Timing performance of a digital SiPM prototype

Studies with a fast injection laser

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PIXEL24
21.11.2024

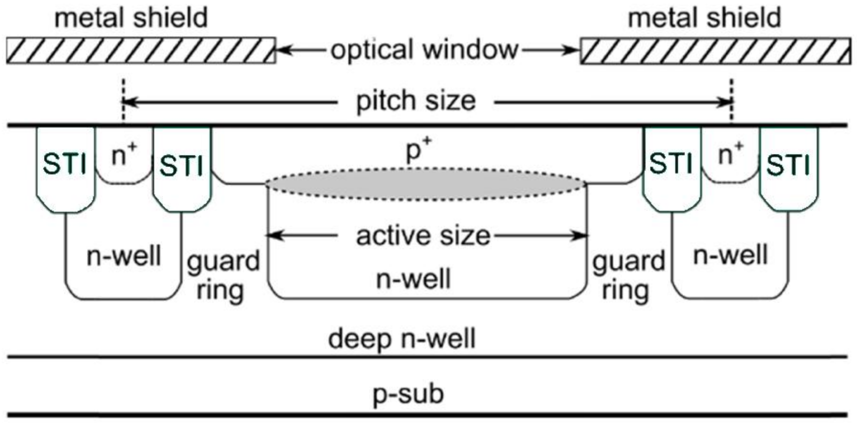
HELMHOLTZ

dSiPM design overview

SPADs meet CMOS

The concept of a digital silicon photomultiplier

Schematic structure of a p^+/n-well SPAD in 150 nm CMOS [1] →



Specialty foundries now offer SPADs in their CMOS PDKs

Here: LFoundry 150 nm

[1] H. Xu et al. *Optics Express* 25(11) (2017) 12765-12778

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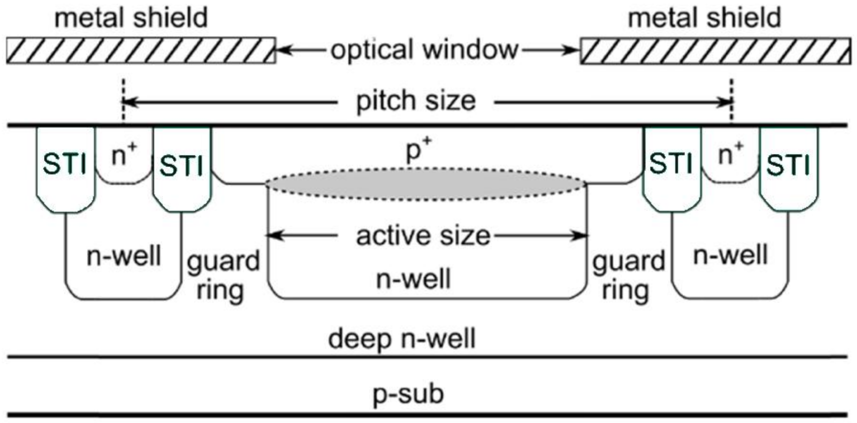

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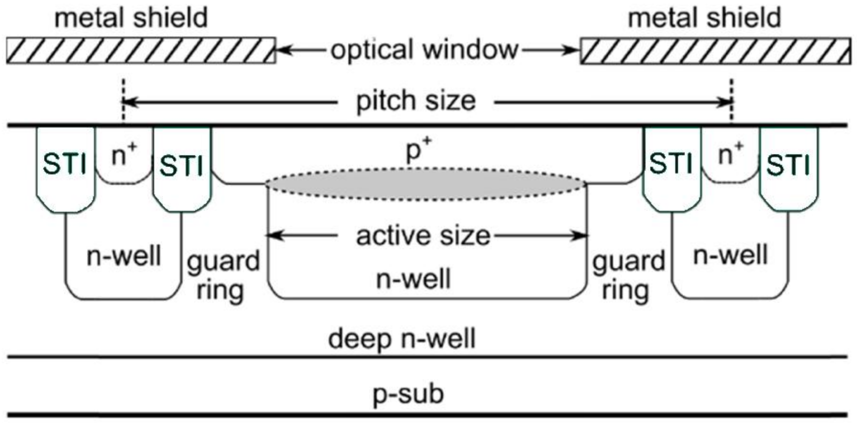

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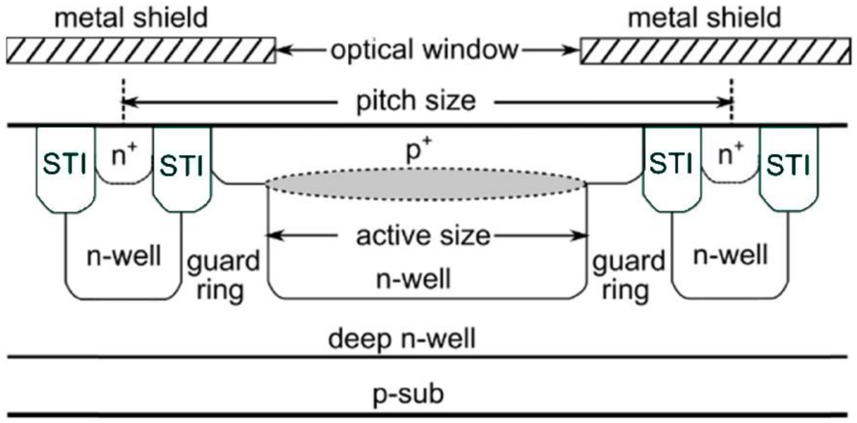

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Front-end and readout similar to pixel detectors

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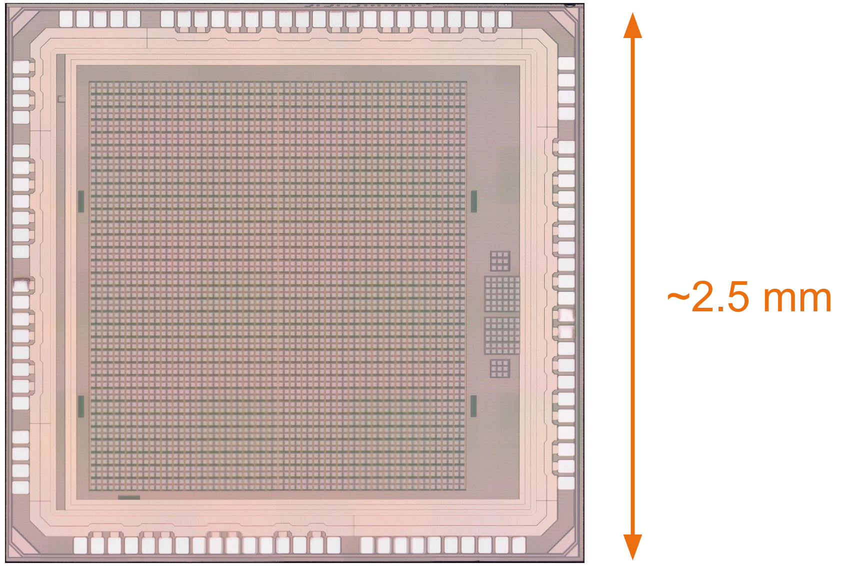
DESY digital SiPM prototype

Designed in 150 nm LFoundry CMOS process

Matrix:

- **32×32** pixels
- **70×76 µm²** pixel pitch



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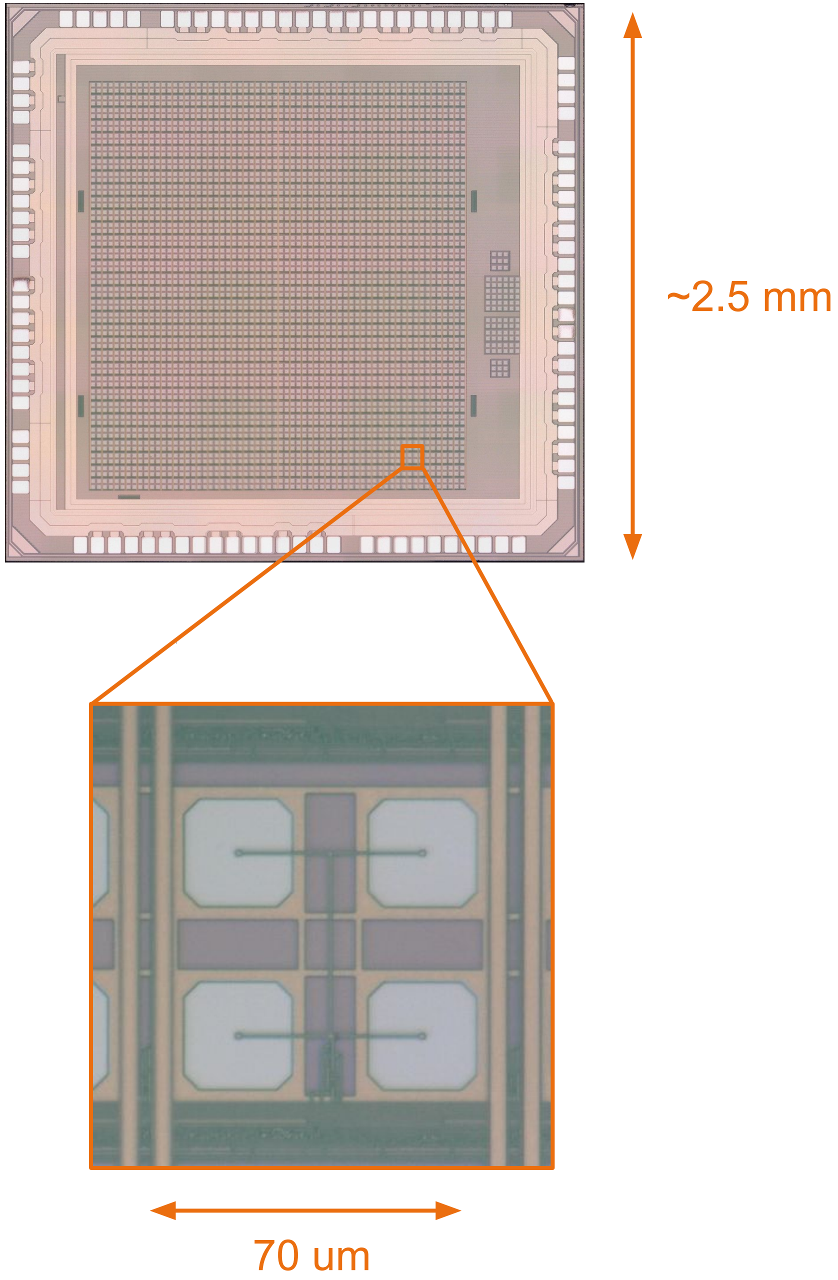

