Dark Matter Searches with Low-energy Cosmic Antinuclei

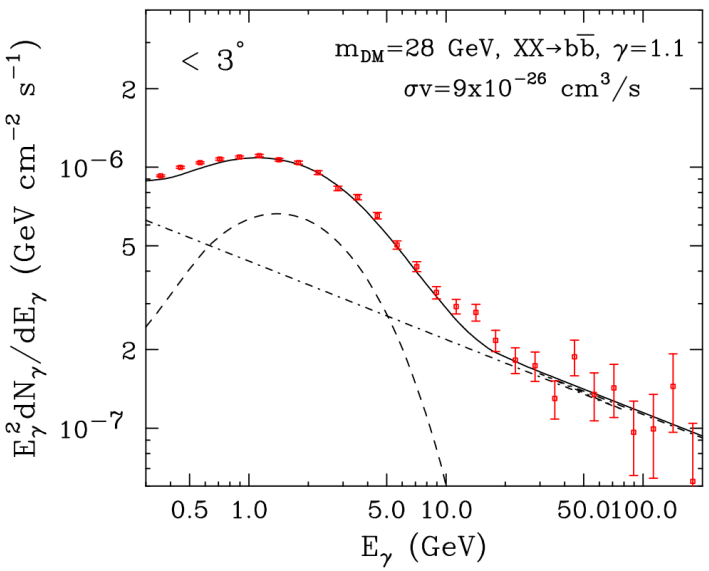
Mengjiao Xiao

Shanghai Jiao Tong University

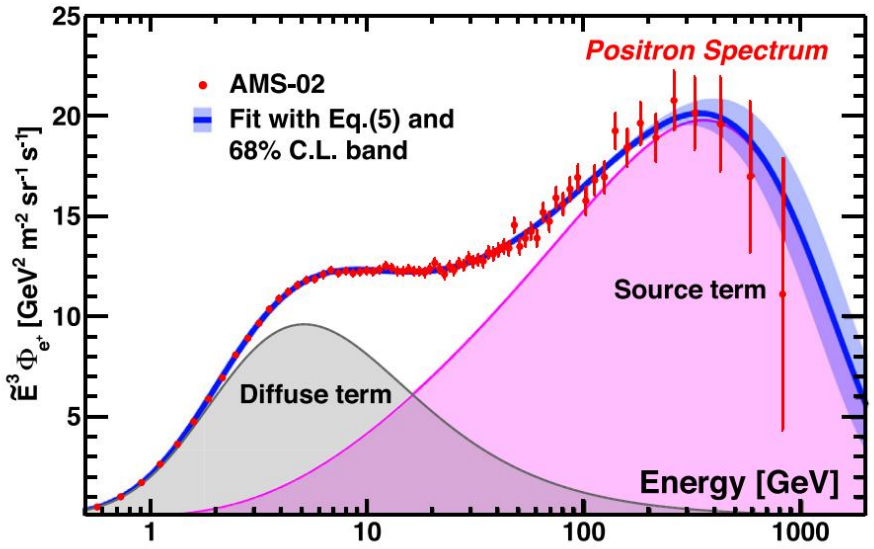
2025-09-30

Dark Matter Hints in Cosmic Rays

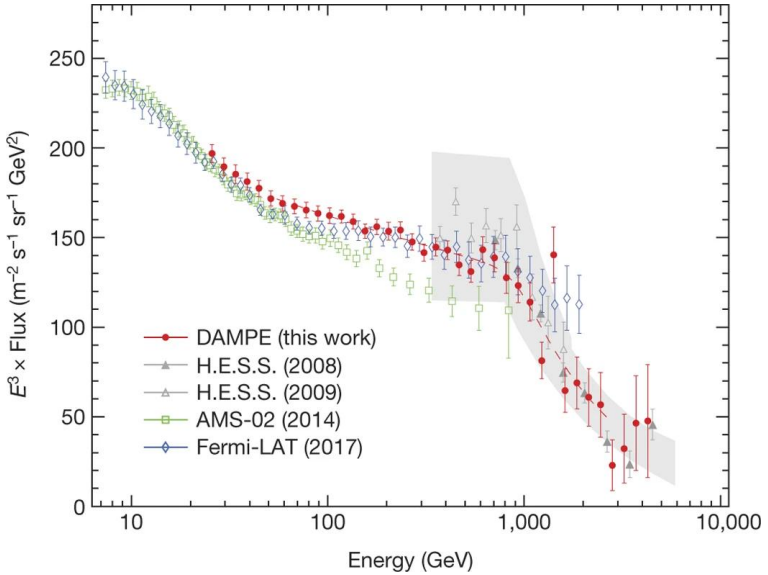
D. Hooper+ *PRD* (2011), I. Cholis+ *JCAP* (2009)



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



DAMPE, *Nature* (2017)



- GeV gamma excess at GC center by Fermi-LAT: *dark matter of O(10-100) GeV?*
- Positron/electron excess by PALEMA, AMS-02, Fermi-LAT, CALET, DAMPE: *~TeV dark matter?*

Dark Matter Hints in Cosmic Rays

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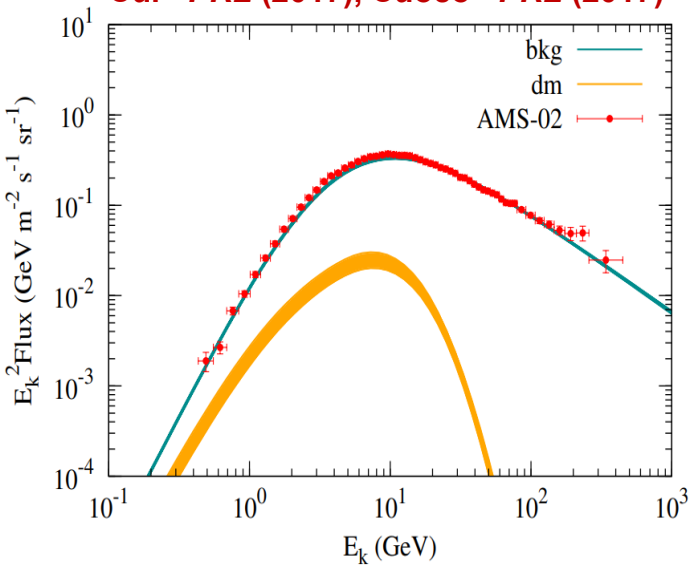

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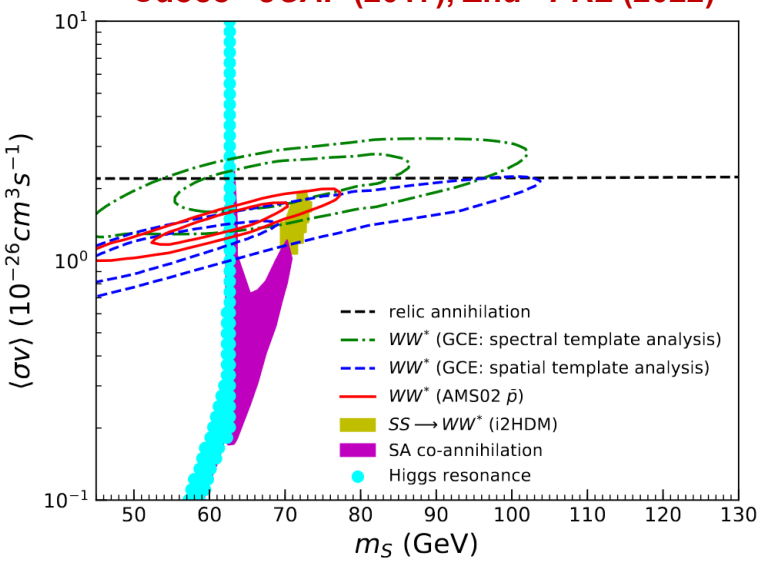

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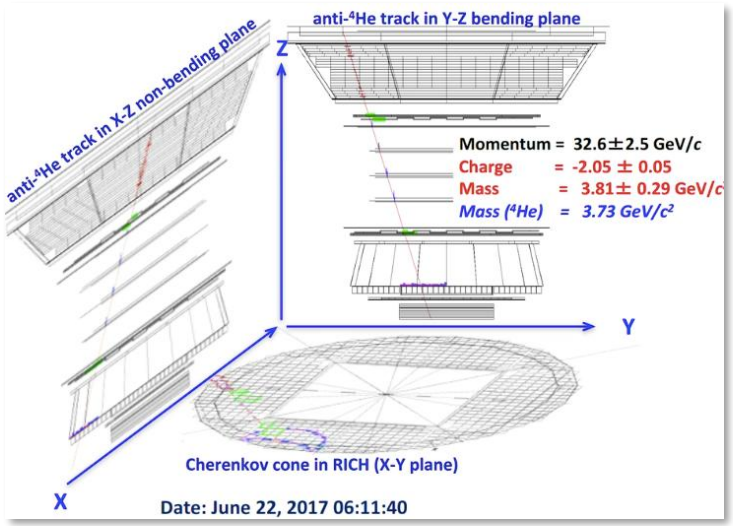

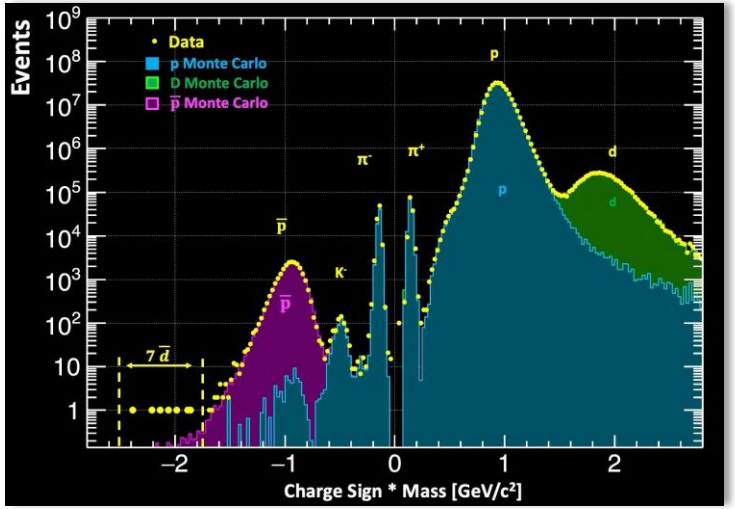

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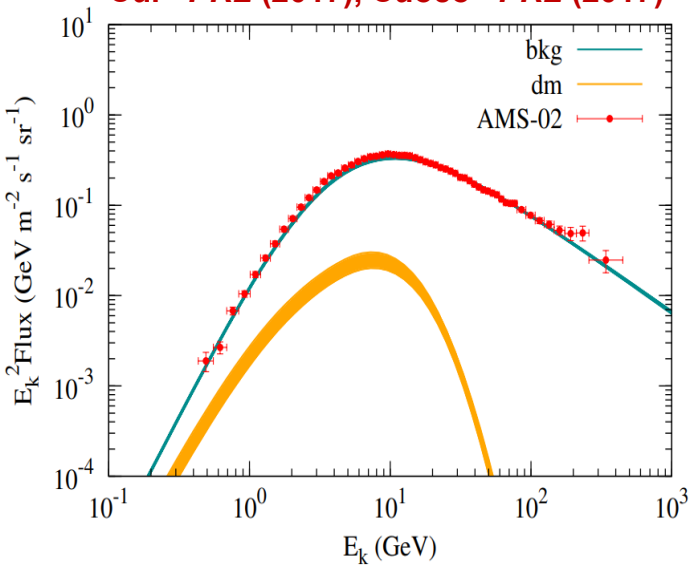

