First results from the Timepix4 Telescope

Kevin Heijhoff — on behalf of the Timepix4 Telescope group

HSTD13 — 4 December 2023

People involved

Testbeam crew

Nikhef: Kazu Akiba, Martin van Beuzekom, Tjip Bischoff, Robbert Geertsema, Kevin Heijhoff, 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

And acknowledgements to everyone making this possible, including

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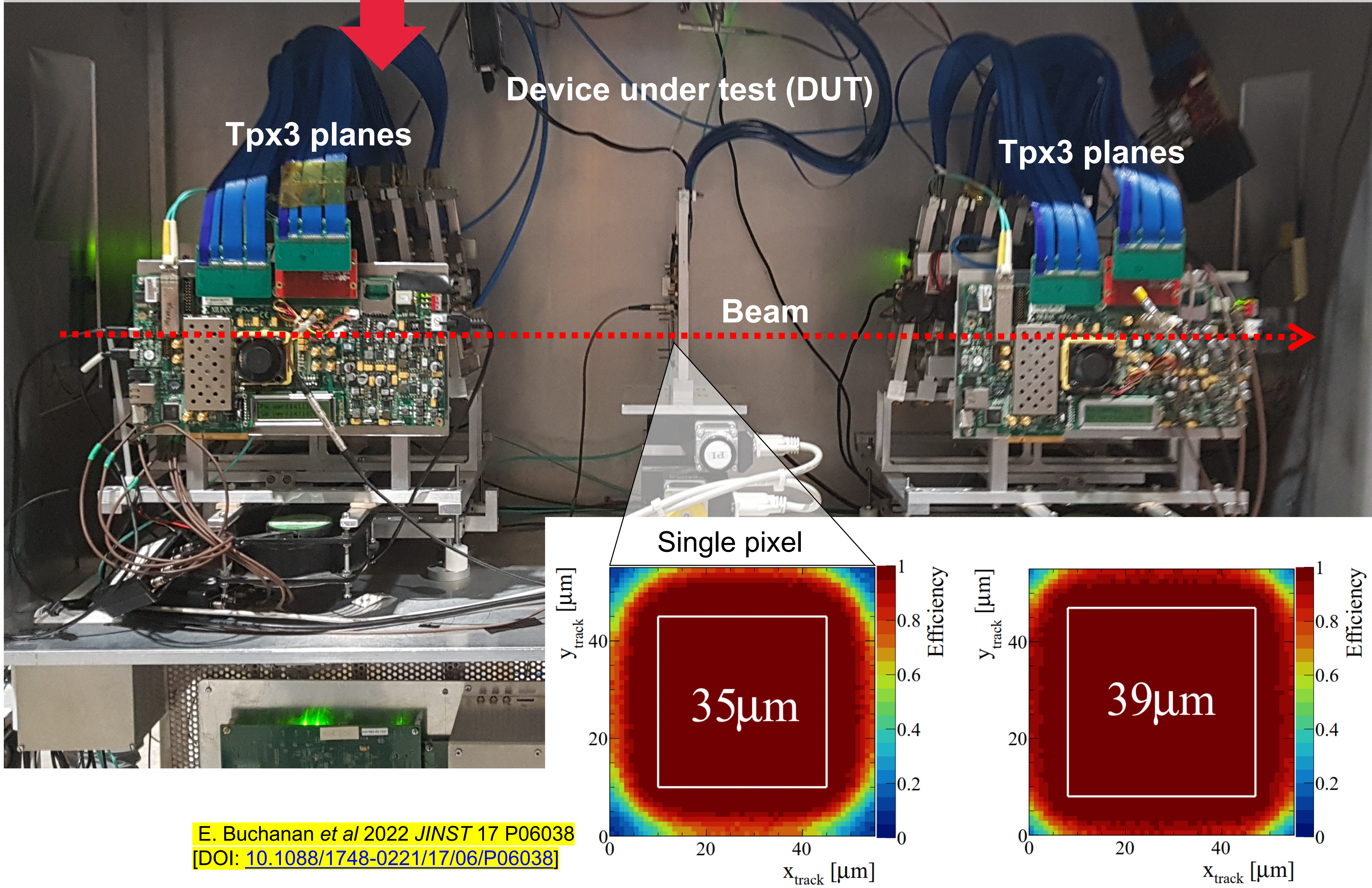
Successor to the LHCb VELO Timepix3 Telescope (2013–2019)

Timepix3 telescope:

- 1.6 µm pointing resolution

Timepix4 telescope goal:

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



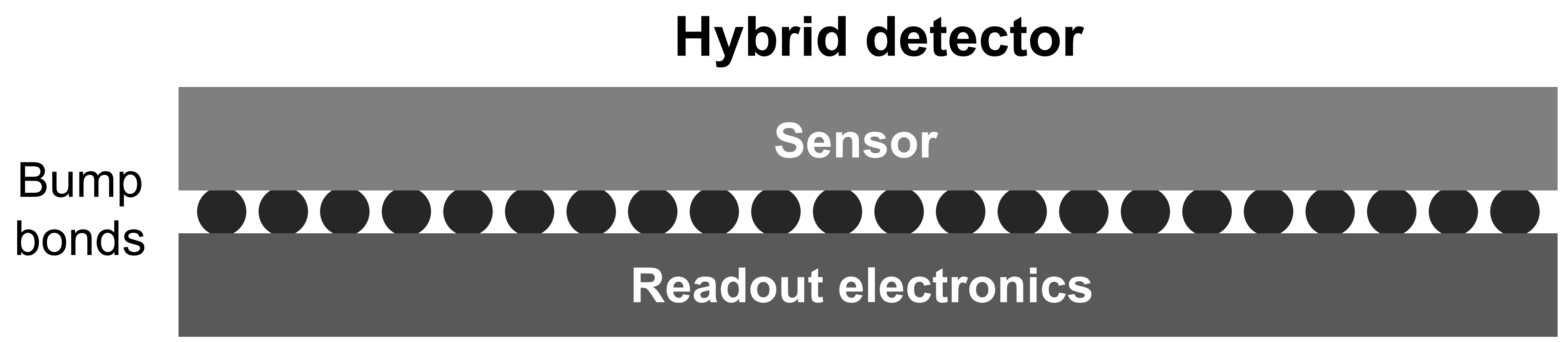
K. Akiba *et al* 2019 *JINST* **14** P05026
[DOI: 10.1088/1748-0221/14/05/P05026]

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

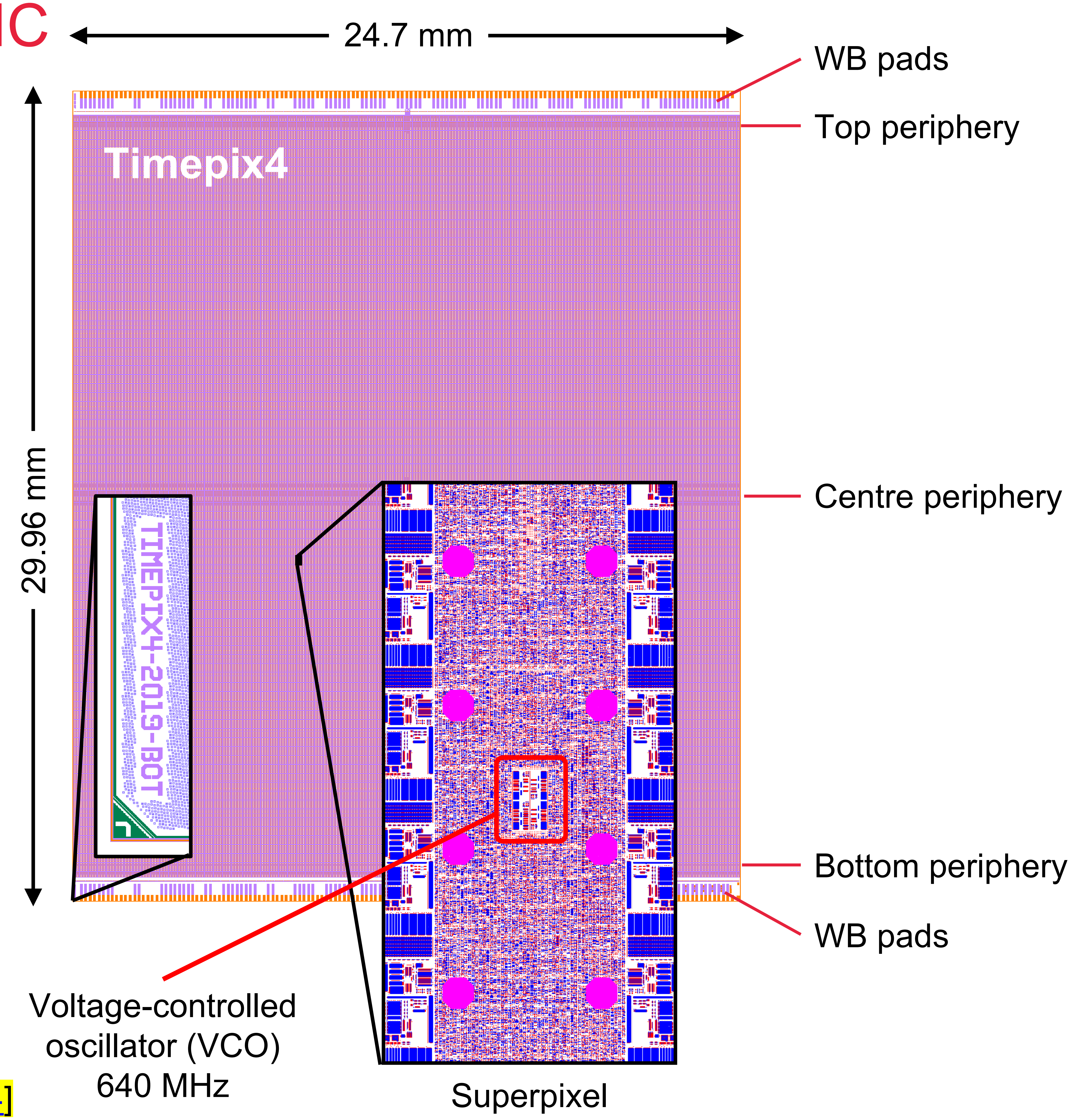
E. Buchanan *et al* 2022 *JINST* 17 P06038
[DOI: 10.1088/1748-0221/17/06/P06038]

Timepix4: Hybrid pixel detector readout ASIC

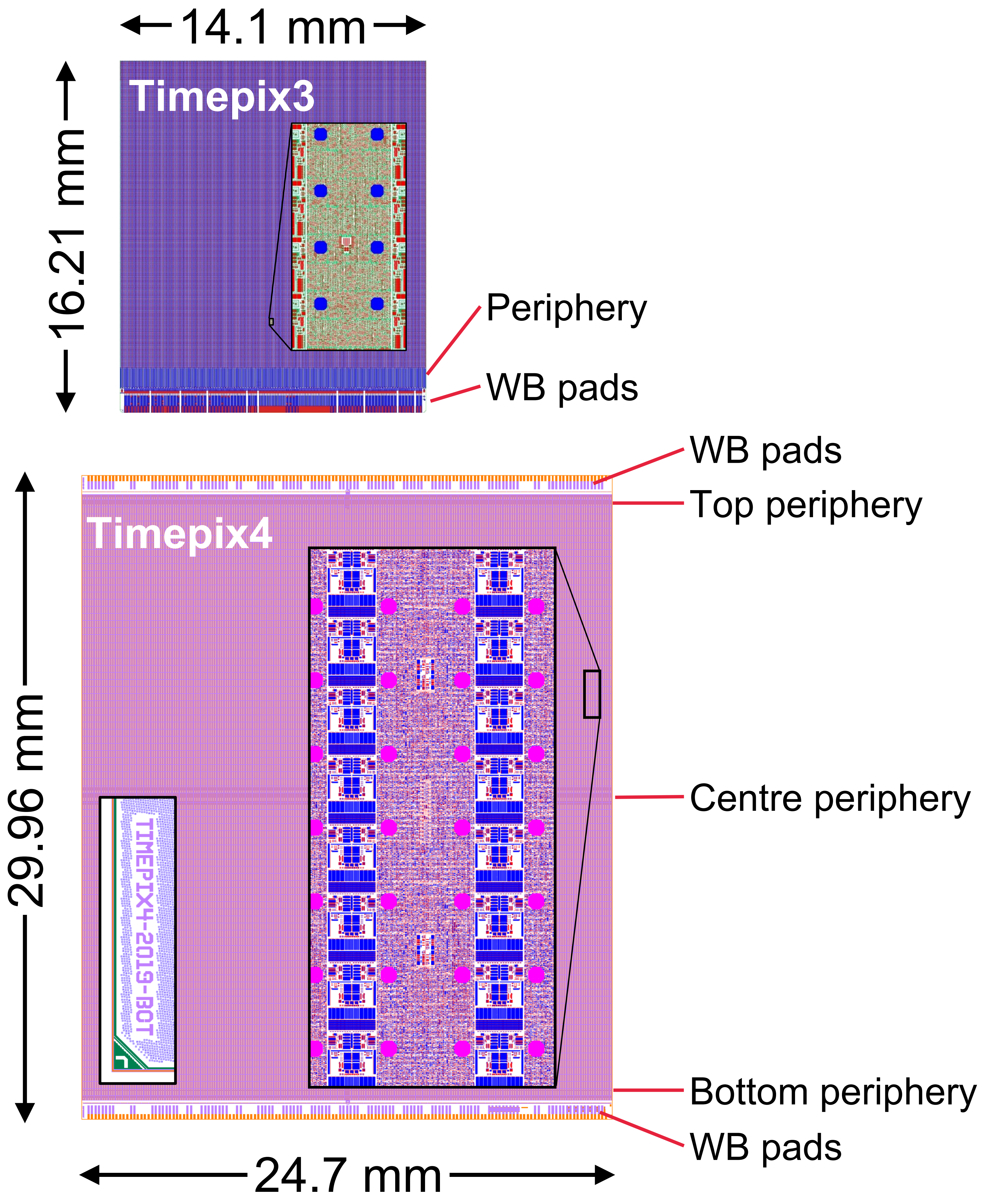
- Developed by CERN, Nikhef, and IFAE
- 65 nm CMOS
- 448×512 pixels, 55×55 μm^2 pitch
- Simultaneous measurement of time and charge deposition (by measuring time over threshold)
- Time-bin size of 25 ns/128 = **195 ps** (Timepix3: 1.56 ns)
- Max rate: 360×10^6 hits/cm^2/s (160 Gb/s for single chip)



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

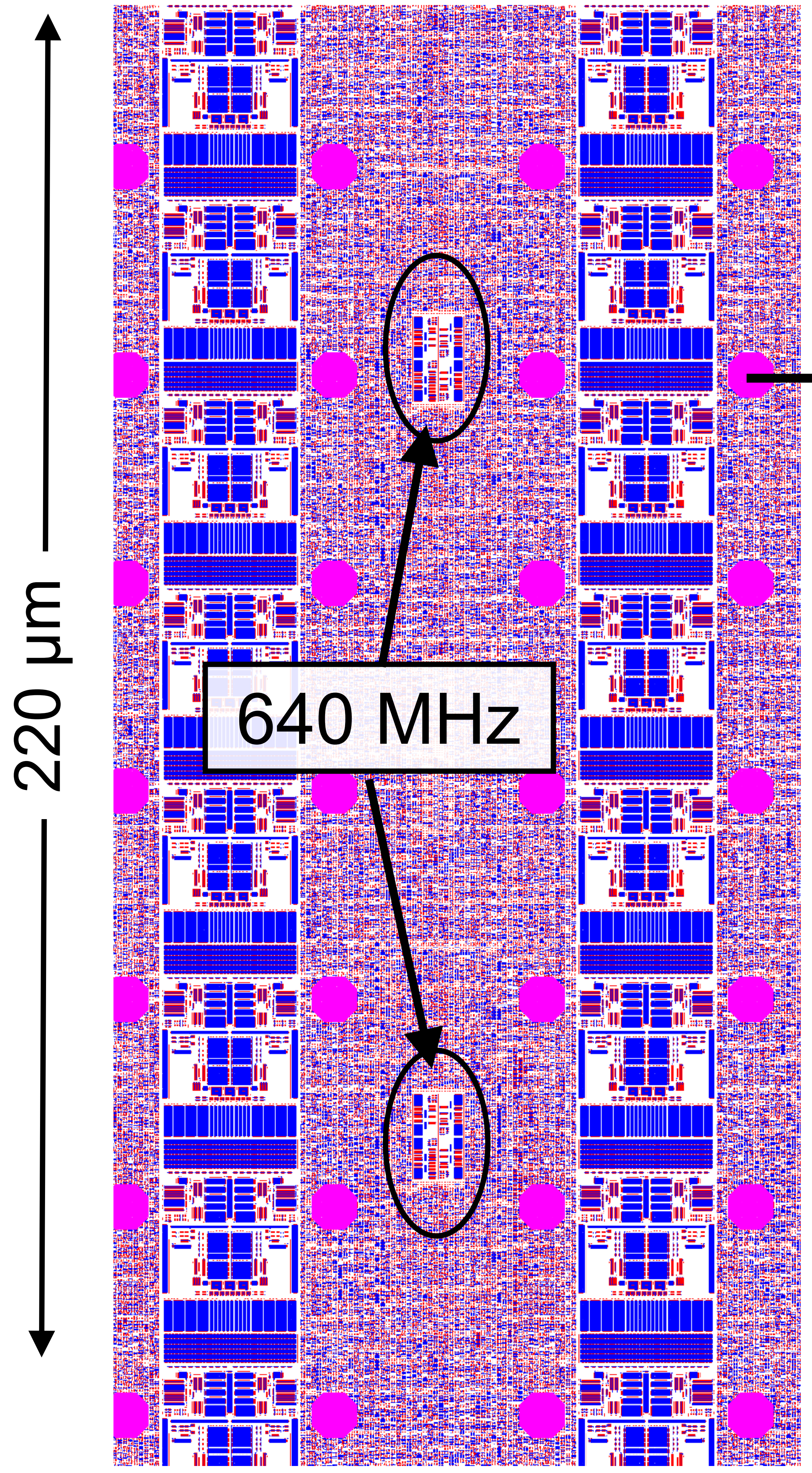


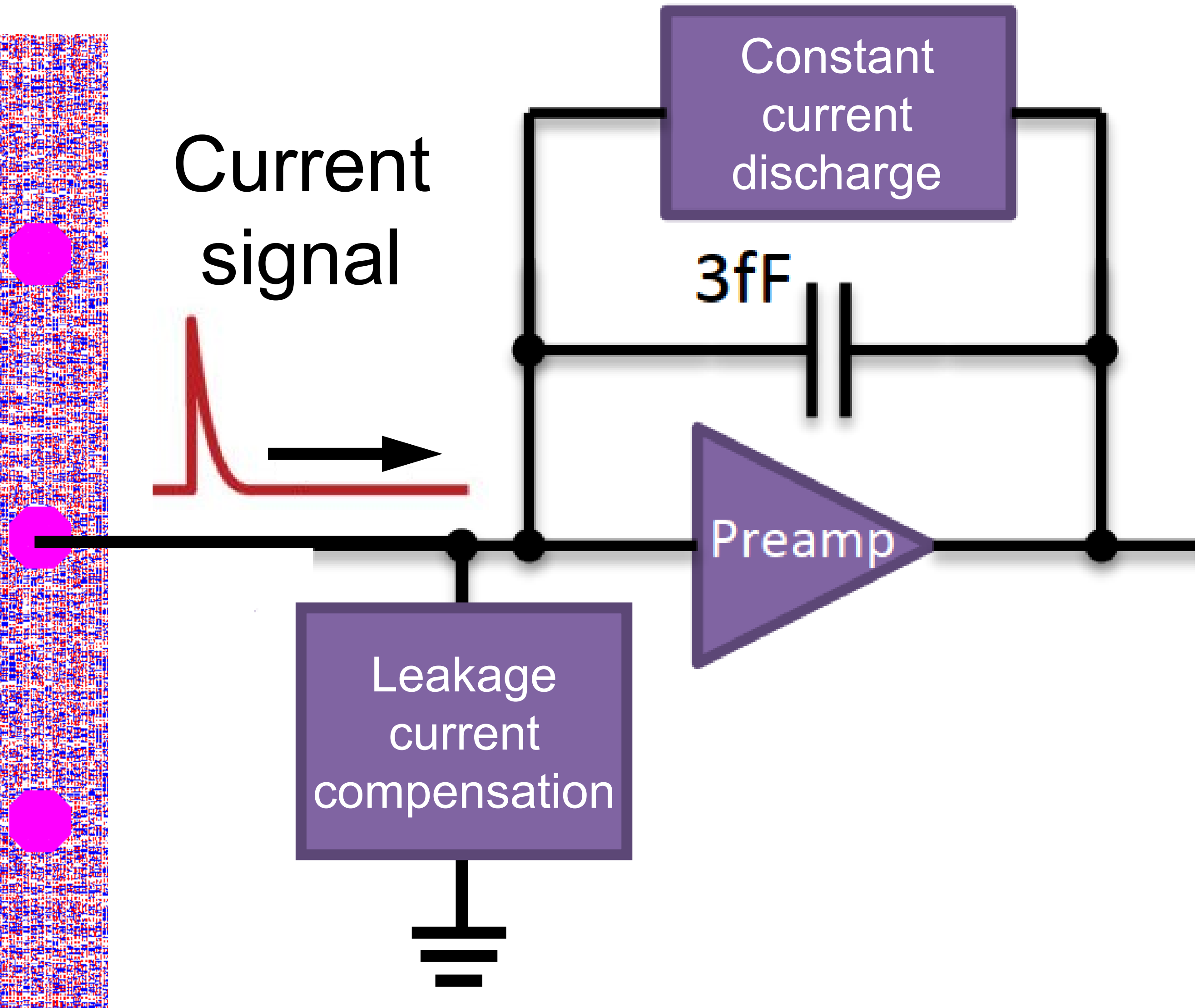
Timepix3 → Timepix4



			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	0.43x10^6 hits/mm^2/s	**3.58x10^6 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 x 10^9 hits/mm^2/s	~5 x 10^9 hits/mm^2/s	
TOT energy resolution			< 2KeV	< **1Kev**	
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^-	

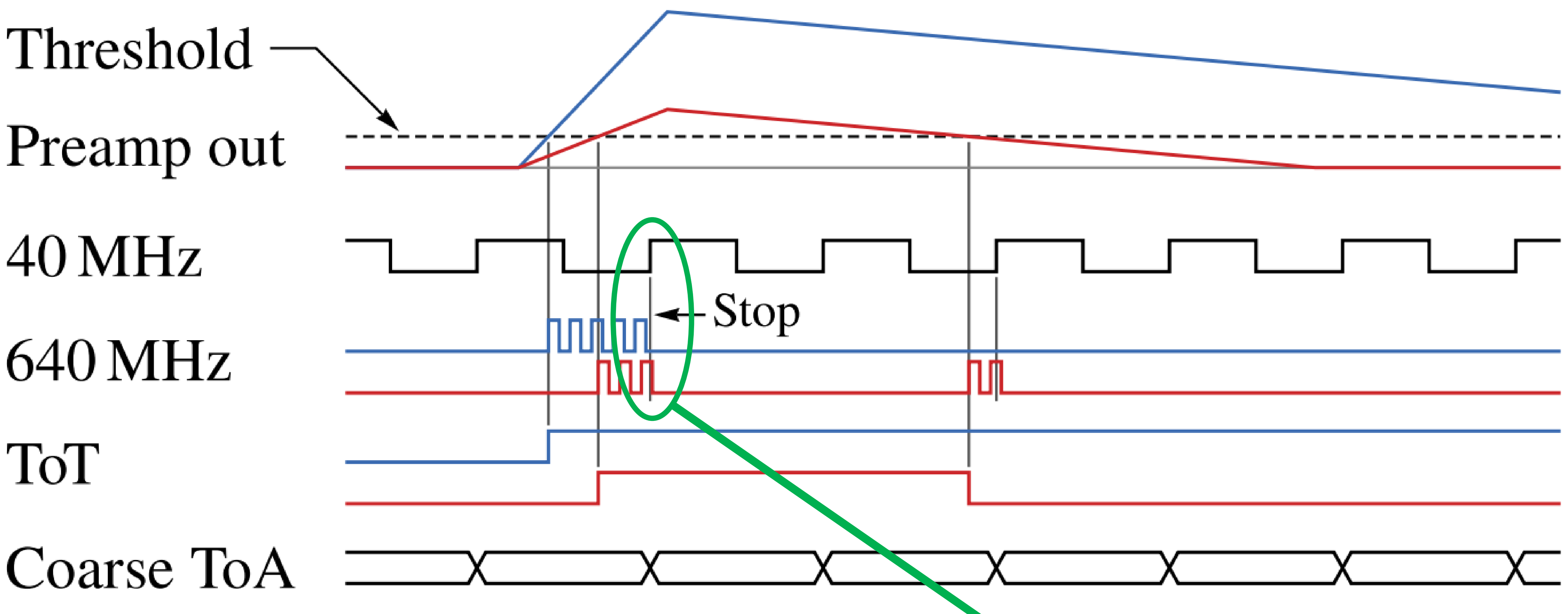
Time measurement in Timepix4



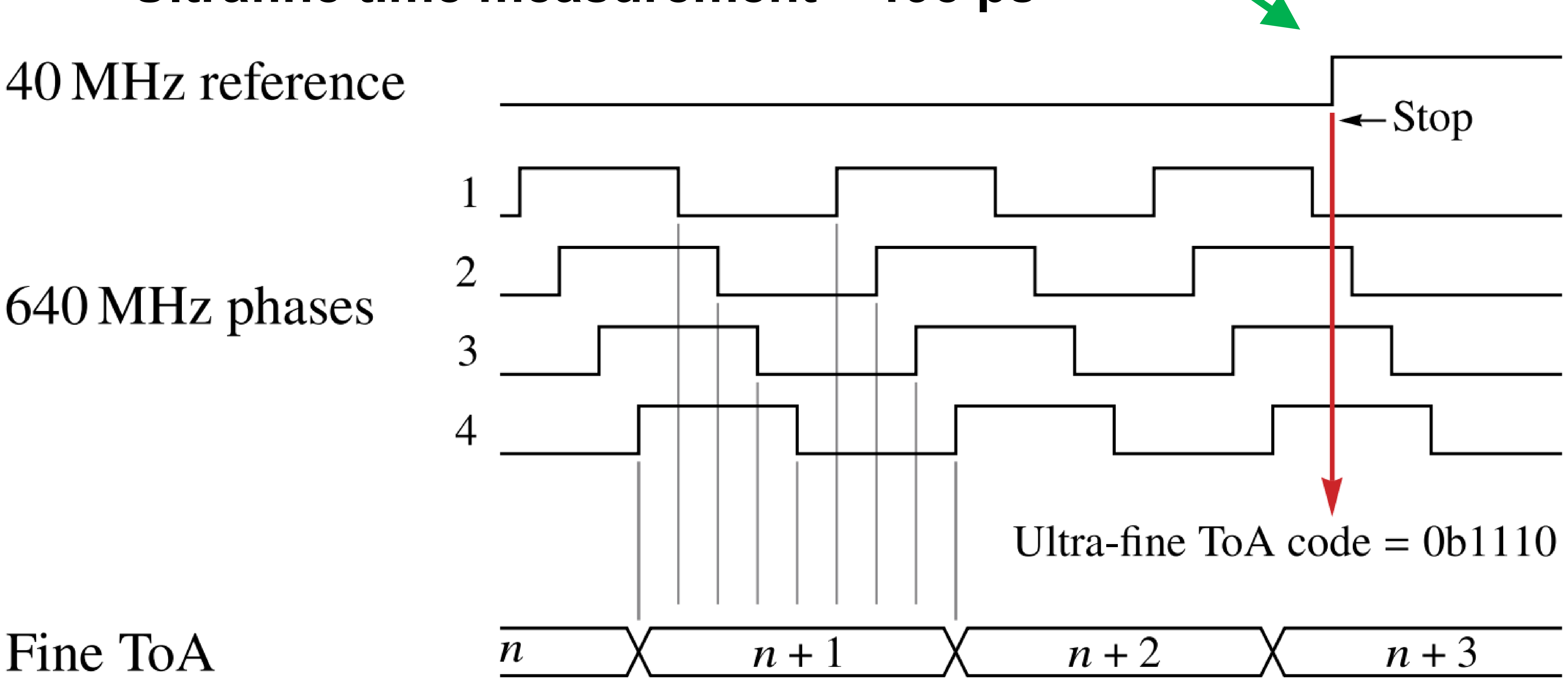


- Nominal TDC resolution: 195 ps/$\sqrt{12}$ = 56 ps
- Time over threshold (ToT) measures signal charge

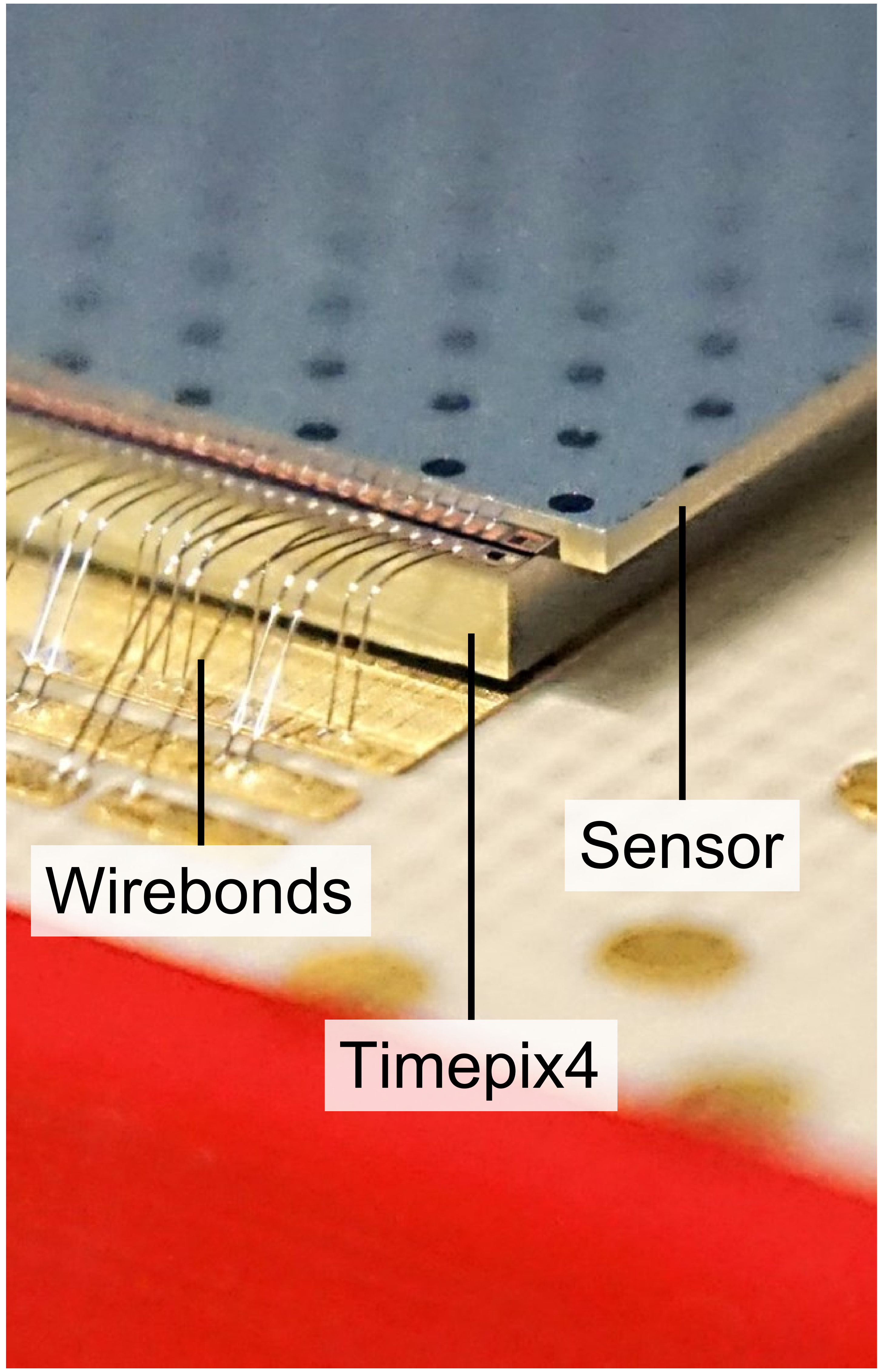
Coarse and fine time measurement – 40 MHz and 640 MHz

