Fast timing at the Timepix4 Telescope

Kevin Heijhoff

Nikhef Jamboree — 14 May 2024

SPS North Area

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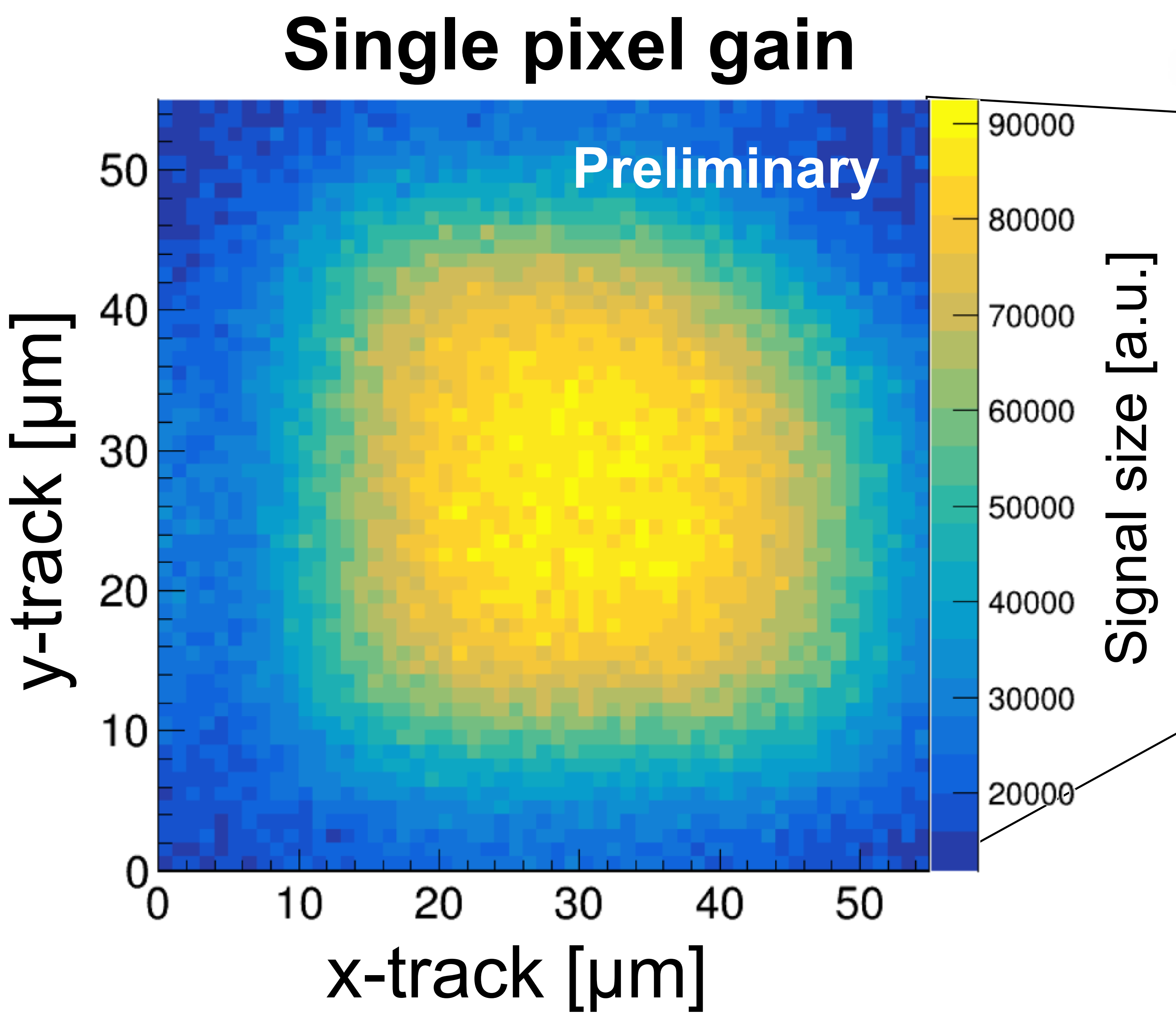
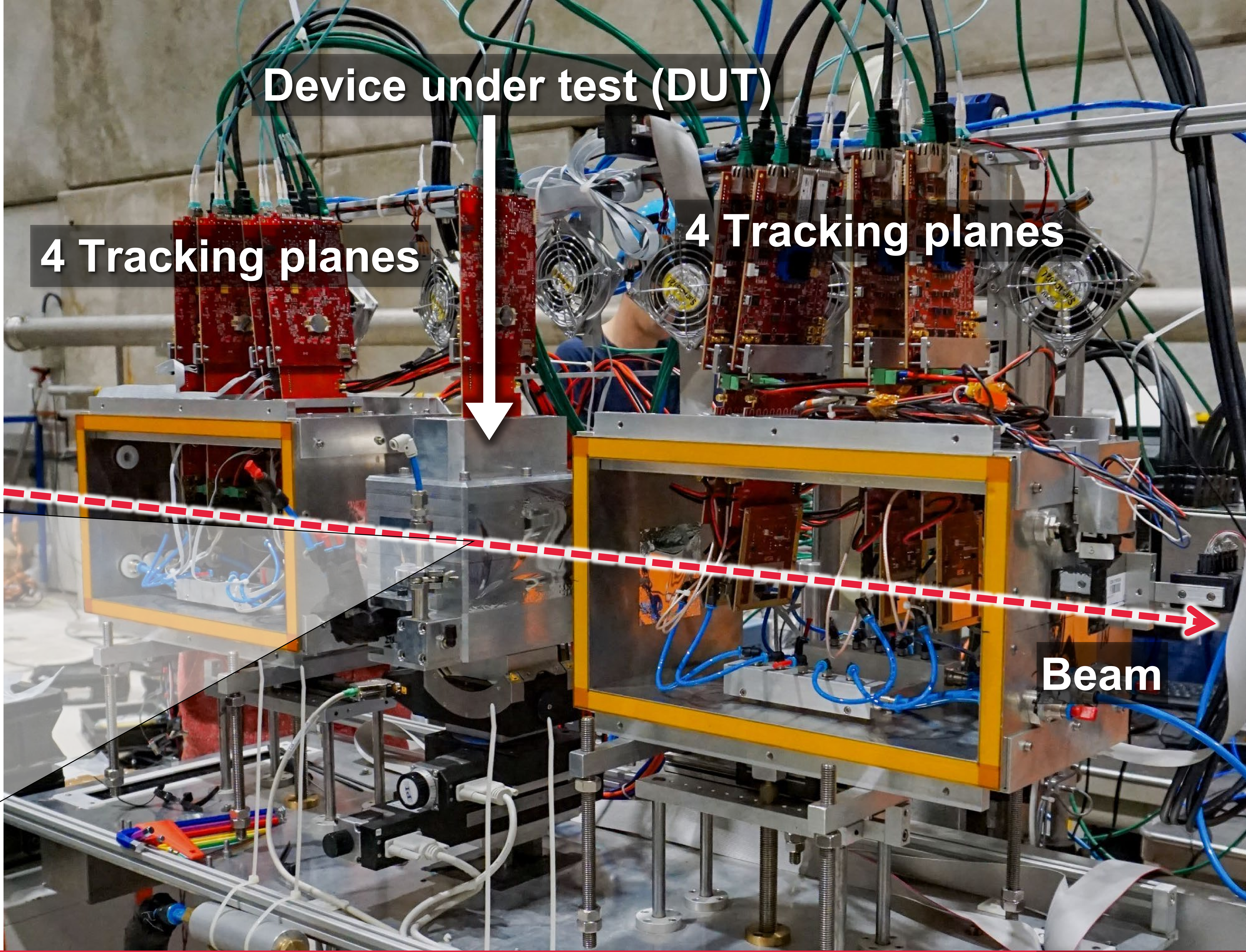
Timepix4 Telescope

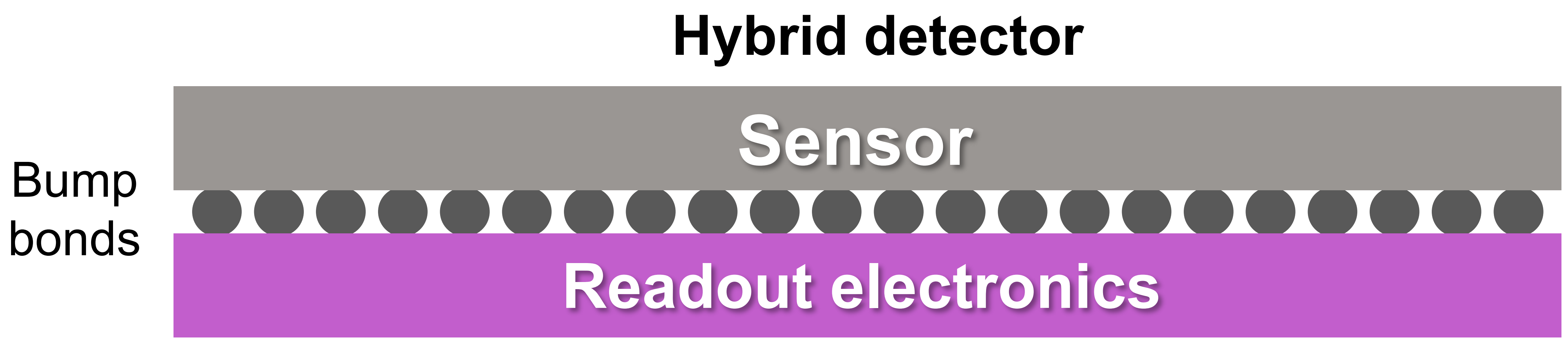
- Study prototype sensors for 4D trackers at high rate
- 4D tracking demonstrator
- < 50 ps track-time resolution at high rate

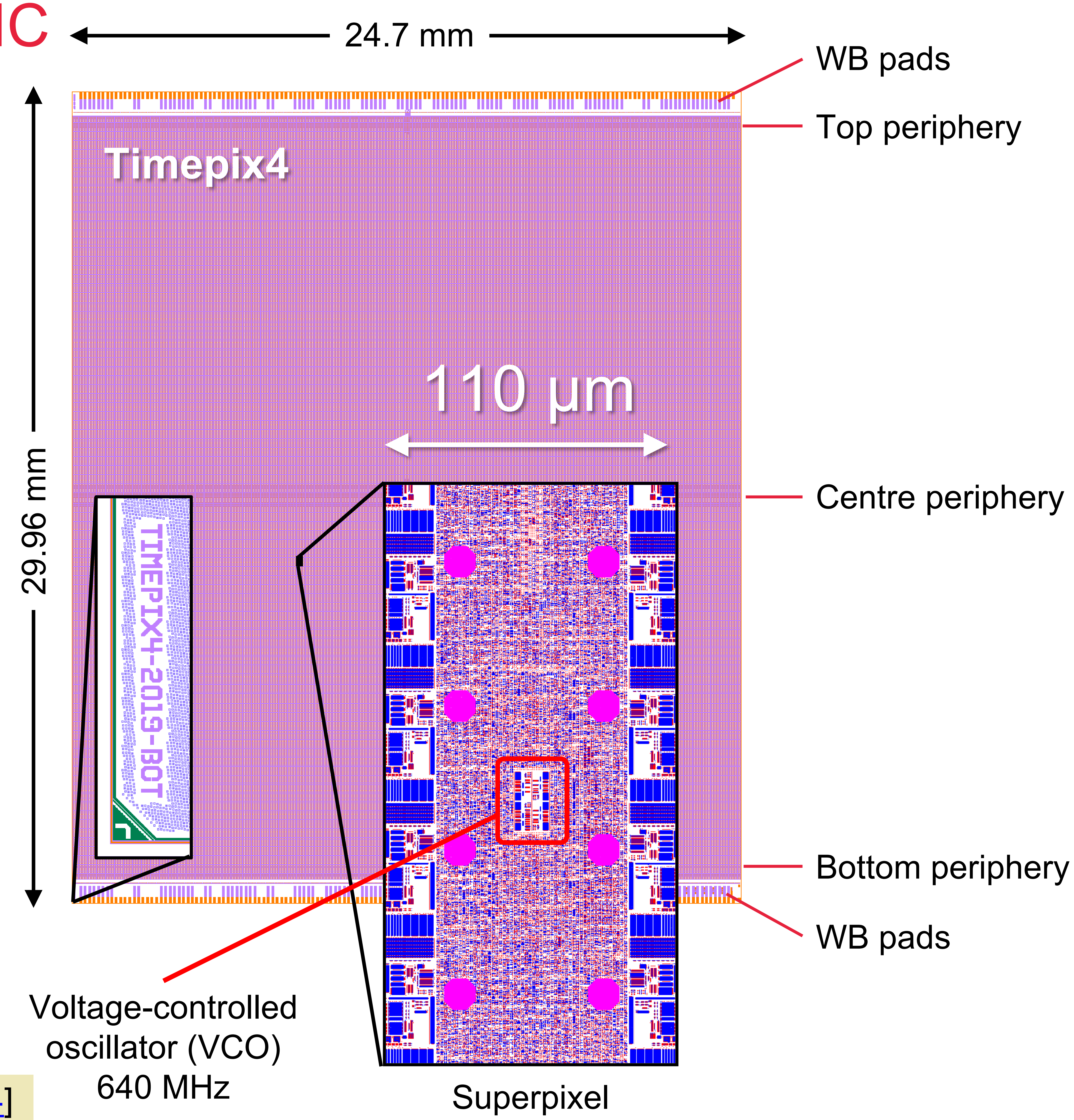




Timepix4: Hybrid pixel detector readout ASIC

- Developed by CERN, Nikhef, and IFAE
- 65 nm CMOS
- 448×512 pixels, 55×55 μm^2 pitch
- Simultaneous measurement of time and charge deposition (by measuring time over threshold)
- Time-bin size of 25 ns/128 = **195 ps (= resolution of 56 ps)**
- Max rate: 360×10^6 hits/cm^2/s (160 Gb/s for single chip)





X. Llopart *et al* 2022 *JINST* **17** C01044 [DOI: 10.1088/1748-0221/17/01/C01044]

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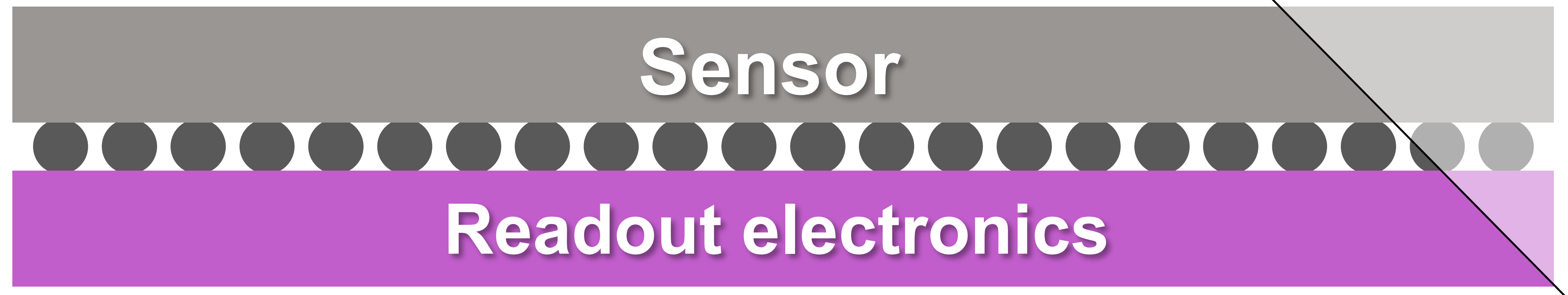
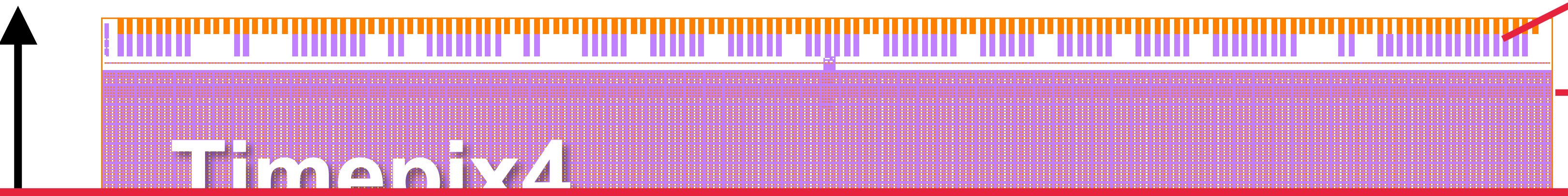
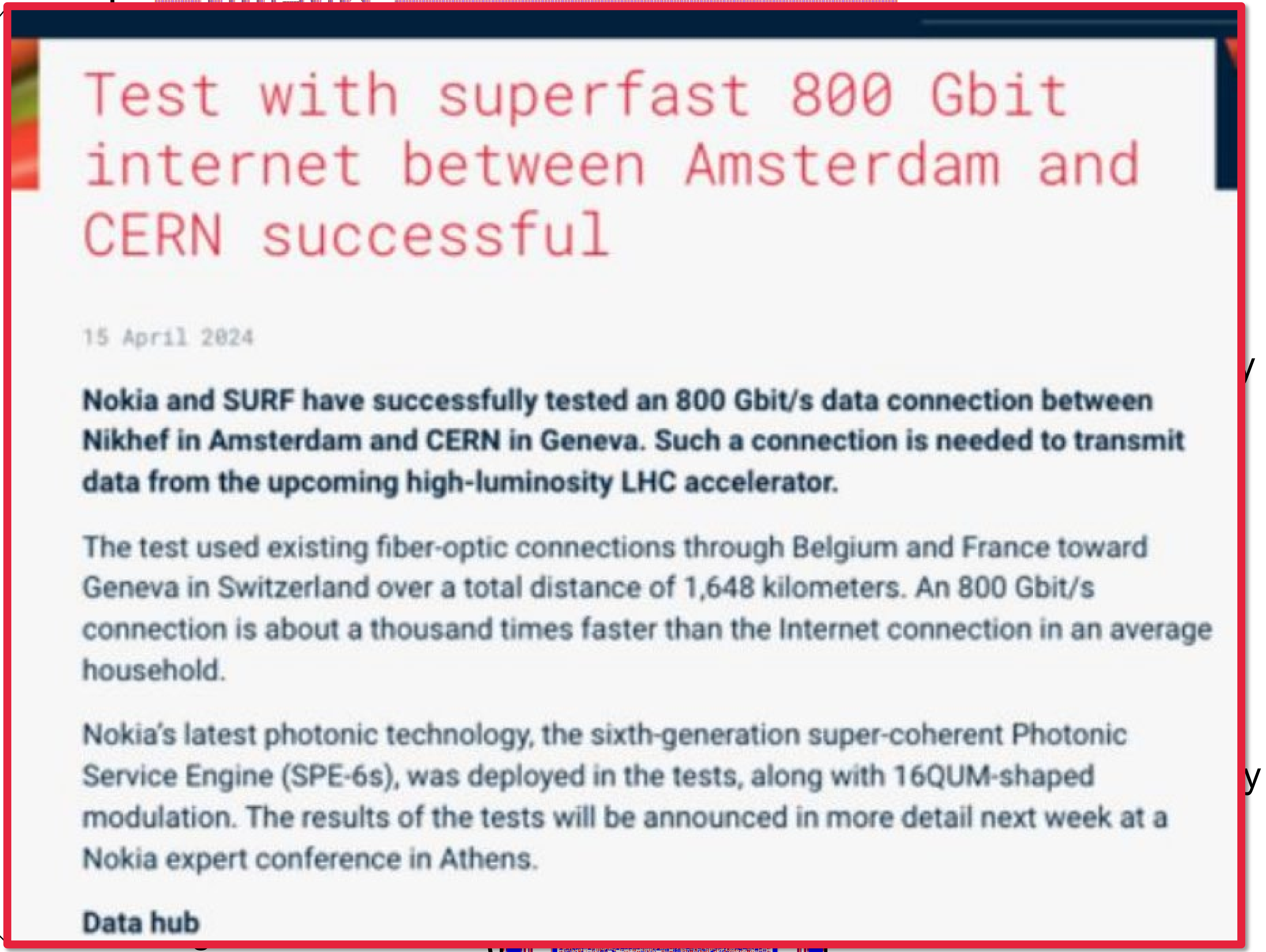
Hybrid detector







Test with superfast 800 Gbit internet between Amsterdam and CERN successful

15 April 2024

Nokia and SURF have successfully tested an 800 Gbit/s data connection between Nikhef in Amsterdam and CERN in Geneva. Such a connection is needed to transmit data from the upcoming high-luminosity LHC accelerator.

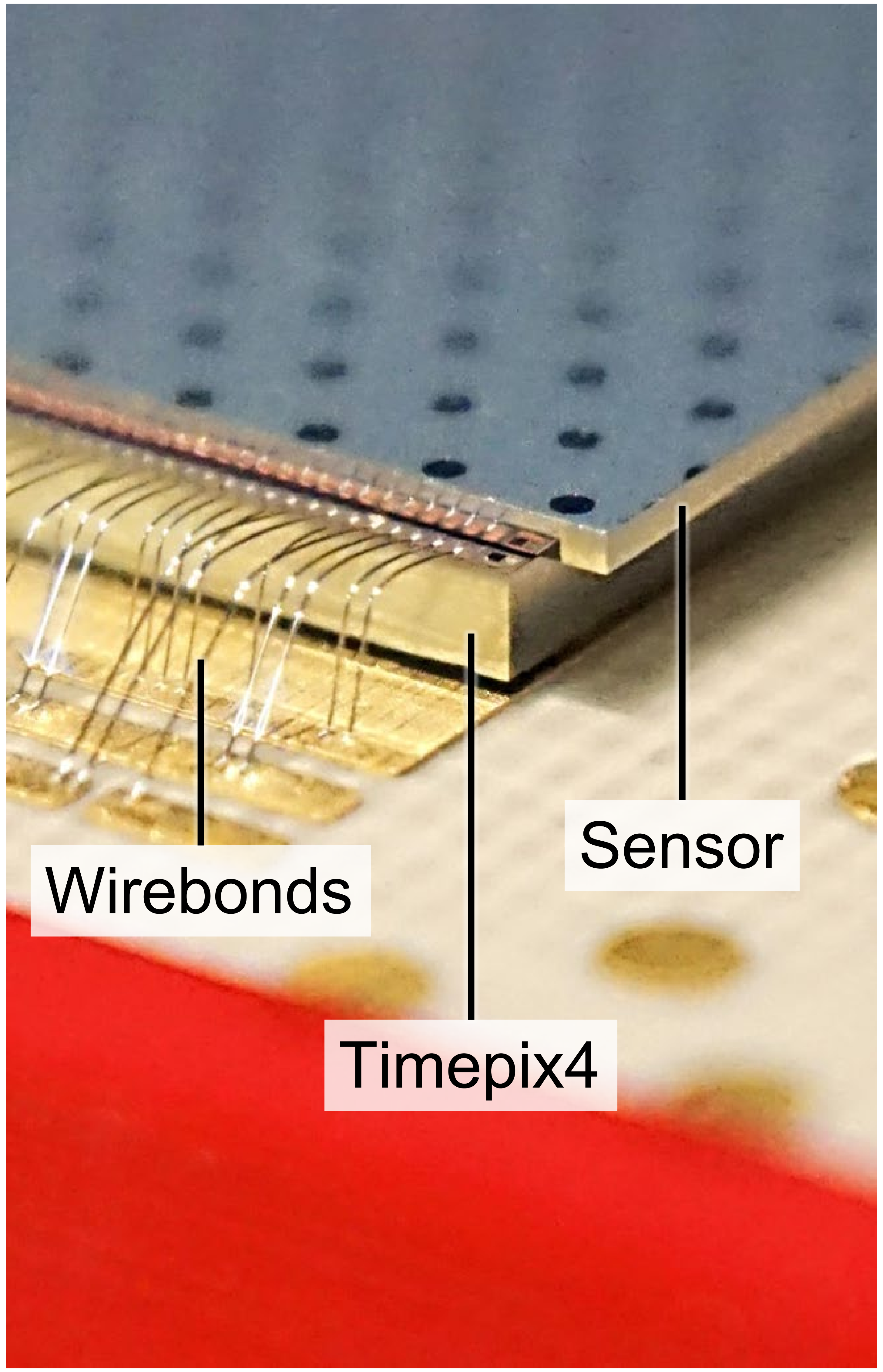
The test used existing fiber-optic connections through Belgium and France toward Geneva in Switzerland over a total distance of 1,648 kilometers. An 800 Gbit/s connection is about a thousand times faster than the Internet connection in an average household.

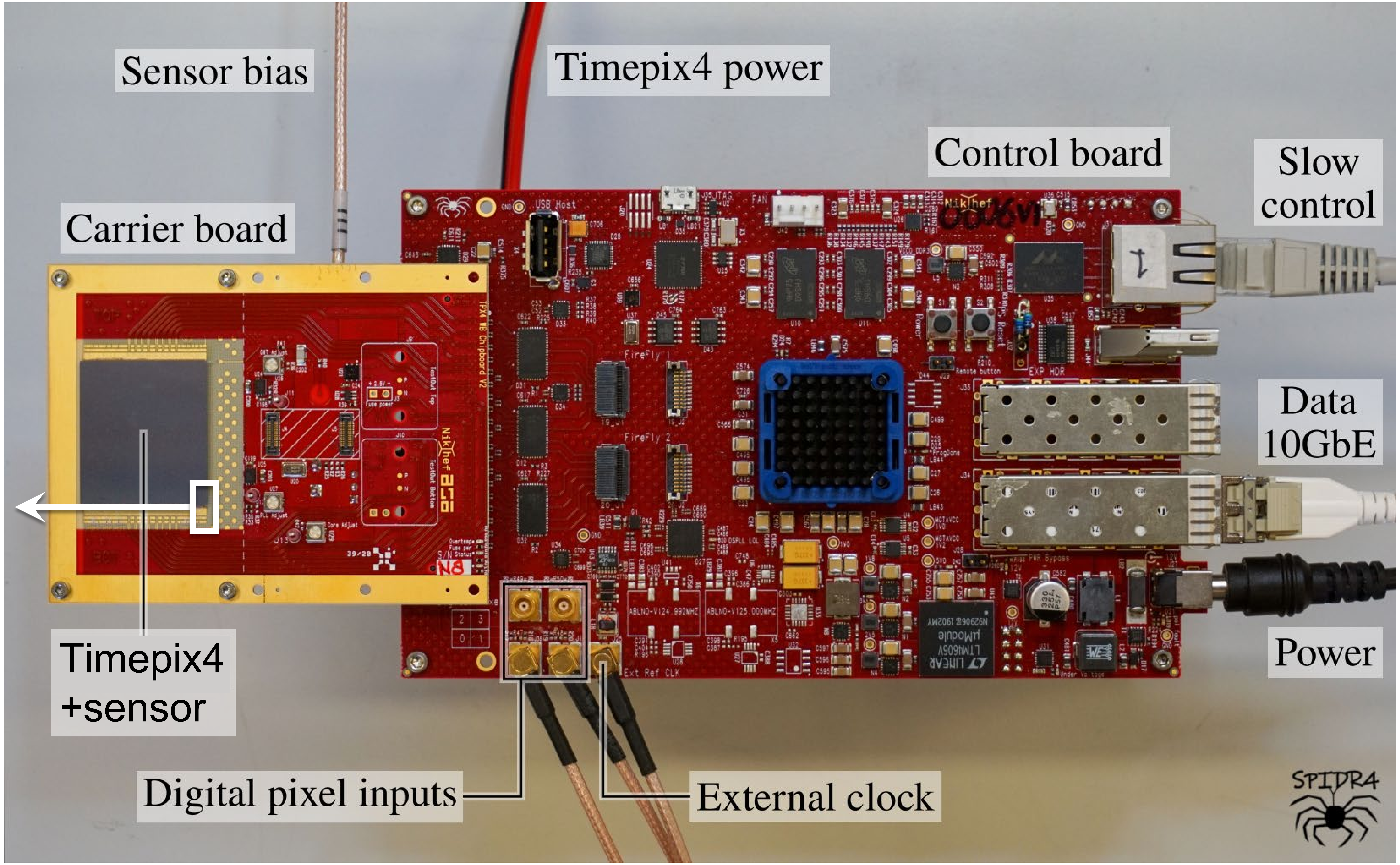
Nokia's latest photonic technology, the sixth-generation super-coherent Photonic Service Engine (PSE-6s), was deployed in the tests, along with 16QUM-shaped modulation. The results of the tests will be announced in more detail next week at a Nokia expert conference in Athens.

Data hub

X. Llopart *et al* 2022 *JINST* **17** C01044 [DOI: 10.1088/1748-0221/17/01/C01044]

Speedy PIxel Detector Readout 4 (SPIDR4)

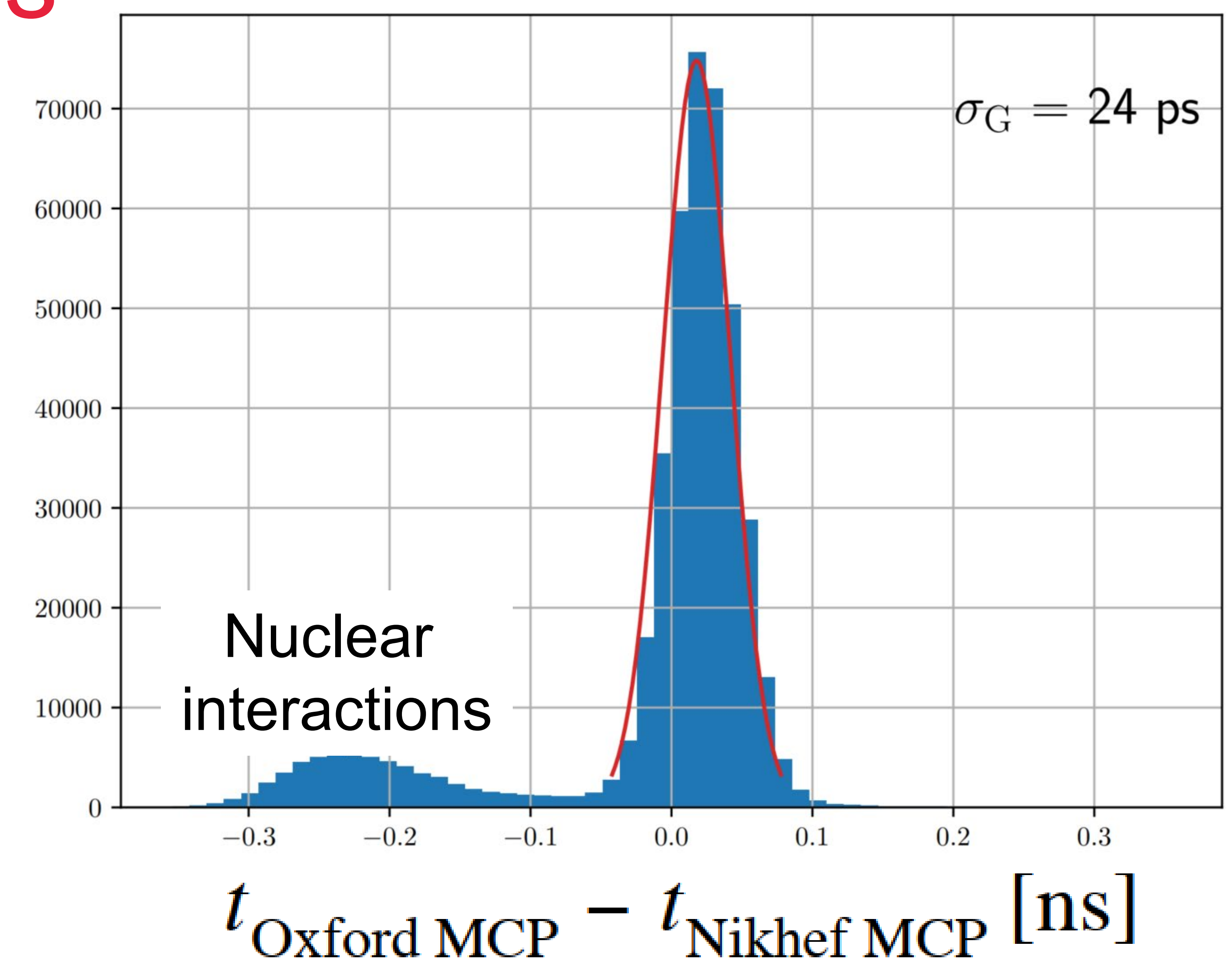


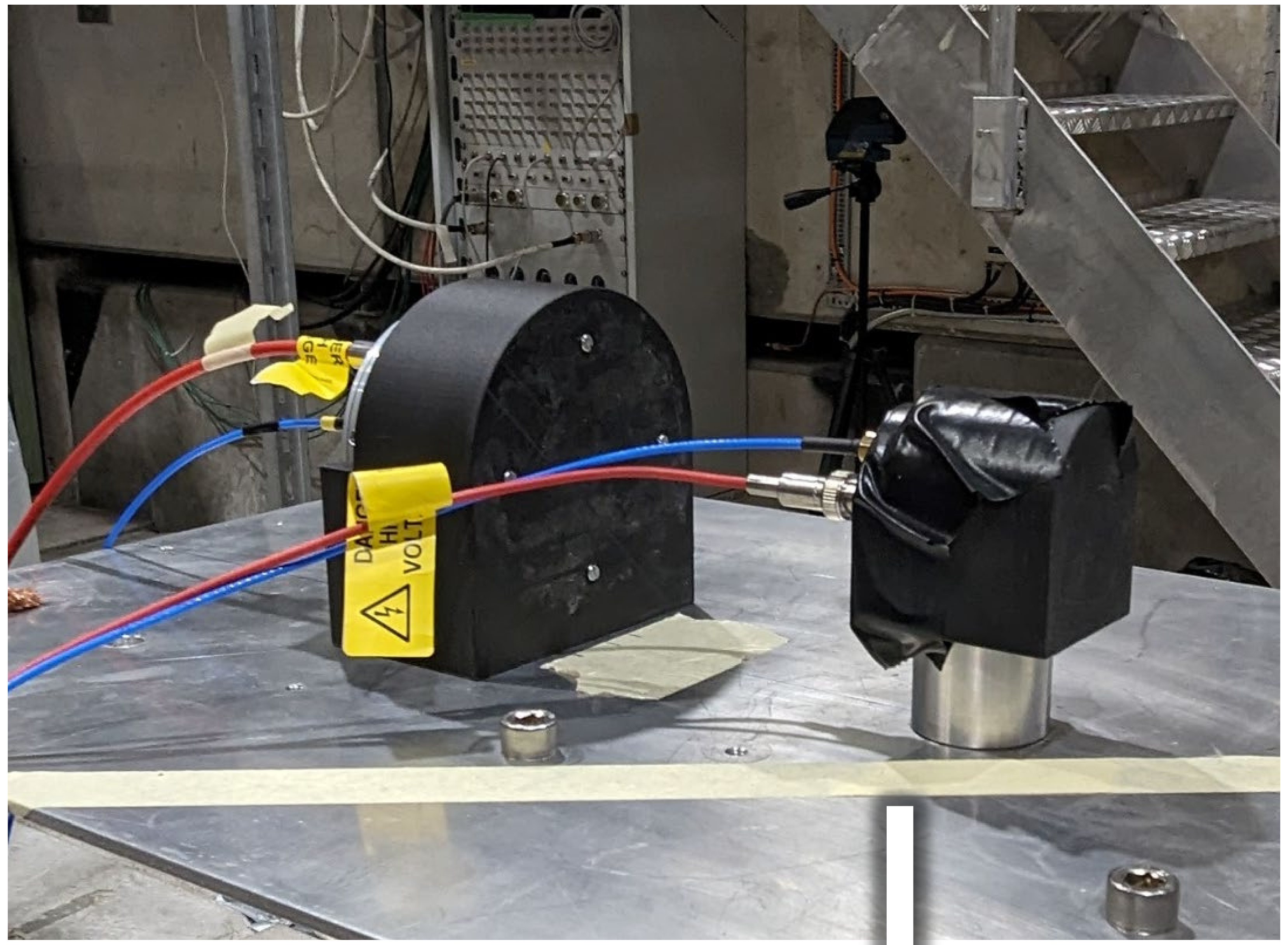


Telescope configuration

Micro channel plate detectors

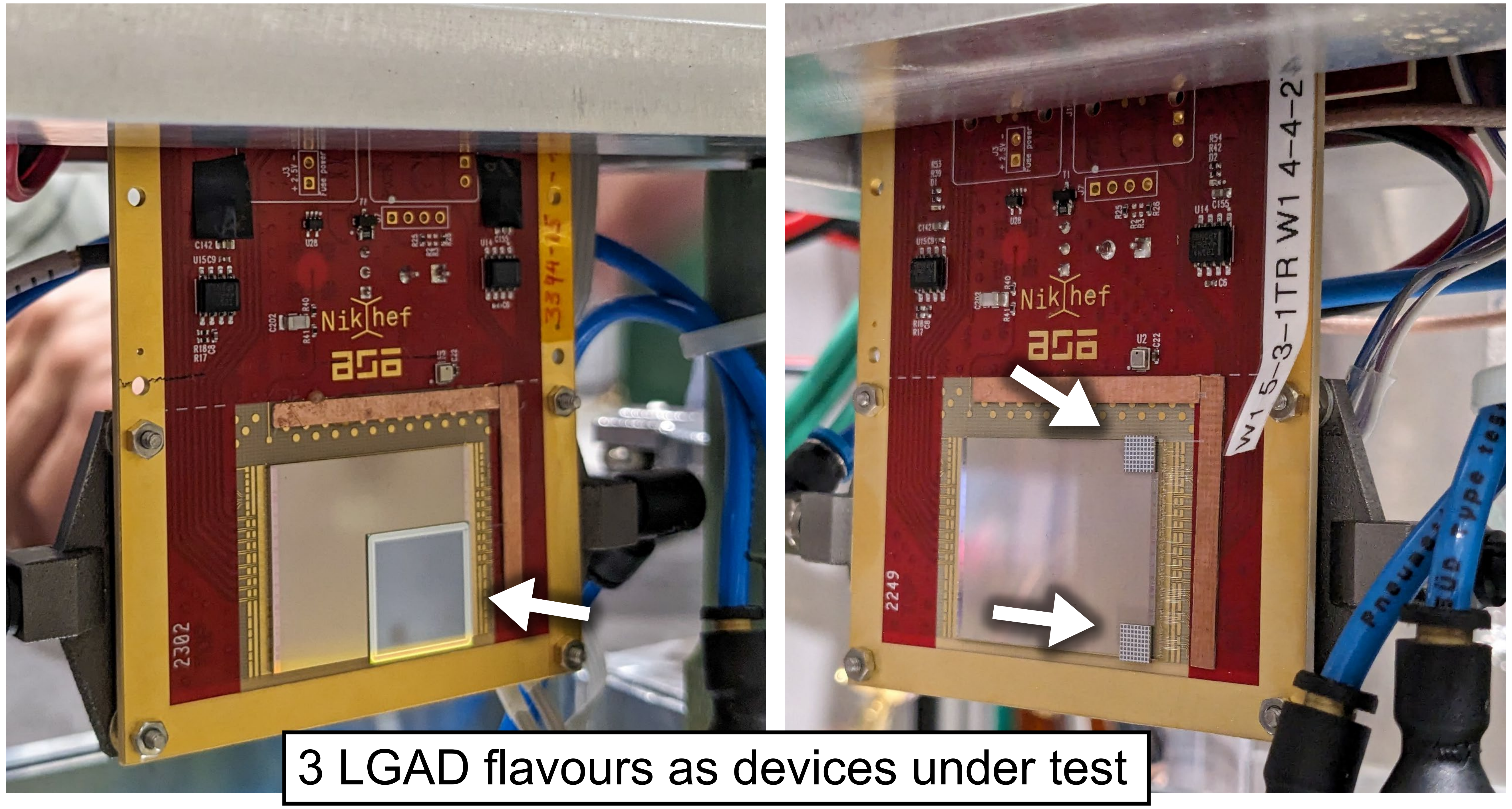
- Time reference to study telescope timing
- Considering installing Timpix4 plane to VETO events with nuclear interactions
- Current time resolution: 17 ps (single MCP)
- Combined MCP resolution: 12 ps



