Experimental Searches for Cosmic-ray Antinuclei with GAPS

Light Anti-Nuclei as a Probe for New Physics
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on behalf of the GAPS collaboration

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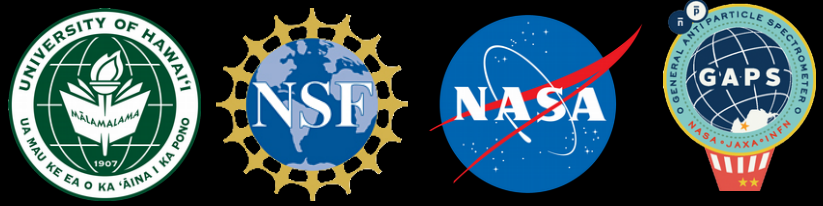


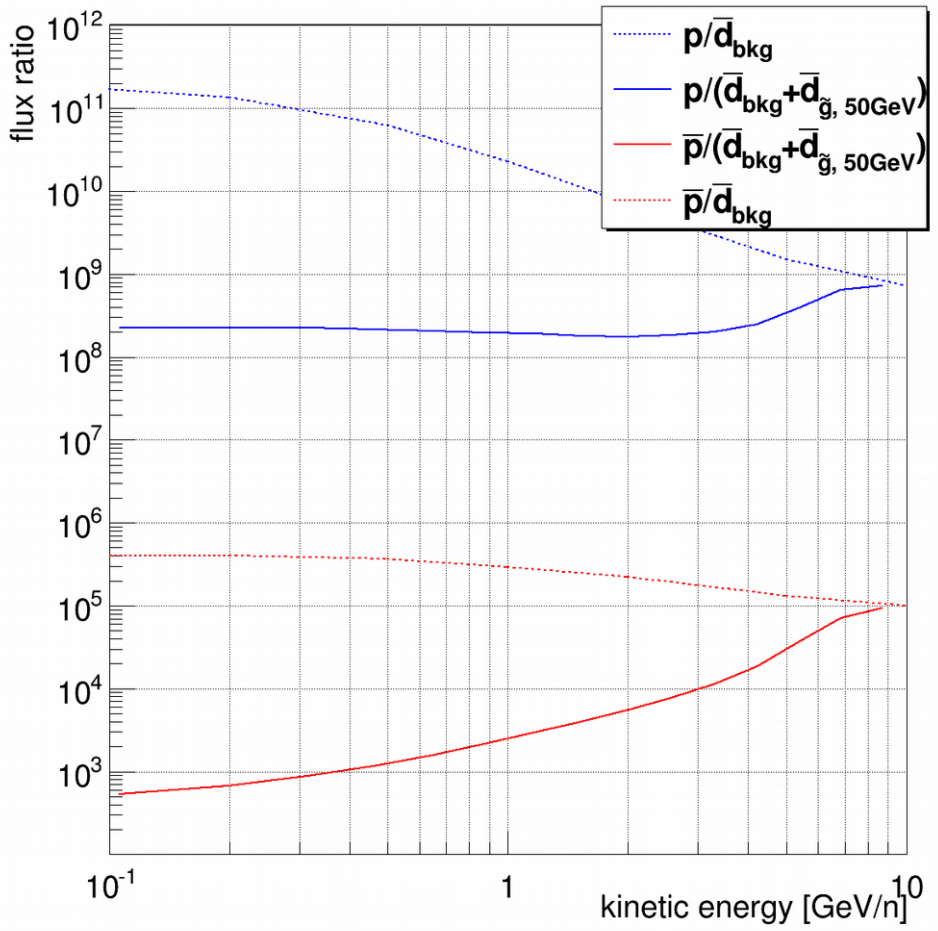
Antideuteron identification challenge

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

Columbia U, UCSD
UCLA, UCB,
U Hawaii, MIT

umbrella TOF

3.6m

cube TOF

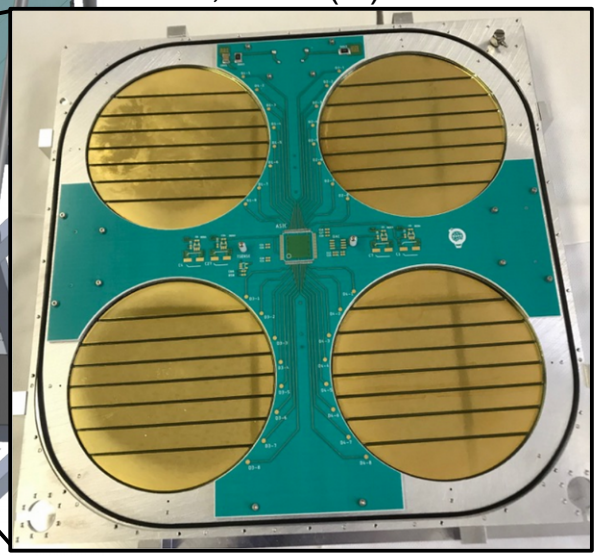
tracker

3m

mass: ~2,500kg
power: 1.5kW

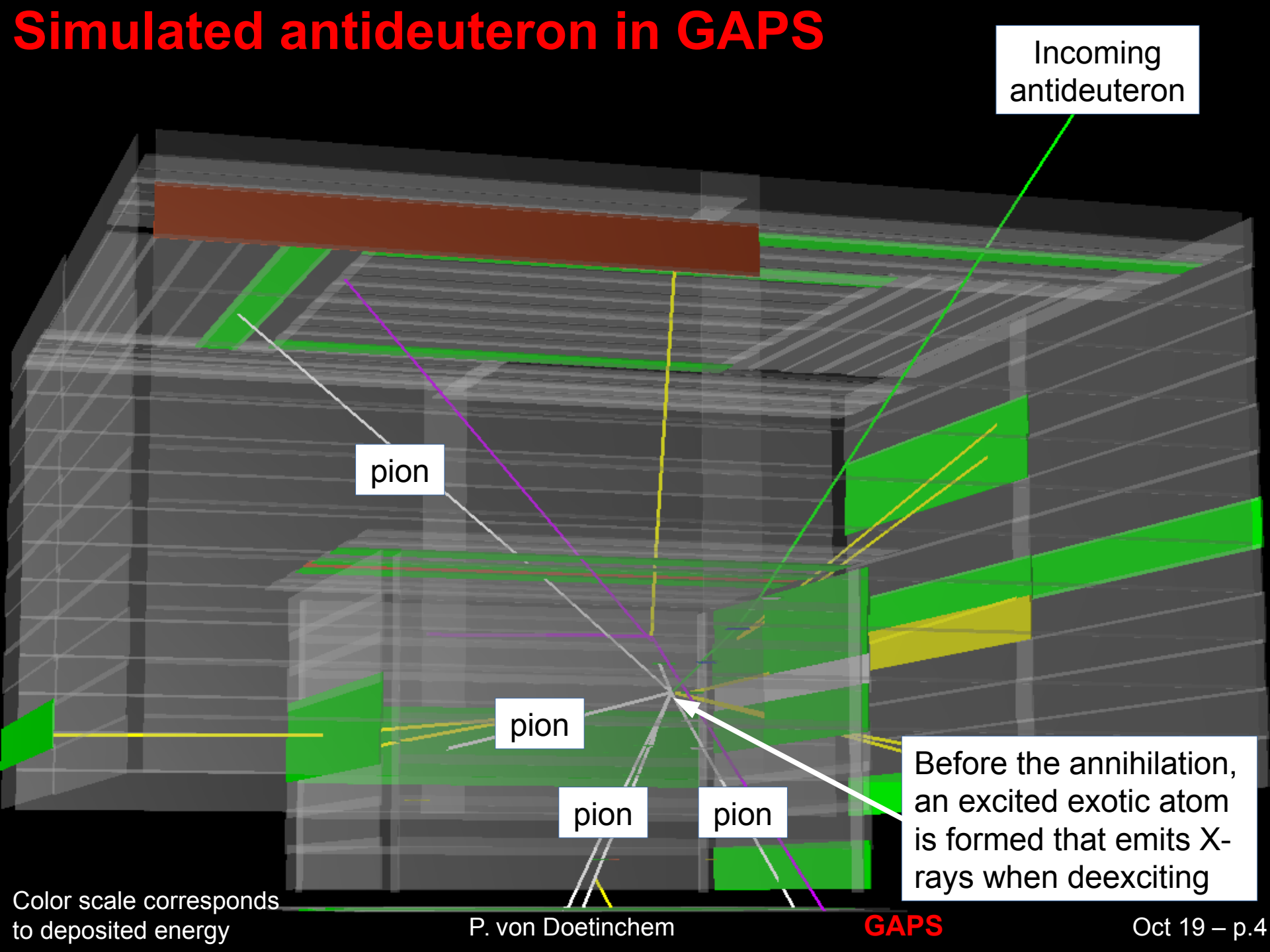
TOF with SiPM readout

More than 1,000 Si(Li) wafers



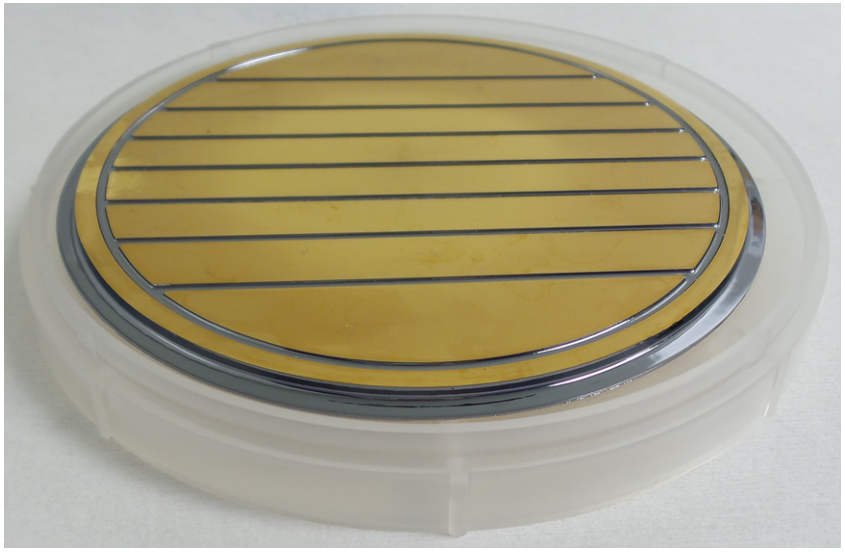
- the **G**eneral **A**nti**P**article **S**pectrometer is specifically designed for low-energy antideuterons, antiprotons and antihelium nuclei
- **GAPS is under construction → first Long Duration Balloon flight from Antarctica in late 2021/early 2022**