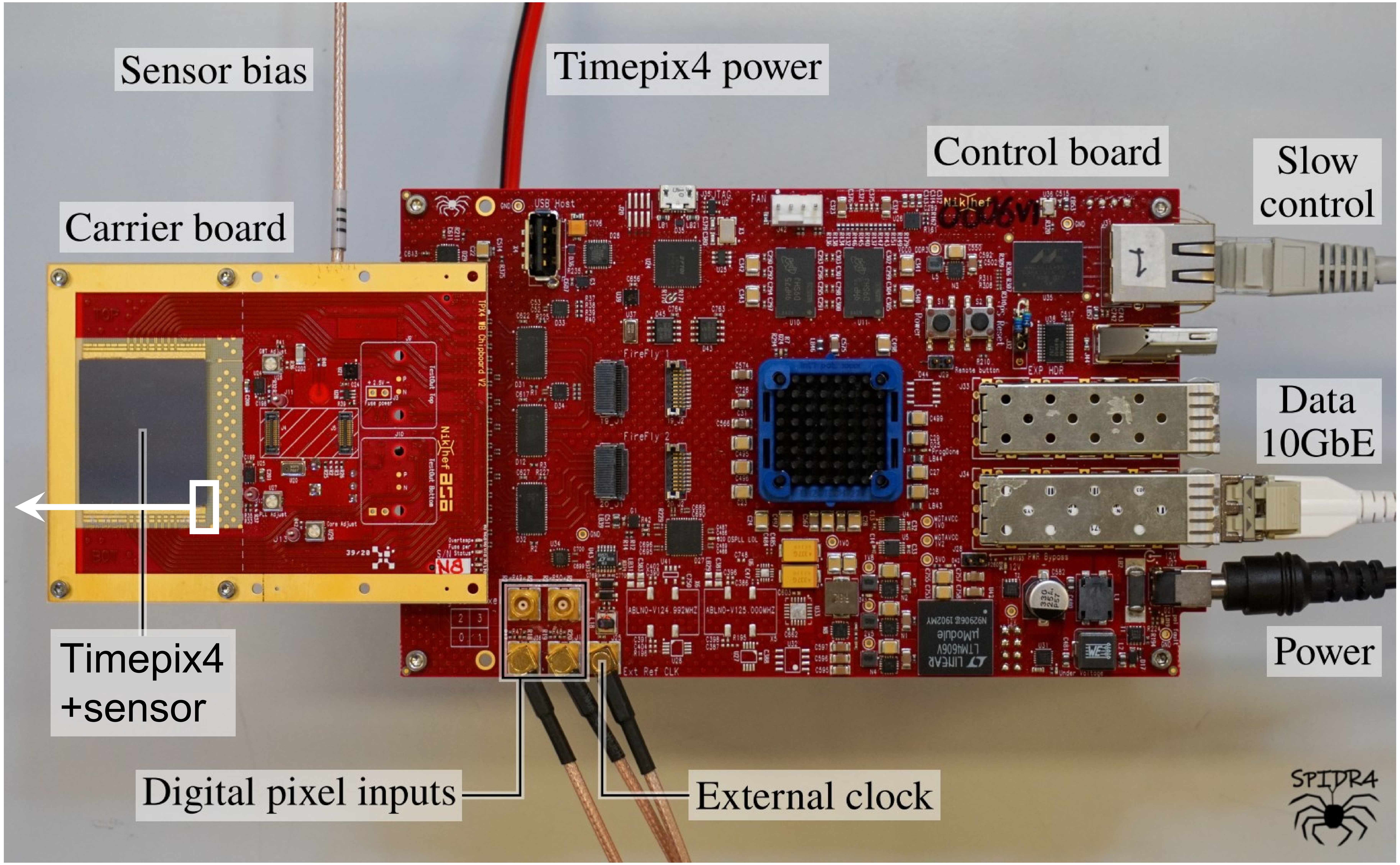


Ultrafine time measurement – 195 ps



Speedy PIxel Detector Readout 4 (SPIDR4)

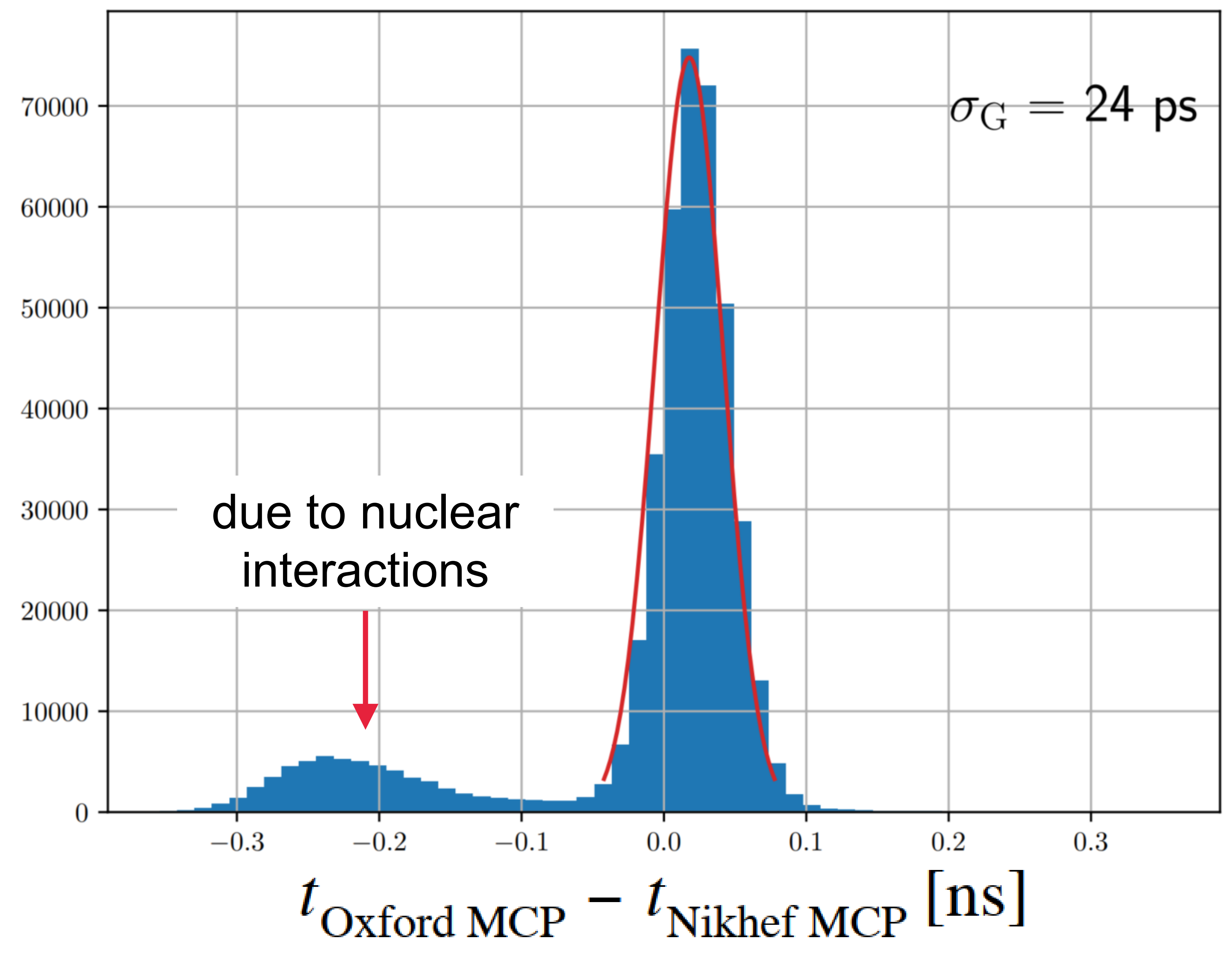


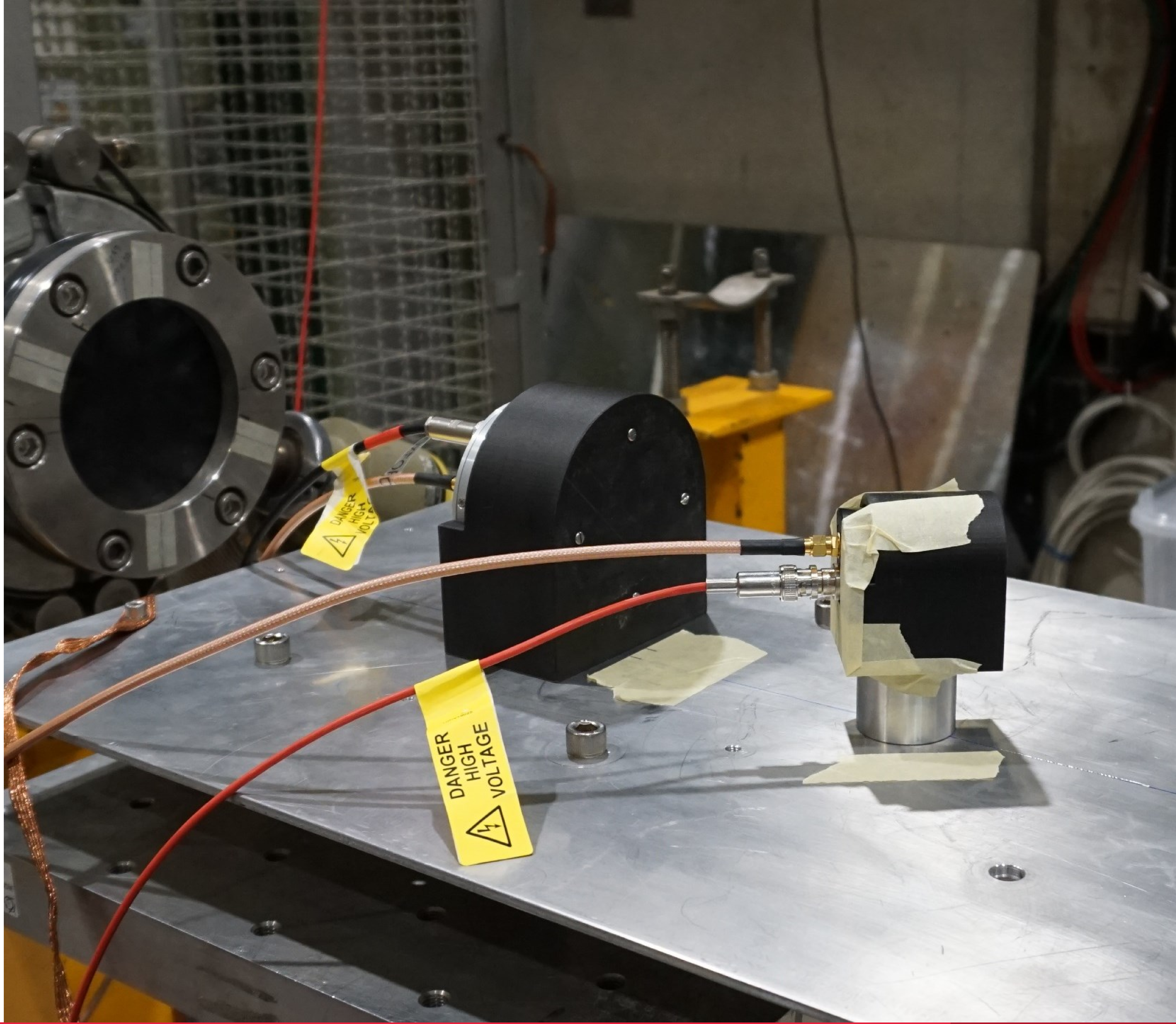


Telescope configuration

Micro channel plate detectors

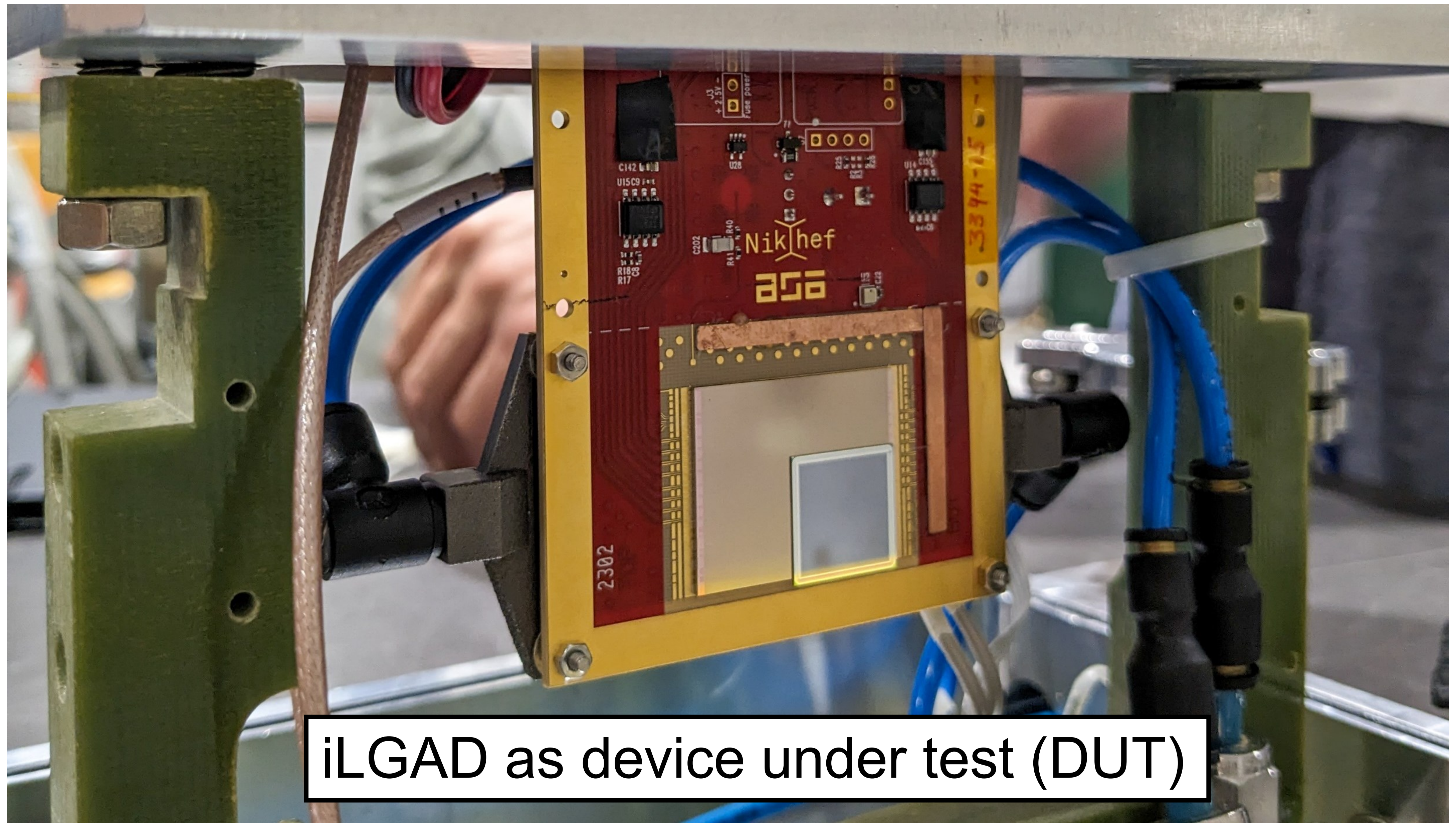
- Time reference to study telescope timing
- Considering installing Timpix4 plane to VETO events with nuclear interactions
- Current time resolution: 17 ps (single MCP)
- Combined MCP resolution: 12 ps

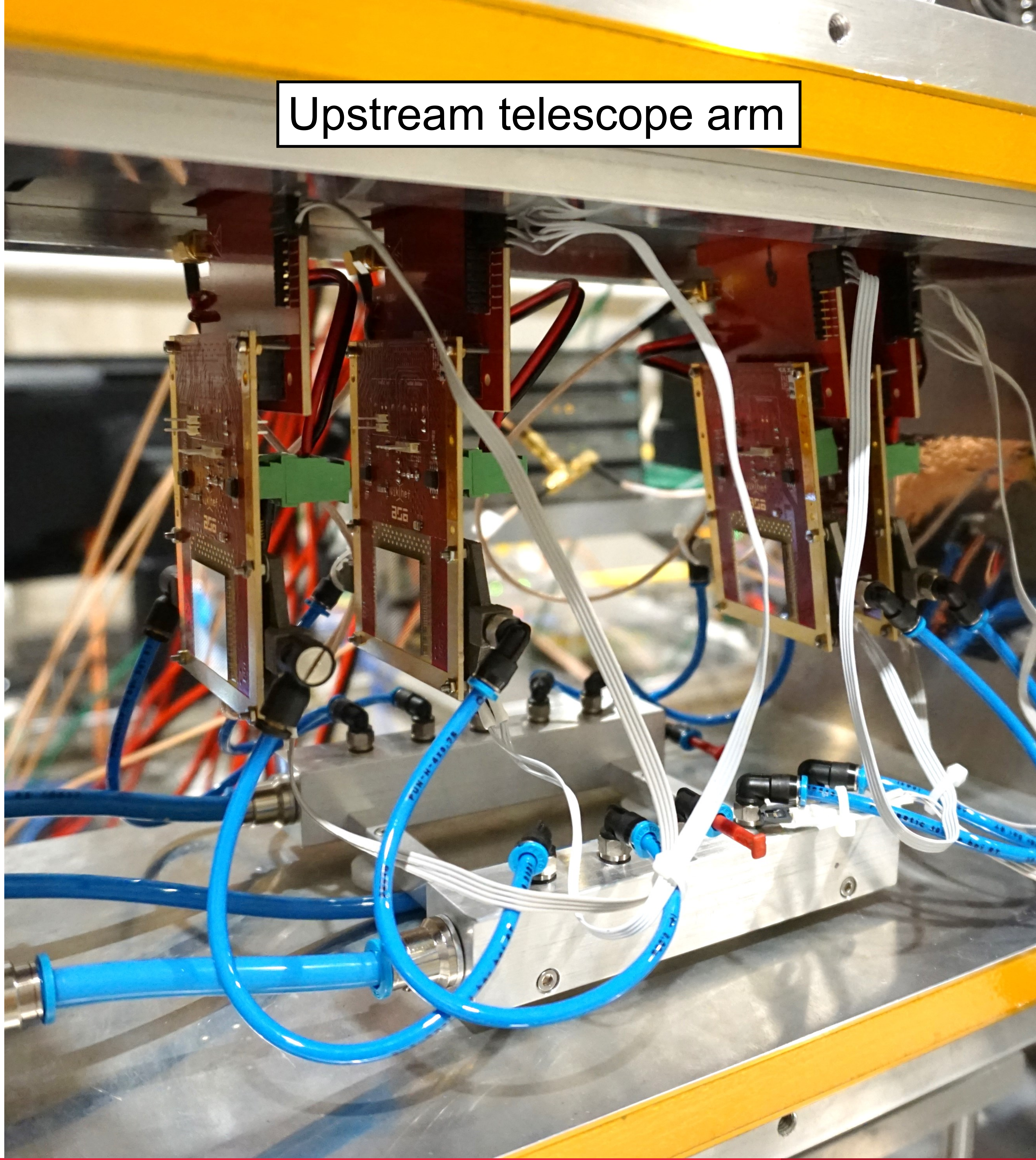




Plane assemblies (all Timepix4v2)

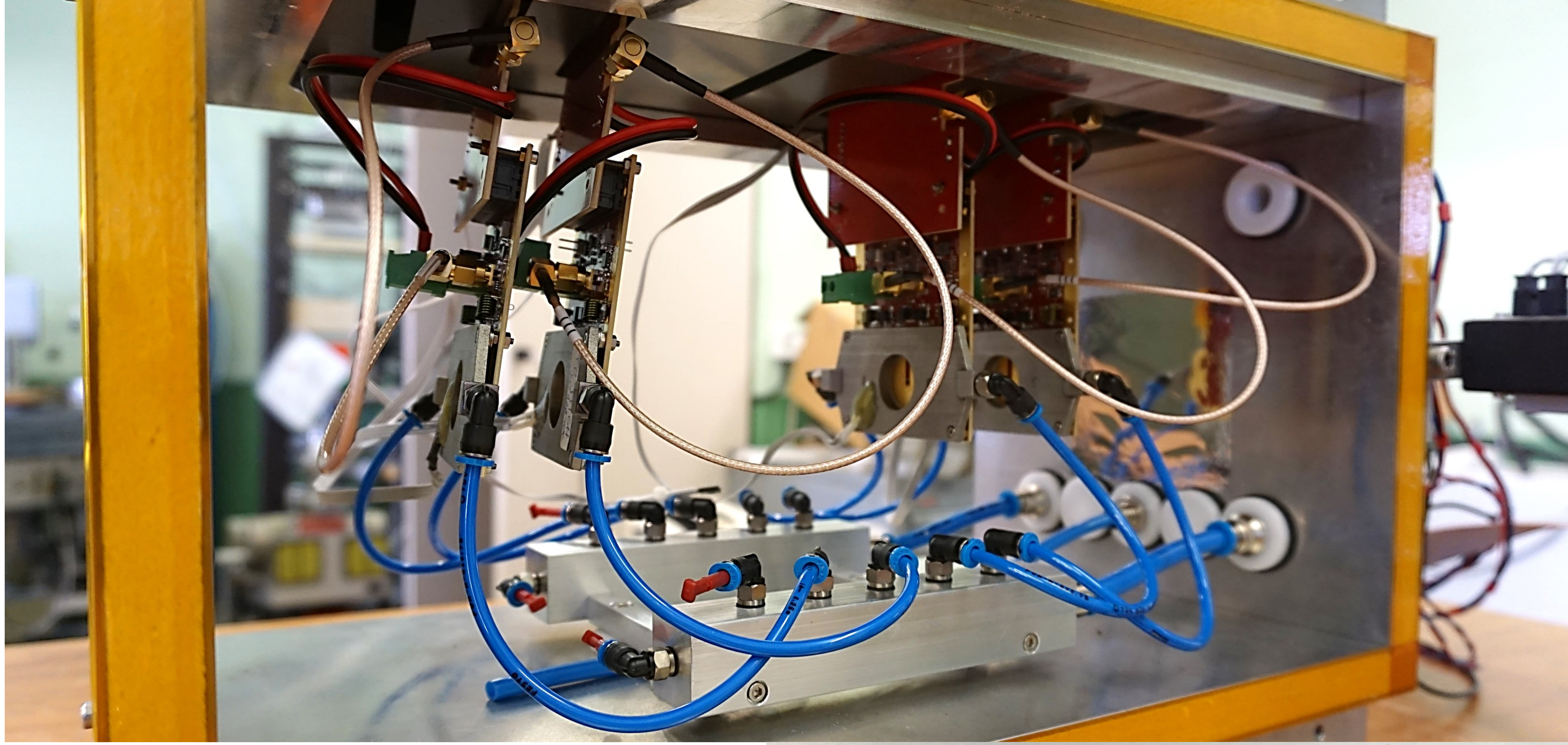
- Eight telescope planes with n-on-p planar silicon sensors:
  - 4 x 300 μm sensors for spatial resolution (angled)
  - 4 x 100 μm sensors for time resolution (perpendicular)
  - Sensor upgrades are anticipated (LGAD, 3D, …)
- Several DUT assemblies:
  - 50 μm, 100 μm, and 200 μm n-on-p planar silicon
  - 300 μm p-on-n
  - 2 x 250 μm iLGAD sensor 55 and 110 μm pitch (Tpx3 sized)



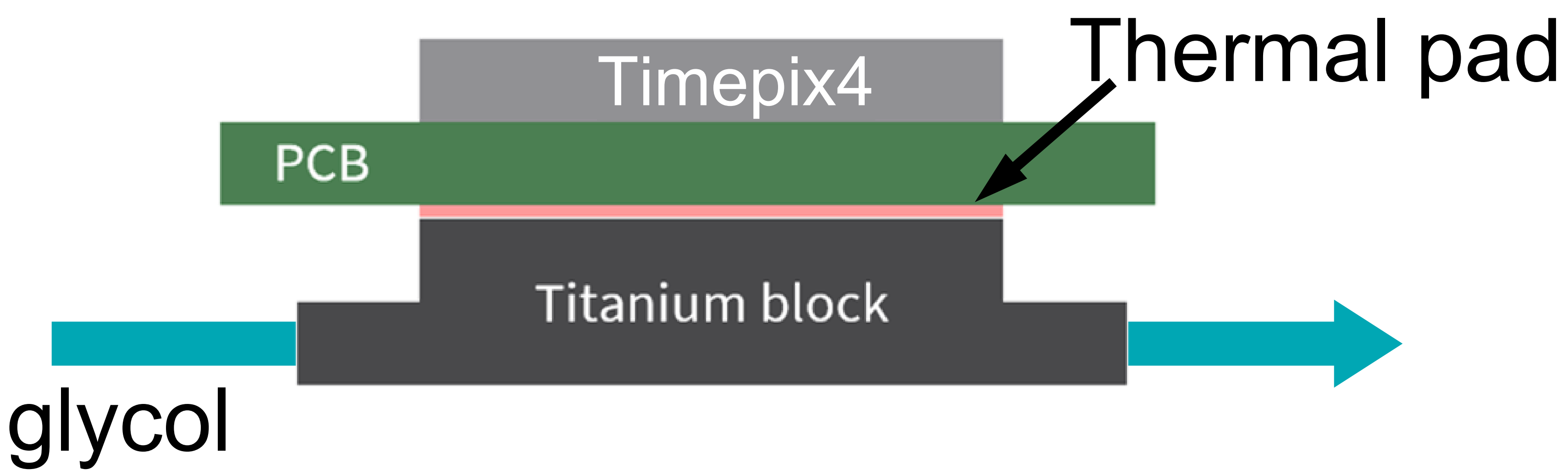


Assembly cooling

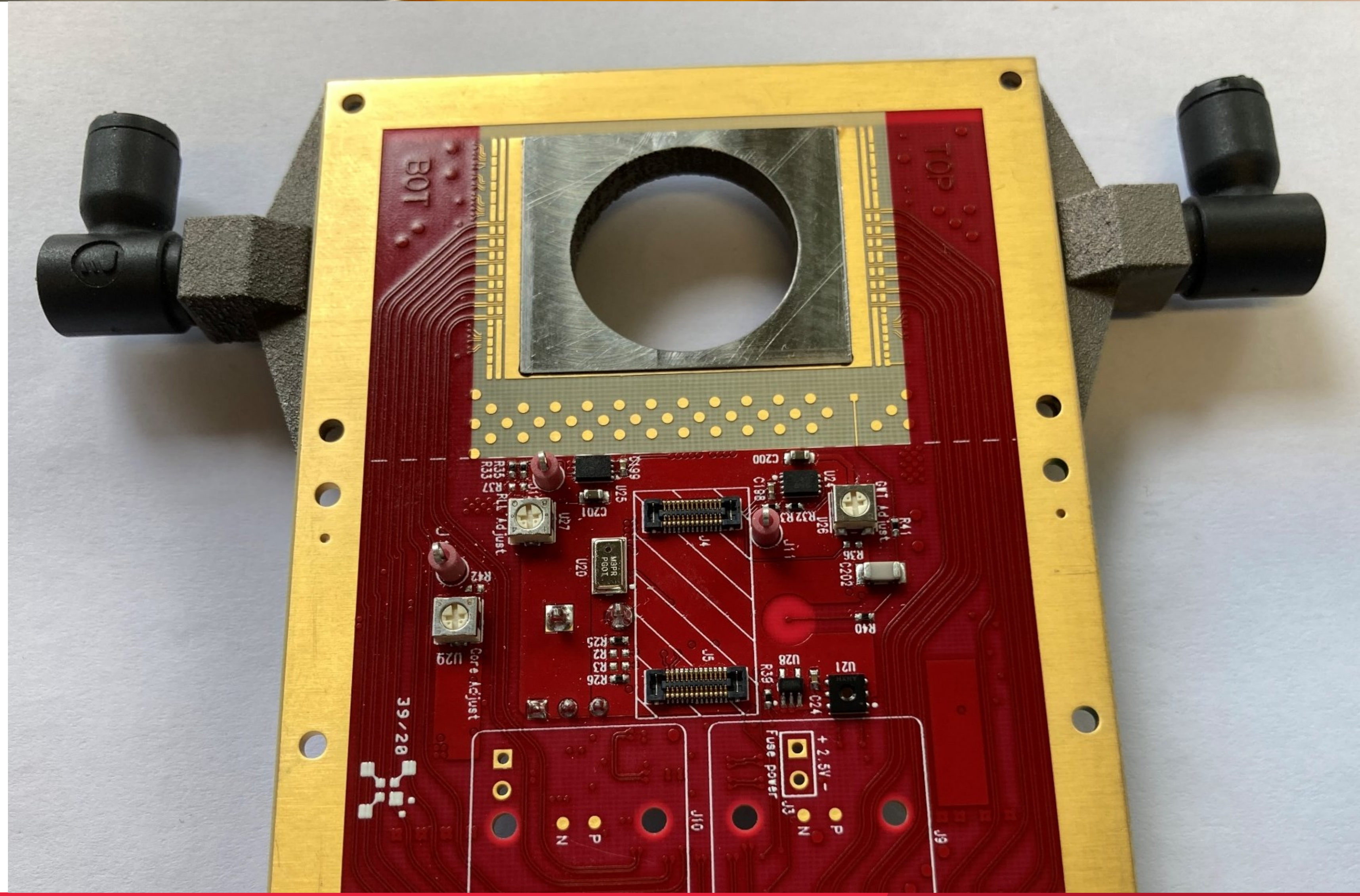
- All assemblies have a 3D-printed titanium cooling block
- Cooled using glycol at 20 °C
- Could go to –20 °C in the future
- Plan to mill PCB to have direct thermal contact with Timepix4



