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

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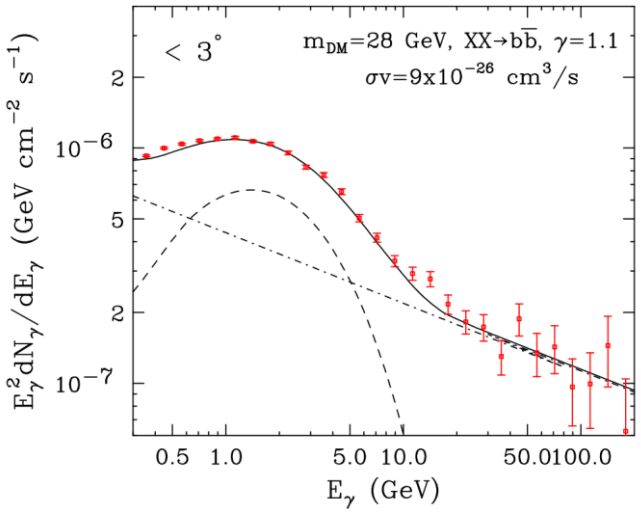
Shanghai Jiao Tong University

2025-08-27

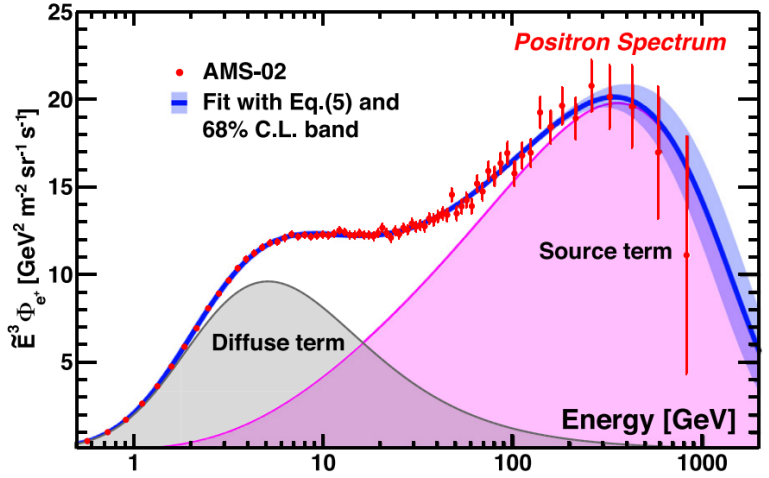
(On behalf of the GAPS collaboration)

Dark Matter Hints in Cosmic Rays

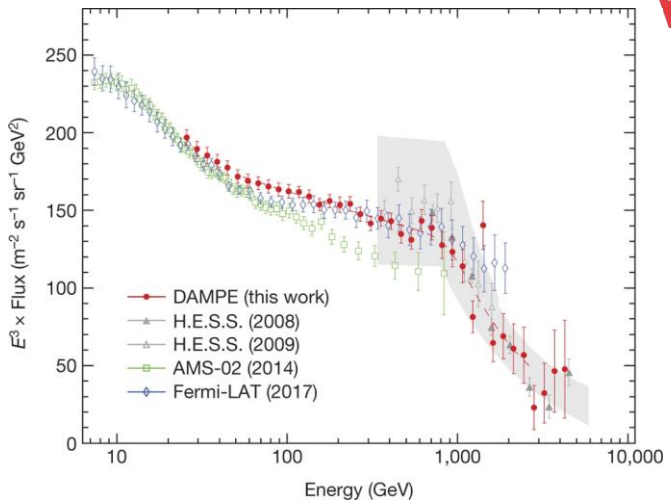
D. Hooper+ *PRD* (2011), I. Cholis+ *JCAP* (2009)



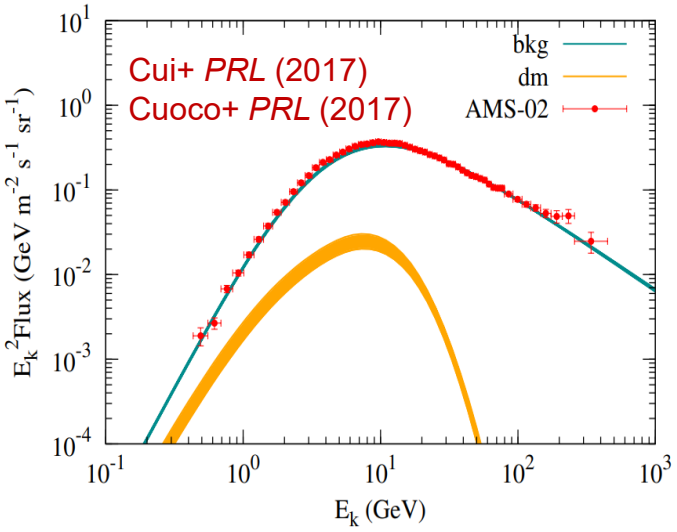
AMS-02: *Physics Reports*, Vol 894 (2021)



DAMPE, *Nature* (2017)



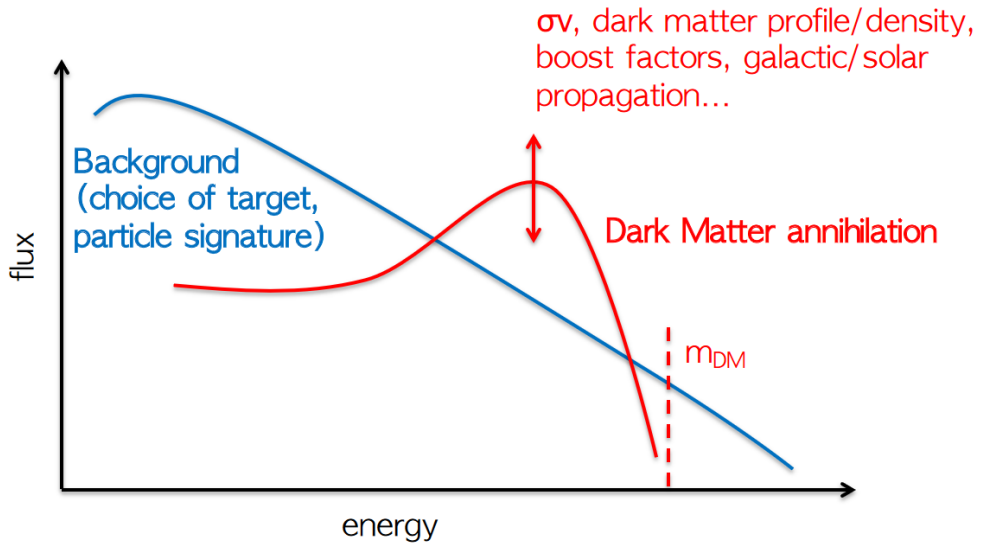
- GeV gamma excess at GC center by Fermi-LAT.
- Positron/Electron (~TeV) excess by PALEMA, AMS-02, Fermi-LAT, CALET, DAMPE.
- Antiproton excess in the 10-20 GV rigidity by AMS-02.
- Antihelium “candidates” by AMS-02.



Dark matter interpretation is complicated by astrophysical backgrounds and systematic uncertainties!

Dark Matter Detection with Cosmic Rays

❑ ***Assumption:*** dark matter annihilation/decay follows different kinematics (i.e. via physics BSM) than conventional productions.

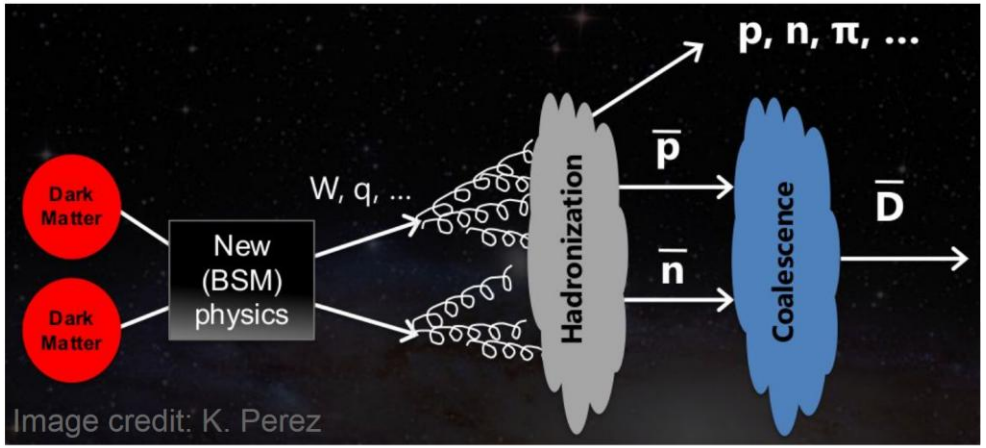


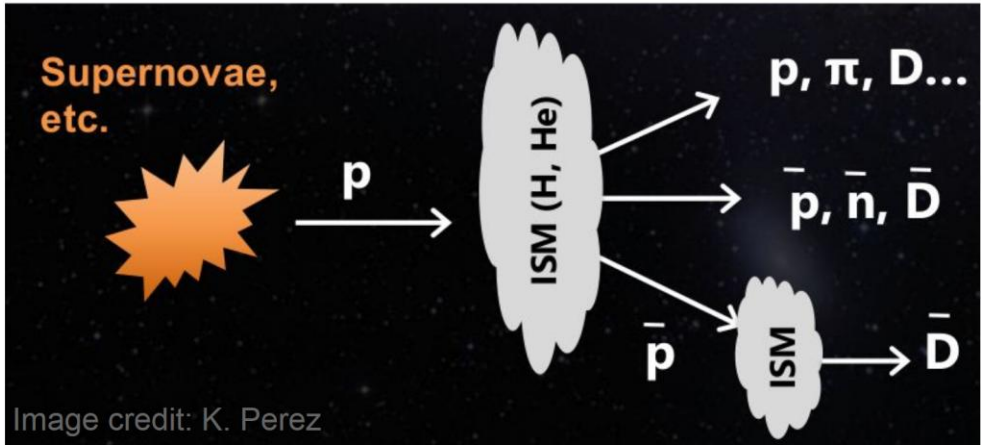
Common challenge (*FUN!*) =
minimize/constrain astrophysical bkg.
maximize predicted dark matter signal.

