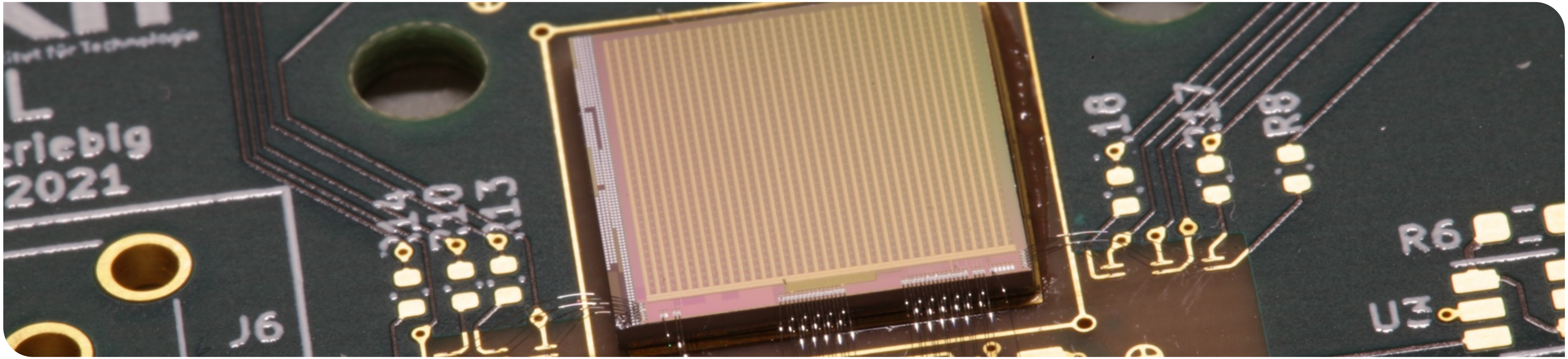
Karlsruhe Institute of Technology

KIT ASIC and Detector Laboratory

AstroPix: A novel HV-CMOS pixel sensor for space-based experiments

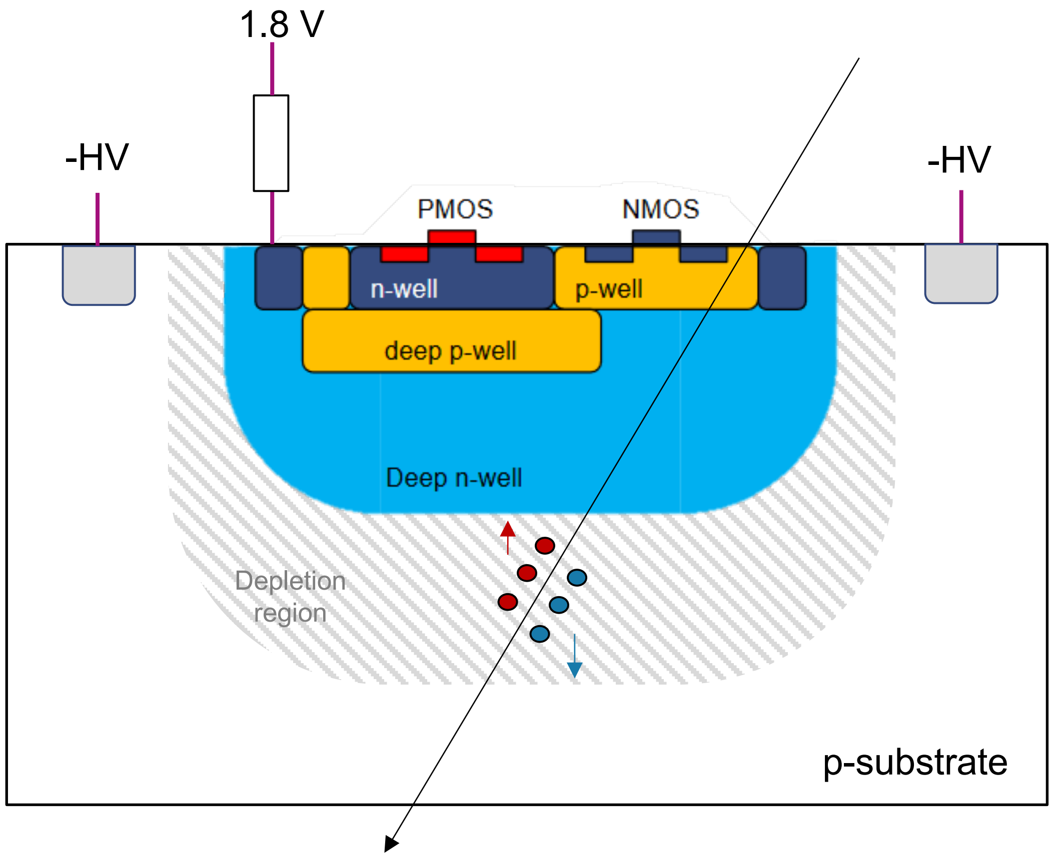
Richard Leys, Ivan Perić, **Nicolas Striebig***
**striebig@kit.edu*



TREDI 2023, March 2023

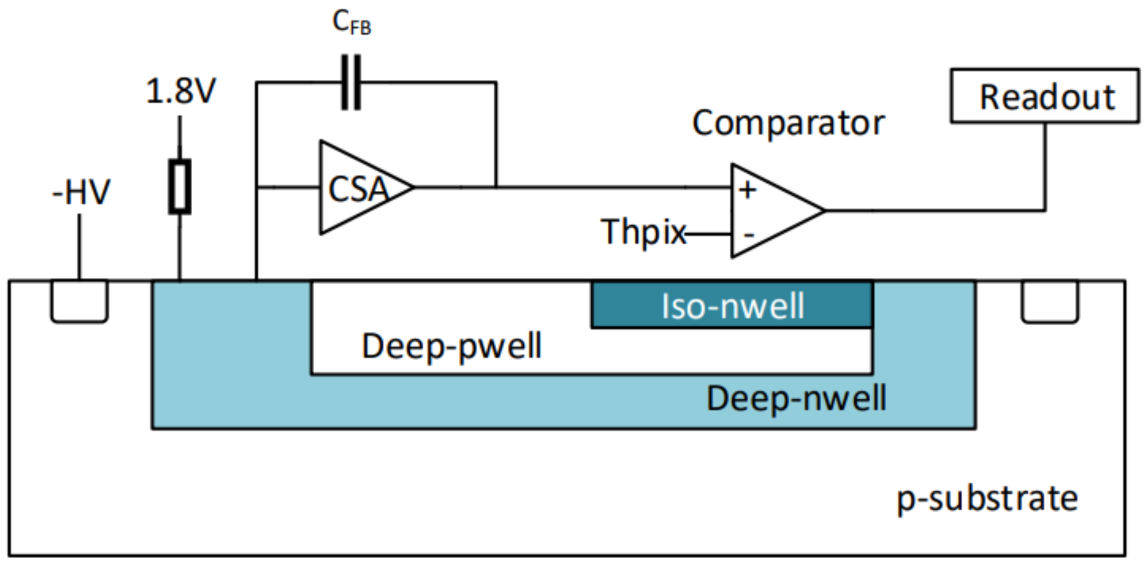
Introduction – HV-CMOS

- Charged particles or photons generate electron-hole pairs in depletion region of the sensing diode formed by deep n-well and p-substrate
- Separated by strong electric field
- Electrons drift to charge-collecting deep n-well
- Deep n-well contains shallow wells for electronics
- **High-Voltage CMOS Active Pixel Sensor (HVMAPS)**