Current thermal interface

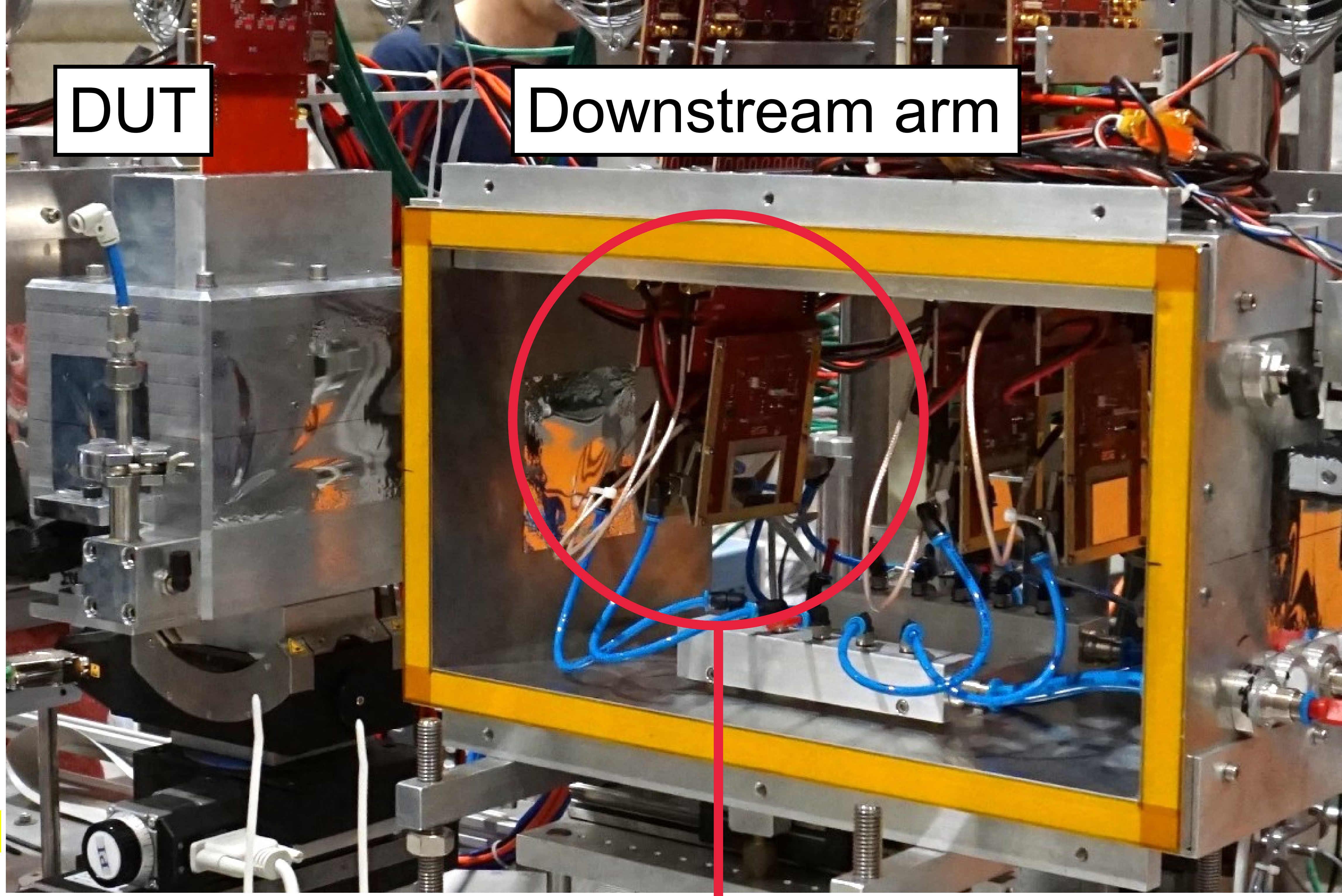


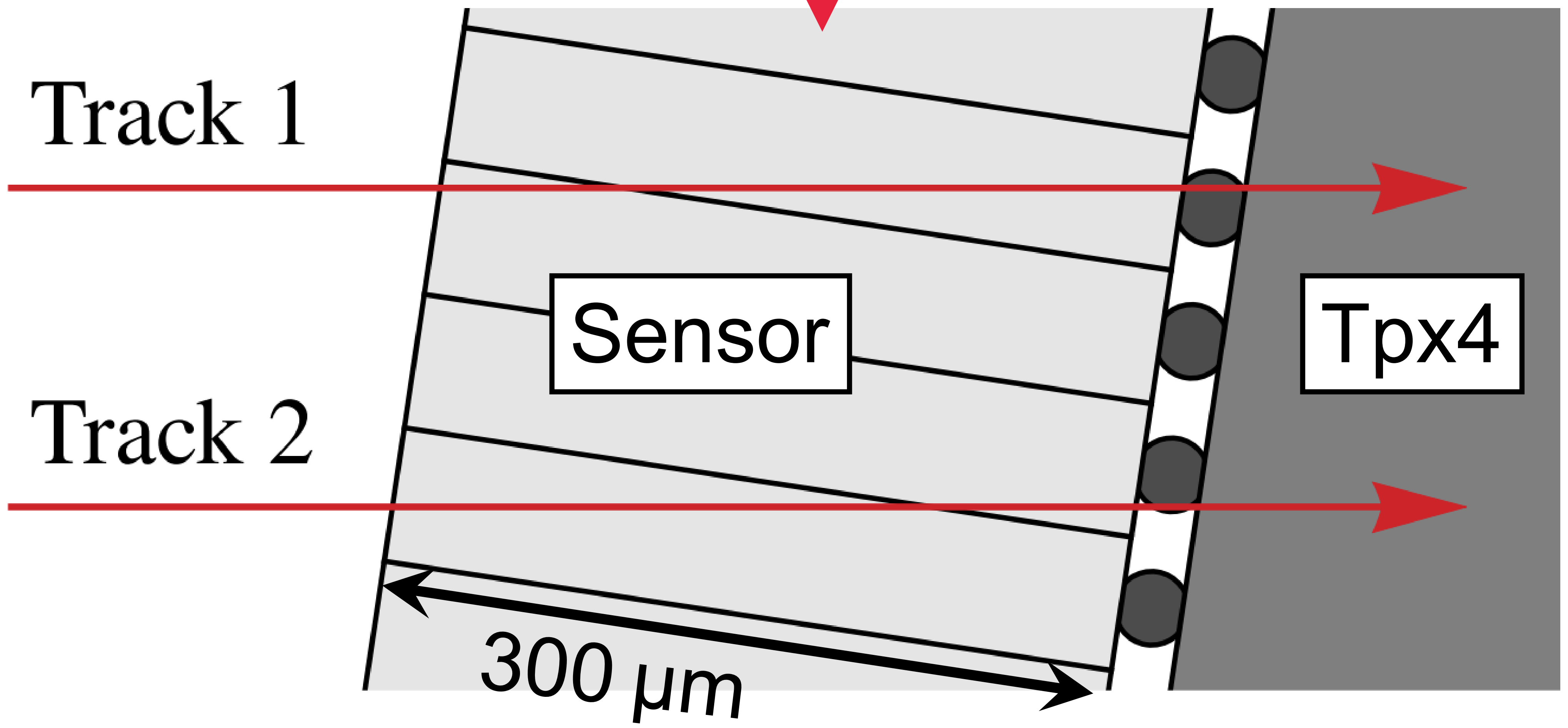
Future thermal interface

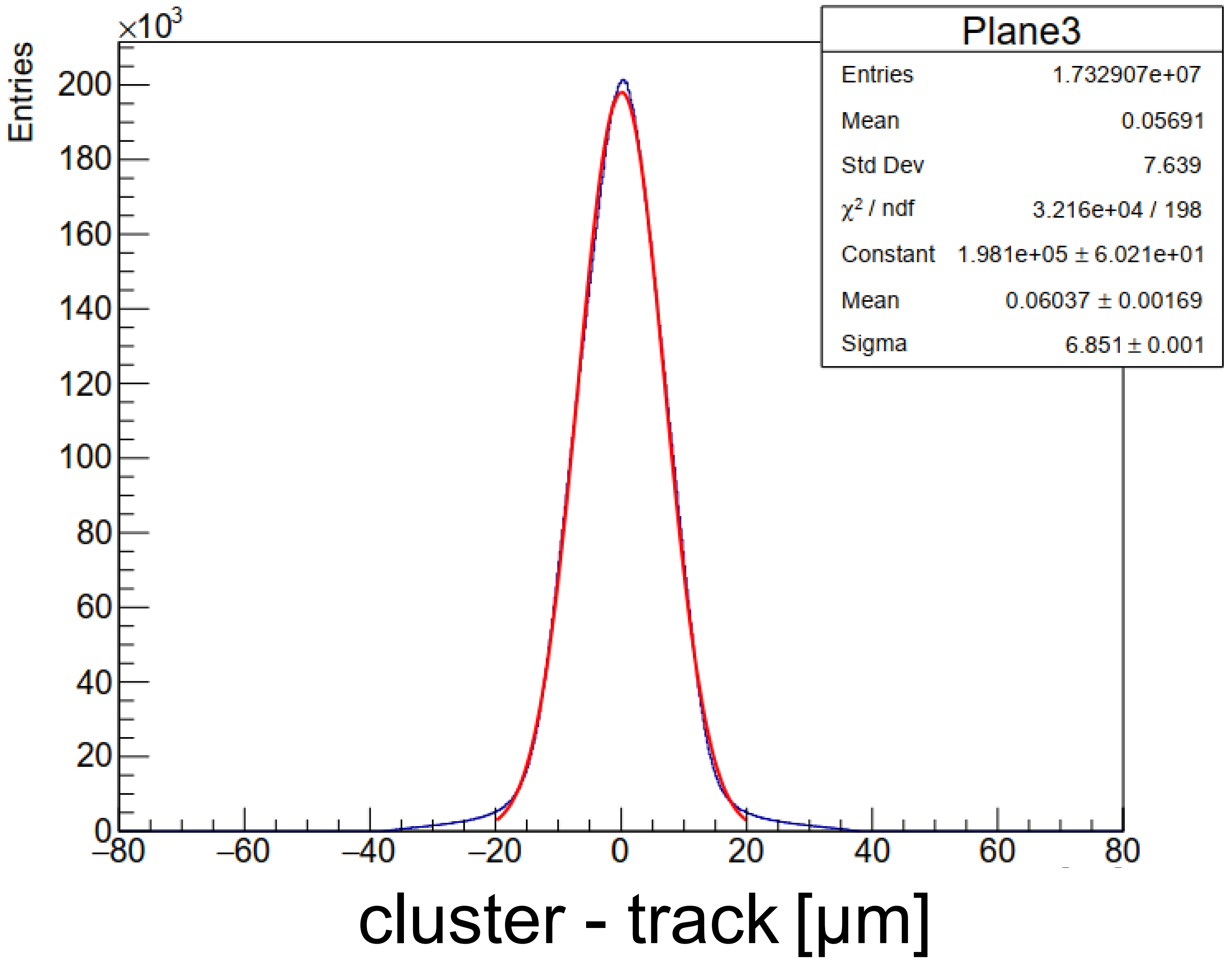


Spatial resolution

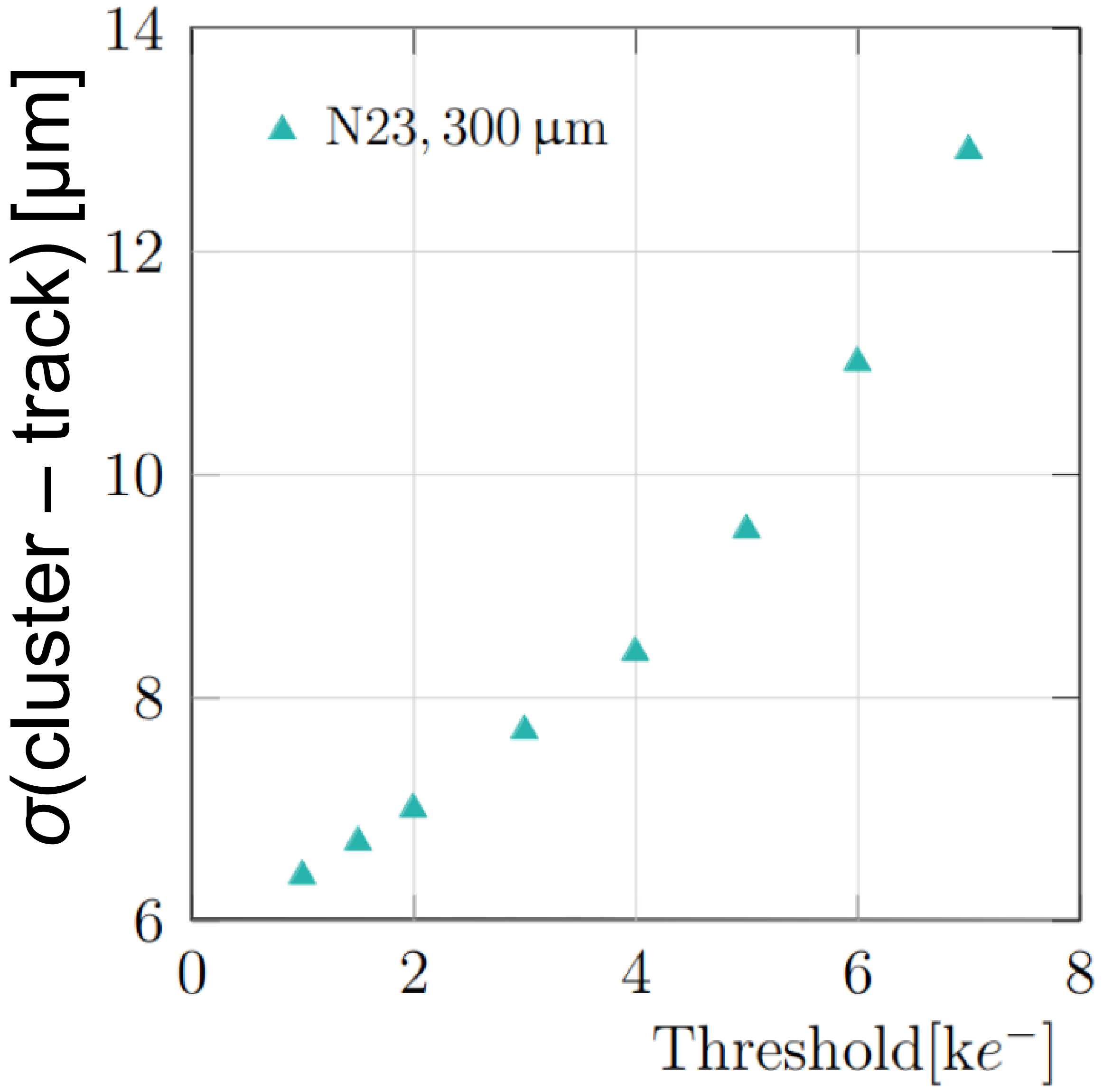
- Pixel size 55 µm × 55 µm
- Four innermost planes rotated 9° around x and y to induce charge sharing between pixels
- Charge-weighted mean gives cluster position
- Single plane resolution: **4.3 µm**
- Resolution depends on detection threshold







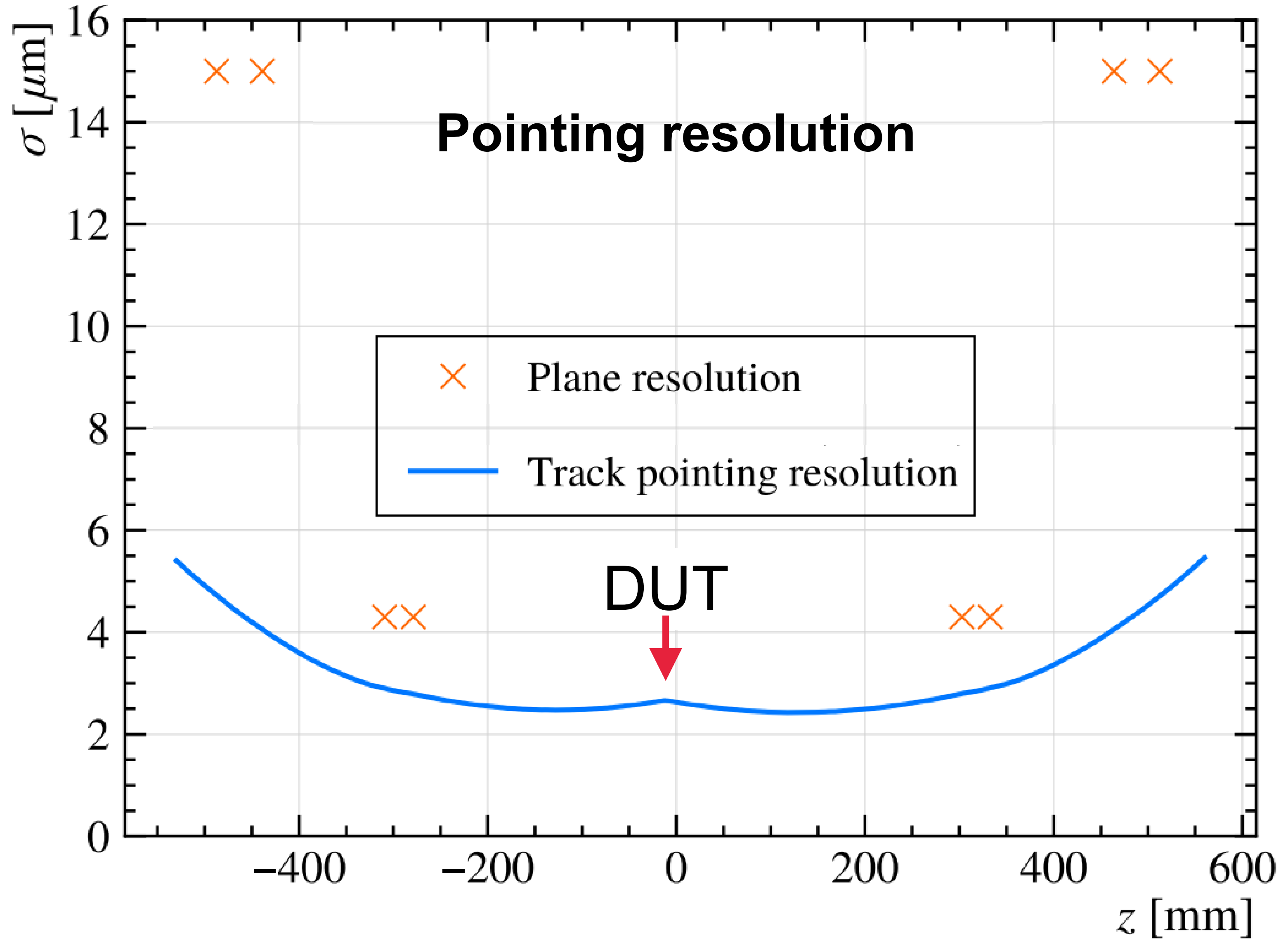
K. Akiba *et al* 2023 *JINST* **18** P02011
[DOI: 10.1088/1748-0221/18/02/P02011]

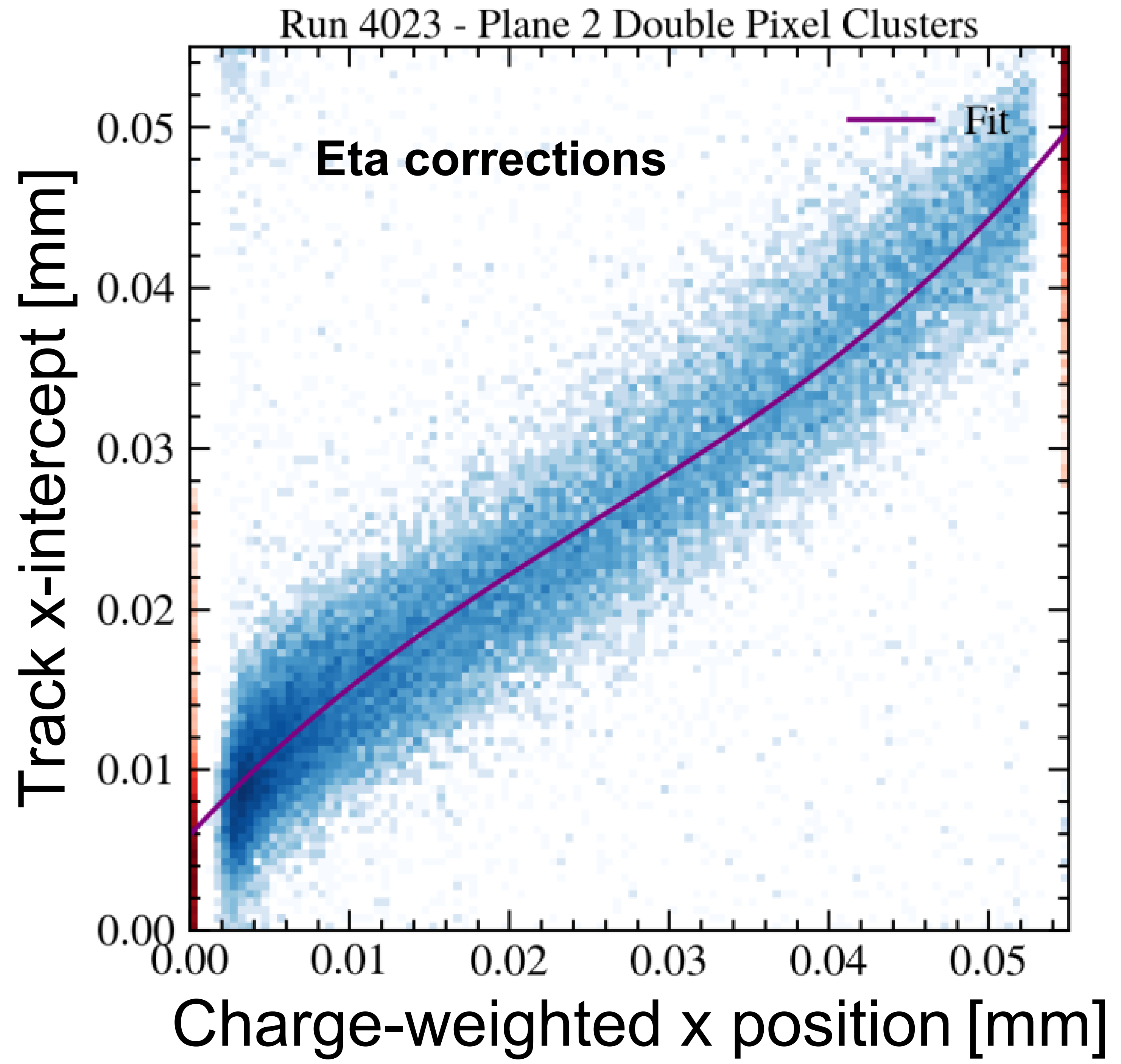


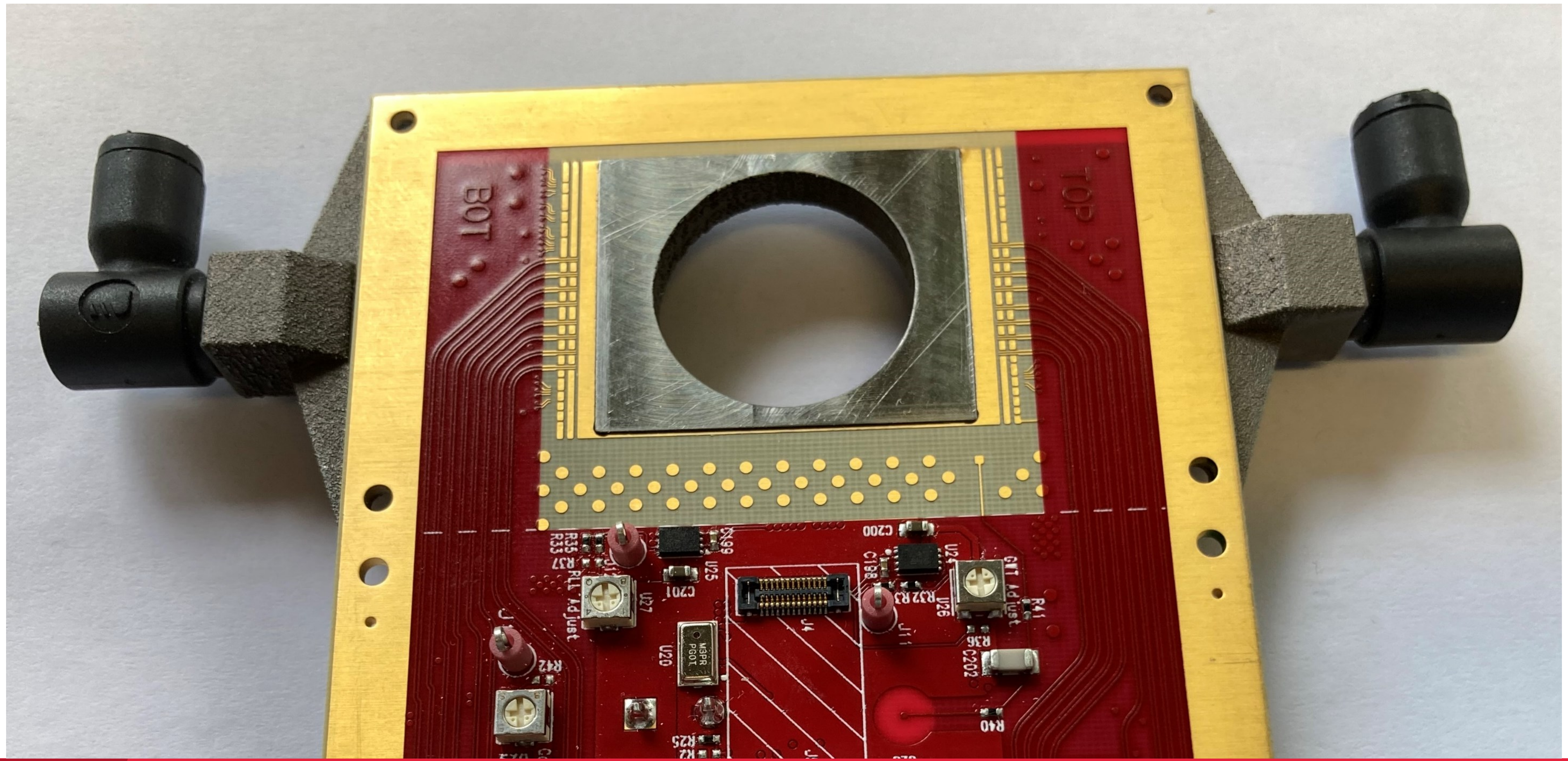
Track pointing resolution

- Pointing resolution at DUT: **2.7 µm** (Mixed hadron beam 180 GeV/c)
- PCB adds 1.8 $\%X_0$ (ASIC + sensor adds 0.8–1.0 $\%X_0$)
- Milling out PCB would improve resolution to **2.2 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 planes

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



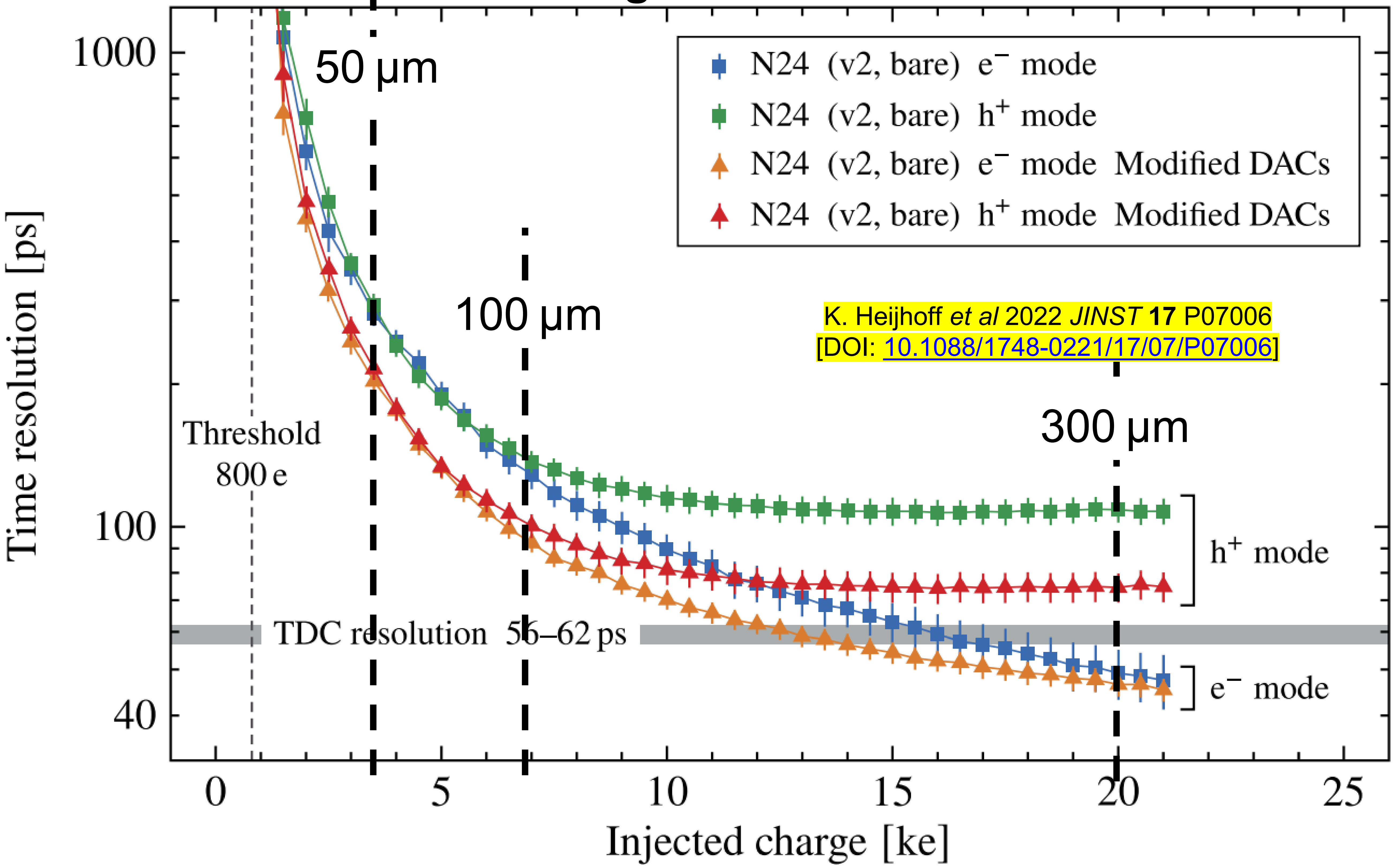




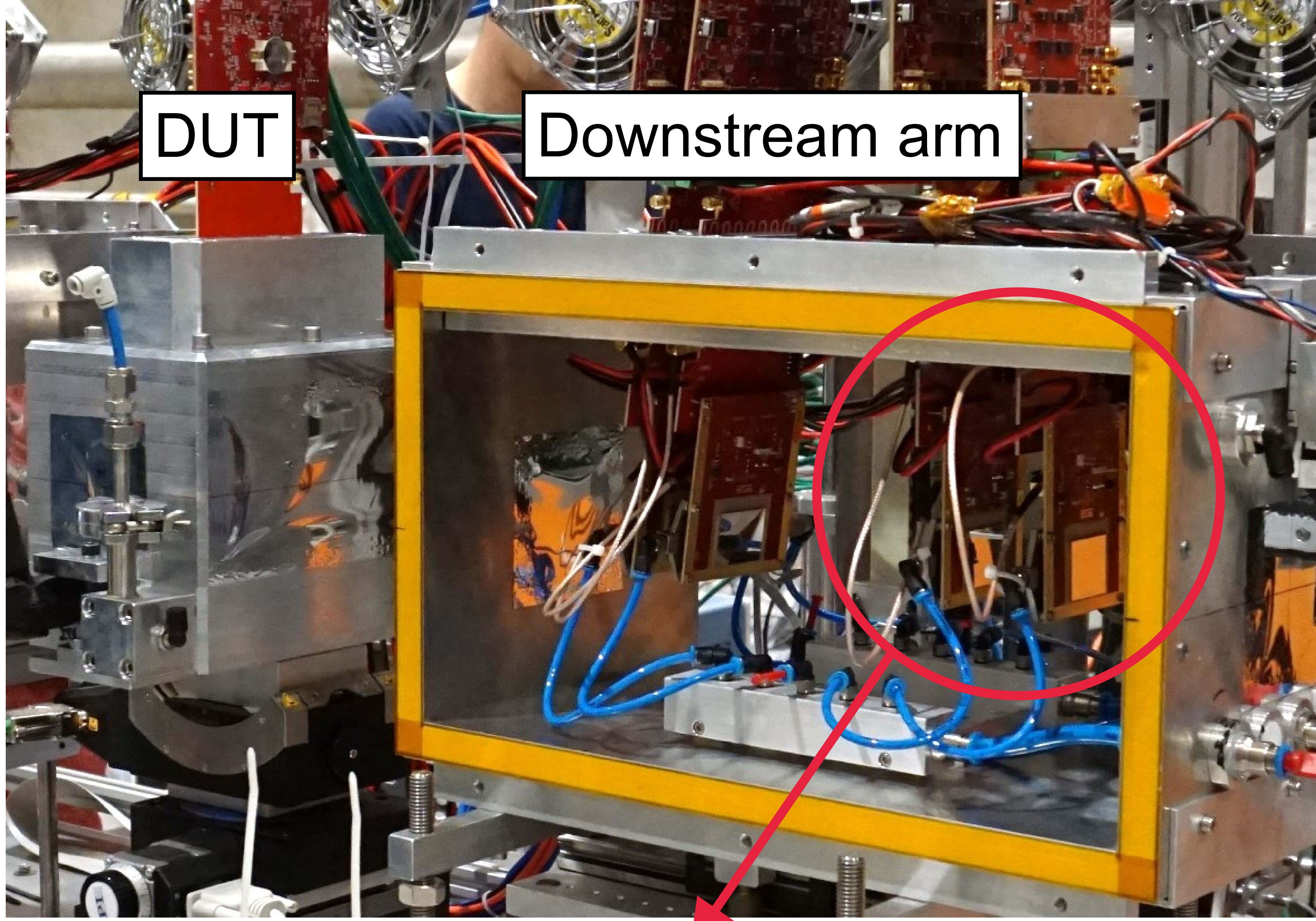
Time resolution

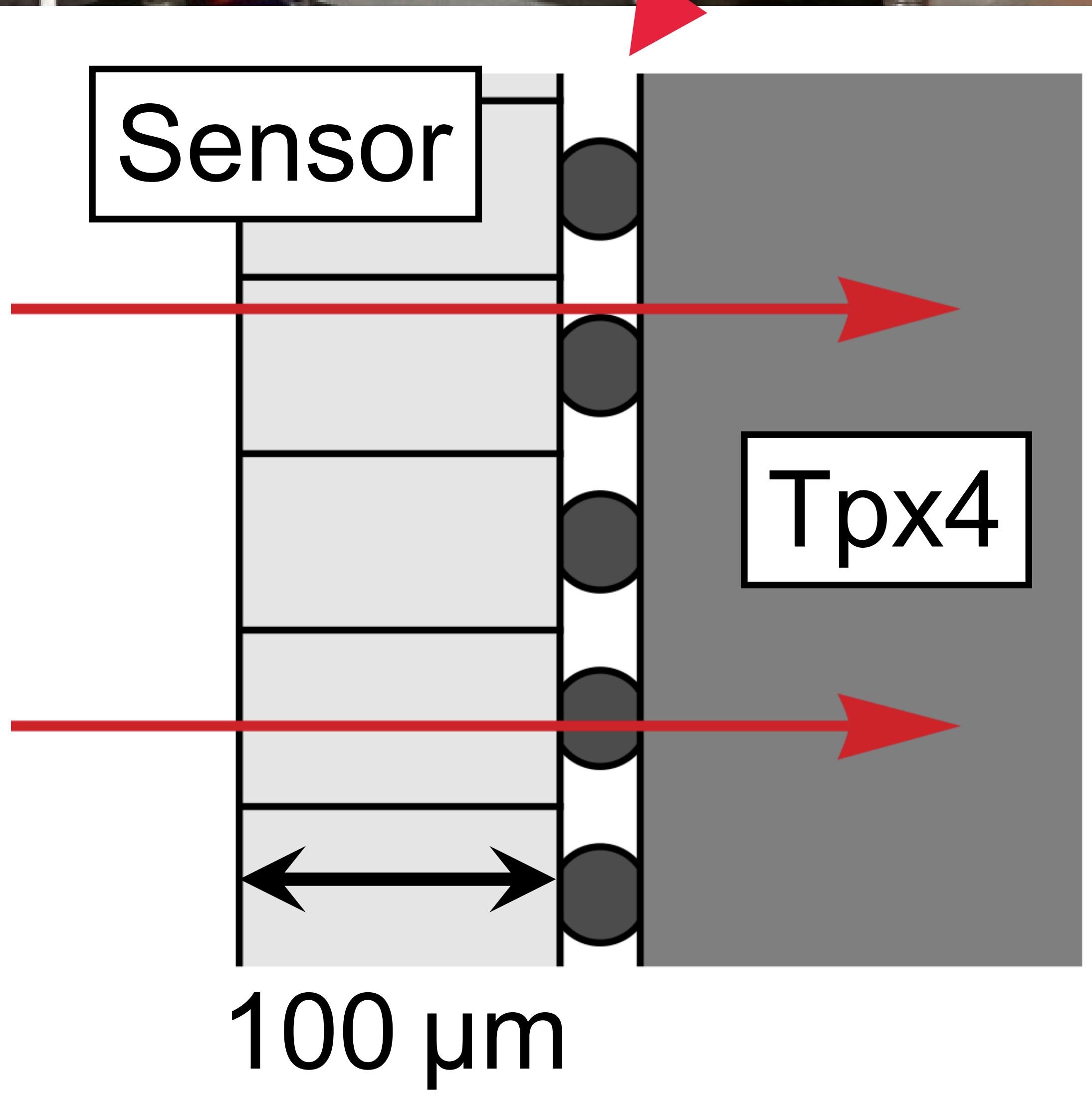
- Thin sensors reduce time errors due to Landau fluctuations
- Perpendicular to beam to maximise signal charge in single pixel
- Reduced signal size reduces analog front-end performance

Analog front-end resolution



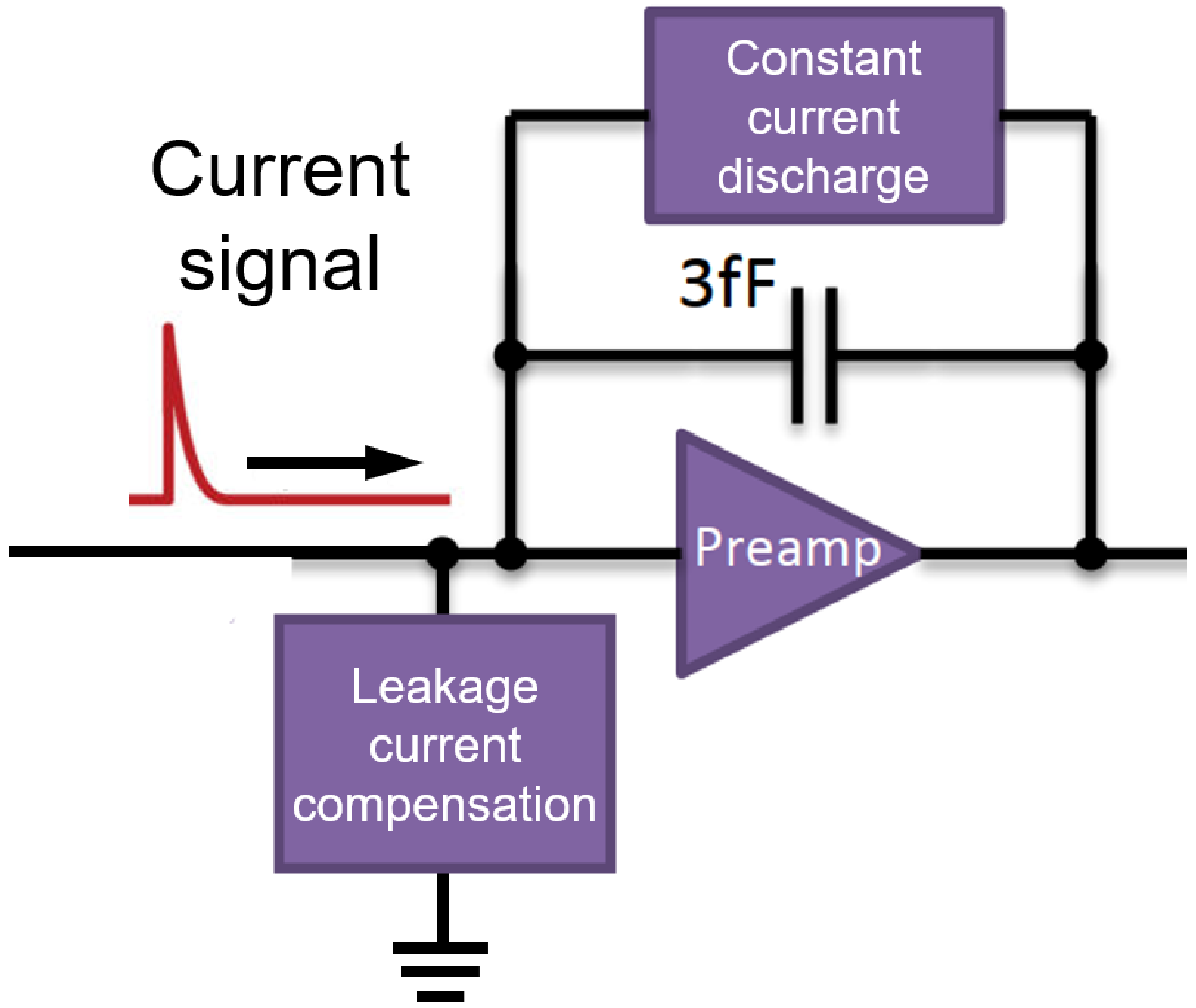
K. Heijhoff *et al* 2022 *JINST* **17** P07006
[DOI: 10.1088/1748-0221/17/07/P07006]

