Performance evaluation of the high-voltage CMOS active pixel sensor AstroPix for gamma-ray space telescopes

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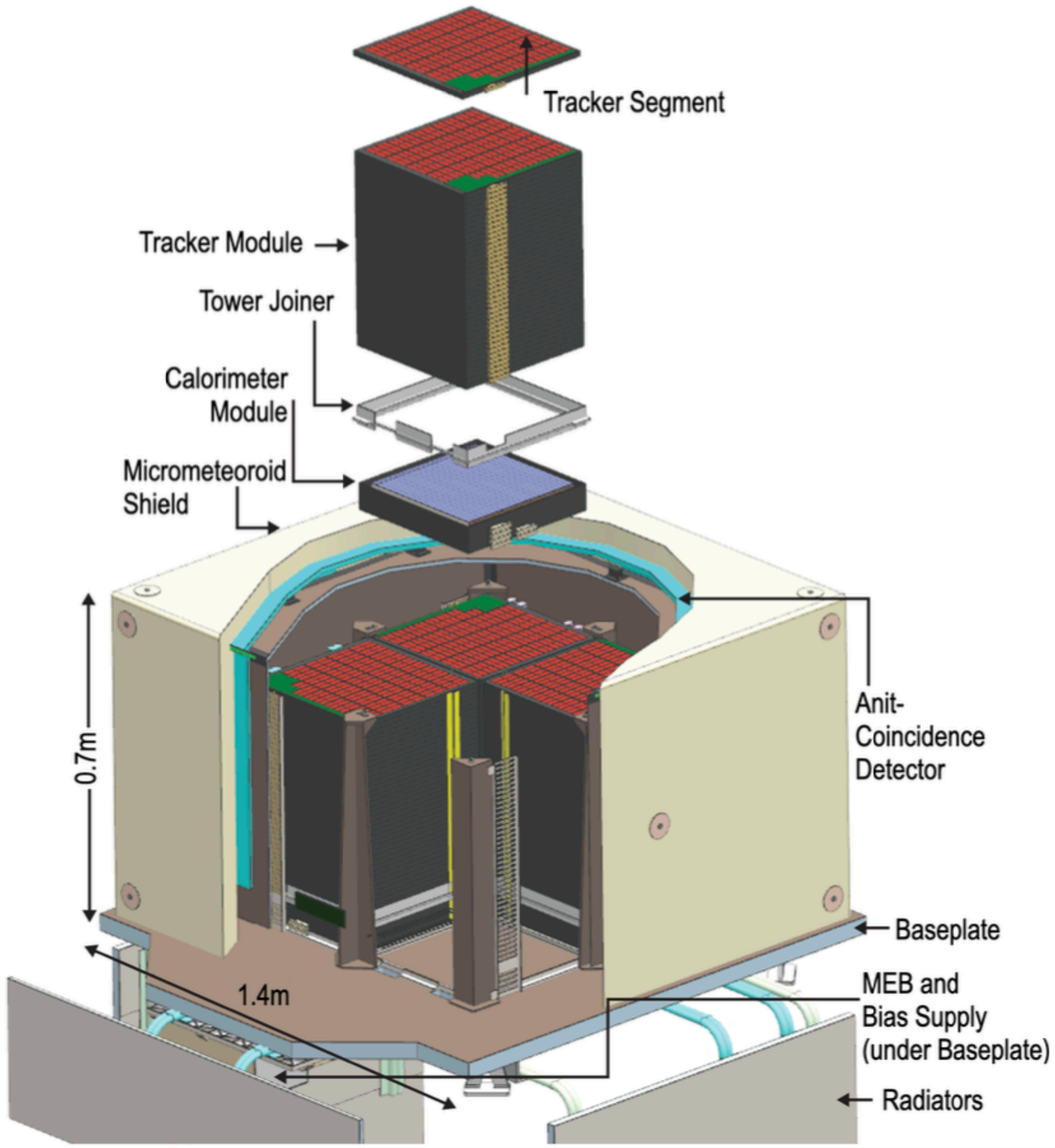
All-Sky MeV Gamma-Ray Observatory

- AMEGO-X (PI: R.Caputo GSFC/NASA) is a proposed explorer to study extreme astrophysical phenomena in MeV regime



R. Caputo+ 2022

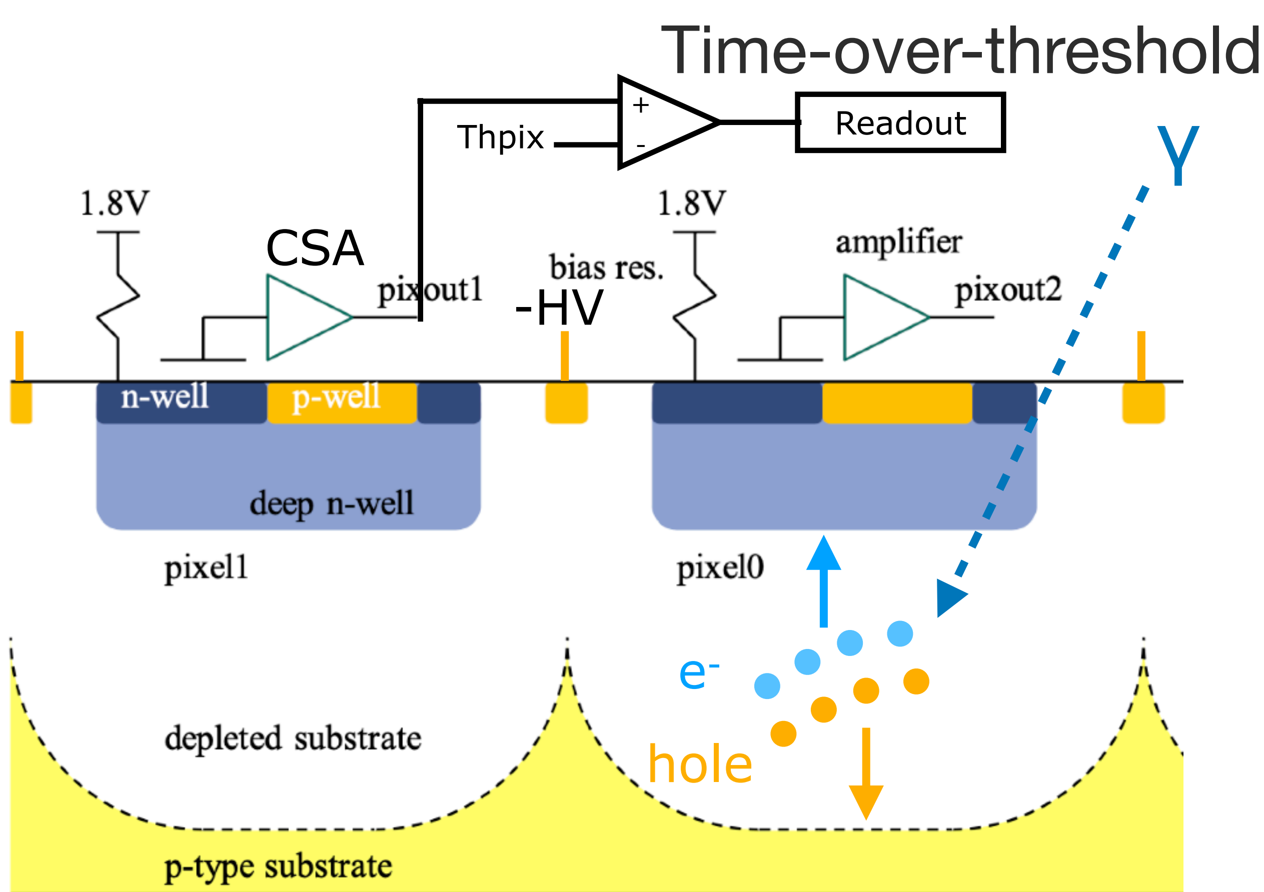
- Shed light on not-well-studied energy regime (25 keV - 1 GeV)
- Huge impact on multi-messenger astronomy thanks to its wide FoV (2π @ $E < 10$ MeV)
- Require a lot of low-noise pixelated silicon sensors ($\sim 2.4\times10^5$ cm^2) with a wide depletion layer to efficiently preform Compton reconstruction
- Power consumption of silicon sensors must be < 1 mW/cm^2

→ AstroPix

AstroPix

- AstroPix is a new monolithic HV-CMOS active pixel sensor
  - Full depletion achieved by applying HV
  - Signal processing (CSA → Comparator for Time-over-threshold) is performed on pixel and digitization is done on chip
- Development based on experience from ATLASPix and MuPix