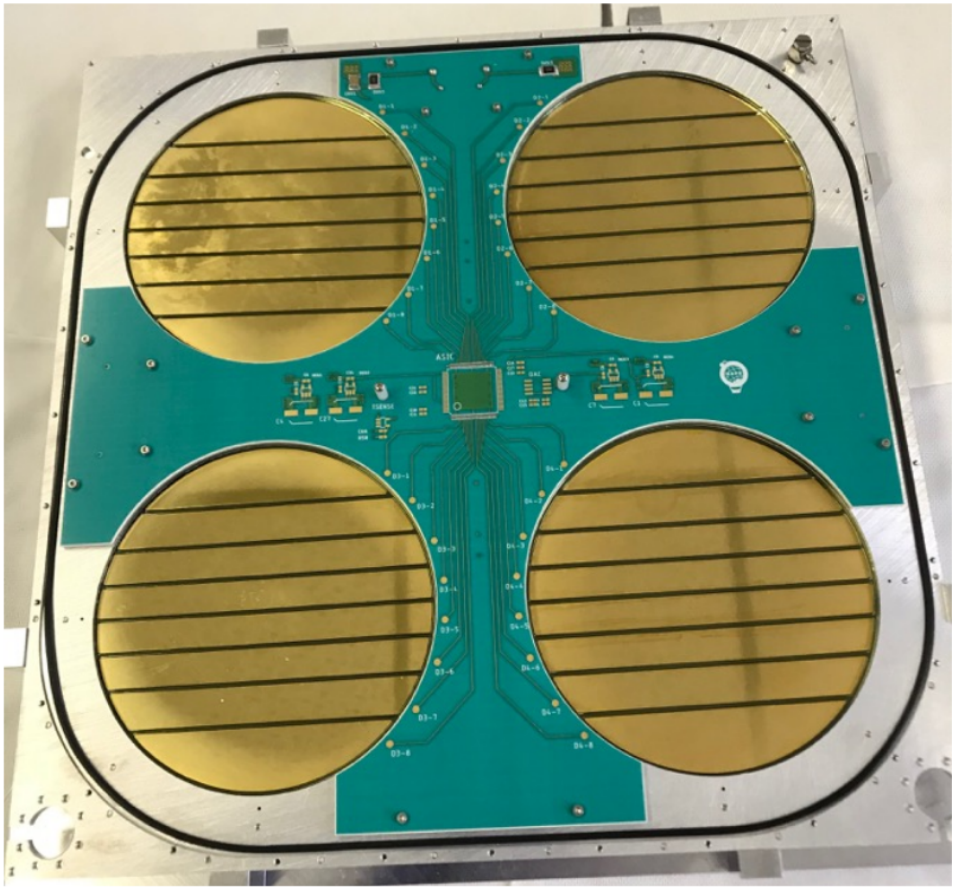
Simulated antideuteron in GAPS



Color scale corresponds to deposited energy

Tracker construction



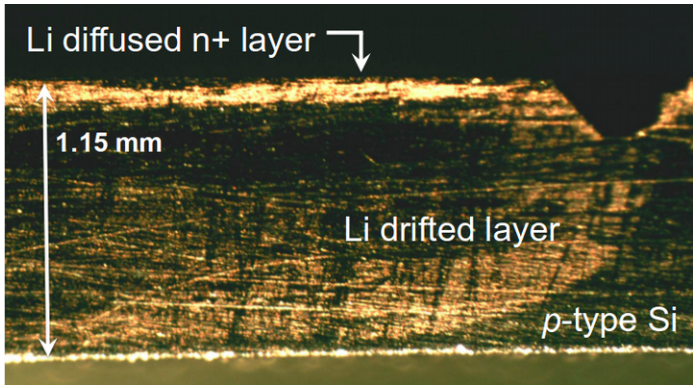


- GAPS will use 1,440 4” Si(Li) detectors, 2.5mm thick
- Operation at relatively high temp of -35C to -45C
- Fabrication scheme developed at Columbia U and MIT, produced by private company Shimadzu, Japan

- **Fabrication started:** 420 detectors produced, 81 detectors are passivated

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



(a) Evaporate and diffuse initial Li layer

(b) Cut circular groove and apply contact

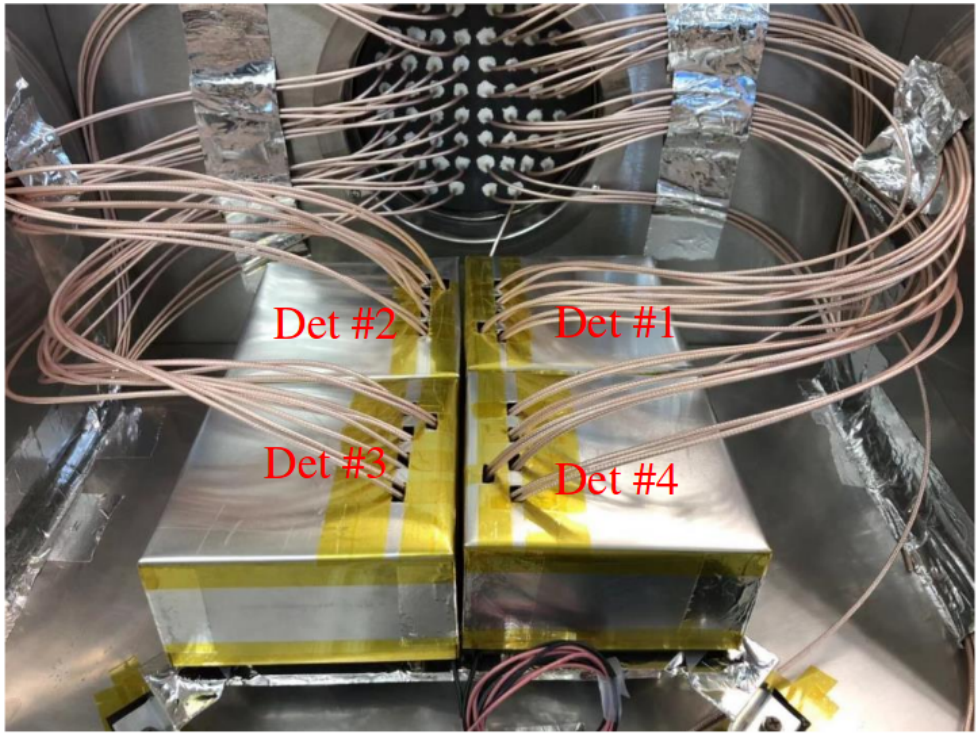
(c) Drift Li through wafer

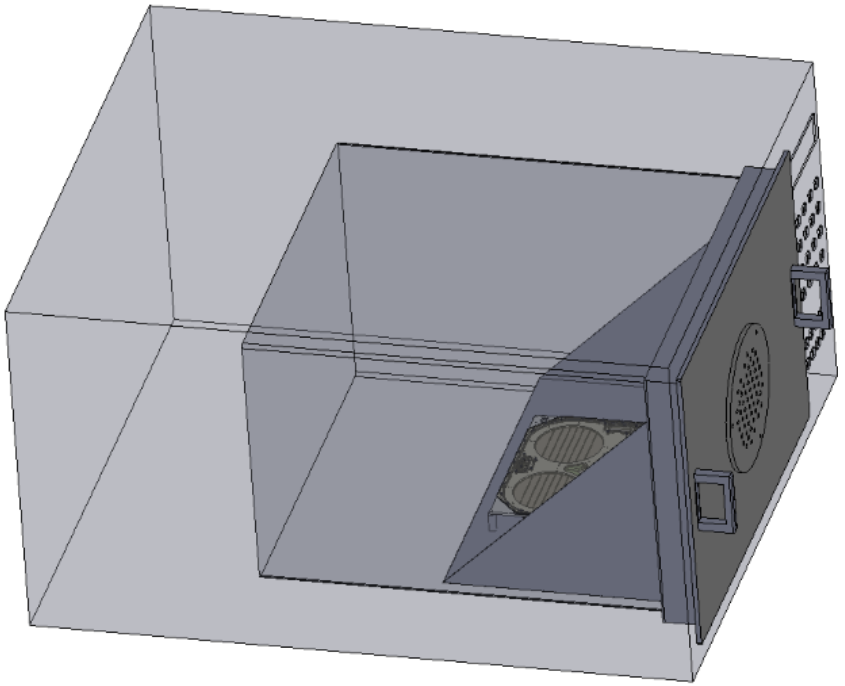
(d) Remove contacts and diffuse second, shallower Li layer

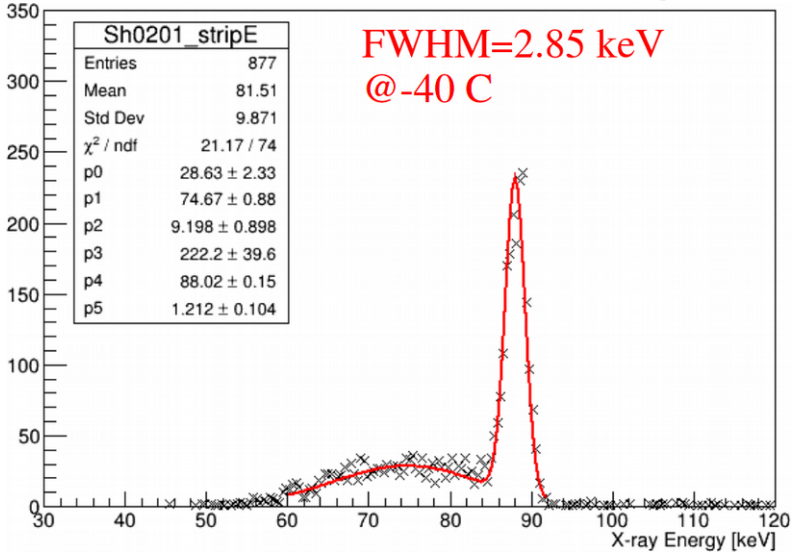
(e) Cut guard ring groove and re-apply contacts

Perez et al., NIM A 905, 12 (2018)
Kozai et al., NIM A 947, 162695 (2019)
Rogers et al., JINST 14, P10009 (2019)

