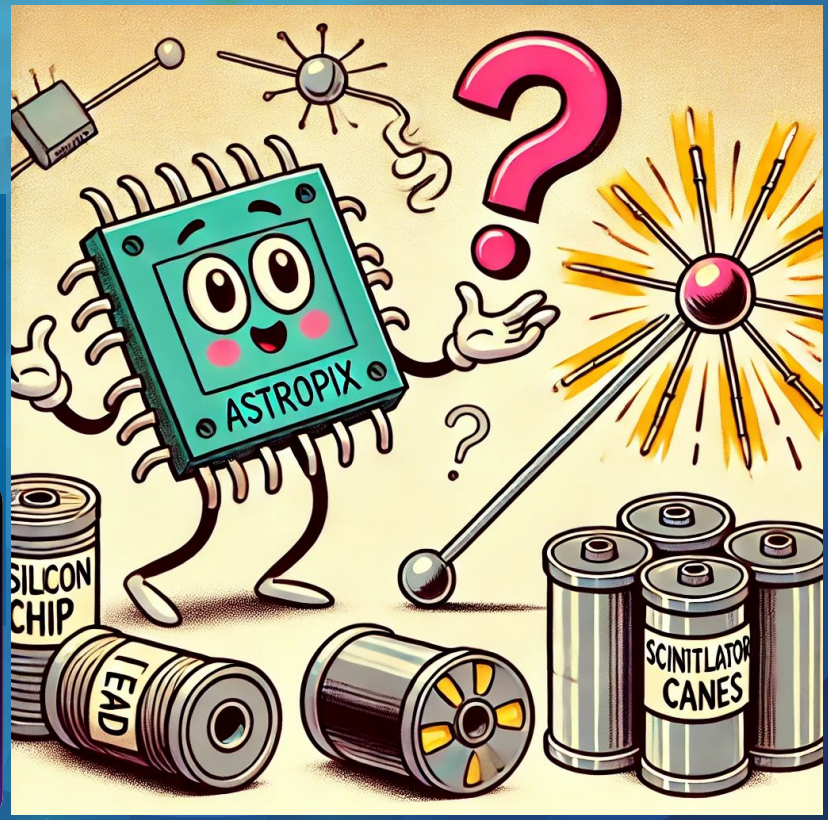
AstroPix

Low power HVCMOS active pixel sensors for space and collider experiments

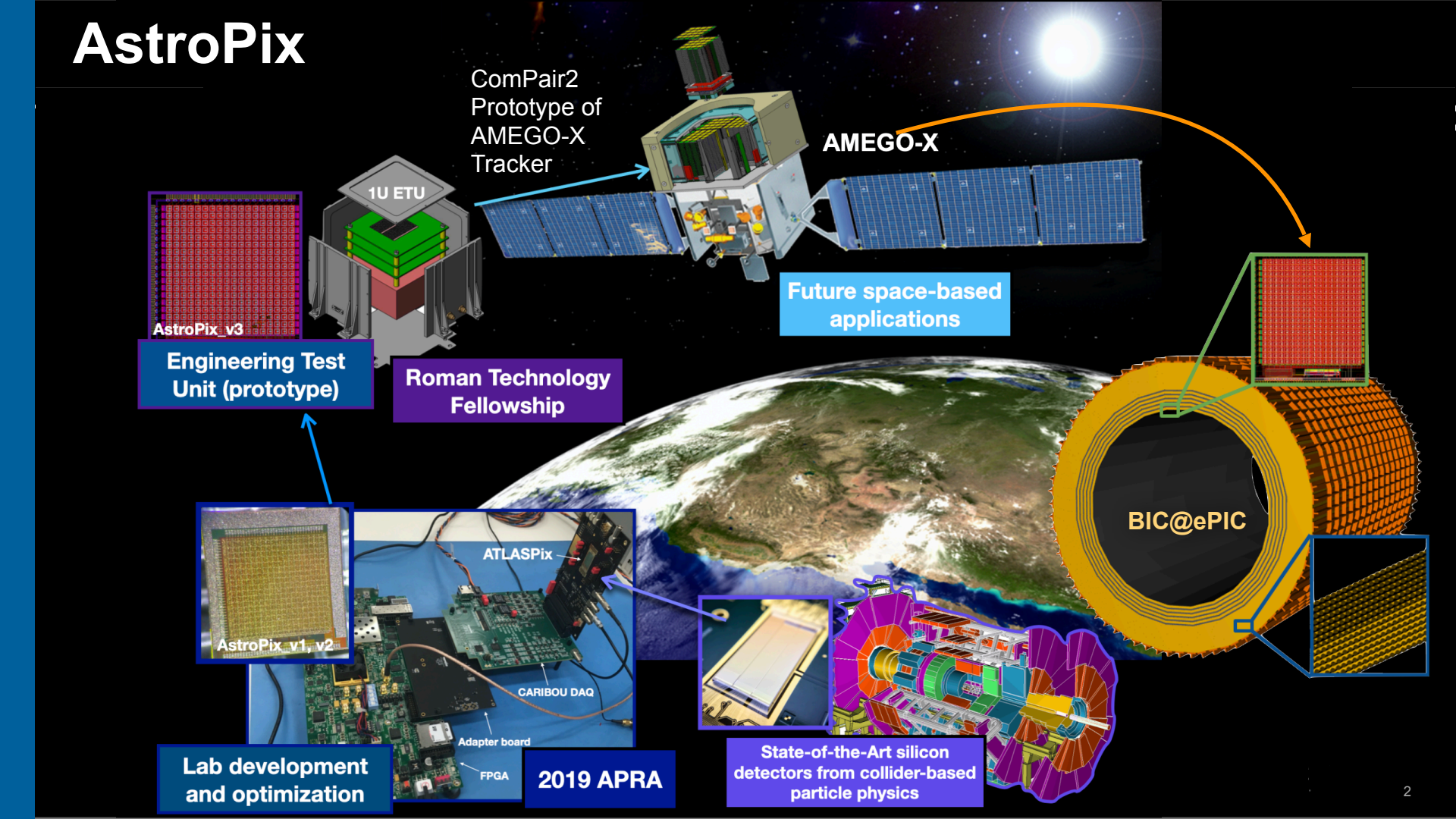


Manoj Jadhav
Argonne National Laboratory

on behalf of AstroPix team

PIXEL 2024, Strasbourg
Nov 18, 2024

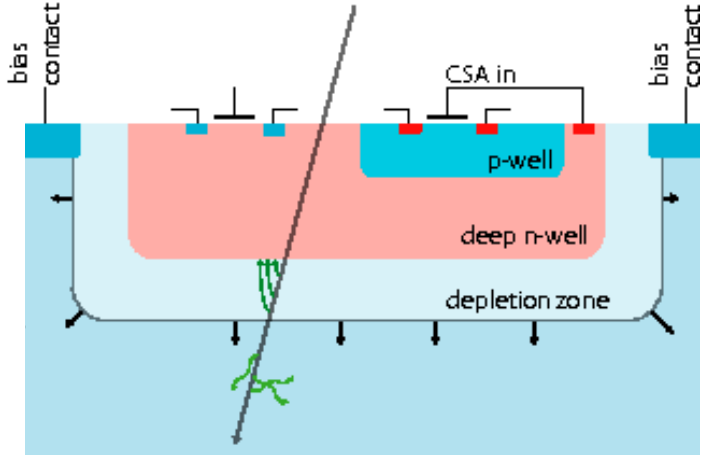
AstroPix


ComPair2
Prototype of
AMEGO-X
Tracker
AMEGO-X
1U ETU
AstroPix_v3
Engineering Test
Unit (prototype)
Roman Technology
Fellowship
Future space-based
applications
BIC@ePIC
AstroPix_v1, v2
ATLASPix
CARIBOU DAQ
Adapter board
FPGA
Lab development
and optimization
2019 APRA
State-of-the-Art silicon
detectors from collider-based
particle physics

