GAPS: Instrument Design and Recent Developments

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on behalf of the GAPS collaboration

2^{nd} Antideuteron workshop

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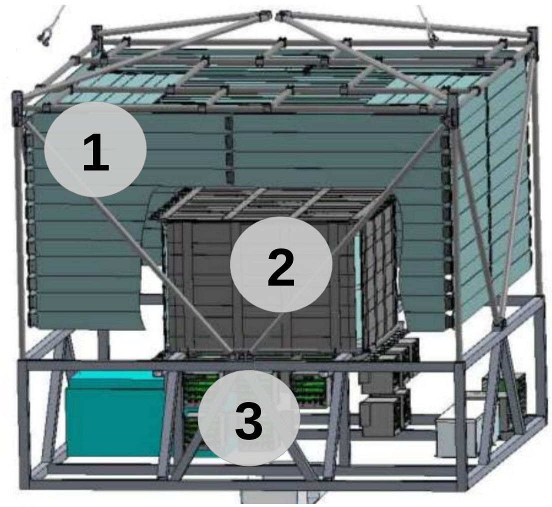
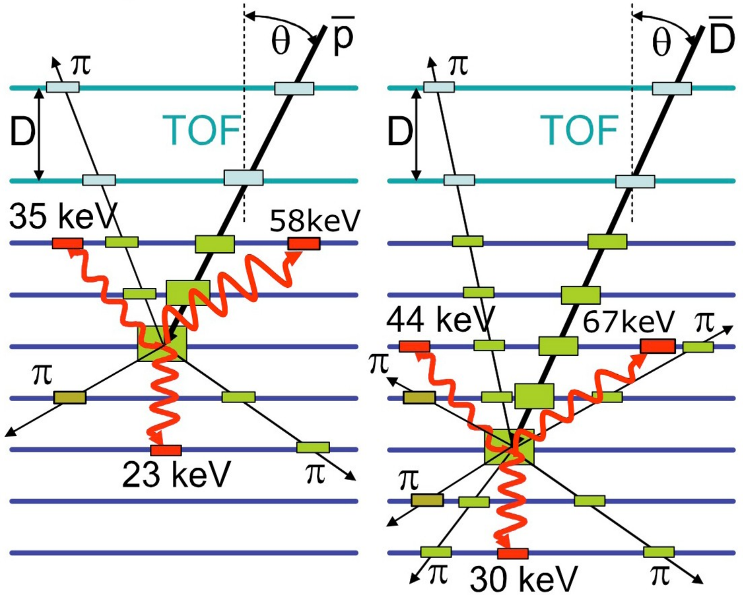
UCLA

Introduction & overview

- General AntiParticle Spectrometer (GAPS)
- Primary arrested in active volume, forms excited exotic atom
- Decay produces unique X-rays associated with primary
- Additional information gleaned from annihilation products
- No permanent magnet
- In this talk
  - GAPS history
  1) TOF
  2) Si(Li) tracker
  3)Ballooncraft system
  4) Thermal regulation system

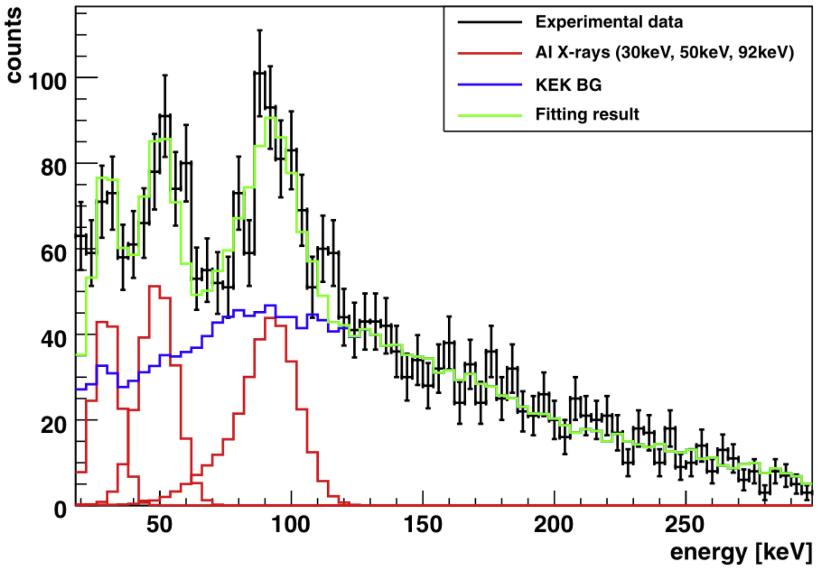


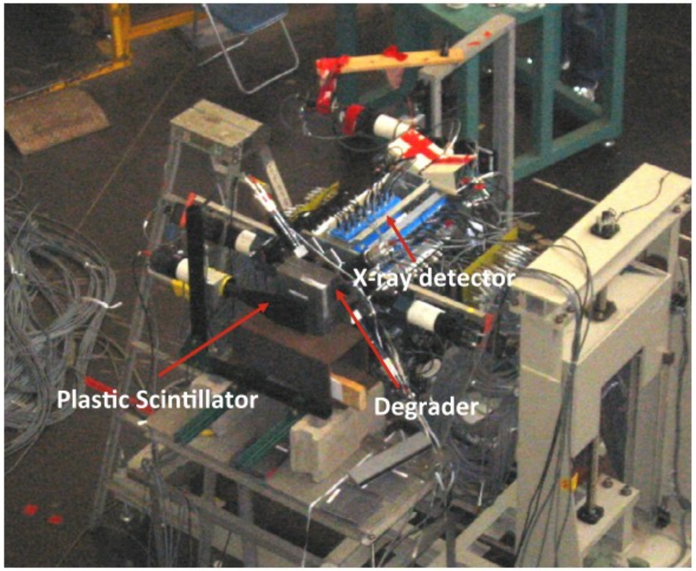


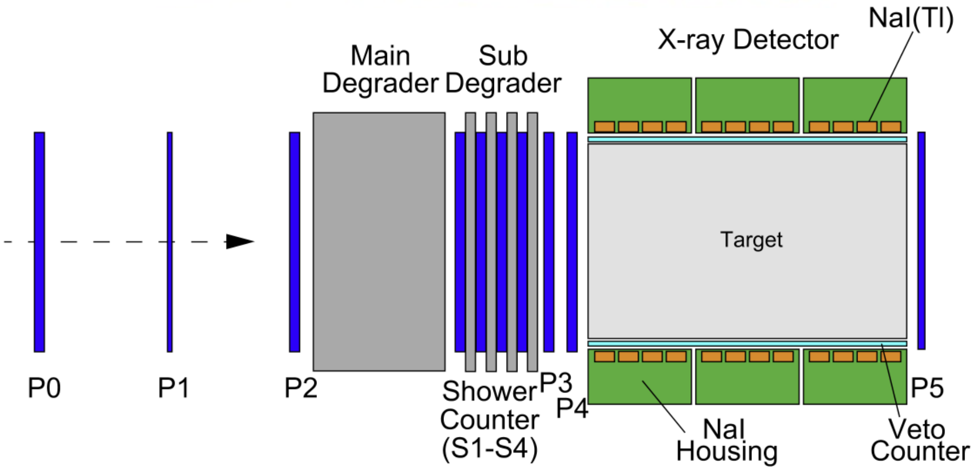
T. Aramaki et al., Astroparticle Physics, Volume 74, 2016, Pages 6-13

Pioneering Si(Li) research and KEK beam tests

- Complete fabrication procedure from raw material to detector developed at Columbia, MIT, JAXA and Shimadzu Corp.
- Beam line targets developed in mid 2000s, GAPS prototypes in mid 2010s
- Detection concept tested and verified at accelerator



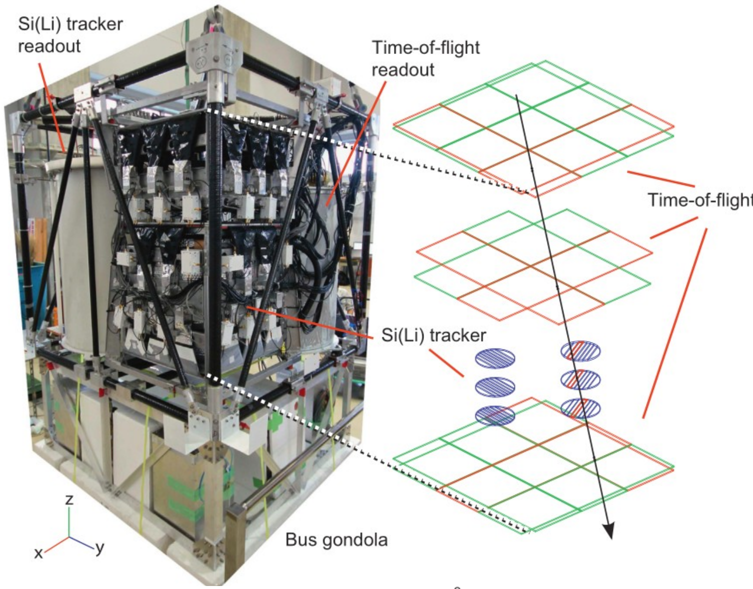


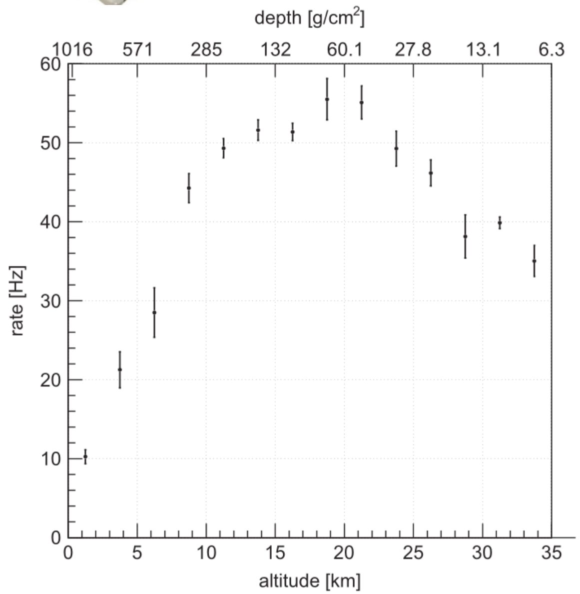


T. Aramaki et al., Astro. Part. Phys., Vol. 49, 2013, pg. 52-62

Prototype GAPS (pGAPS)

- Miniaturized version of GAPS constructed in 2012
  - Included main detector components
    - 3 layer scintillator/PMT TOF
    - 6 commercial Si(Li) disks
- Payload included prototype oscillating heat pipe (OHP) thermal system (test bench)
- Successfully launched from Hokkaido June 3, 2012

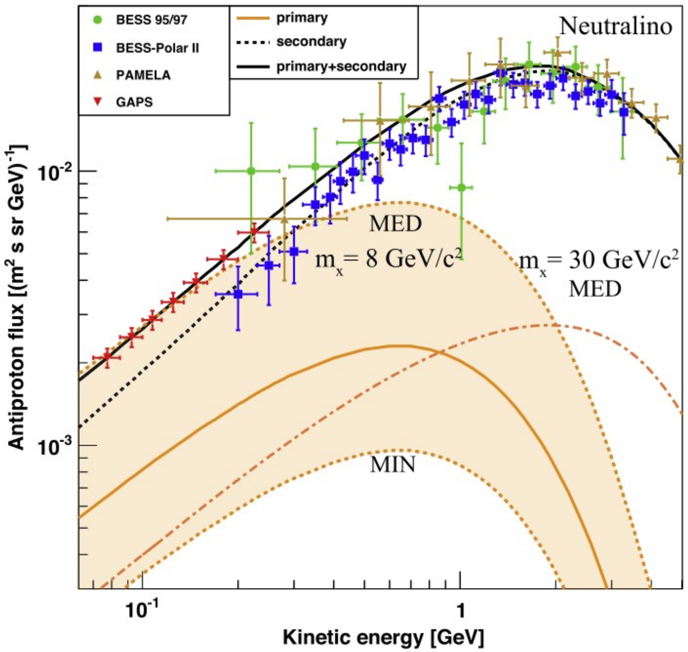


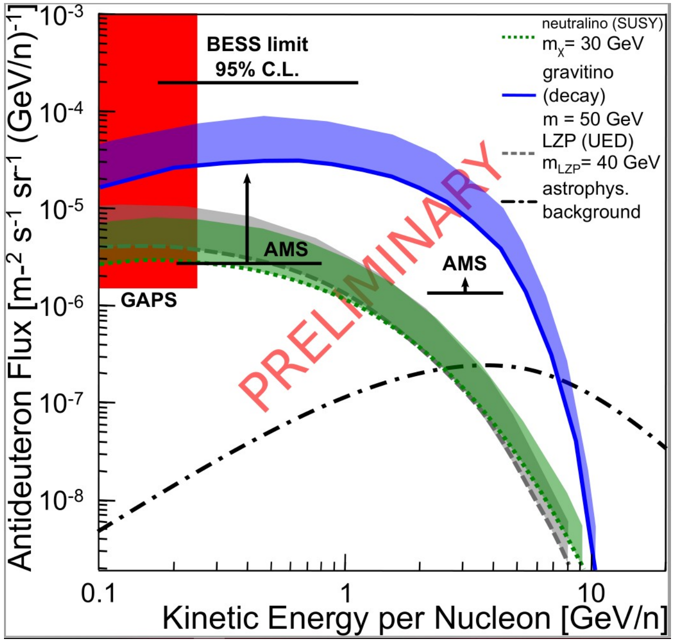


S.A.I. Mognet et al., NIMA, Vol. 735, 2014, Pg. 24-38

Low energy cosmic ray antimatter & DM search

T. Aramaki et al., Astropart. Phys., Vol. 59, 2014, Pg. 12-17





- GAPS designed with 0.05 < T < 0.25 GeV/n antideuterons in mind
- Exotic atom technique gives powerful discrimination between species
- Can look for heavier isotopes (e.g. He), subject to distinct systematics compared to spectrometers
- Some overlap with complimentary experiments (BESS, AMS-02)
- Design permits 1000-2000 antiproton detections in completely new energy regime: one order more than BESS