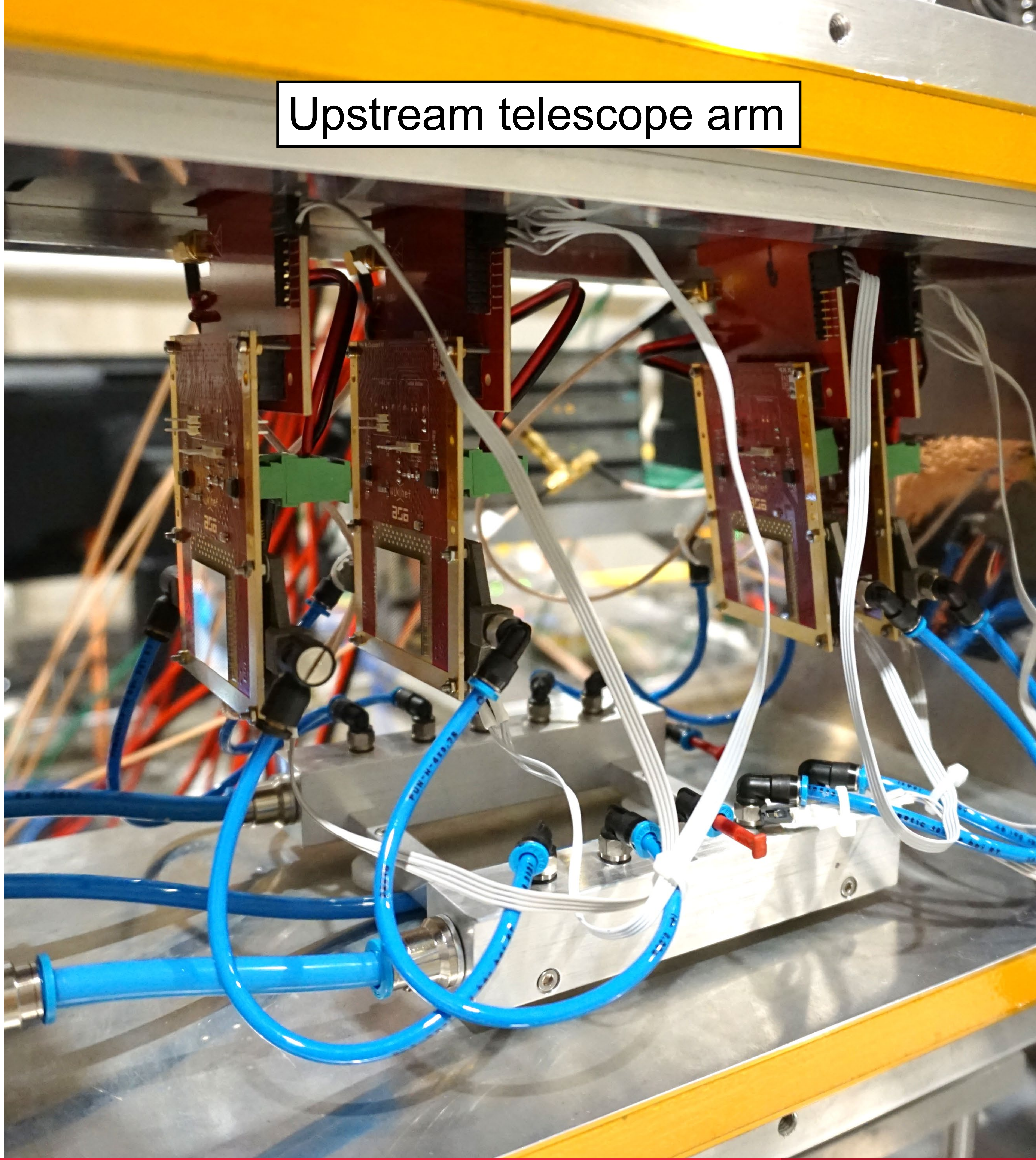


Plane assemblies

- Eight telescope planes with n-on-p planar silicon sensors
- 4 x 300 μm sensors for spatial resolution (angled)
- 4 x 100 μm sensors for time resolution (perpendicular)
- Sensor upgrades are anticipated (LGAD, 3D, …)



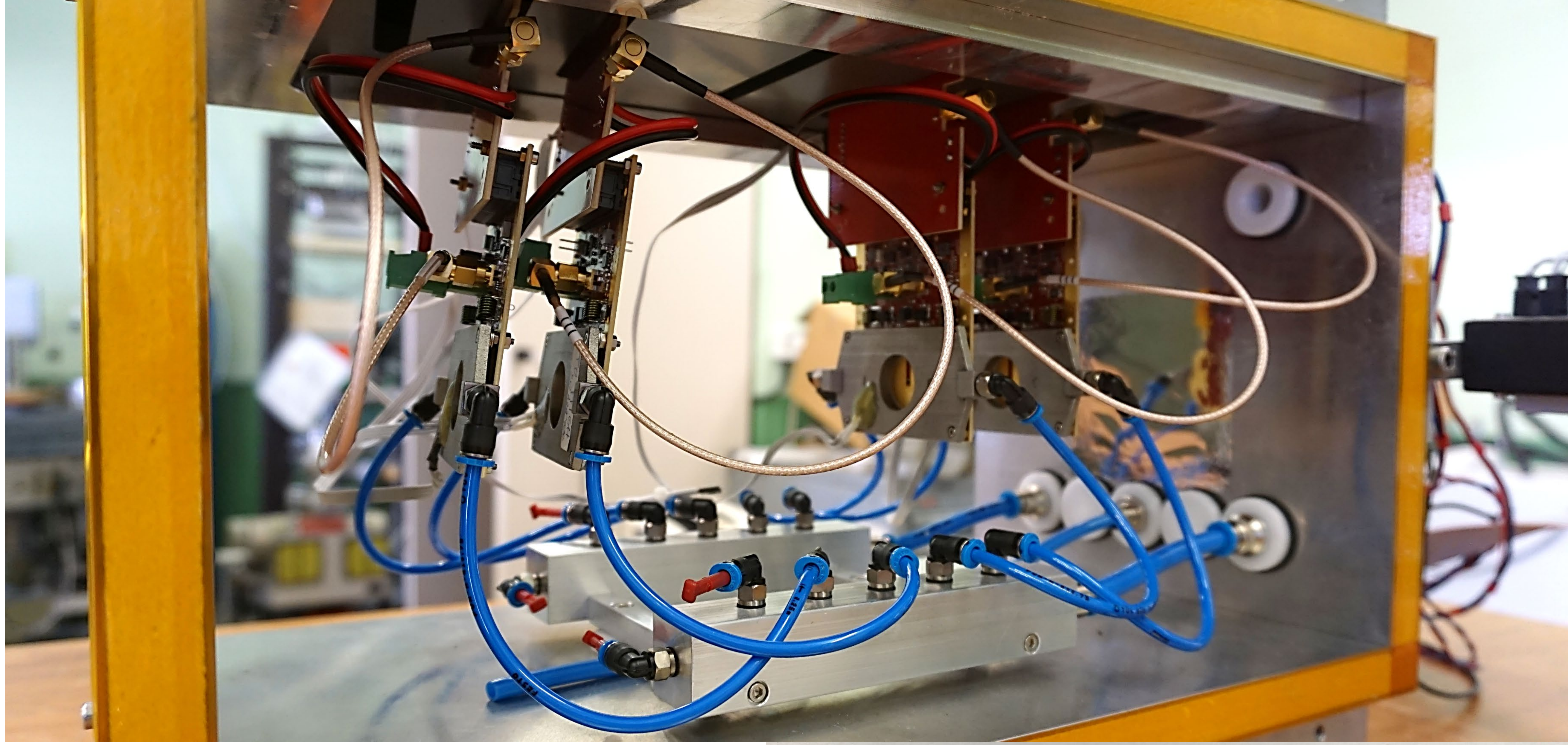
3 LGAD flavours as devices under test



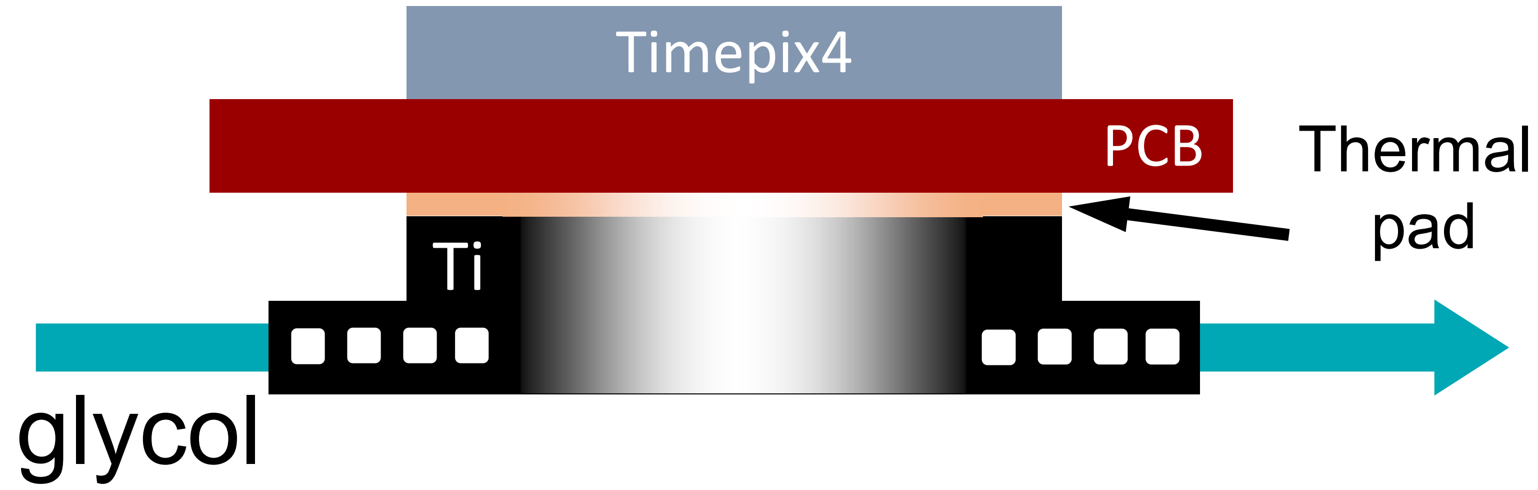
Upstream telescope arm

Assembly cooling

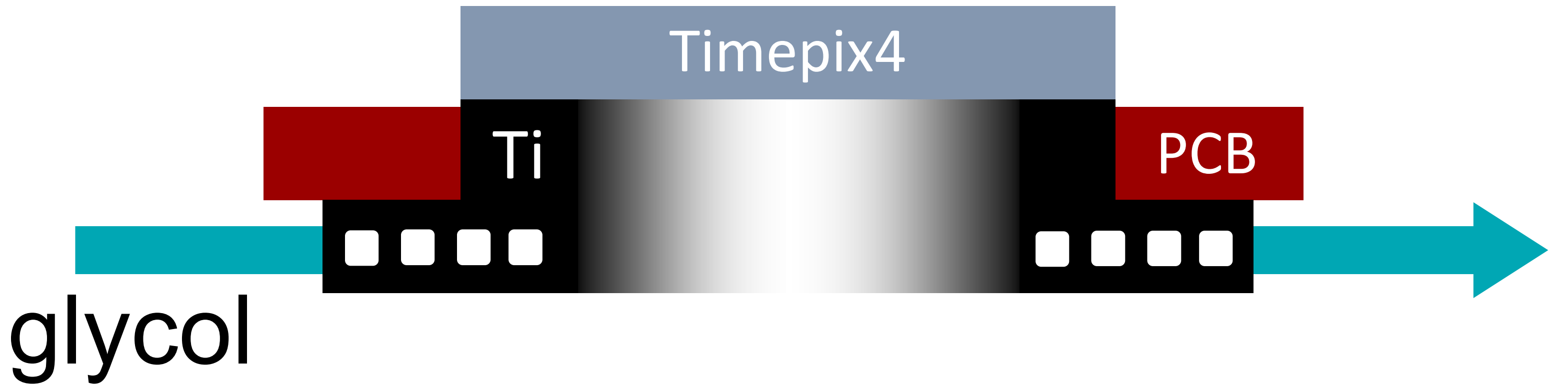
- All assemblies have a 3D-printed titanium cooling block
- Cooled using glycol at 20 °C
- Could go to –20 °C in the future
- Plan to mill PCB to have direct thermal contact with Timepix4

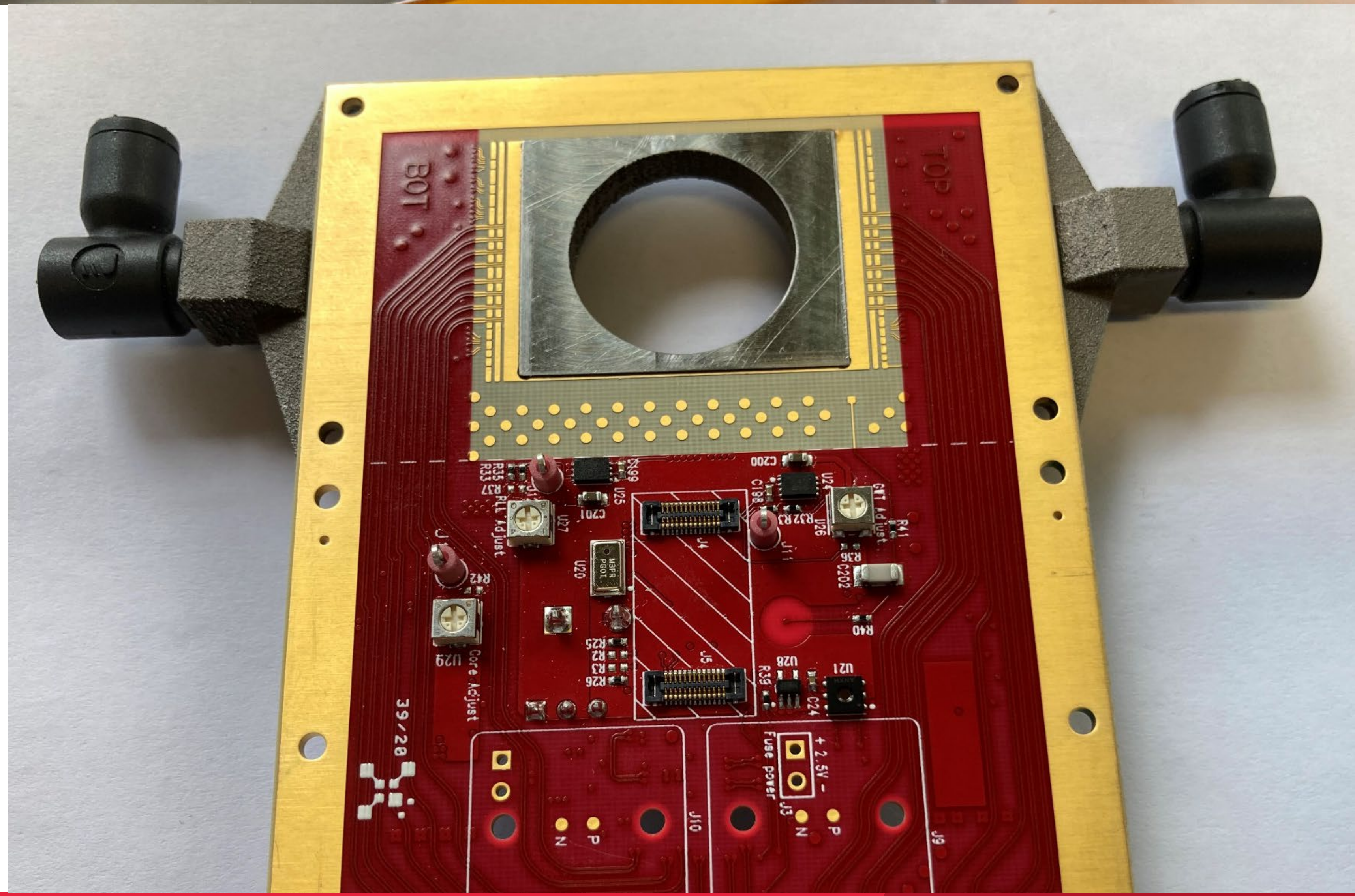


Current thermal interface



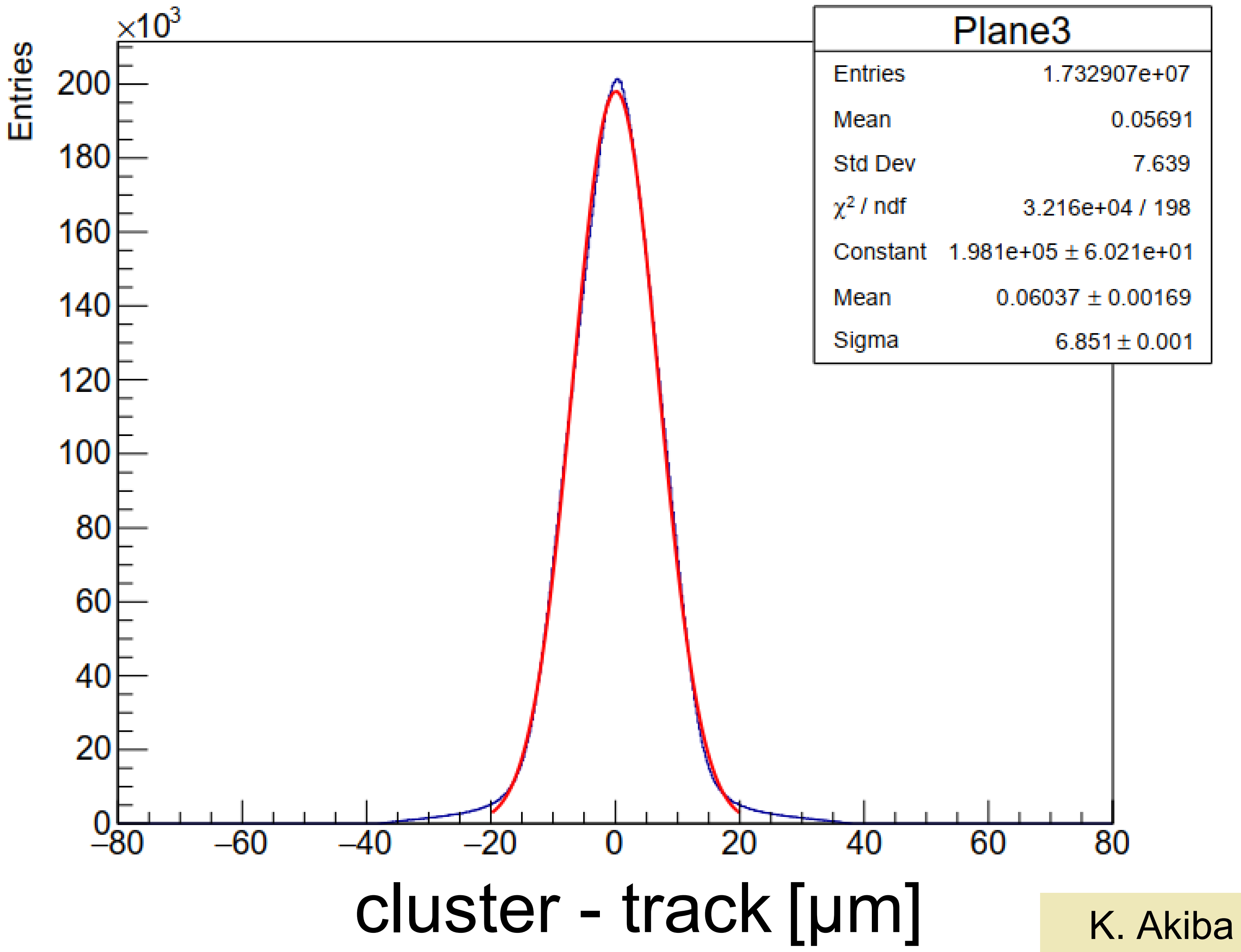
Future thermal interface

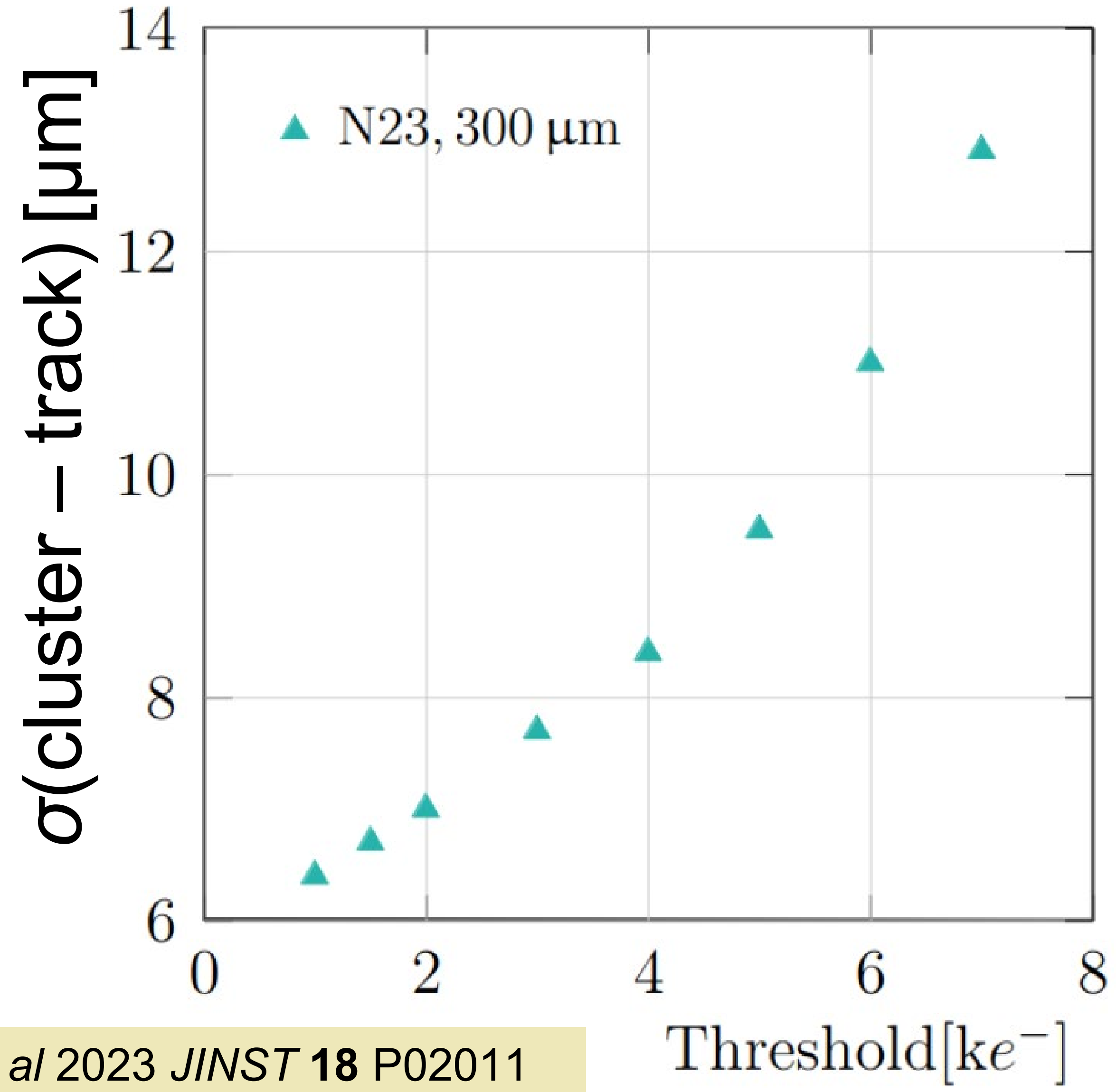




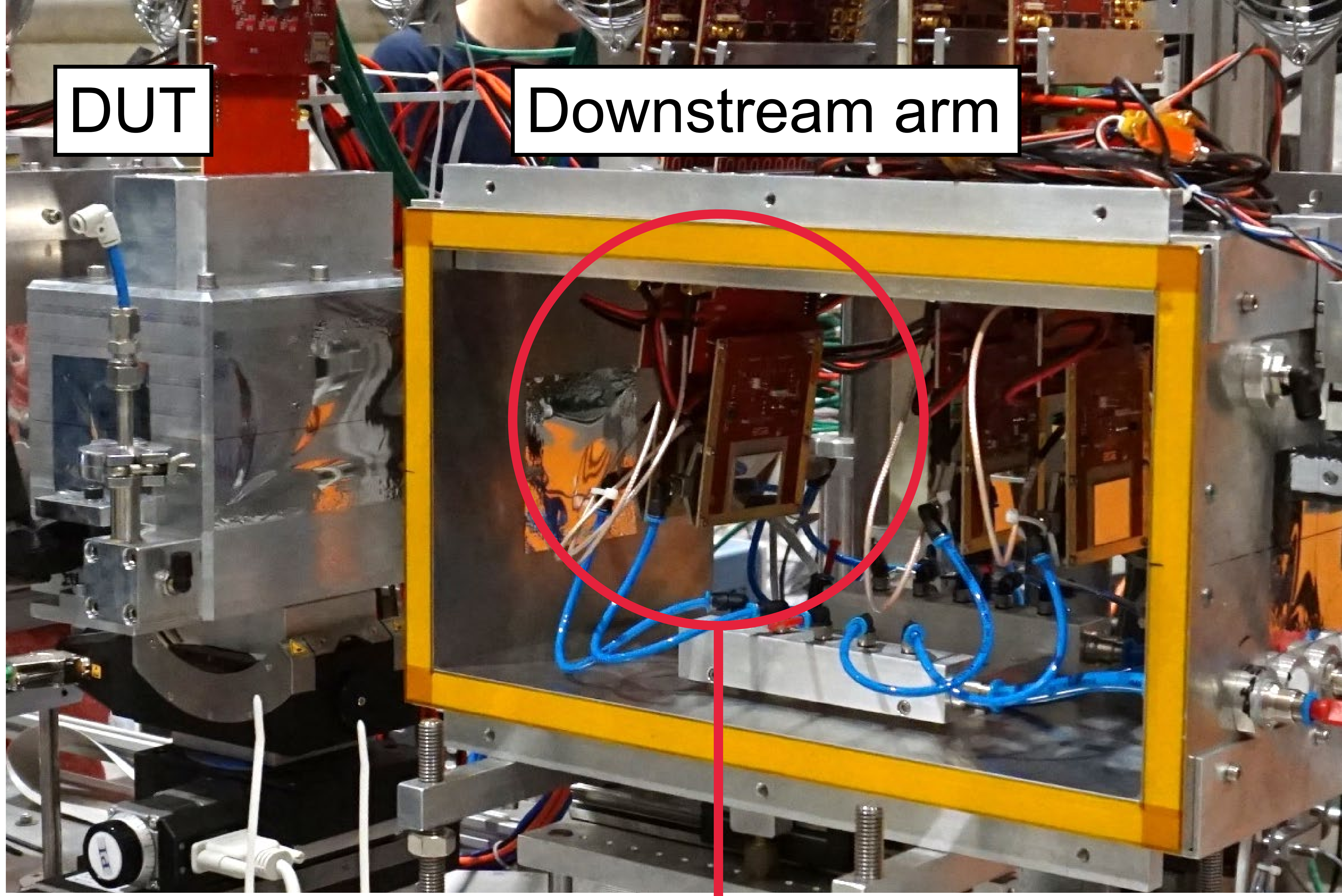
Single plane spatial resolution

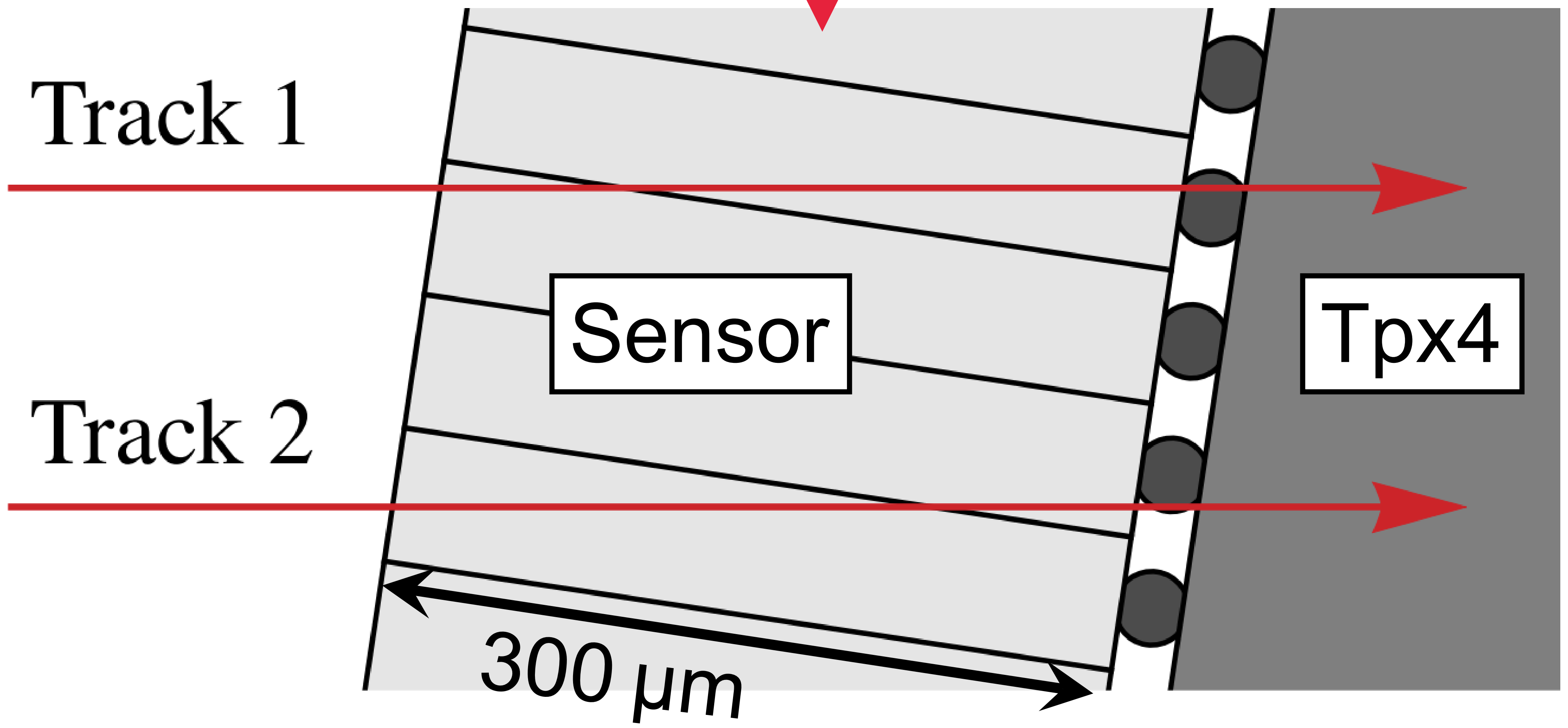
- Pixel size 55 μm × 55 μm
- Four innermost planes rotated 9° around x and y to induce charge sharing between pixels
- Charge-weighted mean gives cluster position
- Single plane resolution: **3.3 μm**
- Resolution depends on detection threshold





K. Akiba *et al* 2023 *JINST* **18** P02011
[DOI: 10.1088/1748-0221/18/02/P02011]

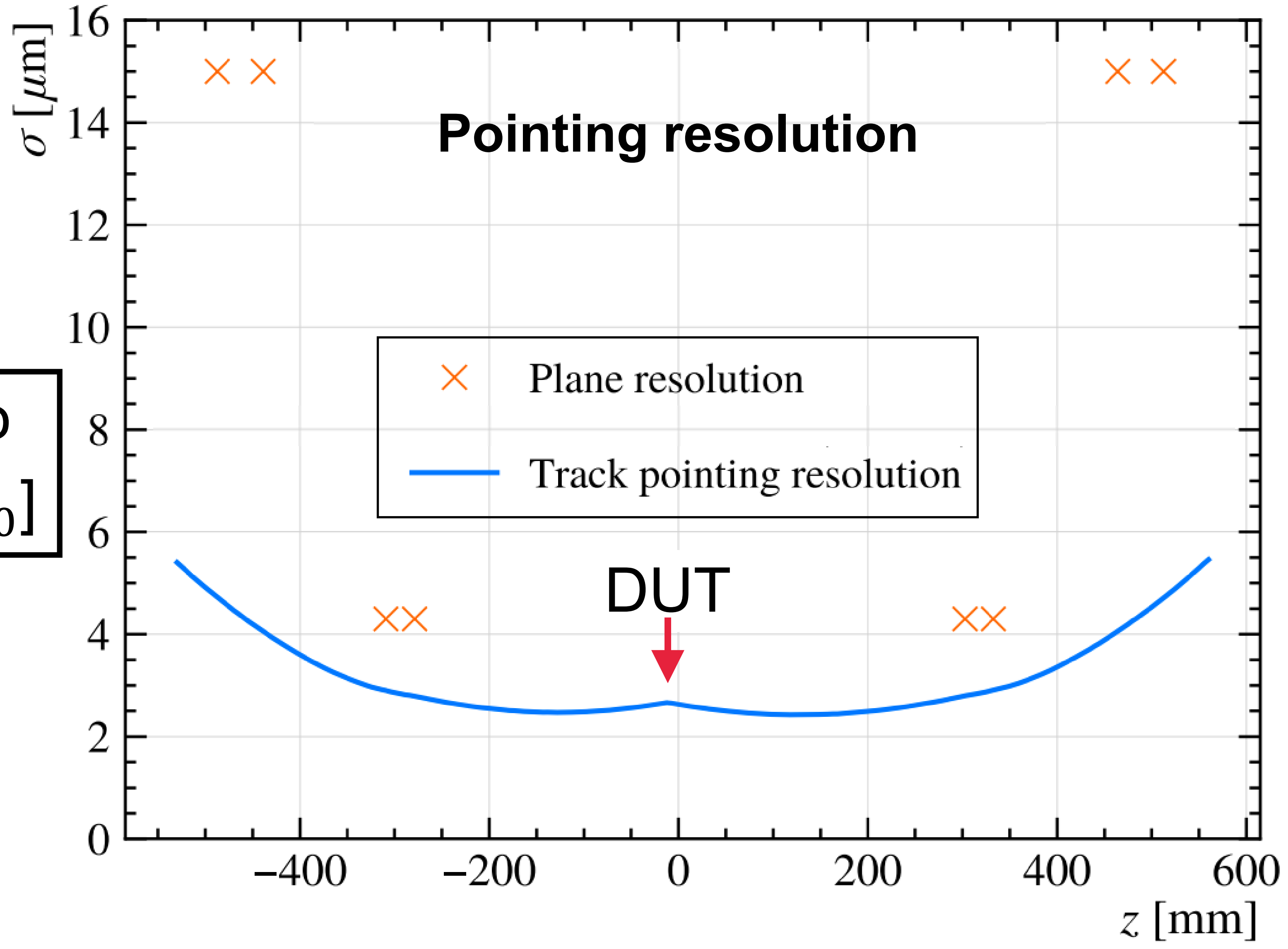


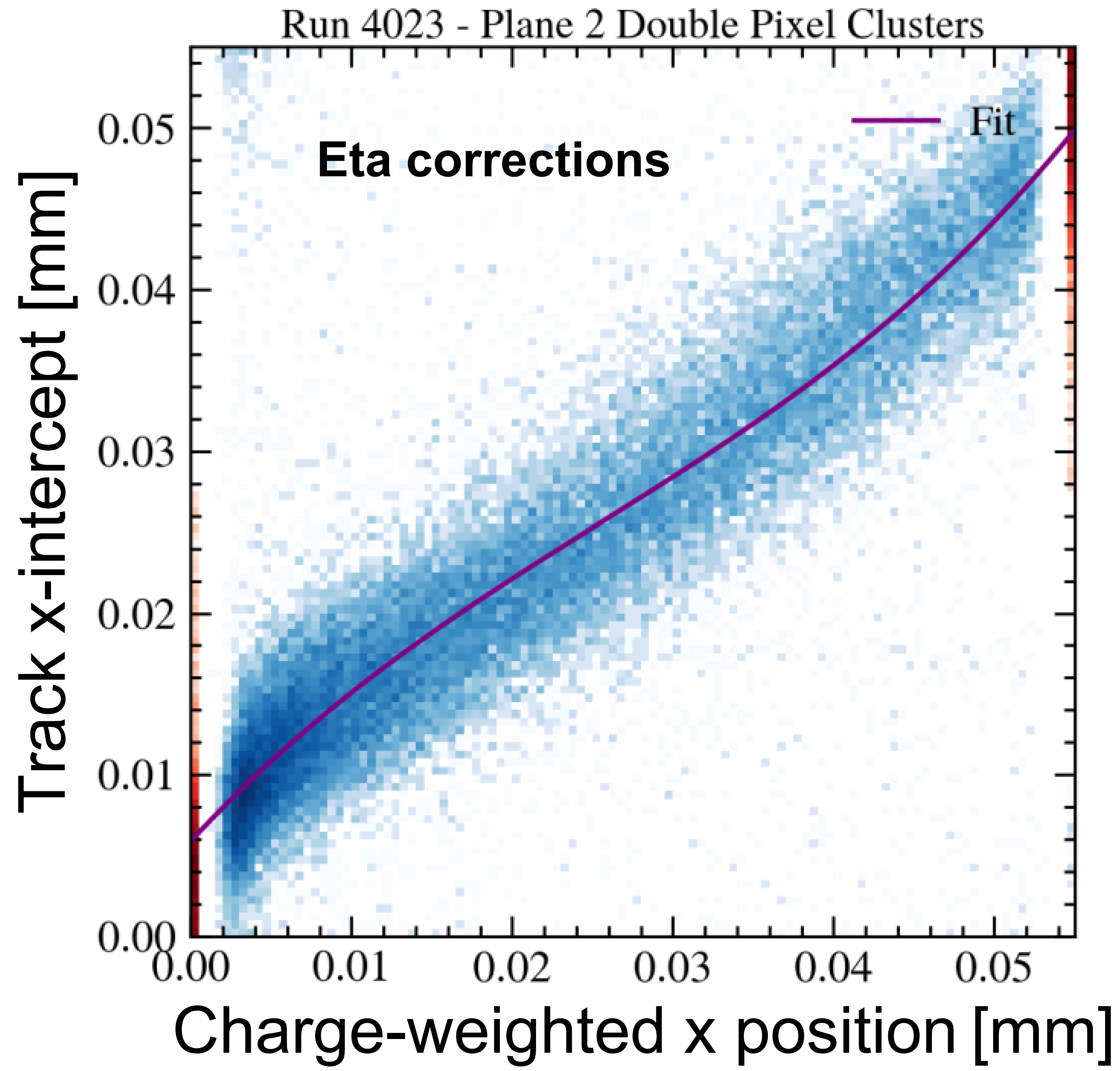


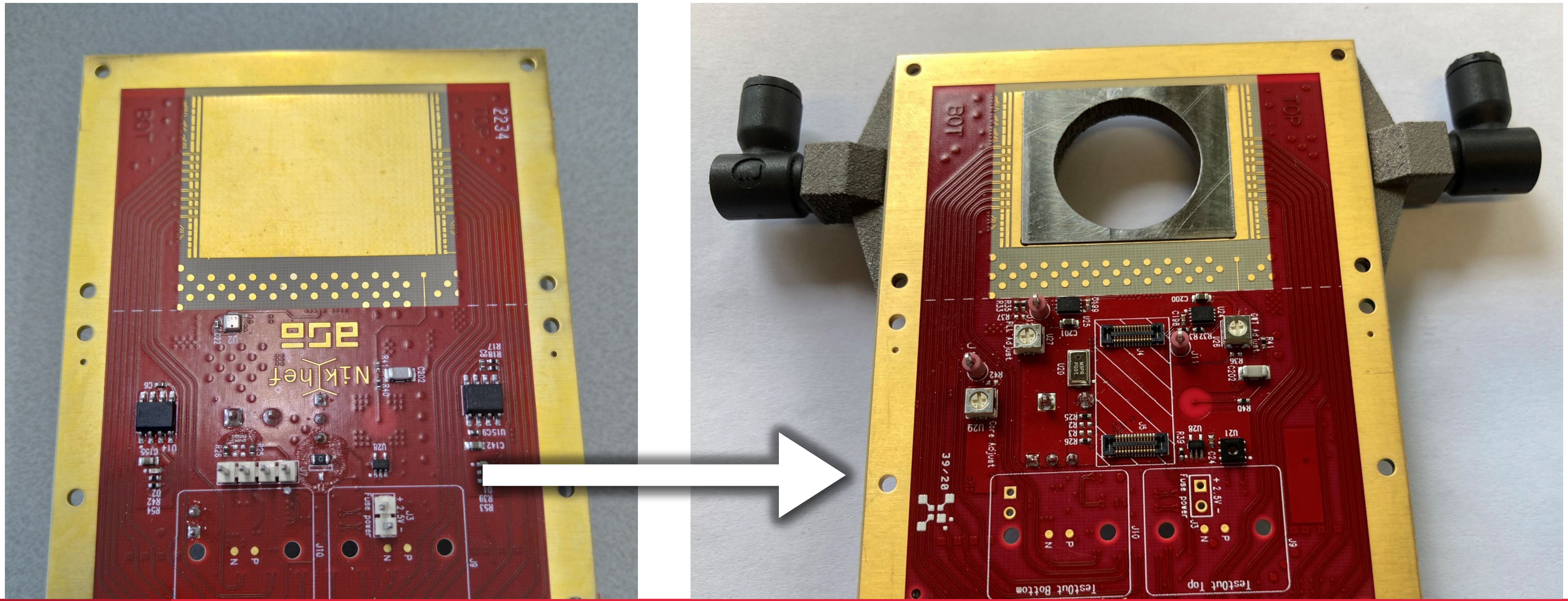
Track pointing resolution

- Pointing resolution at DUT: **2.5 μm** (Mixed hadron beam 180 GeV/*c*)
- PCB adds 1.8–2.4 %X_0 (ASIC + sensor adds 0.7–1.0 %X_0)
- Milling out PCB would improve resolution to ~2.0 μm
- Investigating "eta corrections" for nonlinear charge sharing
- Other possible improvements:
  - Move telescope arms further inward when possible
  - Operate 300 μm planes at lower detection threshold
  - Add additional thick planes