I.Peric&N.Berger 2018



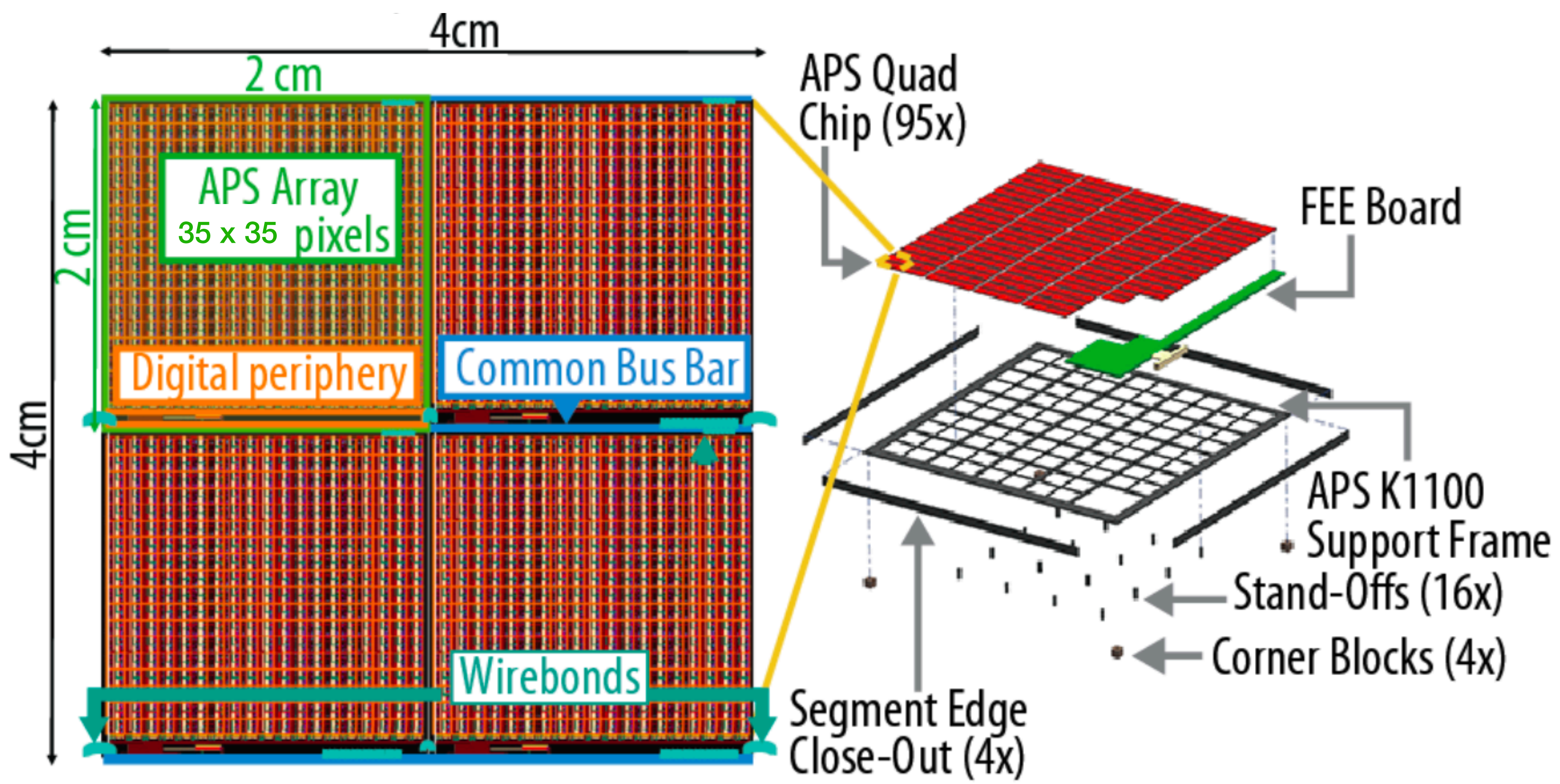
I.Peric with modifications

ASTROPIX

- AstroPix Team
  - PI: R. Caputo (GSFC/NASA)
  - GSFC, ANL, KIT, UCSC, Hiroshima U, Nagoya U

Goal

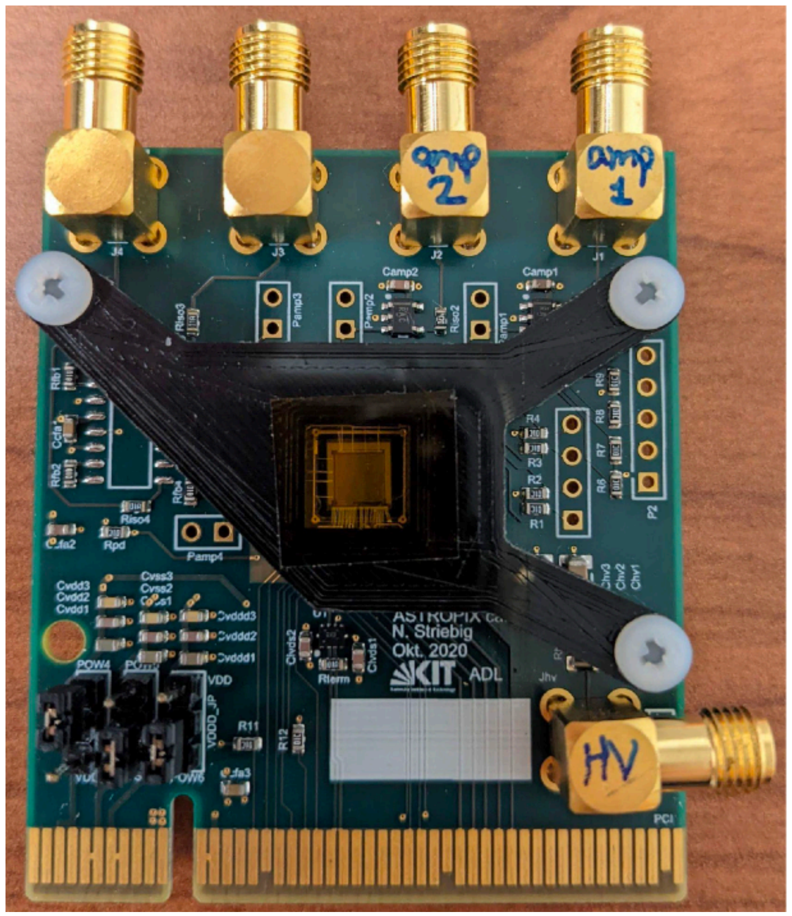
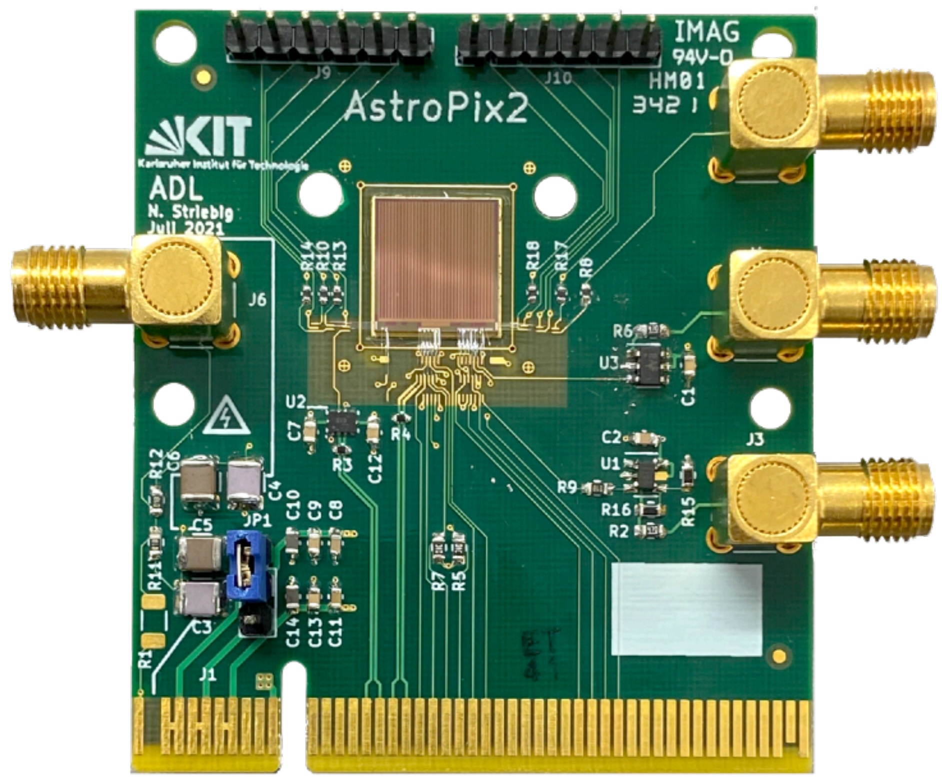
Quad Chip = 4 identical AstroPix array



Requirements

Pixel pitch	$500 \times 500\ \mu\text{m}^2$	Dynamic range	25 keV - 700 keV
Thichness	$500\ \mu\text{m}$	Energy resolution	< 10% (FWHM) at 60 keV
Power consumption	$< 1\ \text{mW/cm}^2$		

