The GAPS Instrument: An Antarctic Balloon Search for Cosmic Antinuclei

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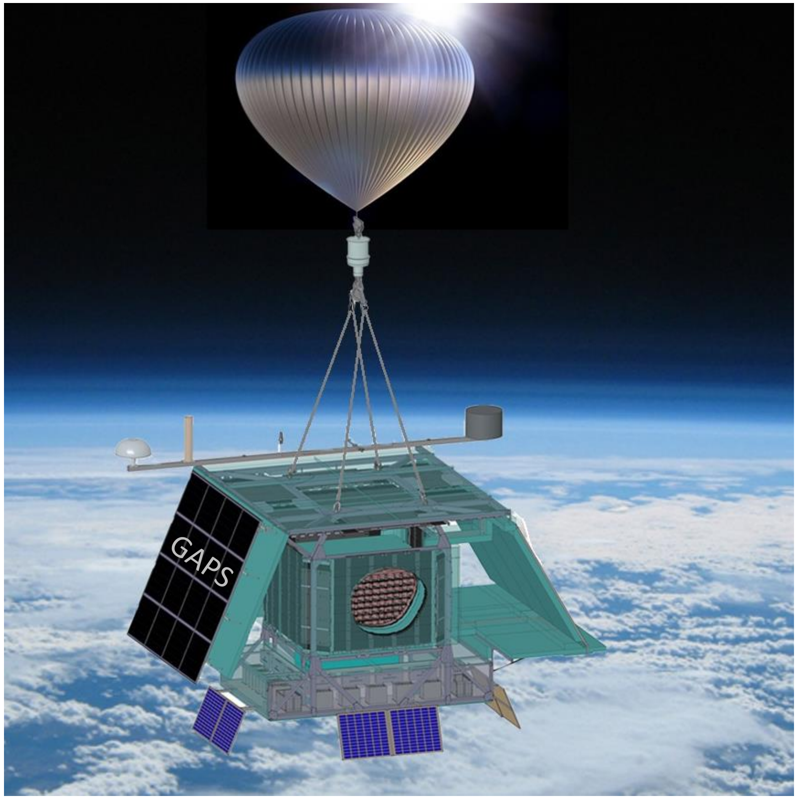
Photo from 33 km up in the air! *Prototype GAPS (pGAPS) balloon flight from Taiki, Japan in June 2012*

The GAPS Experiment

- **GAPS=General Antiparticle Spectrometer**
  - Antarctic balloon experiment
- 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.***

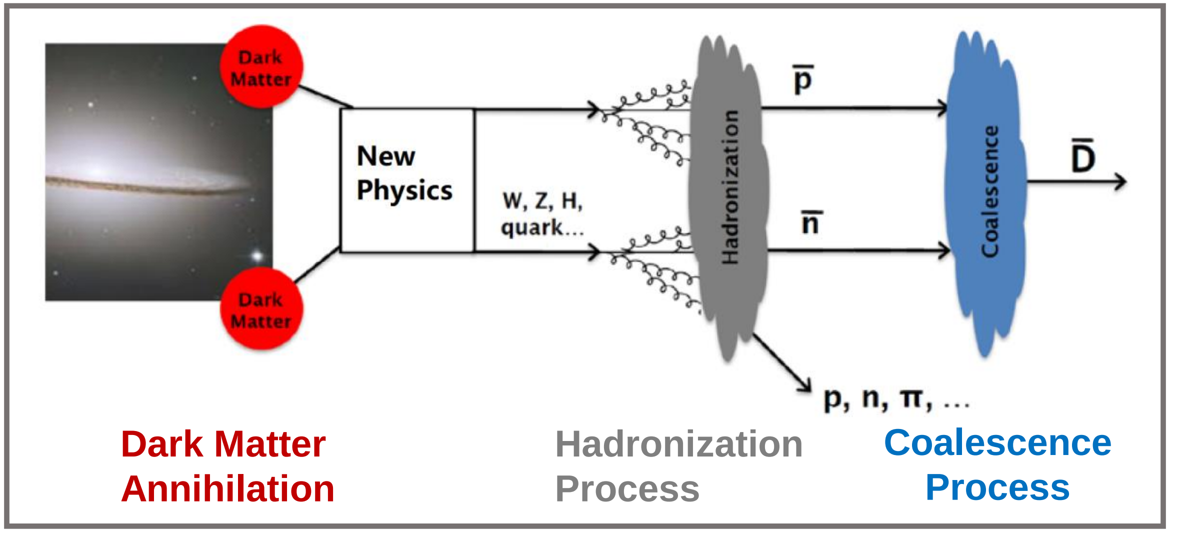


*Balloon photo from Word View

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

Cosmic ***antideuterons*** signal new physics

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



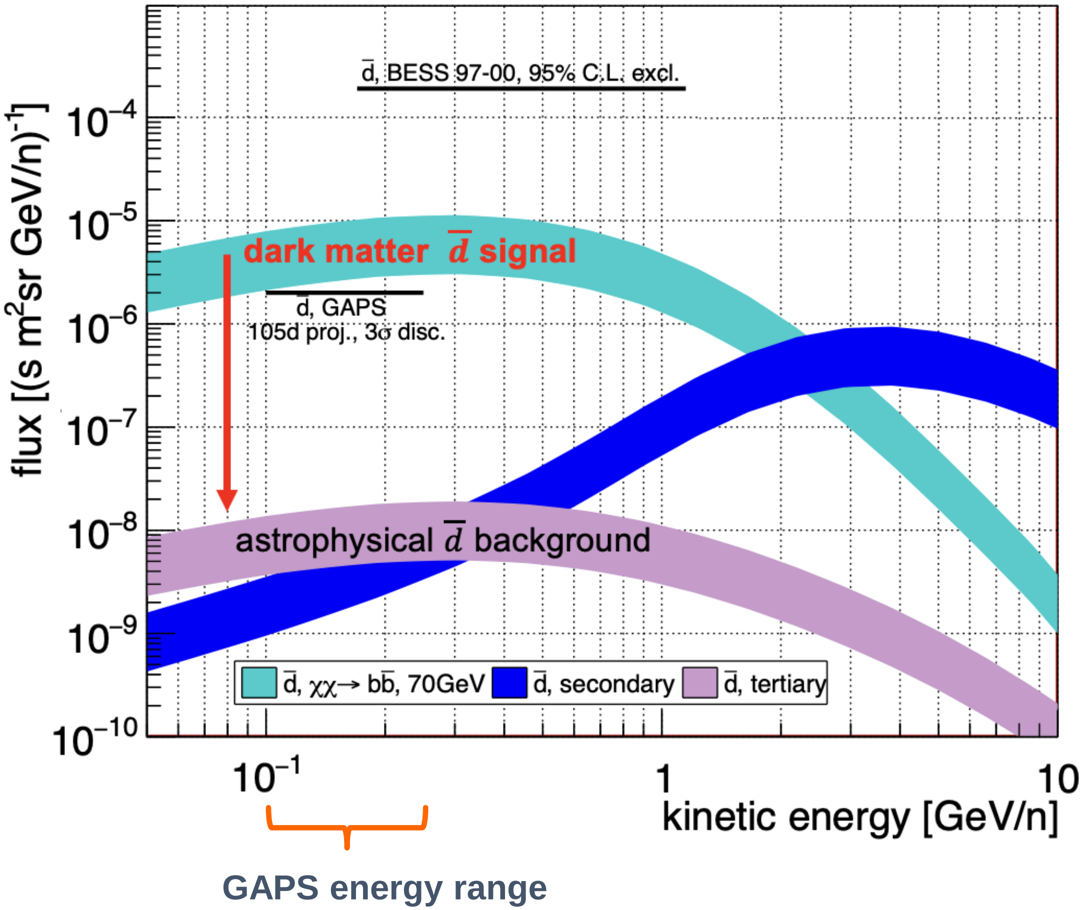
- **Secondary/tertiary background**: cosmic-ray interactions with interstellar medium
  - Much lower (>2 orders of magnitude) than the primary due to collision kinematics and steeply falling primary proton spectrum

$$\text{p (CR)} + \text{H (ISM)} \rightarrow \text{p} + \text{H} + \text{p} + \text{n} + \bar{p} + \bar{n} \quad \bar{d}$$

✓ *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

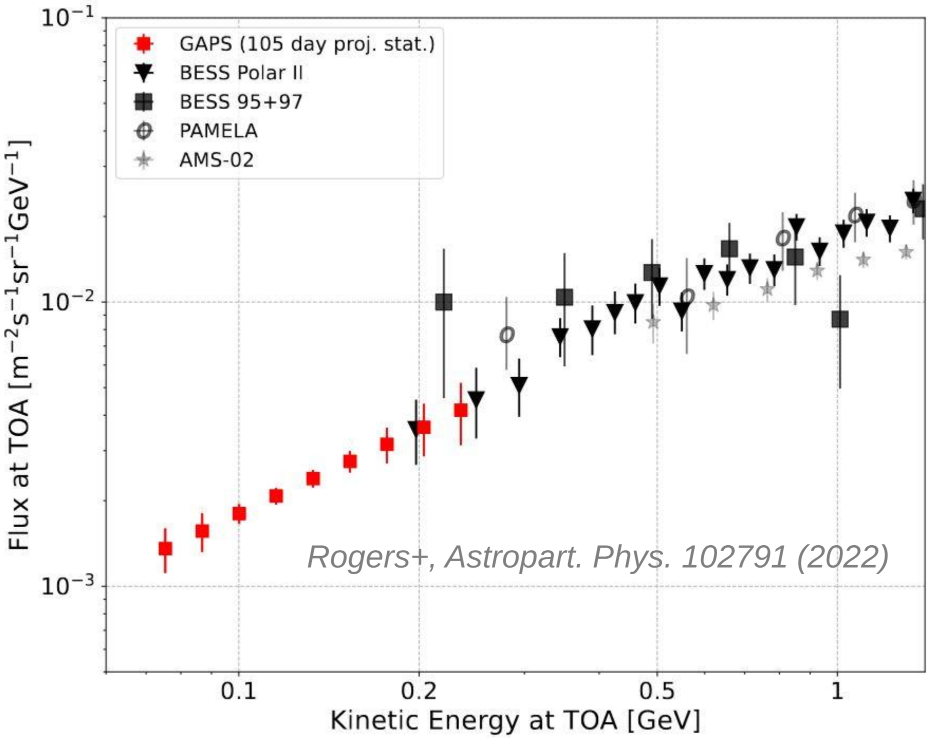


GAPS antideuterons: A generic ***new physics*** signature with *essentially zero* conventional astrophysical background!

- *Sensitivity will be ~2 orders of magnitude below the current best limits.*
- Sensitive to a wide range of dark matter models, e.g.: generic 70-GeV WIMP annihilation (could explain antiproton excess and GC γ-rays), dark matter gravitino decay, extra dimensions, dark photons, etc.

