NUV-HD and NIR-HD SiPMs and Applications

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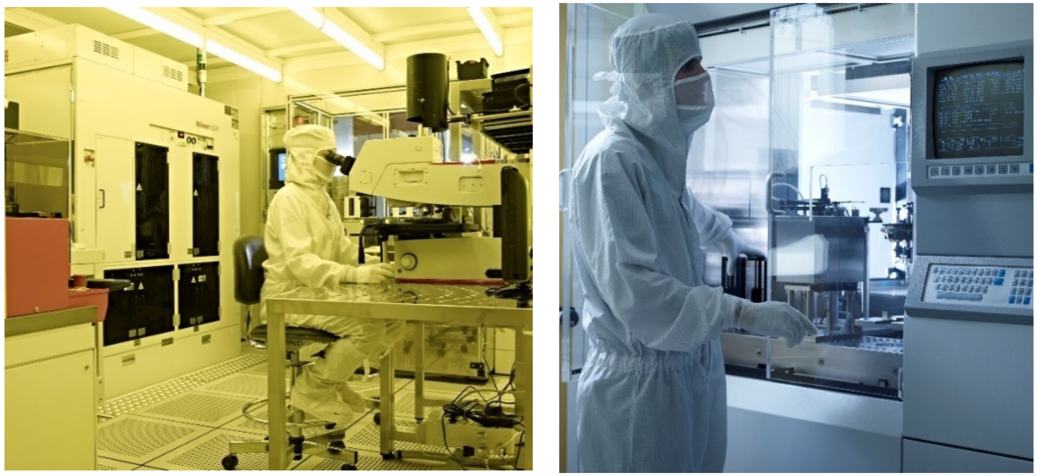
Fondazione Bruno Kessler

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



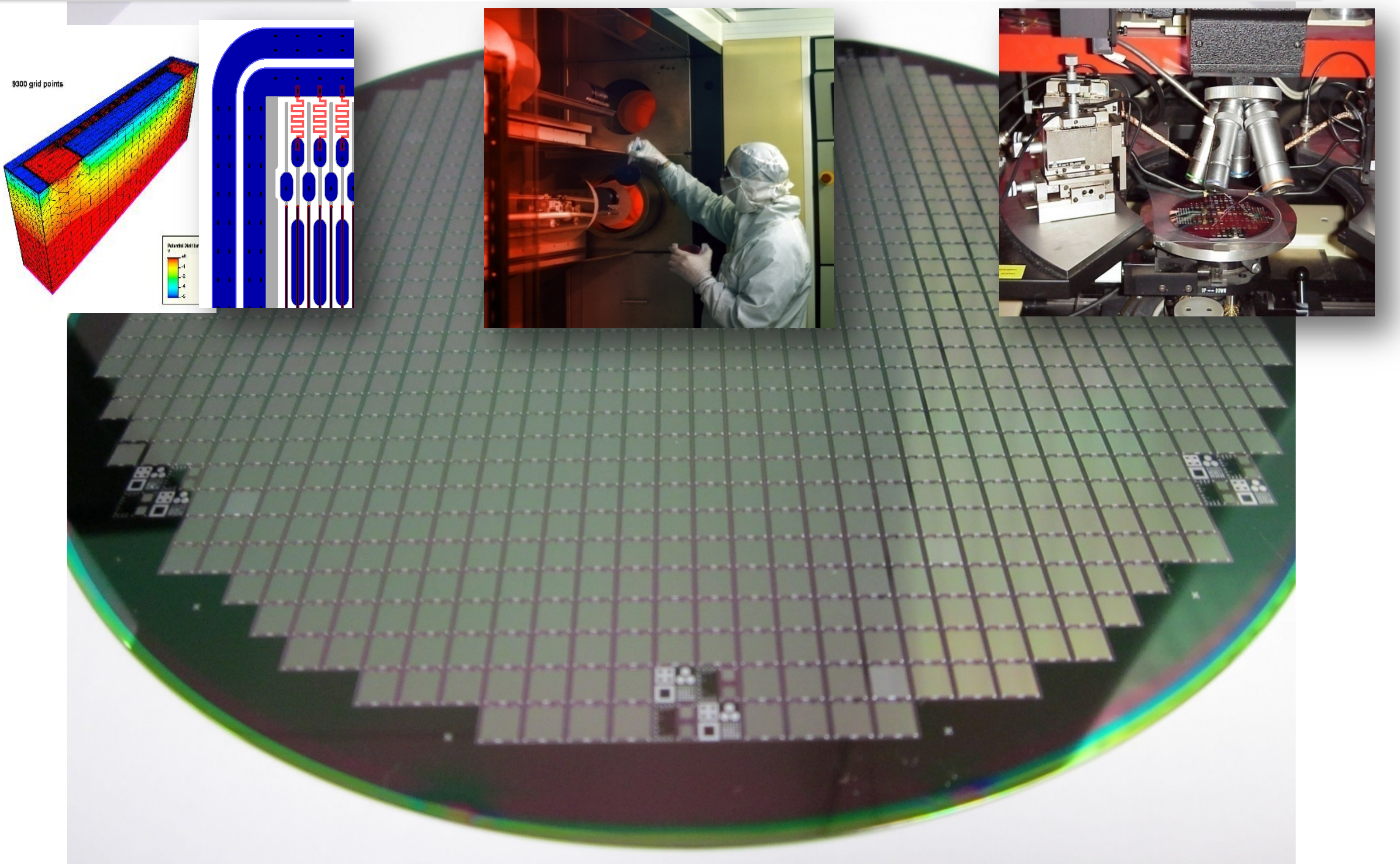
Publicly funded research center

350 researches working in different fields

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

FBK expertise

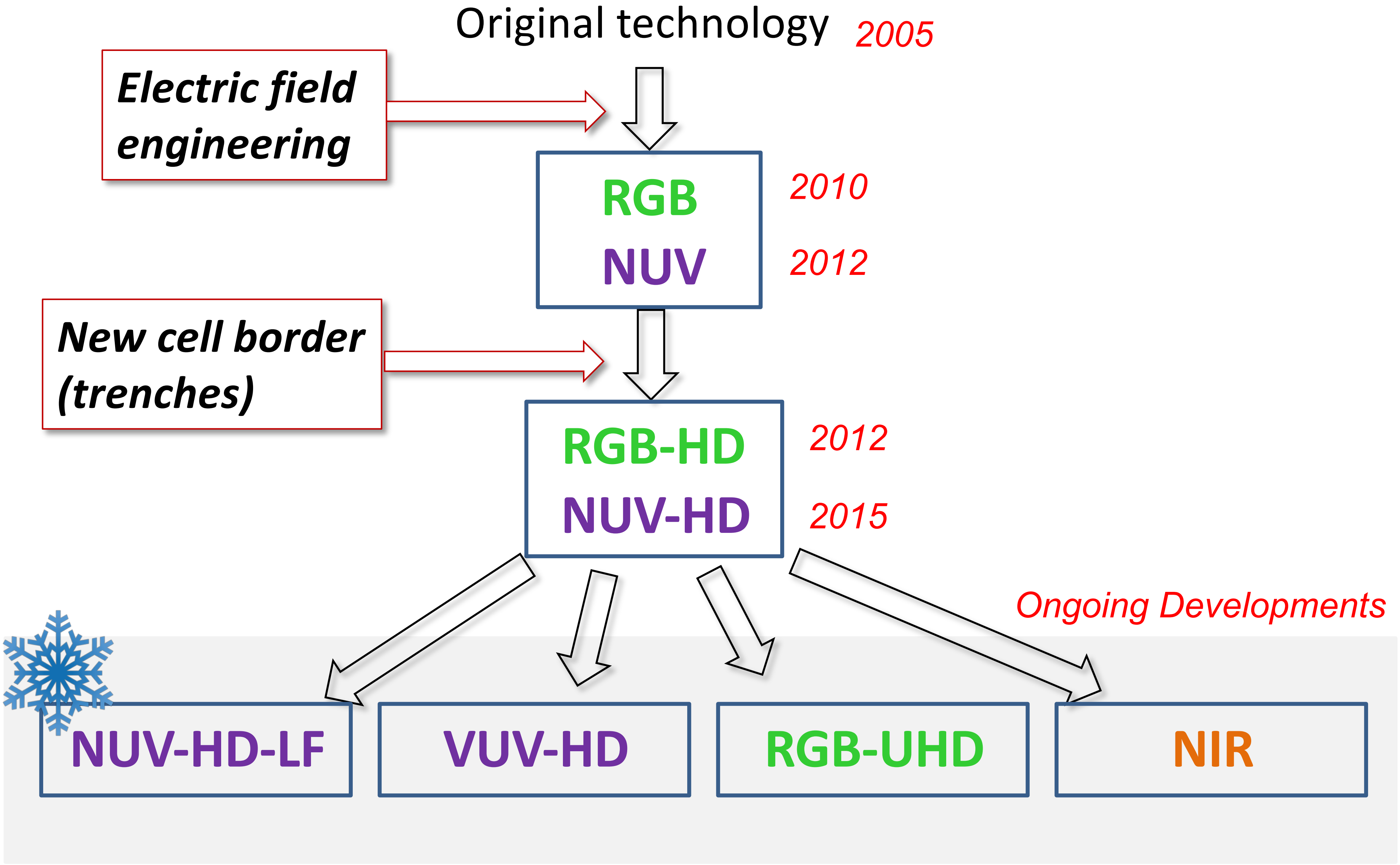
Simulation & design → Fabrication → Device testing



Outline

- NUV-HD SiPM technology
- SPTR of NUV SiPMs
- Cryogenic applications of NUV-HD
- VUV-HD SiPM technology
- NIR-HD SiPM technology

FBK SiPM technology roadmap



Original technology 2005

Electric field engineering

RGB 2010

NUV 2012

New cell border (trenches)

RGB-HD 2012

NUV-HD 2015

Ongoing Developments

NUV-HD-LF

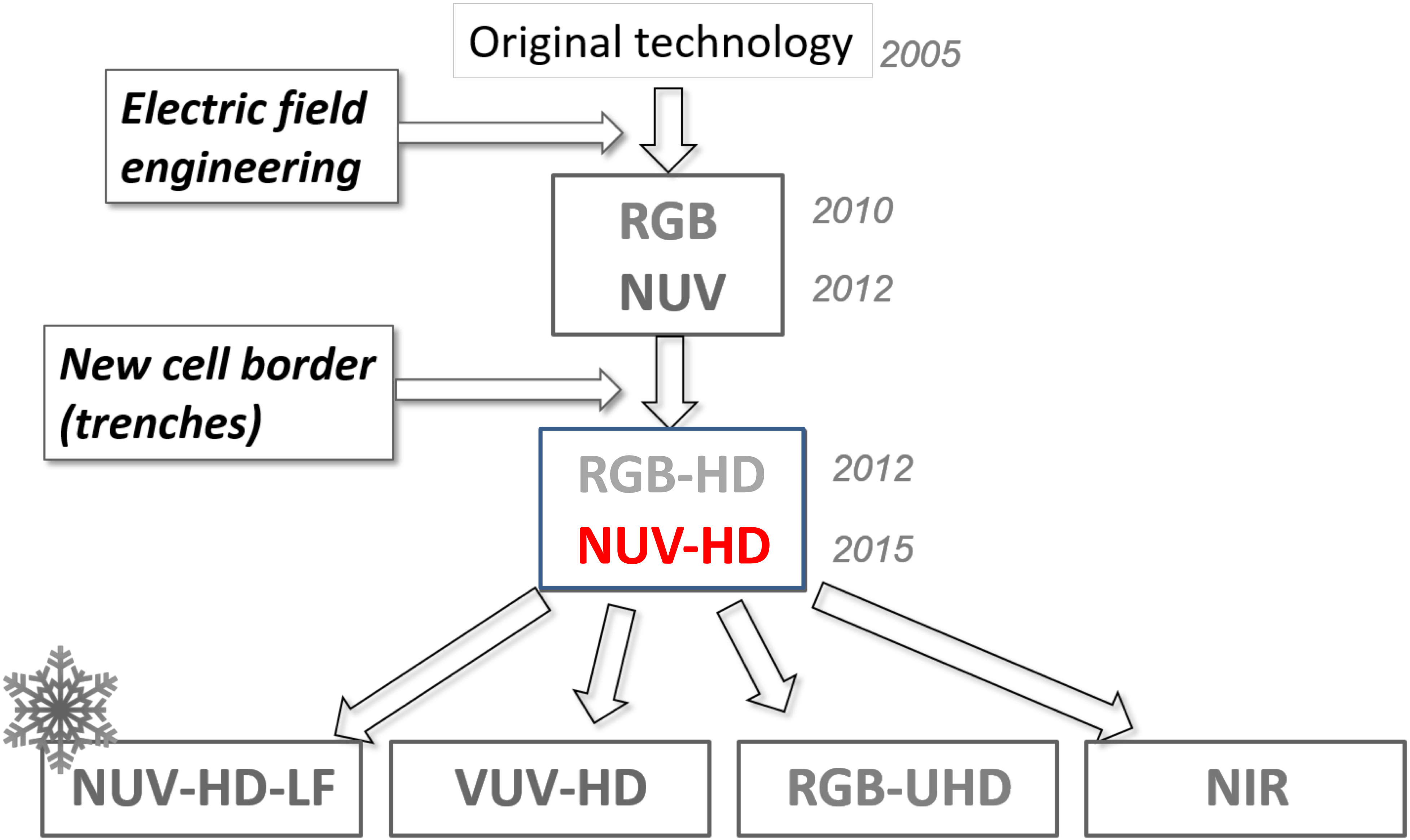
VUV-HD

RGB-UHD

NIR

Near-UV technology
NUV-HD

Near-UV technology: NUV-HD



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NUV-HD 2015

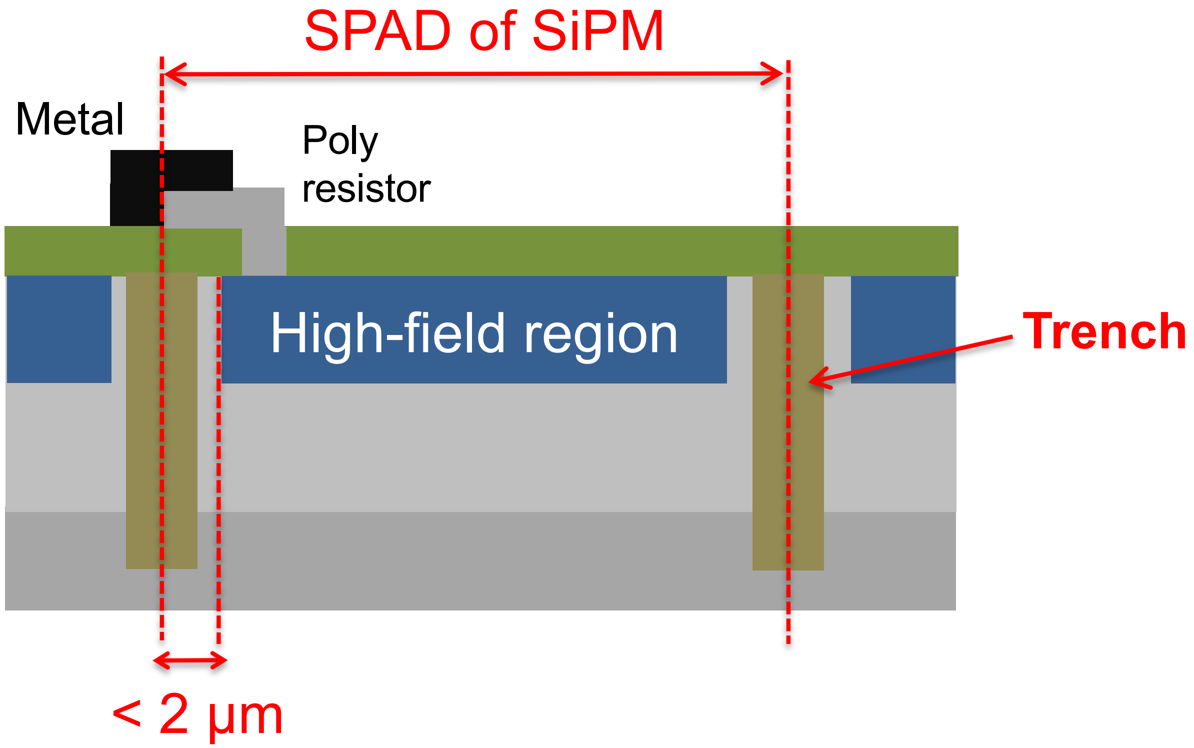
NUV-HD-LF

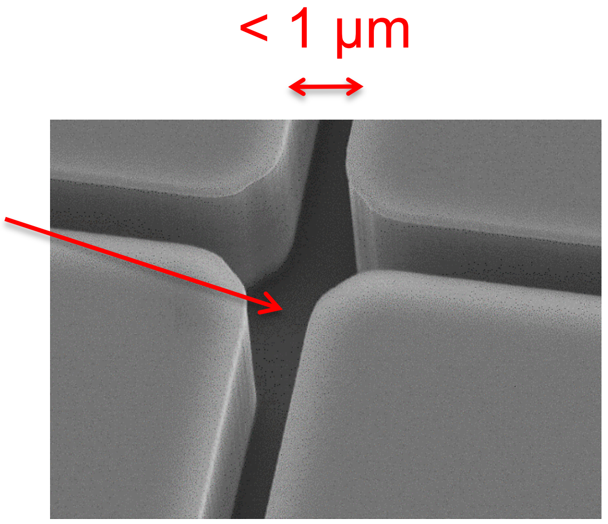
VUV-HD

RGB-UHD

NIR

NUV-HD: technology





- p-on-n junction → higher Pt for UV light
- Narrow dead border region → Higher Fill Factor
- Trenches between cells → Lower Cross-Talk
- Make it simple: 9 lithographic steps

