ALICE

CERN

ELMA Workshop on “Energy loss measurements with MAPS”

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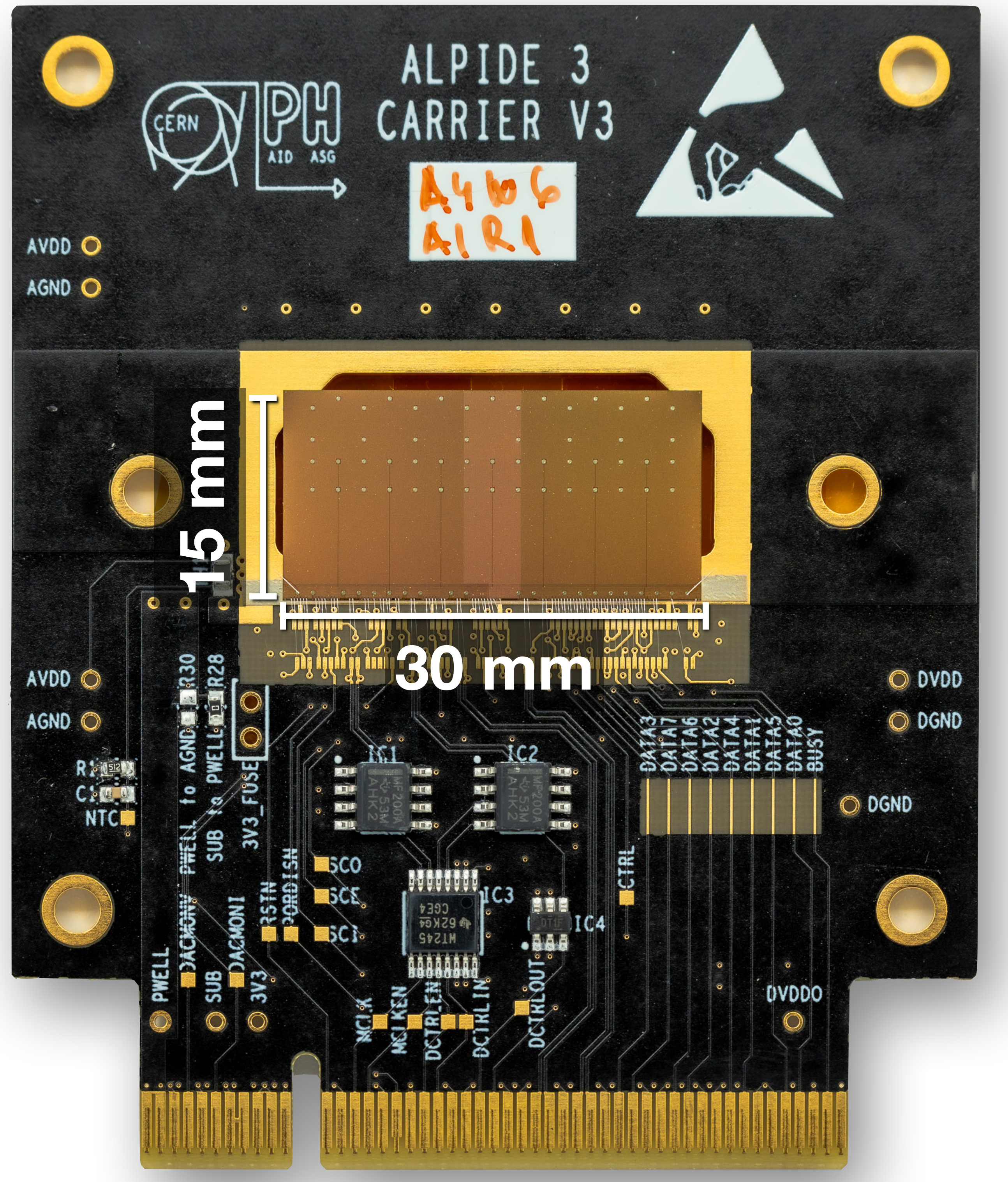
(Monolithic) Active Pixel Sensors

Exmor R

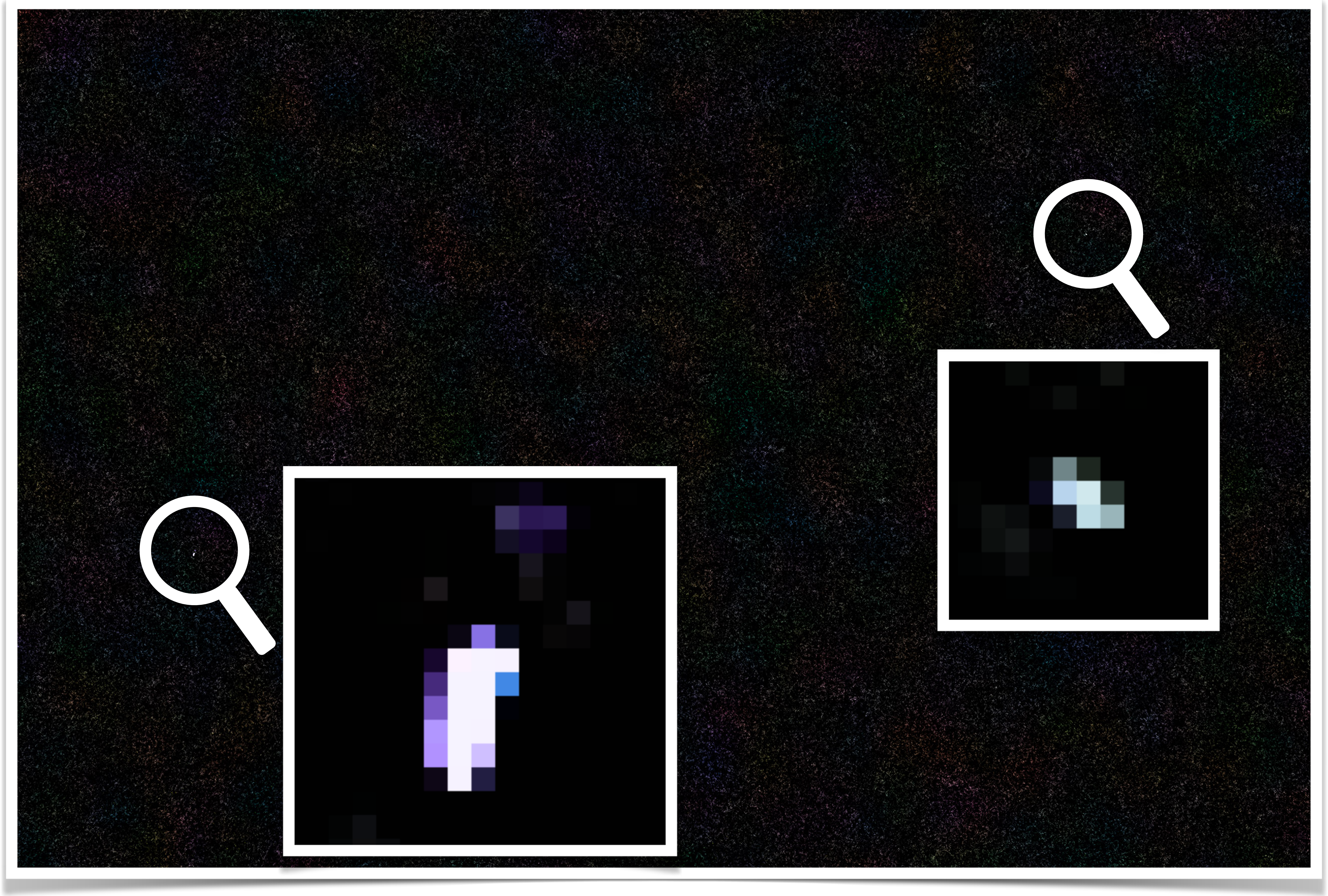
Sony full frame CMOS image sensor
7008 x 4672 pixels with column-parallel digitization
Optimized for visible light

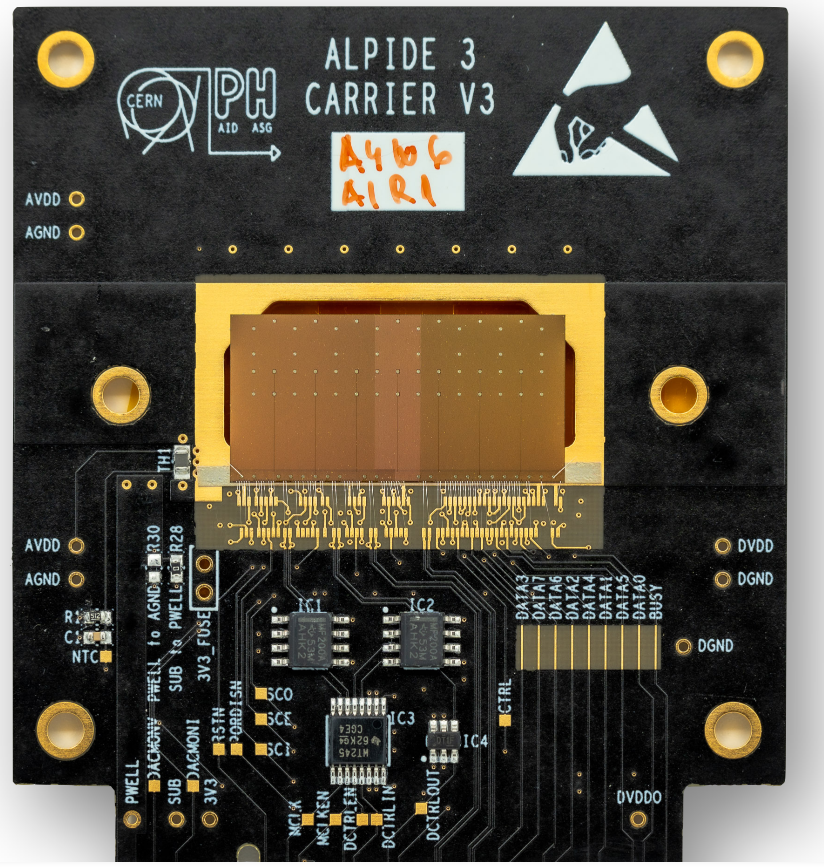


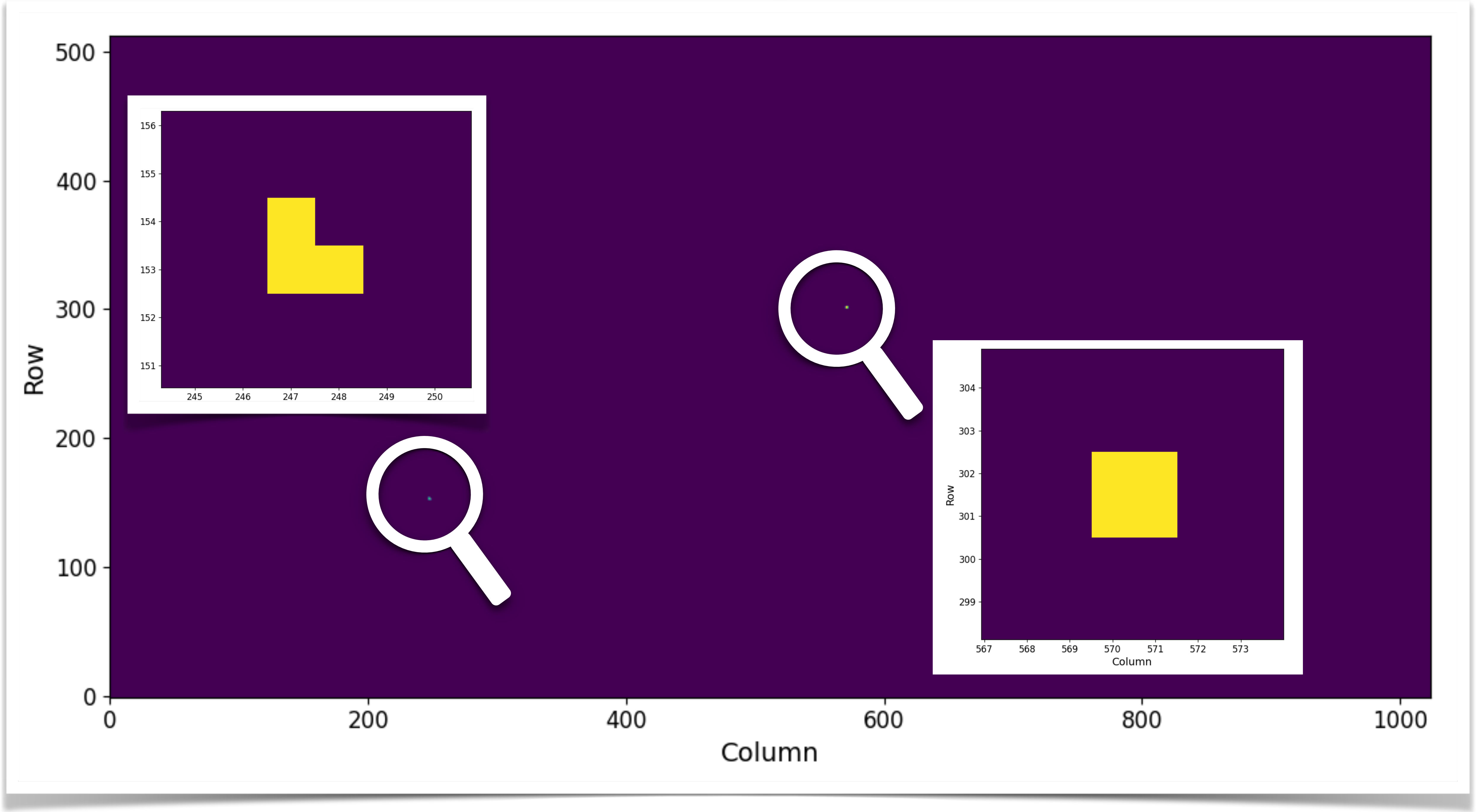
ALPIDE

TowerJazz CMOS imaging sensor process
1024 x 512 pixels with in-pixel discrimination
Optimized for minimum ionizing particles

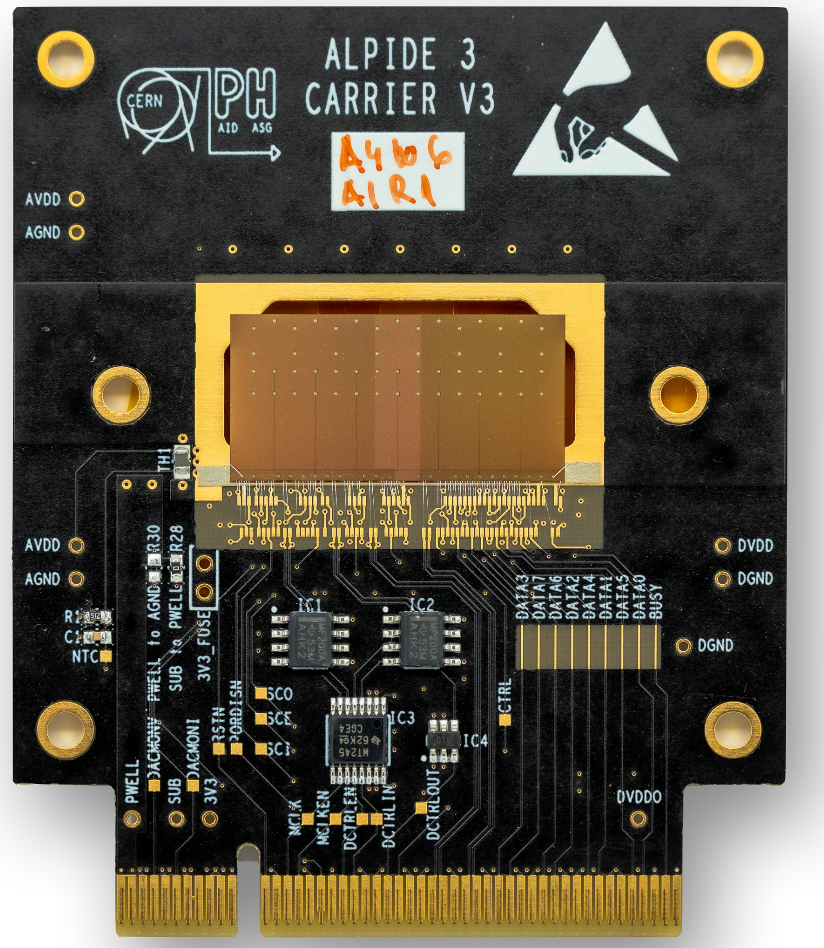
Cosmic ray detection with (M)APS



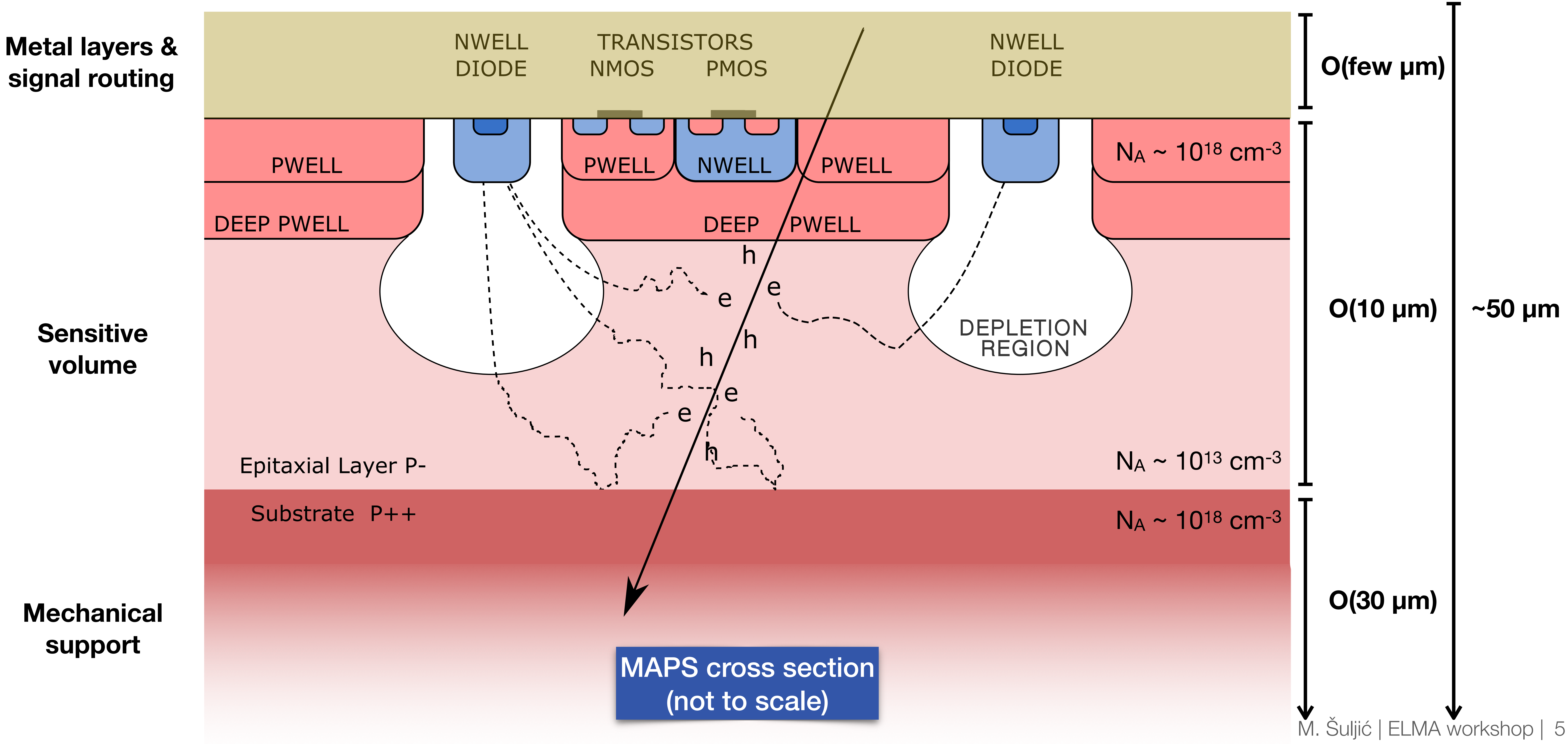




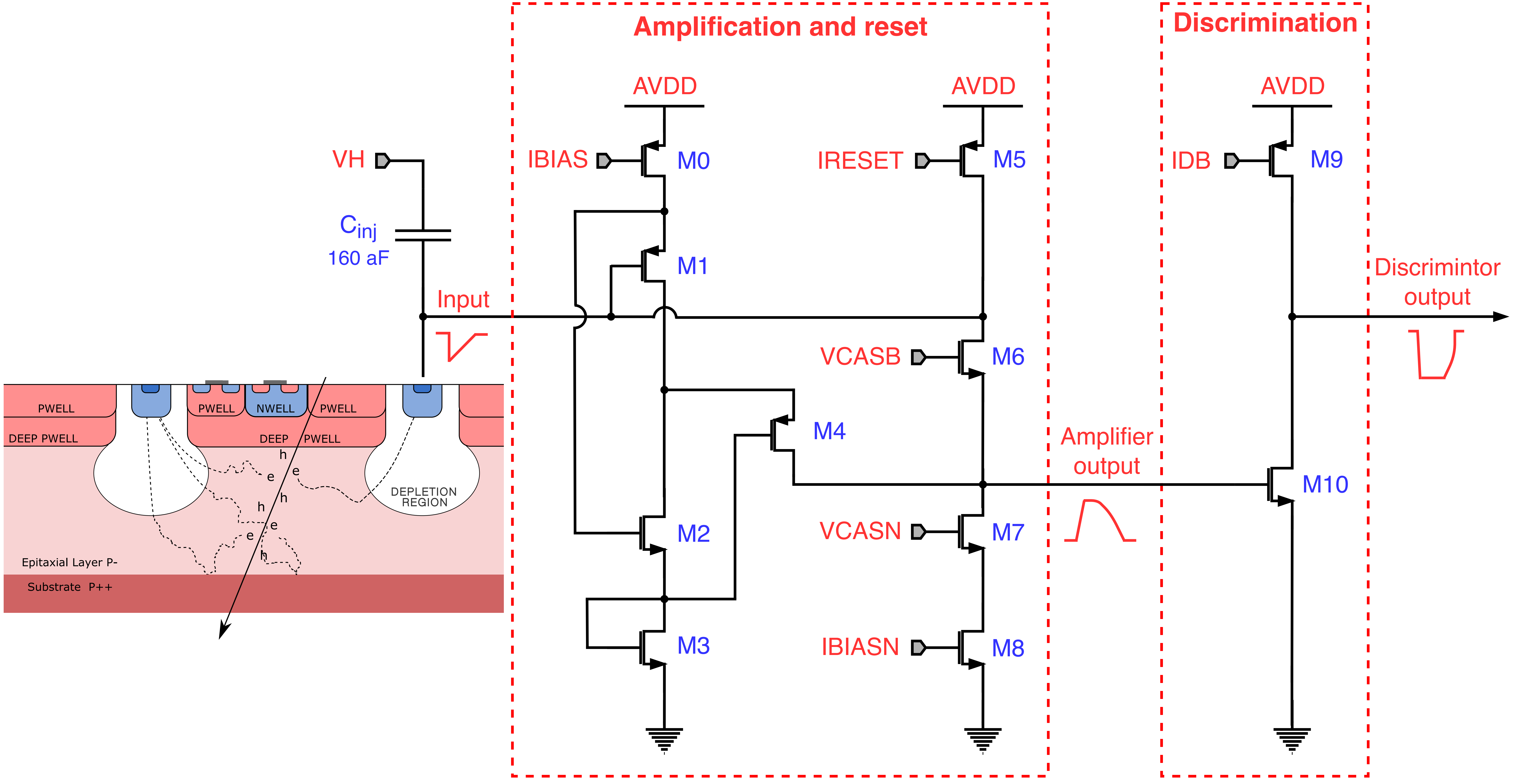
Portrait photography with (M)APS



Principle of operation of MAPS

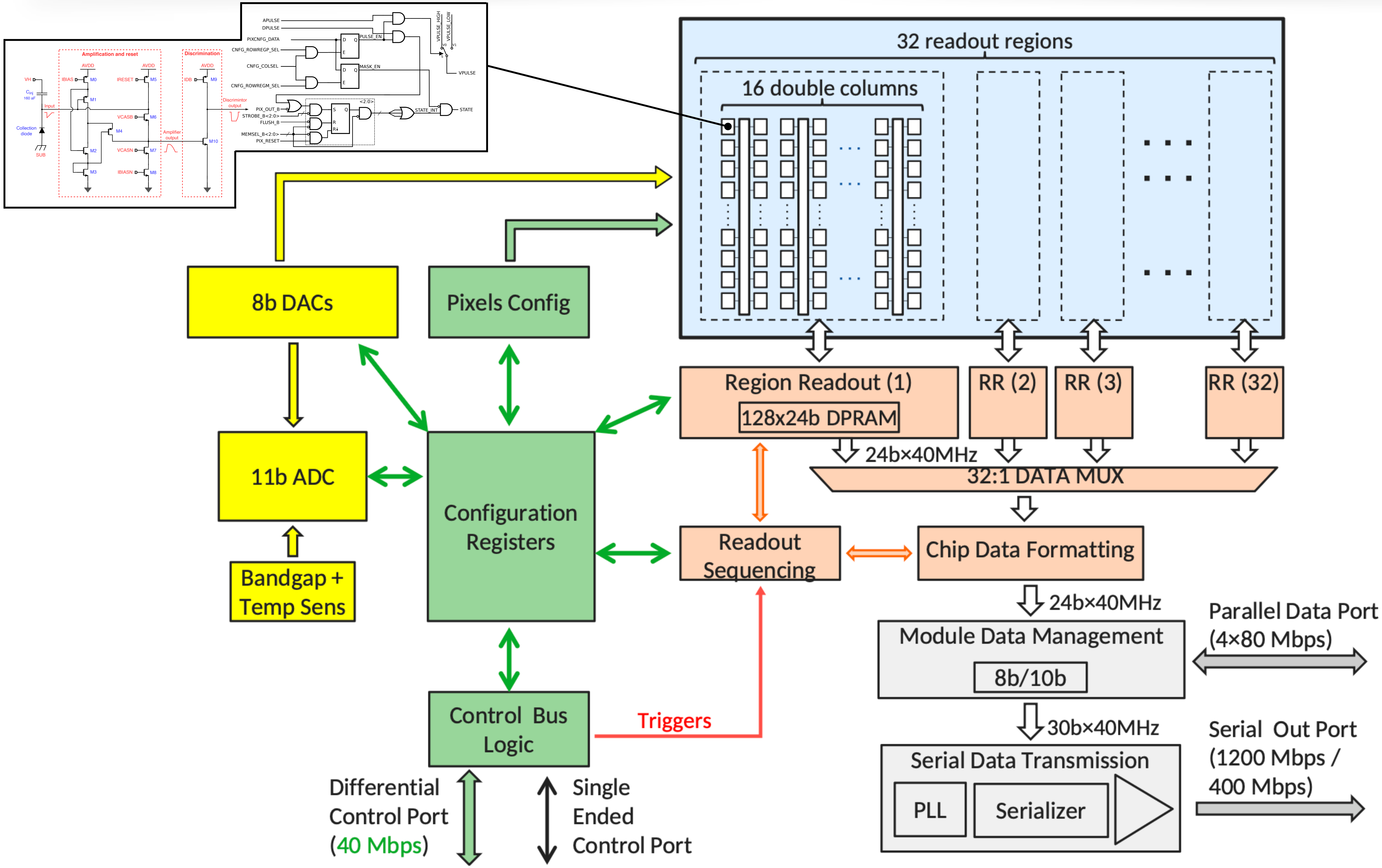


MAPS in-pixel front-end



MAPS in-pixel front-end

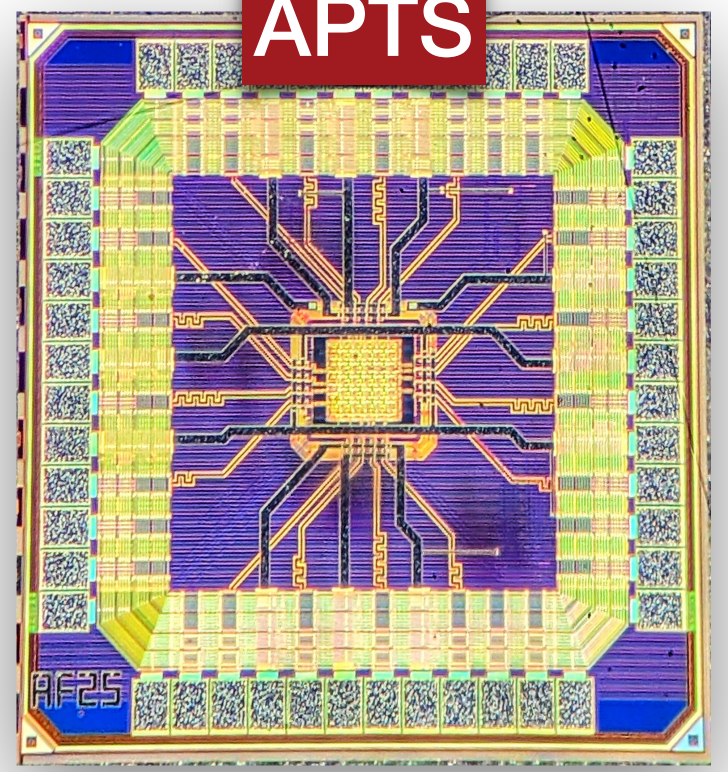
MAPS readout & control



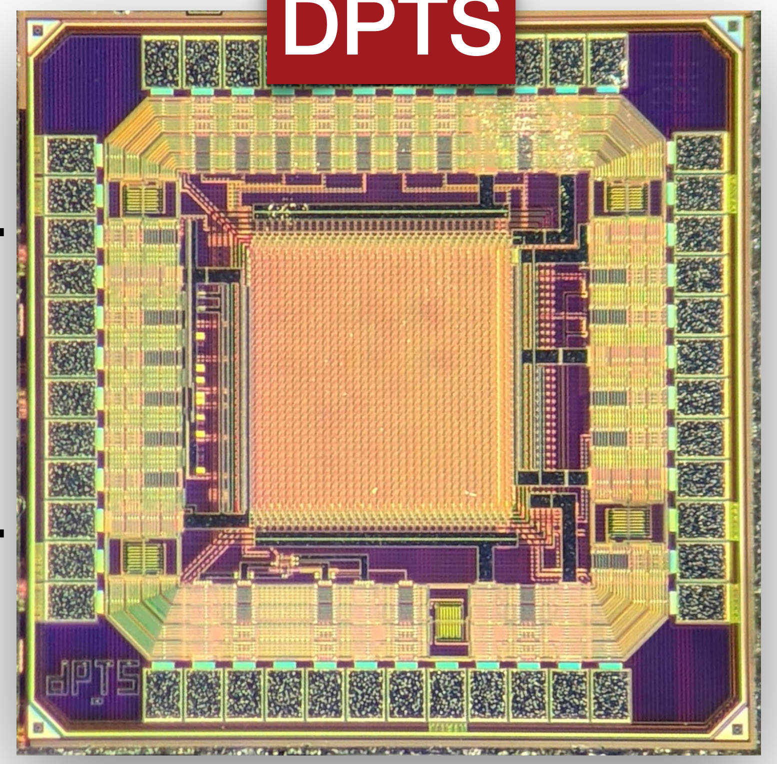
MAPS as ionizing radiation detectors

- Sensitive volume & readout electronics on same chip → simple integration
- Standard CMOS imaging sensor process → cheap
- Pixels as small as $10 \times 10\ \mu m^2$ → excellent spatial resolution, large hit multiplicity
- Possibility to deplete the sensitive volume → good radiation tolerance
- Thin sensitive volume → lightweight, but **limited energy resolution**
- **Excellent for tracking low momentum ionizing particles in high multiplicity and large area environments**

