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The GAPS experiment: sensitive survey of cosmic-ray antinuclei to search dark matter

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Summary

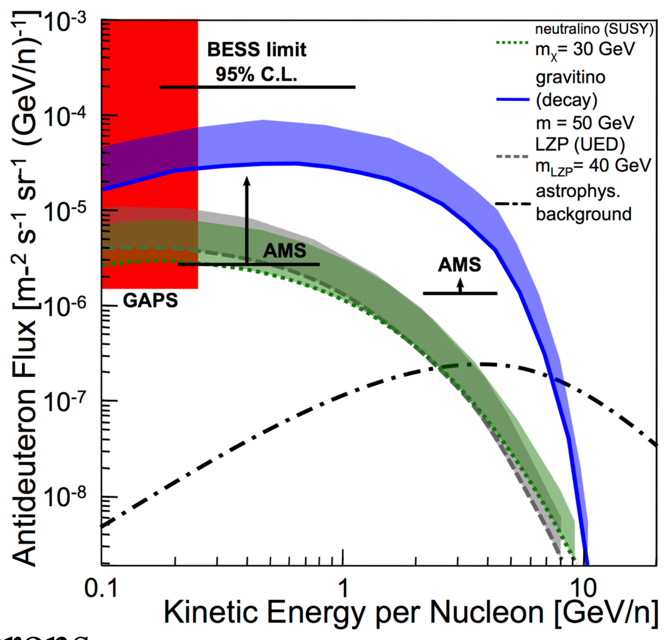
☐ General AntiParticle Spectrometer

- GAPS investigates dark matter (DM) indirectly by searching for low-energy cosmic-ray antinuclei.
- GAPS is an international balloon-borne project and will use NASA long duration balloon flights over Antarctica. The first GAPS flight is scheduled for late 2021.
- All individual subsystems, such as the lithium-drifted silicon (Si(Li)) tracker, time-of-flight (TOF) system, cooling system, and detailed simulation code of the instrument are being developed.

Scientific Motivation

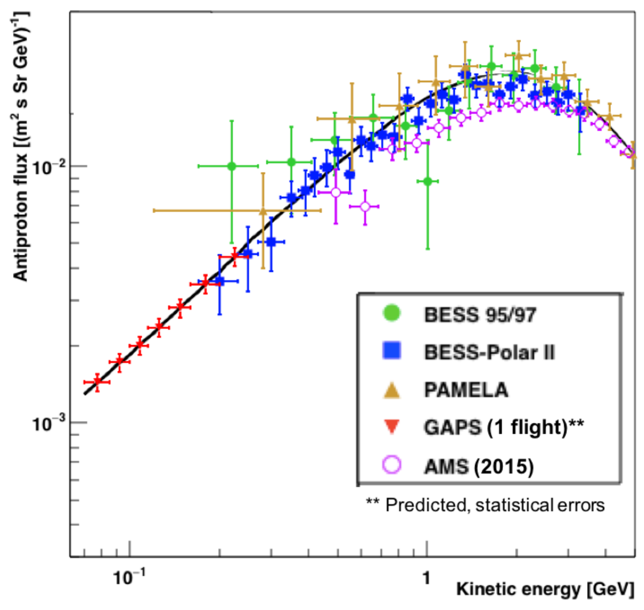
☐ Antideuteron

Low-energy (< ~1 GeV/n) cosmic-ray antideuterons can be produced by self-annihilation or decay of WIMP (weakly interacting massive particle) DM.
The flux of DM-originated antideuterons can be orders of magnitude higher than that of the secondary (or background) component.
Therefore, antideuterons are considered to be a **background-free probe** to search for DM.
GAPS is sensitive below **0.25 GeV/n** to antideuterons.



☐ Antiproton

Low-energy (< ~0.1 GeV/n) antiprotons are unexplored.
GAPS will measure **>1000** antiprotons in each flight.



