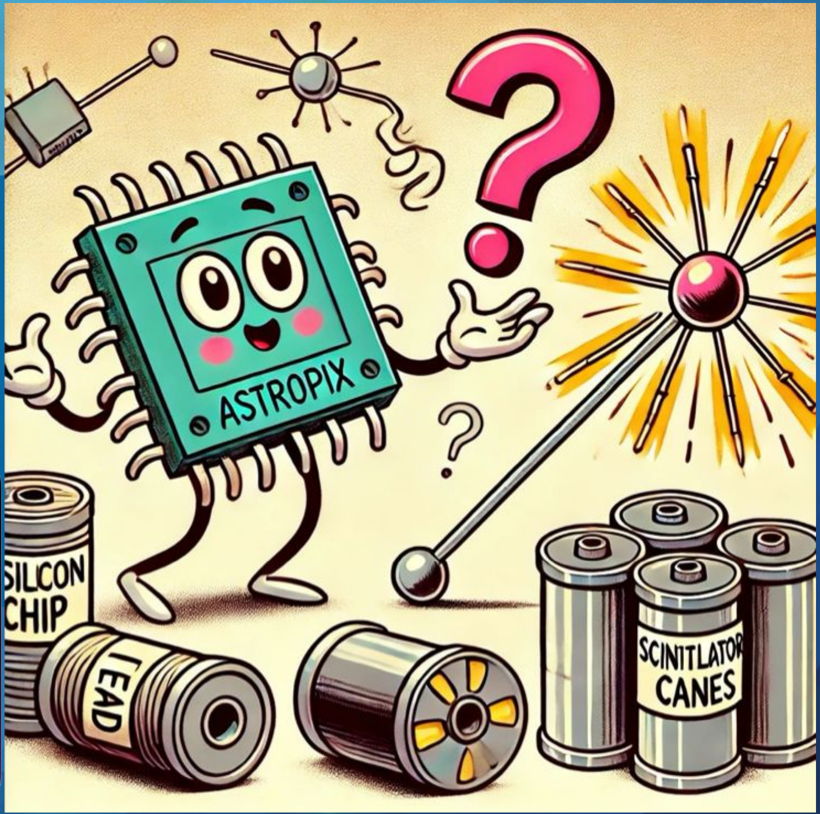
VERTEX25

An overview of the imaging layers of the ePIC Barrel Imaging Calorimeter



Manoj Jadhav for the ePIC Collaboration
Argonne National Laboratory

mjadhav@anl.gov

VERTEX 2025, Knoxville
Aug 26, 2025

ePIC

Argonne NATIONAL LABORATORY

Detector Requirements for Barrel ECal

From the EIC Yellow Report: stringent requirements for Barrel ECal
https://eic.jlab.org/Requirements/

EIC is an electron scattering machine and identifying scattered electrons mainly depends on the electromagnetic calorimetry.

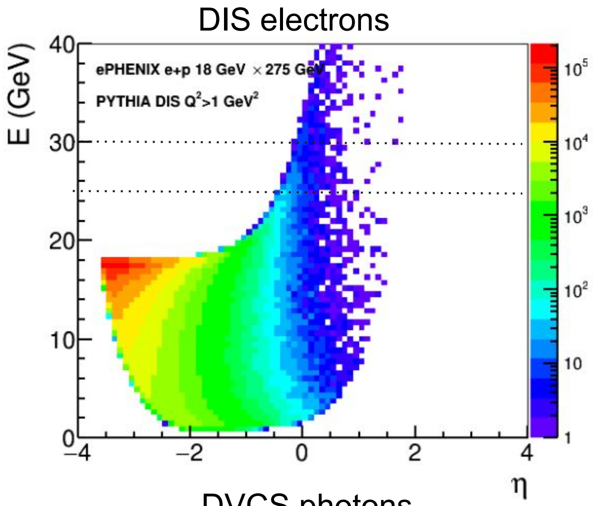
The electromagnetic calorimeter is the main detector for **electron-pion separation**. The inclusive physics program requires up to 10^4 pion suppression at low momenta in the barrel

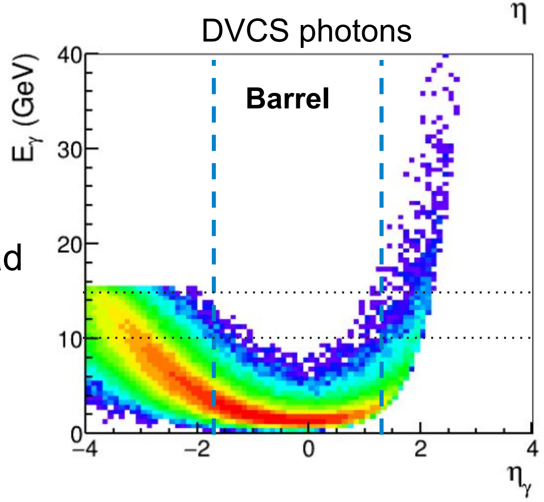
- **Electron ID up to 50 GeV** and down to 1 GeV and below
  - Energy resolution < **10%/√(E) + (2-3)%**
  - High power for **e/π separation down to 1 GeV/c**
- **Photon measurements up to 10 GeV**
- **γ/π⁰ separation up to 10 GeV**
  - Distinguishing two showers with opening angle down to 30 mrad

Assist with muon identification

Sufficient dynamic range to **detect MIP** signals in all layers

The system is space-constrained (limited space inside the solenoid)



