FONDAZIONE BRUNO KESSLER

FUTURE BUILT ON KNOWLEDGE

Status and perspectives of SiPMs

Alberto Gola
Chief Scientist

F. Acerbi, A. Ficorella, S. Merzi, L.P. Monreal, E .Moretti, G. Paternoster, M. Penna, M. Ruzzarin, N. Zorzi

gola@fbk.eu

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

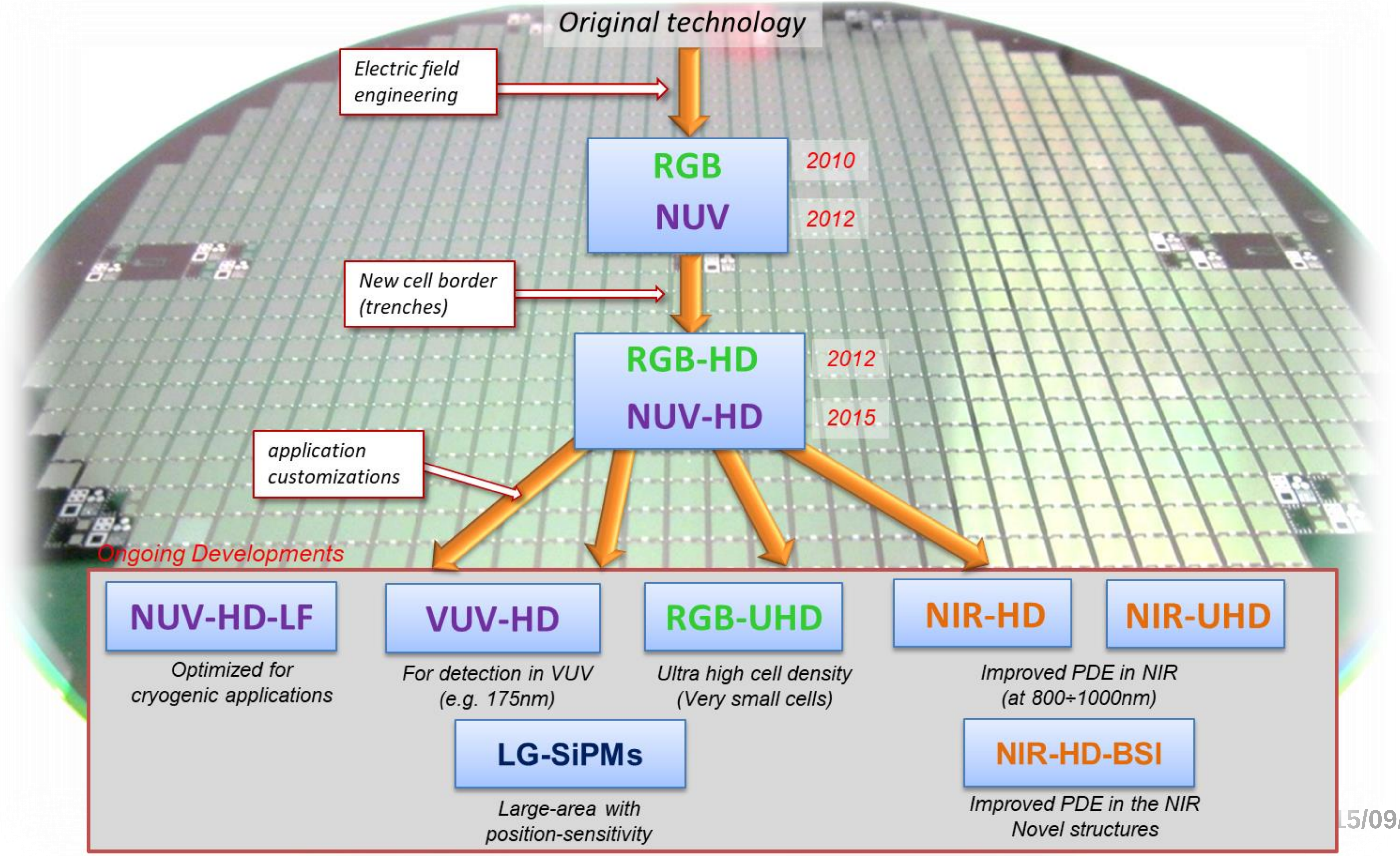
FBK is typically interested in R&D activities and collaborations to <u>improve and customize SiPM technology for specific applications</u>.

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

LFOUNDRY Solutions for great visions

BROADCOM

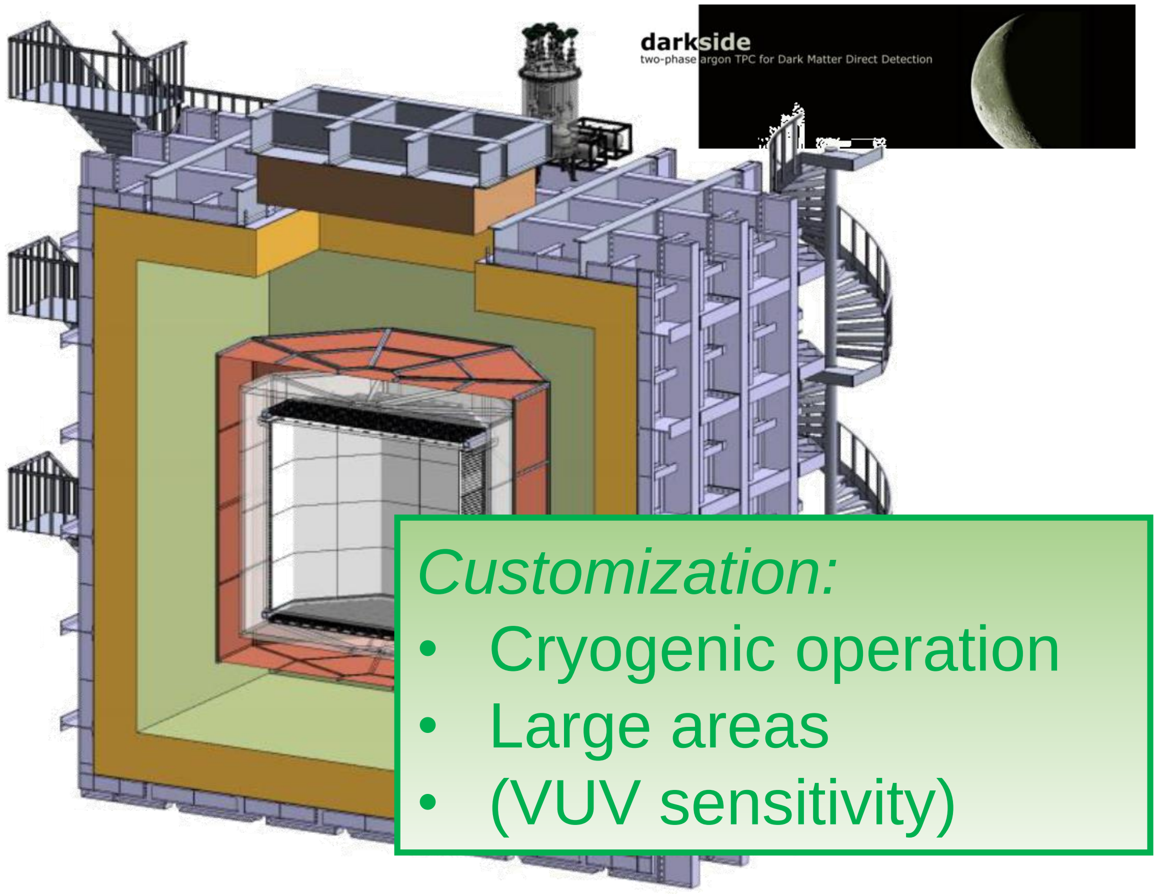
Fondazione Bruno Kessler
Custom SiPM technology roadmap



FBK SiPM technologies
Use in Big Physics Experiments

Thanks to constant *performance improvement,* SiPM technologies are now used in several upgrades of Big Physics Experiments: *deep customization is often required.*

Cryogenic TPCs



Customization:
- Cryogenic operation
- Large areas
- (VUV sensitivity)

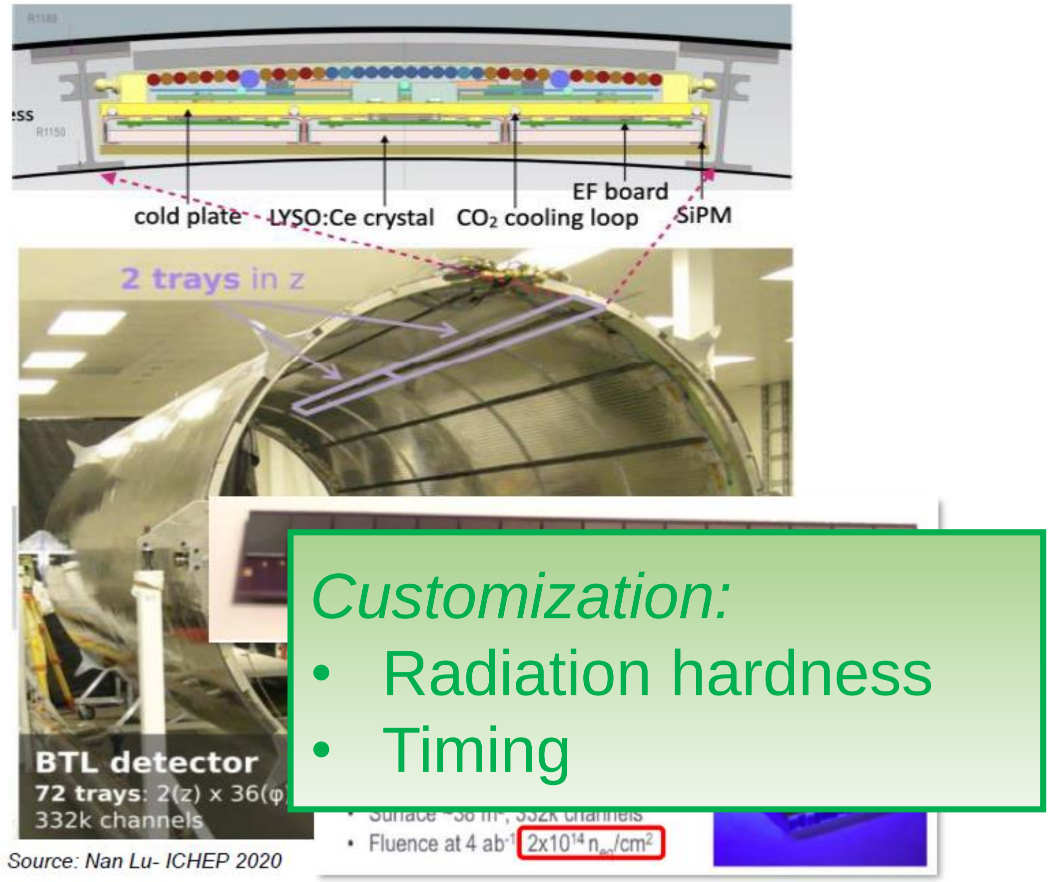
Cryogenic SiPMs will be employed in experiments such as DarkSide-20k

CTA

Customization:
- Low CT
- Maximum PDE

Prototype pSCT installed in the VERITAS, equipped with FBK SiPMs.

HEP



Customization:
- Radiation hardness
- Timing

NUV-HD SiPMs are being evaluated for the MIP timing detector of CMS (LYSO scintillator readout).

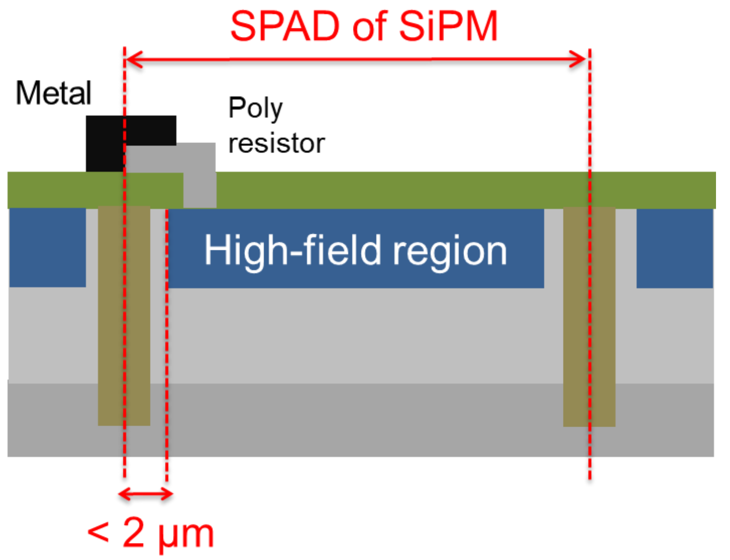
FBK SiPM technologies
Current R&D activities and Roadmap

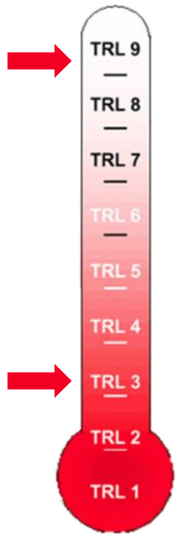
Outline:

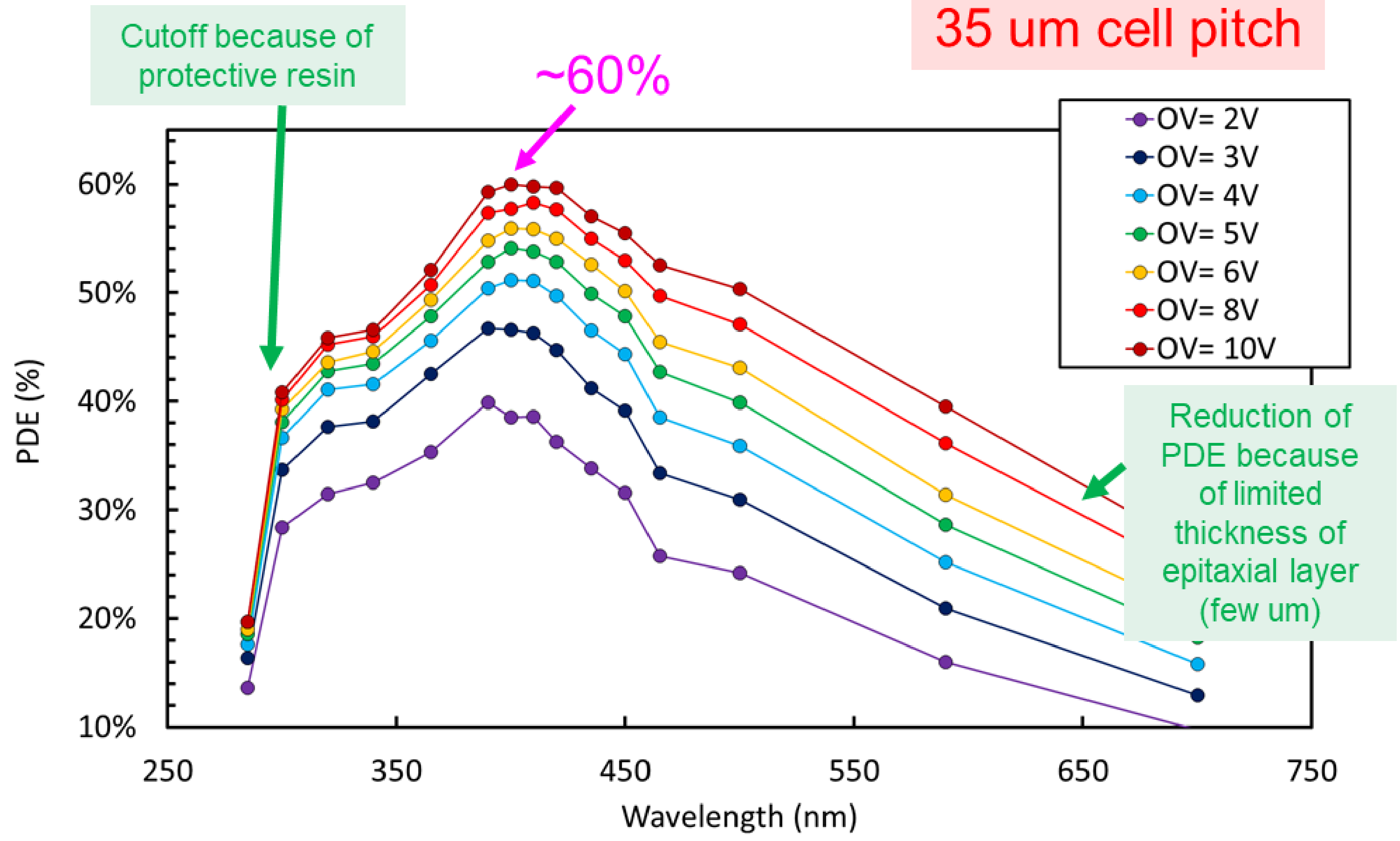
- **Timing performance**
- **Reduction of Optical Crosstalk**
- **Cryogenic operation**
- **Radiation Hardness**
- **Light concentration**
- **Future developments: 2.5 and 3D integration**

FBK SiPM technologies
NUV-HD SiPM technology

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

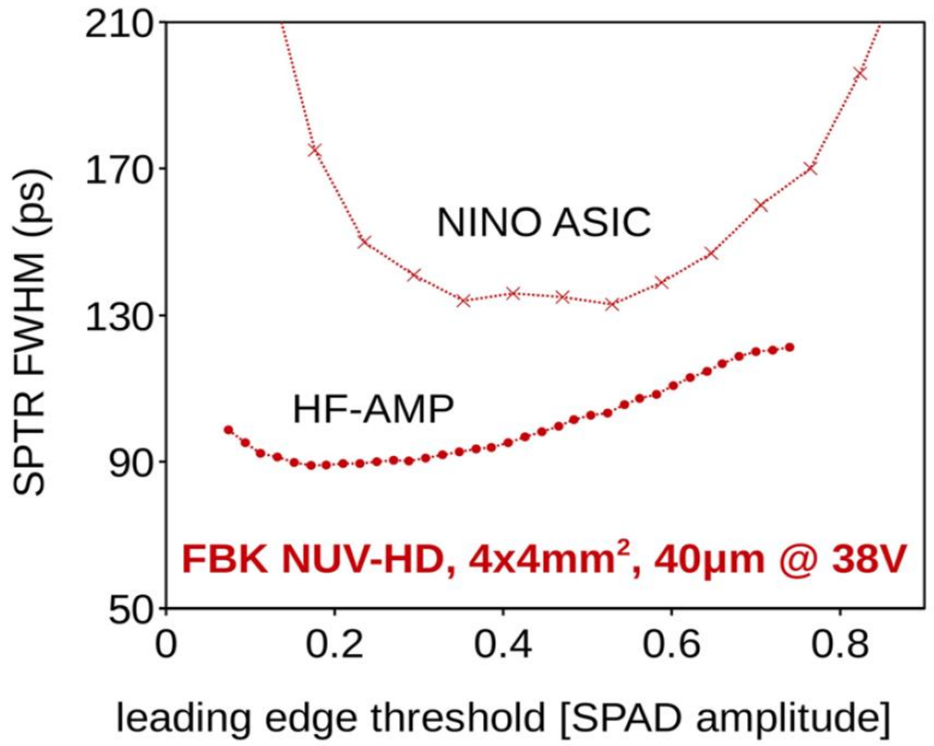


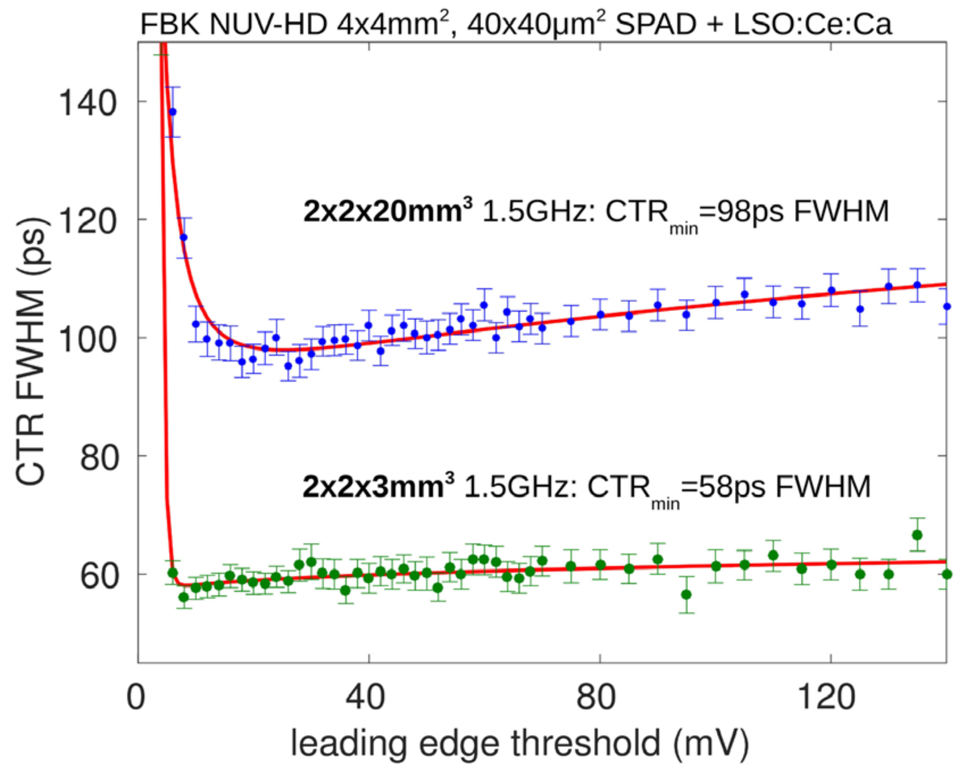




Gola, A et al. (2019). "NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler." *Sensors*, *19*(2), 308.

Timing with High-frequency readout (FWHM)





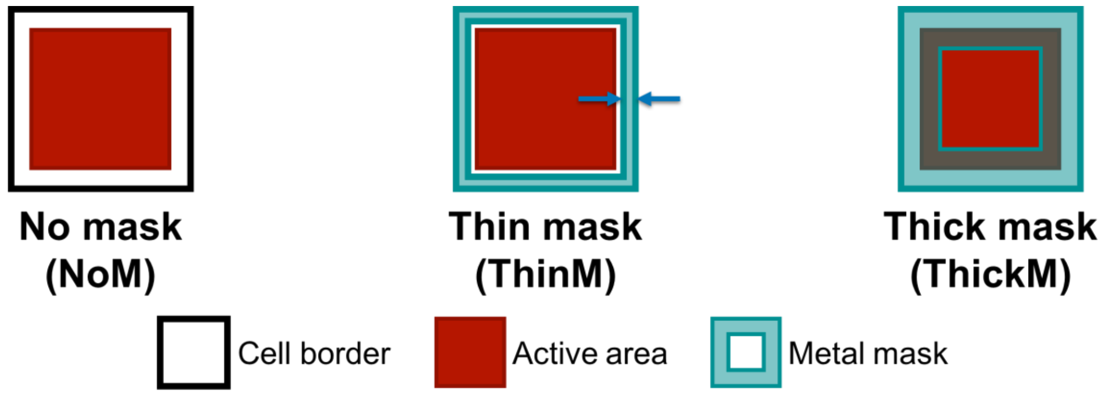
World record timing resolution: Single Photon Time resolution (SPTR, left) and Coincidence Resolving Time (CRT) in LYSO readout (right).

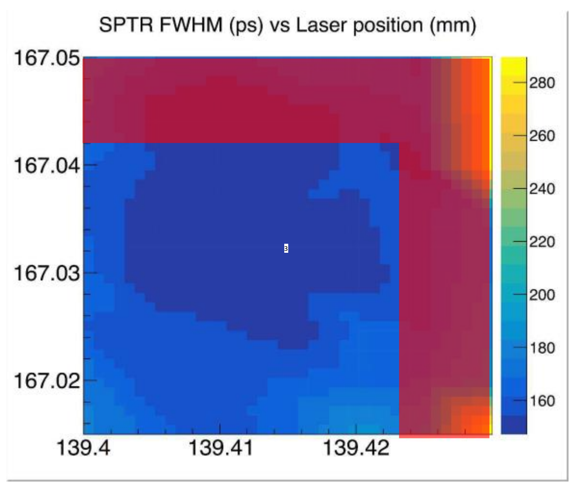
Gundacker, Stefan, et al. "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET." *Physics in Medicine & Biology* 64.5 (2019): 055012.

Timing performance
Optimization of SPTR with masking: CHK-HD

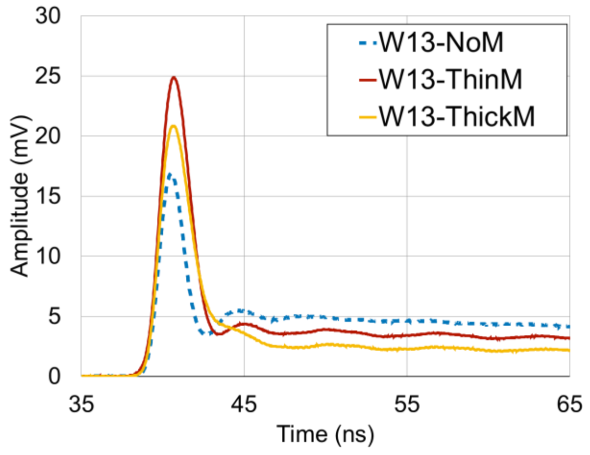
CHK-HD SiPMs is a variant of the NUV-HD SiPMs built to *experiment solutions to improve SPTR and detection efficiency* in applications where it matters the most, such as Cherenkov light readout.

- ***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

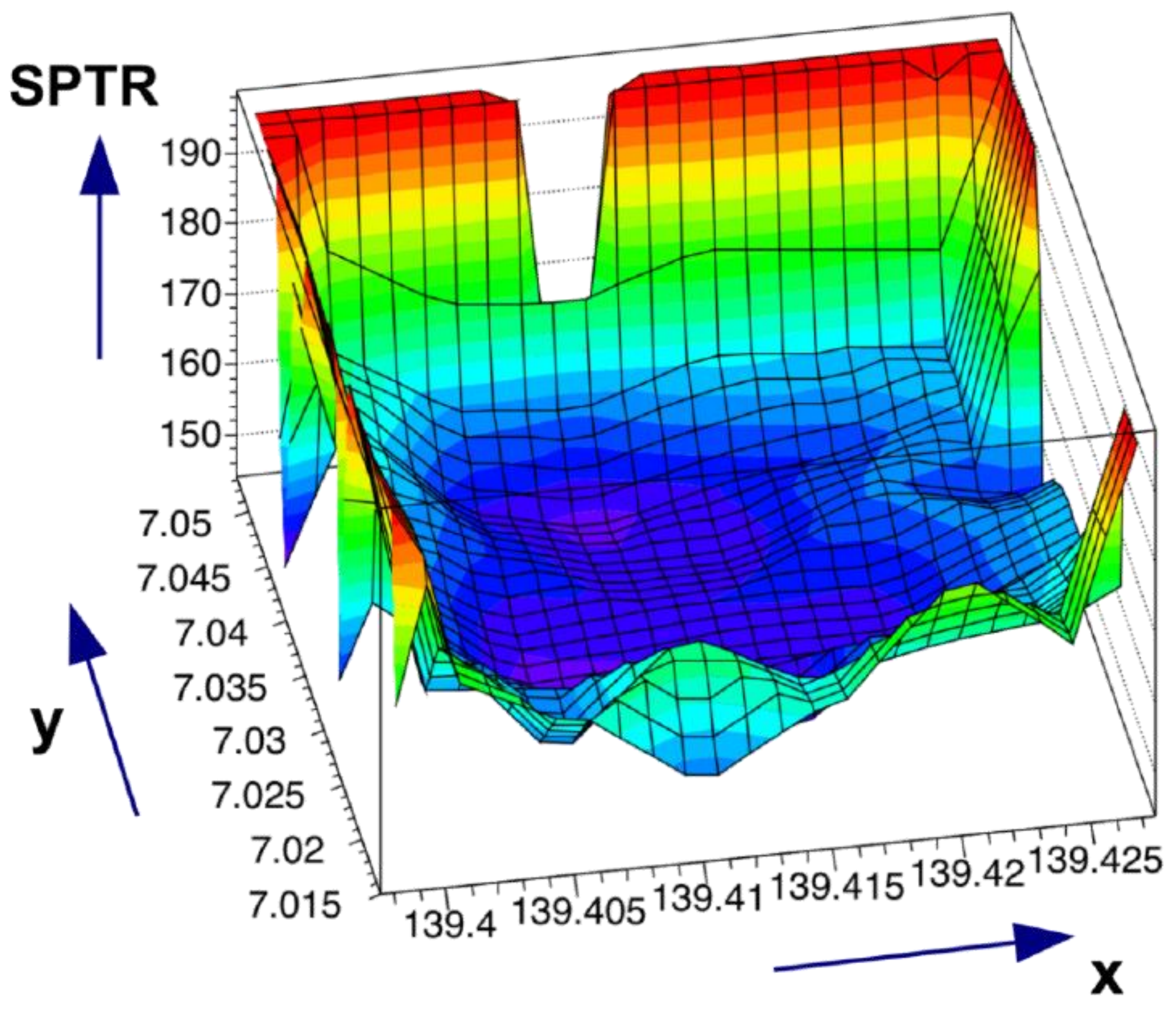




Masking of outer regions of the SPAD that have worse "local" SPTR.



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

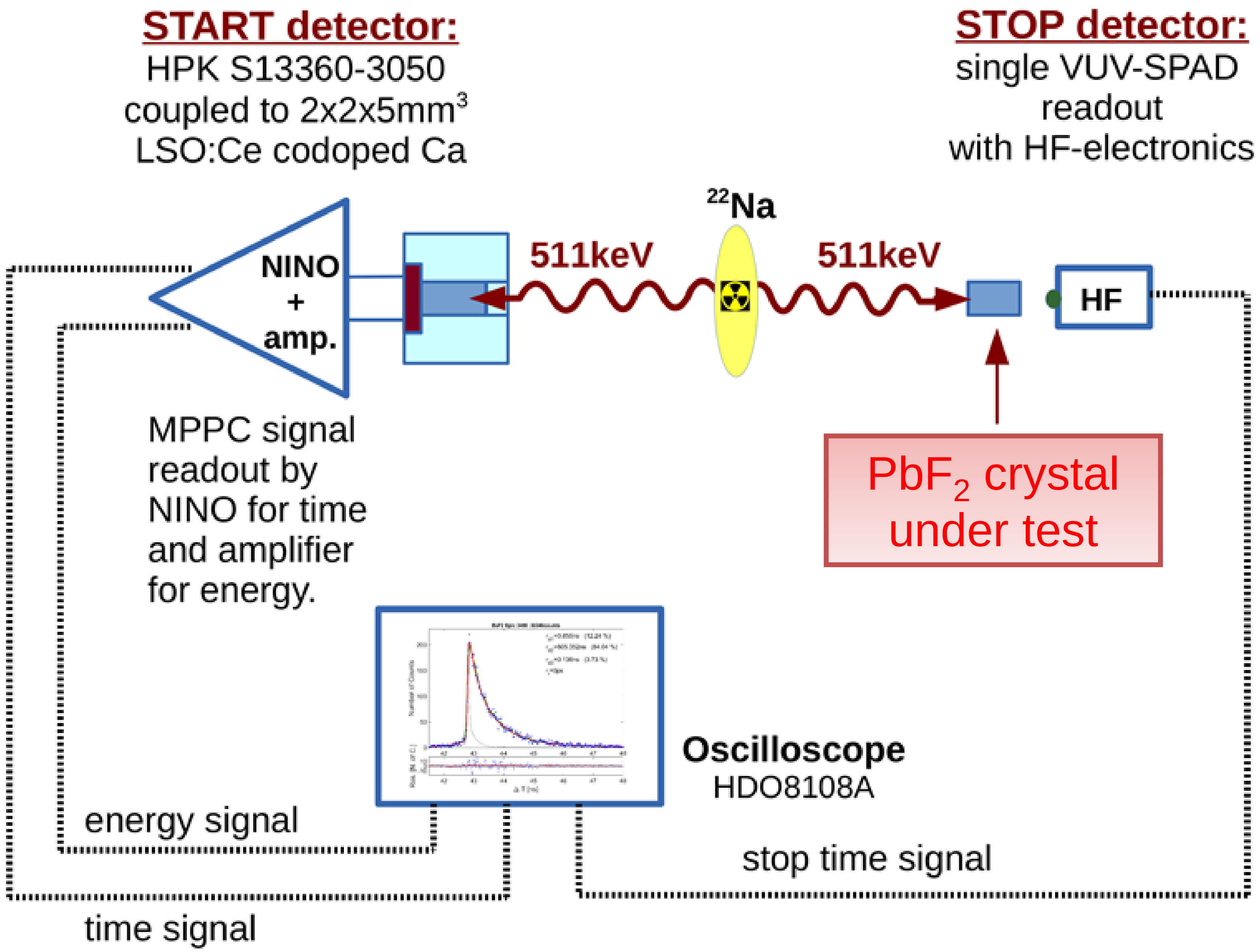


FBK NUV-HD
Traditional readout

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

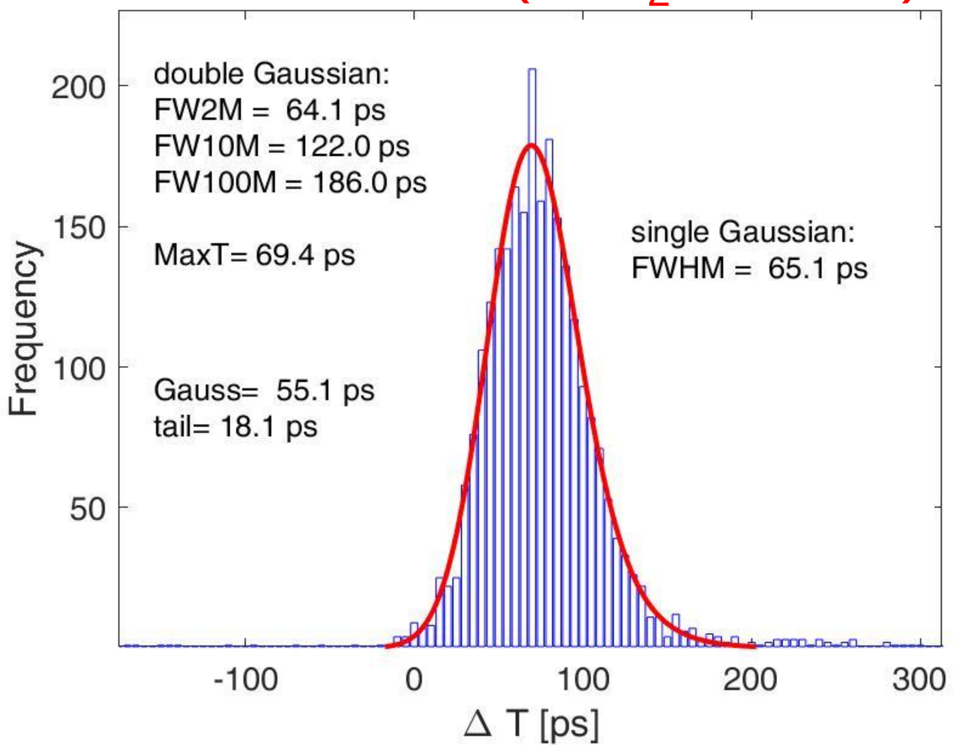
Timing performance
Optimization of SPTR with masking: CHK-HD

Using CHK-HD and high-frequency readout, S. Gundacker was able to measure excellent Single Photon Time Resolution, with a 3x3 mm^2 SiPM.