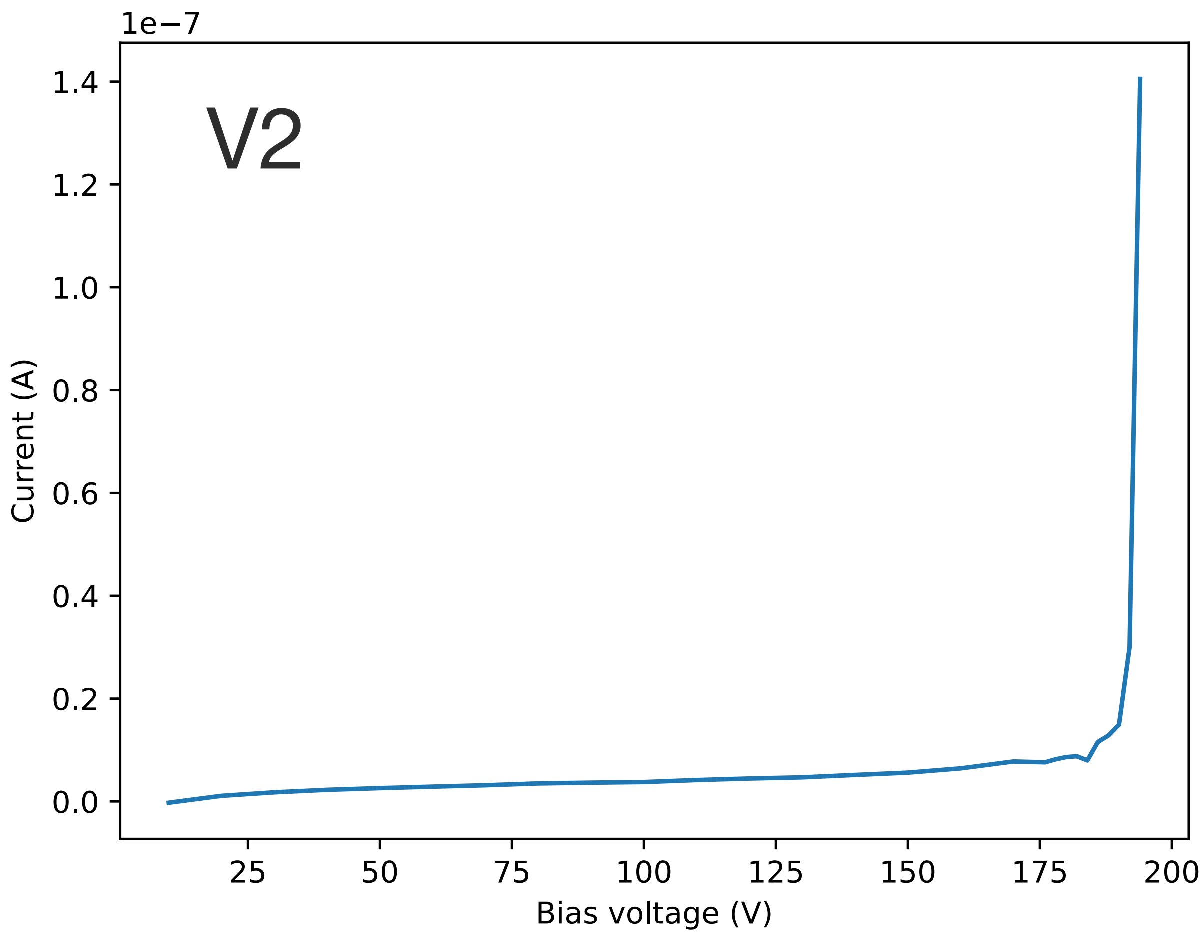
AstroPix Series

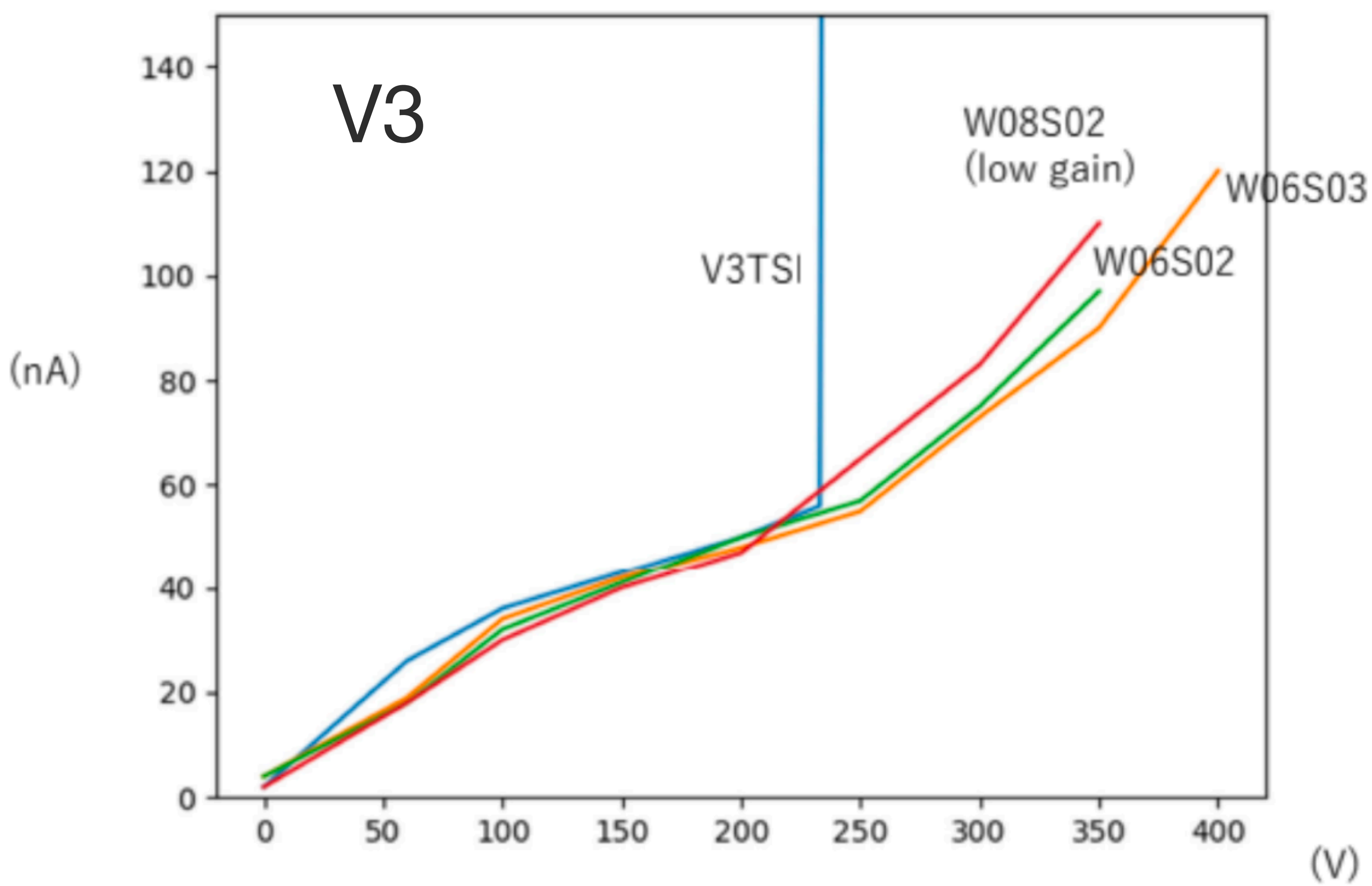
Version 1	Version 2	Version 3
		
0.5 x 0.5 cm² chip	1 x 1 cm² chip	2 x 2 cm² chip
175 x 175 μm² pitch	250 x 250 μm² pitch	500 x 500 μm² pitch
18 x 18 pixels	35 x 35 pixels	35 x 35 pixels
*14.7 mW/cm²	*3.4 mW/cm²	*1.04 mW/cm²
		4.12 mW/cm² (incl. digital)

*CSA+comparator only.

I-V Curves

- V2: 300 Ωcm wafer chip shows breakdown at ~190 V
- V3: 300 Ωcm wafer chip can go up to ~400 V thanks to better clearance to chip-edge ← Results in this talk from this wafer
  - 20 Ωcm wafer chip breakdown at ~230 V
  - 18 kΩcm wafer chip shows high leakage current in the mA range



