NUV-HD and NIR-HD SiPMs and Applications

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Fondazione Bruno Kessler

Publicly funded research center

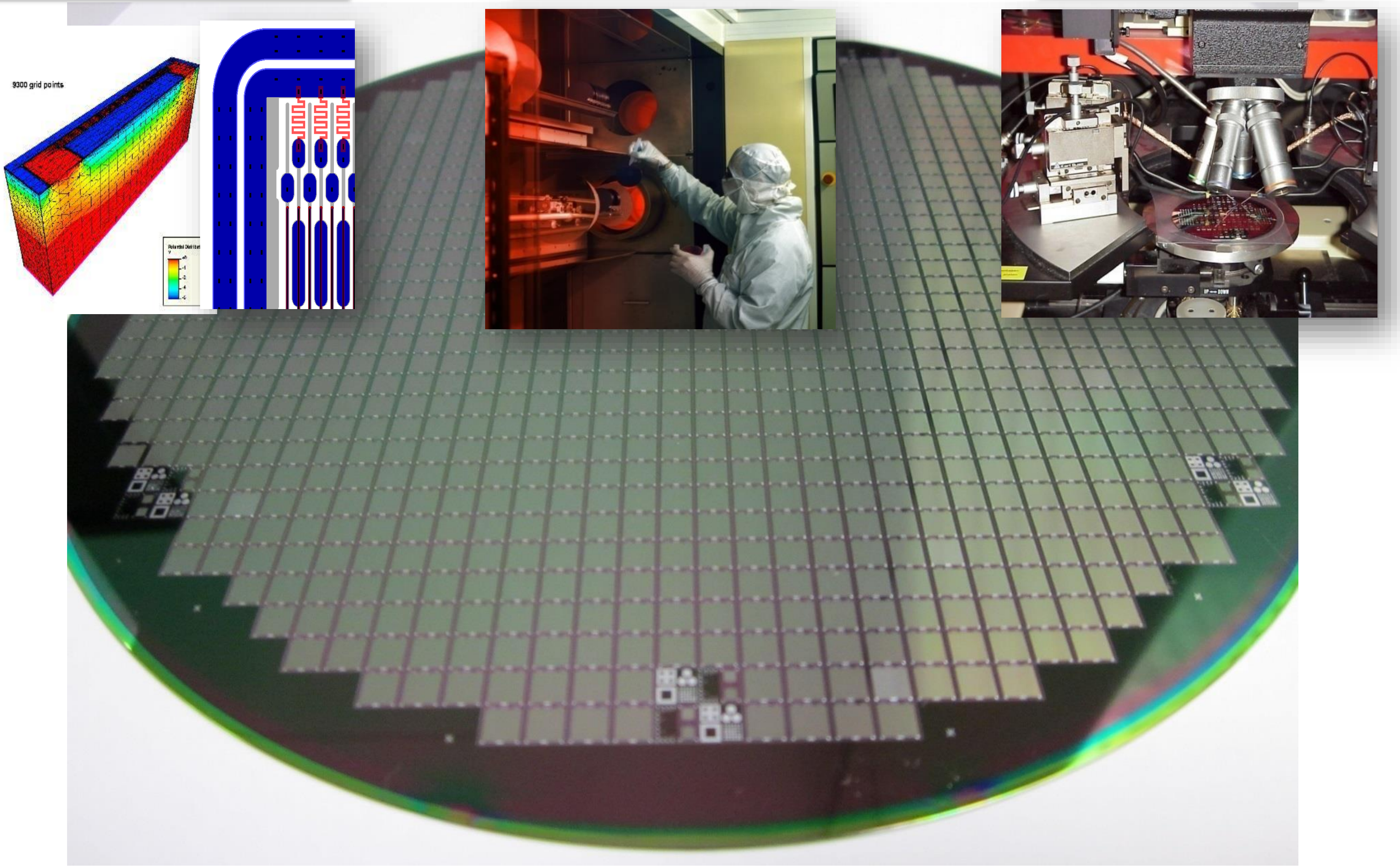
350 researches working in different fields

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

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

FBK expertise

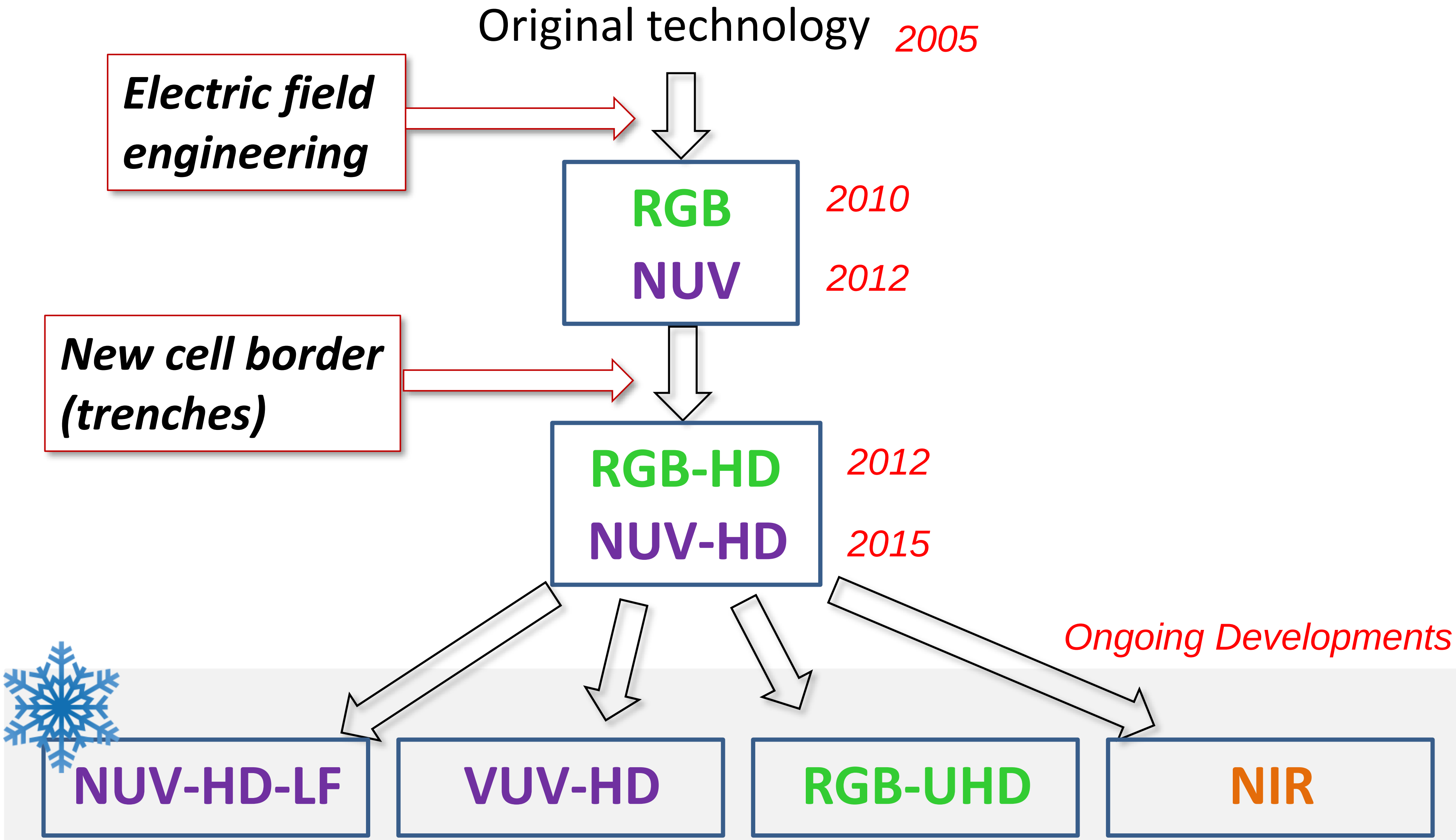
Simulation & design → Fabrication → Device testing



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

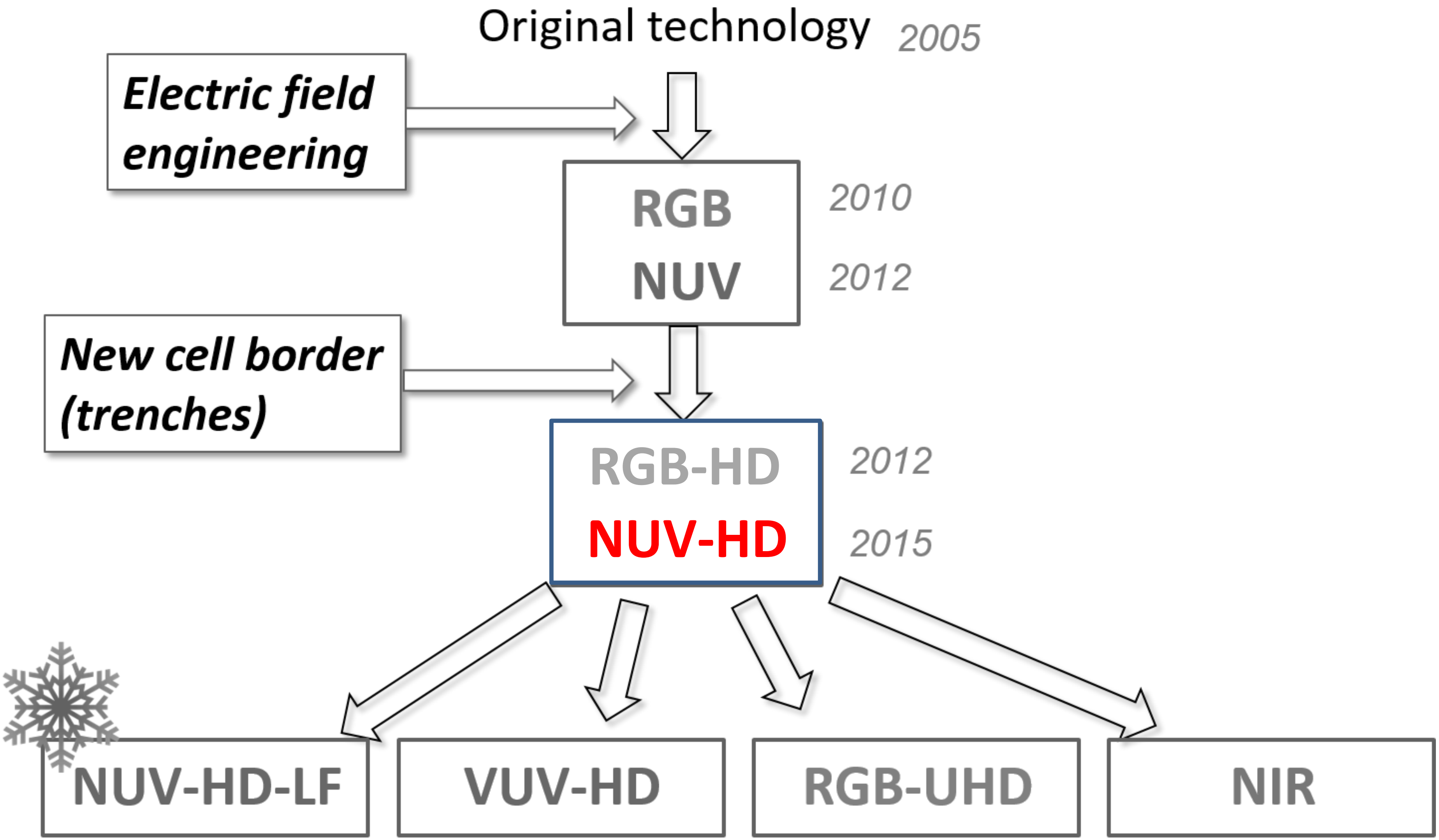
VUV-HD

RGB-UHD

NIR

Near-UV technology
NUV-HD

Near-UV technology: NUV-HD



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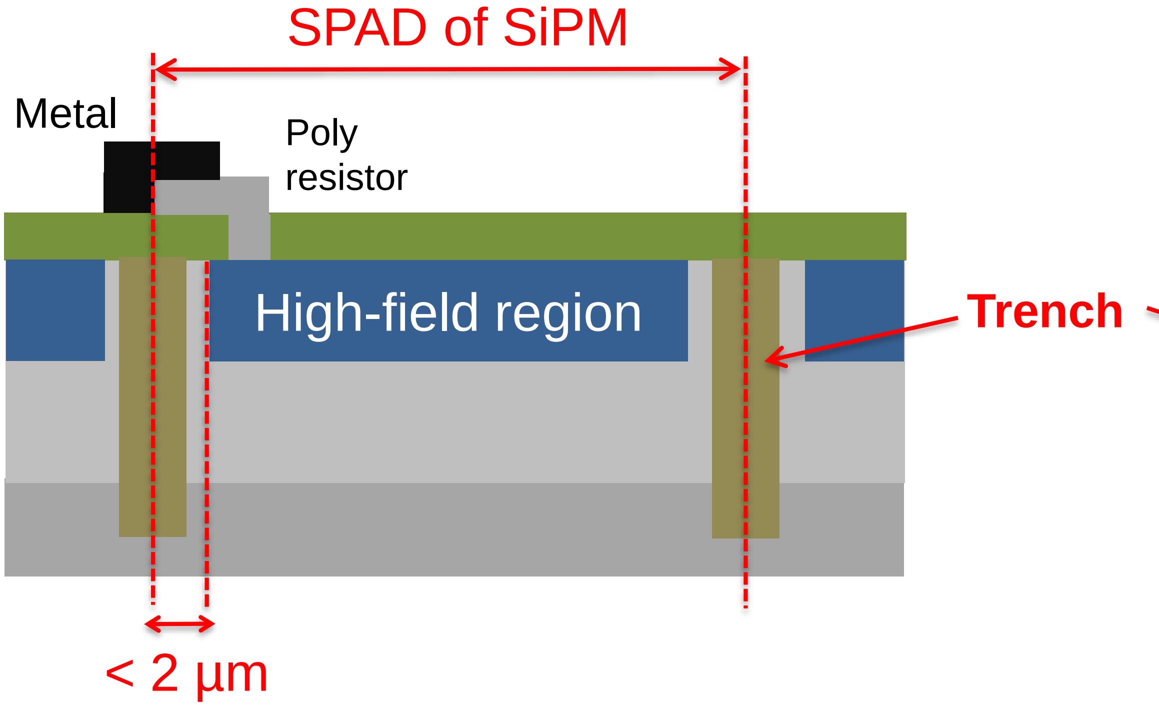
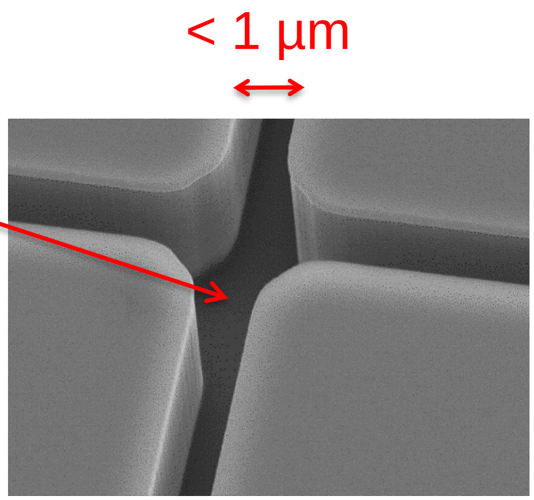
NUV-HD: technology





- 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

(C. Piemonte et. al., (2016) IEEE T. Electr. Dev., 10.1109/TED.2016.2516641)

