Monolithic Active Pixel Sensors

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Outline

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Monolithic Active Pixel Sensors on CMOS technologies

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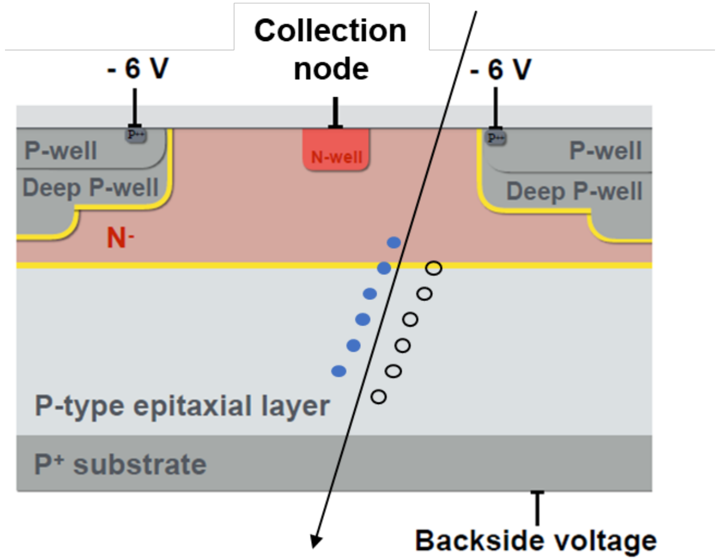
MAPS

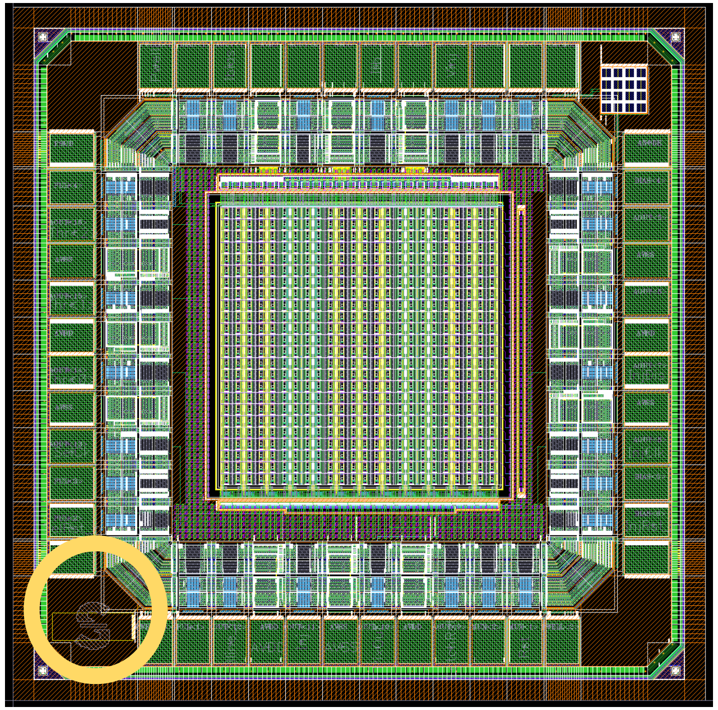
Monolithic Active Pixel Sensors (MAPS) for high precision tracker and high granularity calorimetry

- Monolithic technologies have the potential for providing higher granularity, thinner, intelligent detectors at lower overall cost.
- Significantly lower material budget: sensors and readout electronics are integrated on the same chip
  - Eliminate the need for bump bonding : thinned to less than 100μm
  - Smaller pixel size, not limited by bump bonding
  - Lower costs : implemented in standard commercial CMOS processes



Existing efforts

- The CERN WP1.2 collaboration is investigating the possibility of realizing wafer-scale MAPS devices on the novel TowerSemi 65 nm CMOS imaging process.
- With respect to the 180 nm process:
    - Increased density for circuits
    - Higher spatial resolution
    - Better timing performance
    - Lower power consumption