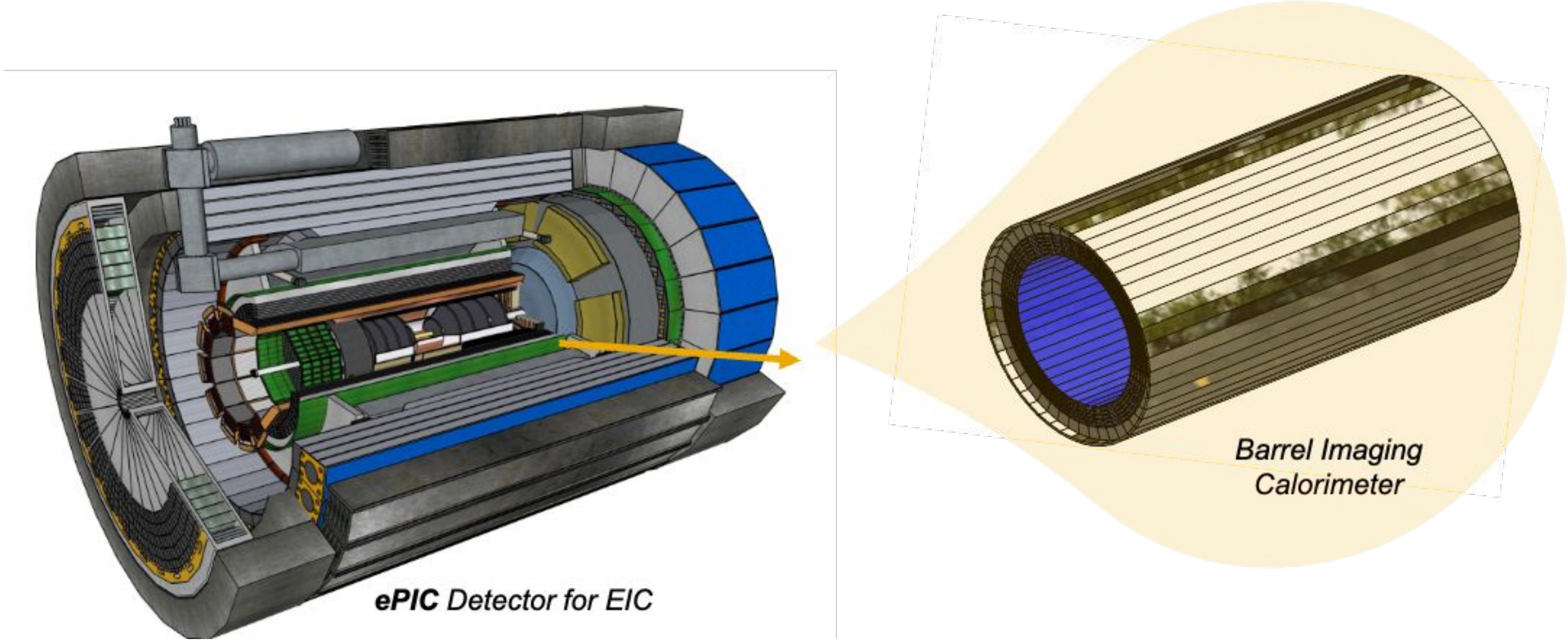


Detector Requirements for Barrel ECal

These stringent requirements for Barrel Electromagnetic Calorimeter can be achieved using Hybrid lead/scintillating fiber calorimeter with a silicon tracker

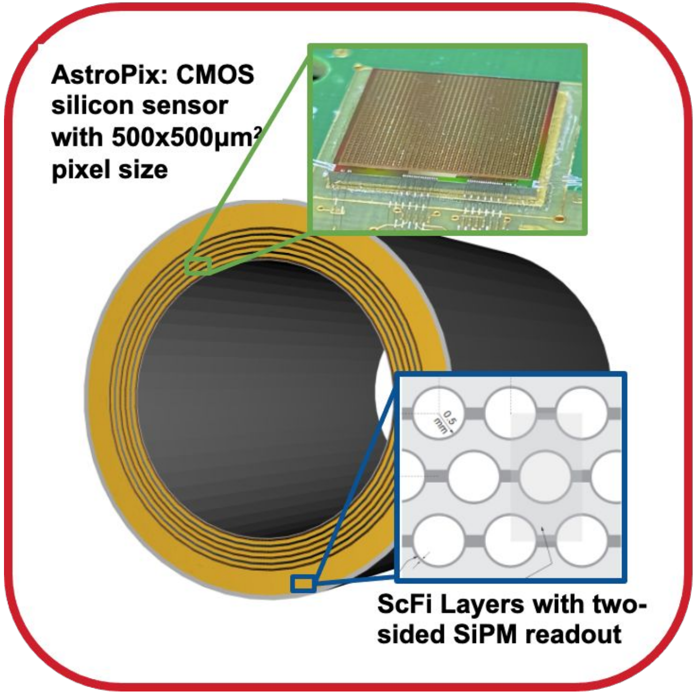
Precisely measure 3D image of electromagnetic shower

- Barrel Imaging Calorimeter (BIC)



The concept of Barrel Imaging Calorimeter (BIC)

High-performance sampling calorimeter with Si sensors for shower profiling

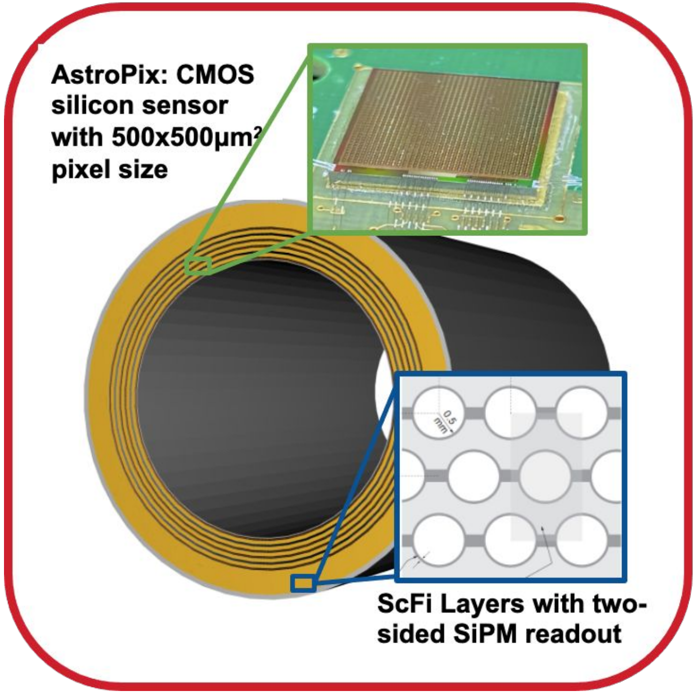


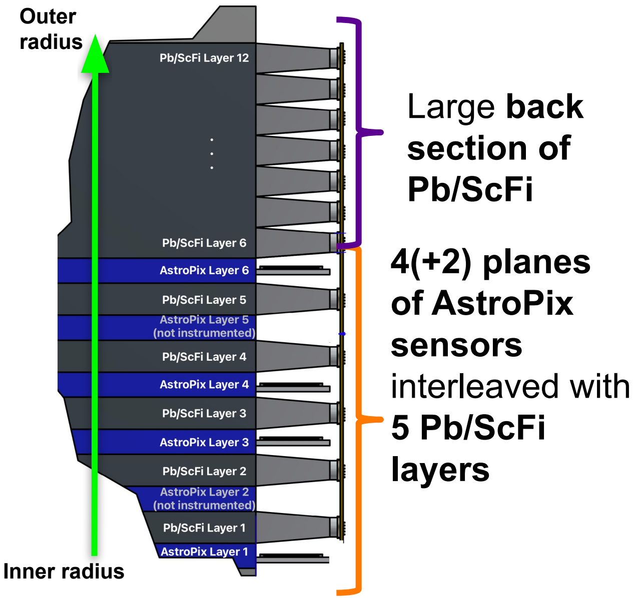
Multiple layers of monolithic AstroPix silicon sensors (Inexpensive low-power silicon sensor developed for NASA space application) to capture a **3D image of the shower**

Start from mature layered Pb/ScFi technology with side-readout (same as the GlueX calorimeter) for **state-of-the-art sampling calorimeter** performance