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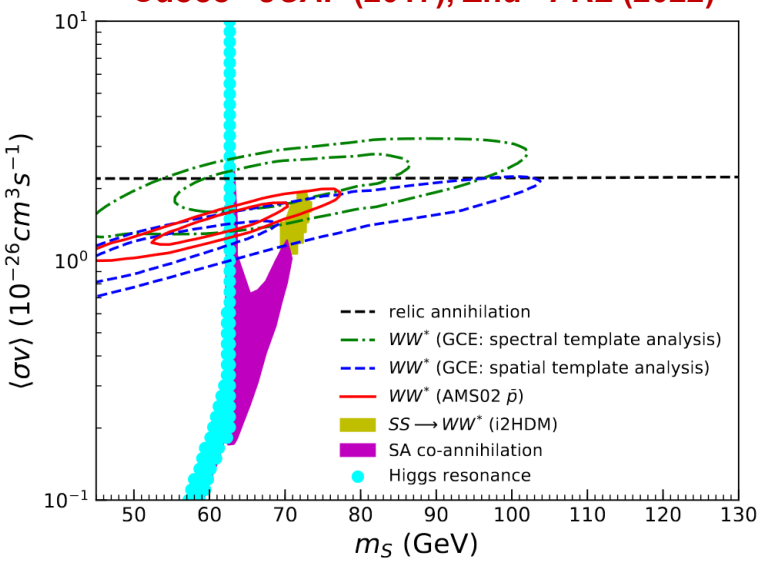
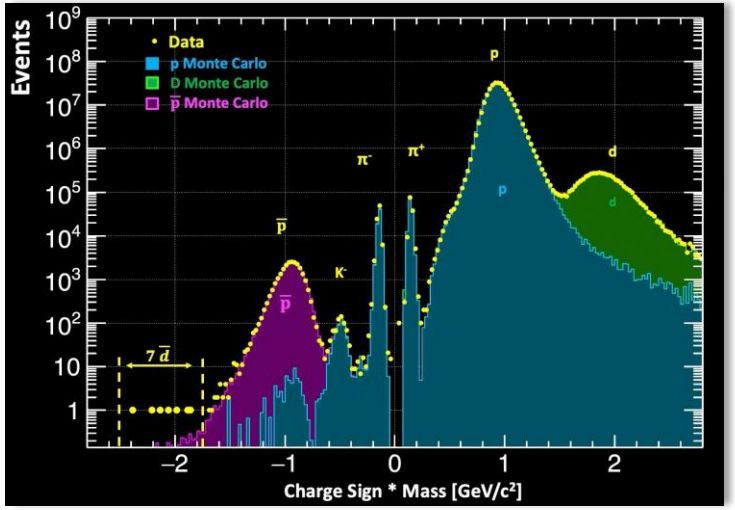
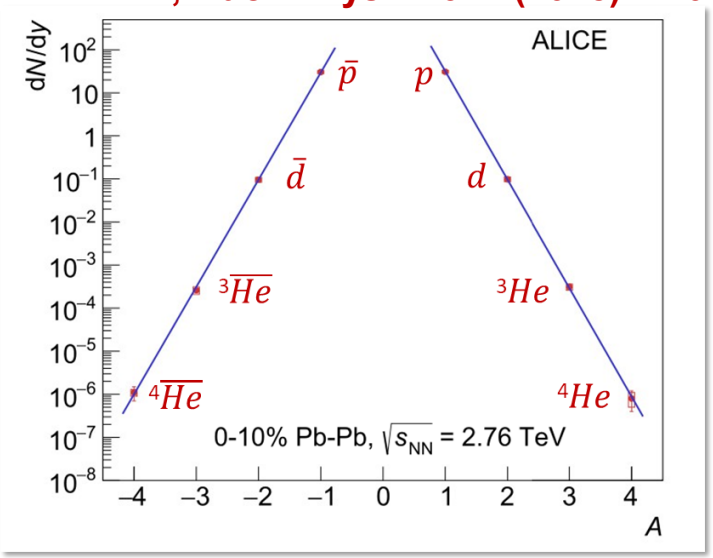




ALICE, Nucl. Phys. A 971 (2018) 1-20



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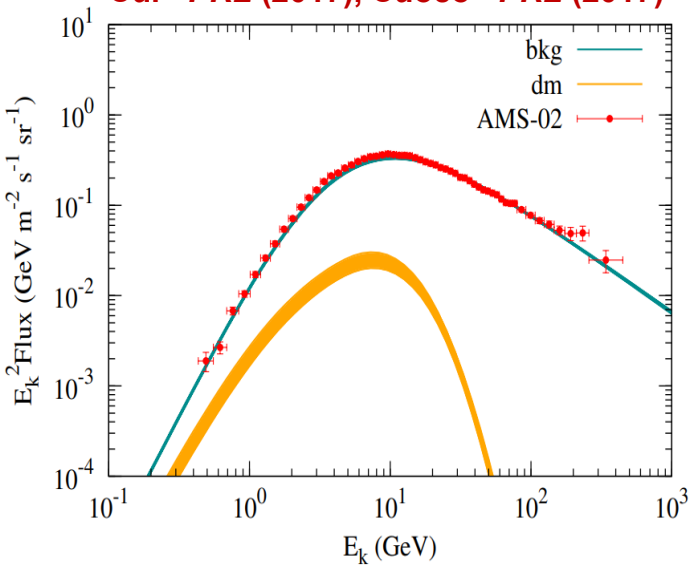

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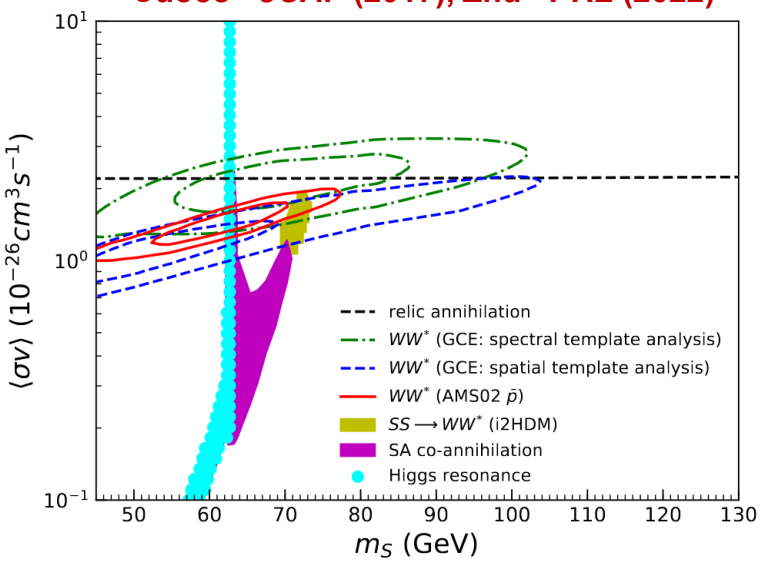
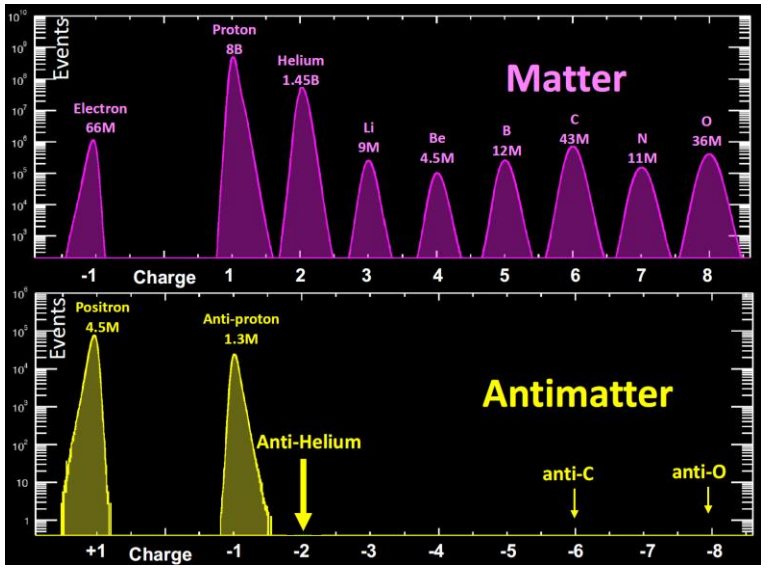
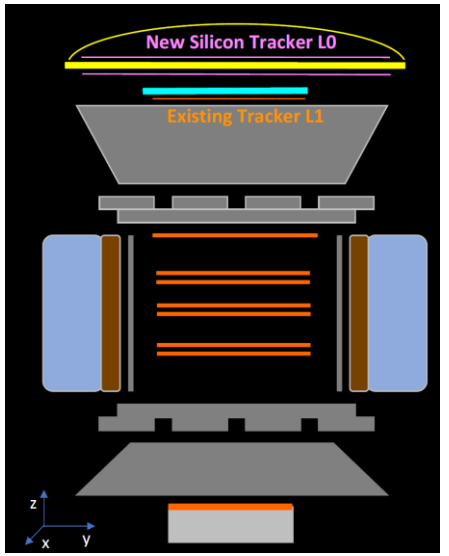




AMS-02 talk on ICRC 2025



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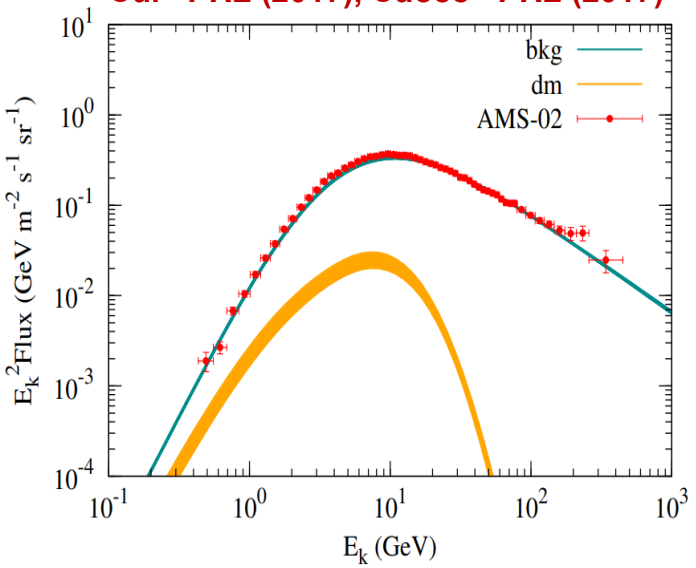

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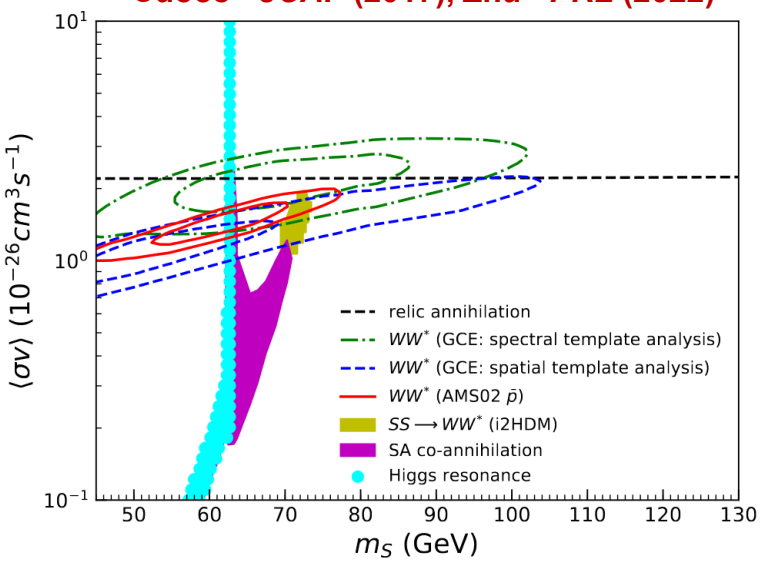

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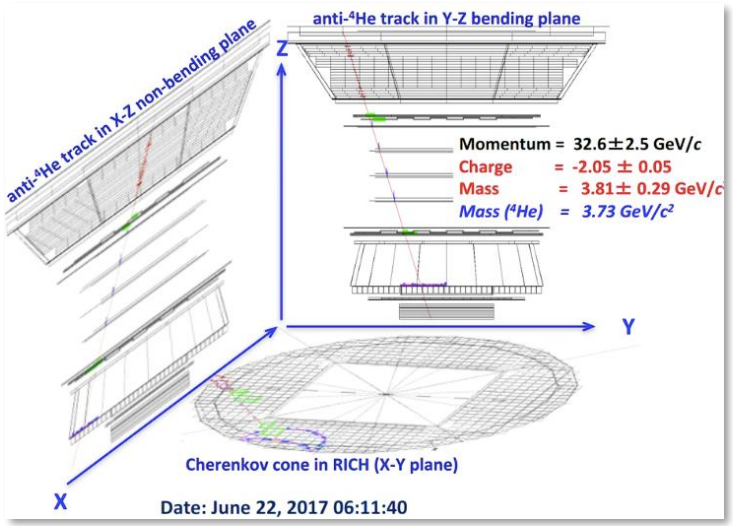

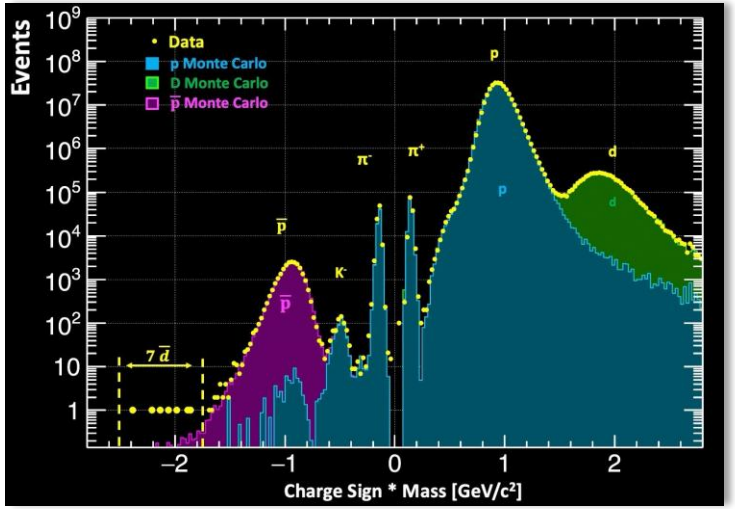

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Cosmic rays are full of surprises, but DM interpretation is complicated by astrophysical backgrounds!

