



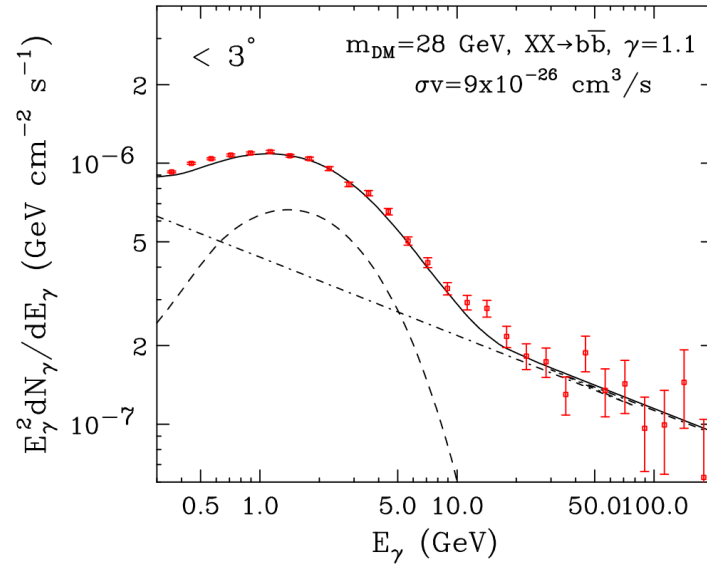
Dark Matter Searches with Low-energy Cosmic Antinuclei

Mengjiao Xiao (肖梦姣)
Shanghai Jiao Tong University
2025-08-24

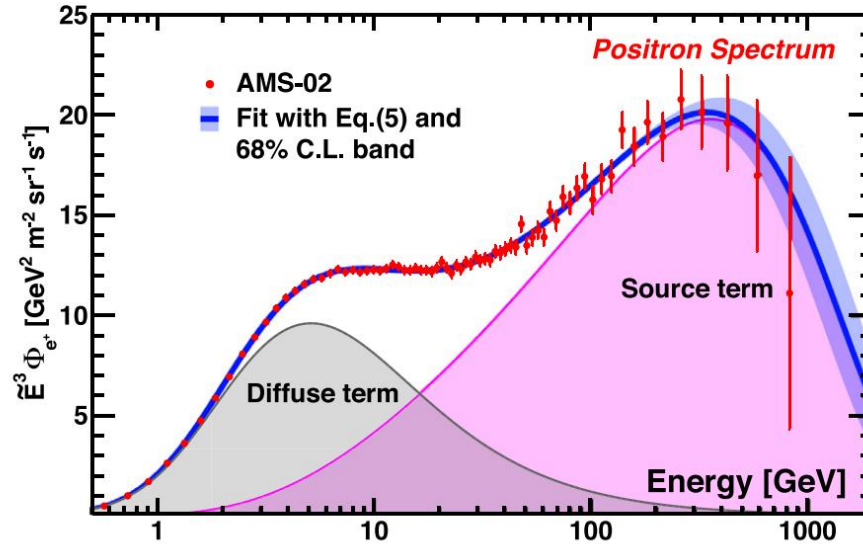


Dark Matter Hints in Cosmic Rays

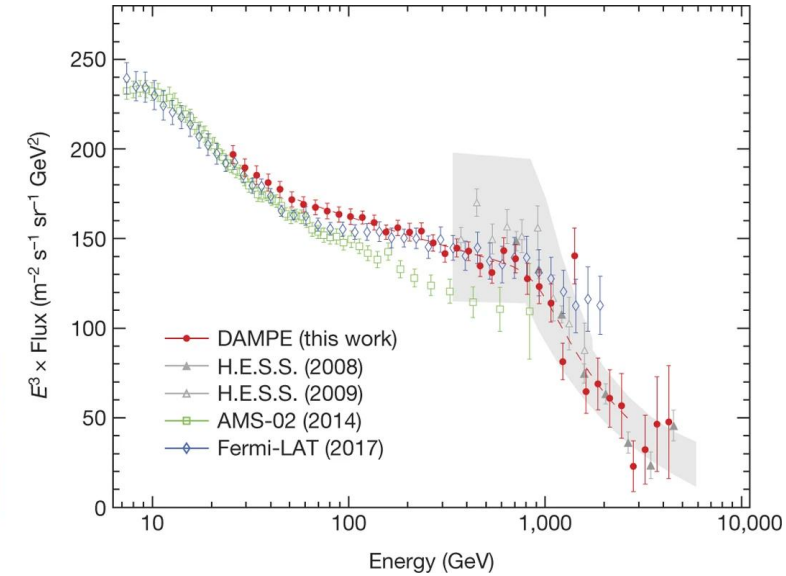
D. Hooper+ *PRD* (2011), I. Cholis+ *JCAP* (2009)



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



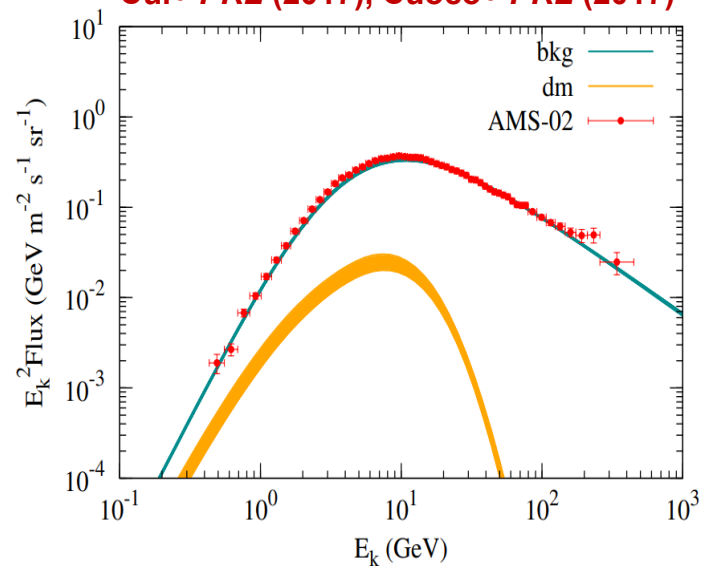
DAMPE, *Nature* (2017)



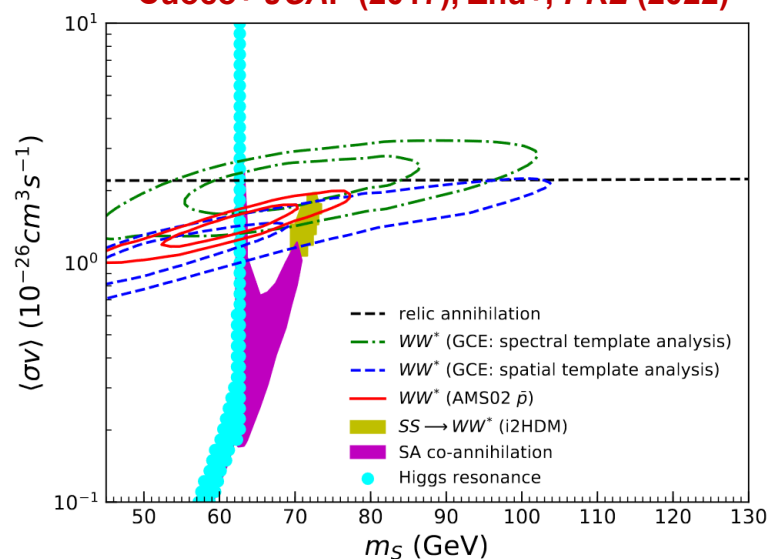
❑ GeV gamma excess at GC center by Fermi-LAT: *dark matter of O(10-100) GeV?*

❑ Positron/electron excess by PALEMA, AMS-02, Fermi-LAT, CALET, DAMPE: *~TeV dark matter?*

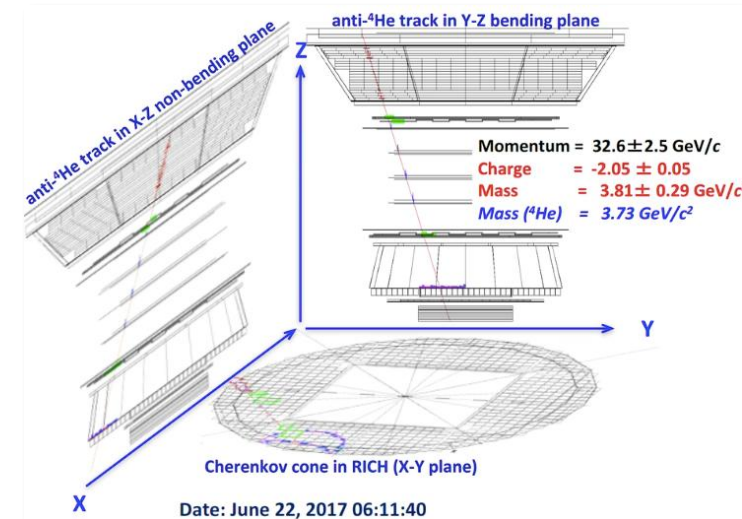
Cui+ *PRL* (2017), Cuoco+ *PRL* (2017)



Cuoco+ *JCAP* (2017), Zhu+, *PRL* (2022)



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

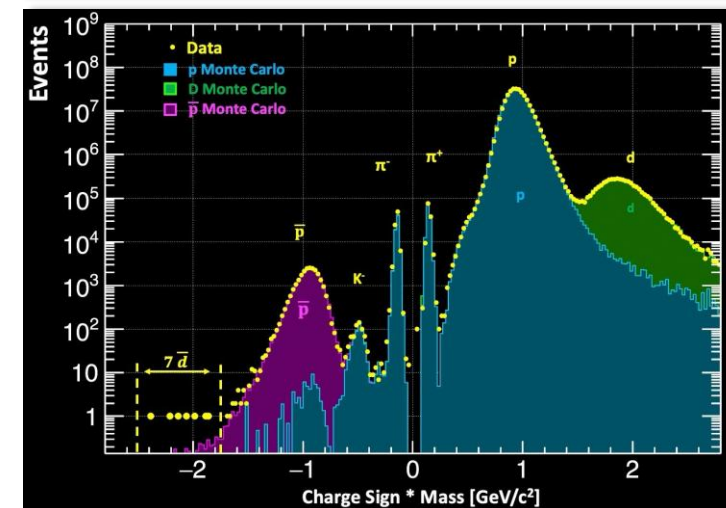


❑ Antiproton excess in the 10-20 GV rigidity by AMS-02:

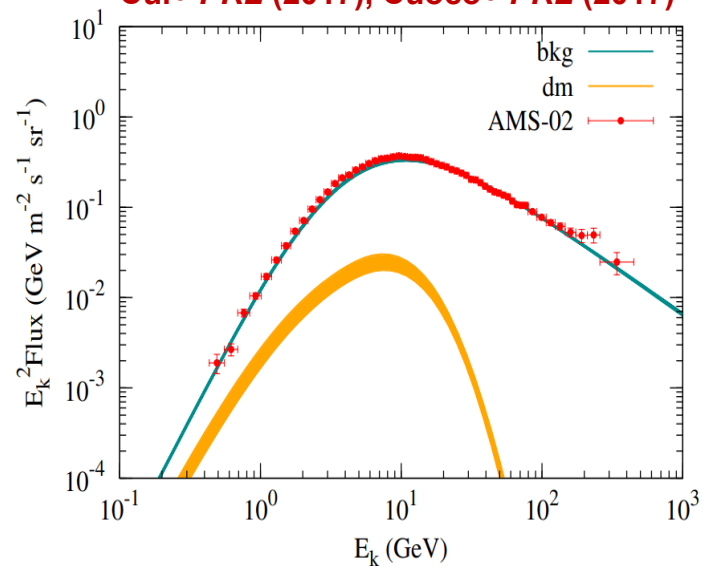
dark matter of $O(10-100)$ GeV?