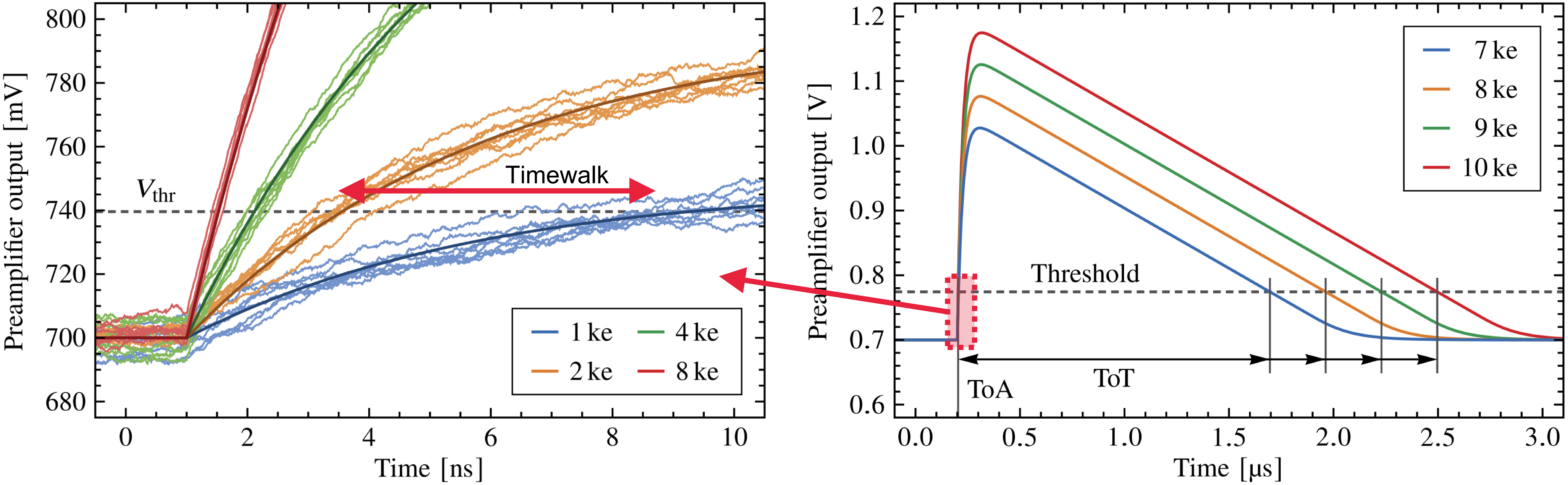




Timewalk

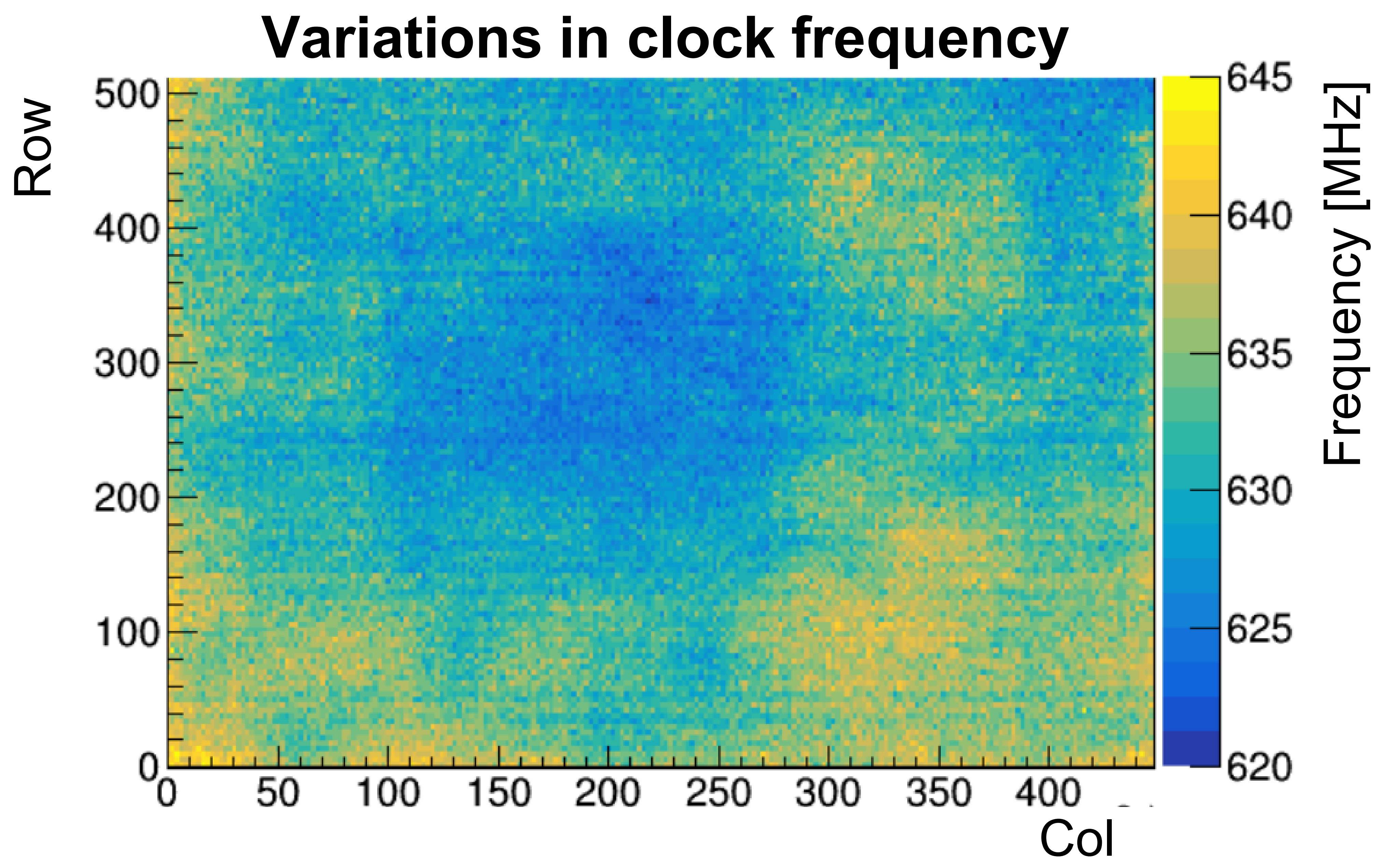
- Time measurement depends on signal size
- Preamplifier output has a fixed risetime
- Reduced signal size makes timewalk corrections crucial

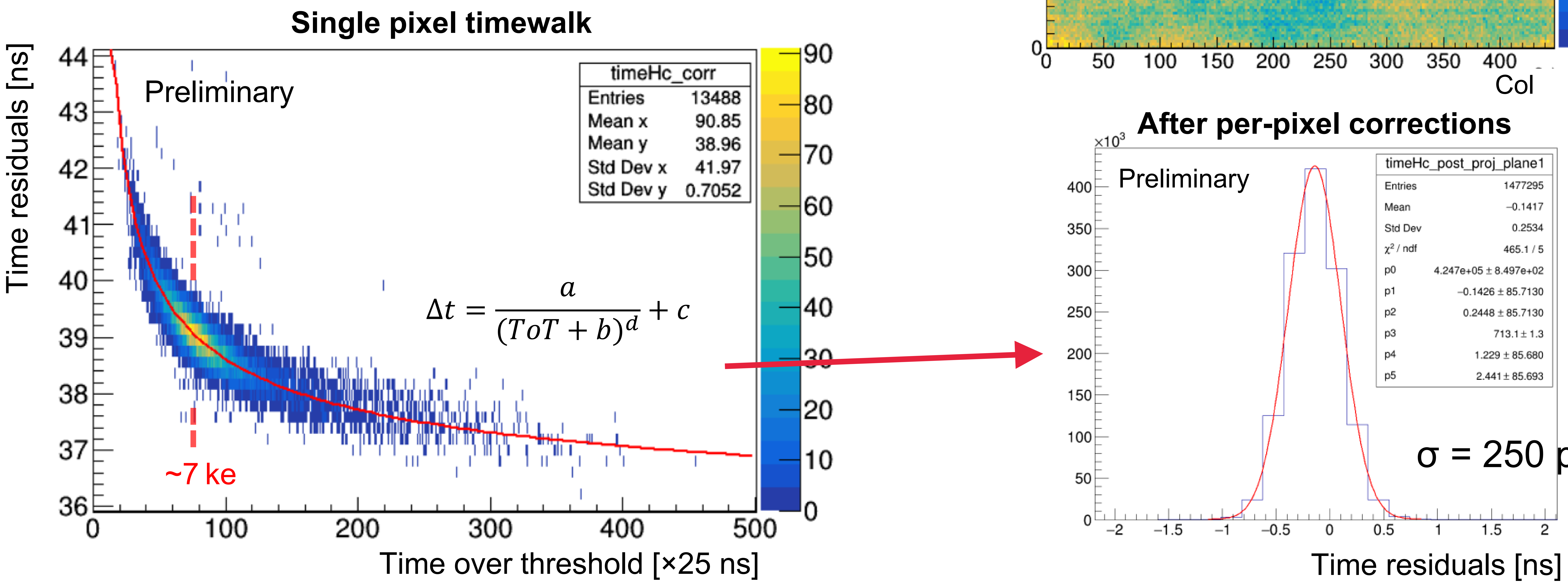




Time resolution

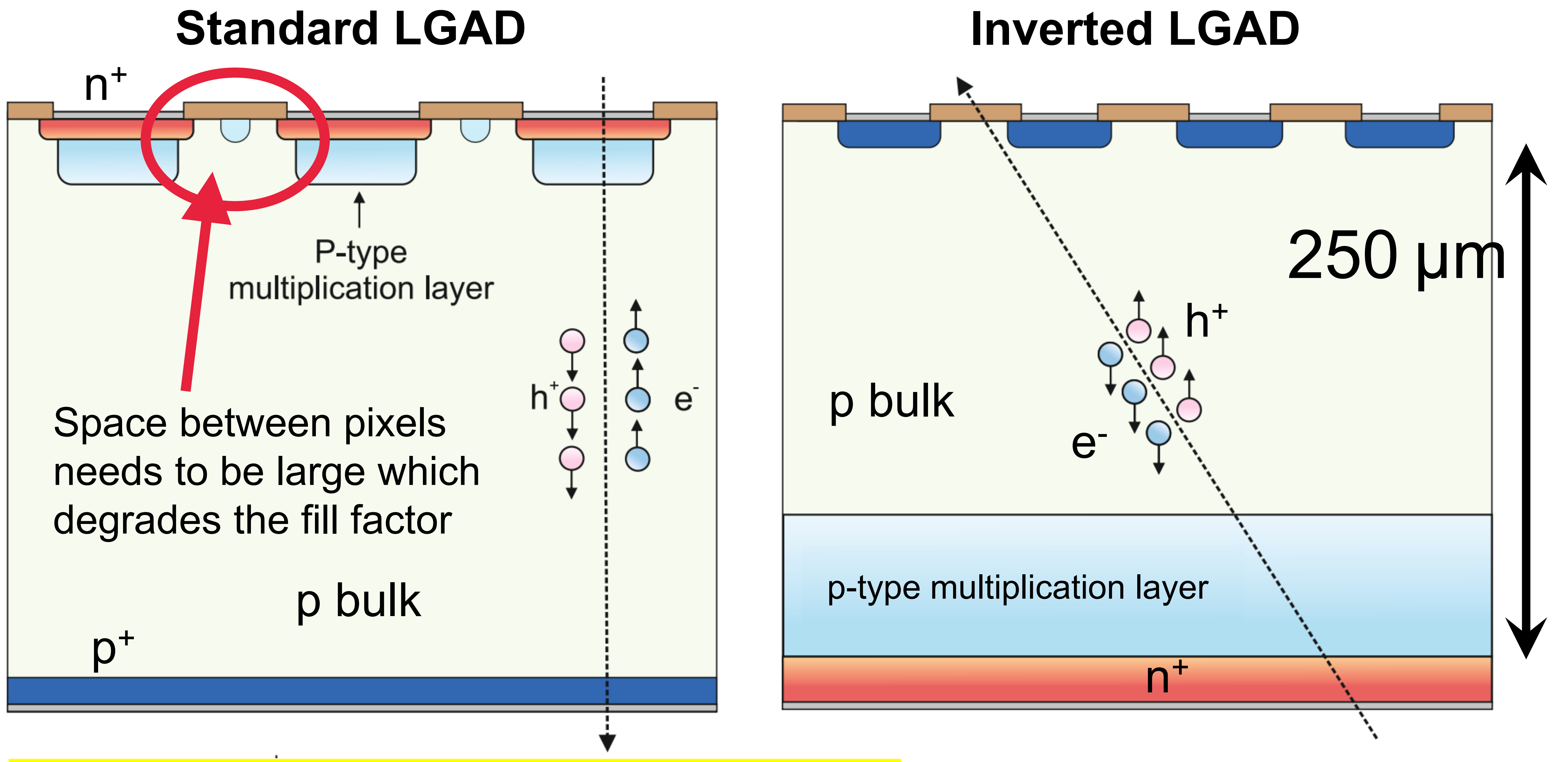
- Working on per-pixel timewalk corrections
- Current cluster-time resolution: ~250 ps
- Expected track-time resolution with 4 planes: ~130 ps
- Working on clock corrections to improve further



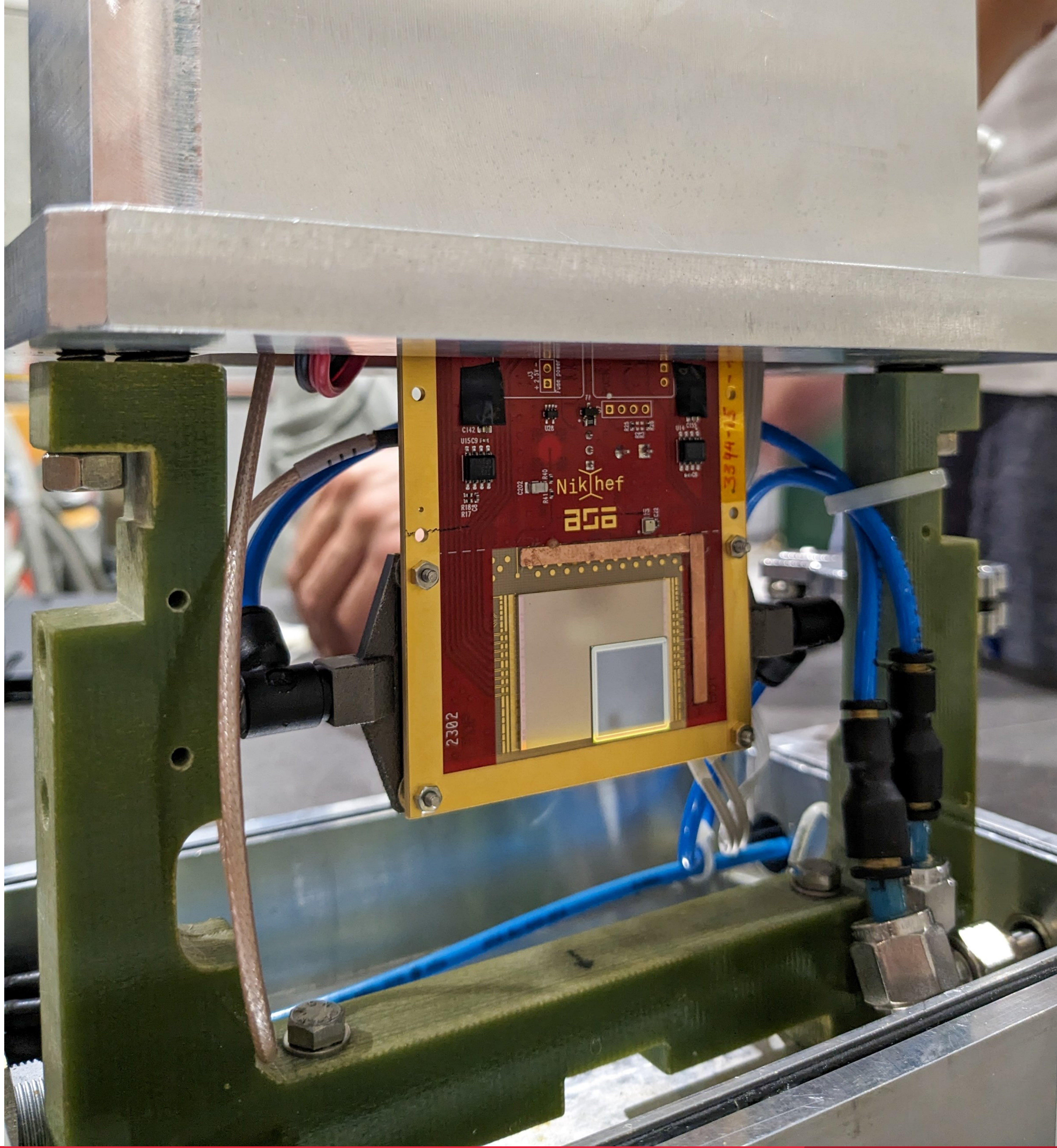


Inverted LGAD on Timepix4 as DUT

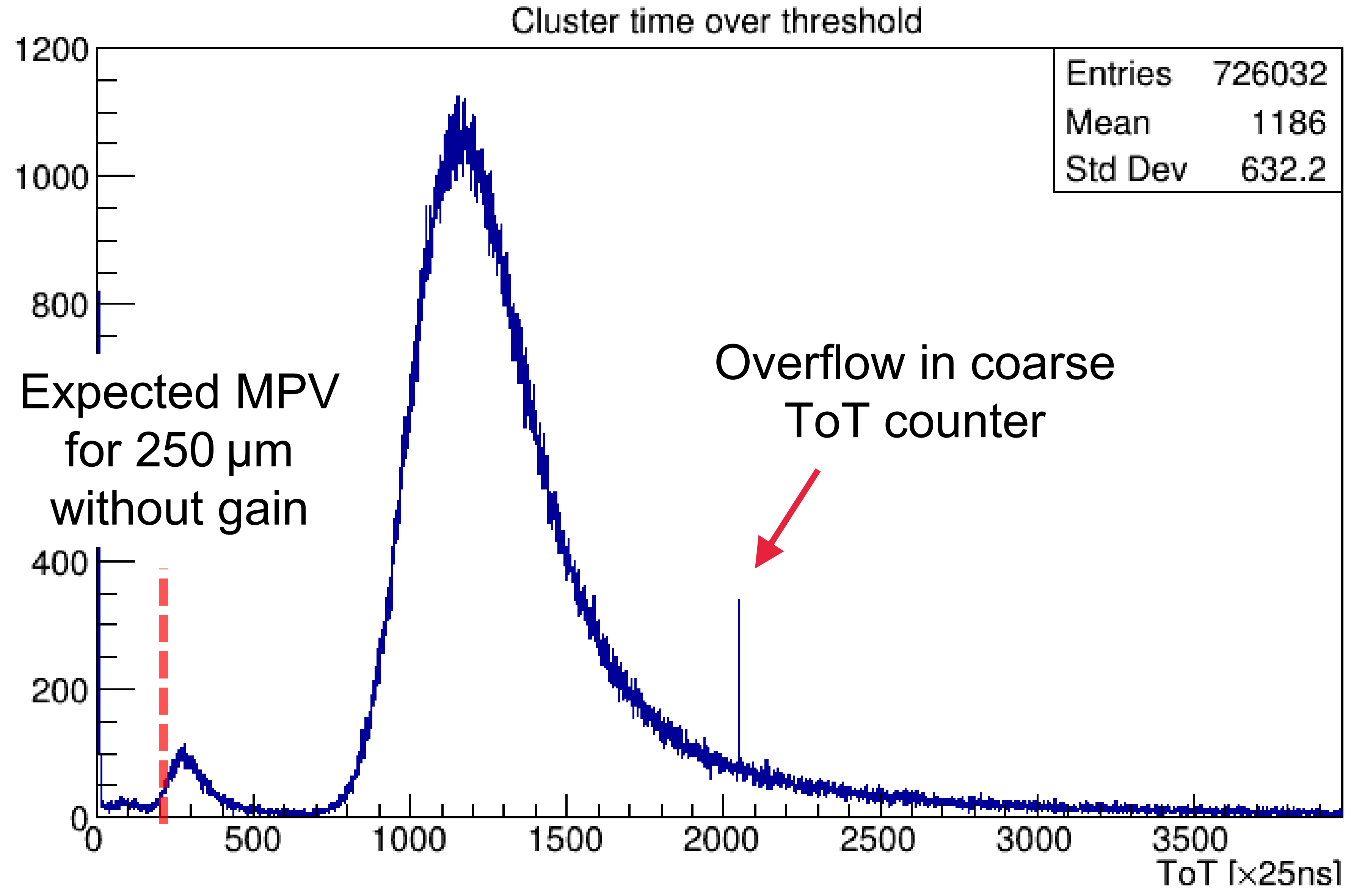
- Low-gain avalanche diodes (LGADs) use charge multiplication to deliver larger input signals
- Small pixel size cannot be achieved in standard LGAD technology (without losing efficiency)
- Inverted LGADs (iLGADs) solve this by placing the gain layer on the backside
- Sensors produced by Micron and provided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

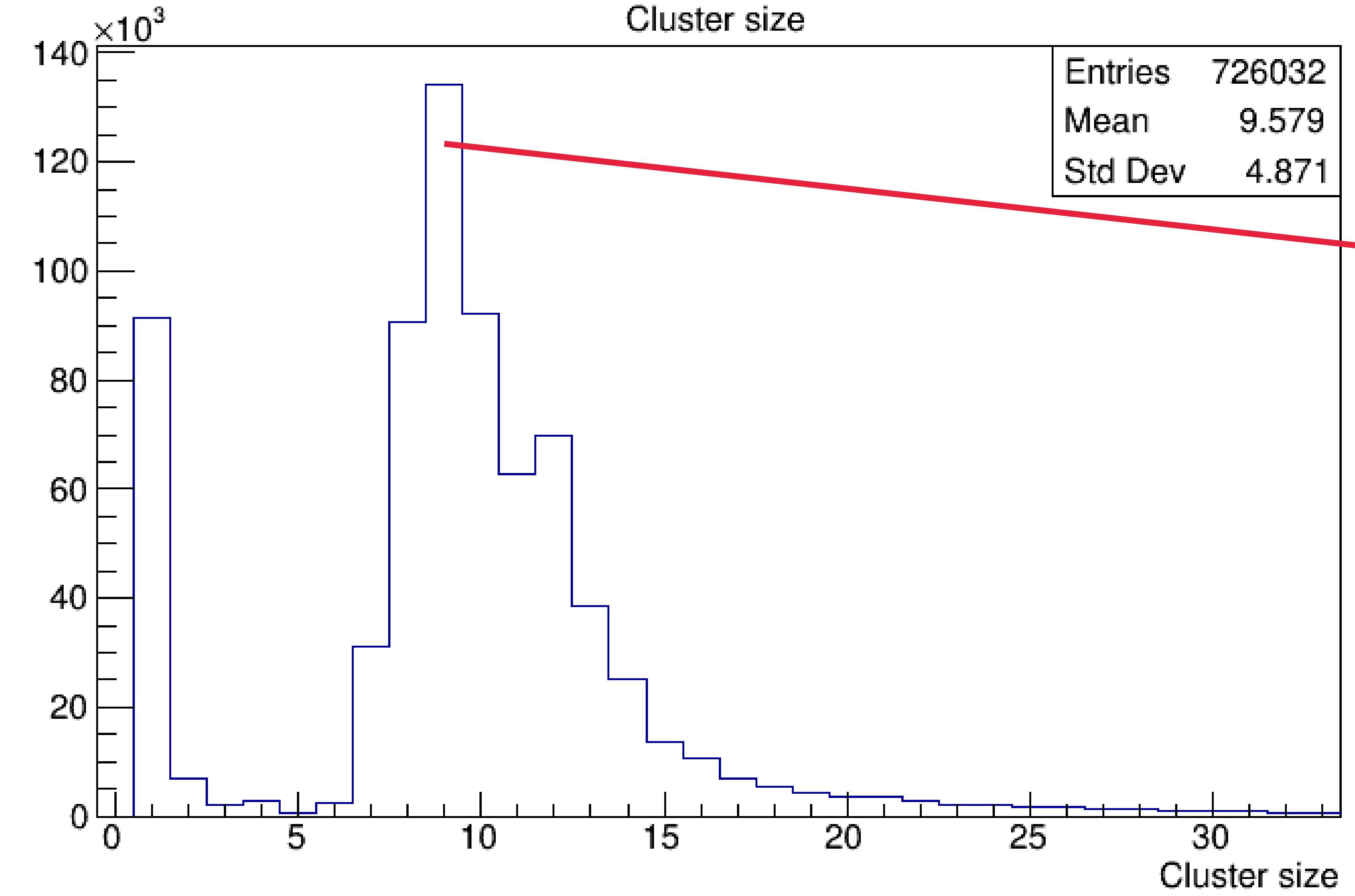


A. Doblas *et al Sensors* **2023**, 23, 3450 [DOI: 10.3390/s23073450]

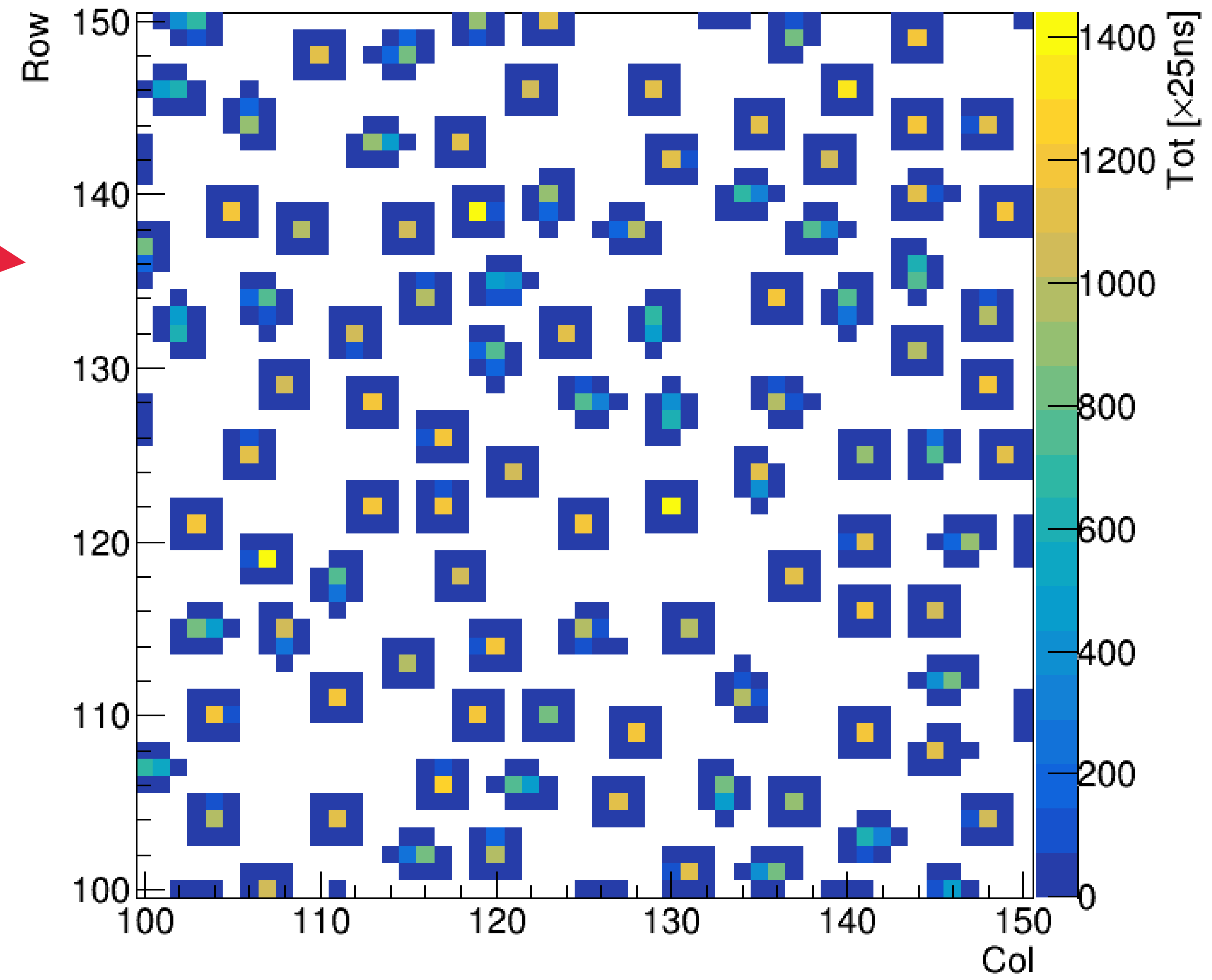


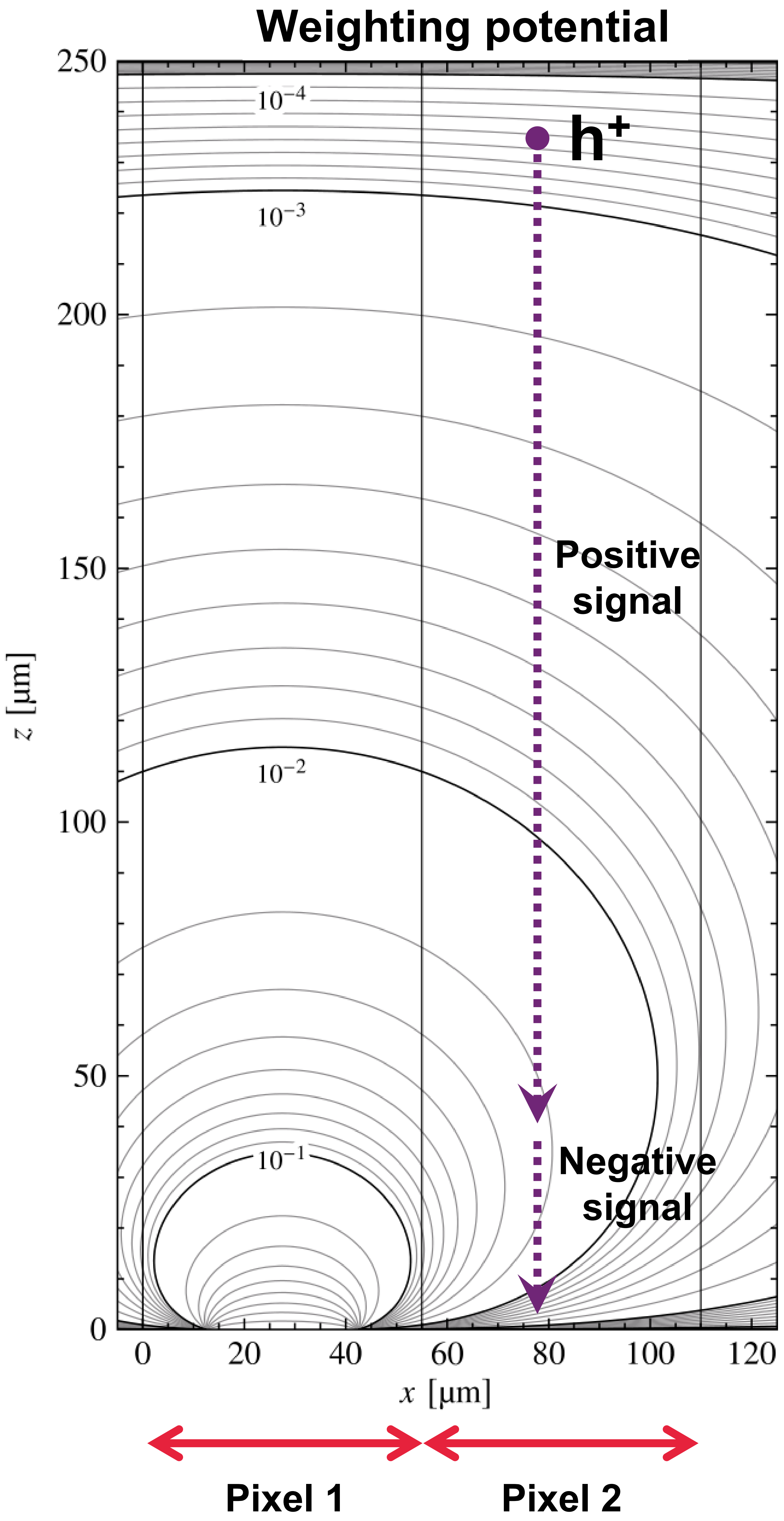
Inverted LGAD on Timepix4 as DUT (first glance)





