In Search of Cosmic-Ray Anti-nuclei from Dark Matter with the GAPS Experiment

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Massachusetts Institute of Technology

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(On behalf of the GAPS Collaboration)

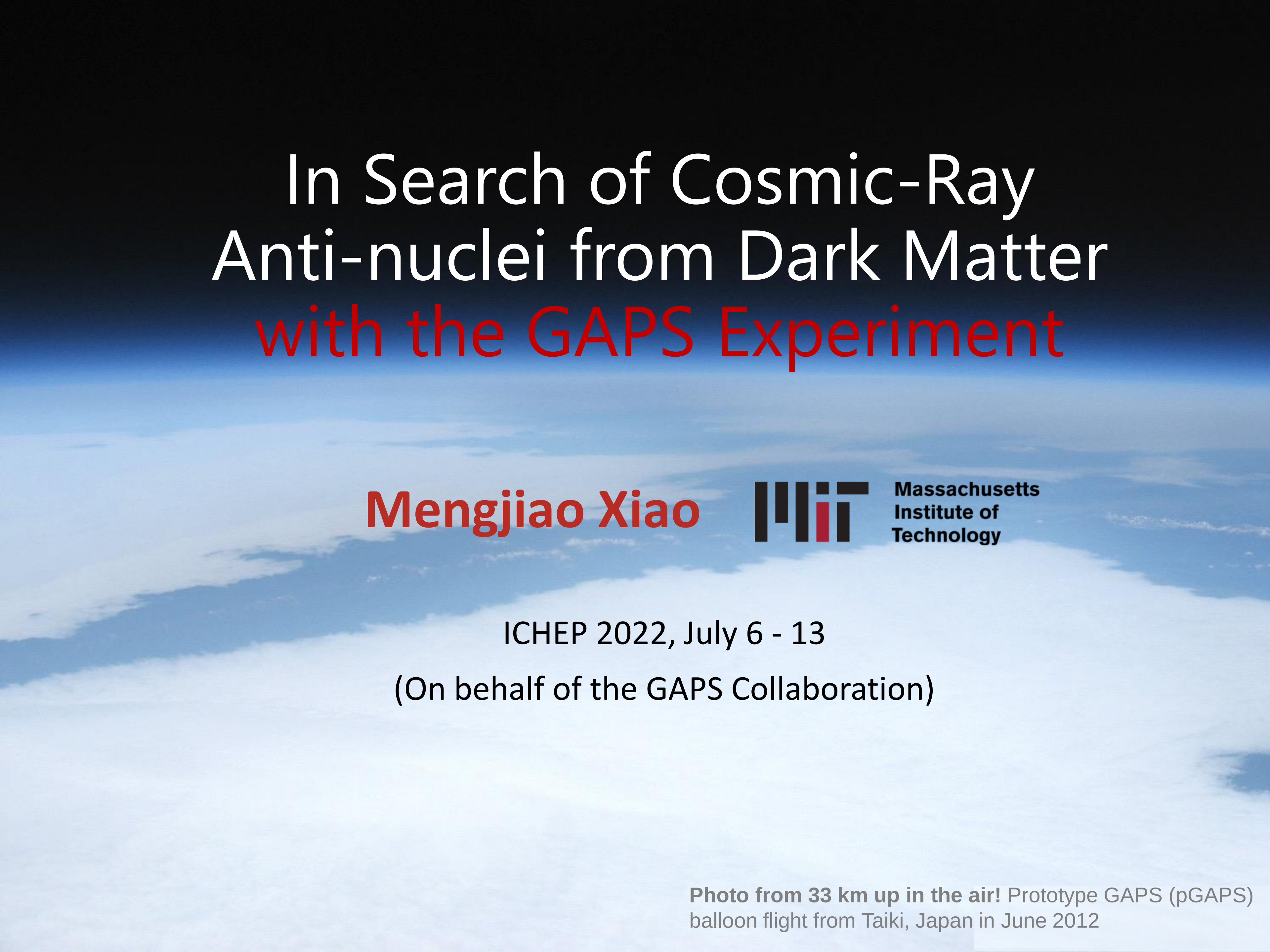


Photo from 33 km up in the air! Prototype GAPS (pGAPS) balloon flight from Taiki, Japan in June 2012

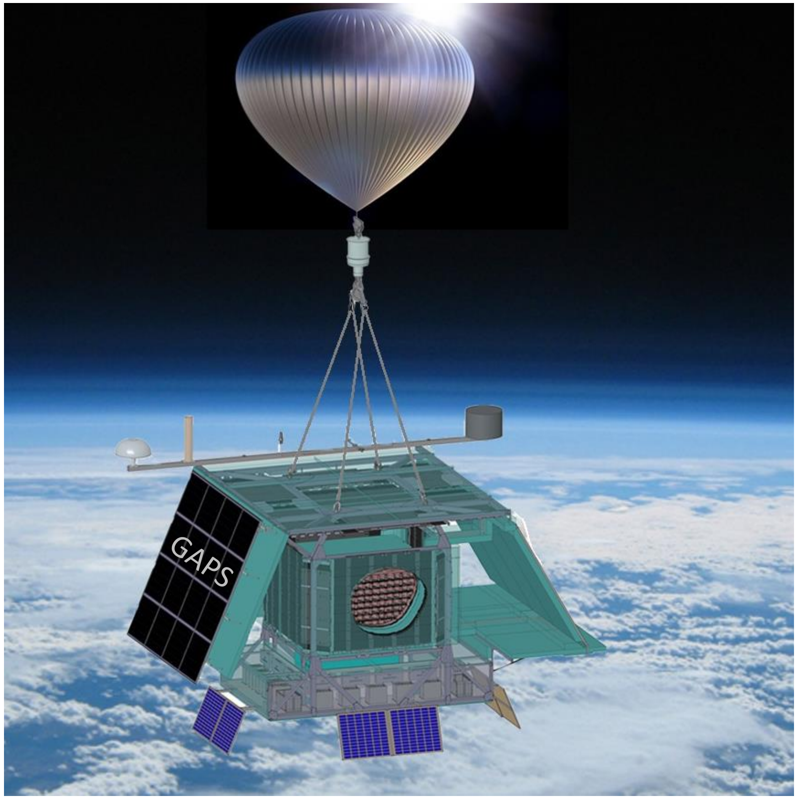
The GAPS Experiment

- **GAPS=General Antiparticle Spectrometer**

- Unique sensitivity to ***low-energy cosmic antinuclei*** using novel exotic atom decay signature: X-rays and charged particles

- Primary goal: low-energy (KE<0.25 GeV/n) ***Antideuteron*** *as signature of new physics*.
  - Can probe many dark matter models.

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

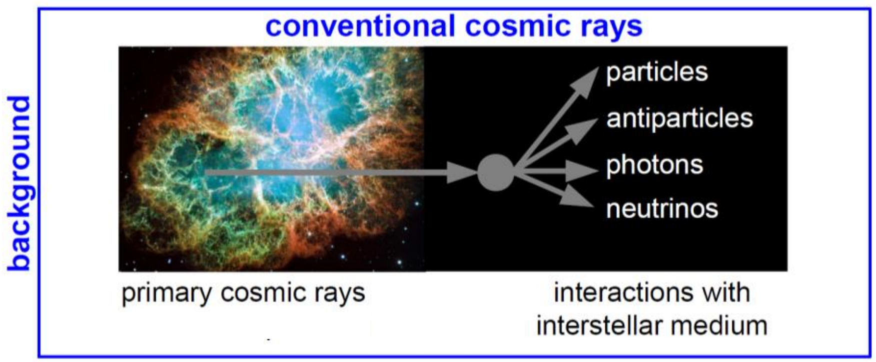


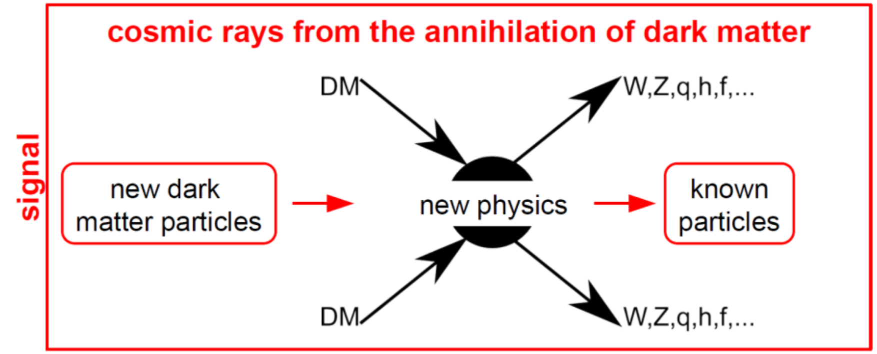
*Balloon photo from Word View

➢ First of a series of Antarctic balloon flights scheduled for late-2023.

Cosmic Rays as unique DM Messengers

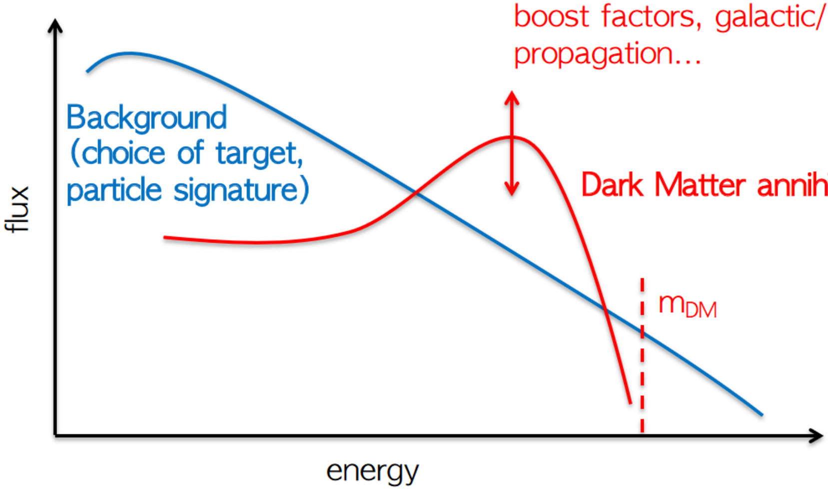
- ***Assumption:*** cosmic rays from dark matter annihilation/decay follow different kinematics than conventional production.