Signal: Photon Detection Efficiency

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

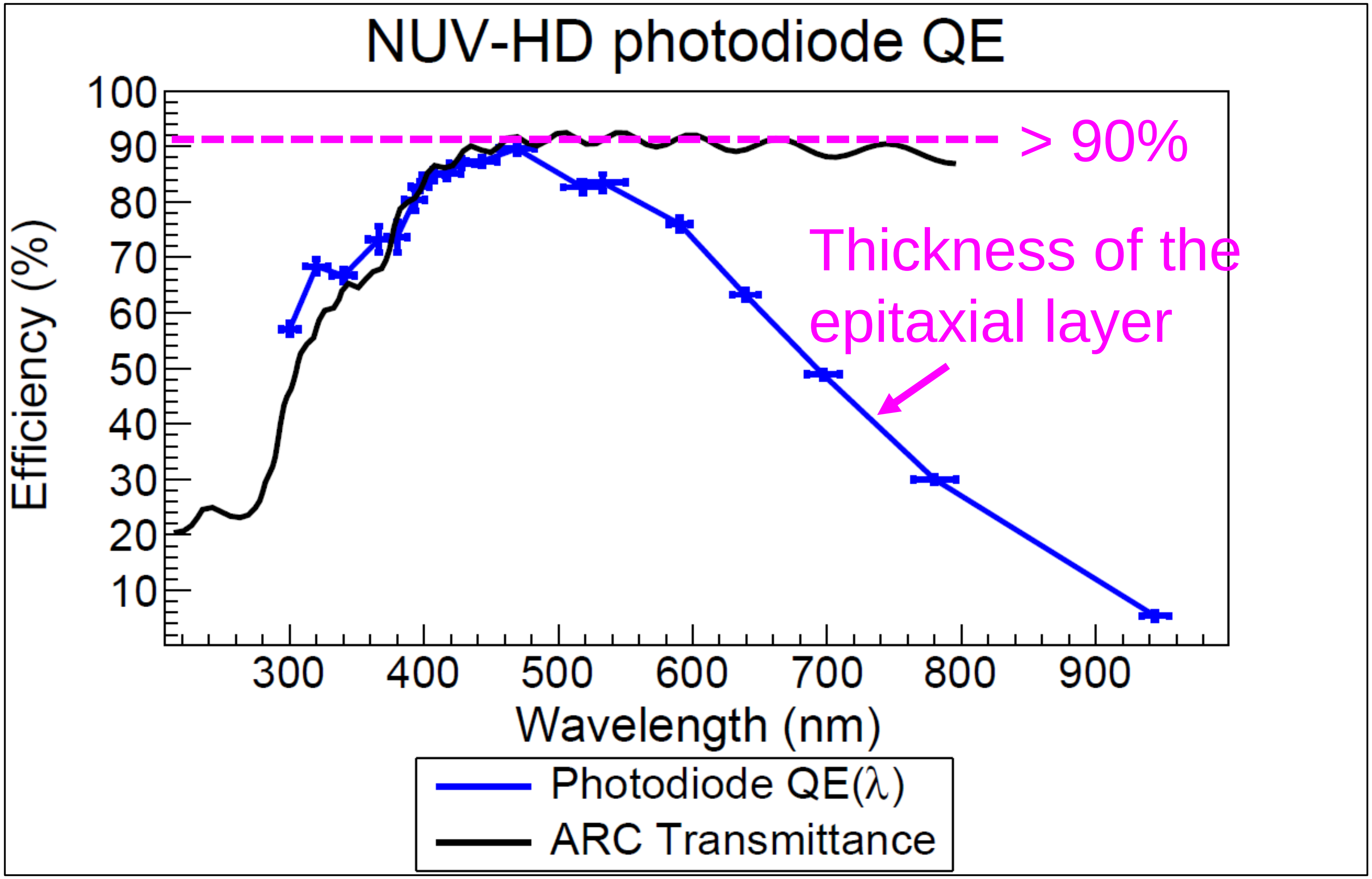
Fill Factor

Quantum Efficiency

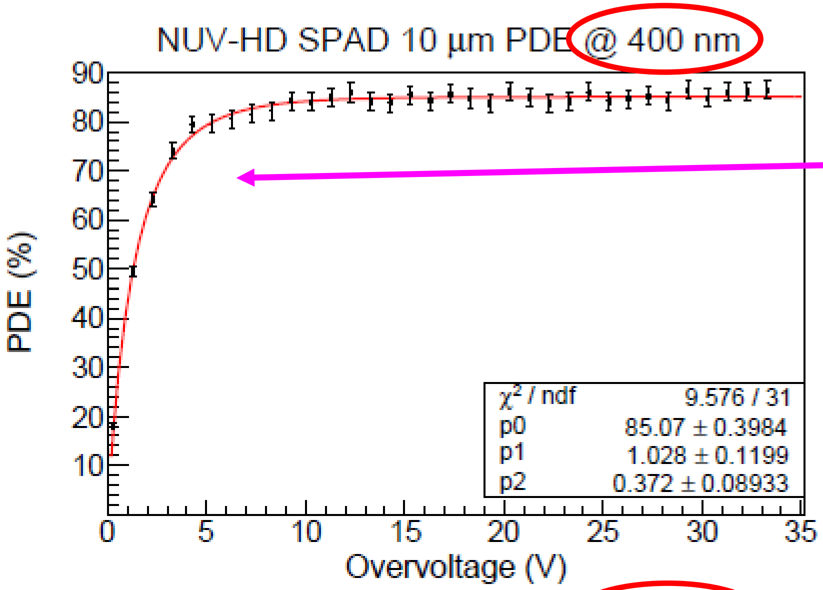
Avalanche Triggering Probability

NUV-HD: QE

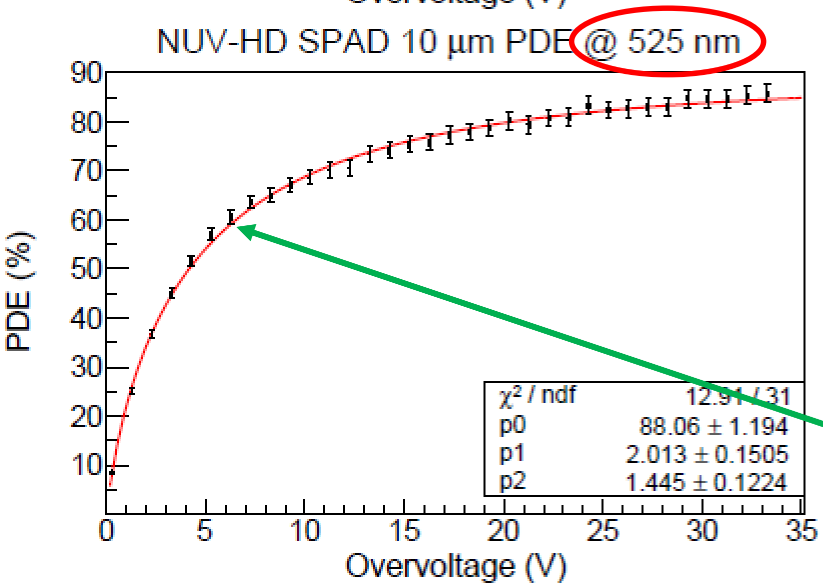
Measured on a photodiode with same layers as SiPM



NUV-HD: QE*Pt

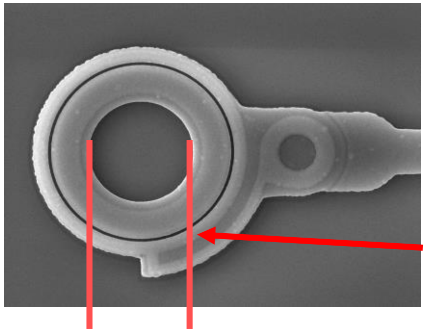


Fast increase with over-voltage:
→ avalanche is initiated by electrons



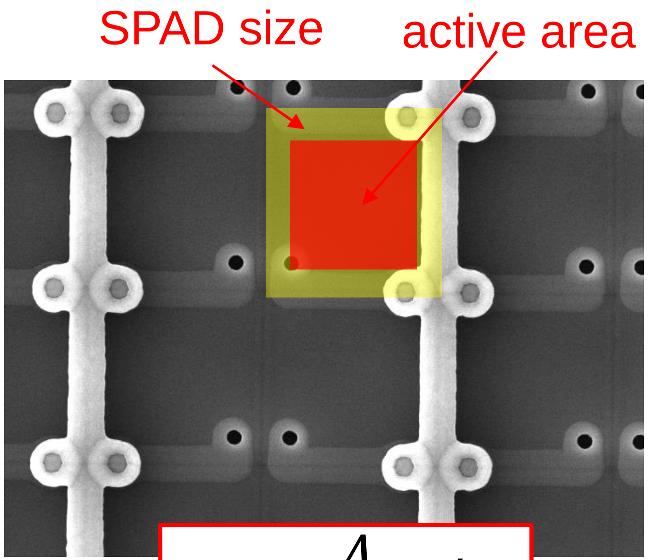
Slower increase with over-voltage:
→ avalanche is initiated by holes (and electrons)