- ❑ Directly probes process that sets DM abundance!
- ❑ But, large systematic uncertainties
  - Comic ray propagation uncertainty
  - Hadronic interaction
  - Backgrounds from astrophysical sources
  - DM distribution profiles
  - DM annihilation final states
  - ….

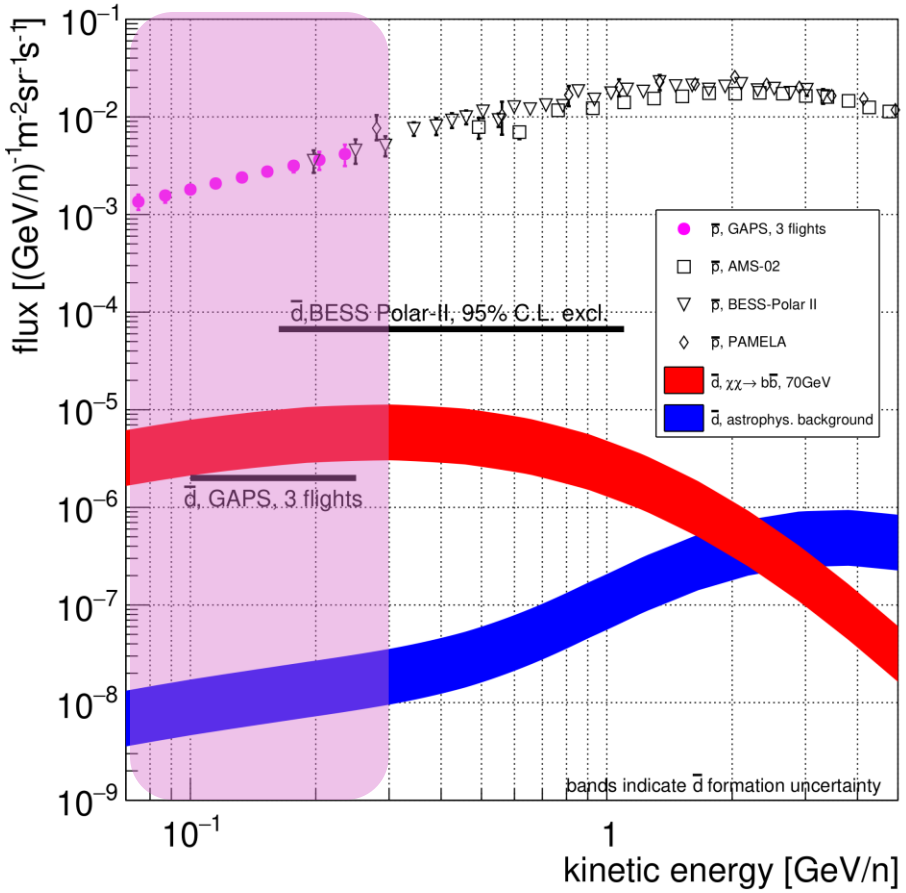
Antideuterons as Dark Matter Signature

- Low-energy cosmic ***antideuterons***: essentially background-free signature of dark matter, and *MEASURABLE!!*





P. von Doetinchem+ JCAP 08 (2020)



The GAPS Balloon Mission

❑ **GAPS=G**eneral **A**nti**P**article **S**pectrometer

- Antarctic balloon experiment

❑ Unique sensitivity to ***low-energy cosmic antinuclei*** using novel exotic atom decay signatures: X-rays + charged particles

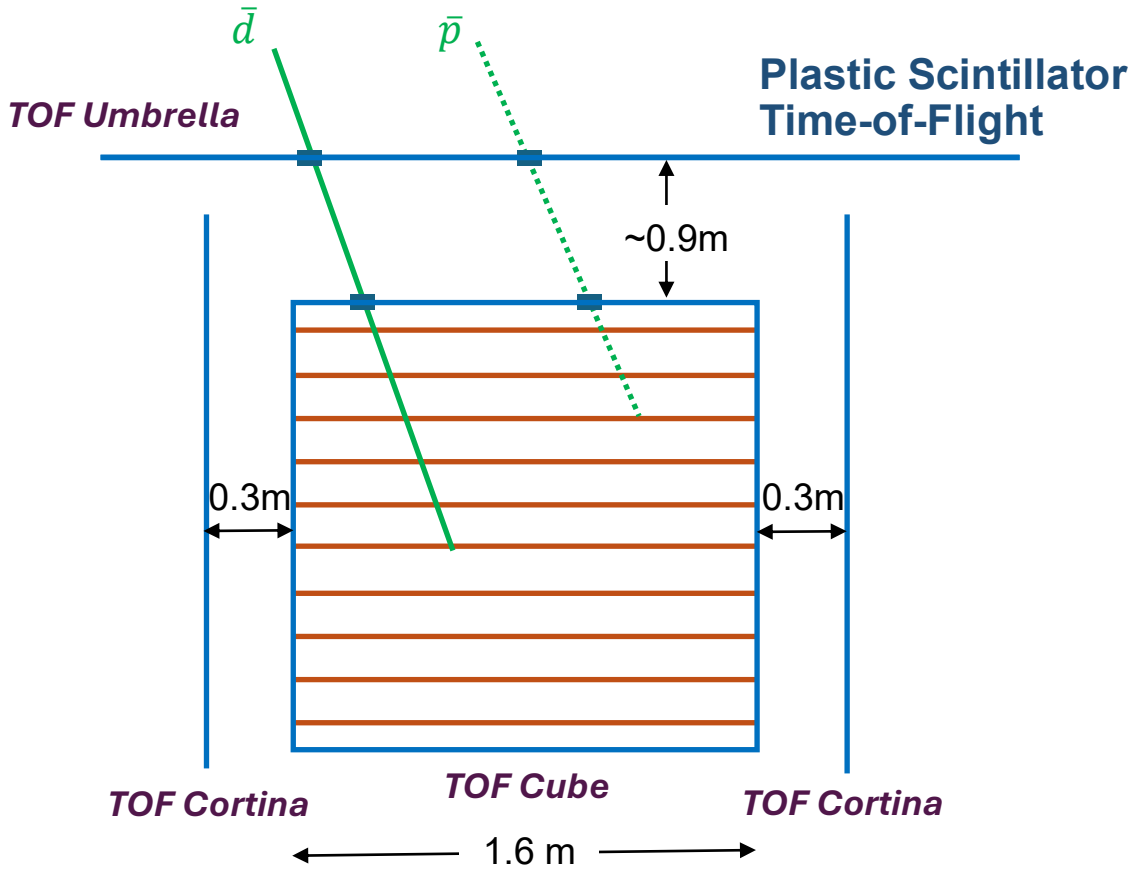
❑ Primary goal: low-energy (KE≲0.25 GeV/*n*) ***Antideuteron*** *as signature of new physics*.

- Can probe many general dark matter models.

+ High statistics measurement of low-energy ***Antiproton*** and leading sensitivity to low-energy ***Antihelium.***

➢ First Antarctic balloon flight late-2025, and two follow-up flights planned.

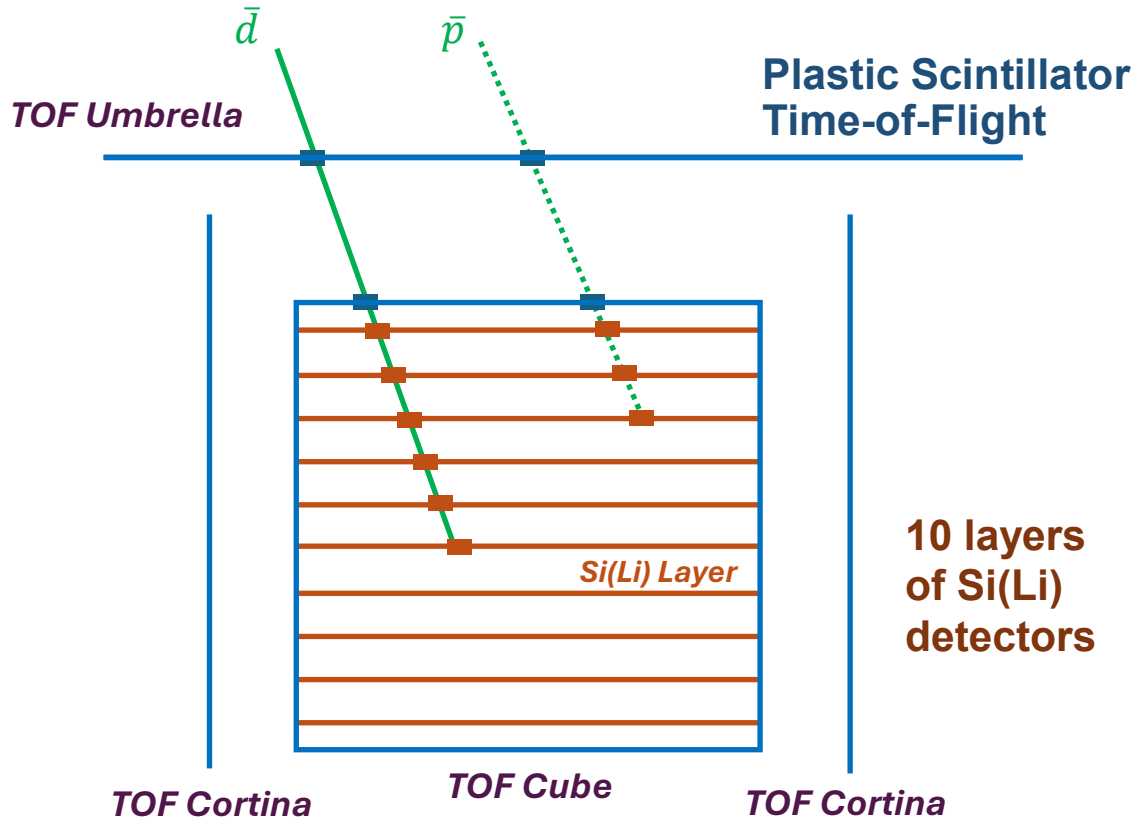
GAPS Novel Detection Technology



Time-of-flight system: measures velocity, incoming angle and dE/dx, fast trigger

Exotic atom technique verified at KEK: Aramaki+ Astropart.Phys. 49, 52-62 (2013)
GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)