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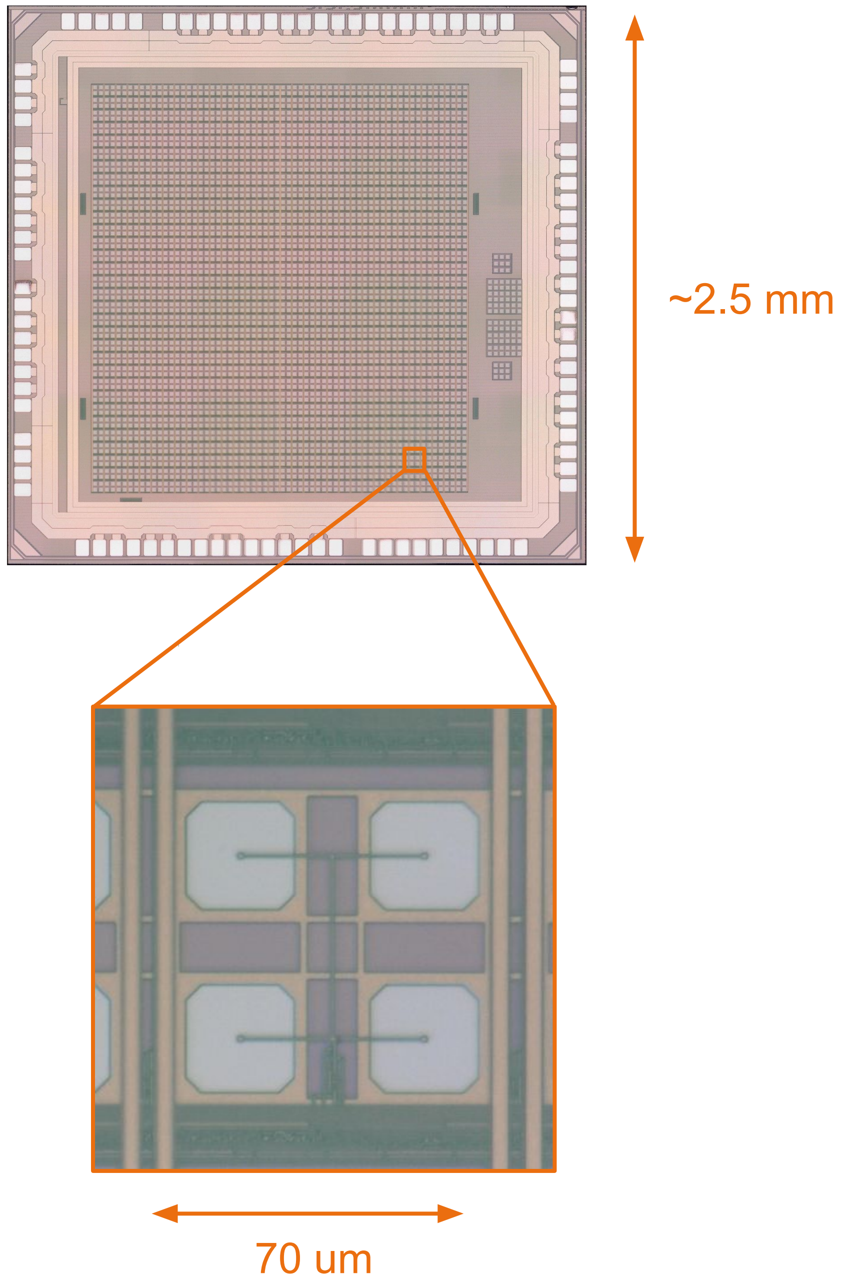
Readout:

- Frame-based
- Full binary hitmaps
- Hit pattern recognition
- Pixel masking (with disabling bias on masked pixels)
- Fine hit timestamping via 12-bit TDC (bin size ~77 ps)



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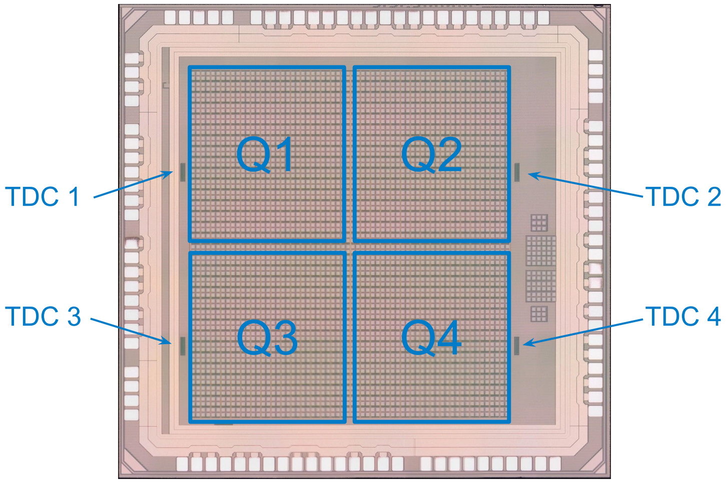
How timing works on the chip

Timestampping mechanism and quadrants



- Each pixel is connected to a shared **time-to-digital converter** (TDC) (located on the **periphery of each quadrant**, 4 total)
- **First pixel to fire** within each frame triggers the TDC of the quadrant it's in
- Thus, up to 4 timestamps are set for each frame (1 per quadrant)

In the following measurements the masking feature is used to ensure that timestamps only come from a known pixel

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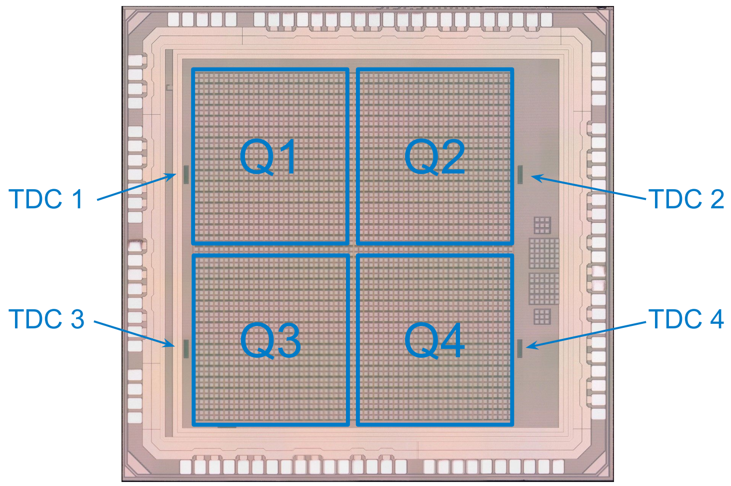


Timestamp
within a frame (333 ns)

=

Coarse timestamp
bin = 2.45 ns
7 bits @ 408 MHz chip clock

+

Fine timestamp
bin = 77 ps
within a chip clock cycle,
(5-bit delay-locked loop)

manufacturing variation: real bin size = ~95 ps

In the following measurements the masking feature is used to ensure that timestamps only come from a known pixel

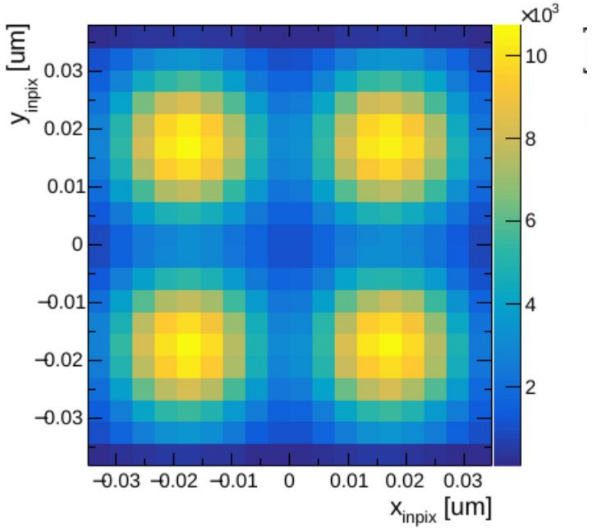
Timing measurements

Timing performance @ minimum-ionizing particle detection

A story of peculiar things in the test beam results

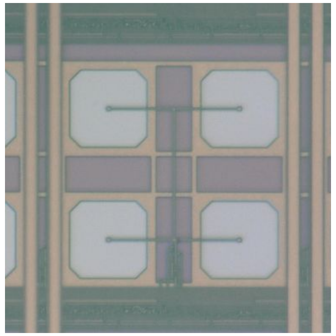
Test-beam campaign @ DESY II:
chip characterization
via direct m.i.p. detection (5 GeV e^-)

In-pixel hitmaps for m.i.p. detection at a testbeam



All events

Pixel layout →



Test beam studies: [F. Feindt et al. *NIMA* 1064 (2024) 169321]
[Thesis by S. Lachnit (2024)]

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

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sub-100 ps is reached, but:
for a fraction of events,
significantly slower response is observed (**few ns**)

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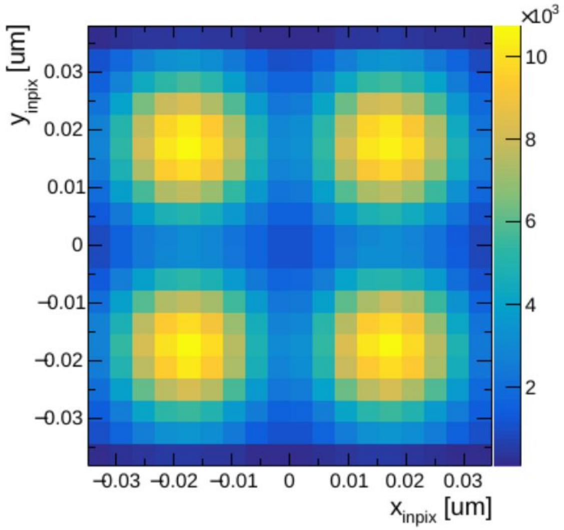