Measured on a SPAD with 100% FF

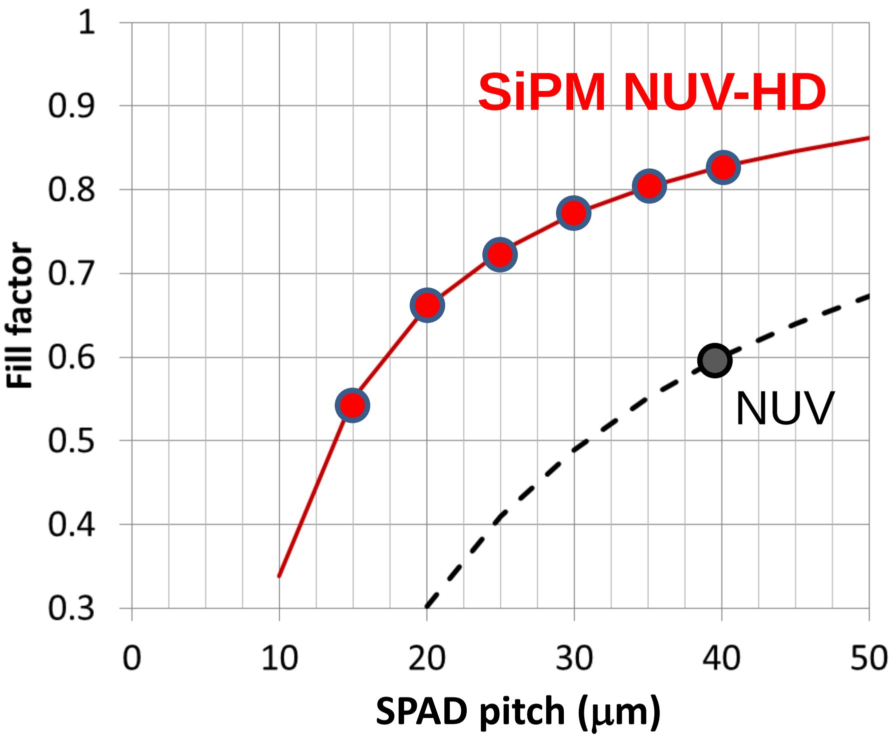


SPAD size is defined by metal opening which is within the high-field region

NUV-HD: Fill Factor



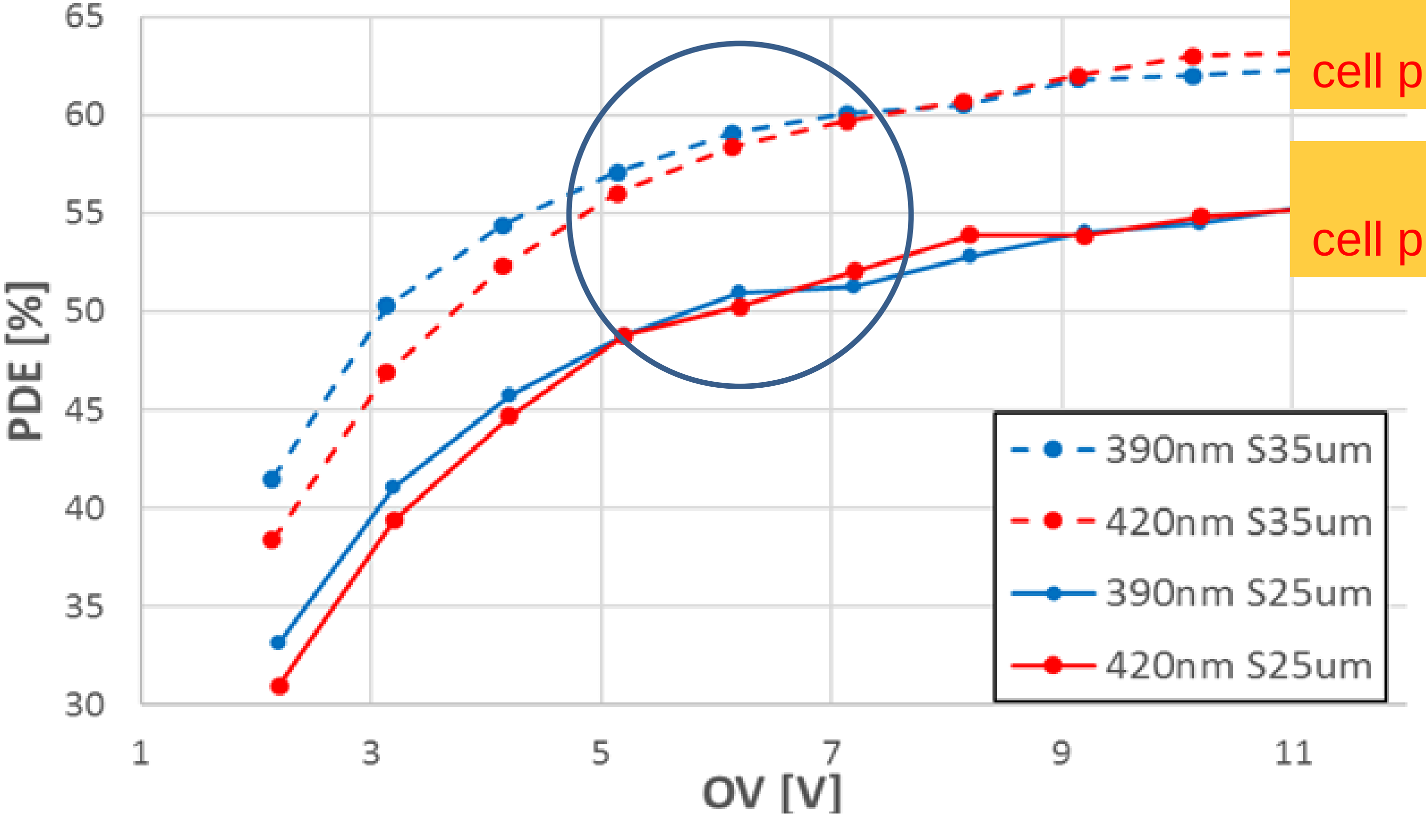
$$FF = \frac{A_{active}}{A_{total}}$$



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 ↔ **High PDE** ↔

Photon detection efficiency

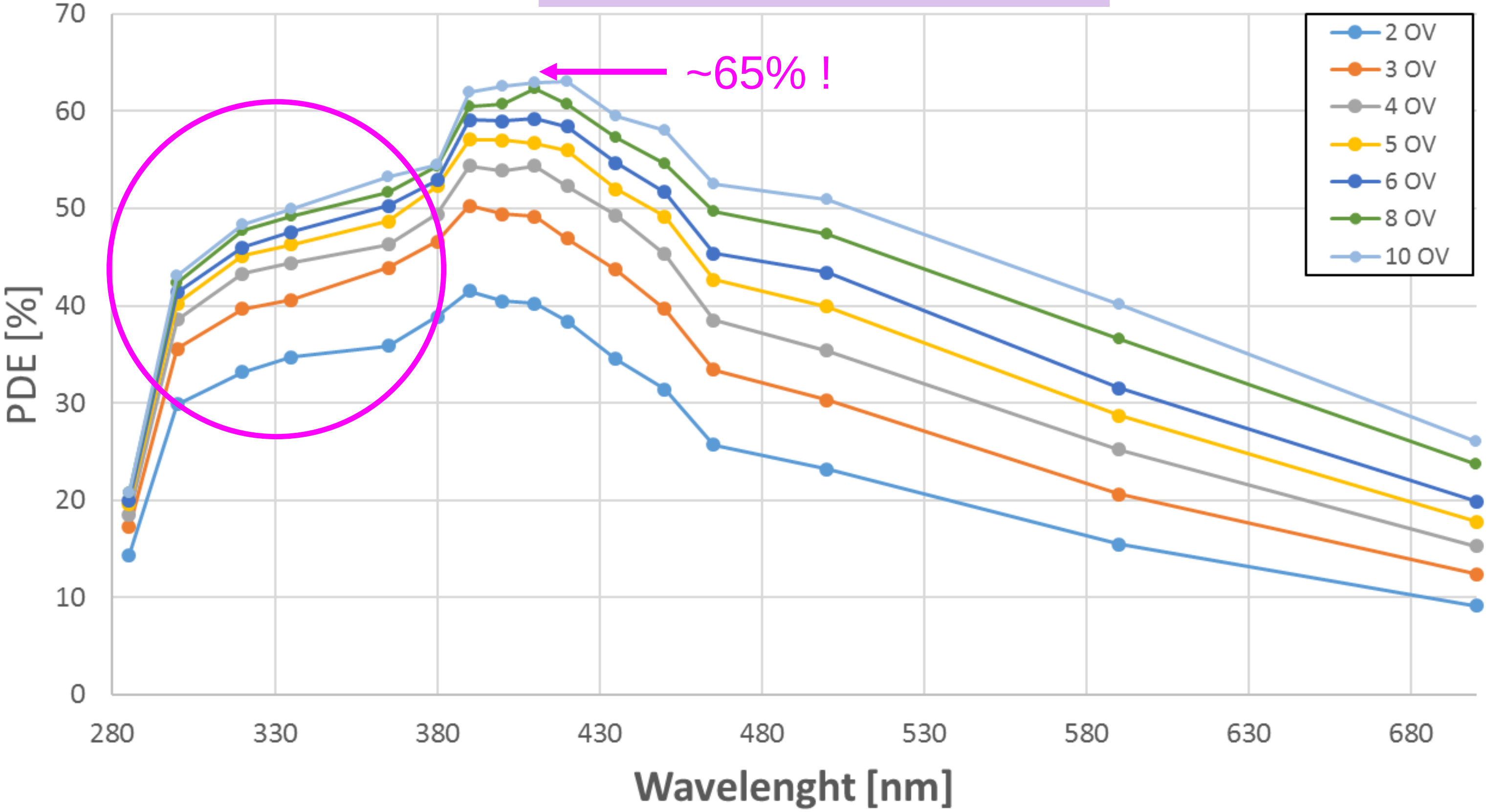


35µm
cell pitch (FF=83%)

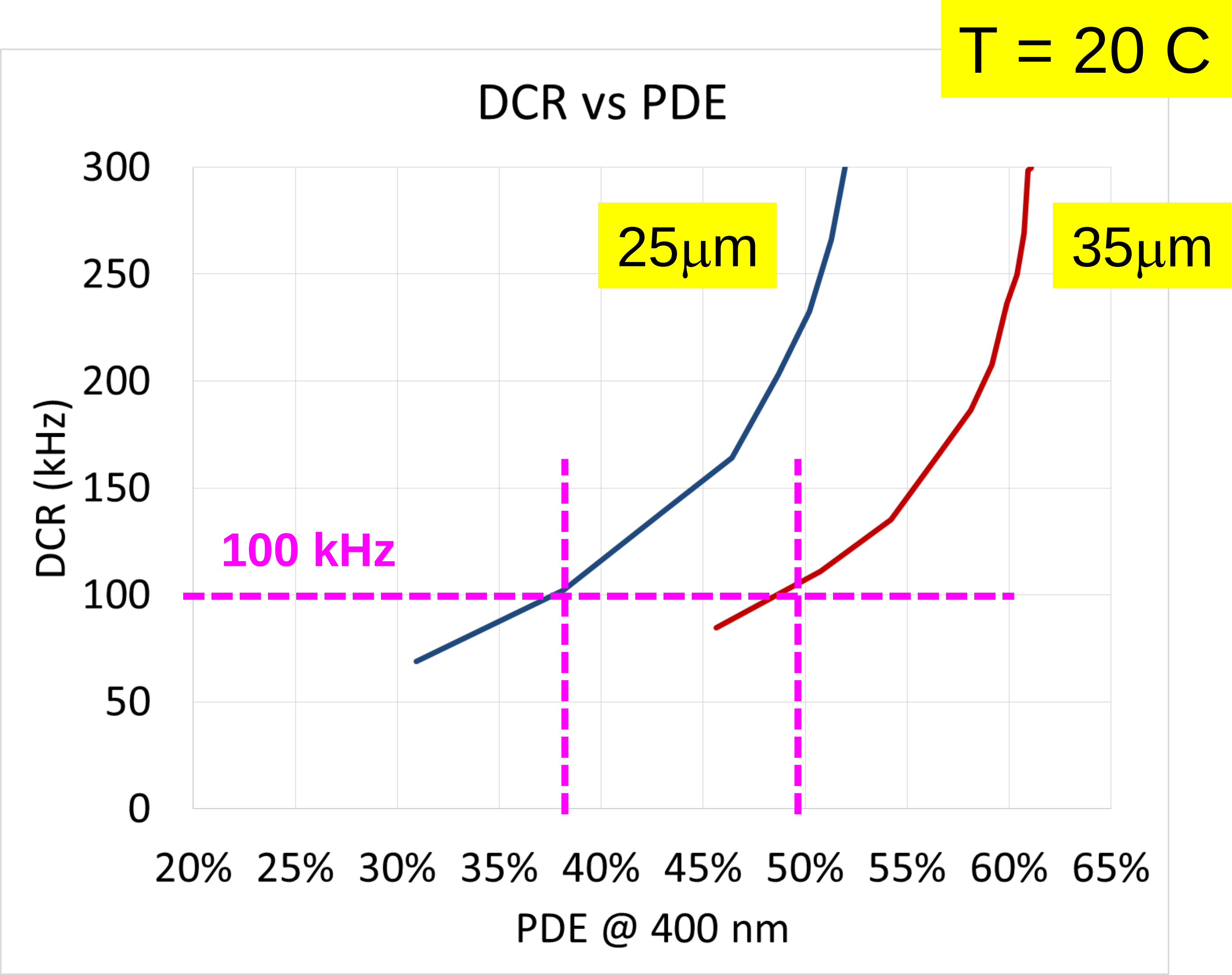
25mm
cell pitch (FF=73%)

Photon detection efficiency

35mm cell pitch



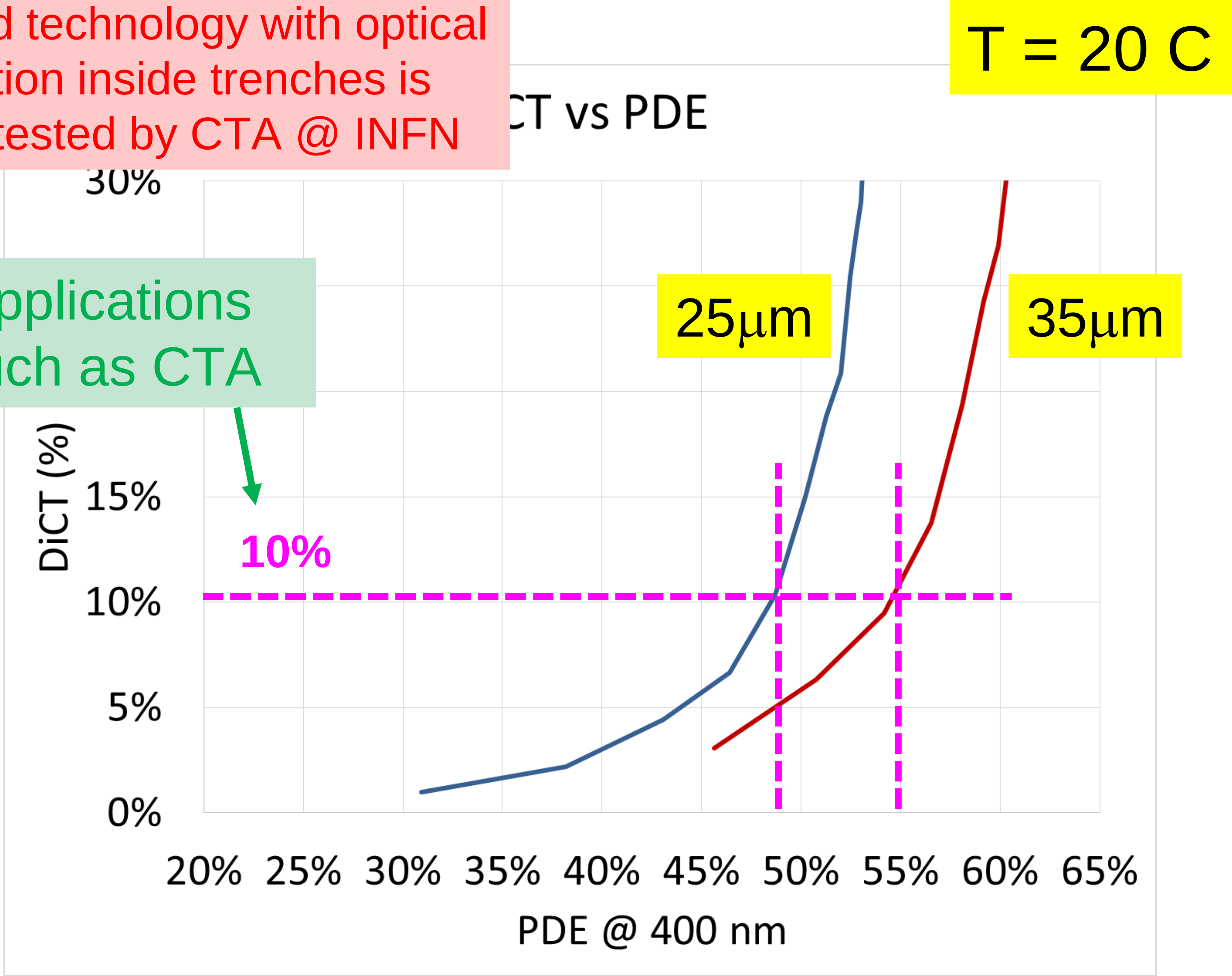
Dark Count Rate



Optical Cross-Talk

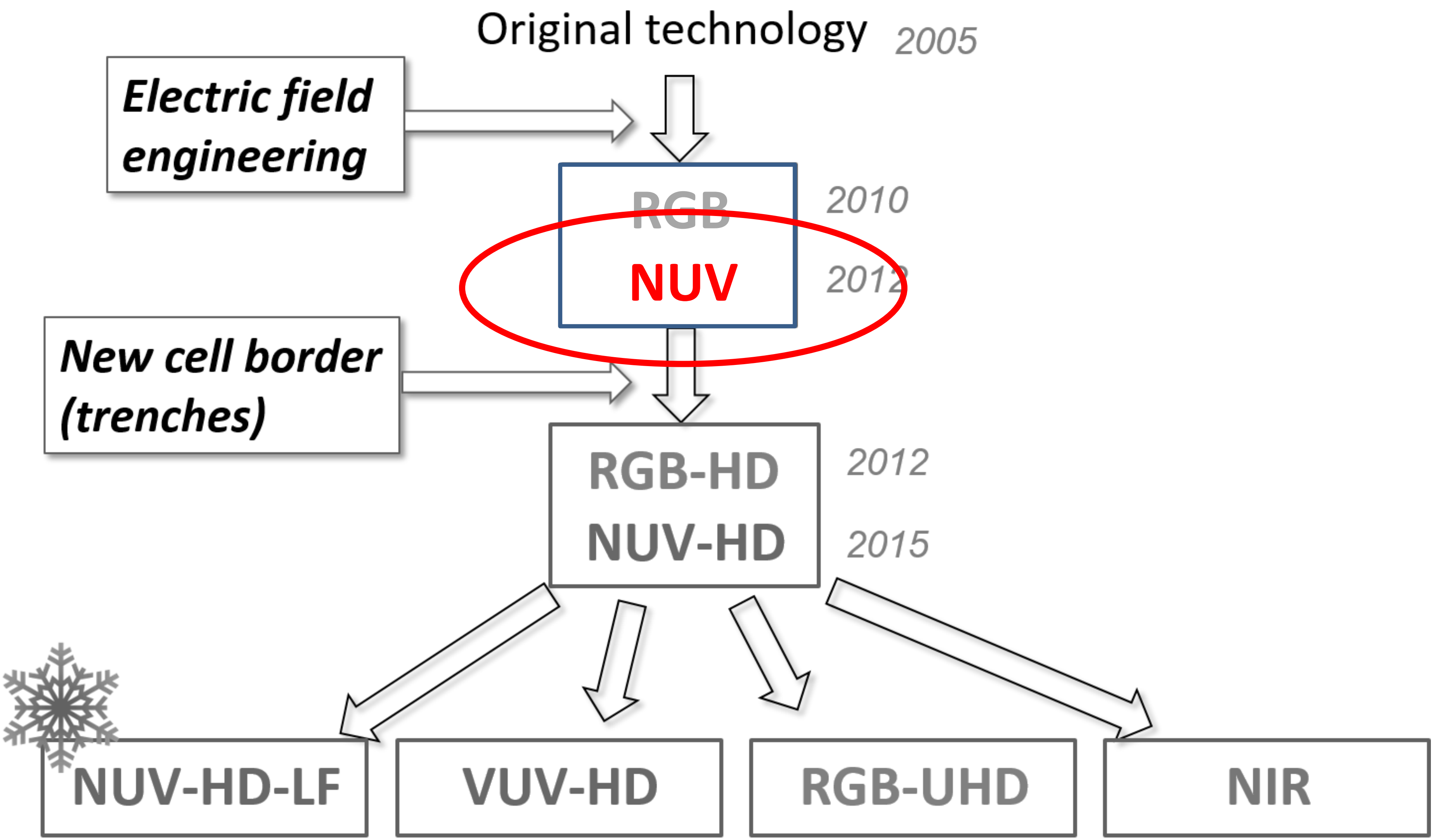
Updated technology with optical isolation inside trenches is being tested by CTA @ INFN

