Development of novel pixel sensor "AstroPix" for future space-based MeV γ-ray telescopes

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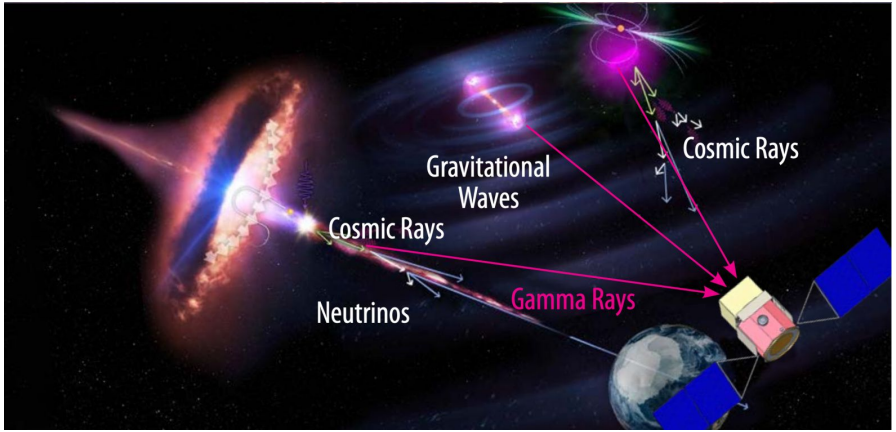
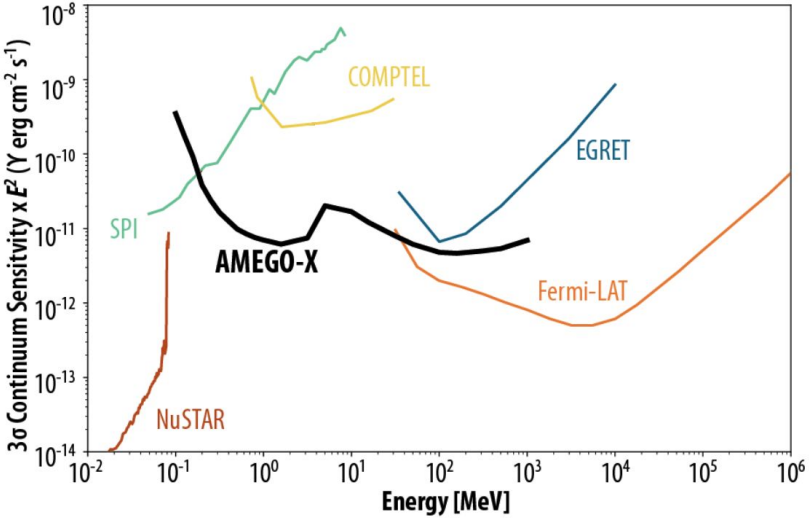
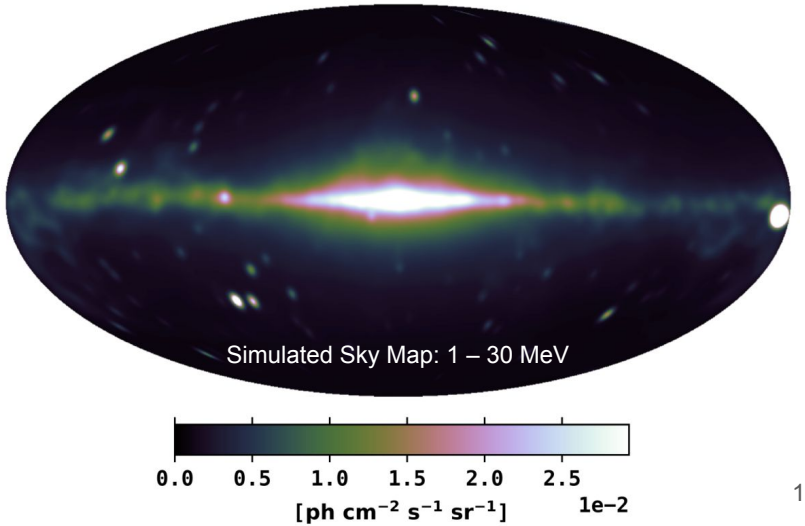
Multi-messenger Annual Conference 2025

AMEGO-X: Introduction

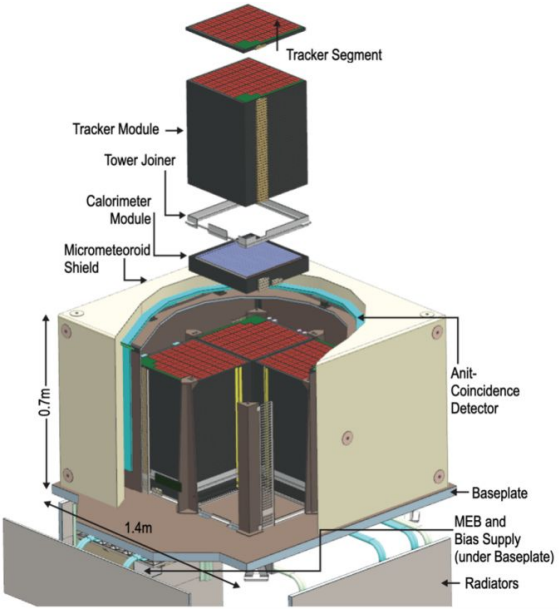
- **A**ll-Sky **M**edium **E**nergy **G**amma-ray **O**bservatory e**X**plorer: proposed space mission (Caputo et al. 2022)
- Energy range: 25 keV – 1 GeV
- Study of supermassive black holes using AGN: expects detection of ~400 blazars and ~150 blazar flares/year
- Polarization measurement of bright blazars: Leptonic or hadronic origin?
- Binary Neutron Star (BNS) mergers: >200 SGRBs/year
- Galactic cosmic ray sources: Supernova remnants, Novae, star-forming regions, Pulsars, PWN
- Important role in multi-messenger astronomy.