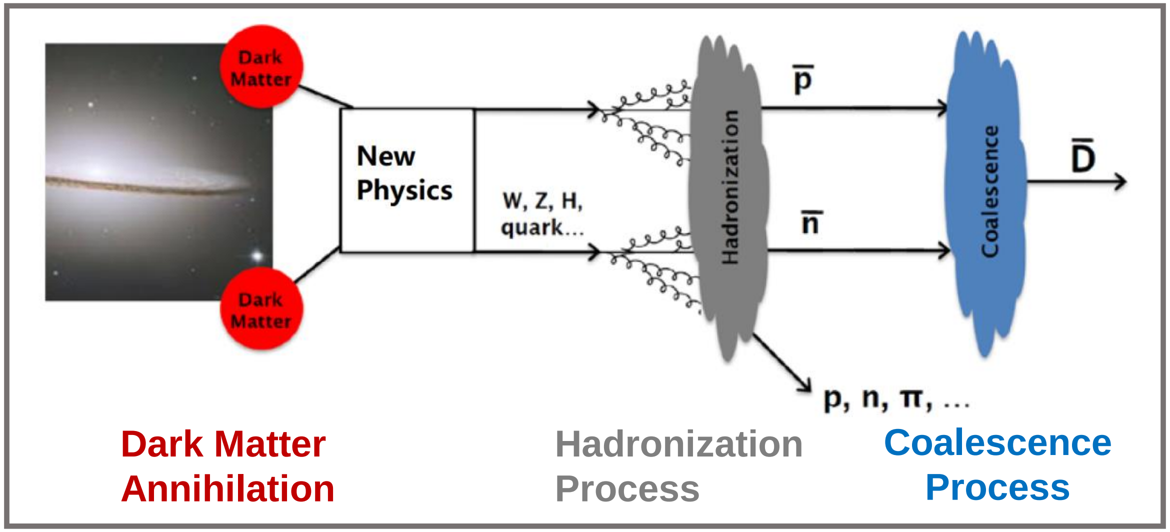
- ***Typical astro-particle DM searches:*** DM signal: peak/bump/shoulder on top of conventional spectrum.

- ***Common challenge:*** minimize/constrain astrophysical background, maximize predicted dark matter signal.



Cosmic ***antideuterons*** signal new physics

- Antideuterons are a generic prediction of many annihilating/decaying dark matter models (primary flux)



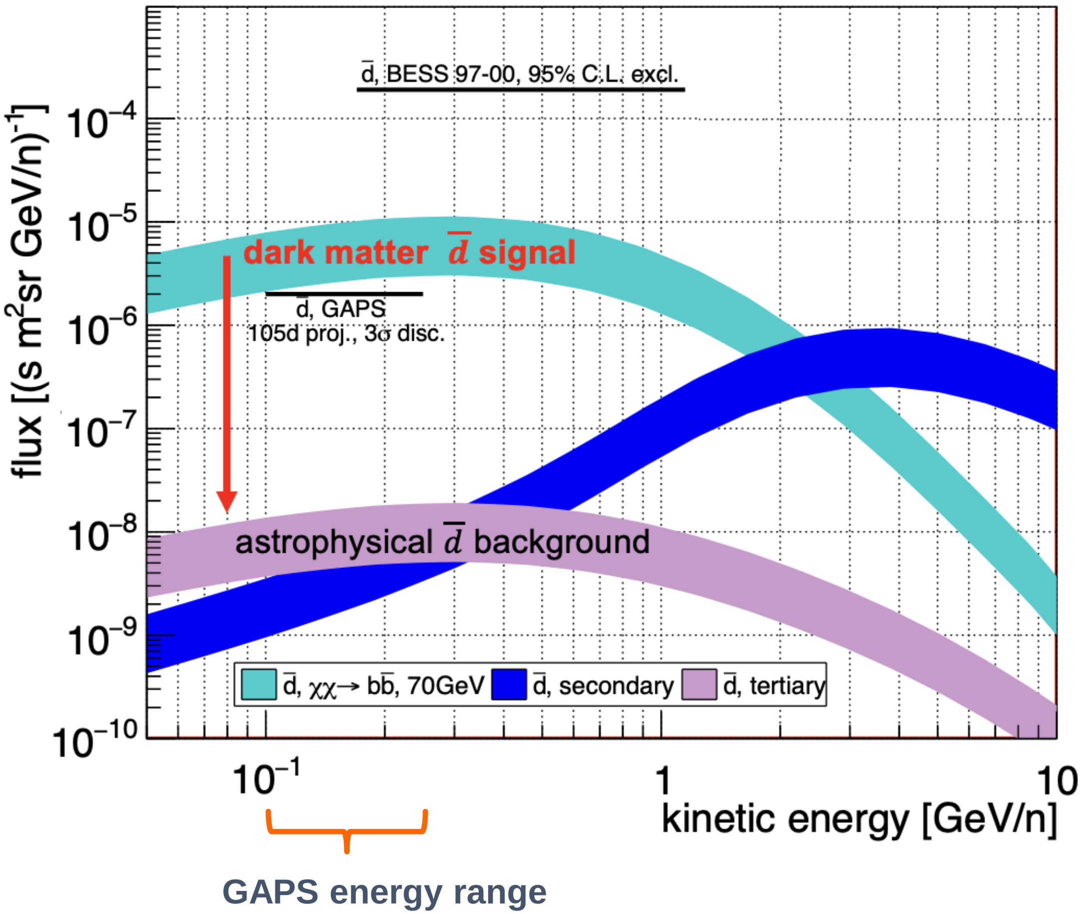
- **Secondary/tertiary background**: cosmic-ray interactions with interstellar medium
  - Much lower (> 2 orders of magnitude) than the primary due to collision kinematics and steeply falling primary proton spectrum

p (CR) + H (ISM) → p + H + p + n + $\bar{p} + \bar{n}$ $\bar{d}$

✓ *GAPS is first experiment optimized for low-energy cosmic antideuterons.*

GAPS: new physics in cosmic ***antideuterons***

Cosmic-ray antinuclei as messengers of new physics: status and outlook for the new decade: JCAP08 (2020) 035



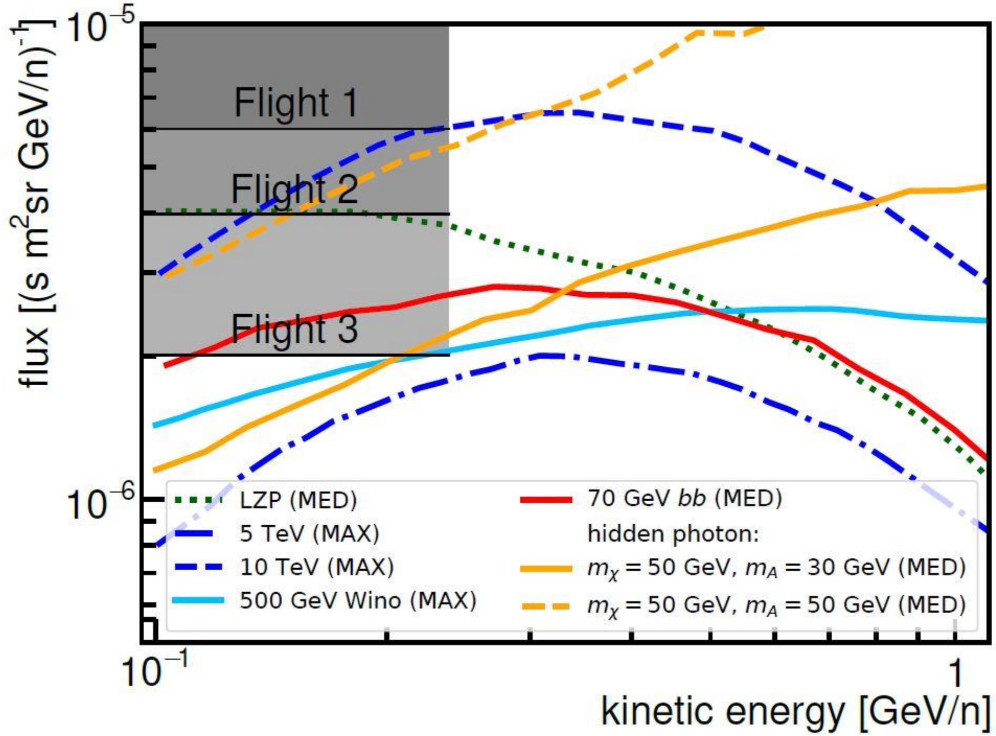
GAPS antideuterons: A generic ***new physics*** signature with *essentially zero* conventional astrophysical background!

sensitivity will be ~2 orders of magnitude below the current best limits.