Key design requirements

Science Drivers

- Largest possible aperture
- Restrictive trigger
- Particle velocity measurement
- Extreme background rejection

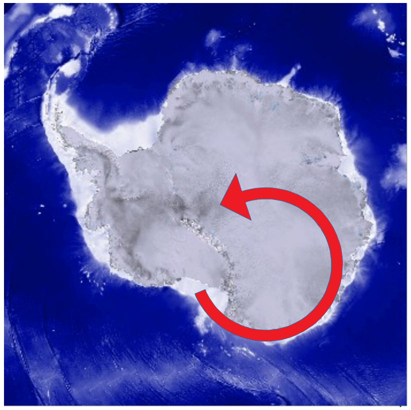
System Tasks

- Large-area TOF
- Detect exotic atom X-rays
- Track primary
- Track annihilation products

Technical Challenges

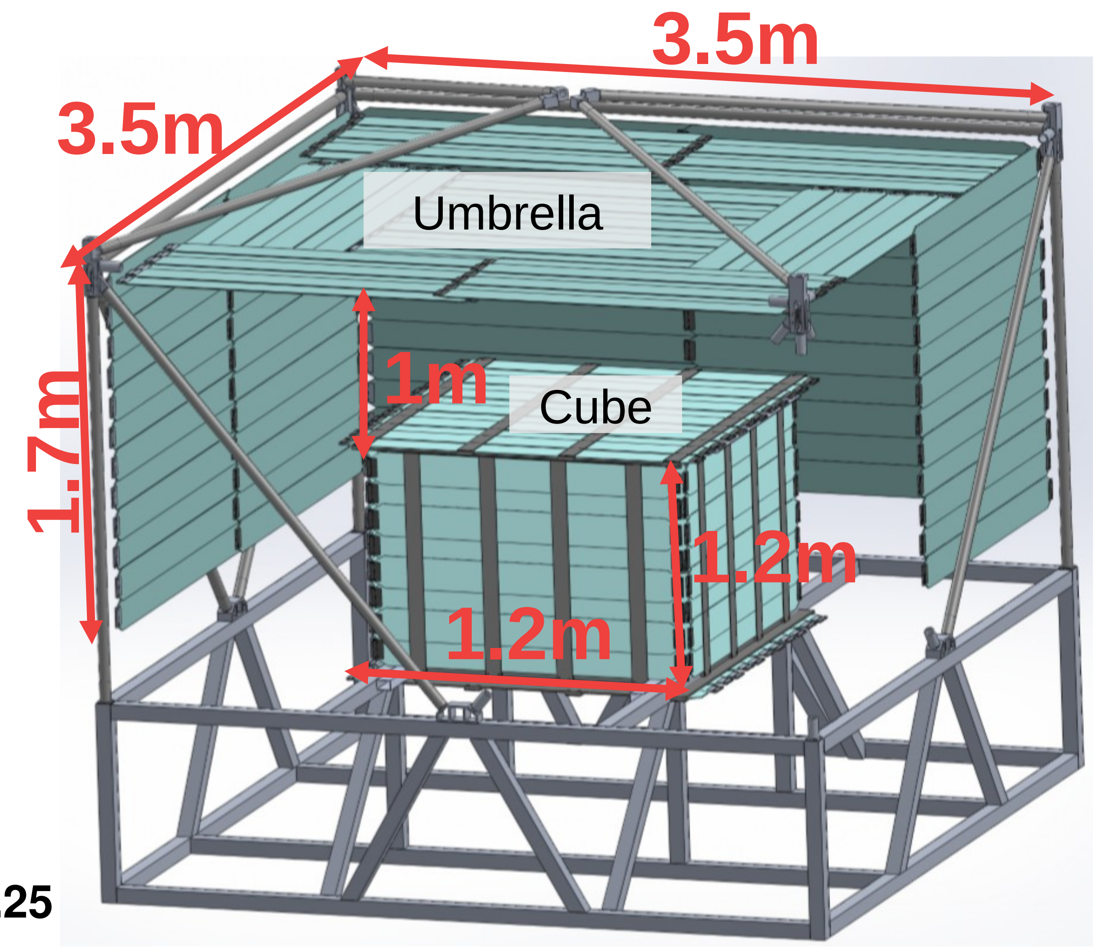
- Aperture does not scale linearly with gondola size
- Large Si(Li) array w/ good energy resolution
- Si(Li) at high temperature
- Segmented array – high channel count,→ power
- Multiple flights needed →survivability

- Online DAQ run time of 1000 hours
- One antideuteron detection at 99% confidence for expected sensitivity



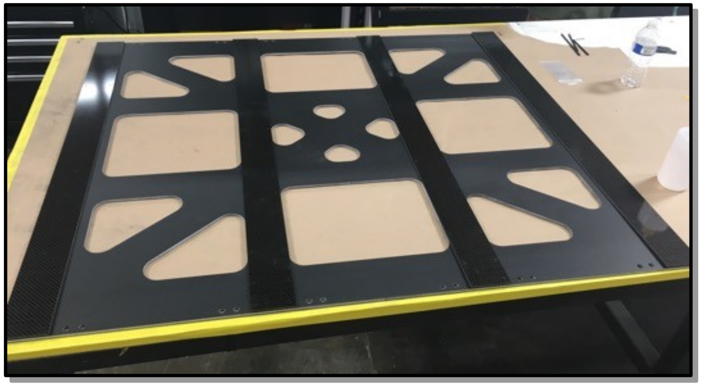
TOF System

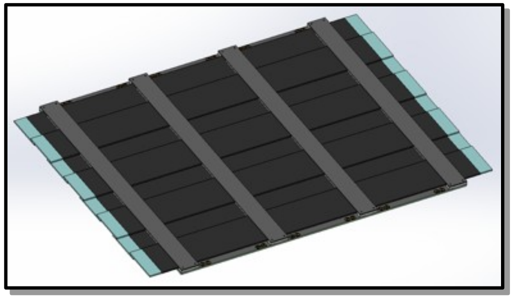
- 2 layer design: umbrella & cube
- Plastic scintillator: Eljen EJ-200
  - Counter form factors:
    - 1.8 m x 16 cm x 6.35 mm
    - 1.1 m x 16 cm x 6.35 mm
  - SiPM base optically coupled to counter ends
  - 2 outputs per end
  - **Timing requirement: ~500 ps**
  - **β resolution better than 12%**
  - **Primary charge resolution of 0.25**
  - **Horizontal position within ± 10 cm**
  - Two level hierarchical trigger system

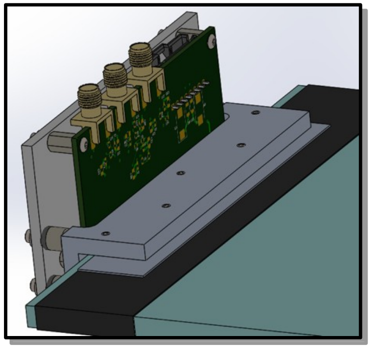


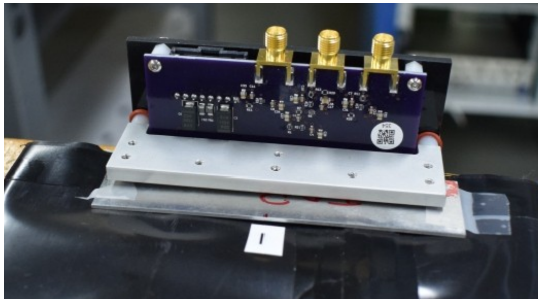
TOF System: mechanical

- Spatial extent and large area presents unique mechanical challenge
- Novel carbon fiber structure provides mounting point for counters
- Initial Aluminum clamp assembly tested, moving toward simpler fabric strap
- SiPM base attached to counter end with U-channel assembly
- Sealed with blackout material



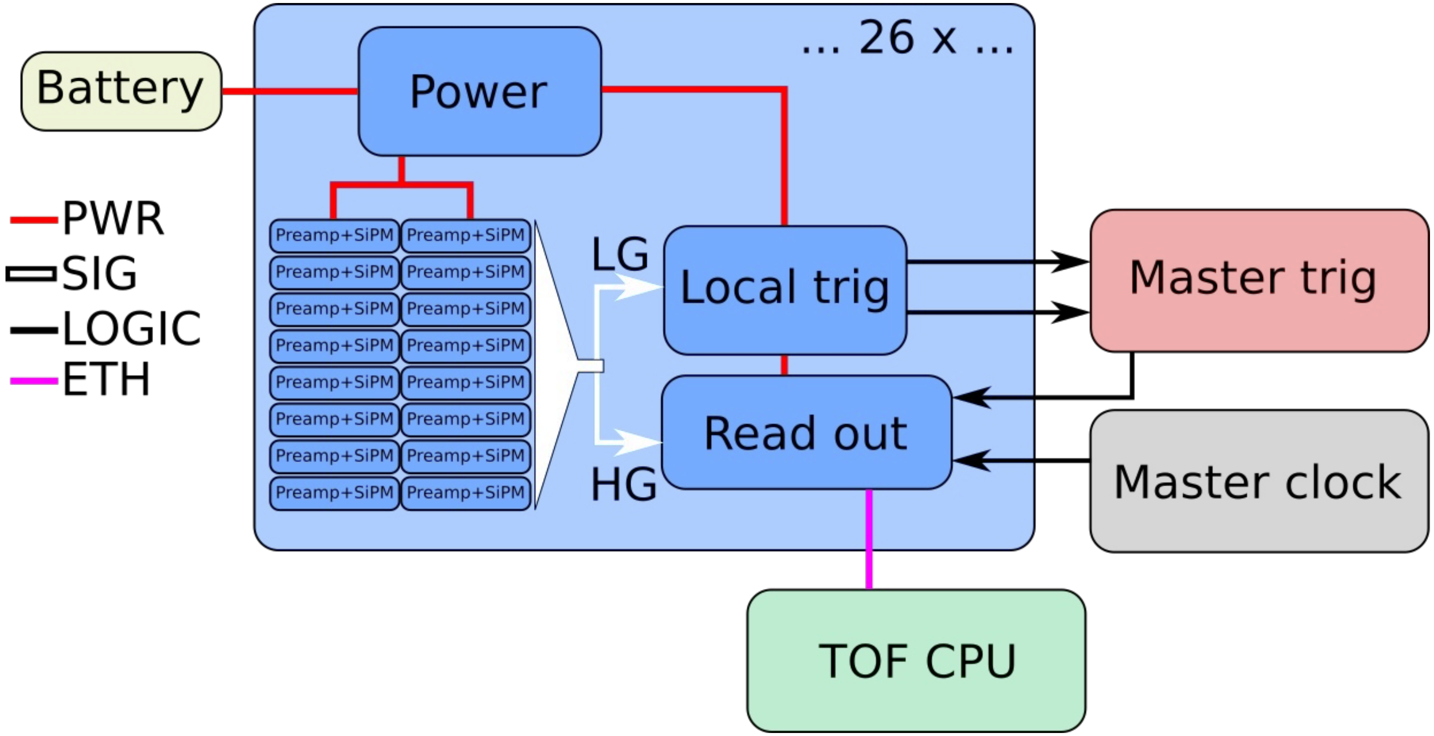




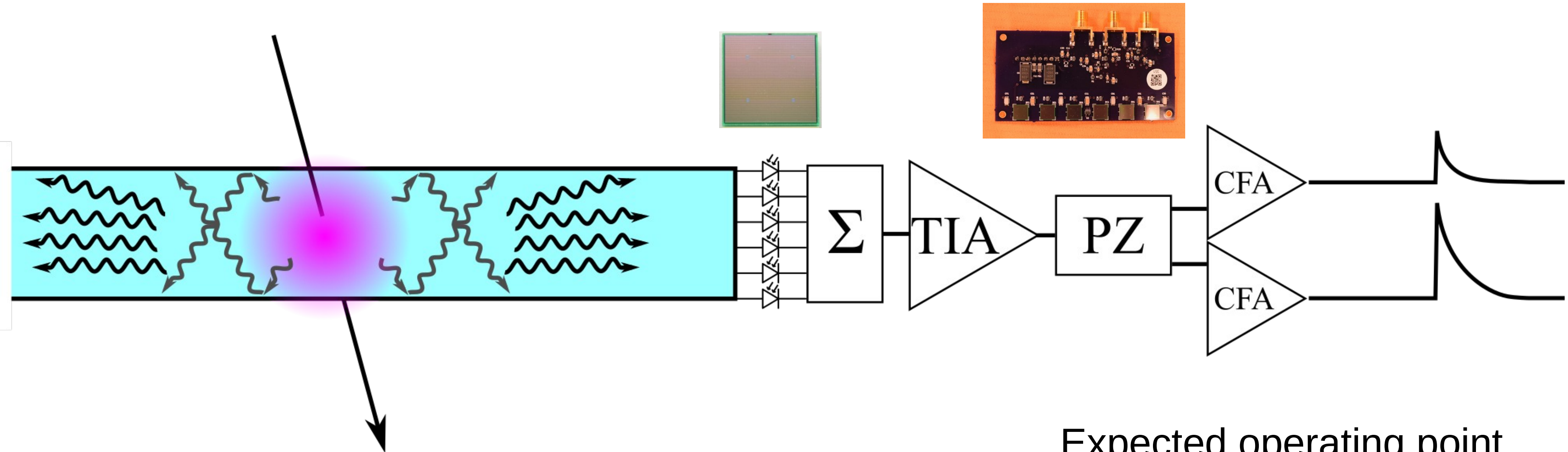


TOF system overview

- 4 main subsystems:
  - Power distribution board
  - SiPM/preamp + read out (digitizer)
  - Local + master trigger board (initiates TOF & Si(Li) read out)
  - TOF CPU (ingests all data, organizes compressed format for telemetry)