Layout of MAPS SLAC prototype for WP1.2 shared submission

Outline

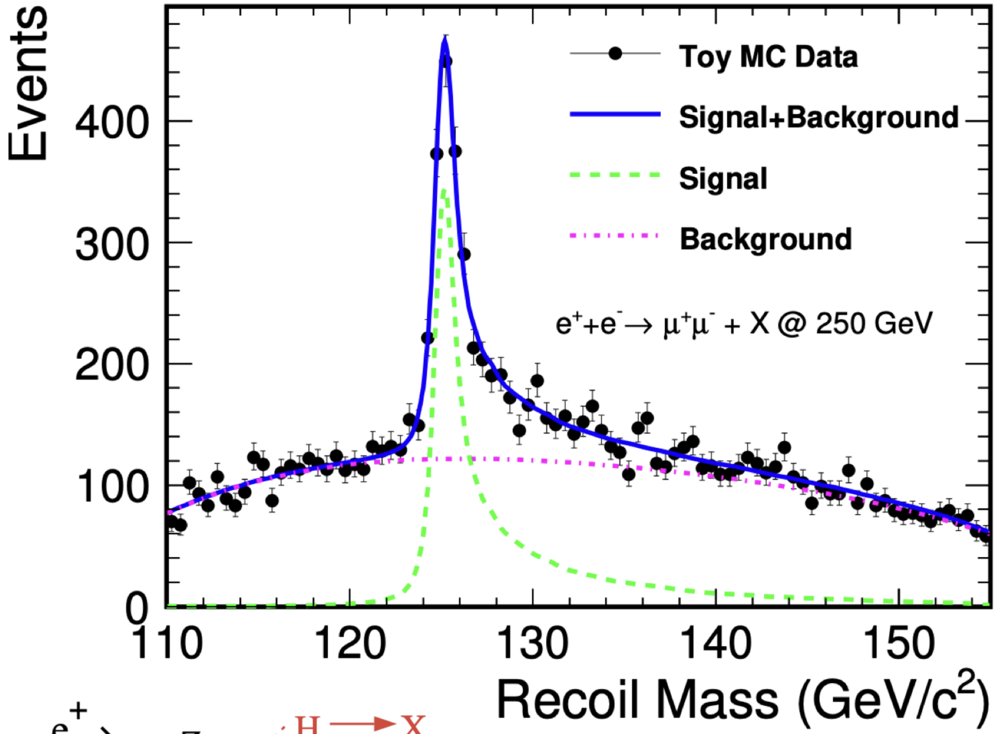
Next MAPS developments will target a diverse set of goals and applications: speed, resolution, scalability

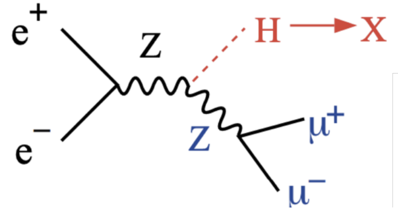
- MAPS with characteristics suitable for trackers and electromagnetic calorimeters (ECal) at future e^+e^- colliders.
    - large areas of silicon sensors, several hundred m^2 , for low mass trackers and sampling calorimetry
- HighPerformance Tracking (HPT) MAPS for the Electron-Ion Collider (EIC) at BNL
    - synergistic with the ALICE ITS3 developments as the performance requirements are similar
- Space-born applications for MeV γ-ray experiments with MAPS based trackers (AstroPix).

Physics Requirements for detectors at e+e-

Need new generation of ultra low mass vertex detectors with dedicated sensor designs

- ZH process: Higgs recoil reconstructed from Z →$\mu\mu$
  - Drives requirement on charged track momentum and jet resolutions
  - Sets need for high field magnets and high precision / low mass trackers
  - Bunch time structure allows high precision trackers with very low X0 at linear lepton colliders
- Particle Flow reconstruction
- Higgs → bb/cc decays: Flavor tagging & quark charge tagging at unprecedented level
  - Drives requirement on charged track impact parameter resolution → low mass trackers near IP
  - <0.3% X0 per layer (ideally 0.1% X0) for vertex detector
  - Sensors will have to be less than 75 μm thick with at least 5 μm hit resolution (17-25μm pitch)





MAPS at future e^+e^-

The detectors at future e^+e^- machines will need unprecedented precision on Higgs & SM physics measurements.

