FONDAZIONE BRUNO KESSLER

FUTURE BUILT ON KNOWLEDGE

Status and perspectives of SiPMs at FBK

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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

- ~500 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.

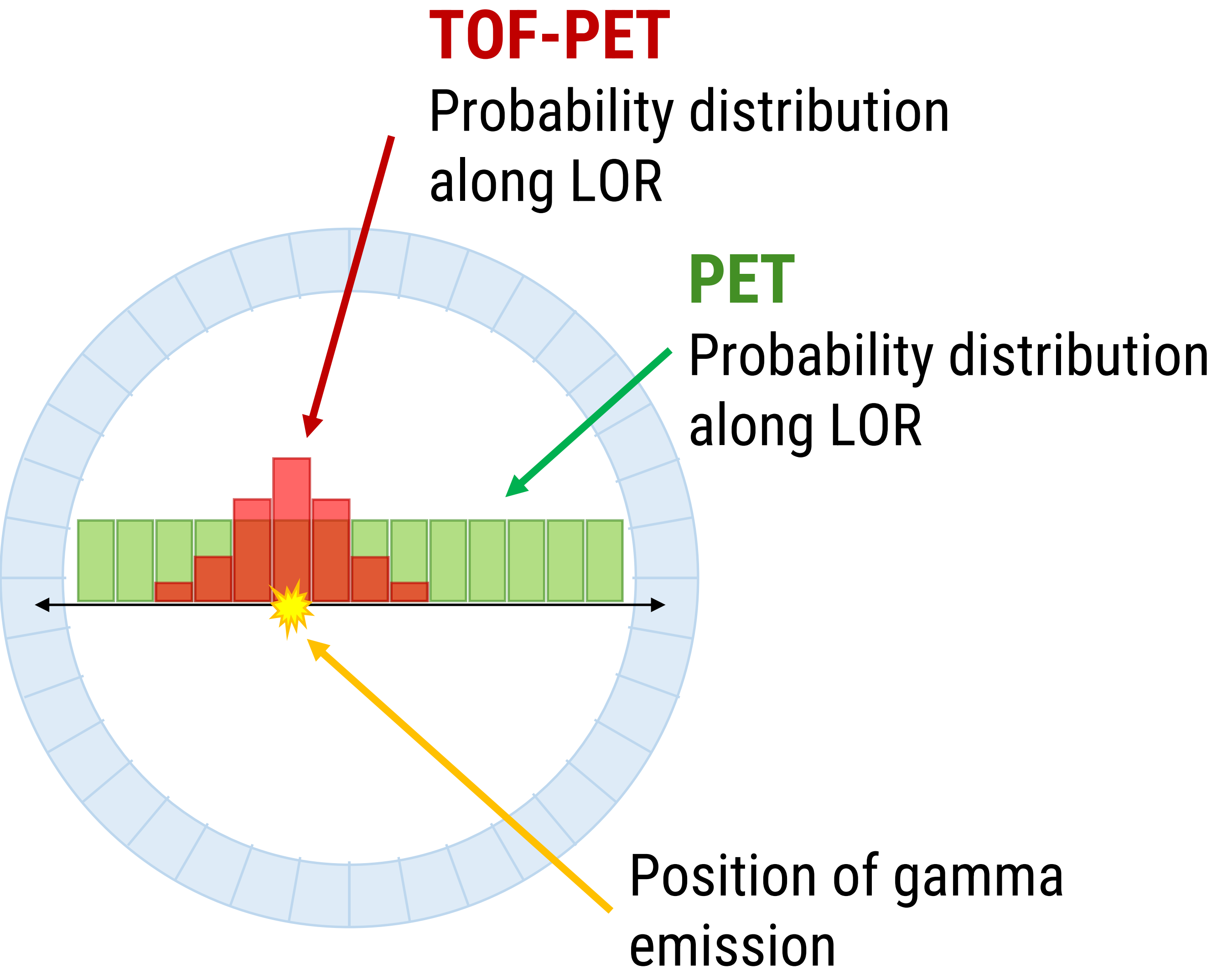
LFOUNDRY Solutions for great visions

BROADCOM

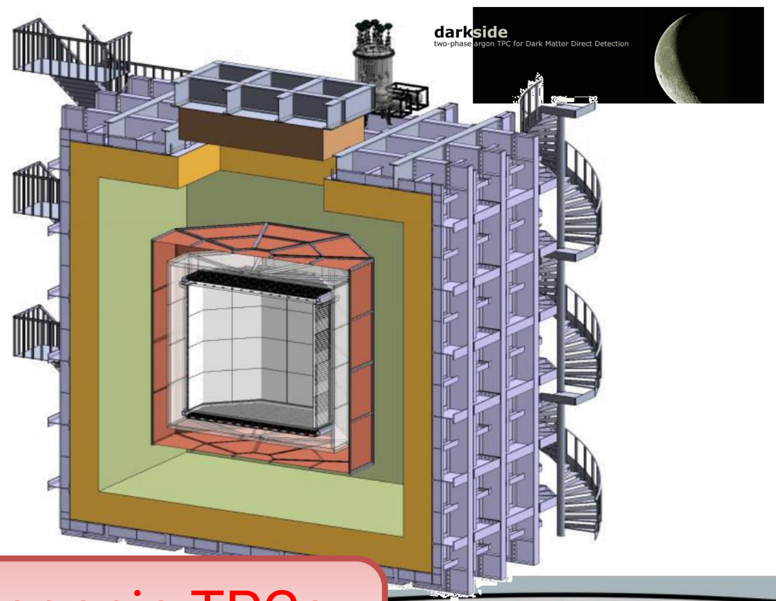
FBK SiPM technologies
Typical Applications

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*.

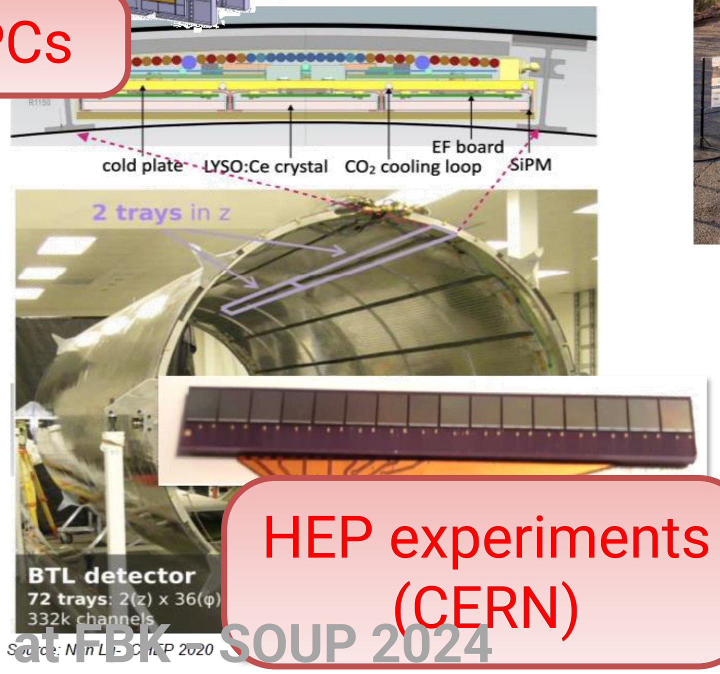
Positron Emission Tomography



Big Physics Experiments



Cryogenic TPCs



HEP experiments (CERN)

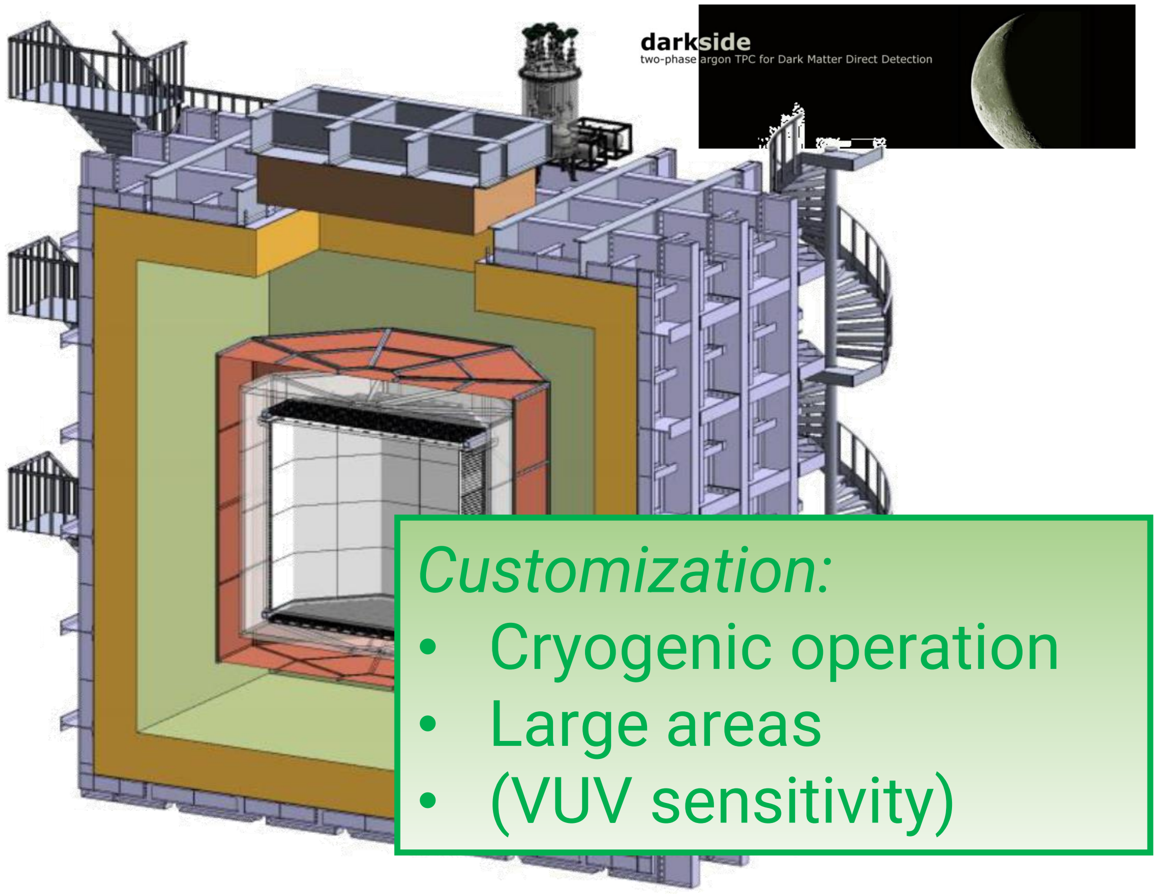
Astrophysics and space

Examples of Big Physics experiments FBK is currently working on.

FBK SiPM technologies
Use in Big Physics Experiments

Especially for Big Physics Experiments, *deep customization of the detector is often required.*

Cryogenic TPCs



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

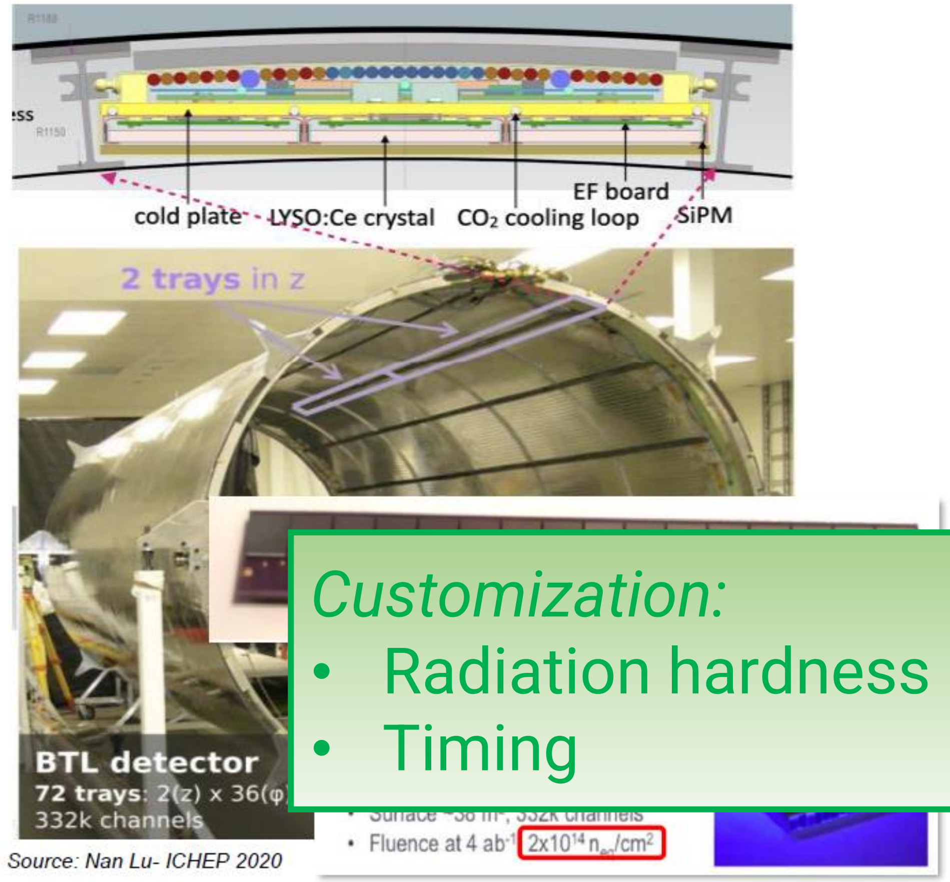
Cryogenic SiPMs will be employed in experiments such as DarkSide-20k

CTA

Customization:
- Low CT
- Maximum PDE

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

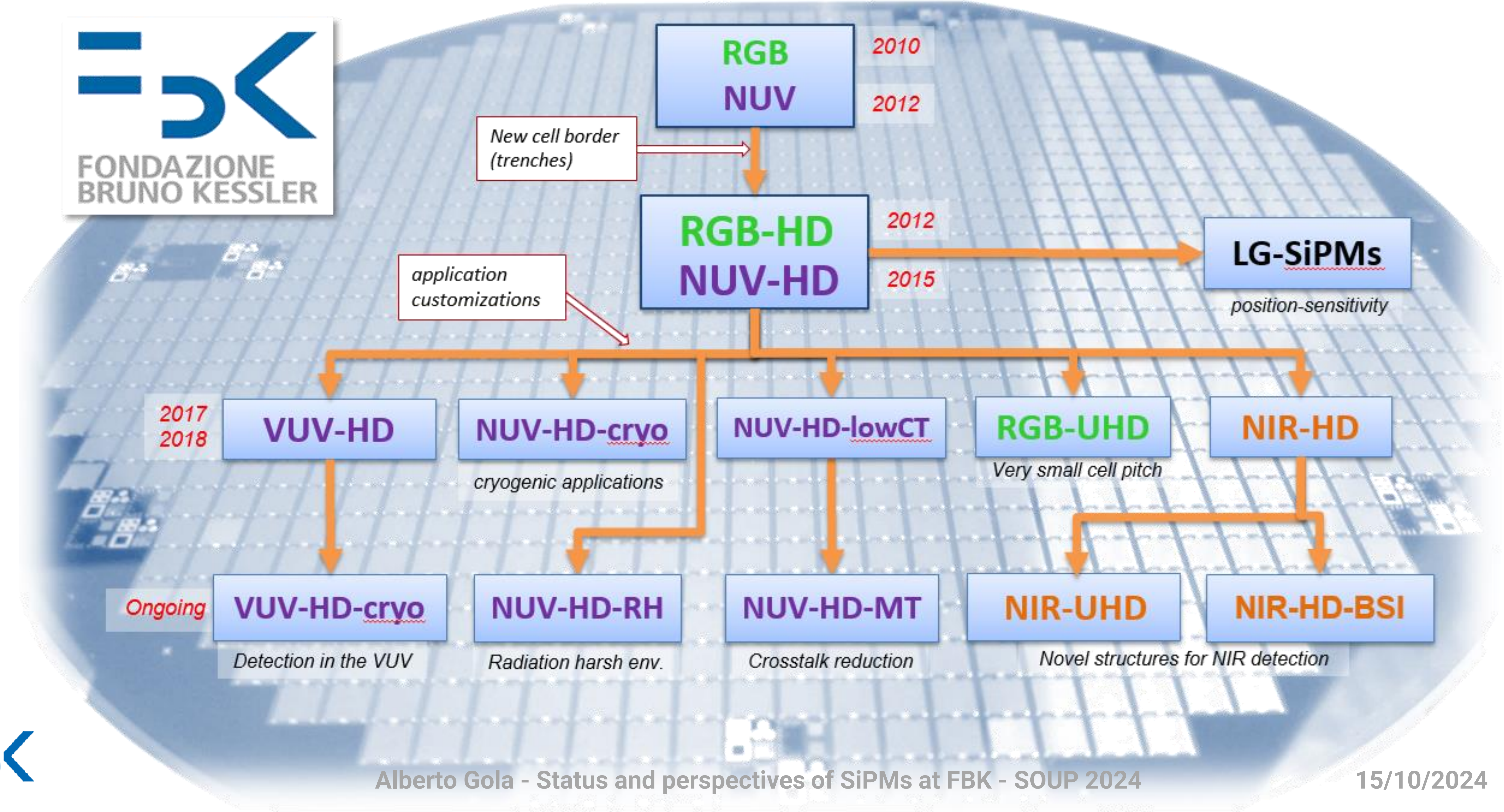
HEP



Customization:
- Radiation hardness
- Timing

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

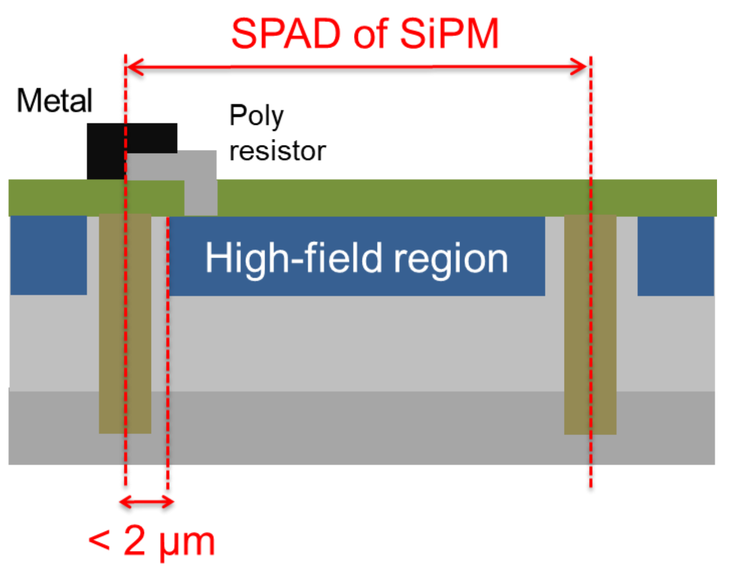
Fondazione Bruno Kessler
Custom SiPM technology roadmap

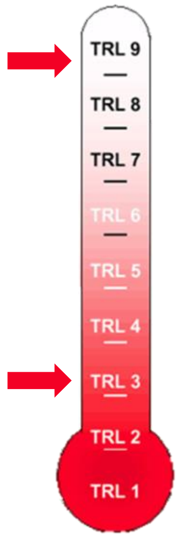


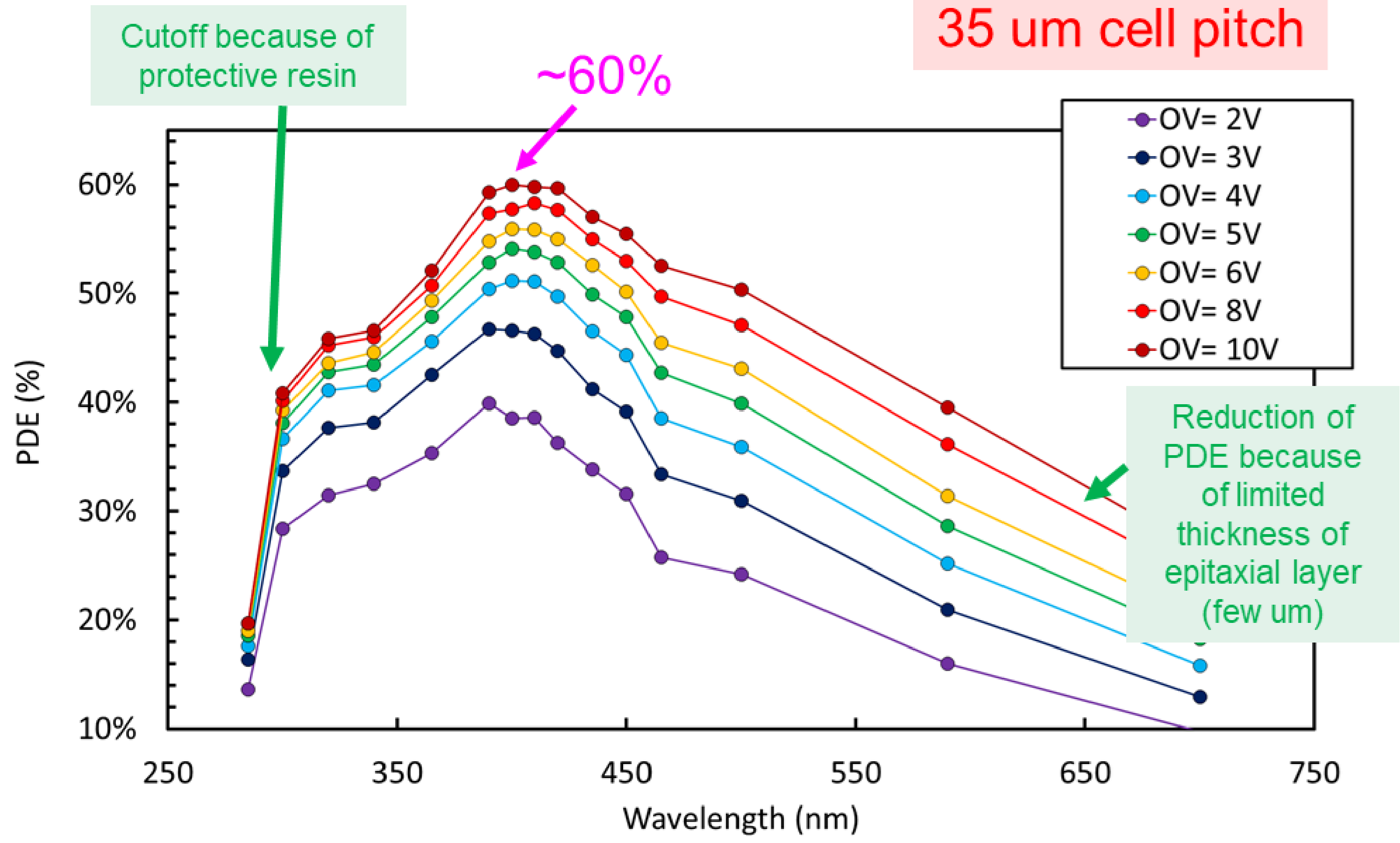
Timing performance in PET

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.*

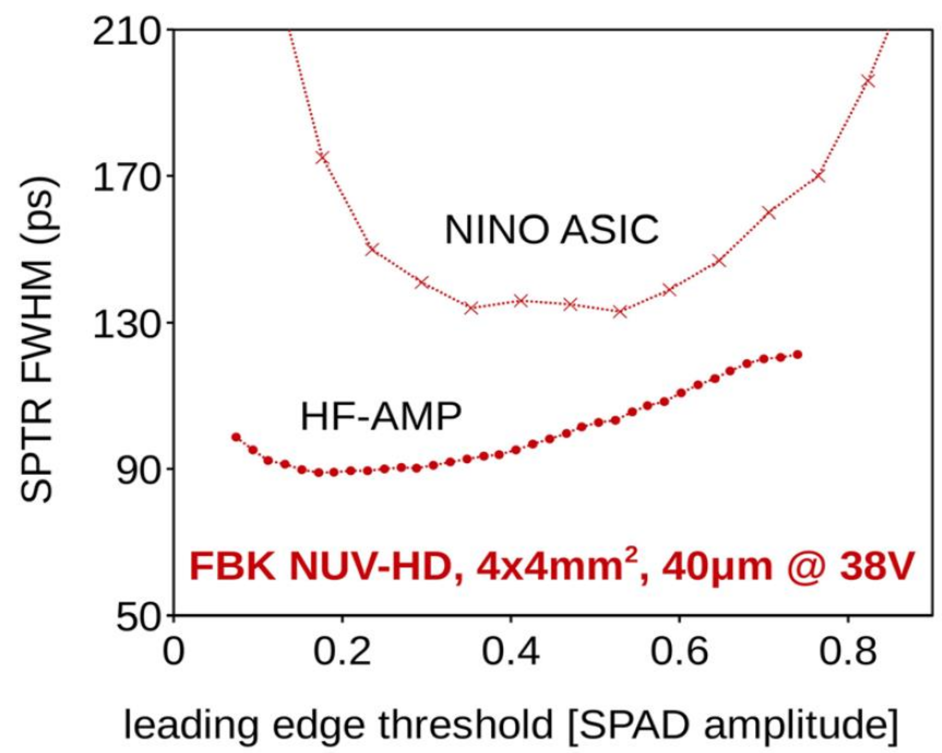


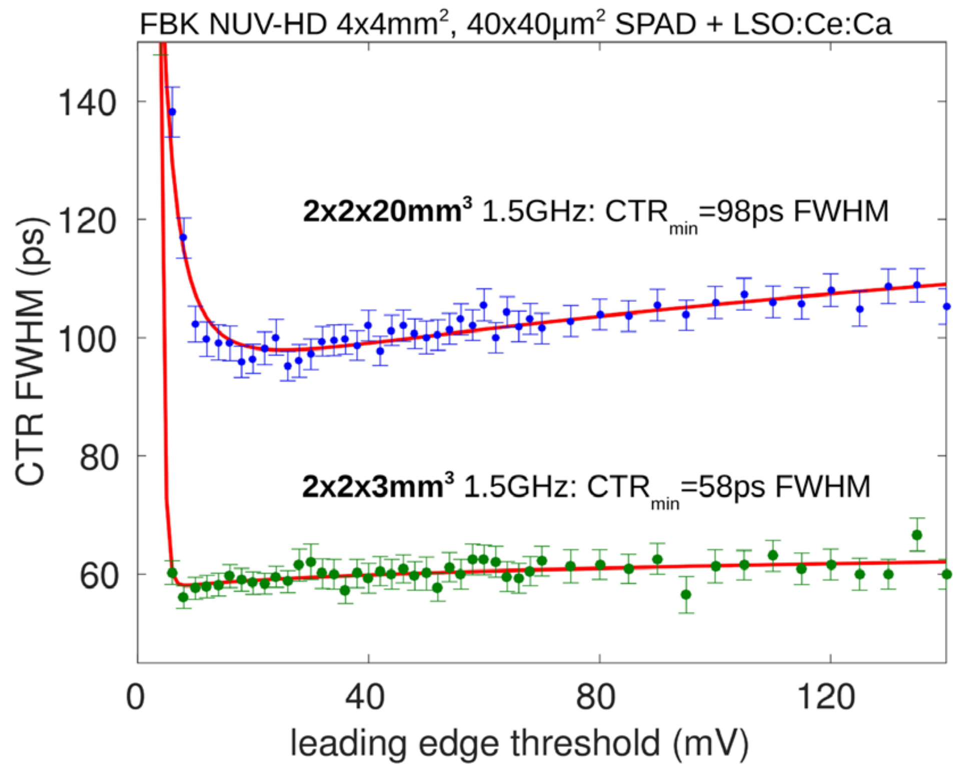




Gola, A et al. (2019). "NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler." *Sensors*, *19*(2), 308.

Timing with High-frequency readout (FWHM)





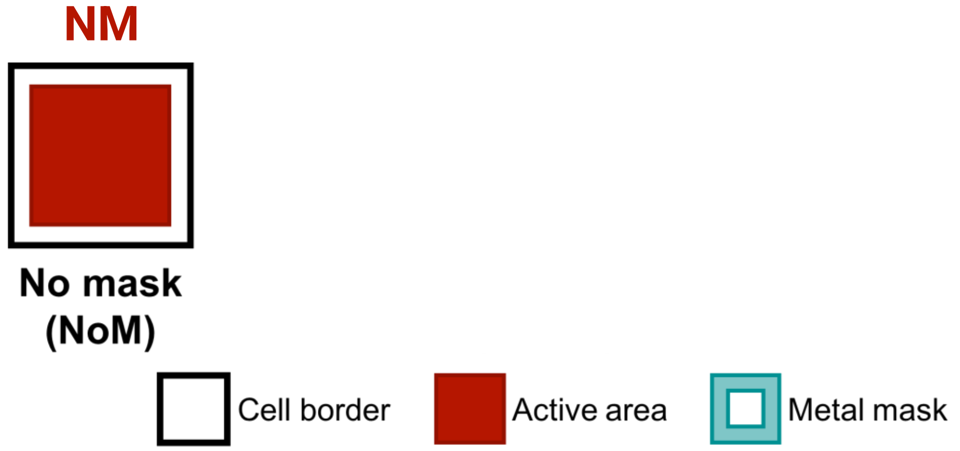
World record timing resolution: Single Photon Time resolution (SPTR, left) and Coincidence Resolving Time (CRT) in LYSO readout (right).

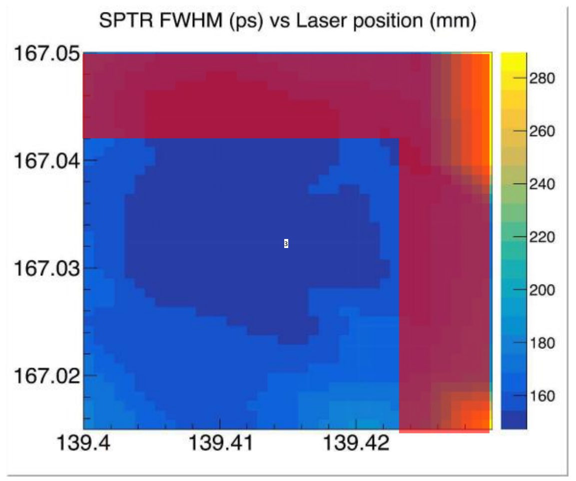
Gundacker, Stefan, et al. "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET." *Physics in Medicine & Biology* 64.5 (2019): 055012.

Masking
Optimization of SPTR with masking: CHK-HD

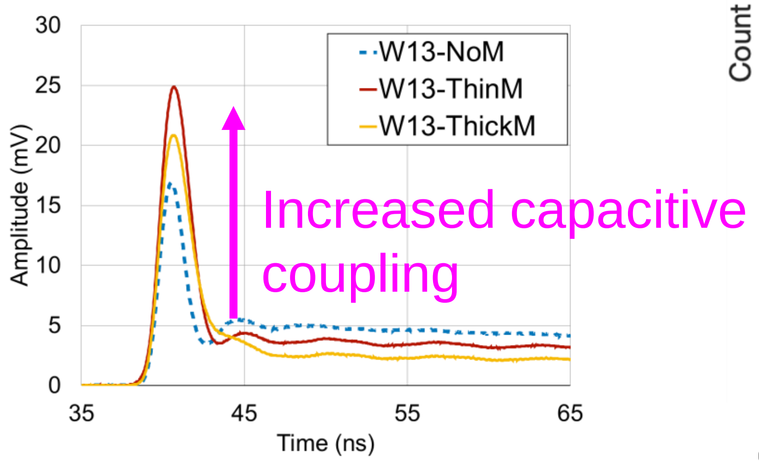
CHK-HD SiPMs is a variant of the NUV-HD SiPMs built to *experiment solutions to improve SPTR and detection efficiency* in applications where it matters the most, such as Cherenkov light readout.

- ***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

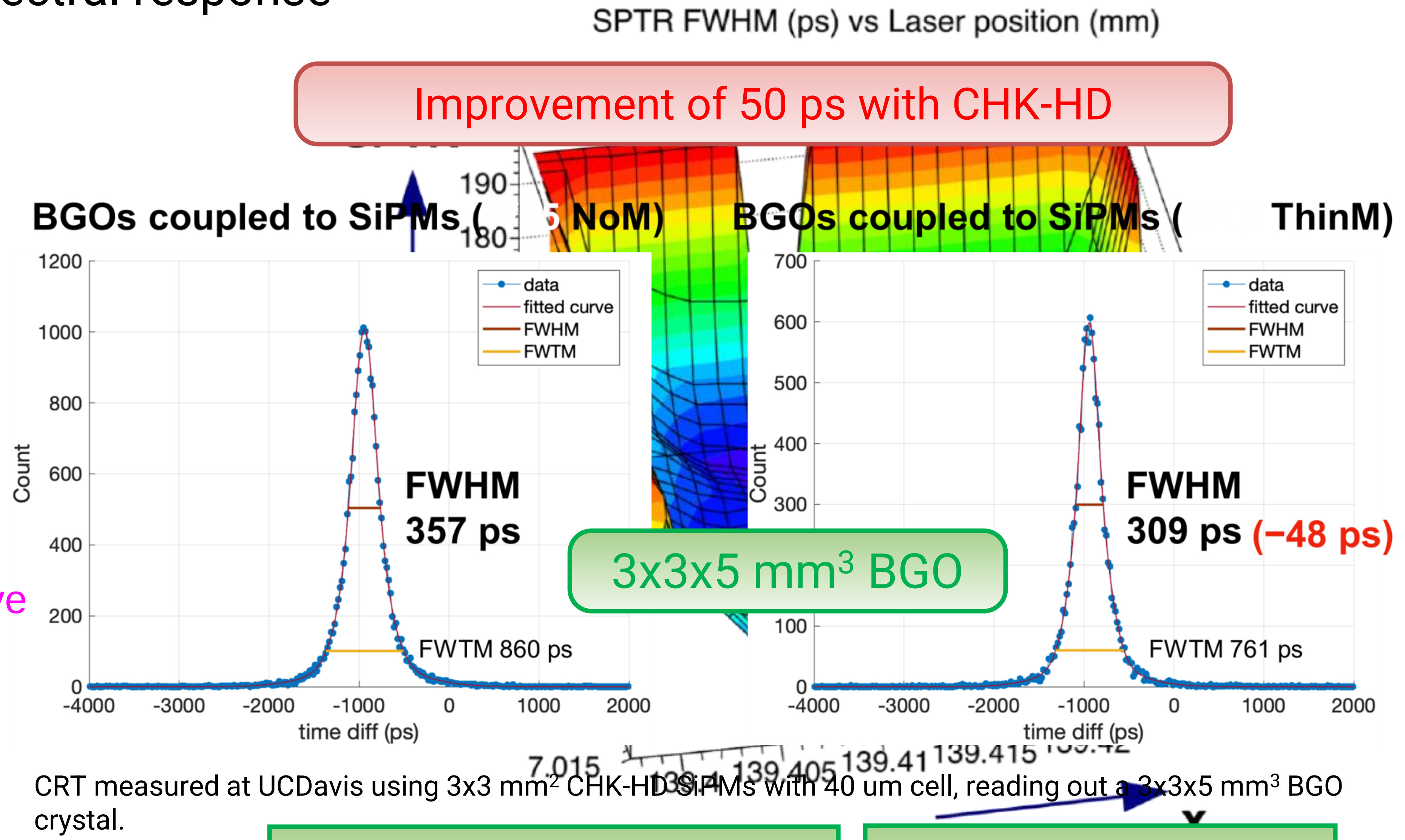




Masking of outer regions of the SPAD that have worse "local" SPTR.



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



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

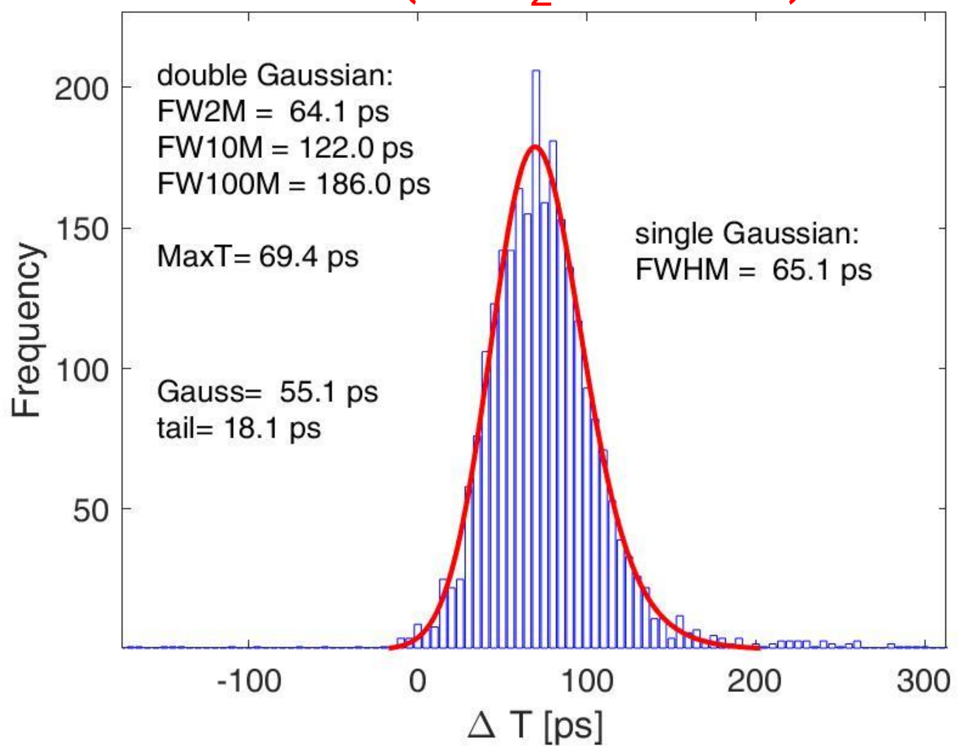
Nemallapudi, M. V., et al. "Single photon time resolution of state of the art SiPMs." *Journal of Instrumentation* 11.10 (2016): P10016.

Masking
CHK-HD measurements with upgraded amplifiers

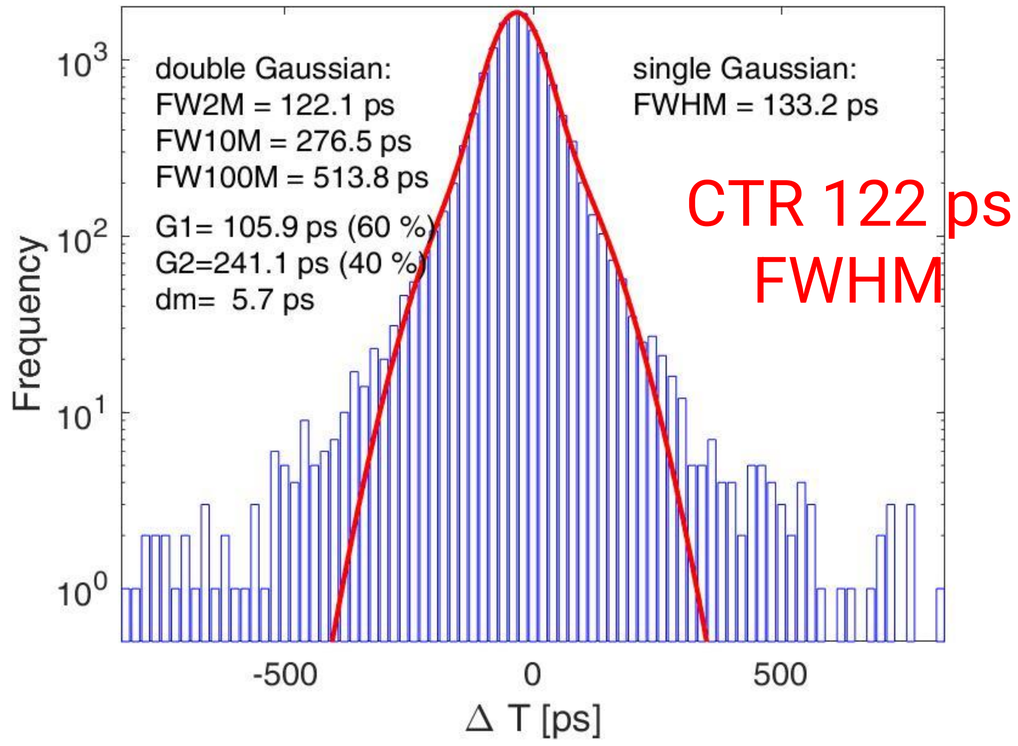
SPTR performance is *highly affected by the front-end electronic performance*: studies with different readout electronics.
3x3 mm^2 CHK-HD SiPMs, 40 um cell.

