The GAPS Experiment: Indirect Dark Matter Searches with Low-energy Cosmic-ray Antinuclei

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On Behalf of the GAPS Collaboration

August 15th, 2024

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

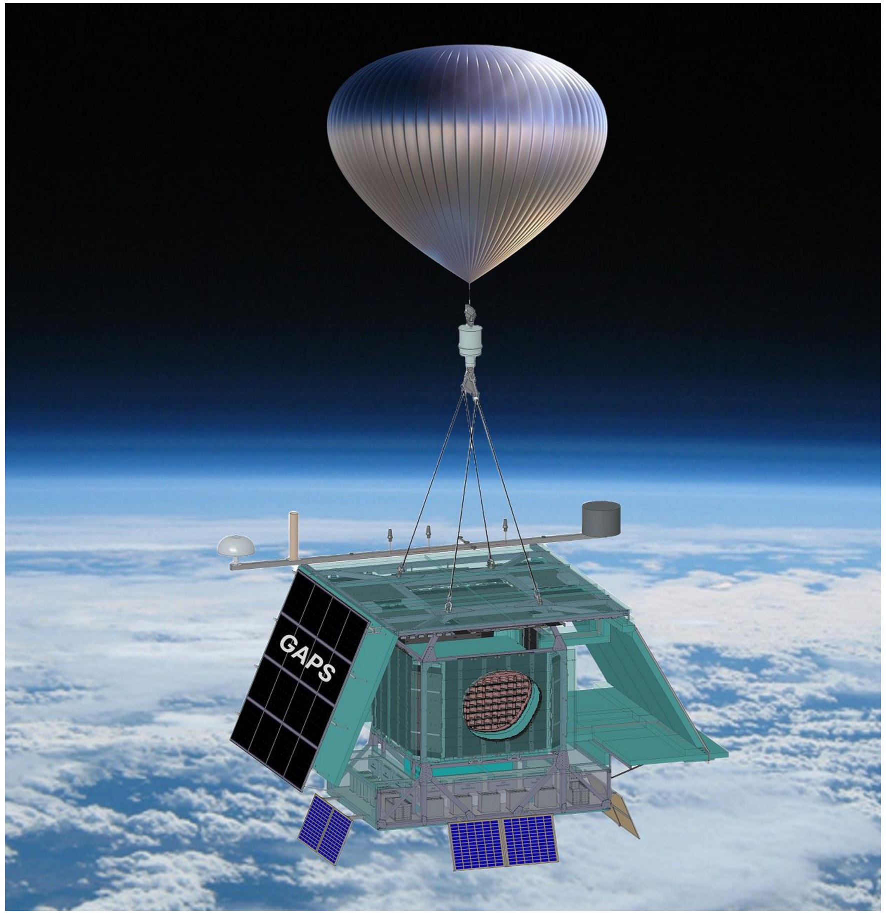
The GAPS Mission

- 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 open sensitivity to ***Antihelium.***

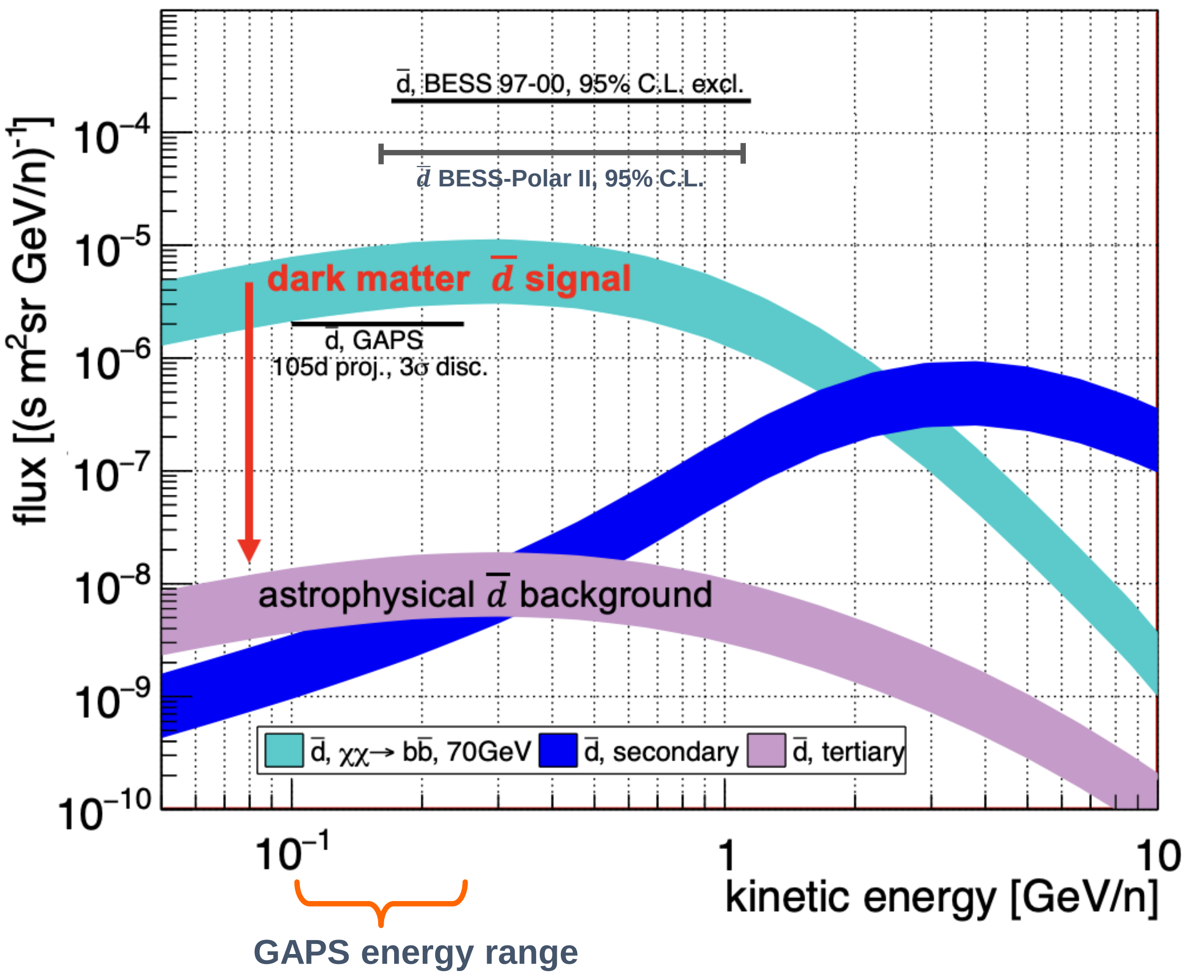


*Balloon photo from Word View

- First Antarctic balloon flight late-2024, and two follow-up flights planned.

Low-energy $\bar{d}$: clean signature of new physics

P. von Doetinchem, K. Perez et al., JCAP08 (2020) 035



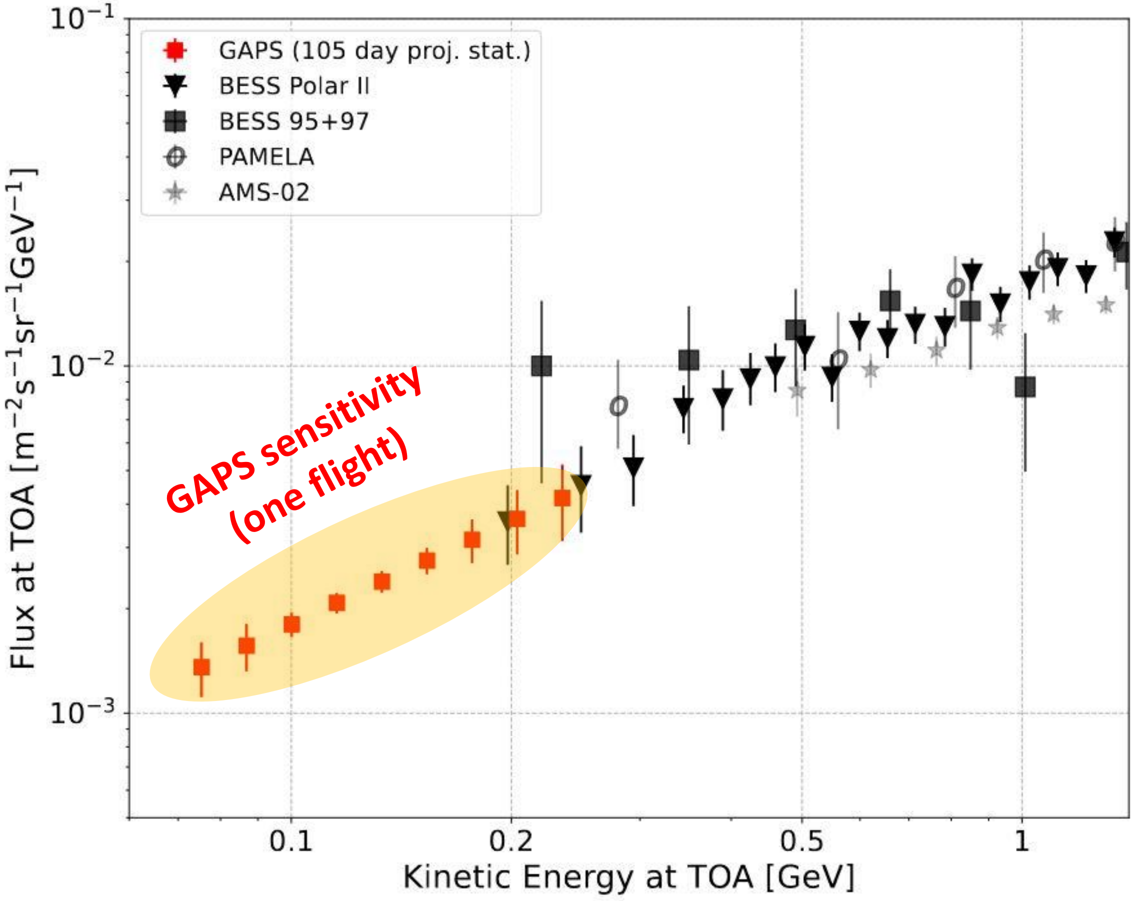
GAPS antideuterons: A generic ***new physics*** signature with *essentially zero* conventional astrophysical background!

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

Any antideuteron signal needs to be compatible with antiproton constraints!

Low-energy $\bar{p}$: unprecedented precision spectrum

Rogers+ (GAPS), Astropart. Phys. 102791 (2022)



- ~500 antiprotons ($\lesssim$0.25 GeV/n) for each flight
  - BESS : 29 at ~0.2 GeV
  - PAMELA: 7 at ~0.25 GeV
  - AMS-02: E>0.25 GeV

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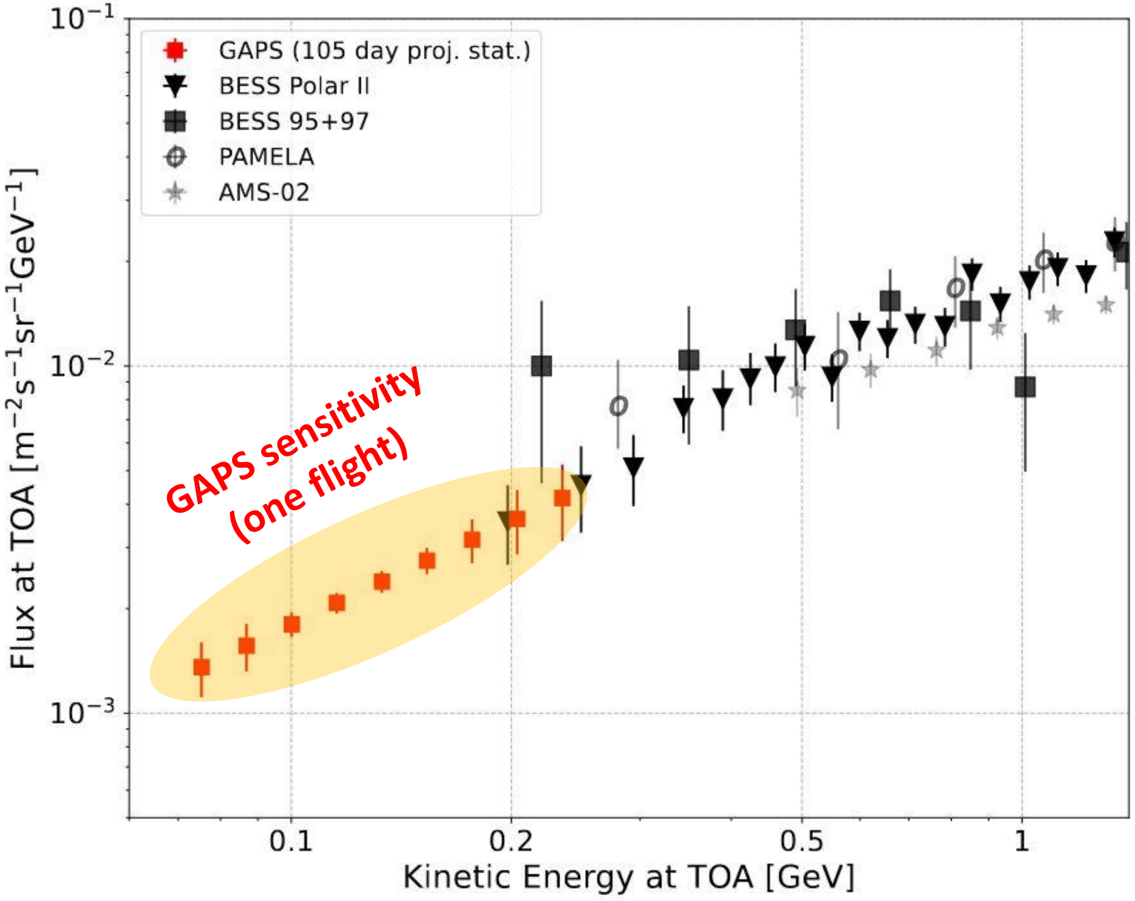