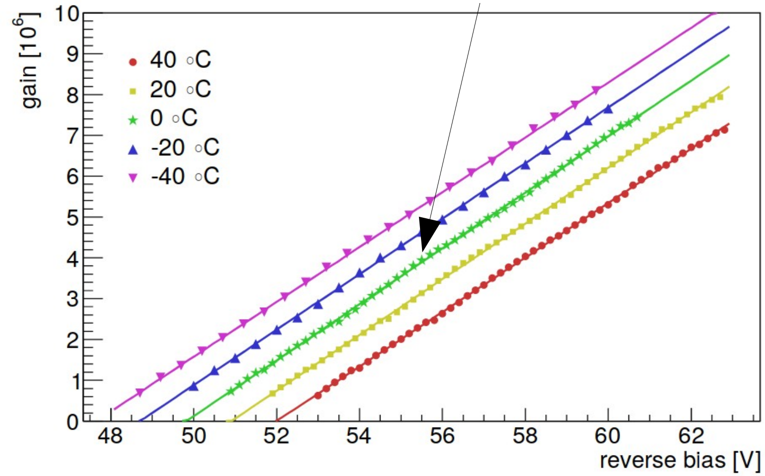


TOF system: signal path



- SiPM: Hamamatsu S13360-6050VE @ 4×10^6
- Transimpedance architecture (op-amp) w/ pole zero cancellation. 90 mW
  - High gain timing channel: 0-33 MIP (to readout board)
  - Low gain trigger/veto channel: 1-110 MIP (to local trigger board)
  - Gain actively controlled by power distribution board

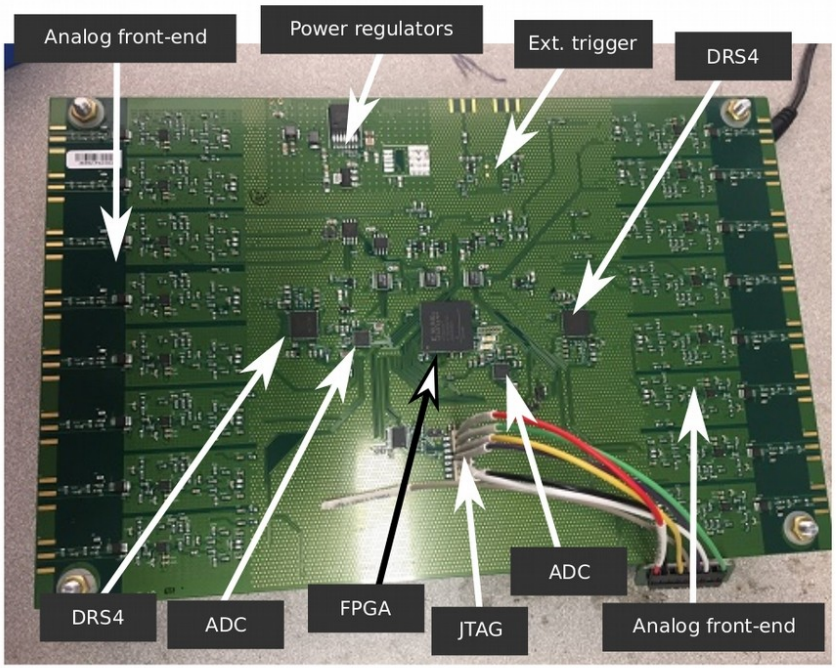
Expected operating point

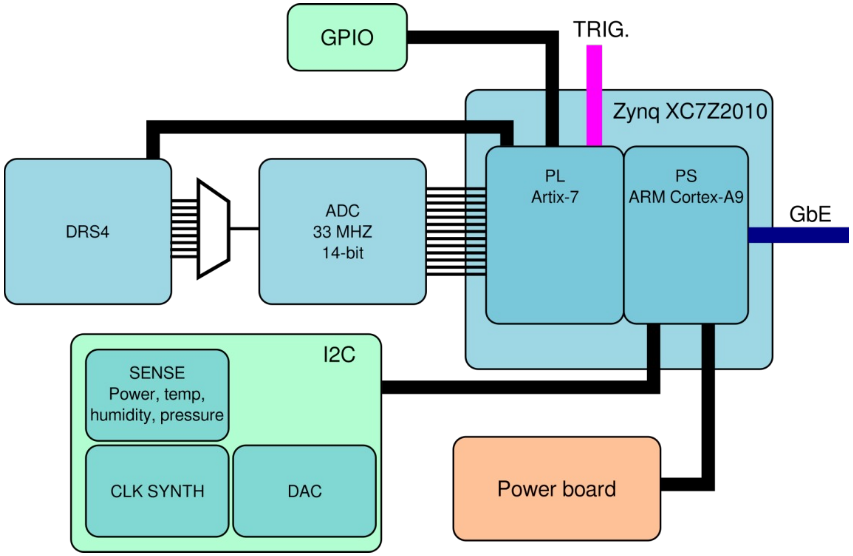


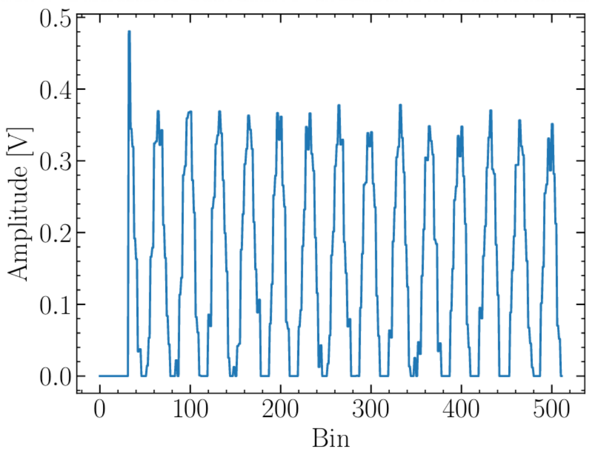
[NIMA 846, pp. 106-125, 2017](#)

Read out board prototype

- DRS4 based sampler
- V1 board fab + assembly, April 2018
- Testing & debugging: April-August 2018
- Basic control of DRS4 and successful readout
- V2 design complete: moves to SOC architecture

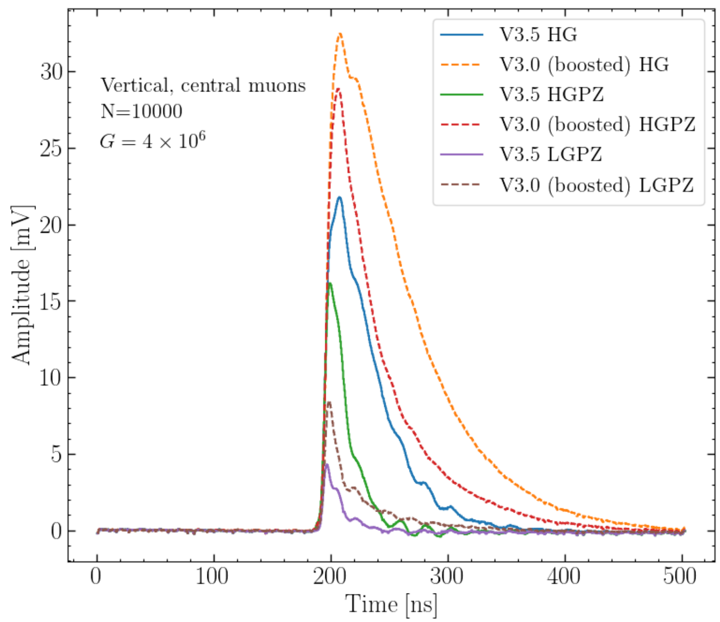


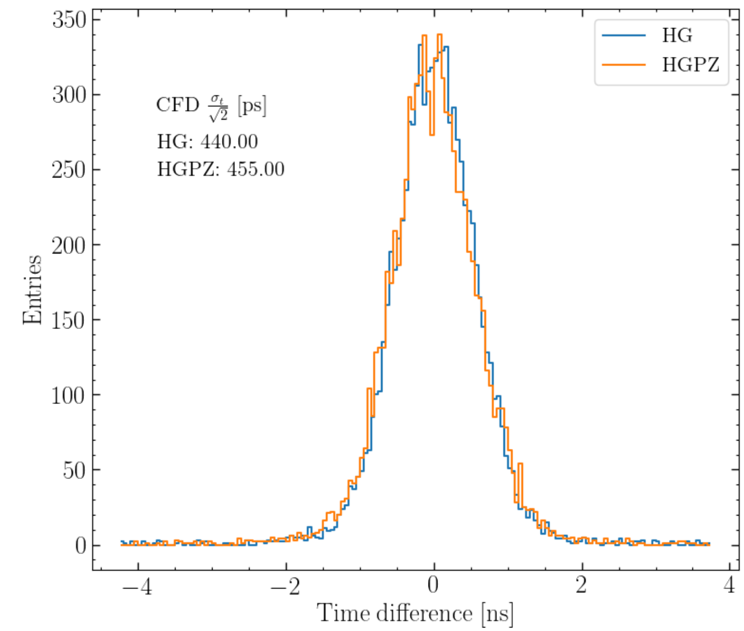




Example muon data, sims

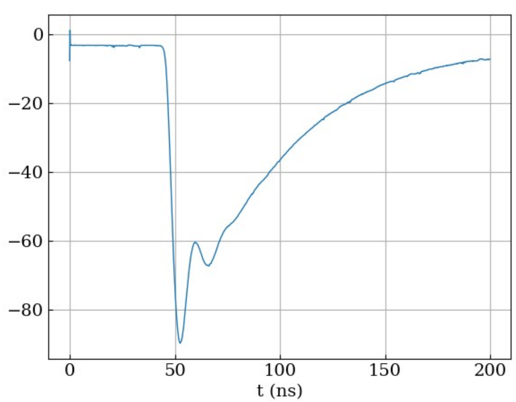
Data





Simulation

1 MIP



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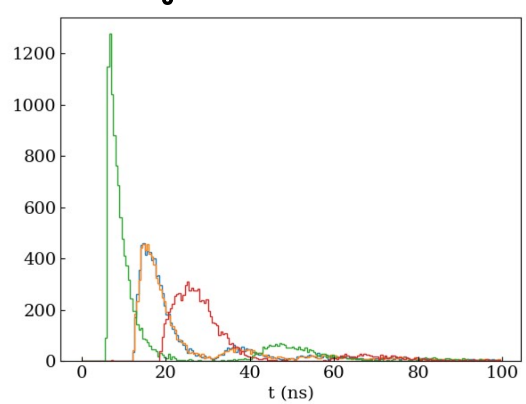
γ arrival times



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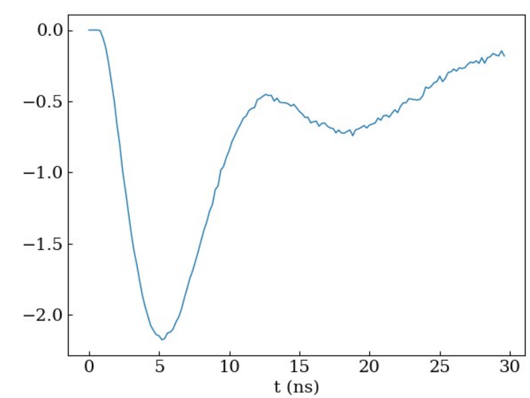
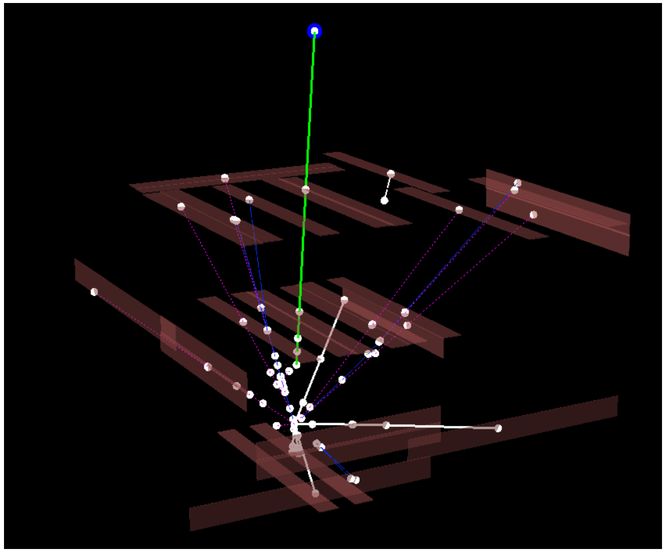
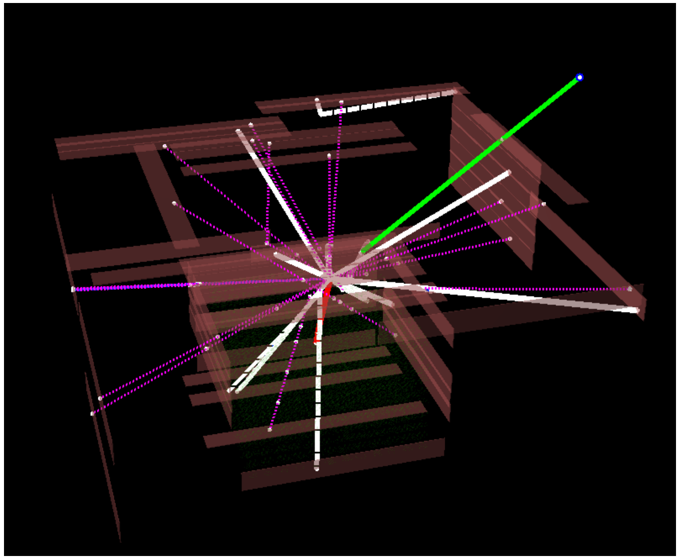
s.p.e response