- High precision and low mass trackers and highly granular calorimeters, will be critical
    - O(ns) timing capabilities are key to suppress beam induced backgrounds

Monolithic Active Pixel Sensors (MAPS), which combine the sensing element and readout electronics on the same device, are a key technology to further reduce dead material

State-of-the-art MAPS can achieve ~*μ*sec timing resolution - in the future we are planning to achieve simultaneously:

- **improved timing resolution by an order of magnitude beyond the state-of-the art**
- **low power consumption compatible with large area and low material budget constraints**

Fast MAPS: challenges

Achieving ns timing while maintaining low-power consumption requires a dedicated strategy

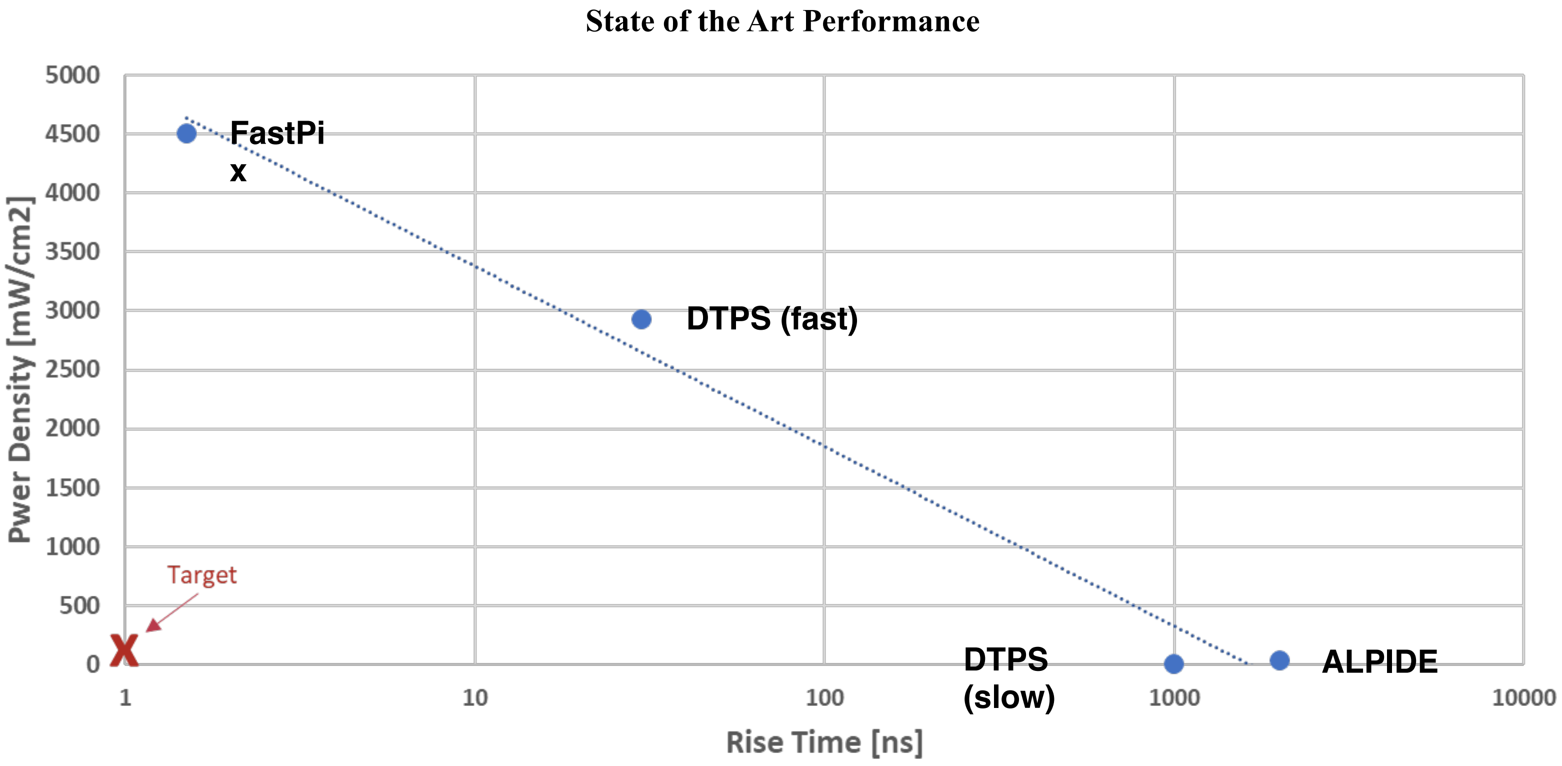
- One major design challenge for MAPS is achieving fast timing while maintaining low-power
  - The average power consumption must be minimized to permit gas cooling, as well as to minimize the voltage drop over long metal lines.
- Three main strategies will be investigated :
  - **Power pulsing scheme**: the analog front-end circuitry will be powered off during the dead-time between different bunch trains, thus reducing the average power consumption.
    - With low duty cycle machines (ILC, C^3) this technique enables a power reduction by more than two orders of magnitude - leveraging the experience with KPiX
  - **Front-end architecture timed with the accelerator**
    - the noise and timing performance of the circuitry can be optimized while maintaining low-power consumption - leveraging ASICs developed for LCLS
  - **Sparse asynchronous readout**