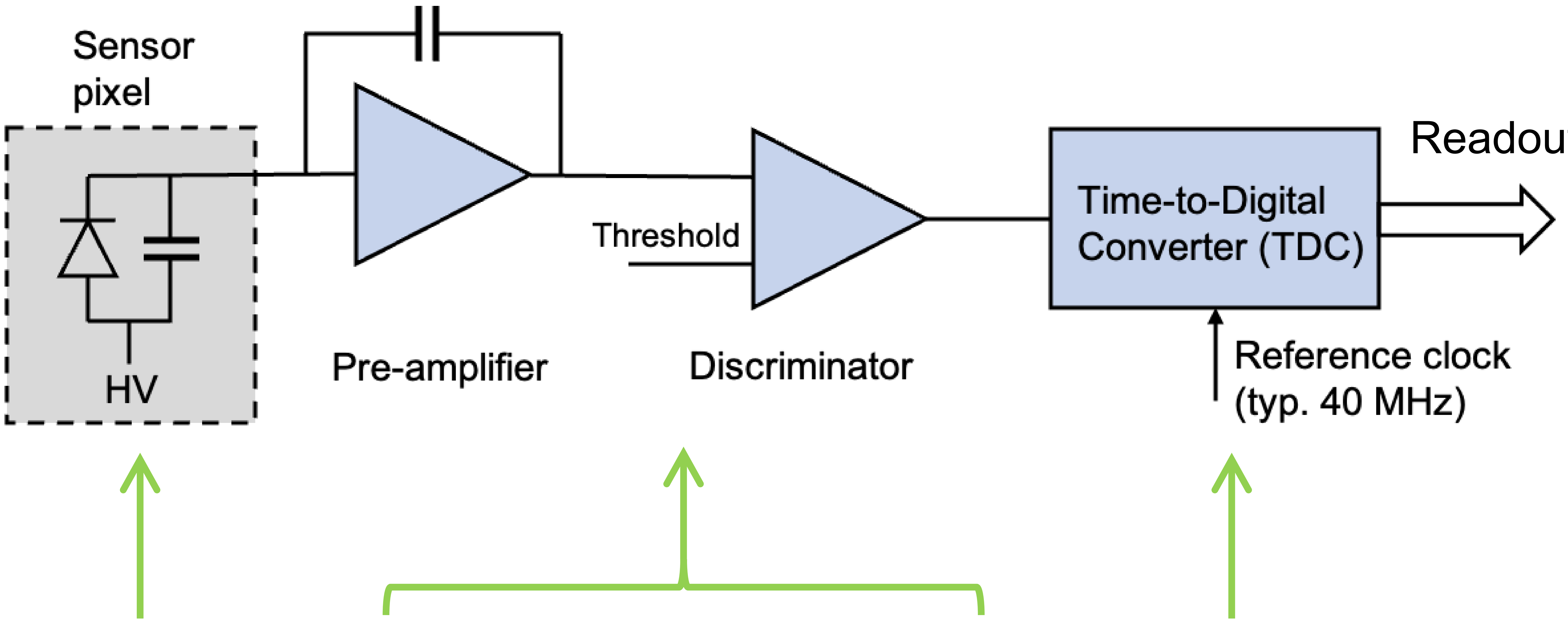
Scattering proportional to
$\sqrt{x/X_0}\,[1 + 0.038 \log x/X_0]$







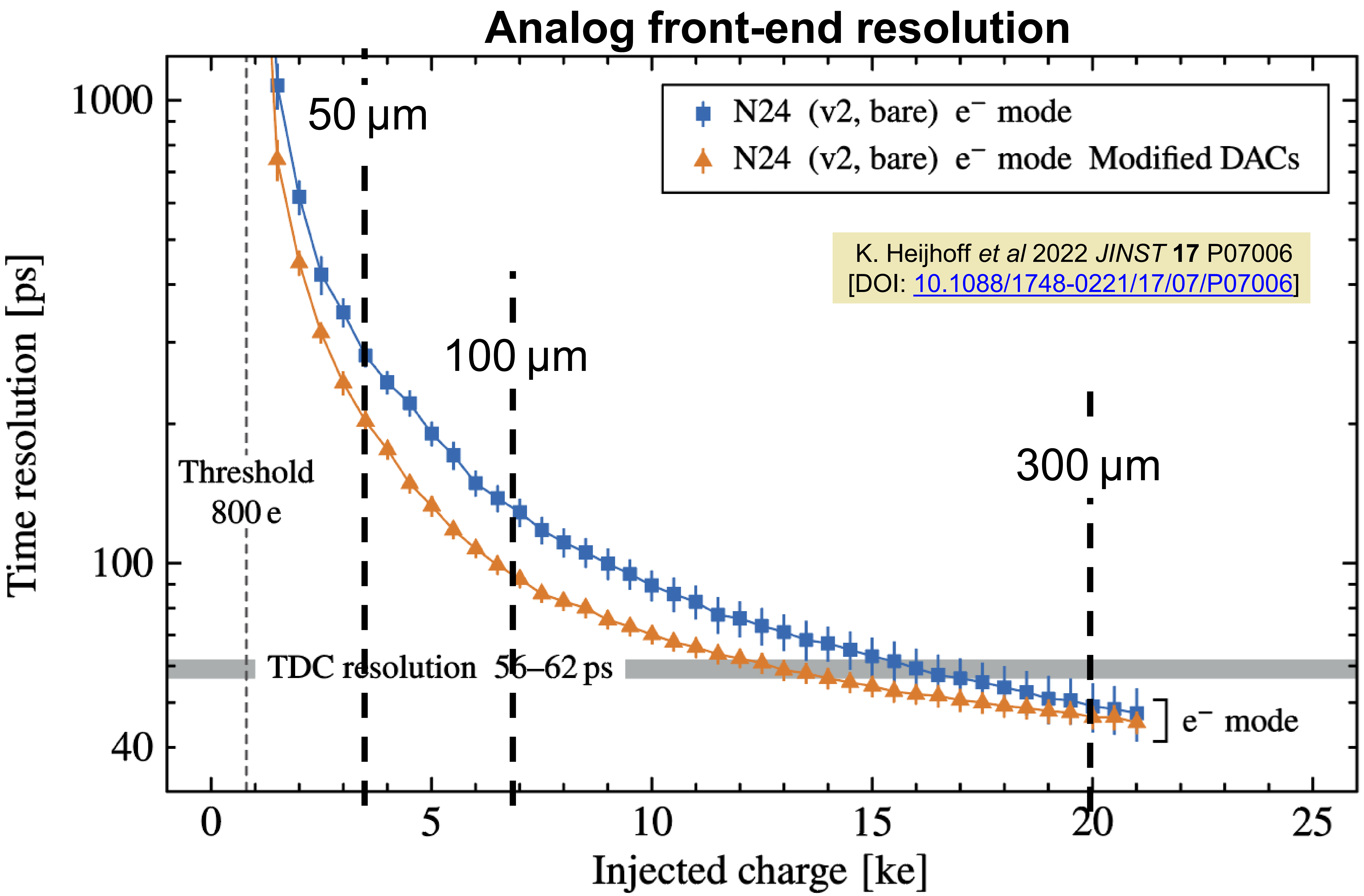
Time measurements in pixel detectors

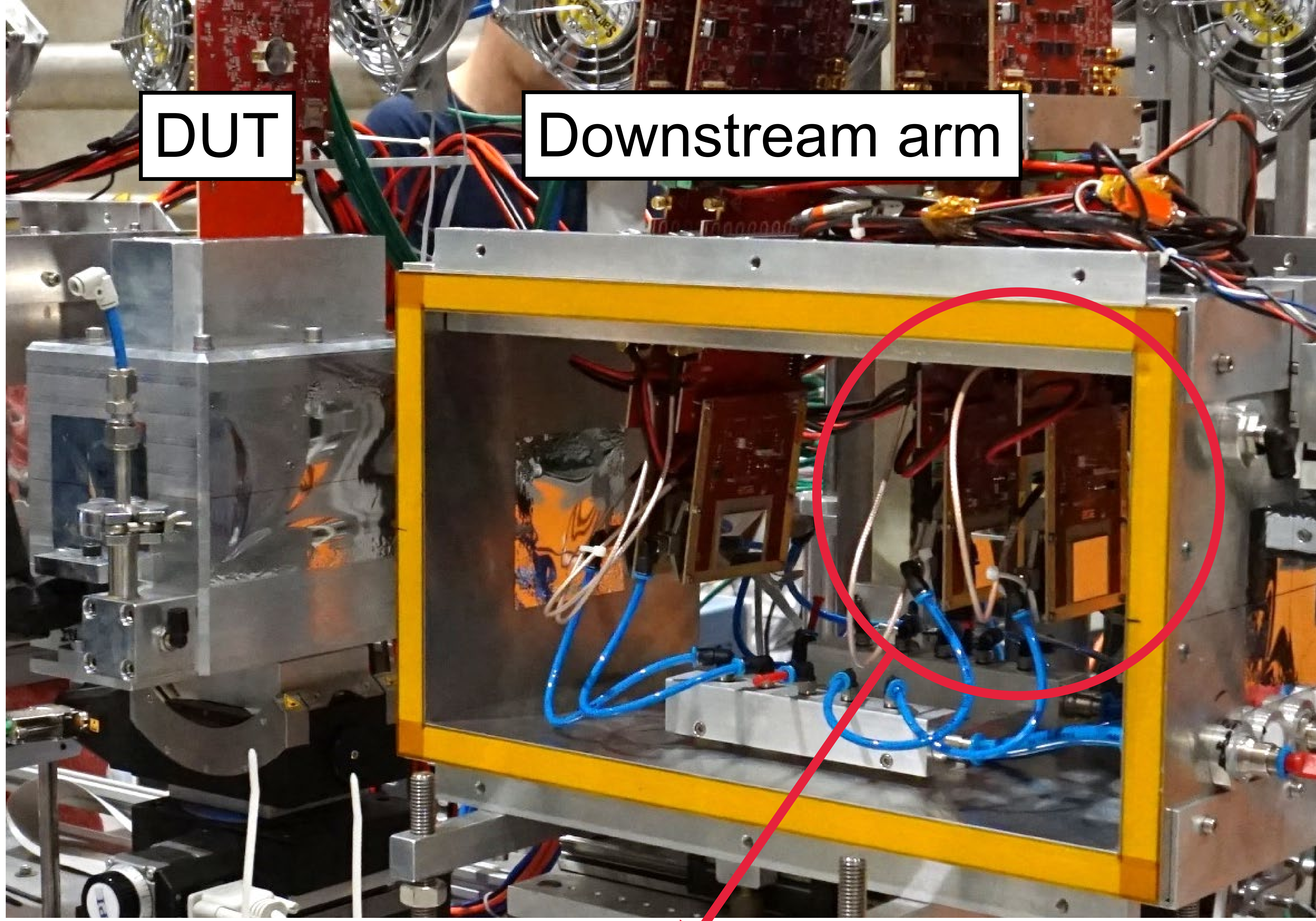


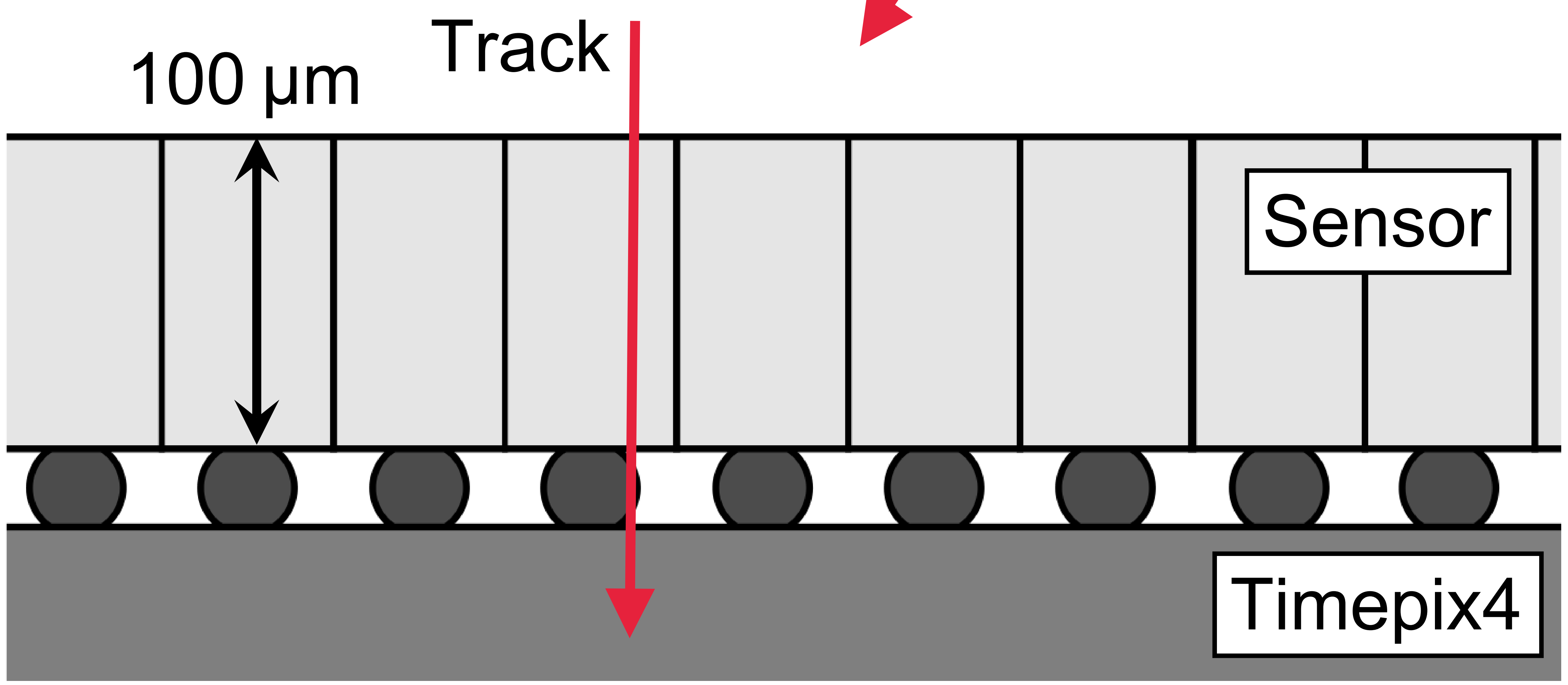
Time resolution = $\sigma_t^2(\text{sensor})$ + $\sigma_t^2(\text{jitter}) + \sigma_t^2(\text{timewalk})$ + $\sigma_t^2(\text{TDC})$

Single plane time resolution

- Thin sensors reduce time errors due to Landau fluctuations
- Perpendicular to beam to maximise signal charge in single pixel
- Reduced signal size reduces analog front-end performance

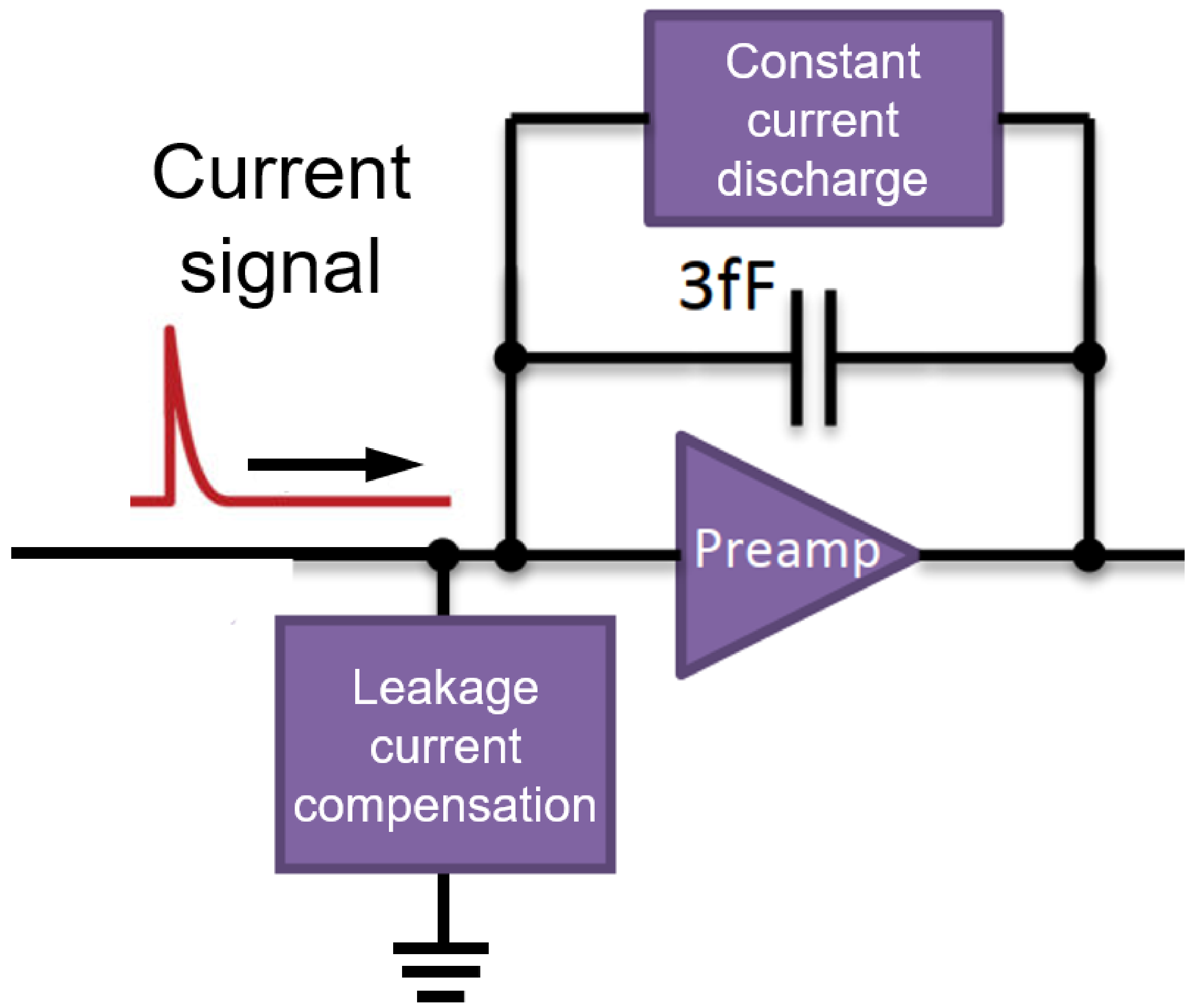


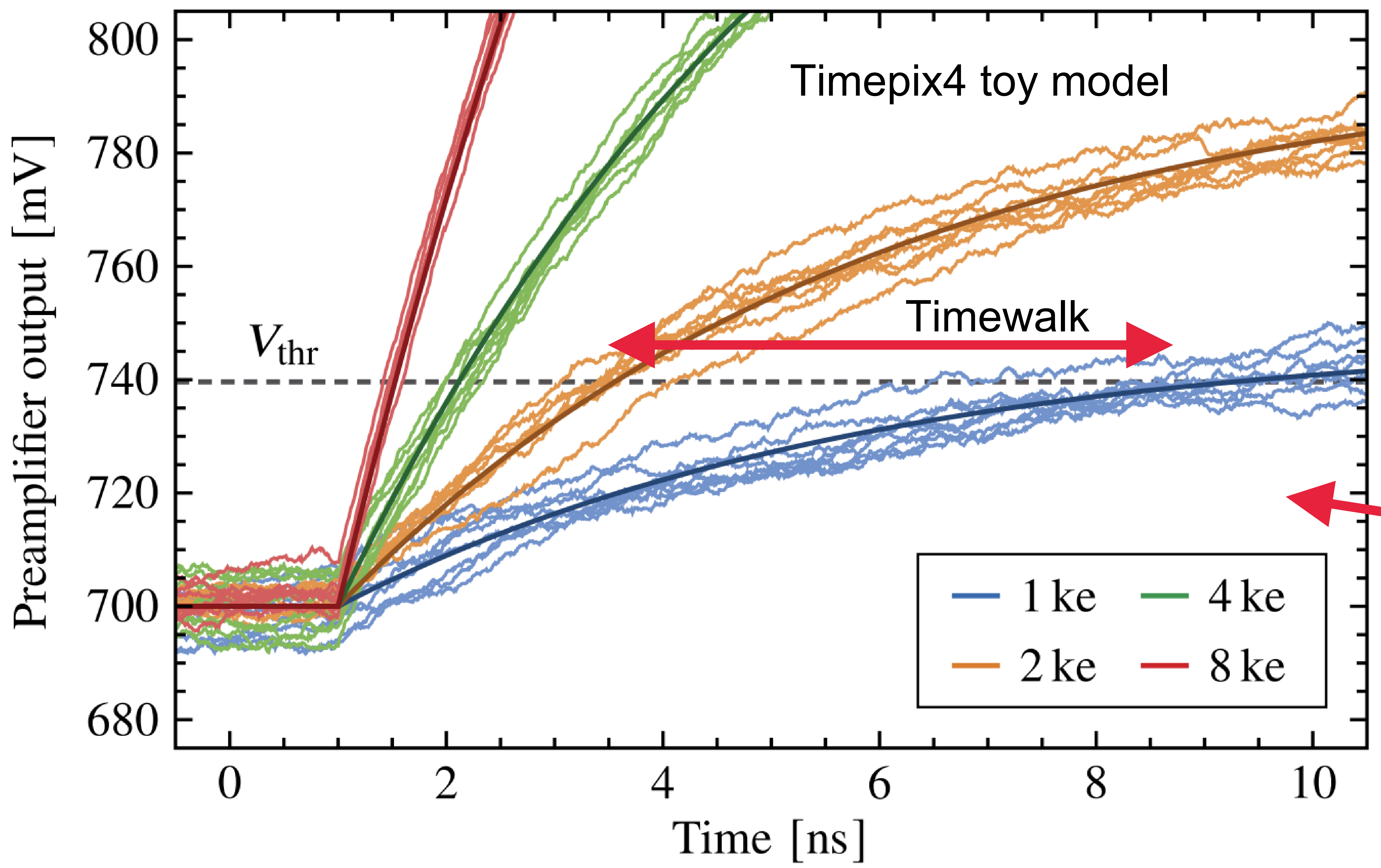


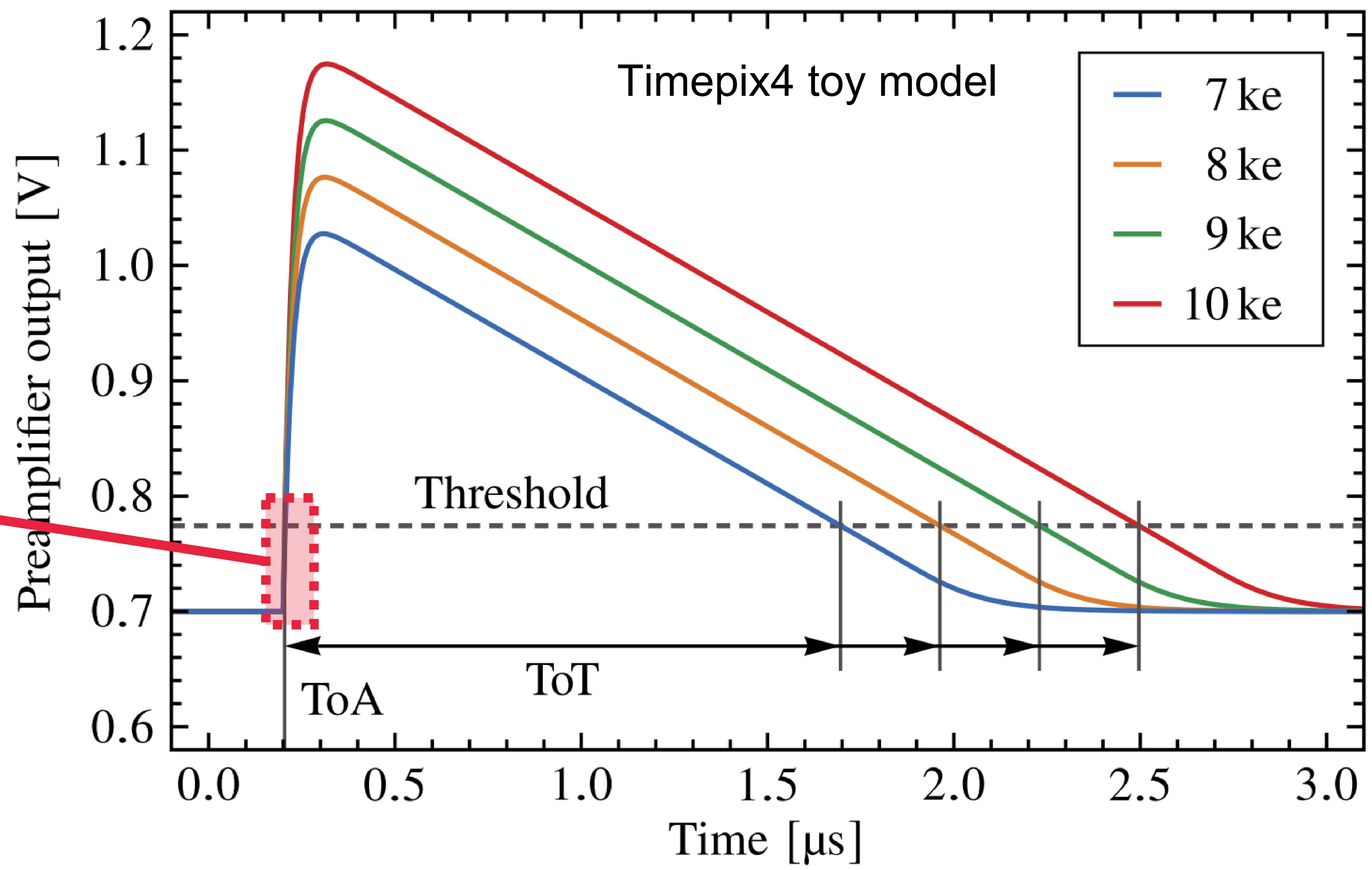


Timewalk

- Time measurement depends on signal size
- Preamplifier output has a fixed risetime
- Reduced signal size makes timewalk corrections crucial

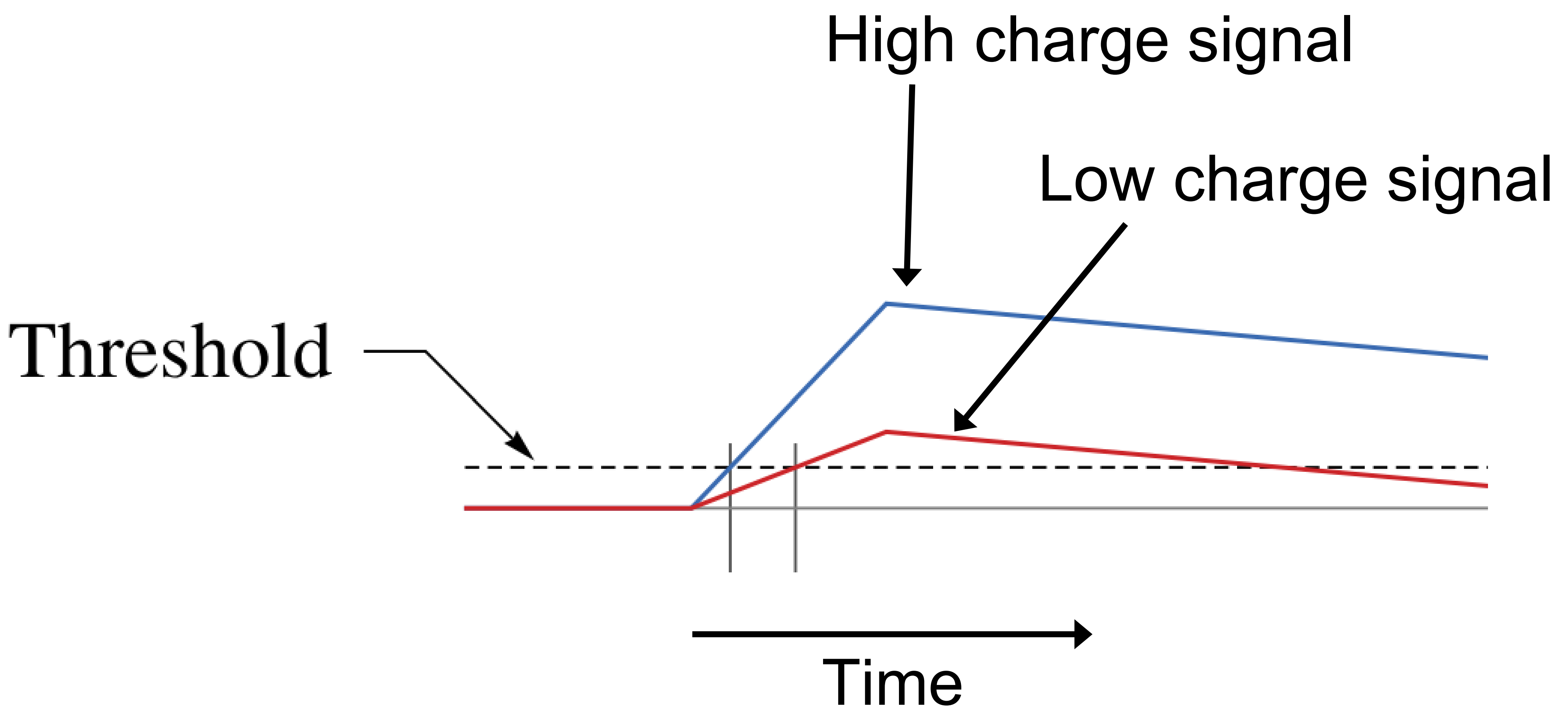


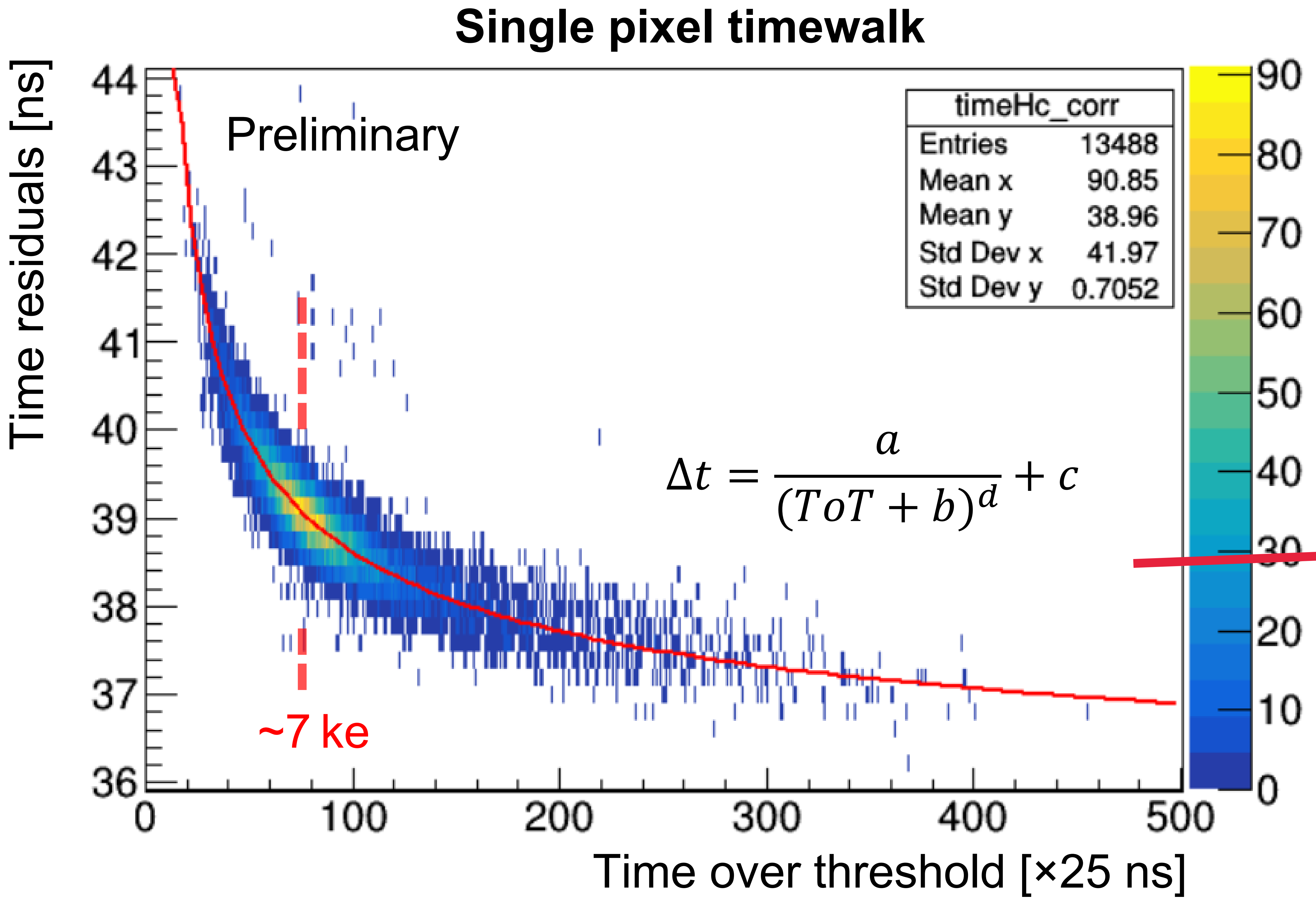


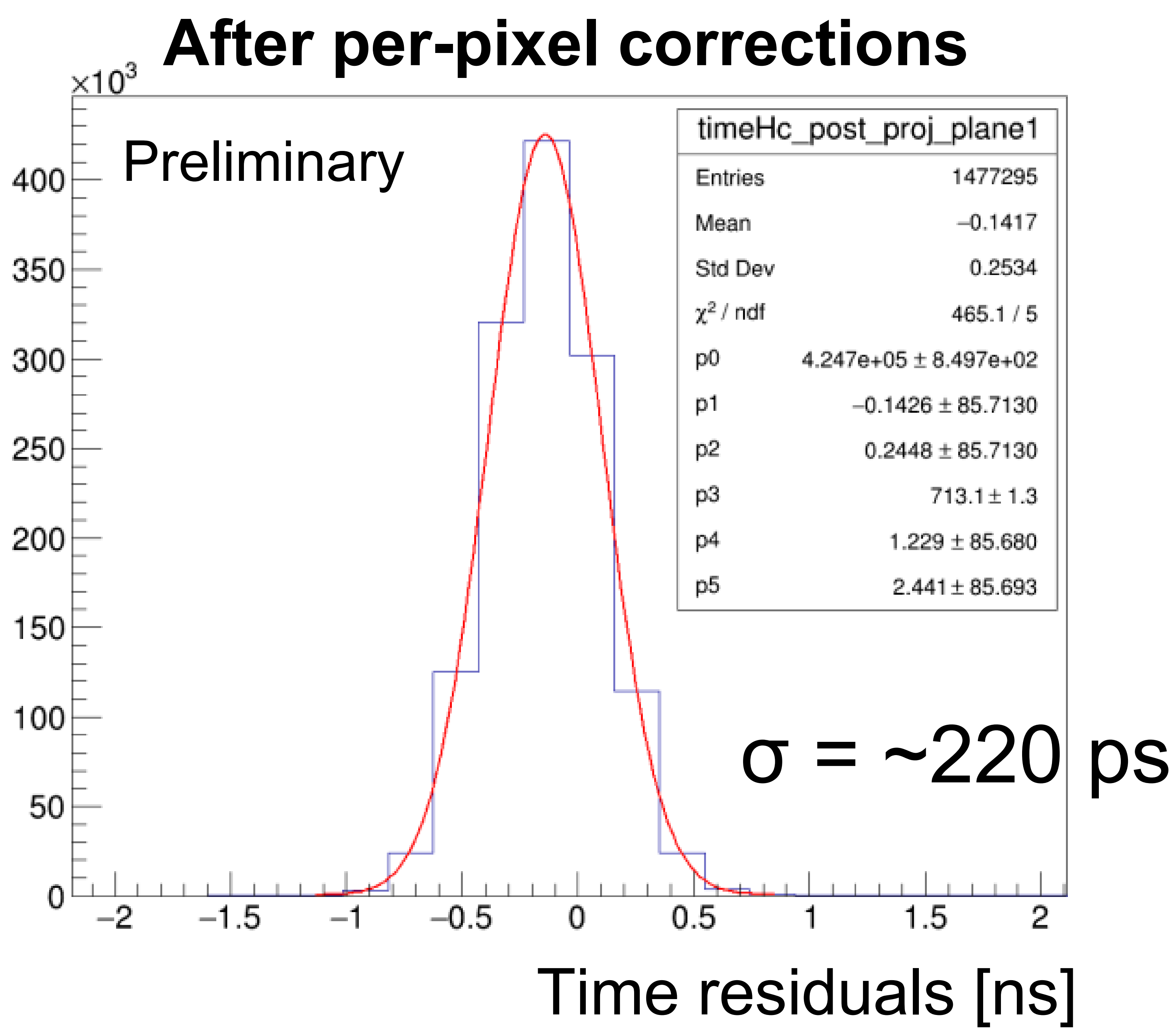


Single plane time resolution

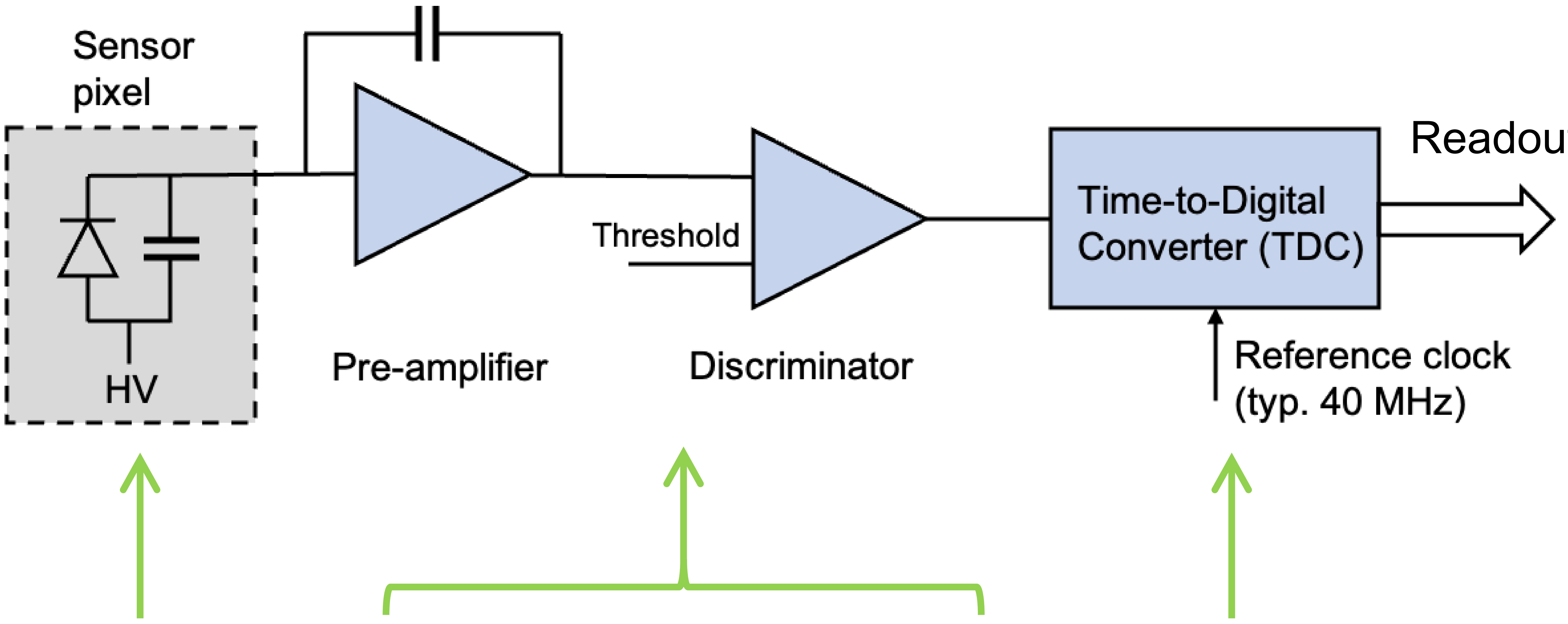
- Per-pixel timewalk corrections are applied
- Improves Time resolution: ~500 ps → ~220 ps
- Next: clock corrections to improve further