Introduction – HV-CMOS sensor

- Pixel contains amplifier, pulse shaping and comparator
- Pixel electronics isolated by deep n-well
- CMOS comparator n-well isolated by deep p-well → TSI 180nm quadruple well

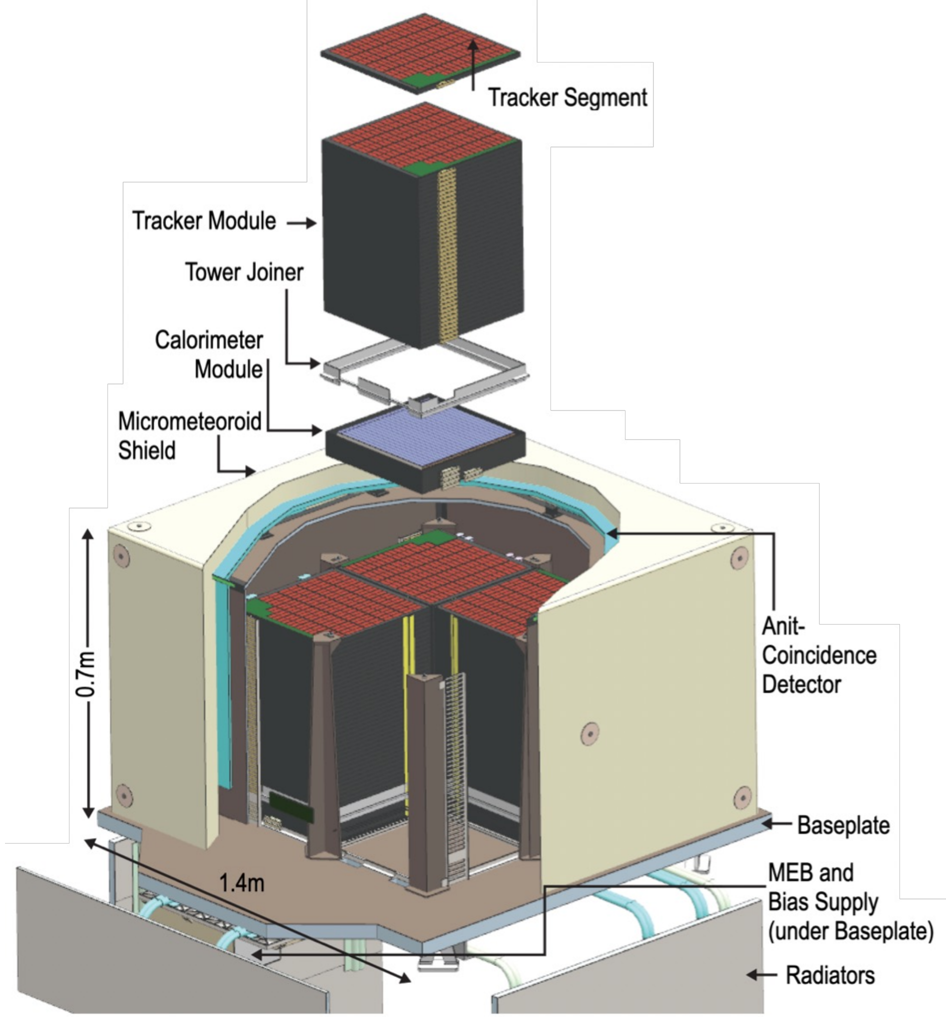


Introduction – Why HV-CMOS?

- Low cost:
  - Standard CMOS process
  - No backside processing, no epi layers needed
  - 85k € (HV-CMOS) vs 2M € (hybrid) per m^2
- High fill factor
- High reverse bias (>200 V) leads to fast charge collection by drift

Introduction – AMEGO-x

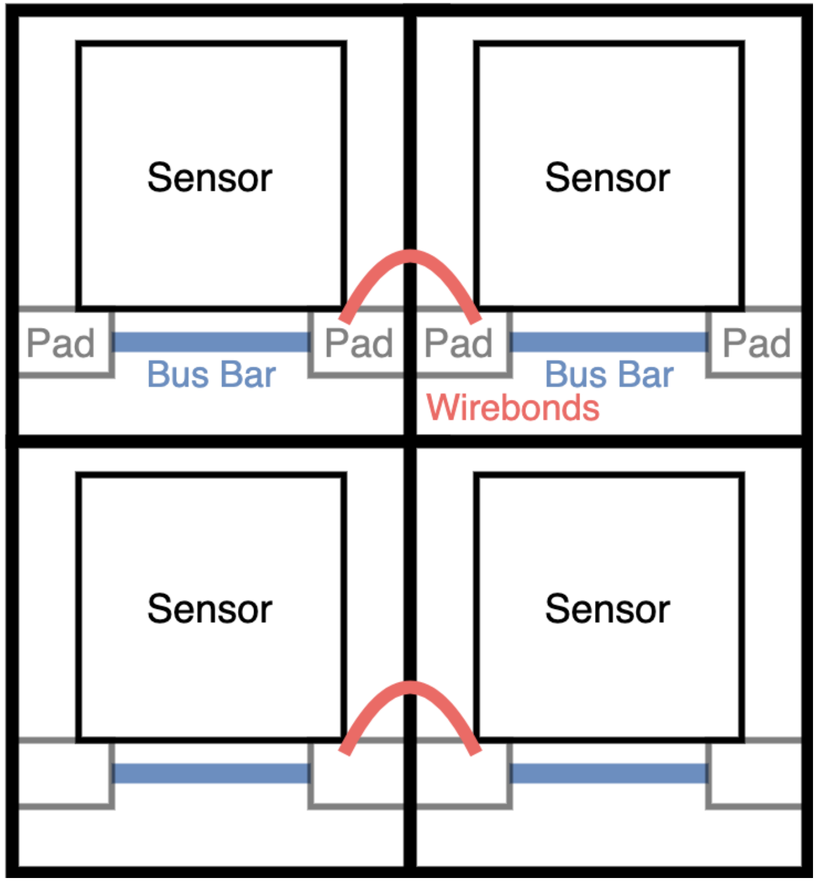
- NASA prosed MIDEX concept for space based observatory
- Wide-field survey telescope designed to discover and characterize gamma-ray emission
- 3 year mission
- HV-CMOS sensor for Compton camera