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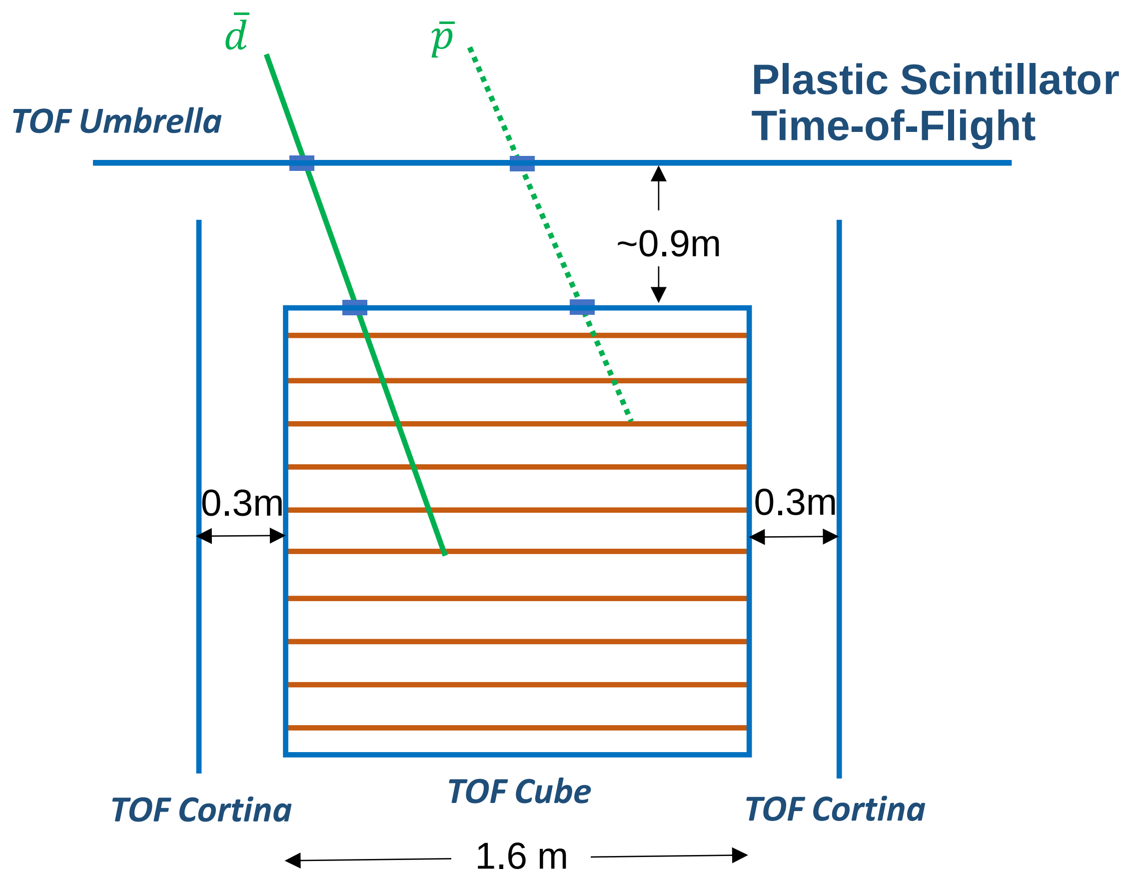
- ✓ Validate the GAPS novel anti-nuclei identification technologies → *Reduce systematic uncertainties for antideuteron search*

- ➢ Probe *light dark matter*, leading constraints on *primordial black hole* evaporation…

GAPS novel detection using exotic atoms



Extoic 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

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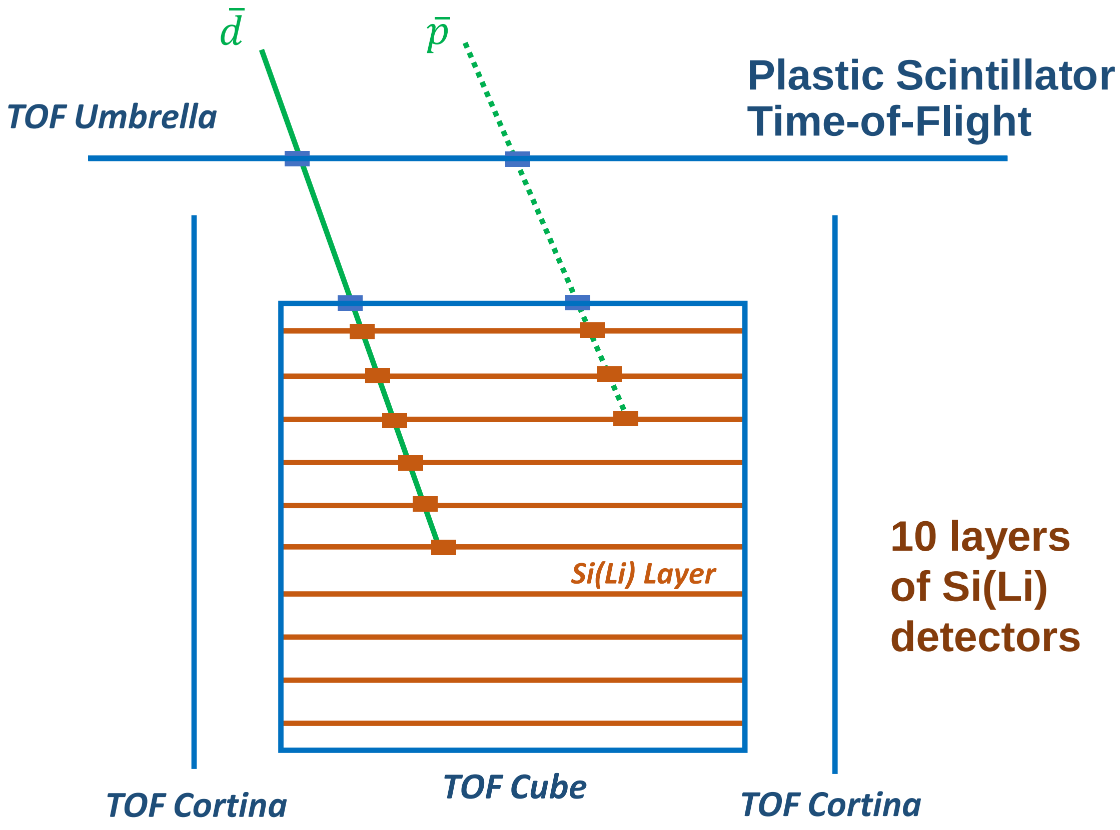

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- Slows/captures an incoming antiparticle

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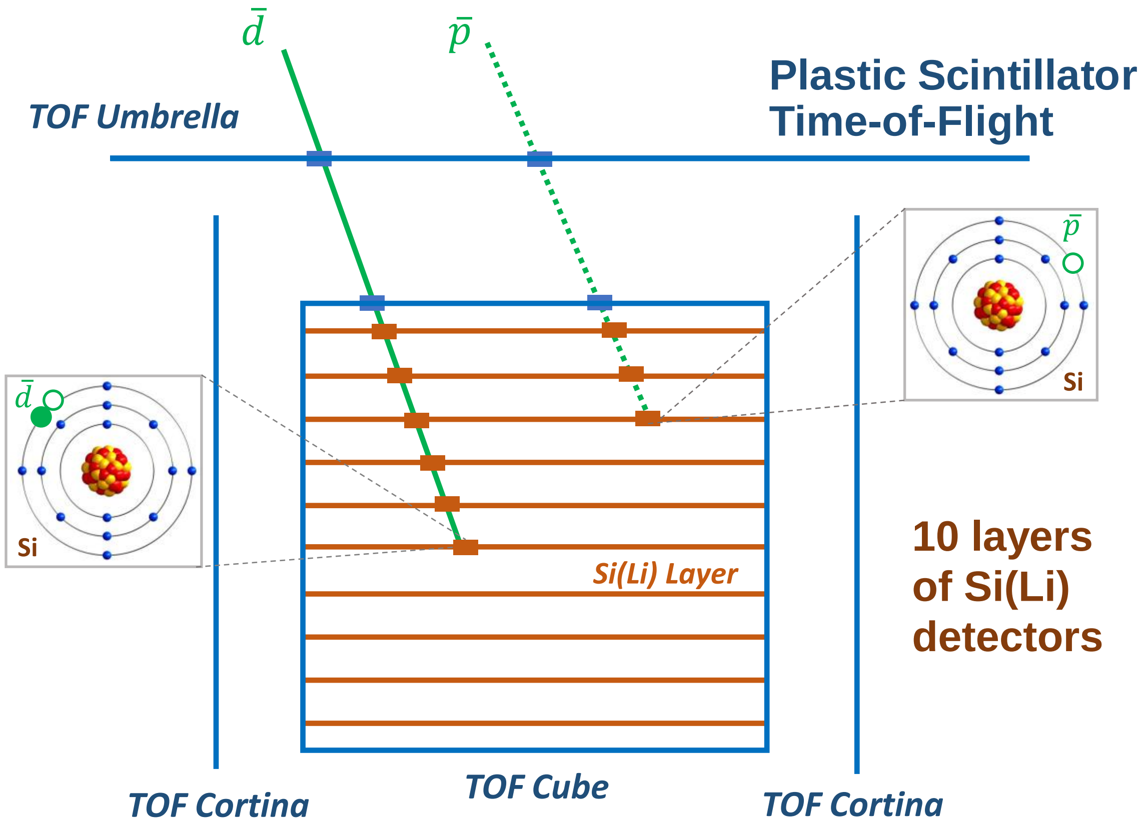

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- Slows/captures an incoming antiparticle into an ***exotic atom***

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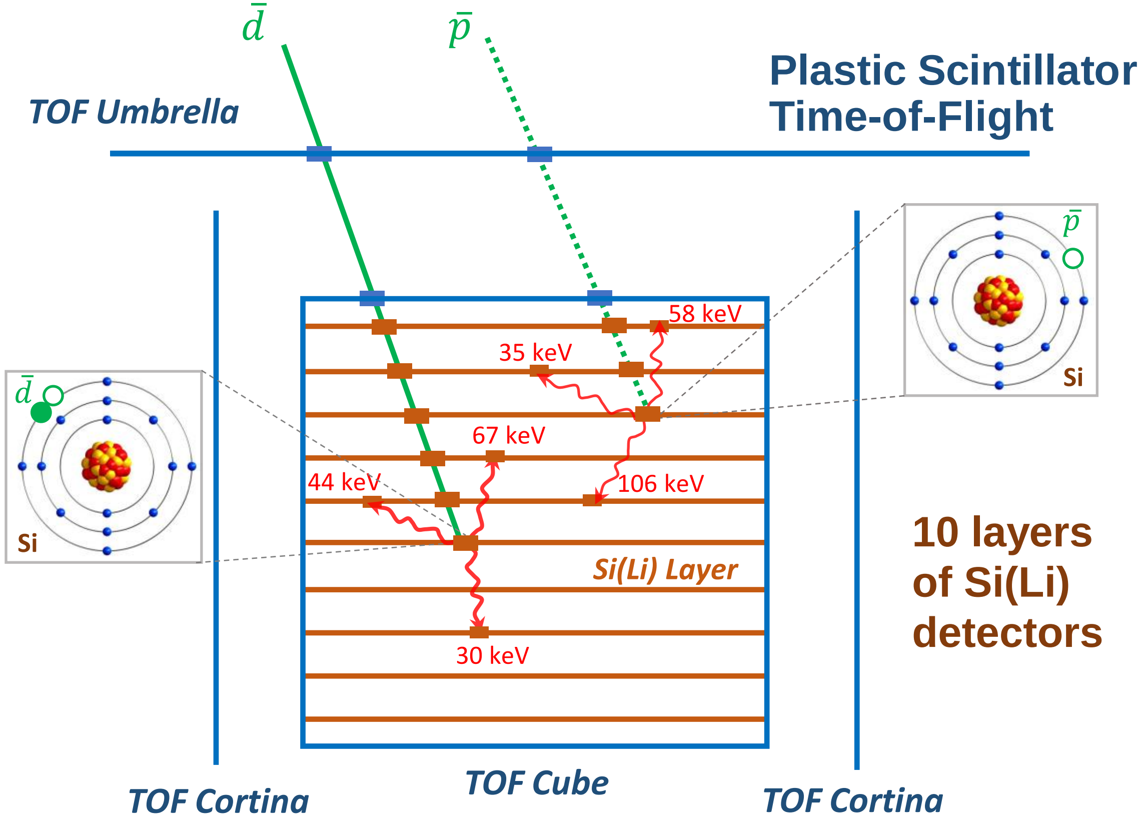