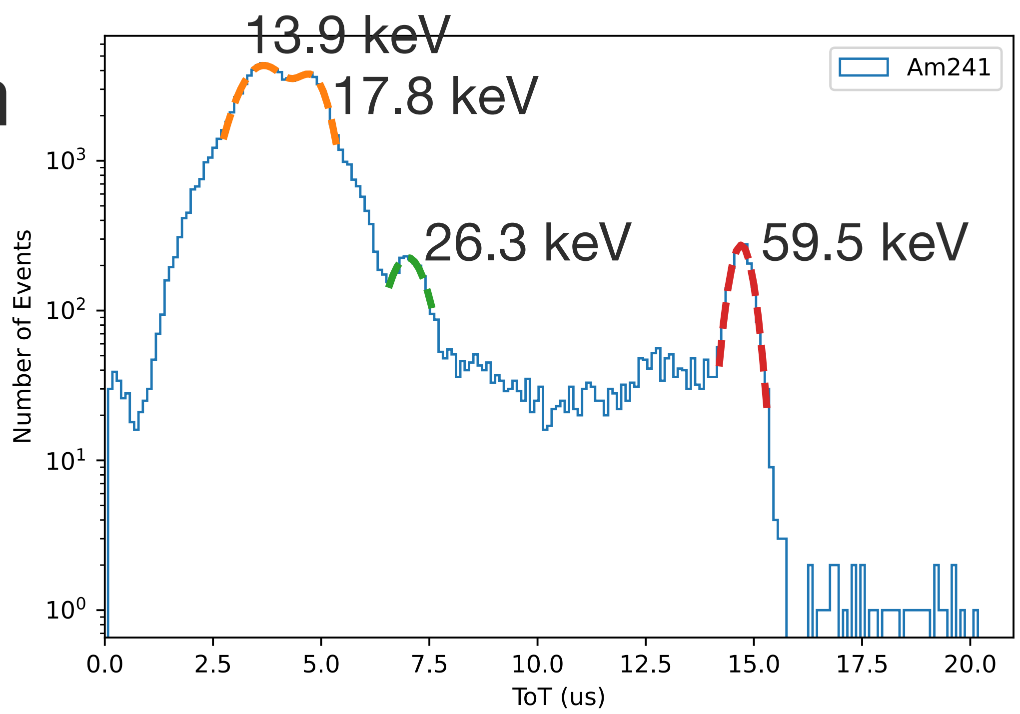


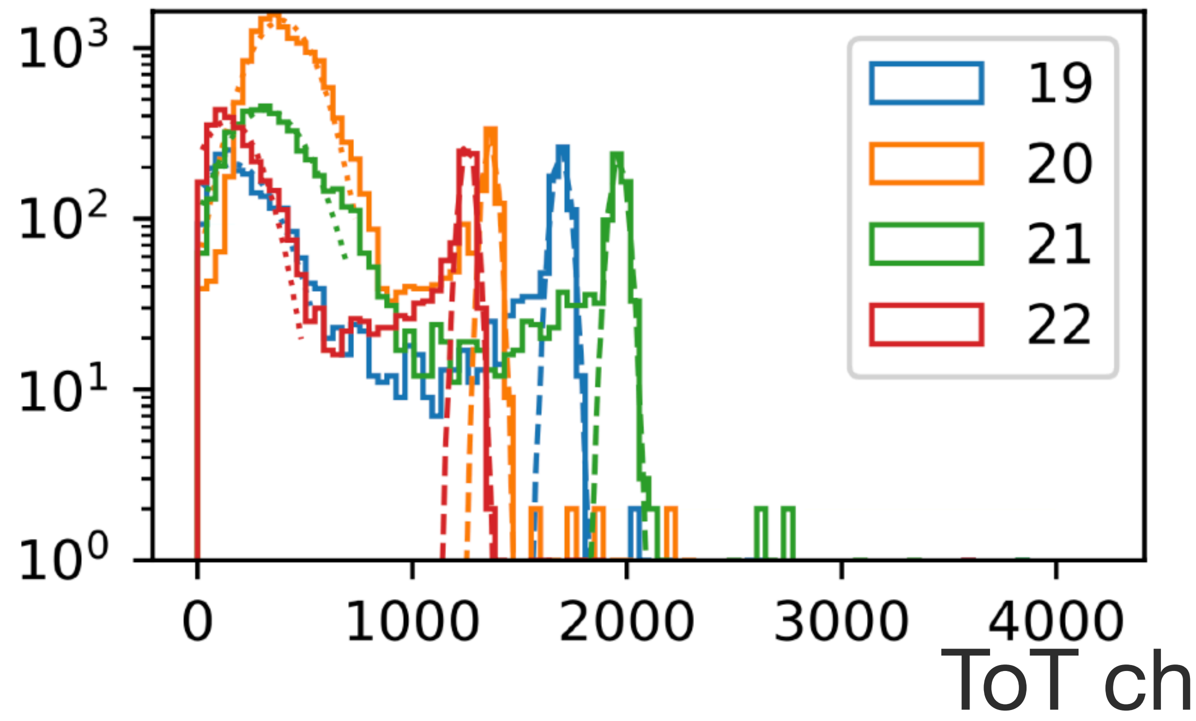
Energy Spectra

V2

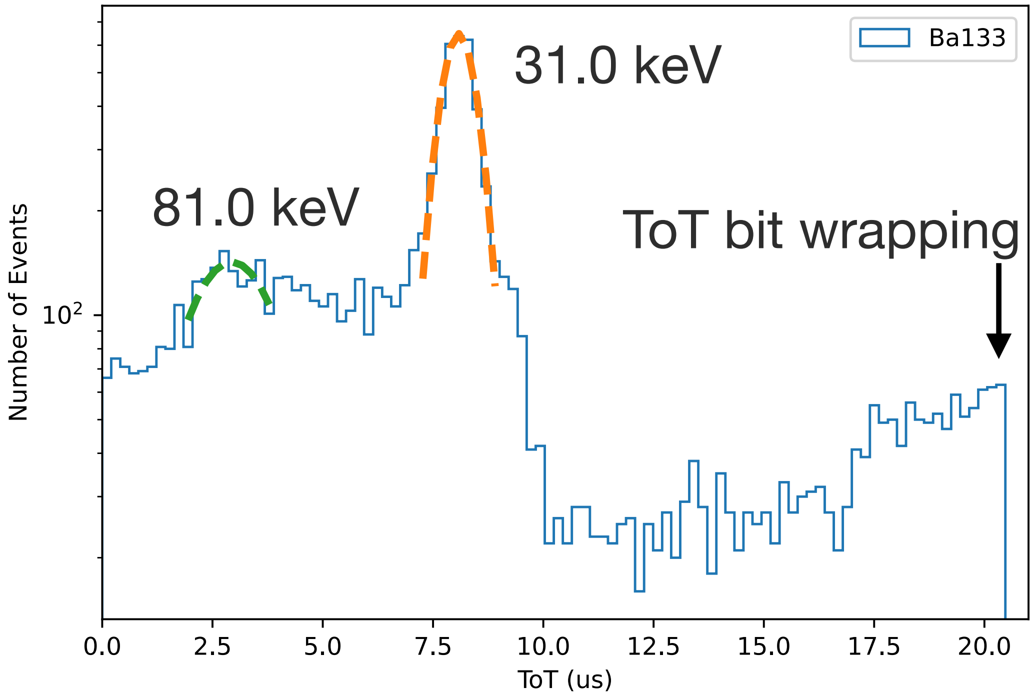
V3

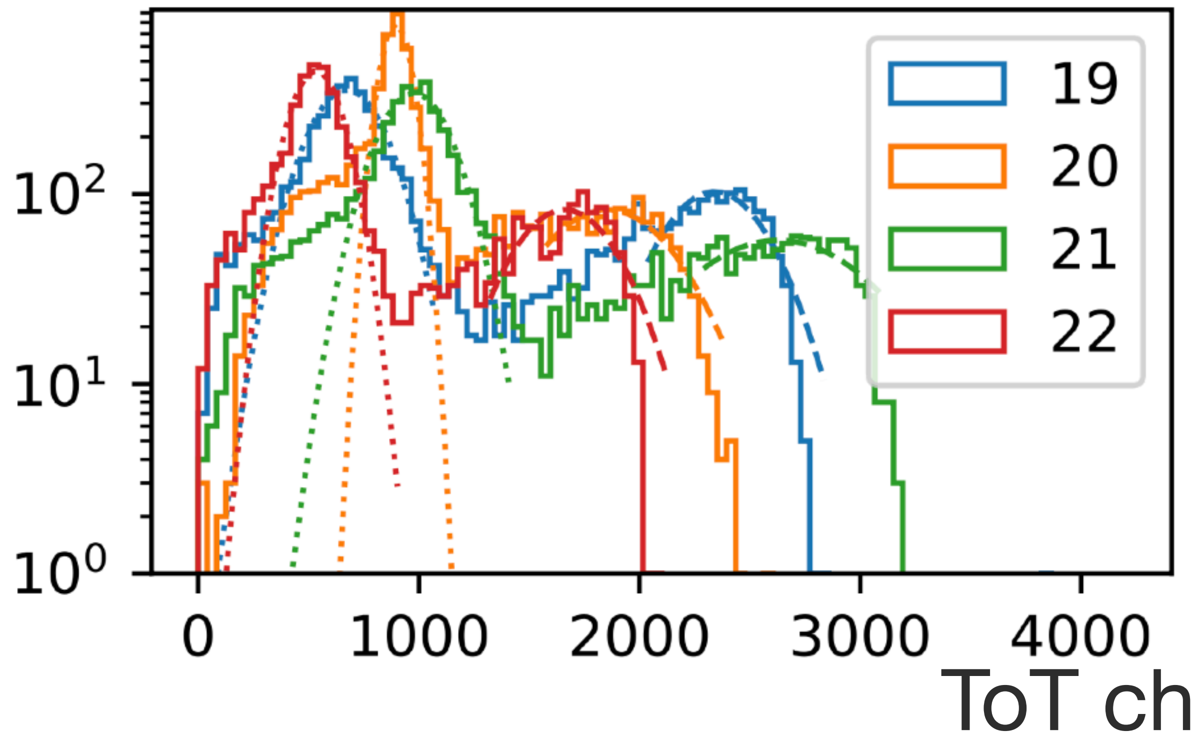
^{241}Am





^{133}Ba

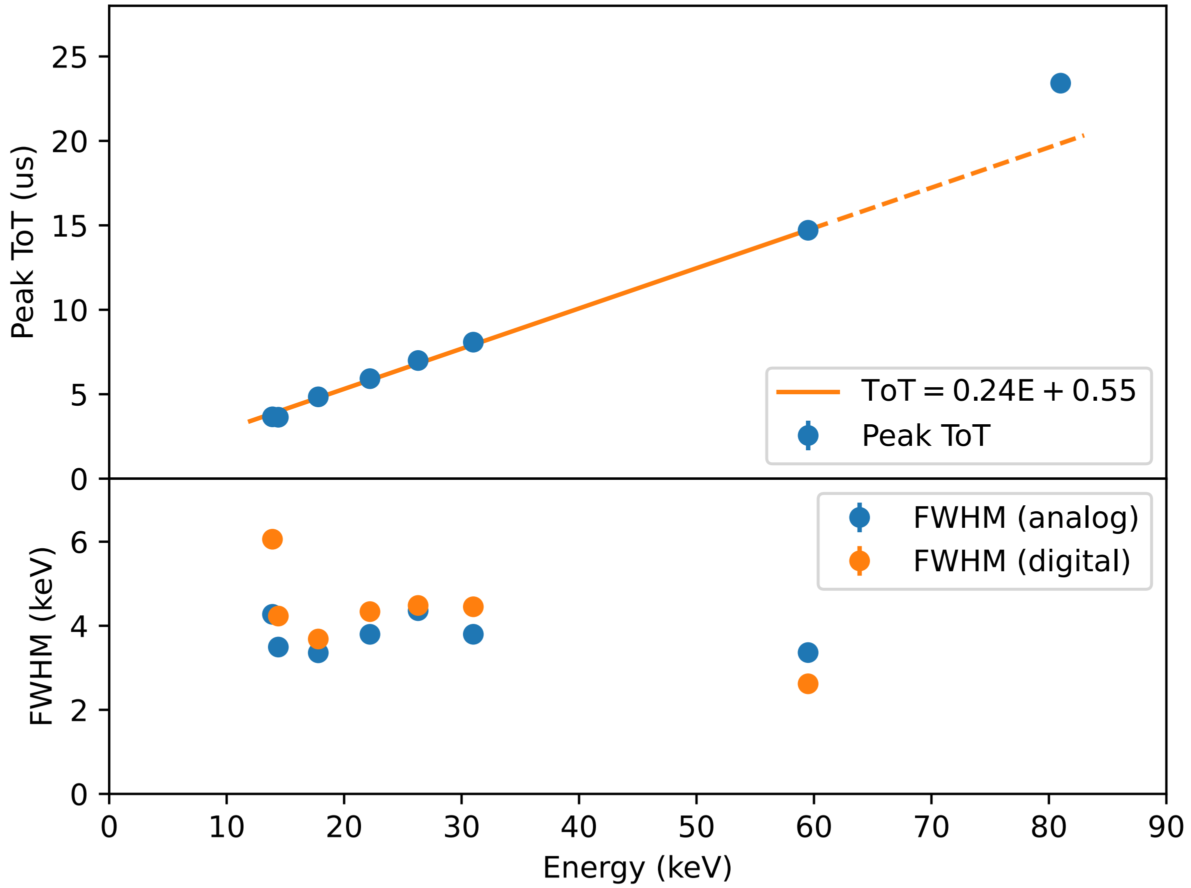




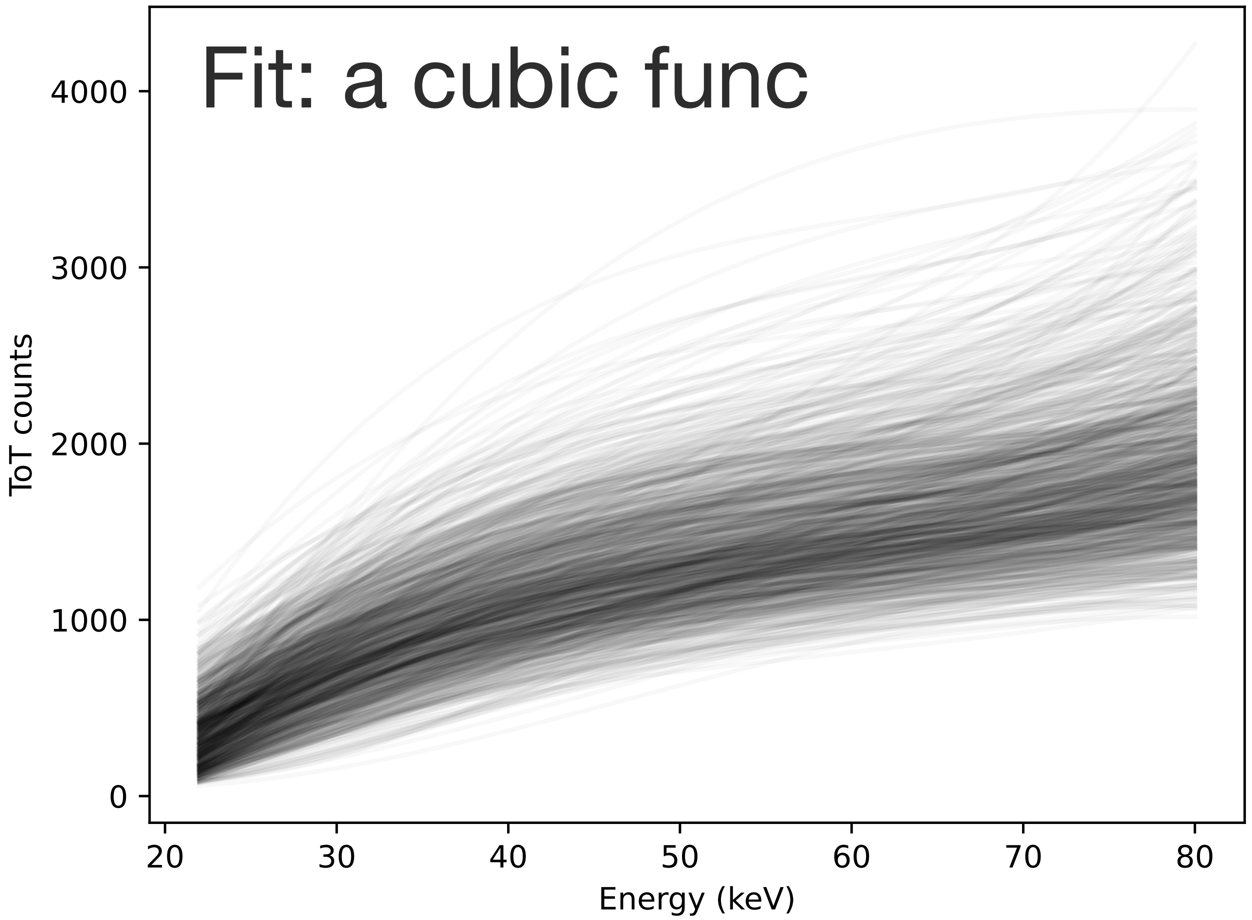
Energy Calibration

