Karlsruhe Institute of Technology

KIT ASIC and Detector Laboratory

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

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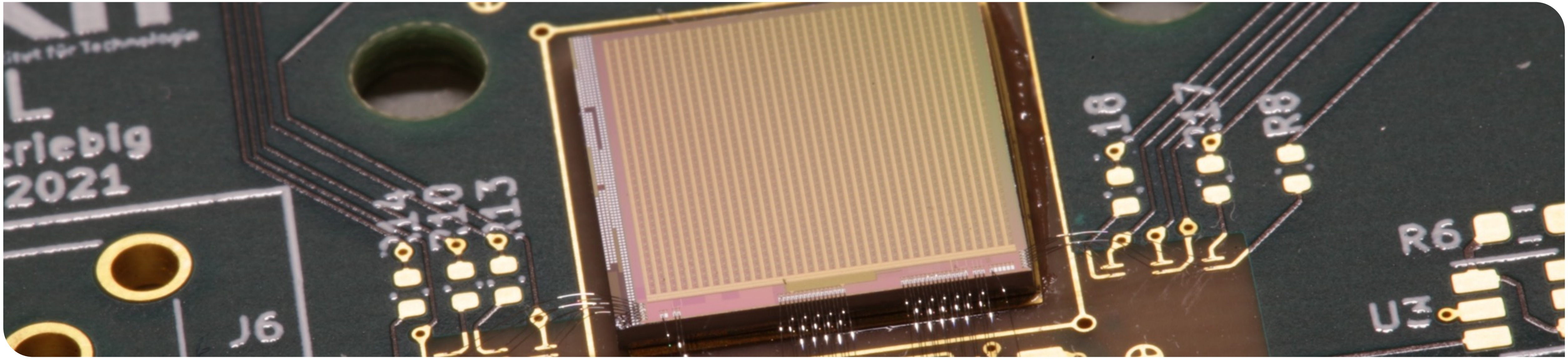
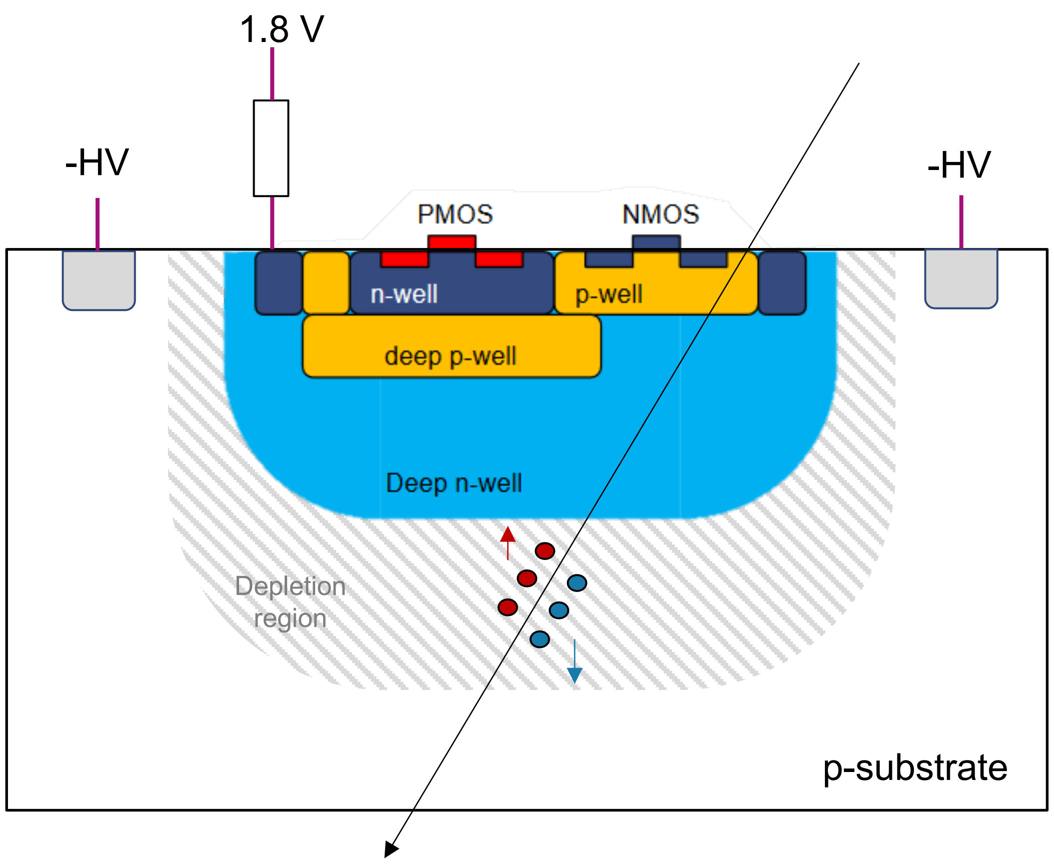