Trigger design & performance

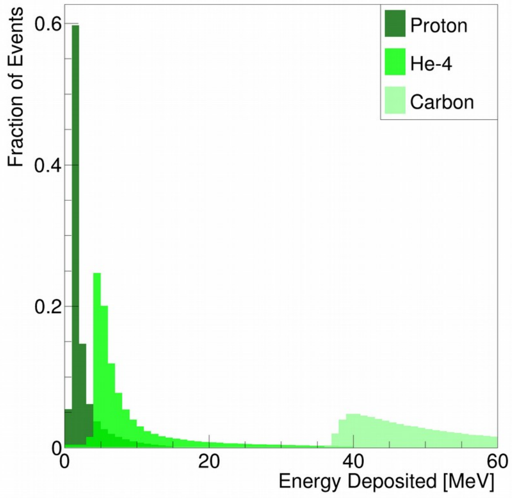
- Trigger efficiency
  - >80% for antideuterons
  - >50% for antiprotons
- Level 1 based on multiple threshold levels
- Level 2 based on L1 hit patterns
- Level 3 based on online processing of event topology
- Raw background rate ~1 MHz
- L1 & L2 background rej.: ~ 300
  - L3 background rej.: ~25
  - Total: ~7500, expected rate 280 Hz

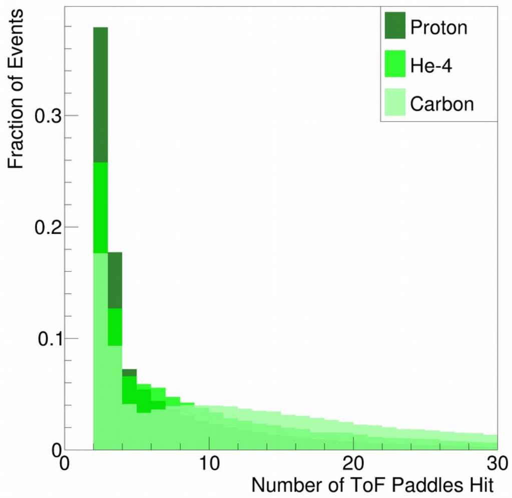




Trigger Inputs

Particles





Key Parameters

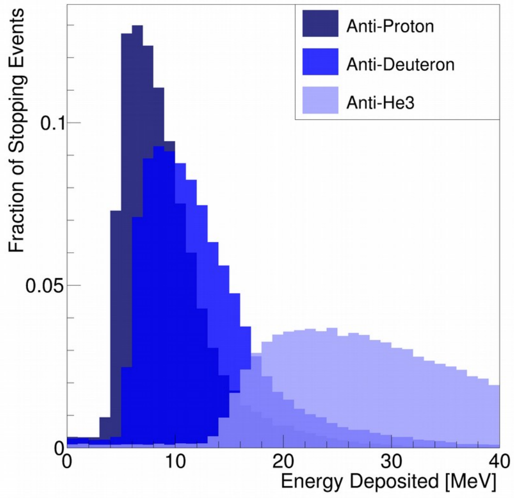
Stopping events deposit more energy (lower beta).

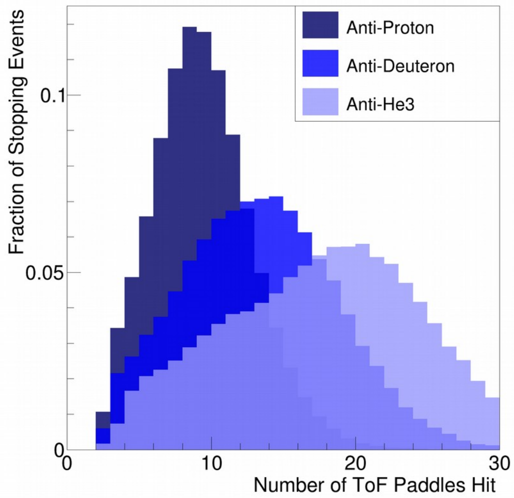
Background events have shorter time between Umbrella and Cube (higher beta).

Annihilation events produce more ToF hits.

Paddle combinations can be used to constrain to zenith angle.

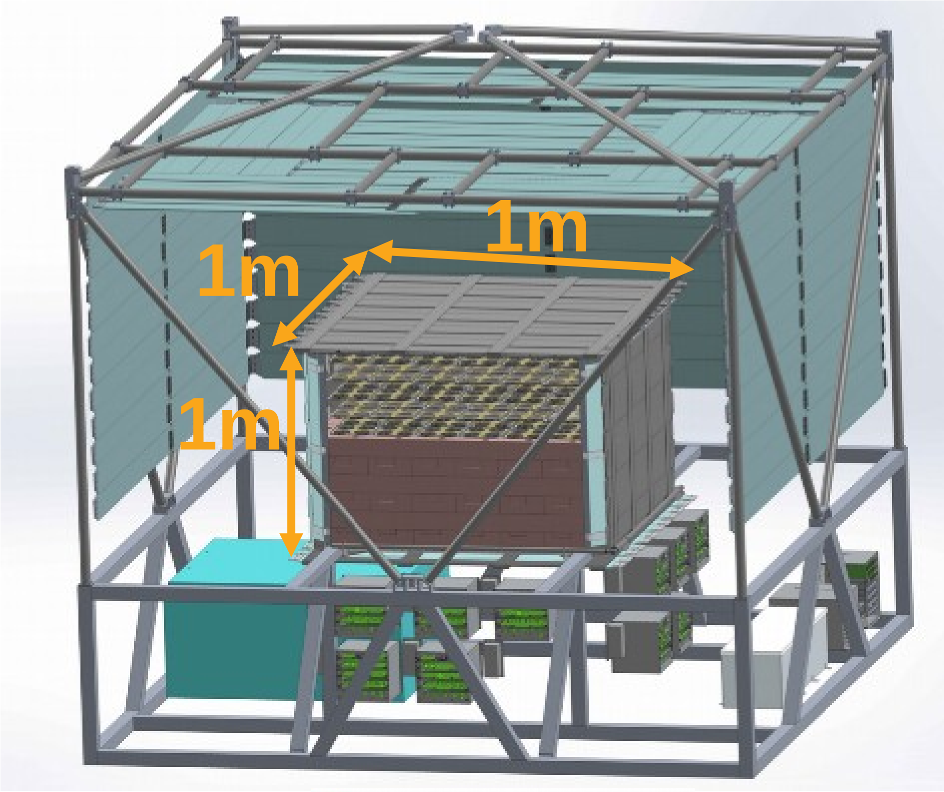
Anti-Particles

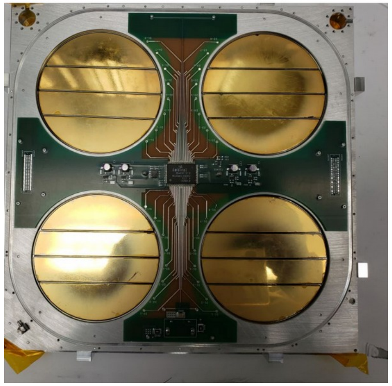




Tracker System

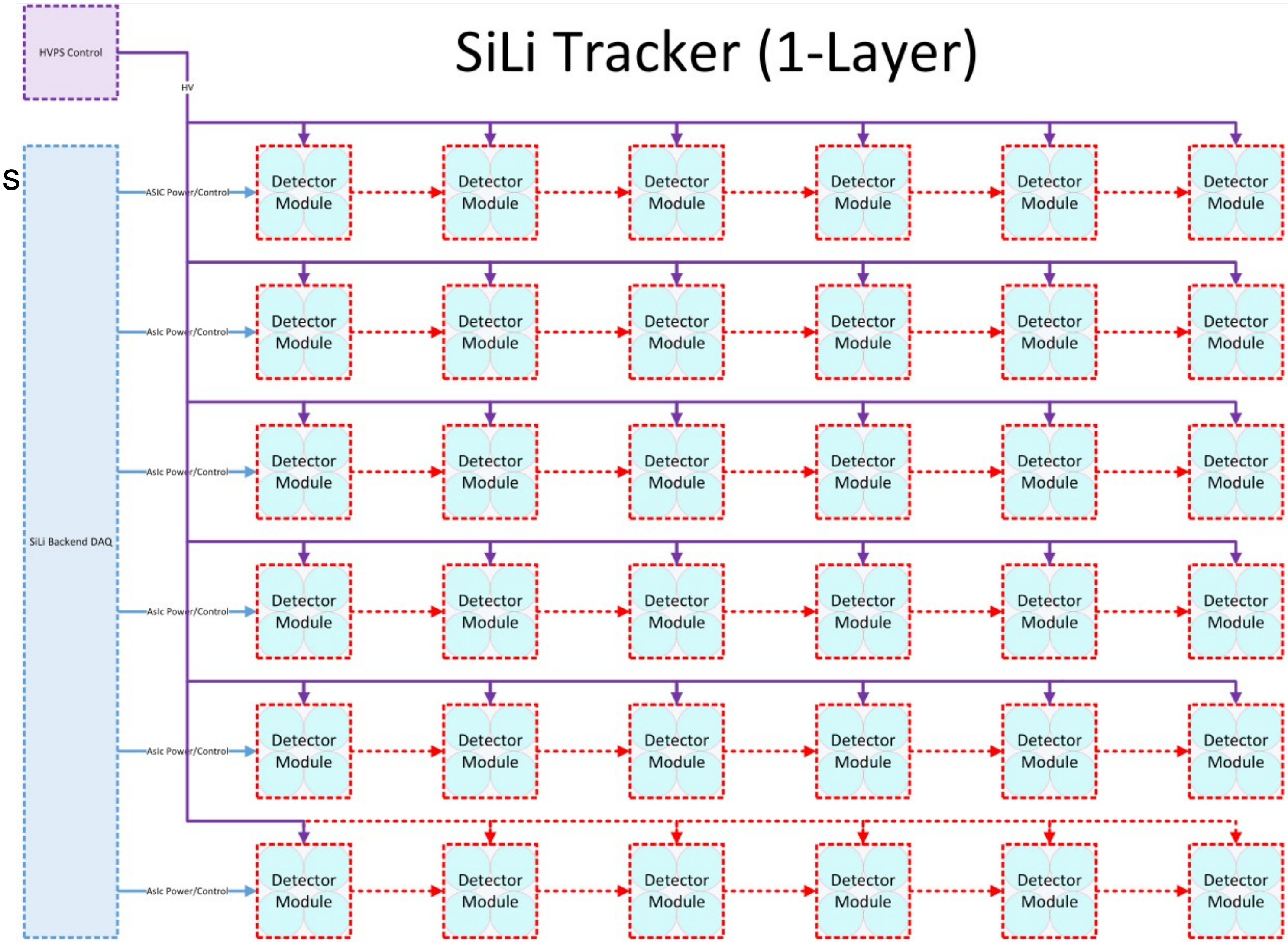
- **10 layers** with 10 cm separation
- 100 mm dia. Si(Li) wafers, 2.5 mm thick
- 8 strips per wafer
- EPS foam + Al support structure
- 11520 channels
- **Operating temp: -40±5 C**
- **4 keV spectral resolution**
- Total instrumented mass: 470 kg





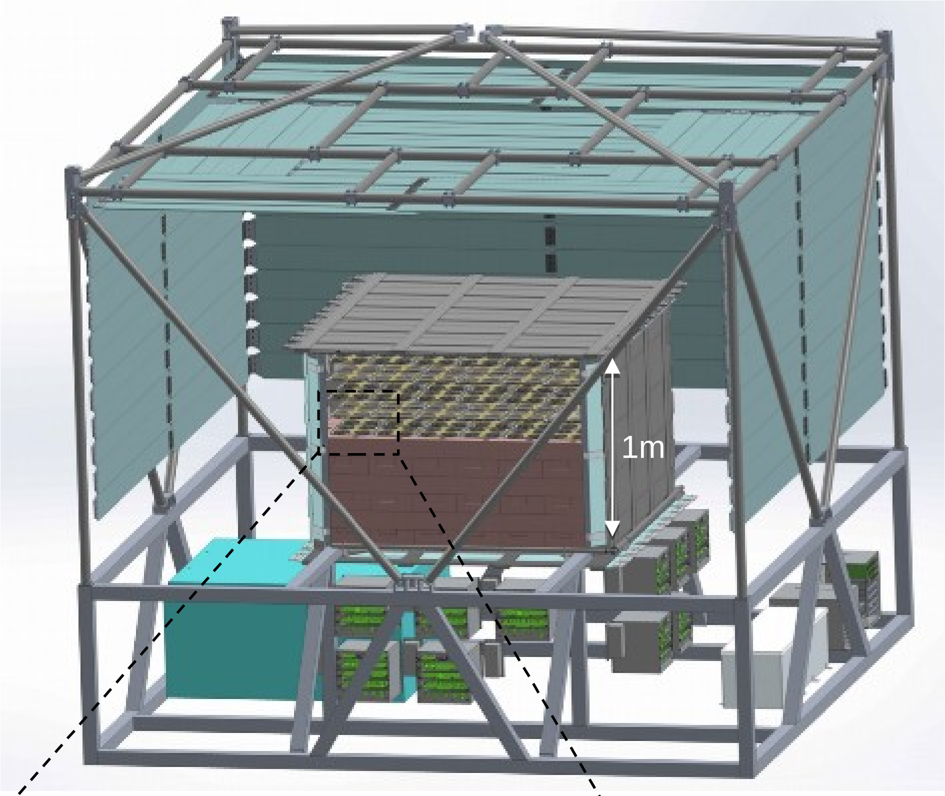
Si(Li) tracker overview

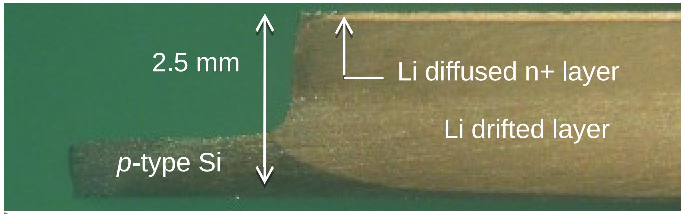
- Main subsystems
  - High voltage supply
  - Integral preamp
  - 16 ch. ASIC digitizer
  - FPGA DAQ backend



