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CENTER FOR SENSORS & DEVICES

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Politecnico di Torino

INFN

19th TREDI Workshop on Advanced Silicon Radiation Detectors

FBK NUV-HD SiPMs with metal-filled trenches: from simulations to timing performances

Turin, 20-22 February 2024

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FBK NUV-HD-MT SiPMs: simulations and timing performances
Outline

Introduction

- SiPM overview and NUV-HD-MT technology

Timing Performances

- Single Photon Time Resolution (SPTR)

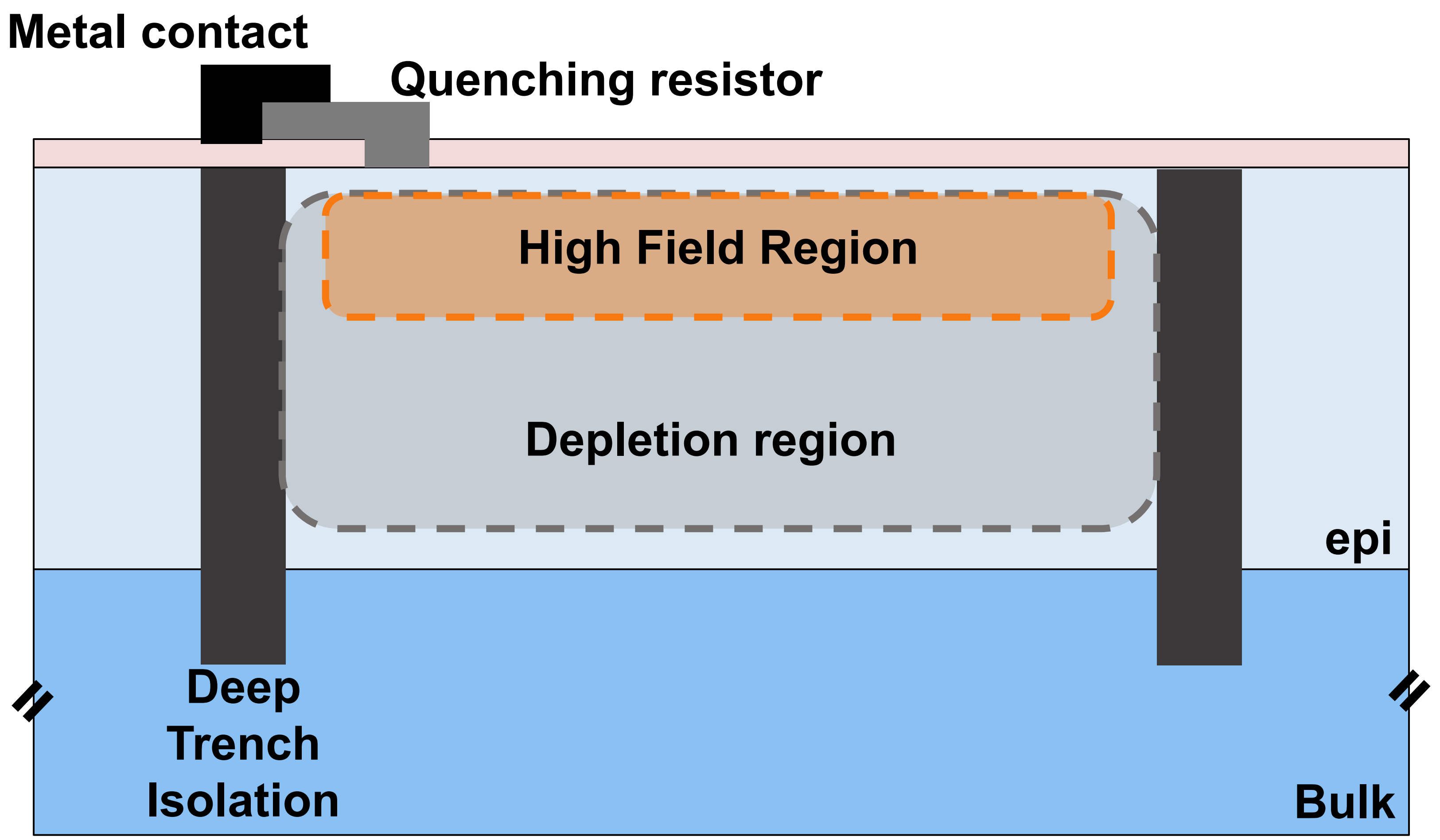
SPAD signal electrical simulations

- SPAD equivalent electrical circuit
- Electrical parameters extraction
- Improved SPICE model

Conclusions and next steps

Introduction

Introduction
Single Photon Avalanche Diode (SPAD)

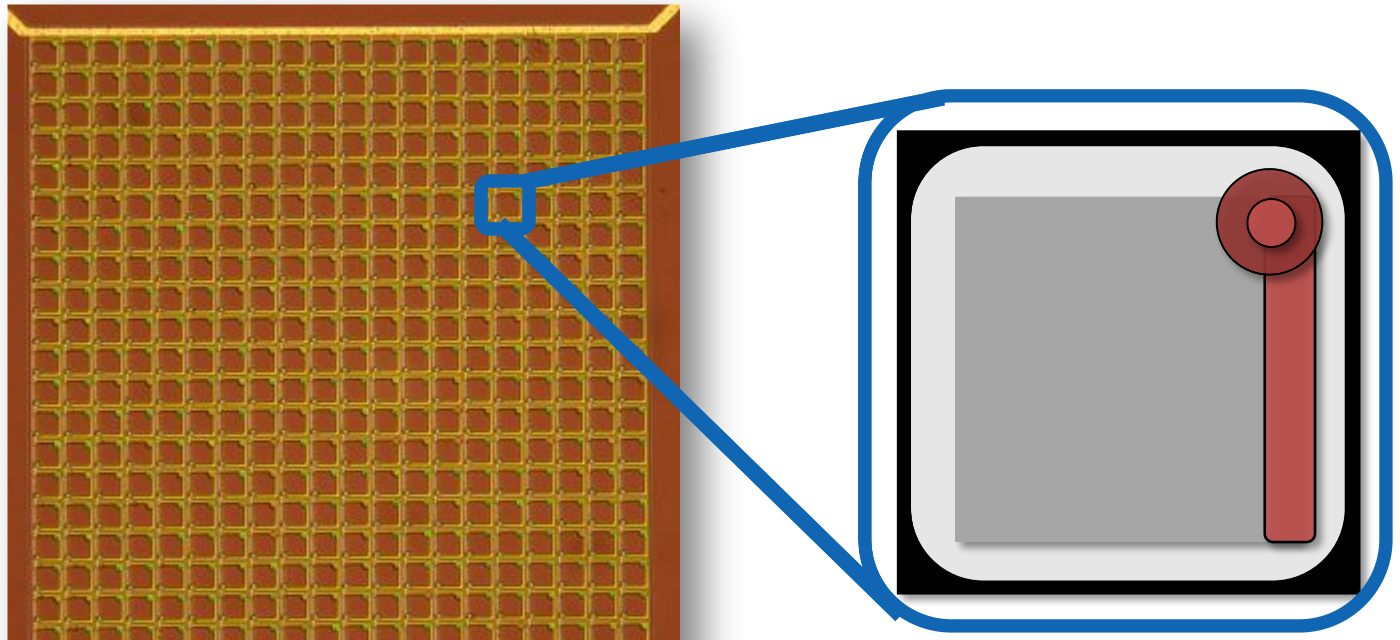


- p-n junction biased above the breakdown voltage (V_{bd})
  - Photon absorption or thermally generated carriers trigger the avalanche process → macroscopic current
  - Avalanche quenched by an external circuit
    - Quenching resistor

Properties:

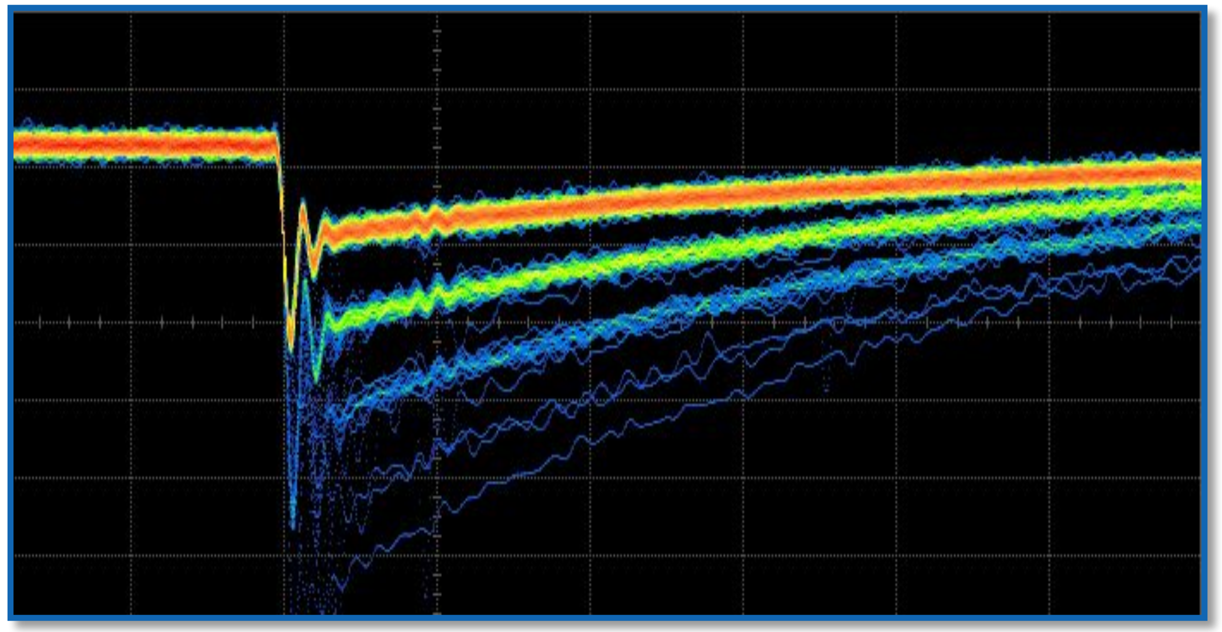
- High Gain ($G \sim 10^5 - 10^7$)
- Excellent timing (~ 20 ps FWHM)
- Low operating bias voltage ($30 - 50\ V$)
- Single photon sensitivity

Introduction
Silicon PhotoMultiplier (SiPM)



$\sim 10\,\mu m - 100\,\mu m$

$\sim 1\,mm - 10\,mm$



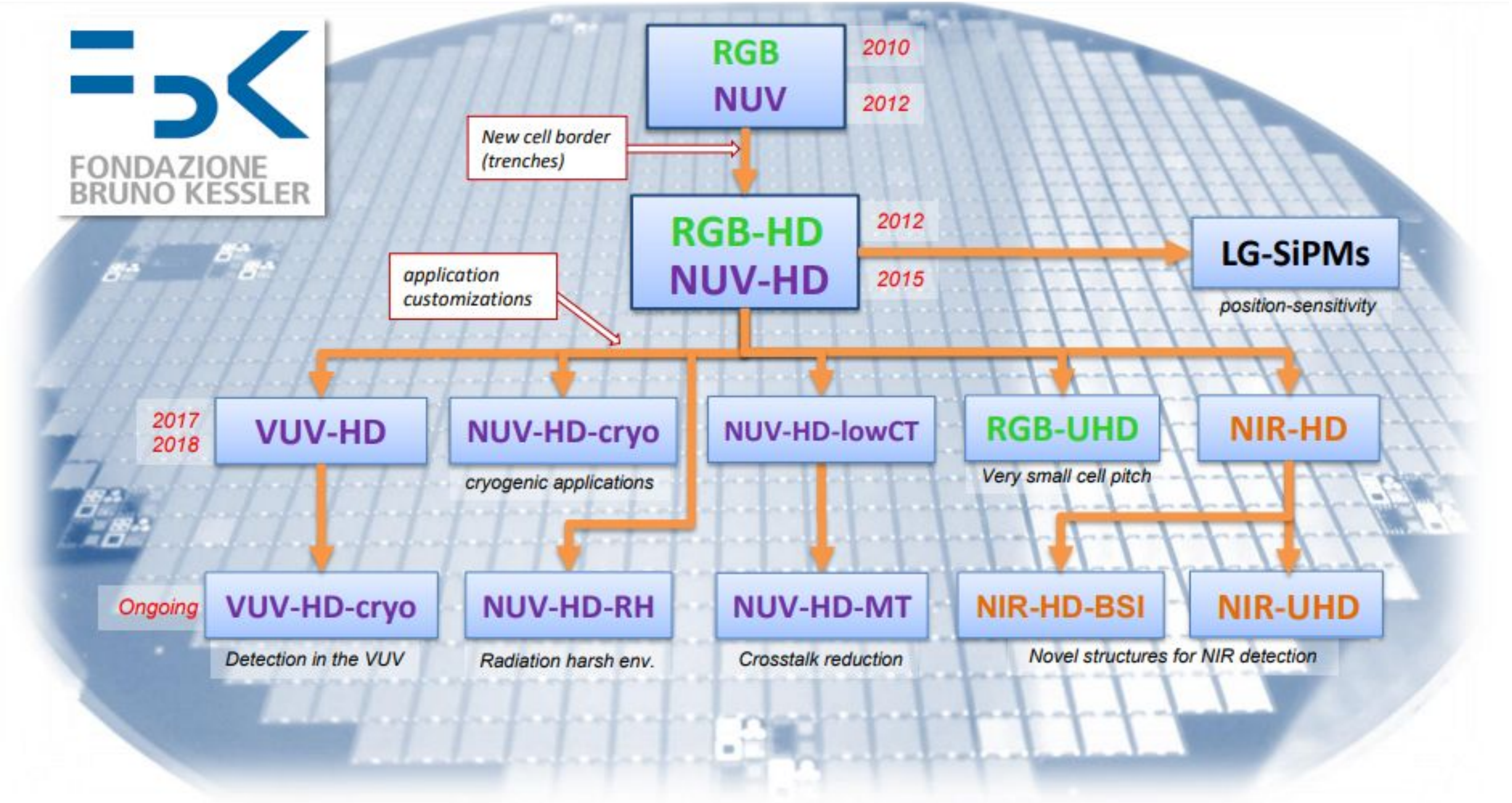
SPADs connected in parallel and arranged in arrays

- $Q_{out} \propto N_{triggered\ cells} \propto N_{photons}$

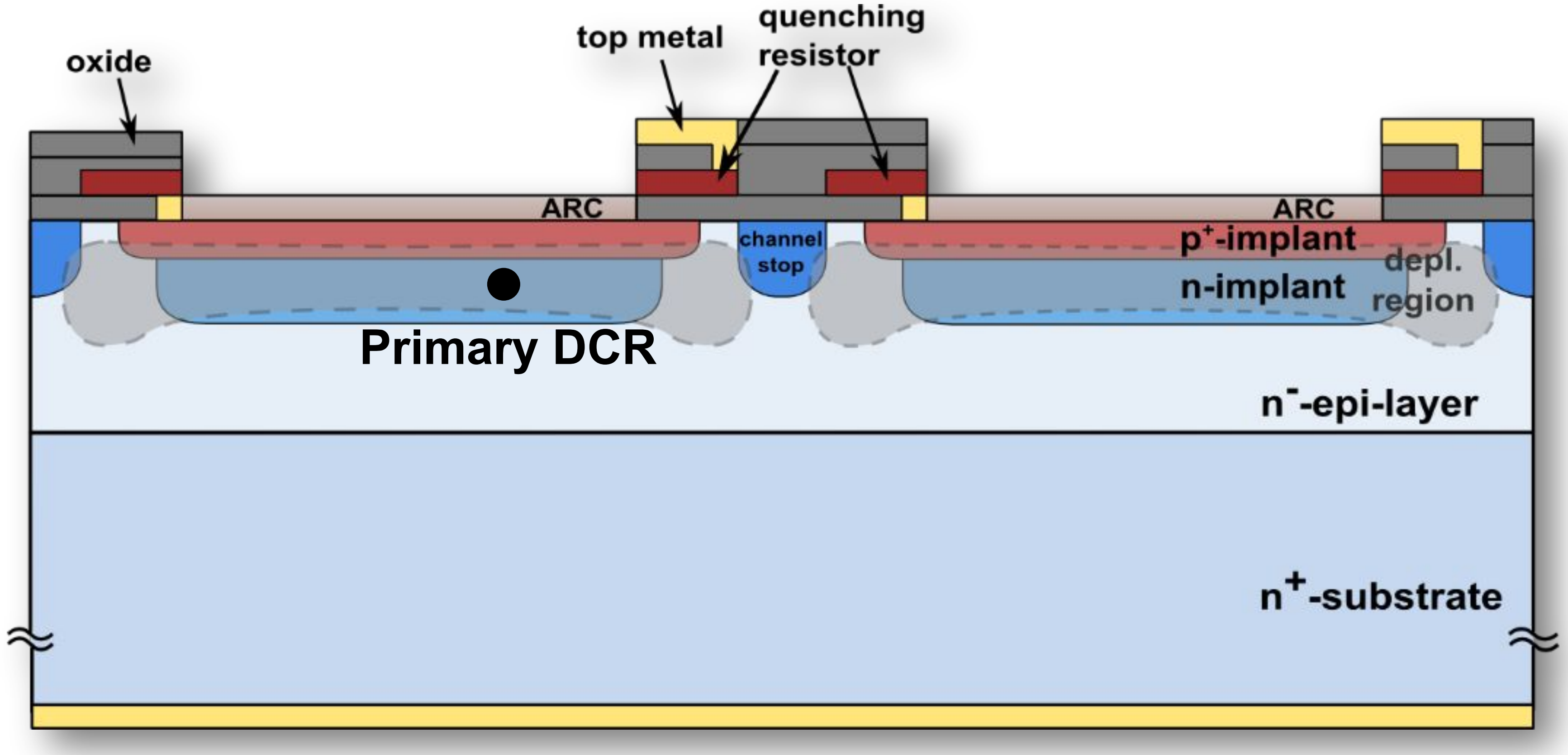
Applications:

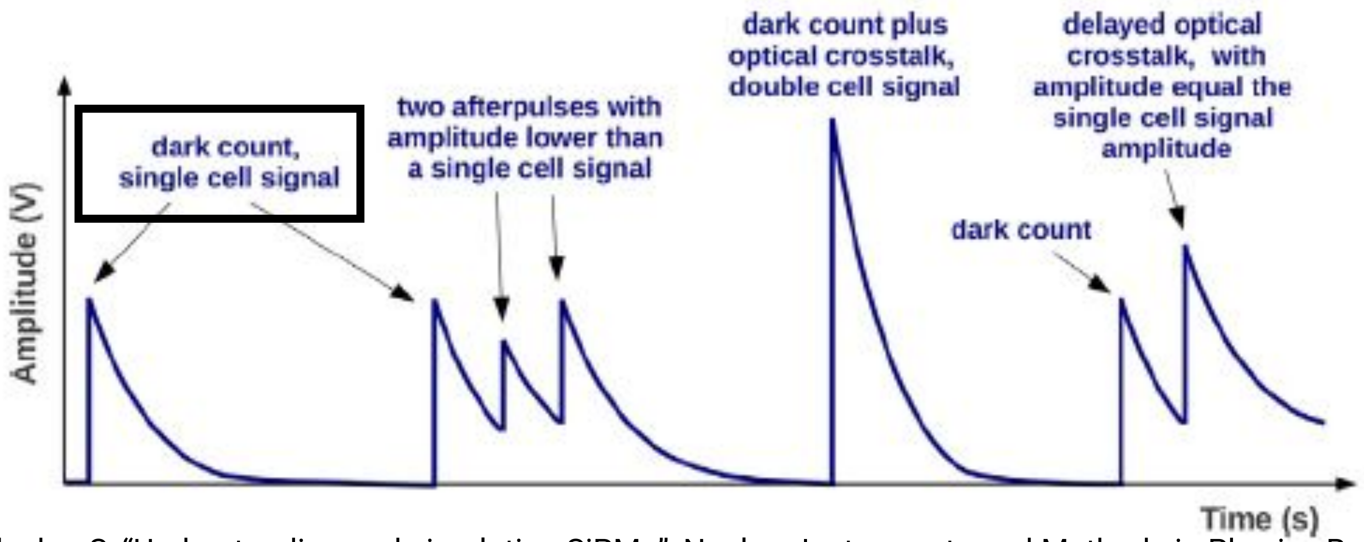
- Big Physics experiments
- Biomedical Imaging (PET, ToF-PET…)
- Industrial, automotive, …

Introduction
FBK SiPM technologies



Introduction
Noise in SiPM





Primary Dark Count Rate

- Thermally generated carriers or tunneling

Acerbi F., Gundacker S, "Understanding and simulating SiPMs", Nuclear Instruments and Methods in Physics Research Section A, 926, 2019,16-35,, https://doi.org/10.1016/j.nima.2018.11.118.

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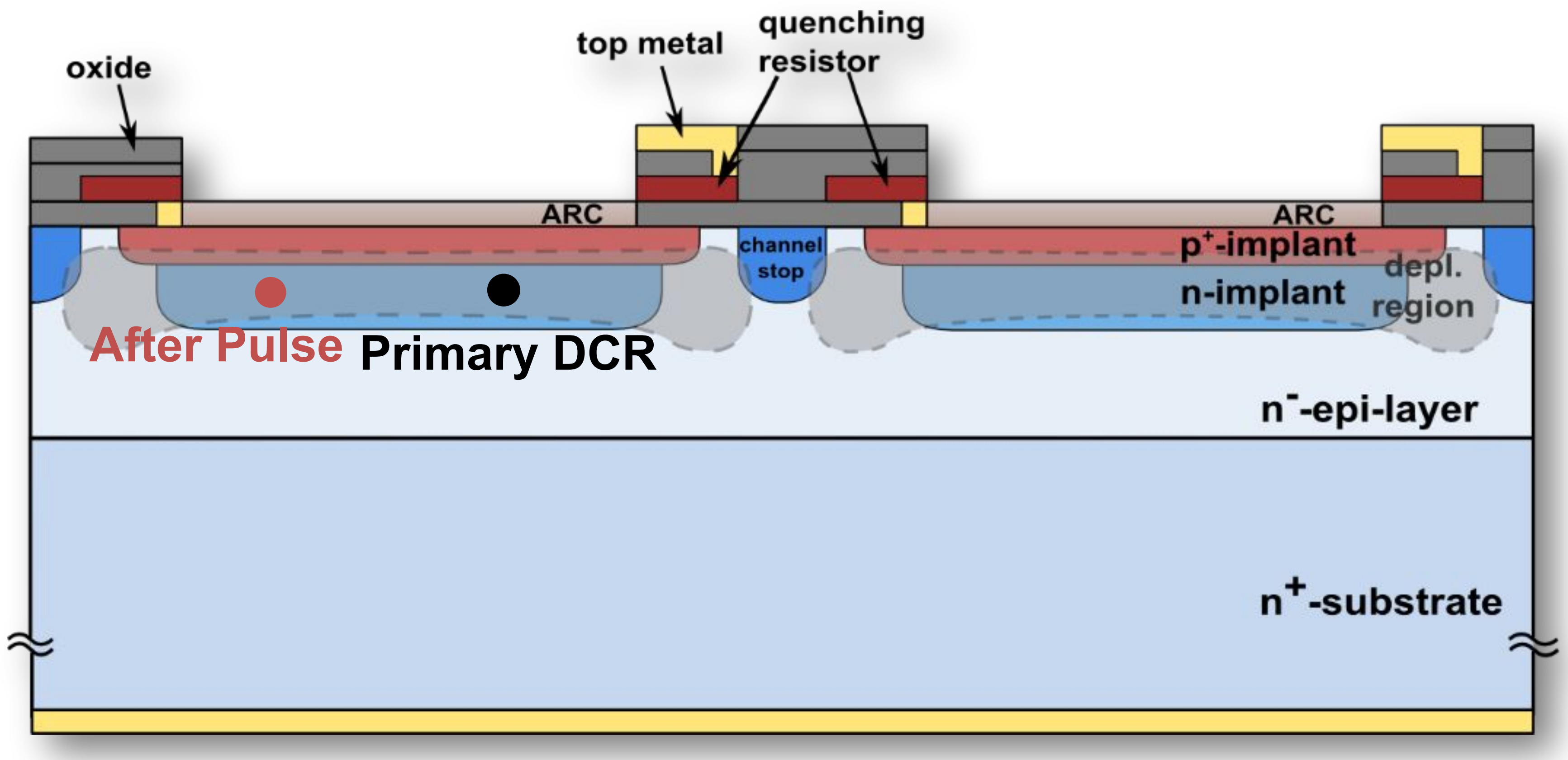

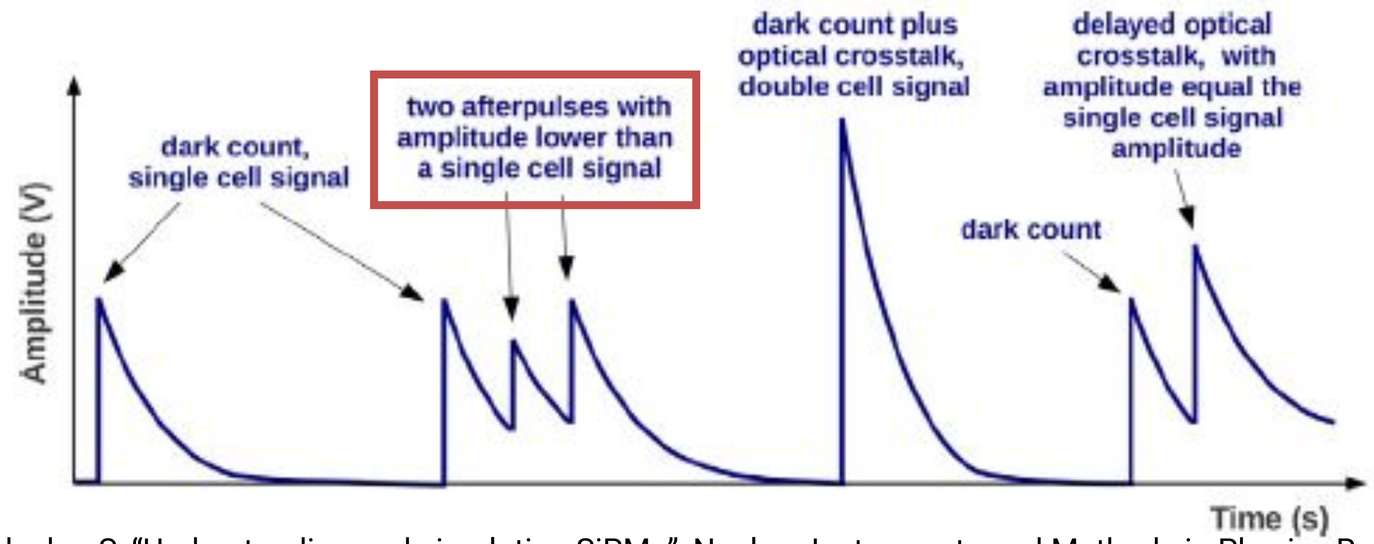

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Primary Dark Count Rate

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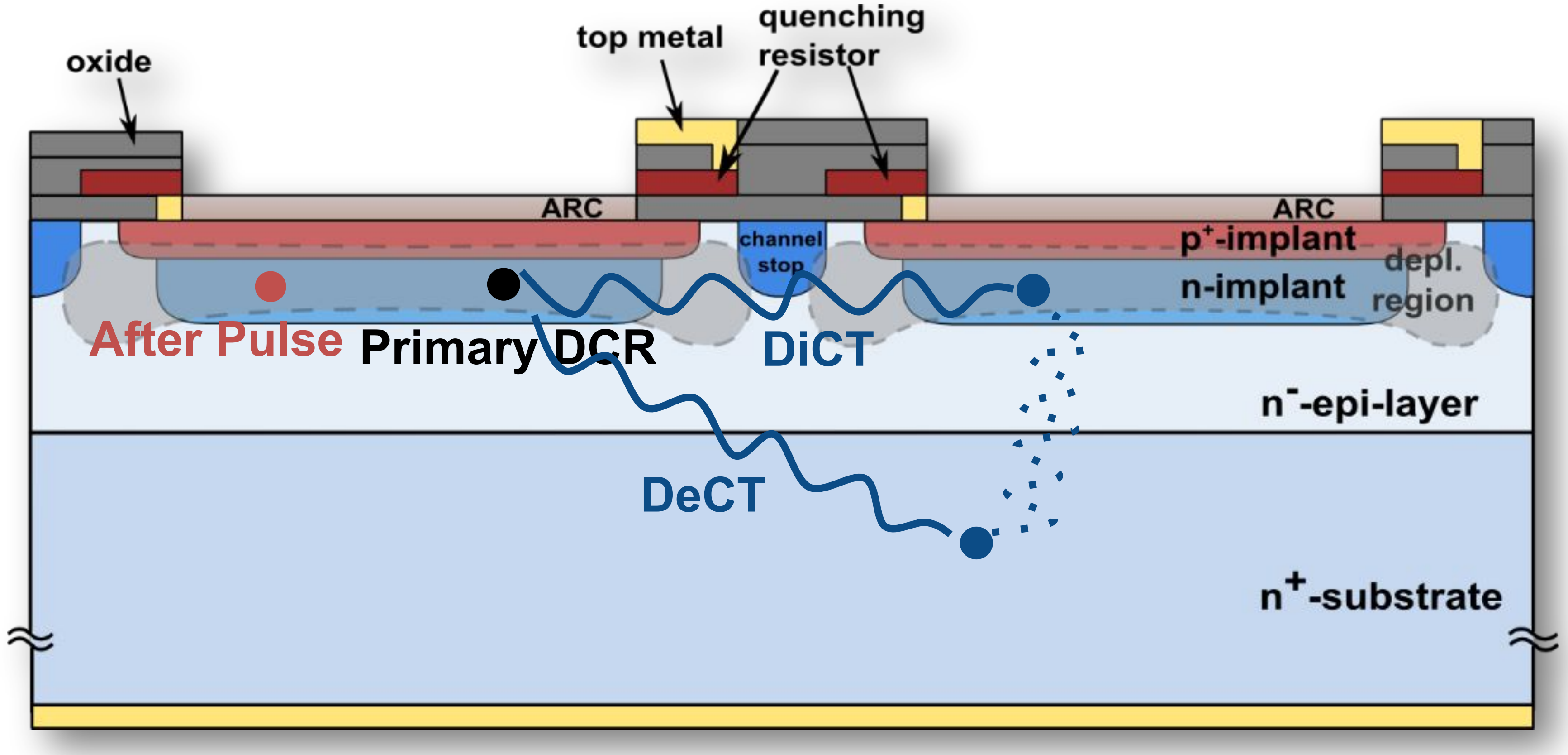
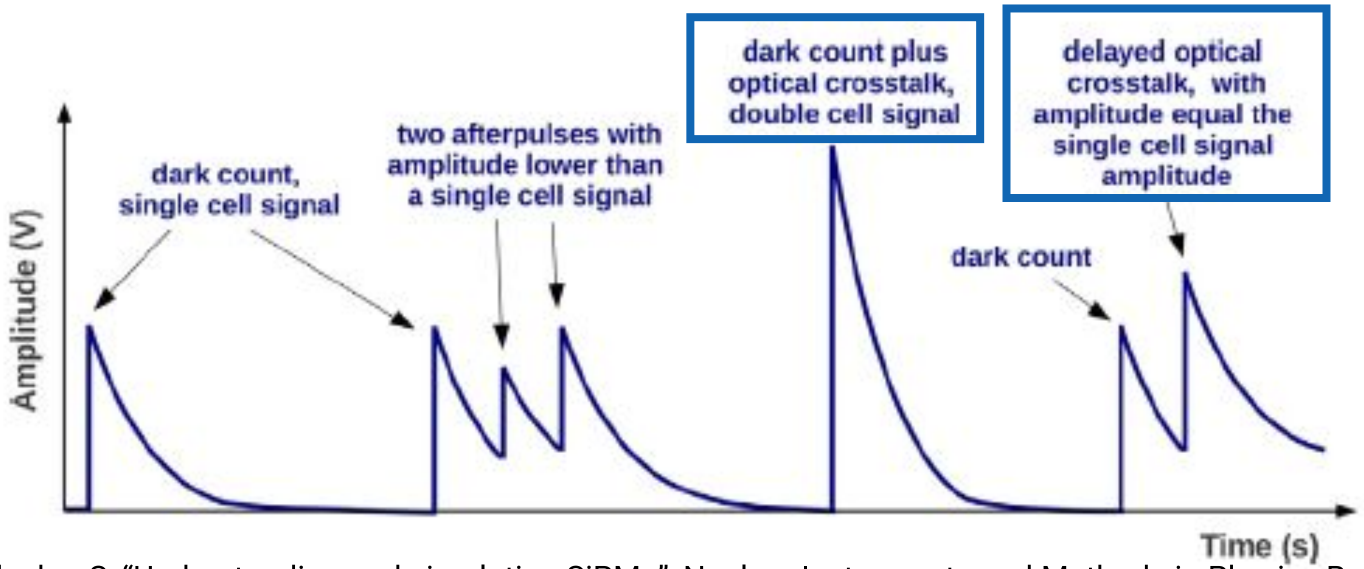
Afterpulsing