Antideuterons generic signature of DM

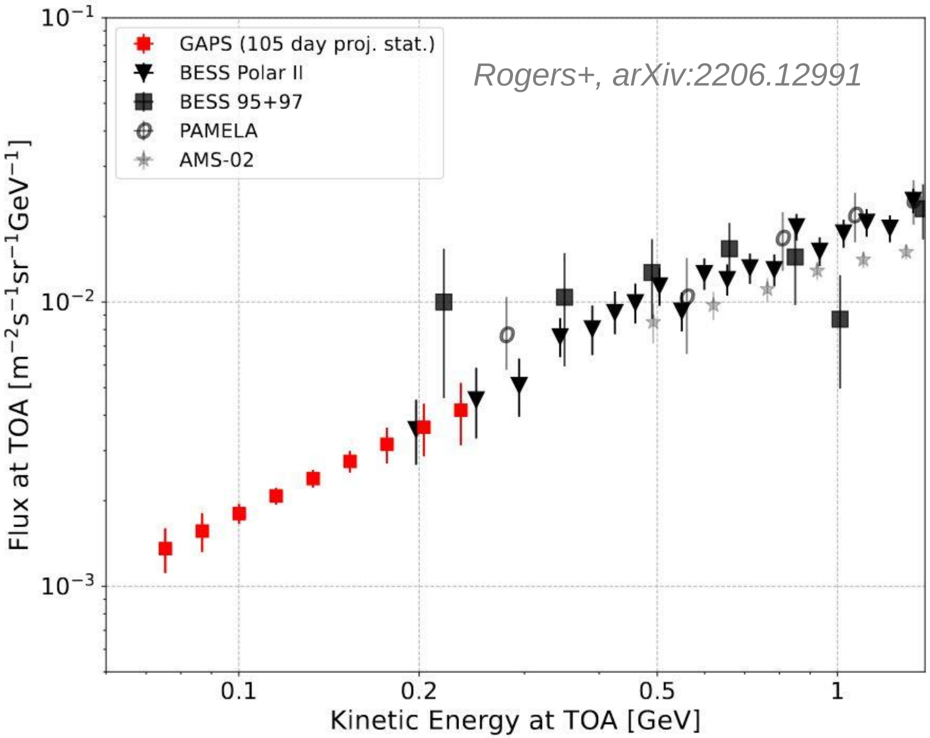
- The GAPS antideuteron search is sensitive to a wide range of dark matter models, e.g.:

- Generic 70-GeV WIMP annihilation model that explains antiproton excess and γ-rays from the Galactic Center
- Dark matter gravitino decay
- Extra dimensions
- Dark photons
- Heavy DM models with Sommerfeld enhancement



Any antideuteron signal needs to be compatible with antiproton constraints!

Unprecedented low-energy ***antiproton*** sensitivity



Precision antiproton spectrum in unexplored low-energy range (<0.25 GeV/n)

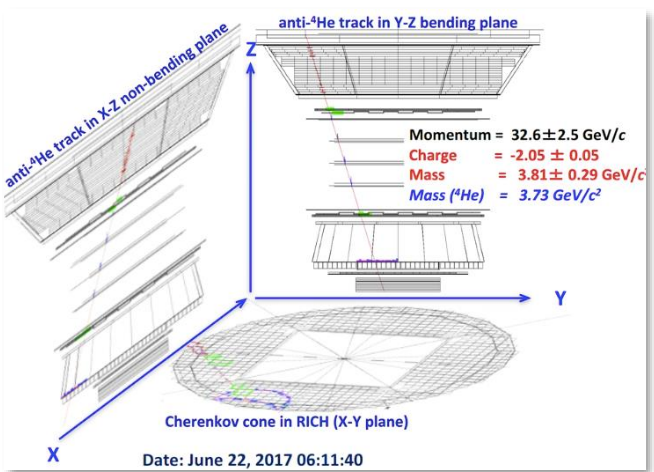
- ~500 antiprotons for each long-duration balloon flight.
  - BESS : 29 at ~0.2 GeV
  - PAMELA: 7 at ~0.25 GeV
  - AMS-02: E>0.25 GeV

- ✓ Validate the novel antinuclei identification technique technologies: exotic atomic X-rays from antiproton, track reconstruction, etc.
  - ➢ *Reduces the systematic uncertainties for antideuteron search.*
- ✓ Probe light dark matter, leading constraints on primordial black hole evaporation on Galactic length scales
- ✓ Provide a novel insight on cosmic-ray propagation models.

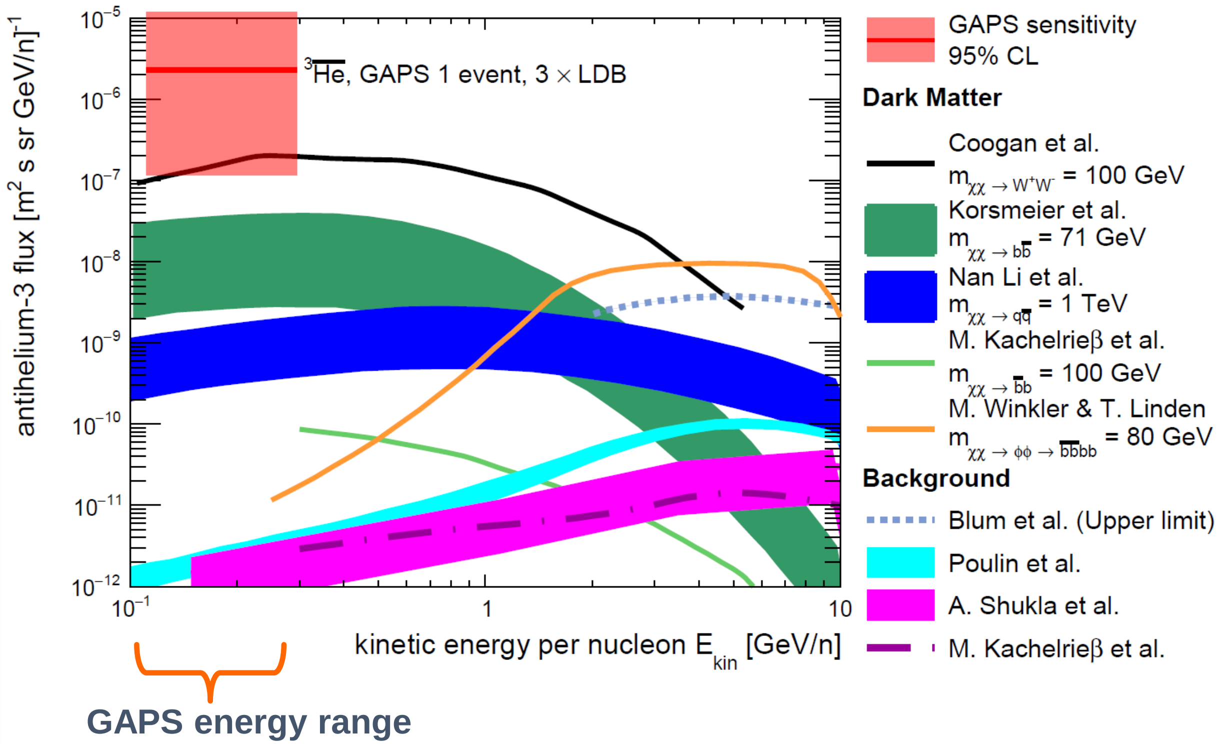
Sensitivity to novel cosmic ***antihelium***

- **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)

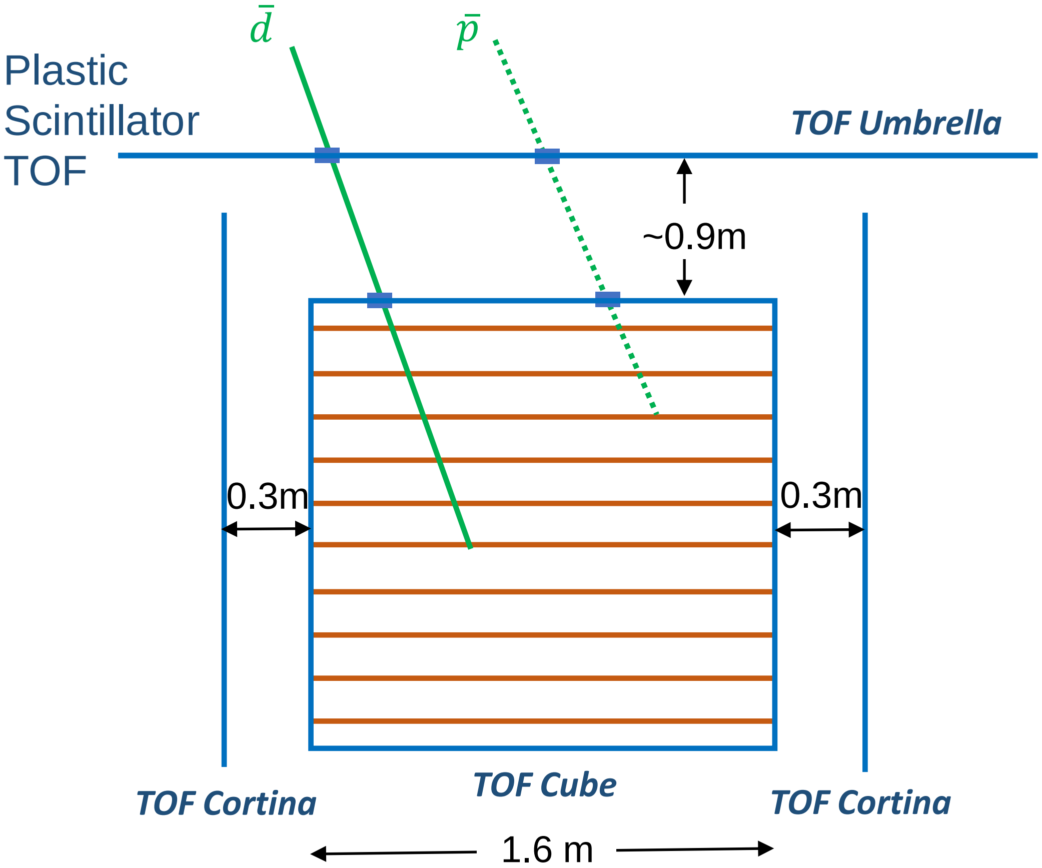


N. Saffold et al. Astropart. Phys. 102580 (2021).



> ➢ *GAPS extends to lower energies (0.11-0.3 GeV/n), complementary to AMS-02.*
>   - *Only experiment capable of confirming signal, using an orthogonal detection technique, in a uniquely low-background energy range*

Novel detection using exotic atoms



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

Extoic atom technique verified at KEK: 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)