Latest MAPS prototypes for ITS3



- 6×6 pixel matrix
- 10, 15, 20, 25 µm pitch
- Direct analog readout
- 32 variants



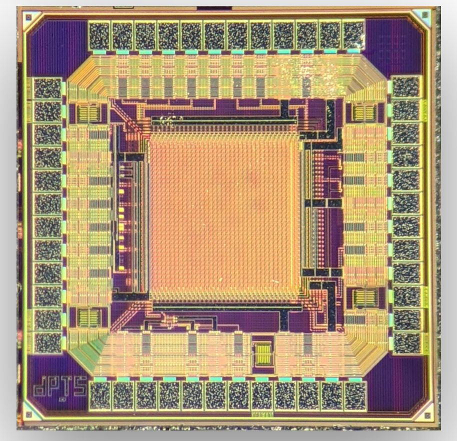
- 32×32 pixel matrix
- 15 µm pitch
- Async. digital readout
- 3 variants

MLR1 (2021)

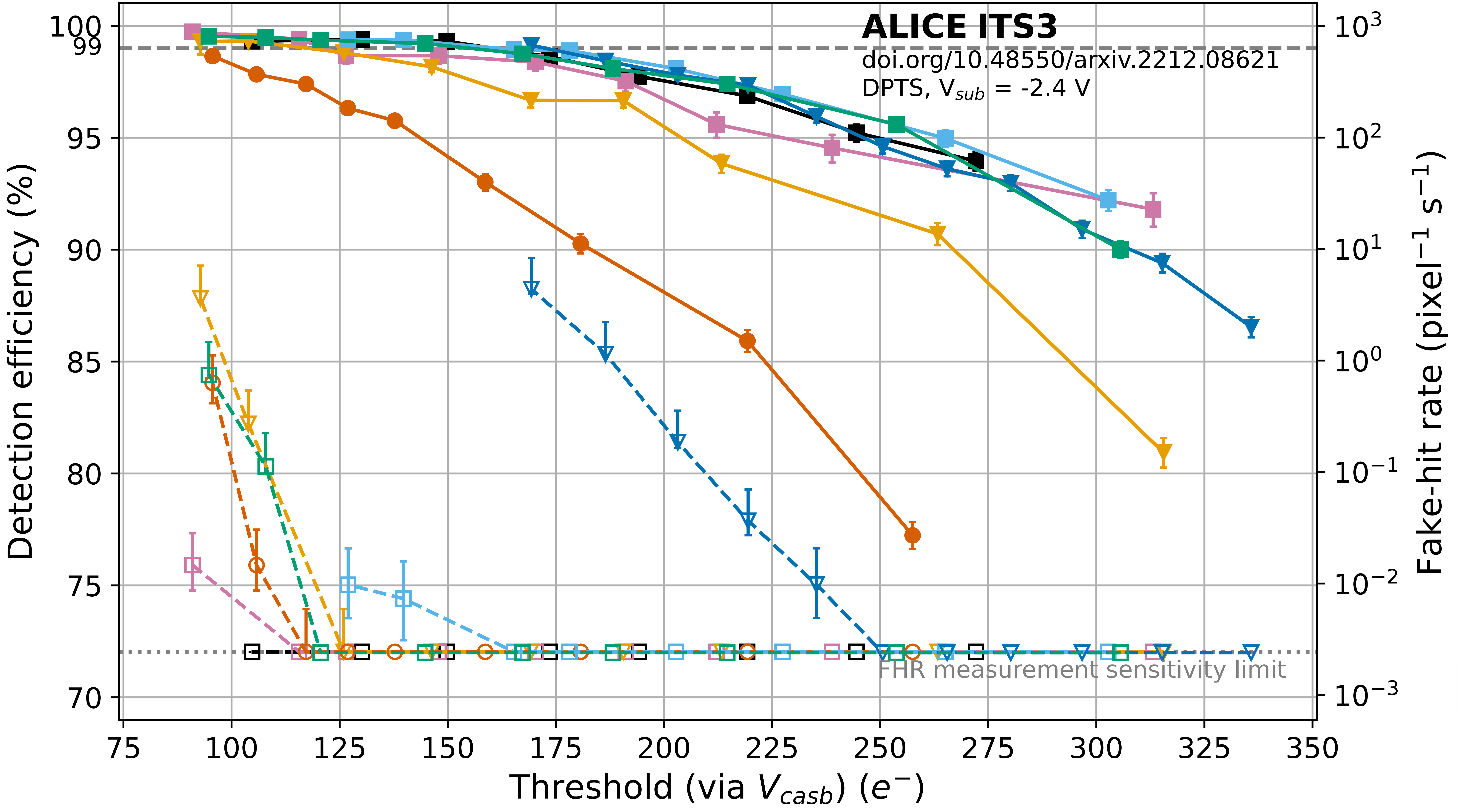
ER1 (2023)

- 40×256×256 pixel matrices (22.5 µm pitch)
- 40×320×320 pixel matrices (18 µm pitch)
- DPTS like in-pixel front-end, 6 variants
- On-chip DACs, bandgaps, hit encoding
- Parallel readout over twenty 8-bit ports on long edge or two 10-bit port on short edge

Detection efficiency: small scale prototypes

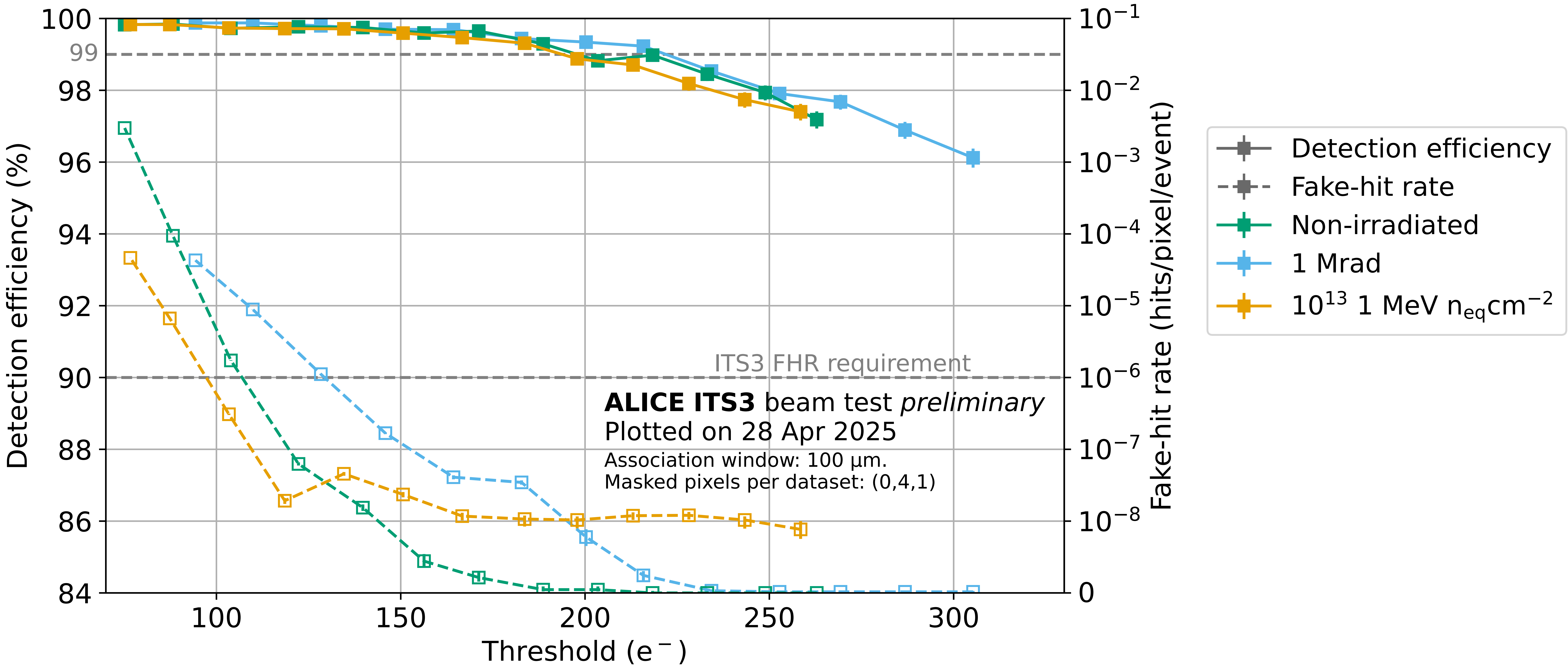


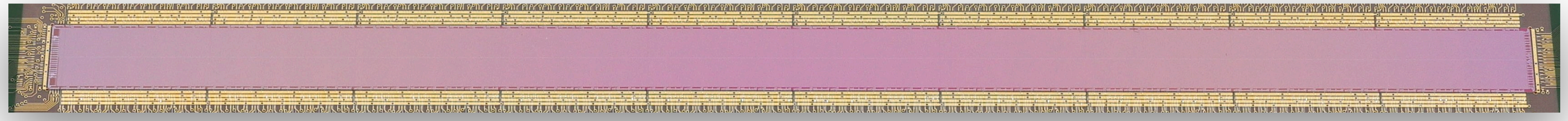
DPTS, 15 µm pixel pitch @ 20°C



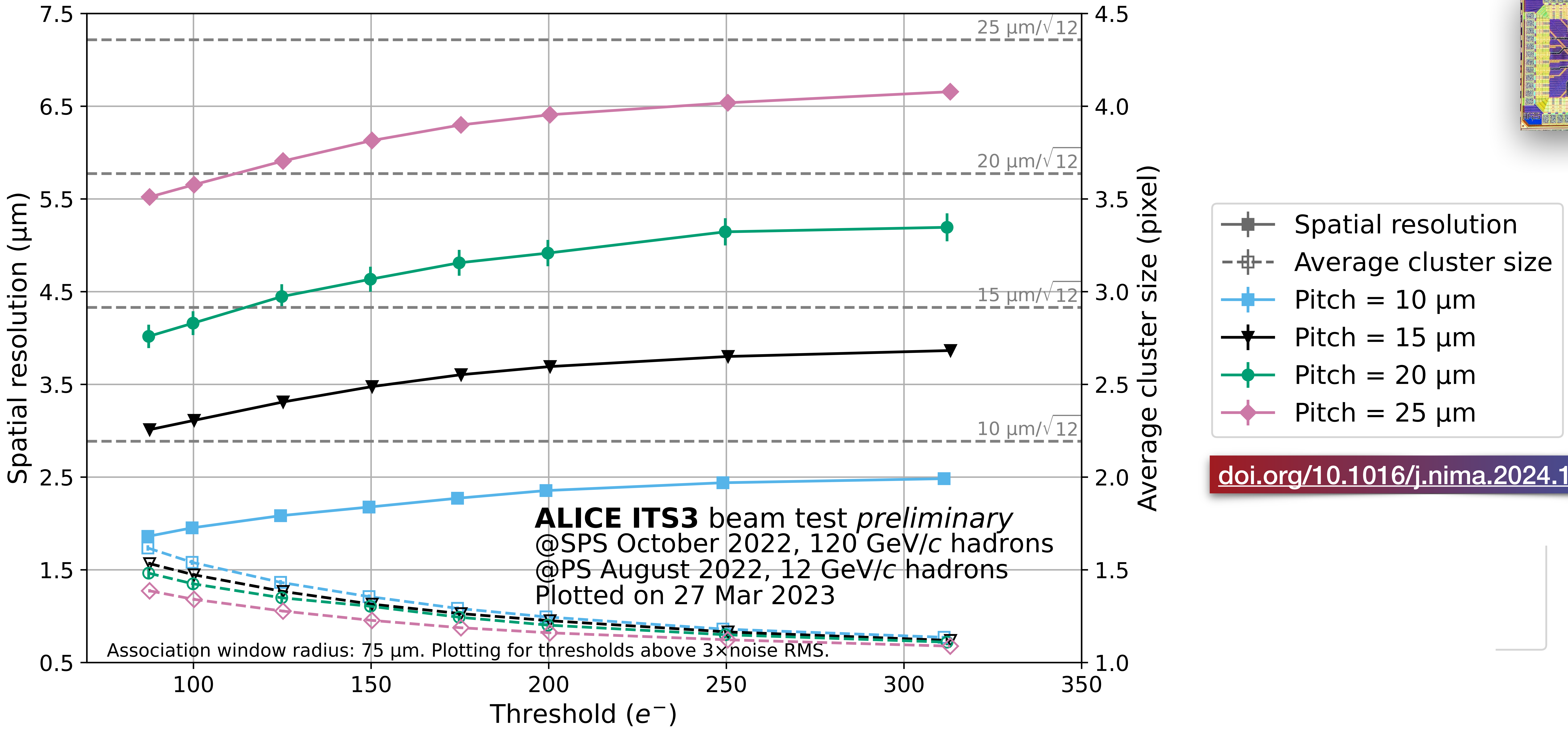
doi.org/10.1016/j.nima.2023.168589

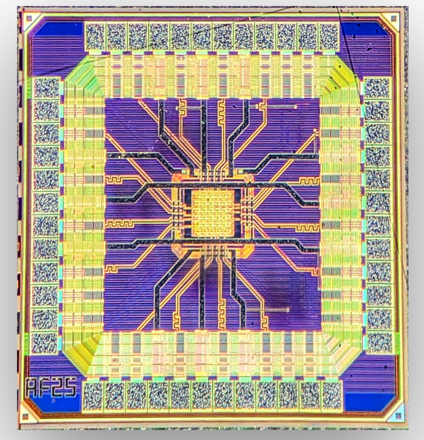
Detection efficiency: stitched sensor





Spatial resolution & pixel pitch

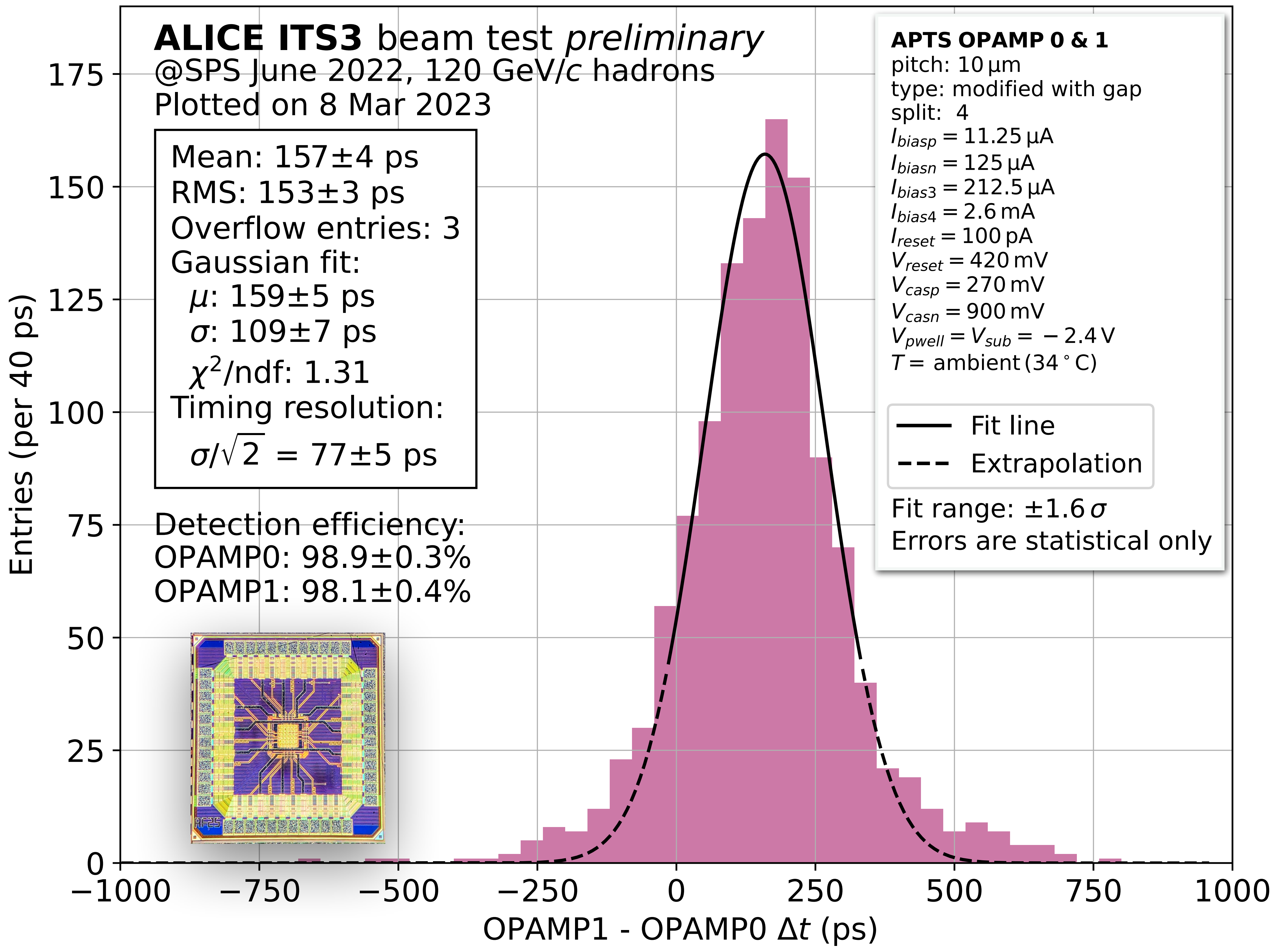




doi.org/10.1016/j.nima.2024.169896

Timing resolution: technology limits

Sensor only

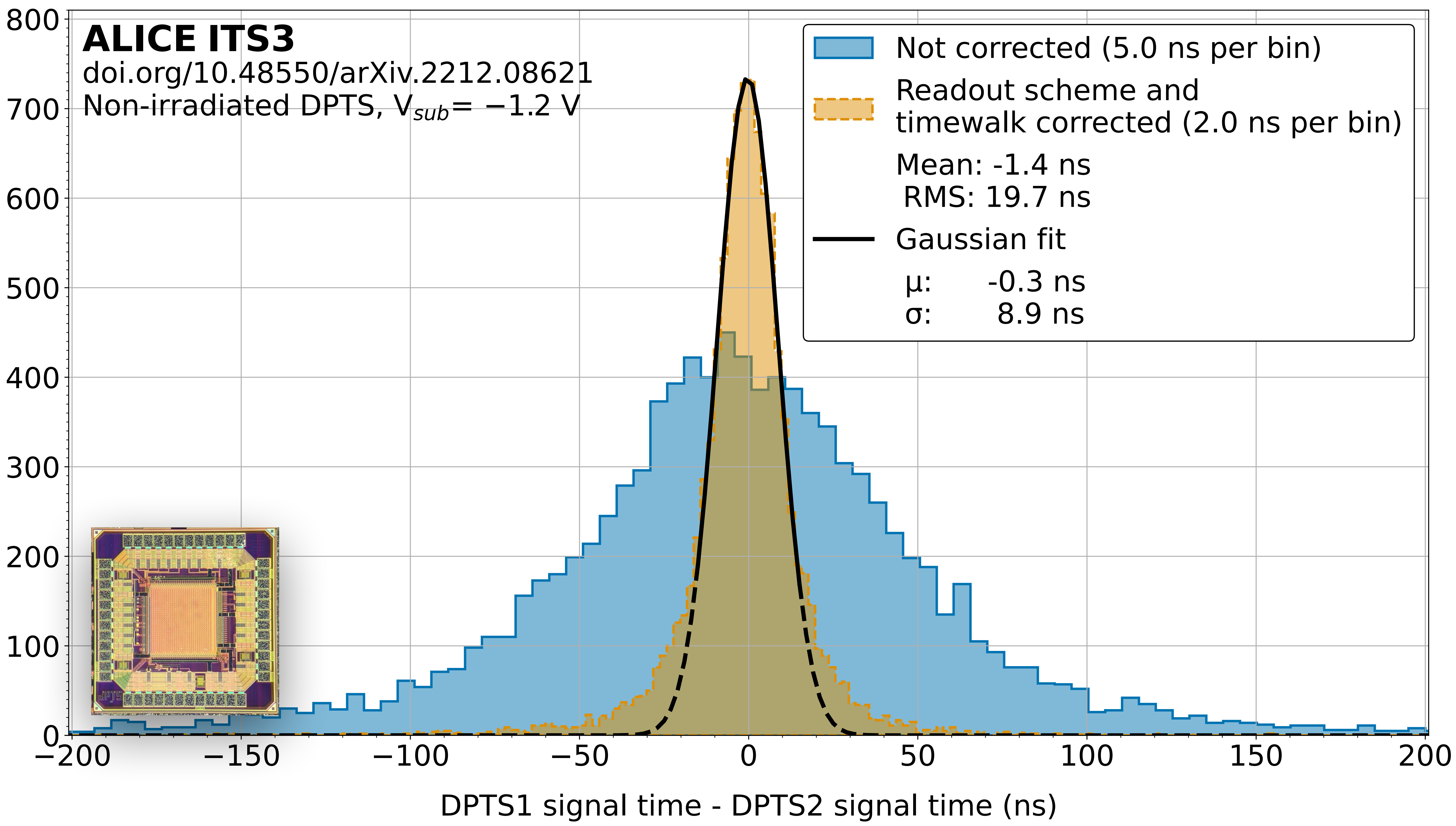


~80 ps timing resolution

~3 μW in-pixel | ~3 mW in-chip

doi.org/10.1016/j.nima.2024.170034

With front end

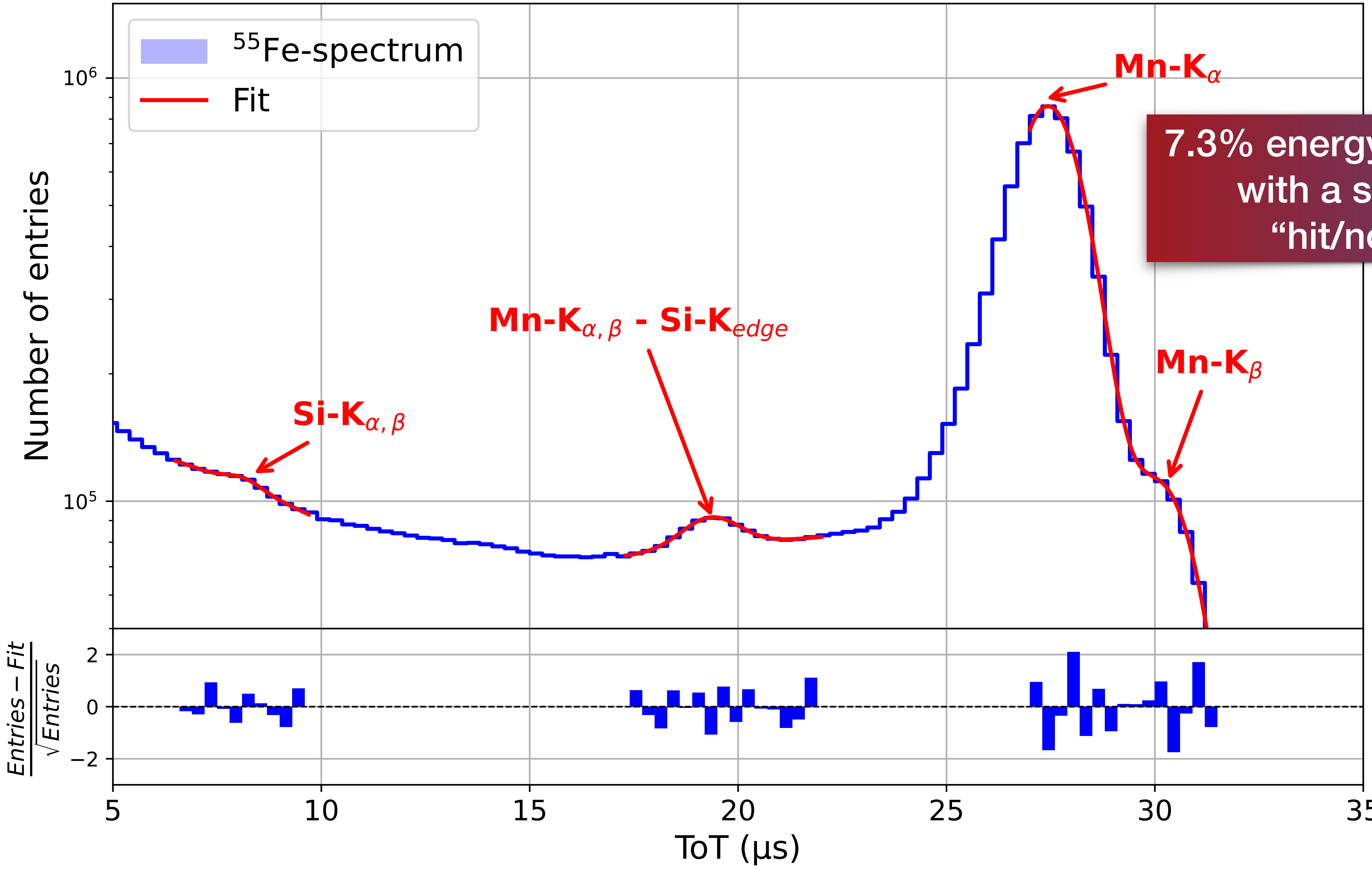


~6 ns timing resolution | (~30 ns not corrected)

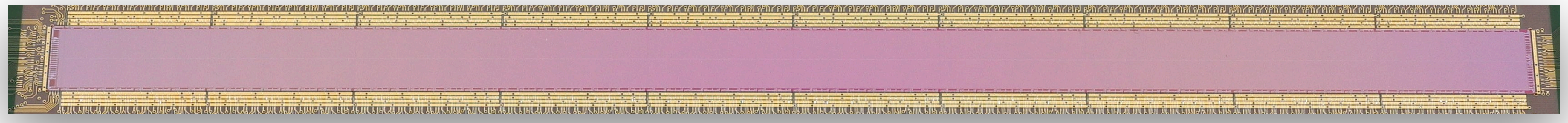
~120 nW in-pixel

doi.org/10.1016/j.nima.2023.168589

Energy measurement via time-over-threshold



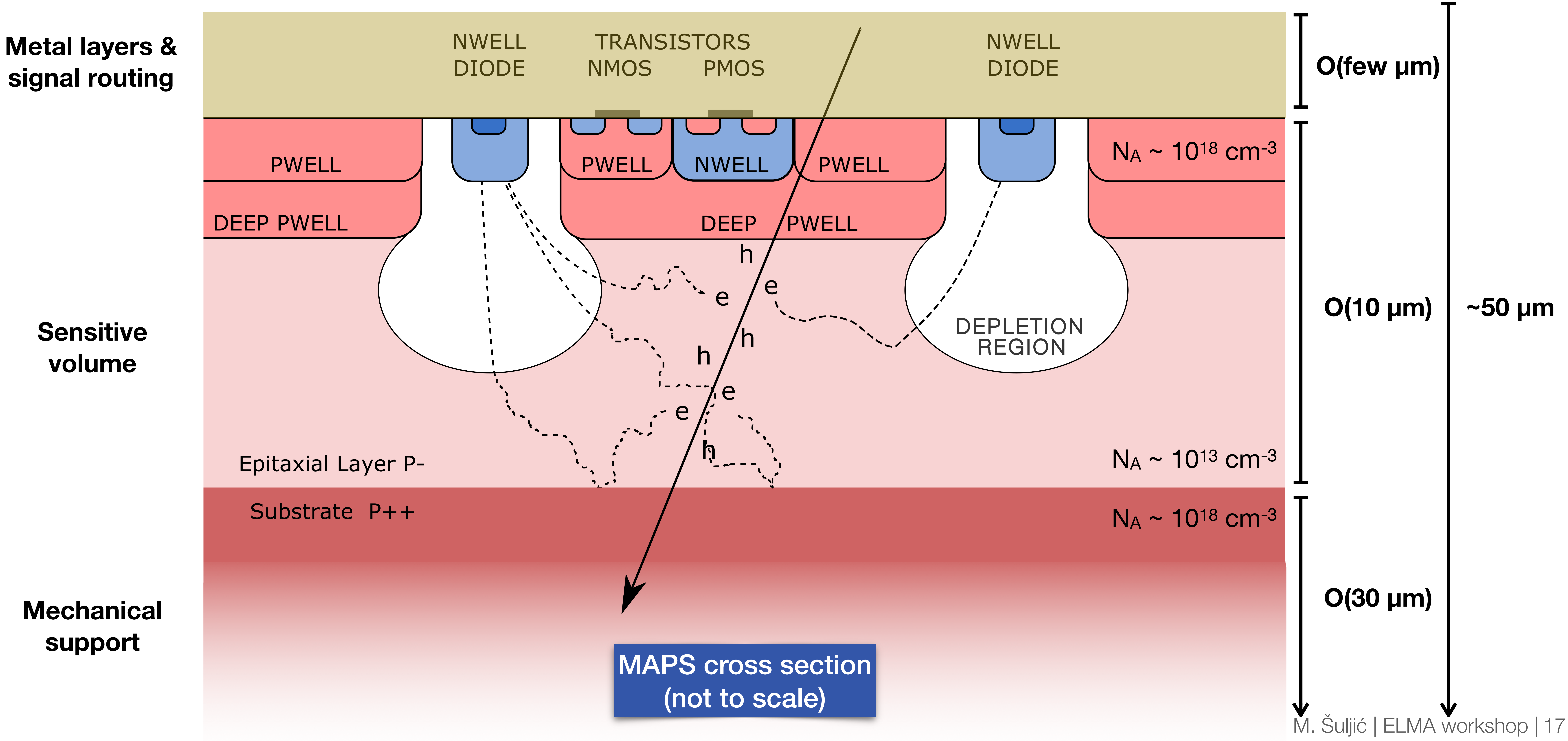
7.3% energy resolution at 5.9 keV with a sensor with simple “hit/no-hit” response!