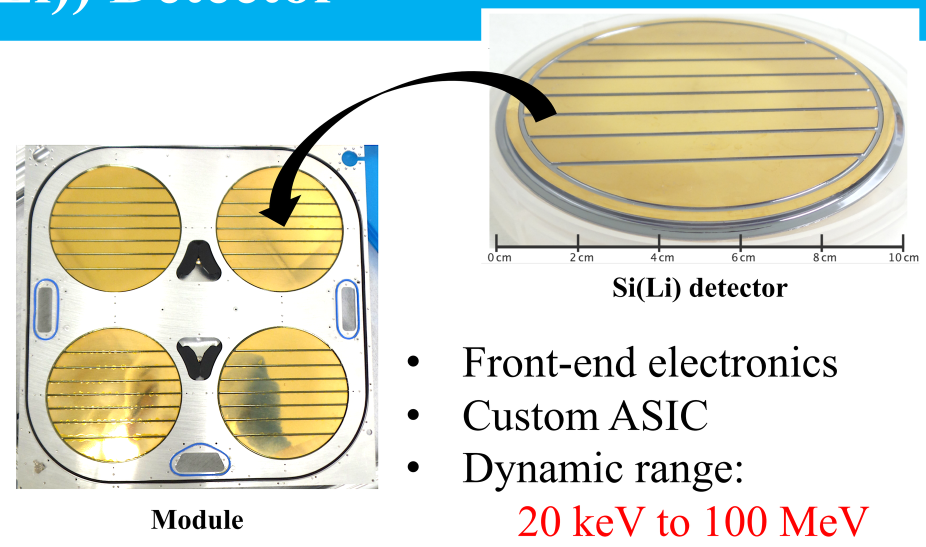
☐ Antihelium

GAPS is also sensitive for antihelium, and will provide a search for DM models.

Lithium Drifted Silicon (Si(Li)) Detector

☐ Si(Li) detector

- **10 cm** diameter, **2.5 mm** thick
- Segmented into **8 strips**
- 4 detectors/module
- The Si(Li) detector serves as:
  - depth sensing detector
  - X-ray spectrometer
  - charged particle tracker



- Front-end electronics
- Custom ASIC
- Dynamic range: 20 keV to 100 MeV

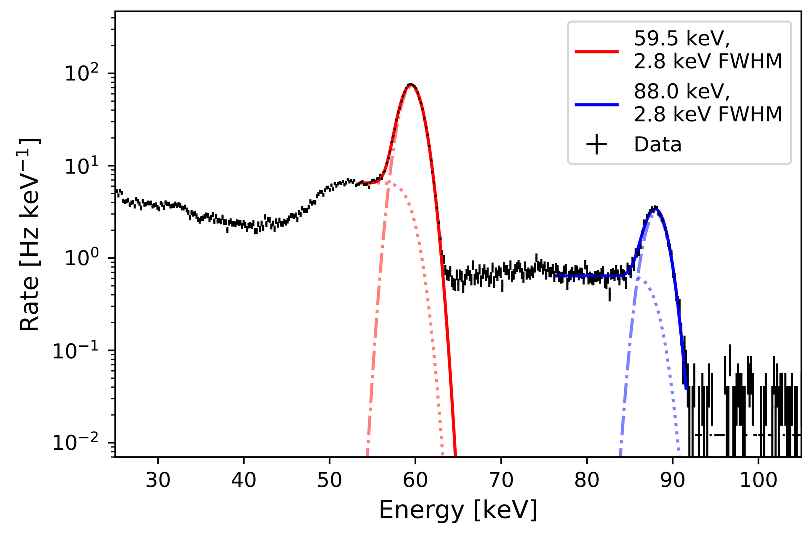
☐ Requirements to achieve a sufficient capability to identify antinuclei

- The energy resolution for X-rays: **< 4 keV** FWHM
- Detector leakage current: **5-10 nA/strip**
- Operating temperature: **~-40°C**

☐ Development status

- ✓ Representative data confirms ~3 keV FWHM for X-rays at -41°C with a few nA/strip
- ✓ Mass production of > 1000 detectors started from January, 2019 ~70 detectors/month, Yield ~90%
- ➢ Detector module calibration is in progress

◆ Collaboration with Shimadzu corp. and SUMCO corp.

