Experimental Search for Cosmic-ray Antinuclei with GAPS

MIAPP – Antinuclei in the Universe?
February 2022

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on behalf of the GAPS collaboration

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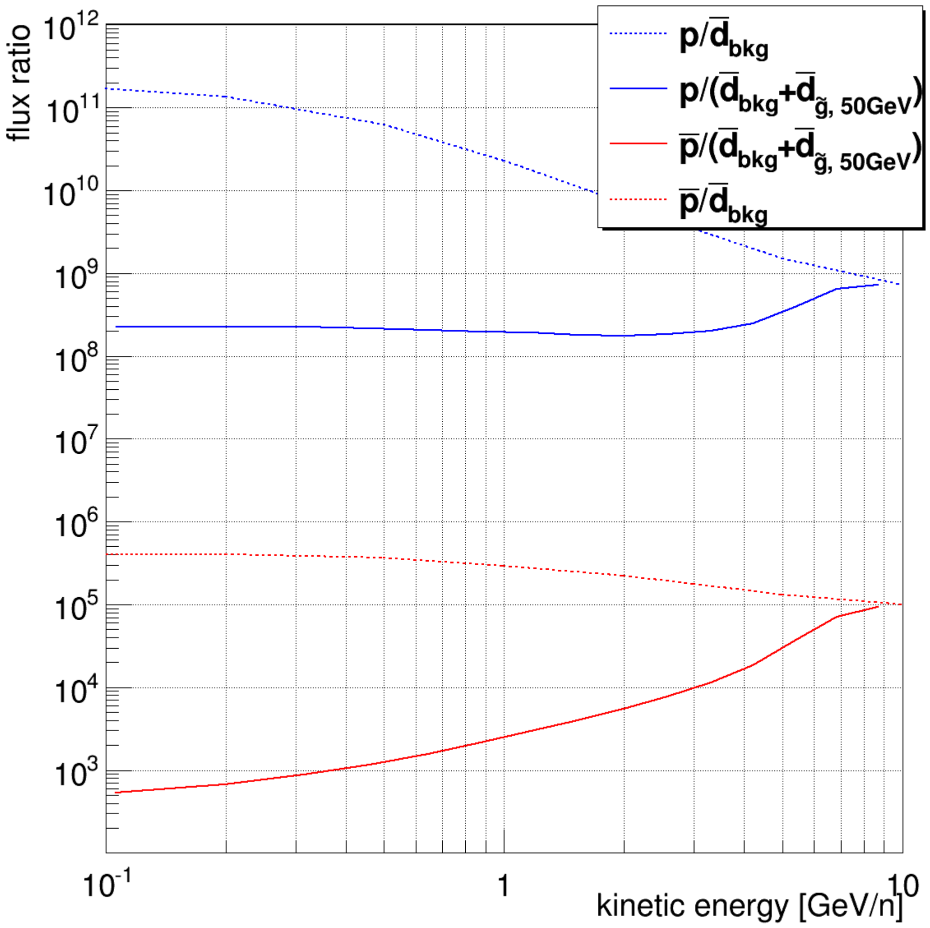
Antideuteron identification challenge

Required rejections for antideuteron detection:

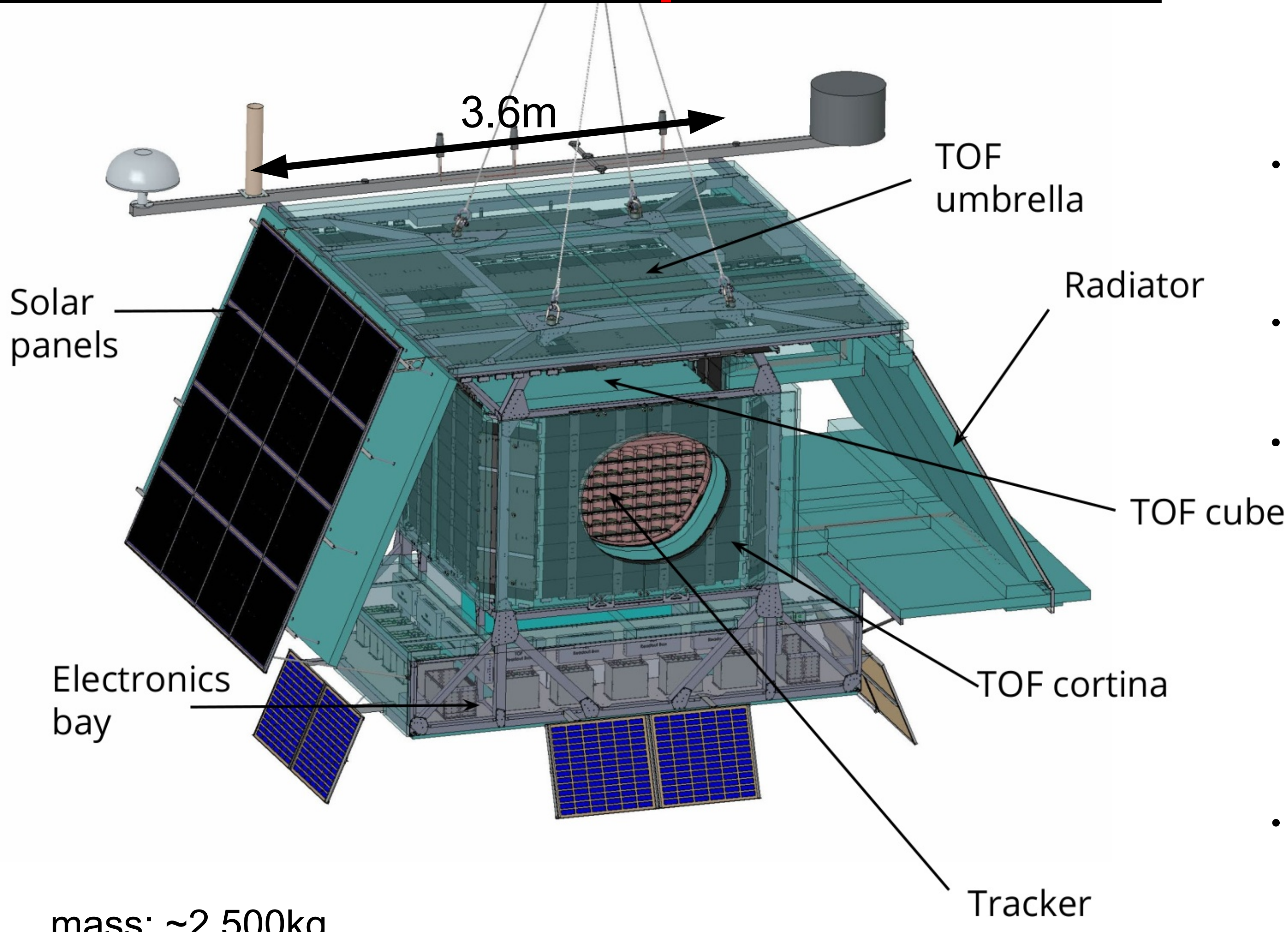
- **protons**: > 10^8 - 10^{10}
- **He-4**: > 10^7 - 10^9
- **electrons**: > 10^6 - 10^8
- **positrons**: > 10^5 - 10^7
- **antiprotons**: > 10^4 - 10^6

Antideuteron measurement with balloon and space experiments require:

- **strong background suppression**
- **long flight time and large acceptance**



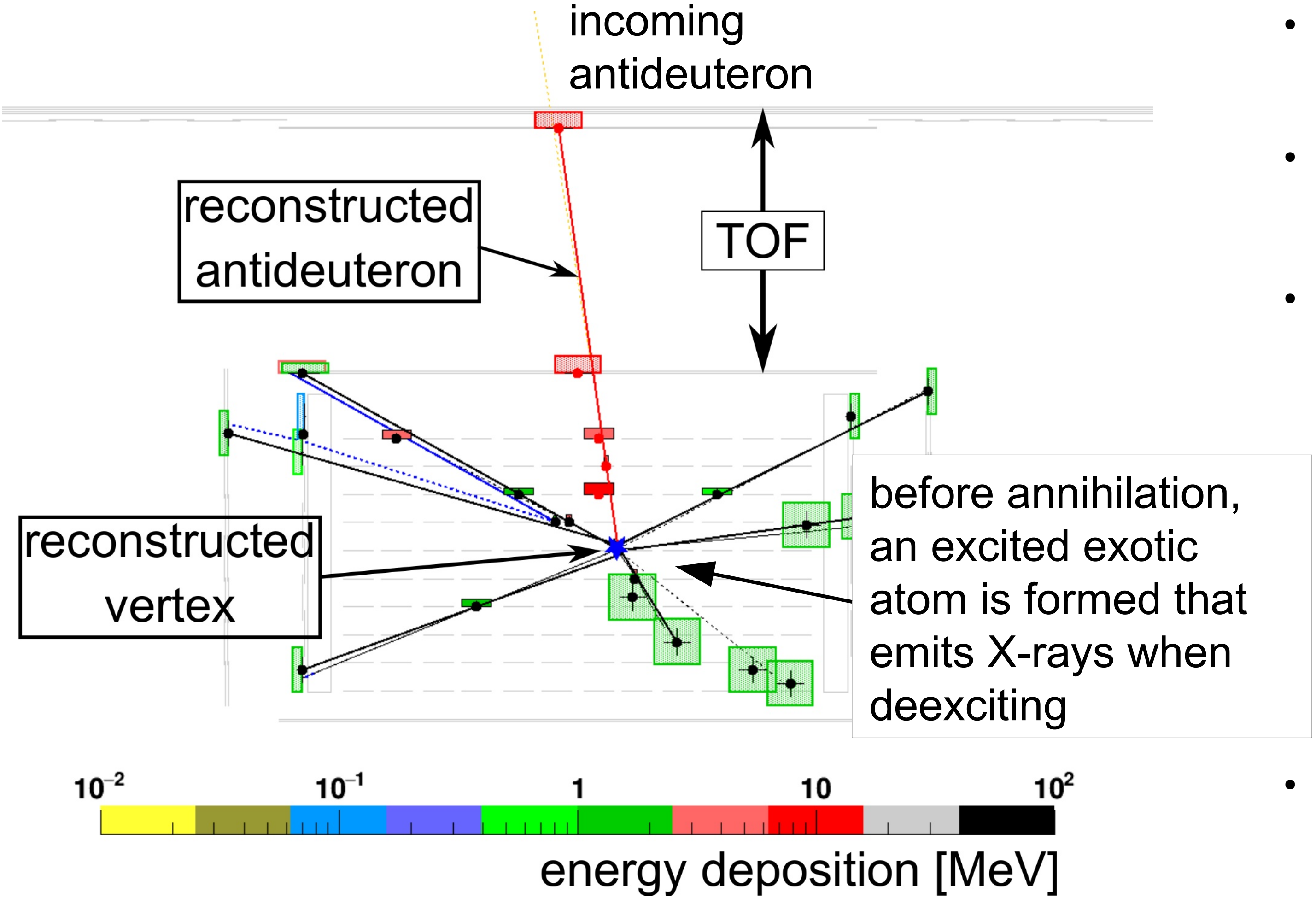
The GAPS experiment



mass: ~2,500kg
power: 1.3kW

- The **G**eneral **A**nti**P**article **S**pectrometer is the first experiment dedicated and optimized for low-energy cosmic-ray antinuclei search
- Requirements: long flight time, large acceptance, large identification power
- **GAPS will deliver:**
  - a precision antiproton measurement in an unexplored energy range <0.25 GeV/n
  - antideuteron sensitivity 2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range
  - provide leading sensitivity to low-energy cosmic antihelium nuclei
- **GAPS is under construction, preparing for first Antarctic Long Duration Balloon flight**

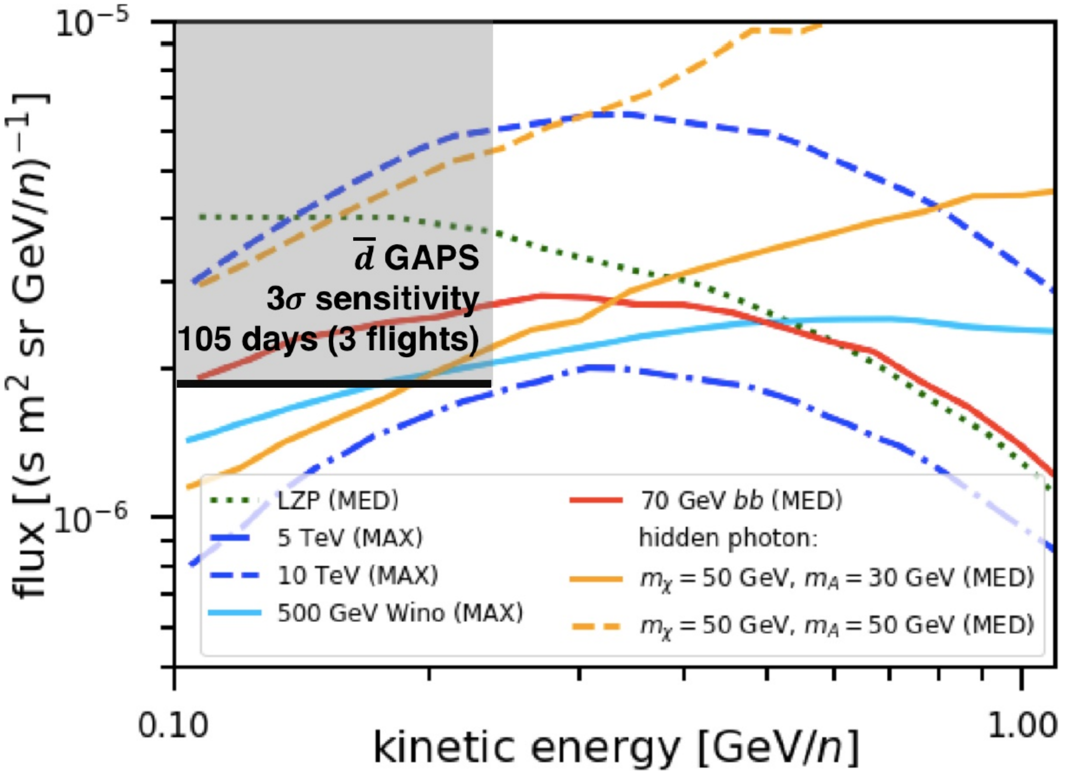
GAPS principle



- antiparticle slows down and stops in material
- large chance for creation of an excited exotic atom (E_{kin}~E_{I})
- deexcitation:
  fast ionization of bound electrons (Auger)
  → complete depletion of bound electrons
  Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic X-ray transitions depending on antiparticle mass
- Nuclear annihilation with characteristic number of annihilation products