- Consistent with dark matter interpretation of GeV γ excess

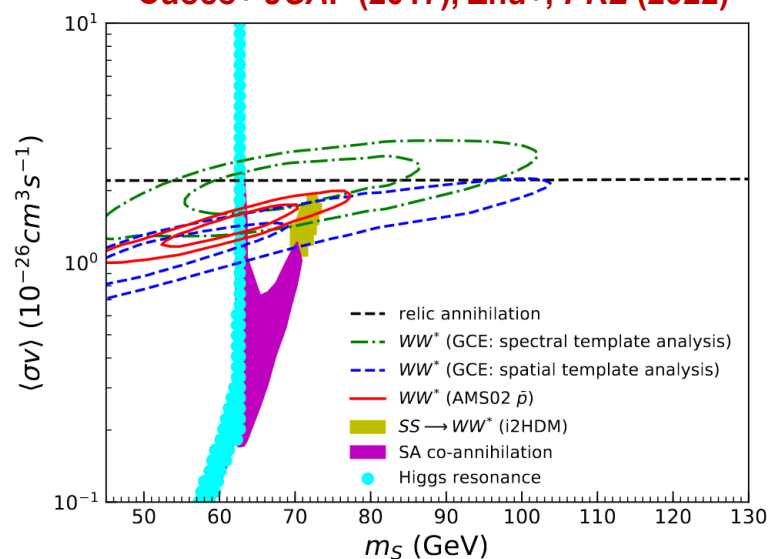
❑ Antihelium “candidates” by AMS-02.



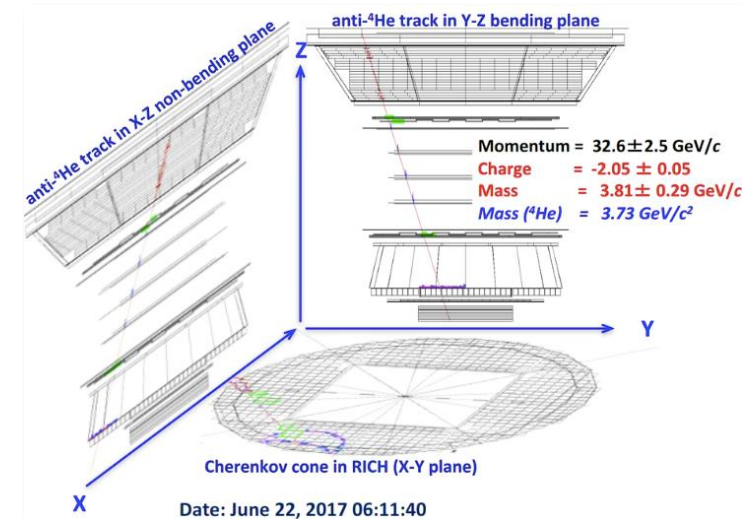
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AMS Candidate Anti-He4 event ($p = 32.6 \text{ GeV/c}$)



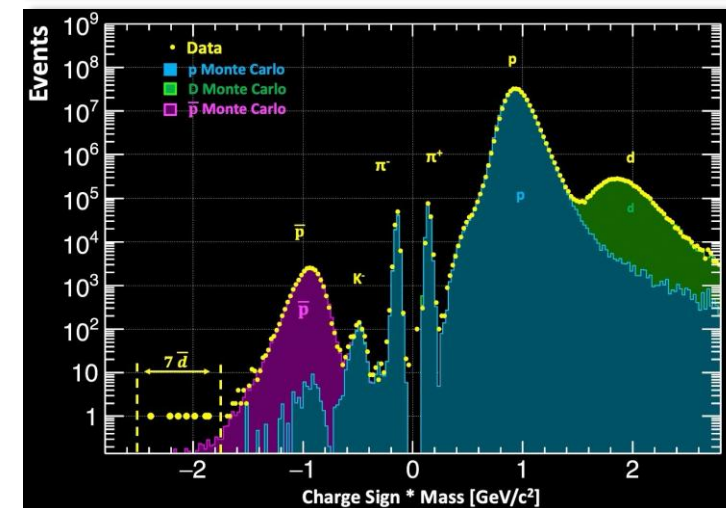
❑ Antiproton excess in the 10-20 GV rigidity by AMS-02:

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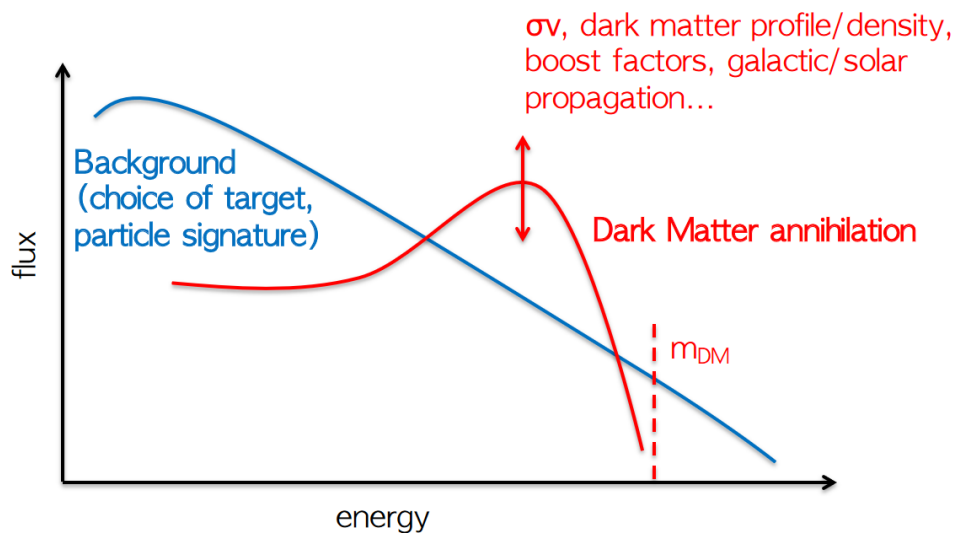
- Consistent with dark matter interpretation of GeV γ excess

❑ Antihelium “candidates” by AMS-02.

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



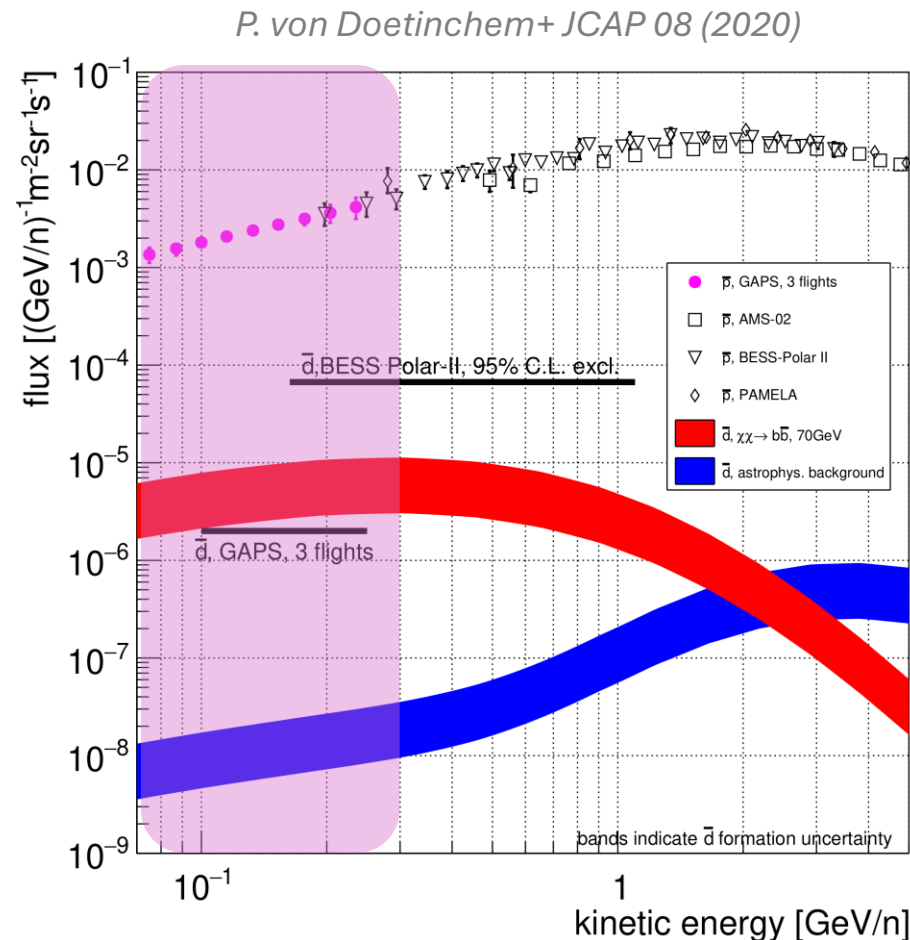
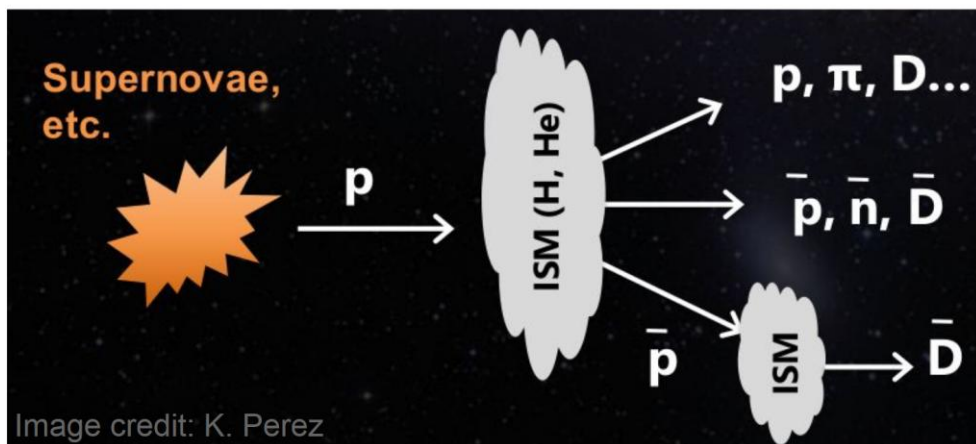
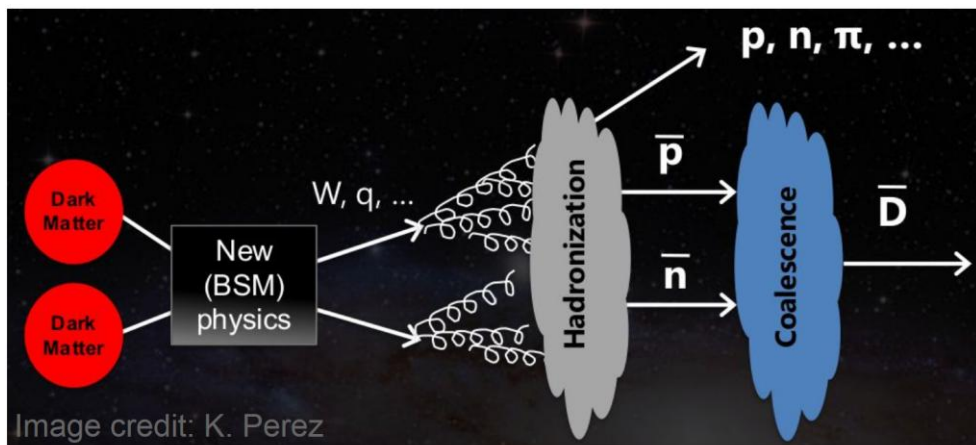
❑ **Assumption:** dark matter annihilation/decay follows different kinematics (i.e. via new physics) than conventional productions.



