4D tracking results with the Timepix4 Telescope

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Pixel 2024 — 21 November 2024

People involved

Testbeam crew

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University of Manchester:	T. Evans
University of Oxford:	D. Bacher, F. Goncalves Abrantes,
University of Birmingham:	R. Gao, D. Johnson, M. J. Madurai
University of Glasgow:	N. Cooke, A. Docheva

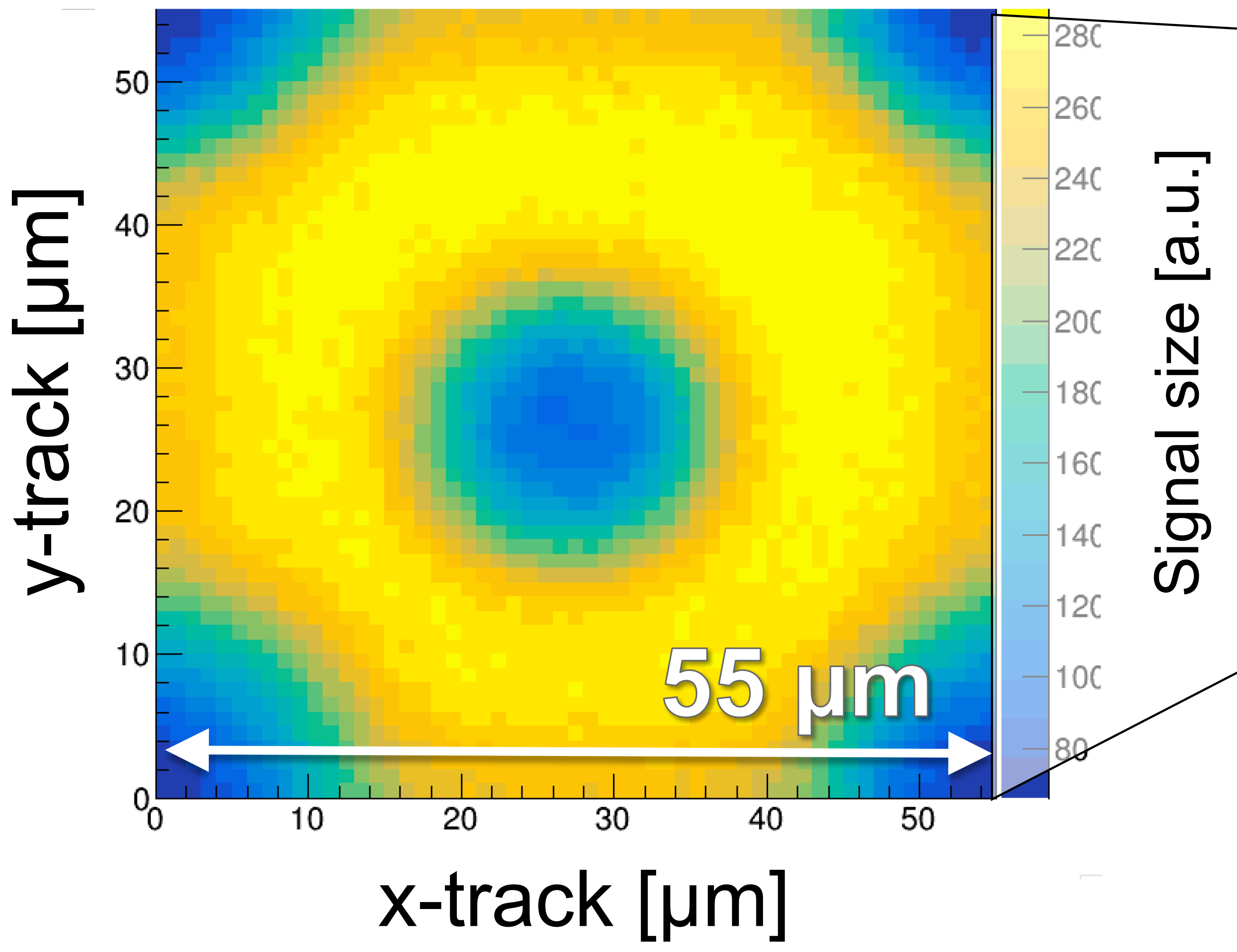
And acknowledgements to everyone making this possible, including

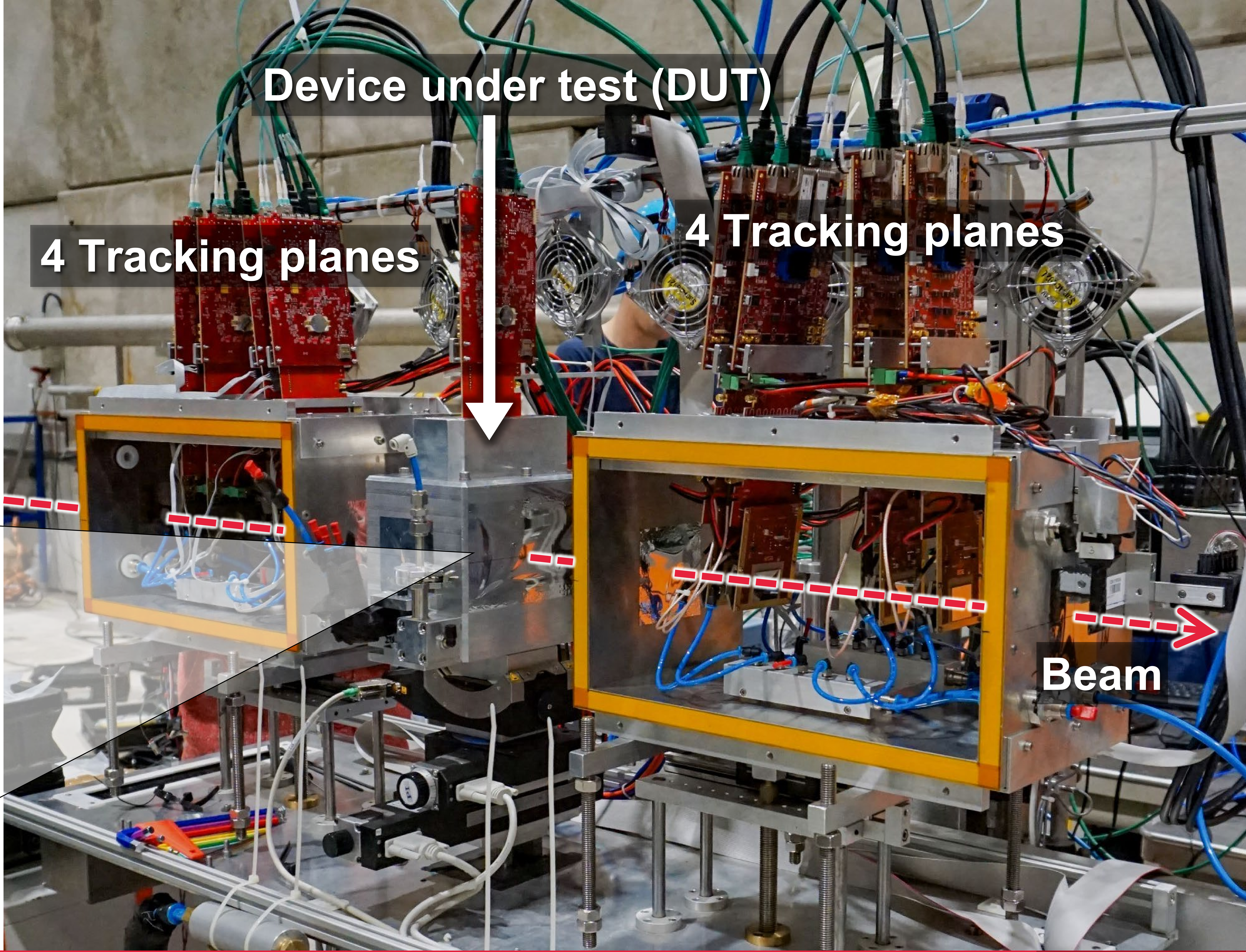
J. Alozy, R. Ballabriga Sune, R. Bates, V. van Beveren, H. Boterenbrood, M. Campbell, P. Collins, M. van Dijk, M. Fransen, A. Gallas Torreira, T. Gys, V. Gromov, E. L. Gkougkousis, M. M. Halvorsen, B. van der Heijden, M. John, X. Llopart Cudie, L. Martinazolli, H. Schindler, P. Vázquez Regueiro, A. Vitkovksiy

Timepix4 Telescope

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

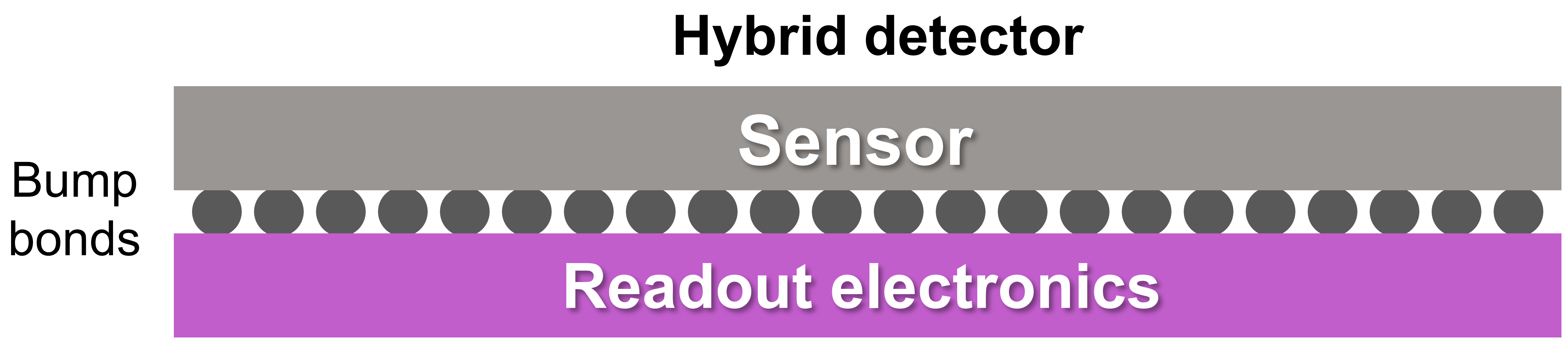
Intrapixel signal size

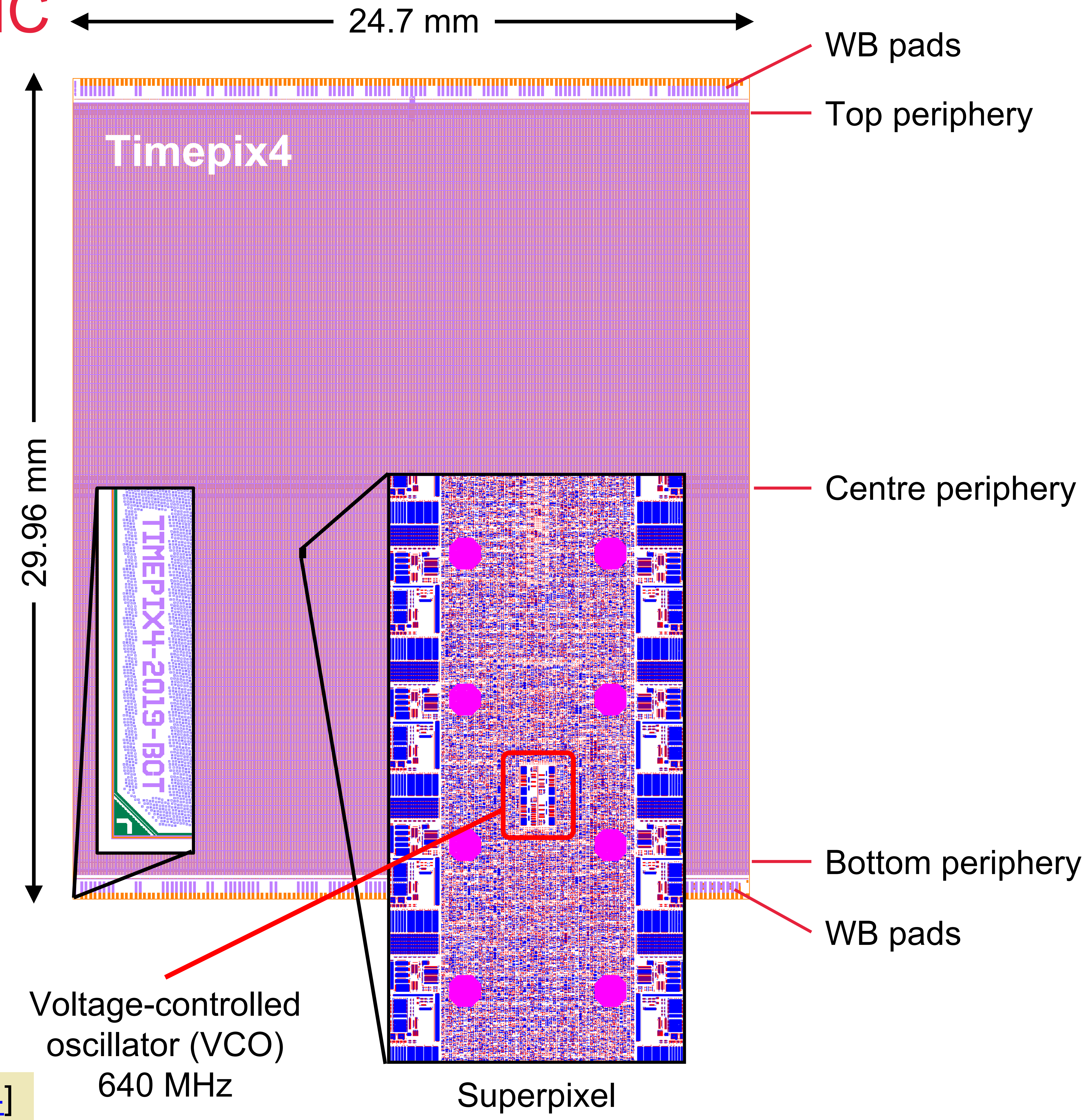




Timepix4: Hybrid pixel detector readout ASIC

- 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)





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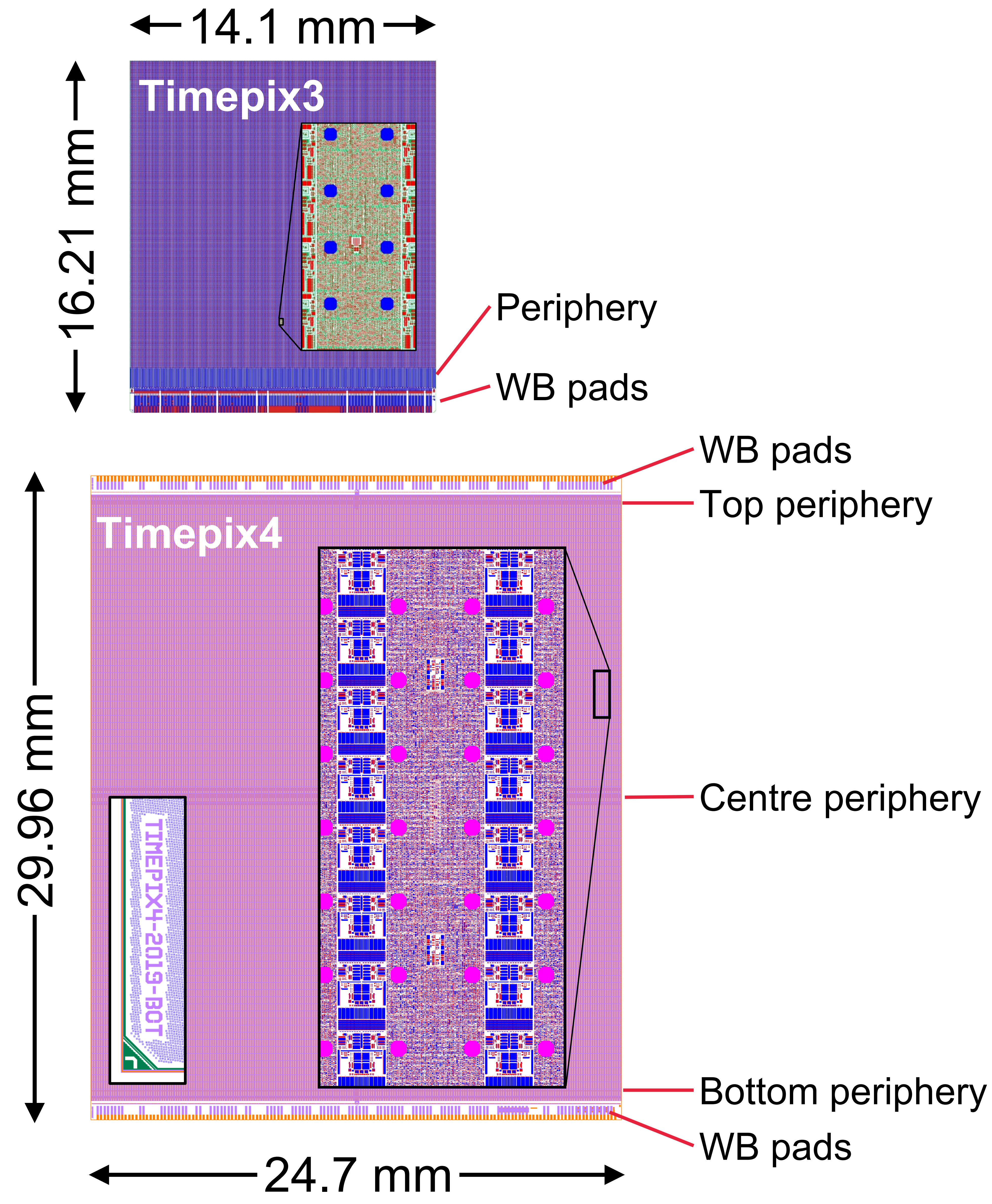
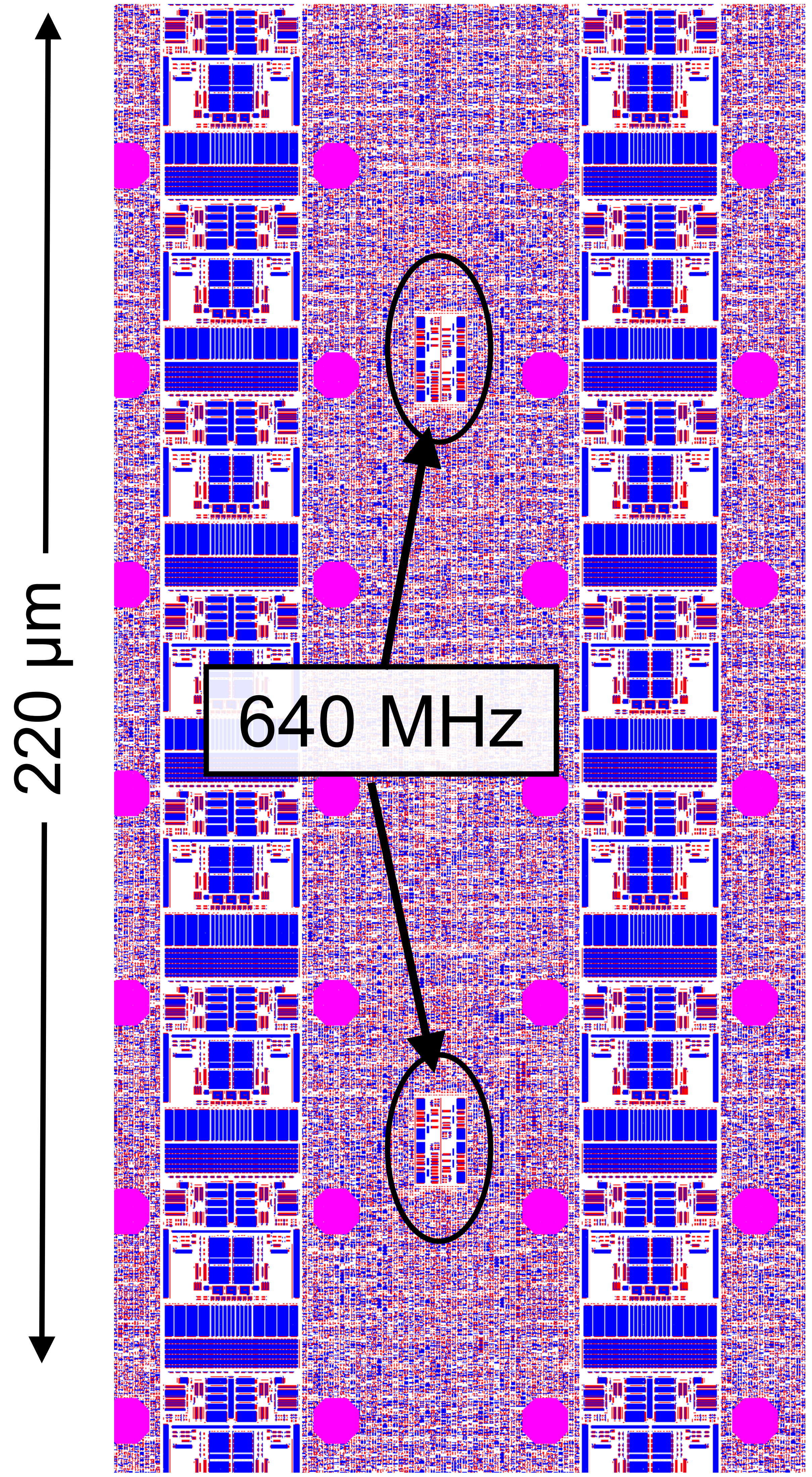
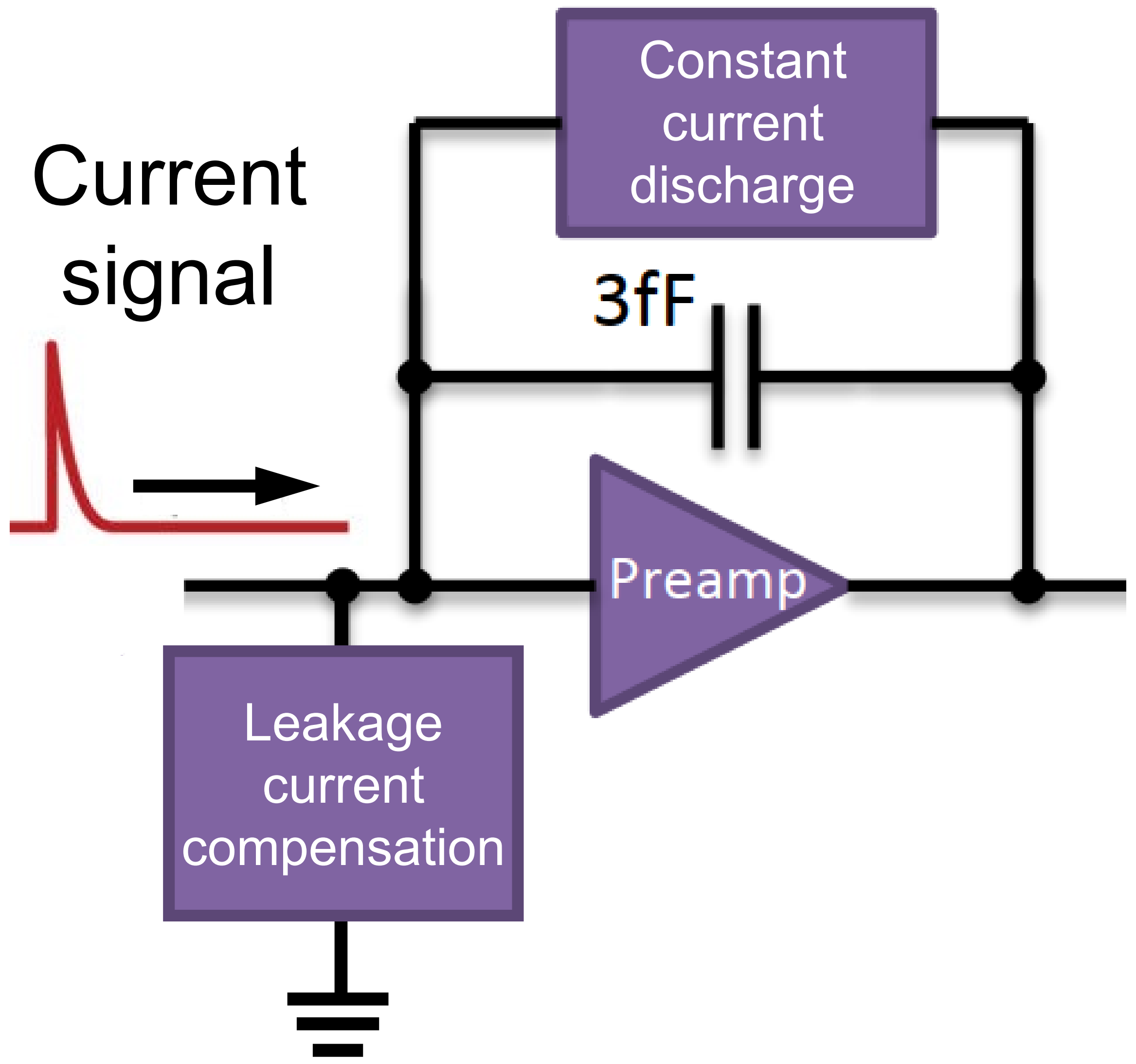
Timepix3 → Timepix4



			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
Sensitive area			1.98 cm^2	**6.94 cm^2** (3.5x)
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	< **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^-

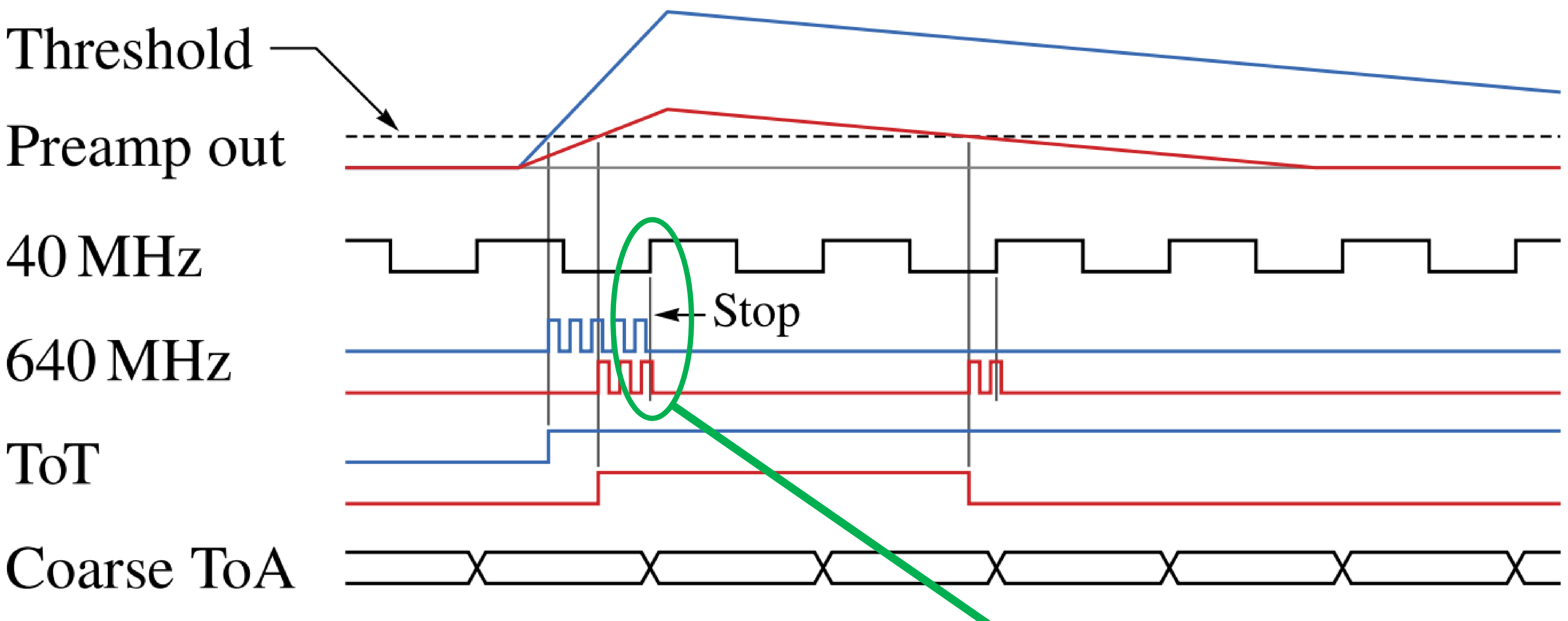
Time measurement in Timepix4



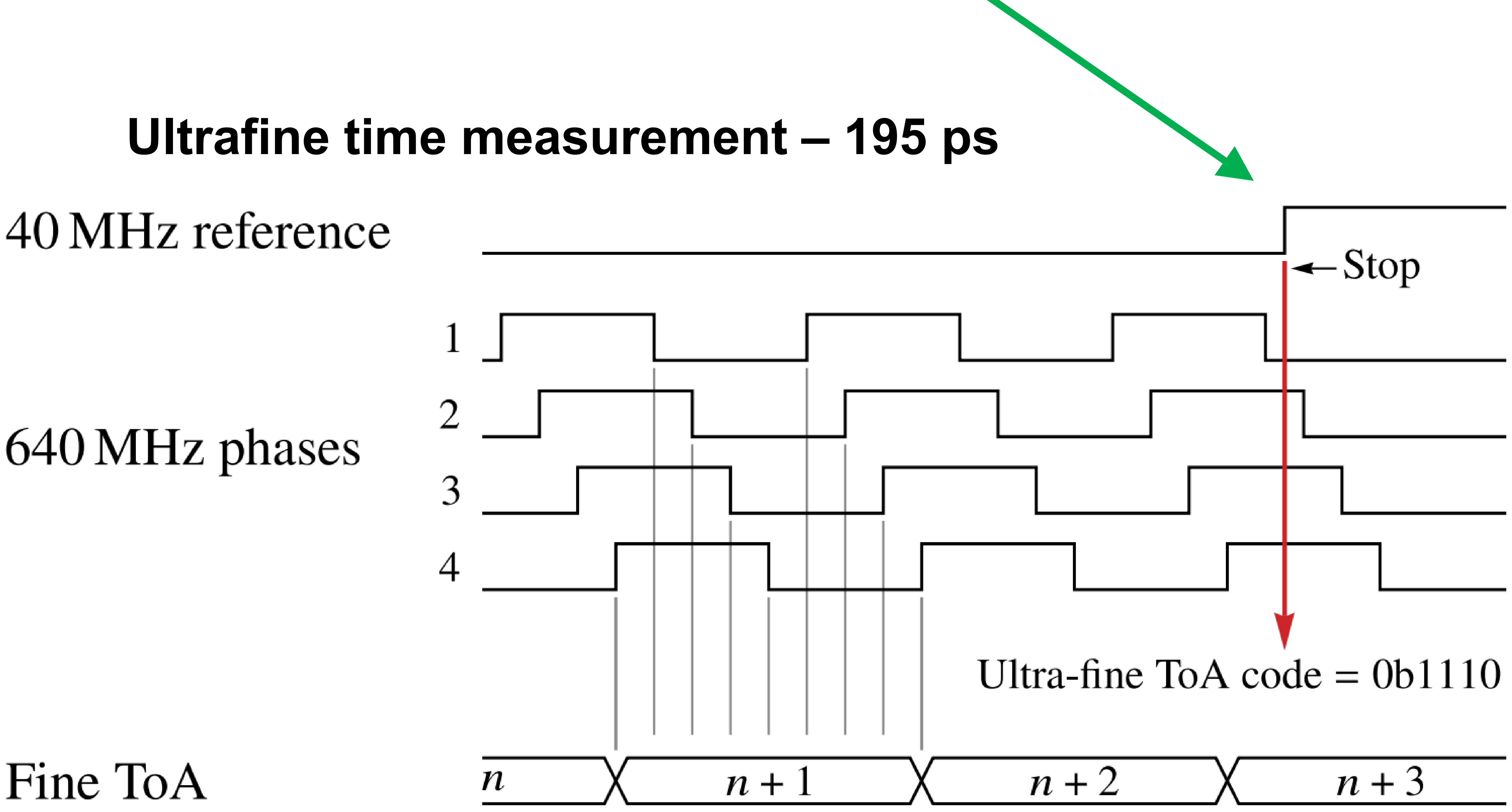


- Nominal TDC resolution: $195 \text{ ps}/\sqrt{12} = 56 \text{ ps}$
- Time over threshold (ToT) measures signal charge