GAPS model sensitivity

- GAPS is sensitive to a **wide range of dark matter models**, e.g.:
  - Generic 70GeV WIMP annihilation model that explains antiproton excess and γ-rays from Galactic center
  - Dark matter gravitino decay
  - Extra dimensions
  - Dark photons
  - Heavy DM models with Sommerfeld enhancement
- Primordial black holes (antiprotons)

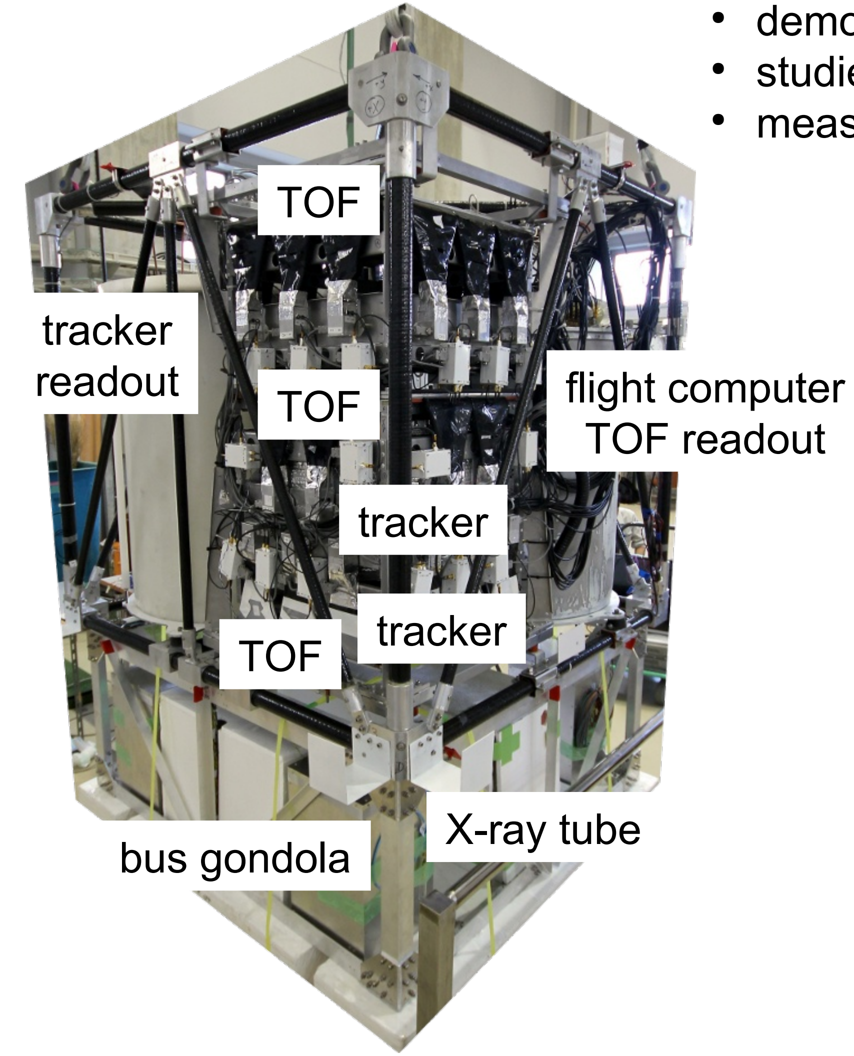


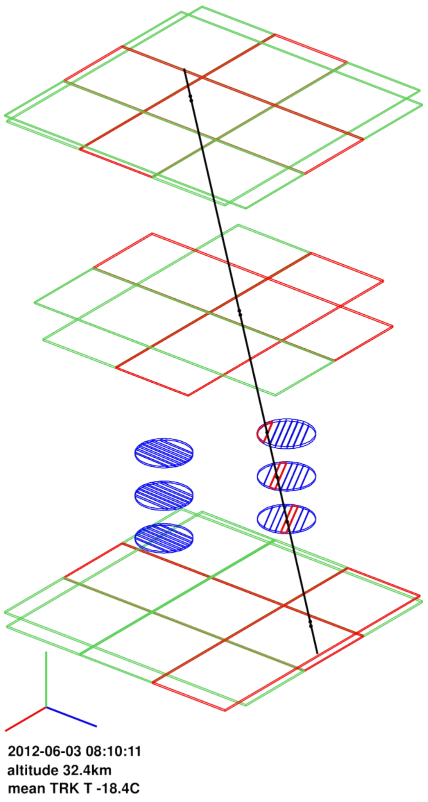
- **Finding low-energy antihelium would be truly revolutionary new physics**

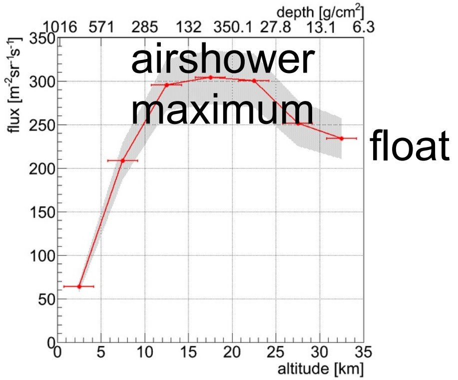
Prototype GAPS [2012]

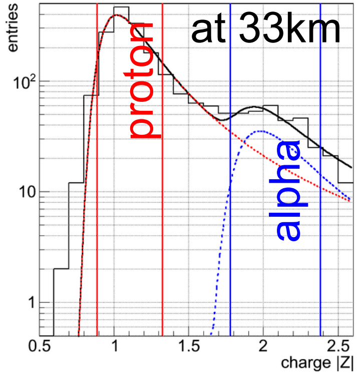
von Doetinchem et al., Astropart. Phys. 54, 93 (2014)

- demonstrated stable operation of the detector components during flight
- studied Si(Li) cooling approach for thermal model
- measured background levels









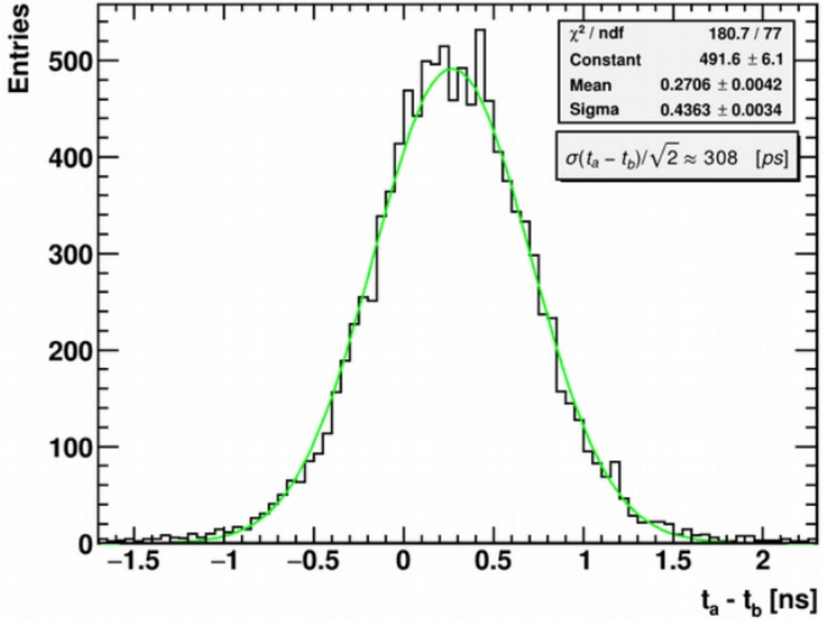
Time-of-Flight

- Tasks:
  - main trigger system, critical to reduce data rate to manageable level (~500Hz)
  - velocity measurement

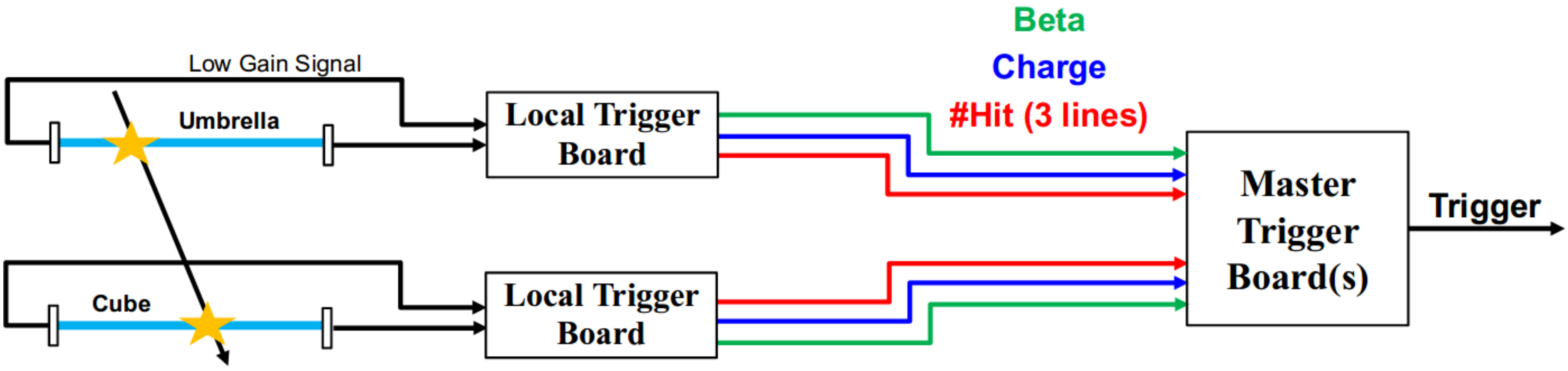
- Plastic scintillator: Eljen EJ-200: 160-180cm long, 0.6 cm thick

- SiPM: Hamamatsu S13360-6050VE

- fast sampling with DRS4 ASIC: ~300ps timing resolution end-to-end/√2 timing has been demonstrated in the lab



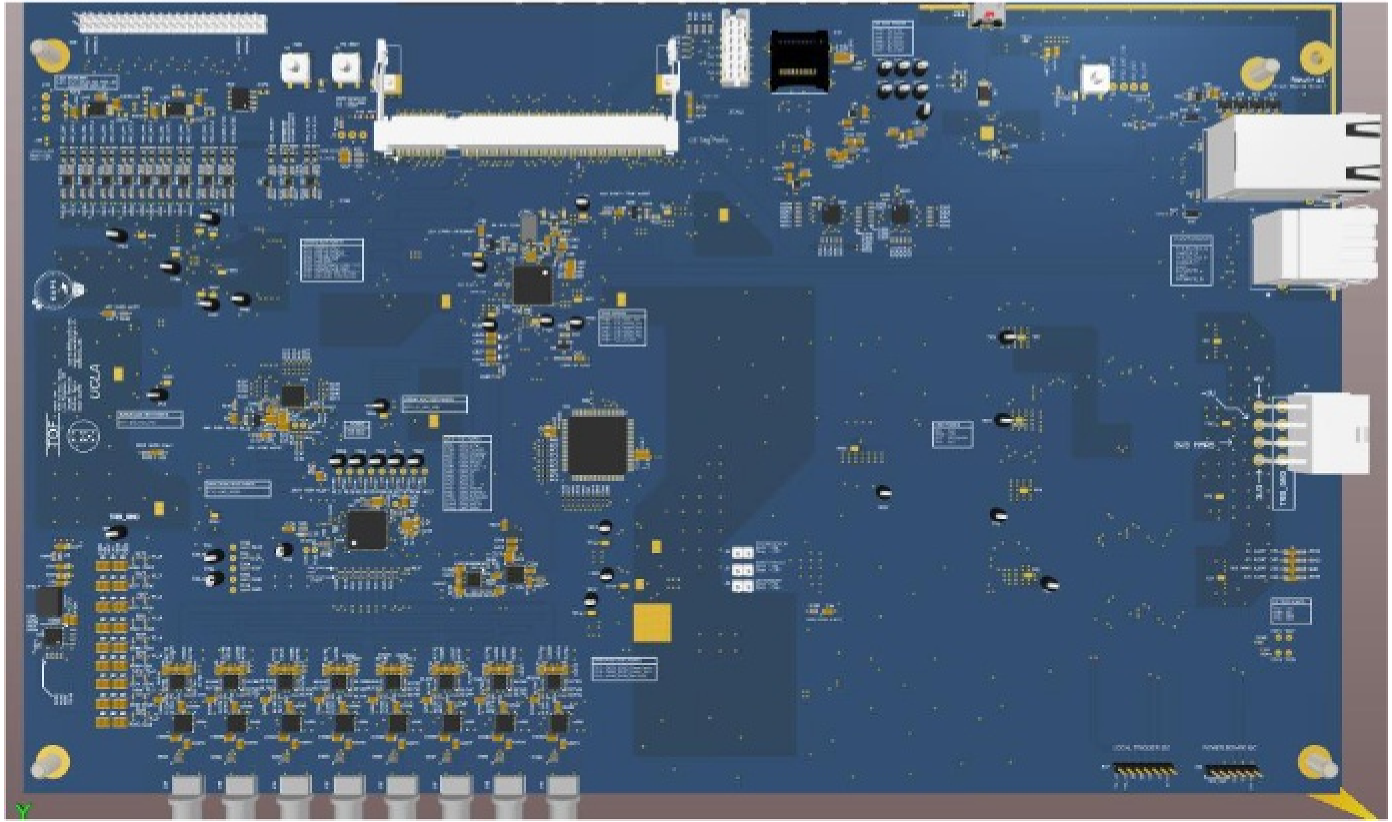
Trigger design



- main background: protons, alpha, carbon
- High-speed trigger and veto:
    - stopping events deposit more energy (lower beta)
    - annihilation events produce more TOF hits
    - paddle combinations can be used to constrain to zenith angle
- **smart combination reduces trigger rate to be low 500Hz**