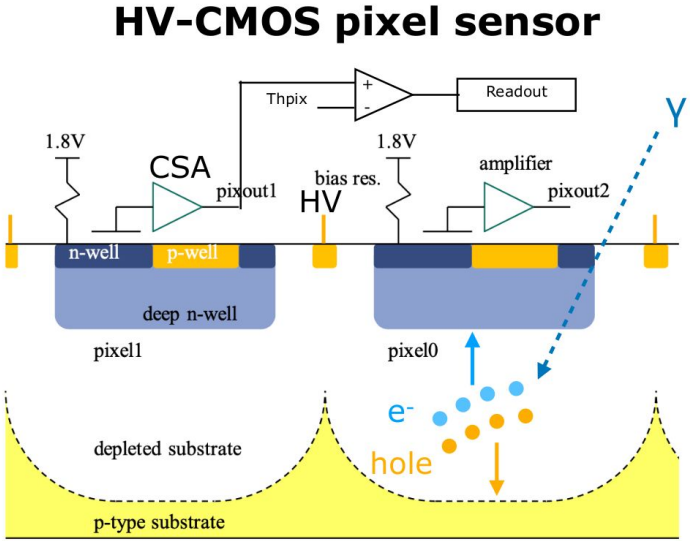


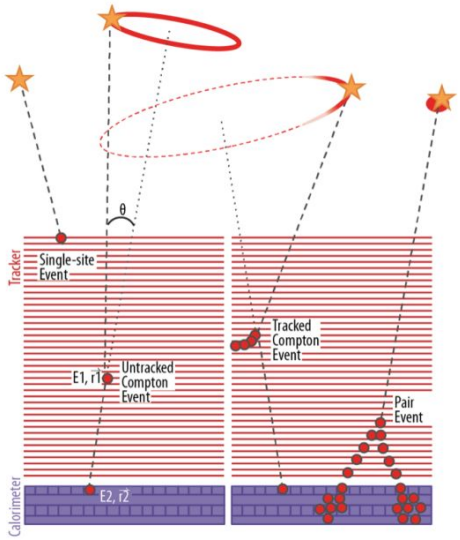


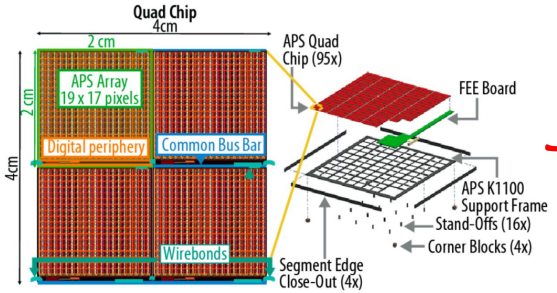


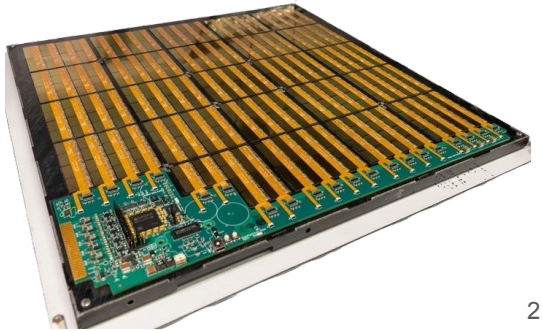
AMEGO-X: Structure & Components











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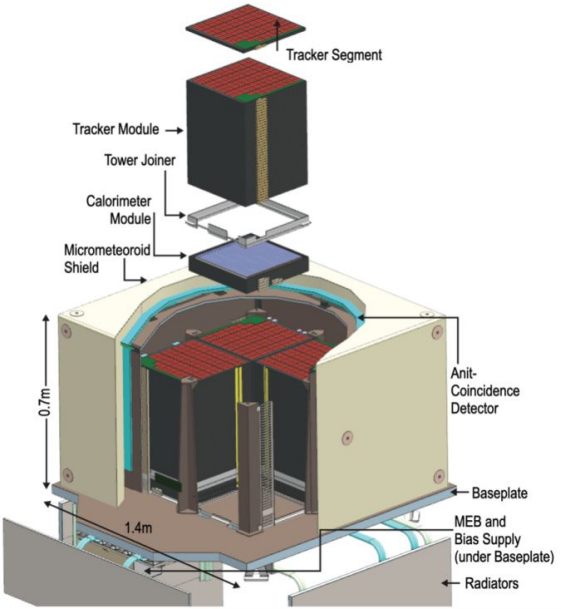
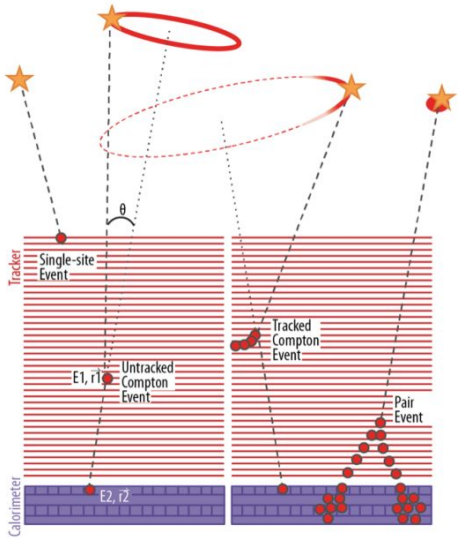


