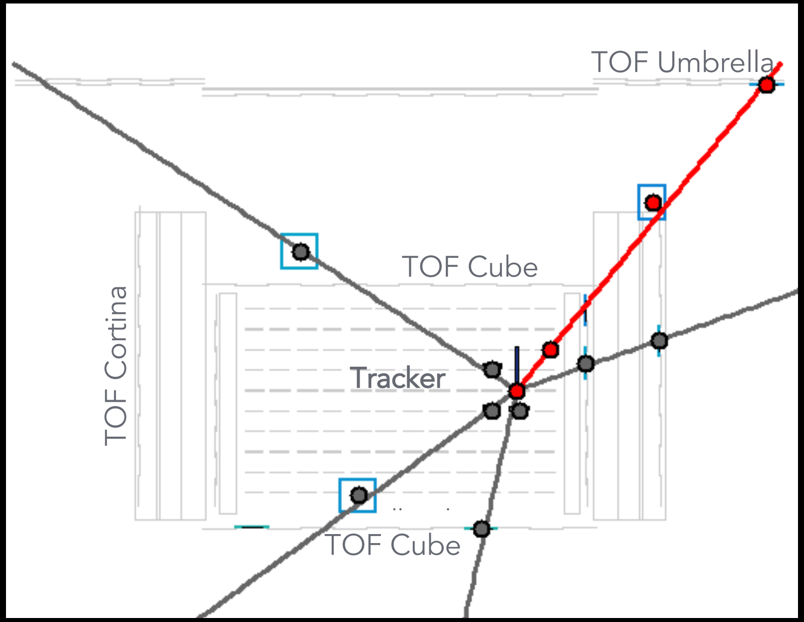
Complex morphology event reconstruction



Simulated antinucleus event

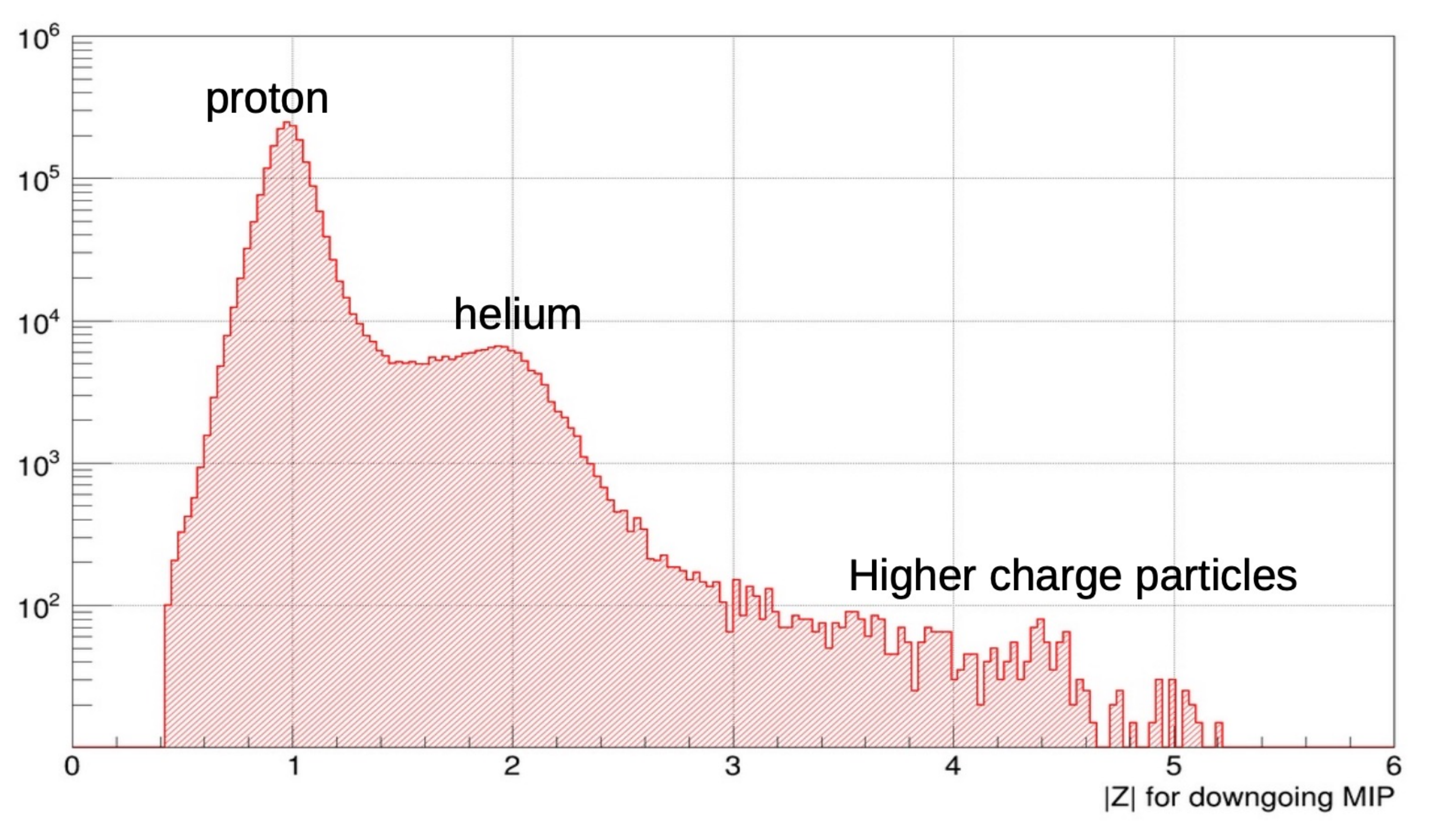


Isotropic event during flight

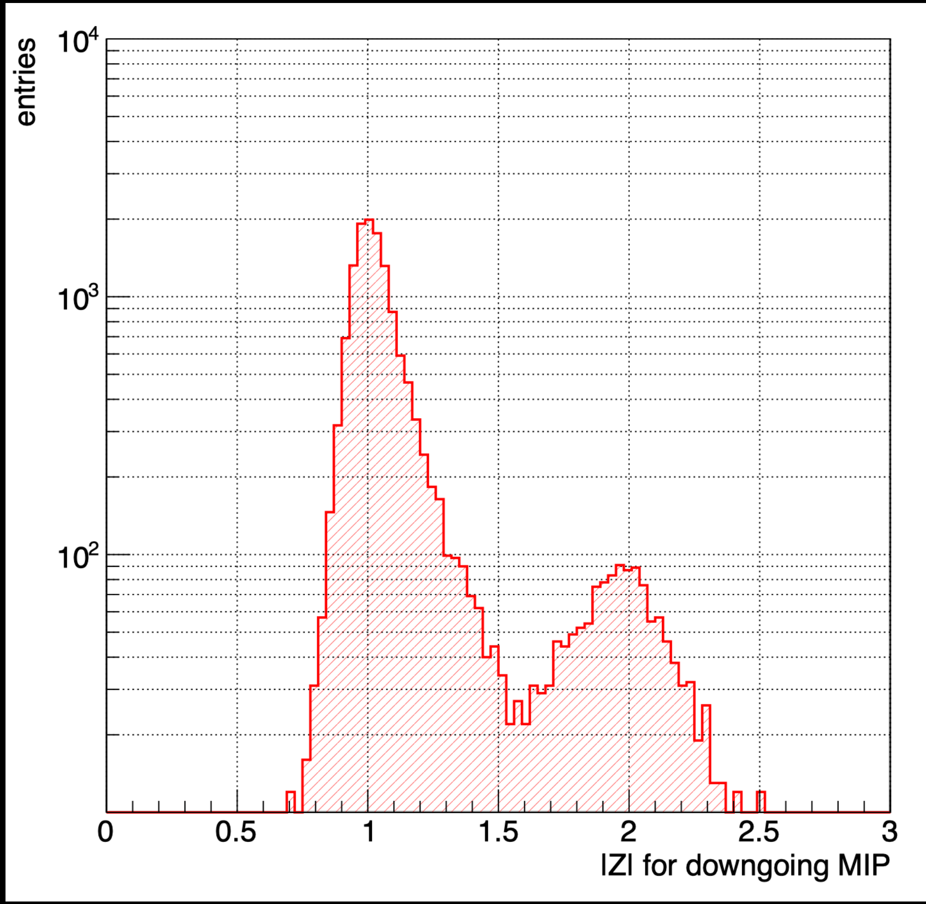


Isotropic event during flight

Charge distributions of single-track MIPs



Charge spectrum before instrument TOF timing, TOF/tracker energy calibrations, reconstruction optimization, etc.