GAPS Novel Detection Technology



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Si(Li) tracker:

- Slows/captures an incoming antiparticle

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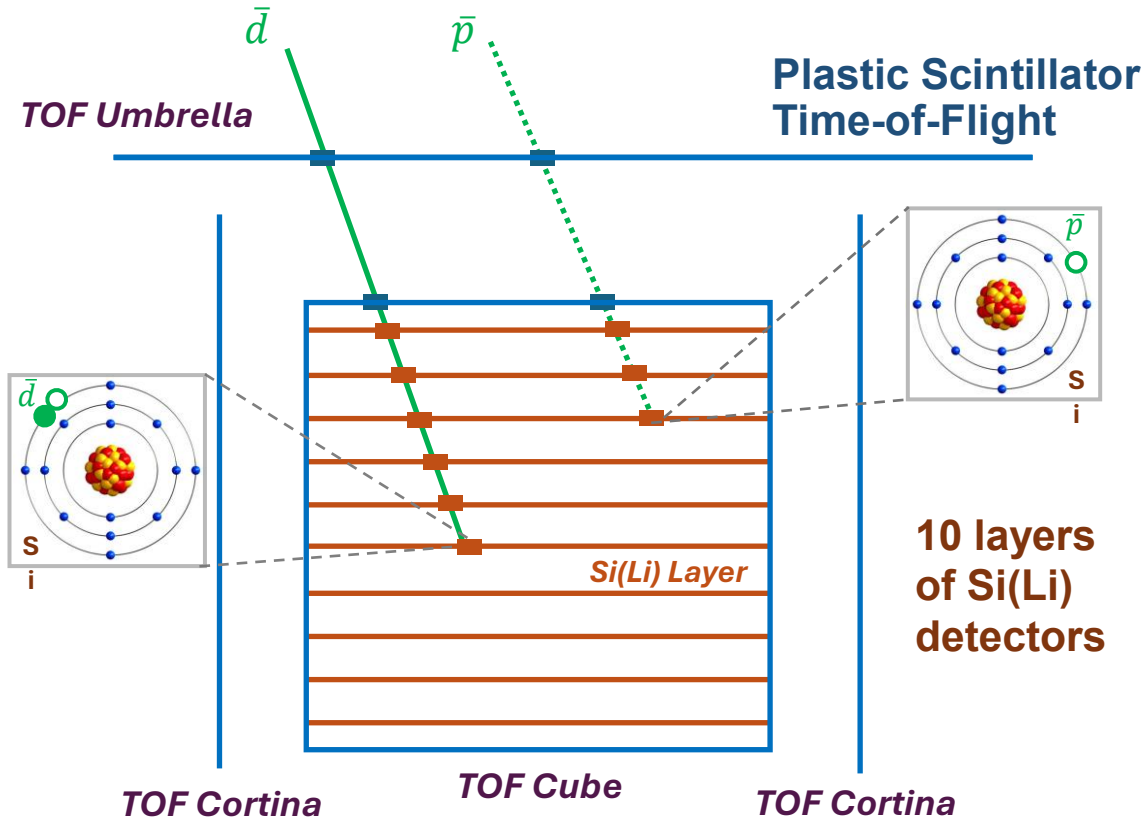

Time-of-flight system: measures velocity, incoming angle and dE/dx, fast trigger

Si(Li) tracker:

- Slows/captures an incoming antiparticle into an ***exotic atom***

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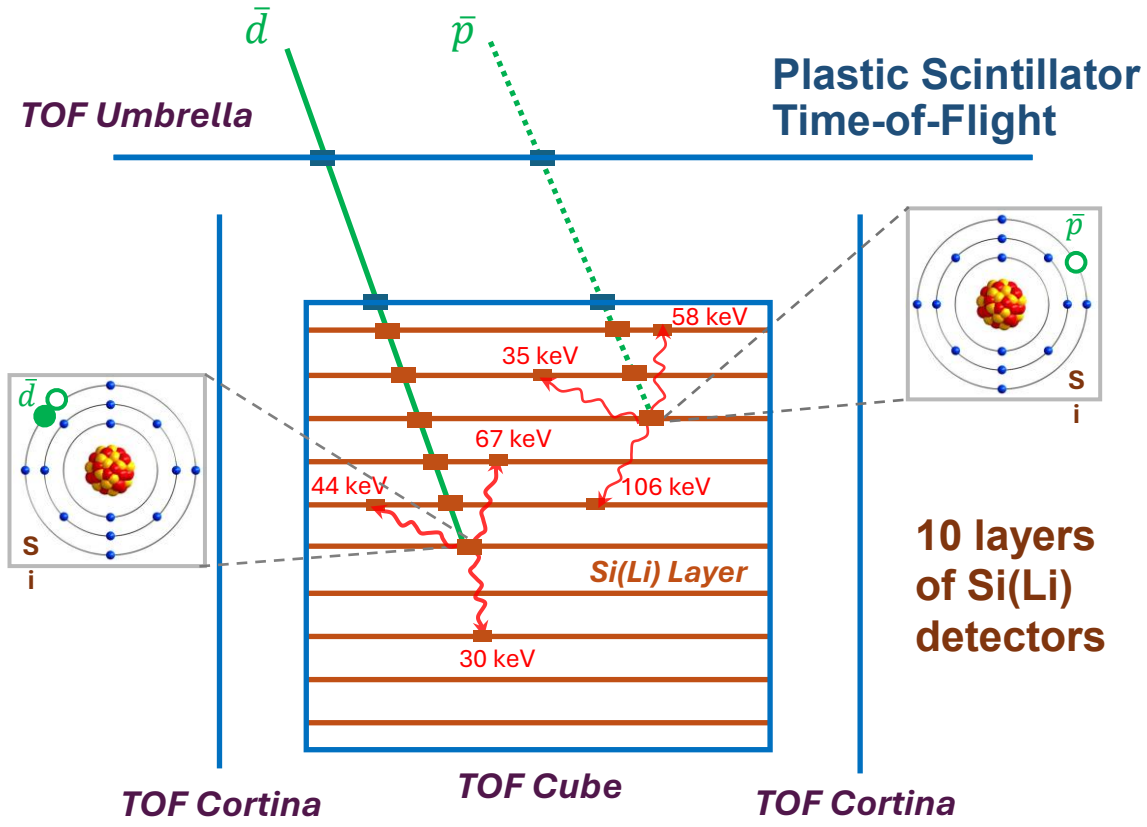
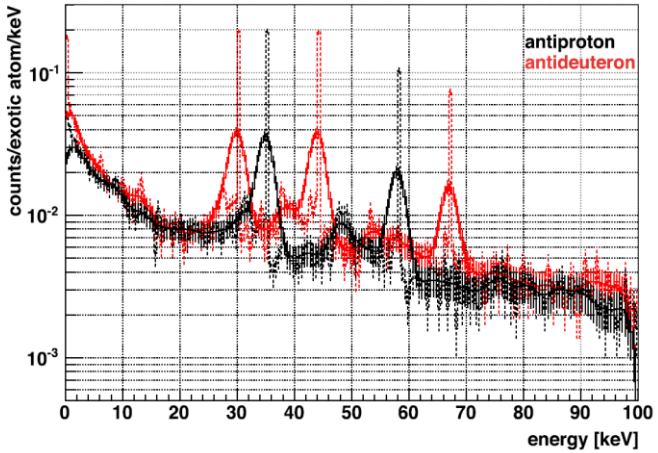


Time-of-flight system: measures velocity, incoming angle and dE/dx, fast trigger

Si(Li) tracker:

- Slows/captures an incoming antiparticle into an ***exotic atom***
- Measures the decay ***X-rays***