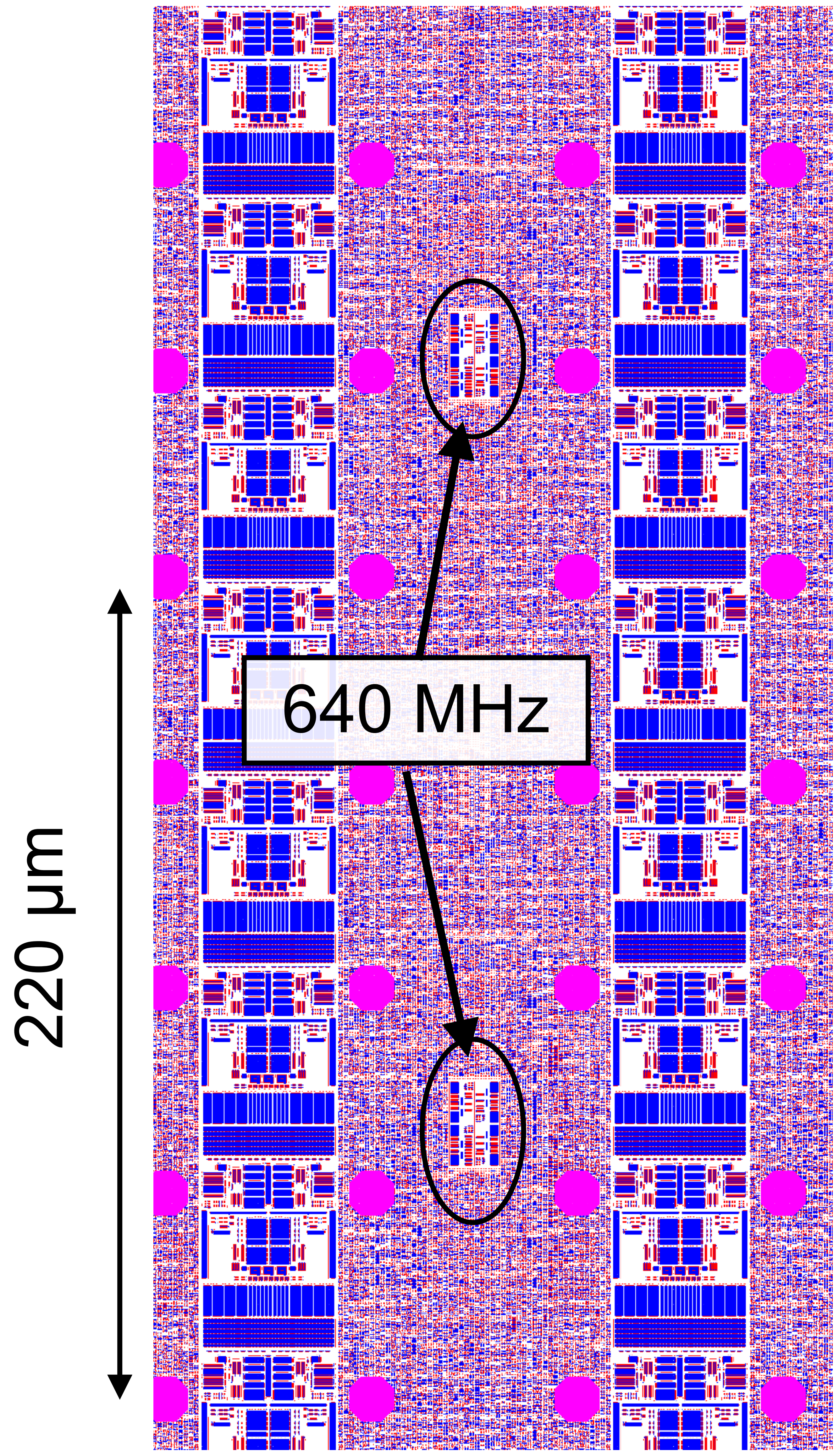


Time measurements in pixel detectors

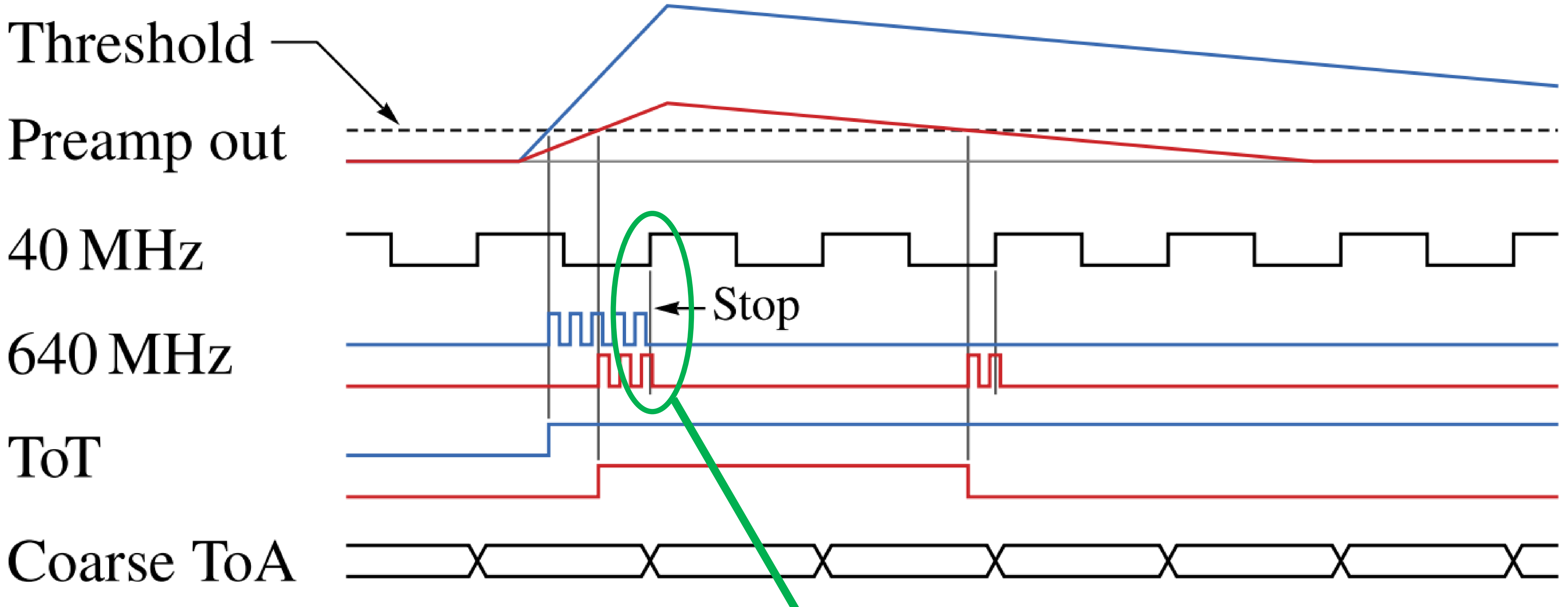


Time resolution = σ_t^2(sensor) + σ_t^2(jitter) + σ_t^2(timewalk) + σ_t^2(TDC)

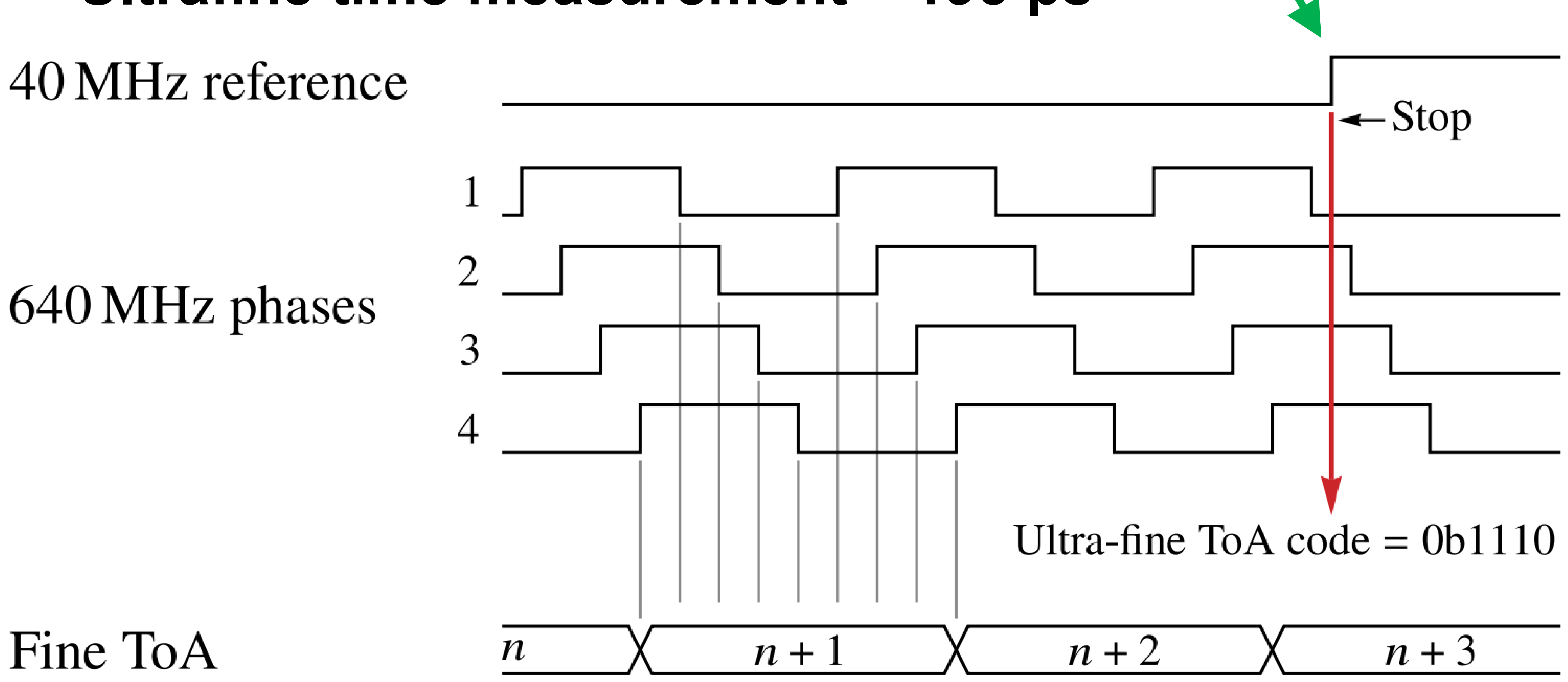
Time measurement in Timepix4



Coarse and fine time measurement – 40 MHz and 640 MHz

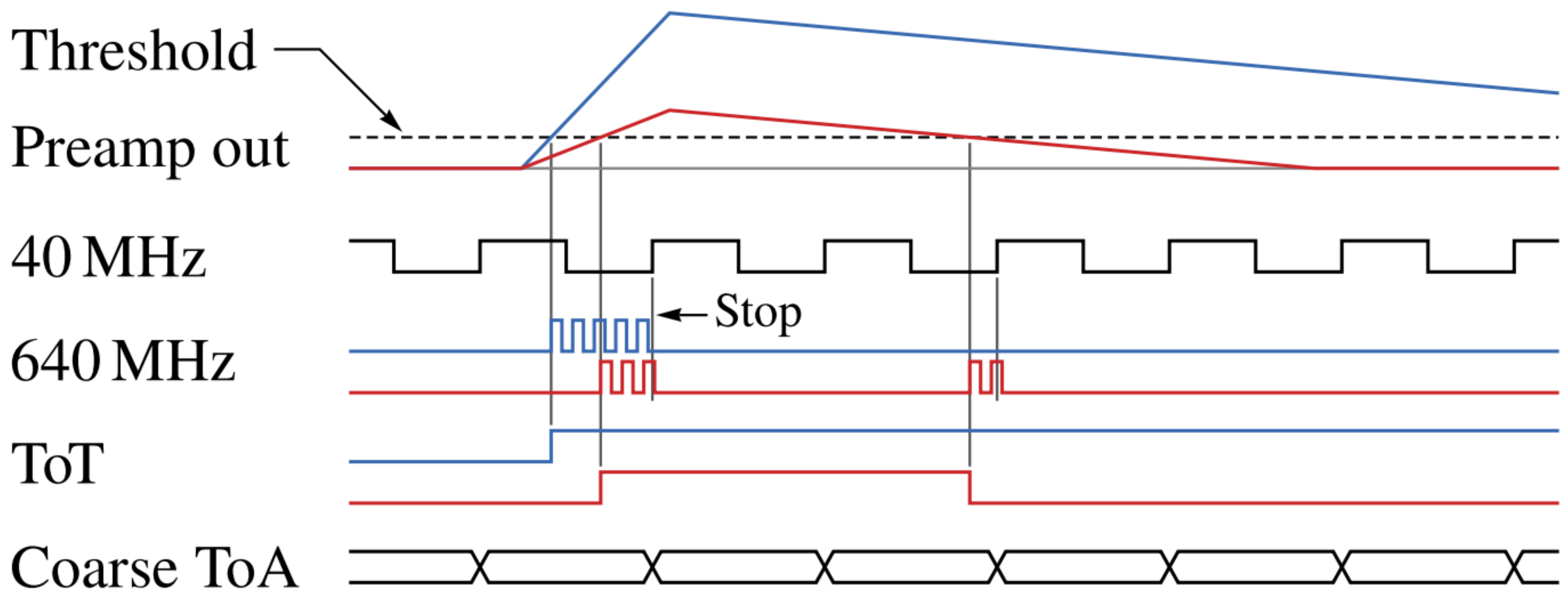


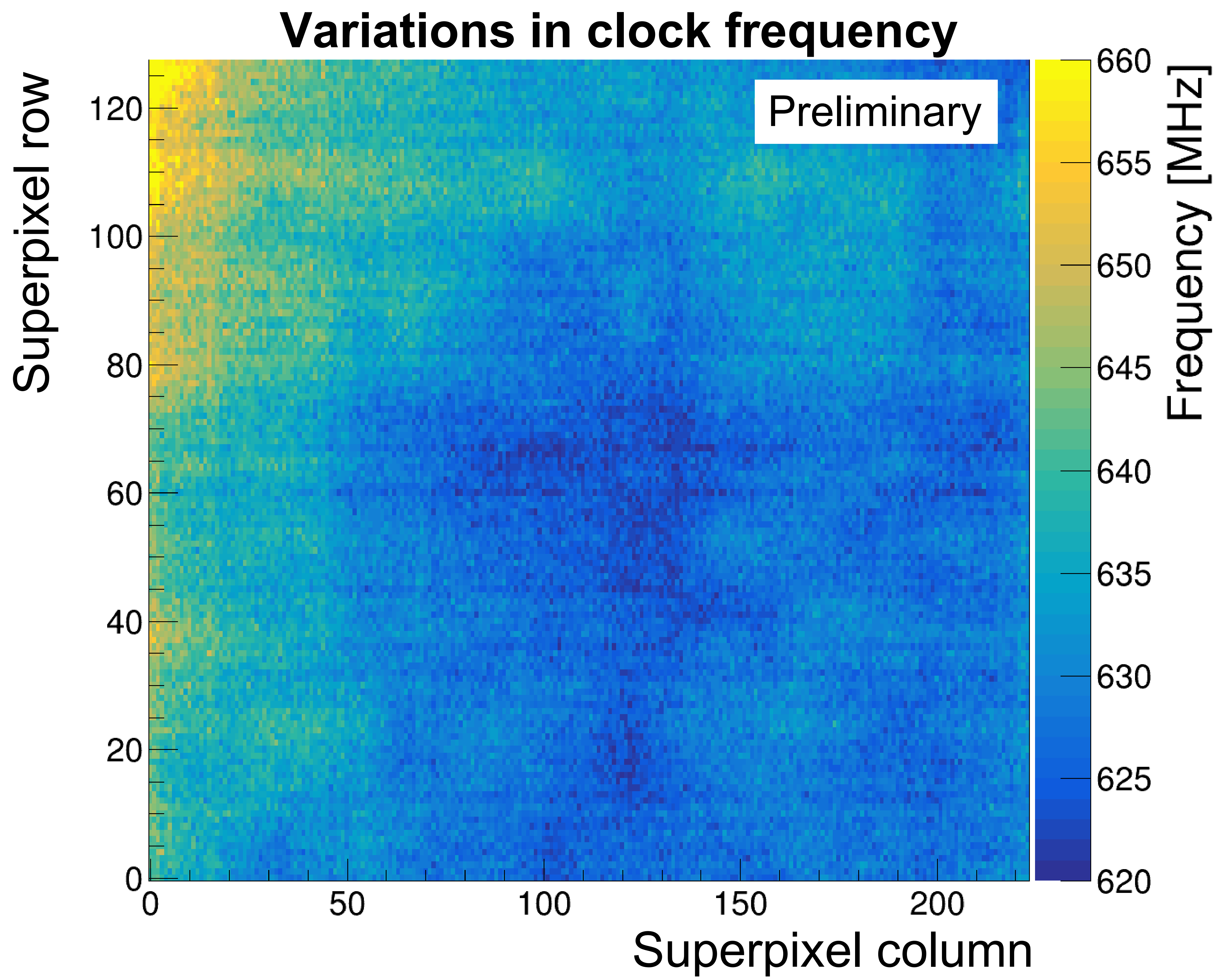
Ultrafine time measurement – 195 ps

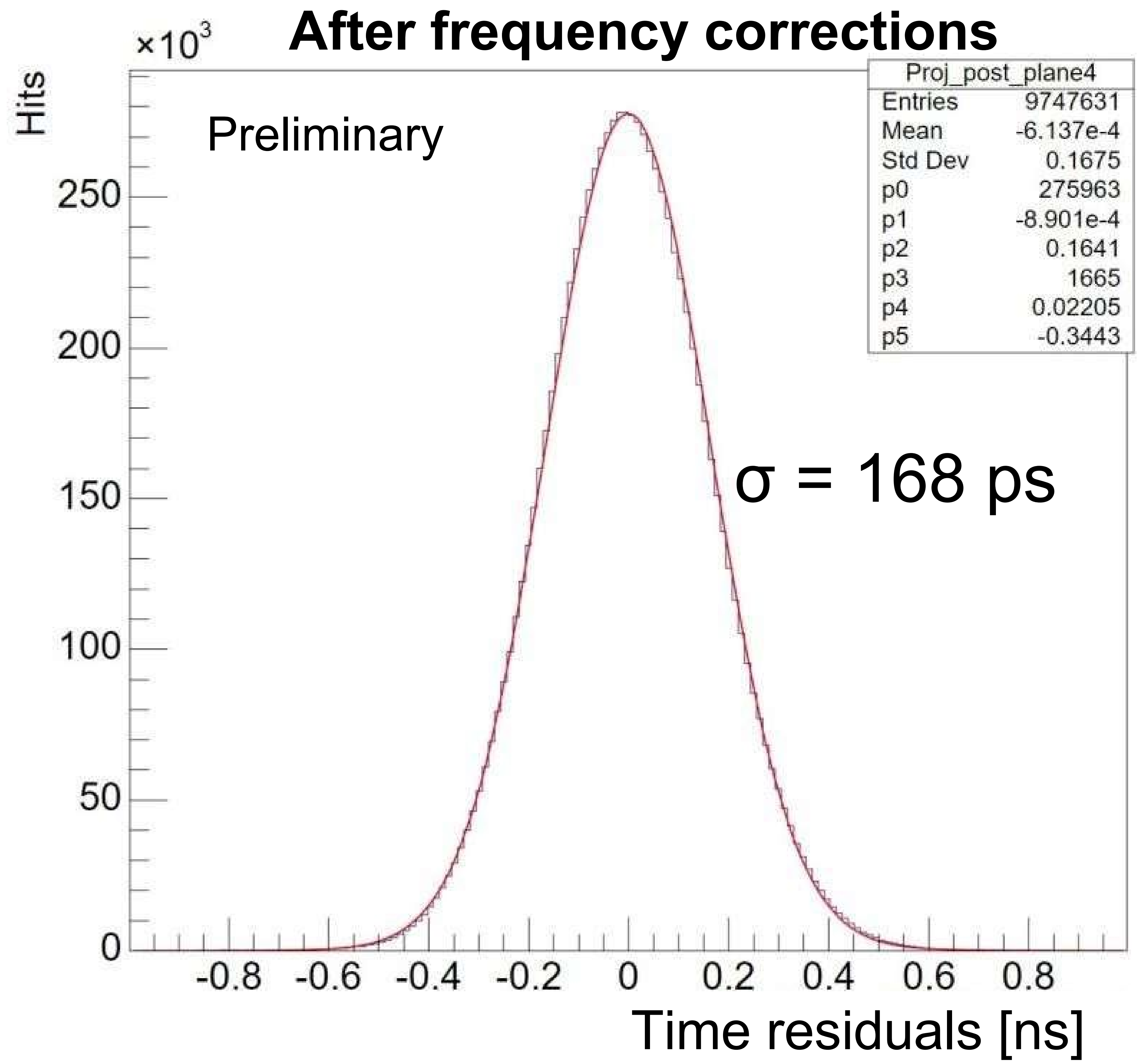


Time resolution

- VCO frequency must also be calibrated for each superpixel
- Variations are due to design constraints
- Improves single-plane time resolution to: ~170 ps
- Four timing planes → 90 ps track time resolution







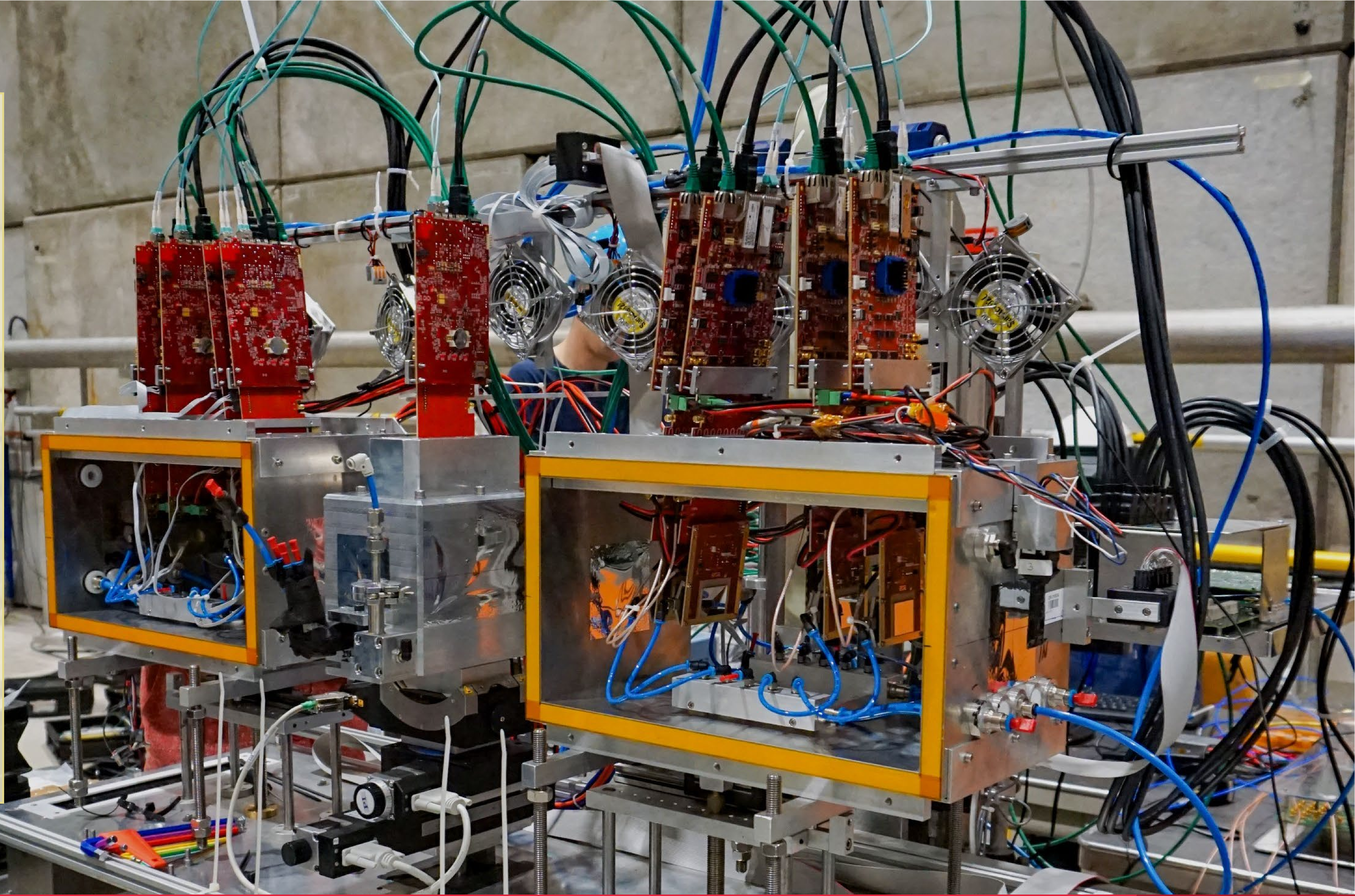
Outlook

Only telescope to simultaneously have

- Good spatial resolution
- Precise time measurements
- High-rate capability

Next:

- Study fast sensors!
  (Actually started last week)
- Upgrade timing planes
  (30 ps track time resolution)
- Or maybe
  fully equip with 3D sensors
  (20 ps track time resolution??)



People involved

Testbeam crew

Nikhef: Kazu Akiba, Martin van Beuzekom, Tjip Bischoff, Evridiki Chatzianagnostou, Robbert Geertsema, Kevin Heijhoff, Uwe Kraemer, Daan Oppenhuis, Ganrong Wang
CERN: Federico De Benedetti, Wiktor Byczynski, Victor Coco, Raphael Dumps, Mohammadtaghi Hajheidari
IGFAE: Edgar Lemos Cid, Efrén Rodríguez Rodríguez
TU Dortmund: Elena Dall'Occo, David Rolf
University of Manchester/CERN: Tim Evans
University of Oxford: David Bacher, Rui Gao, Fernanda Goncalves Abrantes, Tommaso Pajero,
University of Birmingham: Dan Johnson, Marcus Jonathan Madurai
University of Glasgow: Naomi Cooke, Aleksandrina Docheva

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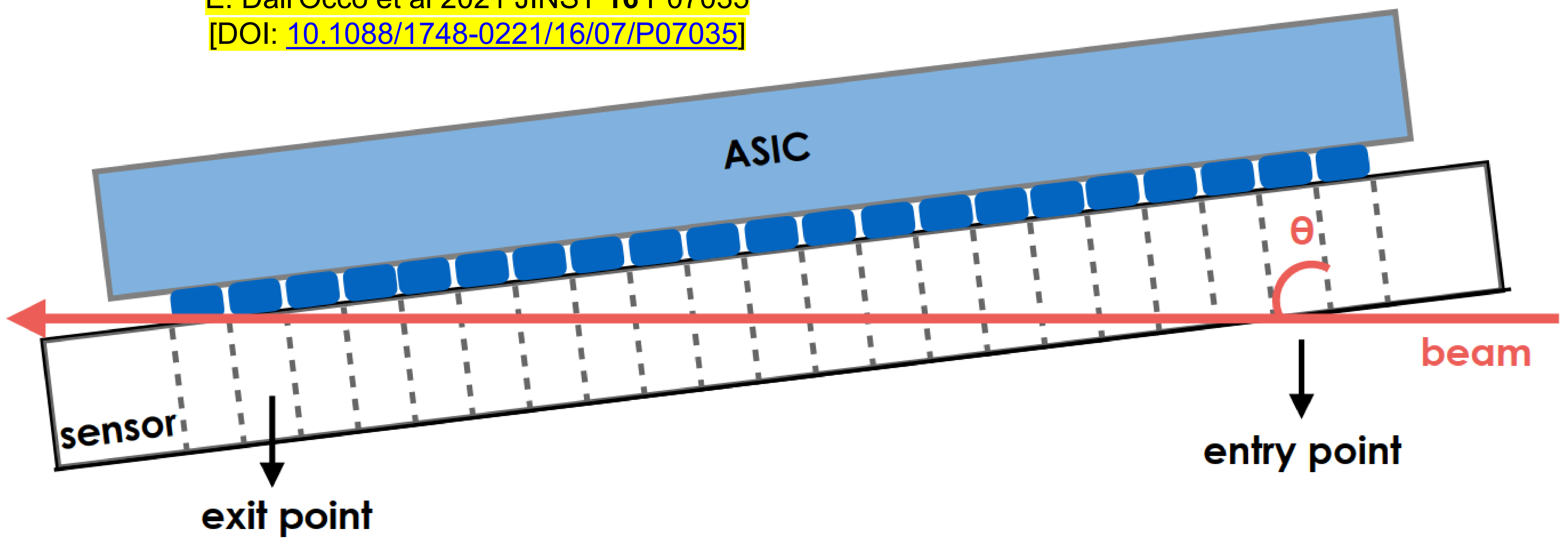
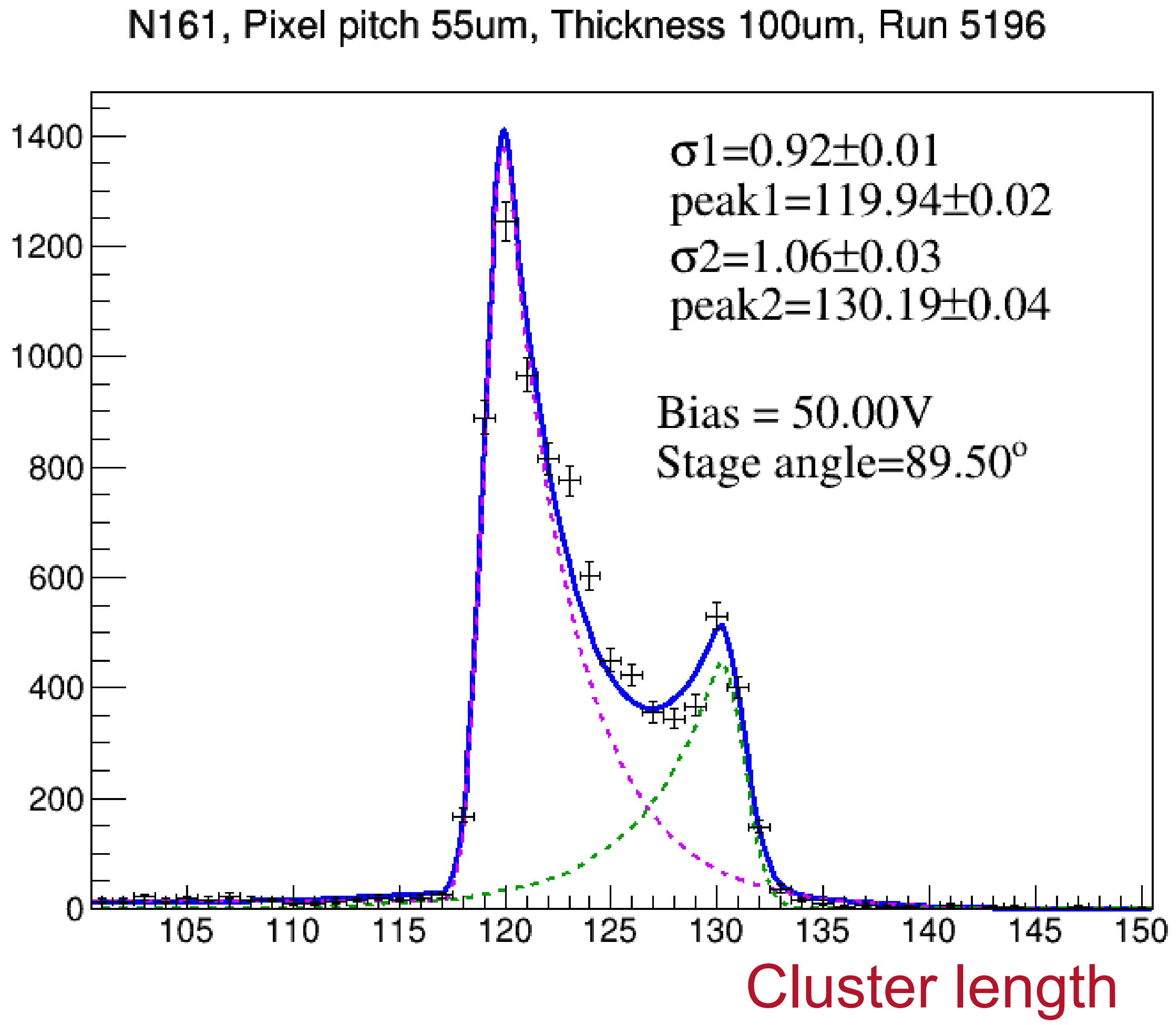
Backup slides

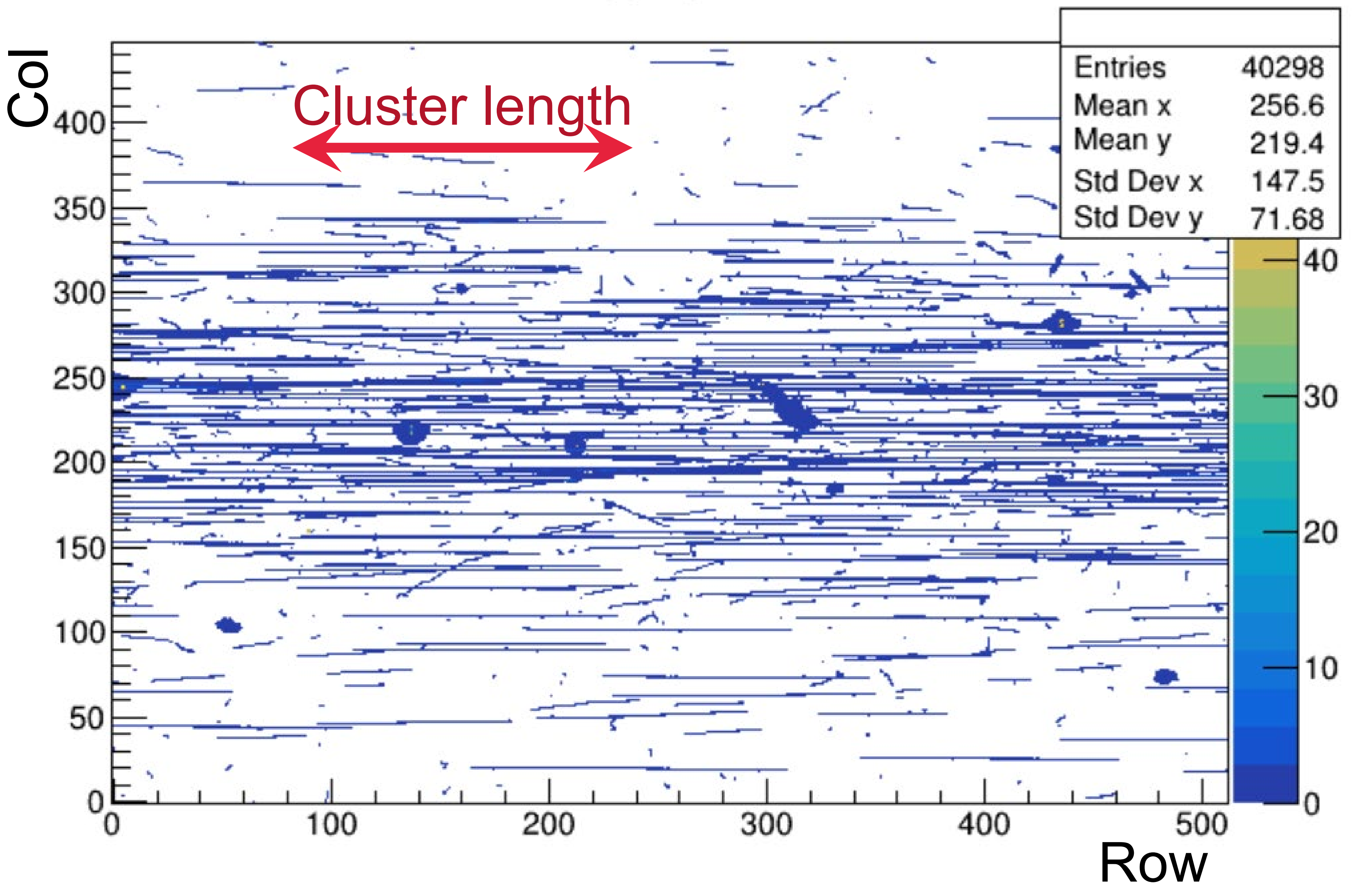
Grazing angle measurements

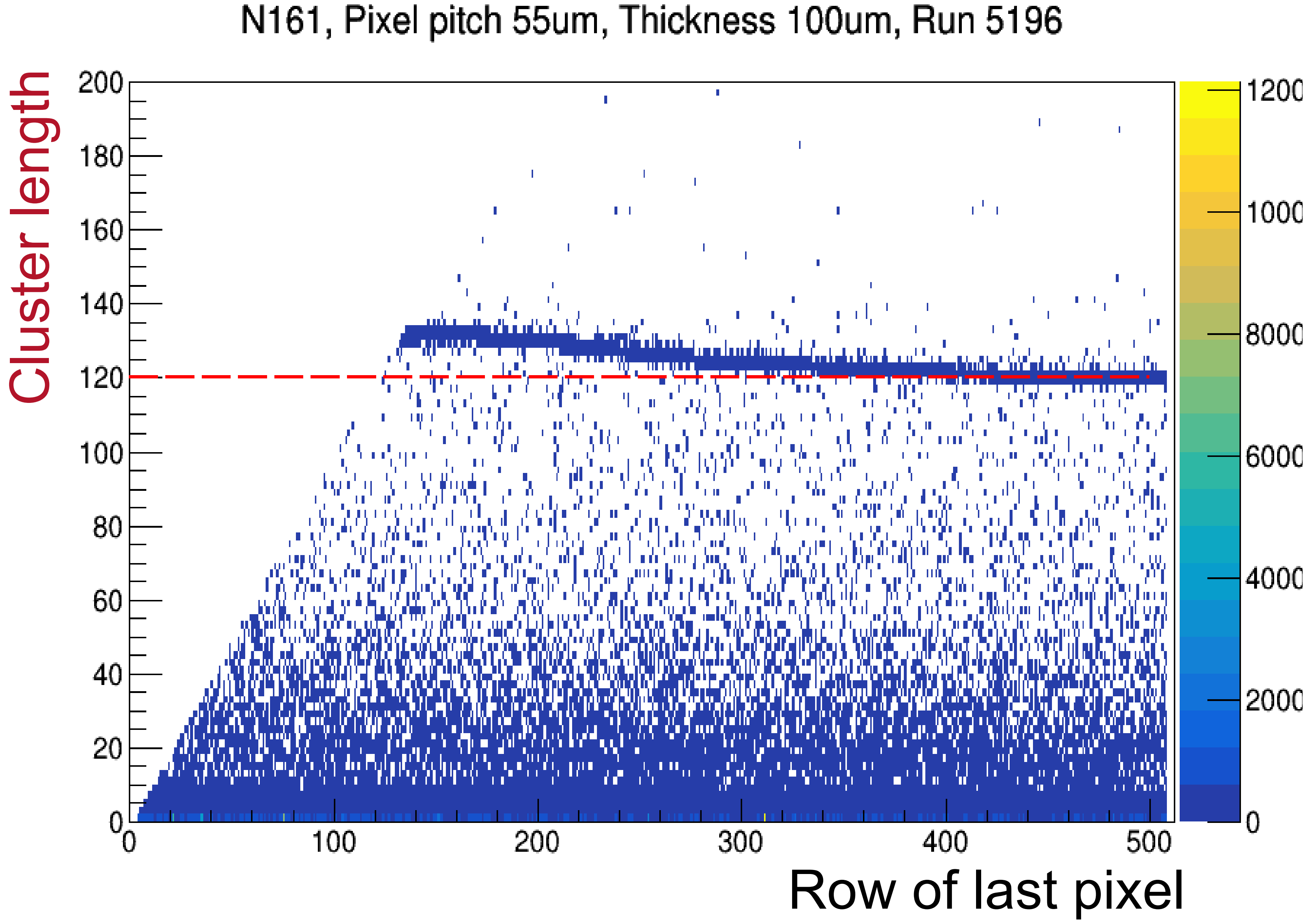
- Grazing angle measurements probe different depths of the sensor
- Can be used to determine thickness by measuring cluster length at various angles
- Sensors are thin, but not flat