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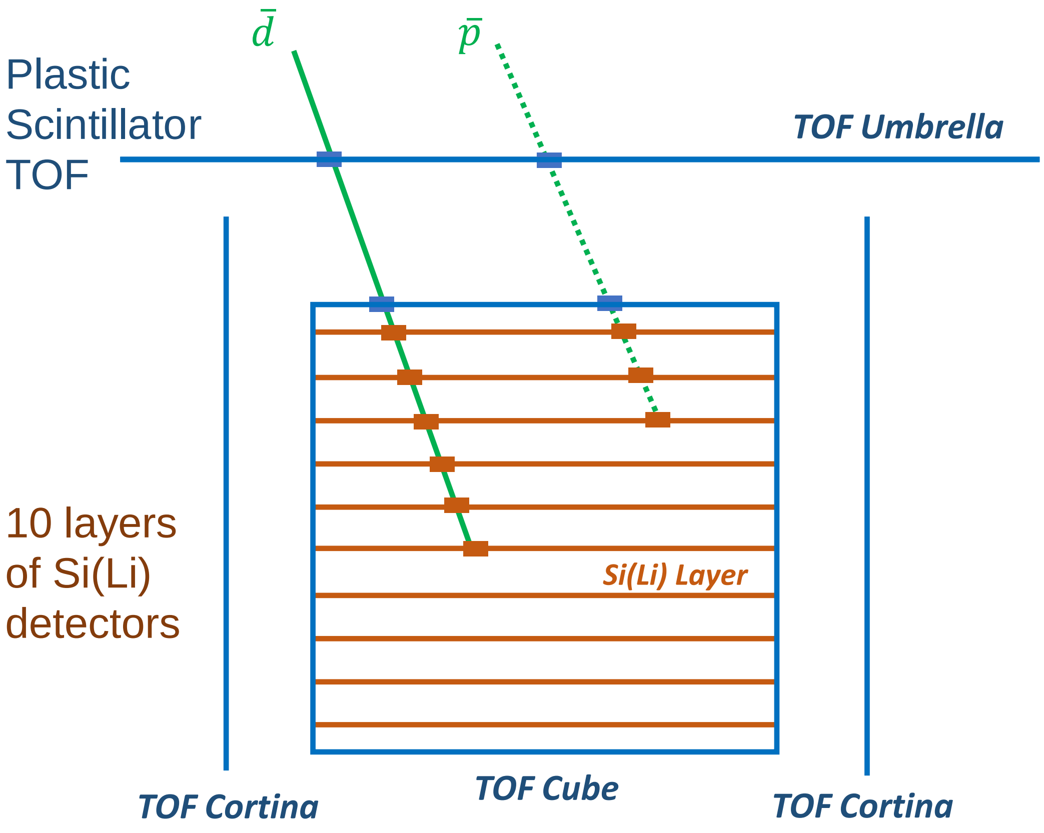

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Si(Li) tracker acts as:

- ***Target*** to slow and capture an incoming antiparticle

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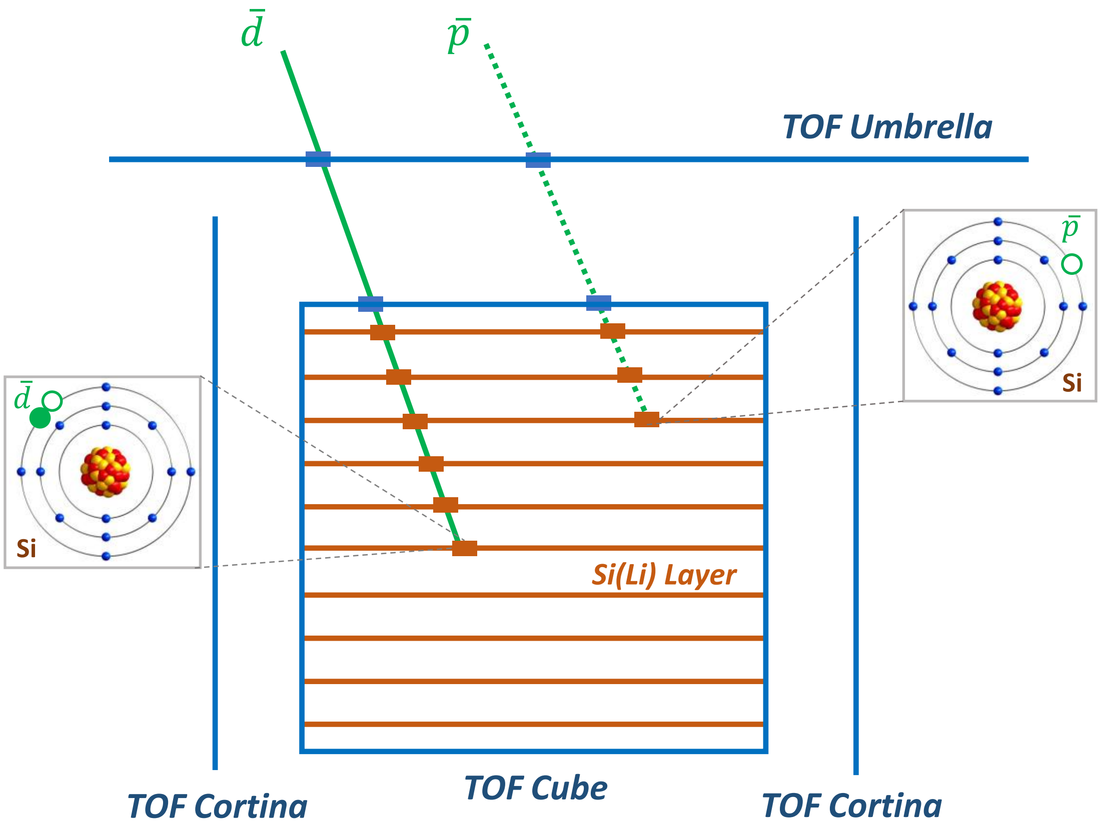

Time-of-flight system measures velocity, incoming angle and dE/dx

Si(Li) tracker acts as:

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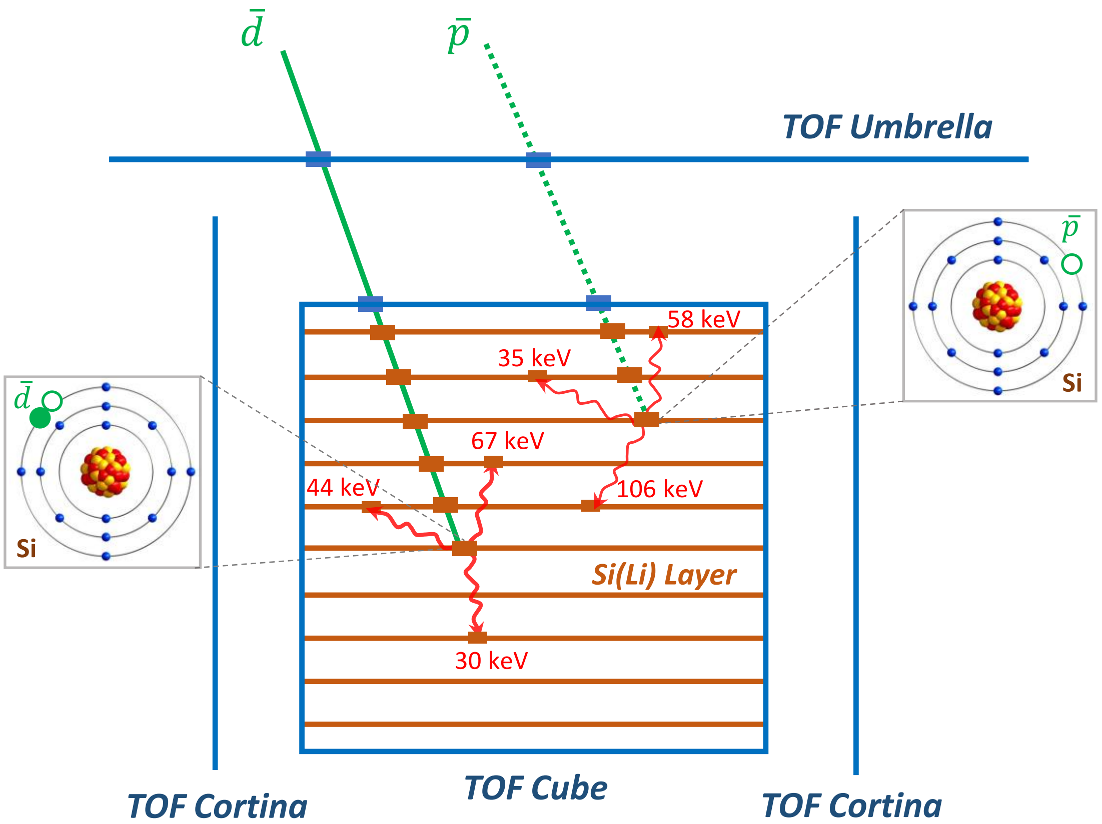

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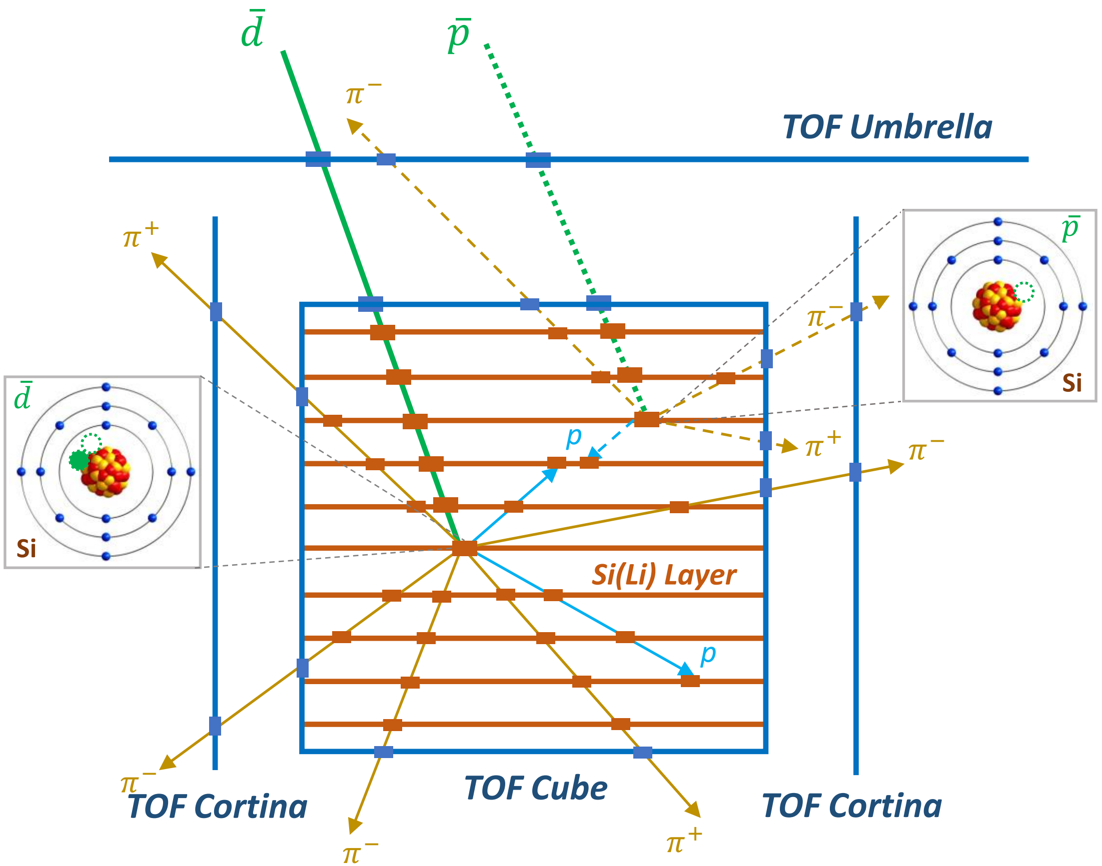

Time-of-flight system measures velocity, incoming angle and dE/dx, tracks of the outgoing particles.