Dark Matter Detection with Cosmic Rays

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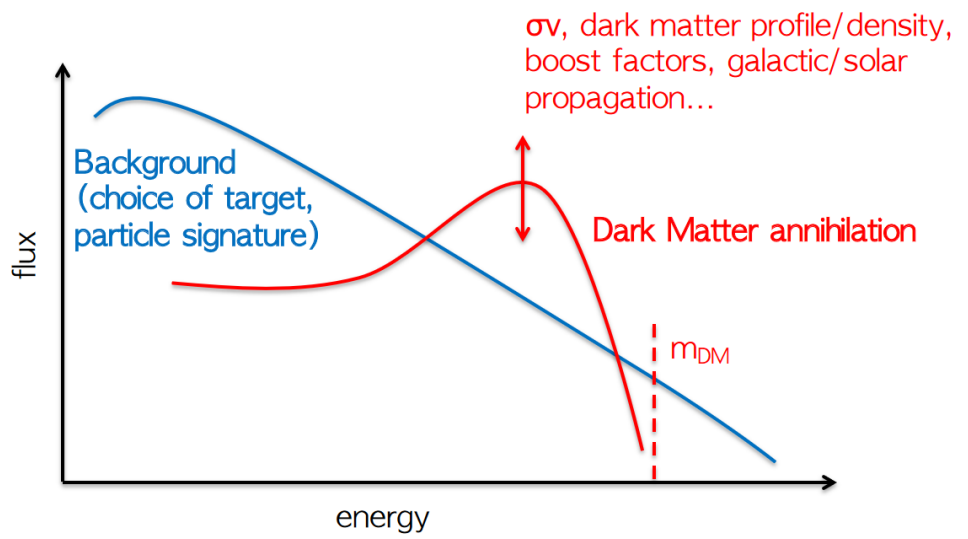
❑ ***Assumption:*** dark matter annihilation/decay follows different kinematics (i.e. via new physics) than conventional productions.



Common challenge (*FUN!*) =

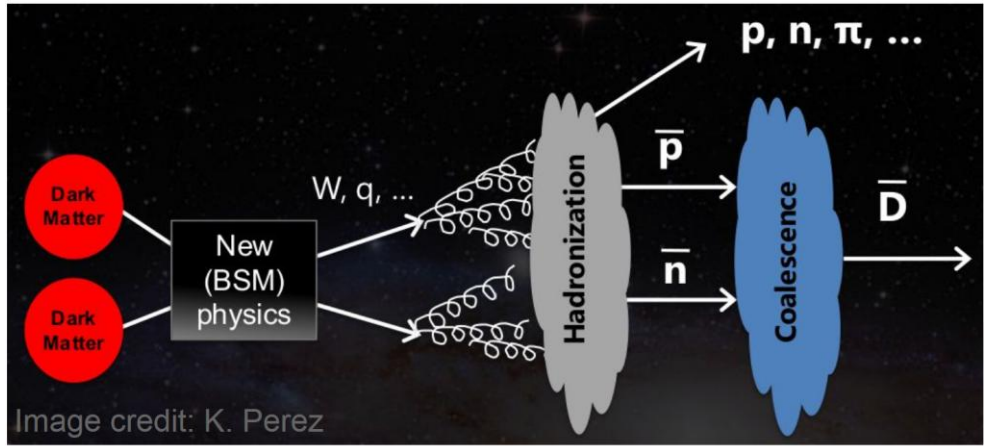
minimize/constrain astrophysical bkg.

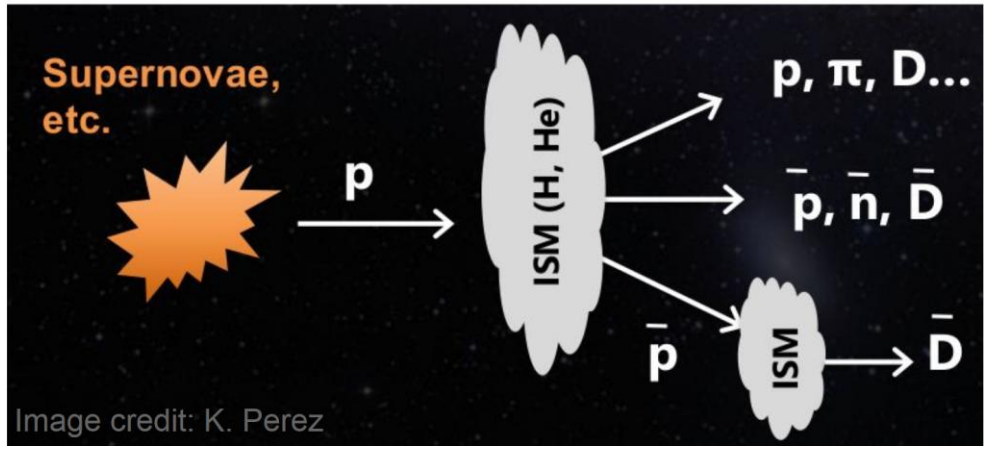
maximize predicted dark matter signal

- ❑ 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
  - ….

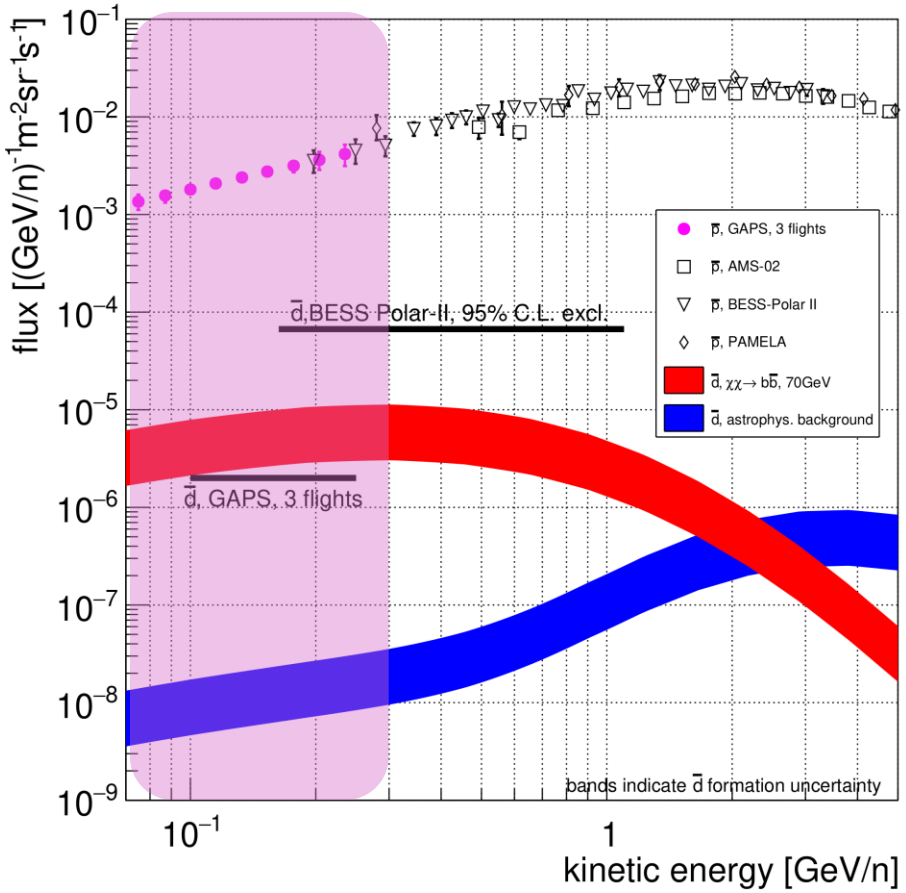
Antideuterons as Dark Matter Signature

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





P. von Doetinchem+ JCAP 08 (2020)



Antideuterons as Dark Matter Signature

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

> *"A confirmed detection of low-energy antideuterons or antihelium would be transformative, as these channels are thought to be essentially background-free…"*
>
> *— from Snowmass 2021 Cosmic Frontier Particle Dark Matter Report*

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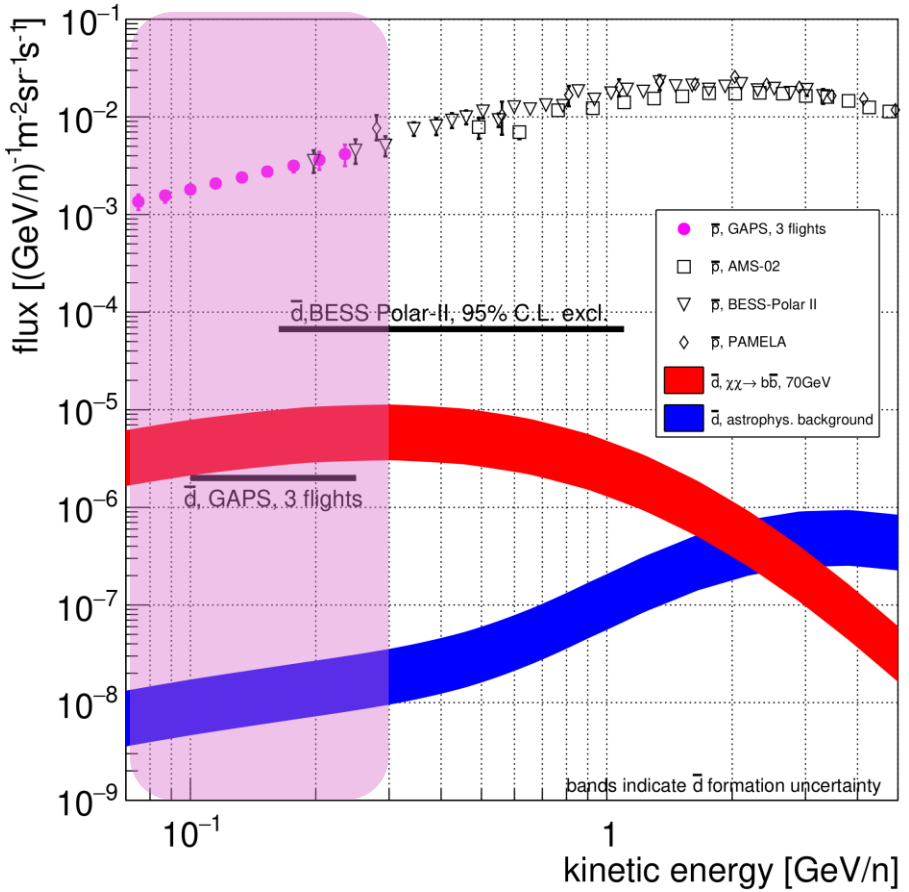