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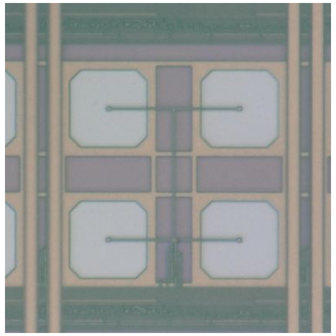

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Finding 2:
slow response occurs when a particle track crosses the chip at a **SPAD edge**

Hypothesis:
this effect is caused by avalanches being preceded by **drift**

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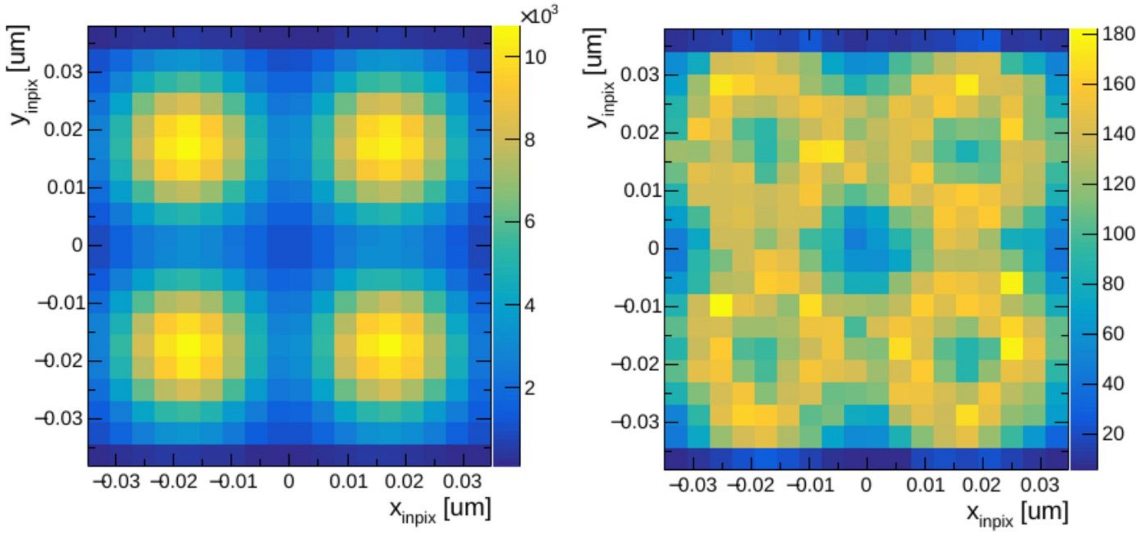
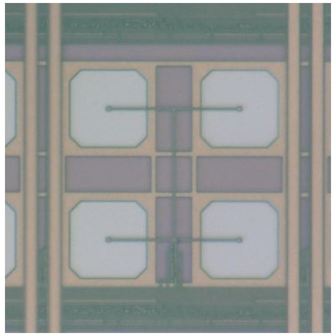


All events

Cut on delay >1 ns

Pixel layout →



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Laserbox

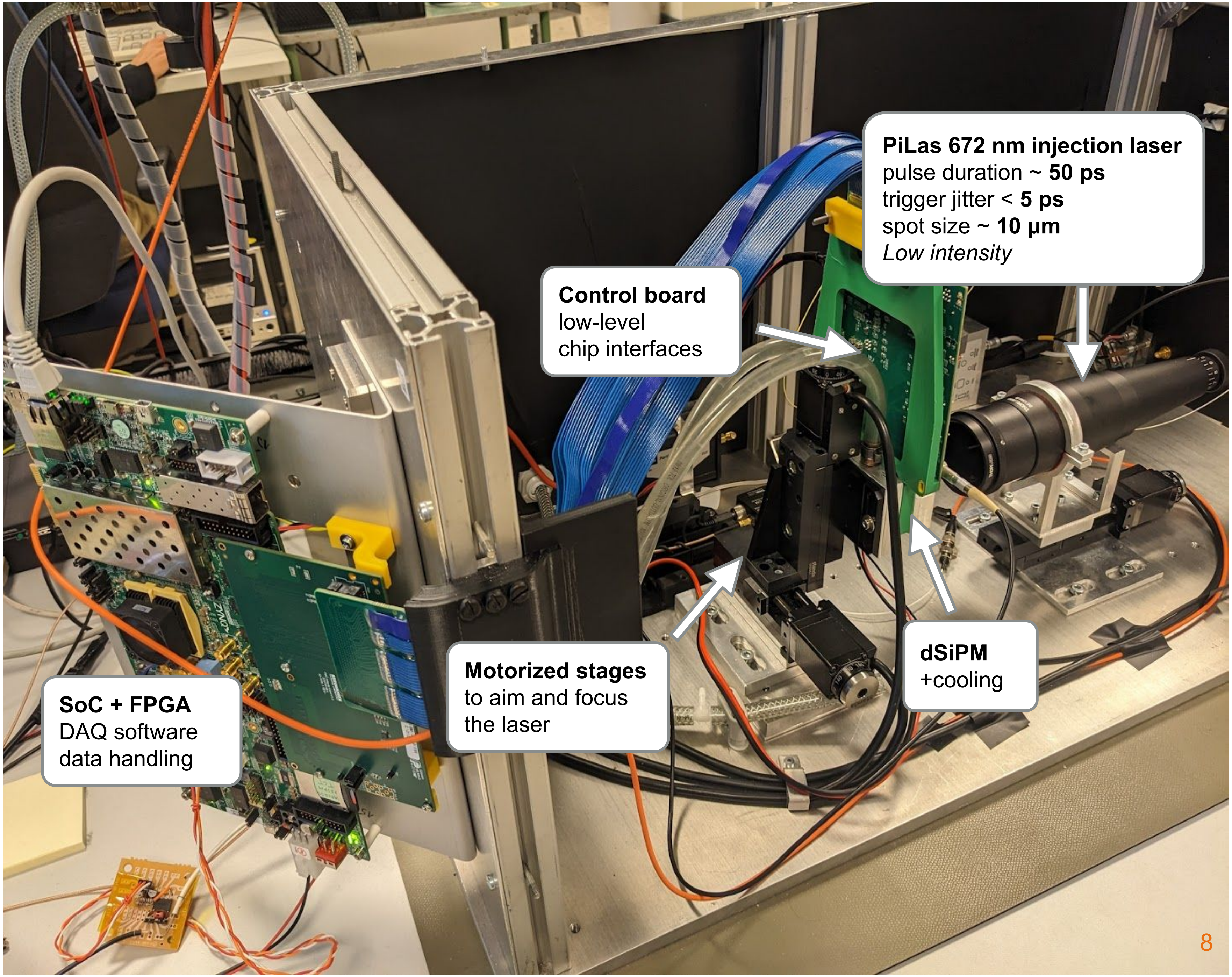
and how to measure timing resolution with it

Pulsed lasers
are great for charge injection:

- micrometer aim precision
- controllable trigger
- high repetition rate
- tunable intensity

Measurement scheme:

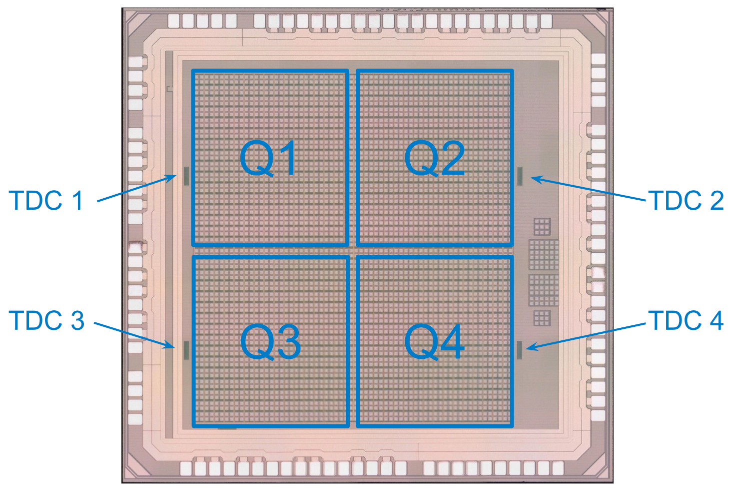
- DAQ+control via Caribou [1]
- laser trigger pulses in sync with readout frames