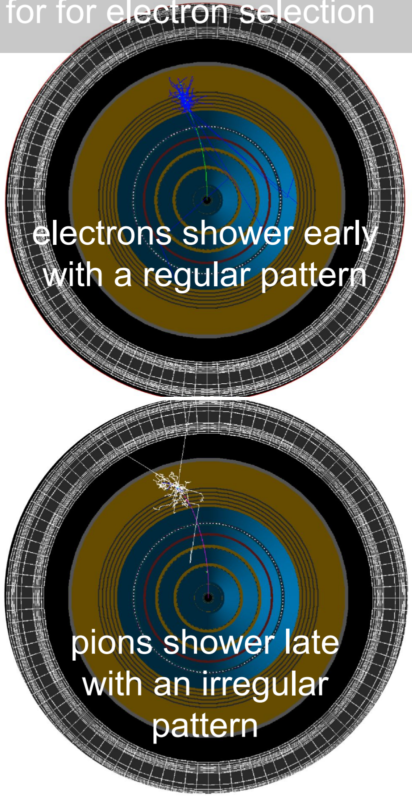
The concept of Barrel Imaging Calorimeter (BIC)

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





Example: 3D Shower Imaging for for electron selection

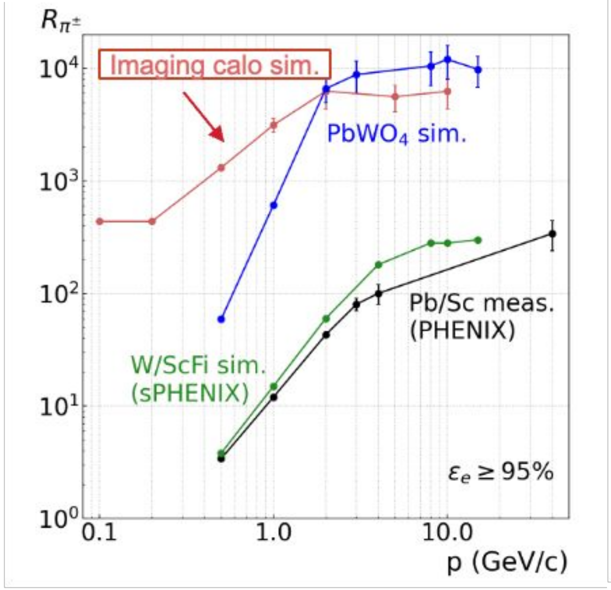


Energy resolution - Primarily from Pb/ScFi layers (+ AstroPix energy information)

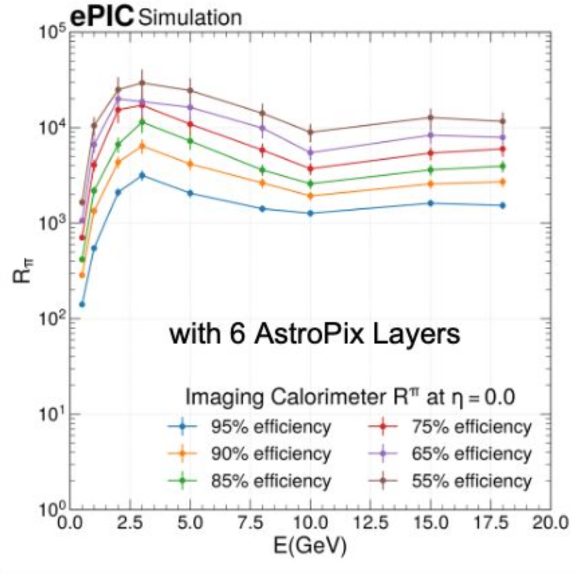
Position resolution - Primarily from Imaging Layers (+ 2-sided Pb/ScFi readout and φ-R segmentation)

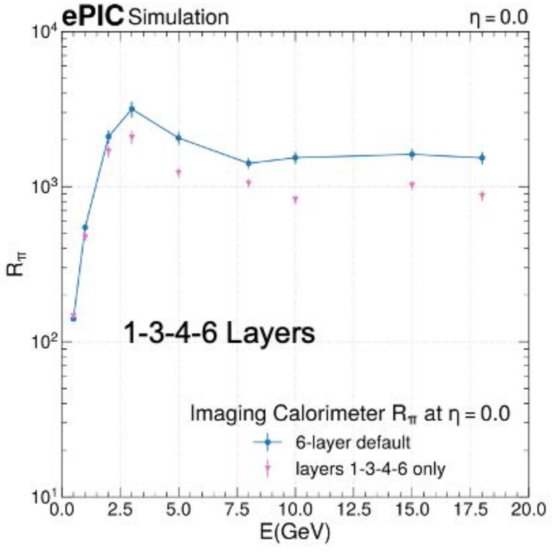
The concept of Barrel Imaging Calorimeter (BIC)

Standalone simulation



Realistic ePIC simulation





Goal: Separation of electrons from background in Deep Inelastic Scattering (DIS) processes

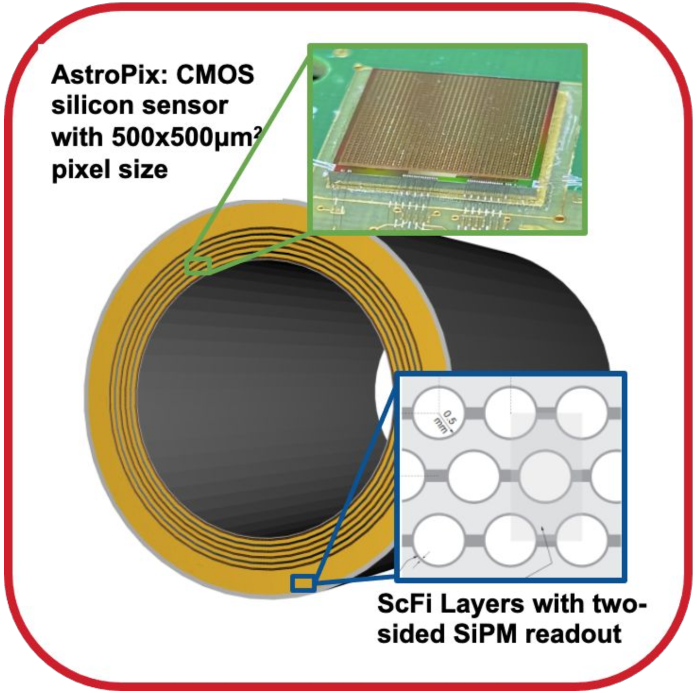
Method: **E/p cut (Pb/ScFi) + Neural Network** using 3D position and energy info from imaging layers

Eventually will perform holistic reconstruction, incorporate SciFi/AstroPix information together in ML

e-π separation exceeds **10^3** in pion suppression at **95% efficiency** above 1 GeV in realistic conditions!