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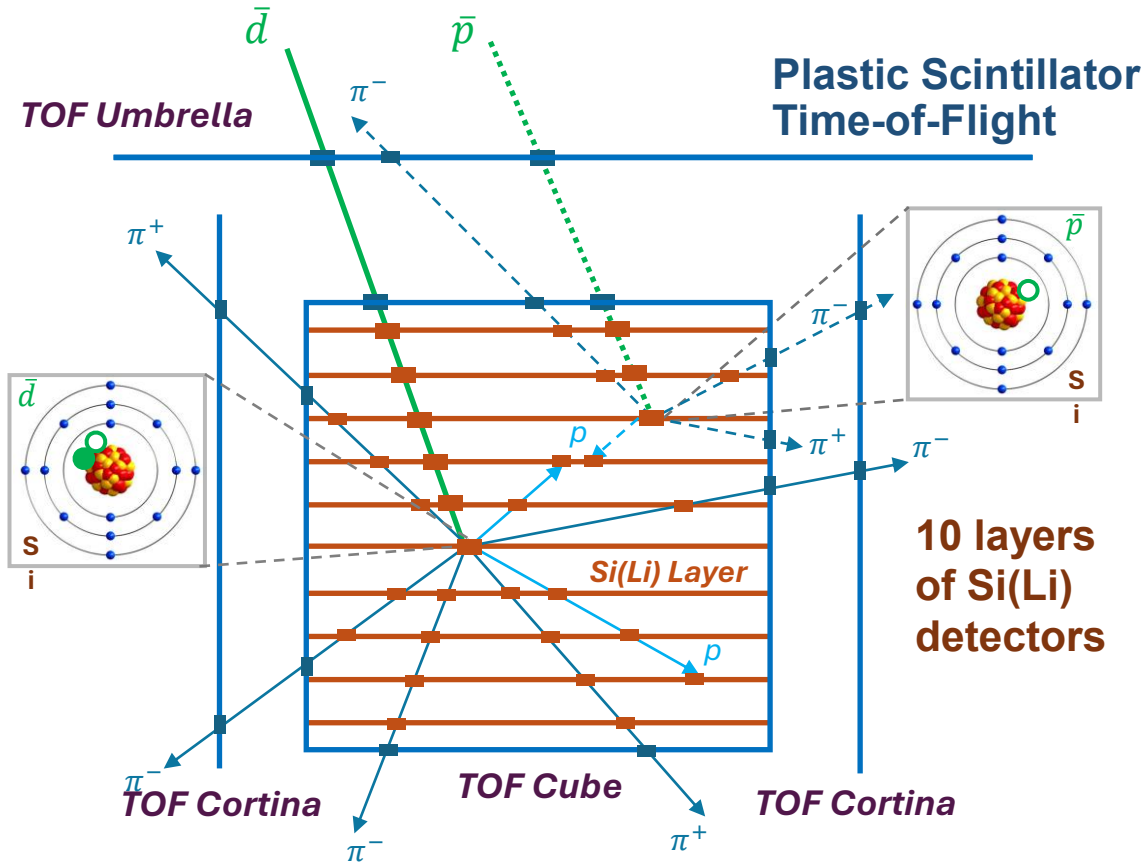

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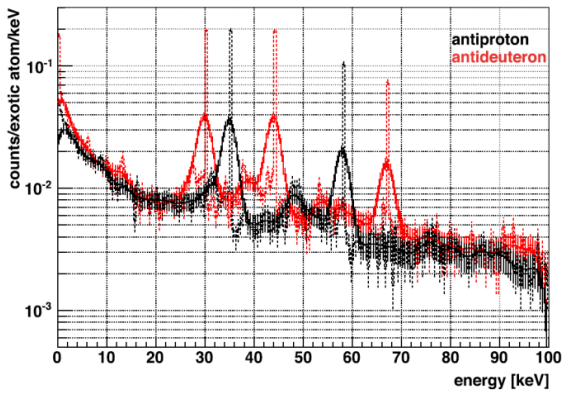
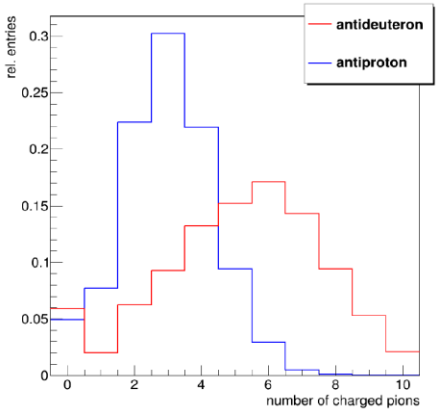
Time-of-flight system: measures velocity, incoming angle and dE/dx, fast trigger, tracks of outgoing particles

Si(Li) tracker:

- Slows/captures an incoming antiparticle into an ***exotic atom***
- Measures the decay ***X-rays***
- Tracks the annihilated products (***charged π & p***)





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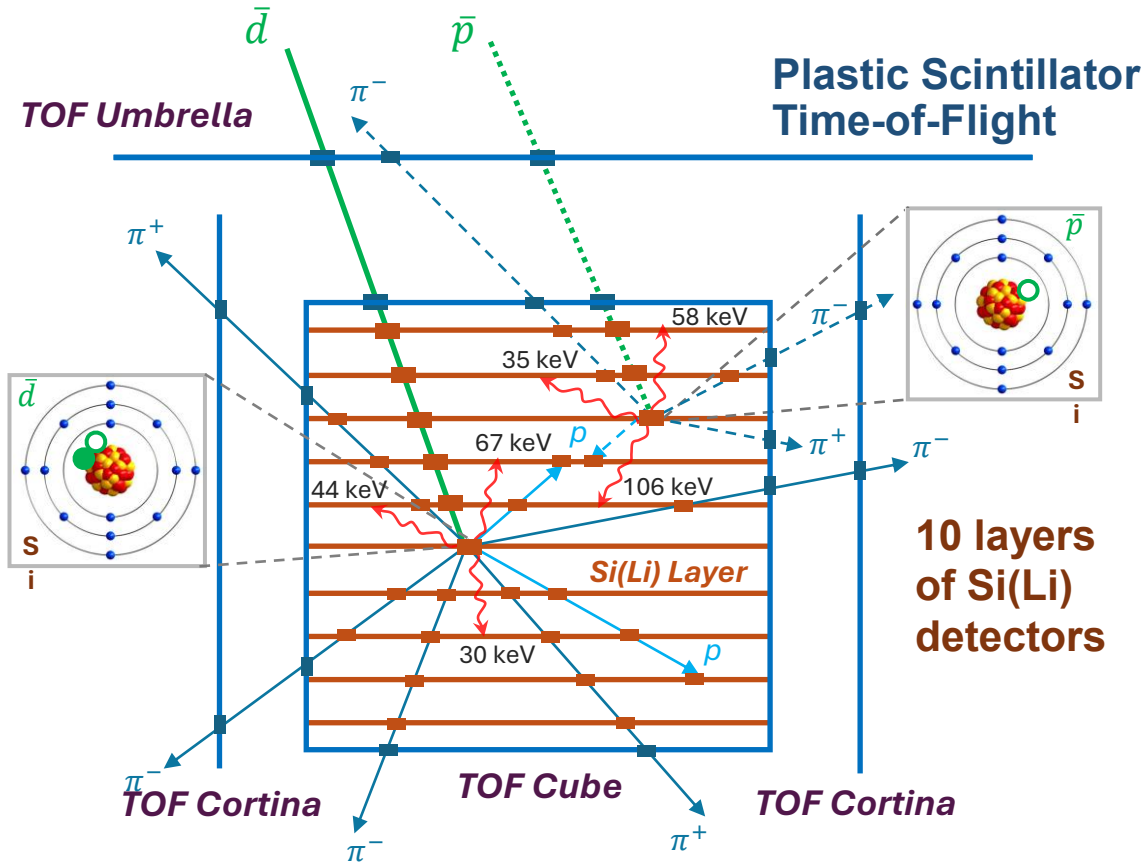

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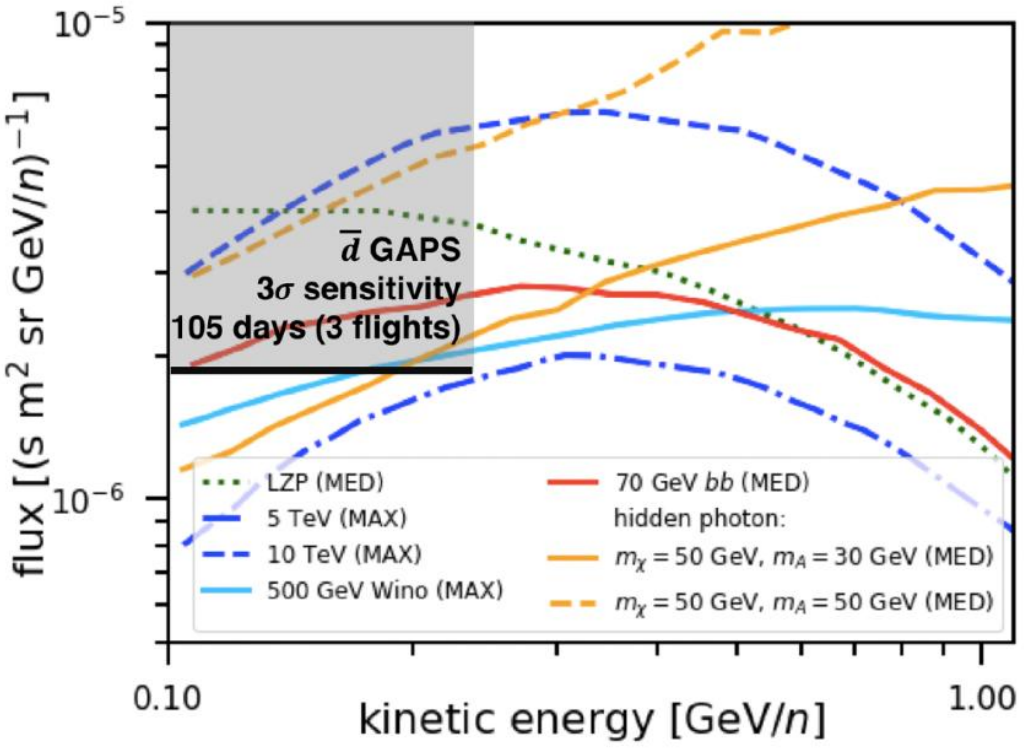
Time-of-flight system: measures velocity, incoming angle and dE/dx, fast trigger, tracks of outgoing particles