Signal: Photon Detection Efficiency

$$PDE = FF \cdot QE \cdot P_t$$

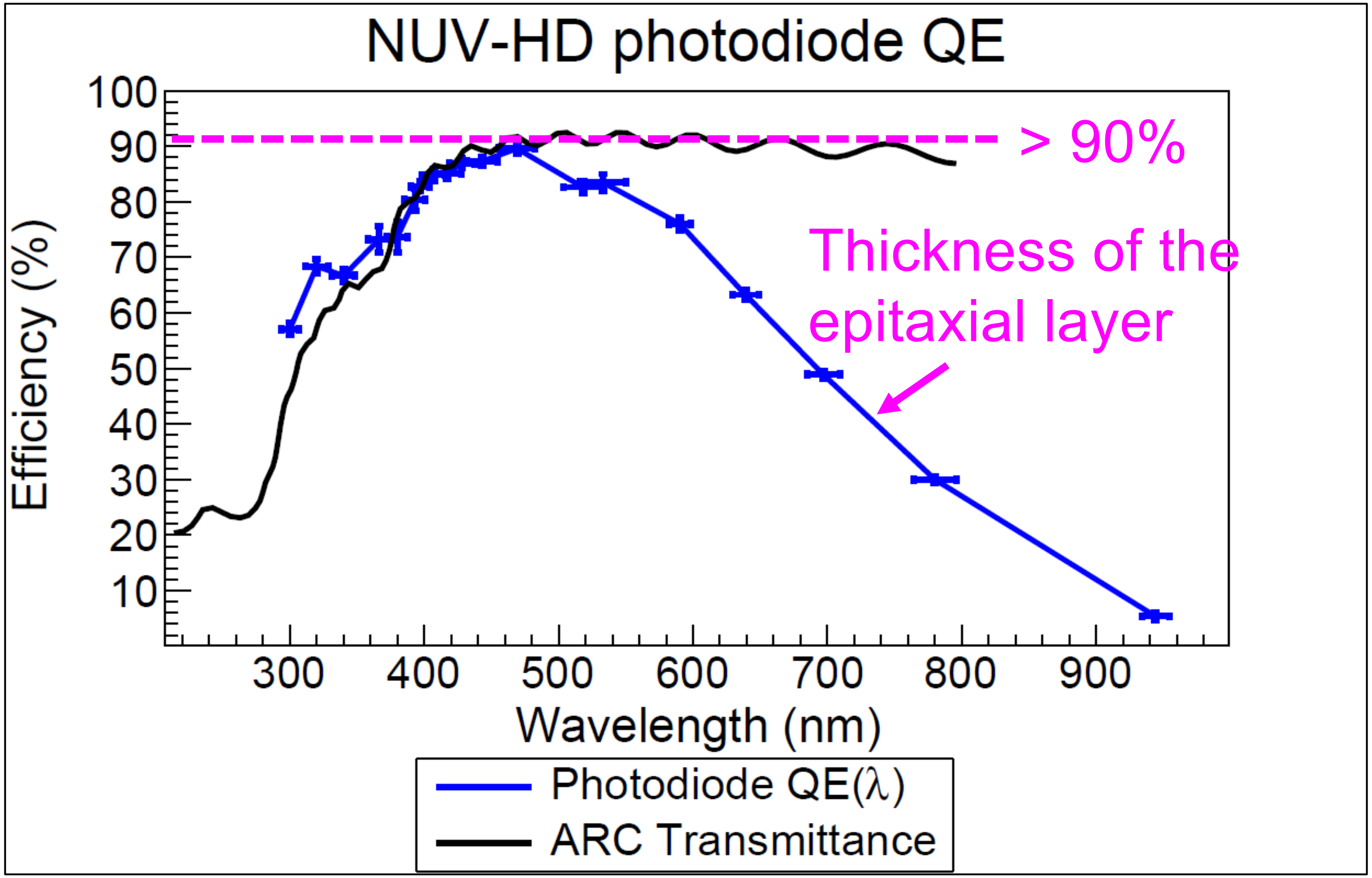
Fill Factor

Quantum Efficiency

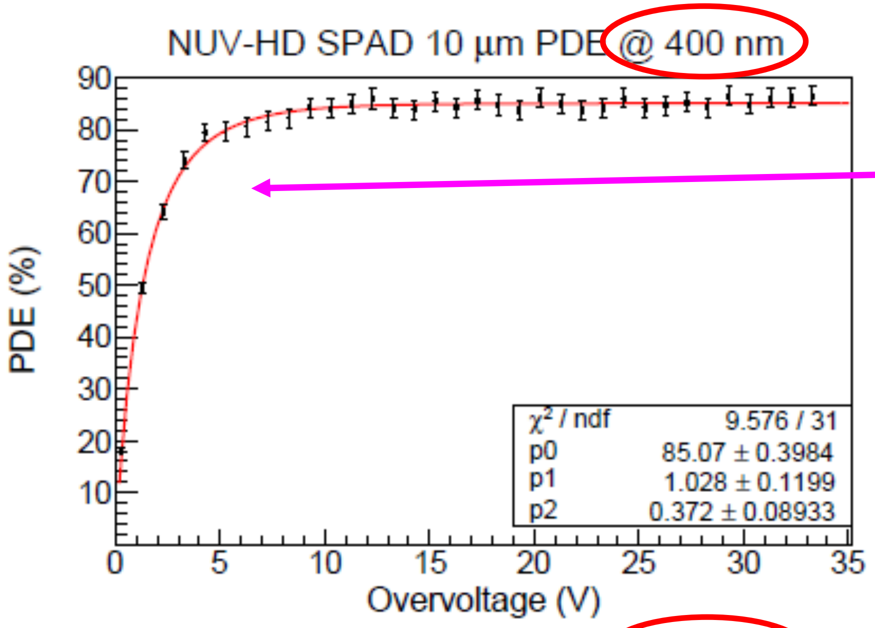
Avalanche Triggering Probability

NUV-HD: QE

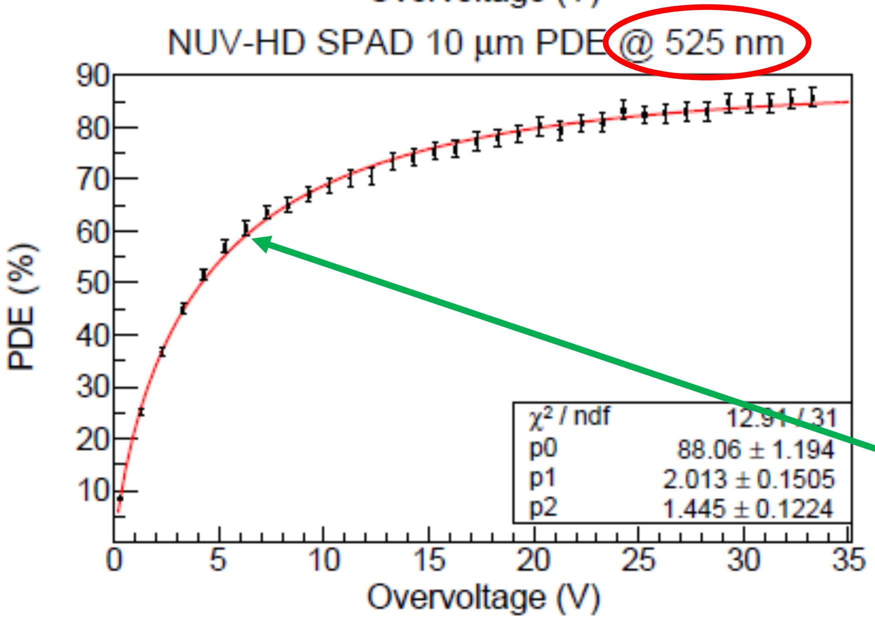
Measured on a photodiode with same layers as SiPM



NUV-HD: QE*Pt

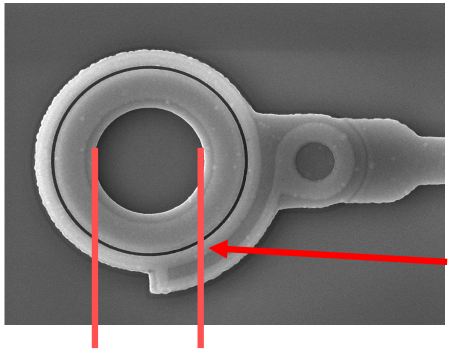


Fast increase with over-voltage:
→ avalanche is initiated by electrons



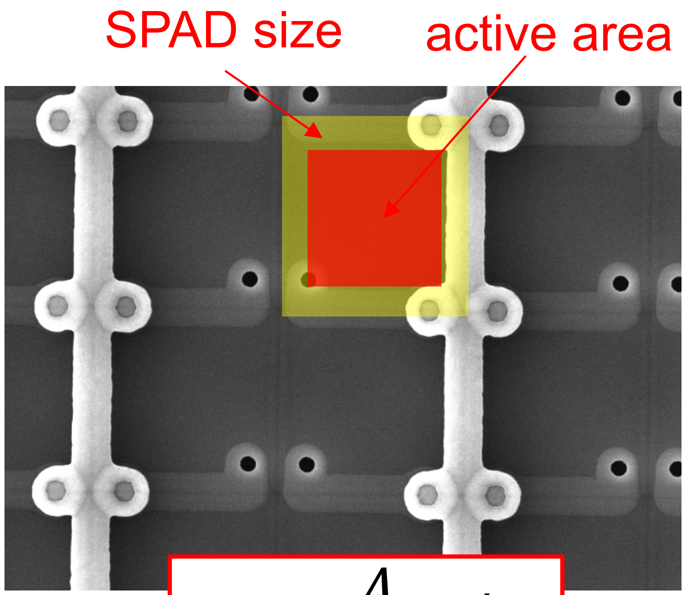
Slower increase with over-voltage:
→ avalanche is initiated by holes (and electrons)

Measured on a SPAD with 100% FF

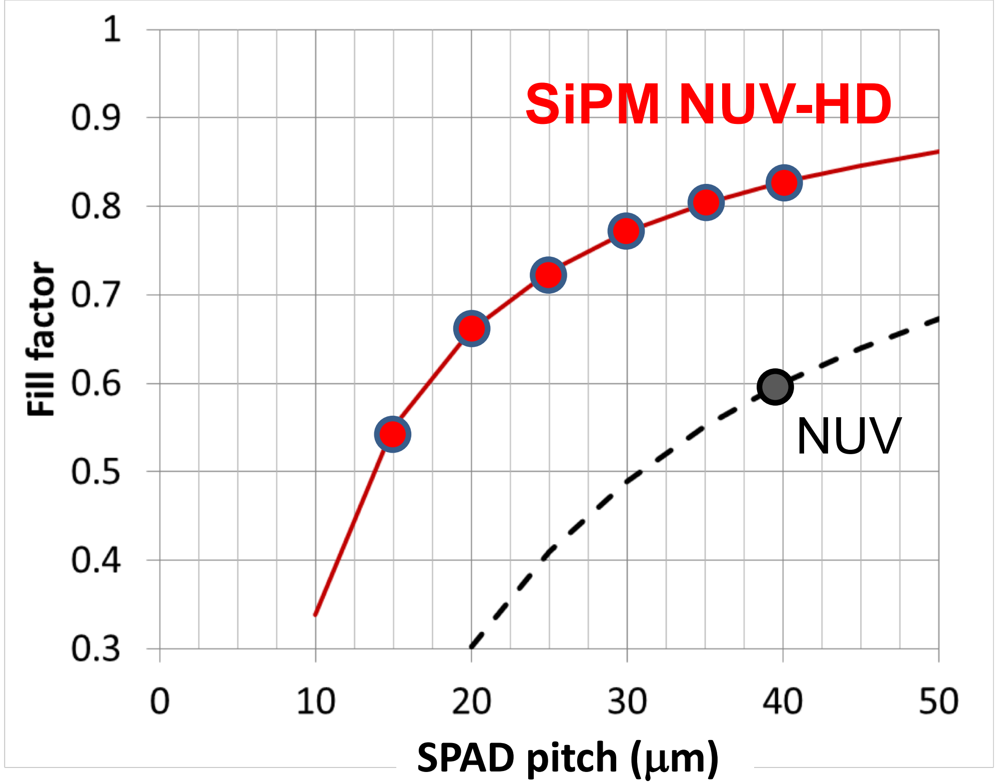


SPAD size is defined by metal opening which is within the high-field region

NUV-HD: Fill Factor



$$FF = \frac{A_{active}}{A_{total}}$$



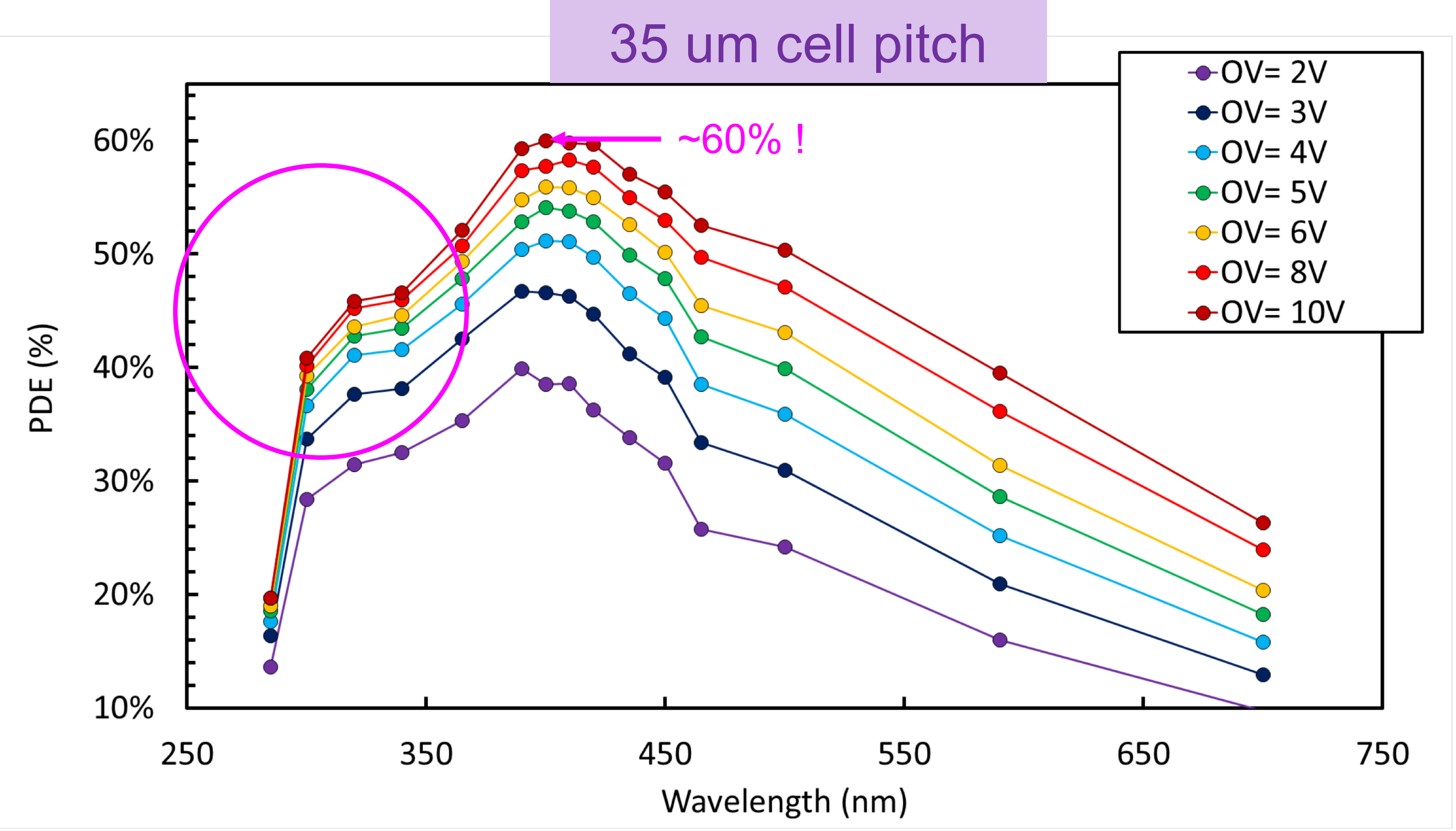
SPAD Pitch	**15 μm**	**20 μm**	**25 μm**	**30 μm**	**35 μm**	**40 μm**
Fill Factor (%)	55	66	73	77	81	83
SPAD/mm^2	4444	2500	1600	1111	816	625