Introduction – HV-CMOS

- 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)**

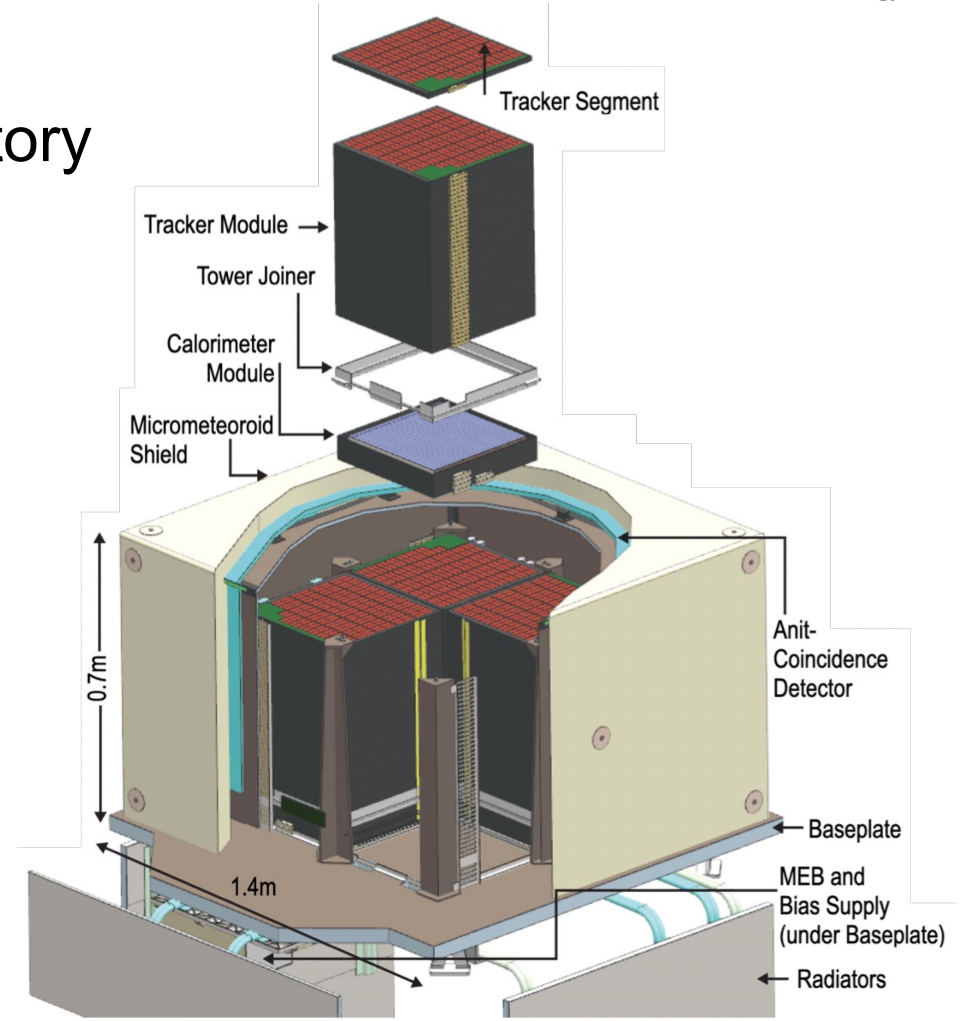


Introduction – Why HV-CMOS?

- Low cost:
  - Standard CMOS process
  - Single chip, 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

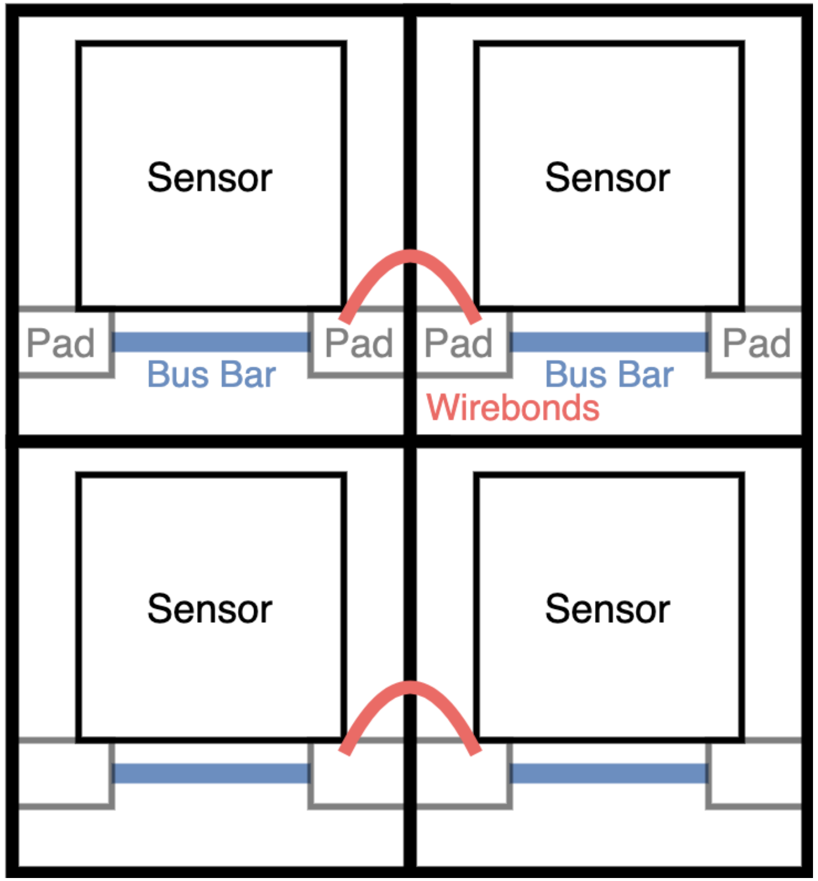
- NASA MIDEX concept for space based observatory
- Wide-field survey telescope designed to discover and characterize gamma-ray emission
- 3 year mission
- Set to take off in 2028
- HV-CMOS sensor for Compton camera