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

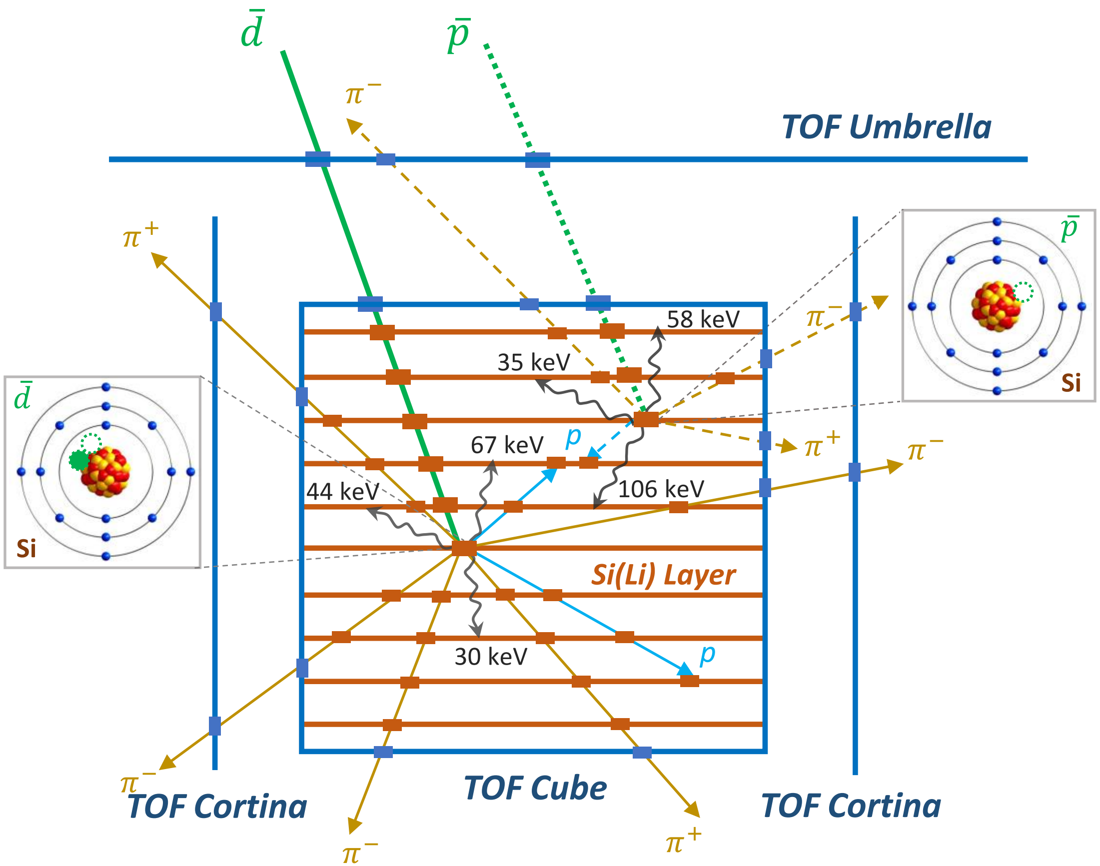
✓ Validate the novel antinuclei identification technologies: exotic atomic X-rays from antiproton, track reconstruction, etc.

➢ *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.

Novel detection using exotic atoms



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

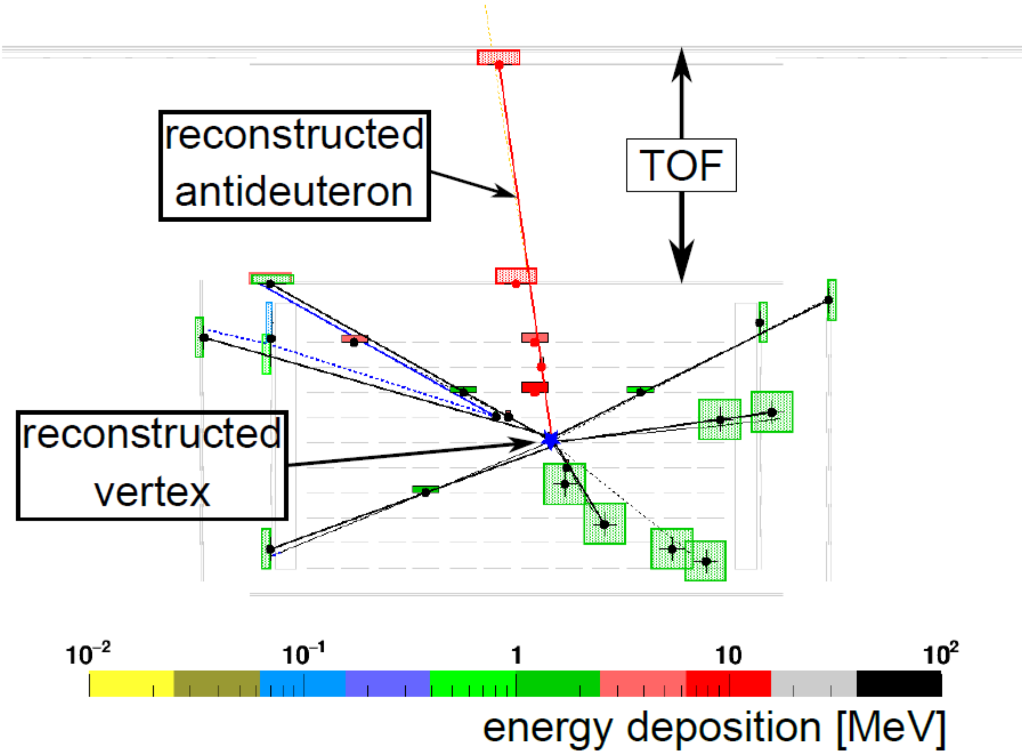
Si(Li) tracker acts as:

- ***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 annihilated *charge particles*.

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

Novel detection using exotic atoms

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

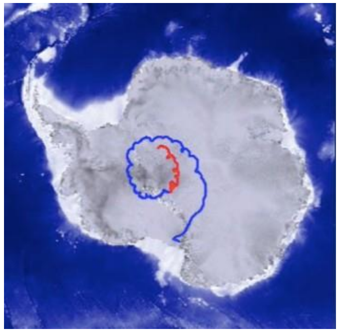


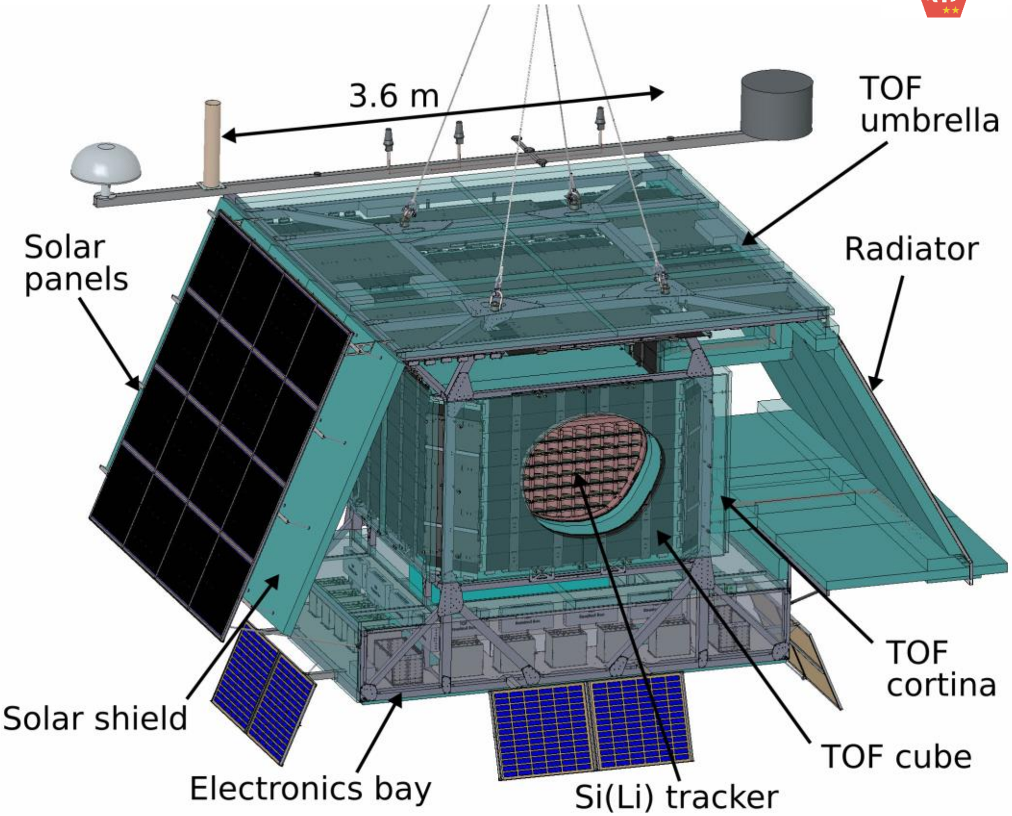
- ***Red line***: the reconstruction of the primary antideuteron
- ***Black lines***: reconstructed secondary tracks from the stopping vertex inside the tracker.
- *Colored boxes*: represent energy depositions in the sensitive detector volumes

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

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 ℃

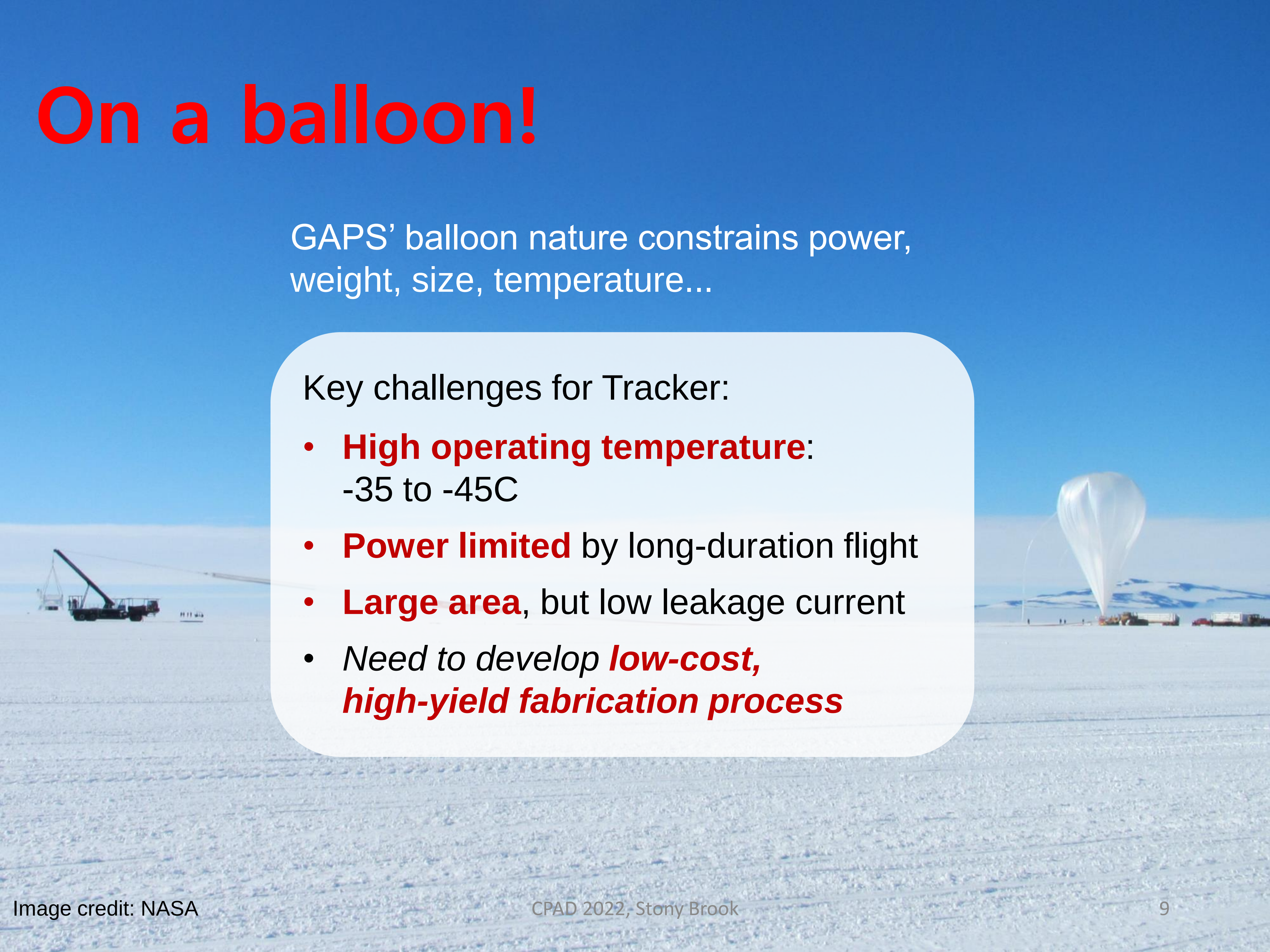




Total mass: ~2500 kg, Power: 1.3 kW

- ❑ 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 for Tracker:

- **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.
  - ✓ ***active area*** totaling ***~10 m²***
  - ✓ ***stopping power*** up to 0.25 GeV/n
  - ✓ ***tracking efficiency*** in low-multiplicity events
  - ✓ ***energy resolution*** < 4 keV to distinguish X-rays

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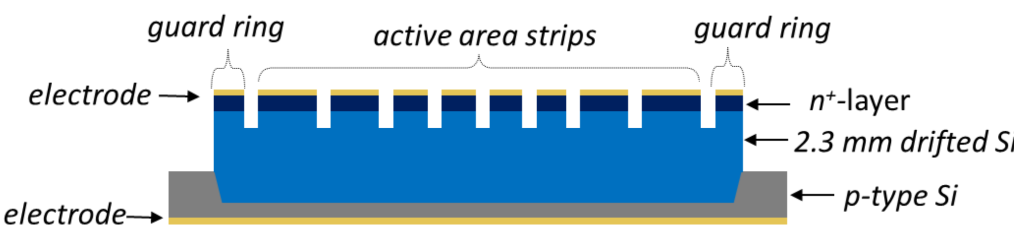
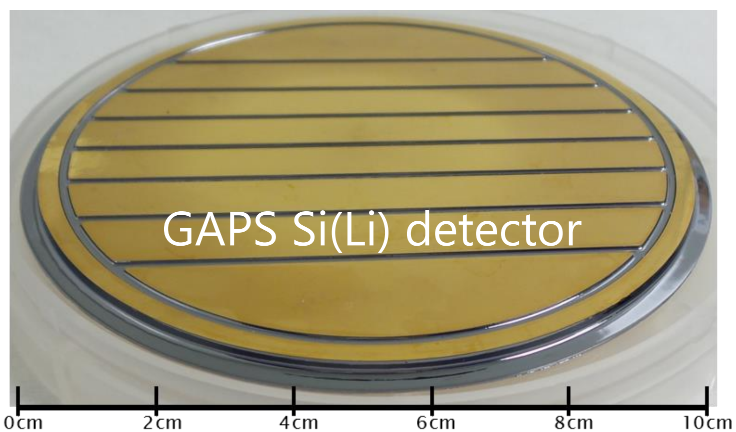
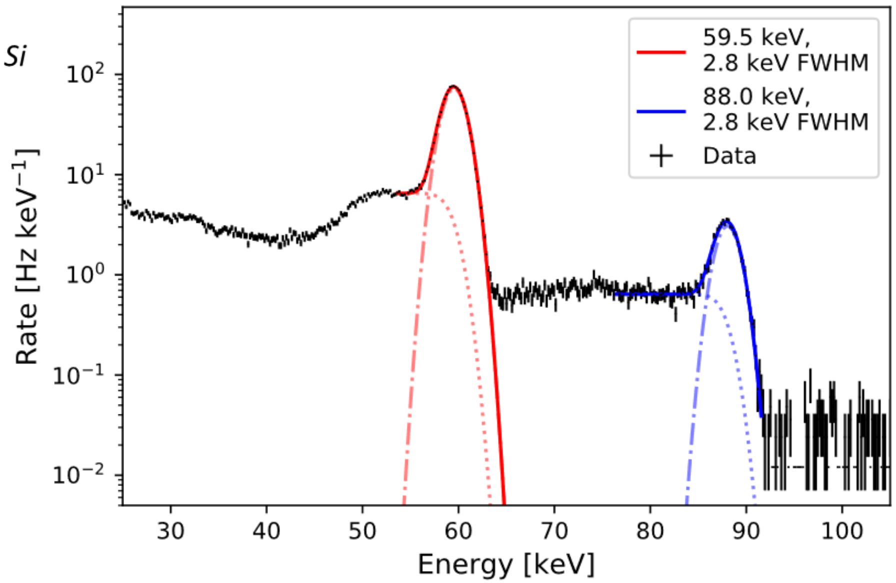
Xiao, Stoessl, Roach, et al. (2022) in prep.
Rogers, Xiao, Perez et al. (2019) JINST
Saffold, Rogers, Xiao, et al. (2021) NIMA
Kozai, Fuke, Yamada, et al. (2019) NIMA

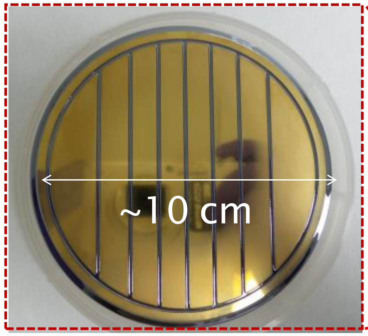




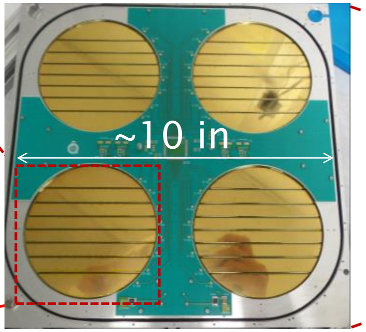


GAPS Instrument-*Si(Li) Tracker*

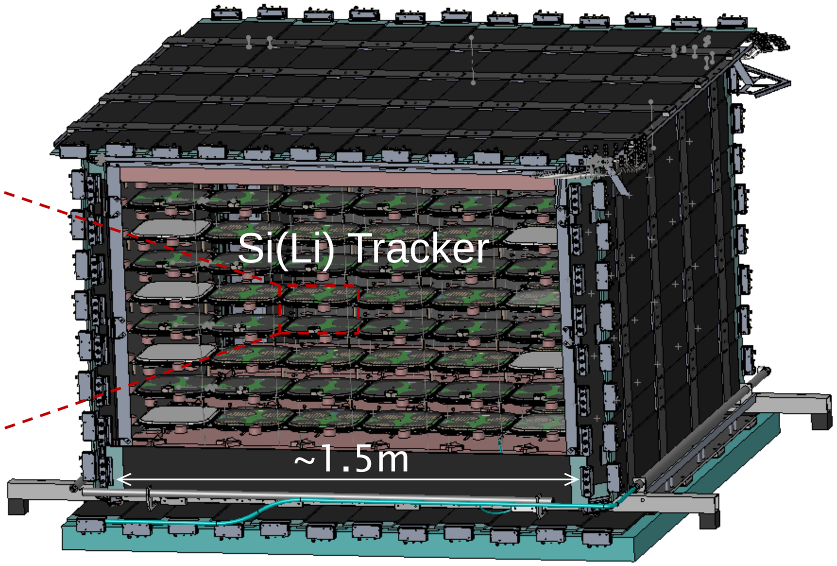
- GAPS Tracker, ~1.5 x1.5 x1.1m
  - 10 layers, ~1100 Si(Li) detectors.



- Single Si(Li) Detector

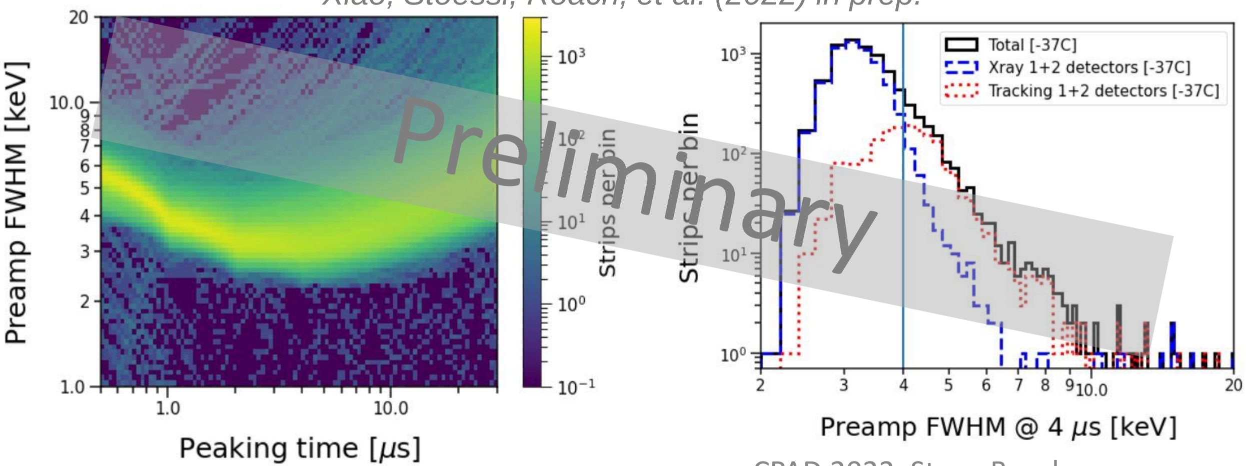


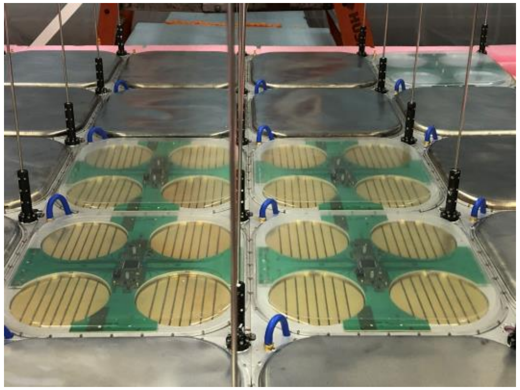
- 4-detector Module (with ASIC electronics)



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

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



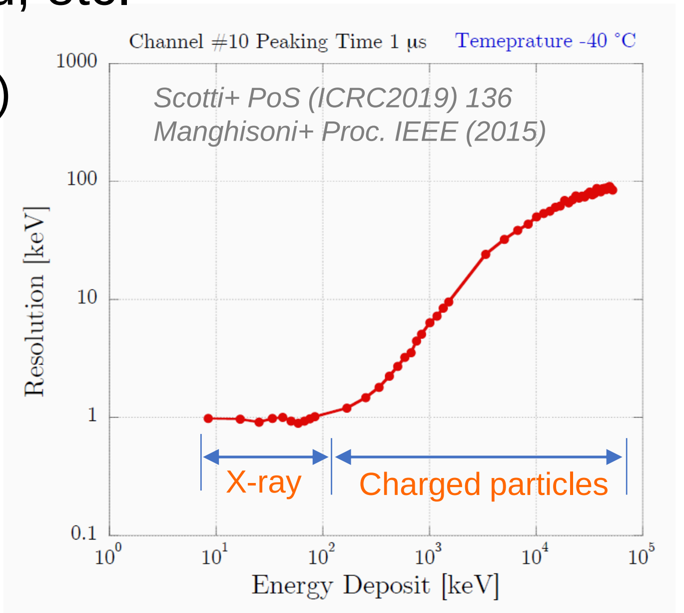


GAPS Instrument-*Si(Li) Tracker*

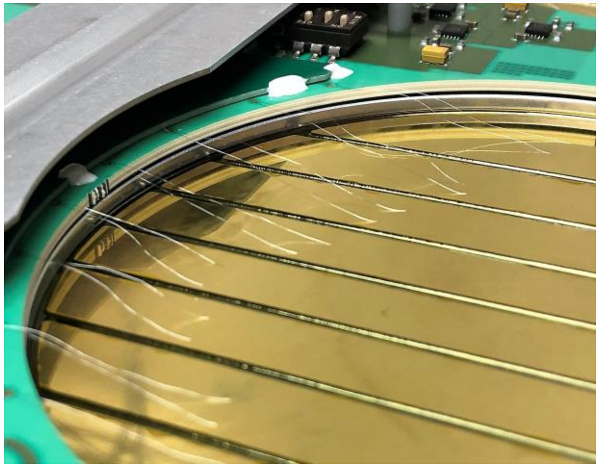
- GAPS on *balloon*: power limited, payload limited, etc.