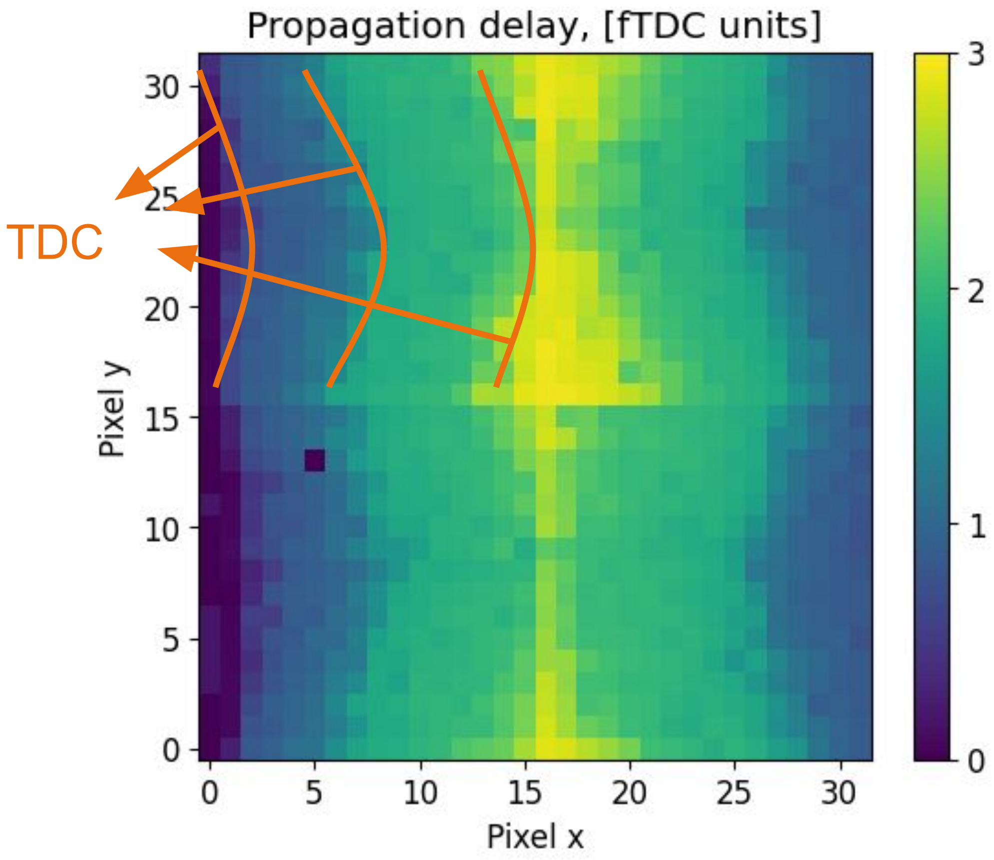


[1] T. Vanat *PoS TWEPP2019* (2020) 100

Propagation delay

Corrections for pixel position w.r.t. TDC block

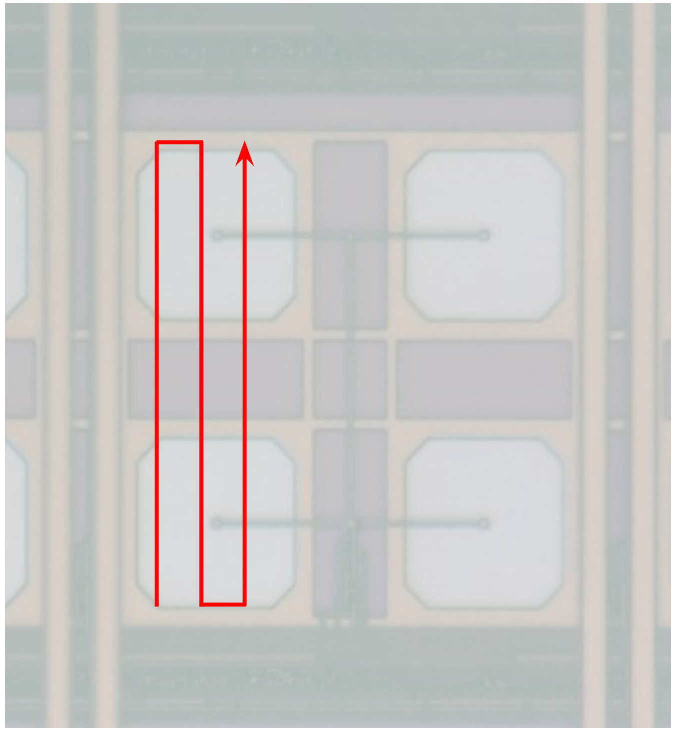




- Additional delay for pixels in the matrix centre, as signals need to **propagate to the periphery**
- This delay can be quantified with a grain of exactly 1 TDC bin
- Results are used as an **lookup table** to **compensate for propagation** delay e.g. in the testbeam

In-pixel laser characterization

xy-scan



1. Laser is triggered synchronously with the frame clock → always the same ToA expected
2. Accumulate multiple frames to get the *timing residual distribution*
3. Repeat for all *xy*

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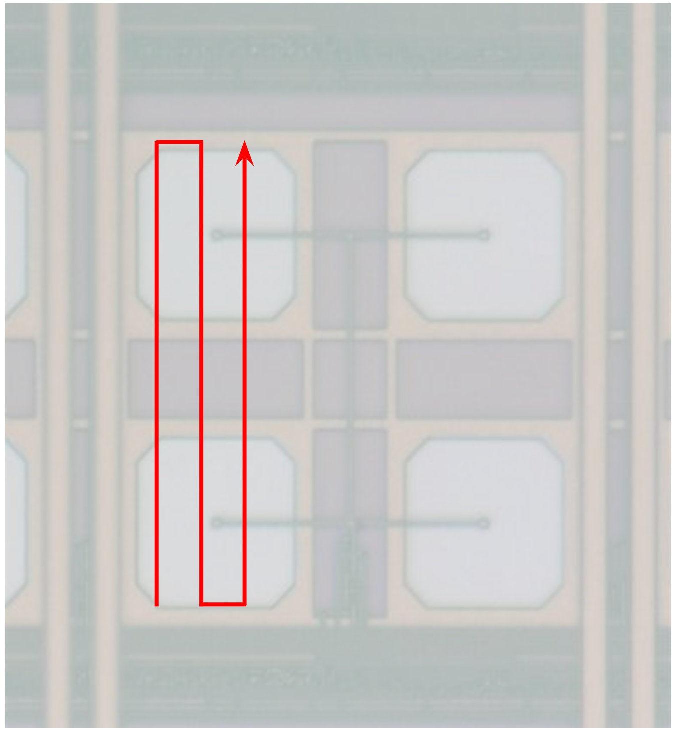

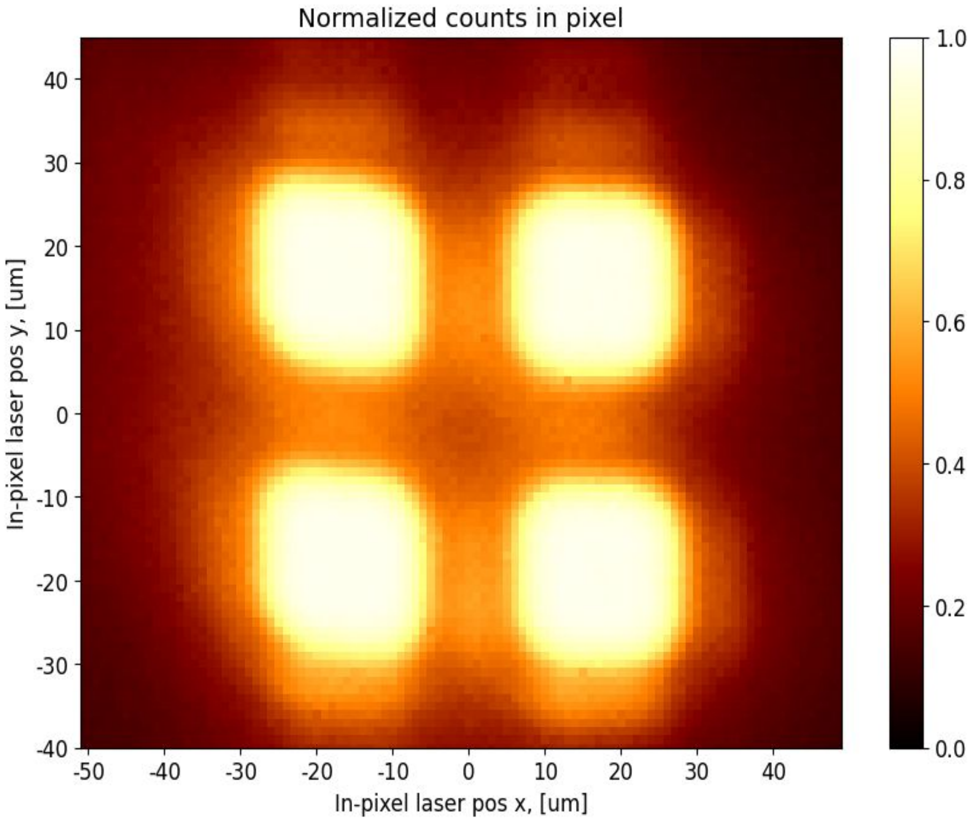

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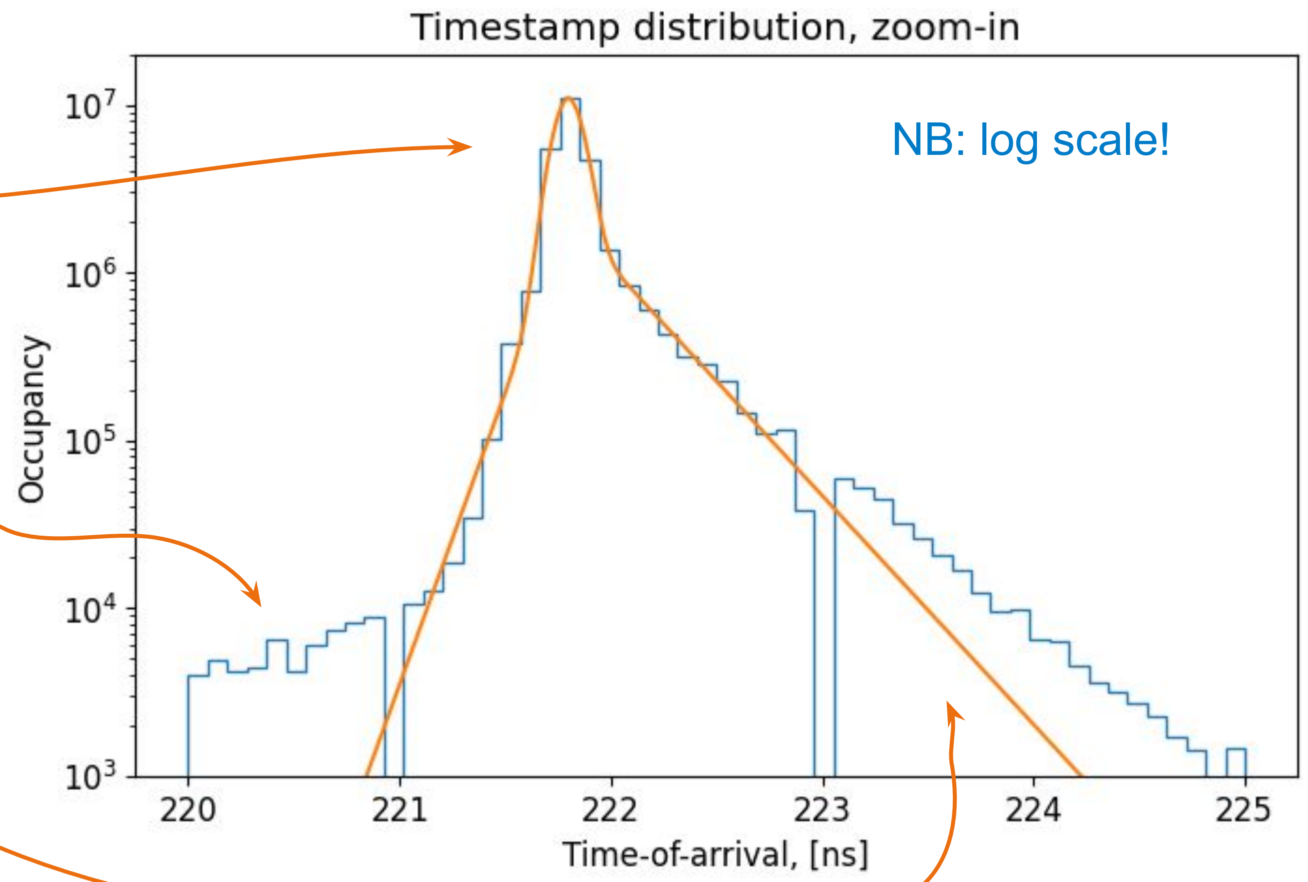
In-pixel timing (1)