Exploded view of AMEGO-x instrument. [1]

Introduction – Tracker modules

- Quadchip: 2 x 2 chips
- Layer: 10 x 10 Quadchips
- Tower: 40 Layers
- Tracker: 4 Towers



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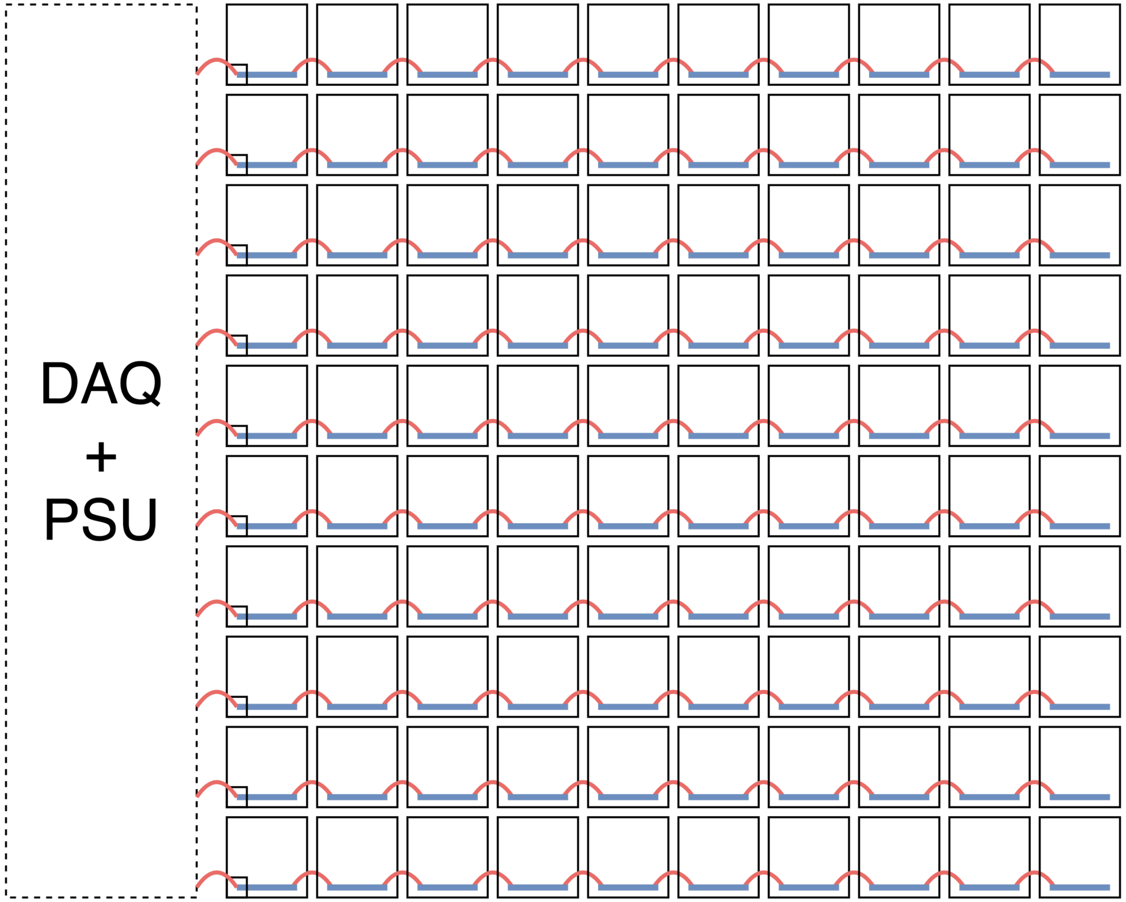

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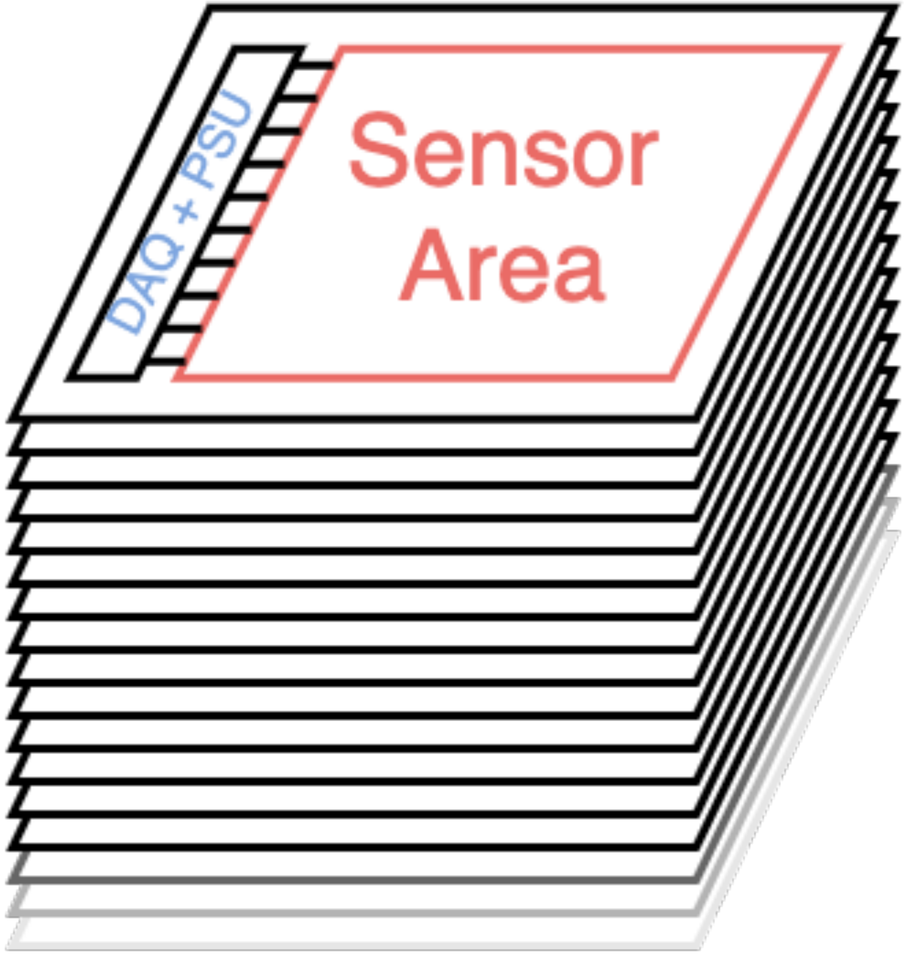