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

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

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





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 ($KE \lesssim 0.25 \text{ GeV}/n$) **Antideuteron** as signature of new physics.

- Can probe many general dark matter models.

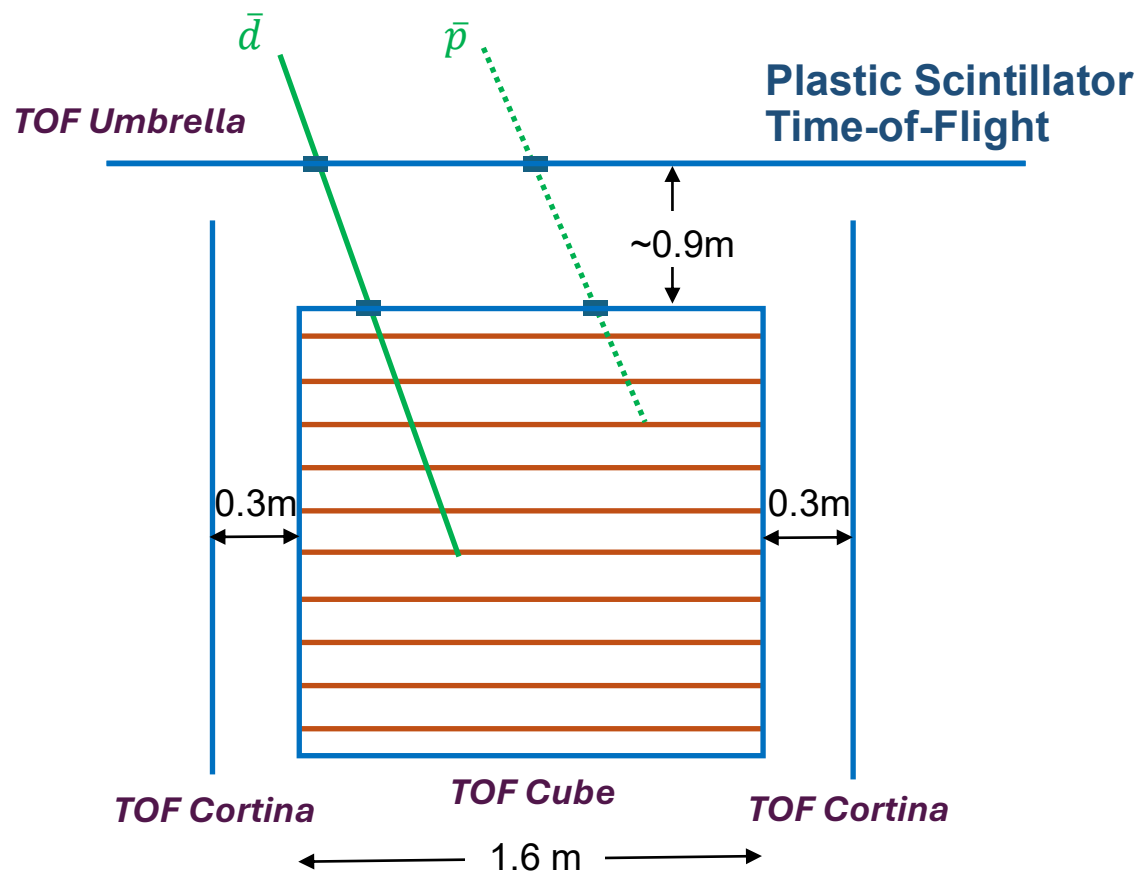
+ High statistics measurement of low-energy **Antiproton** and open sensitivity to **Antihelium**.



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



GAPS Novel Detection Technology



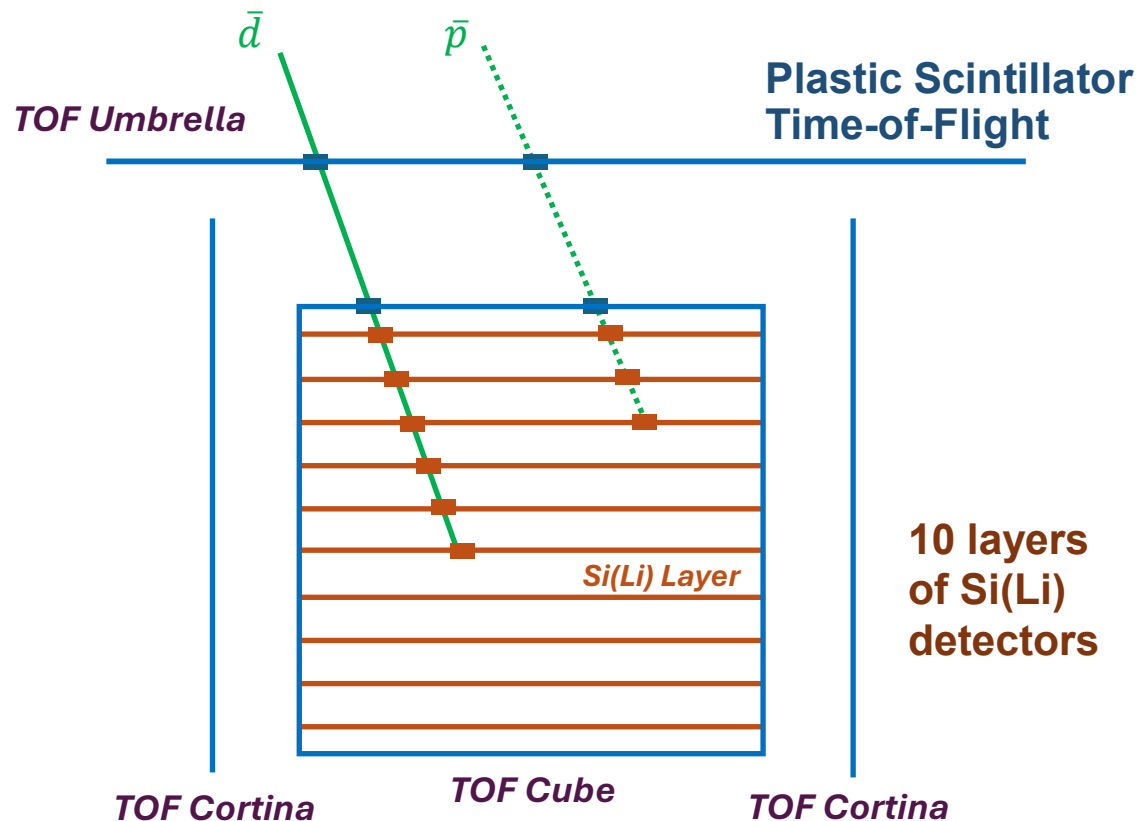
Time-of-flight system: measures velocity, incoming angle and dE/dx , fast trigger

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



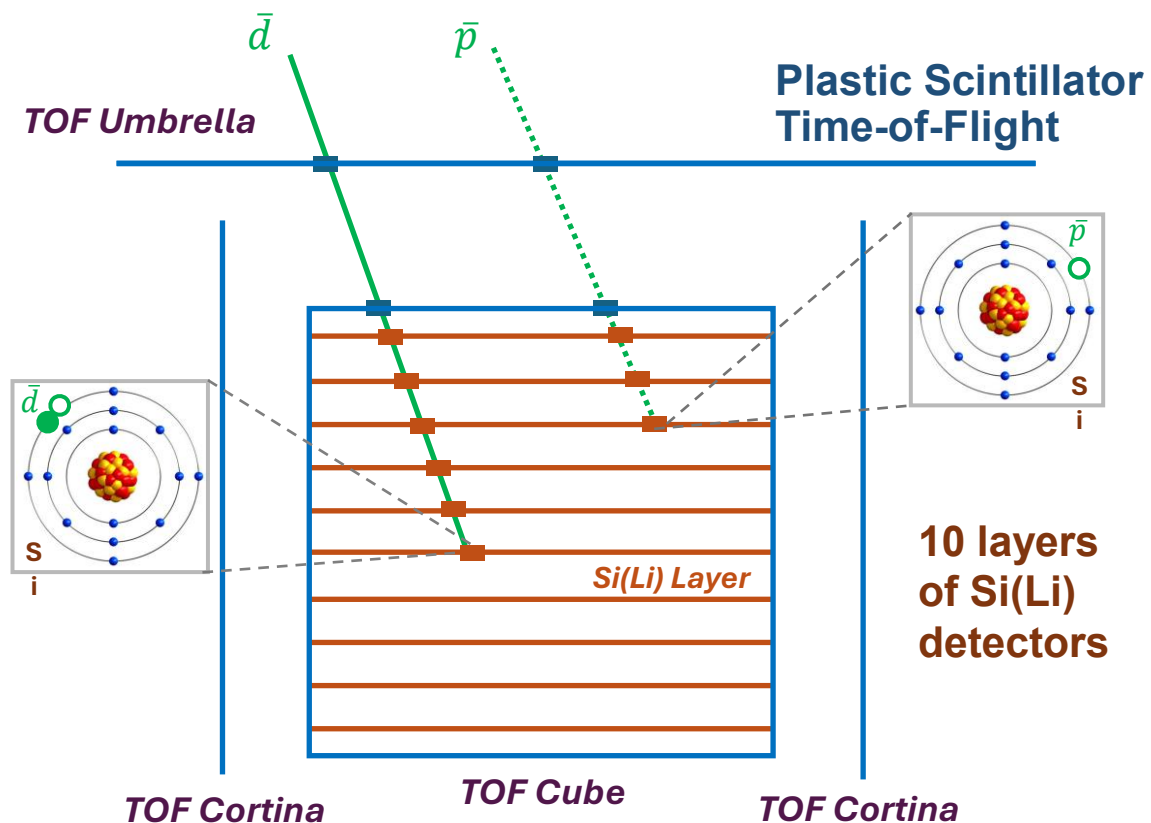
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Si(Li) tracker:

- Slows/captures an incoming antiparticle

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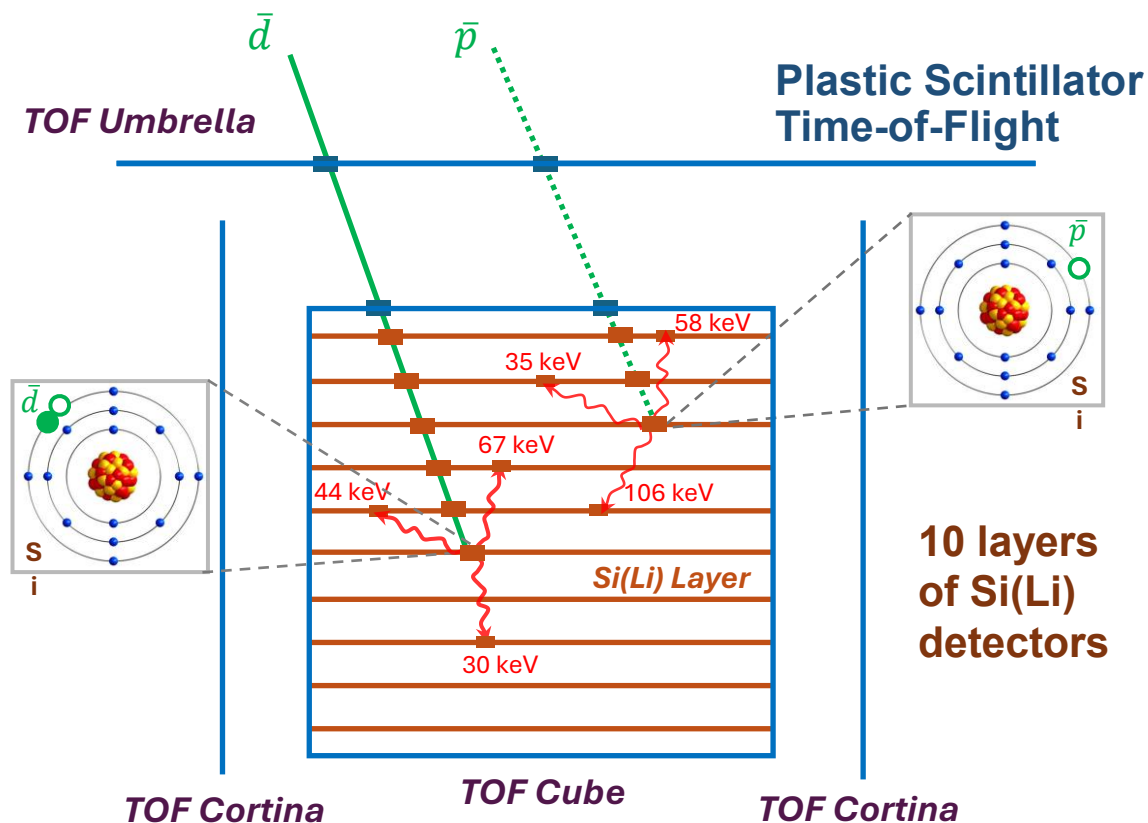
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Si(Li) tracker:

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

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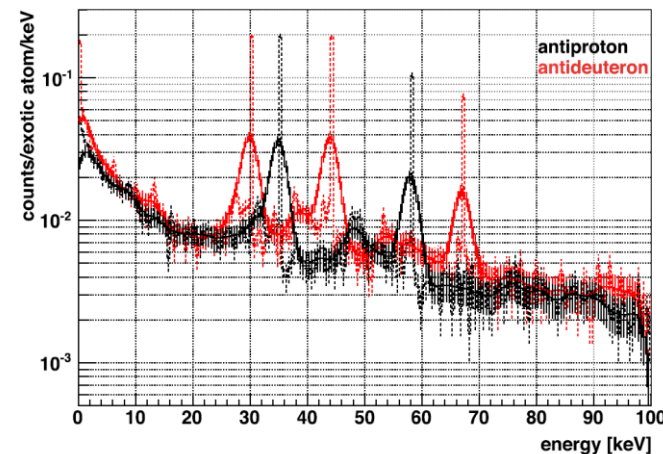
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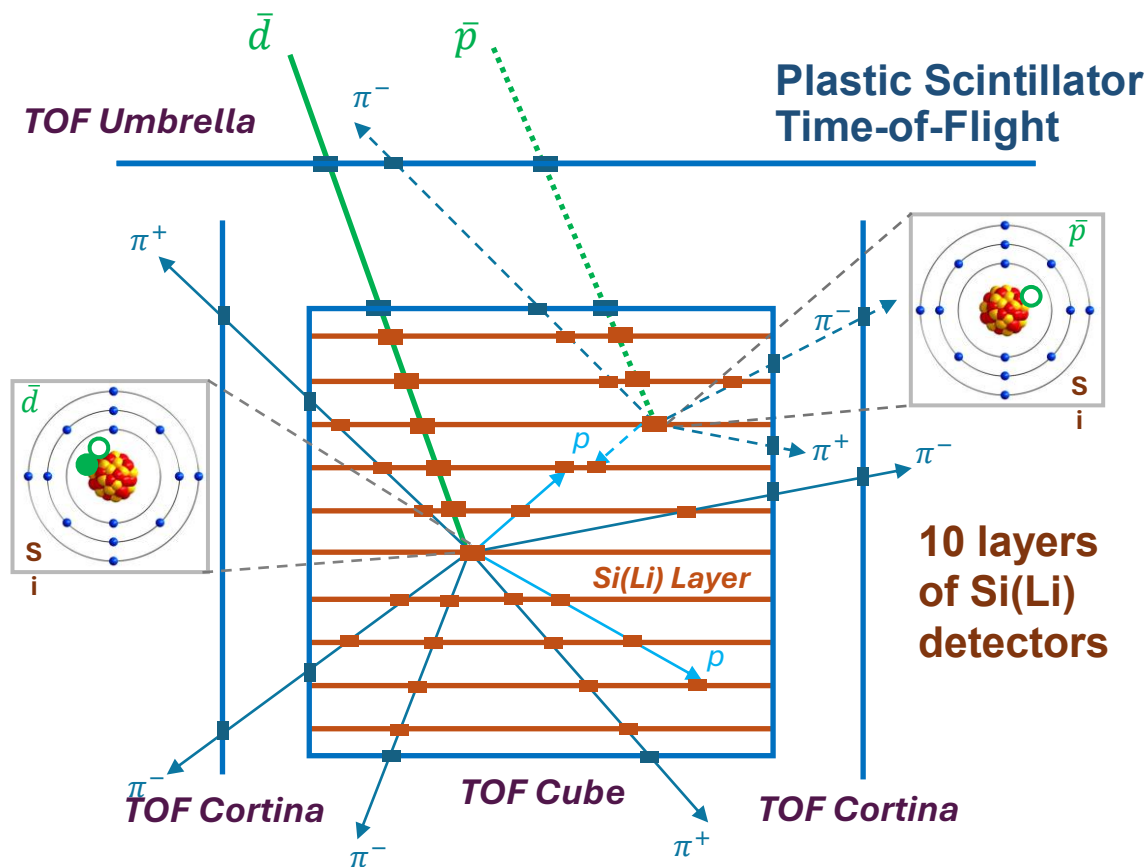
Si(Li) tracker:

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



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

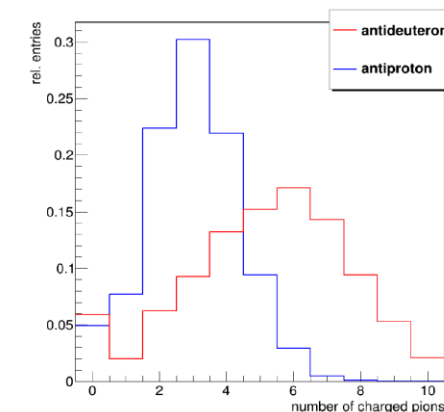
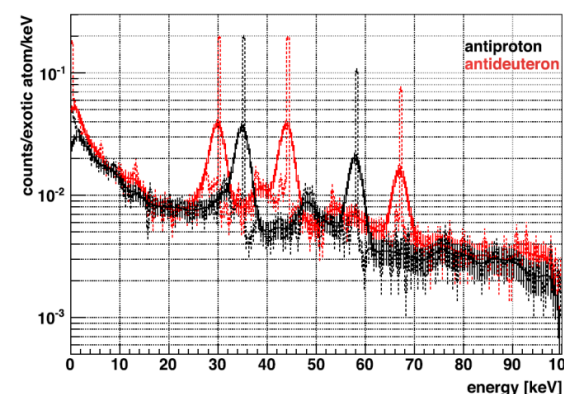
GAPS sensitivity to antideuterons: Aramaki+ *Astropart.Phys.* 74, 6 (2016)



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

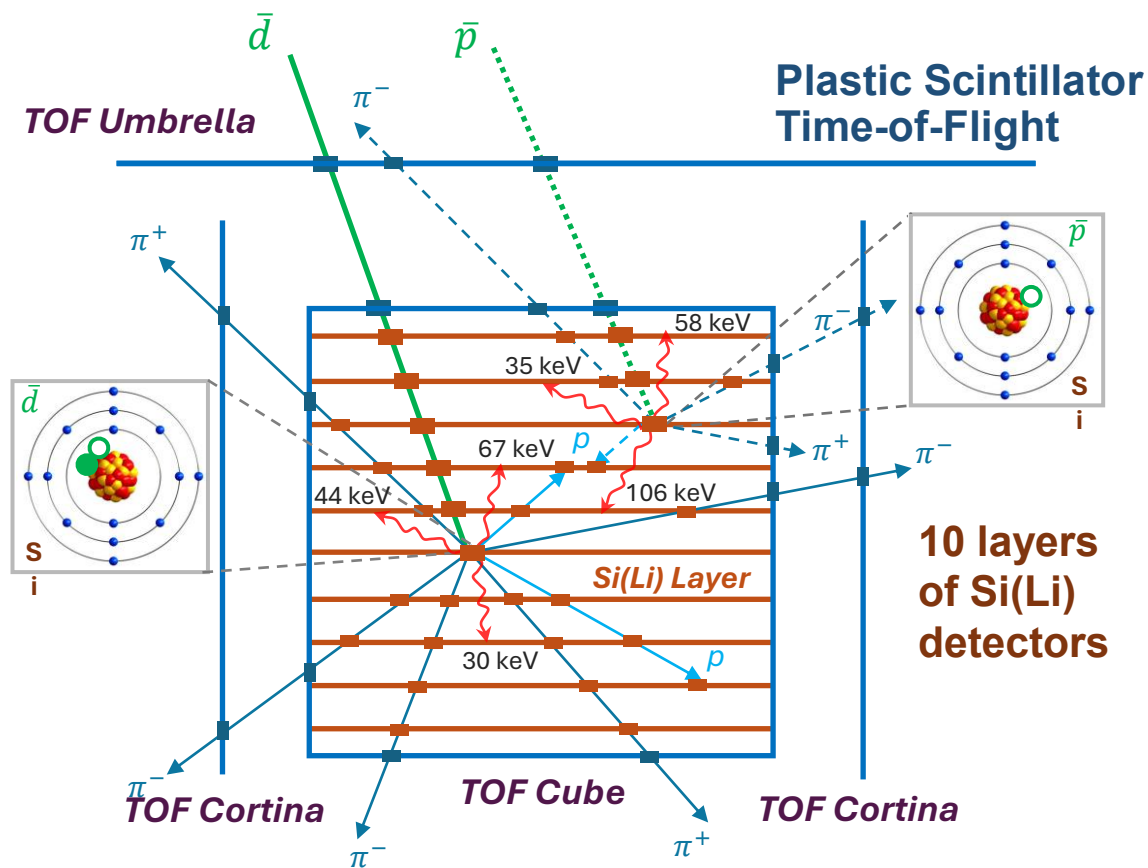
Si(Li) tracker:

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

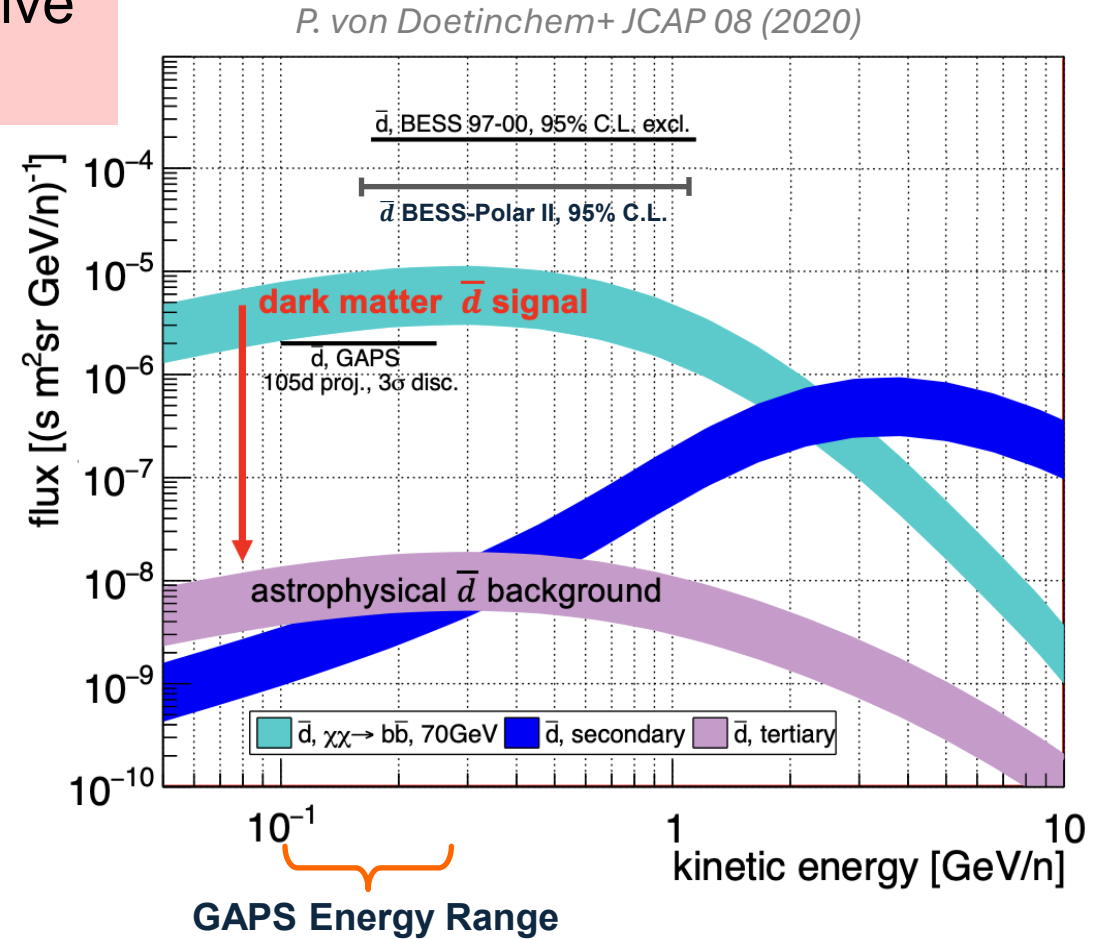
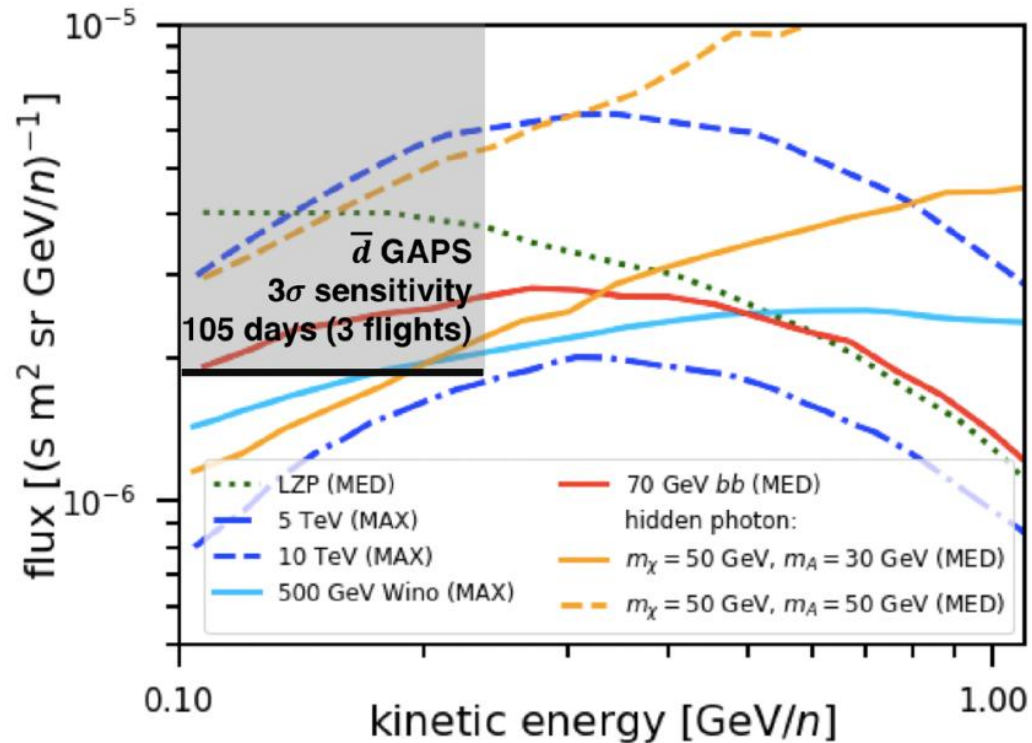
Si(Li) tracker acts as:

- **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*

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

GAPS sensitivity to antideuterons: Aramaki+ *Astropart.Phys.* 74, 6 (2016)

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



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

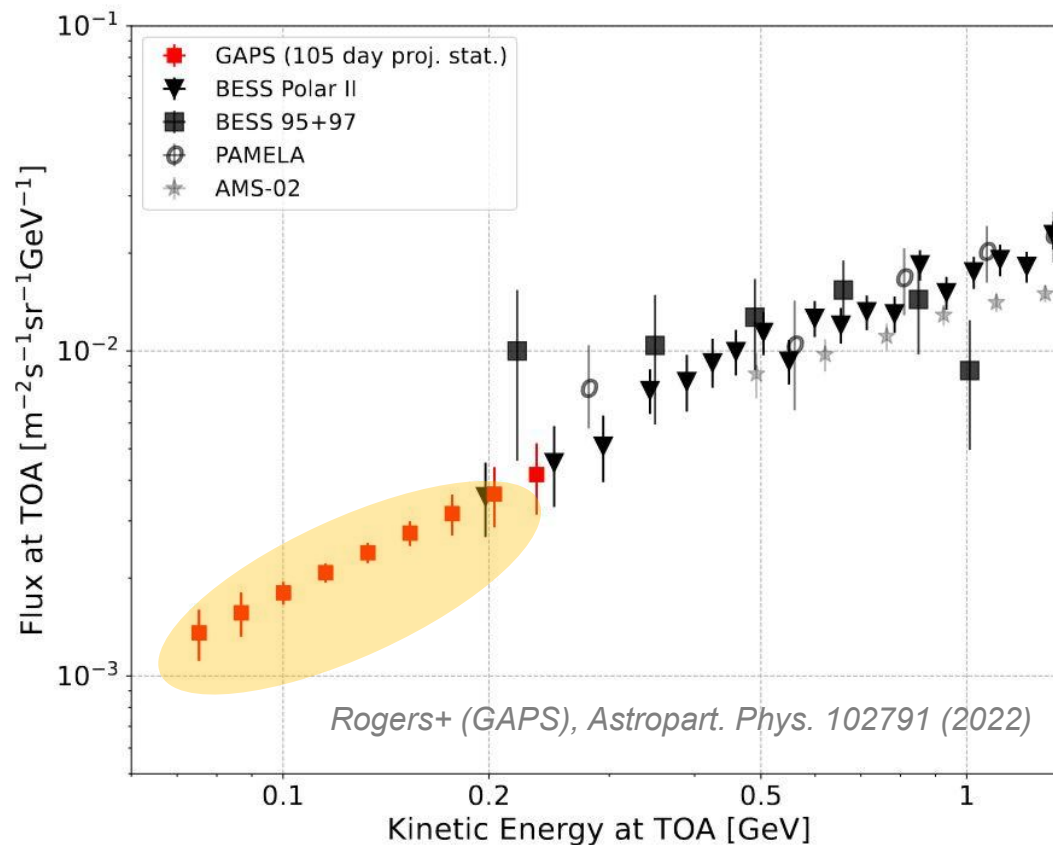
❑ ~500 **antiprotons** ($\lesssim 0.25$ GeV/n)
for each balloon flight.

- 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.

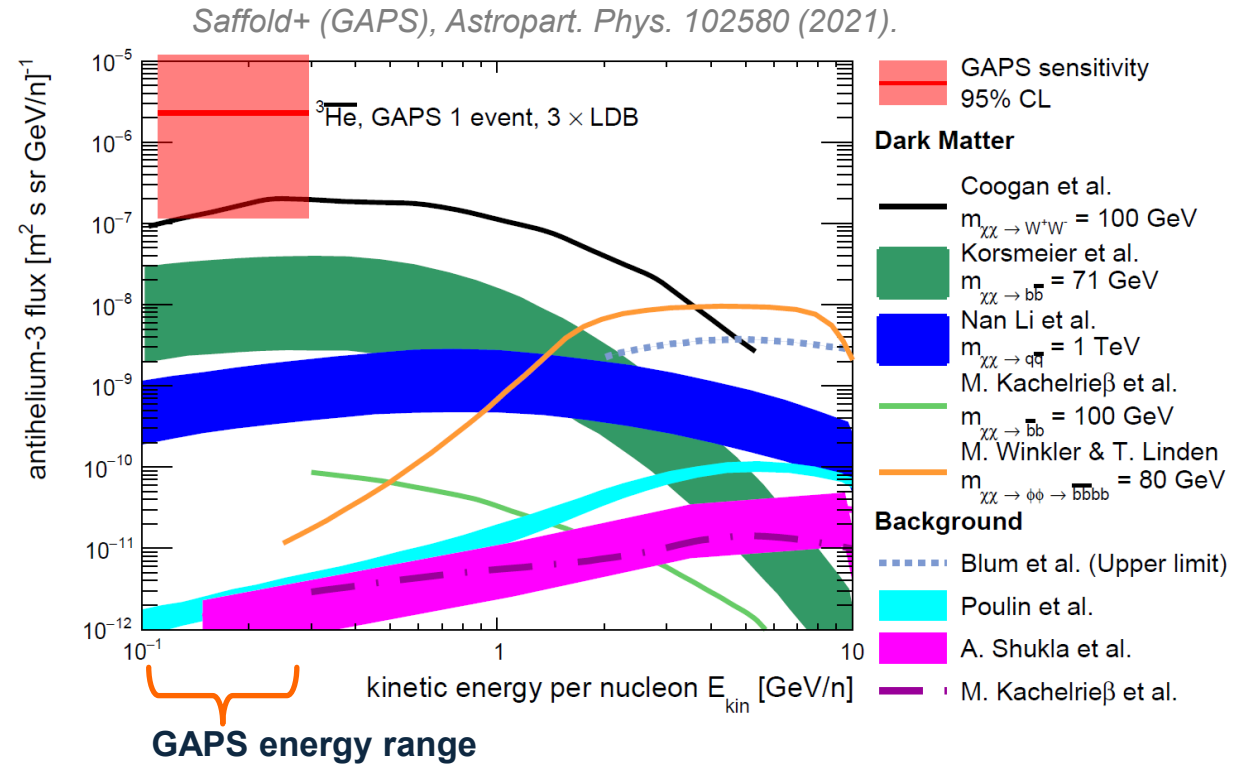
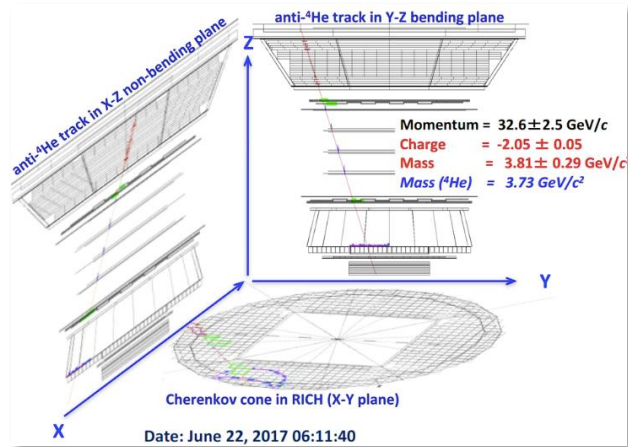


- Probe *light dark matter*, leading constraints on *primordial black hole* evaporation.
- Provide a novel insight on *cosmic-ray propagation* models.