Applications such as CTA



Single Photon Time Resolution

Single Photon Timing Resolution



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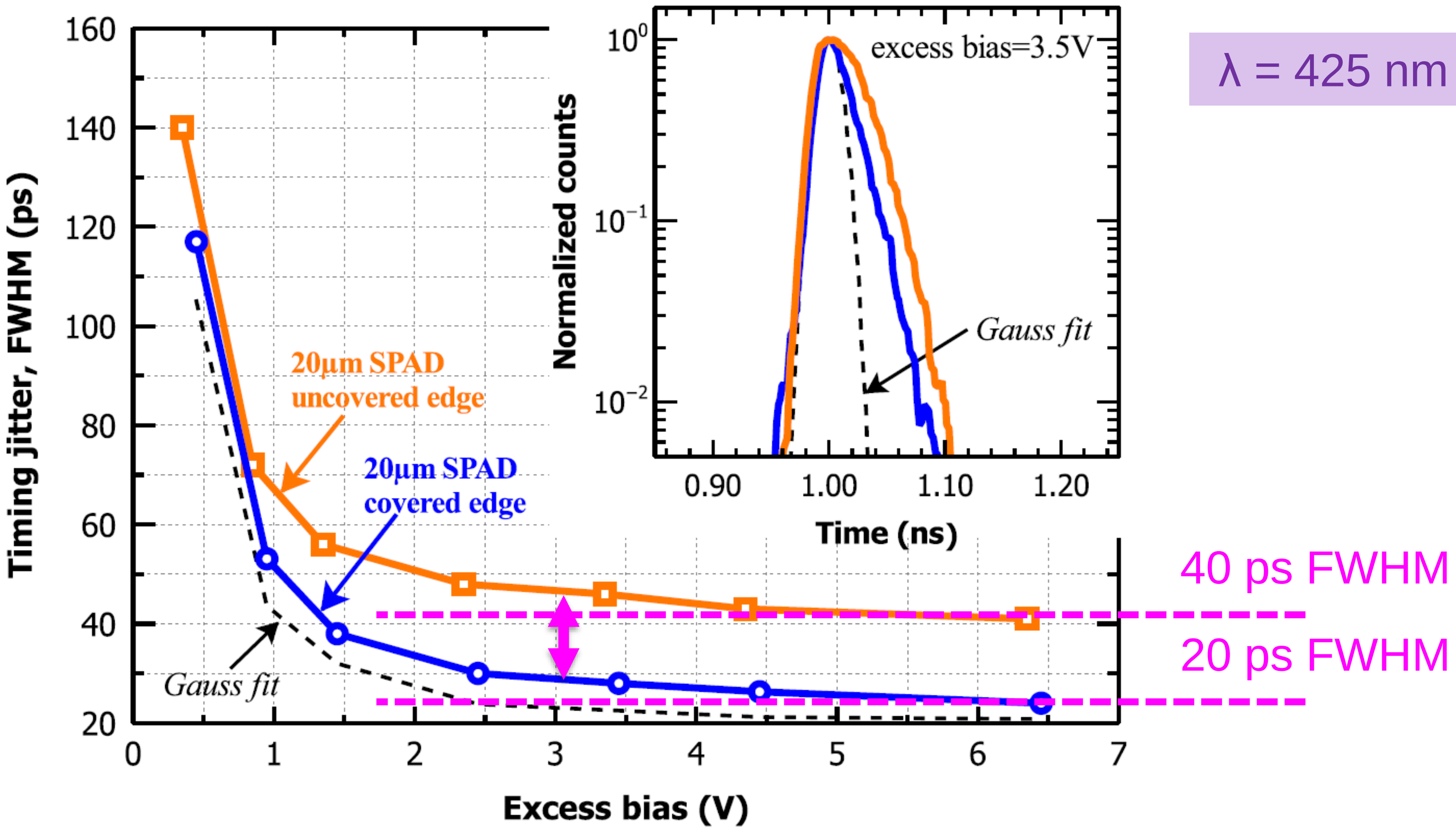
NUV SPAD – SPTR



λ = 425 nm

Worse charge collection at SPAD edges

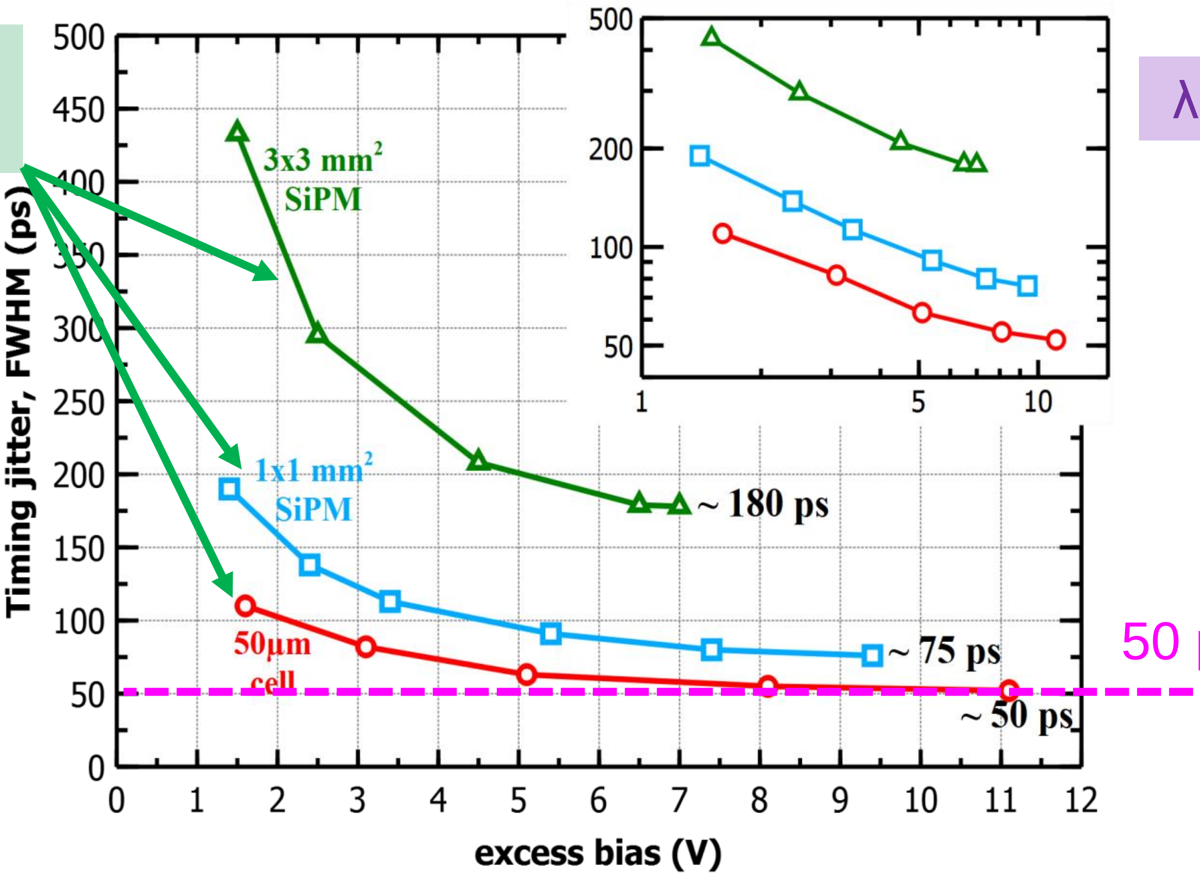
Covering the SPAD edges reduces the SPTR by 20 ps

FONDAZIONE
BRUNO KESSLER

NUV SiPM – SPTR

Different SiPM sizes

λ = 425 nm

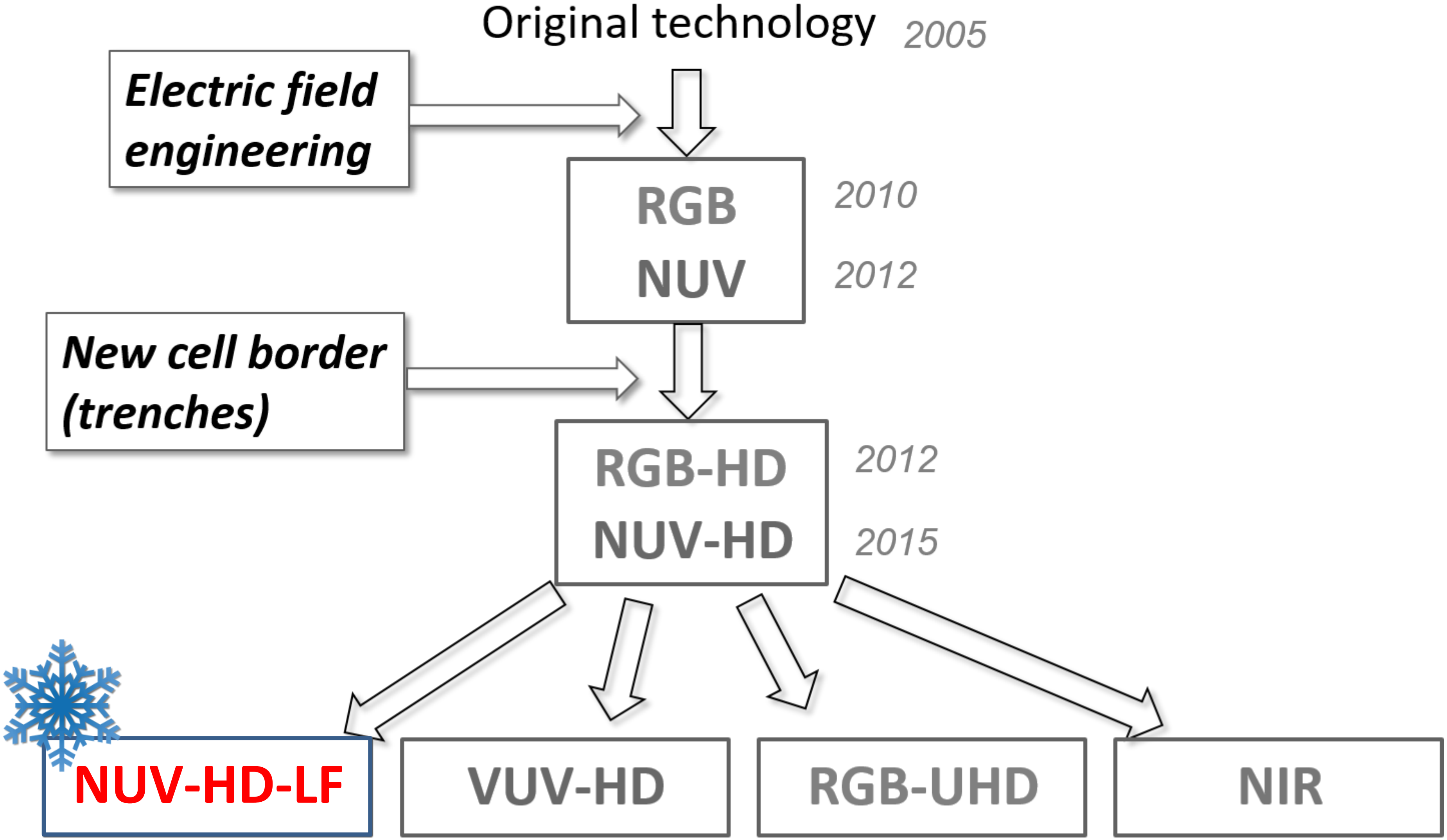


50 ps FWHM!

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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RGB-HD 2012

NUV-HD 2015

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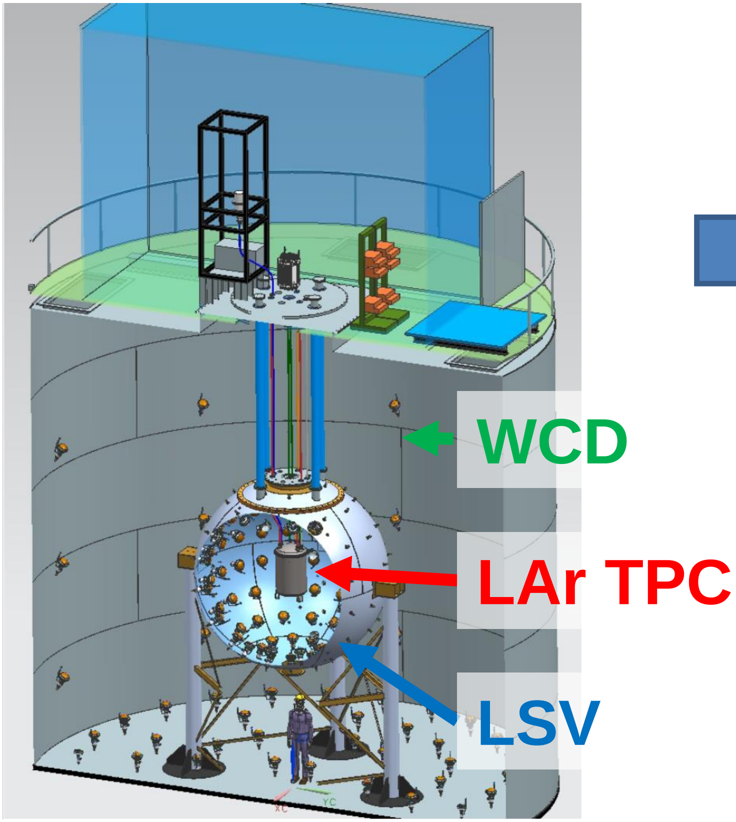
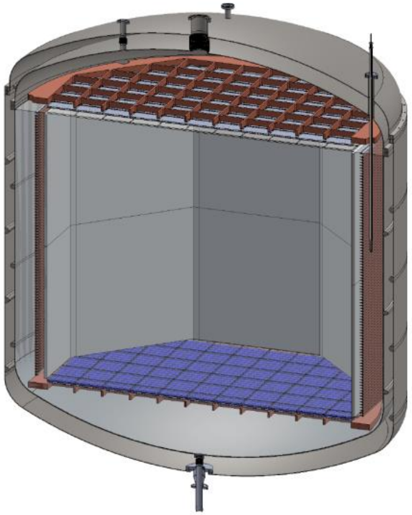
Cryogenic Applications of SiPMs

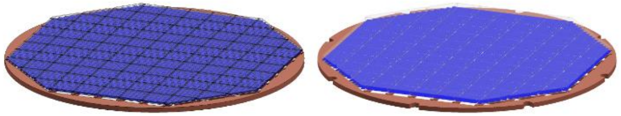
There is a growing interest in using SiPMs for the readout of liquid scintillators at cryogenic temperatures.



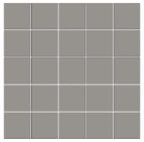


~ 23t of UAr

TPB WLS: emission at 400 – 450 nm



2 light readout planes: 15 m^2



SiPM tiles

DarkSide-50
PMT-based TPC

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%

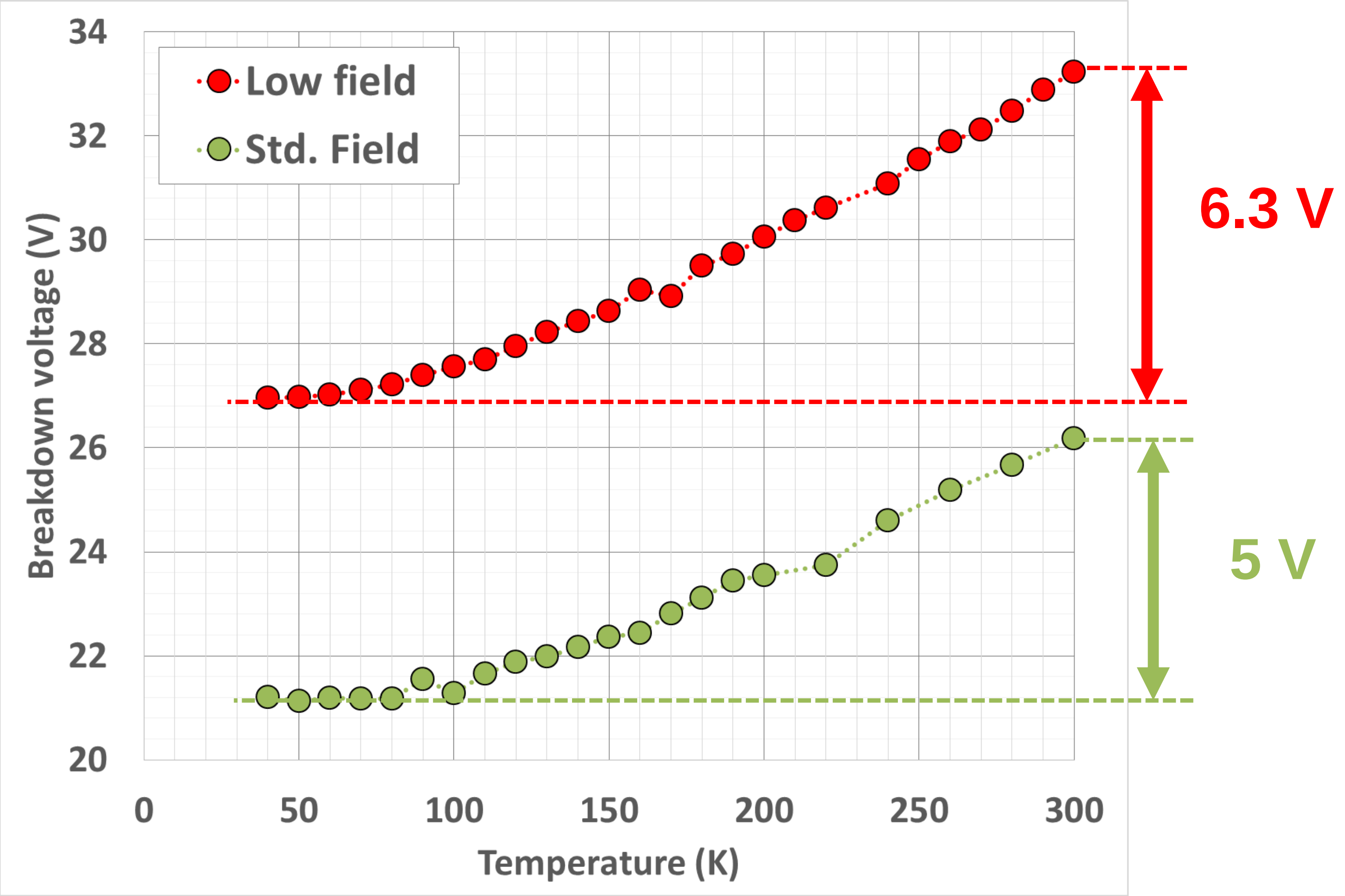
SiPM characteristics tested **form 300 K to 40 K**