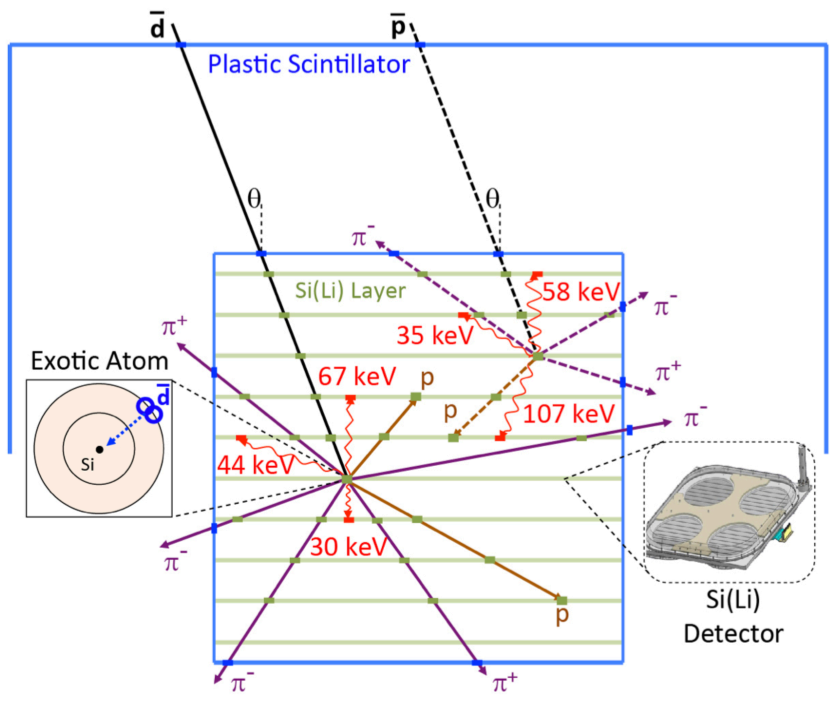


Detection Concept

☐ Applying the physics of exotic atom

GAPS uses a unique concept to identify antinuclei by applying the physics of exotic atom creation and decay.

1. An incoming antinucleus is **slowed down** by the energy losses in the TOF counters and in Si(Li) tracker as target material.
2. It is **captured** by Si(Li) detector and forms an excited exotic atom with silicon atom.
3. Through the deexcitation and nuclear annihilation processes of the exotic atom, **characteristic X-rays** and **charged particles** are emitted.
4. It enables us to identify rare antinucleus by detecting and tracking those X-rays and particles.



■ This technique allows us to build an instrument with a large grasp and low-energy range.

Instrument

☐ GAPS Instrument

- A central tracker composed of **Si(Li) tracker** is surrounded by the inner and outer **TOF plastic scintillation counters**.
- Instrument size: ~4m × 4m × 3m
- Total mass: 3.5t