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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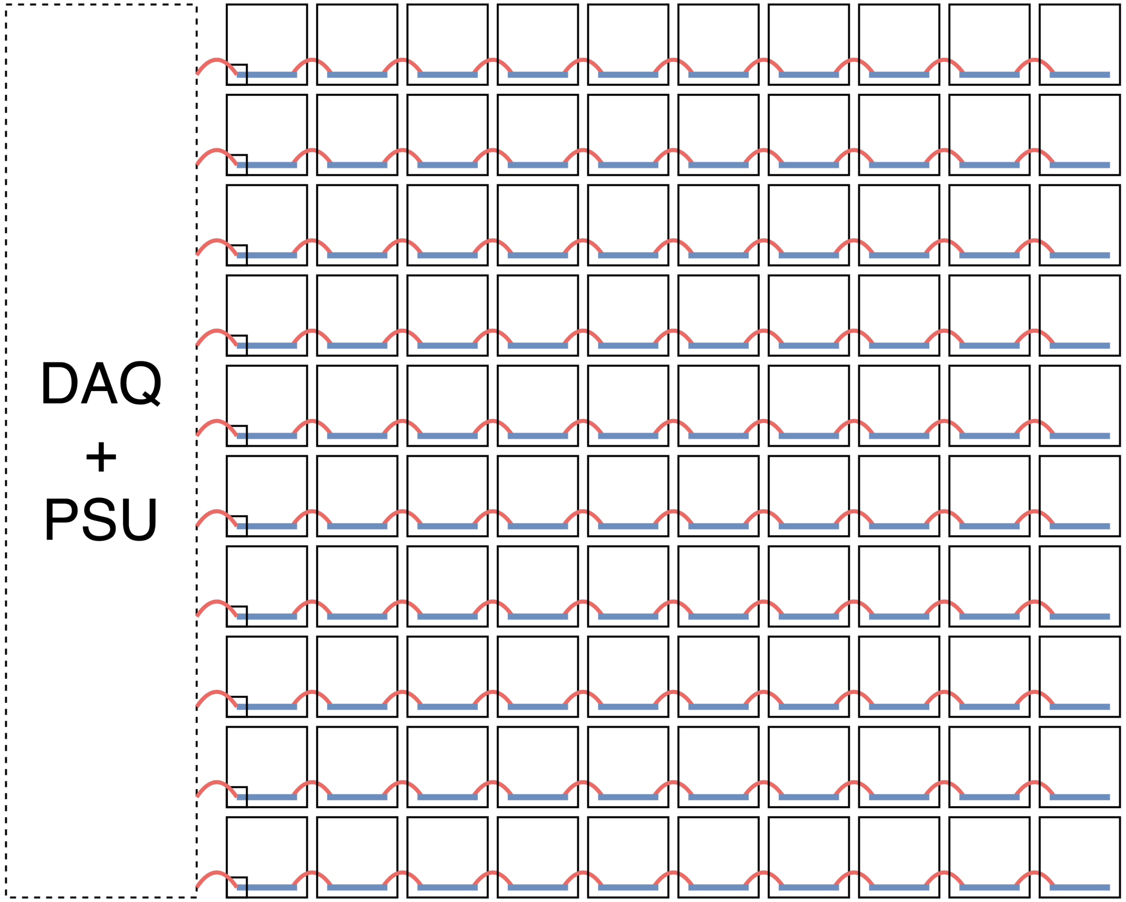

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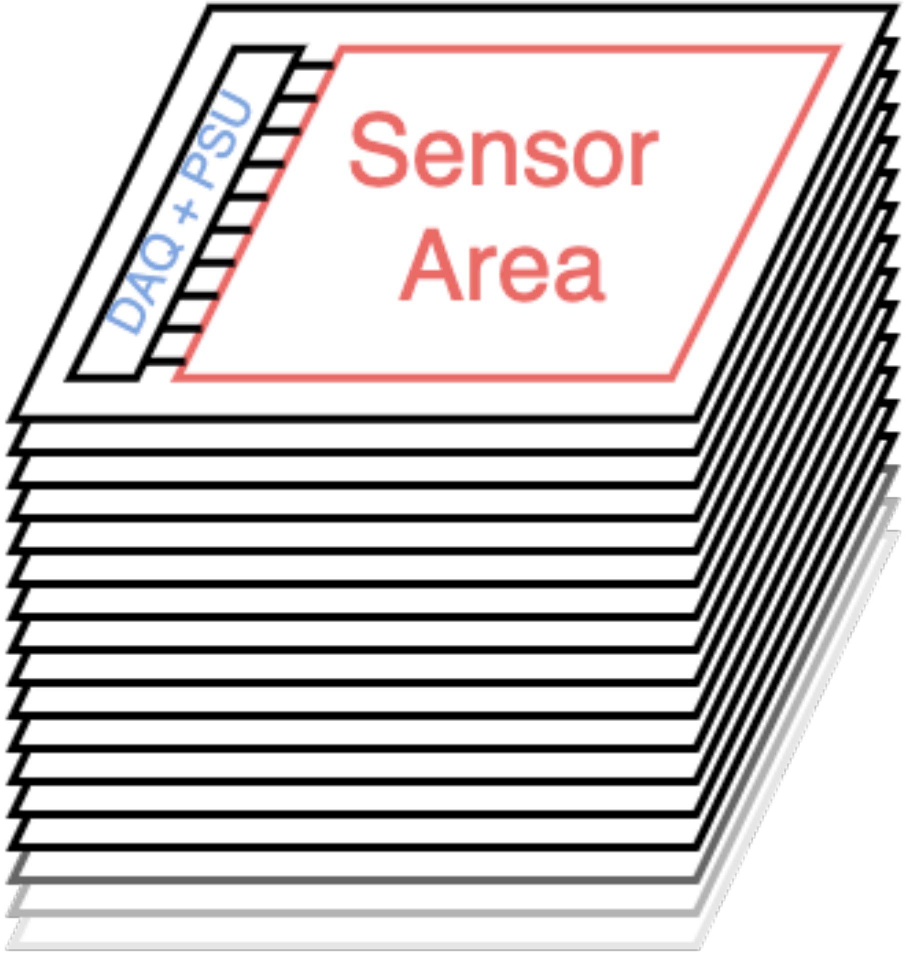