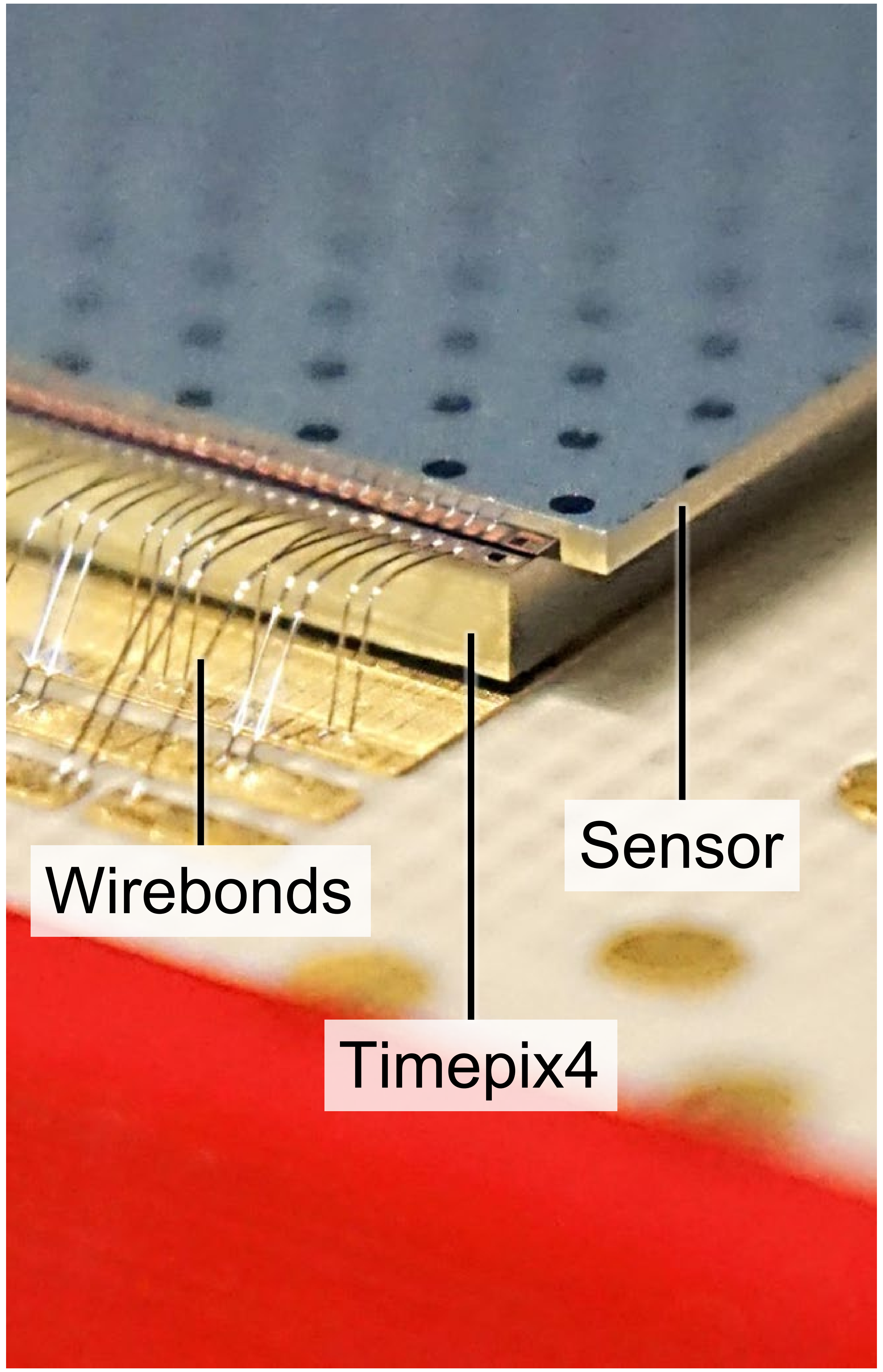
Coarse and fine time measurement – 40 MHz and 640 MHz

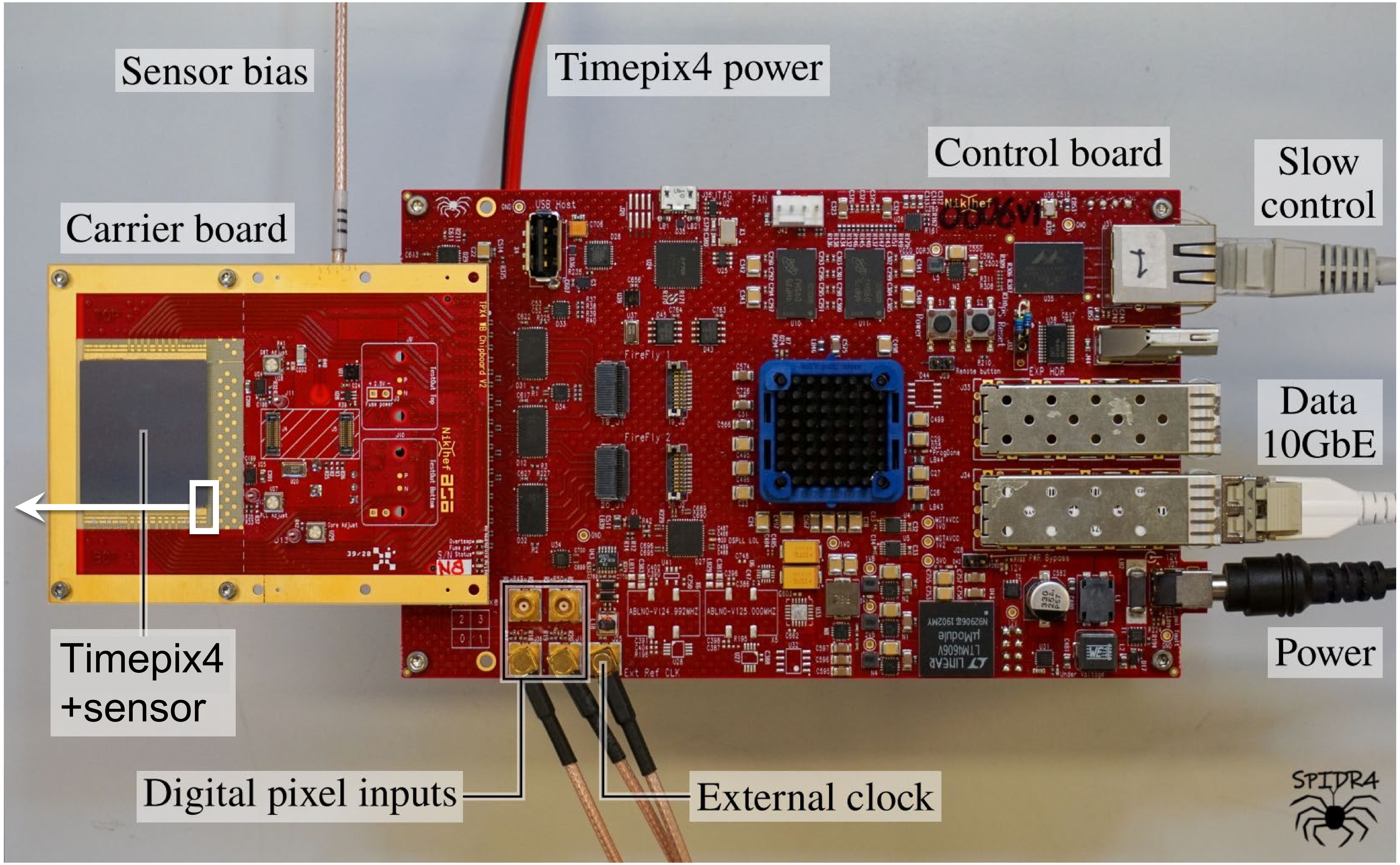


Ultrafine time measurement – 195 ps



Speedy PIxel Detector Readout 4 (SPIDR4)

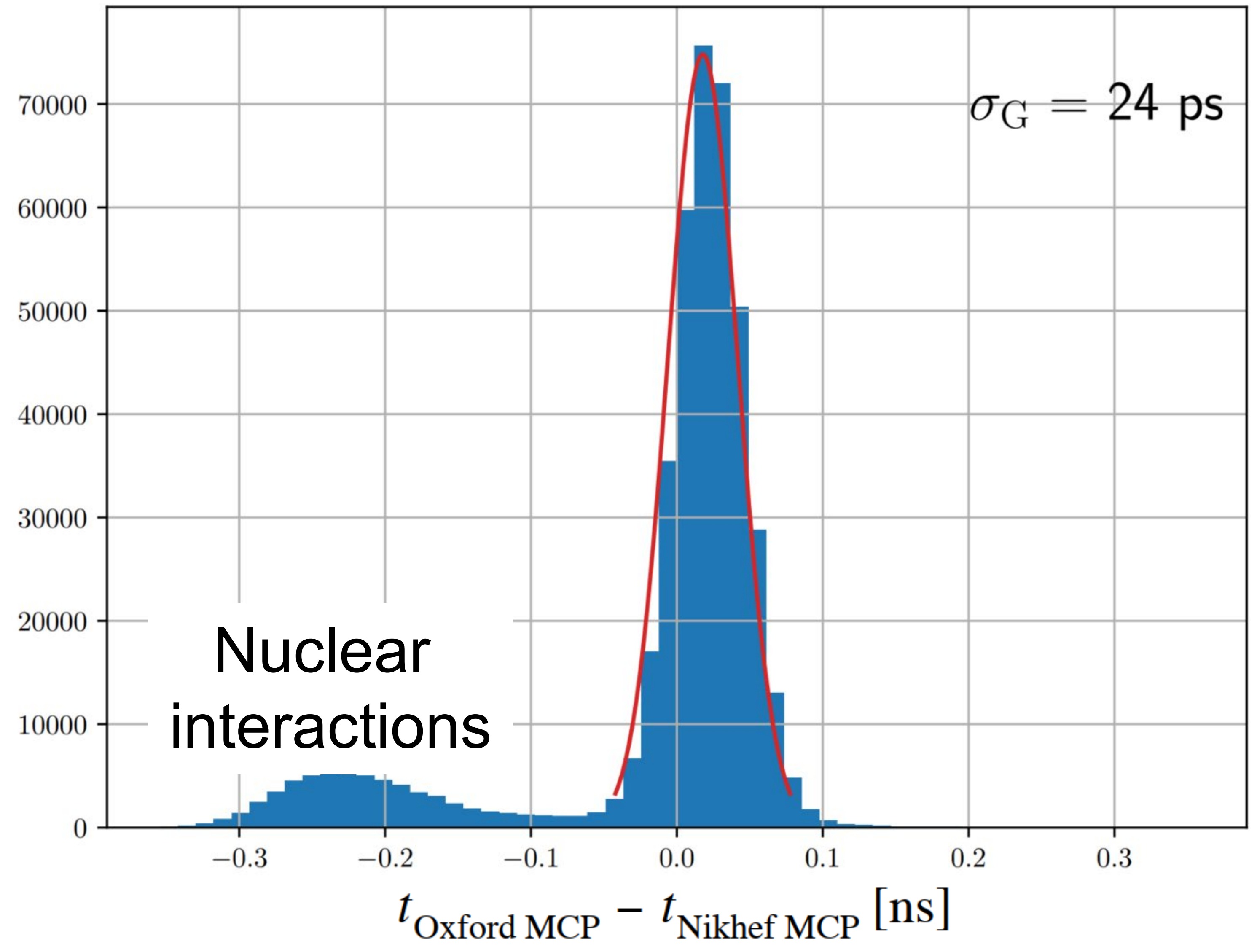


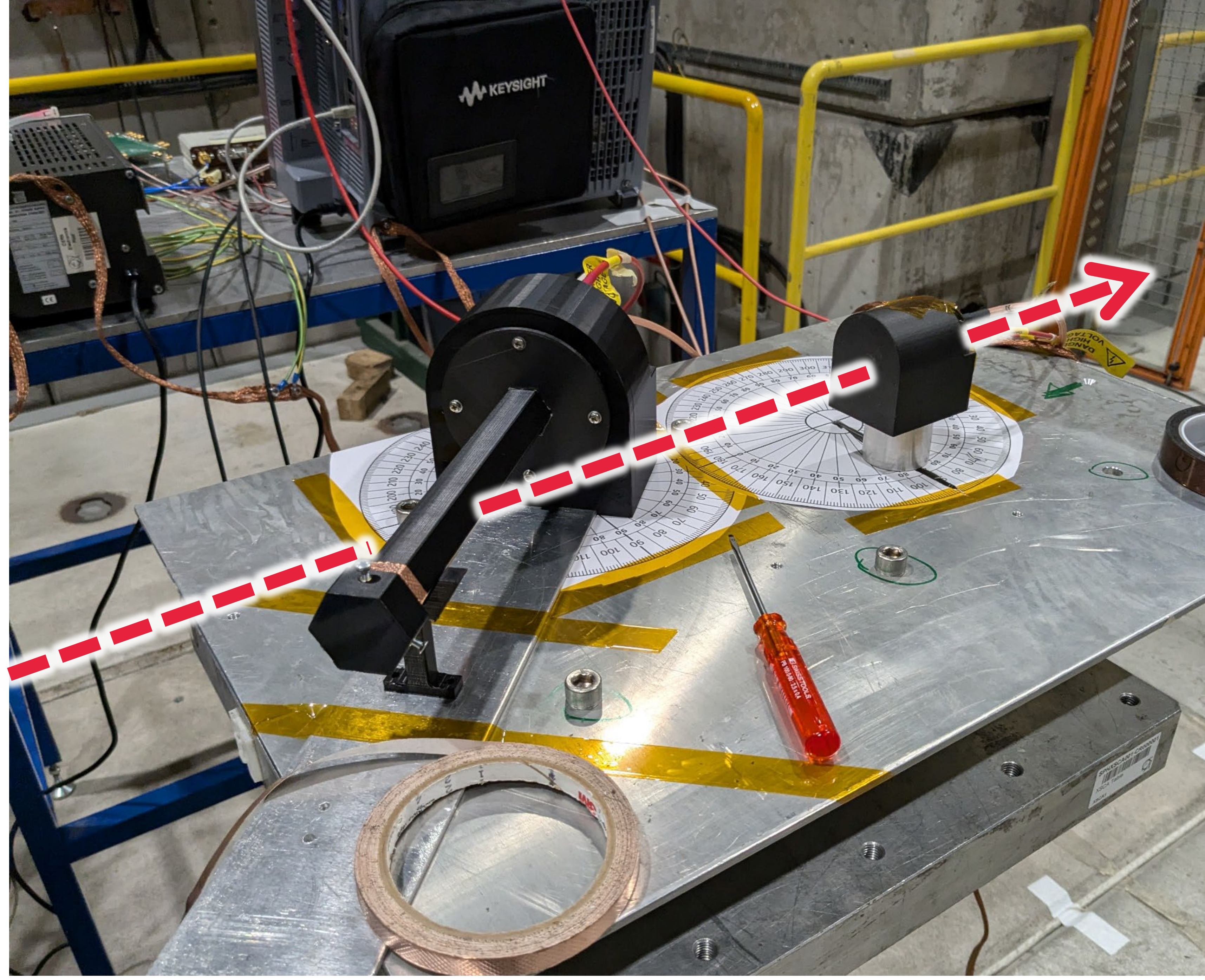


Telescope configuration

Micro channel plate detectors for time reference

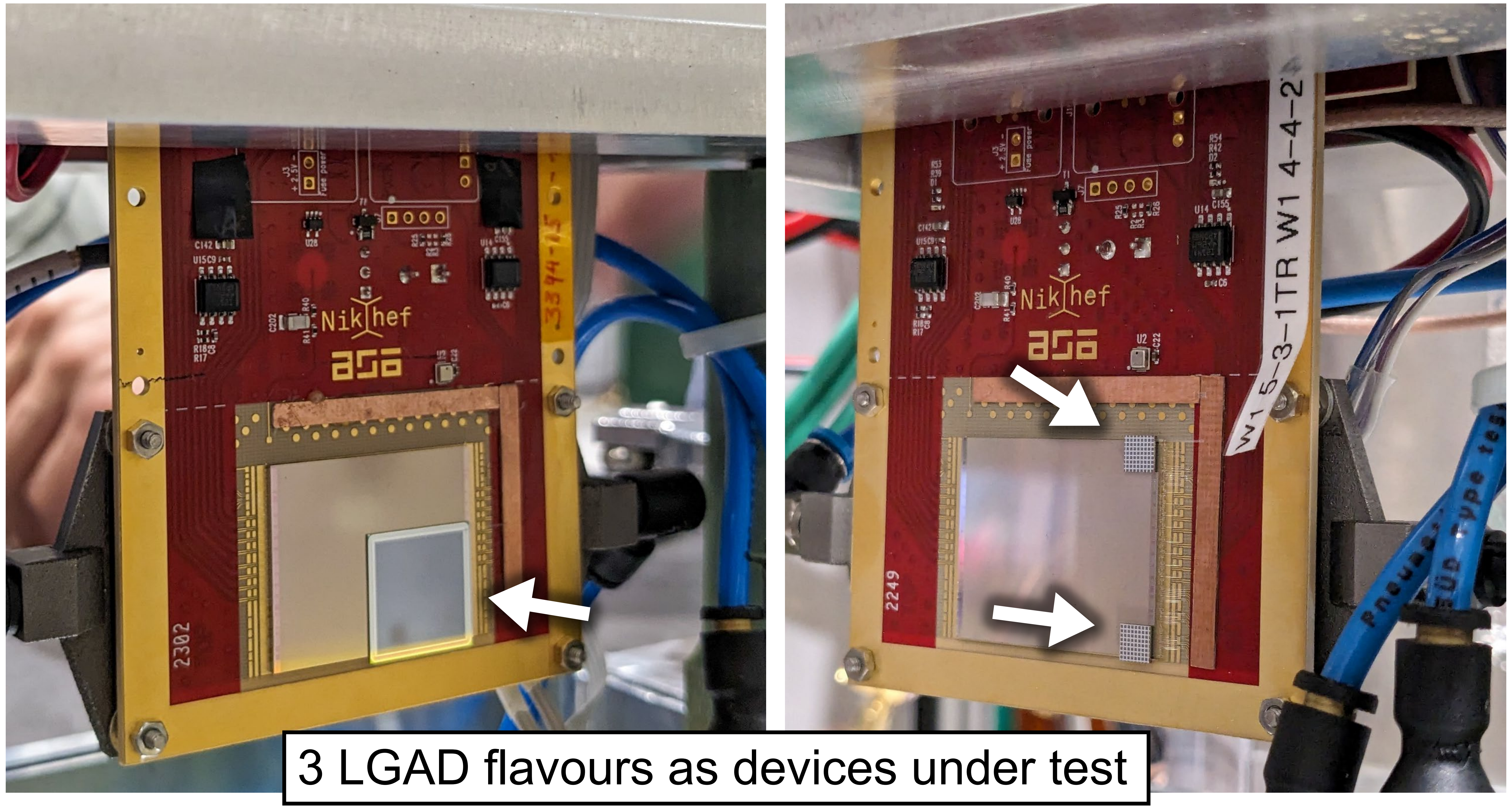
- Time reference to study telescope timing
- Considering installing Timpix4 plane to VETO events with nuclear interactions
- Current time resolution: 17 ps (single MCP)
- Combined MCP resolution: 12 ps
- Experimenting with quartz/borosilicate fingers to get MCP out of beam

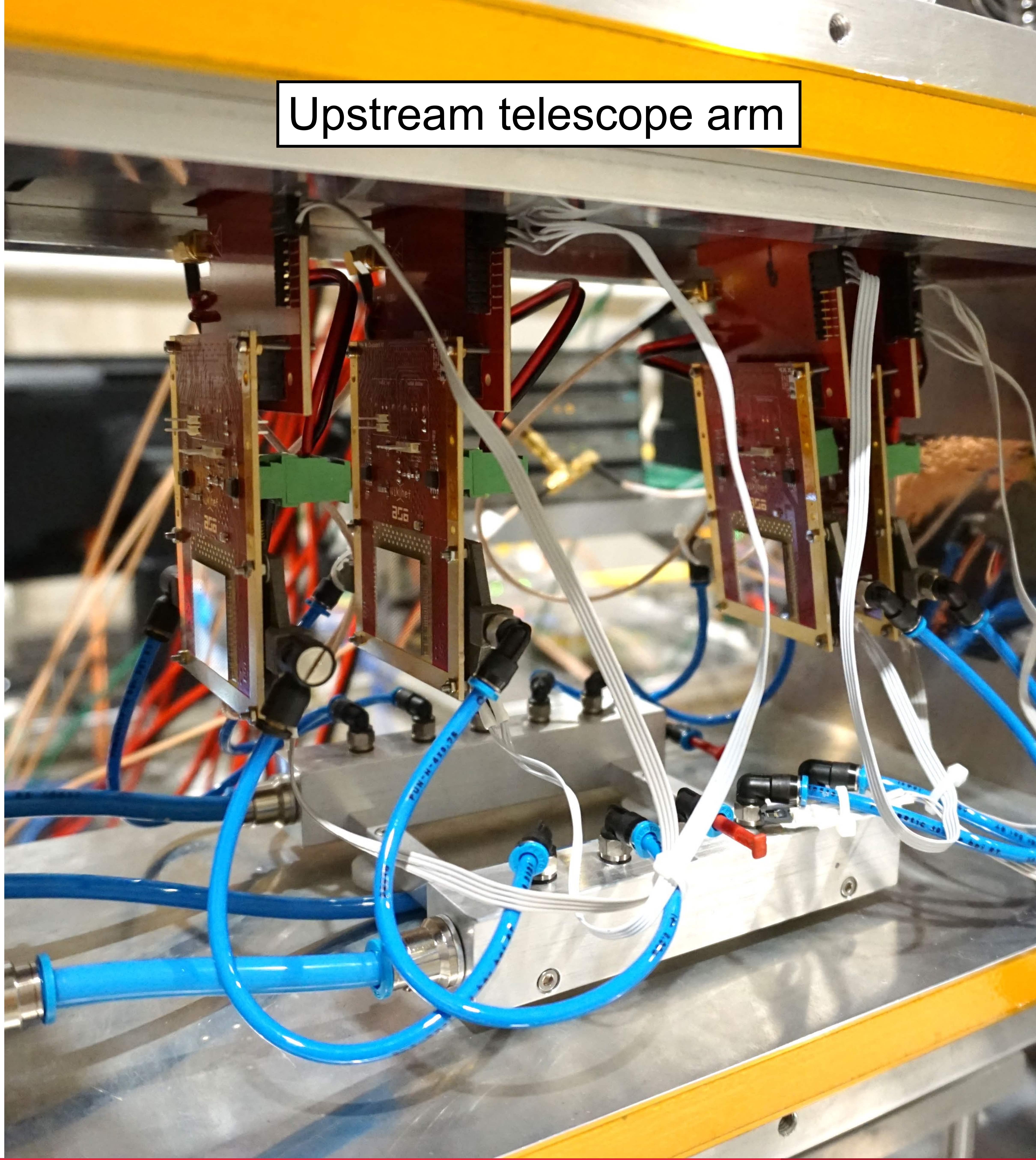




Plane assemblies

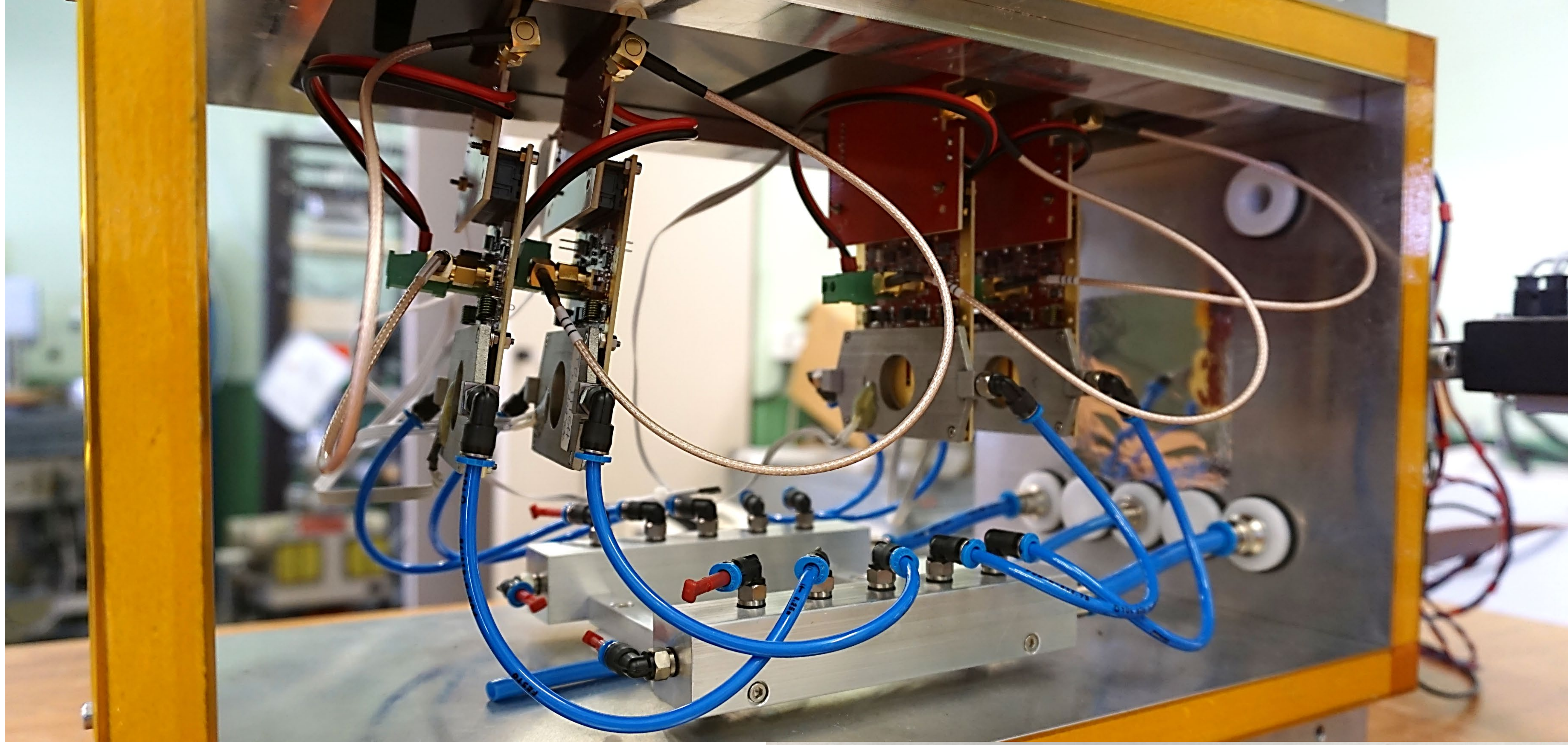
- Eight telescope planes with n-on-p planar silicon sensors
- 4 x 300 µm sensors for spatial resolution (angled)
- 4 x 100 µm sensors for time resolution (perpendicular)
- Sensor upgrades are anticipated (LGAD, 3D, …)



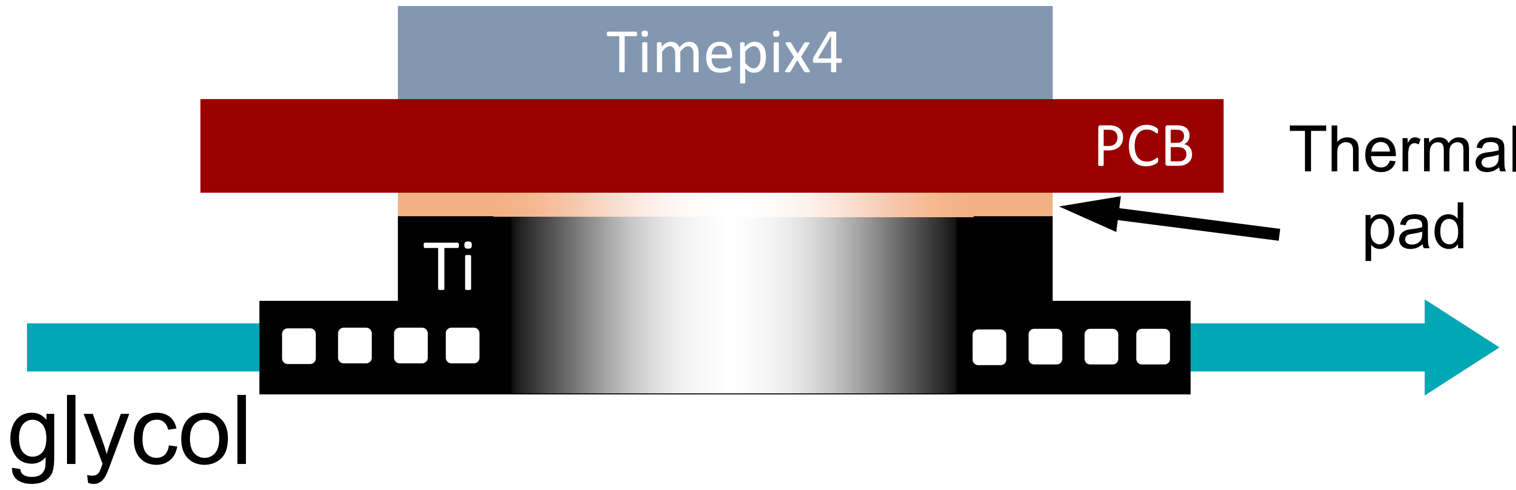


Assembly cooling

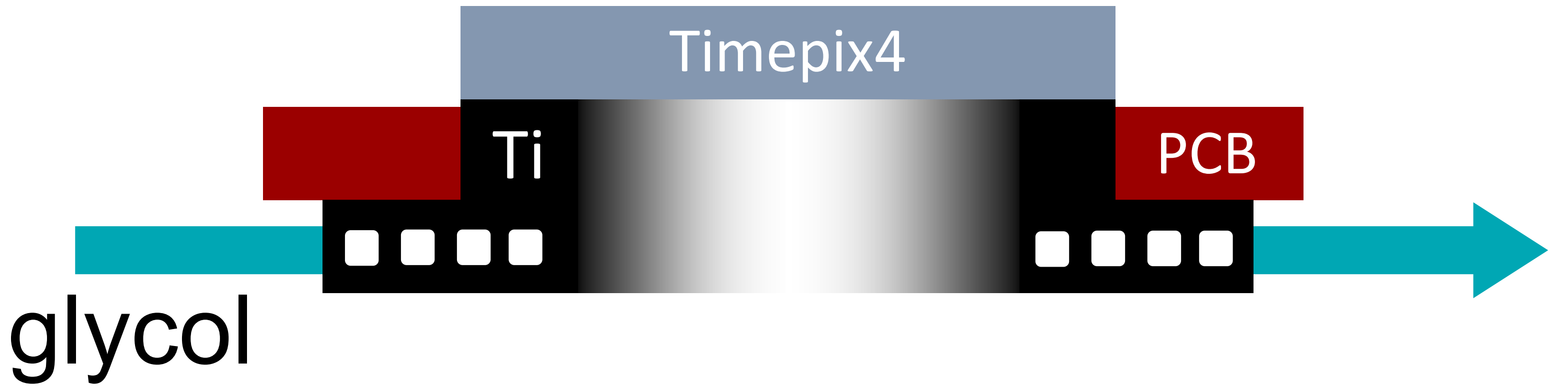
- All assemblies have a 3D-printed titanium cooling block
- Cooled using glycol at 18 °C
- Could go to –20 °C in the future
- Plan to mill PCB to have direct thermal contact with Timepix4