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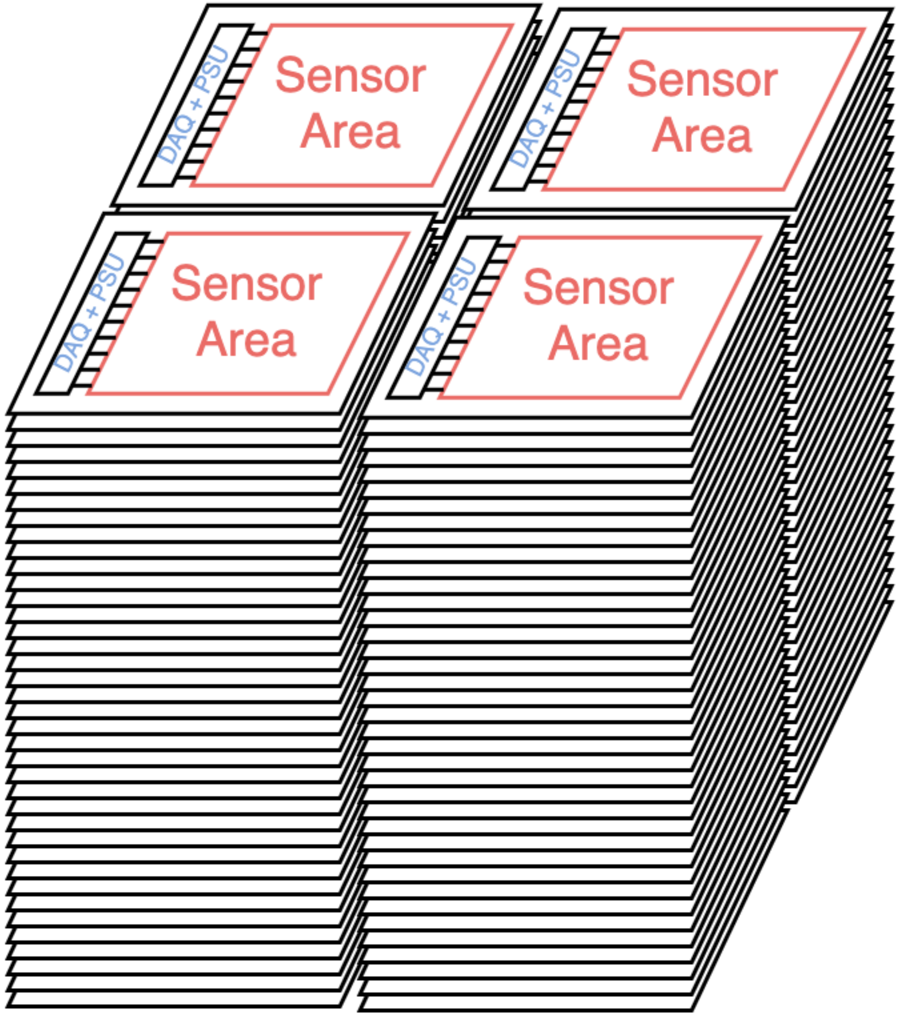
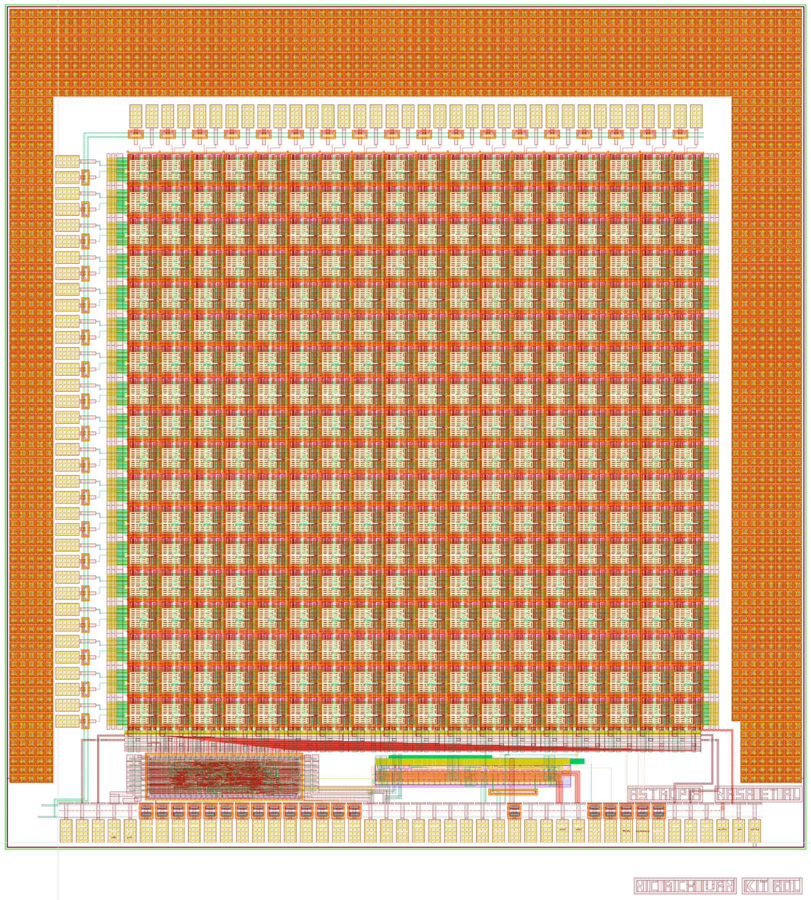


