FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

FBK SiPM roadmap for ultimate timing performance

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Fondazione Bruno Kessler
Custom Silicon Photomultipliers

Detector-grade clean-room, 6 inches, class 10 and 100

Silicon Photomultipliers account for a significant portion of the detectors fabricated here.

Private Research Foundation

- ~400 researchers in different fields, ranging from Microelectronics to Information Technology
- 50% funding from local government
- 50% self-funding rate
  - 25% from publicly funded research
  - 25% from collaboration with companies

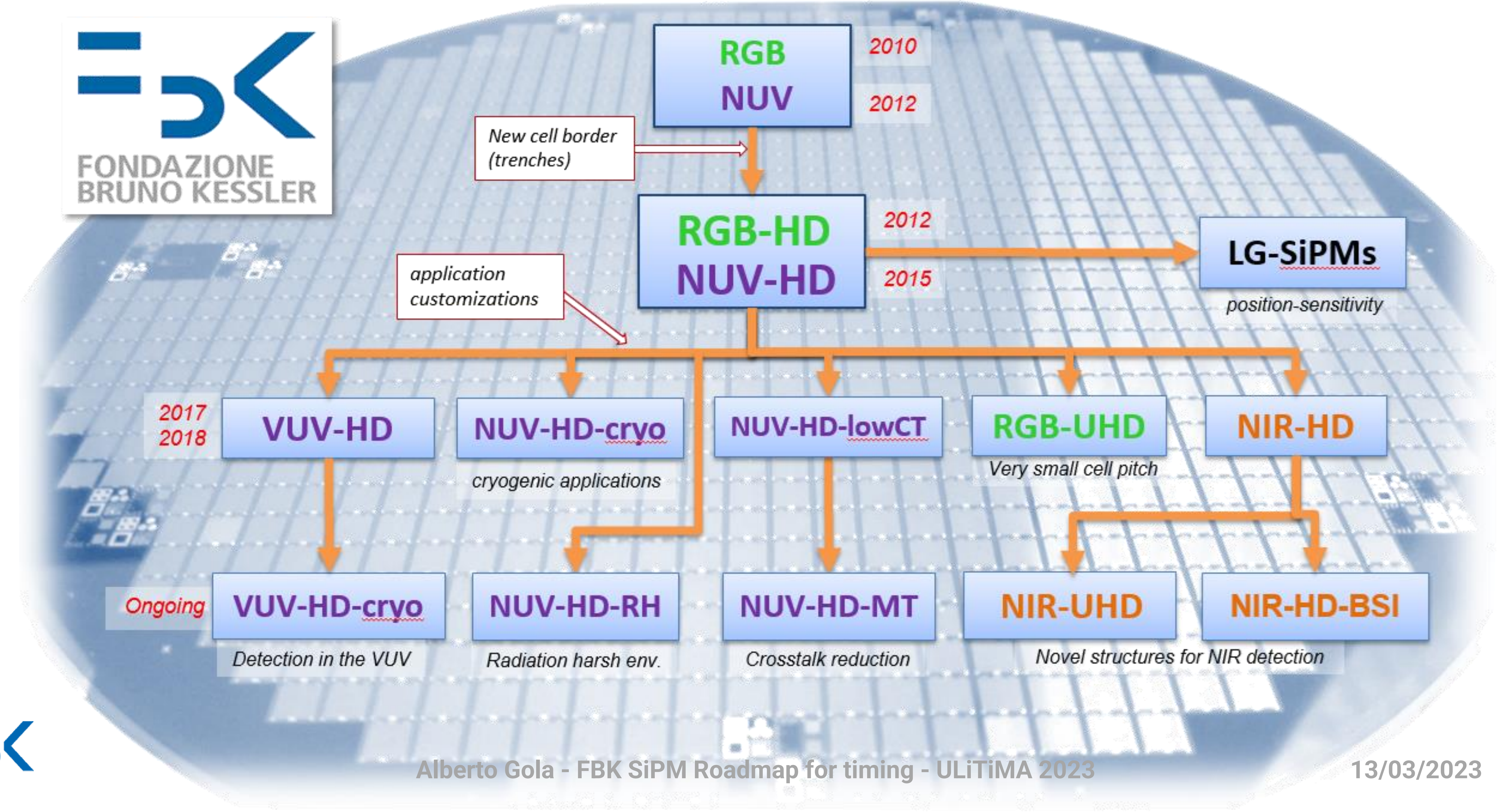
FBK is typically interested in R&D activities and collaborations to <u>improve and customize SiPM technology for specific applications</u>.

Large area productions can be carried out in FBK (up to ~5 sqm) or relying on external partners: success stories of technology transfers.

LFOUNDRY Solutions for great visions

BROADCOM

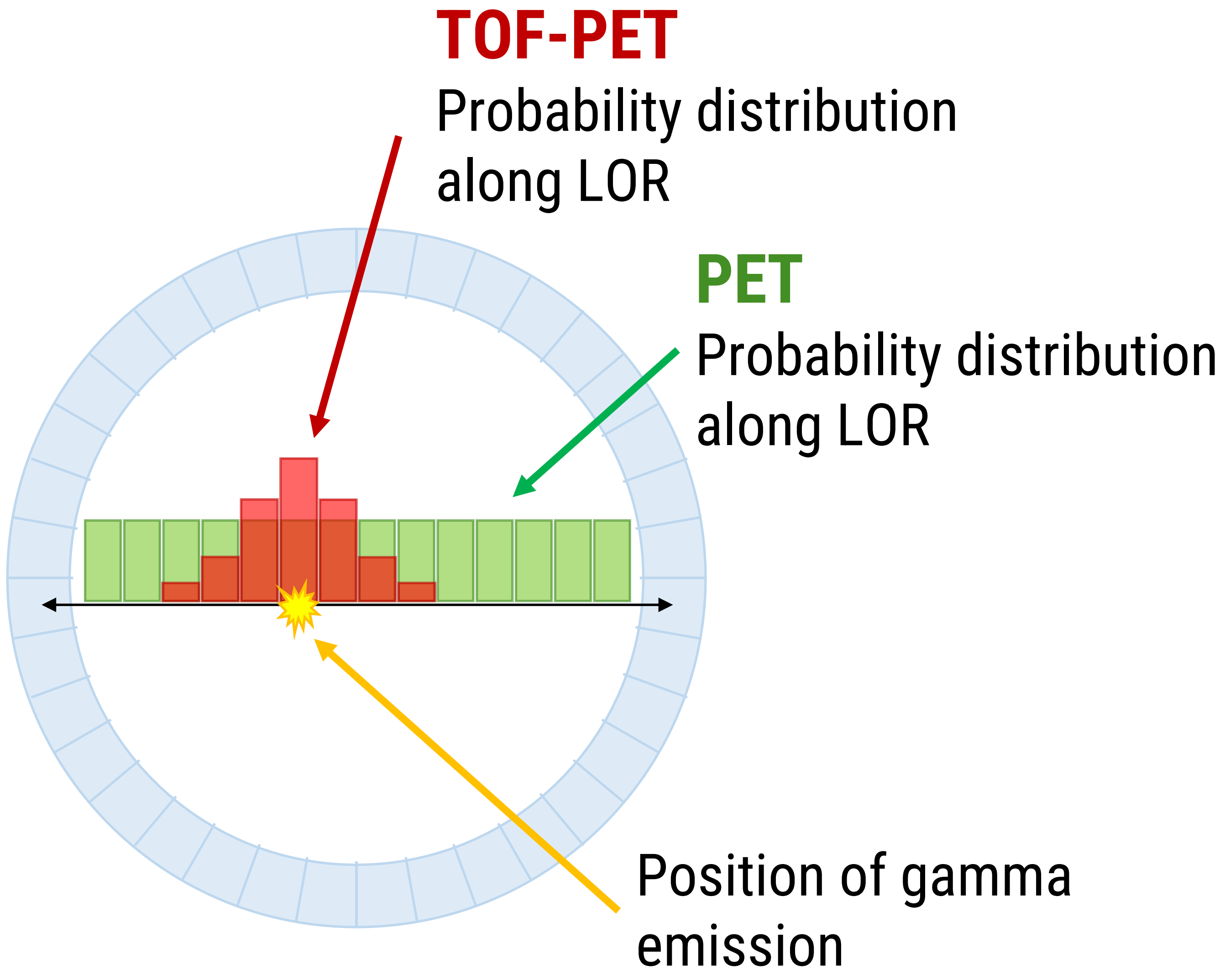
Fondazione Bruno Kessler
Custom SiPM technology roadmap



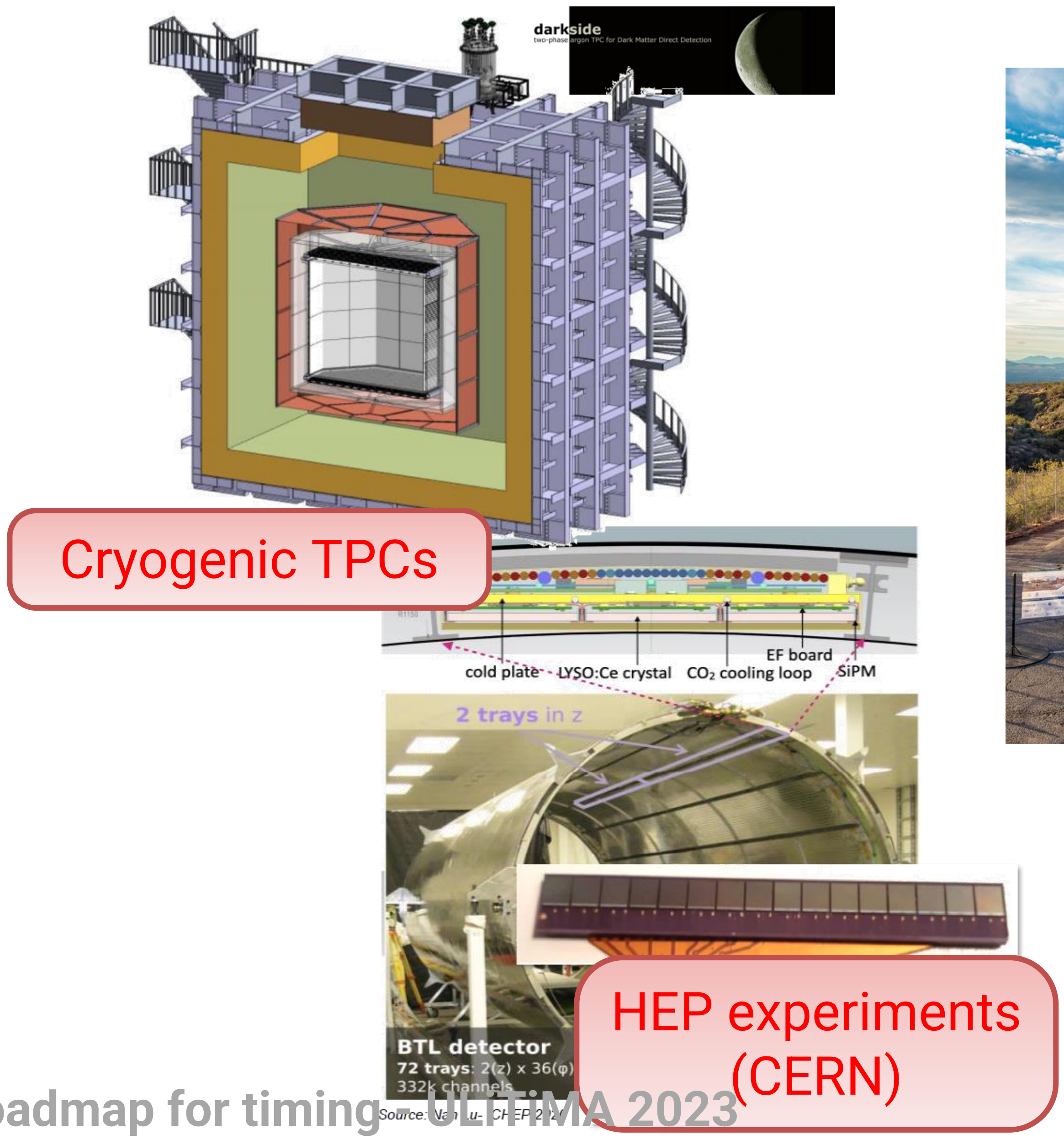
FBK SiPM technologies
Typical Applications

The traditional application of SiPMs is the ToF-PET. In addition, thanks to the *constant improvement of SiPM performance*, they are being evaluated in the *upgrade of several Big Physics Experiments*.

Positron Emission Tomography



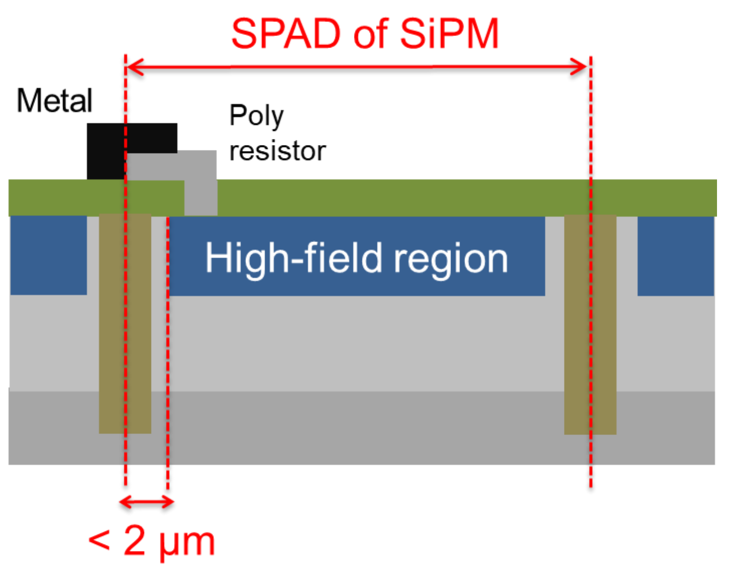
Big Physics Experiments

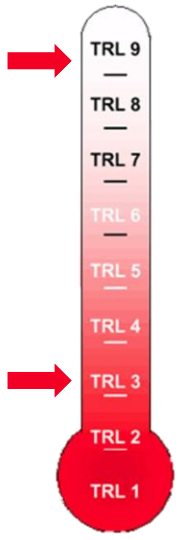


Examples of Big Physics experiments FBK is currently working on.

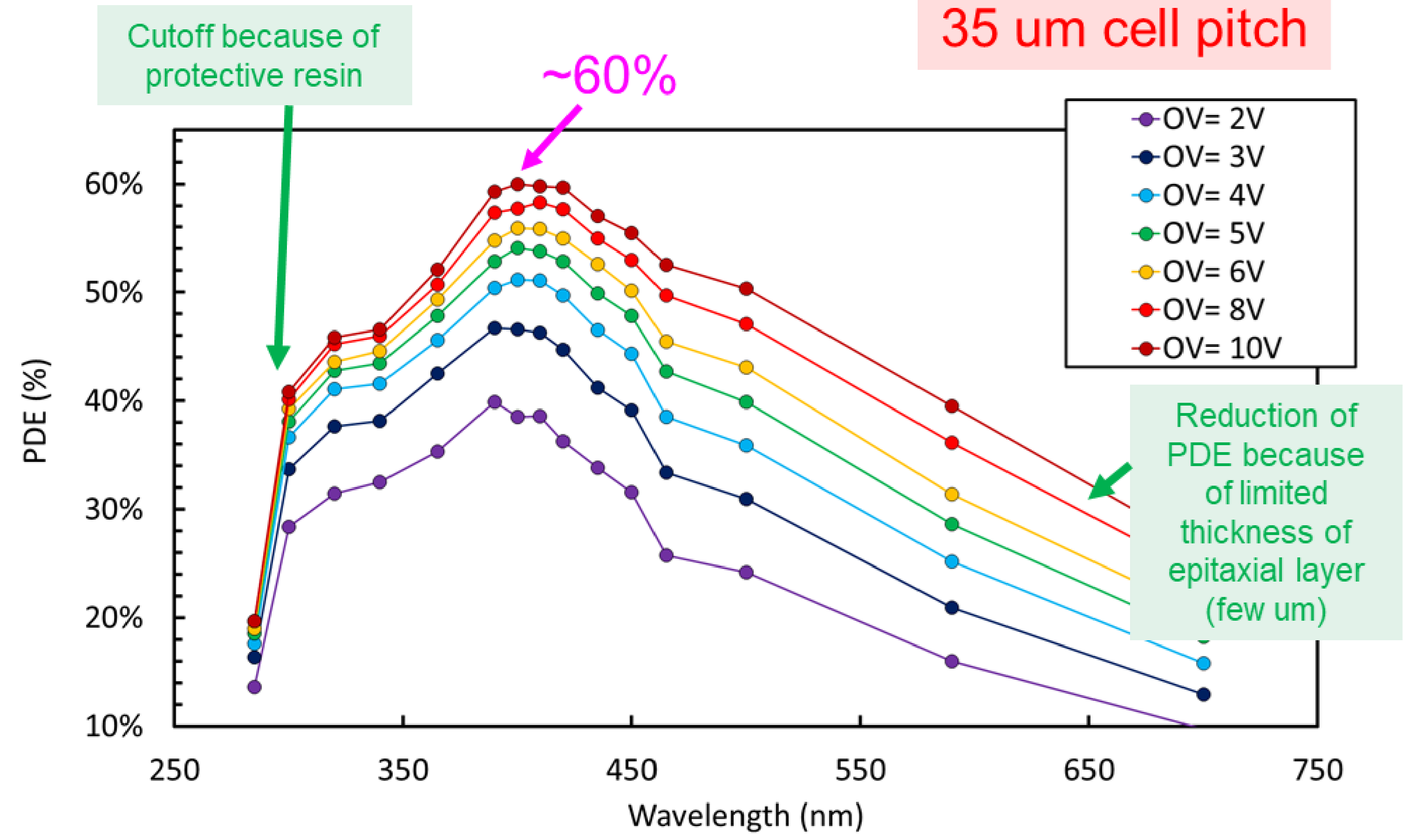
NUV-HD SiPM technology
Timing performance

NUV-HD SiPMs provide *state-of-the-art performance for single photon detection, timing and for scintillation light readout.*



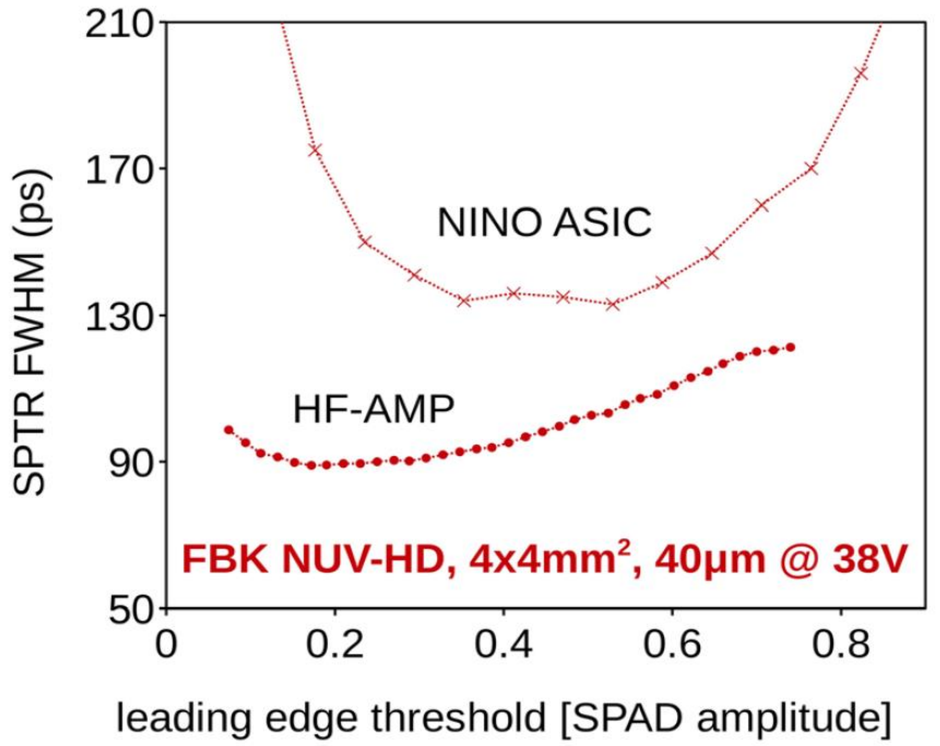


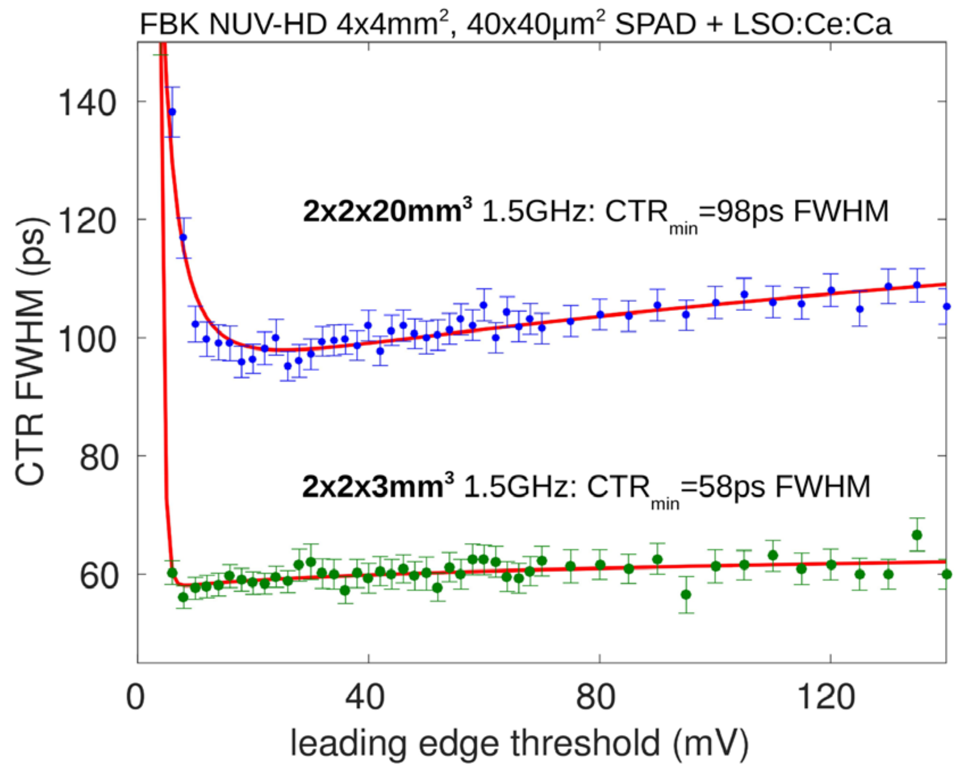
35 um cell pitch



Gola, A et al. (2019). "NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler." *Sensors*, *19*(2), 308.