- Analysis not yet started
- 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

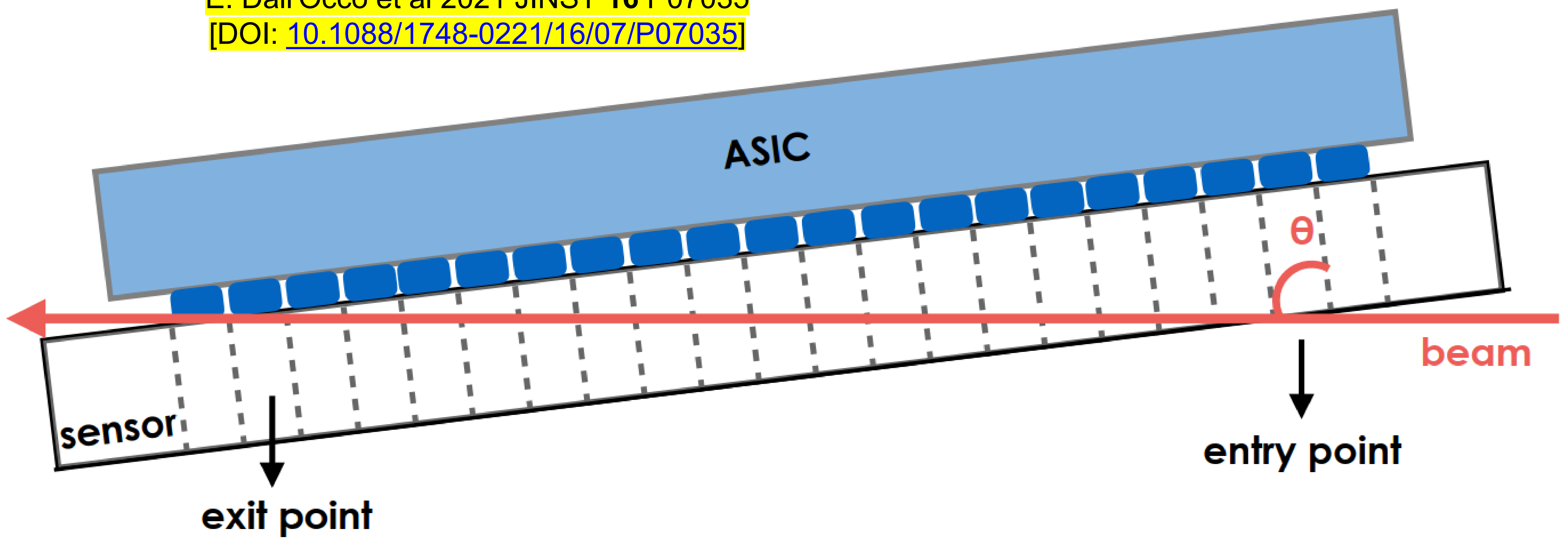


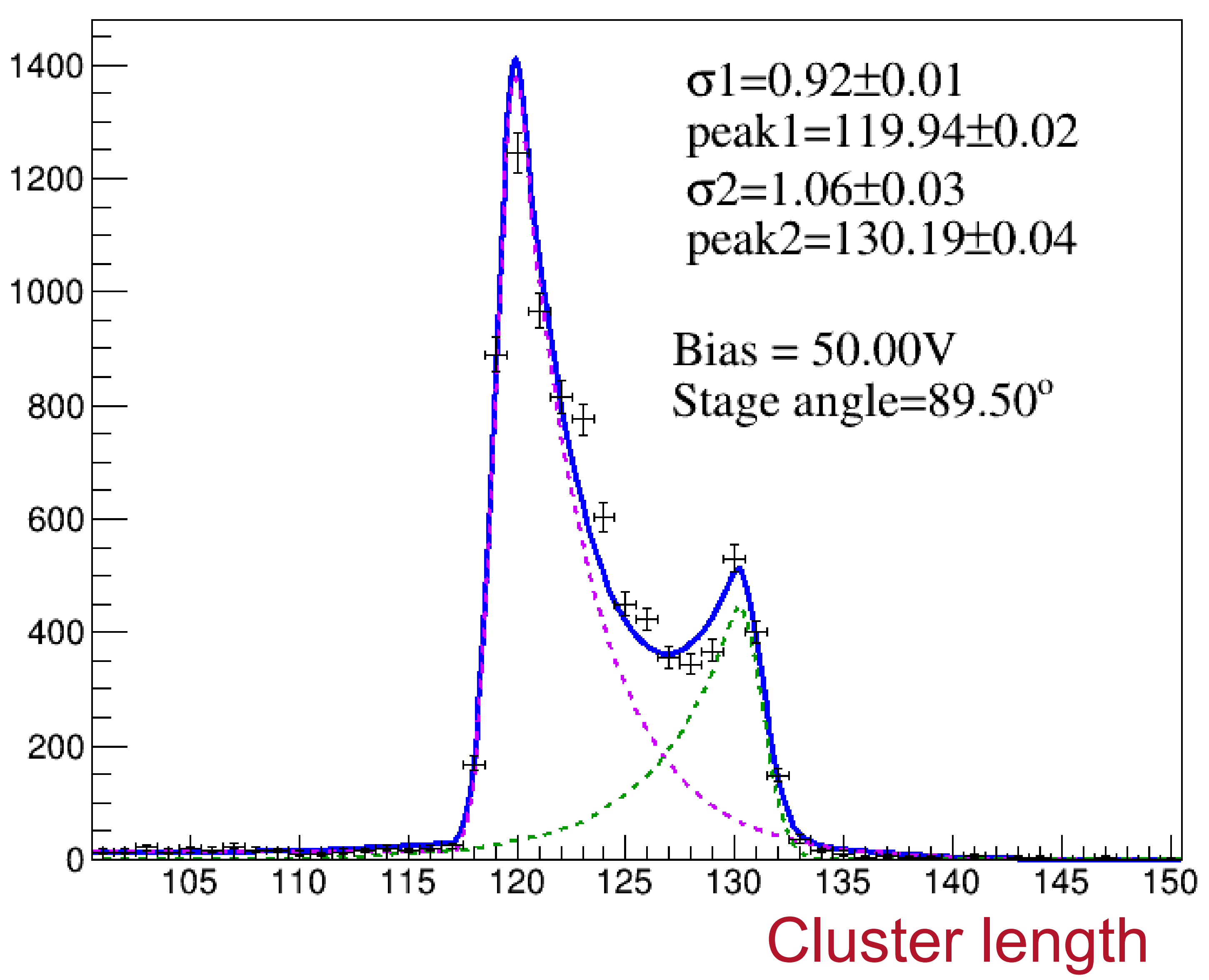


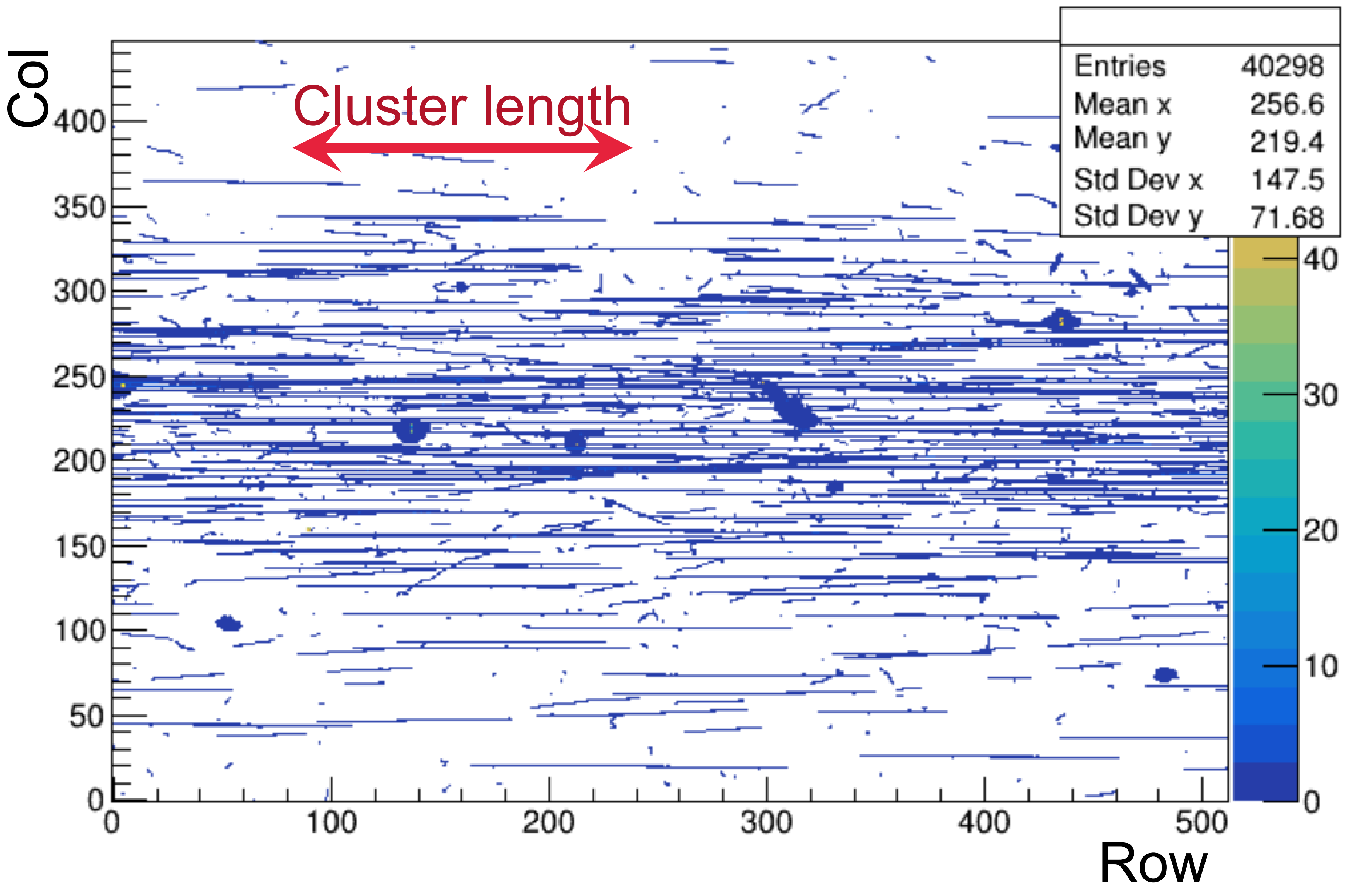
Grazing angle measurements

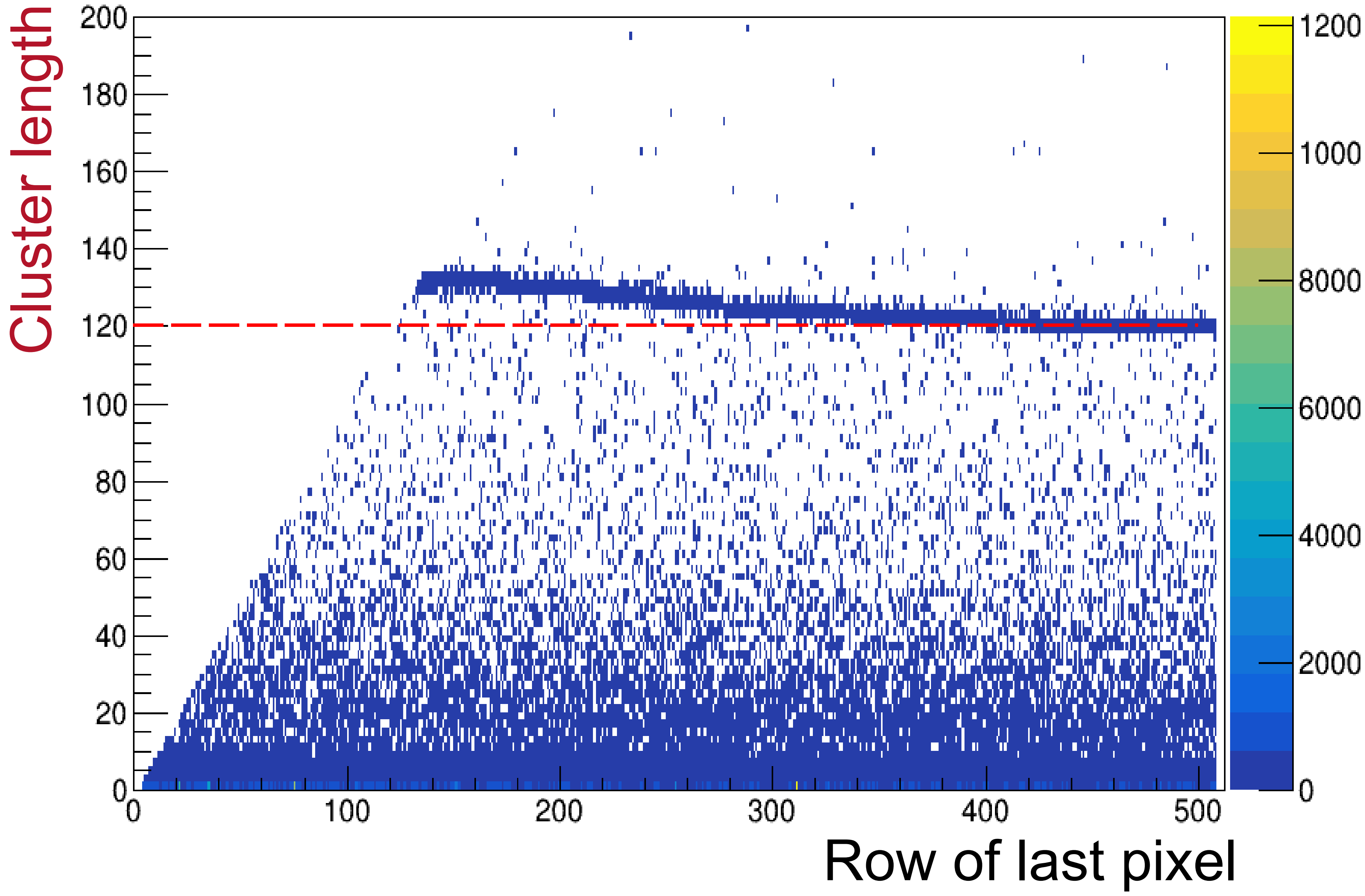
- Grazing angle measurements probe different depths of the sensor
- Can be used to determine thickness by measuring cluster length at various angles
- Sensors are thin, but not flat

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



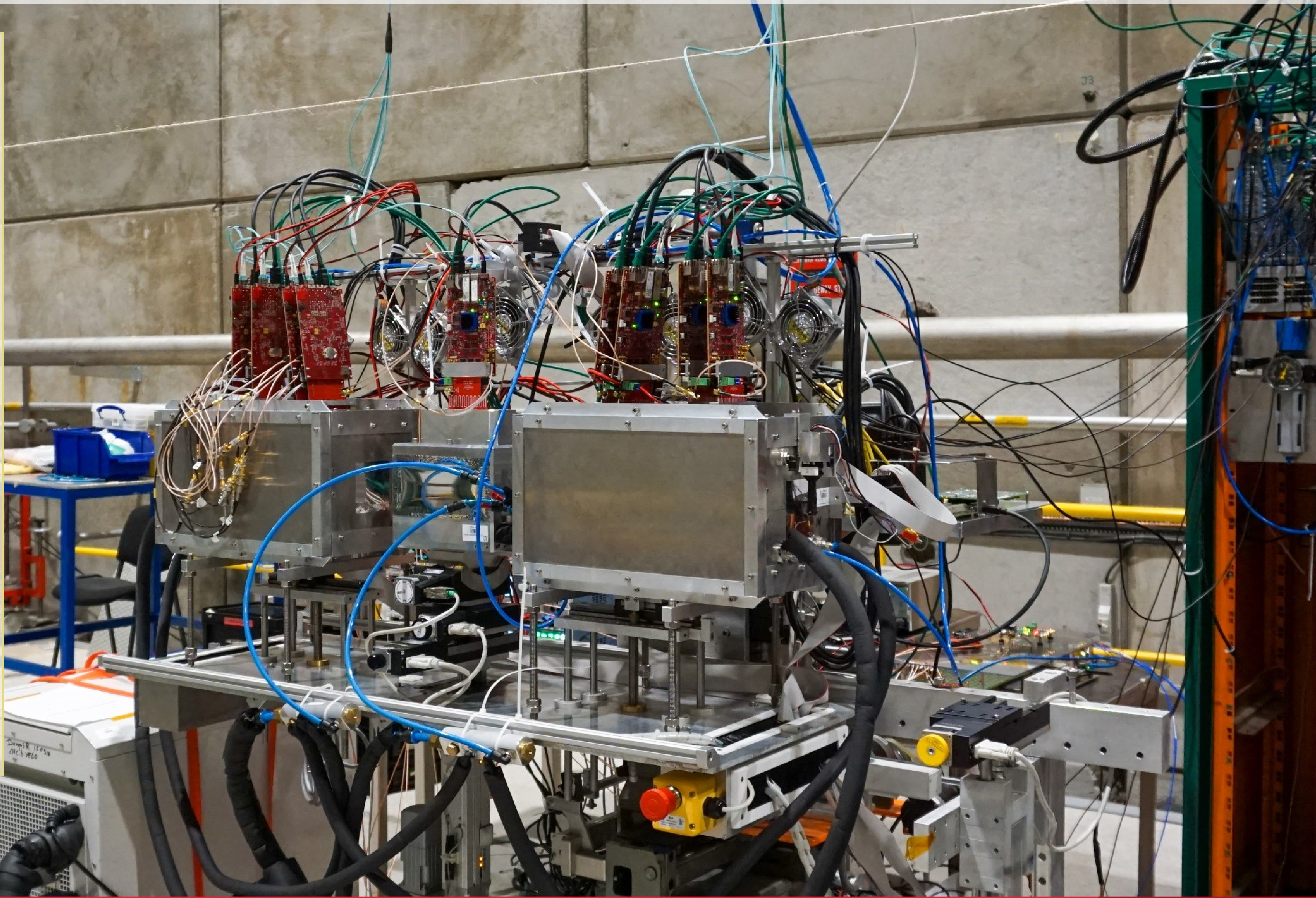






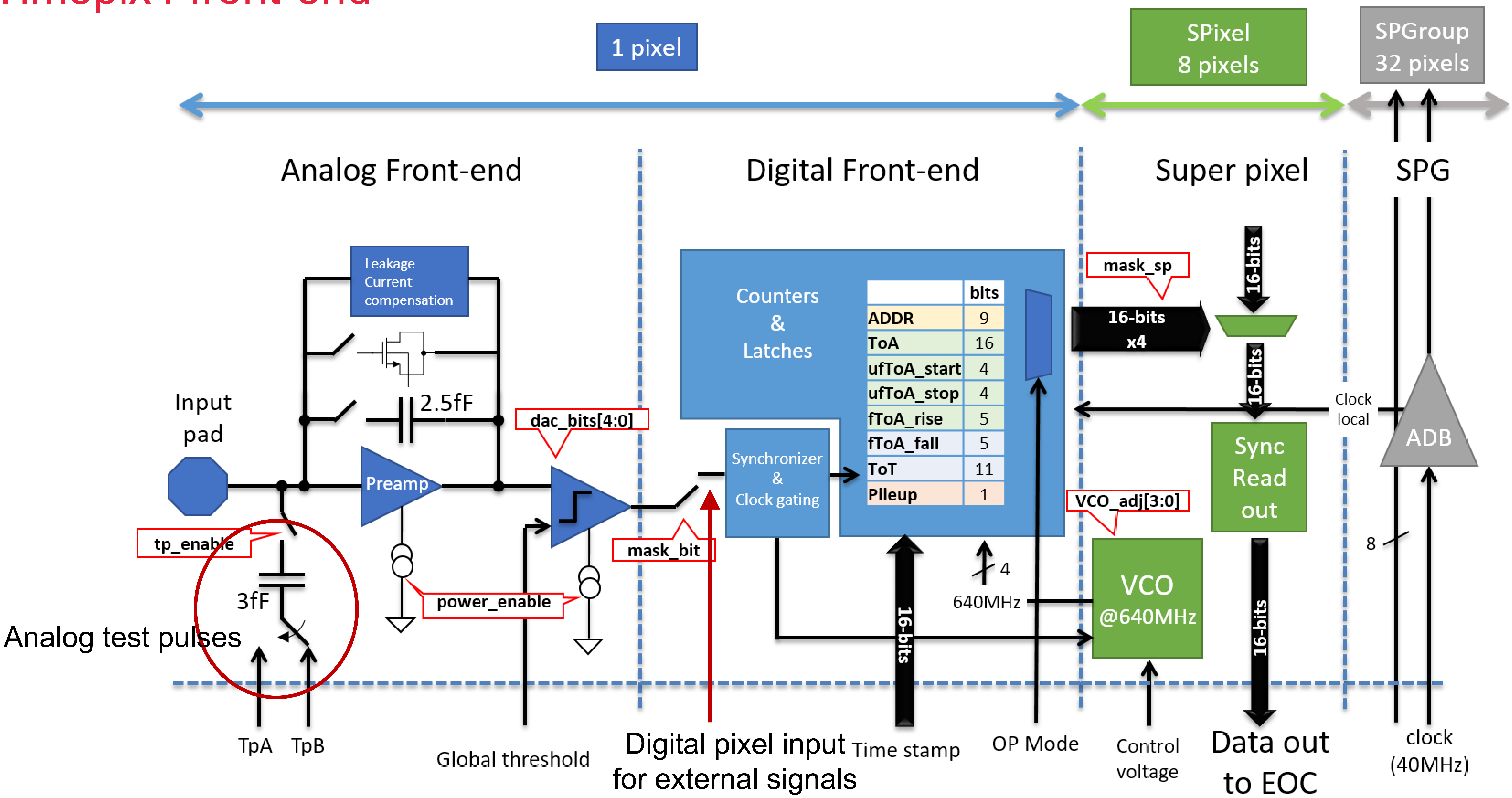
Conclusion

- First stable operation of complete telescope
- Current pointing resolution: 2.7 μm
- Current cluster-time resolution: 250 ps
- Expected track-time resolution: 130 ps
- Plenty of data to be analysed (Better corrections/understanding of chip)
- Ready to move on to faster sensor technologies



Backup slides

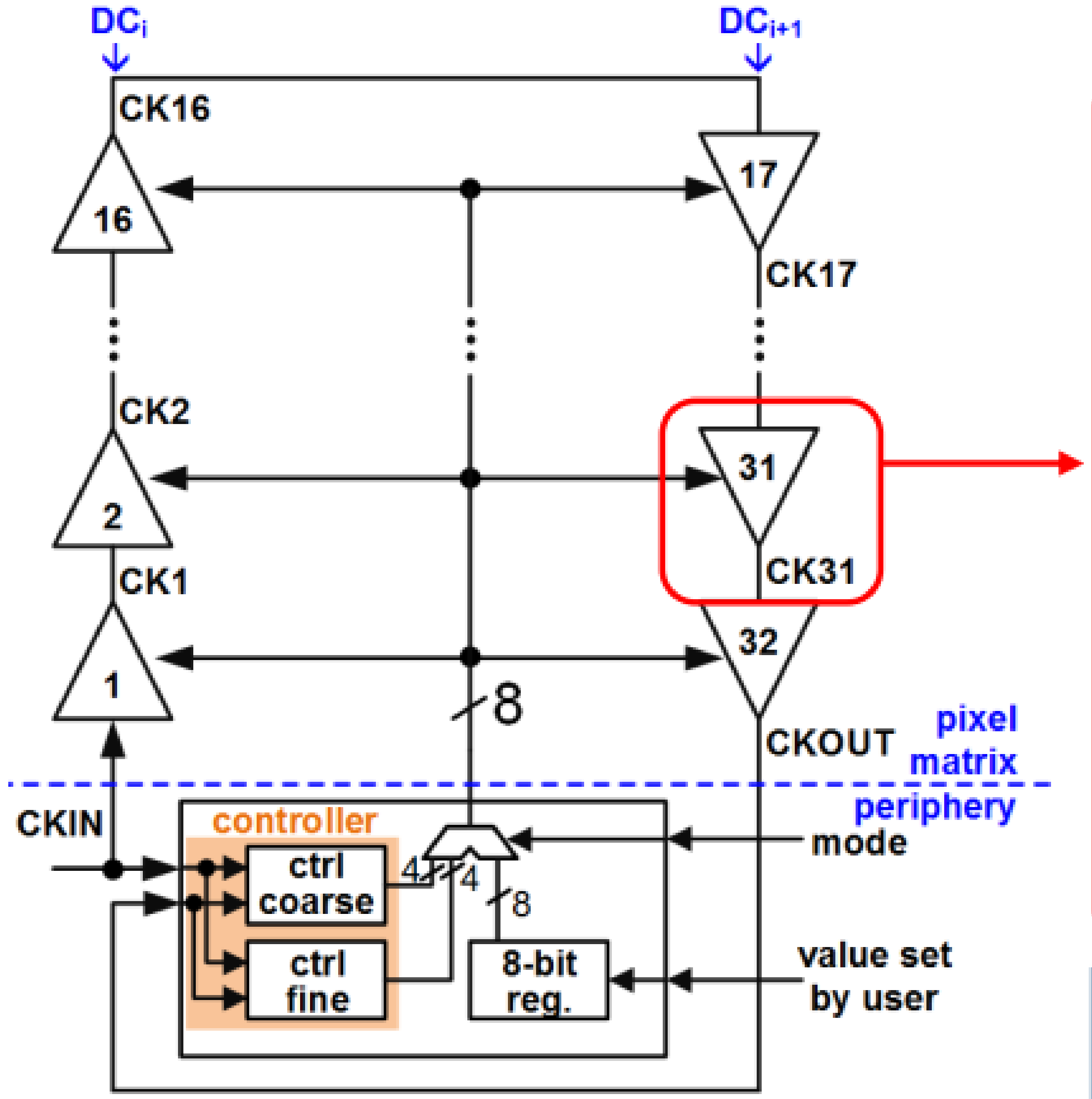
Timepix4 front-end

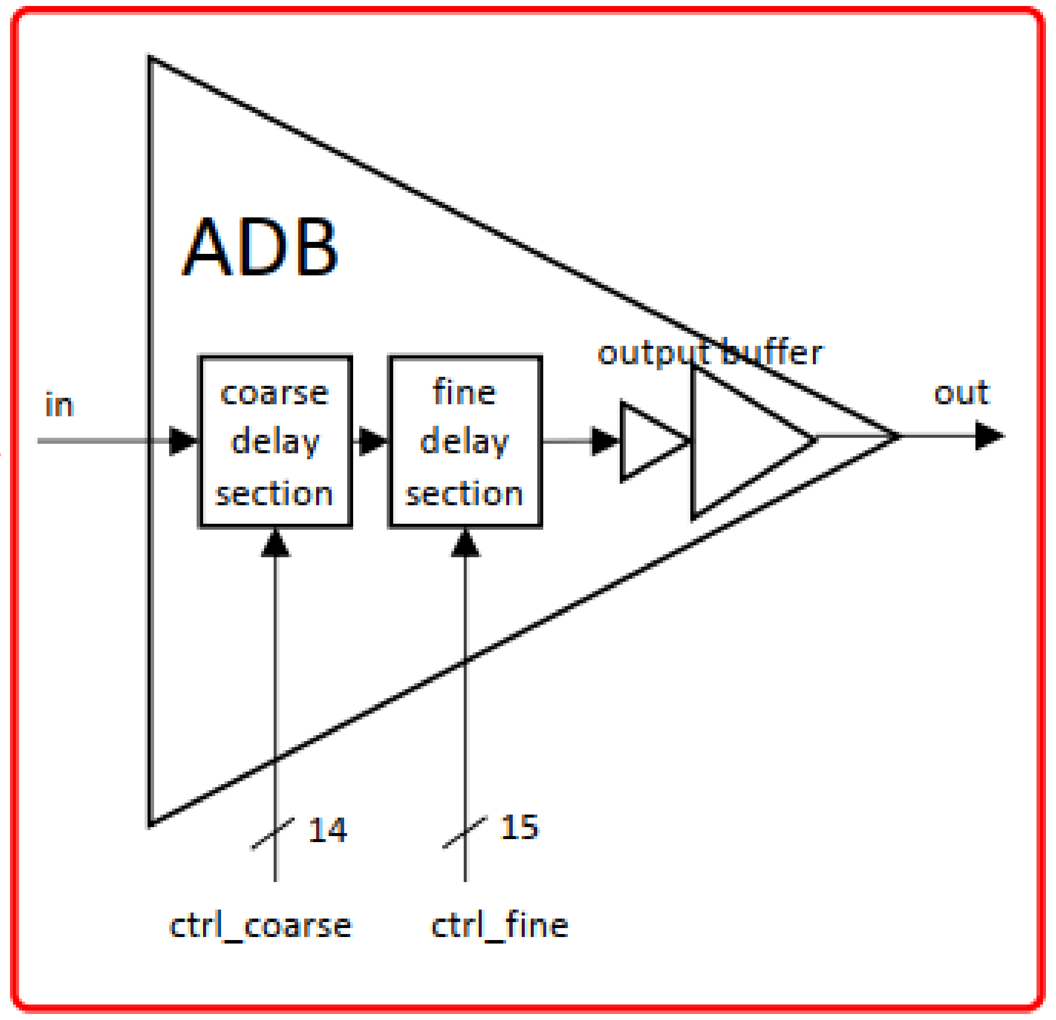


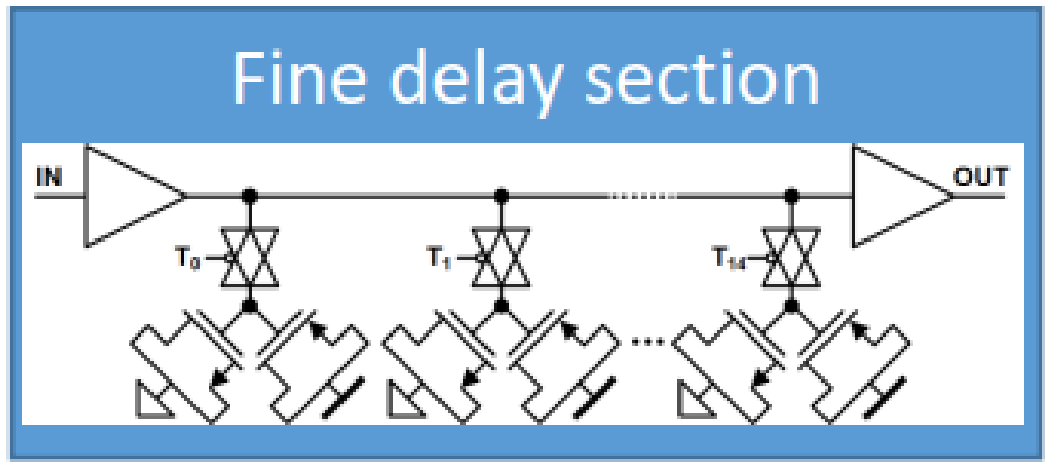
Clock distribution – Column digital locked look (DLL)

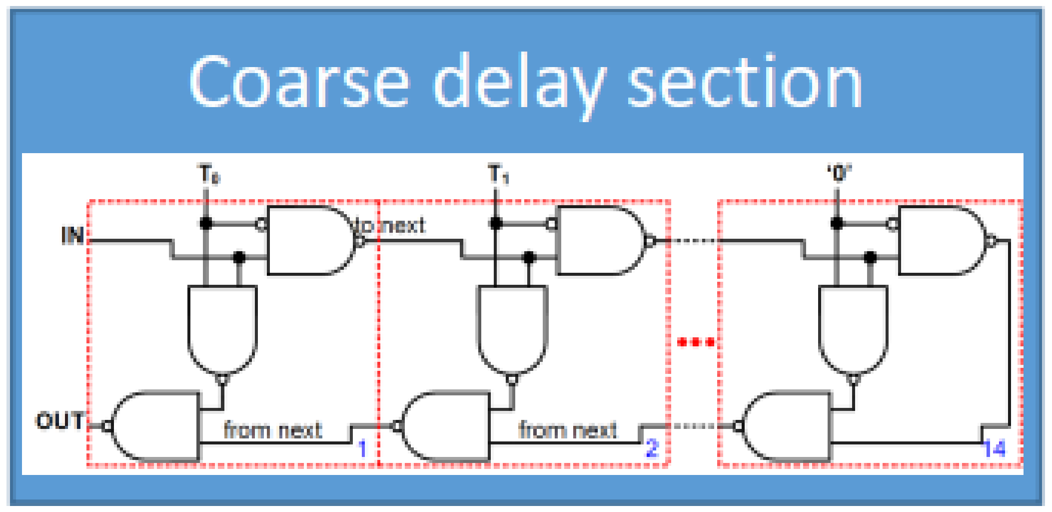
iWoRID 2018
X. Llopart et al 2019 JINST 14 C01024