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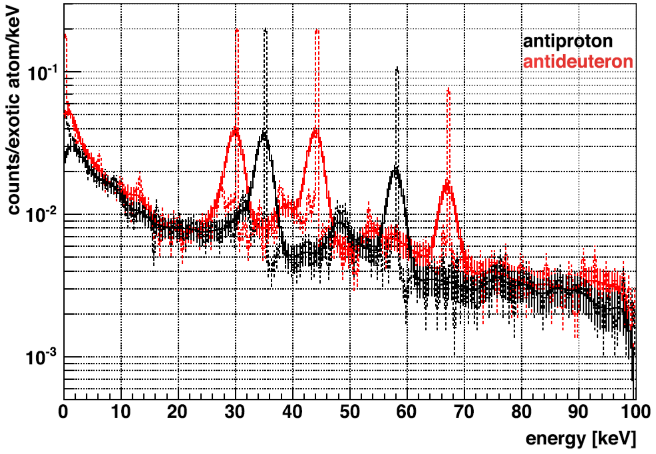
Time-of-flight system: measures velocity, incoming angle and dE/dx, fast trigger

Si(Li) tracker:

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



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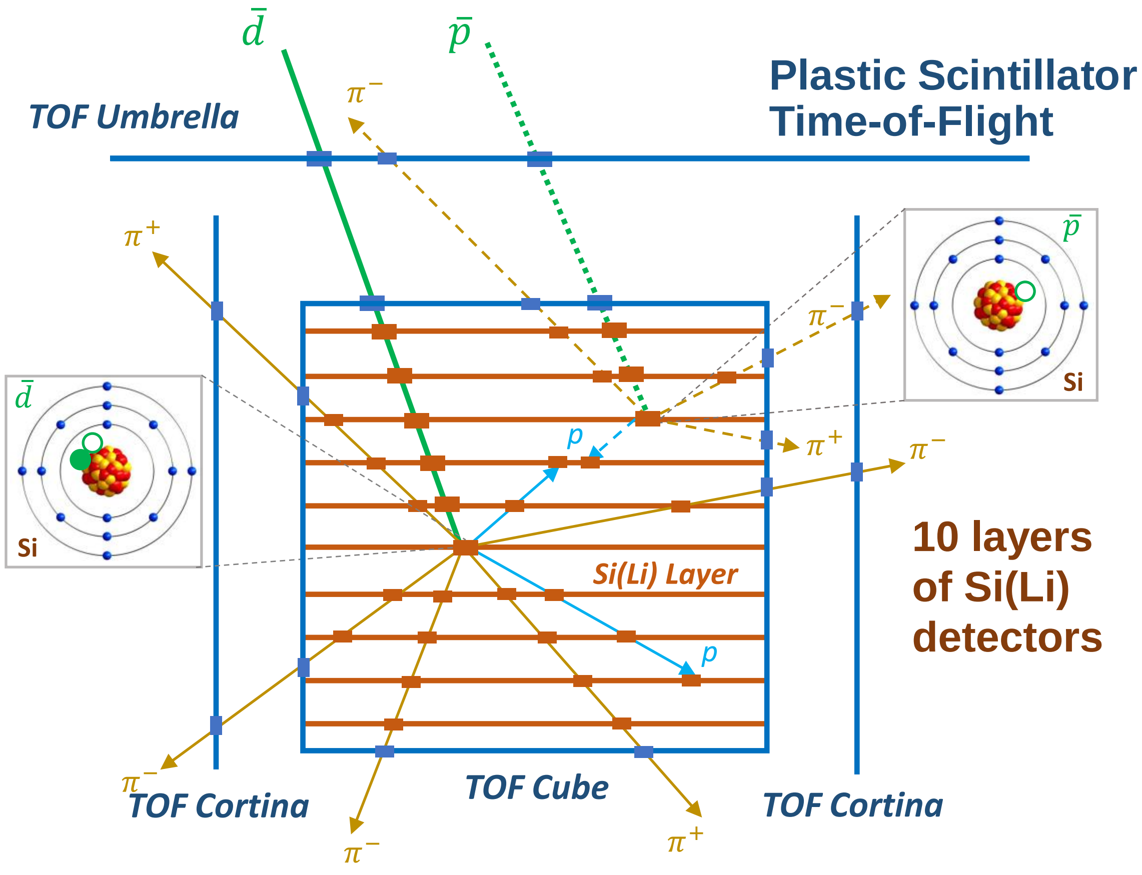

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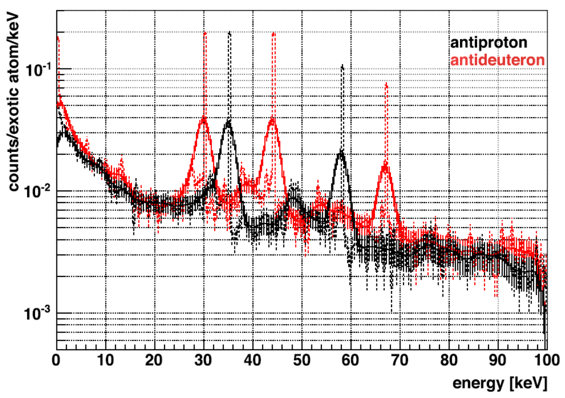
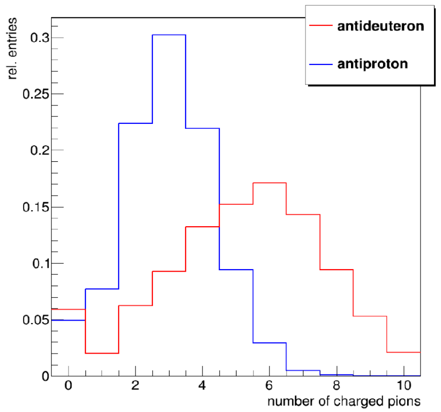
Time-of-flight system: measures velocity, incoming angle and dE/dx, fast trigger, tracks of outgoing particles

Si(Li) tracker:

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





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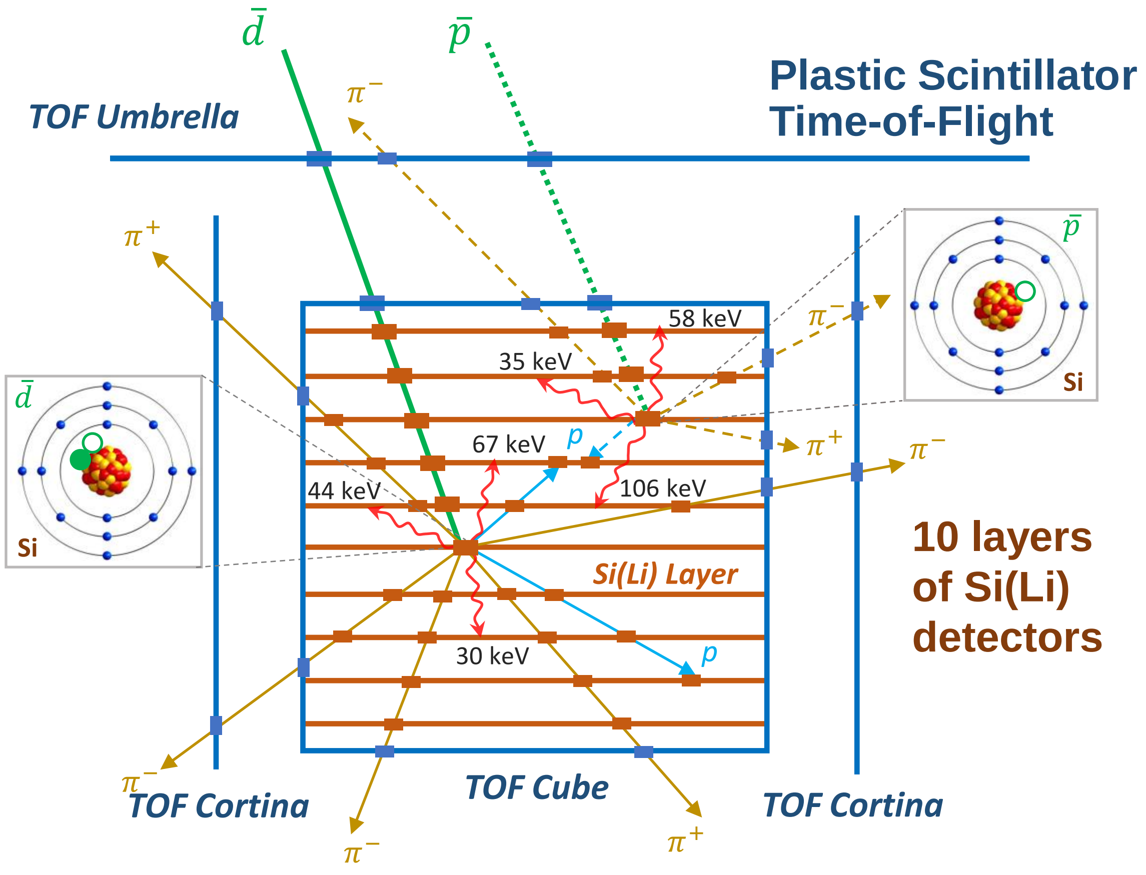

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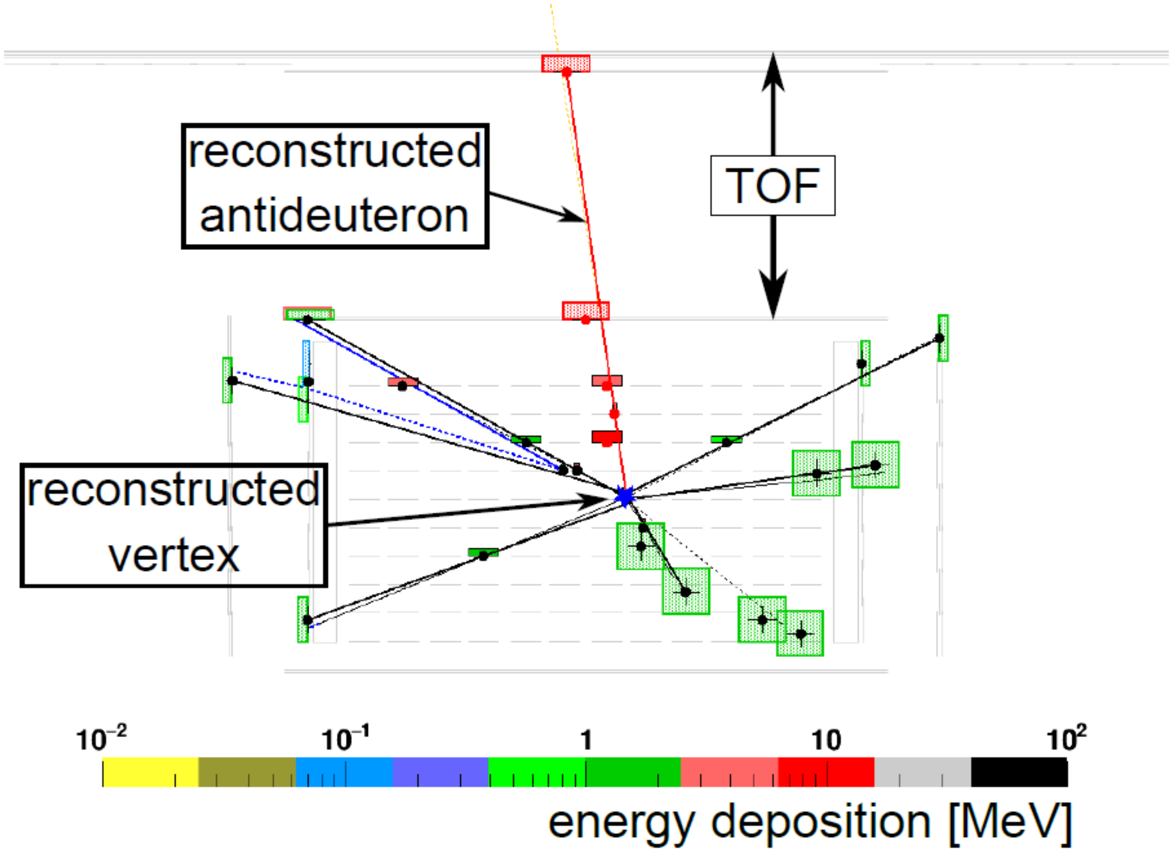
Time-of-flight system: measures velocity, incoming angle and dE/dx, fast trigger, tracks of outgoing particles