The GAPS Balloon Mission

❑ **GAPS=General AntiParticle Spectrometer**

- Antarctic balloon experiment

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

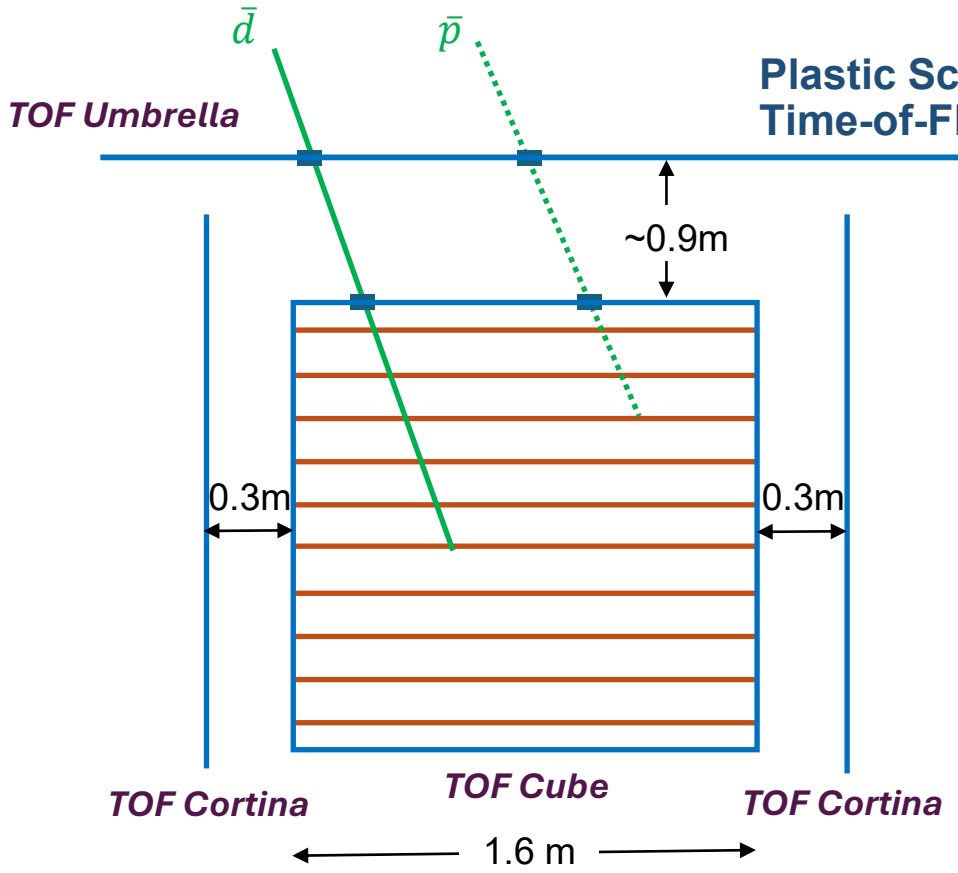
❑ Primary goal: low-energy (KE≲0.25 GeV/*n*) ***Antideuteron*** *as signature of new physics*.

- Can probe many general dark matter models.

+ High statistics measurement of low-energy ***Antiproton*** and open sensitivity to ***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

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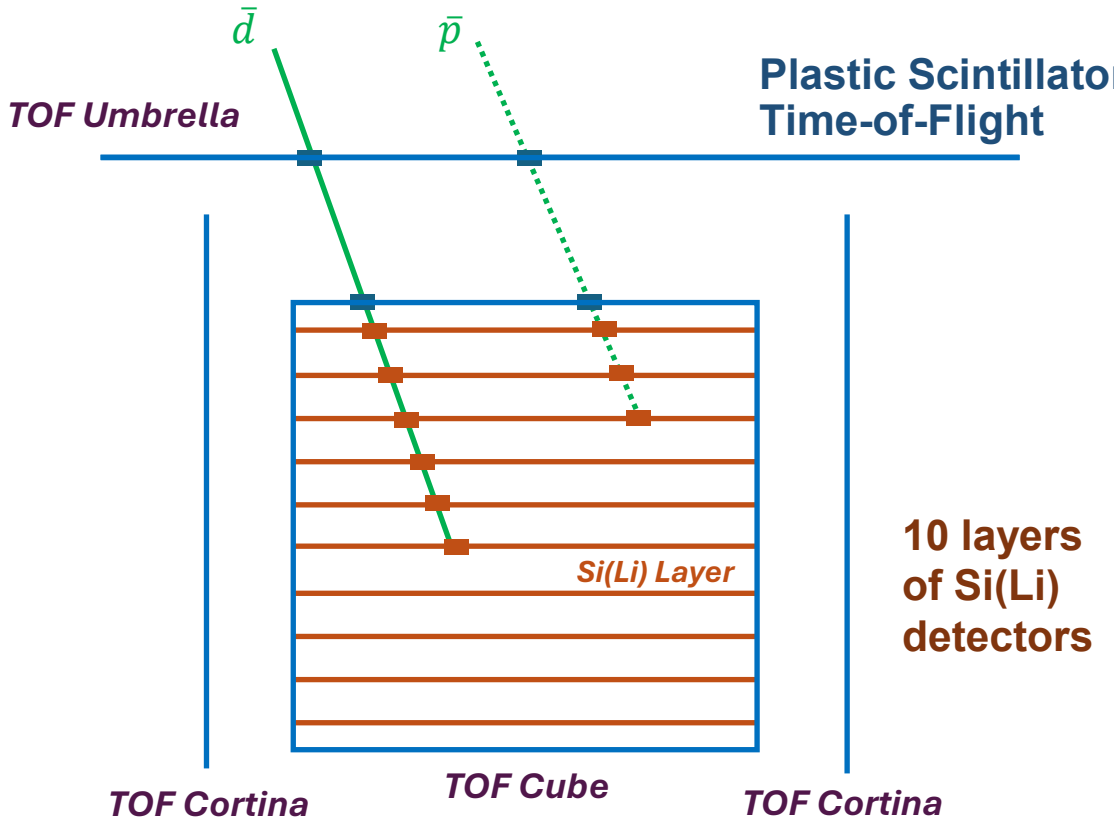

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Si(Li) tracker:

- Slows/captures an incoming antiparticle

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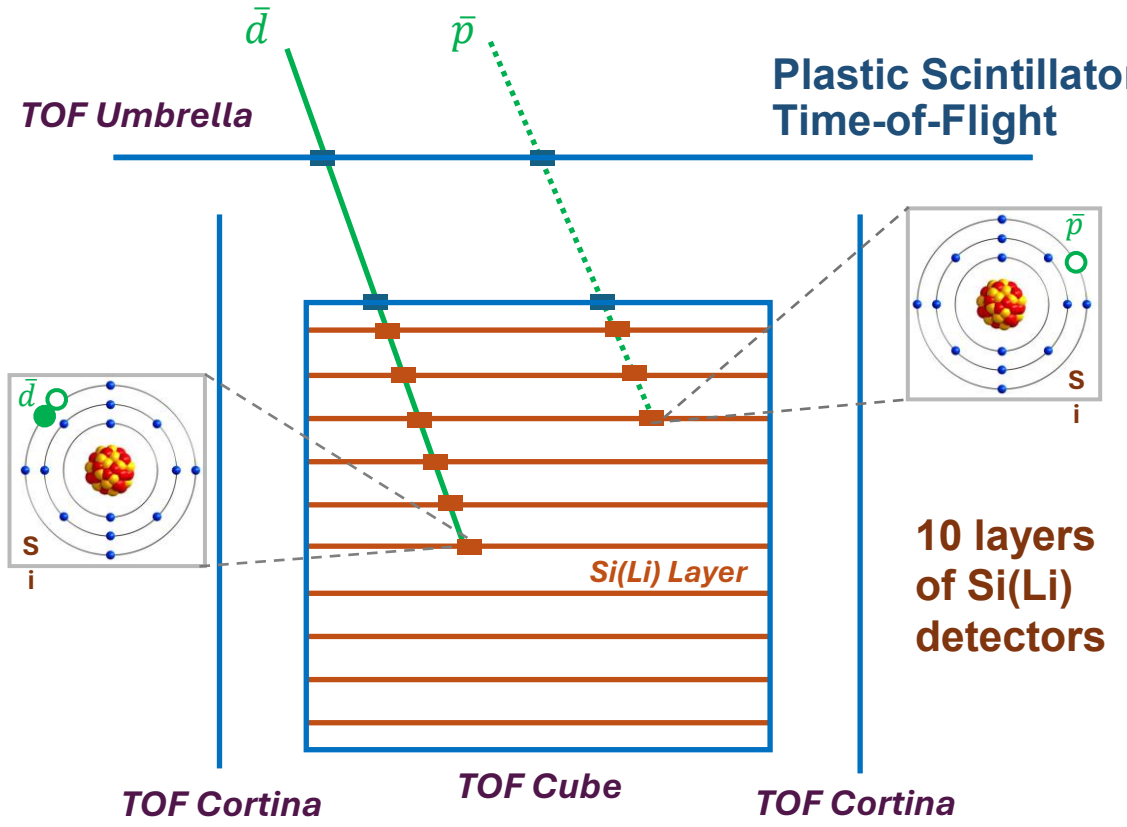

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Si(Li) tracker:

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

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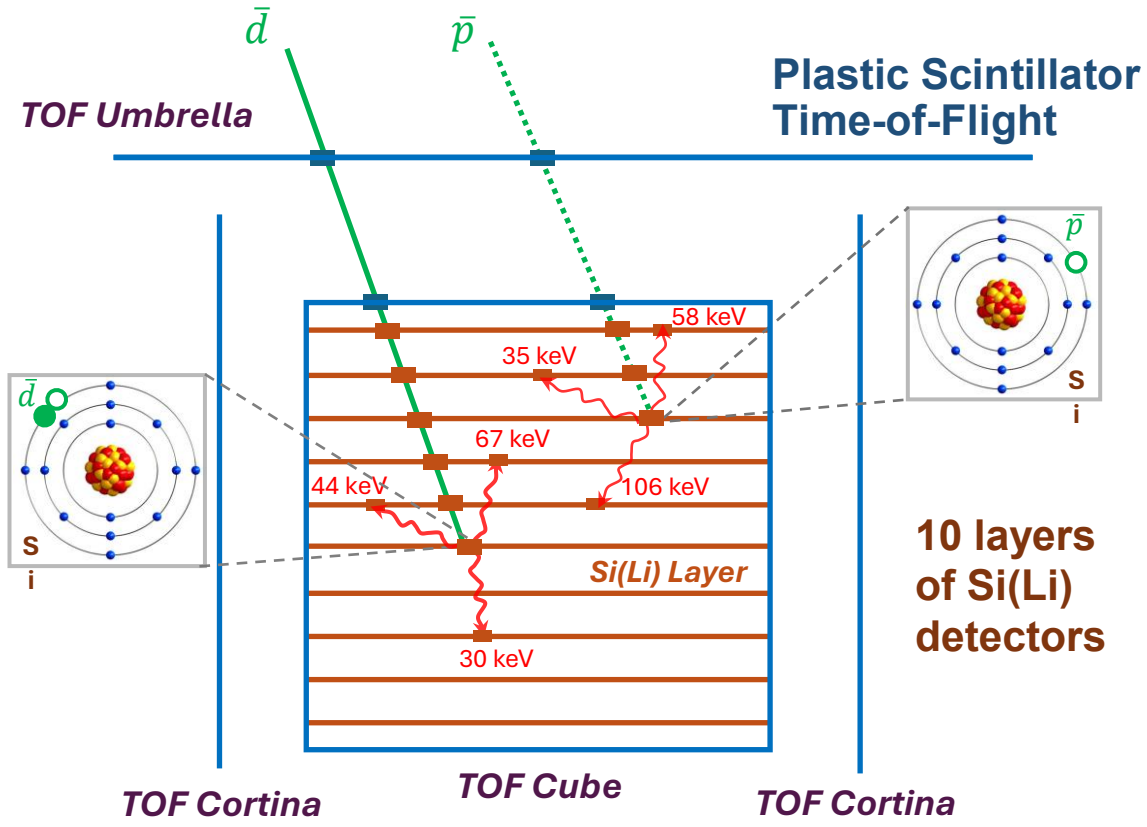