AstroPix

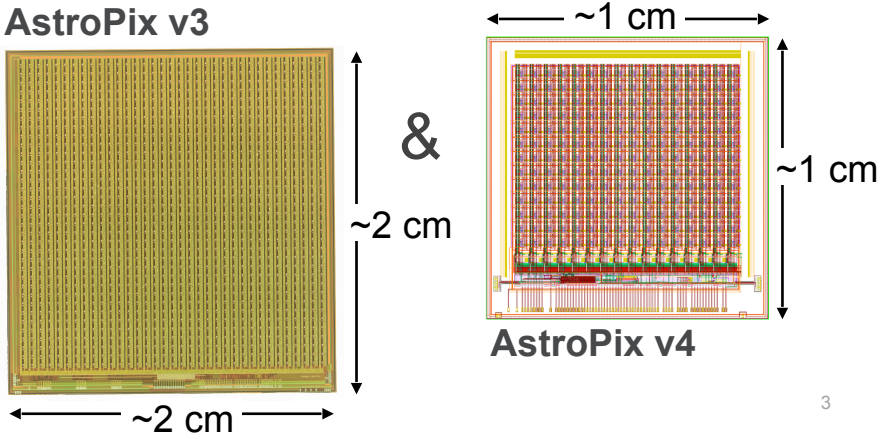
HV-CMOS Monolithic Active Pixel Sensor (MAPS):

- Combination of silicon pixel & Front-End ASIC
- On-pixel charge amplification and digitization
- Technology uses more typical CMOS wafer processing for cost effective mass production
- Fabrication on single wafer enables shorter design cycle
- No need to bump-bond to each pixel - improves yield



AstroPix (based on **ATLASPix3** arXiv:2109.13409)

- 180nm HV-CMOS MAPS sensor
  designed at KIT (also designed ATLASPix, MuPix, etc.)
- Developed for AMEGO-X GSFC/NASA mission
  (Upgrade to the Fermi's LAT)
- Power consumption <1.5 mW/cm^2
- Energy resolution target of 2% @ 662keV

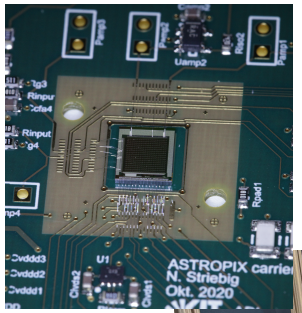


Overview of AstroPix

Monolithic Silicon CMOS sensor for gamma-ray astrophysics

2020 AstroPix_v1

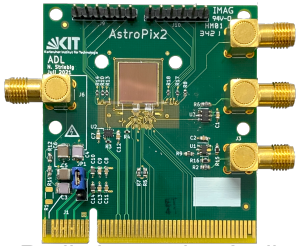
First prototype: testing and characterization



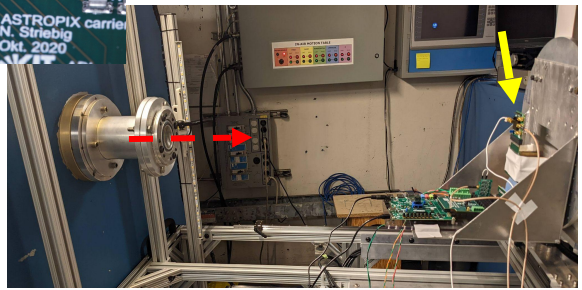
Design based on HV MAPS ~20 years of development at KIT

2021 AstroPix_v2

Second prototype



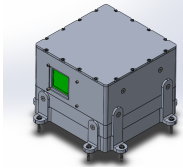
Radiation testing April, June 2022

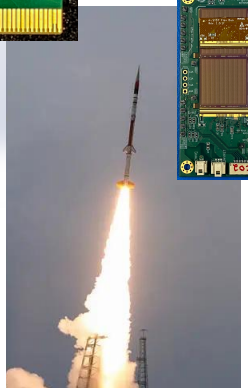


2023 AstroPix_v3

Flight prototype and final design

3-layer Quad-chip Payload Launch: Fall 2025





Beam Test FNAL 2023, 2024*

2024 AstroPix_v4

Pixel readout, power reduced

All produced by TSI Semiconductors

AstroPix selected for BIC

AstroPix Timeline

Not shown:
Early CD4 (Oct 2032)
CD4 (Oct 2034)

Test Readiness Review (TRR)
Critical Design Review (CDR)
Program Implementation Review (PIR)

We are here

FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27 FY28 FY29

Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3

AstroPix v1: Design & Fabr. | Test
AstroPix v2: Design & Fabr. | Test
AstroPix v3: Design & Fabr. | Test | Test
AstroPix v4: Design & Fabr. | Test | Test
AstroPix v5: Design & Fabr. | Test
AstroPix v6: Design & Fabr. | Test
AstroPix v6 (production): Production Fab.

v3 has comprehensive test program: benchtop and testbeam, irradiation, quad-chip readout for NASA payload mission (A-STEP), integration with Pb/SciFi for ePIC (R&D studies and test article production)

first v5 wafers used for preproduction

Start of production driven by project fund availability (estimated ~ 1 year after CD2/3)

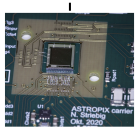
- ComPair2 Milestone
- EIC Project Milestone
- New AstroPix version

ePIC BIC Timeline

Design and generic R&D
Final design and EIC R&D
BIC Preproduction
BIC Production

CD0 CD1 CD3a CD3b CDR CD2/3 Tkr-PIR PIR TRR

Start of BIC installation at BNL



AstroPix v1

HV-CMOS MAPS based on ATLASPix3, designed for the AMEGO-X NASA mission, optimized for power dissipation and energy resolution
Nucl.Instrum.Meth.A 1019 (2021) 165795

0.45 x 0.45 cm² chip, 175 µm pixel pitch
18 x 18 pixel matrix
Power dissipation 14.7 mW/cm²

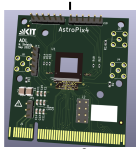
AstroPix v2

1 x 1 cm² chip, 250 µm pixel pitch
35 x 35 pixel matrix
Row/column readout
Power dissipation 3.4 mW/cm²

AstroPix v3

First full-size chip

2 x 2 cm² chip, 500 µm pixel pitch
Row/column readout
Power dissipation <1 mW/cm²
2.5 MHz timestamp, 200 MHz ToT