Reconstruction algorithm optimization ongoing

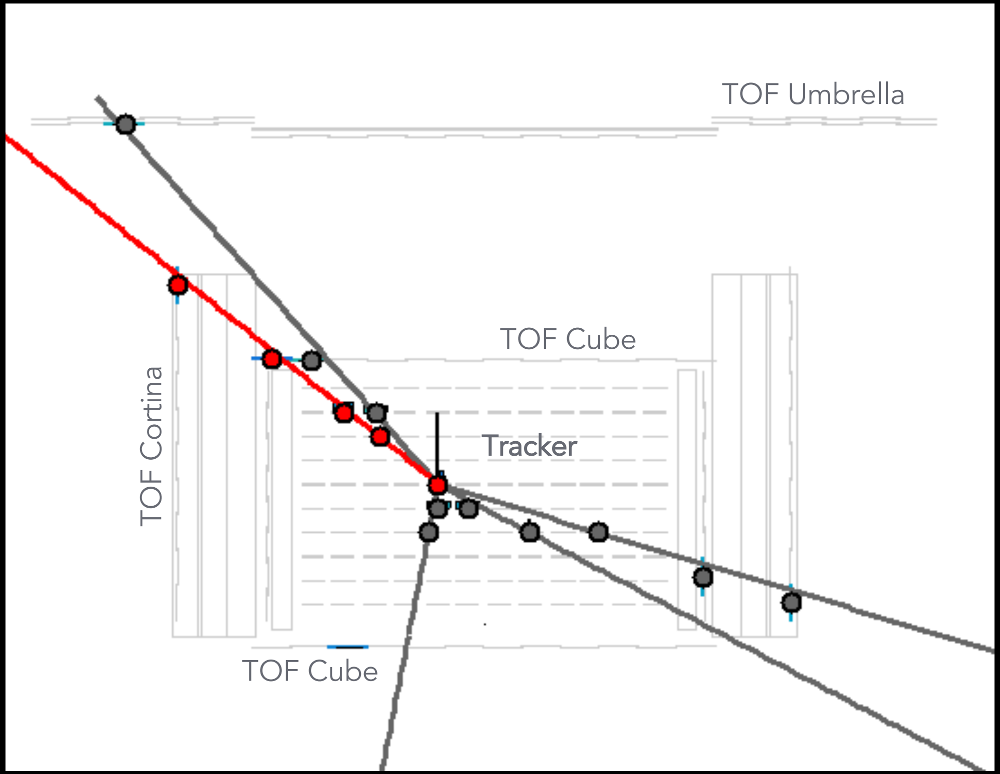
Conclusions

- The GAPS collaboration is analyzing data from the successful 25-day first flight
- Preparations for future flights are underway!
  - The payload is back
  - More Si(Li) detectors
  - Upgrades to tracker electronics