□ GAPS 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)



- Extends to lower energies (0.11-0.3 GeV/n), complementary to AMS-02.
 - Capable of confirming signal, orthogonal detection technique, uniquely low bkg.

❑ Time-of-Flight (TOF)

- Near-hermetic containment of tracker
- Velocity, trajectory and dE/dx measurement
- High-speed trigger and veto

❑ Si(Li) Tracker

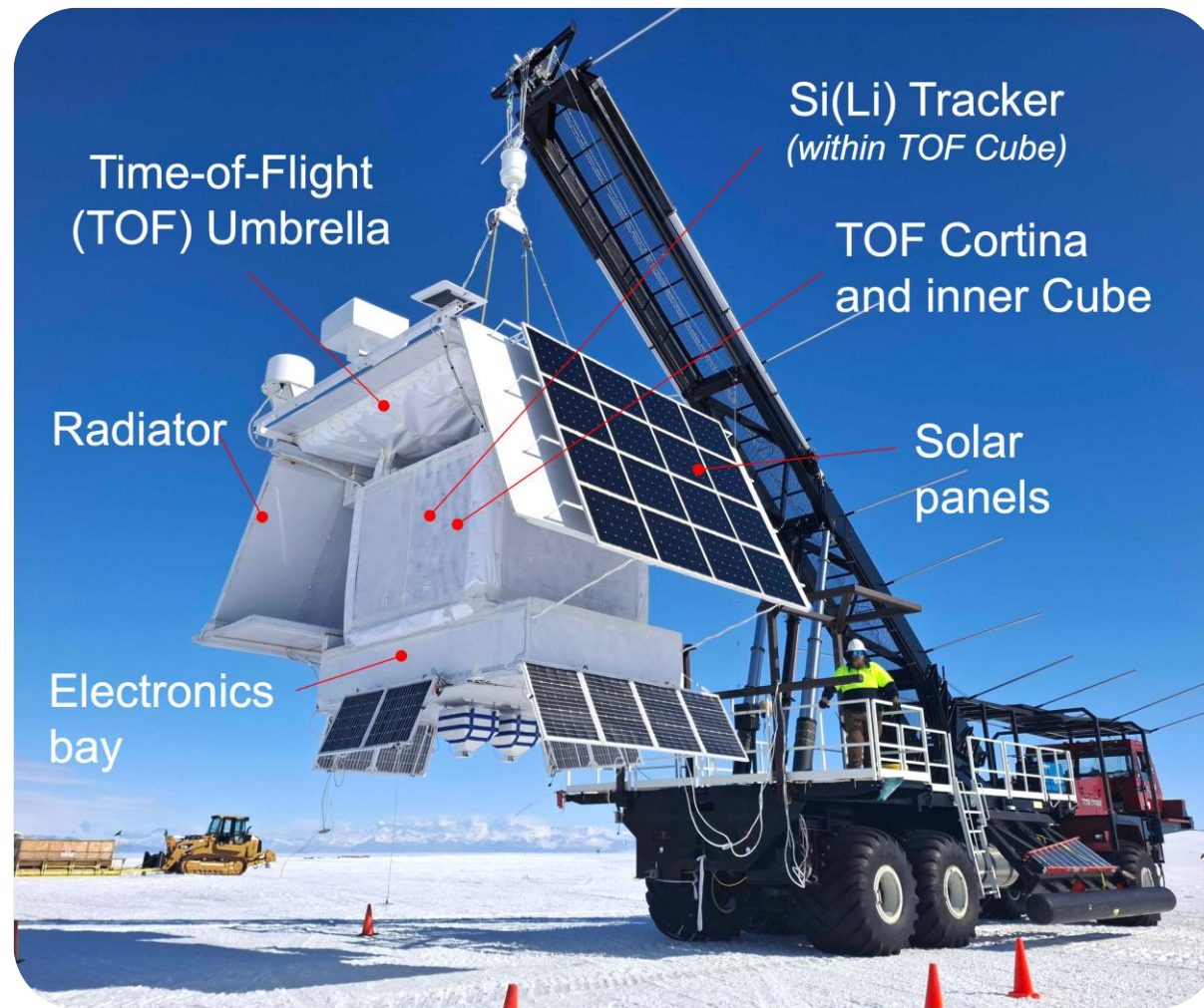
- Target to capture light nuclei $\lesssim 0.25$ GeV/ n
- Tracker for primary and secondary hadrons
- Spectrometer for de-excitation X-rays

❑ Thermal System

- Oscillating Heat Pipe for tracker cooling

❖ Support instrumentation

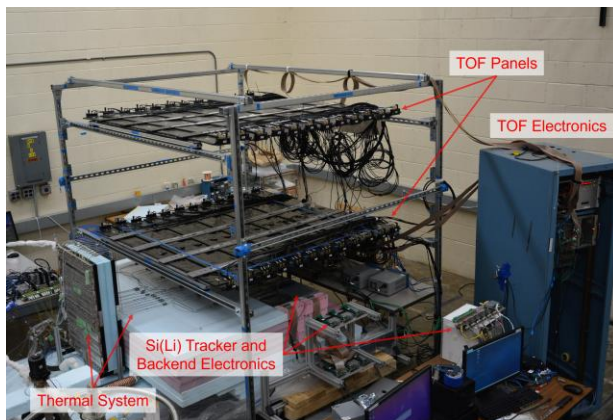
- Electronics, Solar panels, Gondola



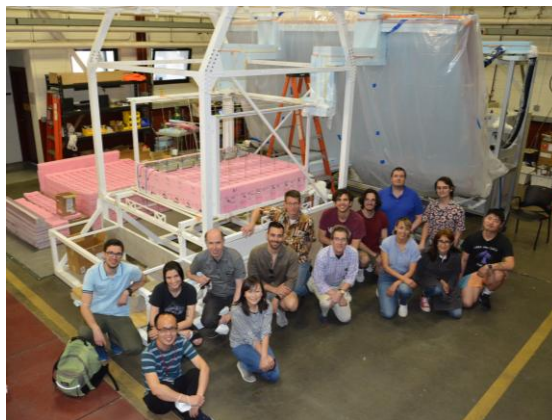


GAPS Instrument Integration

2020/2021, GFP @MIT-Bates, MA



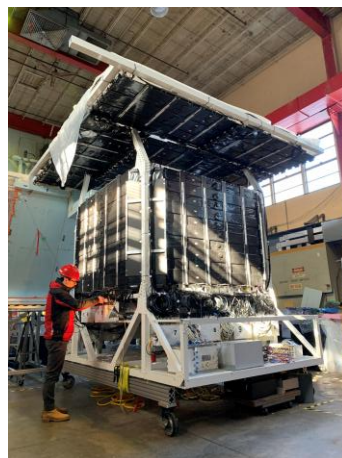
2021, initial integ. @MIT-Bates, MA



2022, full integ. @Berkeley-SSL, CA



6/2023, TVAC test
@NTS, CA



1/2024, upgrades
@CU-Nevis, NY



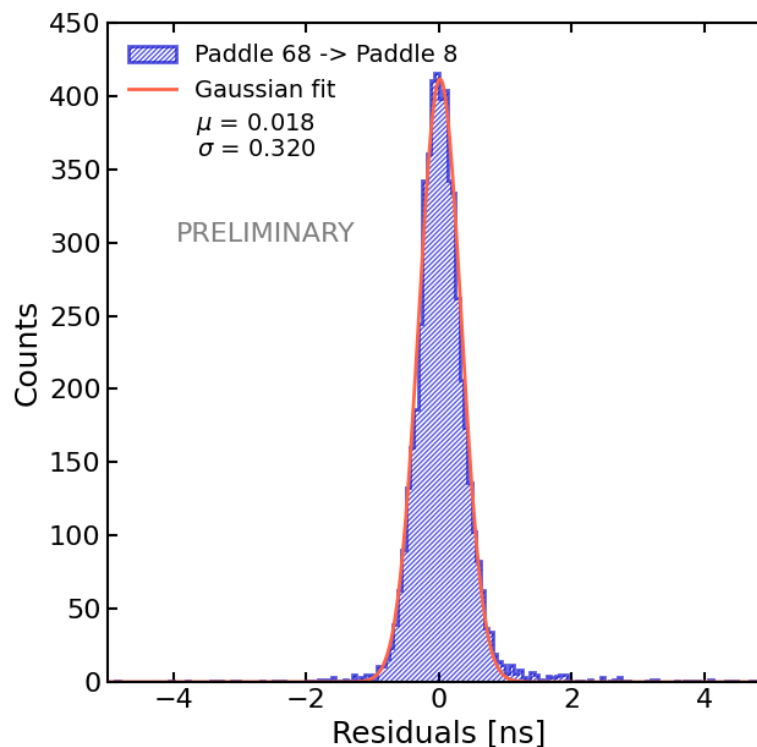
7/2024, compatibility testing
@CSBF, TX



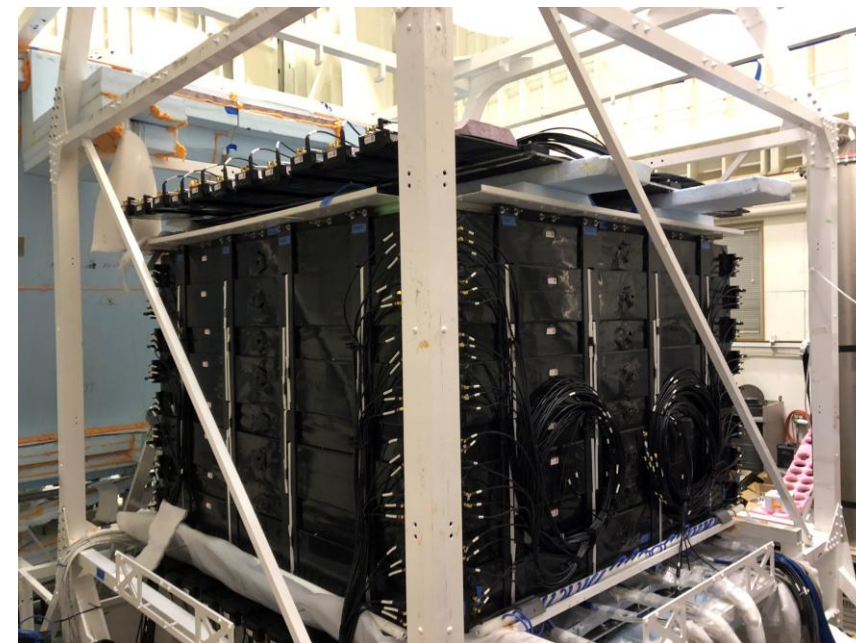
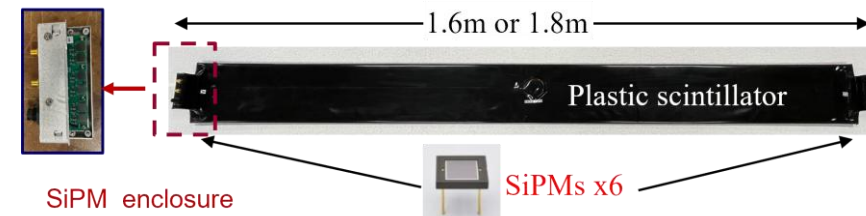
12/2024, commission & launch
attempts @McMurdo, Antarctic