High-frequency readout

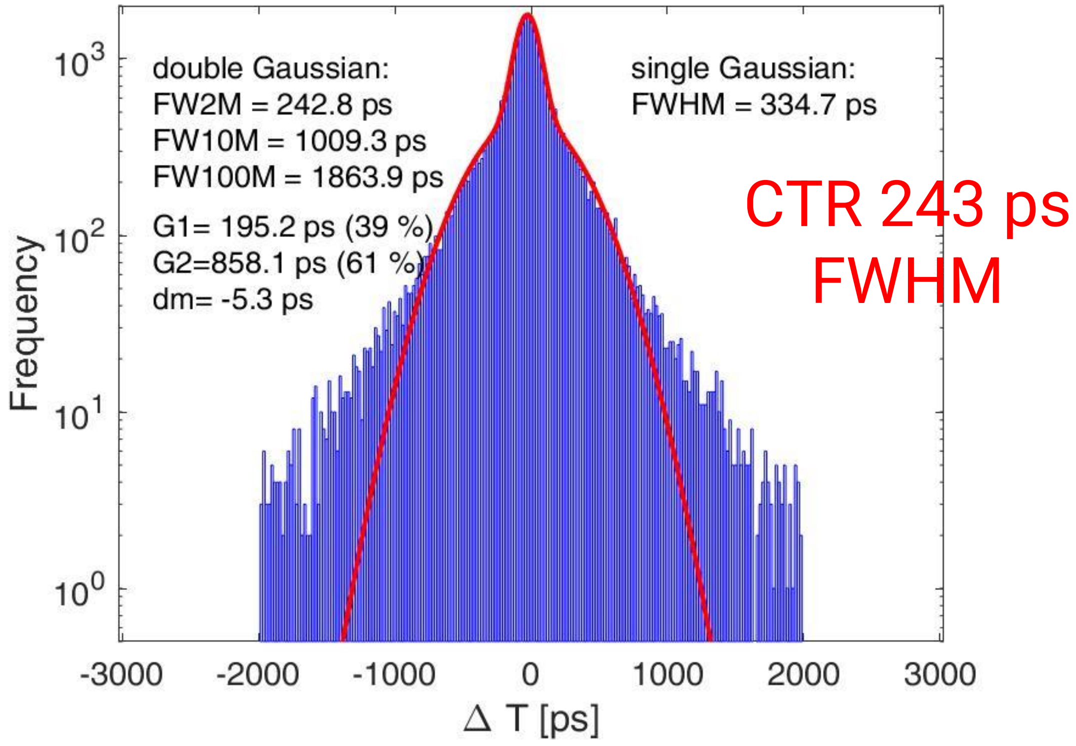
SPTR (PbF_2 method)



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

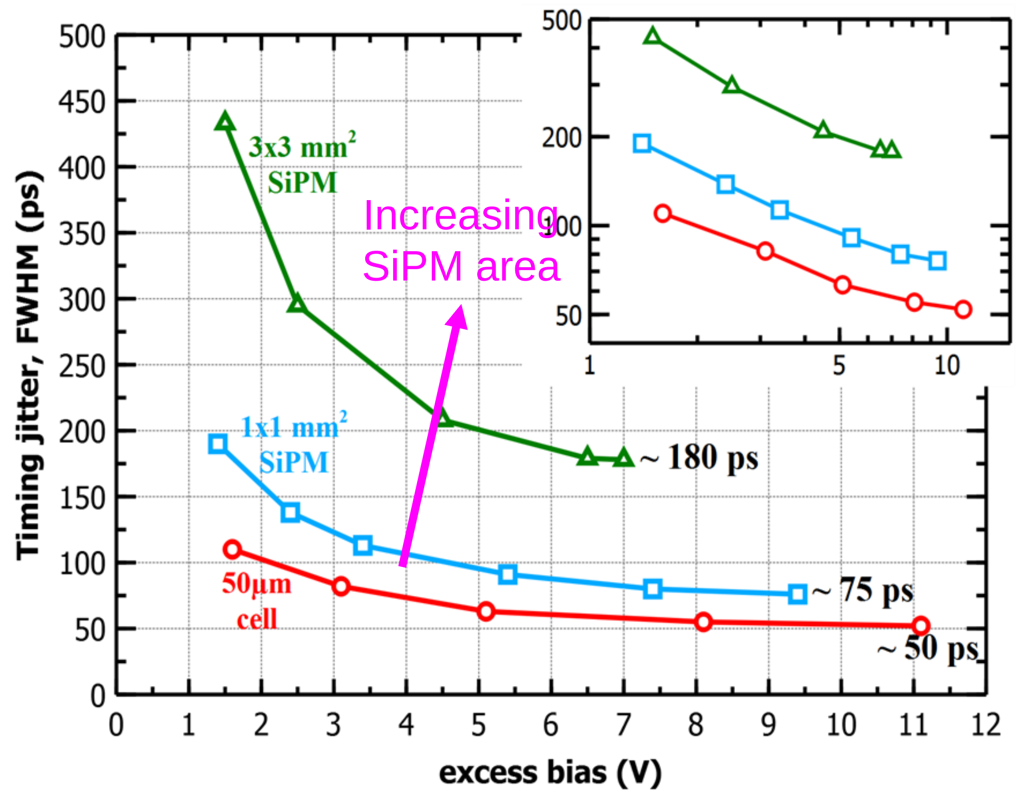
Effect of electronic noise on SPTR is deconvolved.

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.

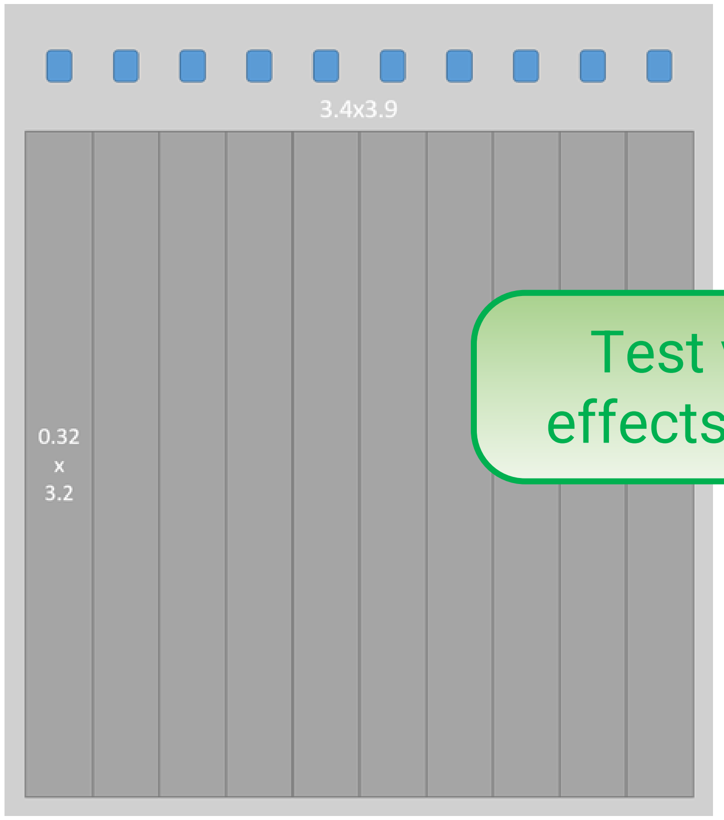
SPTR with standard FBK amplifier



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

Strip SiPMs

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



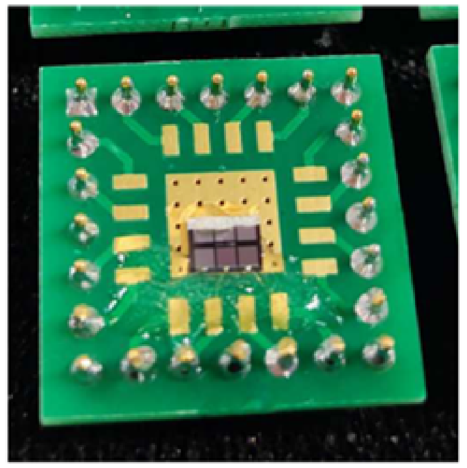
Test vehicle to study effects of segmentation

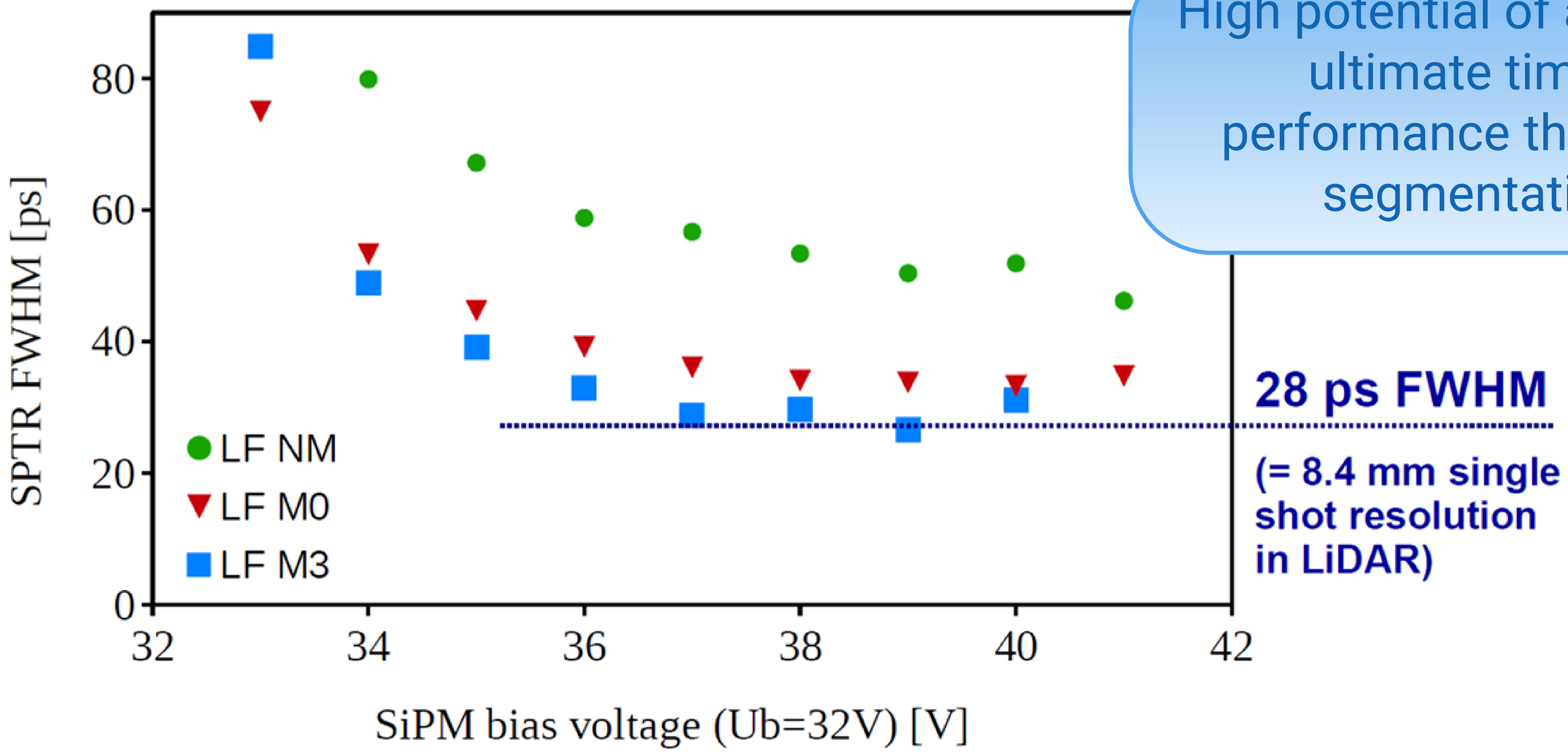
Example of segmented SiPM layout: a 3x3 mm2 active area is divided in 10 0.3x3 mm2 strip-SiPMs.

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

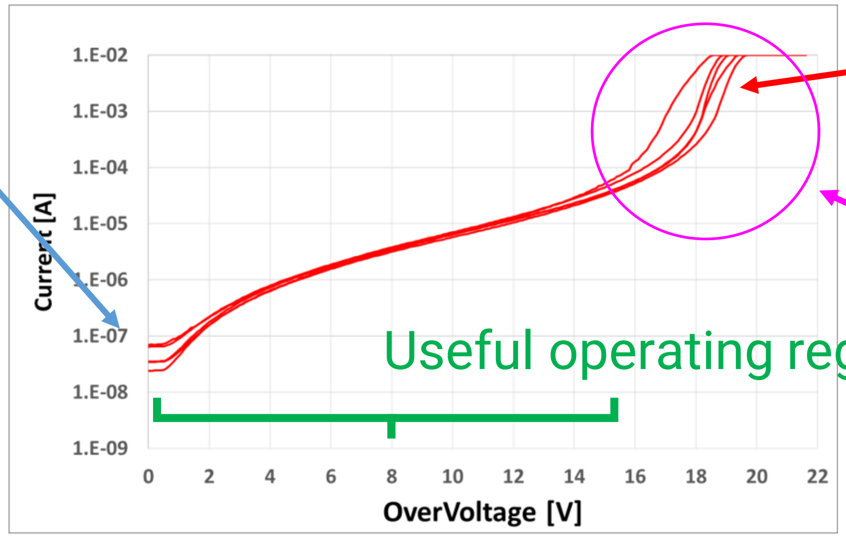
Reduction of Optical Crosstalk

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

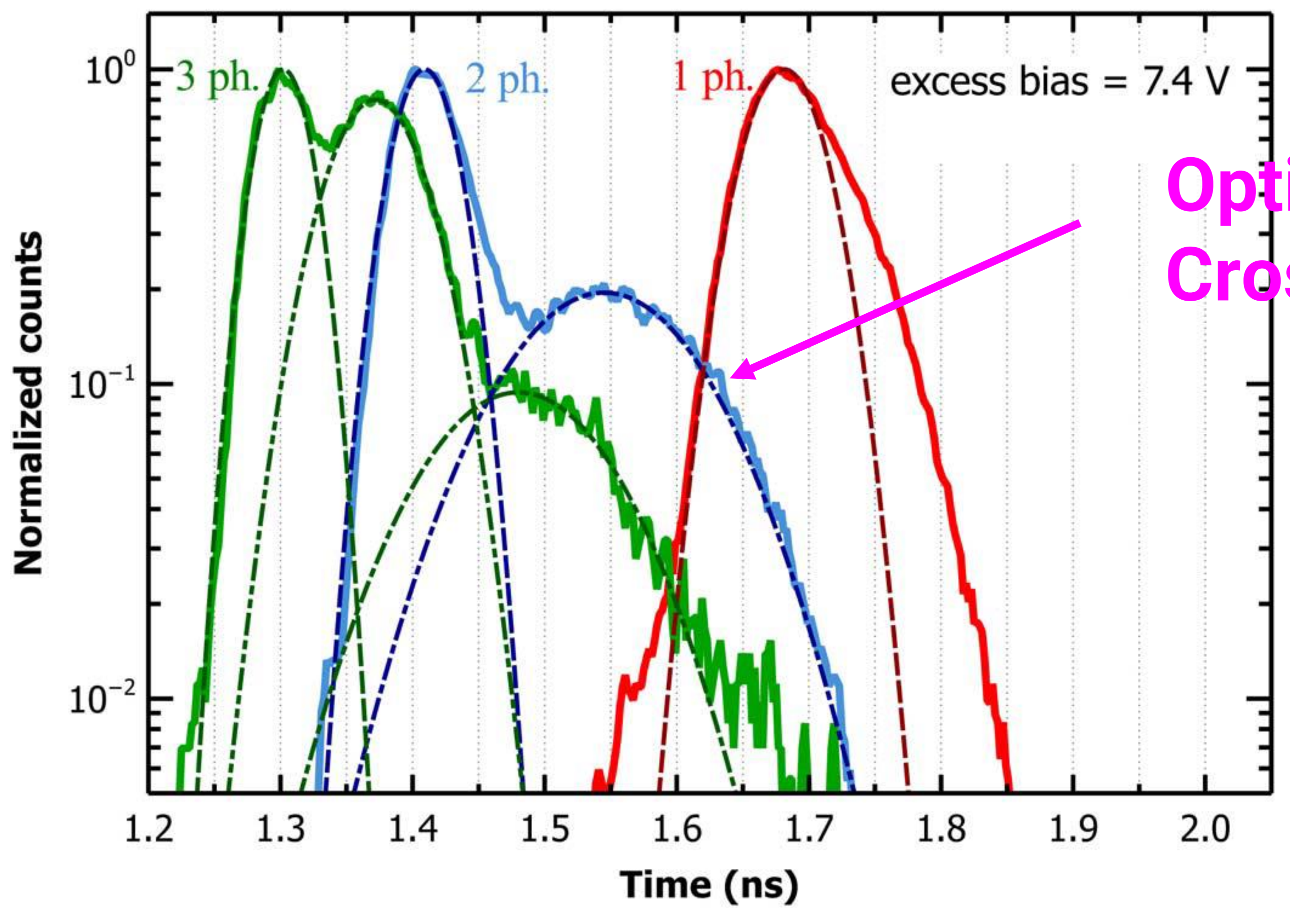


Above a certain over-voltage the number of dark counts and, thus, the reverse current diverge.

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

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

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

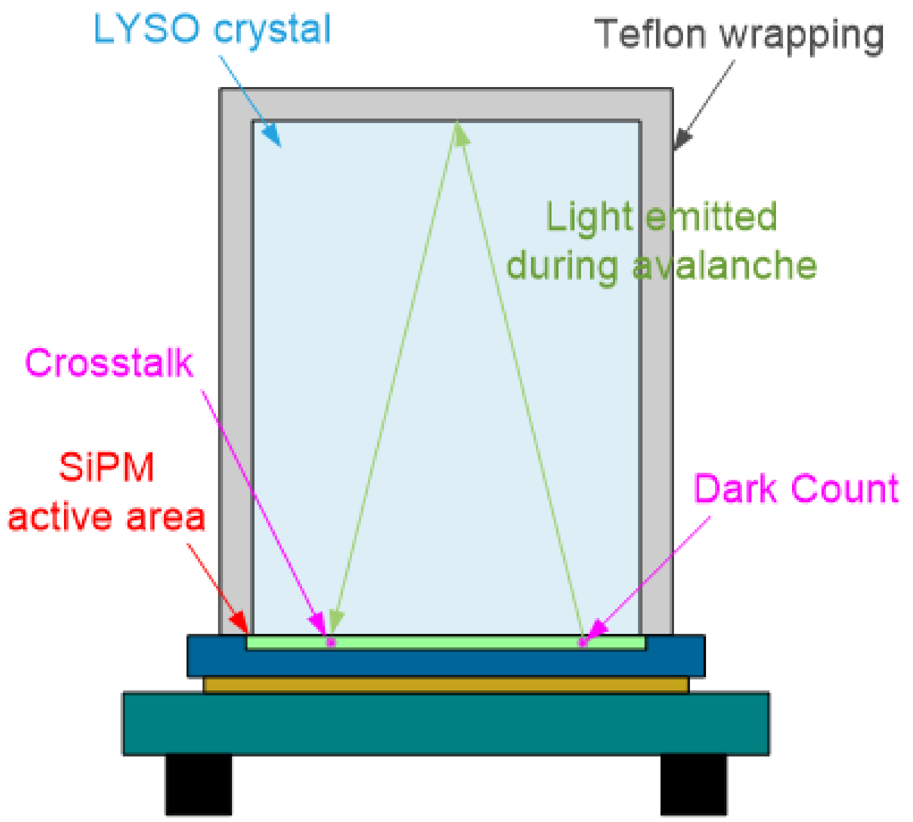


Few-photon time resolution measured with Leading-edge discriminator
Additional peaks are most likely generated by (delayed) correlated noise.

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

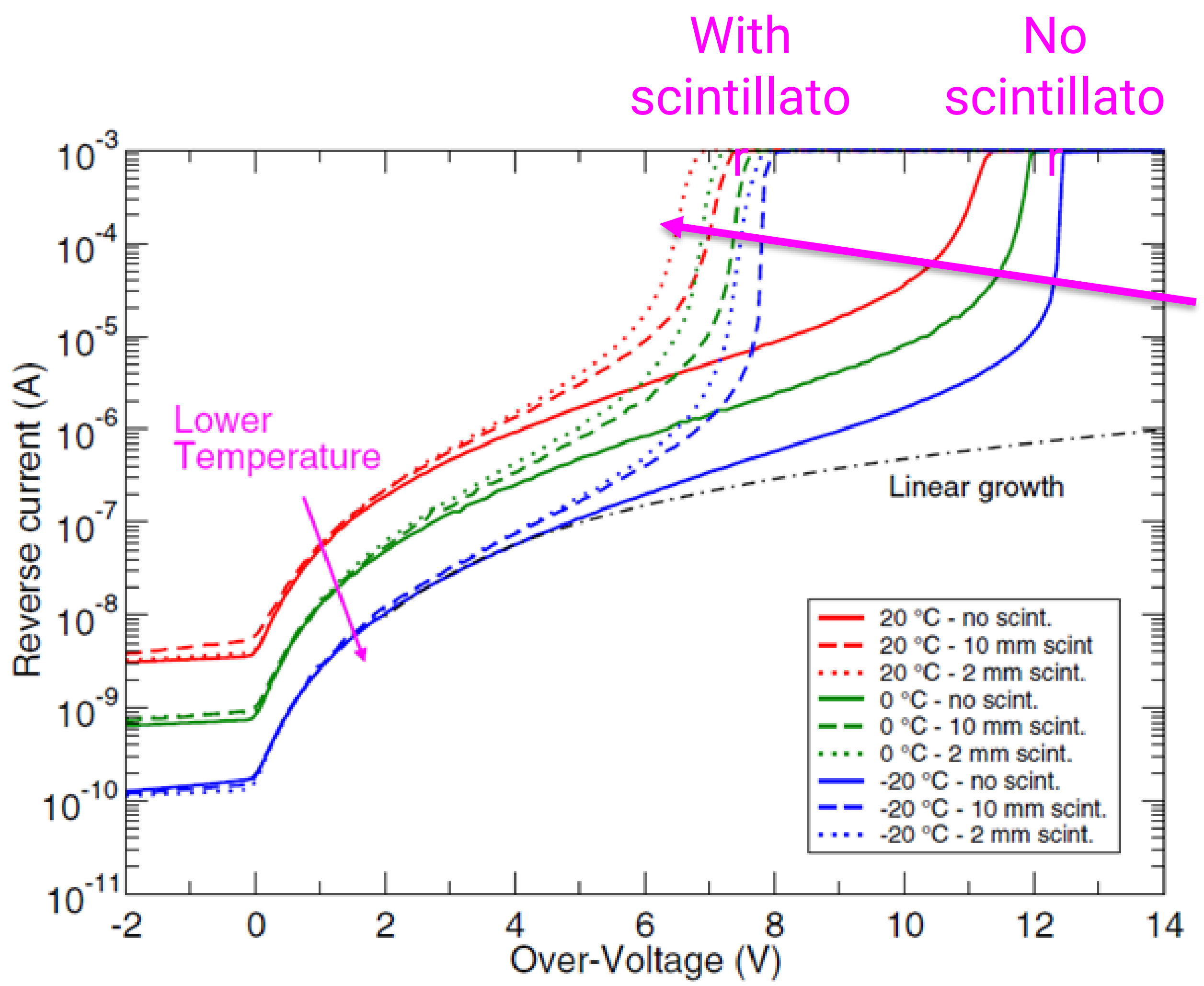
Optical crosstalk probability is enhanced by the presence of the scintillator: external crosstalk.



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***.



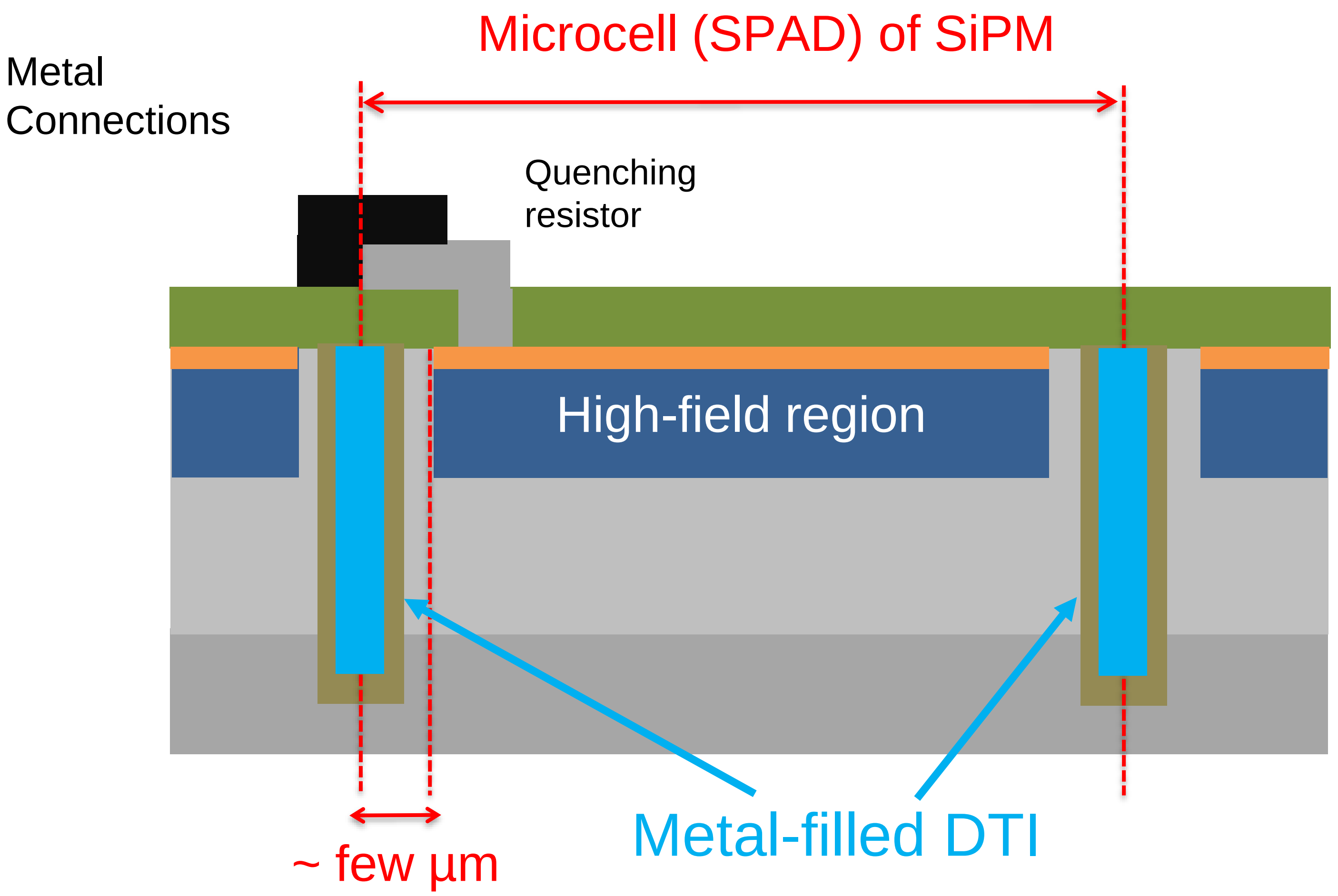
Comparison of SiPM IV with different scintillator sizes placed on top of them, at different temperatures.

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

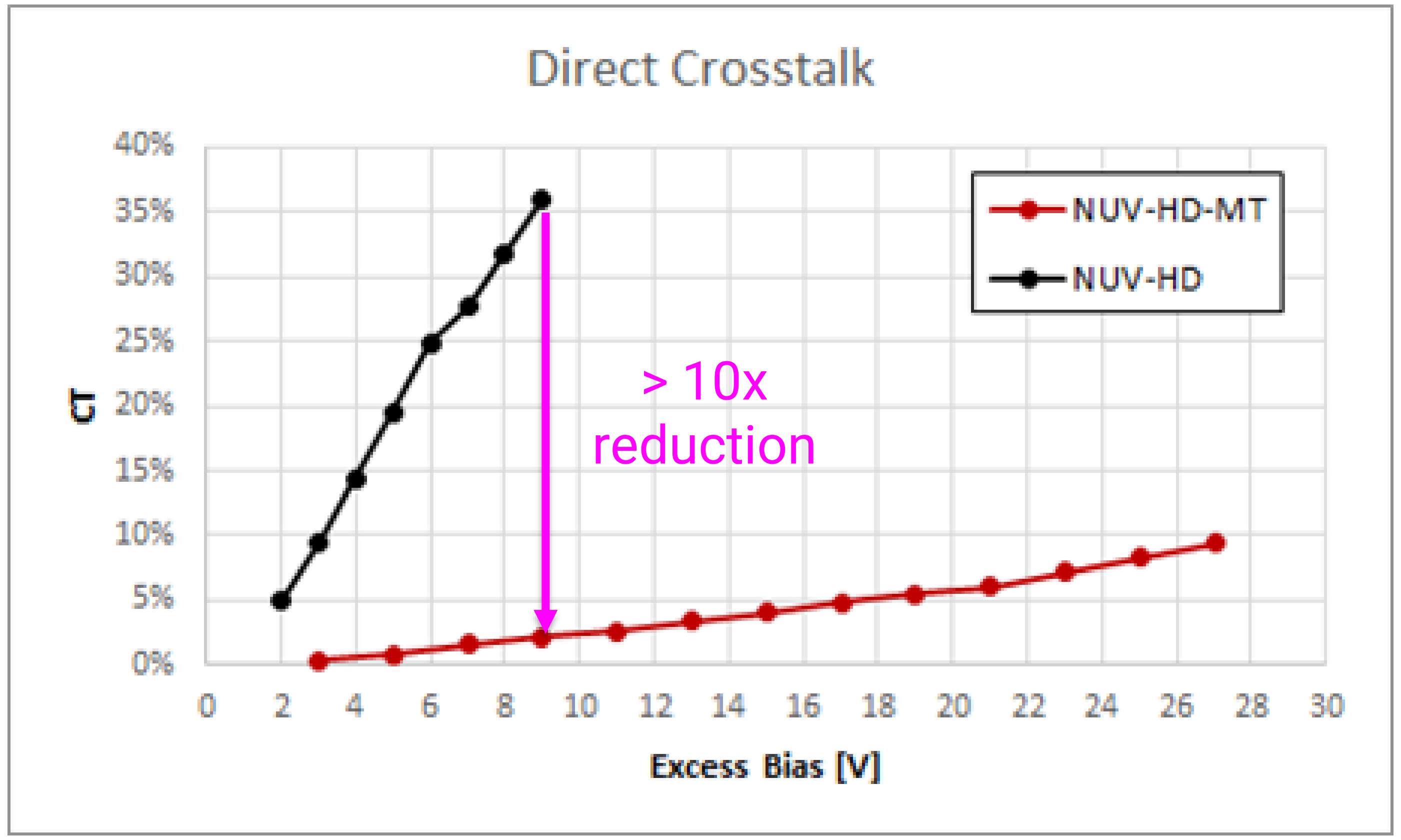
Reduction of optical crosstalk
NUV-HD-MT development

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.

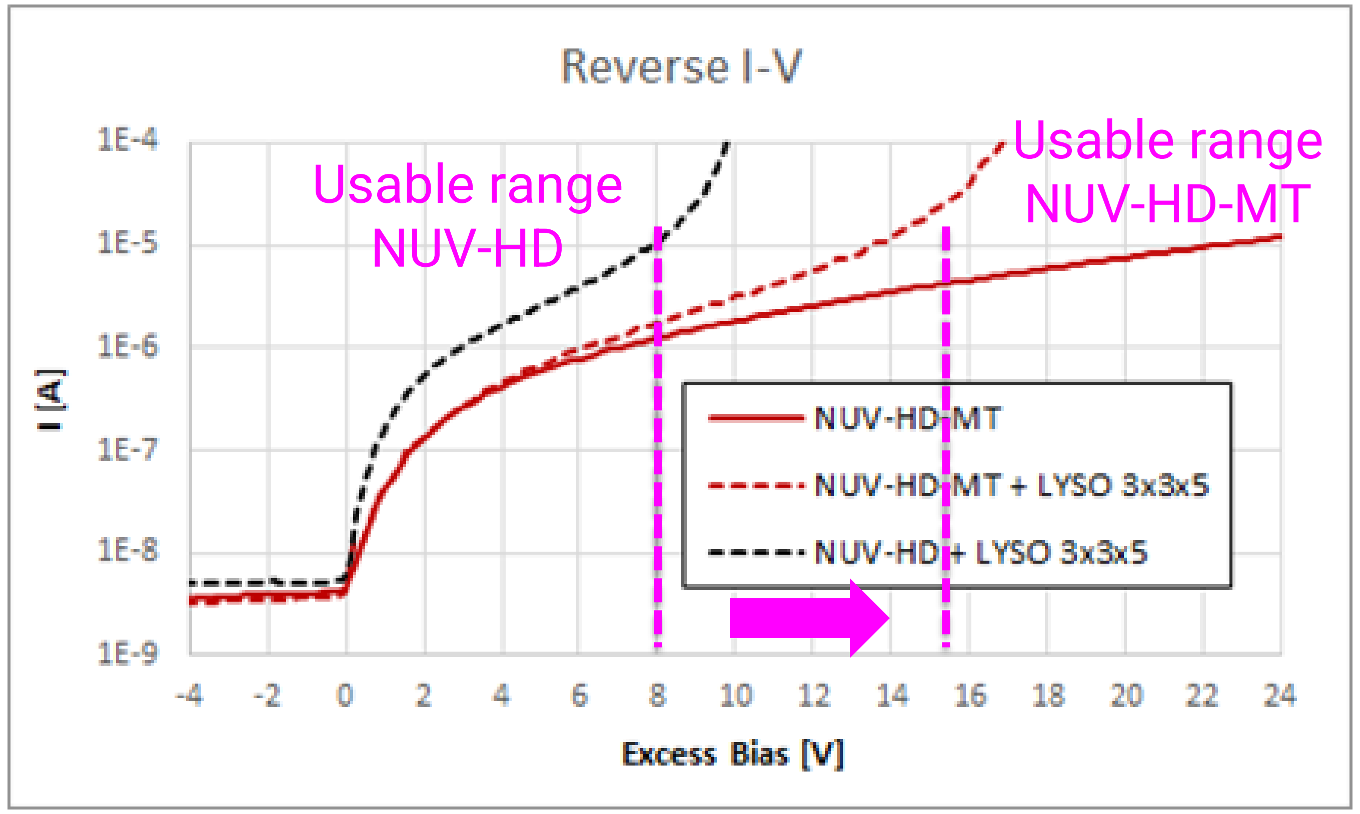


Reduction of optical crosstalk probability in NUV-HD-MT, compared to the "standard" NUV-HD. Measurement without encapsulation resin, i.e. *only considering internal crosstalk probability*.

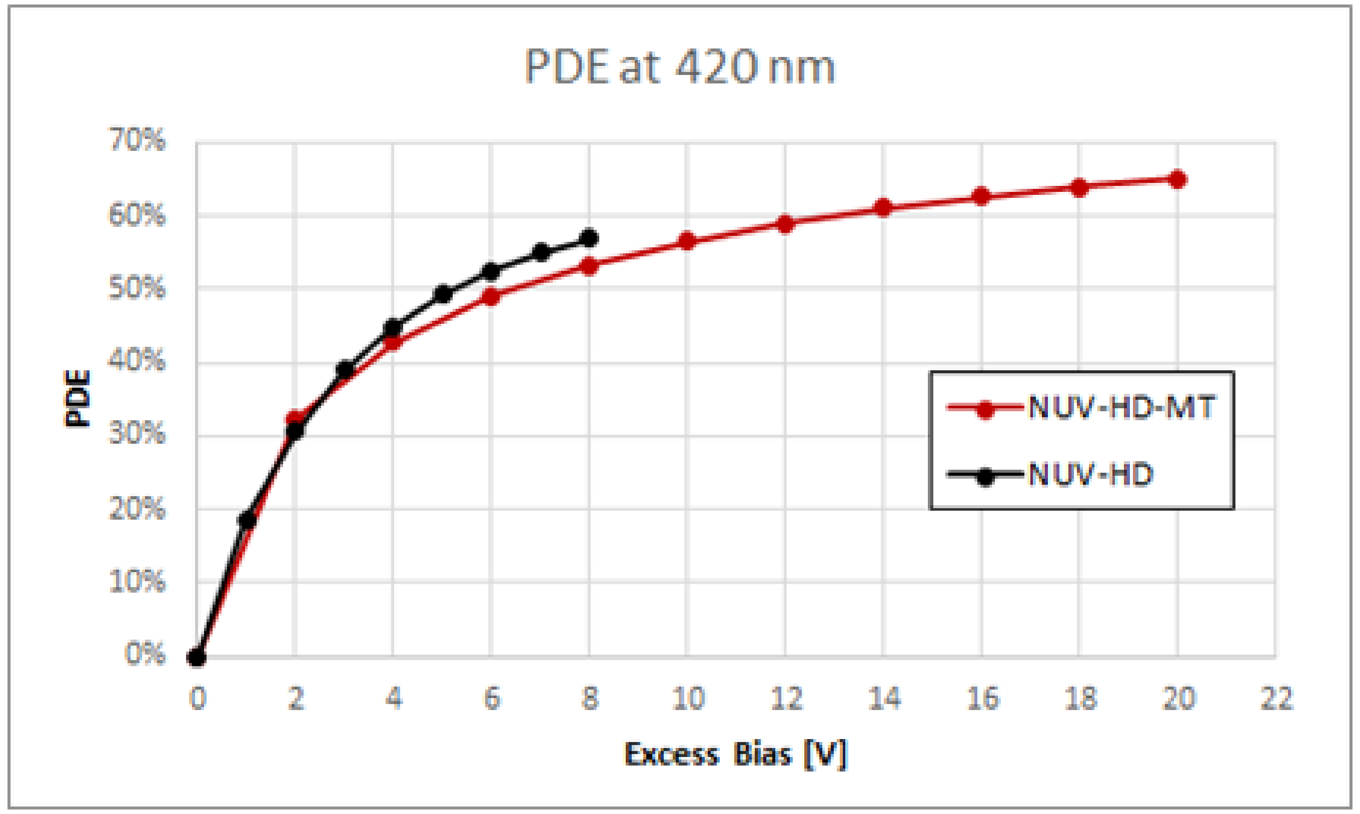
Reduction of optical crosstalk
NUV-HD-MT bias range

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.