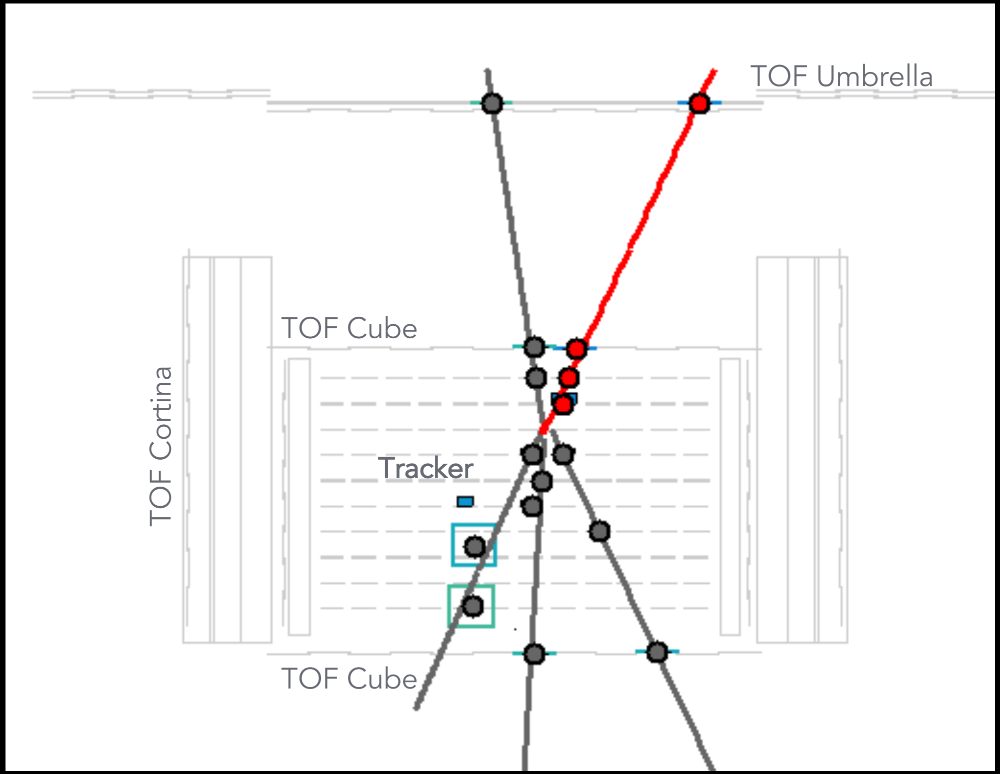
Special thank you to:
Columbia Scientific Balloon Facility
NASA Balloon Program Office
Antarctic Support Contractor
National Science Foundation