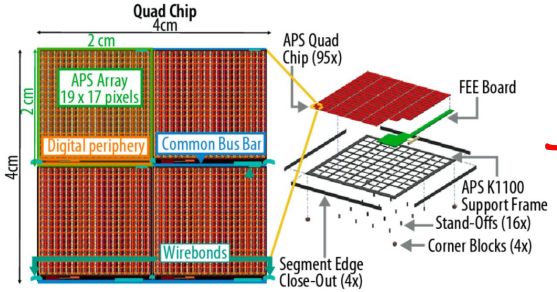
AstroPix (Steinhebel et al. 2025)

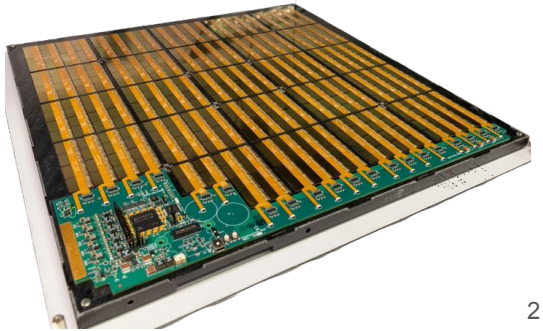
- HV-CMOS pixel sensor: Monolithic active pixels
- Charge collection/amplification/readout co-integrated in pixel – No analog readout required

- **Goal:**
  - Pitch- 500 x 500 μm^2
  - Depletion depth- 500 μm
  - Dynamic range- 25 – 700 keV
  - Energy resolution- 10% at 122 keV
  - Power- <1.5 mW/cm^2

- **Quad-chip:** 2 x 2 AstroPix array
- **Si-tracker:** array of quad-chips
  - Large effective area (1200 cm^2 at 100 keV)
  - Less power consumption
  - good energy and spatial (2.5° at 100 MeV) resolutions

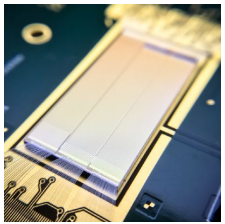


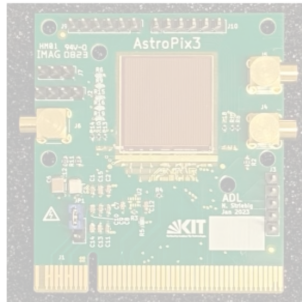




AstroPix: Historical Progress

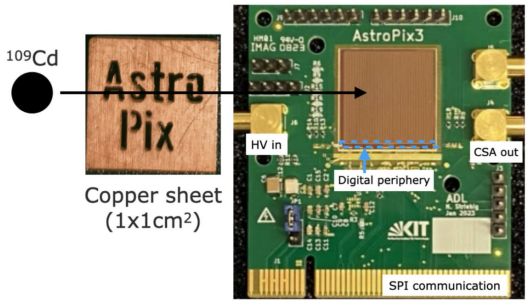
2020	2021	2022	2023	2024	2026

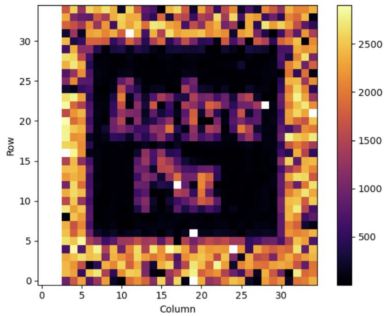




ATLASPix	AstroPix v1	AstroPix v2	AstroPix v3	AstroPix v4	AstroPix v5
					Coming soon!
Pitch: 150 x 50 µm	175 x 175 µm	250 x 250 µm	500 x 500 µm	500 x 500 µm	
Power: 160 mW/cm^2	24.6 mW/cm^2	7.2 mW/cm^2	4.1 mW/cm^2	2 mW/cm^2	

- **AstroPix-1:** Analog readout only
- **AstroPix-2:** Digital readout introduced
- **AstroPix-3:** Full reticle chip – 2x2 cm^2 (Suda et al. 2024)





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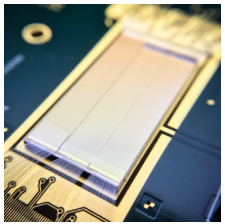

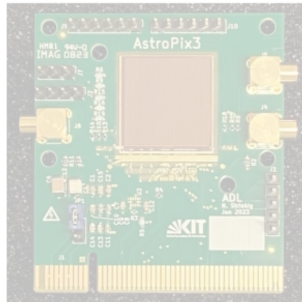

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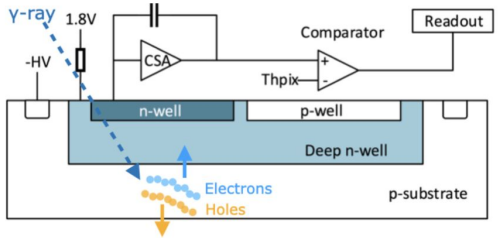

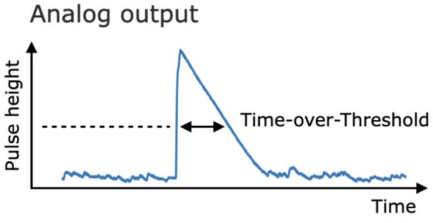

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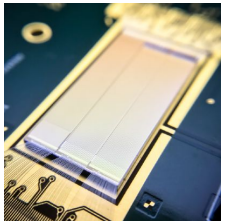