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 novel detection using exotic atoms

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

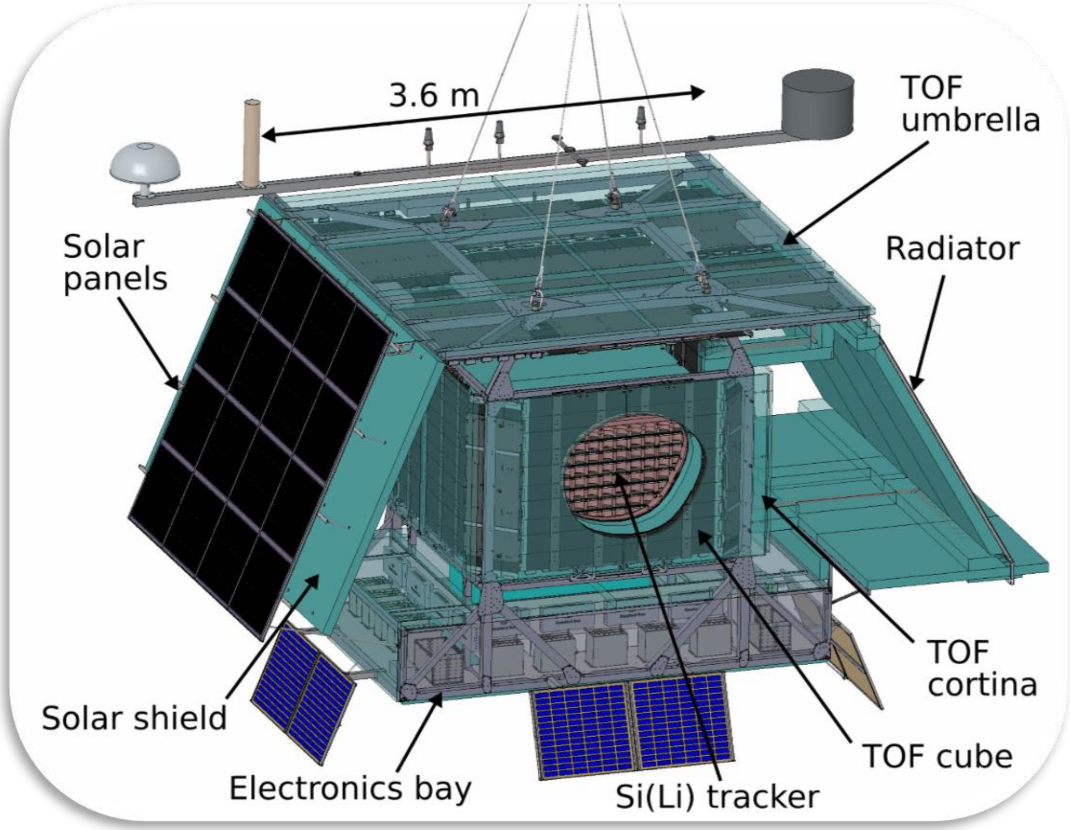


R. Munini et al. (GAPS), Astropart. Phys. 102640 (2021).

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

On a balloon!!

❑ **GAPS' balloon nature constraints: *power*, *weight*, *size*, *temperature*...**



- ❑ **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 mechanics

❑ GAPS Scientific balloon payload:

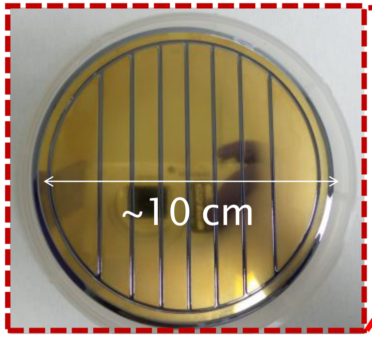
- Size ~3×3×2 m, mass ~2.5 ton, power ~1.4 kW

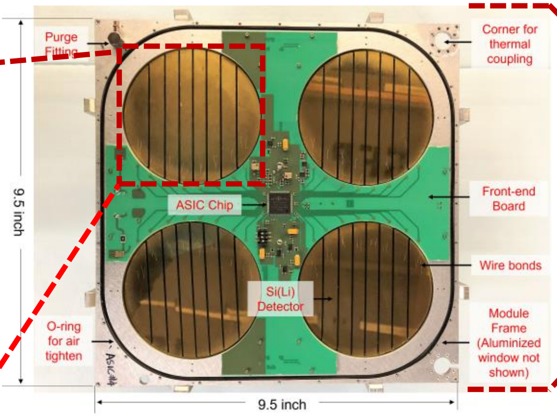
⇨ Recovered after each flight

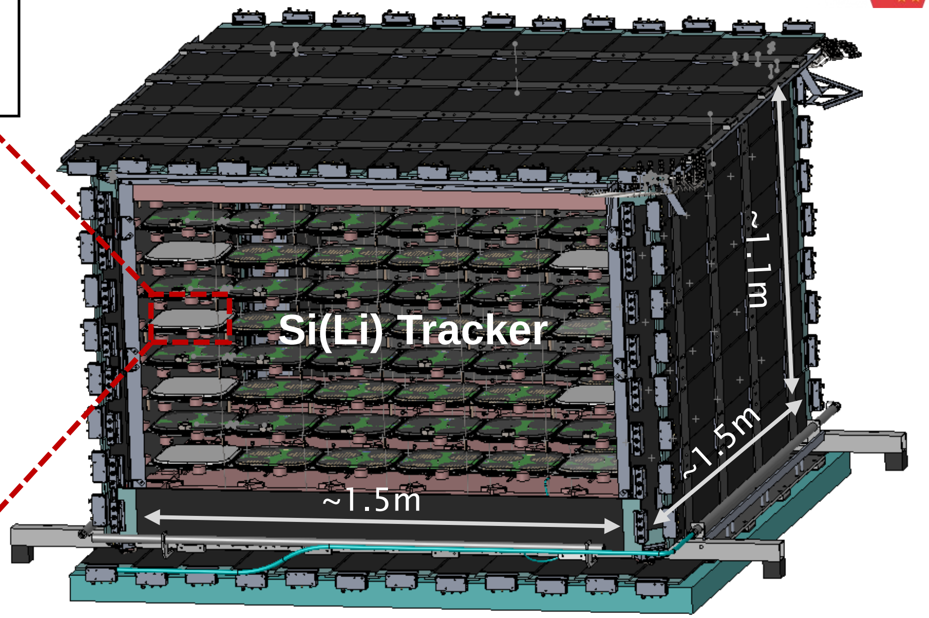
GAPS Key Instrument-*Si(Li) Tracker*

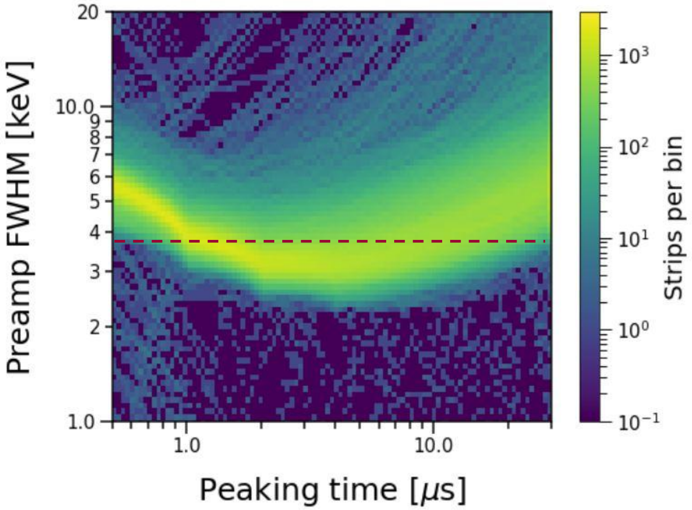
- **Tracker:** ~1100 custom lithium-drifted silicon detectors.
  - ~1.5 x1.5 x1.1 m, 10 layers

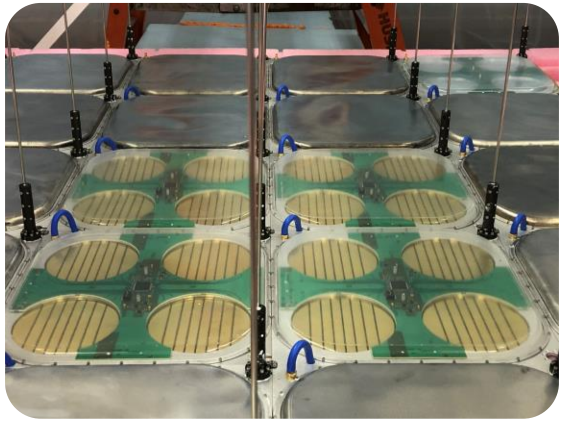
Perez et al., NIM A (2018)
Kozai et al., NIM A (2019)
Rogers et al., JINST (2019)
Saffold et al., NIM A (2021)
Kozai et al., NIM A (2022)
Xiao et al., IEEE 70 (2023)











All Si(Li) detectors have been calibrated and integrated into the tracker!!

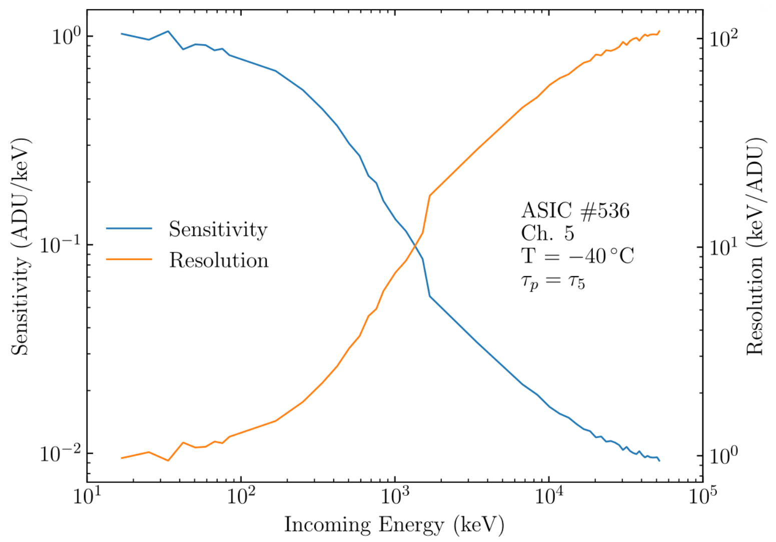
GAPS Key Instrument-***Si(Li) Tracker***

➢ GAPS on *balloon*: power limited, payload limited, etc.

❑ GAPS custom ASIC (SLIDER-32)

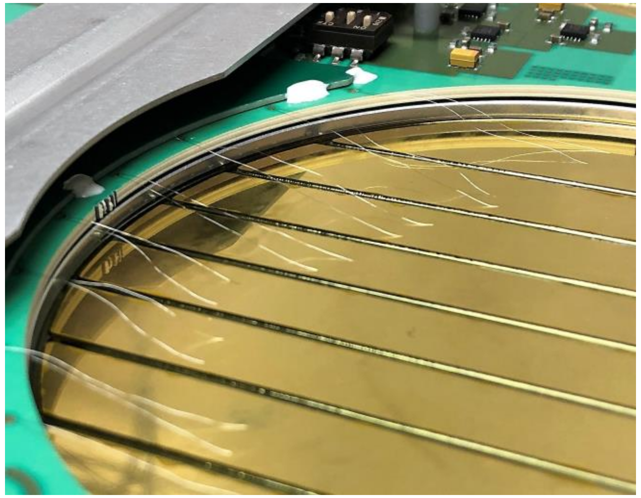
- 180-nm CMOS technology
- 32 channels and 11-bit ADC
- 1 keV resolution in 10-100 keV
- <10% resolution up to 100 MeV

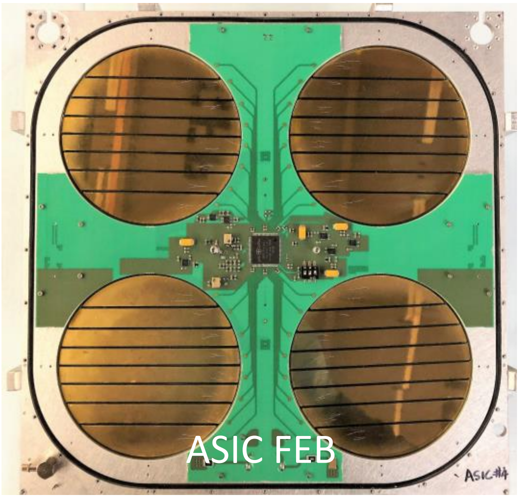
→ ***Power consumption: <10 mW/chan***



\+ Wire bounds connect detector strips to ASIC FEB.