E. Dall'Occo et al 2021 JINST **16** P07035
[DOI: 10.1088/1748-0221/16/07/P07035]



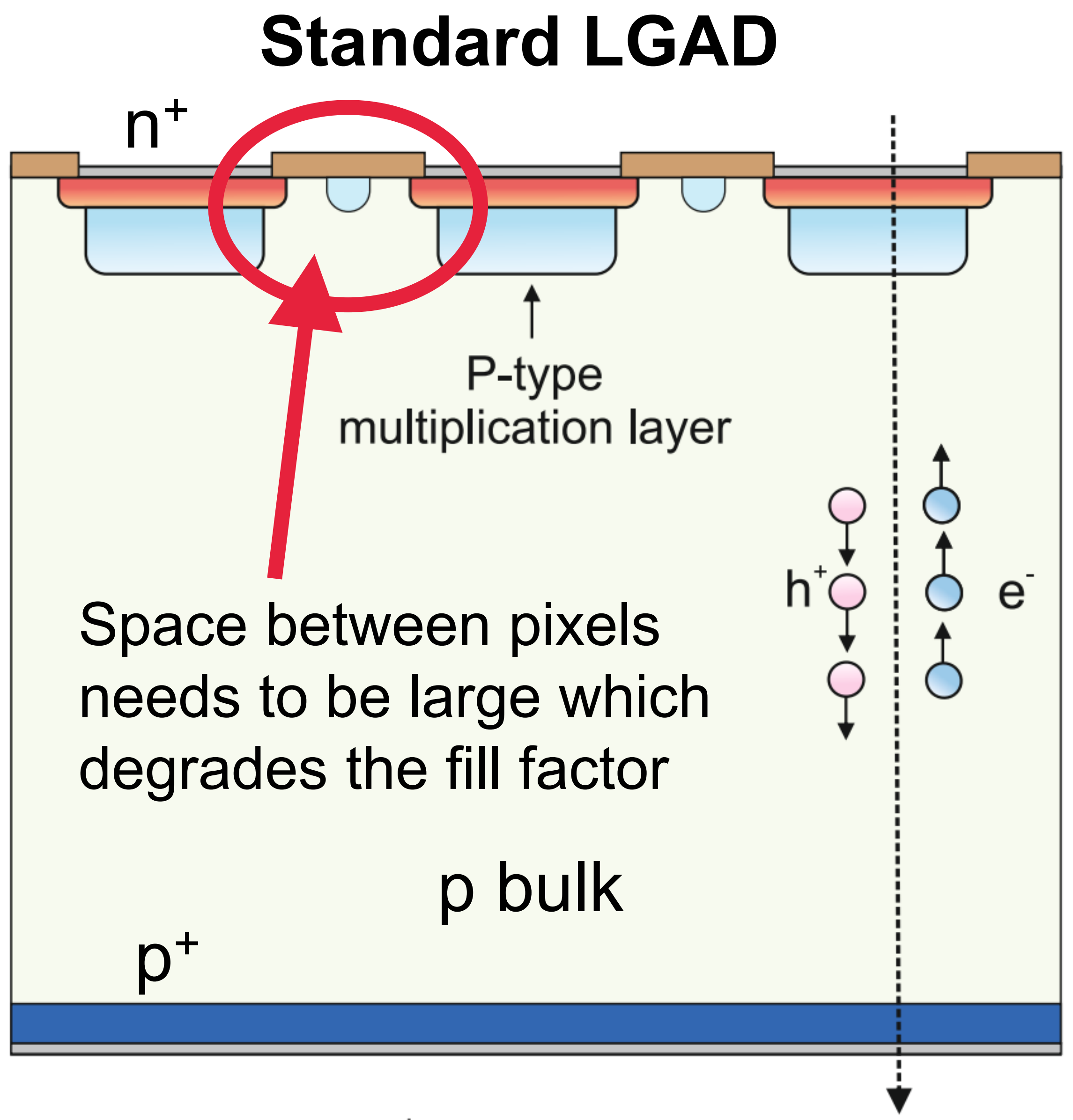


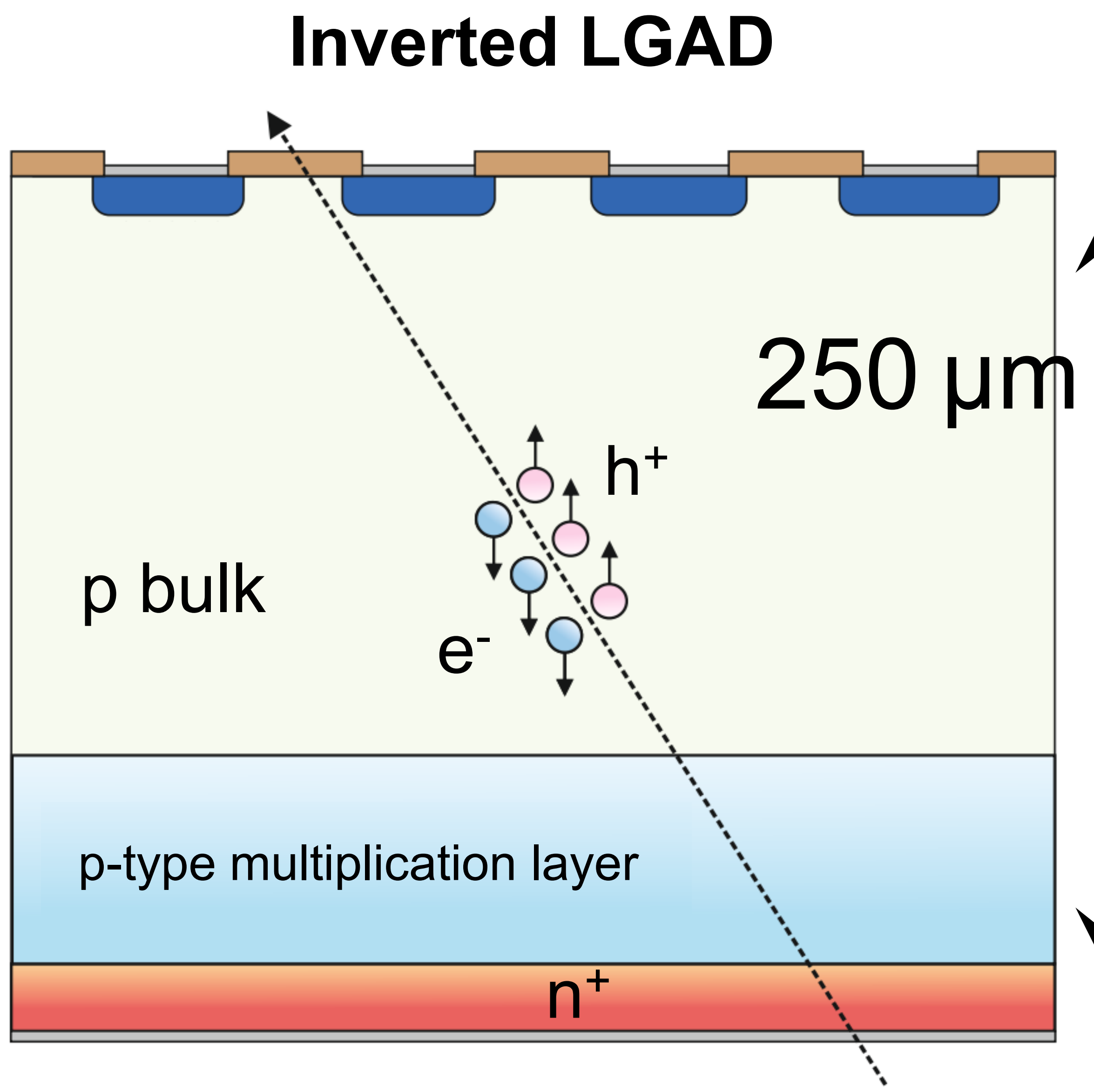




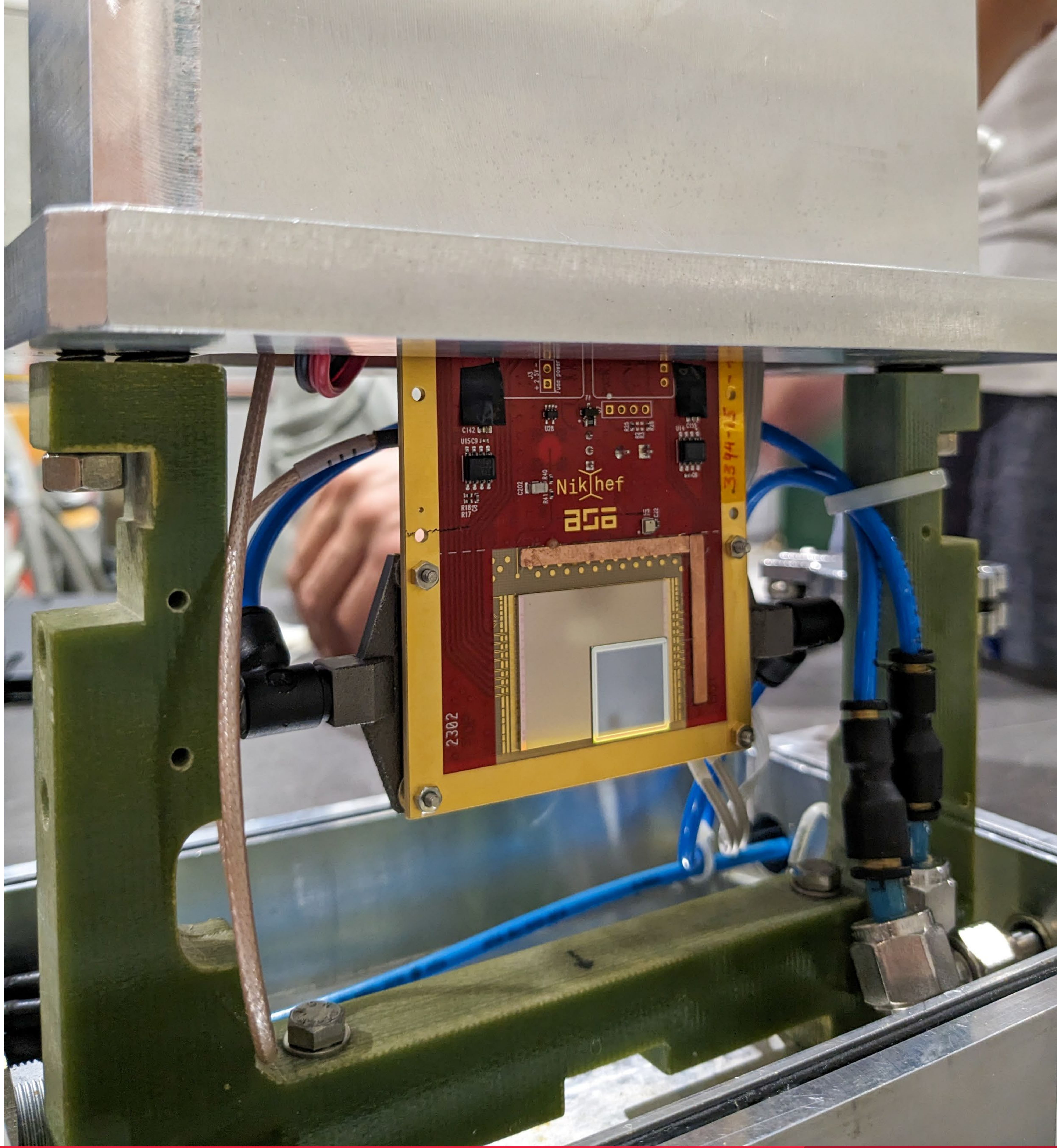
Inverted LGAD on Timepix4 as DUT

- Low-gain avalanche diodes (LGADs) use charge multiplication to deliver larger input signals
- Small pixel size cannot be achieved in standard LGAD technology (without losing efficiency)
- Inverted LGADs (iLGADs) solve this by placing the gain layer on the backside
- Sensors produced by Micron and provided by Glasgow

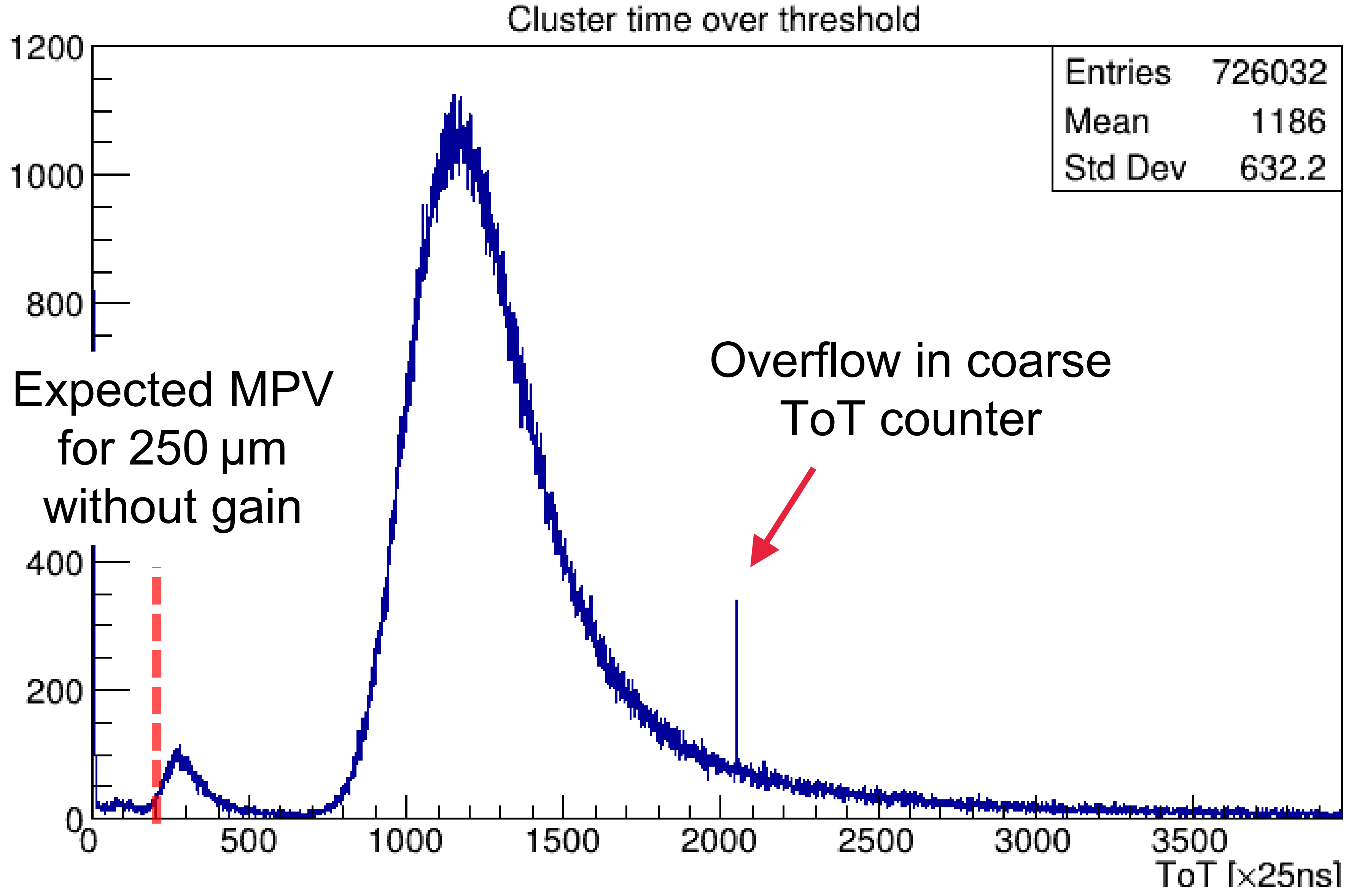


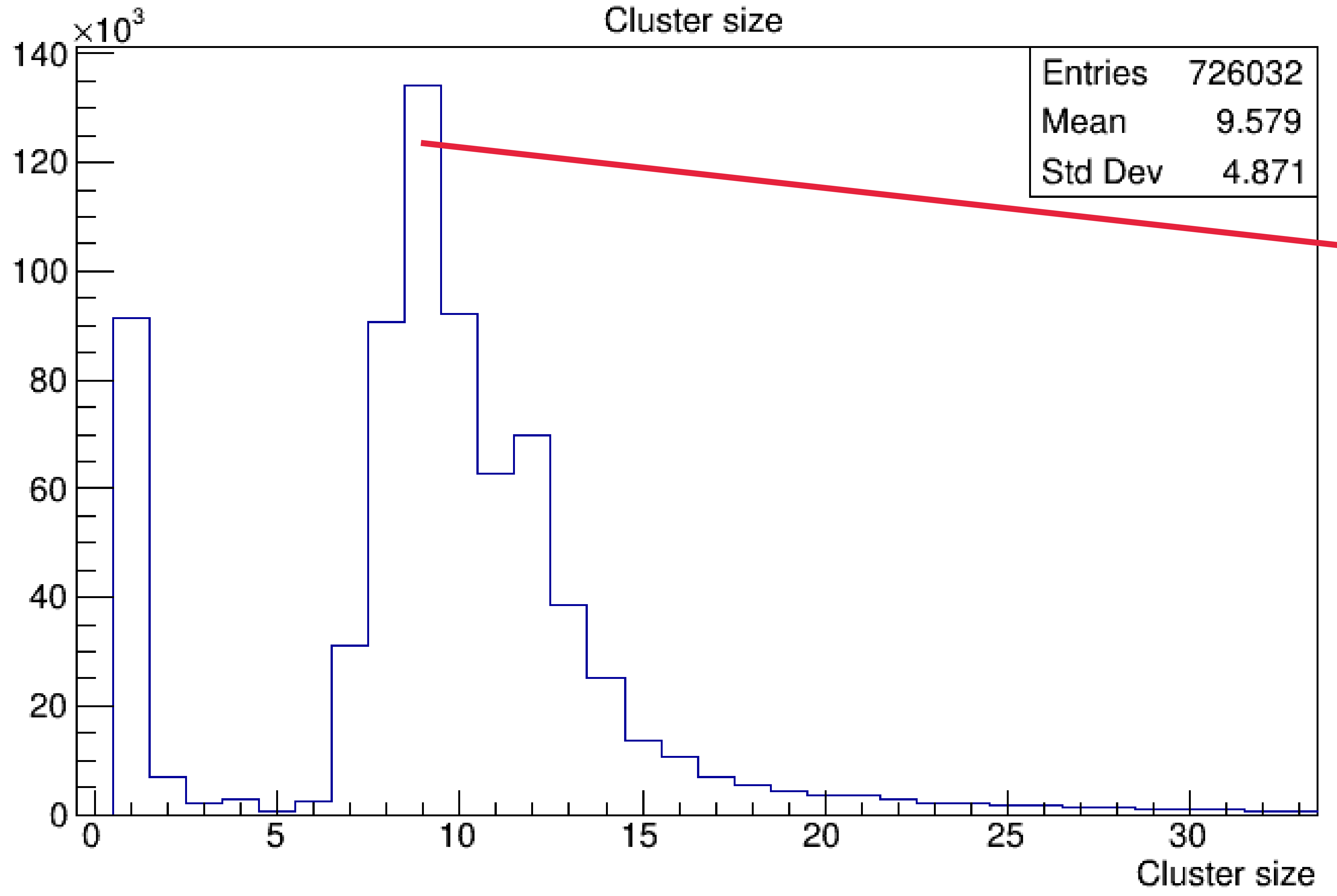


A. Doblas *et al Sensors* **2023**, 23, 3450 [DOI: 10.3390/s23073450]

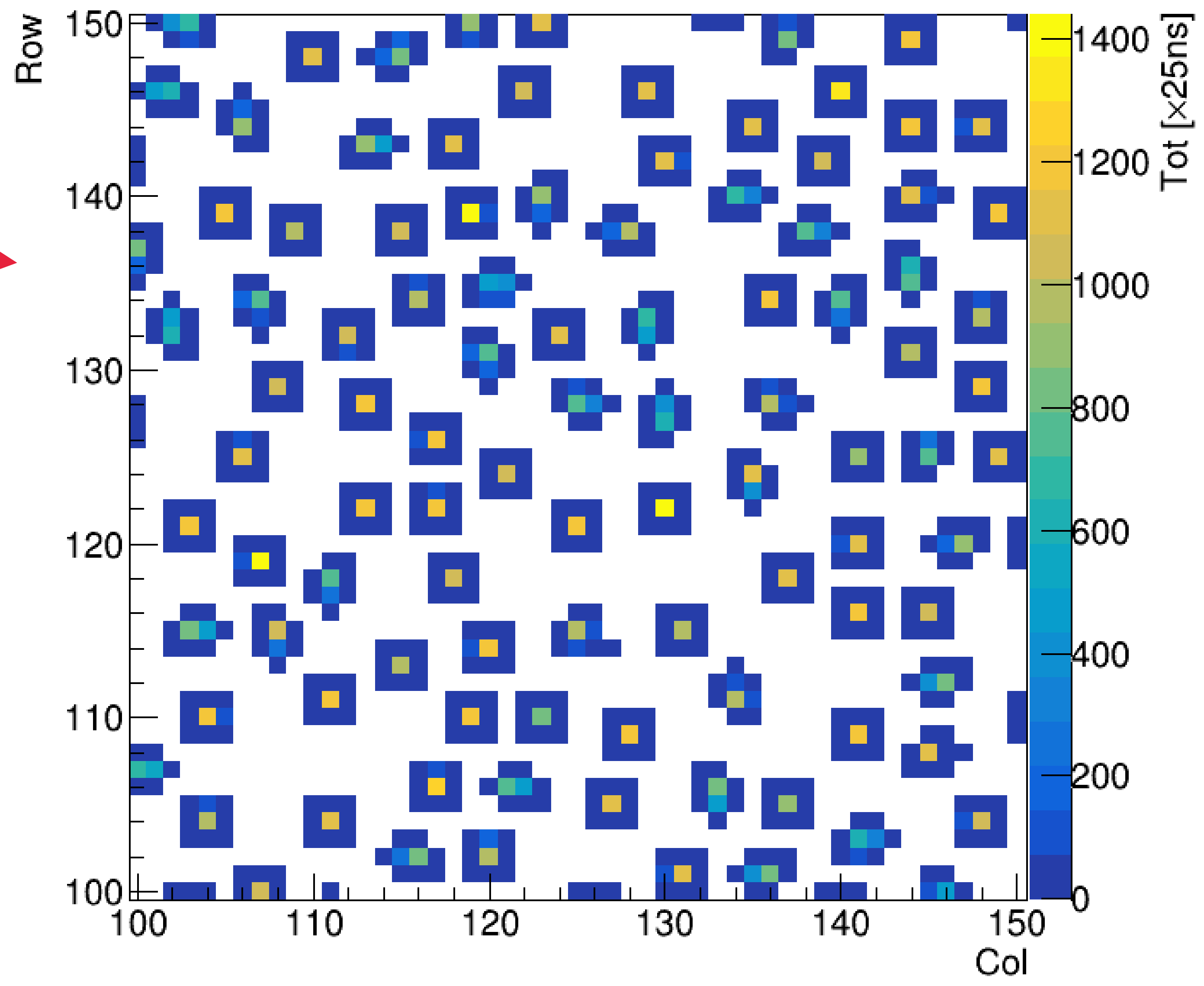


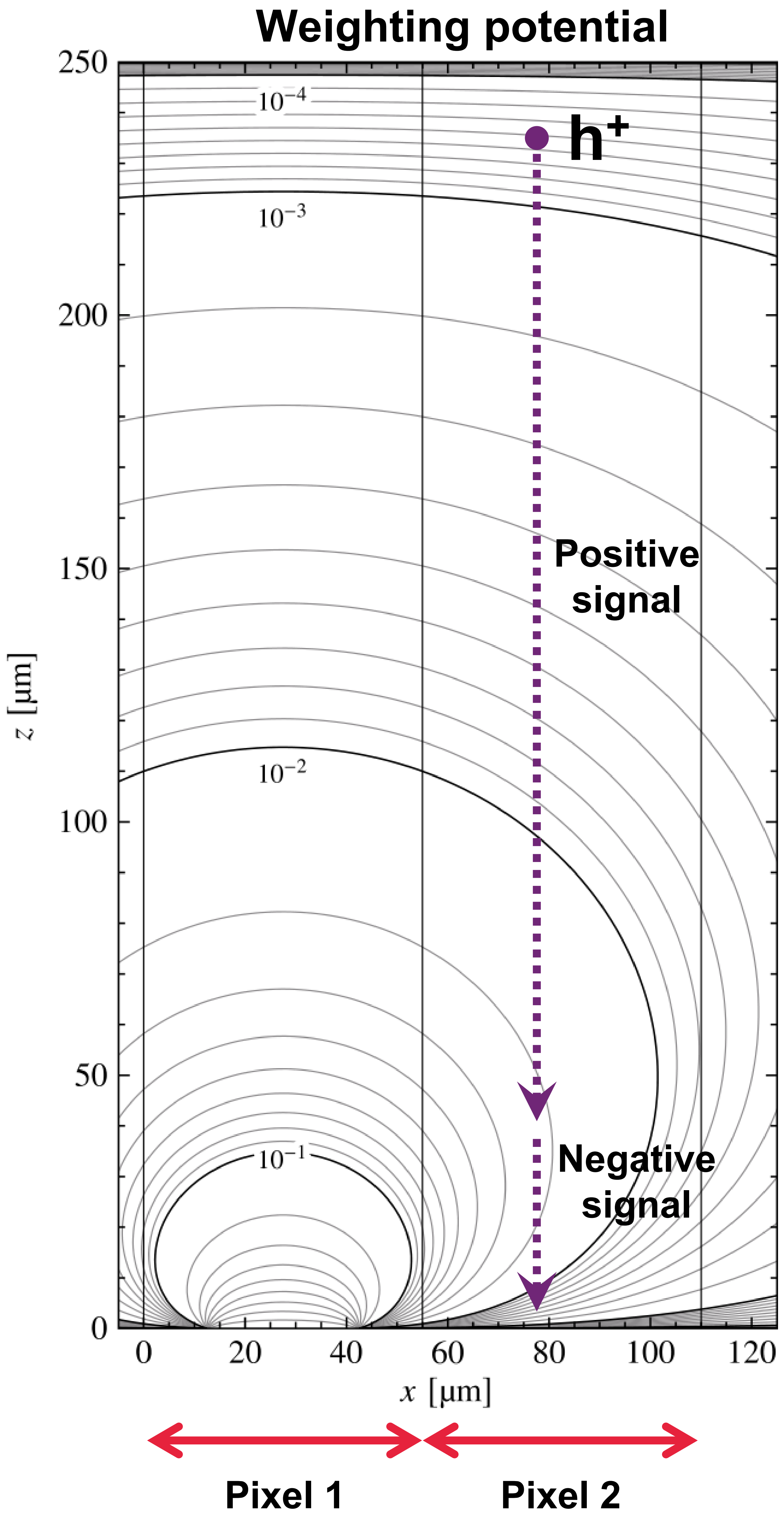
Inverted LGAD on Timepix4 as DUT



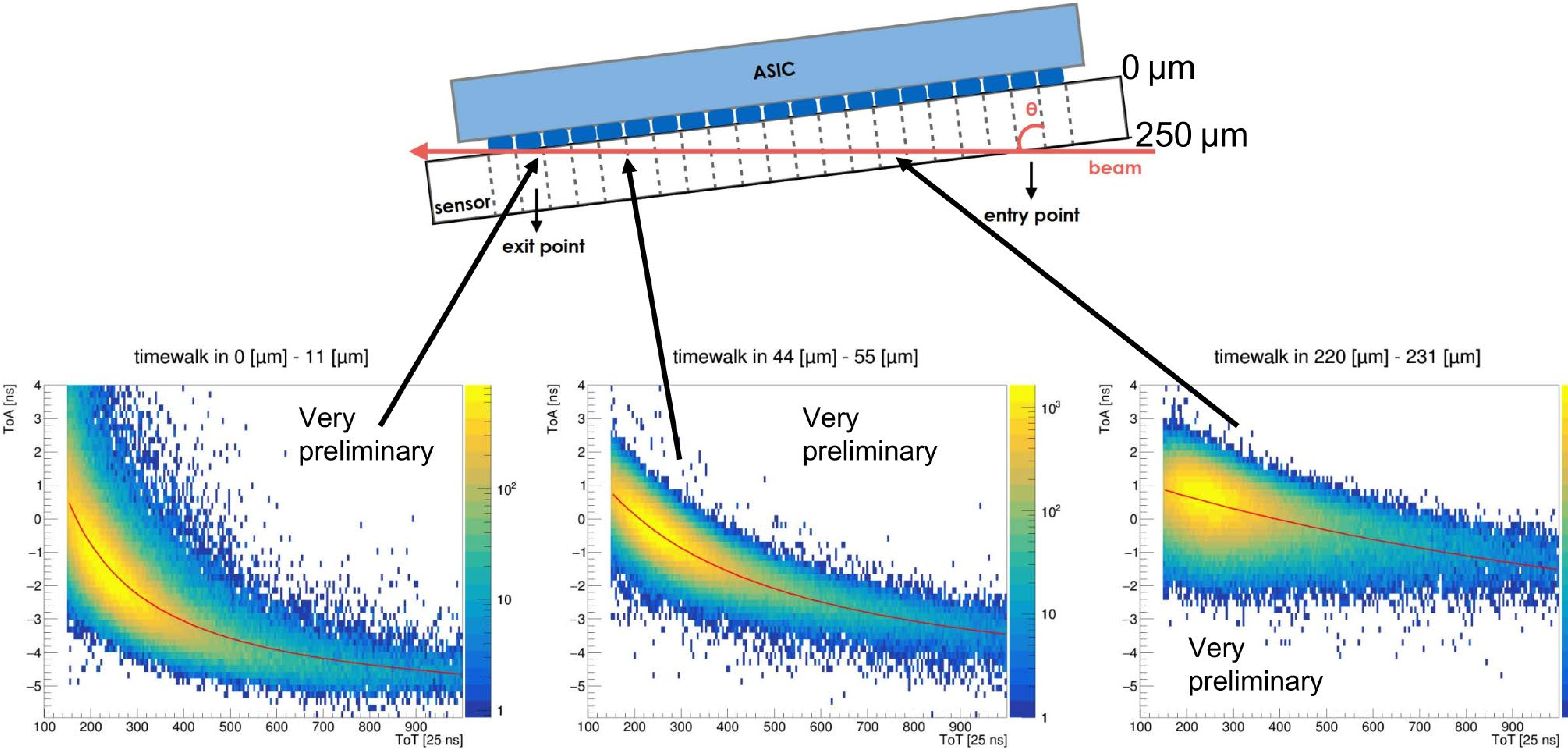


- Large cluster size at perpendicular beam incidence
- Cluster have skirt of low-ToT hits (< 25 ns)
- We suspect due to bipolar signals in neighbouring pixels

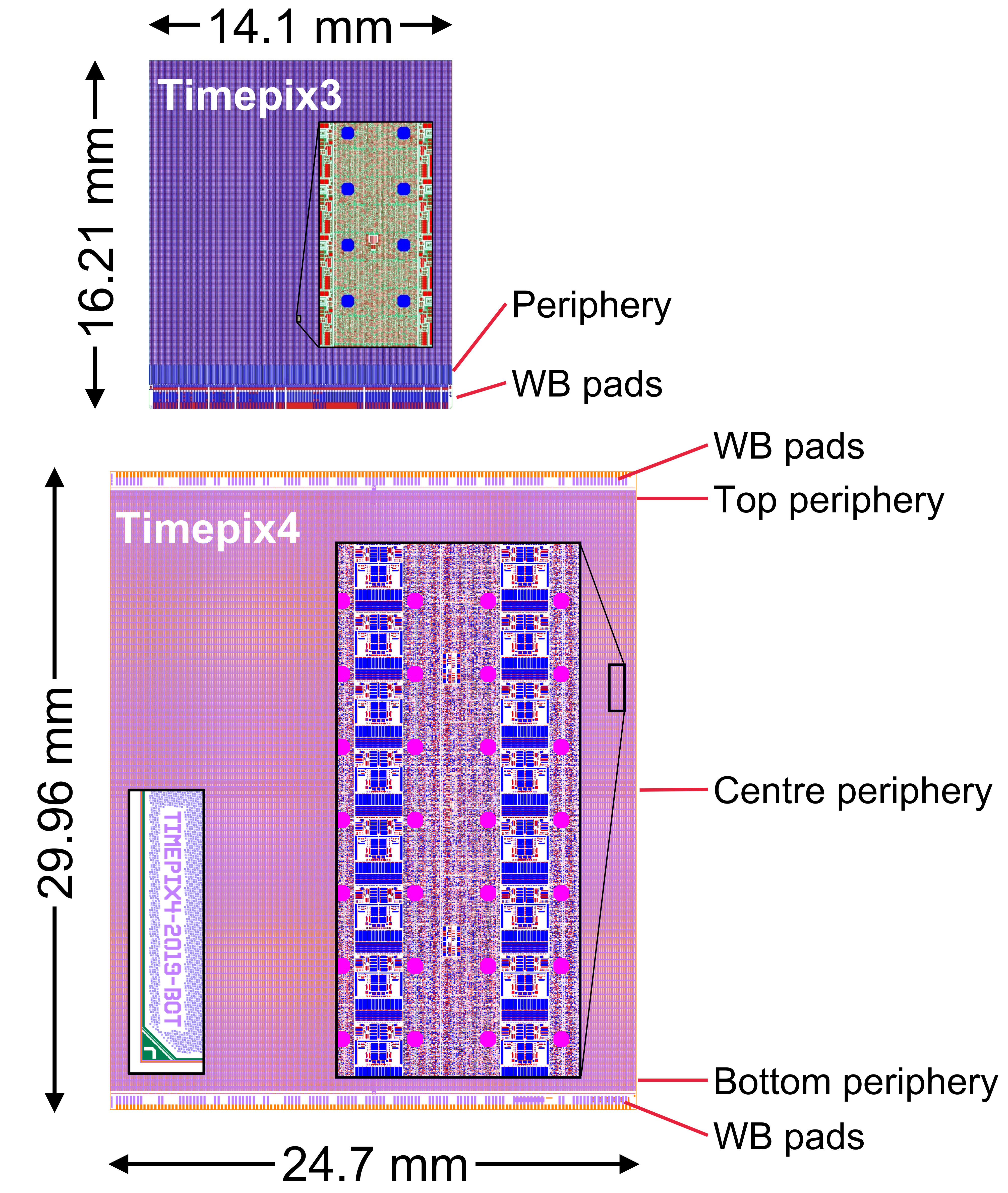




Timewalk behaviour depends on track depth

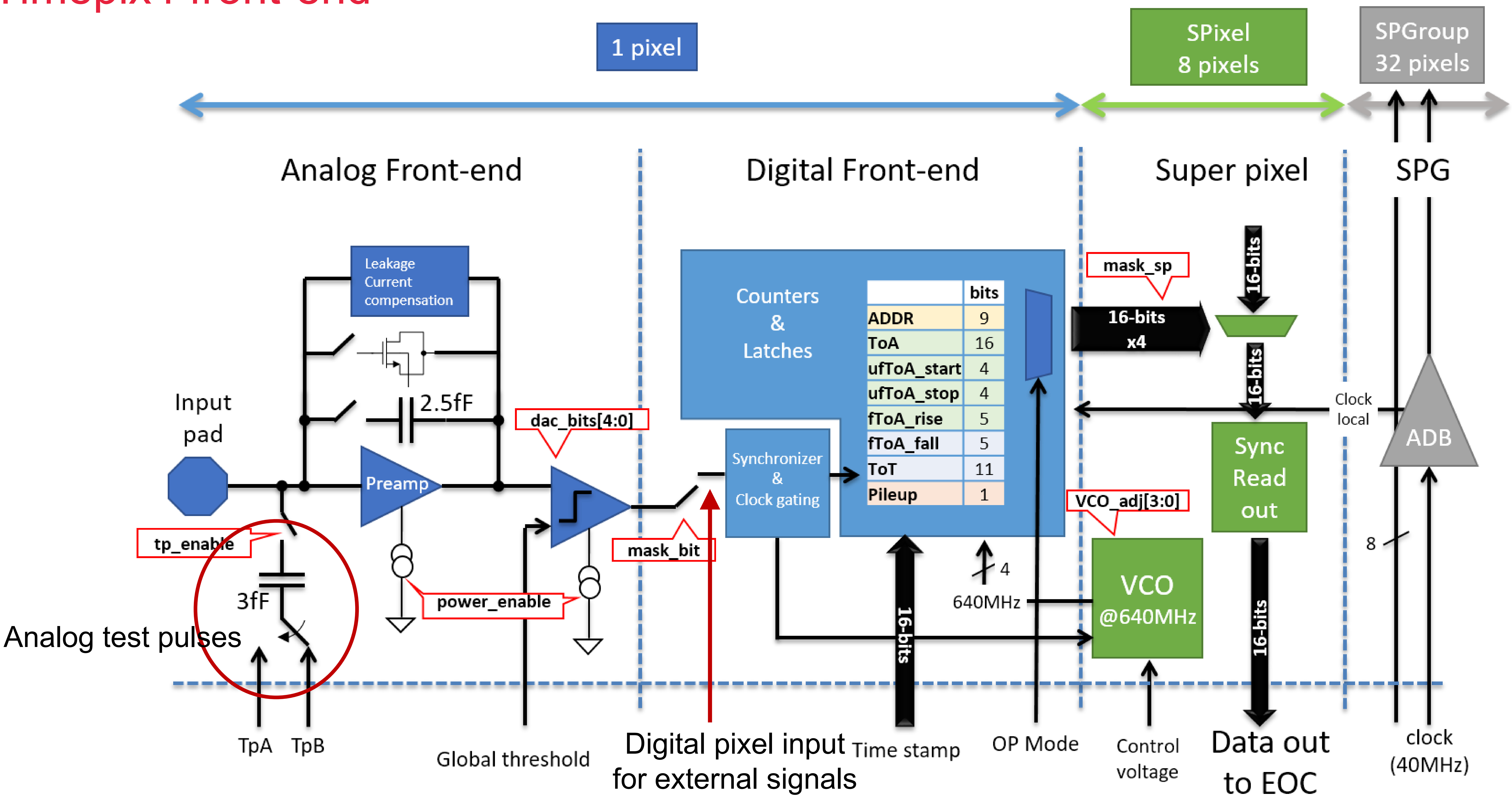


Timepix3 → Timepix4



			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	**3.5x**
Sensitive area			1.98 cm^2	**6.94 cm^2**	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	
		Max rate	0.43×10^6 hits/mm^2/s	**3.58×10^6 hits/mm^2/s**	**8x**
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	
		Max count rate	~0.82×10^9 hits/mm^2/s	~5×10^9 hits/mm^2/s	
TOT energy resolution			< 2KeV	< **1**Kev	
TOA binning resolution			1.56ns	**195ps**	**8x**
TOA dynamic range			409.6 µs (14-bits @ 40MHz)	**1.6384 ms** (16-bits @ 40MHz)	
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps (16x @10.24 Gbps)**	**32x**
Target minimum threshold			<500 e^-	<500 e^-	