Tracker testing

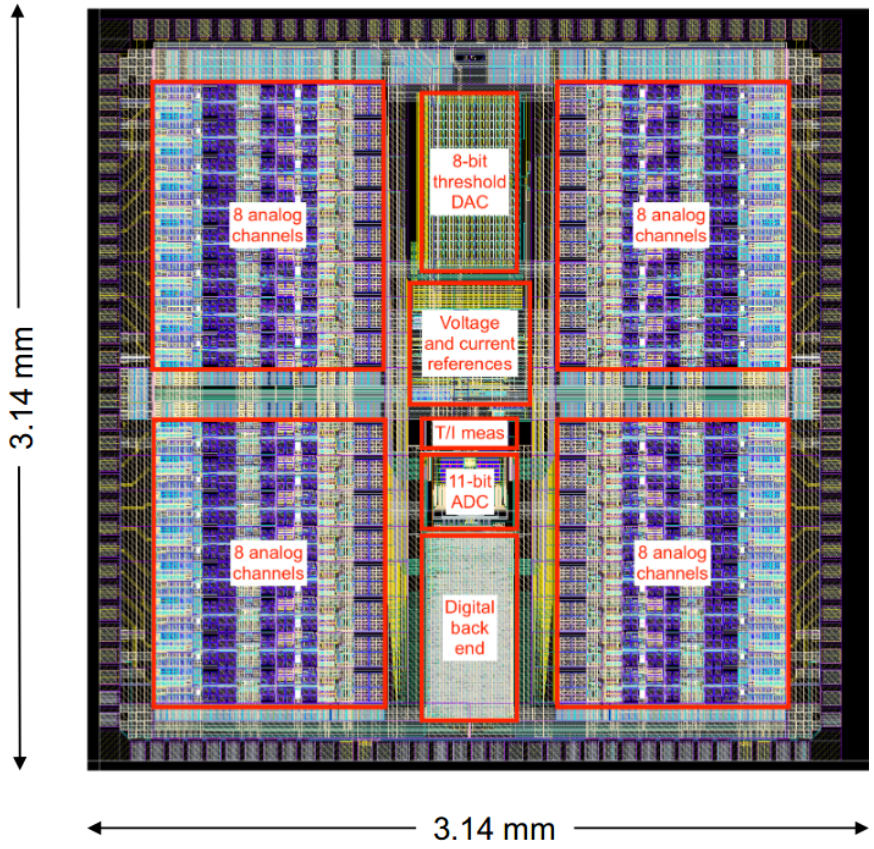


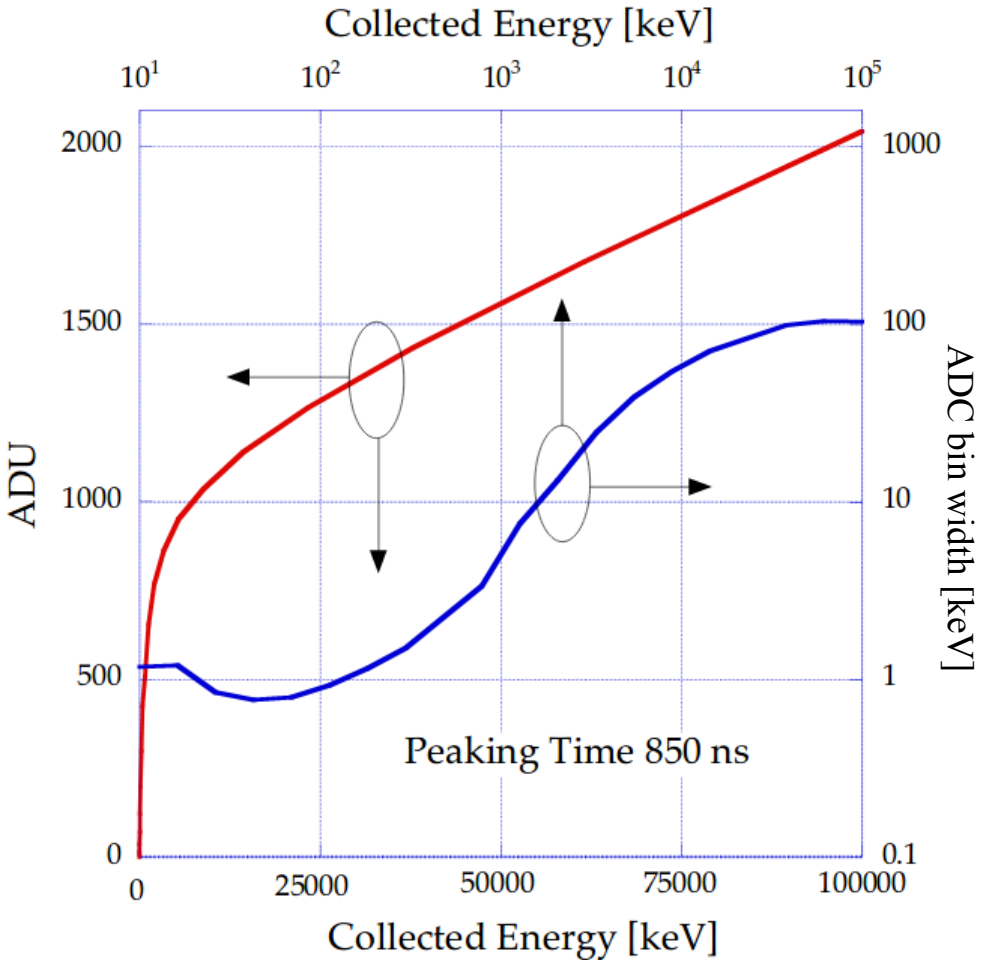




- Single detector test shows the required resolution of the detectors
- Detector module calibration facilities are set up (or in process) at MIT, UH, Columbia

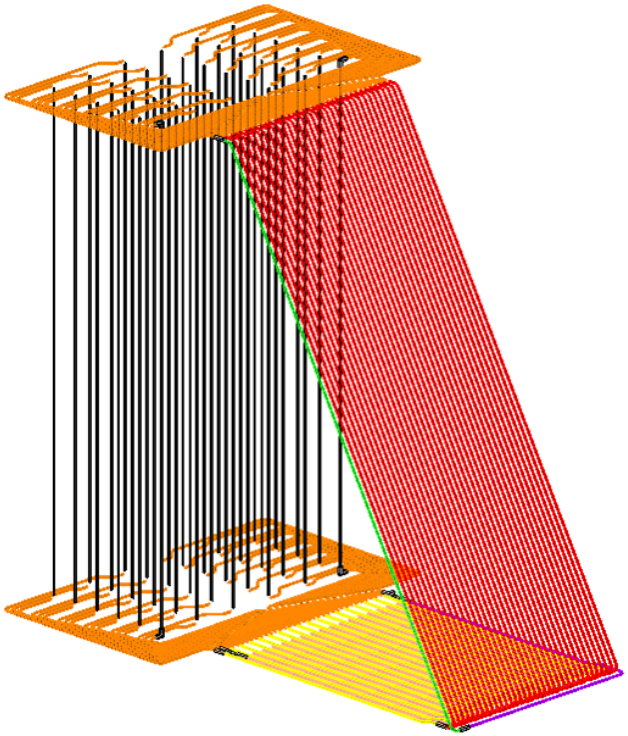
Tracker electronics

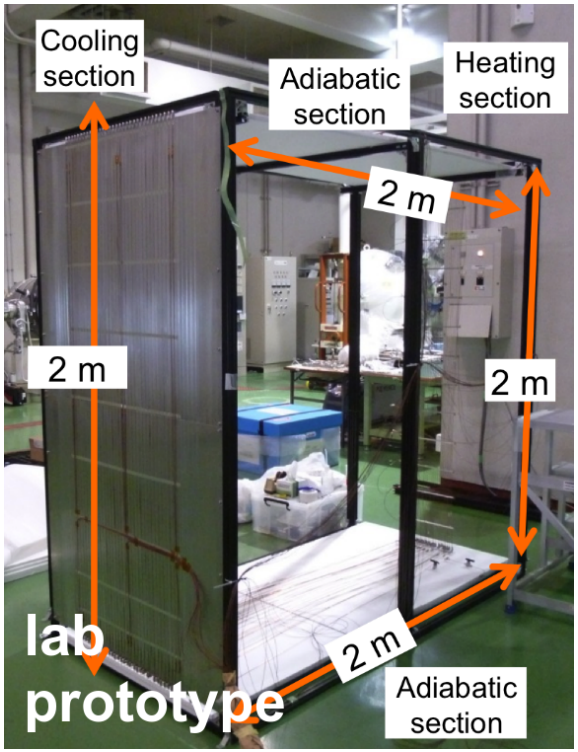


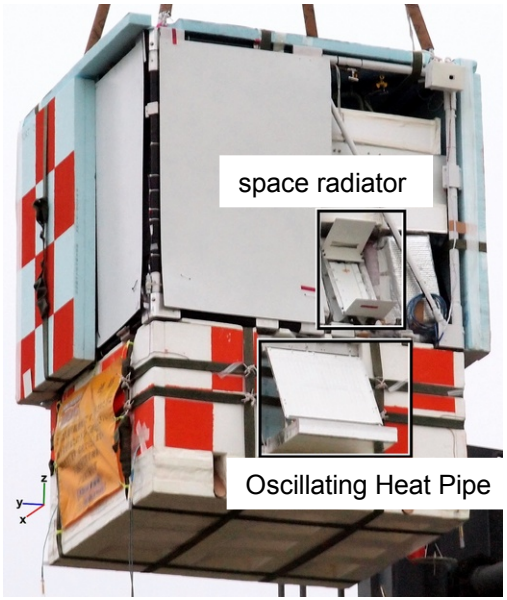


- readout via custom ASIC: integrated low-noise preamplifier
- large dynamic range: 20keV to 100MeV
- 32 analog readout channels
- 11 bits ADC