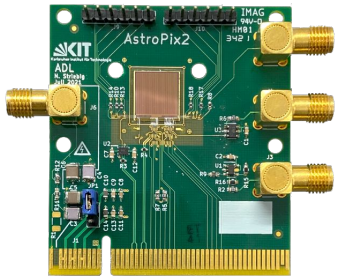

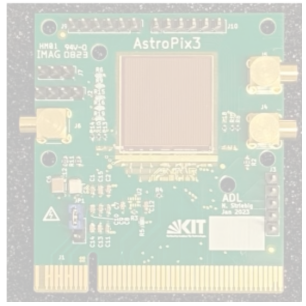

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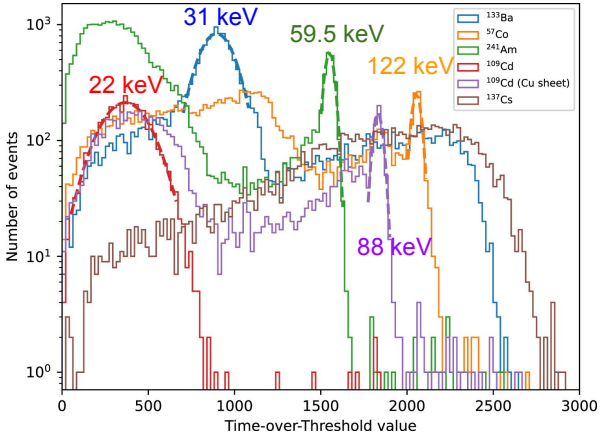
Role of Japanese group-

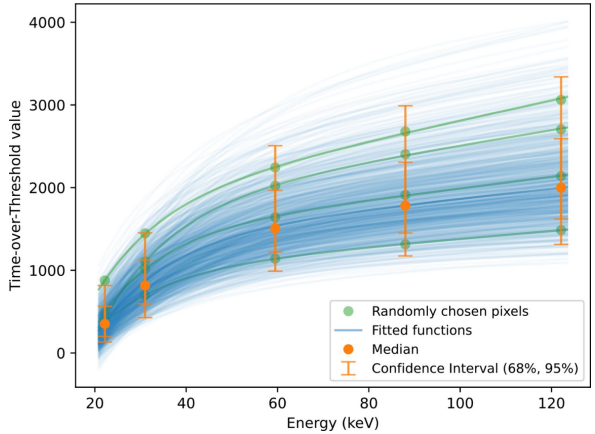
- **AstroPix:** Measurement and validation of gamma-ray response
- **A-STEP:** MC simulation, Quad chip gamma-ray response