64000 sensors
25.6 m^2 area

AstroPix v1 Specs

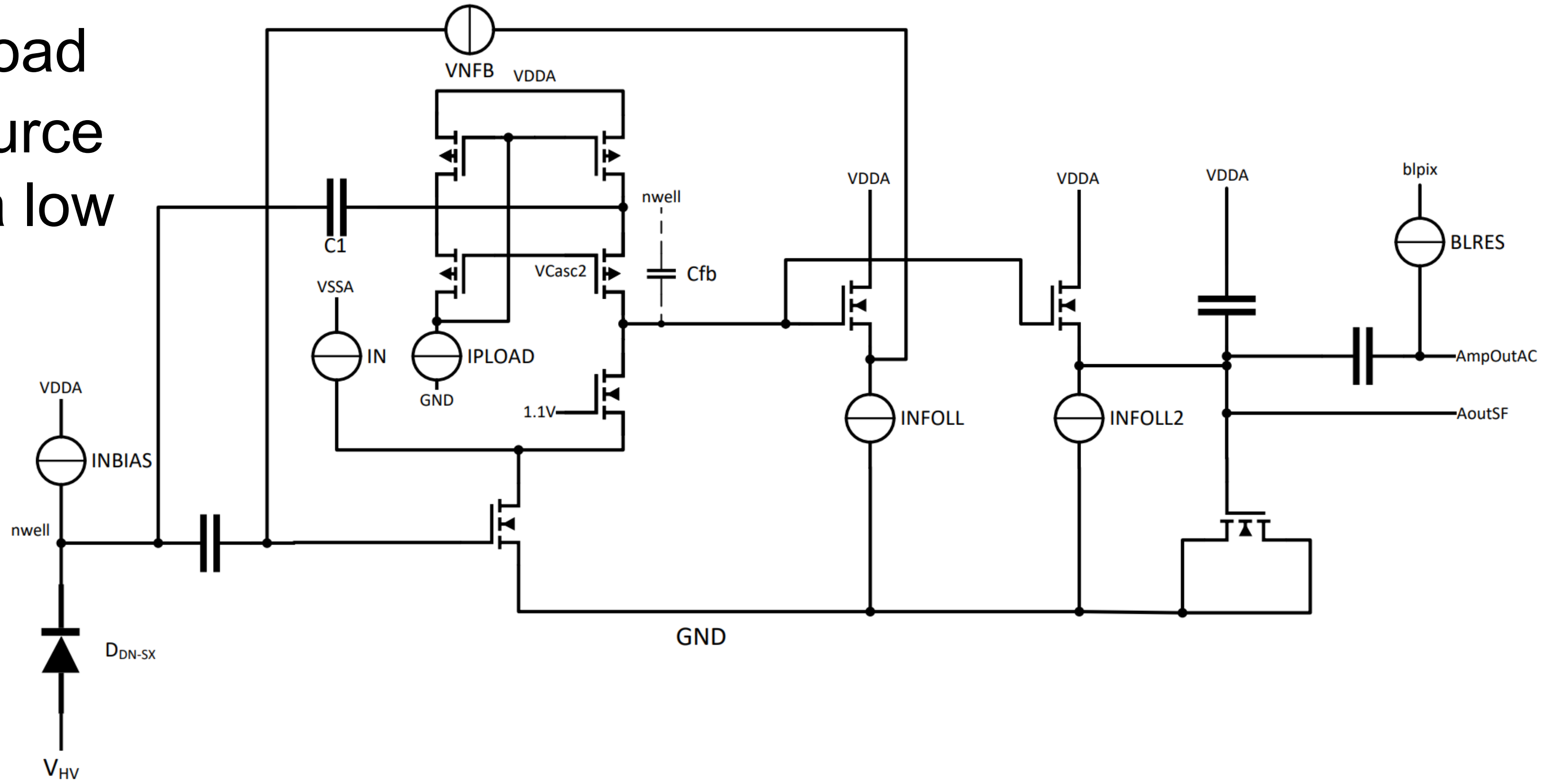
- Chip size: 5 mm x 5 mm
- Matrix: 18 x 18 pixels
- Pixel size/pitch: 175 µm
- DigitalTop
  - SPI Interface
  - 5 byte frame (10 byte per hit)
- Clocks (provided externally):
  - 200 MHz for ToT
  - No global timestamp

Submitted in April 2021
Received back in Dec 2021



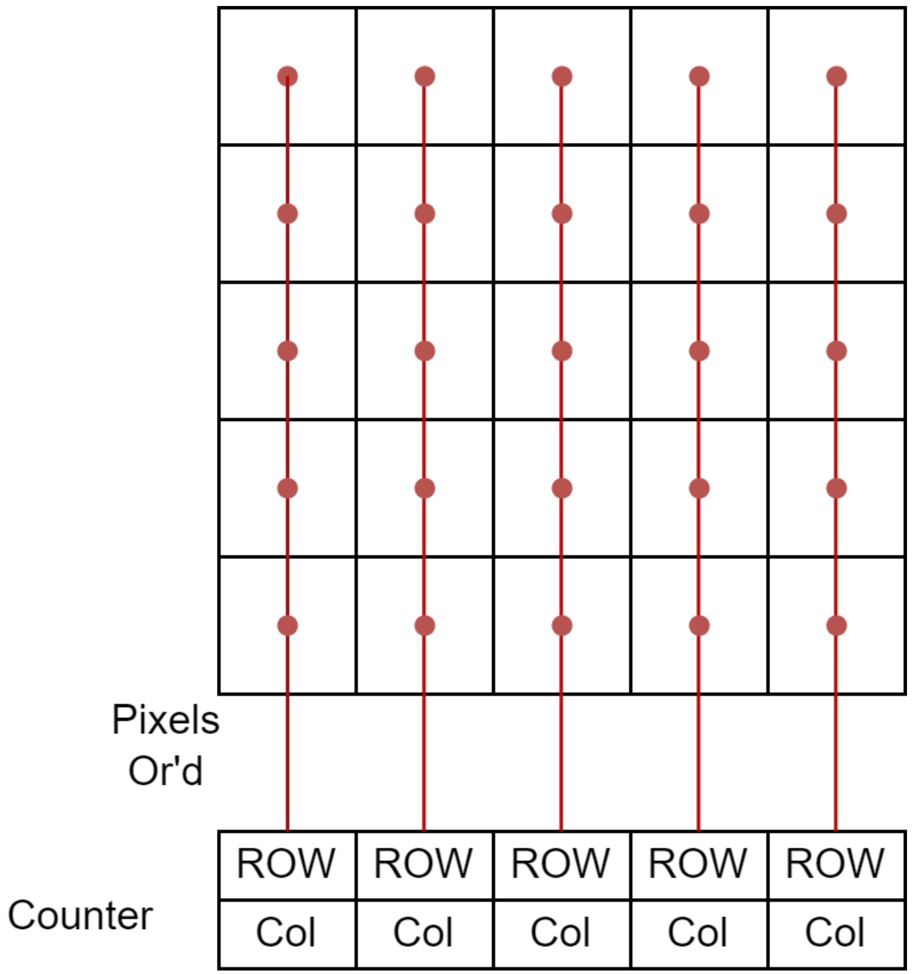
Introduction – AstroPix CSA

- Simplified amplifier schematic
- NMOS type cascoded amplifier with cascode load
- Output connected to source follower SF2 acting as a low pass filter
- High pass filtered to CMOS comparator