Timing with High-frequency readout (FWHM)





World record timing resolution: Single Photon Time resolution (SPTR, left) and Coincidence Resolving Time (CRT) in LYSO readout (right).

Gundacker, Stefan, et al. "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET." *Physics in Medicine & Biology* 64.5 (2019): 055012.

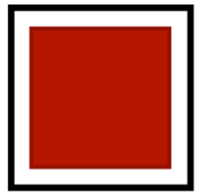
Ongoing R&Ds to optimize timing performance

Masking
Optimization of SPTR with masking: CHK-HD

CHK-HD SiPMs is a variant of the NUV-HD SiPMs built to *experiment solutions to improve SPTR and detection efficiency* in applications where it matters the most, such as Cherenkov light readout.

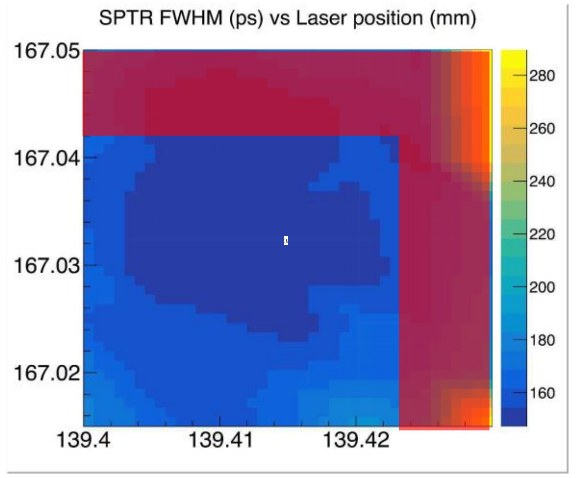
- ***Masking of outer regions of SPAD***: Improve signal peaking and mask areas of SPAD with worse SPTR
- Changes to the ***Electric field***: low-field + different spectral response

NM

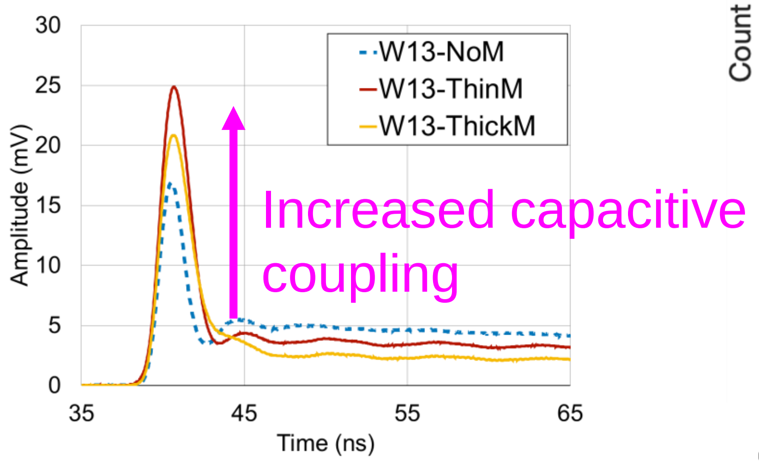


No mask (NoM)

Cell border | Active area | Metal mask



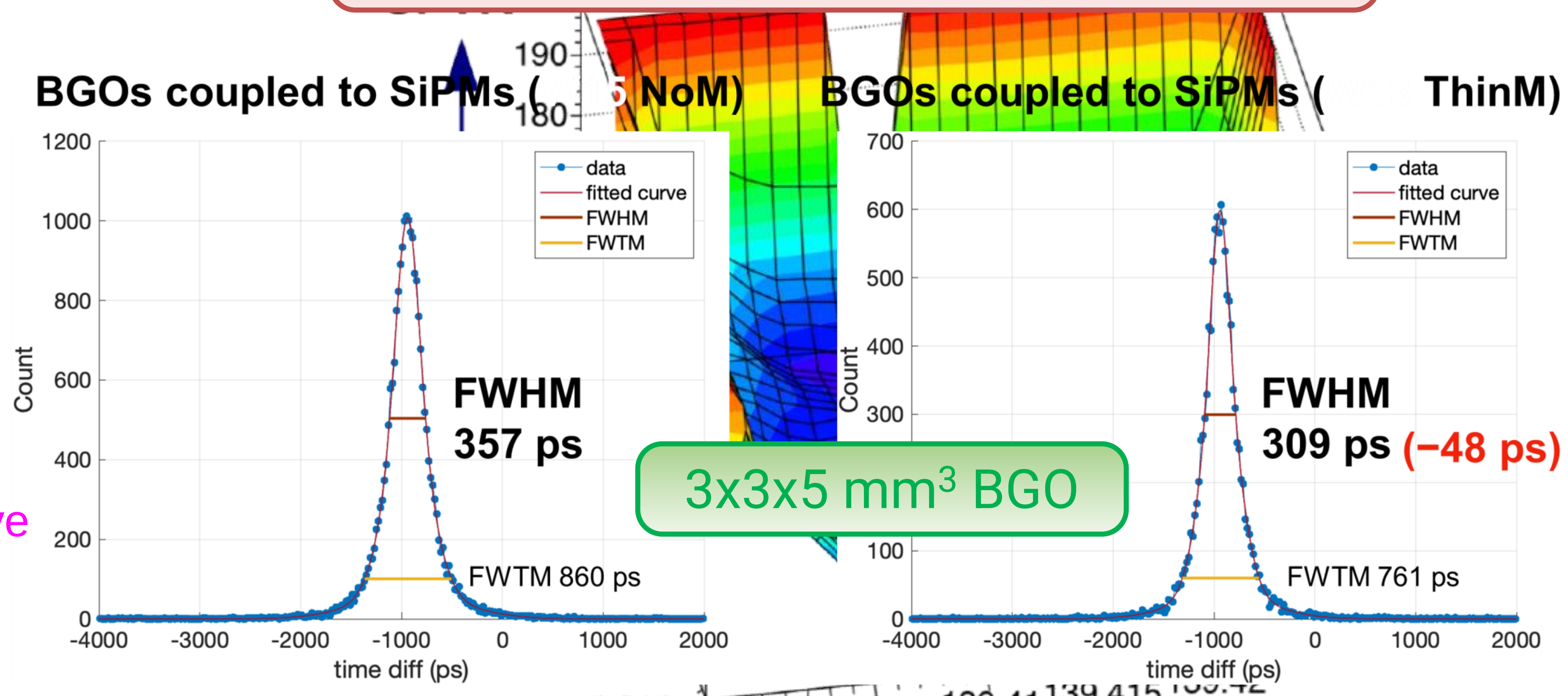
Masking of outer regions of the SPAD that have worse "local" SPTR.



Increase of fast component of single photoelectron signal in accordance with masking extension.

SPTR FWHM (ps) vs Laser position (mm)

Improvement of 50 ps with CHK-HD



CRT measured at UCDavis using 3x3 mm² CHK-HD SiPMs with 40 um cell, reading out a 3x3x5 mm³ BGO crystal.

Measured with standard FBK transimpedance amplifier.

Presented by Sun Il Kwon at NSS/MIC 2021

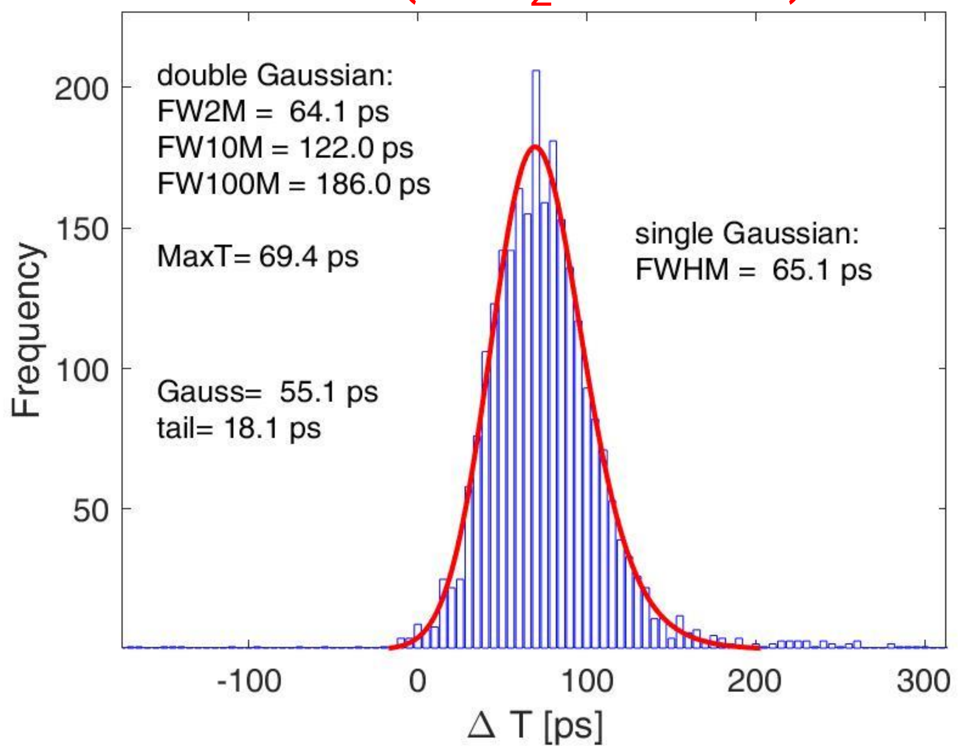
Nemallapudi, M. V., et al. "Single photon time resolution of state of the art SiPMs." *Journal of Instrumentation* 11.10 (2016): P10016.

Masking
CHK-HD measurements with upgraded amplifiers

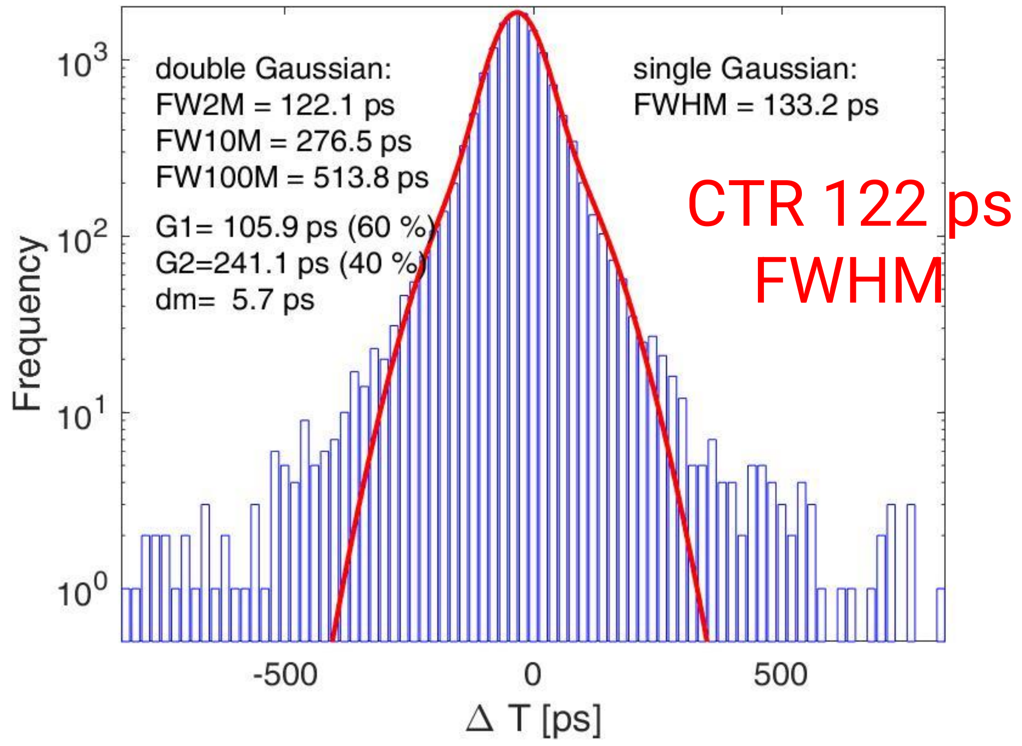
SPTR performance is *highly affected by the front-end electronic performance*: studies with different readout electronics.
3x3 mm^2 CHK-HD SiPMs, 40 um cell.

High-frequency readout

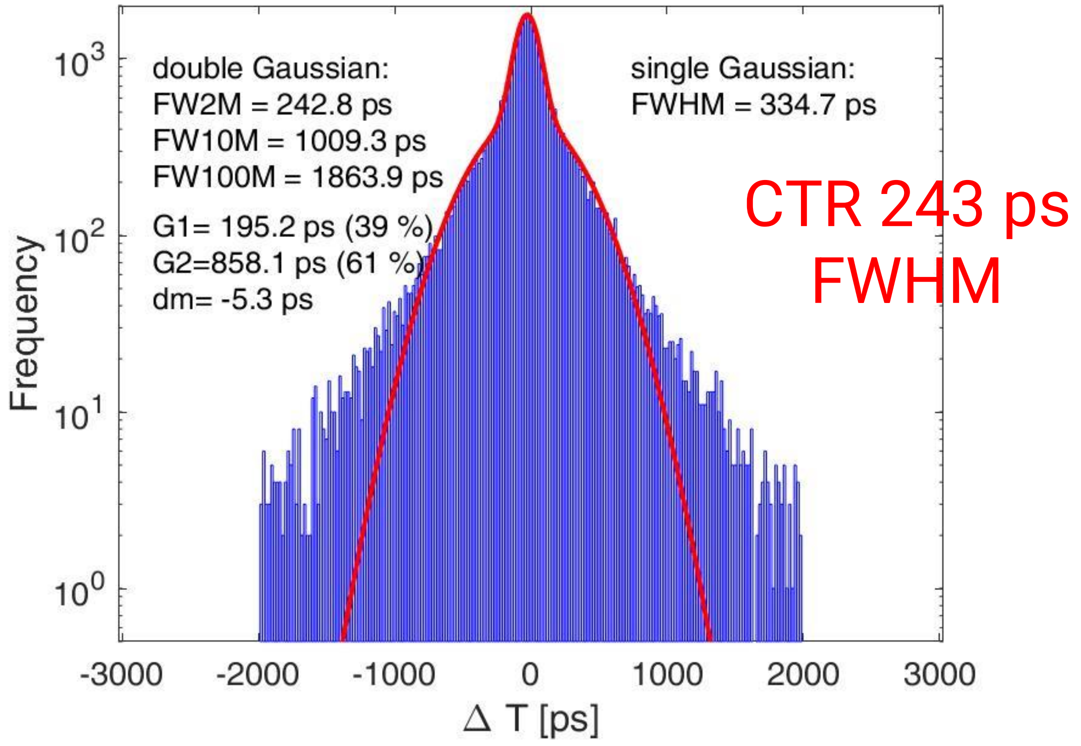
SPTR (PbF_2 method)



2x2x3 mm^3 BGO (Epic)



3x3x20 mm^3 BGO (Epic)



$$SPTR_{intrinsic} = \sqrt{65^2 - 47^2 - 21^2} = 39.6\ ps$$

Measurements by S. Gundacker, presented at FTMI 2022 workshop

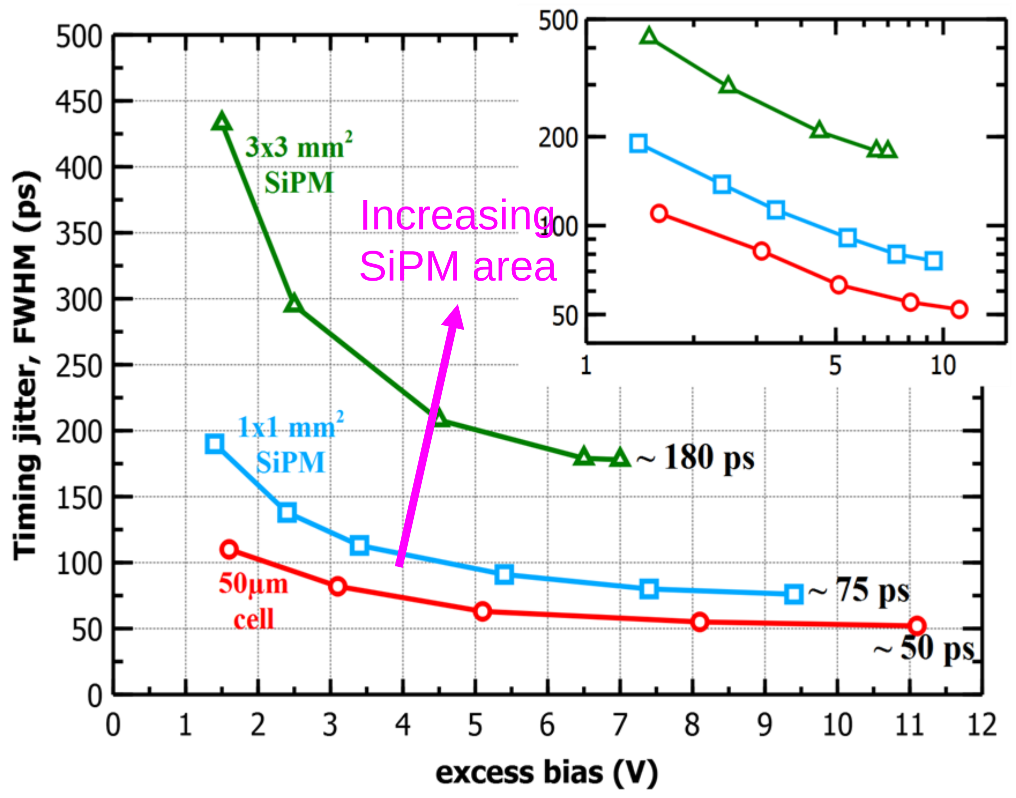
Effect of electronic noise on SPTR is deconvolved.

Segmentation
Effect of SiPM area on SPTR

SPTR and CRT performance is degraded when reading out SiPMs with *large areas*.

A possible solution can be the *segmentation of the active area into small pixels*, with separate readout, followed by signal summation or combination of time pick-off information.

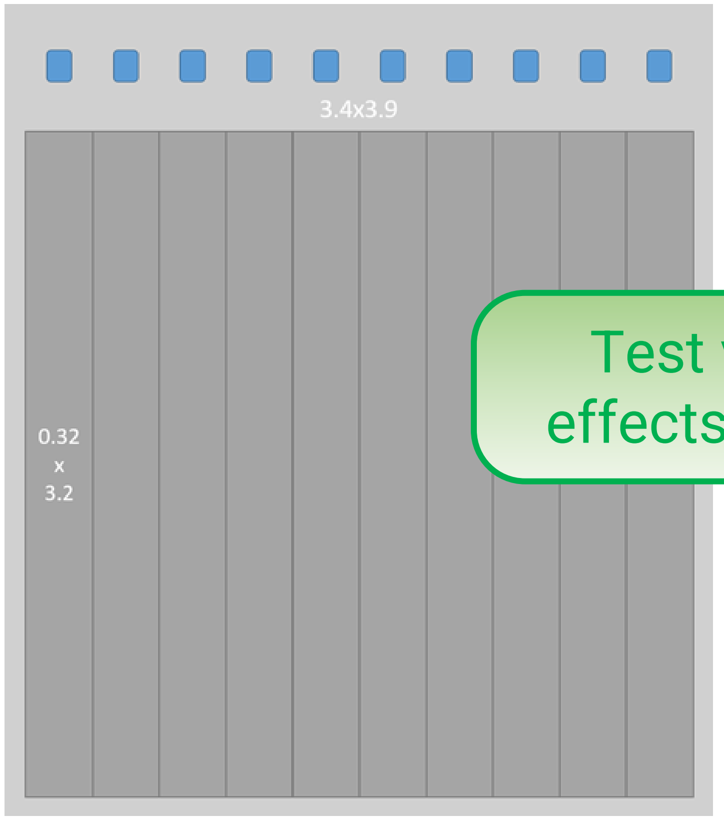
SPTR with standard FBK amplifier



SPTR vs. excess bias for different SiPM sizes, *with traditional amplifier*.