In collaboration with LNGS

Optimized for low temperature operation

Breakdown Voltage vs. Temperature

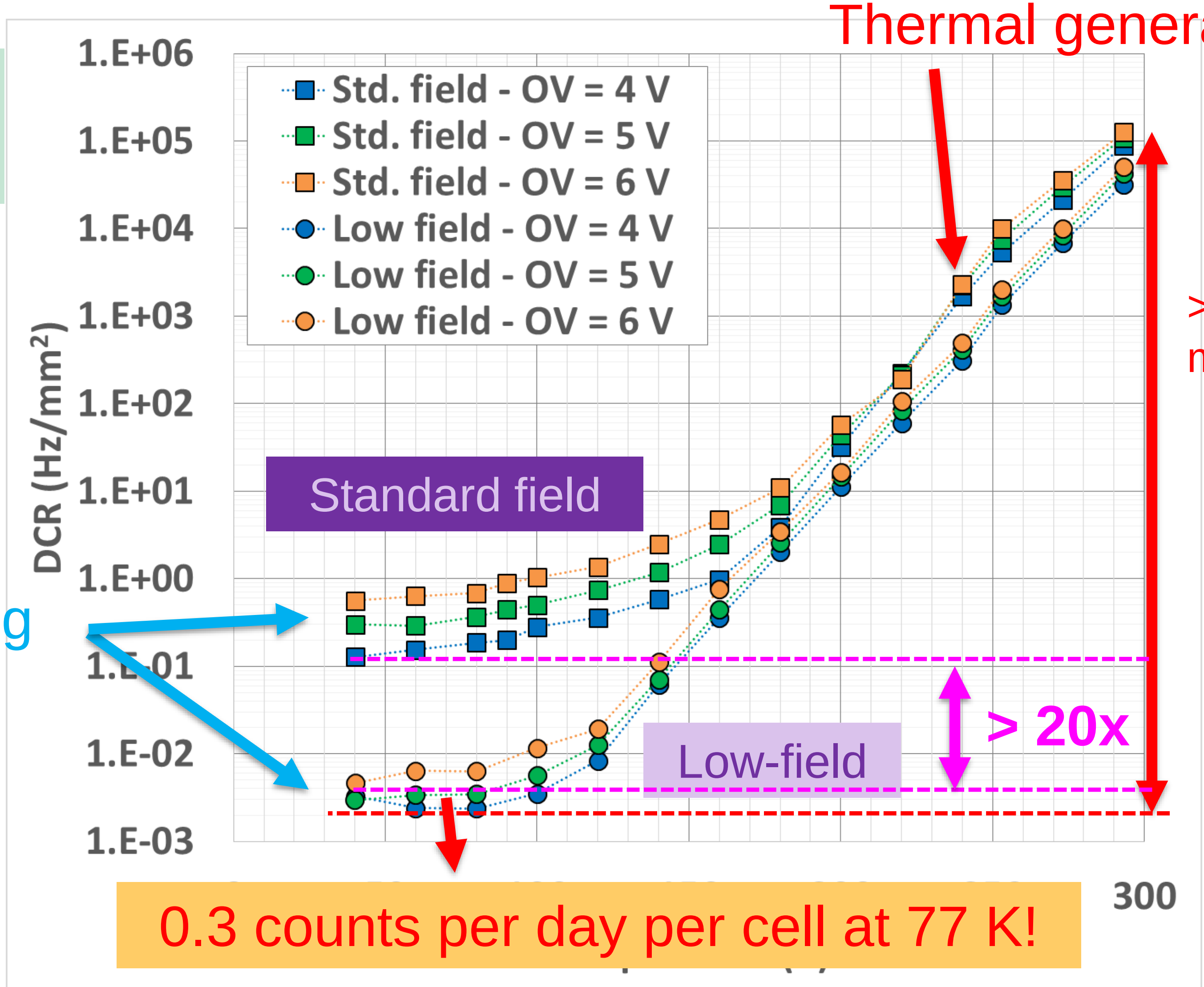
The mean free path of the carriers in the high-field region increases with decreasing temperature.



NUV-HD – Cryogenic DCR Measurements

25 um cell

Thermal generation



Tunneling

Standard field

Low-field

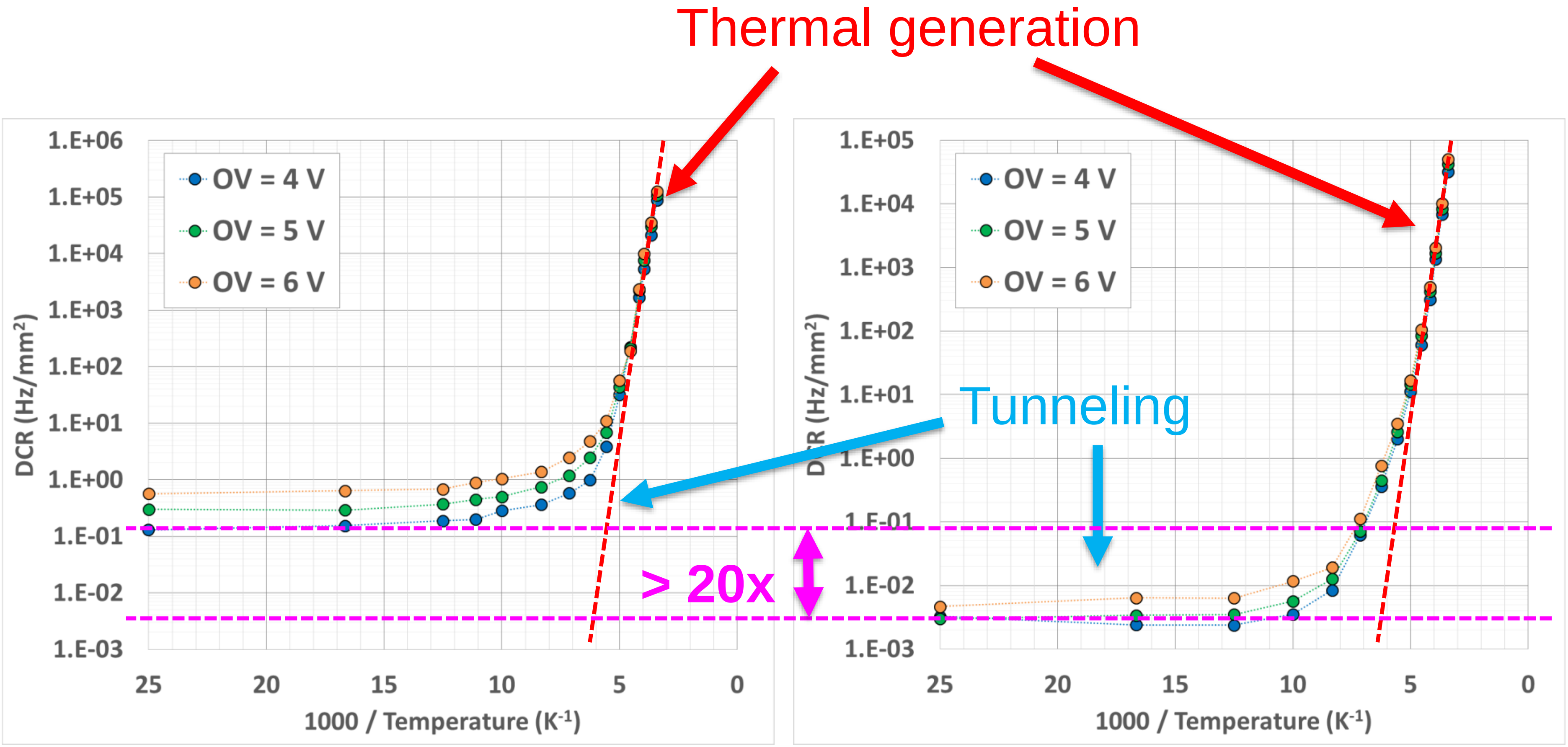
> 20x

> 7 orders of magnitude !

0.3 counts per day per cell at 77 K!

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

DCR / mm² – Arrhenius plot


Thermal generation

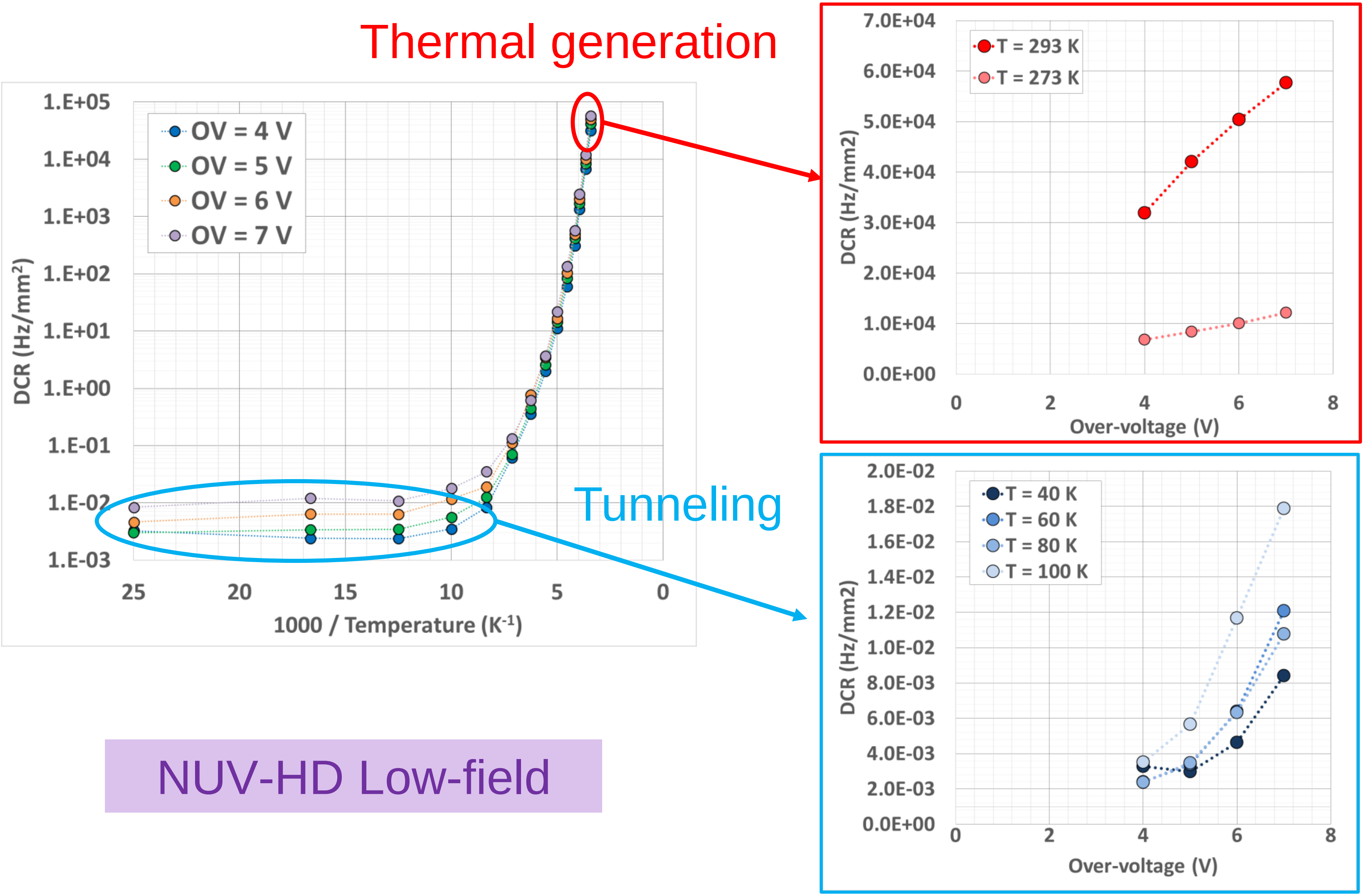
Tunneling

> 20x

Standard field

Low-field

DCR / mm^2 vs. Over-voltage



Thermal generation

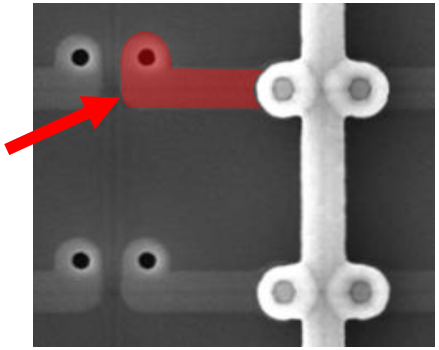
Tunneling

NUV-HD Low-field

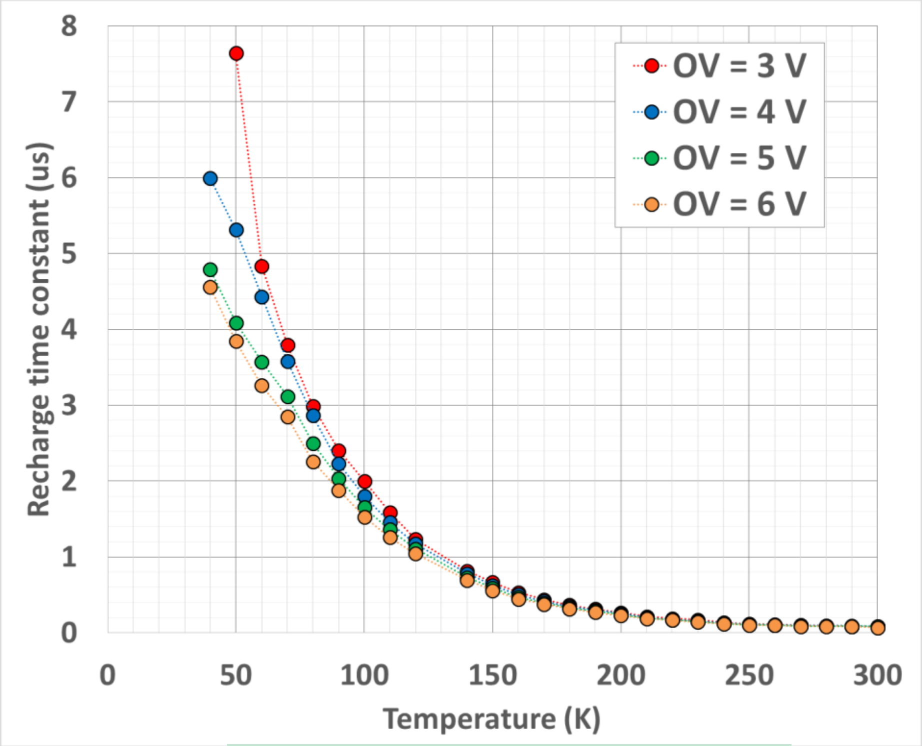
Microcell Recharge Time constant

The variation of the polysilicon quenching resistor with temperature causes a variation of the recharge time.

