Timing performance of a digital SiPM prototype

Studies with a fast injection laser

Daniil Rastorguev daniil.rastorguev@desy.de
Inge Diehl, Finn Feindt, Karsten Hansen, Stephan Lachnit, Frauke Poblotzki, Tomas Vanat, Gianpiero Vignola
DPG Spring Meeting 2024, Karlsruhe
08.03.2024

HELMHOLTZ

dSiPM design overview

The concept of a digital SiPM

Implementing avalanche photodiodes on a CMOS ASIC

Silicon photomultipliers (SiPMs),
made of **single-photon avalanche diodes (SPADs):**

- high internal gain
- single-photon detection capability
- no external amplification required
- O(10 ps) timing resolution

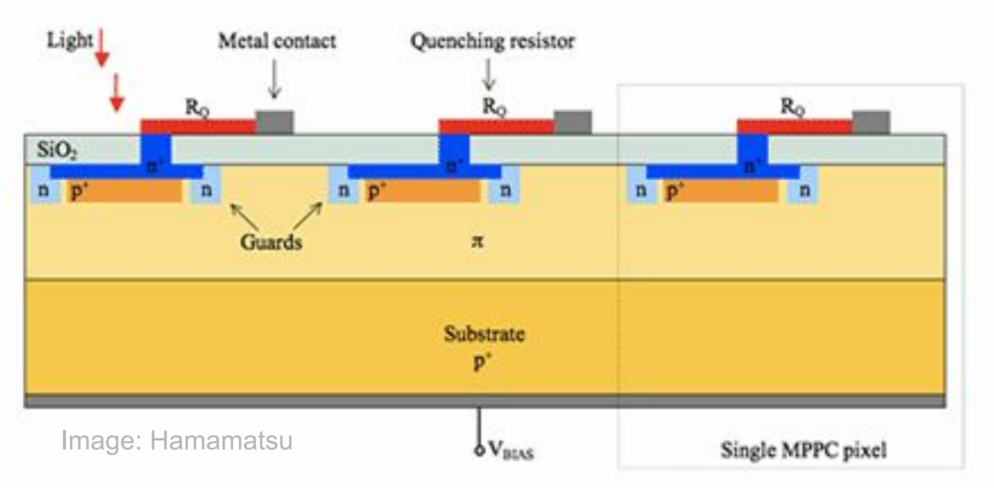


Image: Hamamatsu

CMOS ASICs as particle detectors:

- large analog and digital component libraries
  → **SPADs are also available**
  → in-pixel hit discrimination
  → full pixel matrix readout
  → on-chip data preprocessing
- monolithic design
  → low material budget

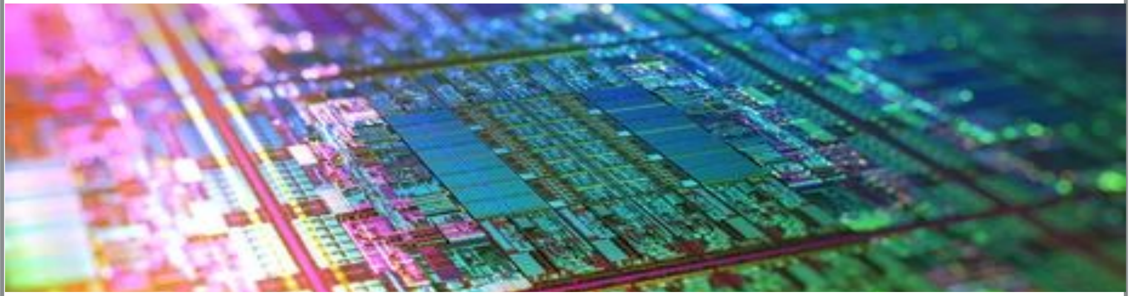
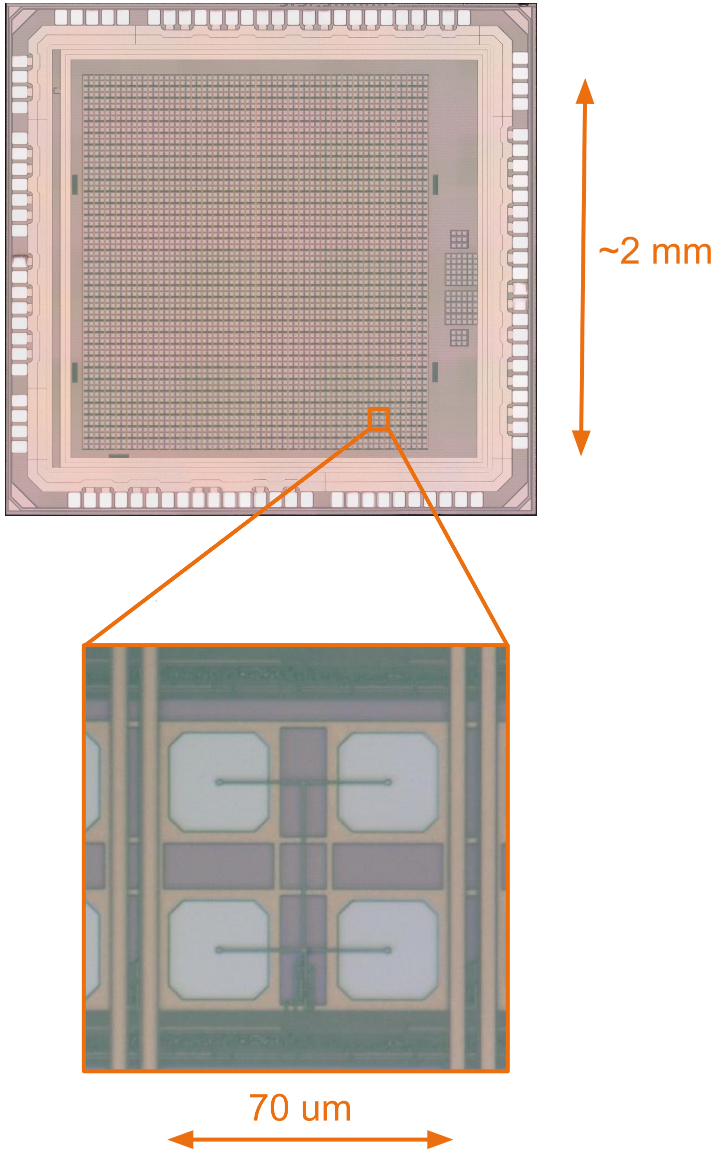


Image: Shutterstock

DESY digital SiPM prototype

Designed in 150 nm LFoundry CMOS process

- 32×32 pixels
- 70 um pixel pitch
- Four parallel 20×20 um SPADs in each pixel
- Frame-based readout
- Full binary hitmaps
- Pixel masking (incl. disabling bias)
- Frame timestamping, defined by the first pixel to fire
- 12-bit TDC with bin size of ~77 ps
- On-chip cluster topology discrimination



See I. Diehl et al 2024 JINST 19 P01020 and T 92.4 by Gianpiero!