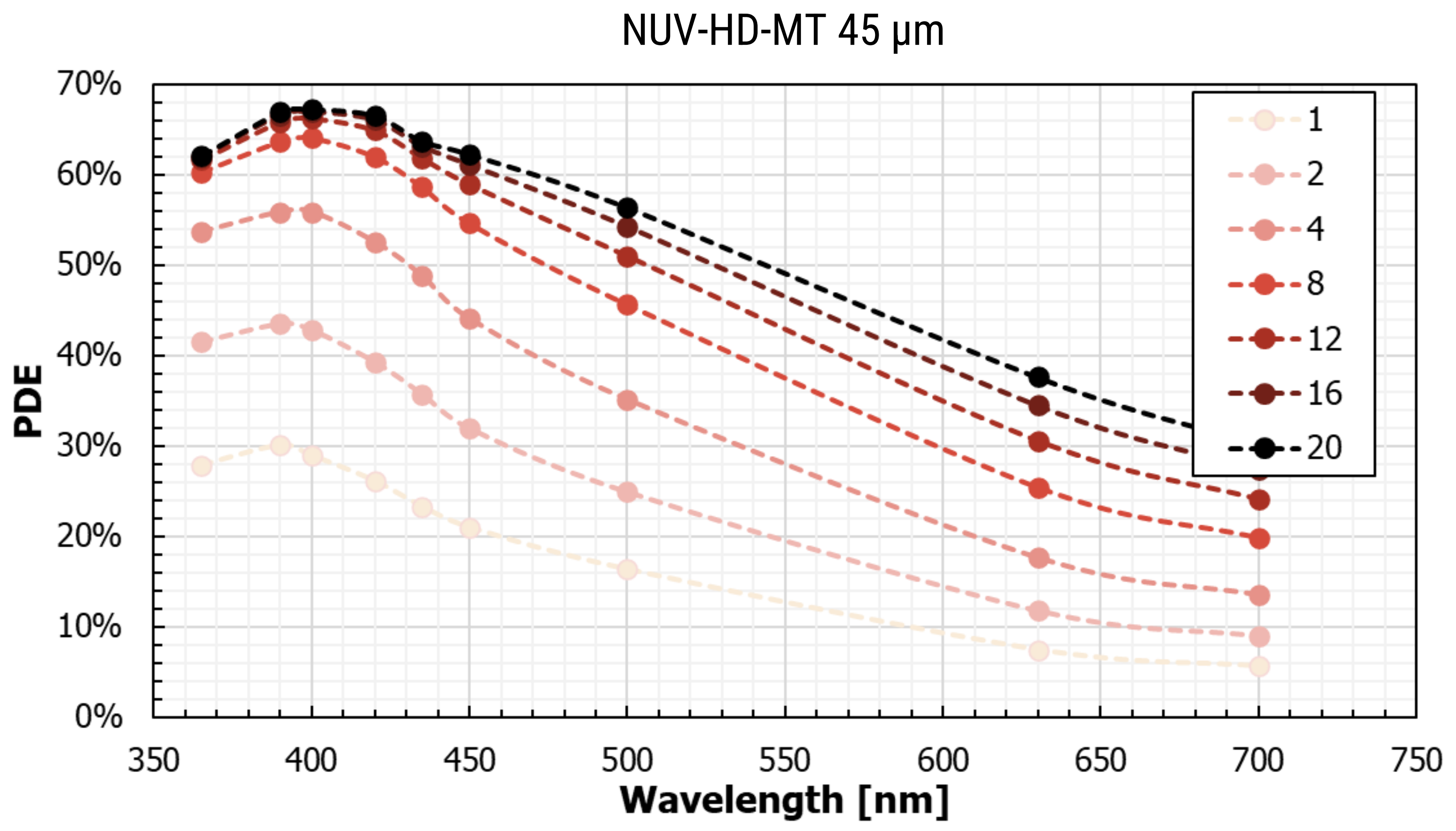


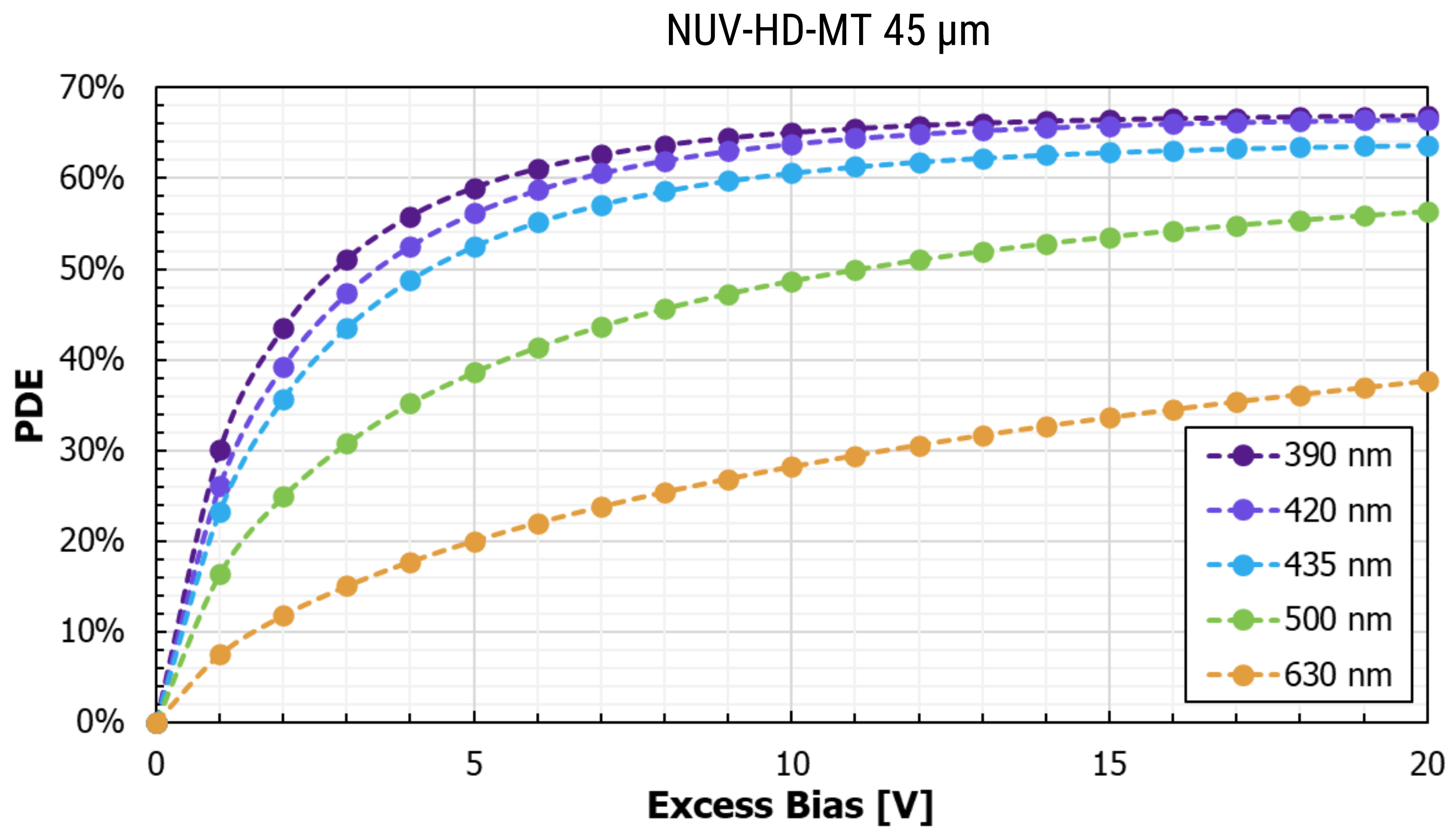
PDE at 420 nm measured on a NUV-HD-MT SiPM with 45 um cell size.

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*.

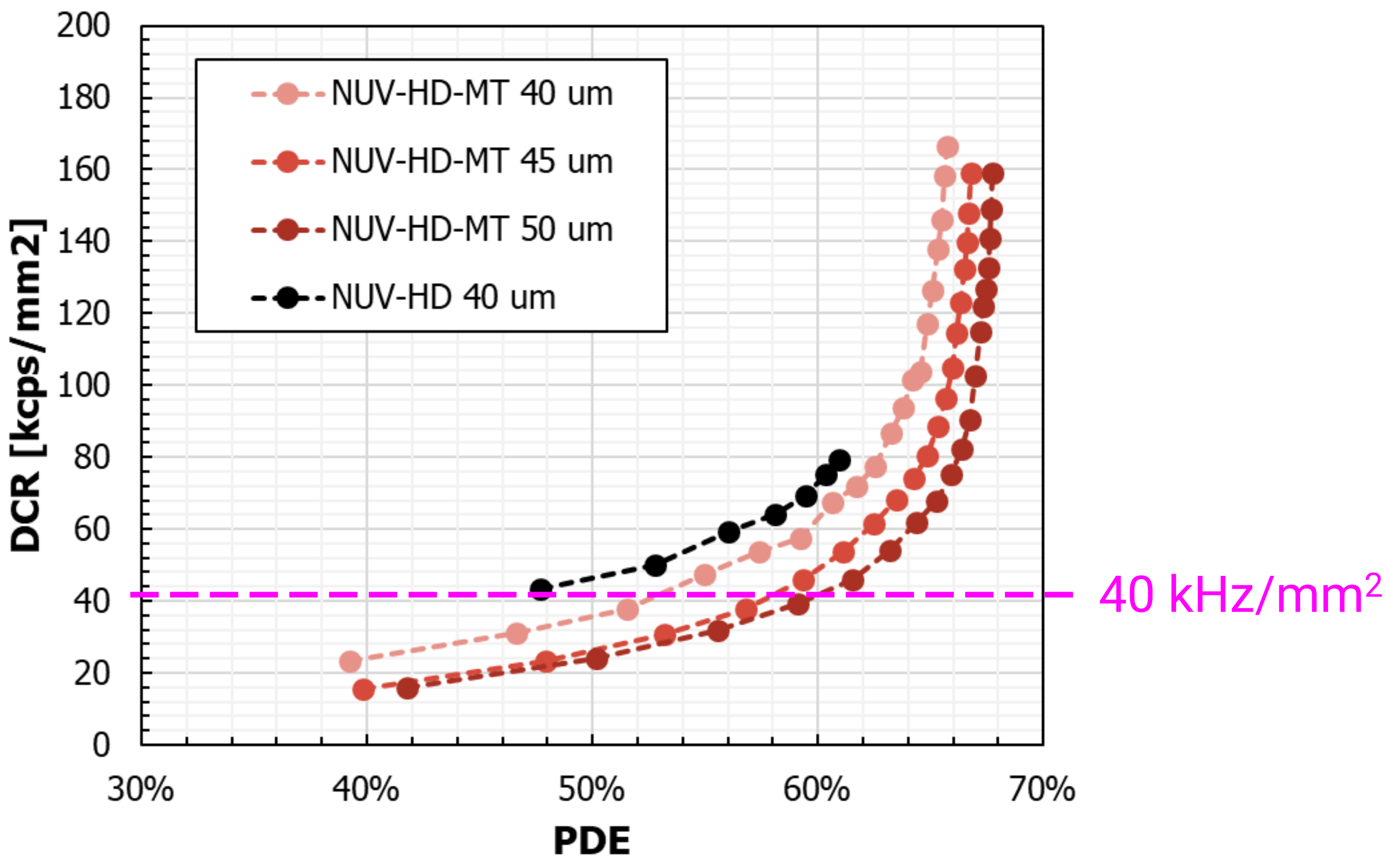




Reduction of optical crosstalk
NUV-HD-MT electro optical performance

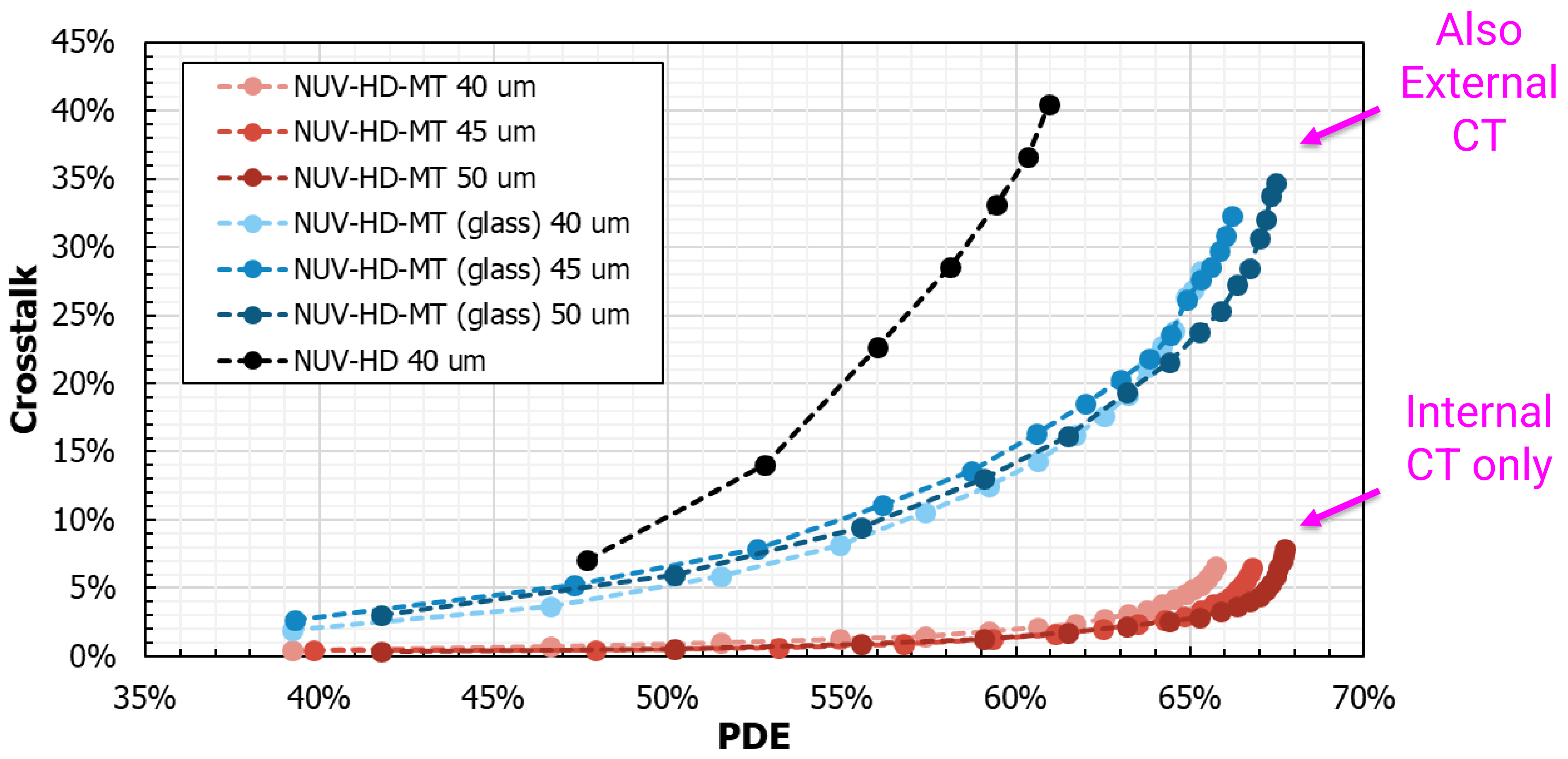
NUV-HD-MT *nuisance parameters are better represented and compared as a function of the PDE*.

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



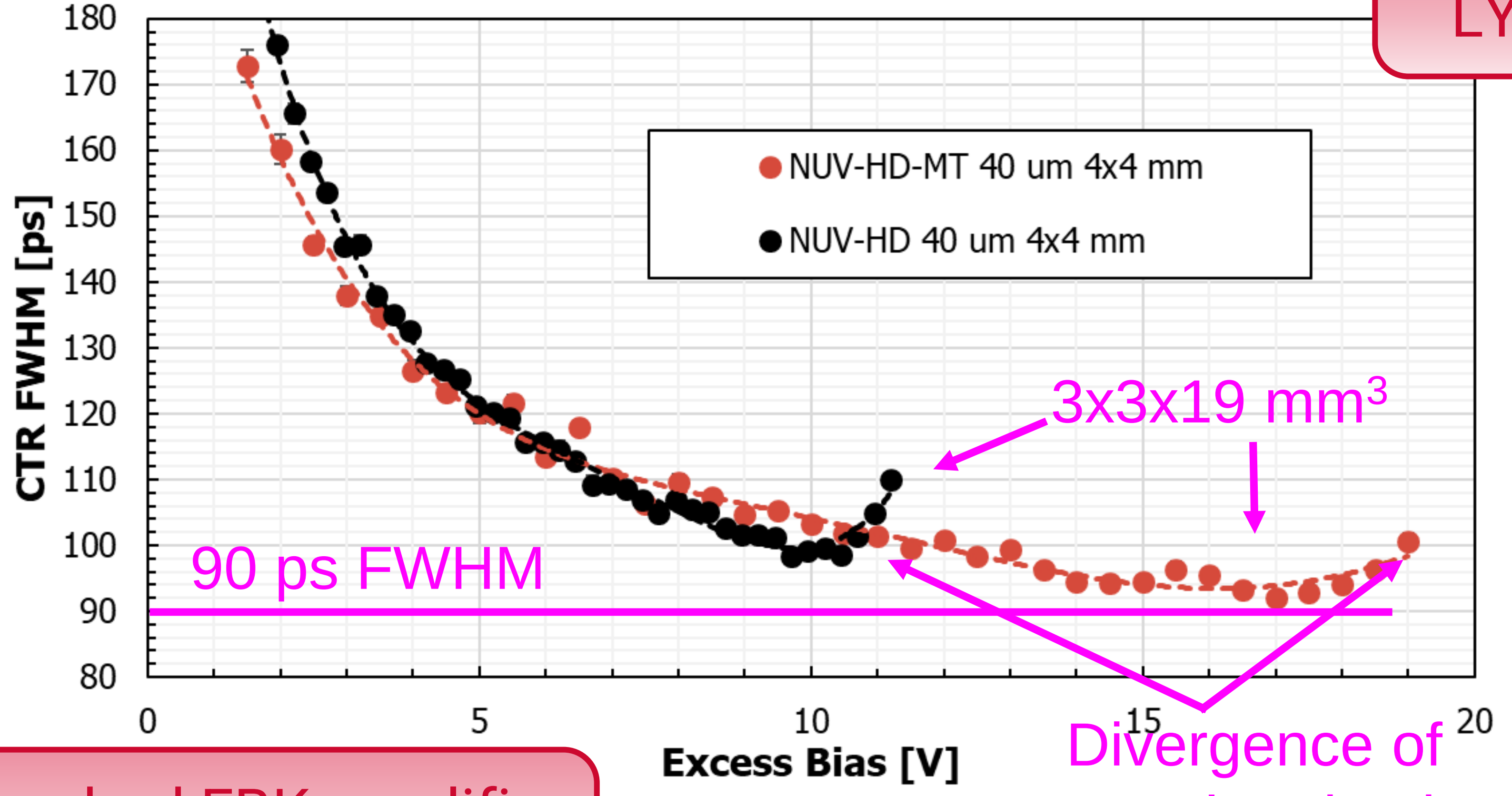
DiCT vs. peak PDE (measured at 420 nm) for different cell sizes of the NUV-HD-MT technology, with and without protective glass on top of the SiPM (used for TSV)

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

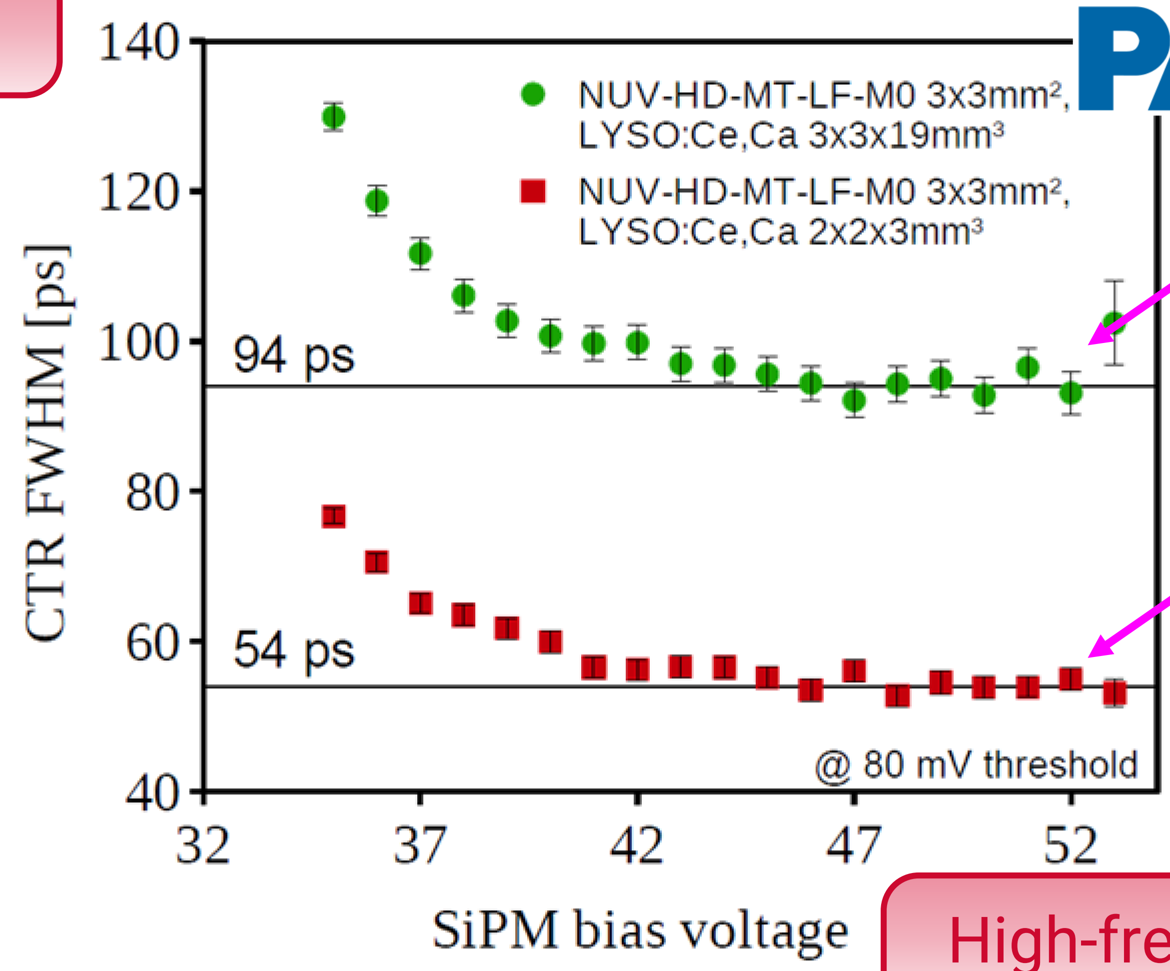
LYSO:Ca,Ce



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

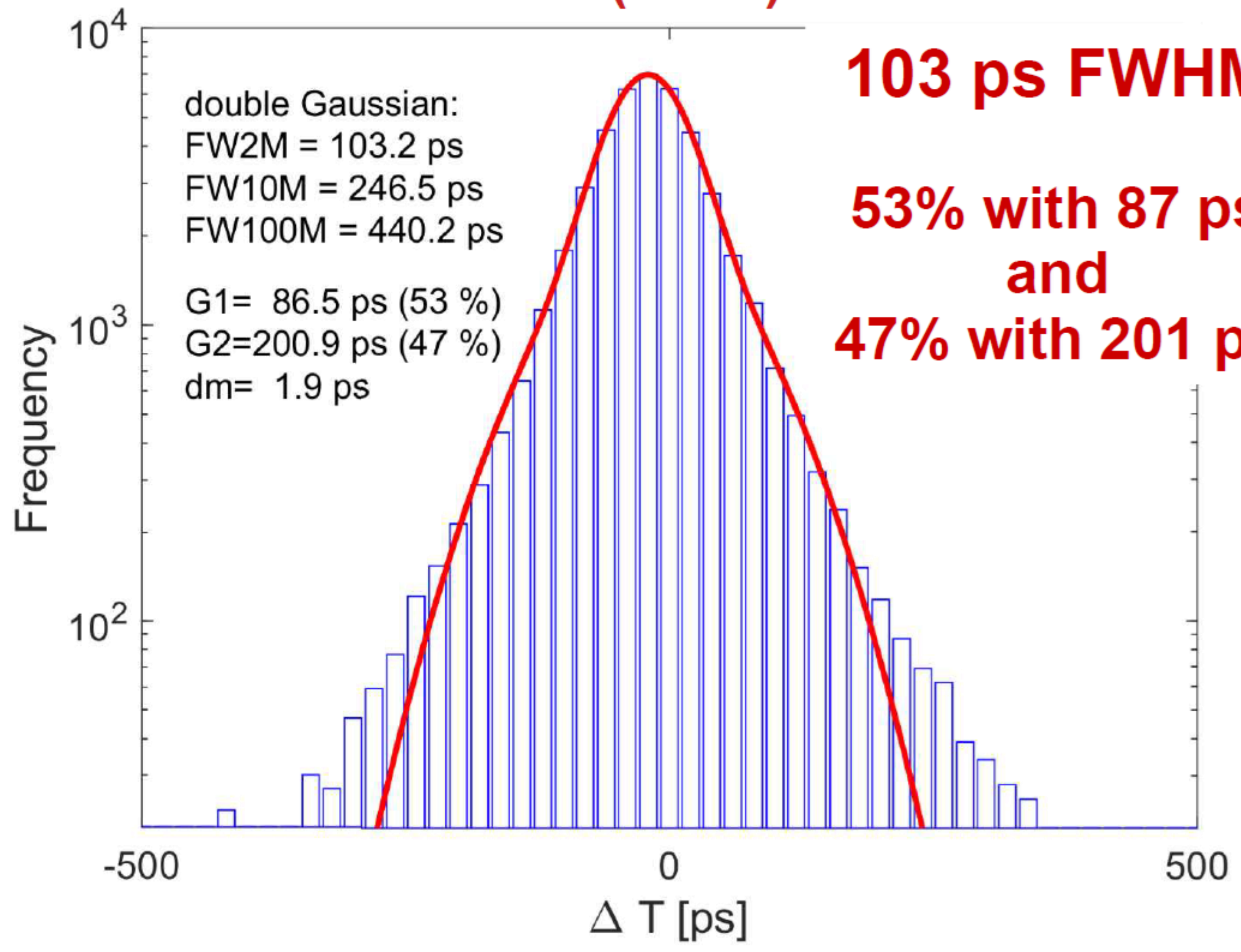
CTR measured with a 3x3 mm^3 NUV-HD-MT SiPM, with M0 masking, COUPLED TO 2X2X3 mm^3 and 3X3X19 mm^3 LYSO:Ce,Ca, using the high-frequency readout.

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.

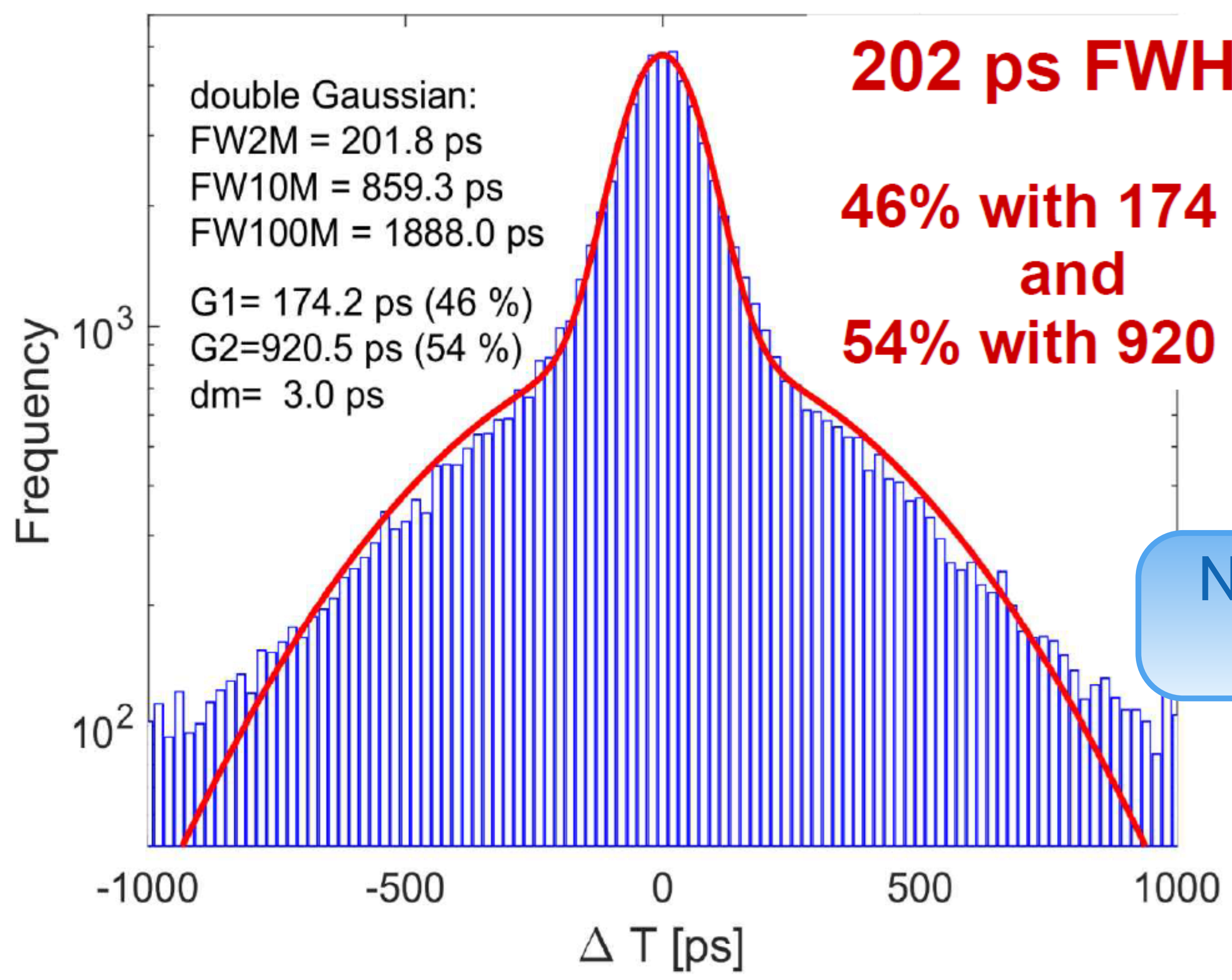
2x2x3 mm³ BGO (EPIC)



103 ps FWHM

53% with 87 ps and 47% with 201 ps

3x3x20 mm³ BGO (EPIC)



202 ps FWHM

46% with 174 ps and 54% with 920 ps

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

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

Cryogenic Time Projection Chambers

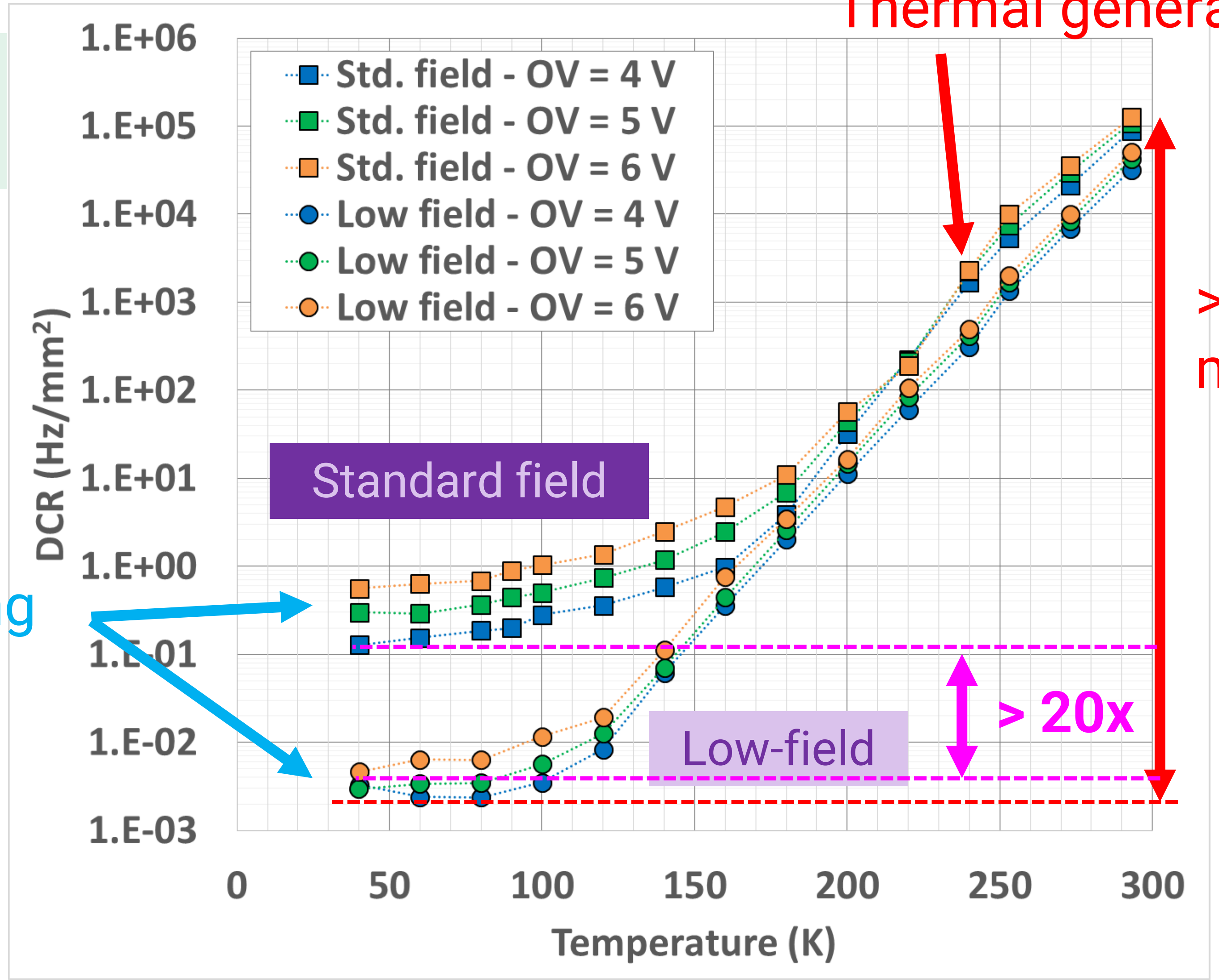
Cryogenic operation
Development #1 – DCR reduction in LN

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

25 um cell

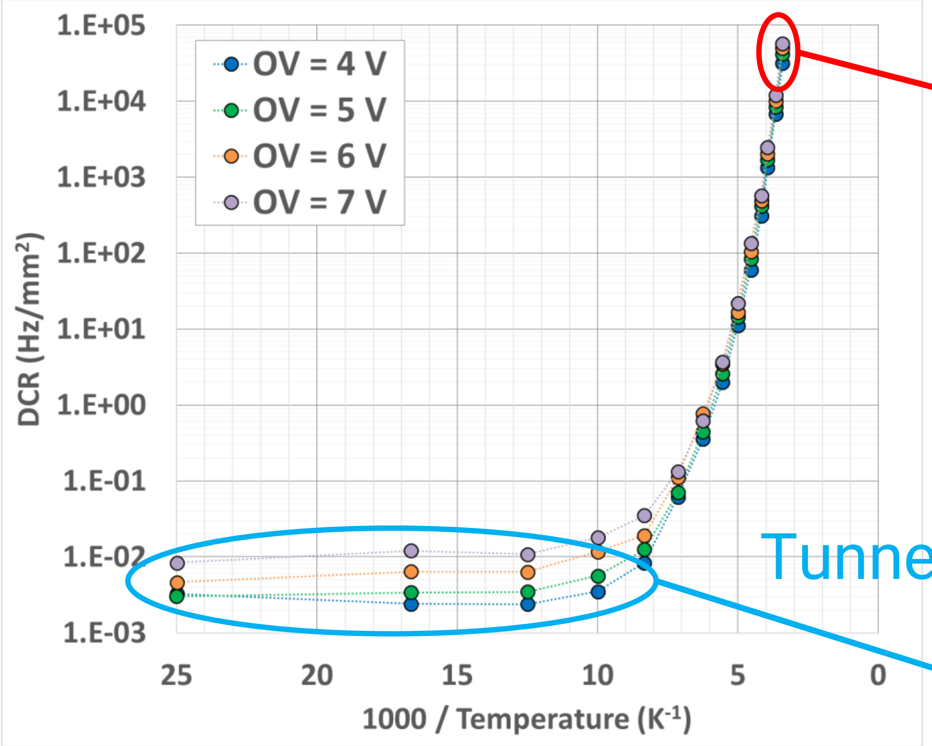
Tunneling

Thermal generation



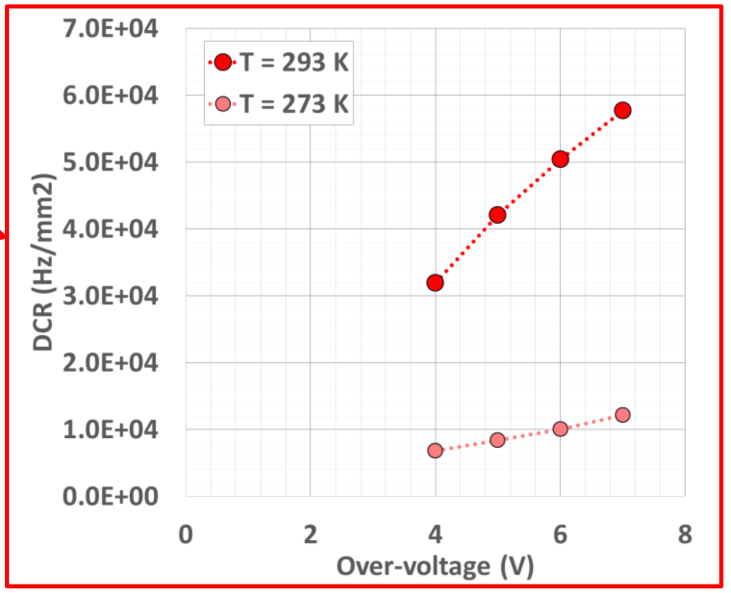
> 7 orders of magnitude !

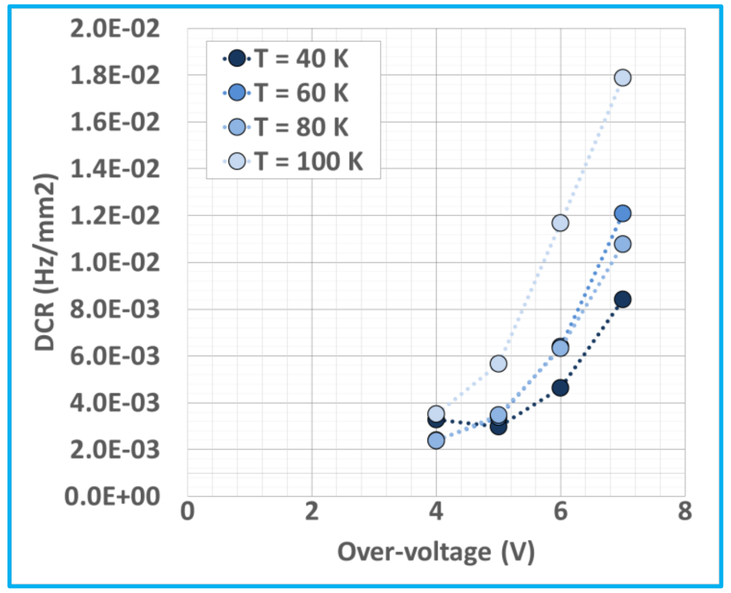
Thermal generation



Tunneling

NUV-HD Low-field



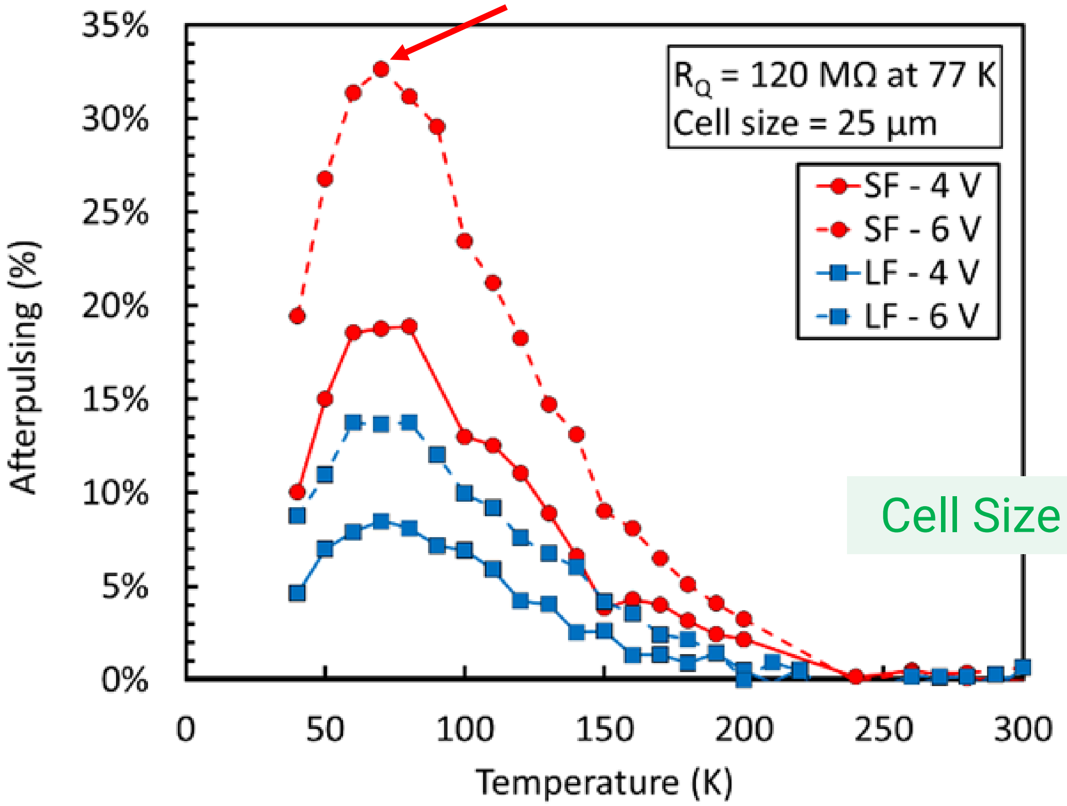


Reduction of Dark Count Rate at cryogenic temperature thanks to electric field engineering in FBK SiPMs.