Si(Li) tracker acts as:

- ***Target*** to slow and 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 annihilation products (charge pions and protons).

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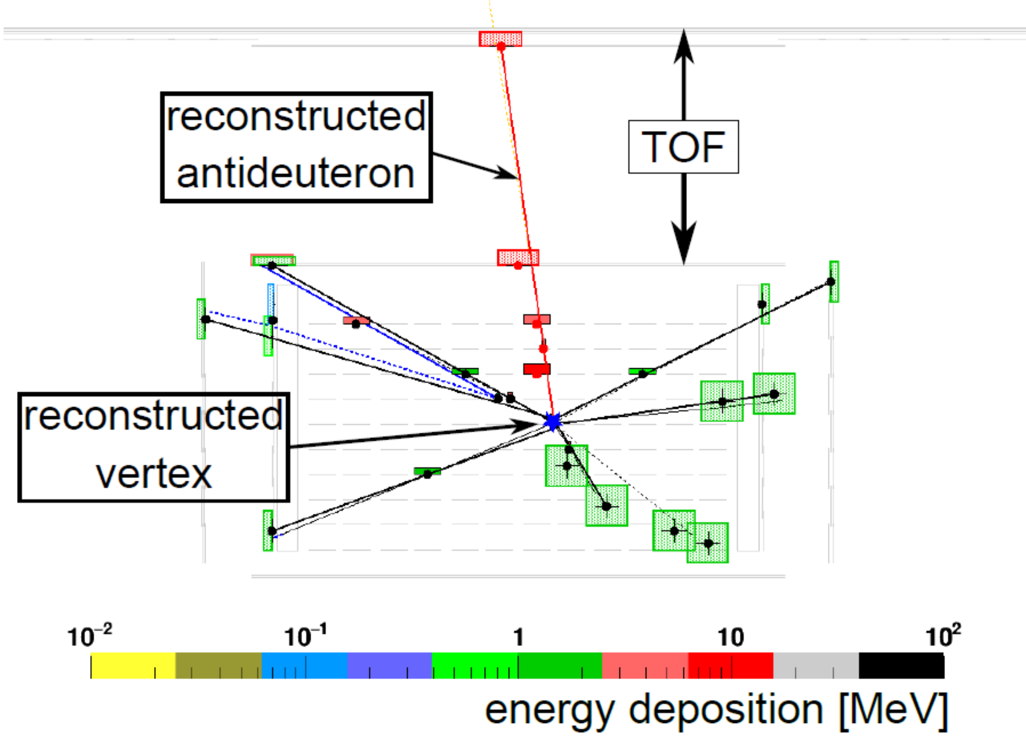
GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)
GAPS sensitivity to antiprotons: Aramaki+ Astropart.Phys. 59, 12-17 (2014)

Novel detection using exotic atoms

- *Antideuteron* event topology in the GAPS full simulation:

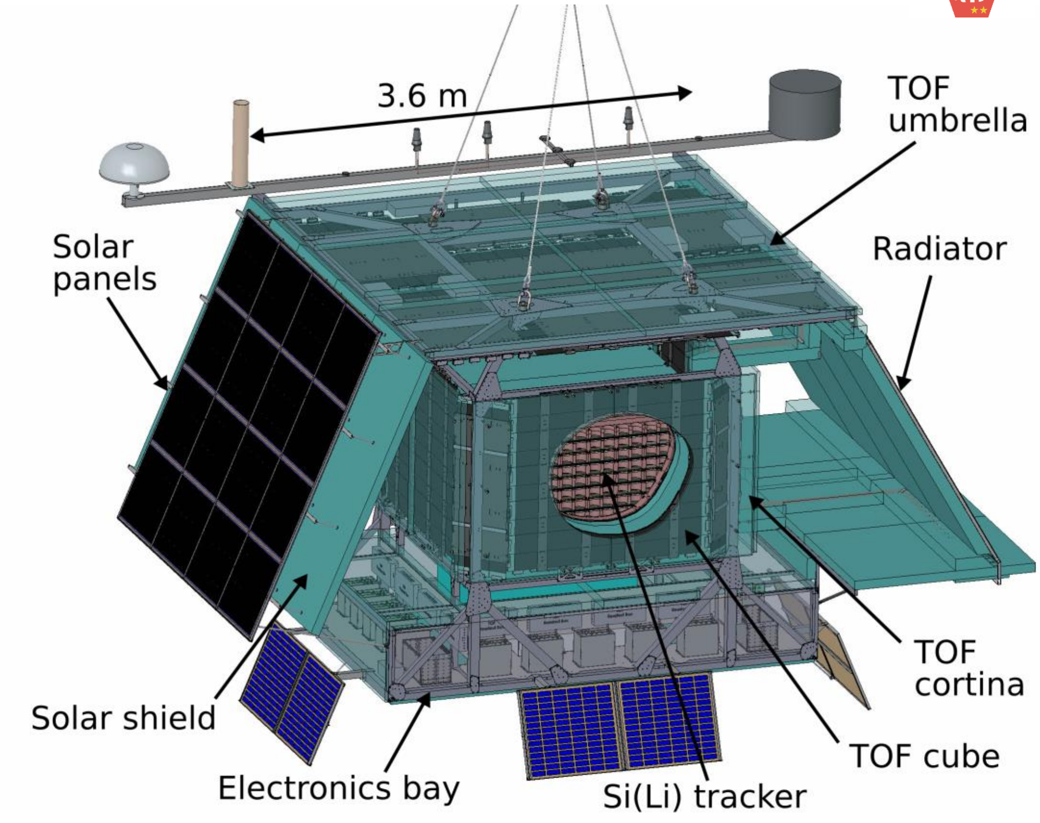
R. Munini et al. Astropart. Phys. 102640 (2021).



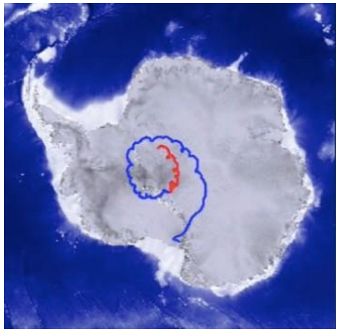
- ***Red line***: the reconstruction of the primary antideuteron
- ***Black lines***: reconstructed secondary tracks from the stopping vertex inside the tracker.
- *Colored boxes*: represent energy depositions in the sensitive detector volumes

GAPS Antarctic Balloon Payload

- ❑ **Time of Flight (TOF)**
  - Velocity measurement
  - High-speed trigger and veto
  - dE/dx measurement
- ❑ **Si(Li) Tracker**
  - Stopping depth, dE/dx
  - Charge particle multiplicity
  - X-ray identification
  - Vertex reconstruction
- ❑ **Thermal: Oscillating Heat Pipe (OHP)**
  - Cools Si(Li) detectors to ~ -40 ℃



Total mass: ~2500 kg, Power: 1.3 kW



- ❑ Service for series of Antarctica long-duration balloon (~35 days) flights.
  - Recovered after each flight

*Photos from NASA.ORG

On a balloon!

GAPS' balloon nature constrains power, weight, size, temperature...

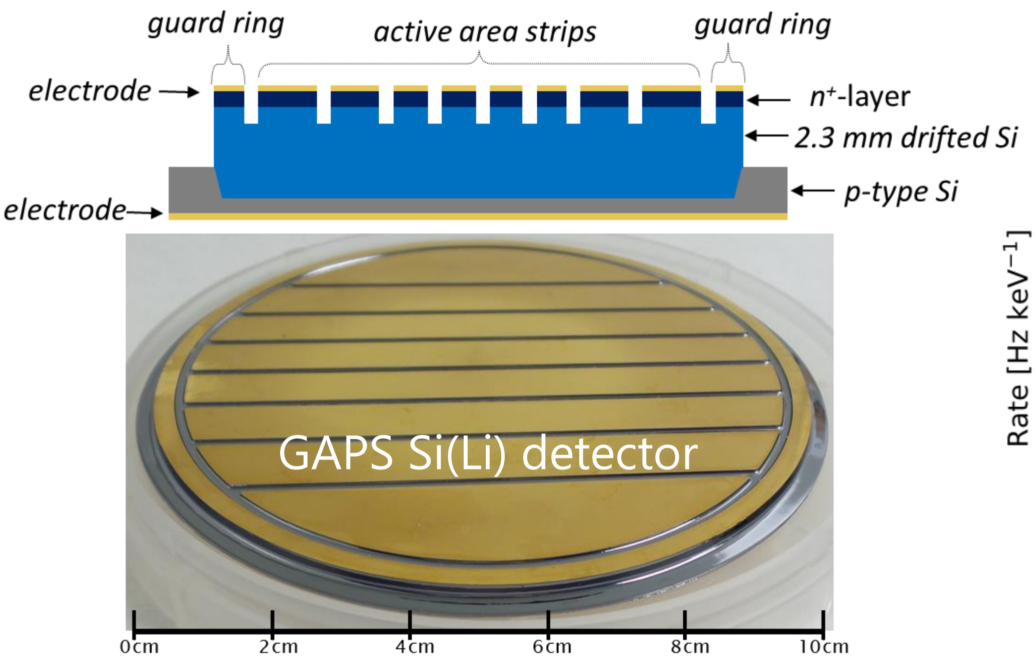
Key challenges:

- **High operating temperature**:
  -35 to -45C
- **Power limited** by long-duration flight
- **Large area**, but low leakage current
- *Need to develop* ***low-cost, high-yield fabrication process***

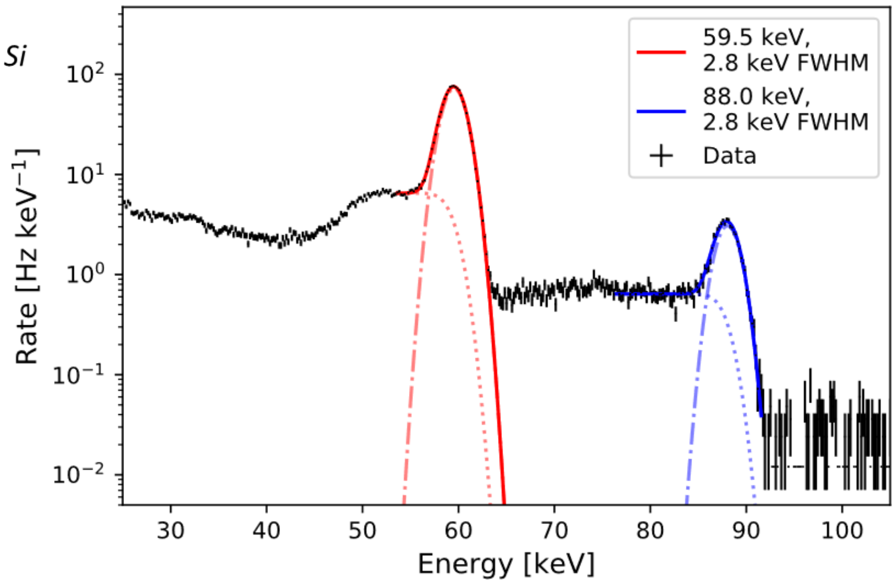
Image credit: NASA

GAPS Instrument-*Si(Li) Tracker*

- Custom made lithium-drifted silicon (Si(Li)) detector: 10-cm diameter and 2.5-mm thickness, 8 strips per detector
  - ✓ ***tracking efficiency*** in low-multiplicity events
  - ✓ ***stopping power*** up to 0.25 GeV/n
  - ✓ ***energy resolution*** < 4 keV to distinguish X-rays
  - ✓ ***active area*** totaling ***~10 m²***

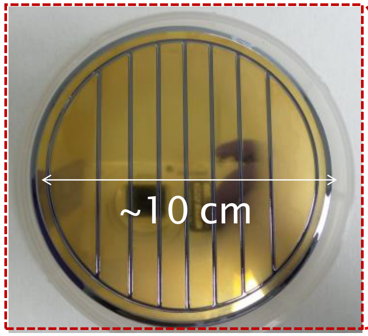


Xiao, Stoessl, Roach, et al. (2022) in prep.
Rogers, Xiao, Perez et al. (2019) JINST
Saffold, Rogers, Xiao, et al. (2021) NIMA
Kozai, Fuke, Yamada, et al. (2019) NIMA

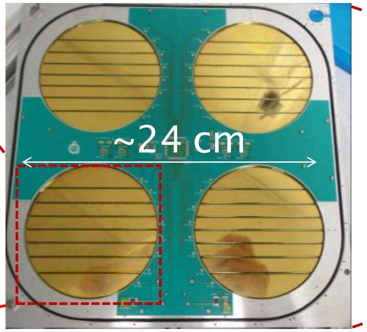


GAPS Instrument-***Si(Li) Tracker***

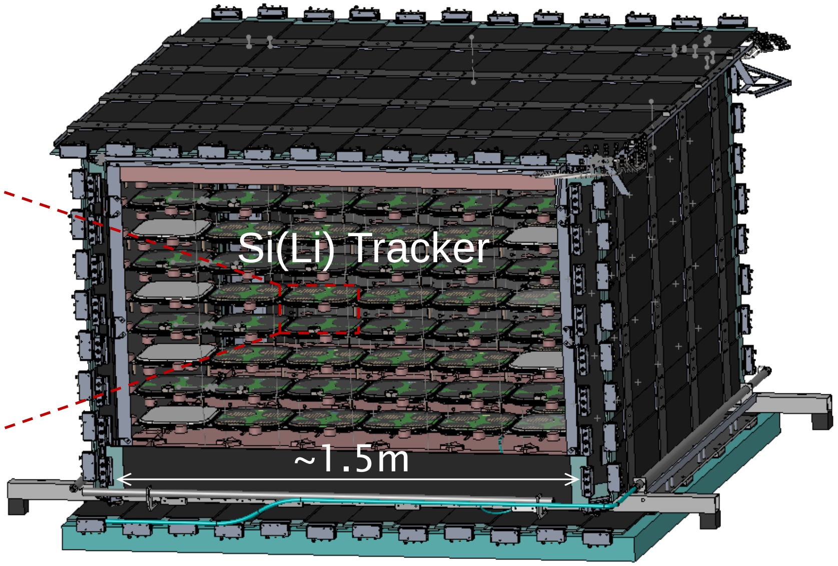
- GAPS Tracker, ~1.5 x1.5 x1.1m
  - 10 layers, ~1100 Si(Li) detectors.



- Single Si(Li) Detector

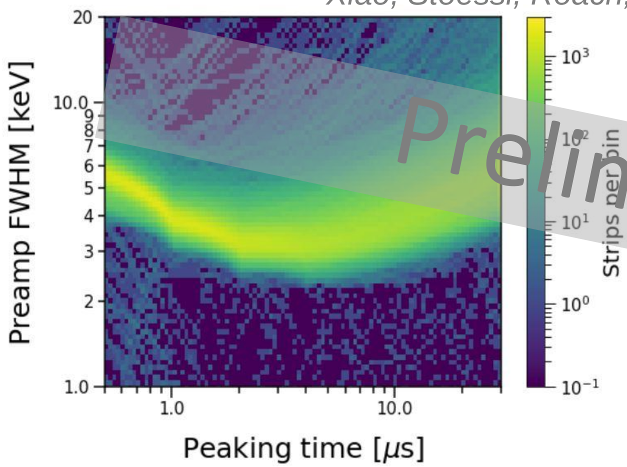


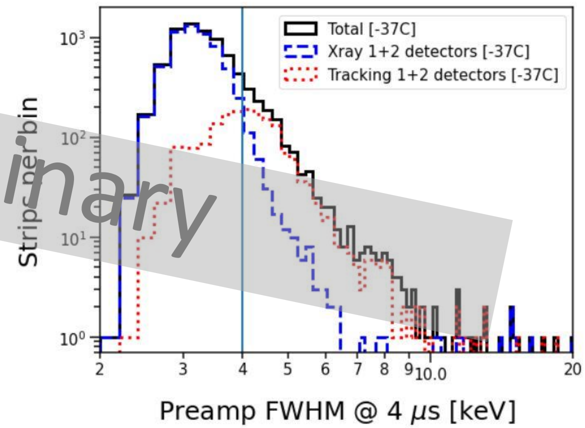
- 4-detector Module
(with ASIC electronics)

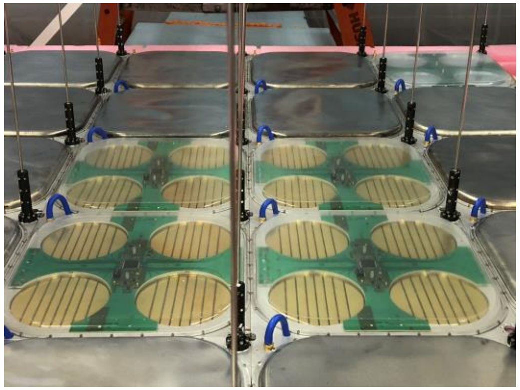


- All Si(Li) detectors have been calibrated, are being integrated into the tracker.