Intrinsic SPTR

SPTR FWHM (PbF_2 method)



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

Nicolaus Kratochwil et al 2021 Phys. Med. Biol. 66 195001

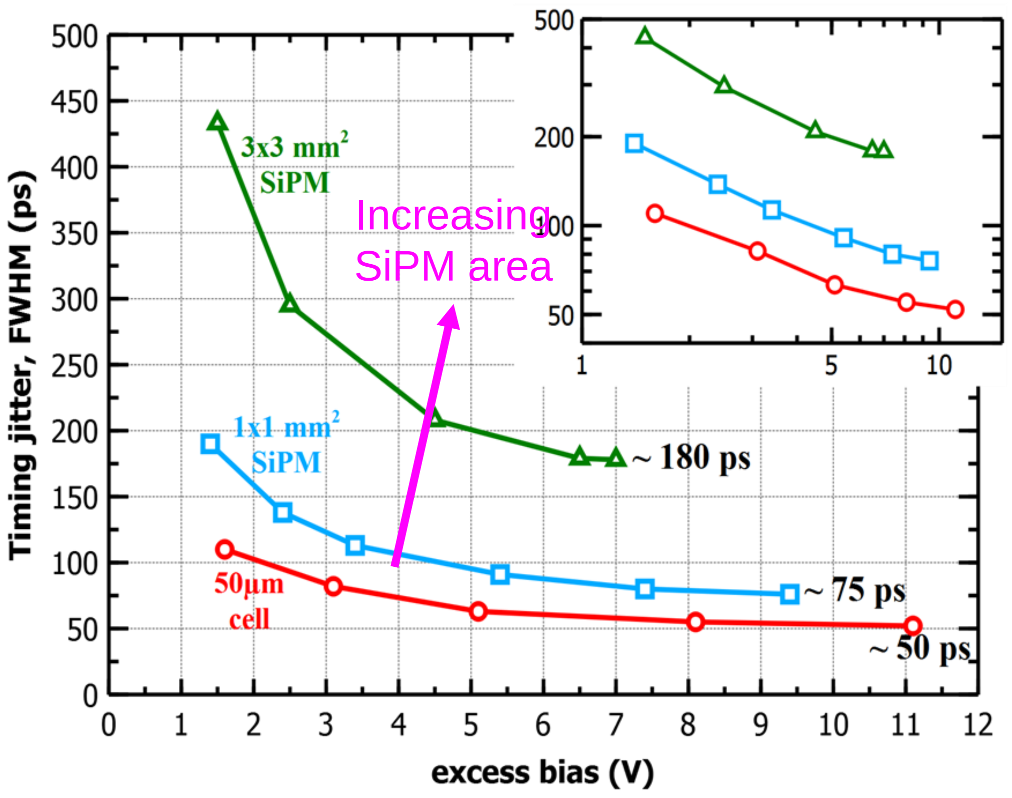
Measurements by S. Gundacker, presented at FTMI 2022 workshop

Timing performance
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

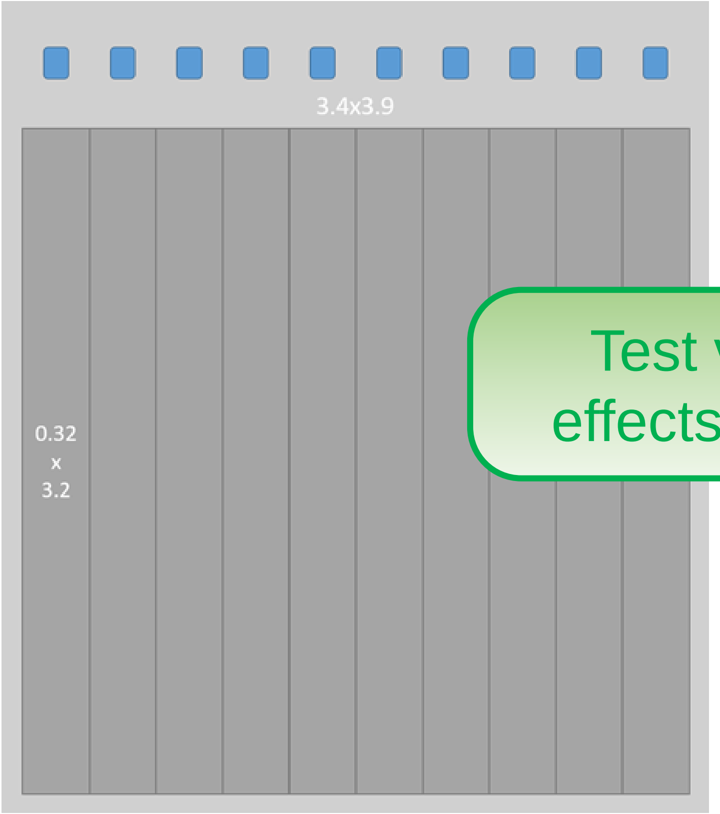


SPTR vs. excess bias for different SiPM sizes, *with traditional amplifier*.

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.

Strip SiPMs

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



Test vehicle to study effects of segmentation

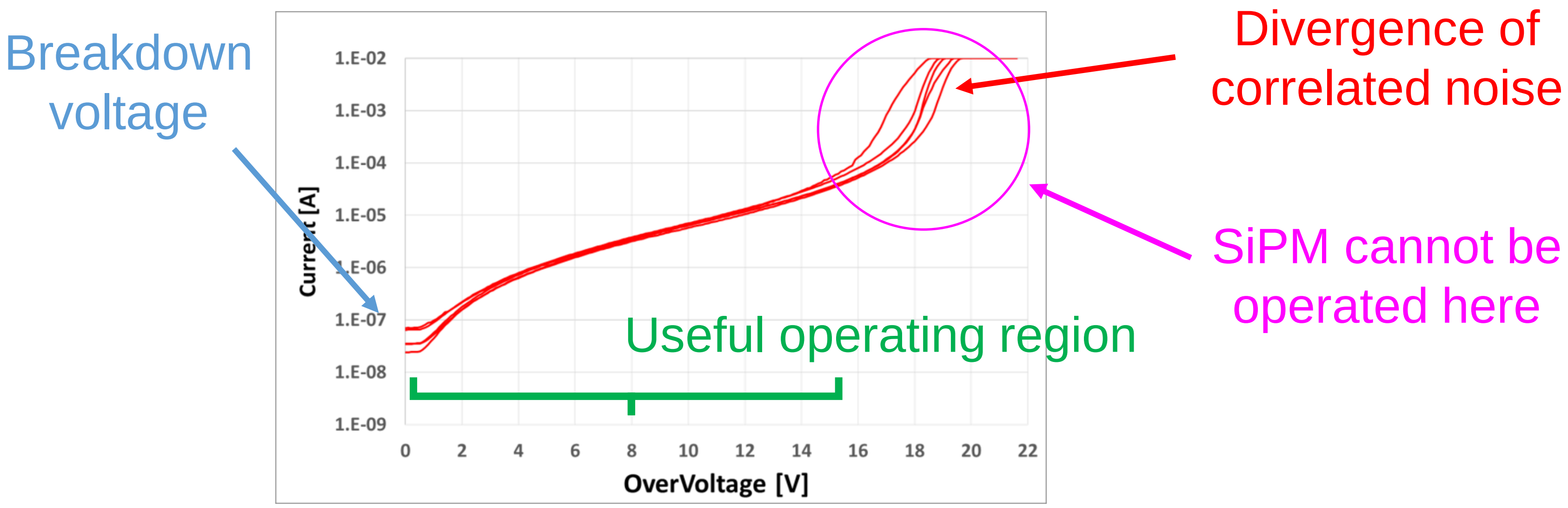
Example of segmented SiPM layout: a 3x3 mm2 active area is divided in 10 0.3x3 mm2 strip-SiPMs.

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

Worsening of the Few Photons Time Resolution

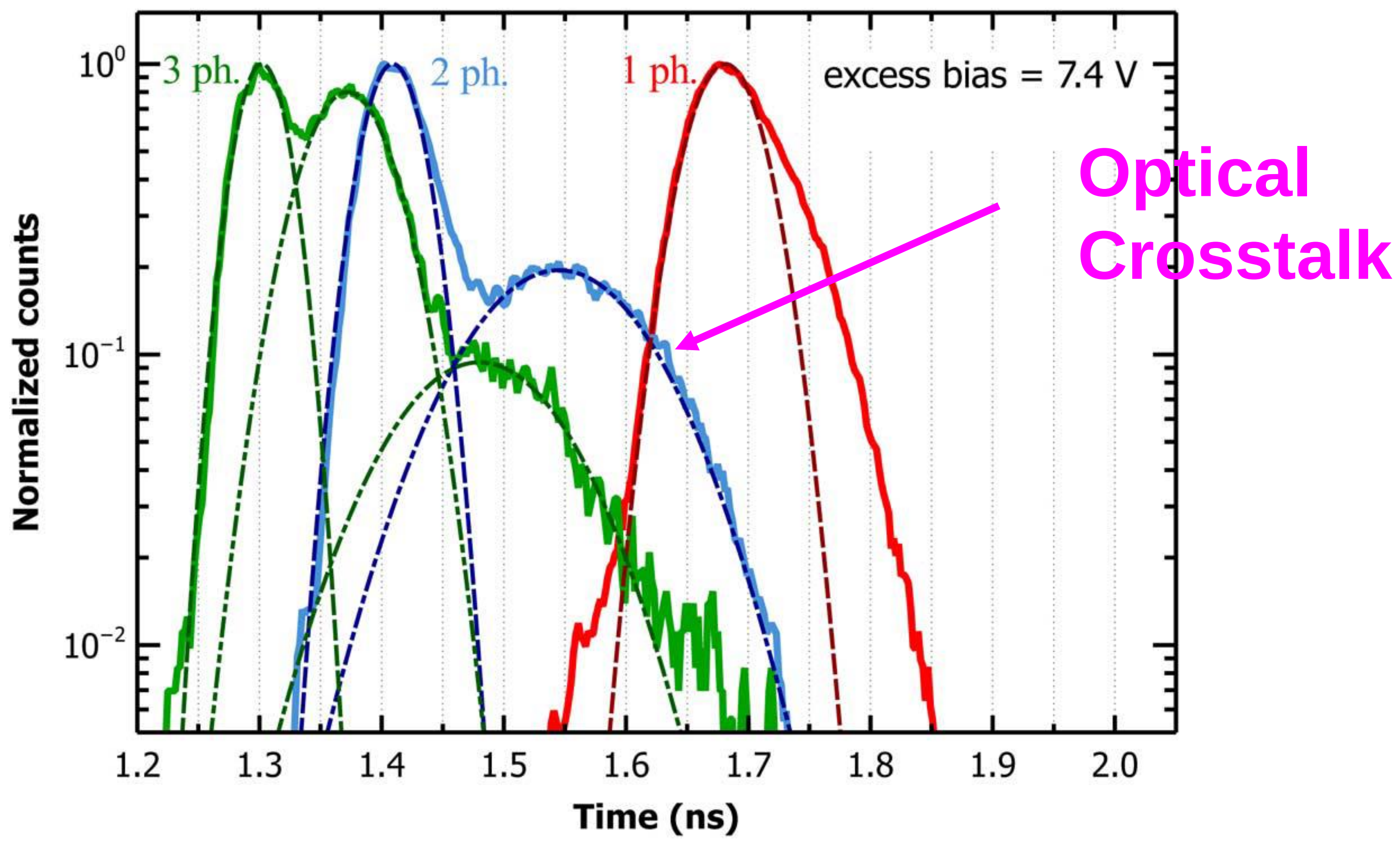


Above a certain over-voltage the number of dark counts and, thus, the reverse current diverge.

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

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

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

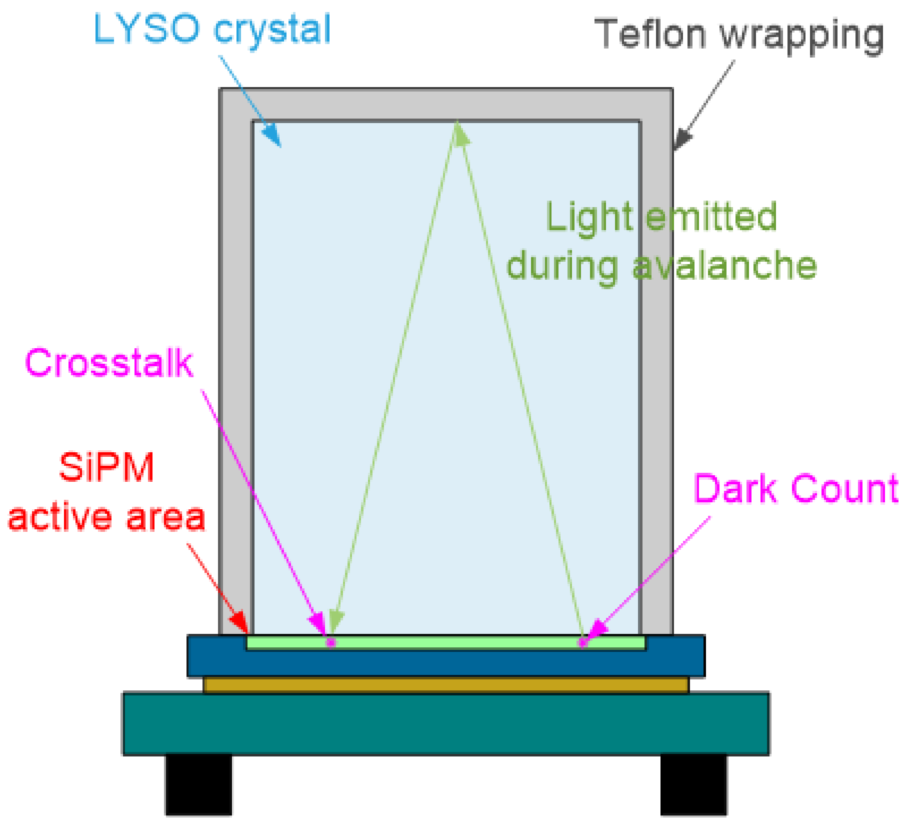


Few-photon time resolution measured with Leading-edge discriminator
Additional peaks are most likely generated by (delayed) correlated noise.

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

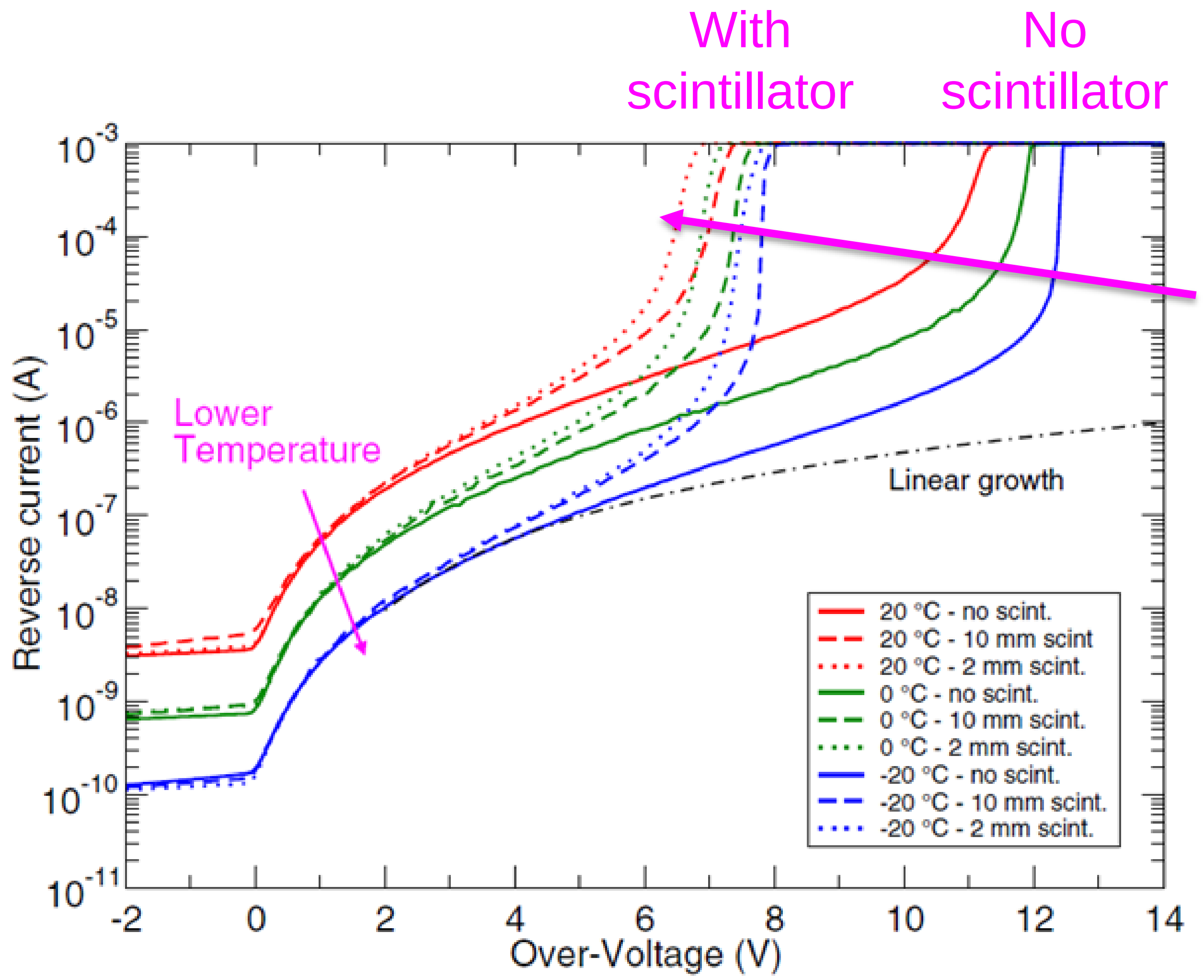
Optical crosstalk probability is enhanced by the presence of the scintillator: external crosstalk.



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***.



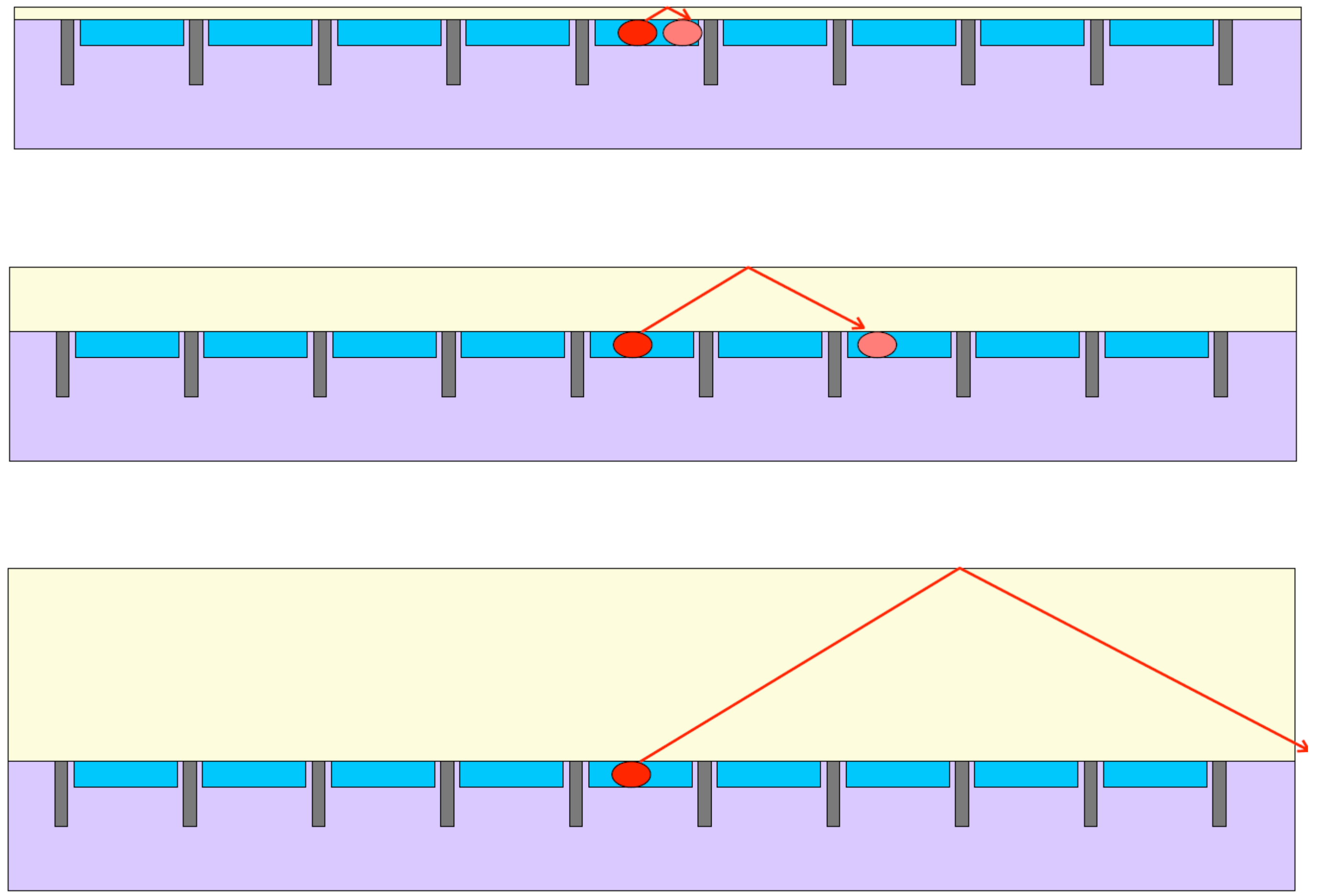
Comparison of SiPM IV with different scintillator sizes placed on top of them, at different temperatures.

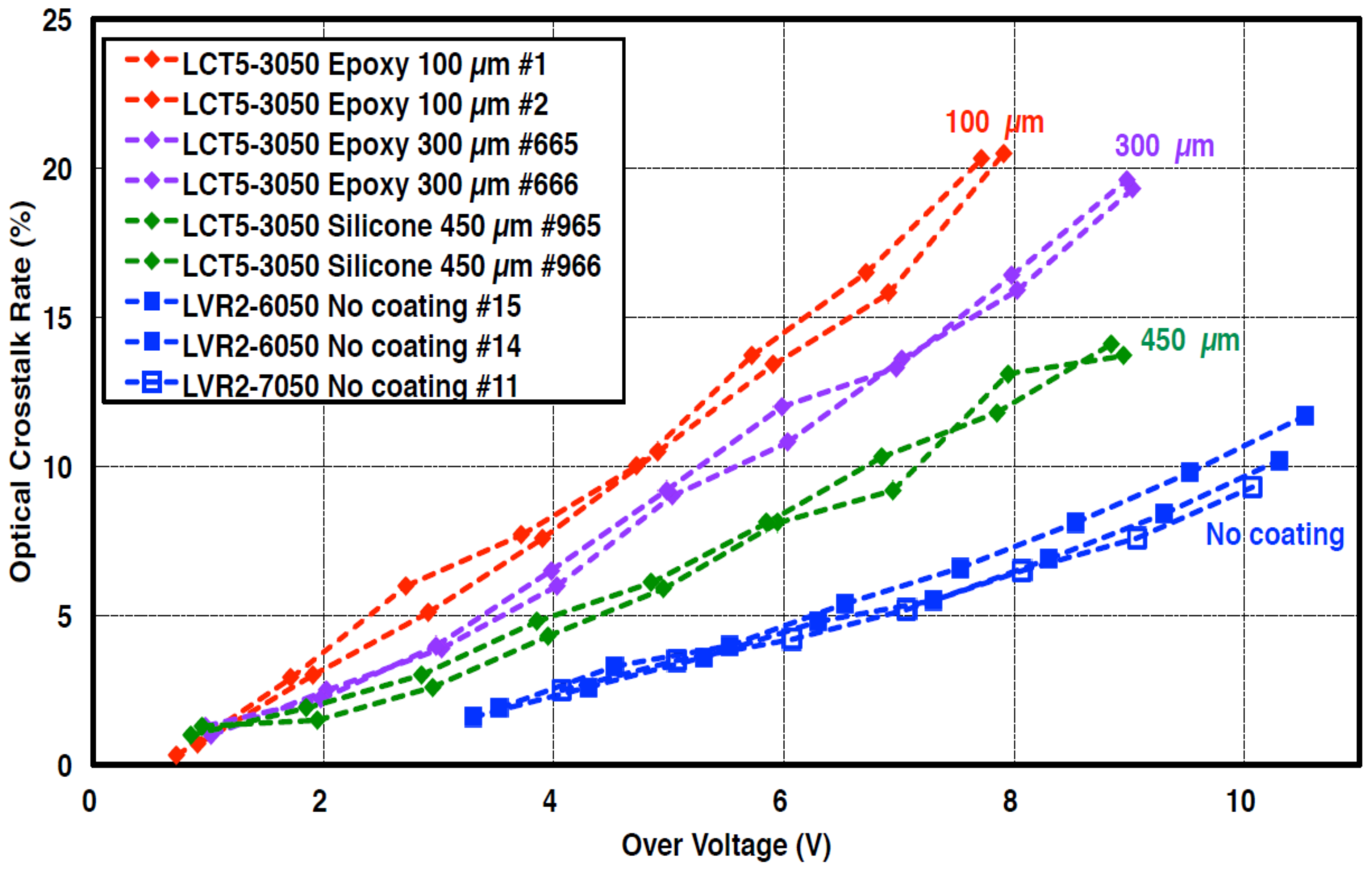
Gola, Alberto, et al. "SiPM optical crosstalk amplification due to scintillator crystal: effects on timing performance." *Physics in Medicine & Biology* 59.13 (2014): 3615.

Optical crosstalk
External Crosstalk and protective resin

The package geometry, in particular the resin thickness, has a significant effect on the optical crosstalk probability.

The effect was studied on Hamamatsu SiPMs and discussed in the ICASiPM conference.





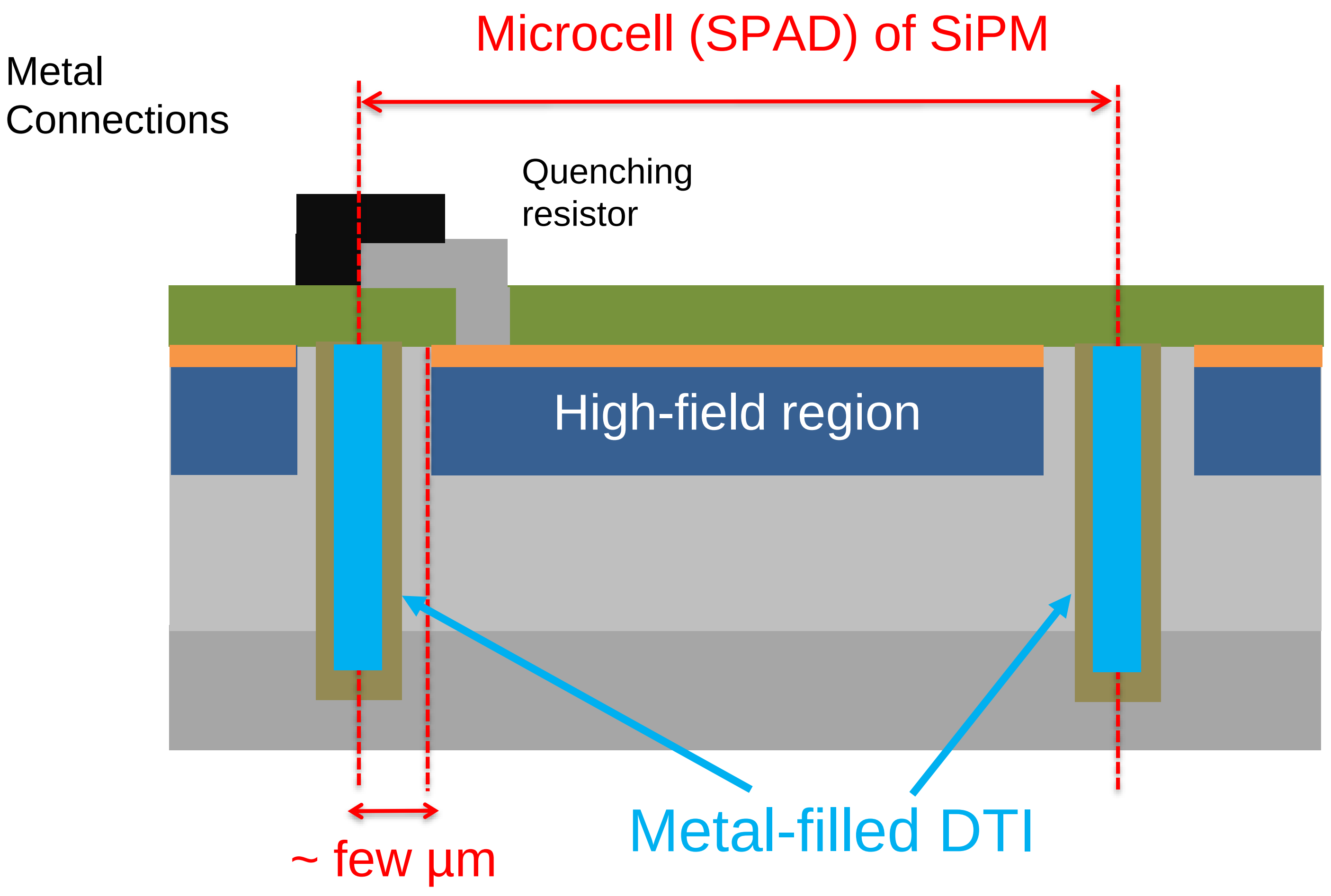
We can identify an *optimal thickness of the encapsulating resin*

Suppressing Optical Cross Talk in Silicon Photomultiplier
ICASiPM, JUN 11–15, 2018, Schwetzingen Germany

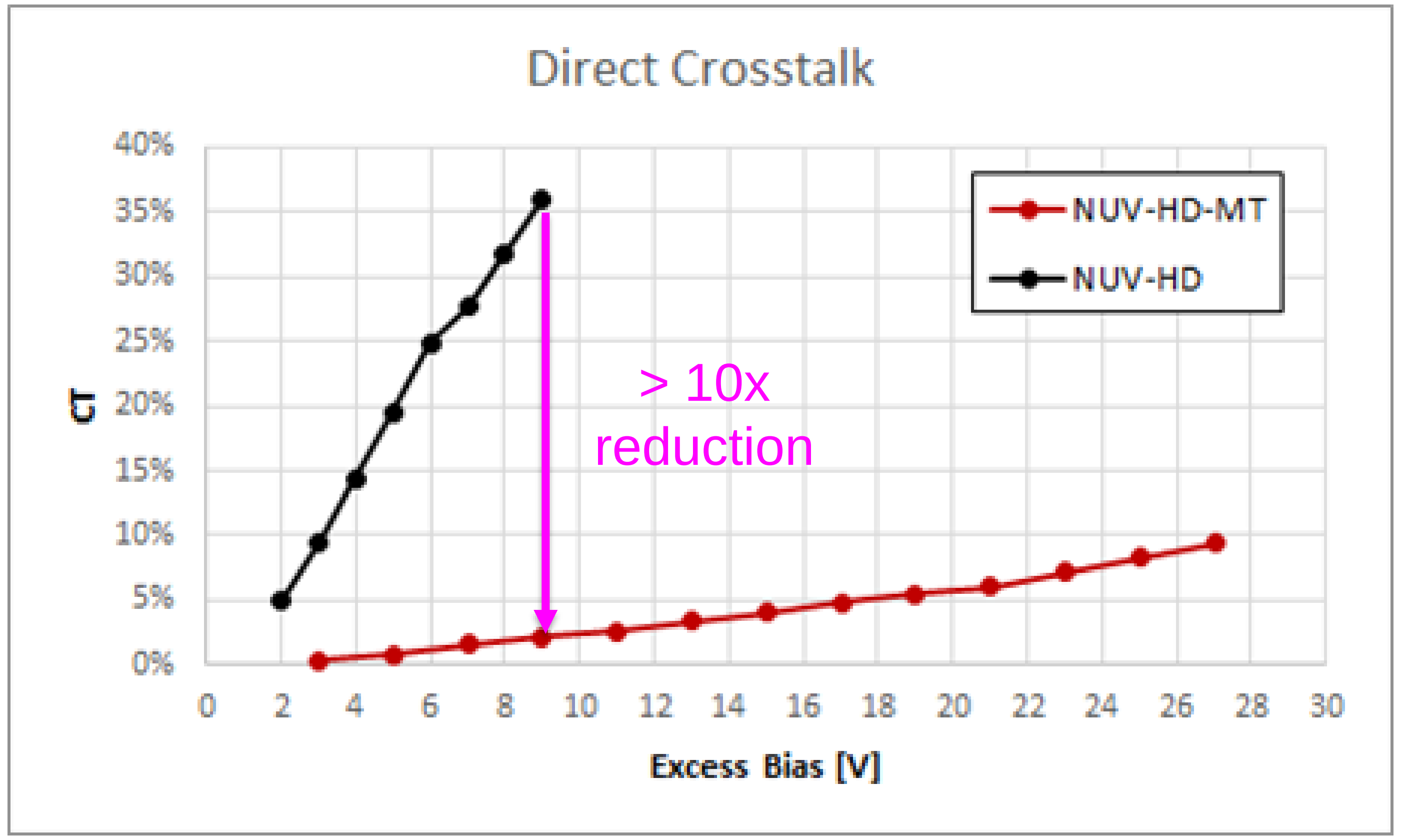
Reduction of optical crosstalk
NUV-HD-MT development

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 drawing of the NUV-HD-MT, with the addition of metal-filled Deep Trench Isolation.

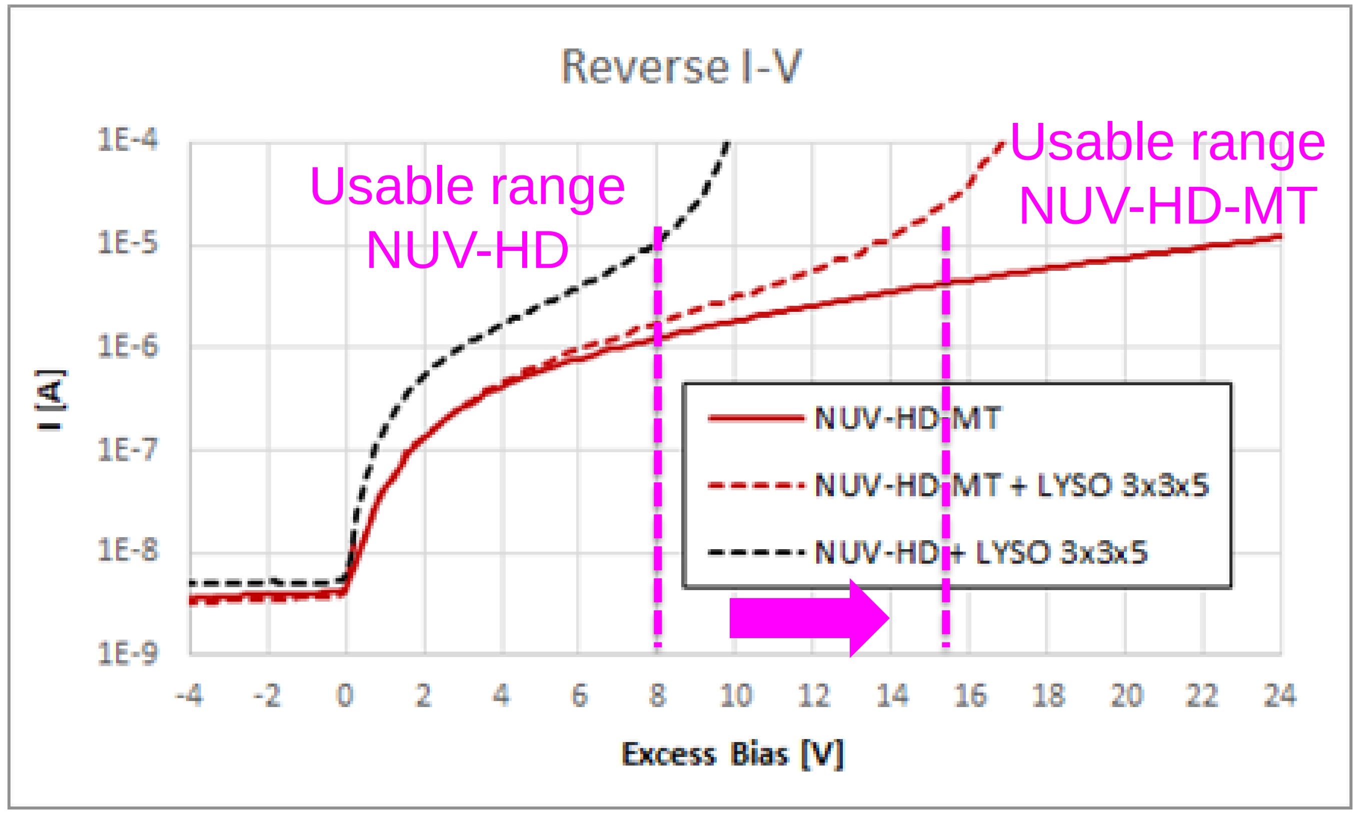


Reduction of optical crosstalk probability in NUV-HD-MT, compared to the “standard” NUV-HD. Measurement without encapsulation resin, i.e. *only considering internal crosstalk probability*.