Strip SiPMs

10 strips
0.32 x 3.2 mm²
each, no dead border between strips



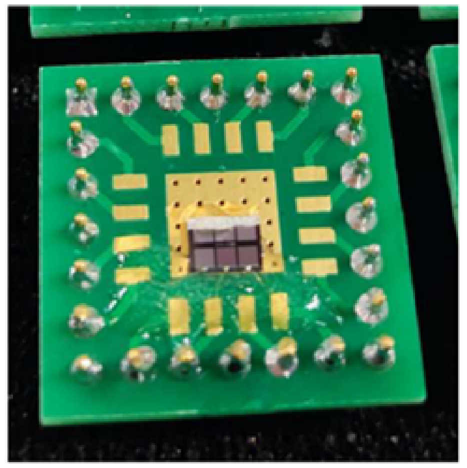
Test vehicle to study effects of segmentation

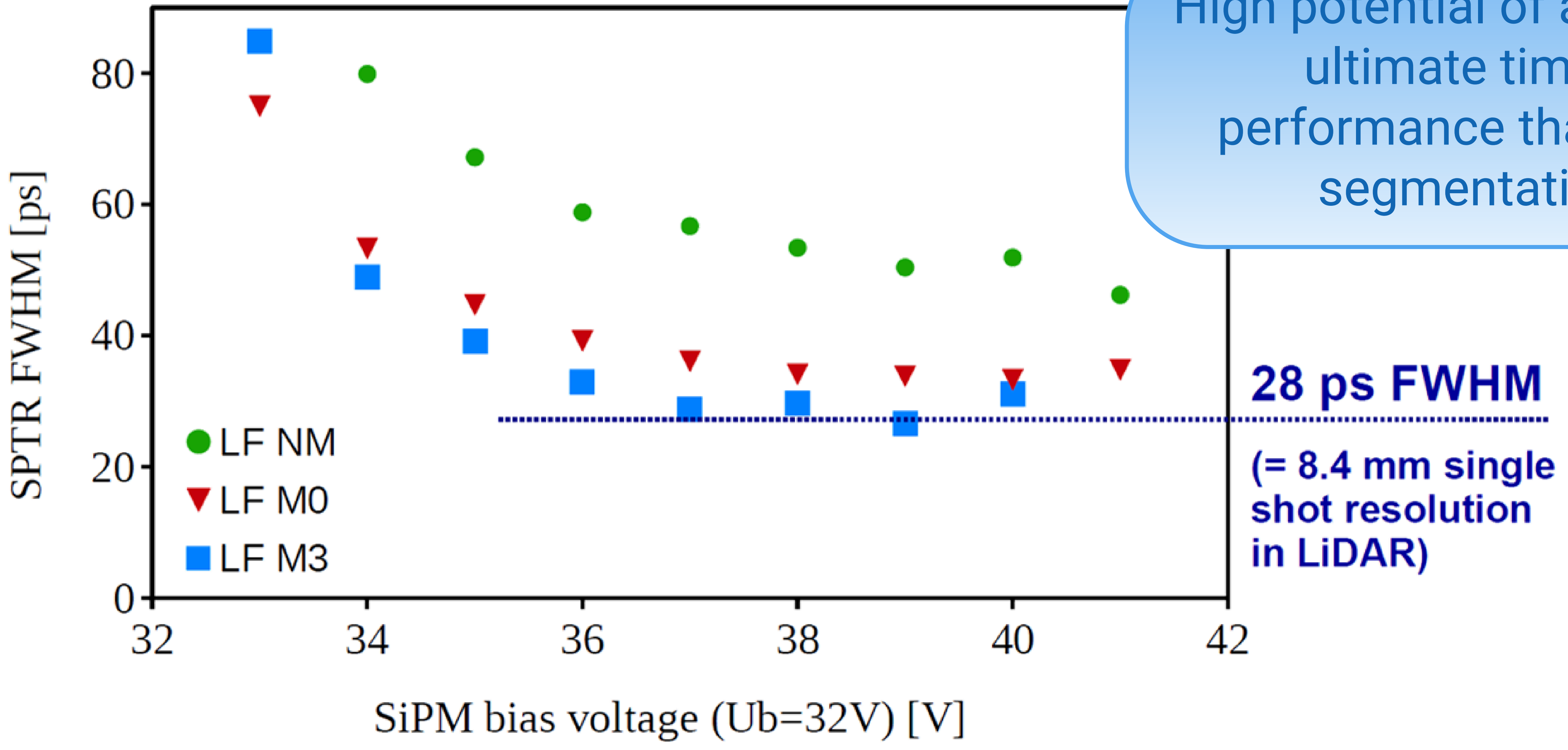
Example of segmented SiPM layout: a 3x3 mm2 active area is divided in 10 0.3x3 mm2 strip-SiPMs.

Acerbi, Fabio, et al. "Characterization of single-photon time resolution: from single SPAD to silicon photomultiplier." *IEEE Transactions on Nuclear Science* 61.5 (2014): 2678-2686.

Segmentation
SPTR of a 1x1 mm² CHK-HD with masking

A *1x1 mm² CHK-HD, with masking,* was measured at Aachen (S. Gundacker) with *high-frequency readout*, achieving a *remarkable Single Photon Time Resolution of 28 ps FWHM*.





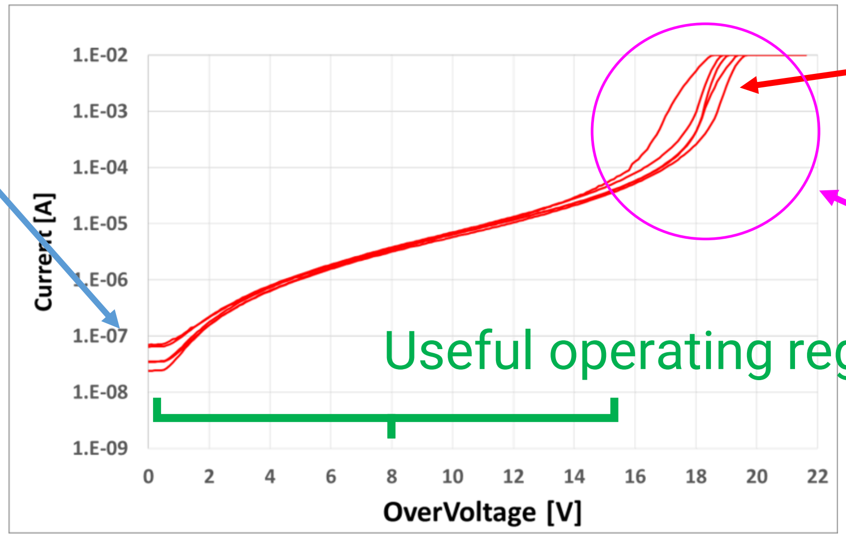
High potential of achieving ultimate timing performance thanks to segmentation

Not corrected for electronic noise

Optical Crosstalk
Worsening of the performance of the detection system

Optical Crosstalk worsens the performance of the detection system both by *limiting the maximum excess bias* that can be applied to the SiPM and by *worsening the photon time of arrival statistics*.

Limiting the maximum excess bias



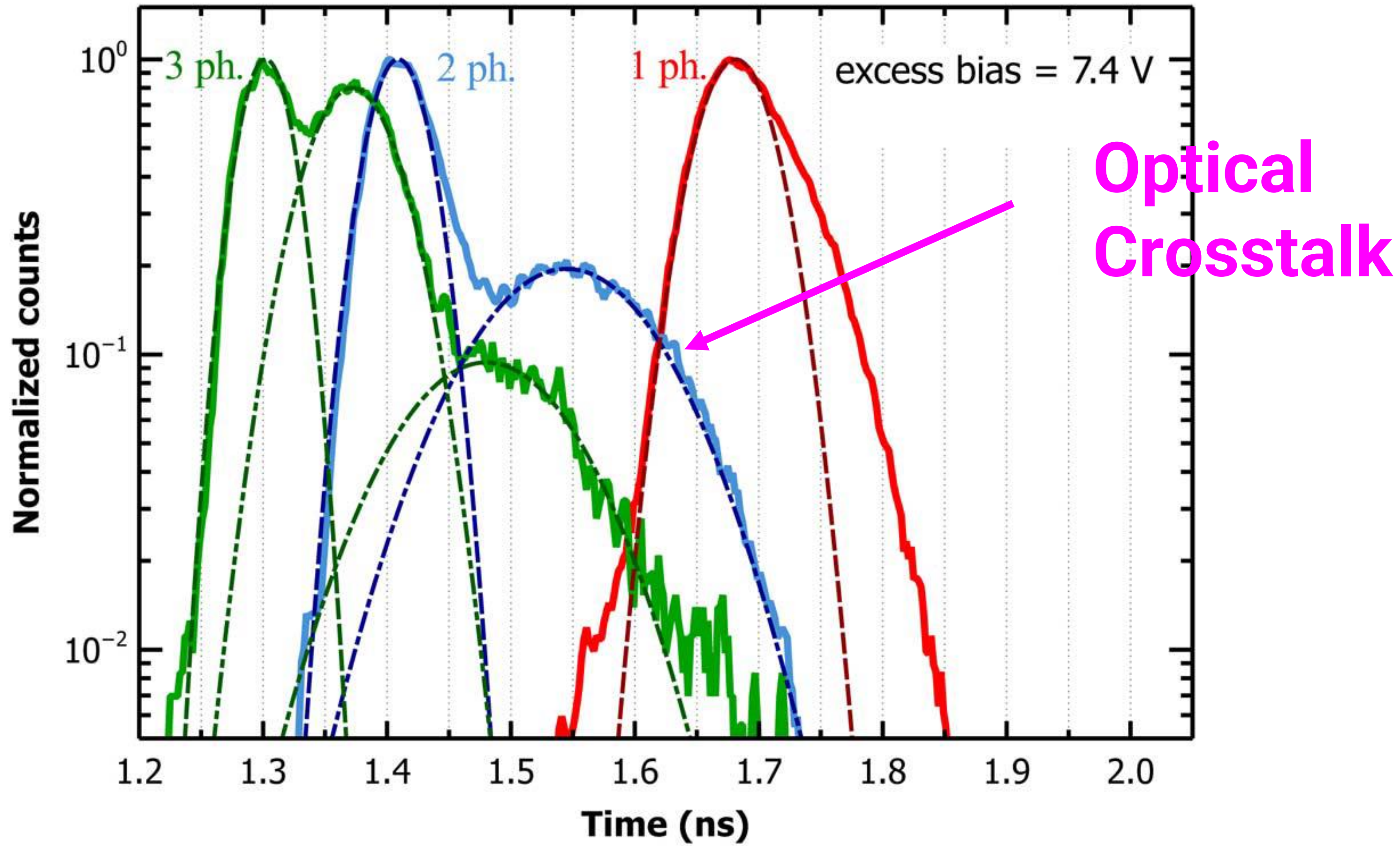
Above a certain over-voltage the number of dark counts and, thus, the reverse current diverge.

- *Lower PDE, Gain.*
- *Worse SPTR*

$$ECF \cong \frac{1}{1 - P_{CN}}$$

Geometric series approximation of the ***Excess Charge Factor***.

Worsening of the Few Photons Time Resolution

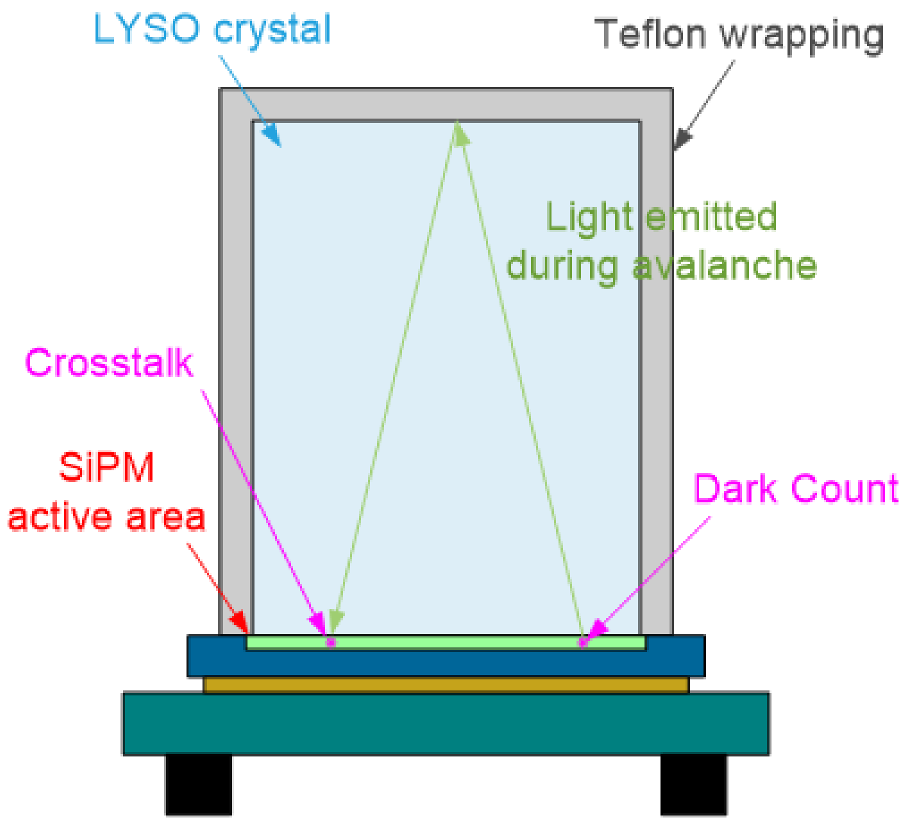


Few-photon time resolution measured with Leading-edge discriminator
Additional peaks are most likely generated by (delayed) correlated noise.

Acerbi, Fabio, et al. "Characterization of single-photon time resolution: from single SPAD to silicon photomultiplier." *IEEE Transactions on Nuclear Science* 61.5 (2014): 2678-2686.

Optical crosstalk
External Crosstalk

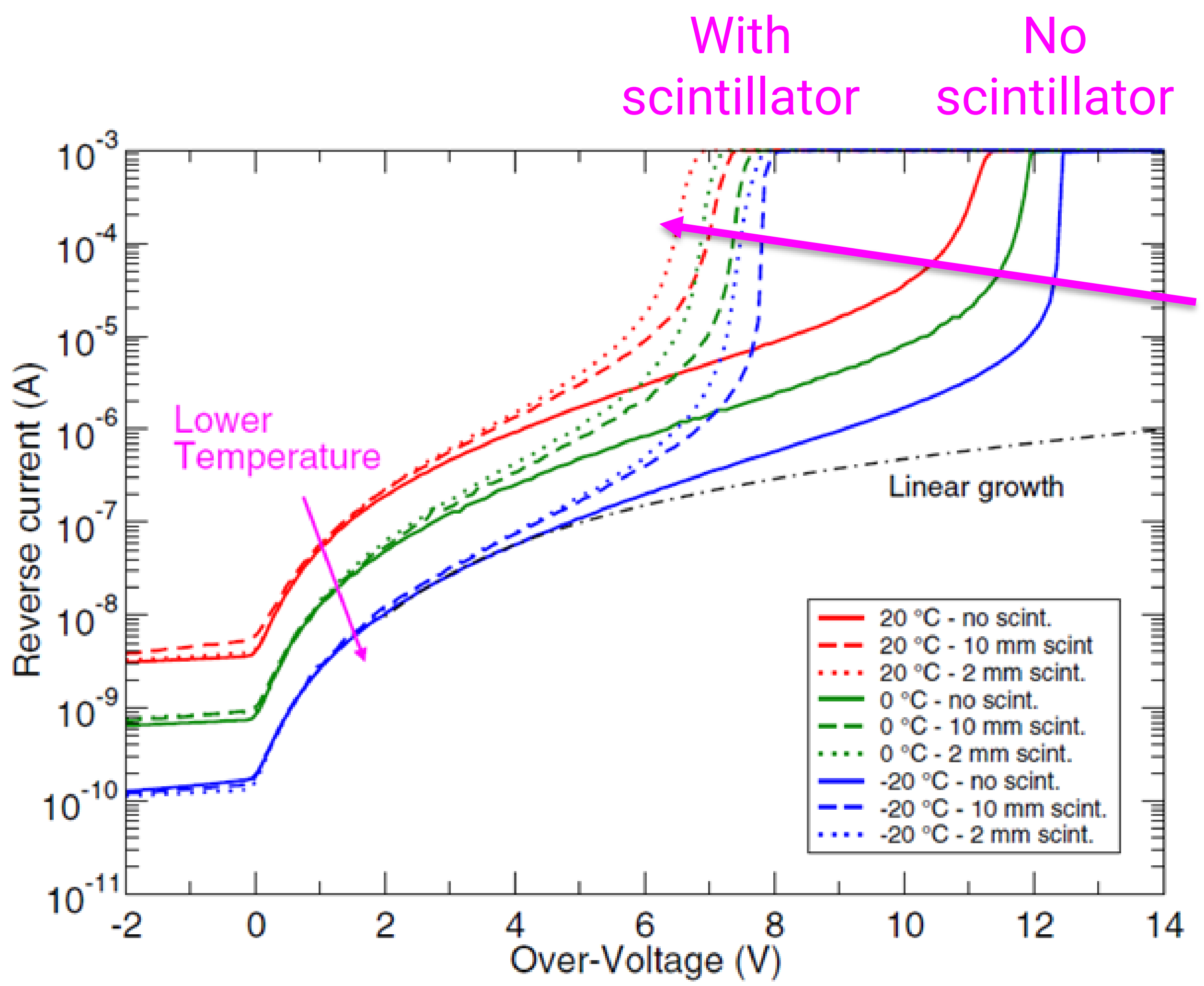
Optical crosstalk probability is enhanced by the presence of the scintillator: external crosstalk.



Mechanism of optical crosstalk probability enhancement because of the scintillator.

$$ECF \cong \frac{1}{1 - P_{CN}}$$

Geometric series approximation of the ***Excess Charge Factor***.



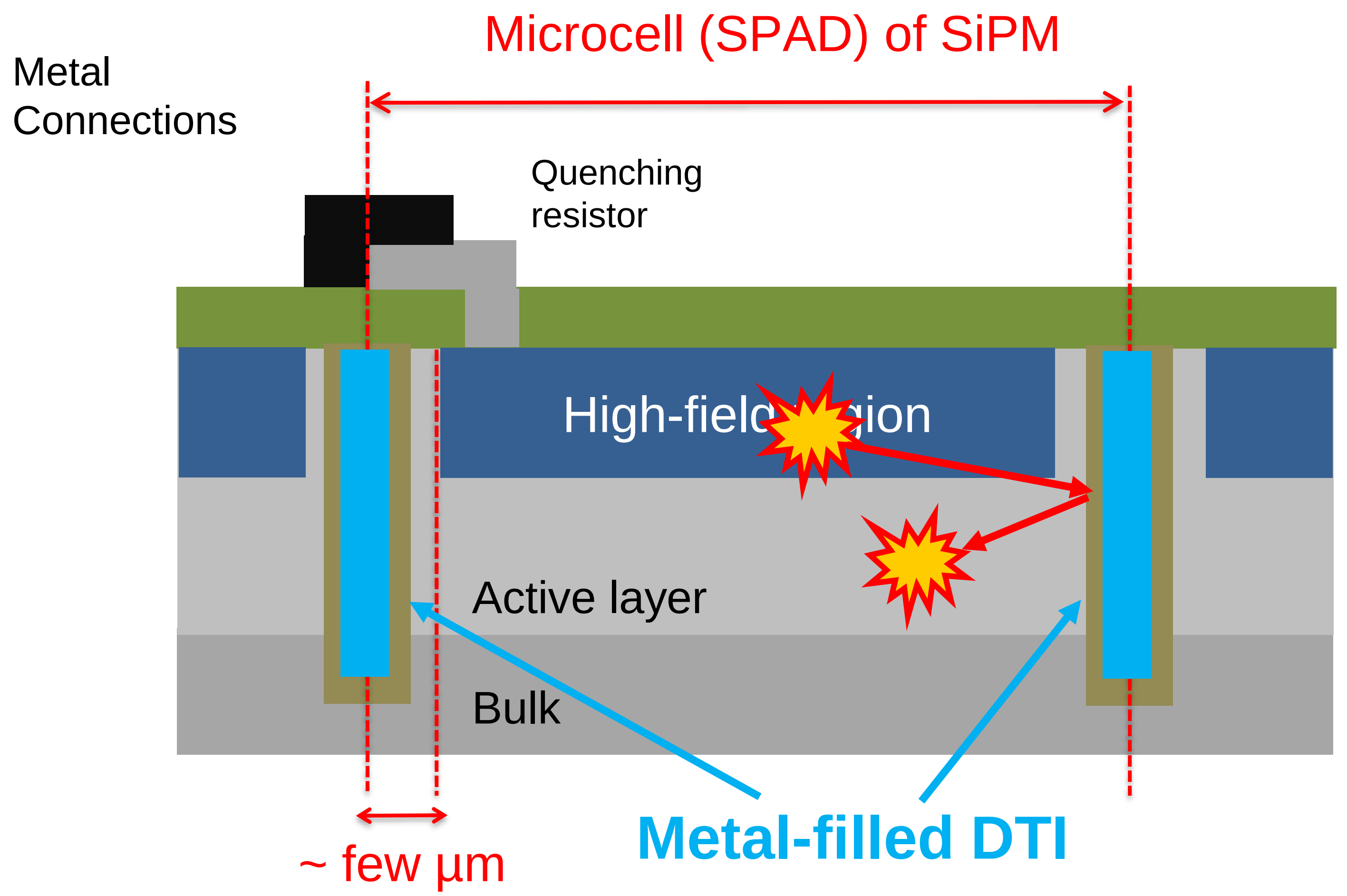
Comparison of SiPM IV with different scintillator sizes placed on top of them, at different temperatures.

Gola, Alberto, et al. "SiPM optical crosstalk amplification due to scintillator crystal: effects on timing performance." *Physics in Medicine & Biology* 59.13 (2014): 3615.