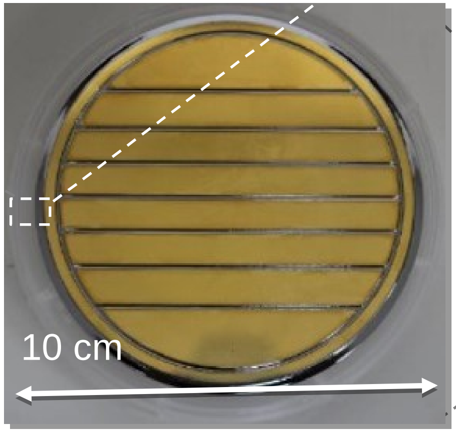
Si(Li) detector

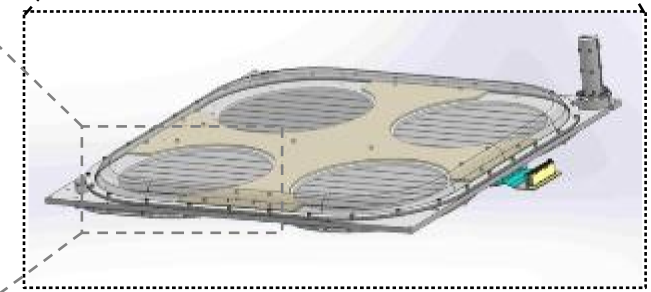
- Tracker composed of ten planes of **lithium-drifted silicon (*Si(Li)*)** semiconducting detectors:
  - 10 cm diameter, 2.5 mm thick, 8-strips
  - Passivation for environmental protection
- Tracker unit = 4-detector module
  - Interface with cooling, power, readout
  - Additional env. protection via "window"





Cross-section (Copper-stained, from Shimadzu)





Detector module

(ASIC and protective window not shown)

Si(Li) detector

SHIMADZU
Excellence in Science

Partnered with **Shimadzu Corp**., a commercial producer of Si(Li) detectors with over 40 years of experience

Commercial products:
~10 mm diameter
~3 mm thick

2015

5 cm wafer diameter, 2.5 mm thick

2016

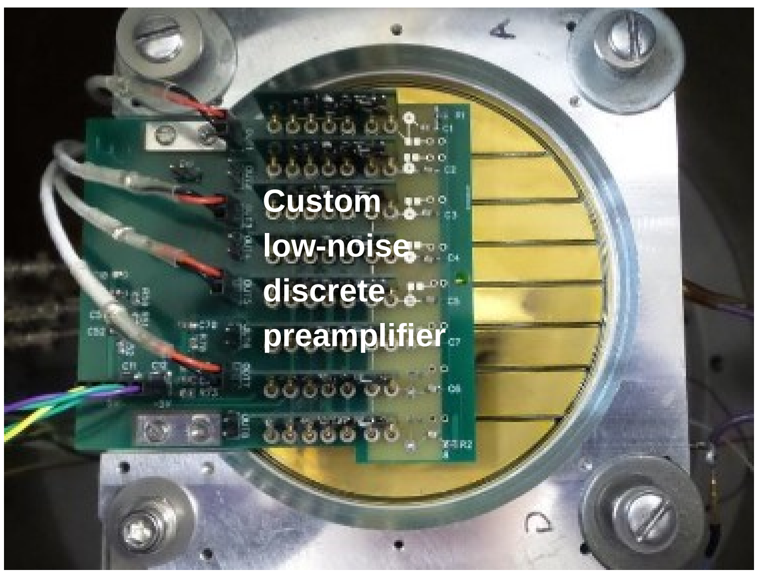
10 cm wafer diameter, 2.5 mm thick

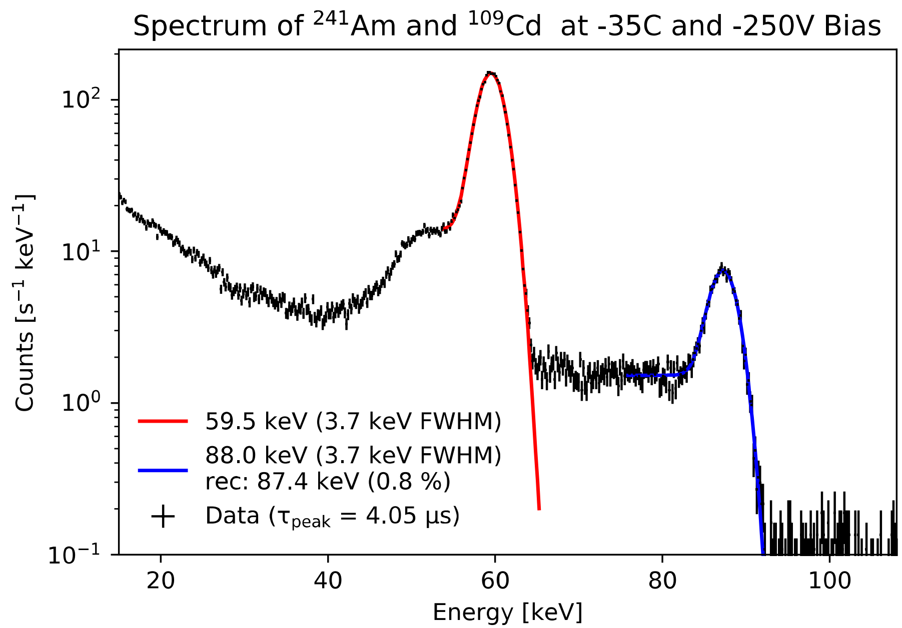
Flight design:
Both 4-strip (**2017**) and 8-strip (**2018, flight design**) validated

Si(Li) detector

- Energy resolution is measured at MIT using a custom low-noise, discrete-component preamplifier and flowing liquid N2 cooling system
  - Same preamplifier design will be used for flight detector calibration

- Demonstrate <4 keV FWHM energy resolution and <1% energy linearity using ^{241}Am 59.5 keV and ^{109}Cd 88 keV X-rays

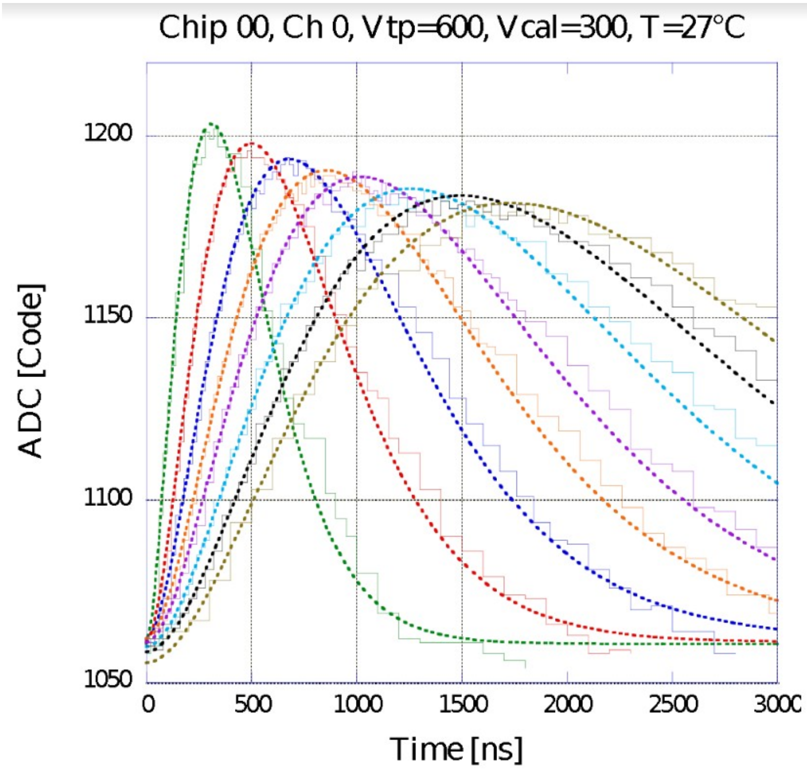




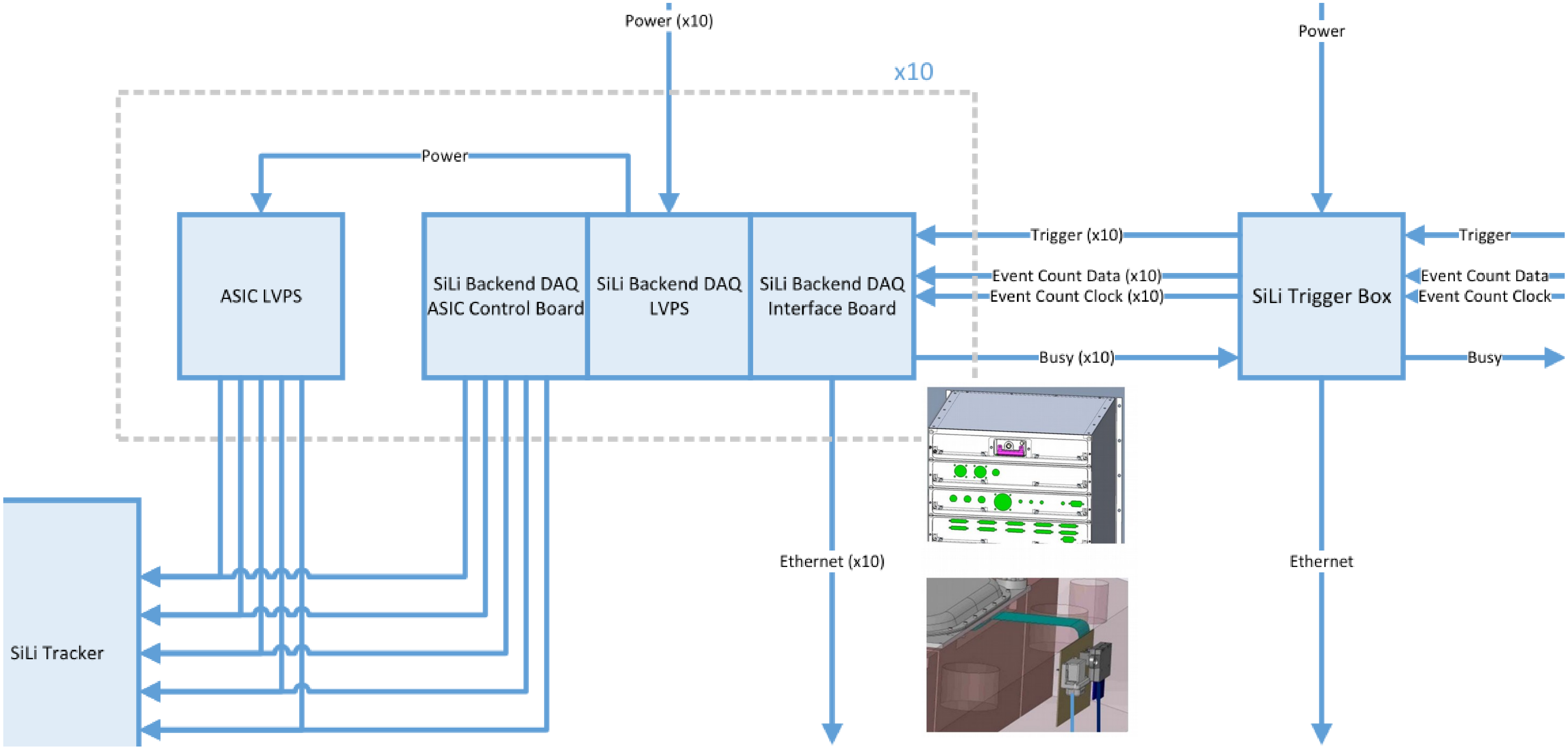
K. Perez et al. NIM A905 12-21 (2018) | M. Kozai et al. Proc. of IEEE (2018) | F. Rogers et al. in prep for JINST (2019)

Si(Li) sampling and digitization

- Custom ASIC developed to satisfy formidable power and density requirements
- 32 channels / chip
- 8 mW / channel
- Dynamic range: 10 keV to 100 MeV
- Tolerates up to I_{leak}= 50 nA