Oscillating heat pipe cooling system

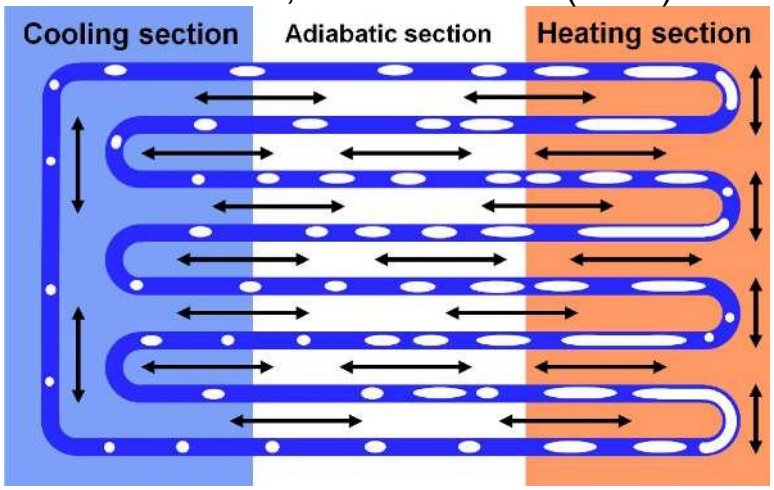






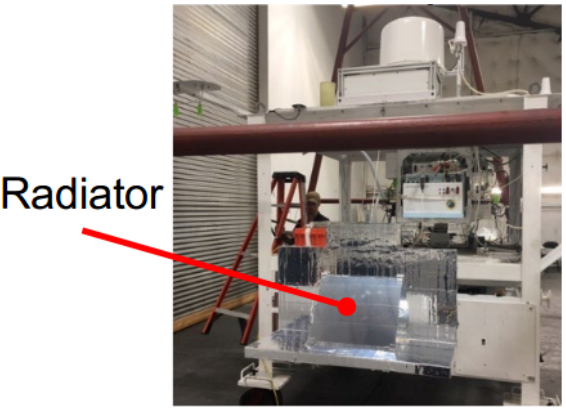
2012 prototype

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



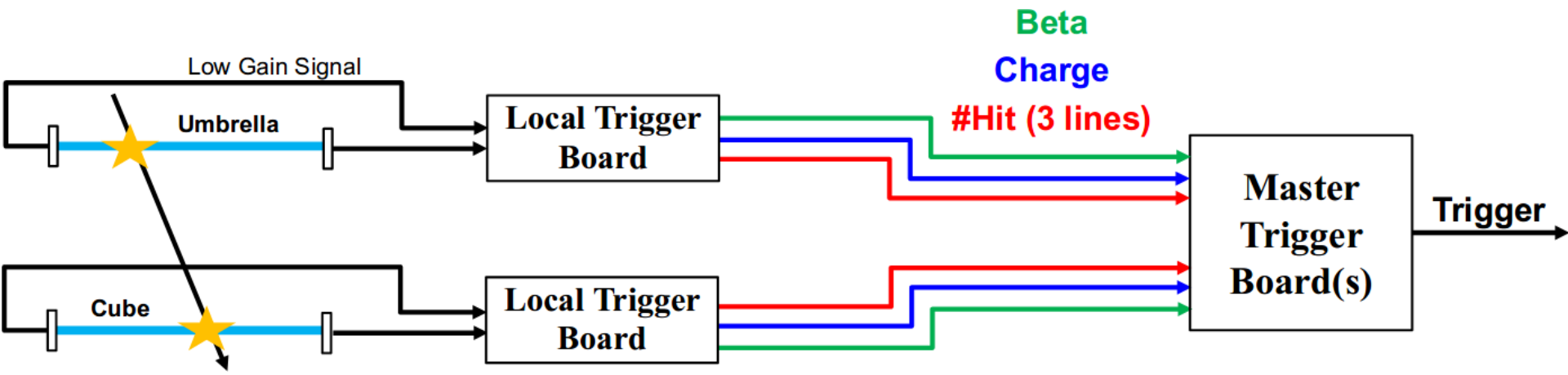
- passive cooling approach:
  - small capillary metal tubes filled with a phase-changing refrigeration liquid
  - small vapor bubbles form in the fluid → expand in warm sections/contract in cool sections
  - rapid expansion and contraction of these bubbles create thermo-contraction hydrodynamic waves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

Radiator test flight



- a scaled radiator was flown from Ft. Sumner on Sep. 23, 2019
- radiator data was stored onboard, successfully recovered on Sep. 25
- data will be compared to thermal model
- the radiator recorded temperatures around -60C at float as expected
- analysis is ongoing

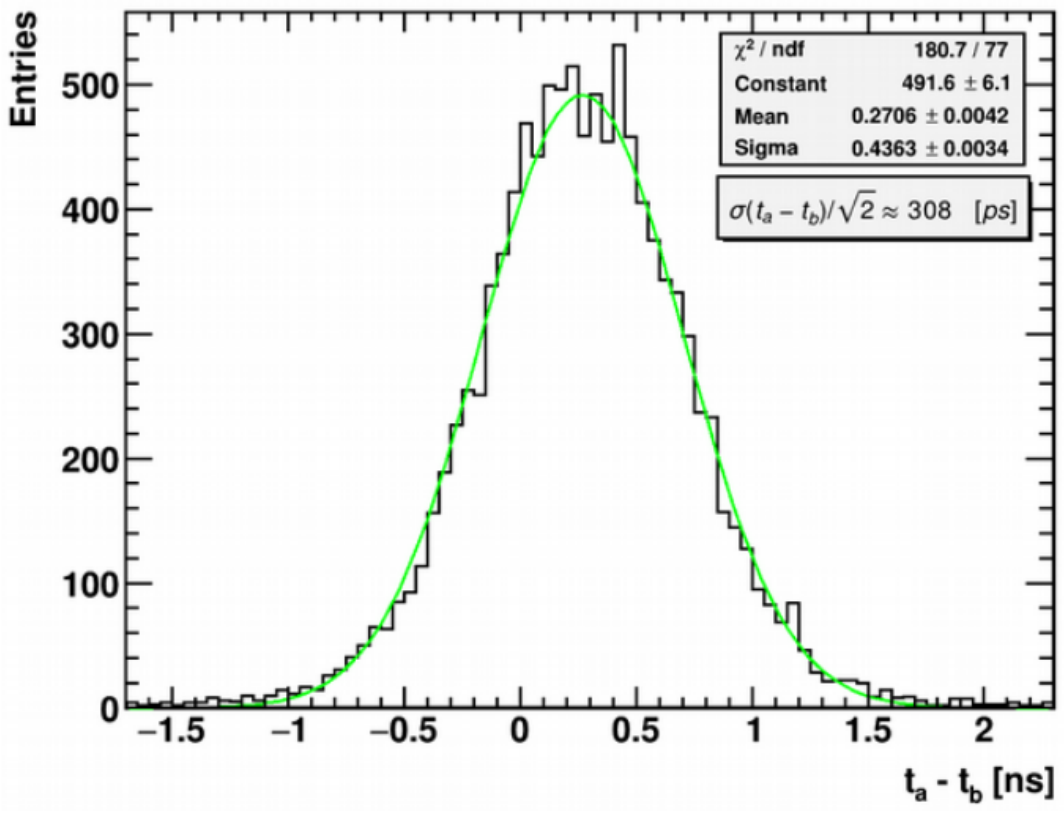
Trigger design



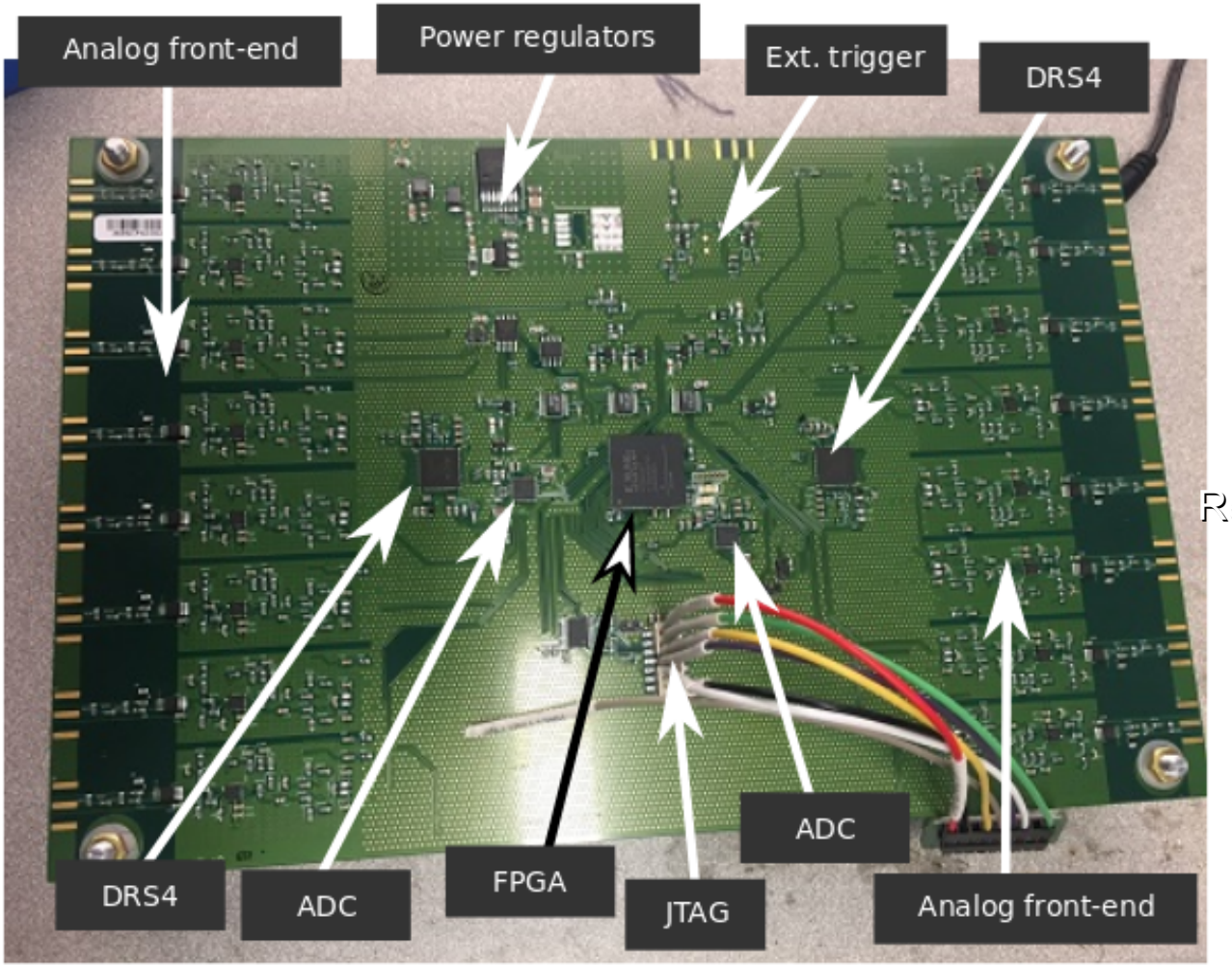
- main background: protons, alpha, carbon
- High-speed trigger and veto:
  - stopping events deposit more energy (lower beta)
  - background events have shorter time between Umbrella and Cube (higher beta)
  - annihilation events produce more TOF hits
  - paddle combinations can be used to constrain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