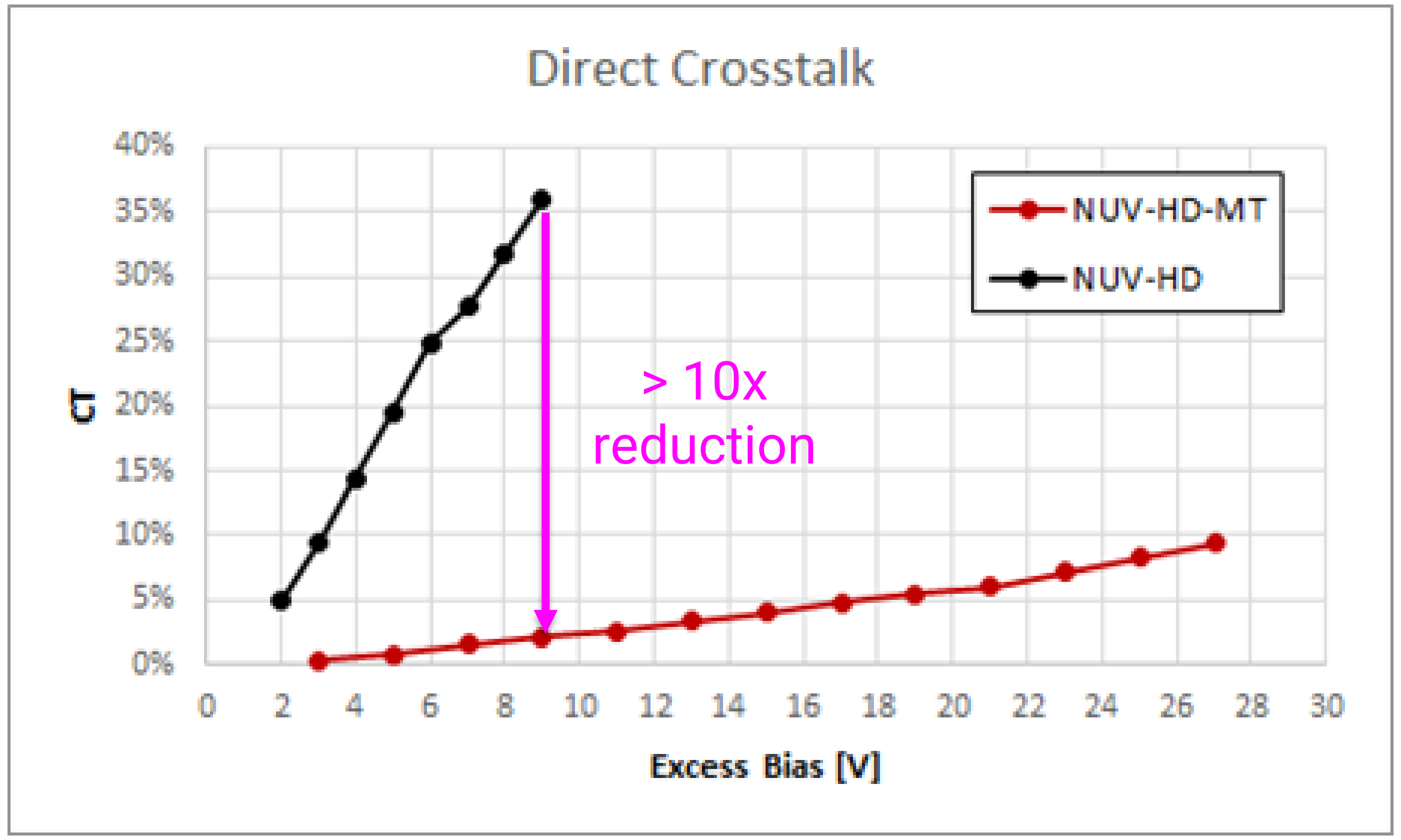
Reduction of optical crosstalk
NUV-HD-MT development

Starting from the NUV-HD technology, FBK and Broadcom jointly developed the NUV-HD-MT technology, adding *metal-filled DTI isolation to strongly suppress optical crosstalk*.

Other changes: low electric field variant, layout optimized for timing.



Conceptual cross-section of a NUV-HD-MT microcell, with the addition of metal-filled Deep Trench Isolation.

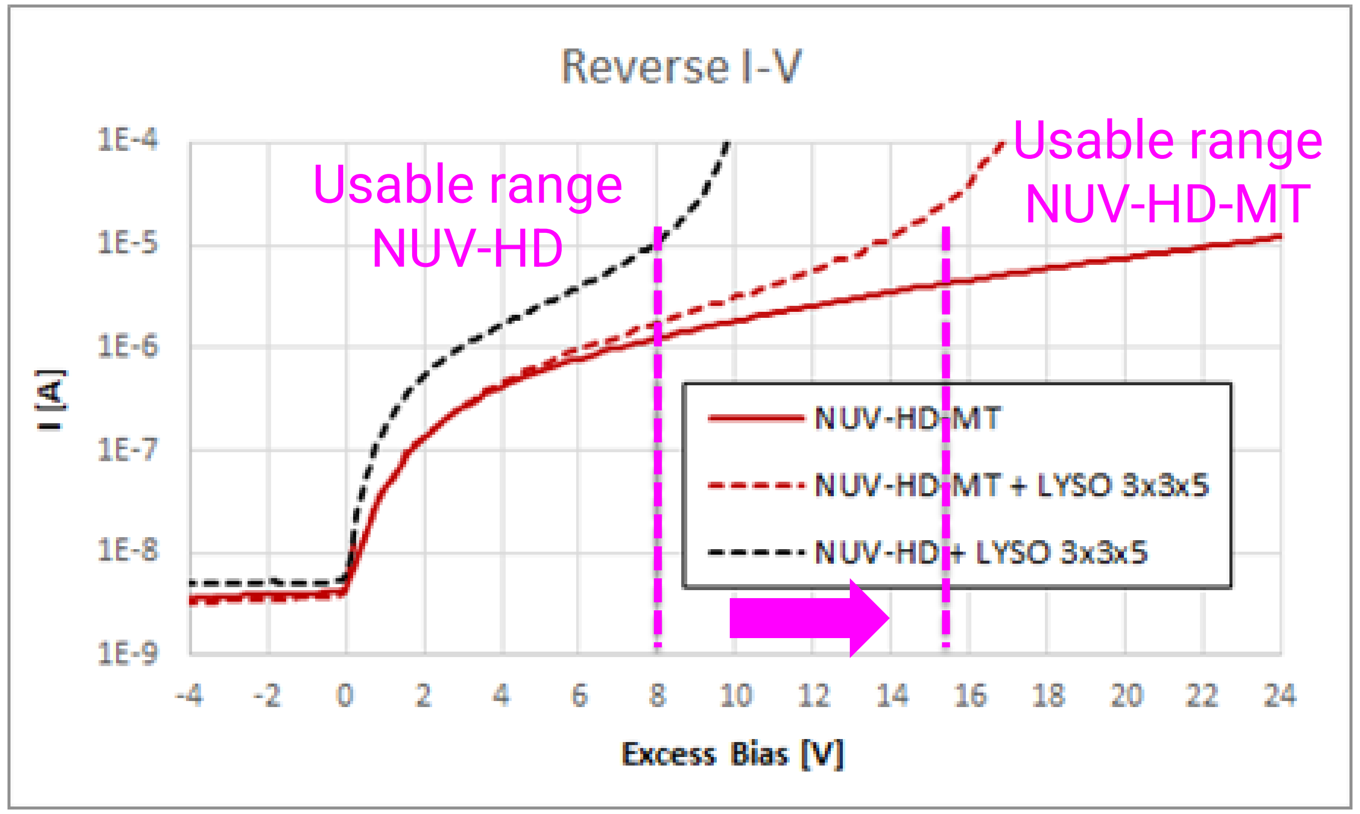


Reduction of optical crosstalk probability in NUV-HD-MT, compared to the “standard” NUV-HD. Measurement without encapsulation resin, i.e. *only considering internal crosstalk probability*.

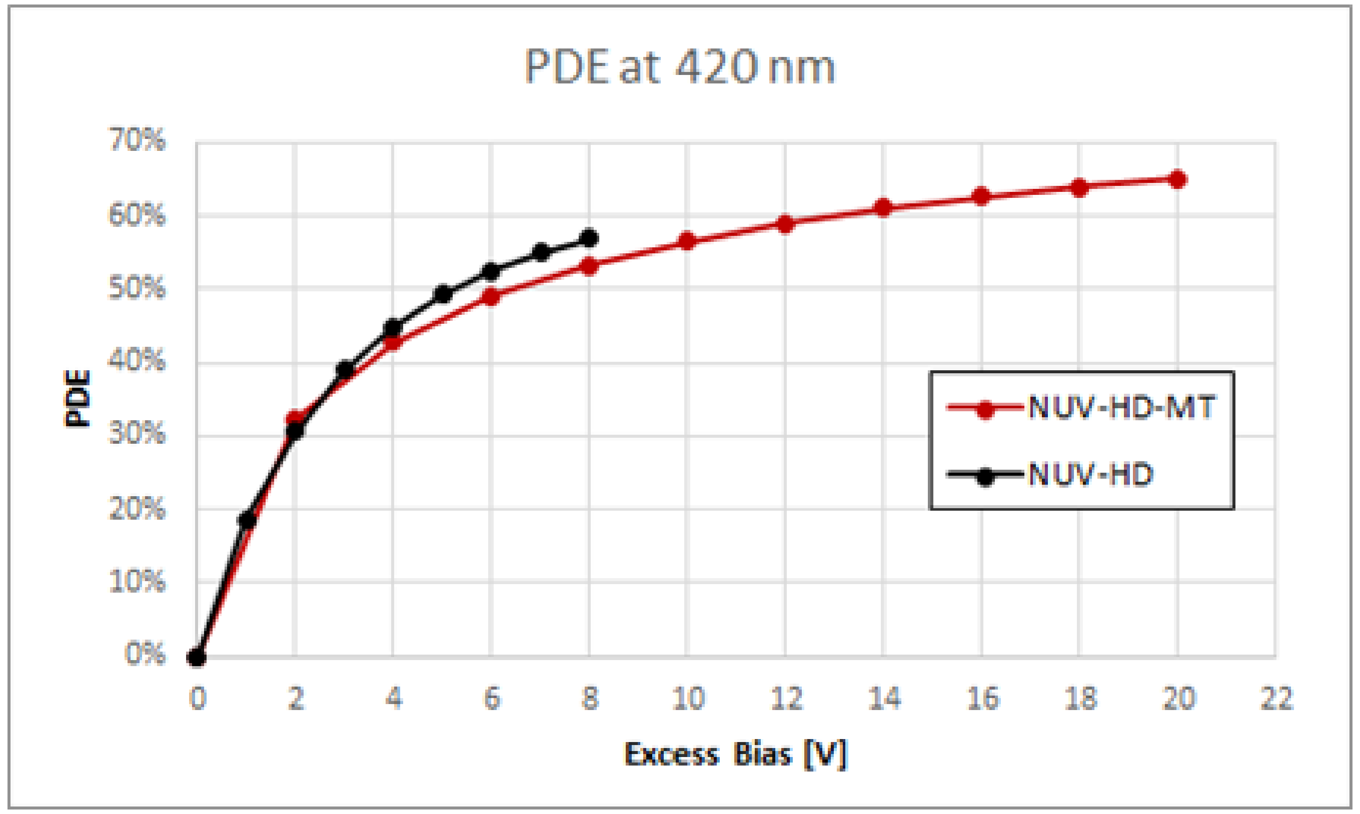
Reduction of optical crosstalk
NUV-HD-MT bias range

Reduction of optical crosstalk probability *increases maximum usable excess bias of SiPM*, also with the scintillator on top of the SiPM.

Increase of excess bias *more than compensates the slight reduction of Fill Factor* caused by the addition of metal inside the DTI.



Reverse IV measured on a 4x4 mm^2 NUV-HD-MT SiPM with 45 um cell pitch under different conditions.

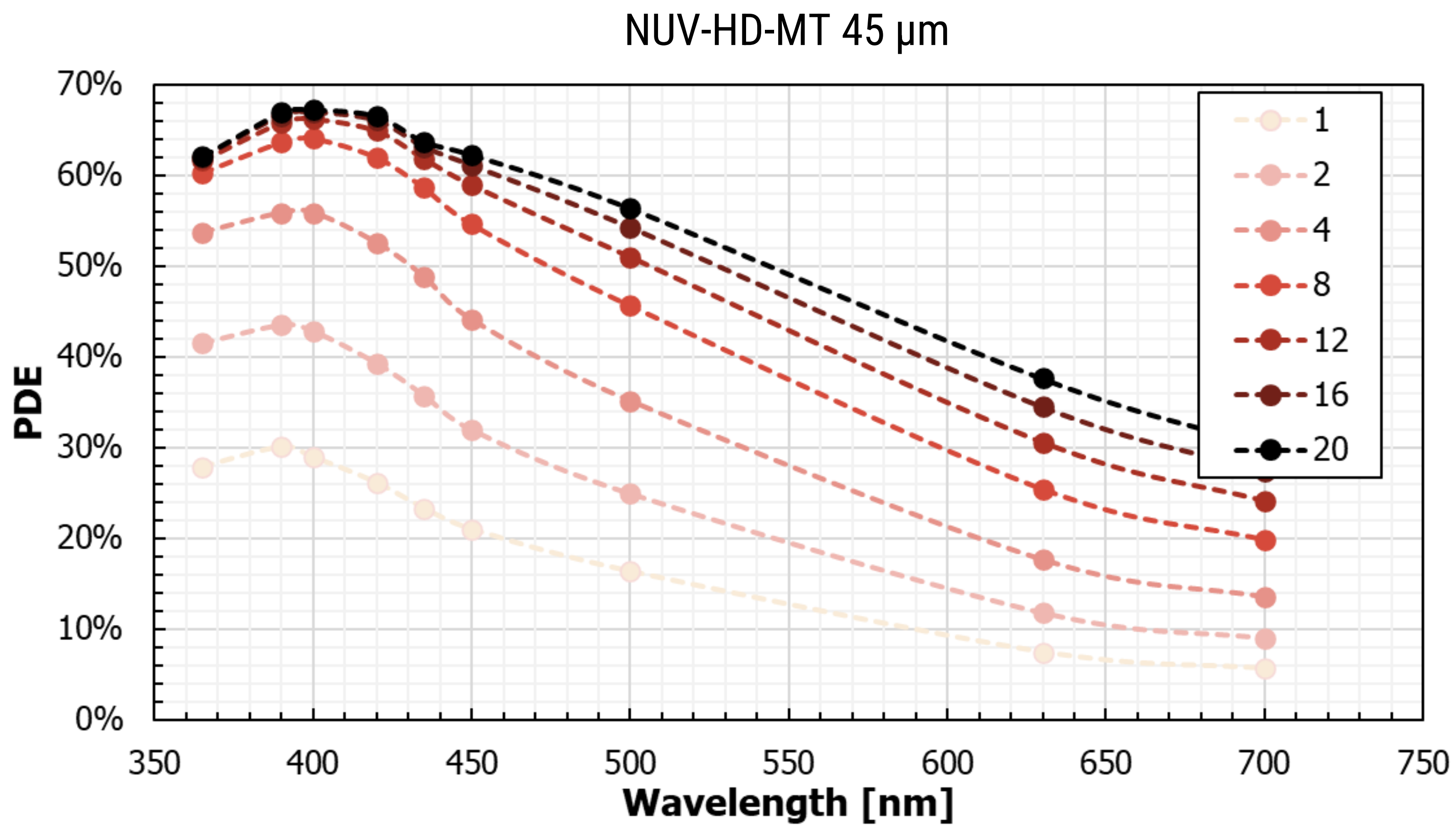


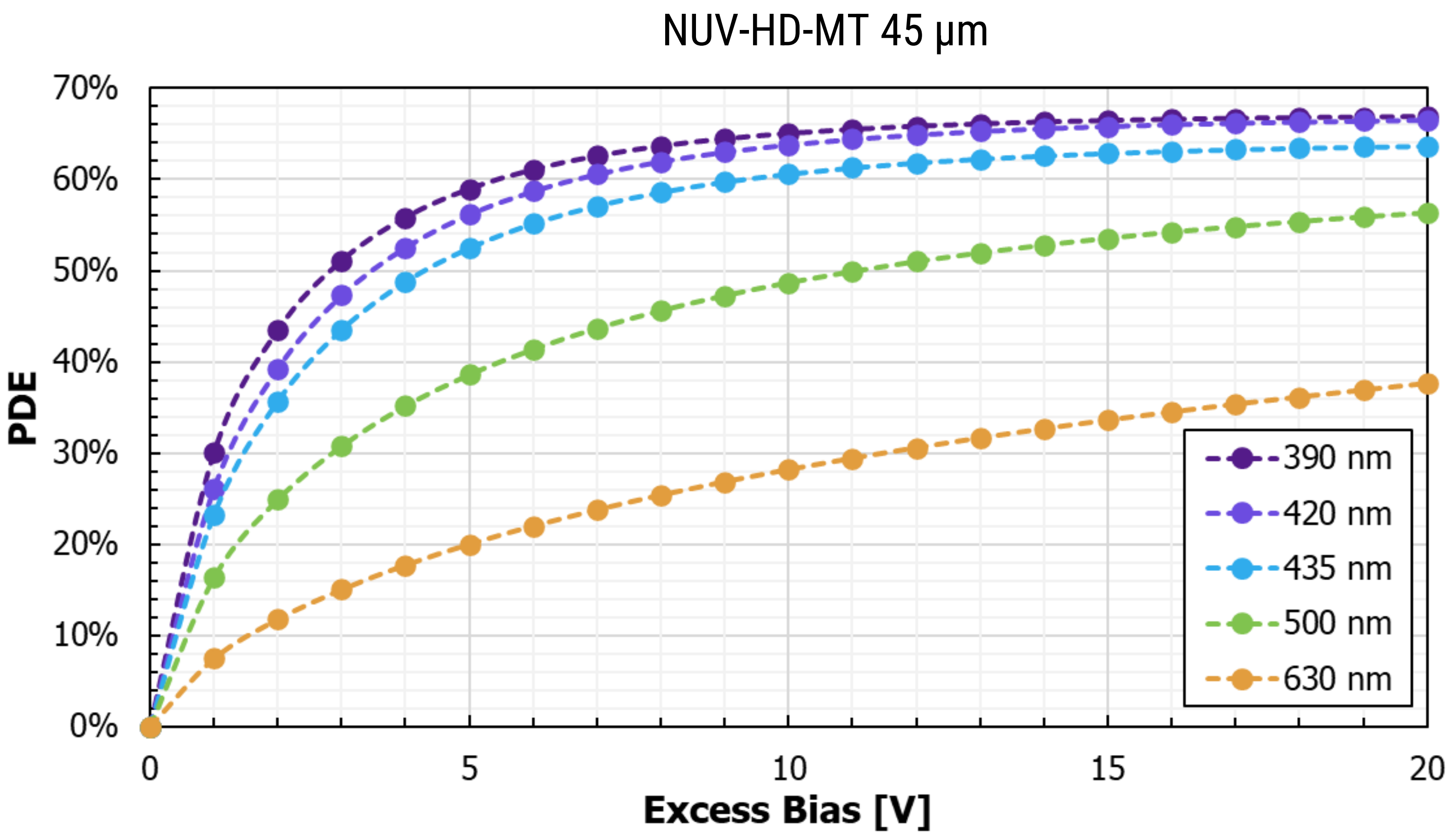
PDE at 420 nm measured on a NUV-HD-MT SiPM with 45 um cell size.

Reduction of optical crosstalk
NUV-HD-MT PDE

NUV-HD-MT is *based on a p-on-n junction*, thus peak PDE is around 390 – 420 nm.

Thanks to the very high maximum excess bias, *also PDE in the red (avalanche triggering by holes) approaches saturation*.