- Trapping and release of carriers in the same cell

Introduction
Noise in SiPM





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Primary Dark Count Rate

- Thermally generated carriers or tunneling

Afterpulsing

- Trapping and release of carriers in the same cell

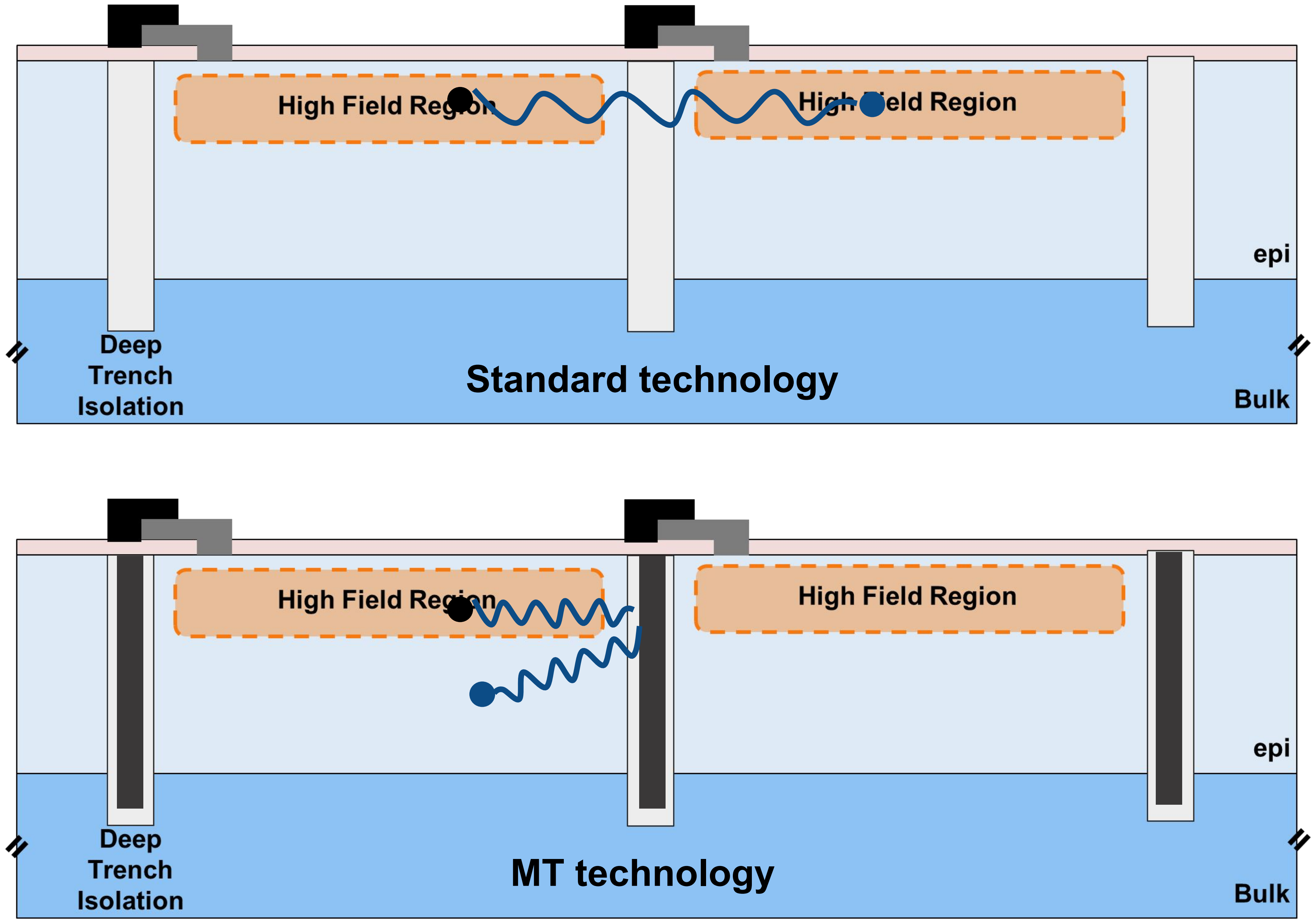
Direct Cross Talk

- Secondary photons produced in the avalanche are absorbed in the neighboring cells

Delayed Crosstalk

- Secondary photons produced in the avalanche are absorbed in the neutral region, then the photo-generated carriers diffuse towards the active region and trigger the avalanche in the neighboring cells

Introduction
FBK NUV-HD SiPMs with metal-filled trenches (MT)

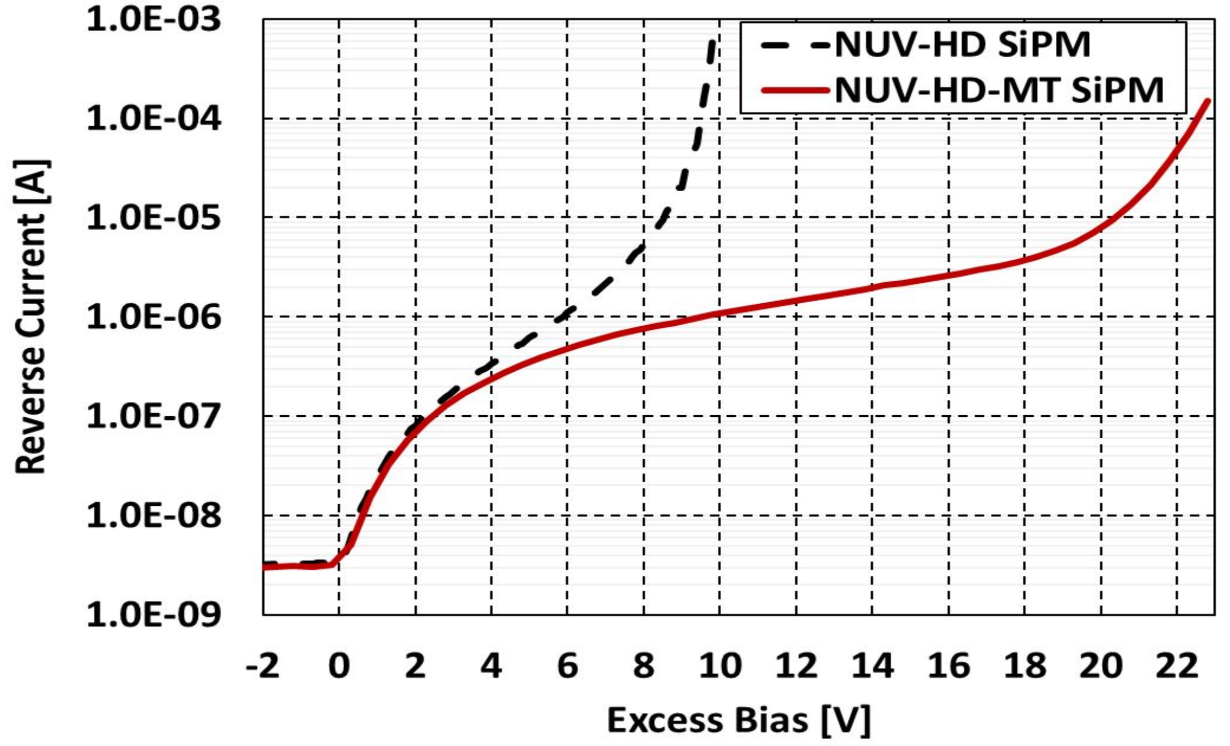


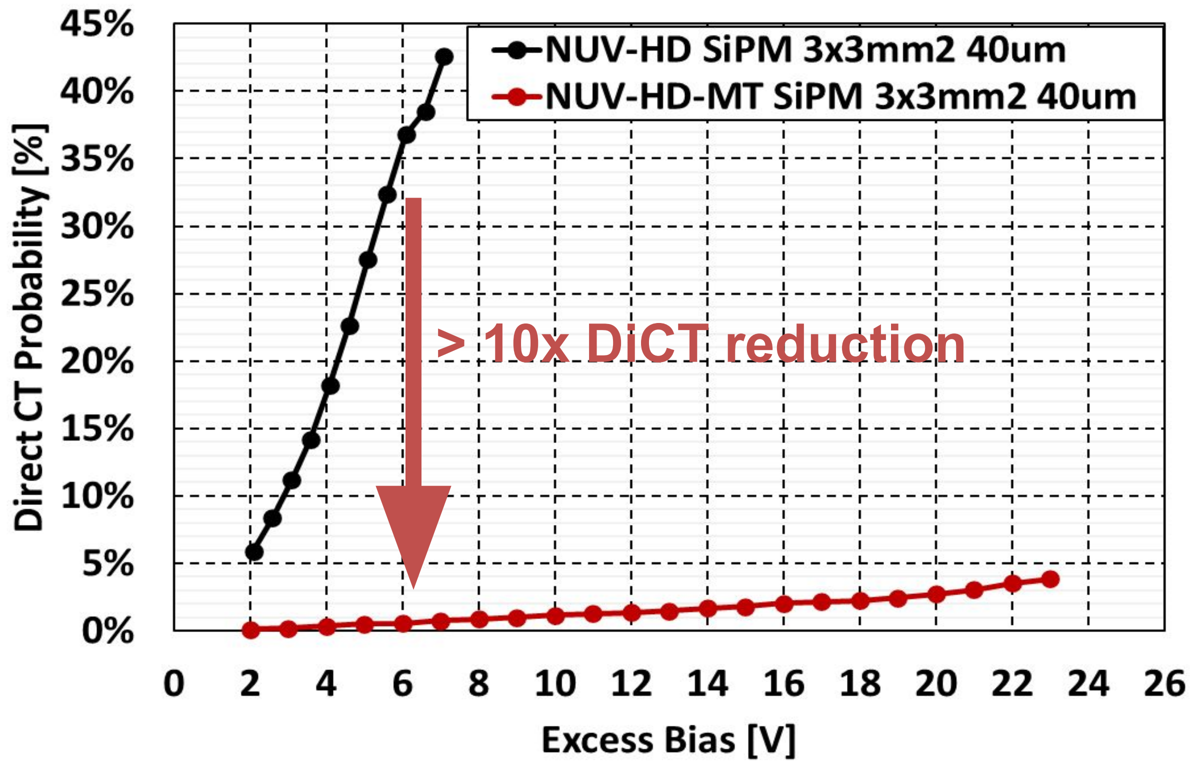
Collaboration with Broadcom

- Metal-filled trenches to optically isolate adjacent microcells

Stefano Merzi et al, "NUV-HD SiPMs with metal-filled trenches", 2023 JINST 18 P05040
DOI 10.1088/1748-0221/18/05/P05040

Introduction
FBK NUV-HD SiPMs with metal-filled trenches (MT)





Collaboration with Broadcom

- Metal-filled trenches to optically isolate adjacent microcells
  - Significant reduction of the internal crosstalk
  - Significant increase of the operating voltage bias

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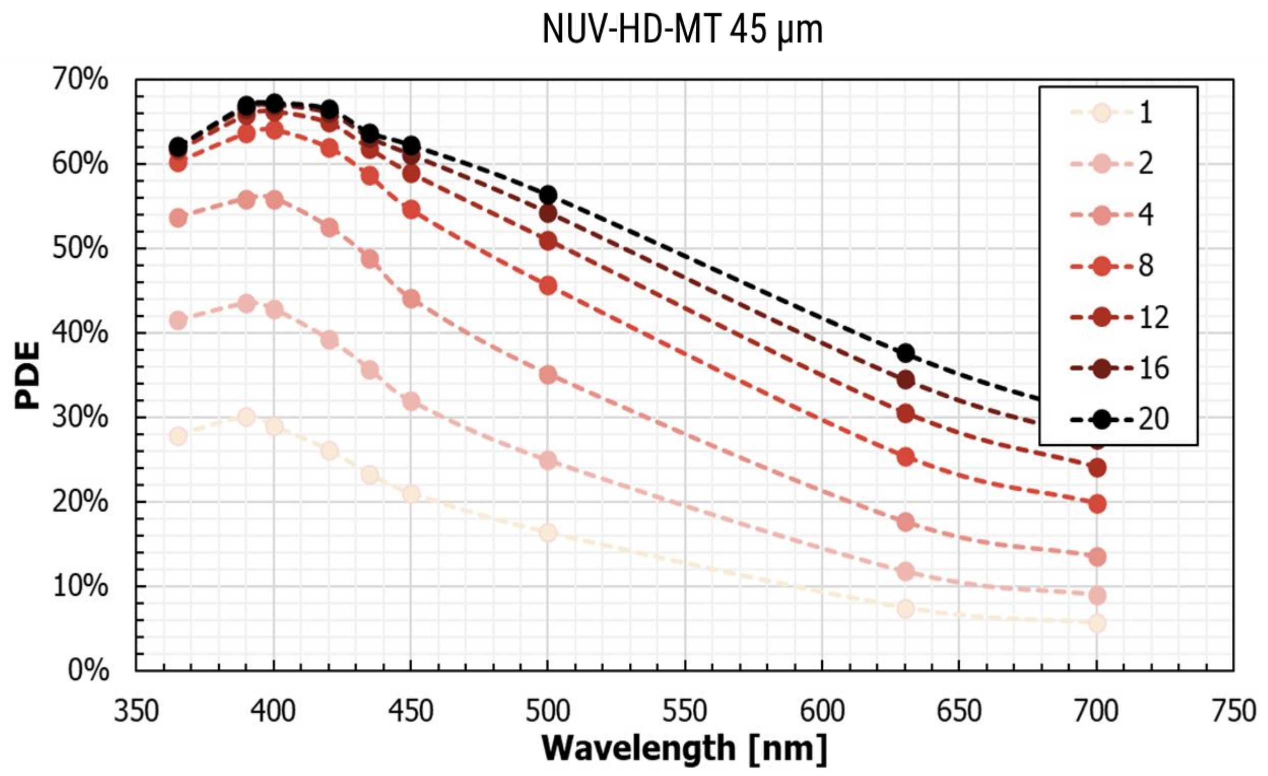
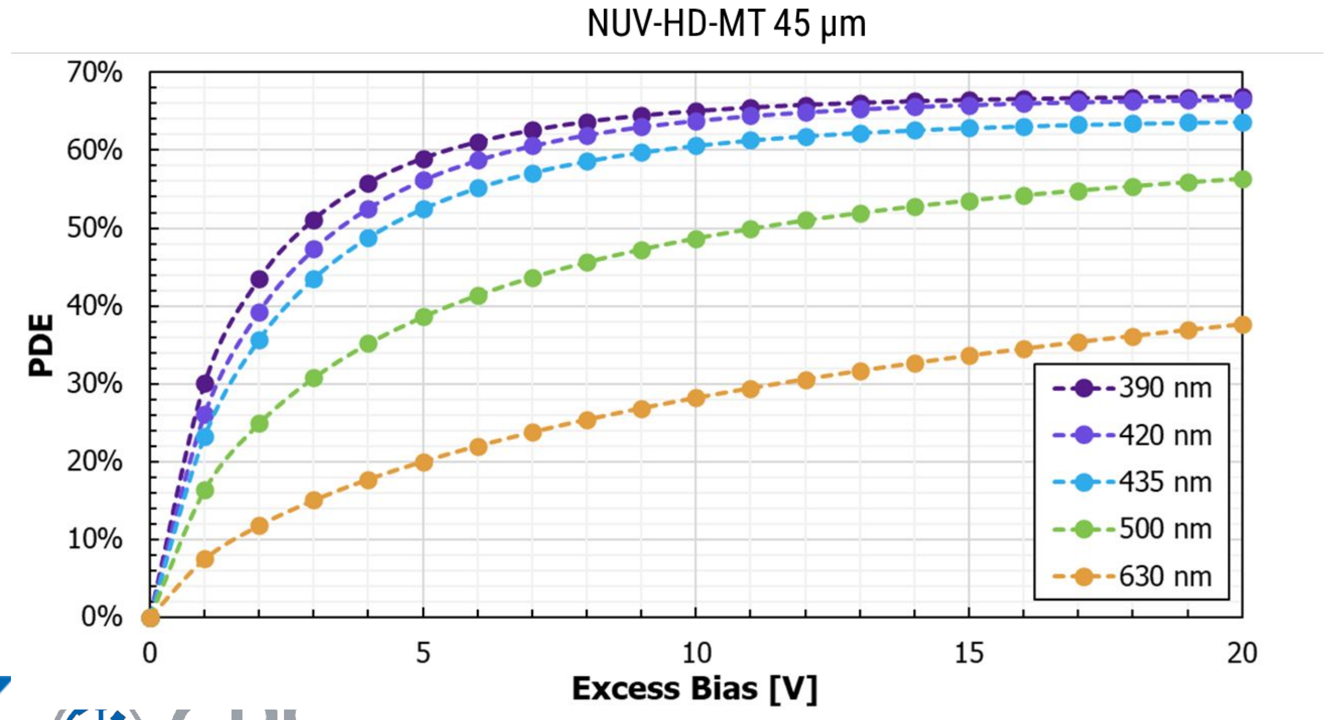
FBK NUV-HD SiPMs with metal-filled trenches (MT)