The end - thank you!

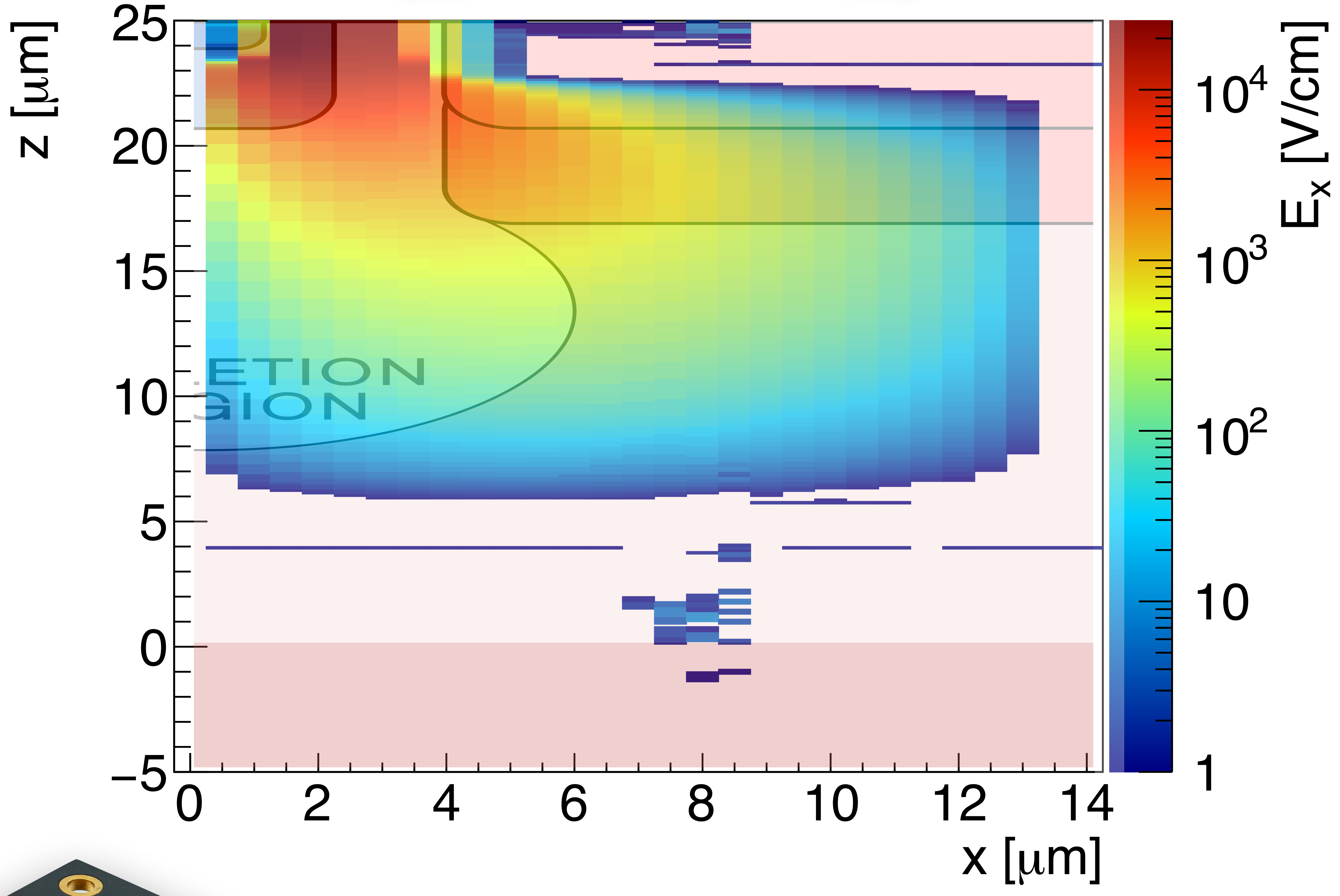
…or not…

Principle of operation of MAPS

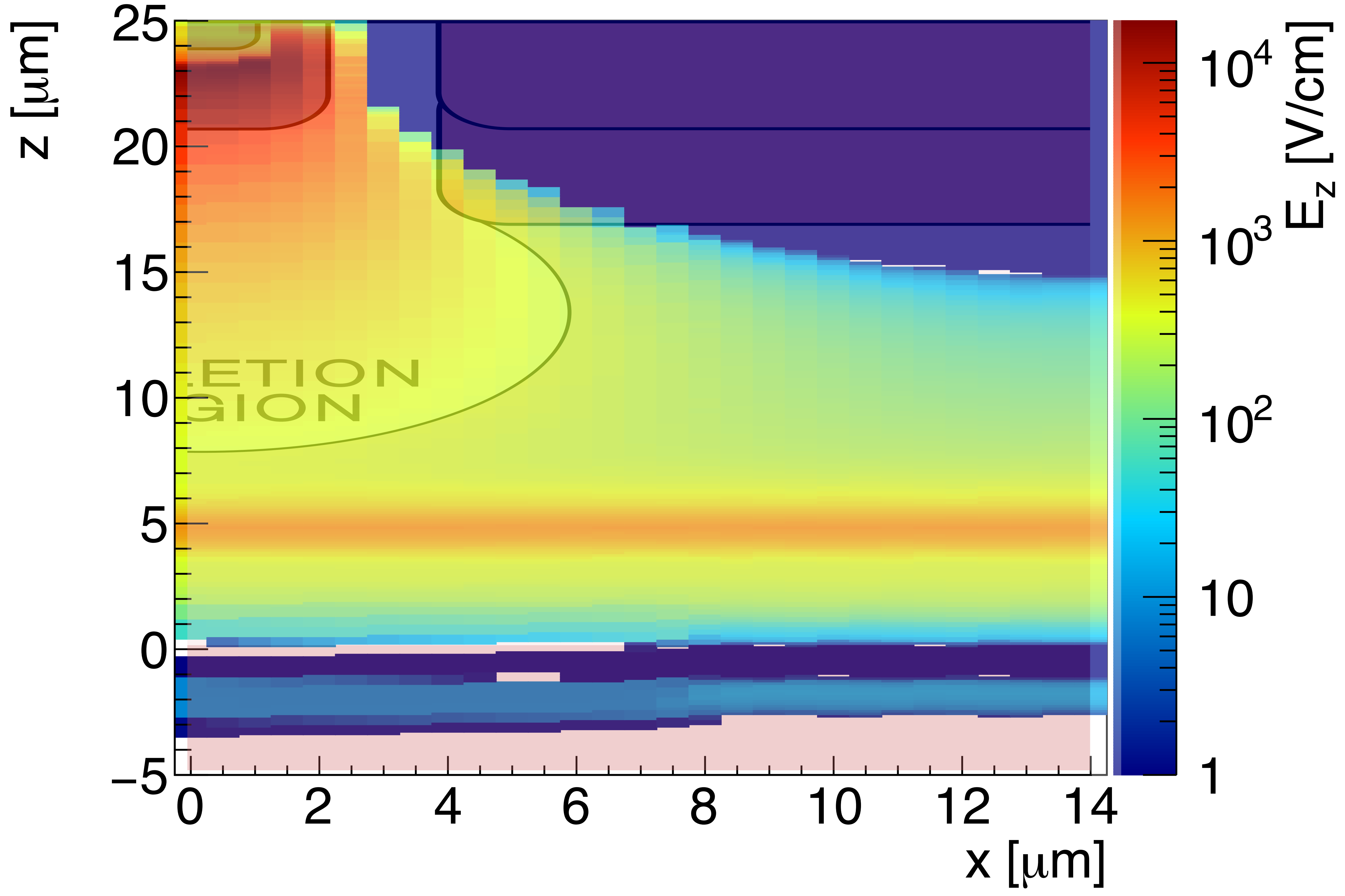


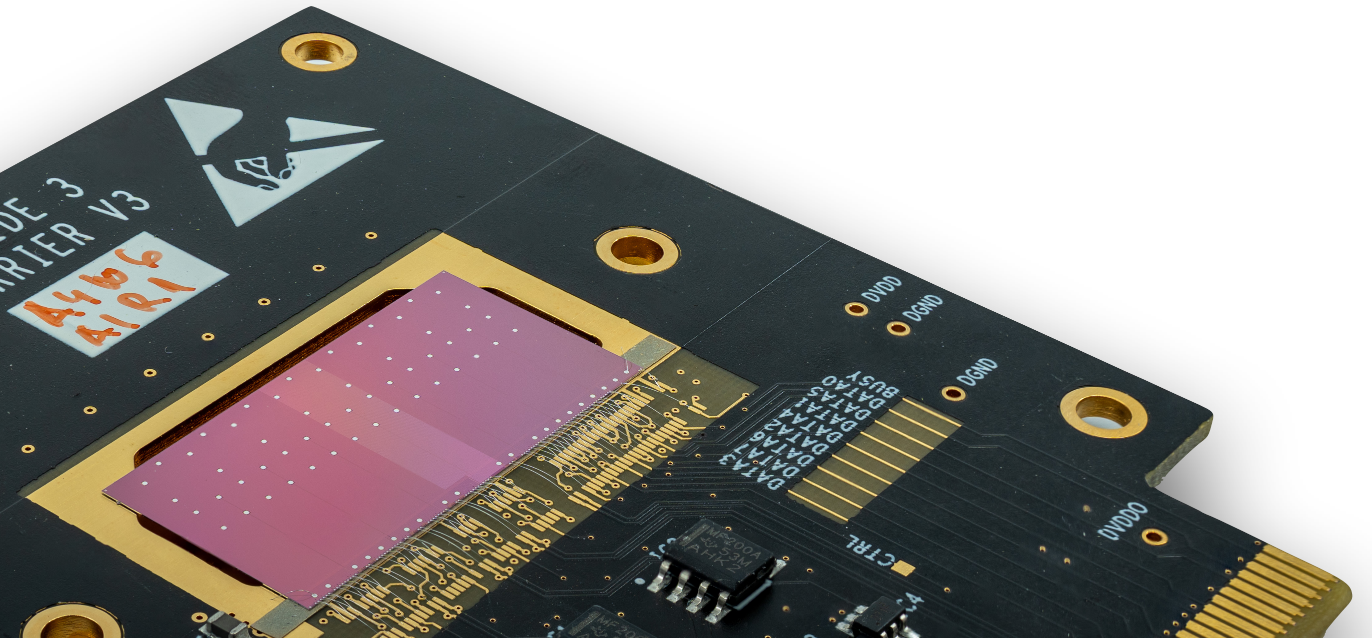
Charge collection - electric field

Electric field:
Horizontal component



Electric field:
Vertical component

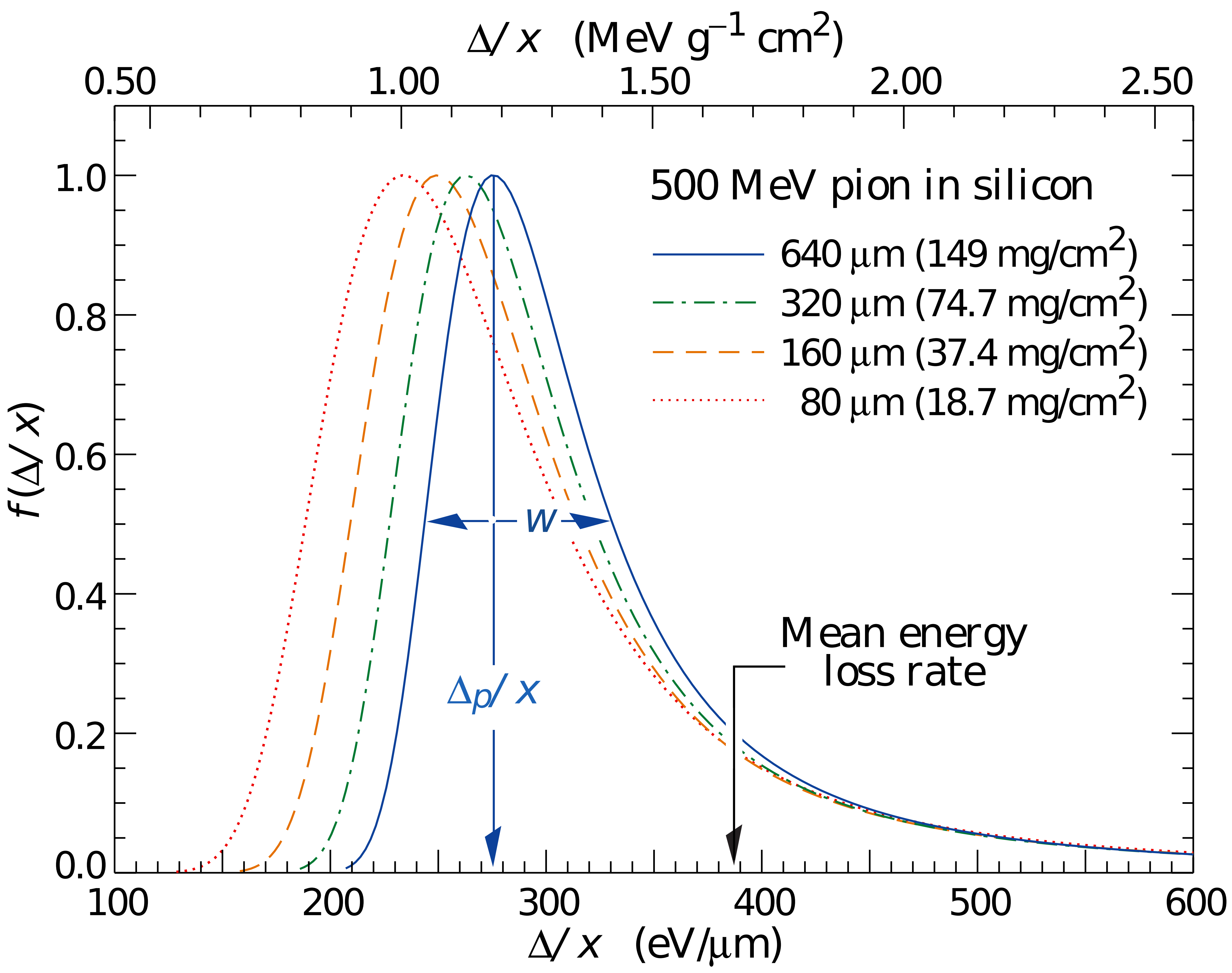




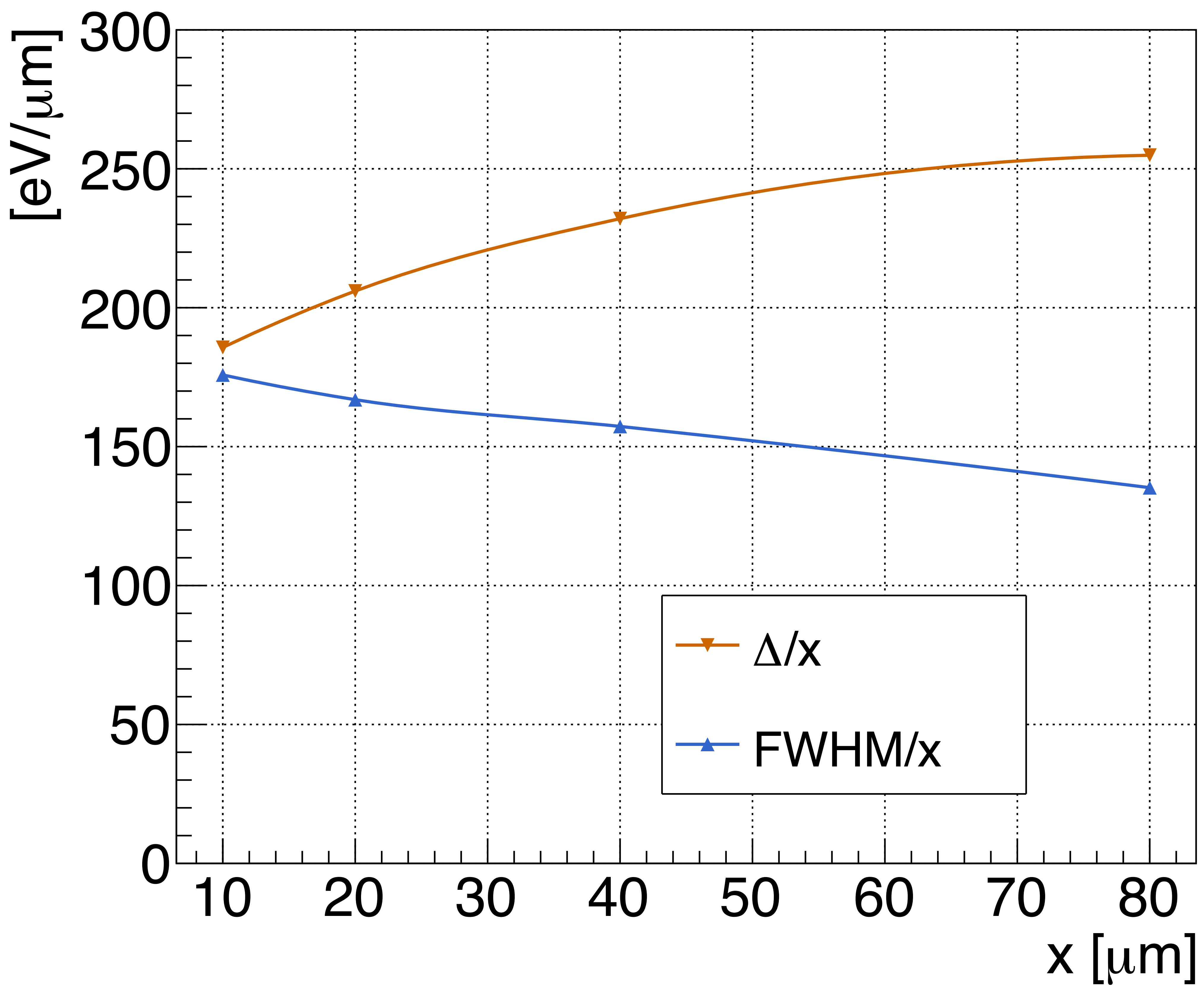
From ALPIDE-like sensor TCAD simulation

Energy straggling in ultra-thin sensors

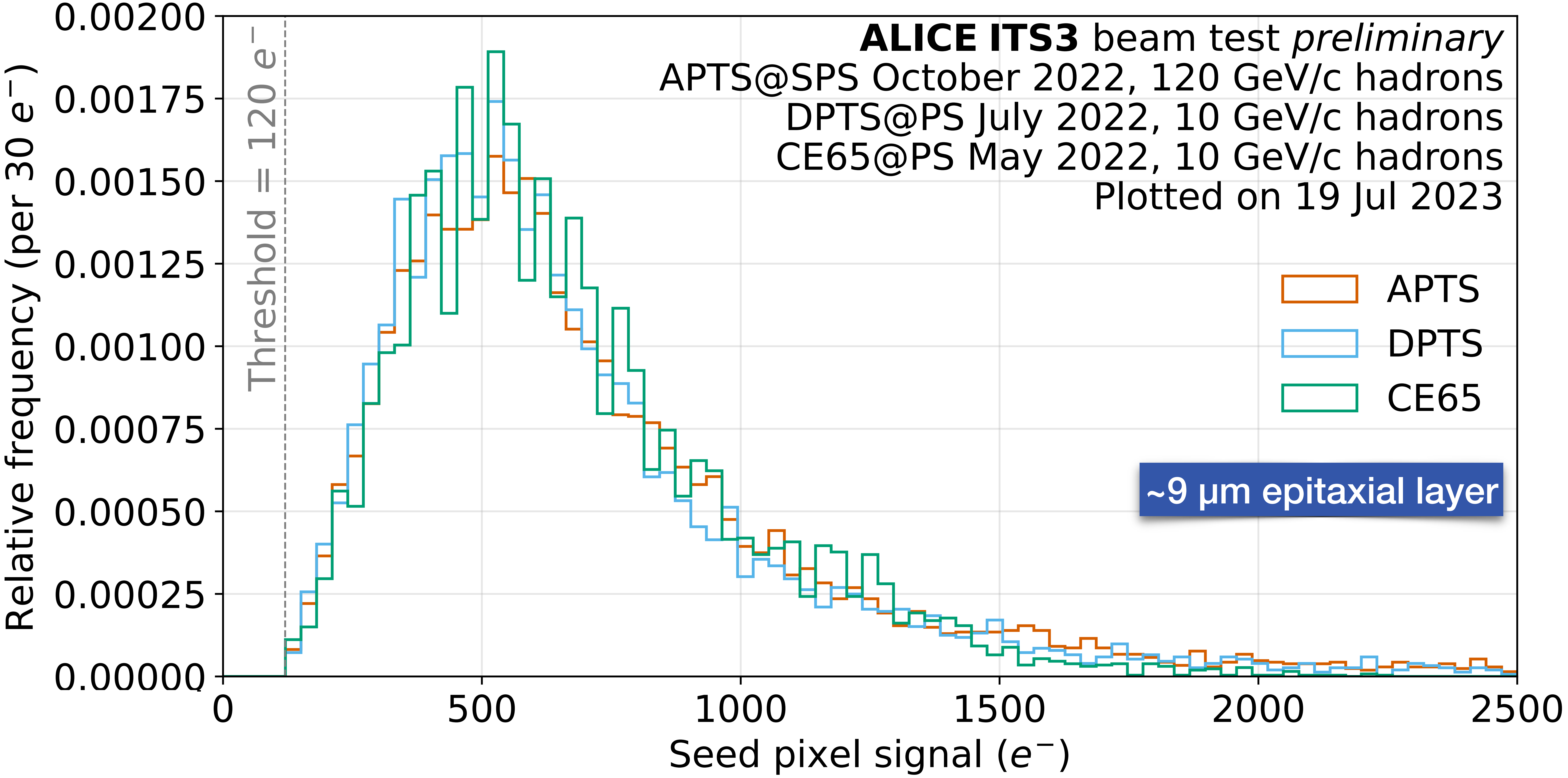
Straggling functions in silicon



Most probable energy loss and FWHM as a function of absorber thickness

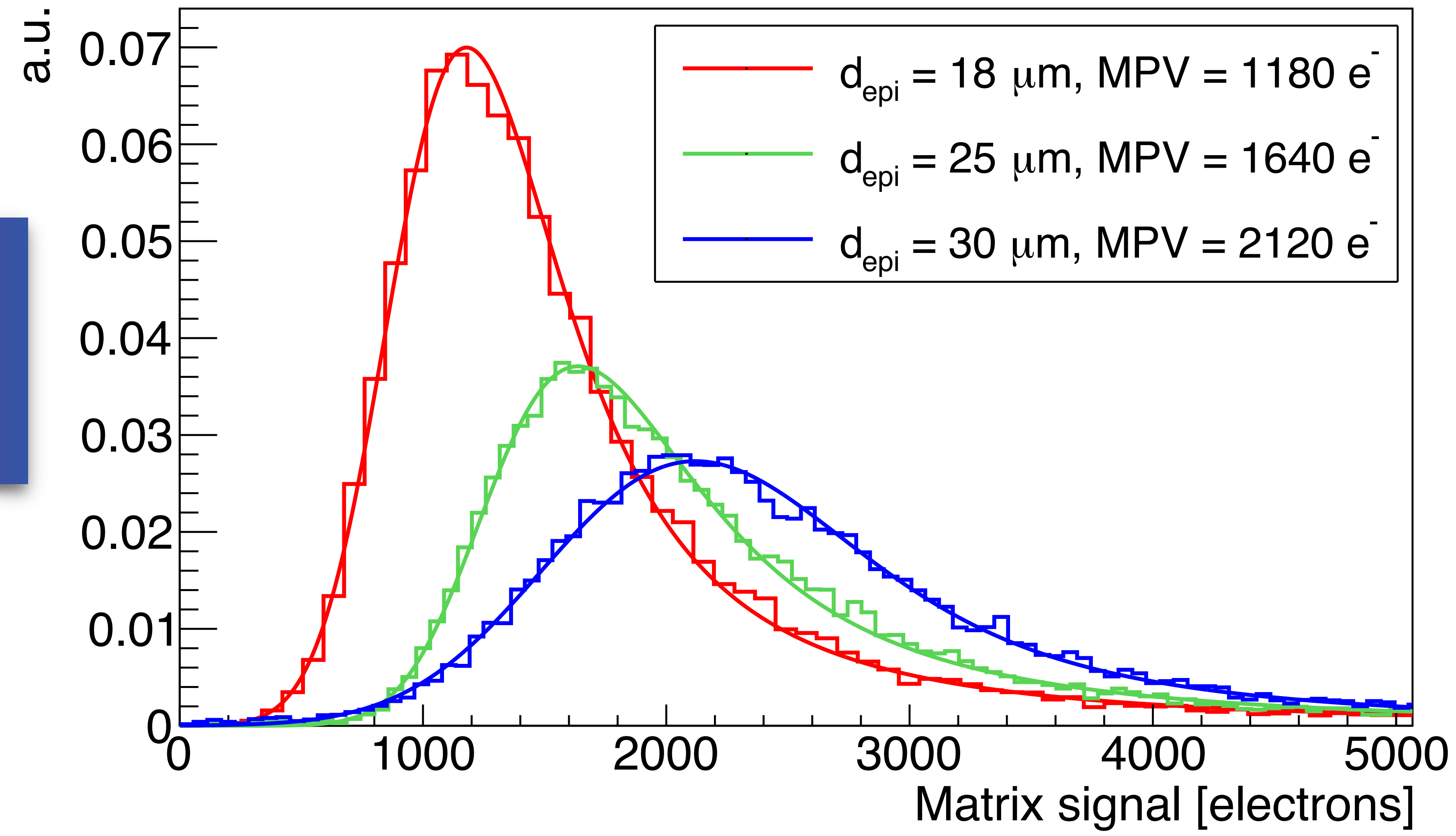


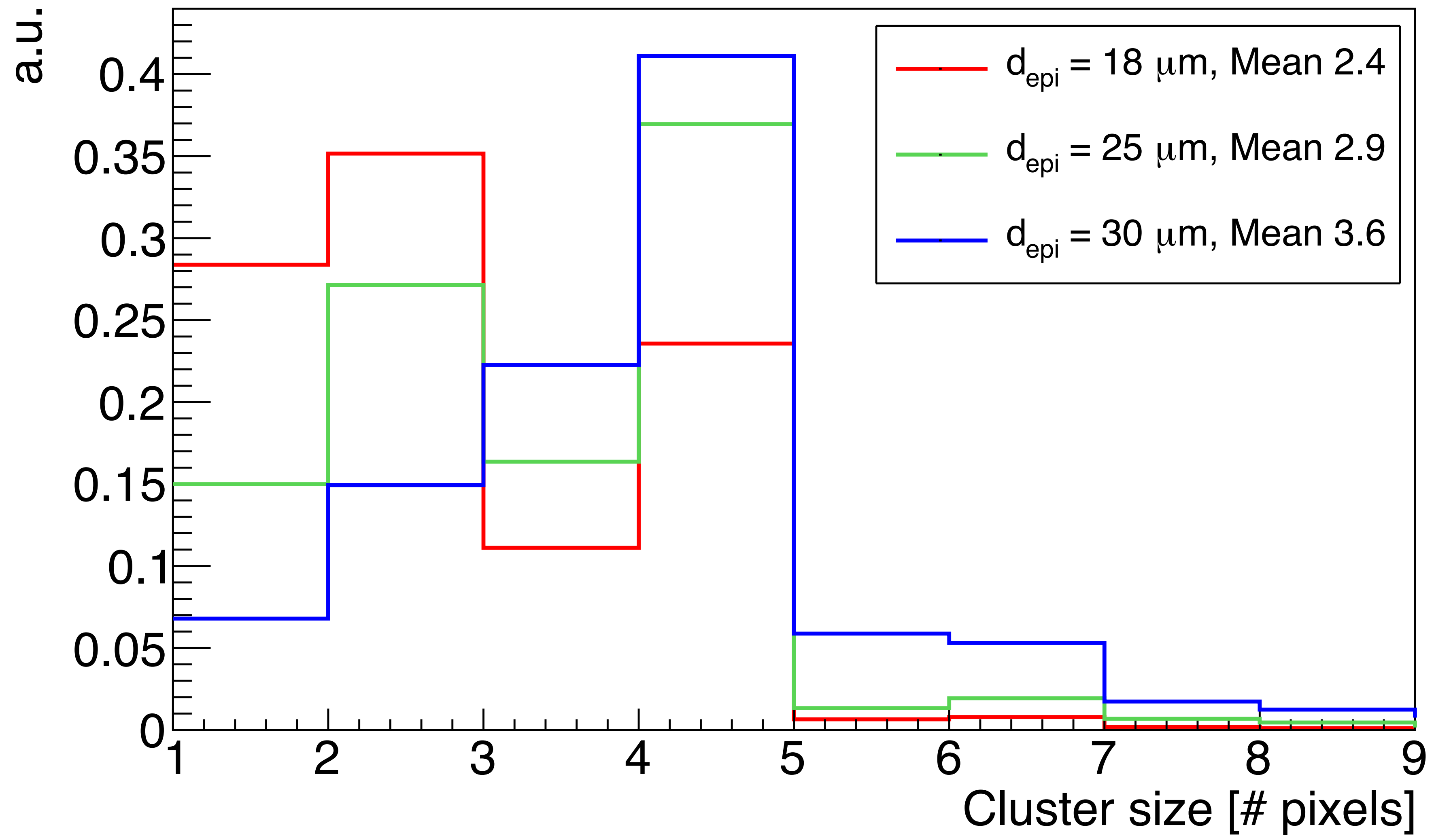
Energy straggling in ultra-thin MAPS



Increasing epitaxial layer thickness

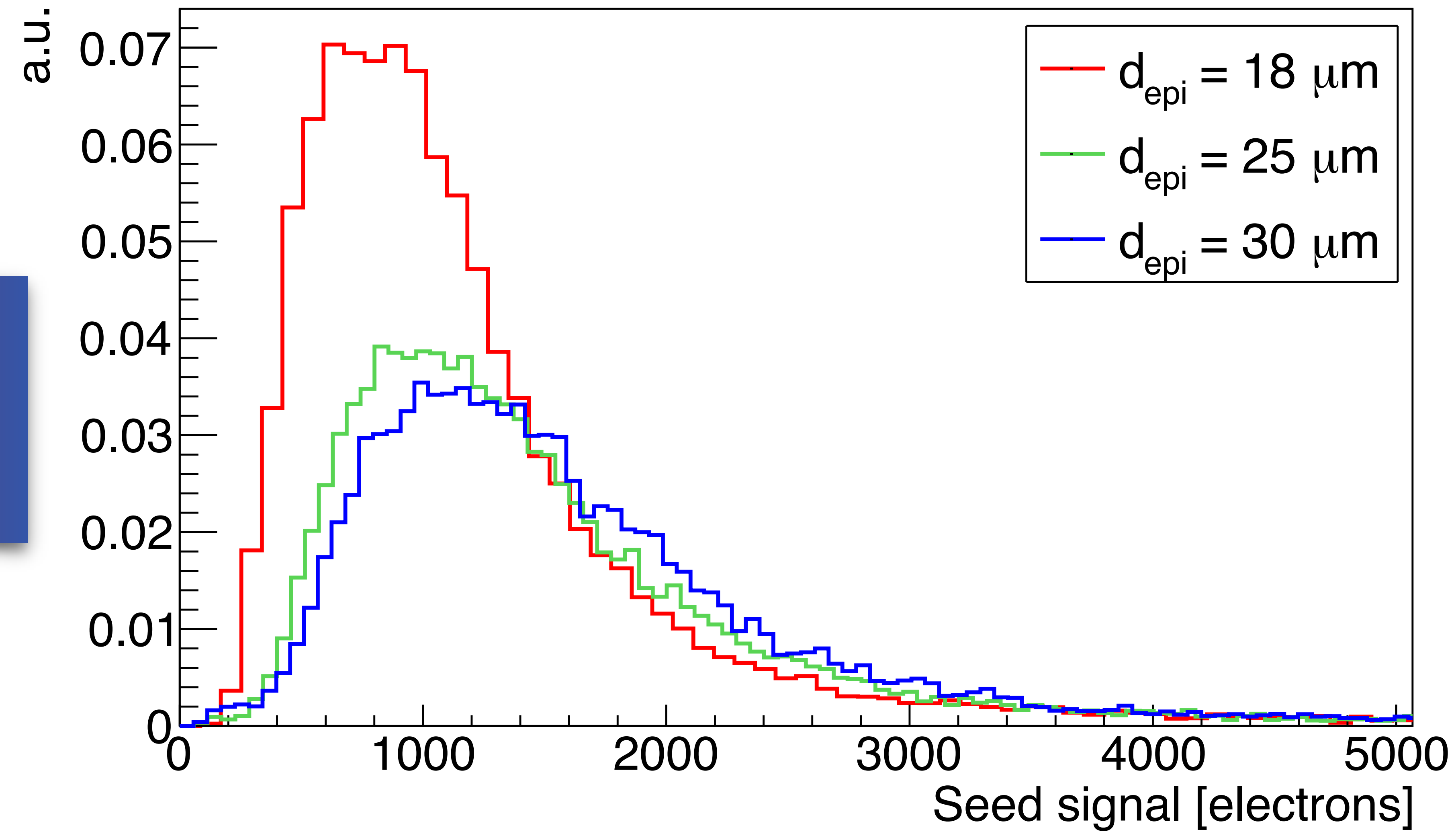
Total charge collected in the matrix

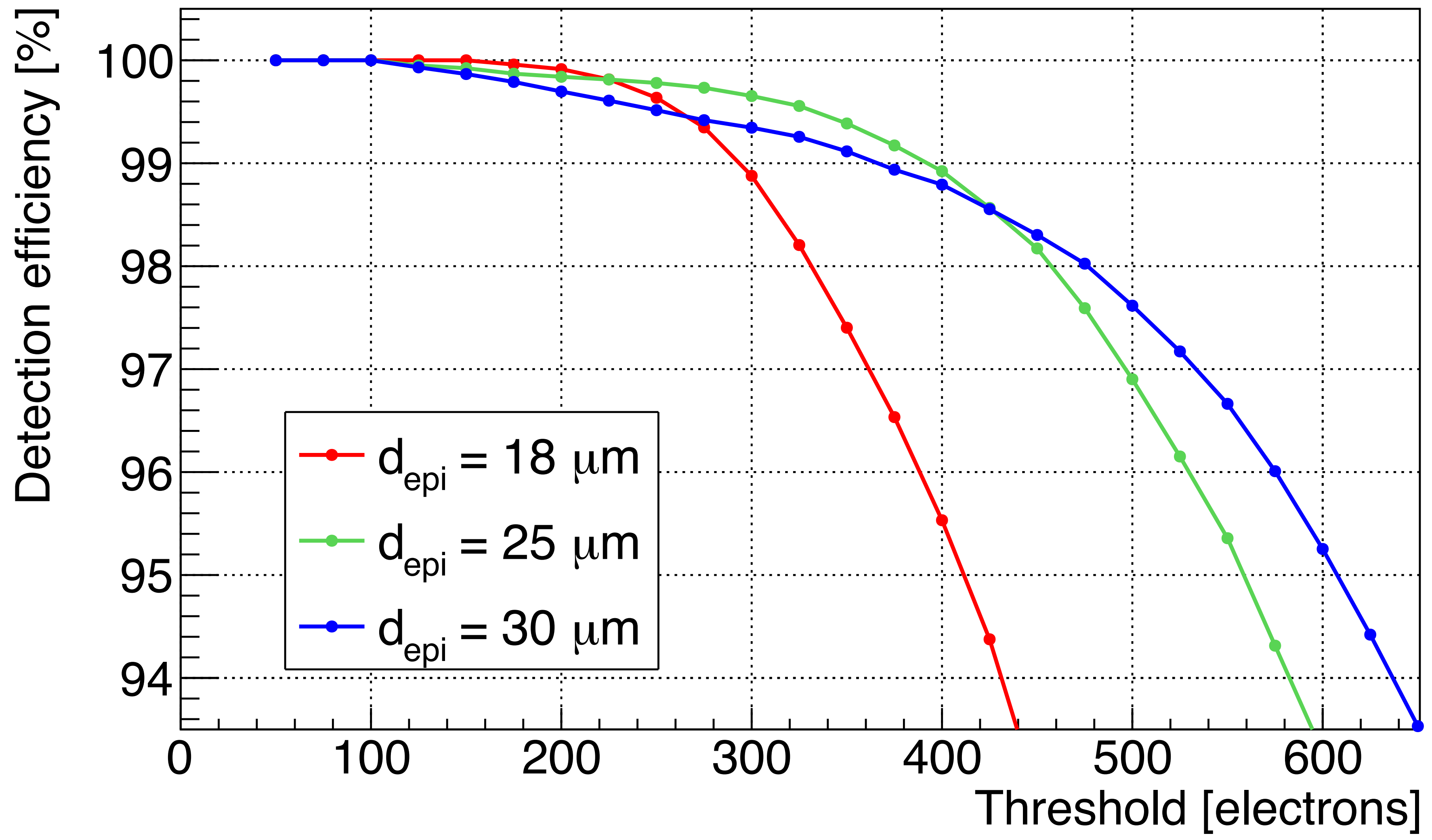




Cluster size