The concept of Barrel Imaging Calorimeter (BIC)

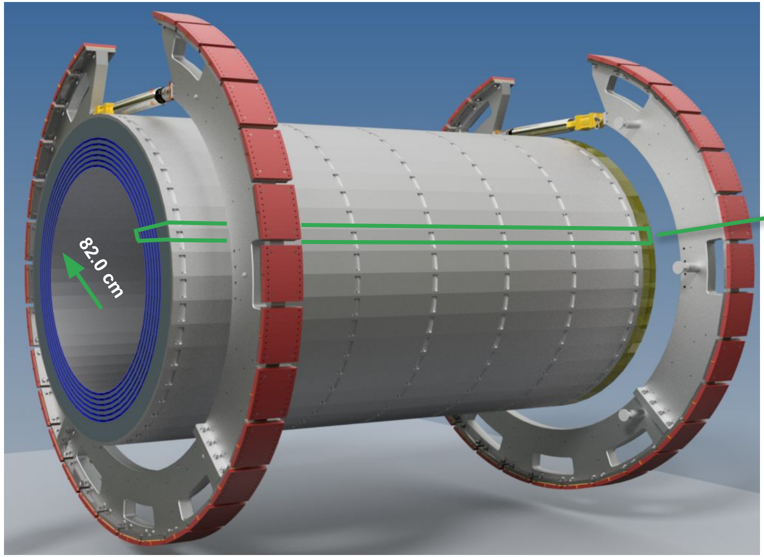
High-performance sampling calorimeter with Si sensors for shower profiling



Multiple layers of monolithic AstroPix silicon sensors (Inexpensive low-power silicon sensor developed for NASA space application) to capture a **3D image of the shower**

Start from mature layered Pb/ScFi technology with side-readout (same as the GlueX calorimeter) for **state-of-the-art sampling calorimeter** performance

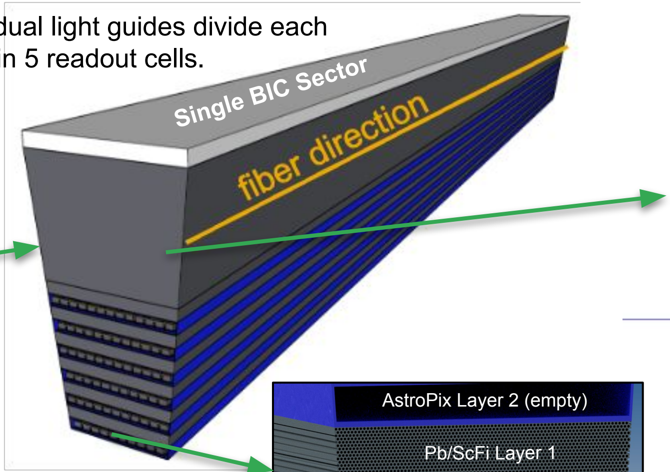
The BIC Design

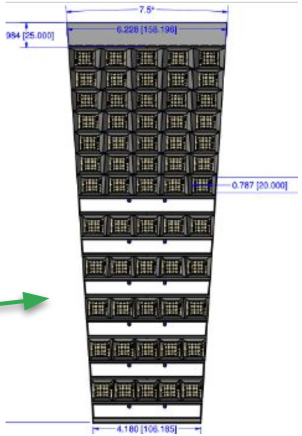


Pb/SciFi Layers - 17 rows of fiber between corrugated lead.

Each sector has 12 Pb/ScFi layers.

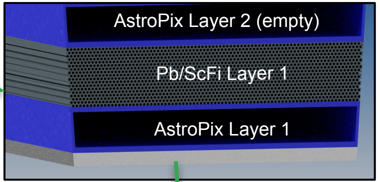
Individual light guides divide each layer in 5 readout cells.





SiPMs - 5 per layer x 12 layers = 60 (Hamamatsu S14161-3050)
1 light guide per cell

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



Length: ~435 cm

Inner Radius: ~81.5 cm

Structure: 48 sectors

η Range: $-1.71 < \eta < 1.31$

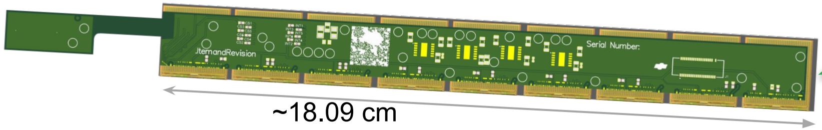
Depth: 17.1X0 at $\eta = 0$

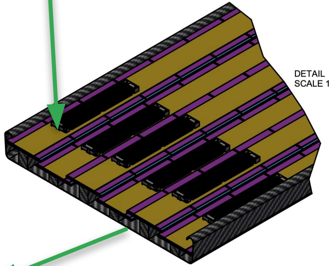
Sampling fraction ~10%

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

A stave consists of 12 modules.

A tray contains of 6-8 staves.

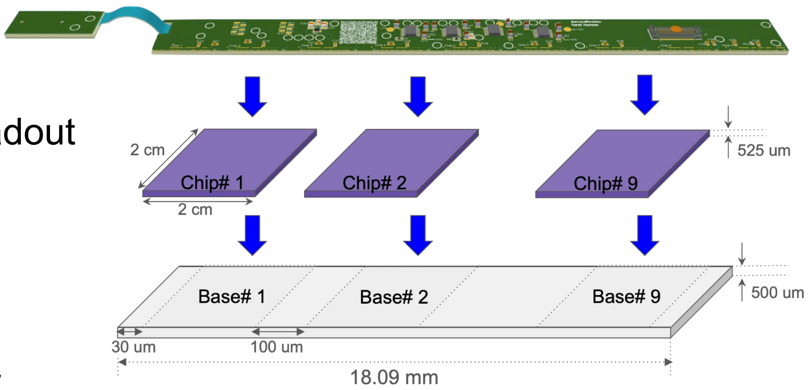




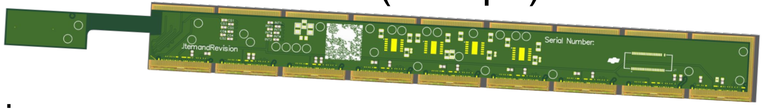
Tray - Structure holding the AstroPix staves for a single layer (217.5 cm long).