AstroPix v4

Final design but smaller size

1 x 1 cm² chip, 500 µm pixel pitch
Individual pixel readout
3 timestamps, 3.25ns time resolution
TuneDAC for pixel-by-pixel thresholds

AstroPix v5

pre-production chip
1.87 x 1.9575 cm² chip, 500 µm pixel pitch
Design identical to v4 (with bug fixes)

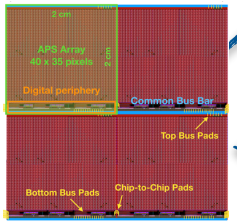
AstroPix v6

production chip
2 x 2 cm² chip, 500 µm pixel pitch
Design identical to v5 (with bug fixes)

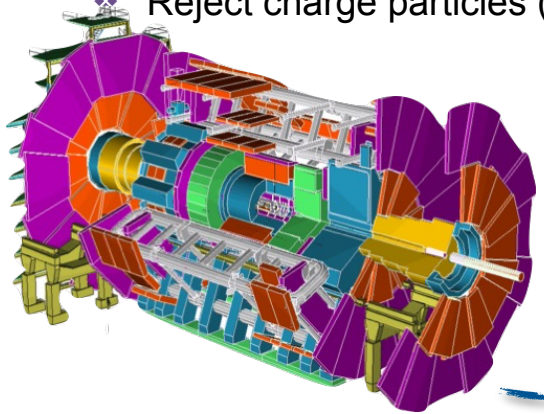
Astropix for AMEGO-X

AMEGO-X is a next generation MeV γ-ray multi-messenger observatory

- AMEGO-X will develop the necessary technologies to enable a future MeV mission spanning the Compton and pair regime
- Gamma-ray Detector (GRD)
  - Tracker Module ⟹ Silicon pixel detectors
    - 40 layers of MAPS detectors
    - 4 towers: 450 mm x 450 mm (each)
  - Calorimeter Module
- Anti-Coincidence Detector (ACD)
  - Reject charge particles (background)

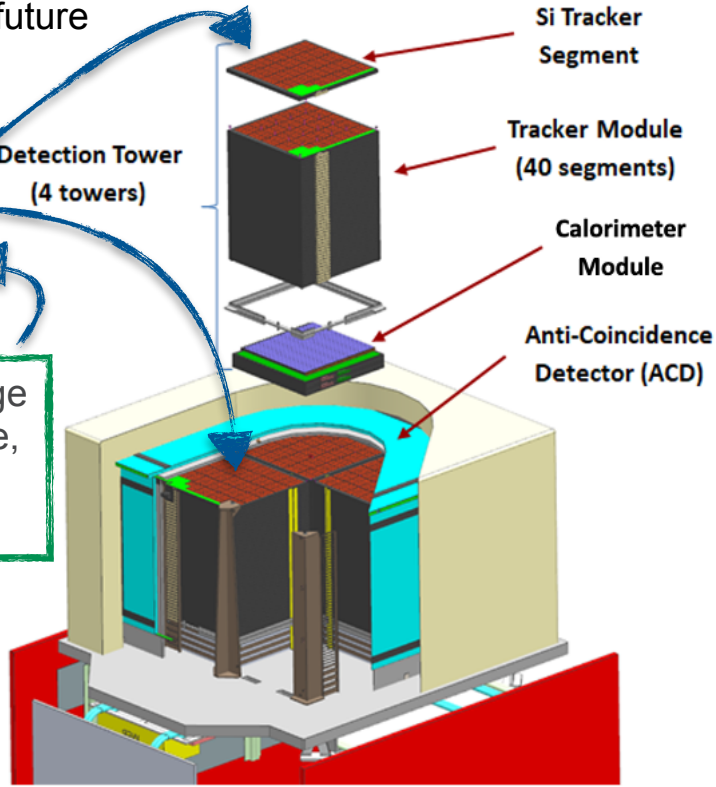


Increase fidelity, large optimized pixels size, slower response, readout architecture



Modified for low power, better energy resolution for space application

ATLASPix: CMOS detector design for ATLAS experiment at CERN

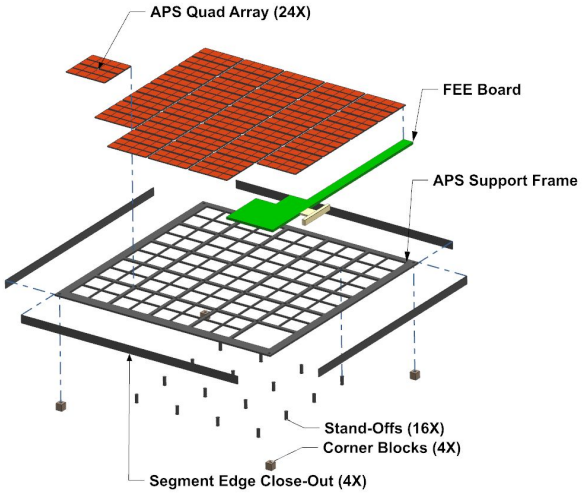


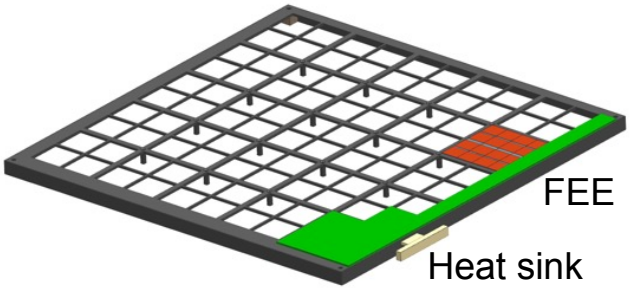
AMEGO-X as a Compton and pair-production telescope to achieve unprecedented sensitivity between 100 keV and 1 GeV