State-of-the-art & our target

Initial specifications for fast MAPS

Parameter	Value
Min. Threshold	140 e^-
Spatial resolution	7 μm
Pixel size	25 x 100 μm^2
Chip size	10 x 10 cm^2
Chip thickness	300 μm
Timing resolution (pixel)	~ns
Total Ionizing Dose	100 kRads
Hit density / train	1000 hits / cm^2
Hits spatial distribution	Clusters
Power density	20 mW / cm^2

Table 1: Target specifications for 65 nm prototype.



AISC	Technology	Rise time [ns]	Power density [mW/cm2]
FastPix	TJ 180	1.5	4500
DTPS(Fast)	TJ 65	30	2933
DTPS(Slow)	TJ 65	1000	6.4
ALPIDE	TJ 180	2000	40

All chips developed by CERN, all in prototype phase except ALPIDE

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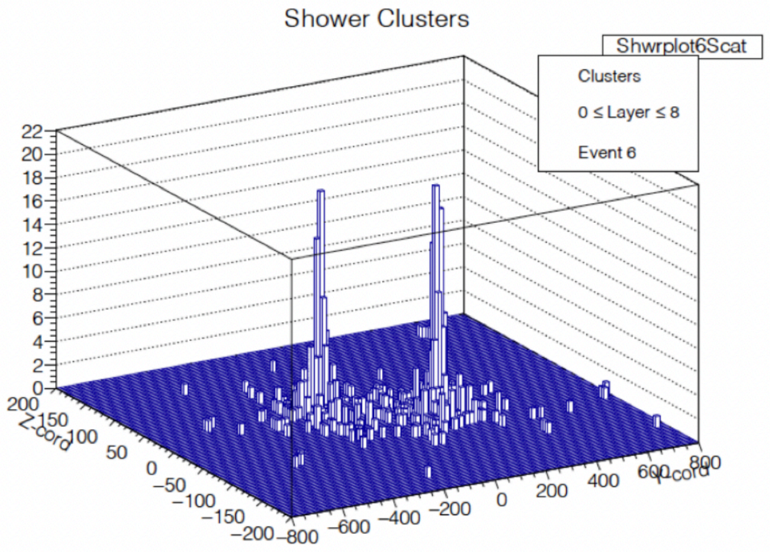
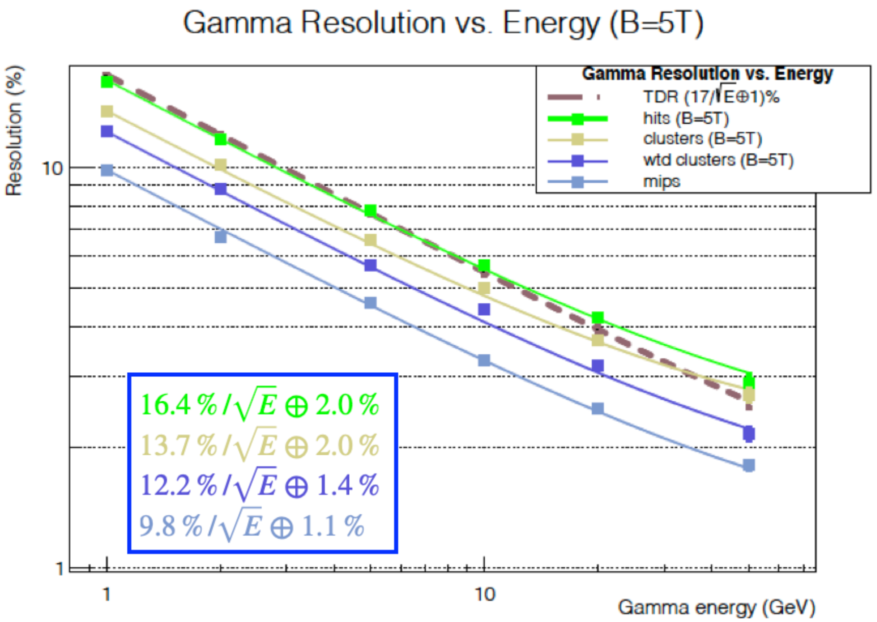
MAPS for ECal