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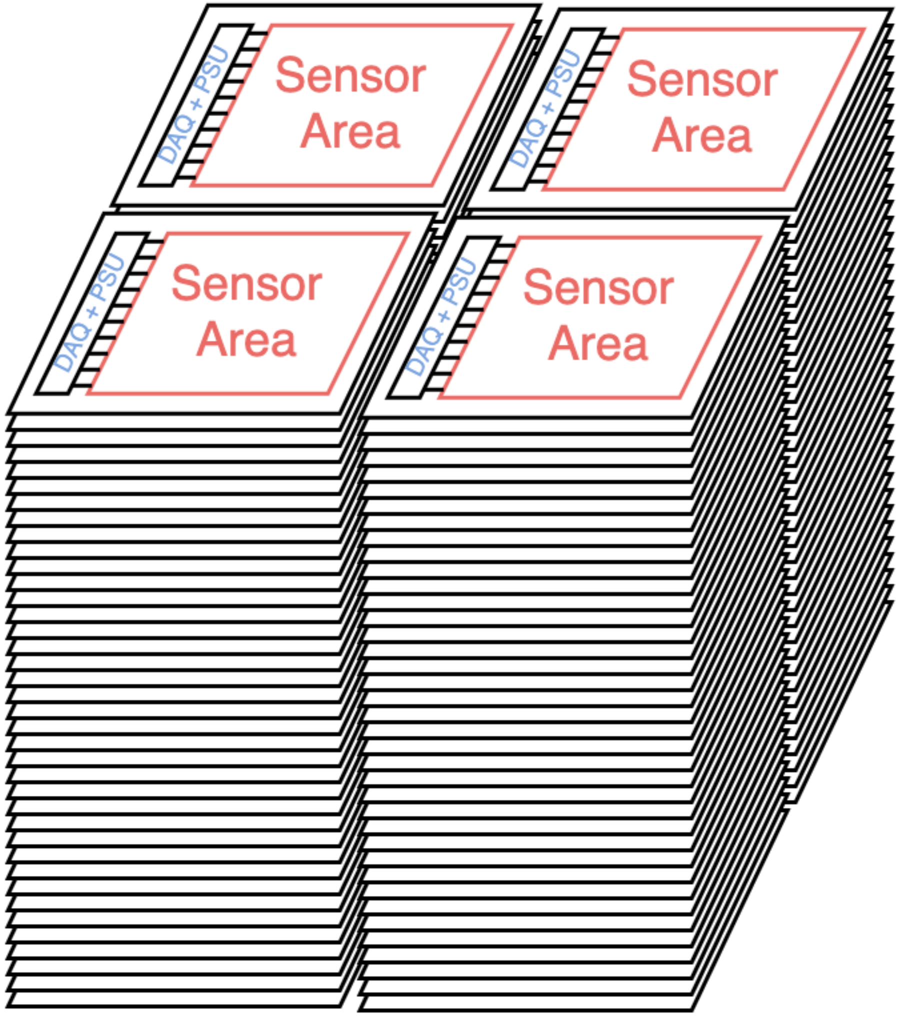


64000 sensors
25.6 m^2 area

Amego-x Requirements

- **Power target:**
  Increase 250 µm pixel pitch (AstroPix v2) to 500 µm to reach 1.5 mW/cm^2
  (ATLASpix3: 150-250 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 → substrate has to be thick and fully depleted

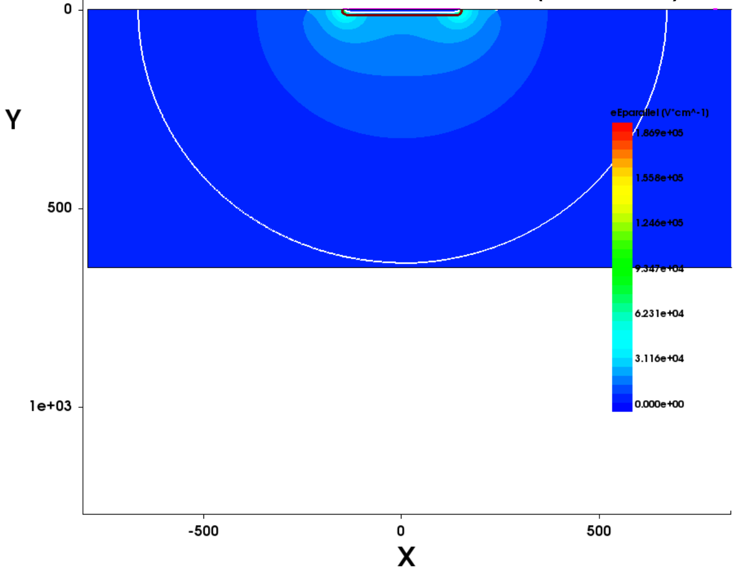
How to satisfy these requirements?

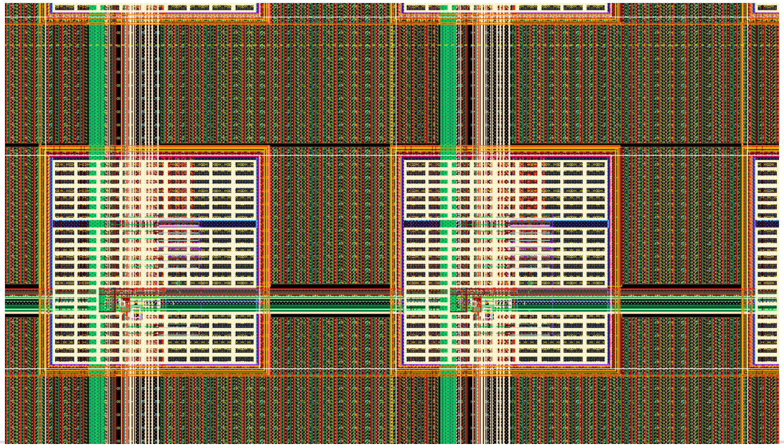
- **Dynamic range:**
  - High resisitivity substrate 10kΩ-cm
  - New guardring design with 400V
  - TCAD simulation shows over 500um depletion thickness