Collaboration with Broadcom

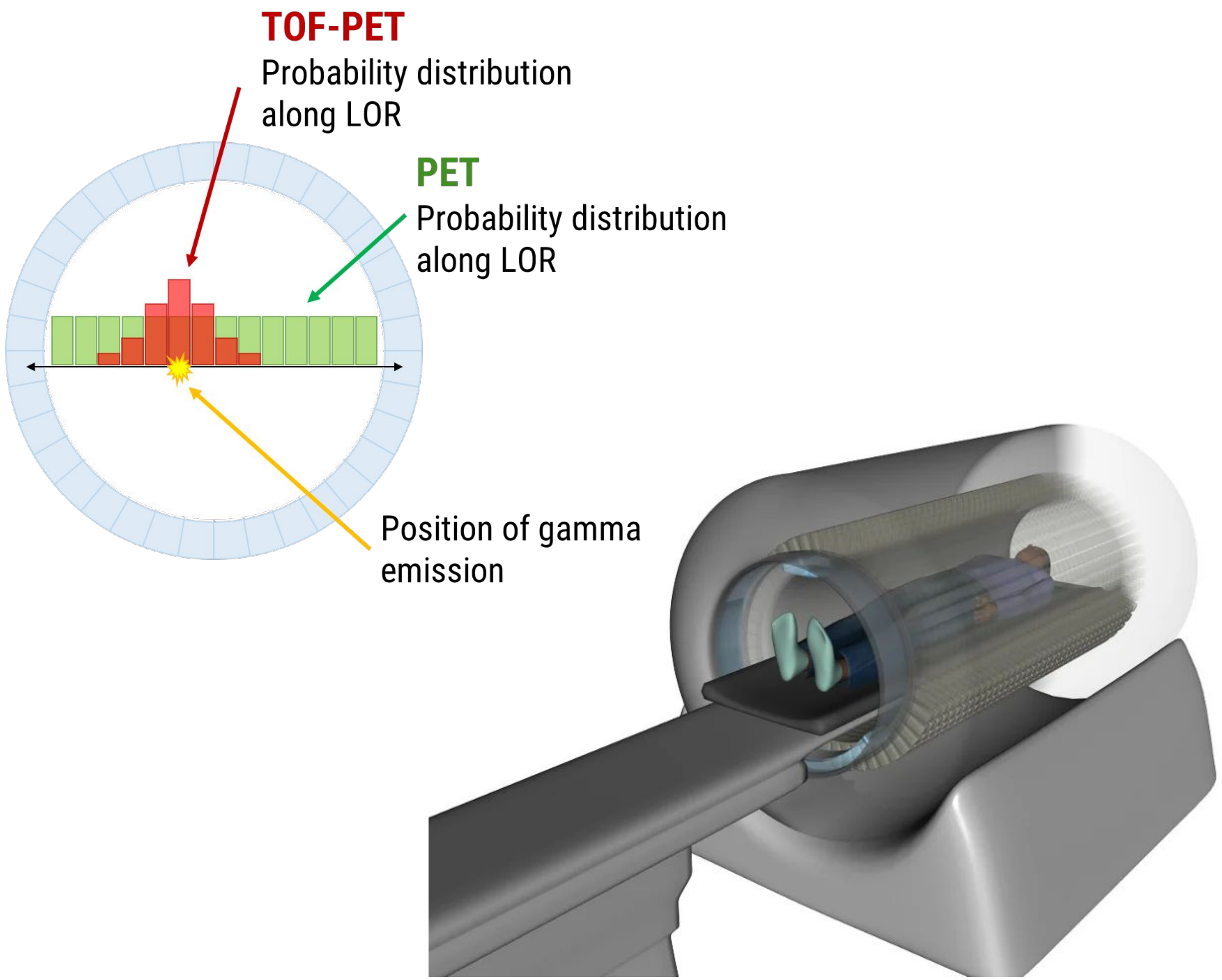
- Metal-filled trenches to optically isolate adjacent microcells
  - Significant reduction of the internal crosstalk
  - Significant increase of the operating voltage bias
  - The extended bias range compensate the slight loss of Fill Factor (thus of PDE) due to the additional space used by the metal filling of the trenches
  - PDE~65%

Stefano Merzi et al, “NUV-HD SiPMs with metal-filled trenches”, 2023 JINST 18 P05040
DOI 10.1088/1748-0221/18/05/P05040

Timing performances

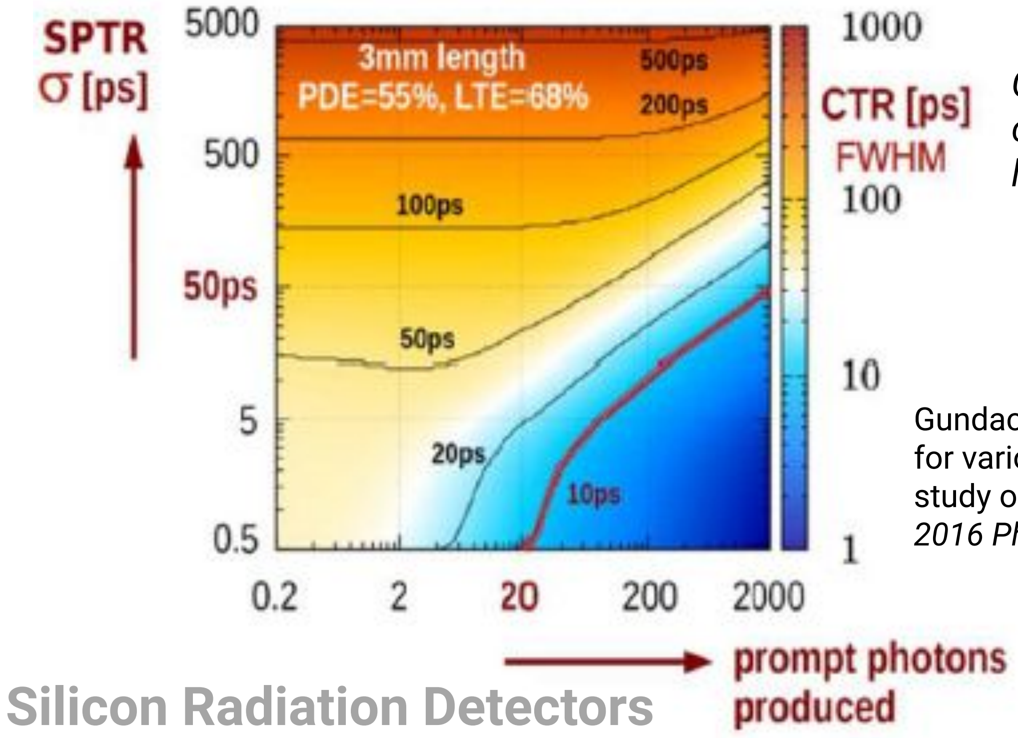
Single Photon Time Resolution (SPTR)

Single Photon Time Resolution
Timing performance applications



Time of Flight – Positron Emission Tomography (ToF-PET)

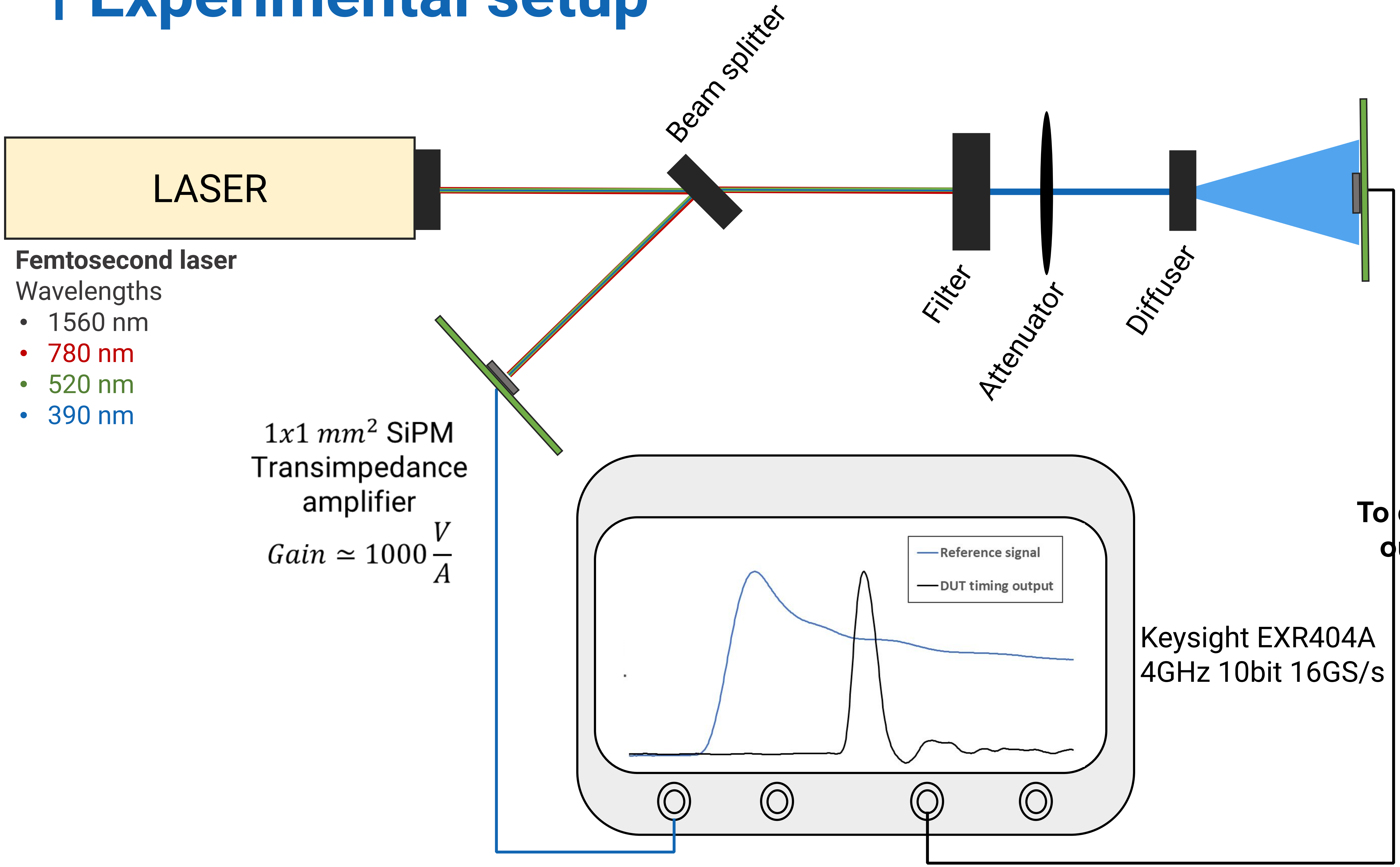
- Coincidence Time Resolution: good CTR → better reconstruction of the emission point along the Line Of Response (LOR)
- SPTR crucial for low light detection applications: timing with Cherenkov light



Cramér–Rao Lower Bound (CRLB) on coincidence time resolution for a 3 mm length LSO:Ce,Ca(0.4%) crystal.

Gundacker et al. "Measurement of intrinsic rise times for various L(Y)SO and LuAG scintillators with a general study of prompt photons to achieve 10 ps in TOF-PET." *2016 Phys. Med. Biol. 61 2802*

Single Photon Time Resolution
Experimental setup

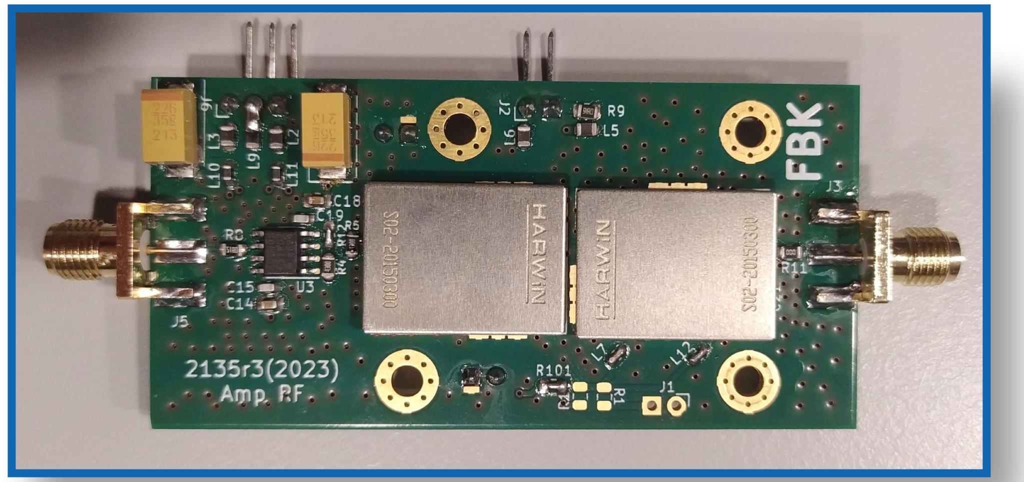


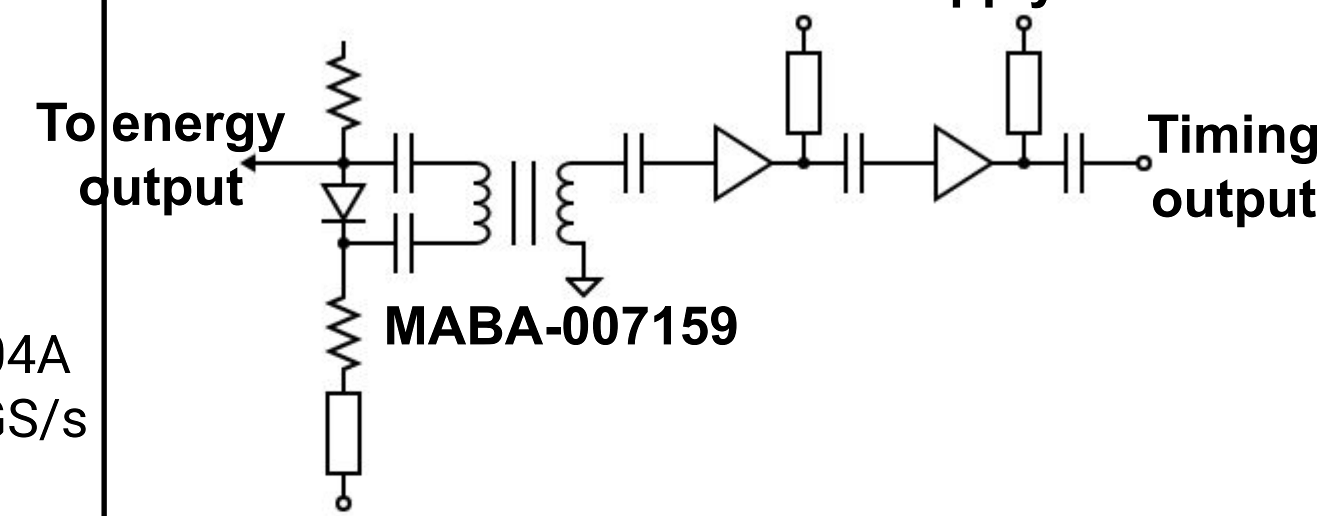
Femtosecond laser
Wavelengths
- 1560 nm
- 780 nm
- 520 nm
- 390 nm

$1x1\ mm^2$ SiPM
Transimpedance amplifier
$Gain \simeq 1000 \frac{V}{A}$

Keysight EXR404A
4GHz 10bit 16GS/s

HF readout developed at FBK
Implemented with BGA616



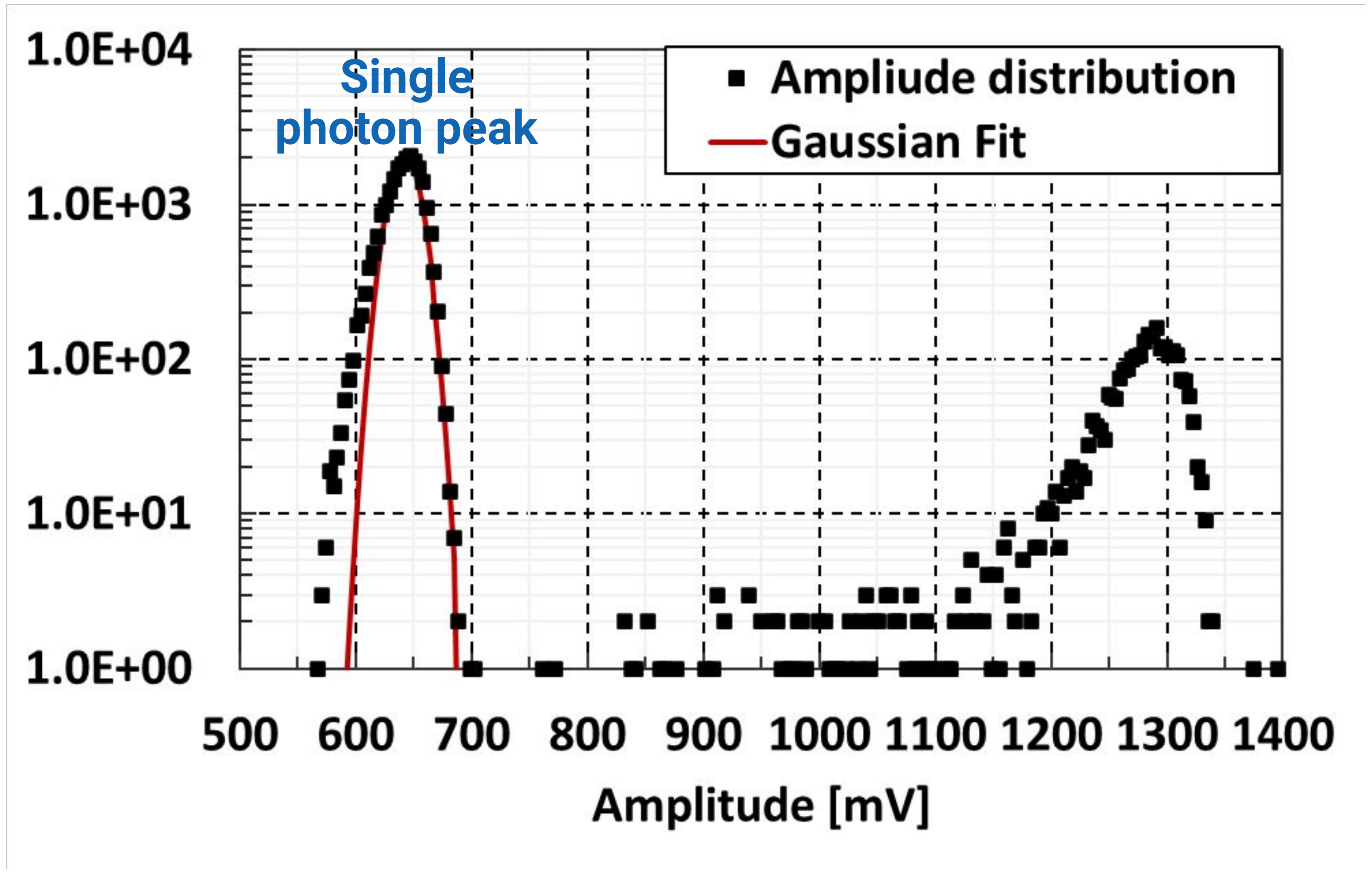


SPTR measurements have been performed with blue light (390nm)