- Reduced mass budget
- Lower power budget
- Improved track reconstruction

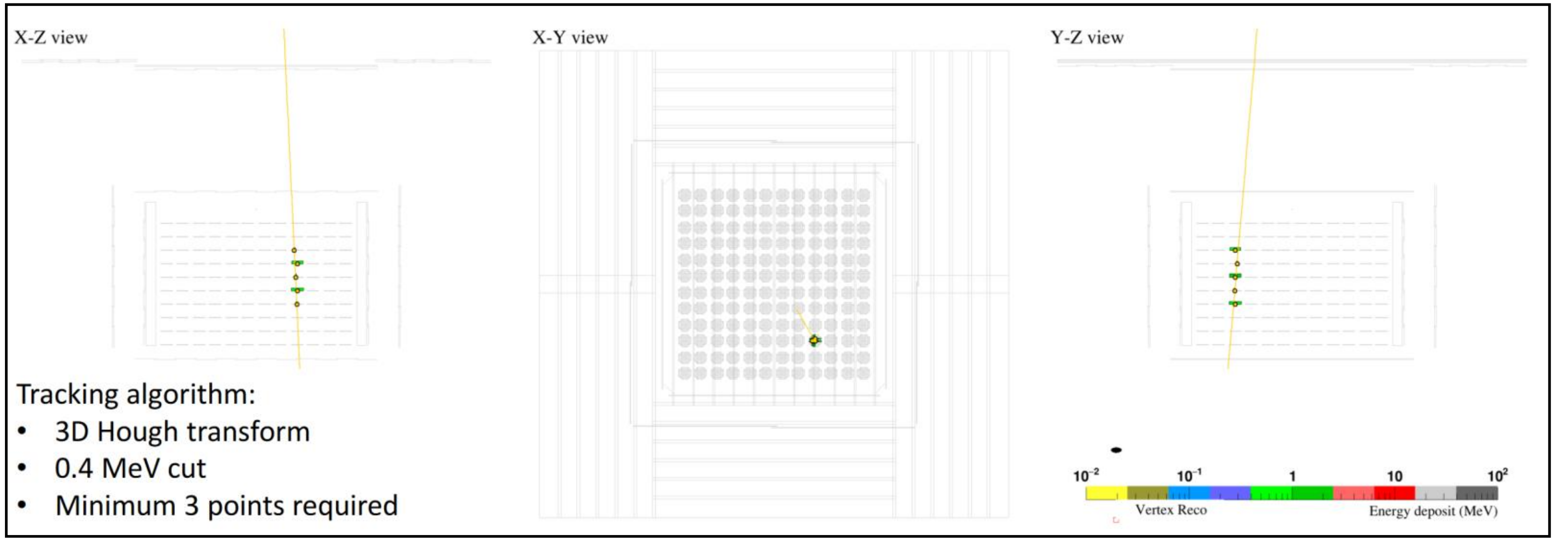




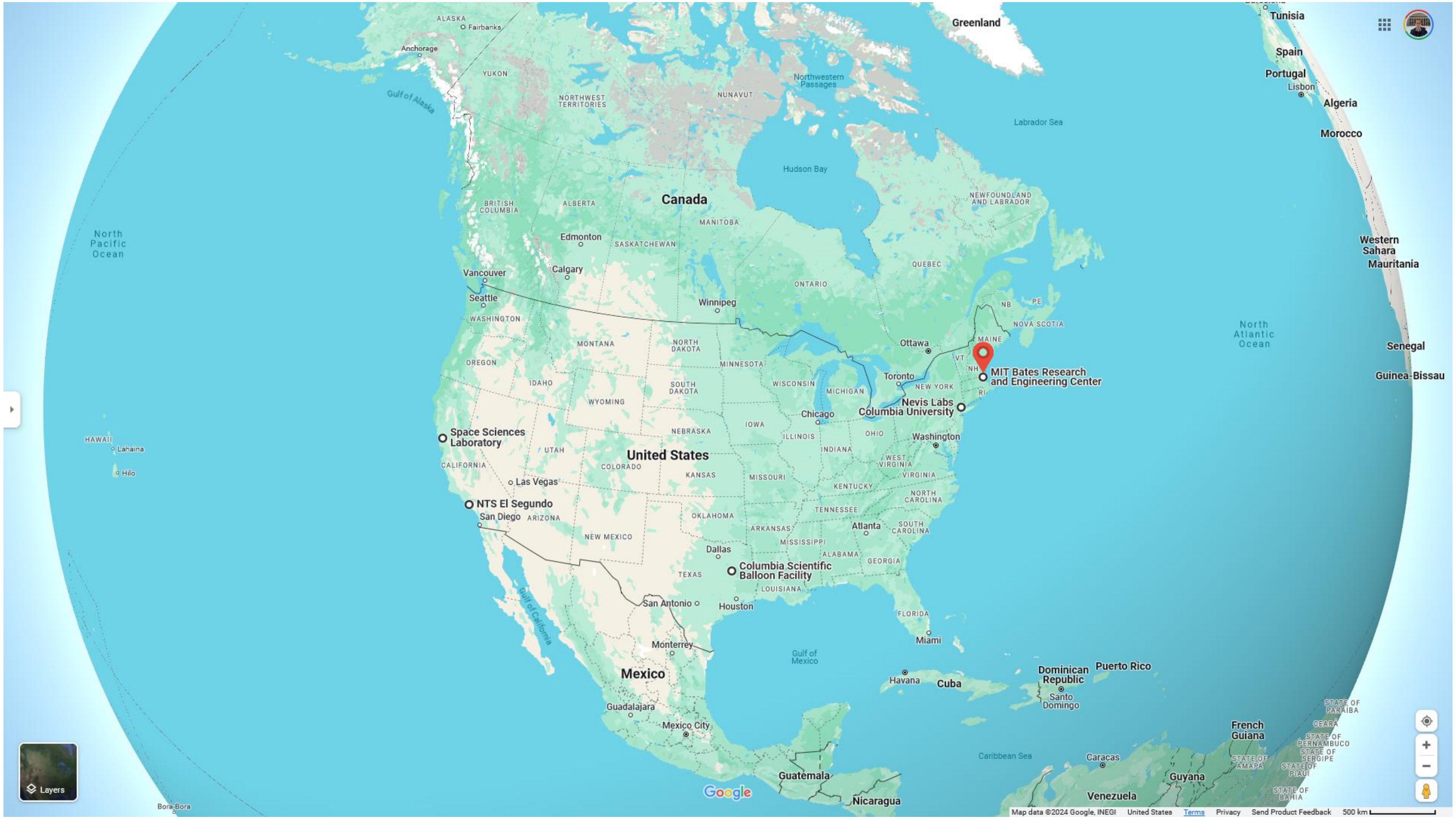
Scotti et al., Proc. (ICRC2019), Manghisoni et al., IEEE 62 (2015)
Manghisoni et al., IEEE 68 (2021), Manghisoni et al., IEEE 71 (2023)

GAPS ***Payload***

- Combined data taking with TOF and Tracker on ground:
  - More than 10 million muon tracks have been collected.
  - Detailed data analysis ongoing.



GAPS Long Path to Antarctica



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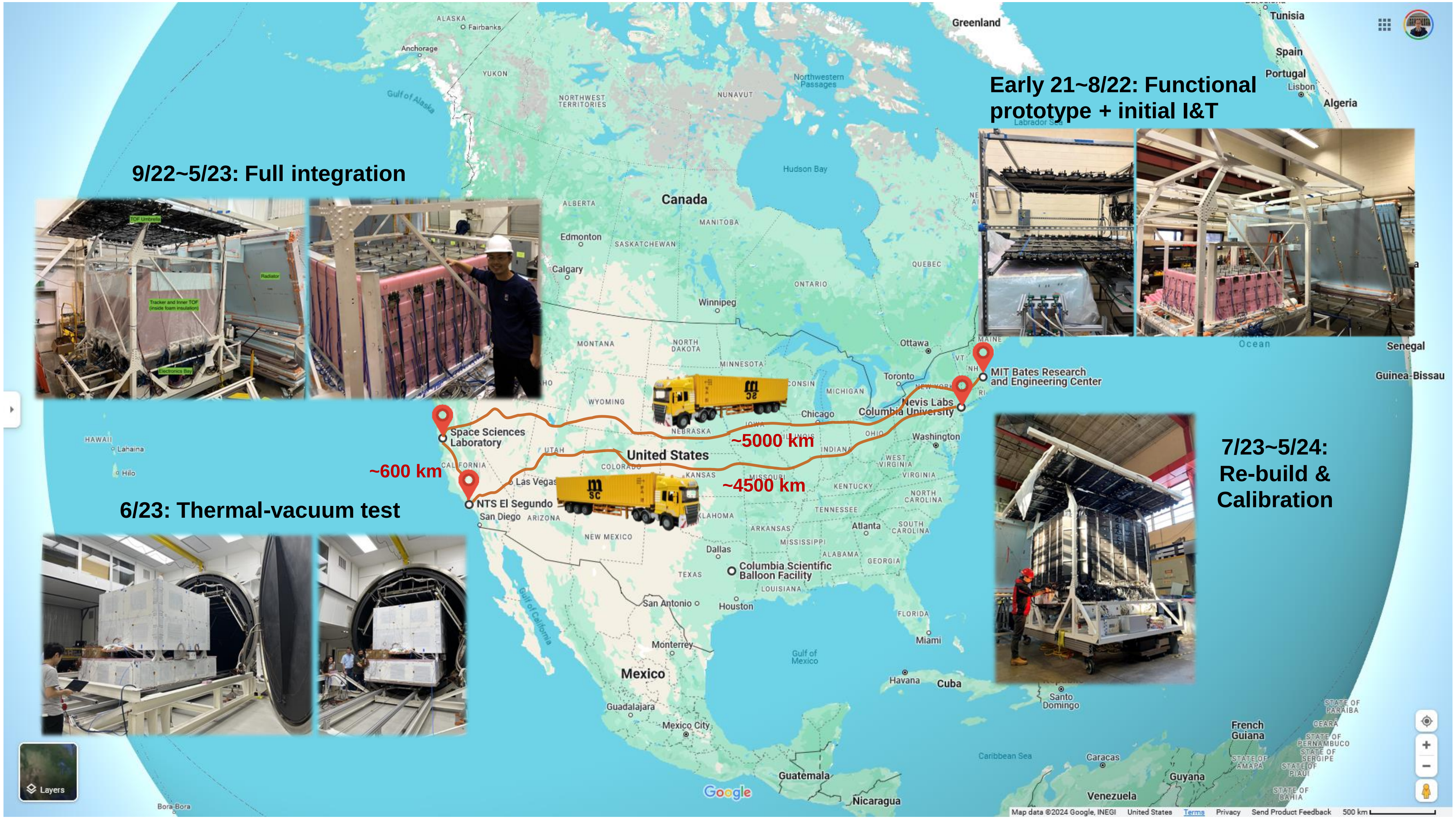
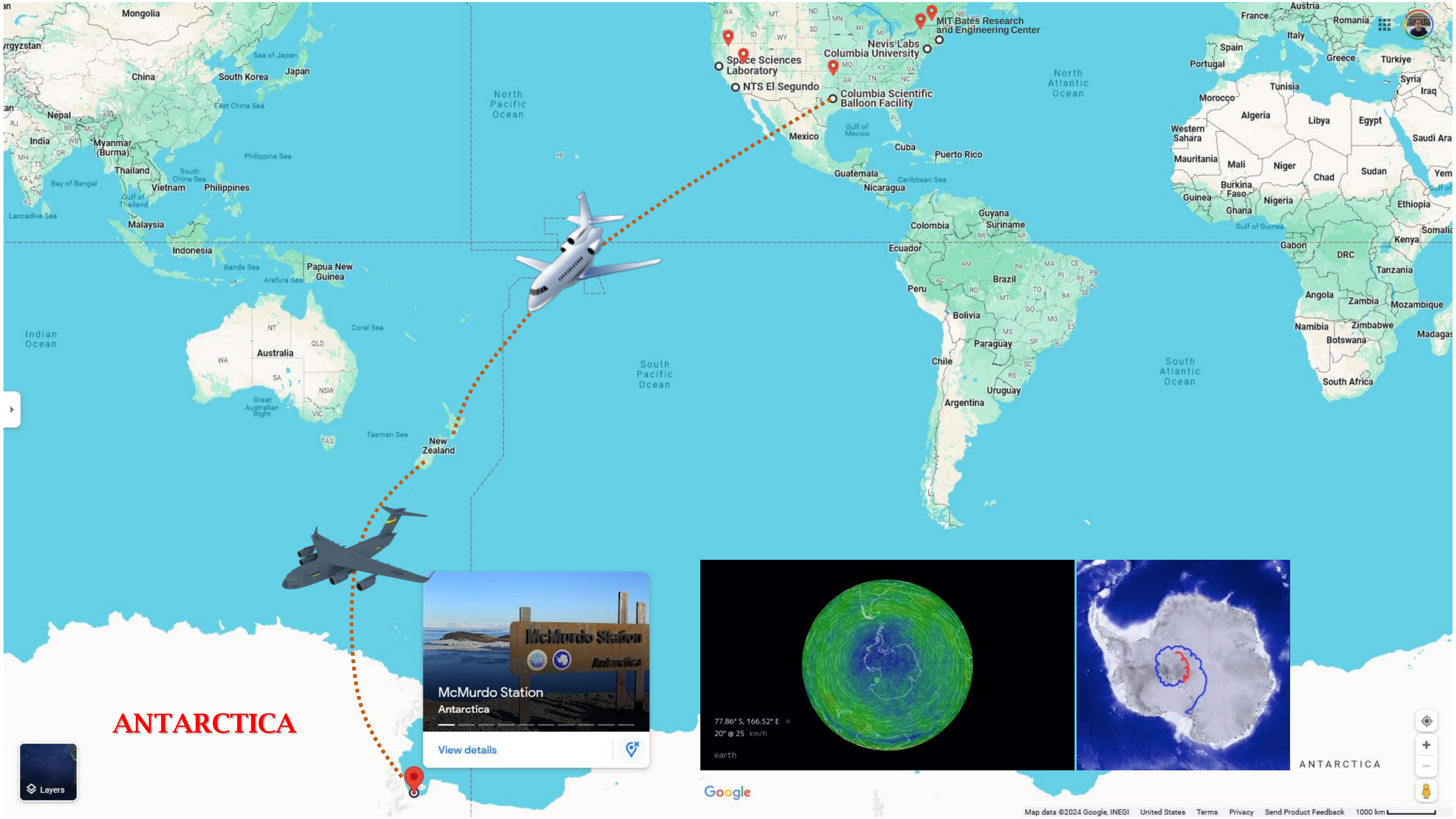