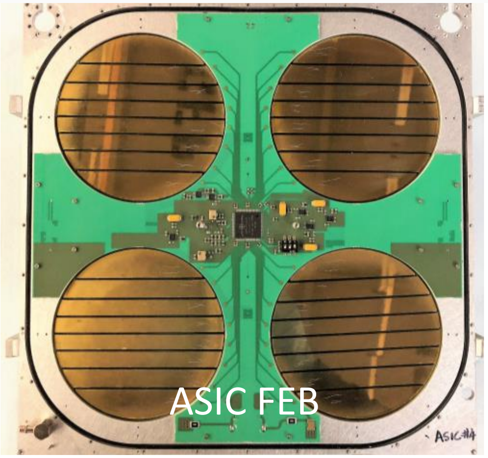
- GAPS custom ASIC (SLIDER-32)
  - 180nm CMOS technology
  - 32 channels and 11-bit ADC
  - Packed in 14x14mm, 128 pins
  - 1 keV resolution in 10-100 keV
  - <10% resolution up to 100 MeV

→low power consumption

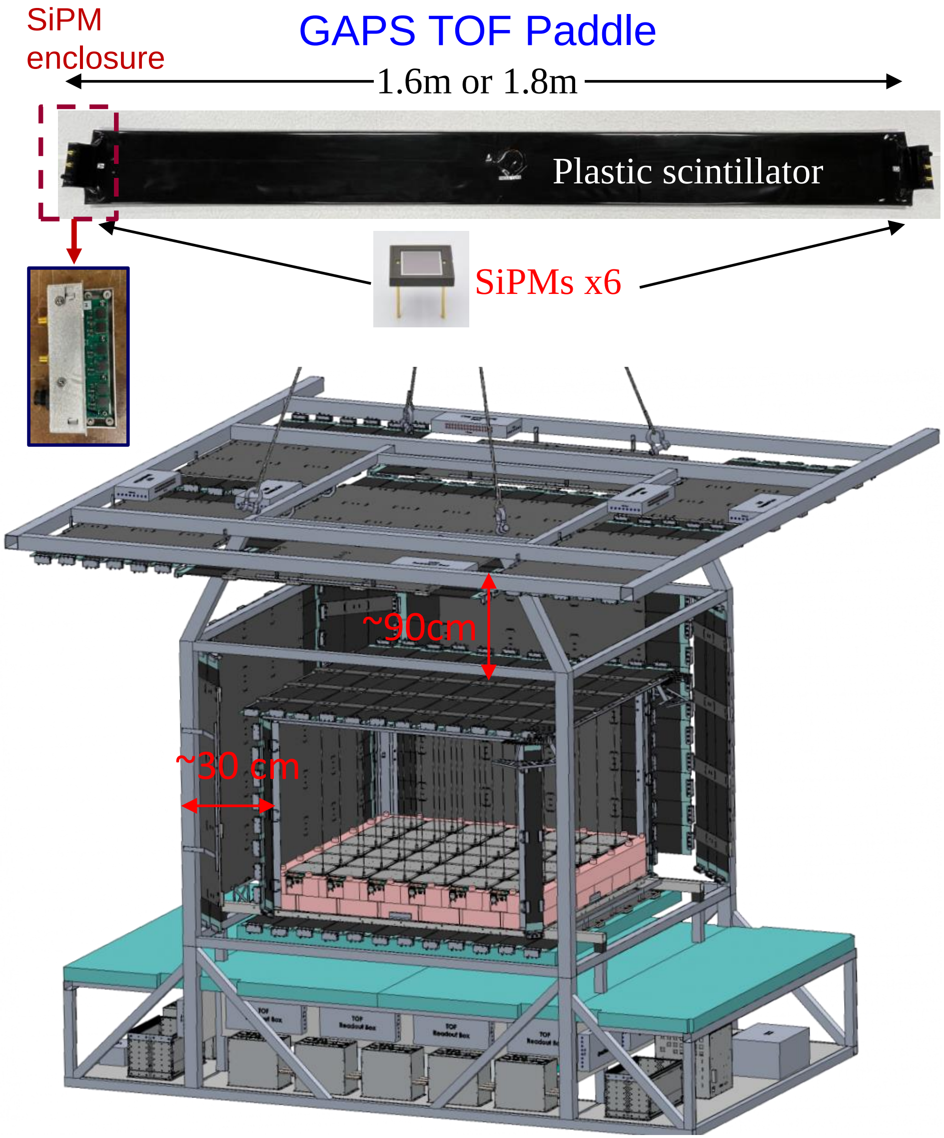


- Wire bounds connect Si(Li) strips to ASIC FEB.
  - Reduced mass budget
  - Lower power budget
  - Improved track reconstruction





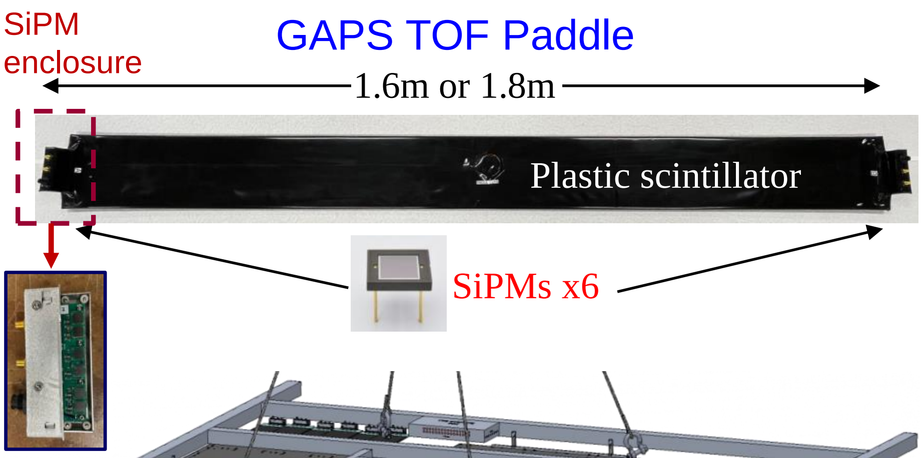
GAPS Instrument-*TOF*

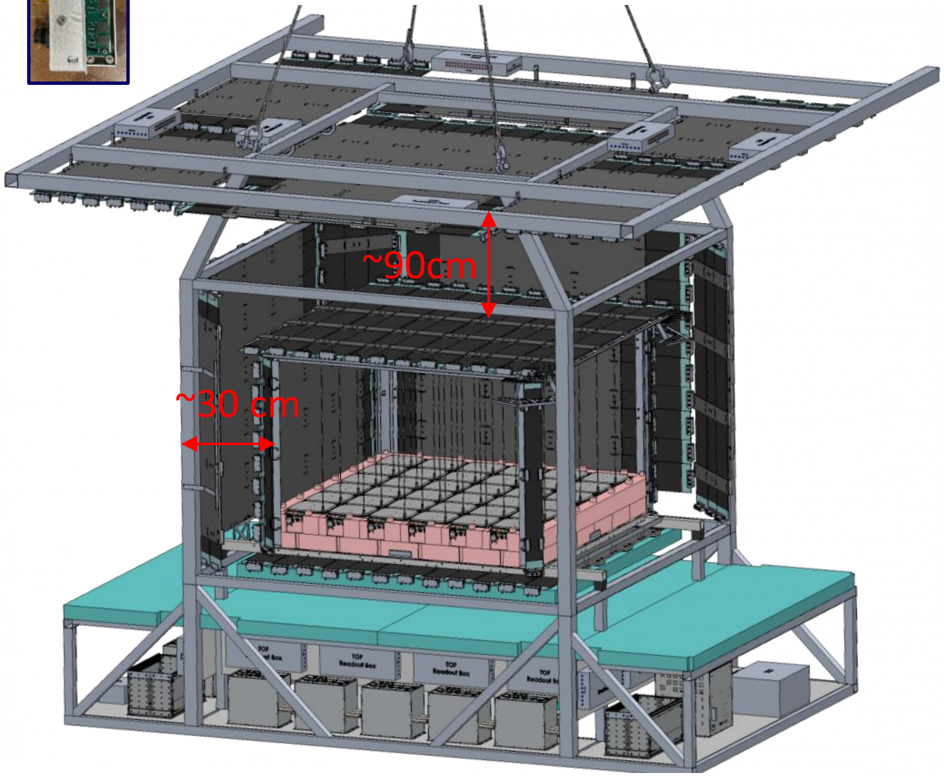


Bird Proc. ICRC (2019): arXiv:1908.03154
Quinn Proc. ICRC (2019)

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

GAPS Instrument-*TOF*





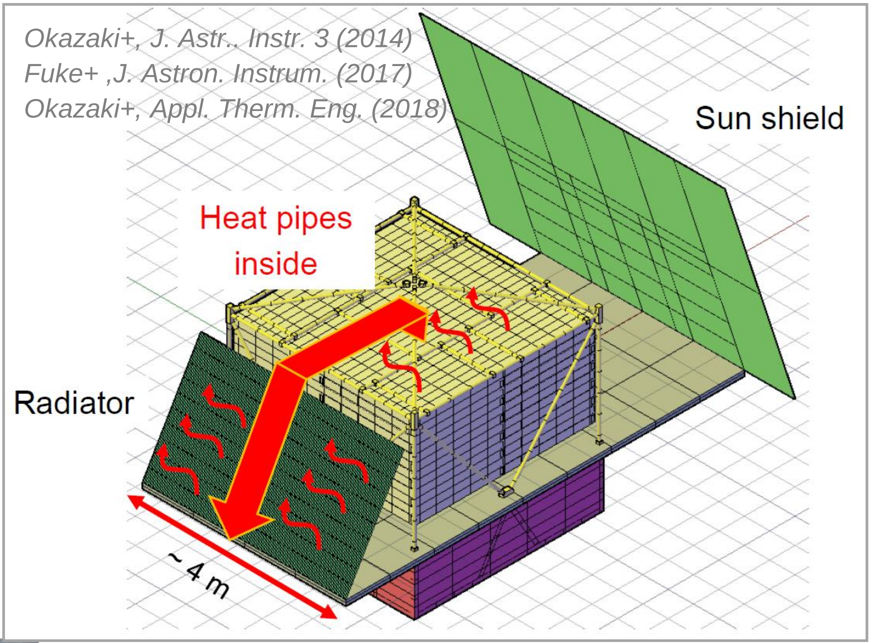
Bird Proc. ICRC (2019): arXiv:1908.03154
Quinn Proc. ICRC (2019)