How timing works on the chip

Timestamping mechanism and quadrants

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

Timestamp = **Frame number** 333 ns 3 MHz frame clock + **Coarse timestamp** 2.45 ns within a frame, 7 bits @ 408 MHz chip clock + **Fine timestamp** 77 ps within a chip clock cycle, (dedicated 5-bit TDC)

manufacturing variation:
real bin size = ~95 ps
full counter depth never reached

Timing measurements with a picosecond laser

Laserbox

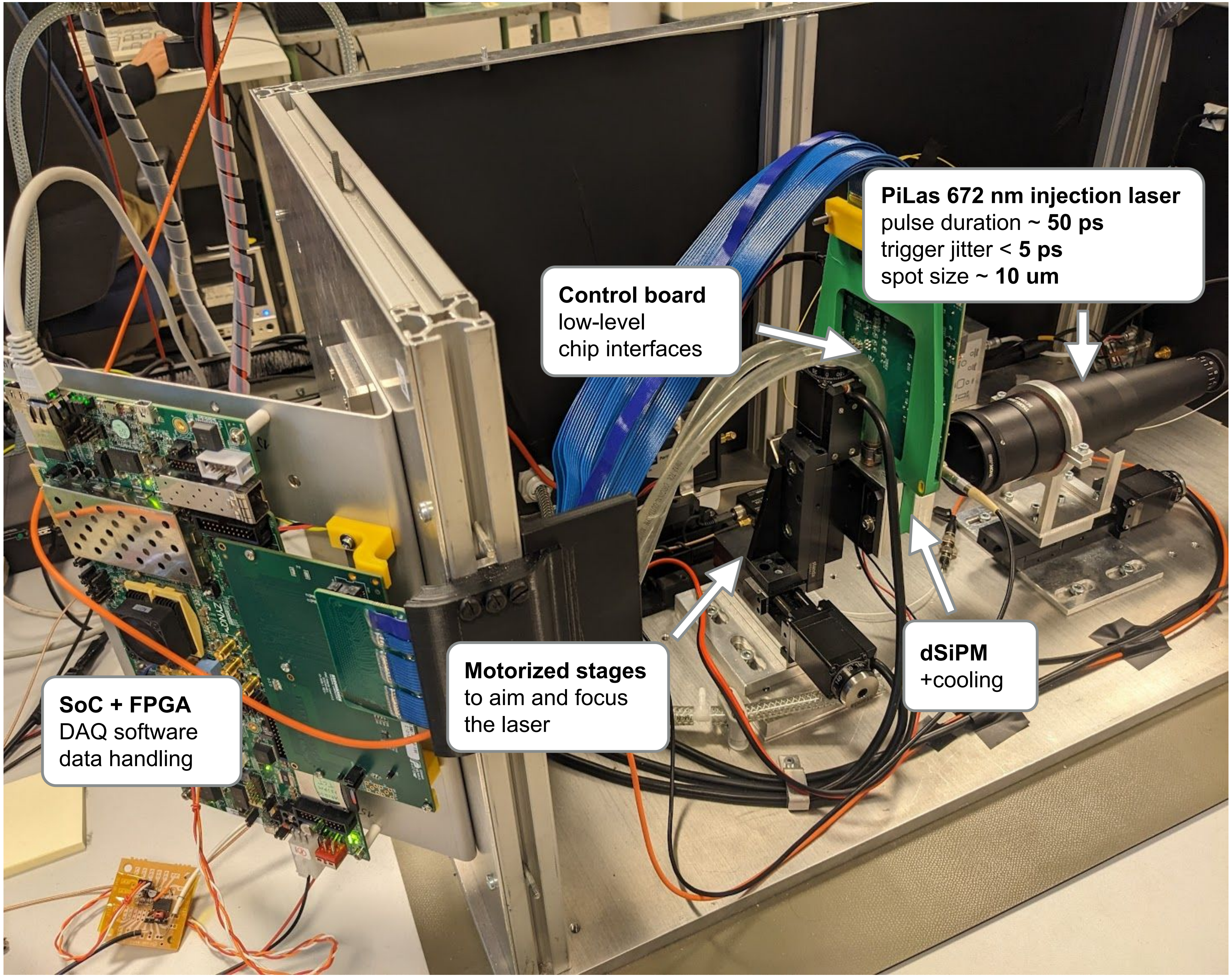
and how to measure timing response with it

Pulsed lasers
are great for charge injection:

- micrometer aim precision
- trigger when you want
- high repetition rate
- tunable intensity

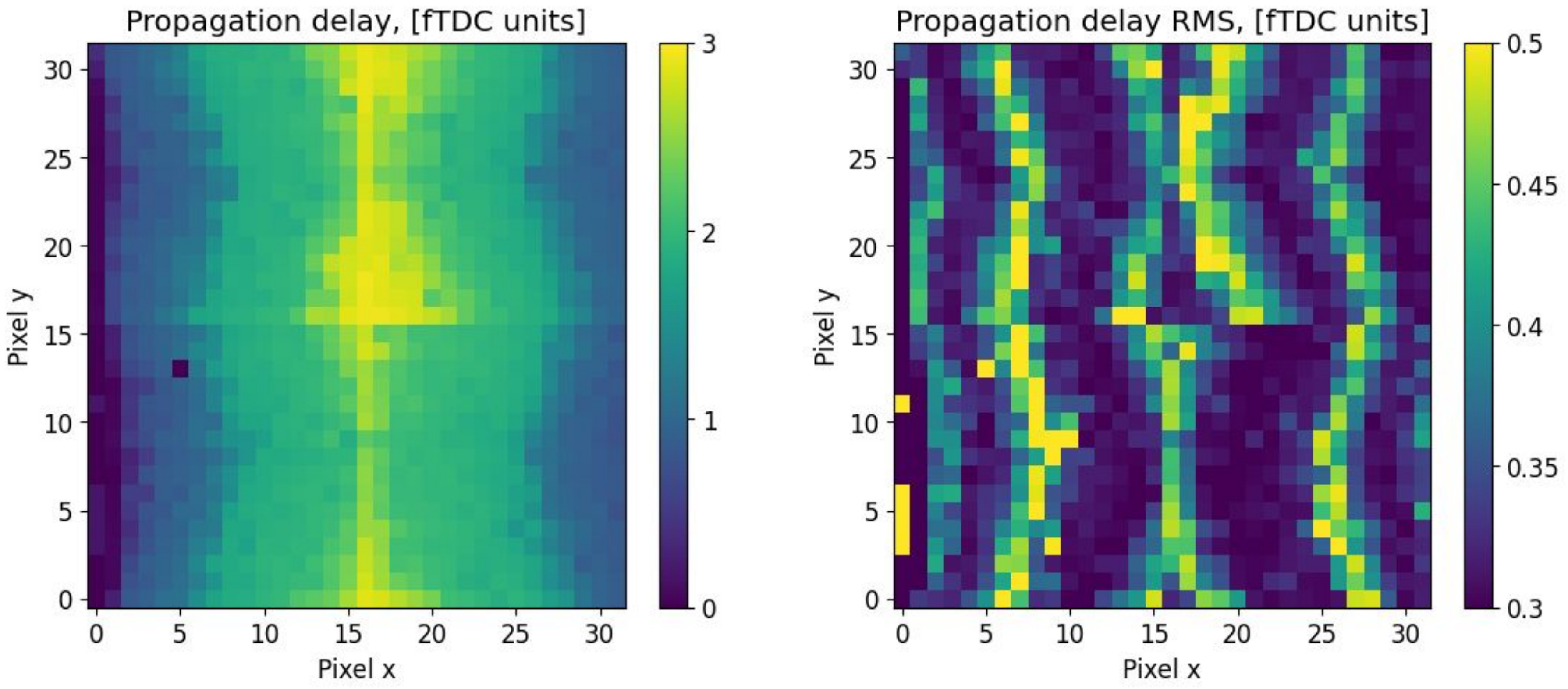
Measurement scheme:

- caribou DAQ+control [1]
- laser trigger pulses in sync with readout frames
- measured ToA should always be the same
  → ToA uncertainty defines timing resolution of the DUT



[1] PoS TWEPP2019 (2020) 100

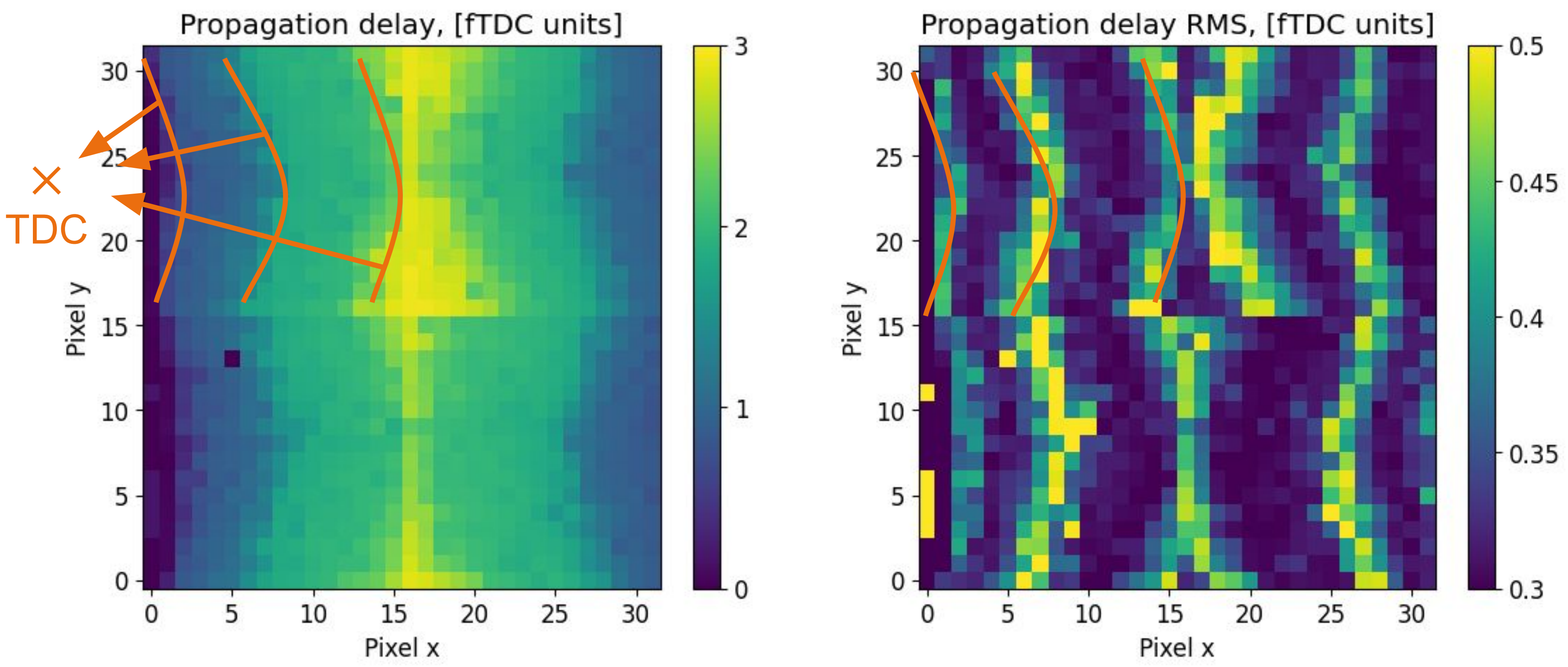
Matrix delay map



Measurement scheme:

1. Trigger the laser synchronously with dSiPM frame clock
2. Unmask just a single pixel → hits to define timestamps are coming only from this pixel
3. Aim the laser at that pixel (high intensity, defocused)
4. Record timestamp distributions
   - Scan across all pixels in the matrix

Matrix delay map



- 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
- Higher uncertainty at the transition between TDC bins
- Results are used as an **lookup table** to **compensate for propagation** delay e.g. in the testbeam

In-pixel timing (1)

A story of peculiar things in the test beam results

Test-beam campaign @ DESY II:
chip characterization via direct m.i.p. detection

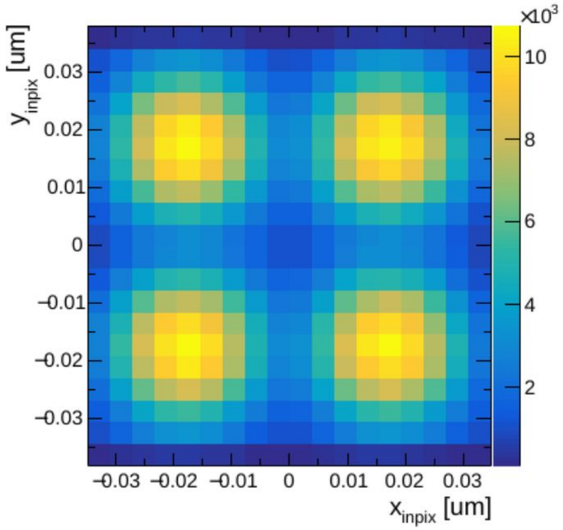
Finding:
for a fraction of events, significantly slower response is observed (**few ns**, whereas **sub-100 ps expected**)

Finding:
these slow events occur when a particle track crosses the chip at a **SPAD edge**