AstroPix-3: Characterization

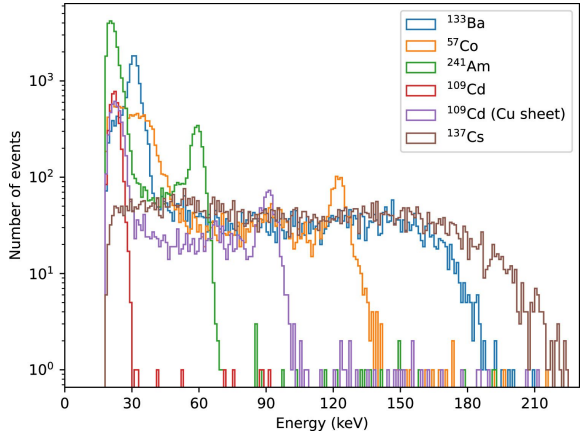
ToT spectra



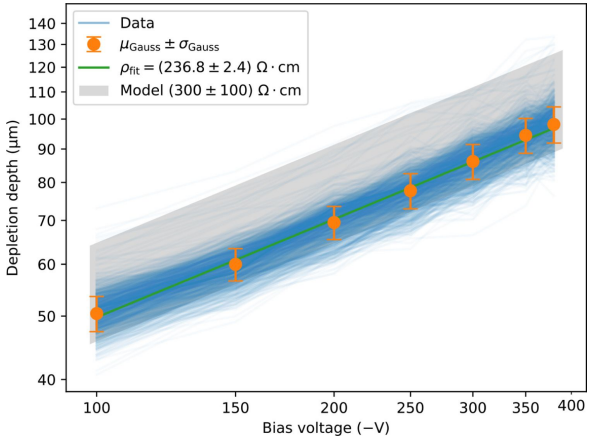
Energy Calibration



Energy spectra

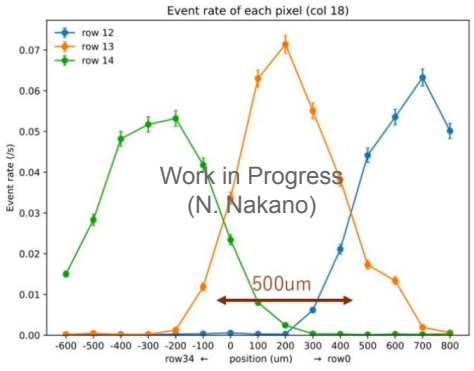


Depletion Depth

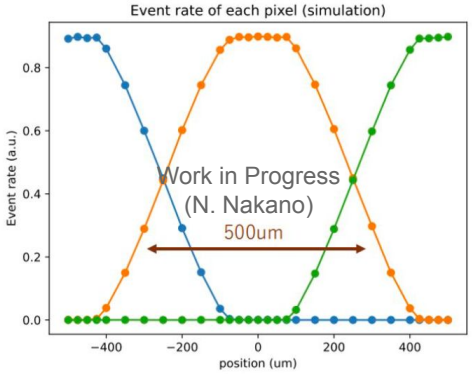


Sub-pixel response

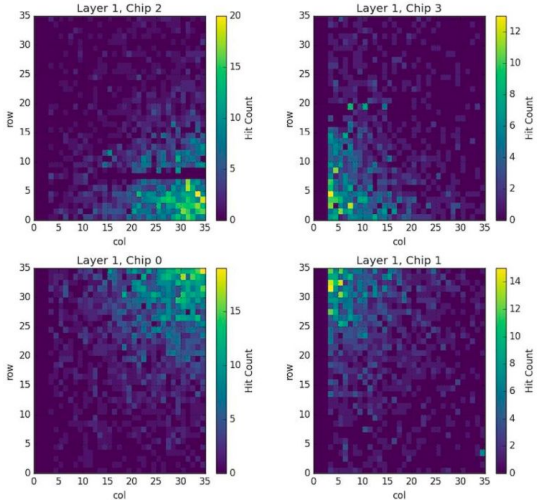
Data



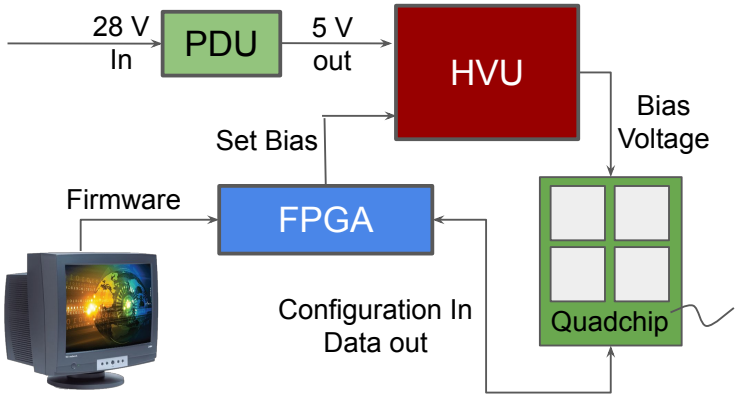
Simulation



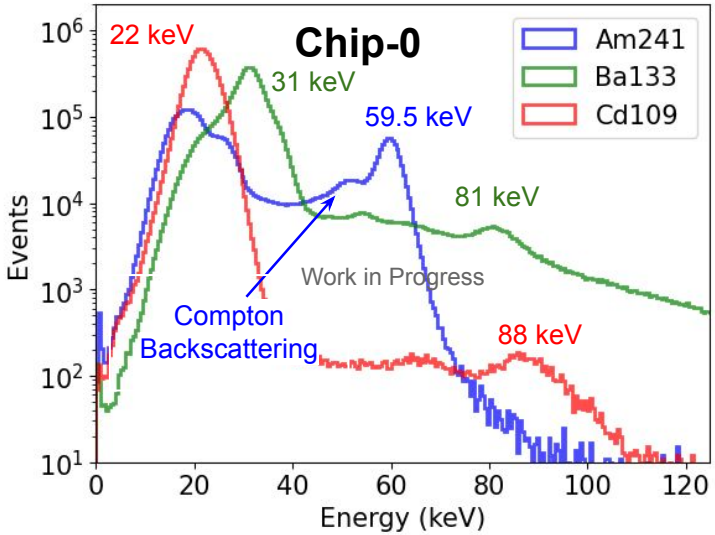
AstroPix-3: Quad-Chip

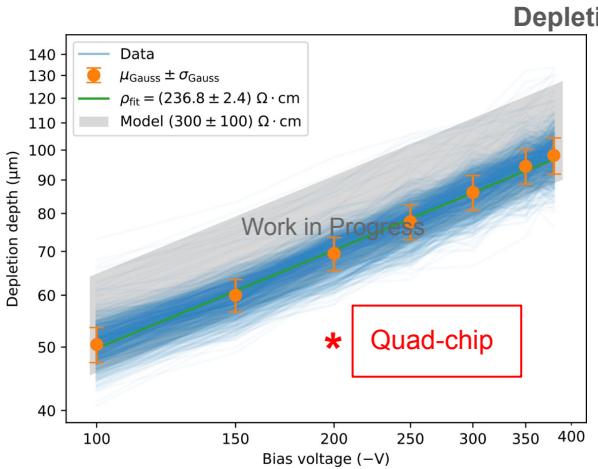


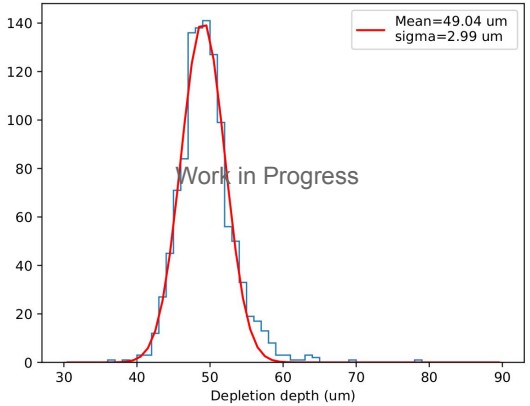
- 2 x 2 array of AstroPix v3 (35 x 35 pixels each with 500 x 500 μm^2 pitch)
- Single SPI line to control 4 chips (Daisy-chained)
- MOSI line: configure chips using FPGA
- MISO lines: carry data to FPGA
- Output: Time-over-threshold (ToT)
- Analog output from pixels of first row for test purpose
- Depends on external clocks–
  - SPI clock: data transfer
  - TS clock for event timestamp
  - ToT clock for ToT measurement
- Power consumption: 4 mW/cm^2