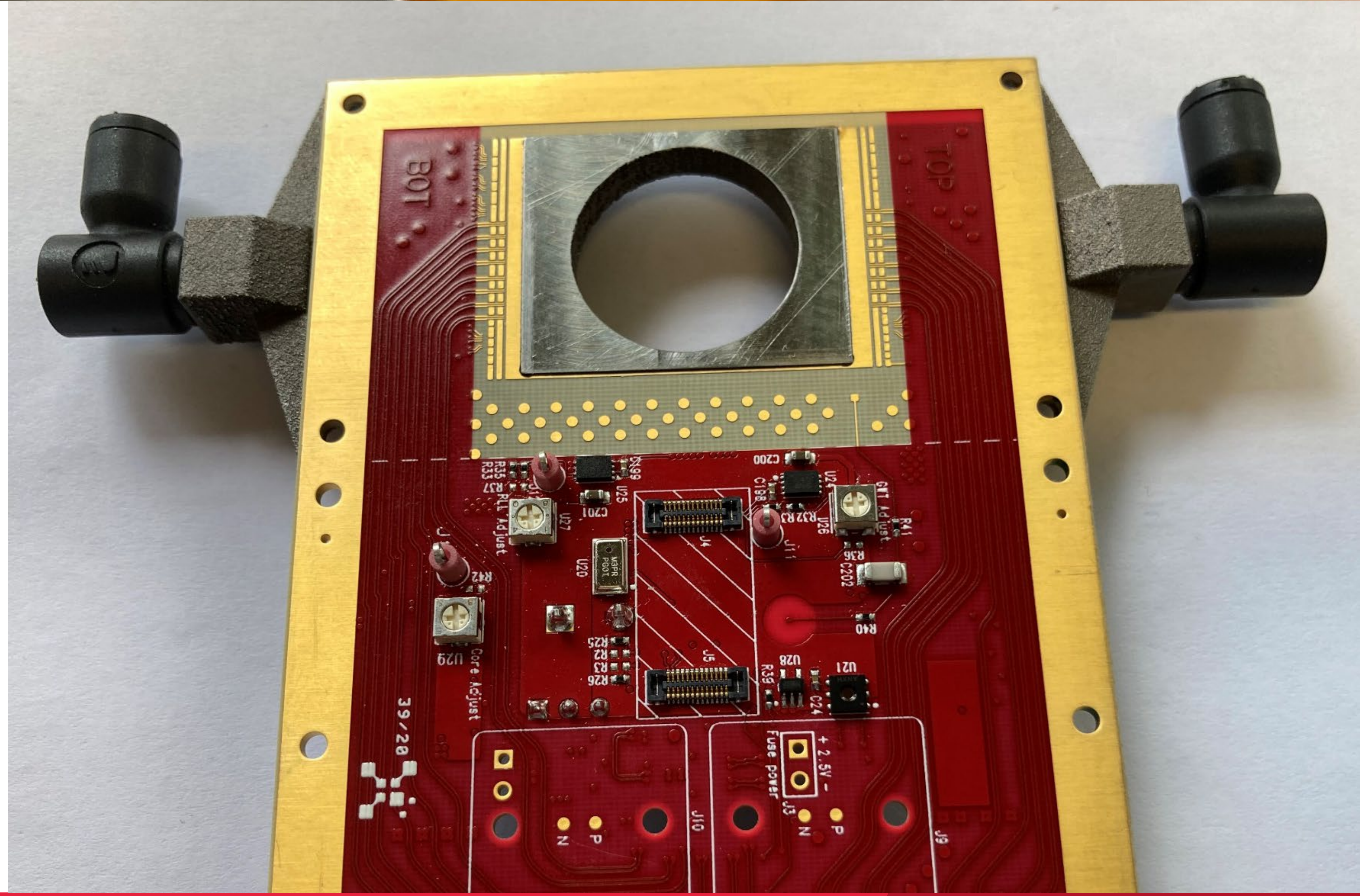


Current thermal interface



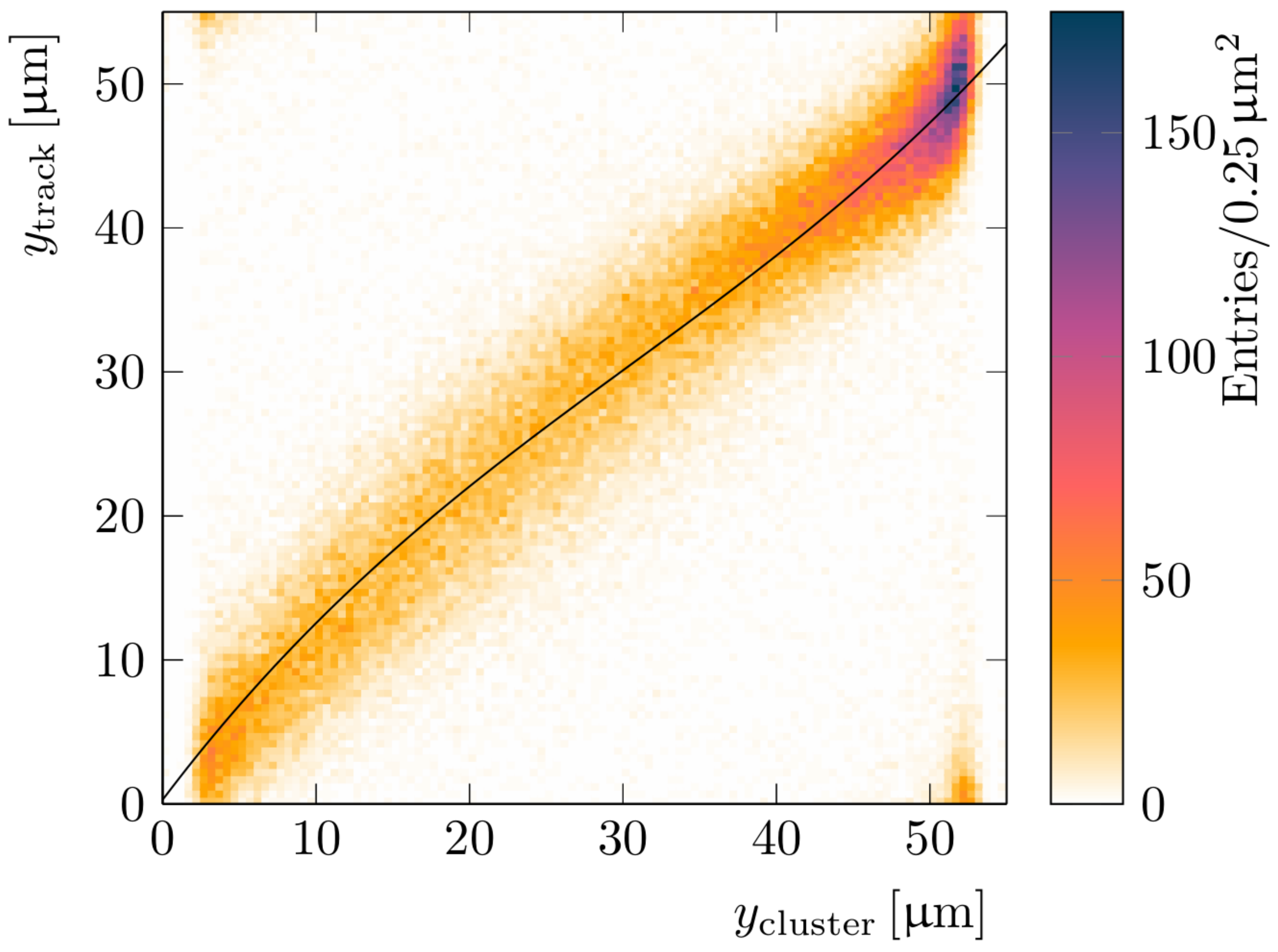
Future thermal interface

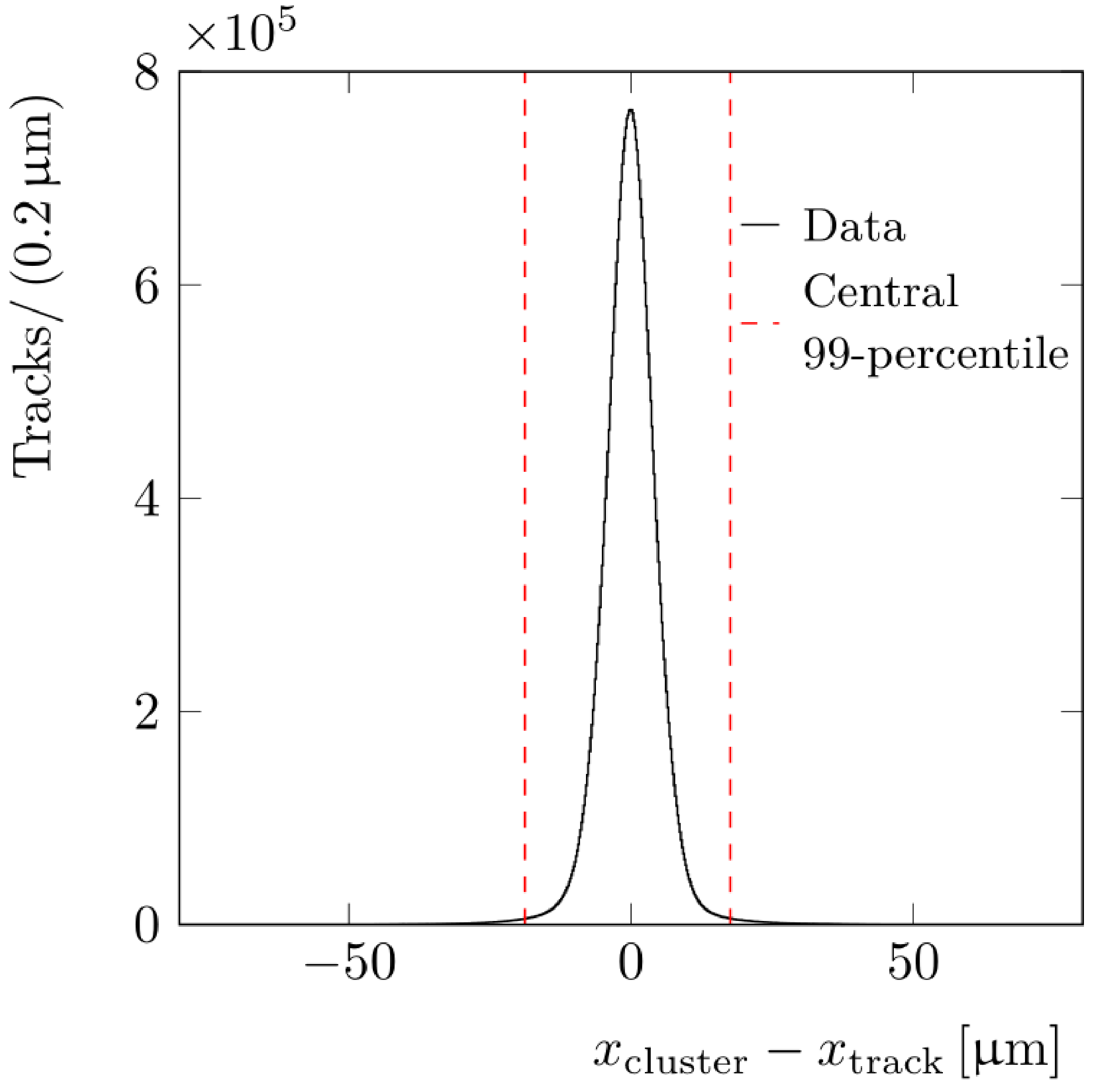


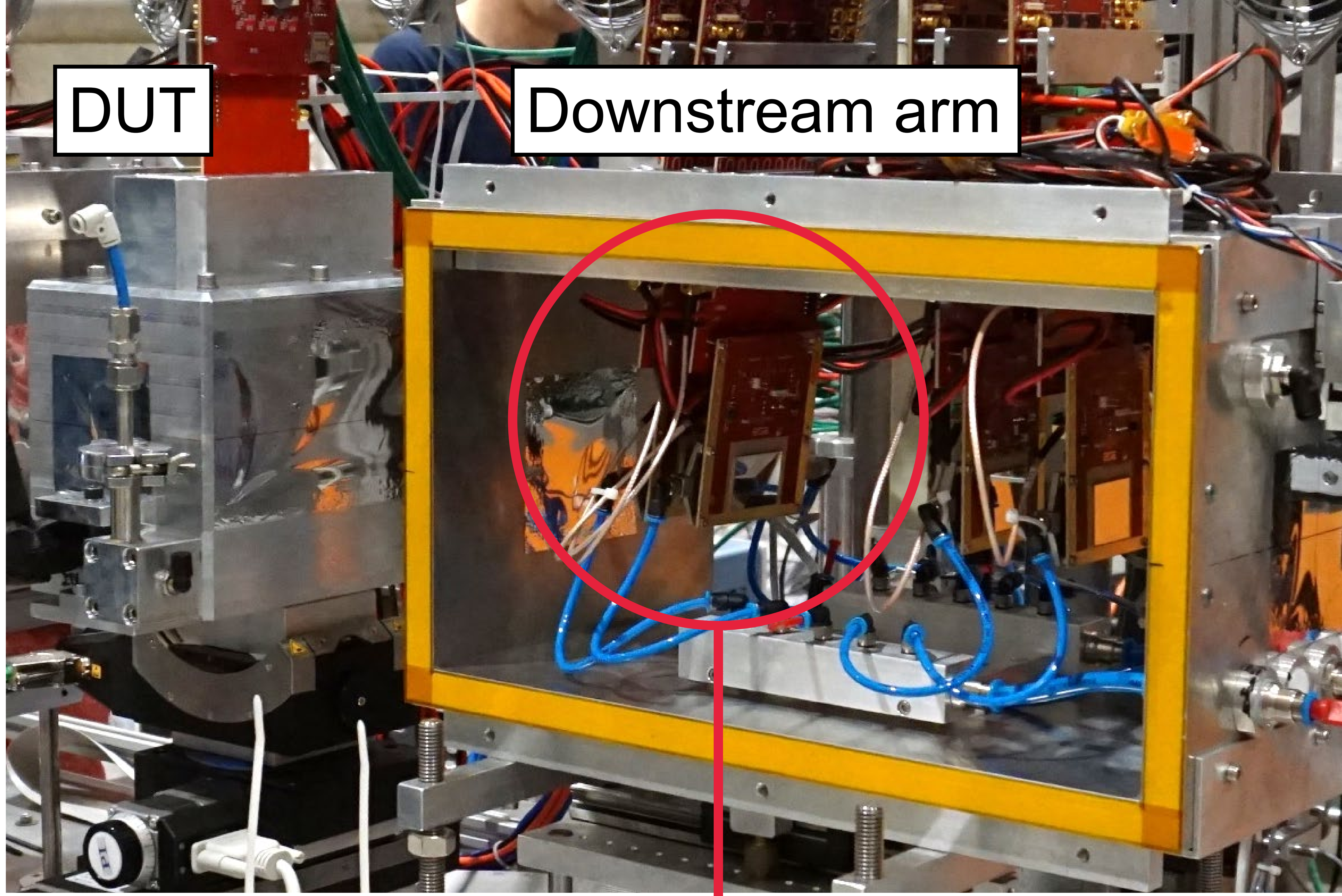


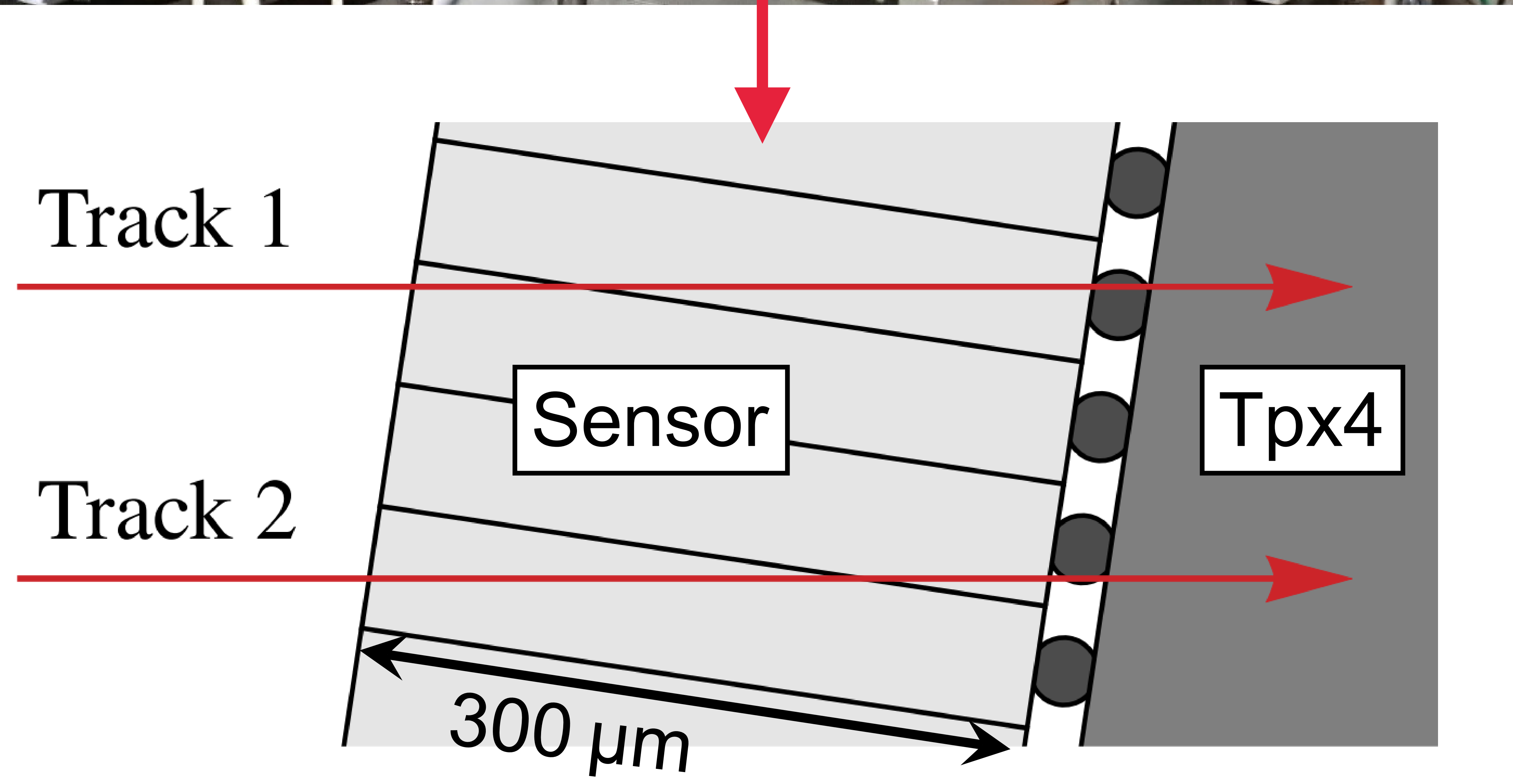
Single plane spatial resolution

- 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
- “Eta corrections” are applied for nonlinear charge sharing
- Single plane resolution: **3.3–3.5 µm**





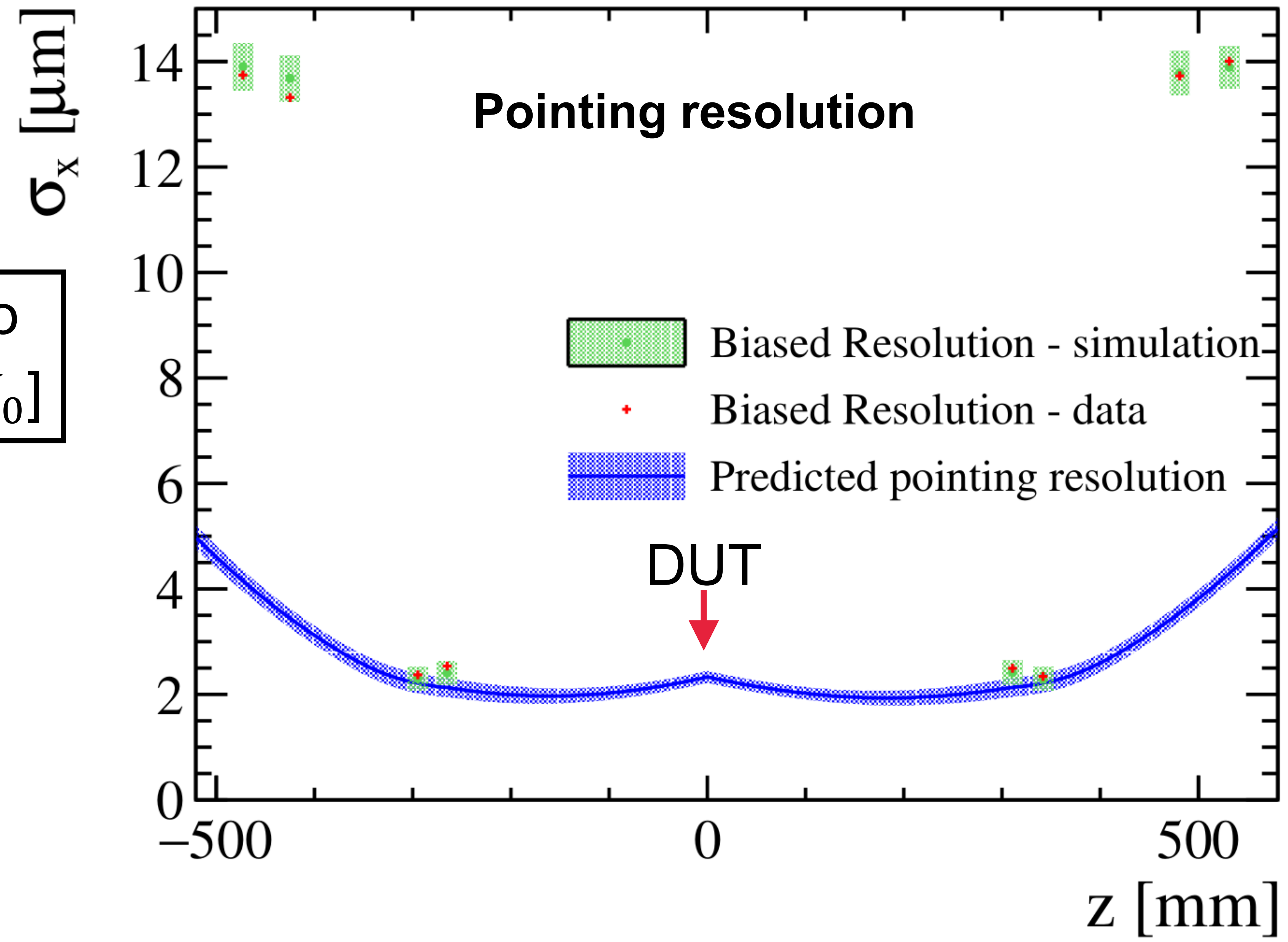


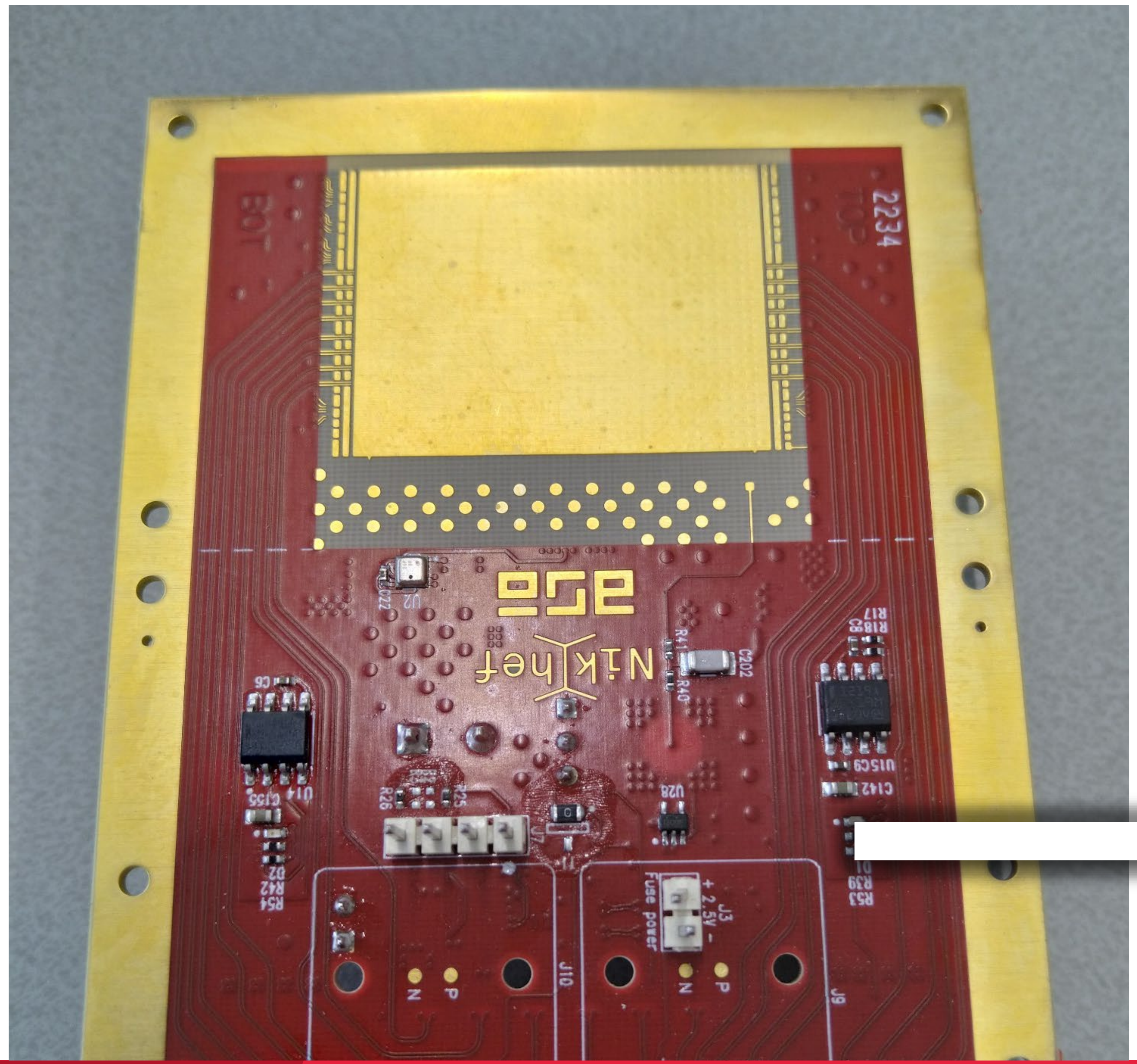


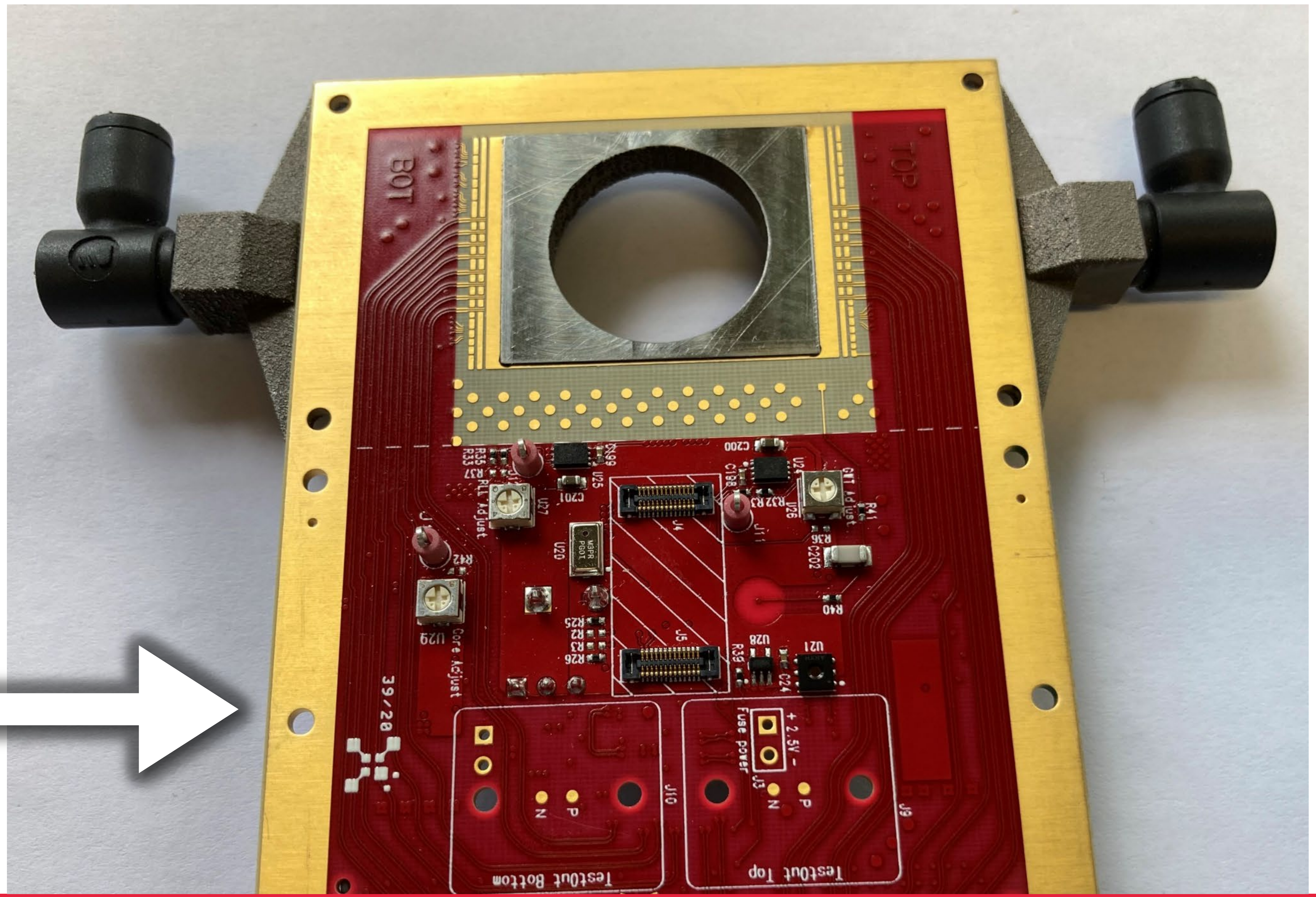
Track pointing resolution

- Pointing resolution at DUT: **2.4 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
- Other possible improvements:
  - Move telescope arms further inward when possible
  - Operate 300 µm planes at lower detection threshold
  - Add additional planes