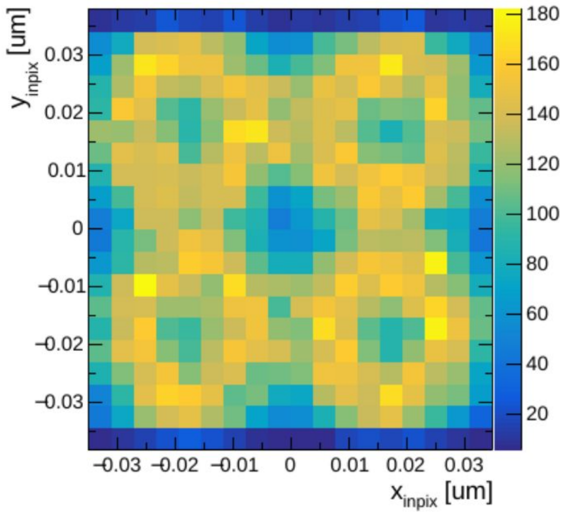
Hypothesis:
this effect is caused by the actual **sensor physics,** namely, avalanches being preceded by **drift**

See T 92.3 by Stephan!

In-pixel hitmaps, correlated events

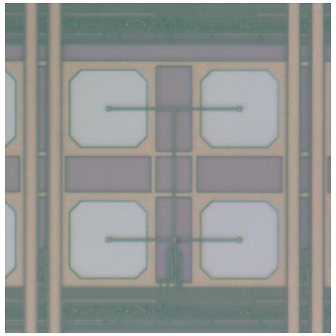


All events



Cut on delay >1 ns

Pixel layout →



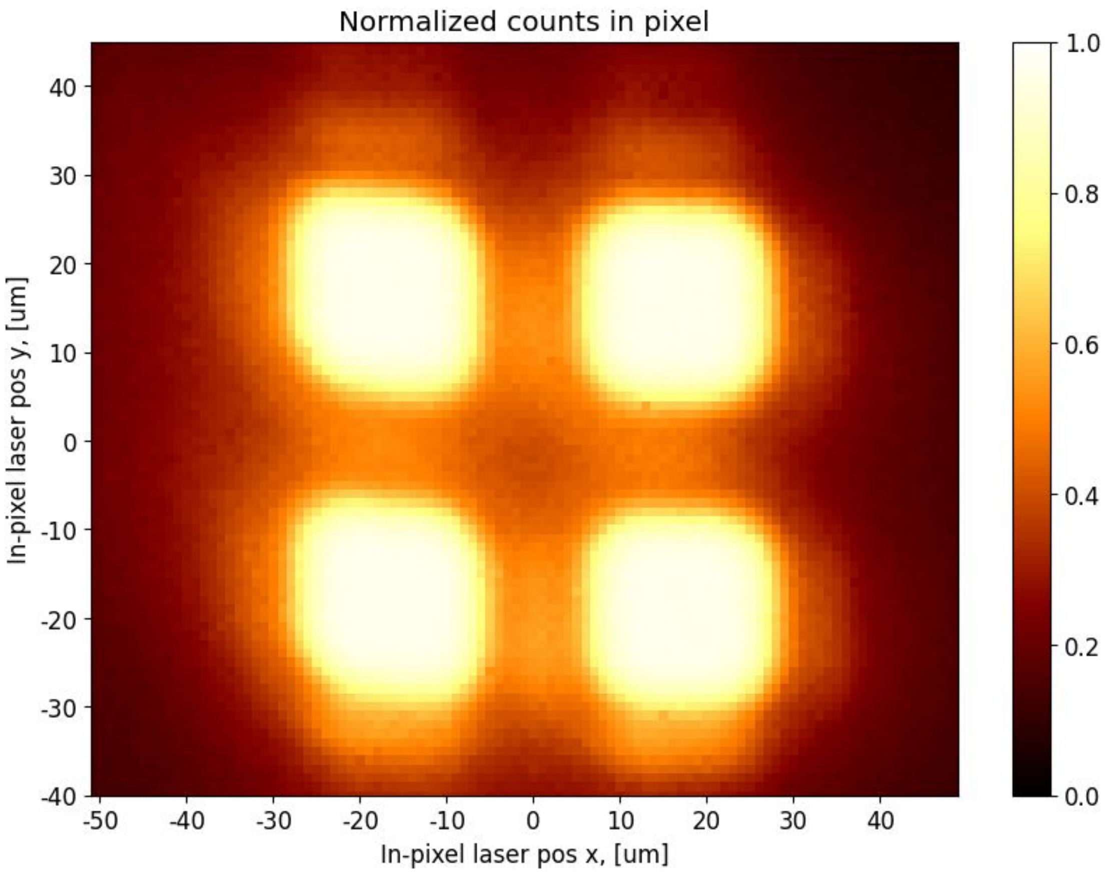
The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

Position-sensitive laser characterization

Sensitivity scan

Measurement scheme:

1. Tune optics: optimize the spot size and avoid charge injection *not in the spot*
   - ~10 um spot size
   - attenuation with ND filters
2. Trigger the laser synchronously with dSiPM frame clock
3. Mask all the matrix but a single pixel → timestamps only come from the studied pixel
4. Record timestamp distributions
   - Scan across a pixel with the laser position