AstroPix-3: Quad-Chip





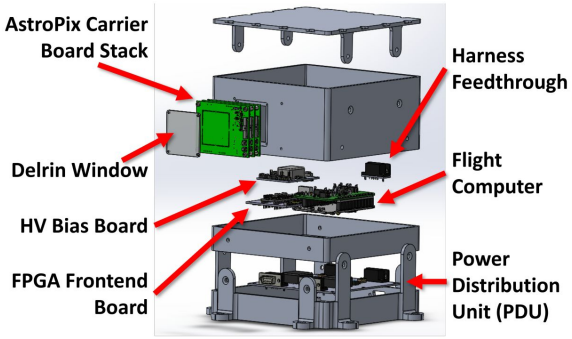


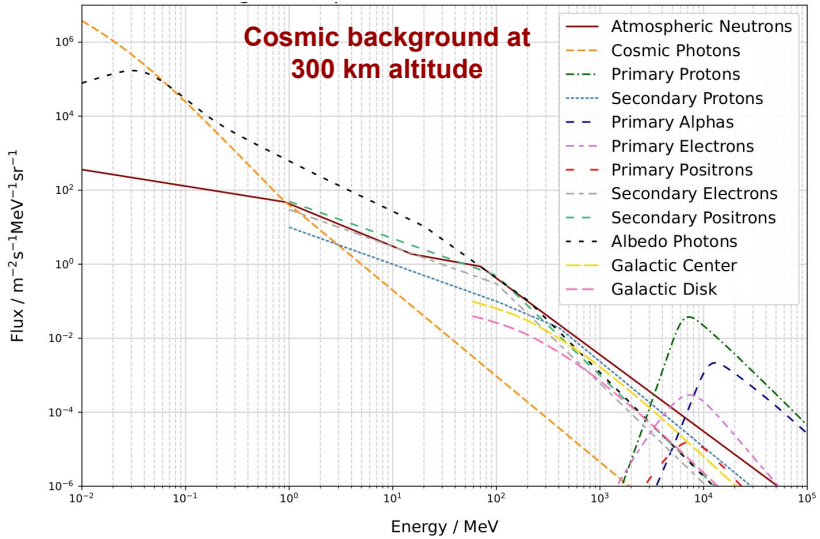
- Successful readout of hits from four V3 chips.
- Reliable energy calibration in 85% pixels.
- Similar performance as AstroPix-3 single chip.

- Measured depletion depth is lower than expected (under investigation)!

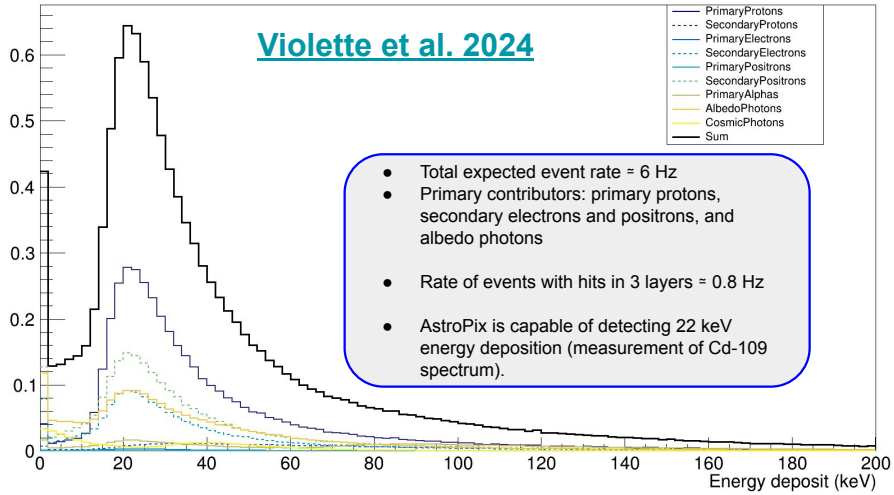
A-STEP

- 3 layers of single quad-chips – mini tracker.
- Launch from Wallops Flight Facility in 2026.
- Flight onboard sounding rocket to test readiness of space operation.
- Performance simulation using MEGALib: Geant4-based simulation tool.



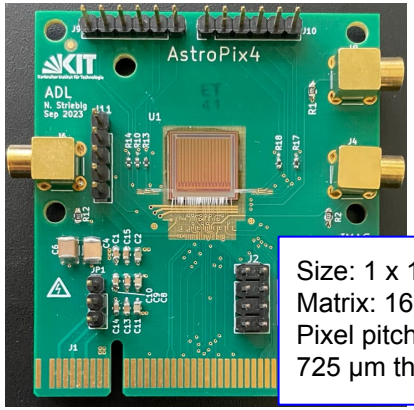


Cumulative deposited energy spectrum distribution (normalized by trigger rate)



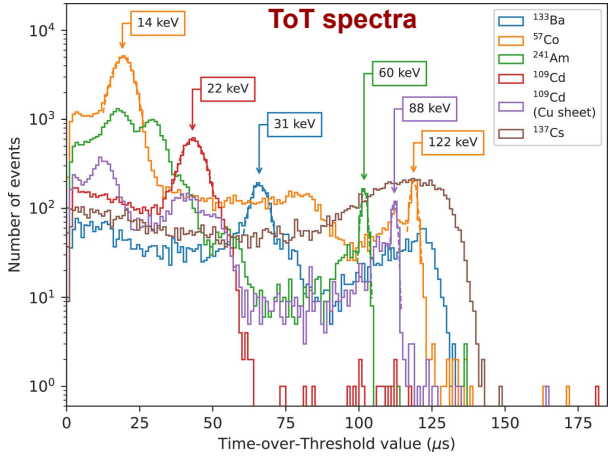
- Total expected event rate ≈ 6 Hz
- Primary contributors: primary protons, secondary electrons and positrons, and albedo photons
- Rate of events with hits in 3 layers ≈ 0.8 Hz
- AstroPix is capable of detecting 22 keV energy deposition (measurement of Cd-109 spectrum).