TOF timing

- 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



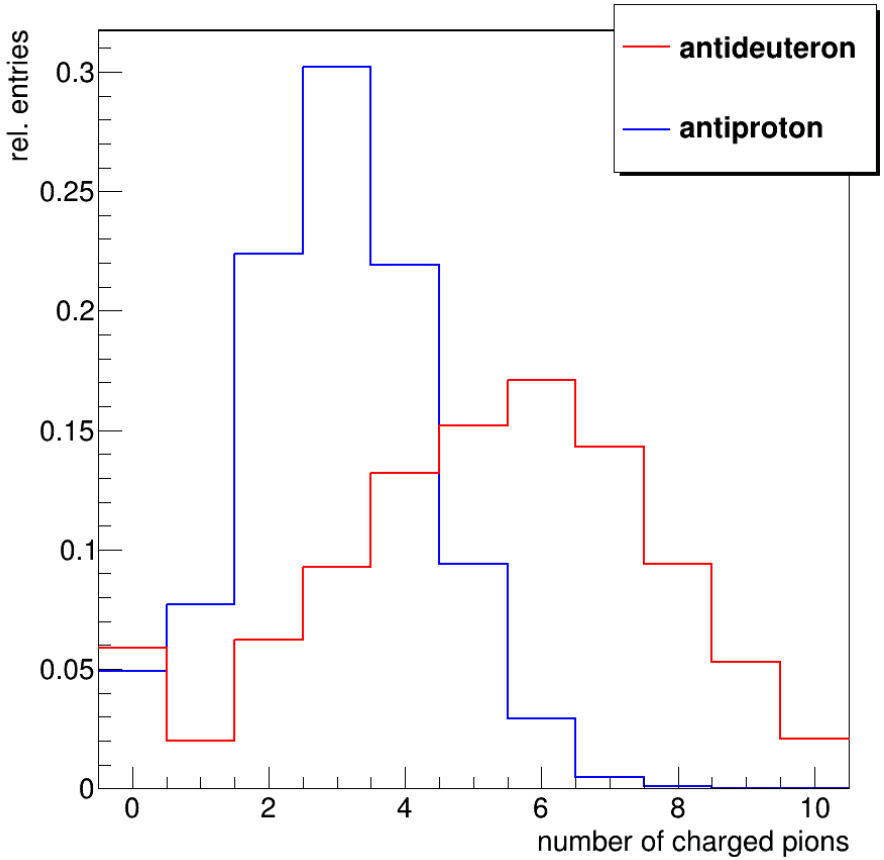
TOF electronics



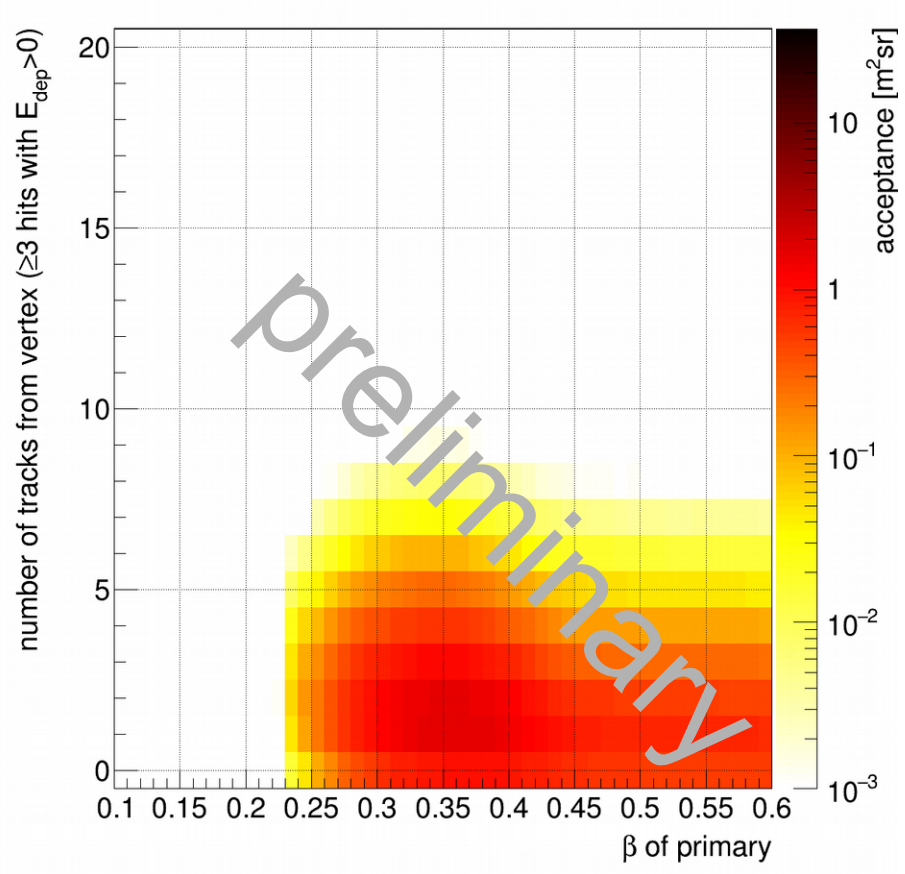
Rev1 board

- TOF testing and development ongoing: Rev1 testing completed, Rev2 read out board ongoing

Hadronic annihilation products



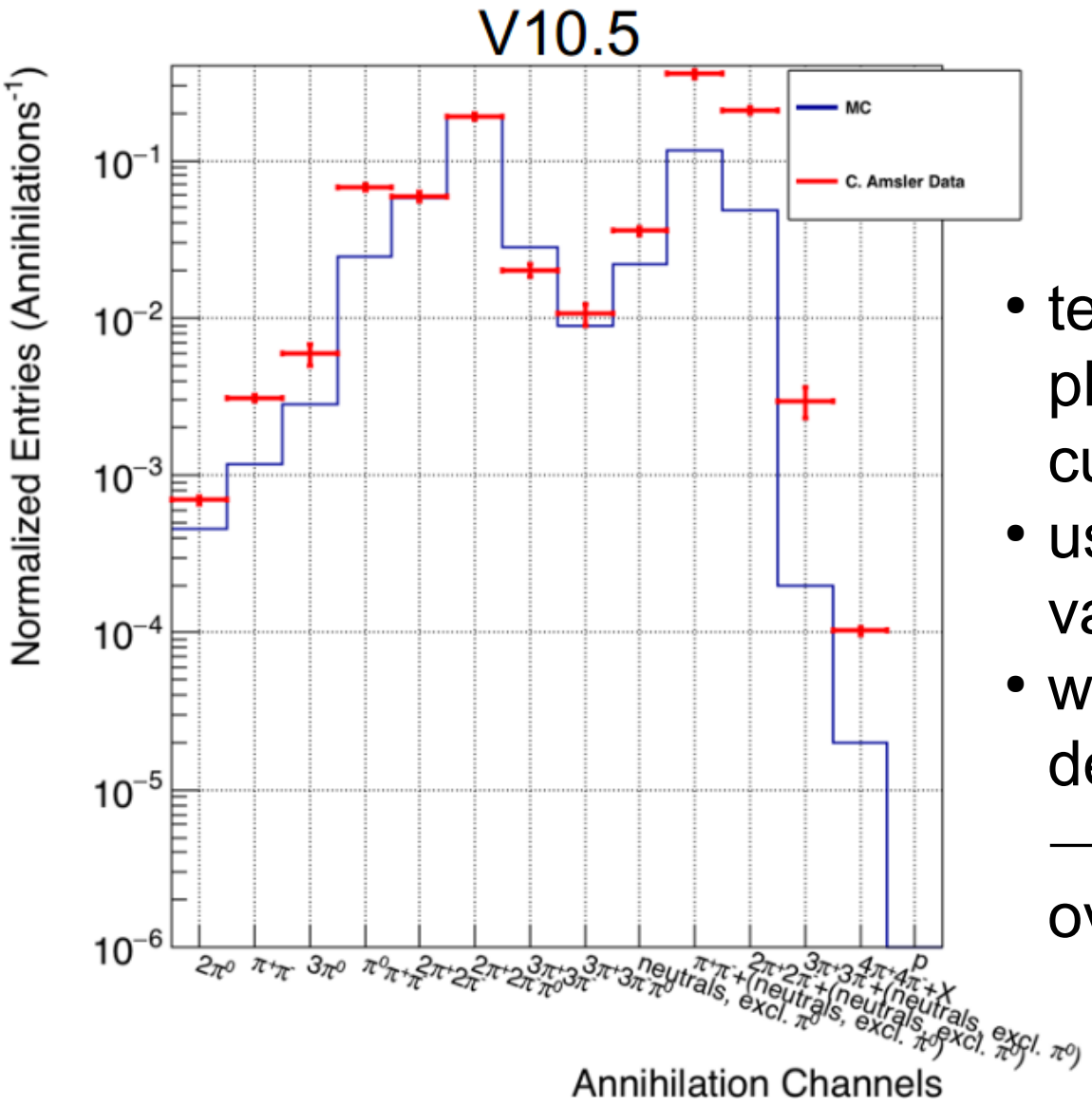
- Number of charged pions for events that stop in the GAPS tracker material



- Number of tracks from the vertex with at least 3 hits on the track for antideuterons

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

Gean4.10.5 simulations



- test of annihilation physics in Geant4 is currently ongoing
- use antiproton data for validation
- work with Geant4 developers
  → lots of improvements over the last 2 years

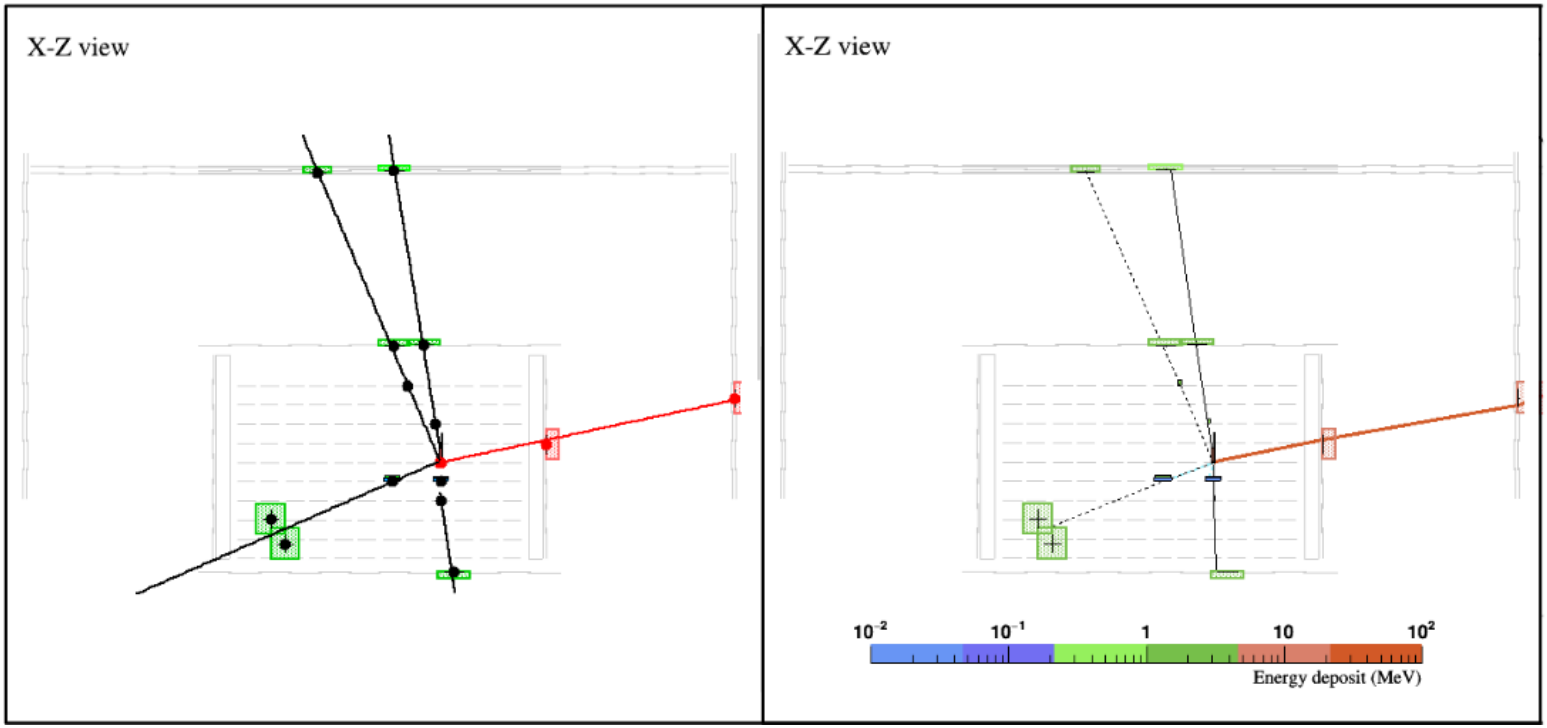
Event reconstruction: antiproton

Primary Reco
Pions Reco

Reconstructed
Beta = 0.38
Secondaries = 4

Monte Carlo
Beta = 0.37
Secondaries = 4

Primary MC
Pions MC



- For the event reconstruction it is critical to identify a well defined primary track → β 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