- SiD detector configuration with 25x100 μm^2 pixel in the calorimeter at ILC
  - The fine granularity of pixels provides excellent separation
- The fine granularity allows for identification of two showers down to the mm scale of separation
  - the energy resolution of each of the showers does not degrade significantly for the mm scale of shower separation
- The 5T magnetic field degrades the resolution by a few per cent due to the impact on the lower energy electrons and positrons in a shower
- Future planned studies include the reconstruction of showers and π^0 within jets, and their impact on jet energy resolution





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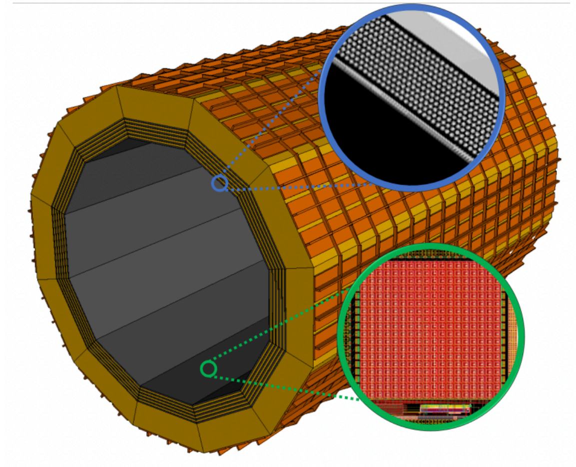
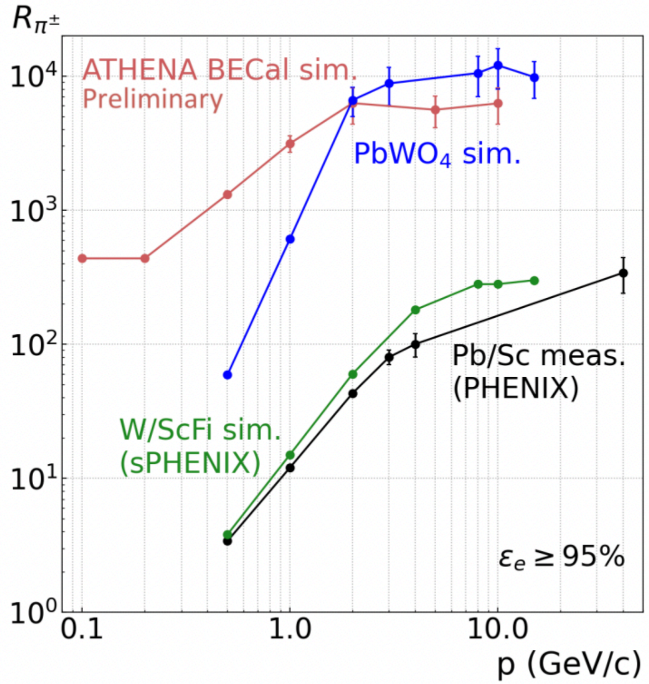
MAPS for EIC

- The EIC aims at resolving the 3D partonic structure of nucleons and nuclei, to address the origin of the nucleon mass and spin, as well as the properties of a dense system of gluons
- MAPS fulfill the requirements of compactness, high segmentation and very low material budget, which is critical to achieve the required momentum resolution.
- The EIC **vertex layers** follow the ALICE ITS3 development of large-area, wafer-scale, stitched sensors that are thinned to less than 50μm, to allow bending them around the beam pipe
  - The current ALICE ITS (ITS2) features vertex layers with a pixel pitch of approximately 30 μm that dissipates 40 mW/cm^2 and 0.35% X/X0 per layer
  - Goal of a pixel pitch down to 10 μm, with power dissipation below 20 mW/cm^2 and a material thickness of 0.05% X/X0 per layer
- The development of the sensors is going to be assisted by the development of support structures and services.
  - The BNL group has been advancing developments of optimized readout architectures in order to read out data from highly granular pixel detectors: *e.g.* Event Driven with Access and Reset Decoder (EDWARD)