Backup Slides

Complex morphology event reconstruction, additional isotropic events

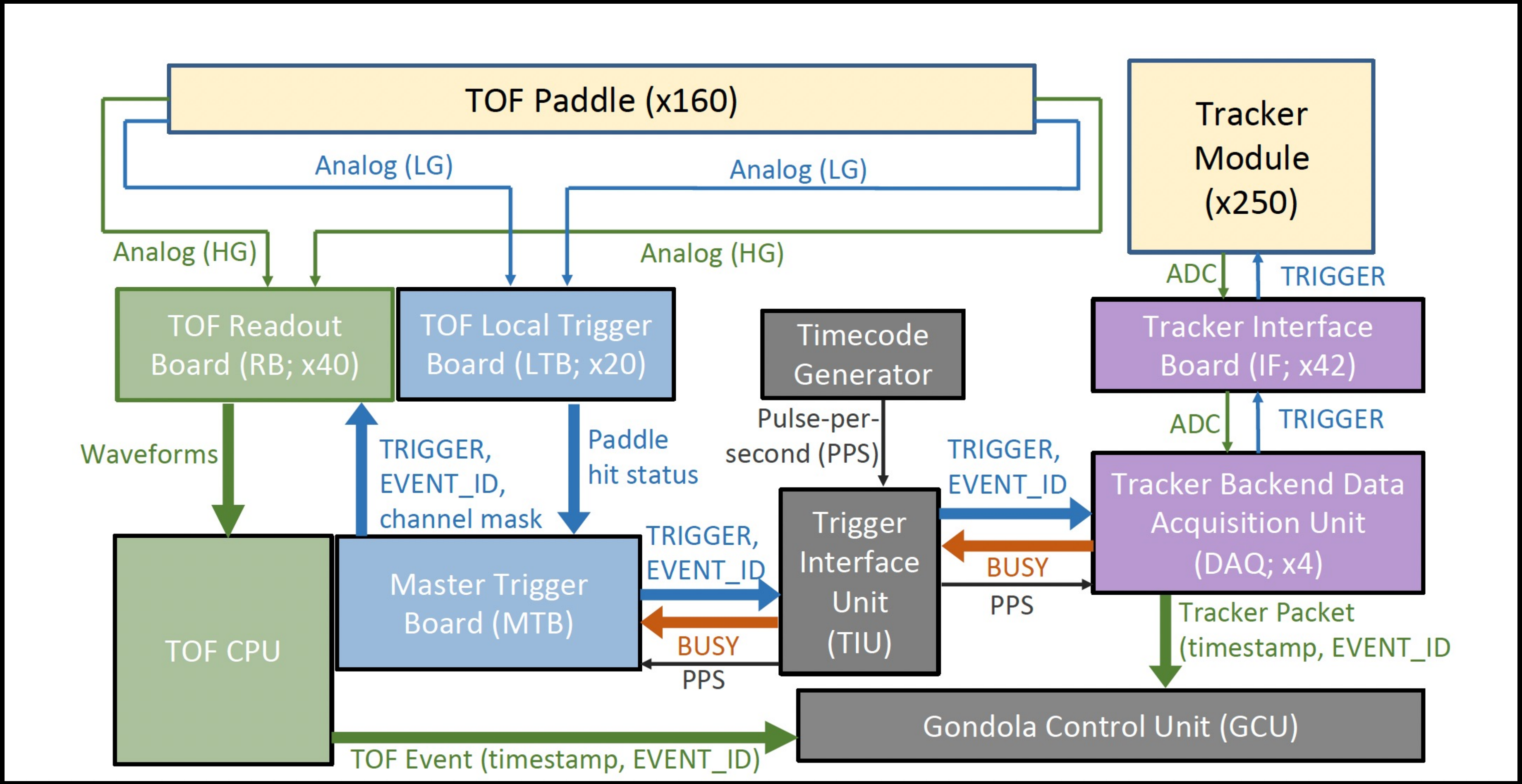


Isotropic event during flight



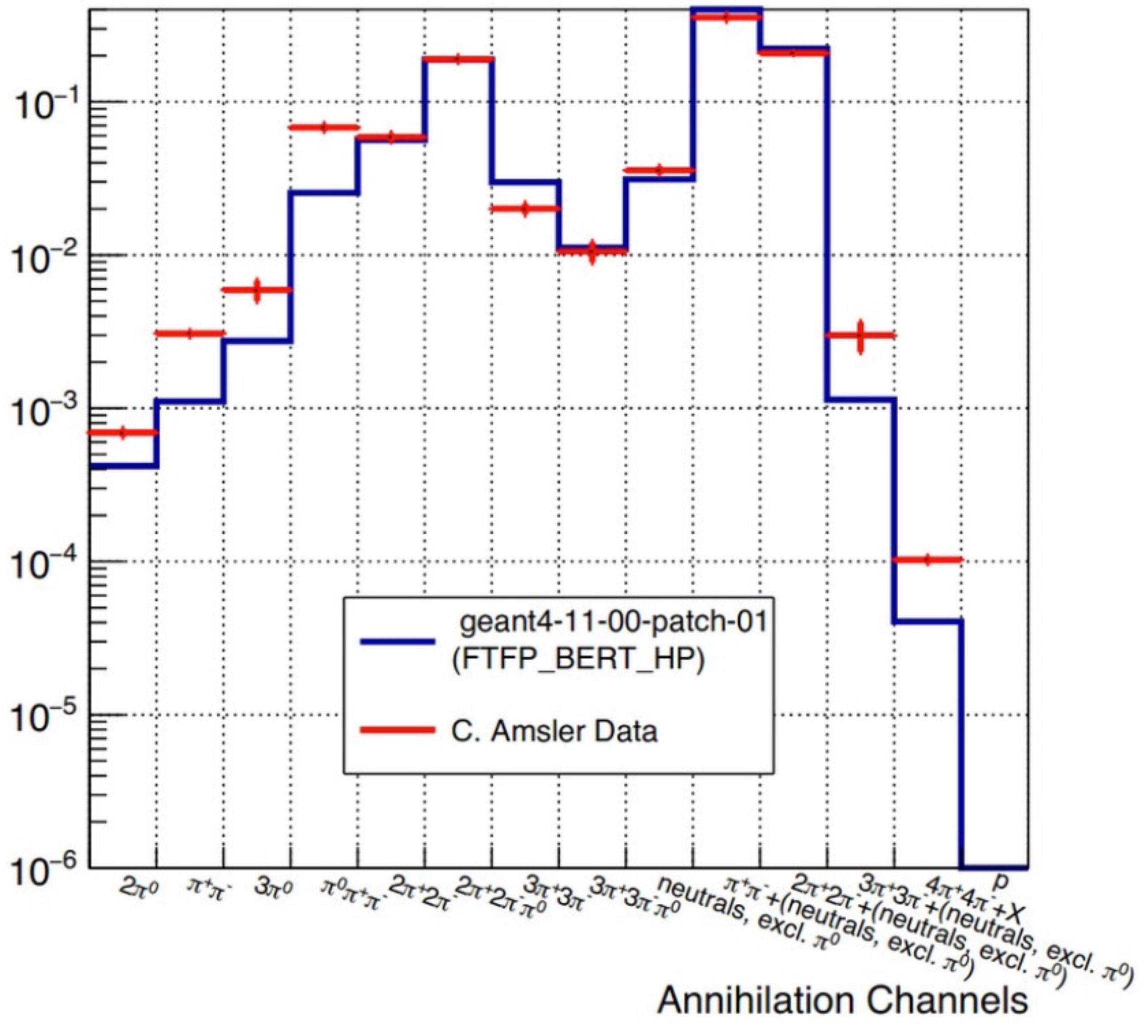
Isotropic event during flight

Power and Signal Flow



GAPS Collaboration: arXiv:2604.19830v1 (2026)

p̄+p annihilation at rest

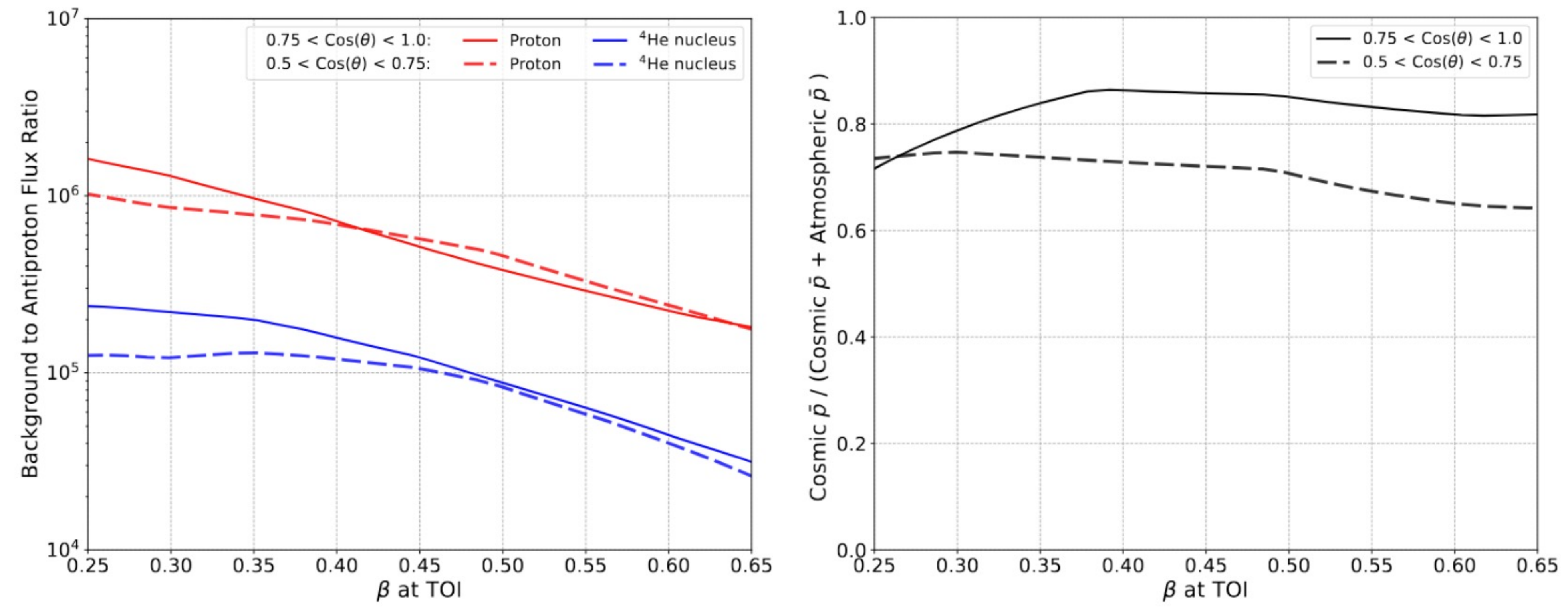


Slide Credit: P. von Doetinchem

- Worked with Geant4 physics lists developers on improving annihilation at-rest physics (ongoing)
- use antiproton data for validation