- With updated readout FW/SWs for V3, energy calibration can be performed over the full sensor at once
- Dynamic range: 14 - 80 keV for one pixel of V2 chip
  22 - 80 keV for V3 chip

V2



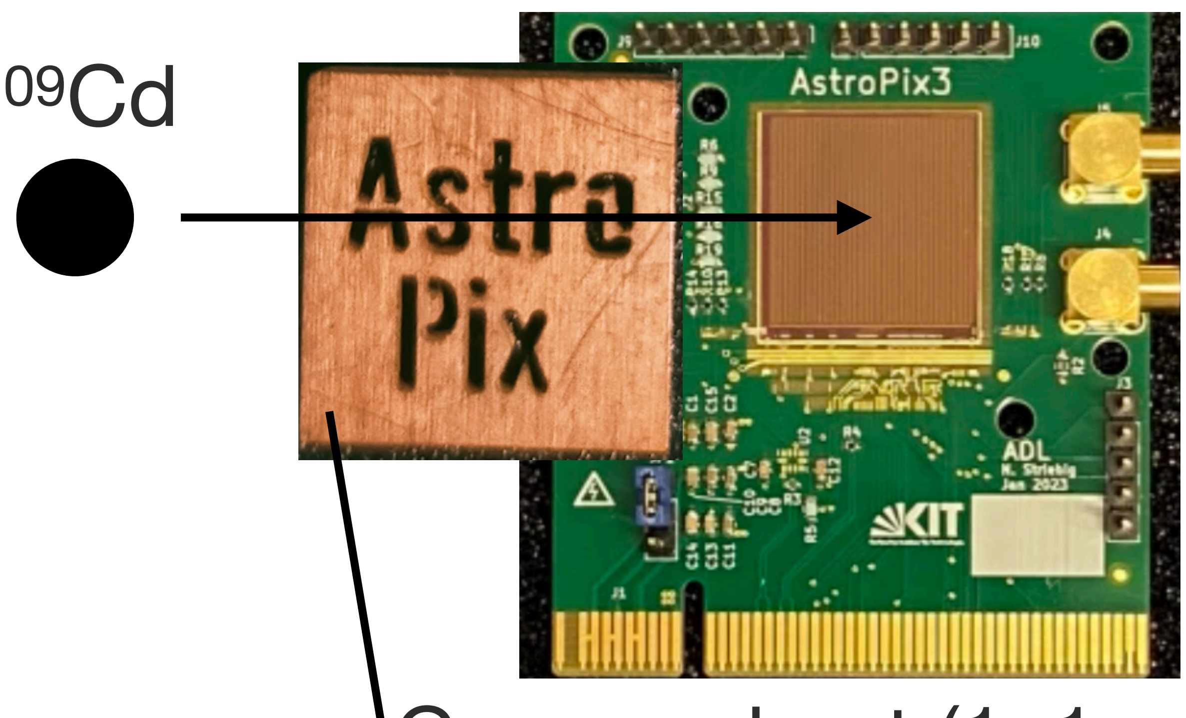
V3



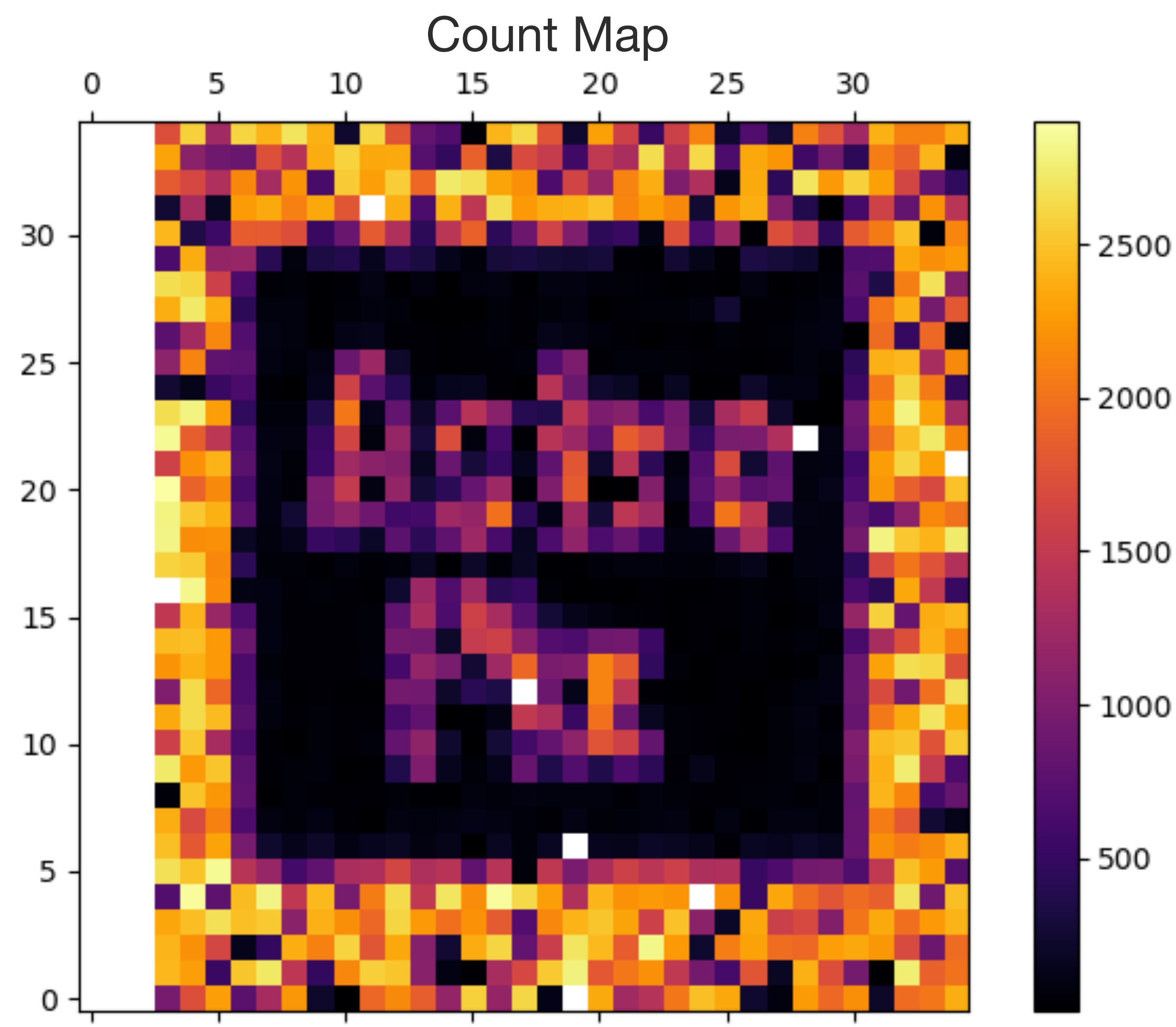
AstroPix V3: Imaging

- First picture taken by AstroPix
- Only 0.7% of pixels are noisy (masked)