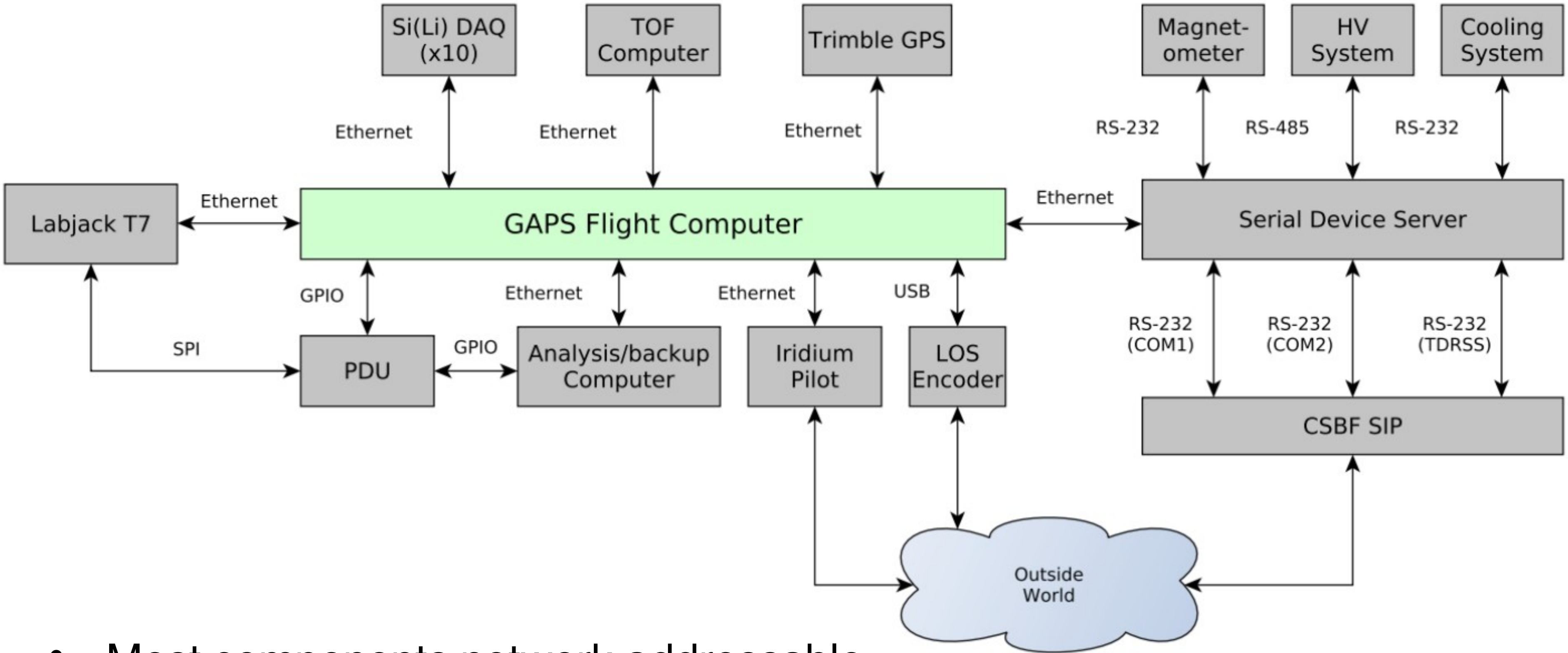


Si(Li) digital back end



- Backend handles interface with TOF trigger, control/monitoring of tracker, and DAQ
- Proven design based on COSI and GRIPS missions

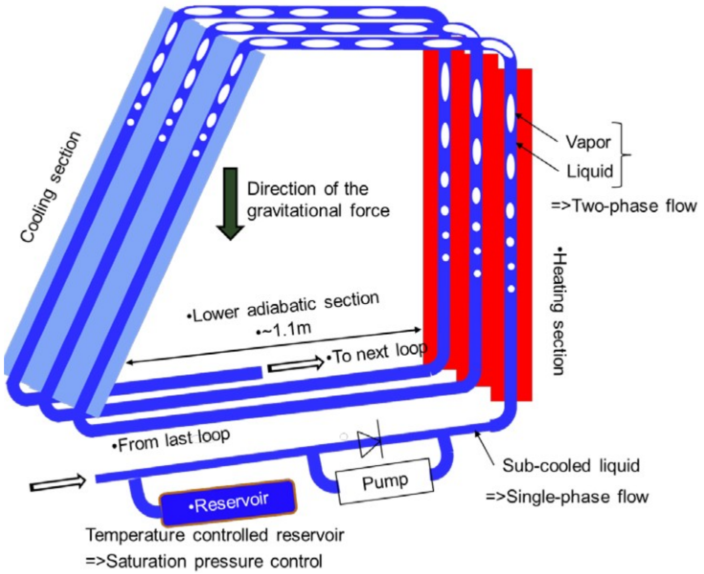
Ballooncraft & telemetry

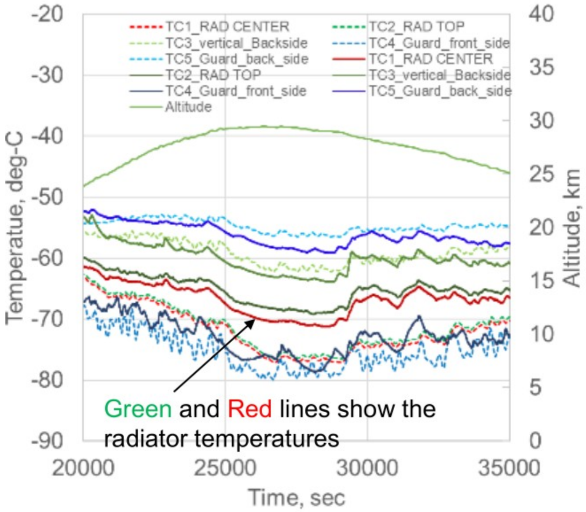


- Most components network addressable
- All links combined provide ~100 kB/s
- 2x redundant flight/analysis computers
- Flight software performs real time analysis (1000s evt/s)

Thermal regulation

- Low power, low mass, semi-passive design
- Si(Li) detectors passively cooled to achieve maximum energy resolution
- TOF system insulated from Si(Li)
- Scaled model of system recently validated on engineering flight





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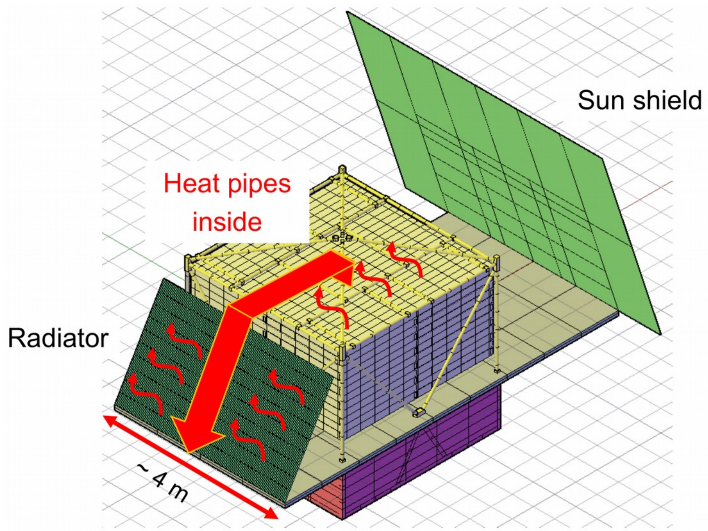


Conclusion

- GAPS will make use of a new detection technique that is complimentary to existing experiments
- Challenging requirements have resulted in a unique novel design for many systems
- Early prototypes (TOF preamp, 8 strip detectors, Si(Li) ASIC) fabricated. Early testing shows good results
- Moving forward with aggressive timeline for 2020 or 2021 launch

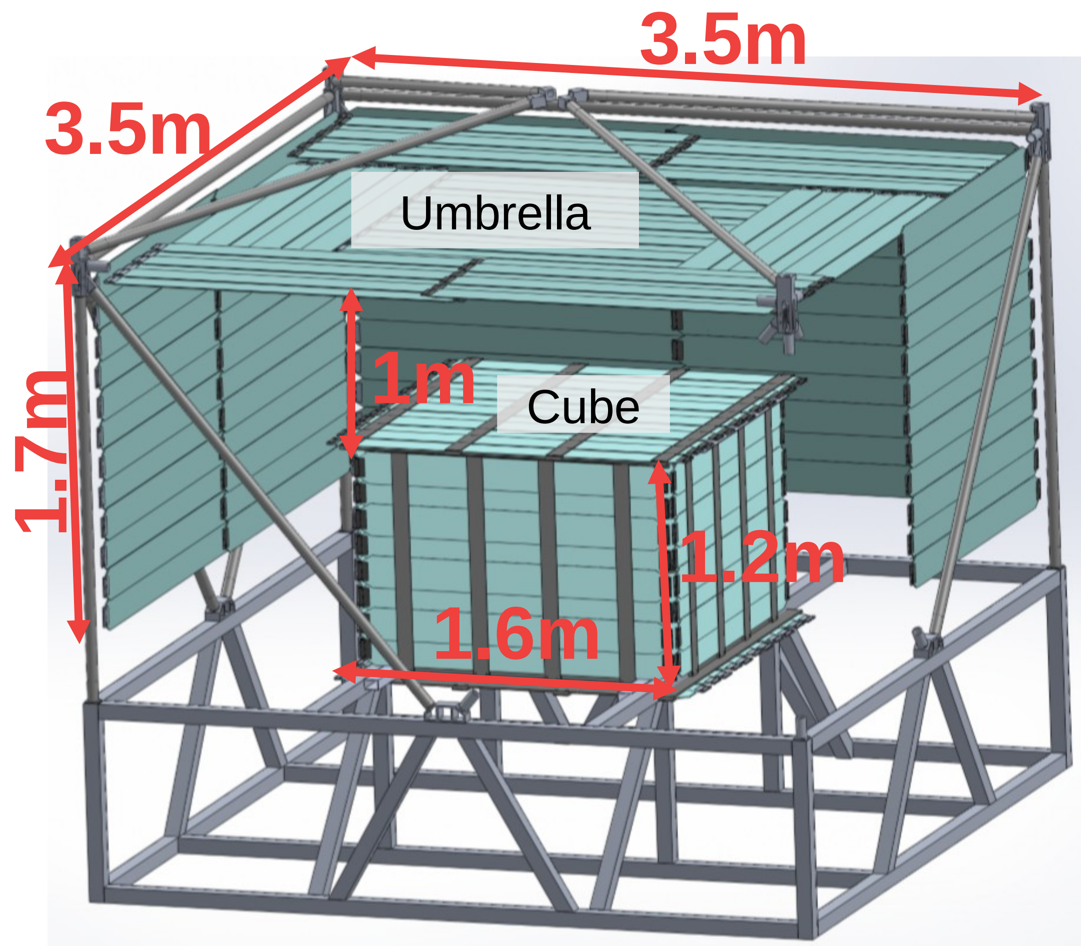
Funding agencies

Thanks for your attention!

Backup

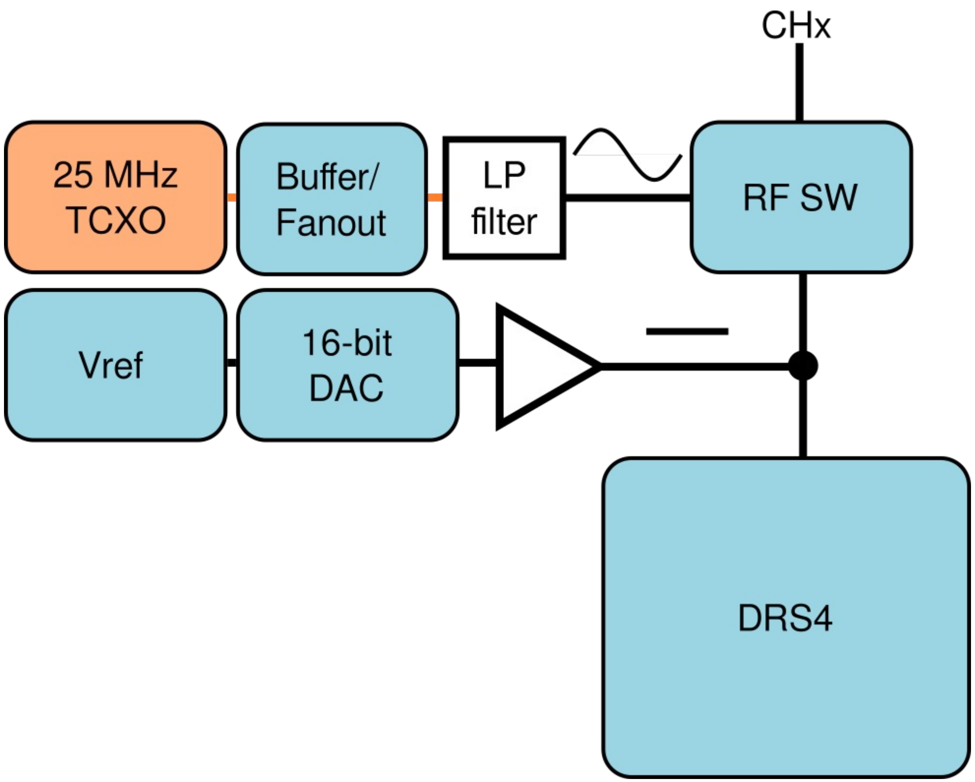
TOF System: key specs

- Umbrella
  - 132 counters
  - Active area: ~35 m²
  - Channels: 576
- Cube
  - 60 counters
  - Active area: ~15 m²
  - Channels: 240
- Total instrumented mass: ~870 kg