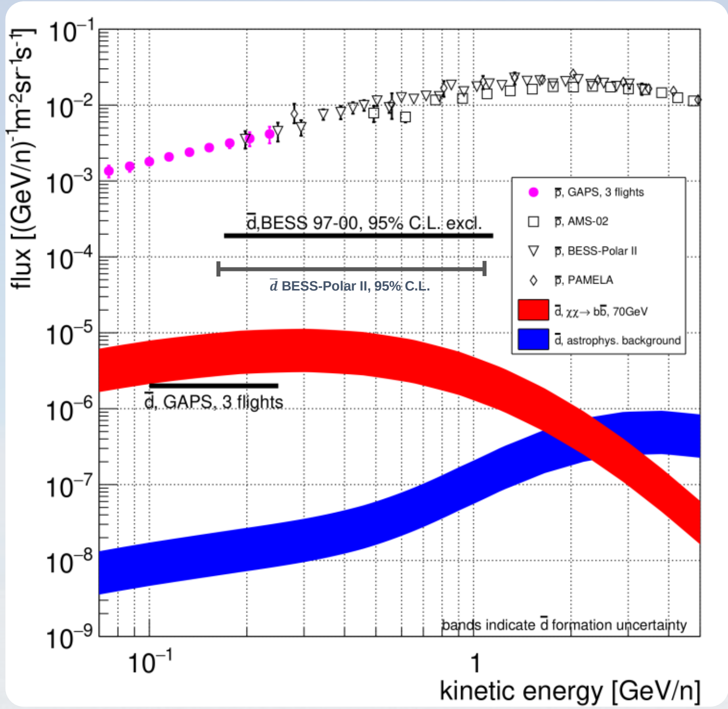
GAPS Long Path to Antarctica

Countdown to ***Blast-off !!***



Summary & Outlook

❑GAPS: first experiment optimized specifically for low-energy (≲0.25 GeV/*n*) cosmic anti-p, anti-d, and anti-He.



❑**GAPS aims to deliver:**

- *first-time detection of cosmic antideuterons with an unprecedented* sensitivity ~2 orders of magnitude below the current best limits, "smoking-gun" DM signature.
- *precision antiproton measurement in an unexplored energy range*
- *open sensitivity to low-energy cosmic anti-He*

❑GAPS has completed the on-ground commissioning, towards the ***first science flight from the Antarctica this year!***

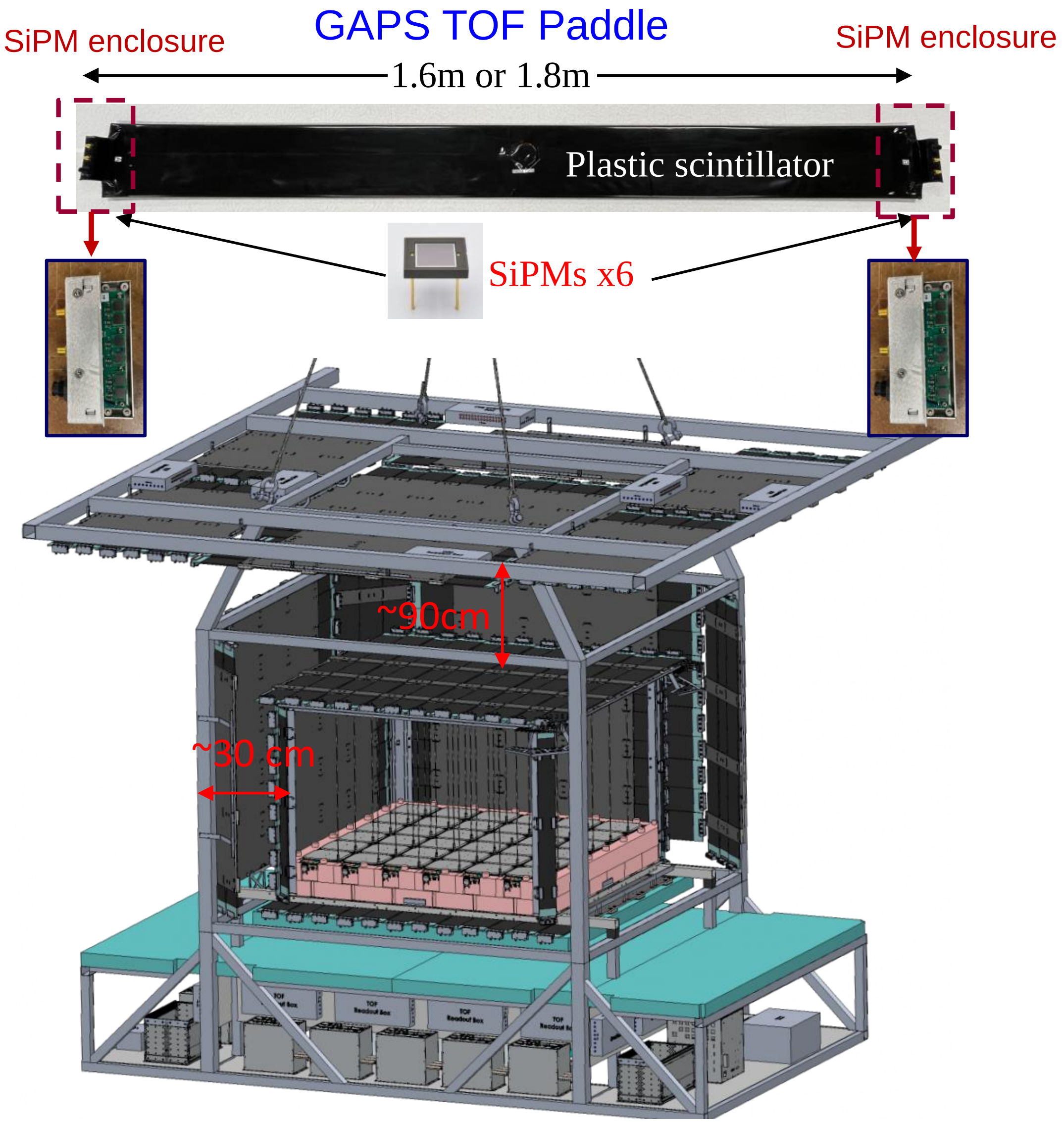
Stay tuned!!!

GAPS Collaboration

Thank You!

Backup Slides

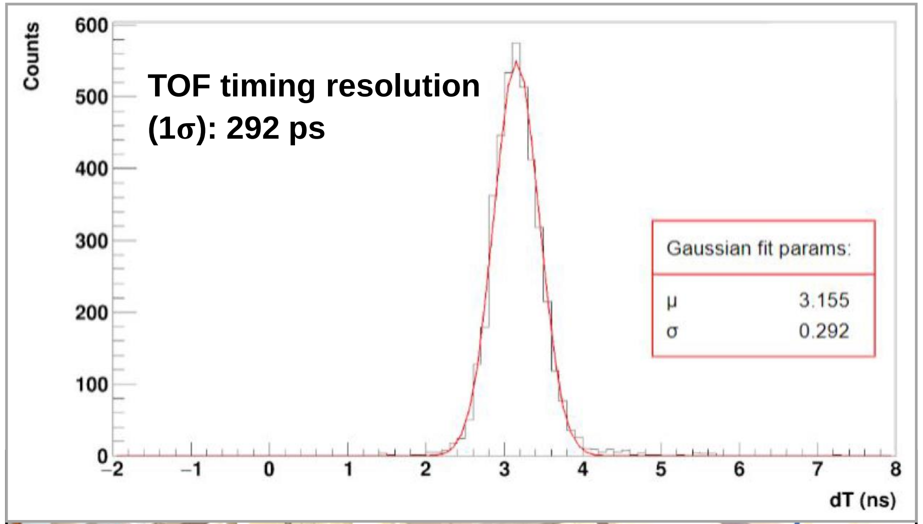
GAPS Instrument-***TOF***

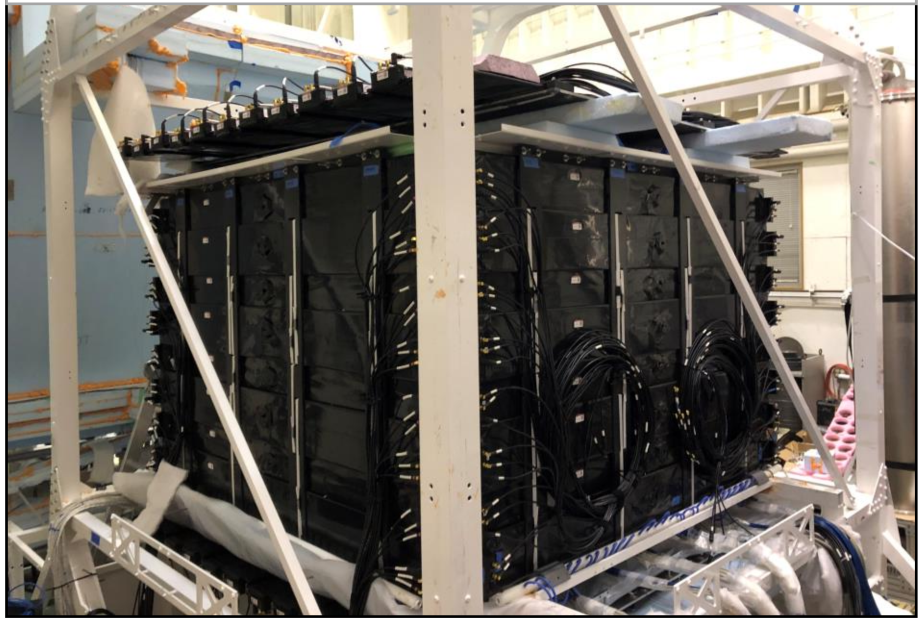


- Time of Flight plastic scintillator:
  - Covers ~15 m^2 inner cube and ~25 m^2 outer layer (top umbrella + side cortina).