Charge collected by seed pixel



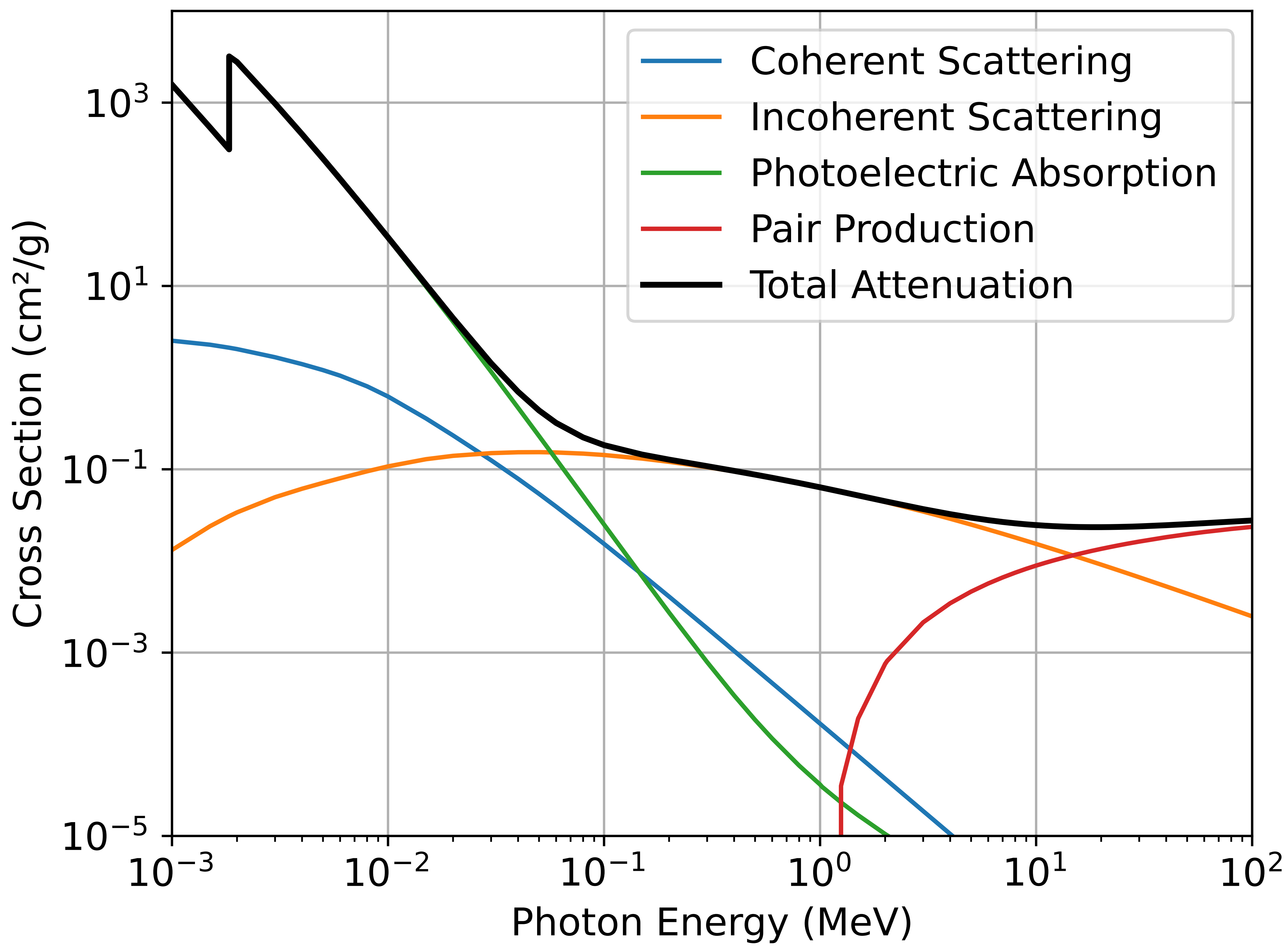


Detection efficiency

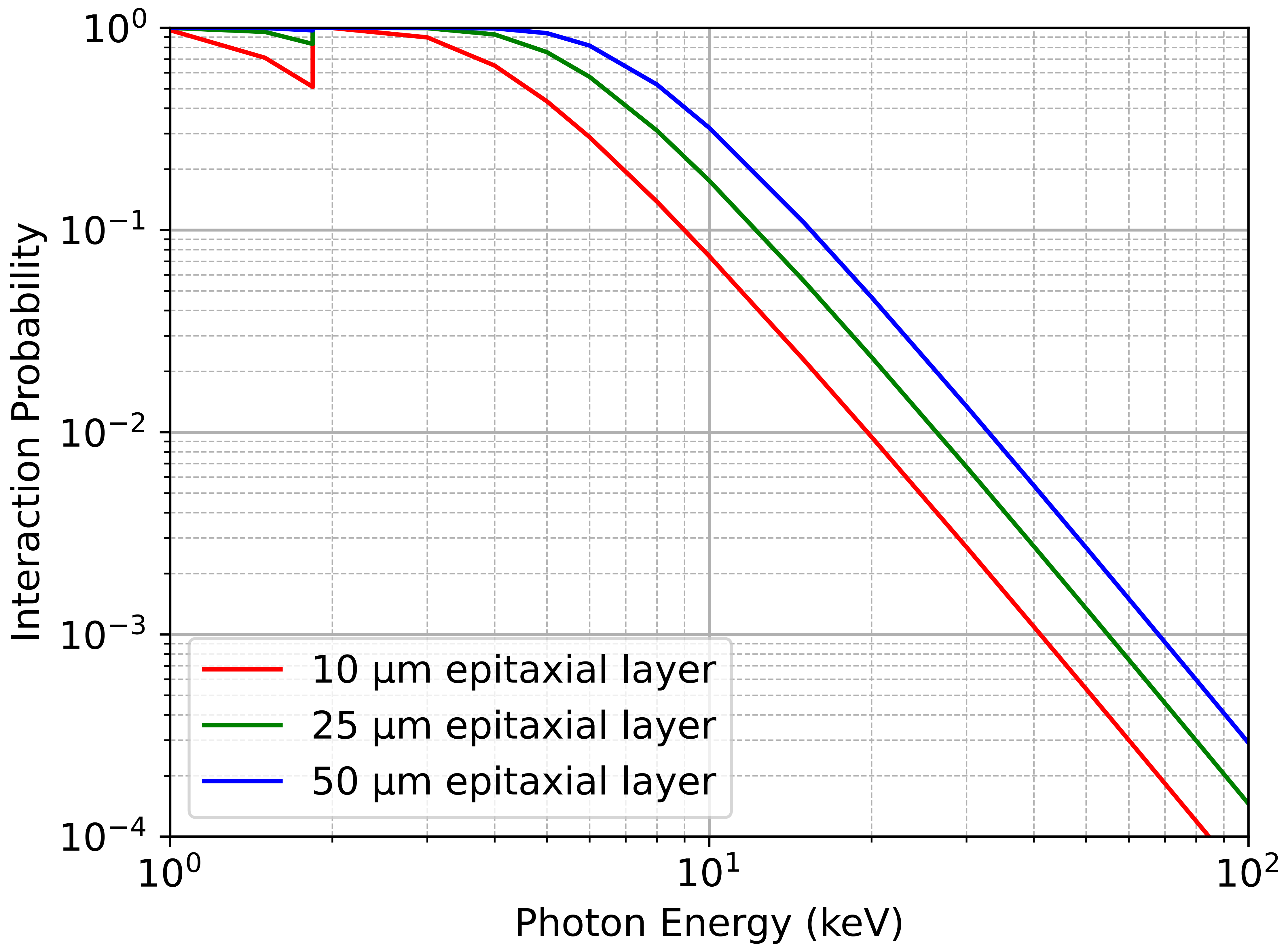
Data from the Investigator chip

Energy loss of electromagnetic radiation

Photon interaction cross section in silicon

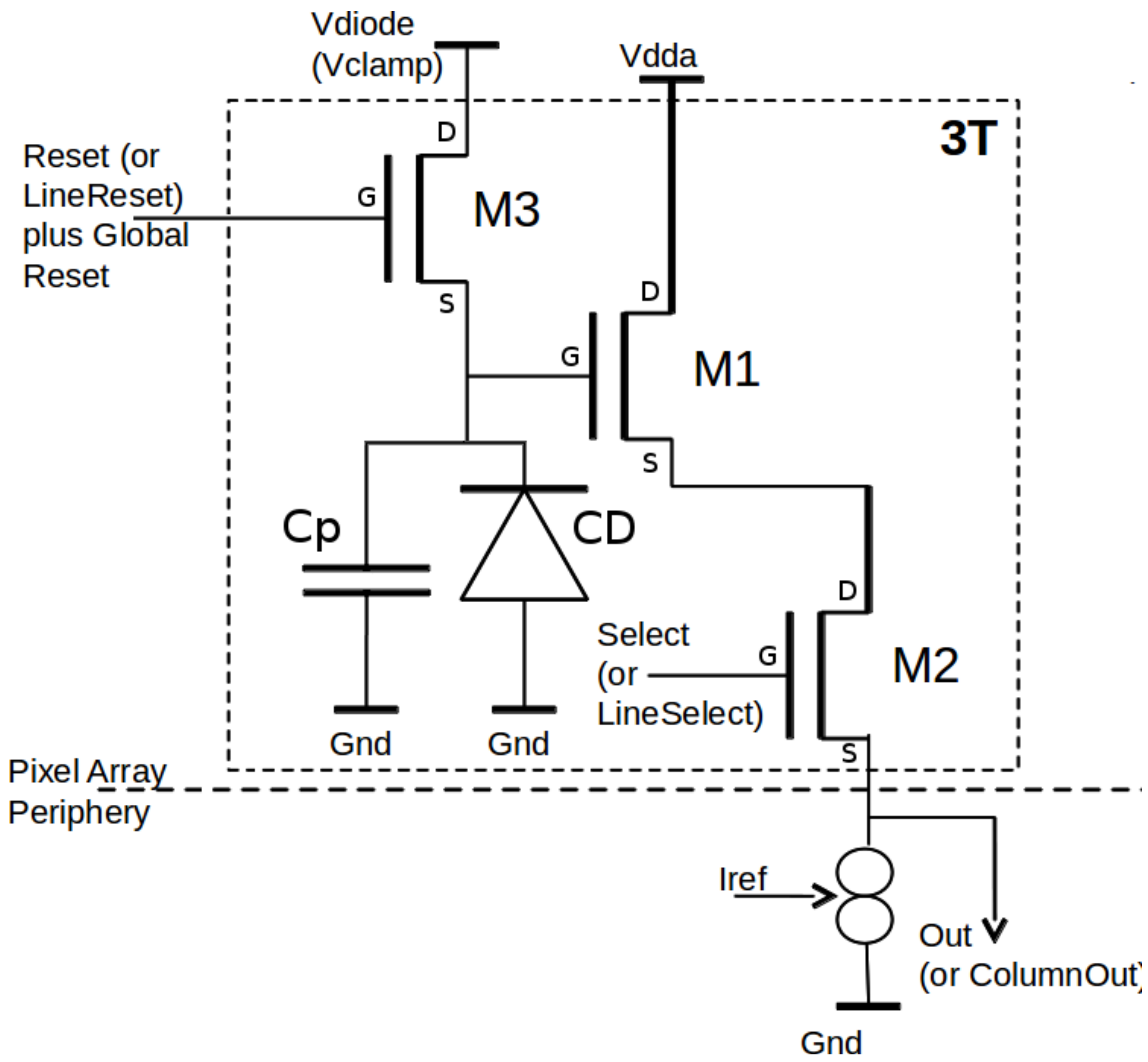


Photoelectric interaction probability

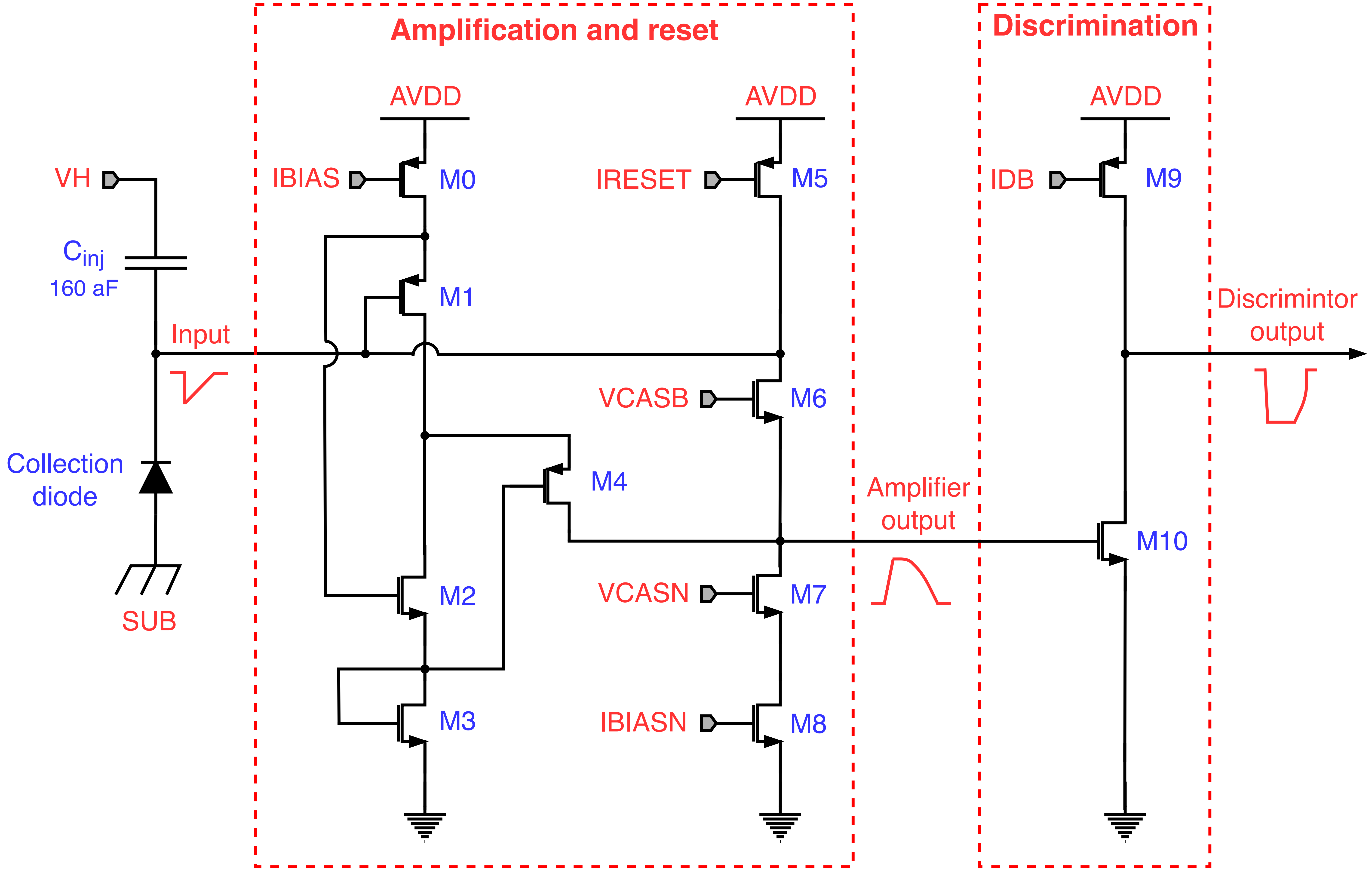


Analog in-pixel front-end

Direct analog readout



With in-pixel amplification & digitization



Extracting analog signal

- **Direct analog readout**
  - ***Precise*** charge information for ***every*** pixel
  - Slow readout (row-by-row digitization)
  - Large bandwidth (# pixels × # ADC bits × ~2 samples)

- **Oversampling discriminated signal**
  - ***Rough*** charge information for each pixel ***above threshold***
  - Very fast readout (zero suppression, but requires high speed data transmission)
  - Moderate bandwidth (# ***hit*** pixels × # samples)