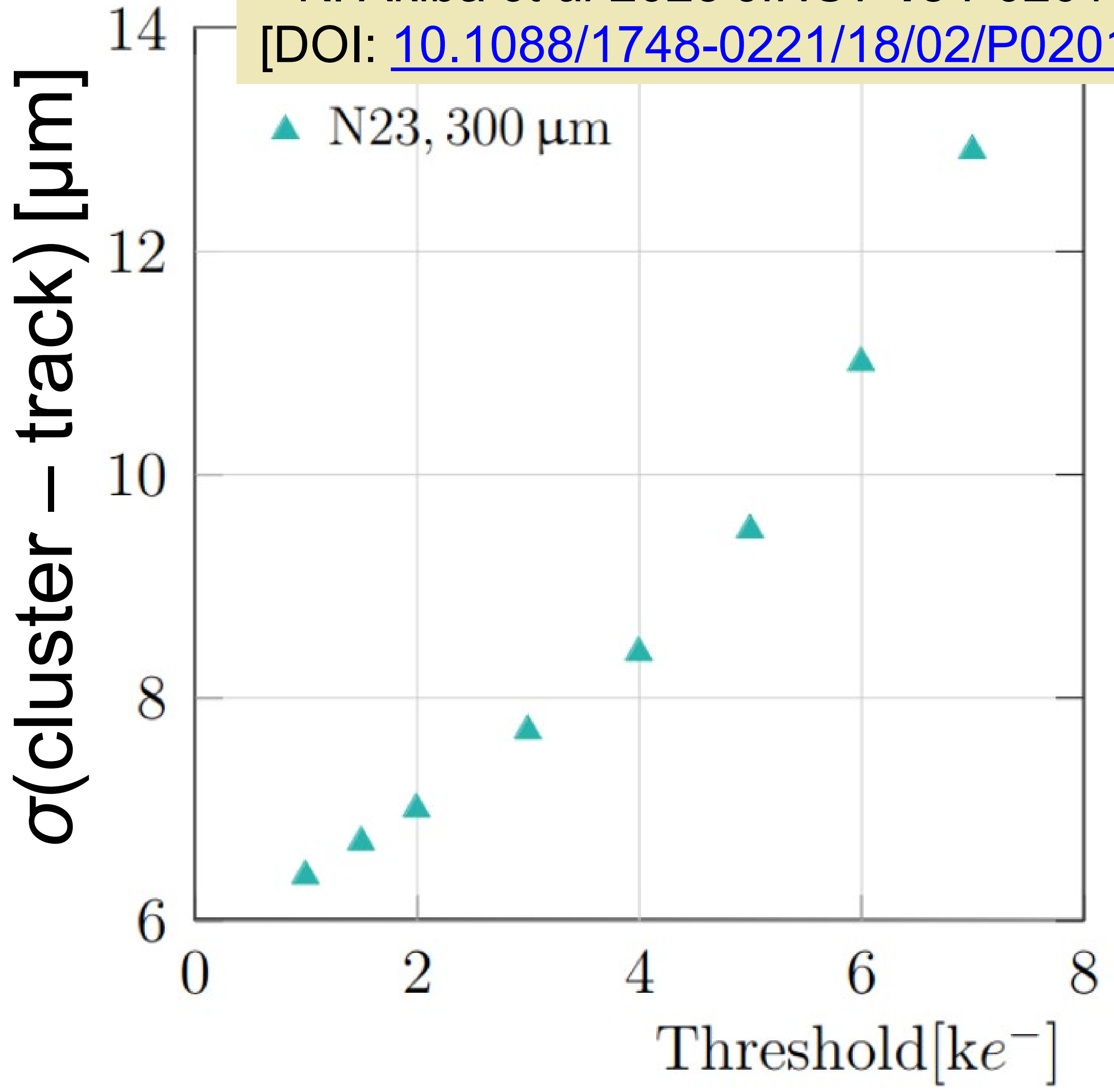
Scattering proportional to $\sqrt{x/X_0}\,[1 + 0.038 \log x/X_0]$





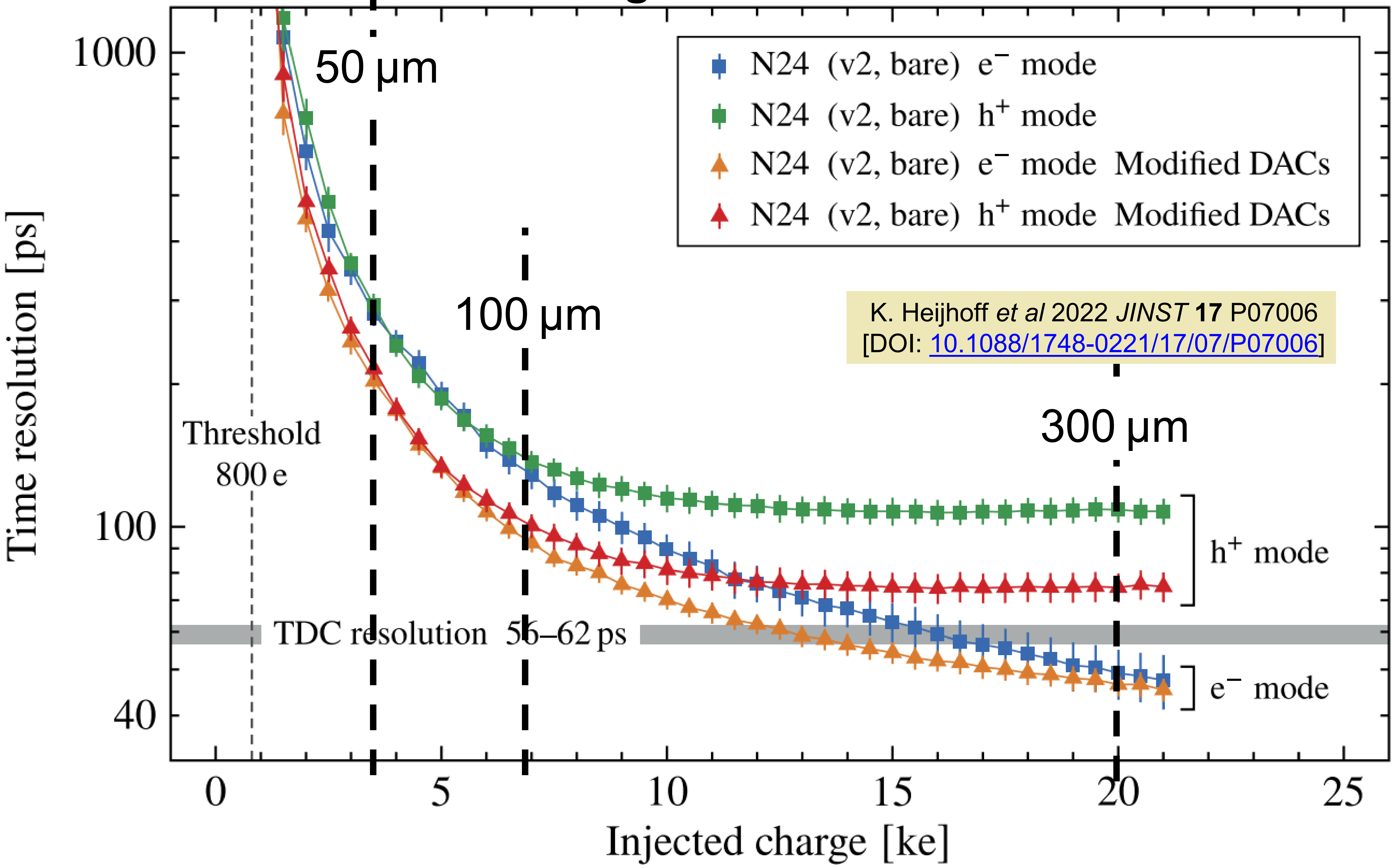


K. Akiba *et al* 2023 *JINST* **18** P02011 [DOI: 10.1088/1748-0221/18/02/P02011]

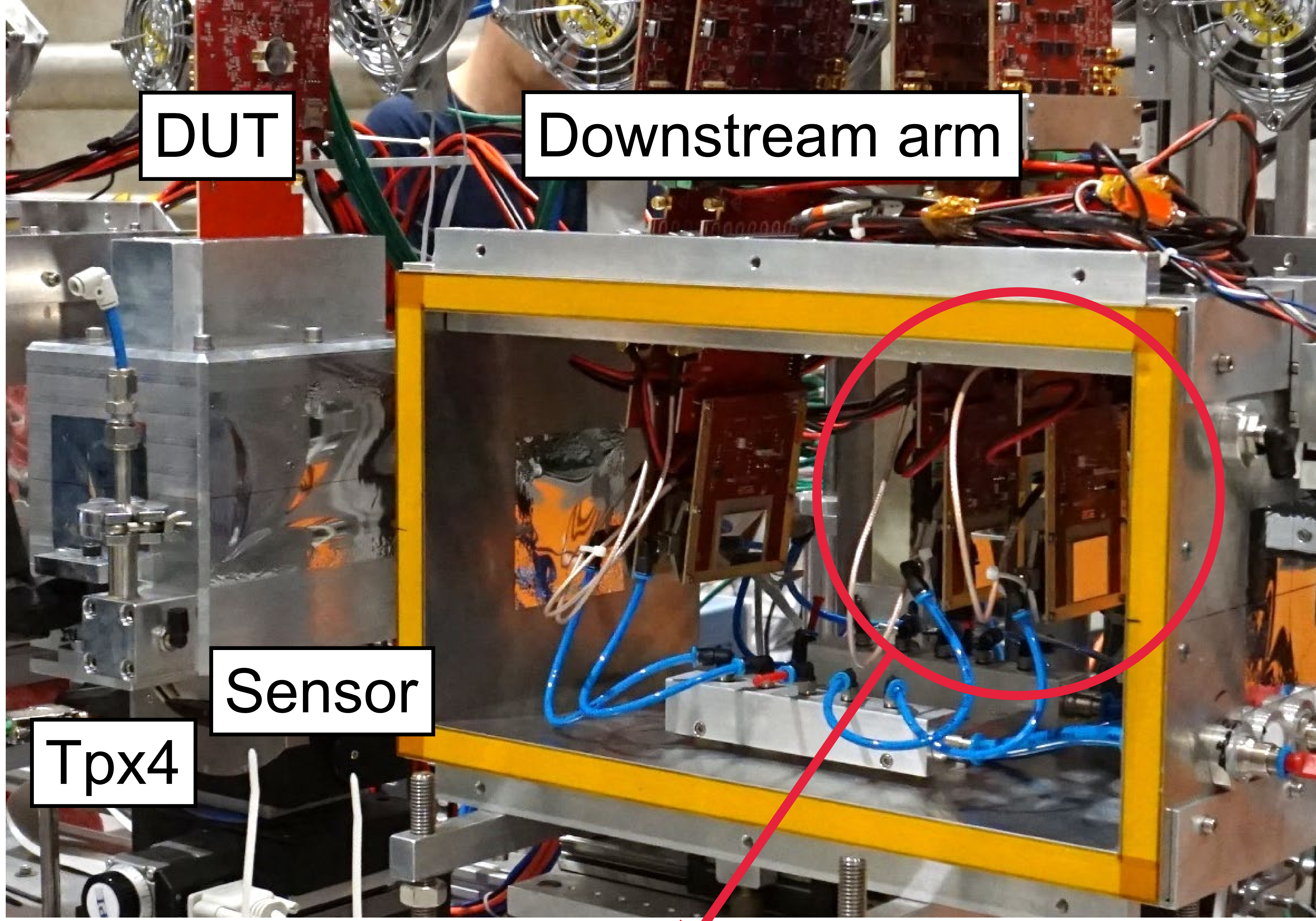


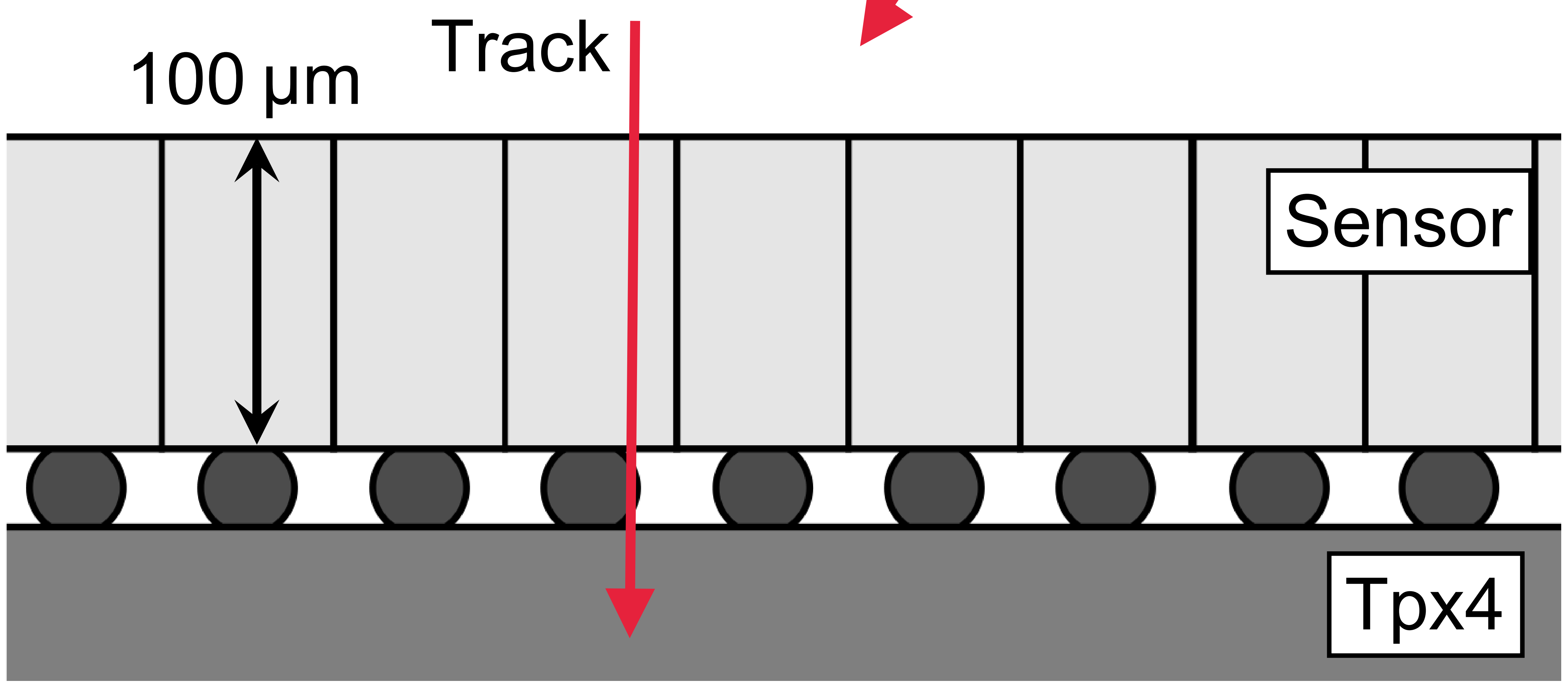
Single plane time resolution

- 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



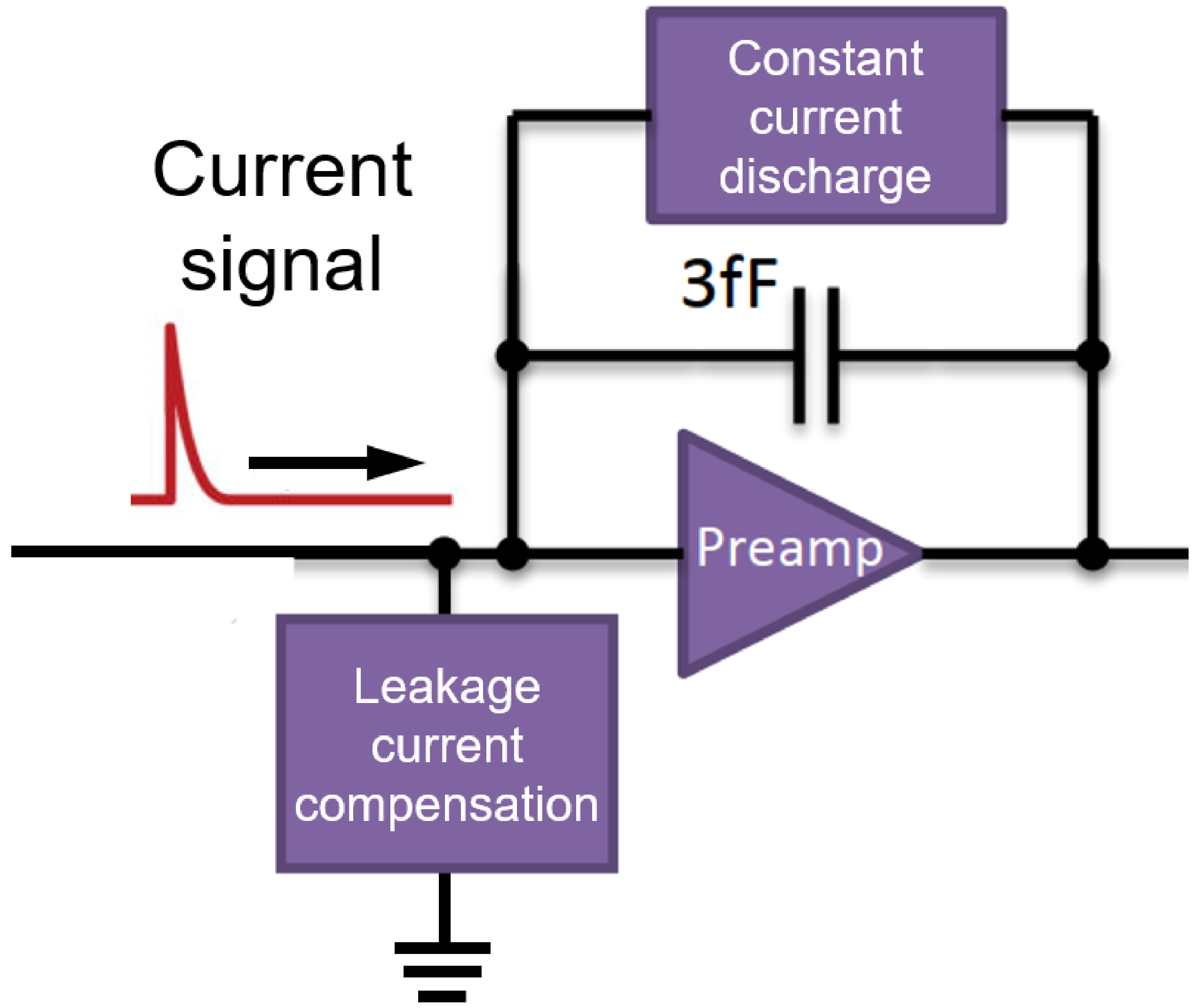
K. Heijhoff *et al* 2022 *JINST* **17** P07006
[DOI: 10.1088/1748-0221/17/07/P07006]