- 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*** (better than the requirement of <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*

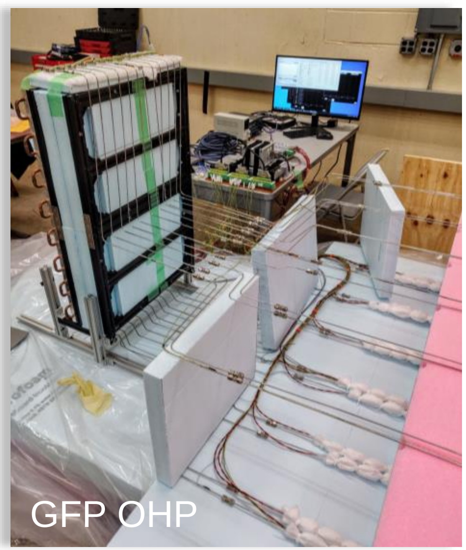
- Design: Low power, low mass, and semi-passive → GAPS *balloon* experiment.
- Oscillating Heating Pipe (OHP)
  - Dual-phase fluid in small pipes (ID ~1mm), phase oscillation efficiently transfers heat.
  - Developed at JAXA/ISAS, firstly used in the balloon experiment.
  - Heating of Si(Li) detectors (~300W) transferred by OHP 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 Integration-*GFP*

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



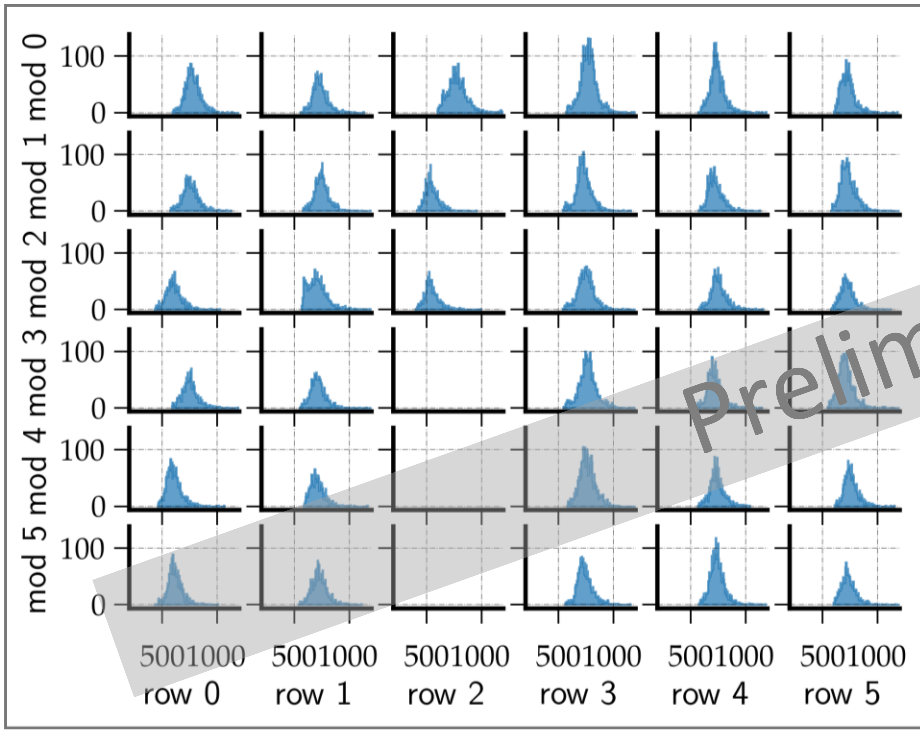
Constructed at MIT during the COVID19 pandemic

~2.5m

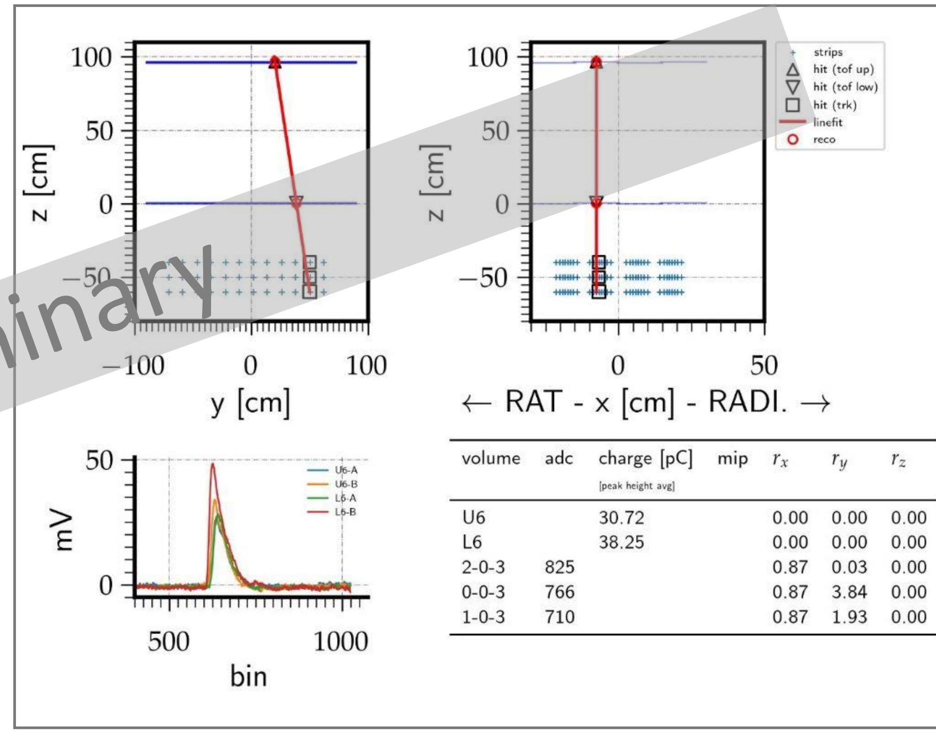
GAPS Integration-*GFP*

- ❑ GFP running with the combination of OHP + TOF + Si(Li) + Backend DAQ + Power system.
- ❑ Completed in early 2022, more data analysis is undergoing!!

- *Muon spectra per Si(Li) module (TOF trigger)*



- *Muon track!!*

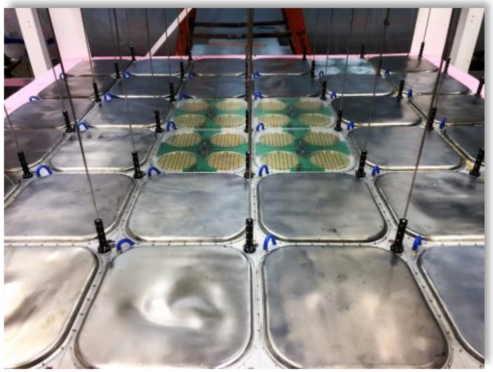


volume	adc	charge [pC] [peak height avg]	mip	r_x	r_y	r_z
U6		30.72		0.00	0.00	0.00
L6		38.25		0.00	0.00	0.00
2-0-3	825			0.87	0.03	0.00
0-0-3	766			0.87	3.84	0.00
1-0-3	710			0.87	1.93	0.00

GAPS Integration-*Full Payload*

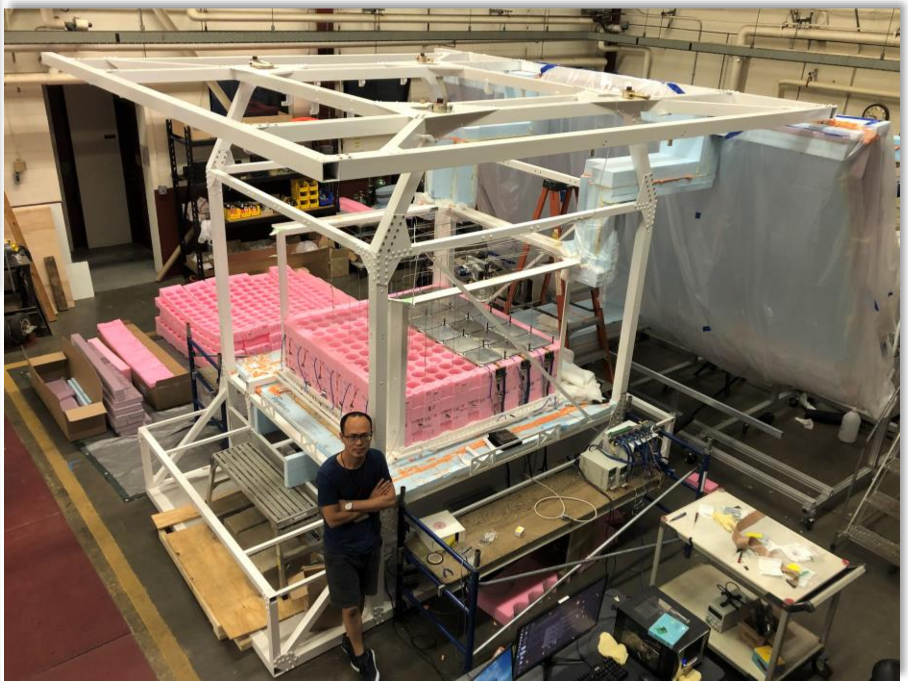
- GAPS full payload integration at MIT Bates Laboratory (Feb. 2022 – Aug. 2022):
  - Si(Li) tracker construction: completed six layers.
  - Integration Si(Li) tracker with thermal system.