The BIC Imaging Layers

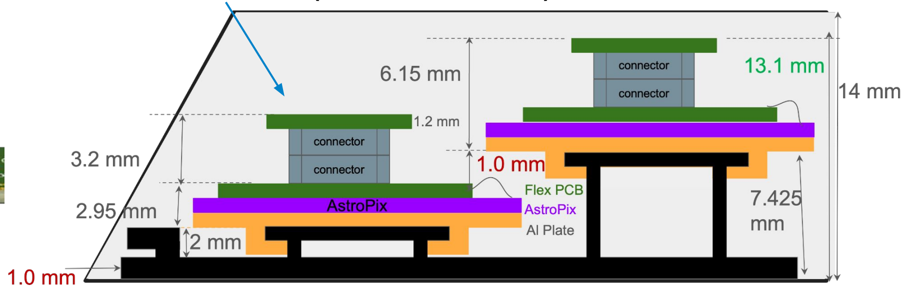
- **Module** is a elementary unit for imaging layers
  - **9 AstroPix HV-CMOS chips** with rigid-flex readout
- It consist of three components
  - Aluminum base rail plate
  - AstroPix chips
  - Hybrid rigid-flex PCB
- 12 modules forms a Stave and readout at the end of Sector using End of Tray Card (FPGA) (~217cm)
- Tray consists of (6, 7, 7, 8) Staves (56 Staves/Sector)
- There are total 48 sectors with length of ~435 cm
- The BIC is made up of 31104 Modules using ~280k chips
- The silicon active area is ~ 100 m^2

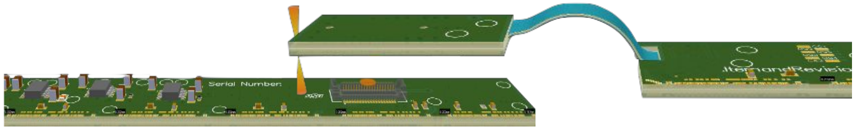


Module (9 chips)



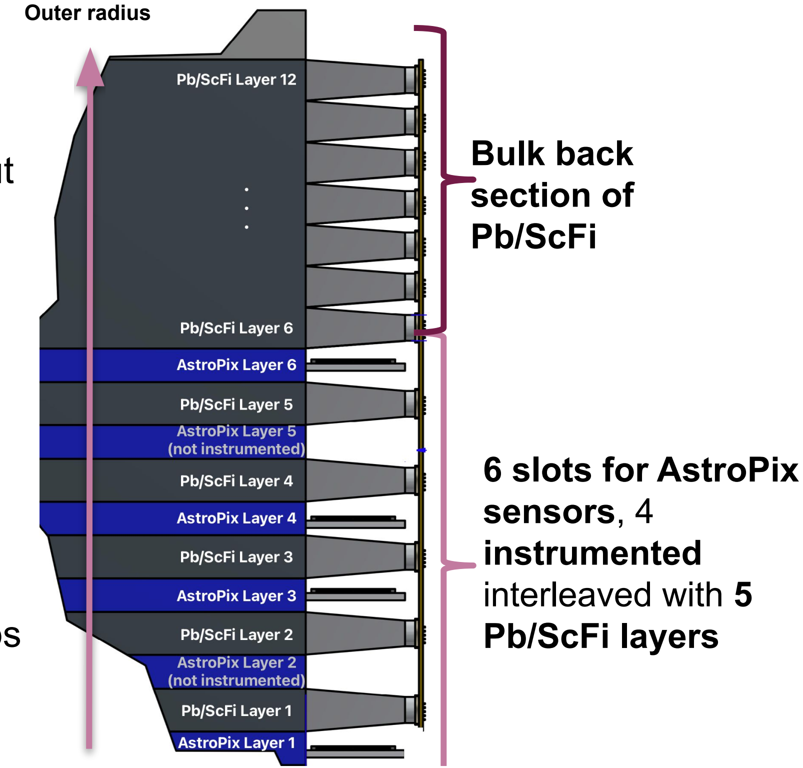
Stave (12 modules)

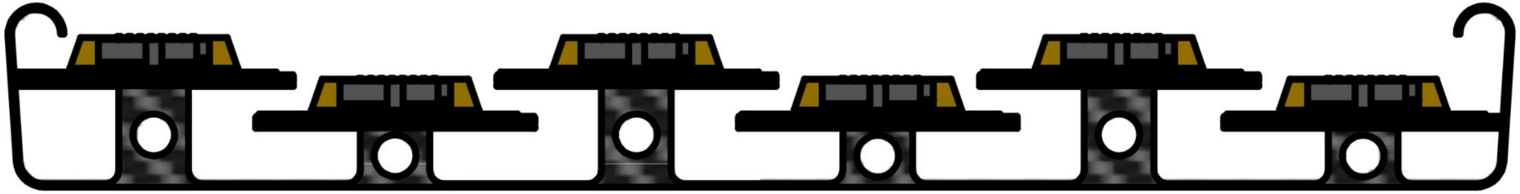




The BIC Imaging Layers

- **Module** is a elementary unit for imaging layers
  - **9 AstroPix HV-CMOS chips** with rigid-flex readout
- It consist of three components
  - Aluminum base rail plate
  - AstroPix chips
  - Hybrid rigid-flex PCB
- 12 modules forms a Stave and readout at the end of Sector using End of Tray Card (FPGA) (~217cm)
- Tray consists of (6, 7, 7, 8) Staves (56 Staves/Sector)
- There are total 48 sectors with length of ~435 cm
- The BIC is made up of 31104 Modules using ~280k chips
- The silicon active area is ~ 100 m^2
  - All this made up of **AstroPix**





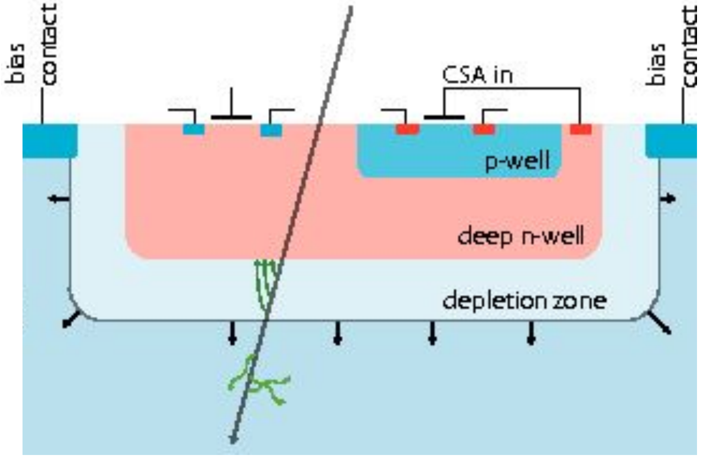
*Old Tray design

AstroPix - where it came from?

AstroPix

HV-CMOS Monolithic Active Pixel Sensor (MAPS):

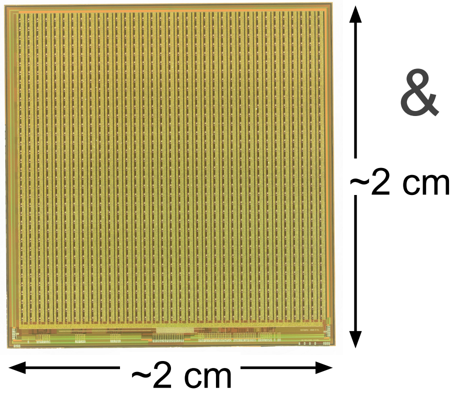
- Combination of silicon pixel & Front-End ASIC
- On-pixel charge amplification and digitization
- Technology uses more typical CMOS wafer processing for cost effective mass production
- Fabrication on single wafer enables shorter design cycle
- No need to bump-bond to each pixel - improves yield