MAPS for EIC

- The proposed design of the barrel ECal aims to provide a precise electron and pion identification required for inclusive DIS physics.
    - excellent electron-pion separation resulting in pions suppression up to 10^4 at low particle-momenta below 4 GeV
    - spatial resolution sufficient to separate photons from $\pi^0 \rightarrow \gamma\gamma$ decay with momentum up to about 15 GeV
    - Detecting photons with energies down to 50 MeV
- ATHENA proposal: barrel electromagnetic calorimeter comprising scintillating fibers embedded in Pb and imaging calorimeter based on MAPS sensors
    - 3-dimensional profile of the electromagnetic or hadronic shower development





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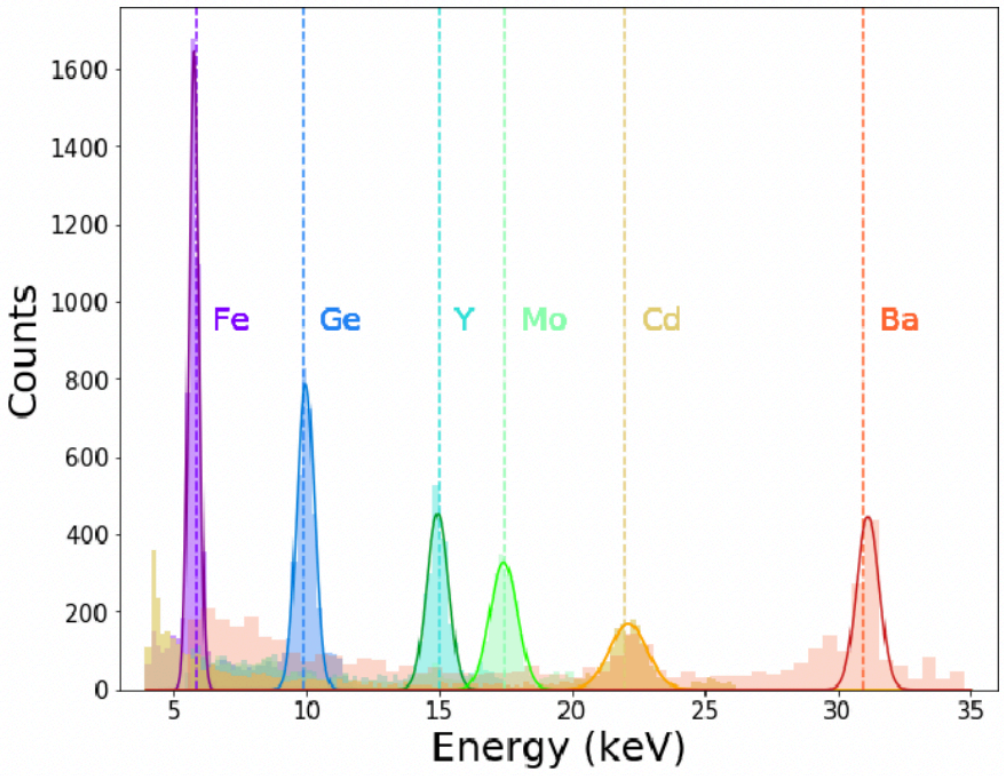
MAPS for space-born applications

- Space-born applications for MeV γ-ray experiments with MAPS based trackers
- The AstroPix sensor is an optimized version of ATLASPix to achieve required intrinsic energy resolution of ≤ 10% at 60 keV for the Compton event reconstruction in gamma-ray astrophysics.
- AstroPix sensors are designed with large pixel size compared to ATLASPix (180 nm CMOS process by TSI) which results in low power consumption, as it is dominated by the amplifiers within the pixel electronics.
    - AstroPix v3 is in progress with pixel size of 500 μm with sensor area of 20 × 20 mm^2 and lower power dissipation



Collaborations and perspectives

- MAPS are of interest to many scientific collaborations, especially within the HEP community.
  - SLAC & BNL have on going collaborations with CERN, in particular the WP1.2 where a shared effort can be imagined in further MAPS developments
- Performance of vertex detector and ECal at EIC and future e+e- detectors based on MAPS could meet the specifications from physics requirements
  - For vertex detectors : synergistic developments with ALICE ITS3
- Promising application to space-born applications for MeV γ-ray experiments with MAPS based trackers
- The know-how developed for this project will benefit other HEP/BES applications requiring low-power designs, fast inter-pixel communications, synchronous architectures, *etc.*
  - MAPS can be of interest for ultra-fast X-ray science