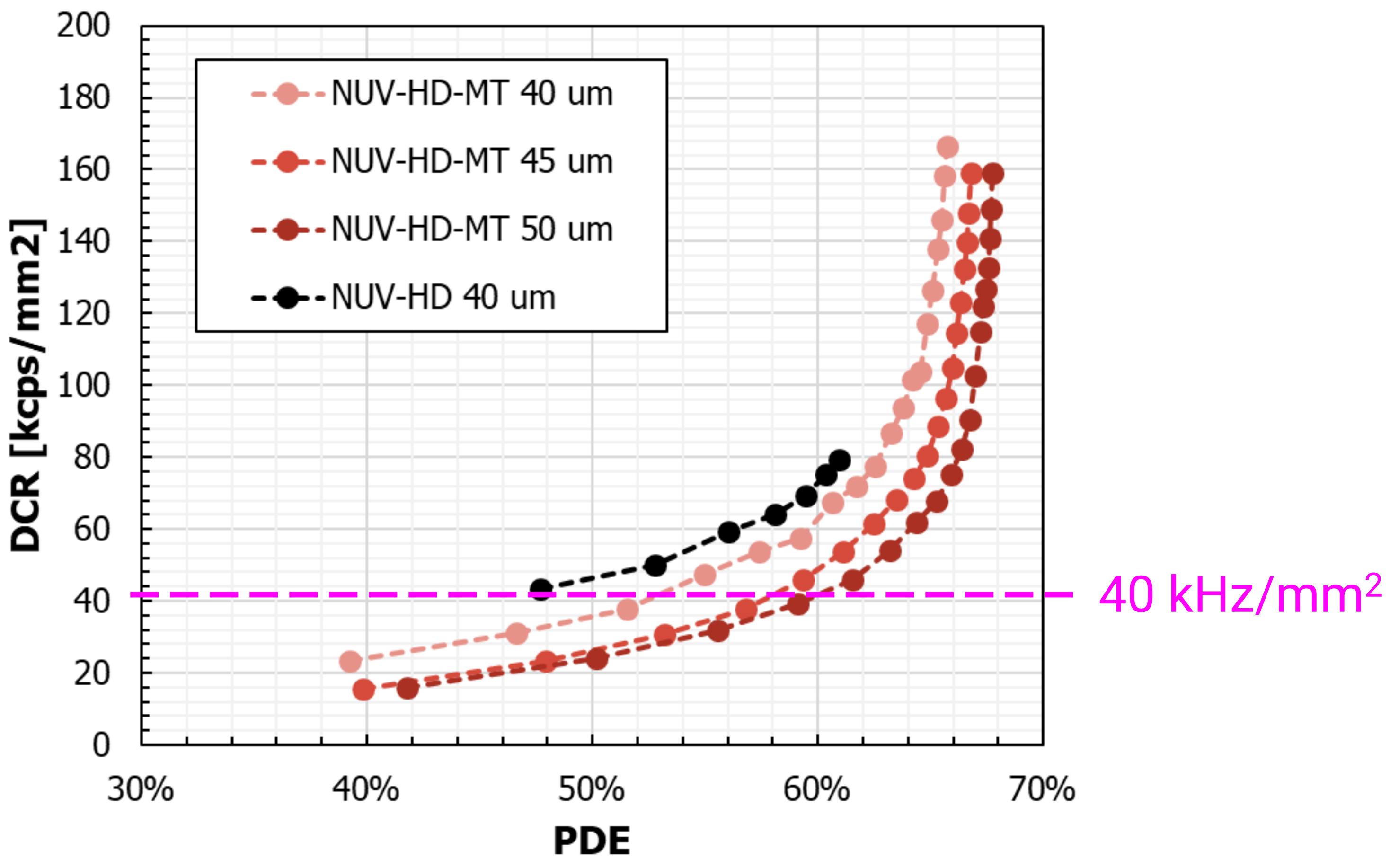




Reduction of optical crosstalk
NUV-HD-MT electro optical performance

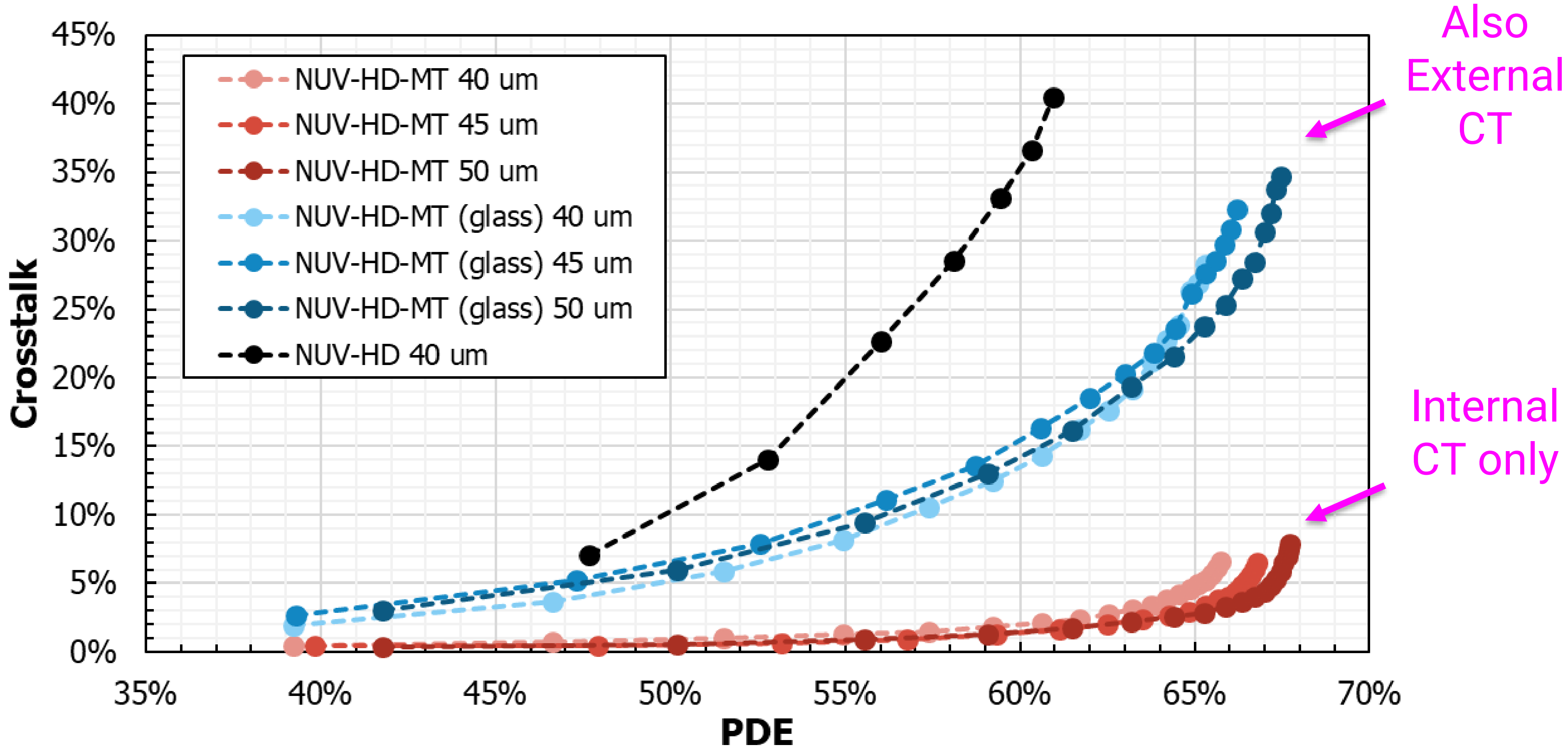
NUV-HD-MT *nuisance parameters are better represented and compared as a function of the PDE*.

DCR vs. PDE



DCR vs. peak PDE (measured at 420 nm) for different cell sizes of the NUV-HD-MT technology.

Direct Optical CT vs. PDE



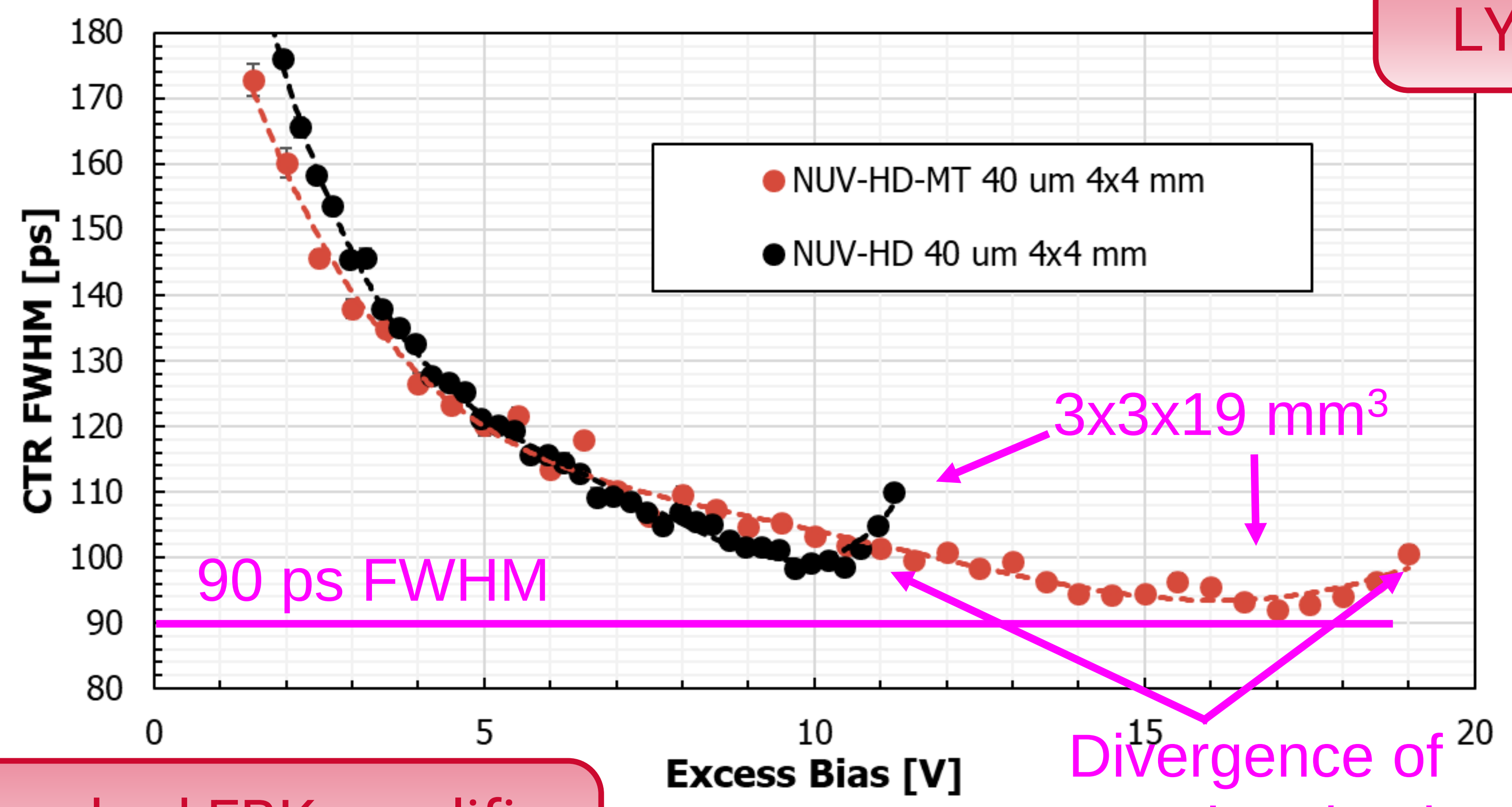
DiCT vs. peak PDE (measured at 420 nm) for different cell sizes of the NUV-HD-MT technology, with and without protective glass on top of the SiPM (used for TSV)

NUV-HD-MT
CTR with LYSO:Ce,Ca

The increase of usable excess bias with scintillator allows *better exploiting the maximum PDE* of the detector and *achieving higher Gain* and *lower SPTR*.

NUV-HD vs. NUV-HD-MT
4x4 mm^2

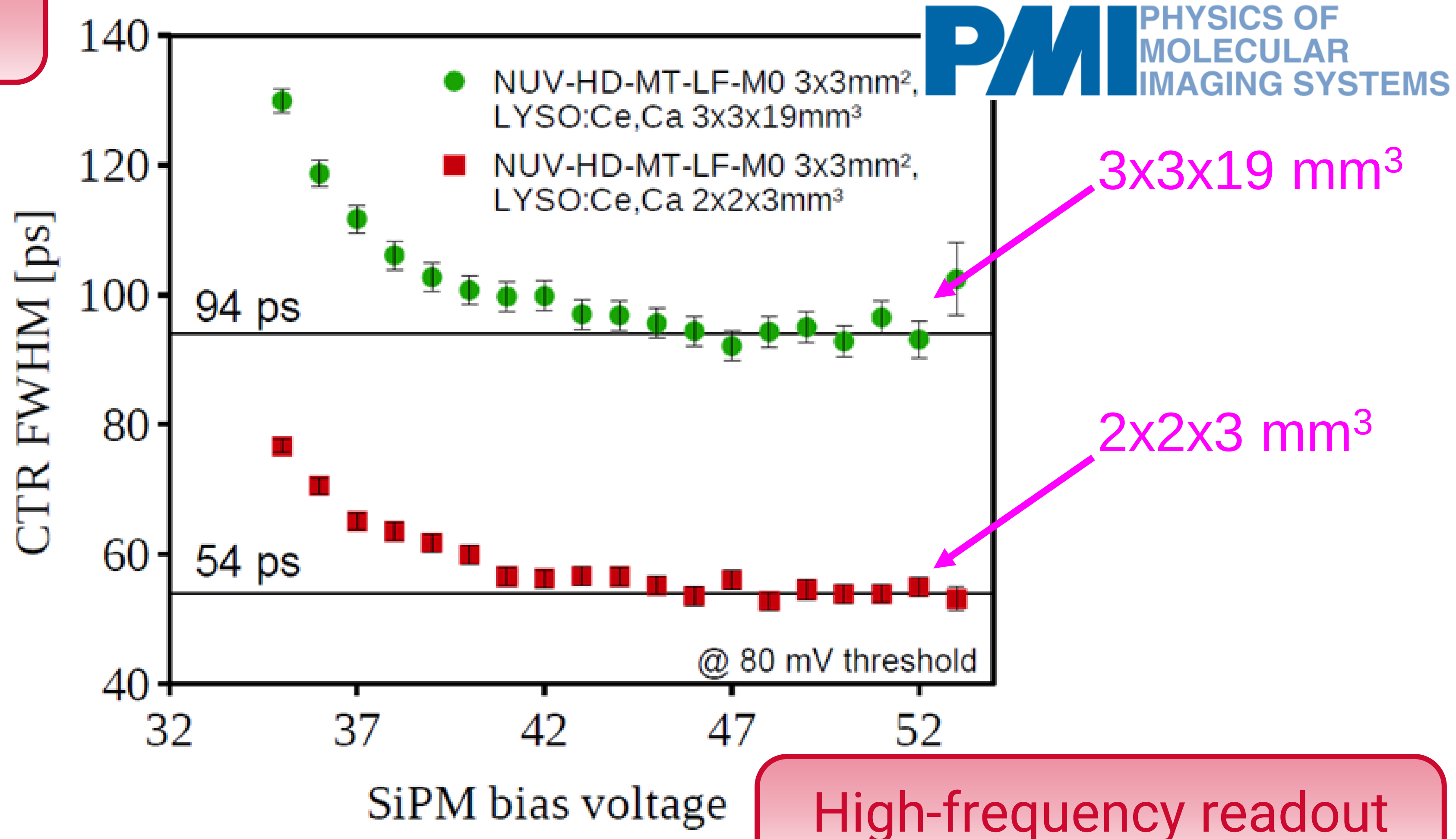
LYSO:Ca,Ce



Standard FBK amplifier

Comparison of CTR measured with 3x3x5 mm^3 LYSO:Ca,Ce coupled to NUV-HD and NUV-HD-MT using the standard FBK transimpedance amplifier.

NUV-HD-MT, M0 masking
3x3 mm^2



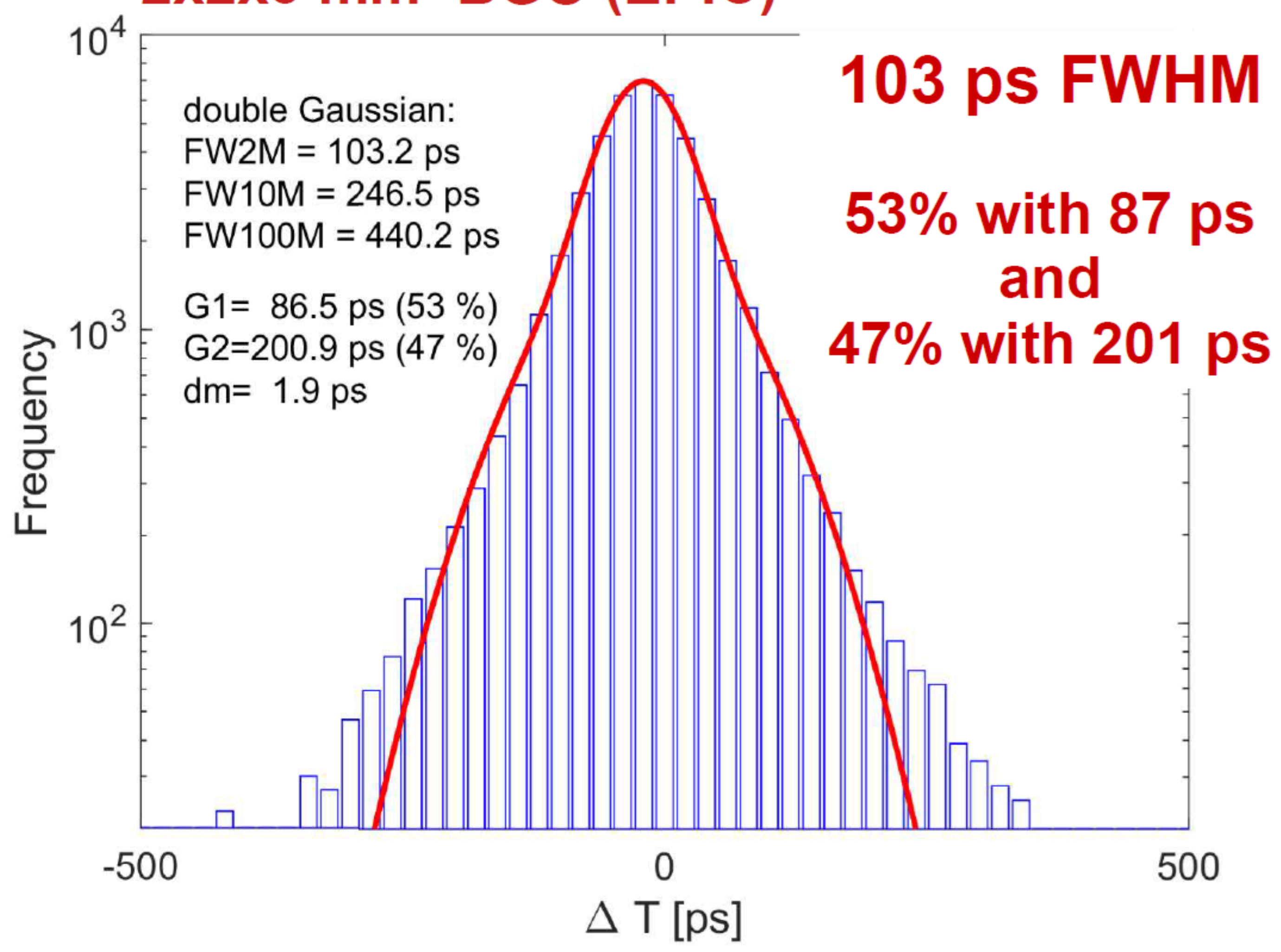
High-frequency readout

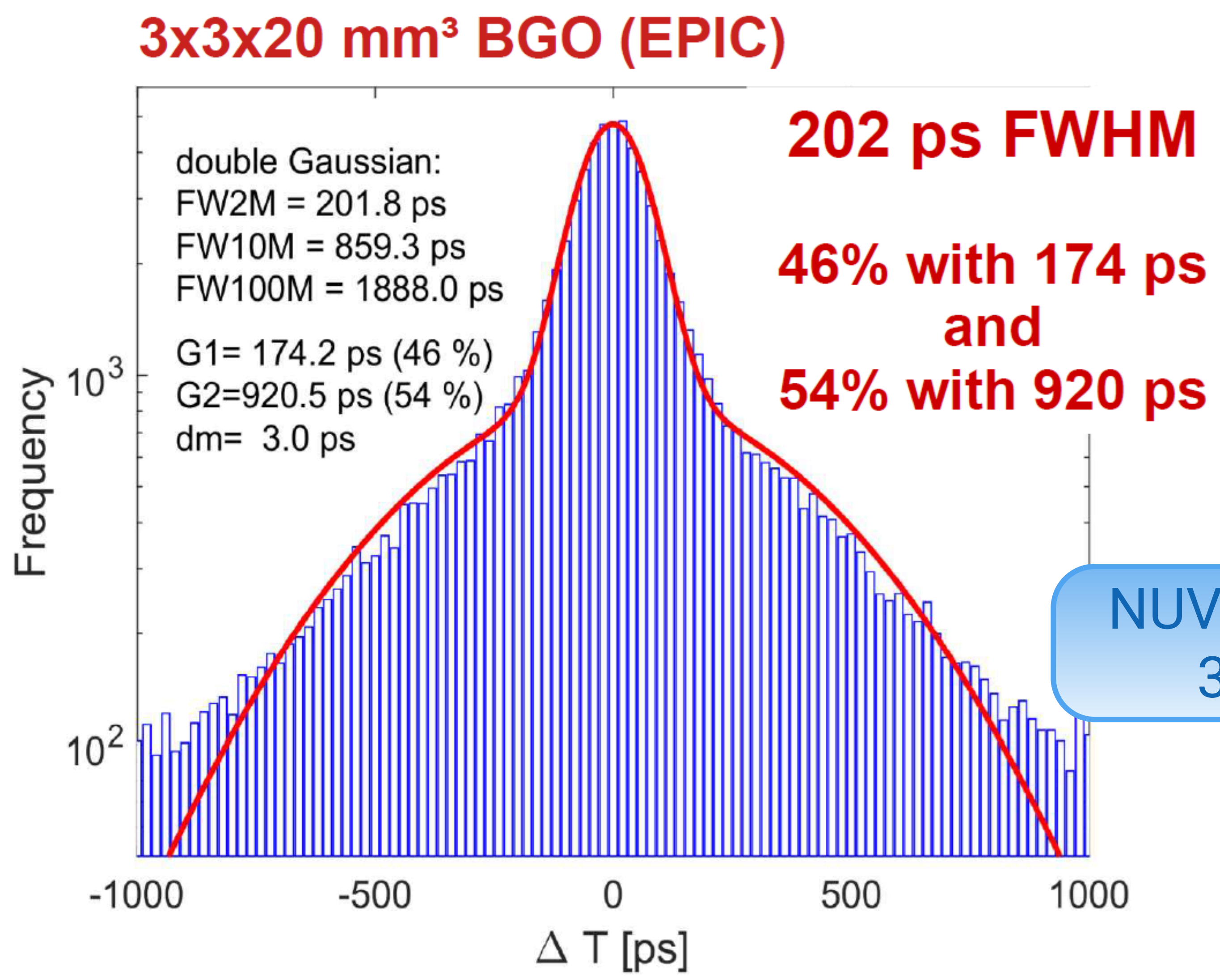
CTR measured with a 3x3 mm^3 NUV-HD-MT SiPM, with M0 masking, COUPLED TO 2X2X3 mm^3 and 3X3X19 mm^3 LYSO:Ce,Ca, using the high-frequency readout.

NUV-HD-MT
BGO CTR with masking and high-frequency readout

SPTR optimization is even more *important in photon-starved applications*, such as Cherenkov-enhanced BGO readout.

SPTR is improved thanks to *high-gain, masking, high-frequency readout*. In addition, *high PDE* allows the collection of more prompt photons.





NUV-HD-MT-M0
3x3 mm^2

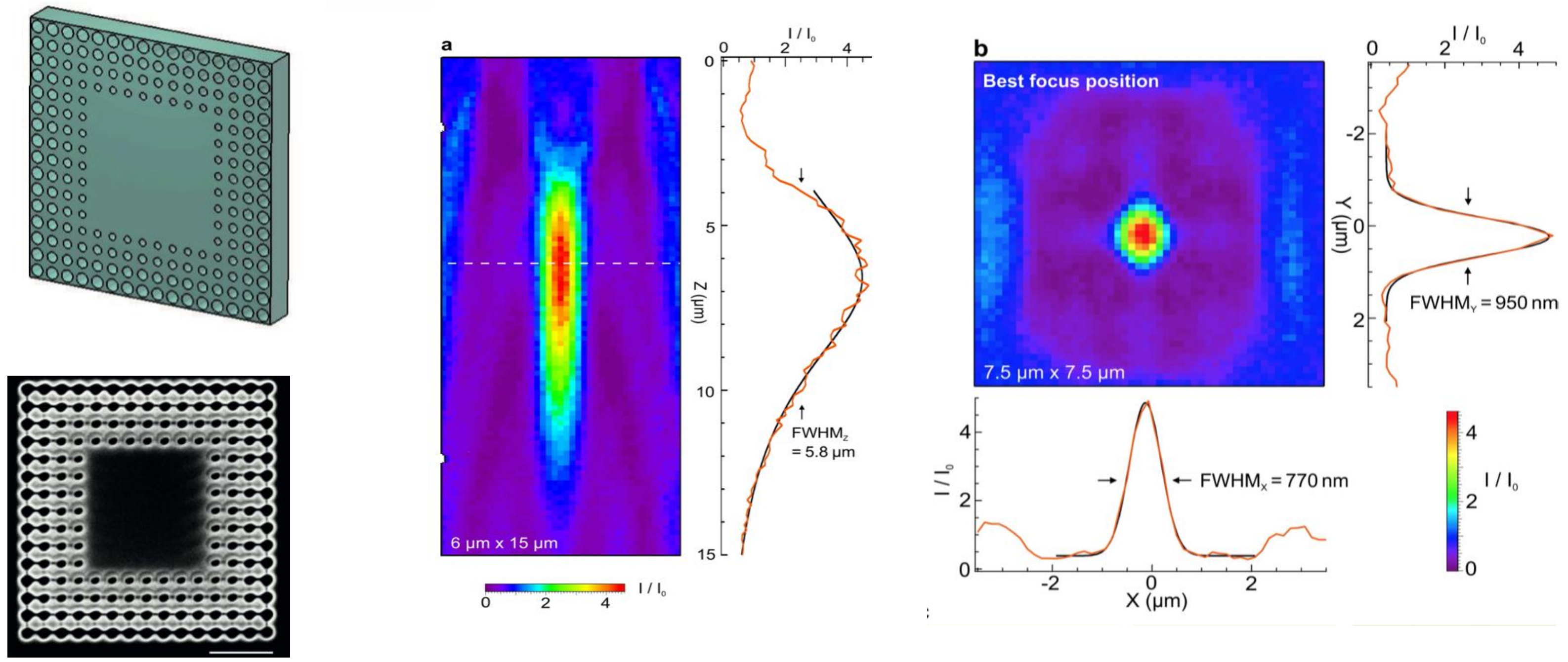
Measurements by S. Gundacker.
Presented at NSS022 (M-02-04)

Light concentration
Metasurfaces and Metamaterials

FBK investigated the possibility of *using nanophotonics to enhance SiPM performance* in the context of the PHOTOQUANT ATTRACT project.