Cryogenic operation
Development #2 – Reduction of Afterpulsing in LN

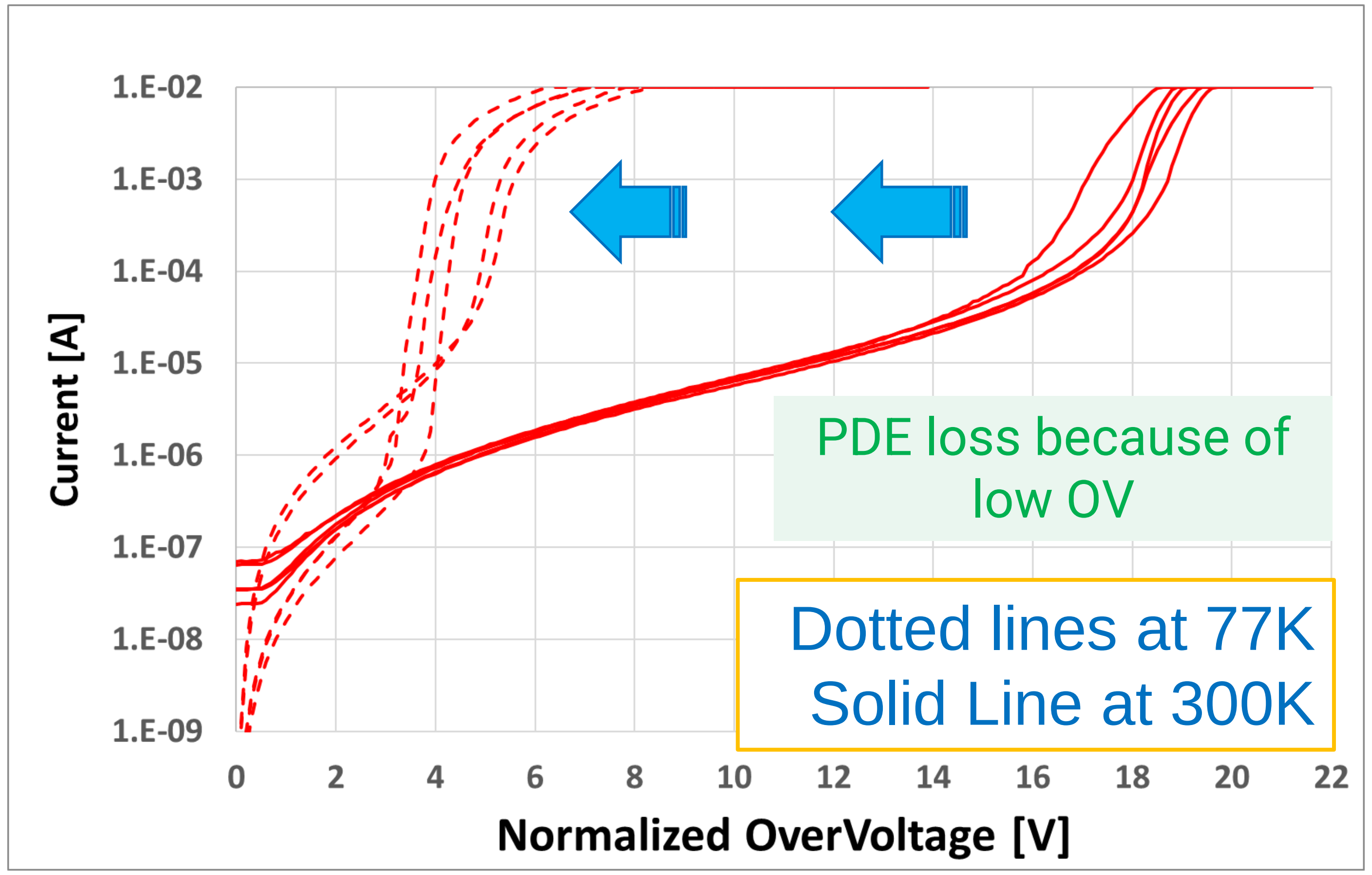
In addition to the reduction of DCR at cryogenic temperature, *two further technology developments were necessary to enable cryogenic operation of SiPMs*.

AP is maximum at ~ 77 K!



Cell Size = 25 um

Reduction of maximum excess bias



30 um cell
Standard Field – "low" Rq

Increase of release time constant of trapping centers at lower temperatures increases AP probability.

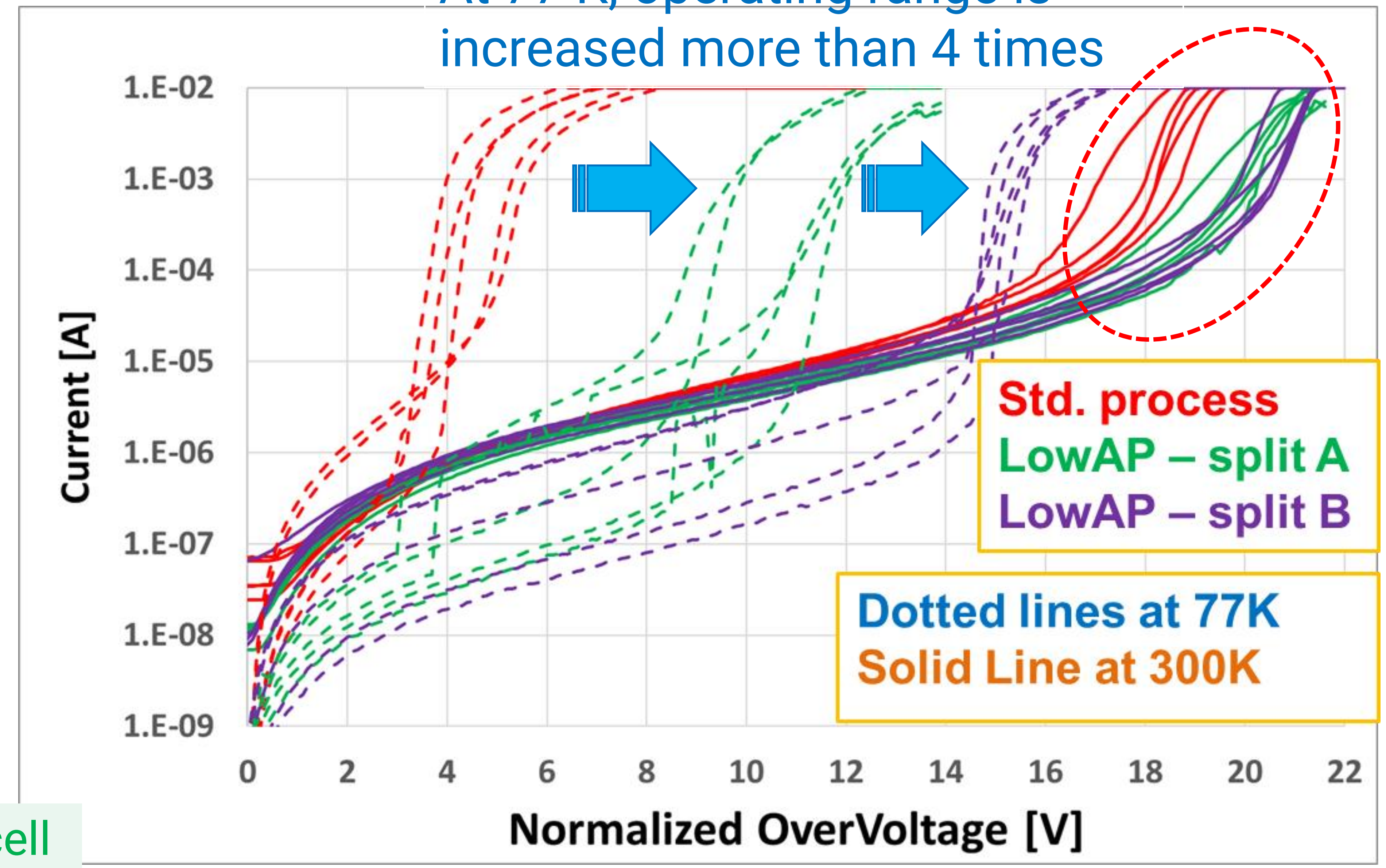
AP increase is partially offset by increase of microcell recharge time constant.

Cryogenic operation
Development #2 – Reduction of Afterpulsing in LN

FBK identified *one process split* that can *significantly reduce afterpulsing probability at cryogenic temperatures*.

- correlated noise *divergence at 77 K is significantly delayed*.

At 77 K, operating range is increased more than 4 times



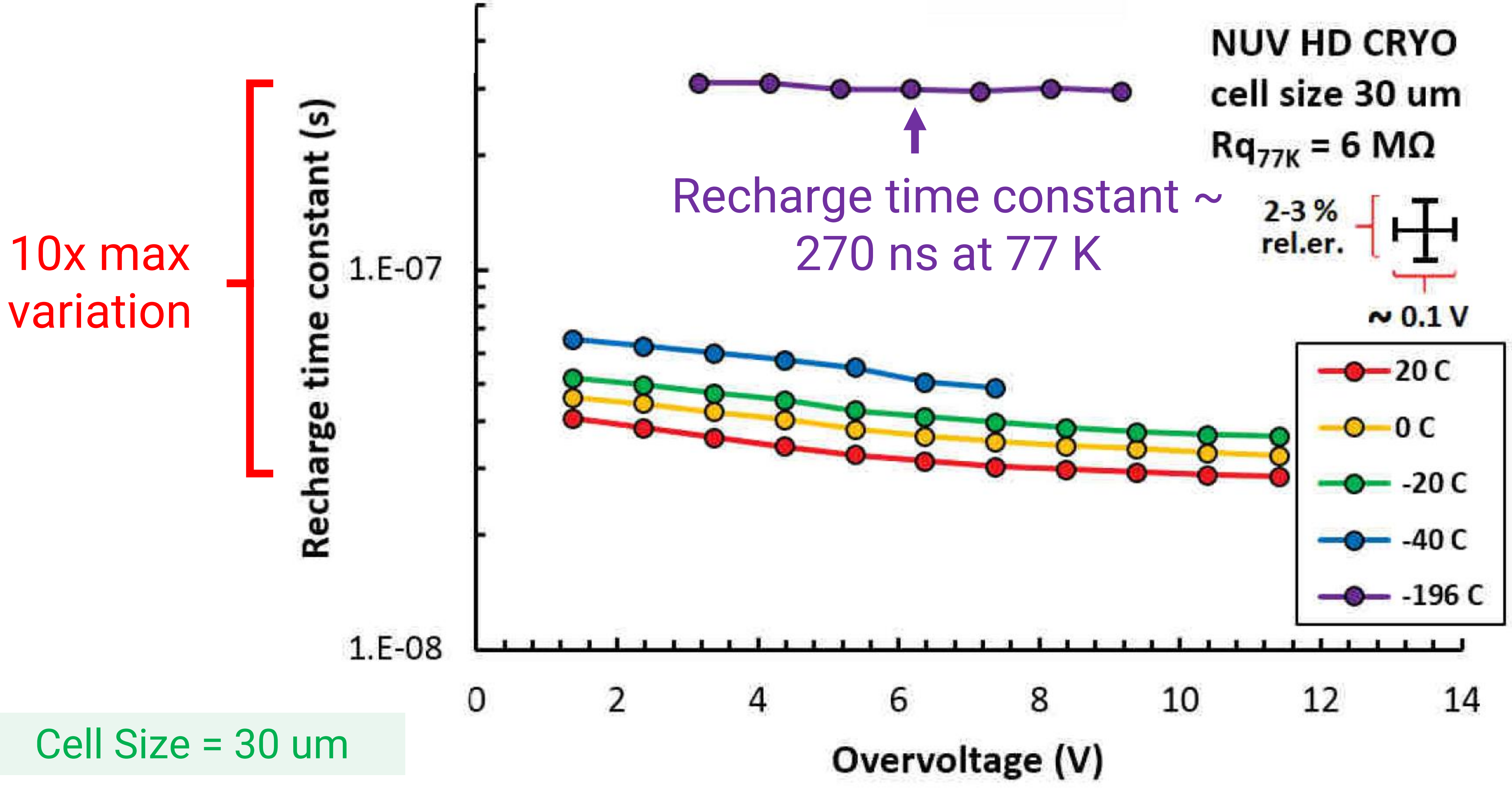
At room temperature The improvement is smaller

30 um cell

Cryogenic operation
Development #3 – Stabilization of quench. resistor

Thanks to the lower Aftrerpulsing probability, *we can reduce the microcell recharge time* constant in LN

- We developed a *new polysilicon resistor with reduced temperature variations*.

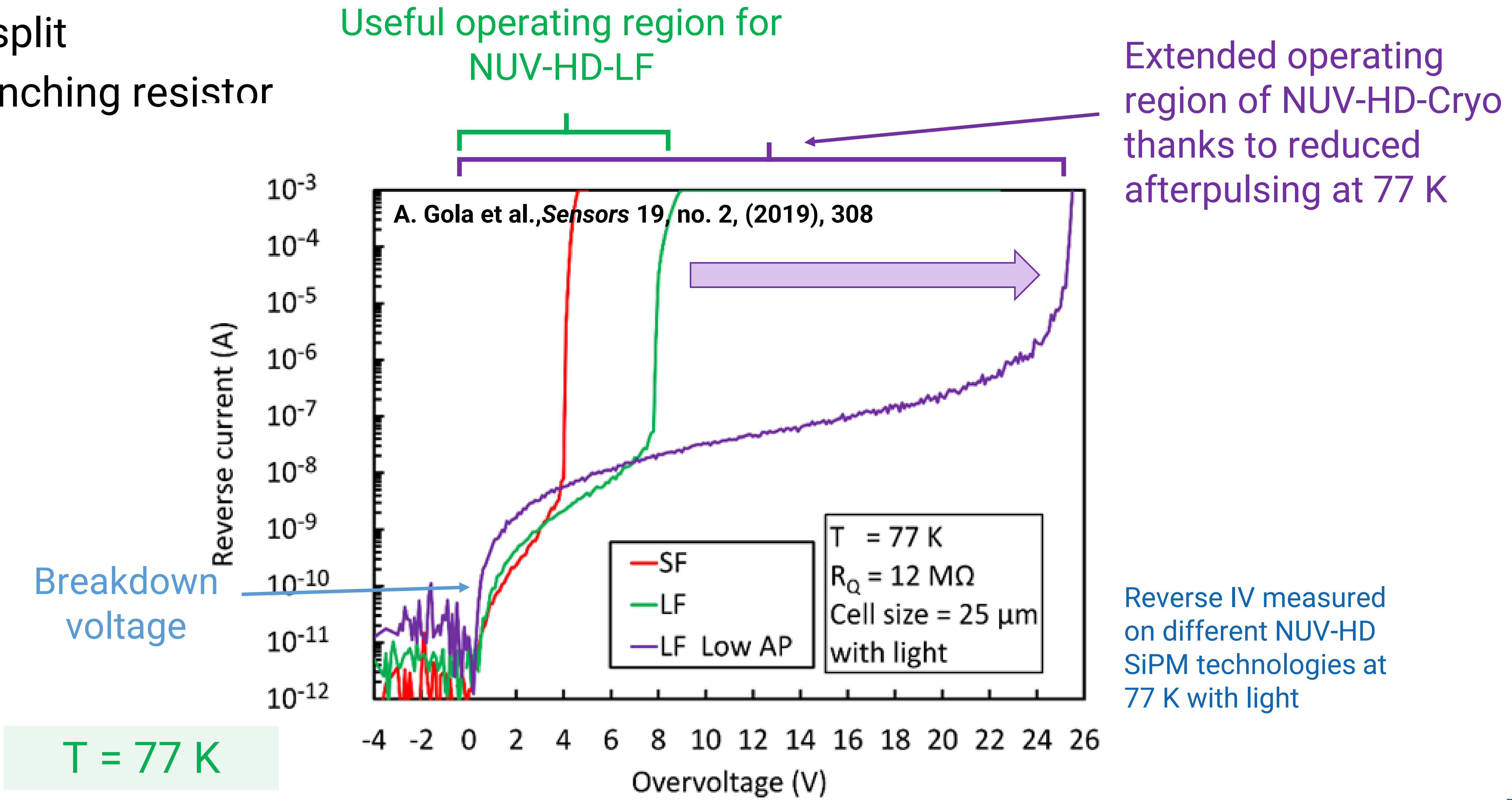


Cell Size = 30 um

Cryogenic operation
Combination of Developments: NUV-HD-Cryo

NUV-HD-Cryo SiPMs *combine three different improvement for optimal performance at cryogenic temperatures*:

- Low-field technology
- Low-AP technology split
- Low variation of quenching resistor



Reverse IV measured on different NUV-HD SiPM technologies at 77 K with light

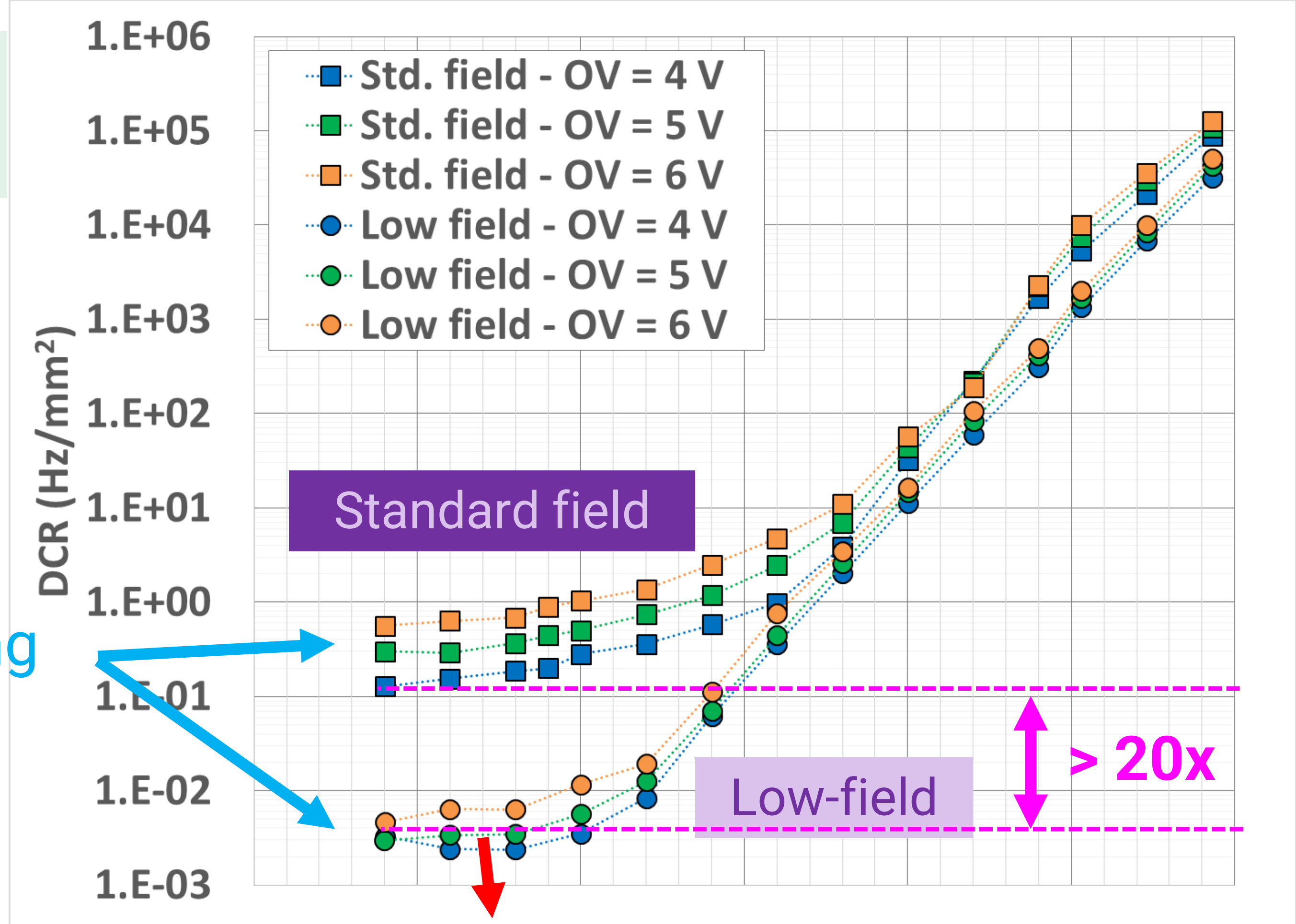
Cryogenic operation
DarkSide-20k SiPMs

darkside
two-phase argon TPC for Dark Matter Direct Detection

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

25 um cell

Tunneling

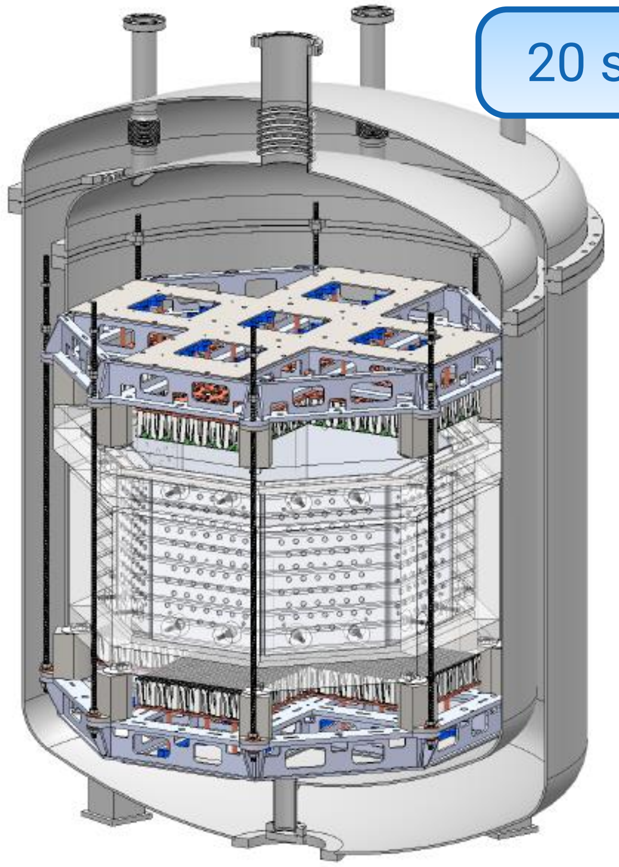


0.3 counts per day per cell at 77 K!

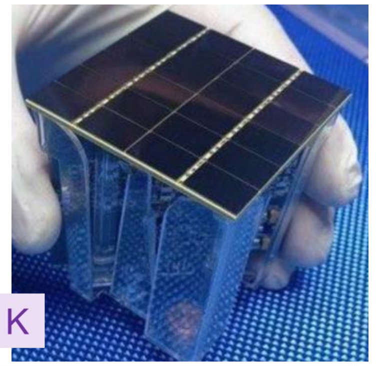
A 10x10 cm² SiPM array would have a total DCR < 100 cps!

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

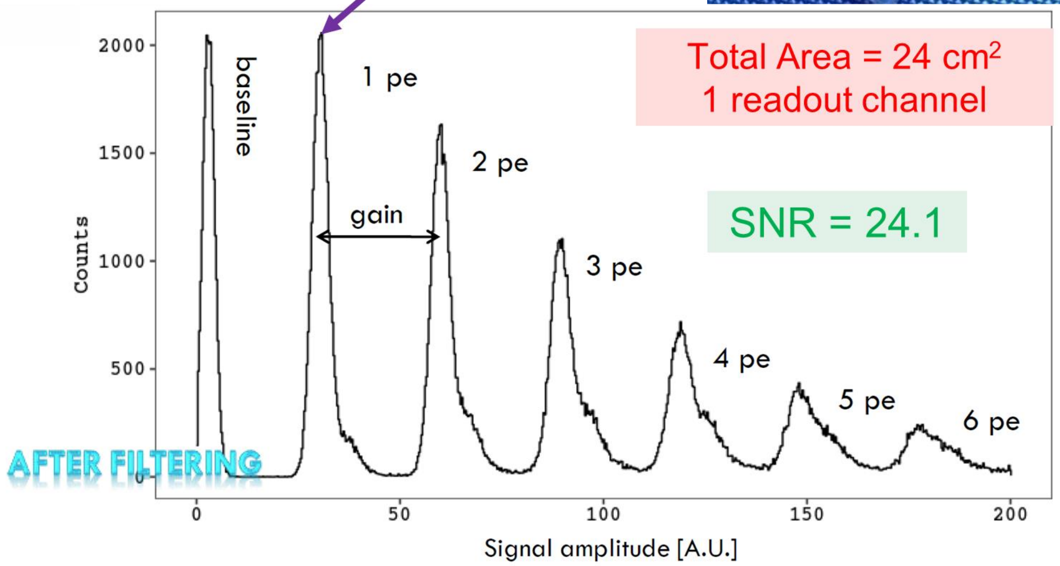
20 sqm of silicon



Darkside-20k experiment under construction at LNGS using FBK SiPMs fabricated at Lfoundry: *20 m² of SiPMs* operated at 87 K.



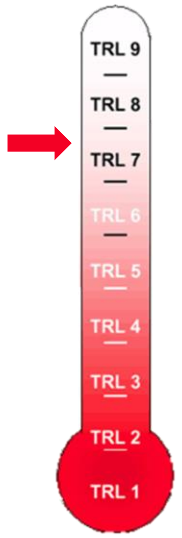
Good gain uniformity of ~ 3M SPADs at 77 K



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.

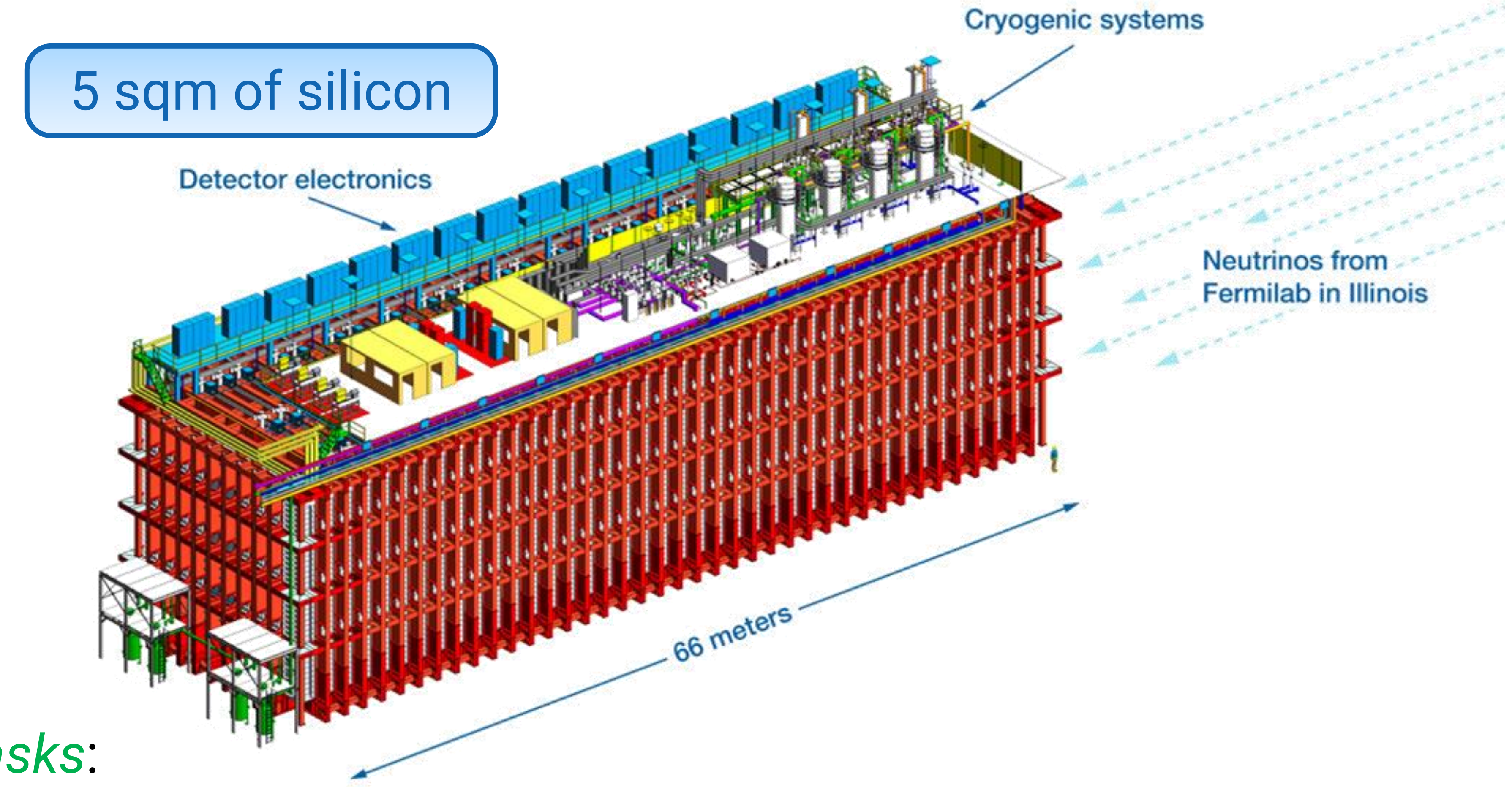
Flagship Research Lines
DUNE mass production



FBK will carry out approximately *half of the production for the DUNE horizontal drift detector*.

FBK will supply a *large volume of SiPMs in a package, capable of operating at cryogenic temperatures*

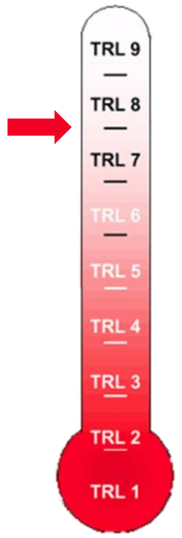
DUNE mass production @ FBK – Fact sheet	
Technology	NUV-HD-Cryo – 54um triple trench
Silicon production	LFoundry
Silicon area	5 sqm
Number of channels	140k – 160k
Number of arrays	23k – 27k
Number of 8” wafers	290 – 330
Duration	2.5 years



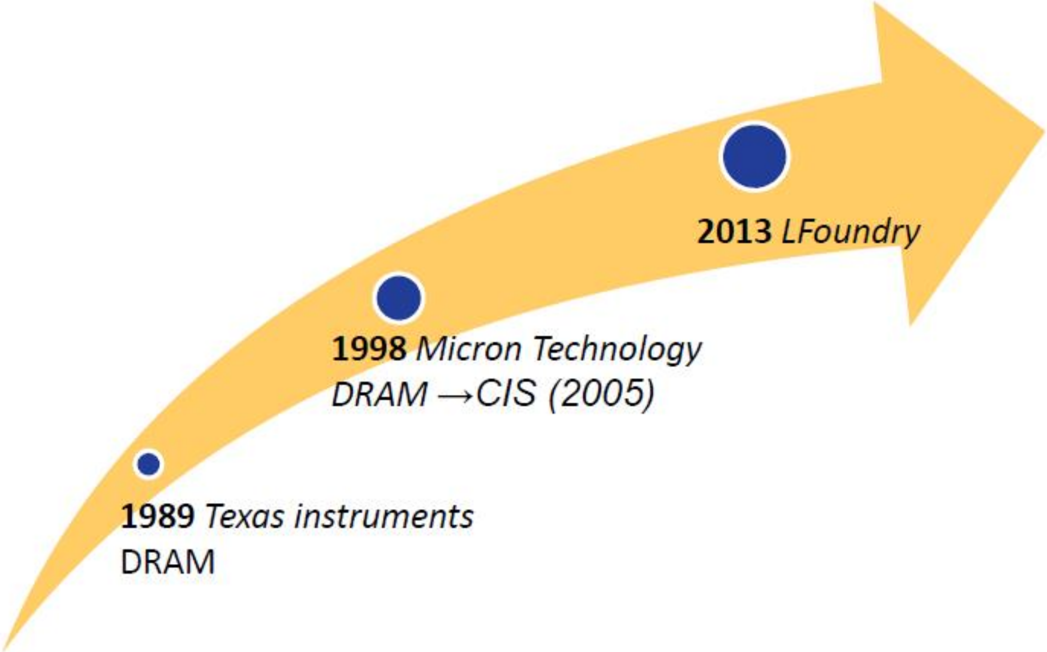
FBK tasks:

- Scientific coordination, Provide technical solutions, Project management, Subcontractor management, design, qualification, microfabrication steps, testing of wafers, of CSPs and of Arrays, cryogenic testing, QA, Warranty

Ecosystem
Technology Transfer



When the experiment / customer needs *very large production volumes* (> 5 sqm) and / or *special certification* (e.g. automotive) it makes sense to transfer FBK SiPM technologies to an external foundry.



- Open silicon foundry, based in Italy and Germany
- 200mm Fab located in Avezzano, (L'Aquila), Italy
- Capacity of 40.000 wafer/month
- Specialized in Optical Sensor Production:
  - CIS (since 2005)
  - Discrete PD (since 2014)
  - SiPM (since 2017)

Success Stories:

NUV-HD-Cryo successfully transferred for the production for DarkSide-20k and DUNE experiments.

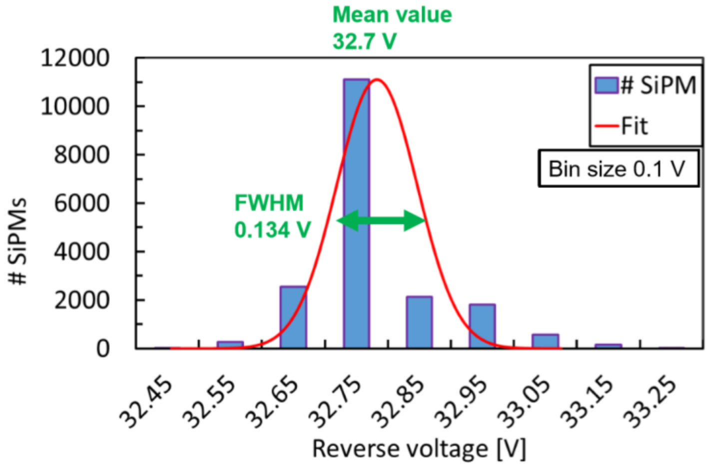
NUV-HD-RH currently being evaluated: first results are promising.

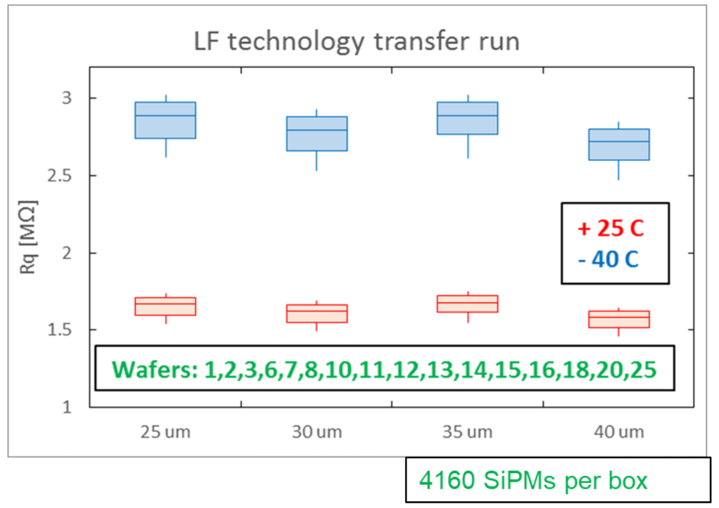
Private-public Partnership:

R&D on detectors, scientific management of project, scouting for new opportunities is carried out by FBK.

Volume production is carried out by LF.

Careful management of the IPR and of licensing is needed.



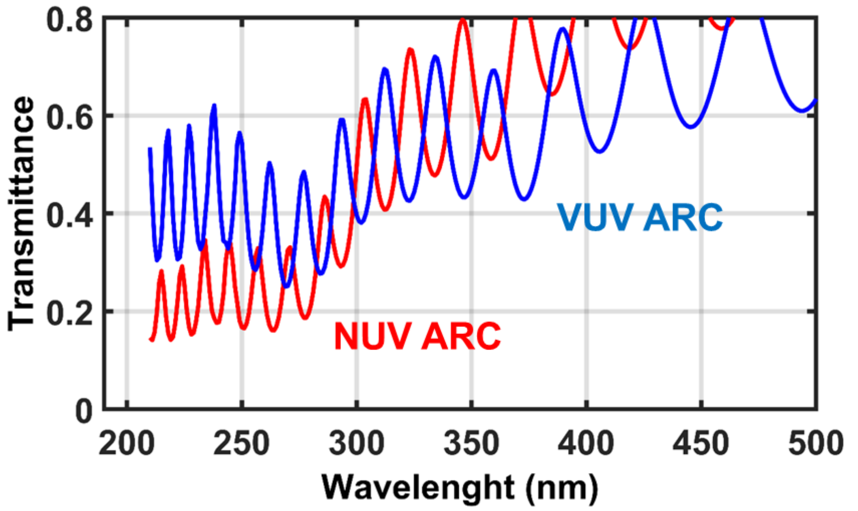


Example of the results from technology transfer runs at LFoundry for DarkSide.

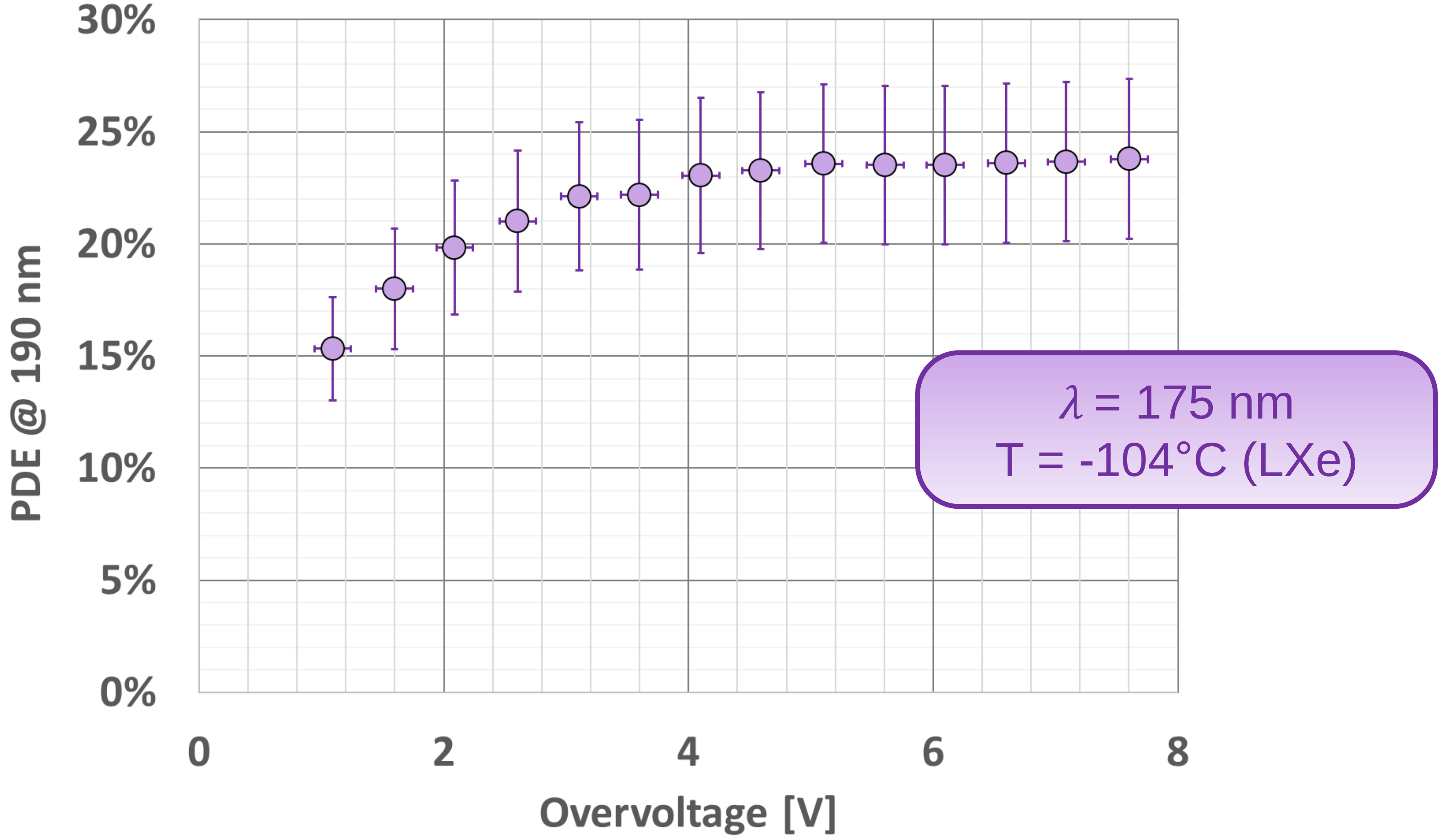
Extended sensitivity range
VUV-sensitive SiPMs: VUV-HD

FBK has developed a *VUV-sensitive SiPM technology based on the NUV-HD*, for big physics experiments (nEXO @ Stanford - 0νββ with LXe).