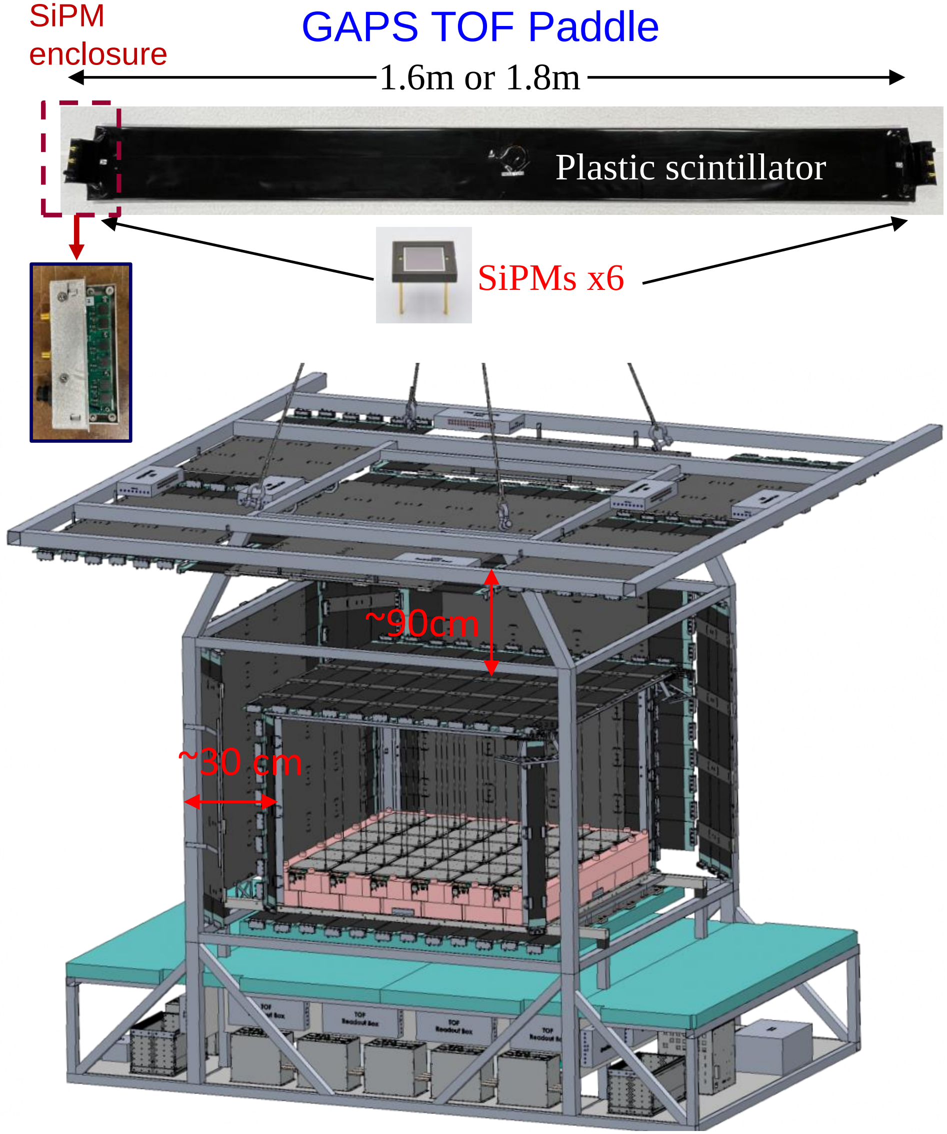
Xiao, Stoessl, Roach, et al. (2022) in prep.







GAPS Instrument-*TOF*



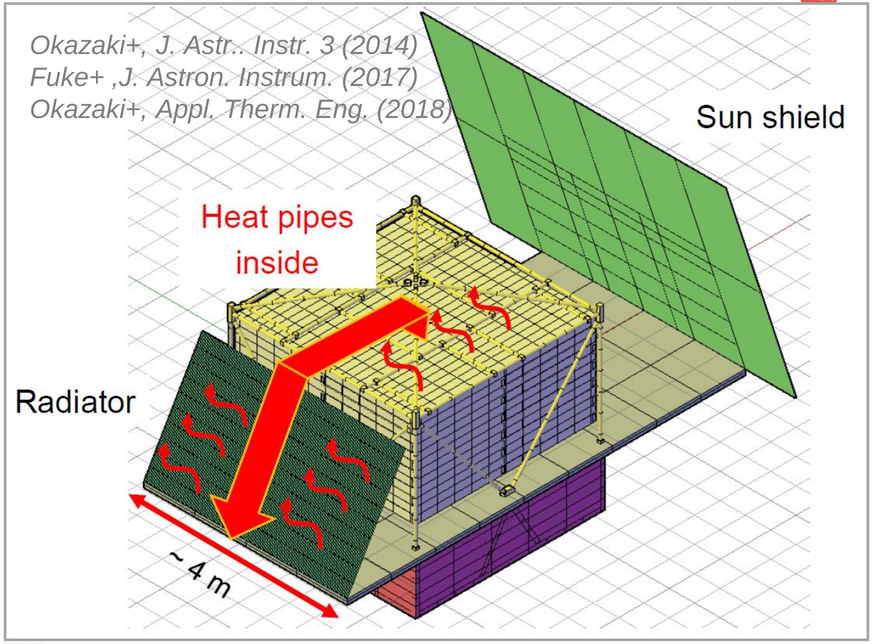
Bird Proc. ICRC (2019): arXiv:1908.03154
Quinn Proc. ICRC (2019)

- Time of Flight plastic scintillator:
  - Covers ~15 m^2 inner cube and ~25 m^2 outer layer (top umbrella + side cortina).
- Measure velocity of incoming particles + fast trigger to Si(Li) tracker.
  - **Time resolution**→ achieved <***400 ps*** (meets the requirement <0.5 ns)
  - **TOF Trigger and Veto**:
    - ✓ ***Beta:*** select slow particles.
    - ✓ ***Charge:*** reject high Z particles.
    - ✓ ***Hit:*** number of fired paddles.

→Accept ~80% of anti-nuclei and suppress event rate <500 Hz!

GAPS Instrument-*Thermal System*

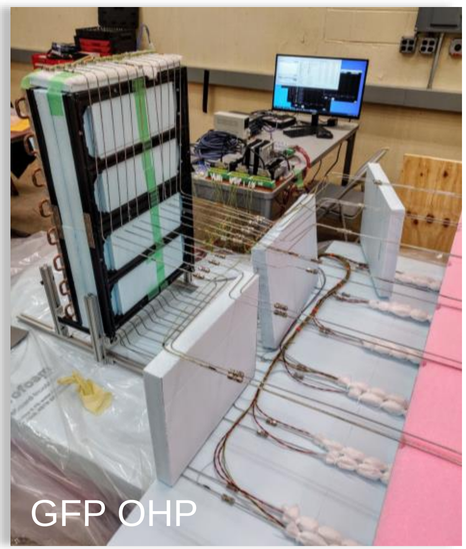
- Design: Low power, low mass, and semi-passive.
- Radiator + Oscillating Heat Pipe (OHP)
  - Developed at JAXA/ISAS, will be firstly used in the balloon experiment by GAPS.
  - Si(Li) detector: heating (~300W) transferred by dual-phase fluid to a radiator then to the space.

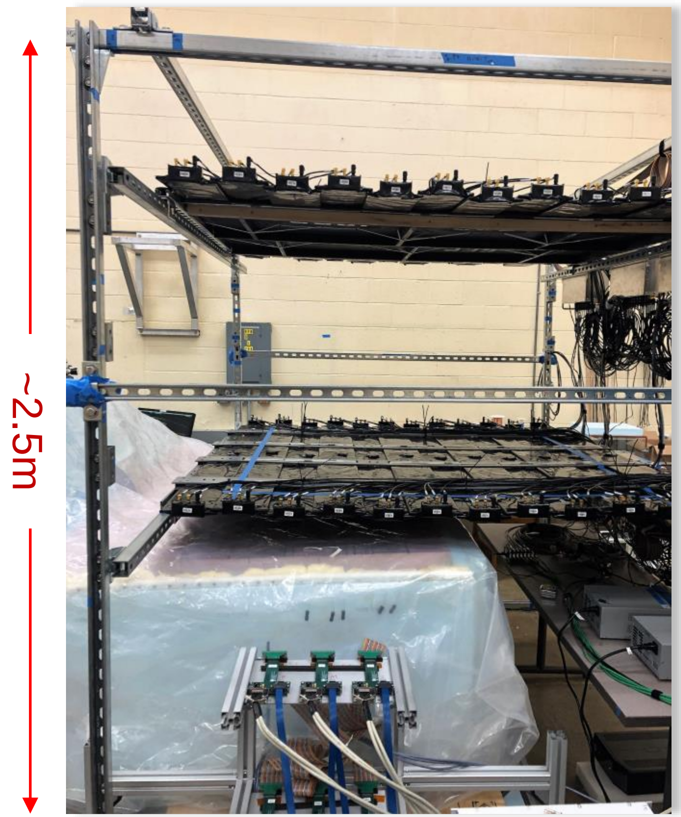


- Scaled radiator model was validated on engineering flight (NASA SIFT)
  - Temperatures measured during 10-hour flight were consistent with the expectations.

GAPS Instrument-***Integration***

- GAPS functional type (GFP): demonstrate the system-level operation/performance; mitigate the risks of flight from system level, *paper in preparation.*
  - Tracker: 3 layers, 12 x 4 Si(Li) detectors per layer, ~10% of full payload.
  - Cooling: oscillating heat pipes (OHP) for Si(Li) tracker.
  - TOF: 2 x 12 paddle panels of plastic scintillator.

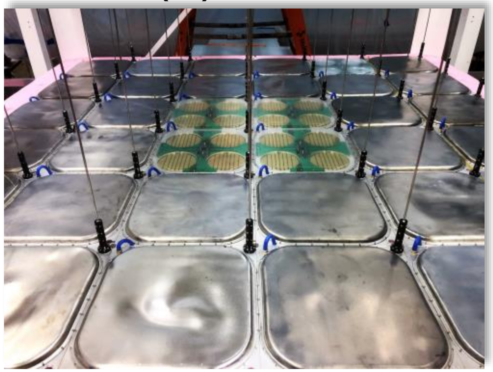




GAPS Instrument-*Integration*

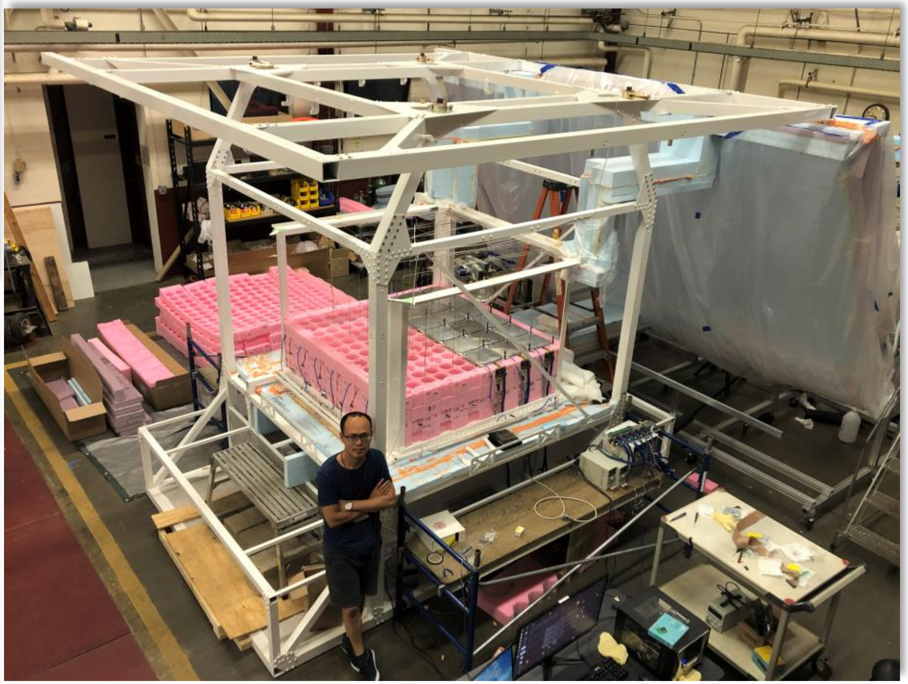
- GAPS integration of full payload is underway, moving steadily towards the first Antarctica flight in late 2023!!