Single Photon Time Resolution
Data acquisition and analysis

Amplitude distribution

- Gaussian fit on the single photon peak
  - $[\mu - 2\sigma, \mu + 2\sigma]$ taken as interval for the timing signals selection



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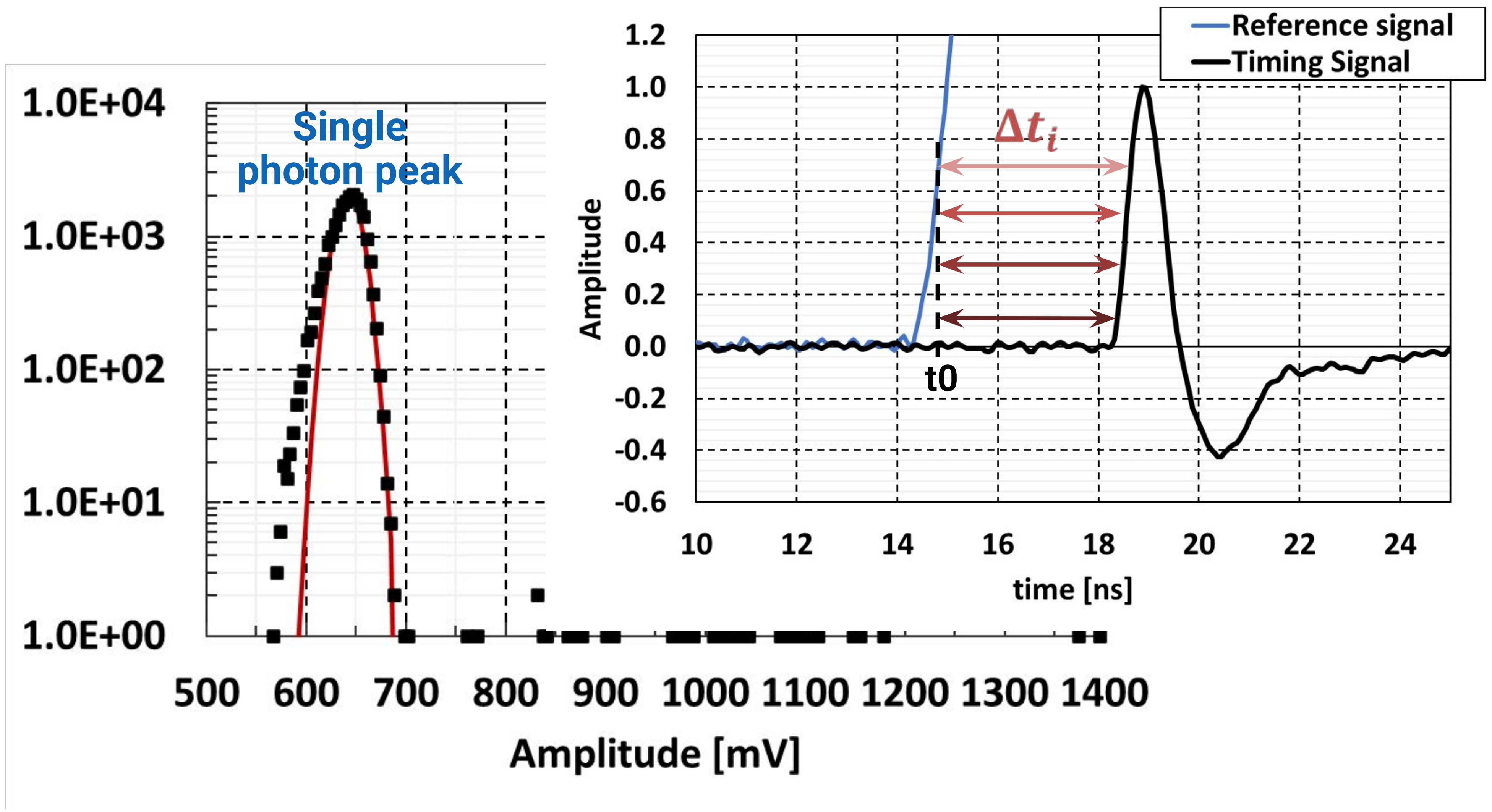
Time delay distributions

- Time delays created from several threshold levels: scan along the leading edge (LED)
  - $\Delta t_i = t_i - t_0$: where t_0 is a single time stamp taken for the reference signal



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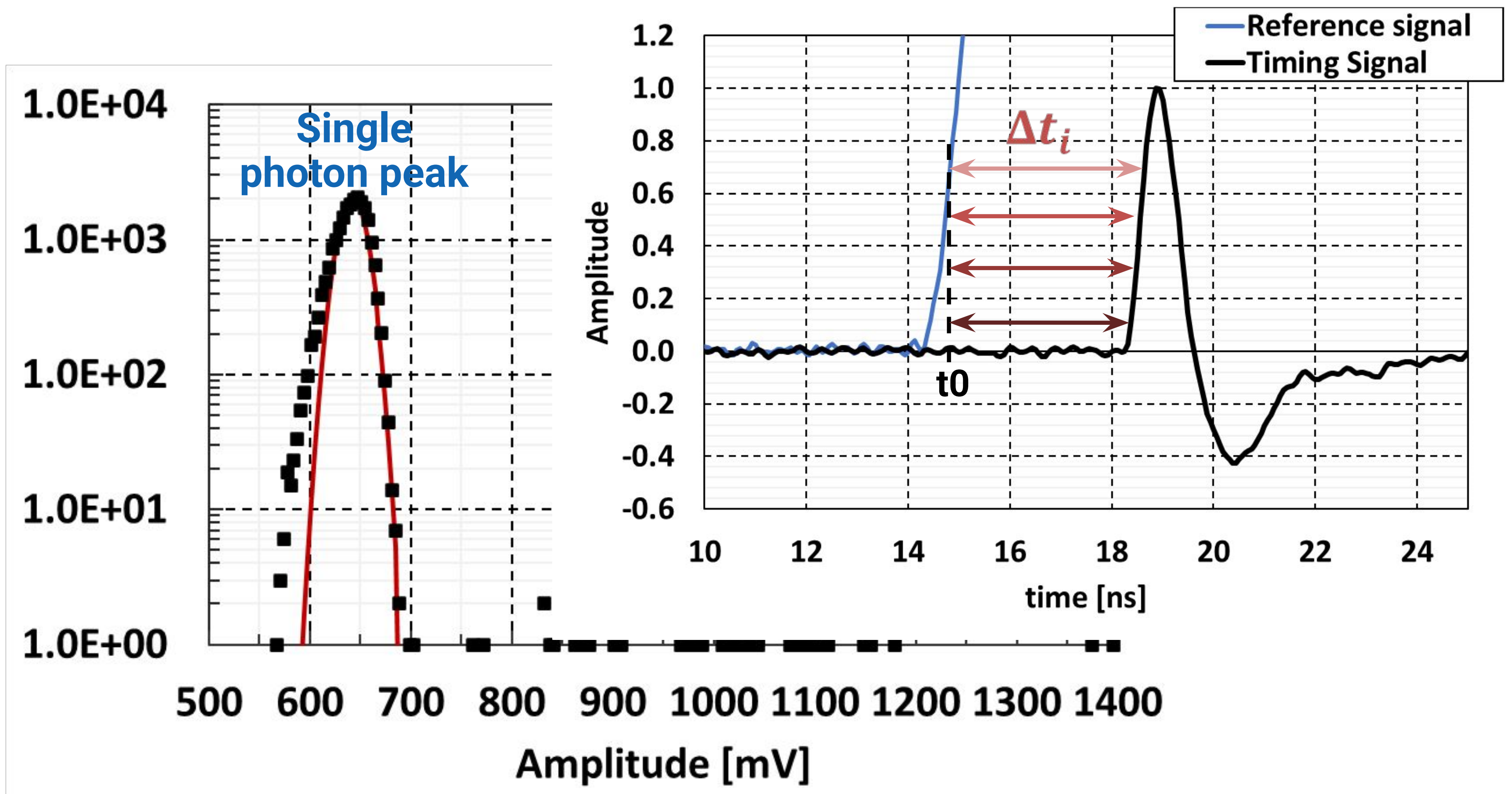
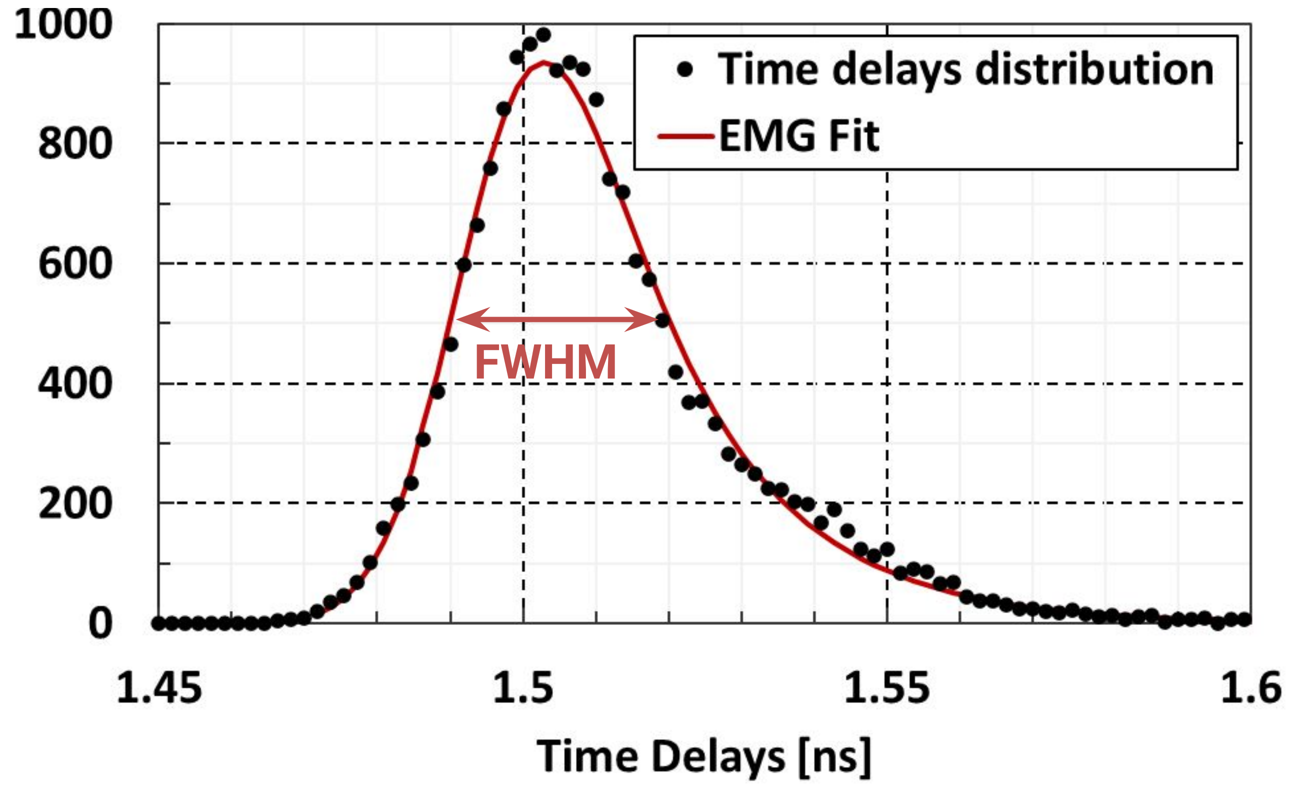
FWHM vs thresholds

- Each time delay distribution is fitted with an Exponential Modified Gaussian
- The FWHM is taken as SPTR

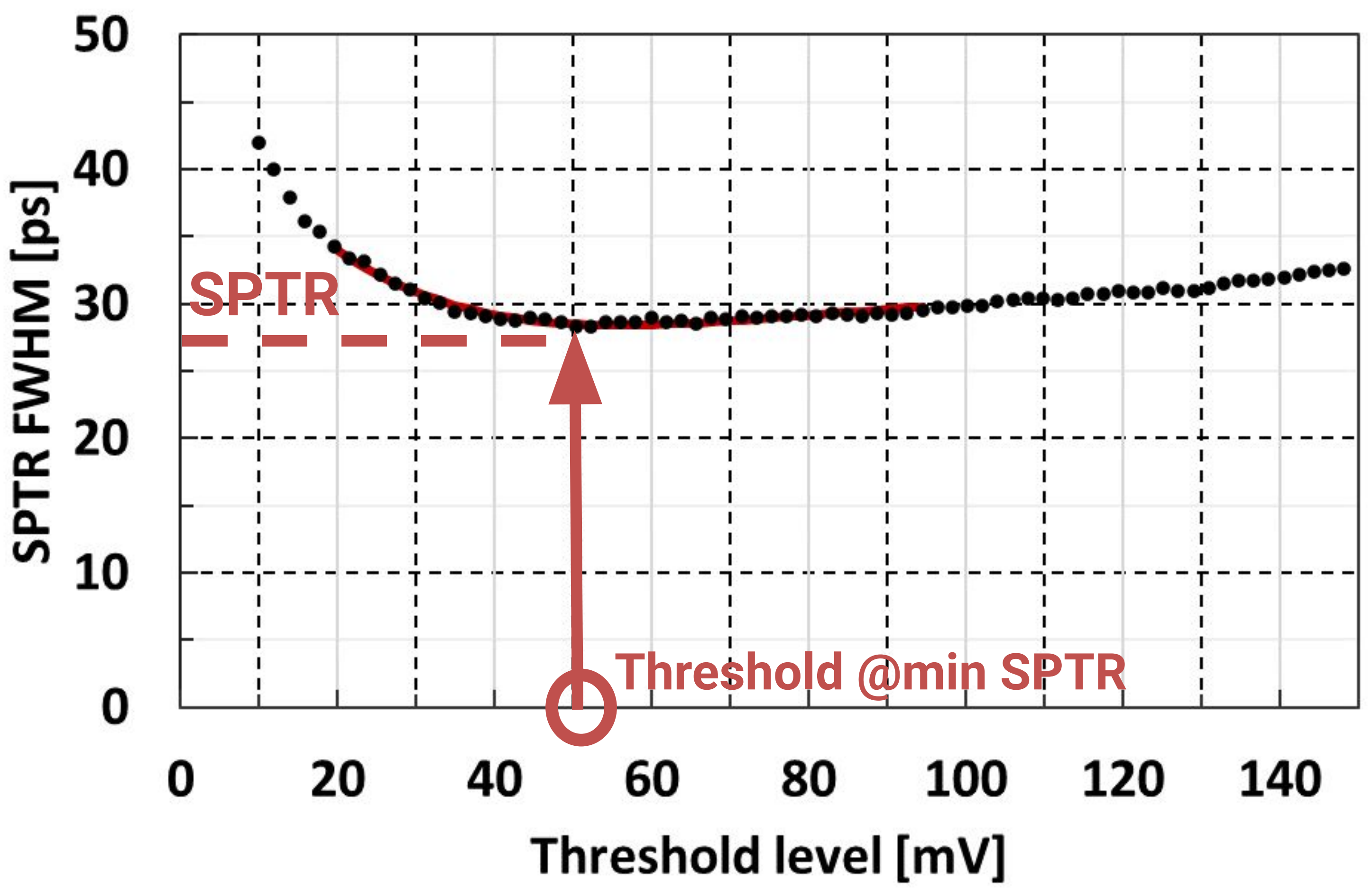




Single Photon Time Resolution
Data selection and methodologies

FWHM vs threshold plot

- Fitted with a polynomial
  - The minimum of the fit is the SPTR measurement
  - The threshold corresponding at the SPTR is the threshold used for the electronic noise jitter contribution