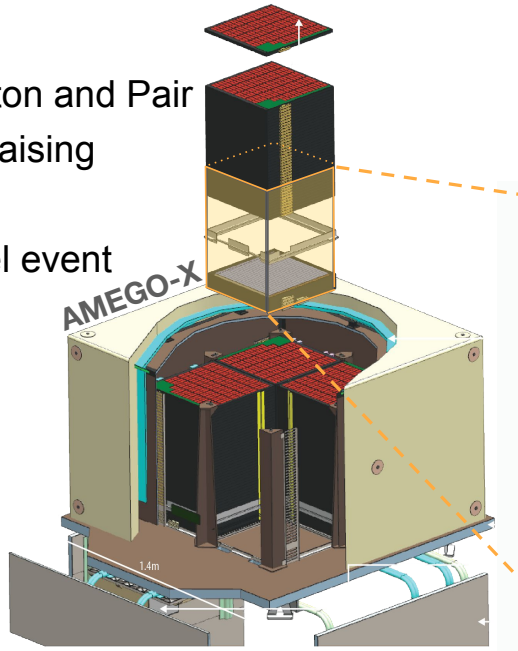
ComPair2, a prototype for AMEGO-X

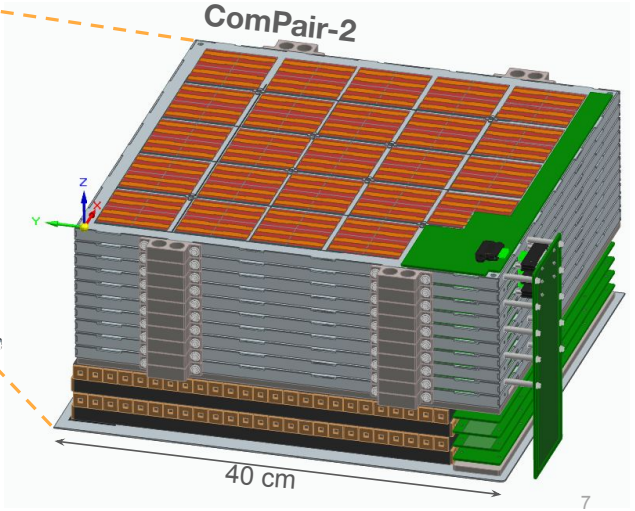
Funded in 2023 through NASA APRA

- A prototype detector consisting of two subsystems of AMEGO-X
- Will be launched with balloon flight
- 450 mm X 450 mm layers
- 10 layers of MAPS detectors
- Confirms performance across the Compton and Pair regimes and in a relevant environment, raising technology readiness level (TRL) to 6
- Provide hardware demonstration of novel event reconstruction techniques









ComPair2, a prototype for AMEGO-X

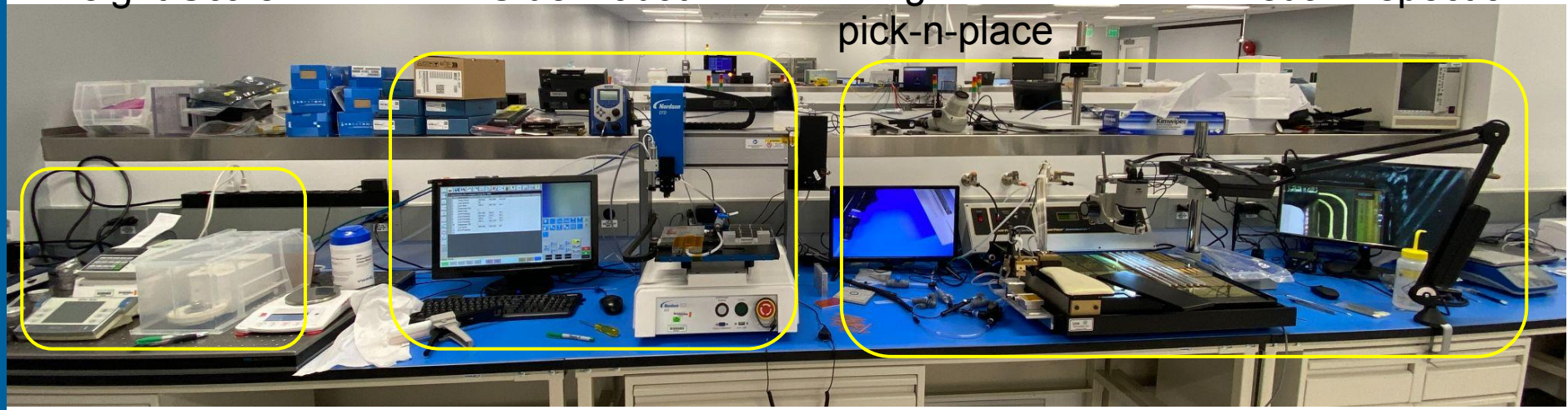
- Reception of Chips
  - Mass measurement, metrology, and Visual Inspection
  - Initial electrical characterization
- AstroPix Chip assembly , Flex bus assembly, FEE board assembly
- Wire-bonding and potting
- Vibration (successful with 3 layers of quad chips), TVAC and electrical tests after assembly

First almost fully assembled ComPair2 Tray

Weight Scale

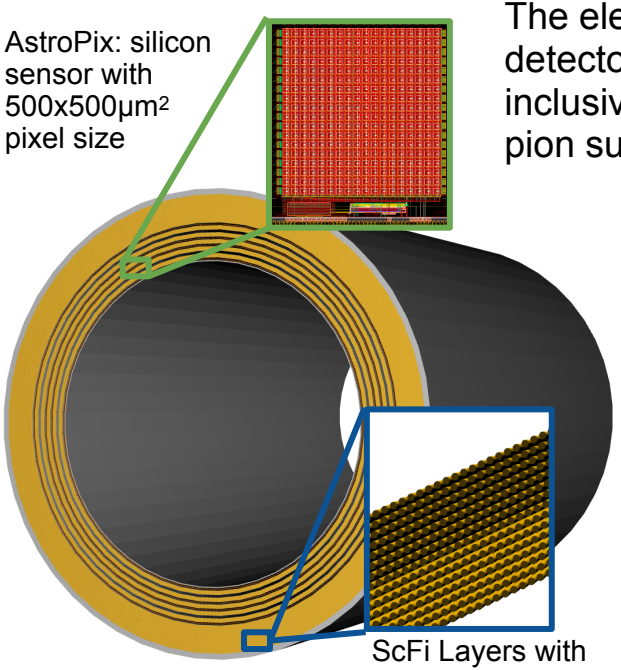
Glue Robot

Integration Desk + Visual Inspection pick-n-place



The ePIC Barrel Imaging Calorimeter (BIC)

AstroPix: silicon sensor with 500x500μm² pixel size

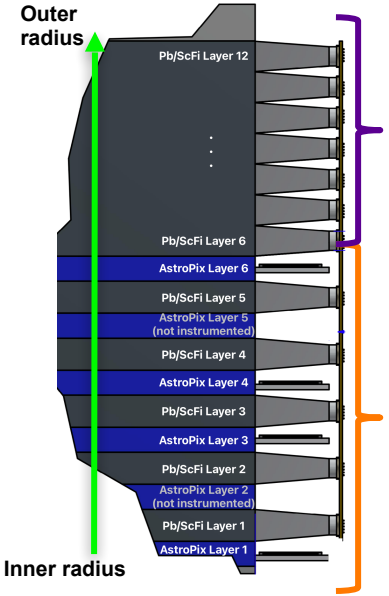


ScFi Layers with **two-sided SiPM readout**

Total thickness > 17.1 X_0

Sampling fraction ~ 10%

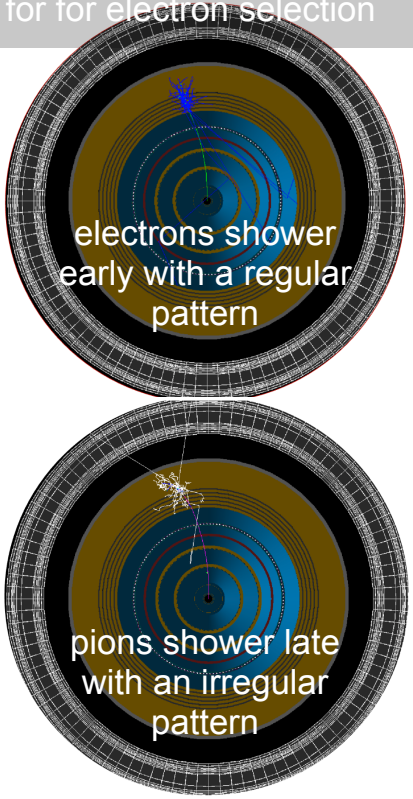
The electromagnetic calorimeter is the main detector for **electron-pion separation**. The inclusive physics program requires up to 10^4 pion suppression at low momenta in the barrel