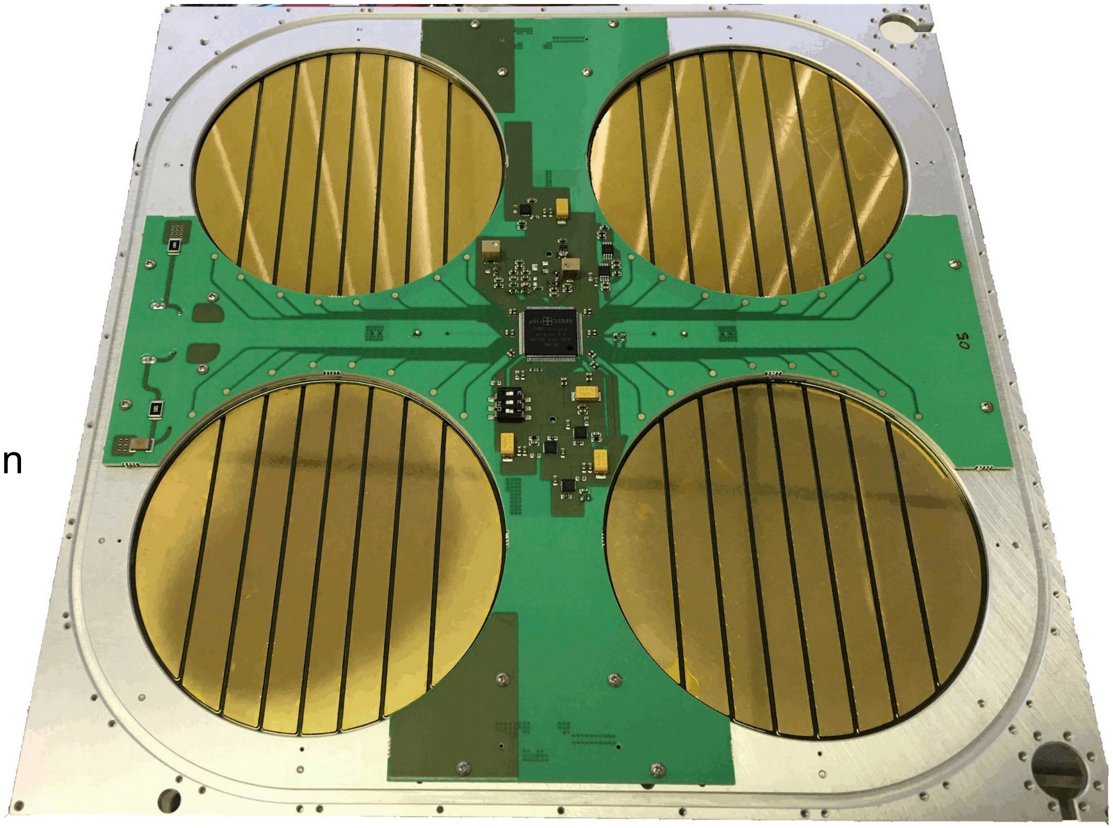
TOF electronics

- Waveforms for every trigger
- Fast timing/complete event: useful for distinguishing multiple hits in a counter
- DRS4 for digitization
  - low power, fast: 2 GS/s (up to 1024 Samples)
  - All chips synchronized to global clock



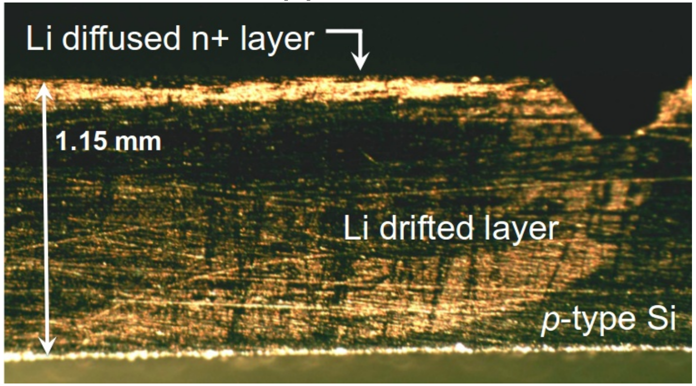
Tracker

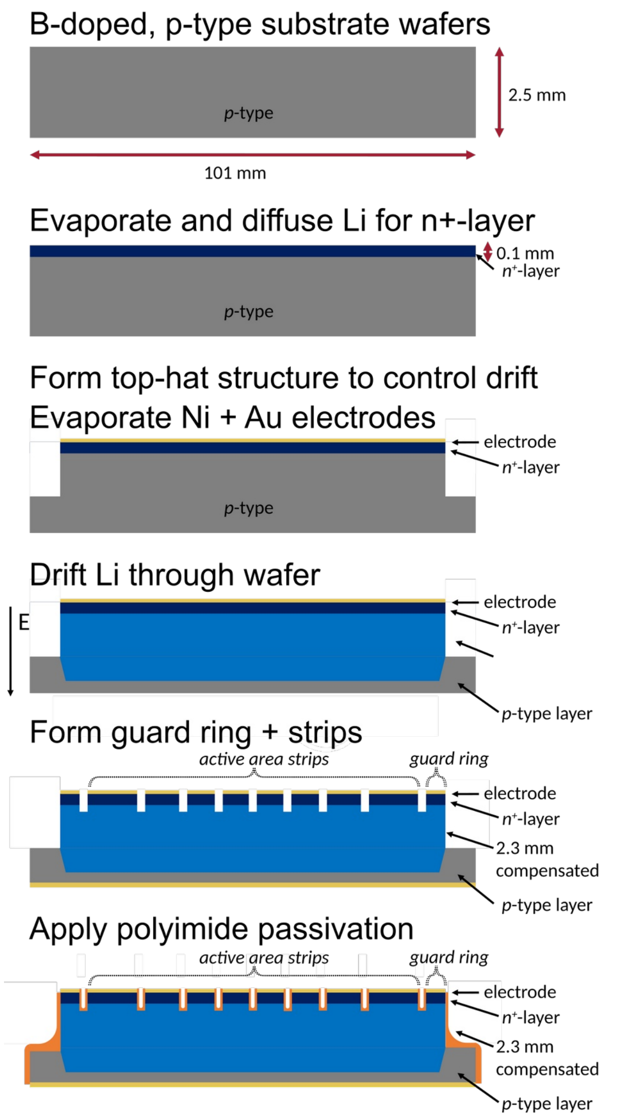
- Tracker acts as target and tracking device
- GAPS can accommodate 1,440 4" Si(Li) detectors, 2.5mm thickness
- Operation at relatively high temp of -35C to -45C, cooling system will use novel OHP approach
- Fabrication scheme developed at Columbia U and MIT, produced by private company Shimadzu, Japan
- Publications:
  - Perez et al., NIM A 905, 12 (2018)
  - Kozai et al., NIM A 947, 162695 (2019)
  - Rogers et al., JINST 14, P10009 (2019)
  - Saffold et al., NIM A 997, 165015 (2021)



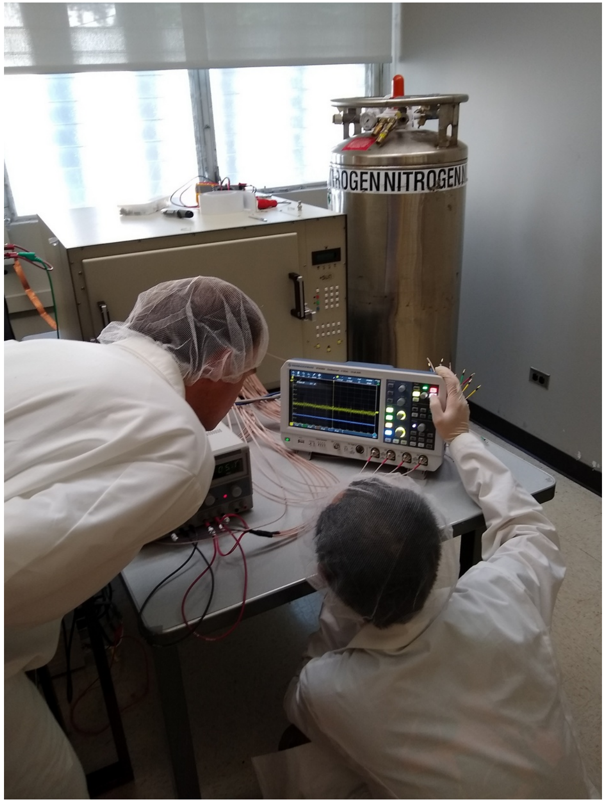
Si(Li) detector development

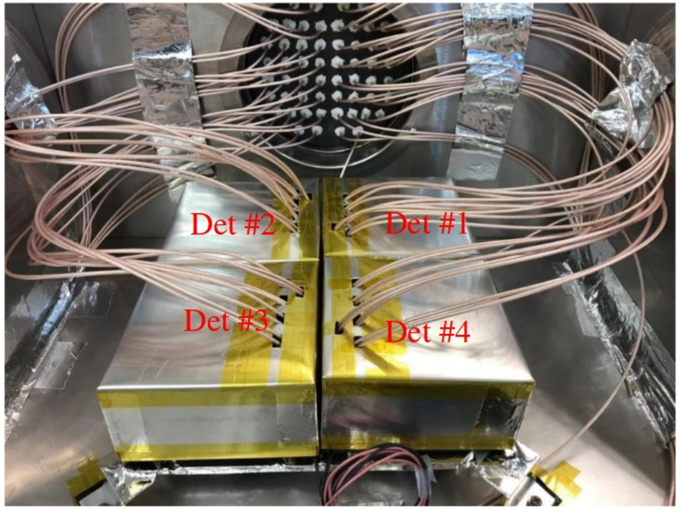
- Lithium is applied to the front surface of B-doped p-type Si and diffused through short depth
- Li atoms donate electrons, resulting in an n-type Si lattice layer and leftover free positive Li ions
- under reverse bias, positive Li ions move away from the n-type region
  → compensate acceptor atoms in the p-type bulk
  → compensate impurities in the Si
- drifting procedure creates a thick compensated region (4.6days at 600V and 100C)
- ultrasonic machining on the n+(Li) contact → guard ring structure, reduces leakage current, much better energy resolution
- electrodes are thermal-evaporated ohmic/blocking contacts
- Passivation is applied