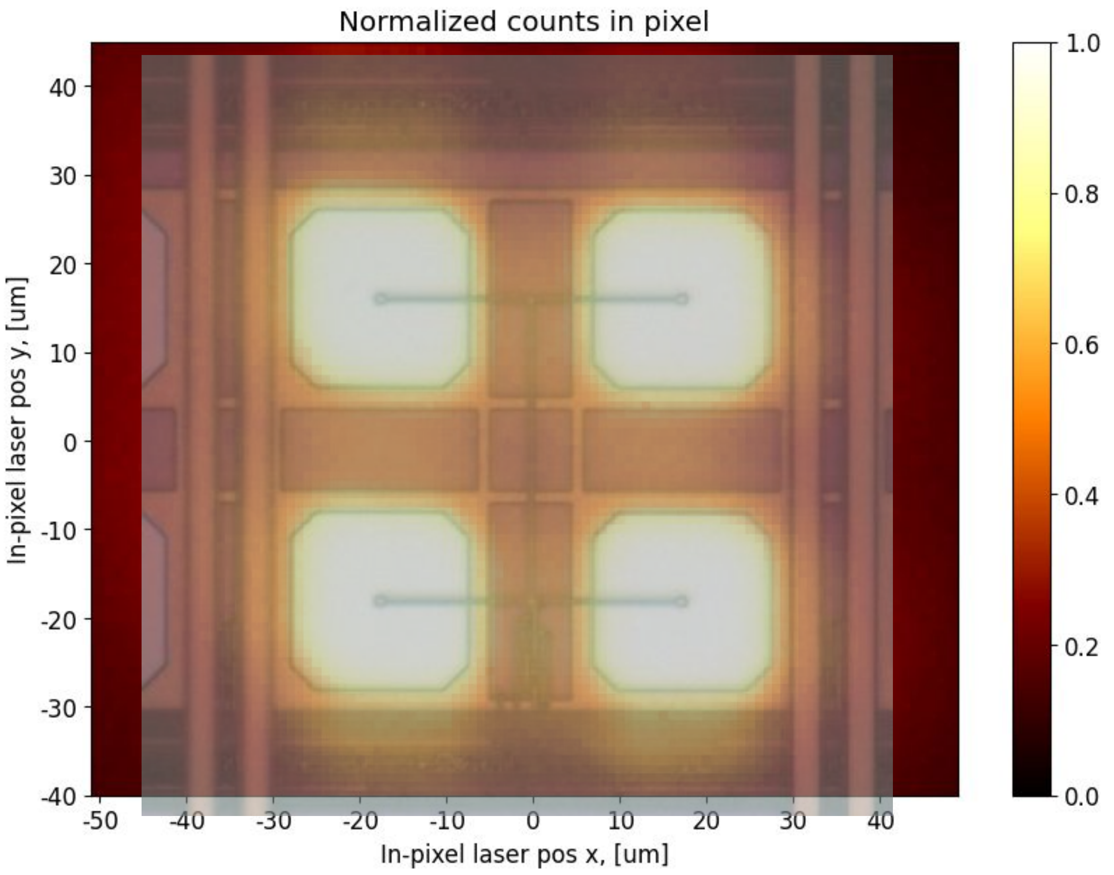
In-pixel hitmap

Position-sensitive laser characterization

Sensitivity scan

Measurement scheme:

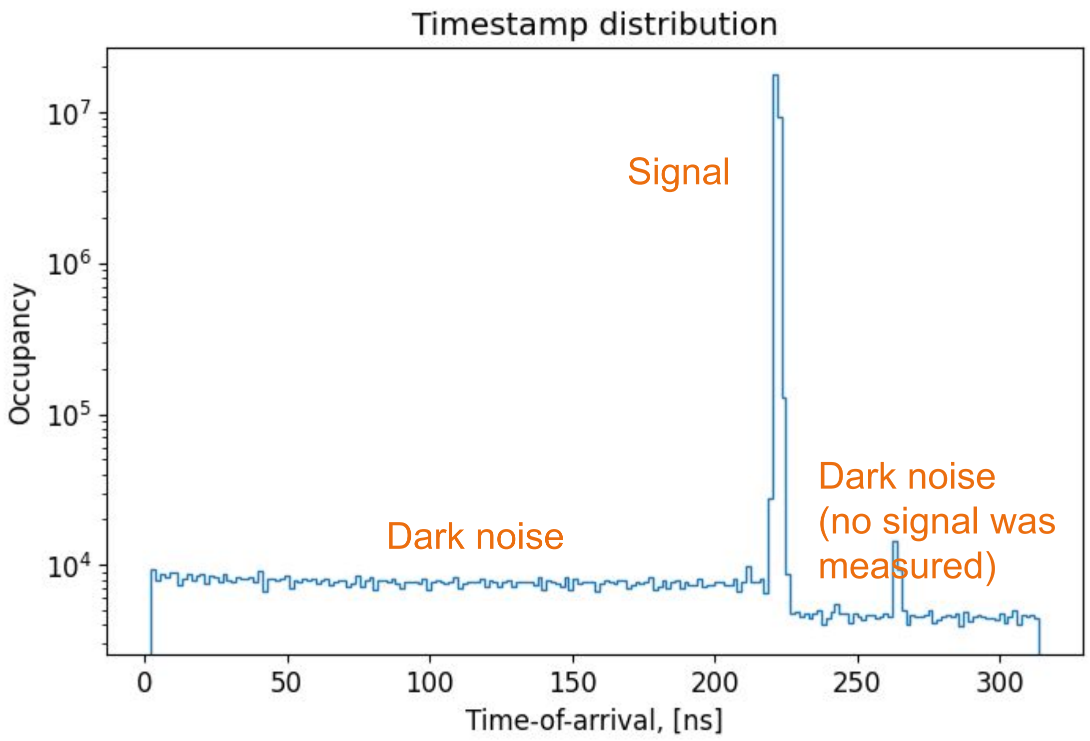
1. Tune optics: optimize the spot size and avoid charge injection *not in the spot*
   - ~10 um spot size
   - attenuation with ND filters
2. Trigger the laser synchronously with dSiPM frame clock
3. Mask all the matrix but a single pixel → timestamps only come from the studied pixel
4. Record timestamp distributions
   - Scan across a pixel with the laser position

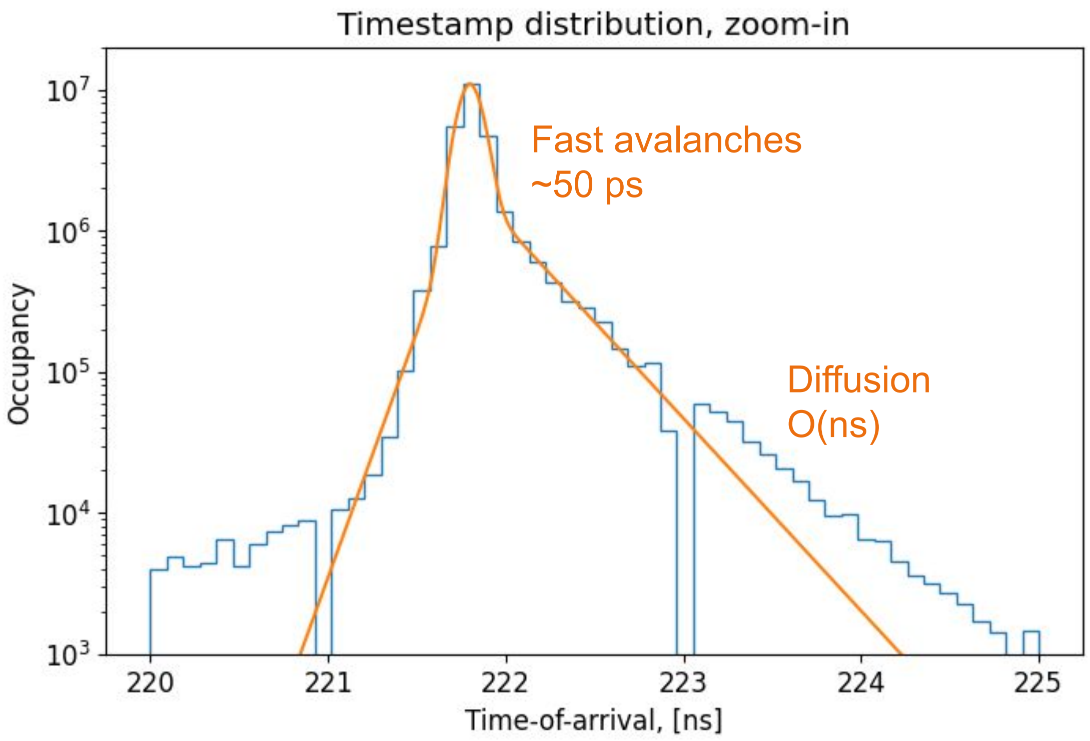


In-pixel hitmap,
overlaid with a pixel photograph

In-pixel timing (2)