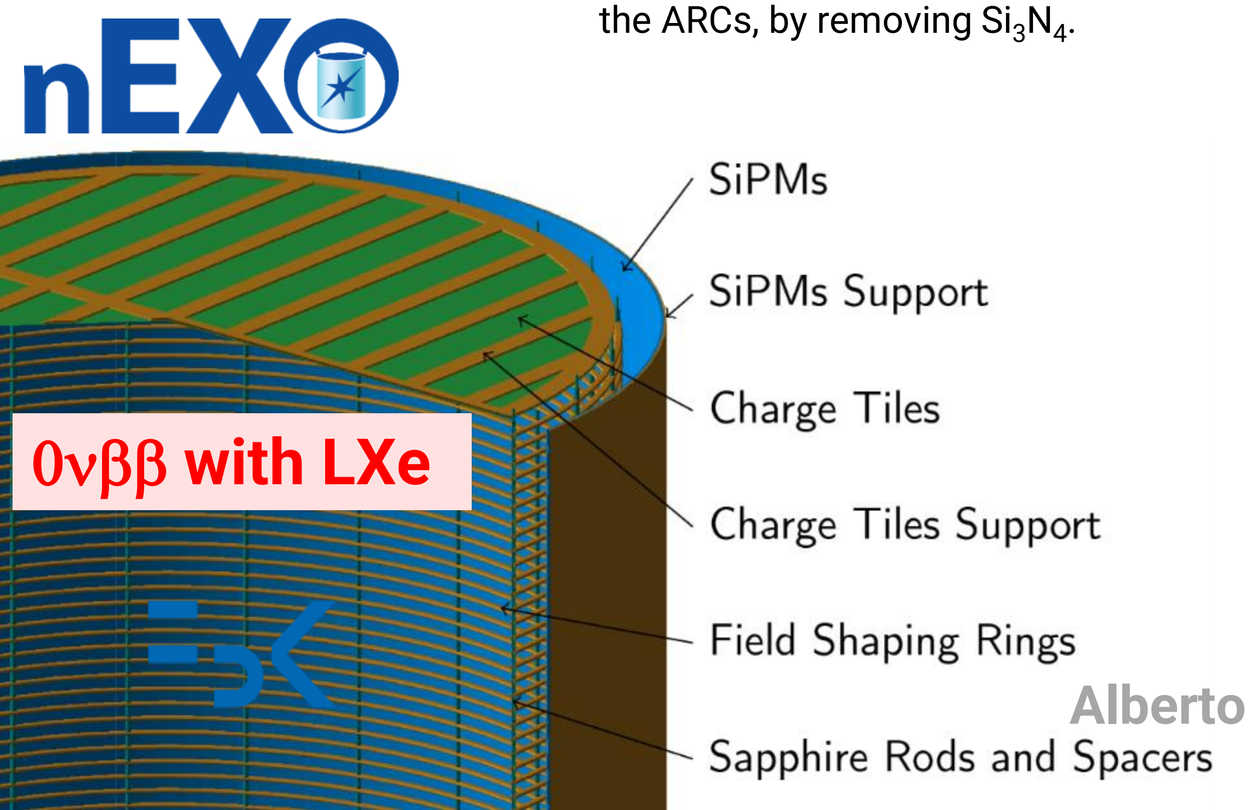
R&D focus on ARC



R&D was focused on enhancing the transmission of the ARCs, by removing Si_3N_4.



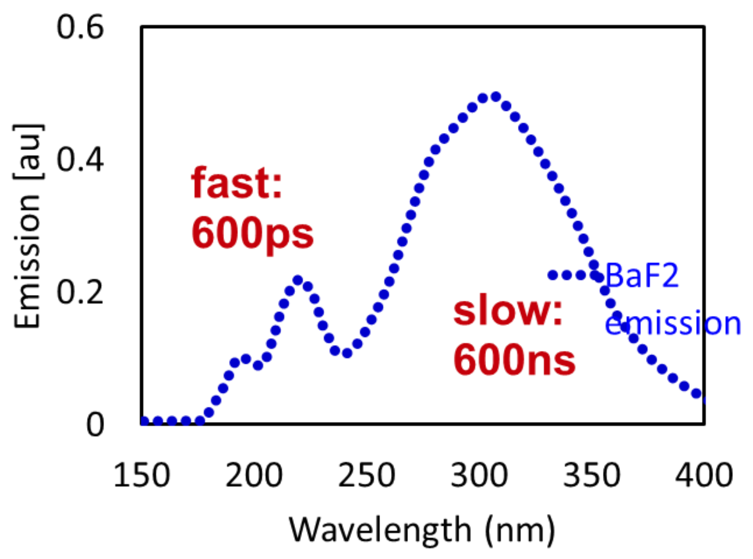
Gallina, G., et al. "Characterization of SiPM avalanche triggering probabilities." *IEEE Transactions on Electron Devices* 66.10 (2019): 4228-4234.



Timing with VUV-sensitive SiPMs

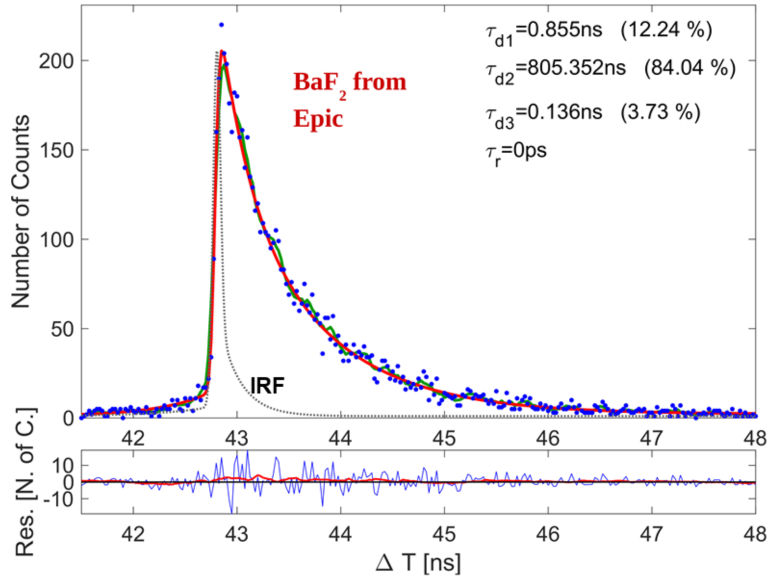
Extended sensitivity range
VUV-HD SiPMs for BaF_2 readout

VUV-HD SiPMs are an excellent candidate for the readout of the *cross-luminescence emission of BaF_2*, which produces photons between less than 200 nm and 250 nm with a very fast emission time constant.



BaF_2 emission spectrum:

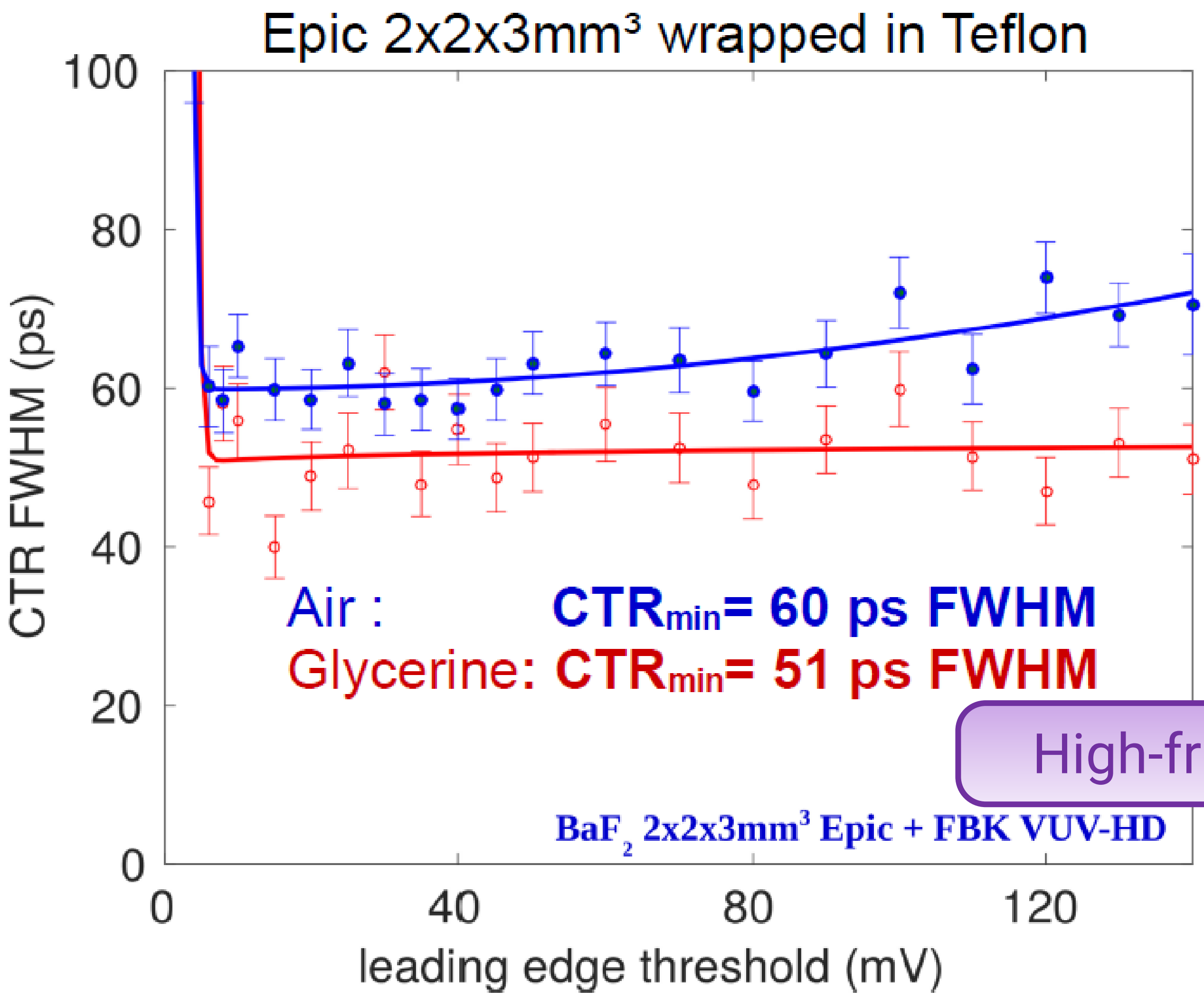
- Cross-luminescence: fast (600 ps) and short wavelength.
- Self trapped exciton (STE): slow (600 ns) and longer wavelength



Ultrafast emission in BaF_2:

- Demonstrated with gamma-rays at PMI with VUV-HD SiPMs.
- Cross luminescence with ***~100 ps decay time constant***
- Light yield of 160 photons / 511 keV

Record CRT with BaF_2

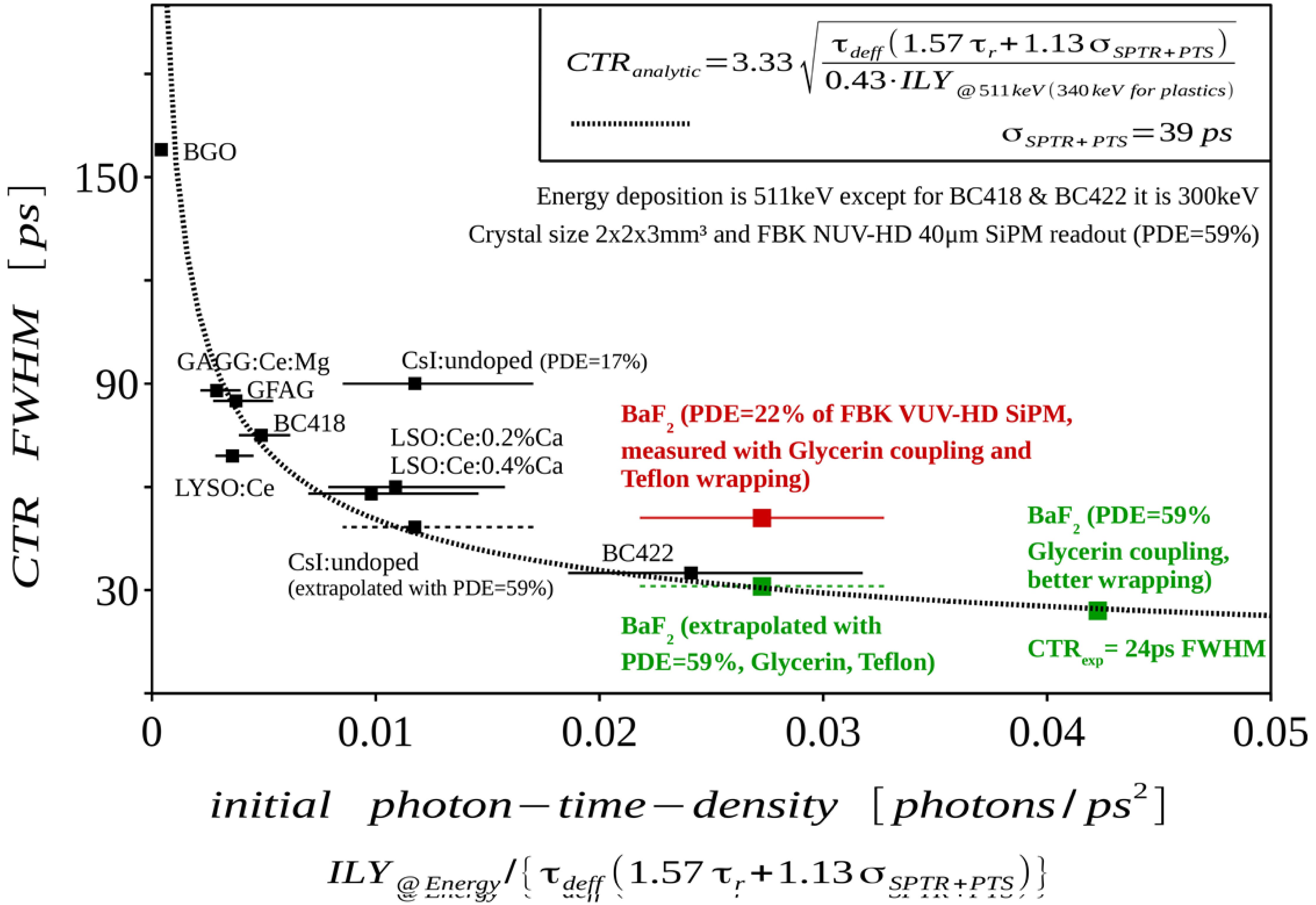


High-frequency readout

CRT performance with VUV-HD SiPM, 35 um cell reading out BaF_2 crystals.

S. Gundacker et.al, "Vacuum ultraviolet silicon photomultipliers applied to BaF2 cross-luminescence detection for high-rate ultrafast timing applications", 2021 Phys. Med. Biol. 66 114002

Extended sensitivity range
BaF_2 + VUV-HD compared to other scintillators



BaF_2 is very interesting for ultrafast timing

Aggressive R&D on SiPMs would allow to break the 30 ps barrier.

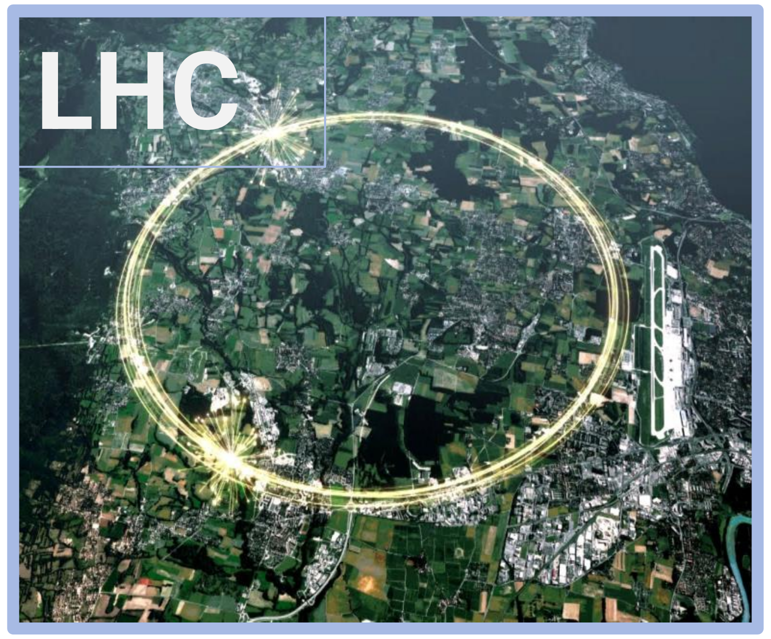
Gundacker, Stefan, et al. "Experimental time resolution limits of modern SiPMs and TOF-PET detectors exploring different scintillators and Cherenkov emission." *Physics in Medicine & Biology* 65.2 (2020): 025001.

Radiation Hardness of SiPMs

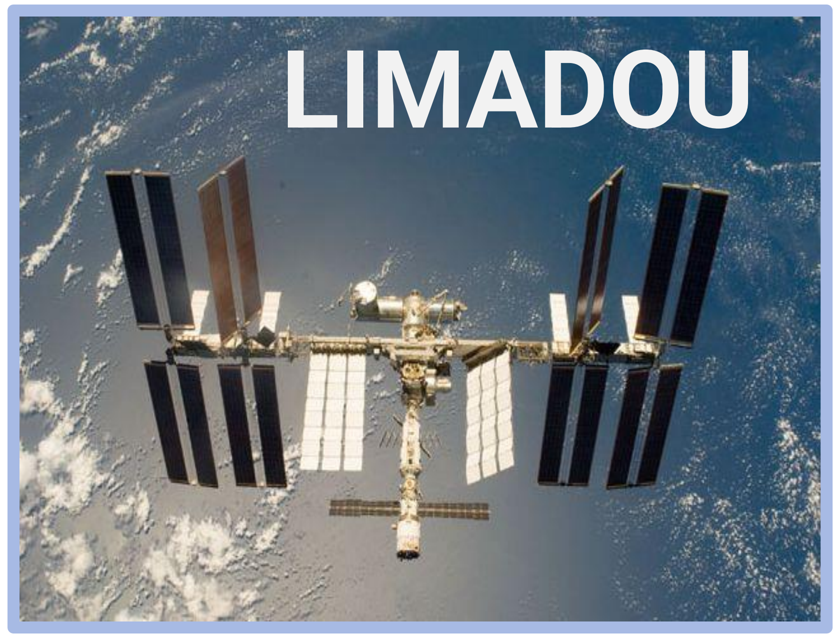
Radiation Hardness
Motivation for R&D

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: $\sim 5\cdot10^{10}$ neq/cm²



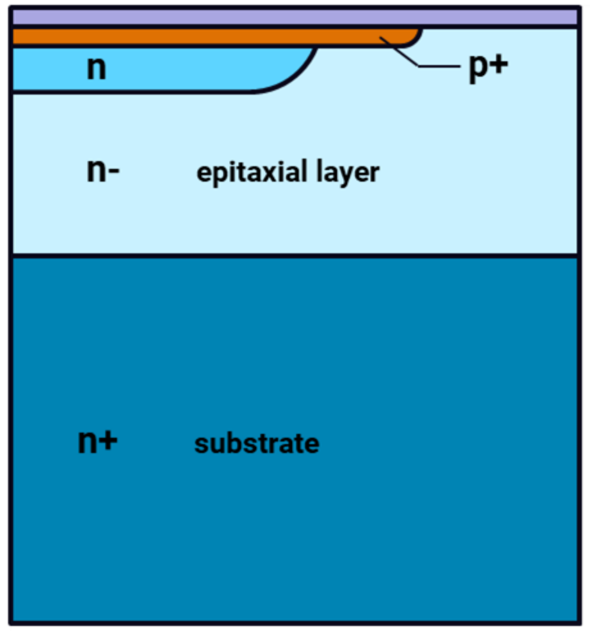
What is the definition of radiation hardness for SiPMs?

R&D approach:
- *Qualification* of radiation tolerance of current SiPM technologies.
- Development of a *highly customized SiPM technology* for optimal performance after irradiation is likely needed.

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

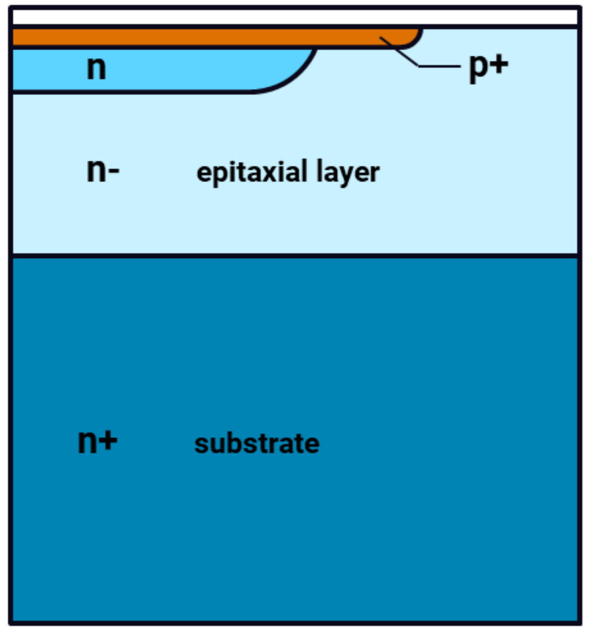


Peak PDE = 420 nm

- Different ARC
- High sensitivity in VUV

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

NUV-HD[3]
Near Ultraviolet

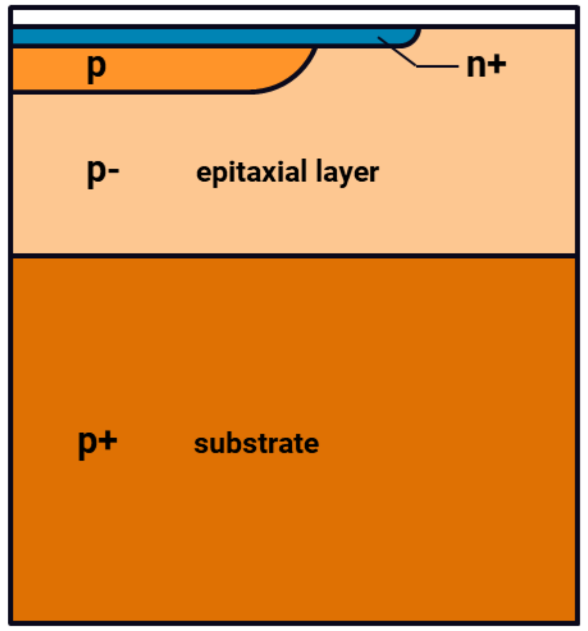


Peak PDE = 420 nm

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

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

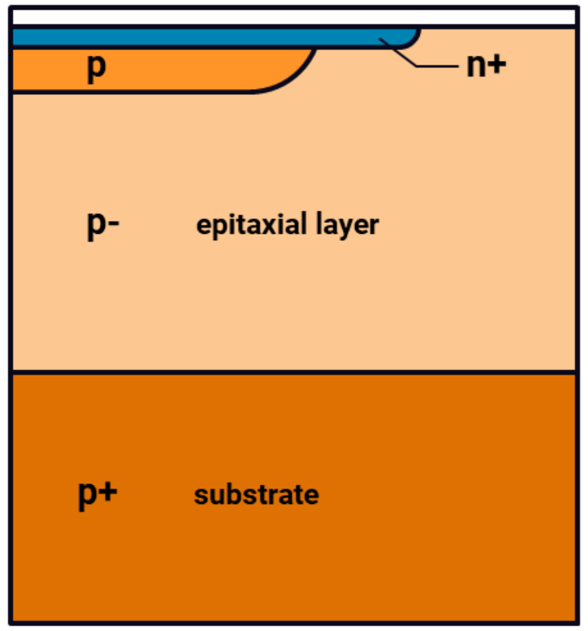
RGB-HD[4]
Visible



Peak PDE = 530 nm

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

NIR-HD[5]
Near Infrared



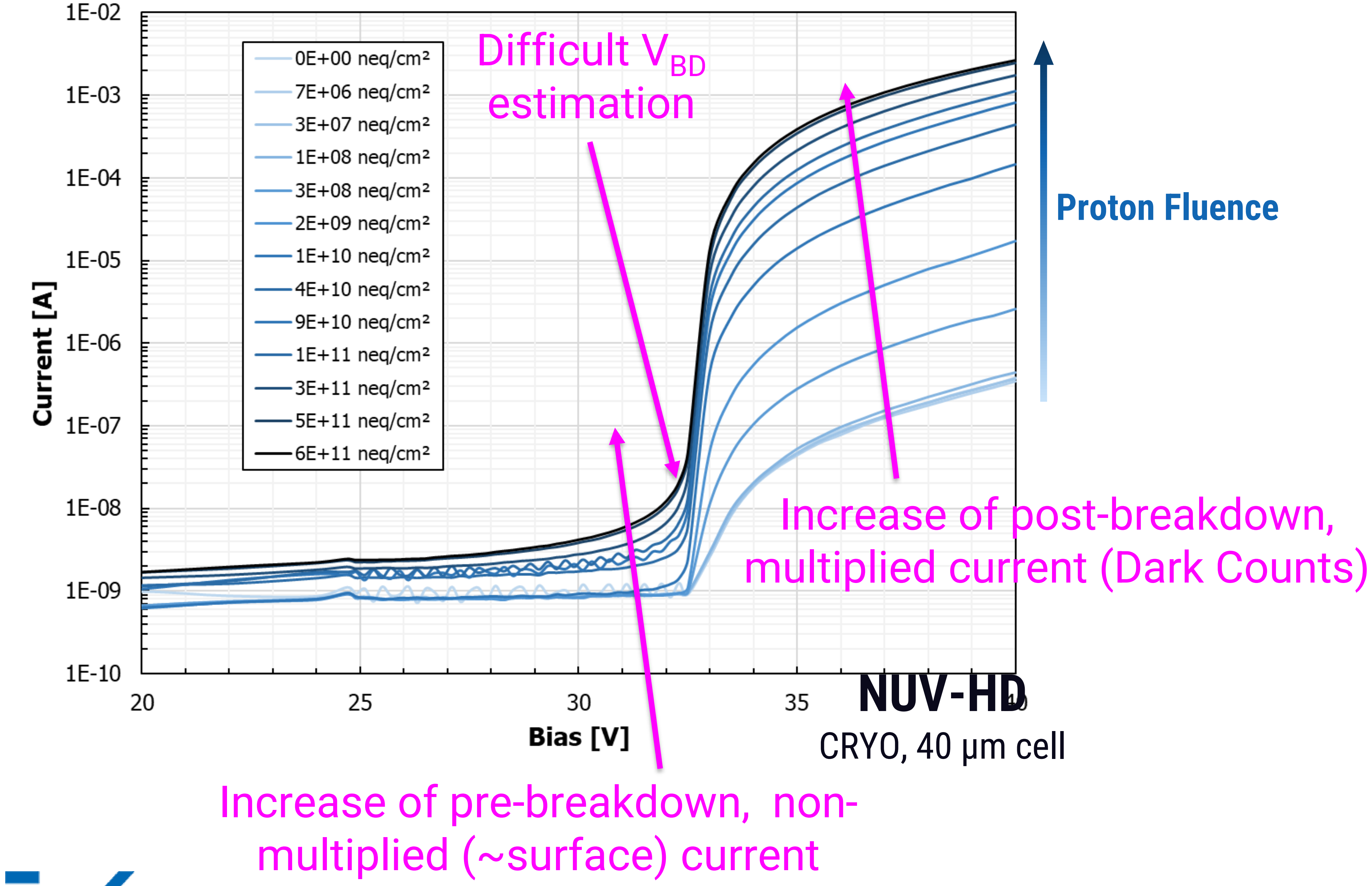
Peak PDE = 530 nm

- Thick epitaxial layer
- High sensitivity in IR

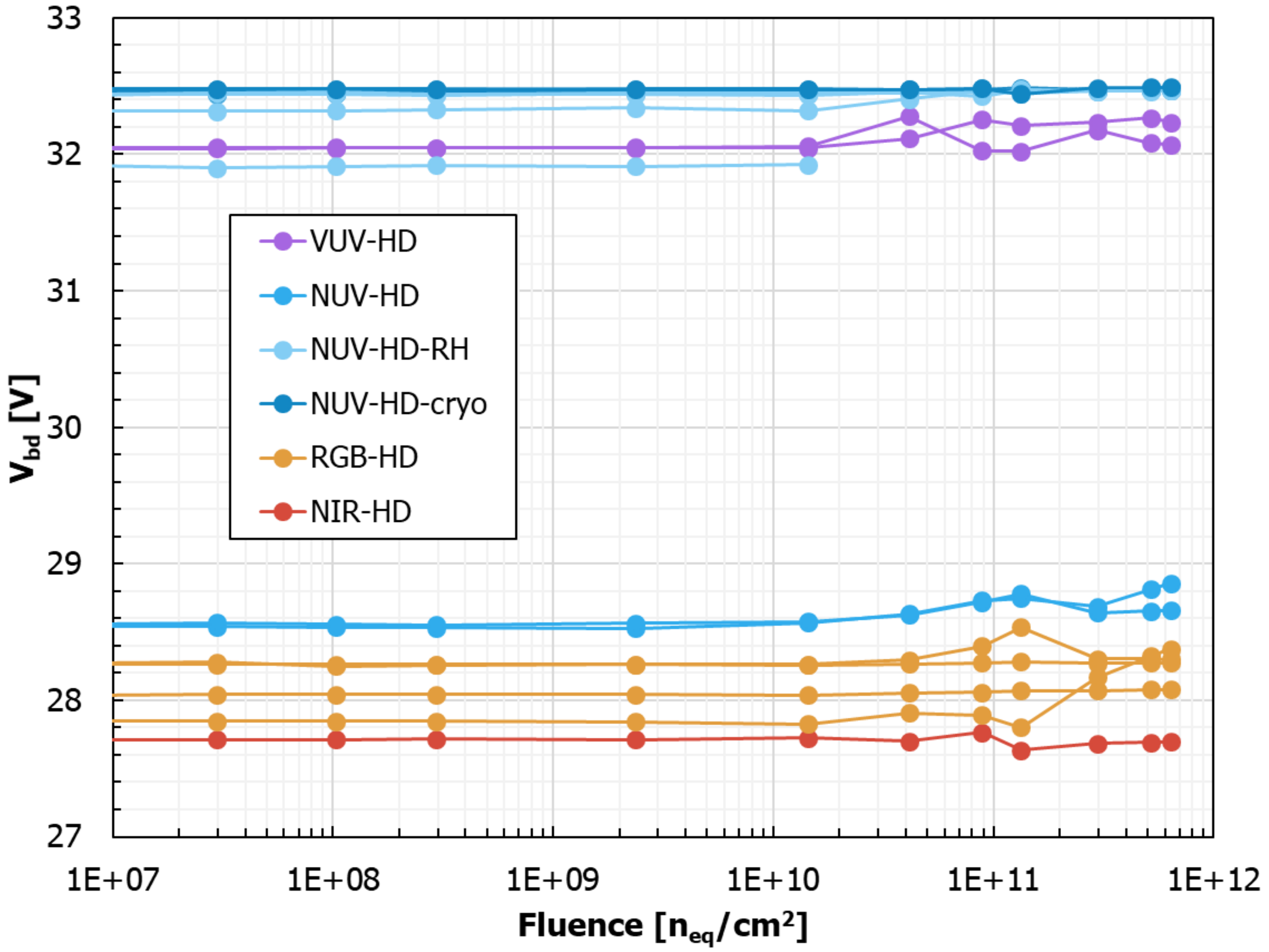
[5] Acerbi (2018)
https://doi.org/10.1016/j.nima.2017.11.098

Test Beam 1 – Trento Proton Therapy
Online IV measurements

Effects of irradiation on reverse IVs



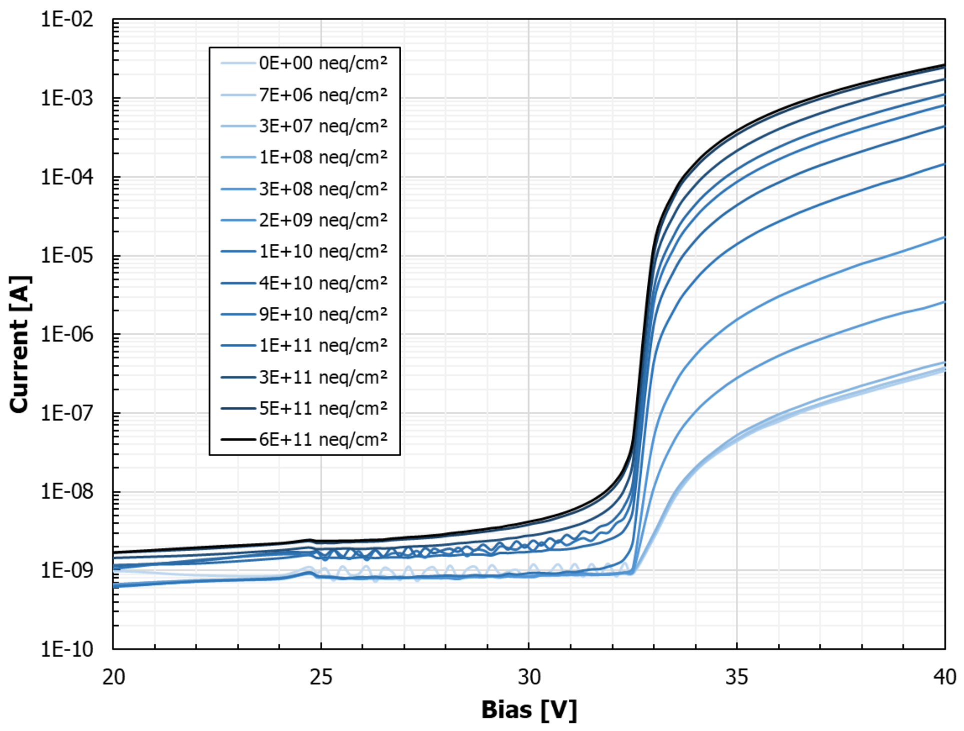
Breakdown Voltage Estimation



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

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

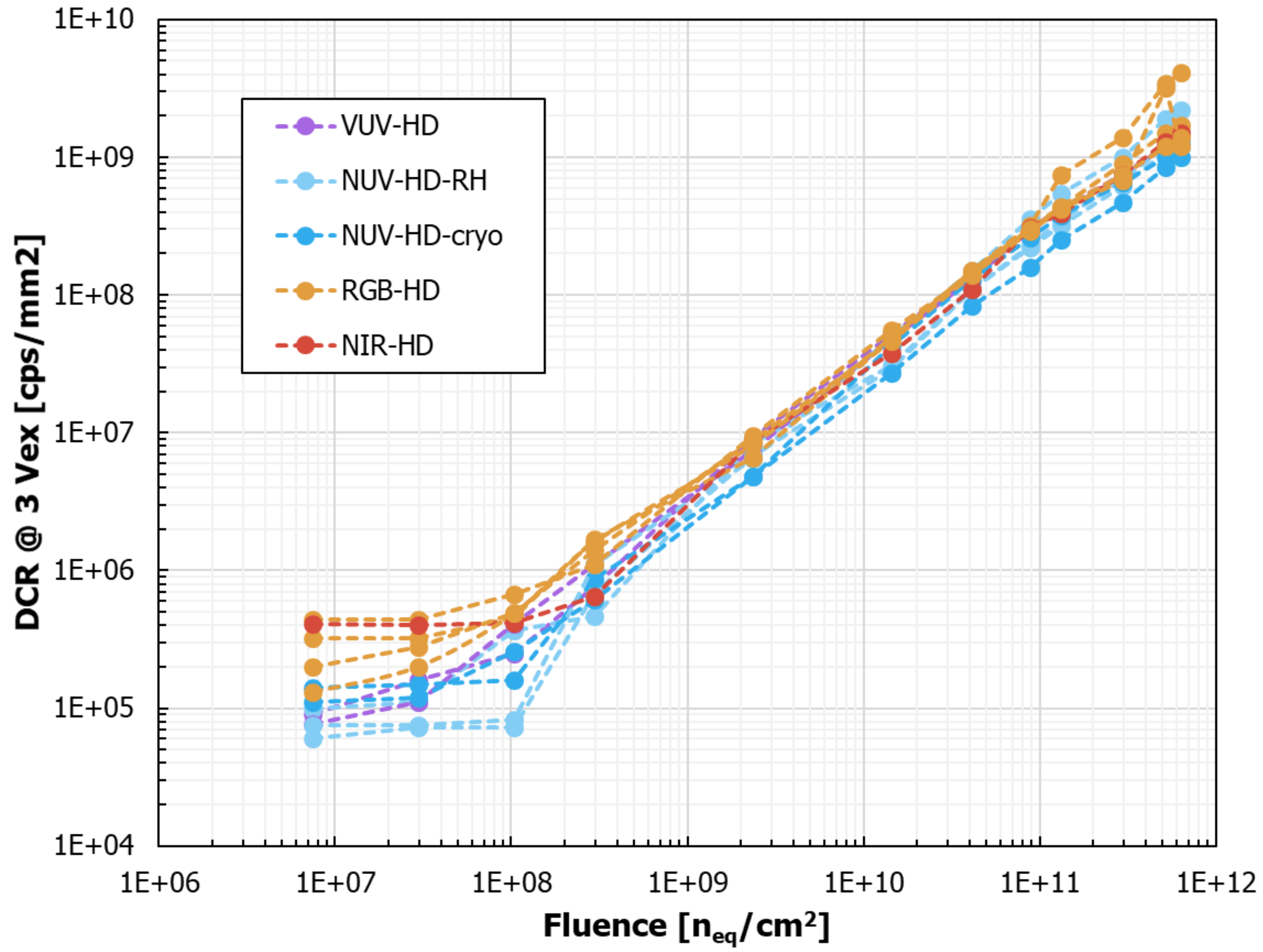
Comparison of radiation hardness of different SiPM technologies *cannot be done directly from their IVs* because they usually have different Gain and correlated noise (ECF).



+

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

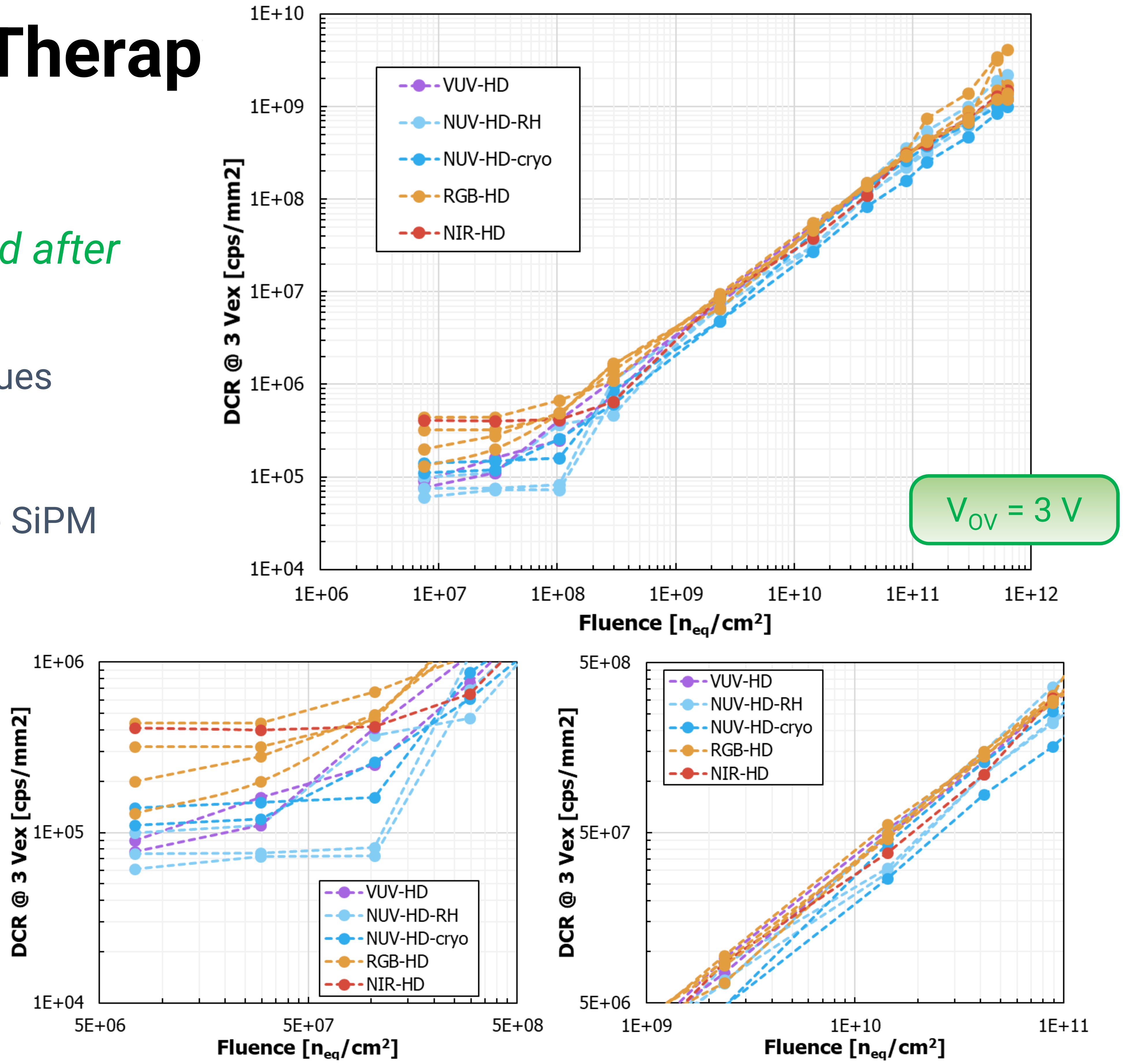
$$G_C = G * ECF = \text{Current Gain}$$
$$ECF = \text{Excess Charge Factor}$$



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 Therap
Dark Count Rate vs. Fluence



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*

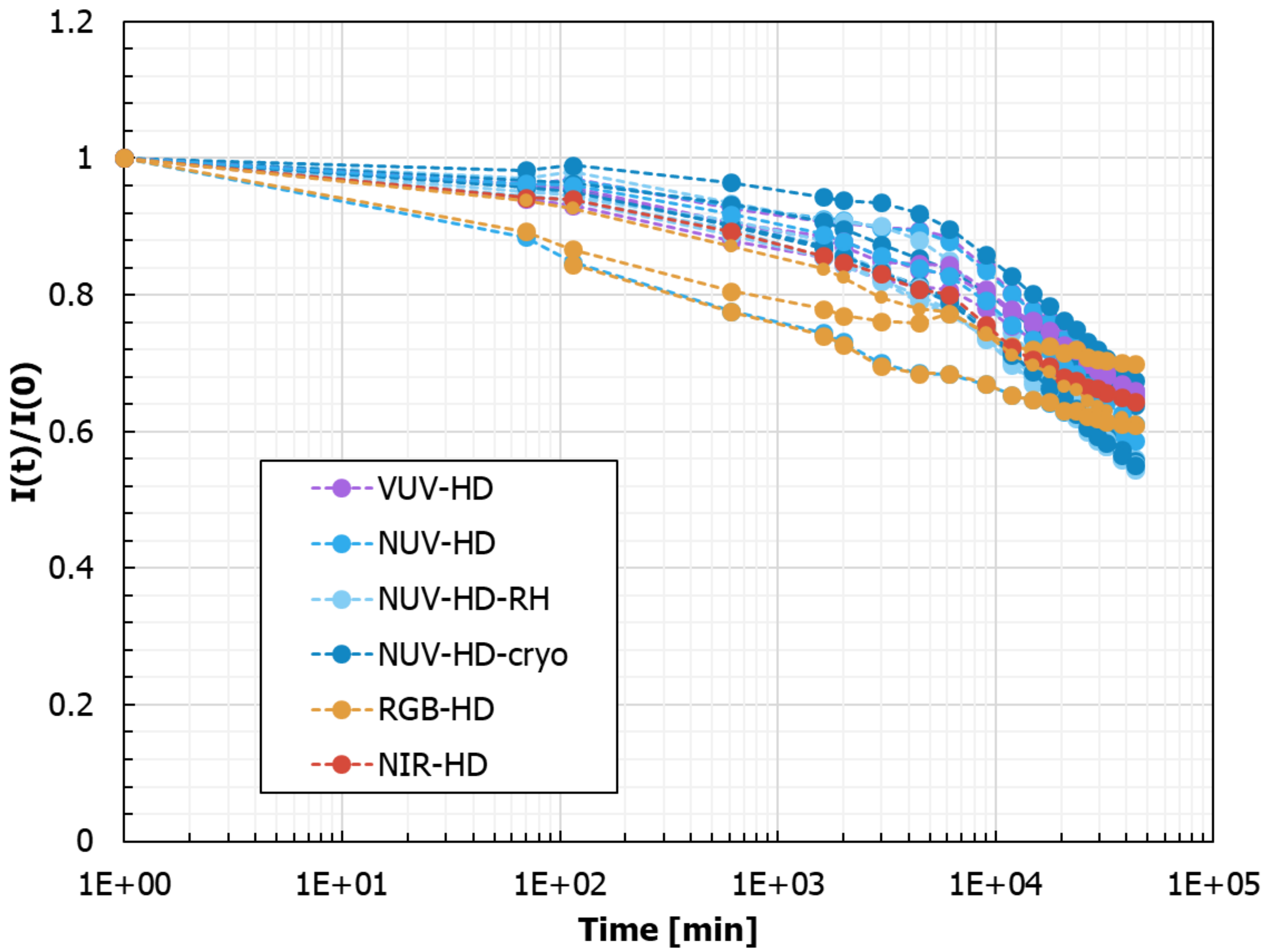
Altamura, Anna Rita, et al. "Radiation damage on SiPMs for space applications." NIM-A 1045 (2023): 167488.