Large **back section of Pb/ScFi**

4(+2) planes of AstroPix sensors interleaved with **5 Pb/ScFi layers**

Example: 3D Shower Imaging for for electron selection

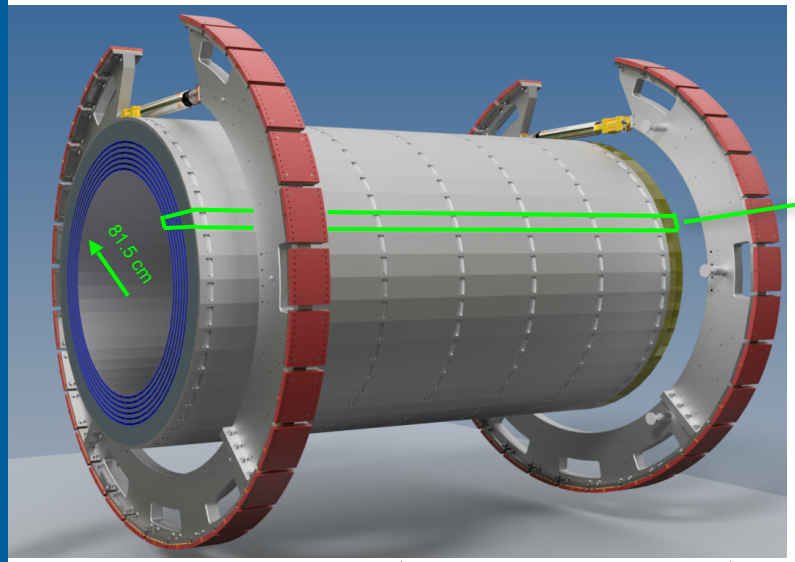


Energy resolution - Primarily from Pb/ScFi layers (+ AstroPix energy information)

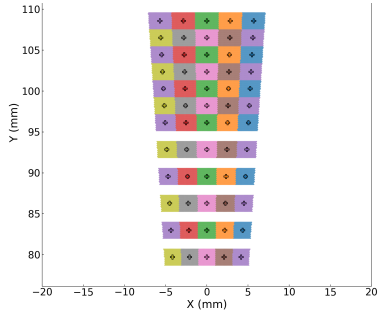
Position resolution - Primarily from Imaging Layers (+ 2-sided Pb/ScFi readout and φ-R segmentation)

The ePIC Barrel Imaging Calorimeter (BIC)

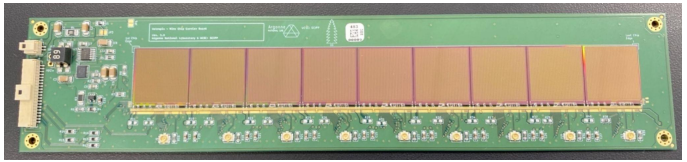
Components and Terminology

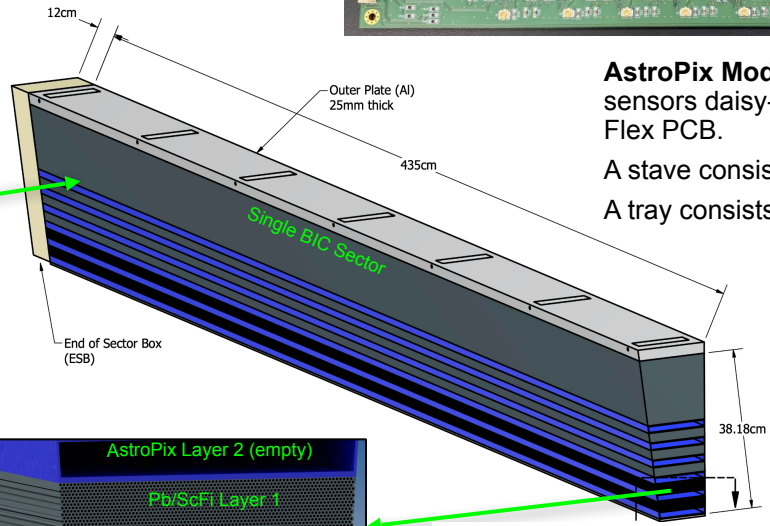


Active Length: 435 cm
Inner Radius: 81.5 cm
Structure: 48 sectors
η Range: -1.71 < η < 1.31



AstroPix Module PCB test article

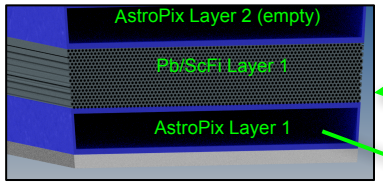




AstroPix Module - Nine AstroPix sensors daisy-chained together on Flex PCB.

A stave consists of 12 modules.

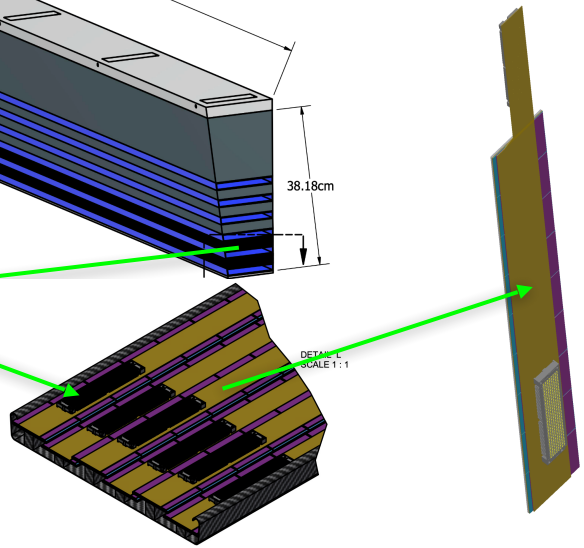
A tray consists of 6-7 staves.



Pb/SciFi Layer - Consists of 17 rows of fiber between corrugated lead.

Each sector has 12 Pb/ScFi layers.

Individual light guides divide each layer in 5 readout cells.

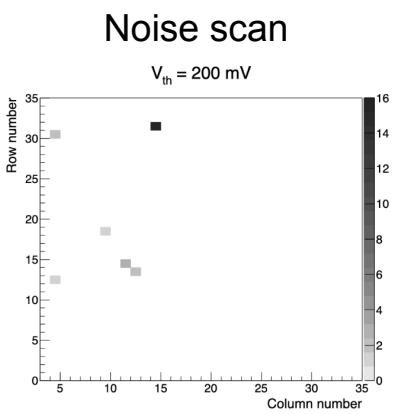


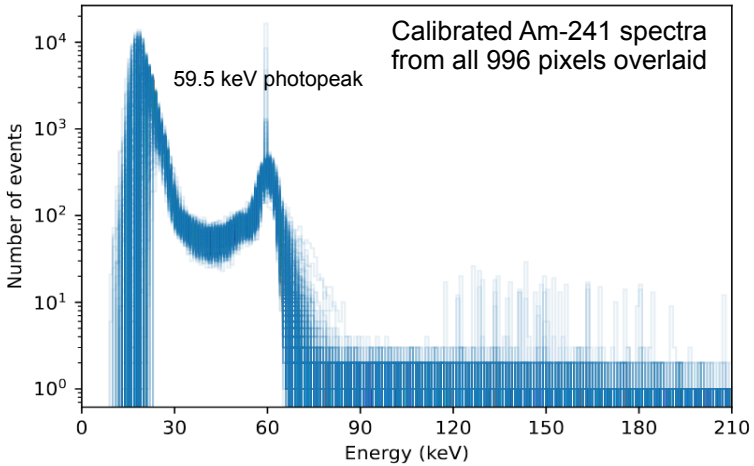
Tray - Structure holding the AstroPix staves for a single layer (217.5 cm long).