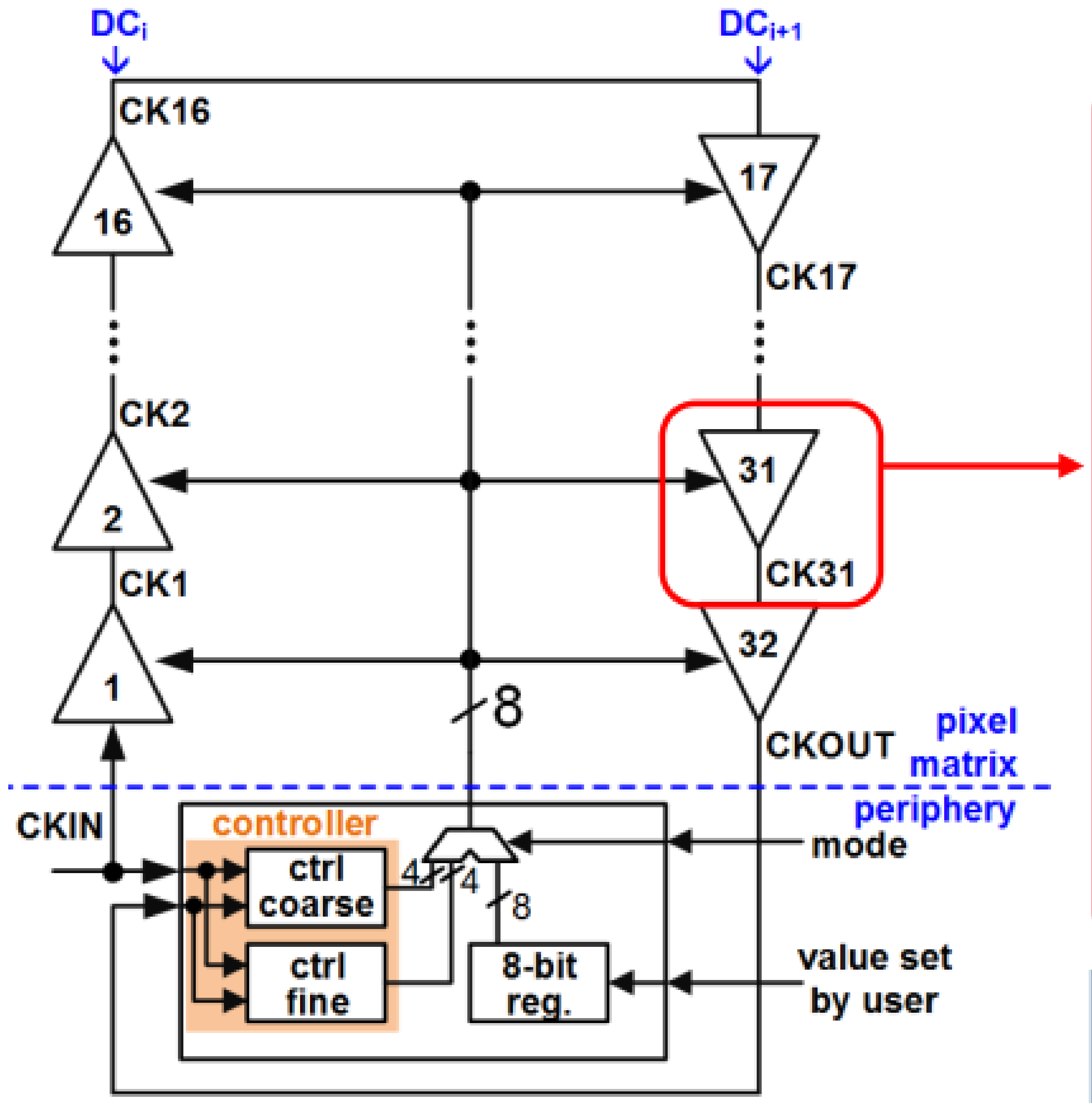
Timepix4 front-end

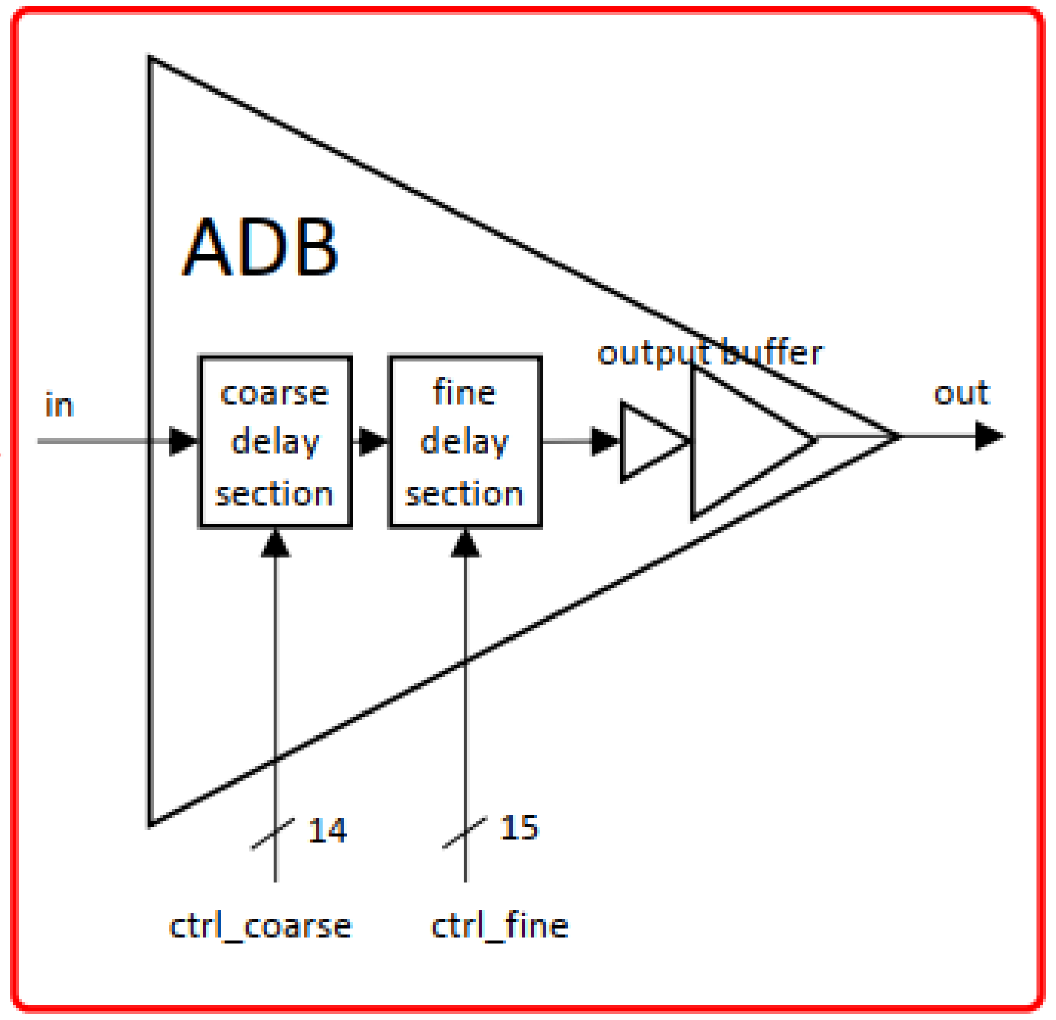


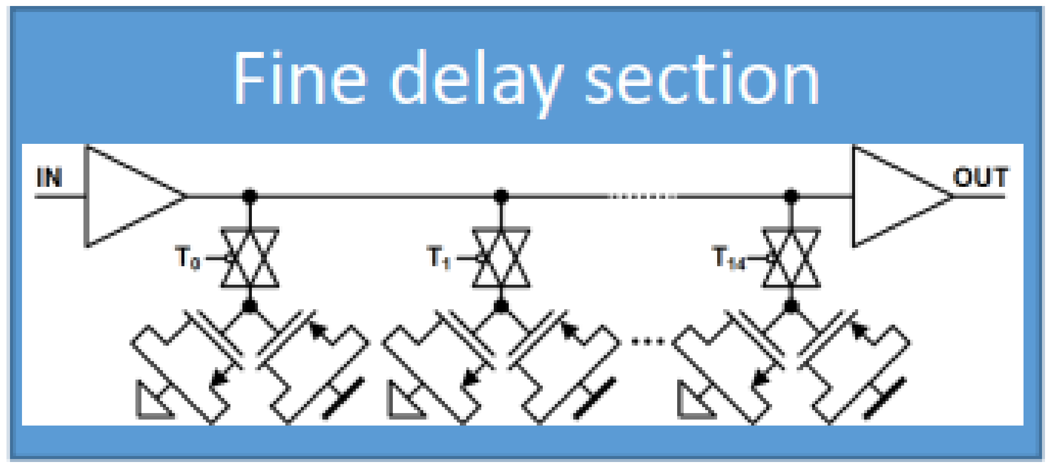
iWoRID 2018
X. Llopart et al 2019 JINST 14 C01024

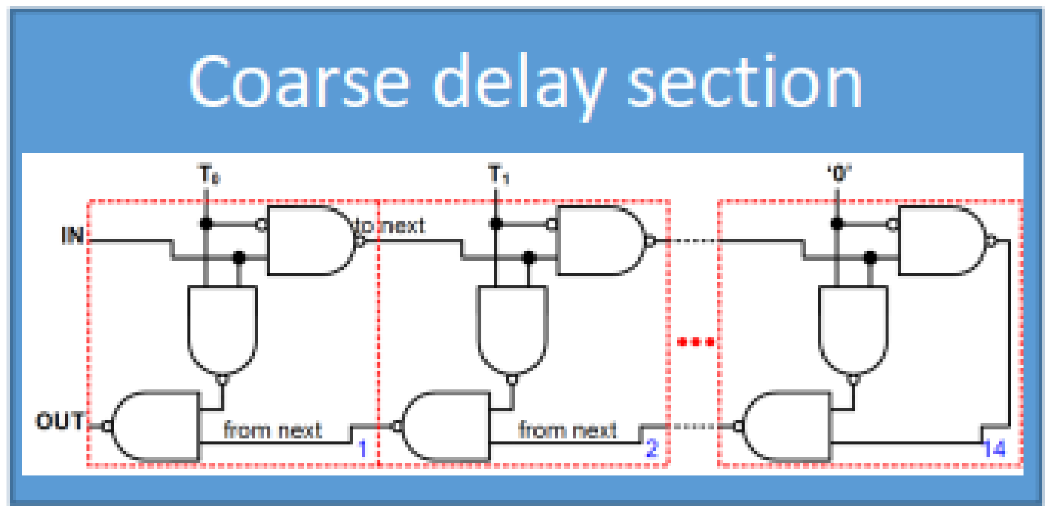
Clock distribution – Column digital locked look (DLL)

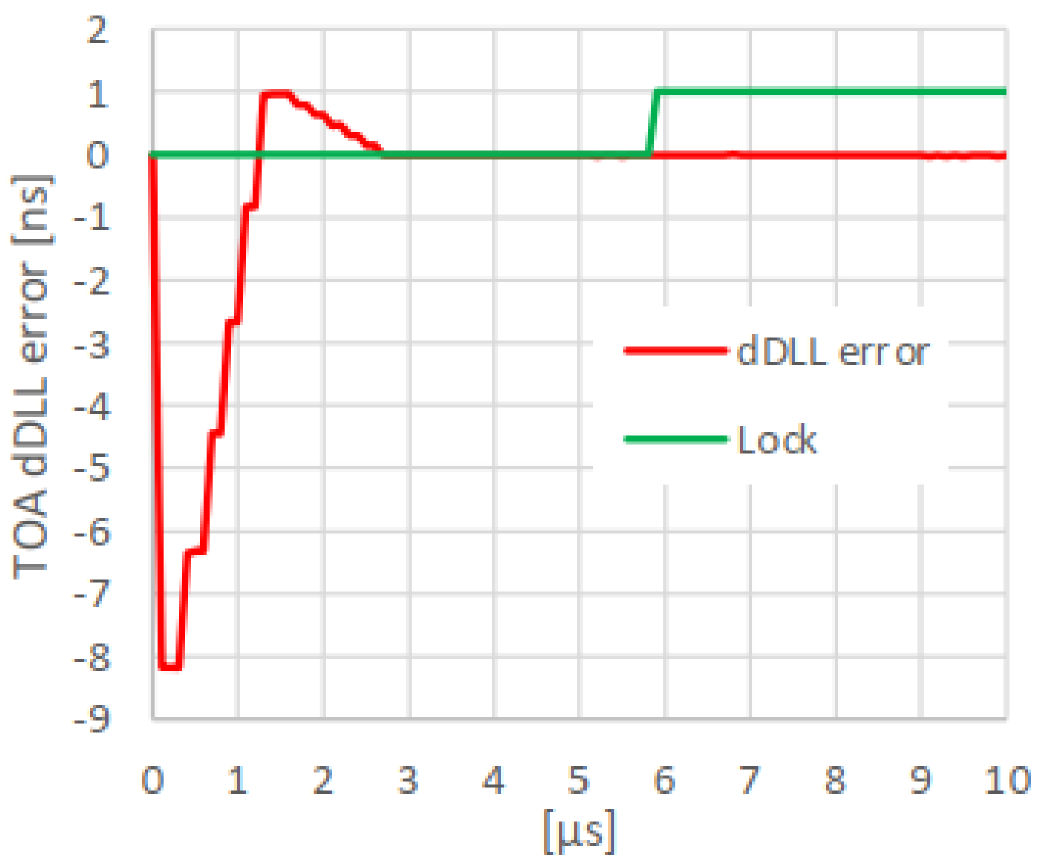
- The column DLL distributes the clock along the columns
- The adjustable delay buffers (ADBs) precisely define the clock phase in each pixel group
- Controller tunes the total delay to 25 ns
- Possible to set the delay manually
- Individual ADB stations can be bypassed

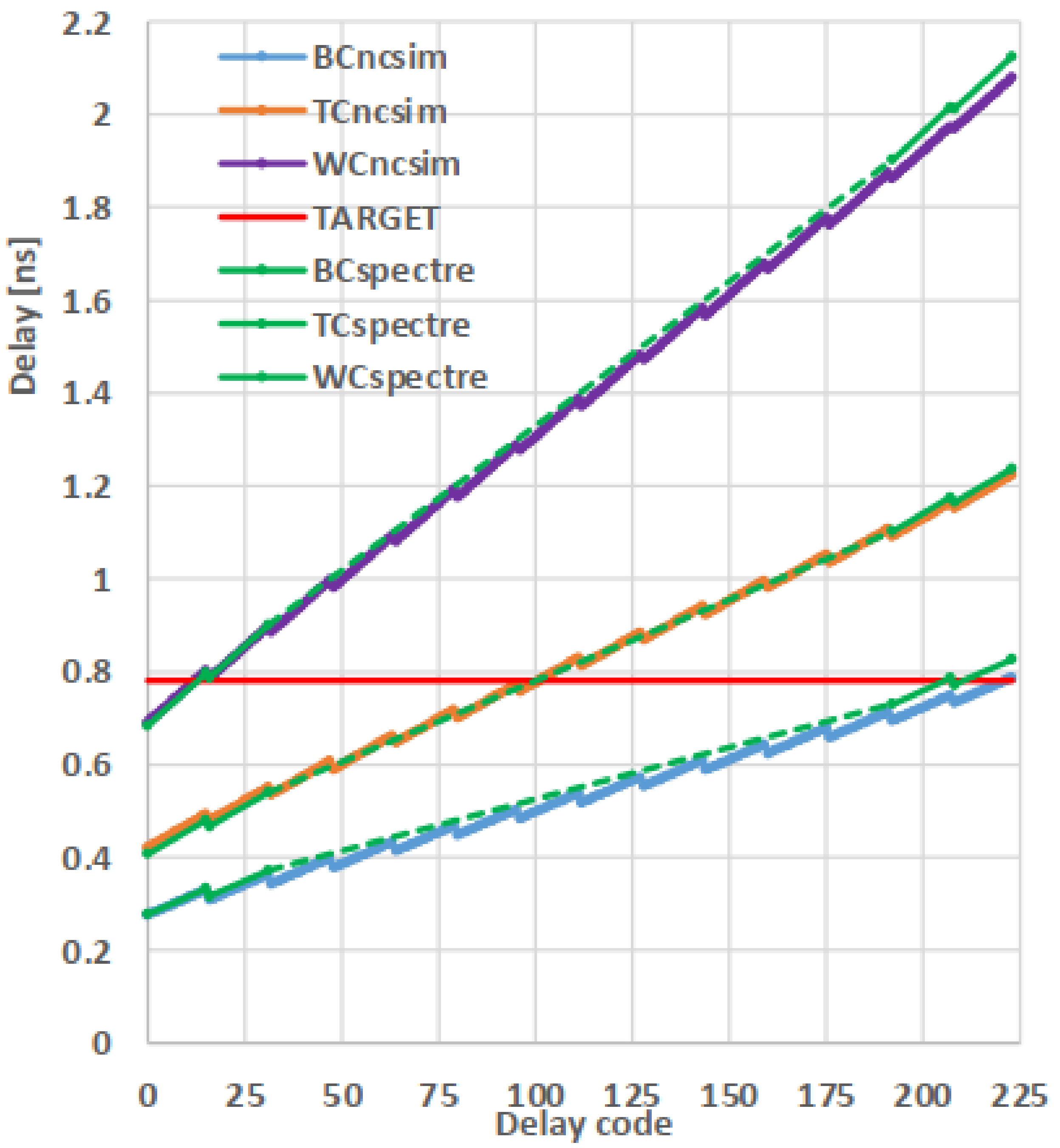










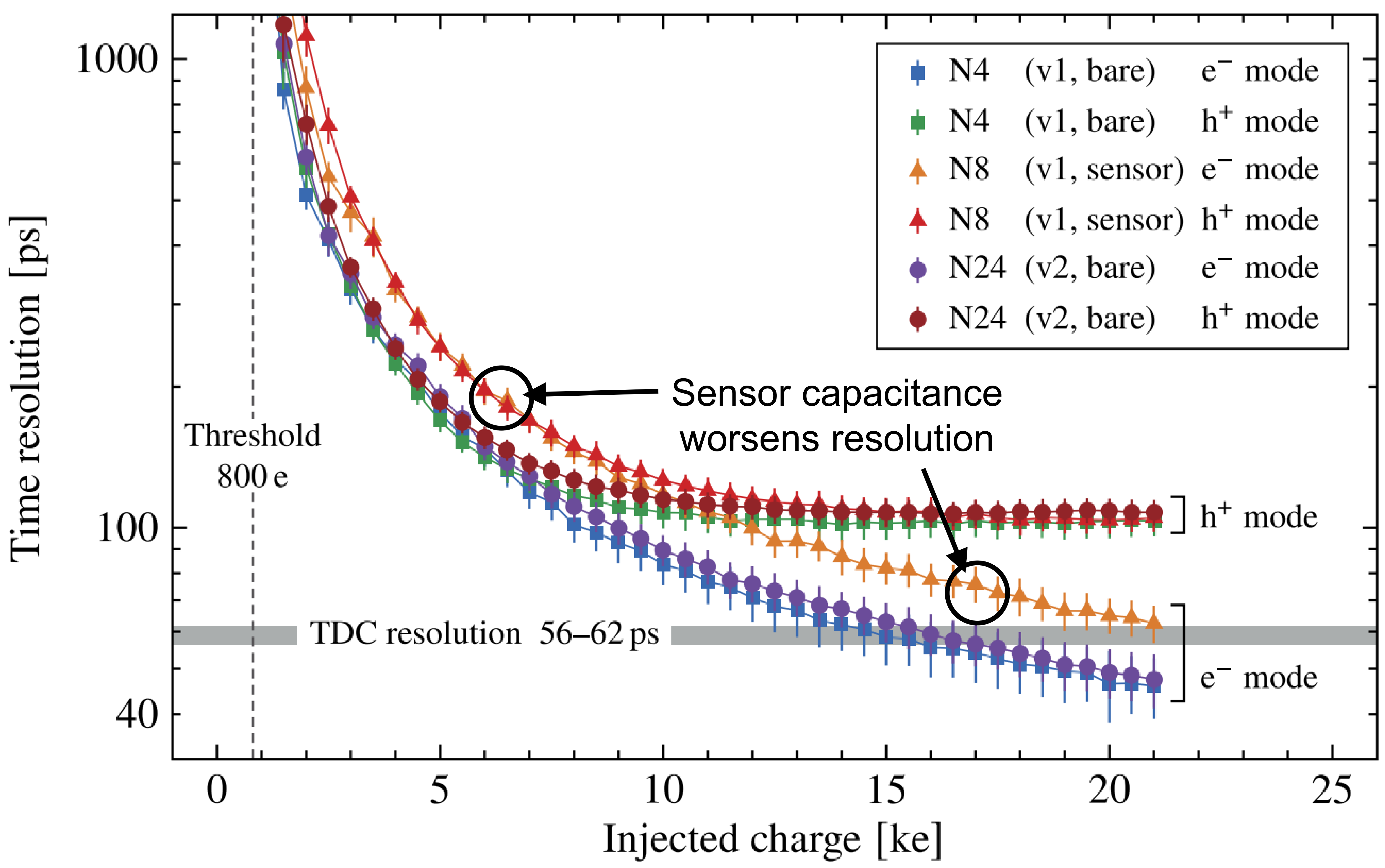


~22.7 mW/cm² to distribute a 40 MHz clock with a 100 ps_{rms}

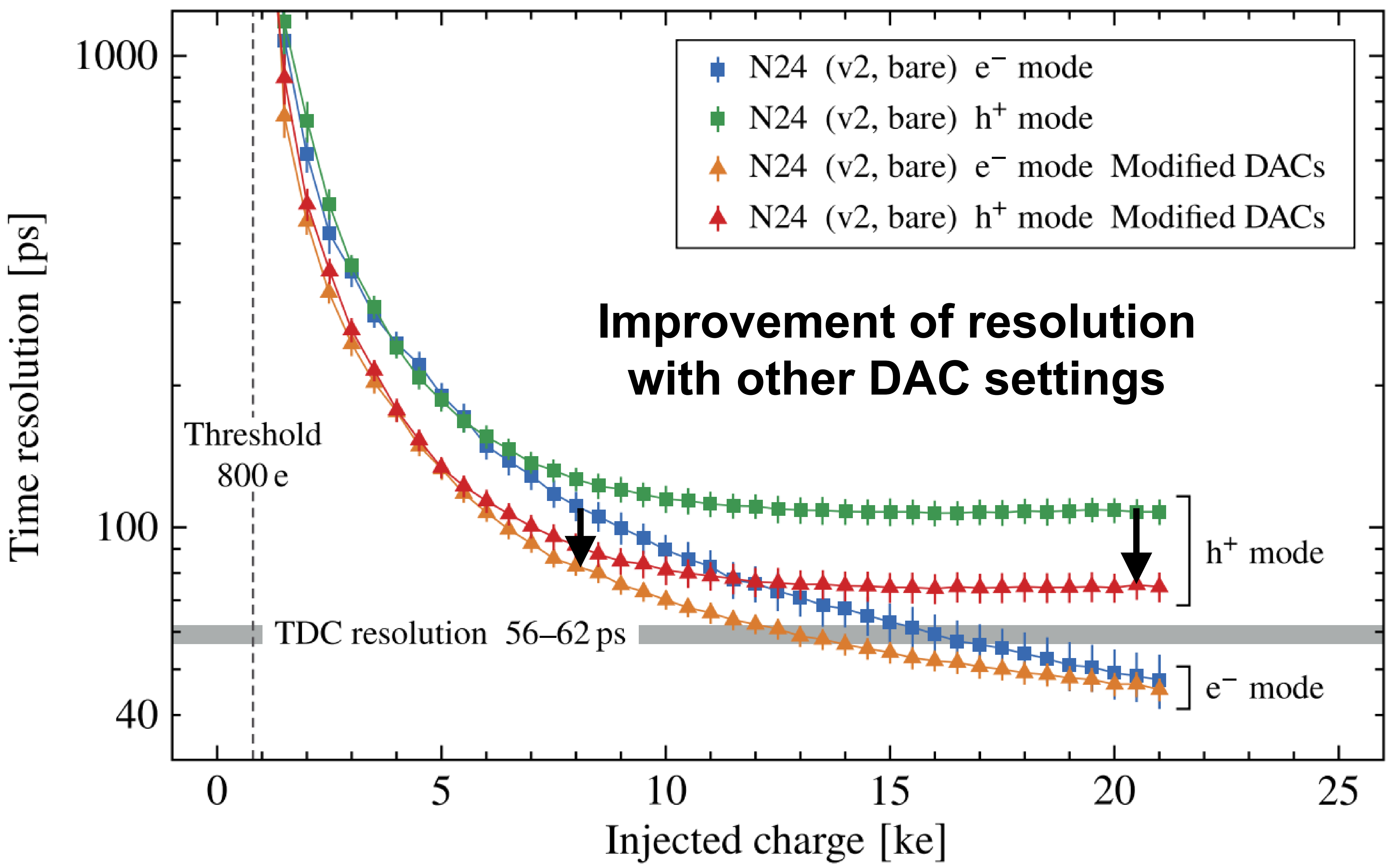
Timepix4 – Analog front-end jitter

- Time resolution in h⁺ mode limited to 75–105 ps depending on DAC settings
- Pixel capacitance decreases the time resolution
  (see R. Ballabriga *et al* NIM A 1045 (2023) 167489 [DOI: 10.1016/j.nima.2022.167489])

Anolog front-end time resolution vs signal charge



K. Heijhoff *et al* 2022 *JINST* **17** P07006 [DOI: 10.1088/1748-0221/17/07/P07006]

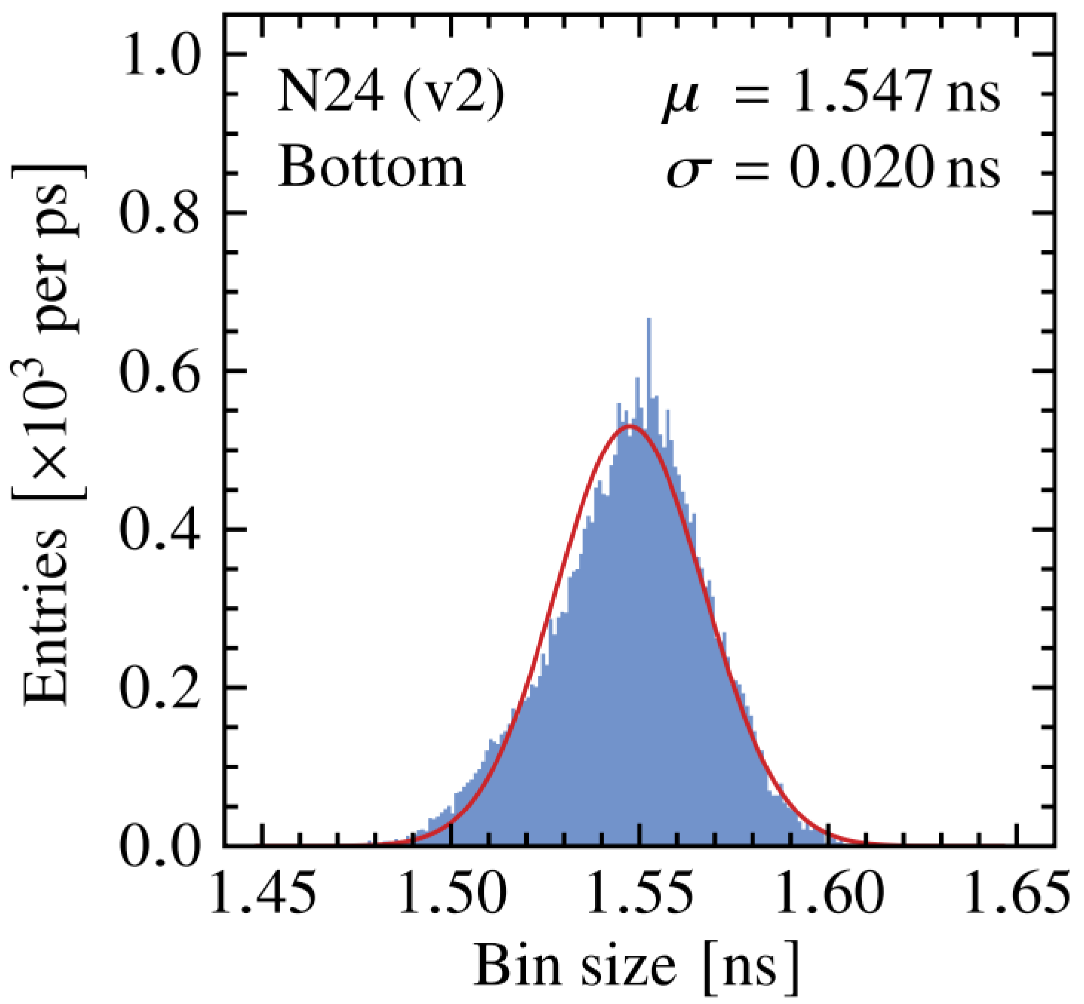


K. Heijhoff *et al* 2022 *JINST* **17** P07006 [DOI: 10.1088/1748-0221/17/07/P07006]

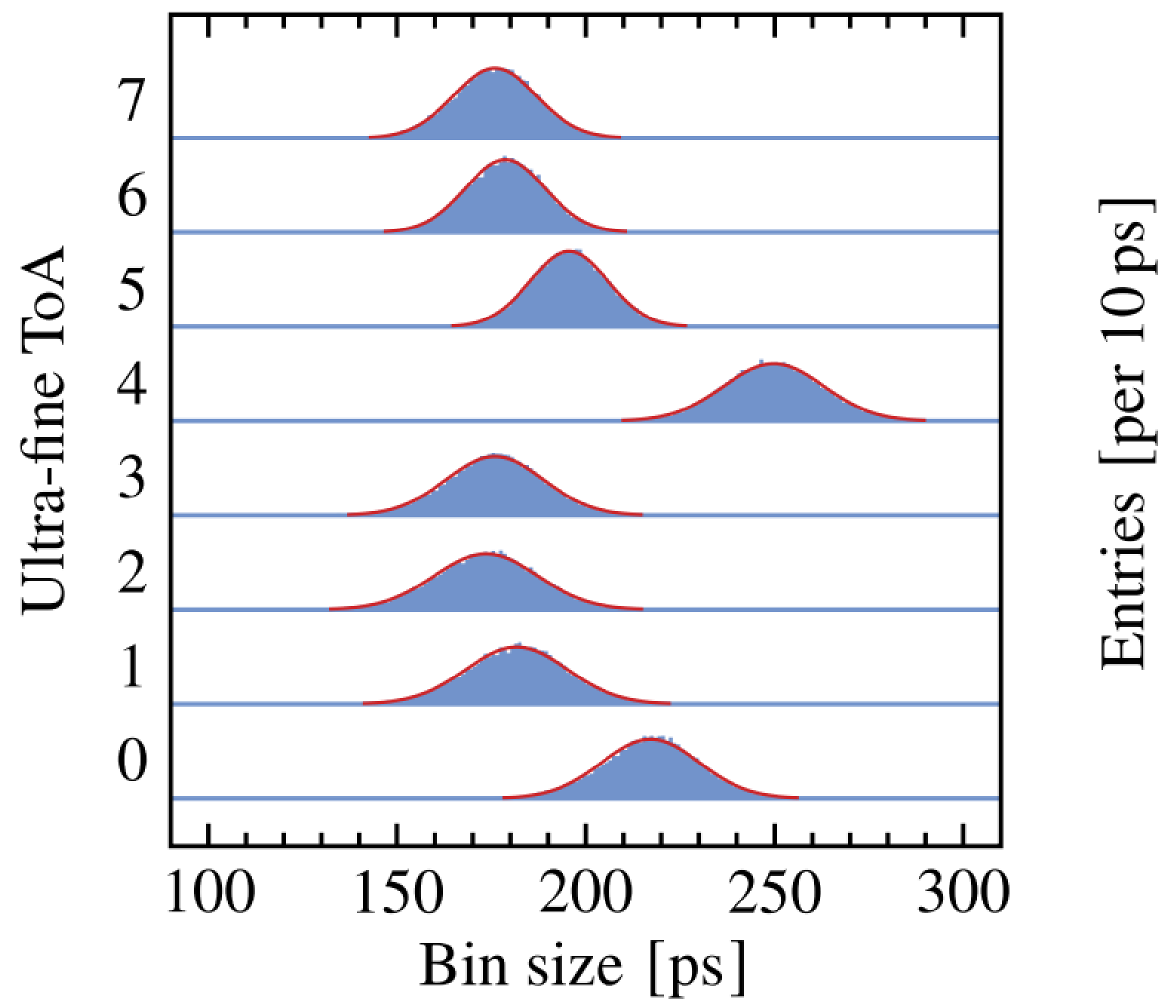
TDC resolution

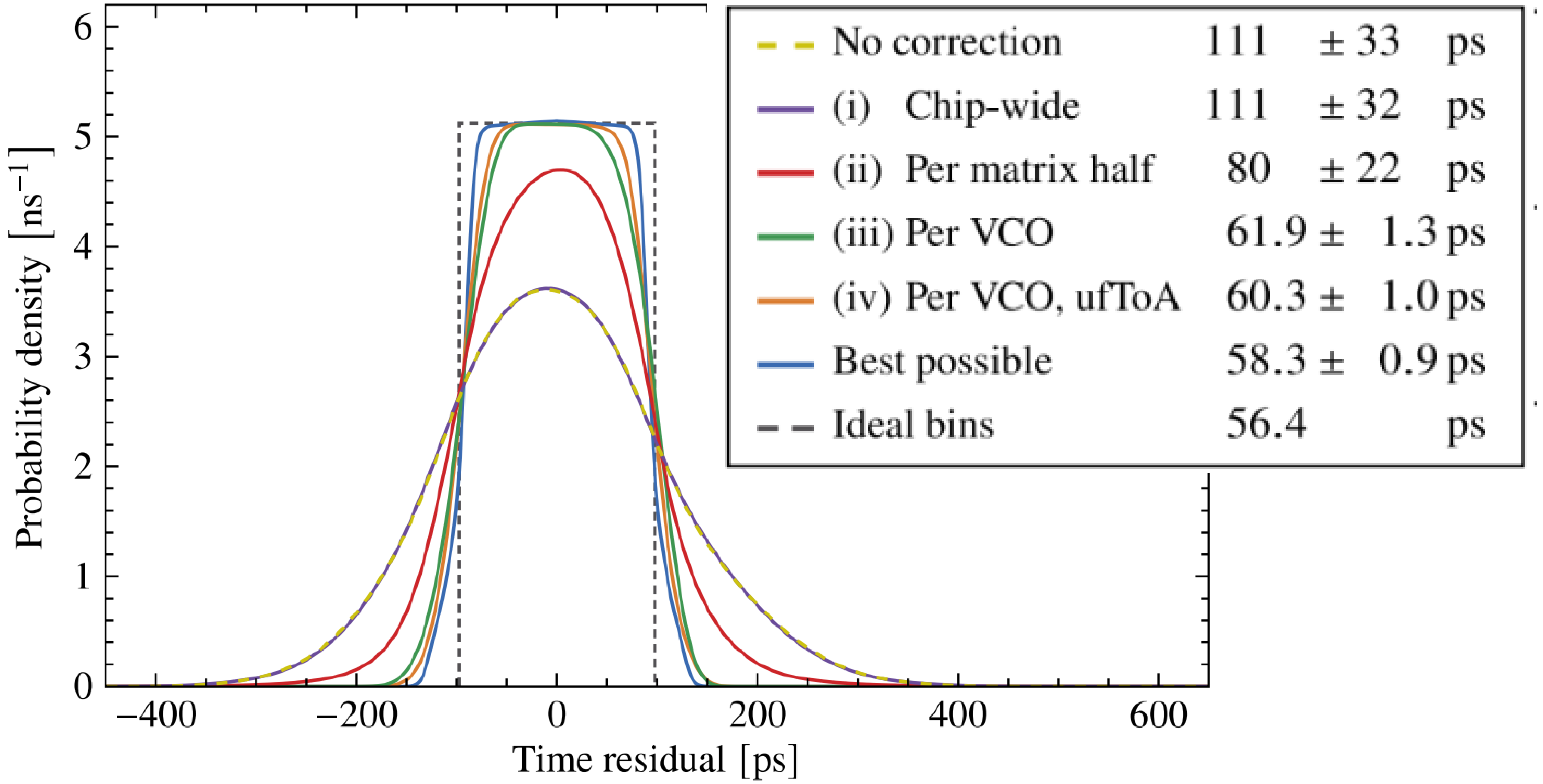
- Variation in the VCO frequency over the pixel matrix observed:
  Bottom half: 1.547 ns ± 20 ps
  Top half: 1.583 ns ± 14 ps
- Structure in ultra-fine time bins has a small impact on TDC resolution (few %)
- We have tried to predict the TDC resolution for correction methods of increasing complexity