Time residual structure

Main peak (~50 ps width)
↦ Instant avalanches

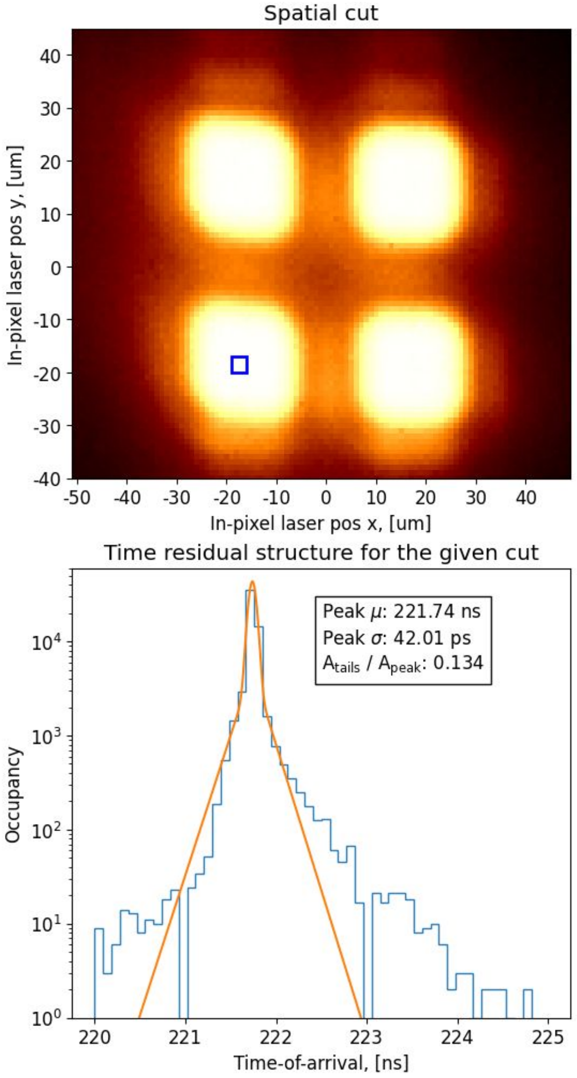
Dark counts
↦ Noise events *before* the laser pulse

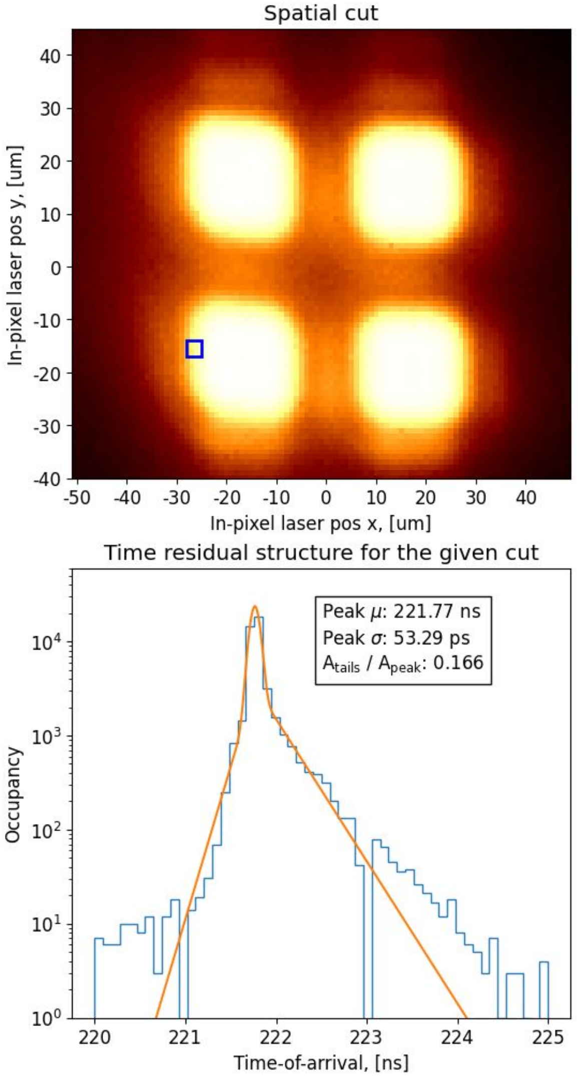
Tail
↦ Avalanches *preceded* by drift



In-pixel timing (2)

SPAD center / SPAD edge variations

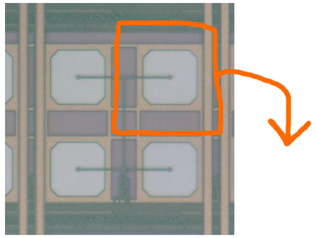


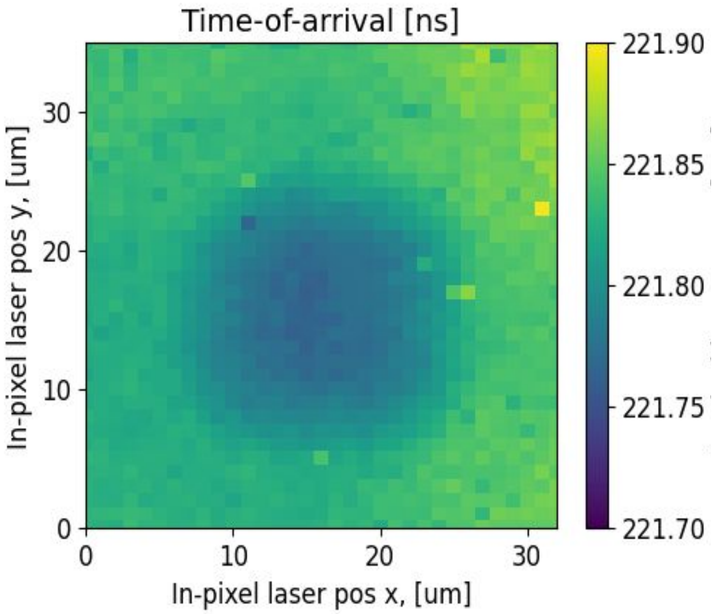


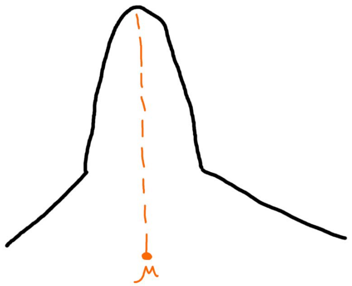
In-pixel timing (3)

ToA fit results

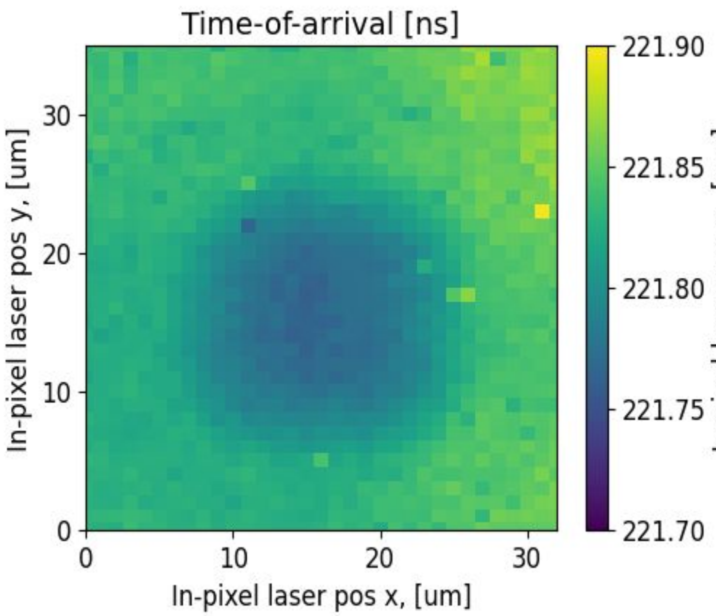
Per-point fits for this region →

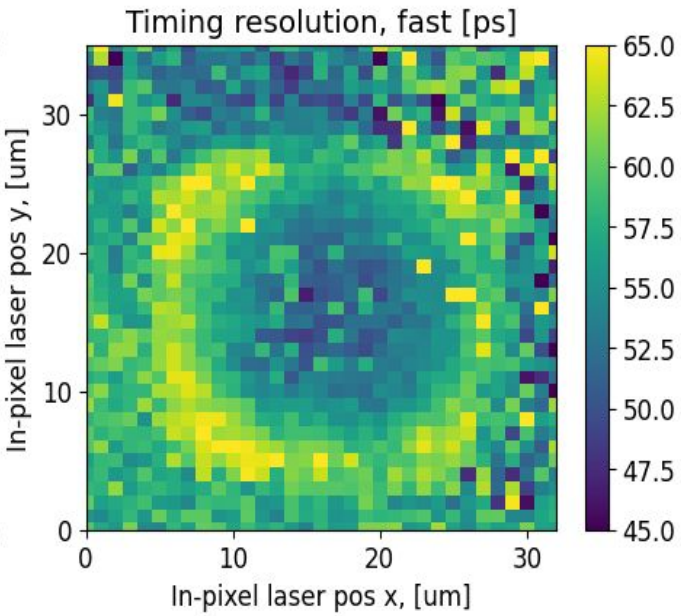


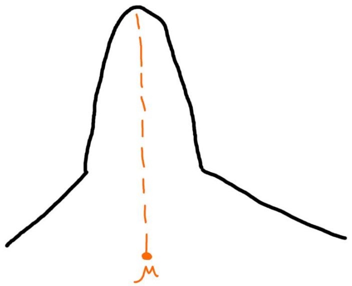


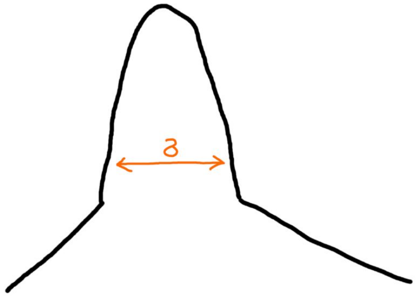


- Stable performance in the SPAD centres → instant fast (~50 ps) avalanches
- Fraction of slower (~ns) events → charges drifting to the avalanche region
    - Becomes more significant when the laser is aimed at a SPAD edge