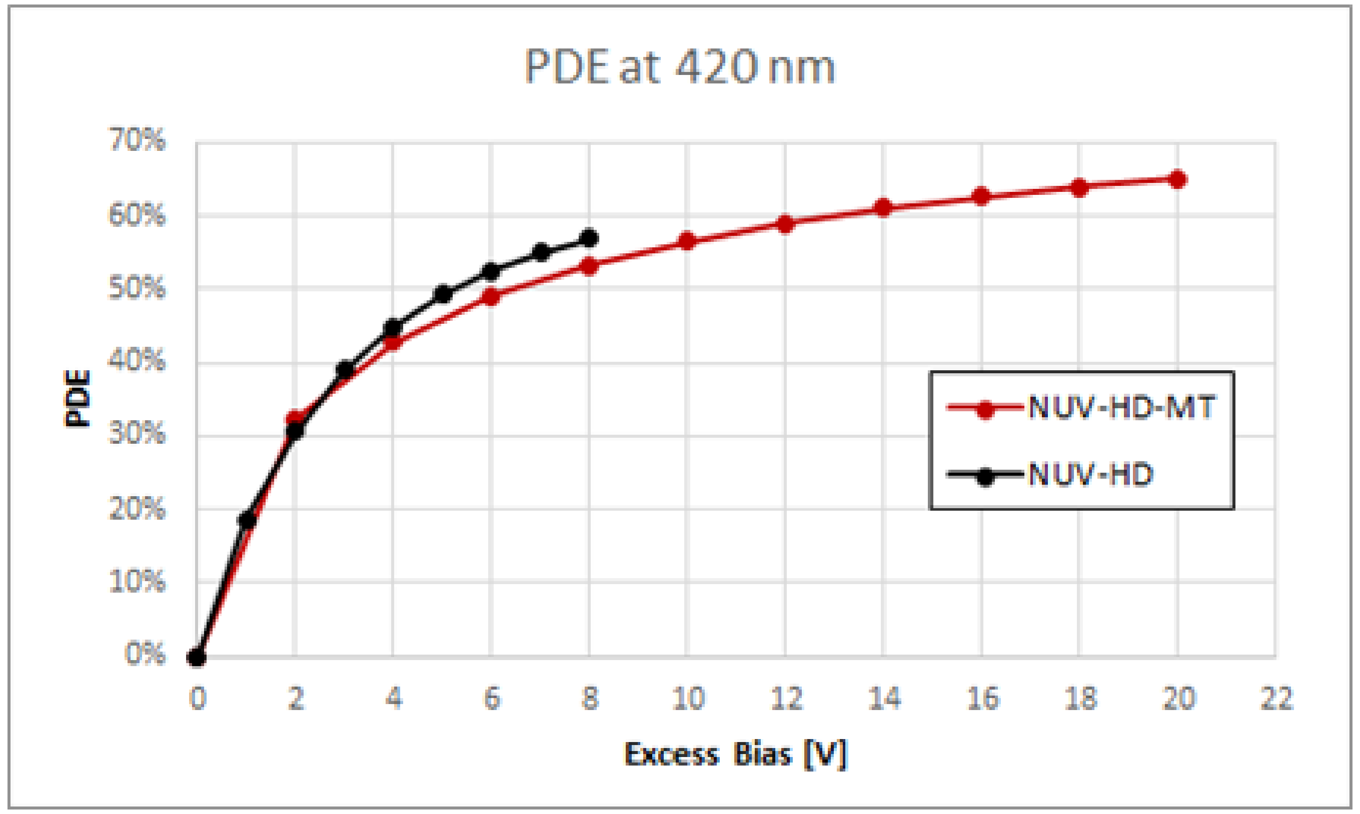
Reduction of optical crosstalk
NUV-HD-MT bias range

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.

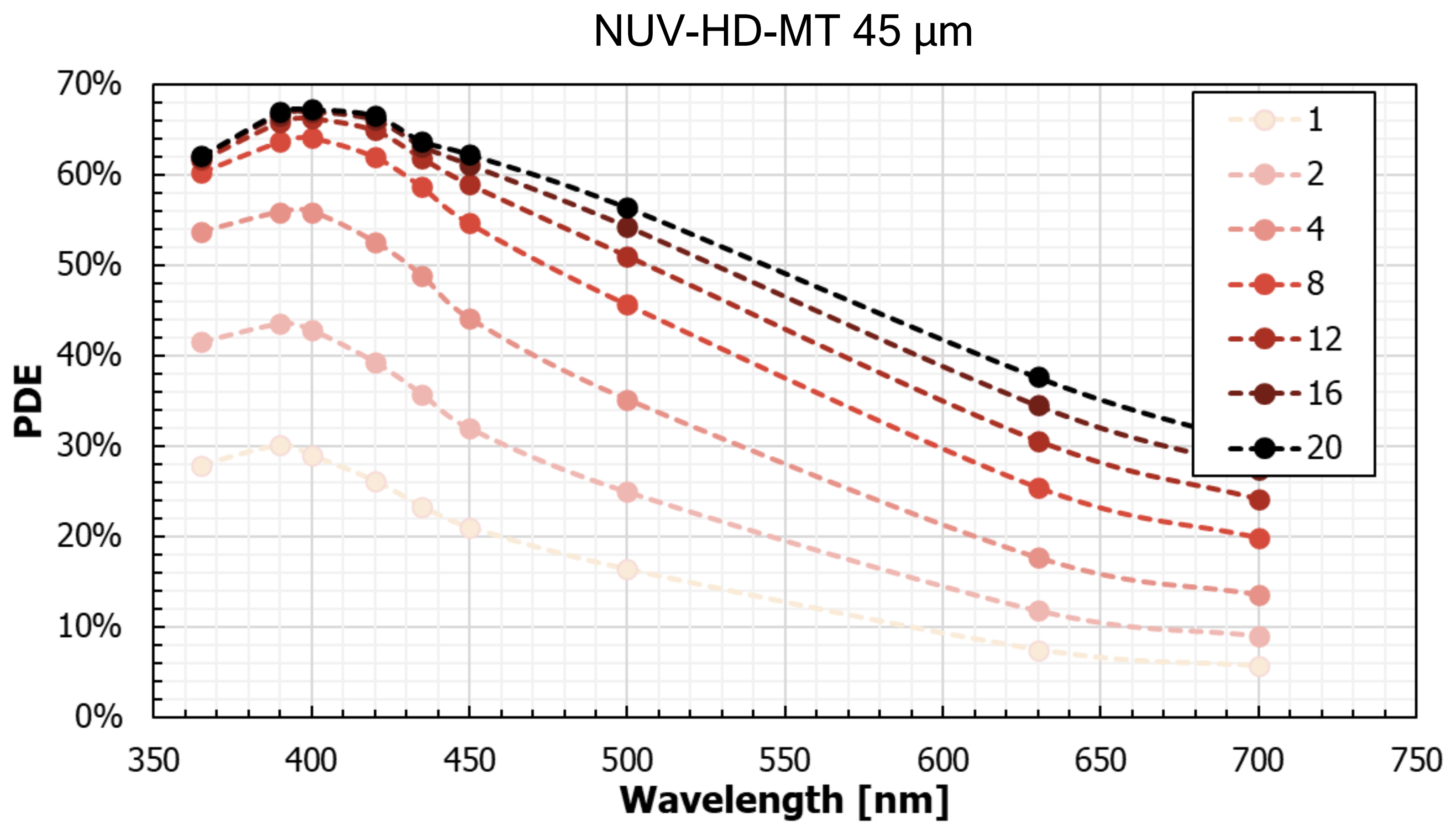


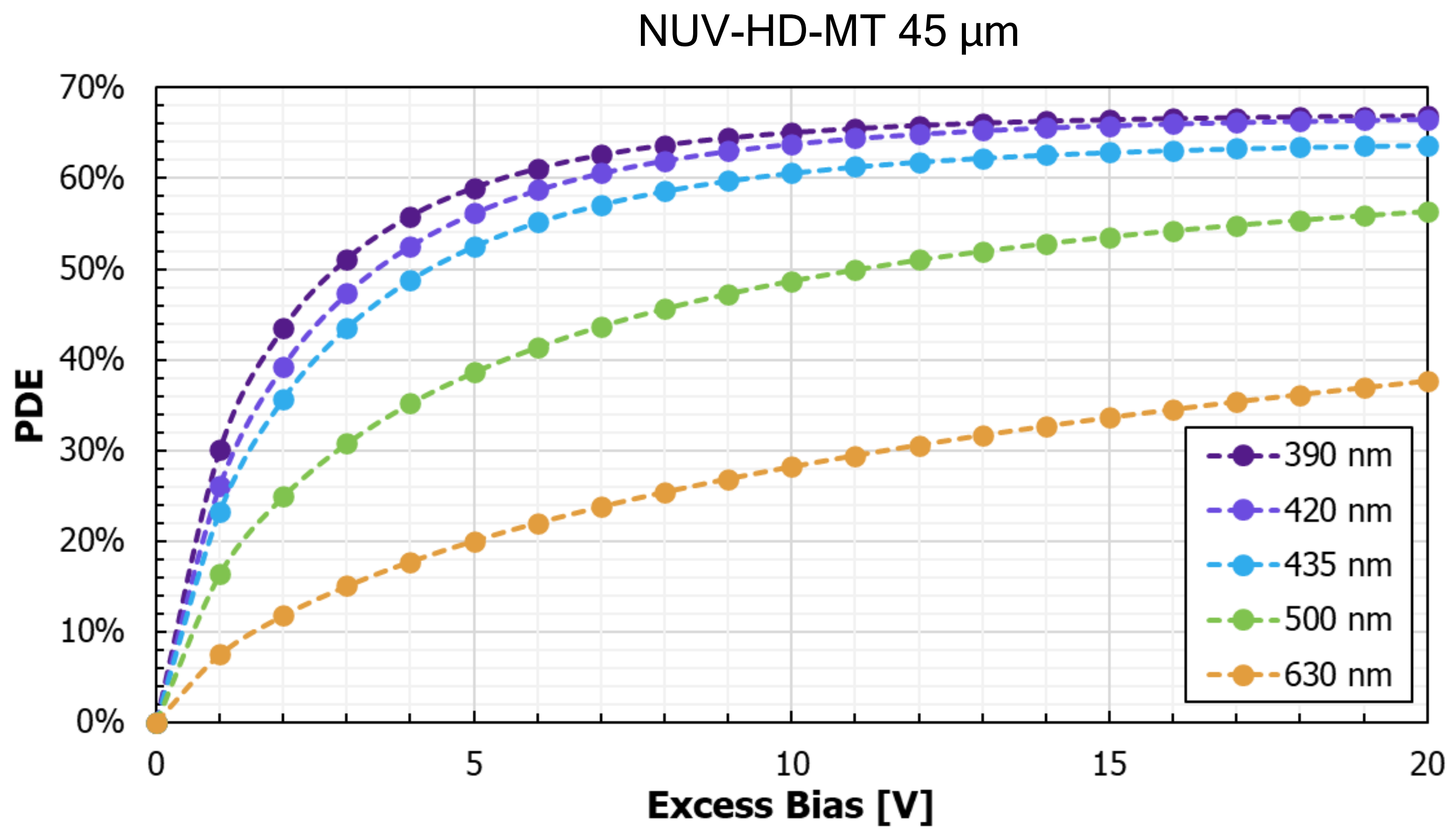
PDE at 420 nm measured on a NUV-HD-MT SiPM with 45 um cell size.

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*.

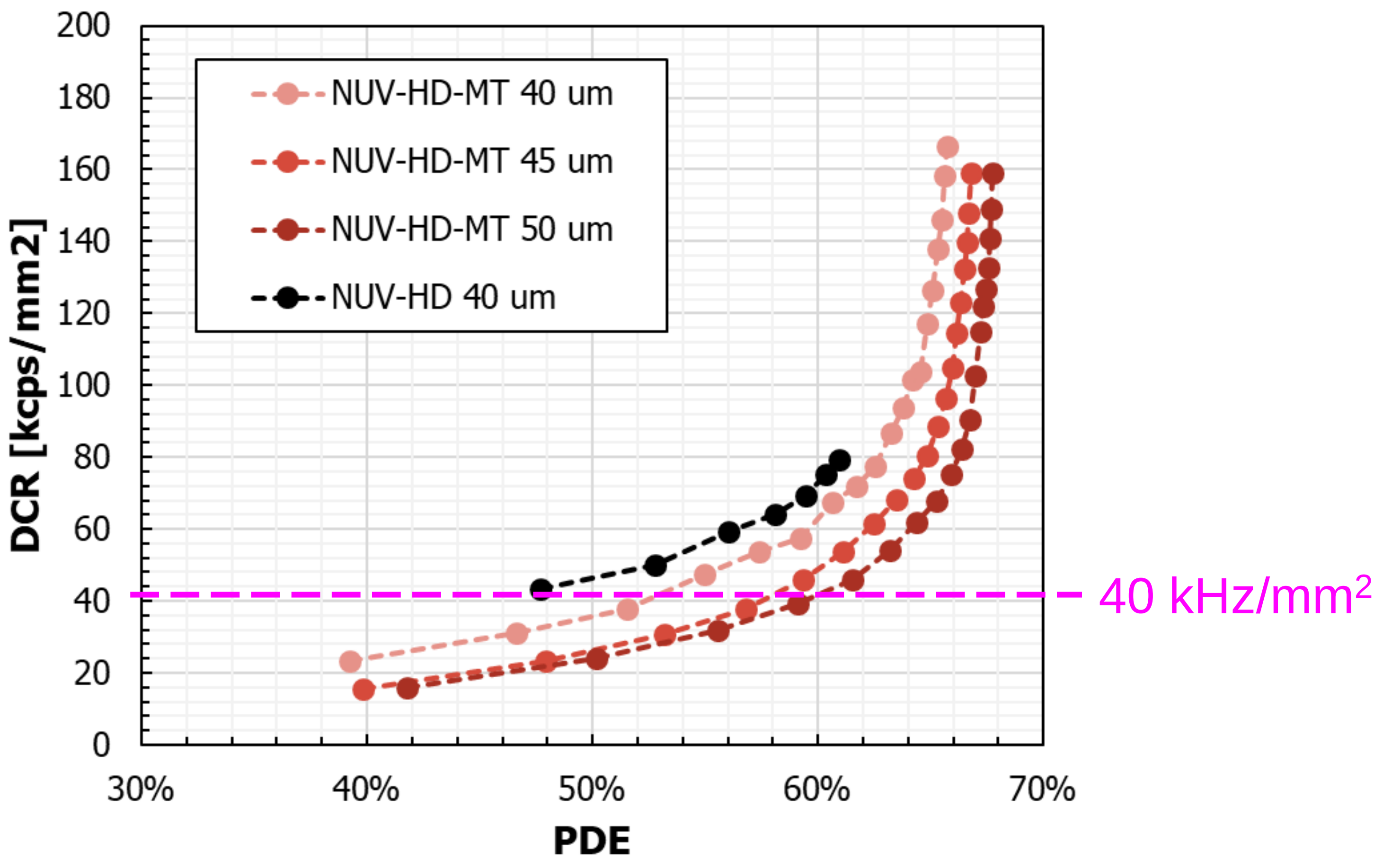




Reduction of optical crosstalk
NUV-HD-MT electro optical performance

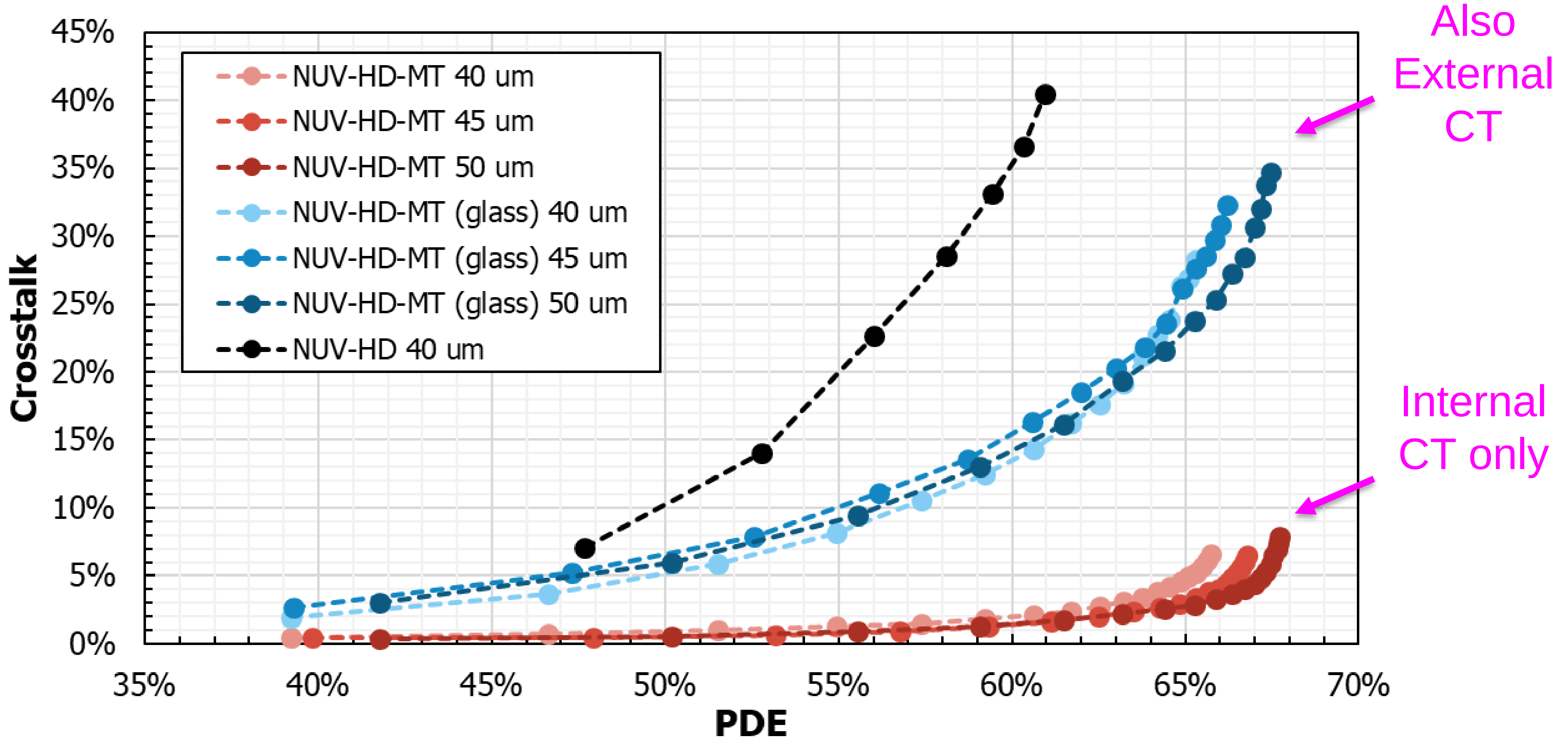
NUV-HD-MT *nuisance parameters are better represented and compared as a function of the PDE*.

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

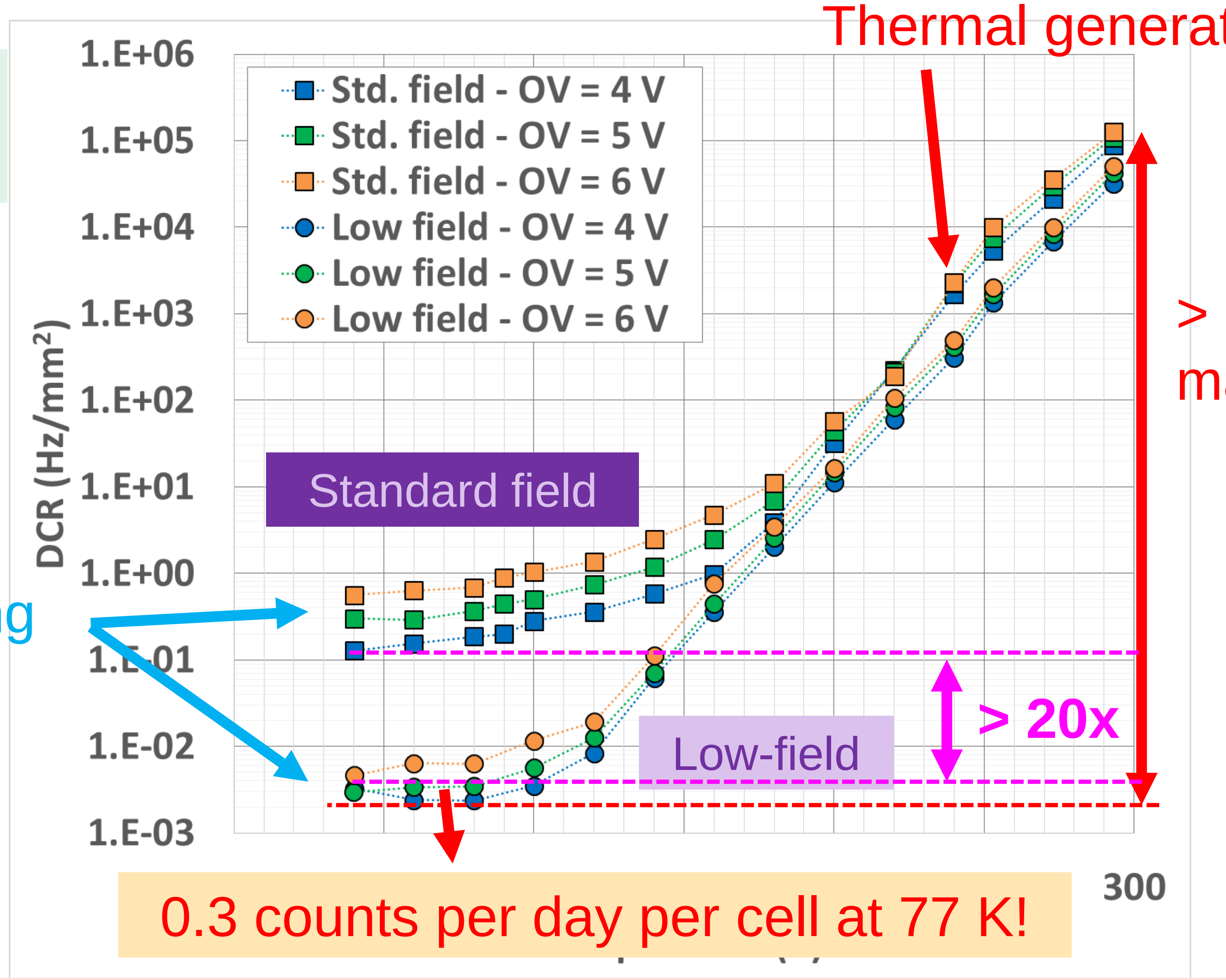


DiCT vs. peak PDE (measured at 420 nm) for different cell sizes of the NUV-HD-MT technology, with and without protective glass on top of the SiPM (used for TSV)

Cryogenic operation
DarkSide-20k SiPMs

NUV-HD-Cryo SiPM technology is an *enabling technology for the DarkSide-20k* experiment, currently under construction.

25 um cell

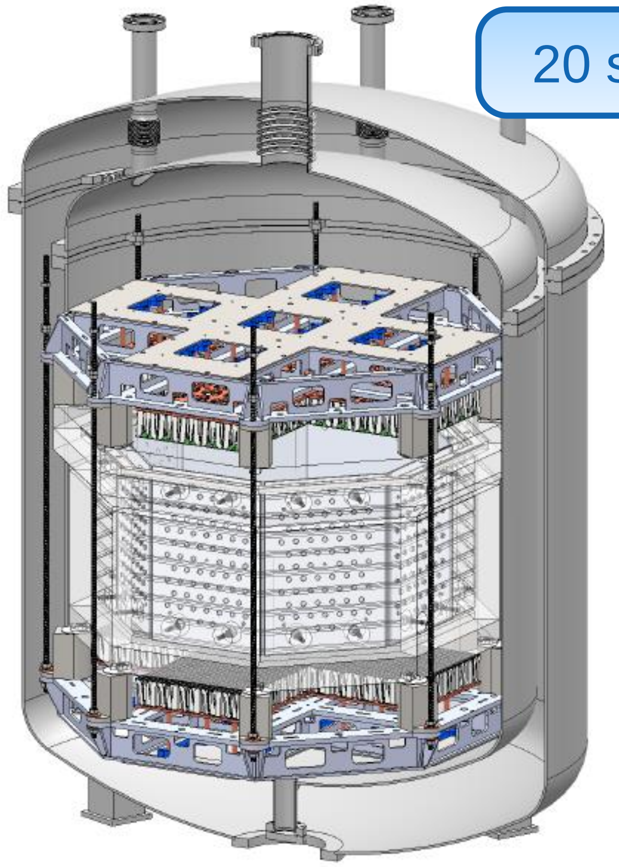


0.3 counts per day per cell at 77 K!

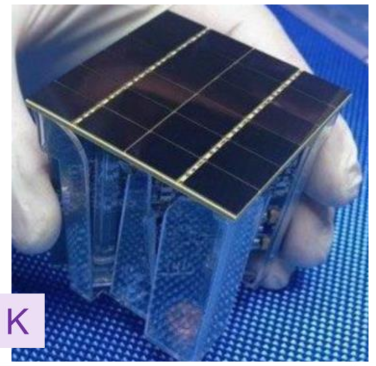
A 10x10 cm^2 SiPM array would have a total DCR < 100 cps!

Reduction of Dark Count Rate at cryogenic temperature thanks to electric field engineering in FBK SiPMs.

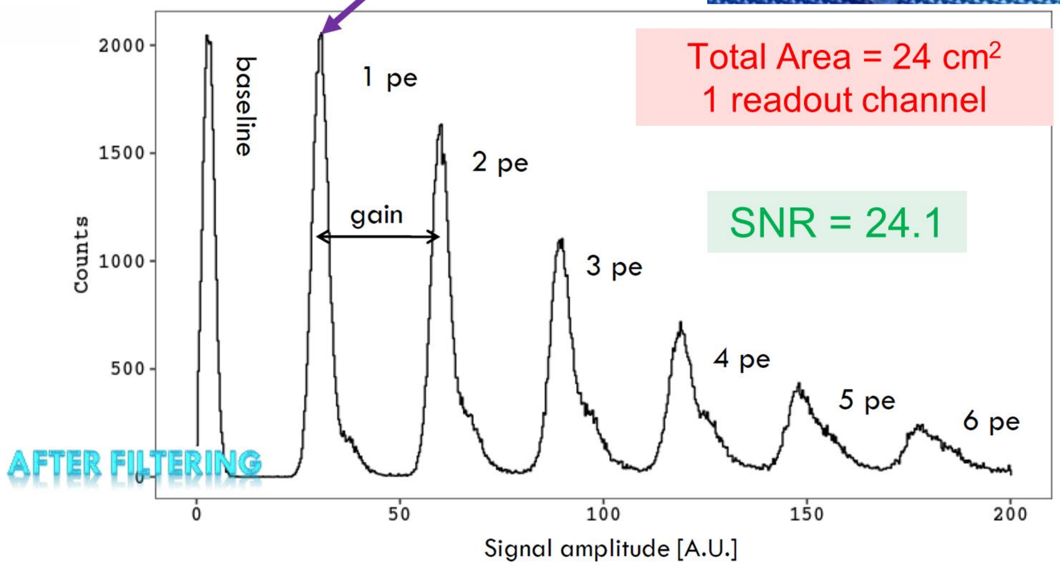
20 sqm of silicon



Darkside-20k experiment under construction at LNGS using FBK SiPMs fabricated at Lfoundry: *20 m^2 of SiPMs* operated at 87 K.



Good gain uniformity of ~ 3M SPADs at 77 K

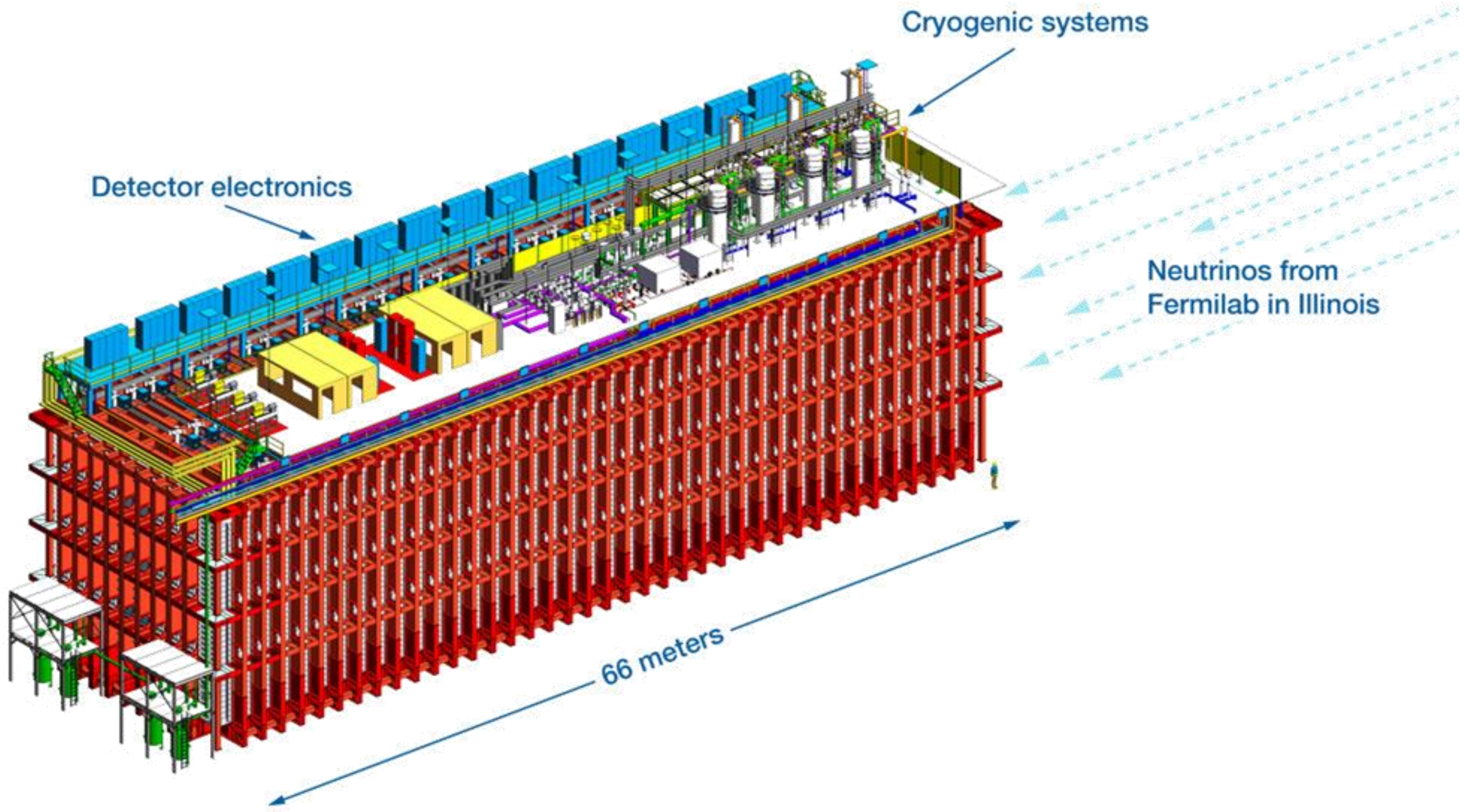


Photon counting at 77 K with a single, 24 cm_2 SiPM Tile.

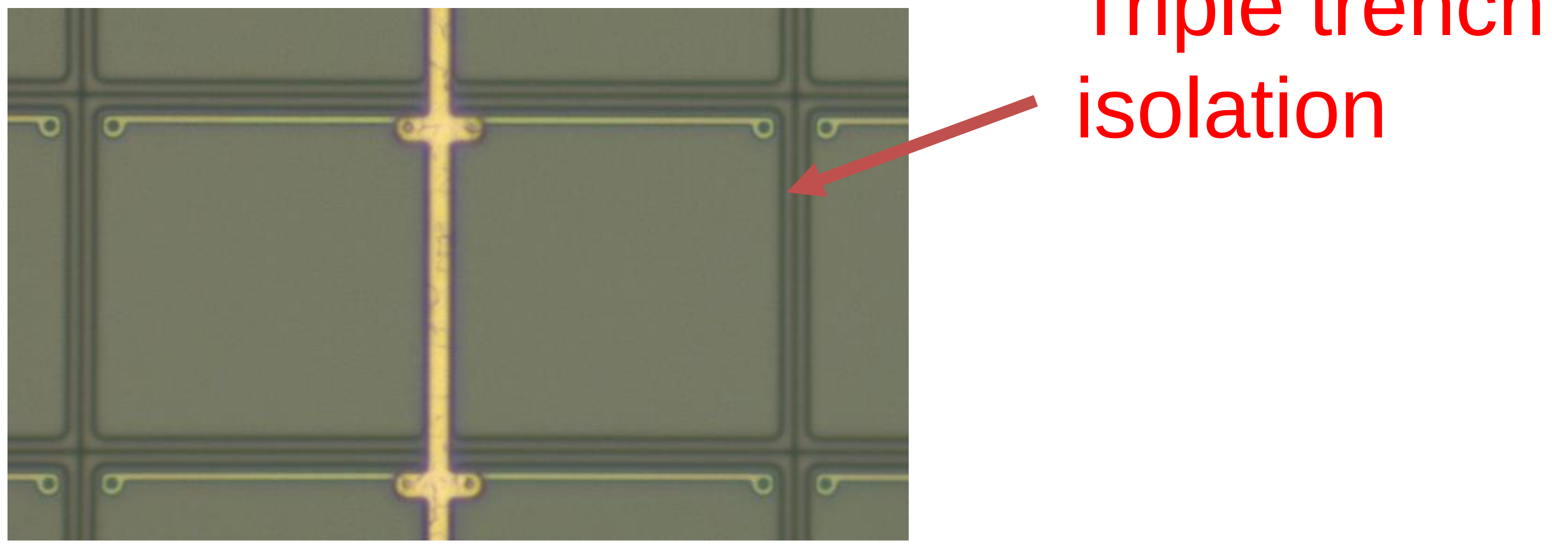
Acerbi, Fabio, et al. "Cryogenic characterization of FBK HD near-UV sensitive SiPMs." *IEEE Transactions on Electron Devices* 64.2 (2017): 521-526.

Cryogenic operation
DUNE SiPMs

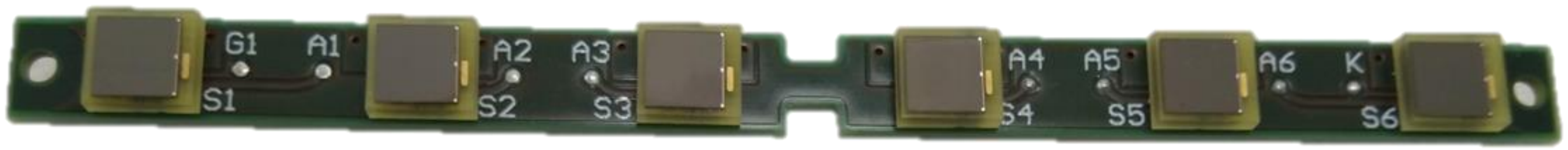
NUV-HD-Cryo SiPM technology is at the basis of the *ongoing R&D collaboration between FBK and UniMiB* for the production of >250k channels for the DUNE experiment.