Antiproton background

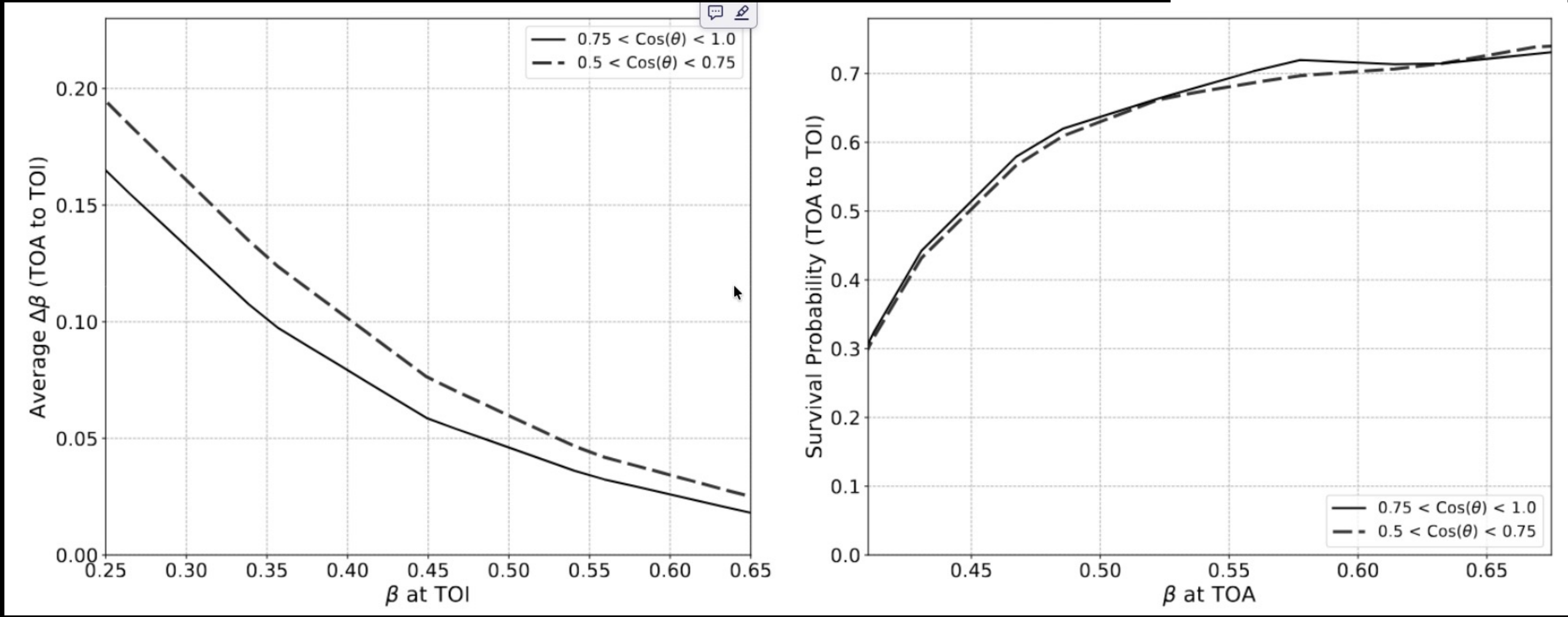
Slide Credit: P. von Doetinchem



- 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

Slide Credit: P. von Doetinchem



- 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 angel of 0.25 < **β** < 0.65 at TOI corresponds to 0.41 < **β** < 0.68 at TOA.

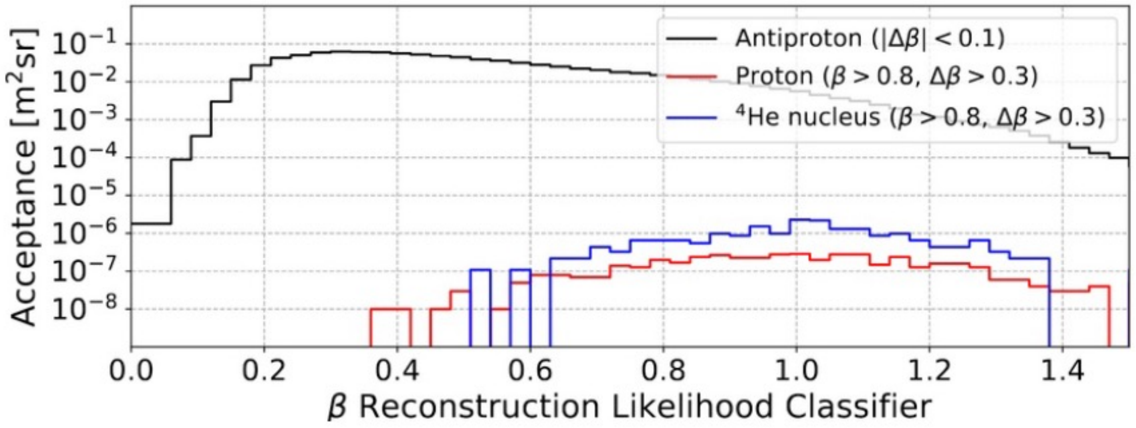
- The survival probability for antiprotons at TOA to reach TOI is given as a function of **β** at TOA and presented in the same angular bins