Time residual structure



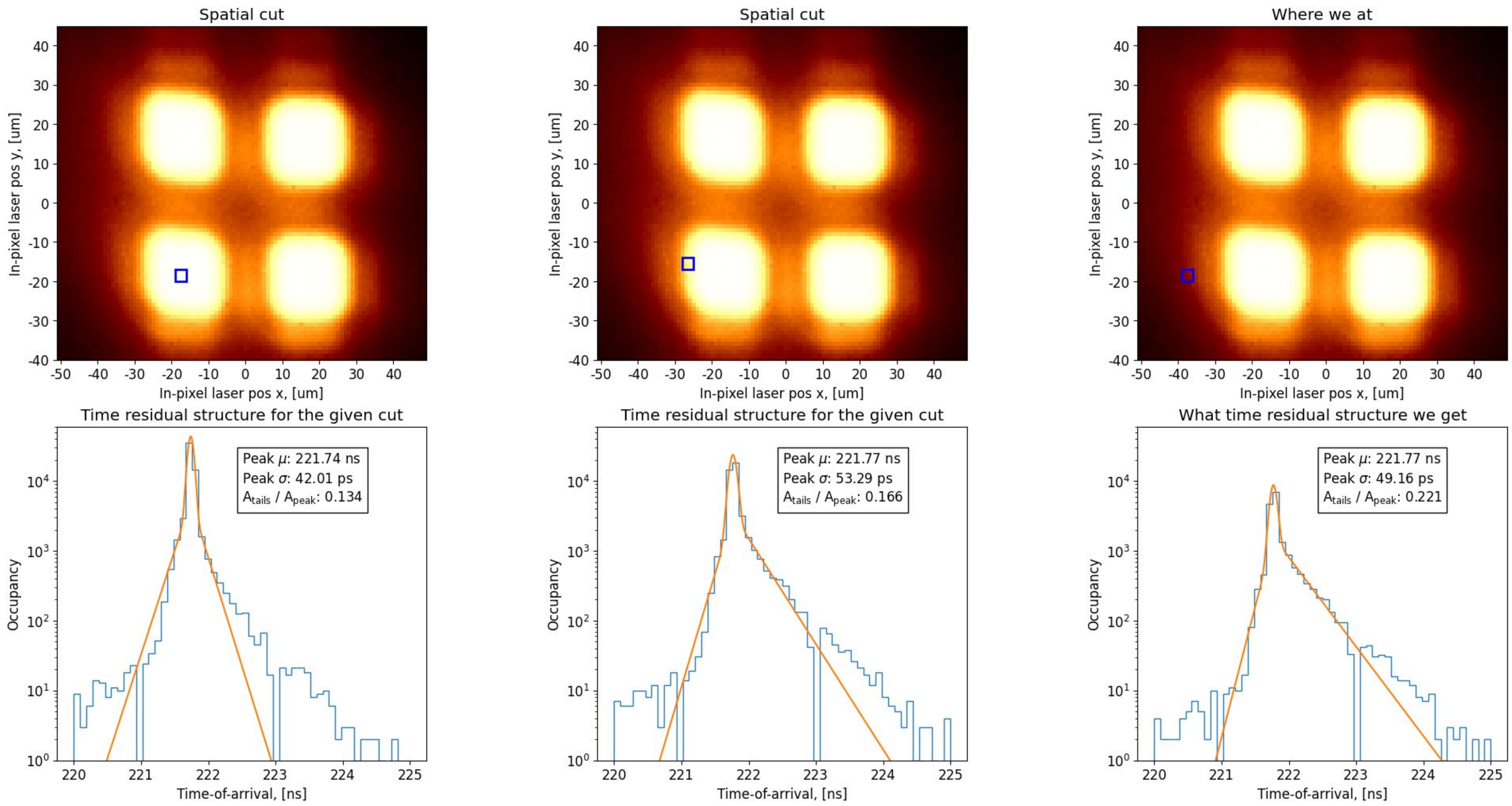


$$f(x) = A_{\text{peak}} * \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) + A_{\text{tails}} * \text{tails}(x-\mu, \lambda_R, \lambda_L)$$

$$\text{tails}(x, \lambda_R, \lambda_L) = \begin{cases} e^{-\frac{x}{\lambda_R}}, & \text{if } x \geq 0 \\ e^{\frac{x}{\lambda_L}}, & \text{if } x < 0 \end{cases}$$

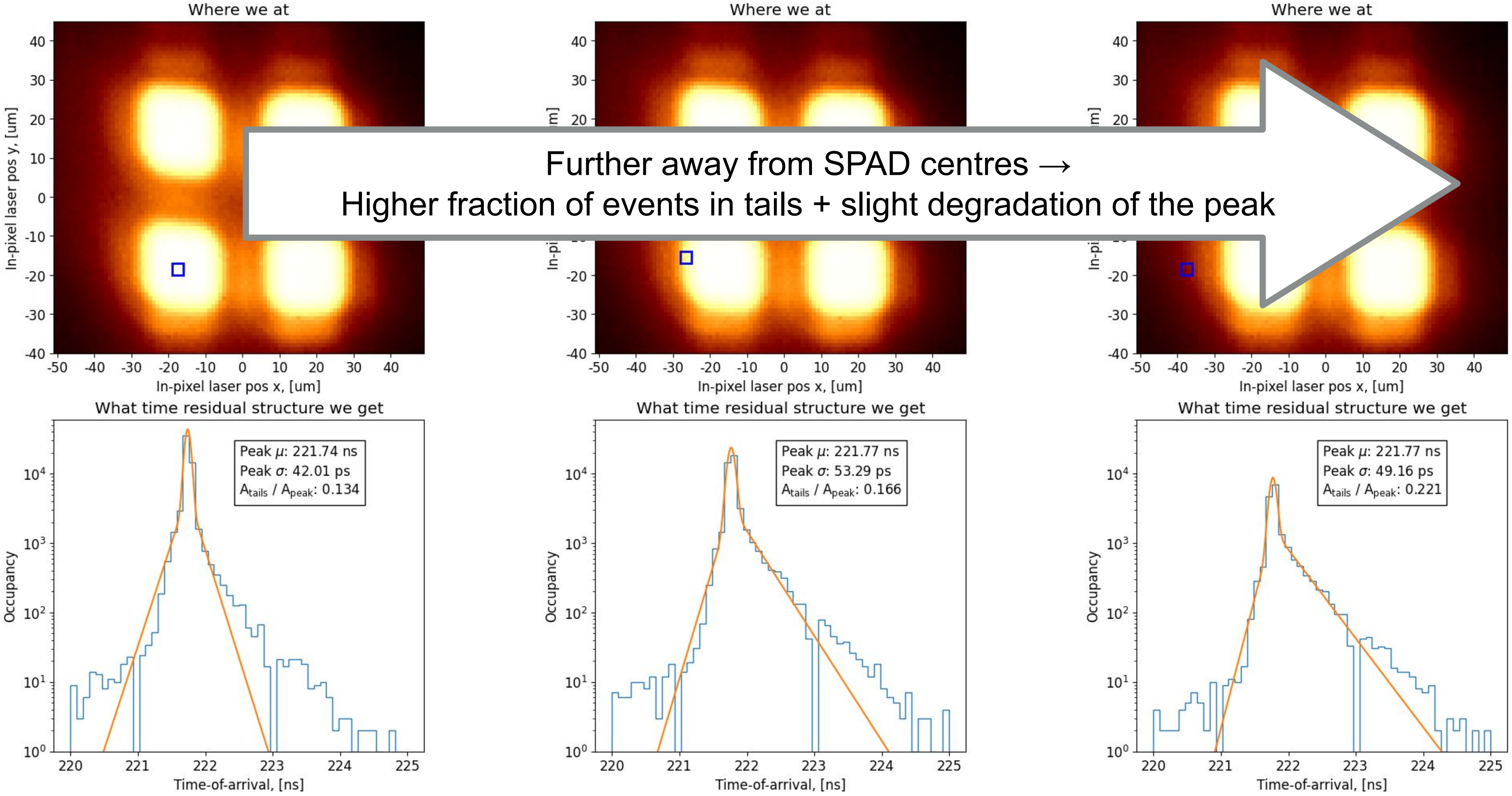
In-pixel timing (3)