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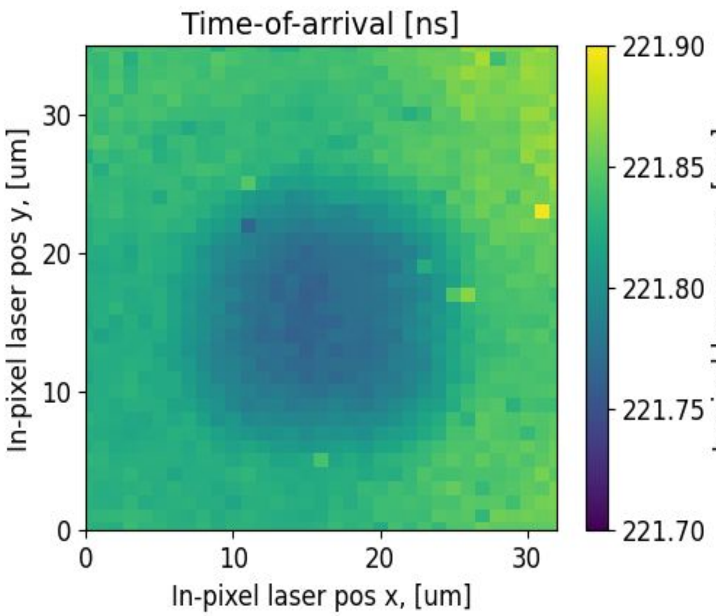

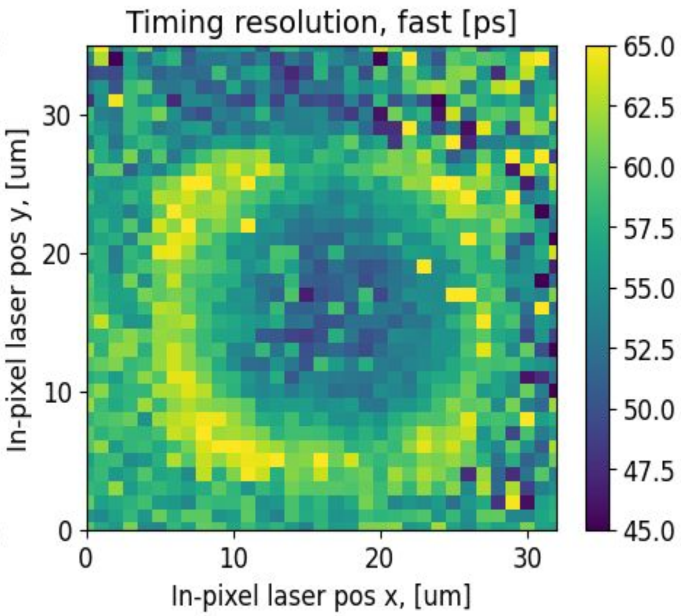

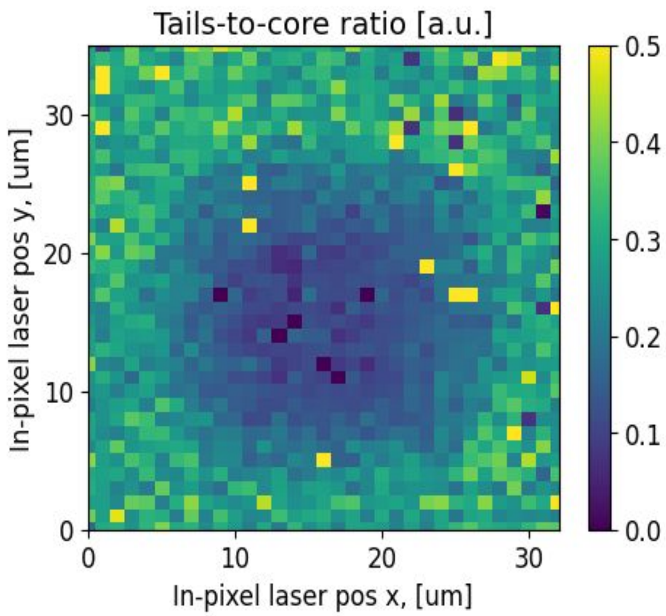

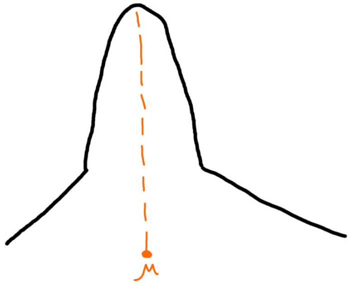

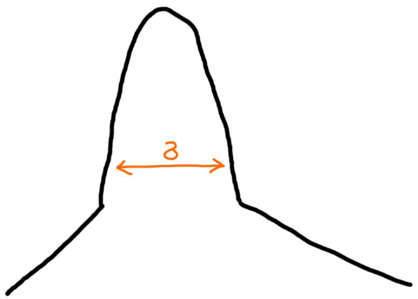

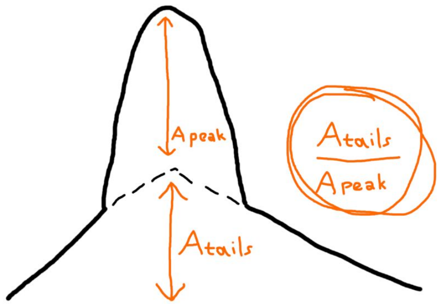

Possible applications

Use cases that require simultaneous spatial and temporal resolution

[1] H. Sadrozinski et al. *Rep. Prog. Phys.* 81 (2018) 026101

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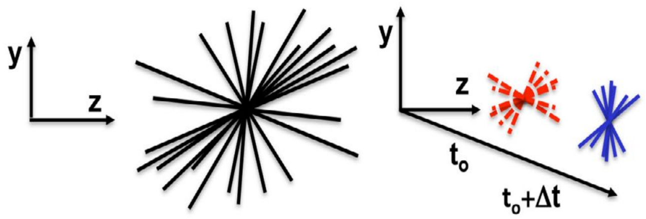
High-energy physics



High-granularity timing,
e.g. 4D-tracking [1]

M.I.P. detection

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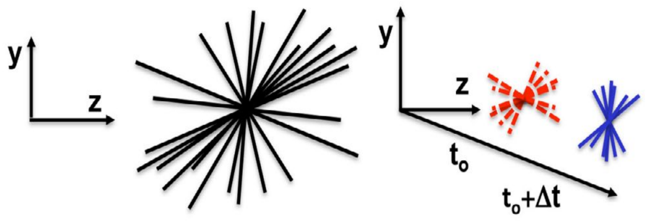
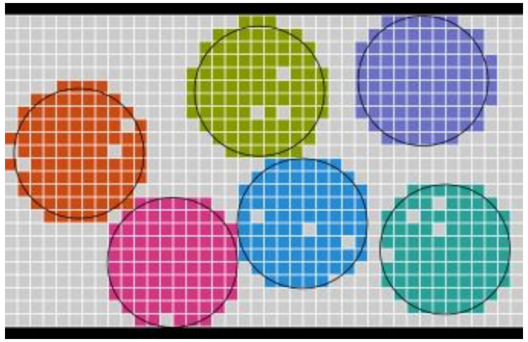




High-granularity timing, e.g. 4D-tracking [1]

Multi-channel fiber readout [2]

M.I.P. detection

Visible (and near-visible) photons

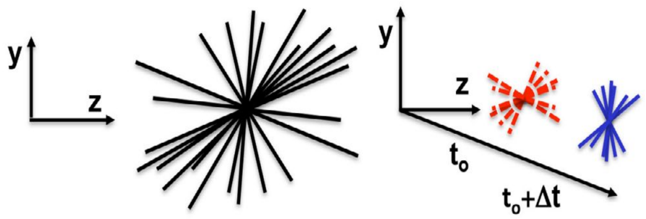
[1] H. Sadrozinski et al. *Rep. Prog. Phys.* 81 (2018) 026101
[2] P. Fischer et al. *NIMA* 1040 (2022) 167033

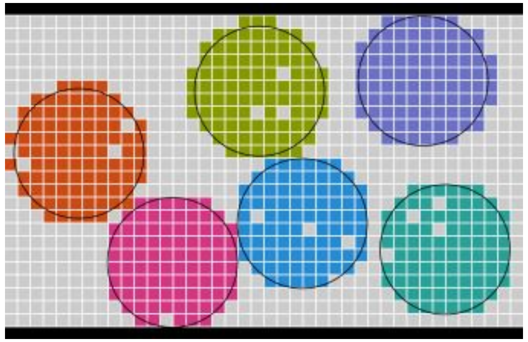
Possible applications

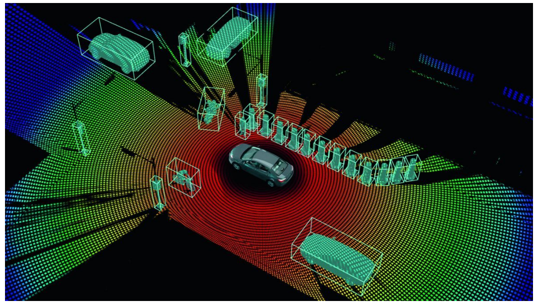
Use cases that require simultaneous spatial and temporal resolution