One of the four far-detector modules for the Deep Underground Neutrino Experiment.



SiPM microcell optimized for DUNE

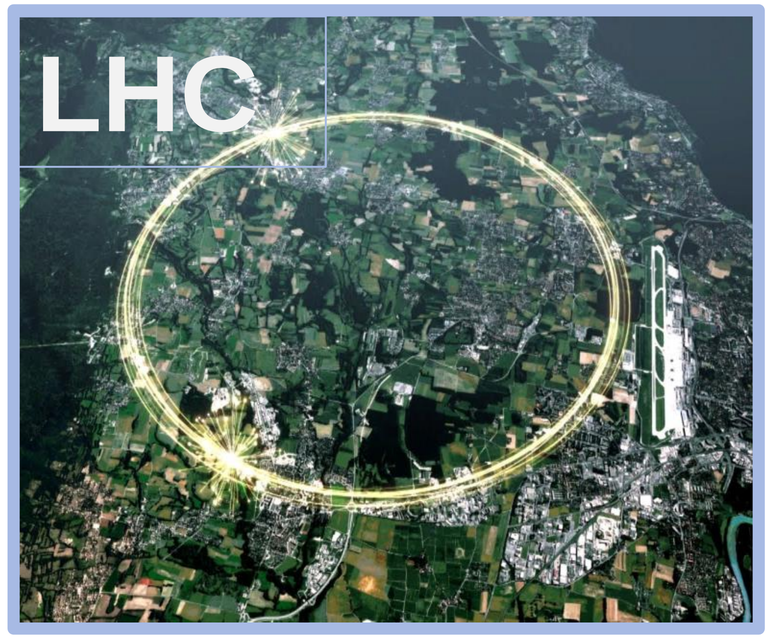


Prototype 6-channel array based on NUV-HD-Cryo fabricated at Lfoundry and packaging developed by FBK.

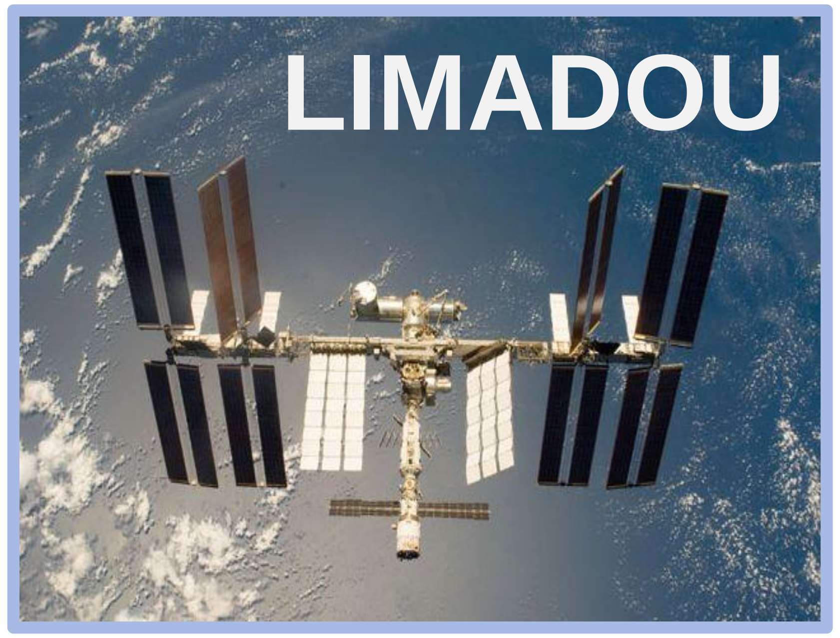
Radiation Hardness
Motivation for R&D

Improving radiation hardness of SiPMs is *one of the next frontiers of development at FBK* for very important applications, both in big science experiments and in space.

Detectors for collider experiments: from 10^{10} neq/cm² to >10^{14} neq/cm²



Geostationary orbit space experiments: ~$5 \cdot 10^{10}$ neq/cm²



What is the definition of radiation hardness for SiPMs?

R&D approach:

- *Qualification* of radiation tolerance of current SiPM technologies.
- *Study / modeling* of the effects of radiation damage on SiPM characteristics, under different sources of radiation.
- Development of a *highly customized SiPM technology* for optimal performance after irradiation is likely needed.

Test Beam 1 – Trento Proton Therapy
Experimental Setup and DoE

Relatively low maximum irradiation dose, targeting space applications and certain HEP experiments.

Energy: 148 MeV source + inhibitor → ***74 MeV proton energy***

Dose: 12 dose steps:

$\sim 5\cdot10^{6} - 4\cdot10^{11}$ p/cm^2

↓ (*NIEL scaling hypothesis*)

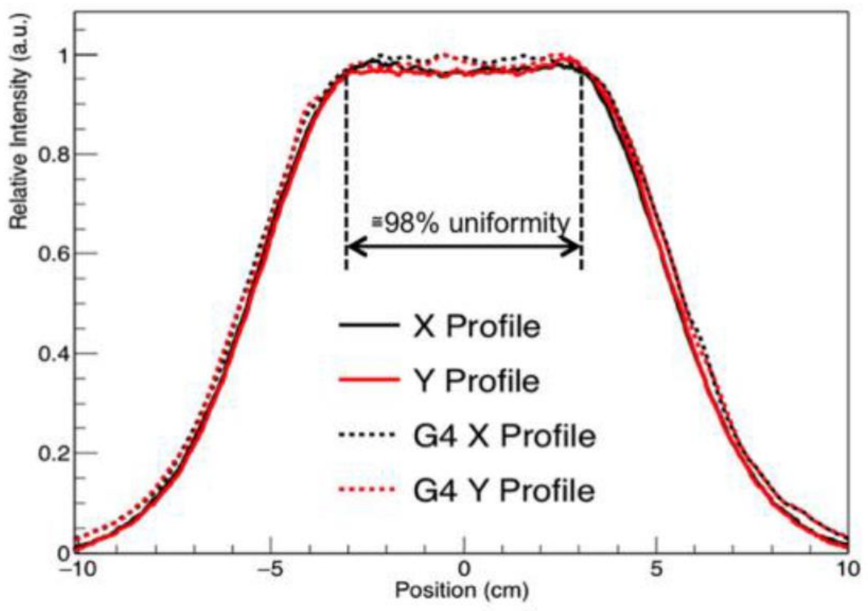
$\sim 7\cdot10^{6} - 6\cdot10^{11}$ ***1 MeV*** n_{eq}/cm^2

Analysis:

- *Online IV measurement* between each irradiation step;

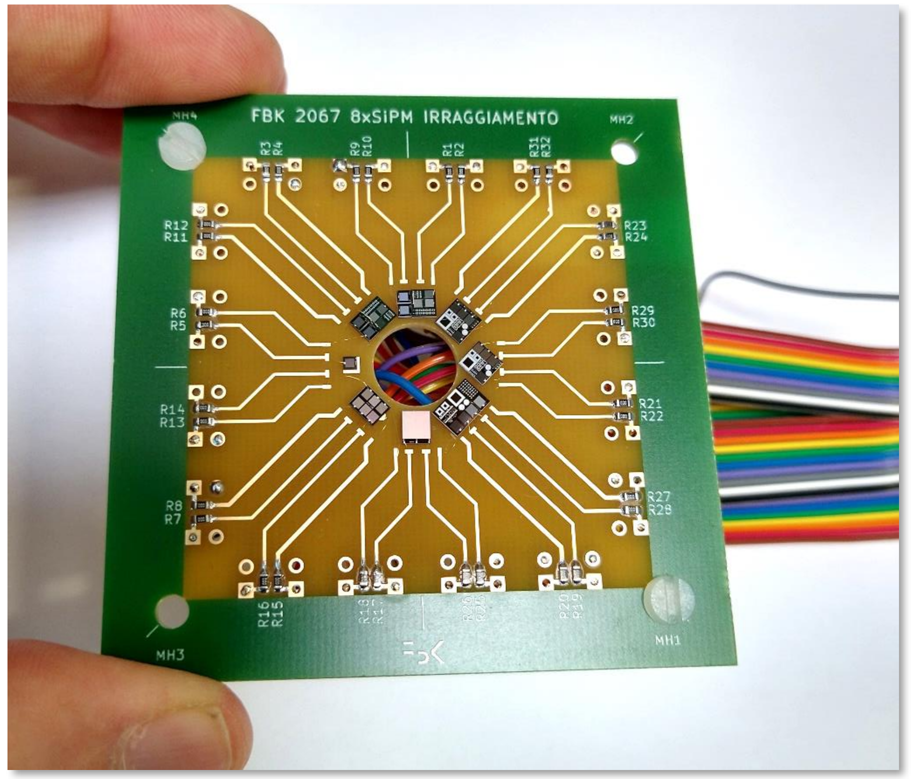
  +

- *Functional measurements* after 1 month RT annealing:
  → Waveform analysis on irradiated samples ***only at -40°C*** (High DCR, event separation is not possible / reliable above 20 Mc.p.s.)



Tommasino (2019) https://doi.org/10.1016/j.ejmp.2019.02.001

"Dual ring setup"[1]: 98% uniformity on ~6 cm diameter



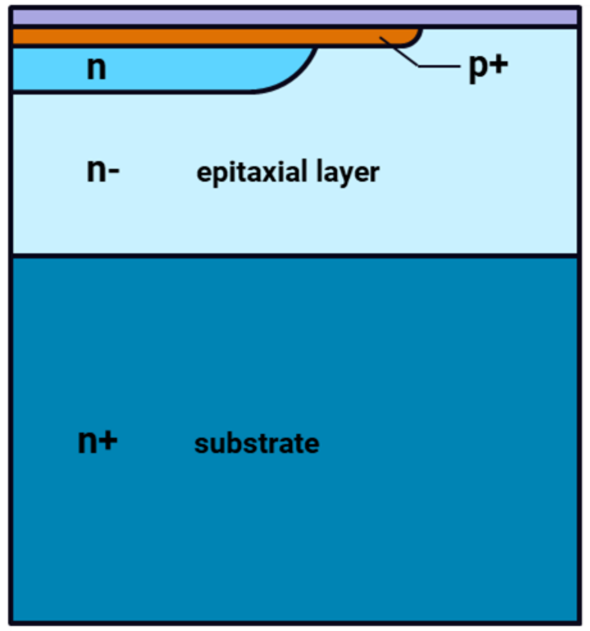
Customized PCB for irradiation tests, housing multiple SiPMs and allowing online IV measurements.

A. Altamura *et al.* (2021) https://doi.org/10.48550/arXiv.2112.08089

Test Beam 1 – Trento Proton Therapy
Tested Technologies

We tested a relatively *wide range of different customized SiPM technologies*, fabricated in FBK internal R&D clean-room, looking for differences, general trends, etc..

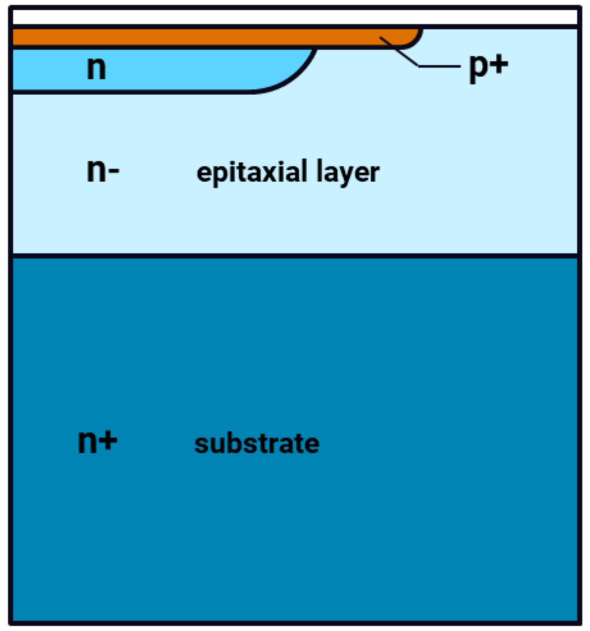
VUV-HD[2]
Vacuum Ultraviolet



Peak PDE = 420 nm

- Different ARC
- High sensitivity in VUV

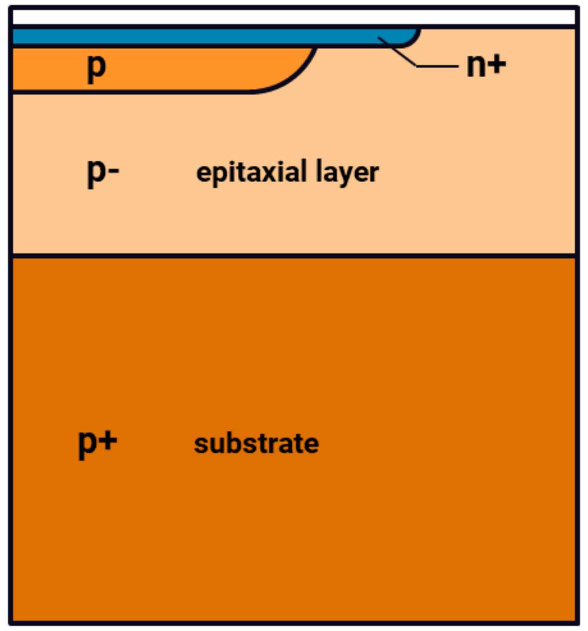
NUV-HD[3]
Near Ultraviolet



Peak PDE = 420 nm

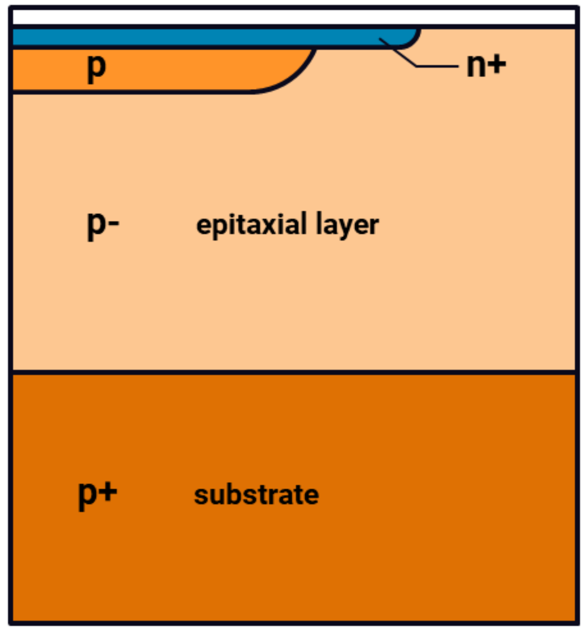
- CRYO = Cryo temp opt.
- RH = High radiation opt.

RGB-HD[4]
Visible



Peak PDE = 530 nm

NIR-HD[5]
Near Infrared



Peak PDE = 530 nm

- Thick epitaxial layer
- High sensitivity in IR

[2] Capasso (2020) https://doi.org/10.1016/j.nima.2020.164478

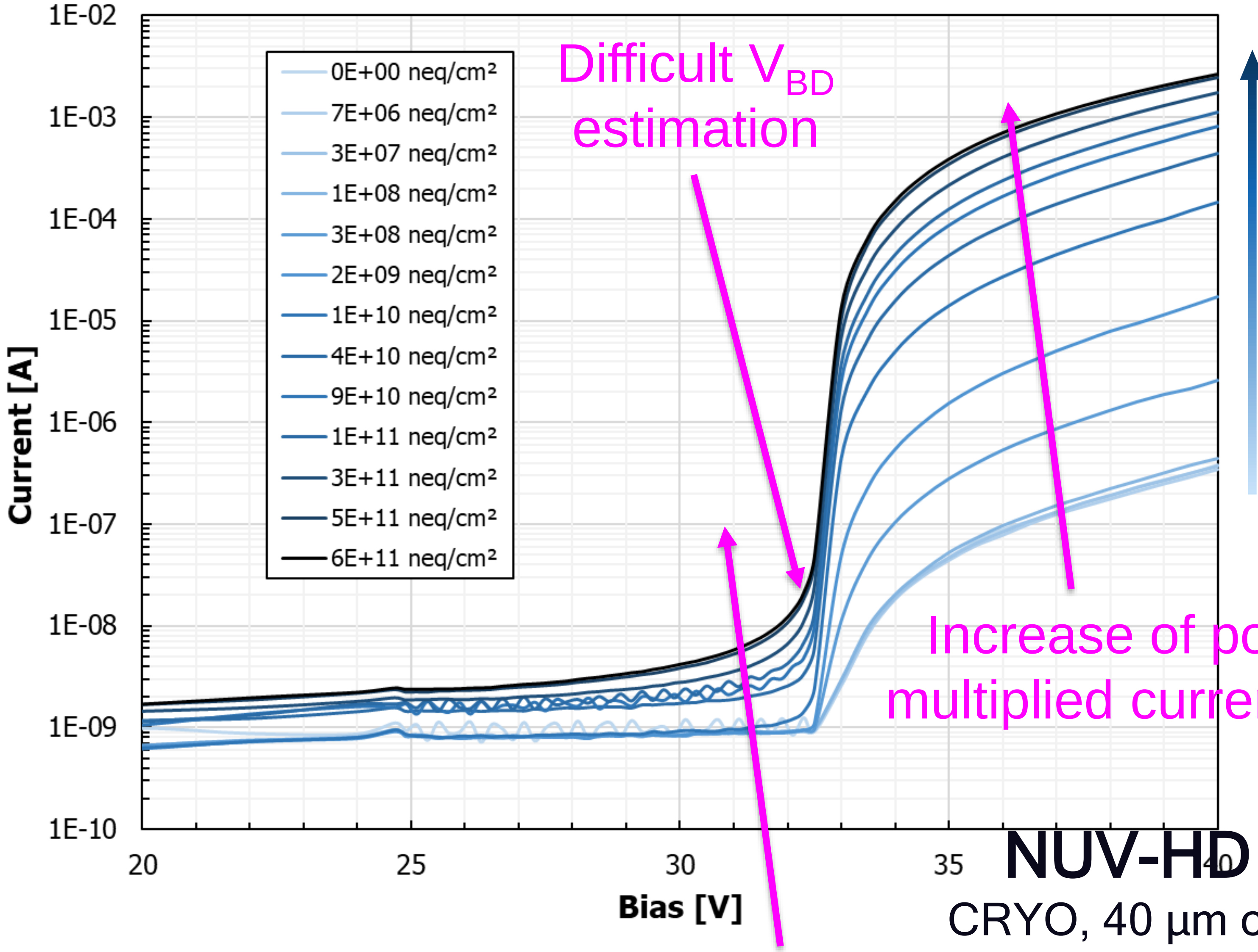
[3] Gola (2019) https://doi.org/10.3390/s19020308

[4] Ferri (2015) https://doi.org/10.1186/2197-7364-2-S1-A86

[5] Acerbi (2018) https://doi.org/10.1016/j.nima.2017.11.098

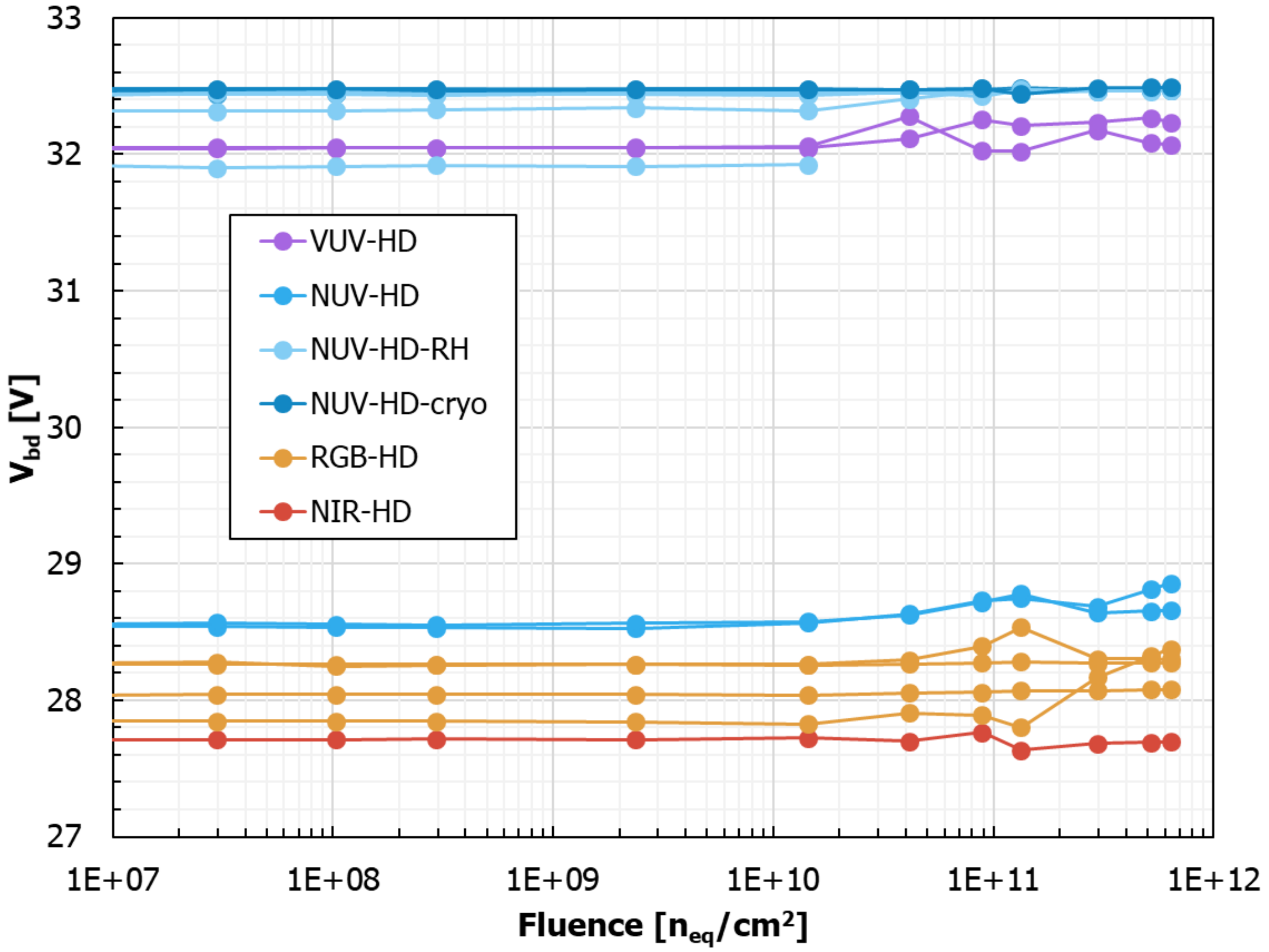
Test Beam 1 – Trento Proton Therapy
Online IV measurements

Effects of irradiation on reverse IVs



Increase of pre-breakdown, non-multiplied (~surface) current

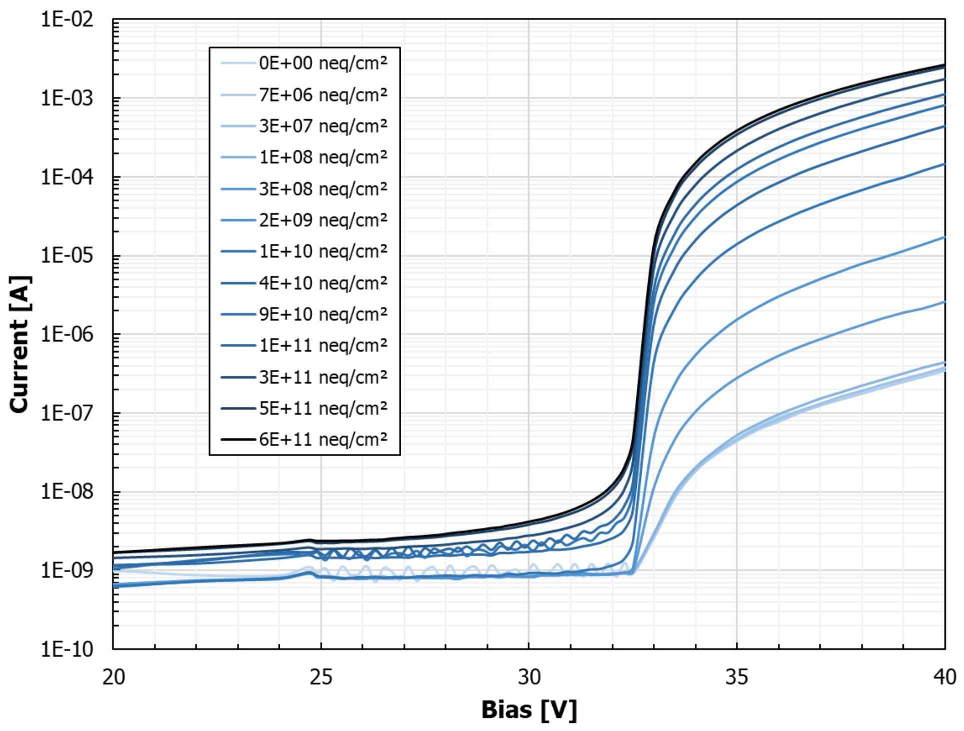
Breakdown Voltage Estimation



No change observed in V_{BD} up to fluence $6 \cdot 10^{11}$ n_{eq}/cm^2 (2nd derivative method, faint illumination)

Test Beam 1 – Trento Proton Therapy
Dark Count Rate Estimation from reverse IV

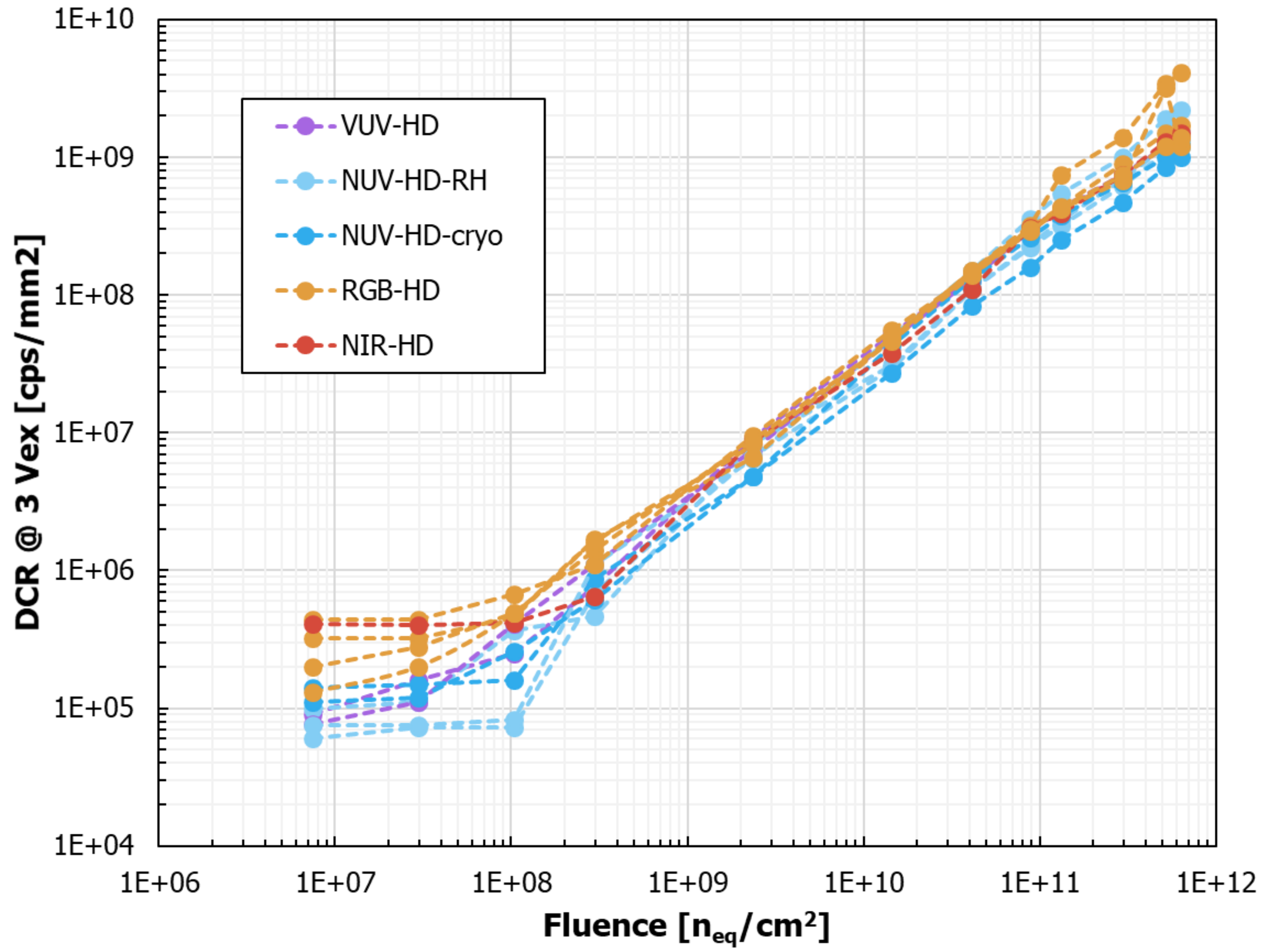
Comparison of radiation hardness of different SiPM technologies *cannot be done directly from their IVs* because they usually have different Gain and correlated noise (ECF).



$$DCR = \frac{I_{dark}}{q * G * ECF} = \frac{I_{dark}}{q * G_C}$$

$$G_C = G * ECF = \text{Current Gain}$$

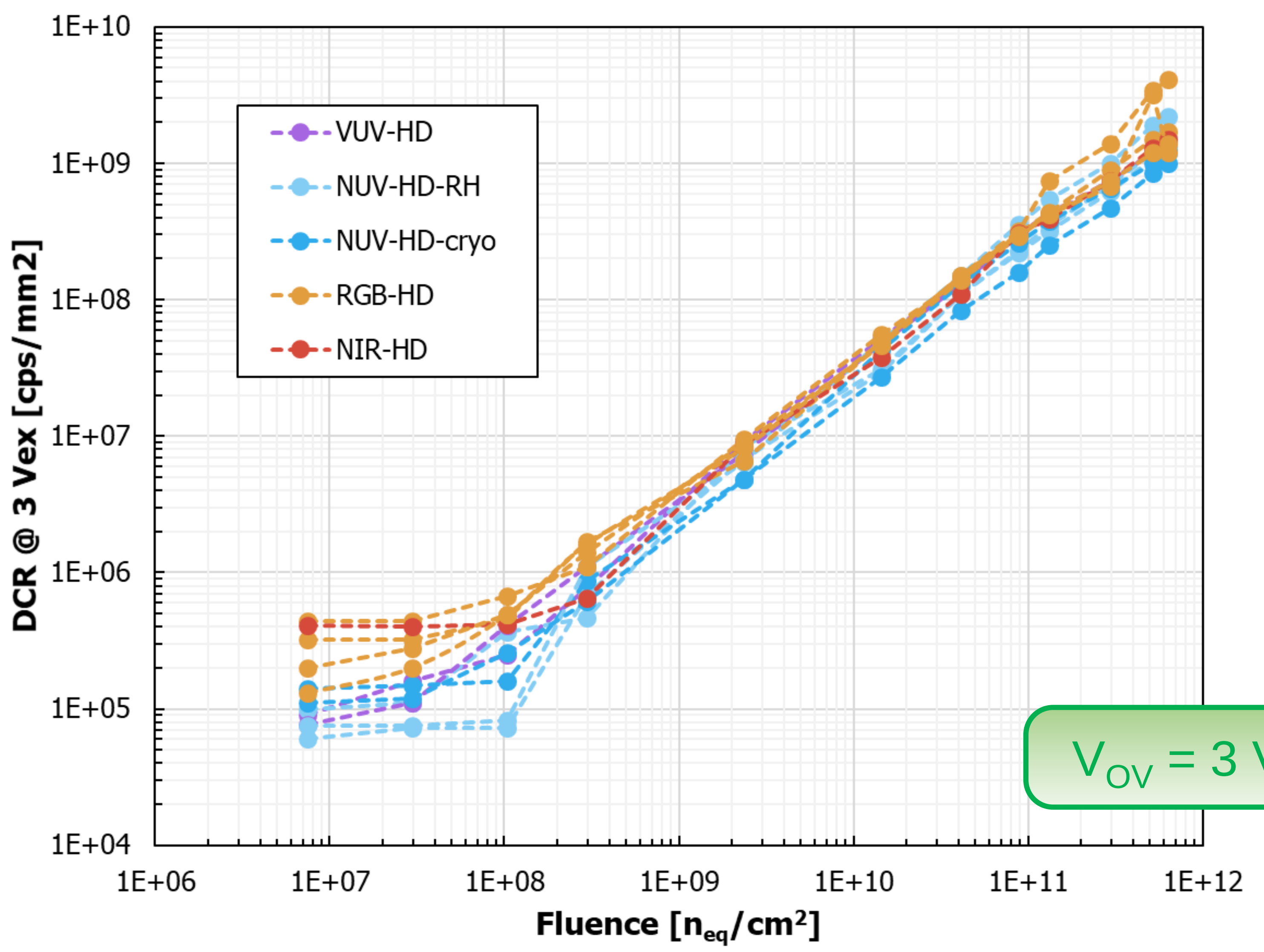
$$ECF = \text{Excess Charge Factor}$$



DCR estimation for different FBK SiPM technologies.

Assumption: ECF and Gain do not change with irradiation (will be shown later)

Test Beam 1 – Trento Proton Thera
Dark Count Rate vs. Fluence



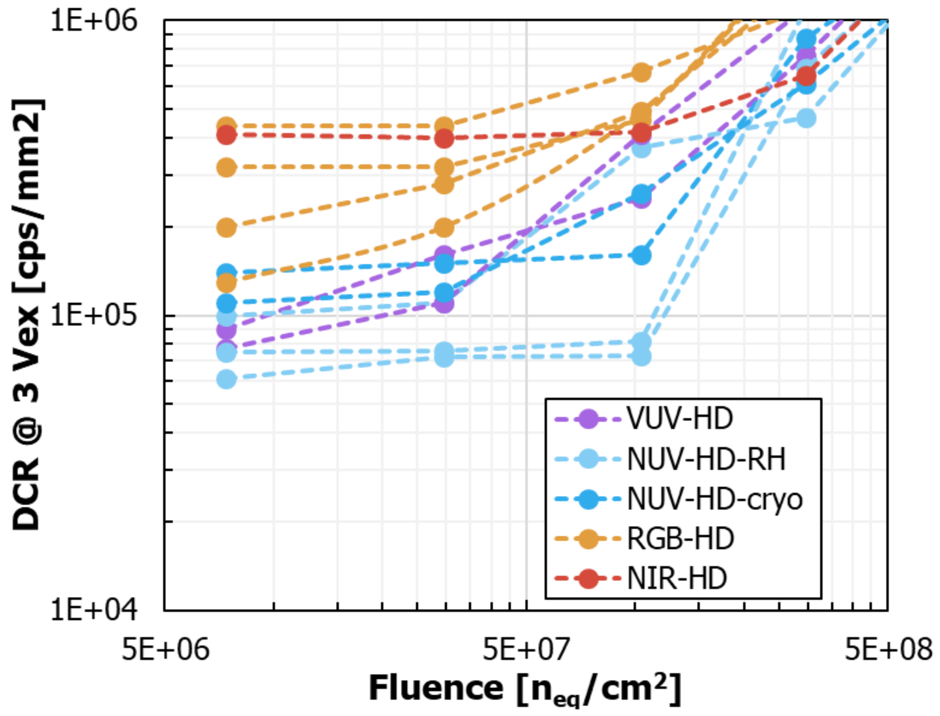
V_{OV} = 3 V

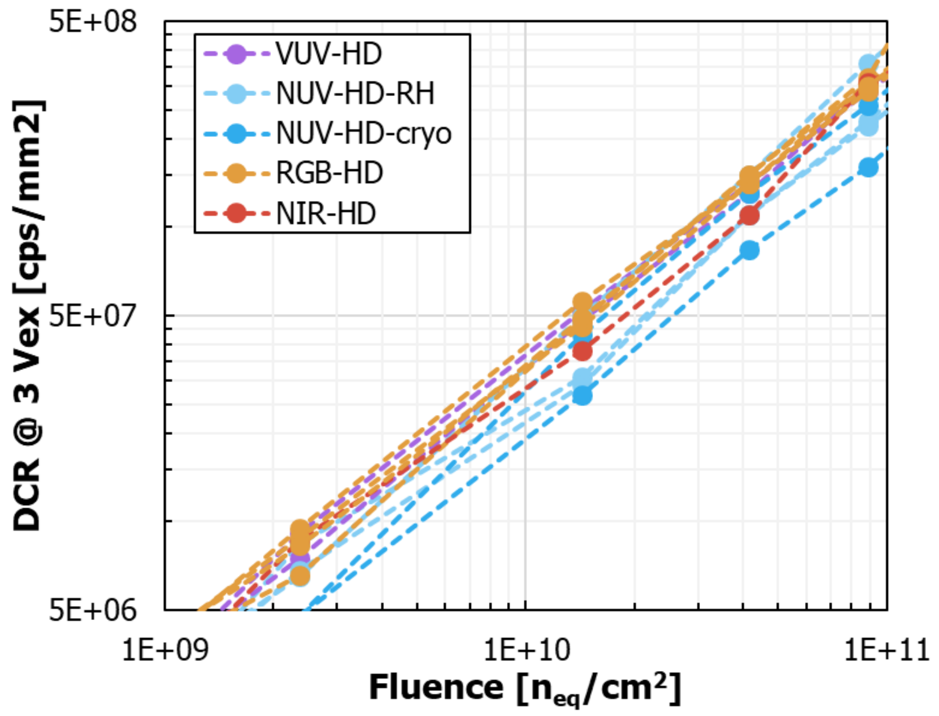
There is *little correlation between the DCR before and after irradiation*:

- All technologies seem to “converge” towards similar values
- Knee between $10^7 \div 10^8$ n_{eq}/cm^2
- Independence of bulk damage from contaminants in the SiPM starting material?