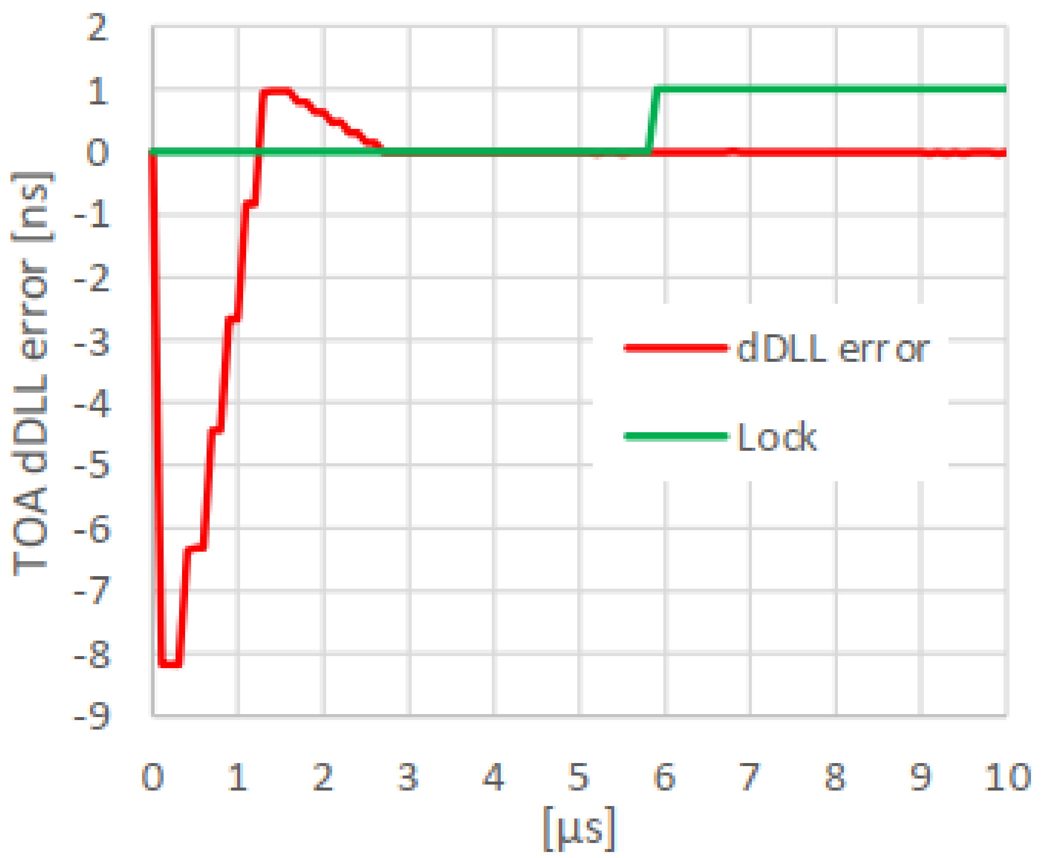
- The column DLL distributes the clock along the columns
- The adjustable delay buffers (ADBs) precisely define the clock phase in each pixel group
- Controller tunes the total delay to 25 ns
- Possible to set the delay manually
- Individual ADB stations can be bypassed

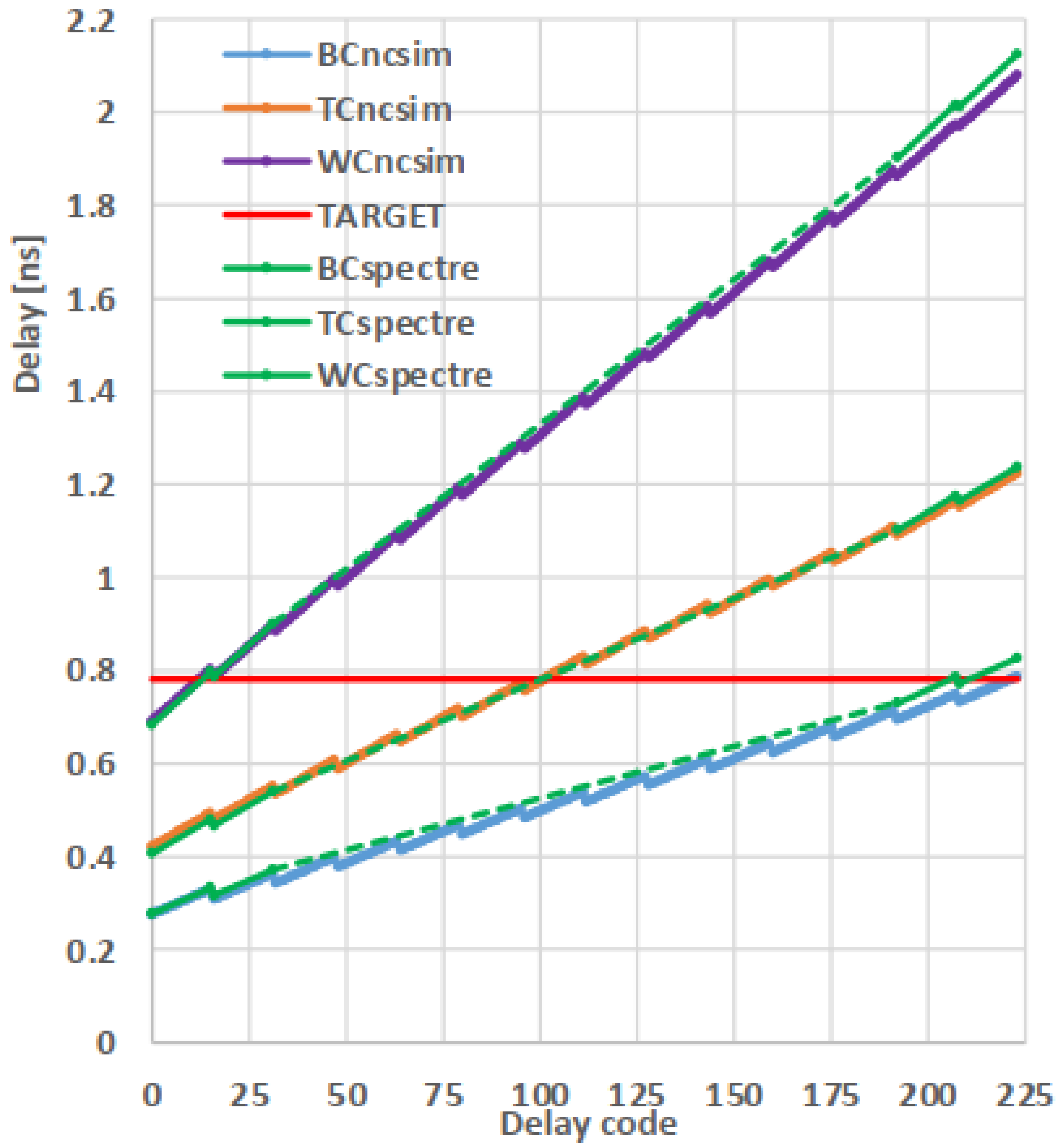










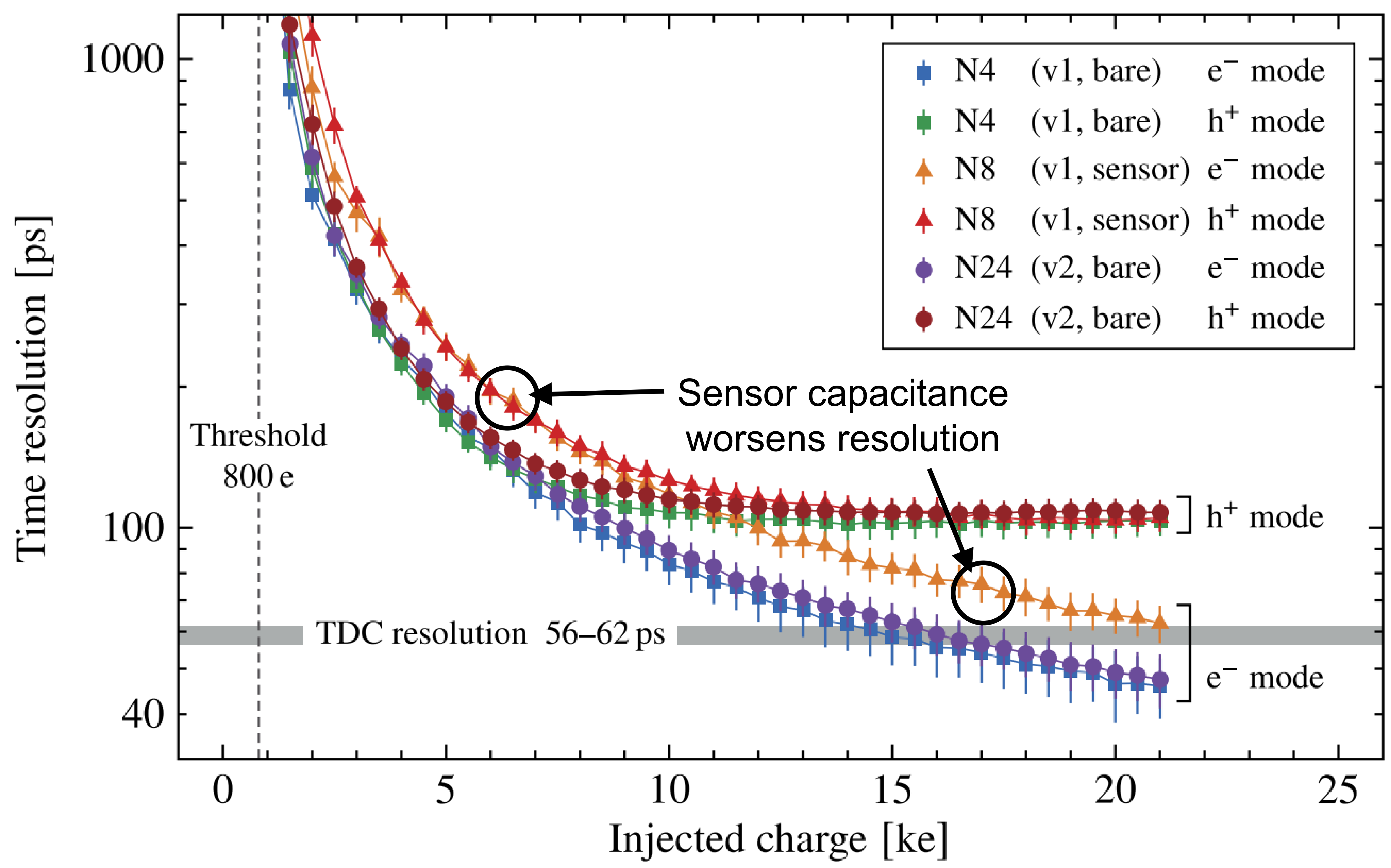


~22.7 mW/cm² to distribute a 40 MHz clock with a 100 ps$_{rms}$

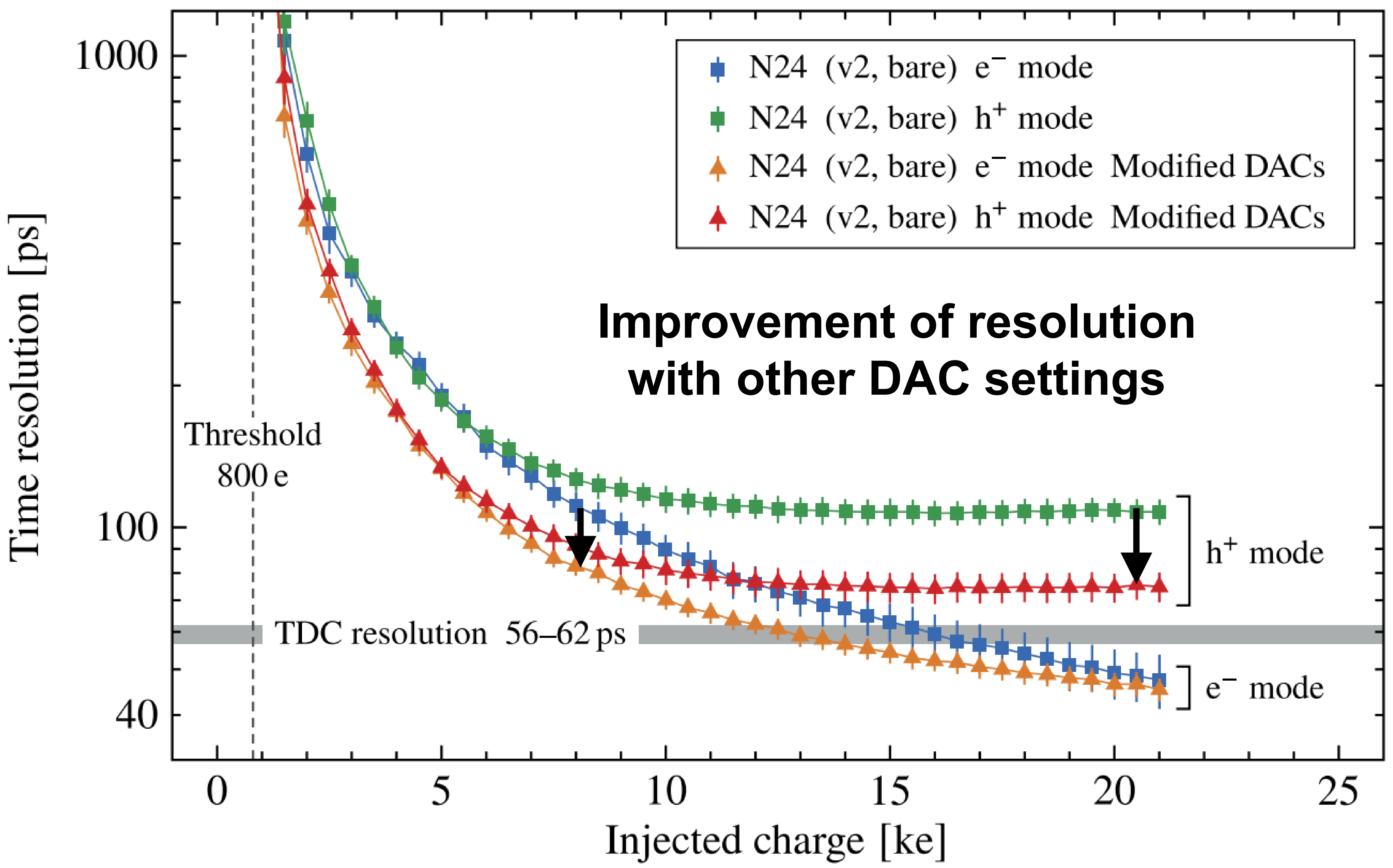
Timepix4 – Analog front-end jitter

- 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]

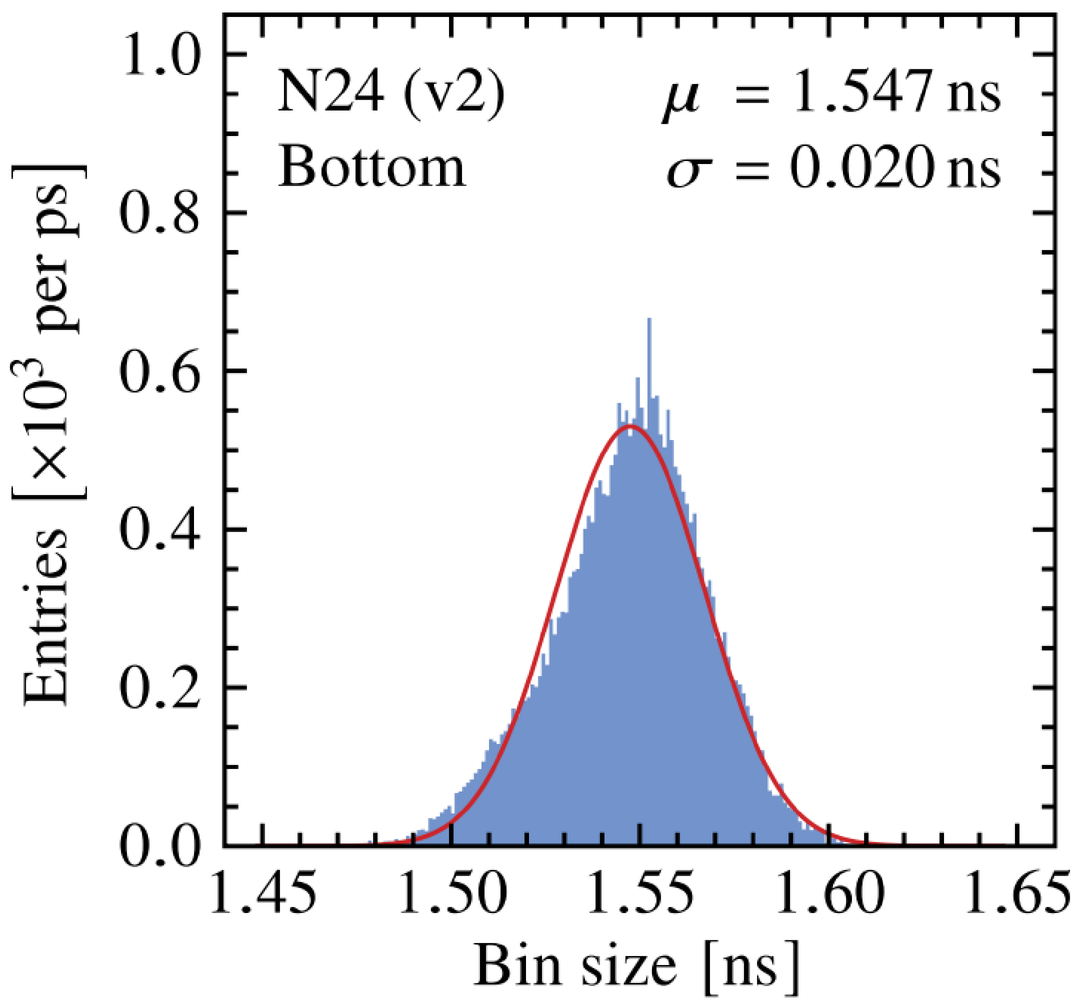


K. Heijhoff *et al* 2022 *JINST* **17** P07006 [DOI: 10.1088/1748-0221/17/07/P07006]

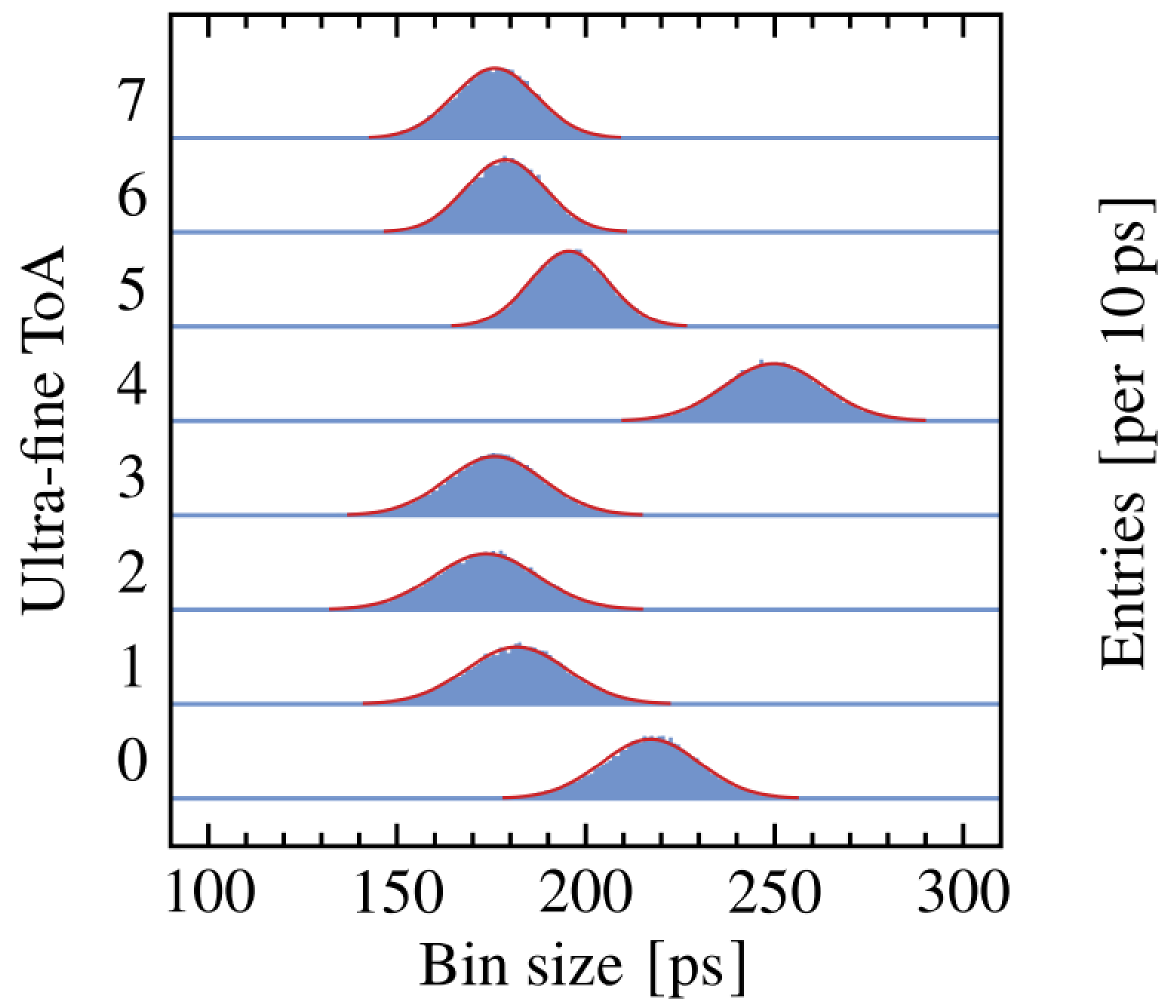
TDC resolution

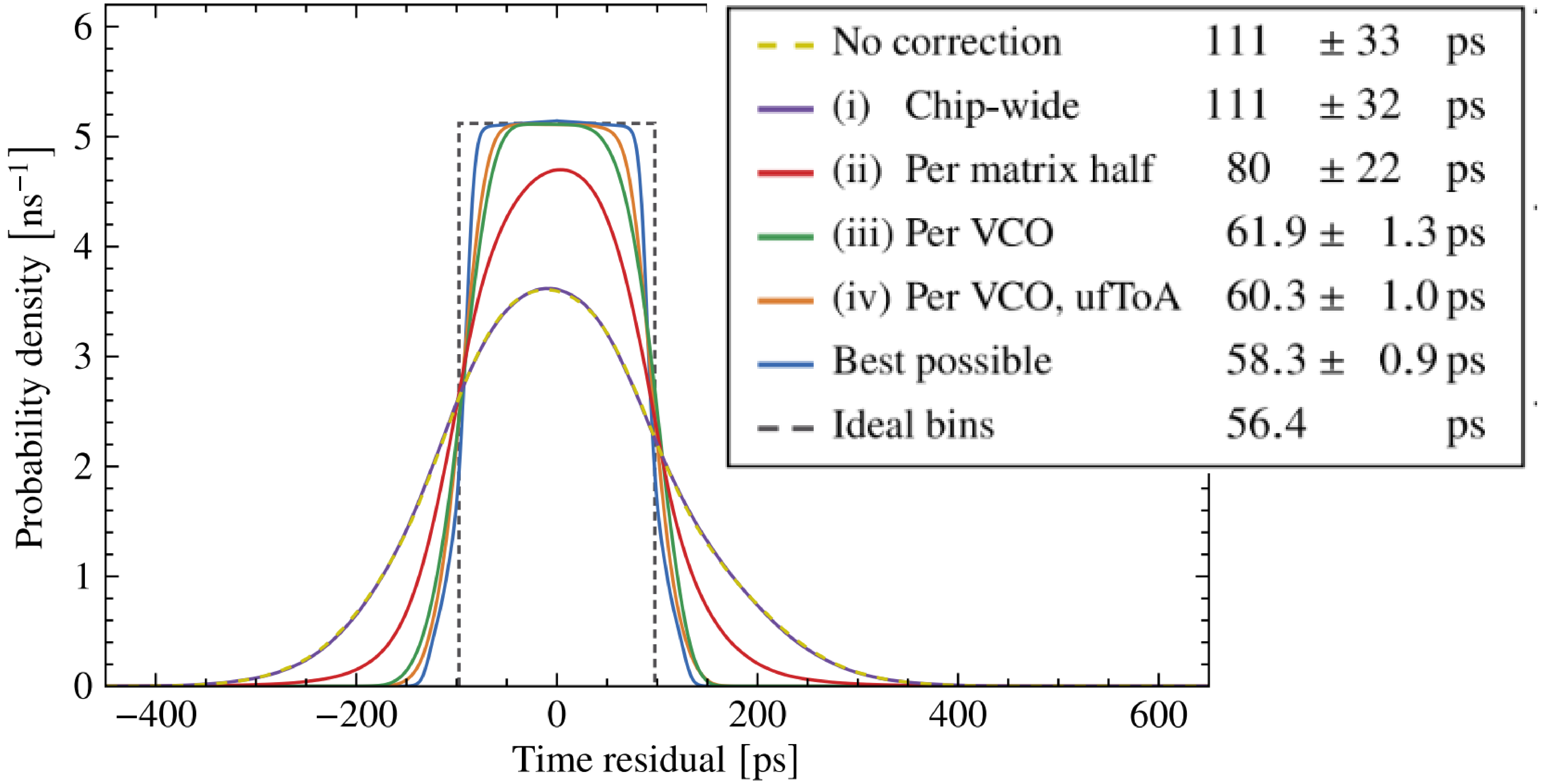
- Variation in the VCO frequency over the pixel matrix observed:
  Bottom half: 1.547 ns ± 20 ps
  Top half: 1.583 ns ± 14 ps
- Structure in ultra-fine time bins has a small impact on TDC resolution (few %)
- We have tried to predict the TDC resolution for correction methods of increasing complexity

Fine time bins (640 MHz)