Acerbi, F., et al. "Characterization of radiation damages on Silicon photomultipliers by X-rays up to 100 kGy." NIM-A 1045 (2023): 167502.

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?

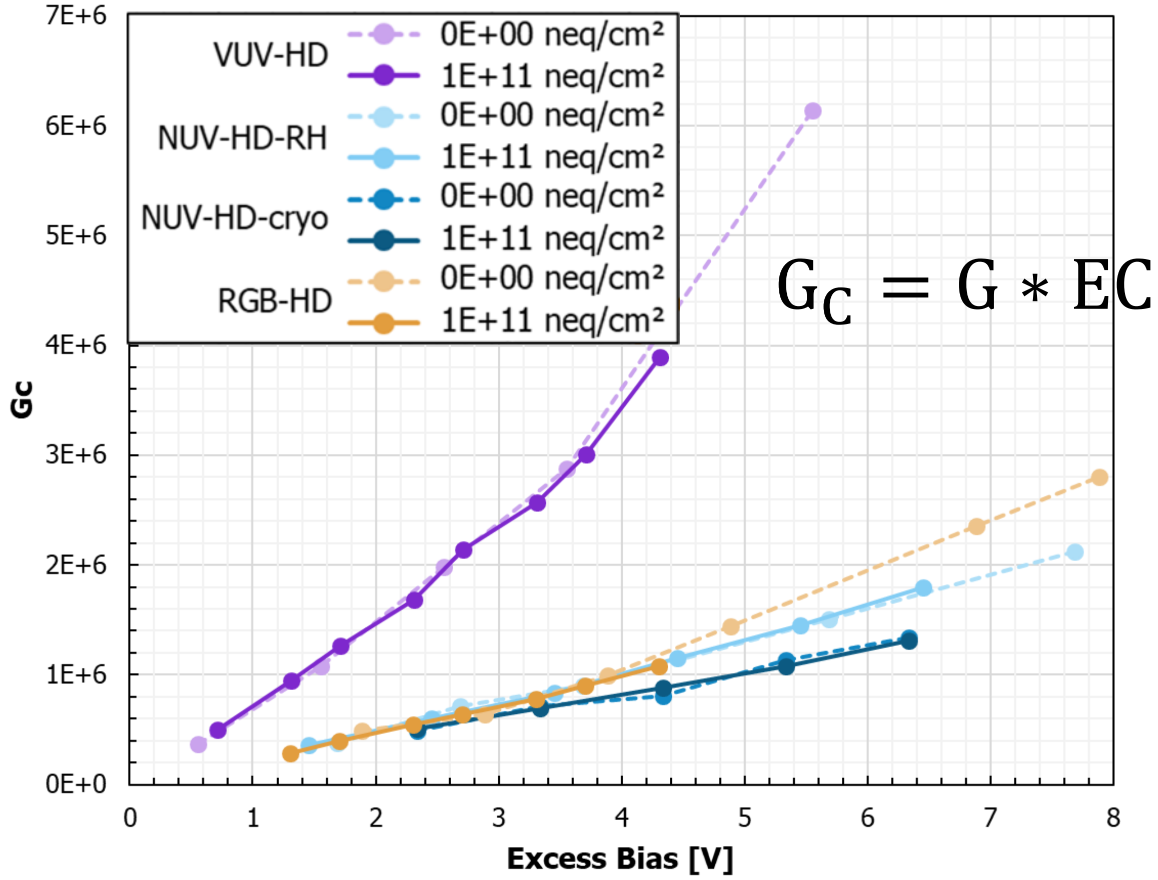


Test Beam 1 – Trento Proton Therapy
Variation of the other SiPM parameters

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.

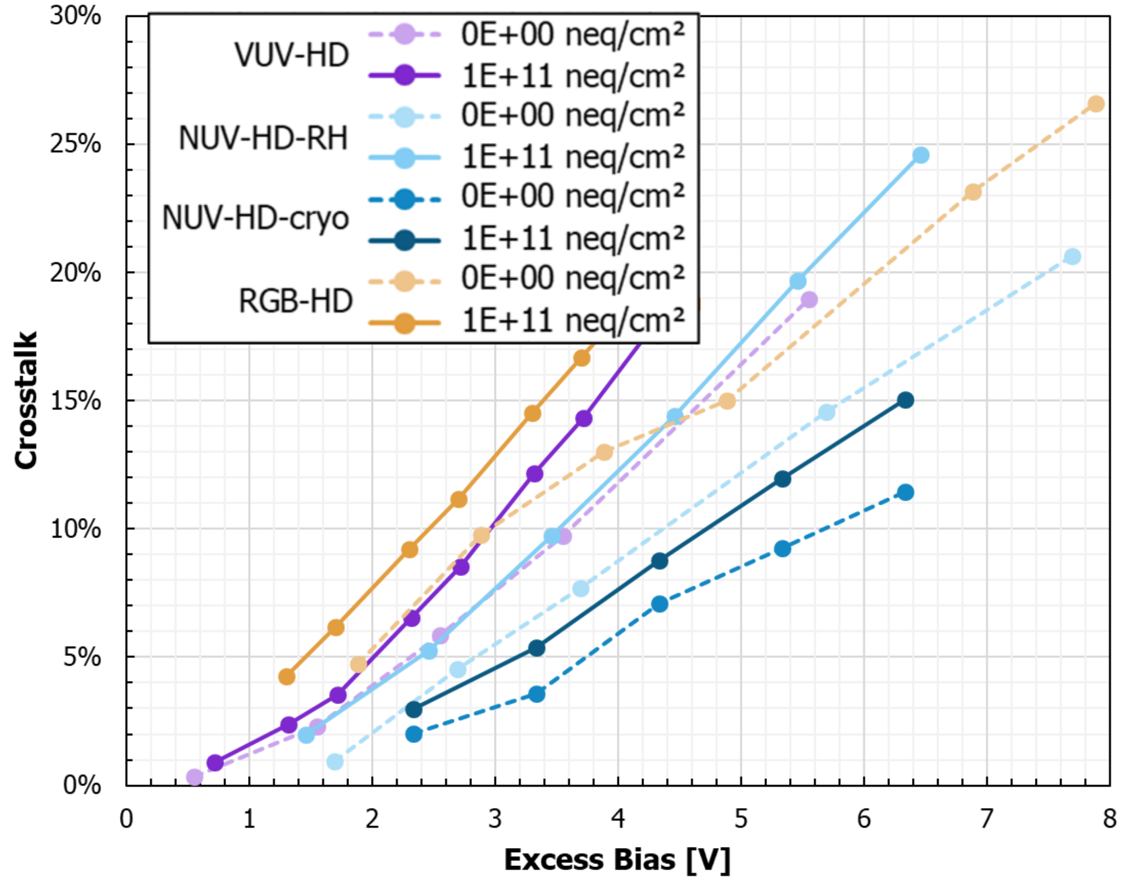
Current Gain



$$G_C = G * ECF$$

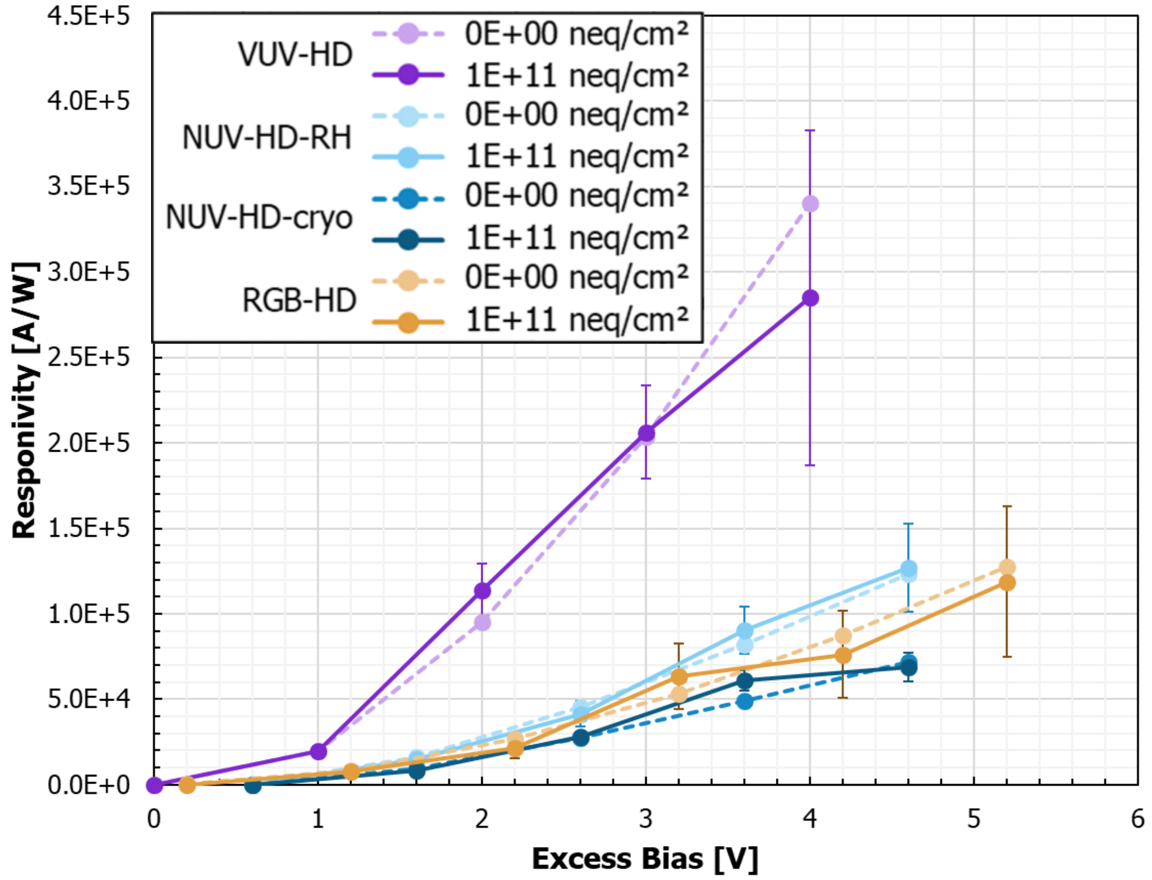
*No change in Gain * ECF* up to $1 \cdot 10^{11}$ n_{eq}/cm^2

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).

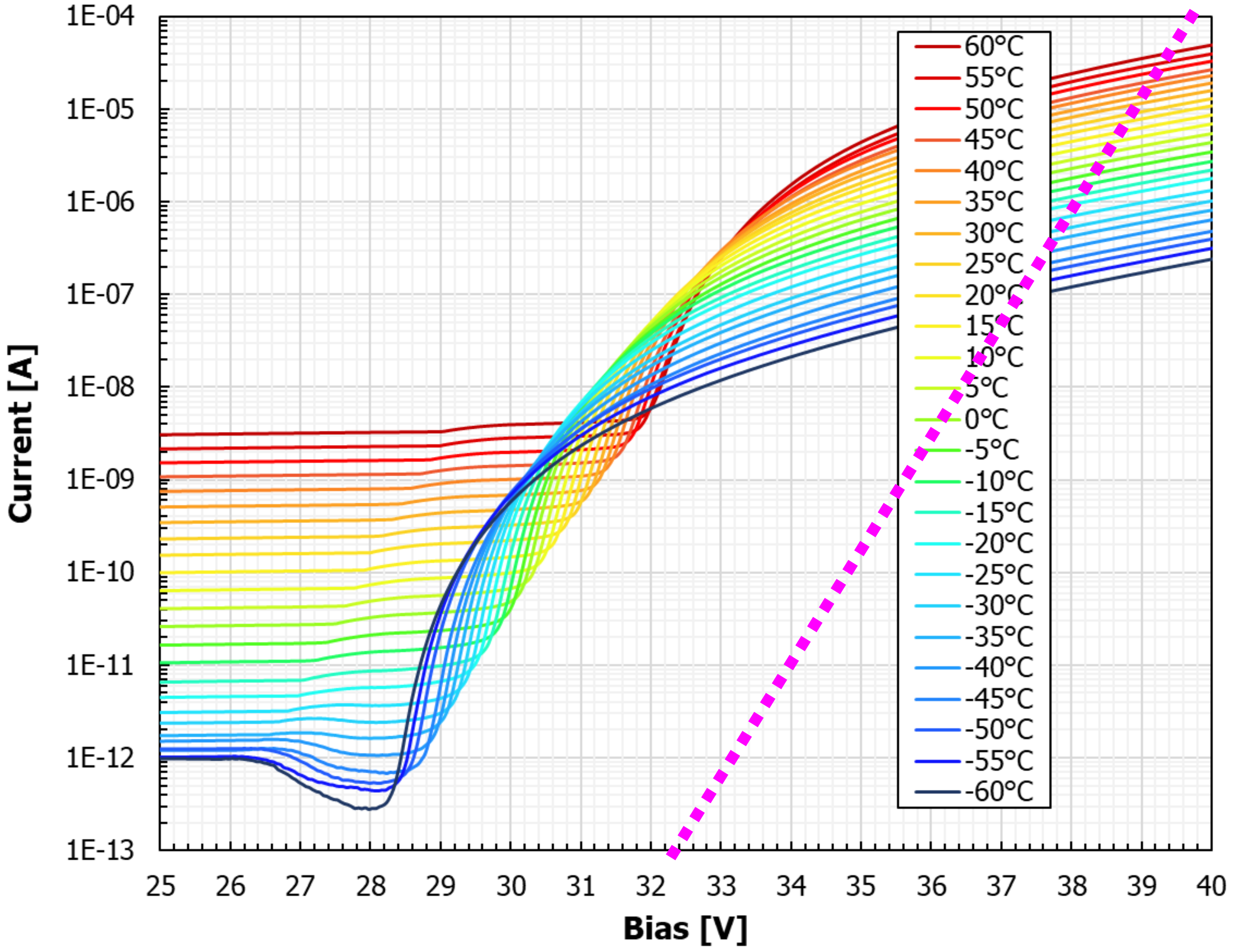
Test Beam 2 – LNS Catania
DCR Analysis

PRELIMINARY

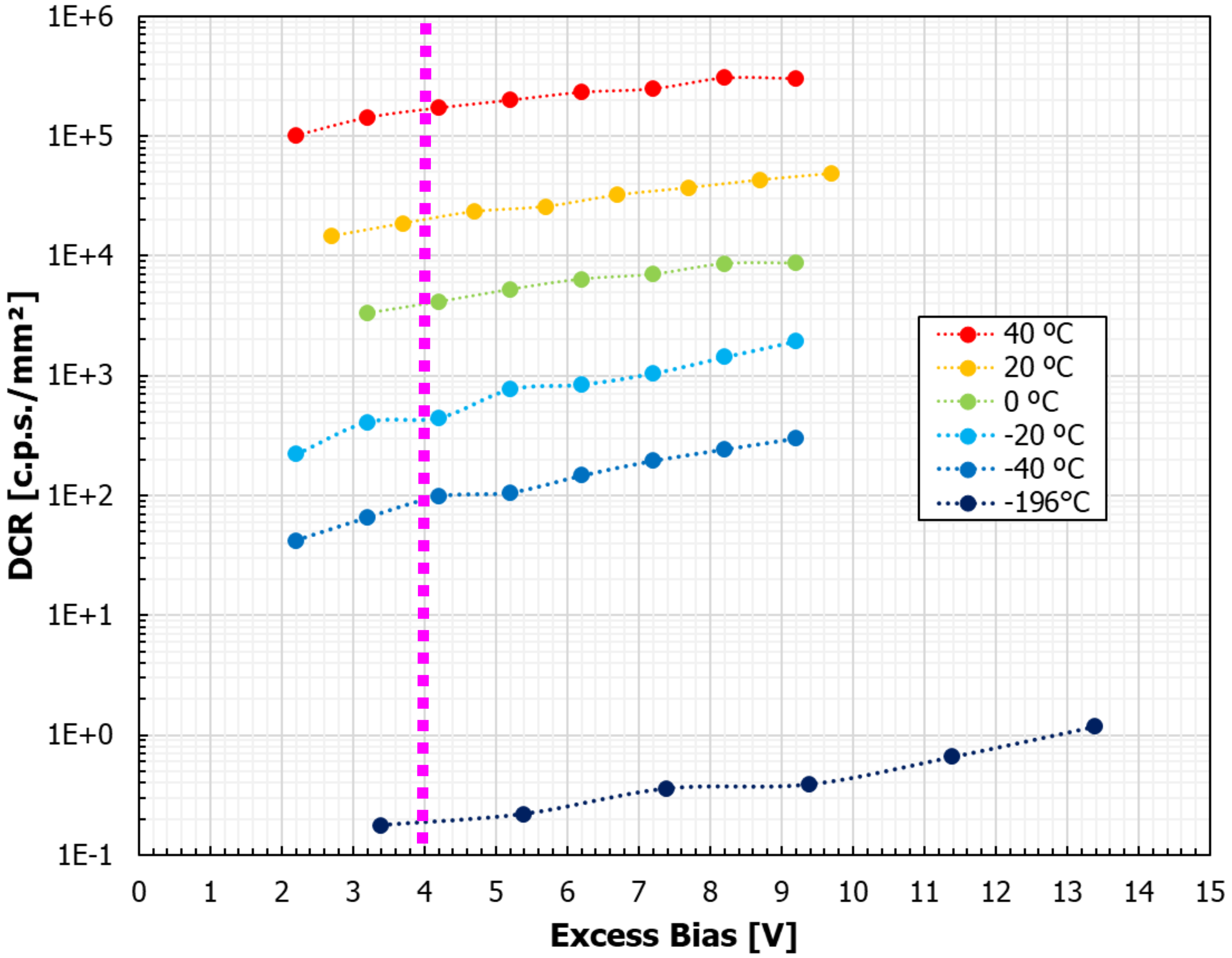
Study of *DCR after irradiation extended to cryogenic temperatures* *(preliminary)*.

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

IV vs. Temperature



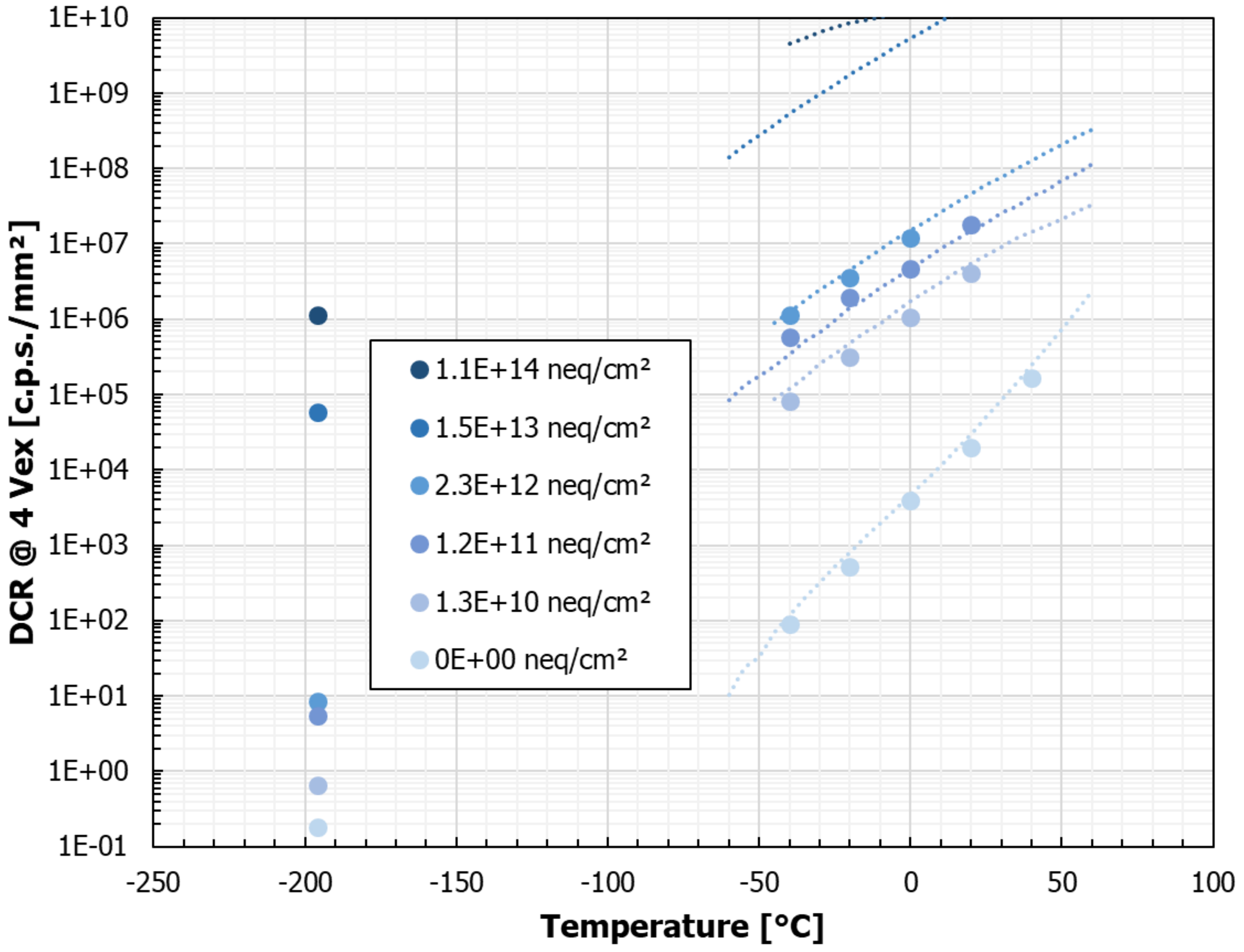
DCR vs Temperature



Altamura, Anna Rita, et al. "Characterization of Silicon Photomultipliers after proton irradiation up to 1014neq/cm2." *NIM-A t* 1040 (2022): 167284.

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

PRELIMINARY

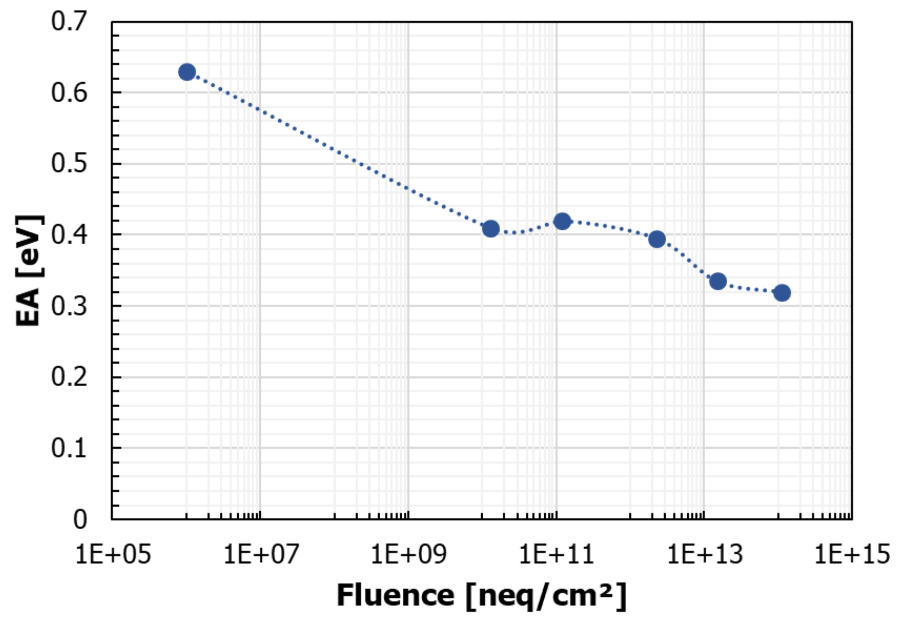


Lines: DCR from IV
Dots: DCR from waveform analysis

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

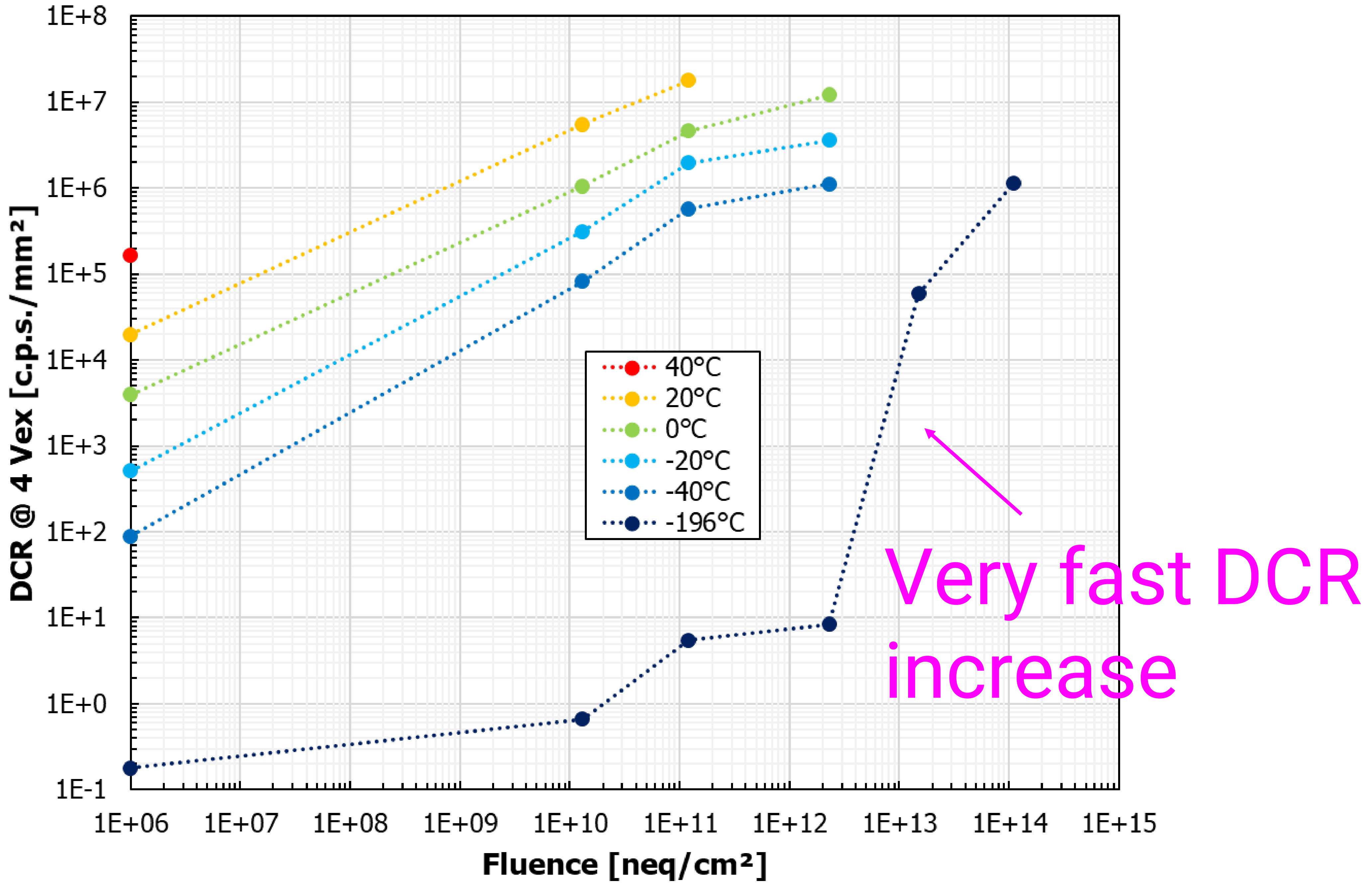
→ Cooling becomes less effective in reducing DCR.

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



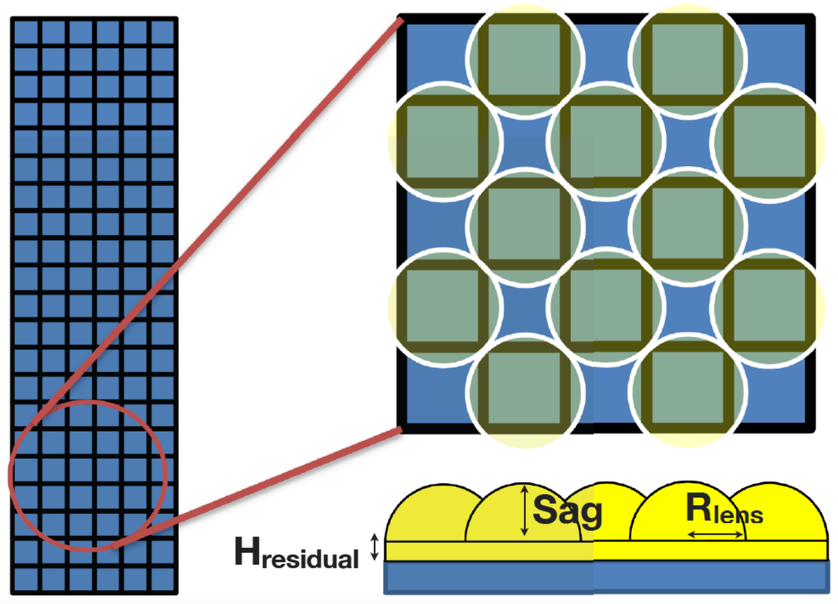
- Cooling is *extremely effective in reducing DCR after irradiation up to ~$1 \cdot 10^{12}$ n_{eq}/cm^2*
- Further investigations needed to understand what happens at the higher doses
- Worth checking different / new SiPM structures
- Check possible effect of annealing

Light Concentration

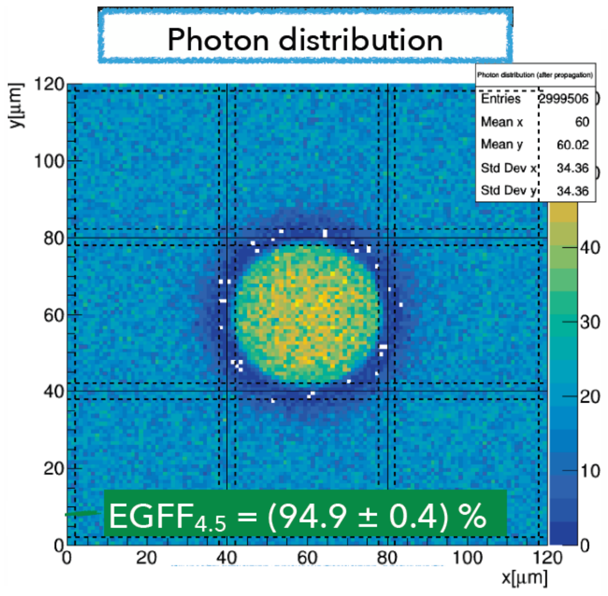
Light concentration
Microlenses

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

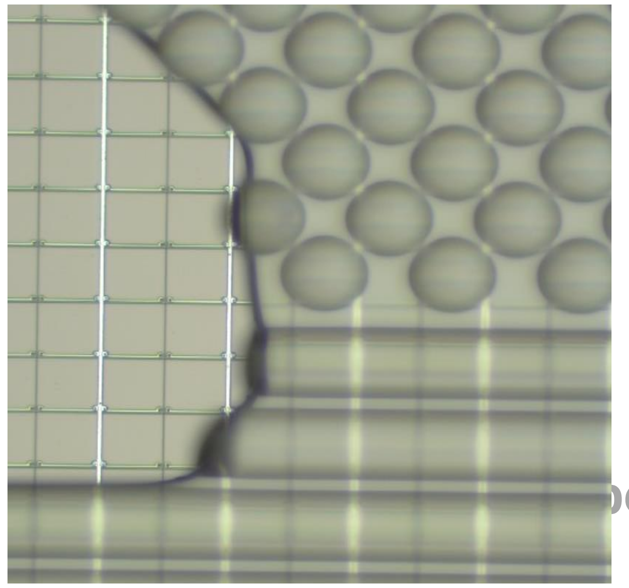
- Exploratory project between FBK and EPFL for LHCb SciFi tracker → Sensitivity-enhanced SiPMs
- Effectiveness *depends on the angular distribution of photons*.



Proposed microlens geometry



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

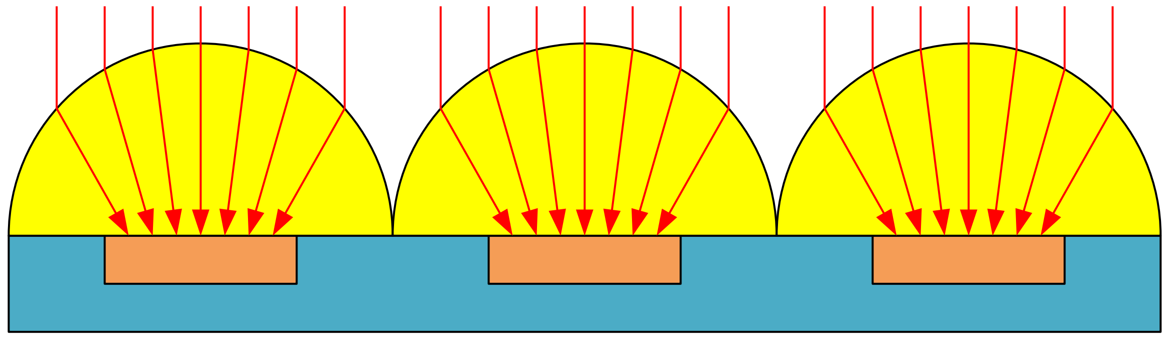


23% improvement!

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*.



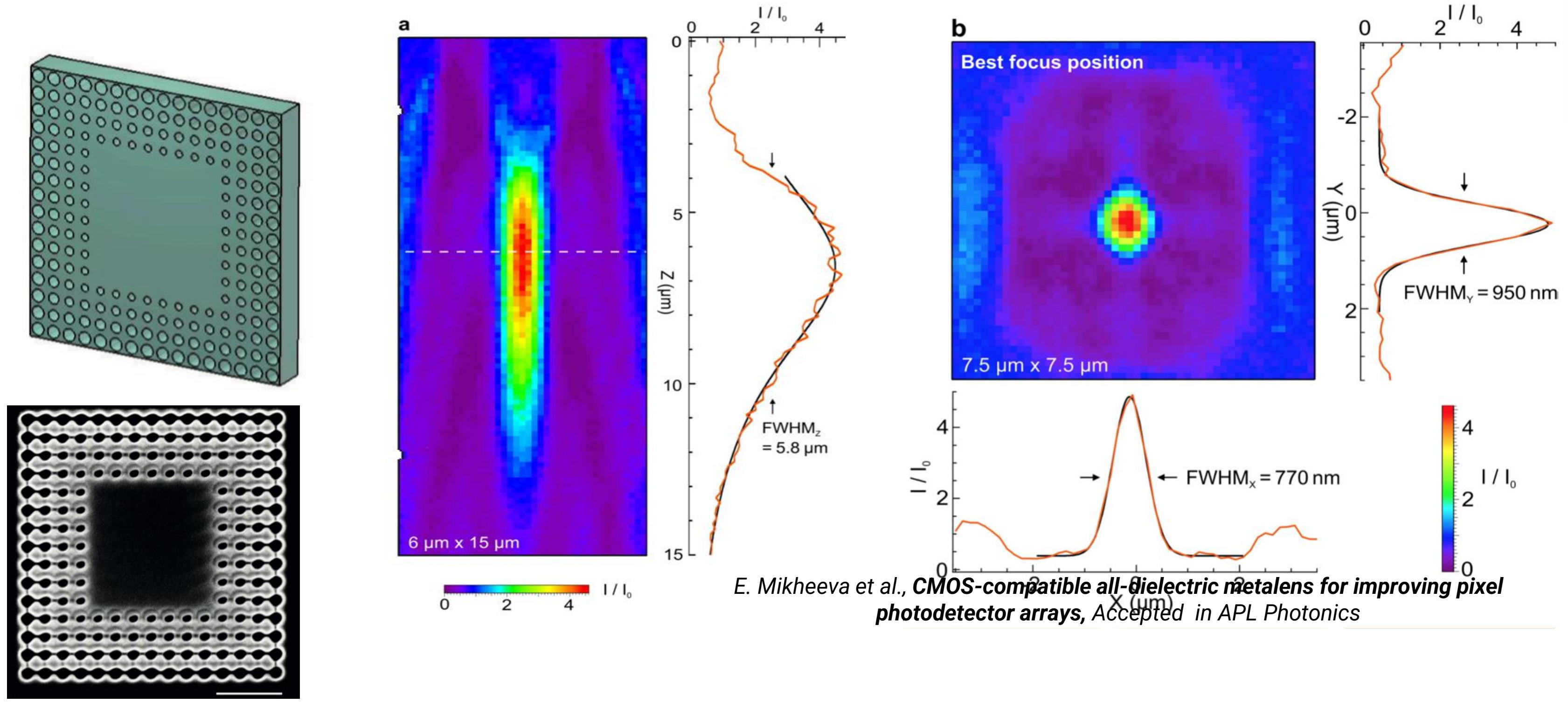
Light concentration
Metasurfaces and Metamaterials

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.)