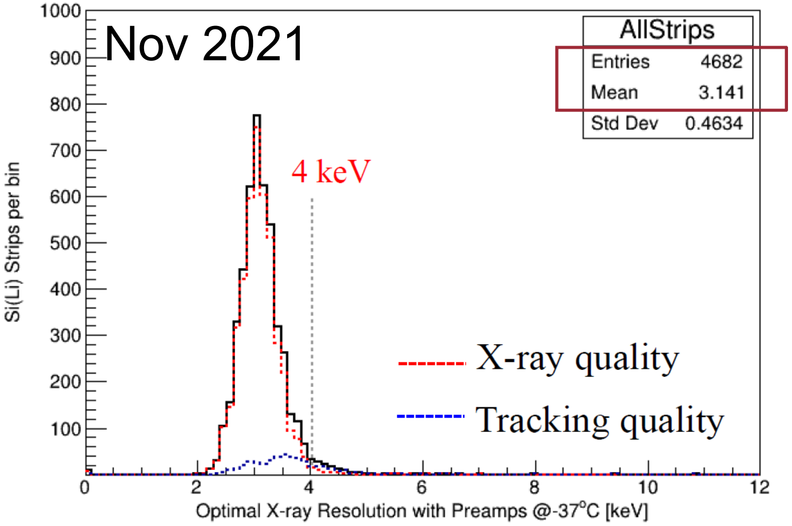




Tracker qualification

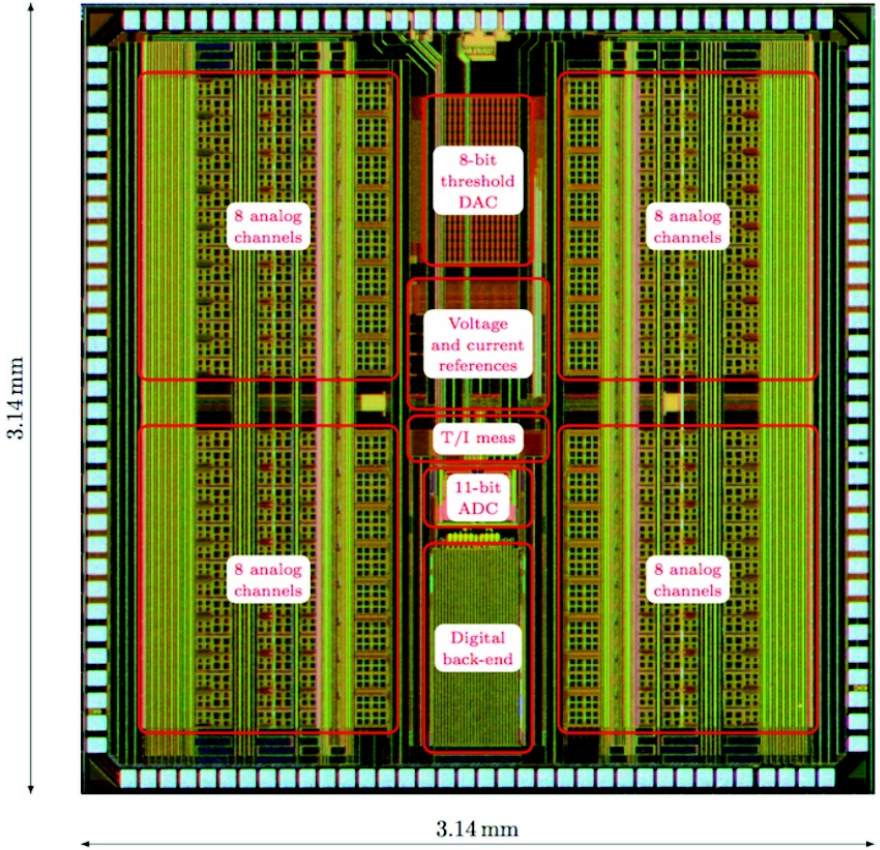


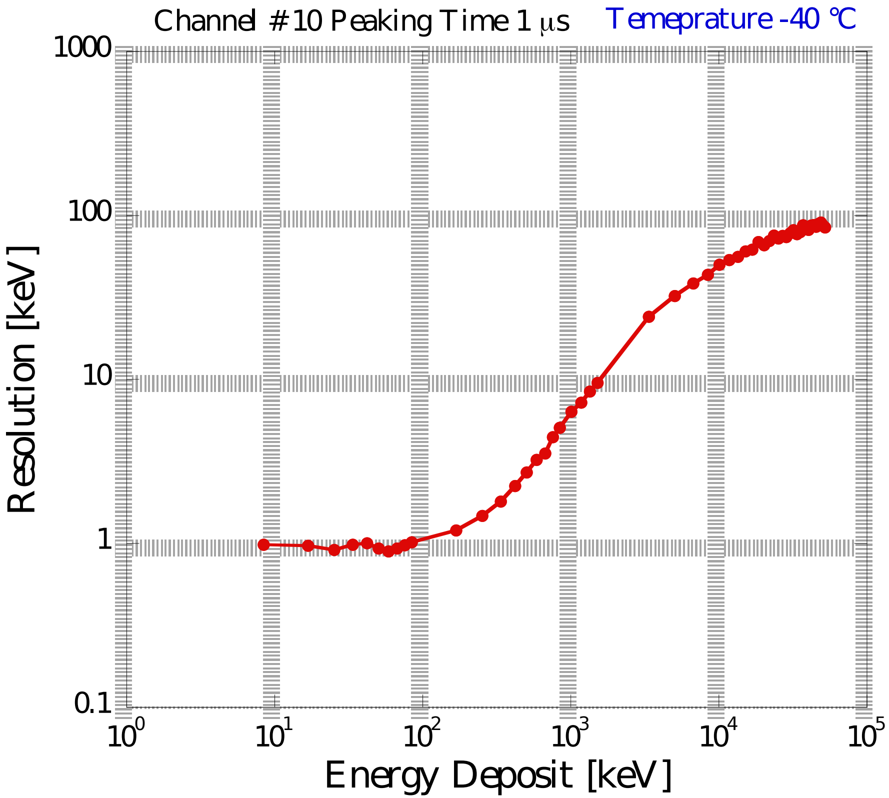




- Single detector test shows the required resolution of the detectors
- Detector module calibration facilities are set up at MIT and UHM
- Status (Feb 2022):
  - 1119 detectors produced
  - 805 calibrated (~95% flight quality)

Tracker electronics

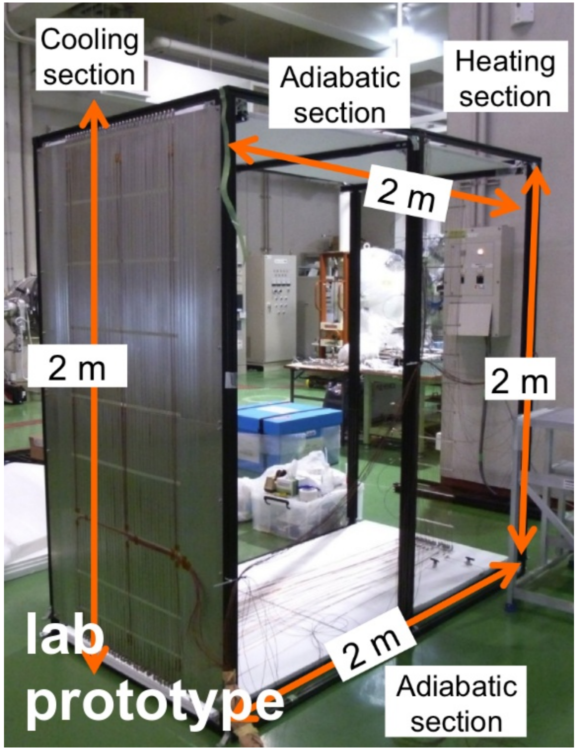




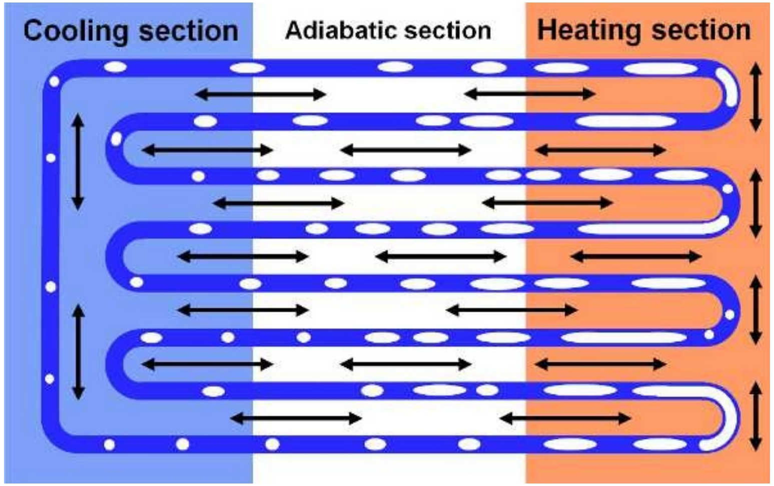
- readout via custom ASIC: integrated low-noise preamplifier
- large dynamic range: 10keV to 100MeV
- 32 analog readout channels
- 11 bits ADC

Manghisoni et al., IEEE Transactions on Nuclear Science 68 (11) 2661 (2021)

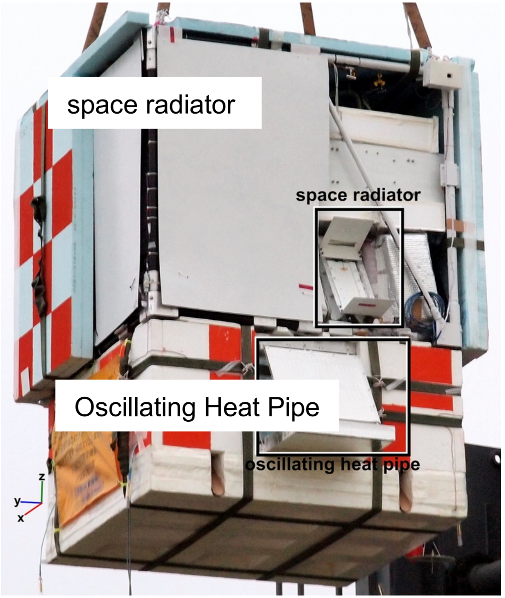
Oscillating heat pipe cooling system



S. Okazaki et al., J. Astr.. Instr. 3 (2014)

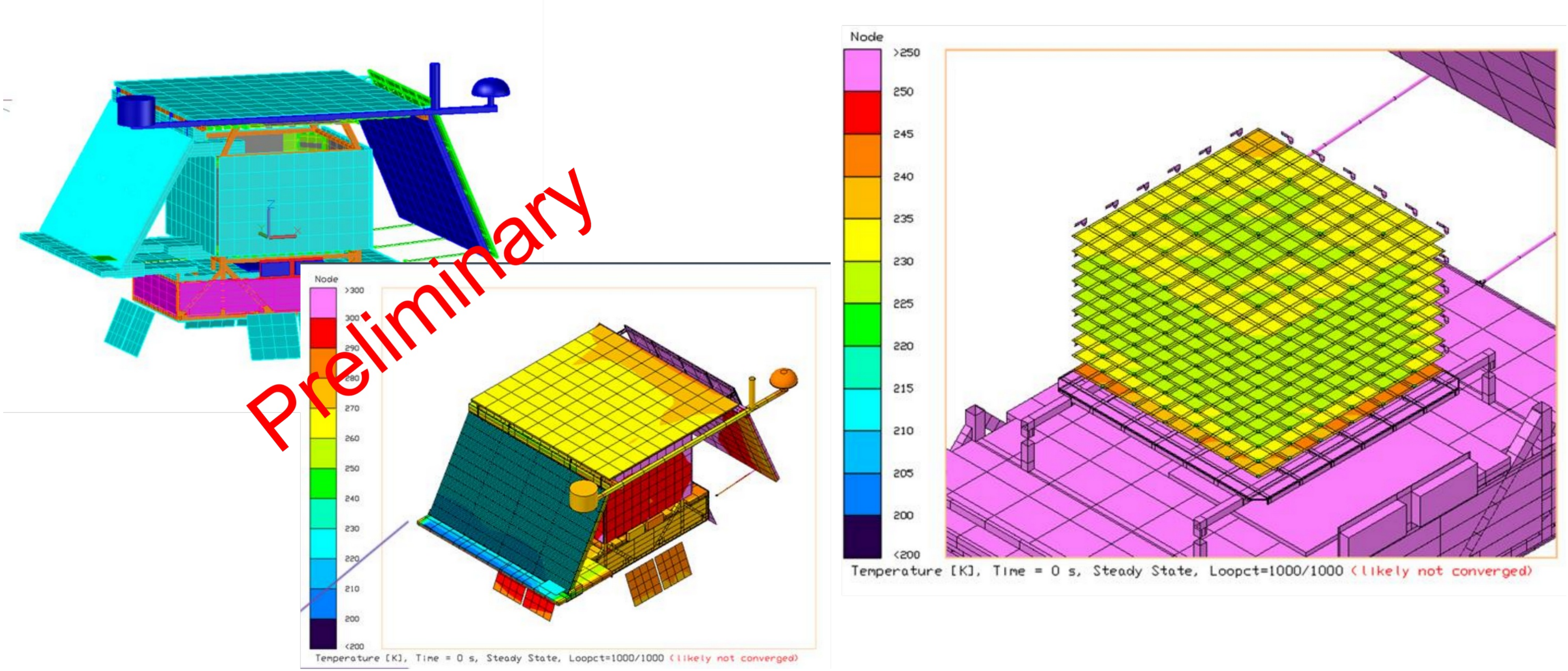


2012 prototype



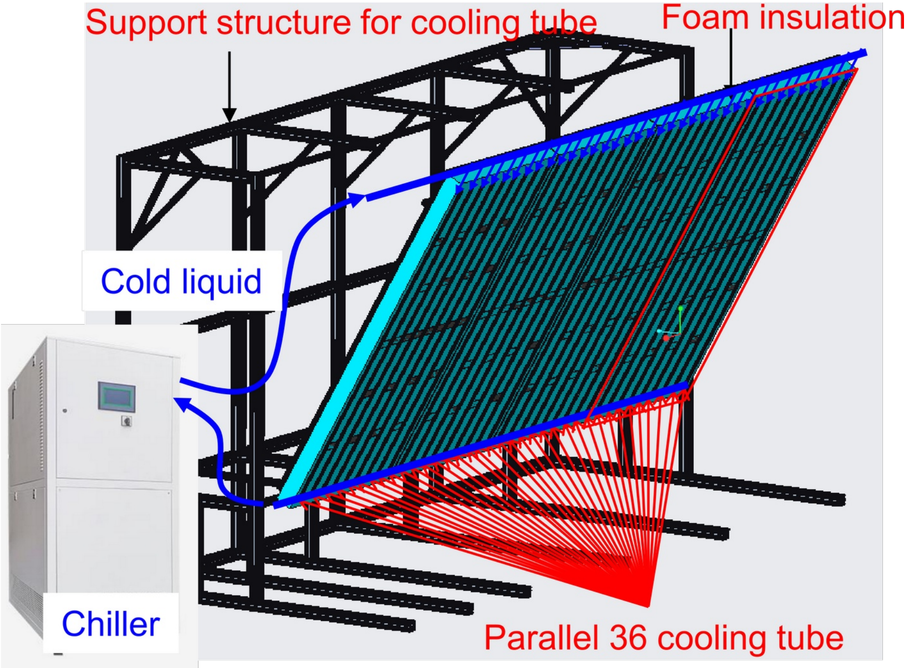
- passive cooling approach developed at JAXA/ISAS:
- small capillary metal tubes filled with a phase-changing refrigeration liquid
- small vapor bubbles form in the fluid
  → expand in warm sections/contract in cool sections
- rapid expansion and contraction of these bubbles create thermo-contraction hydrodynamic waves that transport heat
- no active pump system is required
- First prototype was flown in 2012 and another prototype was flown from Ft. Sumner in 2019

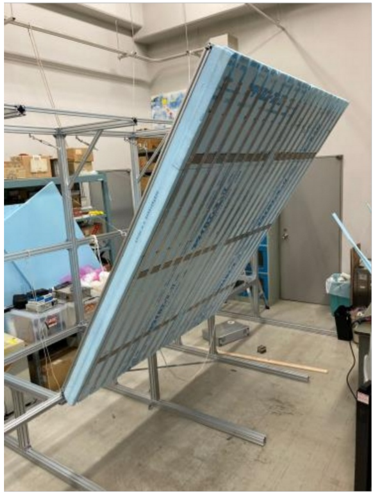
Oscillating heat pipe cooling system



- Most of the Si(Li) detectors are cooled down to lower than -40C. Thermal design will be further optimized to satisfy all detector temperature requirements