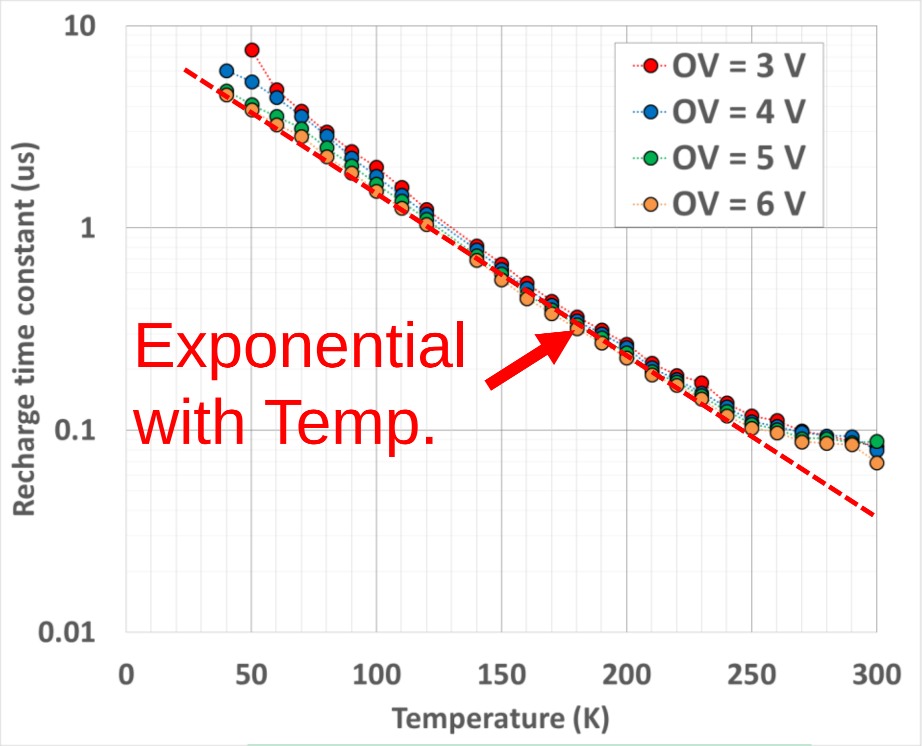
Polysilicon Resistor



NUV-HD Low-field



Linear scale



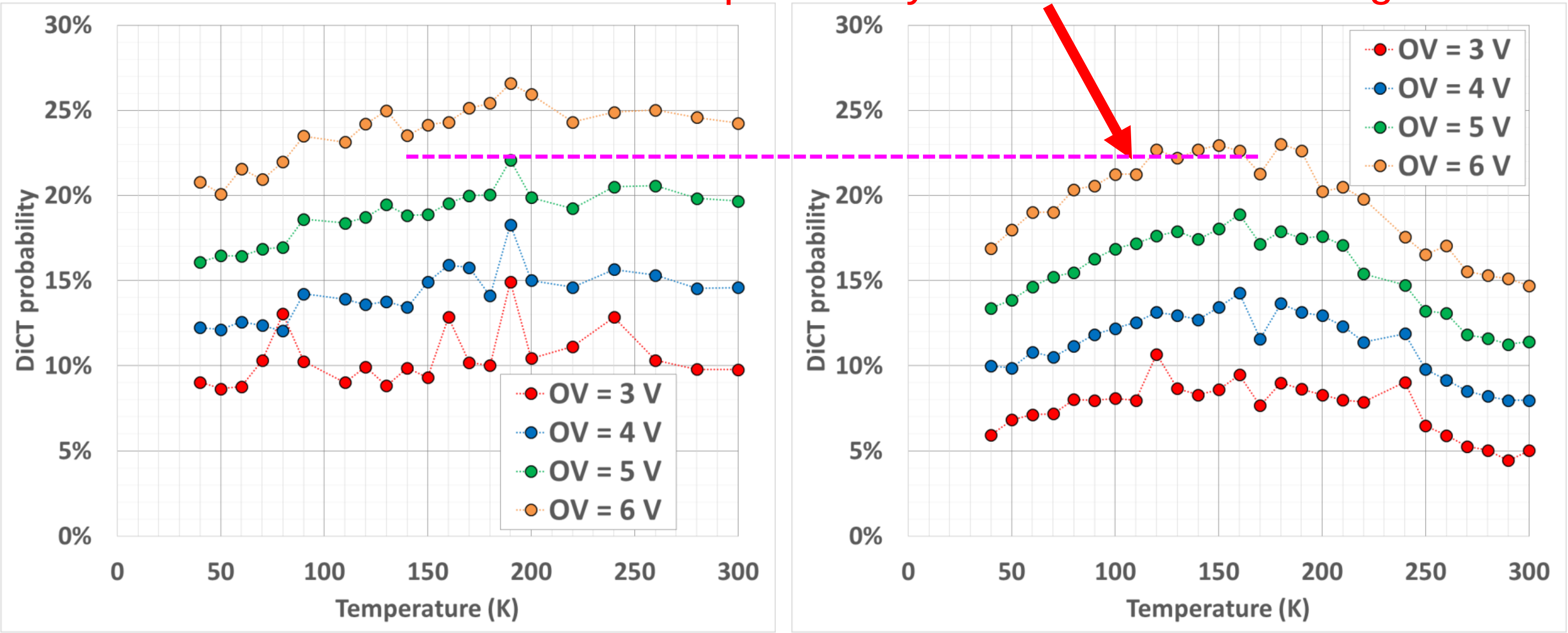
Exponential with Temp.

Log scale

DiCT vs. Temp

The direct crosstalk probability has only minor variations with respect to temperature.

Slightly lower gain and triggering probability at the same overvoltage.

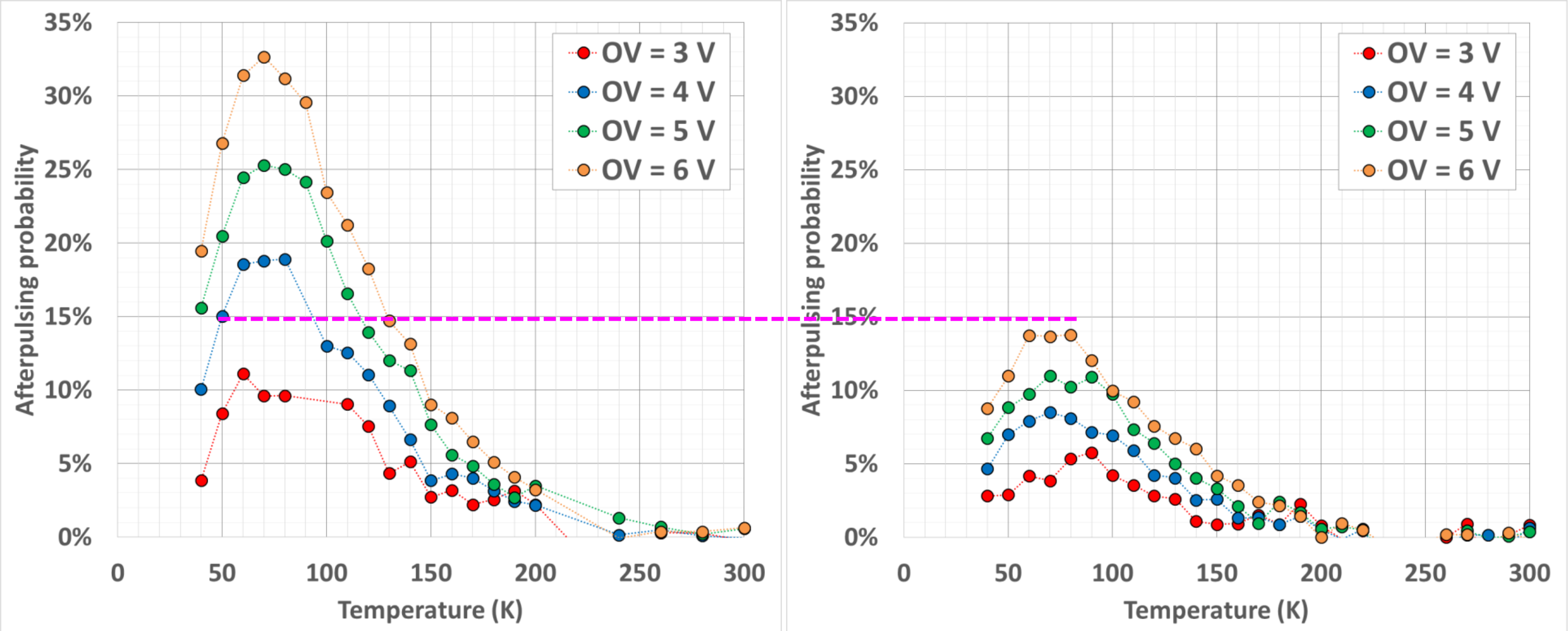


Standard field

Low-field

Afterpulsing Probability vs. Temp

The increase of the microcell recharge time constant helps reducing the afterpulsing at low temperature.



Cell size = 25 um, Rq = 10 MΩ at 77 K

Standard field

Low-field

Divergence of the correlated noise

Afterpulsing probability depends on Cell gain and, thus, overvoltage.

$$P_{AP}(OV) \cong \boxed{Gain(OV)} \cdot P_{trap} \cdot P_{trigger}(OV, \tau_{trap})$$

Number of carriers passing through the junction during an avalanche

$$P_{AP}(OV) \cong OV \cdot C_{SPAD} \cdot \alpha(OV, \tau_{trap})$$

For every SiPM technology, there is a value of over-voltage such as the probability of having a correlated noise event approaches one.

Crosstalk and afterpulsing effect are interacting:
→ Combined correlated noise probability determines divergence

Divergence of the correlated noise

The number of avalanches generated by a primary event, either dark count or photon detection, can be expressed by:

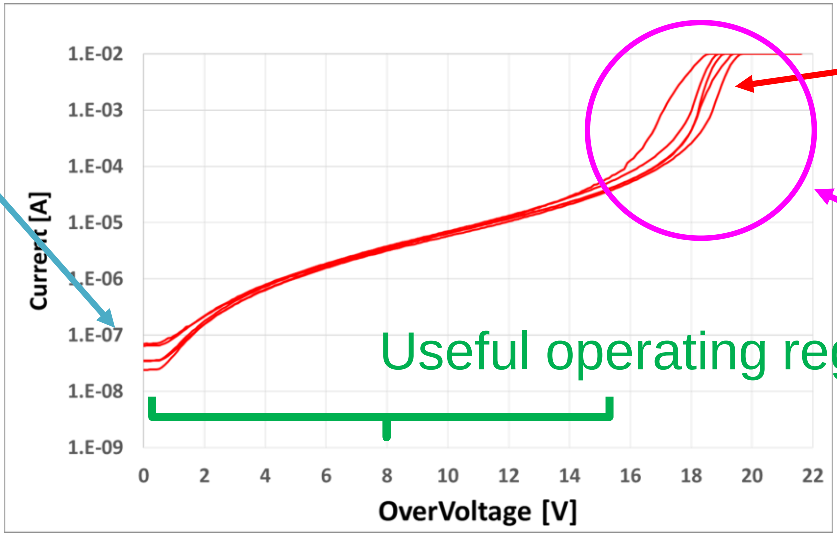
$$ECF \cong \frac{1}{1-P_{CN}} = \frac{1}{1-p'_{CN}(OV)\,Gain(OV)}$$

Excess Charge Factor

Geometric series approximation

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

Breakdown voltage



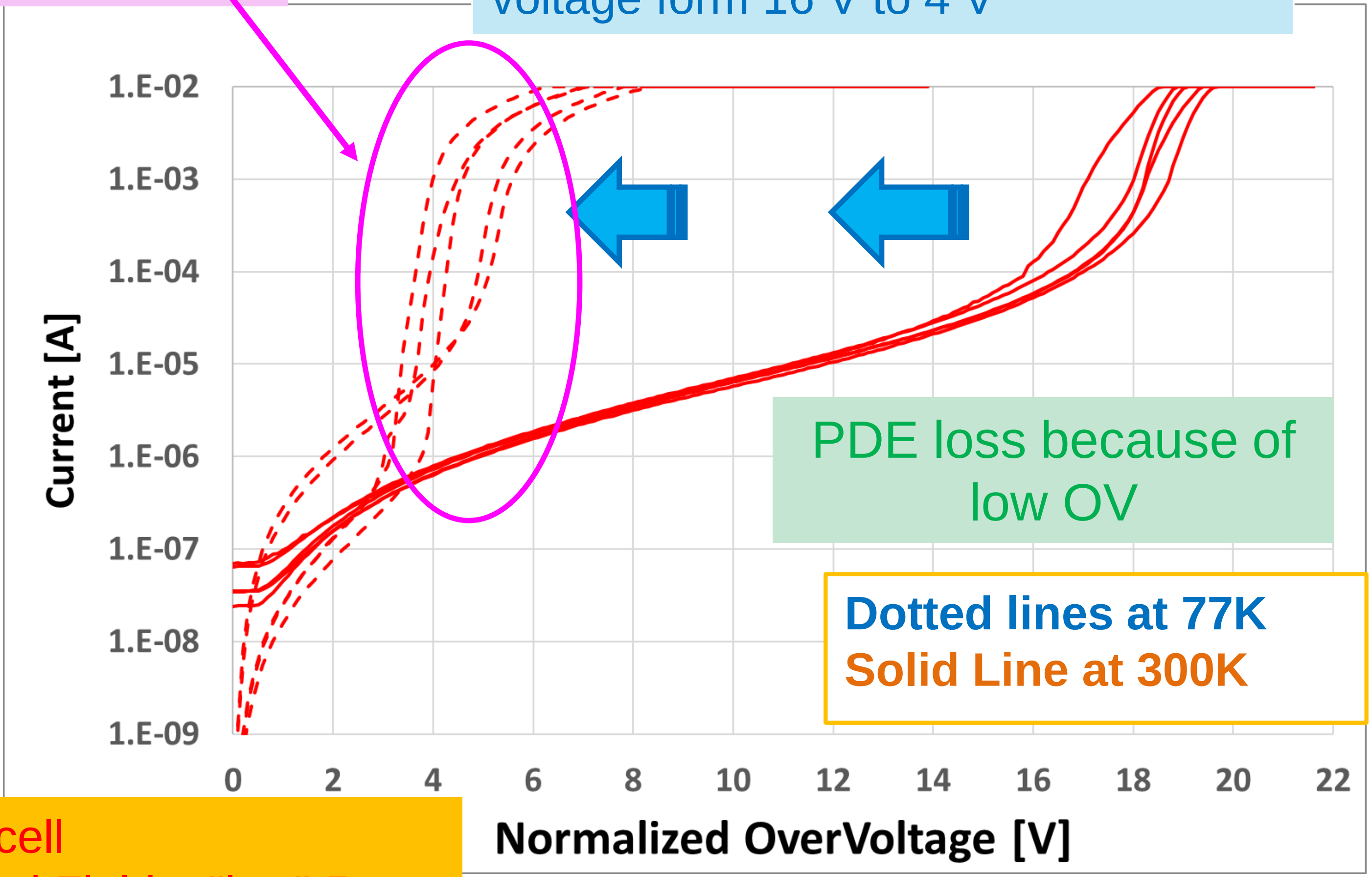
Divergence of correlated noise

SiPM cannot be operated here

Useful operating region

Increase of AP at cryogenic temperatures

The increase of AP at cryogenic temperatures causes a substantial reduction of the useful operating range of the SiPM.