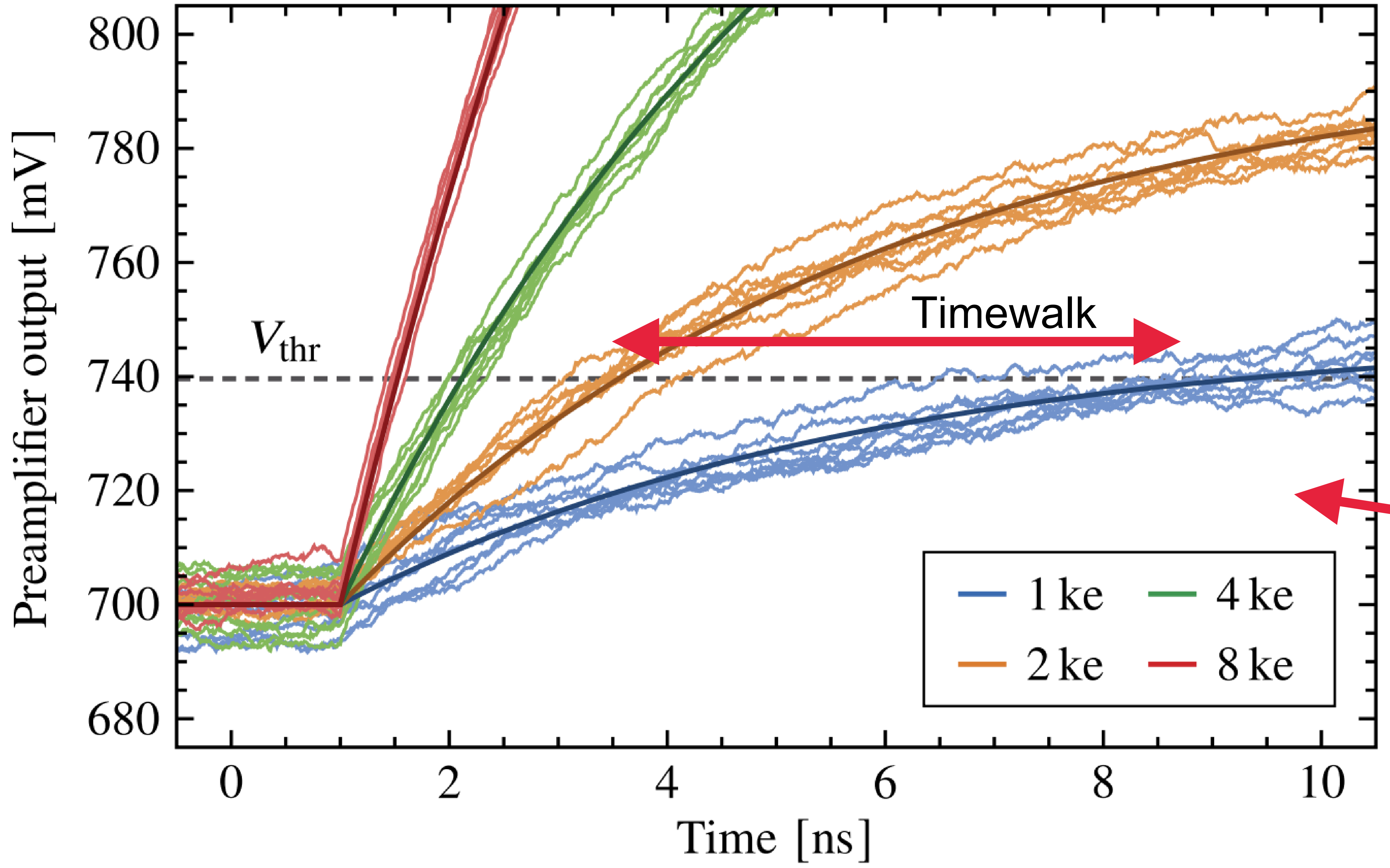


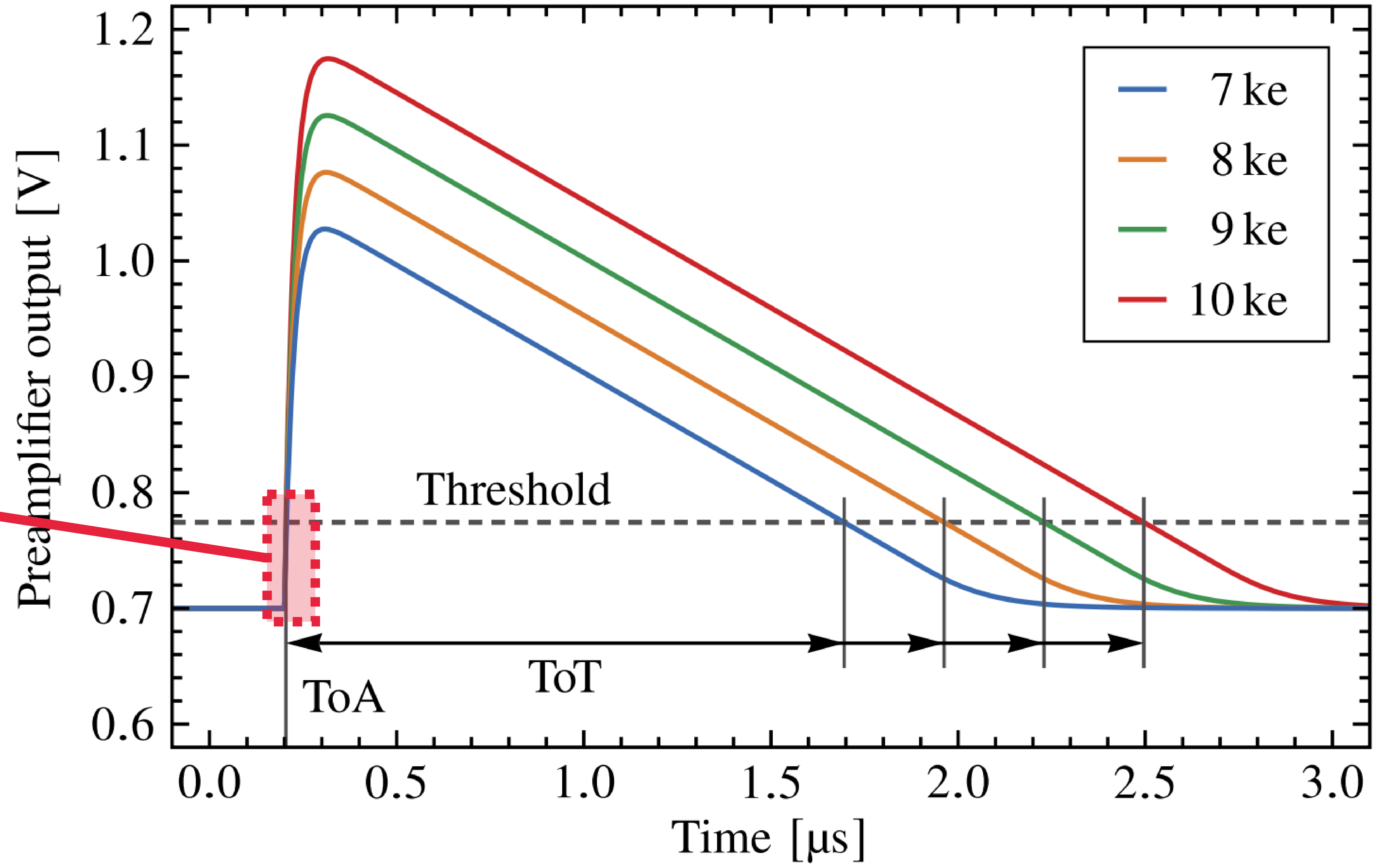


Timewalk

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

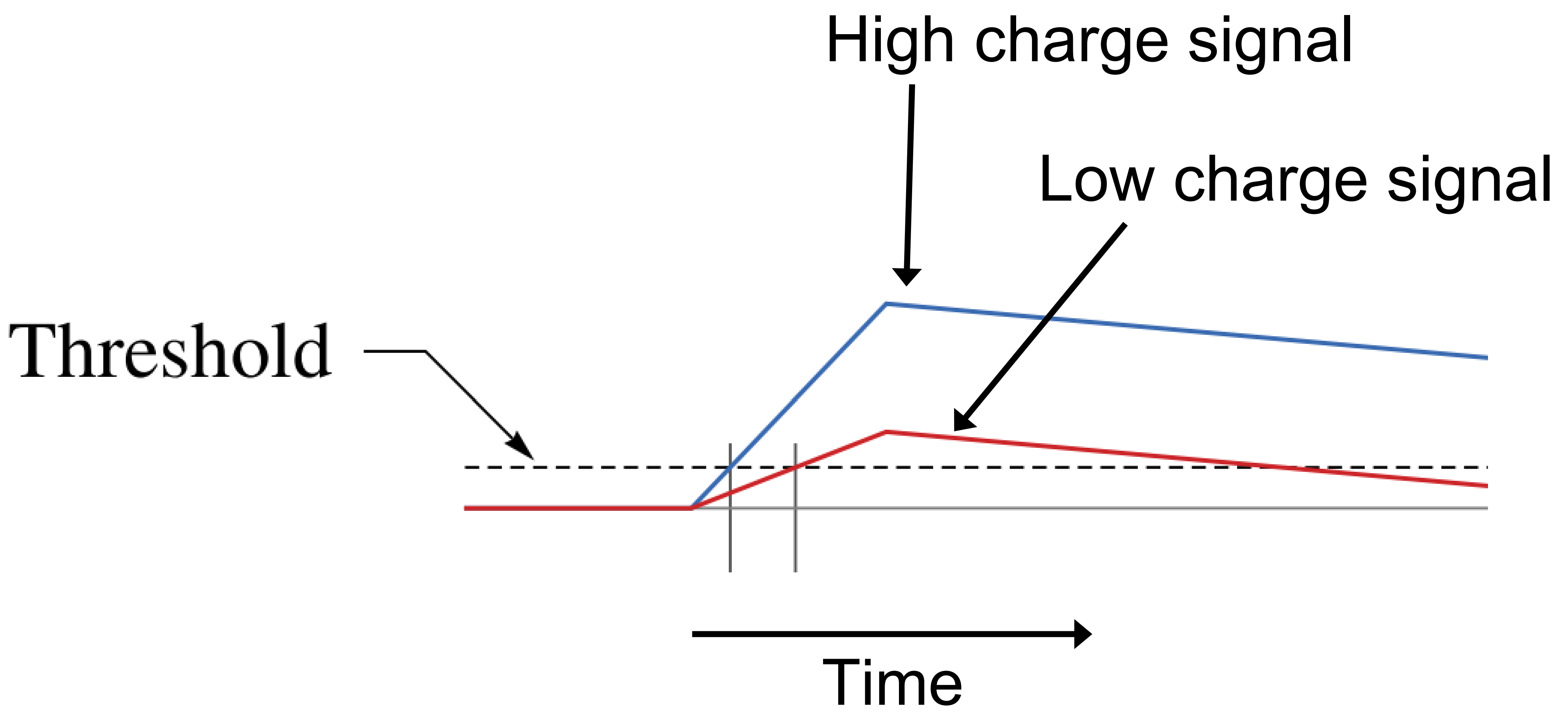


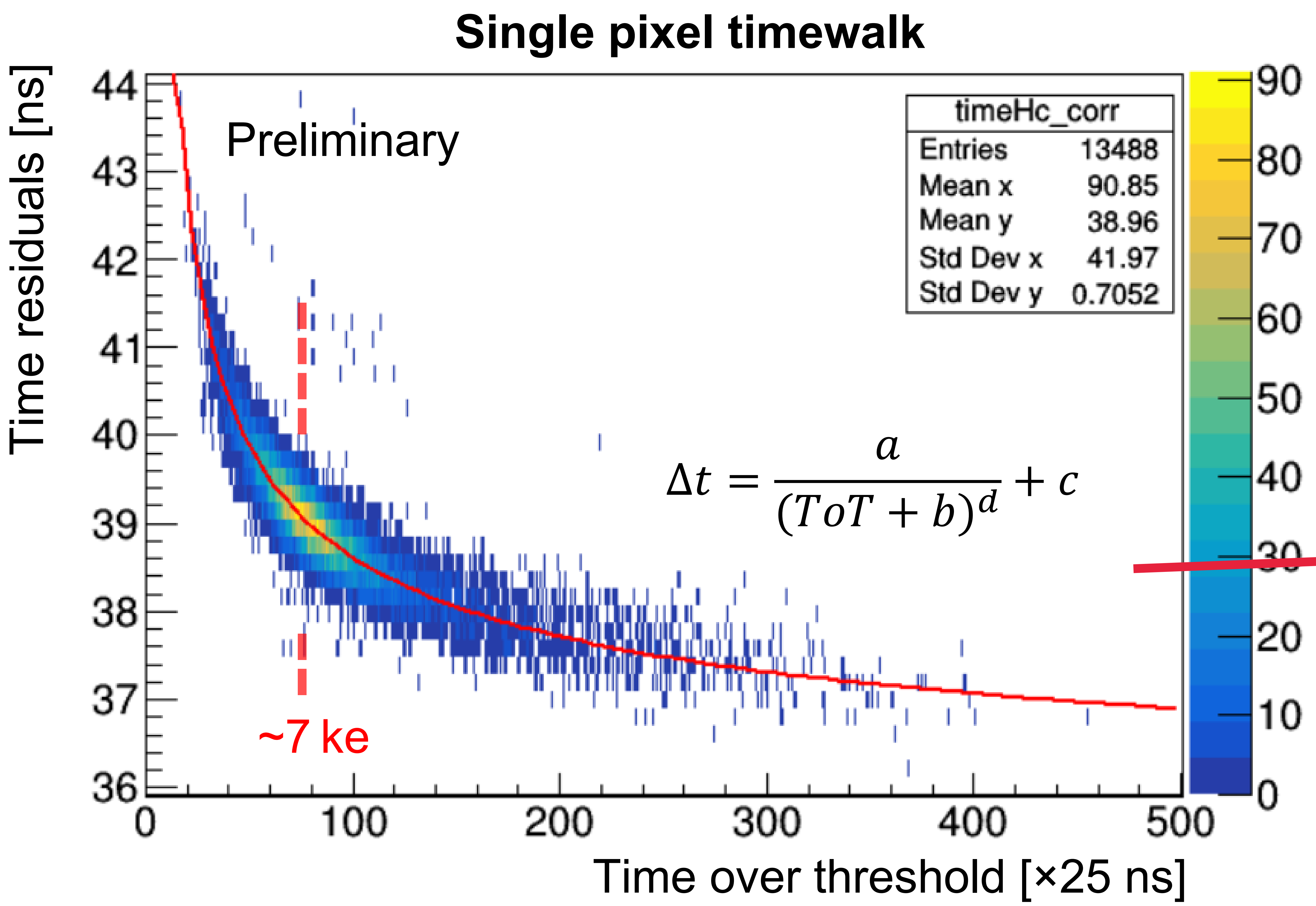




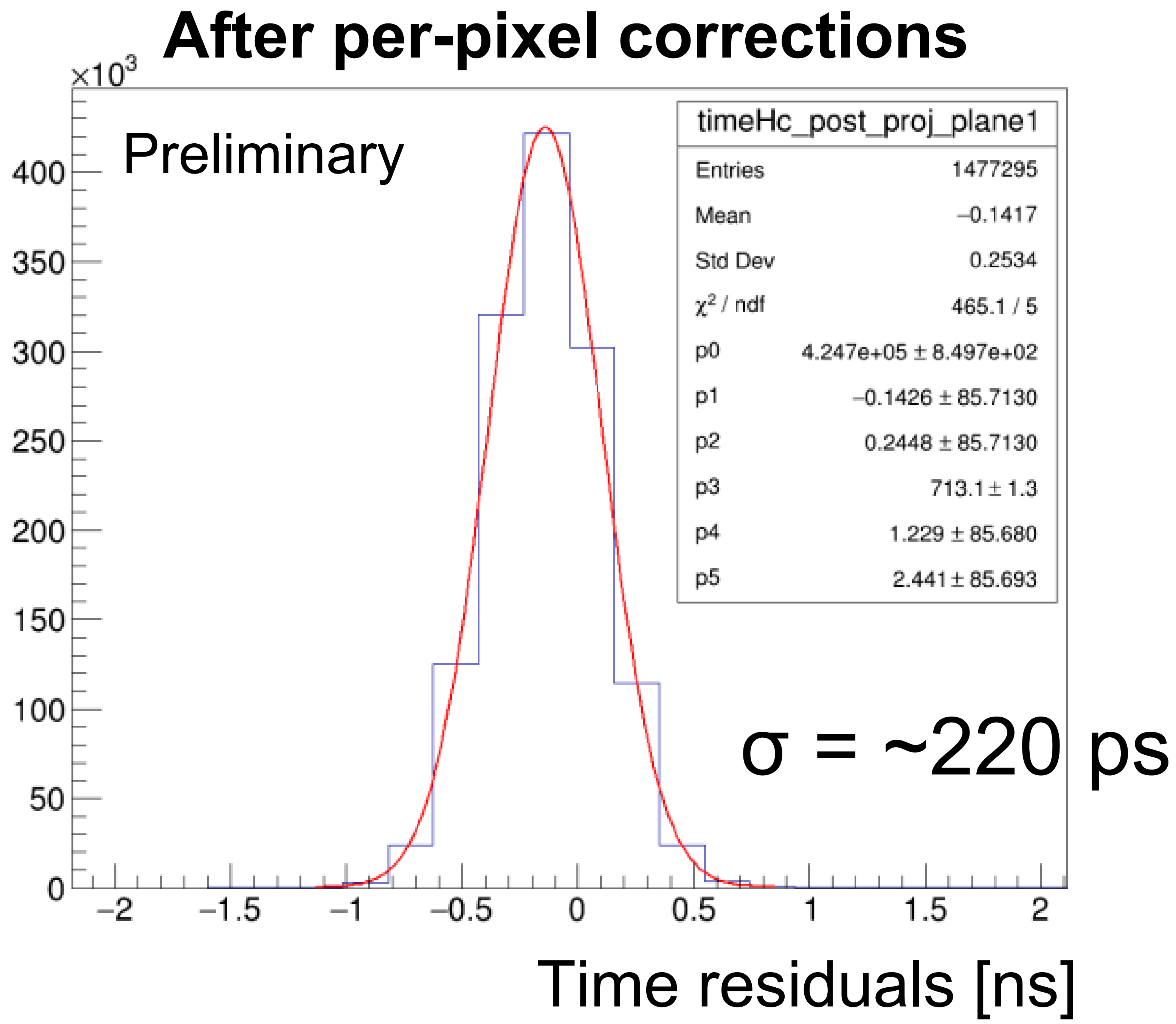
Timewalk correction

- Per-pixel timewalk corrections are applied
- Also corrects pixel time offsets
- Improves cluster time resolution: ~500 ps → ~220 ps



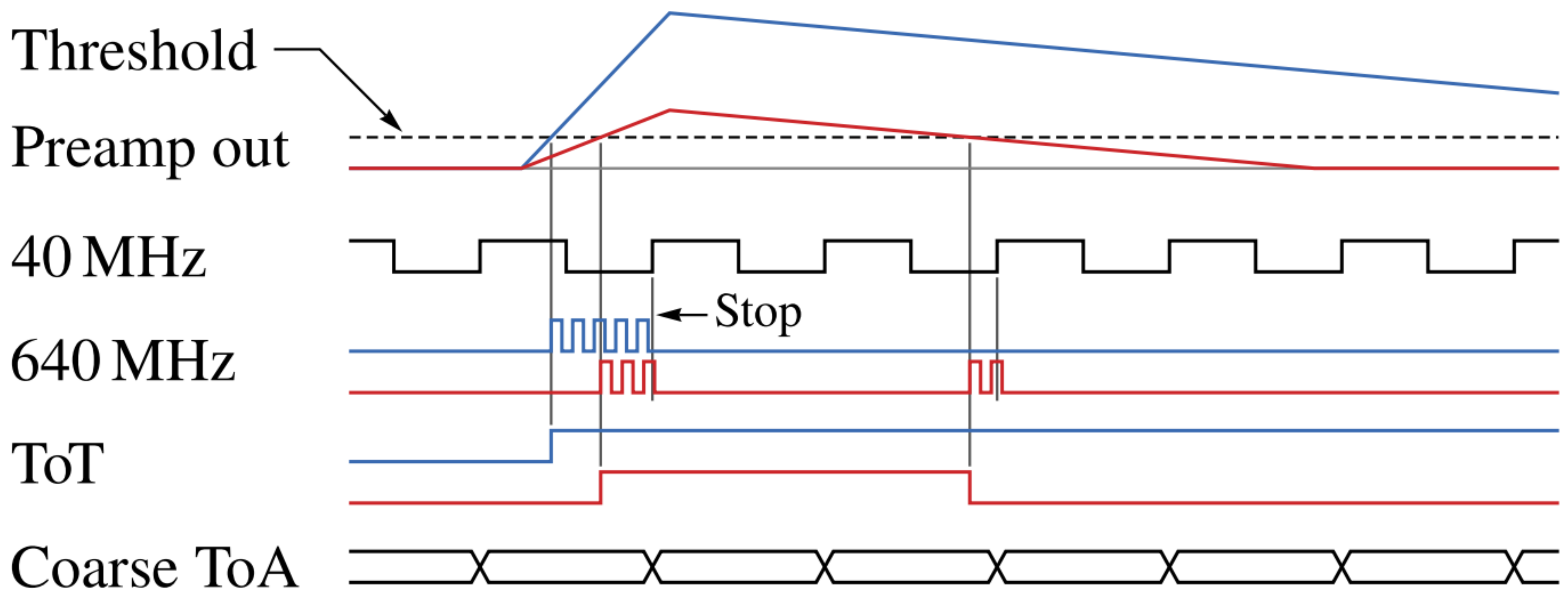


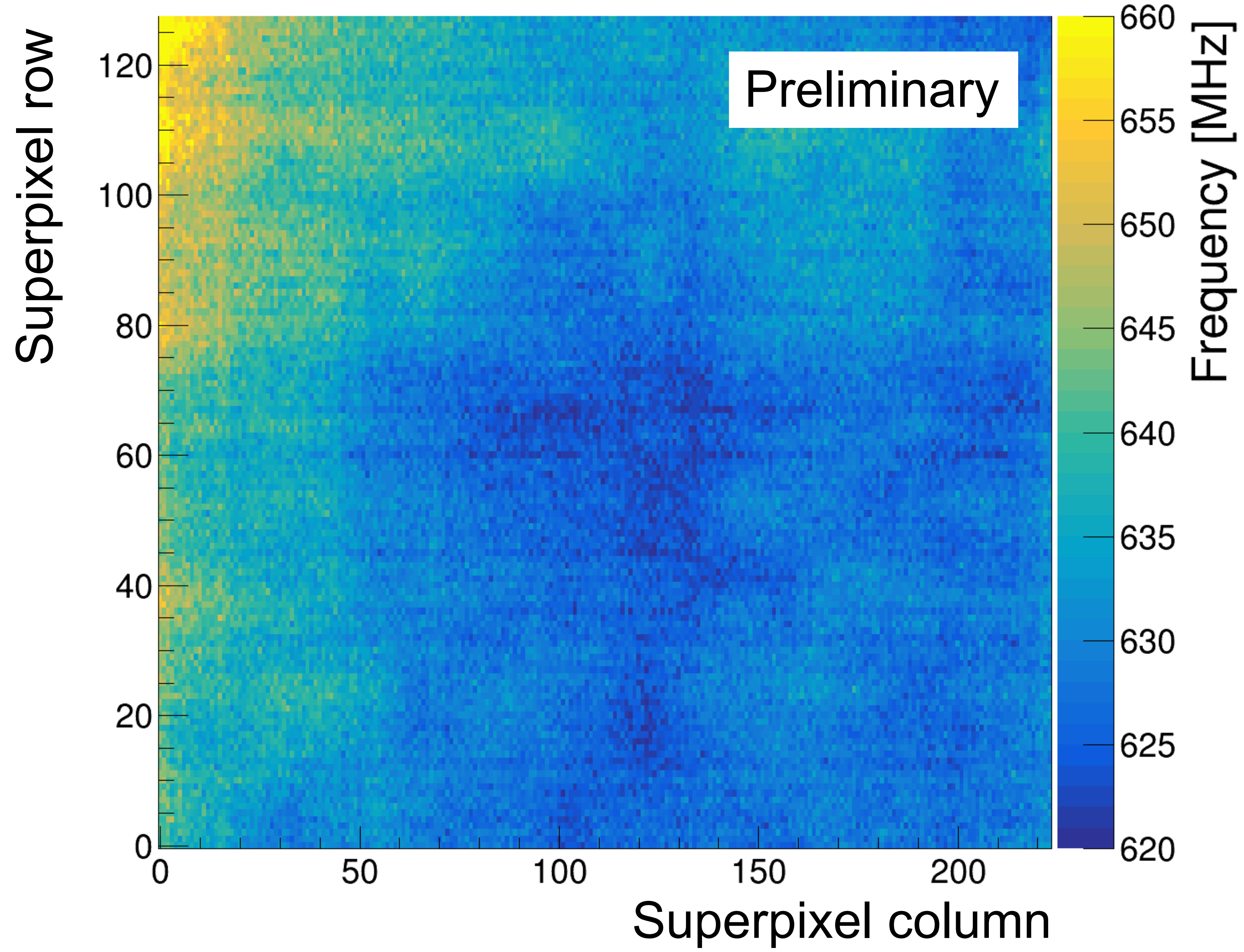
$$\Delta t = \frac{a}{(ToT + b)^d} + c$$

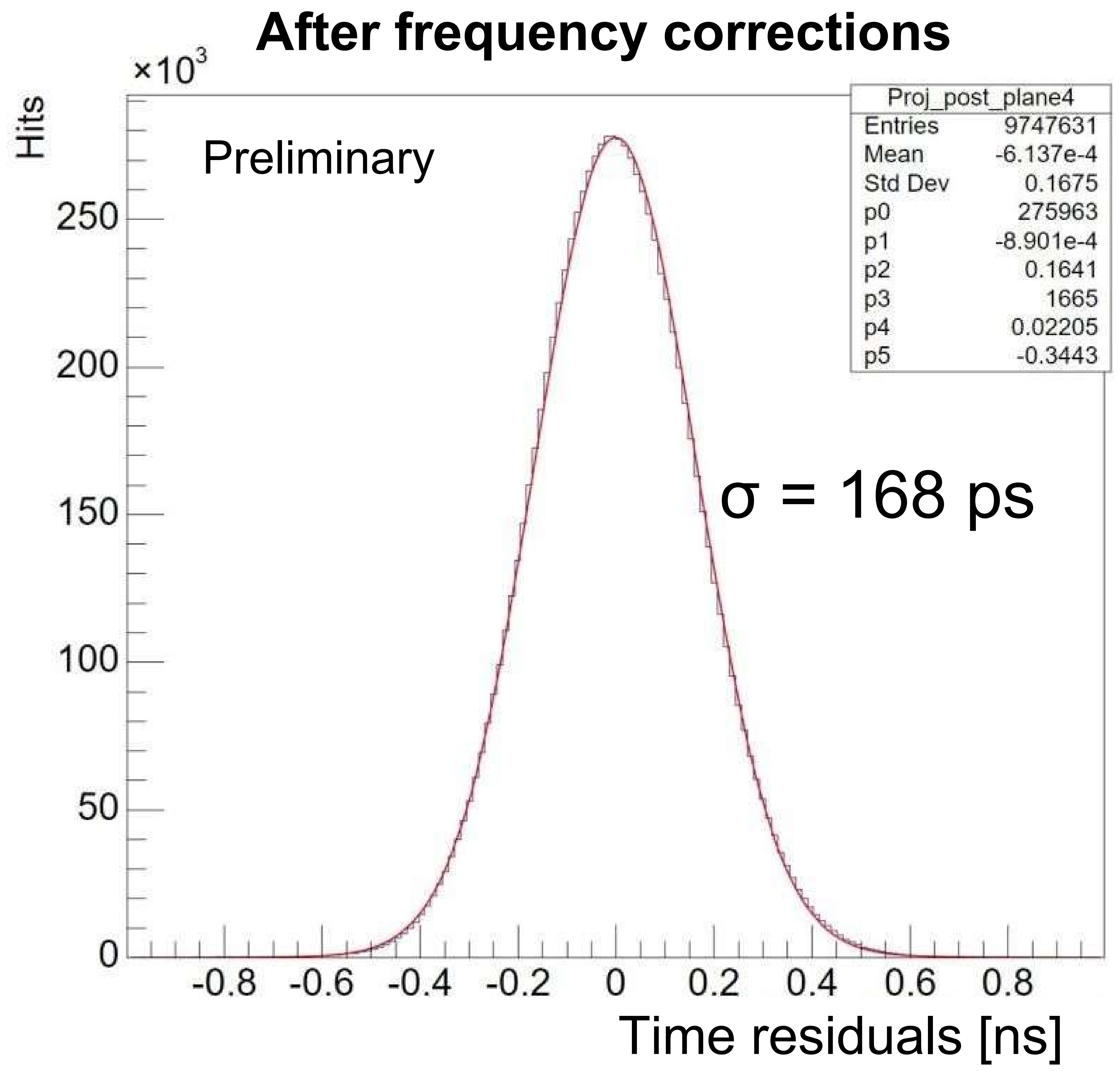


VCO Clock correction

- VCO frequency must also be calibrated for each superpixel
- Many potential causes:
  - Process variation
  - Local power supply differences
  - Non-uniform temperature
- Improves the cluster time resolution to ~160 ps
- Track time resolution after corrections: 90 ps







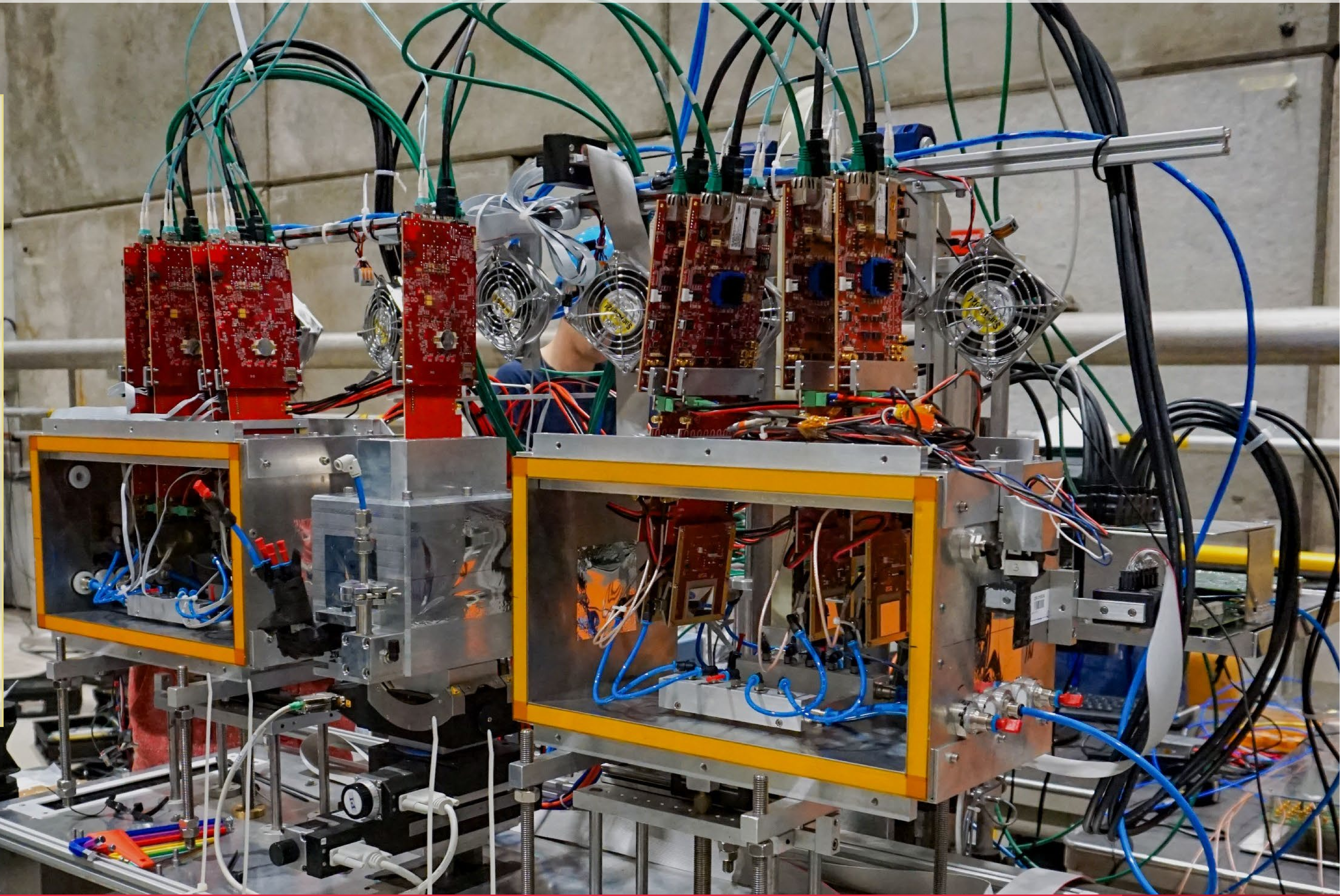
Conclusion

Conclusion

- Only telescope with all three:
  - Good spatial resolution (2.4 μm)
  - Good time resolution (90 ps)
  - And high-rate capability
- Now focus on studying fast sensors. (See next talk!)

Outlook

- Remove material to decrease scattering
- Upgrade timing planes (depends on what is available)



Backup slides

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

Timepix3 telescope:

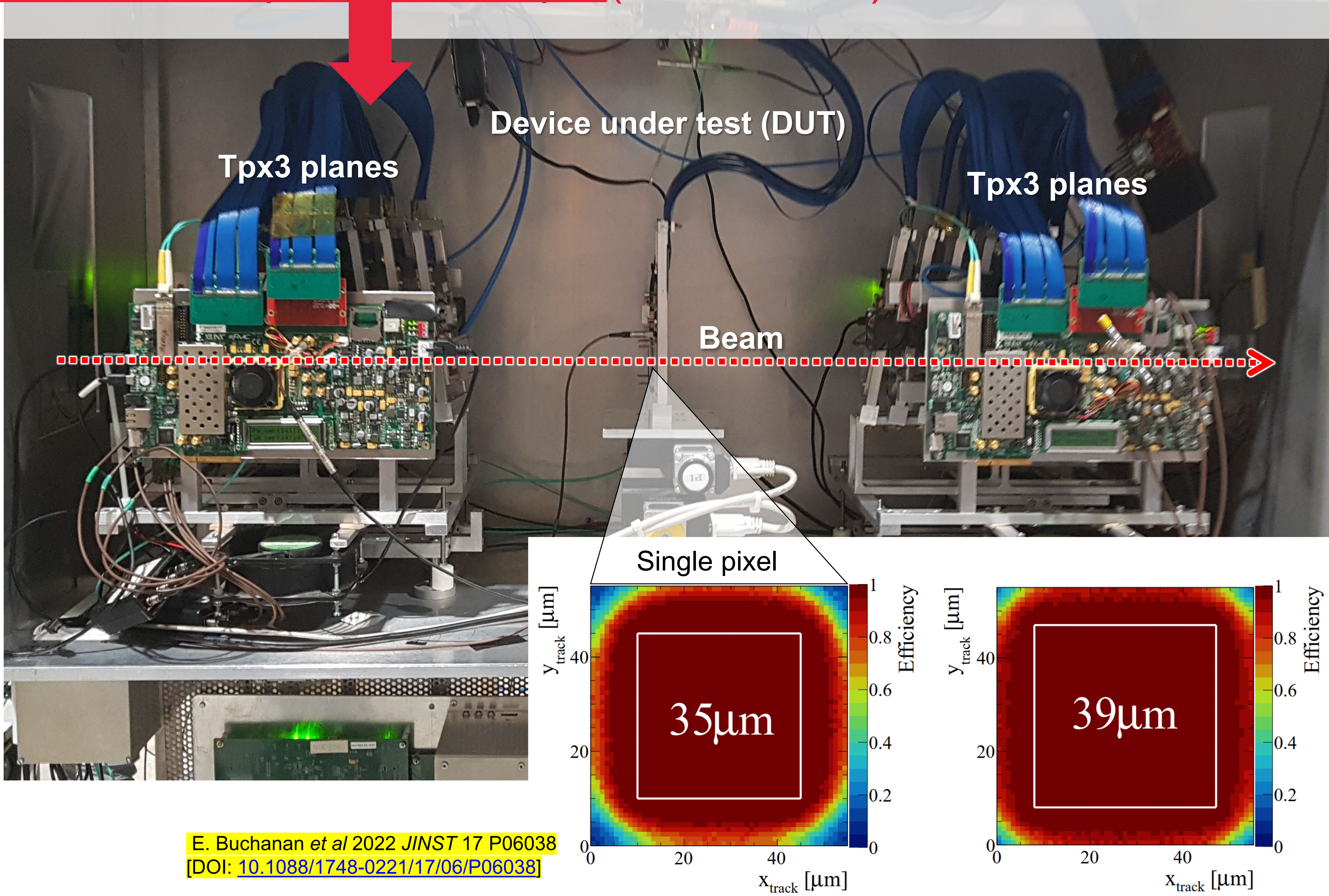
- 1.6 µm pointing resolution

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]