High Dynamic Range, Low correlated noise (15–25 μm) ↔

High PDE (35–40 μm) ↔

Single Photon Time Resolution

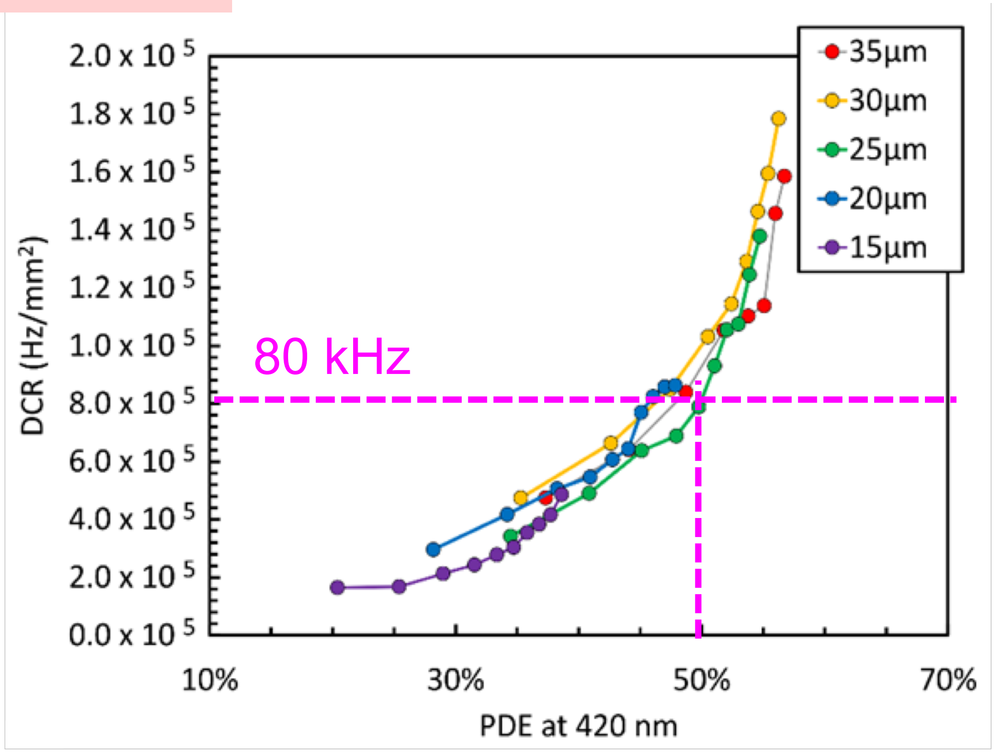
Photon detection efficiency

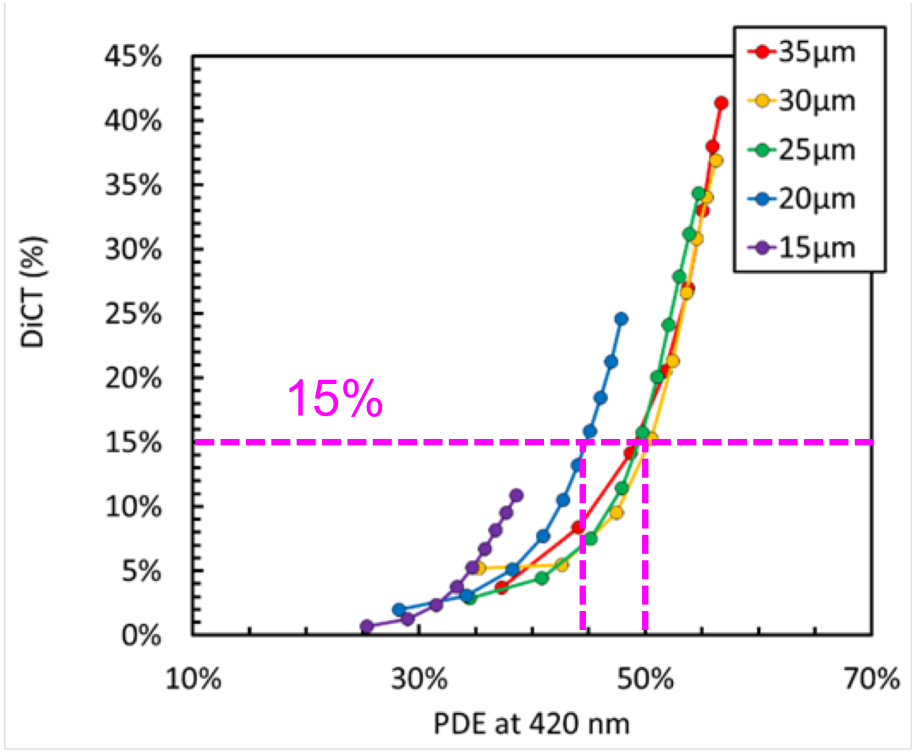


Gola, A et al. (2019). “NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler.” *Sensors*, *19*(2), 308.

Dark Count Rate and Direct Crosstalk

T = 20 C

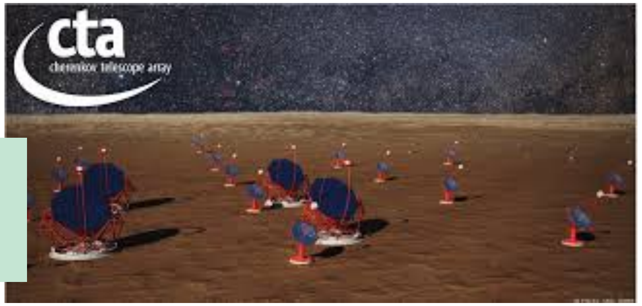




Dark Count Rate

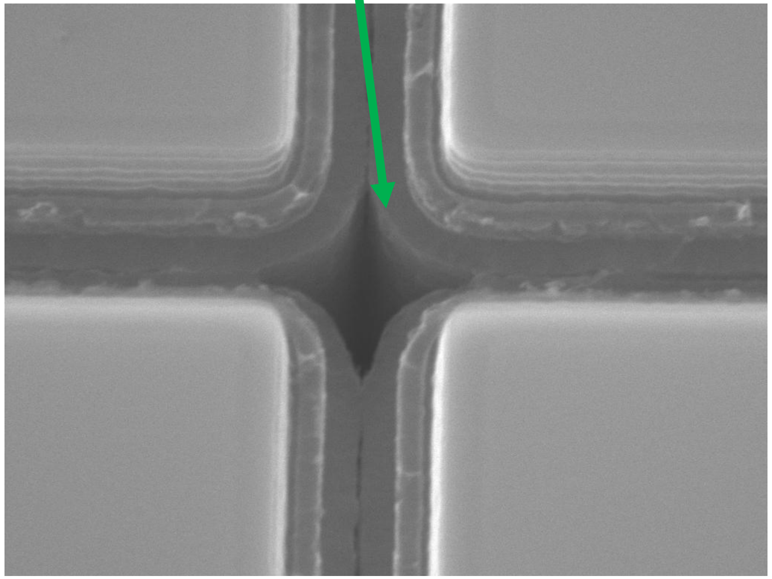
Optical Crosstalk
(Correlated Noise)

NUV-HD-LowCT

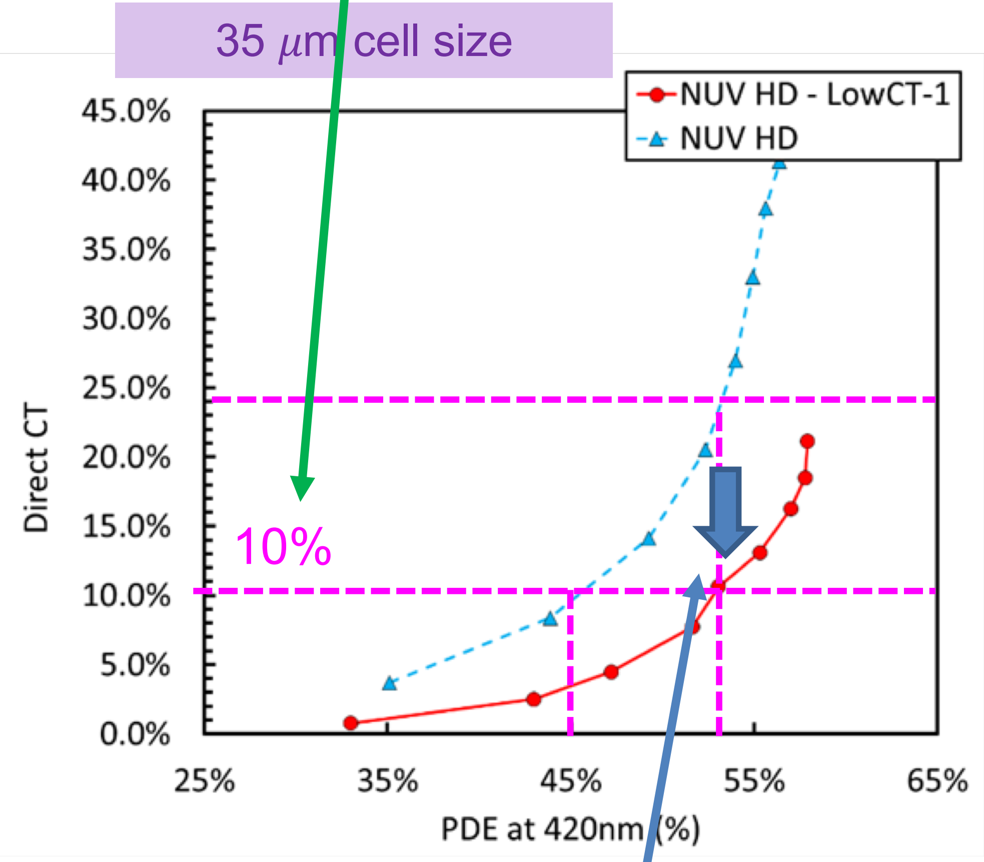


Applications such as CTA

Light absorbing material was inserted inside trenches, between adjacent microcells

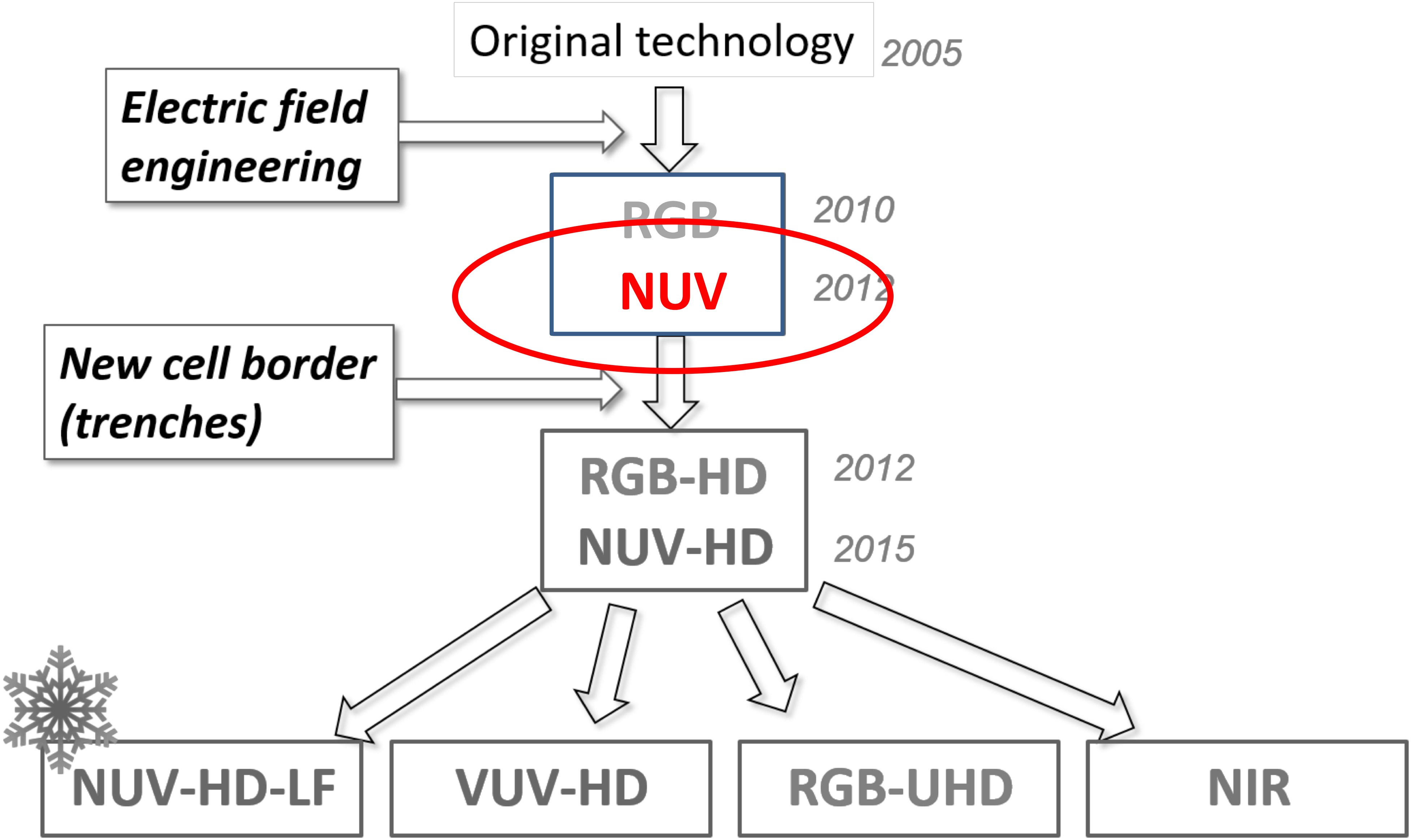


SEM image of trenches, separating adjacent microcells.



2.5x reduction of Optical Crosstalk at same PDE

Single Photon Timing Resolution



Original technology 2005

Electric field engineering

RGB 2010

NUV 2012

New cell border (trenches)