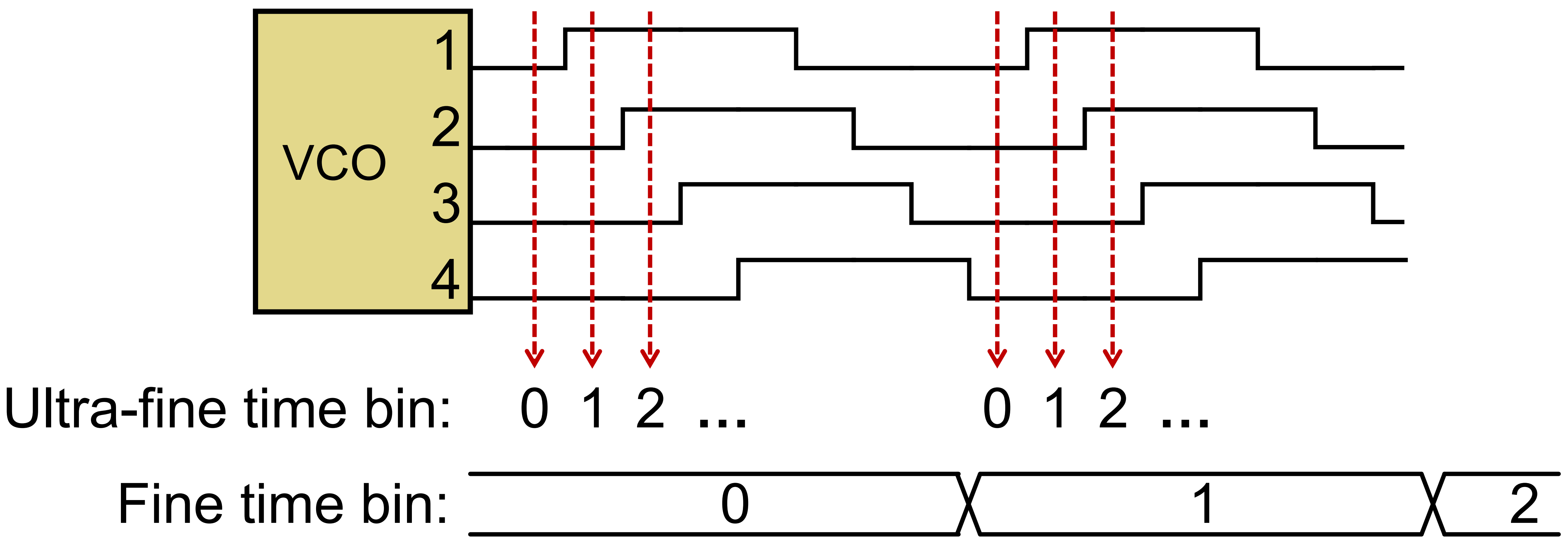


Ultra-fine time bins



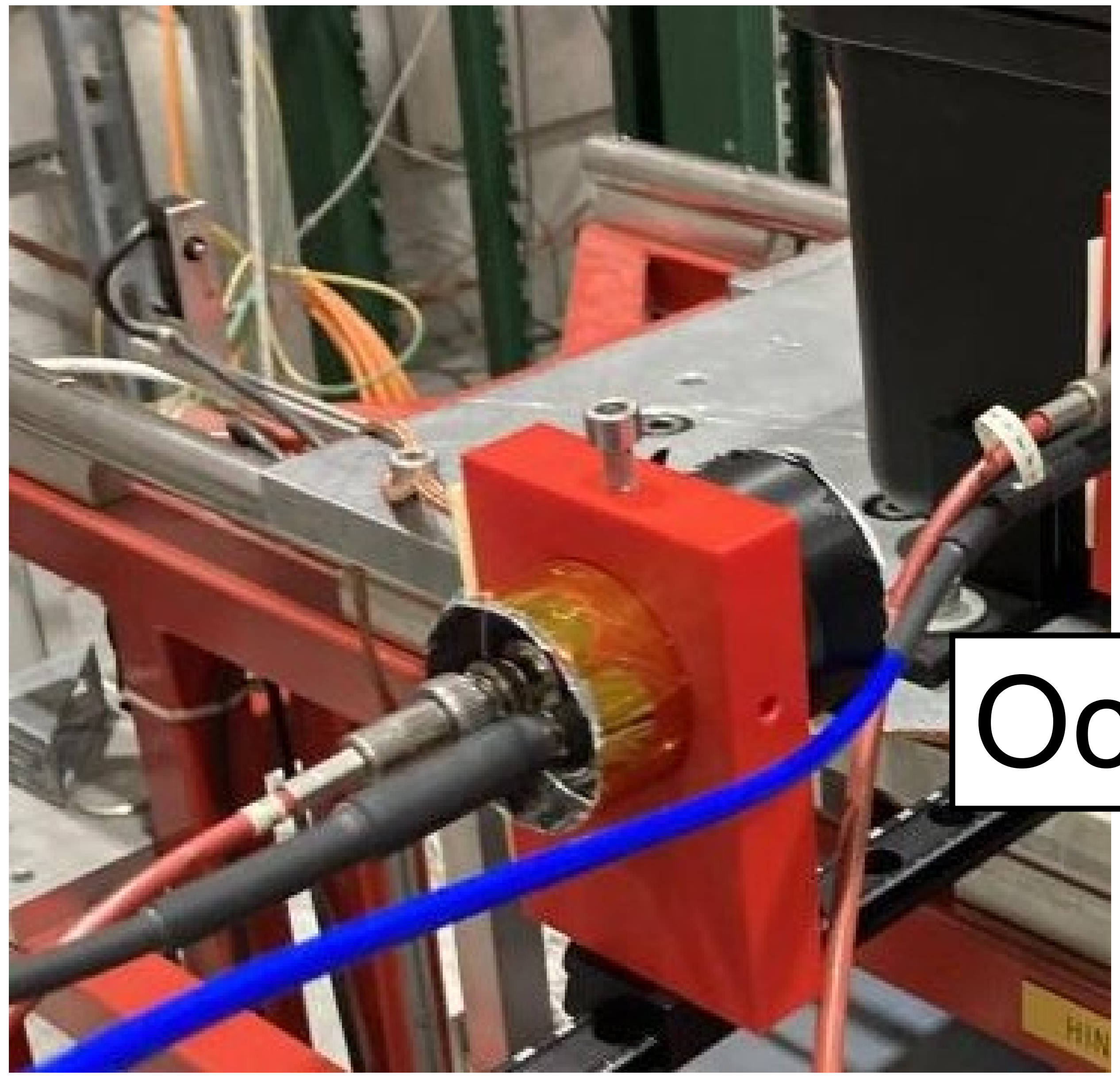


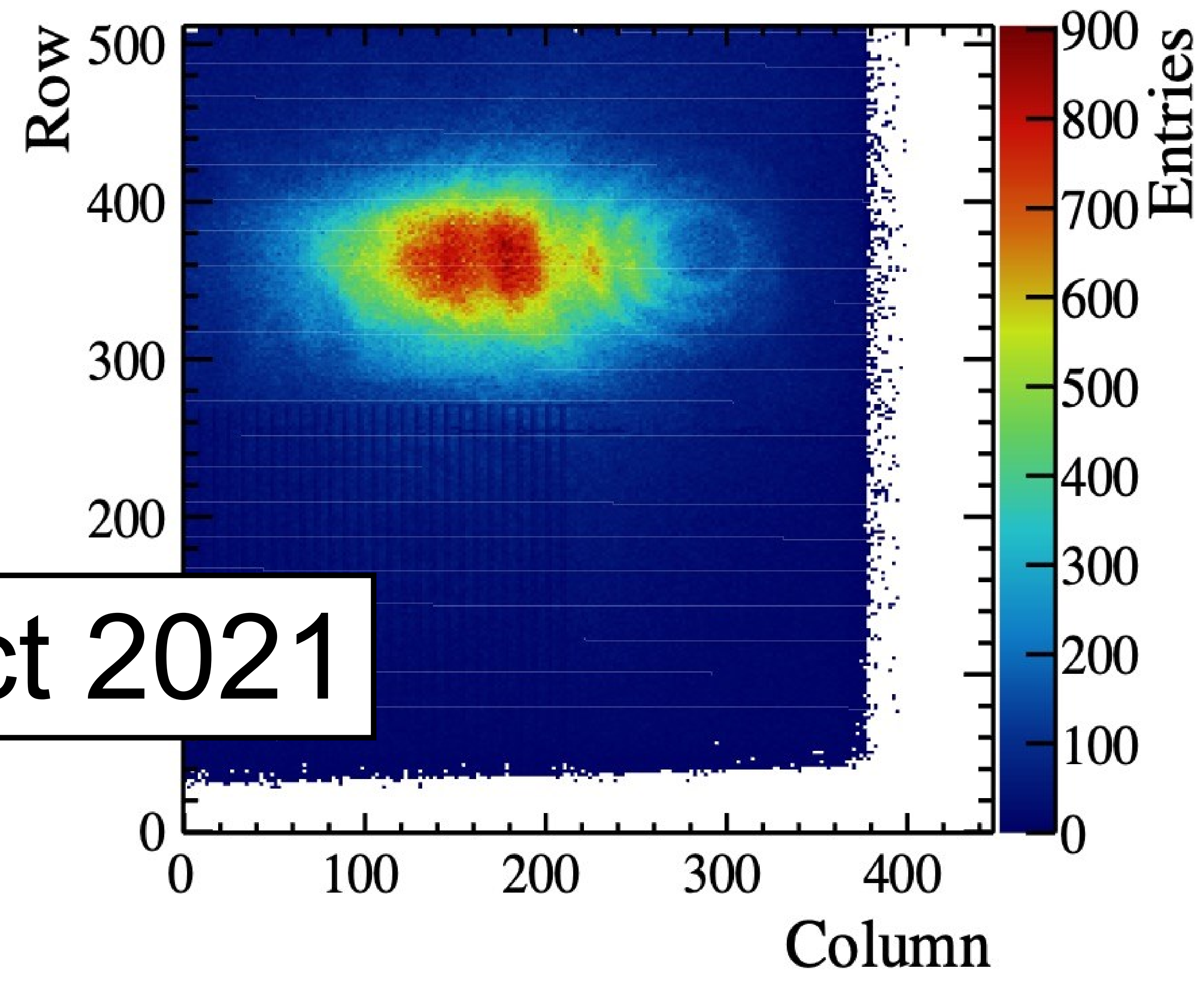
Phase shifted 640 MHz clocks

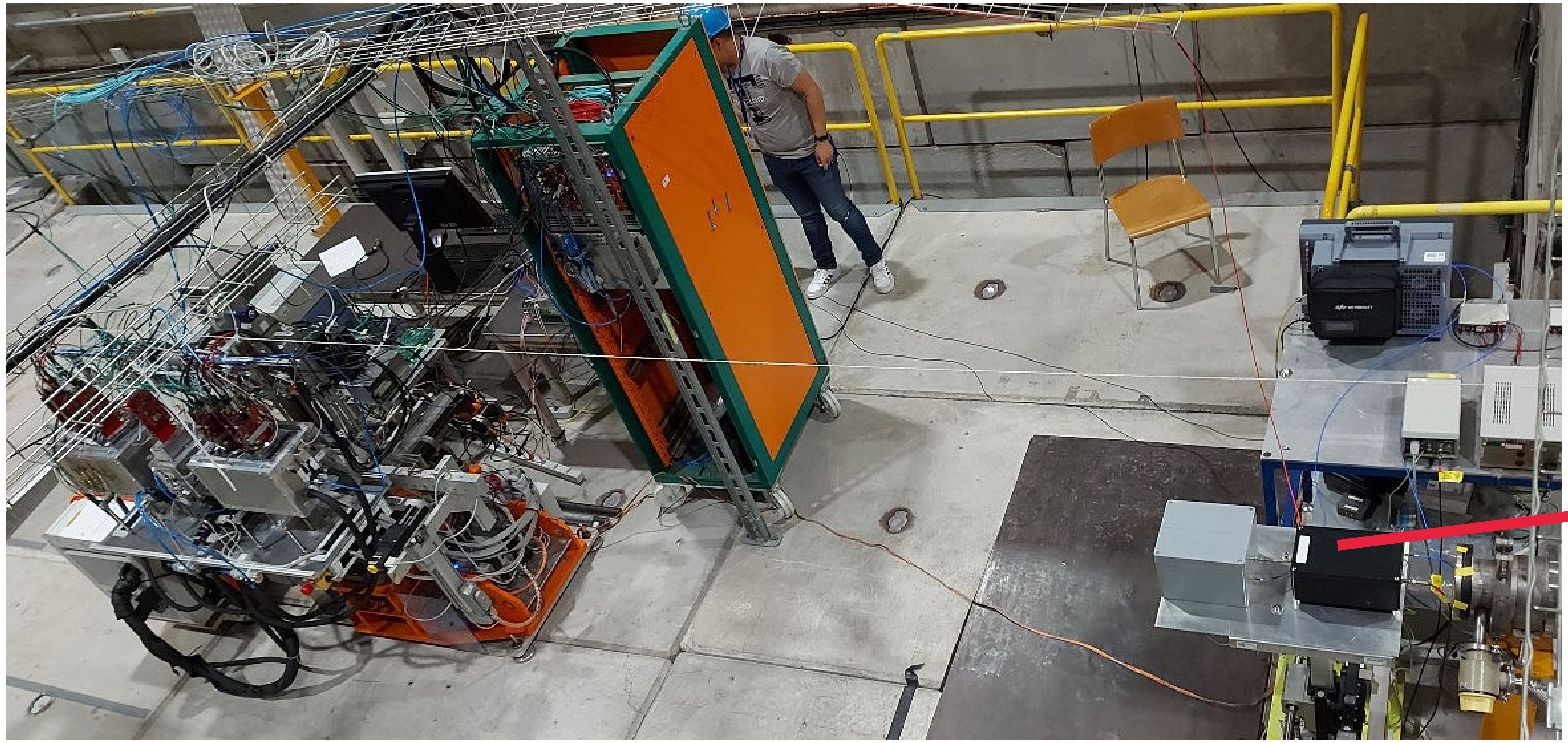


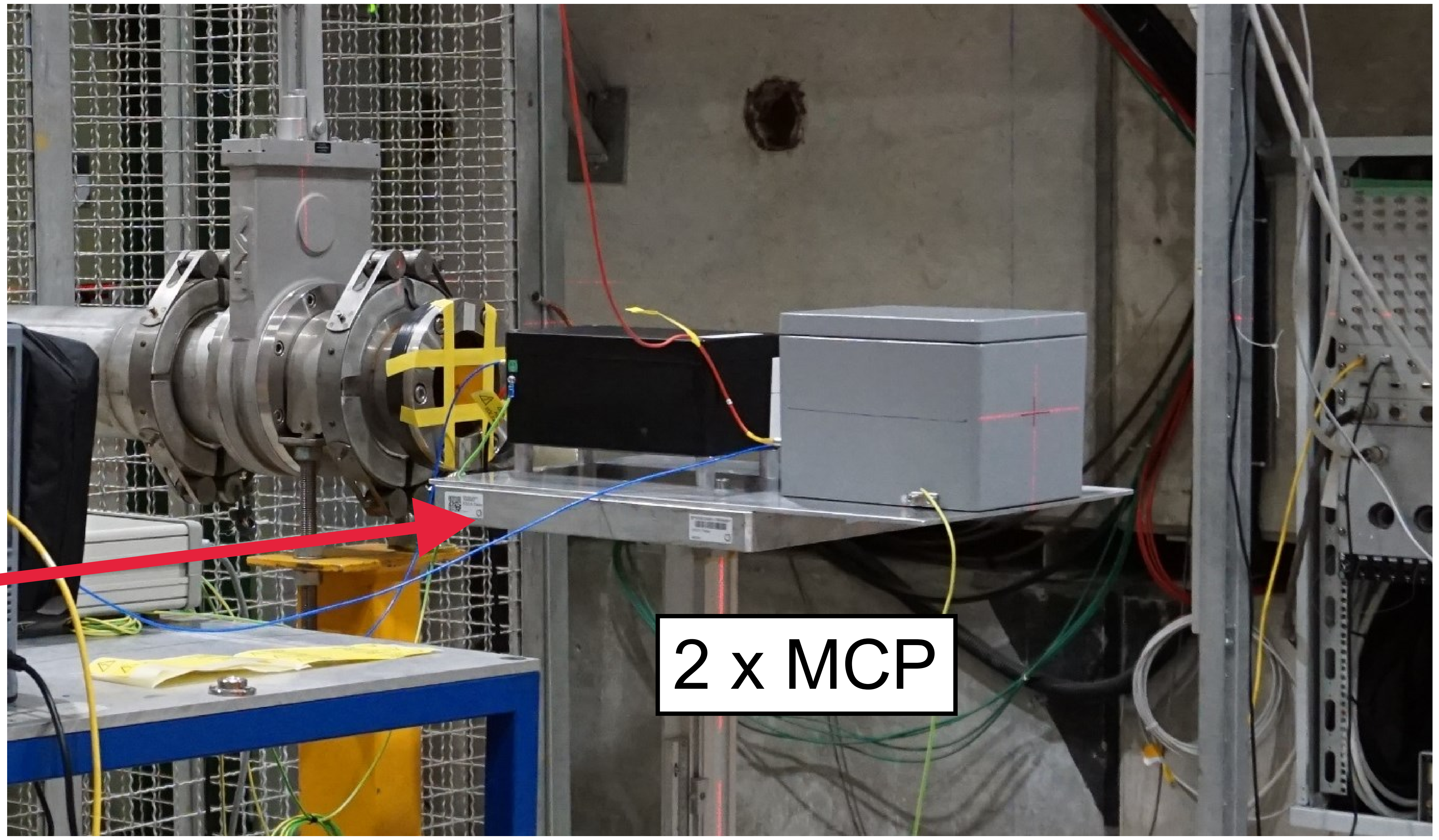
MCP time reference

- 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









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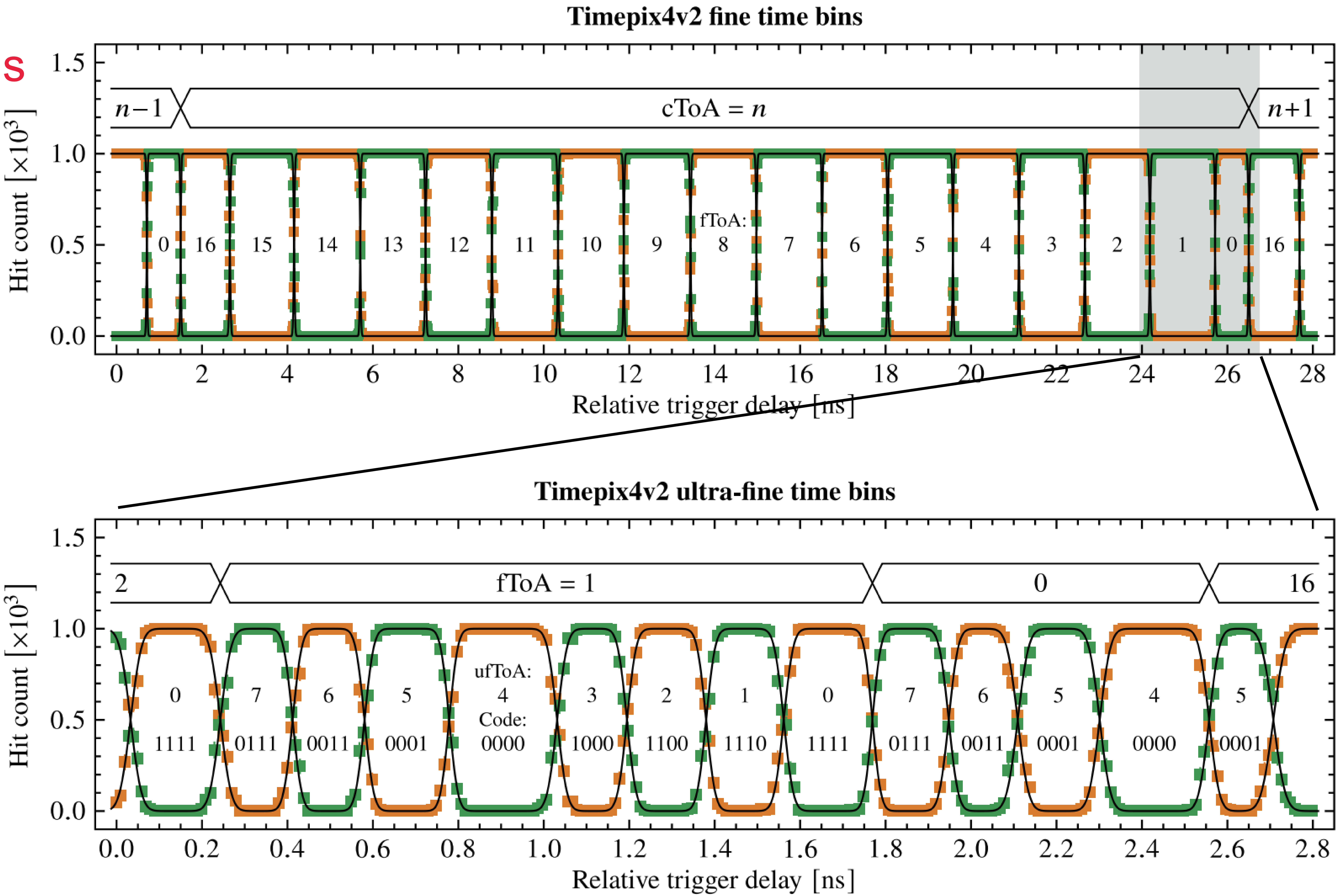
Timing systematics in the LHCb VELO Timepix3 Telescope

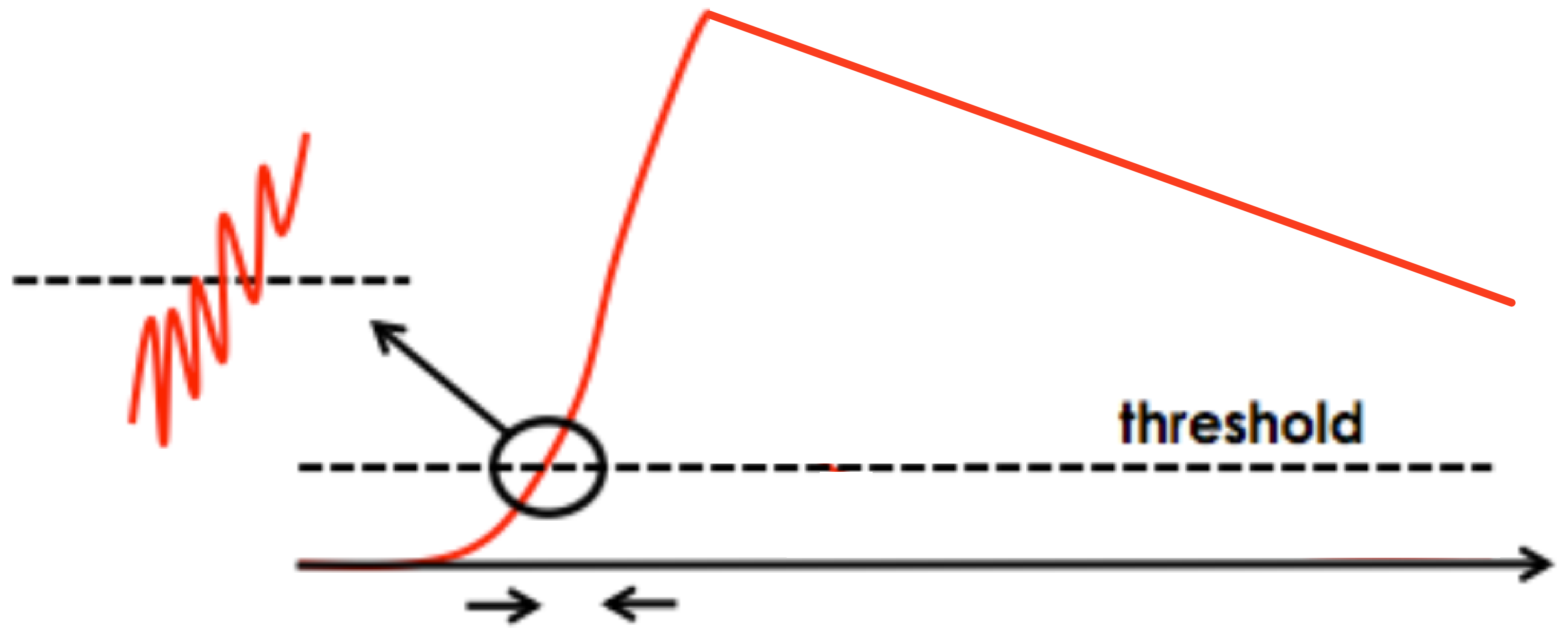
Timepix4 TDC bins

- Time bins measured using digital pixel inputs
- Timepix4v2

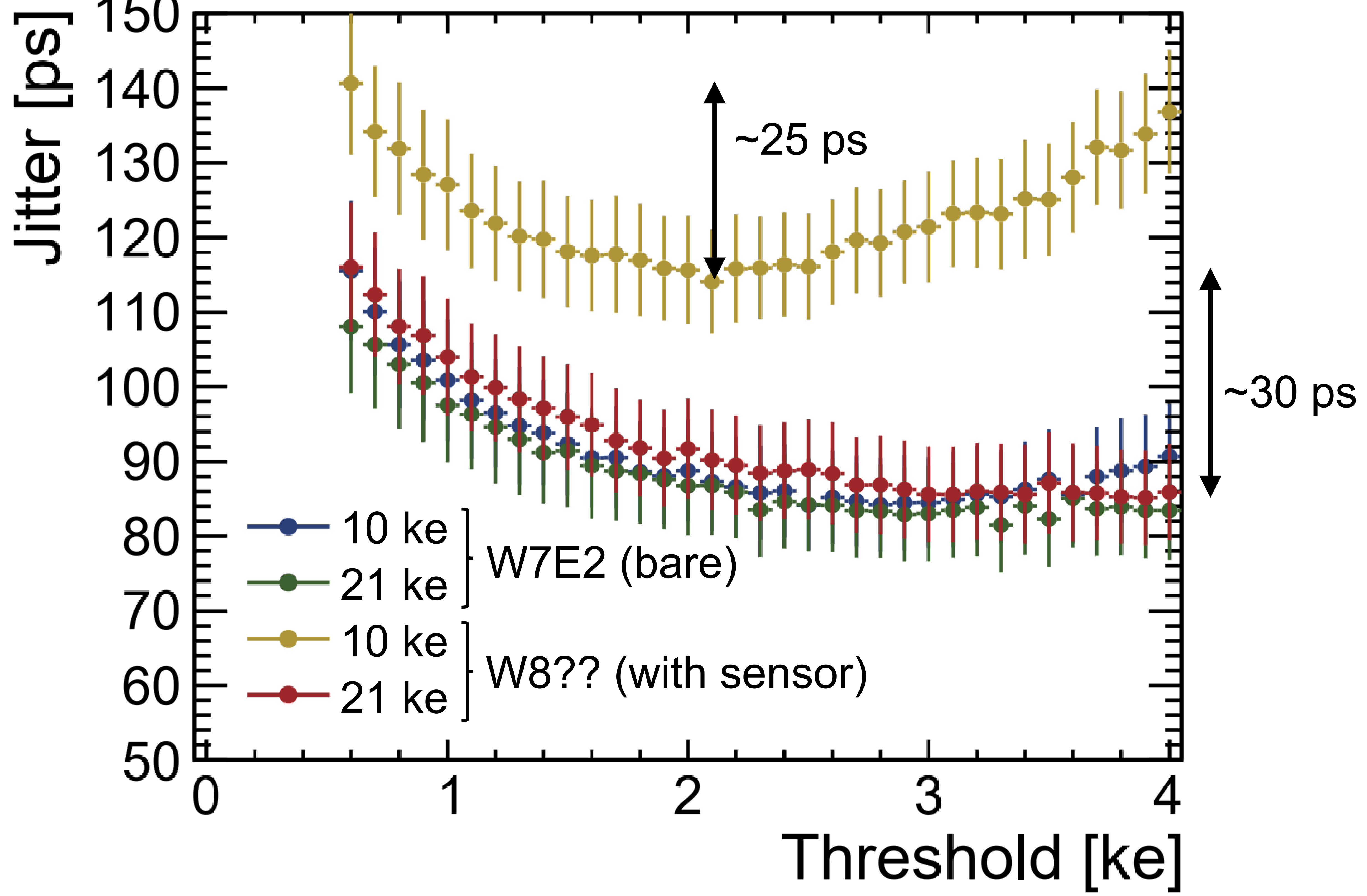


Timepix4 – Jitter vs threshold

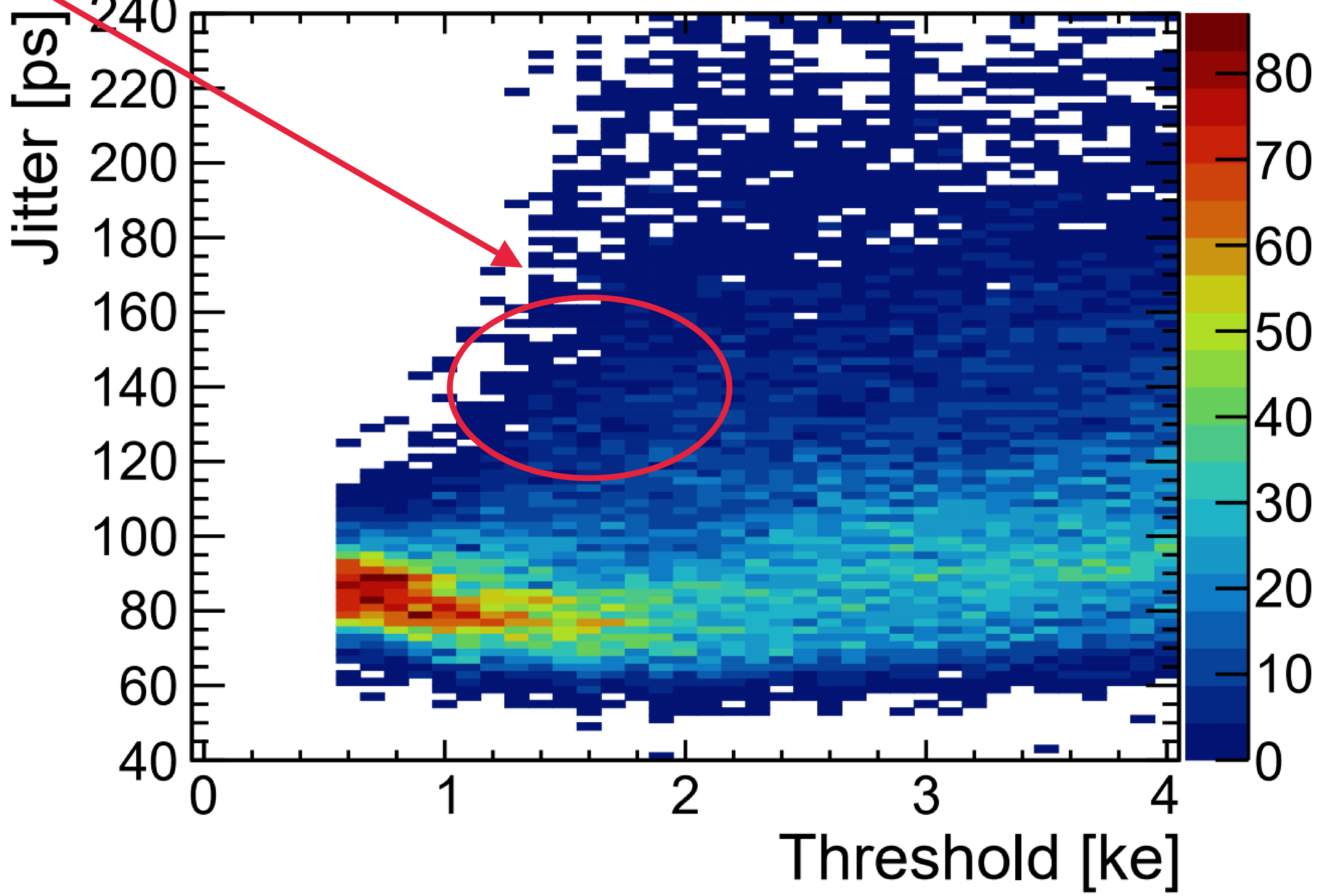
- Jitter depends on threshold
- Tail at high thresholds in electron-collecting mode not understood



Jitter vs threshold (hole collecting)

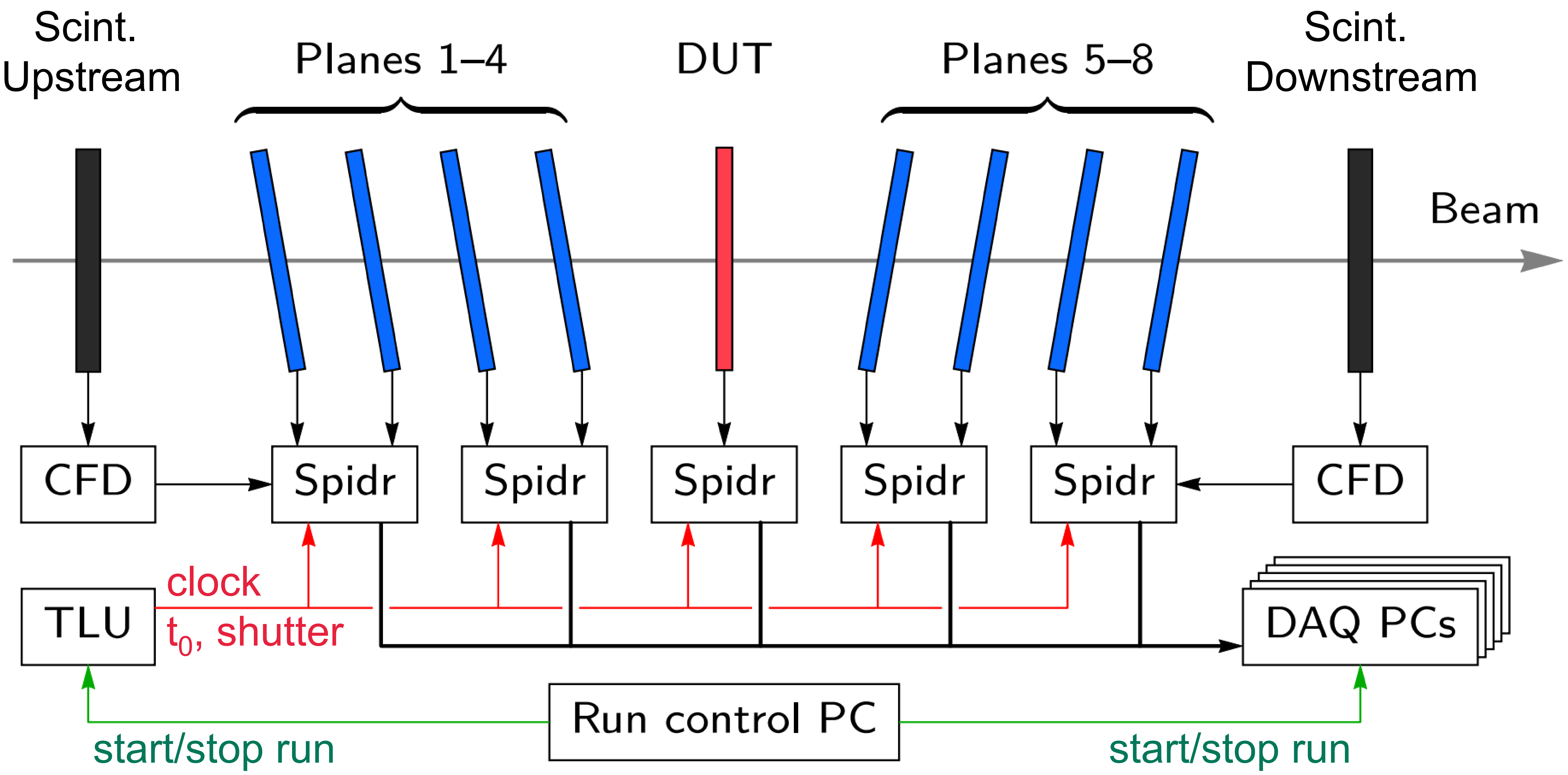


Jitter vs threshold (electron collecting, 10 ke)



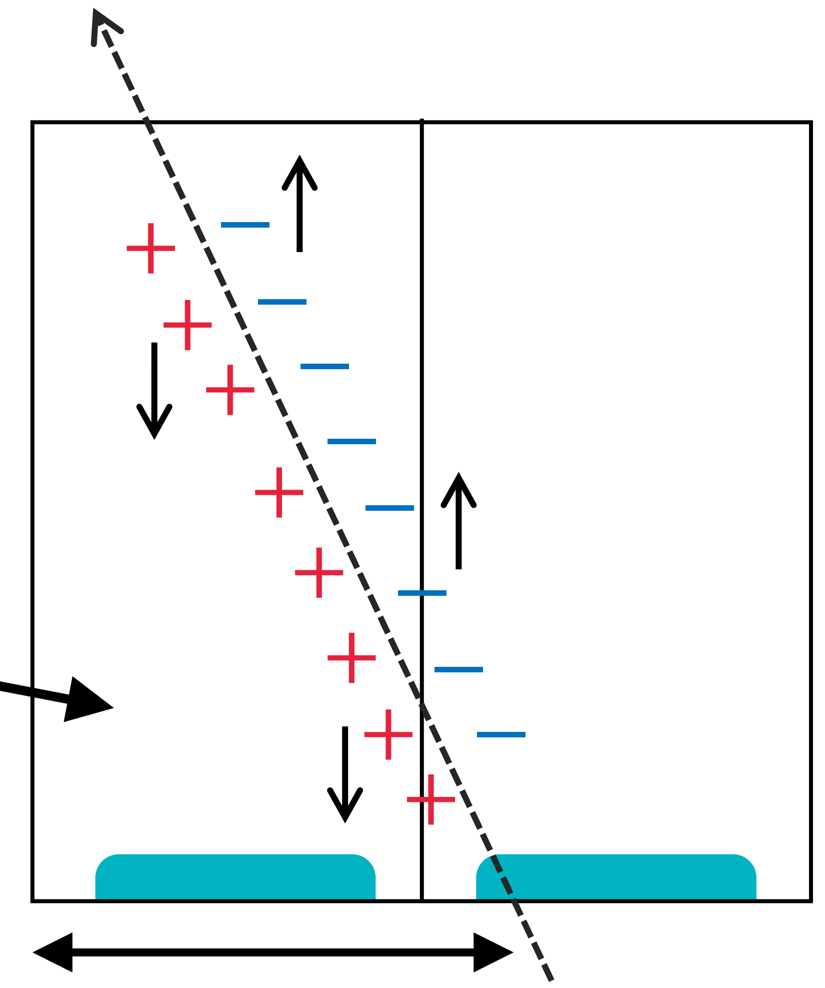
Timepix3 telescope

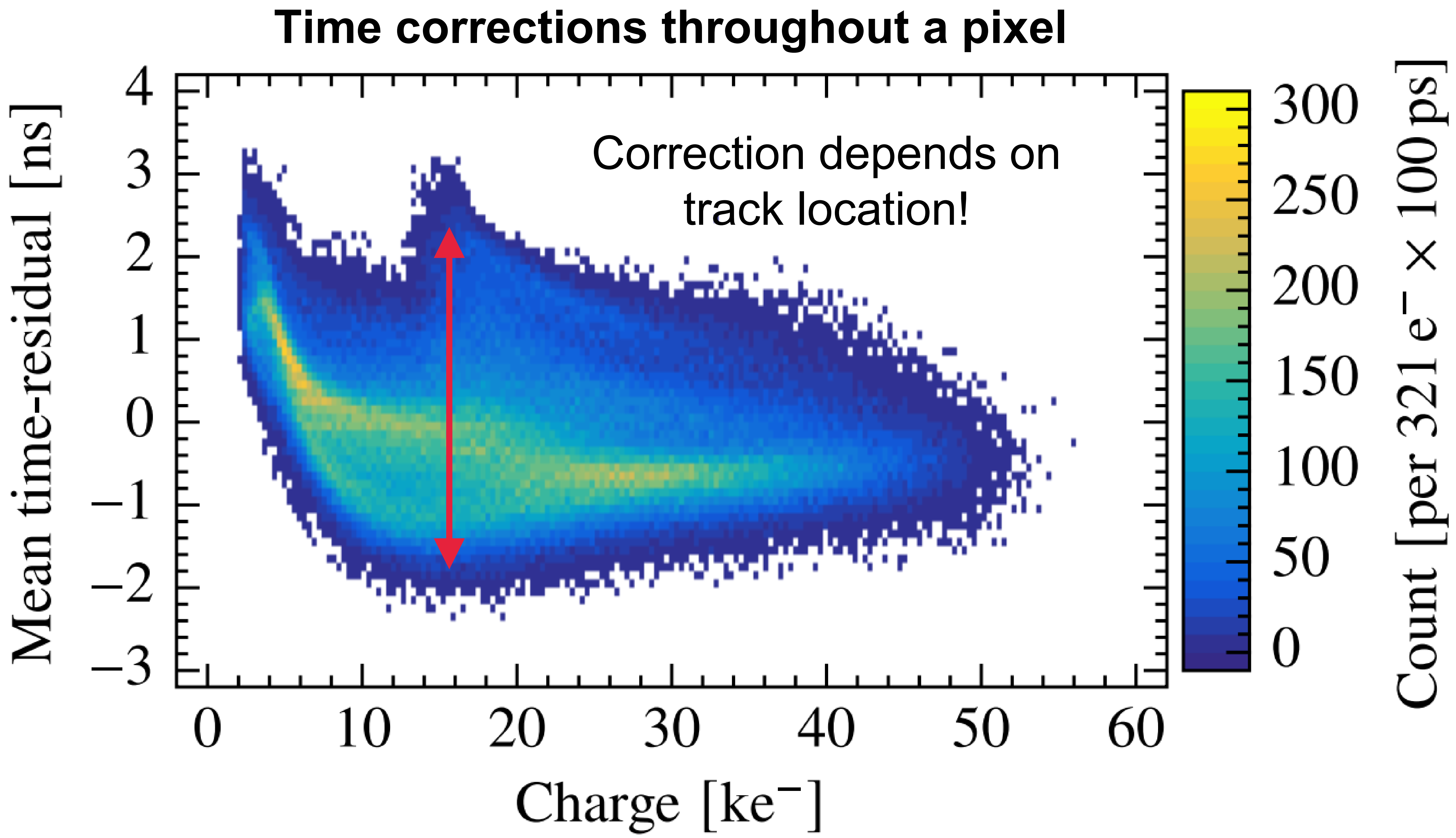
- Eight planes with Timepix3 + sensors
- Planes rotated to optimise spatial resolution
- Scintillators provide a reference time
- Constant fraction discriminators (CFDs) reduce timewalk effects
- All planes run on a common 40 MHz clock