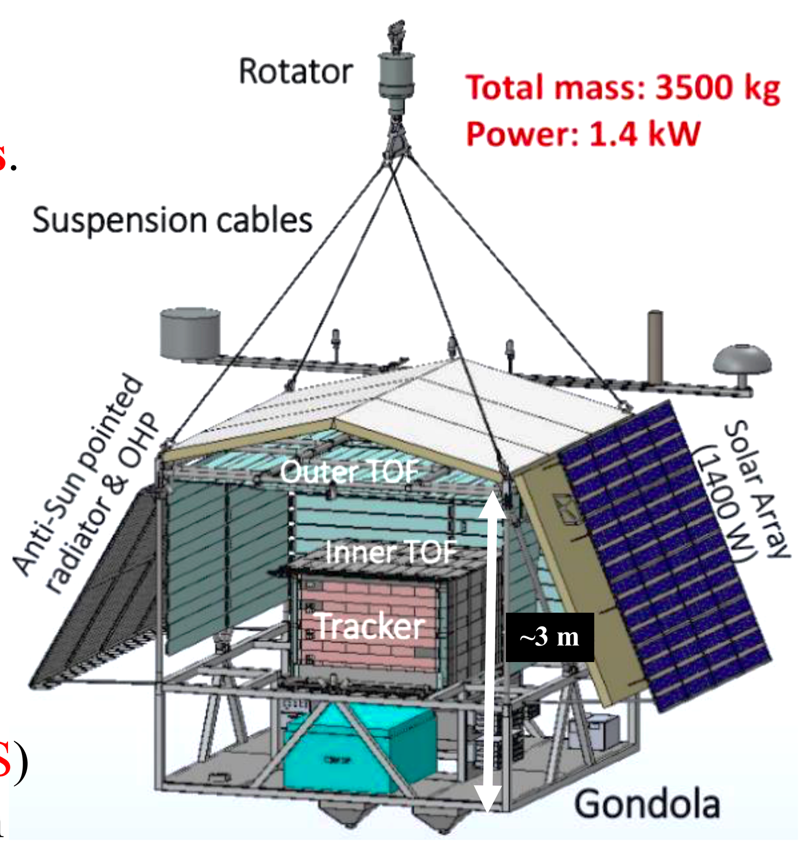
■ **Si(Li) tracker**

- **12 × 12 detectors / layer**
- **10 layers** with 10 cm vertical spacing

■ **Time-of-Flight (TOF) system**

- **~200 paddles** (Outer + Inner)
- **6 mm^t × 16 cm^W × 1.2~1.8 m^L**

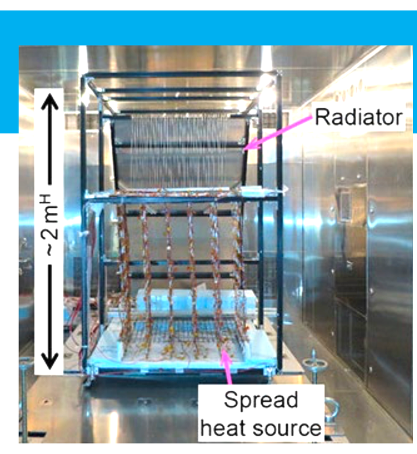
✓ The prototype GAPS instrument (pGAPS) was successfully verified using a balloon flight in June 2012 at Taiki, Japan.



Si(Li) Detector Cooling System

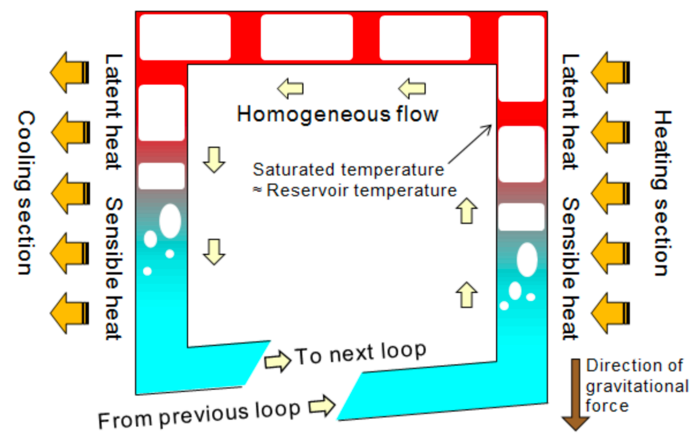
☐ New passive and low-power system for GAPS

- Two-phase coolant fluid
- Drived by **pressure difference** and **gravity** (Oscillating heat pipe + Closed loop thermosyphon)



☐ Requirements

- Cool the Si(Li) detectors to **< -40°C** to reduce leakage current (to transport heat, the radiator itself needs to cool to **< -55°C**)
- Cooling system suitable for **balloon experiment environment**



☐ Development status

- ✓ Basic design concept was verified on pGAPS
- ✓ Scaled radiator was demonstrated using NASA balloon in 2018 & 2019
- ➢ Tests using the engineering model in thermal chamber are in progress