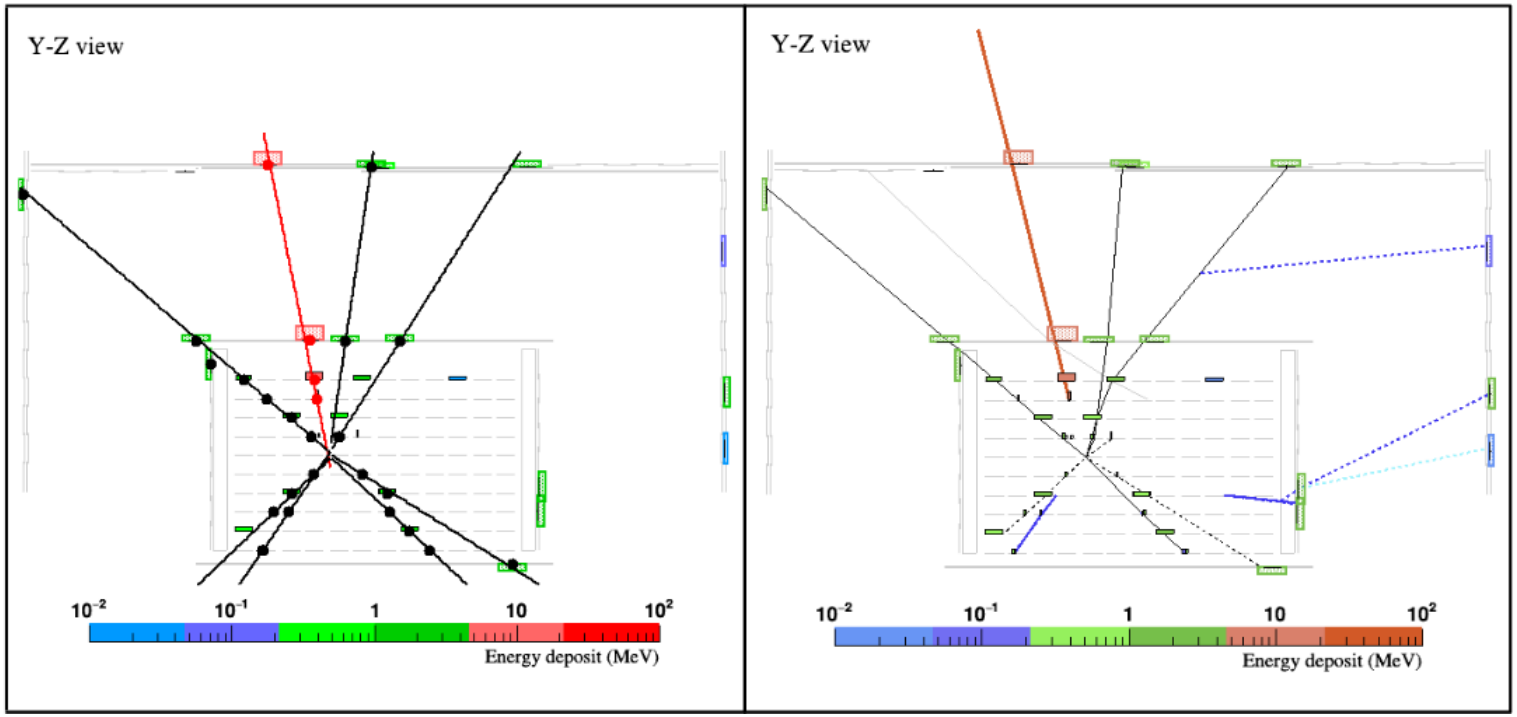
Event reconstruction: antideuteron

Primary Reco
Pions Reco

Reconstructed
Beta = 0.38
Secondaries = 7

Monte Carlo
Beta = 0.37
Secondaries = 7

Primary MC
Pions MC
Electrons MC



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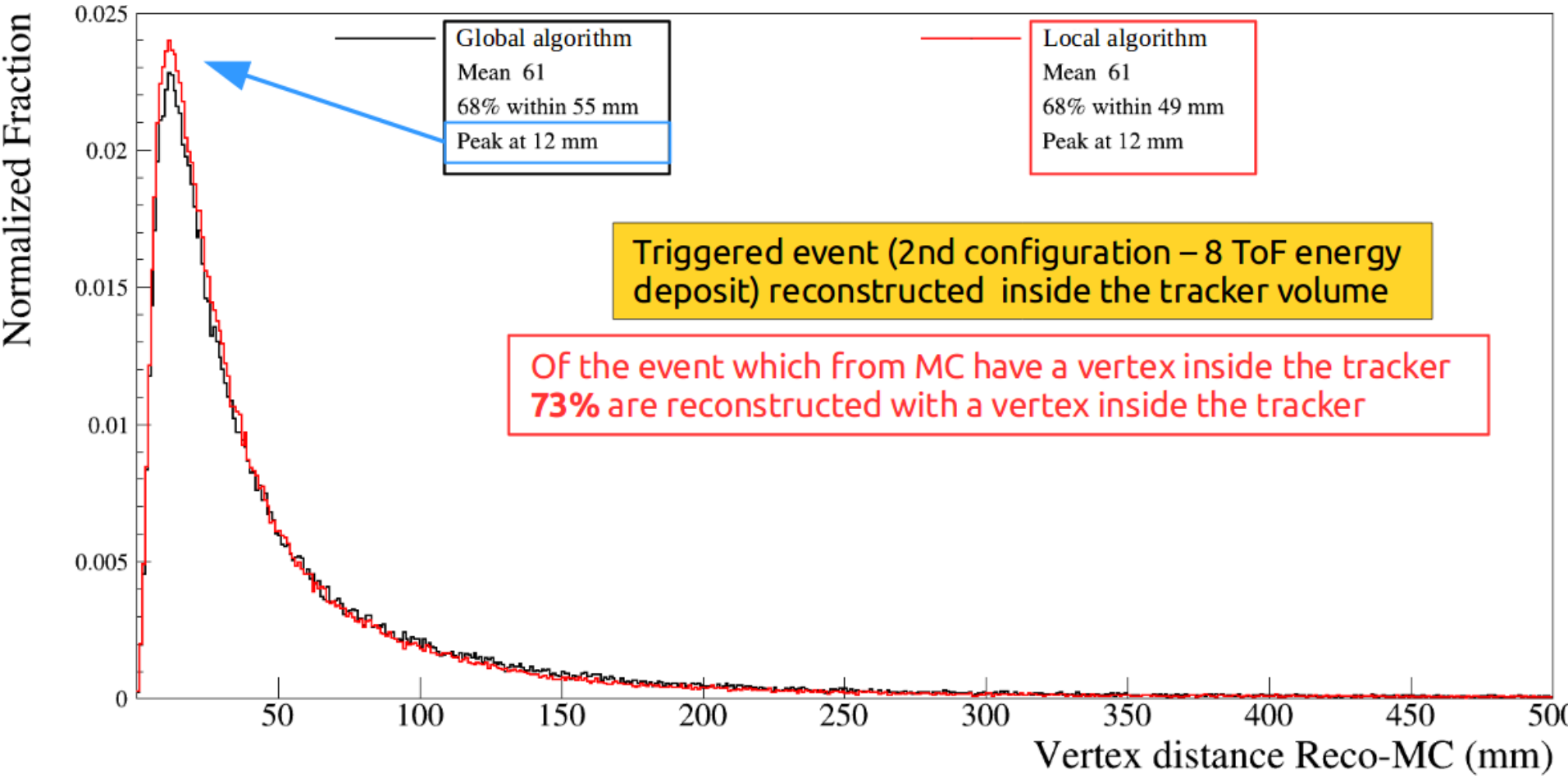
Vertex resolution

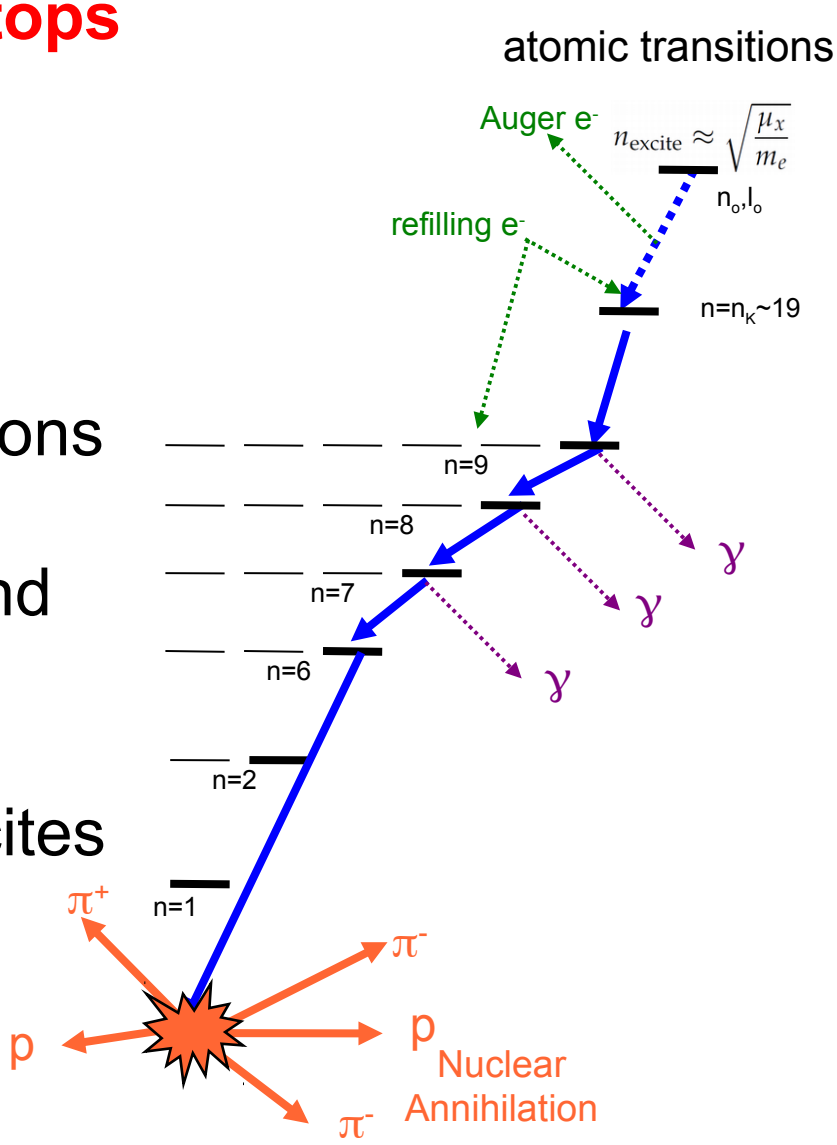


- The vertex is the position in space which minimize the distances from all the reconstructed tracks
- Machine learning techniques for vertex reconstruction are under test