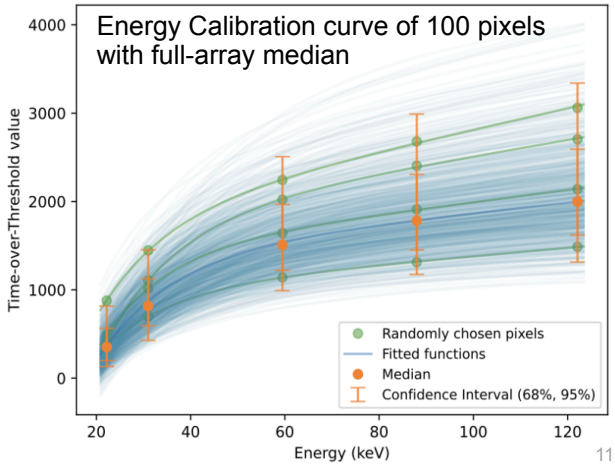
Demonstration of Performance: AstroPix v3

Bench Test: Radiation Source Test on AstroPix v3

- The AstroPix dynamic range floor (25 keV) allows for threshold values of more than 200 mV above baseline.
- Energy resolution/calibration: Cd-109, Ba-133, Am-241, and Co-57 from 22.2 keV to 122 keV
- Dynamic range: 25-200 keV (v5 will test 700 keV dynamic range)
- **44% of pixels meet the energy resolution requirement of 10% at 59.5 keV** with a median full-width half-maximum of 6.2 keV (10.4%).
- **92.4% of pixels achieve the low-energy floor requirement** of 25 keV sensitivity, required for BIC.







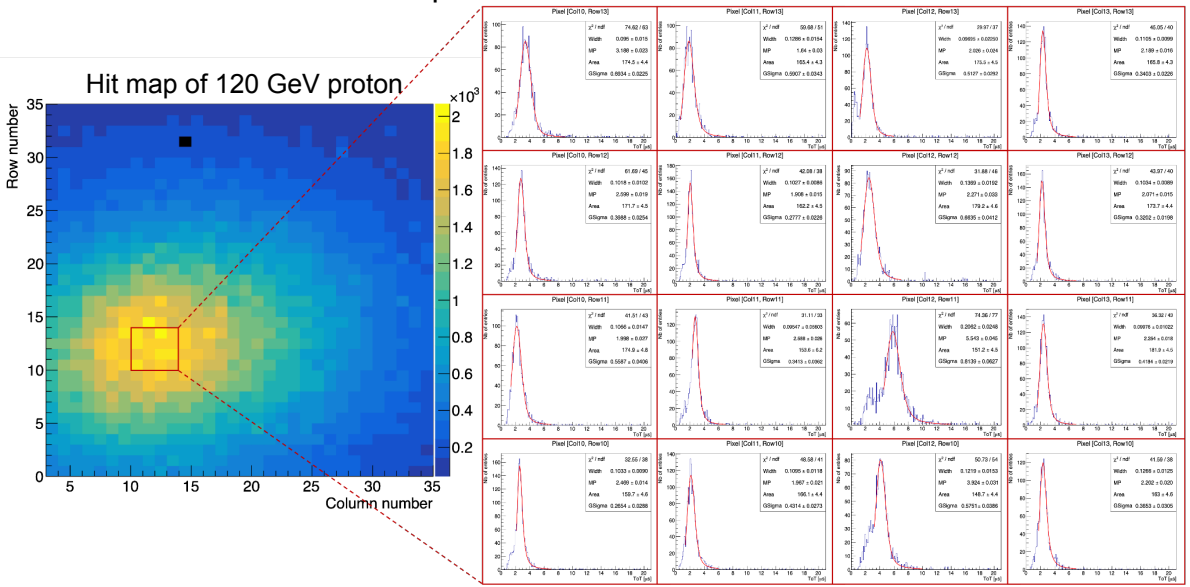
Demonstration of Performance: AstroPix v3

Beam Test of AstroPix v3

Single layer

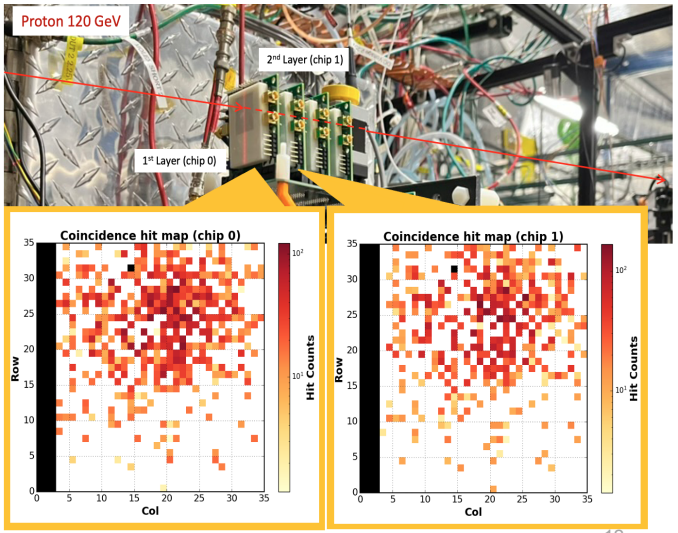
- Data collected with a 120 GeV proton beam.
- The hit map reveals the proton beam profile with 500 um position resolution.
- Collected ToT values for the marked pixels with MIP response.
- Behaves well in the particle rates of 13kHz

Hit map of 120 GeV proton



Double layer

- 120 GeV proton beam events from the first two layers, read in coincidence, showing the position of the hit pixel.
- The **proof-of-concept demonstration of the integration of two daisy-chained AstroPix_v3 layers in a beam-like environment**