DCR variation after irradiation is reduced:

- from ~1 OoM to < ~0.5 OoM
- Still worth investigating *differences between technologies*





Test Beam 1 – Trento Proton Therapy
Damage Factor

To estimate the sensitivity of different SiPM technologies to the radiation damage, we suggest *using a version of the Damage Factor, modified for the Geiger-mode detectors*.

Damage Factor

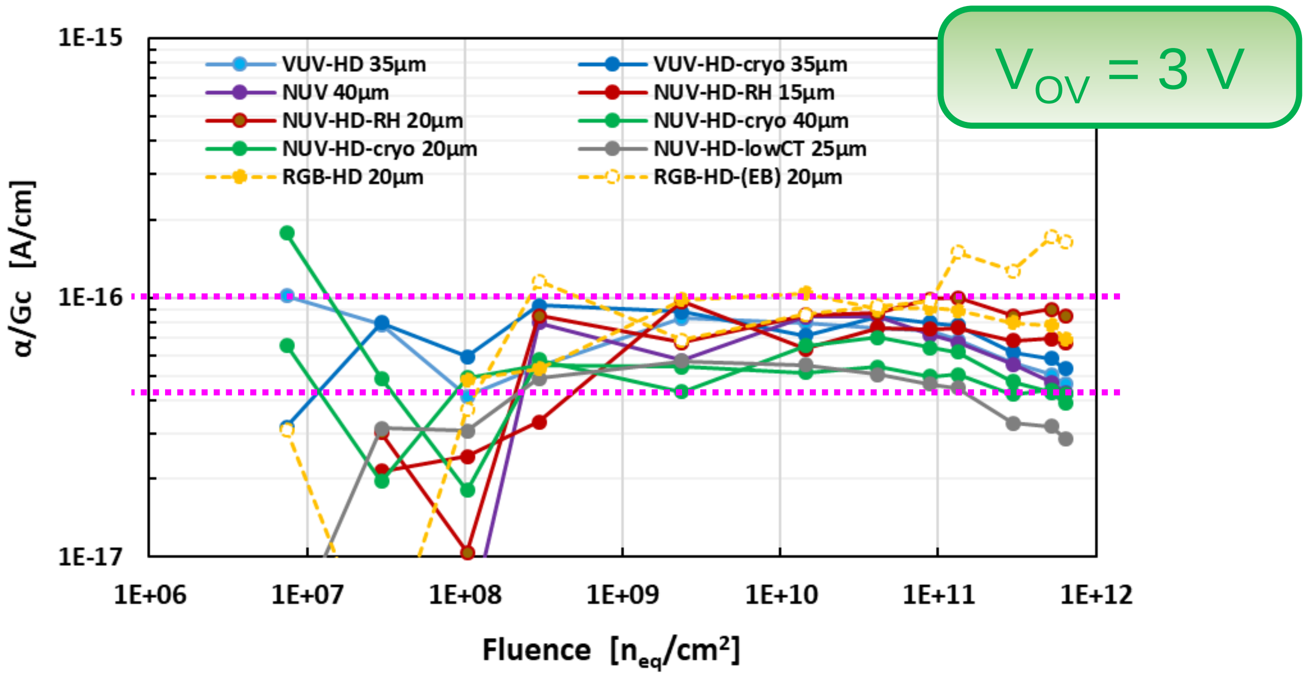
detectors without internal gain

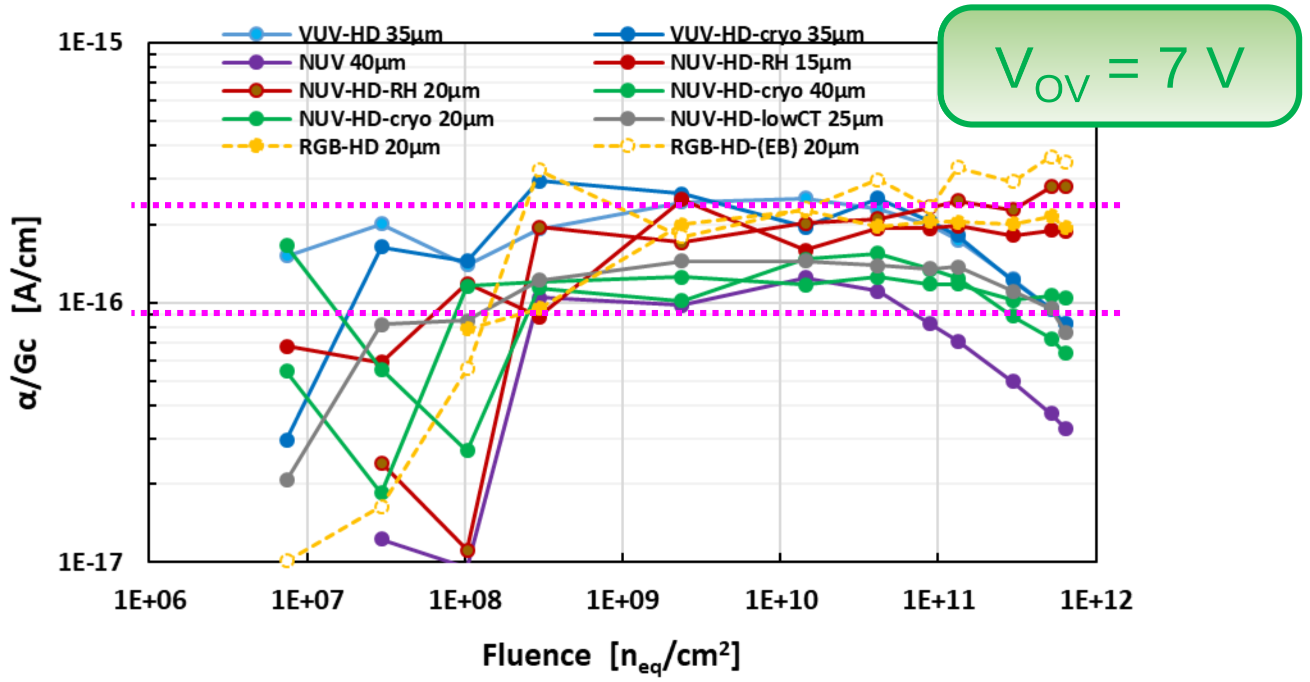
$$\alpha = \frac{\Delta I}{\Phi V}$$

Damage Factor

Geiger-mode detectors

$$\frac{\alpha}{G_C} = \frac{\Delta I}{\Phi \cdot V \cdot G \cdot ECF} = \frac{\Delta I}{\Phi \cdot V \cdot G_C} \approx \frac{\Delta DCR * q}{\Phi V}$$





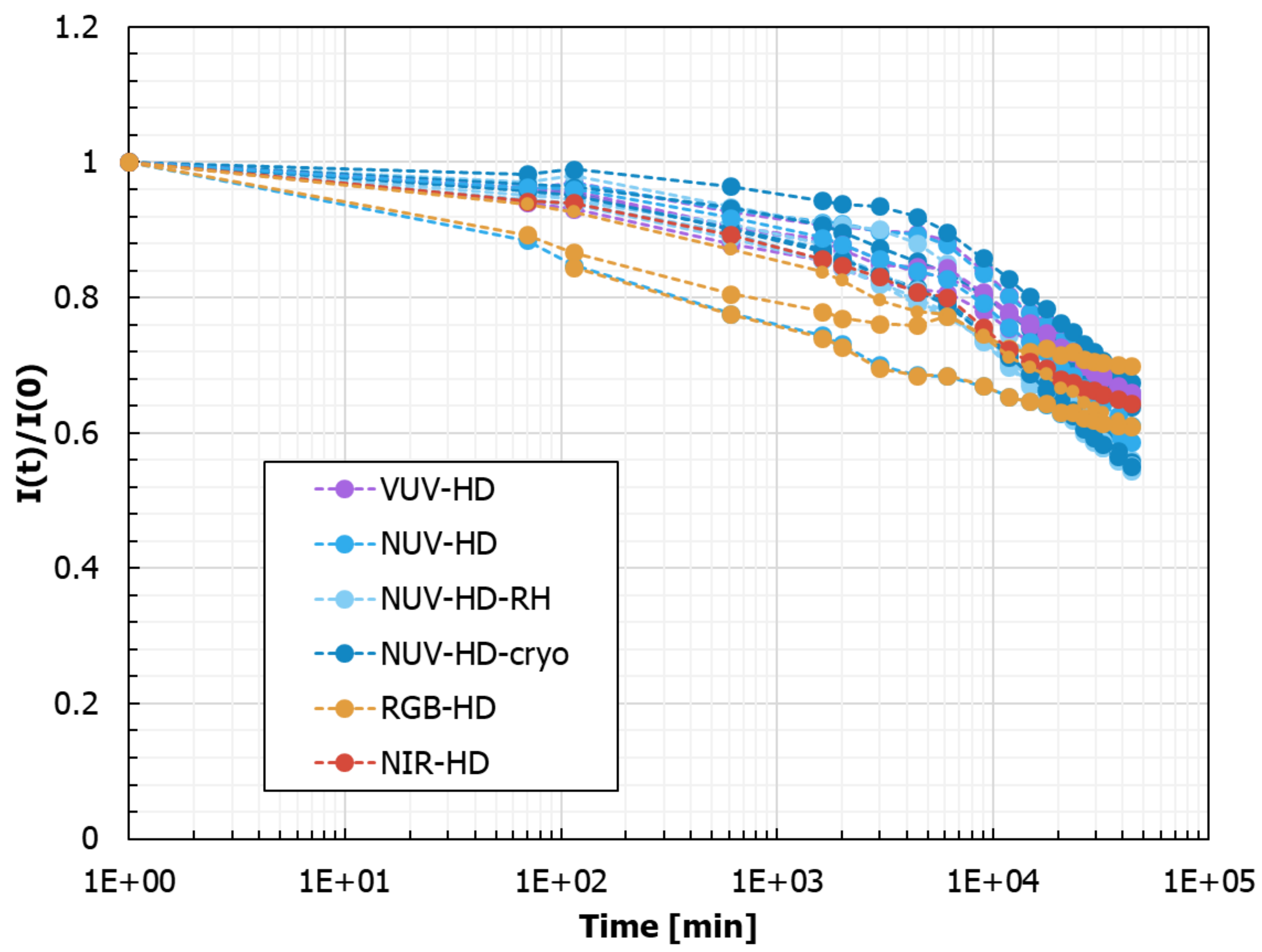
- Constant wrt. Irradiation dose.
- In accordance with literature
- *Uniform* behavior across *different technologies*: 5-10·10^{-17} A/cm^2
- *Dependence on excess bias*: triggering probability and field-enhanced generation
- Which volume should be considered? (high E-field or collection region)

M. Moll (2018) https://doi.org/10.1109/TNS.2018.2819506

Test Beam 1 – Trento Proton Therapy
First Annealing studies

Annealing can be a *powerful mean of reducing DCR after irradiation* to recovers single-photon resolution.

- *Room temperature* annealing (20-25°C) on the highest dose only ($6.4 \cdot 10^{11}$ 1 MeV n_{eq}/cm^2)
- *Two slopes observed*: knee point at around $1.5 \cdot 10^3$ min (~1 day)
- Minor dependence on excess bias for a few samples.
- *Higher annealing temperatures* have demonstrated better annealing:
  - *Factor > 10 after $1 \cdot 10^{11}$ n_{eq}/cm^2 is reported in* *M. Calvi - https://doi.org/10.1016/j.nima.2019.01.013*
  - *Is there a threshold temperature* for the annealing of certain defects?

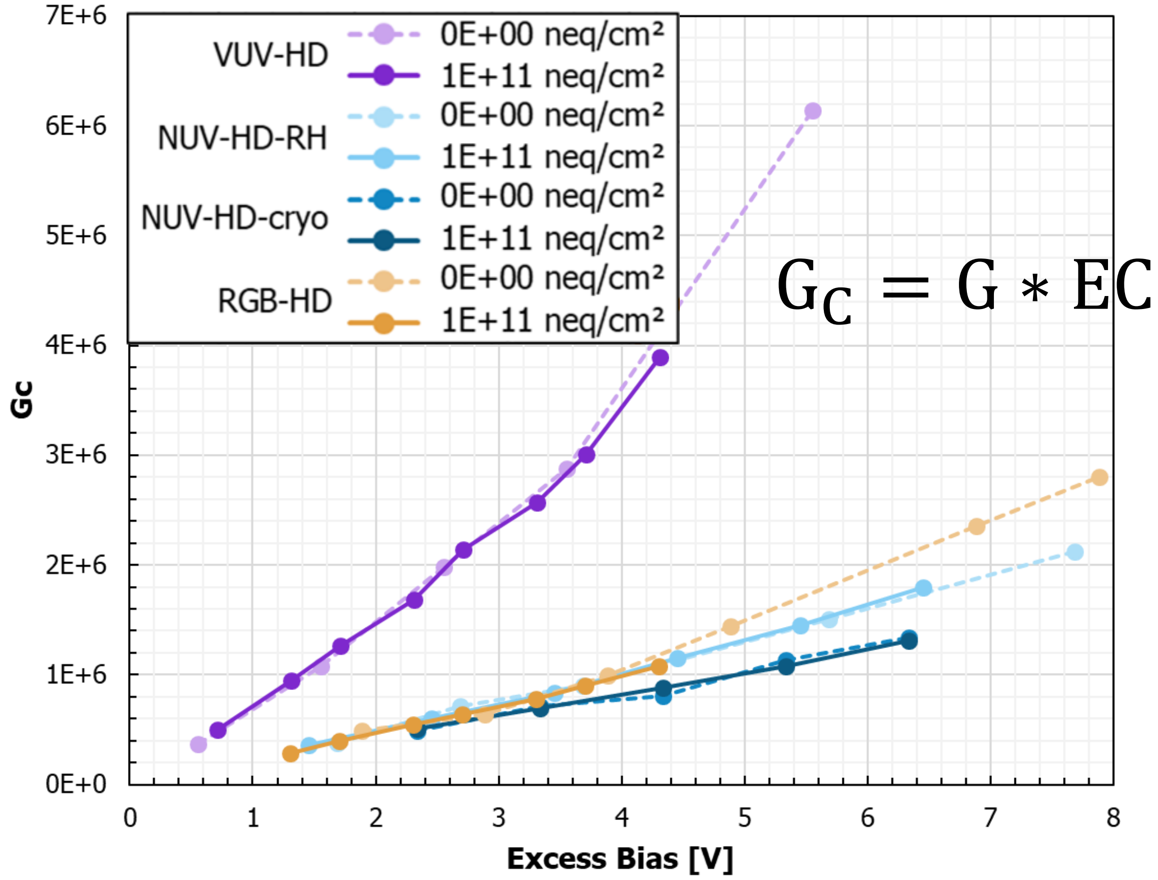


Test Beam 1 – Trento Proton Therapy
Variation of the other SiPM parameters

Waveform analysis carried out at -40°C to reduce pile-up on the highest irradiation dose ($1 \cdot 10^{11}$ n_{eq}/cm^2).

No relevant change of the other SiPM parameters, except for the DCR.

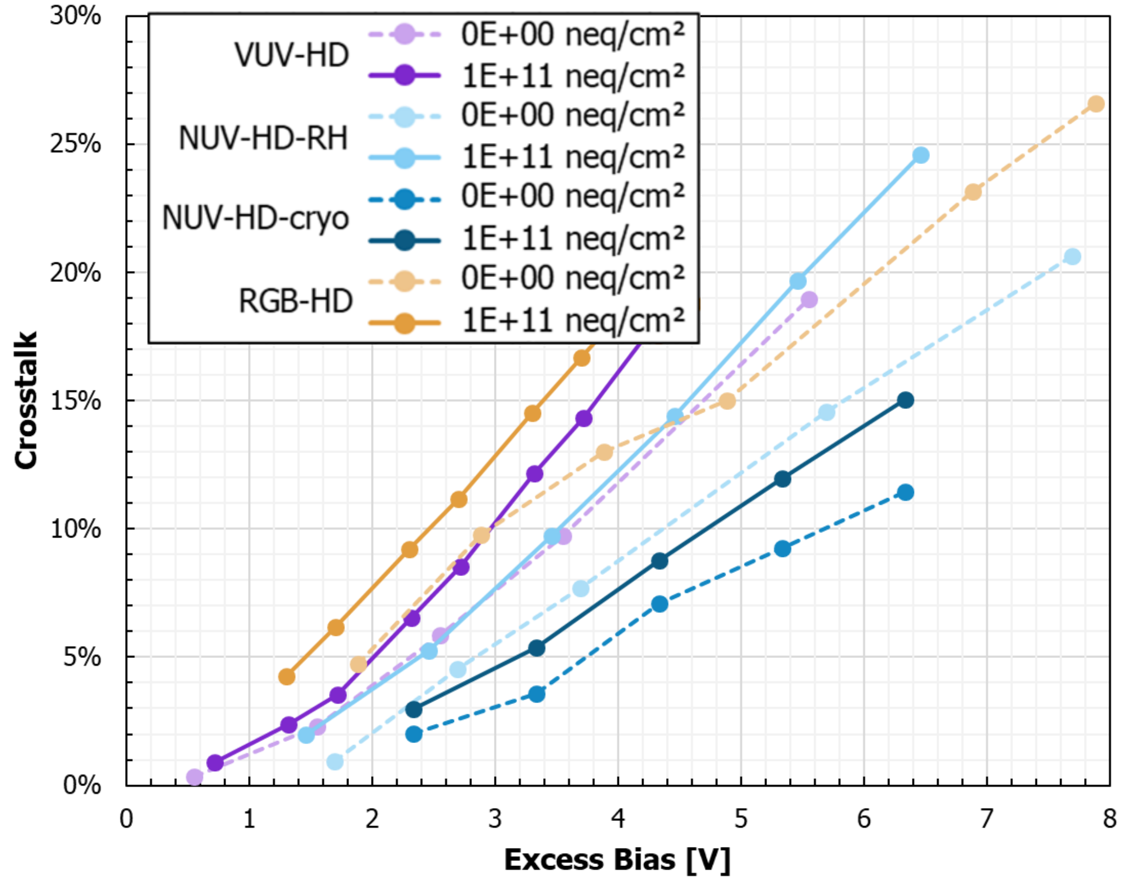
Current Gain



$$G_C = G * ECF$$

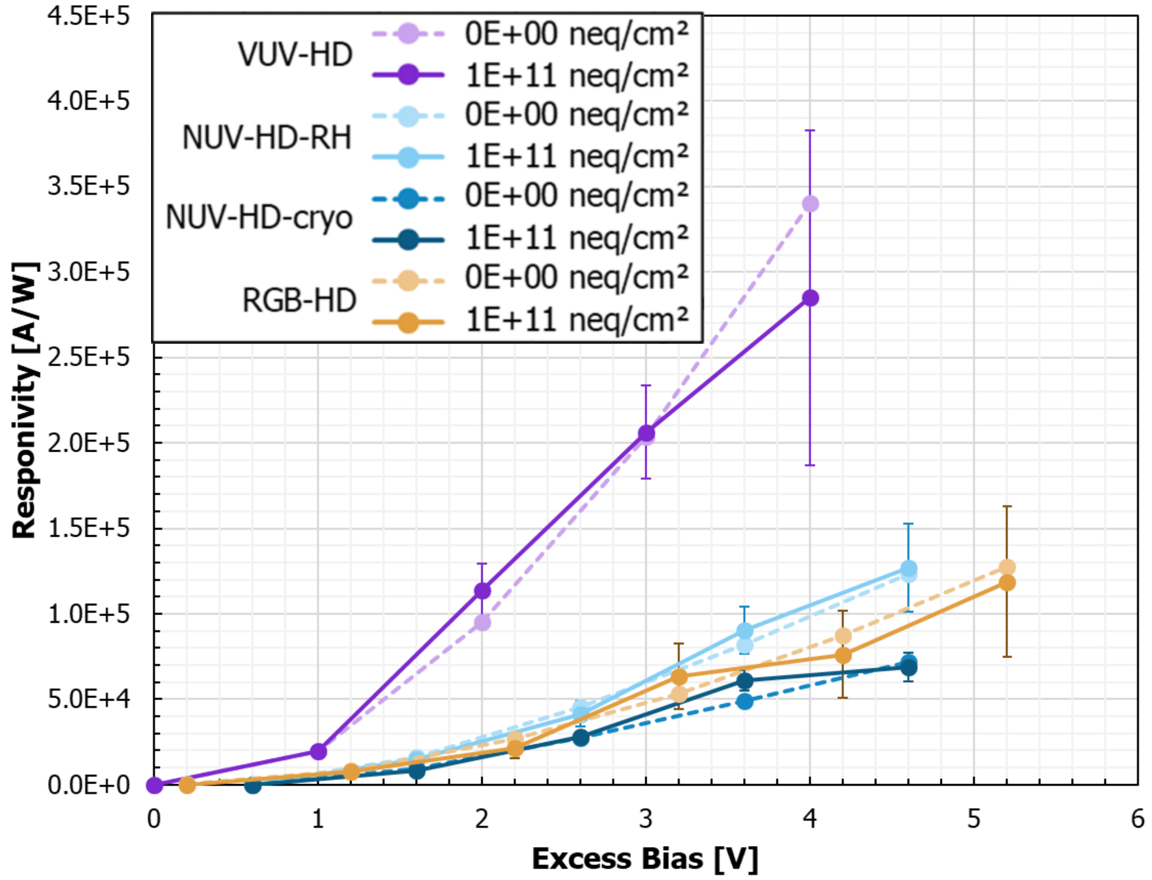
*No change in Gain * ECF* up to $1 \cdot 10^{11}$ n_{eq}/cm^2

Optical Crosstalk



Minor increase of CT is most likely an artifact caused by pile-up.

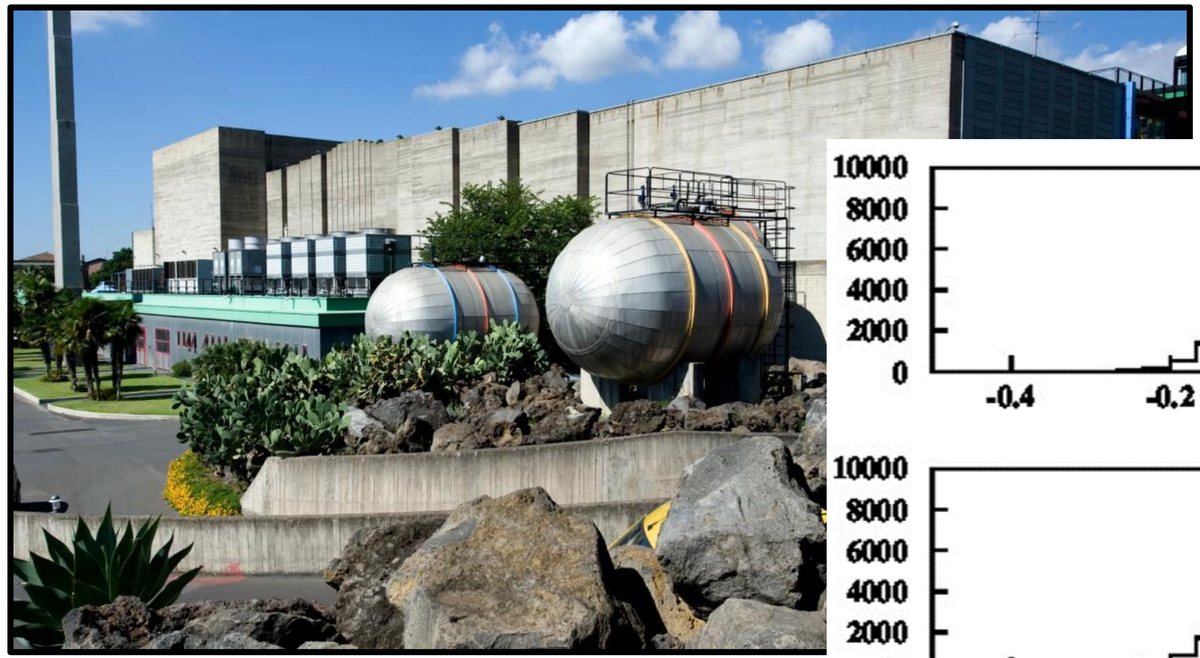
PDE

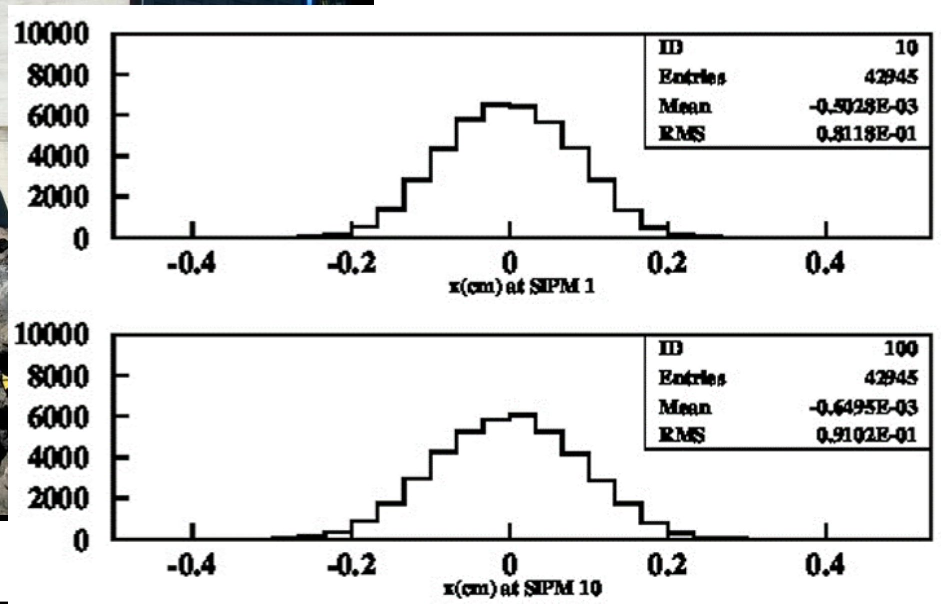


No change in PDE, measured as responsivity (loss of single photon resolution).

Test Beam 2 – LNS Catania
Experimental Setup and DoE

A test beam was carried out at LNS in Catania in 2019, focusing on *higher irradiation doses and temperature dependence studies*.





Energy: 62 MeV protons

Dose: 5 samples irradiated with different doses:

$\sim 7.4 \cdot 10^{9} - 6.5 \cdot 10^{13}$ p/cm^2

↓

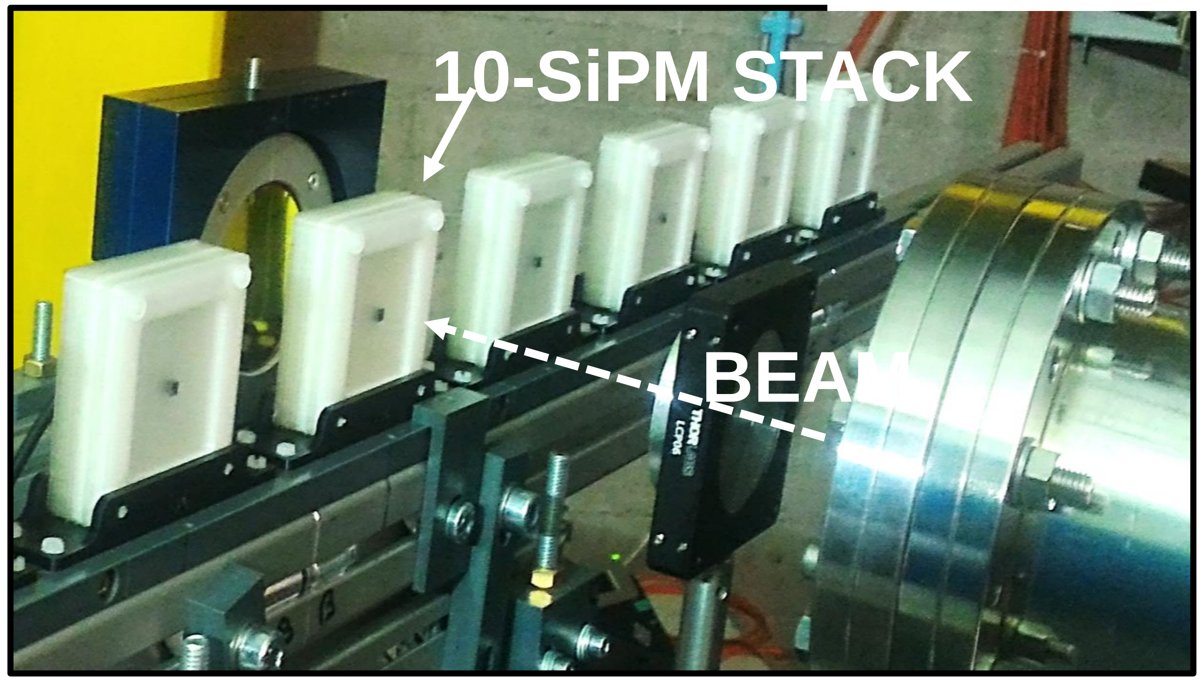
$\sim 1.3 \cdot 10^{10}$ - **$1.1 \cdot 10^{14}$ 1 MeV n_{eq}/cm^2**

Analysis: after irradiation, on each sample:

Devices: **NUV-HD-RH**

15 um cell size

1x1 mm^2 active area



Gaussian beam: 2.7 mm diameter collimator

A. Altamura *et al.* (2022)
https://doi.org/10.1016/j.nima.2022.167284

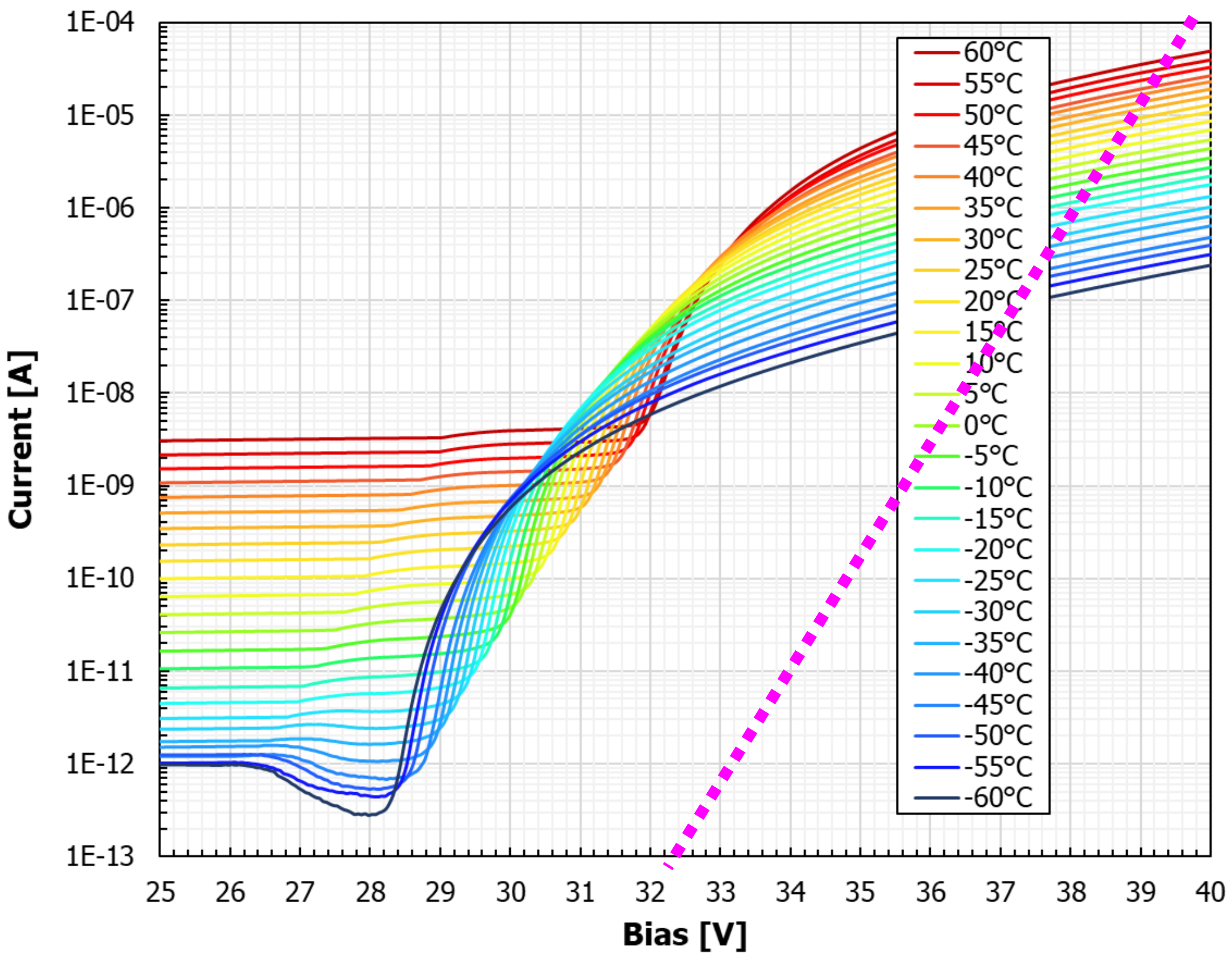
Test Beam 2 – LNS Catania
DCR Analysis

PRELIMINARY

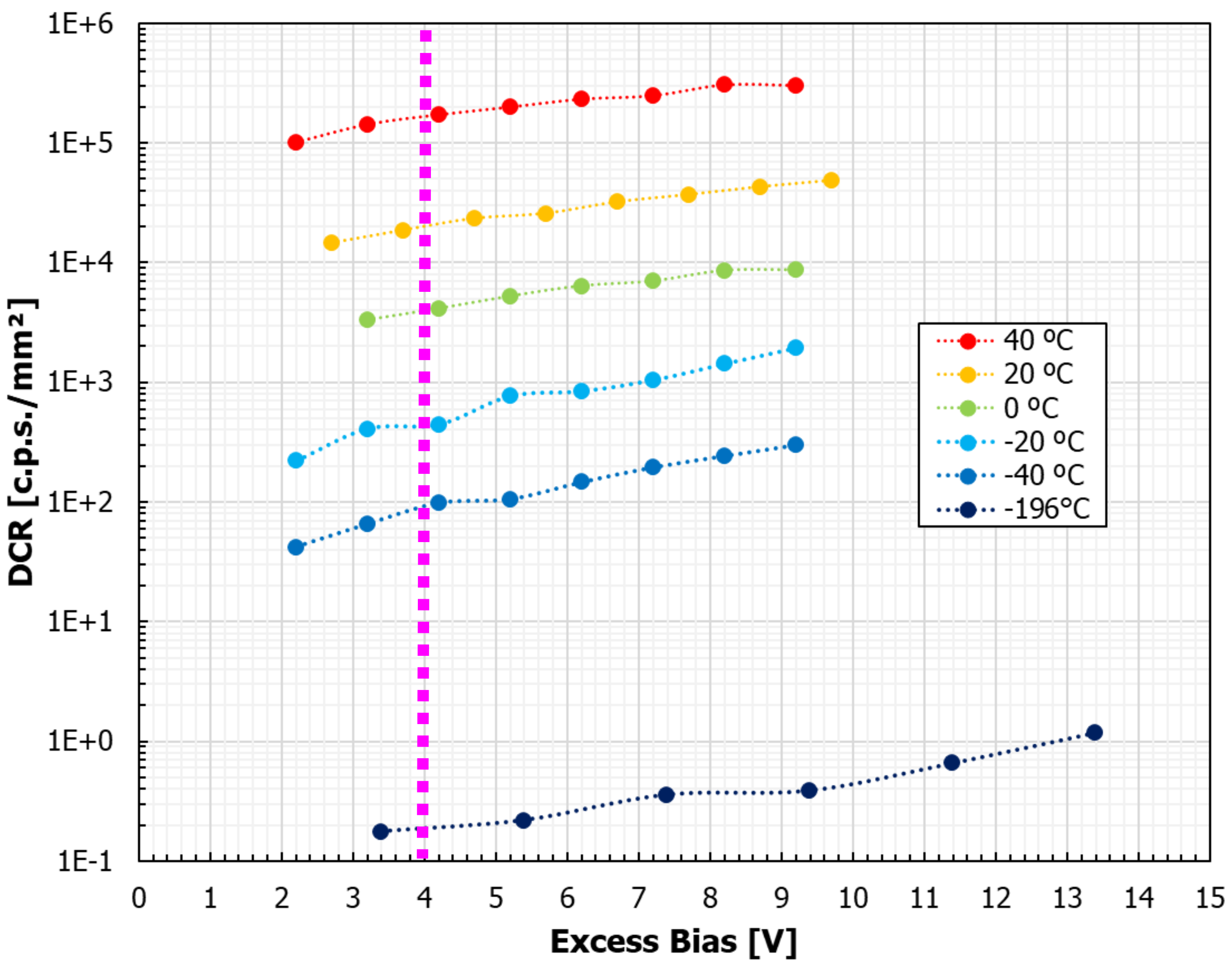
Study of *DCR after irradiation extended to cryogenic temperatures (preliminary)*.