- **Noise:**
  - Depletion region expands in spherical way
  - Sufficient to increase pixel spacing
  - No increase in capacitance -> no additional noise

- **SEU:**
  - Digital circuitry especially FSMs will be triplicated to make readout logic more robust against SEU
  - Existing tool tmrg (tmrg.web.cern.ch)

Source: E. Trifonova (KIT IPE)



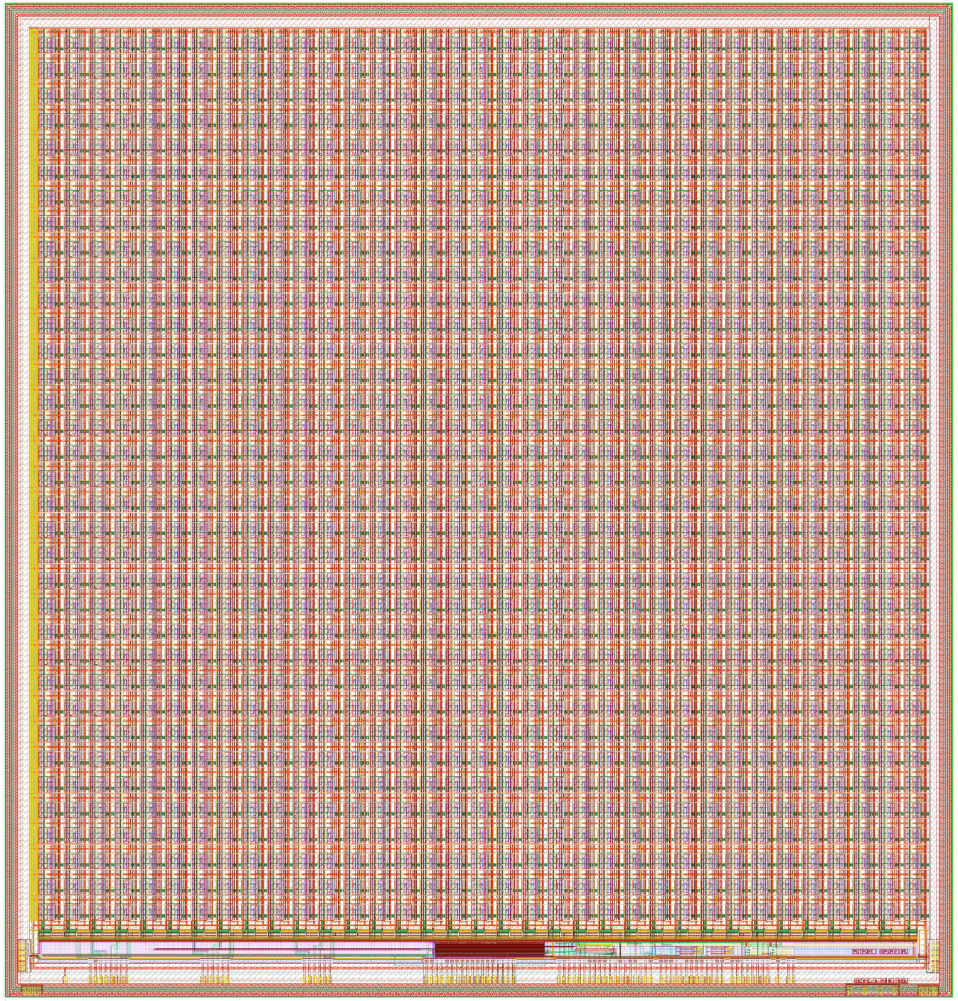


AstroPix v3 Specs

- Chip size: 2 cm x 2 cm
- Matrix: 35 x 35 pixel
- 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

Should arrive this week ☺



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

- What's next:
  - New iteration v4 is currently developed with new readout logic, giving better timing and lower power consumption
  - V3 characterisation

References

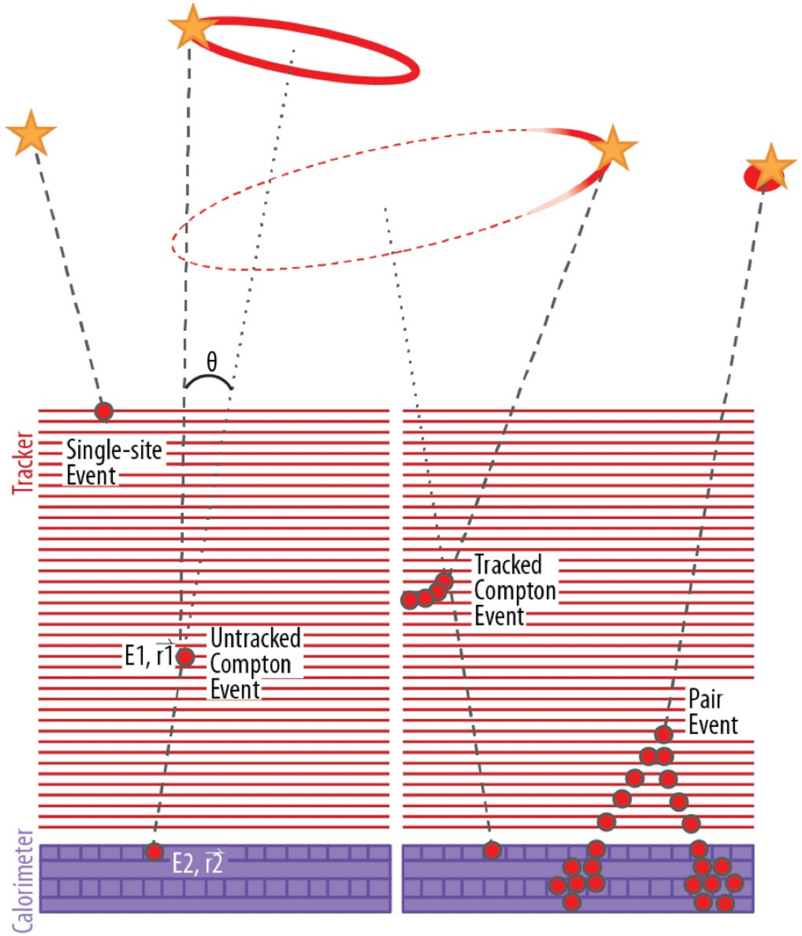
[1] Regina Caputo et al. *The All-sky Medium Energy Gamma-ray Observatory eXplorer (AMEGO-X) Mission Concept.* (Submitted in 2022 to Journal of Astronomical Telescopes, Instruments, and Systems)