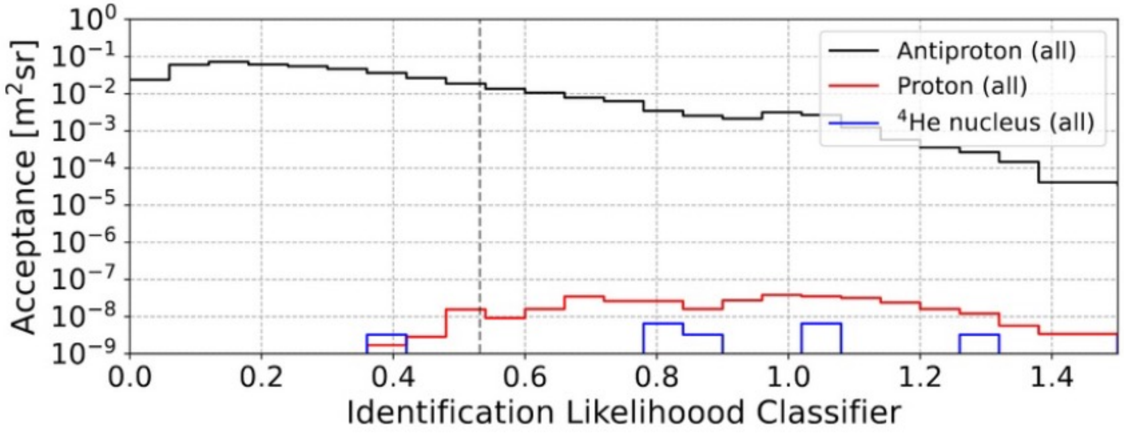
Antiproton Identification

Slide Credit: P. von Doetinchem

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 $\mathrm{d}E/\mathrm{d}x$	✓	
Primary TOF $\mathrm{d}E/\mathrm{d}x$		✓
TOF $\mathrm{d}E/\mathrm{d}x$ over truncated mean $\mathrm{d}E/\mathrm{d}x$	✓	
Vertex energy over truncated mean $\mathrm{d}E/\mathrm{d}x$	✓	
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 $0.34 \leq \beta < 0.40$ and $\cos(\theta) > 0.75$ that have passed the trigger and preselection conditions.

Acceptance for Antiprotons and Antihelium-3

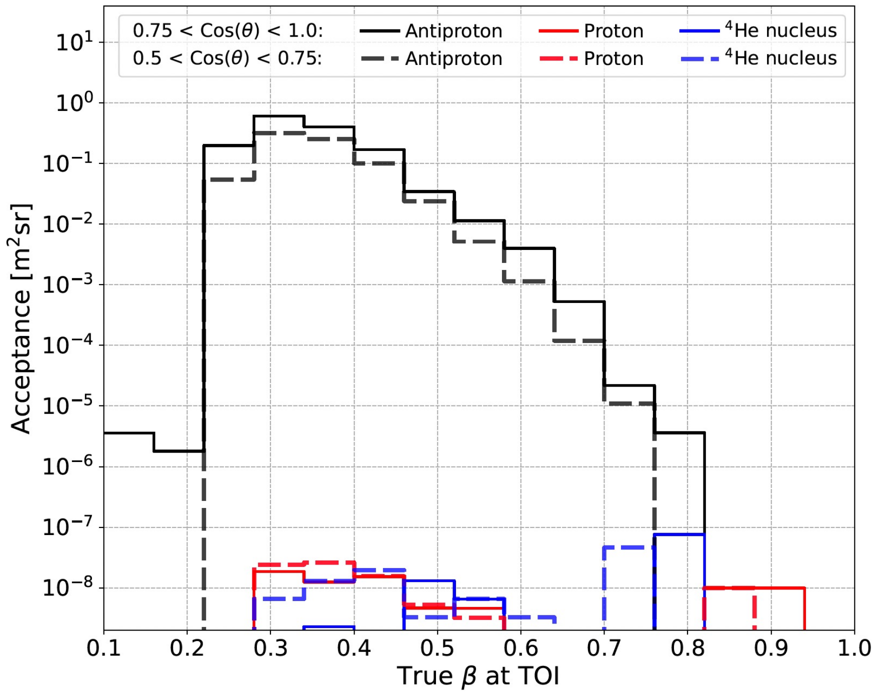


Figure 7: Acceptance of the GAPS instrument for antiprotons (black) as well as background species protons (red) and ^{4}He nuclei (blue) is shown for events passing all selection criteria. Though the analysis is performed in terms of the reconstructed β, the acceptance is binned in the true β at TOI. The acceptance is presented in two bins in $\cos\theta$.