RGB-HD 2012

NUV-HD 2015

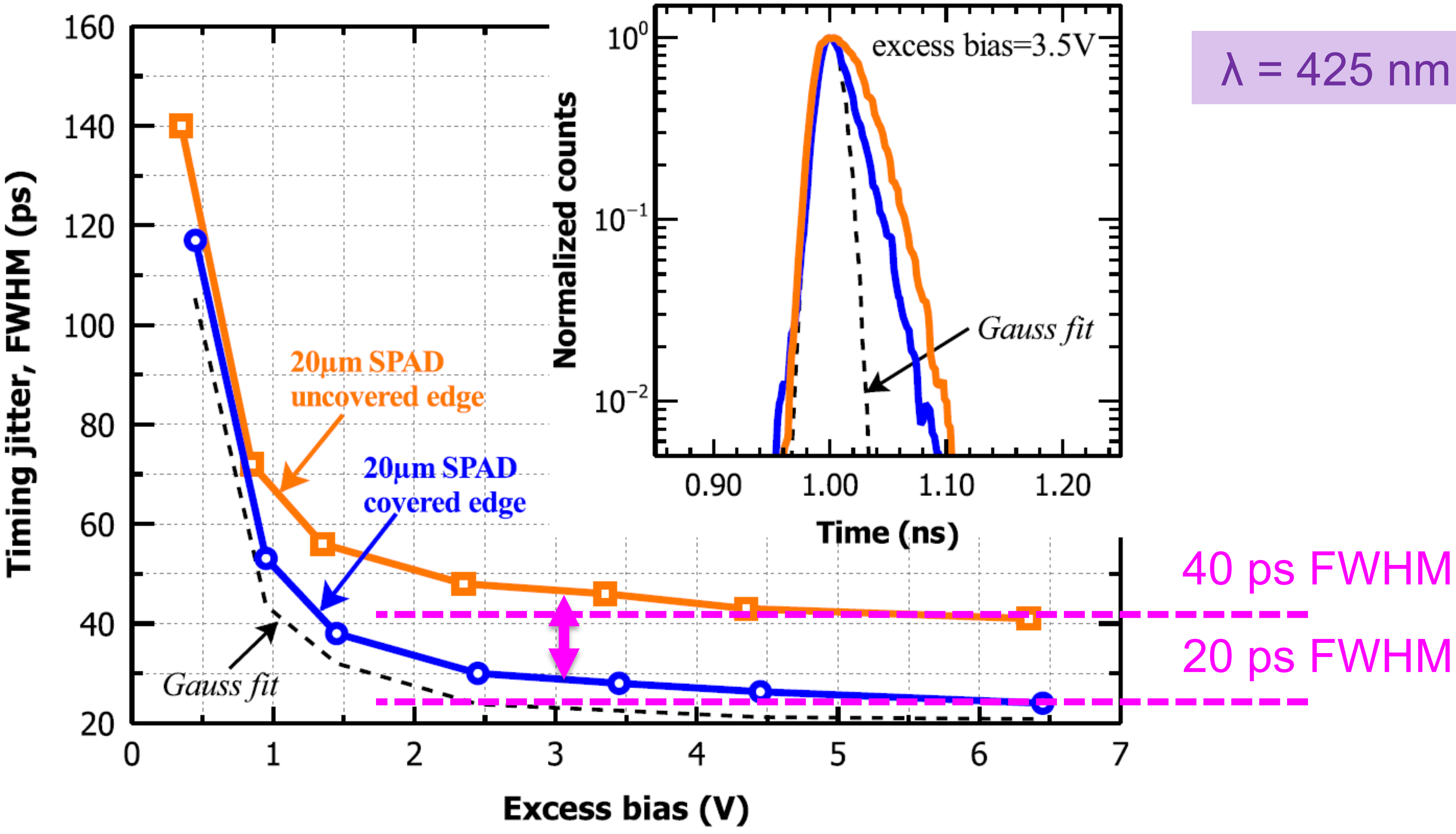
NUV-HD-LF

VUV-HD

RGB-UHD

NIR

NUV SPAD – SPTR



λ = 425 nm

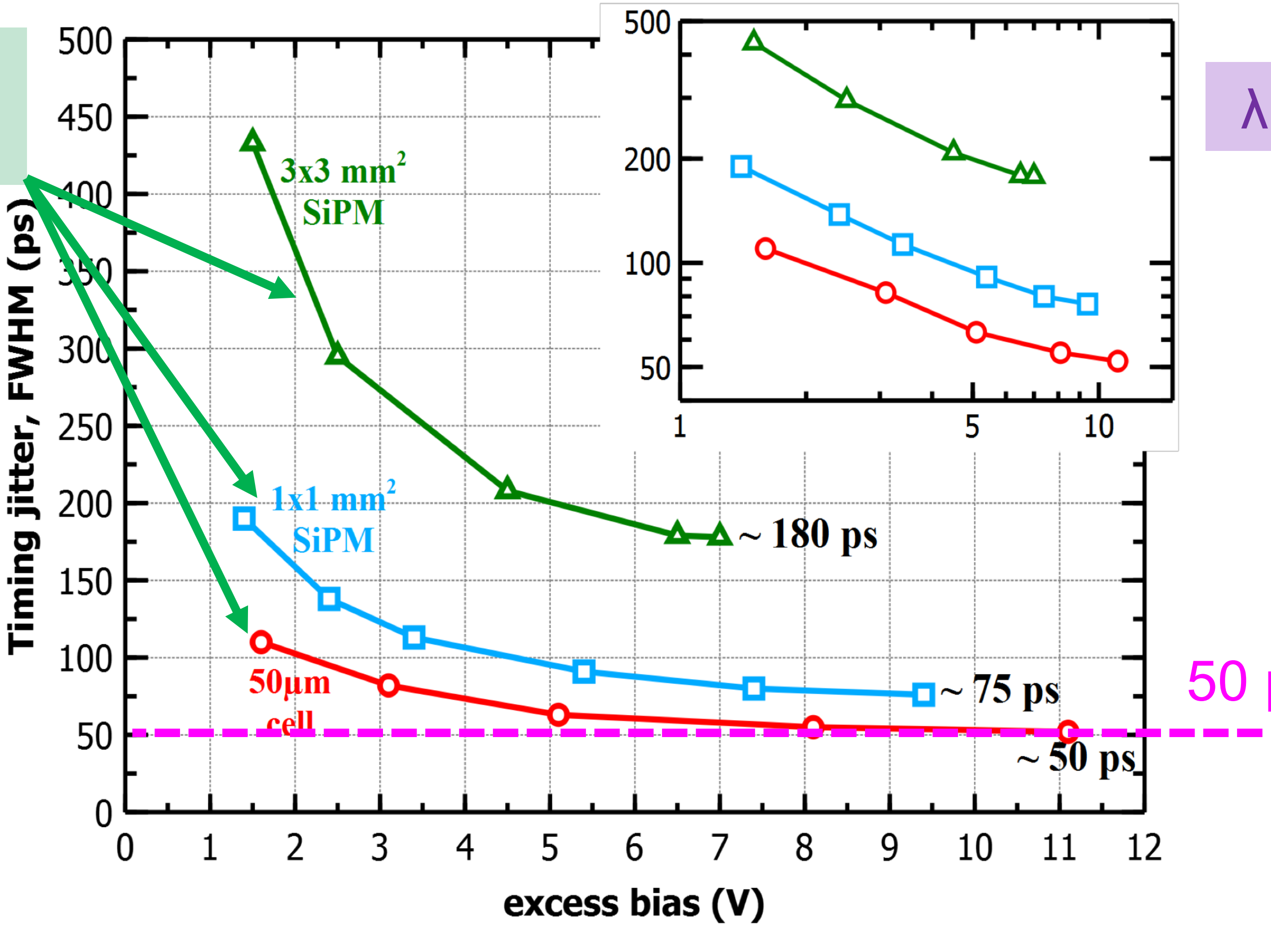
Worse charge collection at SPAD edges

Covering the SPAD edges reduces the SPTR by 20 ps

Acerbi, F. et al. (2015). "Analysis of single-photon time resolution of FBK silicon photomultipliers." *NIMA*, *787*, 34-37.

NUV SiPM – SPTR

Different SiPM sizes



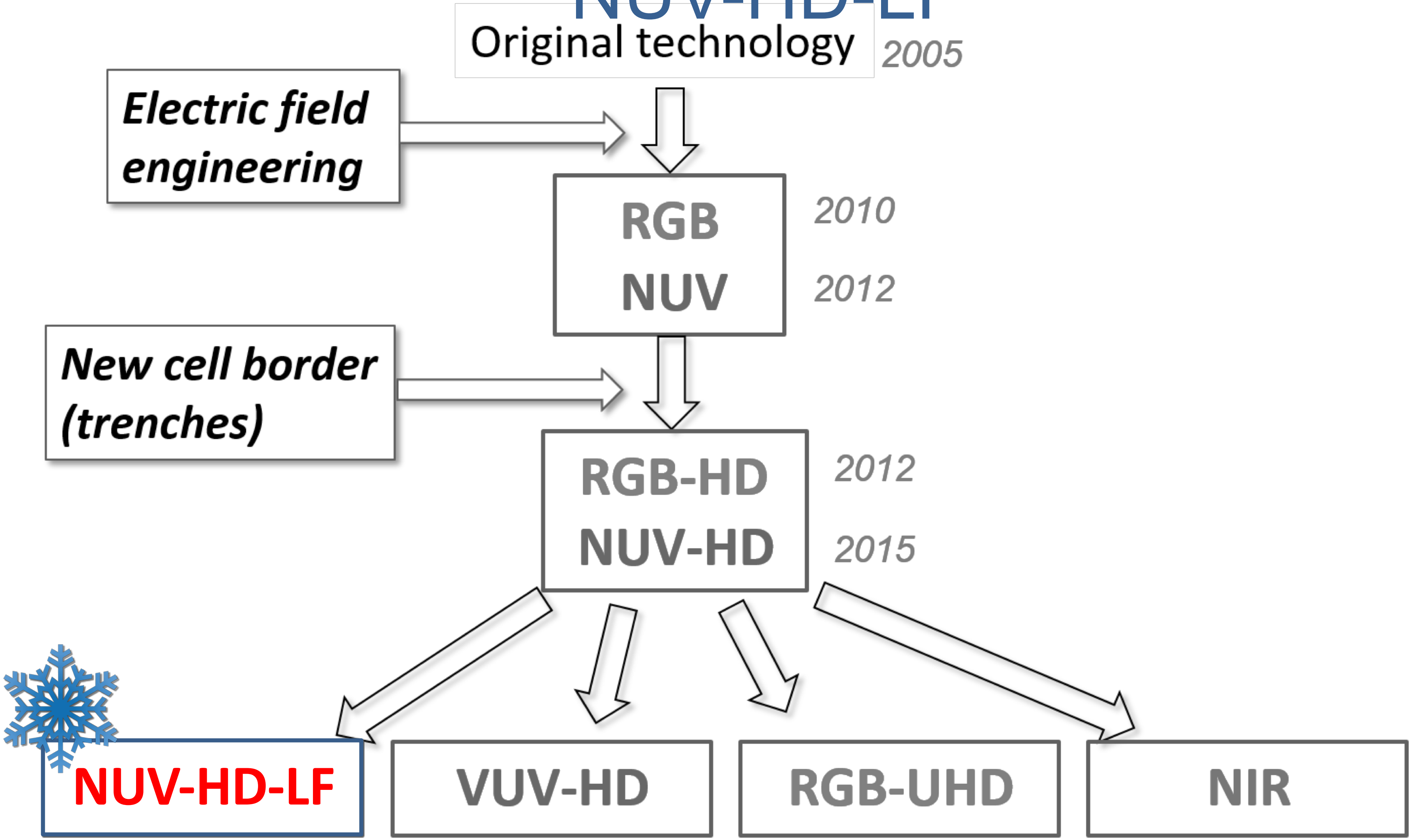
λ = 425 nm

50 ps FWHM!

Larger active are → larger SiPM capacitance → more LP filtering → smaller signal

Bigger effect of the electronic noise on SPTR

NUV-HD for cryogenic applications: NUV-HD-LF



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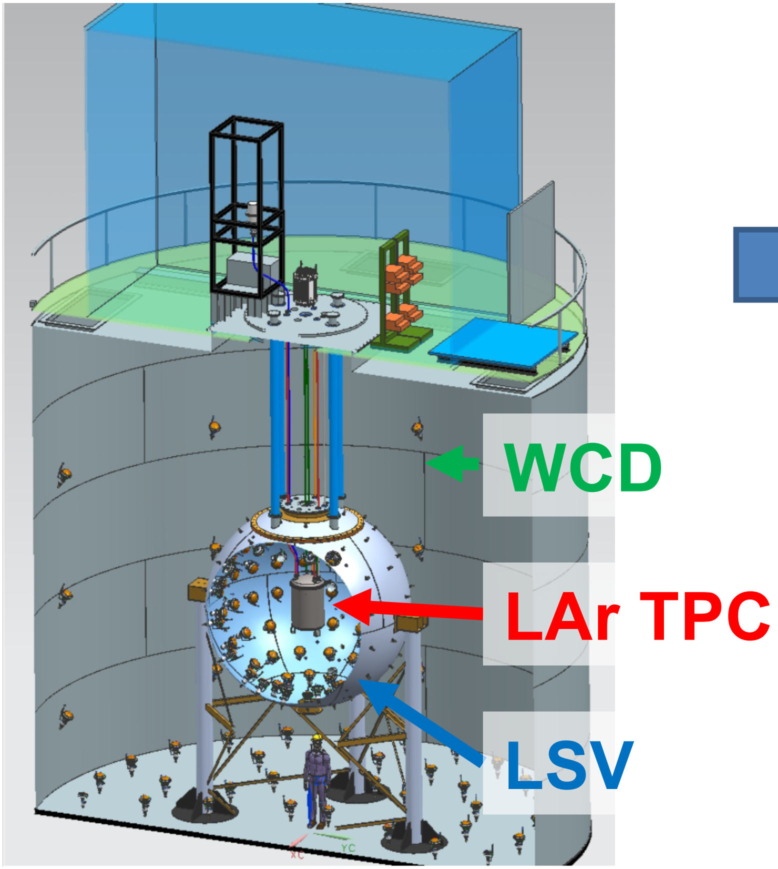
VUV-HD

RGB-UHD

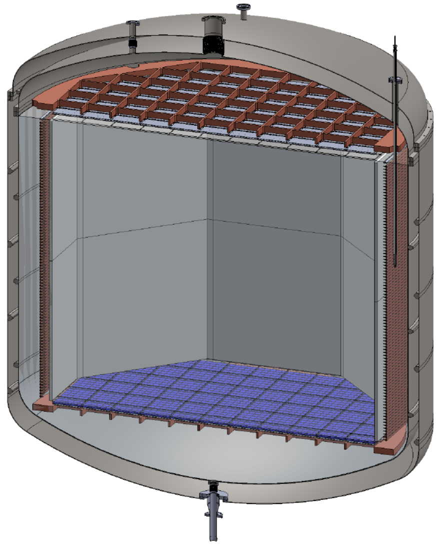
NIR

Cryogenic Applications of SiPMs

There is a growing interest in using SiPMs for the readout of liquid scintillators at cryogenic temperatures.

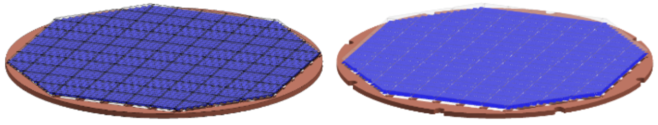


DarkSide-50
PMT-based TPC

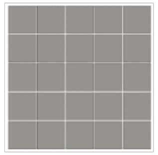


~ 23t of UAr

TPB WLS:
emission at
400 – 450 nm



2 light readout planes: 15 m^2



SiPM tiles

DarkSide-20k
SiPM-based TPC

Devices Under Test

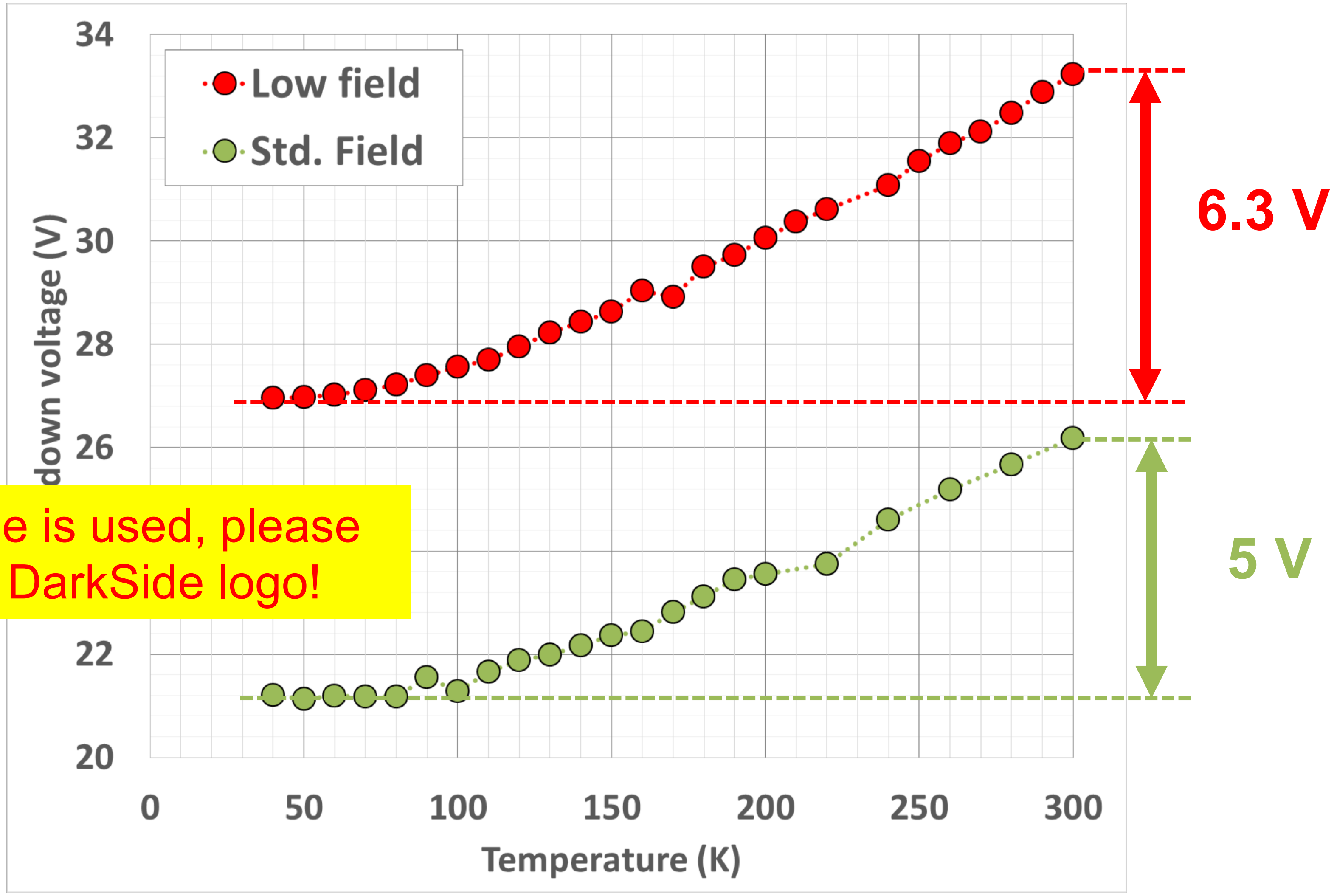
Parameters (@ room T)	**NUV-HD Std. field**	**NUV-HD Low-field**
Cell Size	25 µm	25 µm
Fill Factor	73%	73%
Breakdown Voltage	26.5 V	32 V
Max PDE	50%	50%
Peak PDE λ	410 nm	410 nm
DCR (20°C)	< 150 kHz/mm^2	< 150 kHz/mm^2
DiCT	25%	25%
DeCT + AP	2%	2%

SiPM characteristics tested **form 300 K to 40 K**

Optimized for low temperature operation

Breakdown Voltage vs. Temperature

The mean free path of the carriers in the high-field region increases with decreasing temperature.