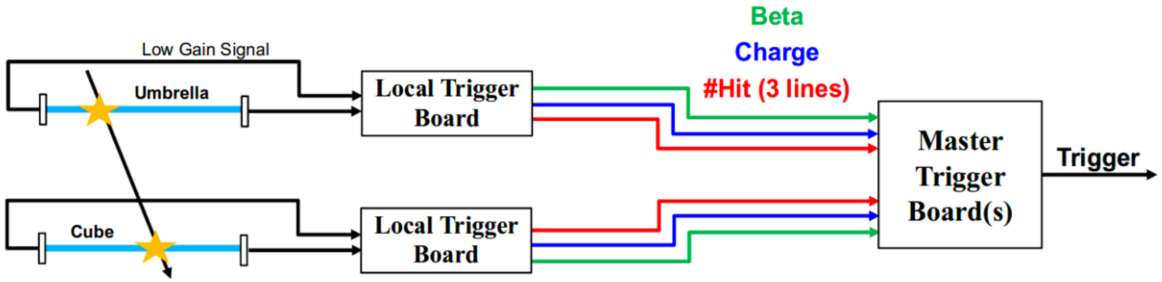
Bird et al., Proc. ICRC (2019), Quinn et al., Proc. ICRC (2019)
Quinn et al., Proc. ICRC (2021), Feldman et al., Proc. ICRC (2023)

GAPS Instrument-*TOF*





- 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 & Veto** → accept ~80% of anti-nuclei and suppress overall event rate <500 Hz!

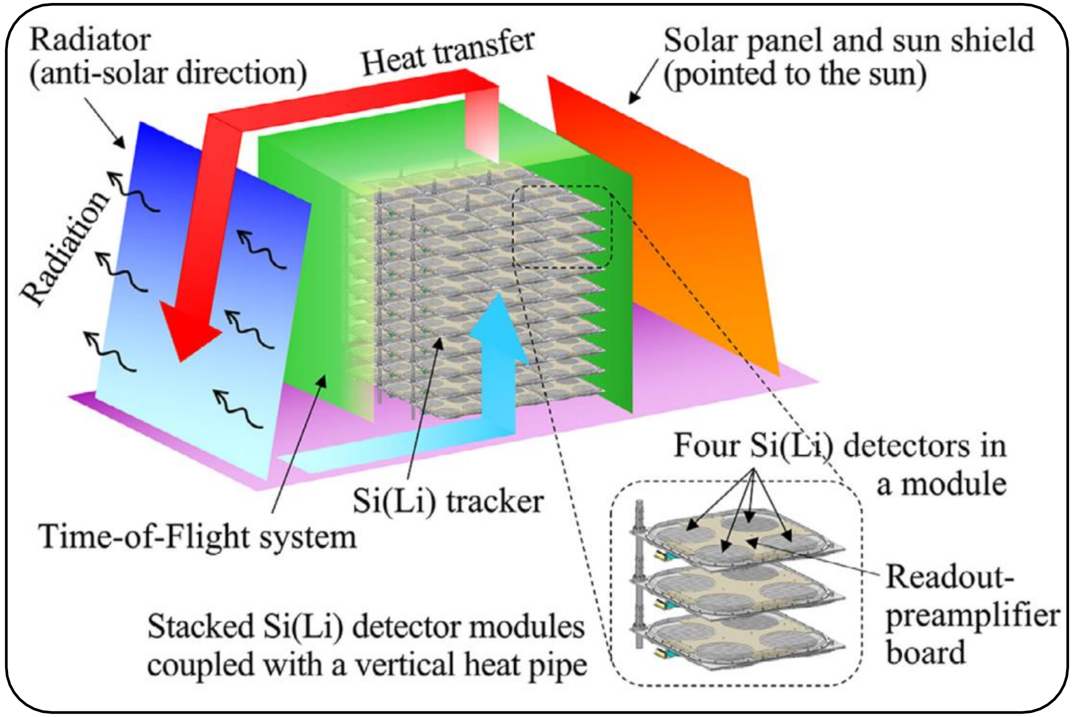


Bird et al., Proc. ICRC (2019), Quinn et al., Proc. ICRC (2019)
Quinn et al., Proc. ICRC (2021), Feldman et al., Proc. ICRC (2023)

GAPS Instrument-***Thermal***

- Oscillating Heating Pipe (OHP)： low power, low mass, and semi-passive
  - Dual-phase fluid in small pipes (ID ~1 mm), heating of Si(Li) detectors (~300 W) transferred by OHP to a radiator then to the space
  - Developed at JAXA/ISAS → firstly used for balloon

Okazaki et al., J. Astr.. Instr. 3 (2014), Fuke et al., J. Astron. Instrum. (2017)
Okazaki et al., Appl. Therm. Eng. (2018), Fuke et al., NIM A (2023)



- Scaled radiator model was validated on engineering flight (NASA SIFT)

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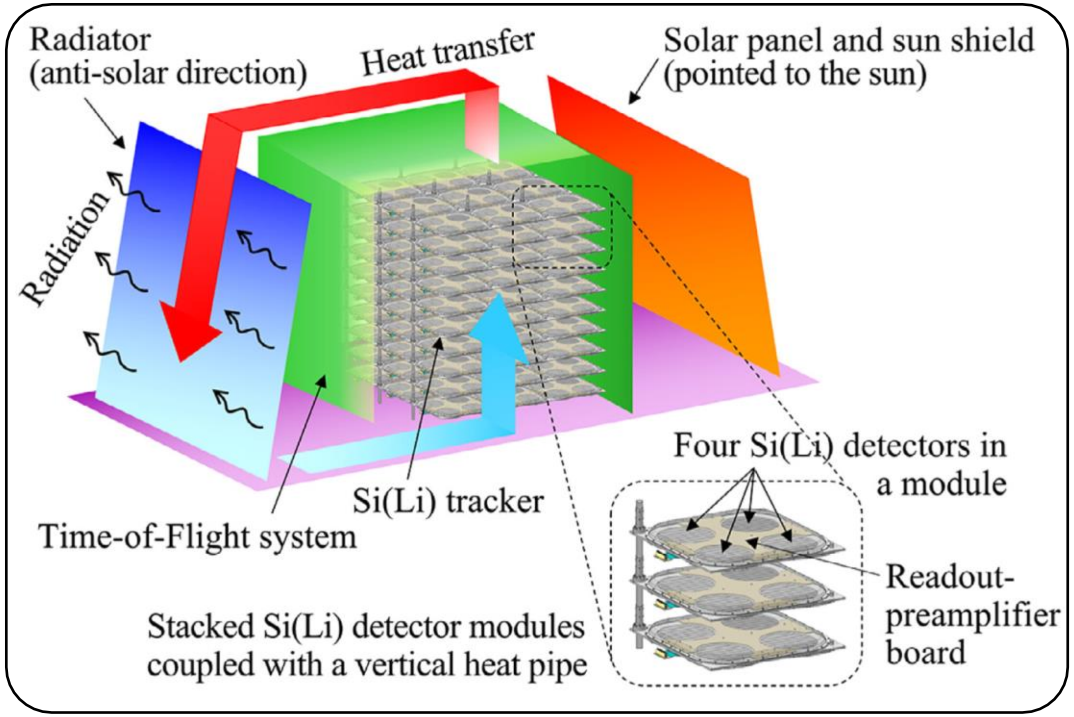
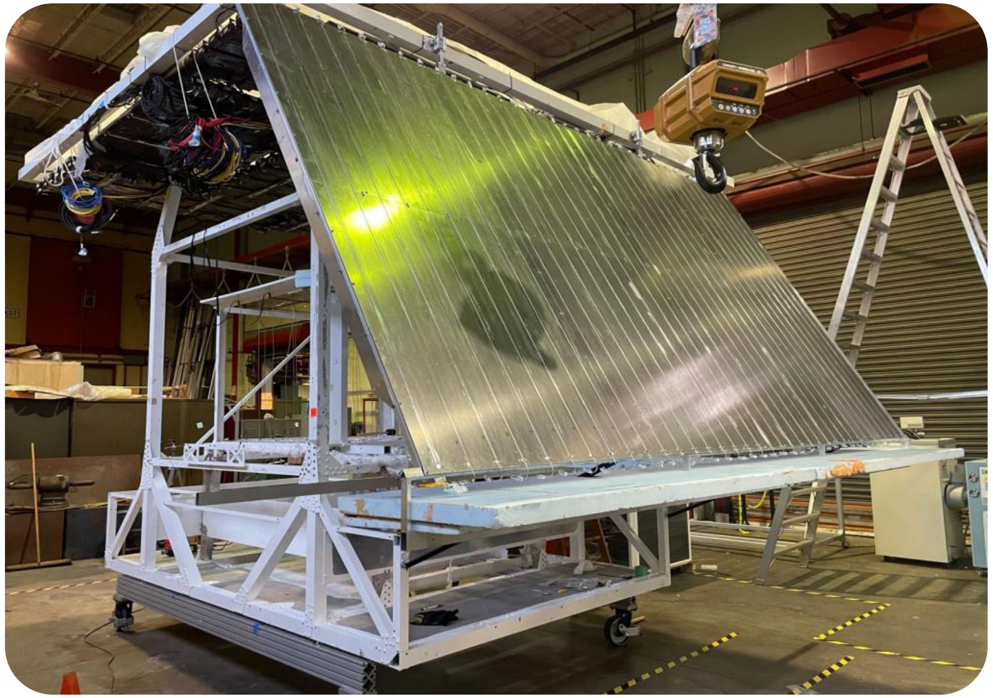
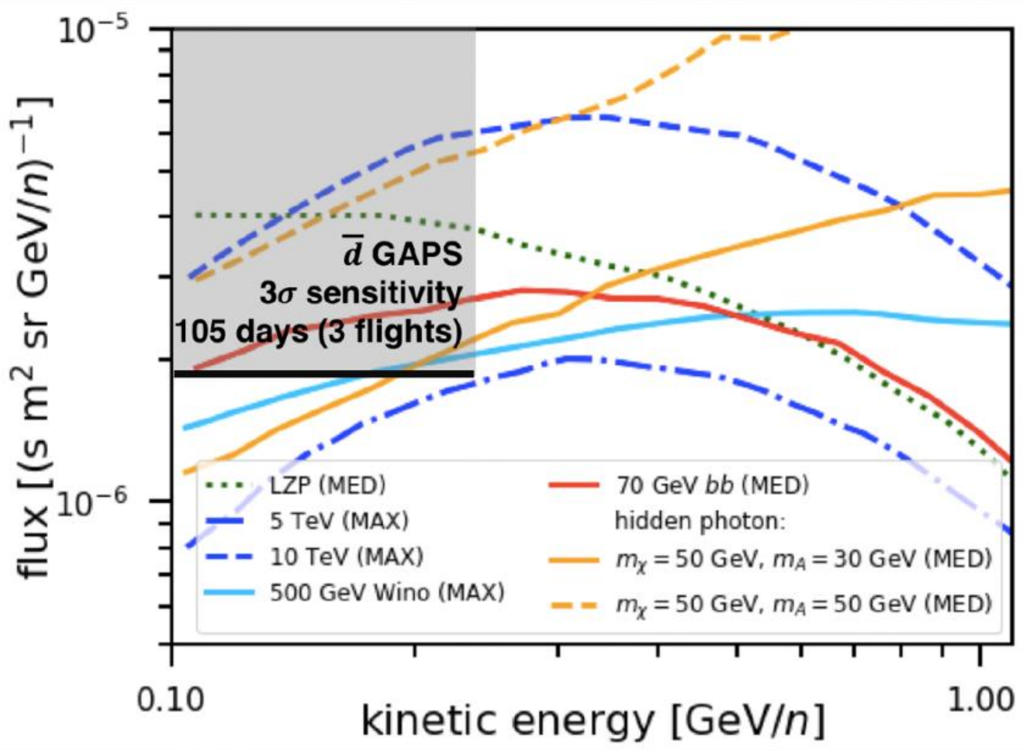




GAPS radiator for flight mounted on the gondola

Low-energy $\bar{d}$: generic signature of dark matter

- The GAPS antideuteron search is sensitive to a wide range of generic dark matter models, e.g.:
  - Generic 70-GeV WIMP annihilation model that explains AMS-02 antiproton excess and GC γ-ray excess
  - Dark matter gravitino decay
  - Extra dimensions
  - Dark photons
  - Heavy DM models with Sommerfeld enhancement



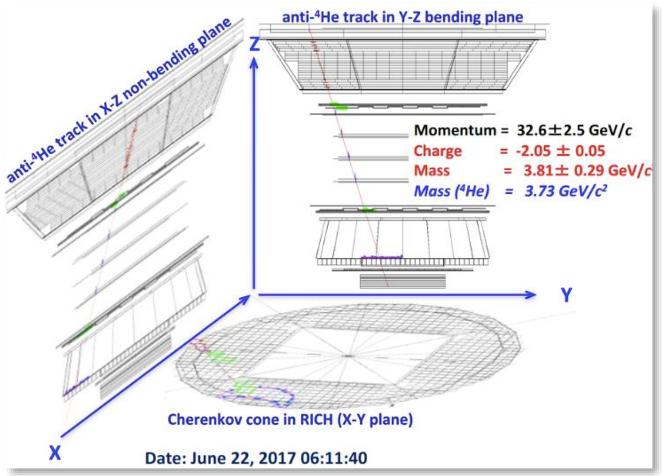
Any antideuteron signal needs to be compatible with antiproton constraints!