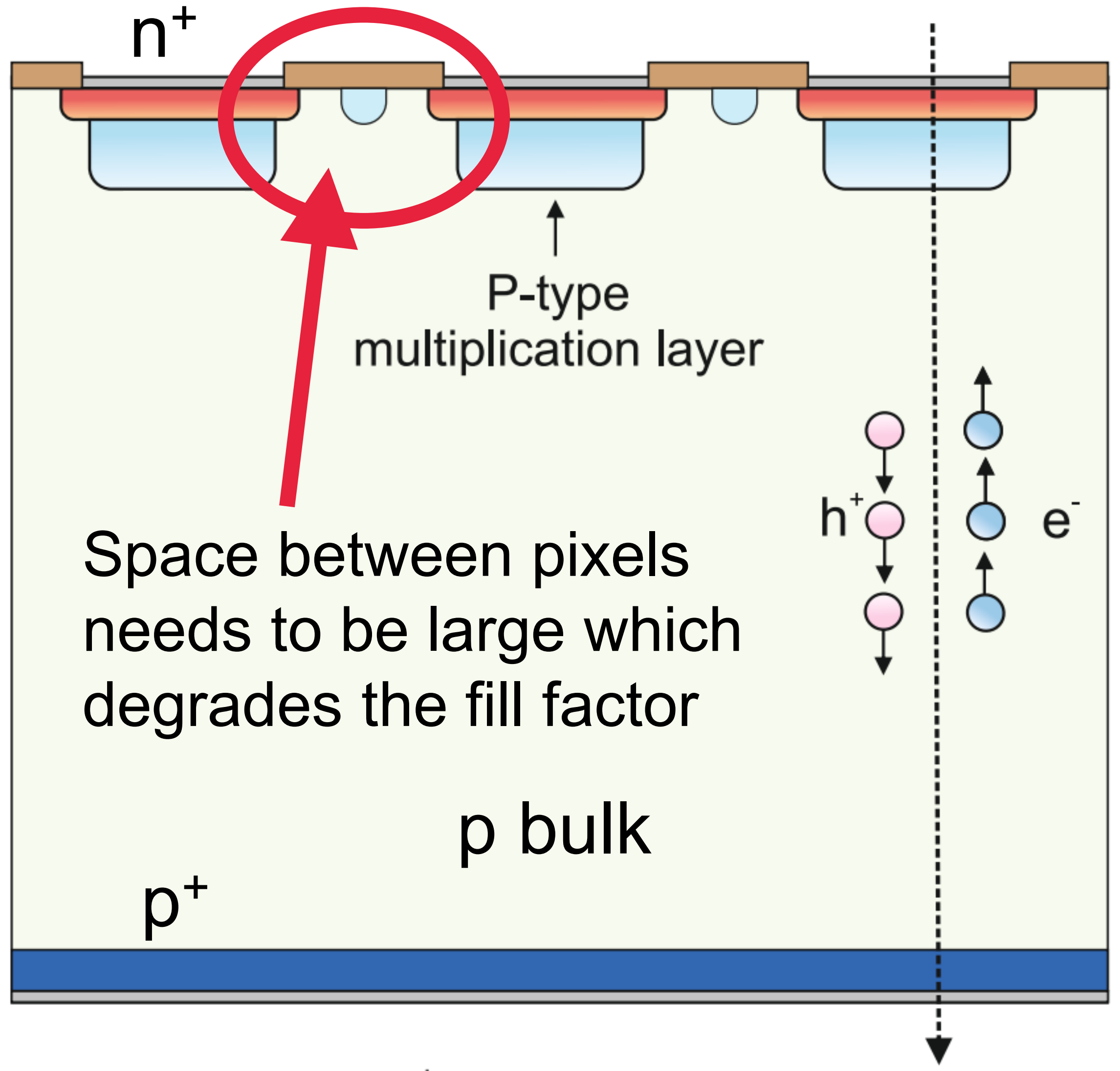


E. Buchanan *et al* 2022 *JINST* 17 P06038
[DOI: 10.1088/1748-0221/17/06/P06038]

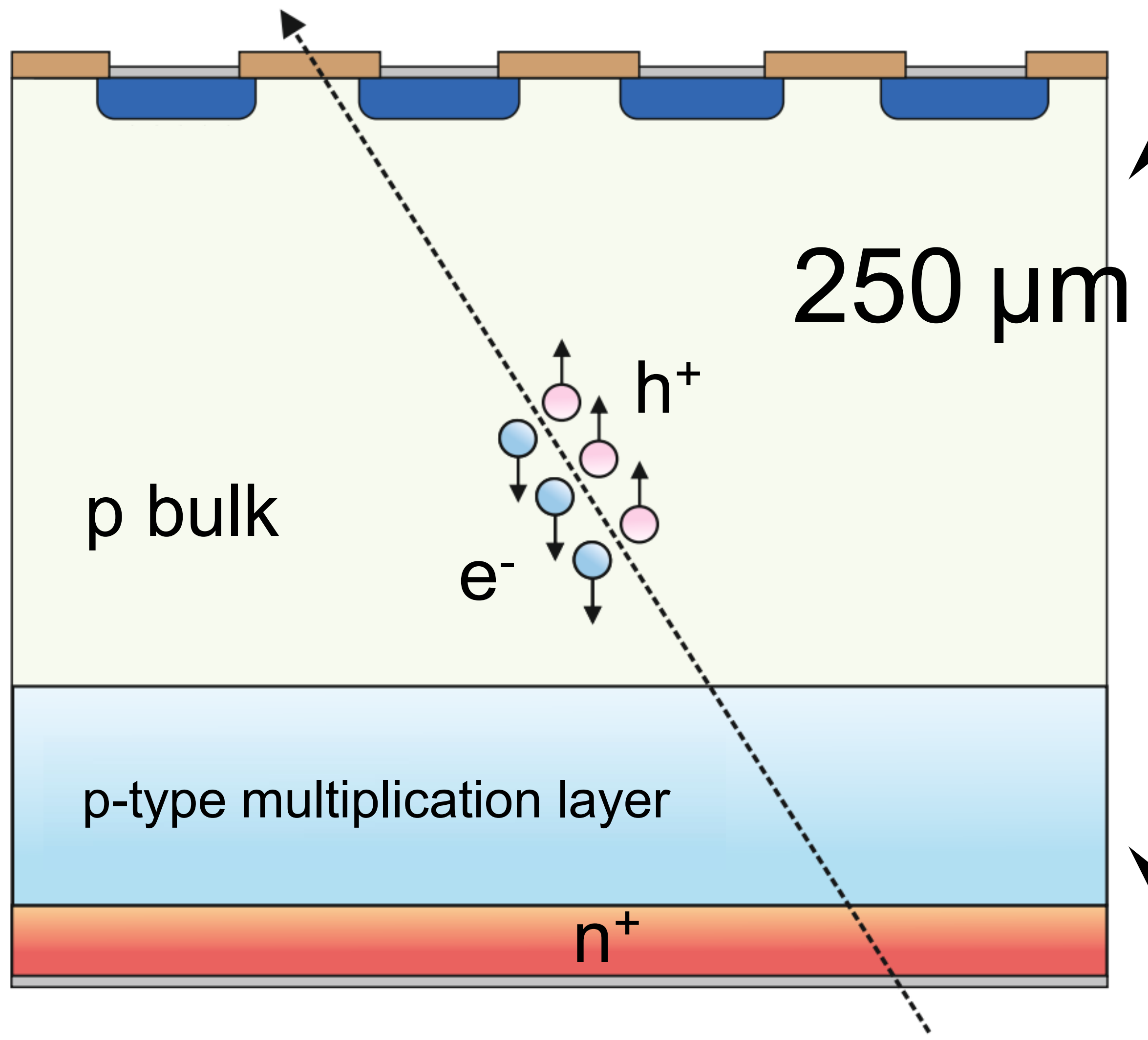
Inverted LGAD on Timepix4 as DUT

- 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

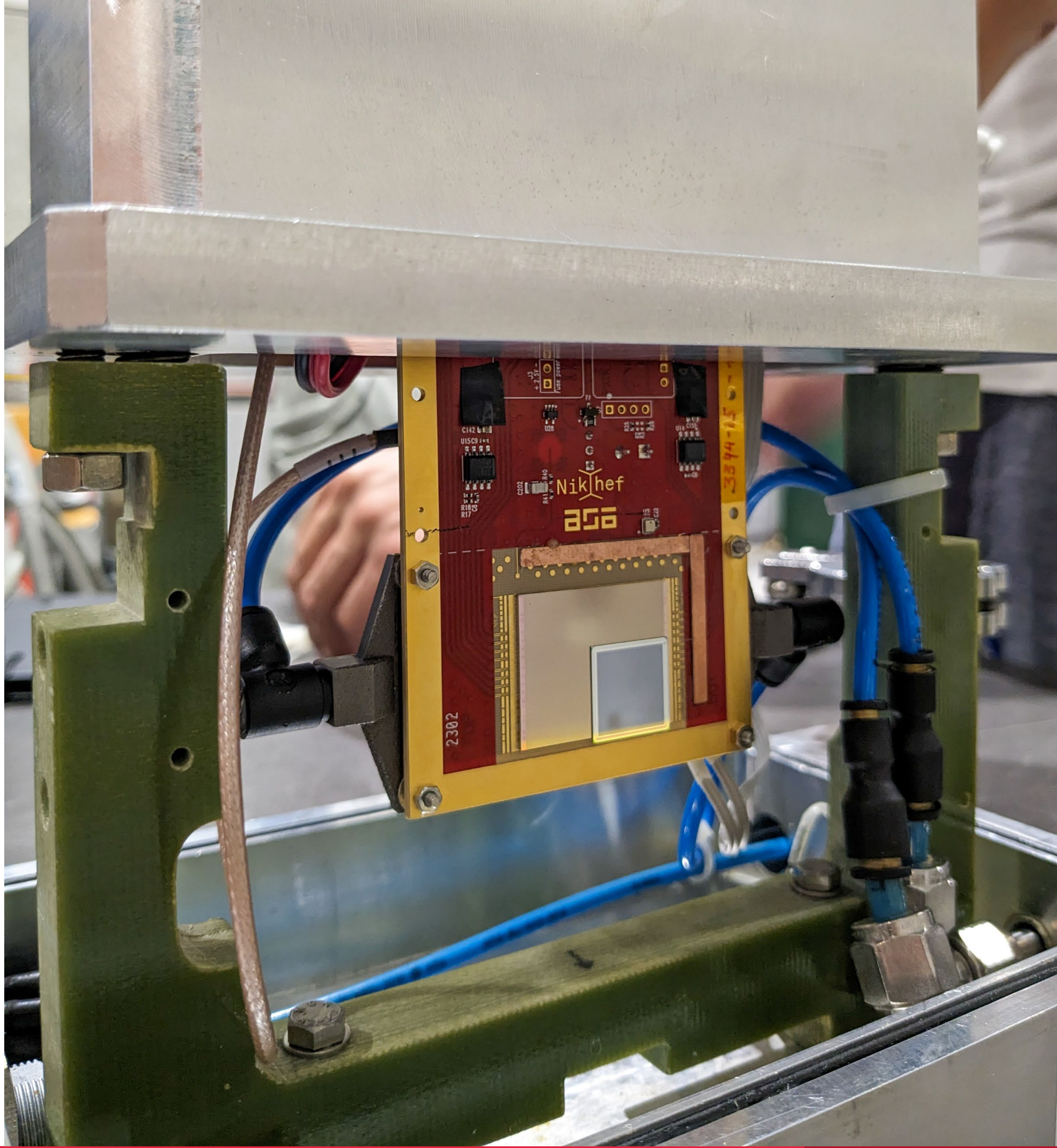
Standard LGAD



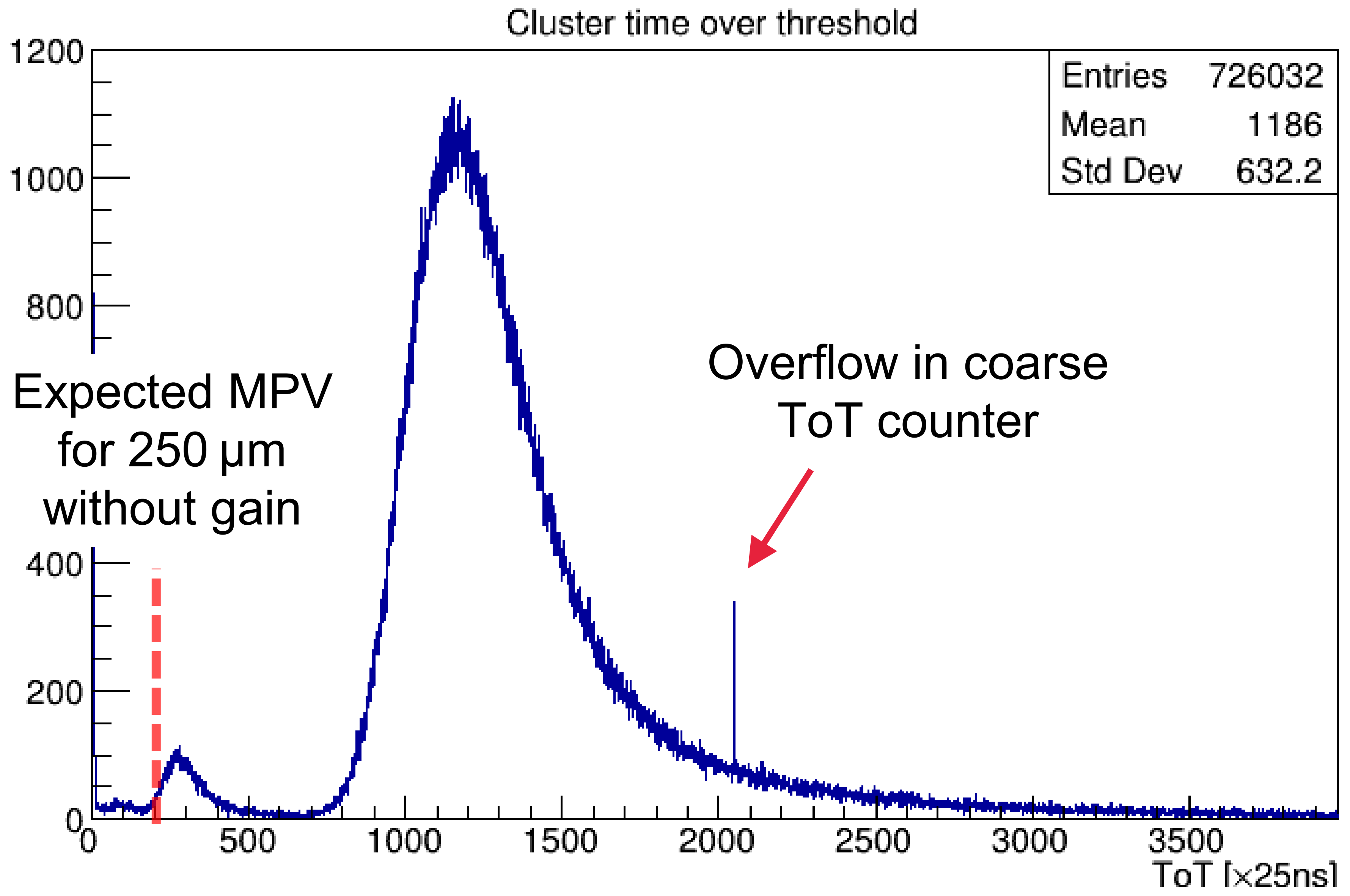
Inverted LGAD

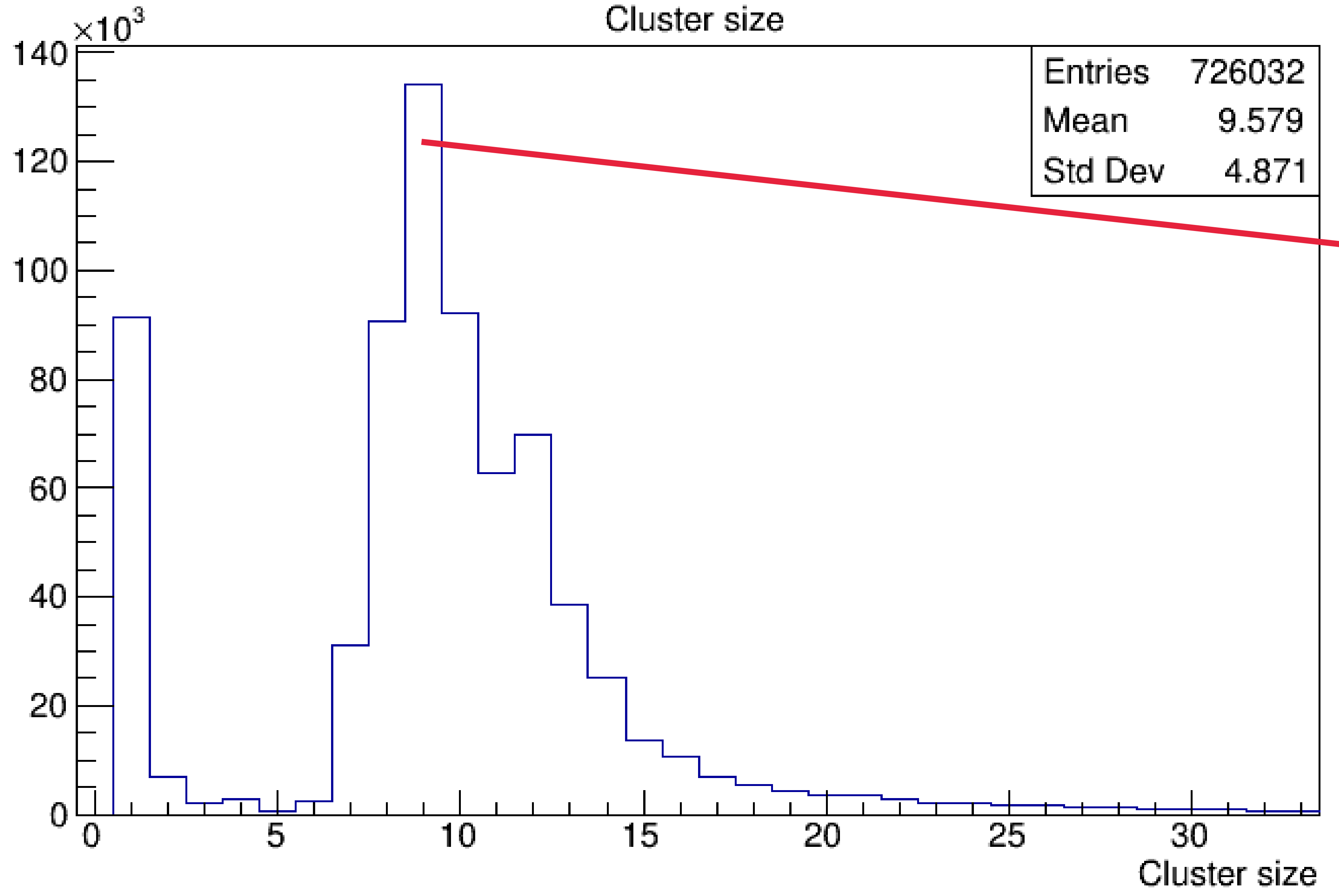


A. Doblas *et al Sensors* **2023**, 23, 3450 [DOI: 10.3390/s23073450]

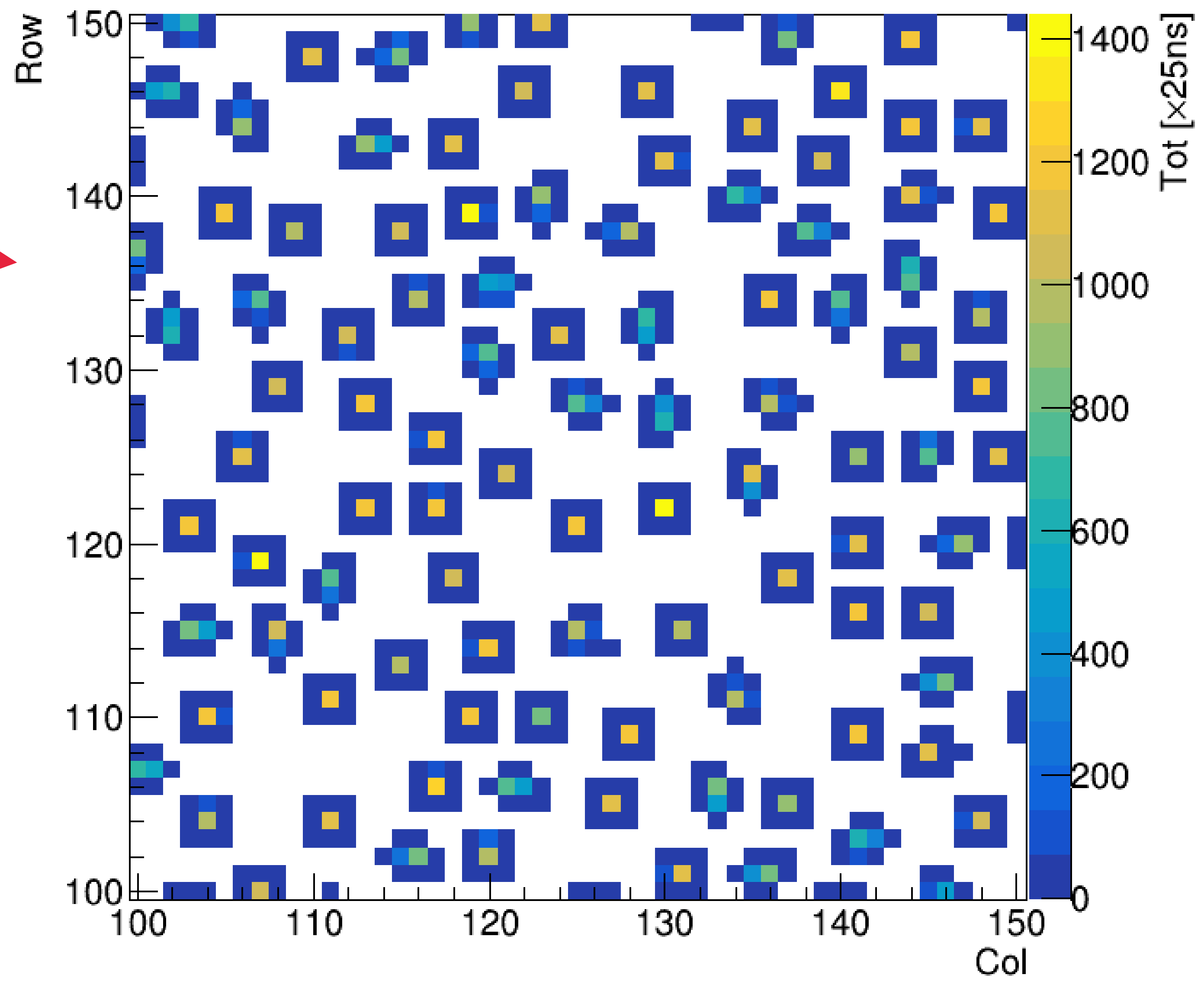


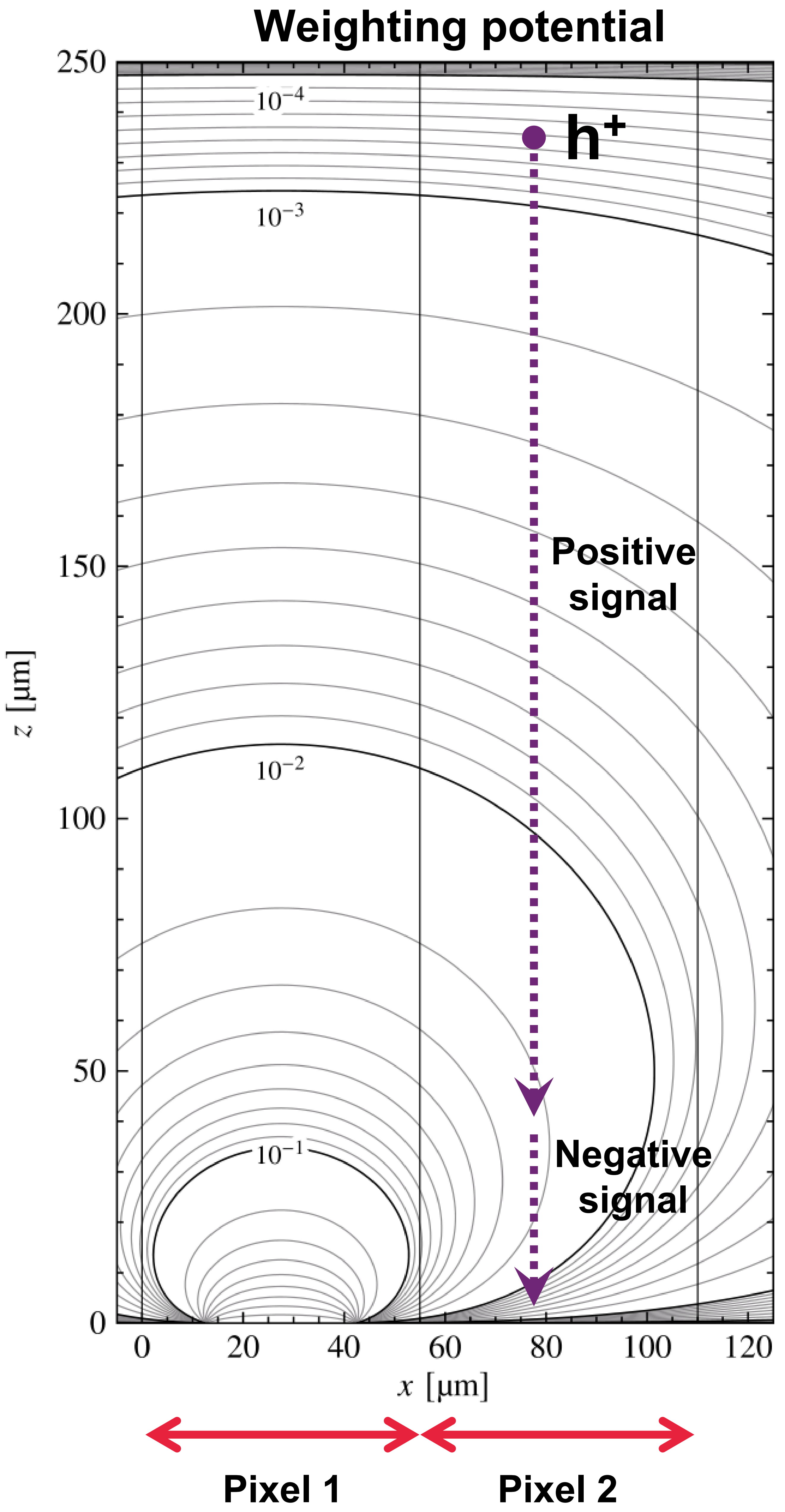
Inverted LGAD on Timepix4 as DUT (first glance)





- 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



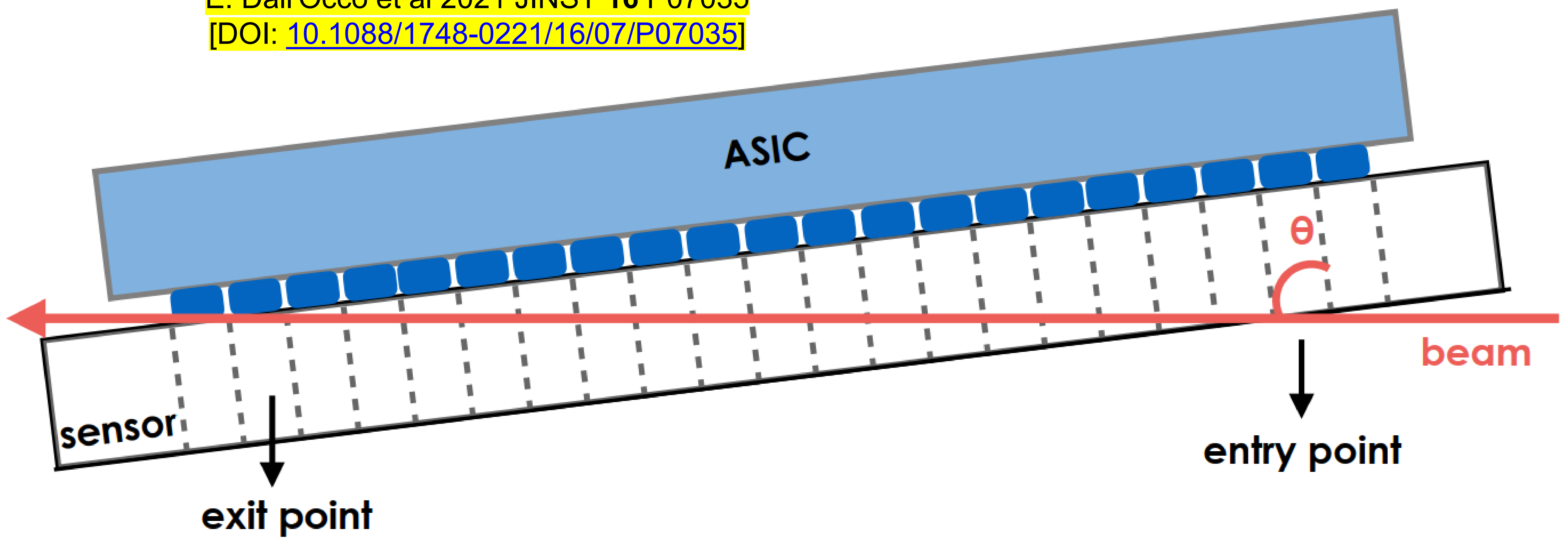


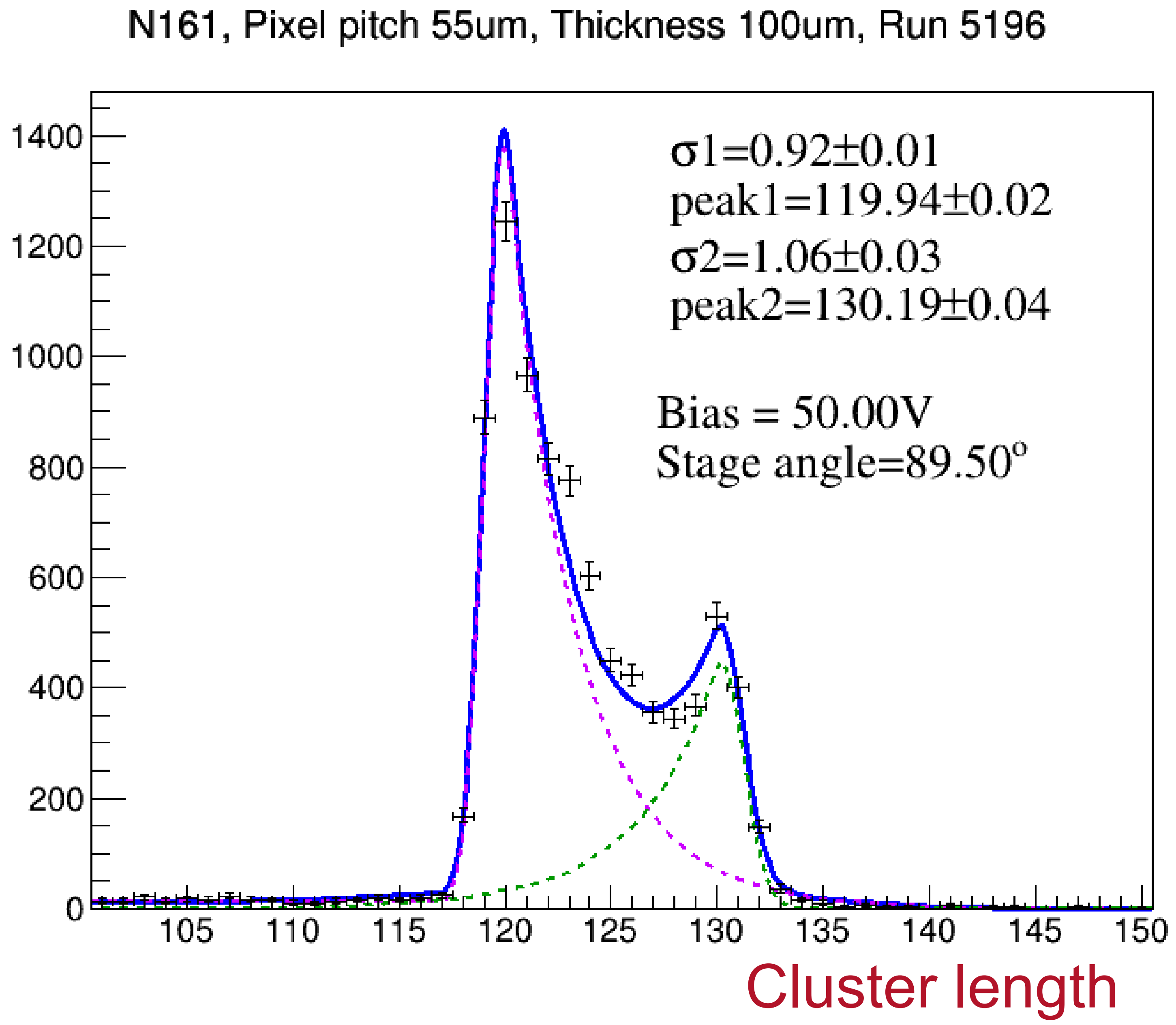
Timewalk behaviour depends on track depth

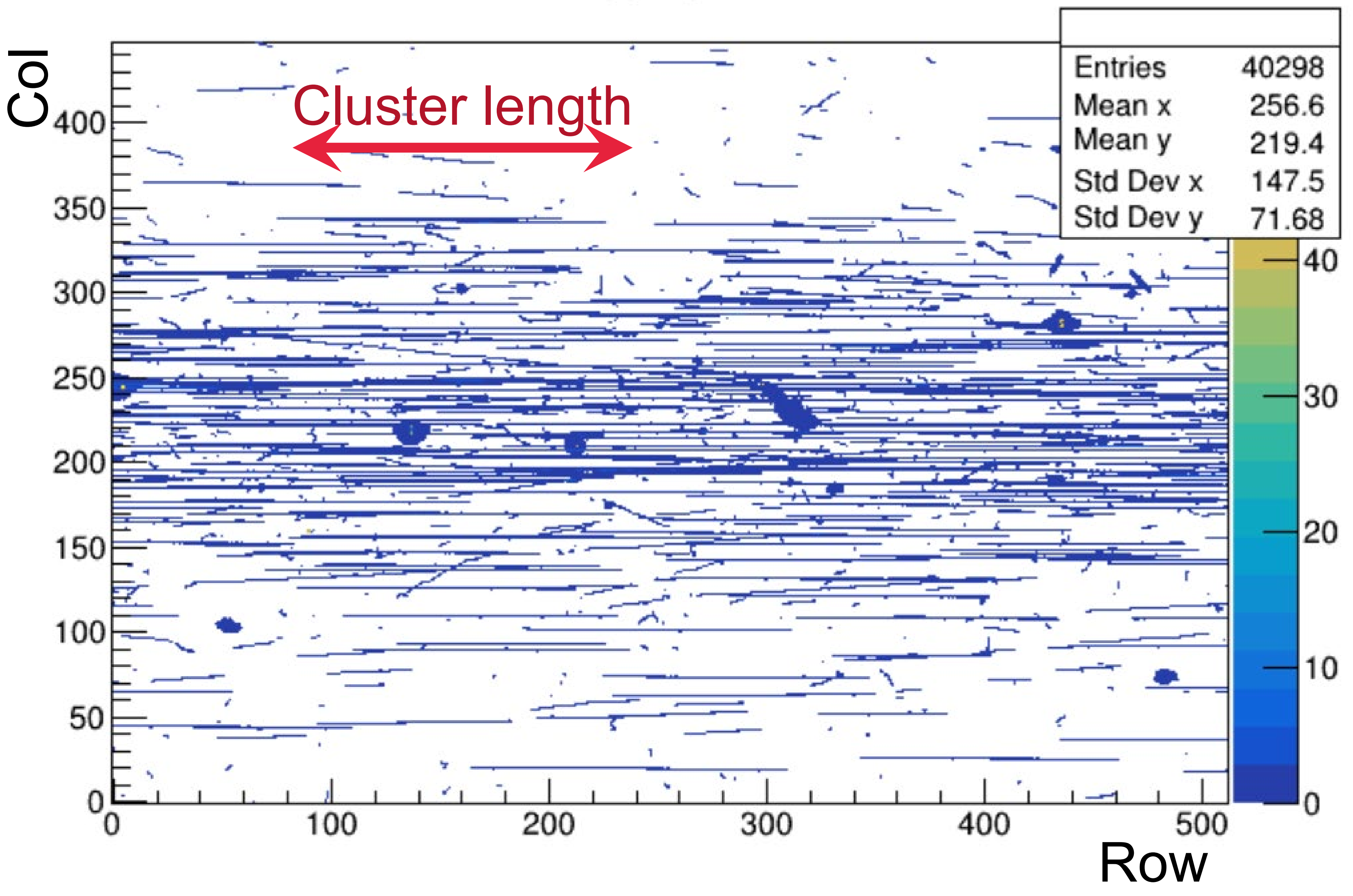
Grazing angle measurements

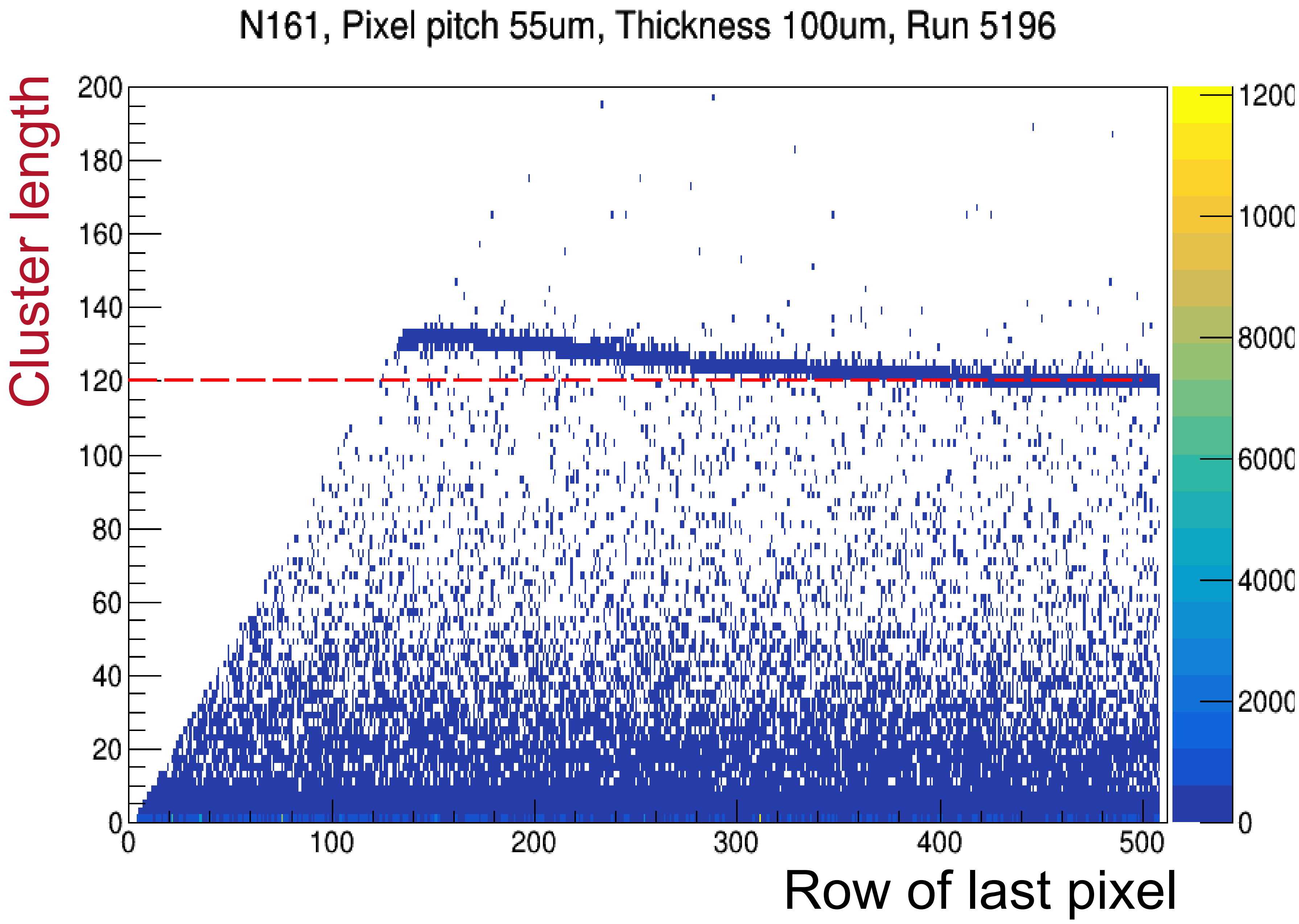
- Grazing angle measurements probe different depths of the sensor
- Can be used to determine thickness by measuring cluster length at various angles
- Sensors are thin, but not flat