Fine time bins (640 MHz)

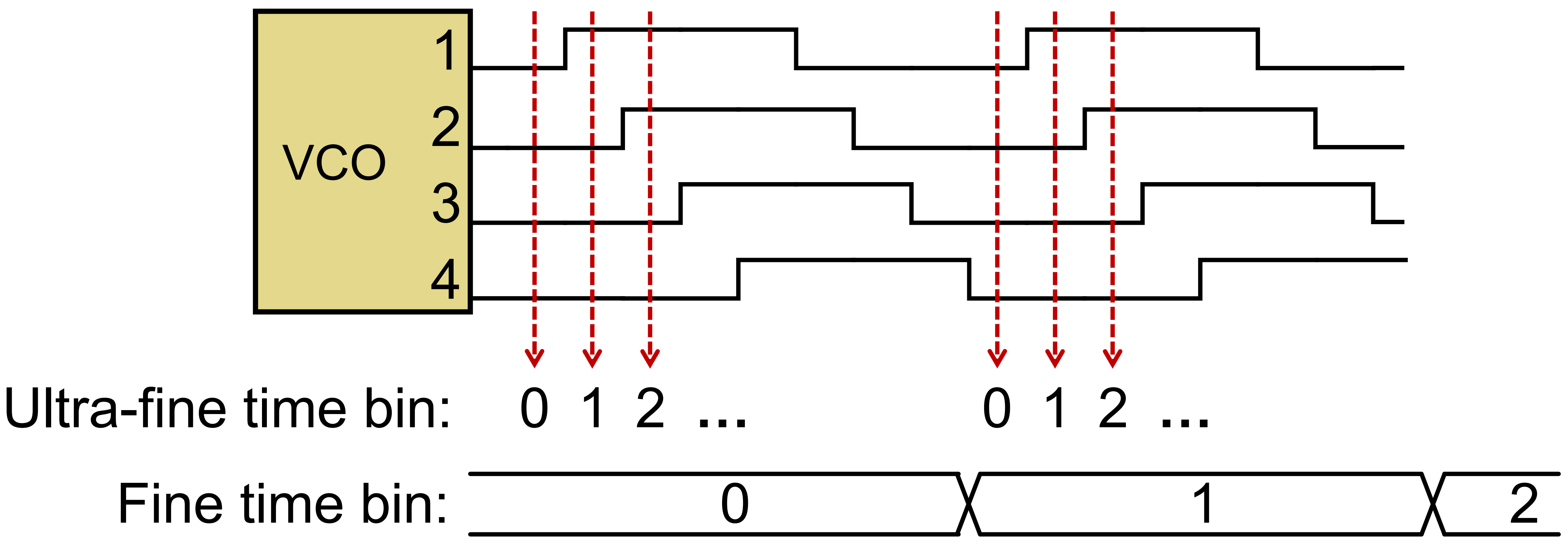


Ultra-fine time bins



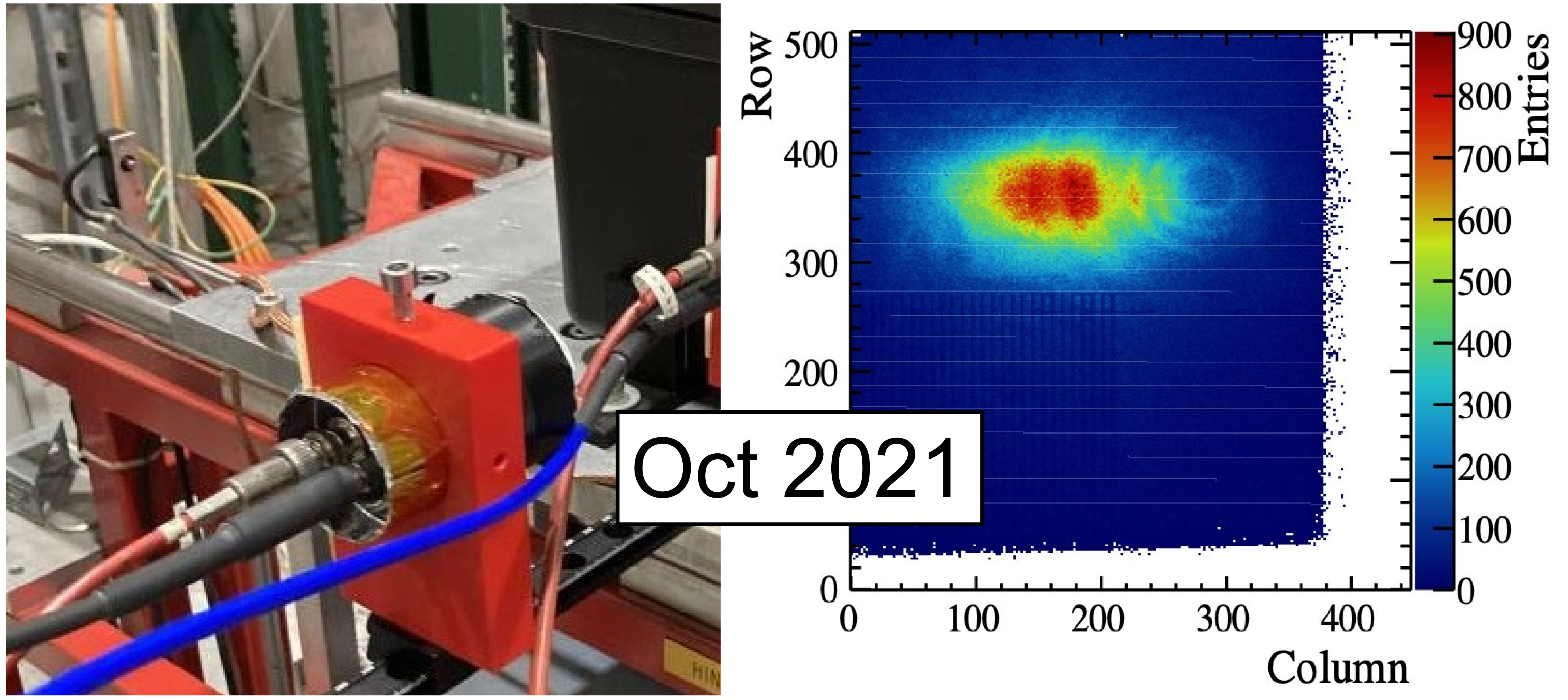


Phase shifted 640 MHz clocks



MCP time reference

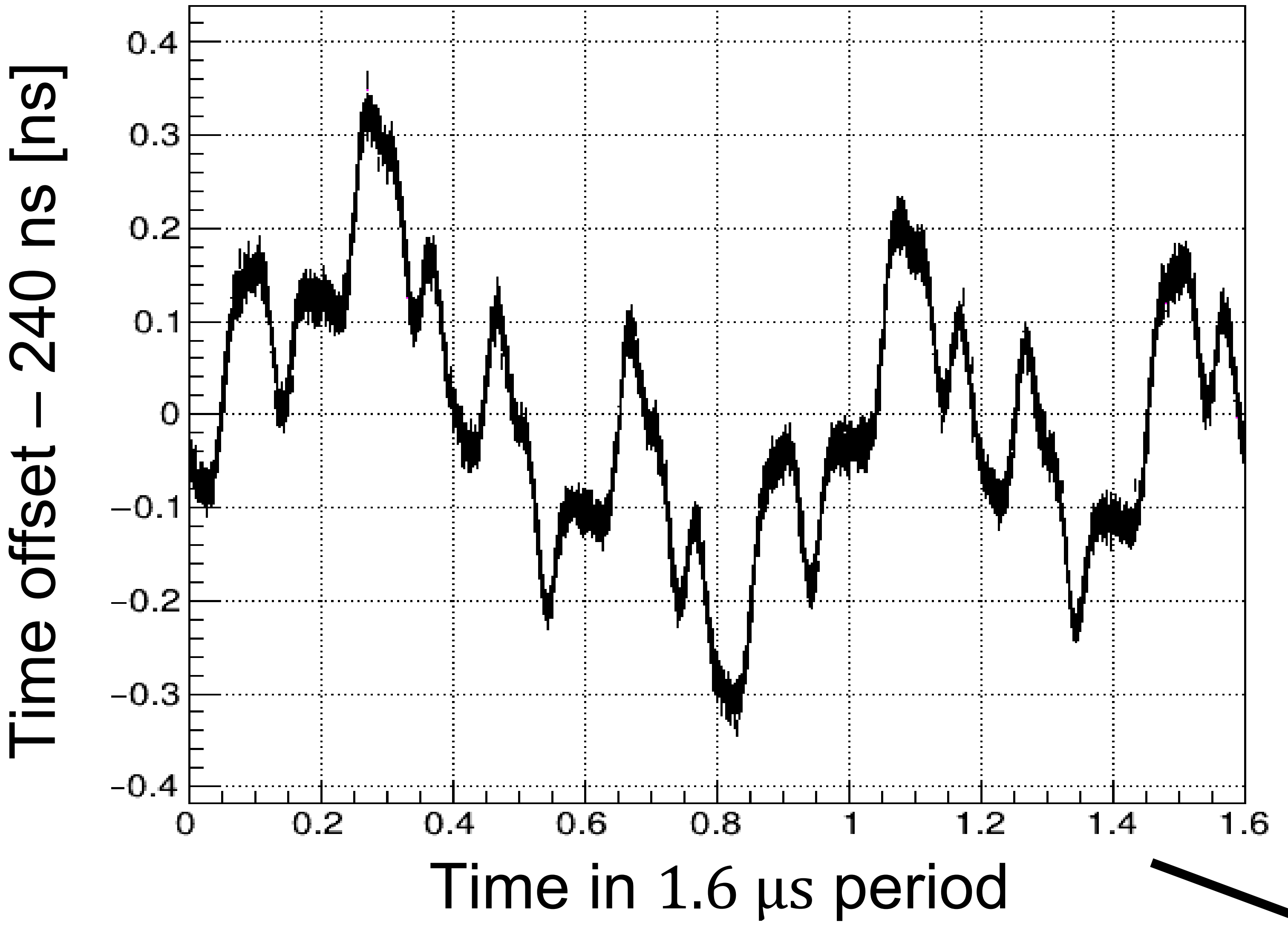
- Two MCPs provide precise time references to study timing performance of telescope
- Placed at end to not hinder other groups in same beam area
- CFDs suffered from large signals due to nuclear interactions



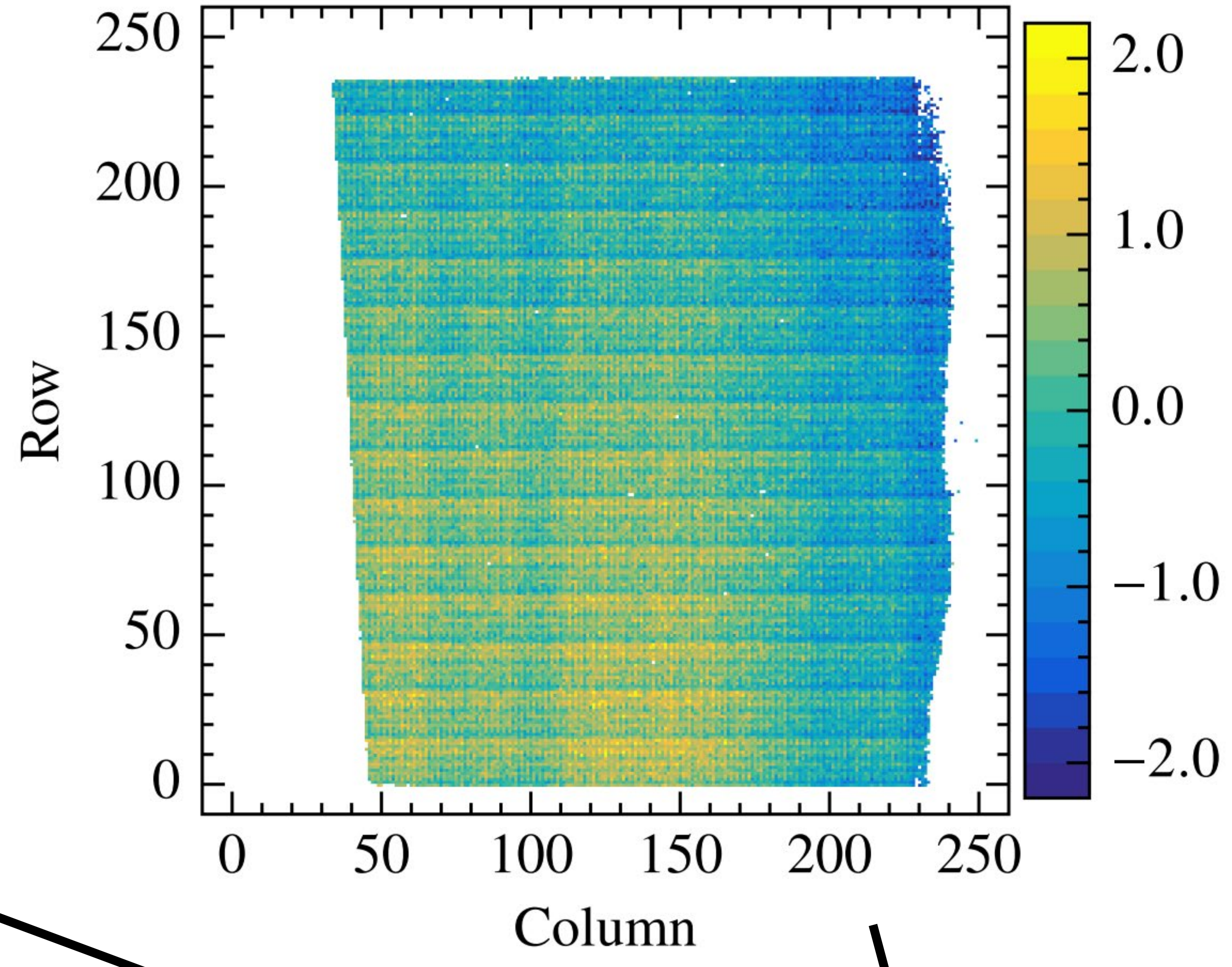
K. Heijhoff *et al* 2020 *JINST* **15** P09035 [DOI: 10.1088/1748-0221/15/09/P09035]

Timing systematics in the LHCb VELO Timepix**3** Telescope

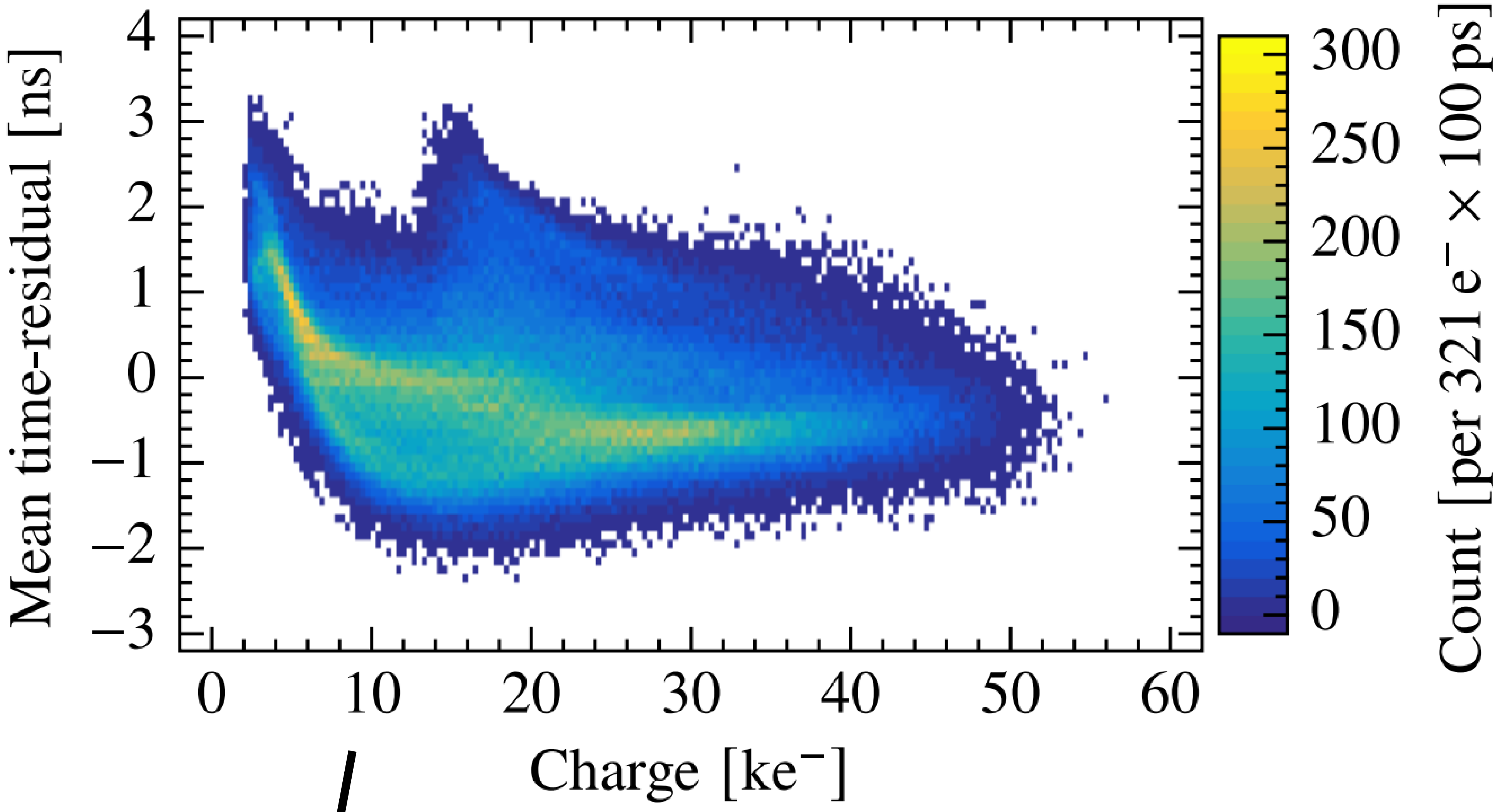
Clock phase variation

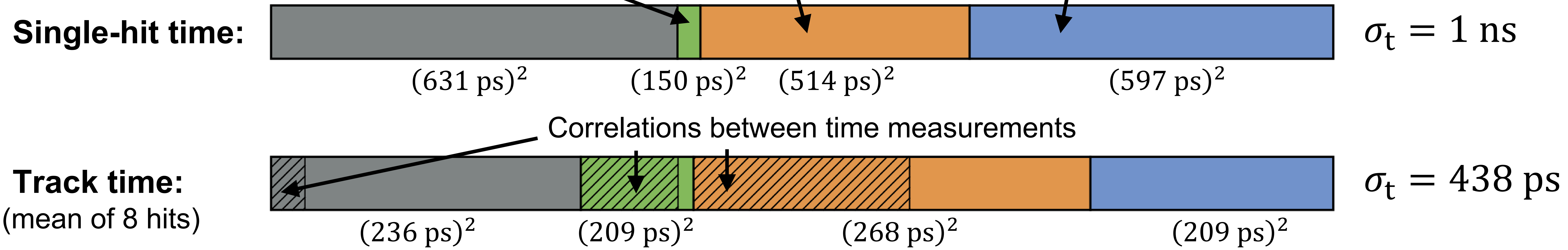


Pixel / TDC systematics



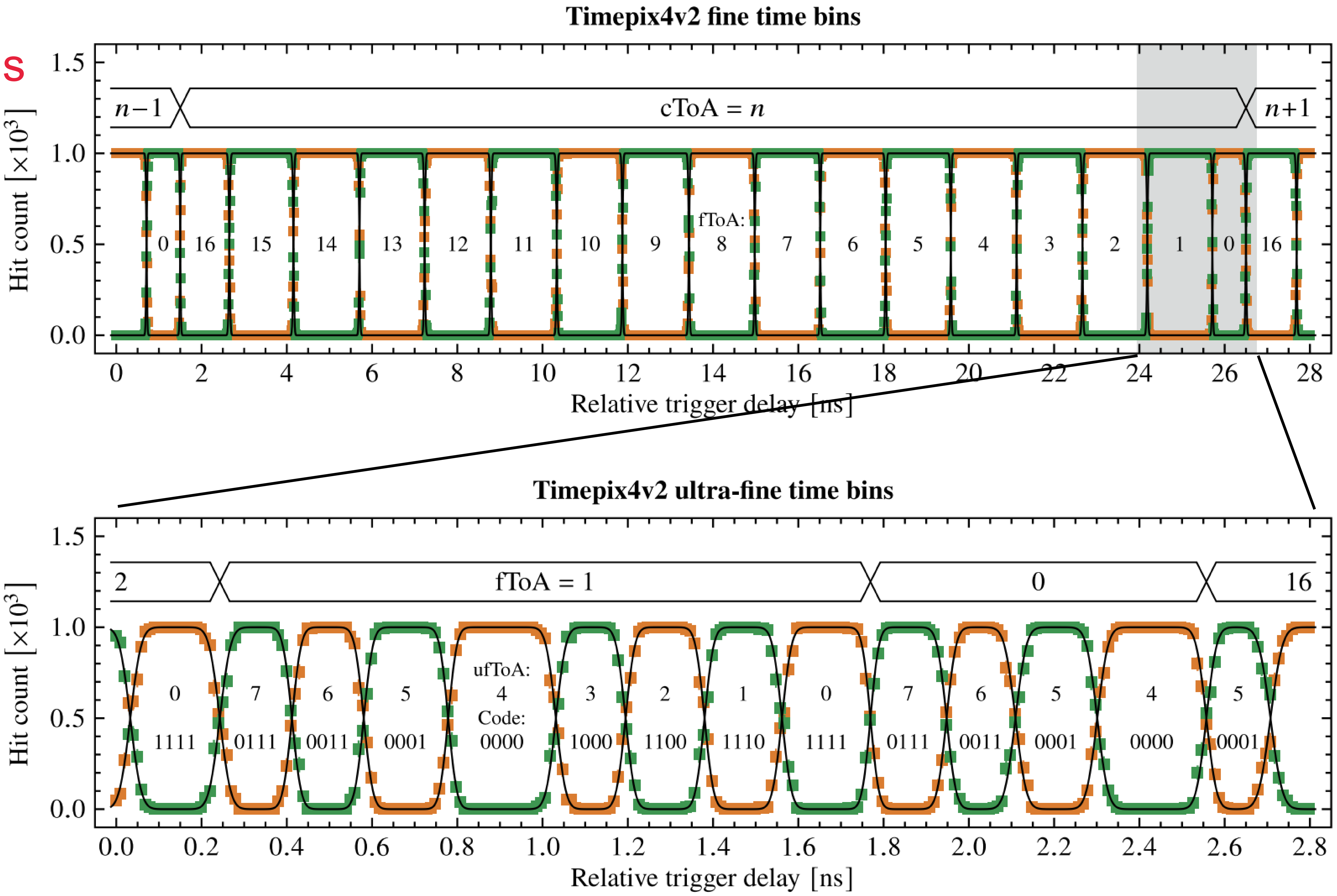
Timewalk and signal induction time in sensor





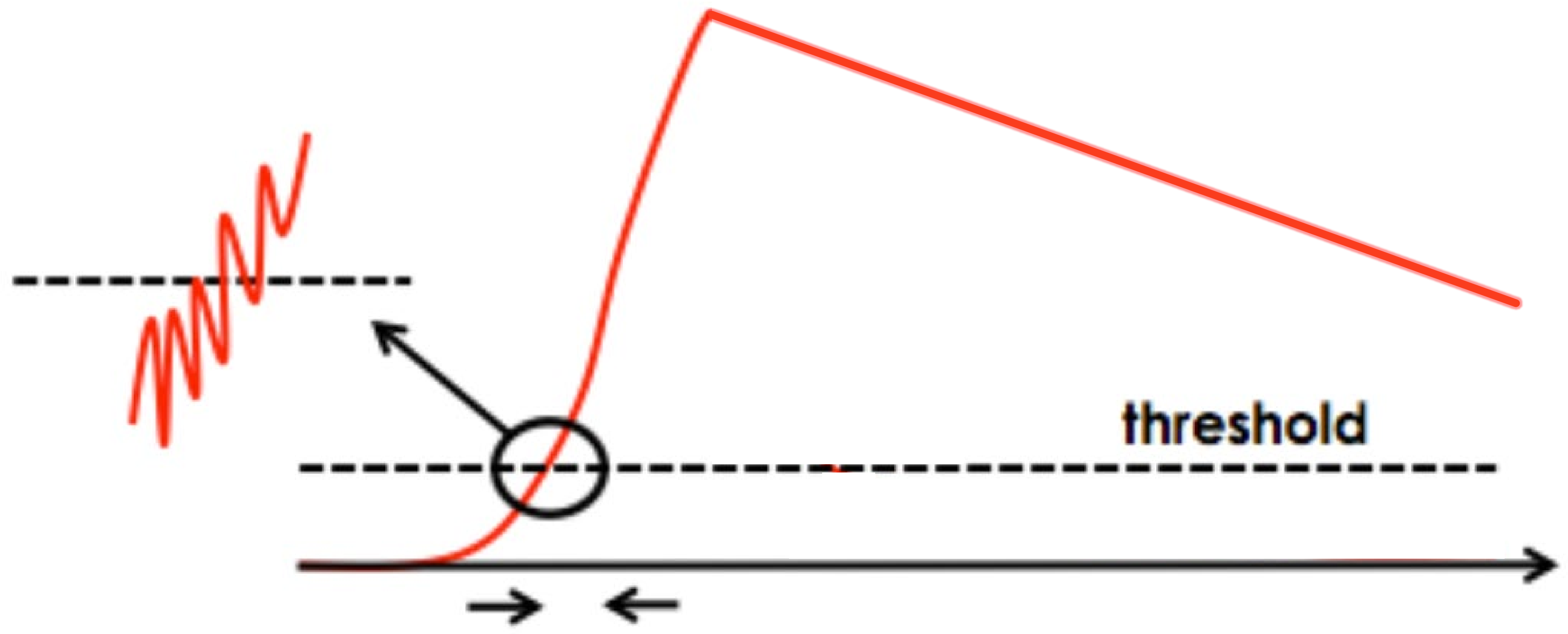
Timepix4 TDC bins

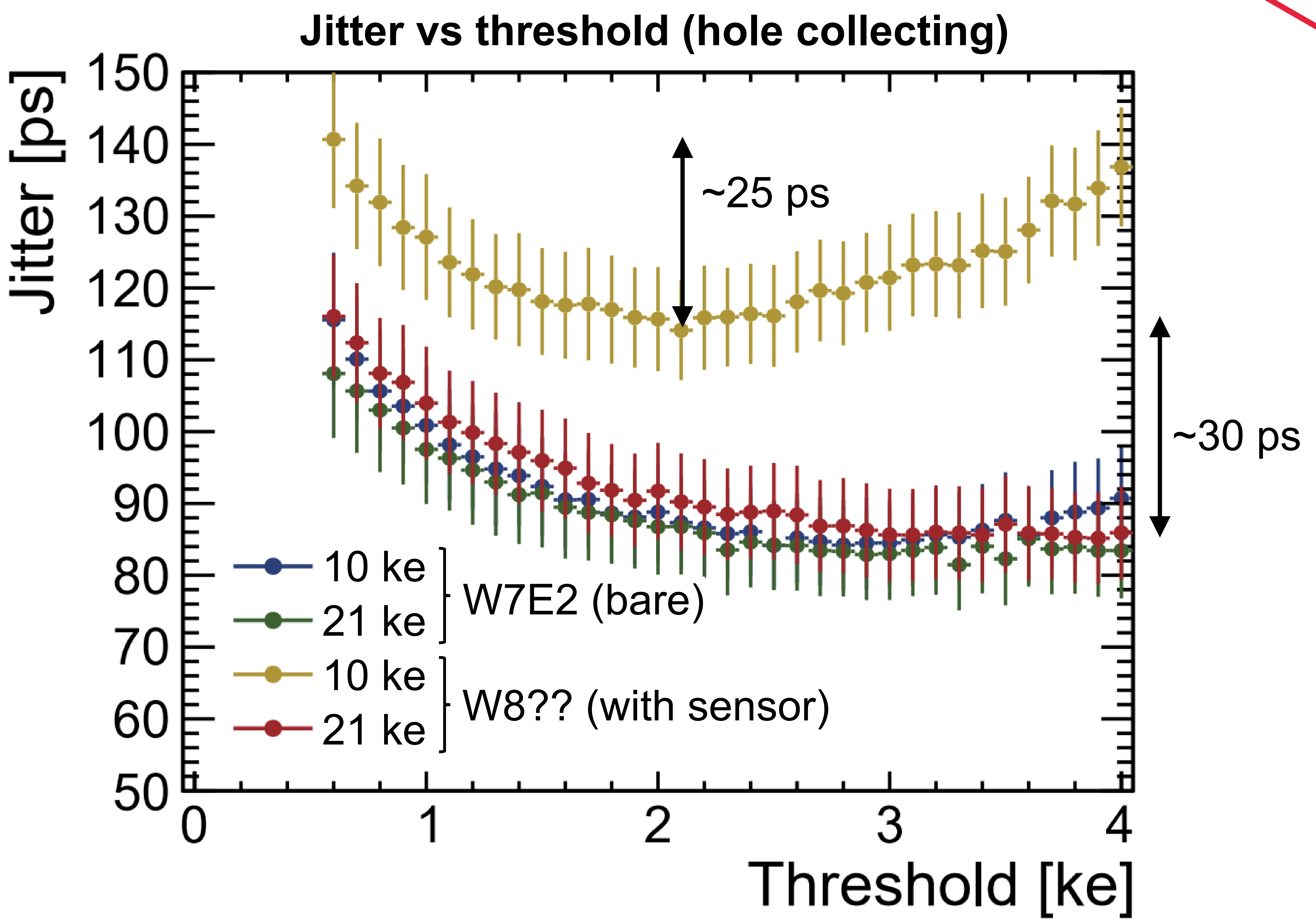
- Time bins measured using digital pixel inputs
- Timepix4v2

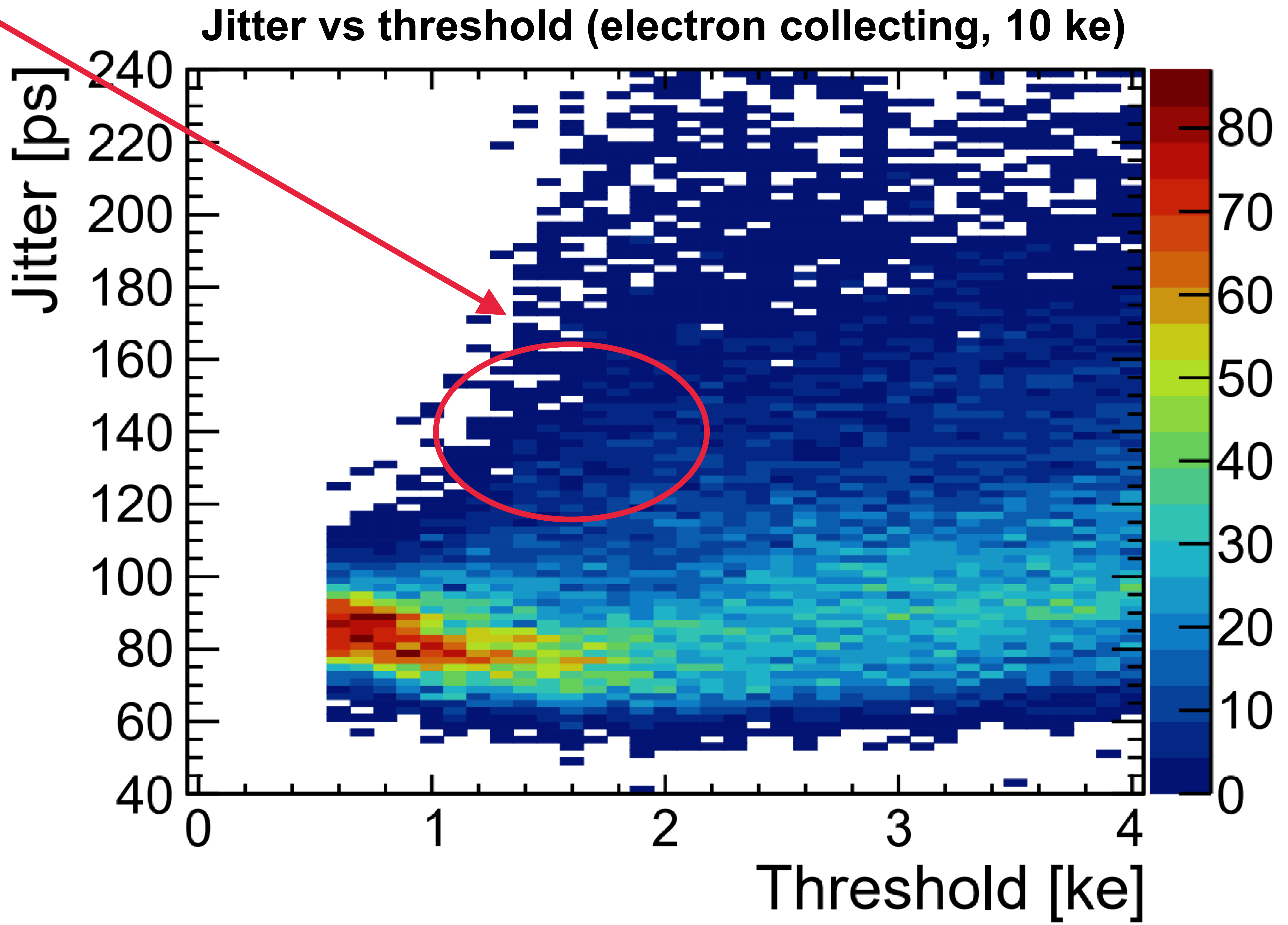


Timepix4 – Jitter vs threshold

- Jitter depends on threshold
- Tail at high thresholds in electron-collecting mode not understood

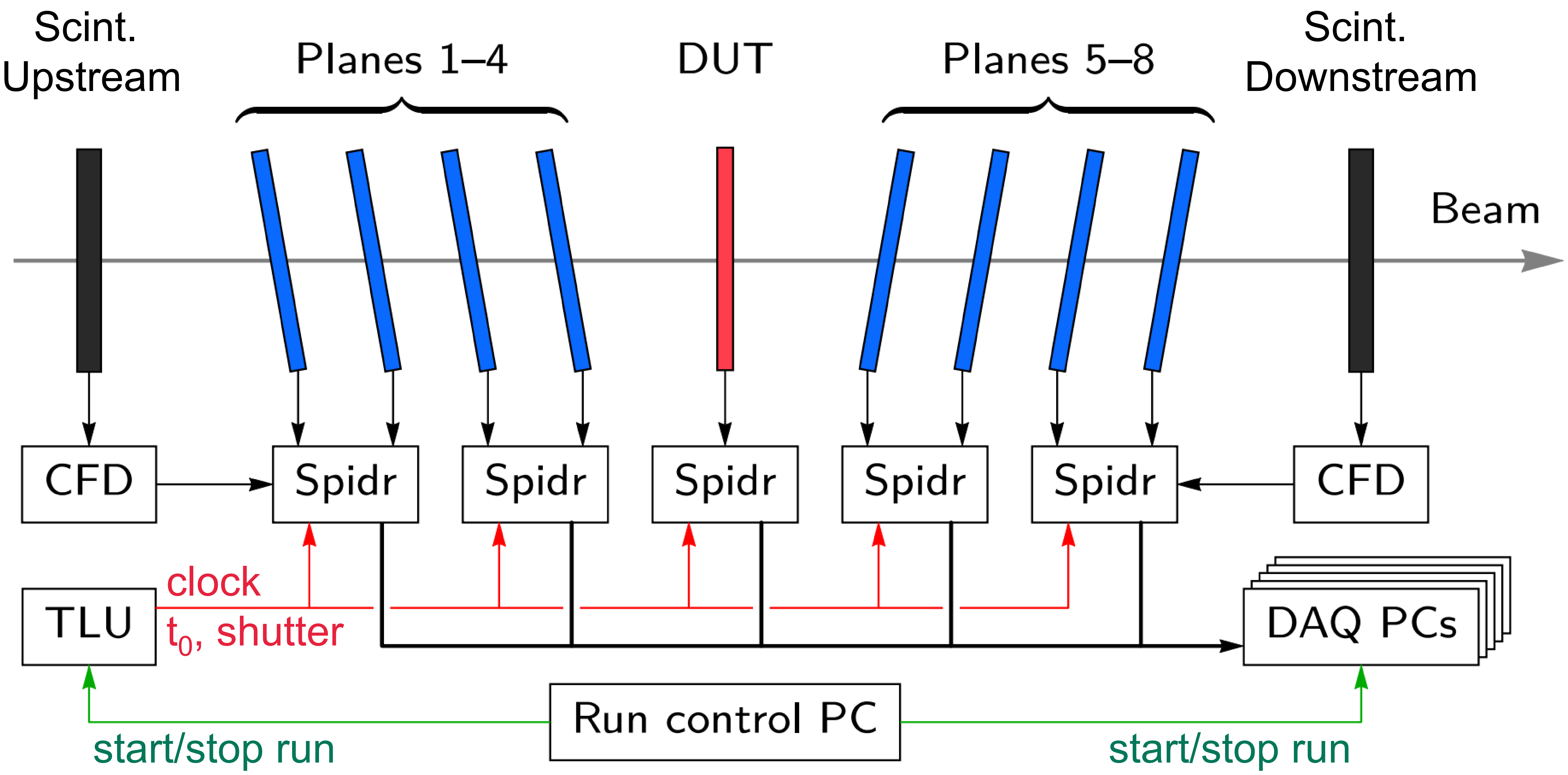






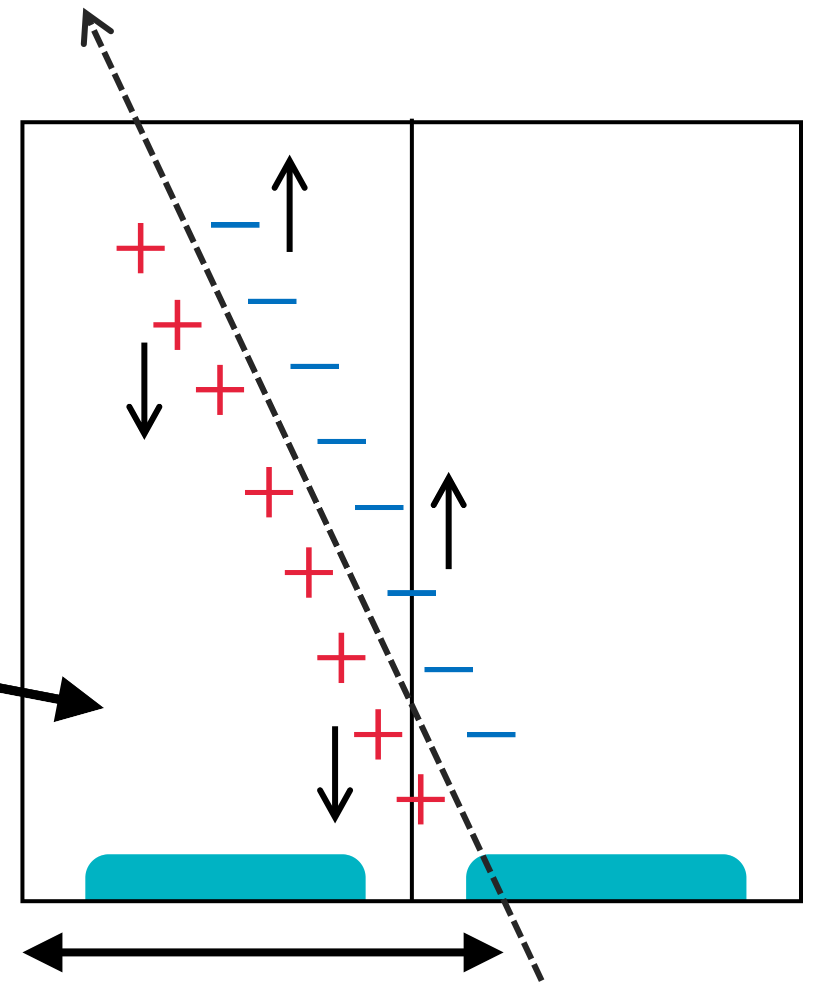
Timepix3 telescope

- Eight planes with Timepix3 + sensors
- Planes rotated to optimise spatial resolution
- Scintillators provide a reference time
- Constant fraction discriminators (CFDs) reduce timewalk effects
- All planes run on a common 40 MHz clock