- *IV vs Temperature*: +60°C → -60°C
- *DCR vs Temperature*: +40°C → -40°C, LN_2 (waveform analysis, when possible)

IV vs. Temperature

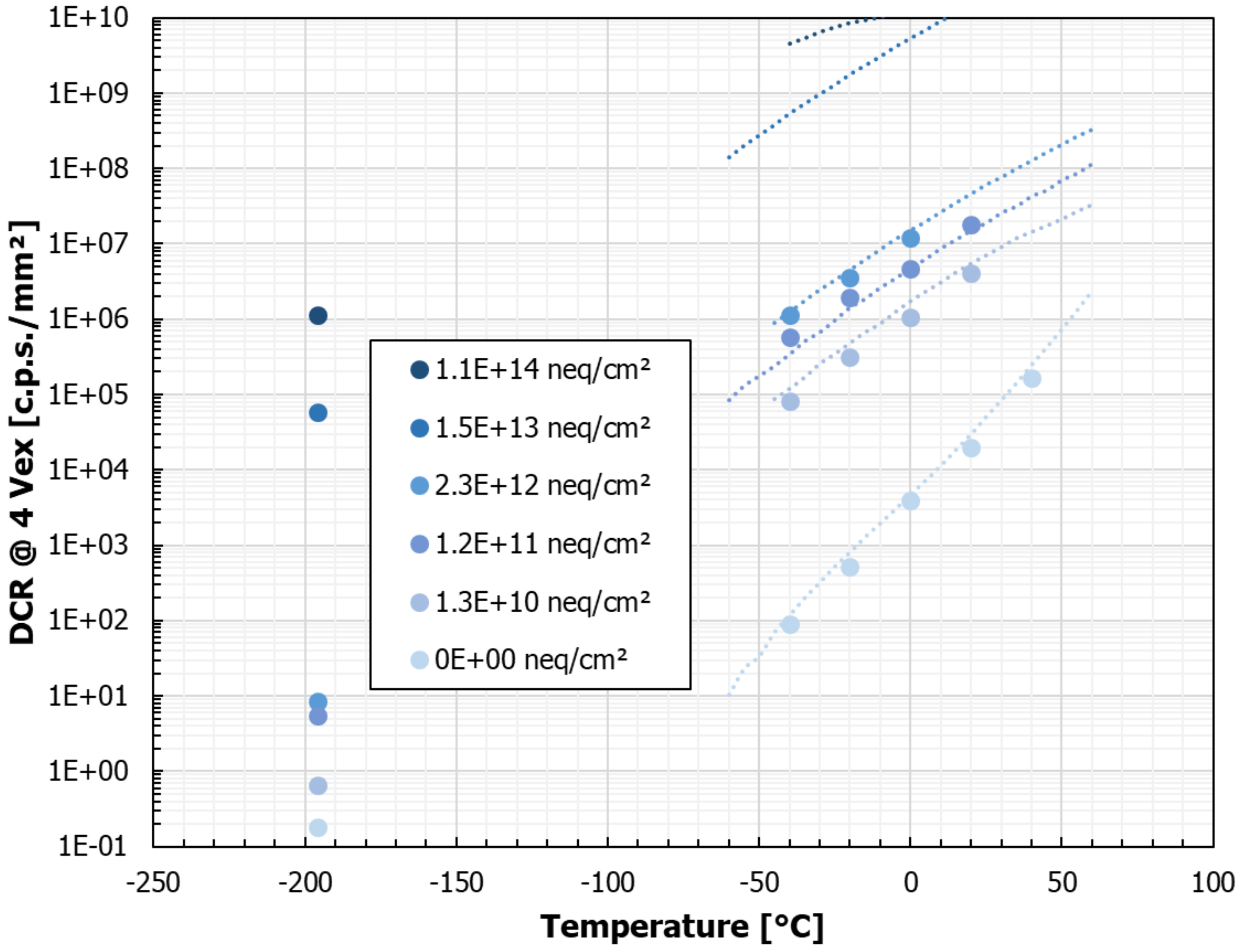


DCR vs Temperature



Test Beam 2 – LNS Catania
DCR vs. Temperature and Dose

PRELIMINARY

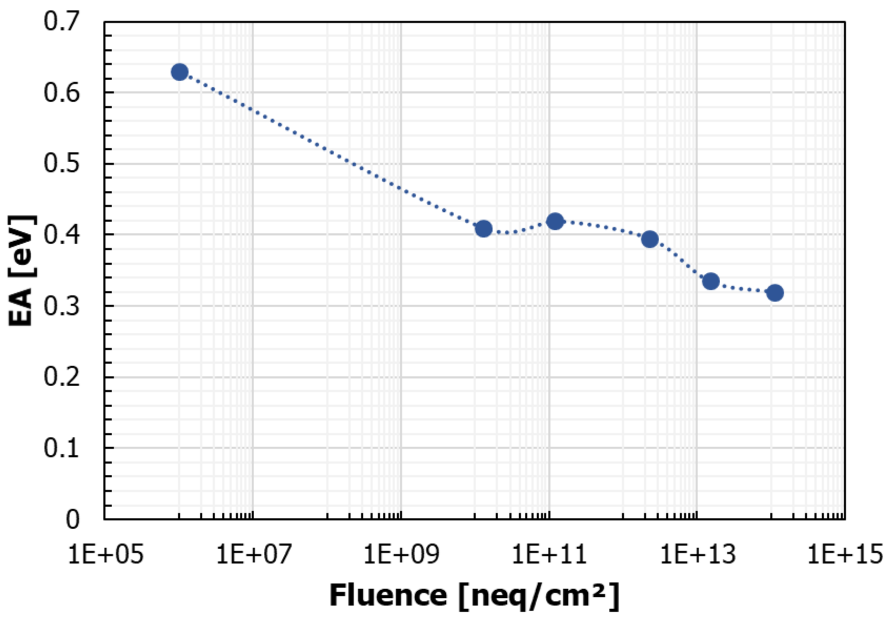


Lines: DCR from IV
Dots: DCR from waveform analysis

Reduction of DCR activation energy near room temperature after irradiation was observed.

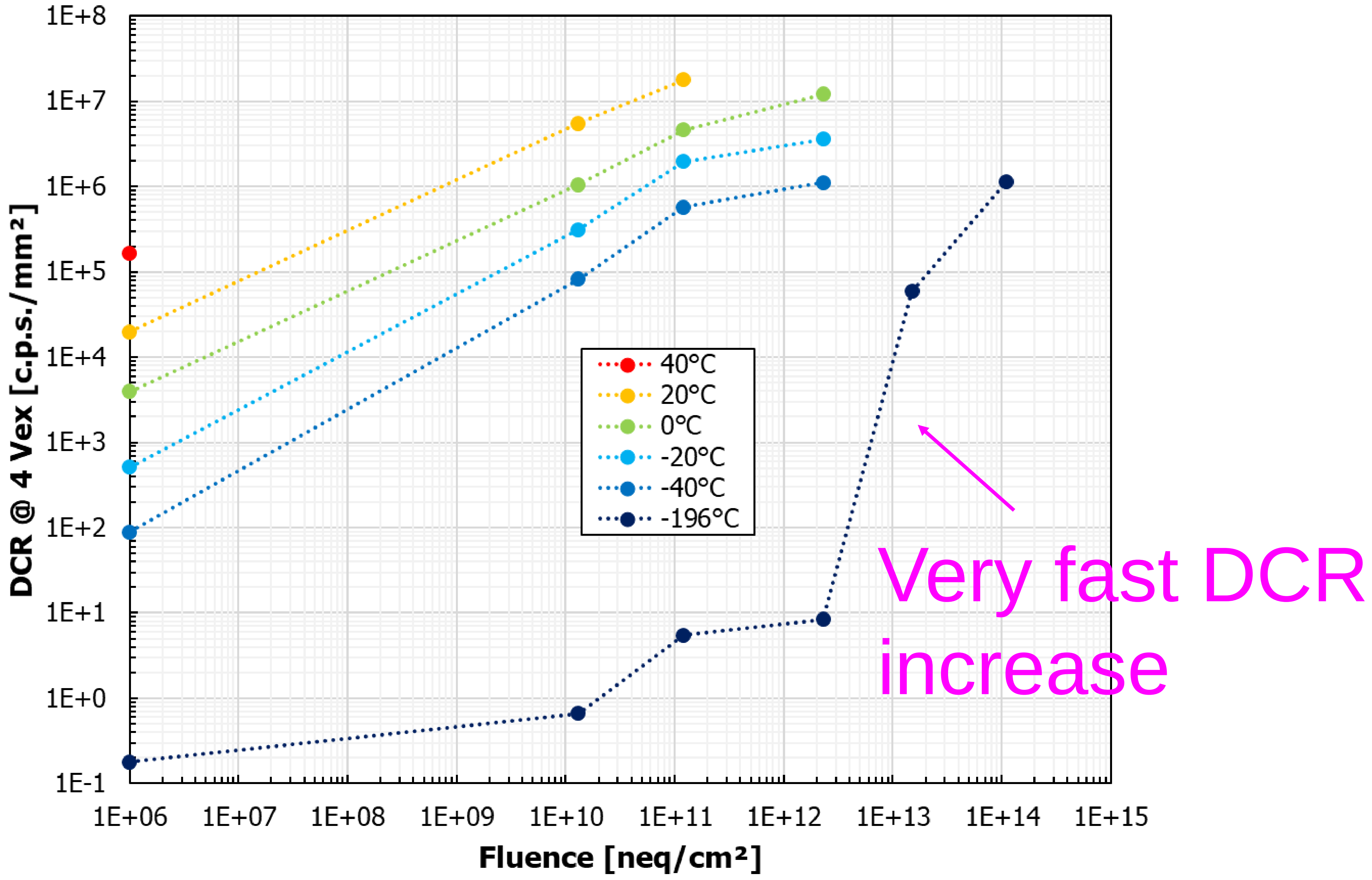
→ Cooling becomes less effective in reducing DCR.

Fluence [n_{eq}/cm^2]	E_A [eV]
0E+00	0.63
1.3E+10	0.41
1.2E+11	0.42
2.3E+12	0.40
1.5E+13	0.34
1.1E+14	0.32



Test Beam 2 – LNS Catania
DCR at LN after irradiation

PRELIMINARY



- Cooling is *extremely effective in reducing DCR after irradiation up to ~$1\cdot10^{12}$ n_{eq}/cm^2*
- Further investigations needed to understand what happens at the higher doses
- Worth checking different / new SiPM structures
- Check possible effect of annealing

Radiation Hardness
Definition + Mitigation strategies

It is rather obvious that *we cannot prevent the bulk damage from increasing the DCR* of the SIPM.

A *possible definition of Rad-Hardened / tolerant SiPM* is a *SiPM that retains its target performance in a given application* even after radiation damage.

→ Depends on the application!

→ *Radiation damage mitigation strategies* (+ annealing)

Use of small cells + Engineering of electric field

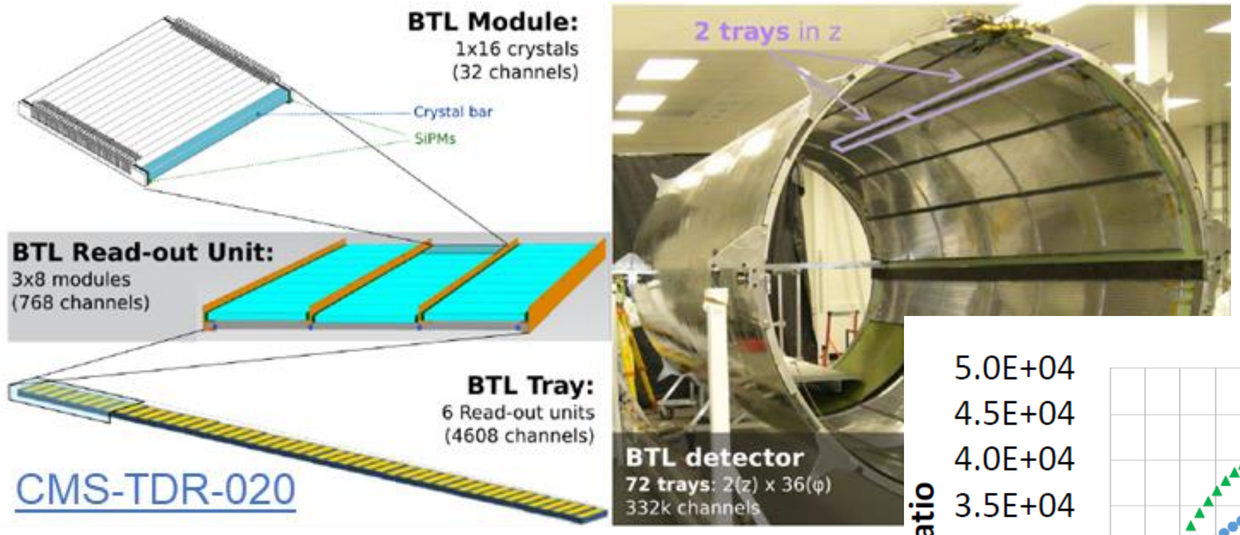
Issue / Hypothesis	Technical Solution	Mitigation
Increase of primary DCR	Electric field engineering	Better DCR temperature coefficient High PDE at lower bias (to reduce field-enhanced effects)
PDE loss due to cells busy triggering dark counts.	Smaller Cells	More cells and faster recharge: lower PDE loss.
Increased power consumption due to higher DCR.	Smaller Cells	Lower gain: less current (for a given DCR).

.. But, at the same time, we need high PDE!

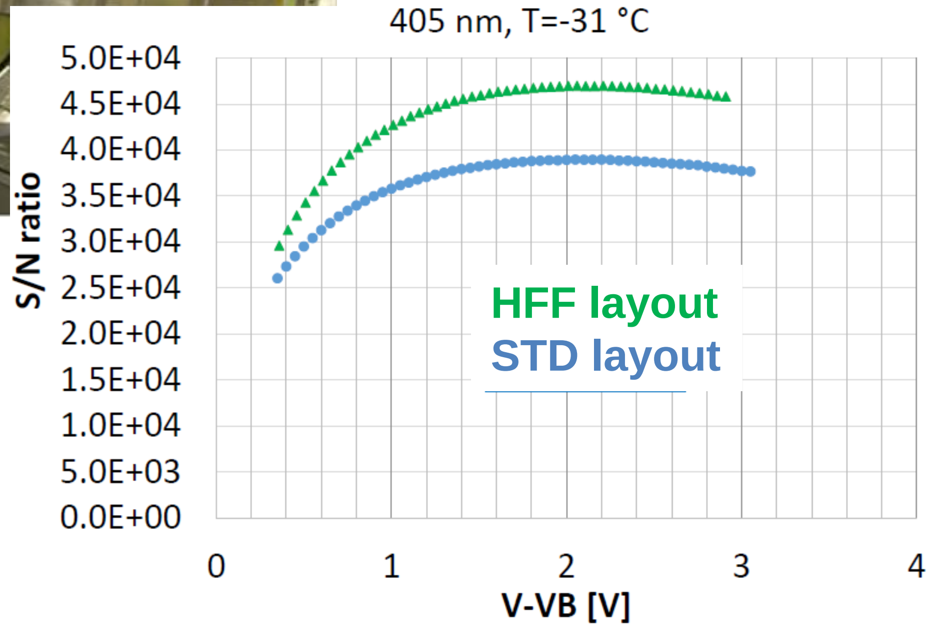
Mitigation of Radiation Damage
NUV-HD-RH SiPMs for CMS-BTL

SiPMs with extreme radiation tolerance are required for the Barrel Timing Layer of the CMS experiment, at CERN: 1.9×10^{14} 1 MeV n_{eq}/cm^2.

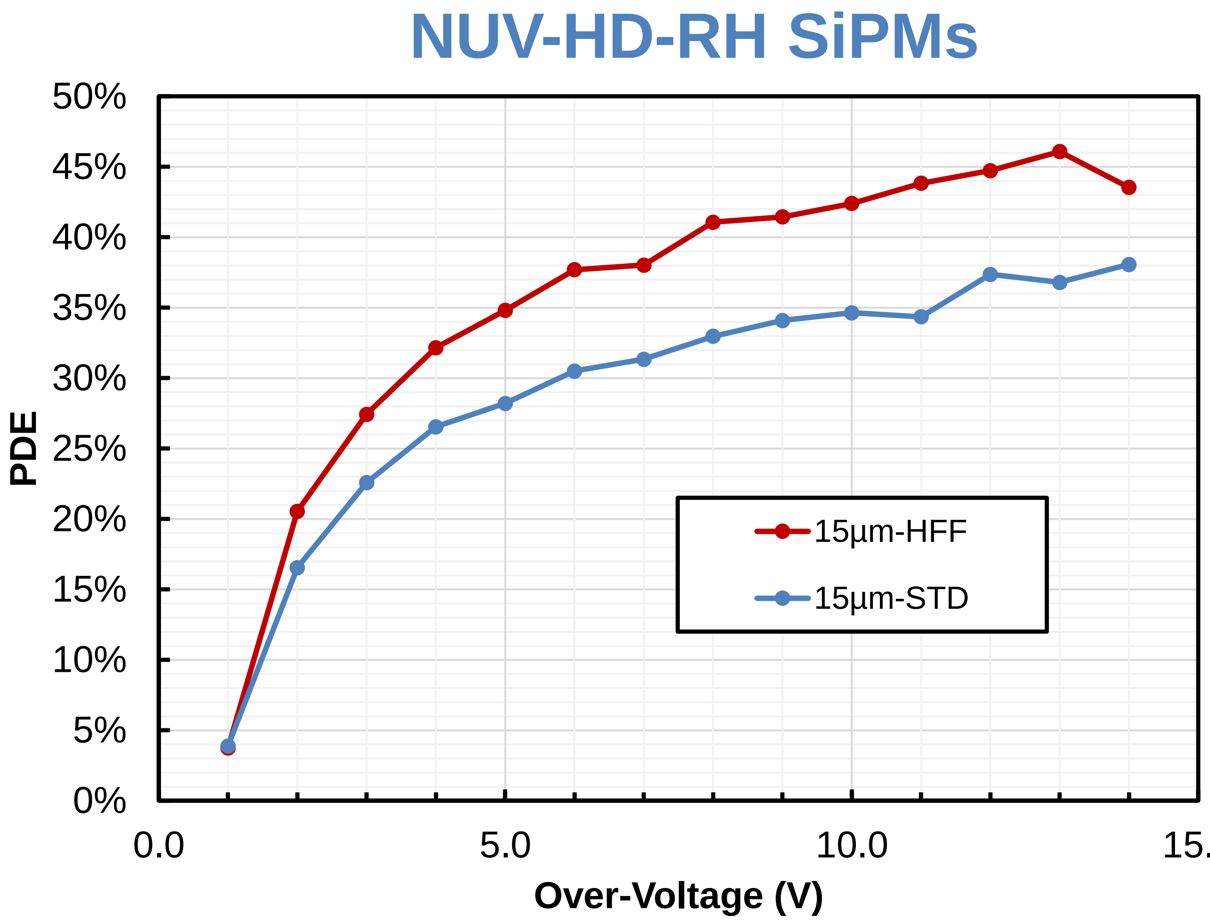
Custom SiPM technology was developed, combining *electric field engineering with small-pitch SiPM technology*, for enhanced radiation hardness.



CMS-TDR-020



FoM measured by from CMS collaboration: A. Heering, Y. Musienko, M. Lucchini et al.)

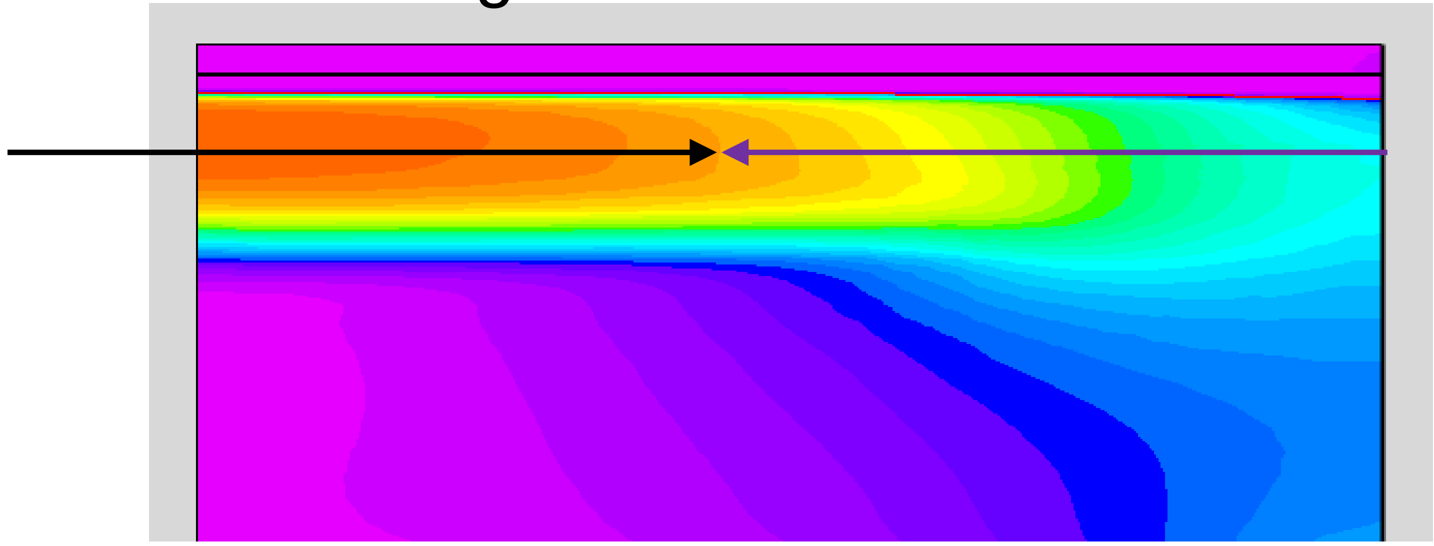


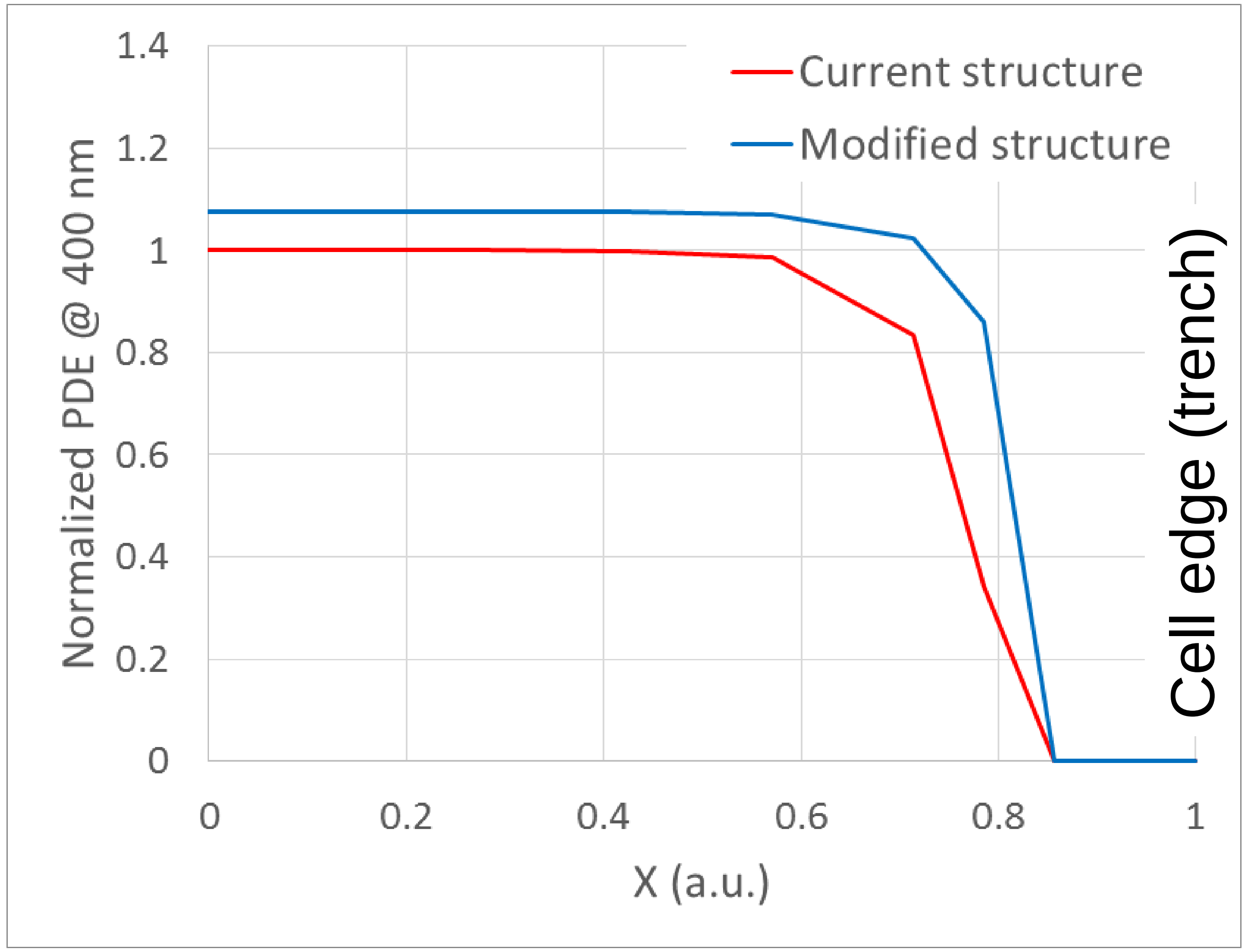
The advantage of using small cells for radiation hardness is relevant *only if they can still provide very high PDE*

Mitigation of Radiation Damage
NUV-HD-RH SiPMs for CMS-BTL

R&D still in progress to improve the electric field profile and to select optimal cell size:

- *Narrower dead border at small OV*
- *Faster increase of PDE vs OV*



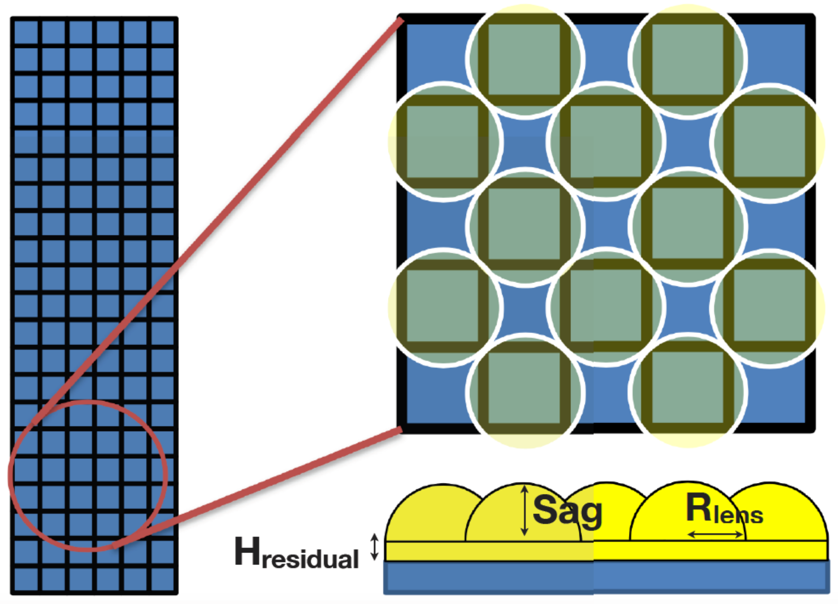


Simulated PDE @ 400 nm vs normalized distance from cell center

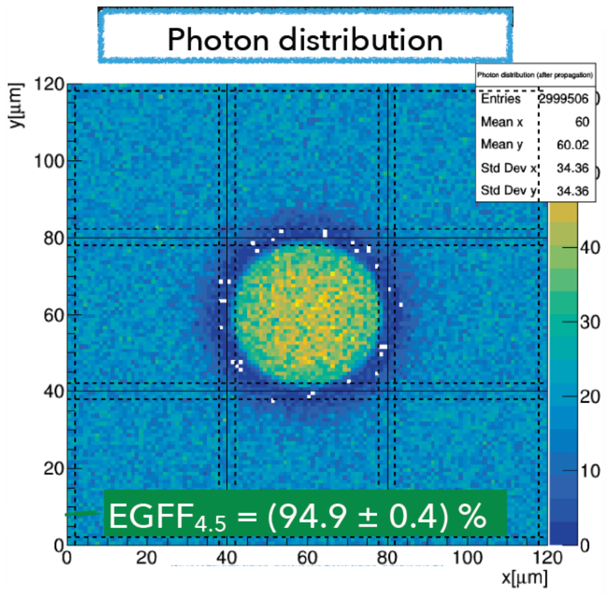
Light concentration
Microlenses

Microlenses can be used to *enhance the Fill Factor (FF) and thus the PDE of the SiPM microcells*.

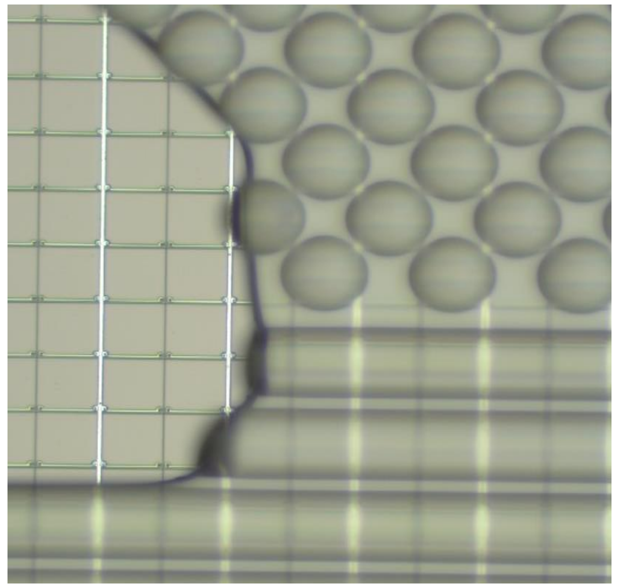
- Exploratory project between FBK and EPFL for LHCb SciFi tracker → Sensitivity-enhanced SiPMs
- Effectiveness *depends on the angular distribution of photons*.



Proposed microlens geometry



95% FF on 40 um SiPM microcells (80% without microlenses)

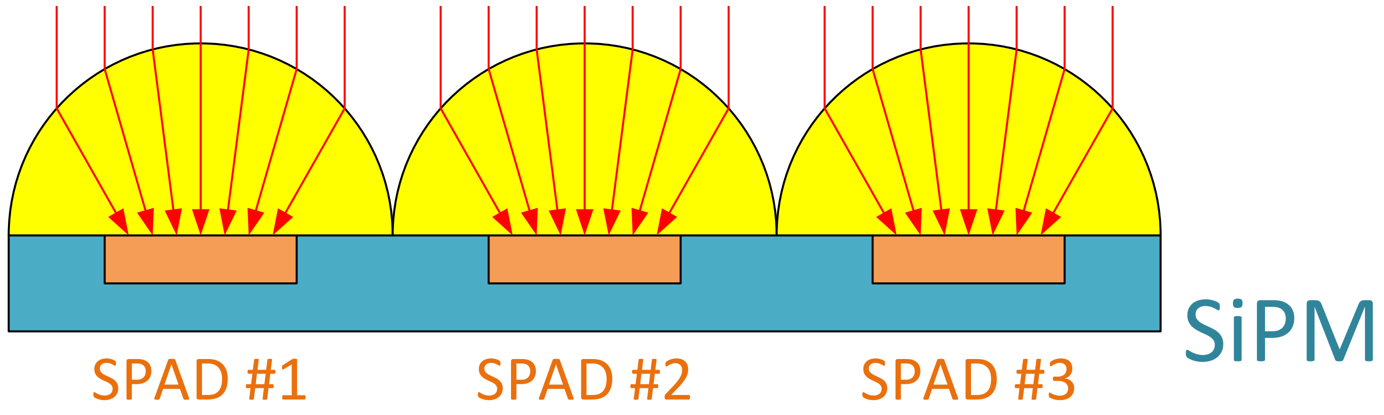


23% improvement!

Courtesy of C. Trippl, G. Haefeli
https://doi.org/10.1016/j.nima.2022.167216

Microlenses to enhance radiation hardness

- Photons can be focused on a much smaller light-sensitive area within each microcell.
- The silicon *area sensitive to radiation damage is reduced*.