Demonstration of Performance: AstroPix v3

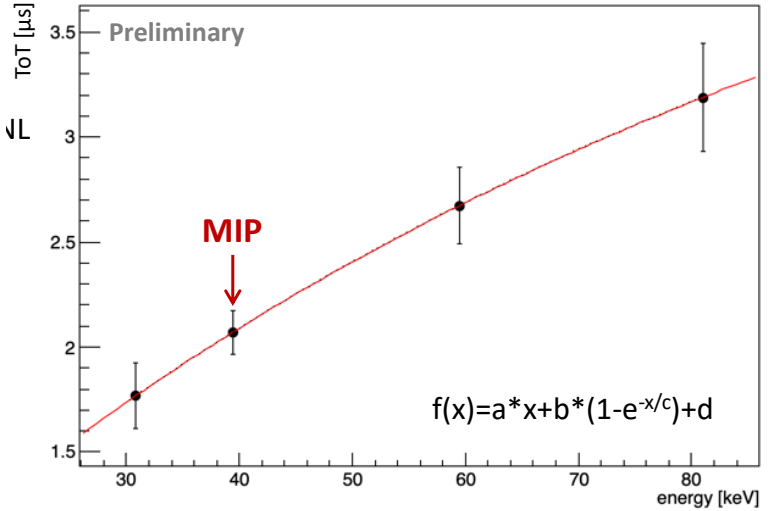
Beam Test of AstroPix v3

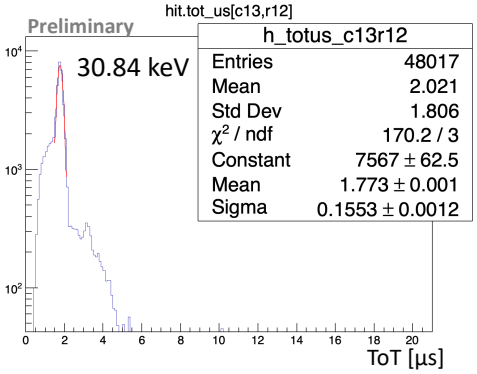
Single layer

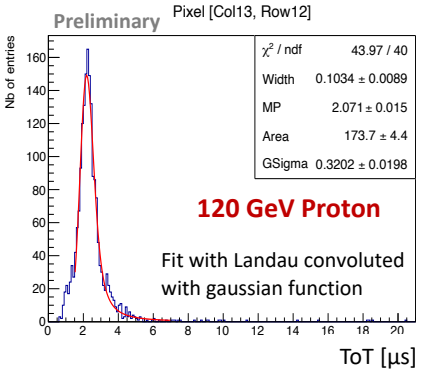
- Calibration using different radiation sources by ToT measurements
  - Ba-133 (30.84 and 81 keV, Am-241 (59.5 keV)
- Pol2 or linear+exponential decay fitting
- MPV of 120 GeV MIPs proton with pixel [C13, R12] is 39.41 keV
  - Preliminary results are ready (manuscript under progress)

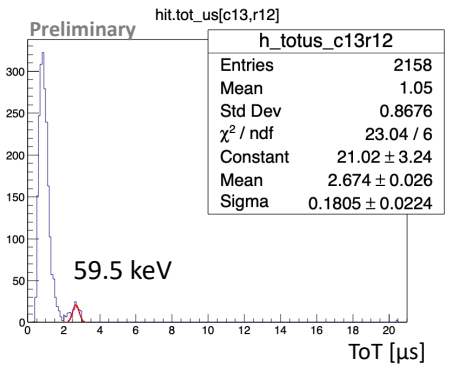
	Ba133 (30.84 keV)	Proton (120 GeV)	Am241 (59.5 keV)	Ba133 (81 keV)
Mean [μs]	1.773 ± 0.1553	2.071 (MPV)	2.674 ± 0.1805	3.178 ± 0.2466
E_{res} (FWHM)	20.6 %	.	15.9 %	18.2 %

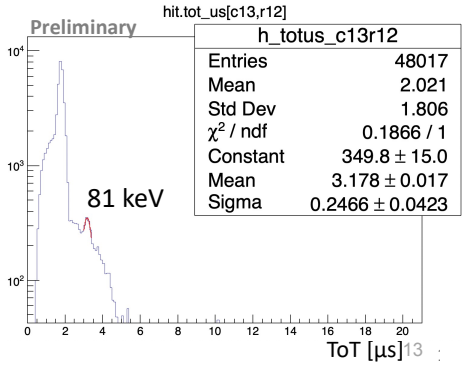
Calibration curve as a function of energies [keV] at [c13, r12]







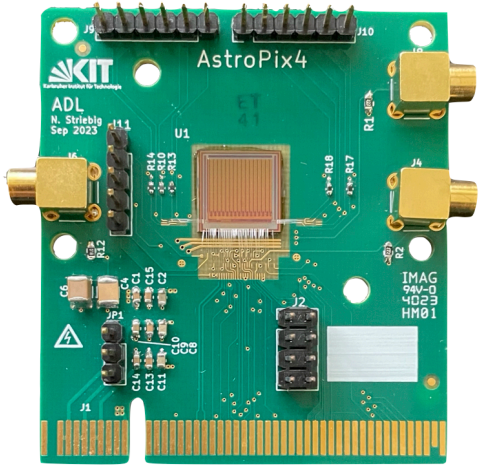


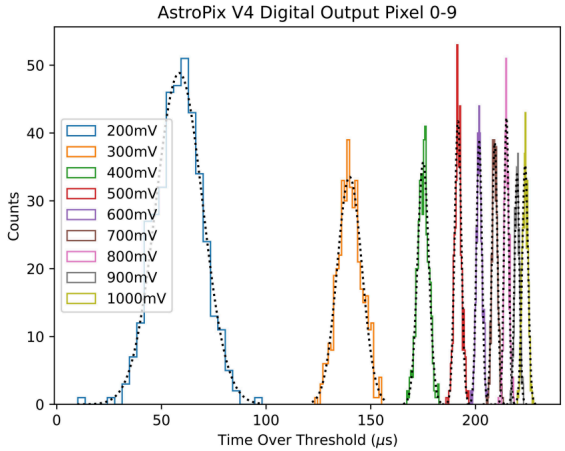


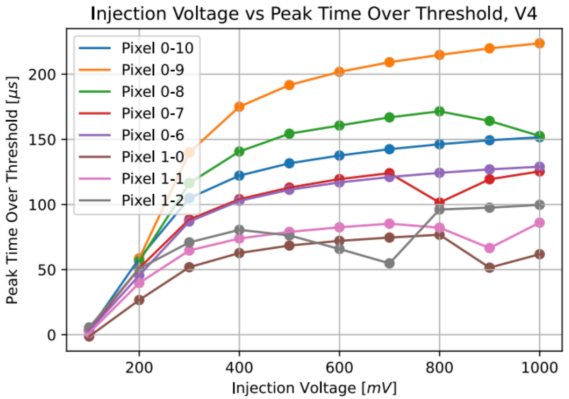
AstroPix v4/v5

AstroPix v4 : Final design engineering version

- Chip size 1 × 1 cm²; Thickness 700 µm, V_{BD} ~ 400V
- Pixel pitch 500 µm with pixel size 300 µm, 16 × 16 pixel matrix
- Individual pixel readout with individual hit buffer
  - No identification issue due to ghost hits
- 3 Timestamps - 2.5MHz (TS), 20 MHz (Fine TS), and 16 bit Flash TDC
  - Fast ToT and Timestamp with 3.125 ns time resolution
- TuneDACs - Pixel-by-pixel threshold tuning and pixel masking
- Daisy Chain readout - pass hits to next chip through QSPI
- Self-triggered (reads out active hits)







Relevant AstroPix v5 Specifications

Pixel Matrix:

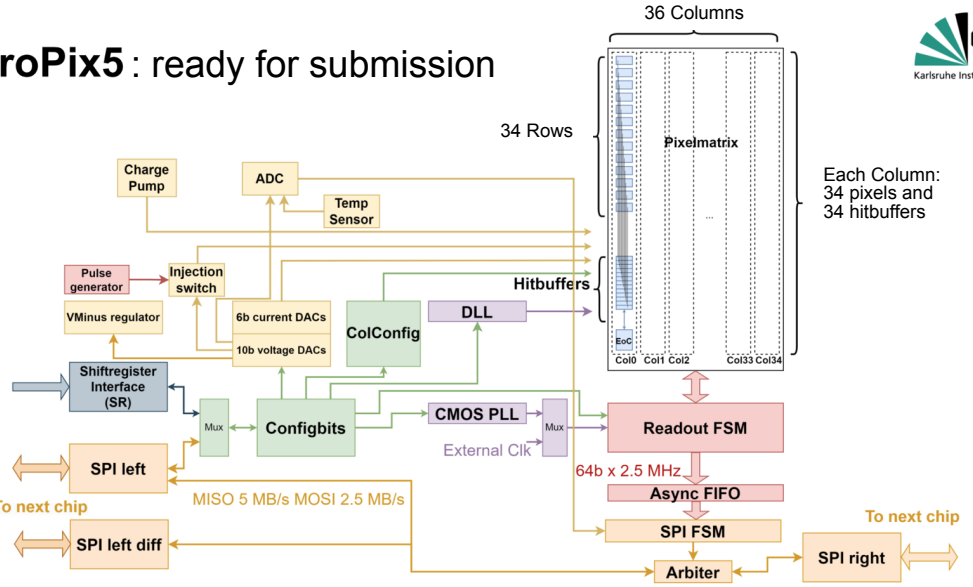
- 36 cols x 34 rows
  - —32 Columns with Standard NMOS Comparator
  - —2 Columns with dynamic Feedback
  - —1 Column with NMOS Comparator and Resistor Load
  - —1 Column with NMOS Comparator and PMOS Load
- 500u Pixel Pitch and 300u Pixel Size
- 3 Tunebits per Pixel
- Pixel Dynamic Range 20 keV - 700 keV
- Noise Floor 5 keV (2%@662 keV)
- Bias Voltage up to 400-500 V to maximize depletion
- Fully NMOS Comparator
- In Pixel amplifier with Dynamic Feedback option for improved Dynamic Range

Power Consumption:

- Pixel 4.6 uW
- Pixel matrix 5.3 mW
- Digital 2.2 mW
  - — 700 uW DigitalTop

Total: ~2 mW/cm^2 for 2x2 cm chip

AstroPix5: ready for submission



Conclusion

HV MAPS are a robust technology >20 years in development and used in various particle physics instruments

- AstroPix development > 5 years and ~$5M investment from NASA
- overlapping design requirements for gamma-ray space telescopes and nuclear physics imaging calorimeters

Testing and characterization of AstroPix_v3 is underway

- specific tests designed for AMEGO-X and ePIC
- meeting our project goals

AstroPix_v5 is designed and will be fabricated by AMS early 2025

Name	Journal	Link	arxiv
Developing the Future of Gamma-ray Astrophysics with Monolithic Silicon Pixels	NIM A	https://www.sciencedirect.com/science/article/pii/S0168900221007804?via%3Dihub	https://arxiv.org/abs/2109.13409
AstroPix: Investigating the Potential of Silicon Pixel Sensors in the Future of Gamma-ray Astrophysics	SPIE 2020	https://www.spiedigitallibrary.org/conference-proceedings-of-spie/11444/114442Q/AstroPix--investigating-the-potential-of-silicon-pixel-sensors-in/10.1117/12.2562327.full#_=_	https://arxiv.org/abs/2101.02665
Monolithic Active Pixel Sensors on CMOS technologies	Snowmass 2021		https://arxiv.org/abs/2203.07626
AstroPix: Novel monolithic active pixel silicon sensors for future gamma-ray telescopes	SPIE 2022	https://www.spiedigitallibrary.org/conference-proceedings-of-spie/12181/2630405/AstroPix--novel-monolithic-active-pixel-silicon-sensors-for-future/10.1117/12.2630405.full#_=_	https://arxiv.org/abs/2209.02631
AstroPix: CMOS pixels in space	PIXEL 2022	https://pos.sissa.it/420/020	https://arxiv.org/abs/2302.00101
Development of an HV-CMOS active pixel sensor "AstroPix" for all-sky medium-energy gamma-ray telescopes	ICRC 2023	https://pos.sissa.it/444/644	not uploaded
AstroPix4 — a novel HV-CMOS sensor developed for space based experiments	JINST	https://iopscience.iop.org/article/10.1088/1748-0221/19/04/C04010	not uploaded
Performance evaluation of the high-voltage CMOS active pixel sensor AstroPix for gamma-ray space telescopes	NIMA	https://doi.org/10.1016/j.nima.2024.169762	https://arxiv.org/abs/2408.12891
The path toward 500 µm depletion of AstroPix, a pixelated silicon HVCMOS sensor for space and EIC	SPIE 2024	https://opticalengineering.spiedigitallibrary.org/conference-proceedings-of-spie/13093/130937S/The-path-toward-500µm-depletion-of-AstroPix-a-pixelated-silicon/10.1117/12.3018495.full#_=_	https://arxiv.org/abs/2407.05947v1
Development of a novel HV-CMOS active pixel sensor AstroPix for gamma-ray space telescopes	SPIE 2024	https://neurophotonics.spiedigitallibrary.org/conference-proceedings-of-spie/13093/130937P/Development-of-a-novel-HV-CMOS-active-pixel-sensor-AstroPix/10.1117/12.3018170.full#_=_	

AMEGO-X Team

With collaborators at INFN, U. Hiroshima, U. Johannesburg, KIT,
U. Western Australia, Georgia Tech, Drexel, UNH and members of LIGO, IceCube, CTA

BIC Collaborating Institutions

USA

- Argonne National Laboratory
- NASA Goddard Space Flight Center
- Oklahome State University
- University of Connecticut
- University of California Santa Cruz

Canada

- University of Manitoba
- University of Regina
- Mount Allison University

Korea

- Kyungpook National University
- Yonsei University
- University of Seoul
- Pusan National University
- Korea University
- Sungkyunkwan University
- Hanyang University
- Gangneung-Wonju National University

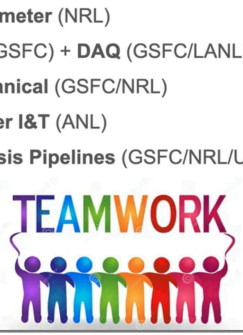
Germany

- Karlsruhe Institute of Technology
- University of Giessen

ePIC

The ComPair-2 Team

Detectors - AstroPix (GSFC/ANL/KIT/Nagoya/Hiroshima)
Calorimeter (NRL)
FEE (GSFC) + **DAQ** (GSFC/LANL)
Mechanical (GSFC/NRL)
Tracker I&T (ANL)
Analysis Pipelines (GSFC/NRL/UCB/SSL)



Thank you!
- AstroPix Team