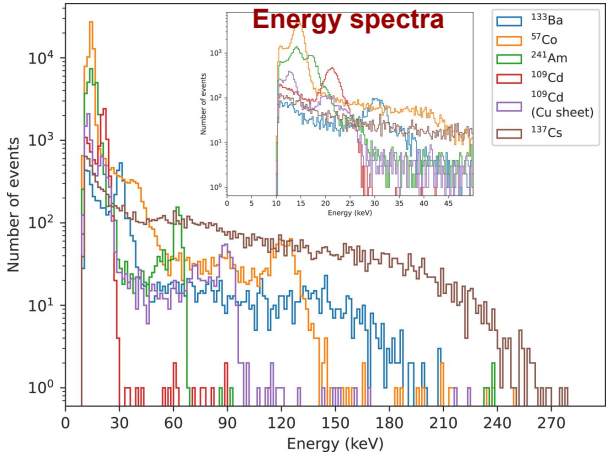
AstroPix-4: Characterization

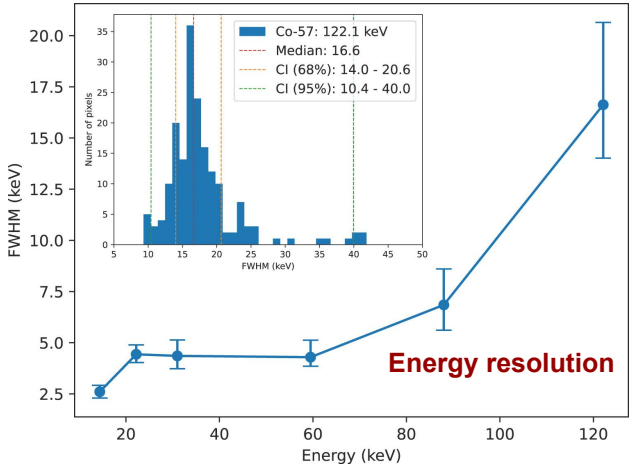


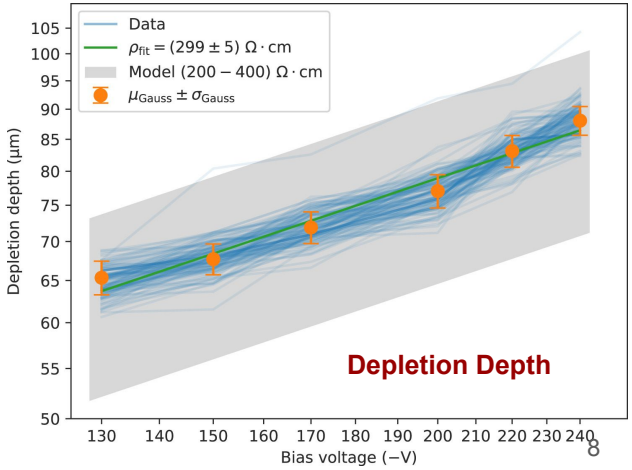
Size: 1 x 1 cm2
Matrix: 16 x 13 pixels
Pixel pitch: 500 µm
725 µm thick

- Reduced input capacitance by optimizing the routing and minimizing the metal-to-n-well capacitance → Lower noise floor and better energy resolution (Suda et al. 2025)
- Pixel-by-pixel comparator threshold tune → reduce ToT variation
- Individual hit buffer → No identification problem with multiple hits in Row/Col
- Improved timestamp structure → 3 ns for timing and ToT