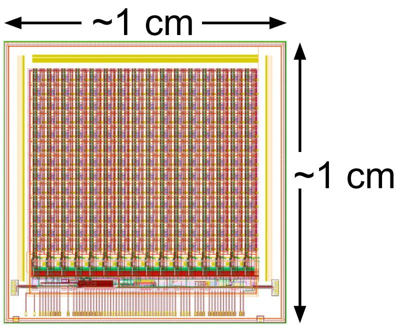
AstroPix (based on **ATLASPix3** [arXiv:2109.13409])

- 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

AstroPix v3



&



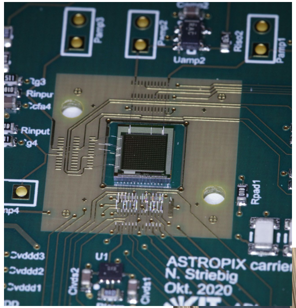
AstroPix v4

Overview of AstroPix

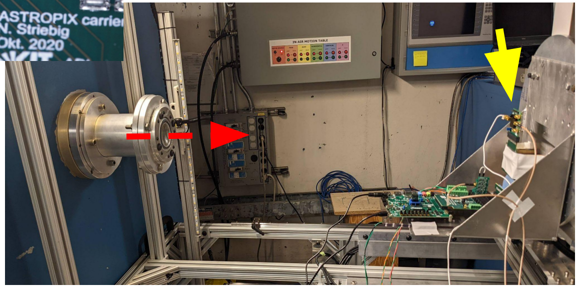
Monolithic Silicon CMOS sensor for gamma-ray astrophysics

2020 AstroPix_v1

First prototype: testing and characterization

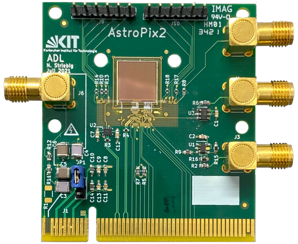


Design based on HV MAPS ~20 years of development at KIT



2021 AstroPix_v2

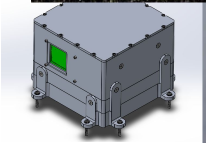
Second prototype



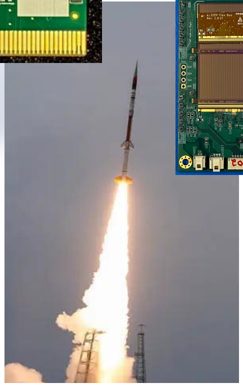
Radiation testing April, June 2022

2023 AstroPix_v3

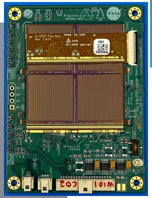
Flight prototype and final design



Beam Test FNAL 2023, 2024*



3-layer Quad-chip Payload Launch: Fall 2025



2024 AstroPix_v4

Pixel readout, power reduced

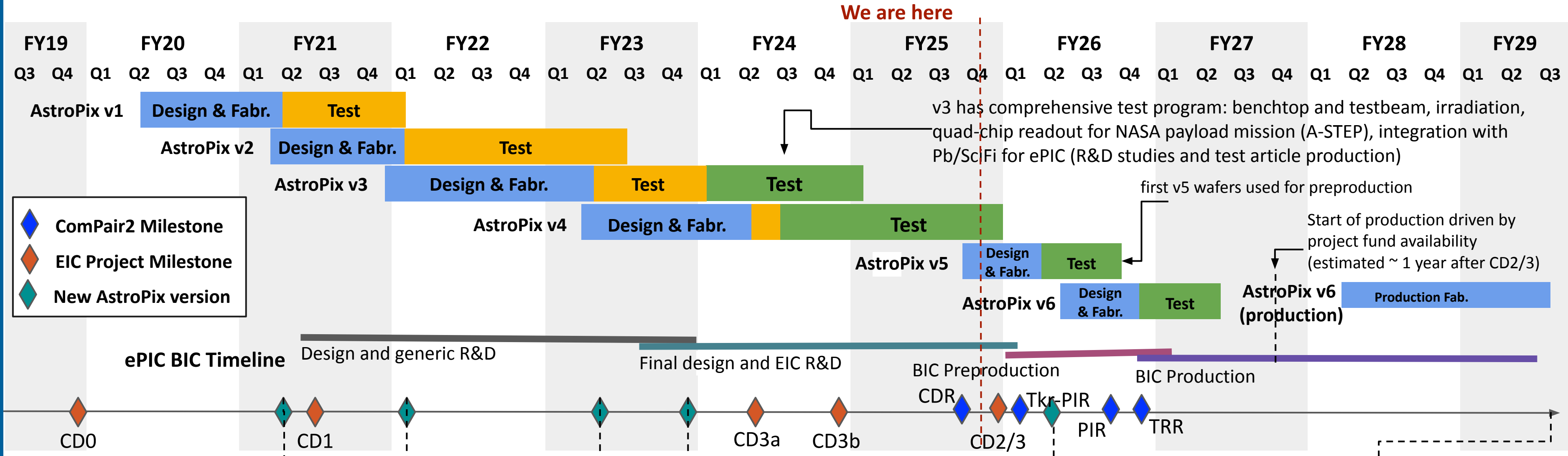
All produced by TSI Semiconductors

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)



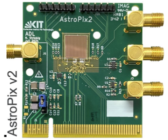
Start of BIC installation at BNL

AstroPix v1

HV-CMOS MAPS based on ATLASPix3, designed for the AMEGO-X NASA mission, optimized for power dissipation and energy resolution

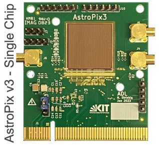
[Nucl.Instrum.Meth.A 1019 (2021) 165795](#)

0.45 x 0.45 cm^2 chip, 175 µm pixel pitch
18 x 18 pixel matrix
Power dissipation 14.7 mW/cm^2



AstroPix v2

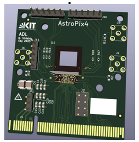
1 x 1 cm^2 chip, 250 µm pixel pitch
35 x 35 pixel matrix
Row/column readout
Power dissipation 3.4 mW/cm^2



AstroPix v3

First full-size chip

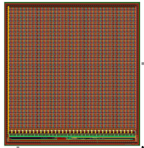
2 x 2 cm^2 chip, 500 µm pixel pitch
Row/column readout
Power dissipation <1 mW/cm^2
2.5 MHz timestamp, 200 MHz ToT



AstroPix v4

Final design but smaller size

1 x 1 cm^2 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 cm^2 chip, 500 µm pixel pitch
Design identical to v4 (with bug fixes)