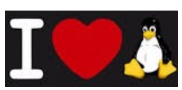


Digital back end: DRS4 operation, calibration

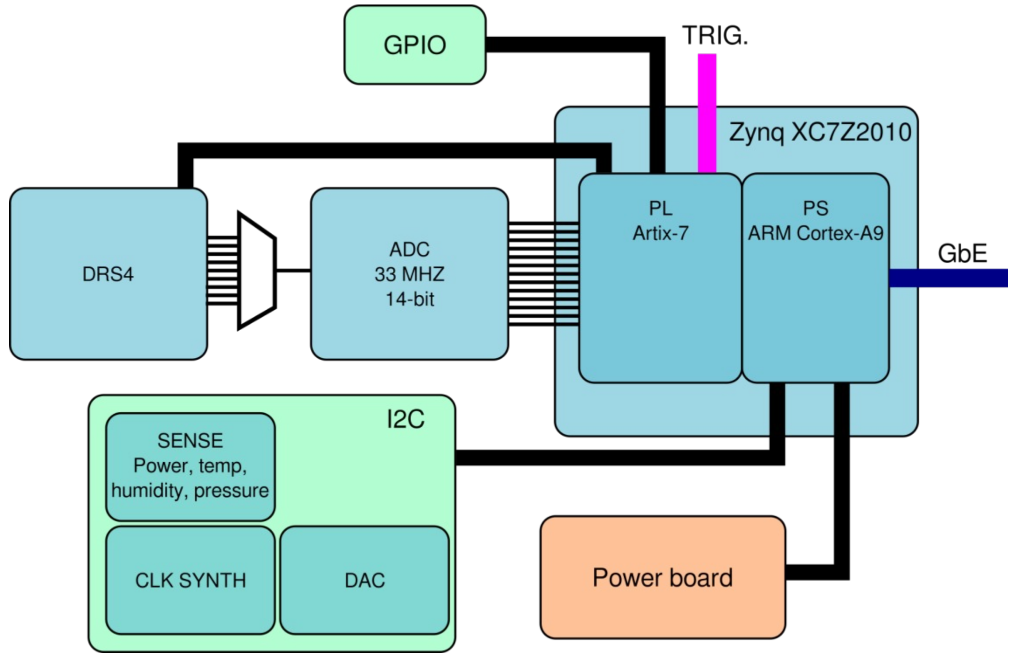
- DRS4 has excellent performance, but must be properly calibrated
- *in-situ* approach
  - 16 bit DAC (w/ precision reference) for amplitude
  - 25 MHz TCXO buffered for 9 input channels
  - Same technique as eval. board
  - Proposed period: every 300 s, 10000 samples at 500 samp. / s requires 20 s duration
- Expected end-to-end RMS noise: 1.5 mV, timing jitter ~100 ps



Digital back end:
Read out technicalities

- Readout board partitioned into analog and digital (logic) domains
- Programmable logic (PL) fabric:
  - Controls DRS4, initiates read out
  - Accepts data from ADC
  - Transfer via AXI bus to processing system (PS)
- PS capabilities
  - Collects monitoring data (environmental, temp, etc.) via I²C
  - Linux OS 

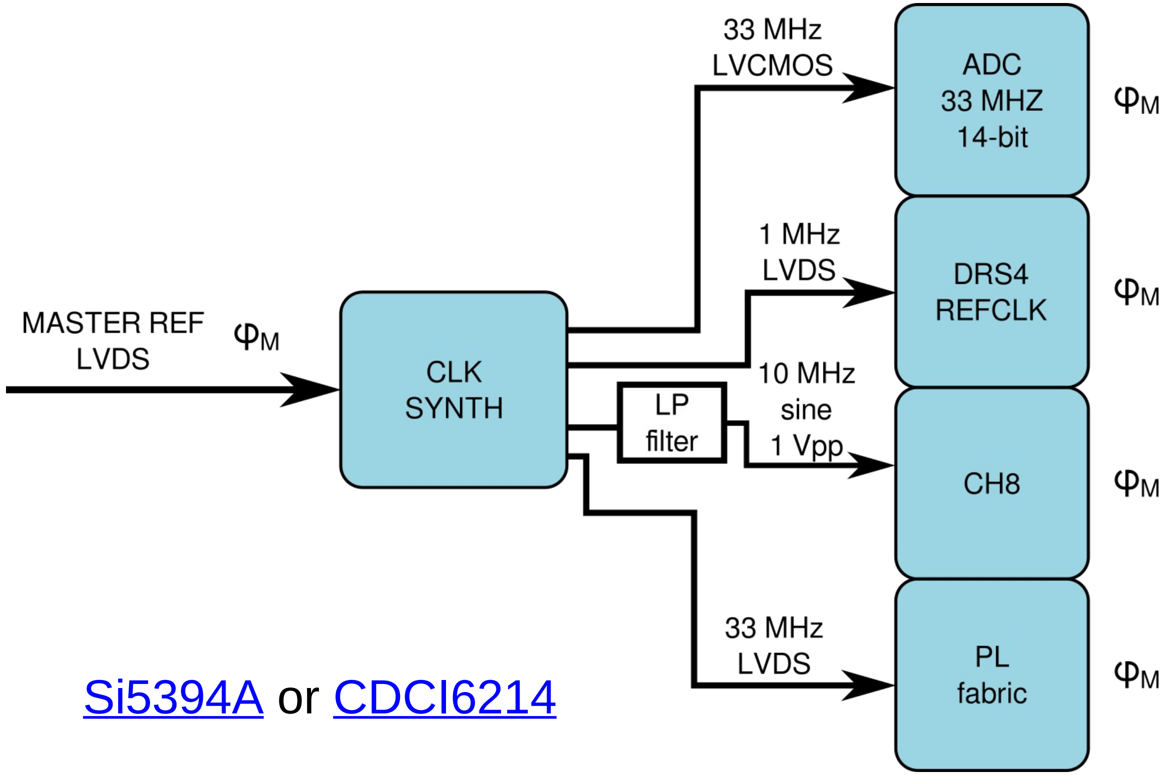
  - 512 MB RAM for deep event buffering
  - GbE link to TOF CPU (80 MB/s)



Off the shelf industrial board: Mars ZX2

Digital back end: Absolute timing

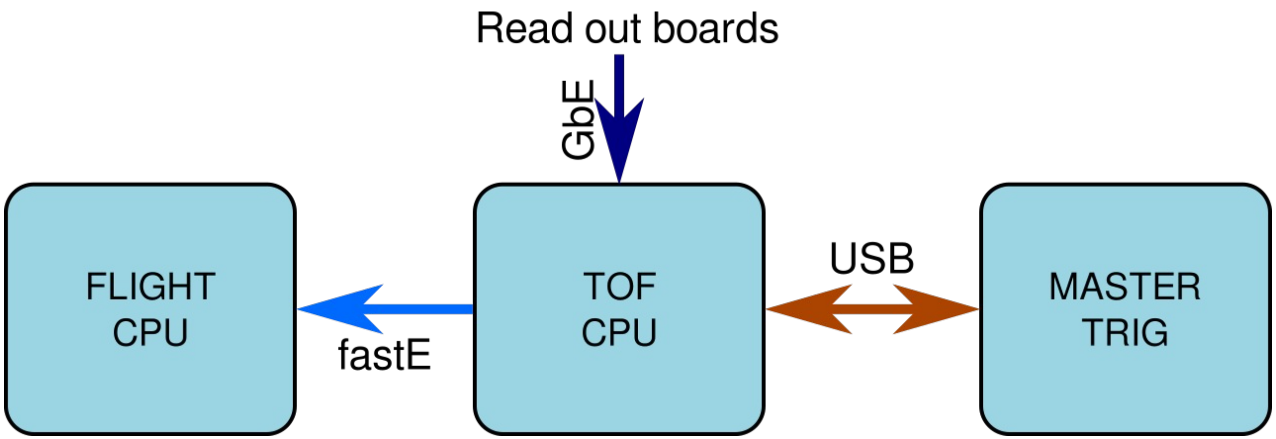
- Clock tree
  - Provides master frequency reference: e.g. 20 MHz
  - Clock recovered on read out boards
  - Clock synthesizer provides low jitter, phase locked references:
    - DRS4
    - ADC
    - PL
    - 9th channel input



Si5394A or CDCI6214

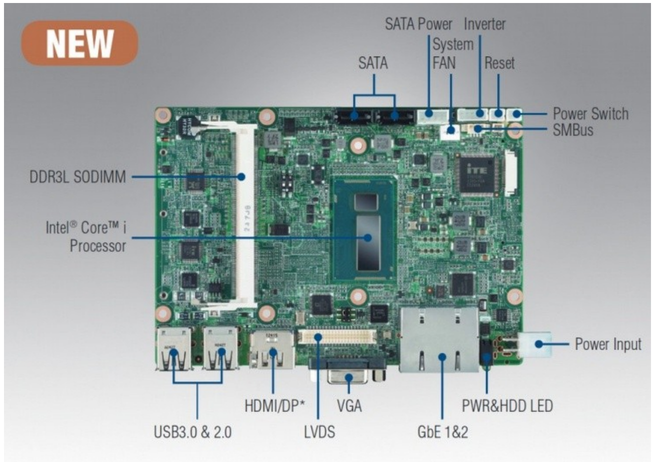
TOF CPU responsibilities

- Ingests all raw TOF data
- Rapid analysis
  - Primary charge estimate
  - Primary β estimate
- Real time event stream to flight computer, ~ 50 kB/s
- Gold-plated events permanently archived and telemetered
- Monitoring of 26 TOF electronic stacks + master trigger



TOF CPU hardware

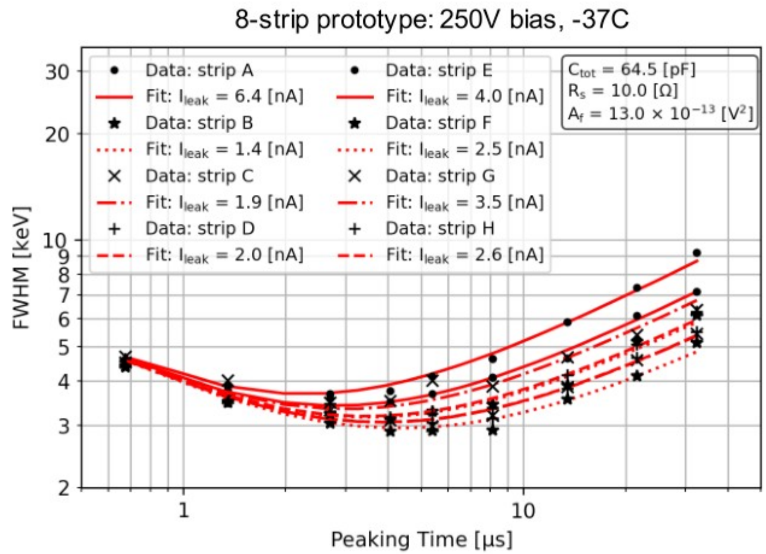
- All components industrial grade
- Advantech for motherboard (products have balloon heritage)
- mPCIe ports expanded to SATA for more storage
- Will test in vacuum, and design custom heat sinks



Qty	Item	P/N	Power (W)	Notes
1	Motherboard			
1	CPU (dual core)		30 max.	Industrial grade
1	RAM			1.35 V, 8 GB
8	SSD		5	512 GB, SLC
2	PCI expander		0.5	
2	Gigabit switch		33	16 port

Si(Li) detailed noise model

- All noise components of detector well characterized
- Added confidence that I_{leak} requirement satisfied
- Allows for accurate prediction of energy resolution with temperature in flight



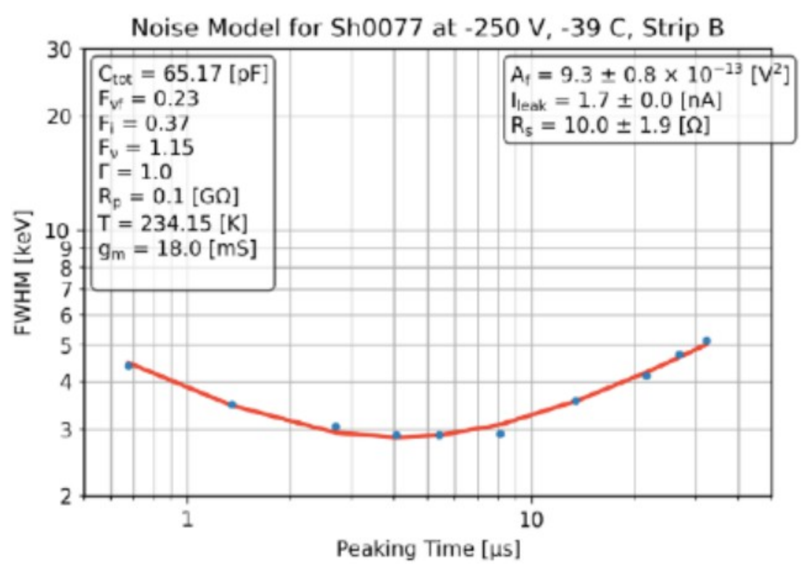
$$ENC^2 = (2qI_{leak} + \frac{4kT}{R_p})F_i\tau$$ *Parallel noise*

$$+4kT(R_s + \frac{1}{g_m})F_\nu \frac{C_{total}^2}{\tau}$$ *Series noise*

$$+A_f C_{total}^2 F_{\nu f}$$ *White noise*

e.g. Goulding, NIM 100 (1972) 493-504; Radeka, BNL (1974)