[2] H. Augustin et al. *The MuPix sensor for the Mu3e experiment.* Nucl. Instrum. Meth. A, 979:164441, 2020.

Backup

Introduction - Compton camera

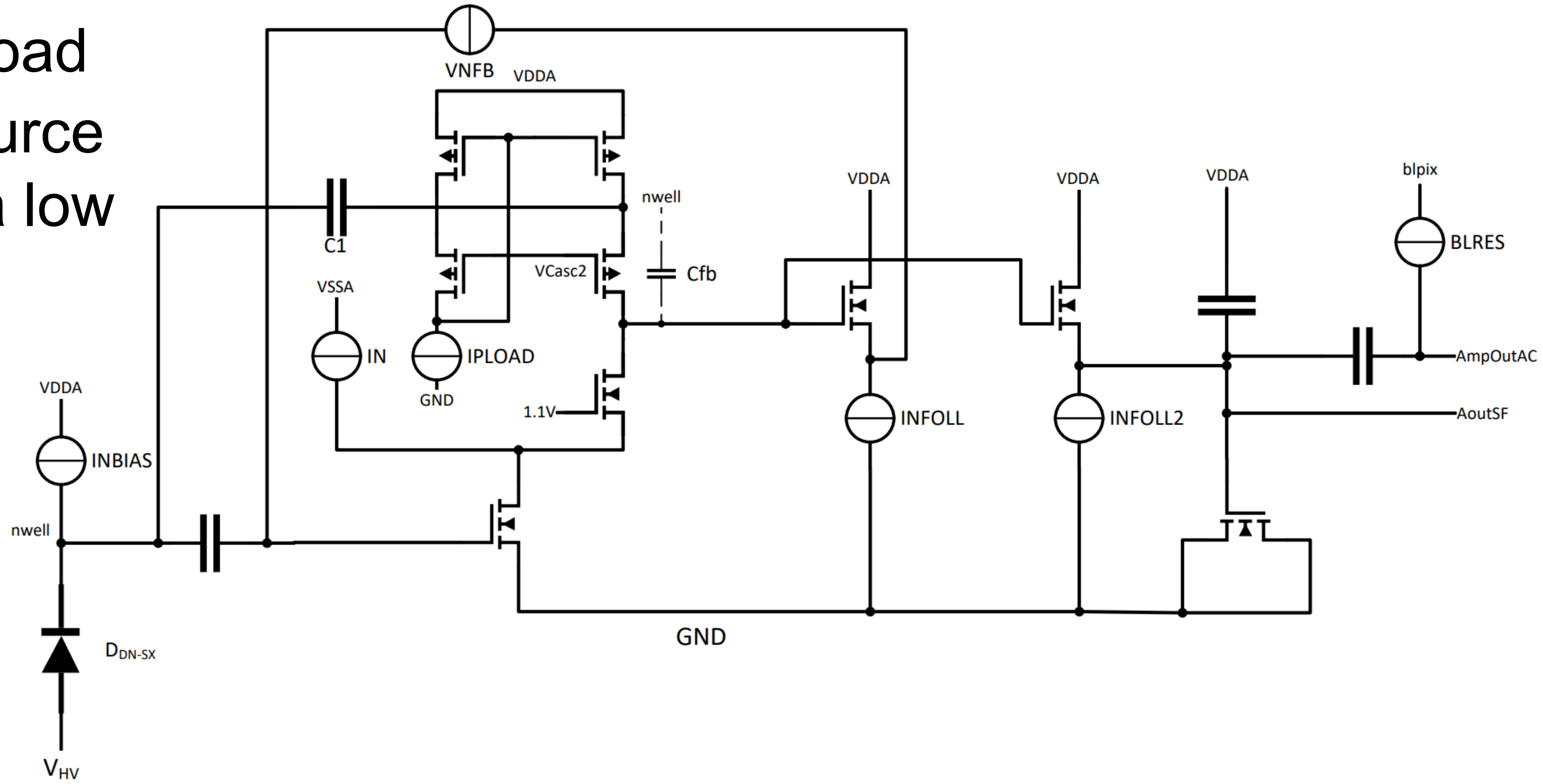
- Primary photon scattering an electron
- Energy of photon decreases
  and angle of movement changes
  → transferred to recoil electron
- Tracker records position and energy deposit of recoil electron through it
- Calorimeter measures position and energy of photon
- Energies and locations of interaction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