Oscillating heat pipe cooling system

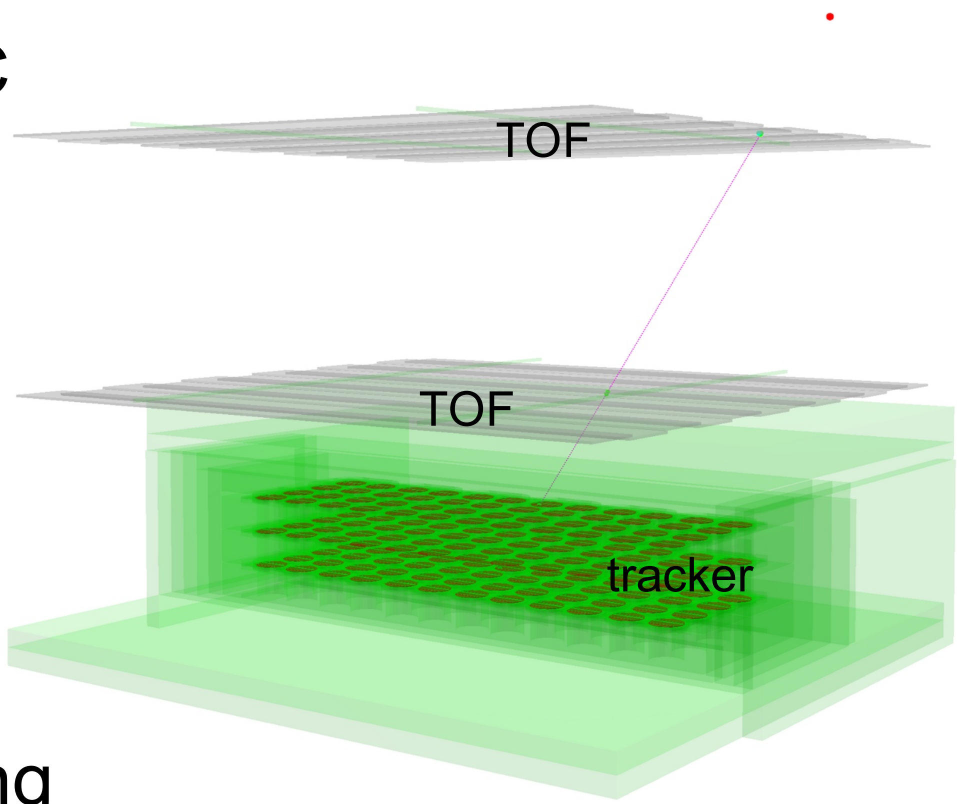




- Ground cooling equipment just arrived in the U.S. in January

GAPS Functional Prototype (GFP)

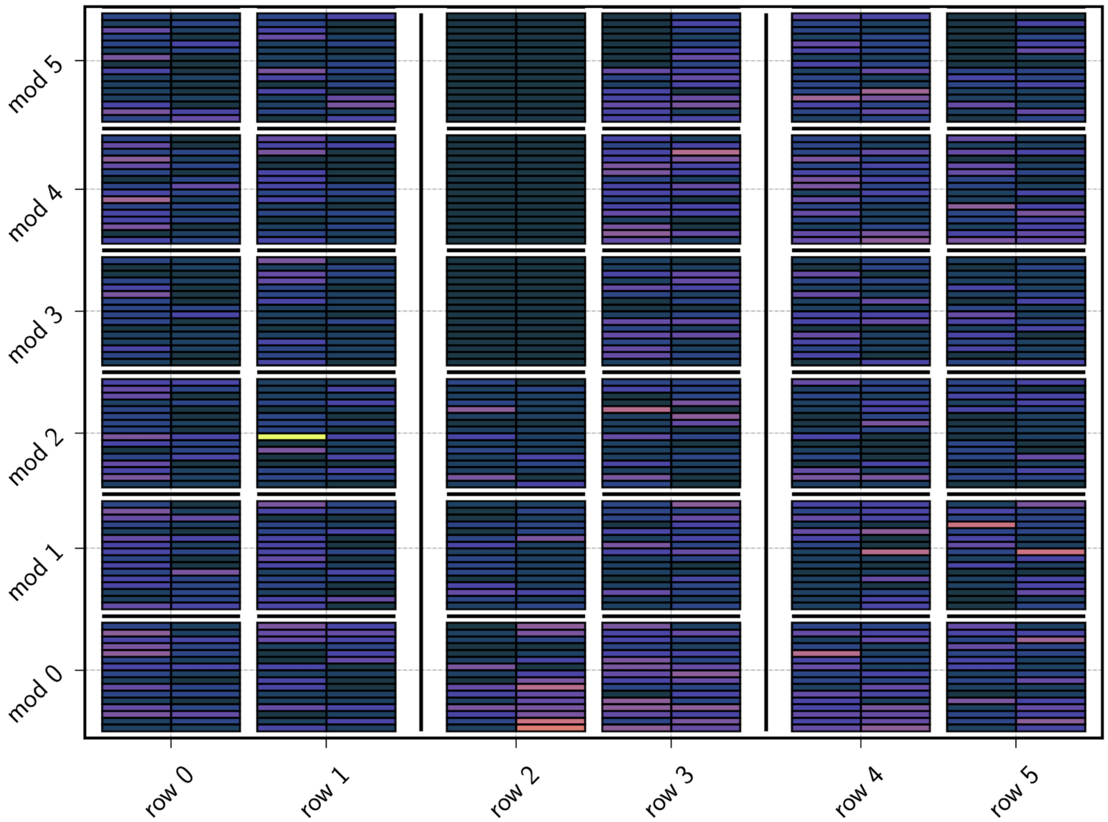
- prototype was built in fall 2021
- 3 layers of Si(Li) tracker (36 modules): readout with flight ASIC
- 2 layers of TOF above



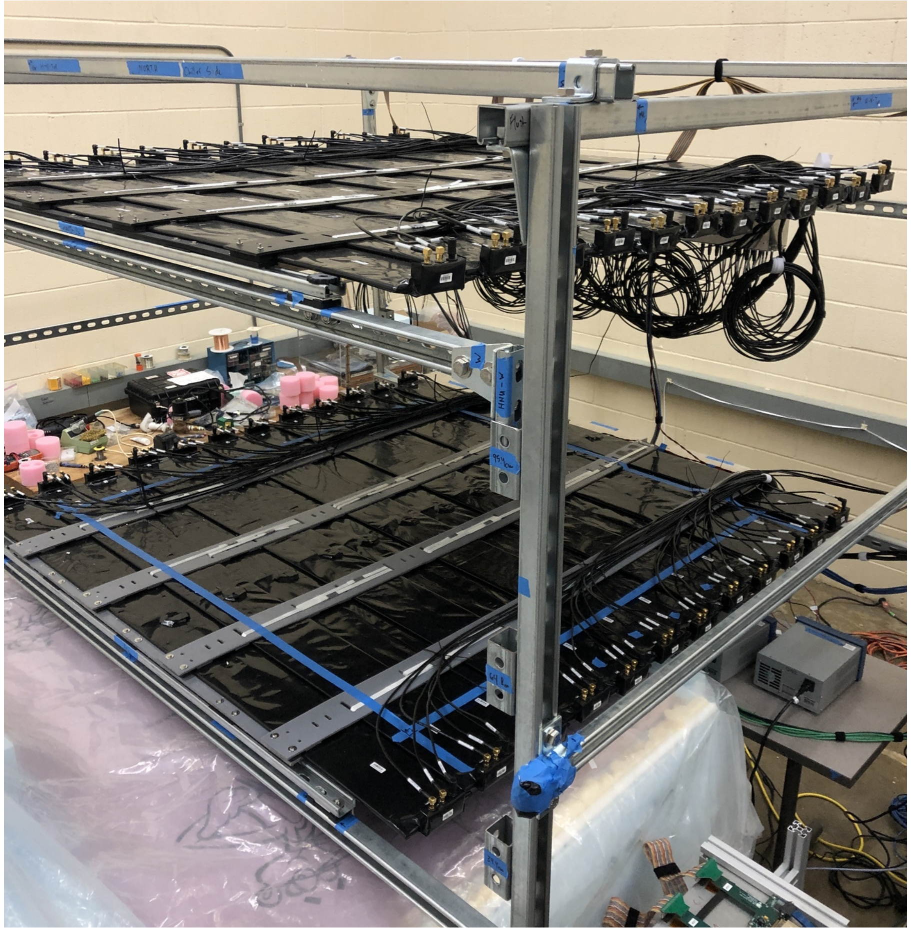
- **Goals:**
  - test and operate all components together
  - test readout chain
  - collect X-ray data
  - collect muon data → tracking

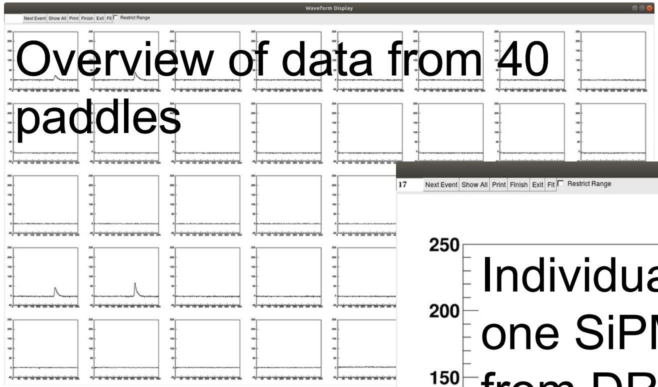
GFP tracker

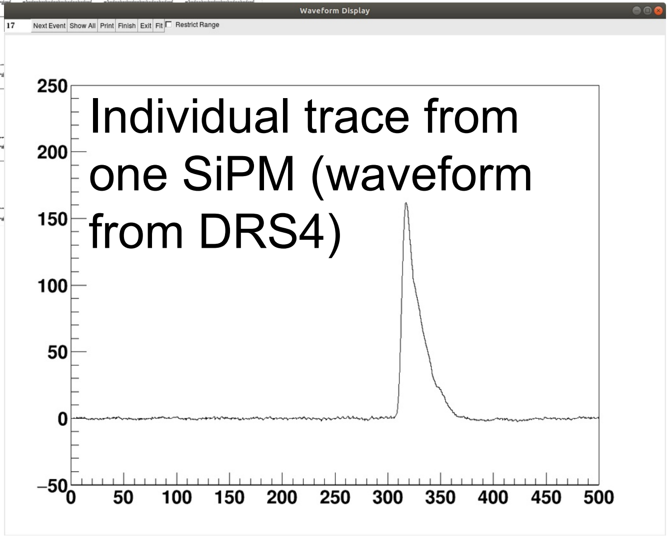
- approx 1h of muon data
- all tracker detectors which we expected to be operating did report data



GFP TOF





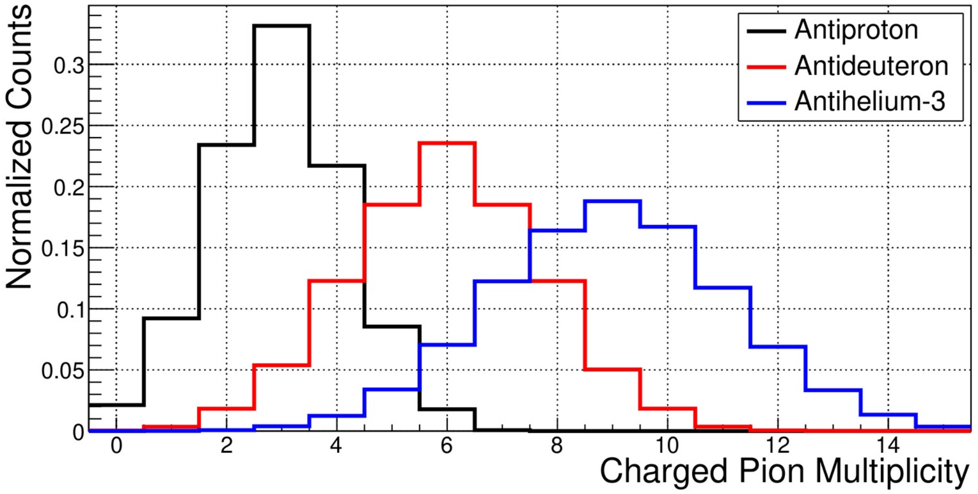


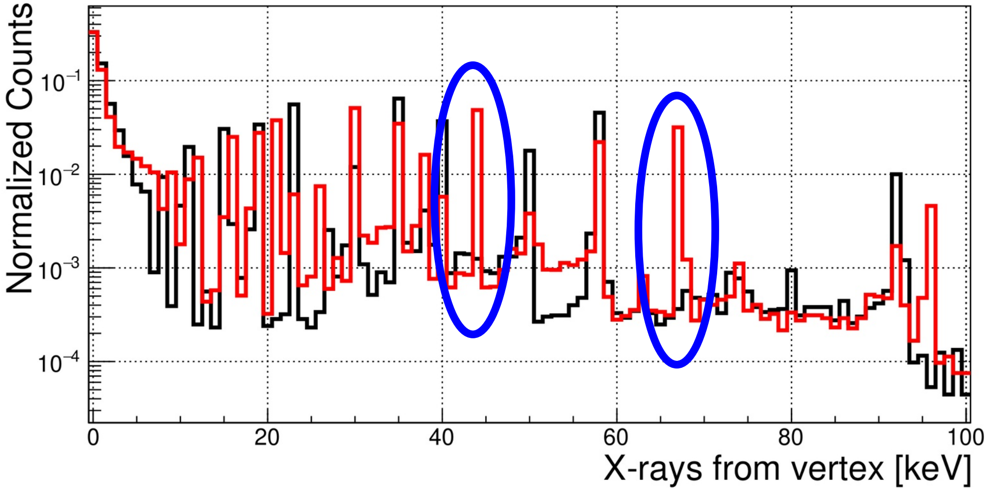
- TOF data look good so far
- Charge and voltage peak distributions look very clean and as expected
- Position resolution about 3cm (using σ_t=400ps)