- Si(Li) layer



- Gondola frame

- OHP

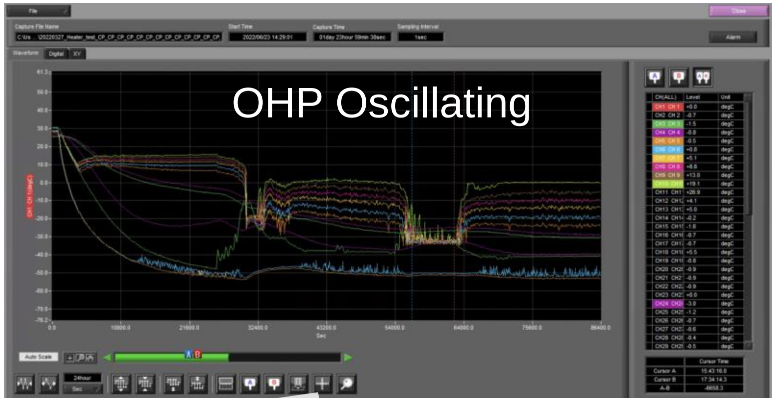


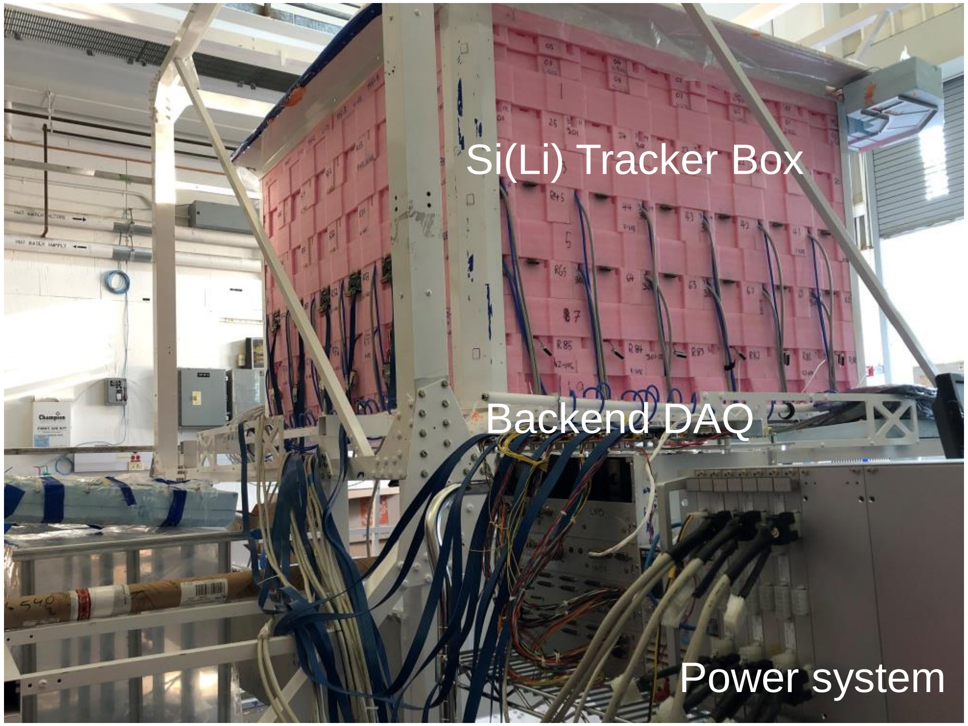
GAPS balloon payload (under integration)

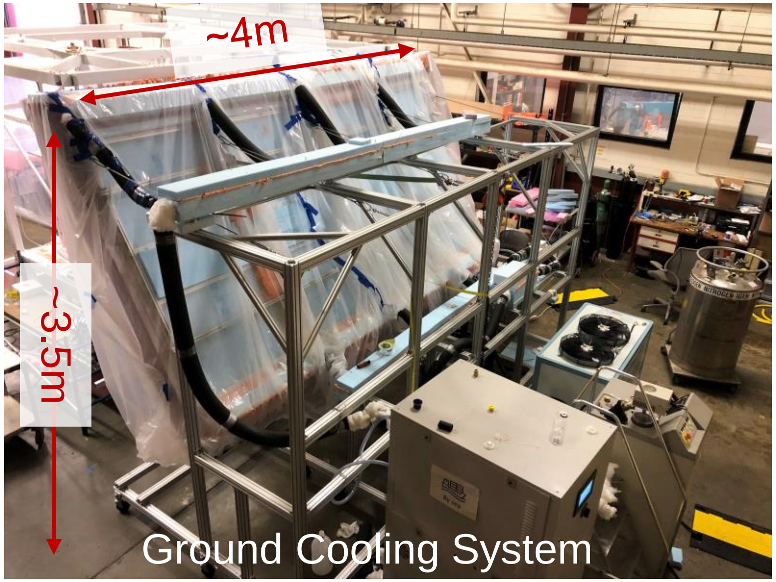
GAPS Integration-*Full Payload*

- GAPS full payload integration at MIT Bates Laboratory (Feb. 2022 – Aug. 2022):
  - Si(Li) tracker construction: completed six layers.
  - Integration Si(Li) tracker with thermal system.
  - *Layer-by-layer testing.*

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







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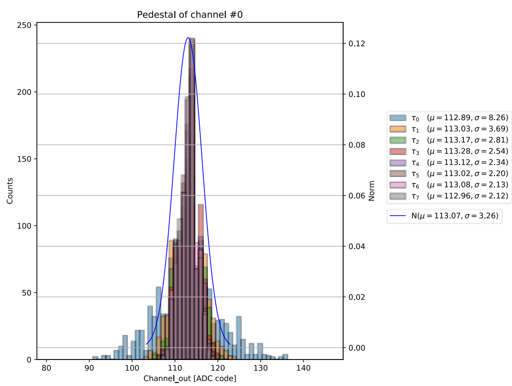
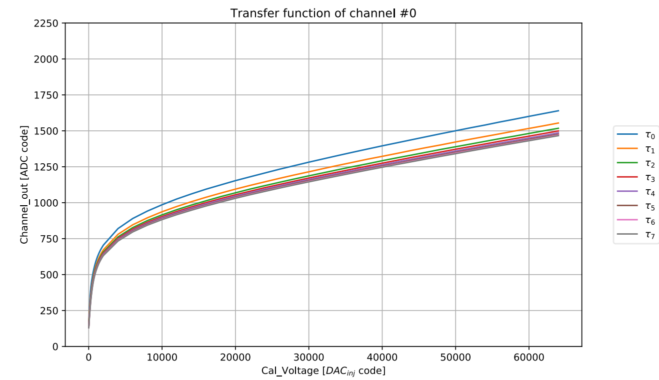
  - Si(Li) tracker construction: completed six layers.
  - Integration Si(Li) tracker with thermal system.
  - *Layer-by-layer testing.*

I. ENC resolution calibration to validate the electronics connection and overall noise:

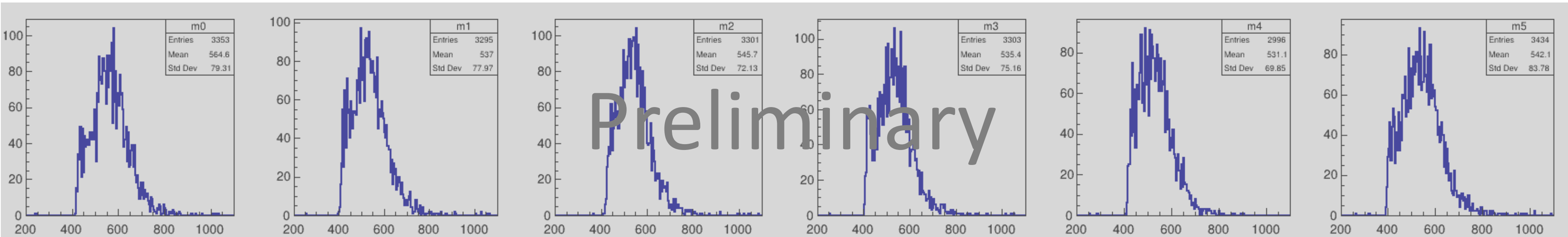
- Pedestal spectra



- Transfer function



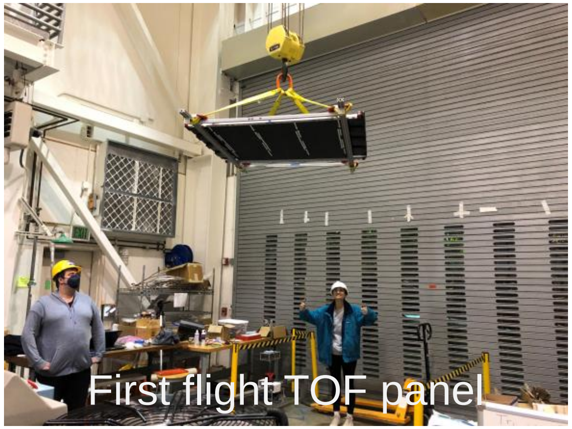
II. MIP spectra (with self-trigger) to validate the tracking function of Si(Li) strips:



GAPS Integration-*Full Payload*

❑ GAPS full payload integration at UC Berkeley Space Science Lab. (Sept. 2022 —):

- Completing the construction of full Si(Li) tracker (integrating the tenth layer).
- Integrated with more subsystems: flight TOF, tracker electronics, etc.
- System testing.

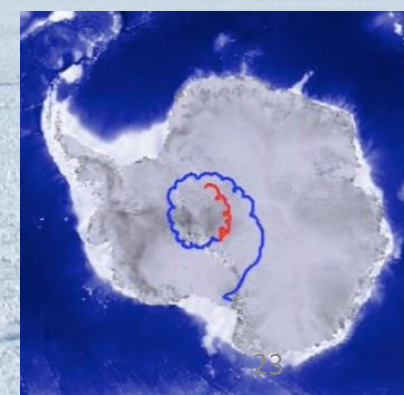


➢ *GAPS is moving steadily towards the first Antarctica flight in late 2023!!*

GAPS Timeline

- **2000** — First idea
- **2004** — KEK beam tests
- **2012** — pGAPS flight
- Detector and system design
- **2018** — TOF and Si(Li) fabrication
- **2020** — Sub-system testing
- **2021/2022** — GAPS payload integration
- **2023** — **First flight!** 2 follow-up flights planned

Long-duration balloon flight (~30 days)




Thank you!

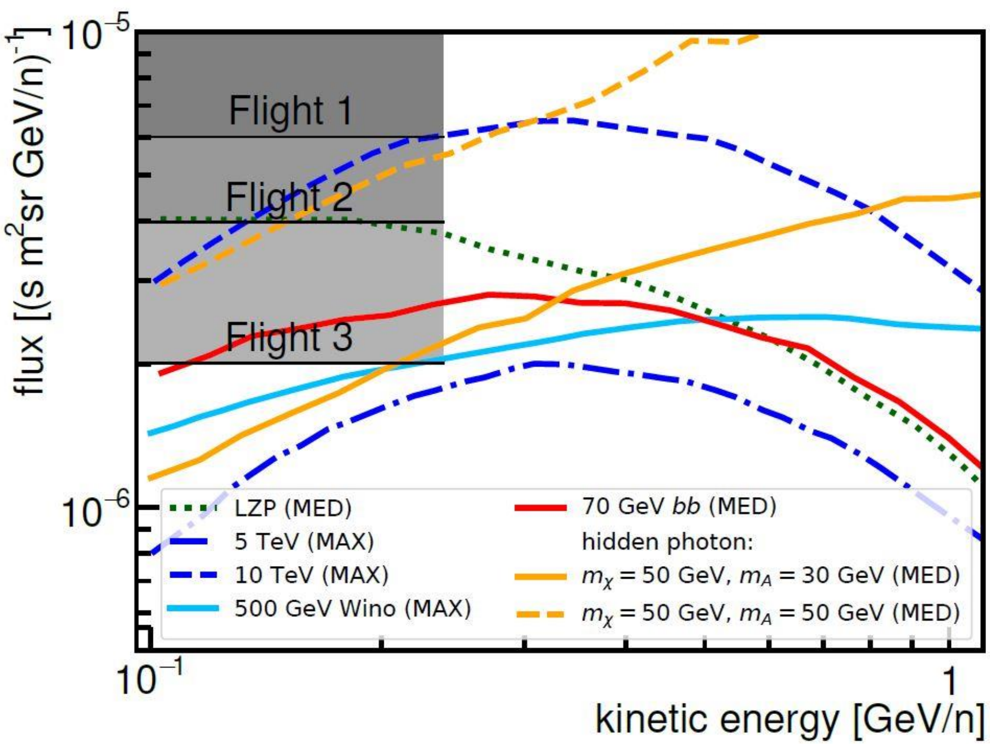
GAPS Collaboration

NASA
Columbia University
Massachusetts Institute of Technology
UCLA
University of Hawai'i Mānoa
UC San Diego
Northeastern University
Oak Ridge National Laboratory
SSL UC Berkeley
JAXA Japan Aerospace Exploration Agency
INFN Istituto Nazionale di Fisica Nucleare
科研費 KAKENHI
Heising-Simons Foundation
NSF

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



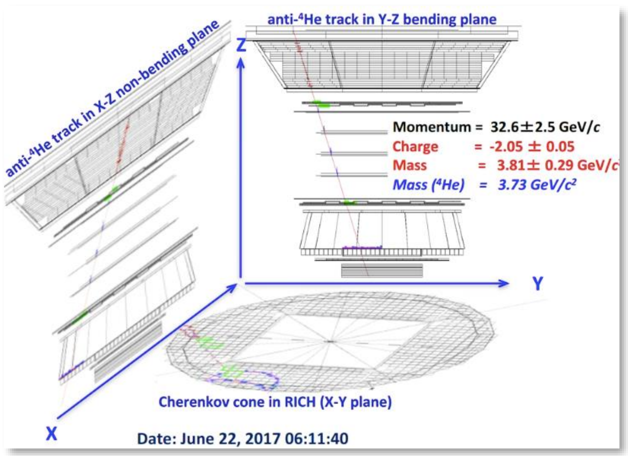
Any antideuteron signal needs to be compatible with antiproton constraints!