AstroPix v6

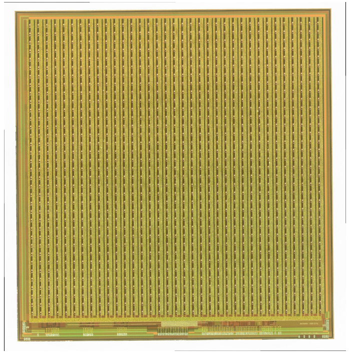
production chip

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

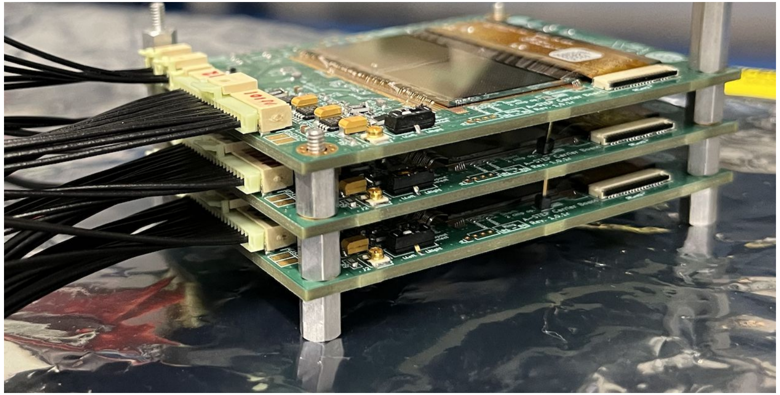
AstroPix v3 Performance

A low-power HV-CMOS monolithic active pixel sensor

- Current AstroPix version: 3 (1.87 cm × 1.96 cm)
- Row and Colums are daisy chained
- Pixel pitch: 500 μm
- Pixel matrix: 35 × 35
- Sensor thickness: 725 μm
- Low power consumption <1.5 mW/cm^2



Multilayer Quadchip boards



Module test article

*More results in next talk by Bobae Kim

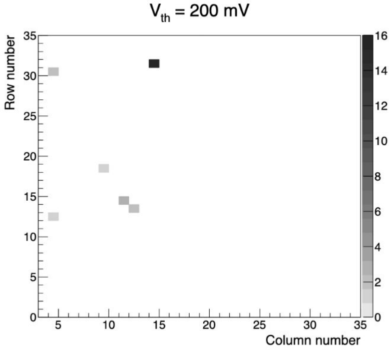
AstroPix v3 Performance - Bench

*Bobae Kim

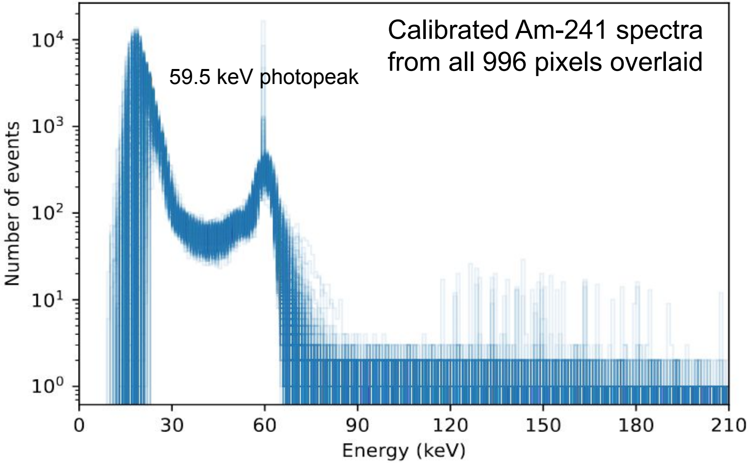
Bench Test: Radiation Source Test on AstroPix v3

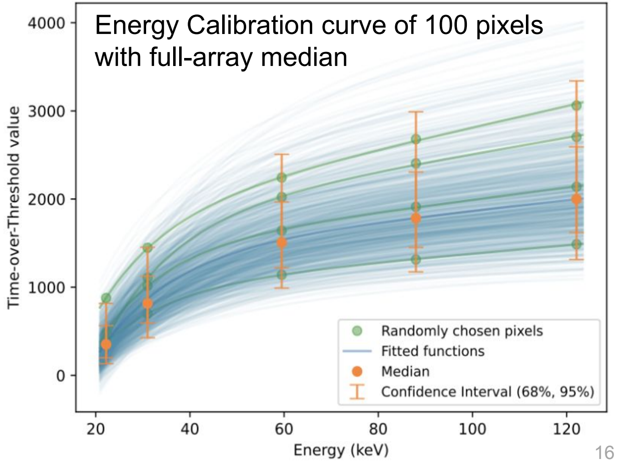
- The AstroPix dynamic range floor (25 keV) allows for threshold values of more than 200 mV above baseline.
- Energy resolution/calibration: Cd-109, Ba-133, Am-241, and Co-57 from 22.2 keV to 122 keV
- Dynamic range: 25-200 keV (v5 will test 700 keV dynamic range)
- **44% of pixels meet the energy resolution 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.