- *Metalens-based light concentrators* can work similarly to microlenses *to enhance SiPM PDE*.
- Potentially compatible with CMOS planar processing.

93% of incident light concentrated
In < 1μm spot diameter or <5% of total area

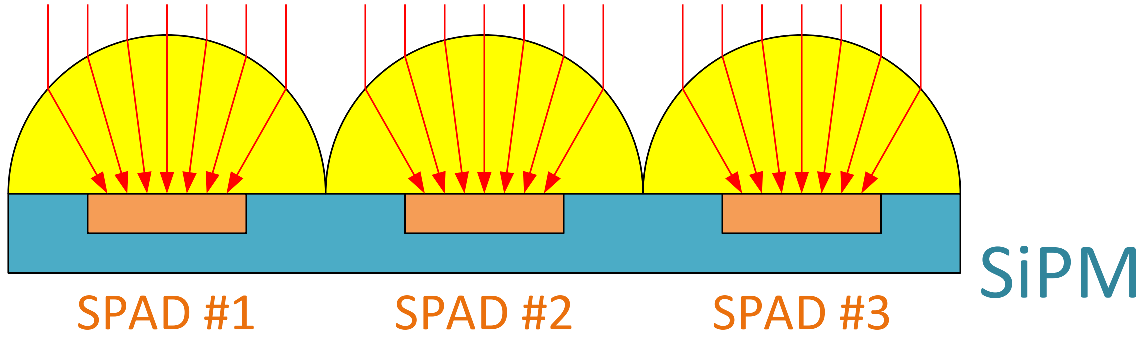


Experimental metalens designed and fabricated 4x4μm Nb_2O_5 metalens with refractive index gradient introduced by holes of varying diameter, (joint ATTRACT project CERN, FBK, Institut Fresnel.)

E. Mikheeva et al., CMOS-compatible all-dielectric metalens for improving pixel photodetector arrays, Accepted in APL Photonics

Metalenses / Microlenses to enhance timing performance

- Increase sensitive area of SiPM up to 100% Fill Factor
- Achieve same PDE with smaller active area
  - → Smaller output capacitance
  - → Better SPTR

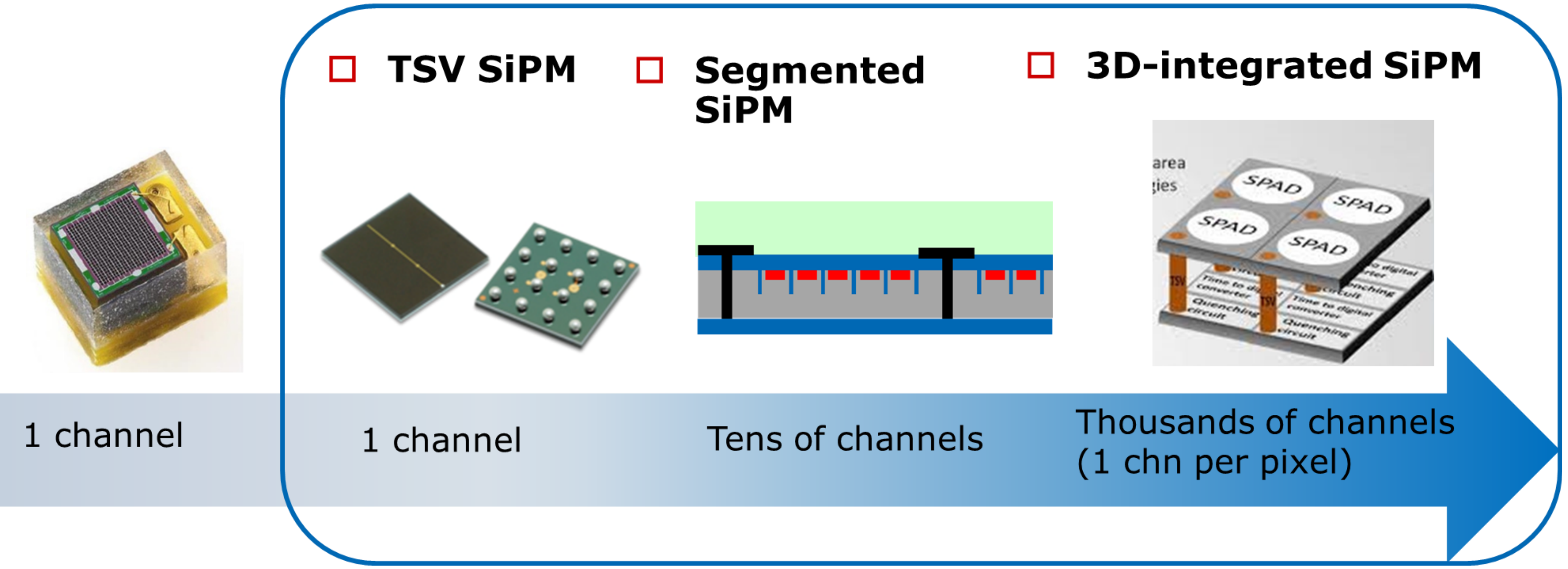


2.5D and 3D Integration
FBK IPCEI clean-room upgrade

FBK is part of the *IPCEI on microelectronics* project (Important Project of Common European Interest - €1.75 billion total public support, 12 M€ to FBK).

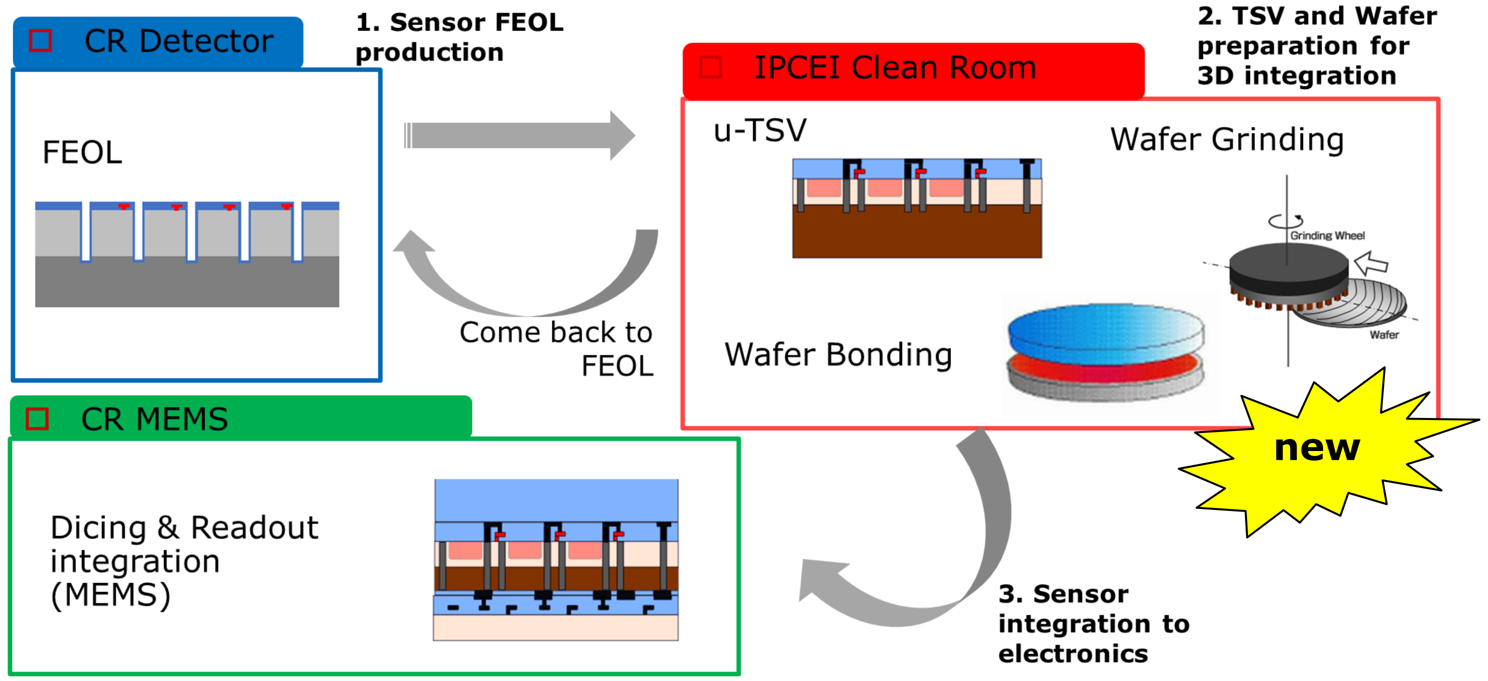
The goal for FBK is upgrading its optical sensors technologies, by *developing TSVs, micro-TSV and Backside Illuminated SiPMs*. This will allow high-density interconnections to the front-end and high-segmentation.

Customized TSVs will be optimized to preserve the NUV-HD electro optical and timing performance.



Range of technologies being developed within IPCEI

New clean-room under construction for 3D integration

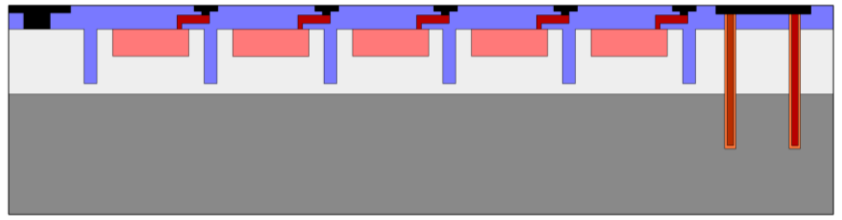


The future system composed of 3 research clean-rooms in FBK.

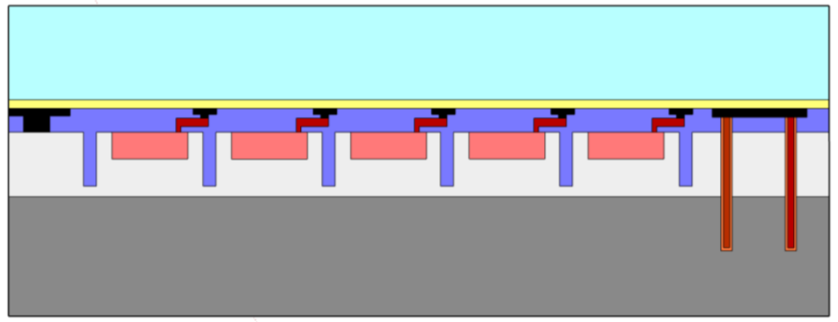
2.5D and 3D Integration
TSV – via mid: process flow

In the via-mid process, the *TSV is formed during the fabrication of the SiPM, modifying its process flow*.

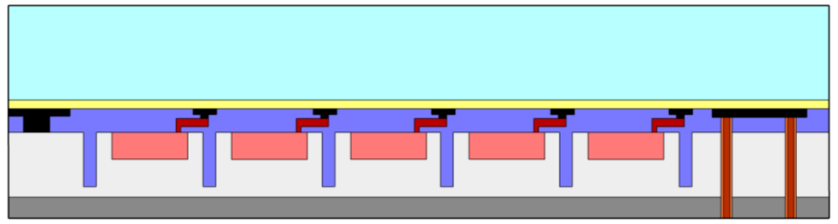
- SiPM fabrication + TSV formation



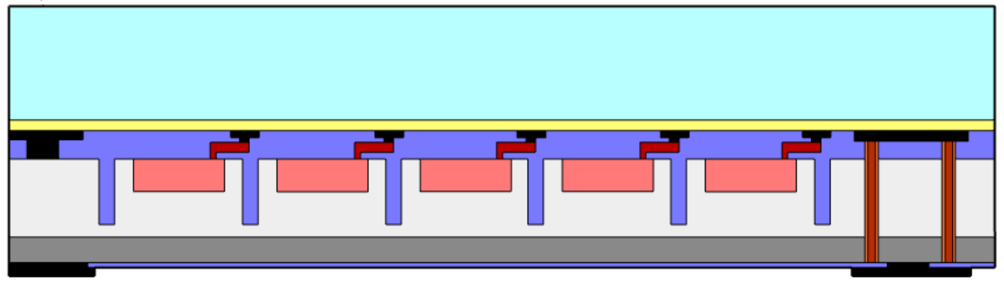
- Edge Trimming + BONDING



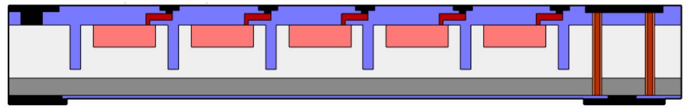
- THINNING



- Contacts formation



- DEBONDING

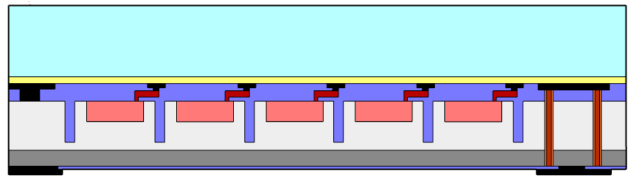


Thickness at least 150 um

Glass-less TSV concept

500 um SiPM pitch

- NO-DEBONDING

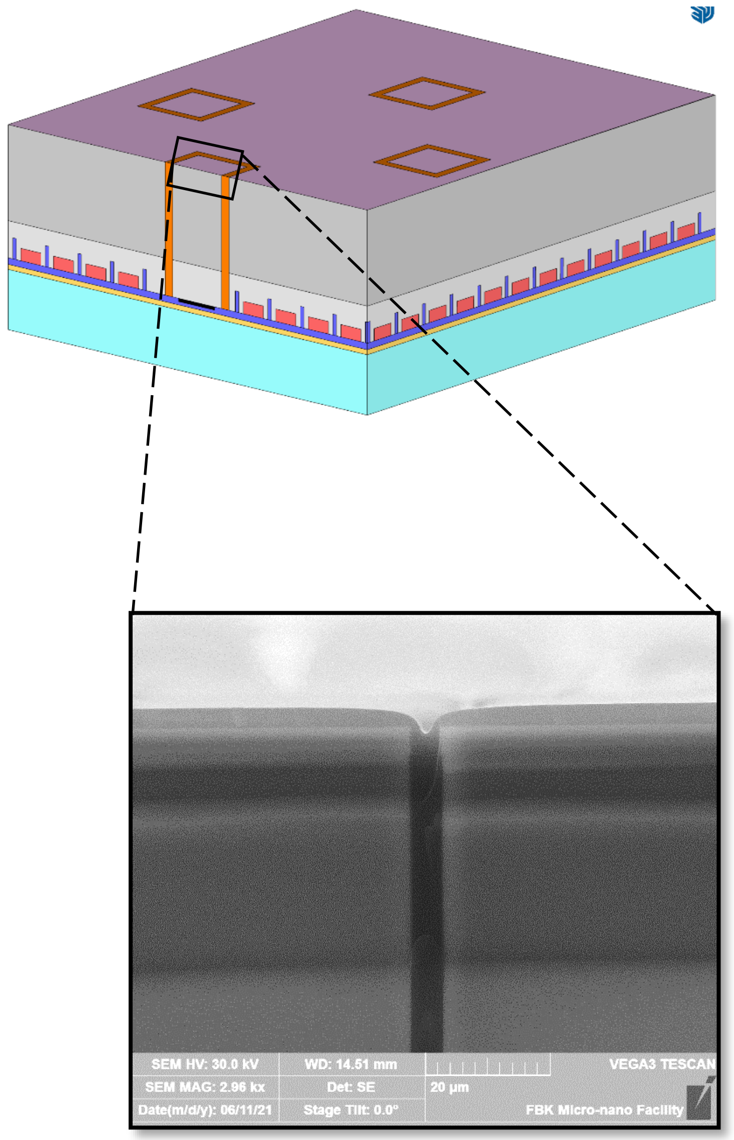


Thickness 10-50 um

Standard TSV

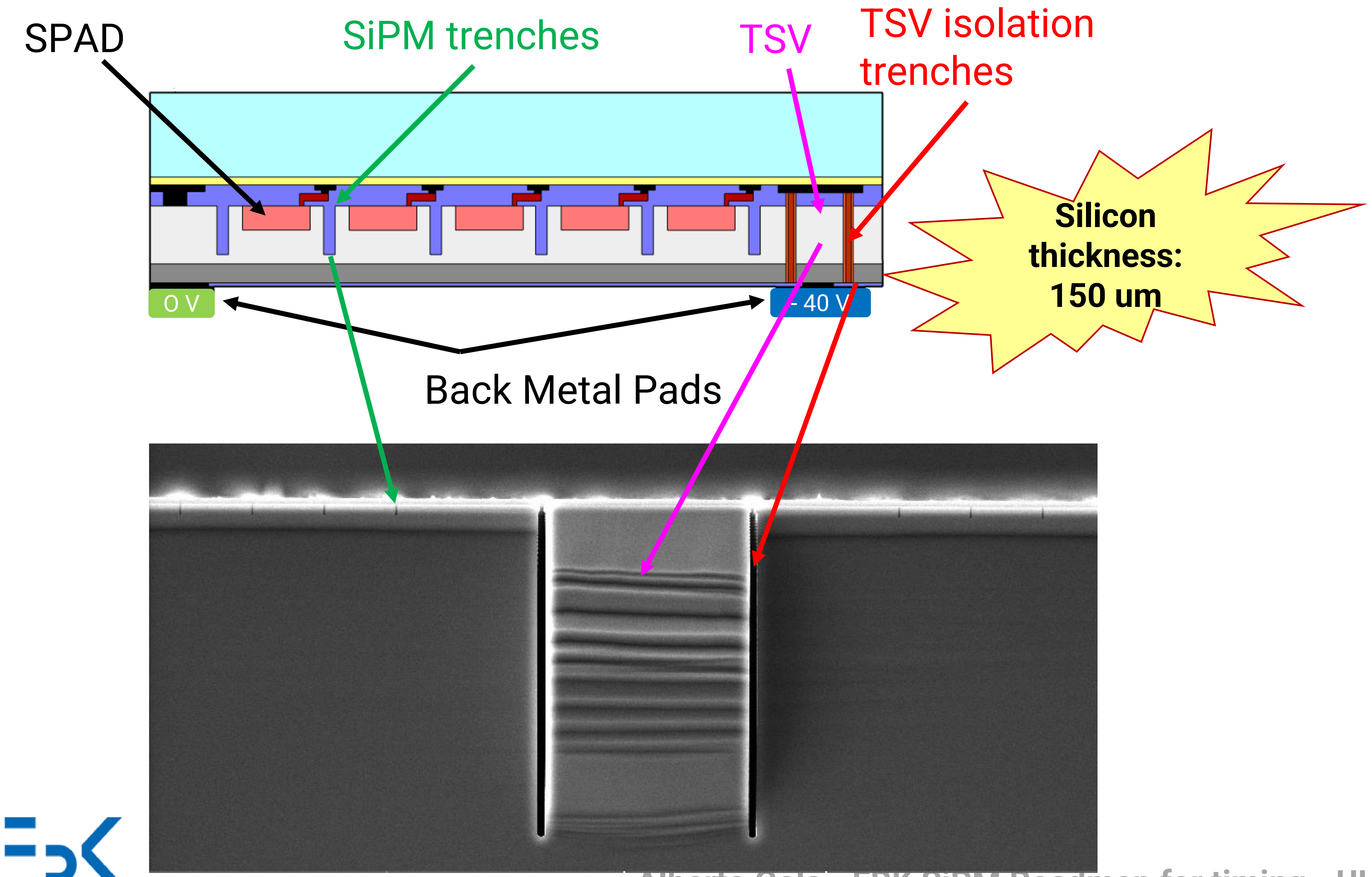
microTSV

50 um SPAD pitch



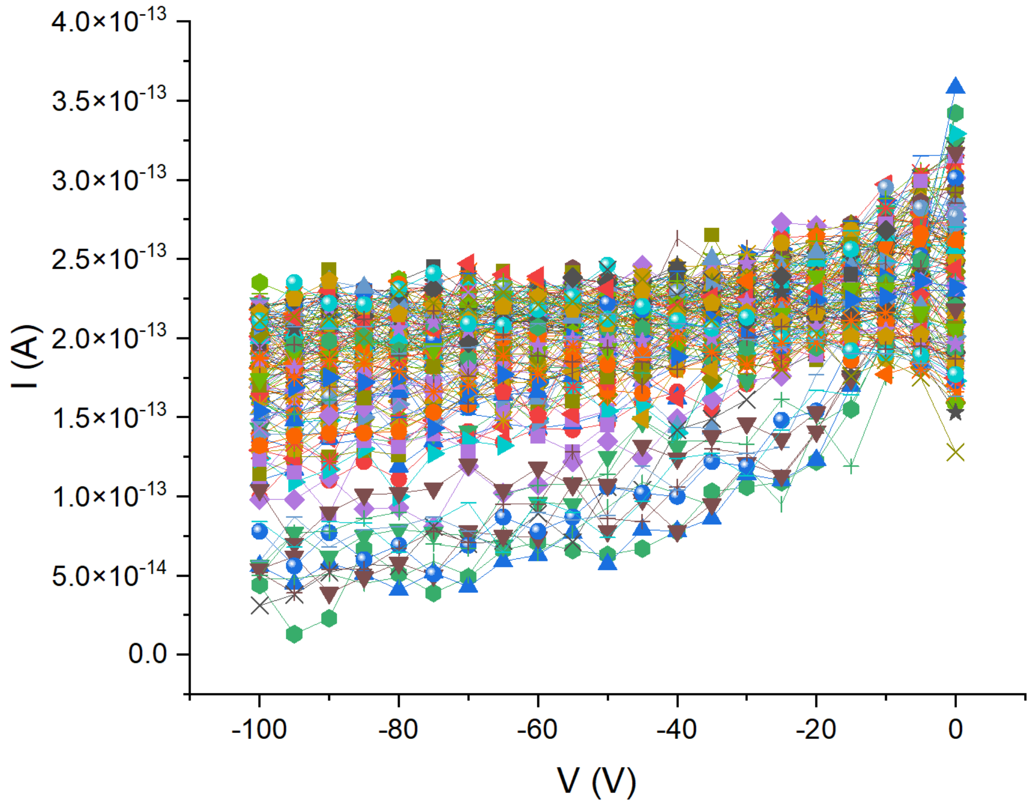
2.5D and 3D Integration
TSV – via mid: first results

Preliminary results on TSV via-mid development, with partial SiPM process, to *check isolation and continuity* (no Geiger-mode multiplication).