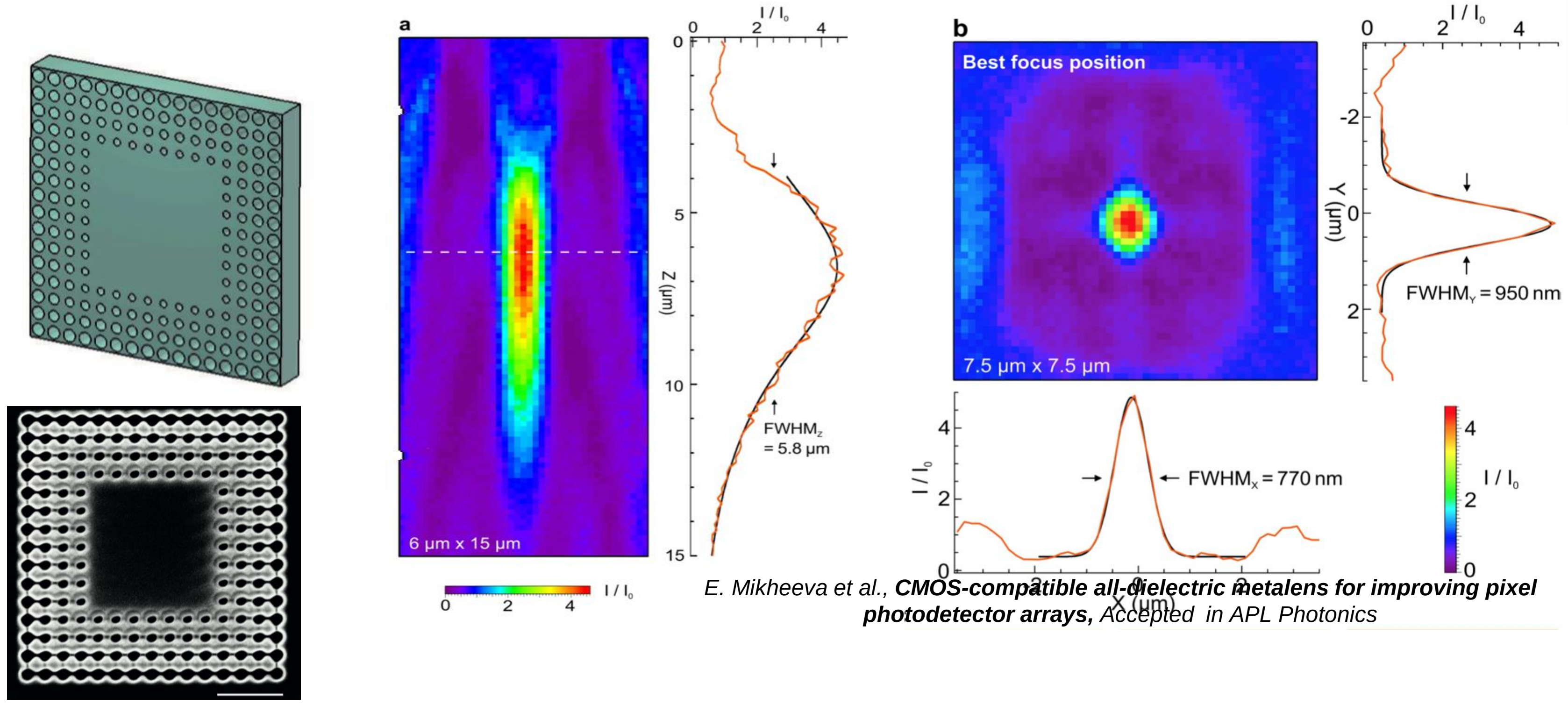
Light concentration
Metasurfaces and Metamaterials

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 radiation hardness*.

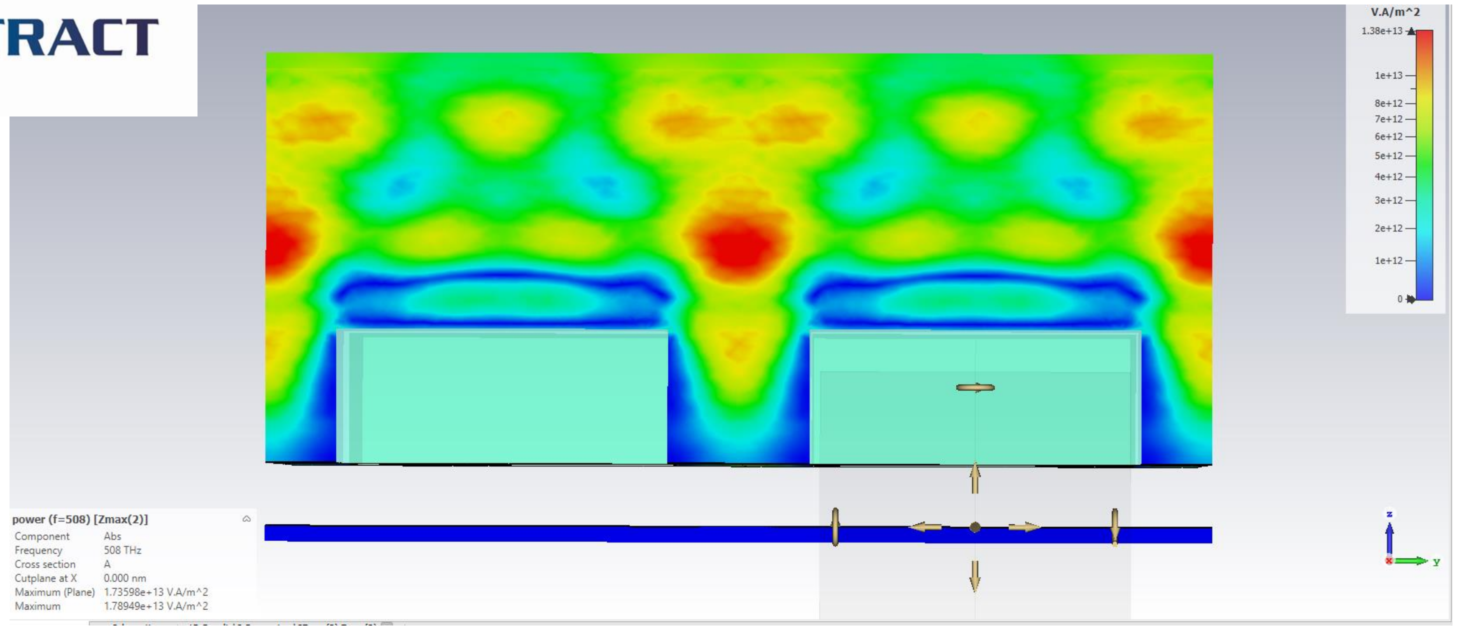
- Advantages: rad-hard metalens material (TBC), compatibility with CMOS planar processing.

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



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

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.)



Deeper modification of the SiPM structure to evaluate enhancment of efficiency with nanophotonics.

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

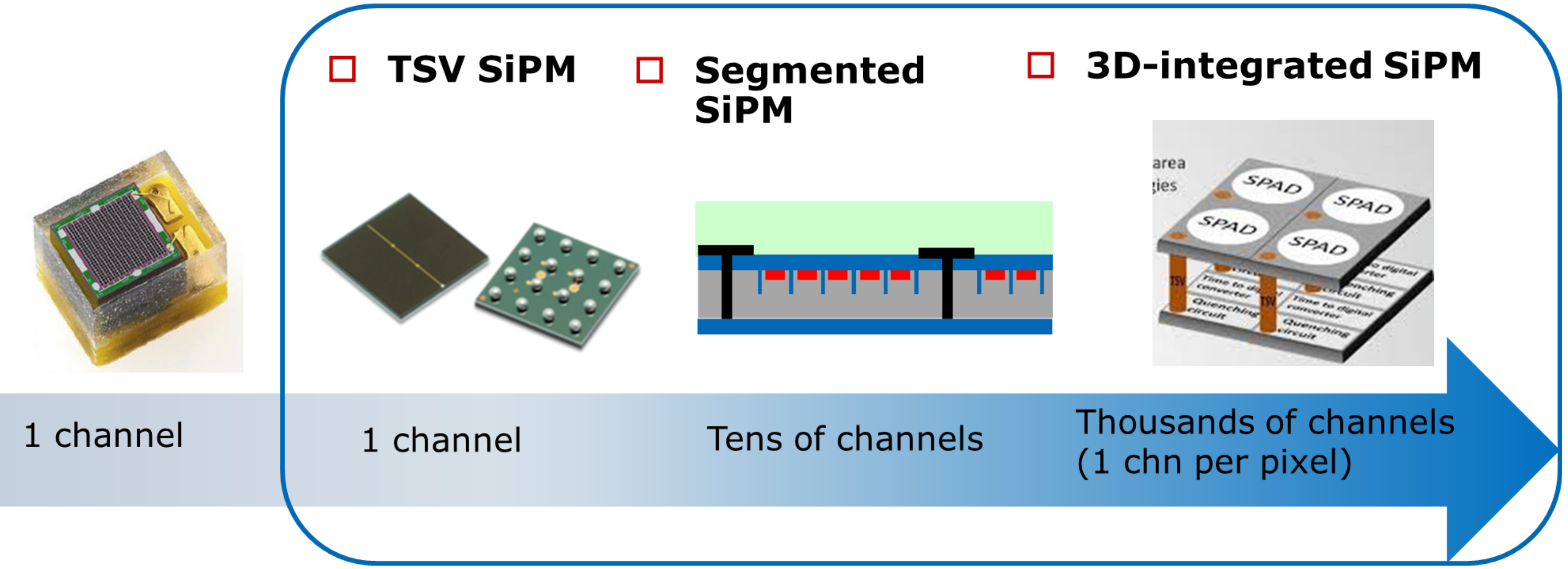
2.5D and 3D Integration
FBK IPCEI clean-room upgrade

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).

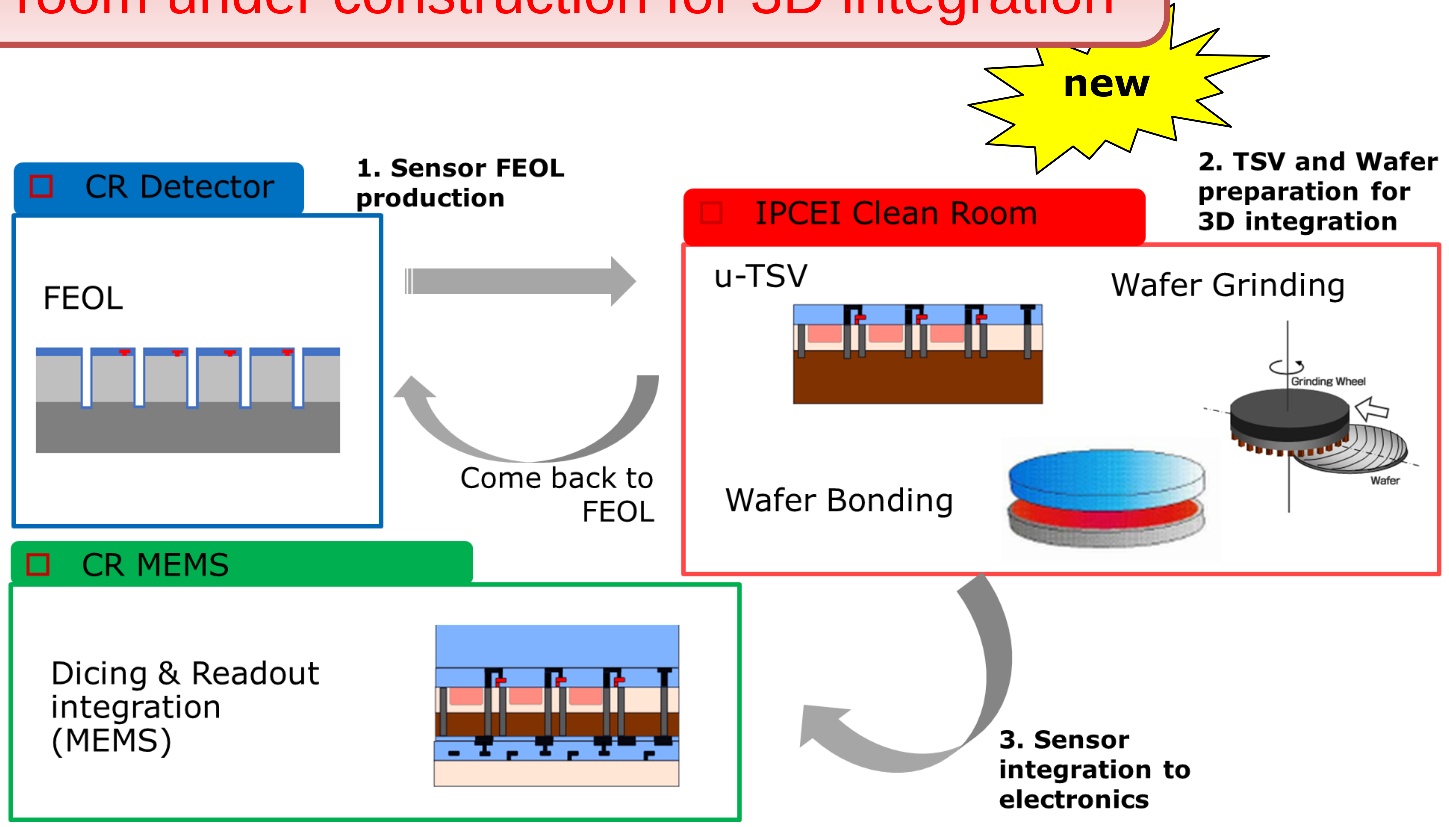
The goal for FBK is upgrading its optical sensors technologies, by *developing TSVs, micro-TSV and Backside Illuminated SiPMs*. This will allow high-density interconnections to the front-end and high-segmentation.

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

New clean-room under construction for 3D integration



Range of technologies being developed within IPCEI

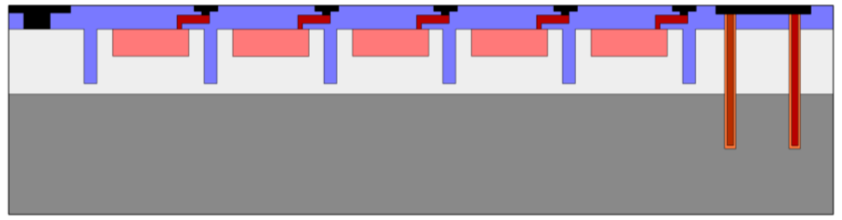


The future system composed of 3 research clean-rooms in FBK.

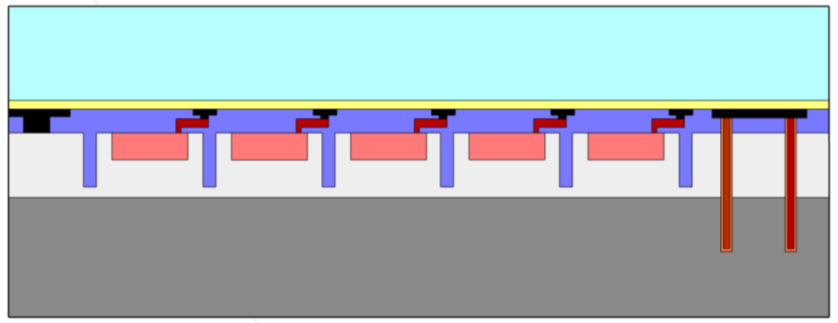
2.5D and 3D Integration
TSV – via mid: process flow

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

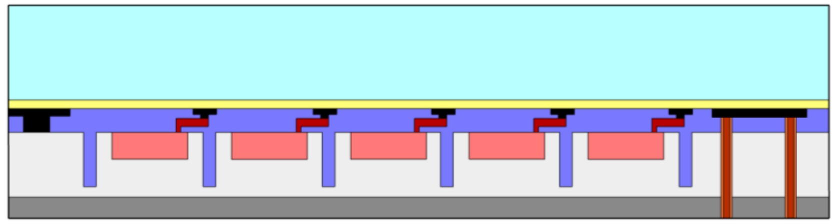
- SiPM fabrication + TSV formation



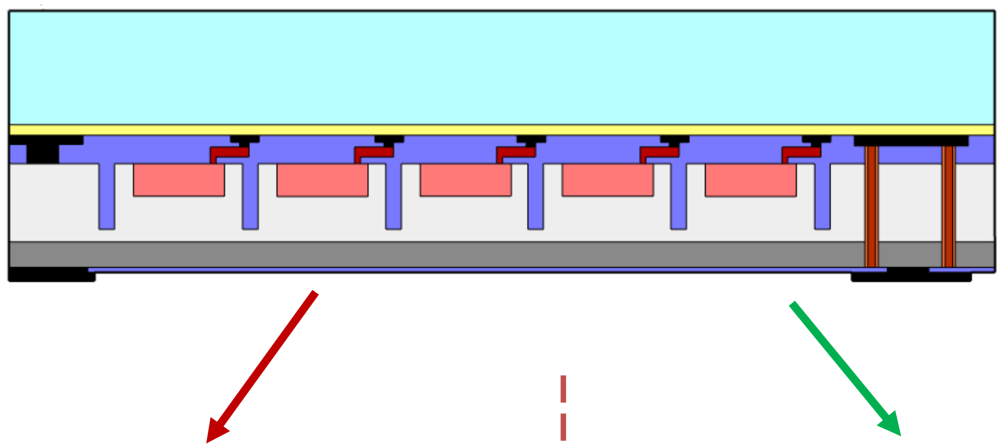
- Edge Trimming + BONDING



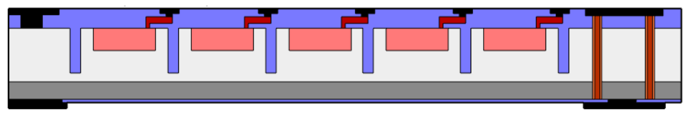
- THINNING



- Contacts formation



- DEBONDING

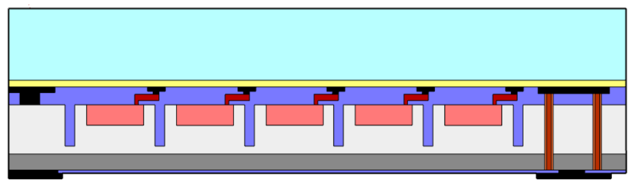


Thickness at least 150 um

Glass-less TSV
concept

500 um SiPM pitch

- NO-DEBONDING

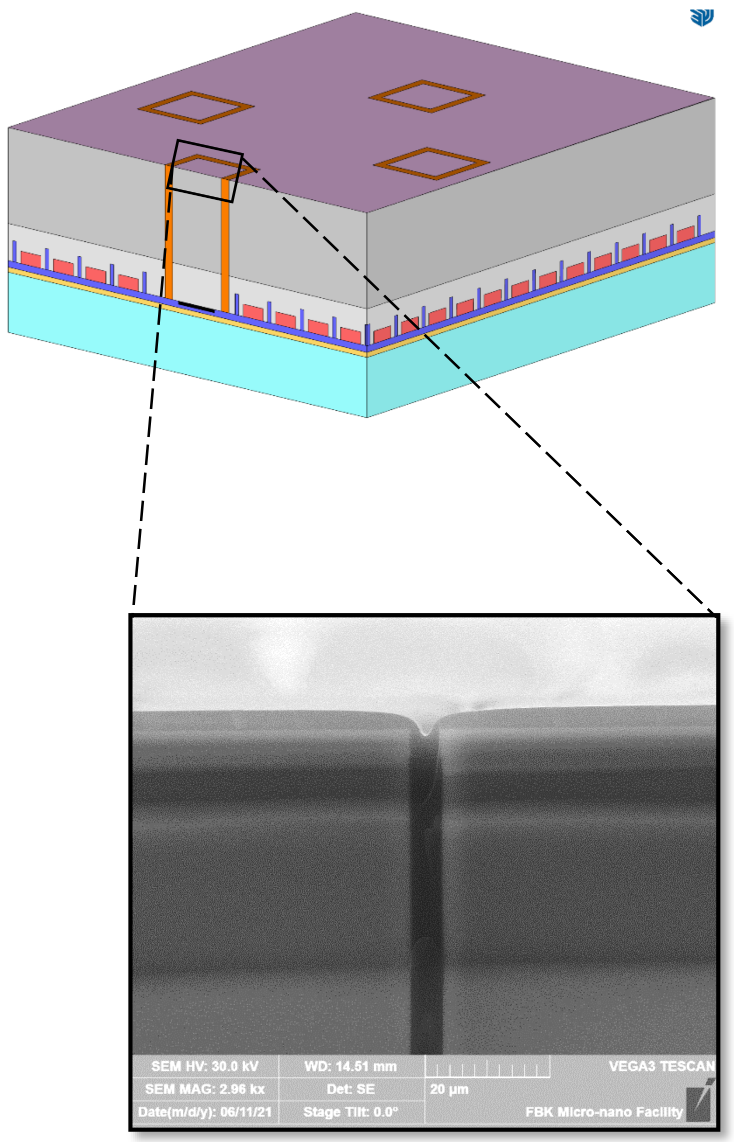


Thickness 10-50 um

Standard TSV

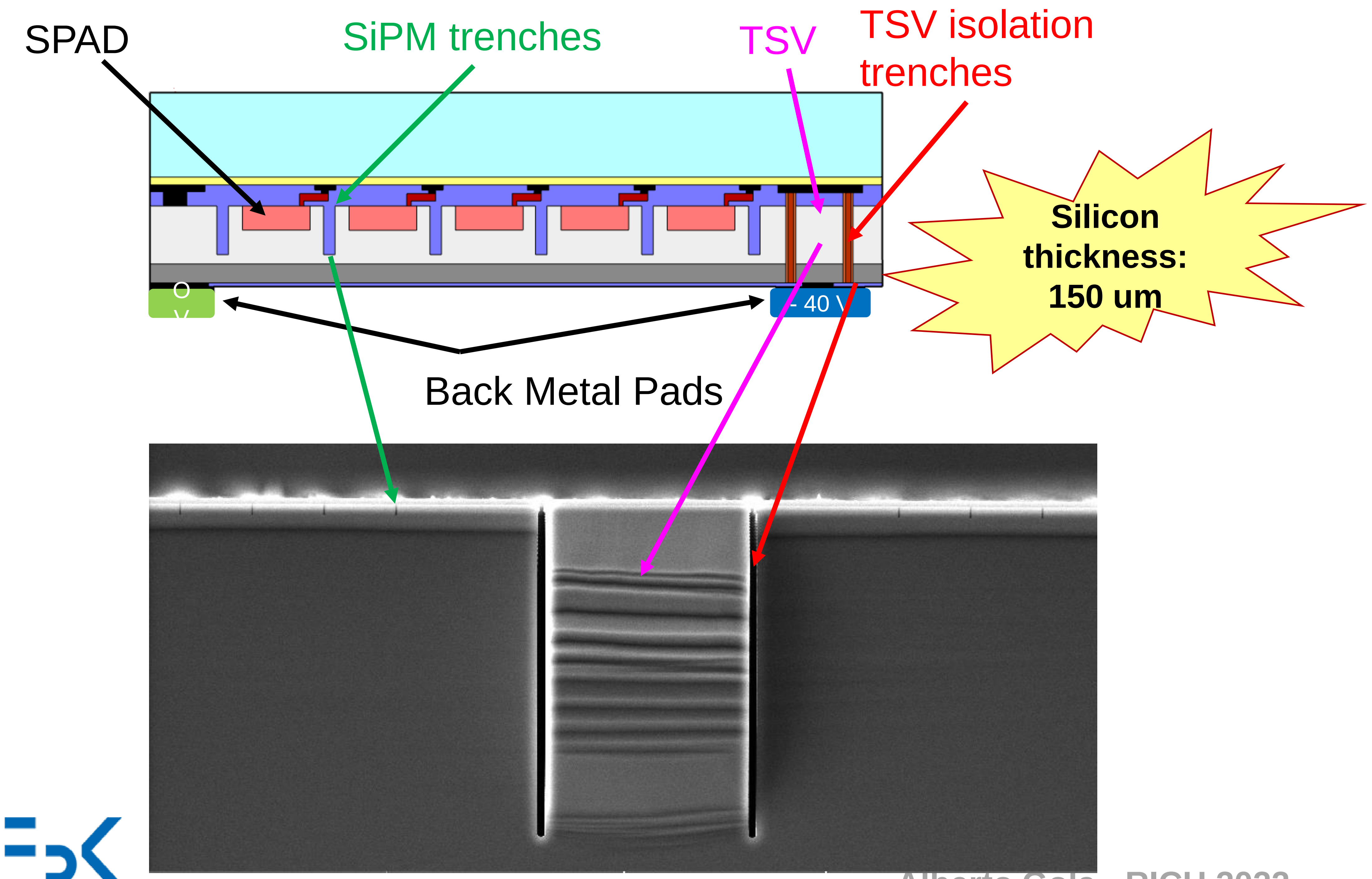
microTSV

< 50 um SPAD pitch



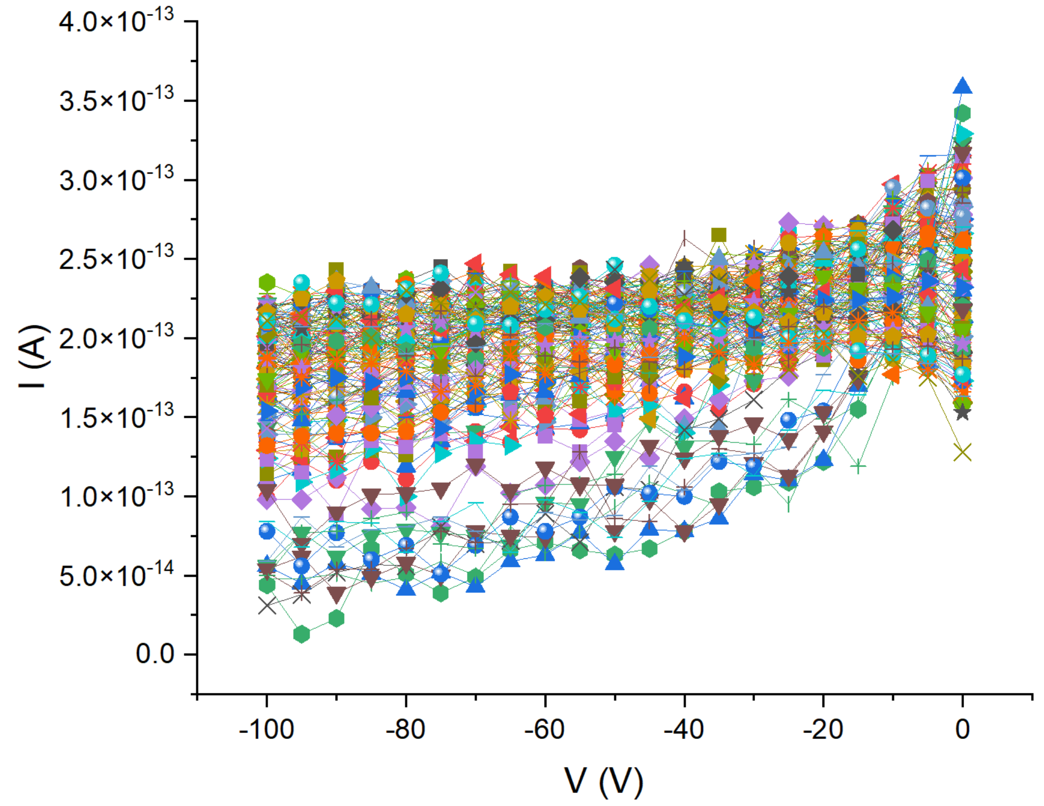
2.5D and 3D Integration
TSV – via mid: first results

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

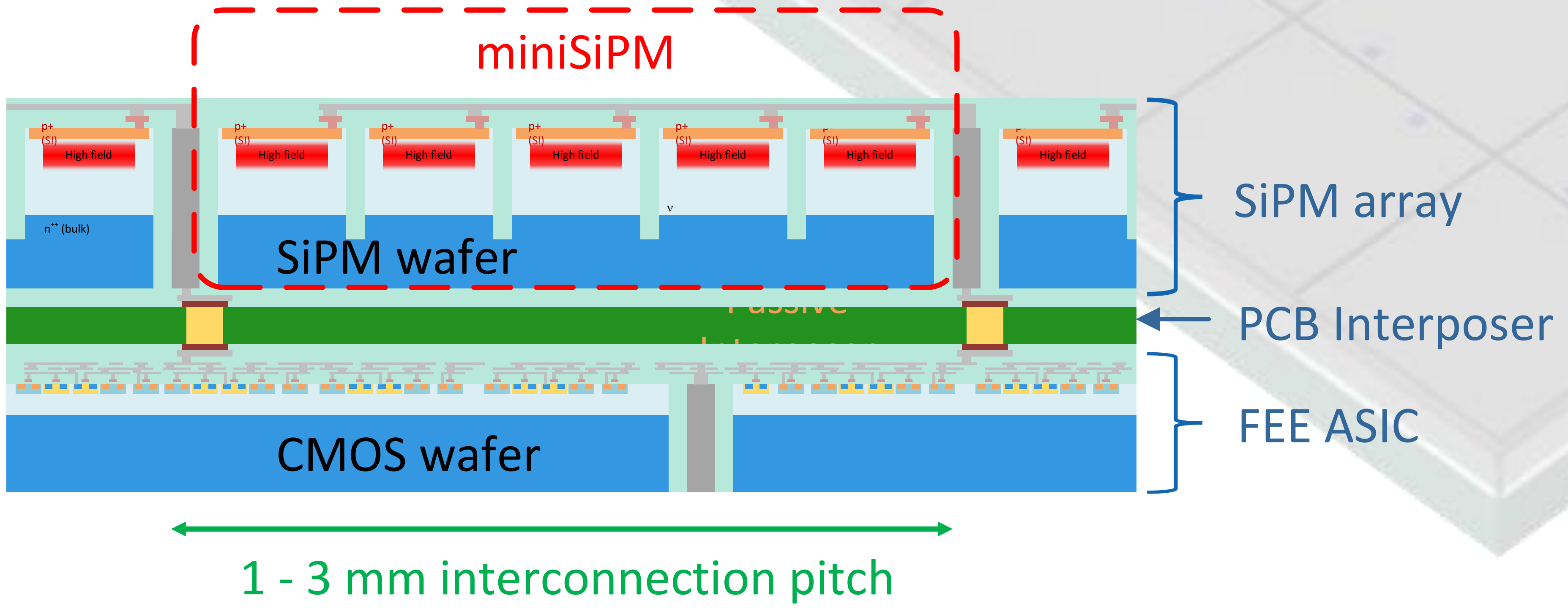


2.5D and 3D Integration
2.5D integrated SiPM tile

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

We propose a Photon Detection Module (PDM) in which *SiPMs with TSVs down to 1 mm pitch* are connected to the *readout ASIC on the opposite side of a passive interposer*, in a *2.5D integration scheme*.

Integrated Photon Detection Module



Core partners:

Jožef Stefan Institute

ICCUB Institut de Ciències del Cosmos

Massachusetts General Hospital

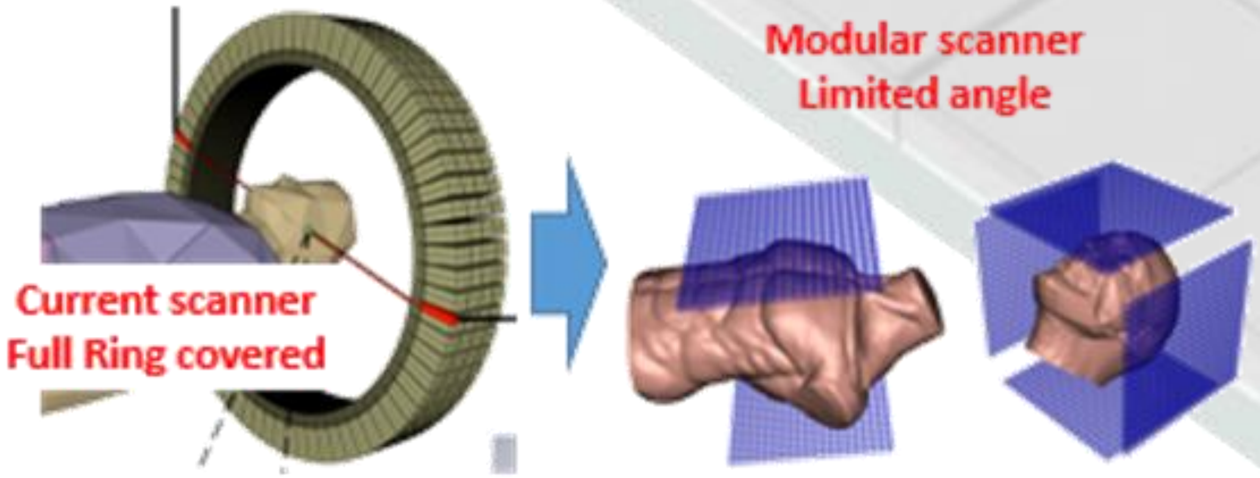
OncoVision

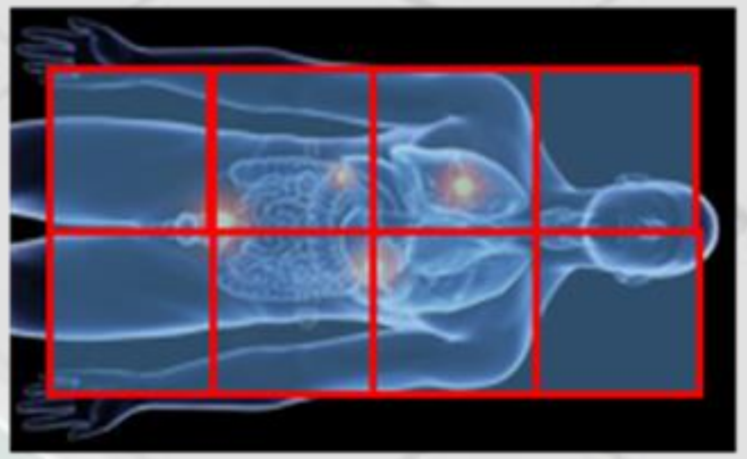
Hybrid SiPM module being developed for ultimate timing performance in ToF-PET

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

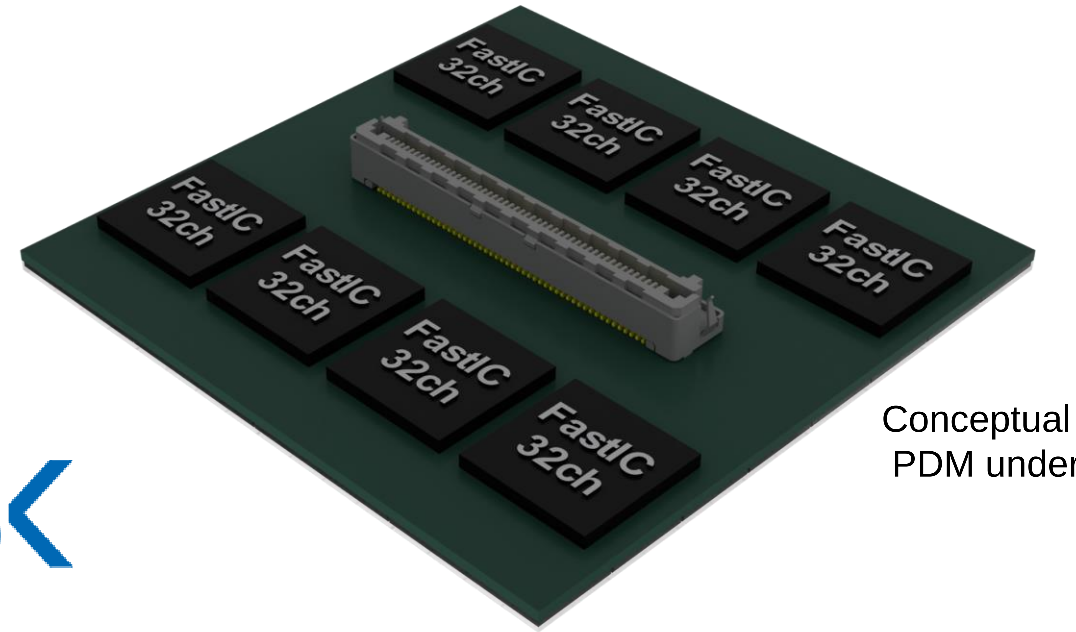
The 2.5D integrated PDM (50x50 mm^2) will be the basis of a *30x30 cm^2 ToF-PET panel*, which will be used to build limited-angle ToF-PET systems, for brain PET, Cardiac PET and full-body scanners.