□ 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



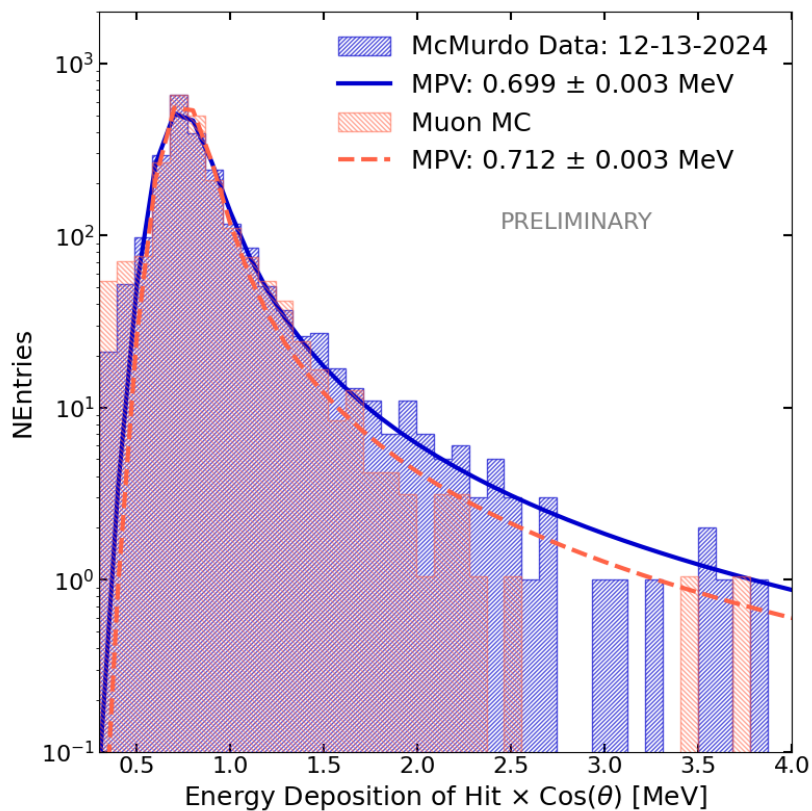
- Timing resolution



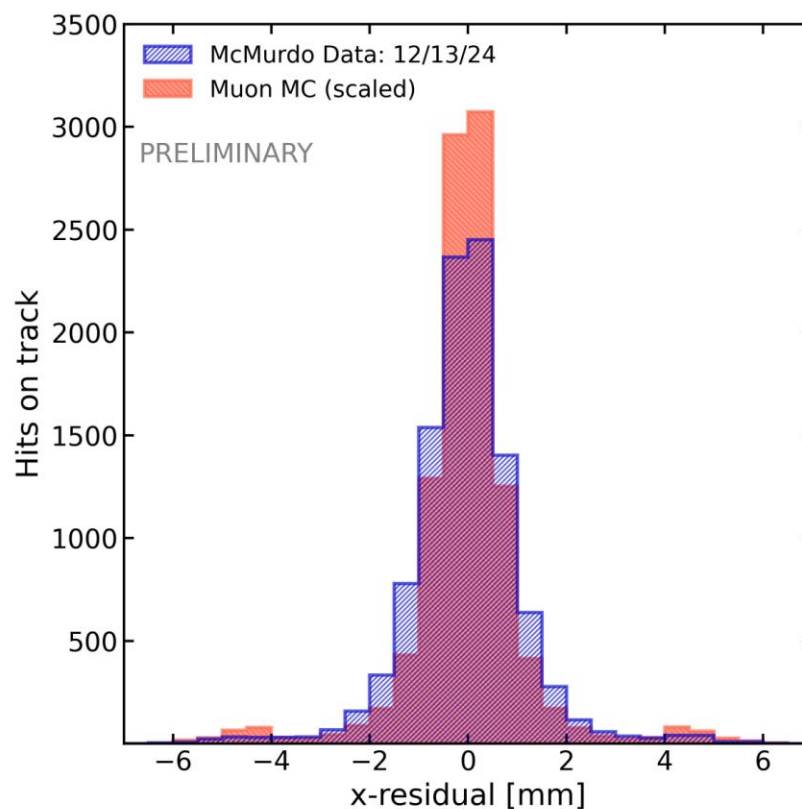
➤ Achieved: measured better than ~350 ps for all paddle combinations!

GAPS Instrument Performance: *Tracker*

❑ Tracker performance from the Antarctic commissioning.

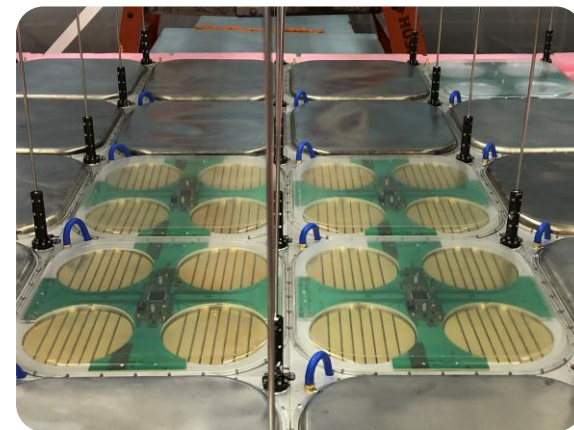
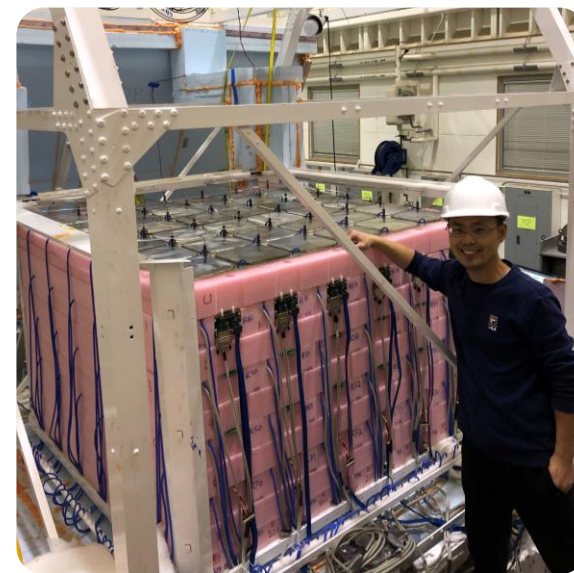


▪ Energy depositions on track

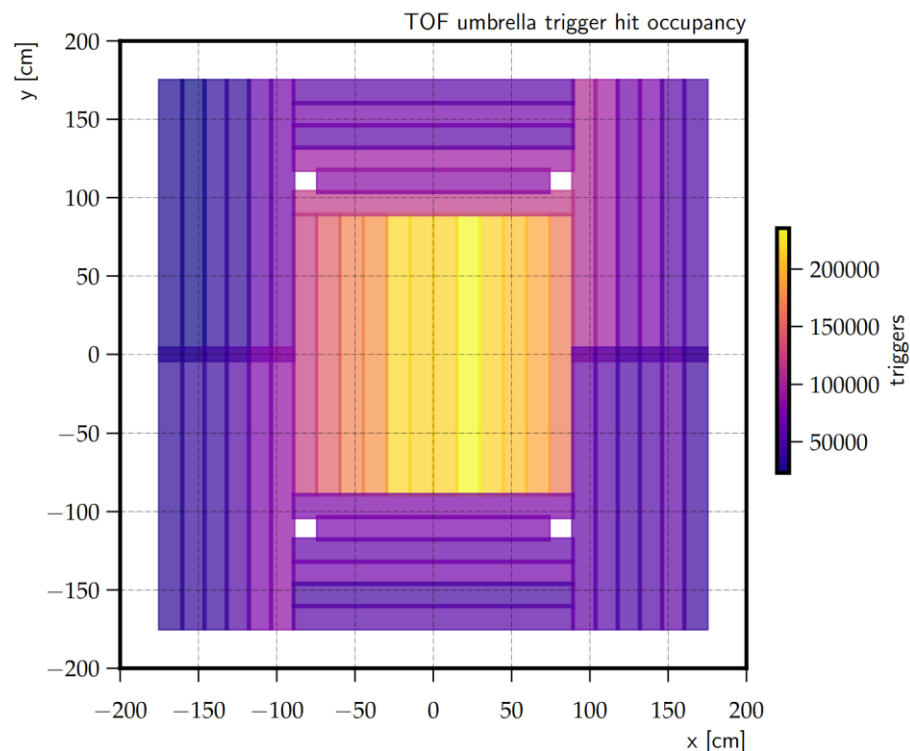


▪ Track position resolution

➤ Energy and track reconstruction validated!



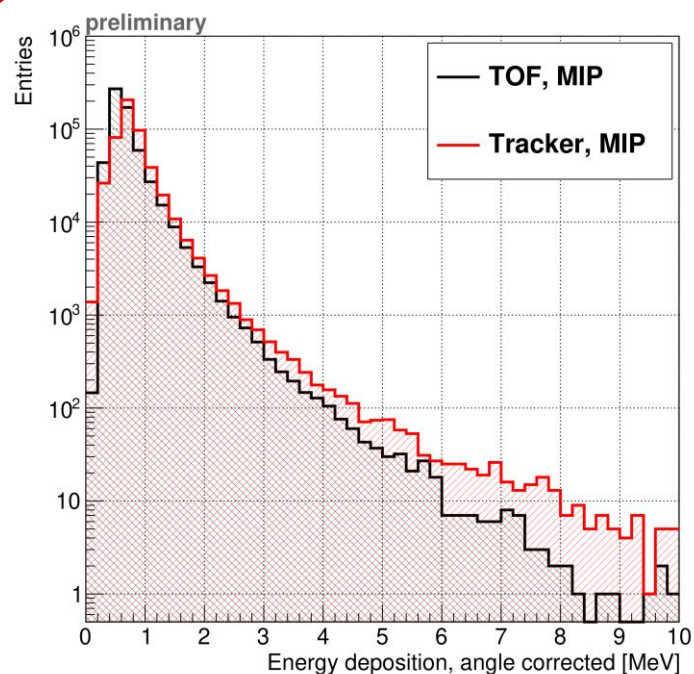
- ❑ Design goal: 450 - 500 Hz trigger rate (maxing out telemetry bandwidth), capability to trigger on multi-track events.