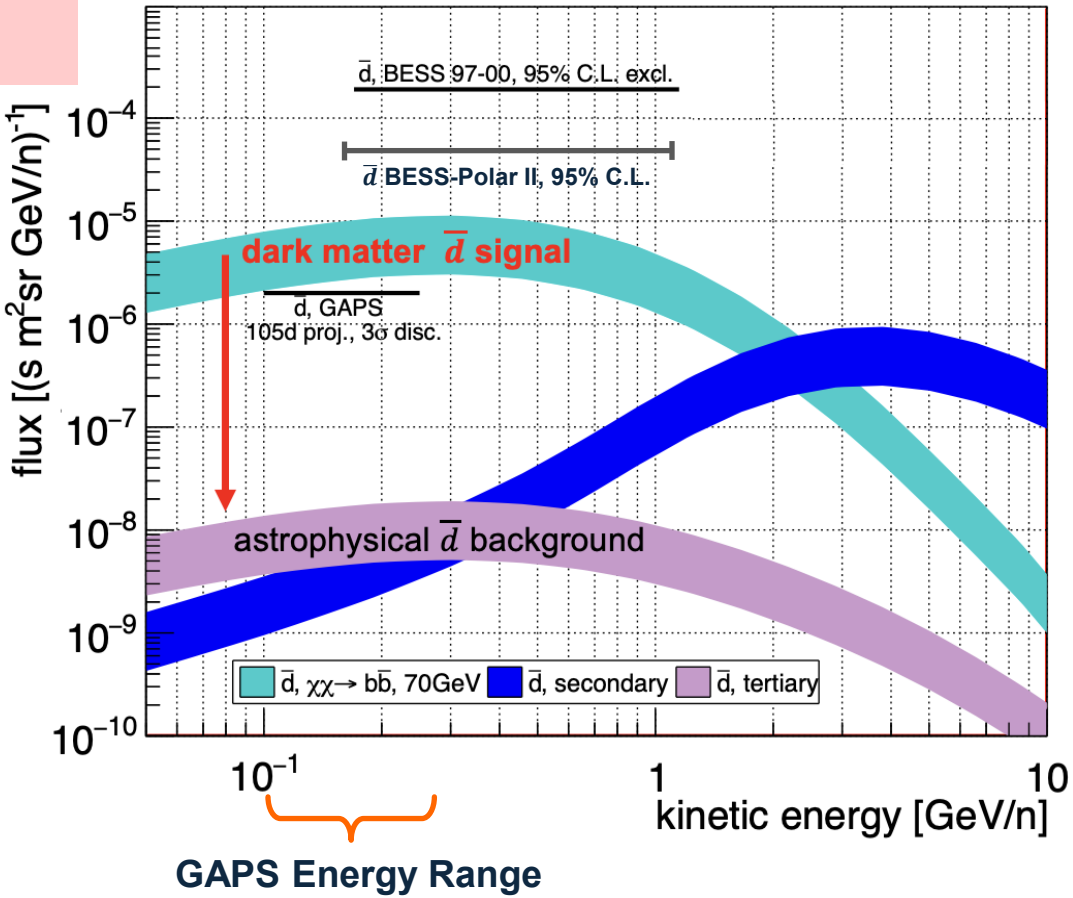
Si(Li) tracker acts as:

- ***Target*** to slow/capture an incoming antiparticle into an *exotic atom*
- ***X-ray Spectrometer*** to measure the decay *X-rays*
- ***Particle Tracker*** to measure the resulting dE/dX, stopping depth and annihilated *hadrons*

GAPS Science: *Antideuteron*

- The GAPS antideuteron search is sensitive to a wide range of generic DM models:



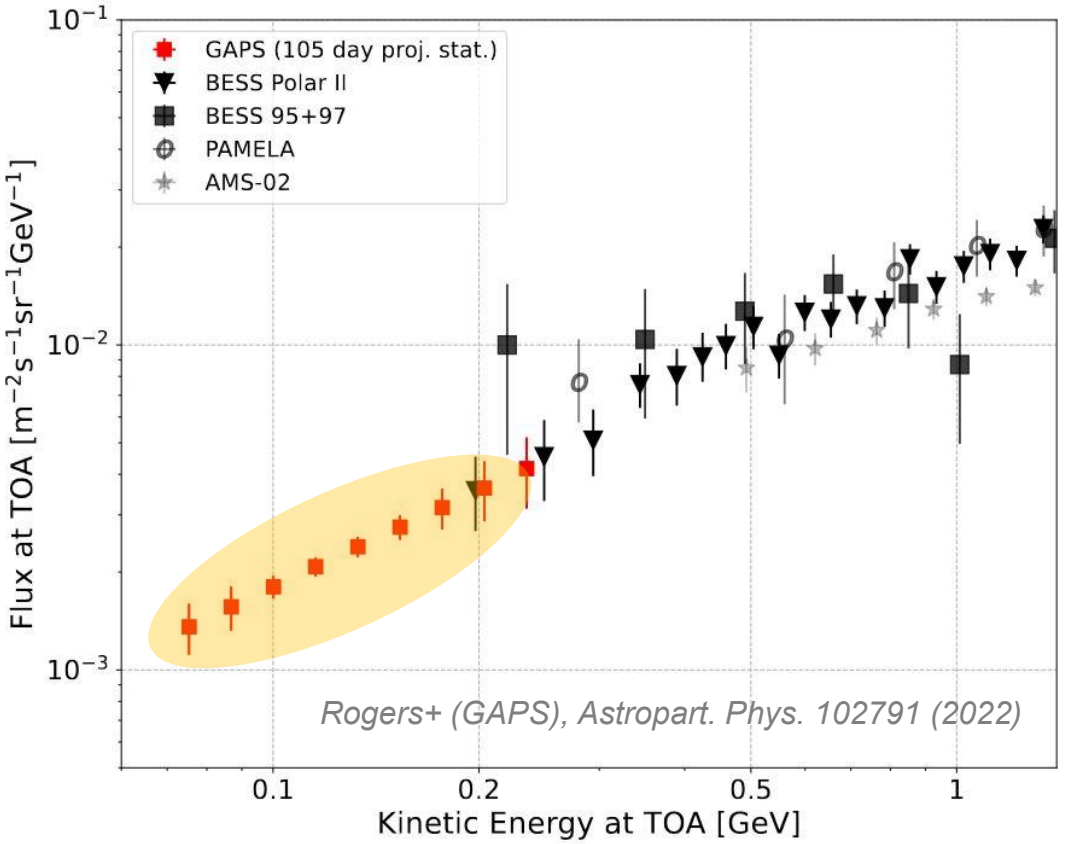


GAPS Energy Range

Note: Any antideuteron signal needs to be compatible with antiproton constraints!

GAPS Science: *Antiproton*

- ~500 *antiprotons* (≲0.25 GeV/*n*) for each balloon flight.
  - BESS : 29 at ~0.2 GeV
  - PAMELA: 7 at ~0.25 GeV
  - AMS-02: E>0.25 GeV



- ✓ Validate GAPS novel anti-nuclei identification technologies.
  - ➢ *Reduce systematic uncertainties for antideuteron search.*

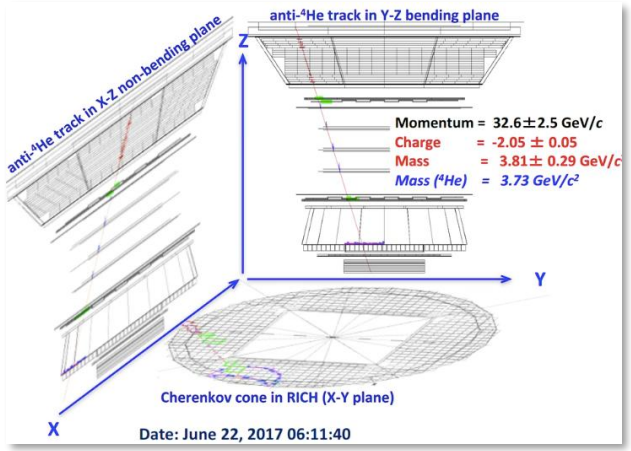
- ➢ Probe *light dark matter*, leading constraints on *primordial black hole* evaporation.
- ➢ Provide a novel insight on *cosmic ray propagation* models.

GAPS Science: *Antihelium*

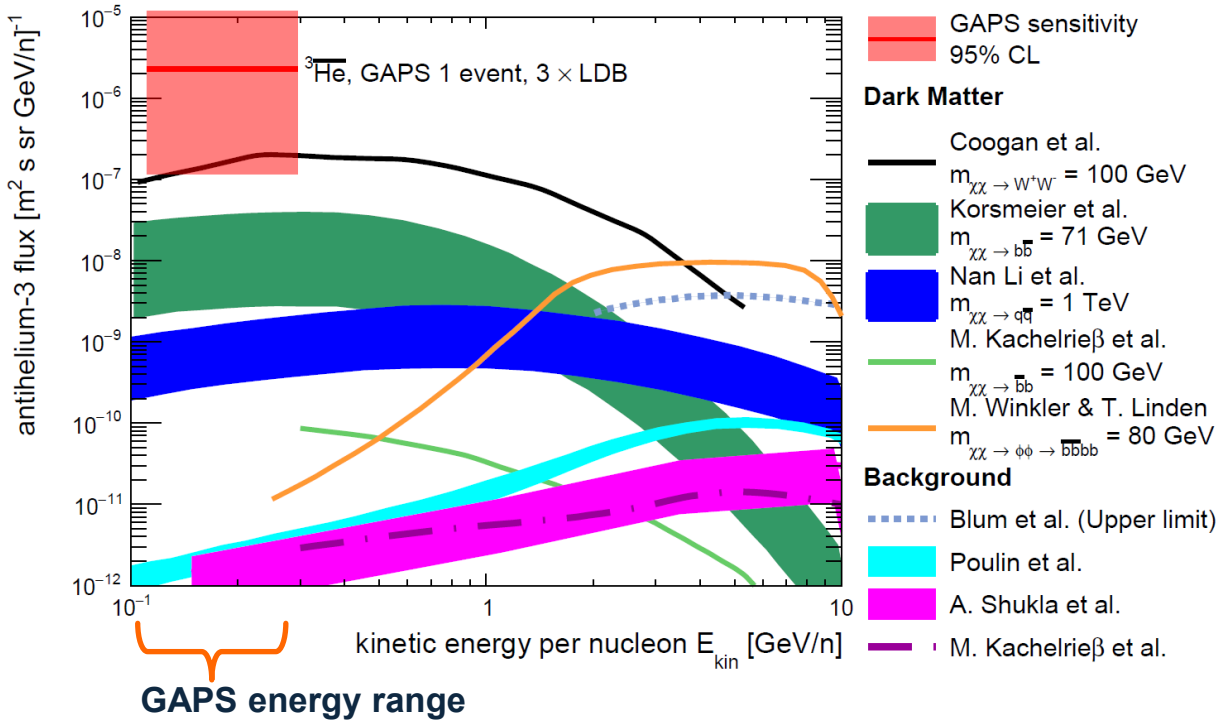
❑ GAPS flux sensitivity to antihelium-3 (three 35-day long duration flights).