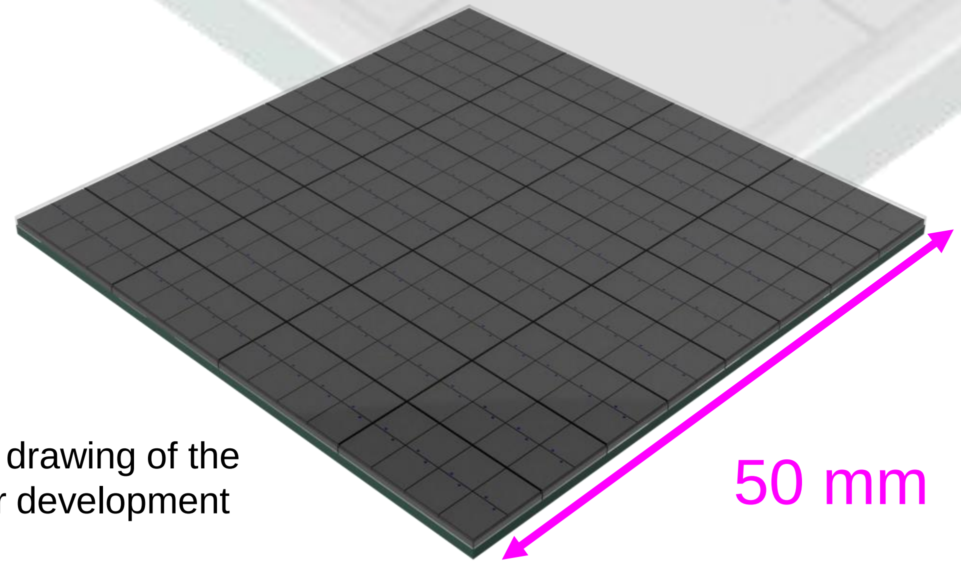
We *expect very good timing performance*, supported by preliminary measurements achieved with NUV-HD SiPMs coupled to FastIC ASIC.



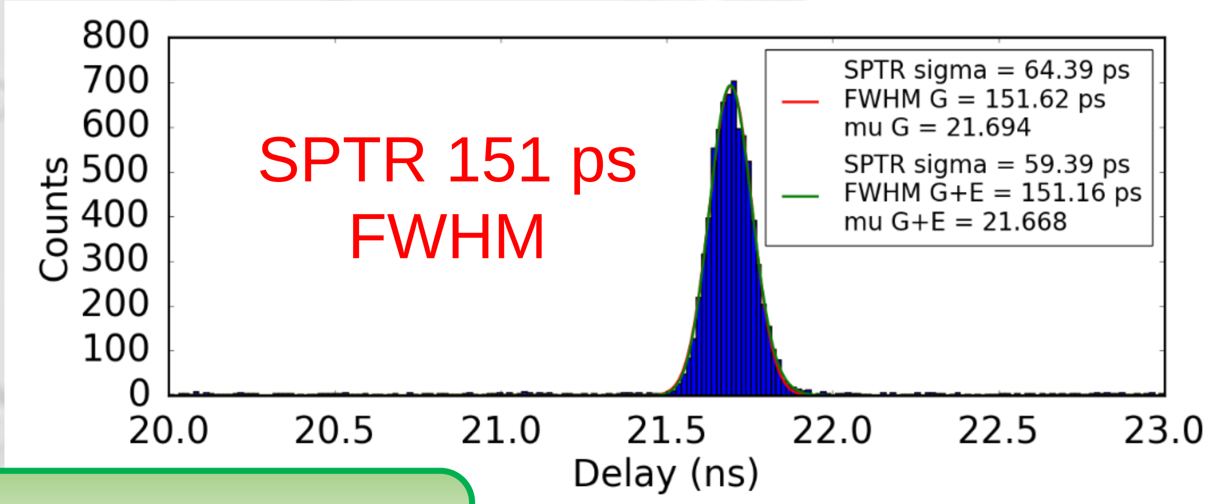


Application of the PDM to build large panes used in new, limted-angle PET applications: Brain Pet, Cardiac PET, while-body PET

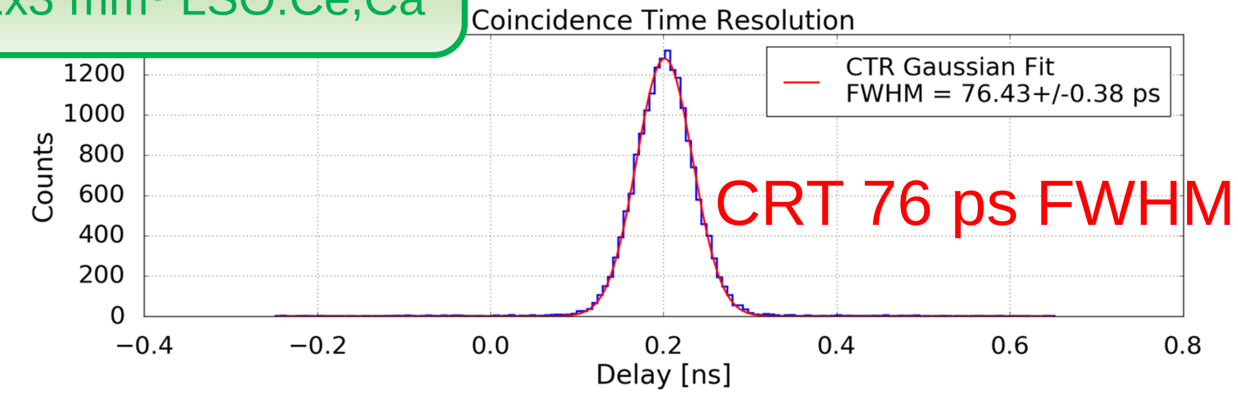




Conceptual drawing of the PDM under development



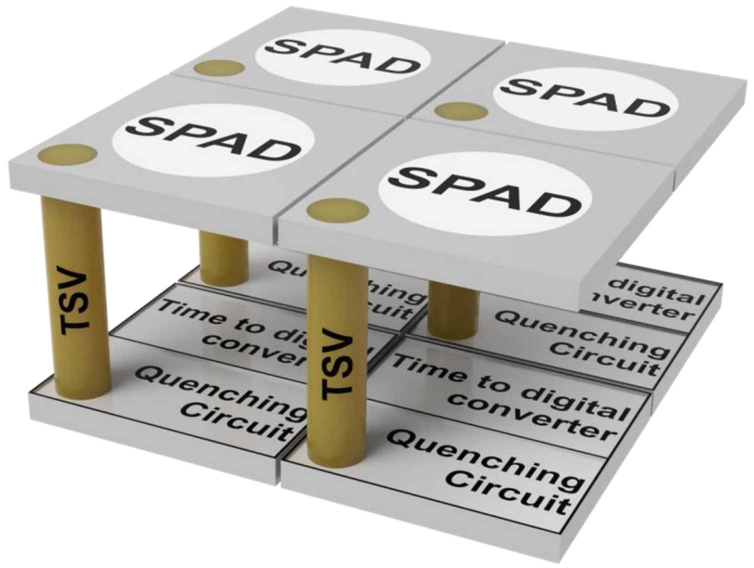
2x2x3 mm^3 LSO:Ce,Ca



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

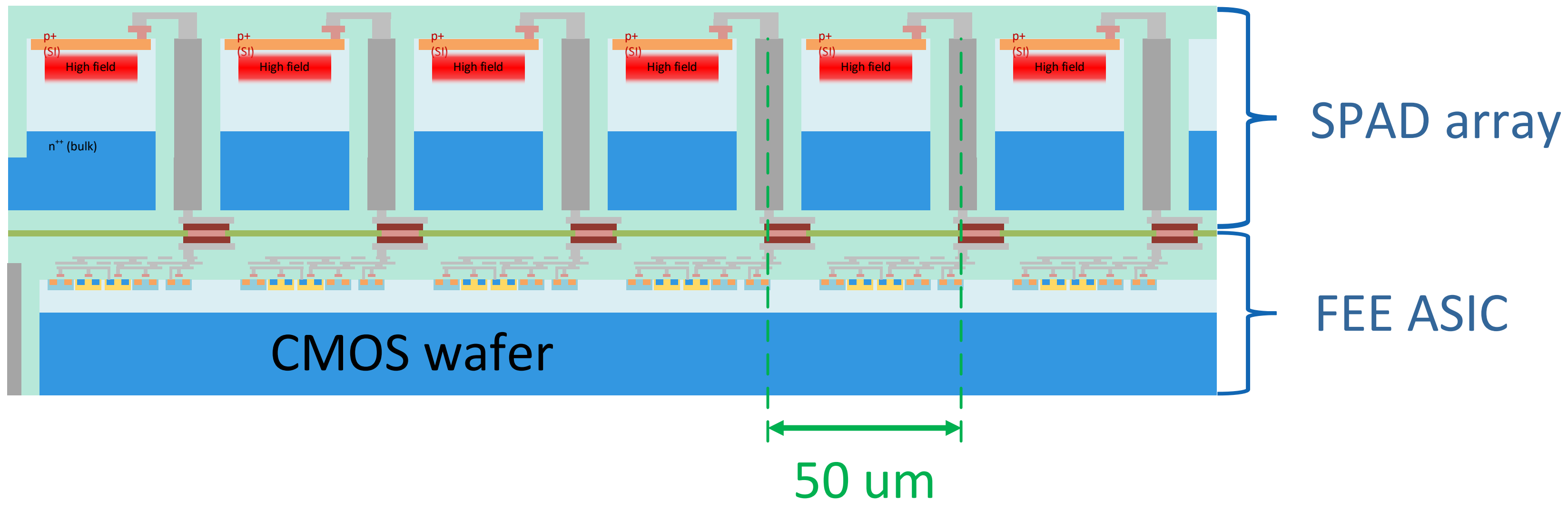
2.5D and 3D Integration
Full 3D integration with micro TSVs: Hybrid SiPM

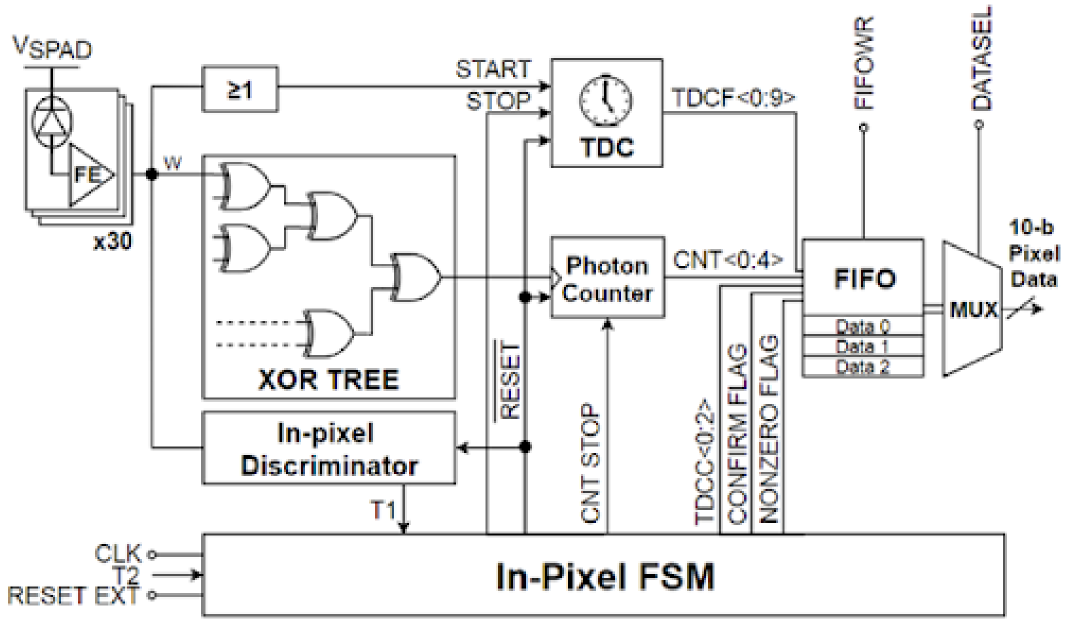
FBK is investigating the potential of microTSVs to achieve *single cell connection*. While complexity of the system increases, it might provide *ultimate timing performance*.

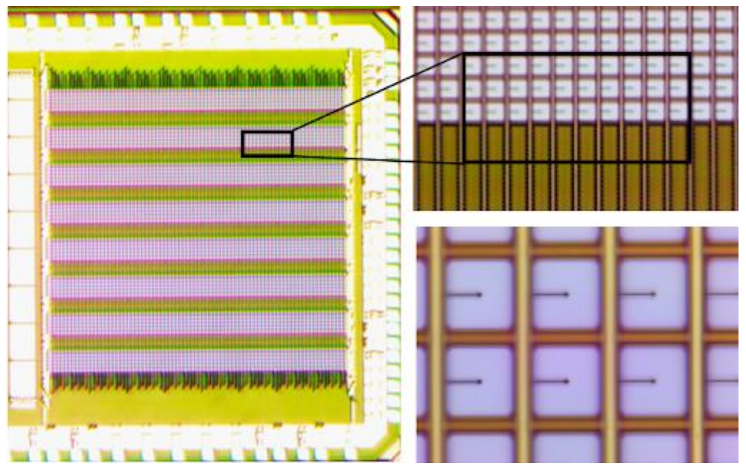


Hybrid SiPM

~50 um SPAD pitch







Example of dSiPM architecture developed at FBK (SBAM project)

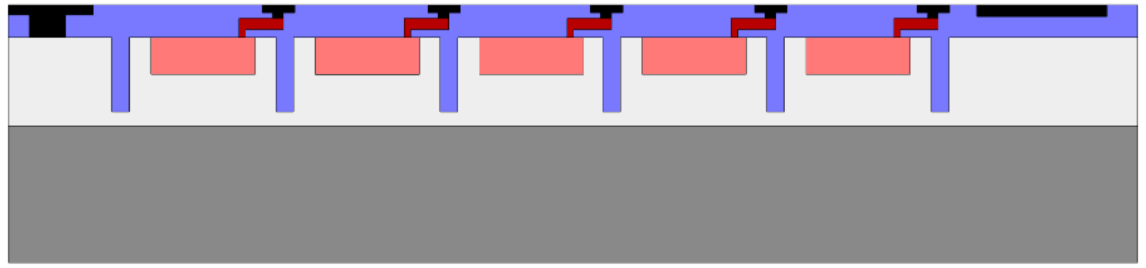
- FBK can apply all the *know-how on system architecture* already developed in the filed of digital SiPMs.
- Finally solve the duality between analog and digital SiPM: *Hybrid SiPM concept*.

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

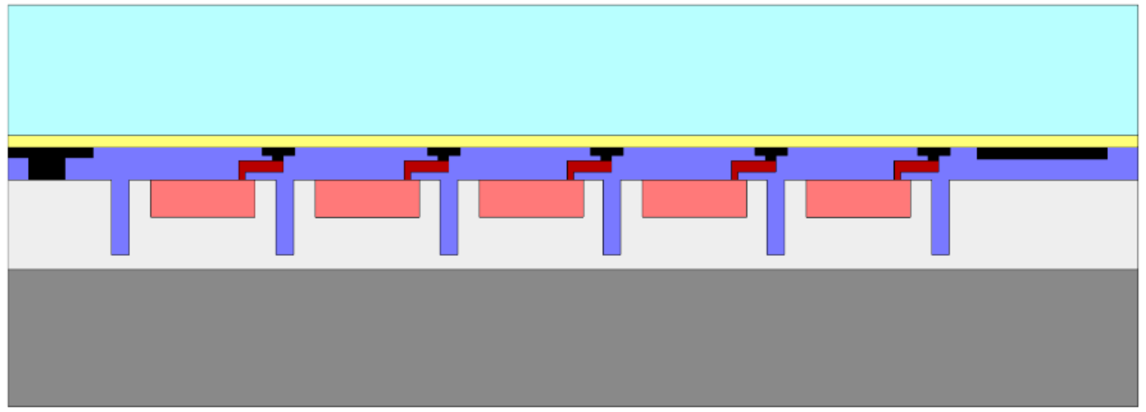
on Microelectronics

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

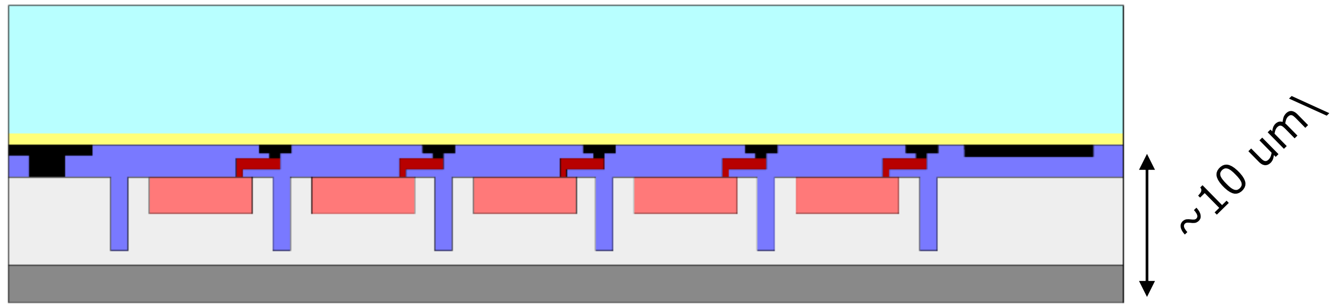
1. SiPM Wafer



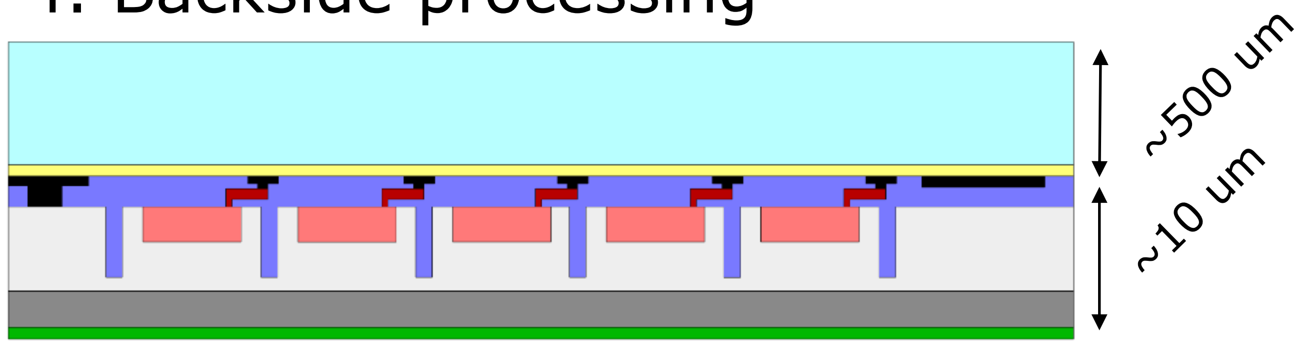
2. Temporary Bonding



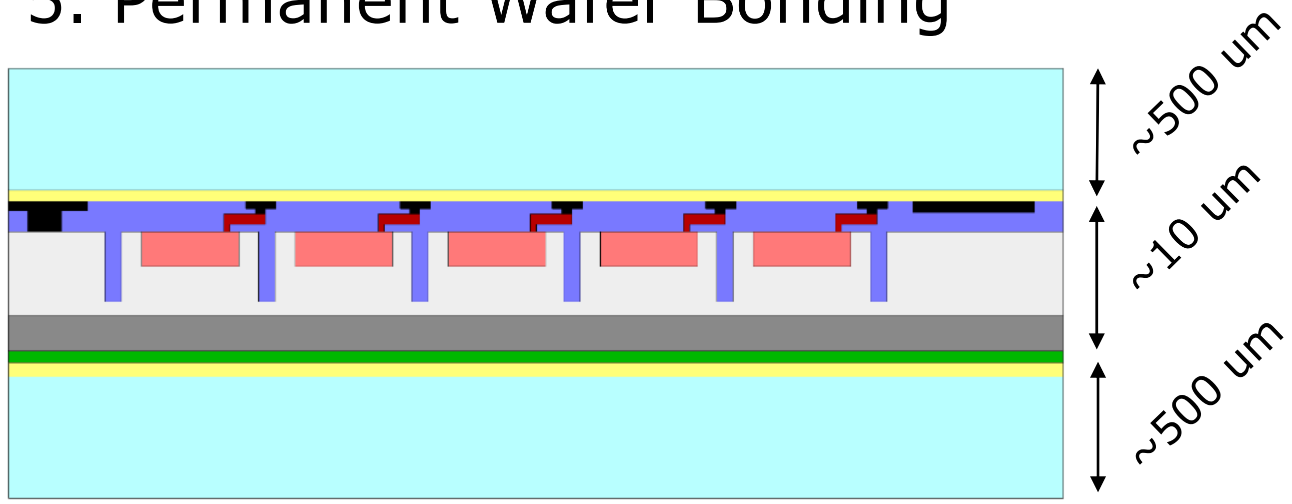
3. Grinding & Polishing



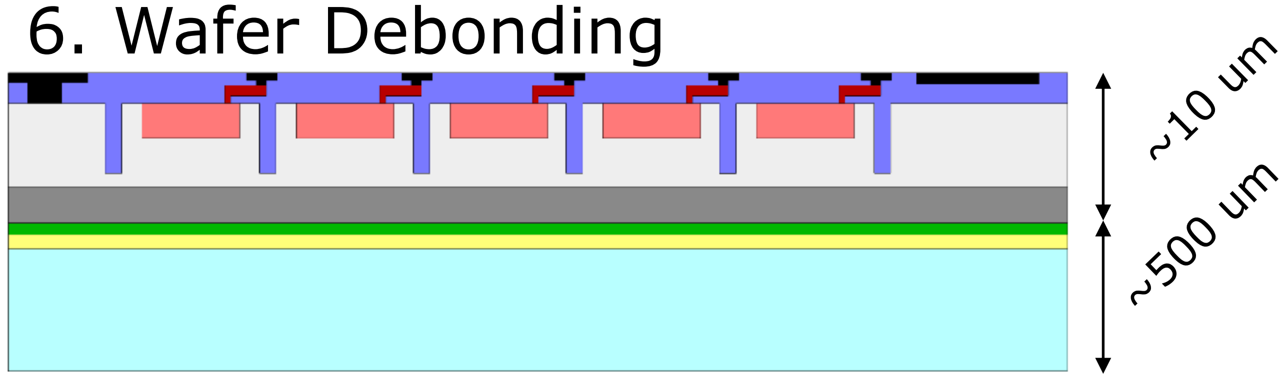
4. Backside processing



5. Permanent Wafer Bonding



6. Wafer Debonding

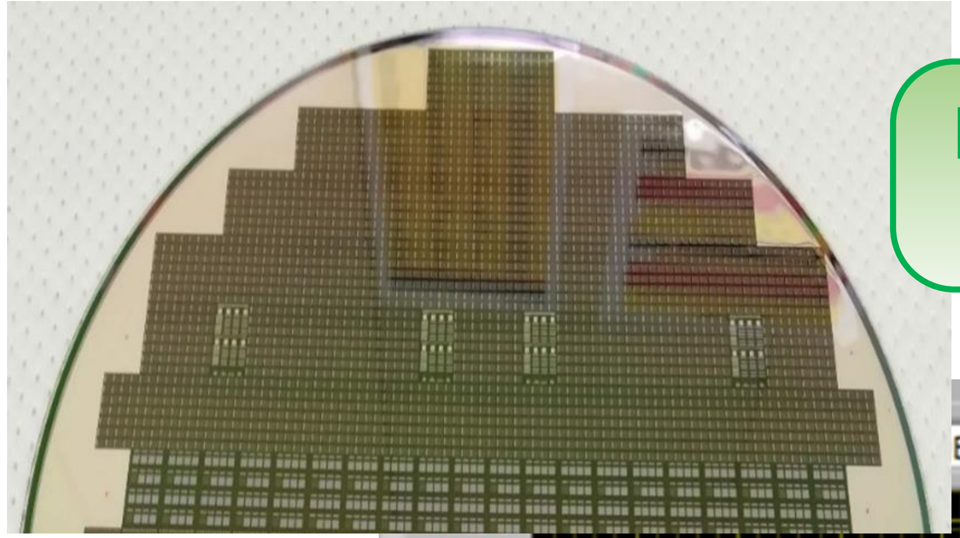


2.5D and 3D Integration
BSI SiPMs: first results

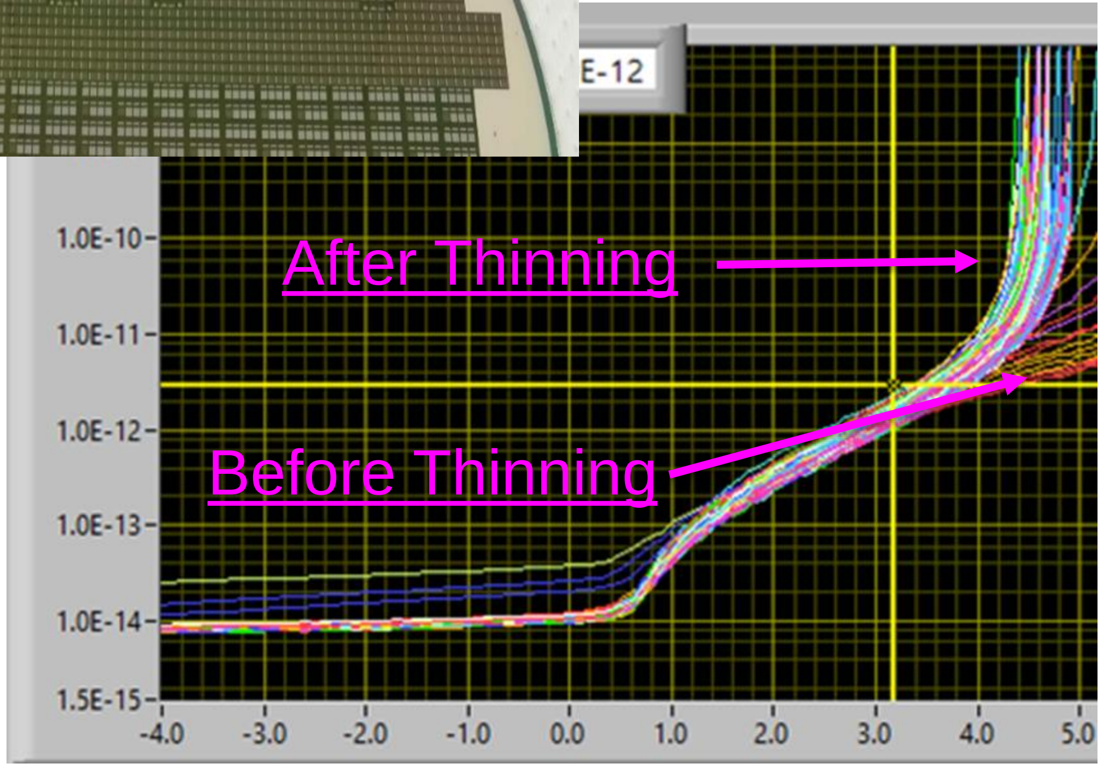
The *first NIR-sensitive BSI wafers were fabricated* in FBK clean room (1x1 mm^2 devices).

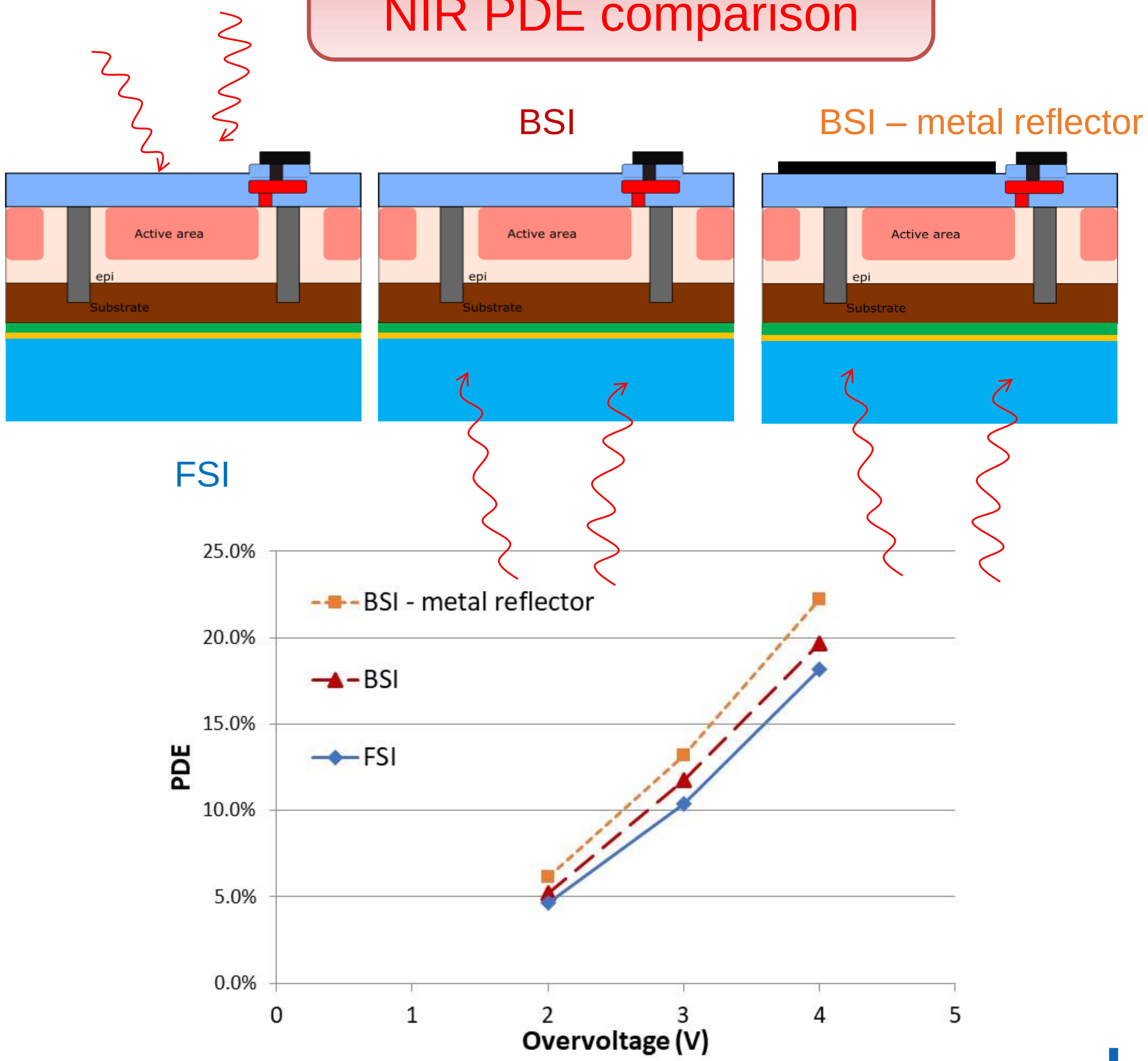
Minor differences in the IVs after thinning, compared to the FSI devices (without thinning).

Ultrathin substrate (~ 10 um)



NIR BSI process is working!

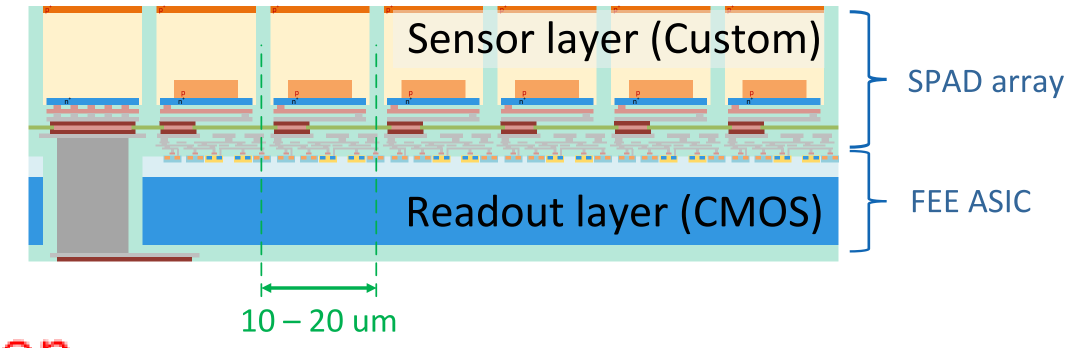




2.5D and 3D Integration
Next-generation development: Backside Illuminated SiPMs

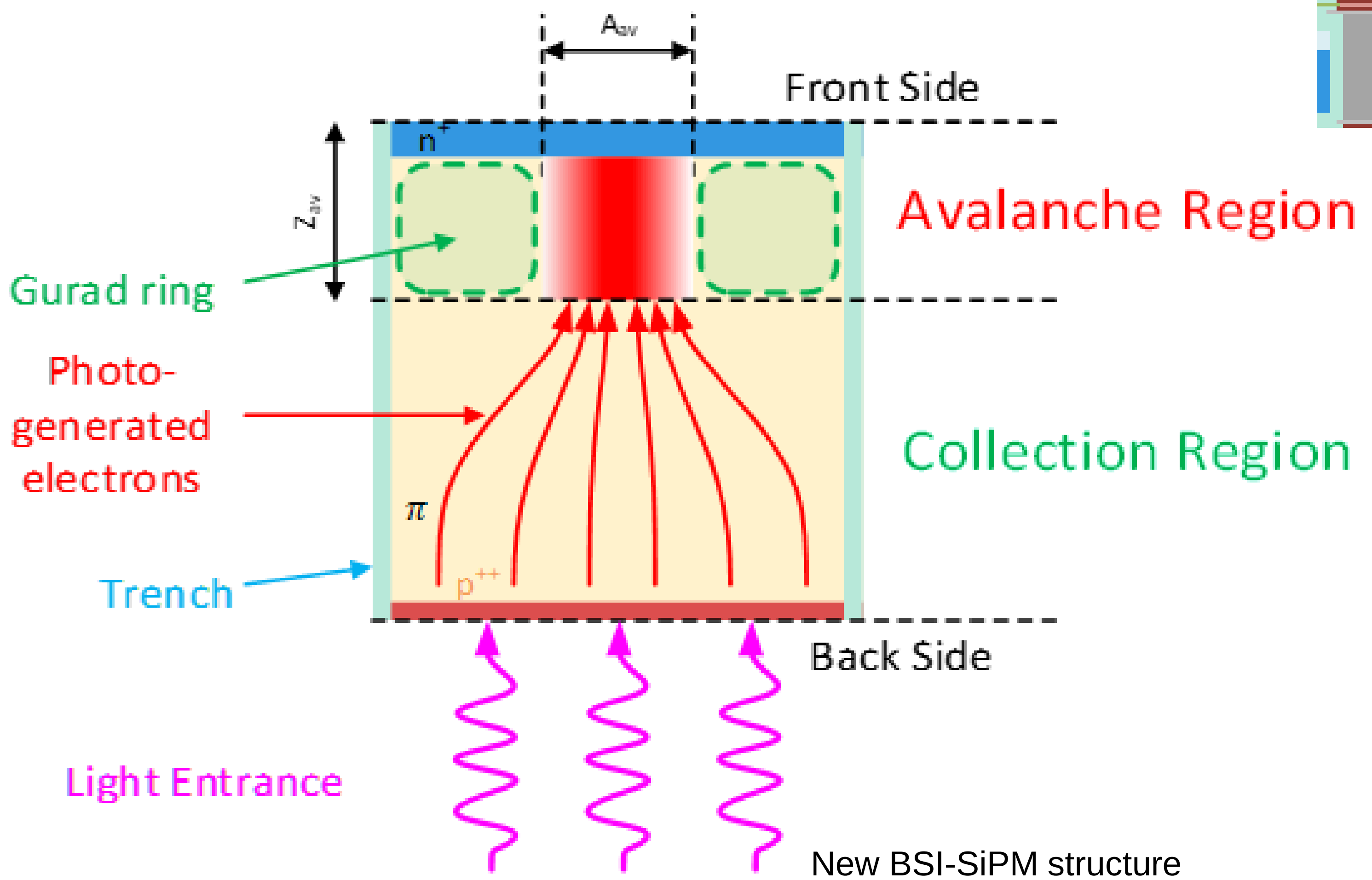
The next-generation of developments, currently being investigated at FBK, is building a *backside-illuminated, NUV-sensitive SiPM*. Several technological challenges should be overcome.

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.



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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- **Giovanni Paternoster**
- **Michele Penna**
- **Maria Ruzzarin**
- **Tiziano Stedile**
- **Nicola Zorzi**