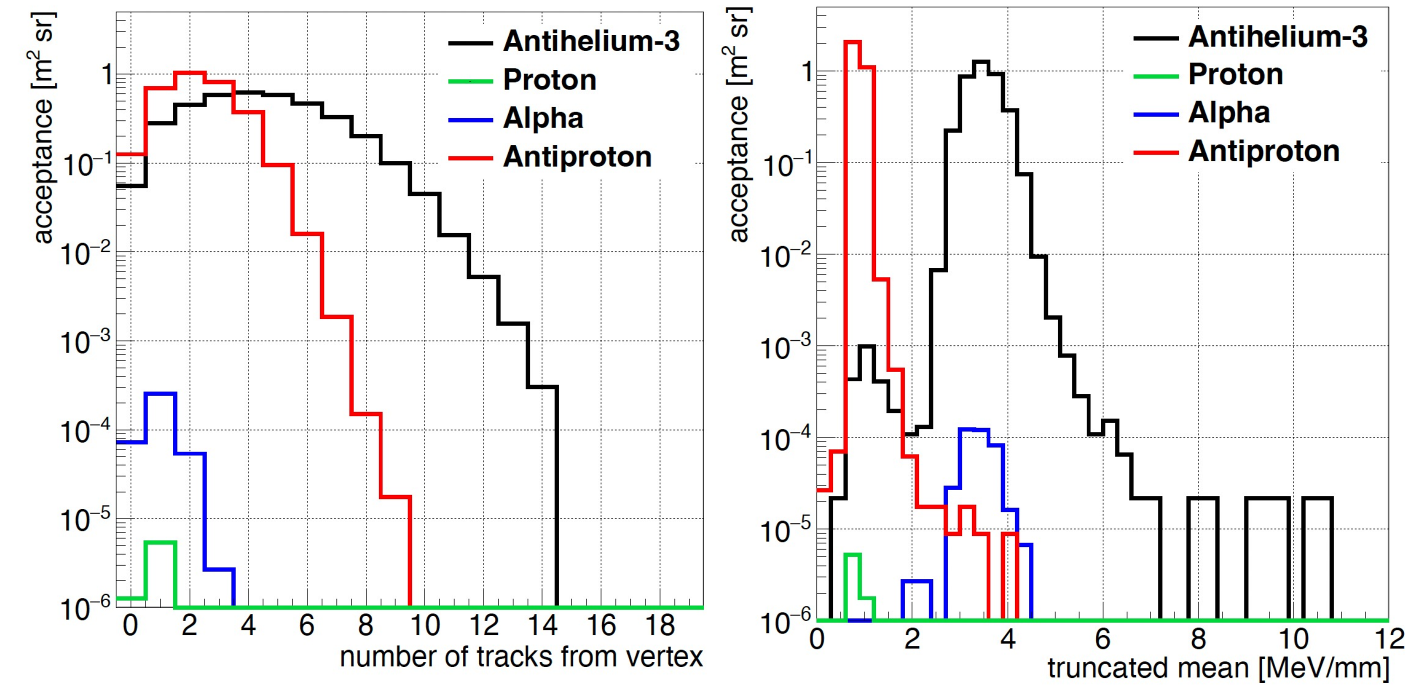
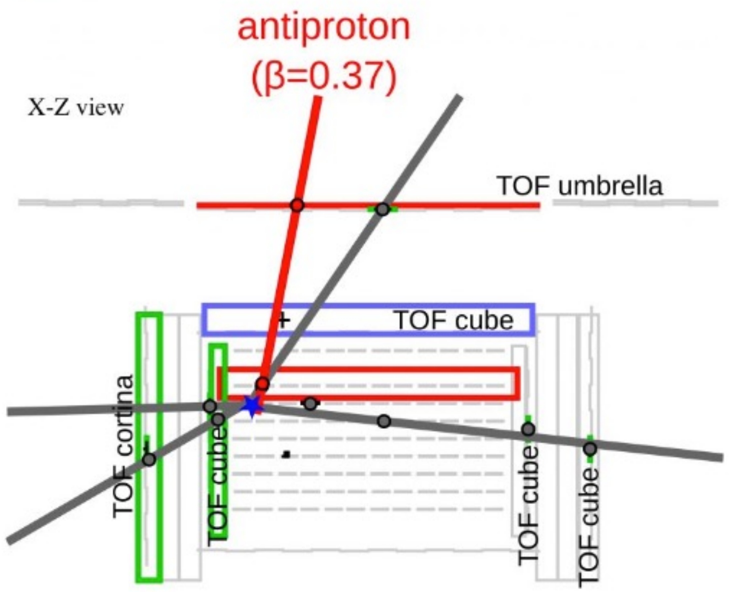


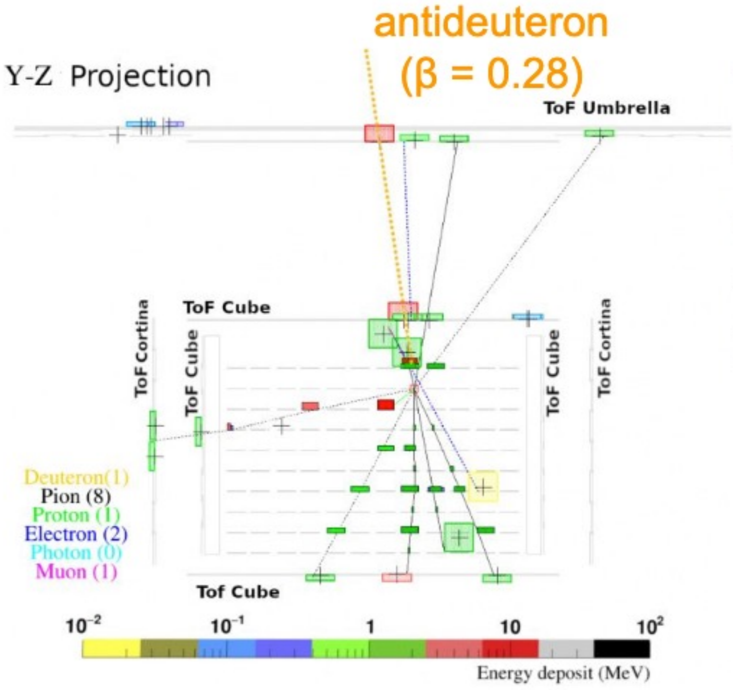
Figure 3: Examples of the estimated acceptance for two identification variables for antihelium-3 nuclei, antiprotons, protons, and α-particles passing trigger and quality cuts (velocity range $0.39 < \beta_{\mathrm{TOI,gen}} < 0.41$): *Left:* Number of reconstructed tracks from the stopping vertex. *Right:* Truncated mean energy deposition on the primary track.