AstroPix Architecture

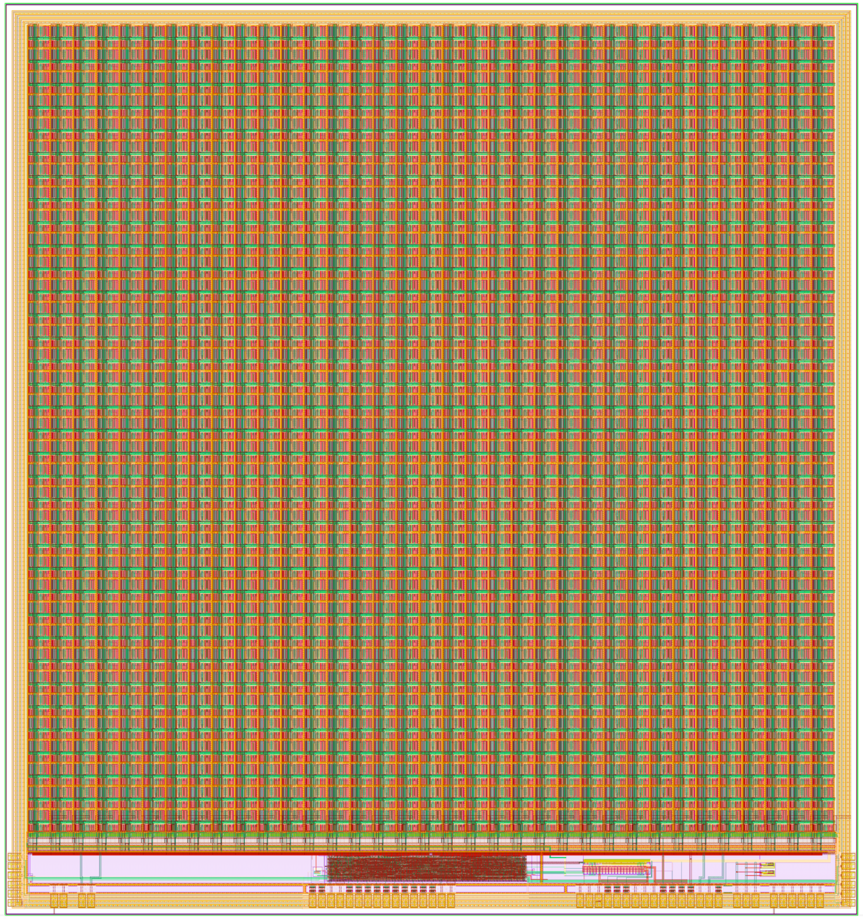
- OR'd Rows and Columns
- ToT measured by 200 MHz counter
- Advantages:
  - Low number of channels
- Disadvantages:
  - Identification problems with multiple hits in Row/Col
  - High bus capacitance → limited time resolution



AstroPix v2 Specs

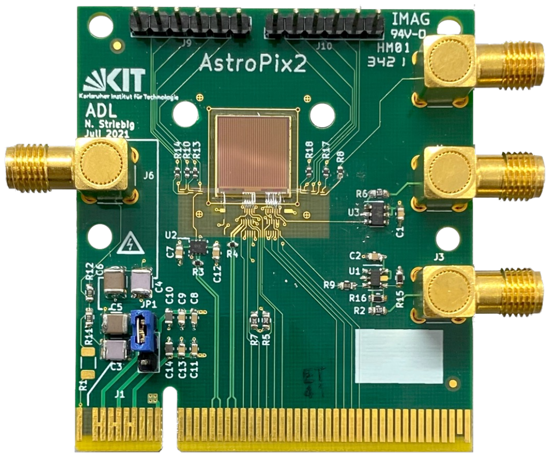
- Chip size: 1 cm x 1 cm
- Matrix: 35 x 35 pixels
- Pixel size/pitch: 250 µm
- DigitalTop
  - QSPI Interface with Daisy-Chaining
  - 5 byte frame (10 byte per hit)
- Clocks (provided externally):
  - 200 MHz for ToT
  - 2 MHz for Timestamp

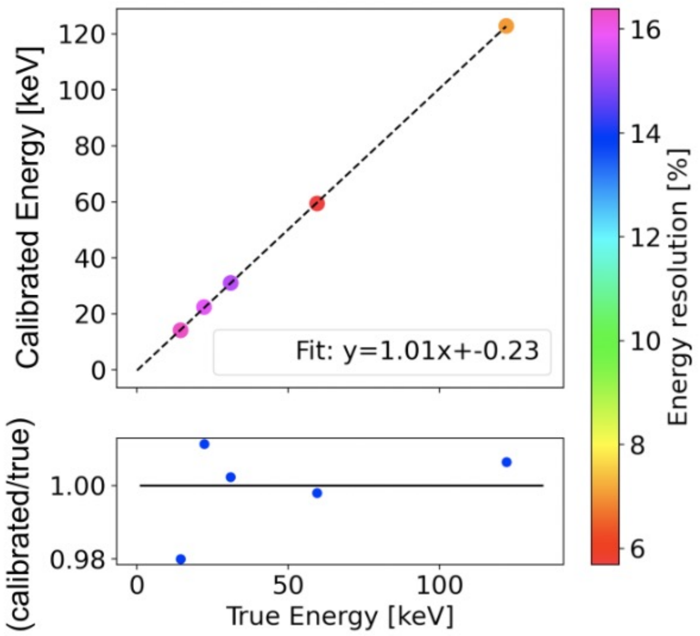
Submitted in April 2021
Received back in Dec 2021