Noise scan



Preliminary results





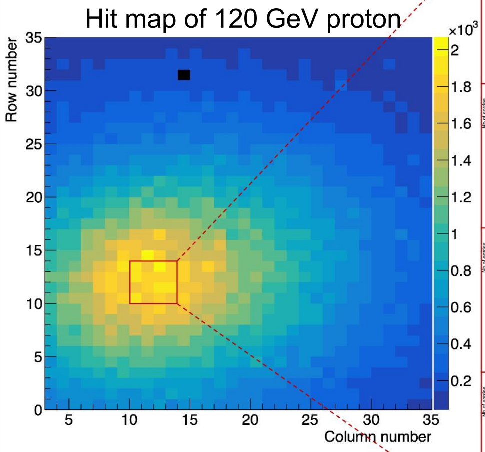
AstroPix v3 Performance - TestBeam

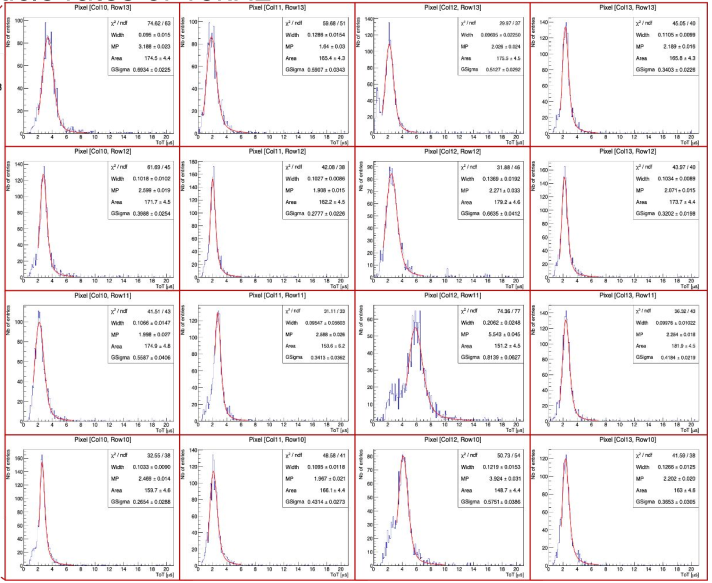
*Bobae Kim

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

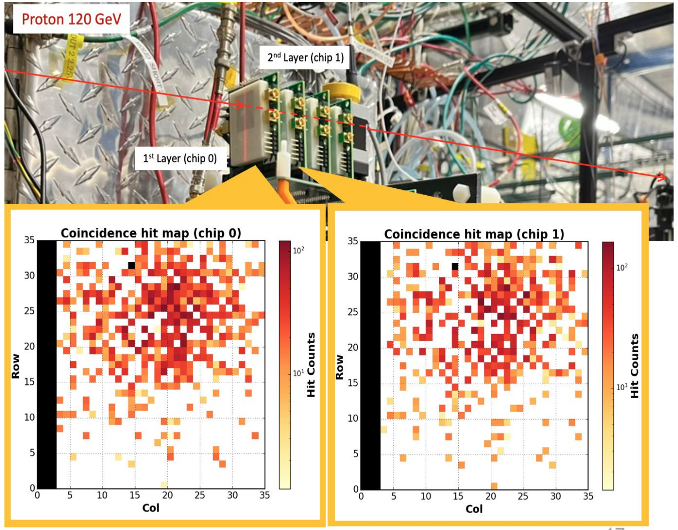




*Preliminary results

Double layer

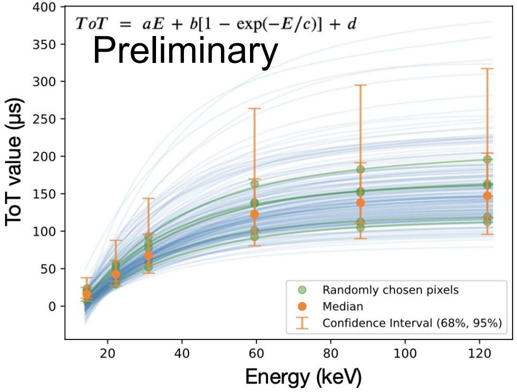
- 120 GeV proton beam events from the first two layers, read in coincidence, showing the position of the hit pixel.
- The **proof-of-concept demonstration of the integration of two daisy-chained AstroPix_v3 layers in a beam-like environment**



AstroPix v4

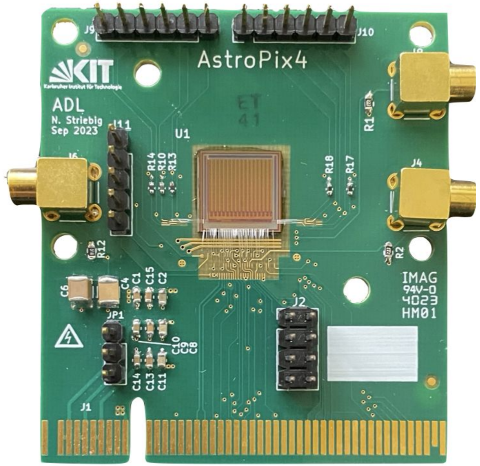
*Yusuke Suda

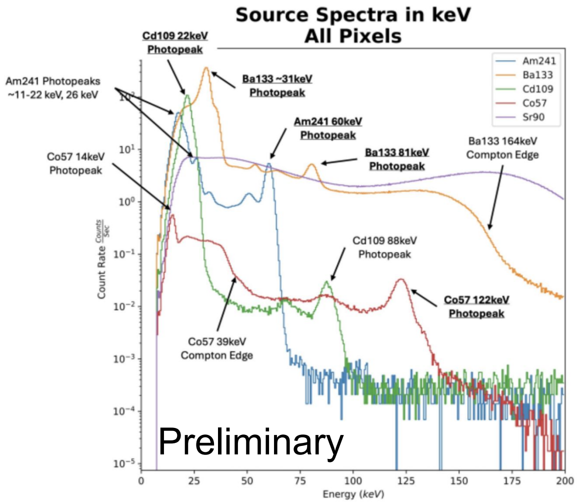
Energy calibration curves



AstroPix v4 : Final design engineering version

- Chip size 1×1 cm^2; 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 thresh-old tuning and pixel masking
- Daisy Chain readout - pass hits to next chip through QSPI
- Self-triggered (reads out active hits)





*Grant Sommer

AstroPix v5 design specifications

Pixel Matrix:

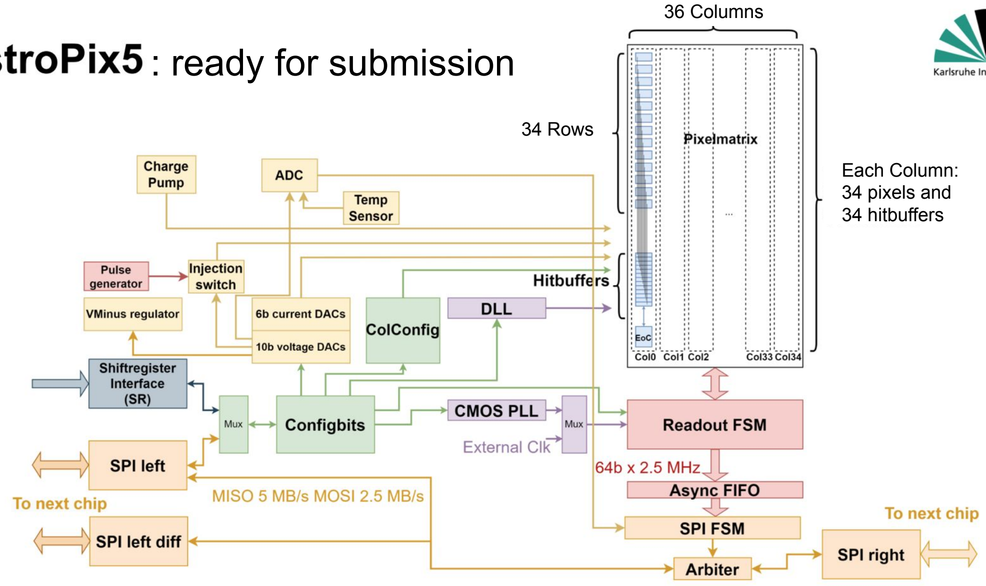
- 36 cols x 34 rows
  - 32 Columns with Standard NMOS Comparator
  - 2 Columns with dynamic Feedback
  - 1 Column with NMOS Comparator and Resistor Load
  - 1 Column with NMOS Comparator and PMOS Load
- 500u Pixel Pitch and 300u Pixel Size
- 3 Tunebits per Pixel
- Pixel Dynamic Range 20 keV - 700 keV
- 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



Karlsruhe Institute of Technology

Conclusion

Overview of Barrel Imaging calorimeter

- Consist of two sub detectors - Hybrid lead/scintillating fiber calorimeter and AstroPix silicon tracker
- High-performance sampling calorimeter with Si sensors provide precision 3D shower profiling

Testing and characterization of AstroPix v3 and v4 is underway

- Specific tests designed for NASA's space mission and ePIC-BIC
- AstroPix v4 is final design version

AstroPix v5 (full size) is designed and will be fabricated by AMS

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#_=_	

ePIC

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

BIC Collaborating Institutions