10 layers of Si(Li) detectors

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

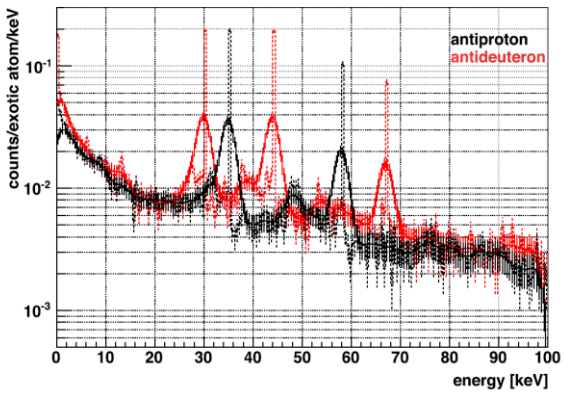
Si(Li) tracker:

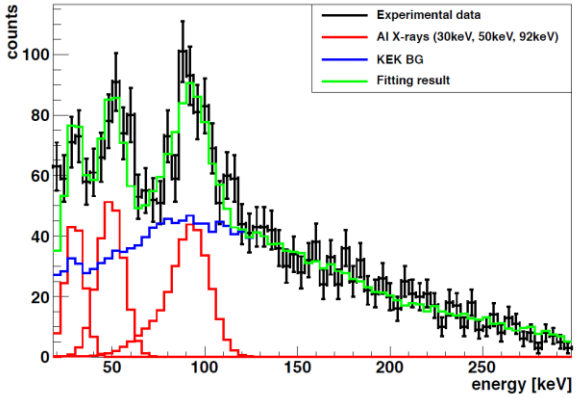
- Slows/captures an incoming antiparticle into an ***exotic atom***
- Measures the decay ***X-rays***

Antiparticle mass

$$E_X = (zZ)^2 \frac{M^*}{m_e^*} R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

Target material





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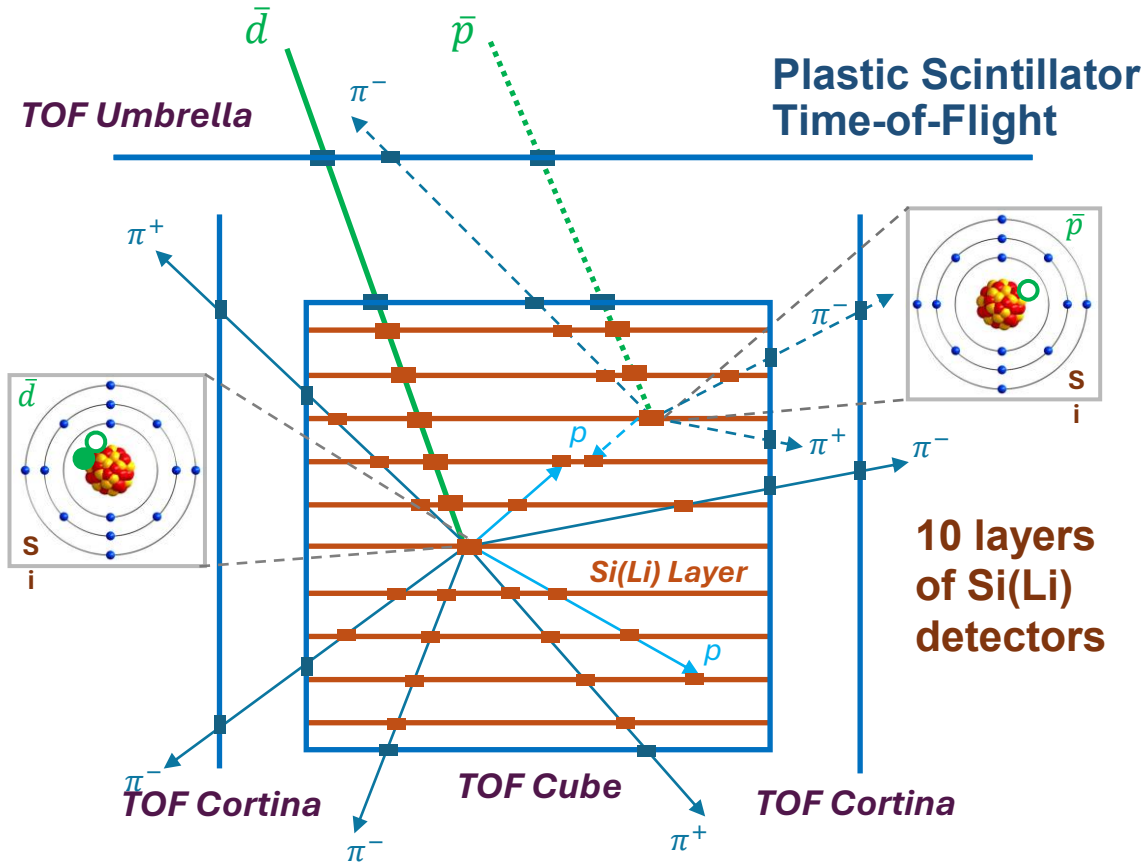

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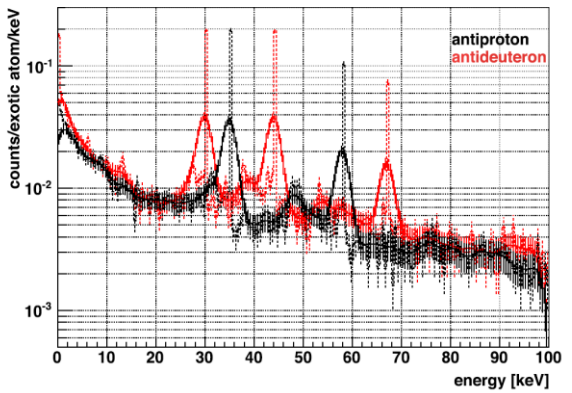
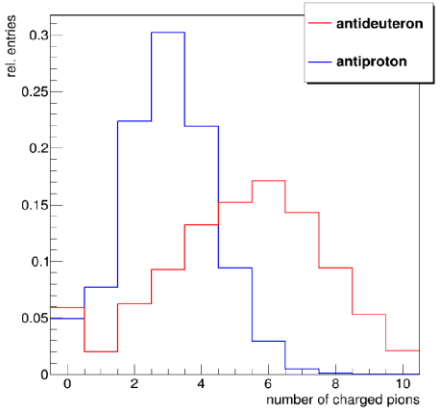
Si(Li) tracker:

- 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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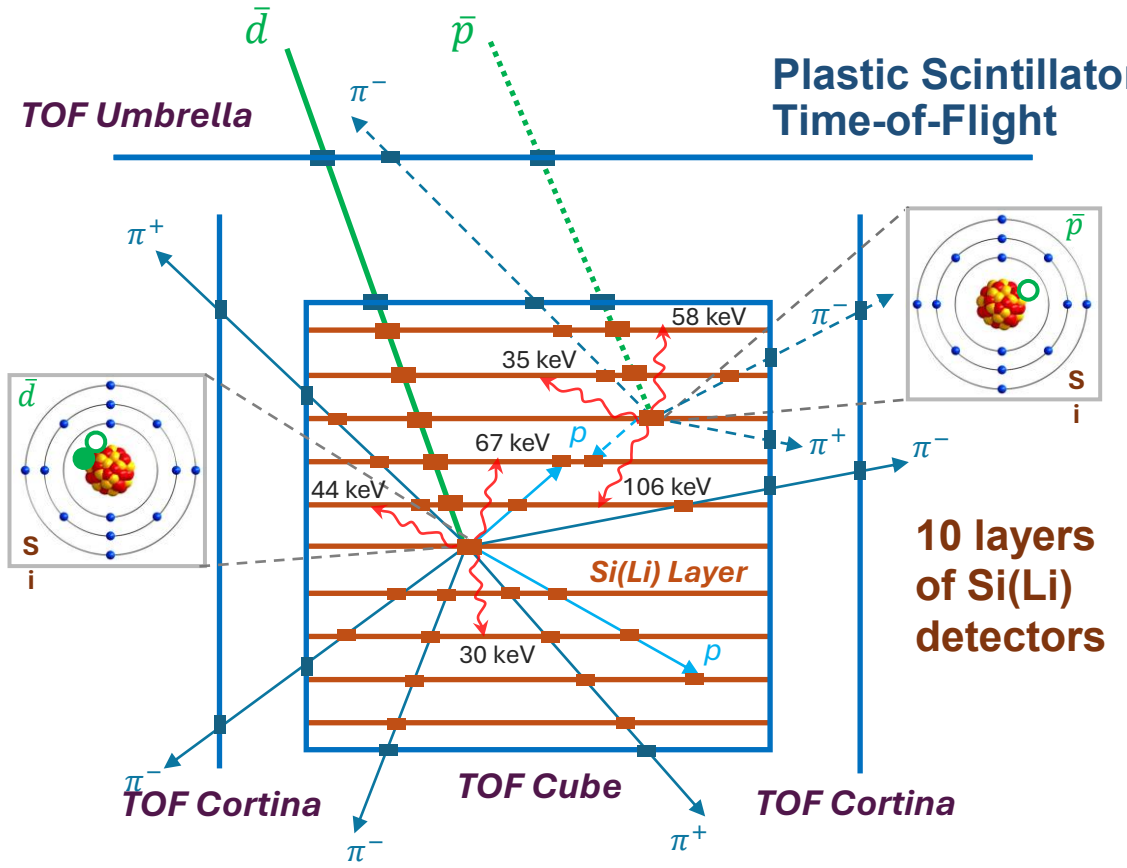

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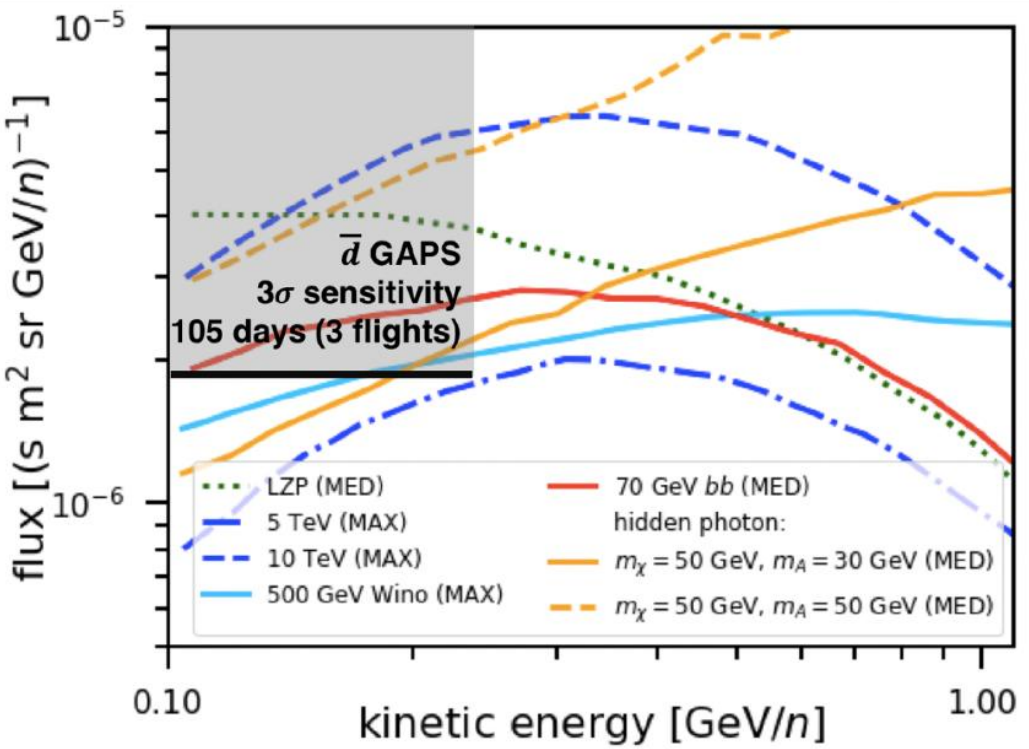
Si(Li) tracker acts as:

- ***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:



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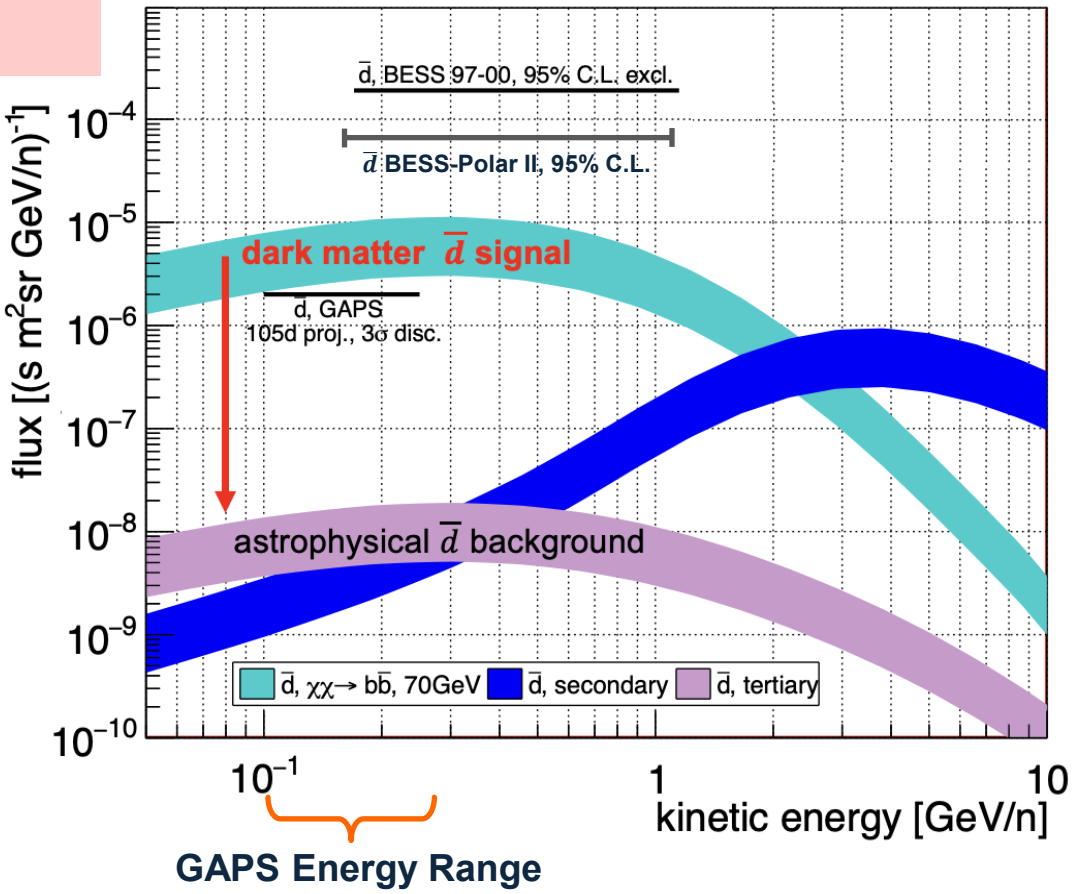

Note: Any antideuteron signal needs to be compatible with antiproton constraints!

GAPS Science: *Antiproton*

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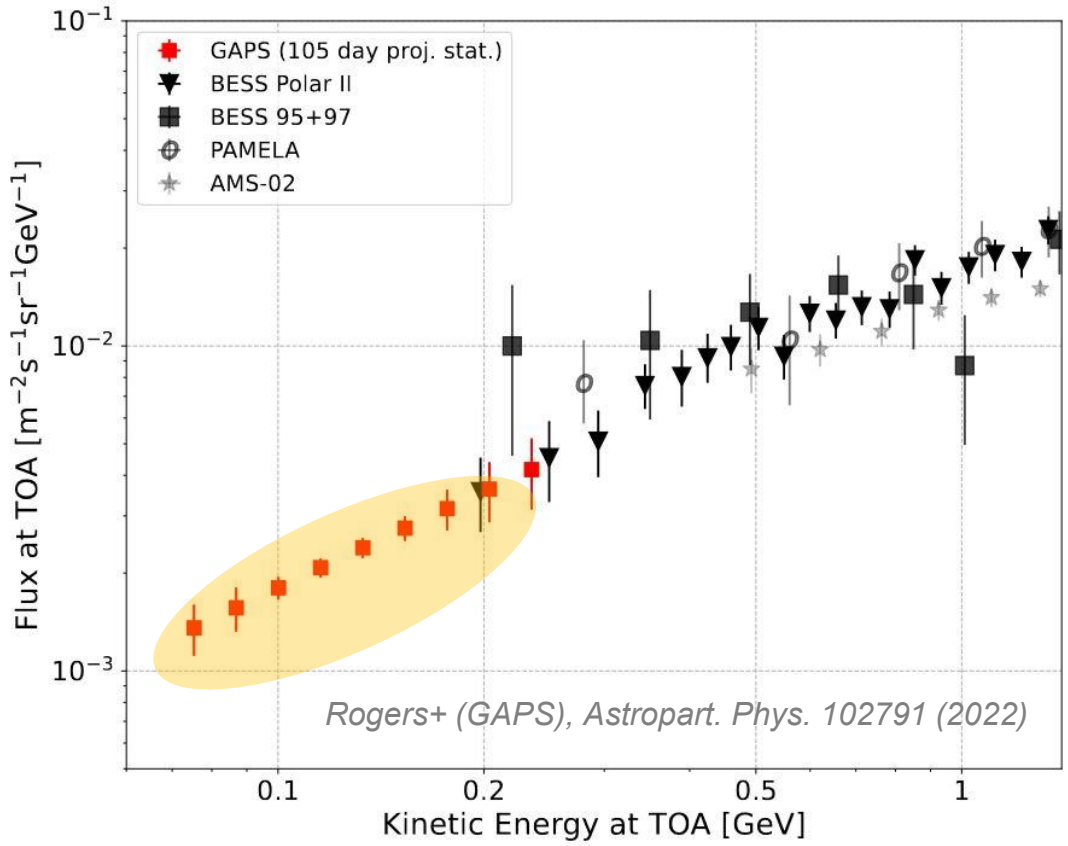
- ~500 antiprotons (≲0.25 GeV/*n*) for each balloon flight.
  - BESS : 29 at ~0.2 GeV
  - PAMELA: 7 at ~0.25 GeV
  - AMS-02: E>0.25 GeV



- ✓ 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)

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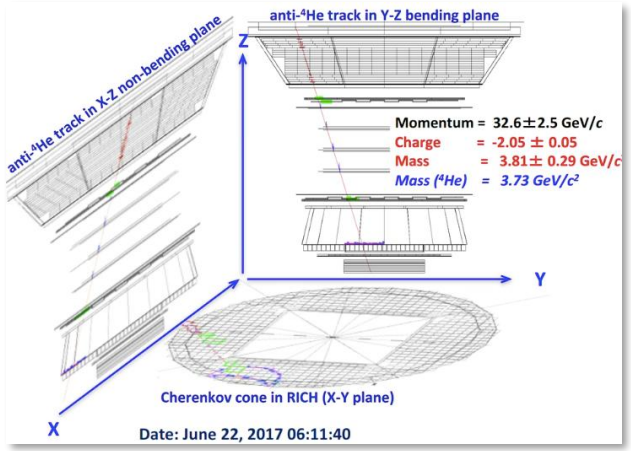
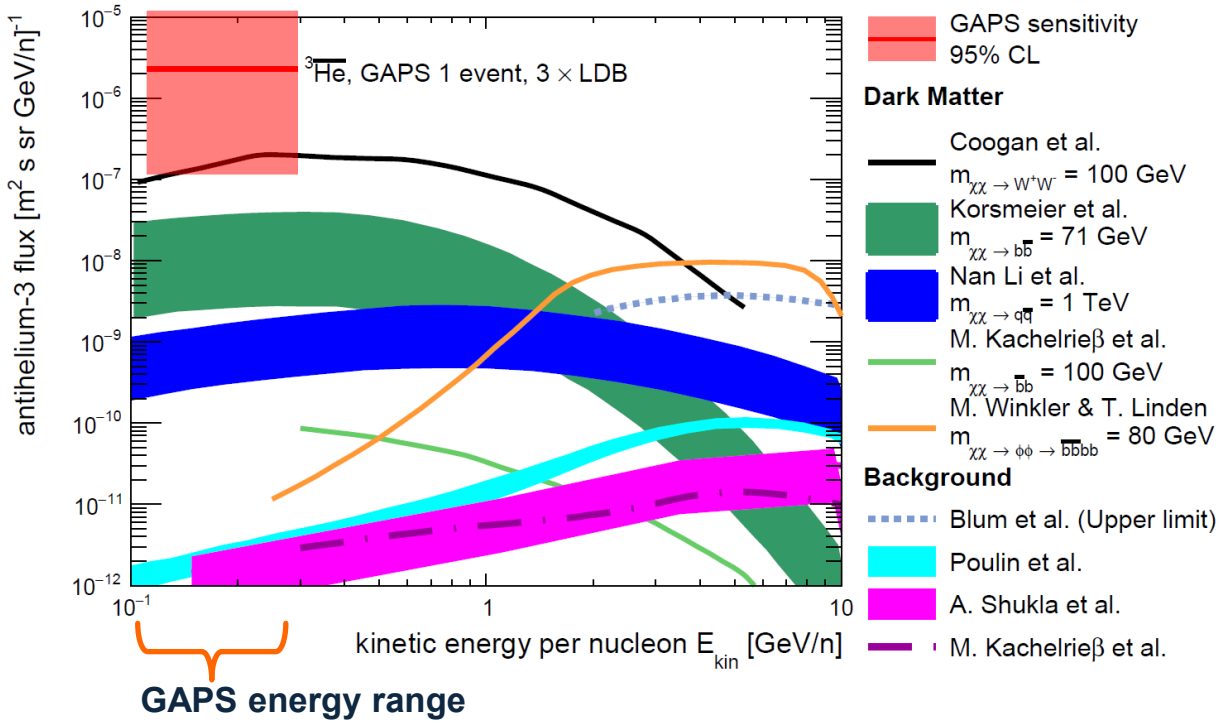


Saffold+ (GAPS), Astropart. Phys. 102580 (2021).