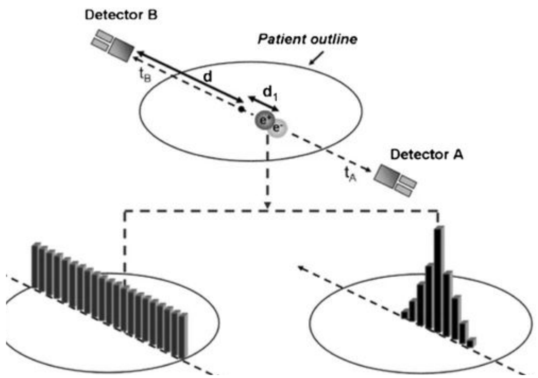
High-energy physics

Industry









High-granularity timing, e.g. 4D-tracking [1]

Multi-channel fiber readout [2]

LiDAR

TOF-PET [3]

M.I.P. detection

Visible (and near-visible) photons

Gamma

[1] H. Sadrozinski et al. *Rep. Prog. Phys.* 81 (2018) 026101
[2] P. Fischer et al. *NIMA* 1040 (2022) 167033
[3] M. Ullah et al. *Nucl Med Mol Imaging* 50 (2016) 112–122

Conclusions

Timing performance of a **novel dSiPM** prototype studied at a test beam and with a fast injection laser

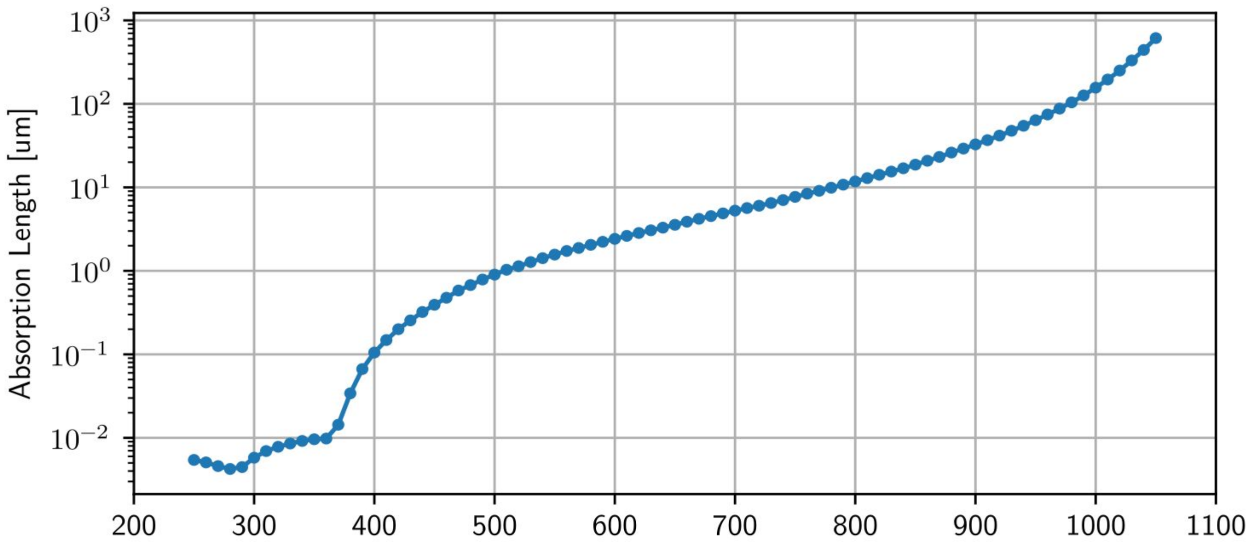
- Timing resolution is characterized
  - **~50 ps** timing resolution within SPADs
    - This is *total* (sensor + front-end) resolution
    - Timing performance deteriorates at the sensitive area edges
- **Laser** and **test beam** results are **in agreement**
- Design expectations reached*

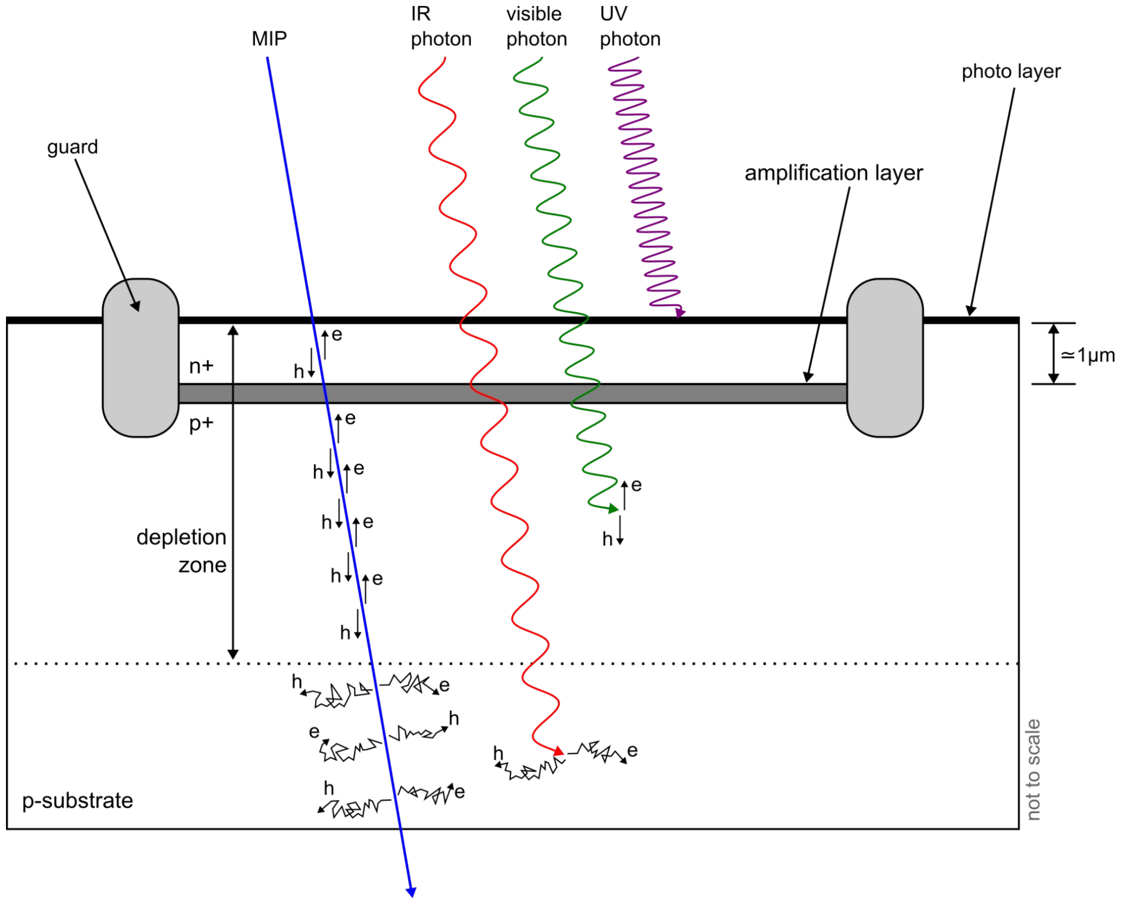
Thank you!

Scintillator-coupled dSiPM: G. Vignola et al. *NIMA* 1069 (2024) 169985

Backup (1)

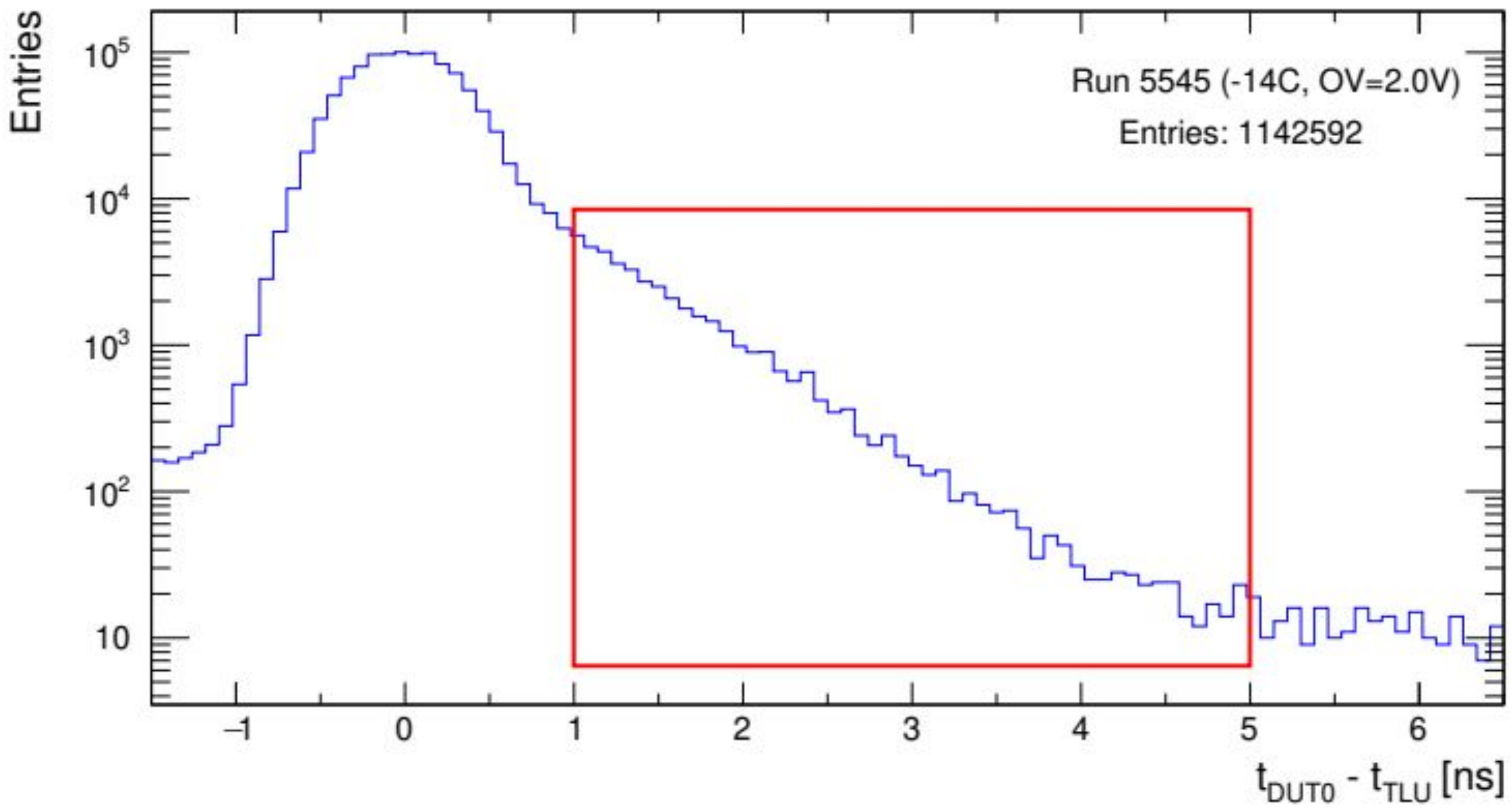
Visible (and near-visible) light in silicon