- 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

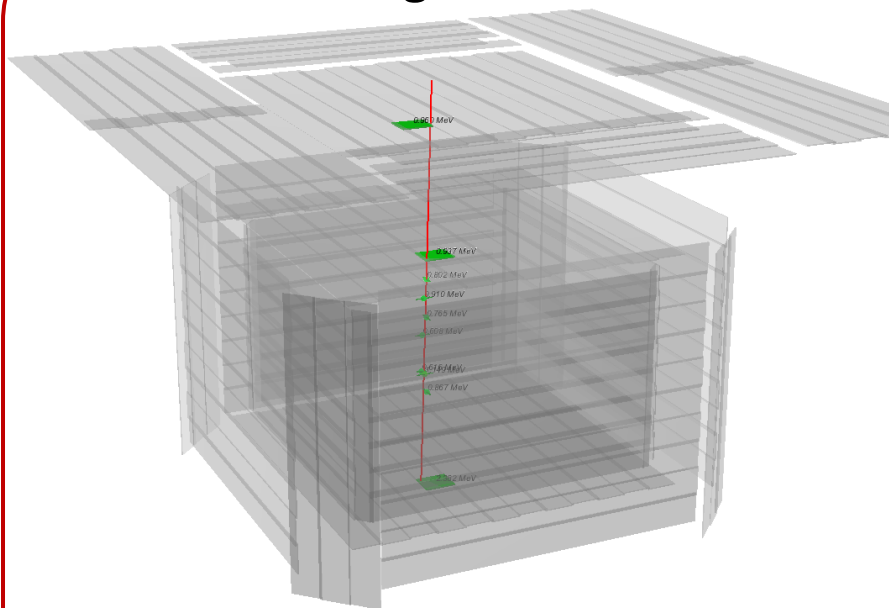
➤ Achieved: stable operations at ground with tuned trigger at 450-500 Hz possible, can record multi track events, trigger acceptance verified with simulations!

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



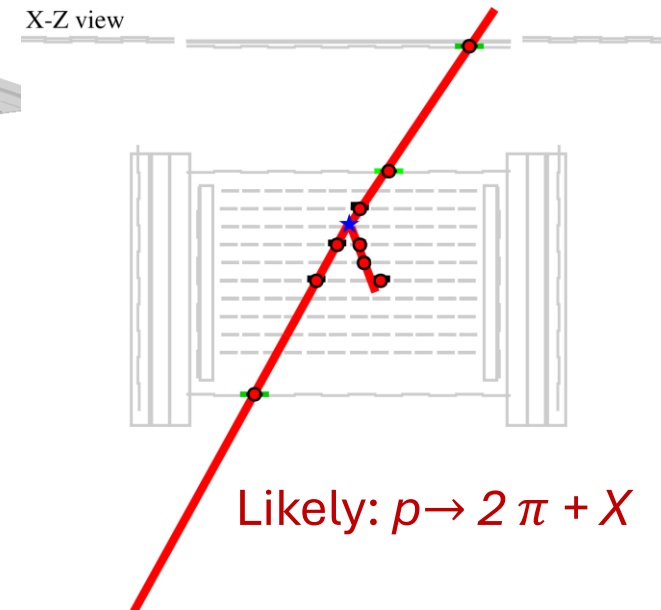
- Energy reconstruction

- Single track



- Track Reconstruction

- Multi track





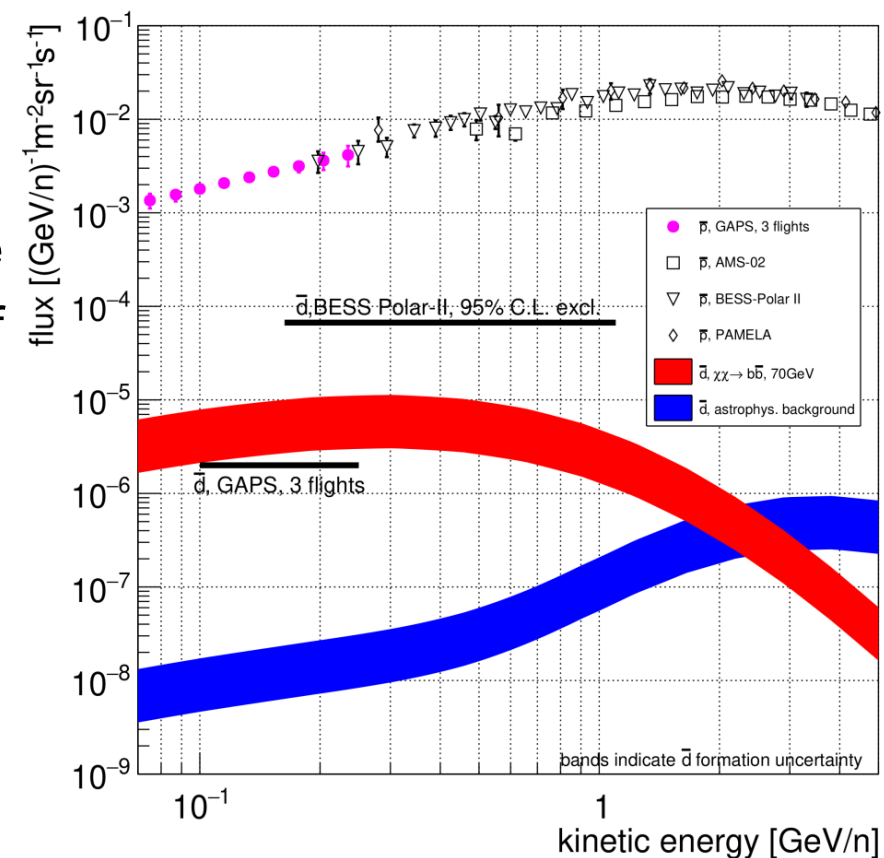
Summary & Conclusions

❑ 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 an unexplored energy range.*
- *open sensitivity to low-energy cosmic anti-He.*

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



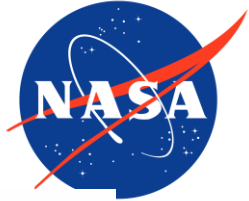
GAPS Collaboration



UNIVERSITY
of HAWAII®
MĀNOA



SSL
UC Berkeley



UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II



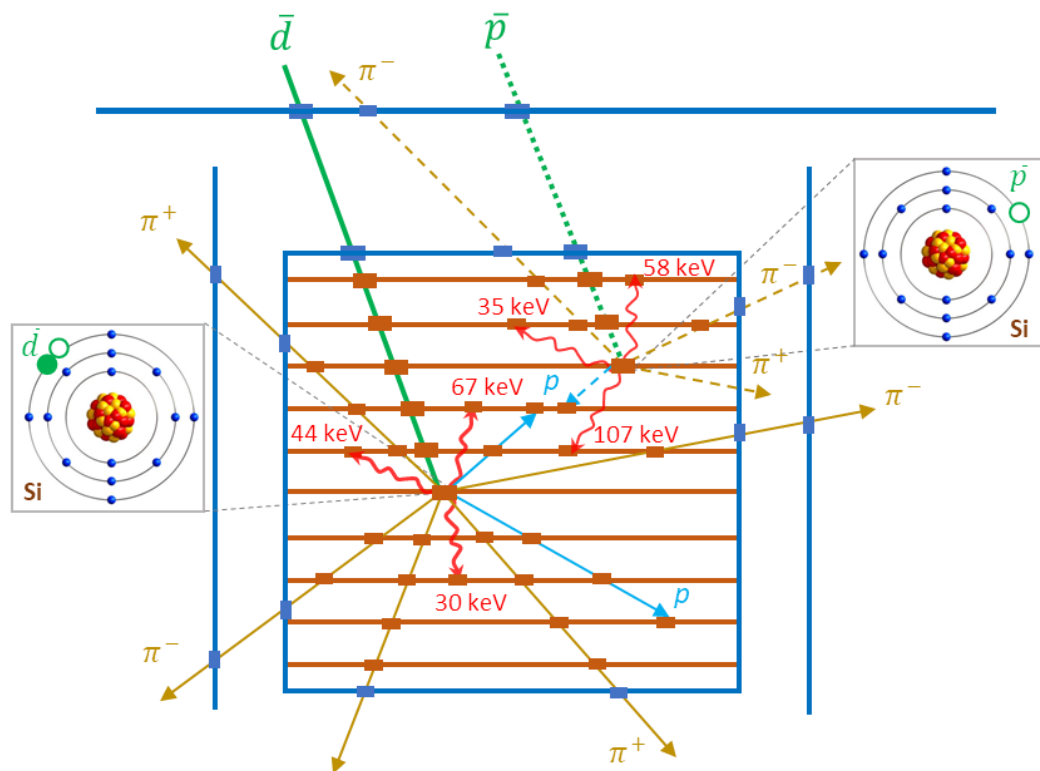
UNIVERSITÀ
DEGLI STUDI
DI TRIESTE



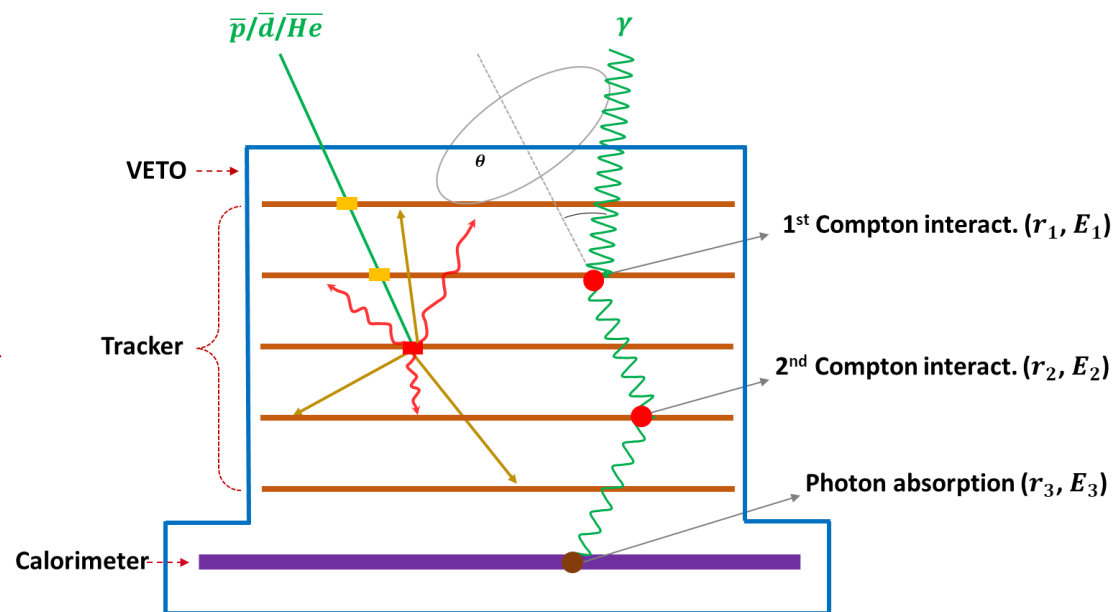
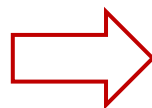
Dark Matter & Neutrino Focus Week @TDLI, Shanghai

THANK YOU!





- ❑ GAPS on balloon:
antinuclei detection



- ❑ Compact satellite payload:
antinuclei and MeV γ ray