GAPS identification technique

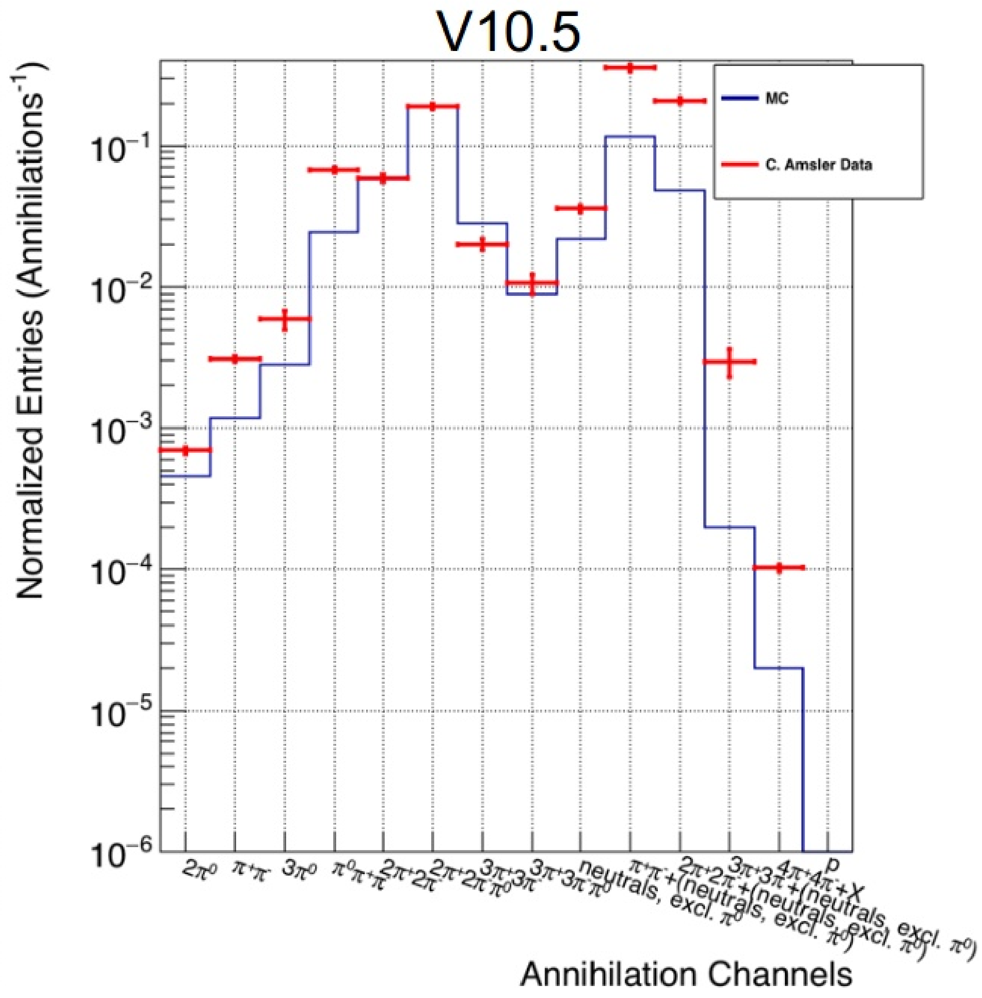
GAPS identification technique uses:

- Energy loss in the detector of the antinucleus (depends on Z and β)
- Deexcitation X-rays from exotic atom
- Multiplicity of charged annihilation products





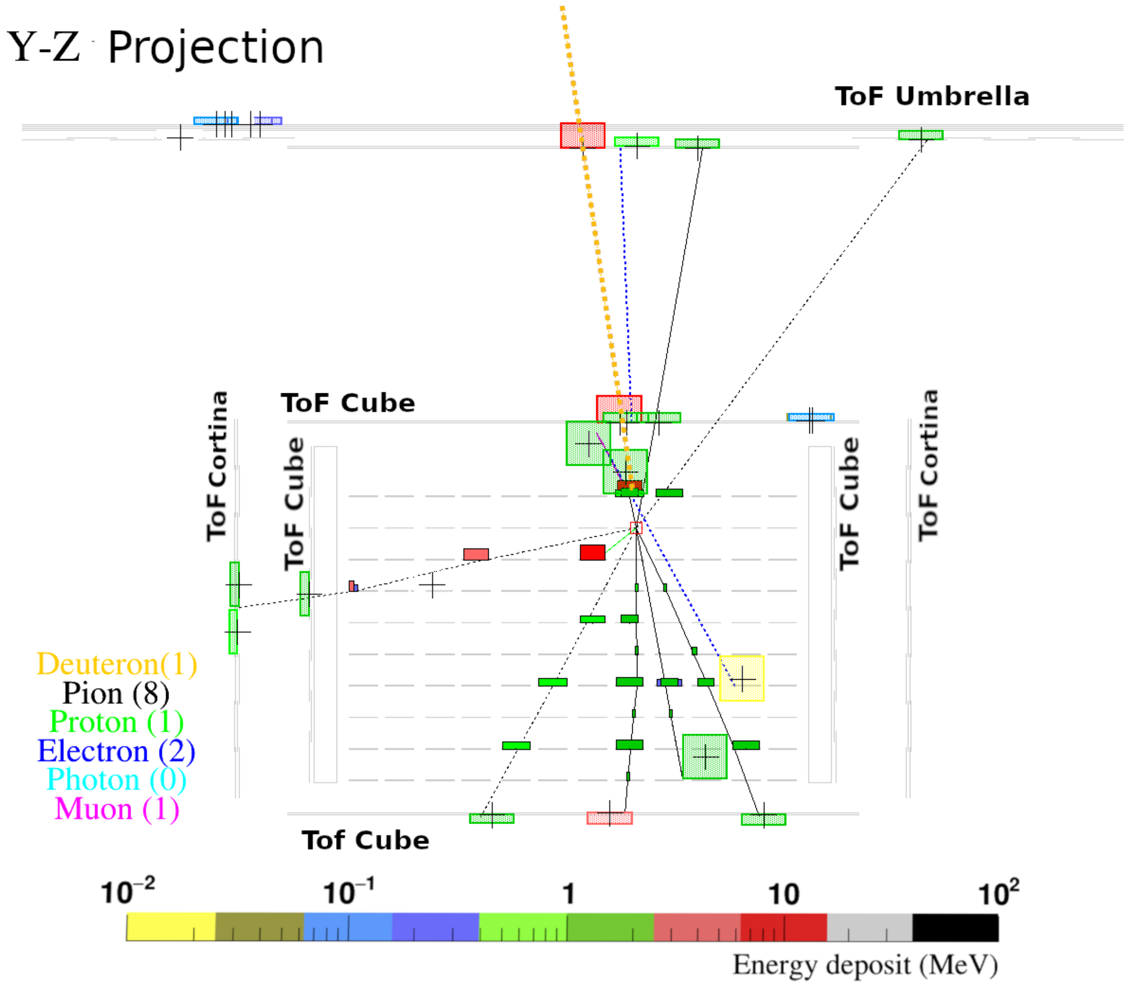
$\bar{p}$+p annihilation at rest



- test of annihilation physics in Geant4 is ongoing
- use antiproton data for validation
- work with Geant4 developers

Event reconstruction

R. Munini et al., Astropart. Phys. 133, 102640 (2021)

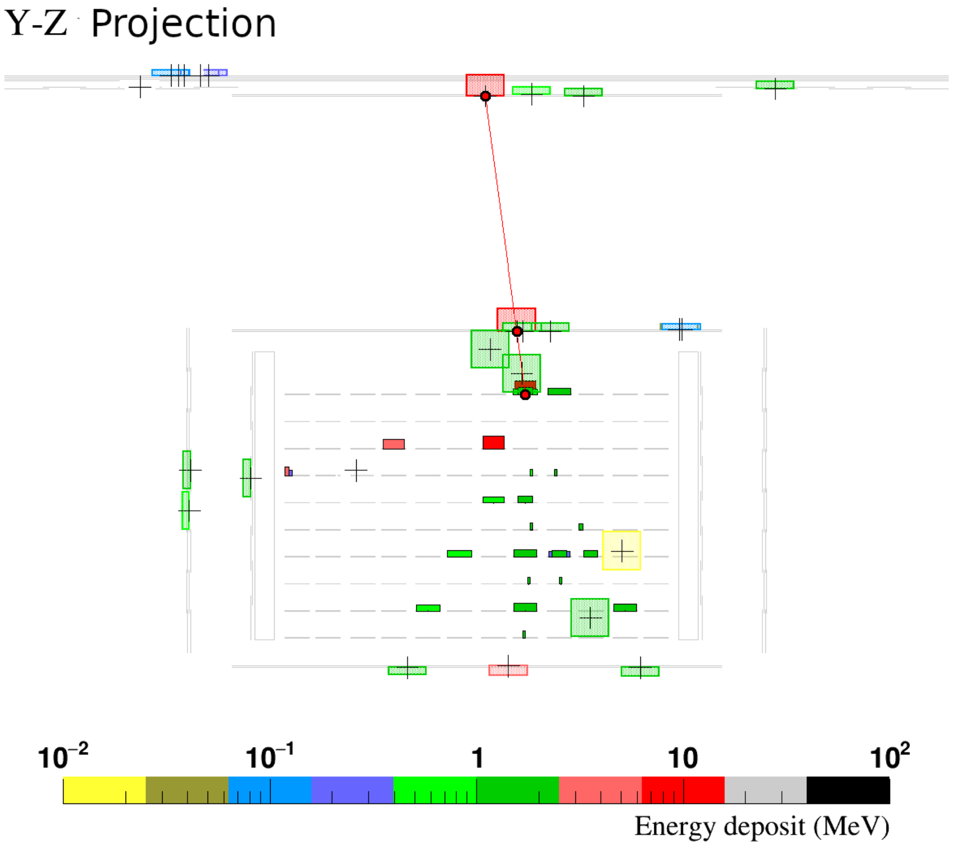


- For the event reconstruction it is critical to identify a well defined primary track $\rightarrow \beta$ measurement, energy deposition, column density
- The primary track is used as a seed for the determination of the stopping vertex with the corresponding secondary tracks