Single Photon Time Resolution
Devices tested

SPAD cell sizes

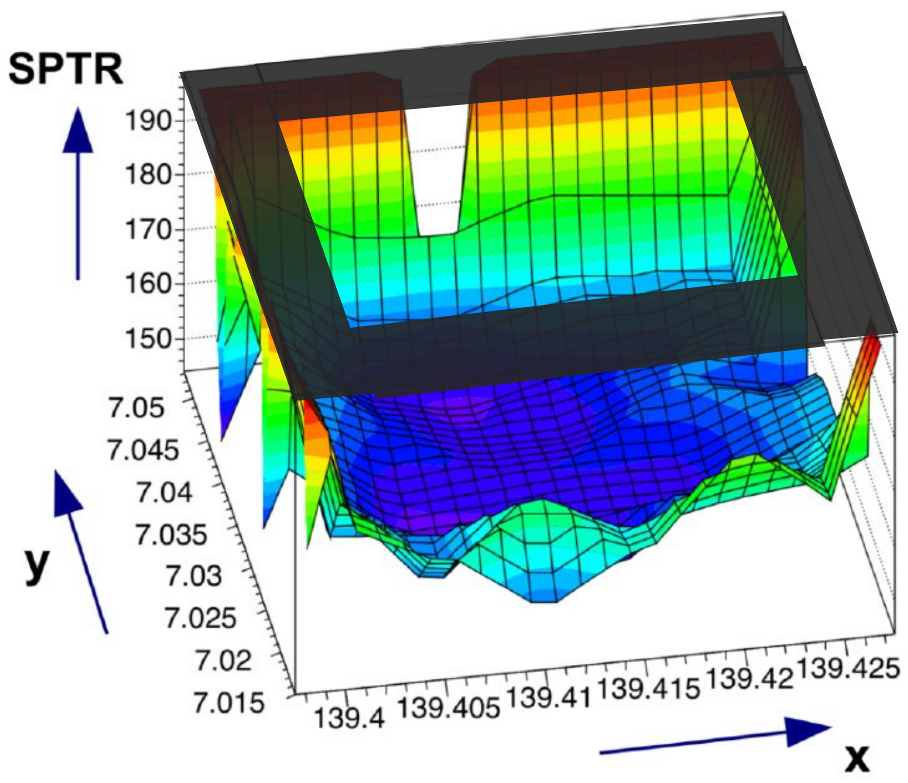
- $30\ \mu m, 40\ \mu m,\ 50\ \mu m$

SiPM dimensions

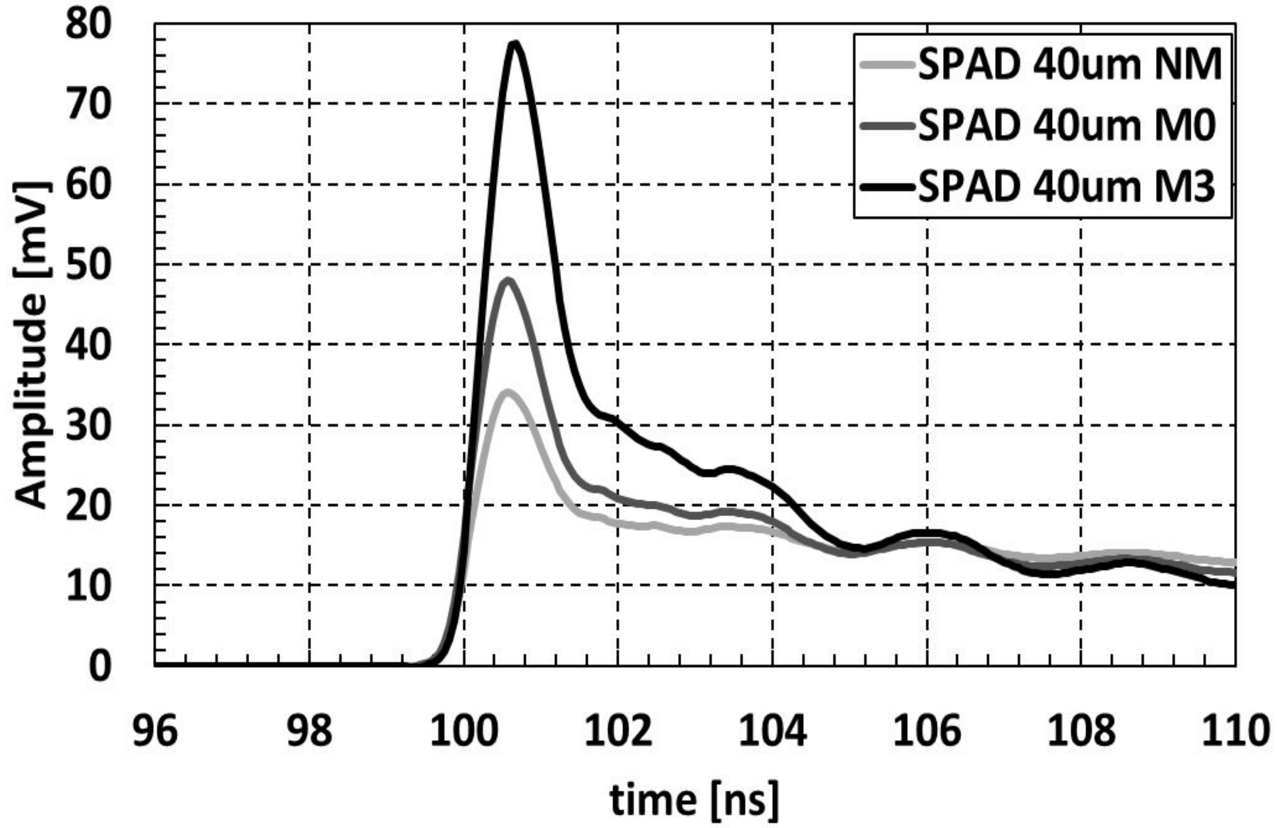
- Cell size: $40\mu m$
- $1x1mm^2, 3x3mm^2, 4x4mm^2$

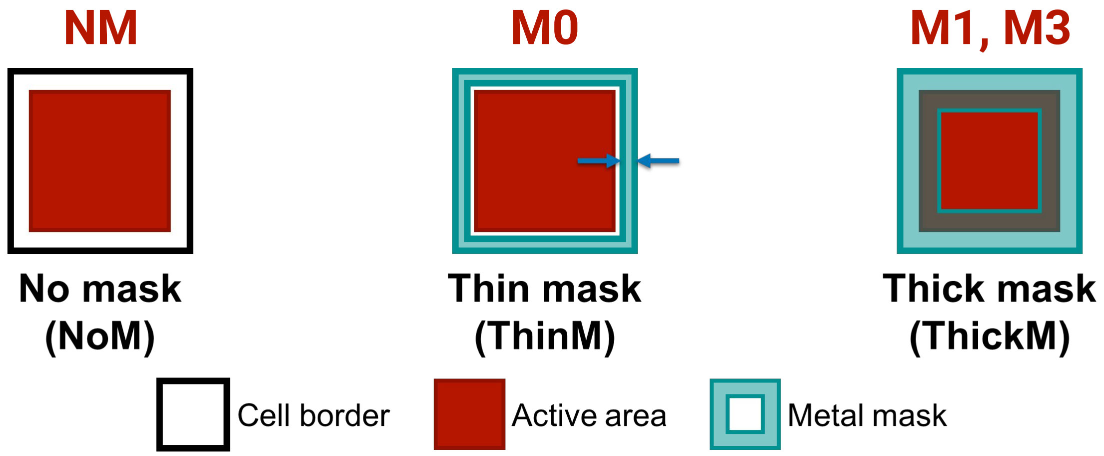
Mask versions

- Masked: $0\mu m, 3\mu m$ overlap with the active area
  - Remove the outer areas of the SPAD which show worse SPTR
  - A higher capacitive coupling between anode and readout: increase the fast peak of the single cell response



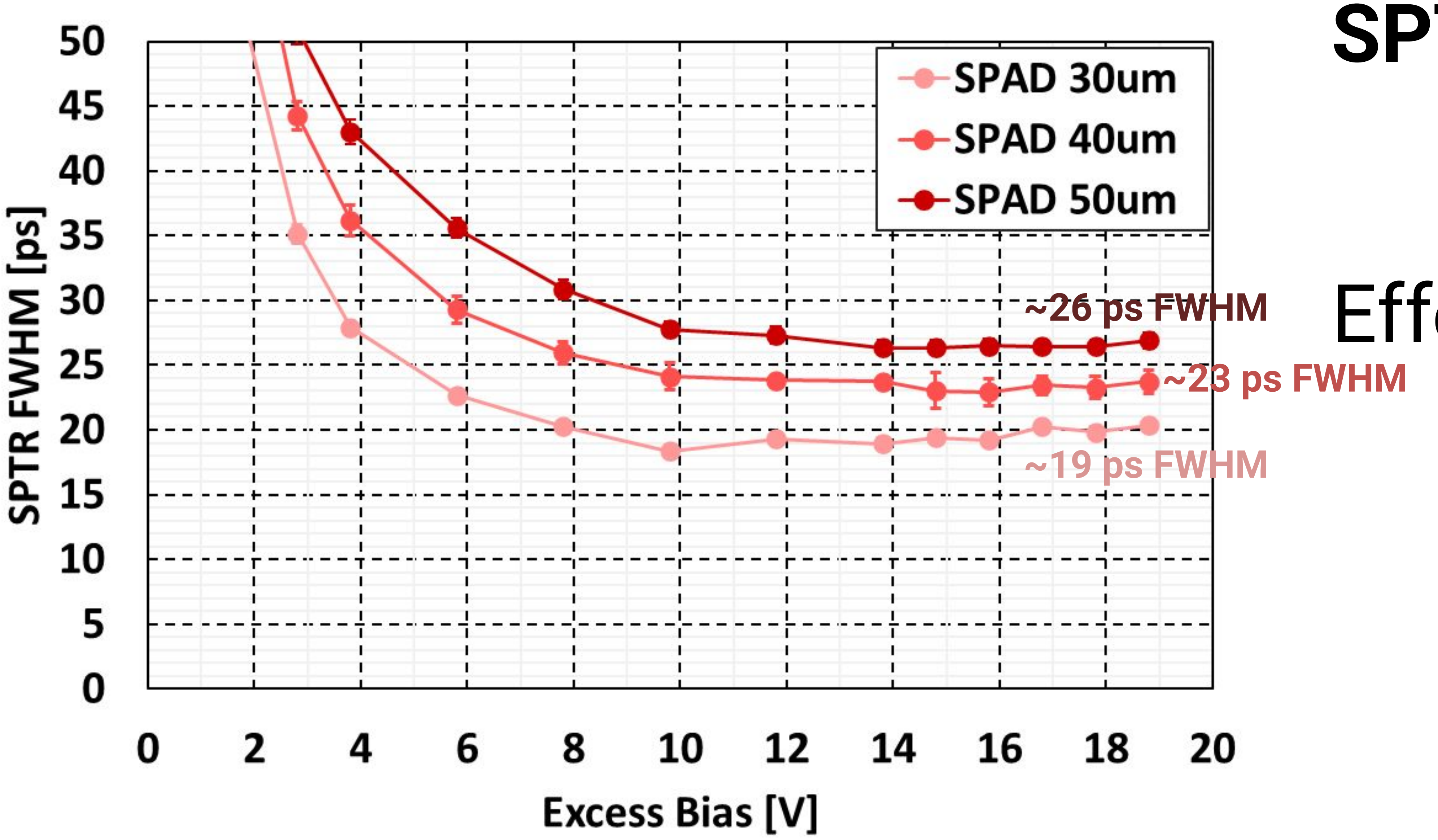
Nemallapudi, M. V., et al. "Single photon time resolution of state-of-the-art SiPMs." *Journal of Instrumentation* 11.10 (2016): P10016.





Stefan Gundacker et al, " On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET", 2023 Phys. Med. Biol. 68 165016