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

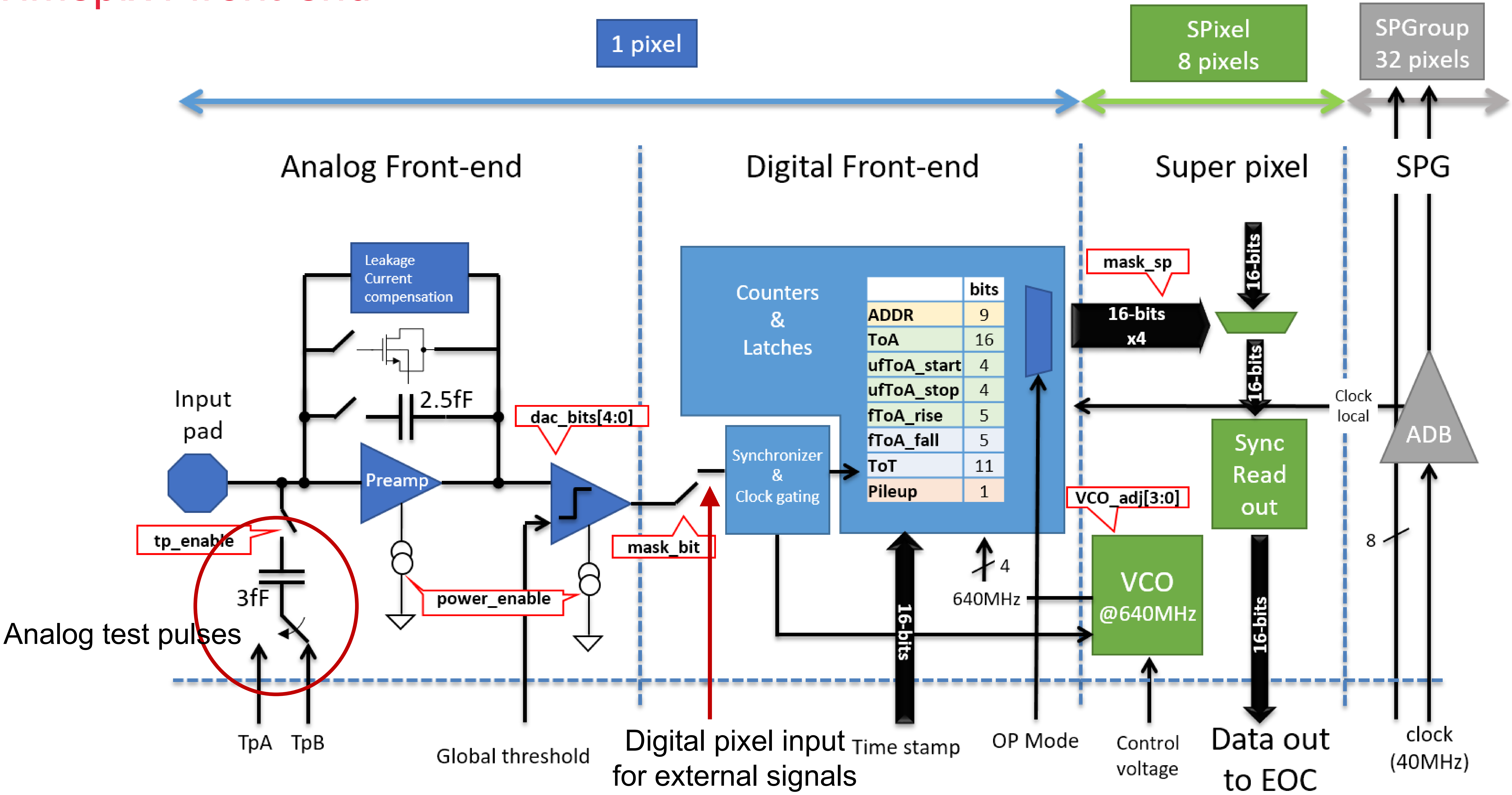








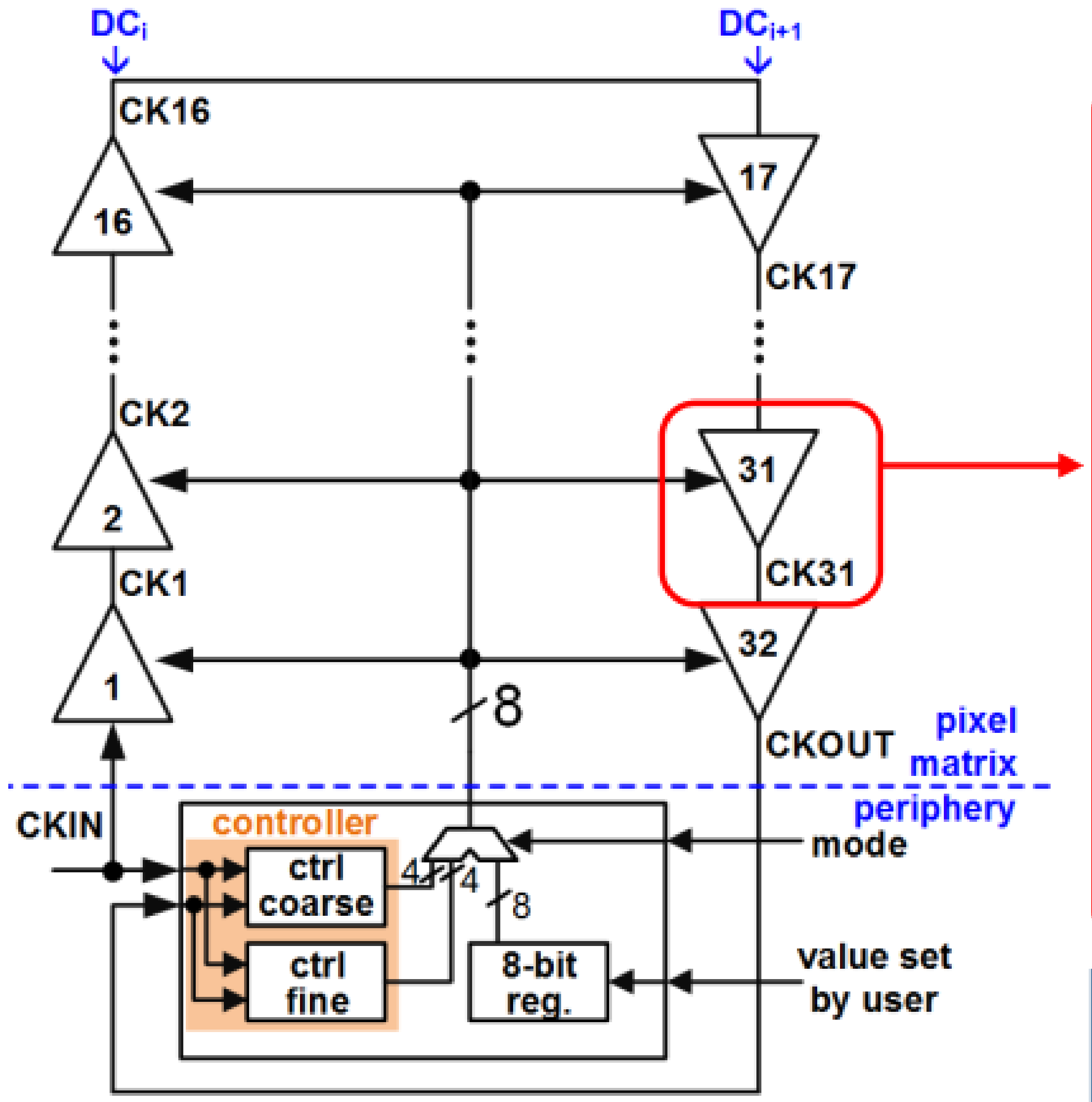
Timepix4 front-end

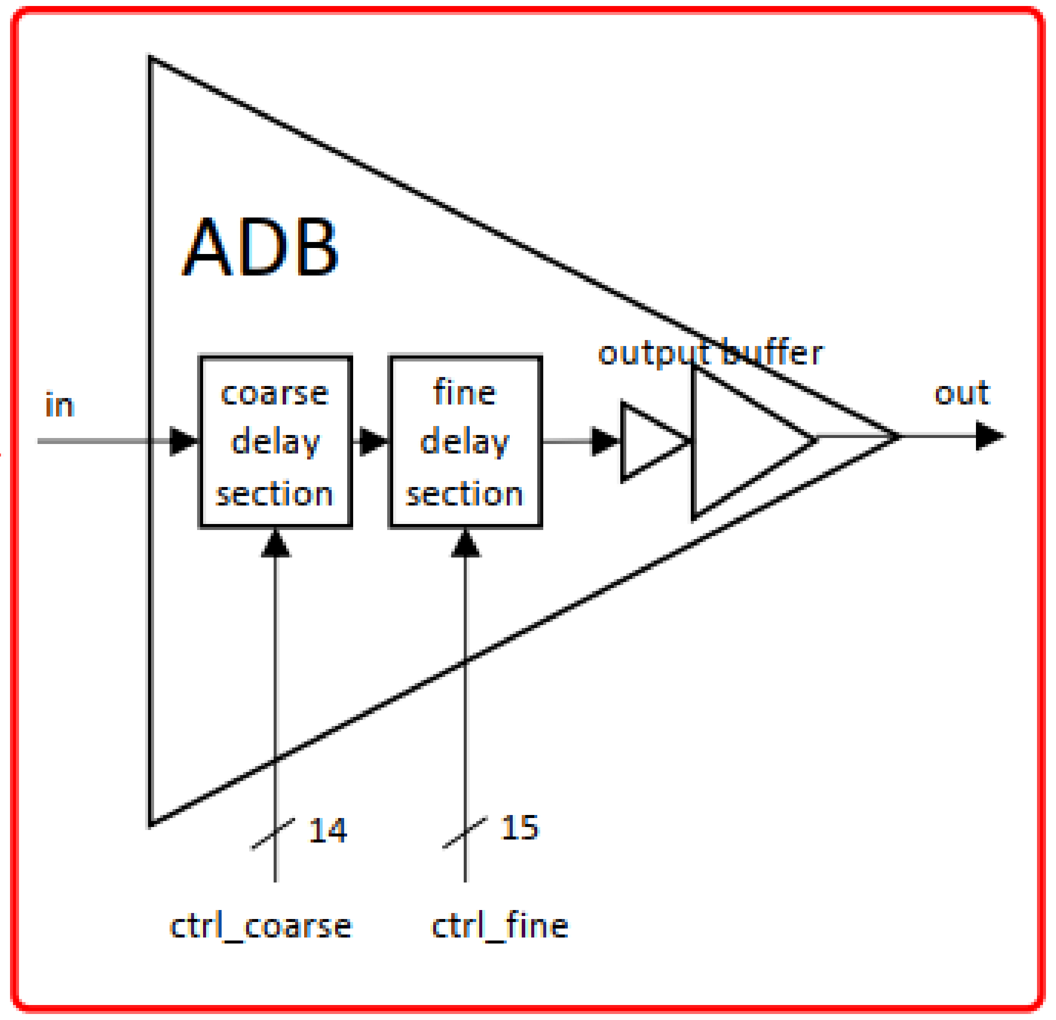


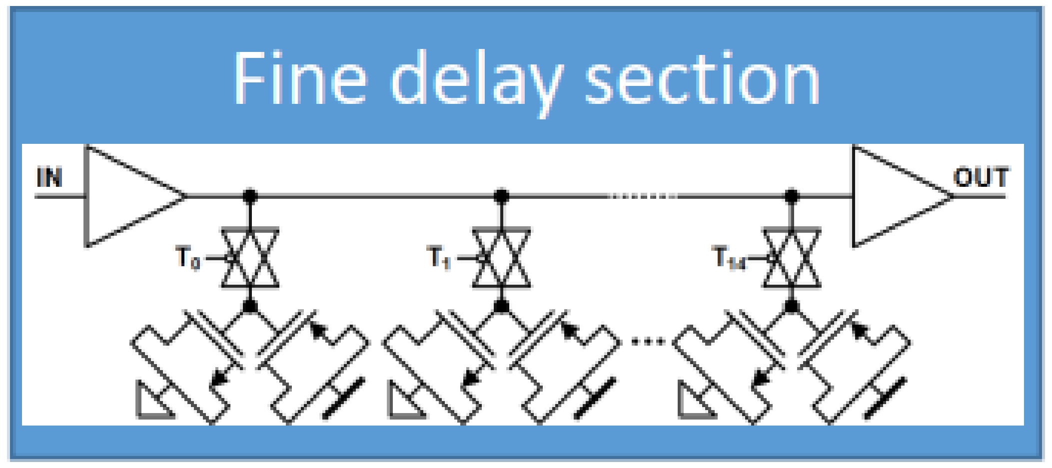
Clock distribution – Column digital locked look (DLL)

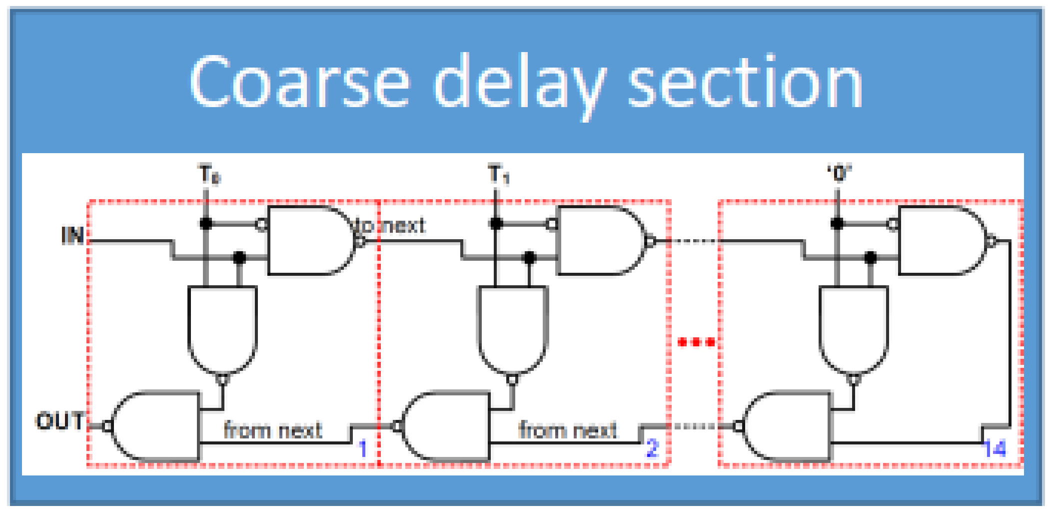
iWoRID 2018
X. Llopart et al 2019 JINST 14 C01024

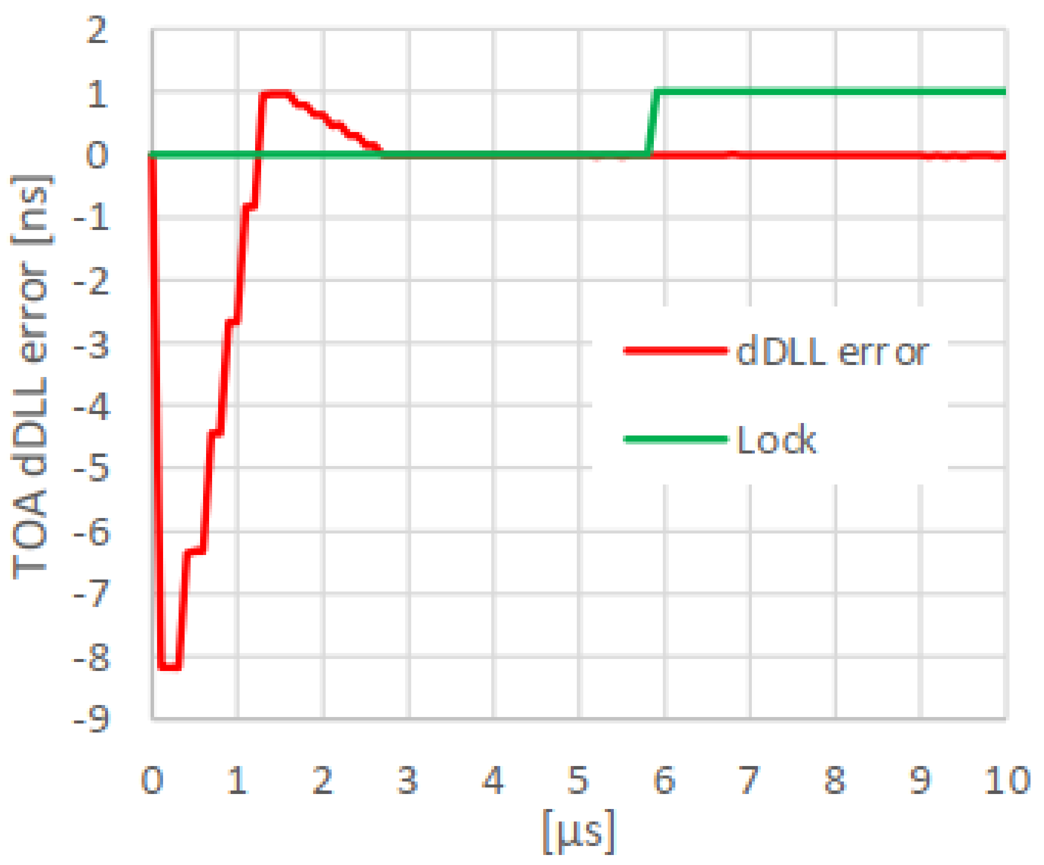
- The column DLL distributes the clock along the columns
- The adjustable delay buffers (ADBs) precisely define the clock phase in each pixel group
- Controller tunes the total delay to 25 ns
- Possible to set the delay manually
- Individual ADB stations can be bypassed

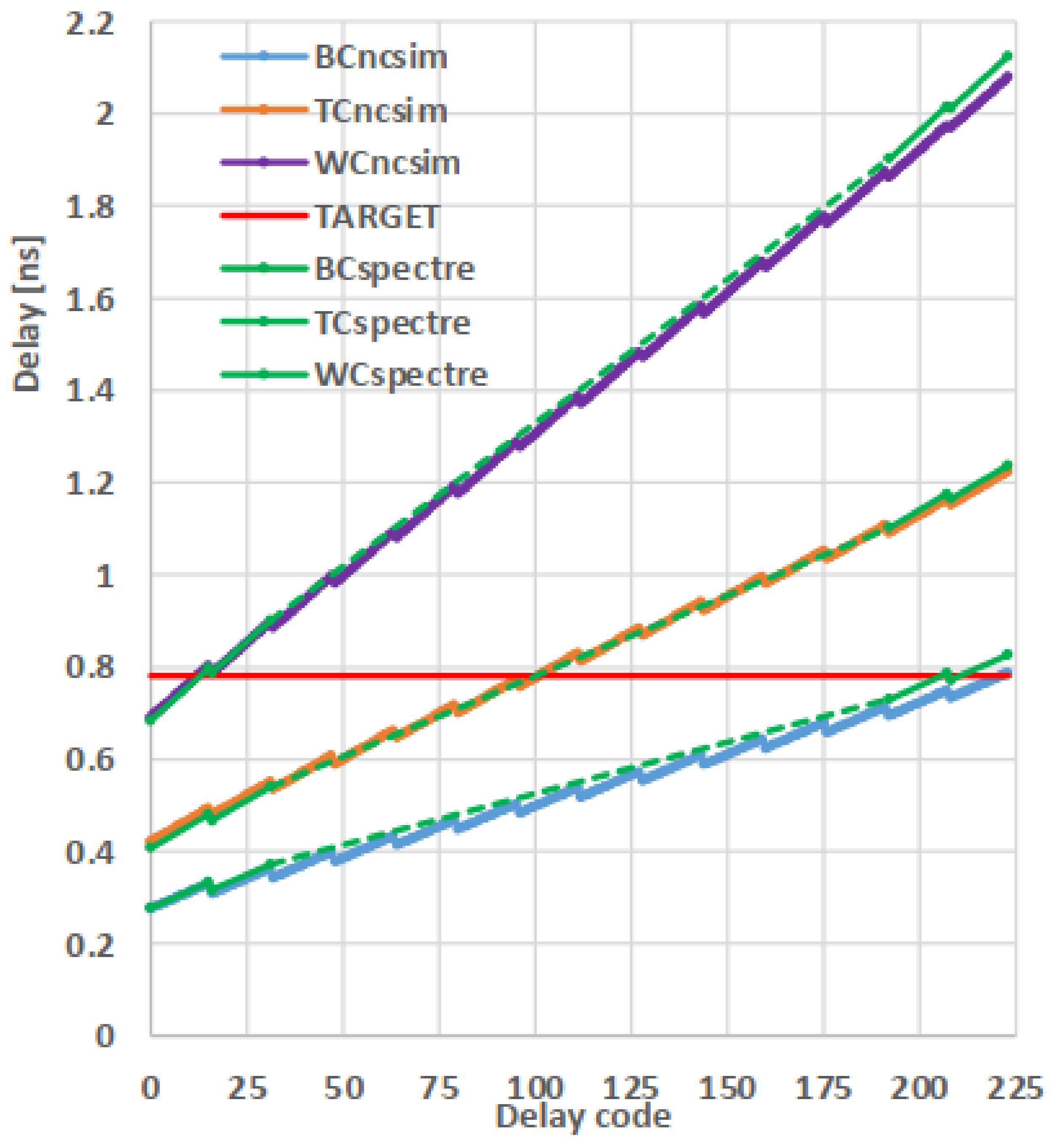










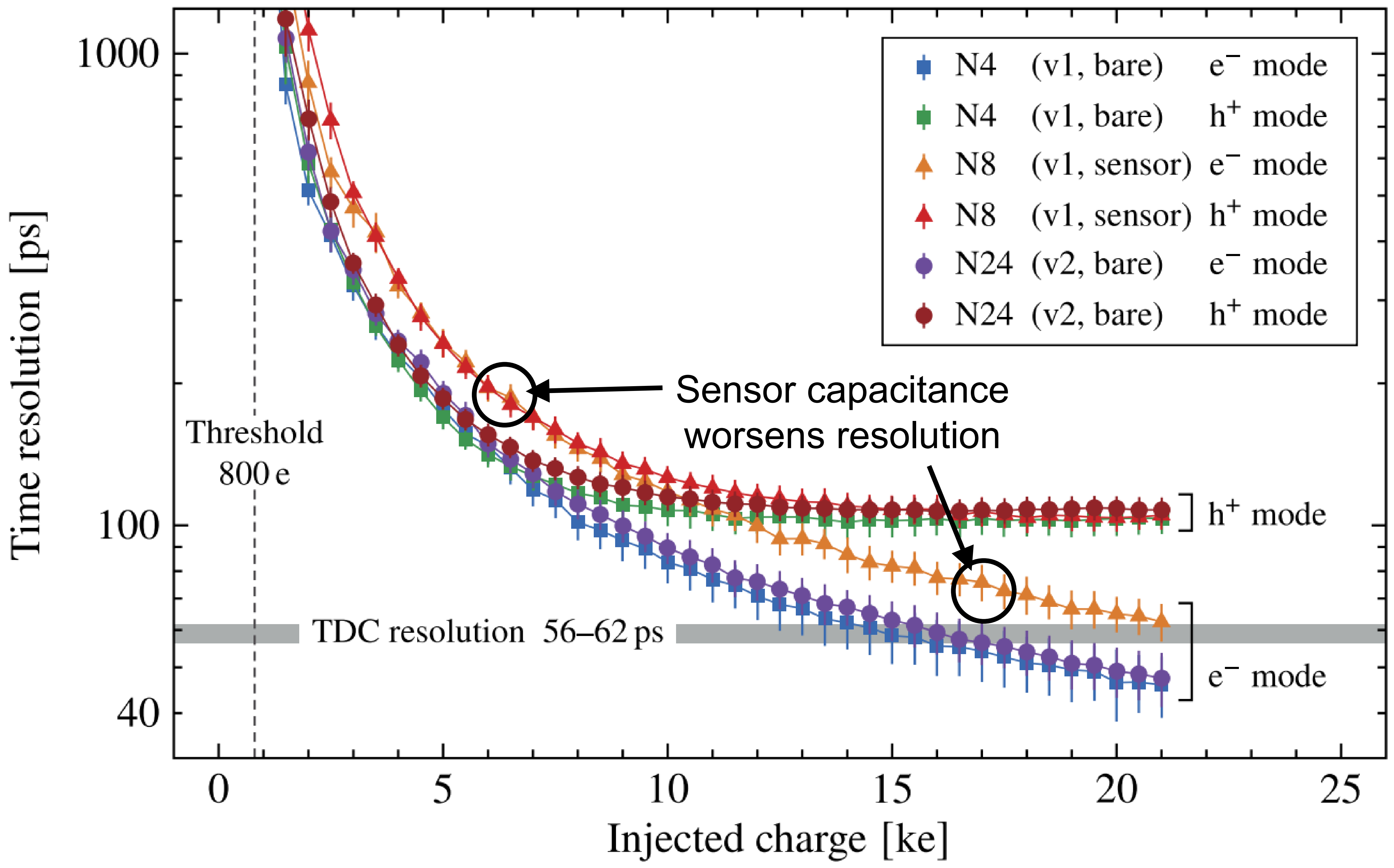


~**22.7 mW/cm²** to distribute a 40 MHz clock with a 100 ps_{rms}

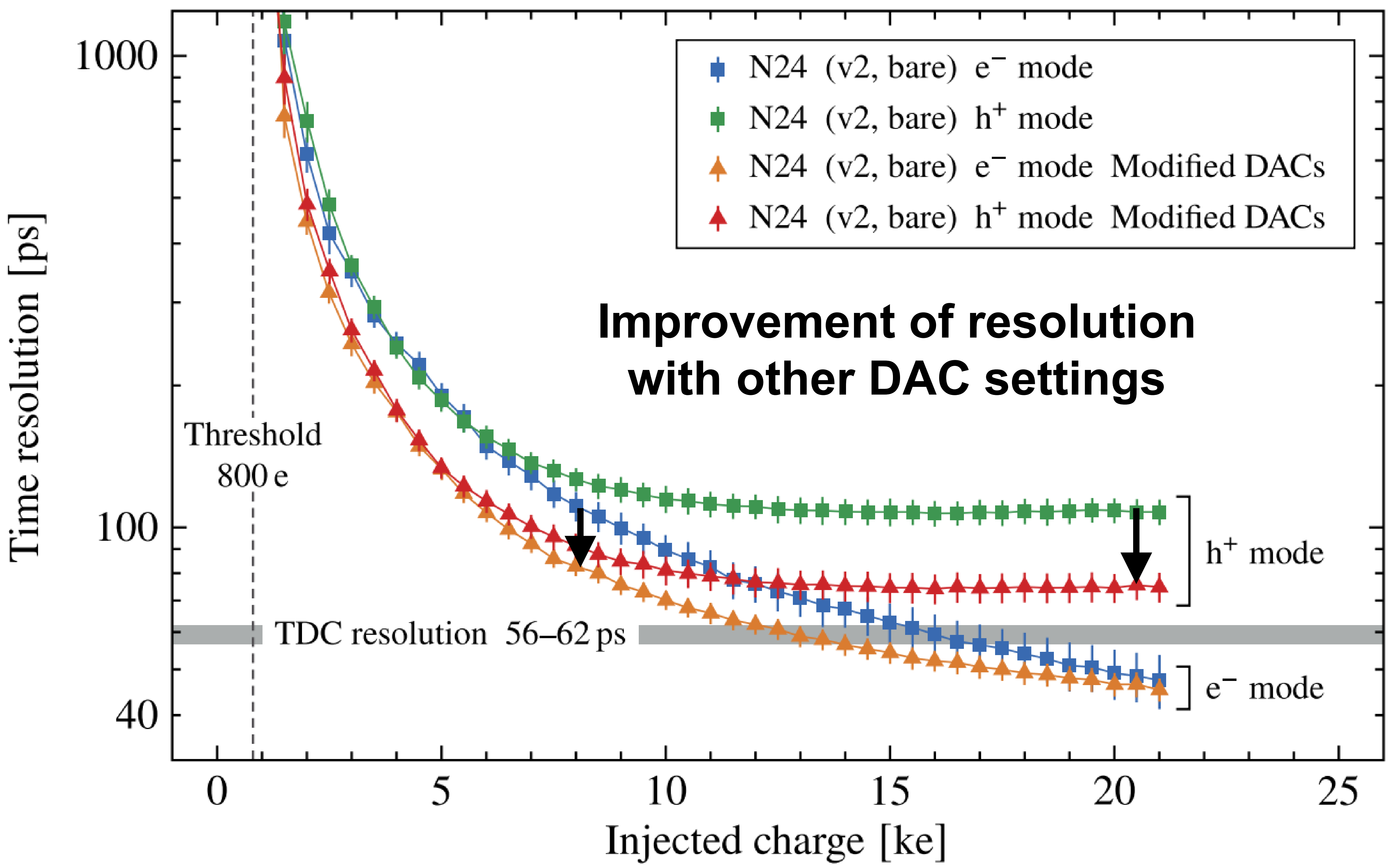
Timepix4 – Analog front-end jitter

- 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]