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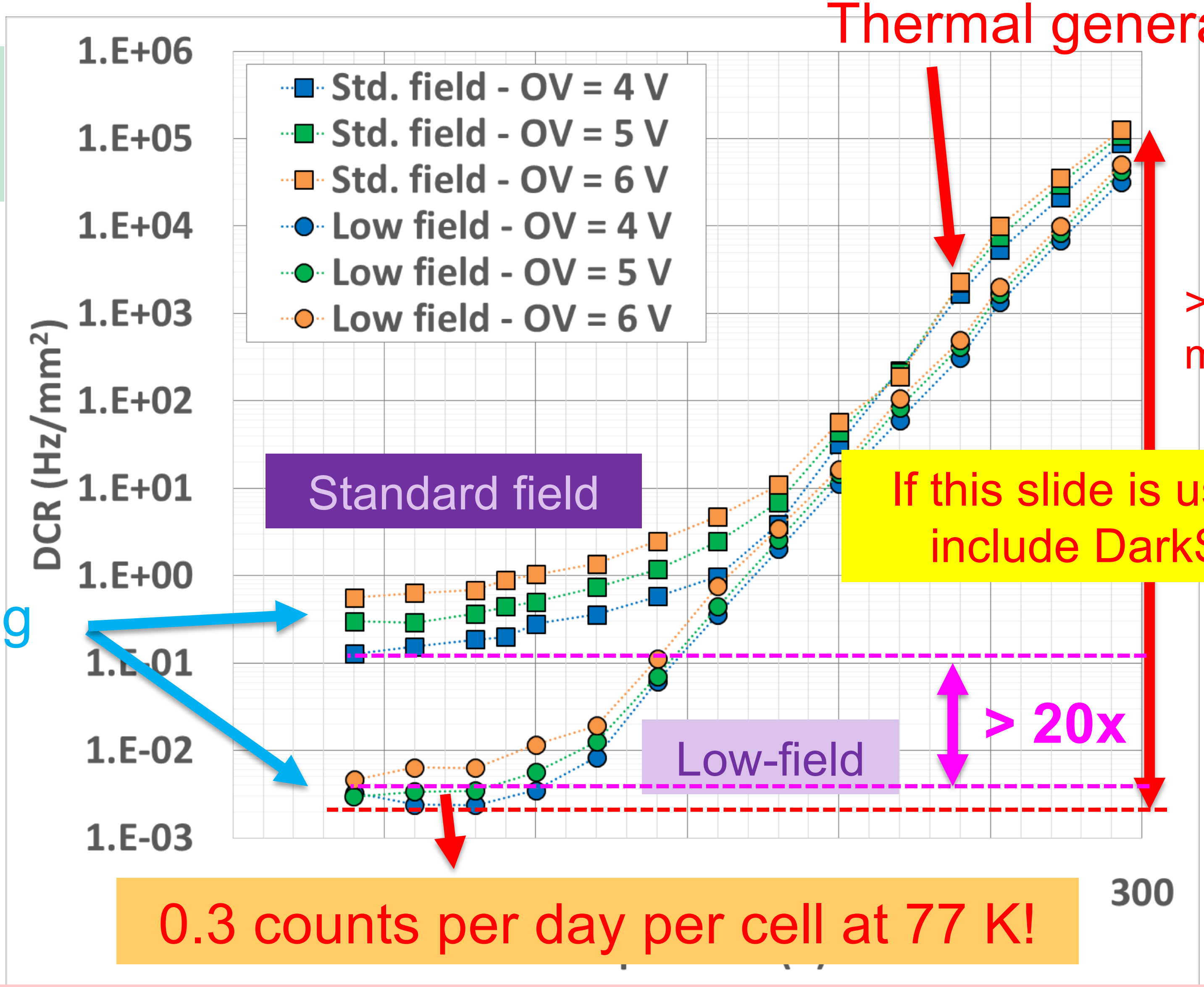
NUV-HD – Cryogenic DCR Measurements

25 um cell



Thermal generation

> 7 orders of magnitude !

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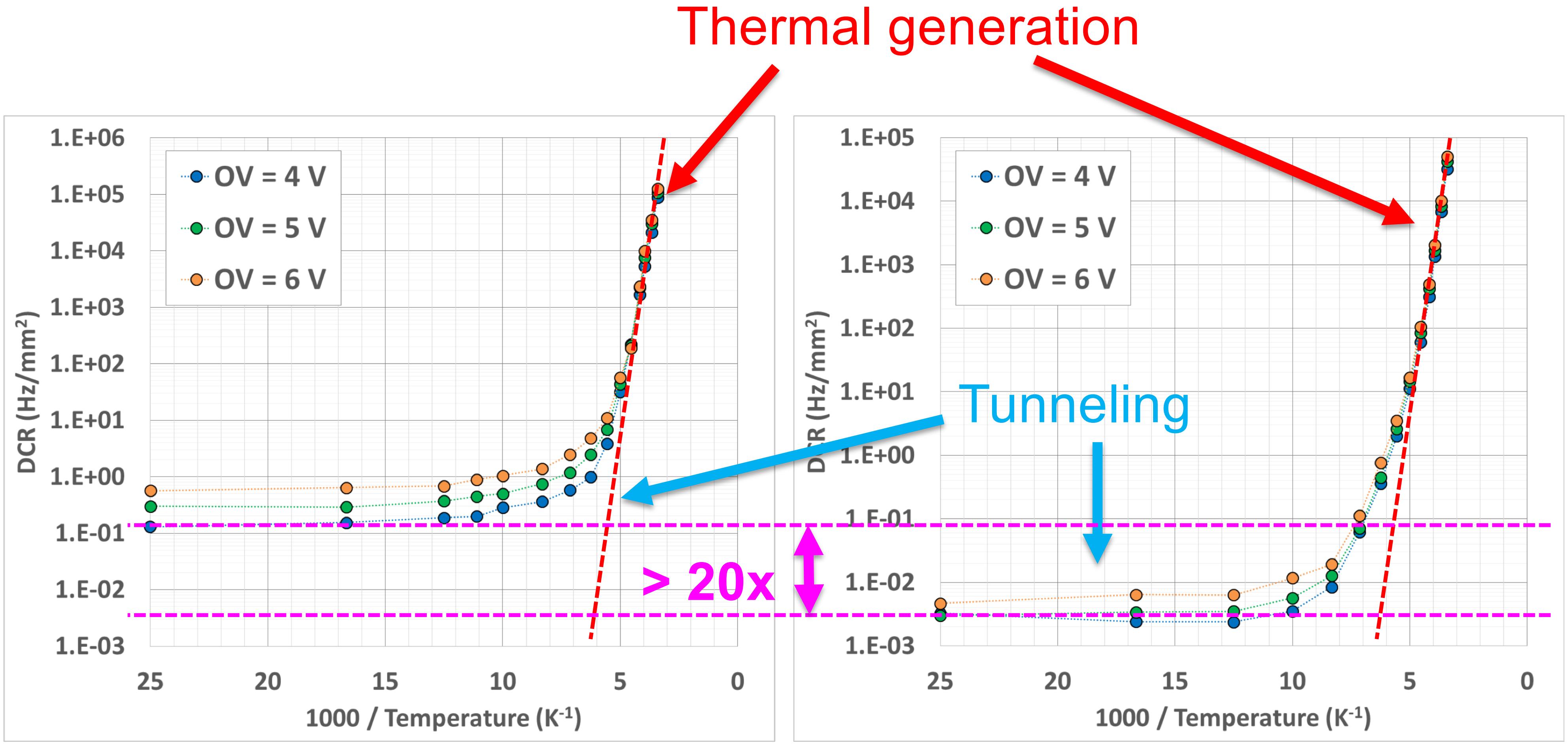
Tunneling

> 20x

0.3 counts per day per cell at 77 K!

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

DCR / mm^2 – Arrhenius plot

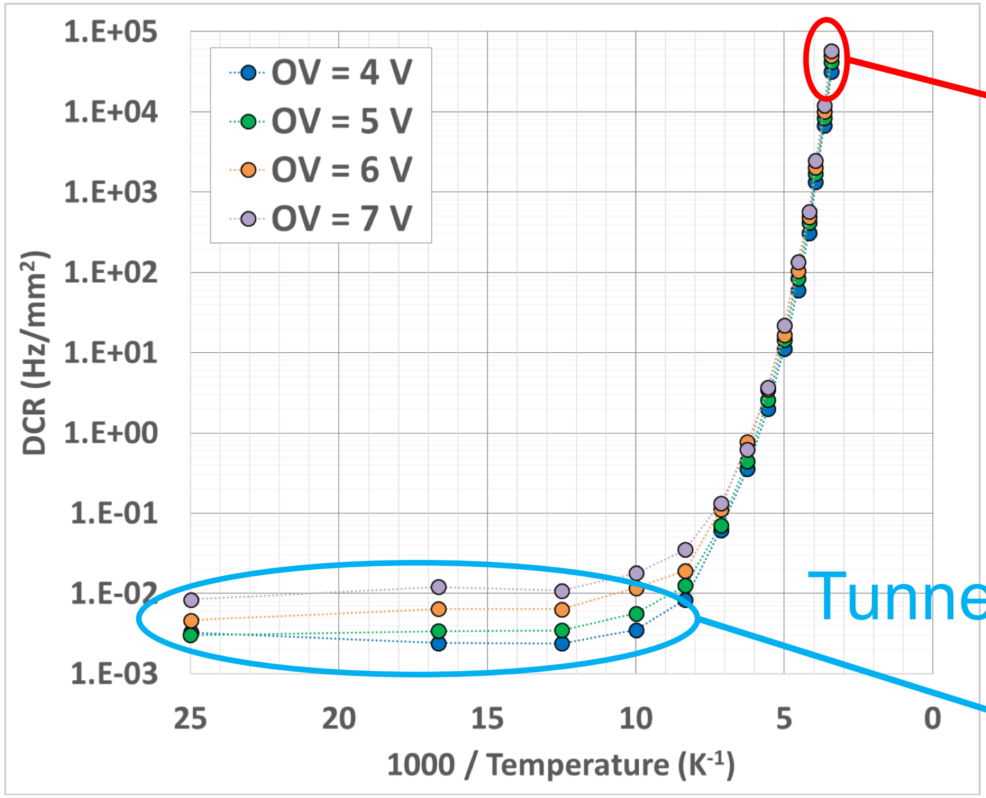


Standard field

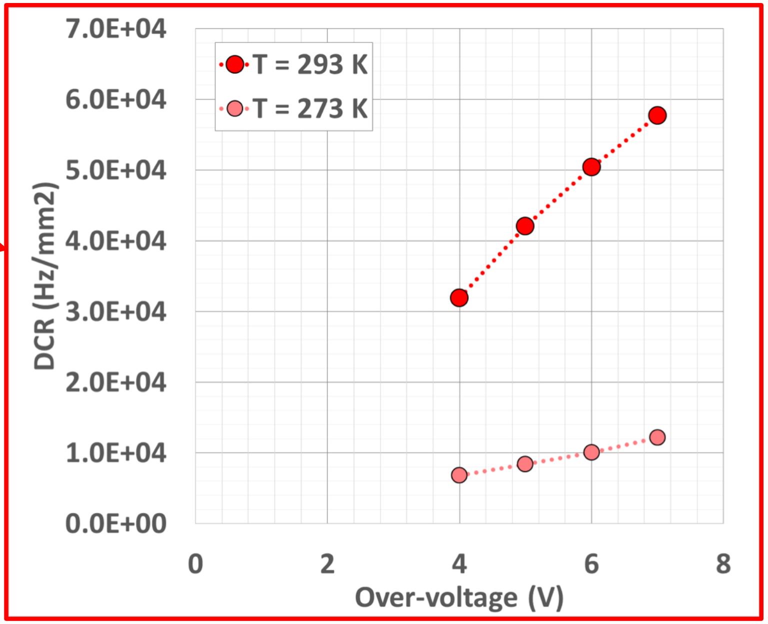
Low-field

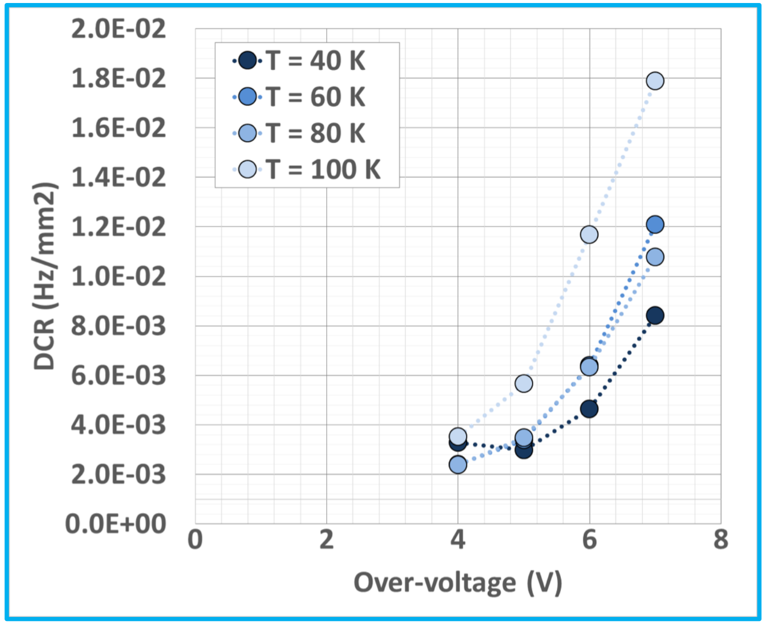
DCR / mm^2 vs. Over-voltage

Thermal generation



Tunneling





NUV-HD Low-field

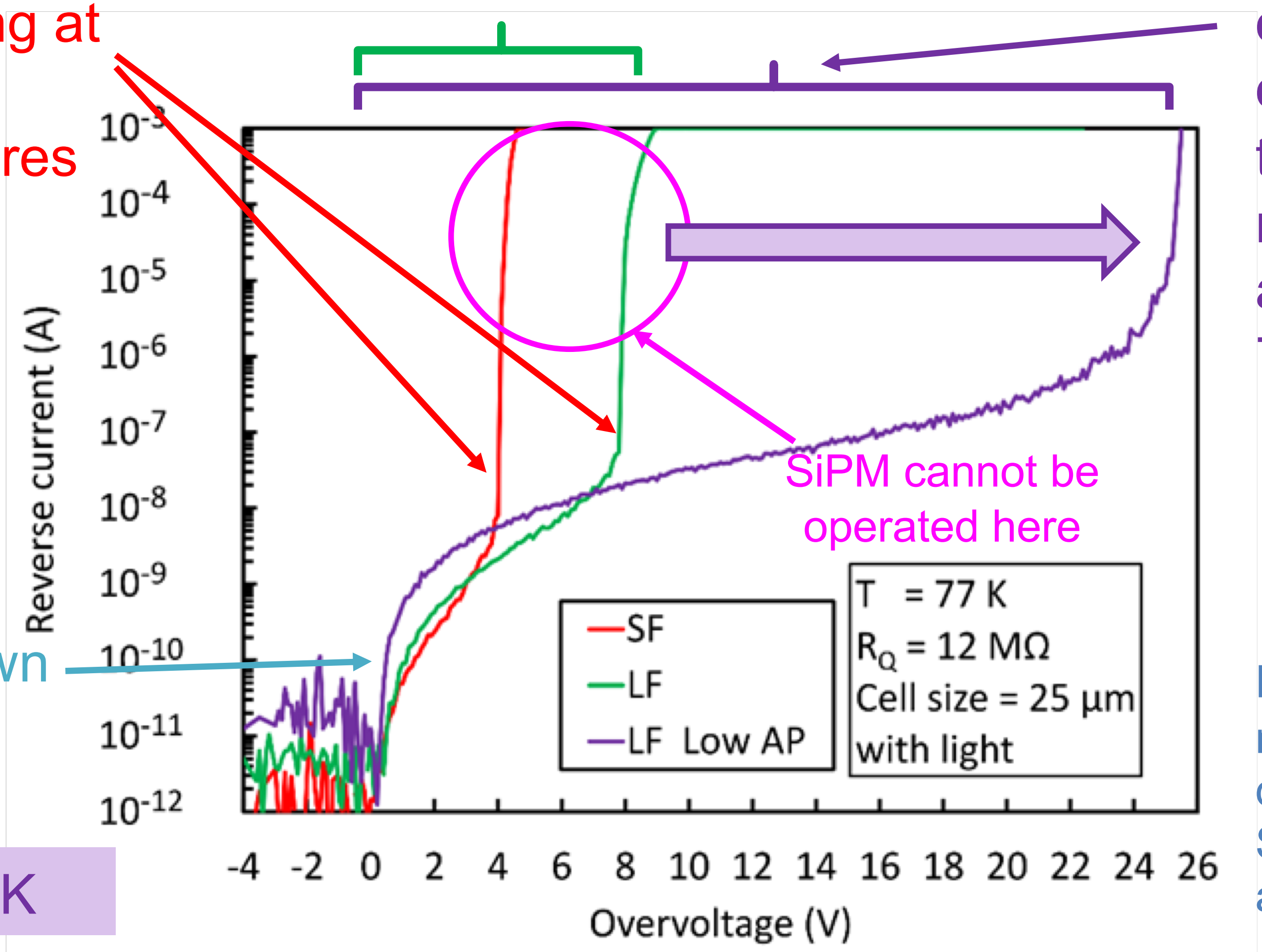
NUV-HD-Cryo – reduction of afterpulsing

New NUV-HD-Cryo SiPM technology allows suppression of afterpulsing at cryogenic temperatures, allowing a much increased operating overvoltage