^{109}Cd



Copper sheet (1x1cm^2)
on top of AstroPix



V3: Depletion Depth Measurements

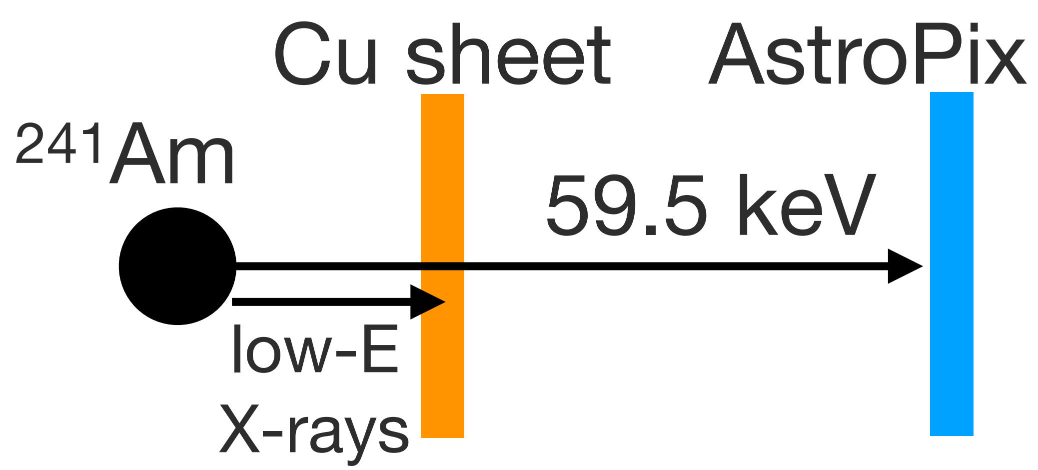
- Estimate from the detection rate of ^{241}Am 59.5 keV events
  - Extract photopeak events from the fitted spectrum
- Compare with a simple model