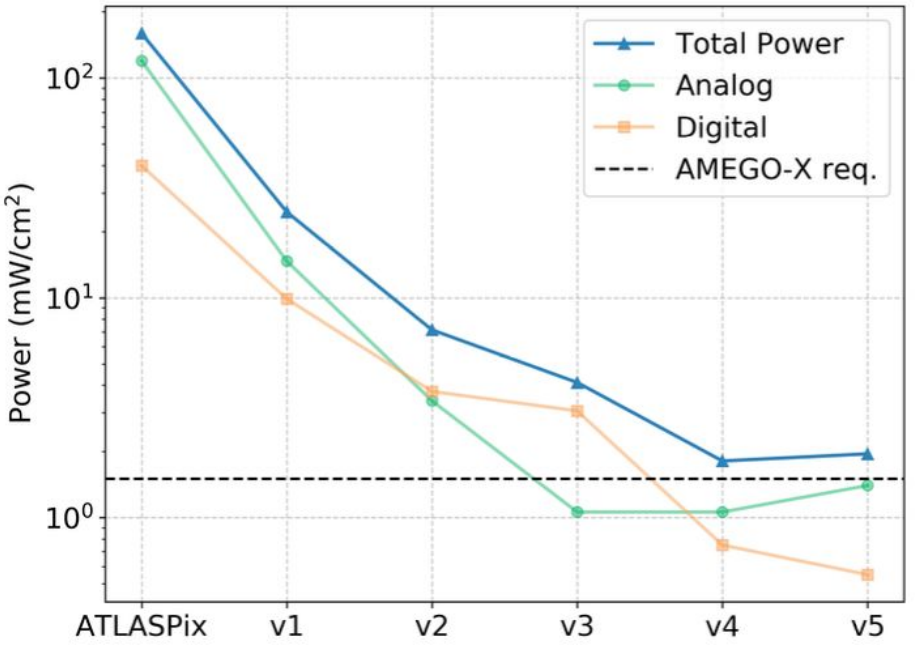




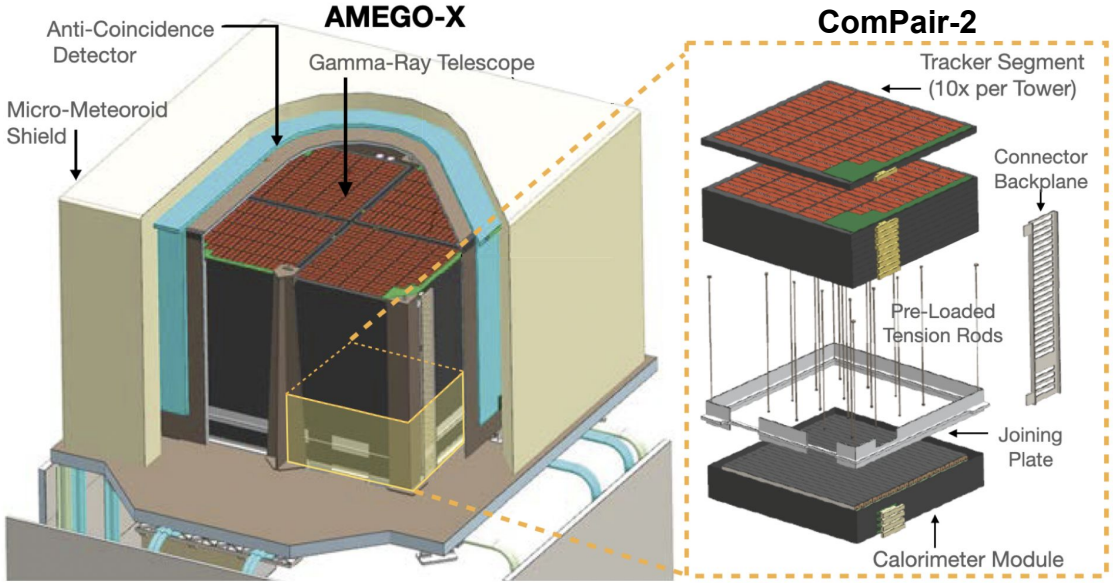


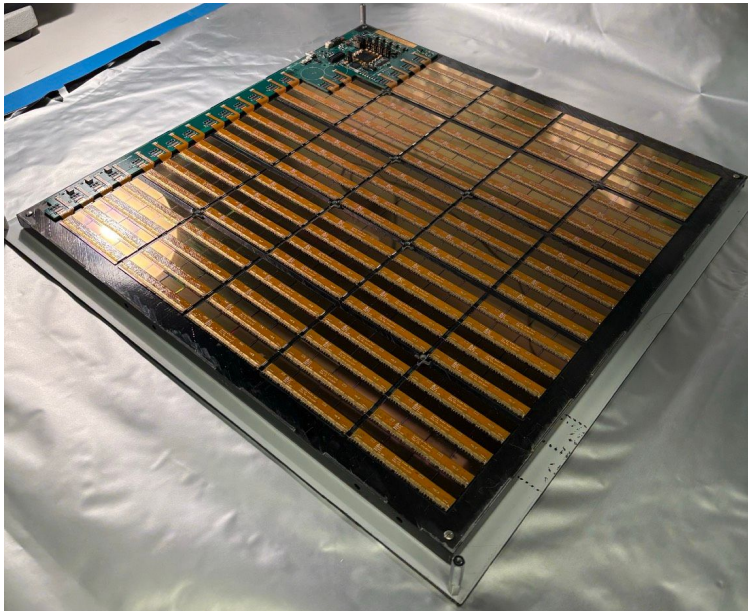
Next version: AstroPix-5

- AstroPix-5 will arrive in Spring of 2026.
- Full 2 x 2 cm^2 reticle chip with 36 x 24 pixels.
- Updated guard-ring design for higher breakdown voltage up to 400-500 V for maximizing depletion depth.
- Two test columns with high dynamic range charge-sensitive amplifier that should not saturate until > 700 keV.
- Pixel Dynamic Range ~14 keV - 700 keV
- Noise Floor 5 keV (2%@662 keV)
- Reduced pixel capacitance.



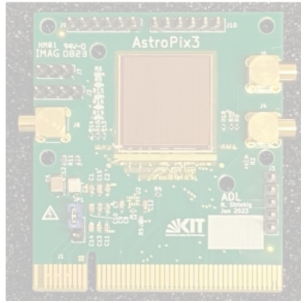
Prototype Telescope





- ComPair-2 [PI: R. Caputo (NASA-GSFC)] is 10 AstroPix trackers + CsI calorimeter ⇒ Demonstration of Compton and pair-production events. [Ref: arxiv.org/2412.02562]
- Instrument integration and testing in 2026.
- Improvement of event classification and reconstruction using Machine Learning.
- Follow-up funding for balloon flight.
- First prototype ComPair-2 tray with 95 quad-chips and FPGA.

Summary

2020	2021	2022	2023	2024	2026	2027
						AstroPix-6?
AstroPix v1	AstroPix v2	AstroPix v3	AstroPix v4		AstroPix v5	

- Development of AstroPix is progressing well. Sounding rocket test flight of A-STEP will be in 2026.
- Quadchip with busbar and a 9-chip array are being successfully tested.
- Low energy threshold (< 22 keV) confirms AstroPix's capability of detecting majority of the events during A-STEP flight.
- Latest version of AstroPix has a low noise floor and moderate energy resolution. Achieved depletion depth is far from the goal.
- Higher breakdown voltage in future AstroPix version to reach full depletion depth of 500 um.