Potential Instability?

Cooling reduces the maximum over-voltage form 16 V to 4 V

PDE loss because of low OV

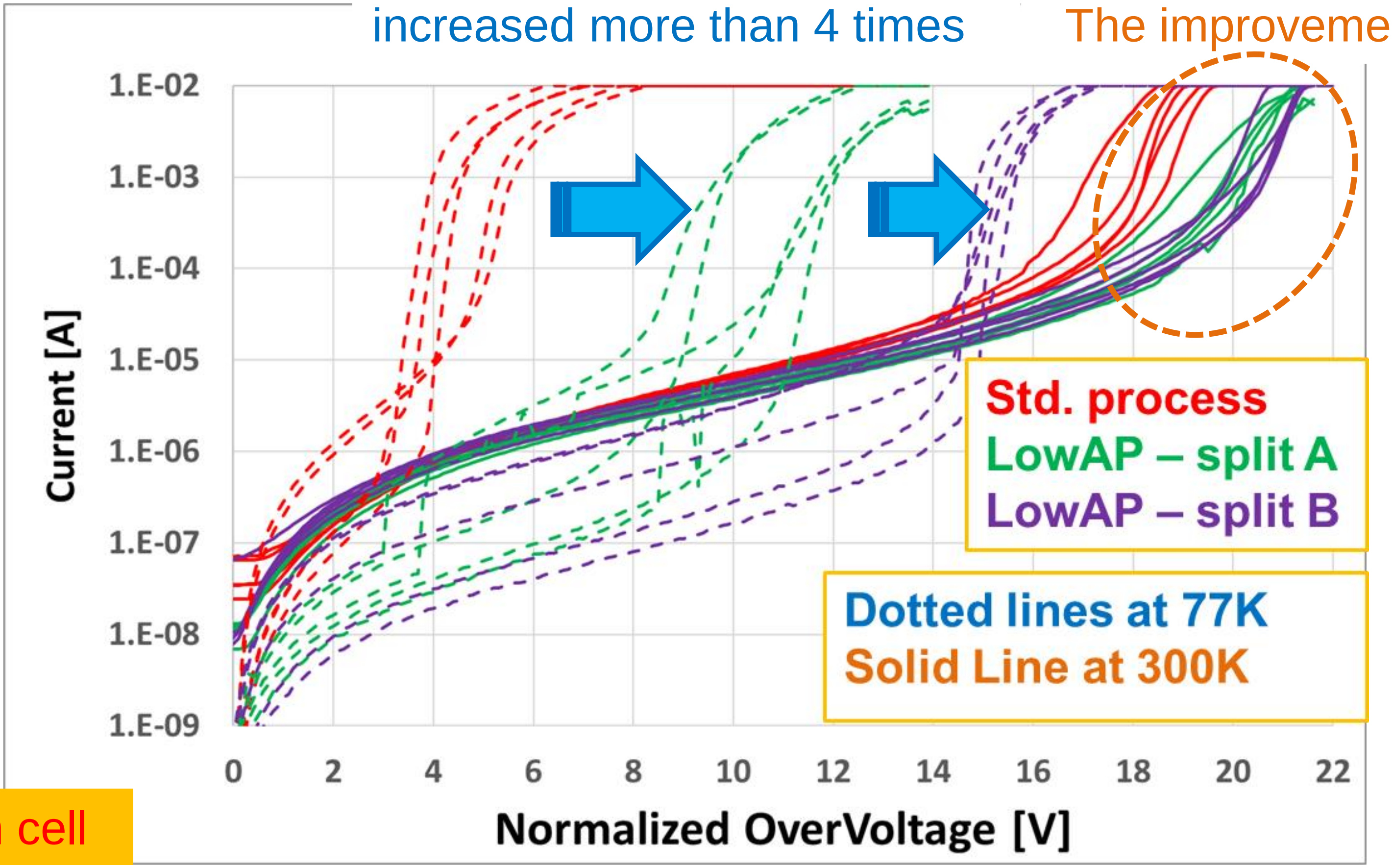
Dotted lines at 77K
Solid Line at 300K

30 um cell
Standard Field – "low" Rq

New process for reduced AP

We 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

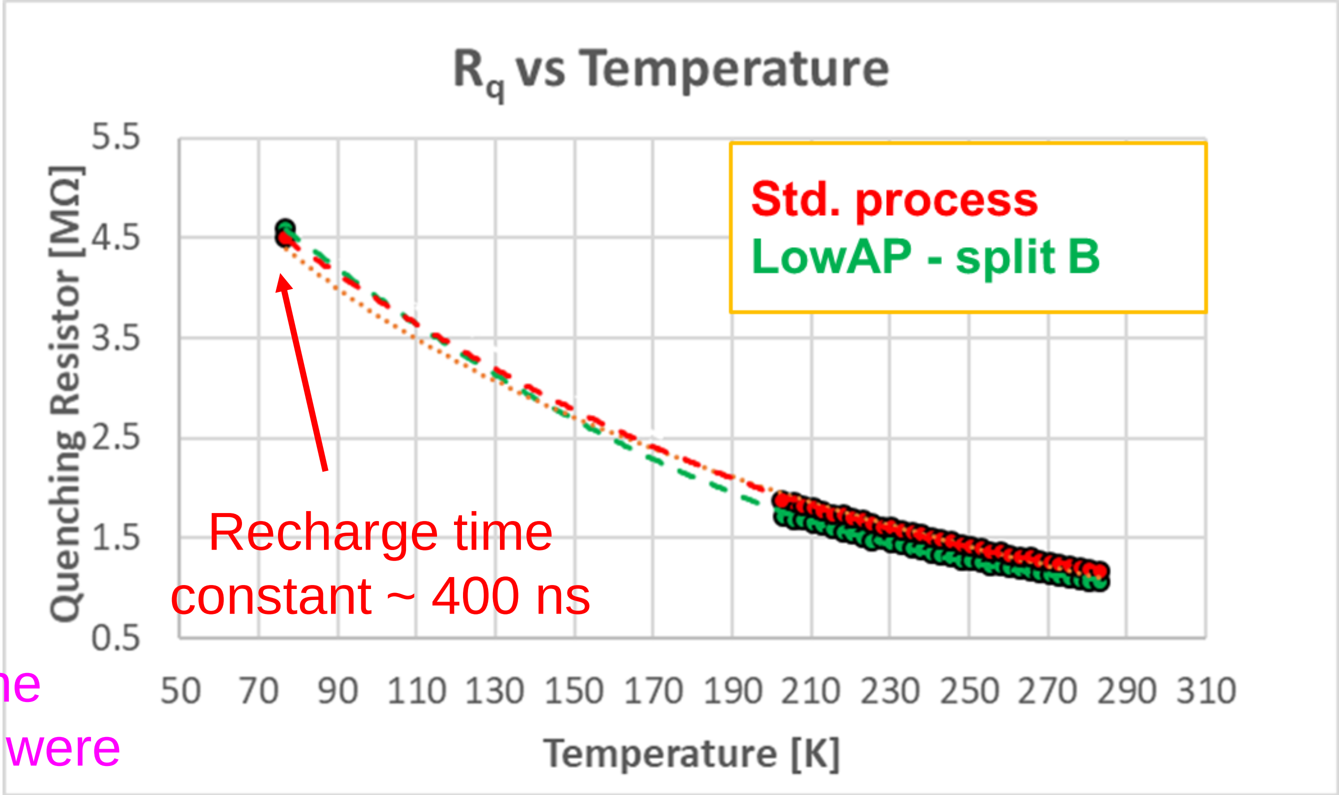
At room temperature
The improvement is smaller

30 um cell

New polysilicon 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.



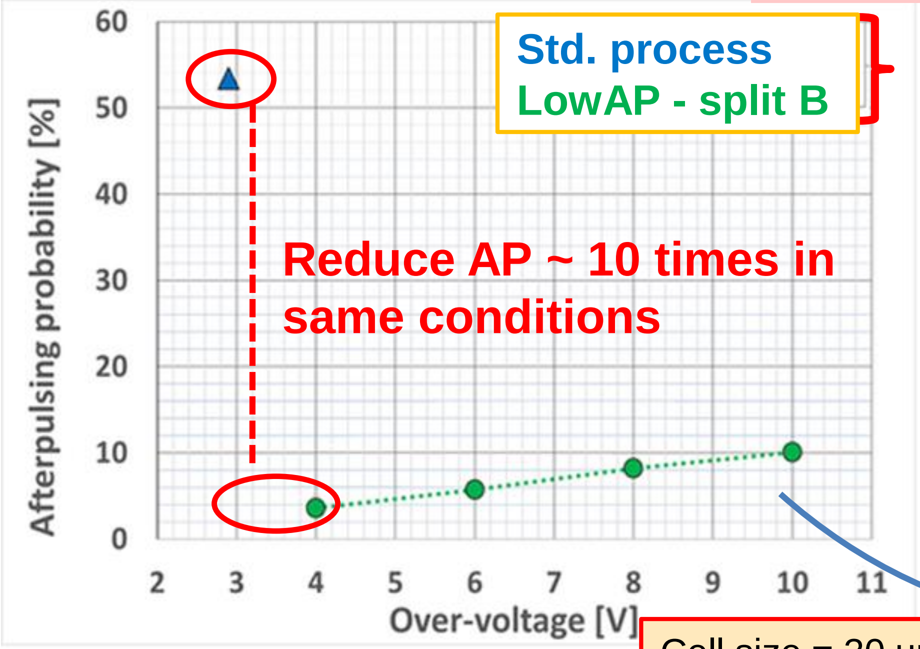
3x max variation

Recharge time constant ~ 400 ns

In previous technology, the resistor changes were almost 10 time larger..

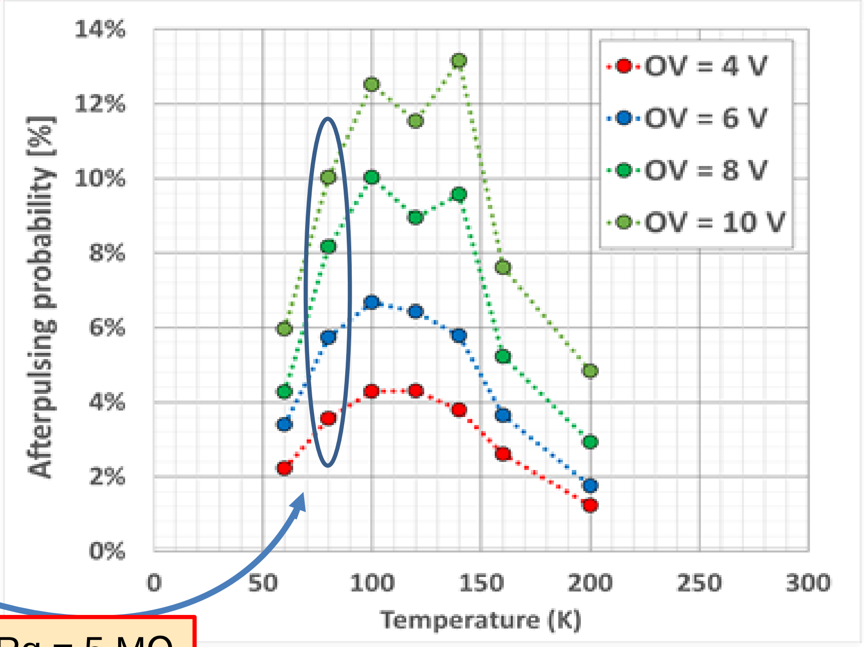
Low Afterpulsing at 77 K

Standard field



Std. process
LowAP - split B

Reduce AP ~ 10 times in same conditions



Cell size = 30 um, Rq = 5 MΩ

Std. vs. LowAP

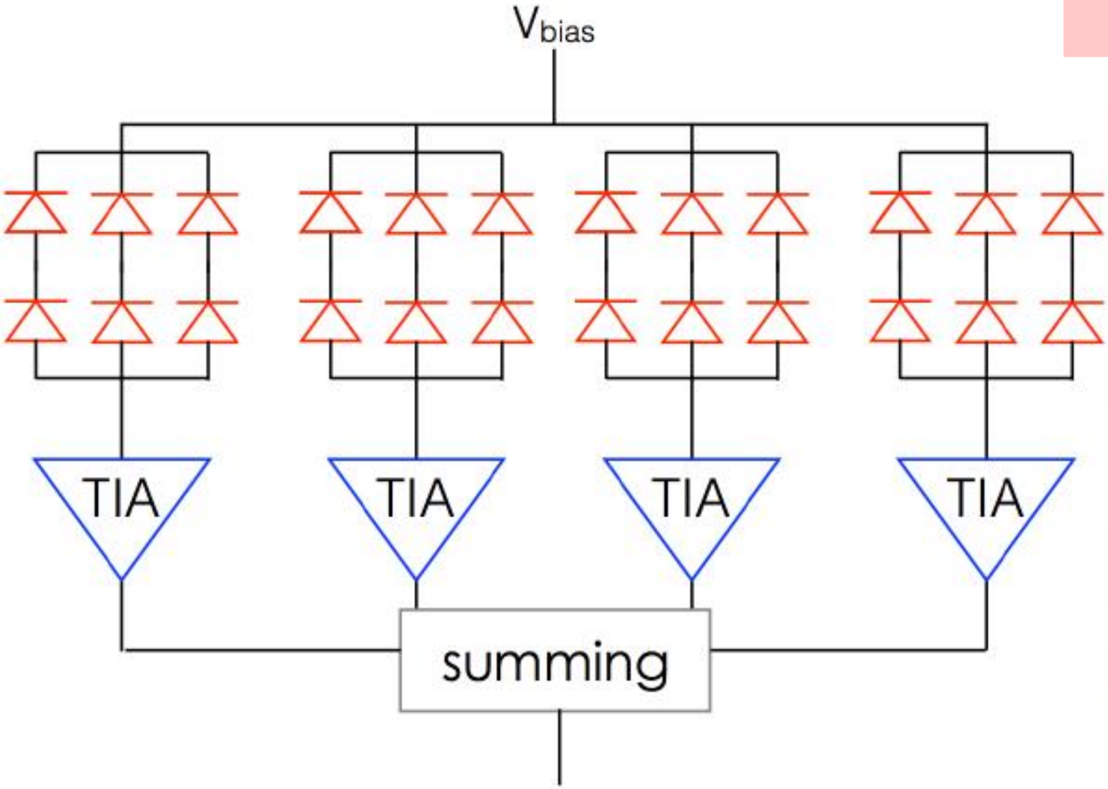
LowAP vs. Temp.

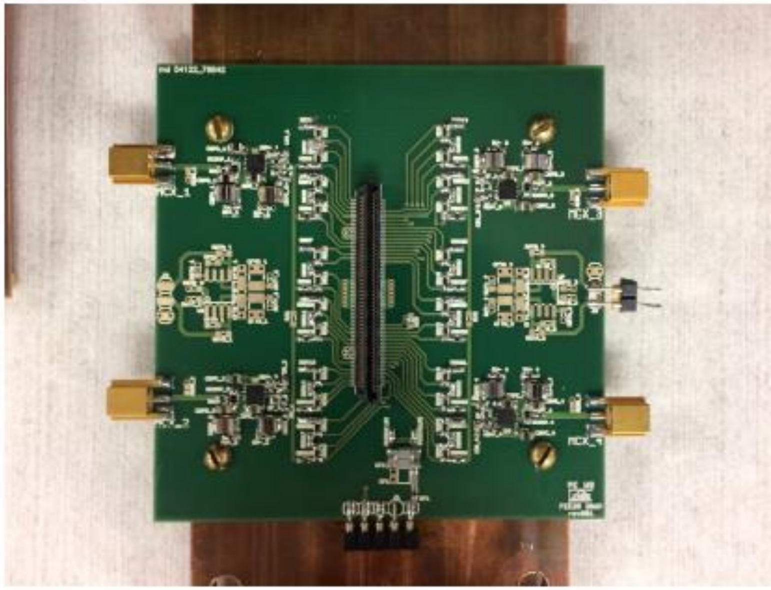
With lower afterpusing probability, we can reduce the value of quenching resistor at 77 K and increase the single cell response speed!
→ Reduced integration of the electronic noise..