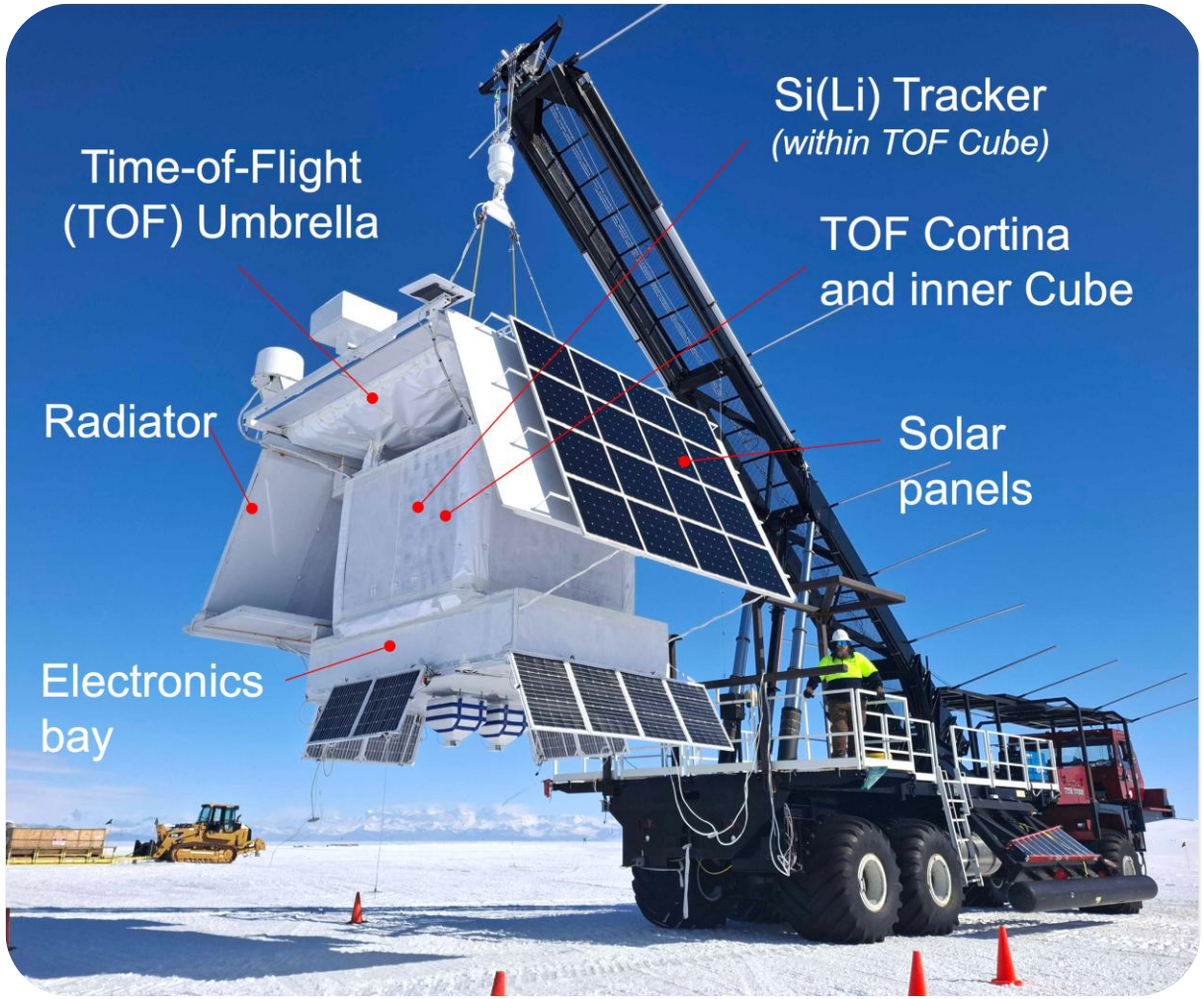


➢ Extends to lower energies (0.11-0.3 GeV/n), complementary to AMS-02.

- 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 → Led by SJTU**
  - 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

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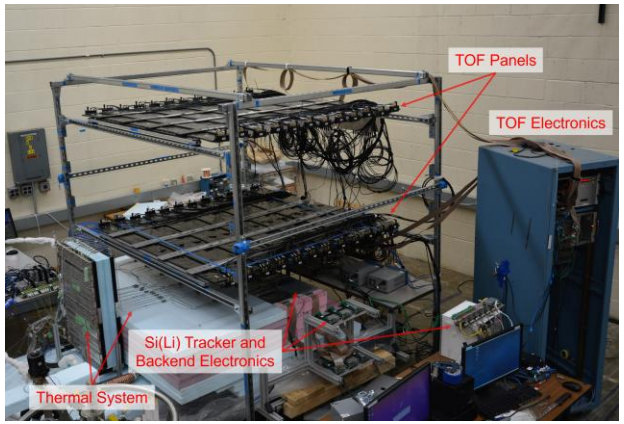
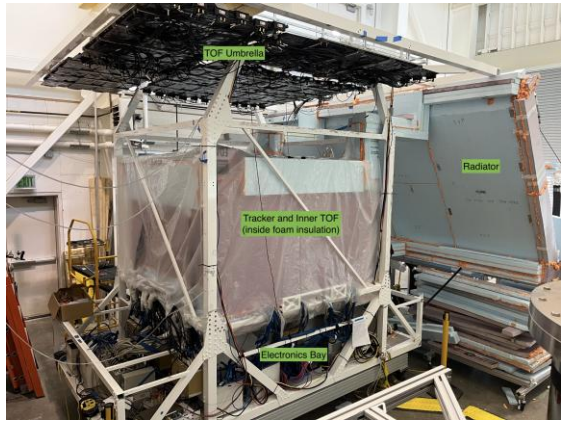
2020/2021, GFP @MIT-Bates, MA



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*

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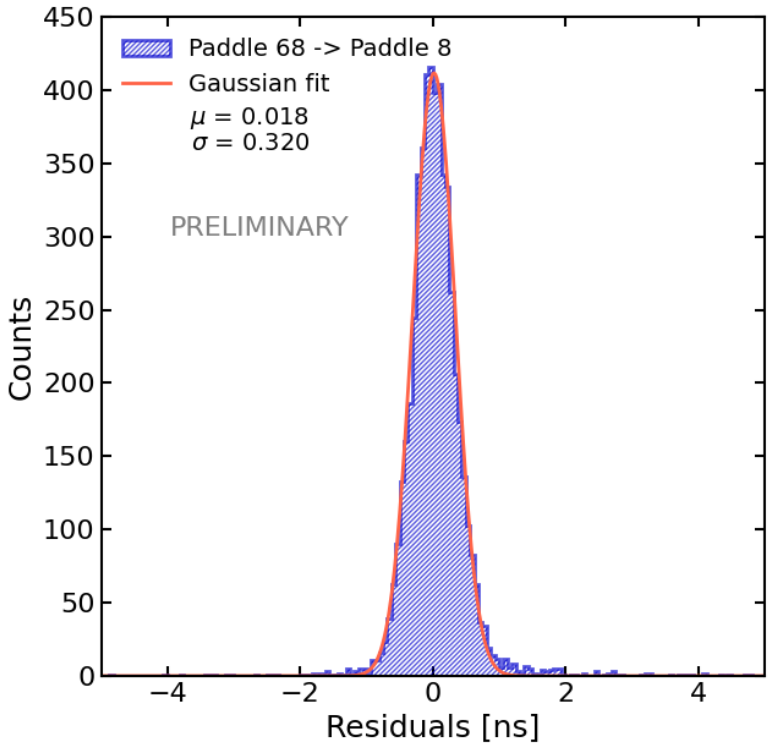
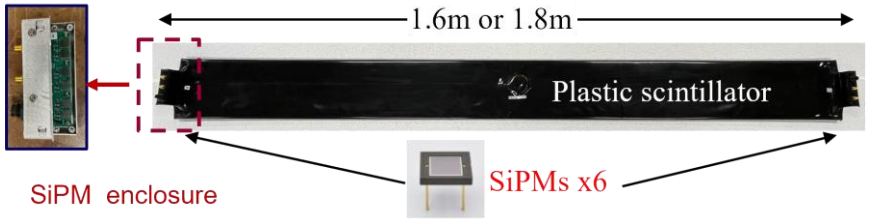
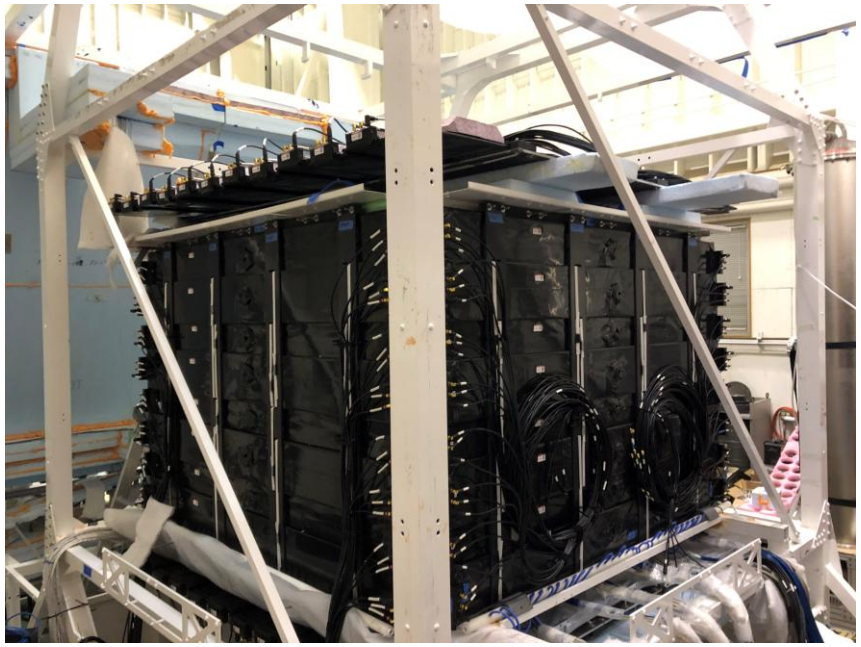
❑ToF performance from the Antarctic commissioning.

- 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

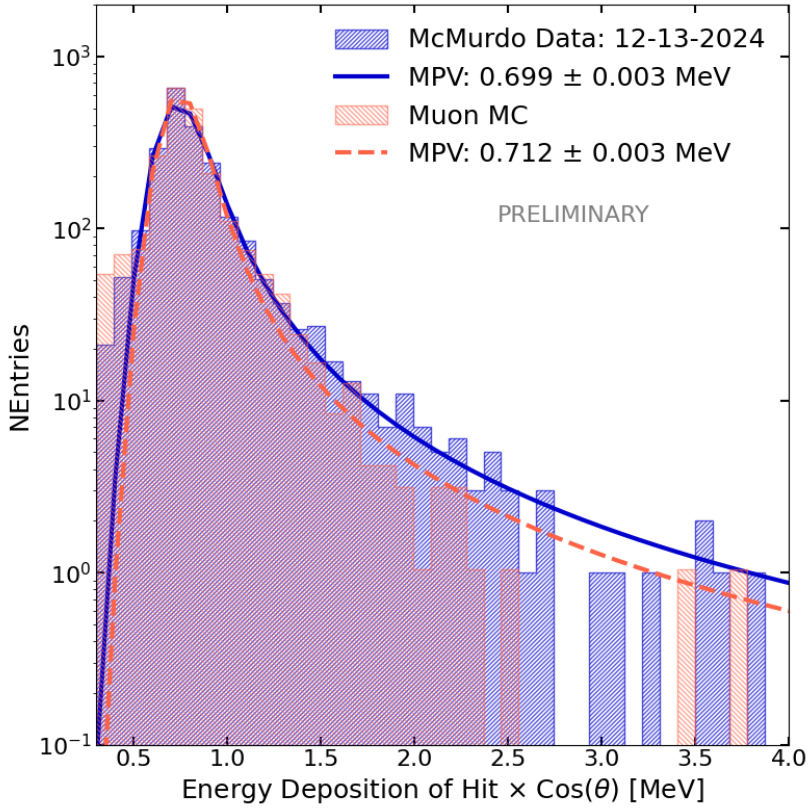




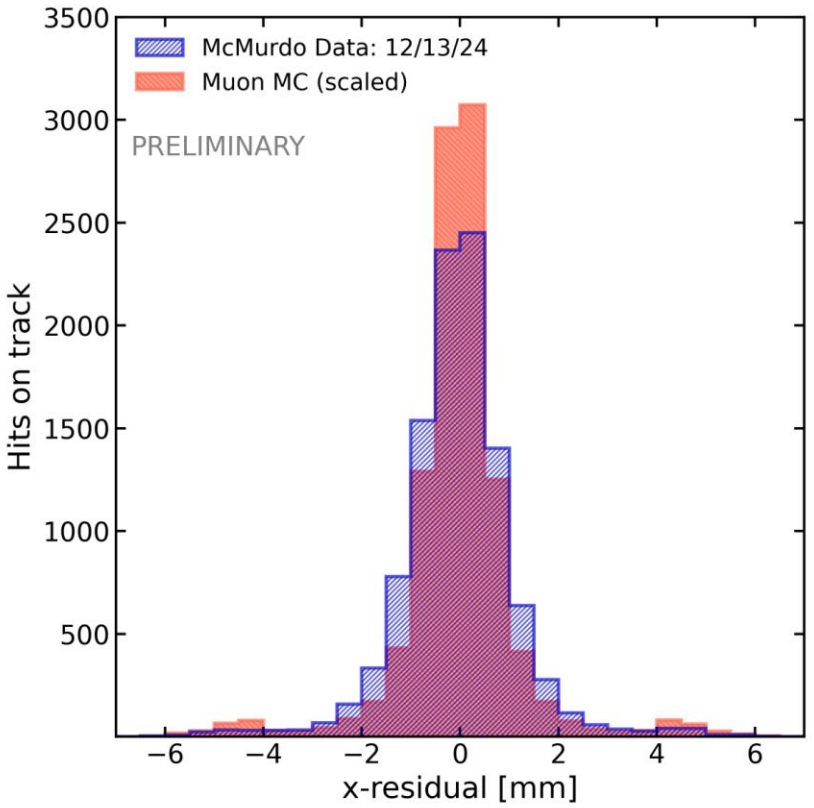
➢ Achieved: measured better than ~350 ps for all paddle combinations!