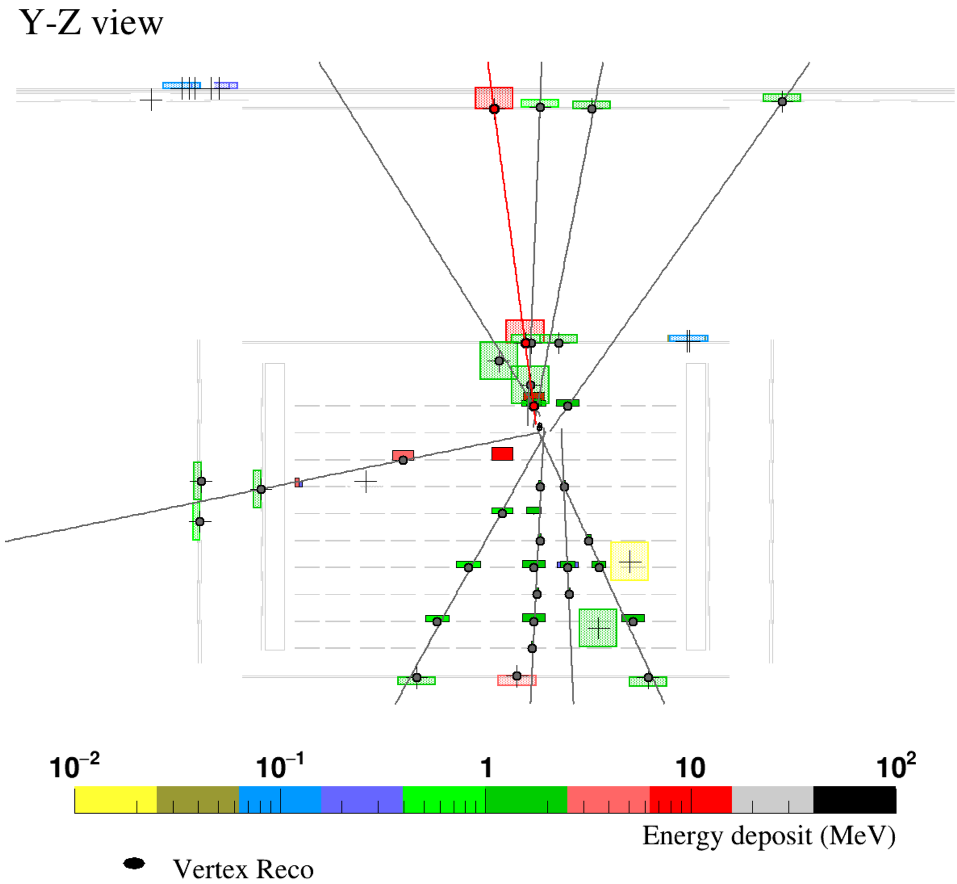
Event reconstruction

R. Munini et al., Astropart. Phys. 133, 102640 (2021)

Primary track reconstruction

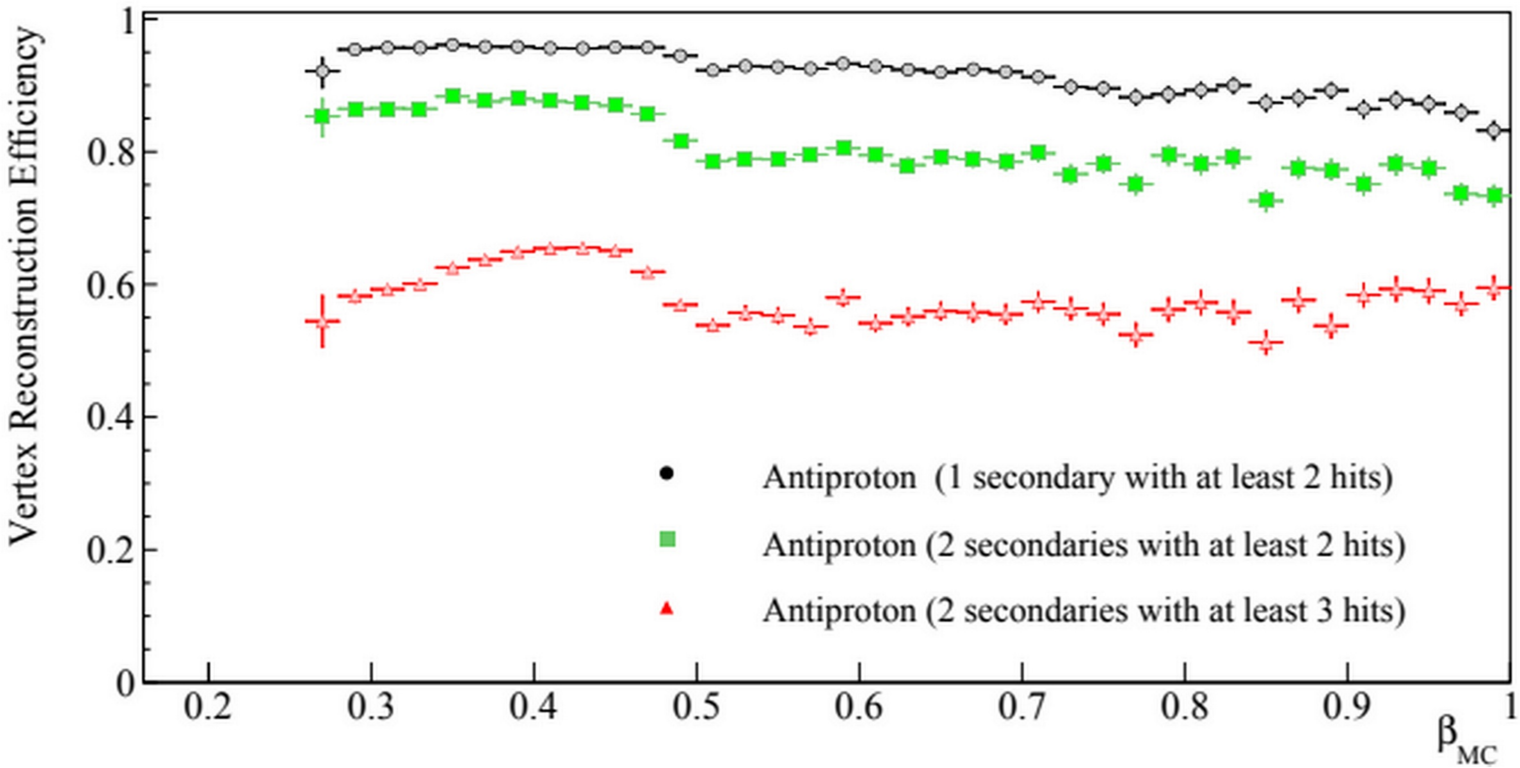


Annihilation track reconstruction



Vertex reconstruction efficiency

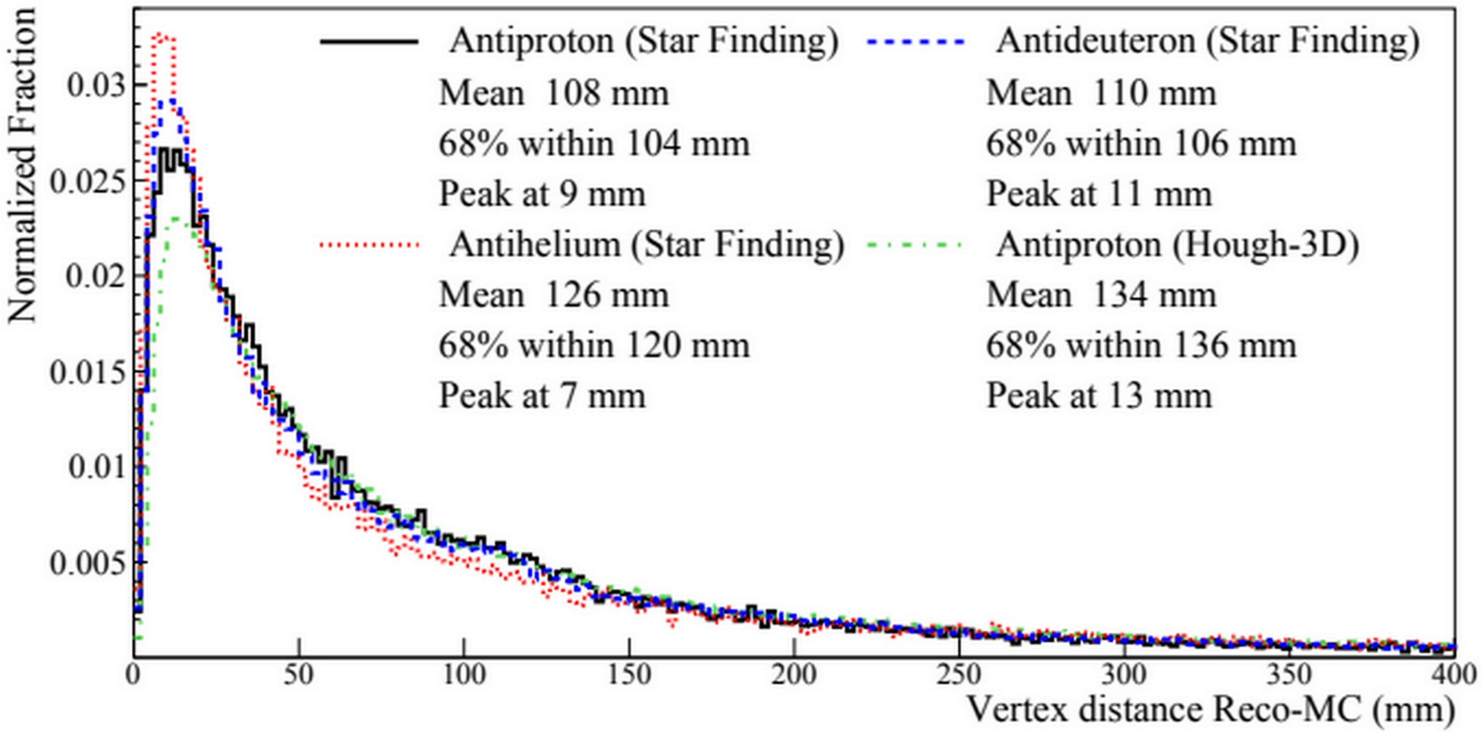
R. Munini et al., Astropart. Phys. 133, 102640 (2021)



- The vertex is the position in space which minimize the distances from all the reconstructed tracks

Vertex resolution

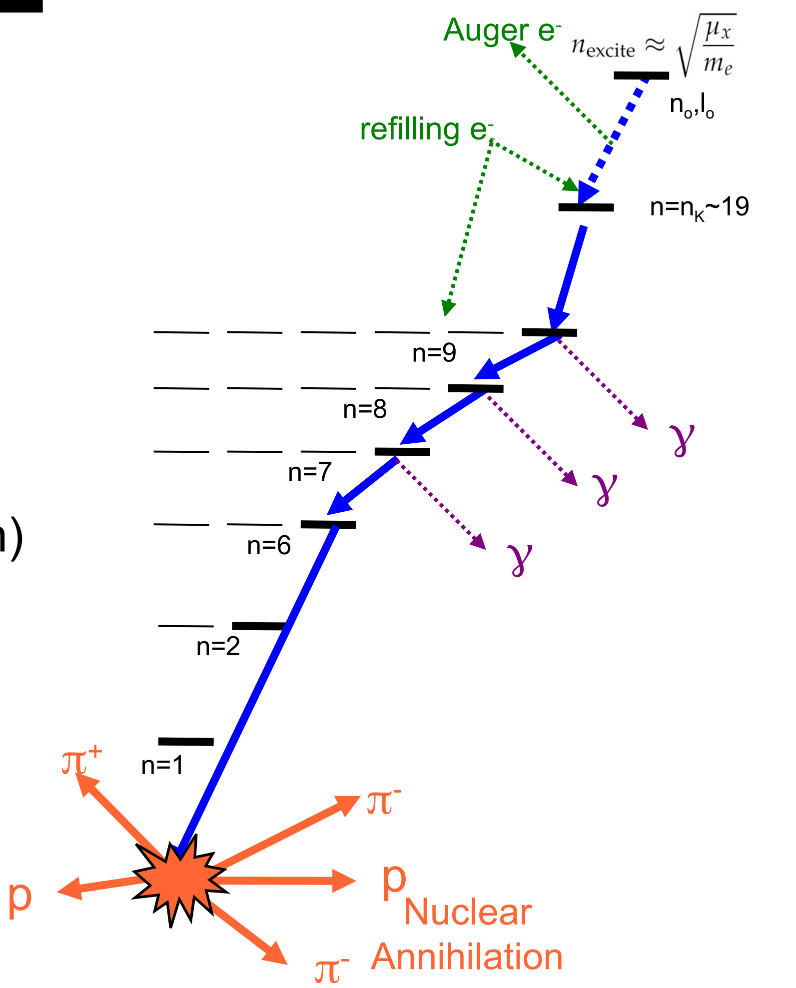
R. Munini et al., Astropart. Phys. 133, 102640 (2021)



- The vertex is the position in space which minimize the distances from all the reconstructed tracks

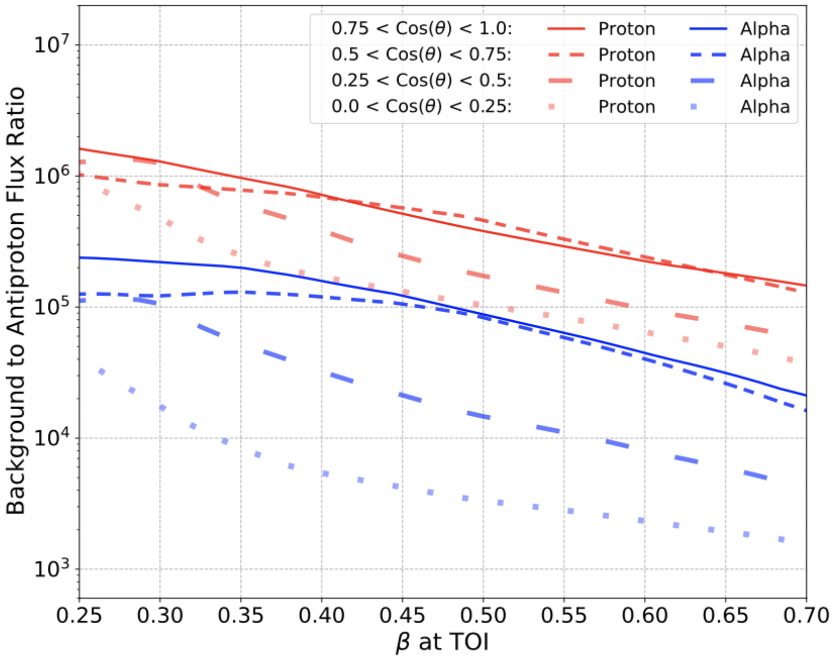
Deexcitation X-rays

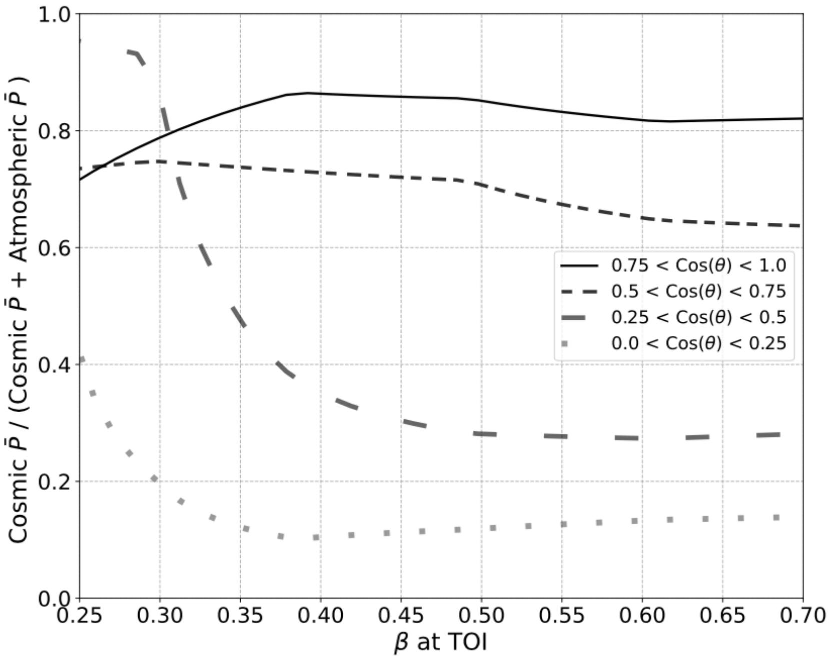
- antiparticle slows down and stops in material
- large chance for creation of an excited exotic atom (E_{kin}~E_I)
- deexcitation:
  - fast ionization of bound electrons (Auger) → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic X-ray transitions depending on antiparticle mass
- exotic atomic X-ray model for antinuclei was implemented in Geant4 for Si, C, Al
- other X-rays: decay of daughter nuclei (e.g., Al, Mg, Na) → good understanding required



Aramaki et al., Astropart. Phys. 74, 6 (2016)