Useful operating region for NUV-HD-LF

Divergence of afterpulsing at cryogenic temperatures

Extended operating region of NUV-HD-Cryo thanks to reduced afterpulsing at 77 K



SiPM cannot be operated here

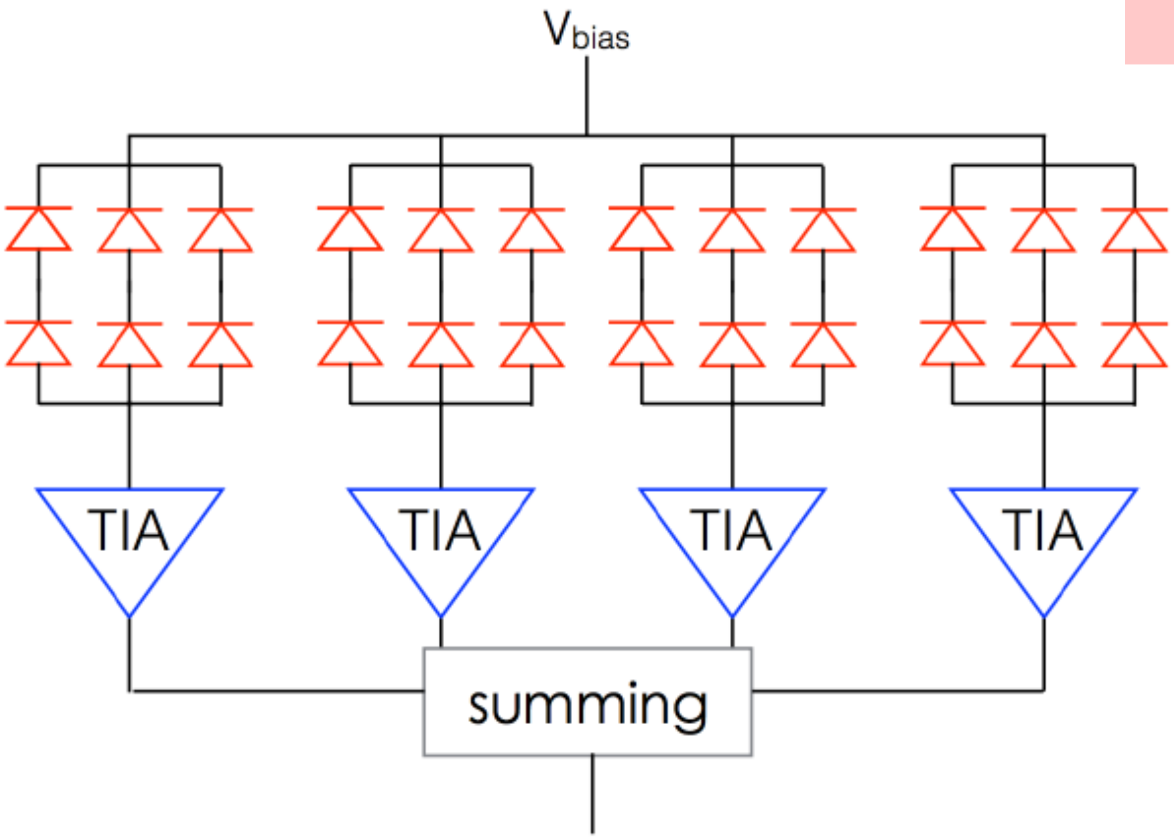
Breakdown voltage

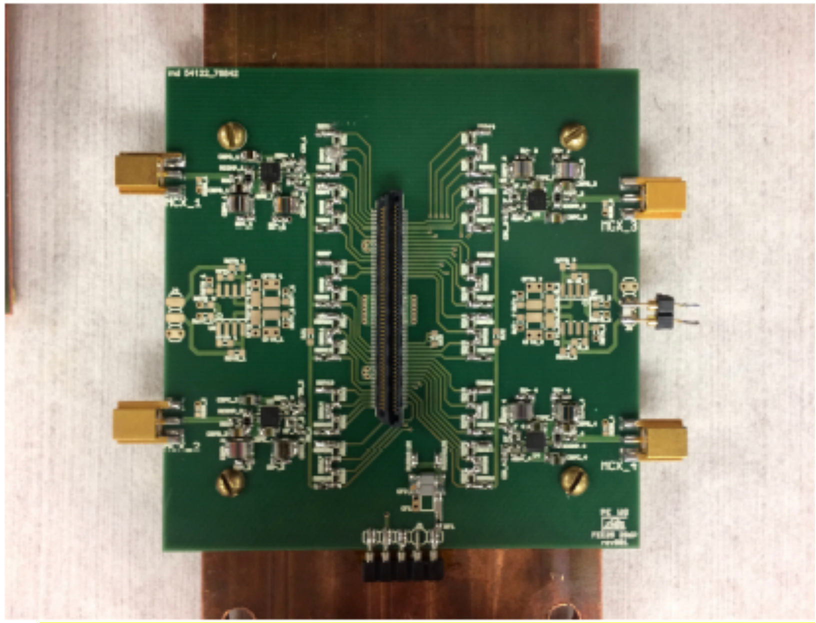
T = 77 K

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

Photon counting at 77 K

Designed at LNGS





If this slide is used, please include DarkSide logo!

- 4 transimpedance amplifier: each TIA reads 6cm²
- Hybrid configuration for SiPMs: 4x2s3p
- Further cold amplification before transmission outside

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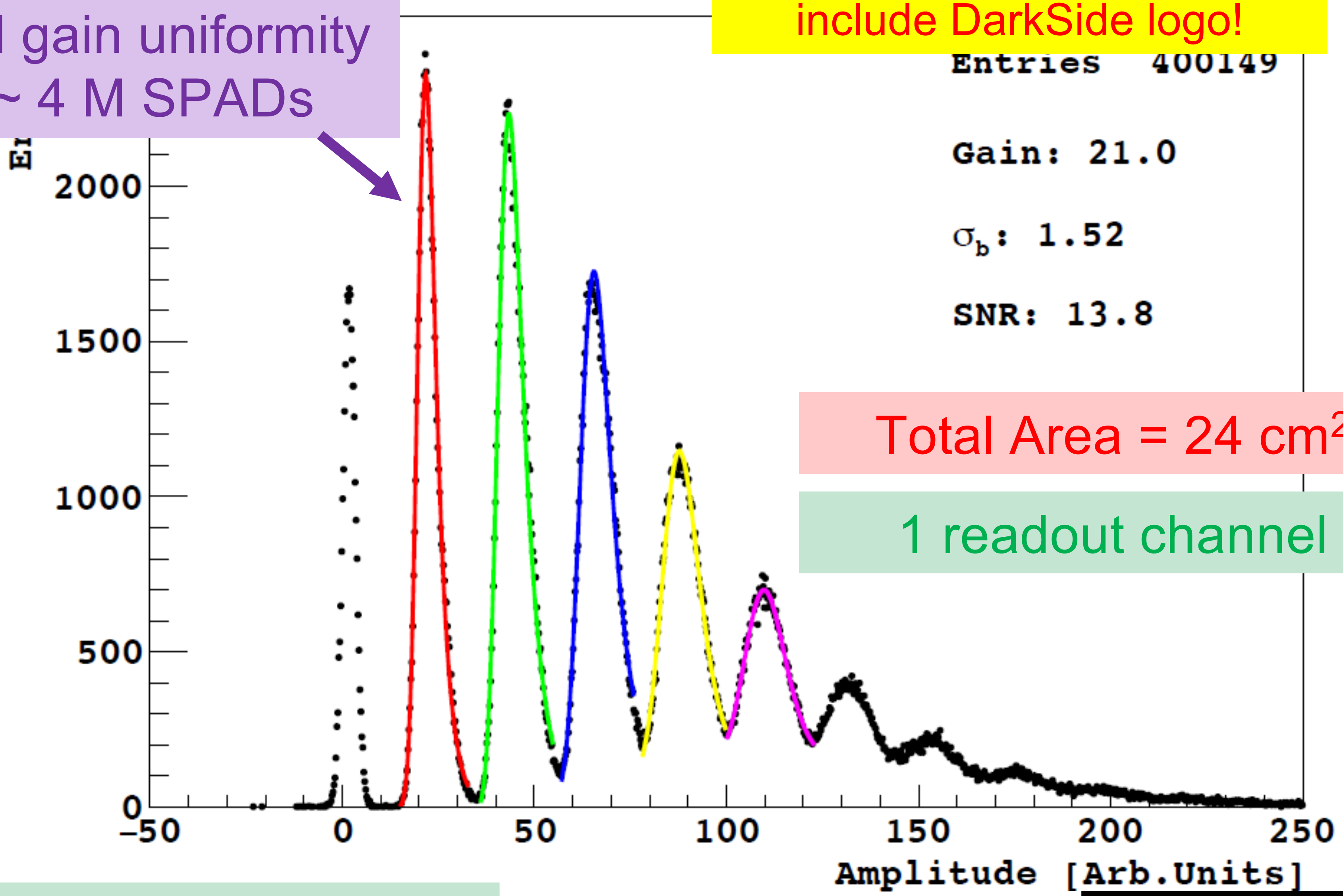
Photon counting at 77 K

If this slide is used, please include DarkSide logo!

Good gain uniformity of ~ 4 M SPADs



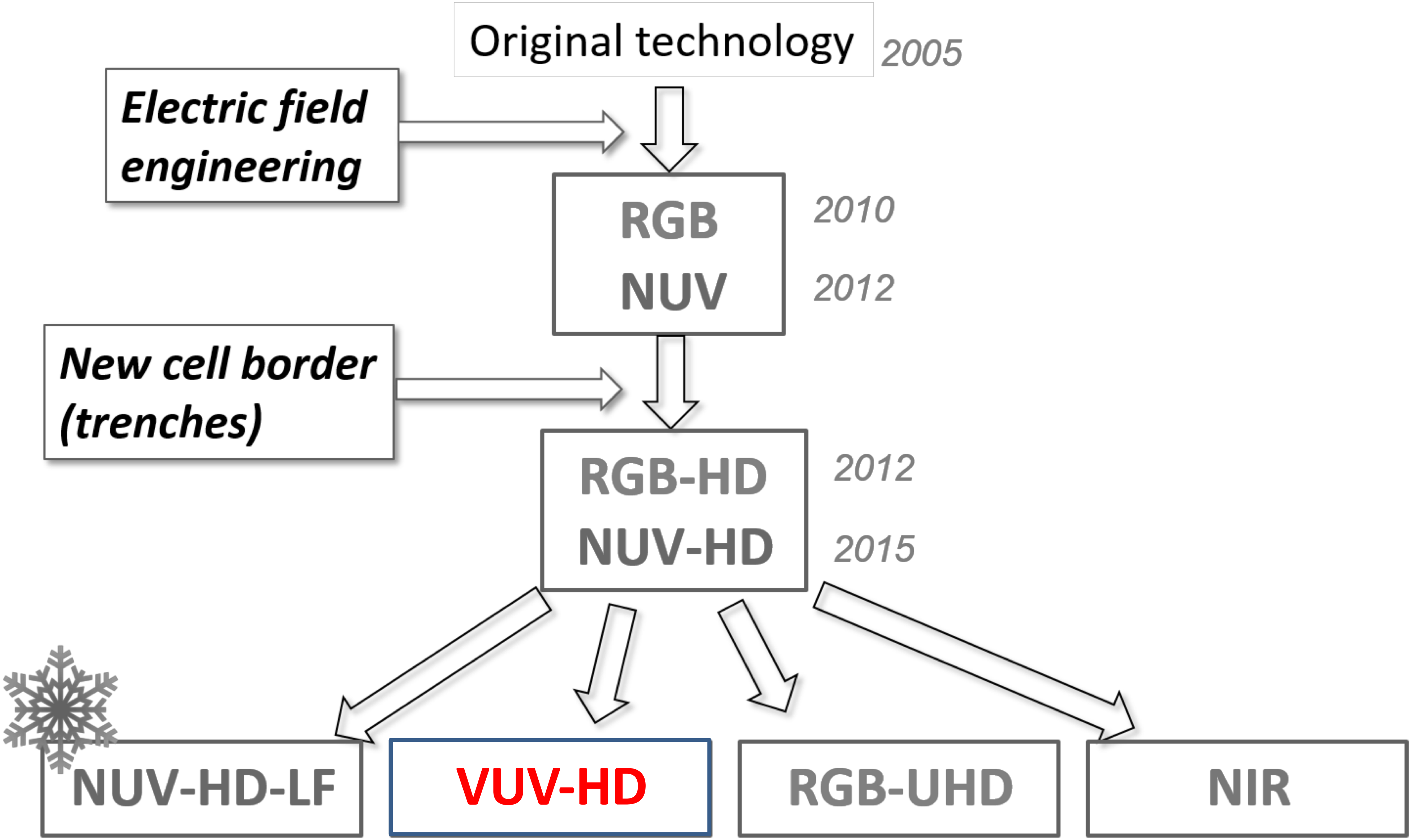
Total Area = 24 cm^2

1 readout channel

25um cells, 5 V over-voltage

darkside
two-phase argon TPC for Dark Matter Direct Detection

NUV-HD technology for VUV



Original technology 2005

Electric field engineering

RGB 2010

NUV 2012

New cell border (trenches)

RGB-HD 2012

NUV-HD 2015

NUV-HD-LF

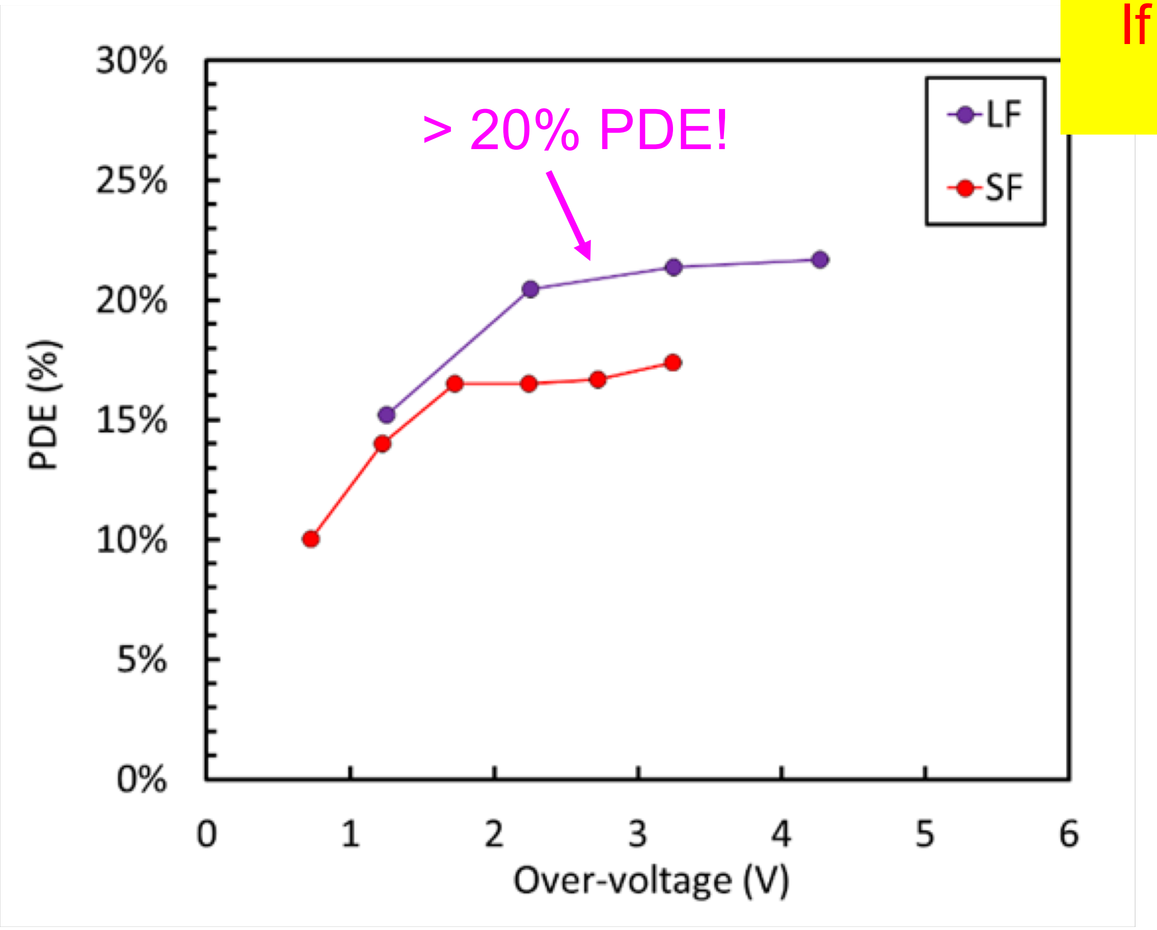
VUV-HD

RGB-UHD

NIR

VUV-HD

We are modifying the NUV-HD to enhance efficiency in the VUV.