Deexcitation X-rays

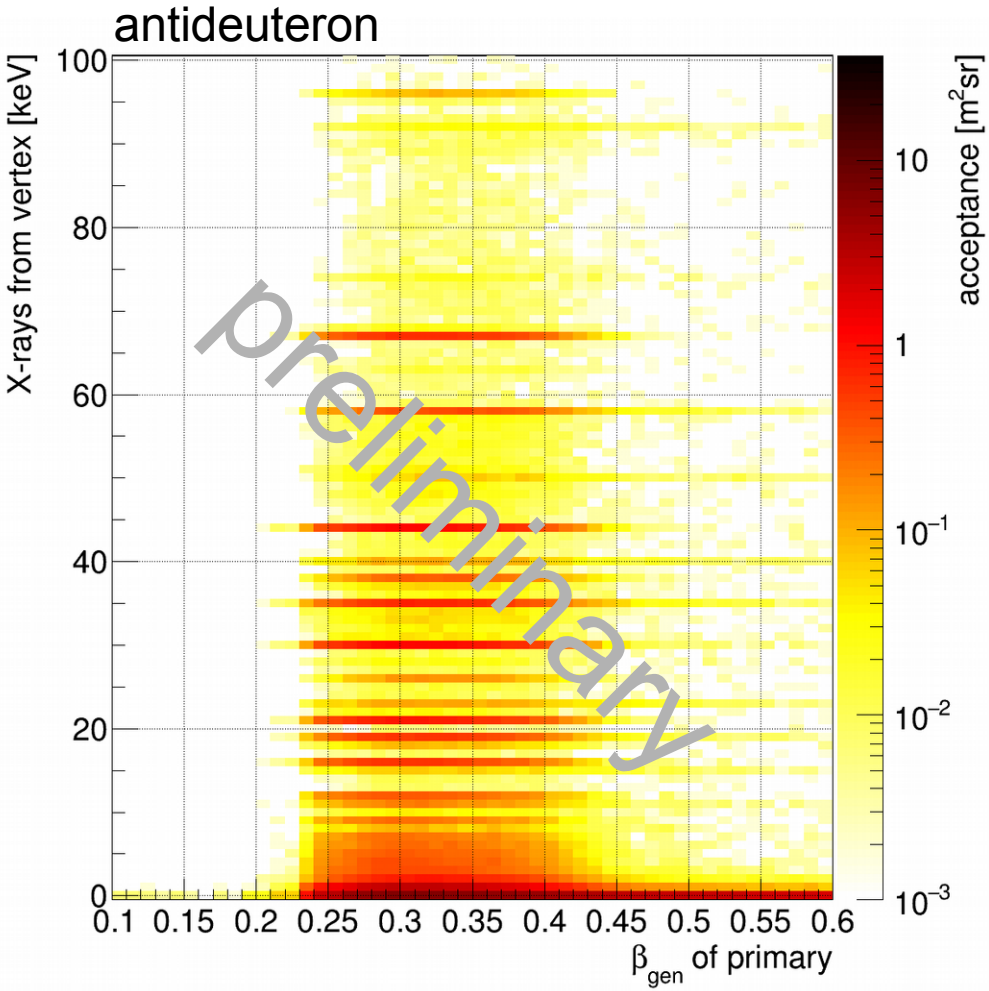
Aramaki et al., Astropart. Phys. 74, 6 (2016)

- **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-rays in Geant4

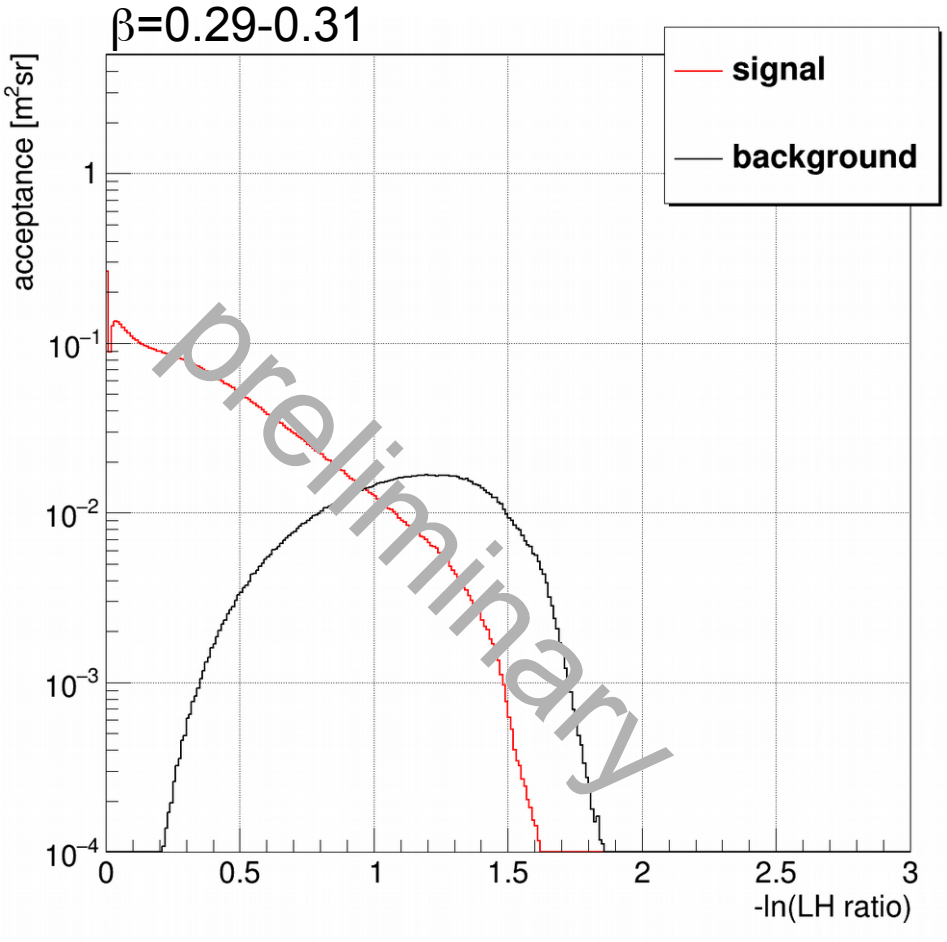
- exotic atomic X-ray model for antinuclei was implemented in Geant4 for Si, C, Al
- other X-rays: decay of daughter nuclei (e.g., Al, Mg, Na) → good understanding on x-rays from other hadronic process
- detailed studies are ongoing



Particle identification

Identification is a task for multivariate identification techniques:

- Number of tracks from the annihilation vertex
- Total energy deposition of the primary particle
- Column density of material that the antiparticle traversed before stopping
- Total energy deposition from all tracks
- Number of hits in tracker
- Number of hits in TOF
- X-rays in association with nuclear annihilation products (will be included soon)

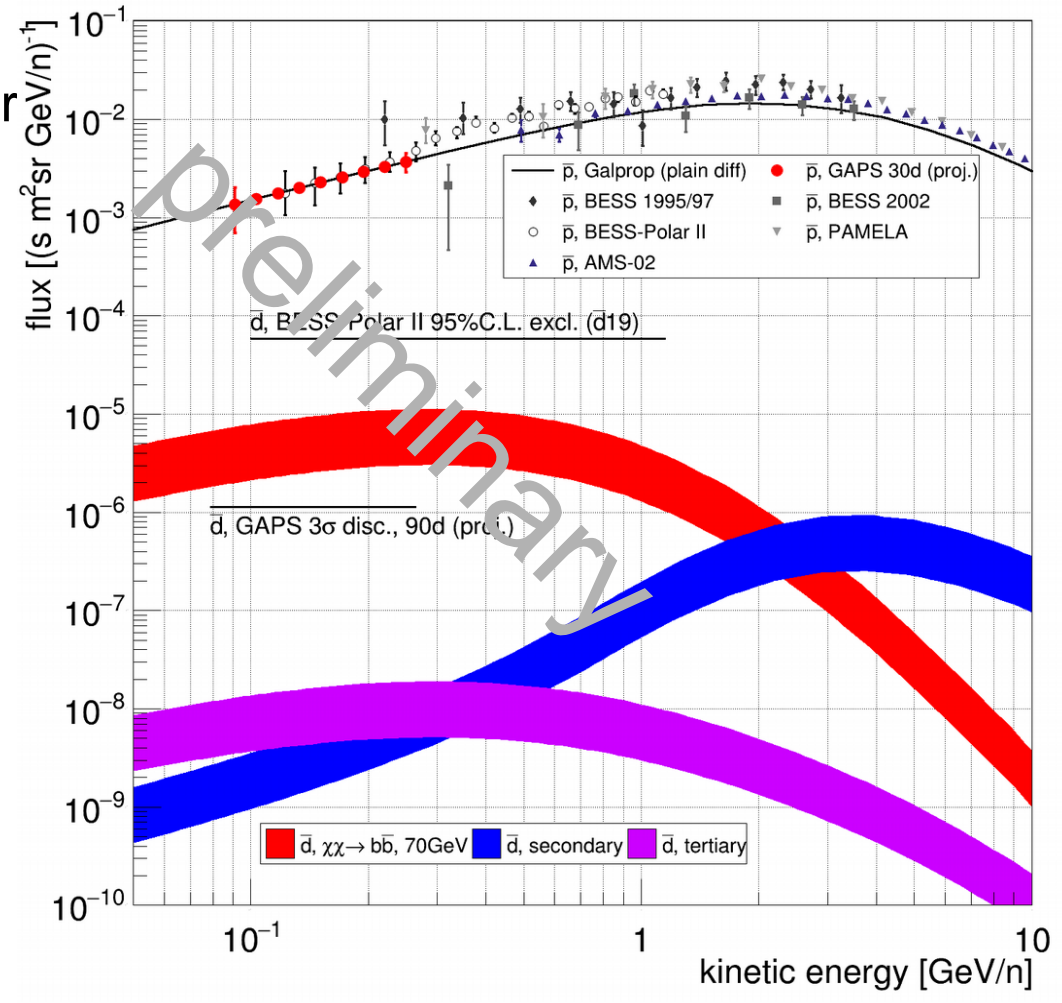


Likelihood for being antideuteron-like:

- antideuteron MC is red
- antiproton MC is black

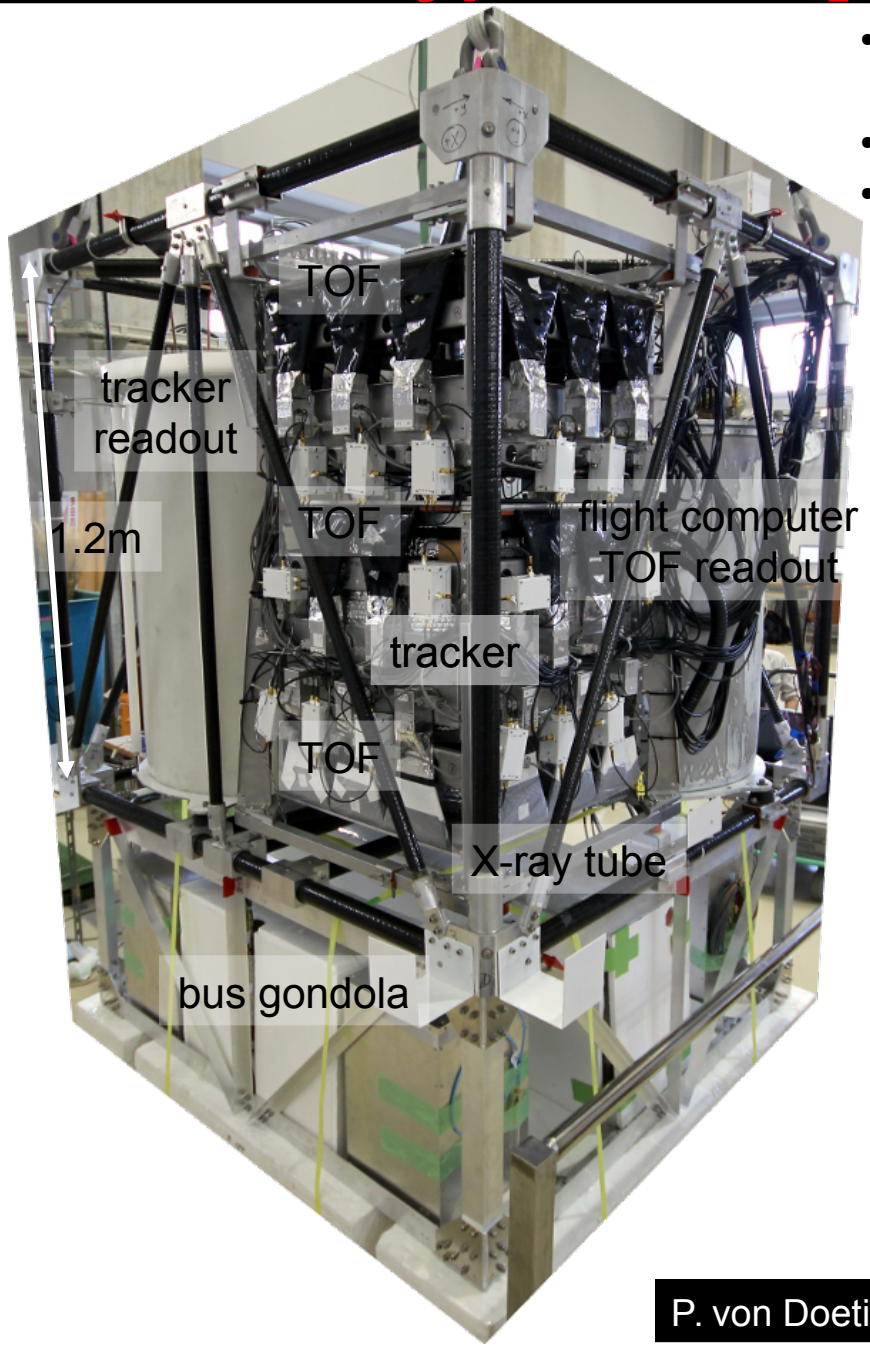
Sensitivity

- GAPS will detect ~1000 antiprotons per 30day flight (order of magnitude more than BESS Polar II)
- antiprotons are essential to:
  - validate the identification technique
  - compare with other experiments
  - estimate antideuteron background
  - antiprotons are sensitive to various DM models: Neutralinos, LZP Gravitinos, primordial black holes
- GAPS is also sensitive to low-energy antihelium-3
- important other measurements: proton, deuteron, helium fluxes

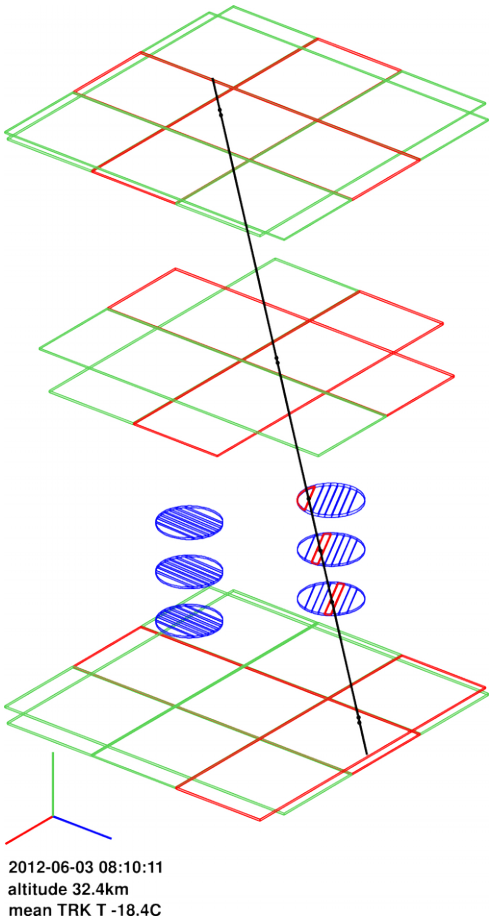


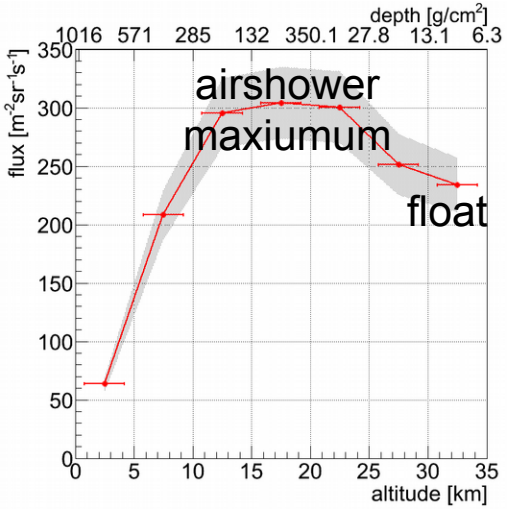
- Theoretical bands from Korsmeier's 2017 paper, upper and lower edges refer to ALICE (248MeV/c) and ALEPH (160MeV/c) coalescence momenta

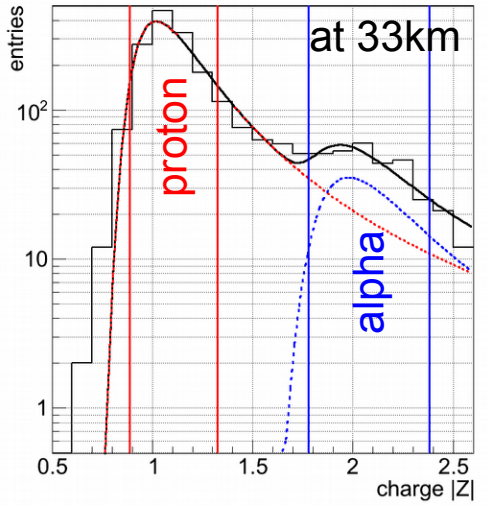
Prototype GAPS [2012]



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

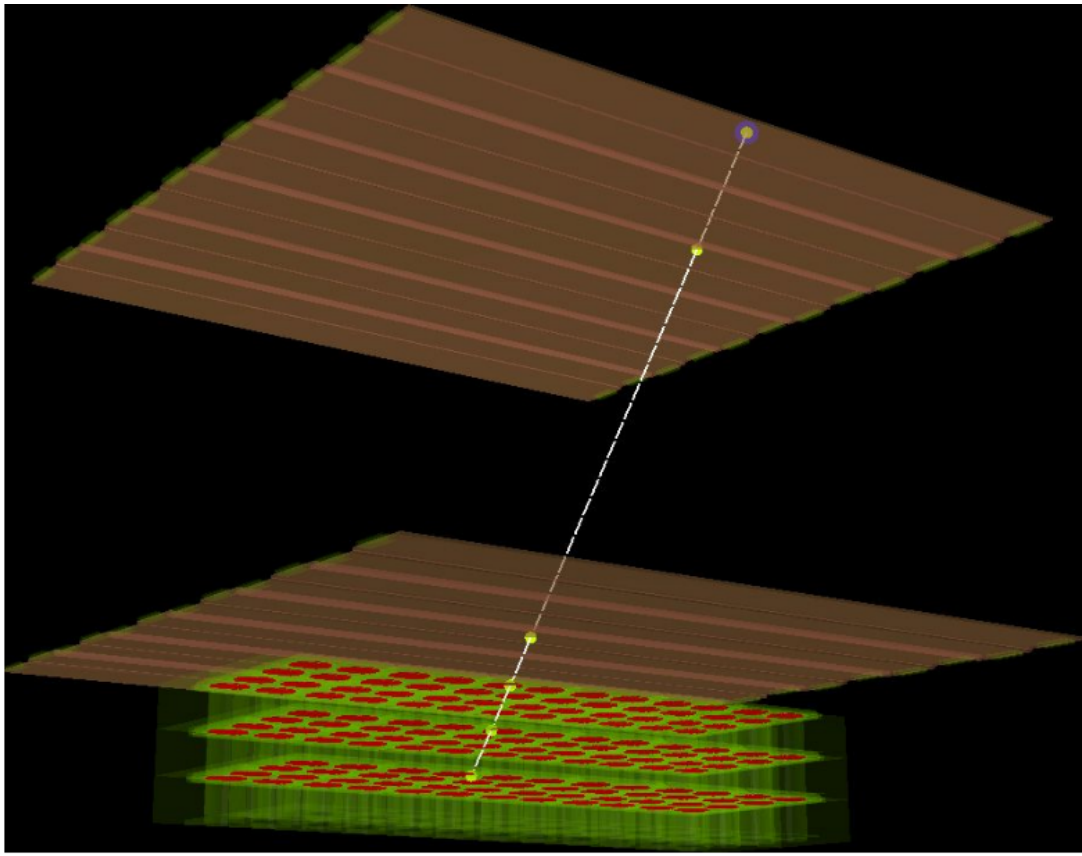






GAPS Functional Prototype [2020]

- prototype will be build in spring 2020
- 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

GAPS path forward

- GAPS is specifically designed for low-energetic antinuclei
- all goals for prototype GAPS were met
- fabrication started, functional prototype coming up
- **first GAPS science flight from Antarctica 2021**