SPAD center / SPAD edge variations



In-pixel timing (3)

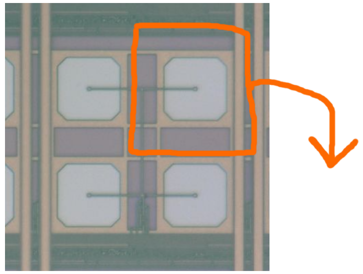
SPAD center / SPAD edge variations



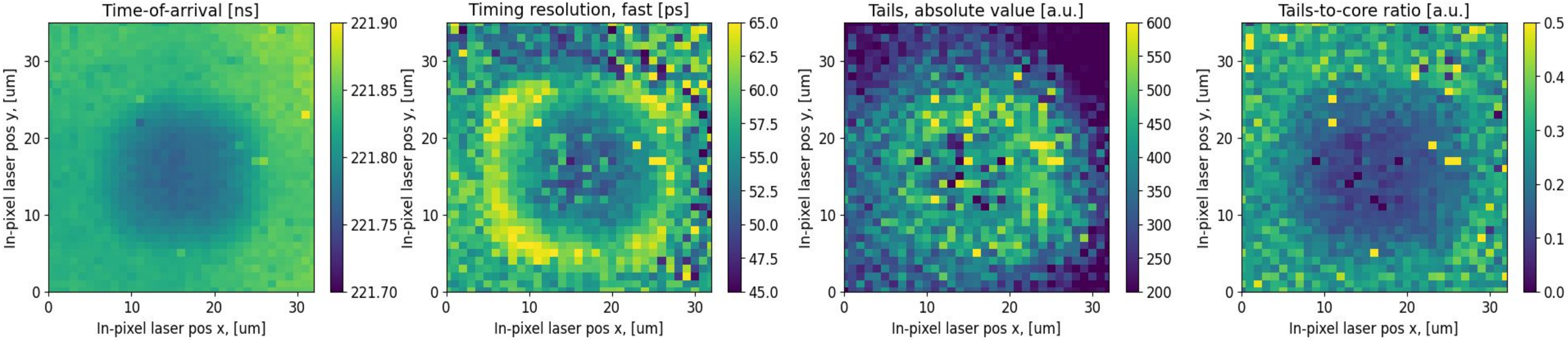
In-pixel timing (4)