At **-100 V** of bias applied the intensity varies from **30 to 200 fA**

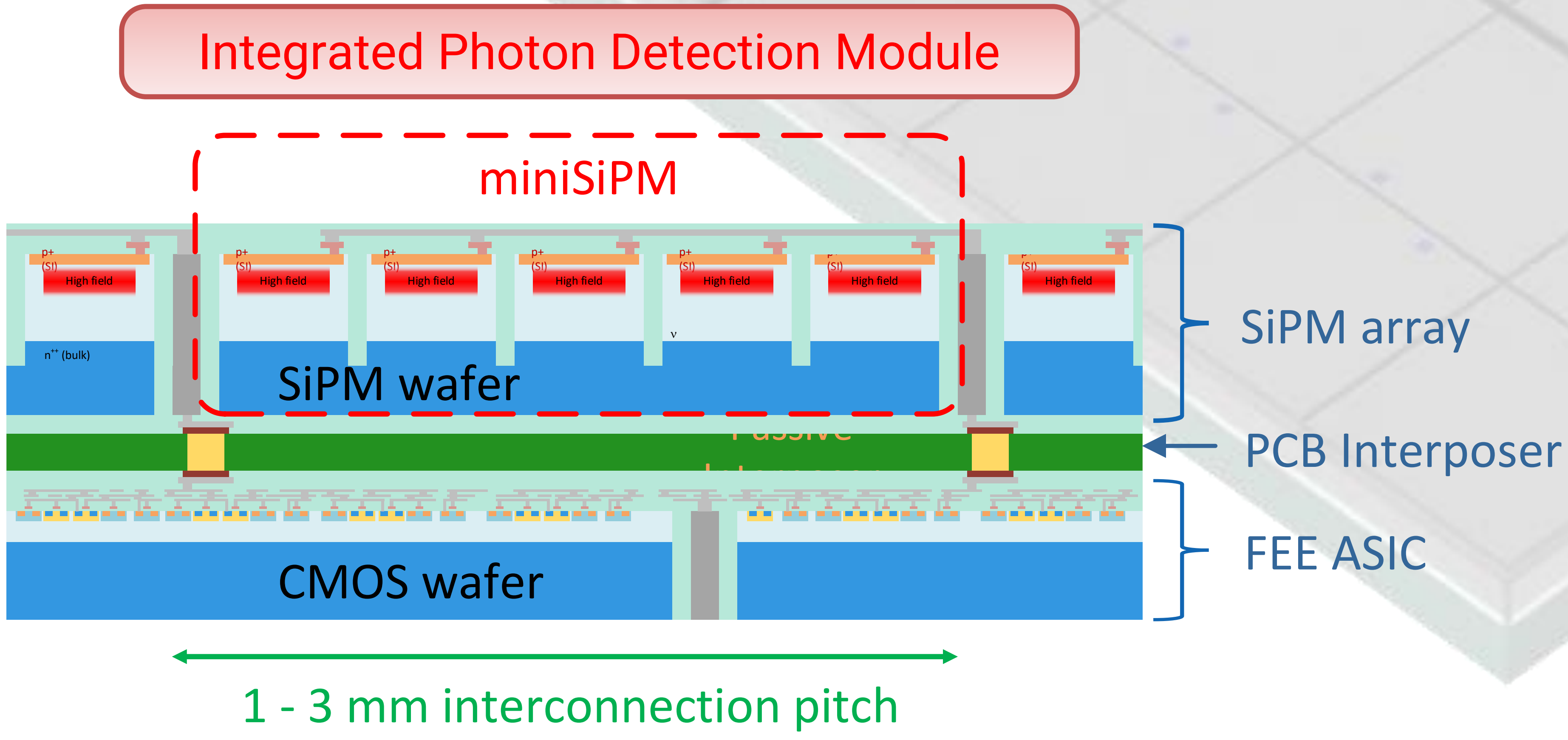
Trough Silicon Vias – Via Mid are isolated from the bulk silicon contact



2.5D and 3D Integration
2.5D integrated SiPM tiles

In the *short and medium term*, medium density interconnection seems the sweet spot to obtain *excellent timing performance on large photosensitive areas while not increasing complexity and cost too much*.

In the PetVision EU Pathfinder project, we will build a Photon Detection Module (PDM) in which *SiPMs with TSV pitch down to 1 mm* are connected to the *readout ASIC on the opposite side of a passive interposer*, in a *2.5D integration scheme*.



Hybrid SiPM module being developed for ultimate timing performance in ToF-PET

Core partners of the *PetVision project*:

Jožef Stefan Institute

ICCUB Institut de Ciències del Cosmos

MGH 1811 MASSACHUSETTS GENERAL HOSPITAL

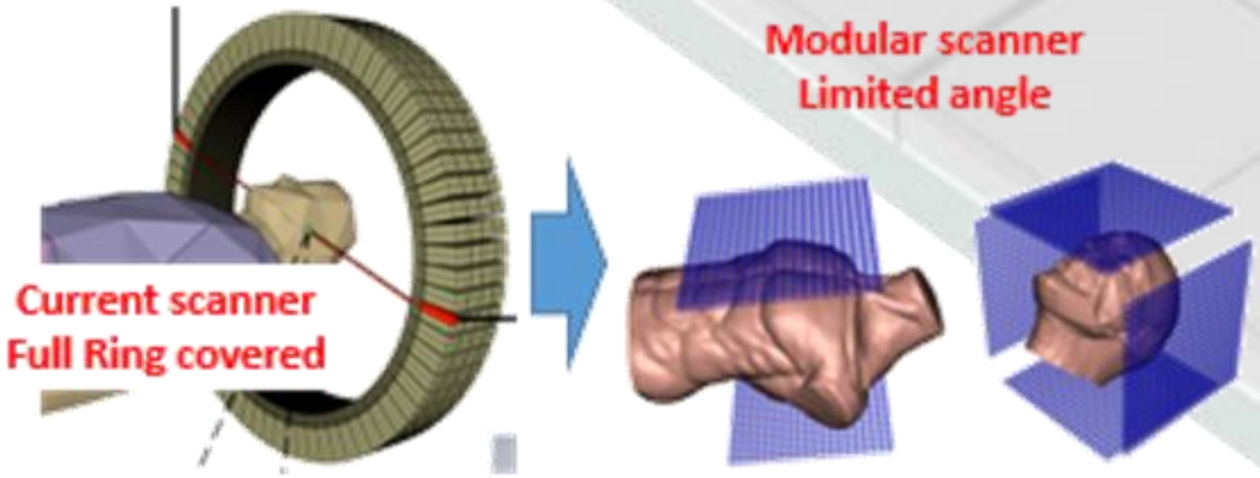
ONCO VISION

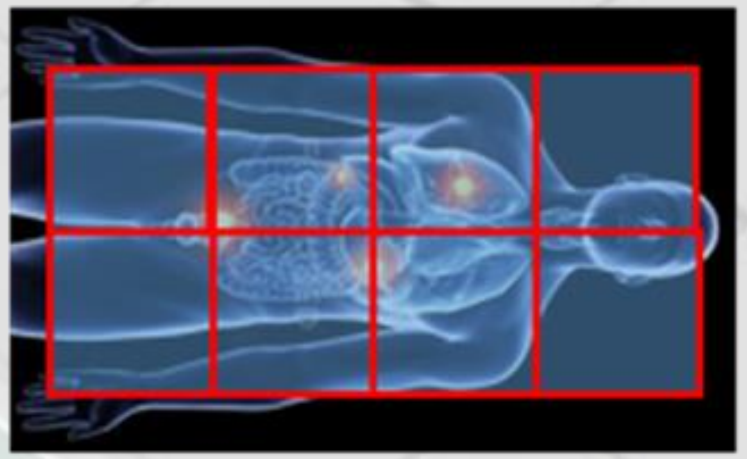
2.5D and 3D Integration
2.5D integrated SiPM tile for timing

Jožef Stefan Institute | ICCUB Institut de Ciències del Cosmos | MASSACHUSETTS GENERAL HOSPITAL | ONCO VISION

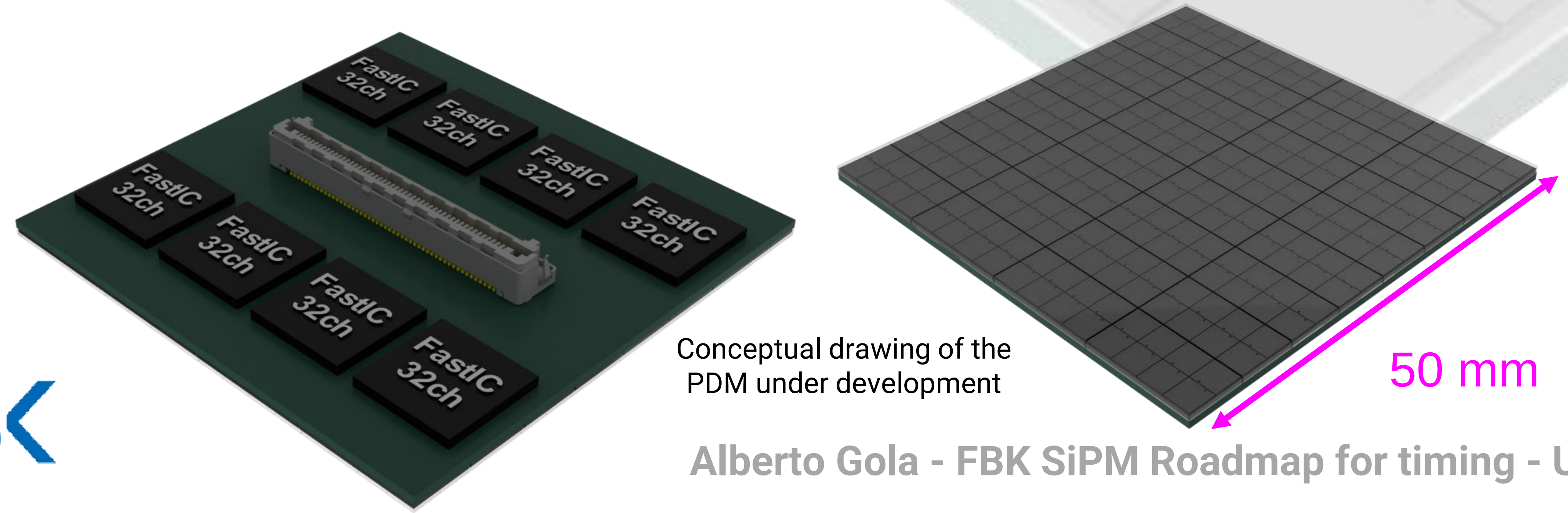
The 2.5D integrated PDM (50x50 mm^2) will be the basis of a *30x30 cm^2 ToF-PET panel*, which will be used to build limited-angle ToF-PET systems, for brain PET, Cardiac PET and full-body scanners.

Thanks to *small SiPM capacitance and enhanced signal integrity*, we *expect very good timing performance*. This is supported by preliminary results achieved with NUV-HD SiPMs coupled to FastIC ASIC.



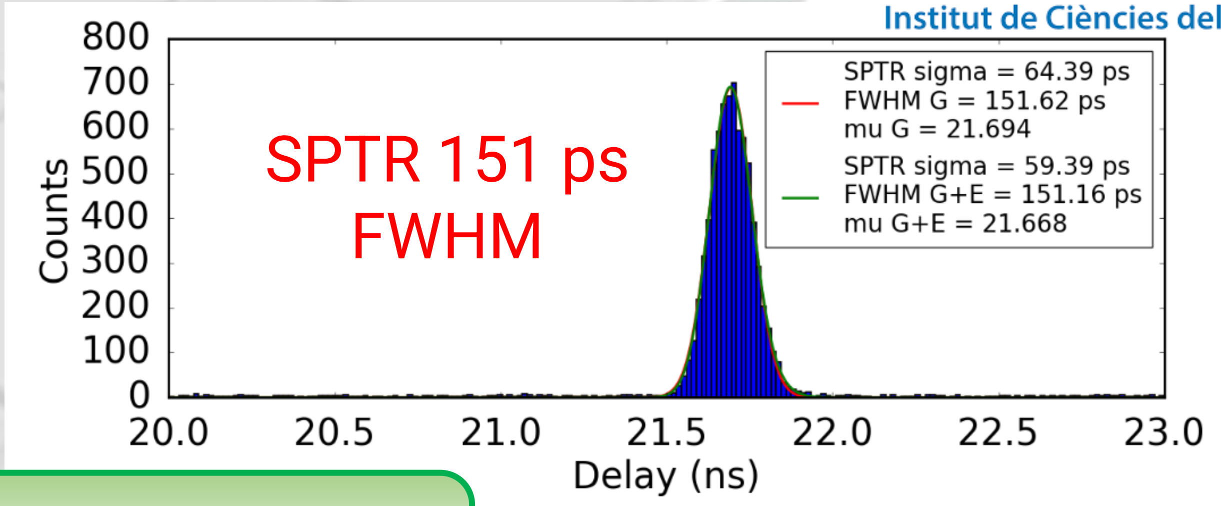


Application of the PDM to build large panes used in new, limted-angle PET applications: Brain Pet, Cardiac PET, while-body PET

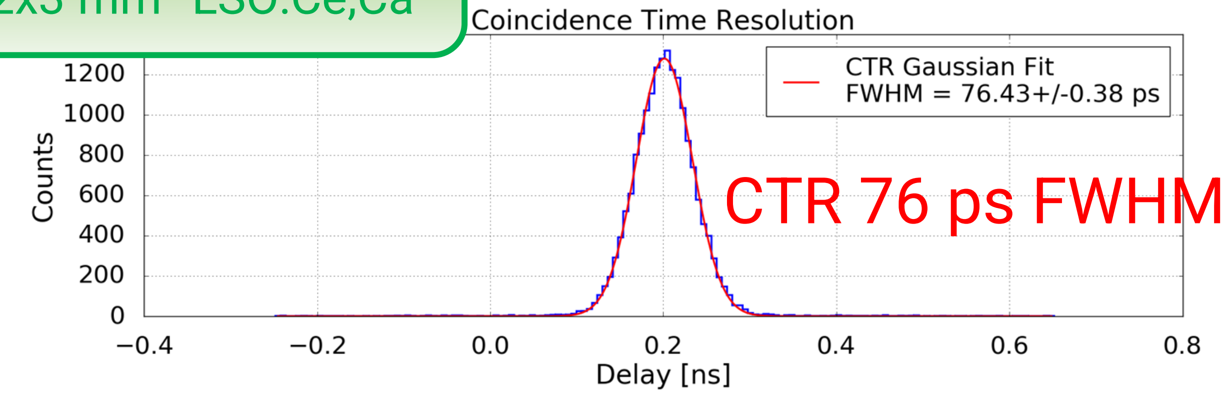


Conceptual drawing of the PDM under development

ICCUB Institut de Ciències del Cosmos



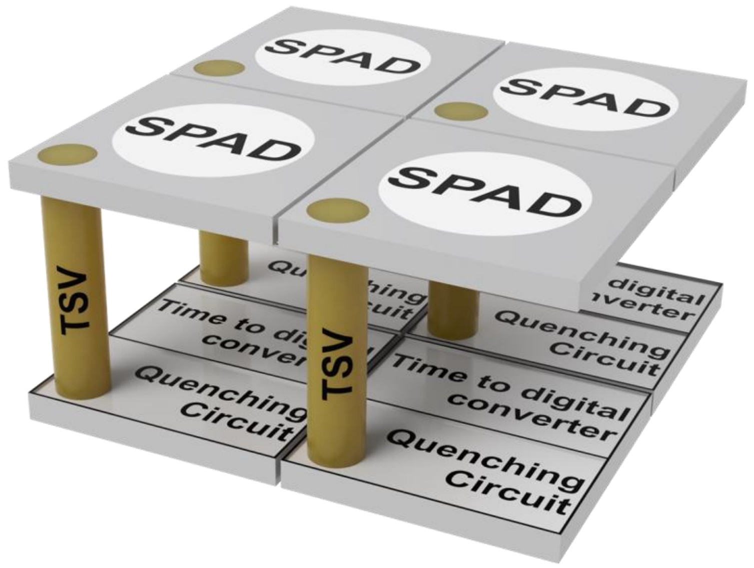
2x2x3 mm^3 LSO:Ce,Ca

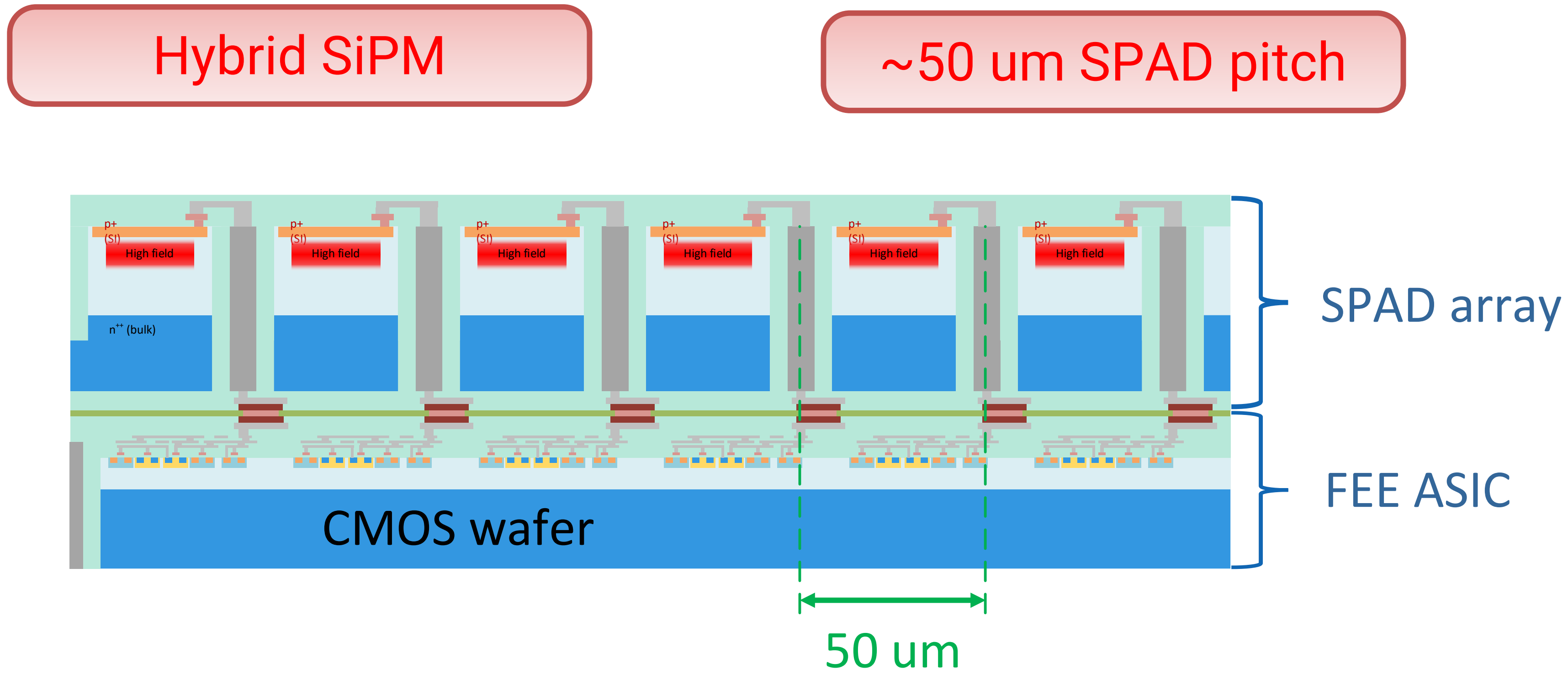


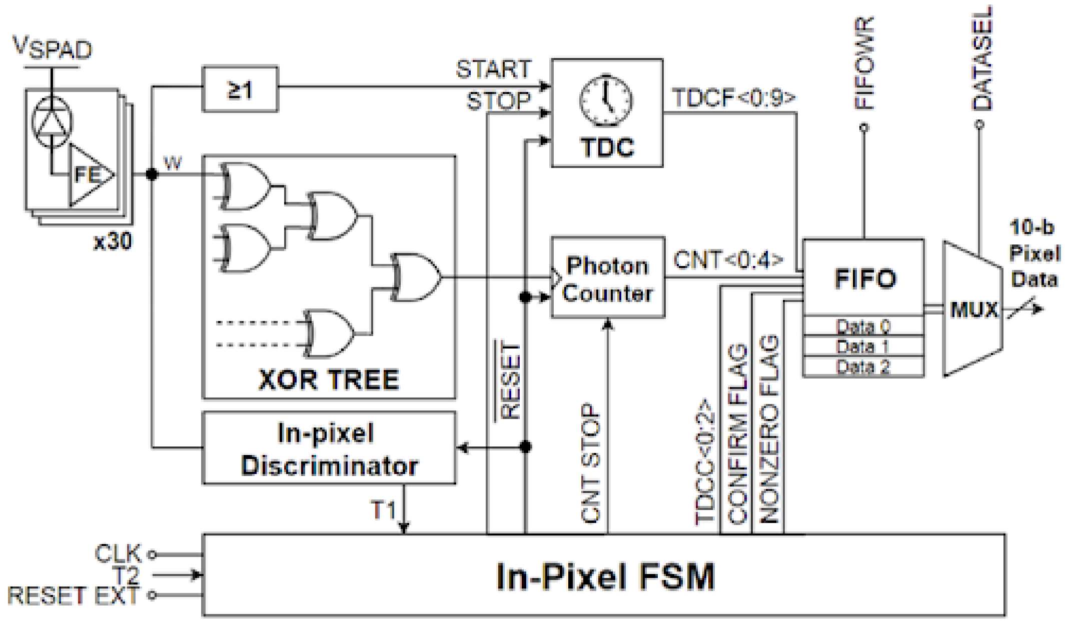
SPTR and CRT measured at FBK NUV-HD-SiPMs read by the FastIC ASIC developed by ICCUB.
Sensor: NUV-HD-LFv2 SiPMs, 3x3 mm^2
Scintillator: 2x2x3 mm^3 LSO:Ce,Ca
Power consumption: 3 mW / channel

2.5D and 3D Integration
Full 3D integration with micro TSVs: Hybrid SiPM

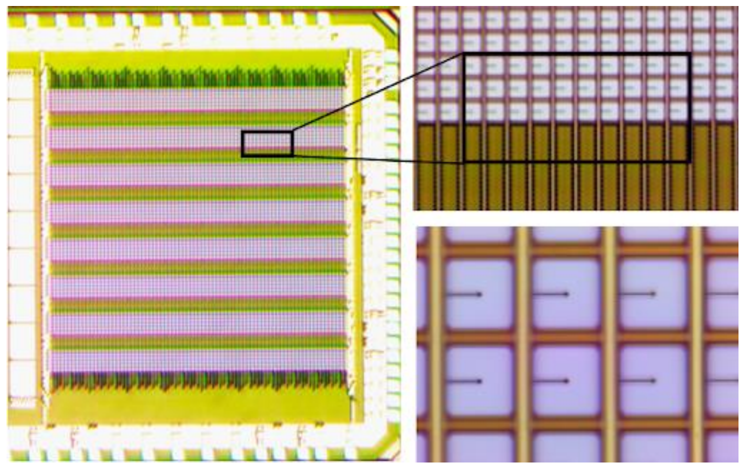
FBK is investigating the potential of microTSVs to achieve *single cell connection*. While complexity of the system increases, it might provide *ultimate timing performance*.