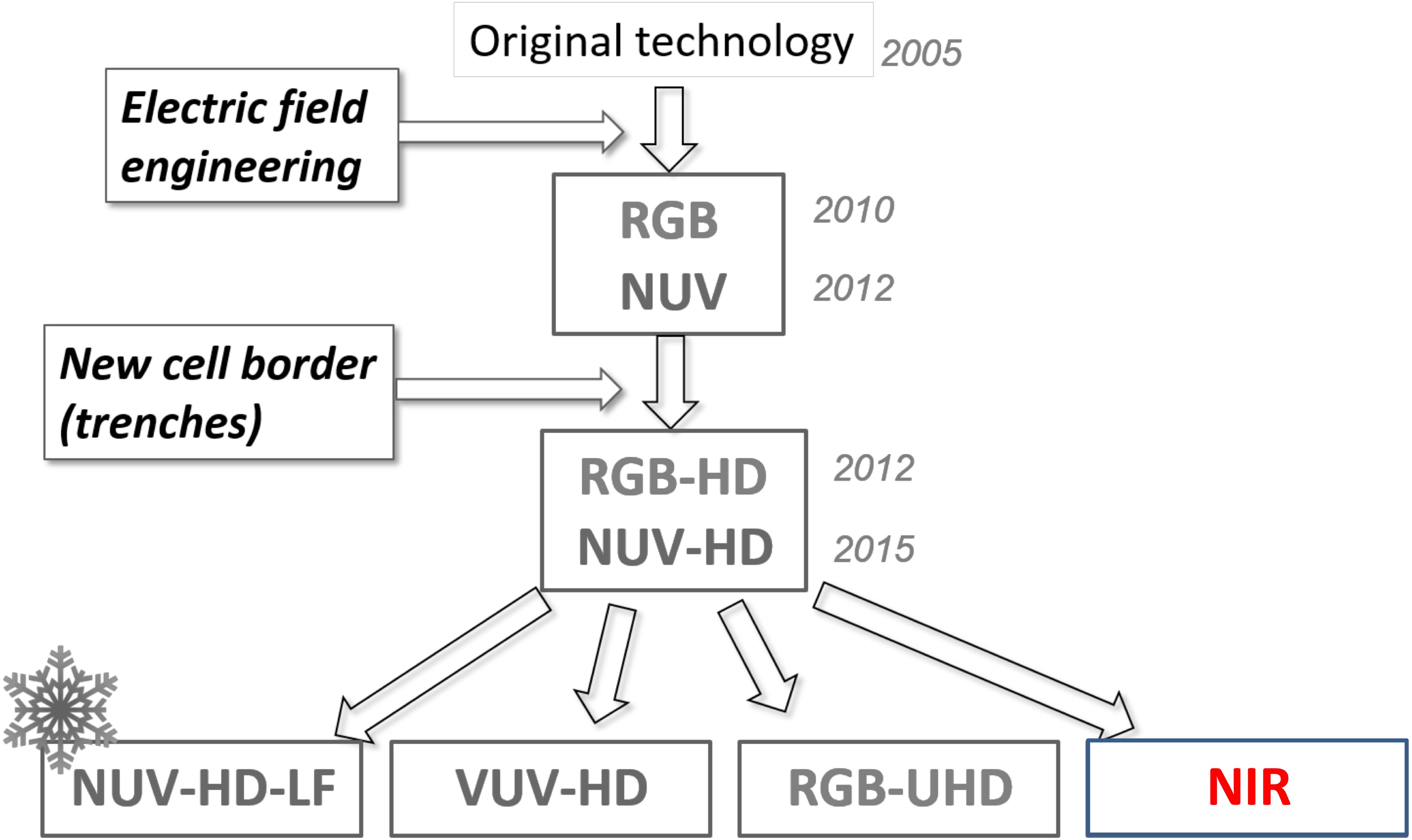


If this slide is used, please include nEXO logo!

nEXO experiment

λ = 175 nm
T = -104°C (LXe)

NIR SiPMs



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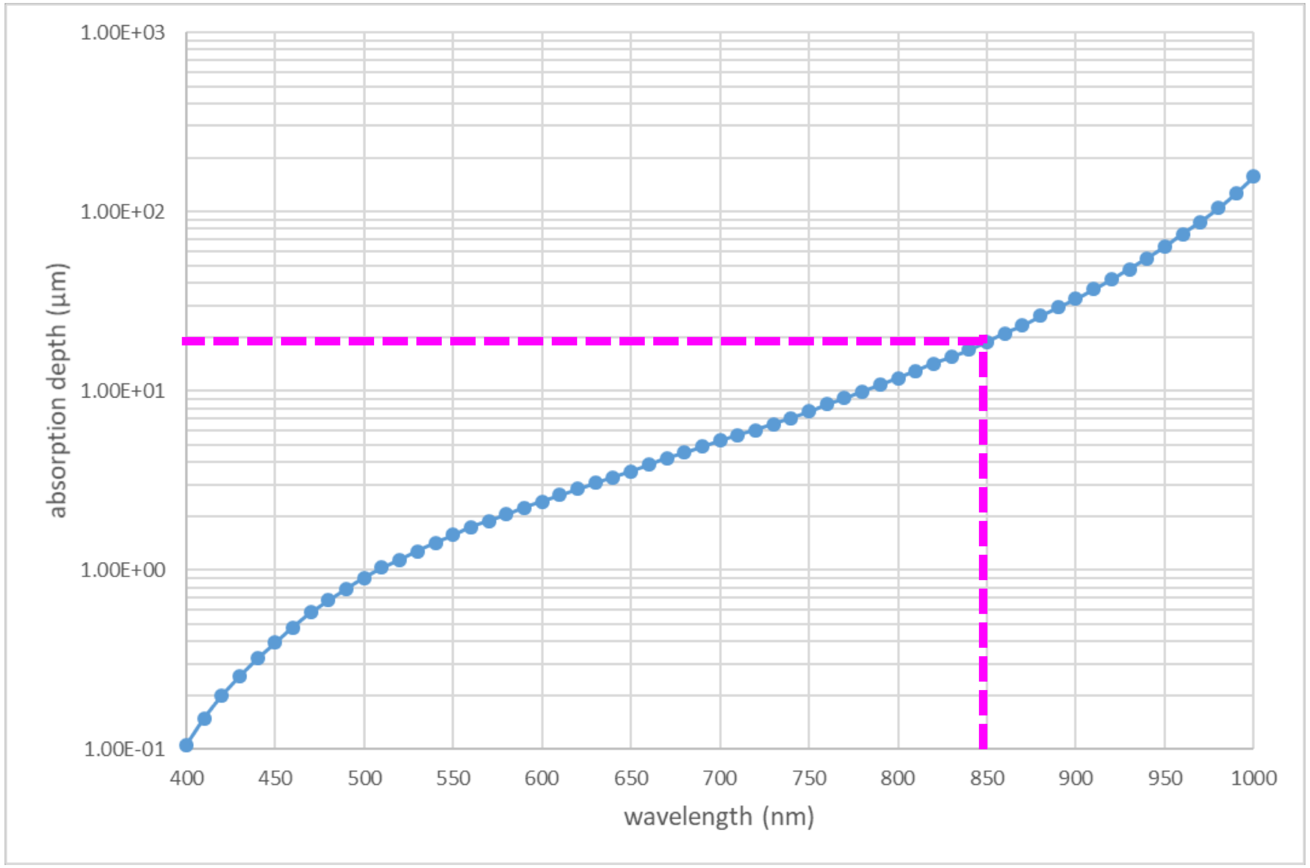
Light attenuation length in Si

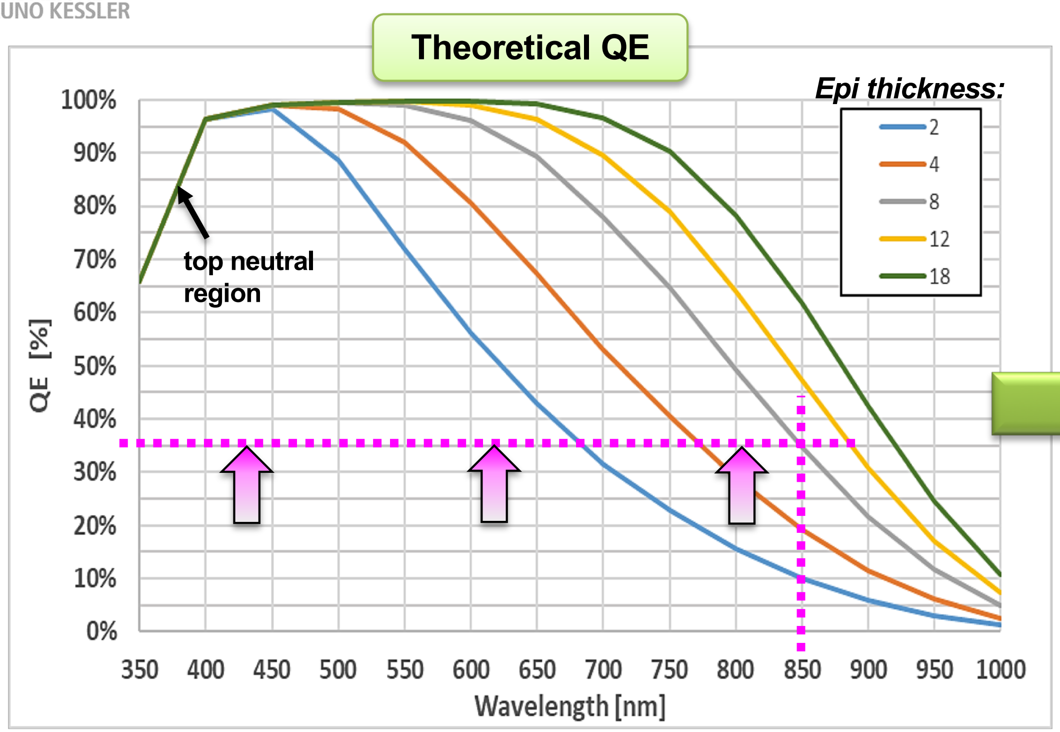


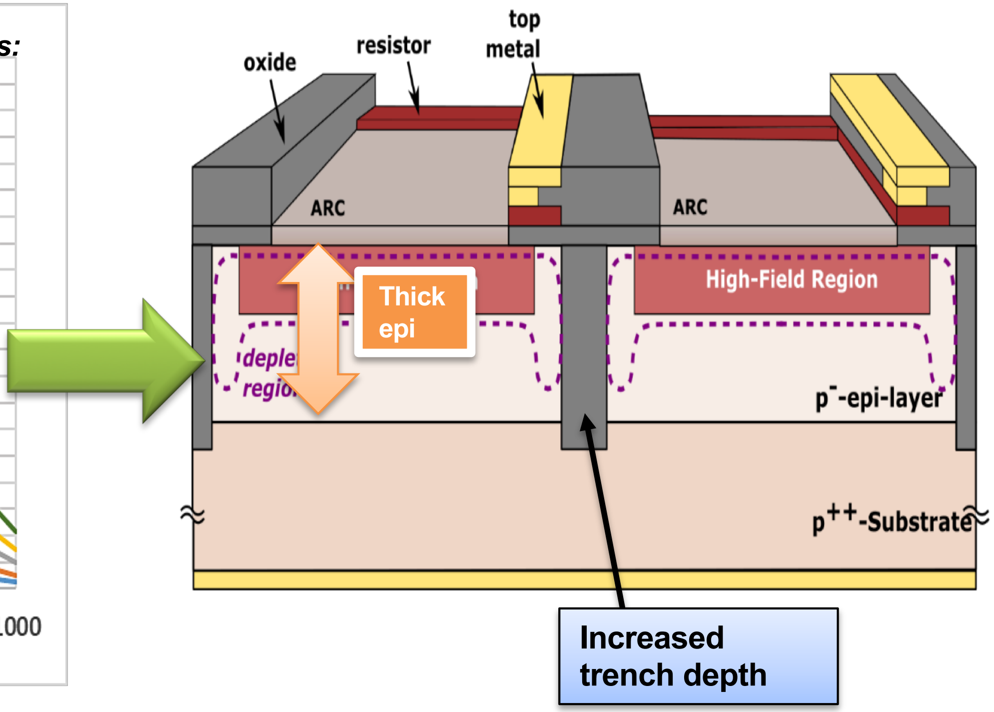
At 850nm → the silicon absorption depth is about 18µm.

→ important to extend the collection depth (with respect to std. SiPMs)

We need to use a thicker epitaxial layer!

Design: thicker epitaxial layer





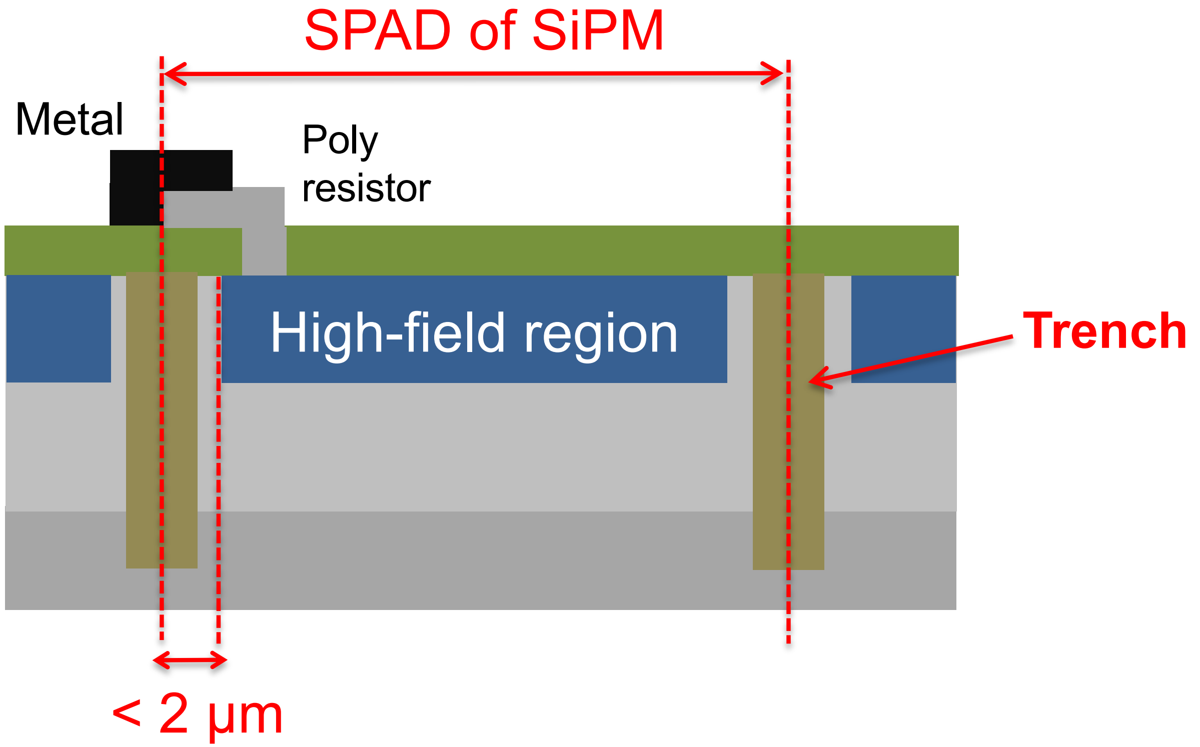
We use a thick epitaxial layer

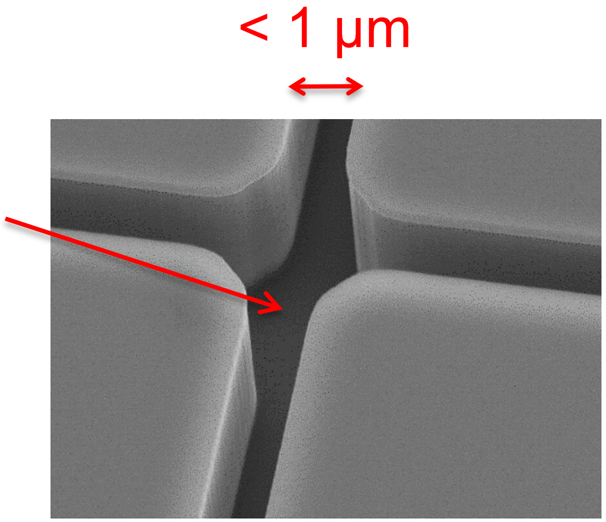
- Theoretical QE at 850 nm: about 35%
- Trench depth increased to: > 8µm

Other factors affect PDE:

- Triggering probability (Pt) increase with over-voltage
- Effective geometric fill-factor (FF)

NIR-HD: technology





- n-on-p junction → higher Pt for NIR light (absorbed at high depth)
- Based on epitaxial layer: sensitive layer
- Narrow dead border region → Higher Fill Factor
- Trenches between cells → Lower Cross-Talk
- Make it simple: 9 lithographic steps

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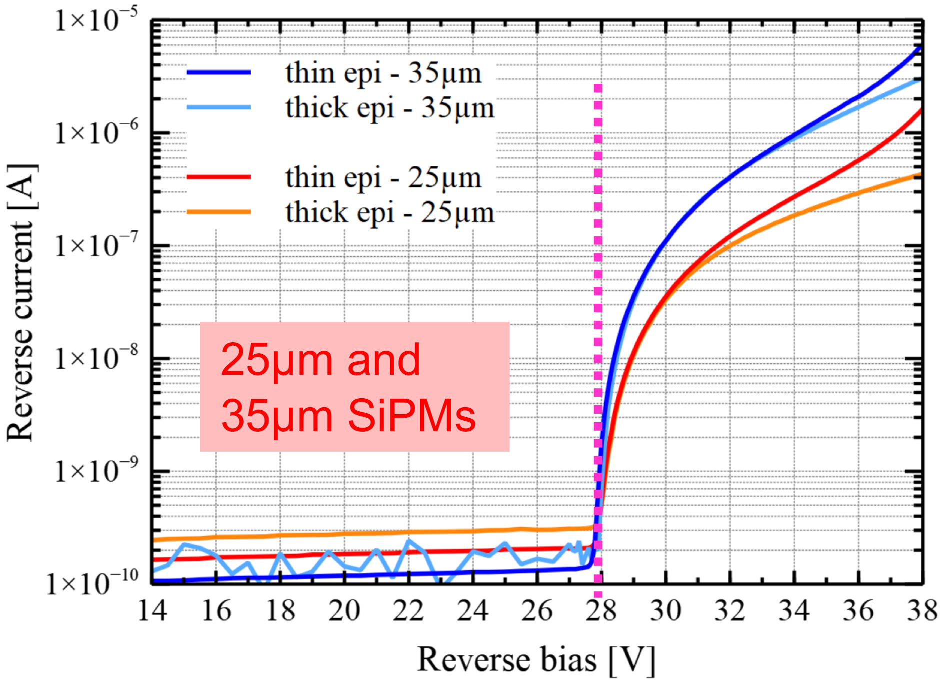
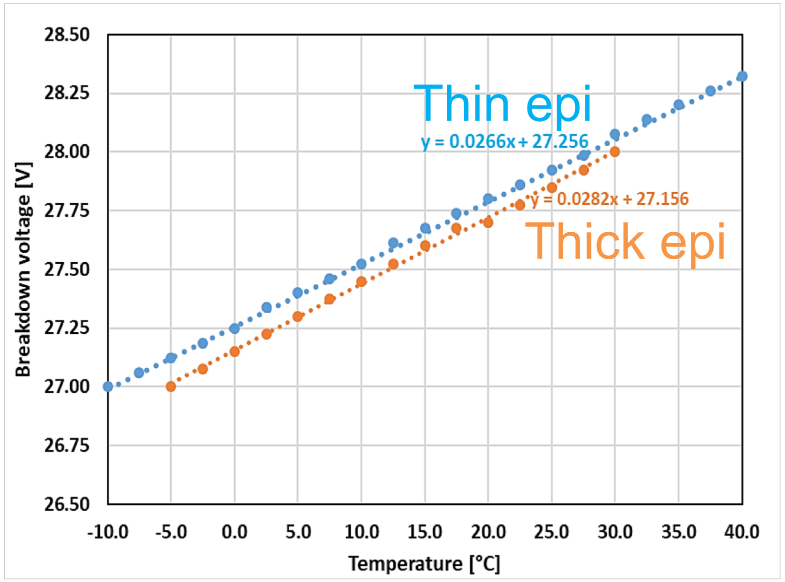
NIR-HD – I-V curve and Breakdown voltage