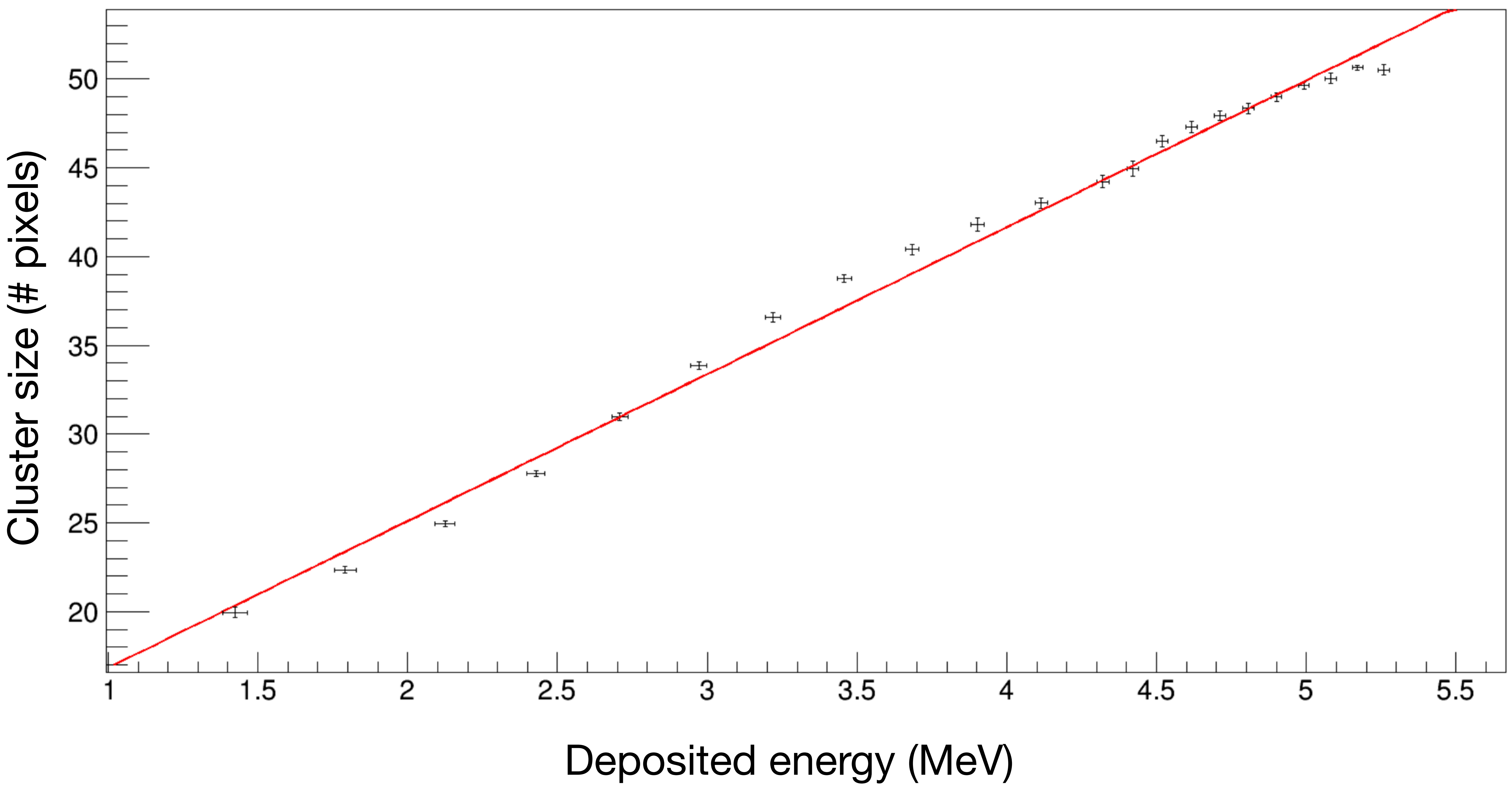
- **Time-over-threshold**
  - Charge information for ***some*** pixels above threshold
  - Readout compromises between analog power consumption, precision and dead time
  - Contained bandwidth (# ***hit*** pixels **+** ToT information for some pixels)

Examples & ideas

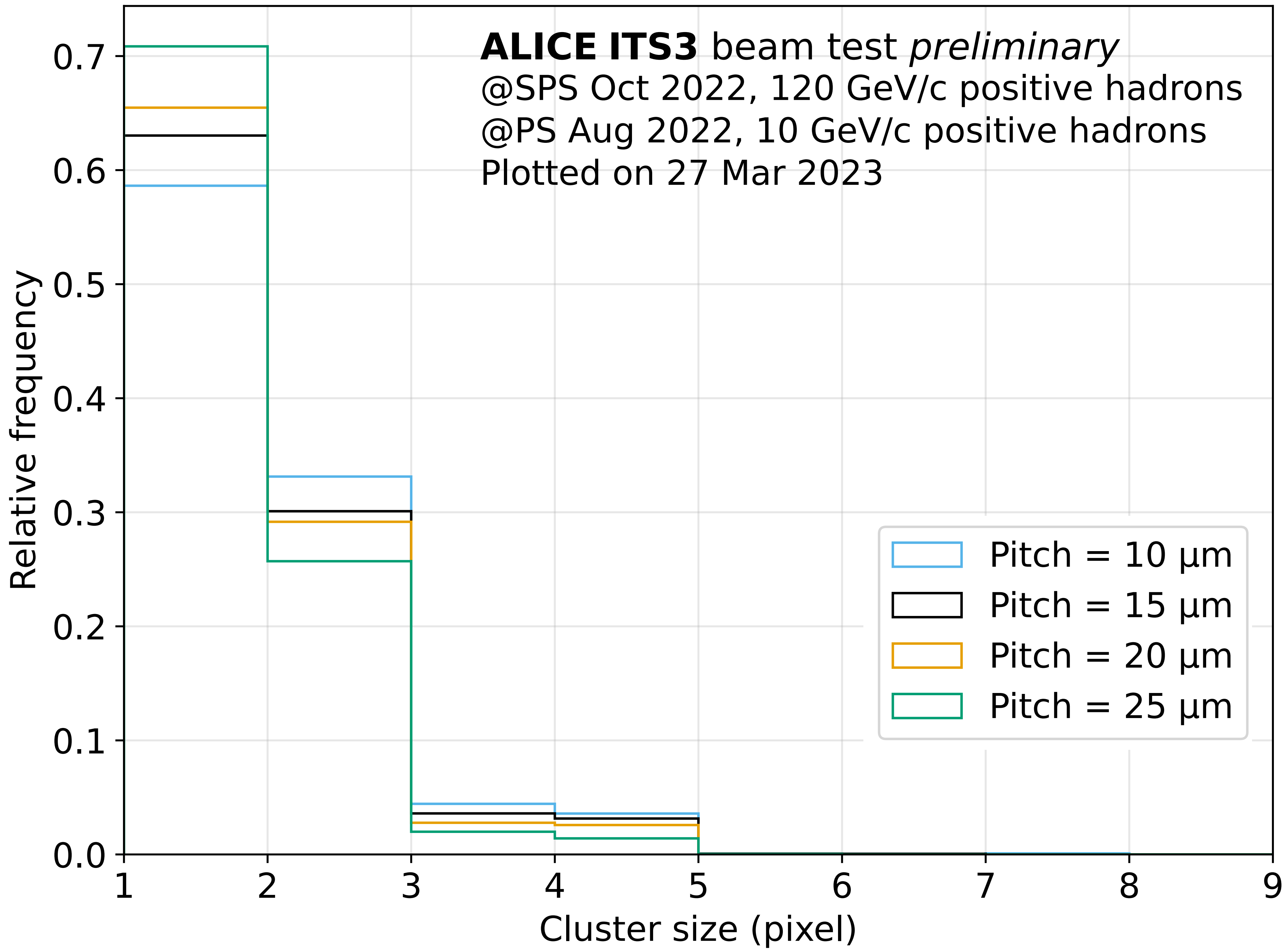
- **ALPIDE ("color runs")**
  - Oversampling relying on high speed transmission and low hit occupancy
  - Large protocol overhead
- **DPTS/MOST**
  - Time-encoding position and ToT of a group of pixels sharing a common line
  - Requires one high precision, continuously active TDC per output line
  - Virtually no dead time, but sharing a line can result in "corrupt" data
- **MOSS**
  - Exploiting readout features - ToT information only for subset of random pixels
  - Dead time proportional to analog front-end pulse length
- **Some possible future concepts:**
  - Column/region ToT (MOSS-like) - works in very low occupancy cases and low charge sharing
  - Column & row ToT (Strip-like) - can mitigate above disadvantages

Inferring deposited energy from cluster size

Measurement with 241-Am and pALPIDE-1



Measurement with MIPs and APTS



Inferring deposited energy from cluster size

- Very **rough** proxy for deposited energy
- Cluster size correlated with deposited energy AND incident position within pixel
  - **Statistical measurement**
- Benefits from more charge sharing (lower electric field in epi-layer)
  - Lower radiation hardness
  - Potentially lower detection efficiency
- **Precise simulations needed** to assess benefit for a specific physics measurement and detector configuration
  - The charge collection must be simulated starting from TCAD based on exact doping profiles

Summary

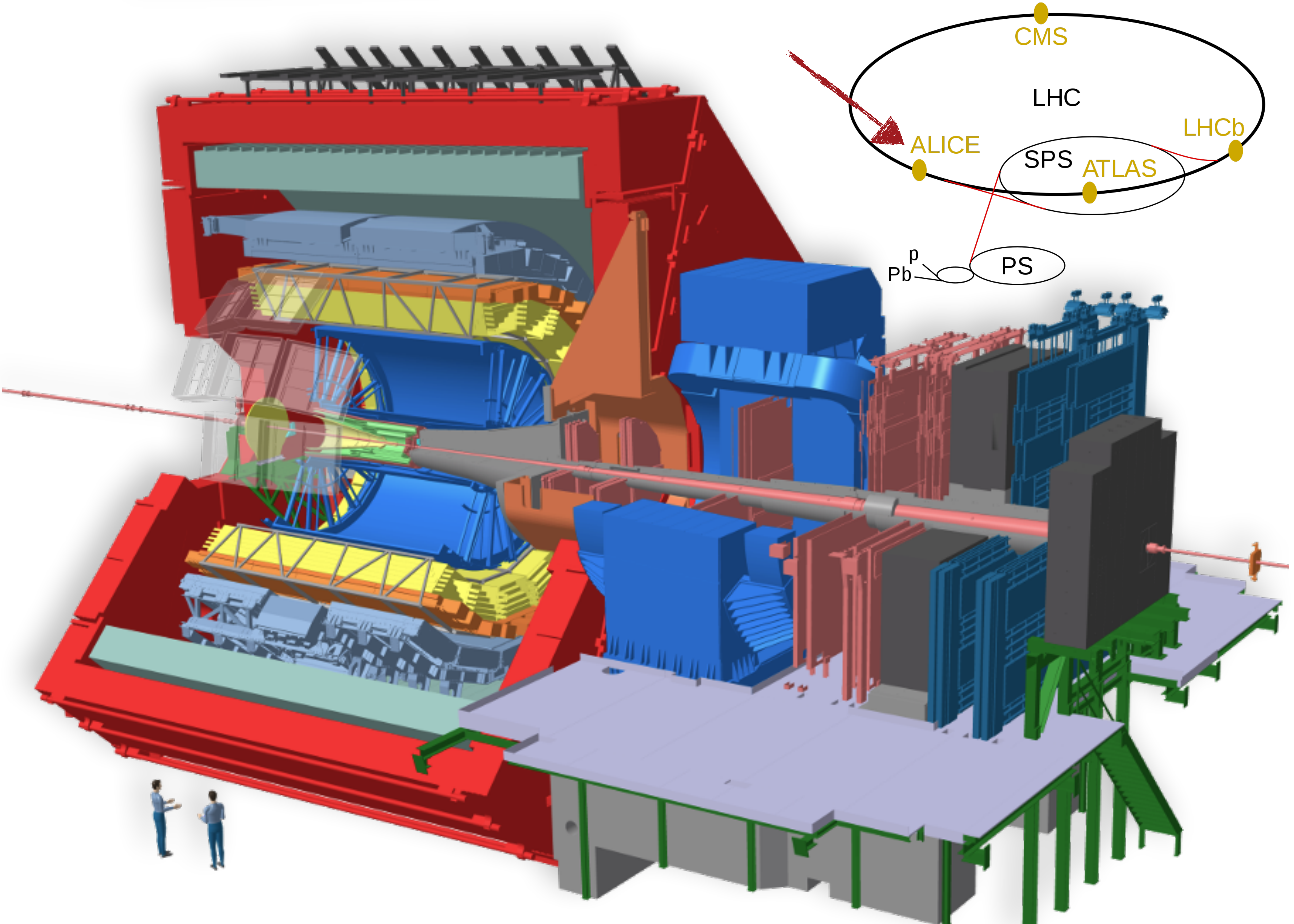
- MAPS are great for tracking at high multiplicities
- **Thin epi-layer** limits energy resolution and photon interaction probability
- Thick epi-layers for inferring deposited energy from cluster size is orthogonal to radiation hardness
- MAPS-based detector capable of energy measurement must be designed with specific application in mind
  - No of-the-shelf solution & no one-size-fits-all solution
  - **Precise physics, device, and readout simulations** needed to drive the detector concept

Energy measurement challenges by field

- **High-energy physics**
  - Readout rate and bandwidth
- **Astro-particle physics (space-borne experiments)**
  - Power consumption
- **X-ray imaging**
  - Interaction probability

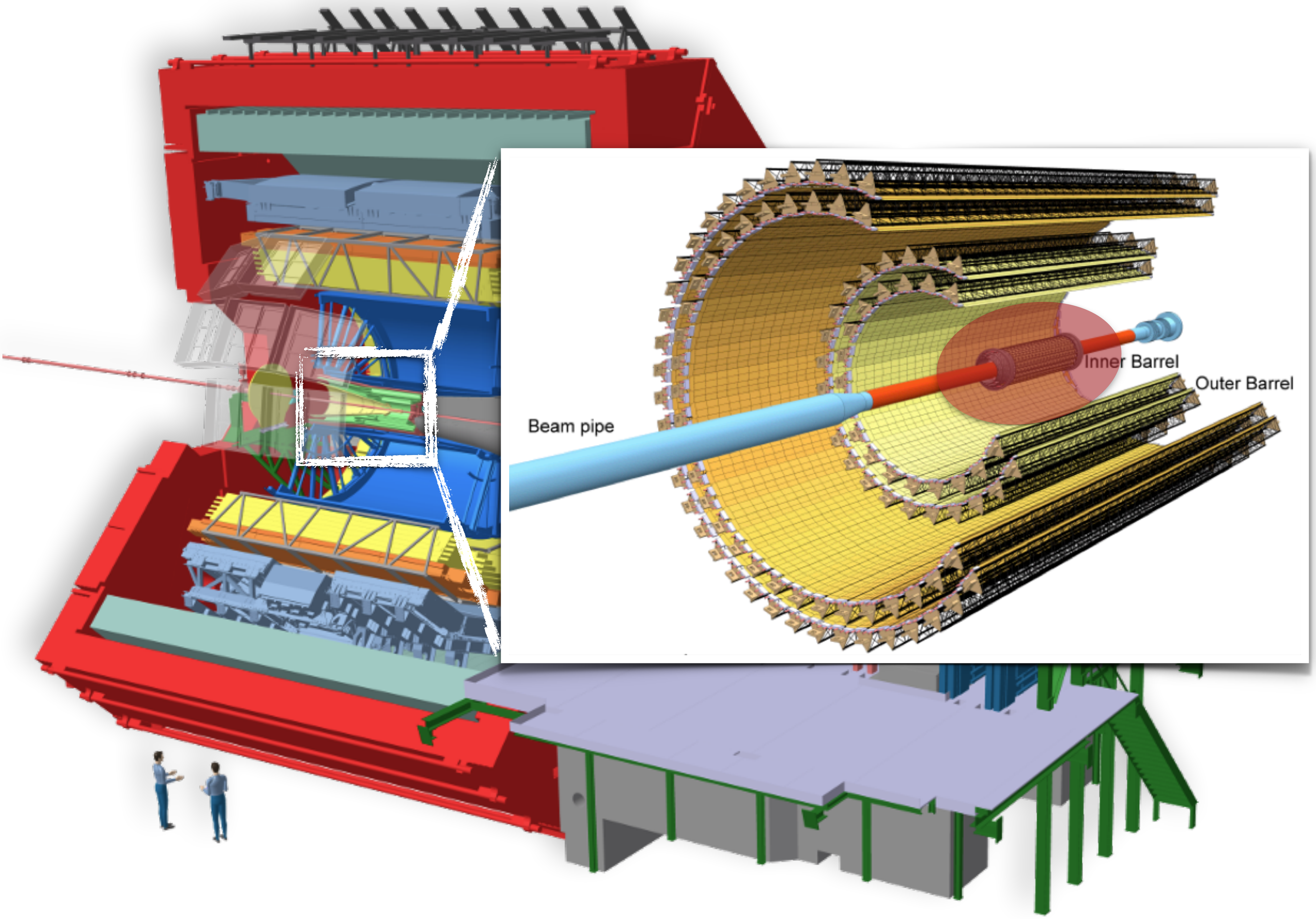

Thank you!
…really the end!

A Large Ion Collider Experiment



- Study of physics of strongly interacting matter at extreme energy densities (QGP) at CERN LHC
- Optimized for:
  - particle identification
  - large particle multiplicities
  - particles with low momenta (p_T < 1 GeV/c)

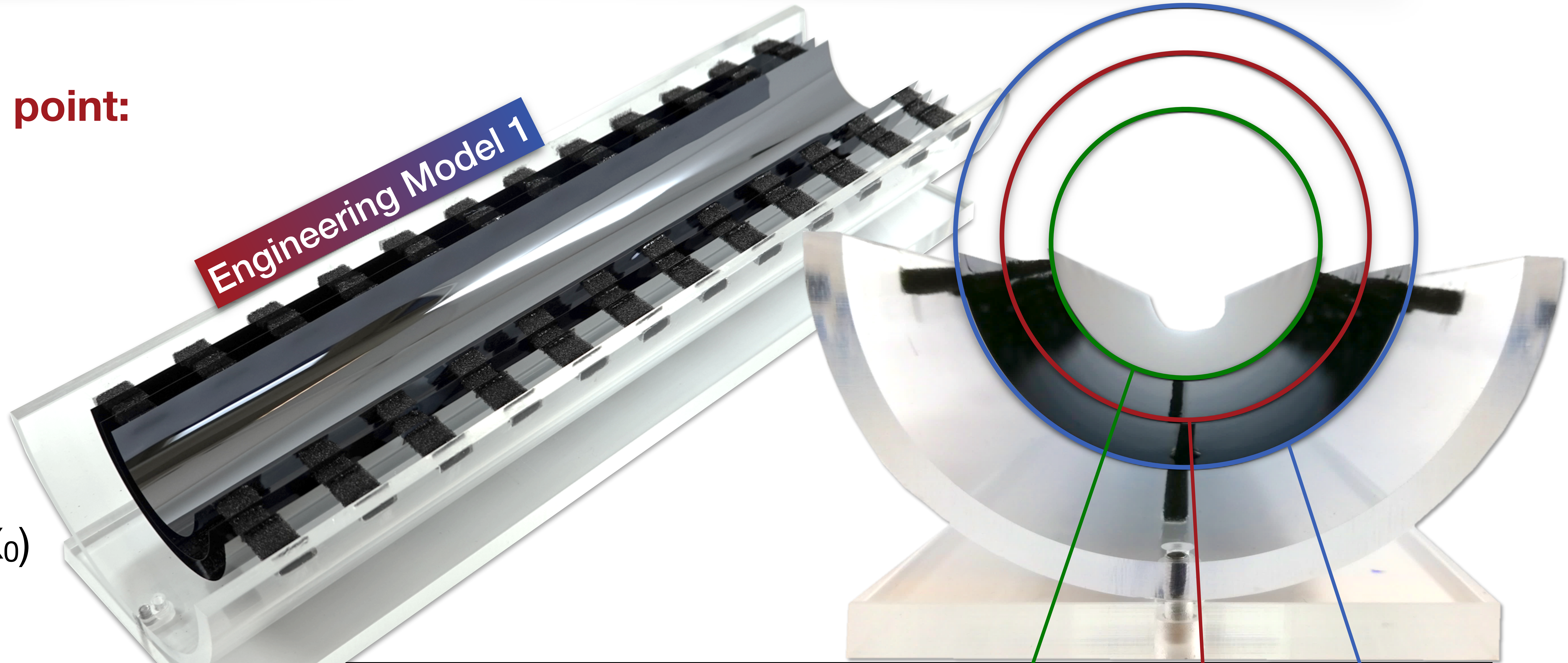
ALICE Inner Tracking System



- New ITS2 commissioned and operational since 2021
  - 10 m² MAPS detector
  - 24000 ALPIDE chips
  - 12.5 Giga pixels
- ITS3 aims at further increasing the detector performance by replacing the inner-most layers of ITS2 during the next Long Shutdown (2026-2028)

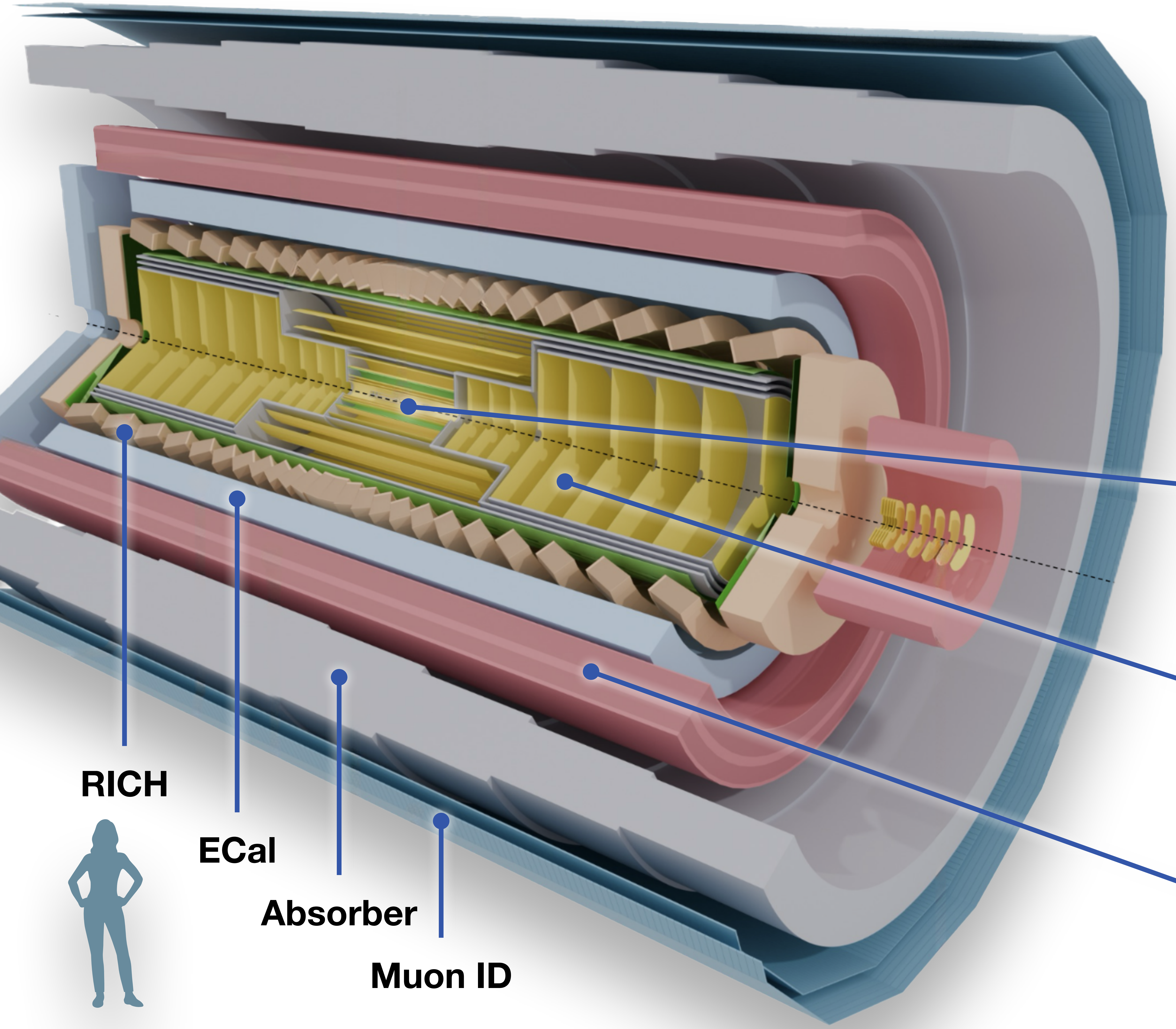
ITS3 layout

- **Getting closer to interaction point:**
  - Beam pipe radius
    18.2 → 16.5 mm
  - Layer 0 position
    23 → 19 mm
- **Reducing material budget:**
  - Beam pipe thickness
    800 → 500 µm (0.14% X_0)
  - Layer thickness
    0.36 → < 0.09% X_0
- Assuming:
  - Power consumption < 40 mW/cm^2
    → air cooling
  - Power supplied only via chip edges



Beam pipe inner/outer radius (mm)	16.0/16.5		
Layer parameters	**Layer 0**	**Layer 1**	**Layer 2**
Radial position (mm)	19.0	25.2	31.5
Pixel sensor dimensions (mm²)	266 × 59	266 × 78	266 × 98
Number of pixel sensors	2		
Pixel size (µm²)	20.8 × 22.8		

ALICE 3

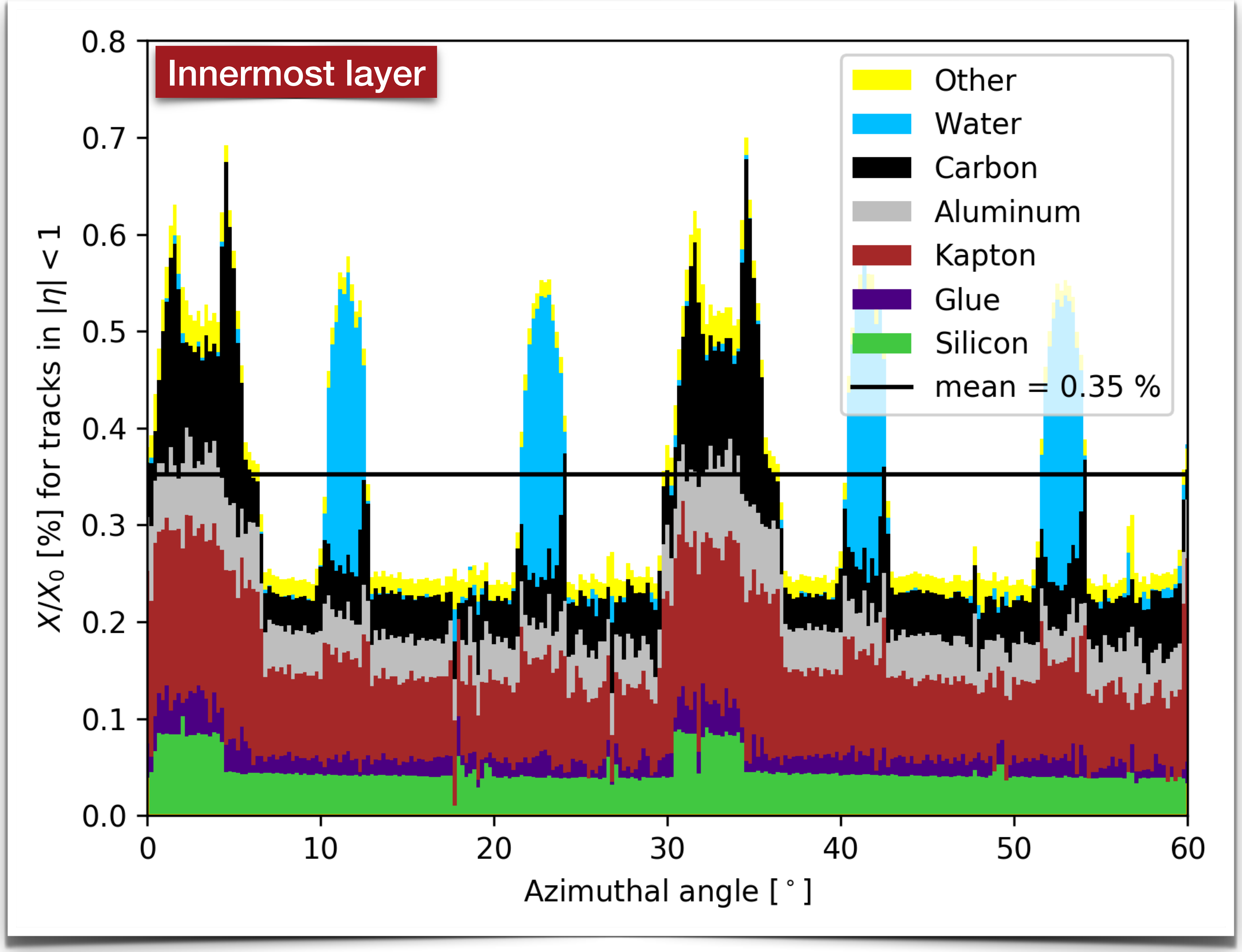


- Planned for LHC Runs 5 & 6 (2035++)
- Ultra-lightweight, large acceptance MAPS tracker with excellent vertex resolution and PID
- First three tracking layers within the beam pipe (“Vertex Detector”)
- ~66 m² total tracker surface with 10 cylindrical layers + disks (“Tracker”)
- Superconducting solenoid - 2 T field