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

Introduction – AstroPix CSA

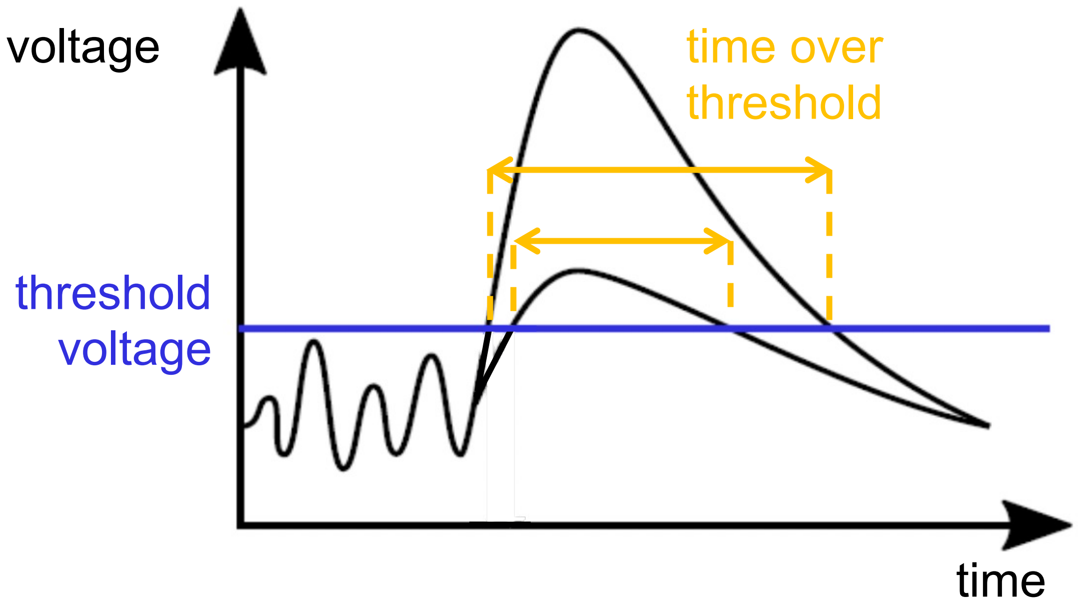
- Simplified amplifier schematic
- NMOS type cascoded amplifier with cascode load
- Output connected to source follower SF2 acting as a low pass filter
- AC coupled to CMOS comparator input



How to measure energy deposit of recoil electron?

- Amplifier output signal proportional to collected charge
- Output amplitude saturates at certain level → peak amplitude not usable to determine energy over large dynamic range
- ToT still non-linearly scales with charge

- Measured with 12bit @ 200 MHz counter
- Expected ToT between 500 ns and 20 µs



Schematic description of time over threshold. Adapted from [2].

Introduction – CSA

- Voltage over feedback capacitance (Inverting amplifier $V_{out} = -AV_{in}$)

$$V_{fb} = V_{in} - V_{out} = V_{in} - (-V_{in} \cdot A) = V_{in}(1 + A)$$

- Charge on Q_fb

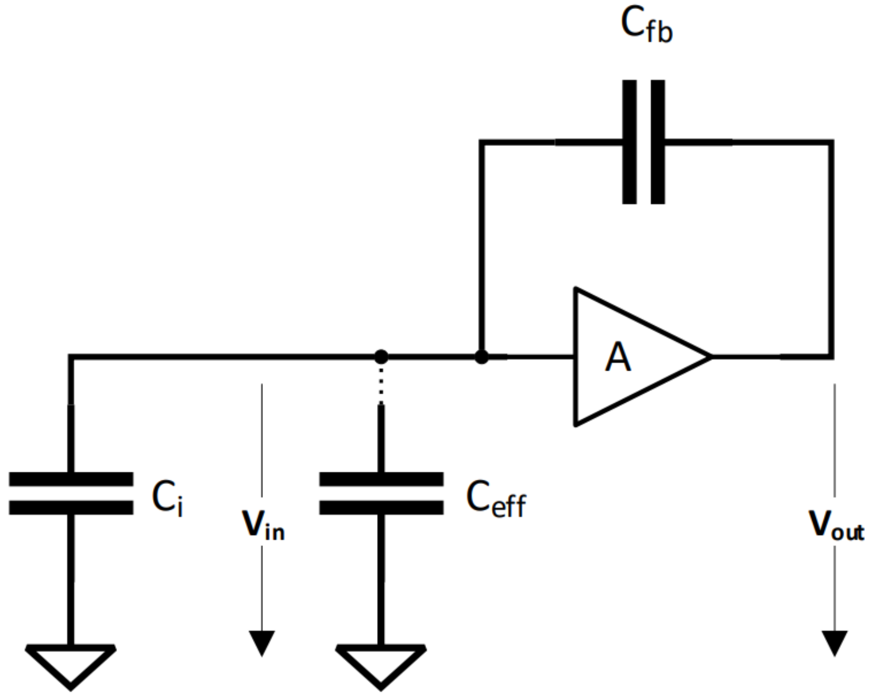
$$Q_{fb} = C_{fb}V_{fb} = C_{fb}V_{in}(1 + A) = C_{\text{eff}}V_{in}$$

- Looking into amplifier the detector sees an effective capacitace C_fb(A+1)
- Input charge is distributed between capacitances

$$V_{in} = \frac{Q_{in}}{C_i + C_{\text{eff}}} = \frac{Q_{in}}{C_i + (1 + A)C_{fb}}$$

- Output voltage (If A >>1 and A Cfb >> Ci)

$$V_{out} = -\frac{Q_{in}A}{C_i + (1 + A)C_{fb}} = -\frac{Q_{in}}{C_{fb}} \frac{1}{\frac{C_i}{AC_{fb}} + \frac{1}{A} + 1}$$