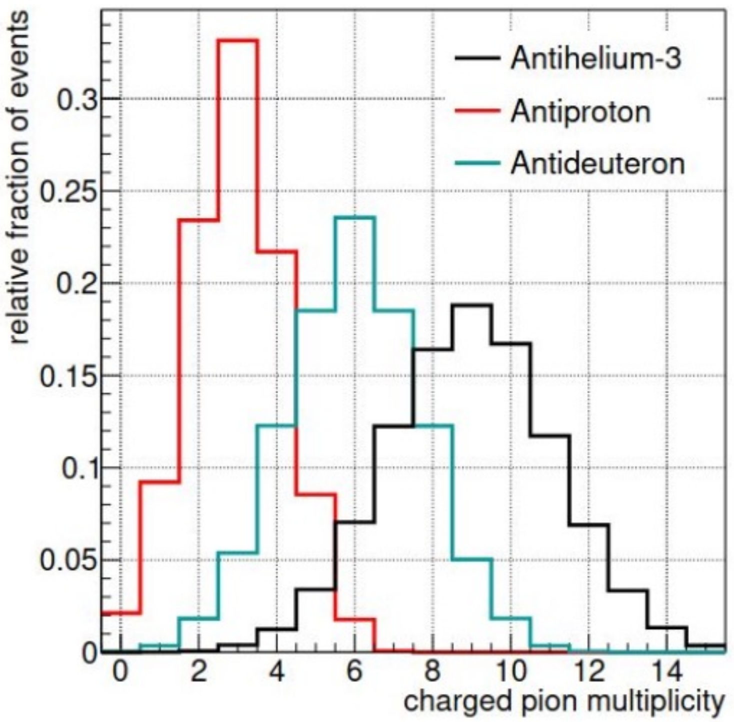
N. Saffold et al., Astropart. Phys. 130 (2021)
F. Rogers+ Astropart. Phys. 145 (2023)

Annihilation Product Multiplicity

Slide Credit: C. Hailey





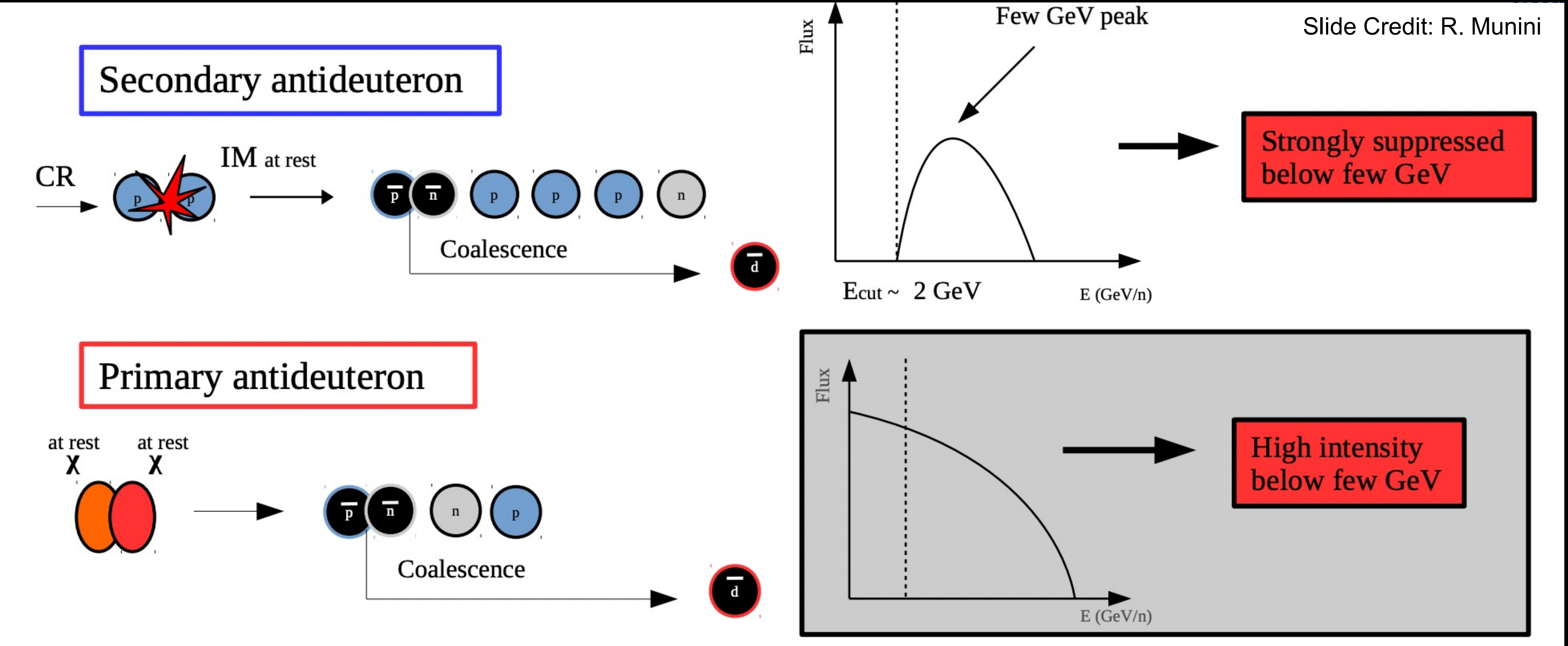


After an incident antinucleus forms an exotic atom, the annihilation that terminates the exotic atom decay is well approximated by an at-rest annihilation event.

Simulated charged-pion multiplicity produced in annihilations of antiprotons, antideuterons, and antihelium-3 nuclei at rest in silicon

N. Saffold+ Astropart. Phys. 130 (2021)

Antideuteron production



Antinculei Formation: Coalescence Model

Slide Credit: K. Perez

Coalescence: n̄ and p̄, merge when relative momentum < $\mathbf{p_0}$ (Yield ~ p_0^3)

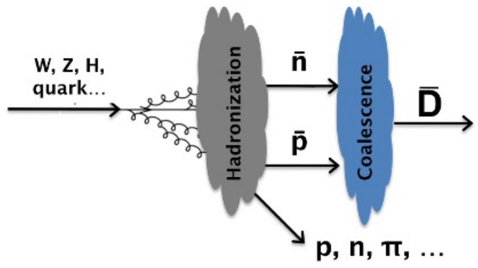
To determine p_0:

- MC generator with antideuteron "afterburner" accounts for correlations due to production channel or center-of-mass energy
- All depends on choice of **hadronization** model (and antiproton cross sections)
- Then tune this to experimental data

Current status: a dominant uncertainty of ~10x on low-E antideuteron production

Prospects for improvement (soon!): measurements at NA61/SHINE, COMPASS, LHCb, ALICE

See also: freeze-out from a quark-gluon plasma aka "**statistical thermal model**", e.g. Floris 1408.6403 (2014), Bellini+Kalweit 1807.05894 (2019)



D.-M. Gomez-Coral+ PRD (2018) 1806.09303