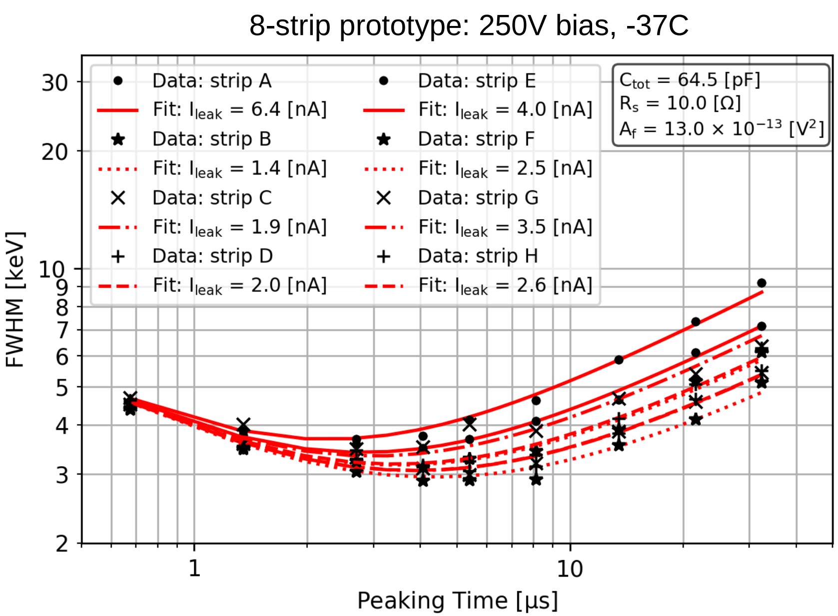
$$FWHM = 2.35\epsilon \frac{ENC}{q}$$

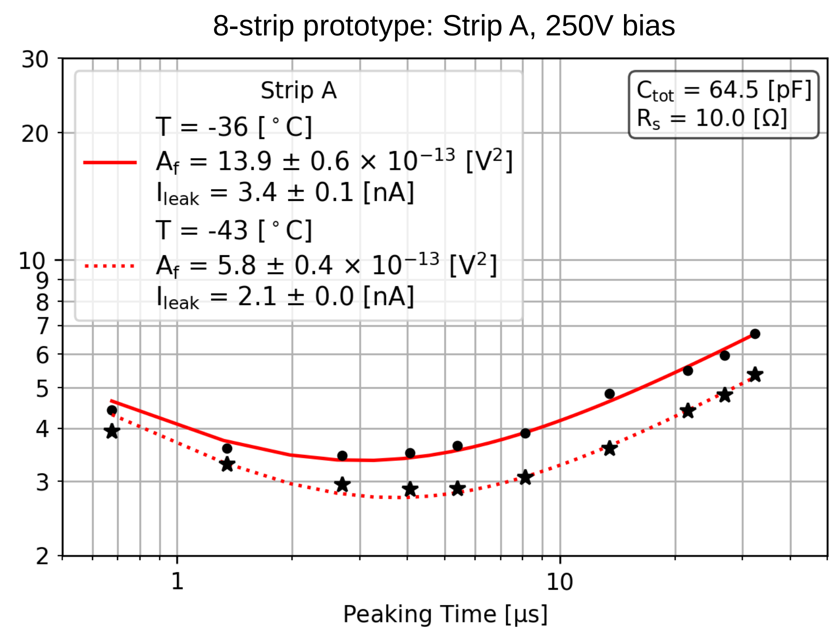


Si(Li) detailed noise model

- Energy resolution scales with **leakage current** as expected from the noise model
- If a detector has one strip with poor leakage current, all other strips will still be useful for X-ray detection

- Energy resolution and leakage current scale with **temperature** as expected
- We will be able to predict energy resolution as a function of in-flight temperature

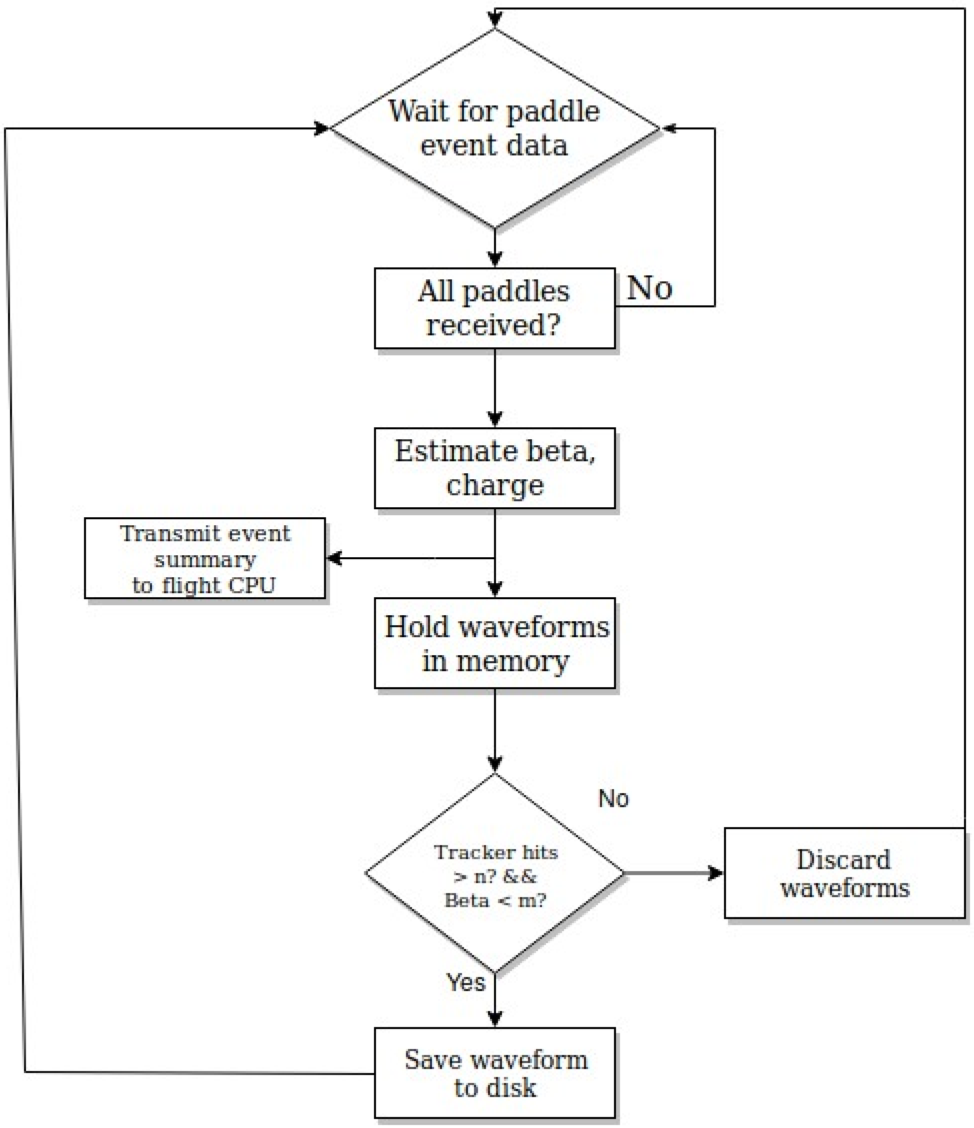




* Note: C_{tot} here includes significant C_{stray} due to discrete preamplifier mounting / noise.

TOF CPU example event

- Expected base rate of 350 Hz
- Presents archiving challenge without further cuts
- Higher quality events selected using β (TOF) & tracker info Si(Li)
- ~4 TB for entire mission w/ 2x redundancy

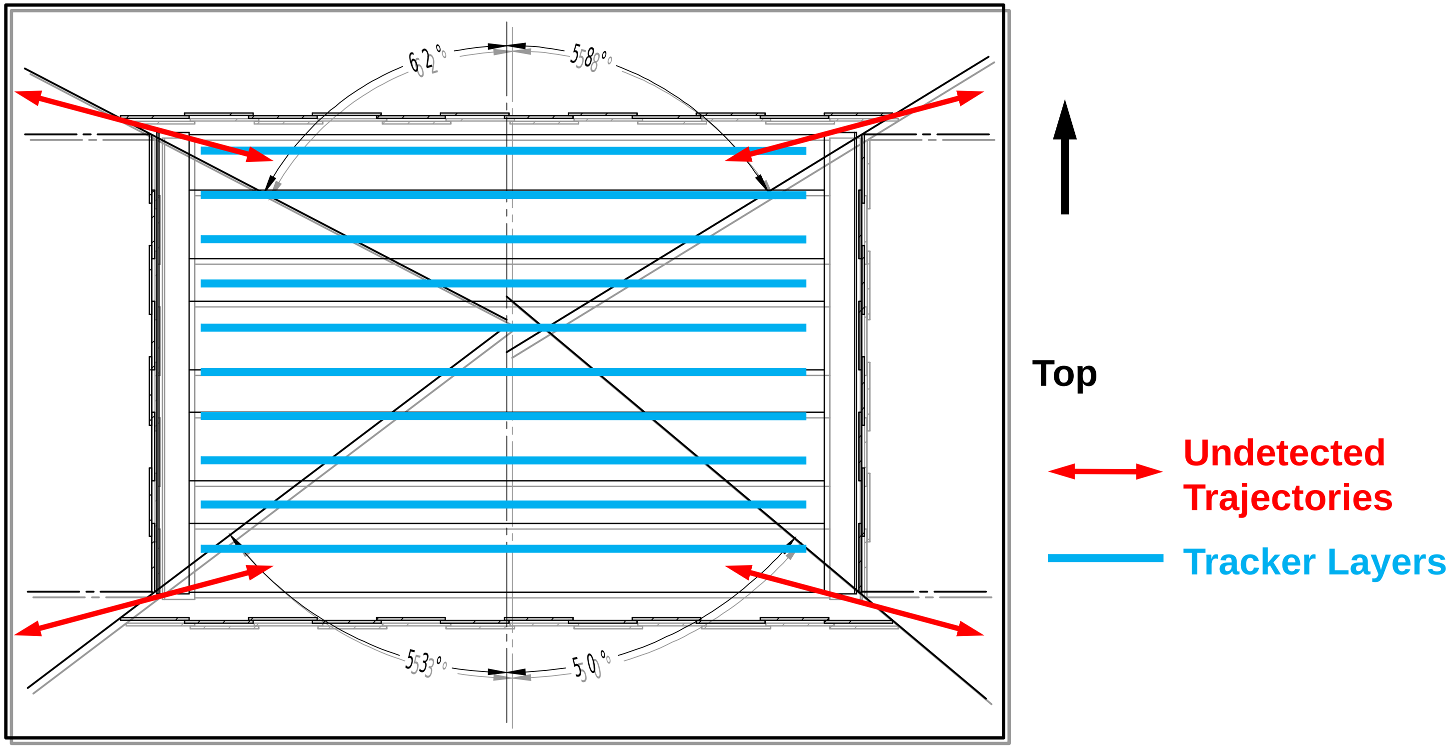


TOF CPU→Flight CPU Data rates

Qty	Item	Unit size [b]	Total size [b]	Notes (range; precision)	
1	Paddle ID	8	8	0 to 256	Paddle data
1	Paddle A end timing	16	16	0 to 100 ns; 1.5 ps	
1	Paddle B end timing	16	16		
1	Paddle A end pulse area	16	16	0 to 250 pC; 0.0038 pC	
1	Paddle B end pulse area	16	16		
1	Calculated paddle total p.e. charge	16	16	0 to 250 pC; 0.0038 pC	
		Packet size per paddle	**88**		
25	Number of paddles in event				
1	Packet start char	8	8	ASCII character: "[" (left square bracket)	Event record
1	Packet length	16	16	Supports up to 65 kb packet size	
1	Primary track beta	24	24	Beta, Beta unc, Beta figure of merit	
1	Primary particle charge estimate	24	24	Charge, Charge unc, Charge figure of merit	
1	Trig. info	8	8	Misc. info about trigger algorithm	
1	Event number	32	32	GAPS event number	
1	UTC timestamp for trigger decision	64	64	Full GPS second & 1 ns precision	
1	Paddle hit pattern	8	8	Hit/no hit bit mask	
1	Paddle data from top section	88	2200	Sorted by absolute time	
1	CRC ETX	8	8		
1	Packet end char	8	8	ASCII character: "]" (right square bracket)	
1	TCP/IP overhead	240	240		
		Packet size per event	**2640**		
280	Trigger rate				
		Data rate [bits / s]	739200		
		Data rate [Bytes / s]	92400		
		Data rate [kilo Bytes / s]	92.4		
Rev.	2019.1				

Cube
- Line-of-Sight (LoS) & Coverage

- Physical/mounting restrictions create gaps in coverage along the Top-Side panel seam and Bottom-Side panel seam
  - Top Gap: 3.8 - 4.5 cm (exit for OHP)
  - Bottom Gap: 6.0 - 6.7 cm (TOF floor Gondola framing members)
- The oversized Top/Bottom panels are meant to mitigate undetected LoS into the Cube
- **Any incoming particles with zenith angle ≲58° are detected by the Cube Top panel**
  - Preliminary Monte Carlo simulations on just the Inner TOF, indicates -- at worst -- 4% of all incoming tracks in 4π are undetected.
- However, “real” coverage depends on the point of interest inside the tracker
  - Locations at the top and bottom of the tracker will have the worst coverage



Cube
- Line-of-Sight (LoS) & Coverage

- **A small fraction of incoming particles with zenith angles 58° ≲ θ ≲ 127° can slip, undetected through the EDGE paddles and Side panels.**
- This won't significantly affect detection of "wanted" incoming particles
- It will affect ability to detect outgoing tracks after annihilation