- Si(Li) modules



- Gondola

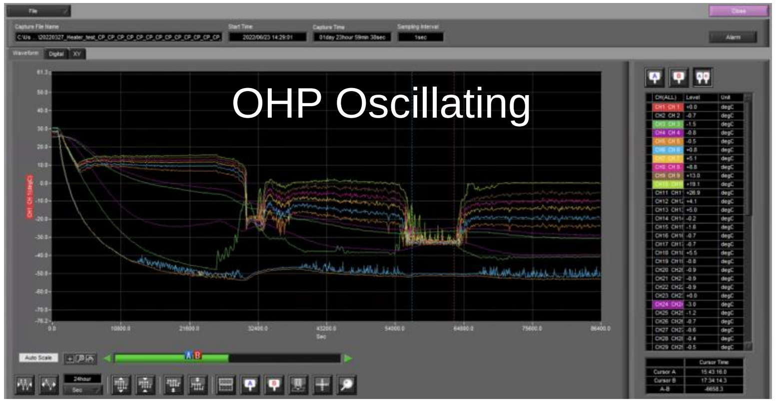
- OHP



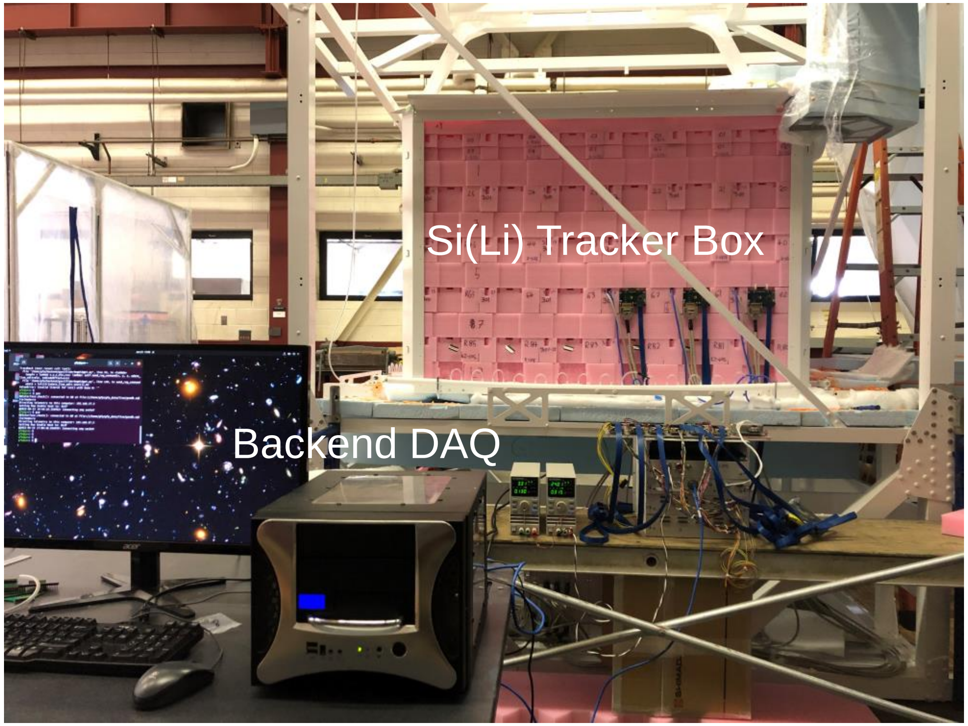
GAPS balloon payload (under integration)

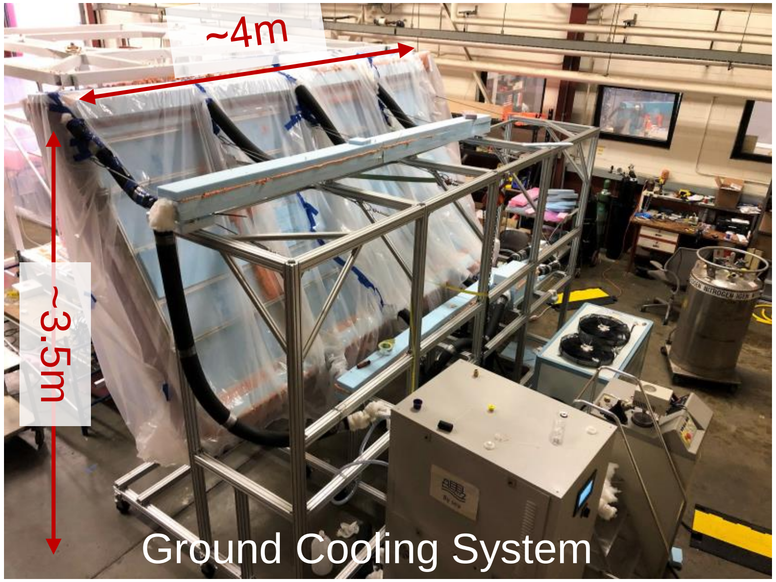
GAPS Instrument-*Integration*

- ❑ GAPS integration of full payload is underway, moving steadily towards the first Antarctica flight in late 2023!!



✓ *Layer-by-layer testing during the payload integration*





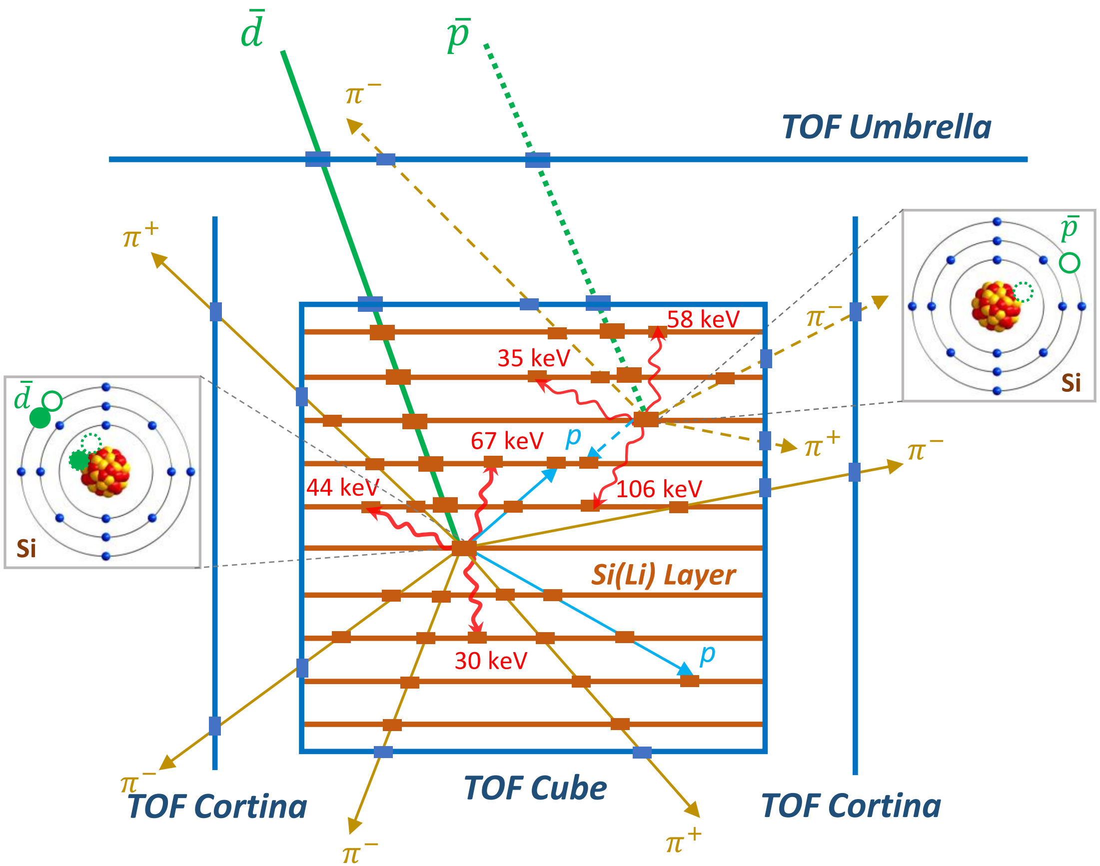
Summary & Conclusions

- GAPS is the first experiment optimized specifically for low-energy (<0.25 GeV/n) antiprotons, antideuterons, and anti-He.
- **GAPS aims to deliver:**
  - *first-time detection of cosmic antideuterons with* sensitivity ~2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range.
  - *a precision antiproton measurement in an unexplored energy range*, permitting leading constraints on light DM, the best limits on primordial black hole evaporation on Galactic length scales, and novel insight on cosmic-ray propagation models.
  - *open sensitivity to low-energy cosmic anti-He*, in particular to investigate the candidate antihelium events reported by AMS-02
- GAPS full instrument integration is undergoing, on schedule for the ***first science flight from Antarctica in late 2023!***

GAPS Collaboration

Thank you!

GAPS “Background” Rejection



- TOF system helps select antinuclei ($\bar{p}$ and $\bar{d}$)
  - Combined with the simultaneous detection in the tracker
- Antiparticle ($\bar{p}/\bar{d}$) identification:
  - Stopping range, dE/dx
  - Pion & proton multiplicity
  - Unique atomic X-rays

➢ “Background” for antideuteron searches ($\bar{p}$ mis-identification) ***rejection power*** $>10^6$ ***!***