- **2018:** "To date, we have observed eight events…with Z = -2. All eight events are in the helium mass region."
  – S. Ting (La Palma, AMS overview)

AMS Candidate Anti-He4 event (p = 32.6 GeV/c)



Saffold+ (GAPS), Astropart. Phys. 102580 (2021).

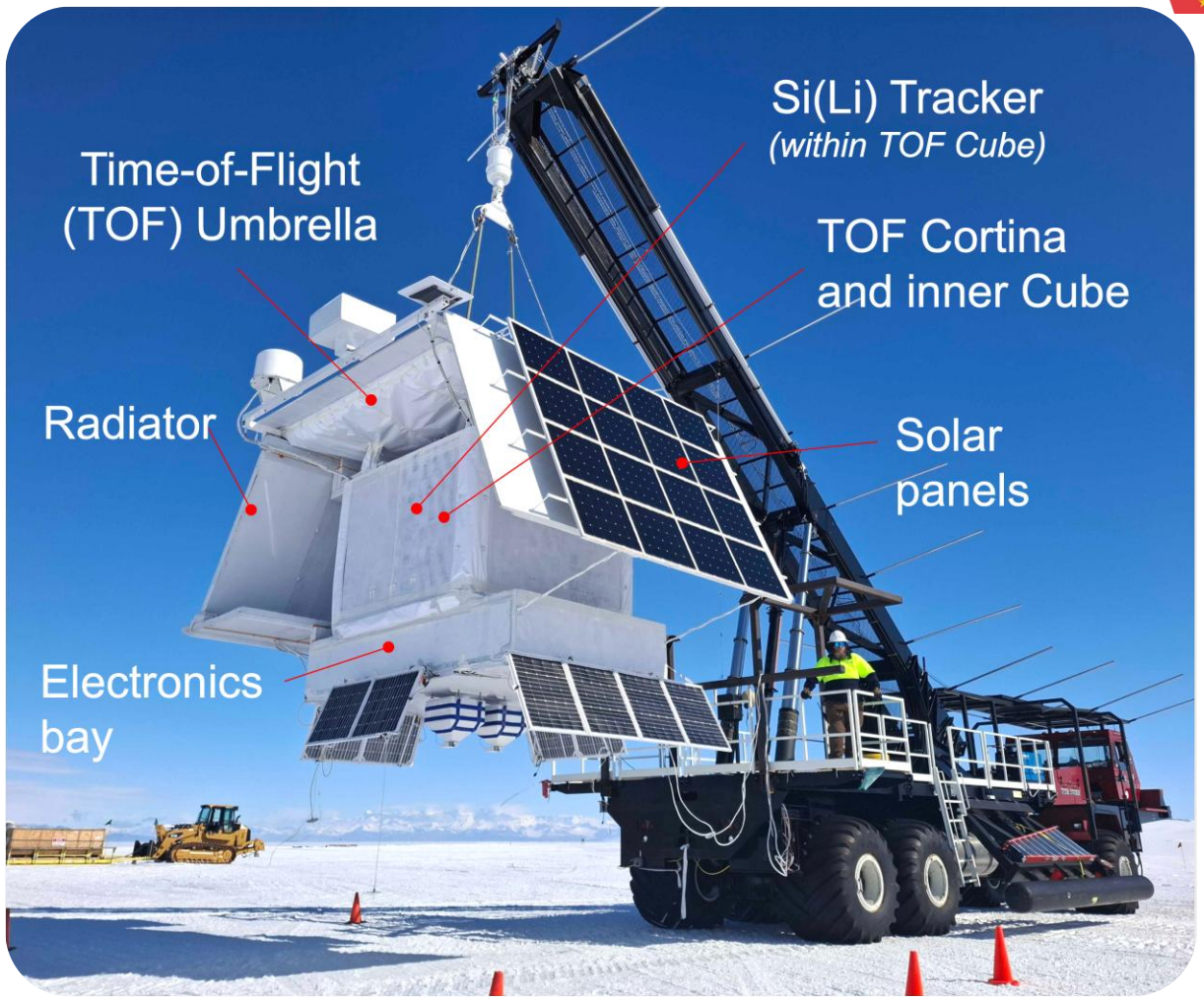


➢ Extends to lower energies (0.11-0.3 GeV/n), complementary to AMS-02.

- Capable of confirming signal, orthogonal detection technique, uniquely low bkg.

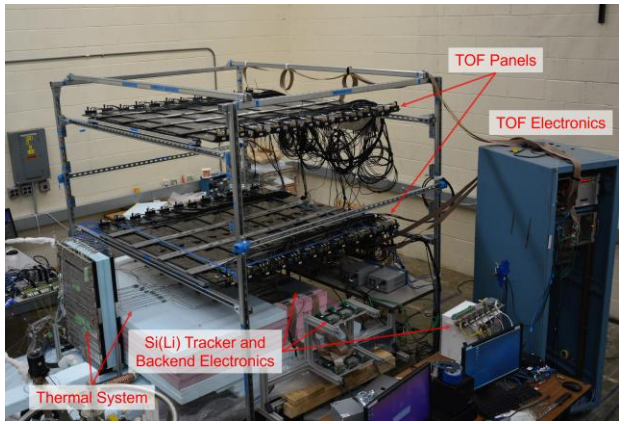
GAPS Instrument

- **Time-of-Flight (TOF)**
  - Near-hermetic containment of tracker
  - Velocity, trajectory and dE/dx measurement
  - High-speed trigger and veto
- **Si(Li) Tracker**
  - Target to capture light nuclei ≲0.25 GeV/*n*
  - Tracker for primary and secondary hadrons
  - Spectrometer for de-excitation X-rays
- **Thermal System**
  - Oscillating Heat Pipe for tracker cooling
- **Support instrumentation**
  - Electronics, Solar panels, Gondola