$$d = \sqrt{2\epsilon\mu\rho(V_{\mathrm{bias}} + V_{built-in})}$$

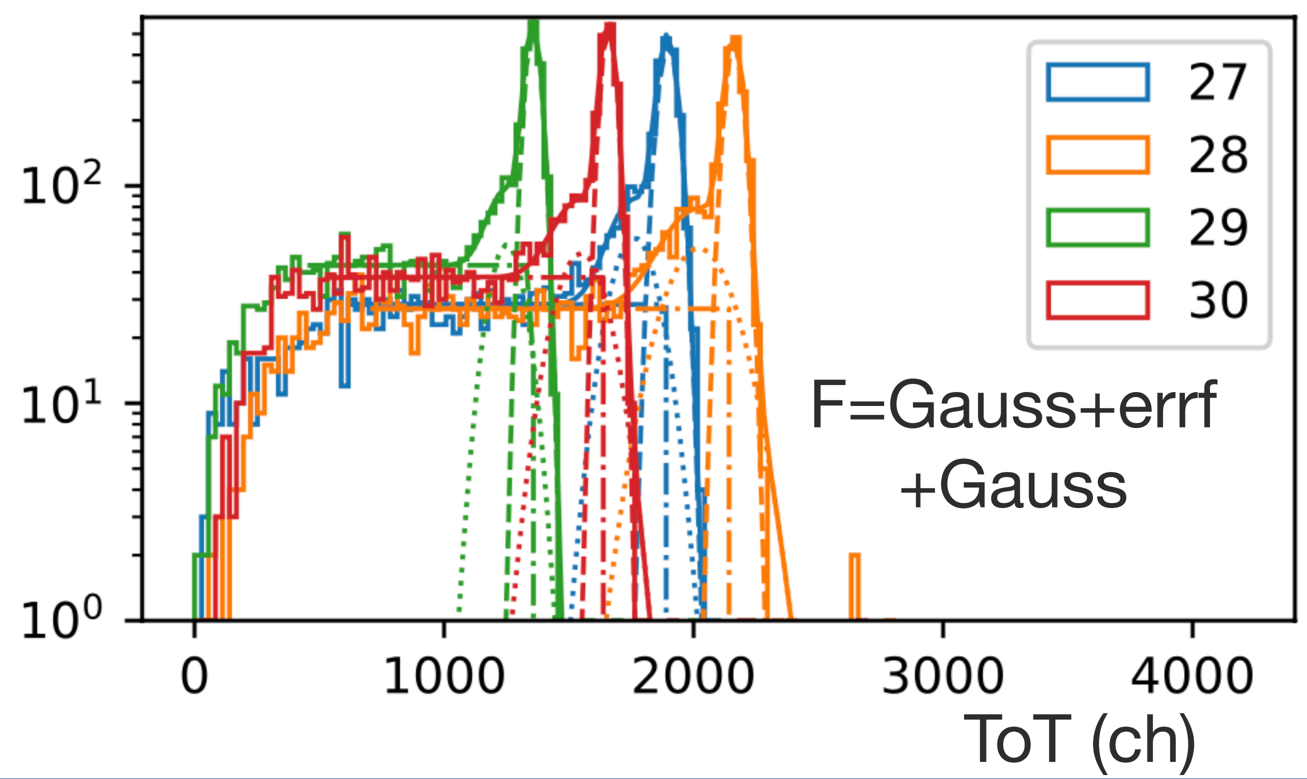
ϵ : Permittivity　　μ : Hole mobility

ρ : Resistivity 200-400 Ohm cm

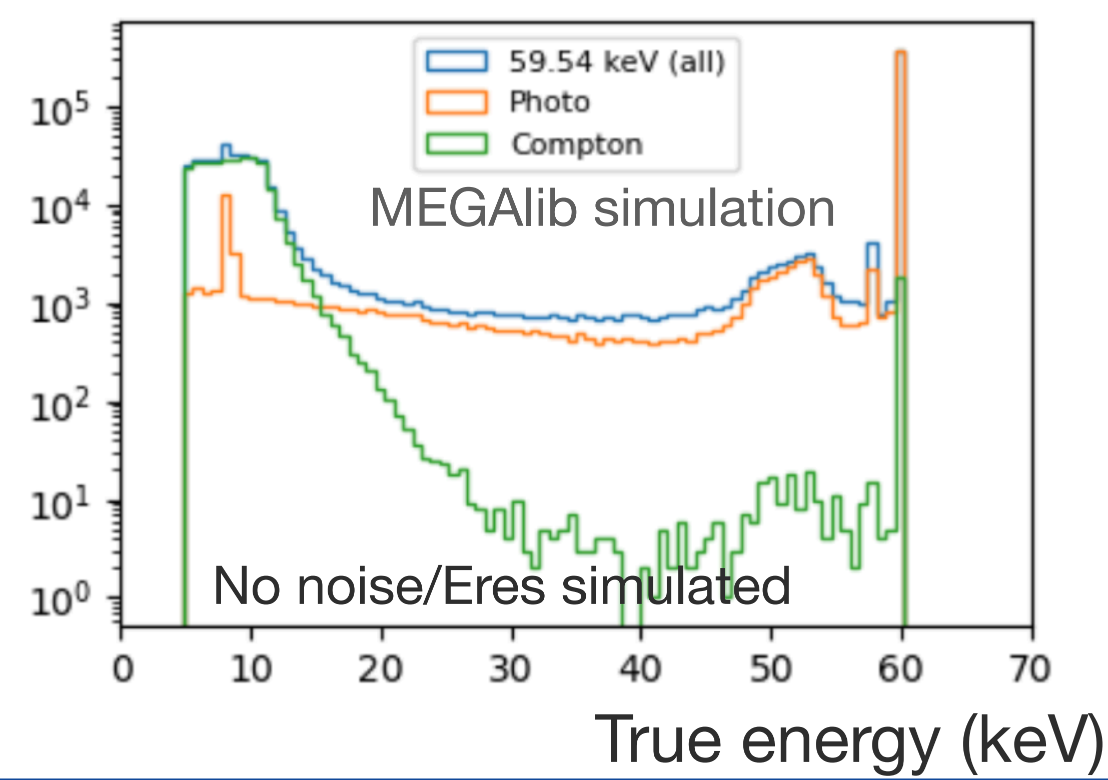
$V_{built-in}$: Built-in potencial



Measured ^{241}Am spectra



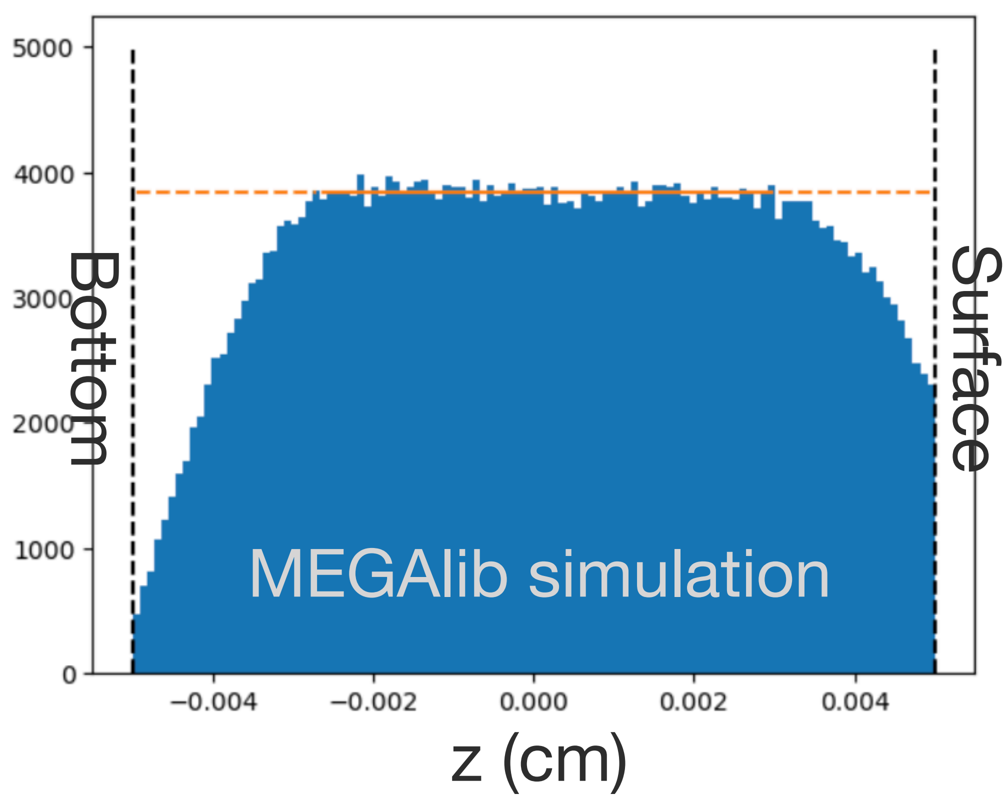
Simulated ^{241}Am spectra

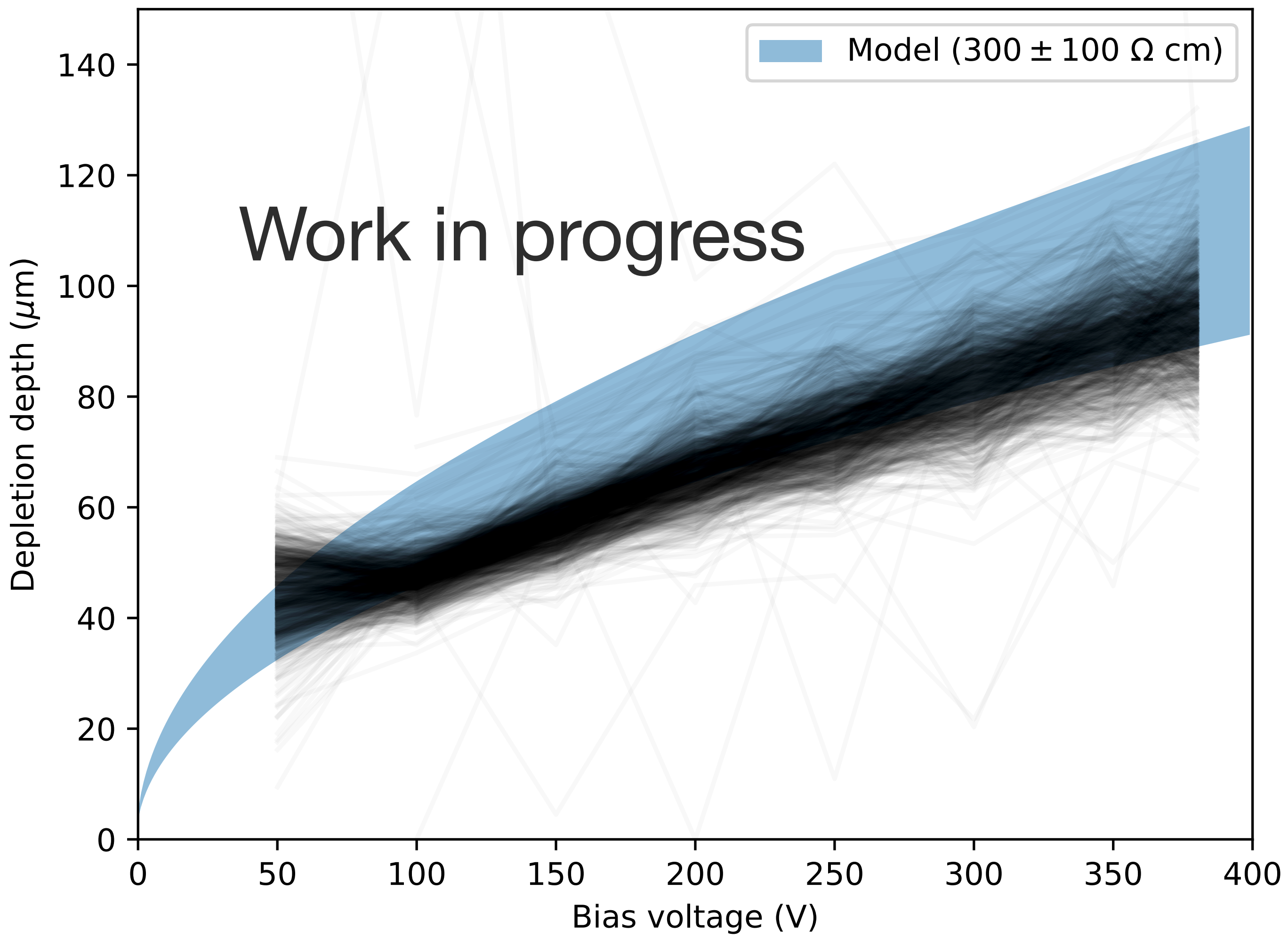


V3: Depletion Depth Measurements

- Sensor volume is corrected for photopeak events
- Measured depths follows the model curve
- Depletion layer develops as expected, but need higher resistivity chips for full depletion

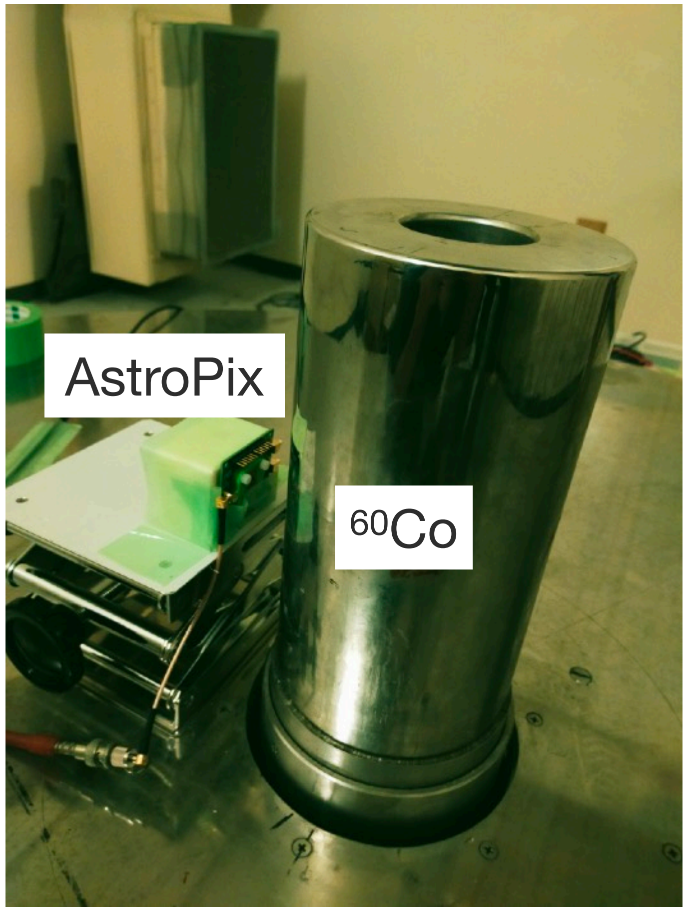
Photopeak events vs. interaction point in z