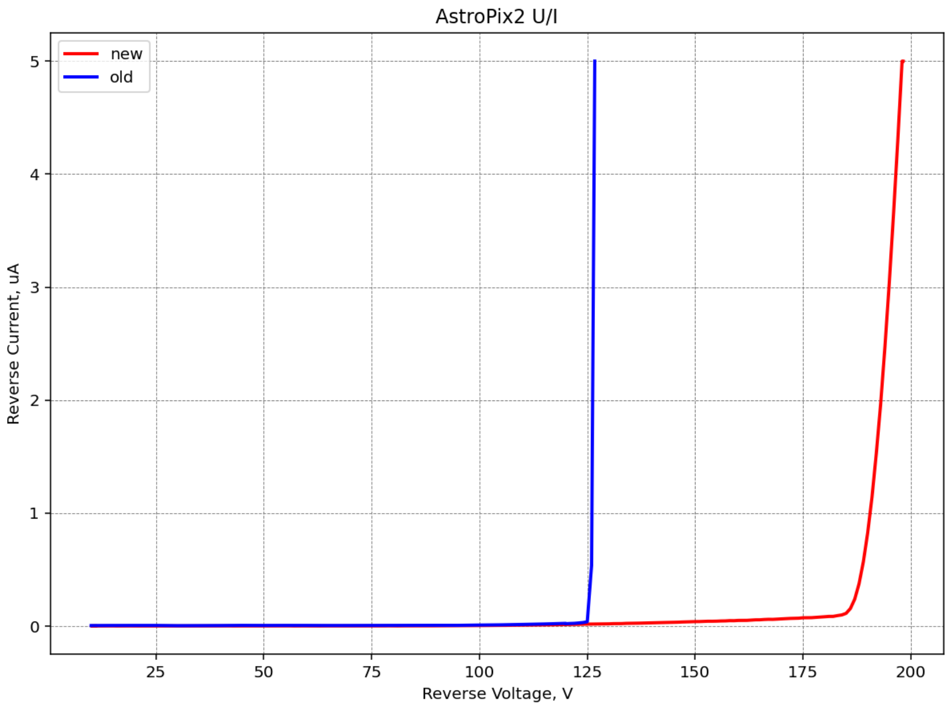


AstroPix v2 Results

- Fixed V1 problems
- Improved breakdown to 190 V
- QSPI daisy-chaining works
- SEU testing at Berkley 65 MeV cm2/mg [3]







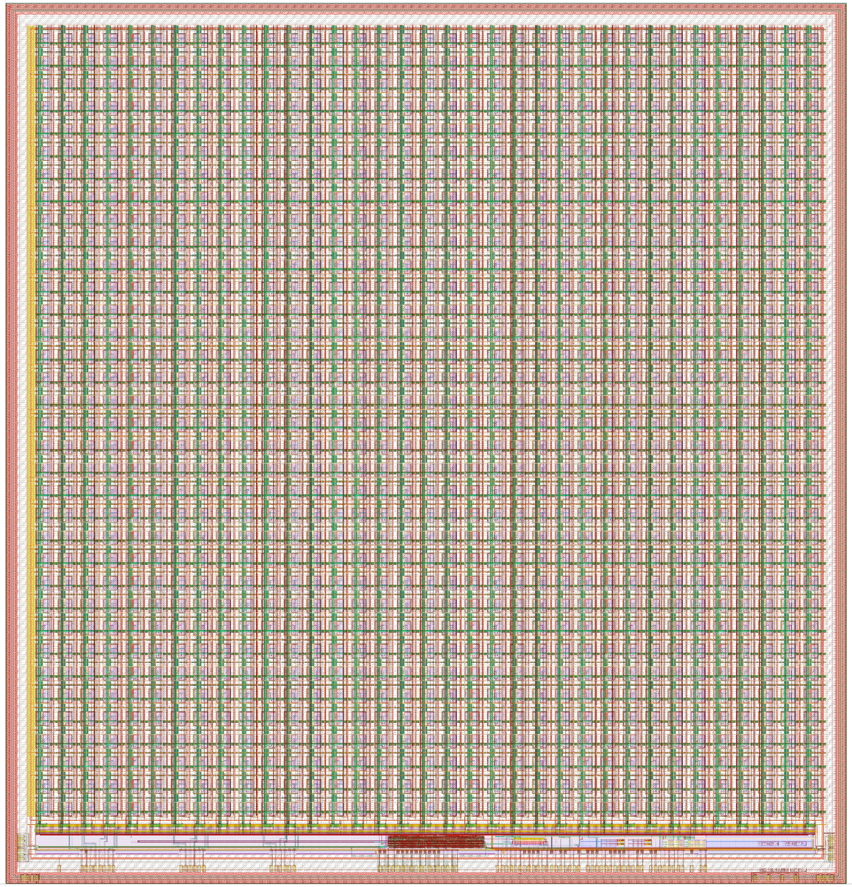
Amego-x Requirements

- **Power target:**
  Increase 250 µm pixel pitch (AstroPix v2) to 500 µm to reach 1.5 mW/cm^2 (ATLASpix3: 150 mW/cm^2)
- **Dynamic range:**
  20 – 700 keV with 5 keV resolution
- **SEU tolerance**

- Problems:
  - Large pixel size results in high noise
  - To absorb high energies → chip has to be fully depleted

AstroPix v3 Specs

- Chip size: 2 cm x 2 cm
- Matrix: 35 x 35 pixels
- Pixel pitch: 500 µm
- DigitalTop from v2
  - QSPI Interface
  - 5 byte frame (10 byte per hit)
- Clocks (provided externally):
  - 200 MHz for ToT
  - 2 MHz for Timestamp
- Integrated 10bit voltage DACs
- Integrated temperature sensors
- Integrated injection switch



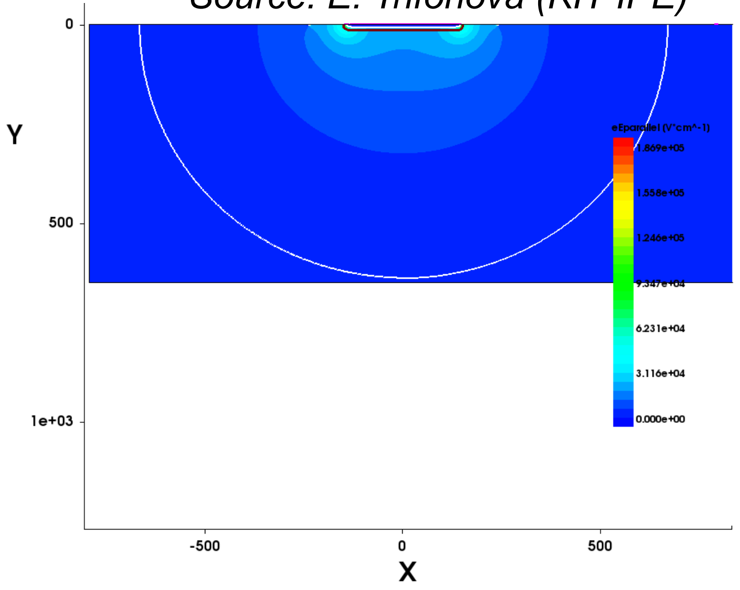
Submitted in July 2022
Received February 2023