MAPS vertex detector specifications

	State-of-the-art	Current R&D	R&D starting (construction in 2030s)	
	ALICE ITS2	**ALICE ITS3**	**ALICE 3 Vertex Detector**	**ALICE 3 Tracker**
Detection efficiency (%)	>99.9	>99		
Position resolution (μm)	<4.5	5	2.5	10
Pixel size (μm^2)	29×27	$O(20\times20)$	$O(10\times10)$	$O(50\times50)$
Time resolution (ns RMS)	$O(1000)$	$O(1000)$	100	
Fake hit rate ($pixel^{-1}$ $event^{-1}$)	$\ll 10^{-7}$	$<10^{-6}$	$<10^{-7}$	
Power consumption ($mW\ cm^{-2}$)	40	40	70	20
Particle hit density ($MHz\ cm^{-2}$)	2	5.8	120	0.8
Non-ionizing energy loss (1 MeV n_{eq} / cm^2)	1.7×10^{12}	1×10^{13}	1×10^{16}	6×10^{12}
Total ionizing dose (Mrad)	0.3	1	300	3
Material budget (%X/X_0 per layer)	0.33 / 1.1	0.09	0.1	1
Total detector surface (m^2)	10	0.12	0.13	66

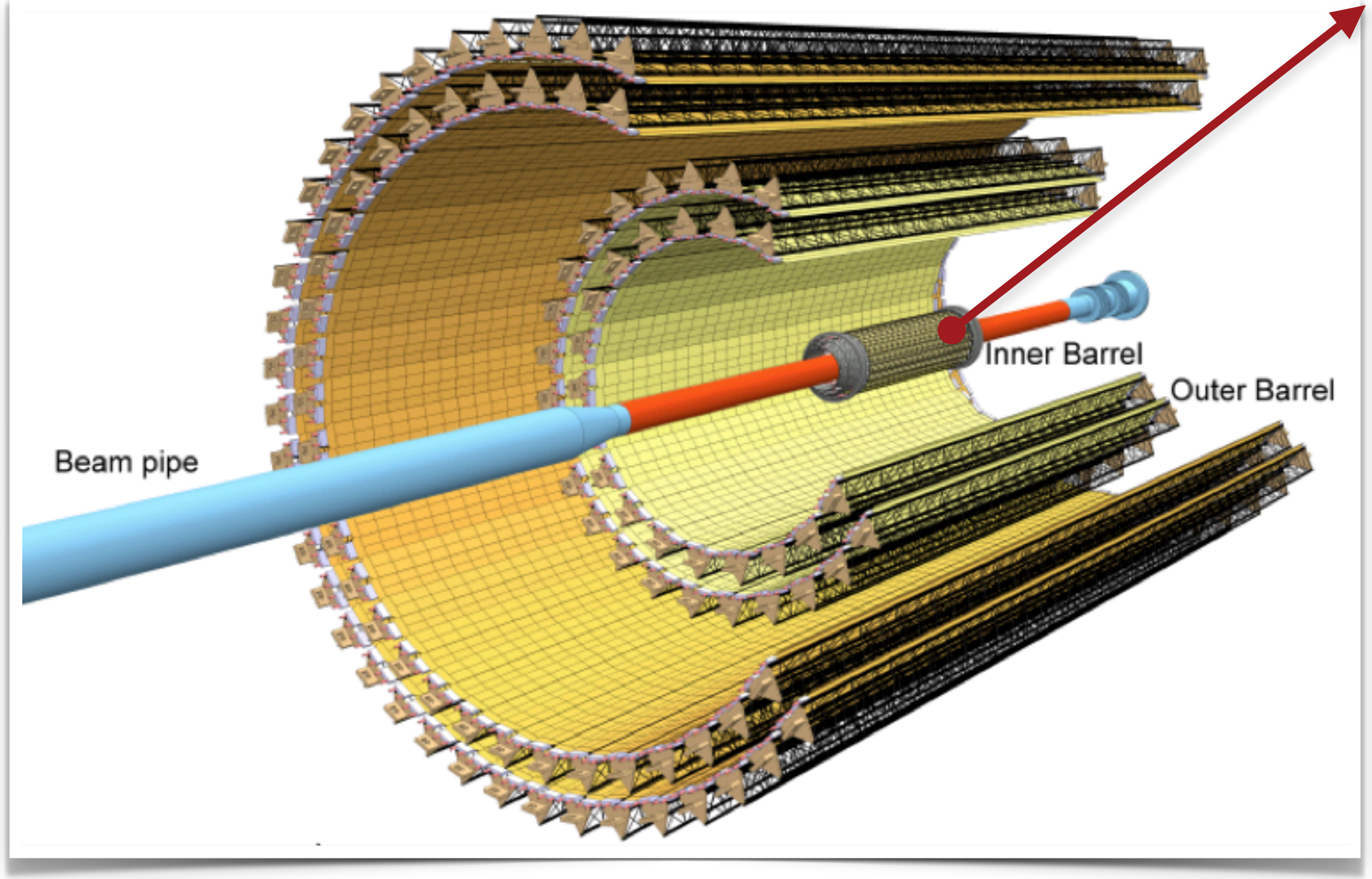
Material budget



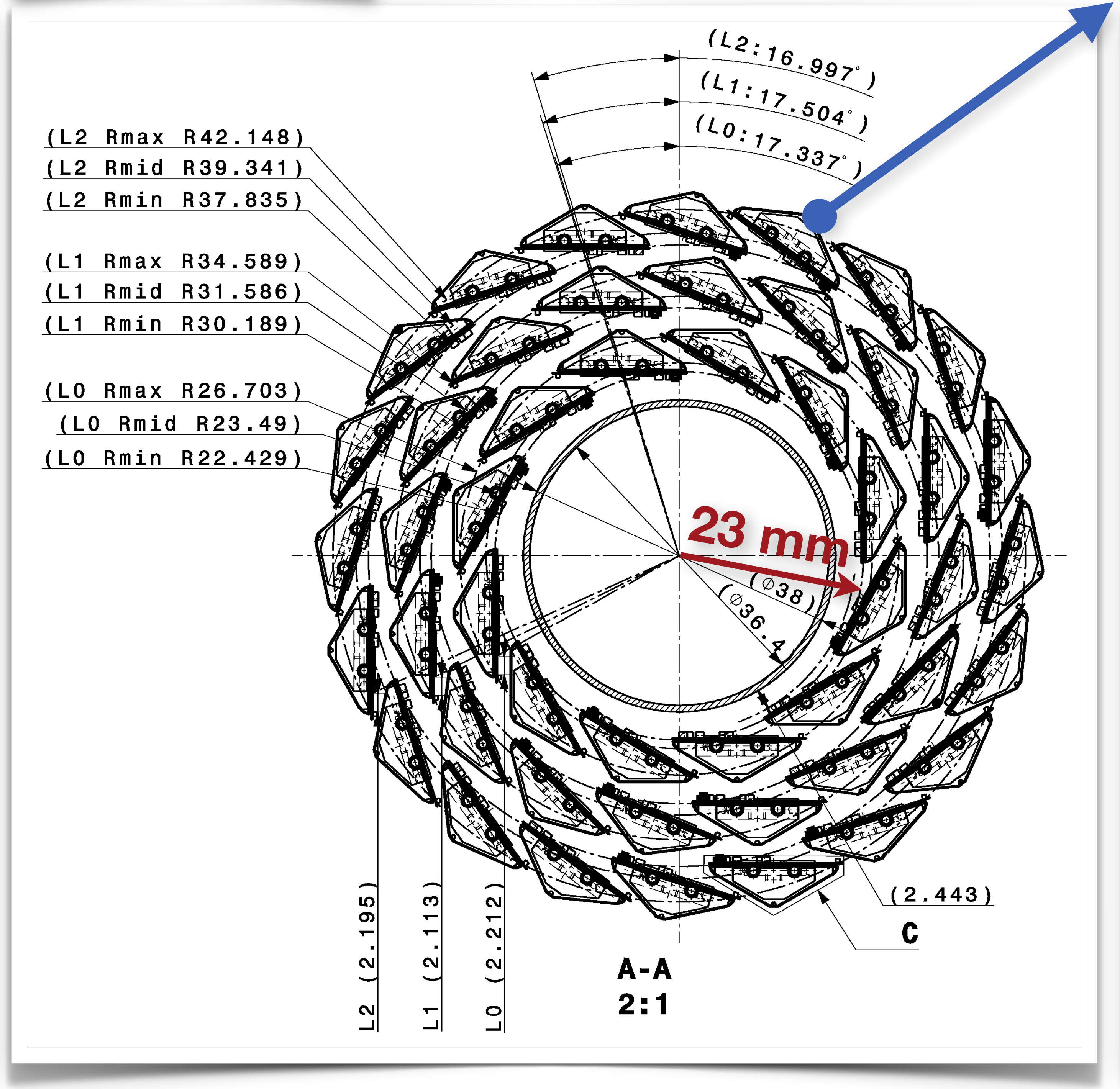
- Observations:
  - Si makes only 1/7-th of total material budget
  - Non-uniformity due to support, cooling & overlaps
- Removal of water cooling:
  - If **power consumption < 40 mW/cm²**
- Removal of the circuit board for power & data:
  - If **integrated on chip**
- Removal of mechanical support:
  - **Self-supporting curved structure**

How to improve on ITS2?

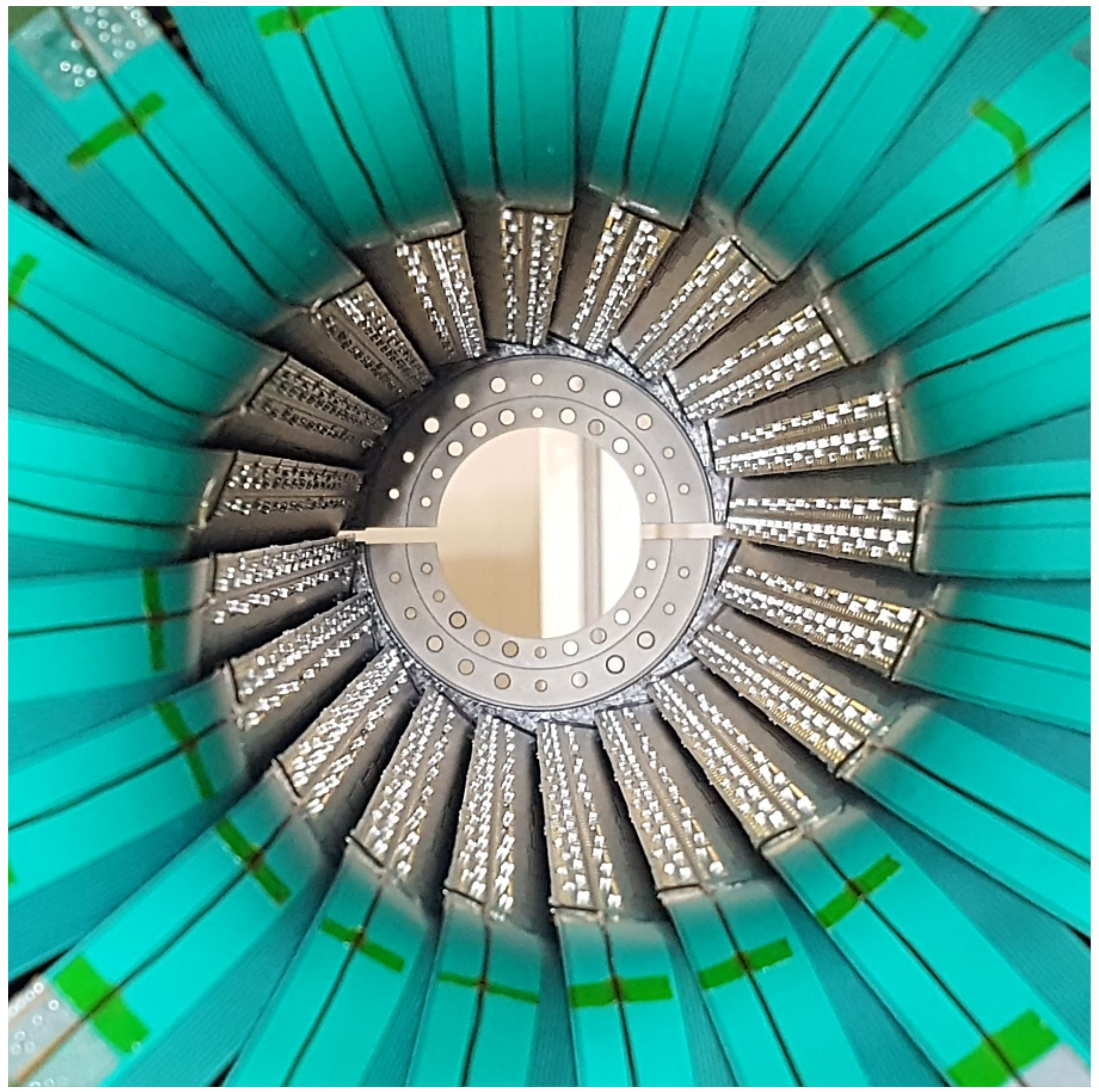
ITS2



Inner barrel



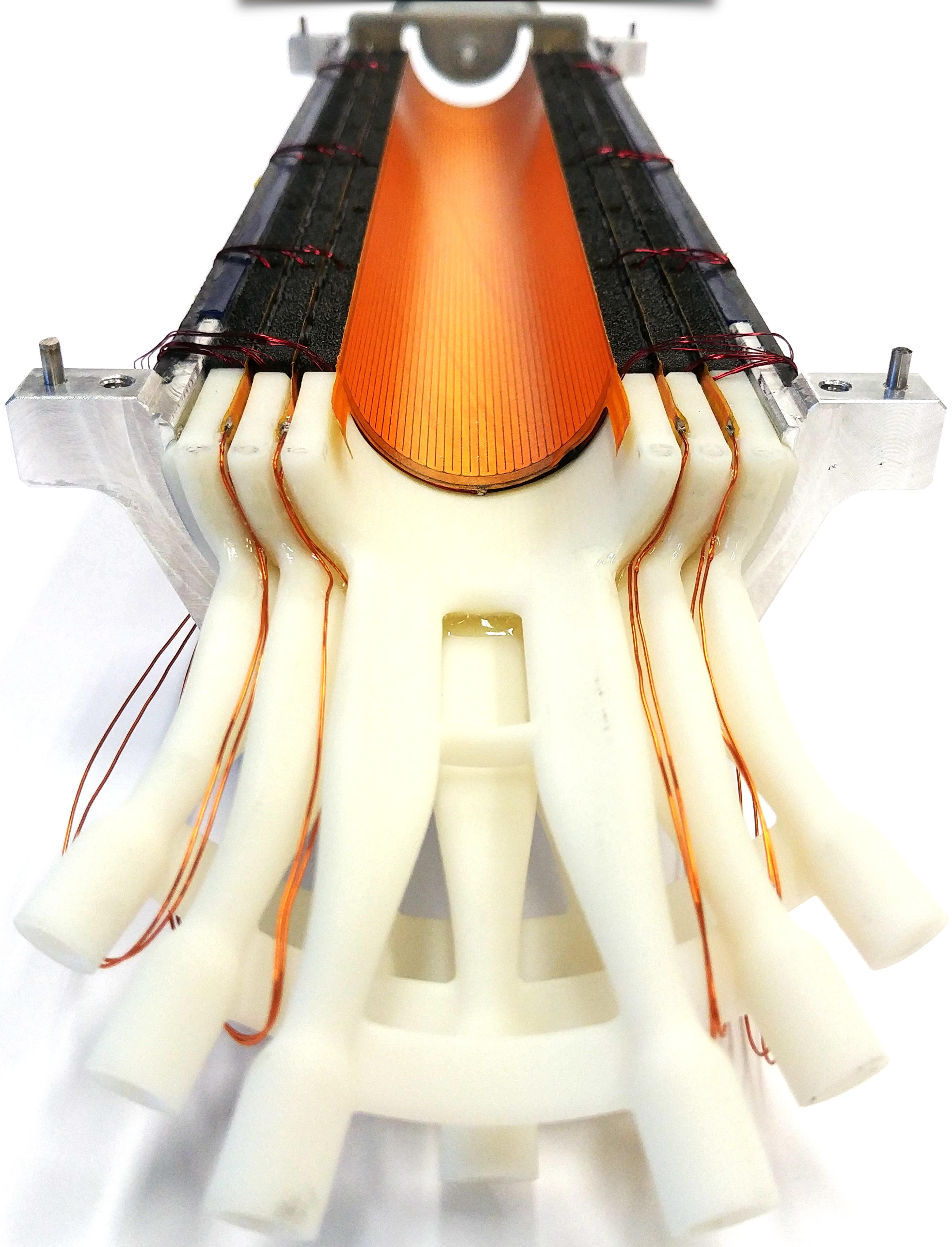
Layer 2 (20 staves)

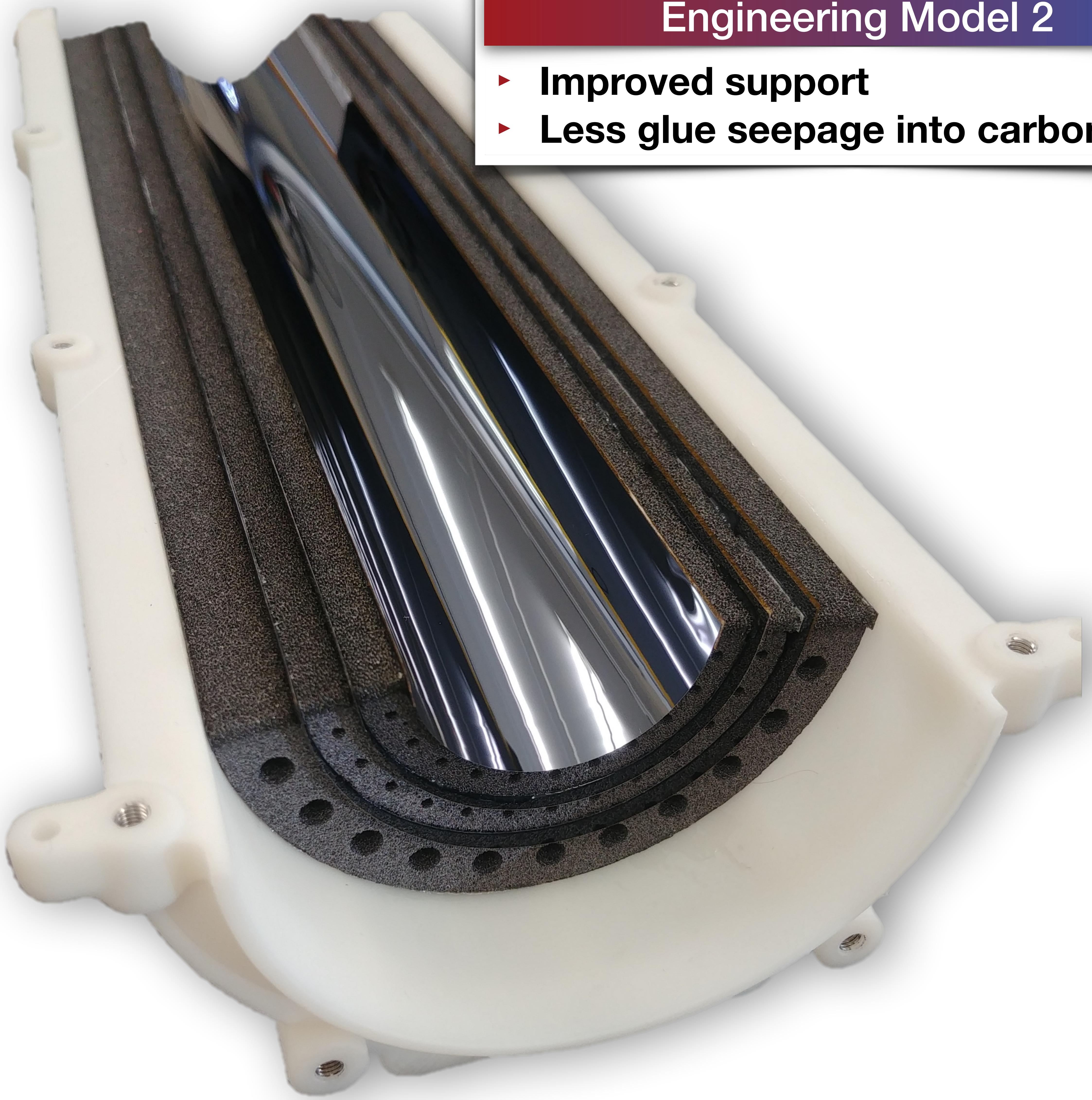


- ITS2 is state-of-the-art MAPS detector
- Ultralight but densely packed → **Can the material be further reduced?**
- **Can we get closer to the interaction point?**

ITS3 mechanical models

Breadboard Model 3

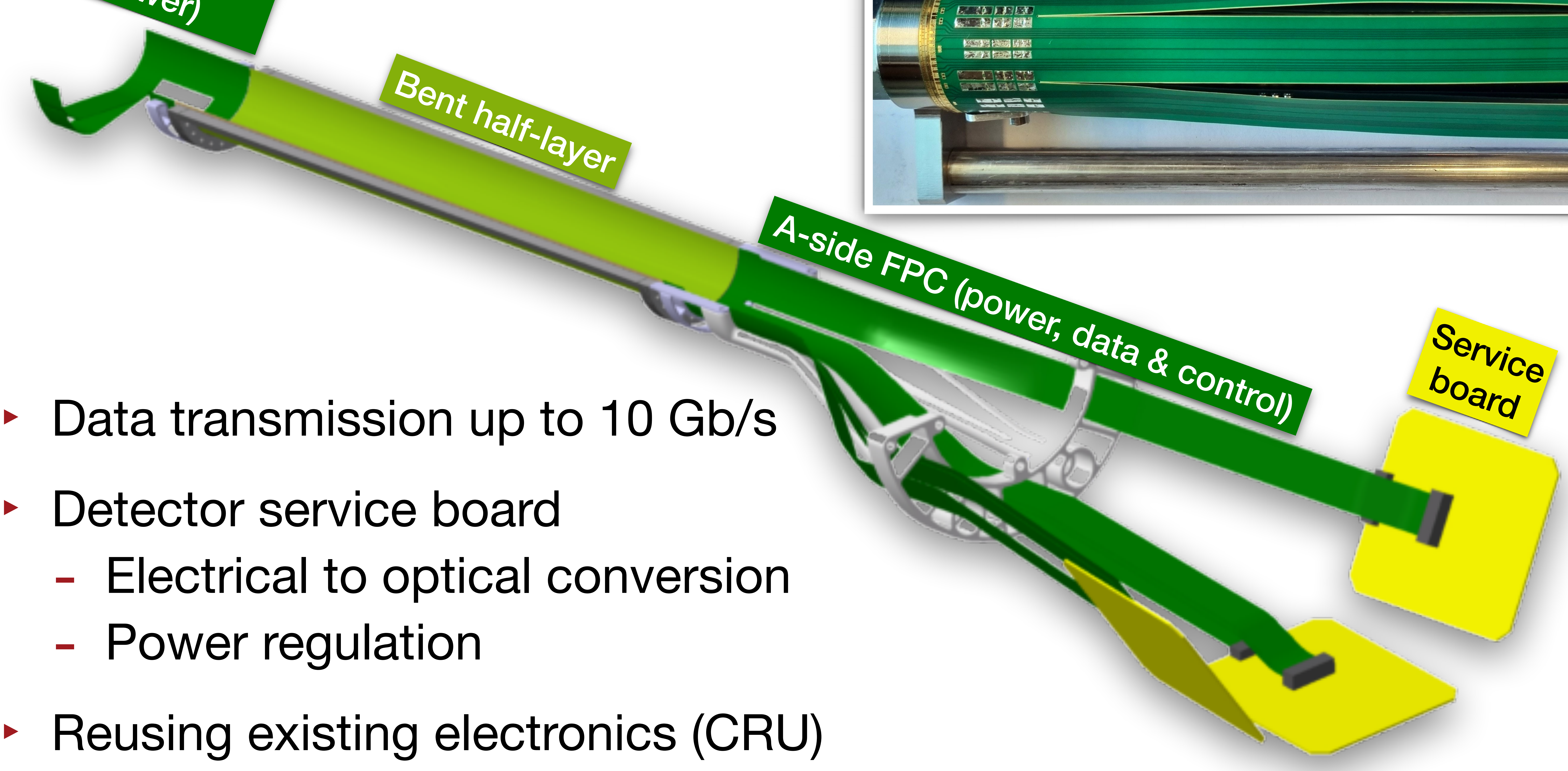


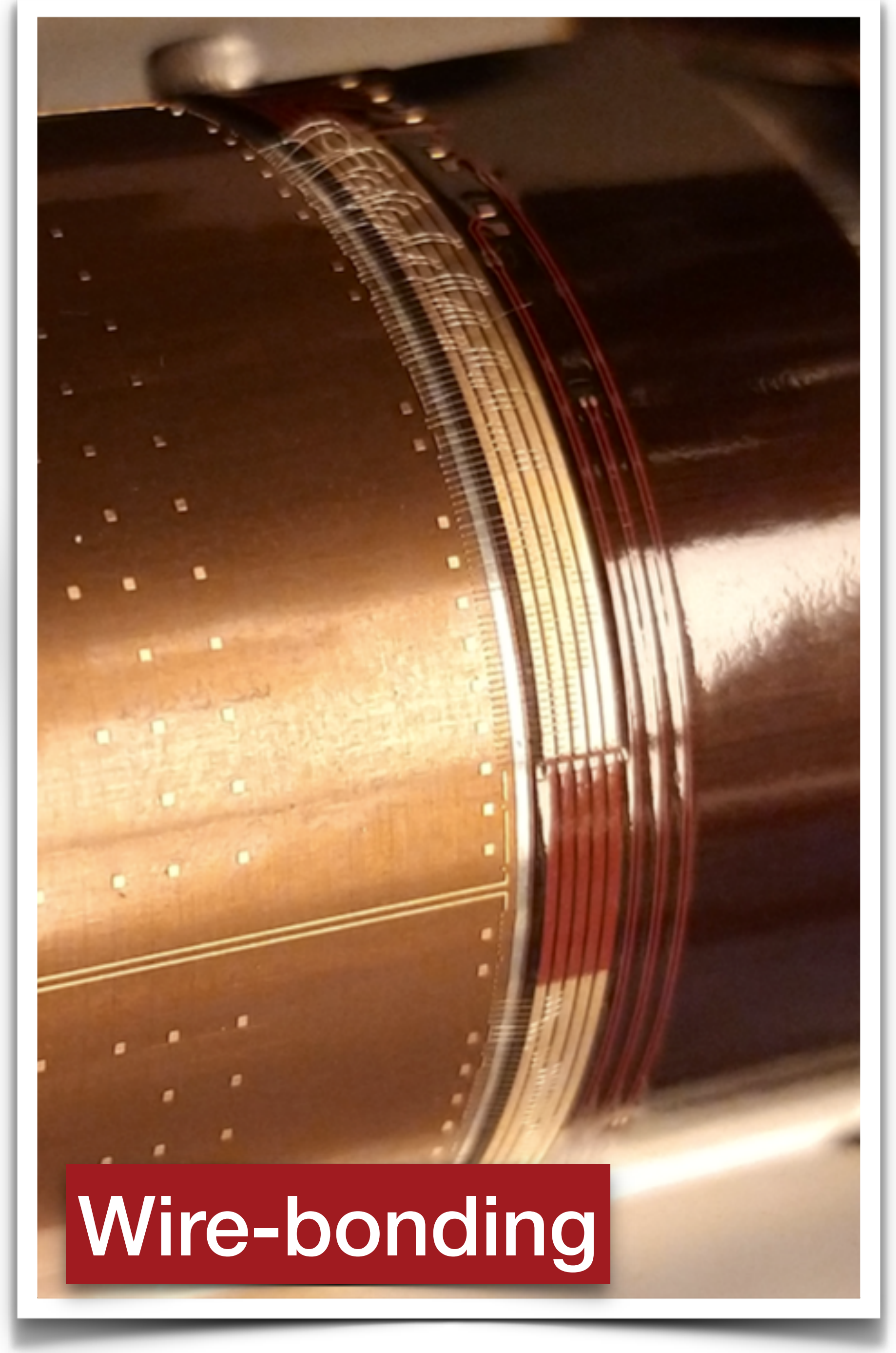


Engineering Model 2

- Improved support
- Less glue seepage into carbon foam

ITS3 integration and services

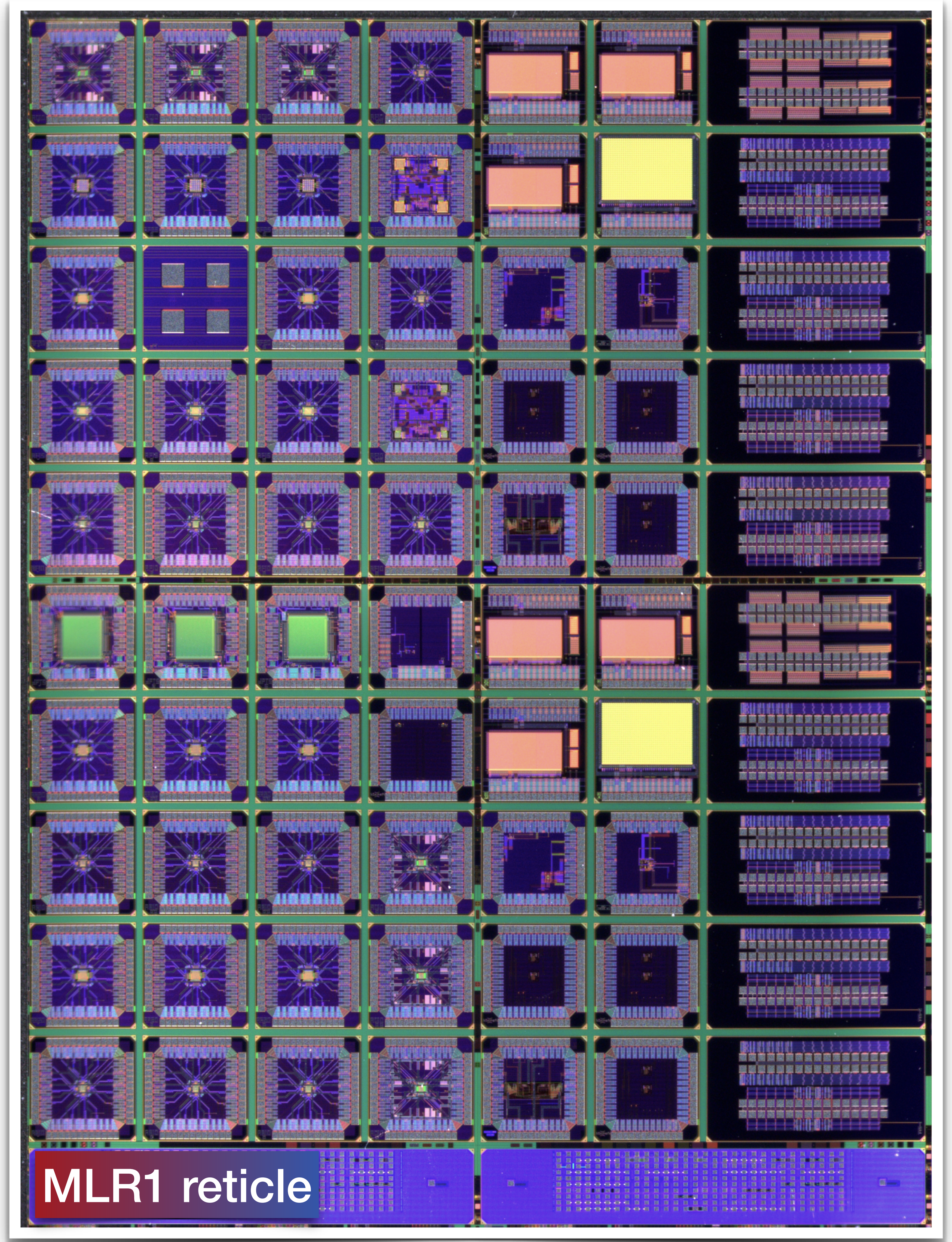




- Data transmission up to 10 Gb/s
- Detector service board
  - Electrical to optical conversion
  - Power regulation
- Reusing existing electronics (CRU)