GAPS Instrument Performance: *Tracker*

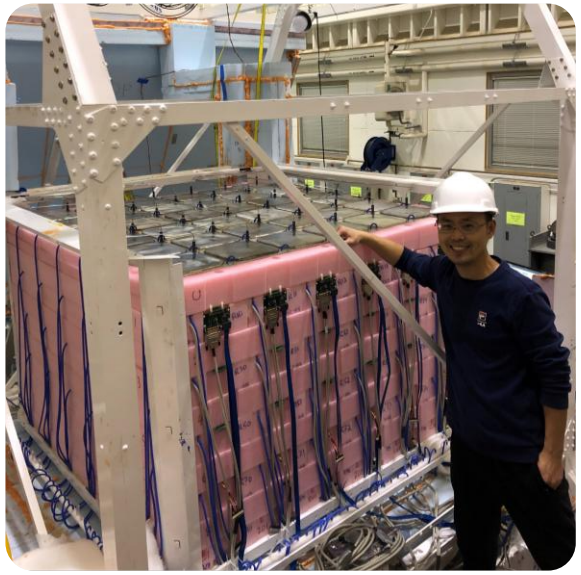
- Tracker performance from the Antarctic commissioning.

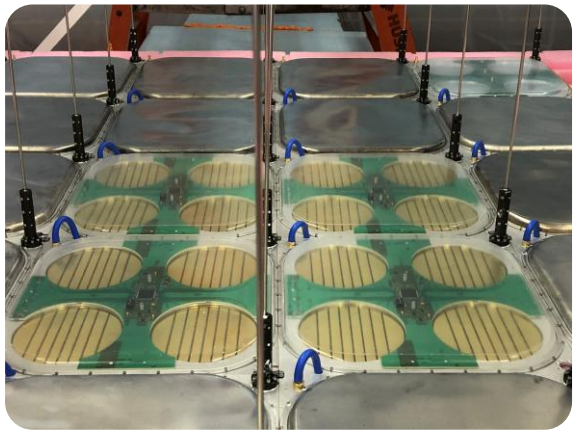


- Energy depositions on track



- Track position resolution

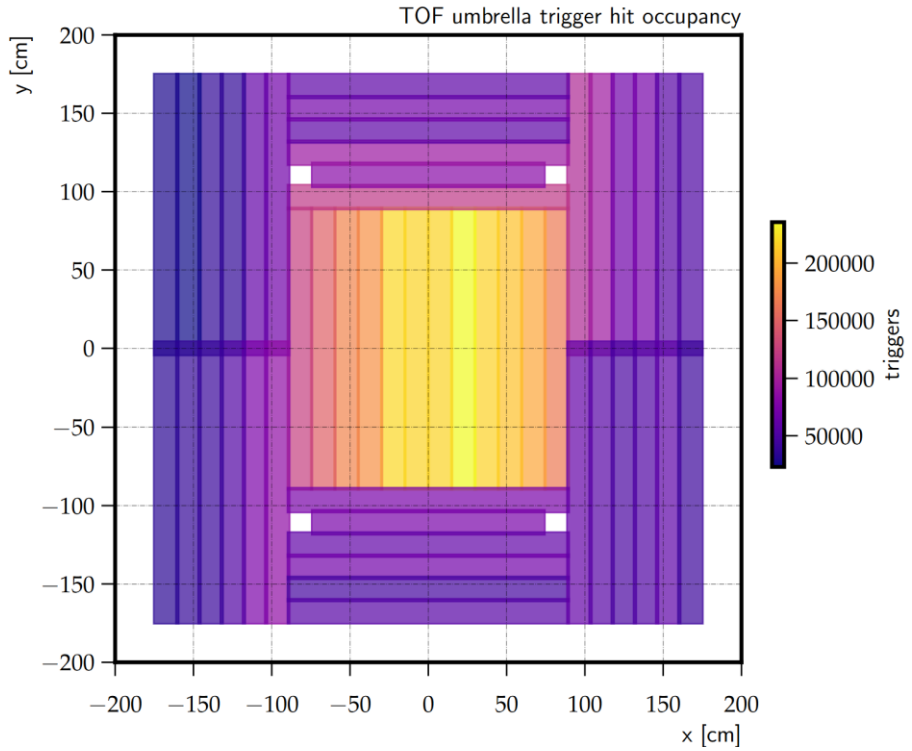




➢ Energy and track reconstruction validated!

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*

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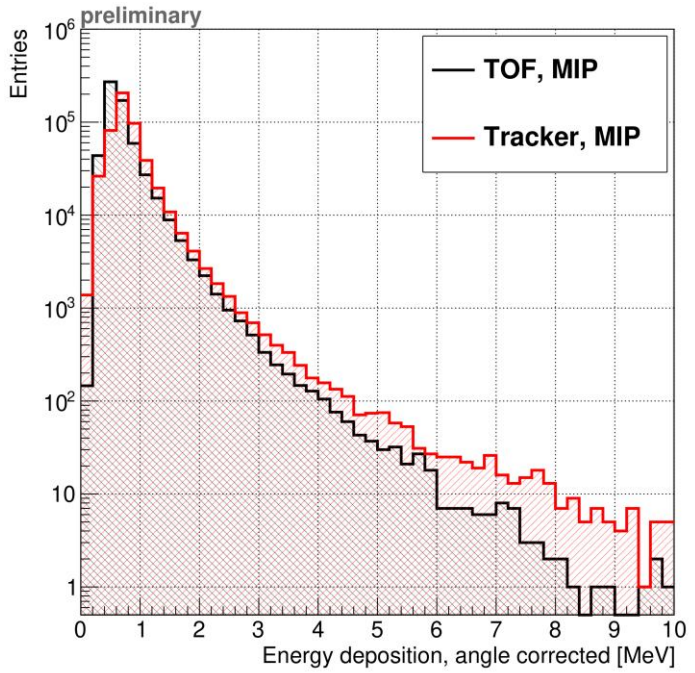
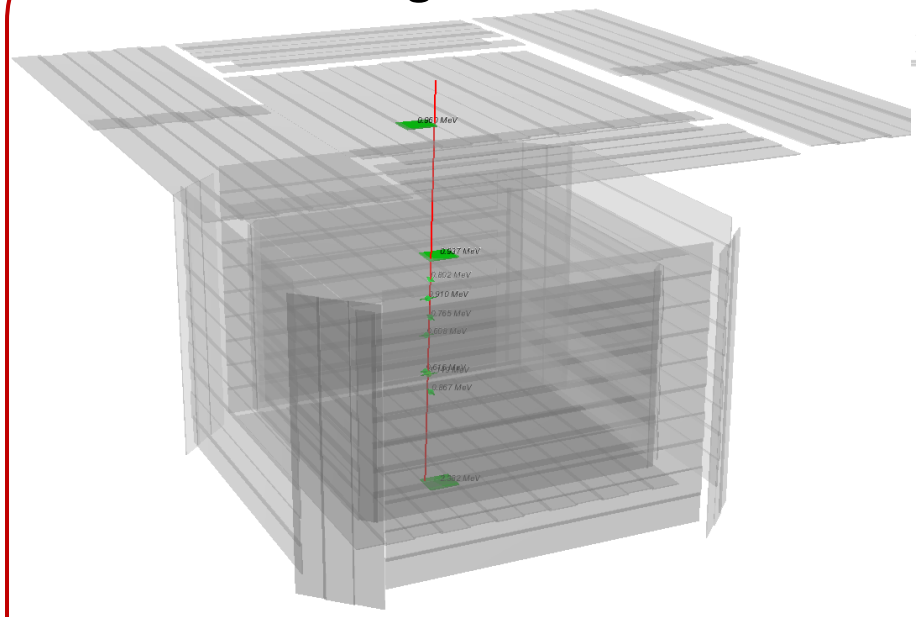
- ~10M muon events are collected from the on-ground testing in the Antarctica.
  - Event signature are well understood and more detailed analysis is undergoing.

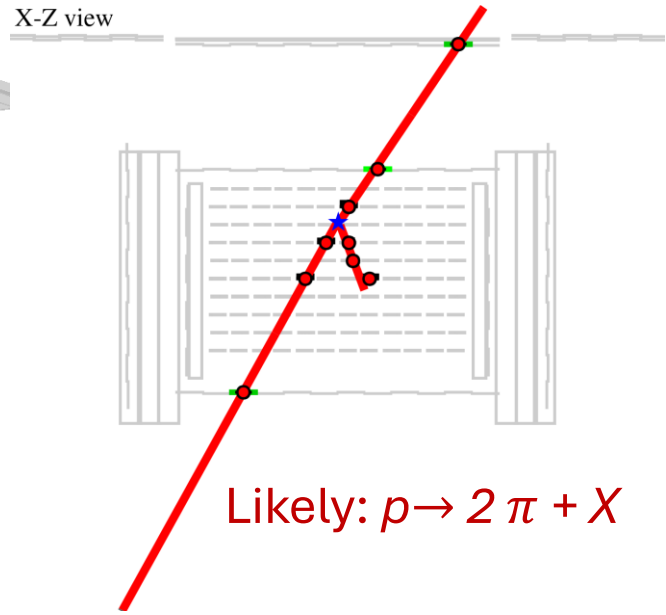


- Energy reconstruction

- Single track



- Multi track



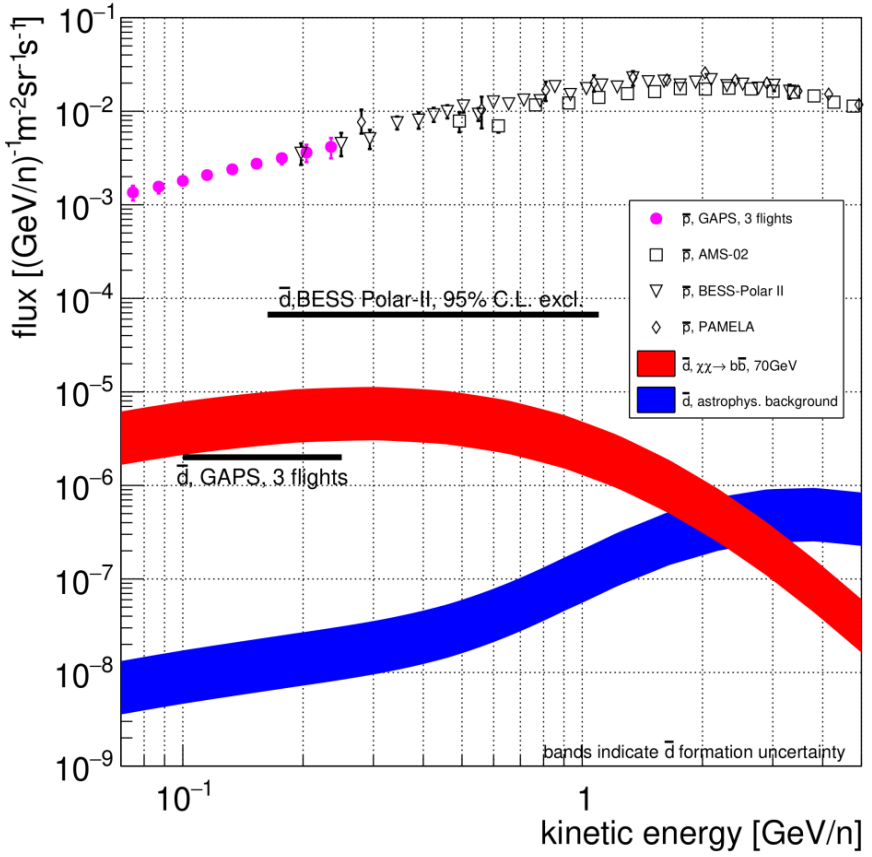
- Track Reconstruction

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 ~2 orders of magnitude below the current best limits, “smoking-gun” signature of dark matter.
  - *precision $\bar{p}$ measurement in unexplored energy range.*
  - *open 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!