GAPS Sensitivity: cosmic ***antihelium***

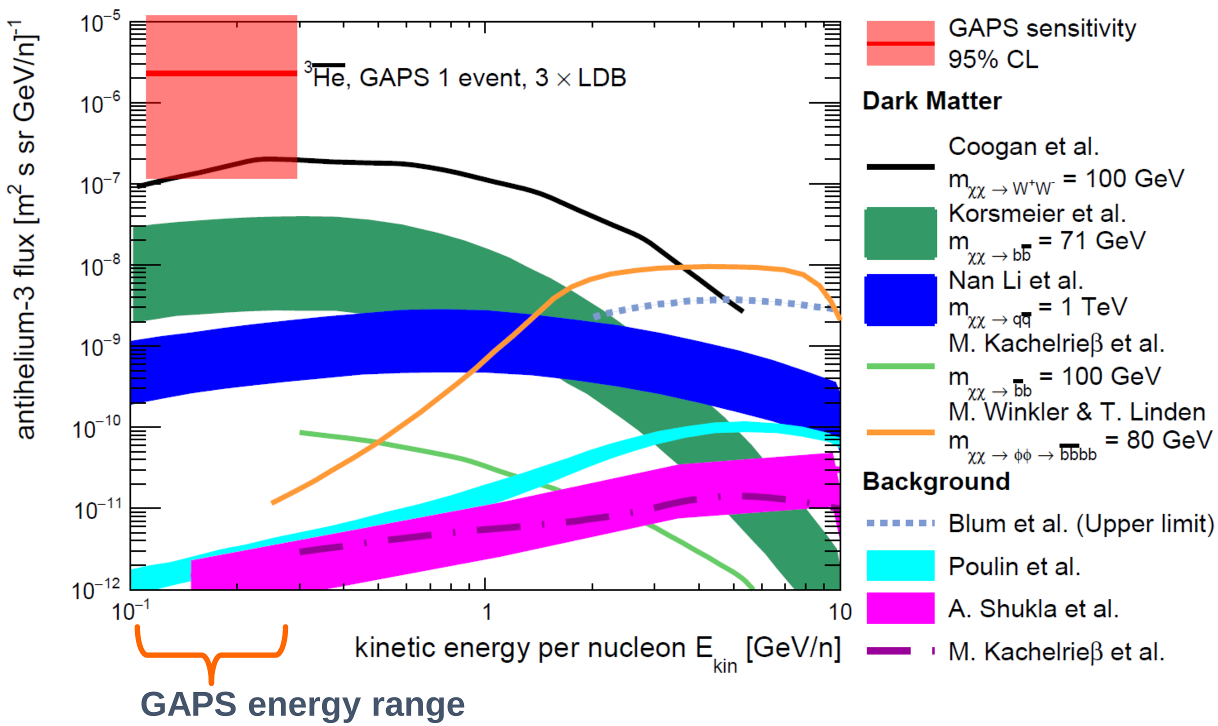
GAPS flux sensitivity to antihelium-3 (three 35-day long duration flights):

- **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+ Astropart. Phys. 102580 (2021).



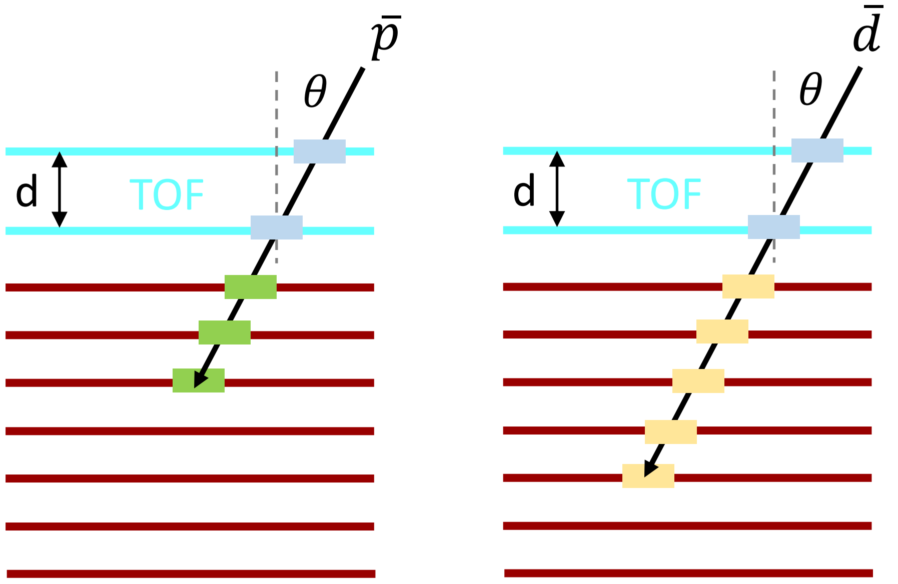
- ➢ *GAPS extends to lower energies (0.11-0.3 GeV/n), complementary to AMS-02.*
  - ▪ *Capable of confirming signal, orthogonal detection technique, uniquely low bkg.*

GAPS “Background” Rejection

- “Background” = antiparticle ($\bar{p}$) mis-identification
  - CR, p, $e^{\pm}$ rejection: select slow particles with TOF, AND simultaneous detection of annihilation products (TOF + Tracker)

- GAPS background 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.
- With the same beta (velocity), antideuterons go deeper and deposit more energies in tracker layers (perform larger *dE/dx*) due to the heavier mass.



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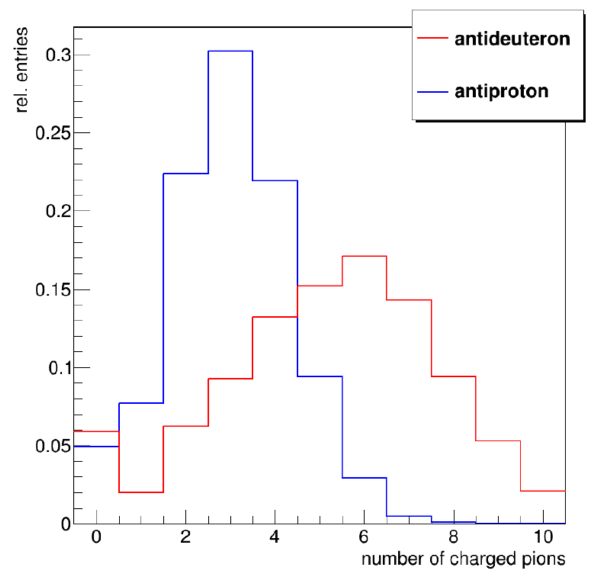
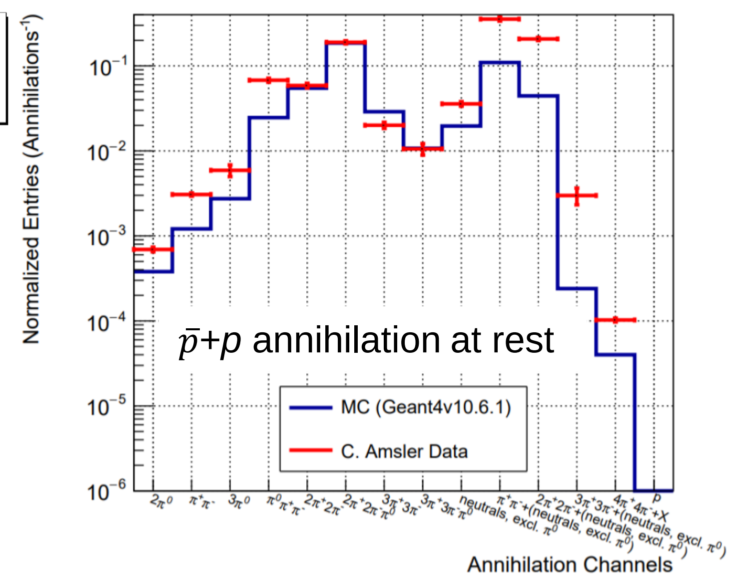
  - Stopping range, *dE/dx*
  - **Charge particle (pion/proton) multiplicity**
  - Characteristic atomic X-ray lines

- More pions/protons from antideuteron annihilation.
- Use antiproton data for validation, test of annihilation physics in Geant4 is ongoing (work with Geant4 developers).

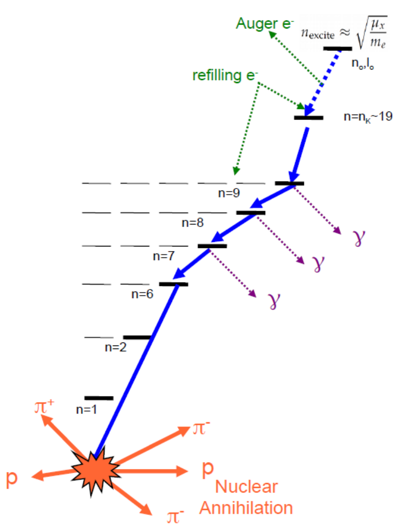




GAPS "Background" Rejection

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

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



- Energies of x-rays from exotic atom depend on the mass of stopped antiparticle.