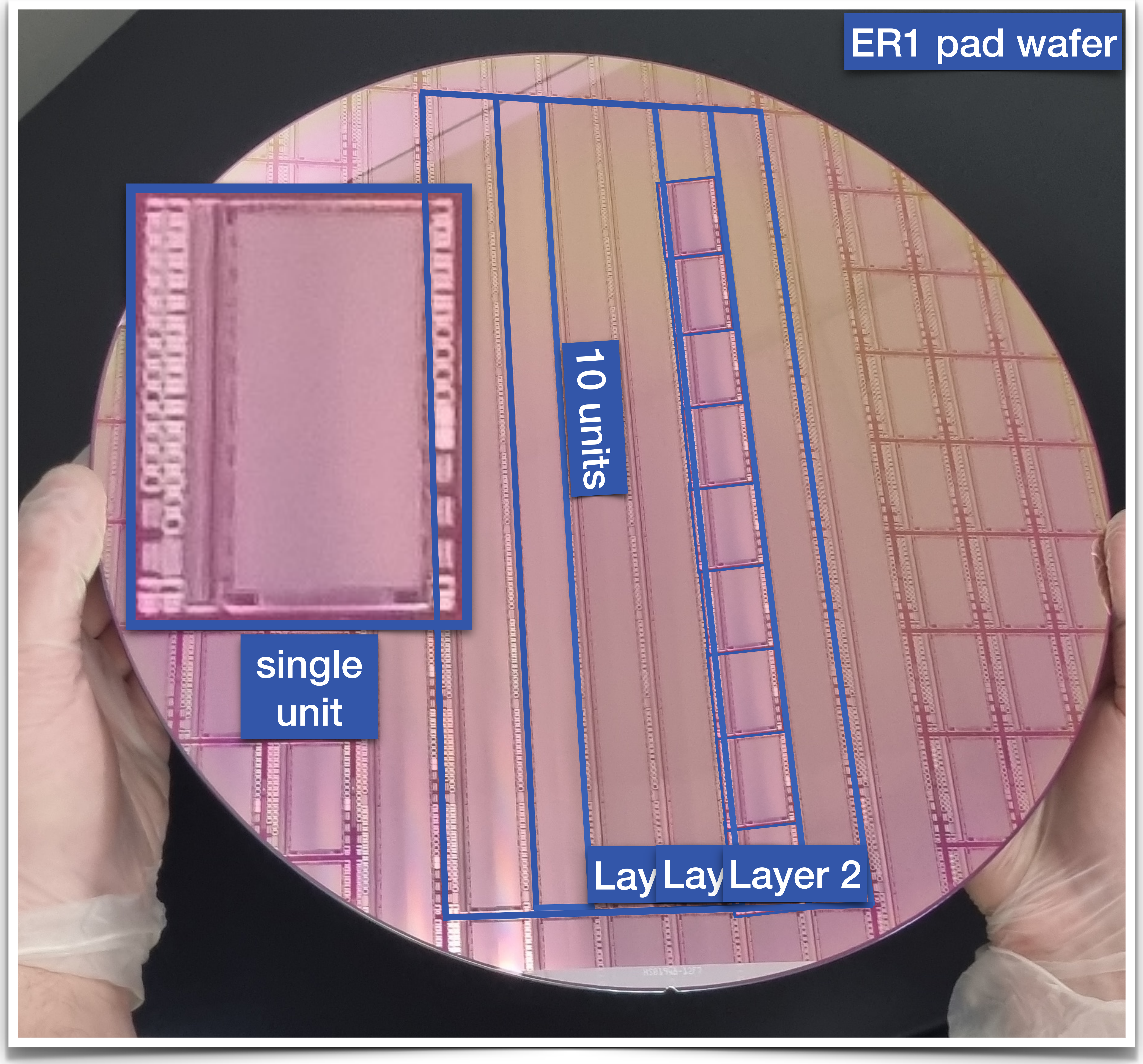
Technology qualification

- Joint effort of **ALICE ITS3** together with **CERN EP R&D**
- TPSCo 65 nm CMOS Imaging Sensor process
- **Key benefits** (over 180 nm technology in ITS2):
  - Smaller features/transistors: higher integration density
  - Smaller pitches
  - Lower power consumption
  - **Larger wafers** (200 → 300 mm)
- **MLR1 (2021)** → technology qualified
  - Comprehensive *first* submission: **55** prototype chips
- **ER1 (2023)** → stitched design validated
  - wafer-scale sensors + various prototypes
- **ER2 (2025)** → final wafer-scale chip

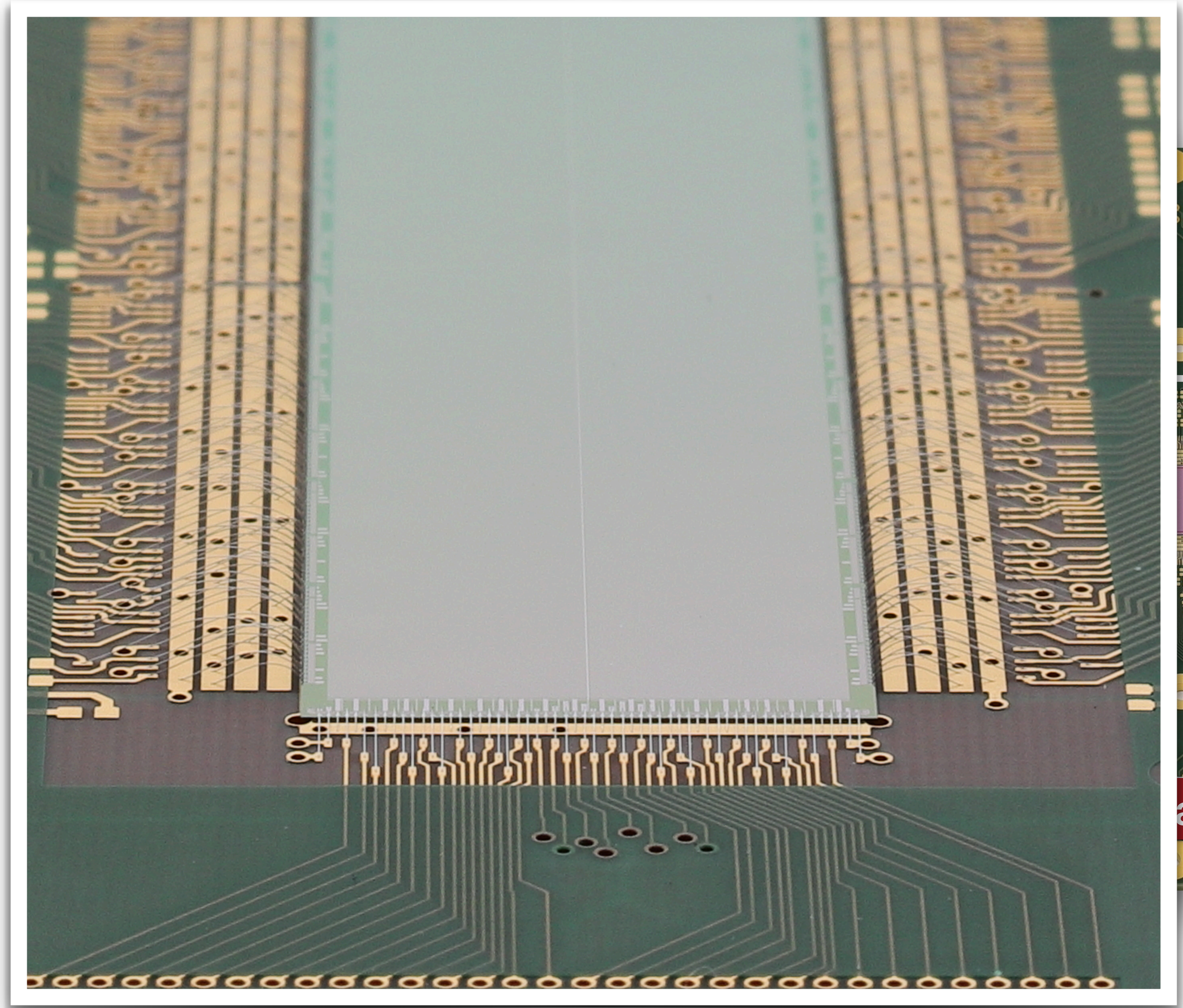


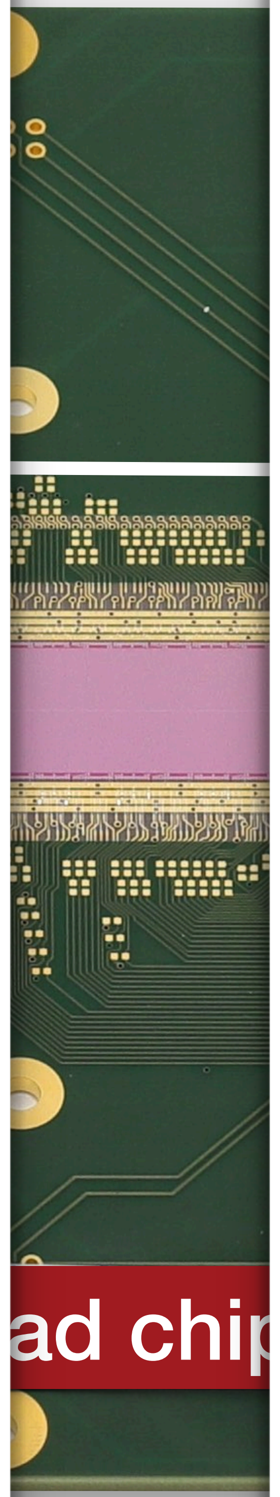
ER1: wafer-scale sensors

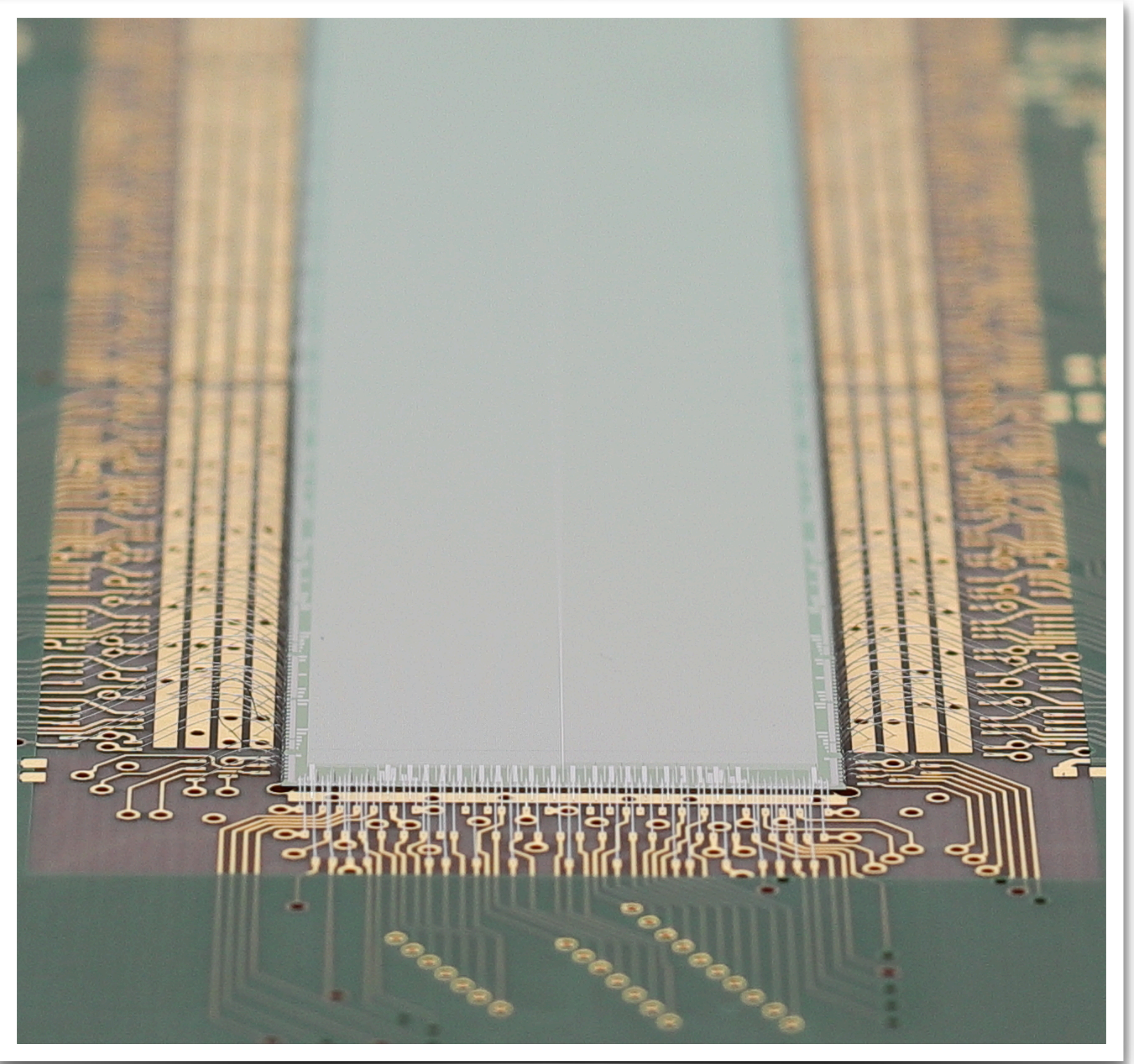
- First MAPS for HEP using stitching
  - one order of magnitude larger than previous chips
- "**MOSS**": 14 × 259 mm, 6.72 MPixel (22.5 × 22.5 and 18 × 18 μm^2)
  - conservative (less dense) design
- "MOST": 2.5 × 259 mm, 0.9 MPixel (18 × 18 μm^2)
  - more dense design
- Plenty of small chips (like MLR1)



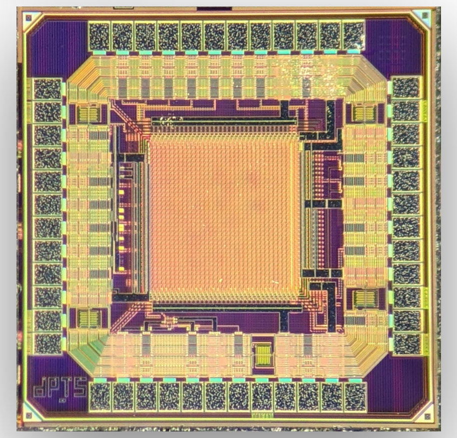
MOnolithic Stitched Sensor







Spatial resolution & radiation hardness



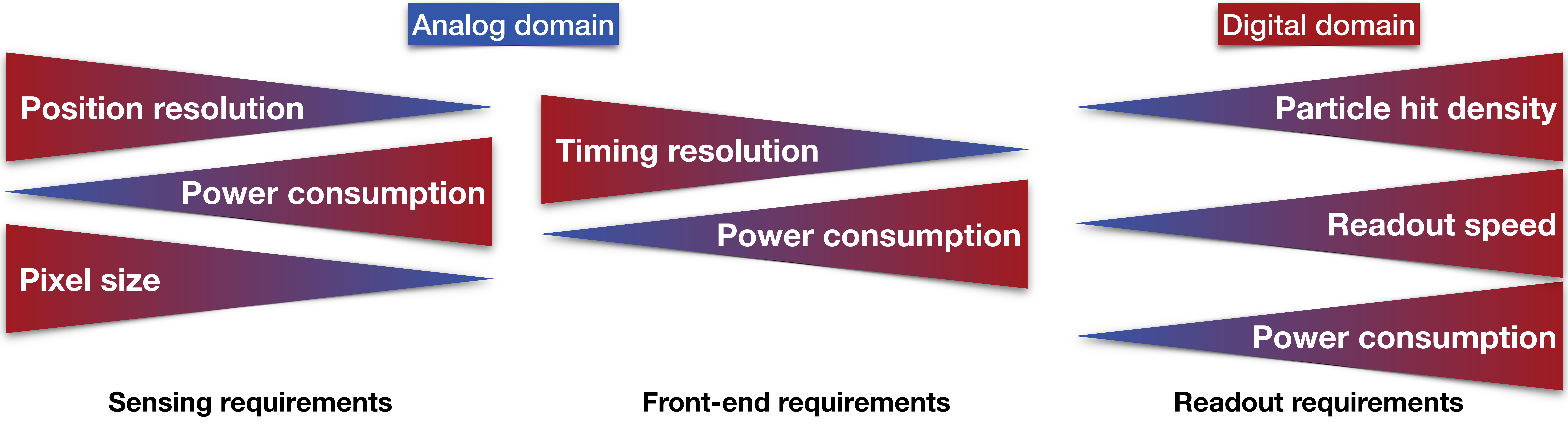
DPTS, 15 μm pixel pitch @ 20°C

No performance degradation after irradiation

doi.org/10.1016/j.nima.2023.168589

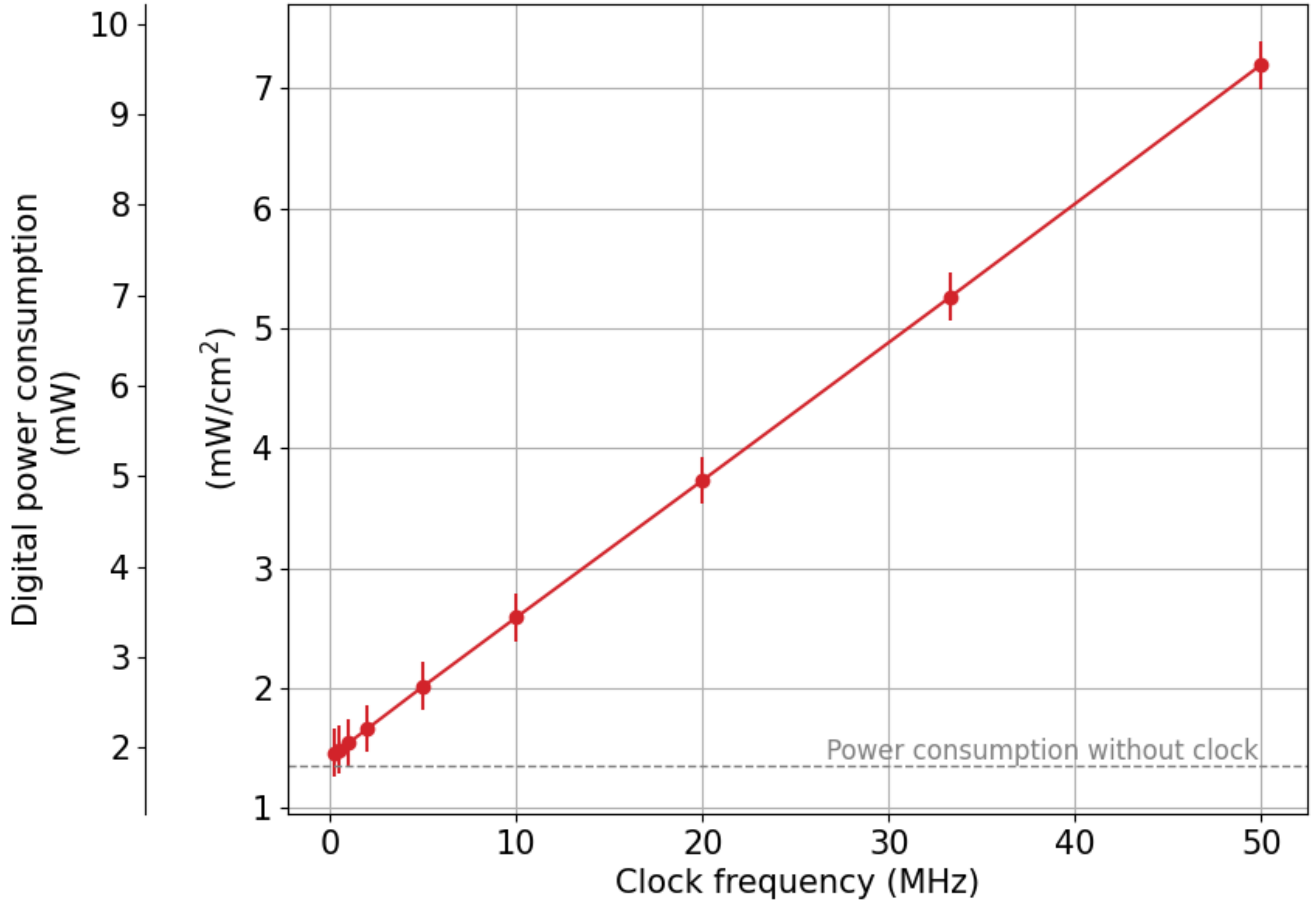
Considerations on MAPS power consumption

- Low power but <1 mW/cm² seems unachievable with the current designs
- MAPS = sensitive volume + in-pixel front-end + readout electronics
- Two power domains: “analog” pixel matrix and “digital” readout/periphery