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

Next generation developments: 2.5D and 3D integration

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

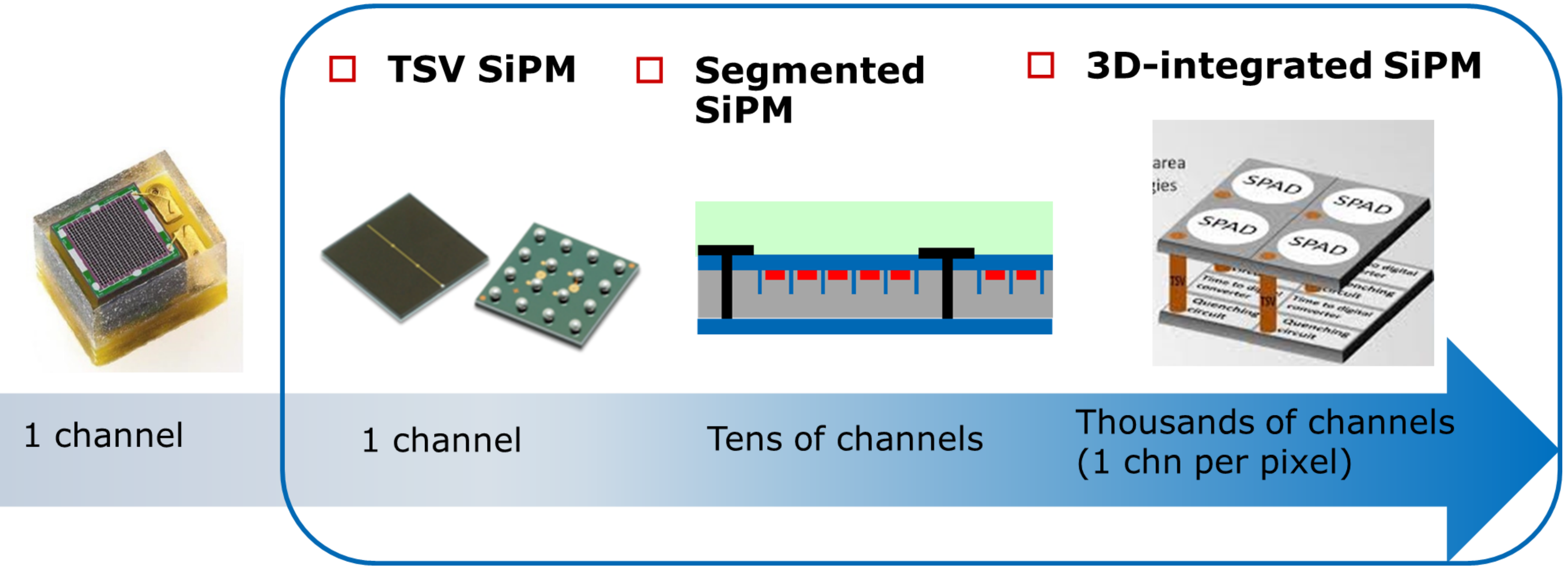
IPCEI on Microelectronics

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).

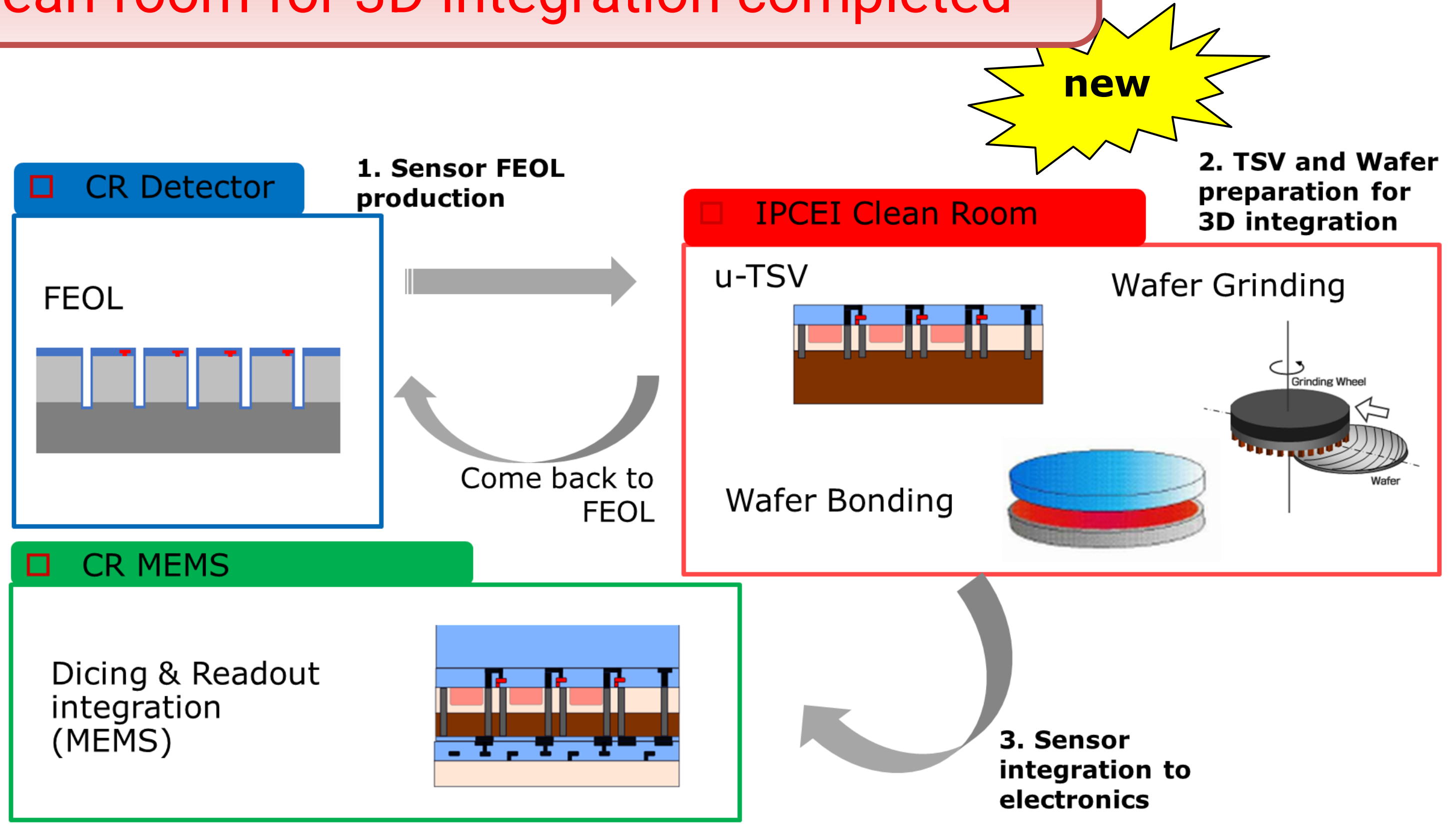
The goal for FBK is upgrading its optical sensors technologies, by *developing TSVs, micro-TSV and Backside Illuminated SiPMs*. This will allow high-density interconnections to the front-end and high-segmentation.

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

New clean-room for 3D integration completed



Range of technologies being developed within IPCEI

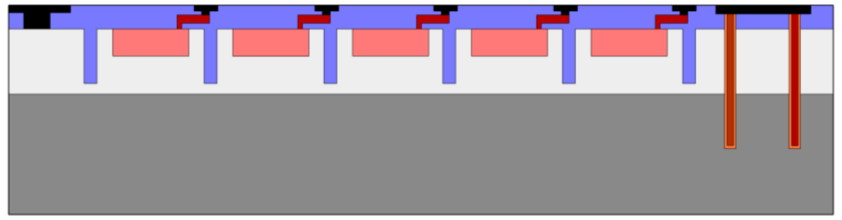


The complete system composed of 3 research clean-rooms in FBK.

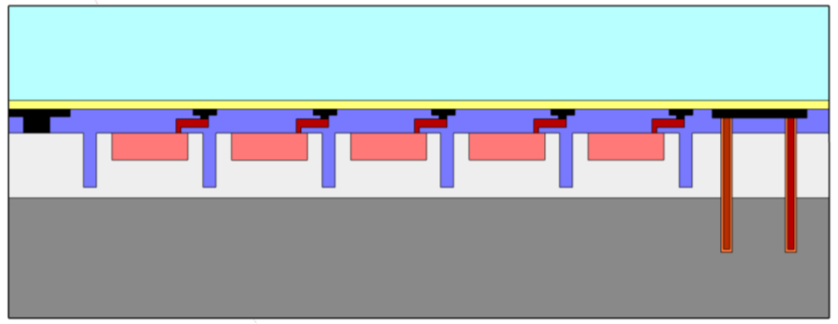
2.5D and 3D Integration
TSV – via mid: process flow

In the via-mid process, the *TSV is formed during the fabrication of the SiPM, modifying its process flow*.
In the via, the *conductor is the highly-doped silicon bulk*.

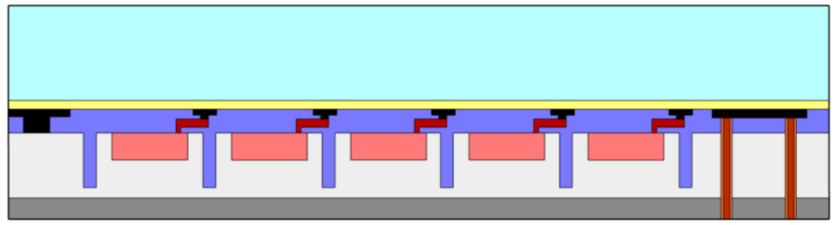
- SiPM fabrication + TSV formation



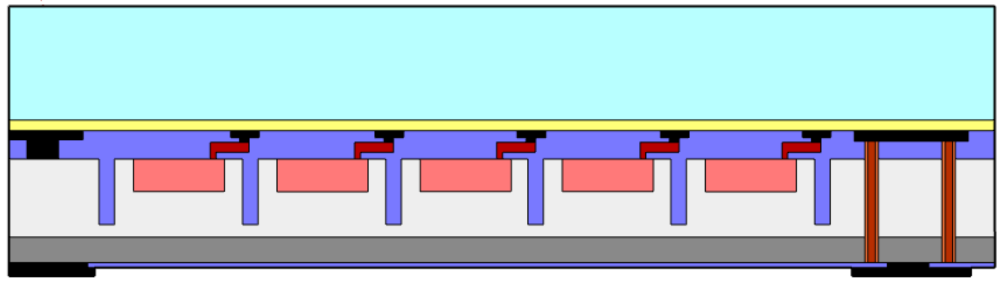
- Edge Trimming + BONDING



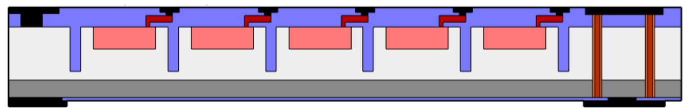
- THINNING



- Contacts formation



- DEBONDING

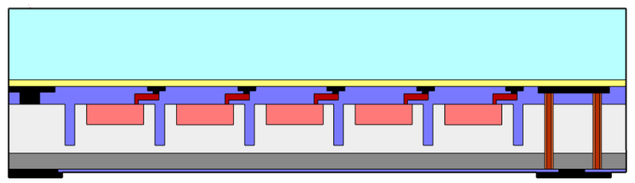


Thickness at least 150 um

Glass-less TSV
concept

500 um SiPM pitch

- NO-DEBONDING

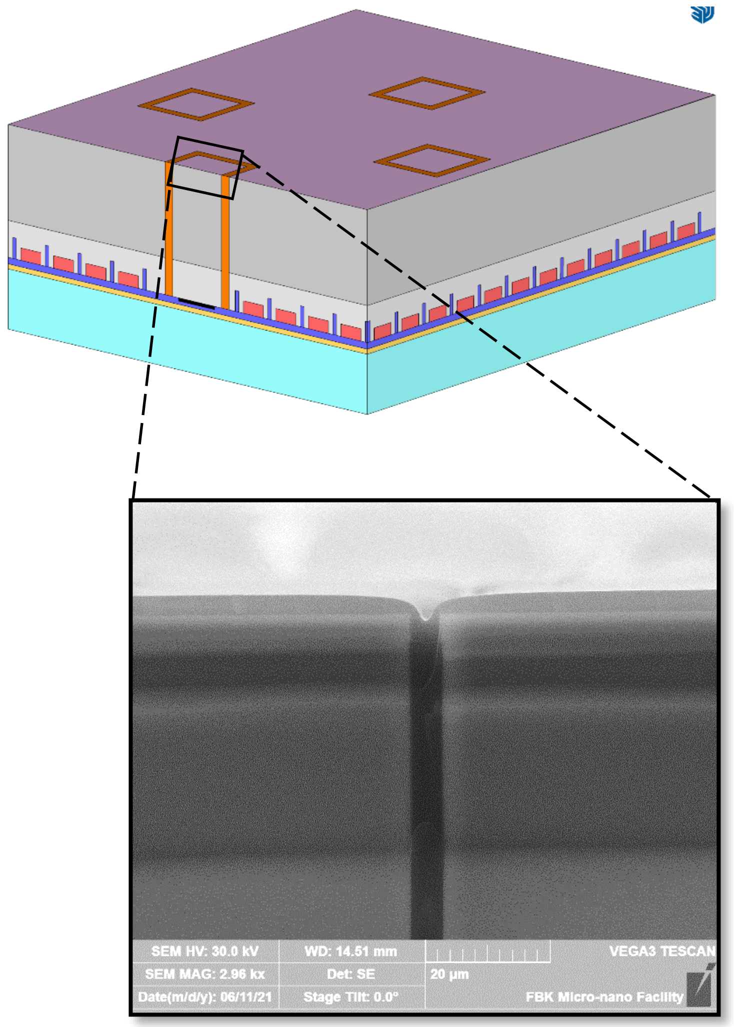


Thickness 10-50 um

Standard TSV

microTSV

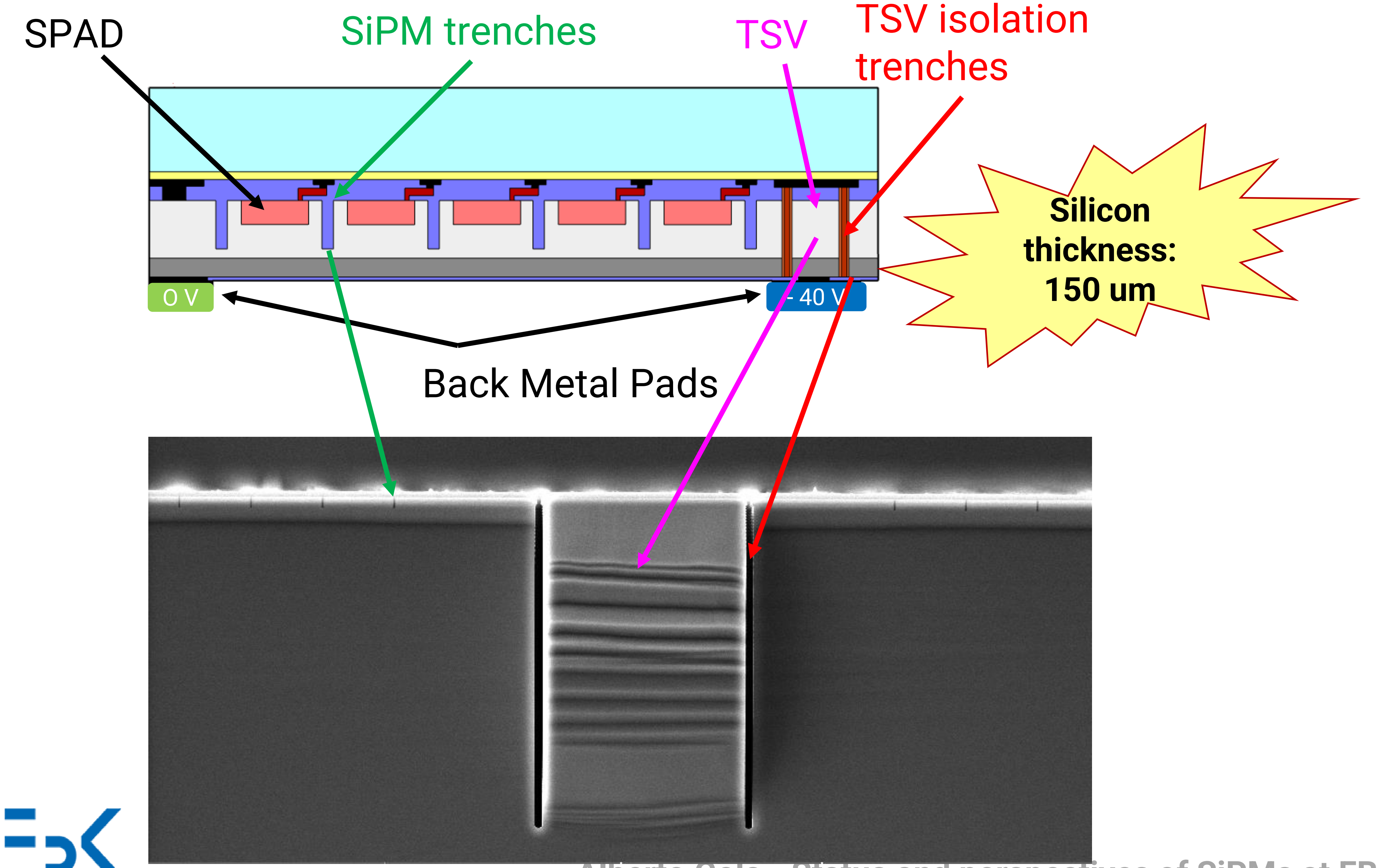
< 50 um SPAD pitch



- Metal-free TSV
- Flexible TSV layout and size
- Low bulk resistivity

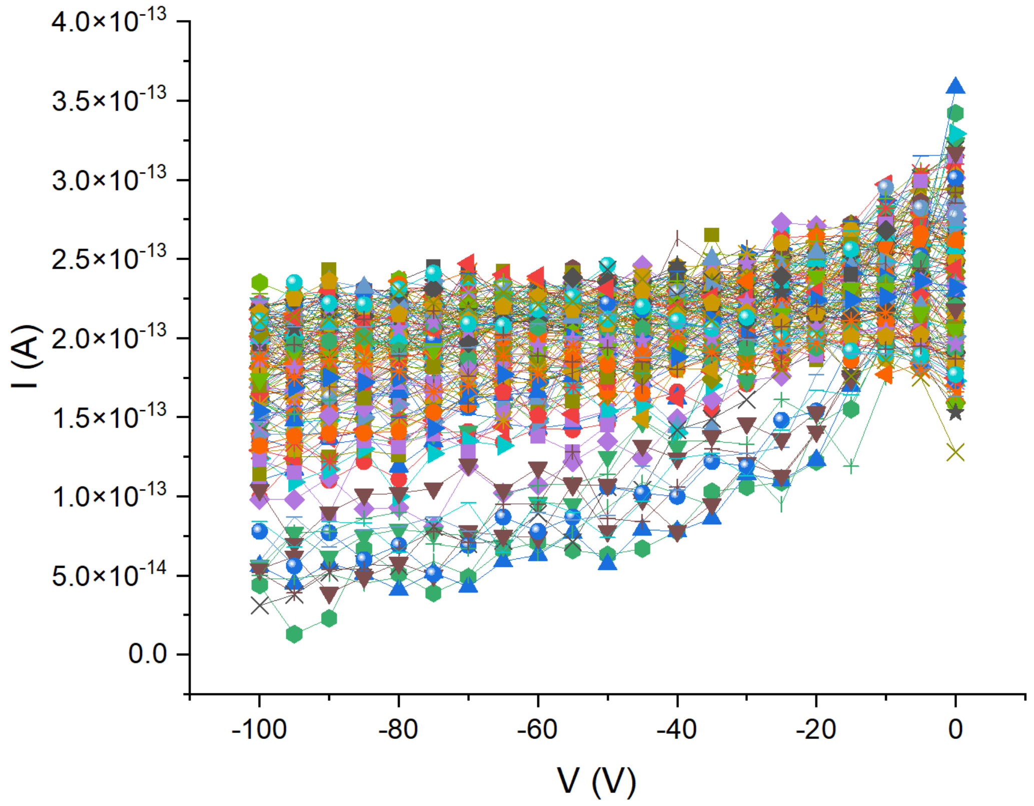
2.5D and 3D Integration
TSV – via mid: first results

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

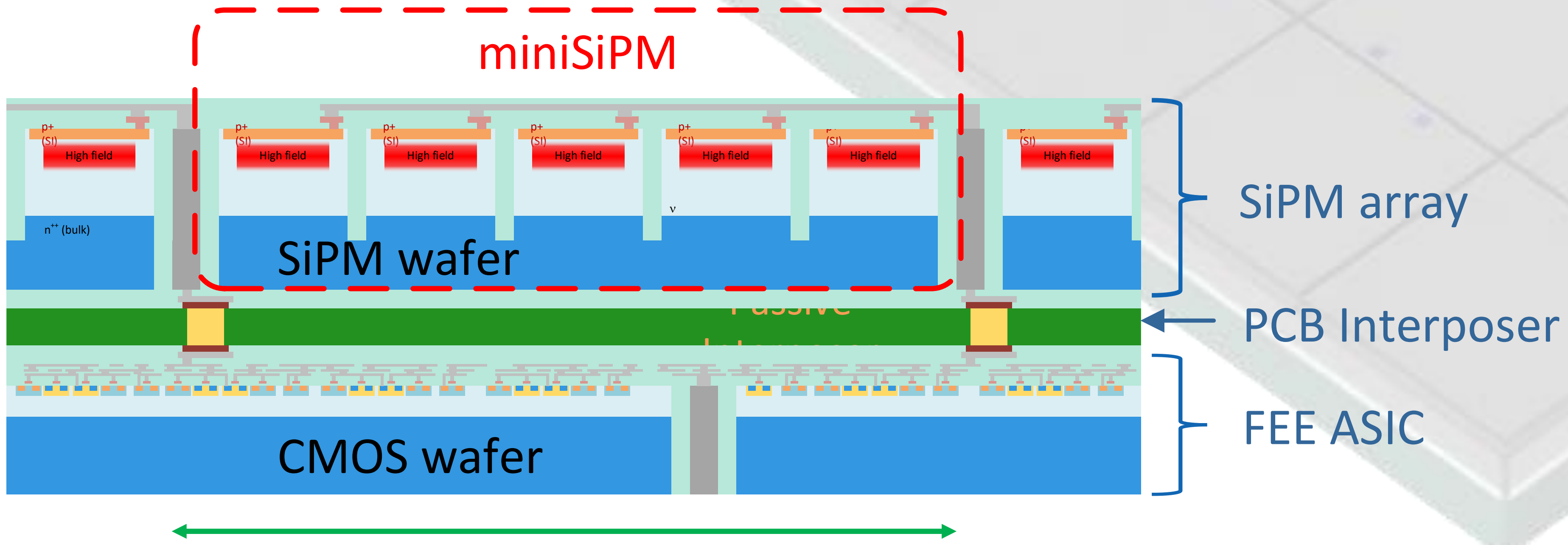


2.5D and 3D Integration
2.5D integrated SiPM tile

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

ONCO VISION

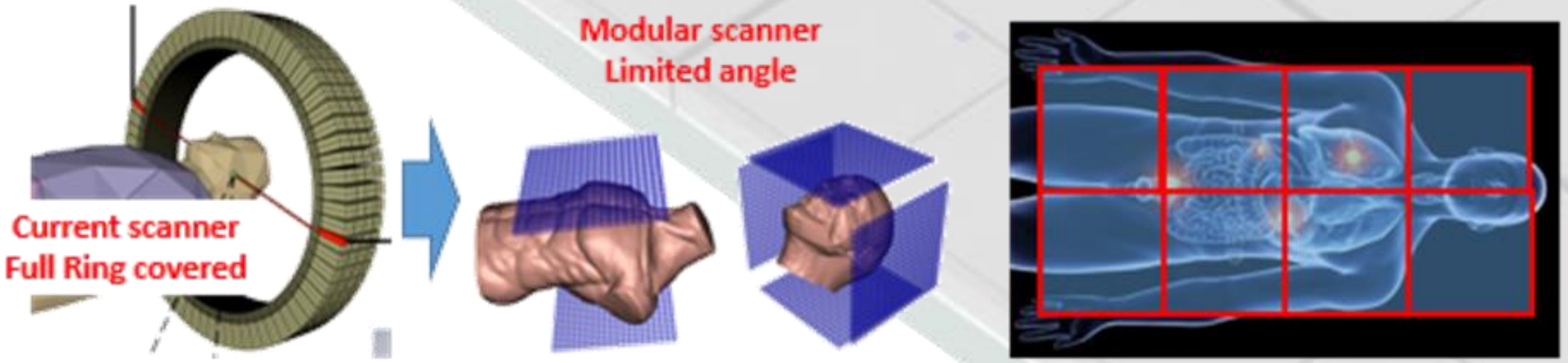
Hybrid SiPM module being developed for ultimate timing performance in ToF-PET

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

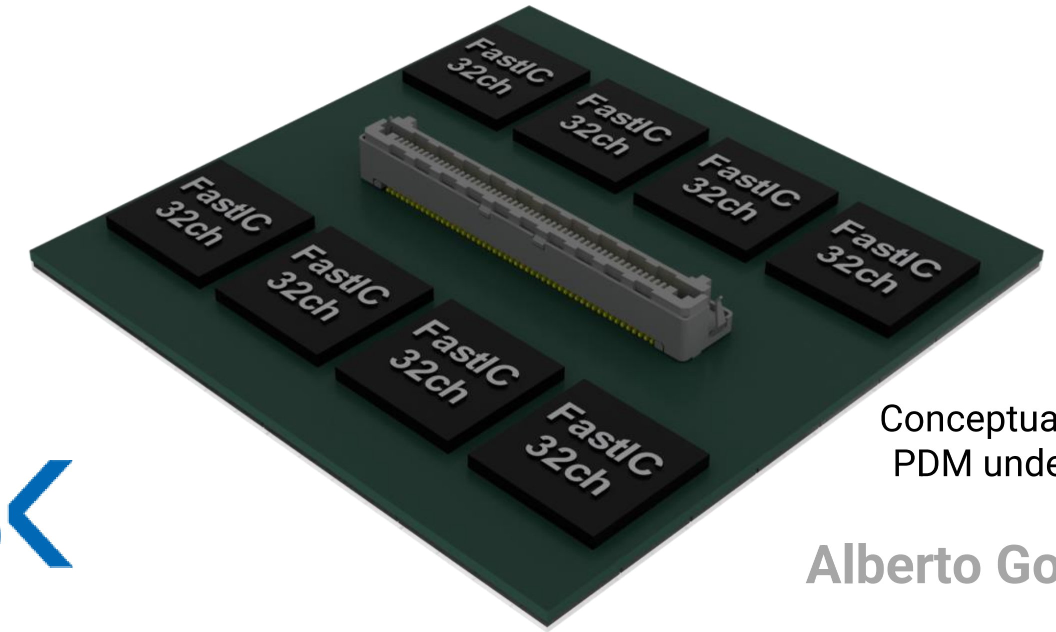
The 2.5D integrated PDM (50x50 mm^2) will be the basis of a *30x30 cm^2 ToF-PET panel*, which will be used to build limited-angle ToF-PET systems, for brain PET, Cardiac PET and full-body scanners.

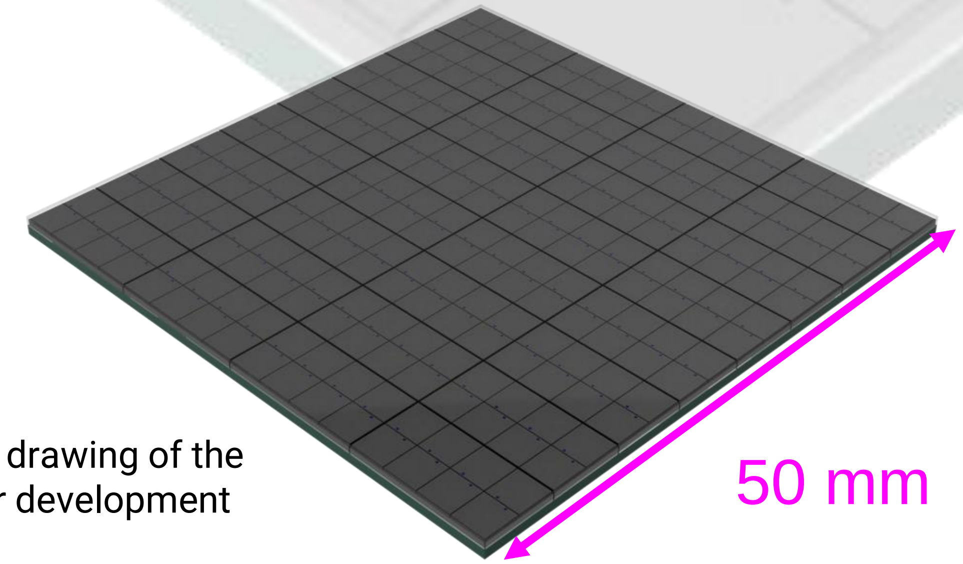
We *expect very good timing performance*, supported by preliminary measurements achieved with NUV-HD SiPMs coupled to FastIC ASIC.

ICCUB
Institut de Ciències del Cosmos

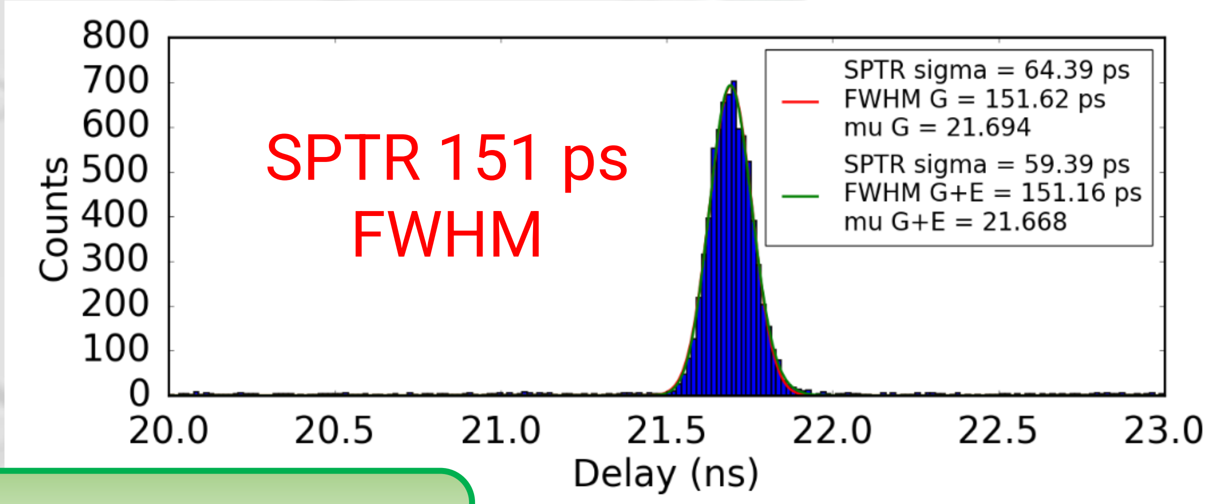


Application of the PDM to build large panes used in new, limted-angle PET applications: Brain Pet, Cardiac PET, while-body PET

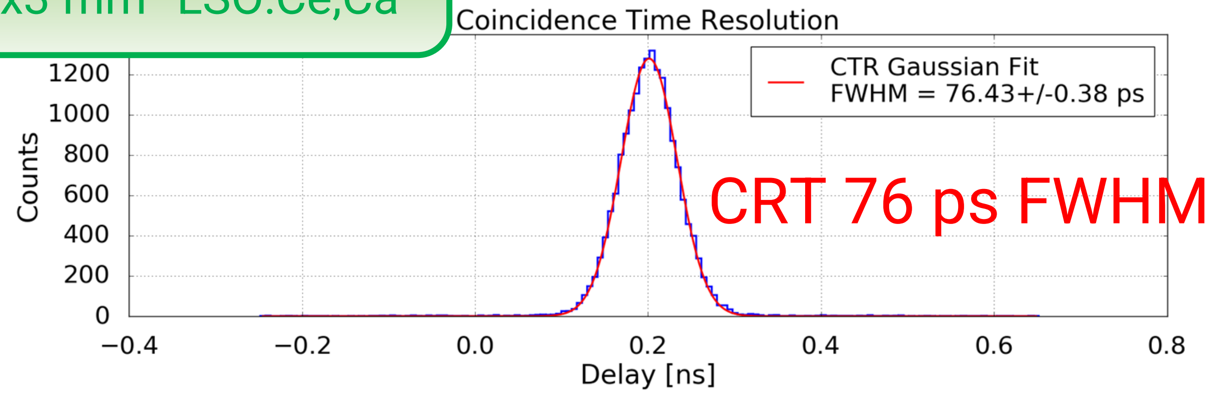




Conceptual drawing of the PDM under development



2x2x3 mm^3 LSO:Ce,Ca

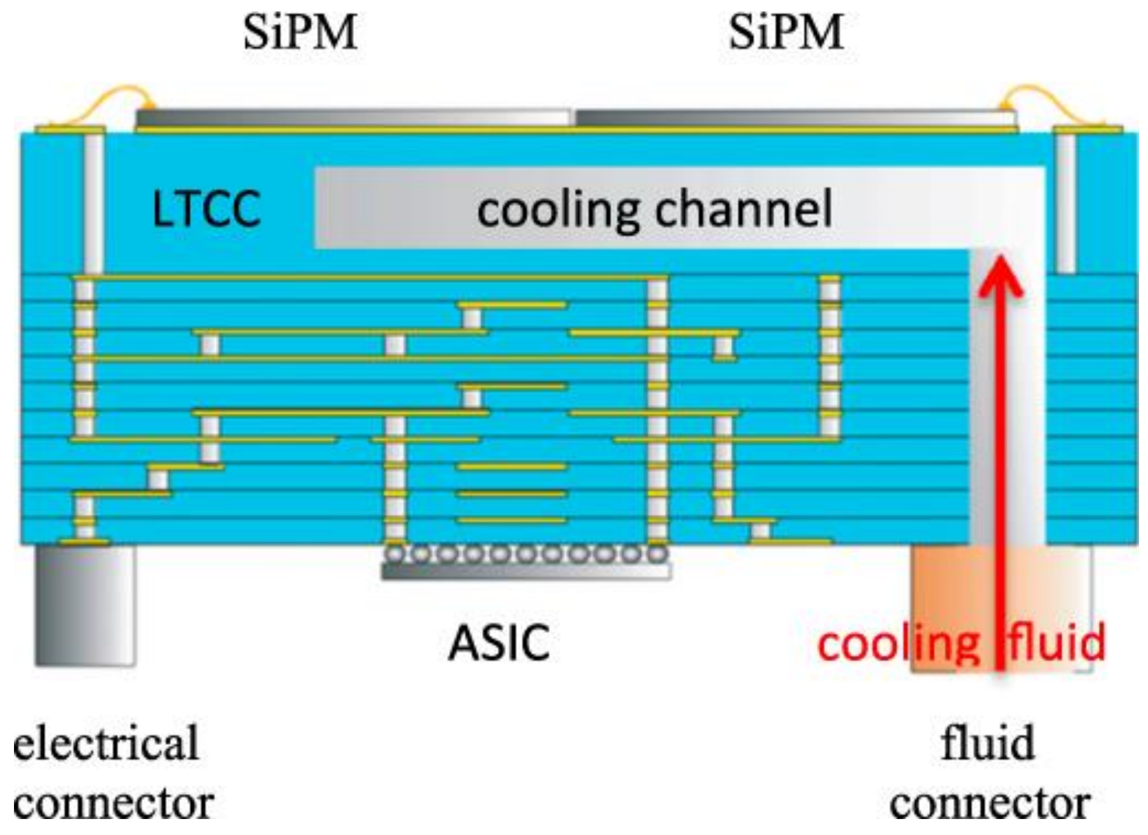


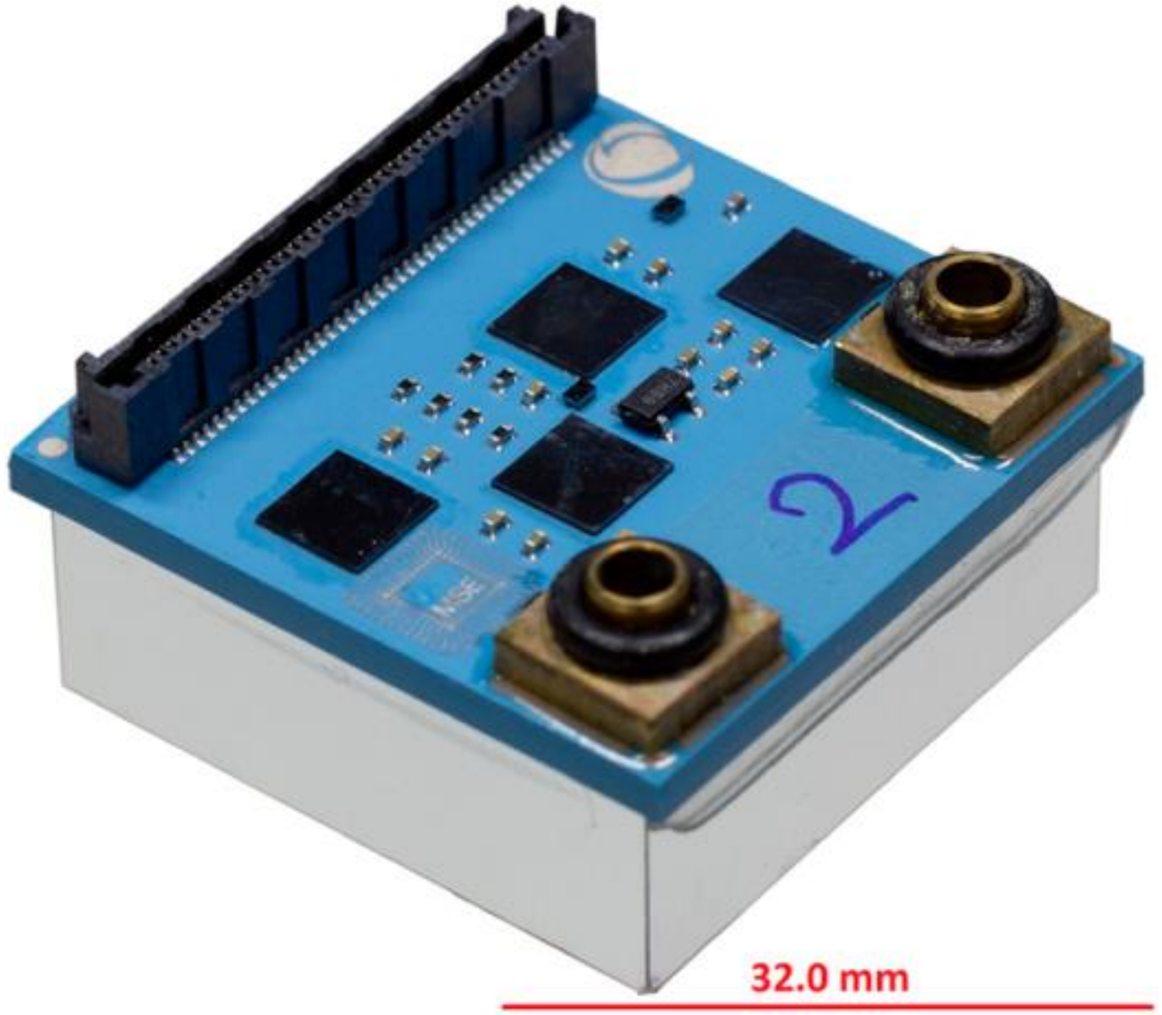
SPTR and CRT measured at FBK NUV-HD-SiPMs read by the FastIC ASIC developed by ICCUB.
Sensor: NUV-HD-LFv2 SiPMs, 3x3 mm^2
Scintillator: 2x2x3 mm^3 LSO:Ce,Ca
Power consumption: 3 mW / channel

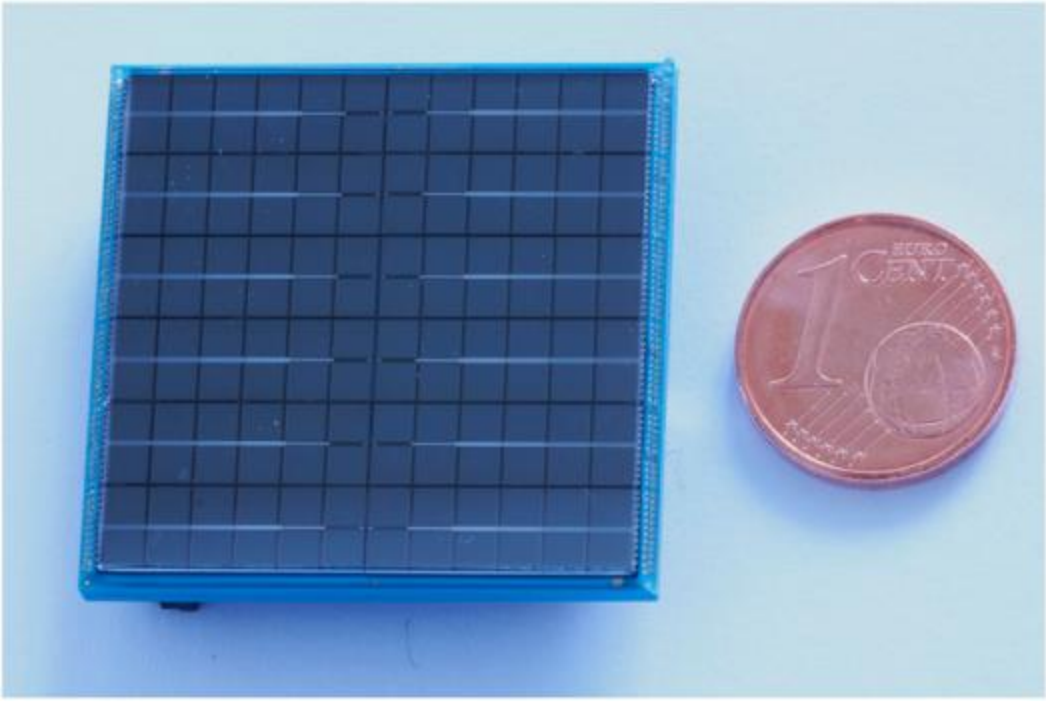
2.5D and 3D Integration
Example of integrated cooling

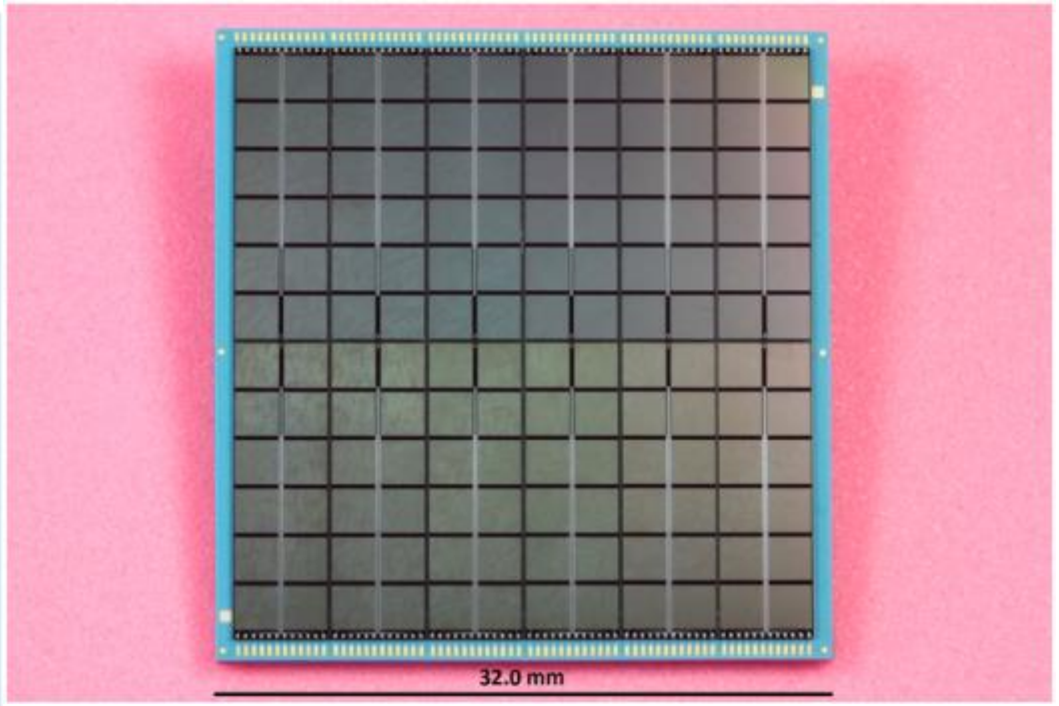
2.5D integration also allows to build *micro cooling channels integrated inside the passive interposer*.