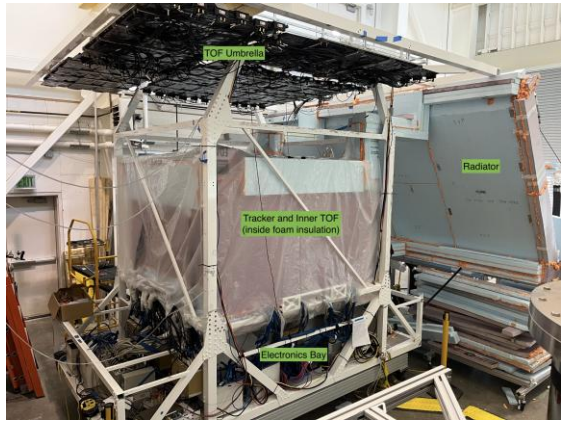
GAPS Instrument Integration

2020, GFP @MIT-Bates, MA



2021, initial integ. @MIT-Bates, MA

2022, full integ. @Berkeley-SSL, CA



6/2023, TVAC test @NTS, CA

1/2024, upgrades @CU-Nevis, NY

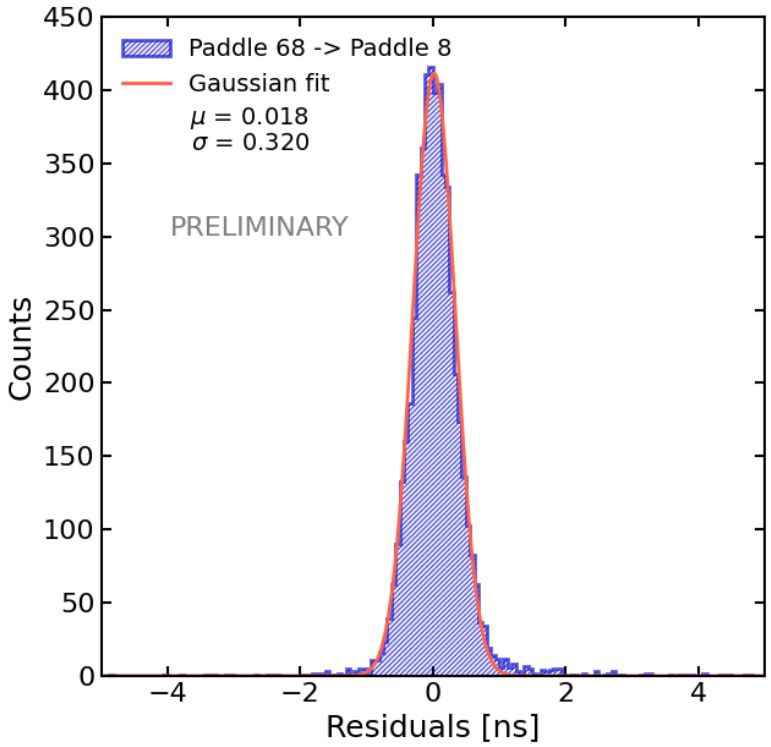
7/2024, compatibility testing @CSBF, TX

12/2024, commission & launch attempts @McMurdo, Antarctic

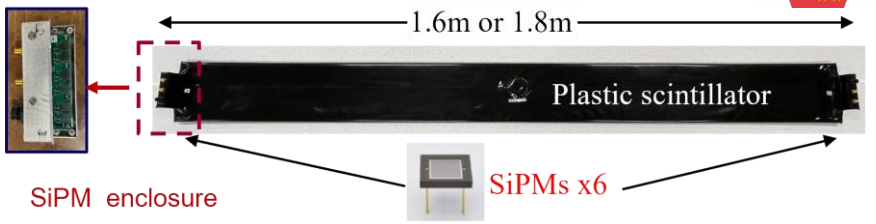
GAPS Instrument Performance: *ToF*

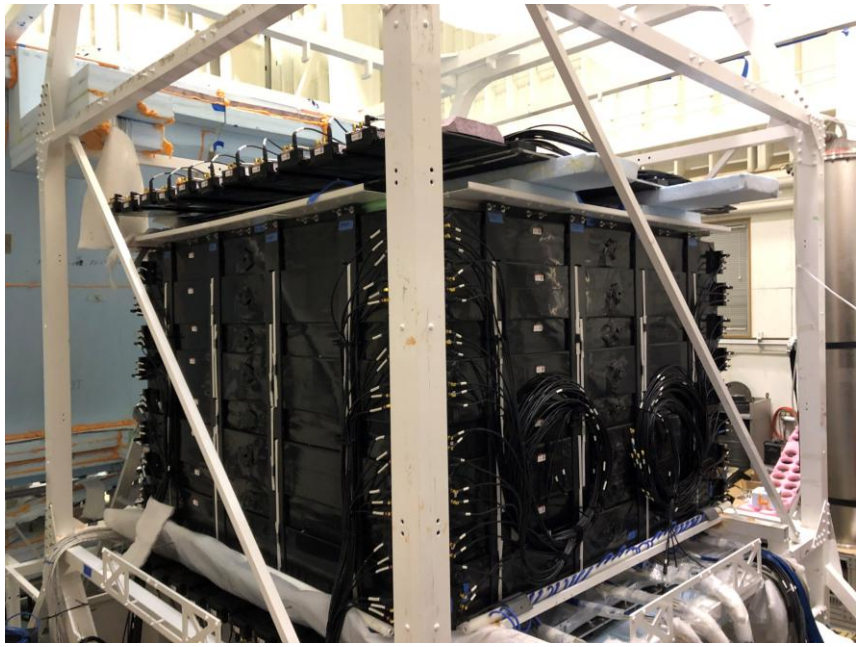
❑ ToF performance from the Antarctic commissioning.

- Design goal: <500 ps timing resolution for TOF system to be able to separate proton and deuteron.
- Cross-calibration with different paddle combinations to estimate timing resolution



▪ Timing resolution

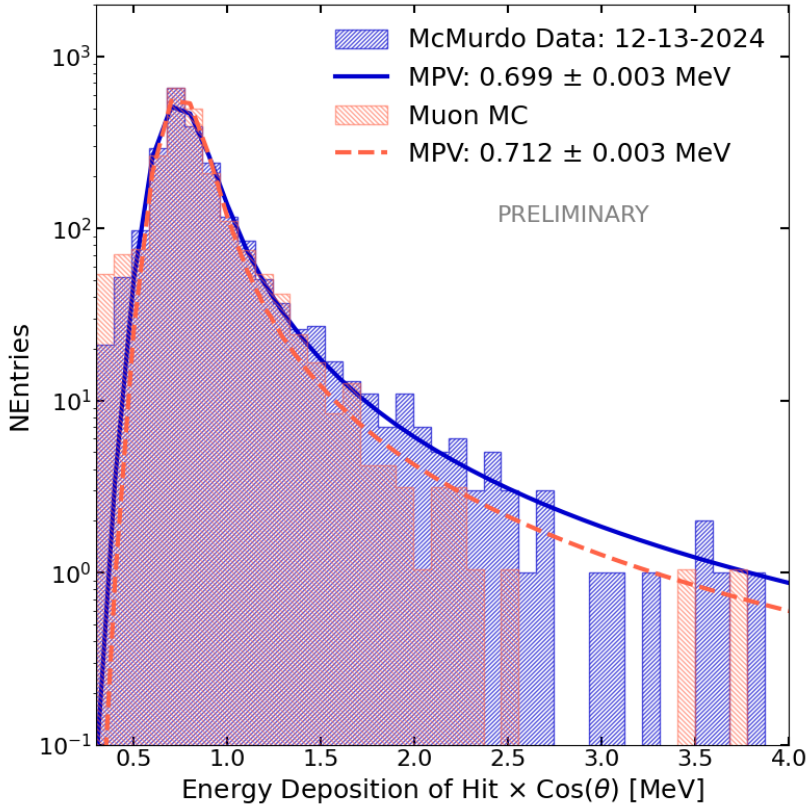




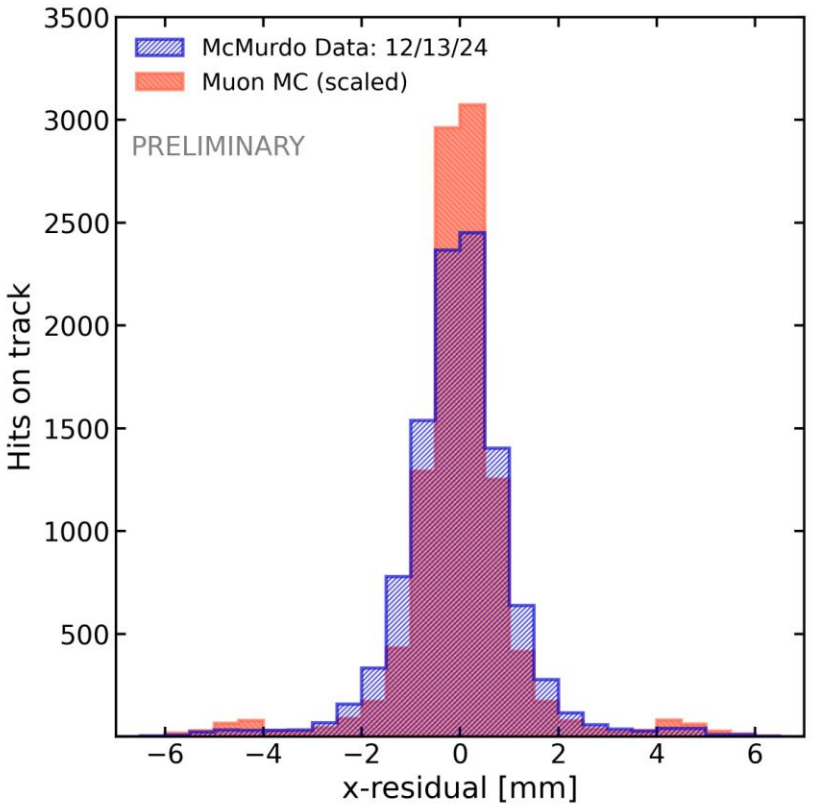
➢ Achieved: measured better than ~350 ps for all paddle combinations!

GAPS Instrument Performance: *Tracker*

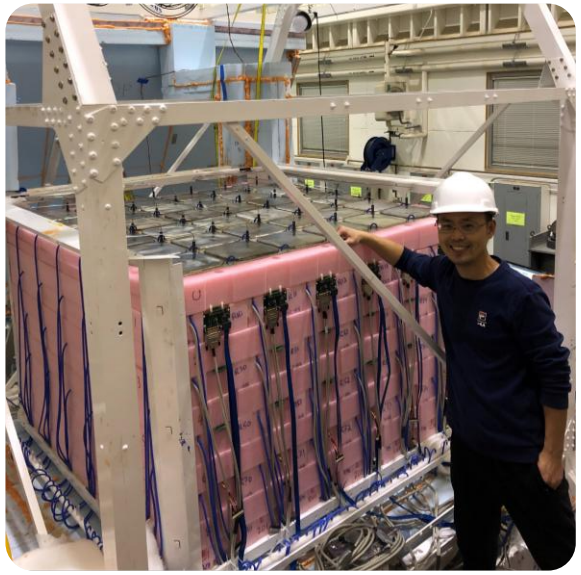
- Tracker performance from the Antarctic commissioning.

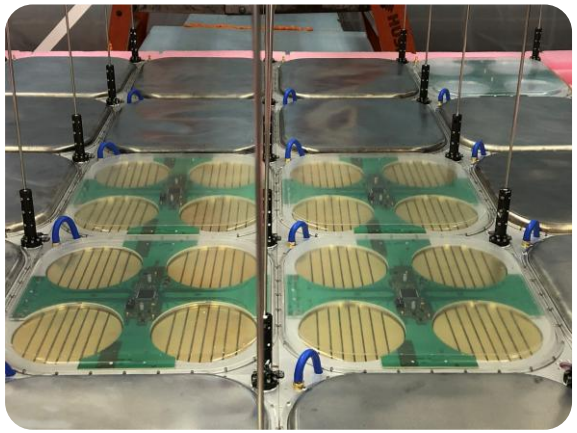


- Energy depositions on track



- Track position resolution

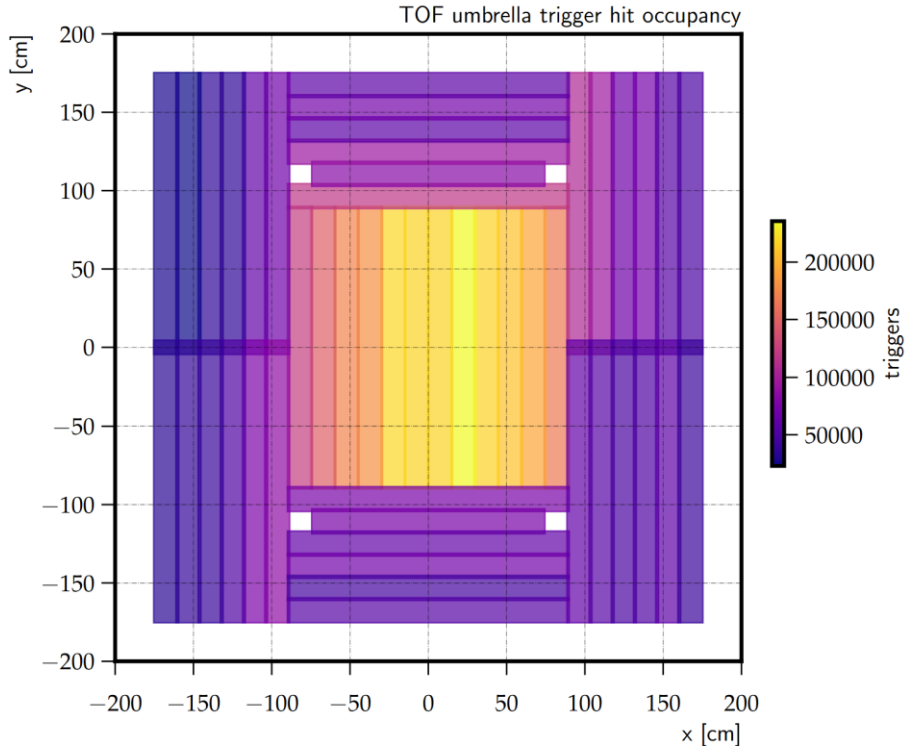




➢ Energy and track reconstruction validated!