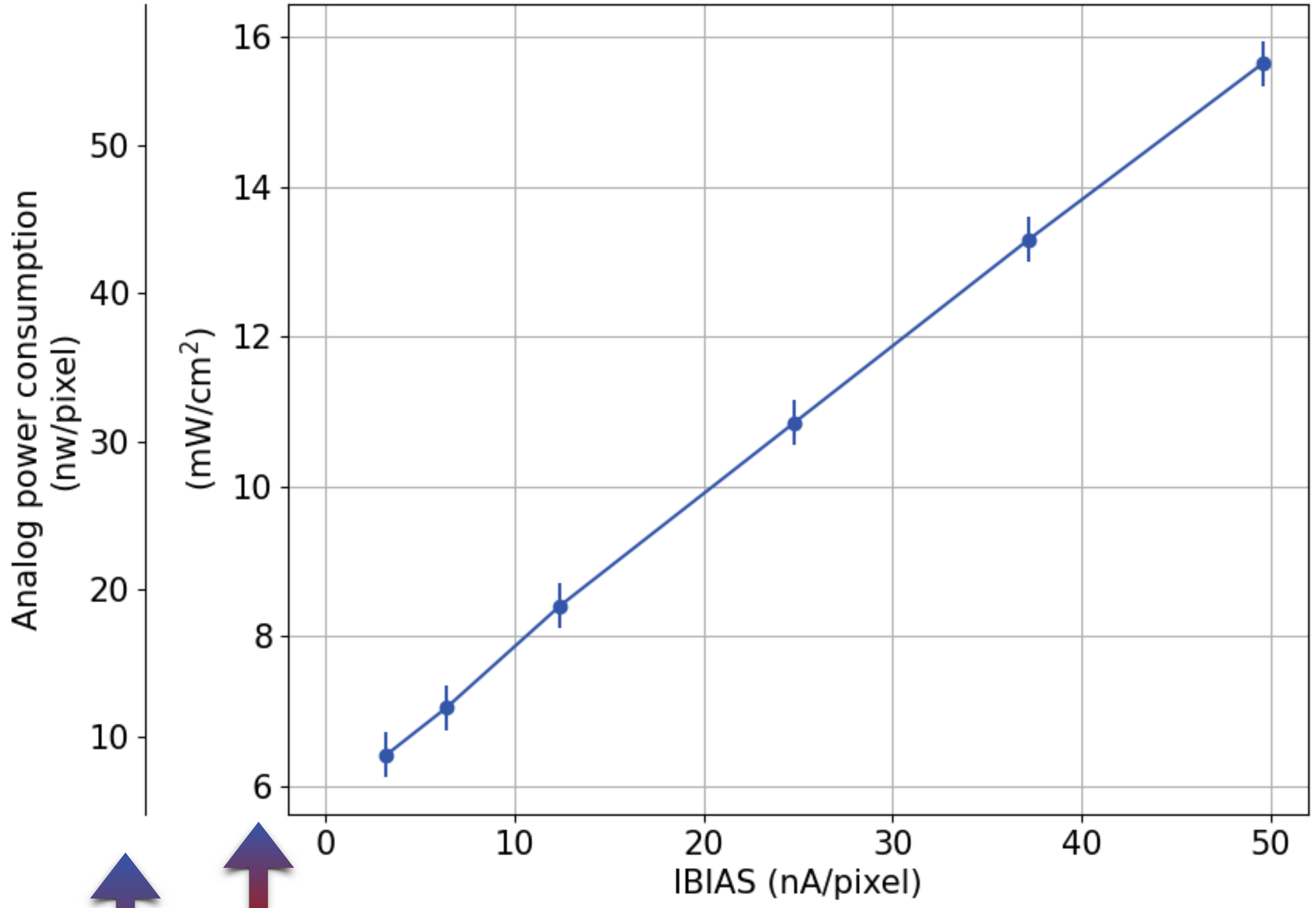


Reducing the power consumption

Digital domain

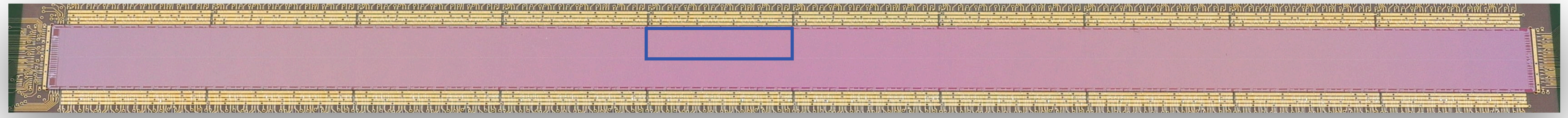


Analog domain

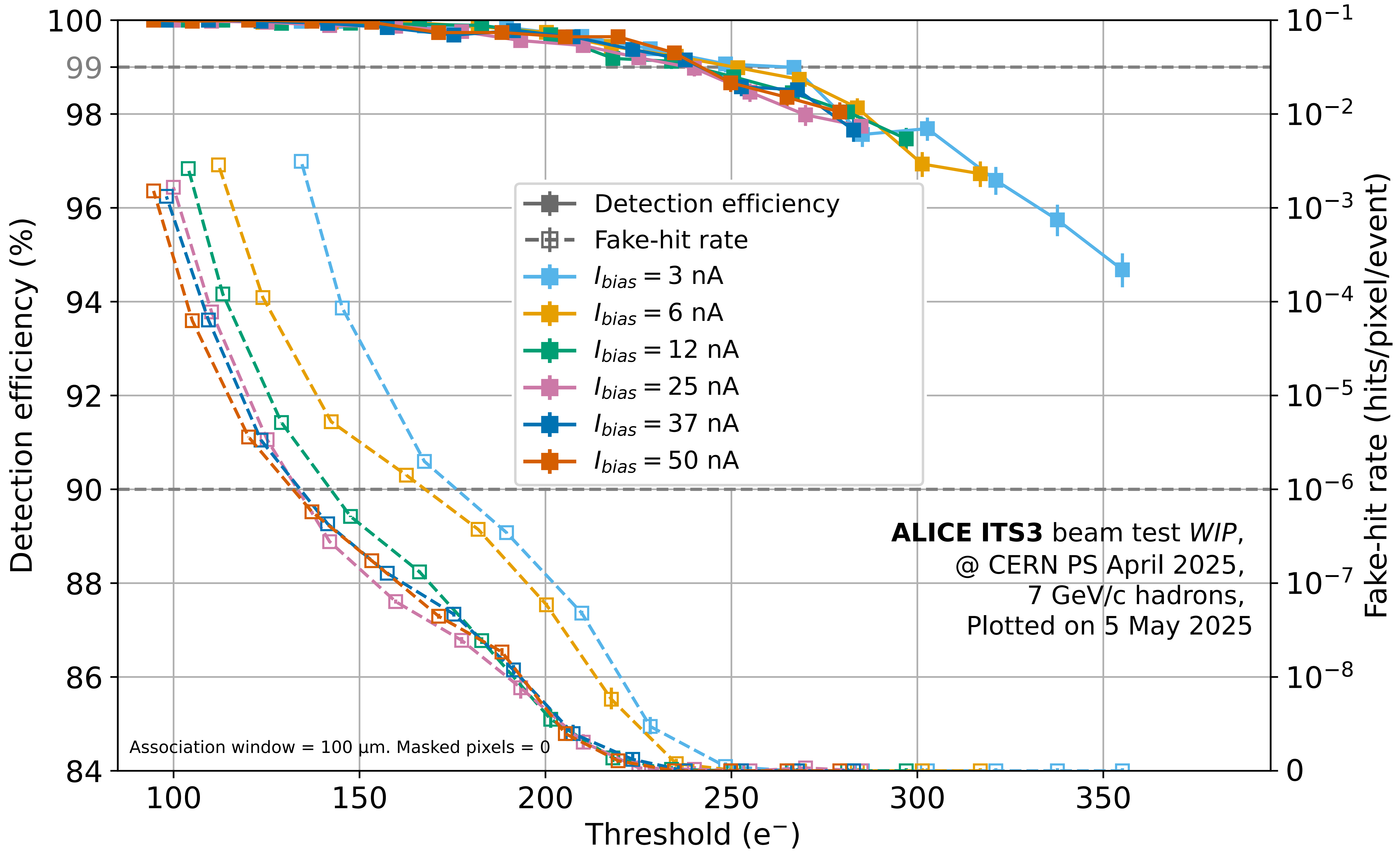


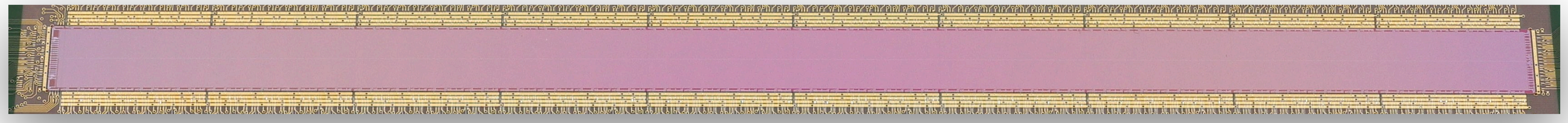
Measured including periphery power consumption

Estimated excluding periphery power consumption

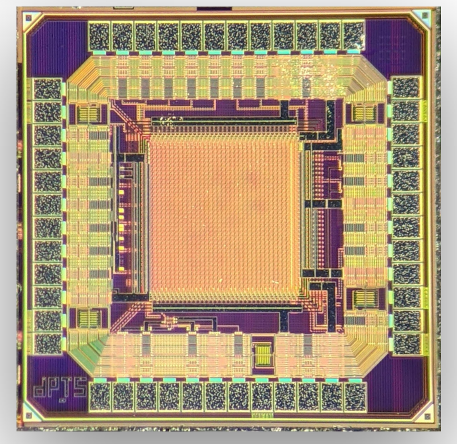


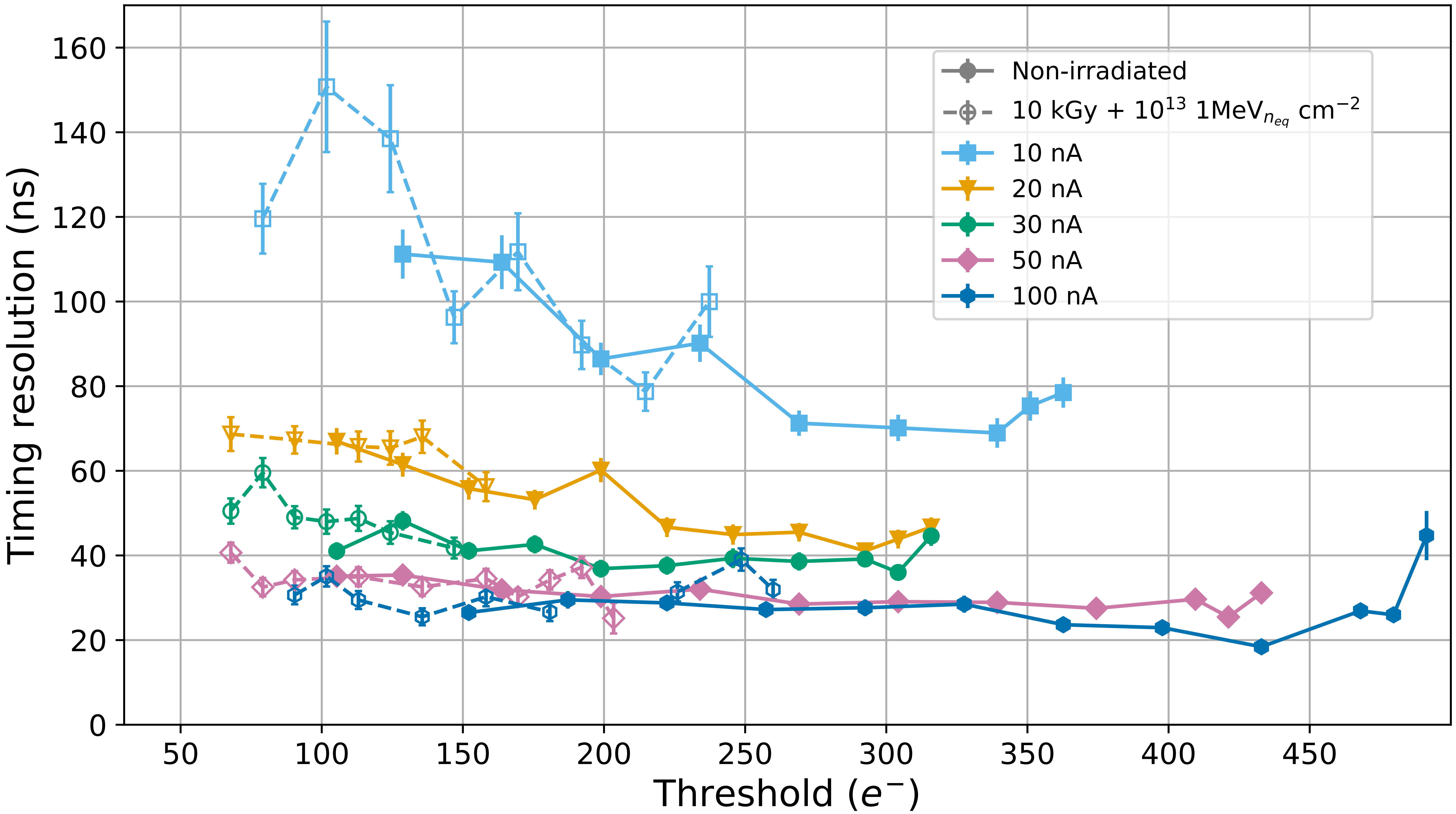
Front-end performance vs power consumption





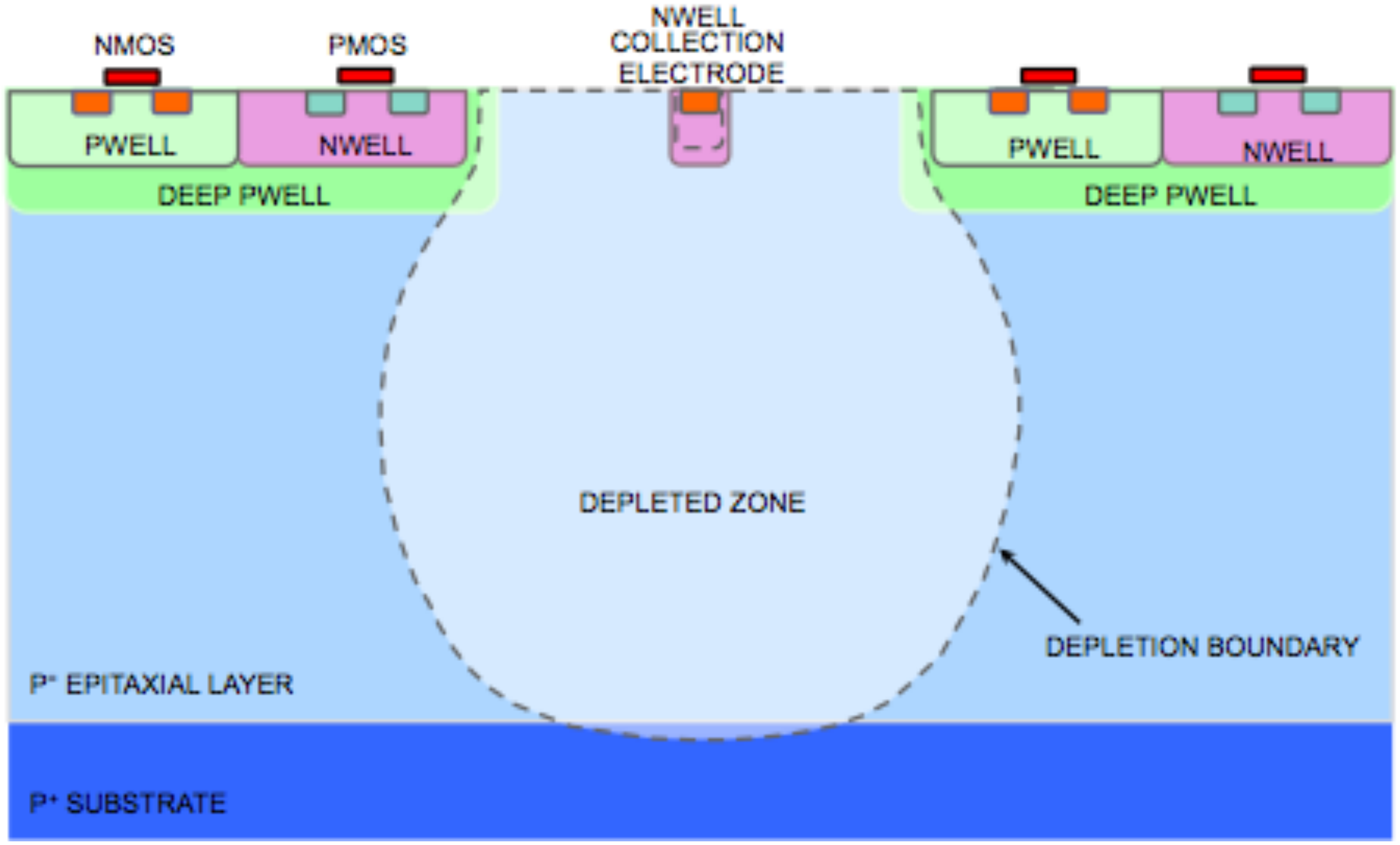
Front-end performance vs power consumption (2)



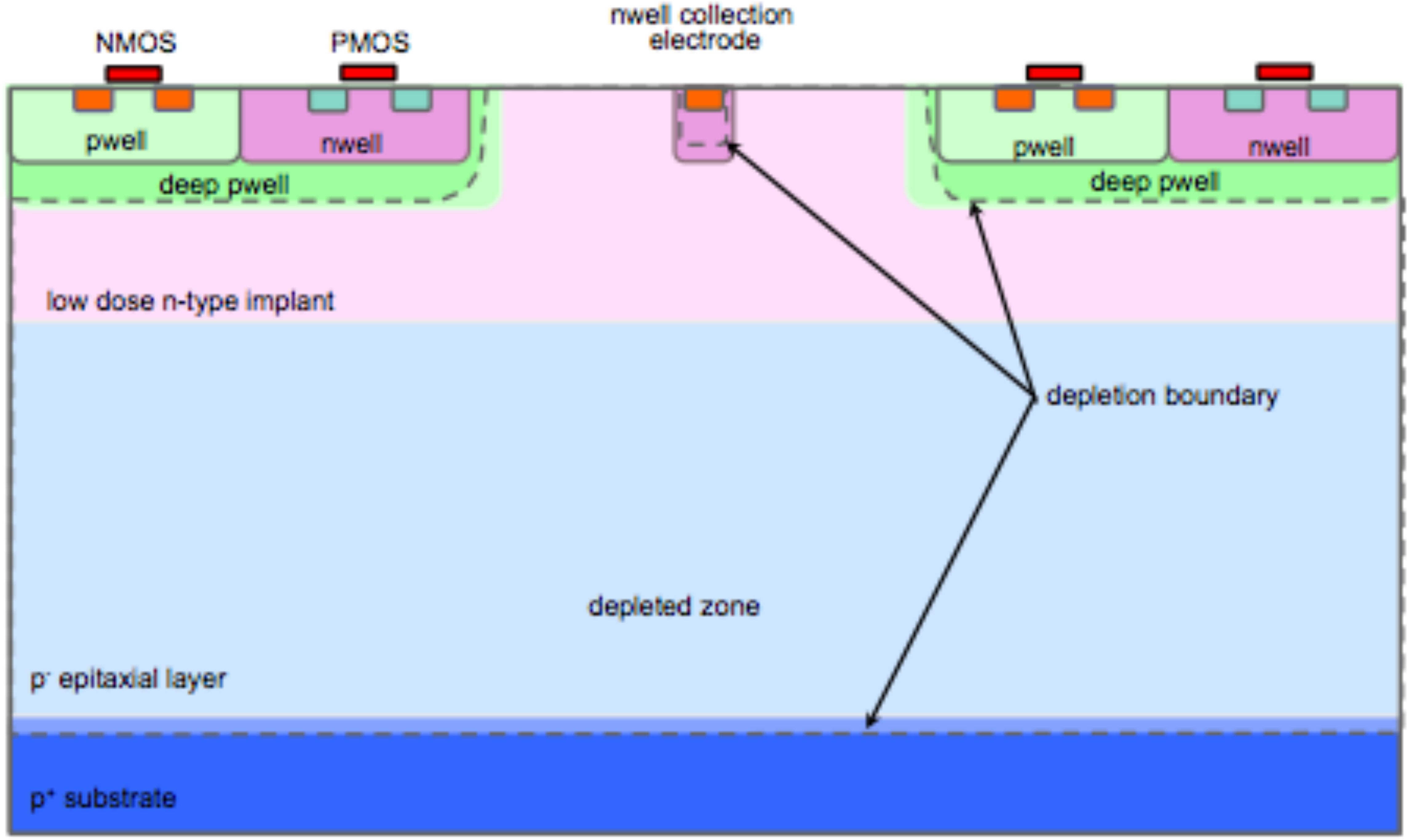


Different MLR1 process types

Standard process

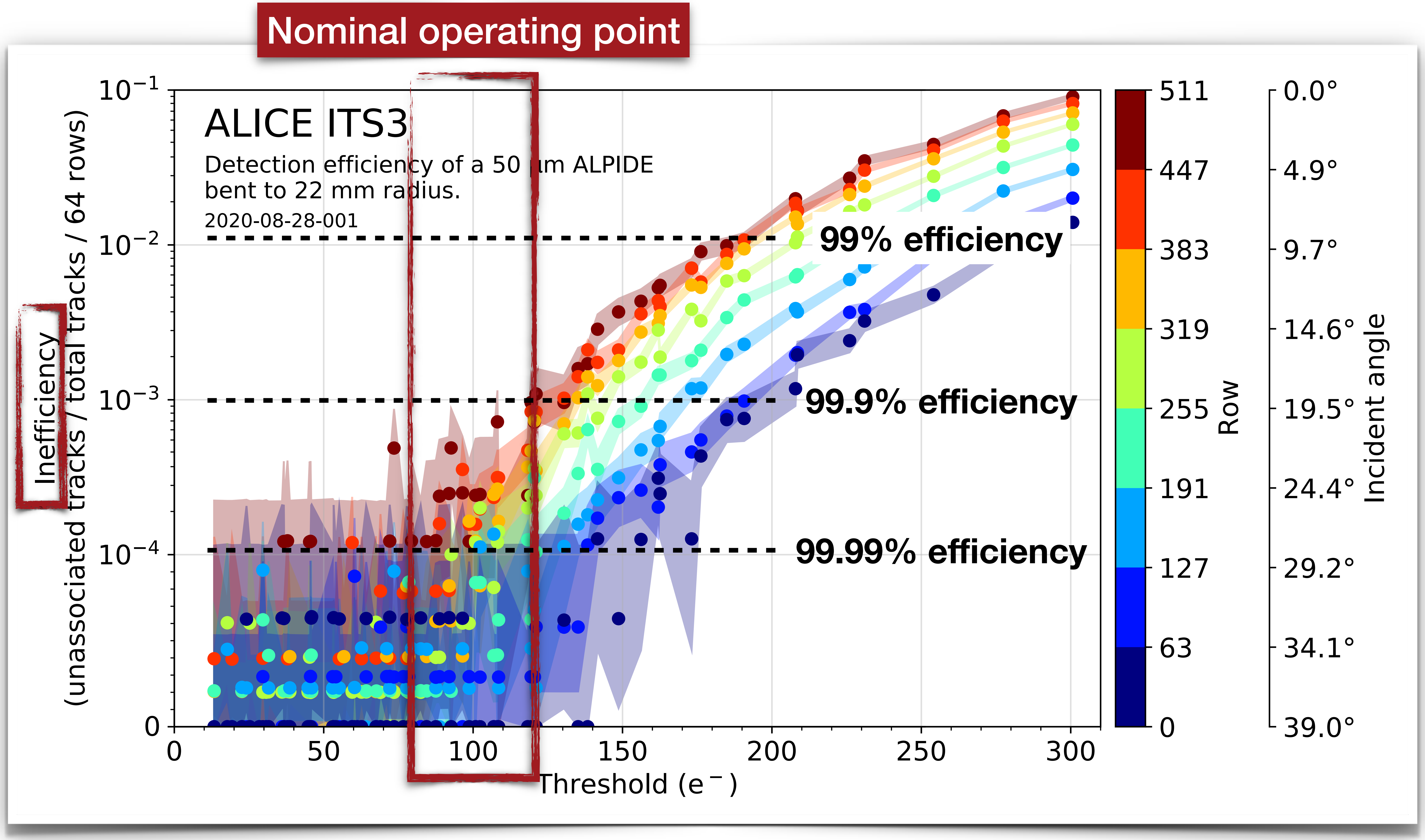


"Modified" process



doi.org/10.1016/j.nima.2017.07.046

Bent MAPS



Clearly proving that bent MAPS are working!

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 1028, 1 April 2022, 166280

First demonstration of in-beam performance of bent Monolithic Active Pixel Sensors

ALICE ITS project [1]

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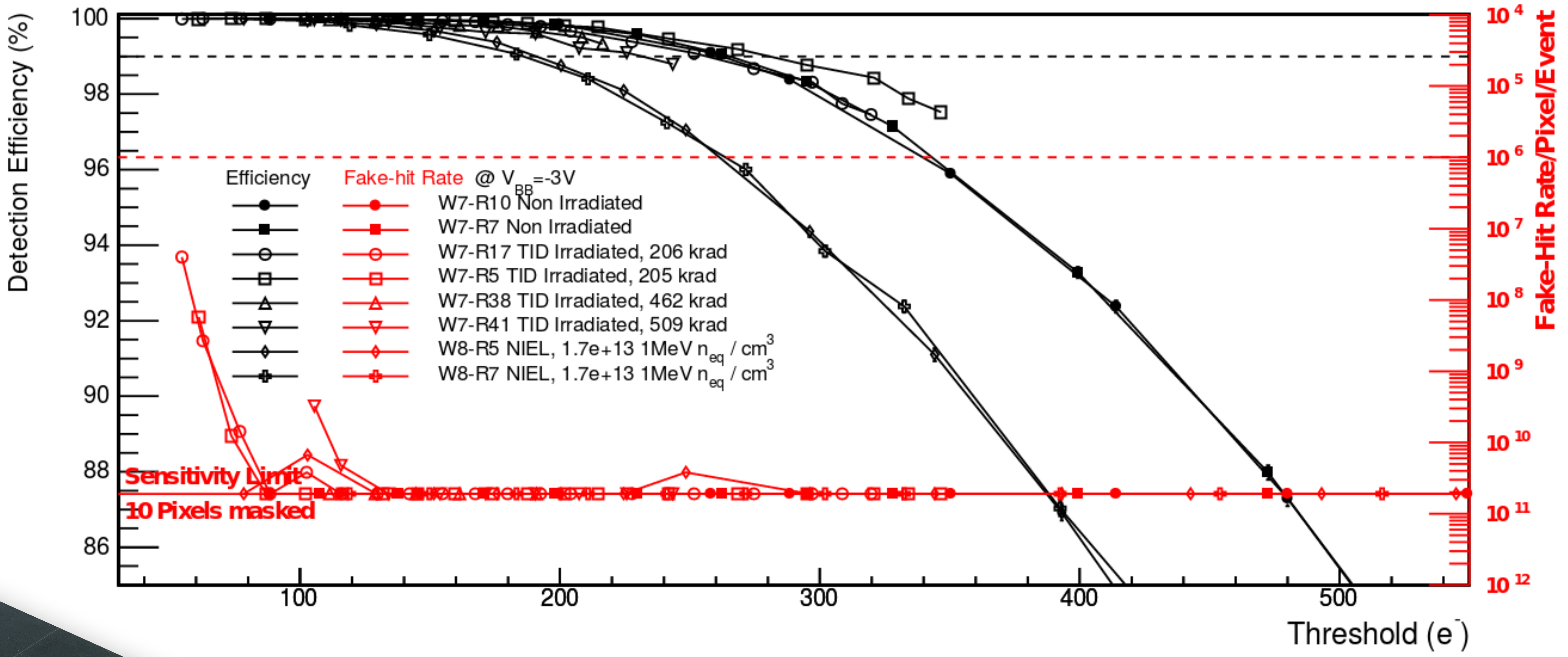
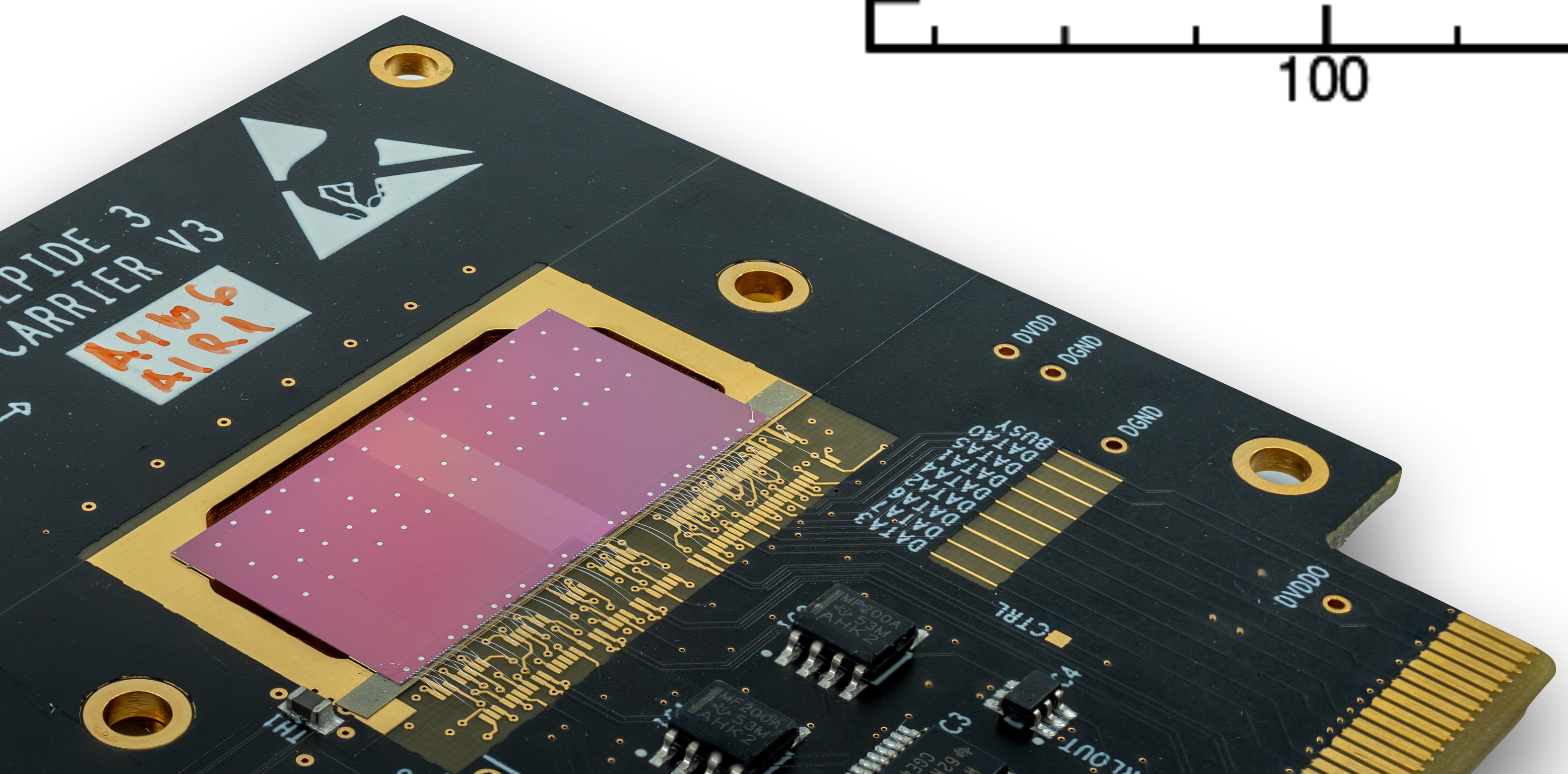
Abstract **doi.org/10.1016/j.nima.2021.166280**

A novel approach for designing the next generation of vertex detectors foresees to employ wafer-scale sensors that can be bent to truly cylindrical geometries after thinning them to thicknesses of 20–40 μm. To solidify this concept, the feasibility of operating bent MAPS was demonstrated using 1.5 cm × 3 cm ALPIDE chips. Already with their thickness of 50 µm, they can be successfully bent to radii of about 2 cm without any signs of mechanical or electrical damage. During a subsequent characterisation using a 5.4 GeV electron beam, it was further confirmed that they preserve their full electrical functionality as well as particle detection performance.

ALPIDE detection efficiency





ALPIDE spatial resolution