Single Photon Time Resolution (SPTR)
Results



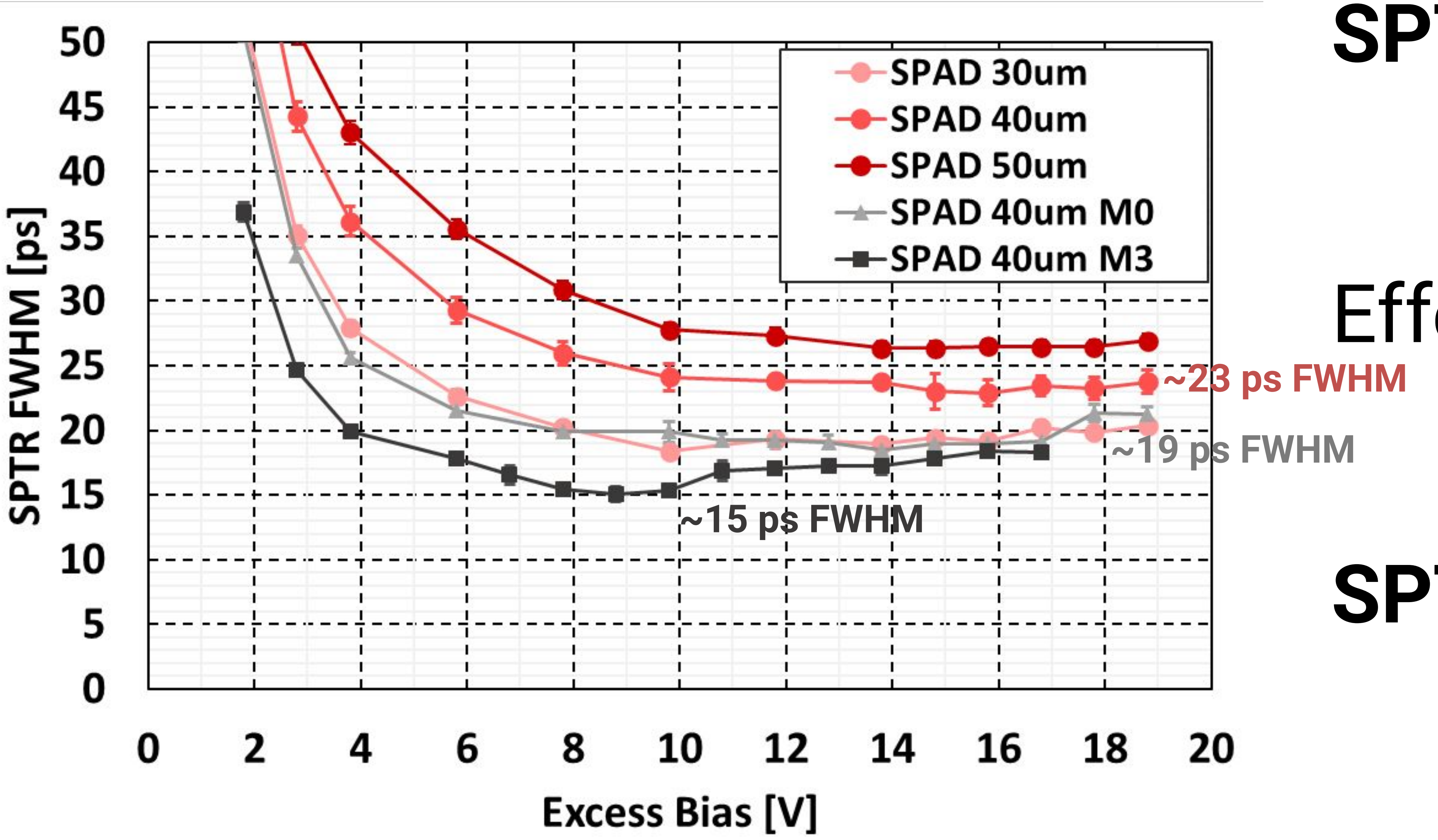
SPTR vs microcell size

- The SPTR get worse with the cell size

Effect under investigation

- Maybe related to the position where the avalanche starts

Single Photon Time Resolution (SPTR)
Results



SPTR vs microcell size

- The SPTR get worse with the cell size

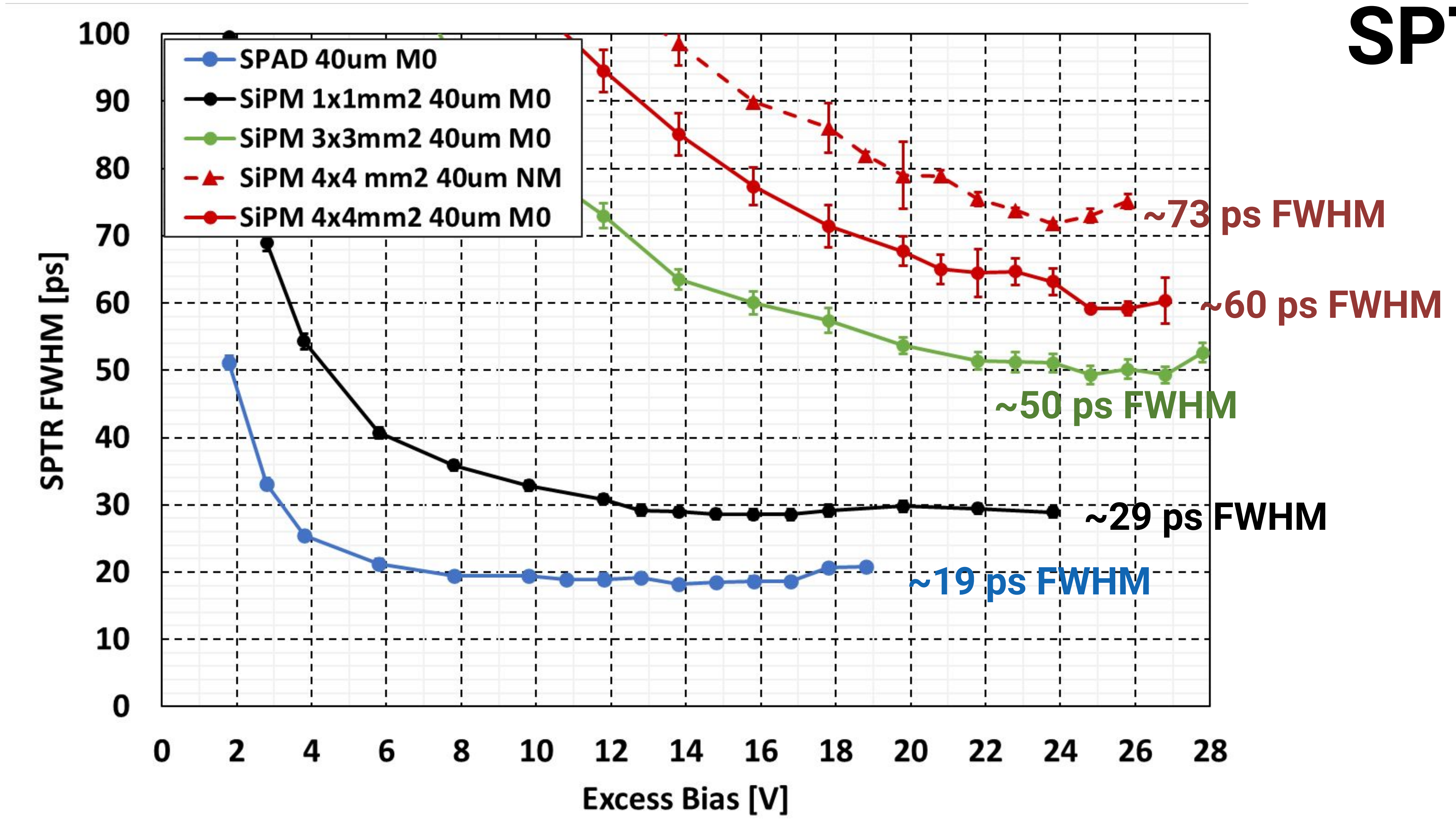
Effect under investigation

- Maybe related to the position where the avalanche starts

SPTR vs mask version

- Strong improvement of the SPTR related to the mask implementation

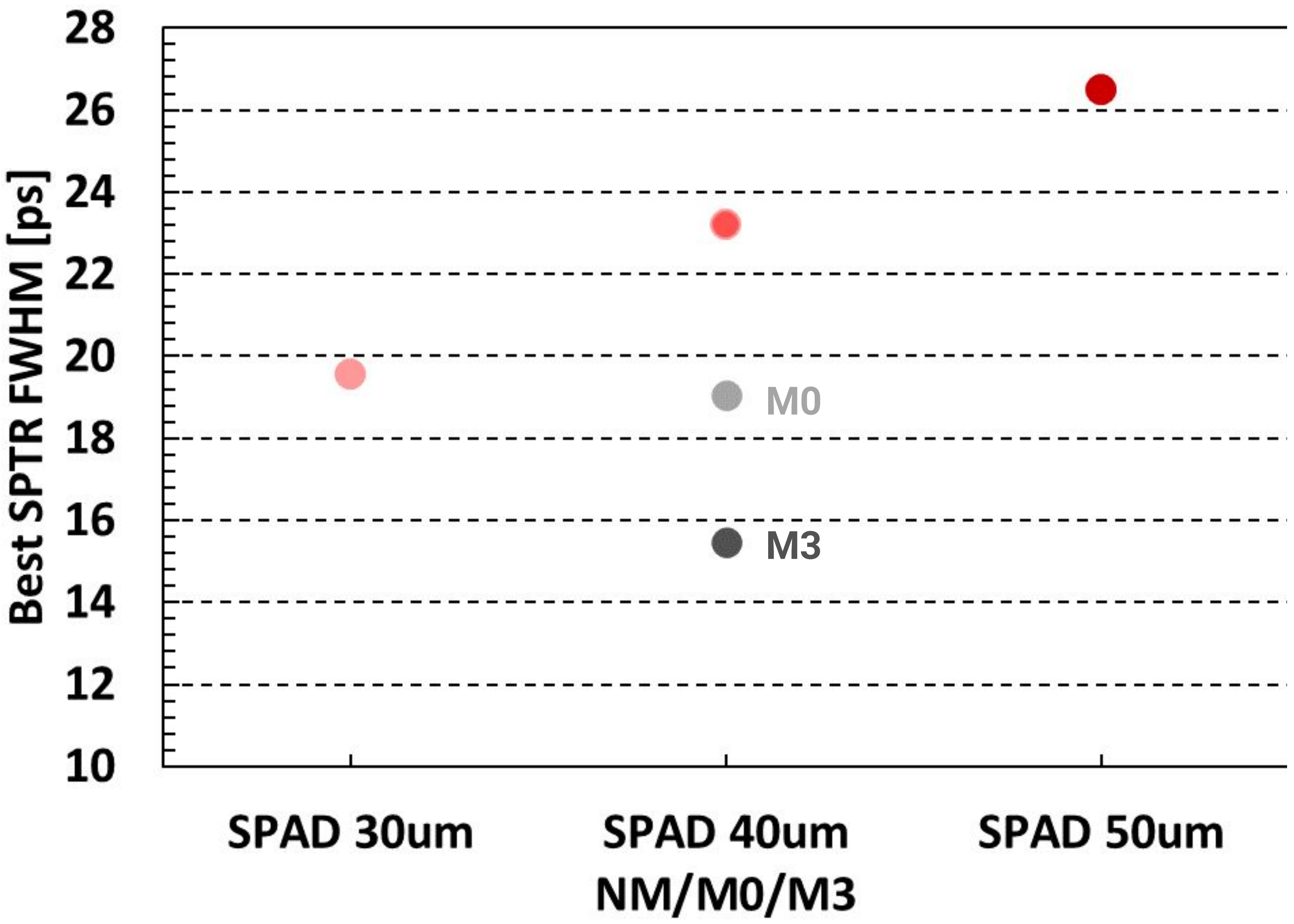
Single Photon Time Resolution (SPTR)
Results

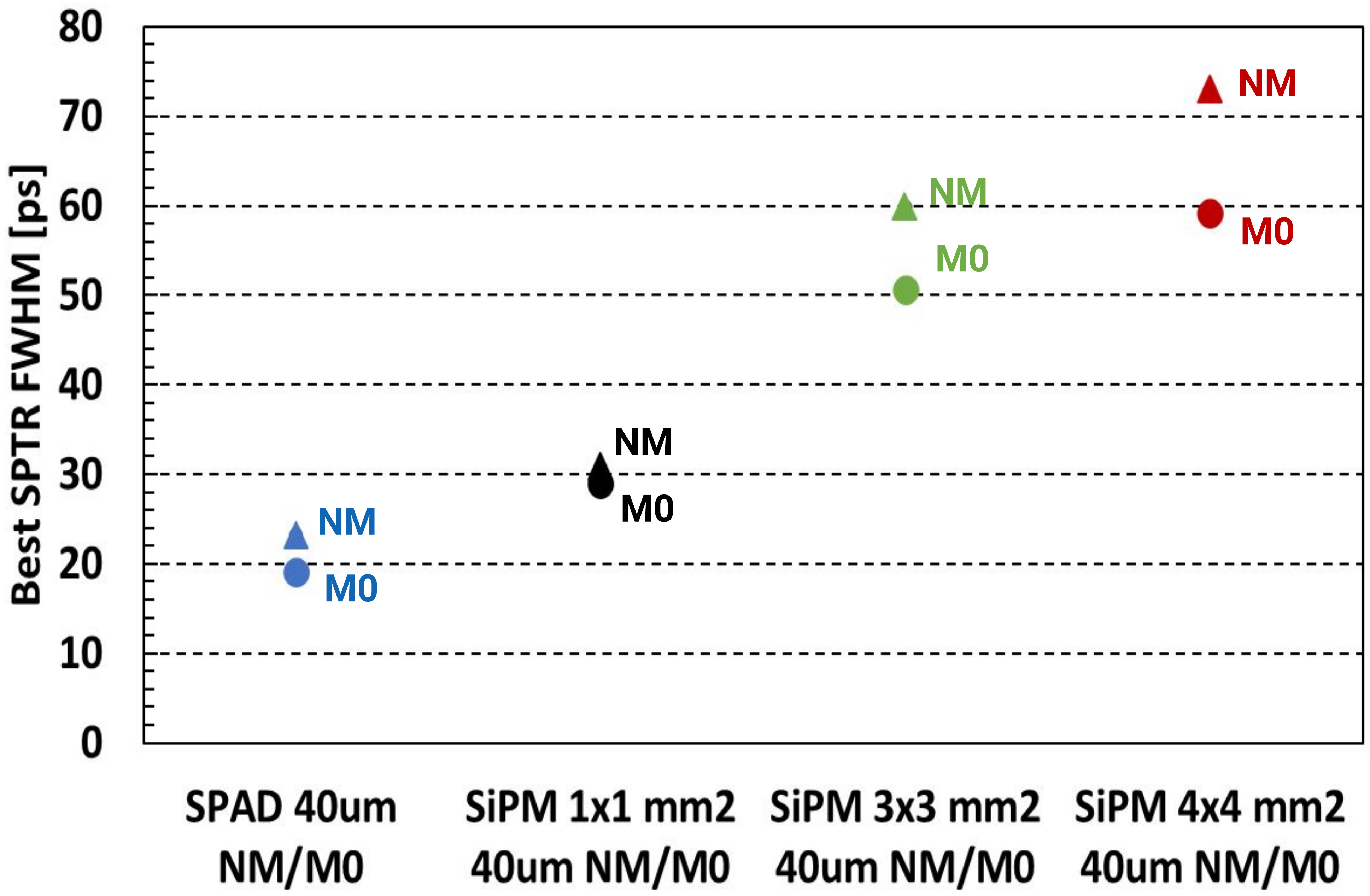


SPTR vs SiPM dimension

- SPTR get worse for bigger SiPMs
  - Self-filtering effect
  - Transit Time Spread
- Importance of the device segmentation

Single Photon Time Resolution (SPTR)
SPTR results summary

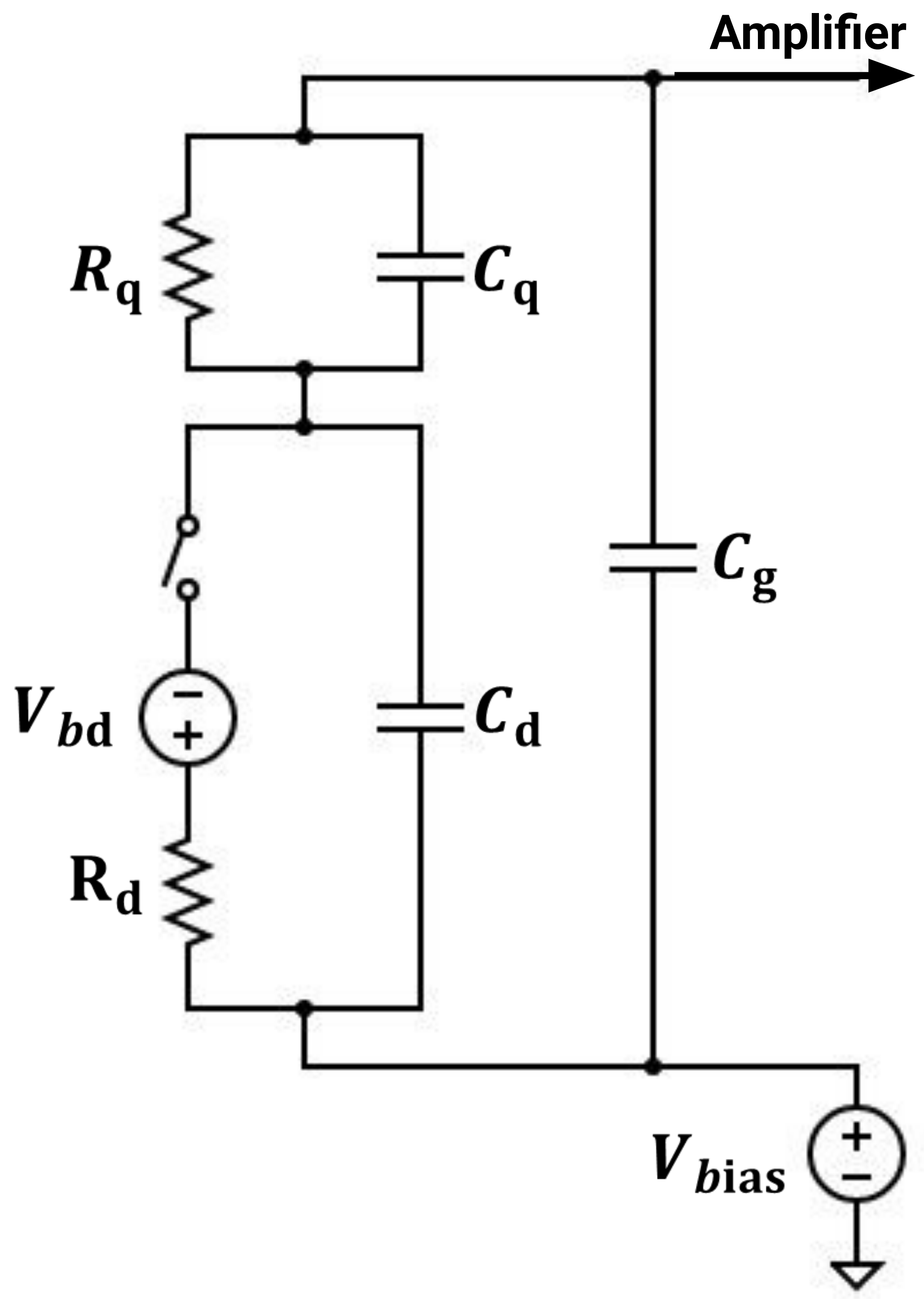




SPAD signal electrical simulations

SPAD equivalent electrical circuit

SPAD equivalent electrical circuit
SPAD equivalent electrical circuit



Crucial to have a reliable model to

- **Tune the design process (e.g. optimize the sensor)**
- **Front-end design**
- **Match the experiment constraints**

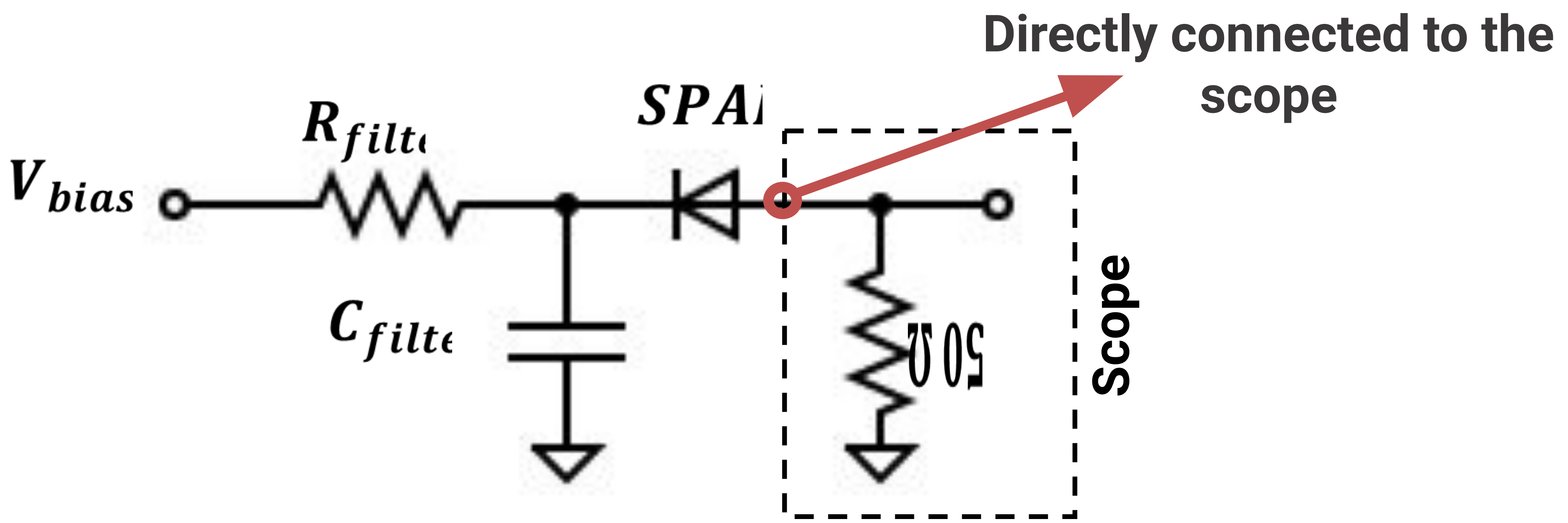
Electrical parameters

- R_d diode resistance
- C_d diode capacitance
- R_q quenching resistance
- C_q quenching capacitance
- C_g grid capacitance