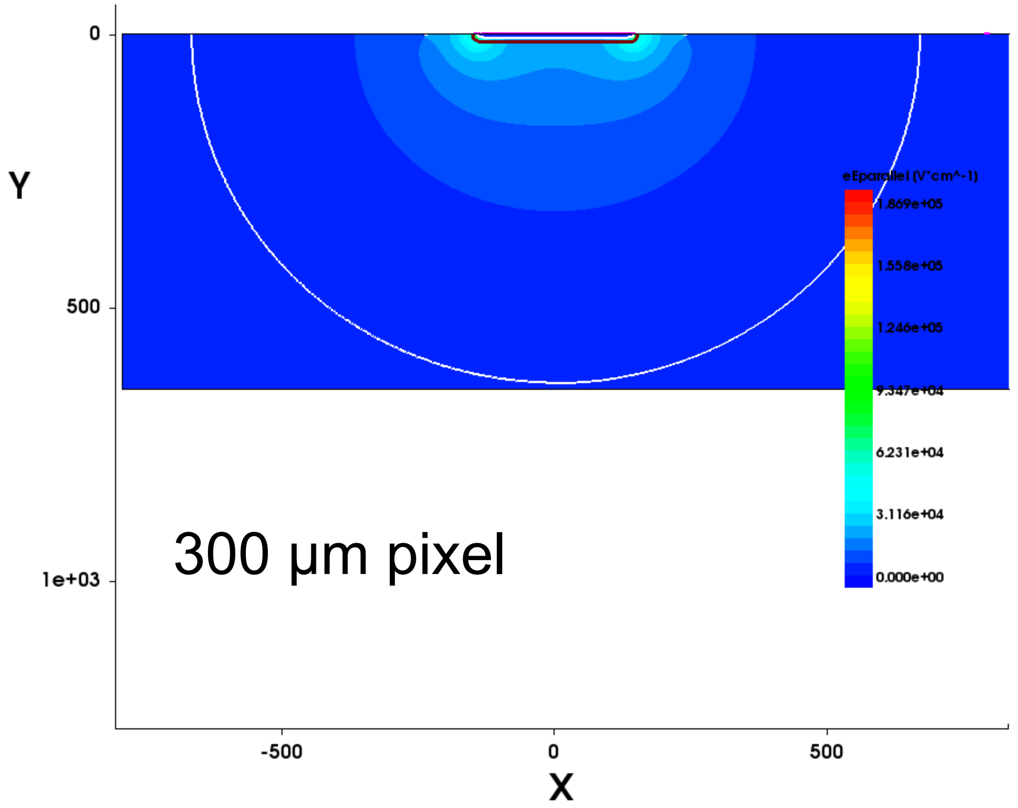


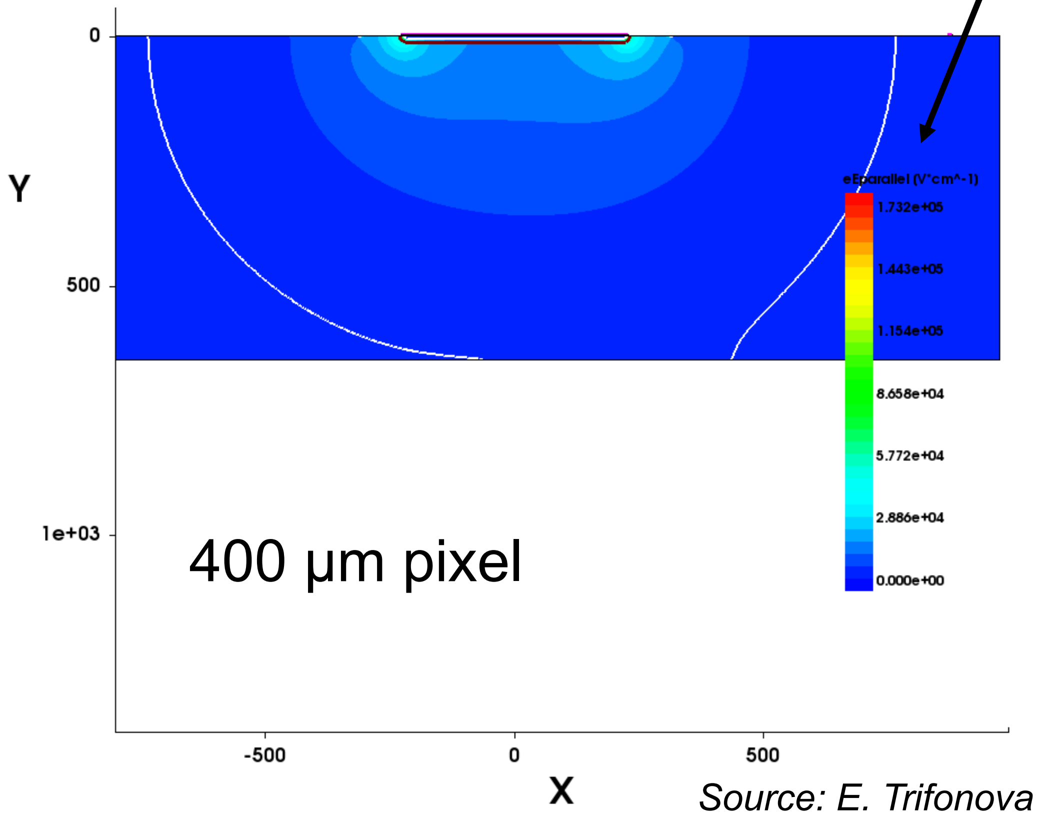
$$V_{out} = -\frac{Q_{in}}{C_{fb}}$$

TCAD Simulations

- 500 µm pitch, 300 µm pixel size, HiRes 10 kOhm-cm substrate
- **New Guardring design** with breakdown improved to **~400 V**

Scale from 0 to $1.869 \times 10^5\ \mathrm{V\ cm^{-1}}$





Source: E. Trifonova (KIT IPE)

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 → quadruple well
- Readout logic located on the bottom of chip