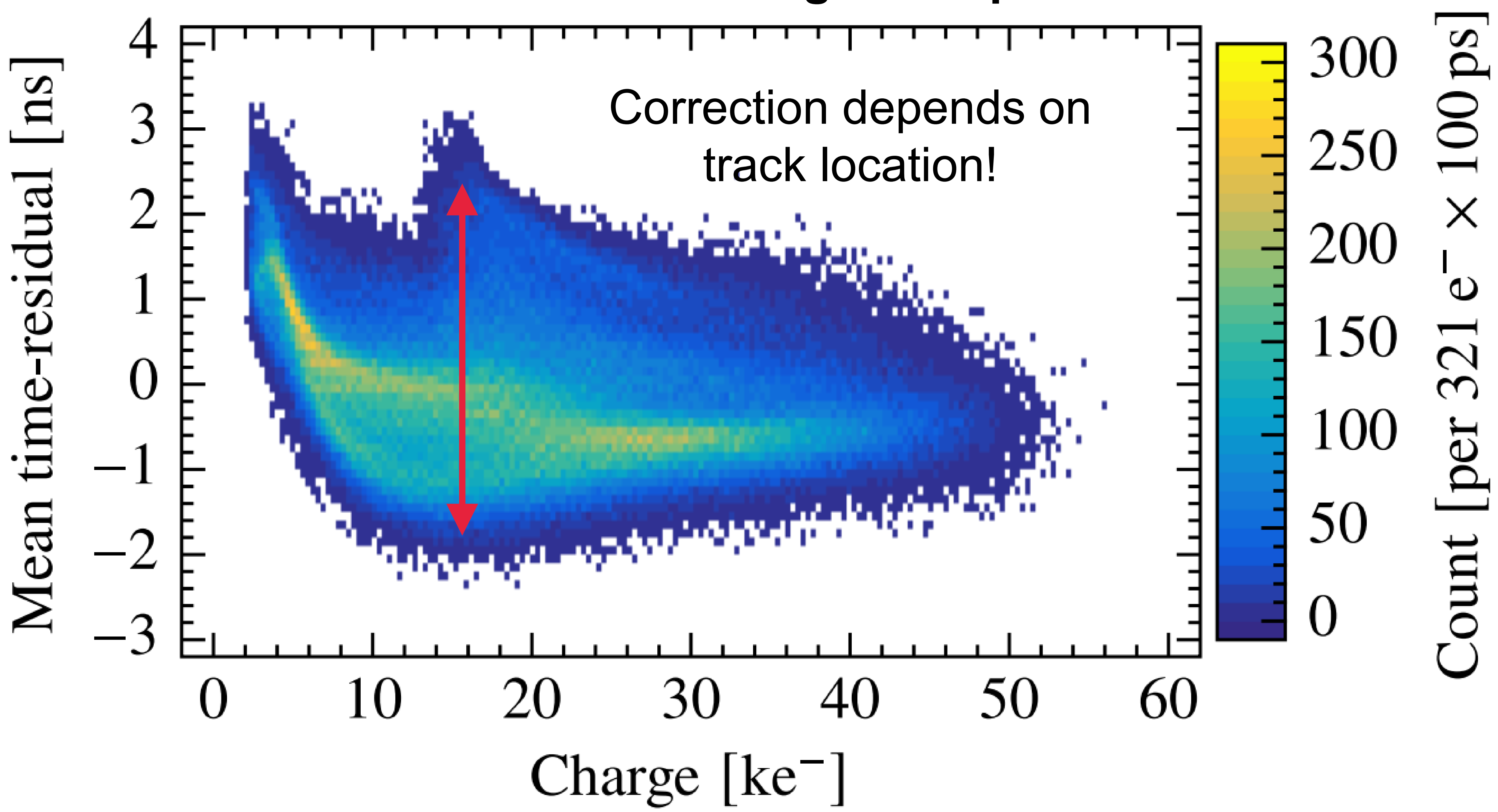


Timewalk and intercept correction

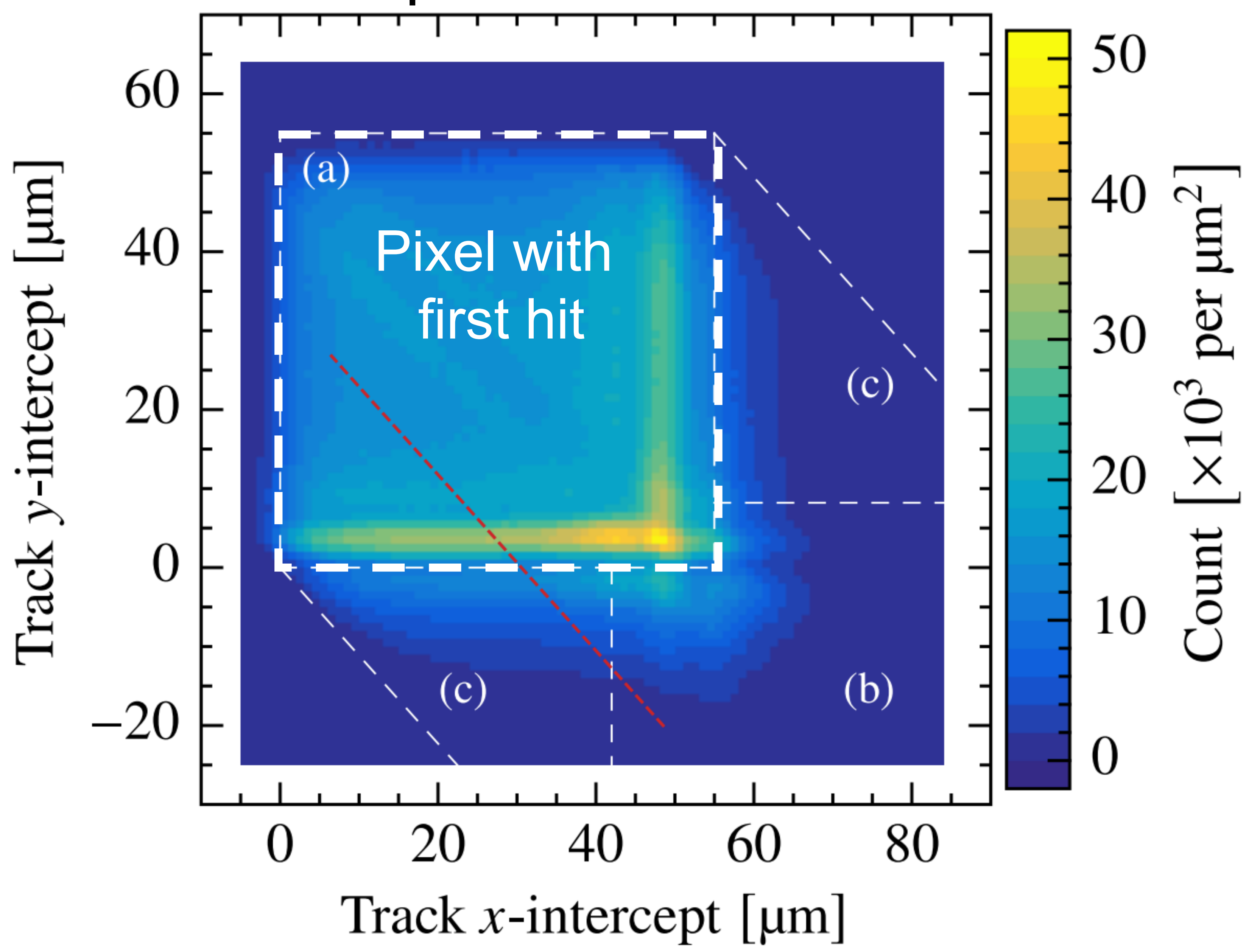
- Use both track intercept and charge to find correction in a lookup table
- Simultaneously corrects for timewalk and signal induction variations
- Improves track time resolution: $\sigma(\text{track}) = 438\ \text{ps} \rightarrow 385\ \text{ps}$



Time corrections throughout a pixel



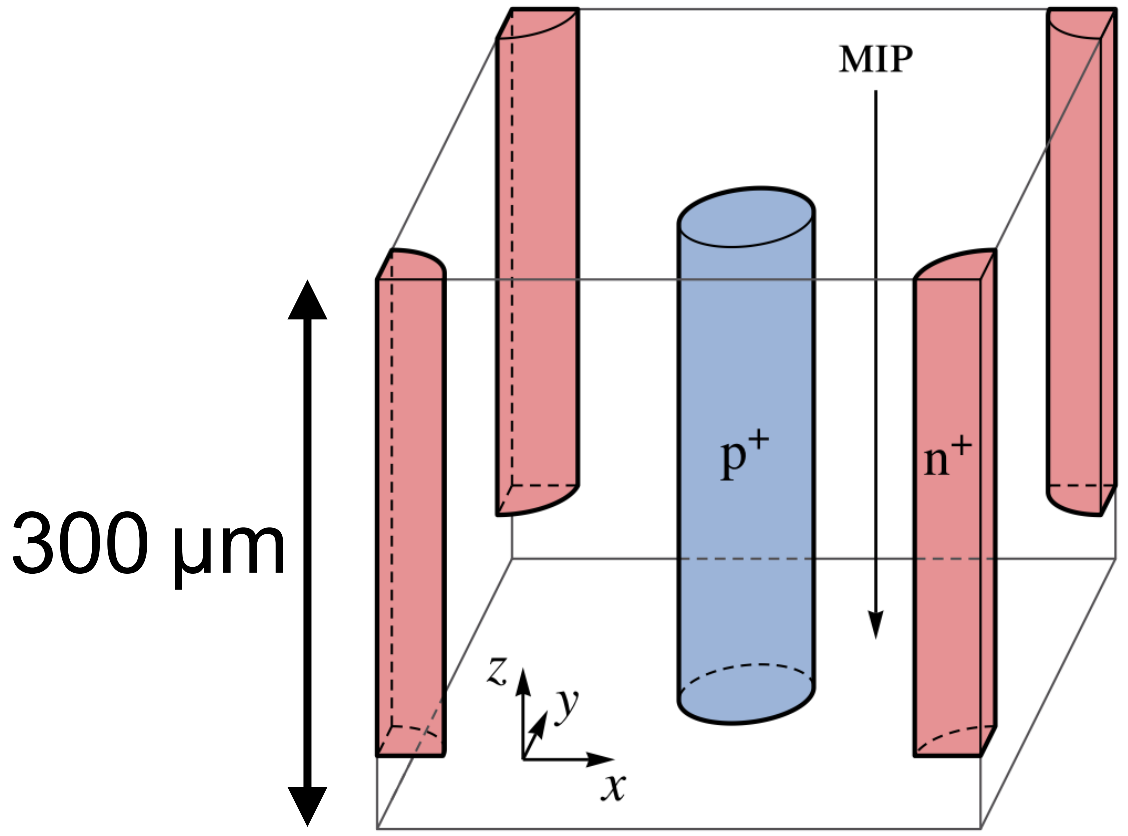
Intercept relative to first hit

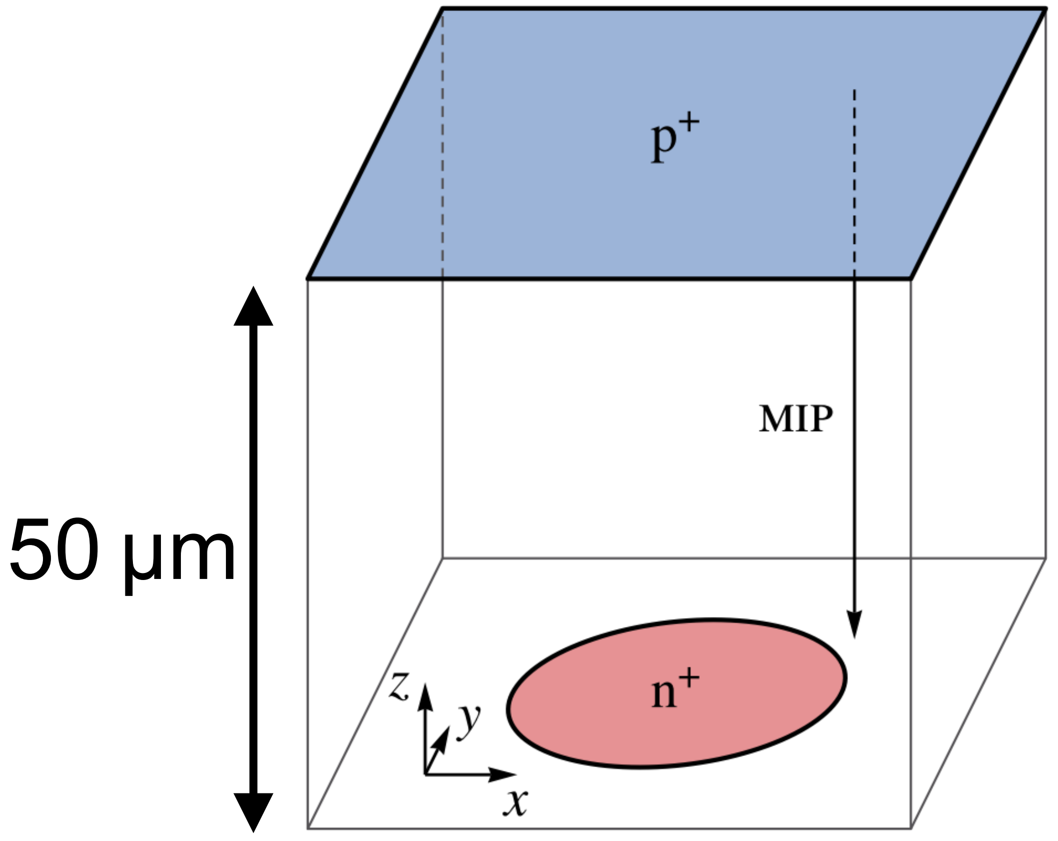


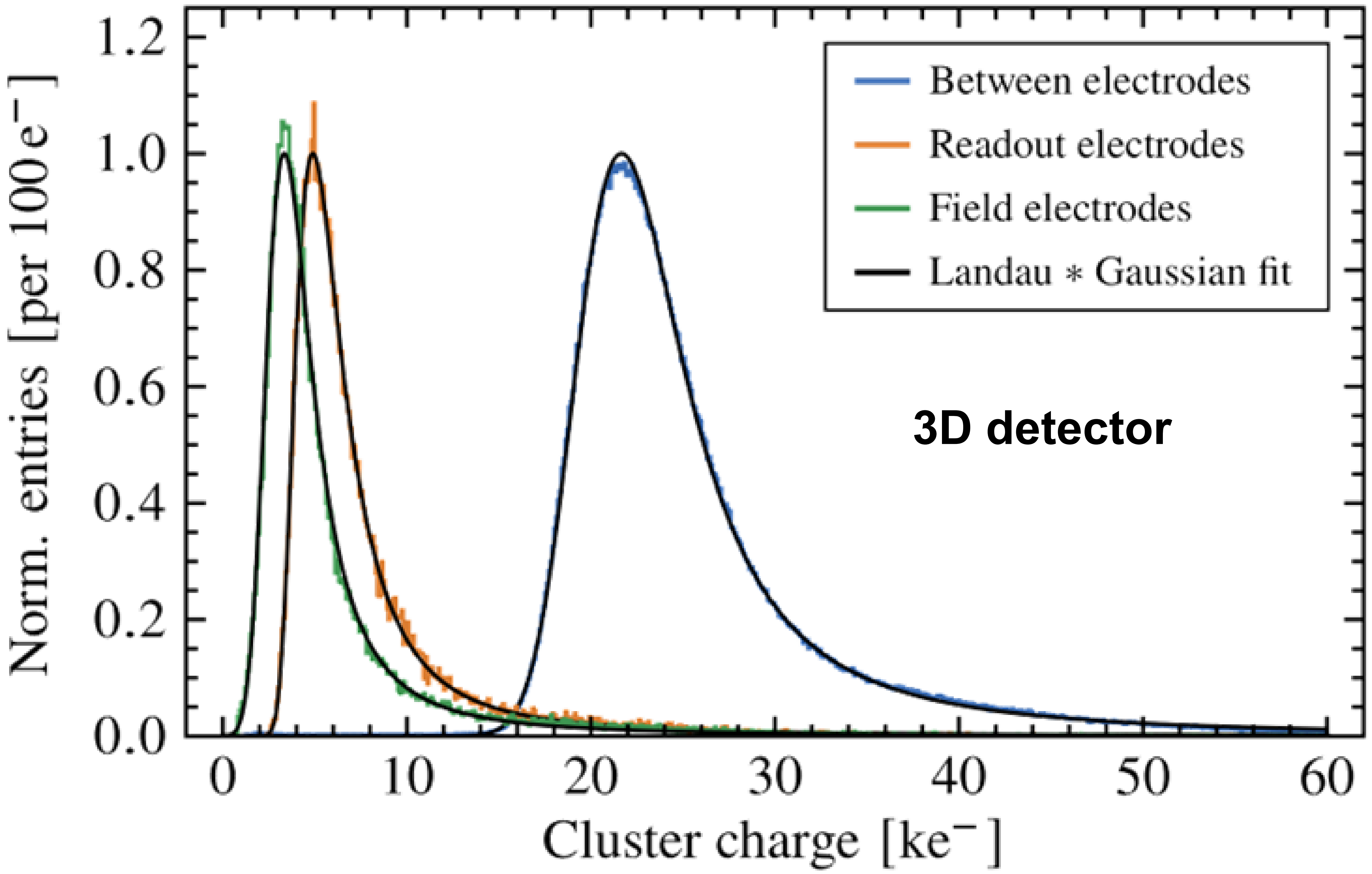
DUT charge distributions

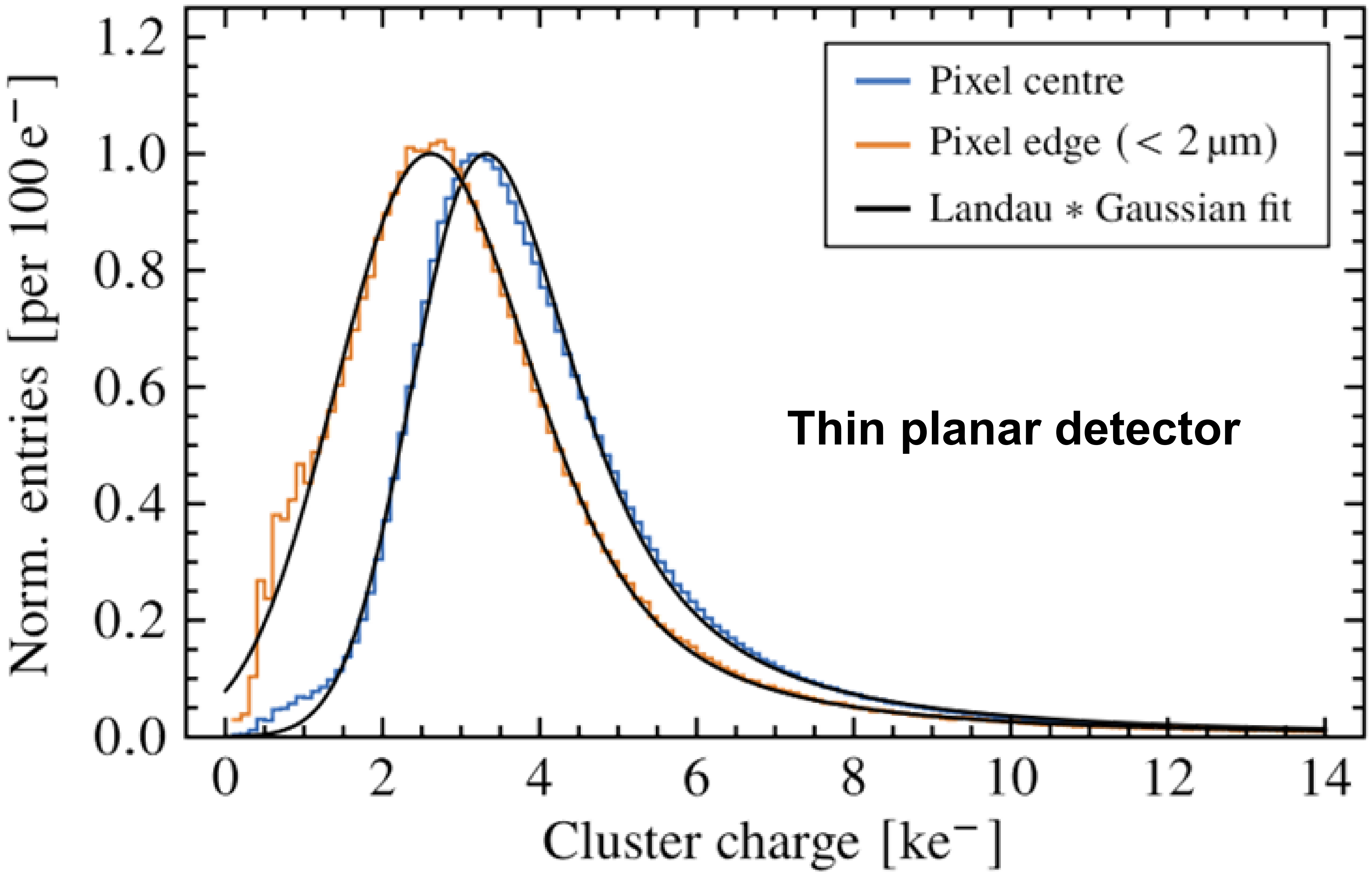
K. Heijhoff *et al* 2021 *JINST* **16** P08009 [DOI: 10.1088/1748-0221/16/08/P08009]

- MIPs going through electrodes of 3D sensor only generate charge in small region



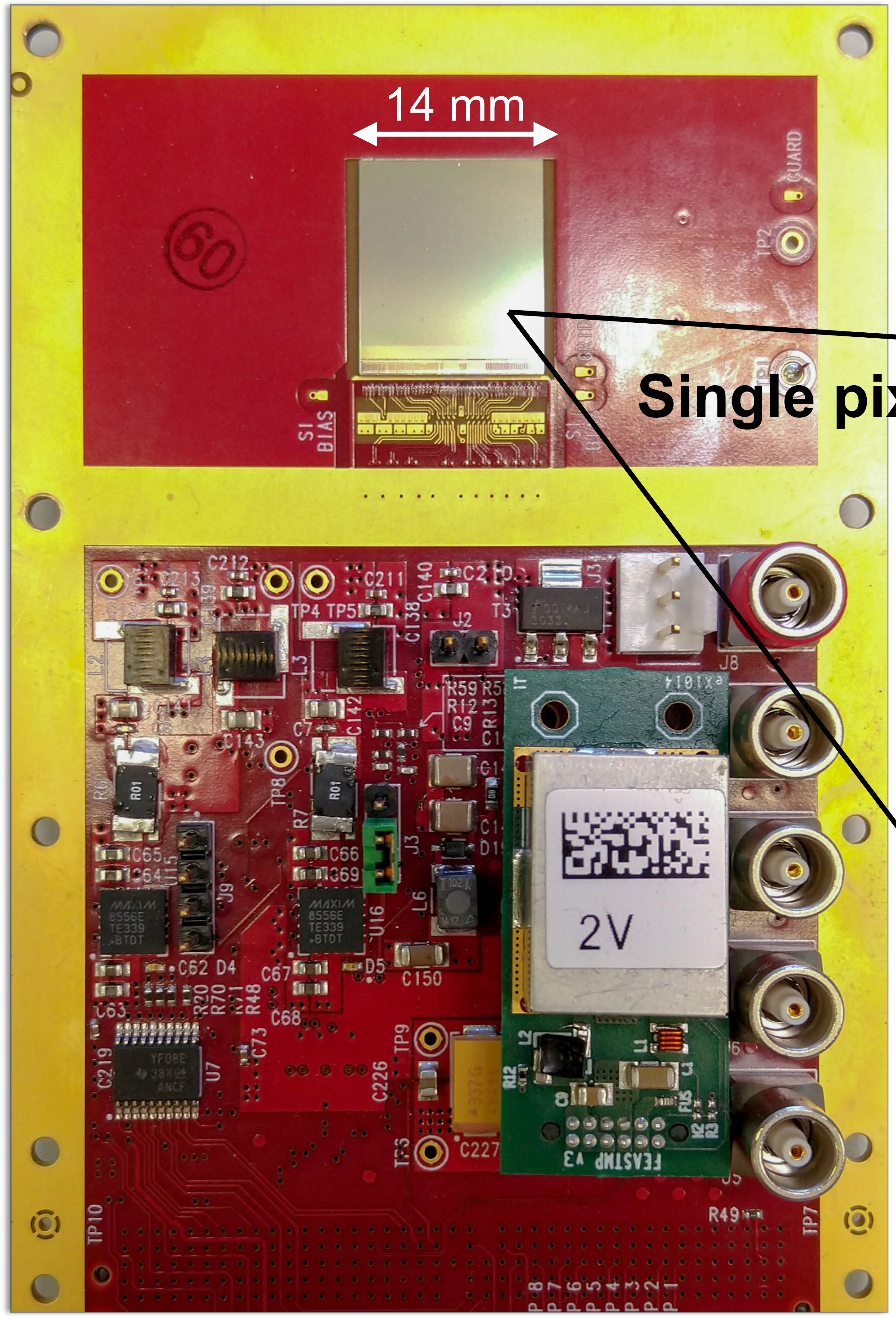




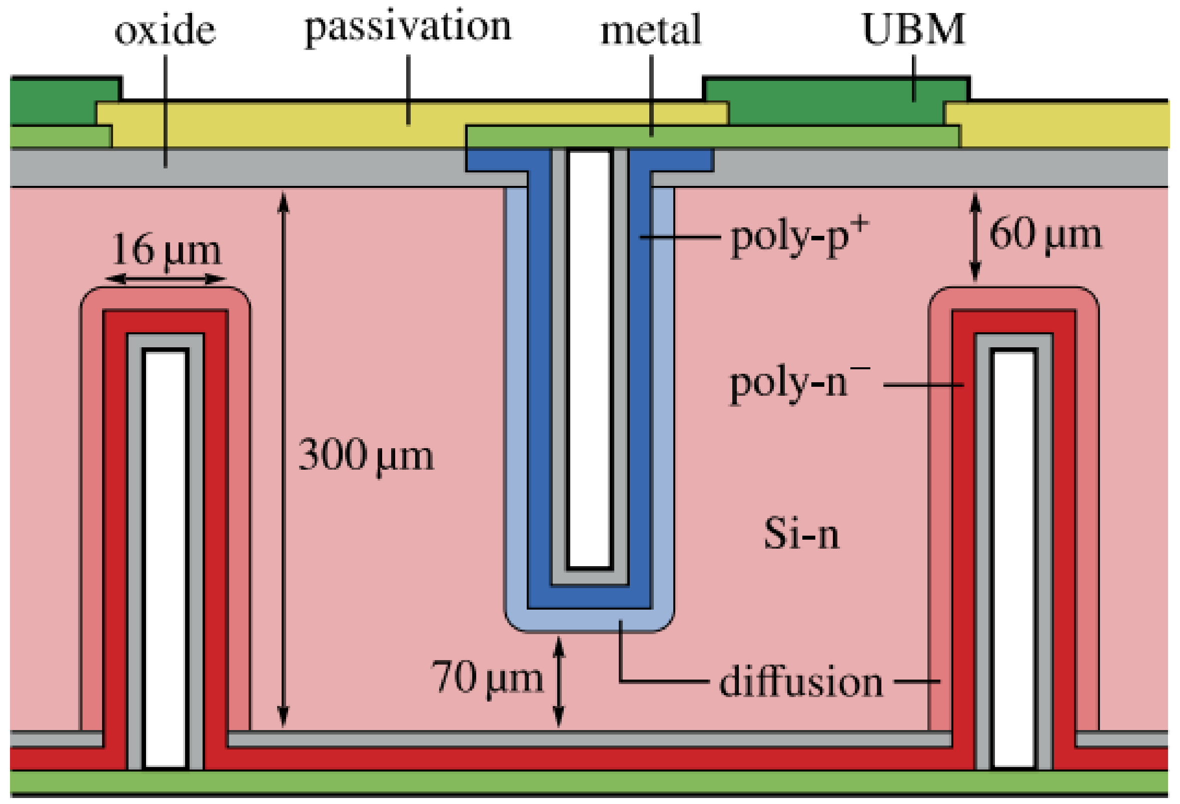


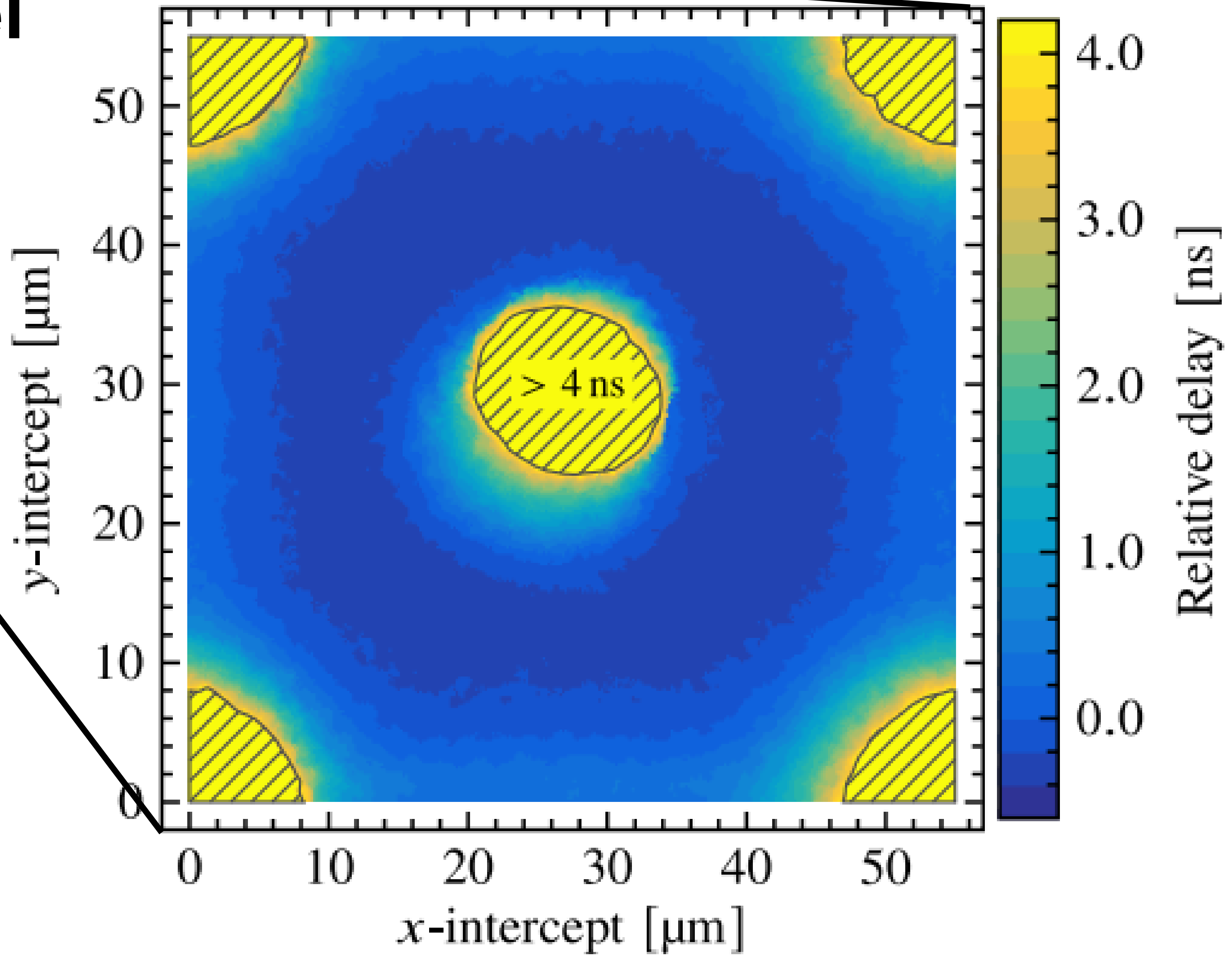
Intrapixel time delay

Timepix3 pixel ASIC + sensor

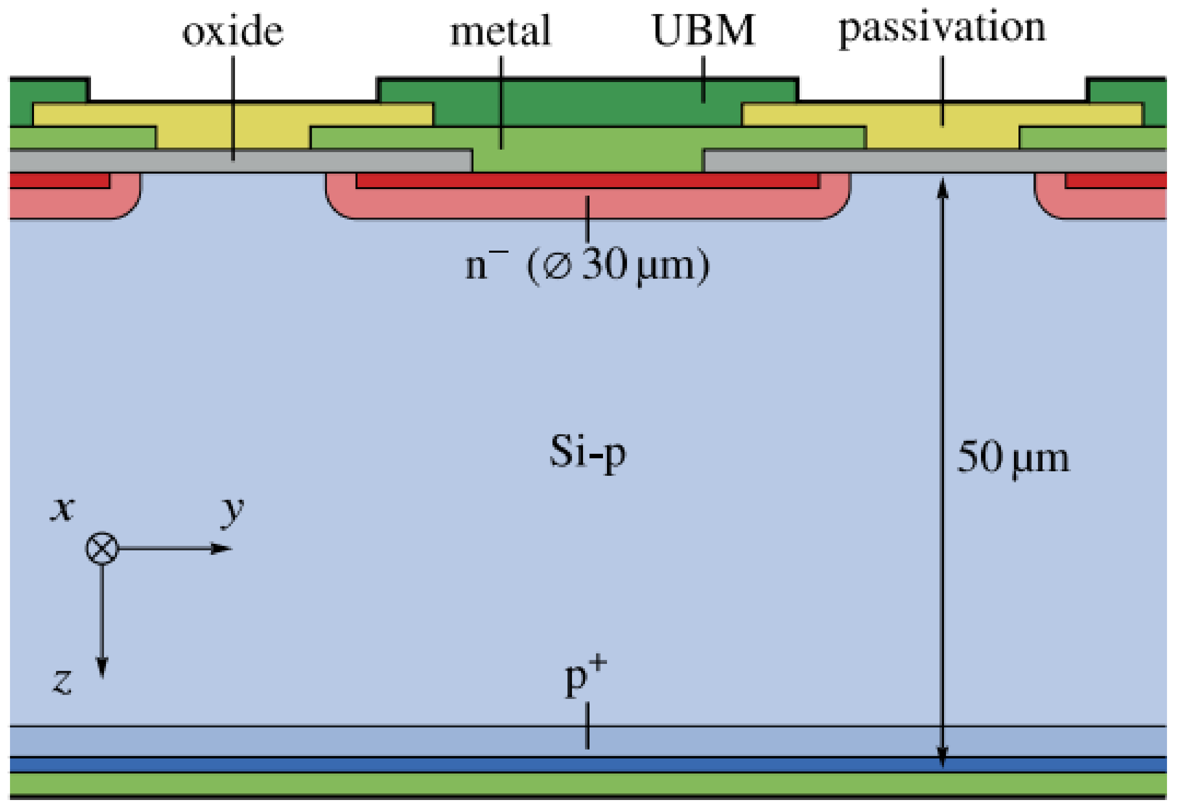


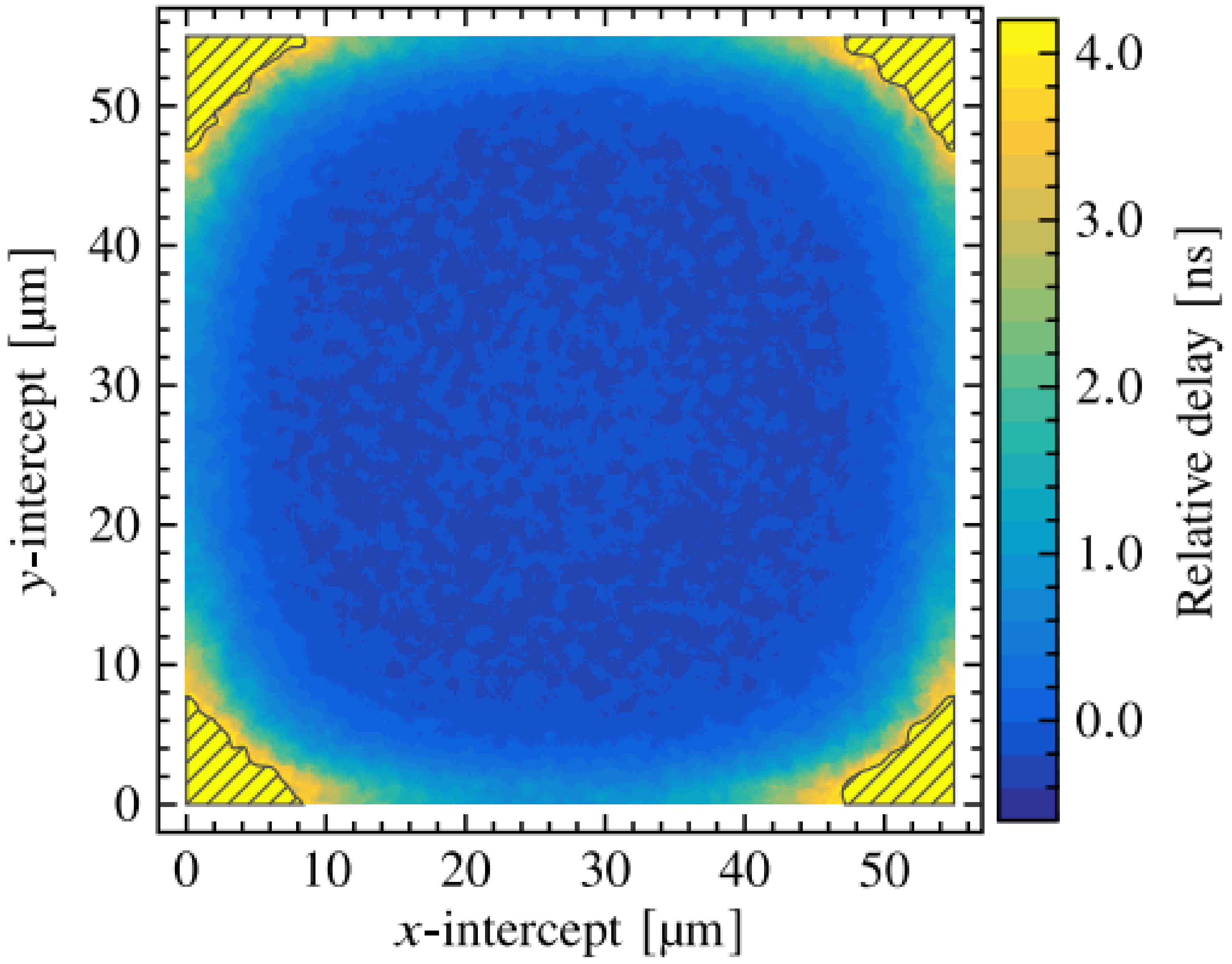
3D sensor technology





Thin planar sensor





K. Heijhoff *et al* 2021 *JINST* **16** P08009 [DOI: 10.1088/1748-0221/16/08/P08009]