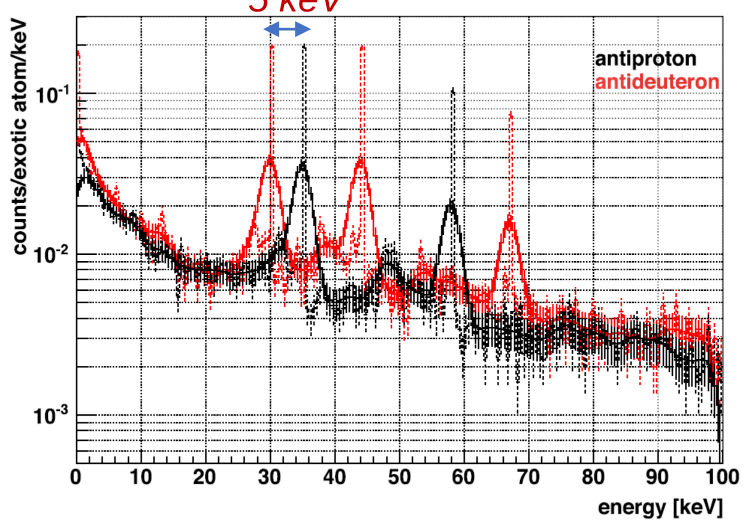
Antiparticle mass

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

Target material

(closest x-ray line for $\bar{p}$ and $\bar{d}$ in Silicon: 5 keV separation)

5 keV



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

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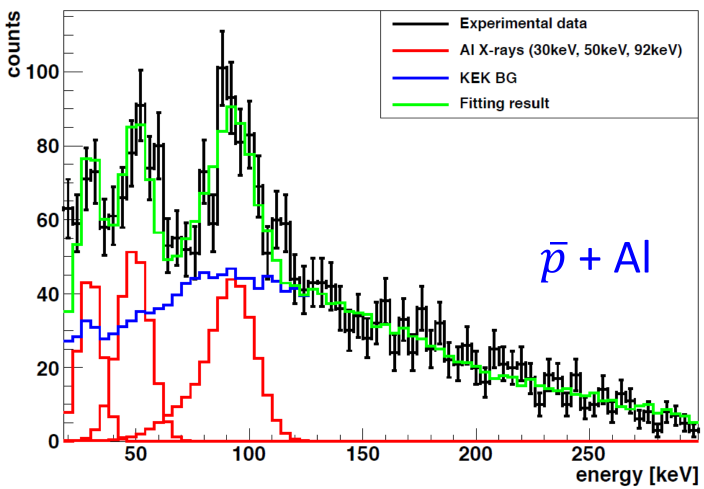
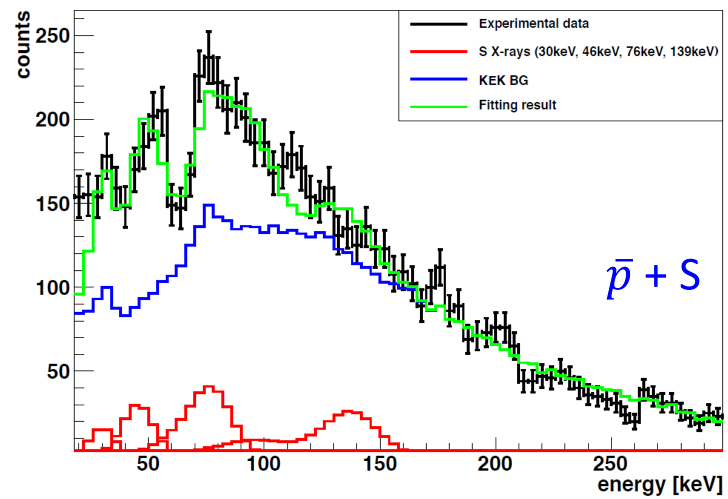
- Validated with the measurement with $\bar{p}$ *beam* at KEK in 2004: the measured X-ray data were consistent with the calculations.





Aramaki+ Astroparticle Physics (2013)

GAPS "Background" Rejection

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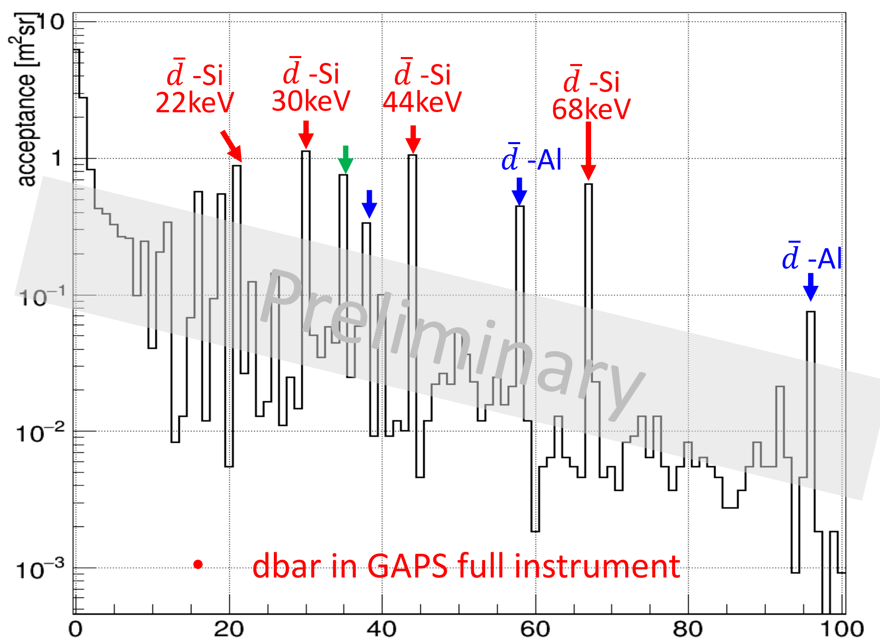
  - Stopping range, *dE/dx*
  - Charge particle (pion/proton) multiplicity
  - **Characteristic atomic X-ray lines**

- Has implemented correct exotic atomic x-rays process in Geant4 (collaborated with SLAC/CU/G4 authors), and GAPS official simulation software.
- Detailed simulations on the exotic atomic x-rays for GAPS full instrument are undergoing.



GAPS “Background” Rejection

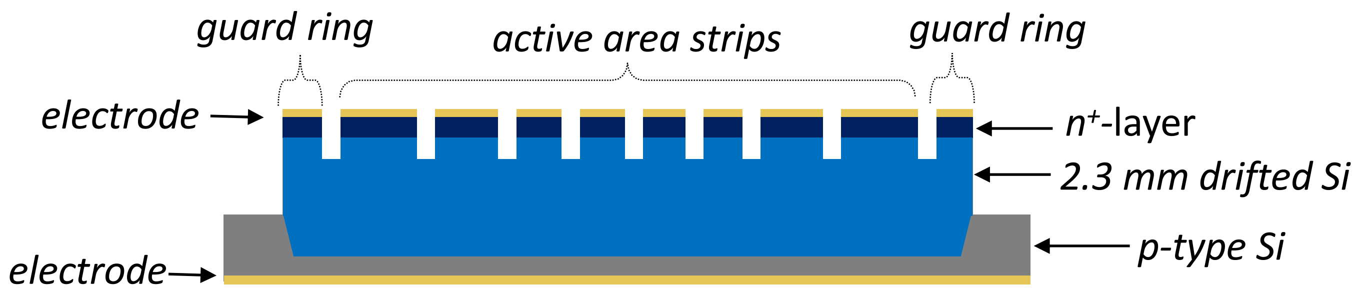
- ❑ “Background” = antiparticle ($\bar{p}$) mis-identification
  - CR, p, $e^{\pm}$ rejection: select slow particles with TOF, AND simultaneous detection of annihilation products (TOF + Tracker)

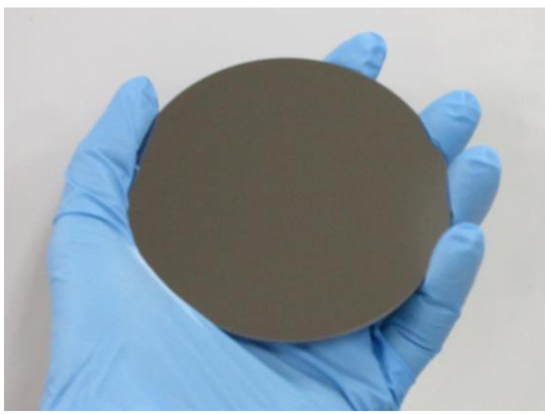
- ❑ GAPS background discrimination power ($\bar{p}$ / $\bar{d}$ identification)
  - ➢ **Stopping range, *dE/dx***
  - ➢ **Charge particle (pion/proton) multiplicity**
  - ➢ **Characteristic atomic X-ray lines**

⇩

GAPS “Background” rejection for antideuteron searches $>10^6$!

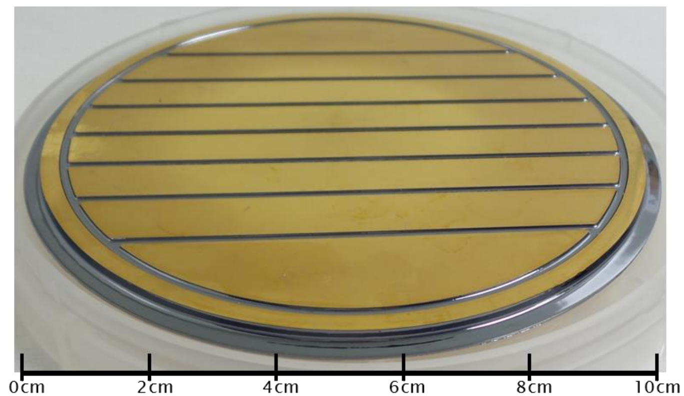
Si(Li) Detector *Fabrication*





B-doped, *p*-type substrate wafer

1. B-doped, *p*-type substrate wafers
2. Evaporate and diffuse Li for n^+-layer
3. Form top-hat structure to control drift
4. Evaporate Ni + Au electrodes
5. Drift Li through wafer
6. Form guard ring + 8 strips



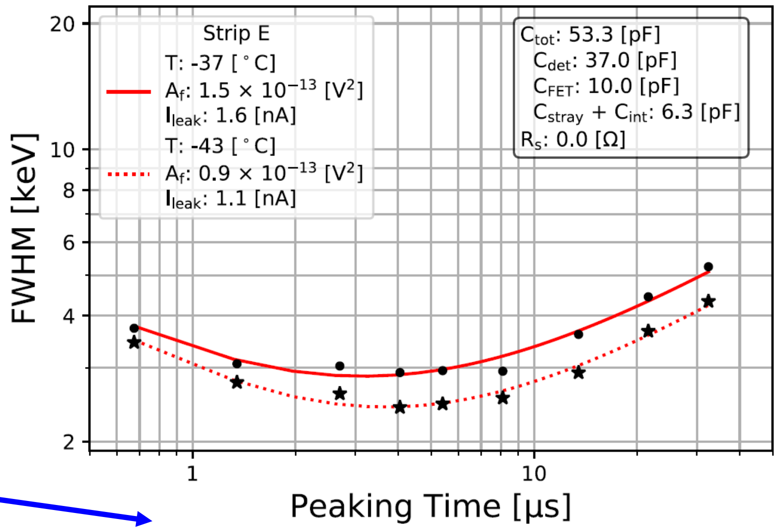
Perez+ NIM A 905 12-21 (2018)
M. Kozai et al. NIM A 947 (2019), co-author

- ❑ Custom made lithium-drifted silicon detector (Si(Li)) by the joint efforts from Columbia Univ./MIT/JAXA/Shimadzu Corp.
  - 10-cm diameter and 2.5-mm thickness, 8 strips per detector

Si(Li) Detector ***Noise Model***

- Noise model combines detector, readout, and pulse shaping characteristics to describe energy resolution varying peaking time and temperature

Data and model for one detector strip at -37°C and -43°C (discrete preamps)



Detector dominated

$$ENC^2 = \left(2q\boxed{I_{leak}} + \frac{4kT}{R_p}\right)\tau F_i + 4kT\left(R_s + \frac{\Gamma}{g_m}\right)\frac{\boxed{C_{tot}^2}}{\tau}F_v + A_f\boxed{C_{tot}^2}F_{vf}\,,$$

$$FWHM = 2.35\epsilon\frac{ENC}{q}$$

➢ Detector + ASIC testing is undergoing at MIT and Italy.