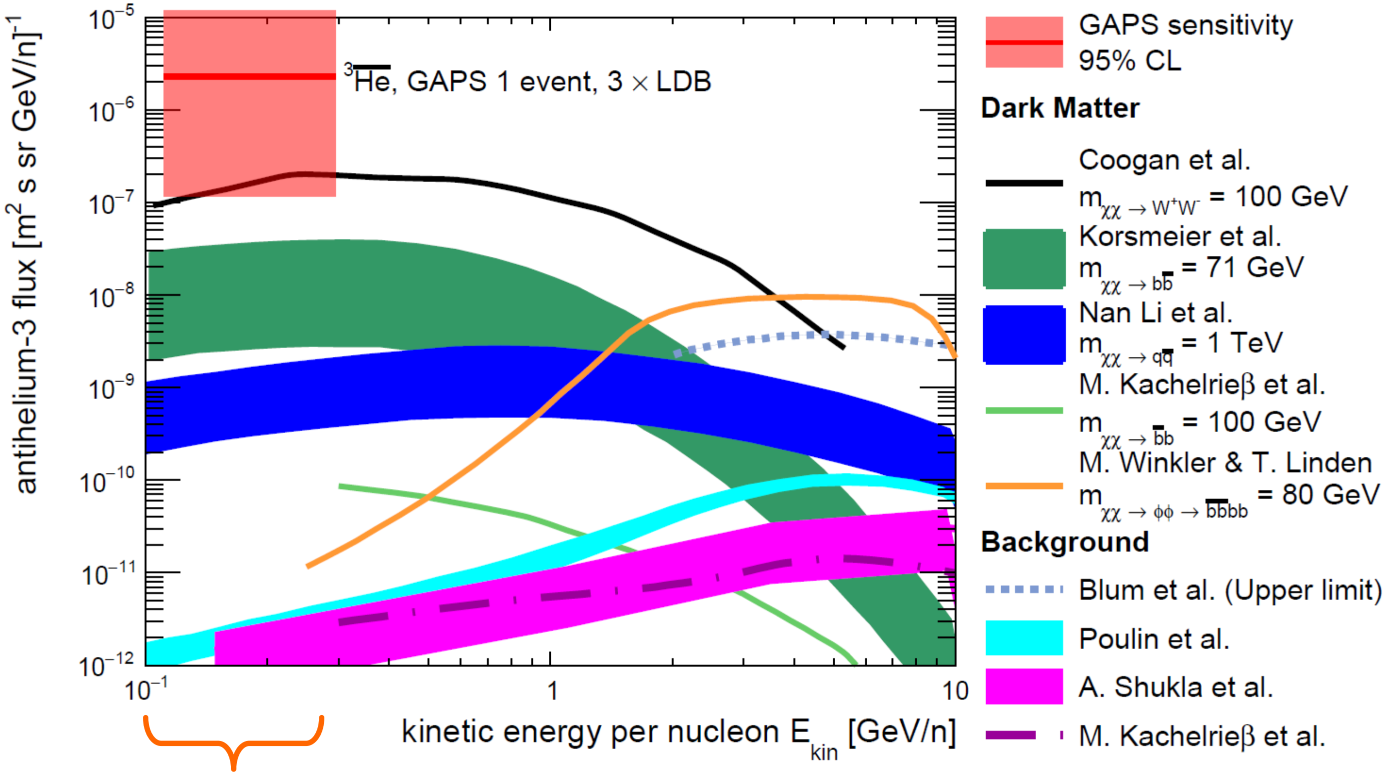
Low-energy $\overline{He}$: new probe of hinted anomalies

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

- **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)





GAPS energy range

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

GAPS “Background” Rejection

- CR, p, $e^{\pm}$ rejection: select slow particles with TOF, AND simultaneous detection of annihilation products (TOF + Tracker)

- Potential “background” for $\bar{d}/\overline{H_e}$ search = antiparticle ($\bar{p}$) mis-identification:
  - $\bar{p}$ /$\bar{d}$/ $\overline{H_e}$ follow same way to form exotic atom and produce the similar annihilation products

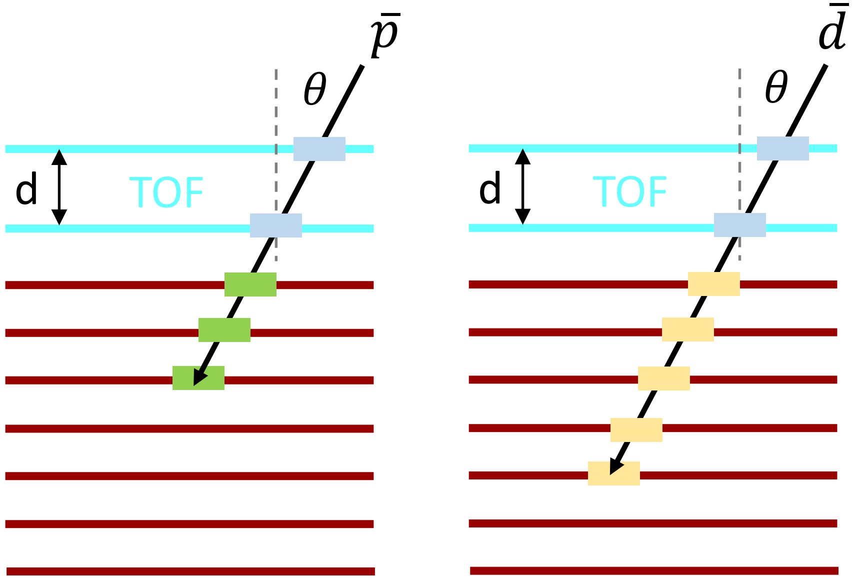
- **GAPS background discrimination power ($\bar{p}$ / $\bar{d}$ identification)**
  - **Stopping range, *dE/dx***
  - **Charge particle (pion/proton) multiplicity**
  - **Characteristic atomic X-ray lines**

GAPS Anti-nuclei Discrimination

Discrimination Power
($\bar{p}$ / $\bar{d}$ identification)

- ***Stopping range, dE/dx***
- Charge particle (pion/proton) multiplicity
- Characteristic atomic x-ray lines

- TOF measures angle & velocity of primary particles precisely.
- With the same velocity (beta), antideuterons go deeper and deposit more energies in tracker layers (larger *dE/dx*) ***due to a heavier mass.***

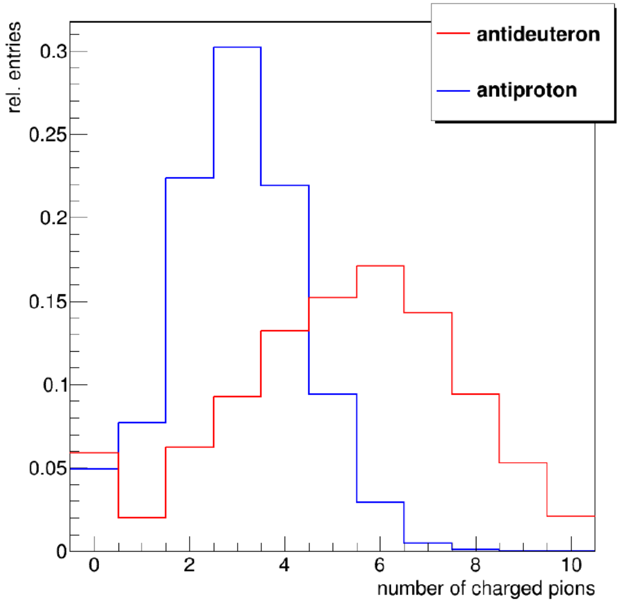


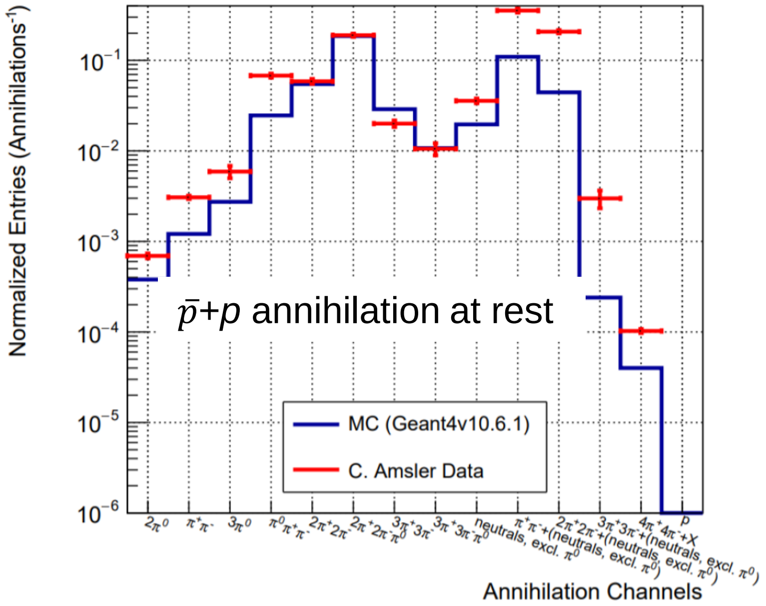
GAPS Anti-nuclei Discrimination

Discrimination Power
($\bar{p}$ / $\bar{d}$ identification)

- Stopping range, dE/dx
- ***Charge particle (pion/proton) multiplicity***
- Characteristic atomic x-ray lines

- More pions/protons from antideuteron annihilation due to a heavier mass.





- Use antiproton data (Crystal Barrel) to tune/validate annihilation physics in Geant4 (work with Geant4 developers).

GAPS Anti-nuclei Discrimination

Discrimination Power
($\bar{p}$ / $\bar{d}$ identification)

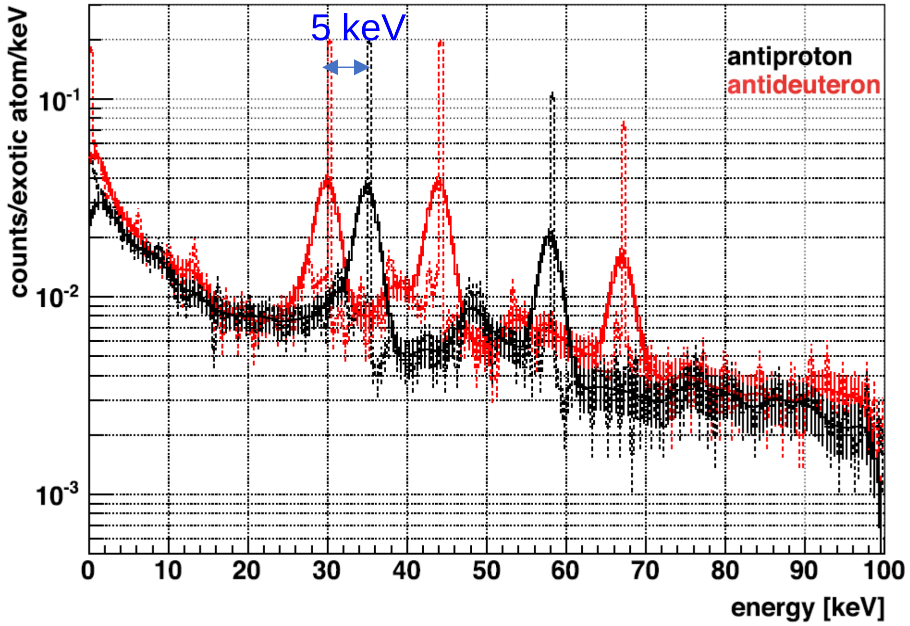
- Stopping range, dE/dx
- Charge particle (pion/proton) multiplicity
- ***Characteristic atomic x-ray lines***

- X-ray energies from exotic atom depend on the mass of the captured antiparticle.

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

Antiparticle mass

Target material



Note: closest x-ray line for $\bar{p}$ and $\bar{d}$ in Silicon is separated by ~5 keV

Aramaki+ Astropart.Phys (2013), Aramaki+ Astropart.Phys.(2016)

GAPS Anti-nuclei Discrimination

Discrimination Power
($\bar{p}$ / $\bar{d}$ identification)

- *Stopping range, dE/dx*
- *Charge particle (pion/proton) multiplicity*
- ***Characteristic atomic x-ray lines***

- Validated with the measurement with $\bar{p}$ *beam* at KEK in 2004
  - Measured X-ray data were well consistent with the calculations.