SPAD signal electrical simulations

Electrical parameters extraction

Electrical parameters extraction
Quenching and diode capacitance



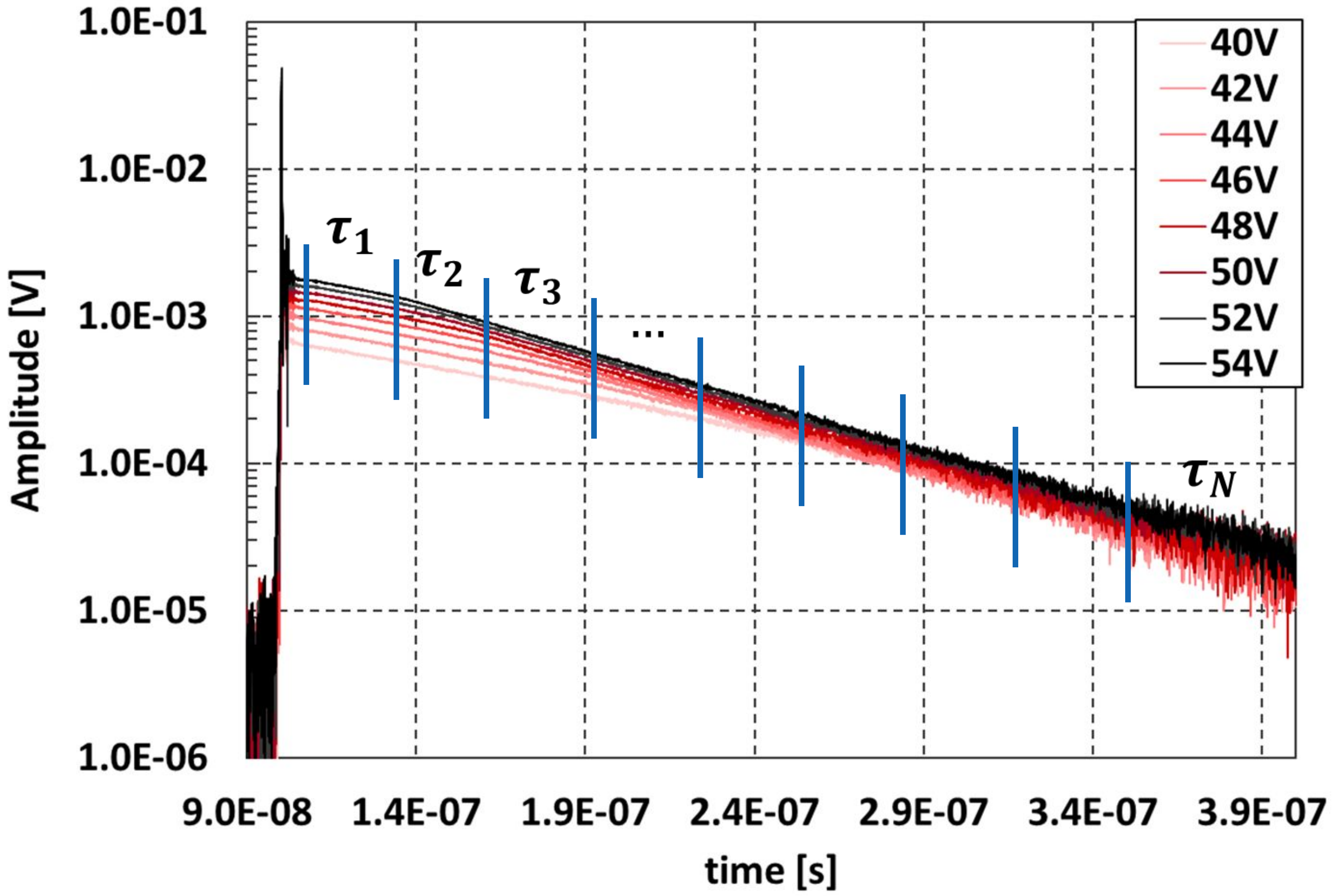
Device Under Test

- NUV-HD-MT SPAD 50um

Oscilloscope

- Sampling rate: 16Gs/s
- 62.5ps/pt
- NO interpolation
- Bandwidth: 4GHz
- Z_{in} scope: 50 Ω

Electrical parameters extraction
Voltage varying capacitance model



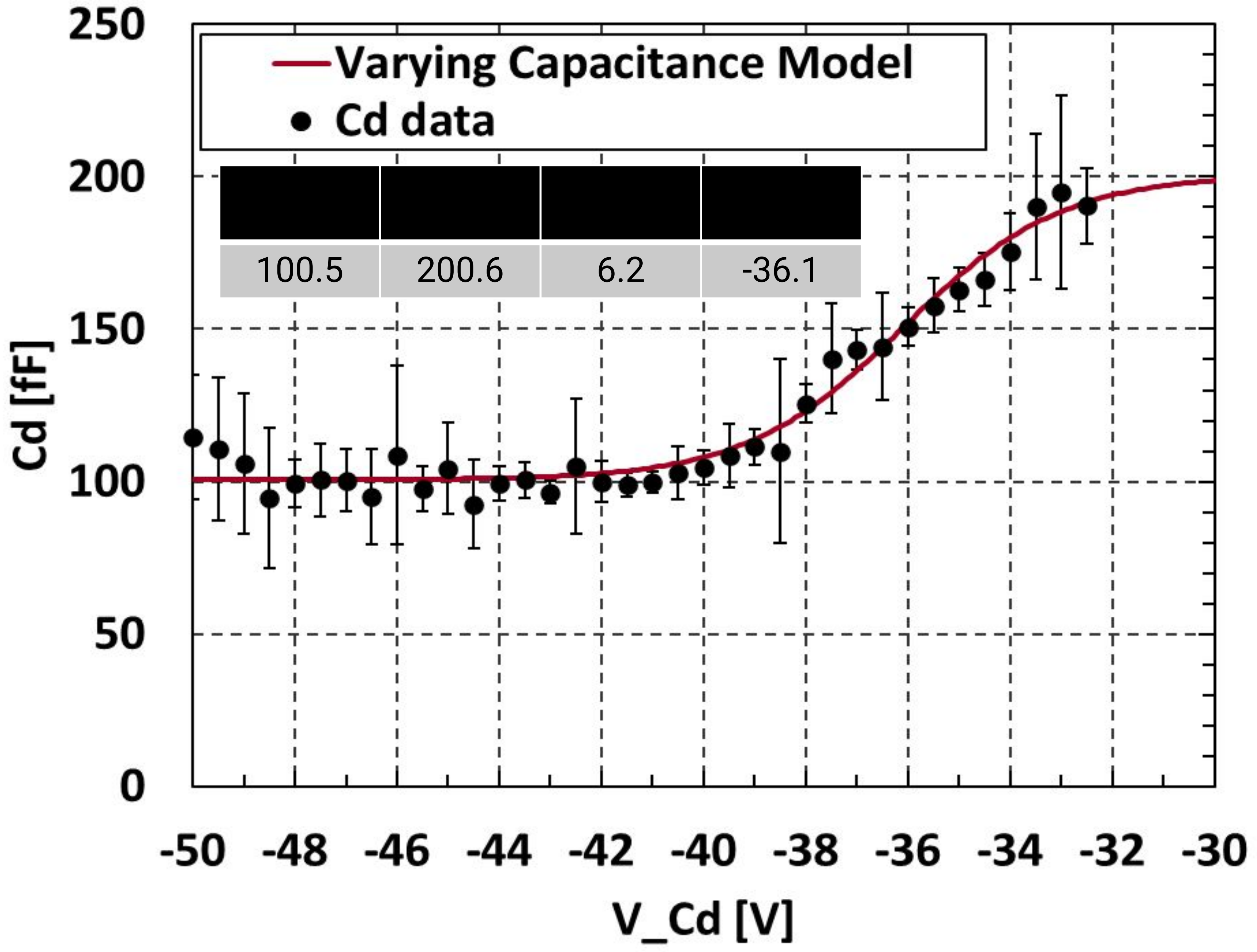
- By assuming that for small time intervals (small variation of the voltage across C_d), C_d is constant…
  - …you can fit the recharge of the signal in several intervals

$$V = A \cdot e^{-\frac{t}{\tau_d}}$$

for each excess bias. Then

$$(C_d + C_q) = \frac{\tau_d}{R_q}$$

Electrical parameters extraction
Voltage varying capacitance model



[redacted]			
100.5	200.6	6.2	-36.1

- Assuming $C_q \simeq 10fF$
- Model based on the hyperbolic tangent (sigmoid-like function) can be used

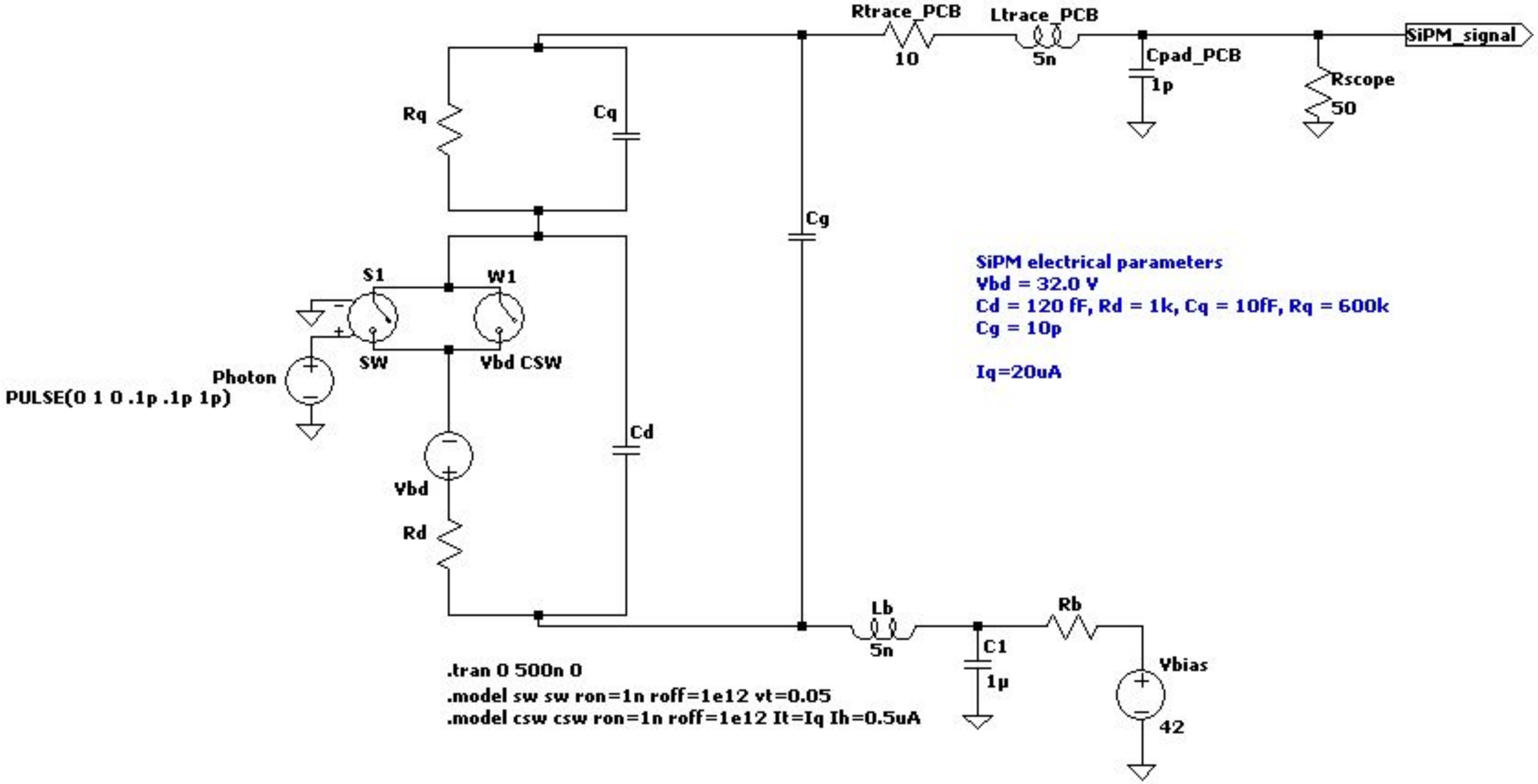
$$C(V_{bias}) = \frac{C_0 - C_{sat}}{2}\left(1 - \tanh\frac{2(V_{bias} - V_{th})}{V_{tra}}\right) + C_{sat}$$

Reiner Bidenbach, RAQ Issue 192: “*How to Use LTspice Simulations to Account for the Effect of Voltage Dependence*”, AnalogDialogue

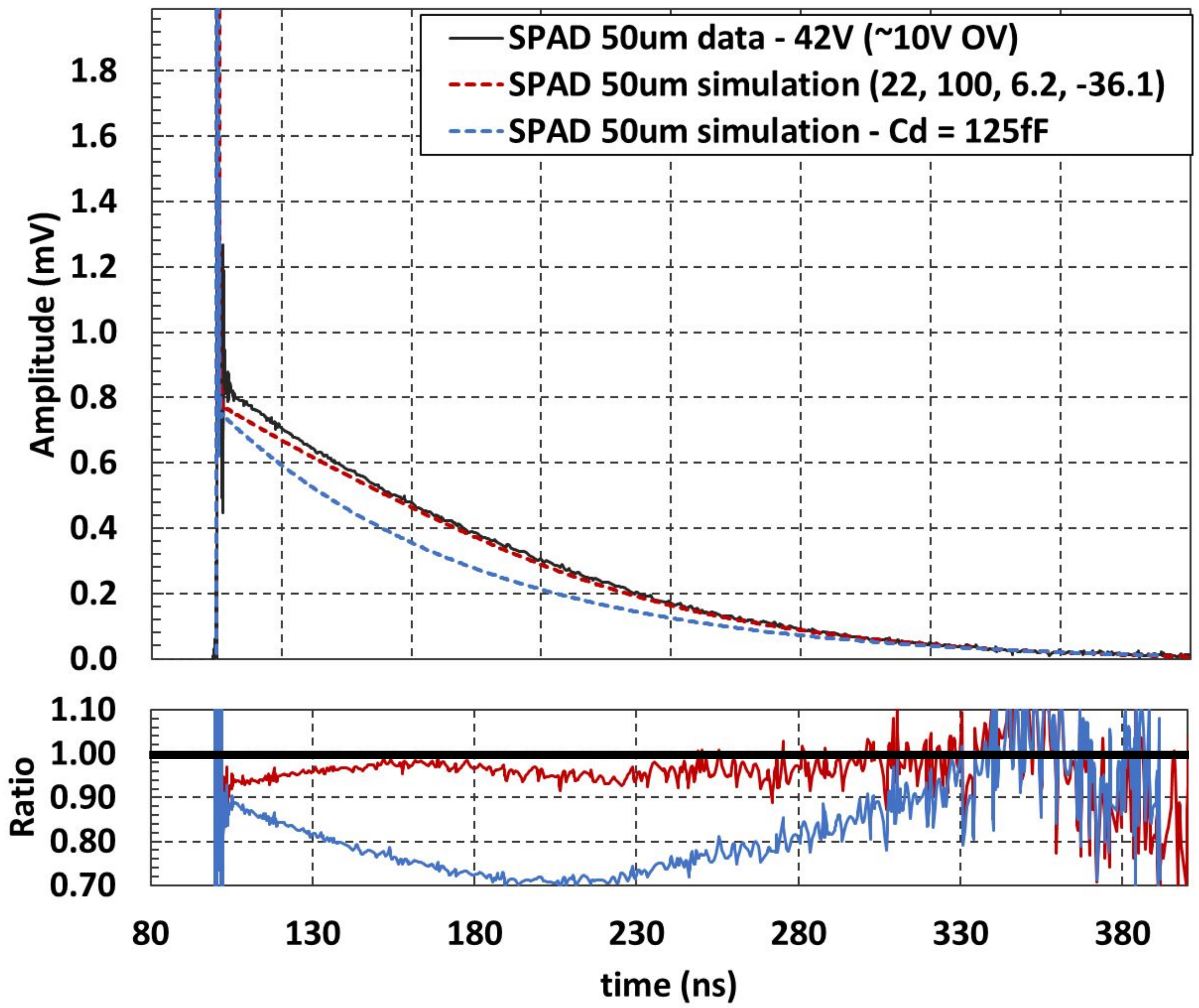
SPAD signal electrical simulations

SPICE simulations

SPICE simulations
SPICE model



SPICE simulations
Simulation vs experimental data



- Comparison between a constant capacitance model and the voltage varying capacitance model
- The improved model fits the experimental data within the **~5%** discrepancy

Conclusion
…next step

Improved SPICE model

- A $50\mu m$ **SPAD** response was studied
  - Simulations fits the experimental data within the **~5%** discrepancy, using the varying capacitance model

FBK NUV-HD-MT SiPMs timing performance

- FBK NUV-HD MT technology shows an excellent SPTR (HF readout was used)
  - SPAD $40\mu m$ $M0$: $(19.1 \pm 0.2)\ ps$
  - SiPM $1\text{x}1\text{mm}^2$ $40\mu m$ $M0$: $(29.0 \pm 0.3)\ ps$
  - SiPM $3x3\text{mm}^2$ $40\mu m$ $M0$: $(50.7 \pm 0.5)\ ps$
  - SiPM $4\text{x}4\text{mm}^2 40\mu m$ $M0$: $(59.2 \pm 0.4)\ ps$

…next steps

- Include the entire SiPM model in the model
- Implement the amplification stages in the model
- Run timing performance simulations
- Investigate the worsening of the SPTR with the increasing of the SPAD cell size
  - Focused SPTR

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FUTURE BUILT
ON KNOWLEDGE