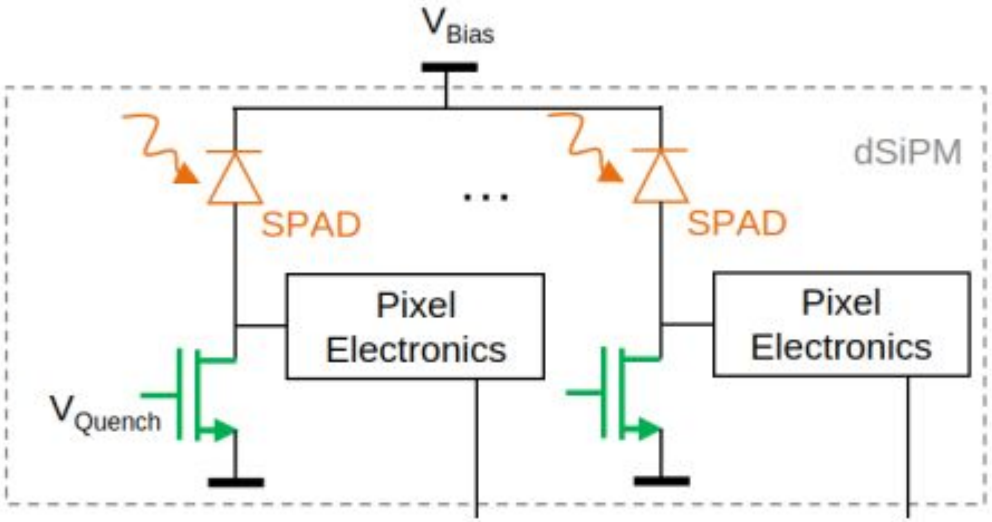
Backup (3)

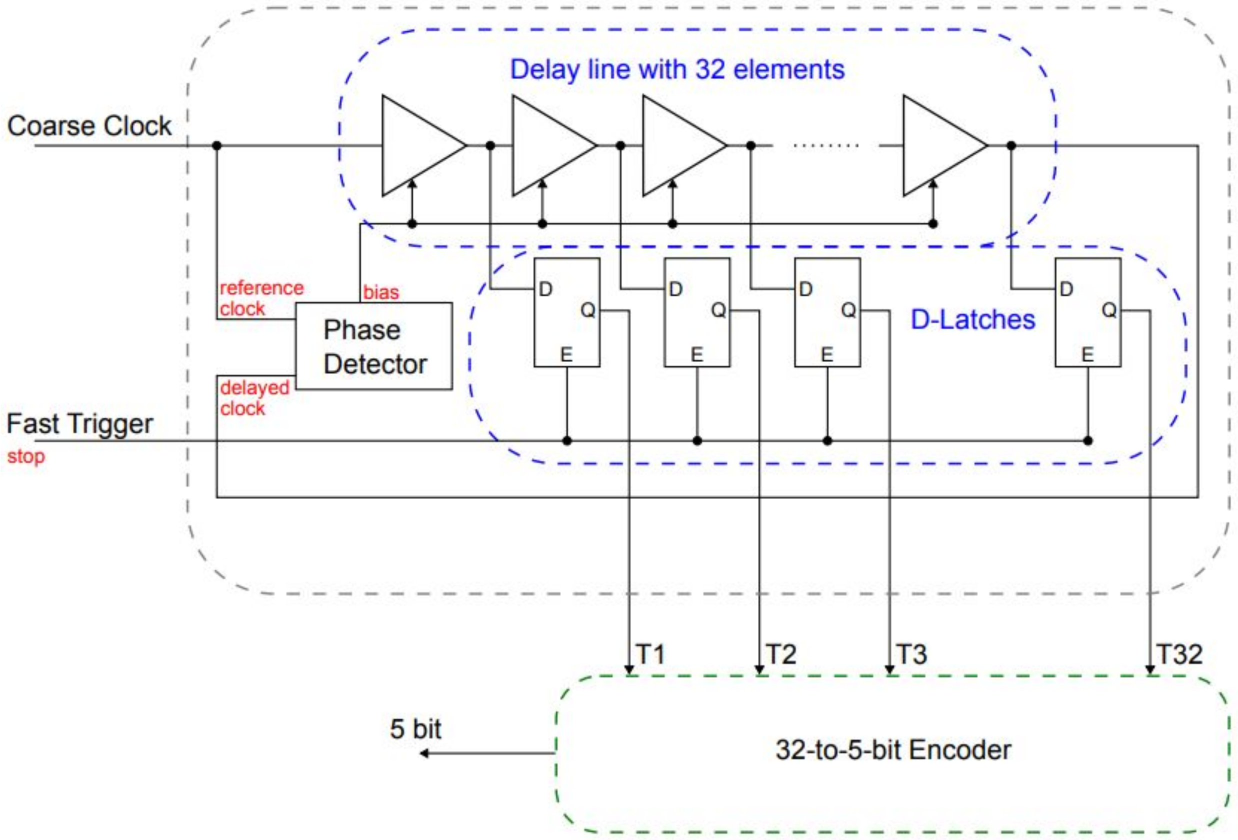
Notes on the testbeam



Backup (4)

Pixel schematics





Backup (5)

Intrinsic SPAD temporal performance

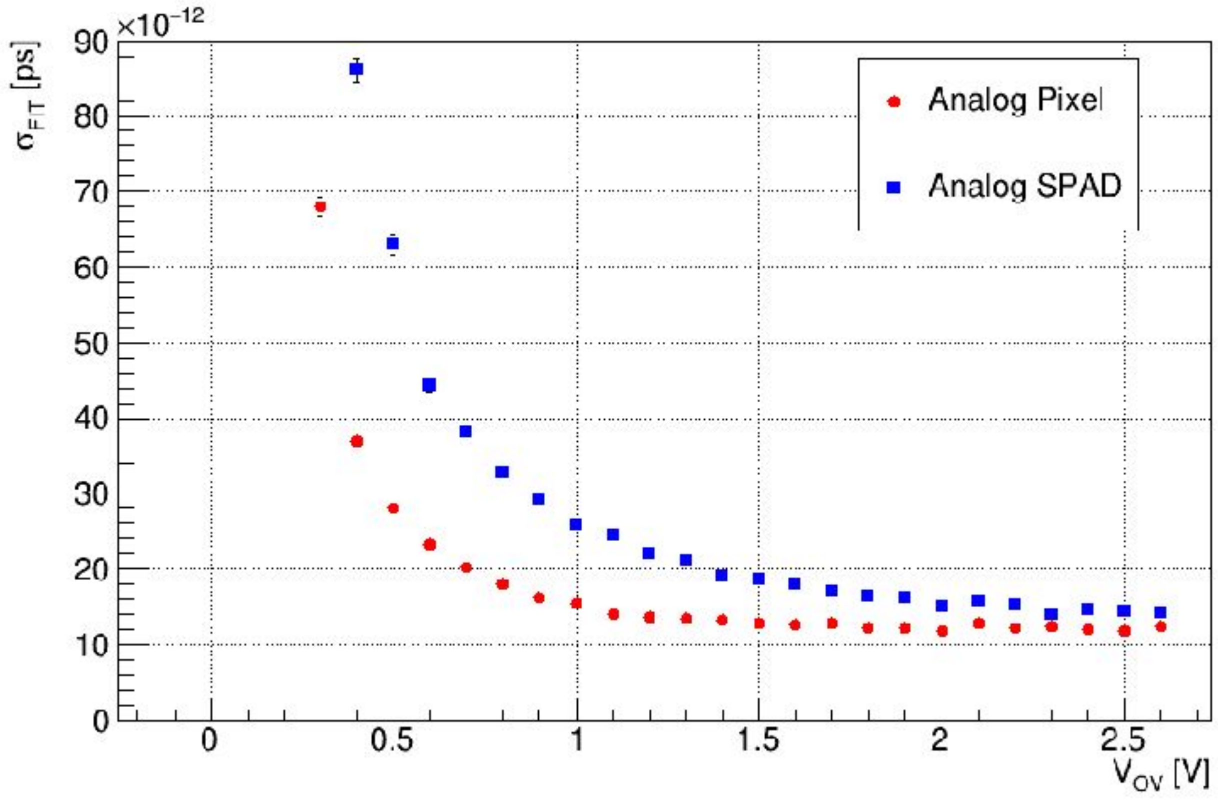


Figure 8.16: Signal TOA as a function of the overvoltage for analogue pixel/SPAD test structures.