Breakdown Voltage



25µm and 35µm SiPMs

BD Temperature dependence



Thin vs. thick epitaxial layer

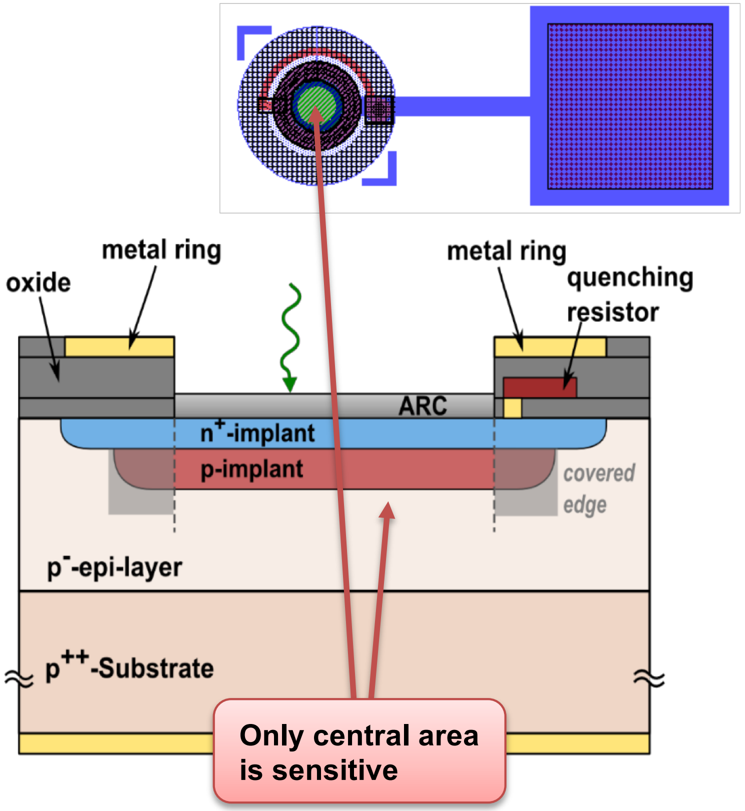
Breakdown voltage is the same of thin-epi (~28V @20°C)

Small Vbd temperature dependence even with thick epitaxial layer

Approx. 28 mV/°C

Acerbi, F. et al (2018). Silicon photomultipliers and single-photon avalanche diodes with enhanced NIR detection efficiency at FBK. *NIMA*, *912*, 309-314.

PDE without border effects: masked SPAD

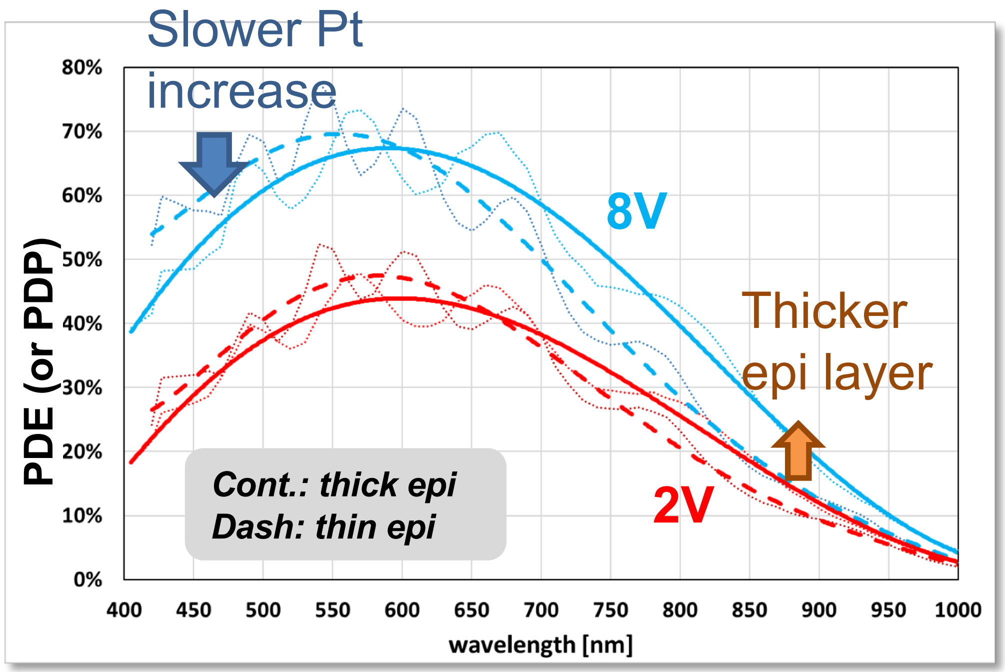


“Masked” SPAD

Single SPAD (circular) with covered edges

Limit of the technology
(without changing epi layer)

Masked SPAD PDE



Without border effect, thicker epitaxial layer provides a significant increase of PDE at long wavelengths

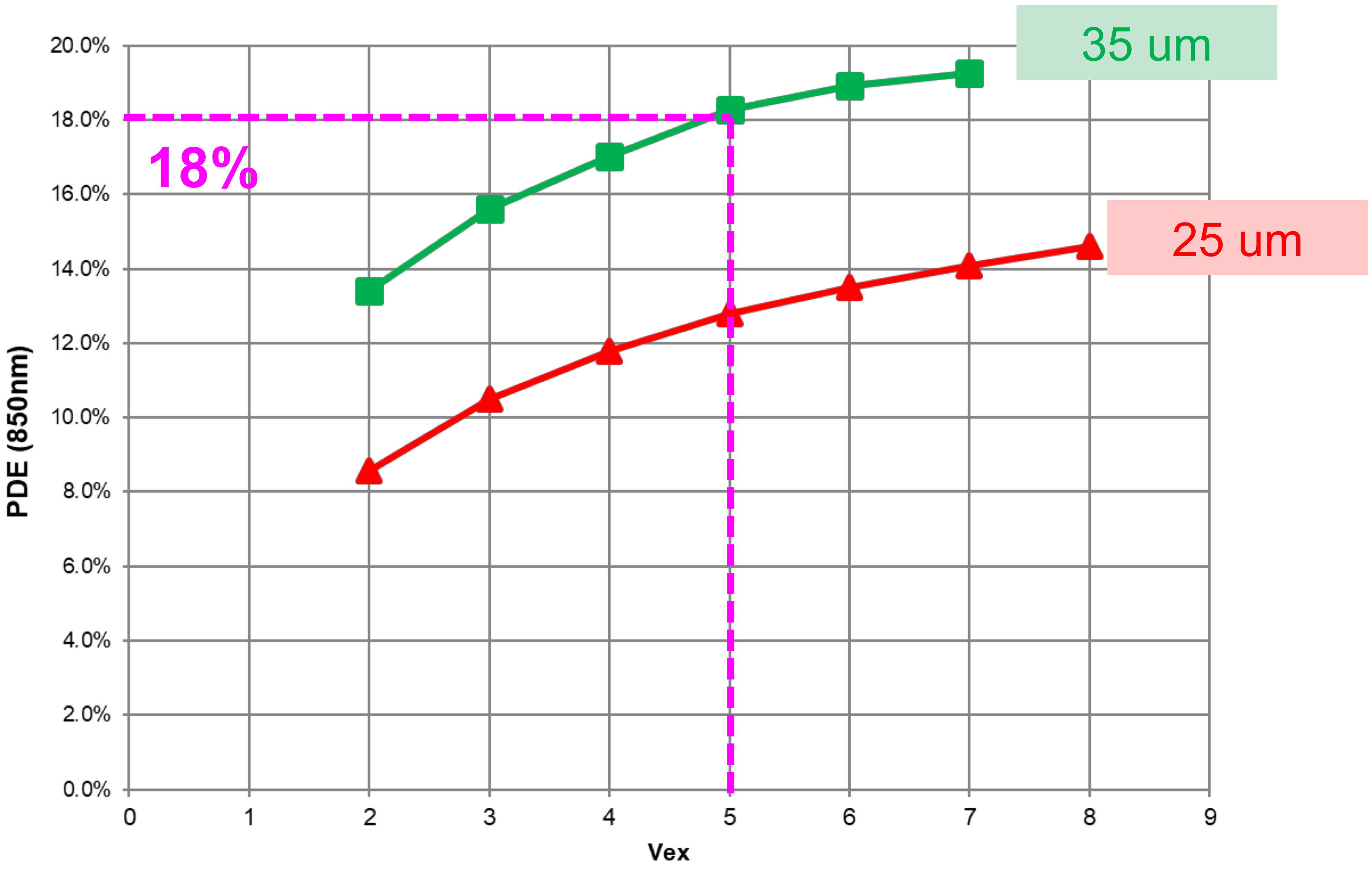
PDE: from 20% to ~ 30% at 850nm
from ~12% to ~18% at 900nm

NIR-HD run @ FBK

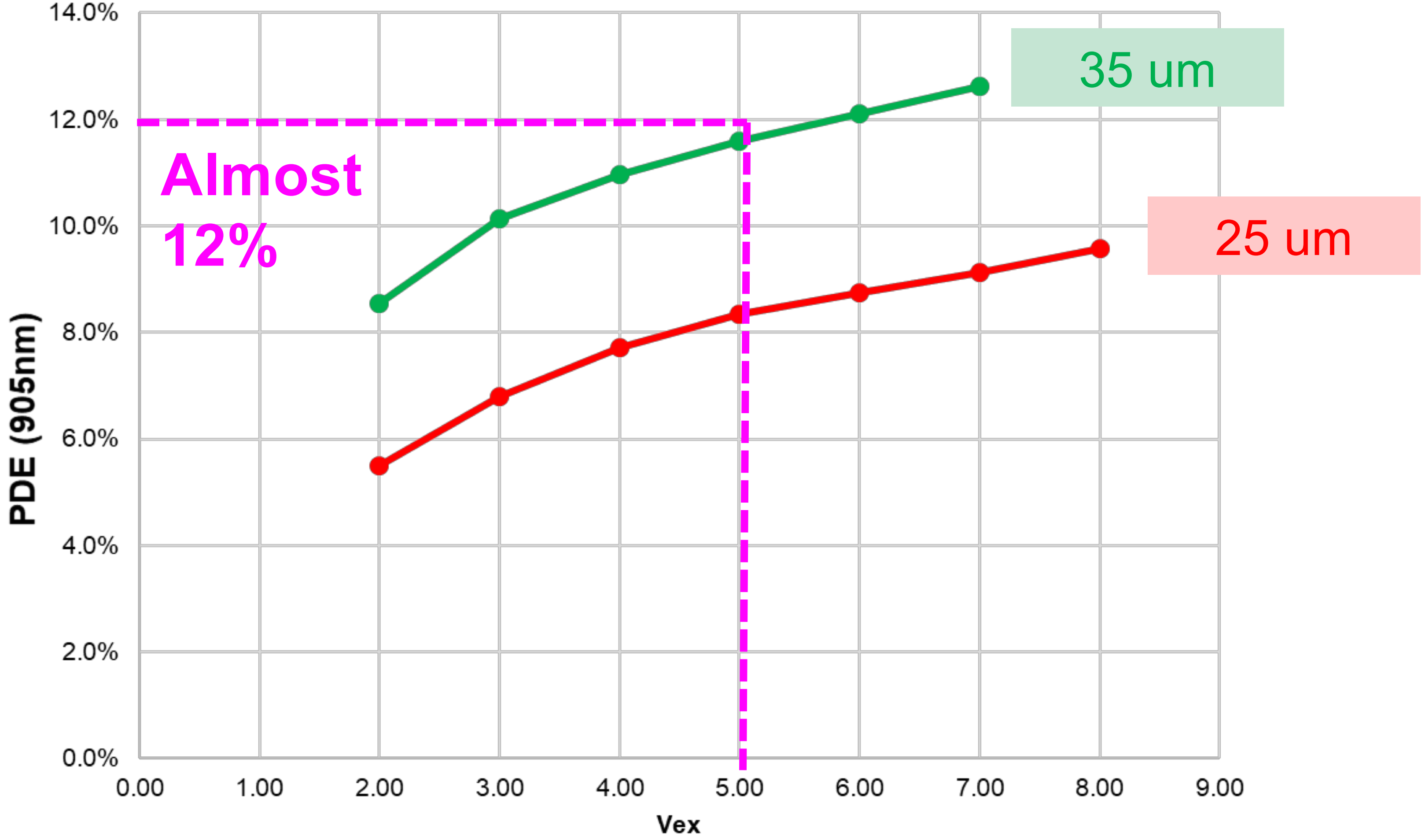
End of 2017

Functional characterization

PDE vs. Over-voltage at 850 nm

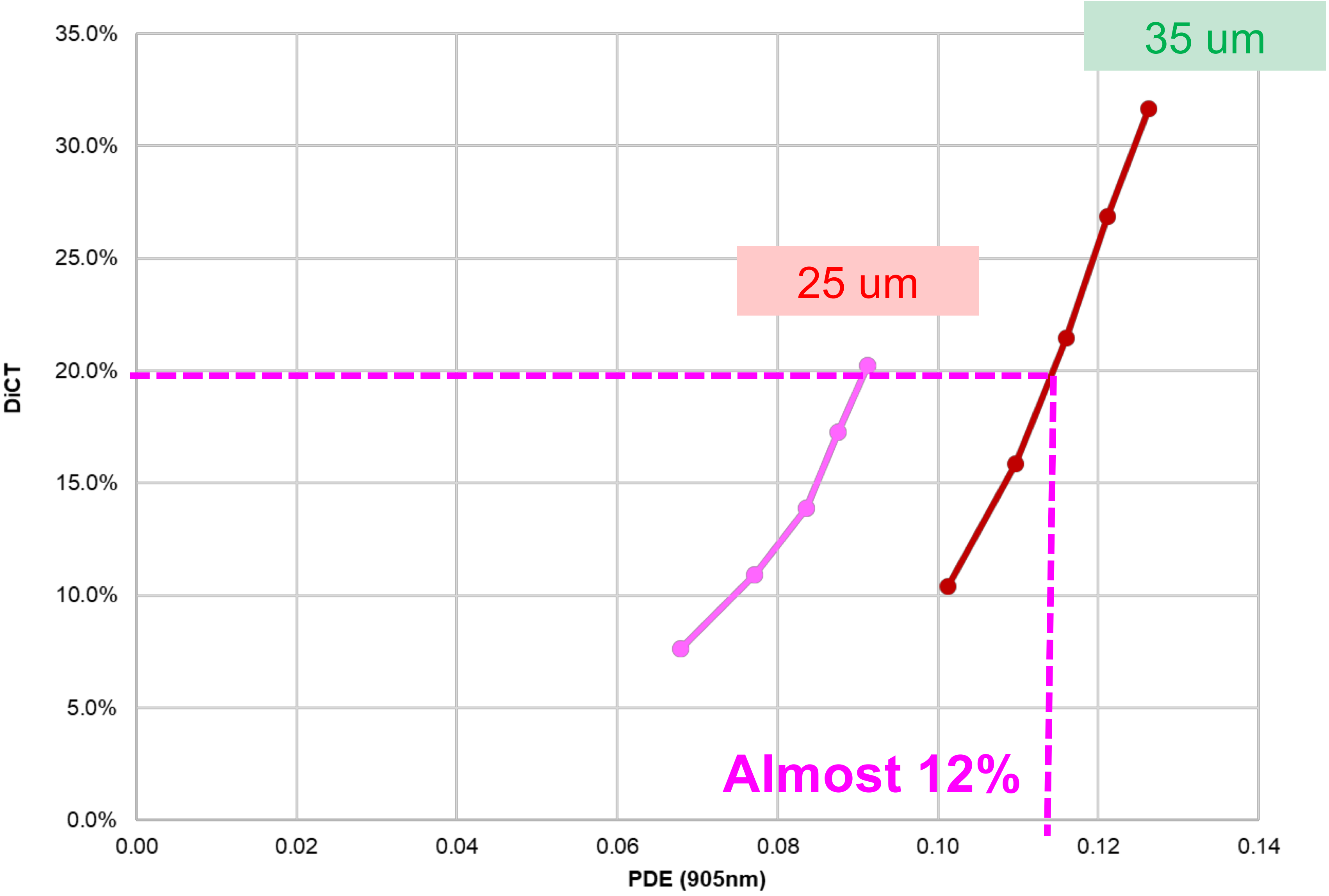


PDE vs. Over-voltage at 905 nm



Almost 12%

Direct Crosstalk vs. PDE



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Thank you!

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

Fabio Acerbi
Massimo Capasso
Gabriele Faes
Nicola Furlan
Marco Marcante
Alberto Mazzi
Stefano Merzi
Claudio Piemonte
Veronica Regazzoni
Nicola Zorzi