GAPS Instrument Performance: *Trigger*

- Design goal: 450-500 Hz trigger rate (maxing out telemetry bandwidth), capability to trigger on multi-track events.

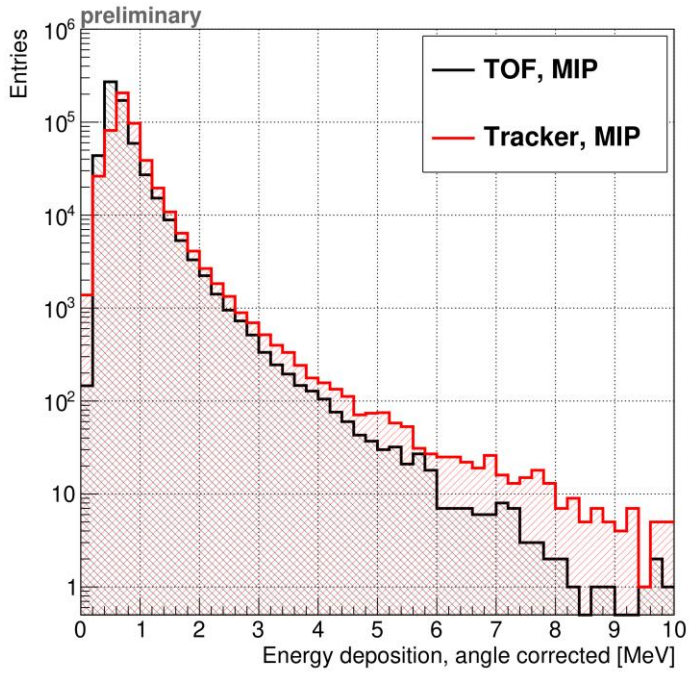


- GAPS trigger allows for 2 modes in parallel (multi + single track)
- Modes can be tuned with pre-scale factor
- On ground multi track ~few Hz, single track (w. prescale) ~450-500 Hz

➢ Achieved: stable operations at ground with tuned trigger at 450-500 Hz possible, can record multi track events, trigger acceptance verified with simulations!

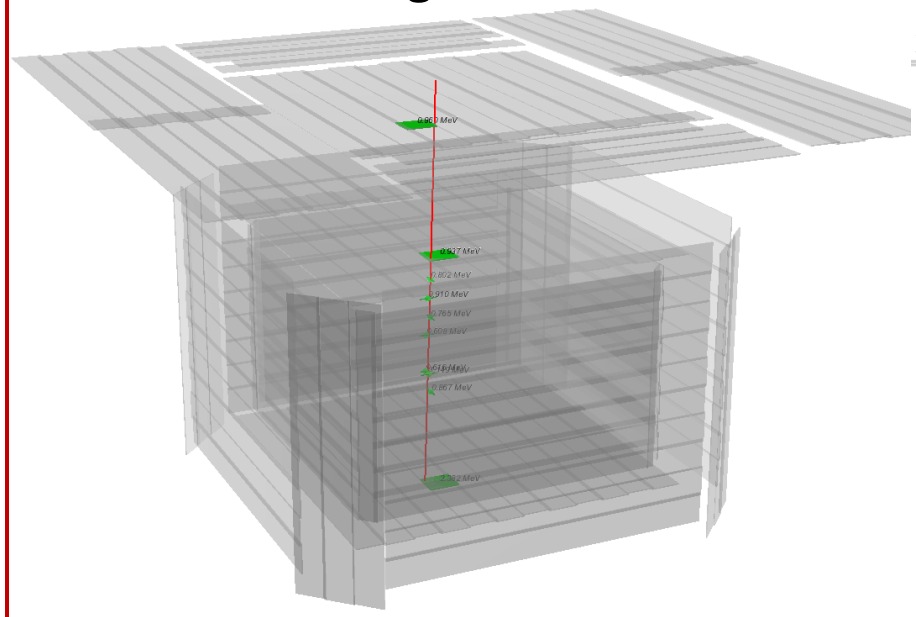
GAPS Instrument Performance: *System*

- ~10M muon events are collected from the on-ground testing in the Antarctica.
  - Event signatures are well understood and more detailed analysis is undergoing.

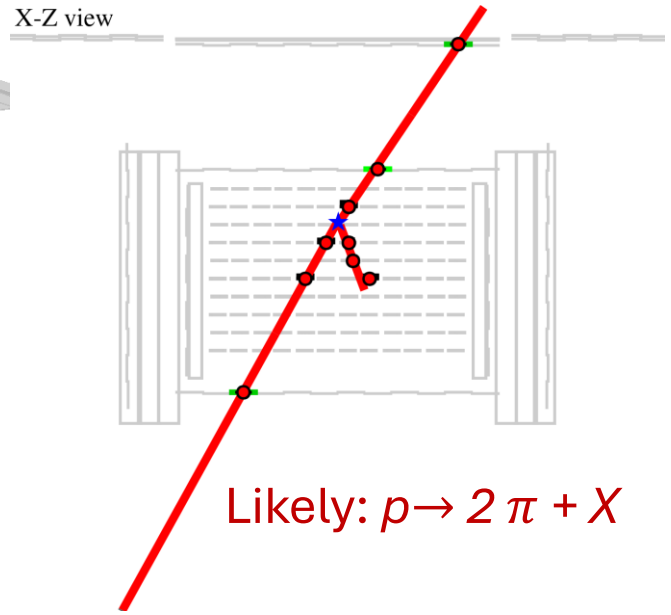


- Energy reconstruction

- Single track



- Multi track



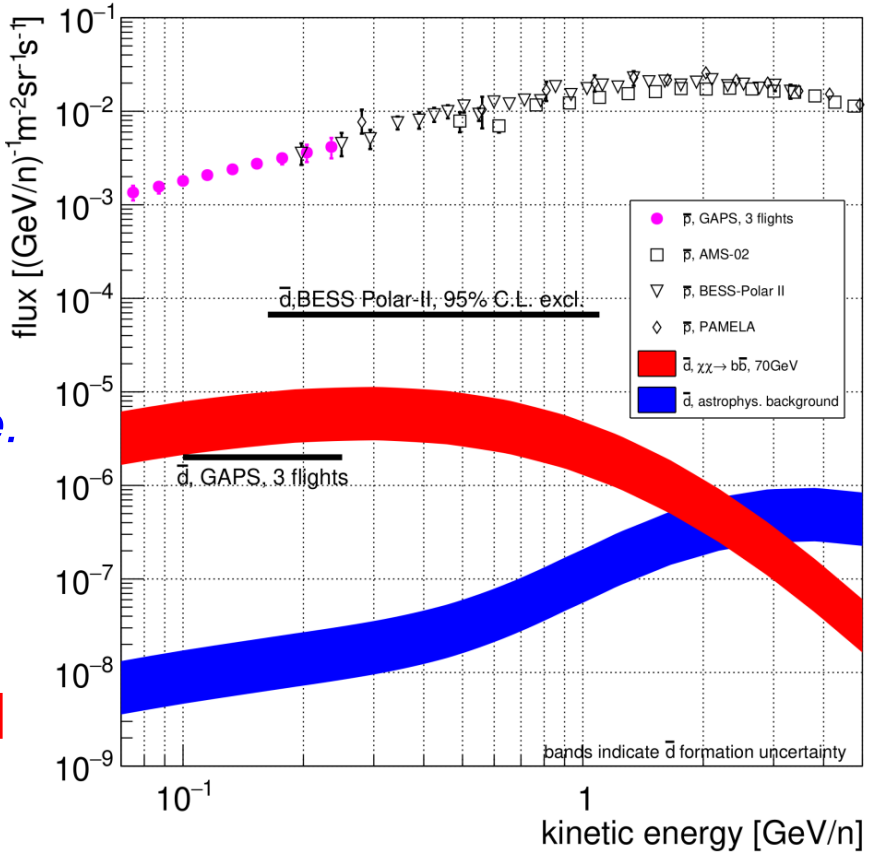
- Track Reconstruction

Summary & Conclusions

- Low-energy cosmic antinuclei are unexplored and unique for new physics (e.g. dark matter) searches.

- GAPS aims to deliver:
  - *unprecedented $\bar{d}$ sensitivity* by ~100 times below the current best limits, “smoking-gun” dark matter signature.
  - *precision $\bar{p}$ measurement in an unexplored energy range.*
  - *leading sensitivity to low-energy cosmic anti-He.*

- **GAPS instrument is READY in Antarctica and planed for flight in late 2025, *Stay tuned!!***



GAPS Collaboration


THANK YOU!