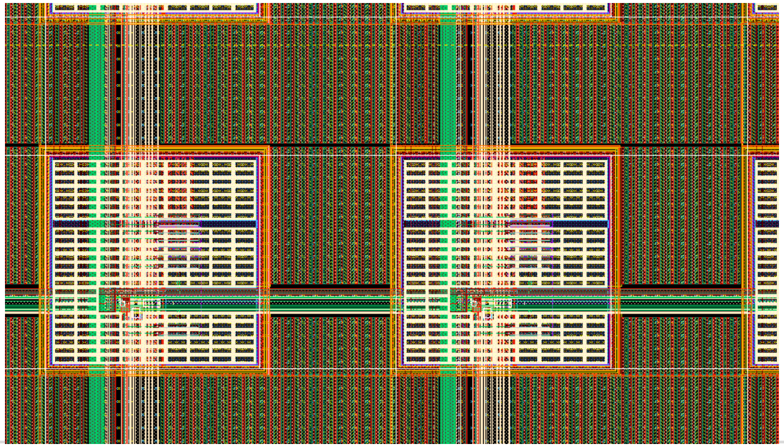
AstroPix v3 main improvements

- **Dynamic range:**
  - High resisitivity substrate 10kΩ-cm
  - New guardring design with 400V
  - TCAD simulation shows over 500um depletion thickness

- **Noise:**
  - Depletion region expands in spherical way
  - Sufficient to increase pixel spacing
  - No huge increase in capacitance
    → not that much additional noise

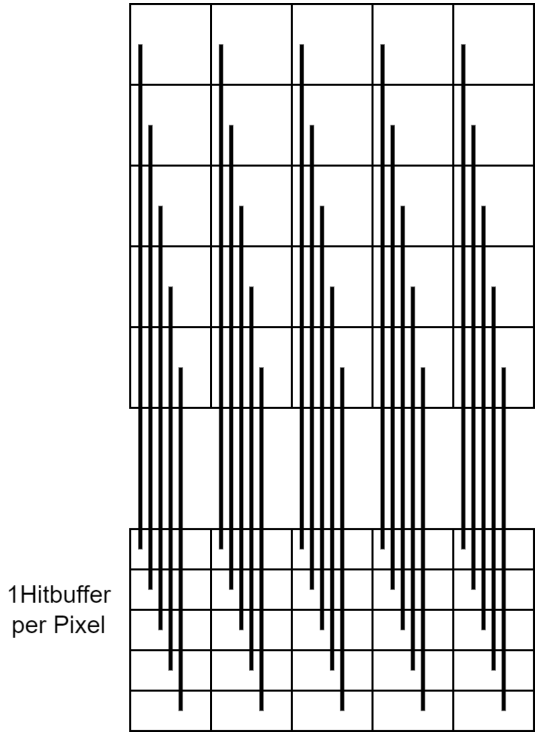
Source: E. Trifonova (KIT IPE)





Outlook on AstroPix v4

- ToT measurement will be performed with Flash TDC
  - No fast clocks
  - Low hit rate → low duty cycle → low power
  - Improved time resolution
- Going back to traditional per pixel readout
  - Problems with hit identification
  - Degraded time resolution



Summary

- AstroPix is a very low power and high dynamic range sensor
- Designed for daisy-chaining → simplifies tracker module design
- Ability to deplete thick sensors would enable new applications of HV-CMOS sensors
  - Detection of high energy photons
  - Direct energy measurement of charged particles

AstroPix Team

- KIT (ASIC design)
  - Ivan Peric, Richard Leys, Nicolas Striebig, Sigrid Scherl
- GSFC
  - Regina Caputo, Carolyn Kierans, Amanda Steinhebel, Henrike Fleischhack, Michela Negro, Dan Violette, Jeremy Perkins, John Mitchell, Jacob Smith, Autumn Bauman, Isabella Brewer, (engineers) Iker Liceaga Indart, Carl Kotecki, Dave Durachka + WFF
- ANL
  - Jessica Metcalfe, Manoj Jadhav, Ricardo Luz, Taylor Shin
- Hiroshima/Nagoya
  - Yasushi Fukazawa, Yusuke Suda, Hiroyasu Tajima

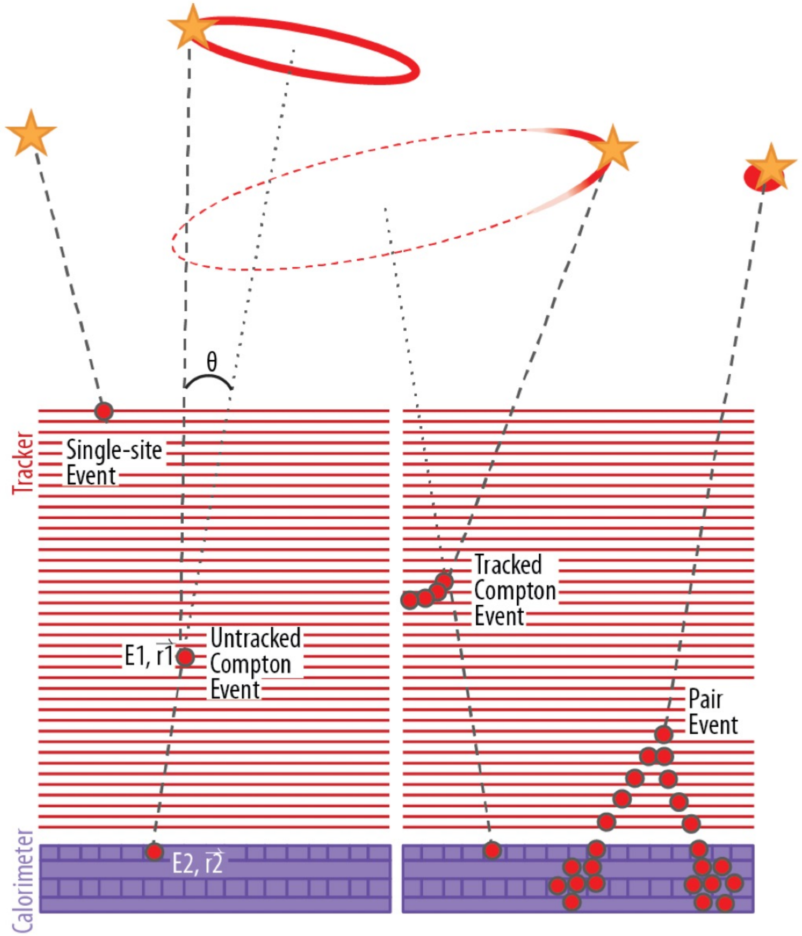
References

[1] R. Caputo et al. *All-sky Medium Energy Gamma-ray Observatory eXplorer mission concept.* Journal of Astronomical Telescopes, Instruments, and Systems 8(4), 2022.

[2] A. Steinhebel et al. *AstroPix: CMOS pixels in space*. Proceedings for PIXEL2022, 2022.

Introduction - Compton camera

- Primary photon scattering an electron
- Energy of photon decreases
  and angle of movement changes
  → transferred to recoil electron
- Tracker records position and energy deposit
  of recoil electron through it
- Calorimeter measures position
  and energy of photon
- Energies and locations of interaction
  used to estimate direction of primary photon



Schematic of Compton and pair events inside tracker. [1]