Time-of-flight (TOF) System

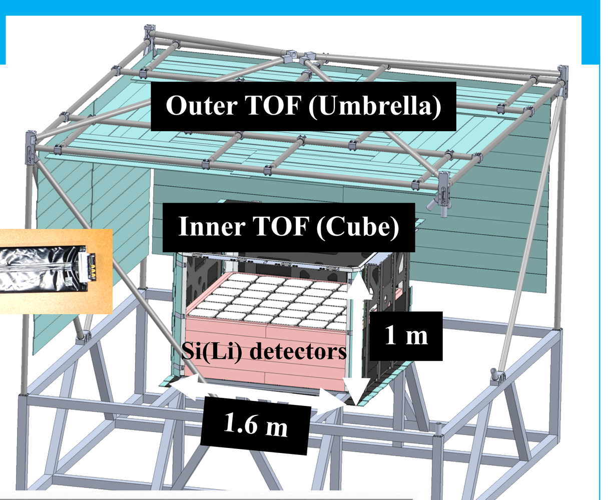
☐ TOF plastic scintillation counters

- Both ends are coupled to 6 silicon photomultipliers each


Prototype counter

■ The TOF system:

- generates **the trigger signal**
- measures **the TOF and the d*E*/d*x***
- determines **the arrival direction**

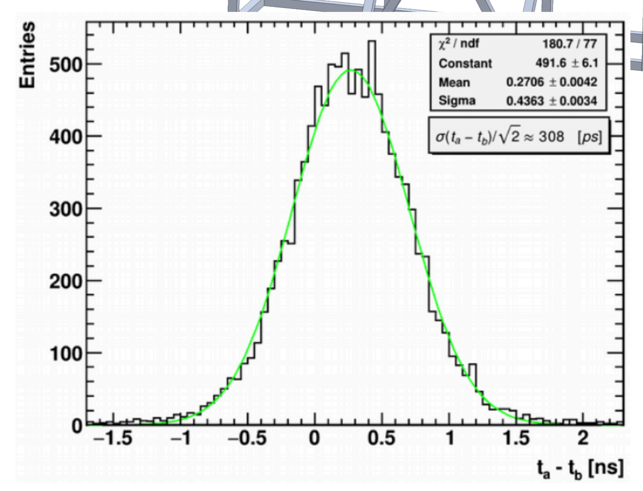


☐ Requirements

- Timing resolution: **< 500 ps**
- Position resolution: **< ±10 cm**
- Angular resolution: **< ±5°** (for vertical)

☐ Development status

- Prototype counter performance
  - ✓ Achieved **340 ps** timing resolution



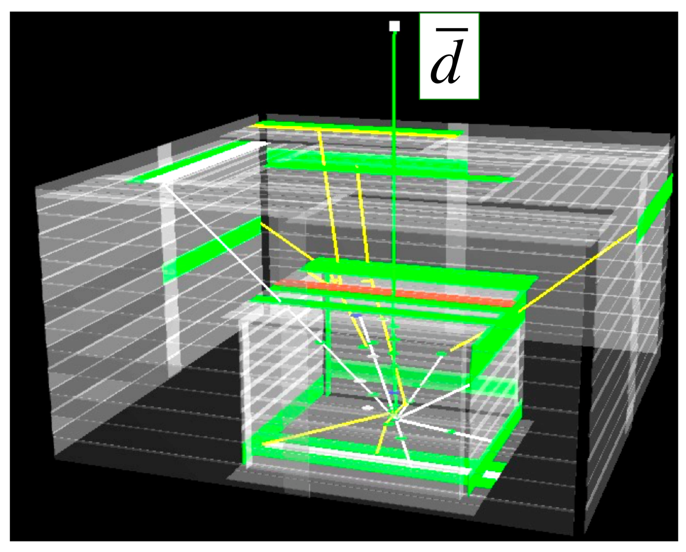
Simulation Study

☐ Geant4 model

- ➢ Full payload design is being implemented
- ➢ Validation of annihilation physics
- ✓ Exotic X-rays from antiparticles

☐ Particle Identification

- ➢ Likelihood analysis (# of secondary particles, stopping depth, etc)
- ➢ Event reconstruction algorithm
- ➢ Neural network (Deep NN, CNN)



An event display

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