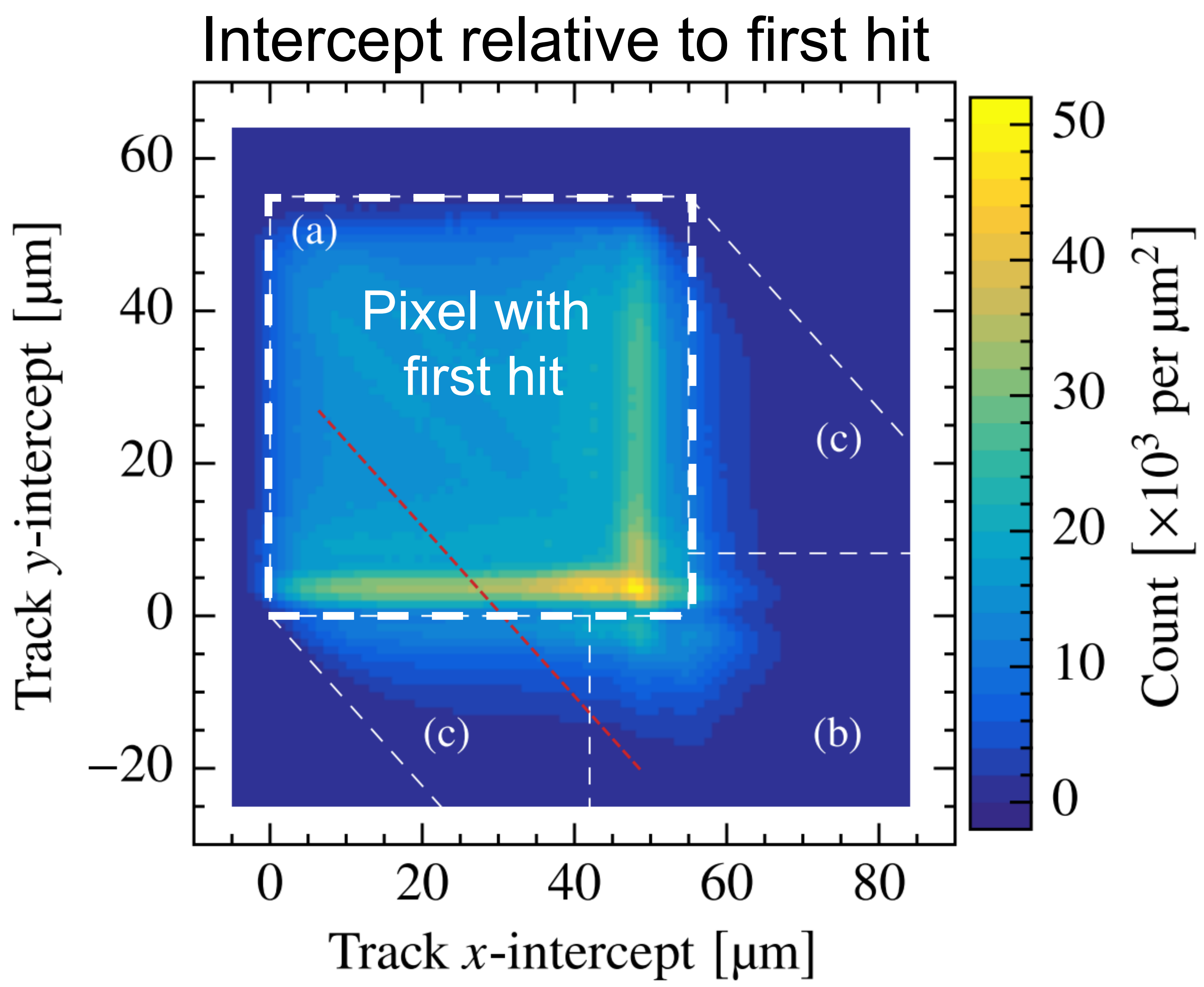


Timewalk and intercept correction

- 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: $\sigma(\text{track}) = 438 \text{ ps} \rightarrow 385 \text{ ps}$







DUT charge distributions

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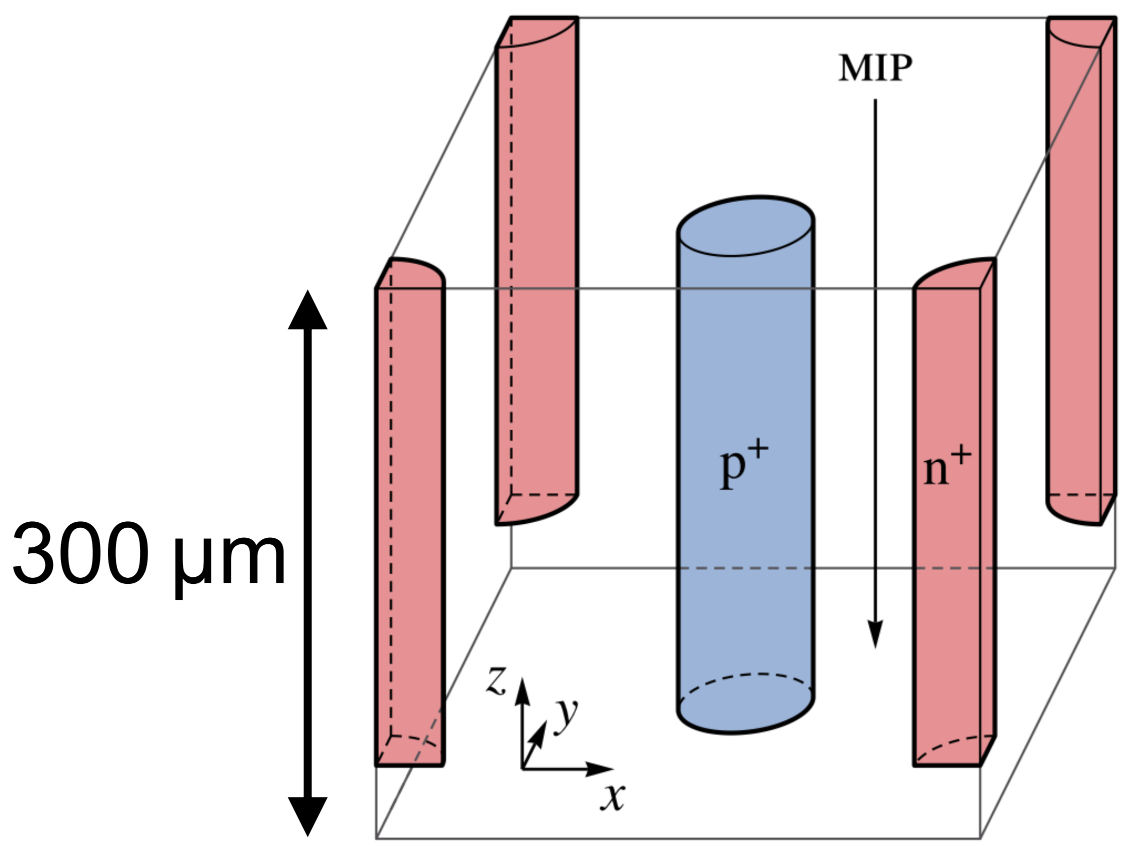
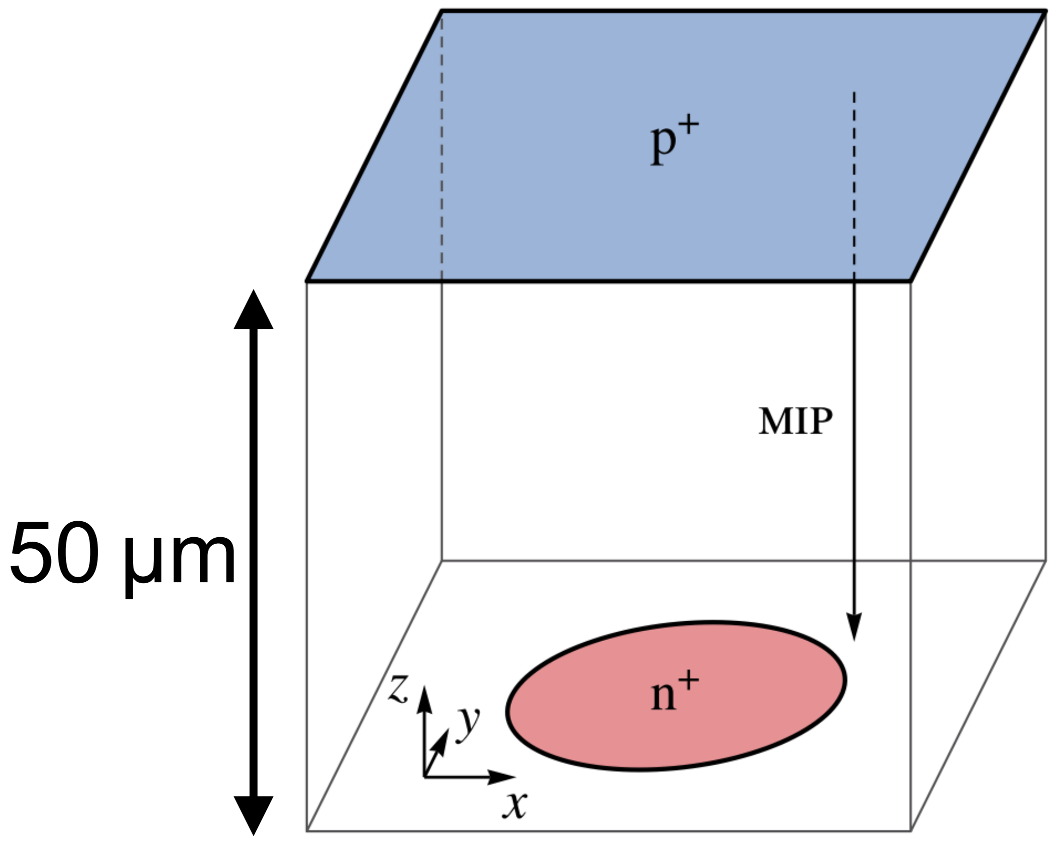
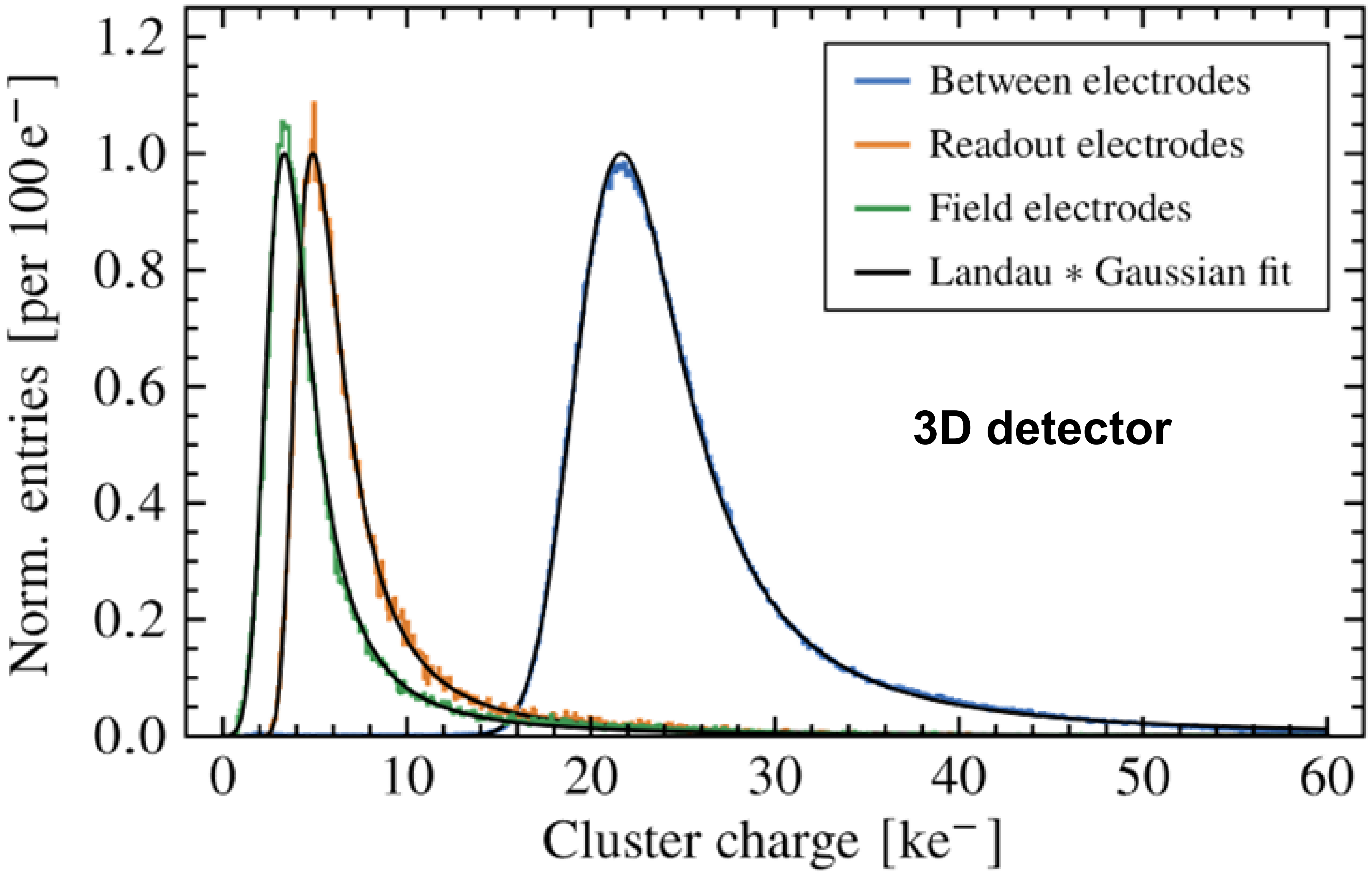
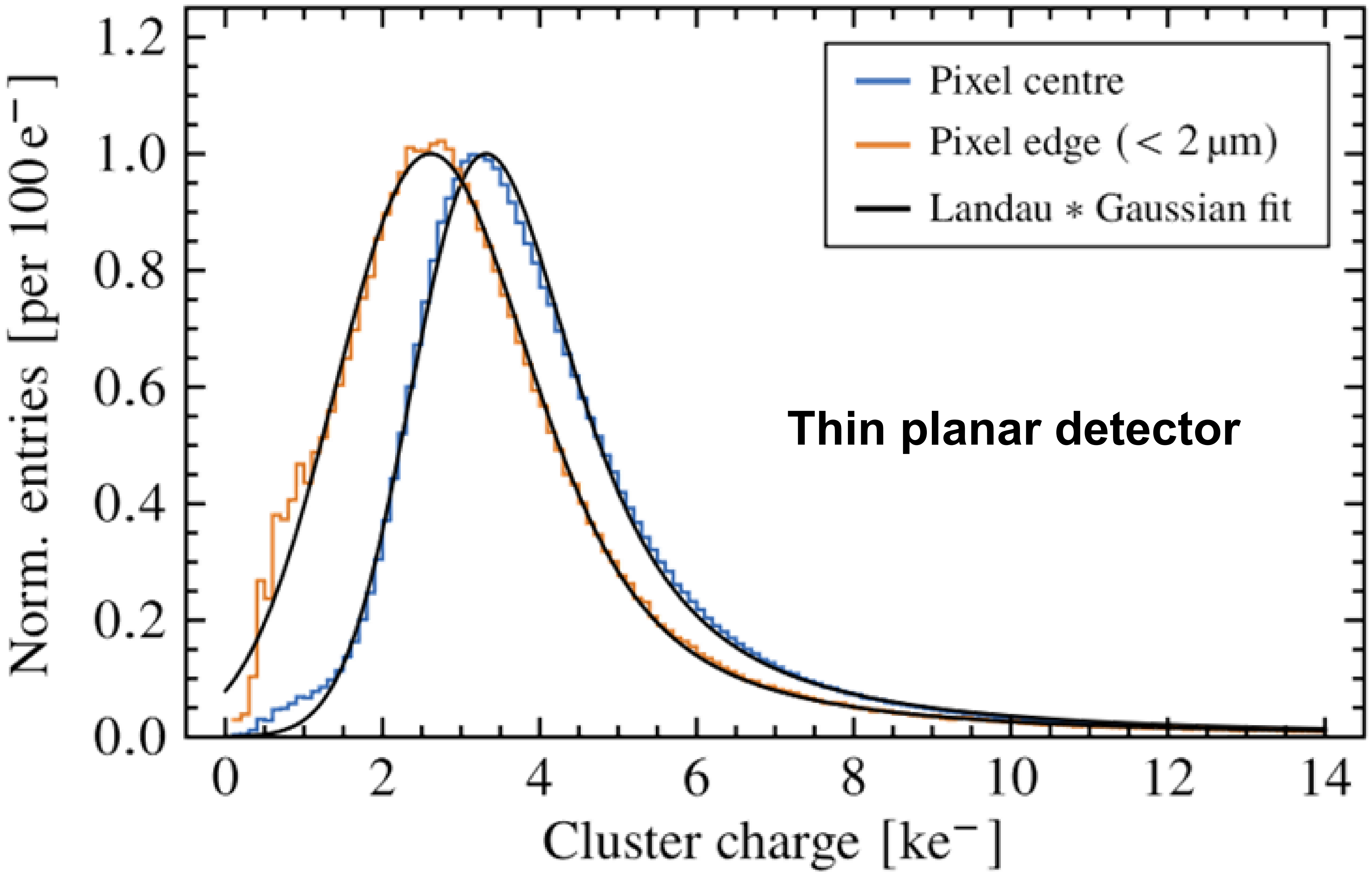
- MIPs going through electrodes of 3D sensor only generate charge in small region



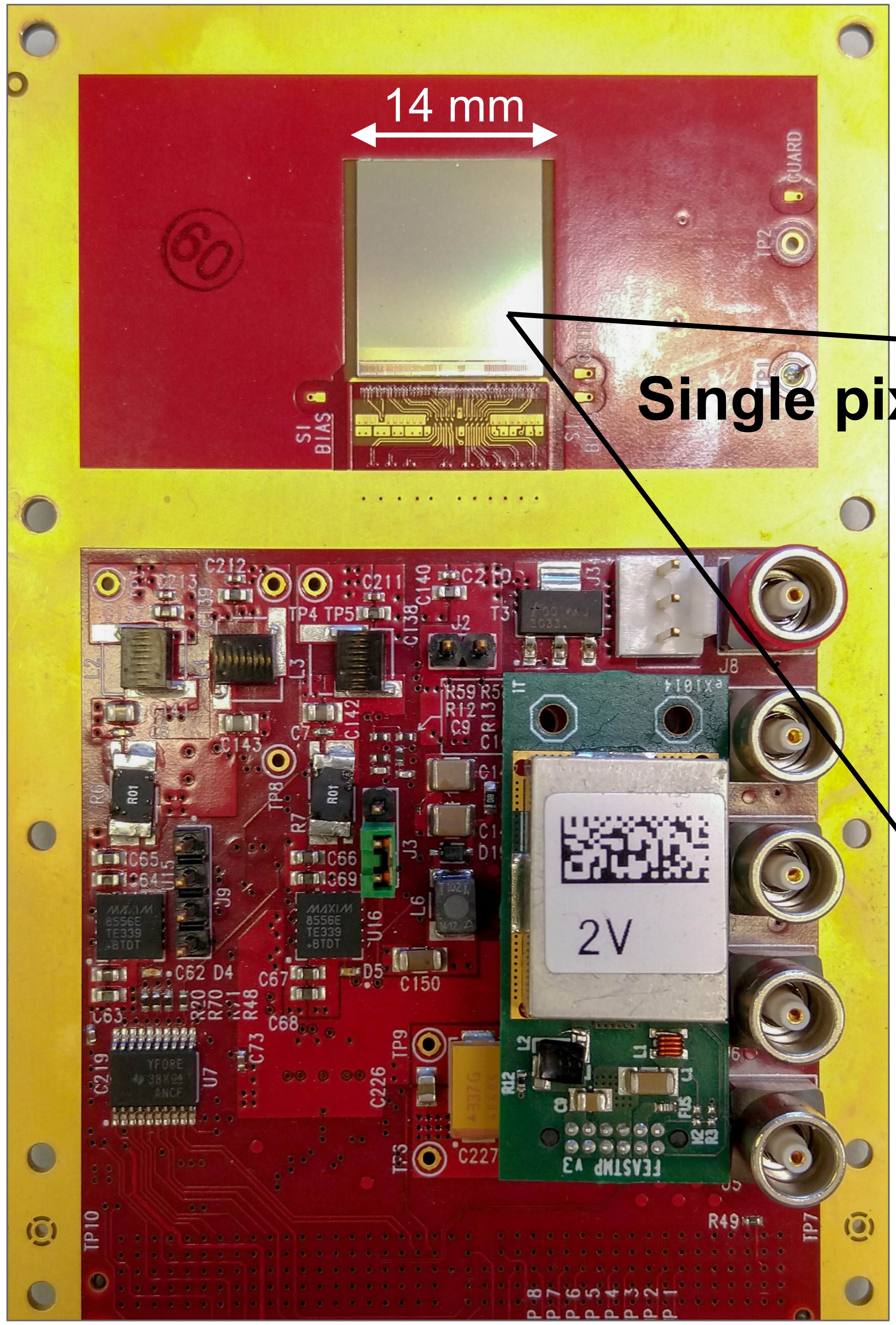




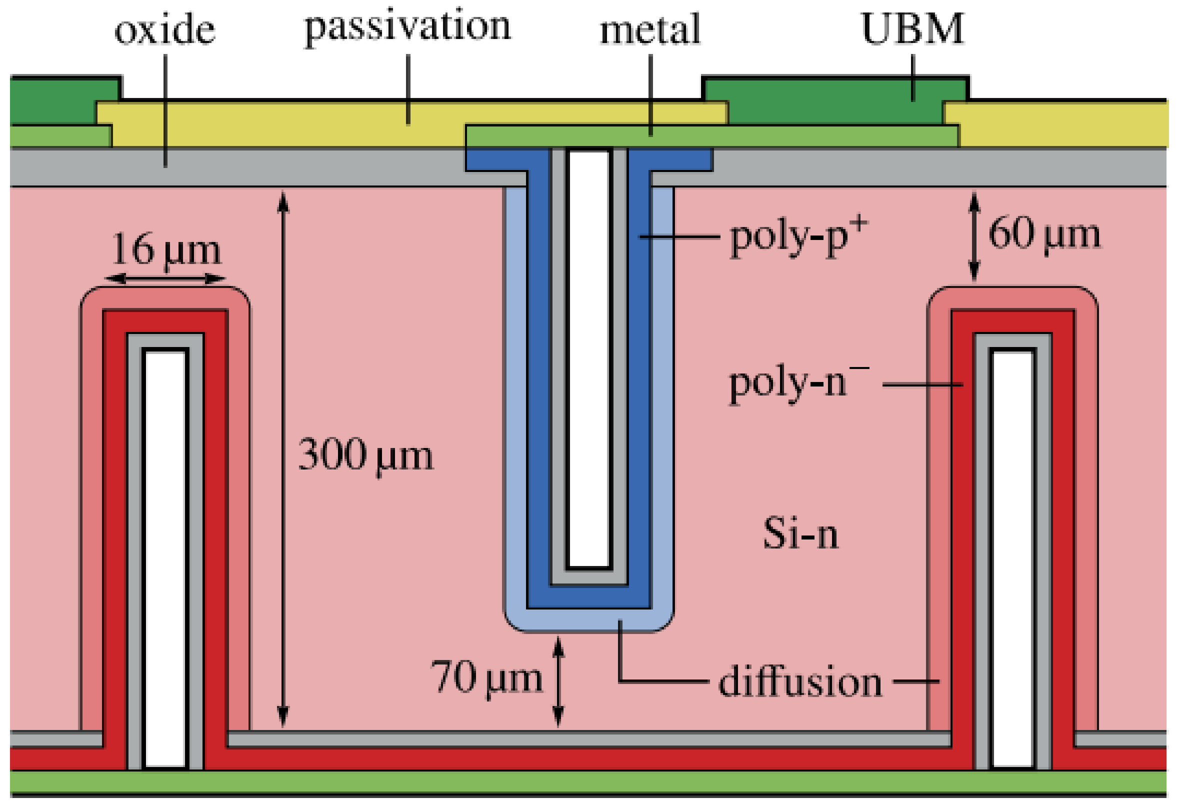


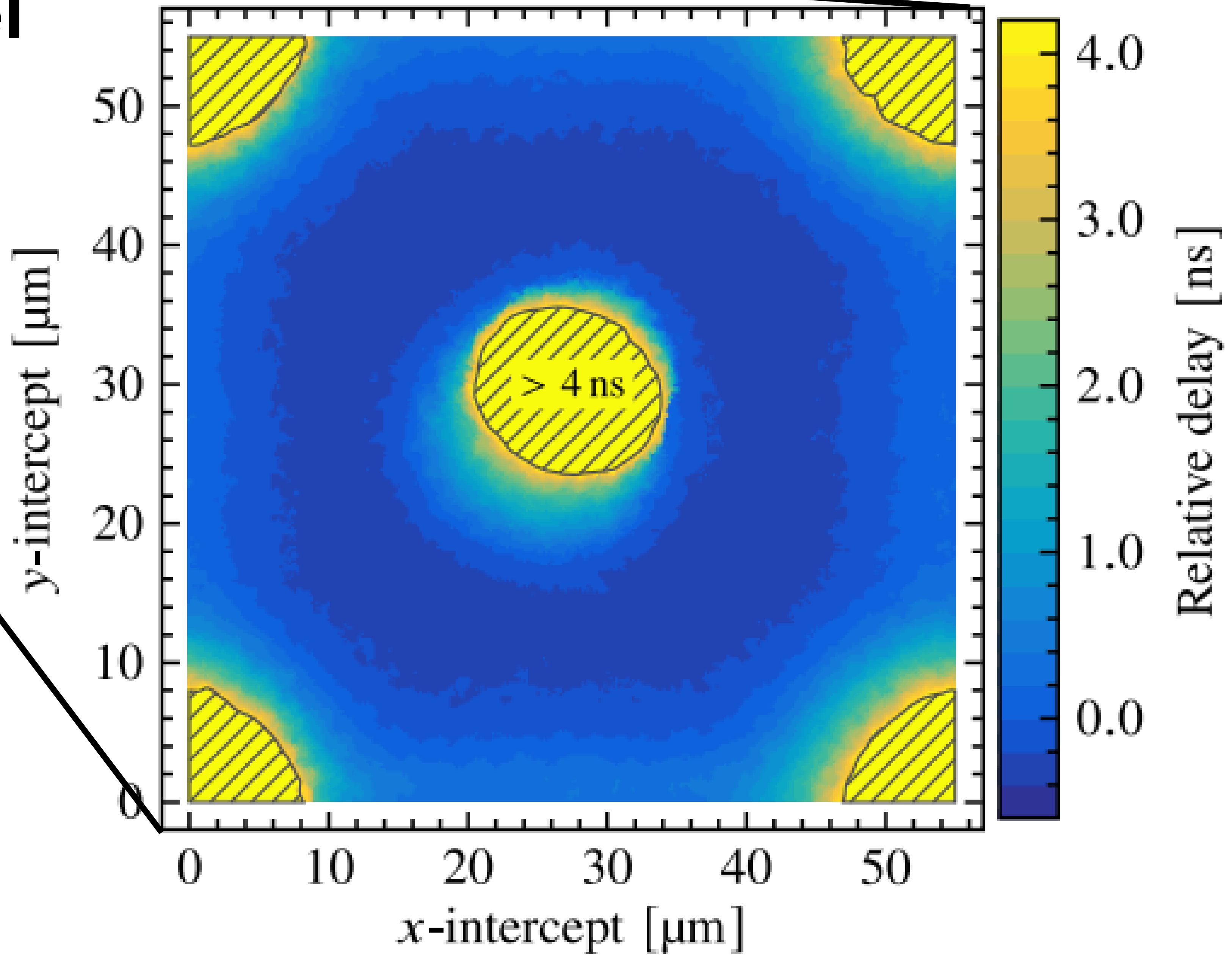
Intrapixel time delay

Timepix3 pixel ASIC + sensor

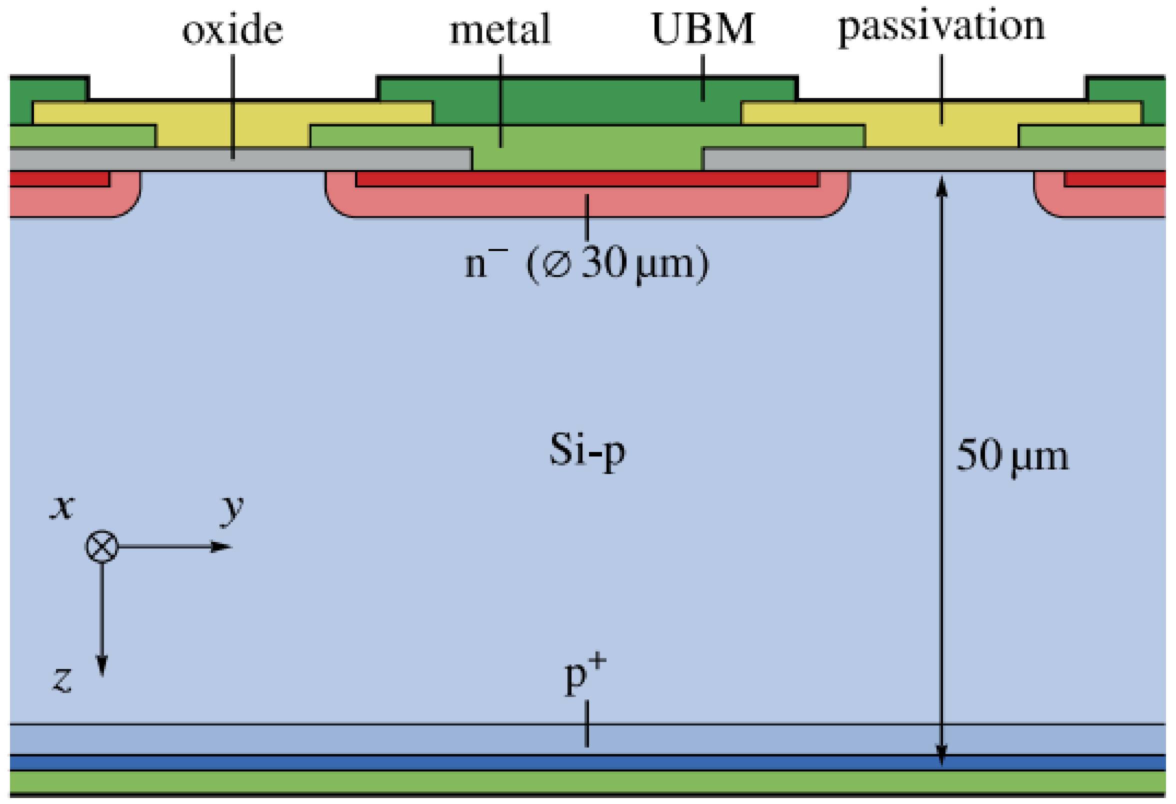


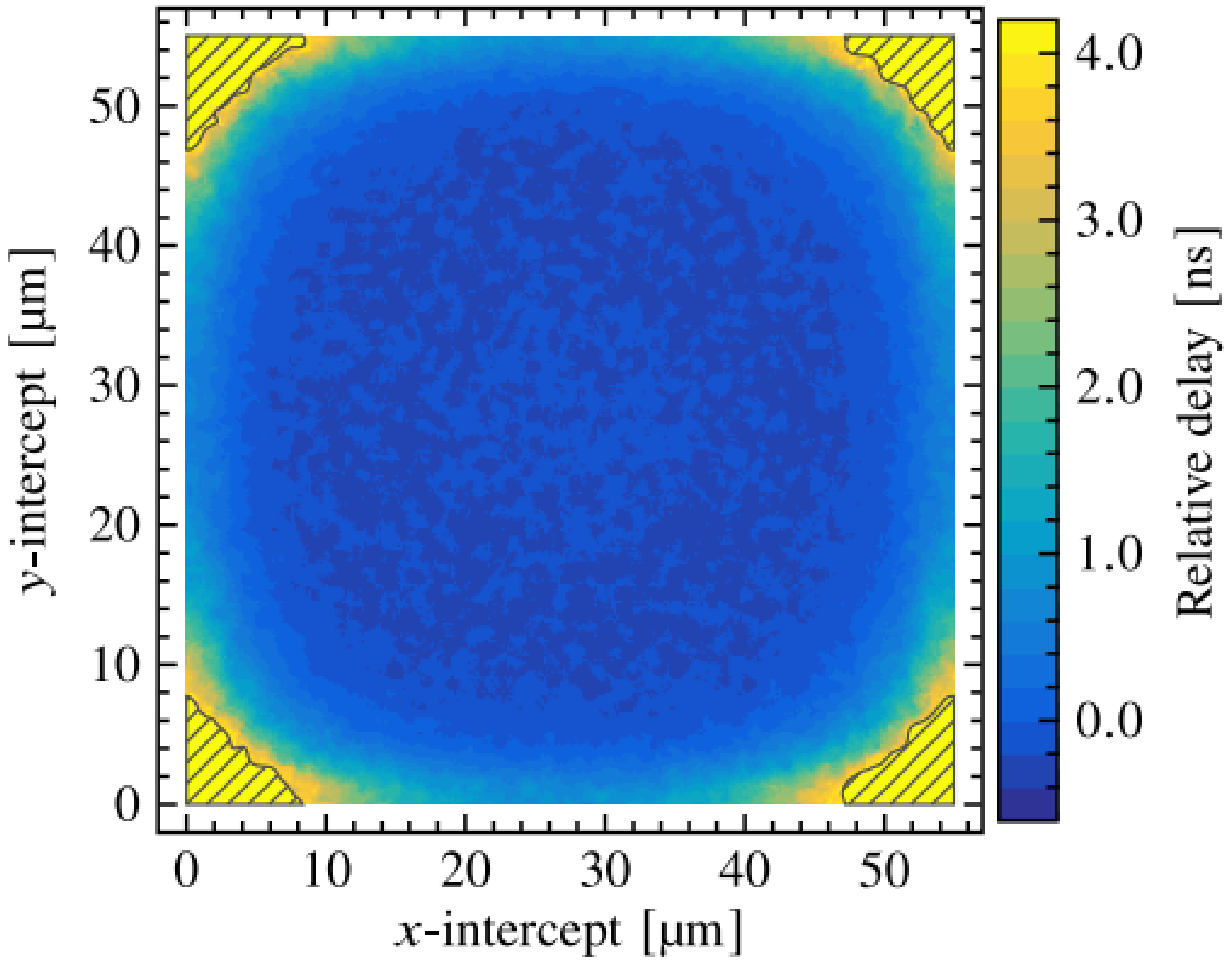
3D sensor technology





Thin planar sensor





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