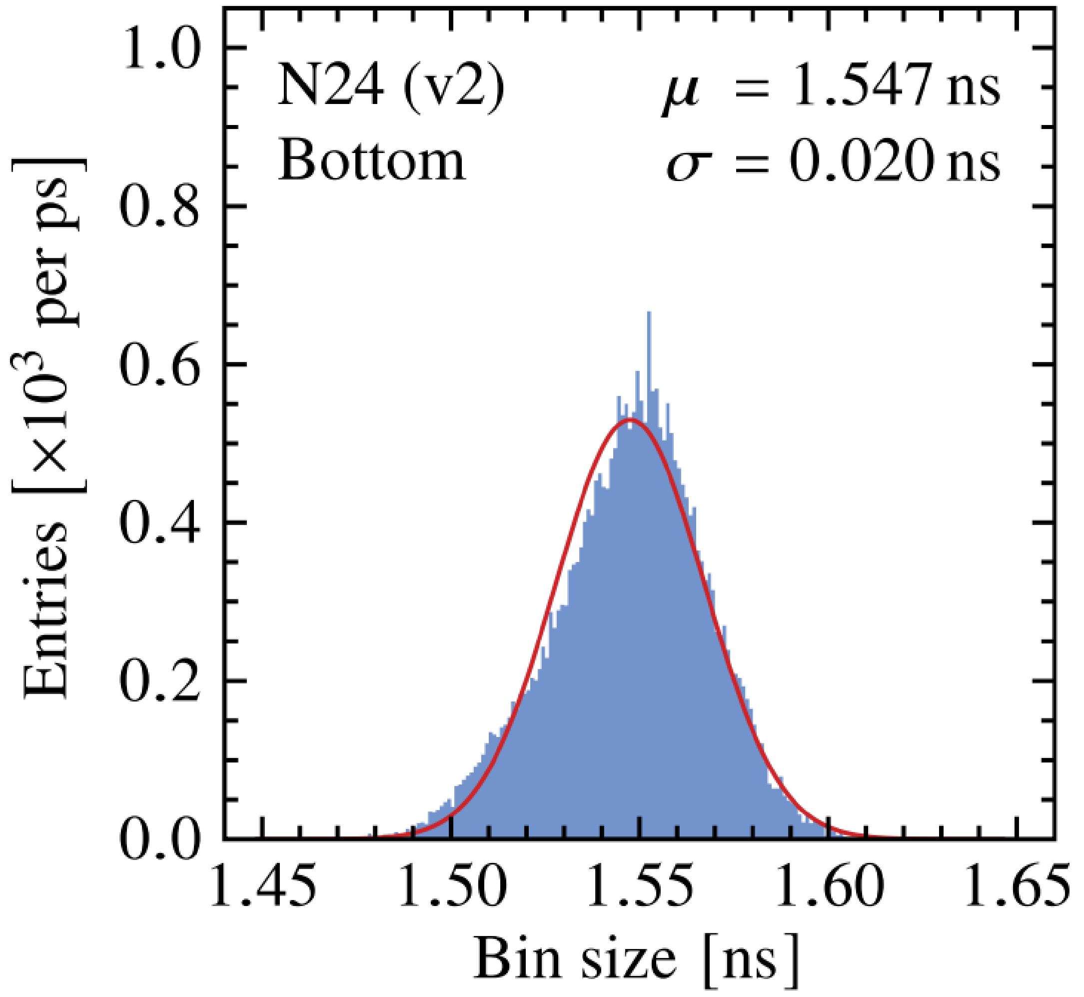


K. Heijhoff *et al* 2022 *JINST* **17** P07006 [DOI: 10.1088/1748-0221/17/07/P07006]

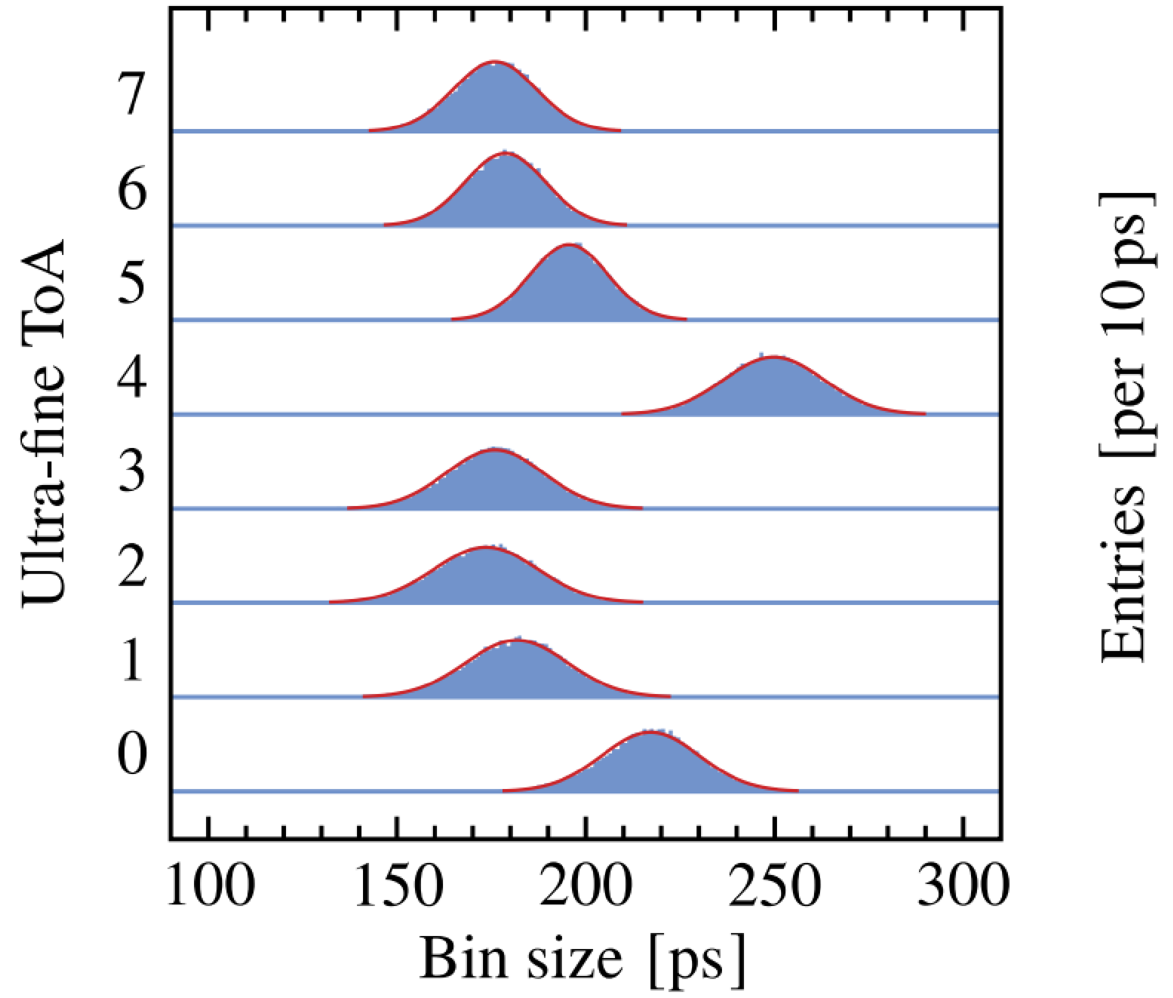
TDC resolution

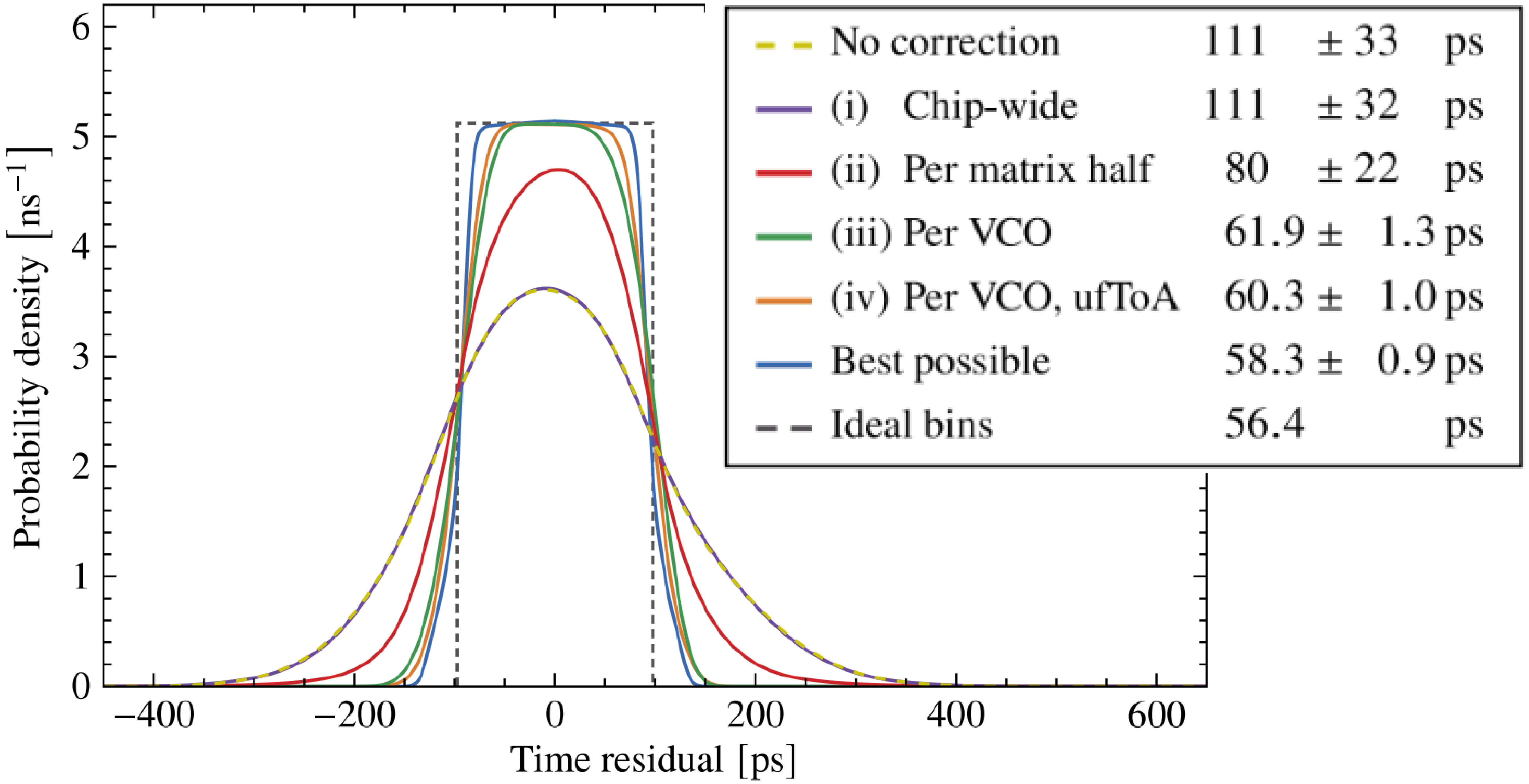
- Variation in the VCO frequency over the pixel matrix observed:
  Bottom half: 1.547 ns ± 20 ps
  Top half: 1.583 ns ± 14 ps
- Structure in ultra-fine time bins has a small impact on TDC resolution (few %)
- We have tried to predict the TDC resolution for correction methods of increasing complexity

Fine time bins (640 MHz)

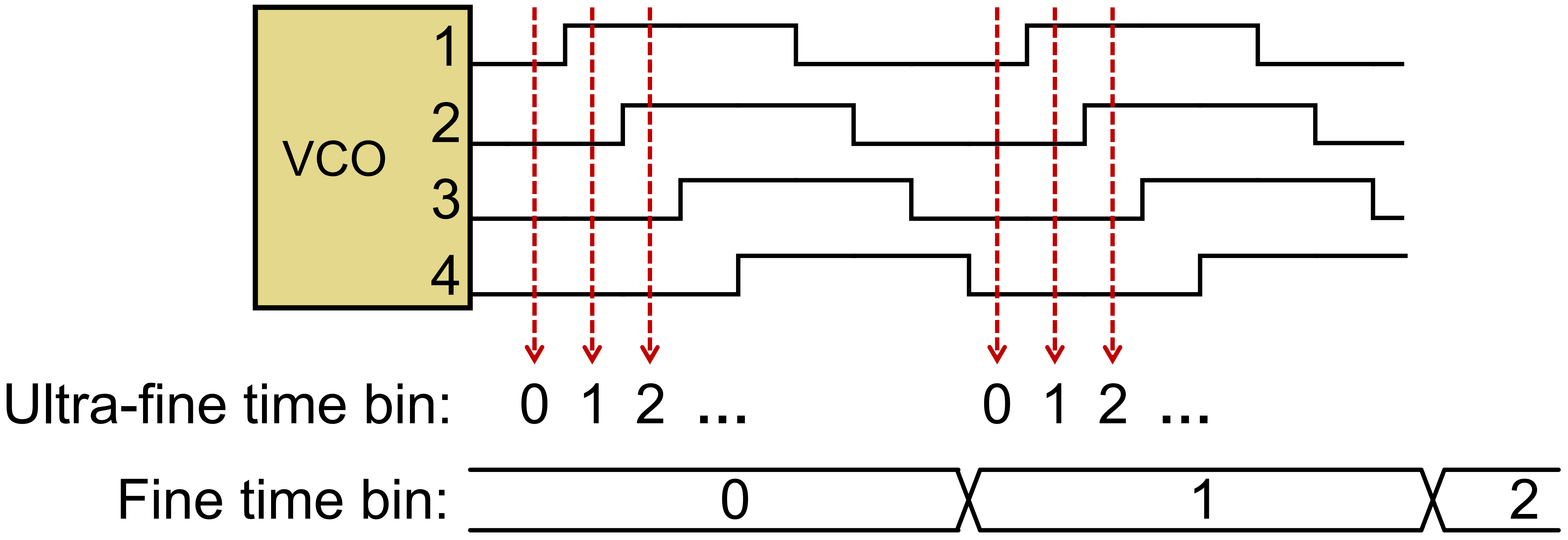


Ultra-fine time bins





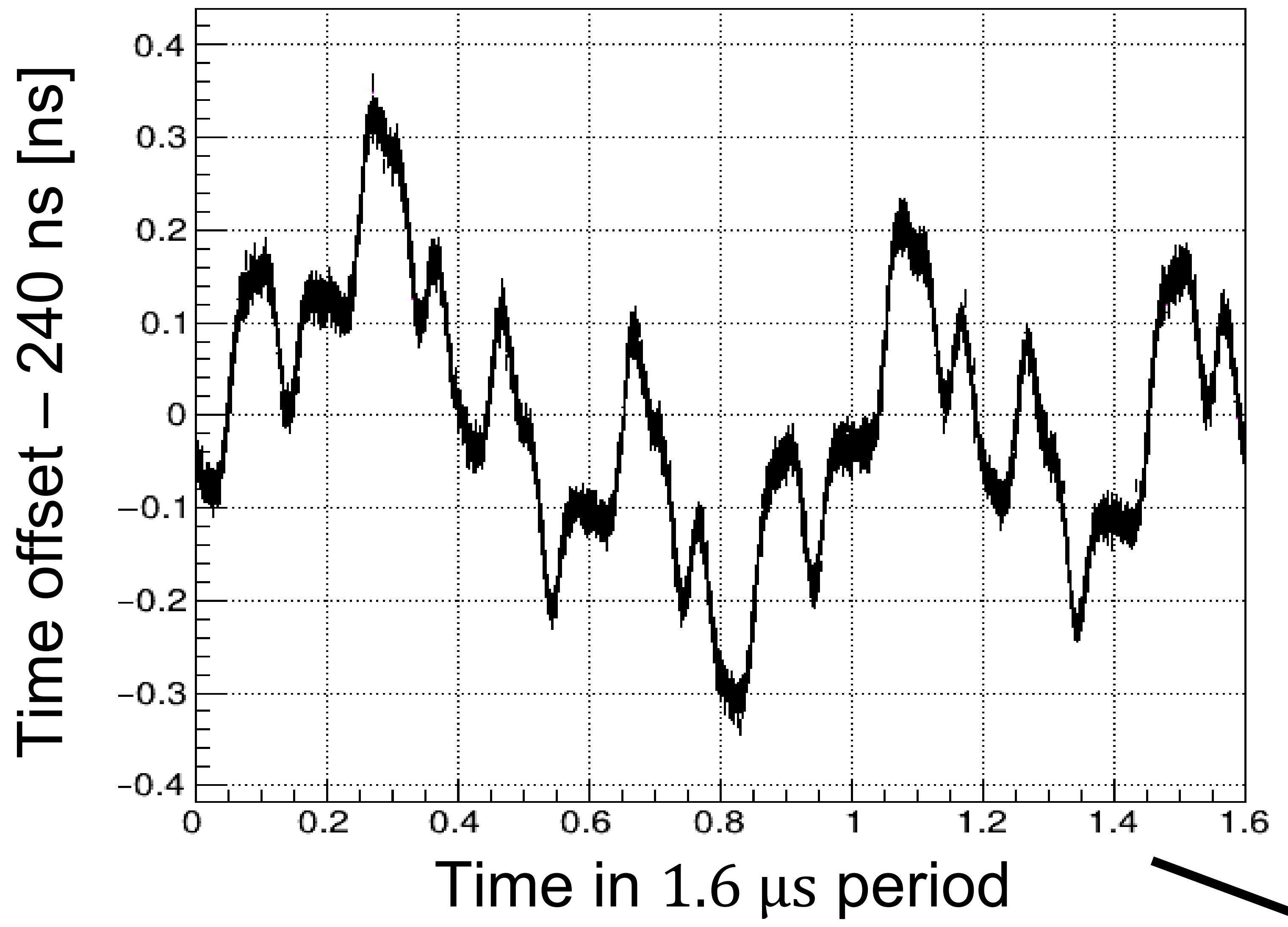
Phase shifted 640 MHz clocks



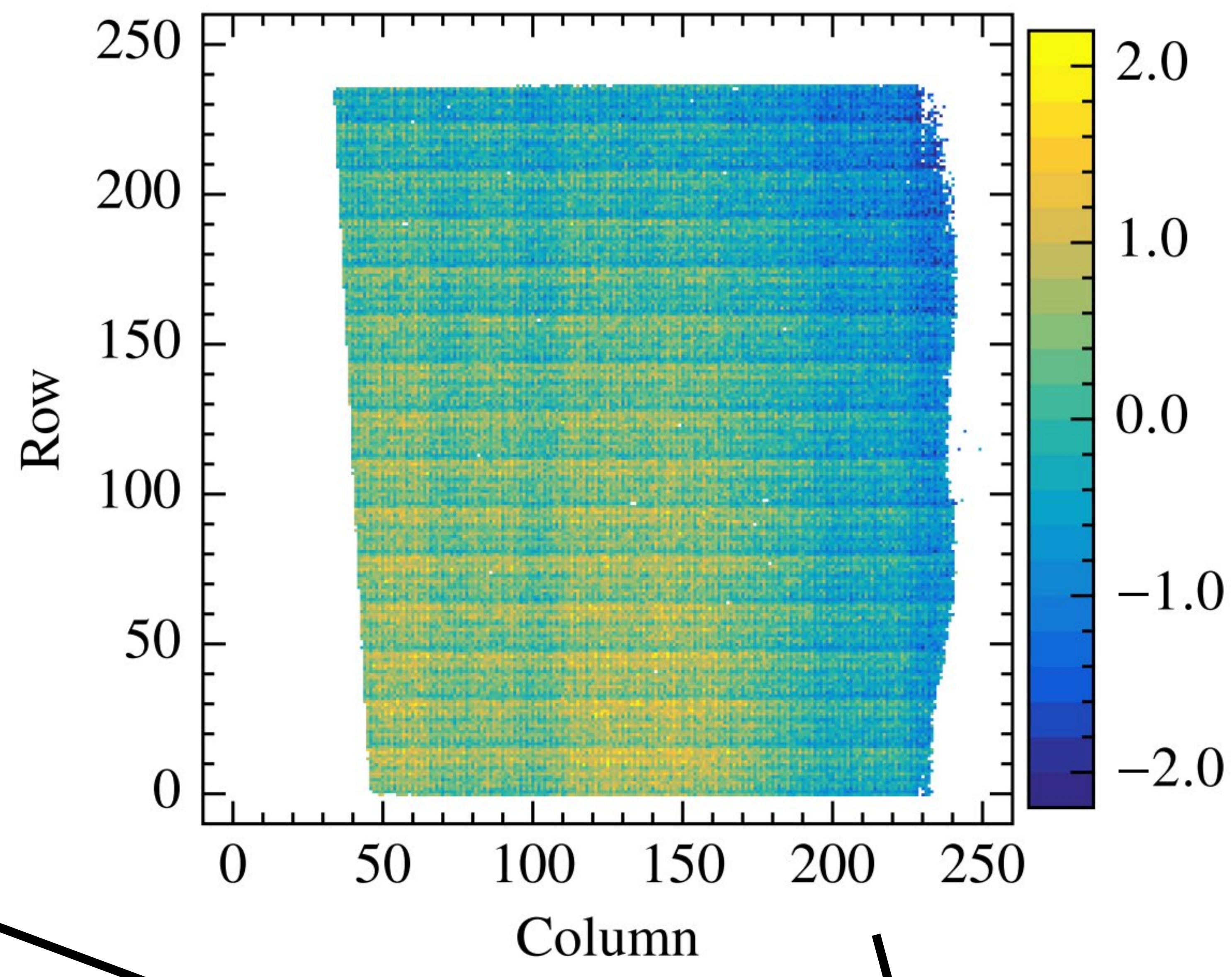
K. Heijhoff *et al* 2020 *JINST* **15** P09035 [DOI: 10.1088/1748-0221/15/09/P09035]

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

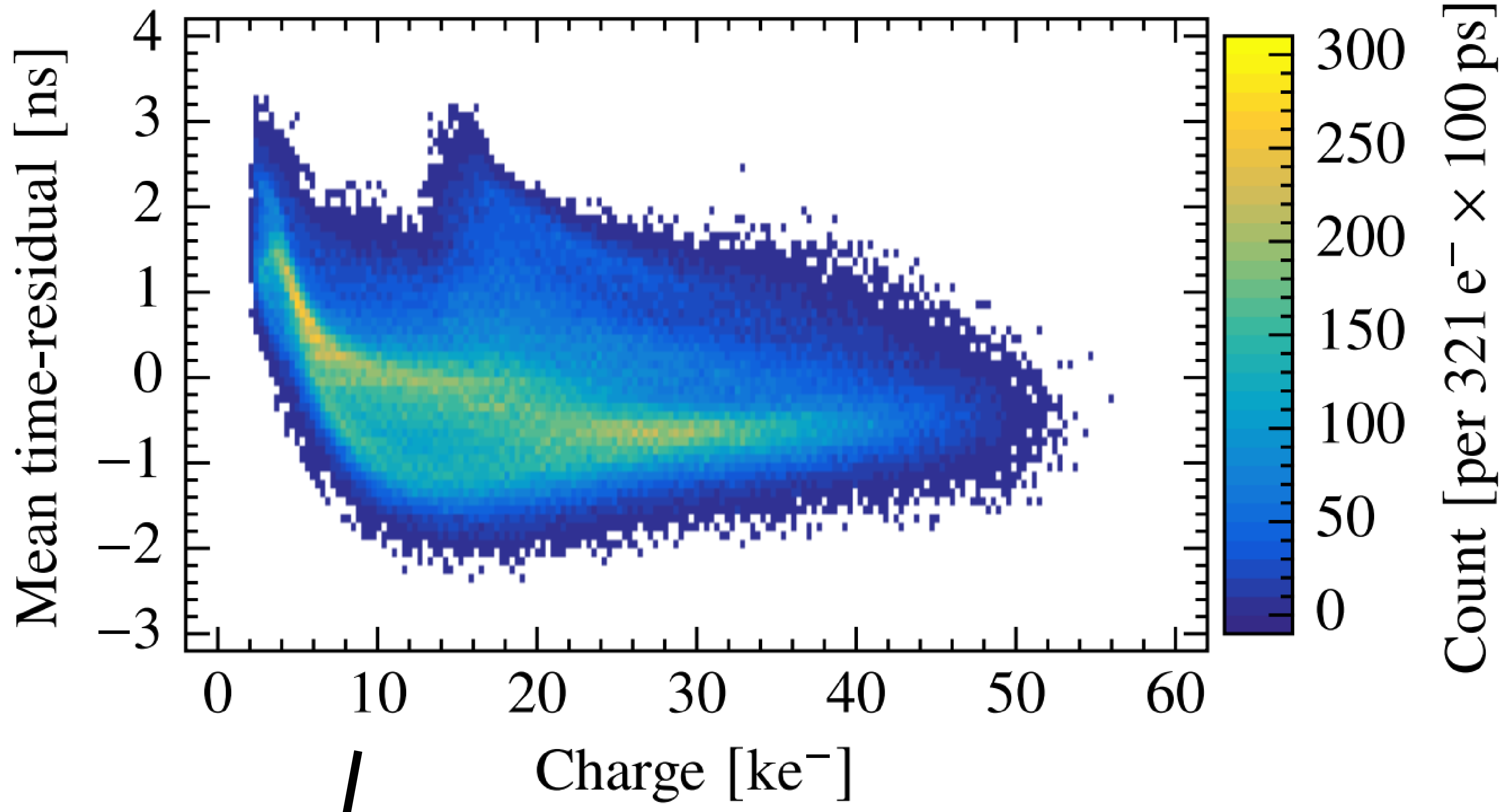
Clock phase variation

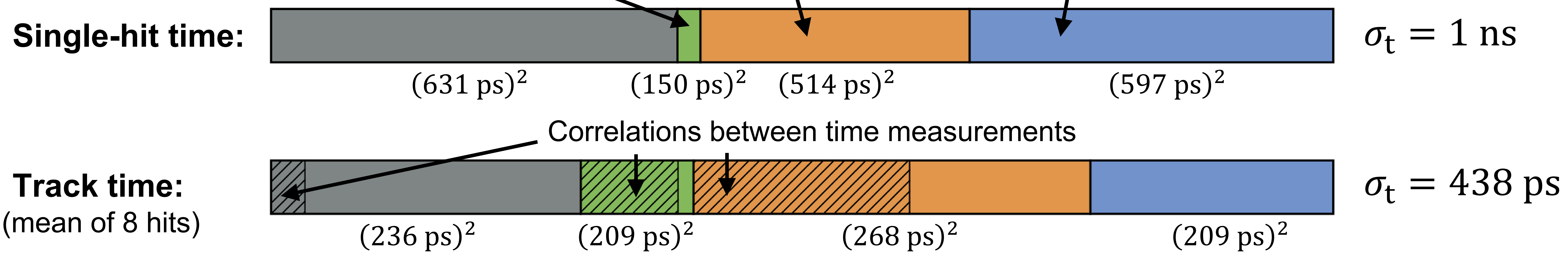


Pixel / TDC systematics



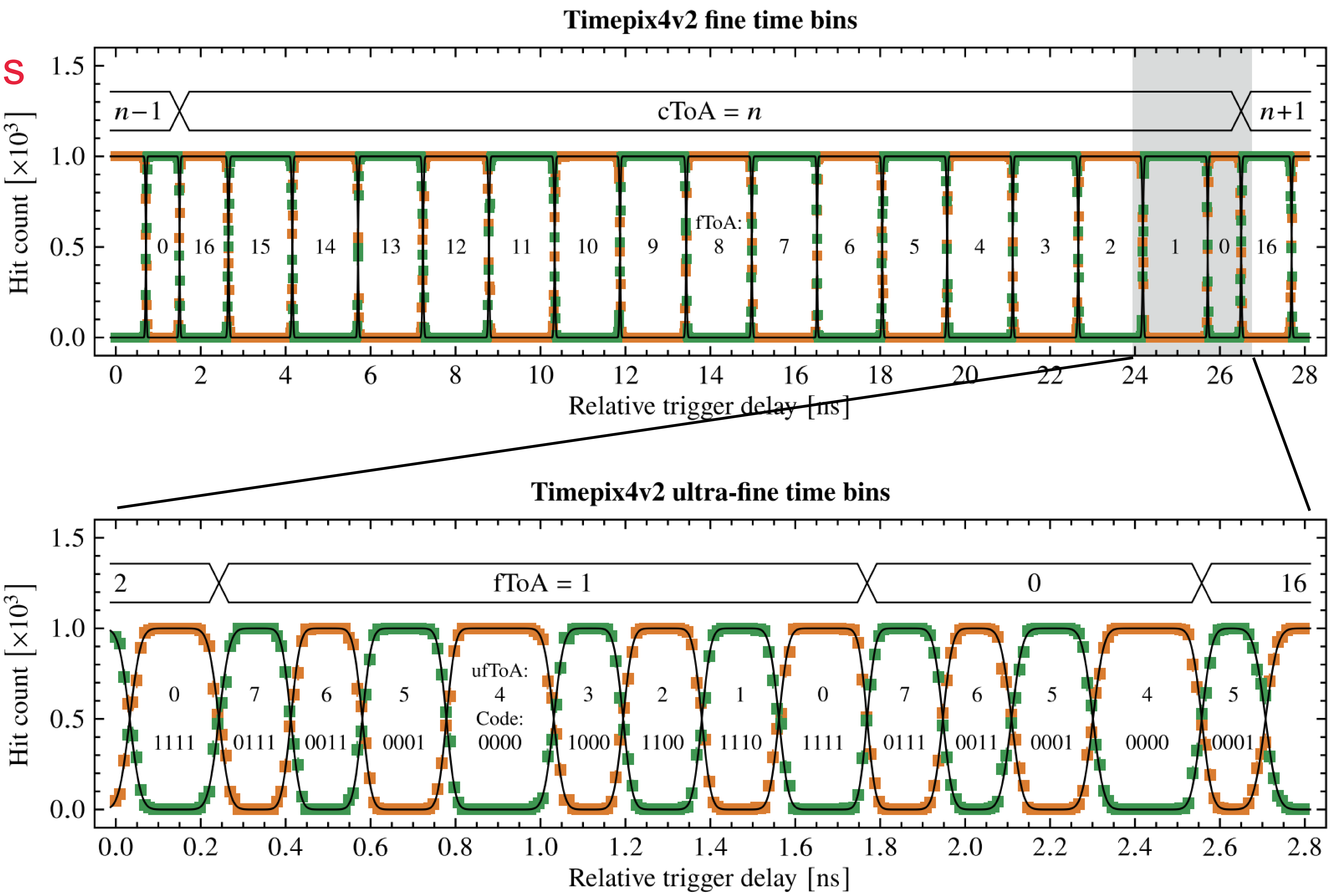
Timewalk and signal induction time in sensor





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