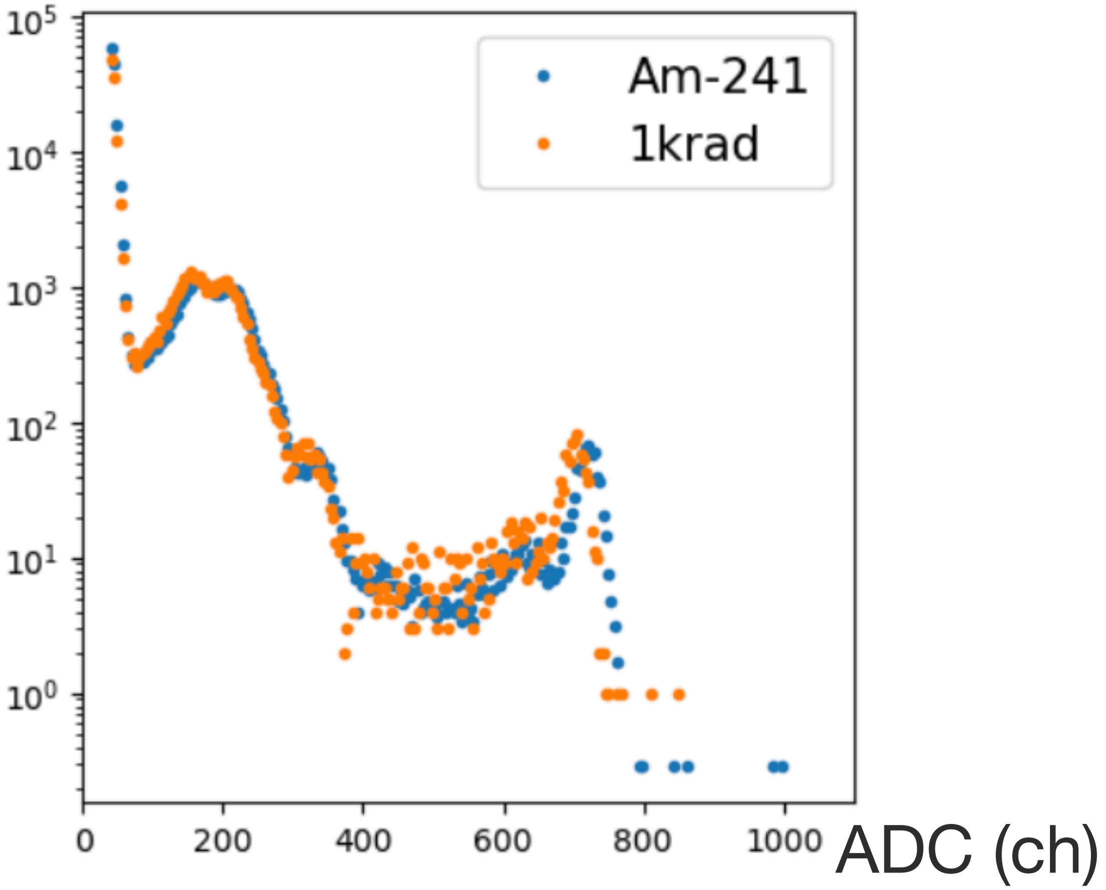




V2: Radiation Tolerance

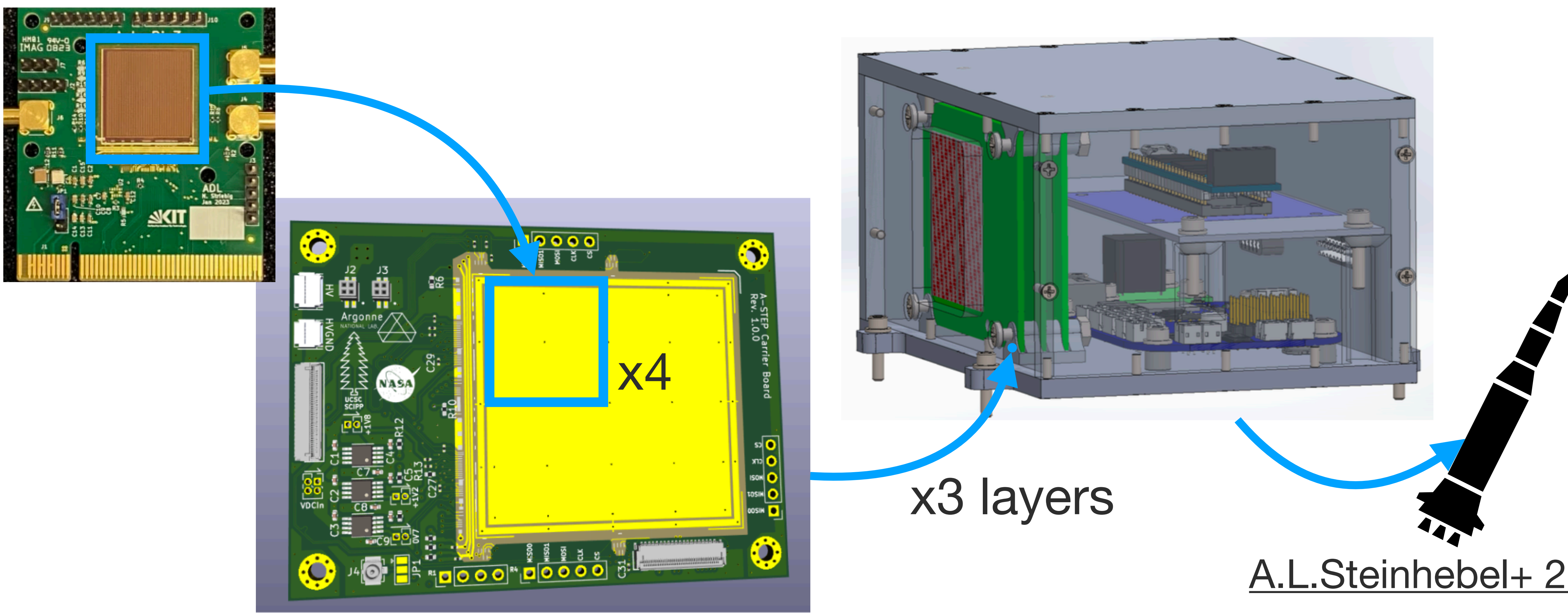
- Expect ~1 krad/yr irradiation on orbit
- One of V2 chips was tested at the high intensity ^{60}Co facility, Hiroshima U.
- After ~1 krad (assumed. TBC) irradiation, the chip works normally, but current draw increases by ~60% and slight change in gain
- Plan to test with V3 as well





Quad-Chip

- Minimum component of the AMEGO-X's tracker
- Quad-chip consists of 4 identical V3 chips diced together. Testing will start soon
- Sounding rocket hosted flight ("A-STEP") is planned in summer 2025 to increase Technical Readiness Level



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AstroPix V4

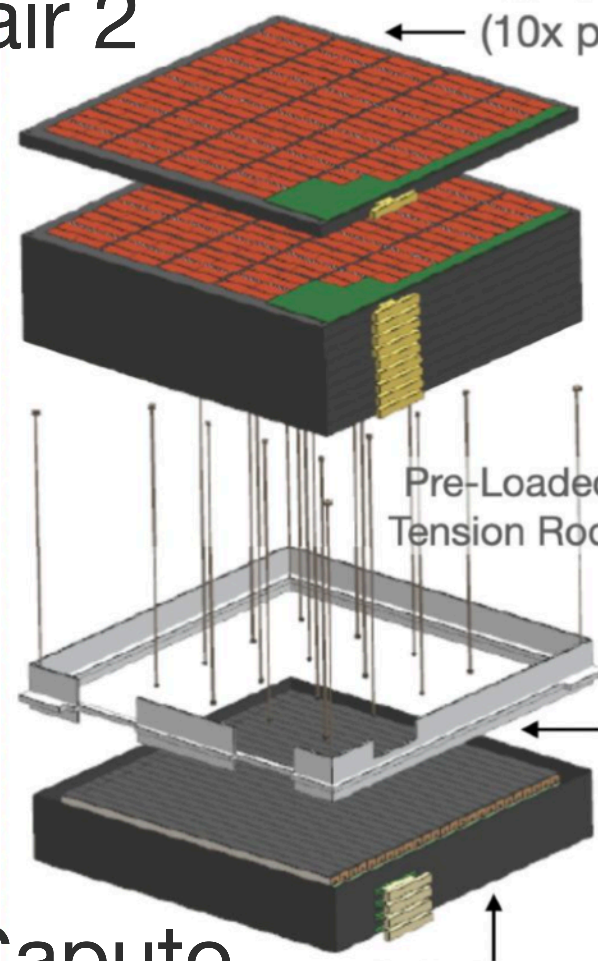
- 500 x 500 μm^2 pixel pitch, 1 x 1 cm^2 chip
- Asynchronous timestamp clocks to reduce power comsuption
  - Previous: 200 MHz clock → 20 MHz clock generated from 2.5 MHz reference clock
- Improved time of arrival resolution: 400 ns → 3.125 ns
- Individual tune-DACs for individual pixel calibration/threshold setting
- Will be available to test in early next year

N.Striebig+ 2023

Future Projects

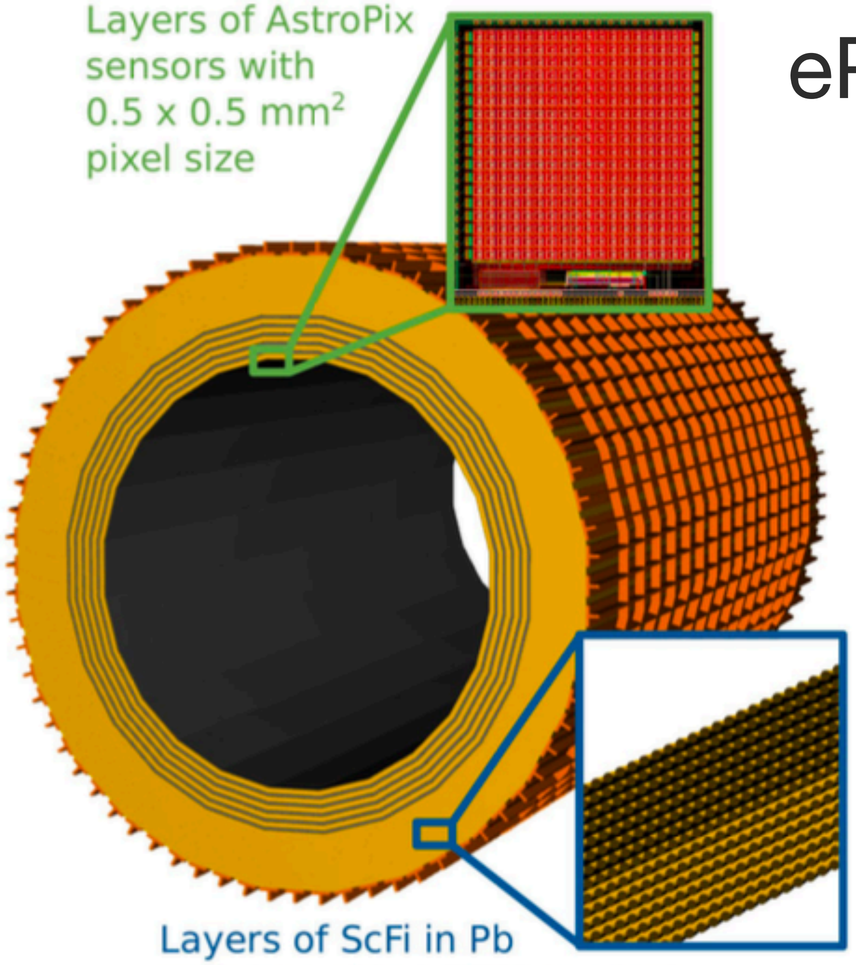
- ComPair 2: Compton-Pair telescope prototype
  - Prototype of AMEGO-X's tracker. Instrument integration in 2026
- ePIC detector in Electron Ion Collider (EIC)
  - Imaging electromagnetic calorimeter. AstroPix delivery in 2029

ComPair 2



PI: R.Caputo

ePIC



J. Lajoie, 2023

Summary

- AstroPix is a new HV-CMOS active pixel sensor being developed for future gamma-ray telescopes on board
- Pixel pitch in V3 reached to the target size
- Dynamic range is limited to 80 keV. Need to lower gain
- Full energy calibration and full imaging are possible in V3
- Measured depletion depth in V3 shows the depletion layer expands as excepted, but only ~90 um. Need high-ρ wafer chips designed to lower leakage current
- V3 quad-chips and V4 chips are coming soon