- FBK can apply all the *know-how on system architecture* already developed in the filed of digital SiPMs.
- Finally solve the duality between analog and digital SiPM: *Hybrid SiPM concept* → get the best of both worlds.

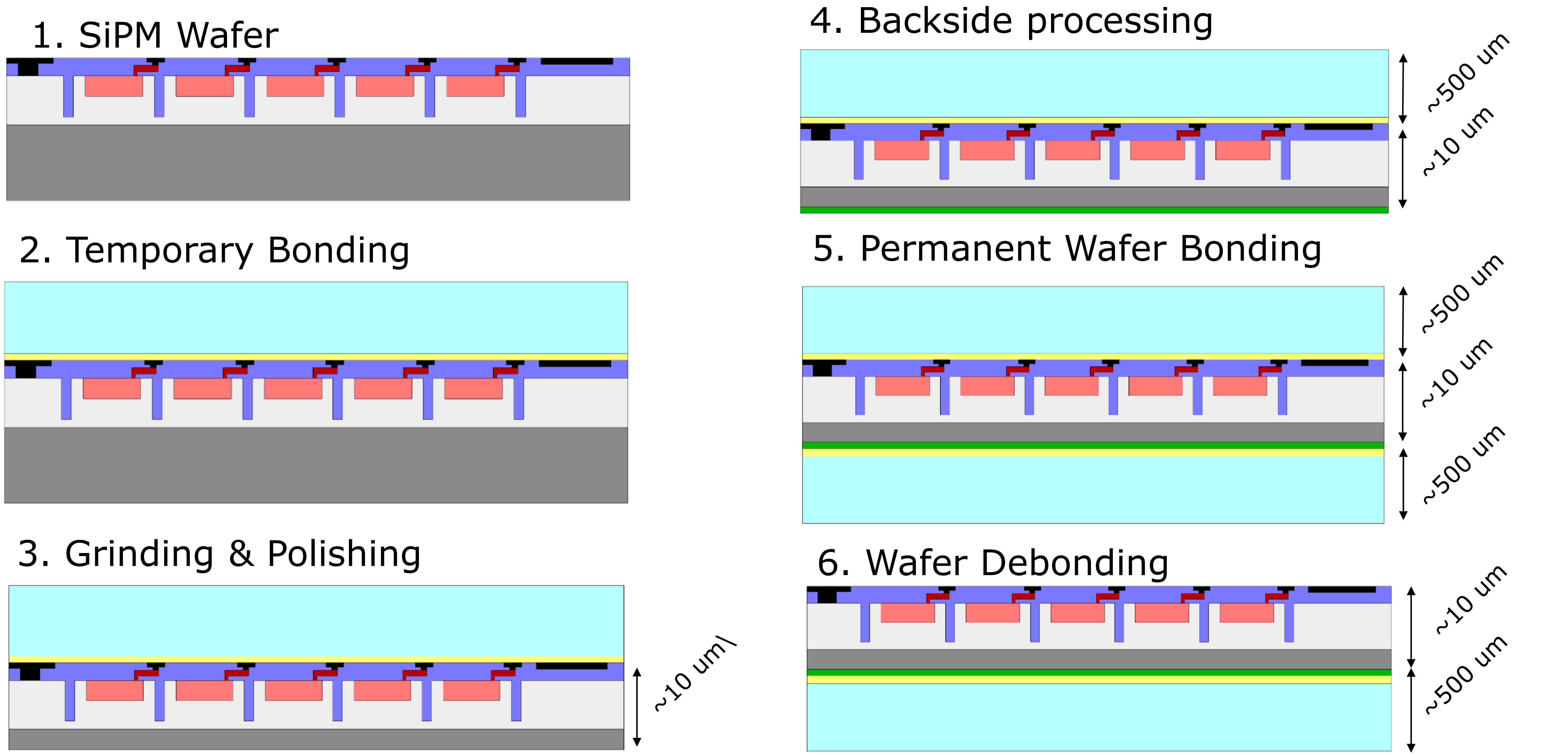


Example of dSiPM architecture developed at FBK (SBAM project)

2.5D and 3D Integration
Backside Illuminated NIR SiPMs: process flow

IPCEI on Microelectronics

BSI development started on *NIR-sensitive SiPMs* → *no need to create a new entrance window* on the backside with high efficiency in the NUV.

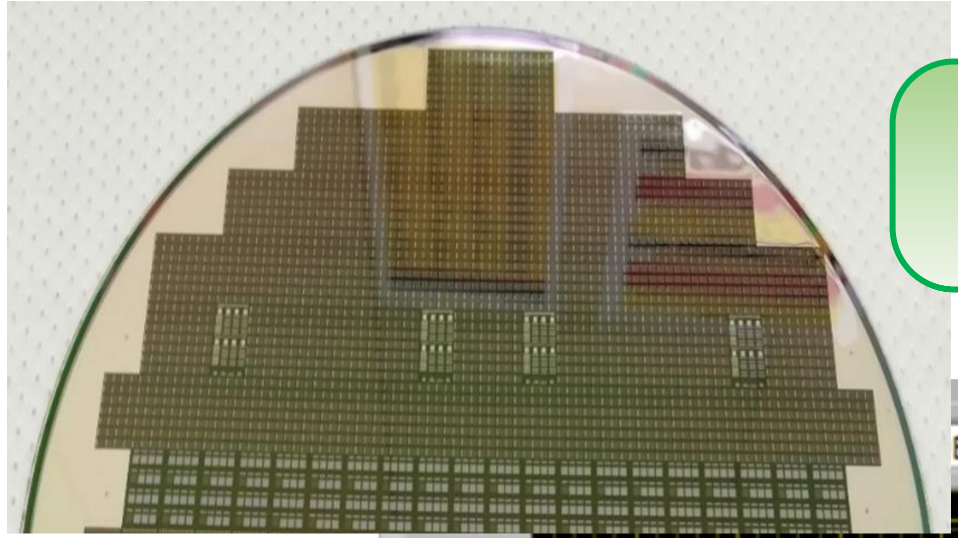


2.5D and 3D Integration
BSI NIR SiPMs: first results

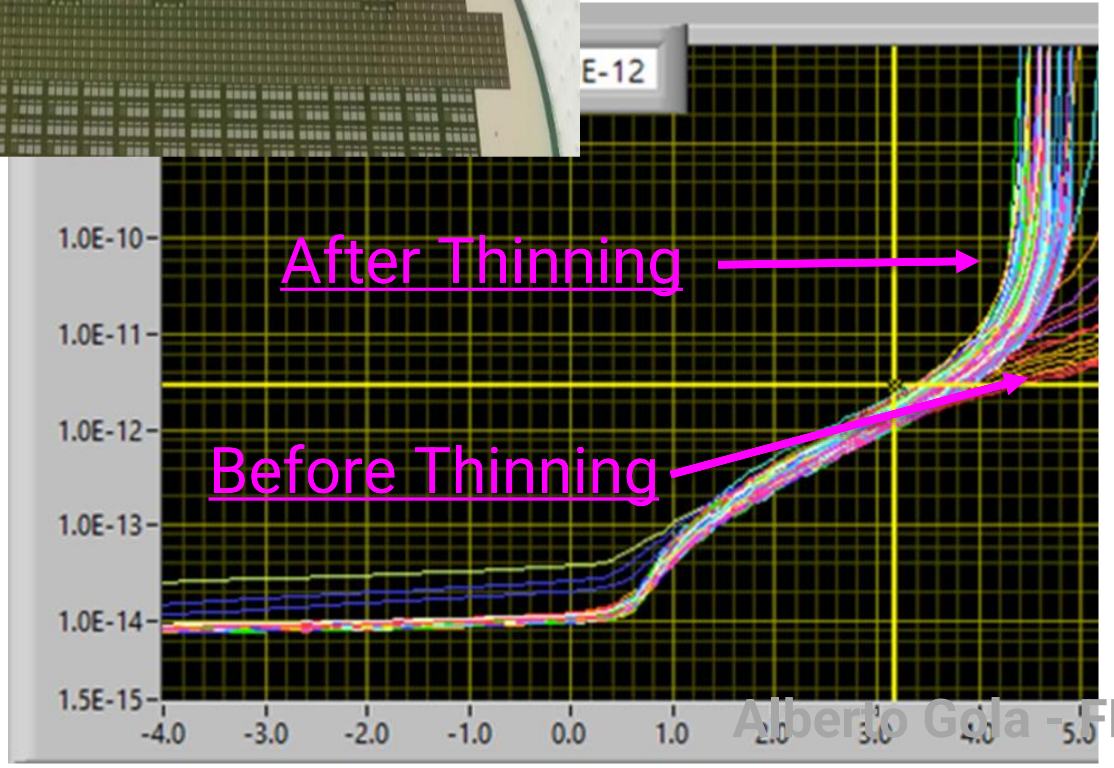
The *first NIR-sensitive BSI wafers were fabricated* in FBK clean room (1x1 mm^2 devices).

Minor differences in the IVs after thinning, compared to the FSI devices (without thinning).

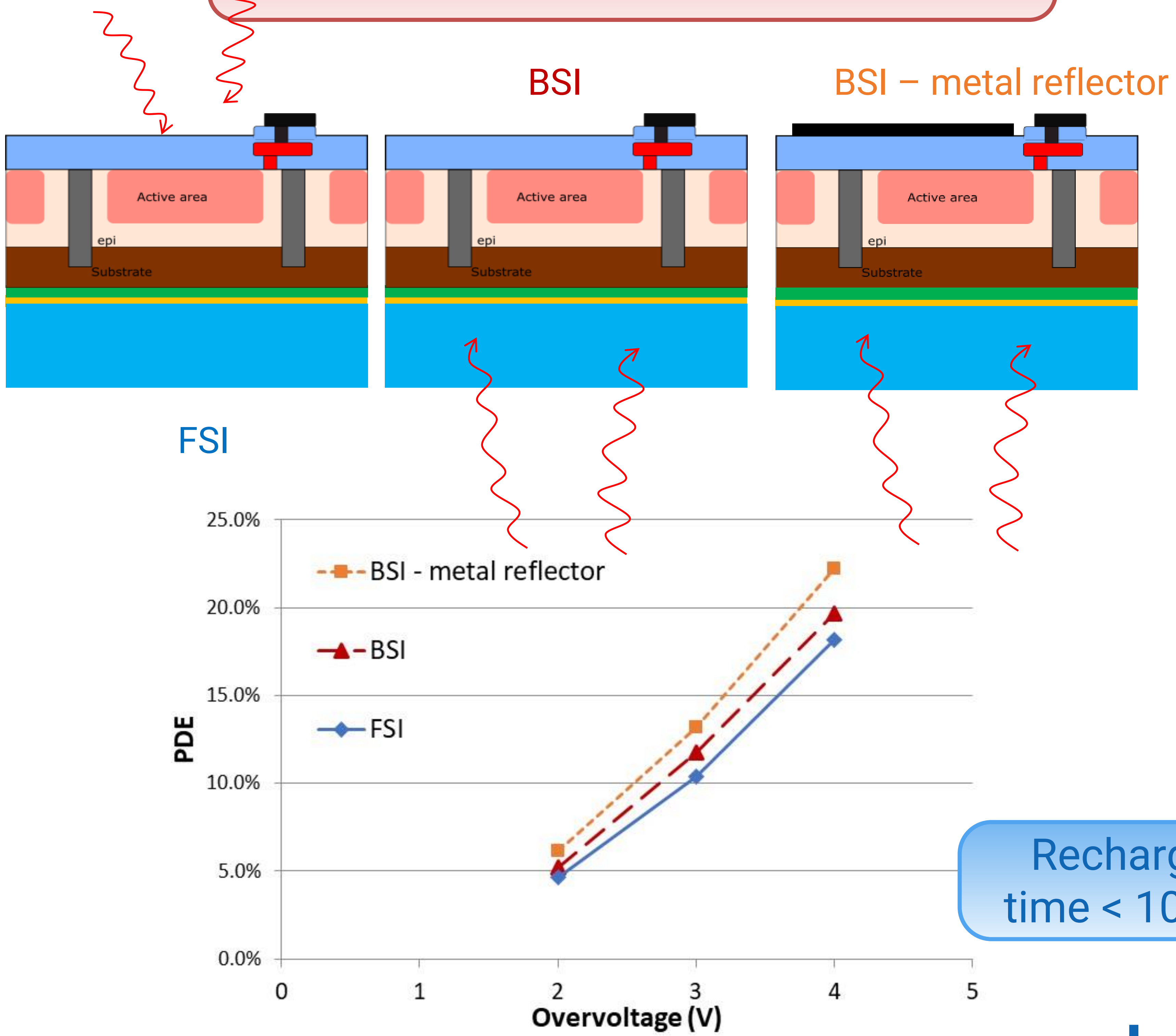
Ultrathin substrate (~ 10 um)



NIR BSI process is working!



NIR PDE comparison at 905 nm

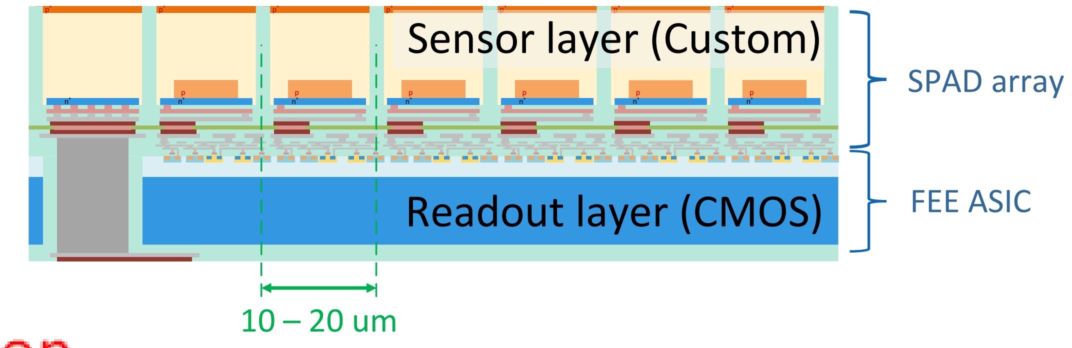


Recharge time < 10 ns

2.5D and 3D Integration
Backside Illuminated NUV SiPMs

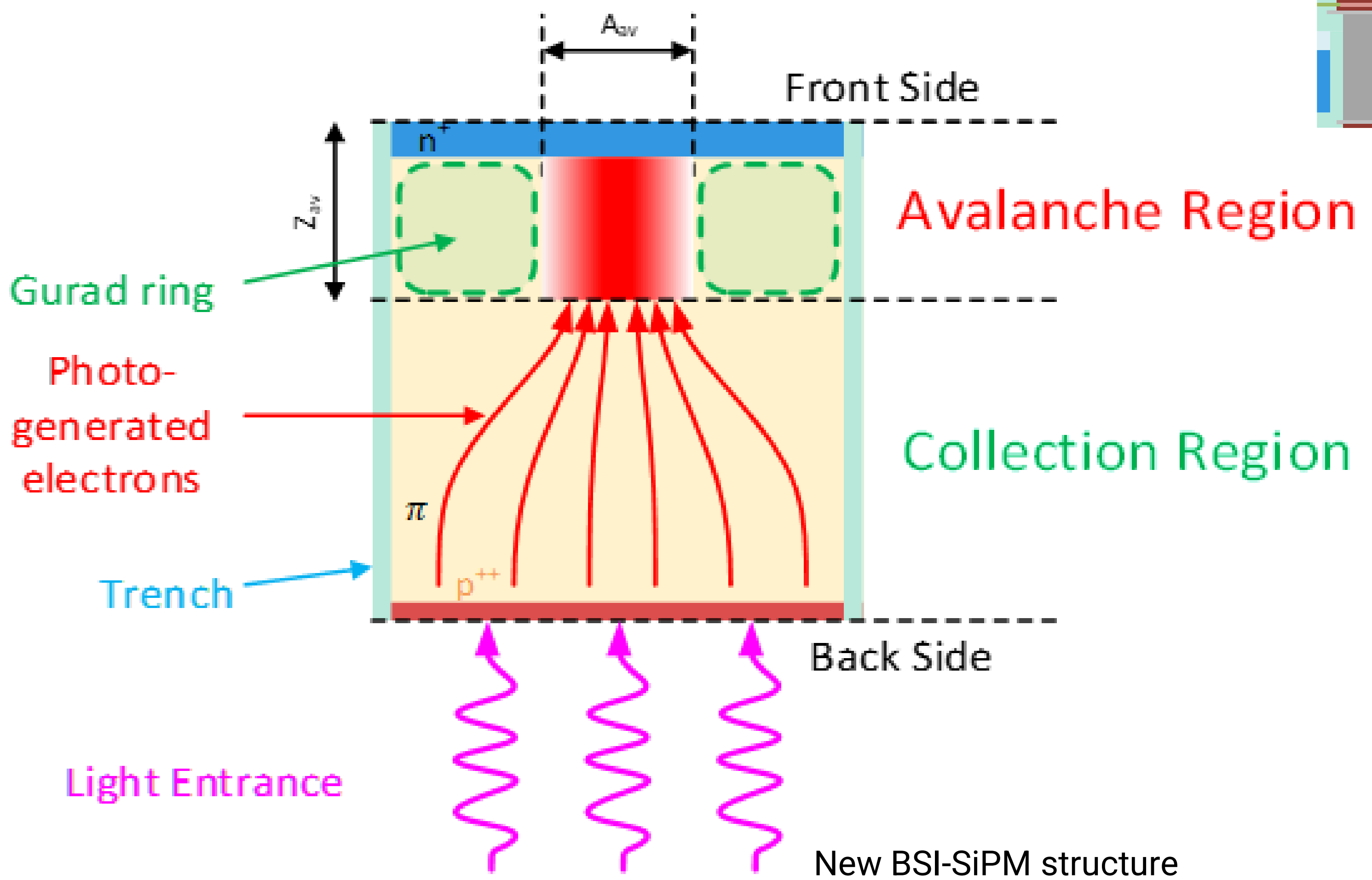
The next-generation of developments, currently being investigated at FBK, is building a *backside-illuminated, NUV-sensitive SiPM*. Several technological challenges should be overcome.

Clear *separation between charge collection and multiplication regions*.



Potential Advantages:

- Up to 100% FF even with small cell pitch
- Ultimate Interconnection density: < 15 um
- High speed and dynamic range
- Low gain and external crosstalk
- (Uniform) entrance window on the backside, ideal for enhanced optical stack (VUV sensitivity, nanophotonics)
- Local electronics: ultra fast and possibly low-power without TSVs.



New BSI-SiPM structure

Development Risks:

- Charge collection time jitter
- Low Gain → SPTR?
- Effectiveness of the new entrance window

Radiation hardness:

- The SiPM area sensitive to radiation damage, is much smaller than the light sensitive area
- **Assumption**: the main source of DCR is field-enhanced generation (or tunneling).

Thank you!

Thanks to all the members of the team working on custom SiPM technology at FBK:

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- **Stefano Merzi**
- **Laura Parellada Monreal**
- **Elena Moretti**
- **Giovanni Palù**
- **Giovanni Paternoster**
- **Michele Penna**
- **Maria Ruzzarin**
- **Tiziano Stedile**
- **Nicola Zorzi**