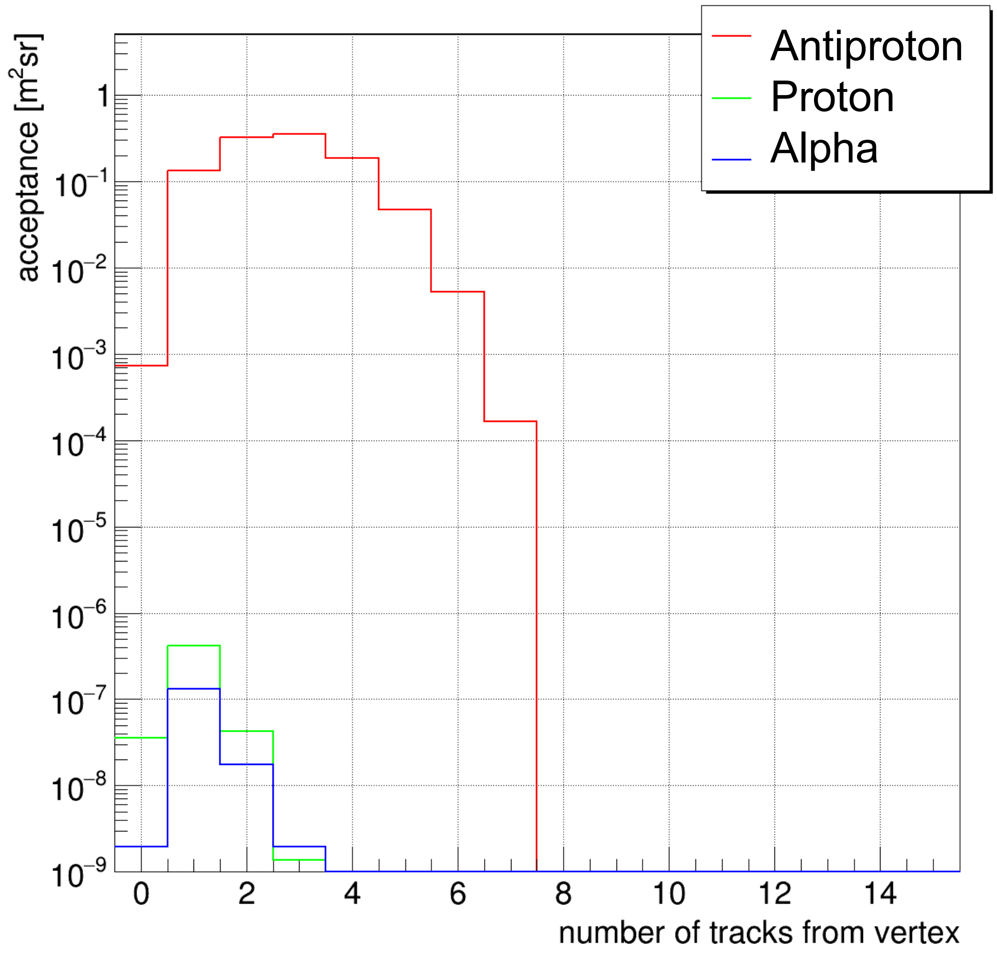
Antiproton sensitivity





- Demonstrate GAPS sensitivity for cosmic antiprotons using the full GAPS simulation and event reconstruction
- Atmospheric interaction have to be taken into account:
  - Propagation top-of-atmosphere (TOA) fluxes through atmosphere to top-of-instrument (TOI) with PLANETOCOSMICS
  - Rejection of positive nucleus backgrounds (primarily p and α) required at the level of ~10^6 for a clean antiproton sample
  - Atmospherically-produced antiprotons are an intrinsic background for the cosmic measurement, forming the bulk of the TOI antiproton flux for cos(θ) < 0.5
  - Attenuation effects of cosmic antiprotons need to be corrected for

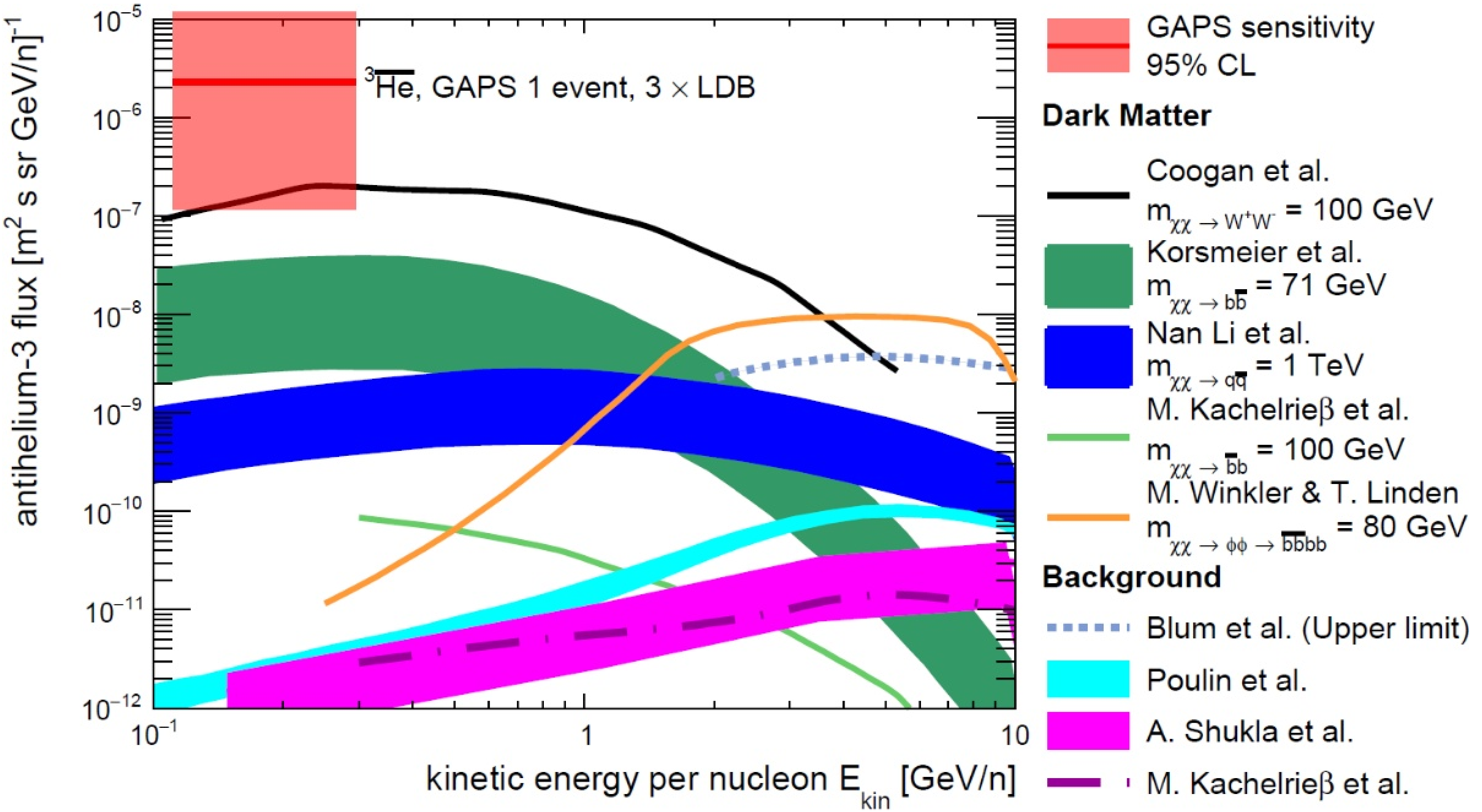
Antiproton identification



- Select events without obvious interactions in the TOF
- Ensure proper velocity reconstruction to reduce background from high-velocity particles
- Use of different identification variables for the final selection of antiprotons:
  - Number of tracks from vertex
  - Average velocity of tracks from vertex (slow for particles, fast for antiparticles)
  - Number of hits in tracker
  - Average energy deposition per hit
  - Energy depositions in outer and inner TOF
  - Total energy depositions on the primary track
  - Isotropy of annihilation signature
- **Updated antiproton sensitivity will be published soon**

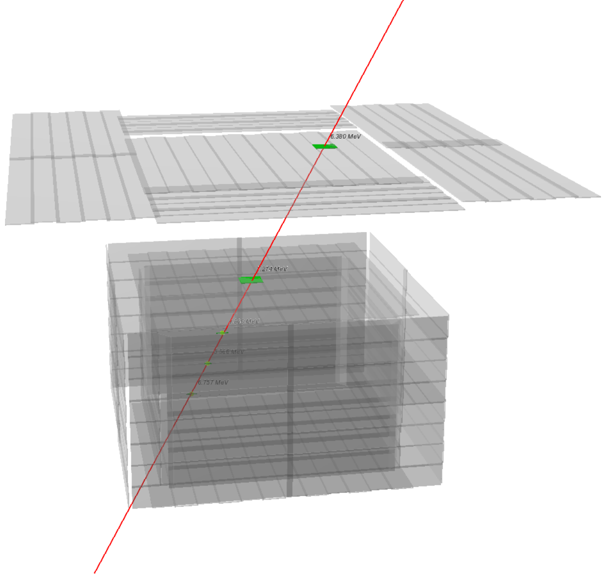
Antihelium-3 sensitivity

N. Saffold et al., Astropart. Phys. 130, 102580 (2021)



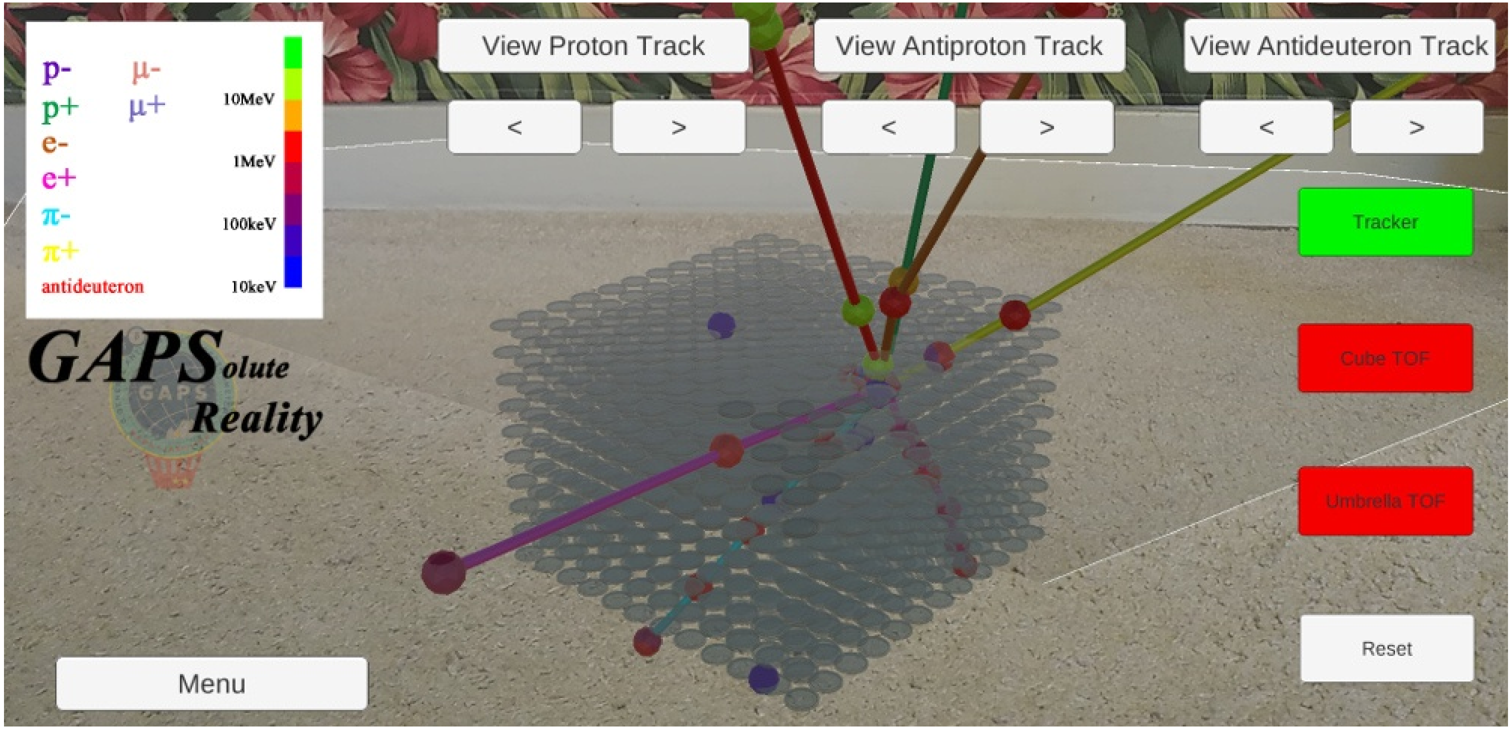
Other analysis development

- Proton, alpha, deuteron: “first light“ physics (~100 million events per flight):
  - Calibrate instrument, understand trigger, atmospheric effects
  - Use in antiparticle analysis: clean way to study energy deposition behavior of deuterons and protons without annihilation products
  - d/He ratio can provide constraints on cosmic-ray galactic propagation
  - alpha break-up in the atmosphere into deuterons will help understand the atmospheric model



- Machine learning techniques for more particle identification power: velocity reconstruction, energy deposition corrections, vertex reconstruction

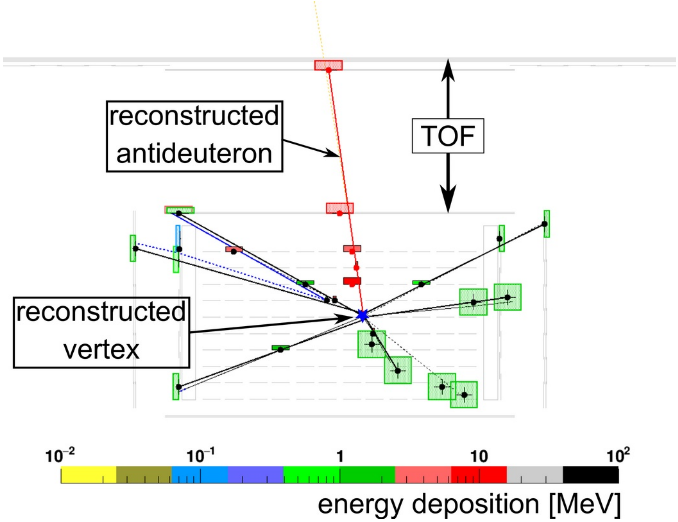
GAPS augmented reality app



- Undergrad L. Fujioka developed AR app for Android with UROP funding: https://www.phys.hawaii.edu/~philipvd/pvd_research_gapsapp.html
- Updates and iOS version are on the way

Integration started

GAPS path forward



- GAPS is the first experiment optimized specifically for low-energy antiprotons, antideuterons, and antihelium

- **GAPS will deliver:**
  - a precision antiproton measurement in an unexplored energy range <0.25 GeV/n
  - antideuteron sensitivity 2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range
  - the only complementary probe of the AMS-02 antinuclei signal

- GAPS instrument integration beginning now