ToA fit results

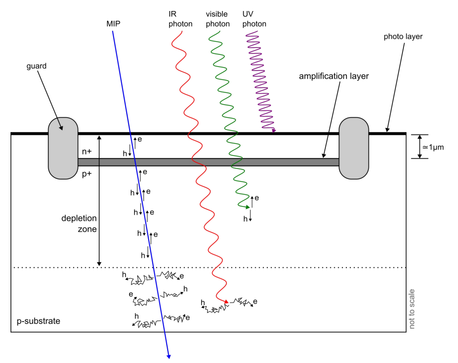
Per-point fits for this region →

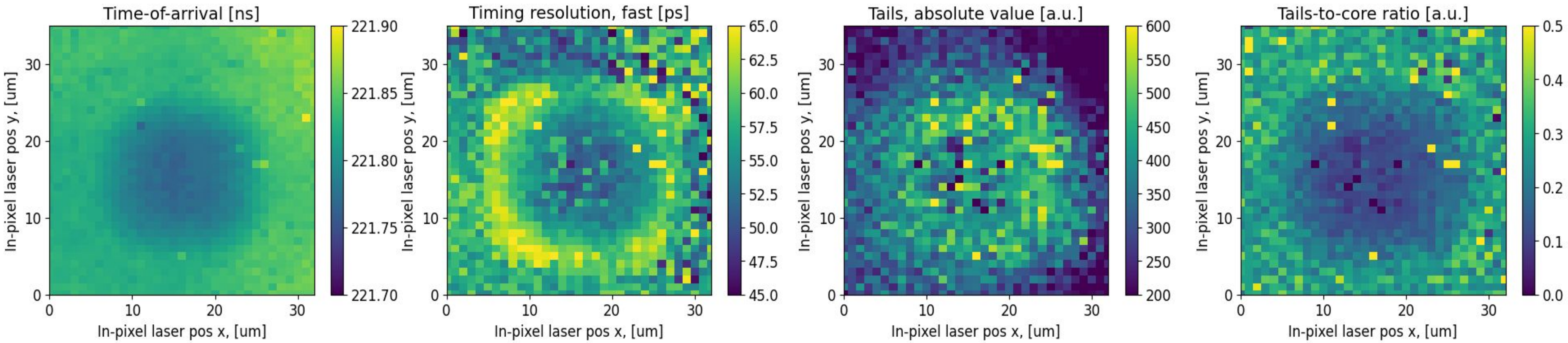


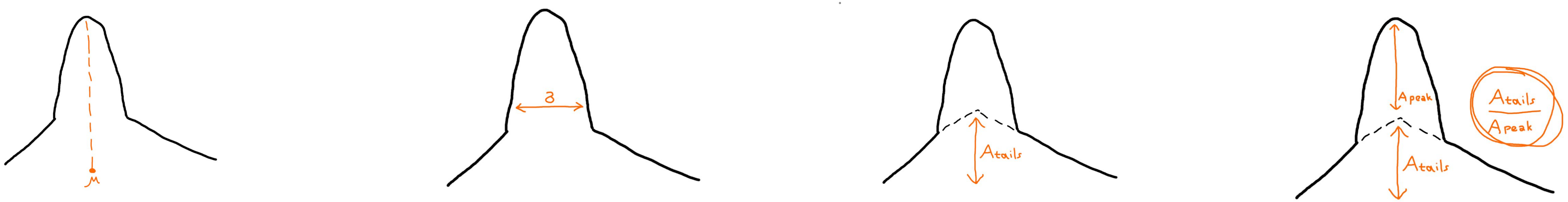
Note: data from regions outside SPADs are irrelevant due to insensitivity / low statistics



- 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







Conclusions

Timing performance of a **novel dSiPM** prototype studied with a fast injection laser

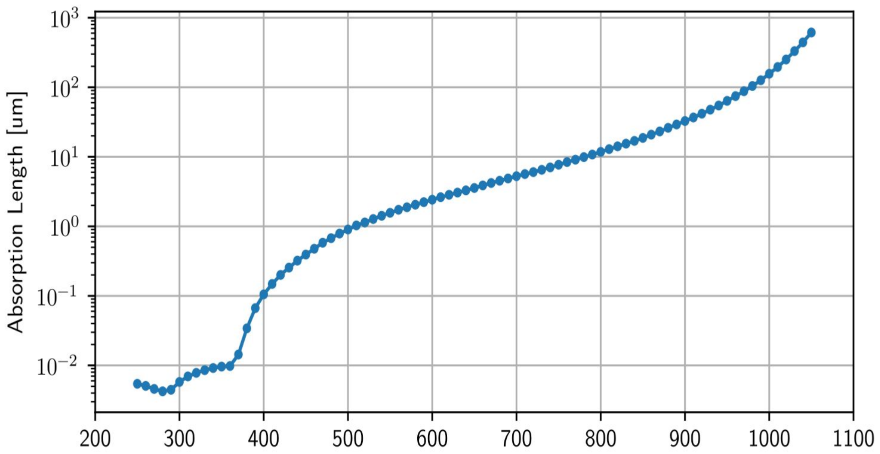
- **Propagation delay** in trigger lines is characterized across the chip matrix
    - This delay can be compensated for
- In-pixel timing performance is characterized
    - **~50 ps** timing resolution within SPADs
    - Timing performance slightly deteriorates at the sensitive area edges
        - This can be explained by slow drift in low E-field
    - **Results match** design expectations
    - **Results match** testbeam data

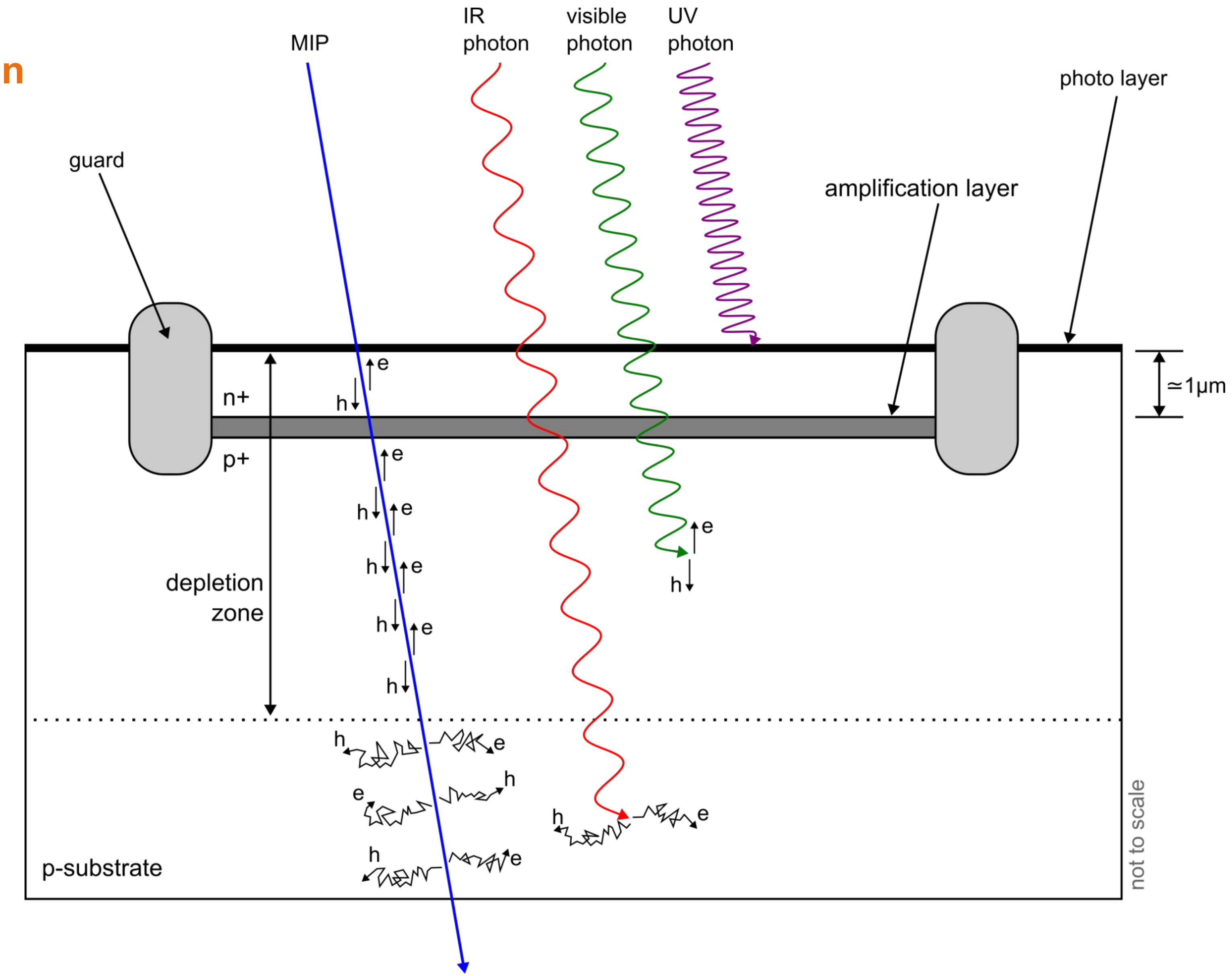
Thank you!

Discussion?

Backup (1)

Visible (and near-visible) light and silicon





Backup (2)

Notes on the testbeam