Demonstrated in 2014 within SUBLIMA project (ToF-PET), using LTCC, FBK sensors and wire bonding.









Dohle, Rainer, et al. "LTCC-based highly integrated SiPM module with integrated liquid cooling channels for high resolution molecular imaging." *Journal of Microelectronics and Electronic Packaging* 15.2 (2018): 86-94.

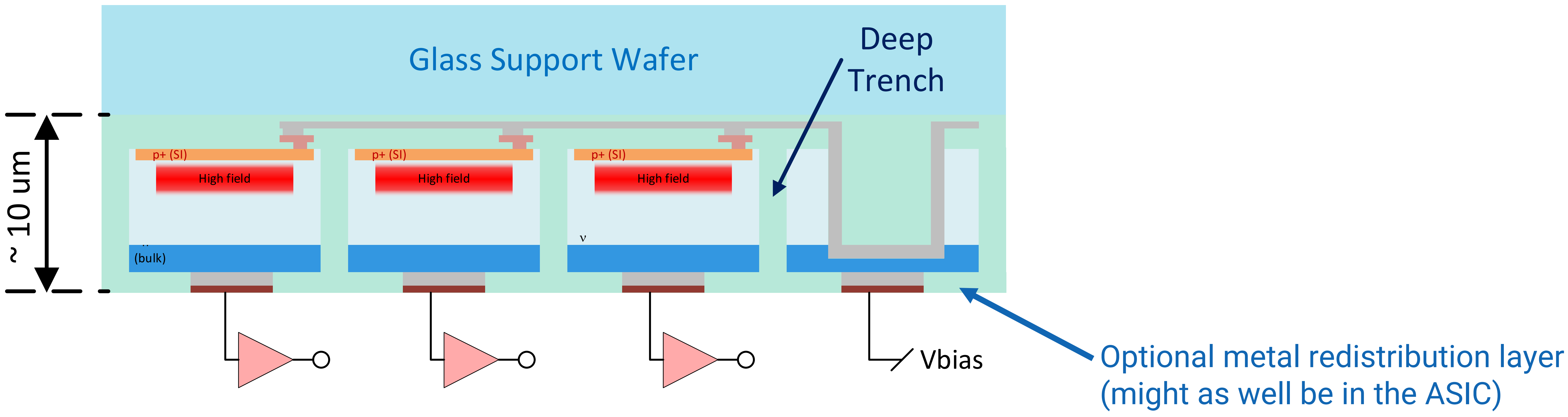
Single-SPAD TSV
Cross-section

Exploiting the Deep Trench Isolation, which is anyway present between adjacent SPADs in most SiPMs, we can achieve single SPAD isolation if we thin the wafer down sufficiently (use of a glass support wafer is needed).

We can exploit this isolation to *build a "bulk" TSV just below and coincident with each single SPAD*.

The *resistors* are still on the front-side (no change in signal shape is expected).

Common connection for bias is on the front and requires a TSV to bring it from the bottom.



Single-SPAD TSV
Advantages / Drawbacks

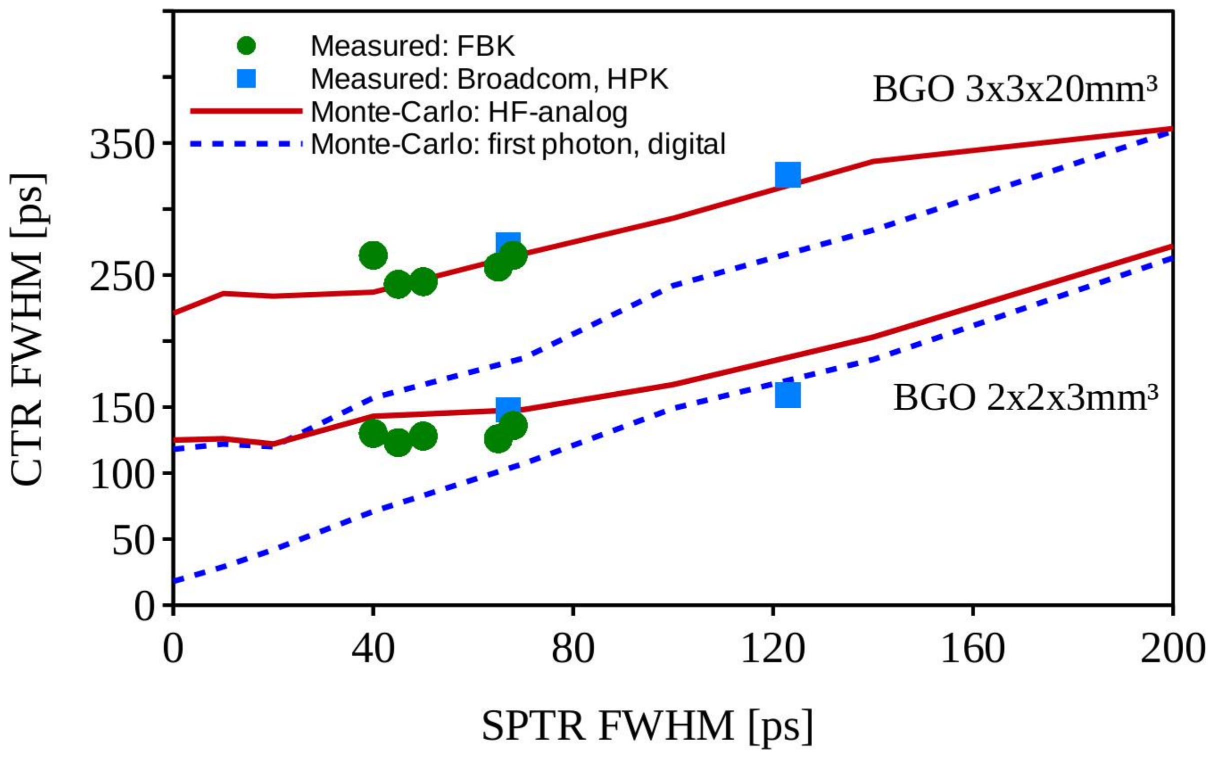
Advantages:

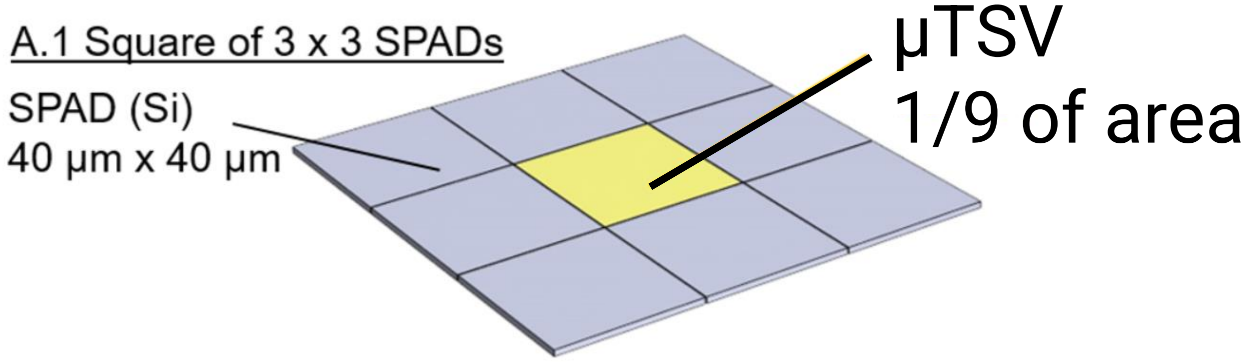
- (Almost) *no changes to the state-of-the-art, FSI, NUV-sensitive SiPMs* → conservative approach.
- It might be the only wat to have fine-pitch TSVs (around 50 um) with ***no loss of FF*** for the SiPMs.
- No additional trenches needed → simpler.
- Flexibility to have single-cell access, when needed, but also miniSiPMs and ***microSiPMs***, through *either a redistribution layer* on the SiPM backside or directly in the *3D integrated ASIC*
- *Connection for the topside metal* can be obtained through the same type of vias (possibly with epitaxial layer removal).

microSiPM
High-density integration: DIGILOG

DIGILOG investigates higher density interconnections to *approach the dSiPM performance without the complexity of single-SPAD access*.

Single-SPAD TSV will be investigated in the DIGILOG project, removing the need to replace the central SPAD in the uSiPMs with a TSV, thus achieving the *highest PDE possible*.



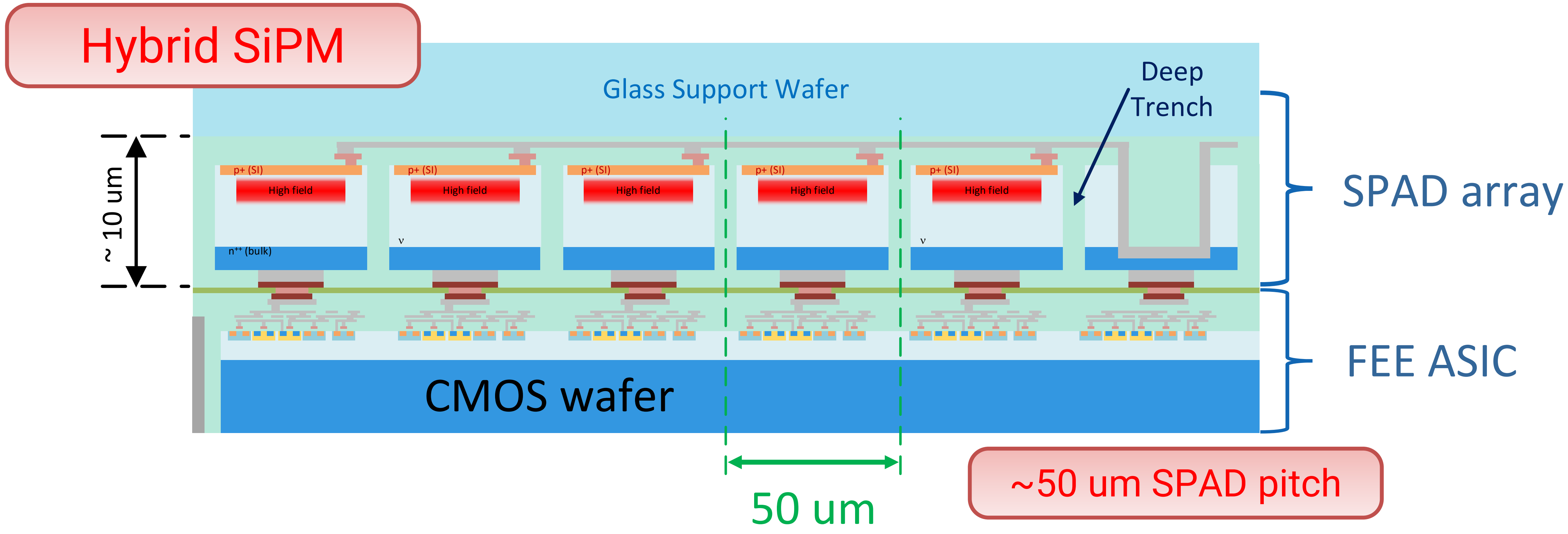


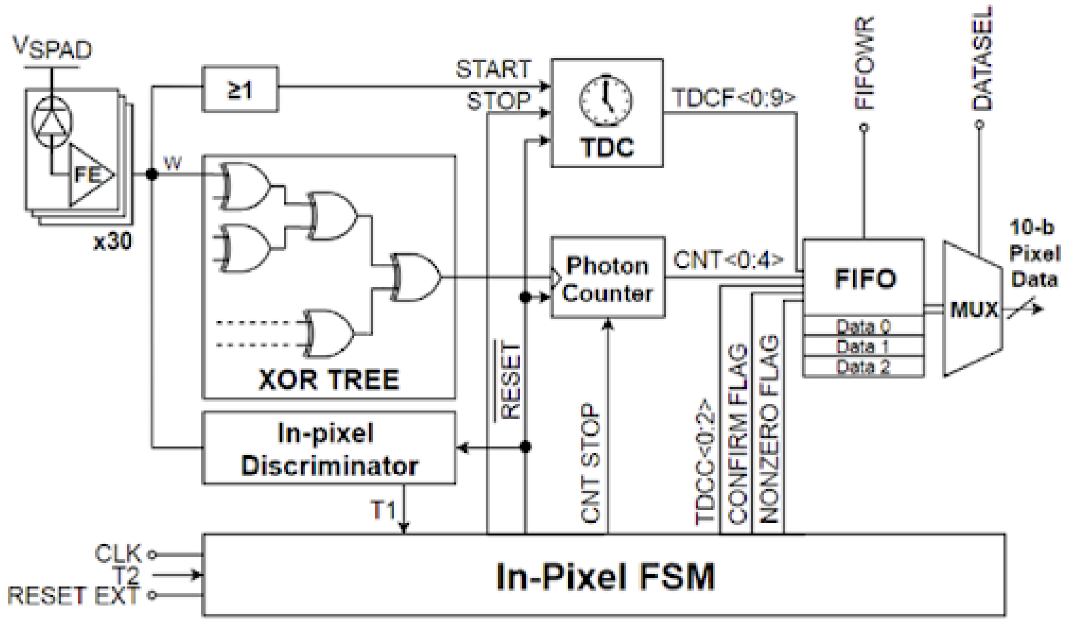
- µSiPMs with µTSVs
- µASICs with *in situ* TDCs
- Embedded ANNs
- **Distributed computing**

S. Gundacker, et al., A. Gola, E. Charbon, V. Schultz *NSS* 2023
S. Gundacker, et al., *to be published* 2023

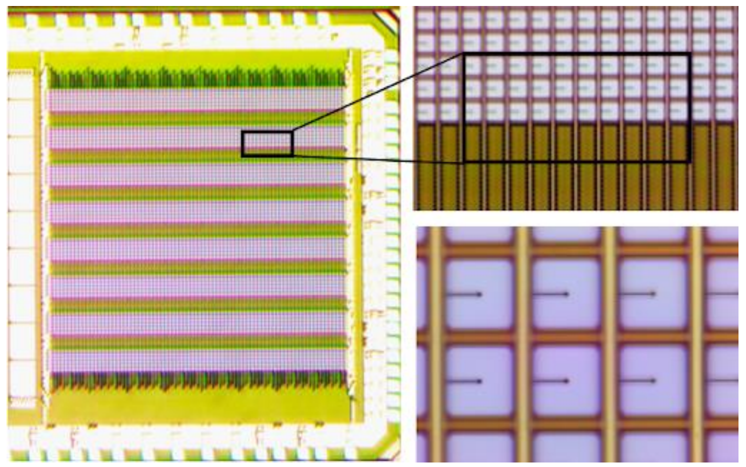
Full 3D integration with micro TSVs: Hybrid SiPM

FBK will also employ the single-SPAD TSV 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*.

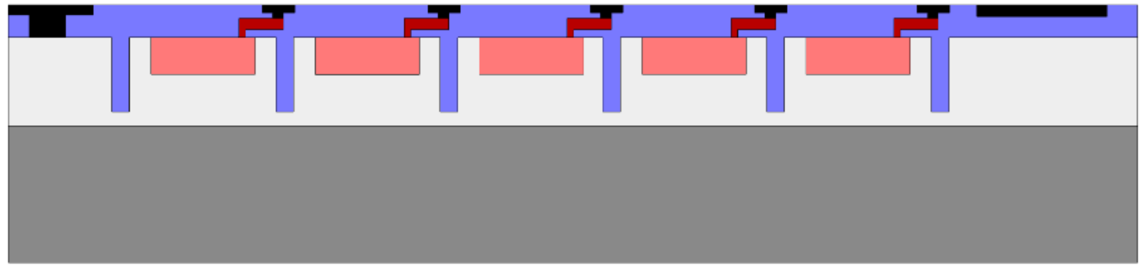


Example of dSiPM architecture developed at FBK (SBAM project)

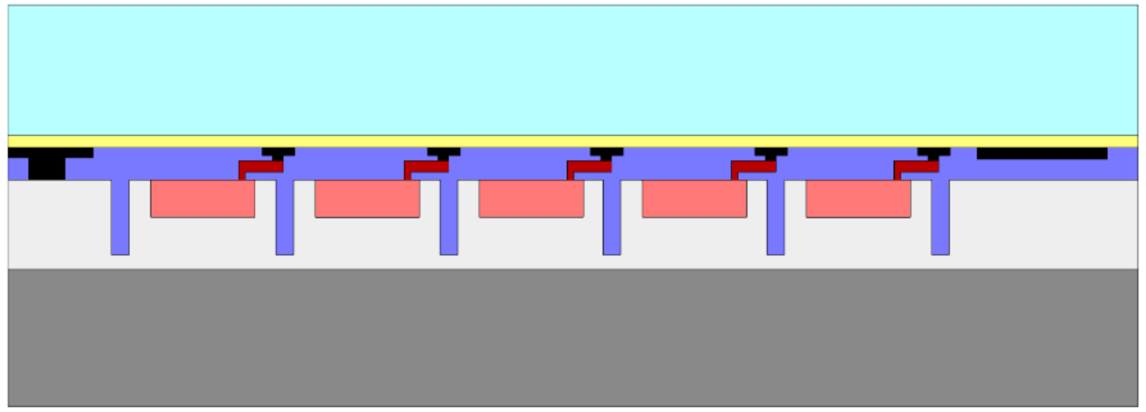
2.5D and 3D Integration
Backside Illuminated SiPMs: process flow

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

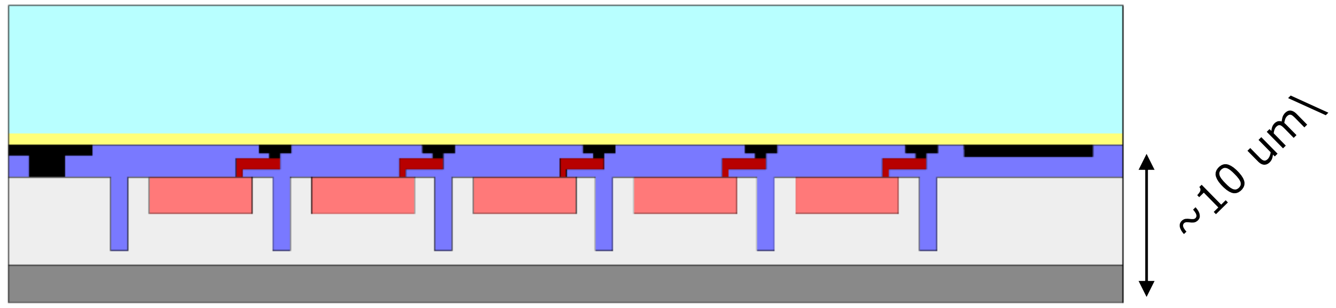
1. SiPM Wafer



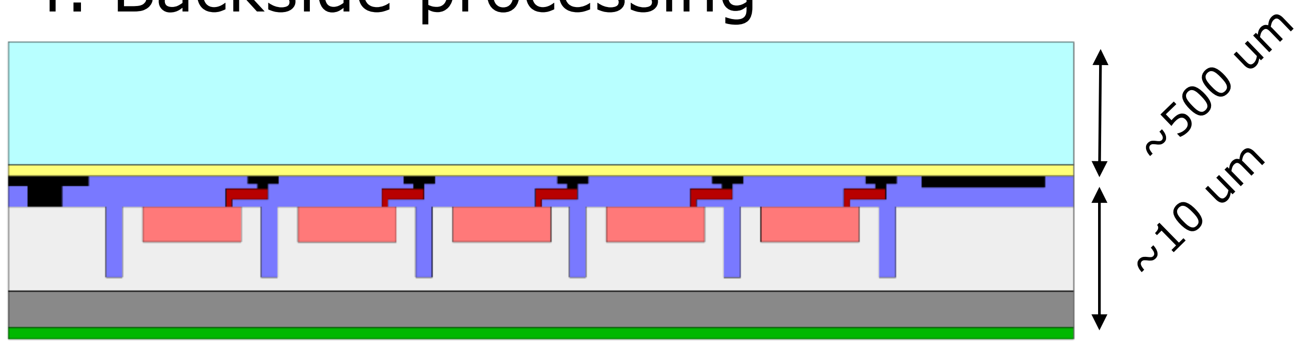
2. Temporary Bonding



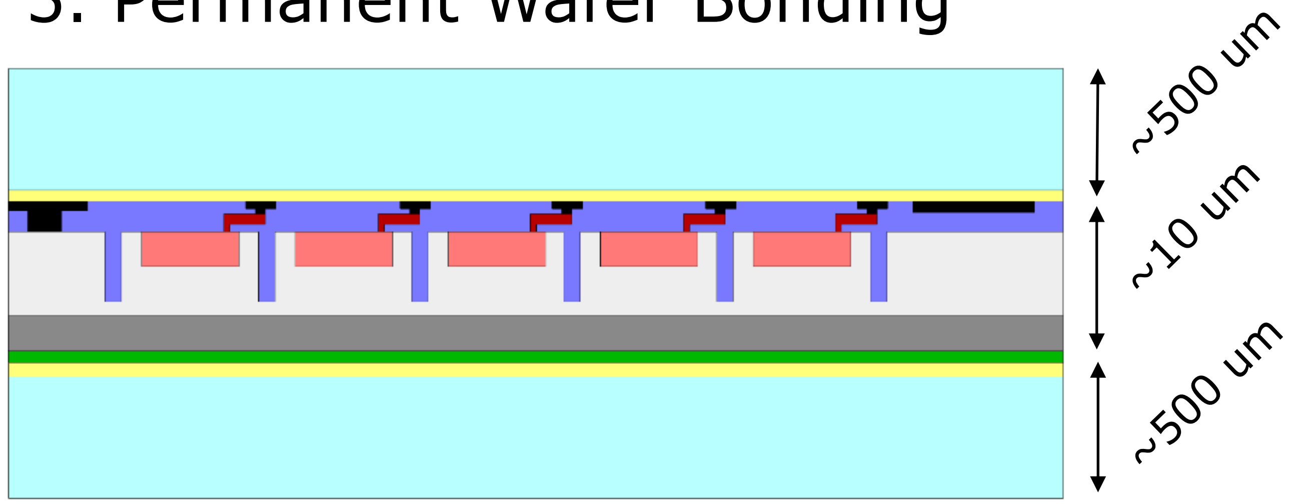
3. Grinding & Polishing



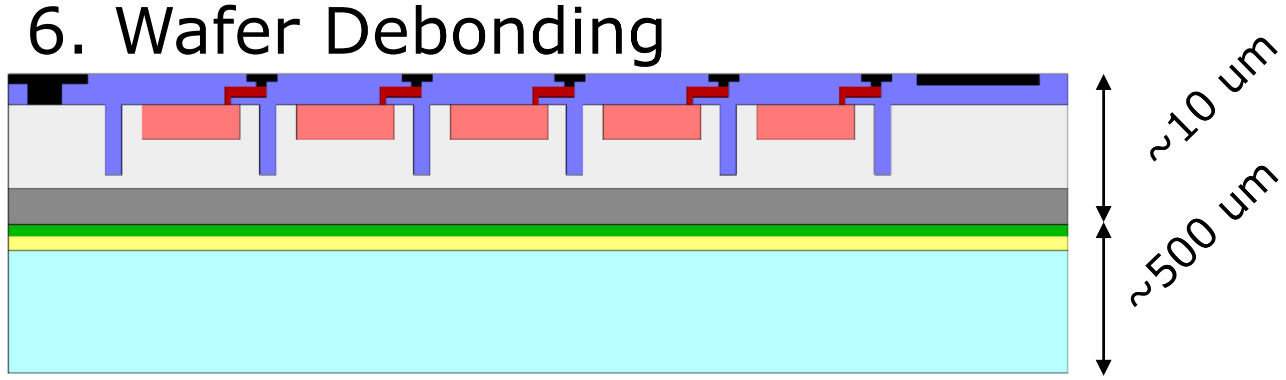
4. Backside processing



5. Permanent Wafer Bonding



6. Wafer Debonding

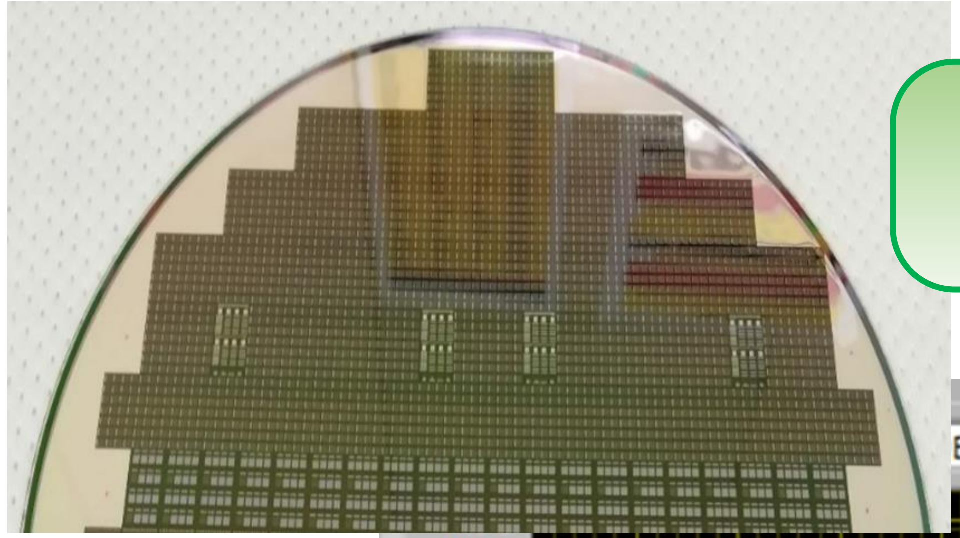


NIR-BSI SiPMs
BSI NIR SiPMs: first results

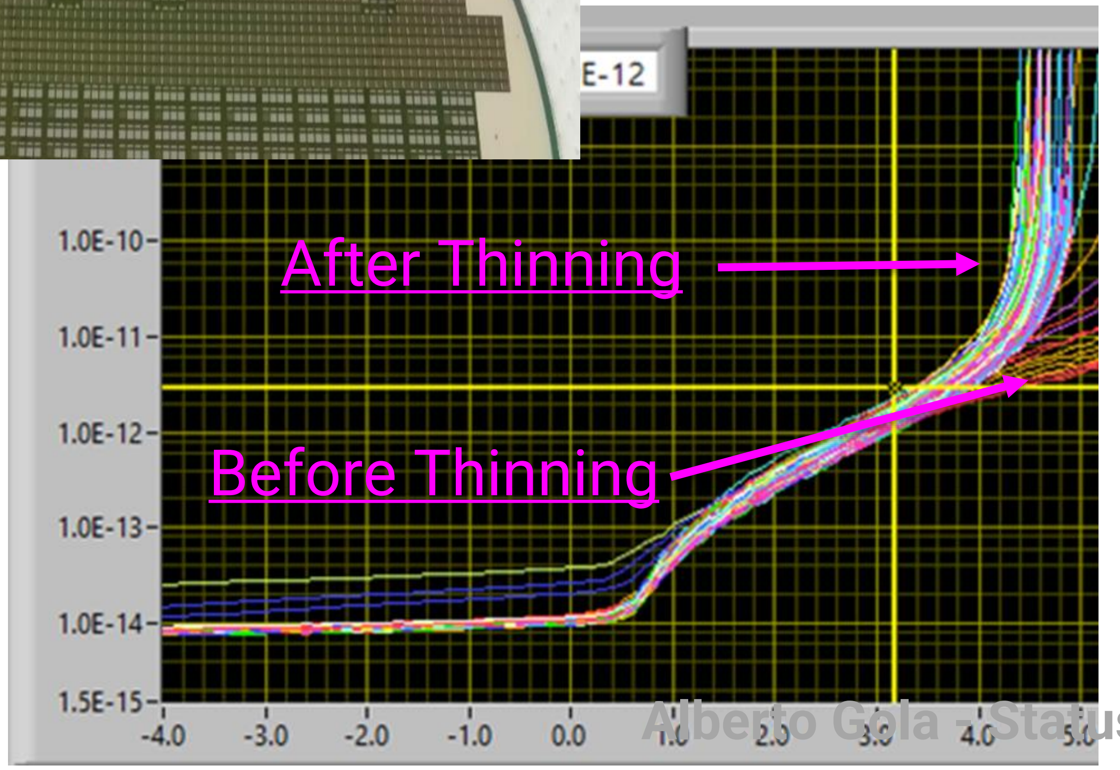
The *first NIR-sensitive BSI wafers were fabricated* in FBK clean room (1x1 mm^2 devices).

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

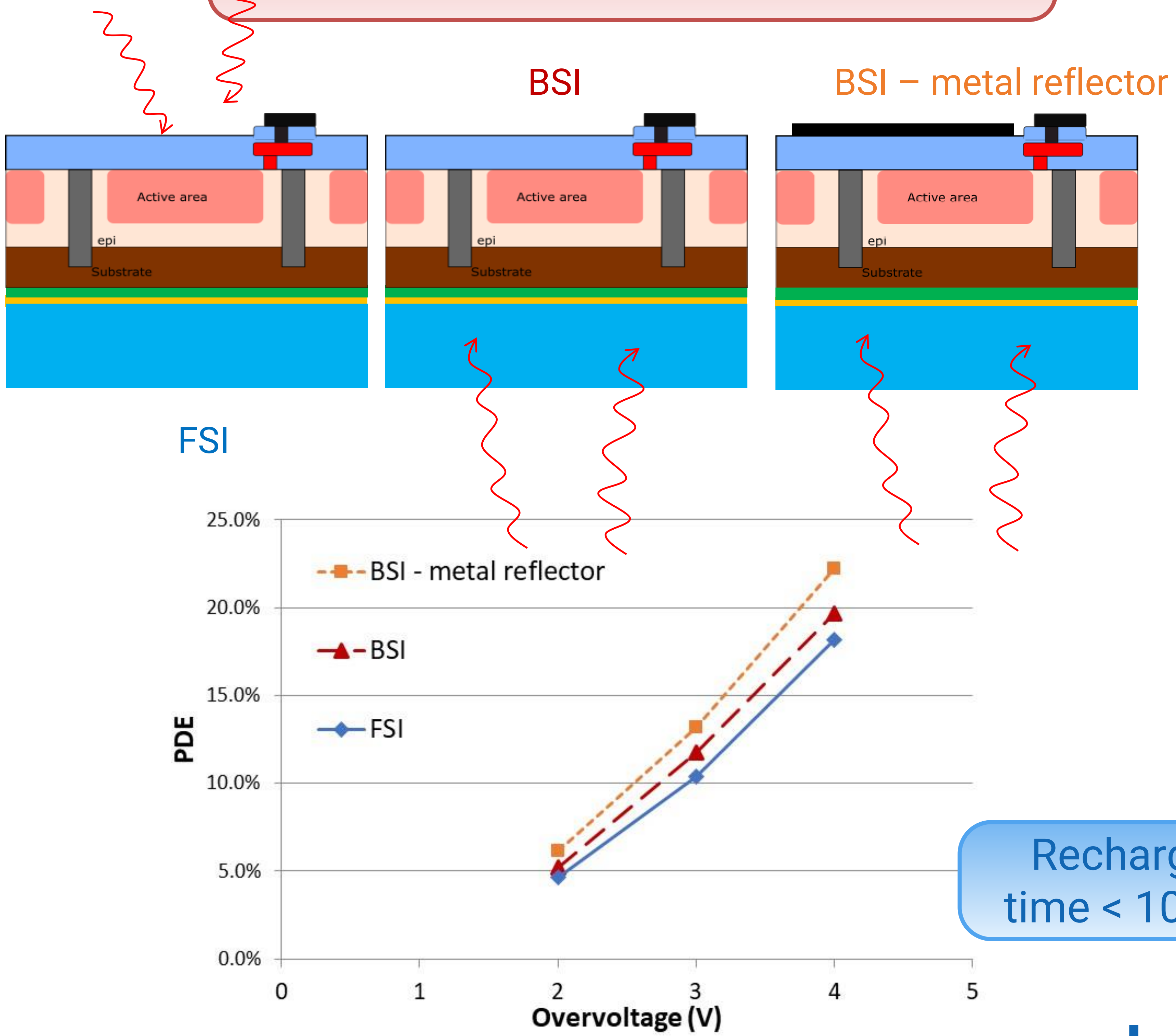
Ultrathin substrate (~ 10 um)



NIR BSI process is working!



NIR PDE comparison at 905 nm



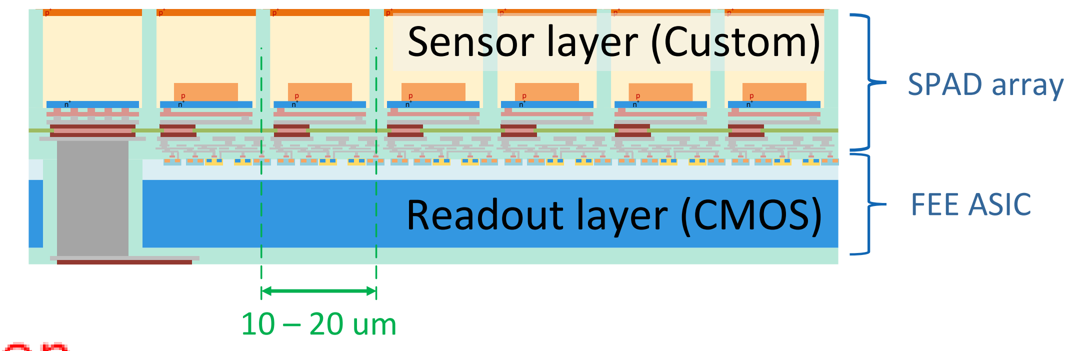
Recharge time < 10 ns

NUV-BSI development

NUV-BSI SiPMs
Next-generation development: Backside Illuminated SiPMs

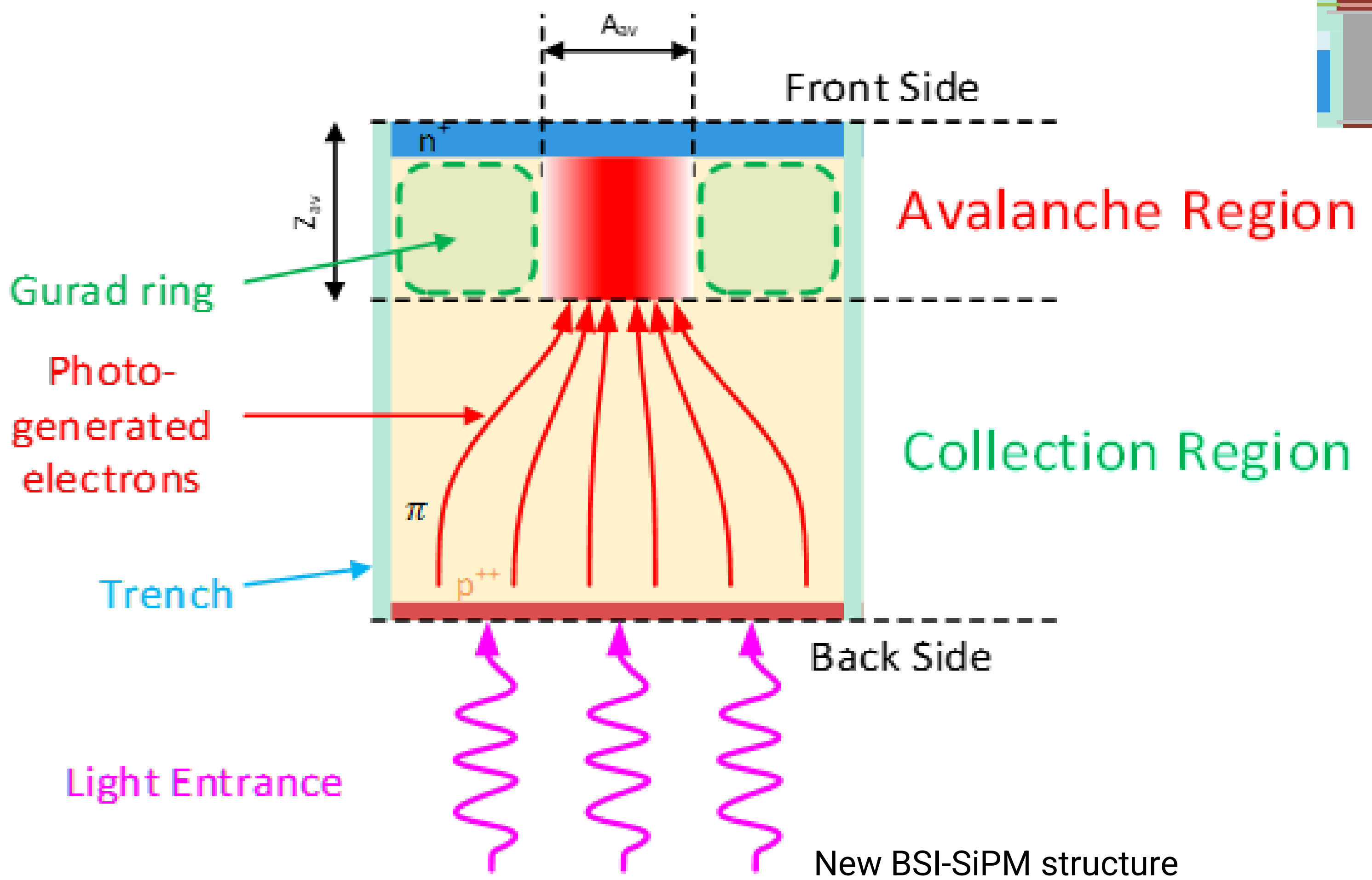
The next-generation of developments, currently being investigated at FBK, is building a *backside-illuminated, NUV-sensitive SiPM*. Several technological challenges should be overcome.

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!

We are hiring!

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

- **Fabio Acerbi**
- **Ibrahim Mohamed Ahmed**
- **Lorenzo Barsotti**
- **Andrea Ficorella**
- **Priyanka Kachru**
- **Oscar Marti Villareal**
- **Stefano Merzi**
- **Elena Moretti**
- **Giovanni Palù**
- **Laura Parellada Monreal**
- **Giovanni Paternoster**
- **Michele Penna**
- **Maria Ruzzarin**
- **Gianluca Vedovelli**
- **Nicola Zorzi**