Low Filed – Low AP is being tested in DarkSide..

Photon counting at 77 K

Designed at LNGS



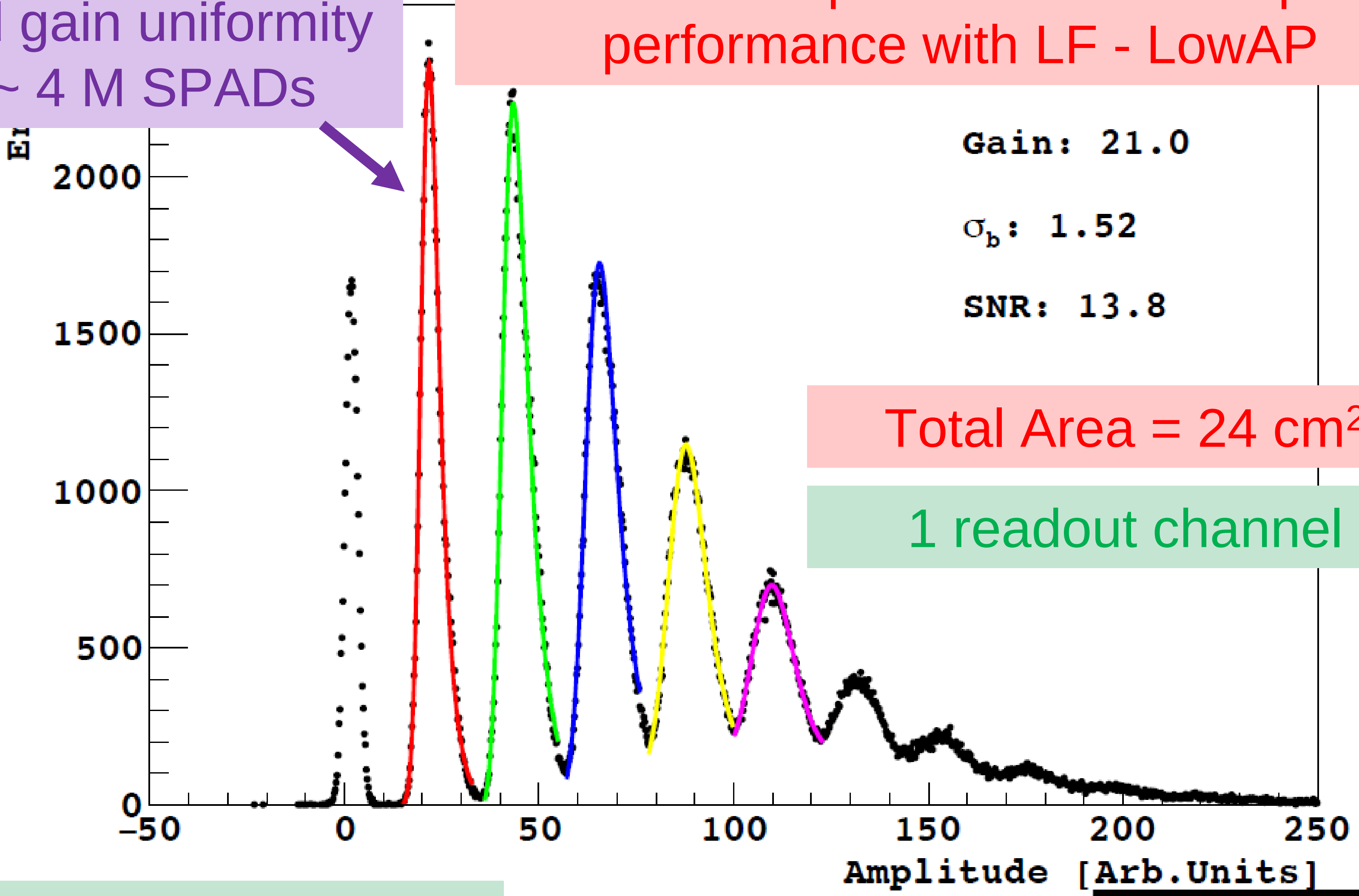


- 4 transimpedance amplifier: each TIA reads 6cm^2
- Hybrid configuration for SiPMs: 4x2s3p
- Further cold amplification before transmission outside

Photon counting at 77 K

See DarkSide presentation for improved performance with LF - LowAP

Good gain uniformity of ~ 4 M SPADs



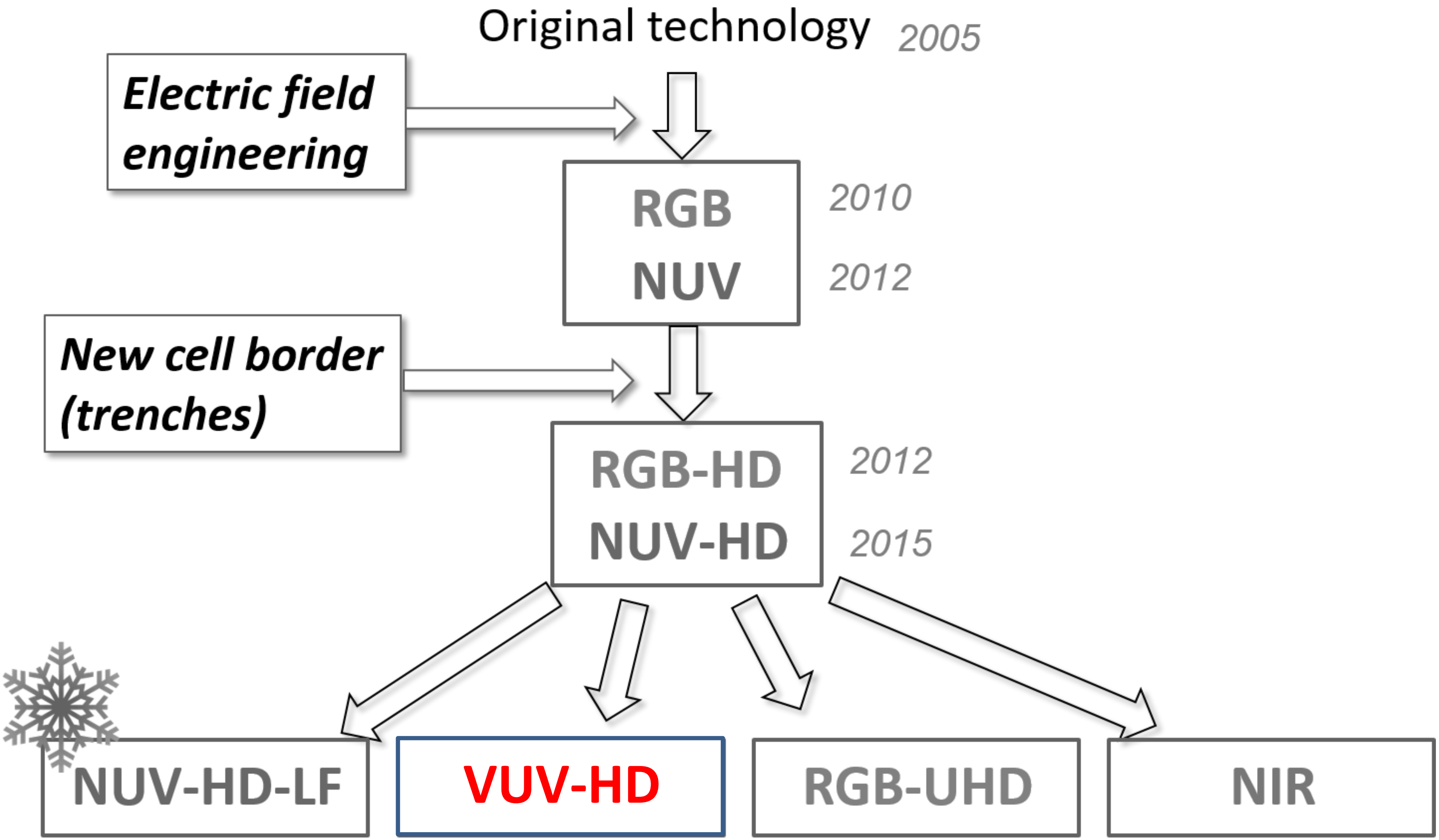
Total Area = 24 cm^2

1 readout channel

25um cells, 5 V over-voltage

darkside
two-phase argon TPC for Dark Matter Direct Detection

NUV-HD technology for VUV



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RGB 2010

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New cell border (trenches)

RGB-HD 2012

NUV-HD 2015

NUV-HD-LF

VUV-HD

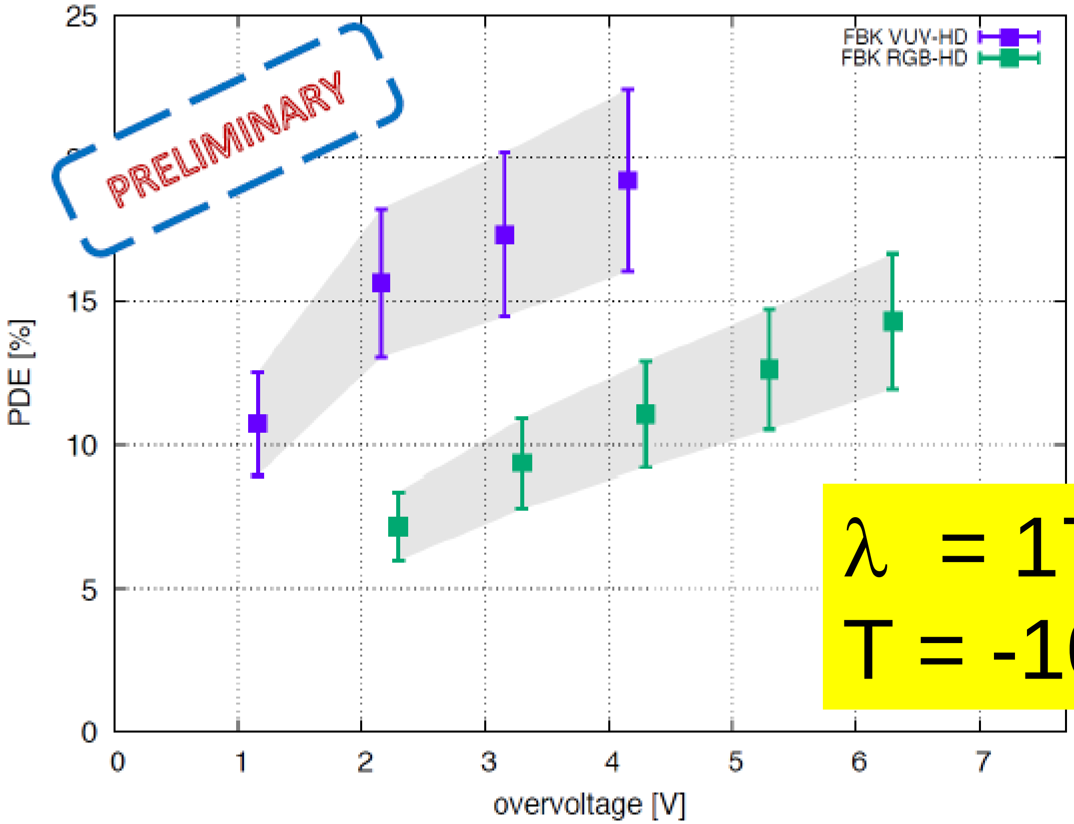
RGB-UHD

NIR

VUV-HD

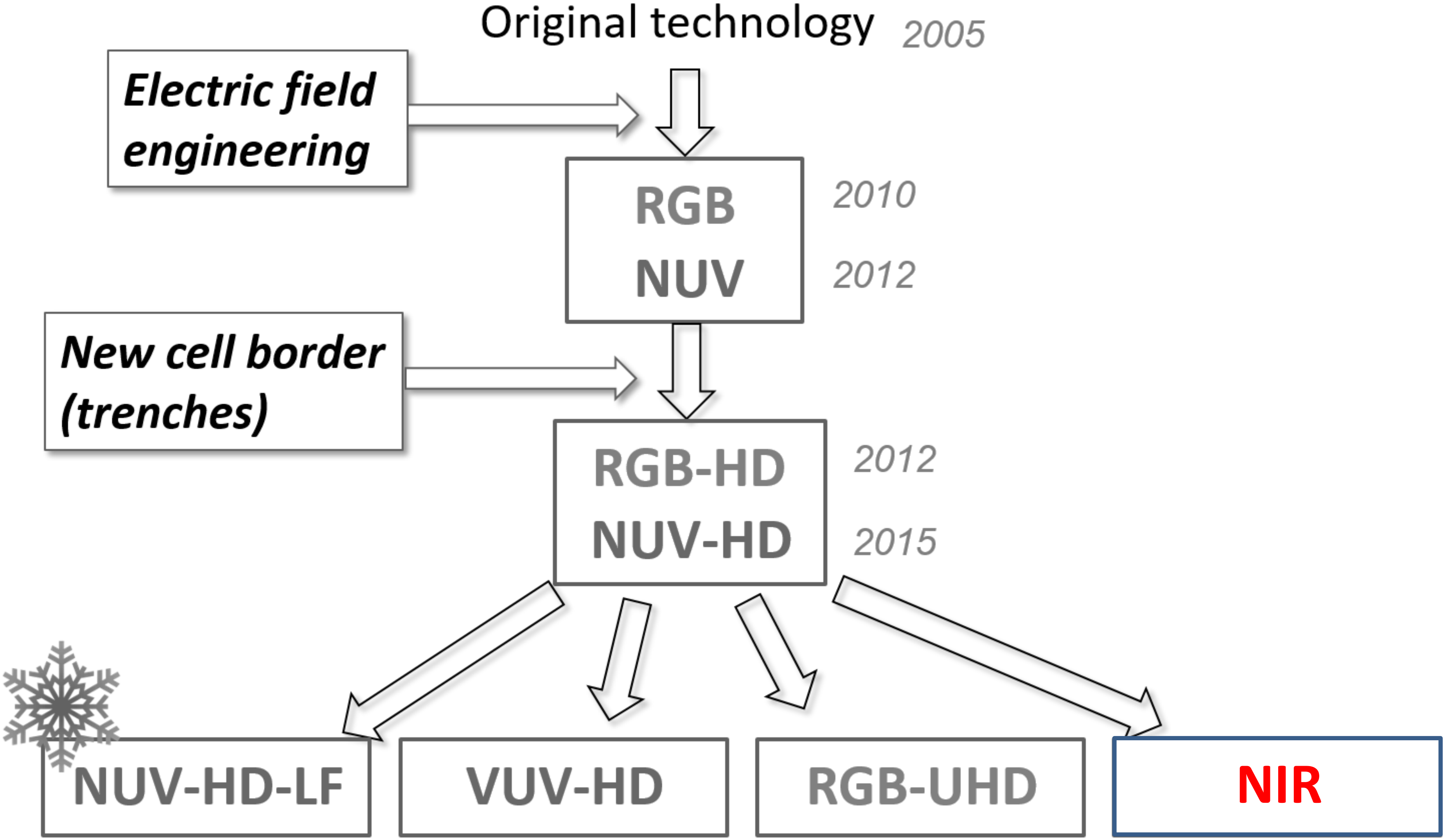
We are modifying the NUV-HD to enhance efficiency in the VUV.

FIRST PRELIMINARY measurement performed at Stanford.



λ = 175 nm
T = -104C (LXe)

NIR SiPMs



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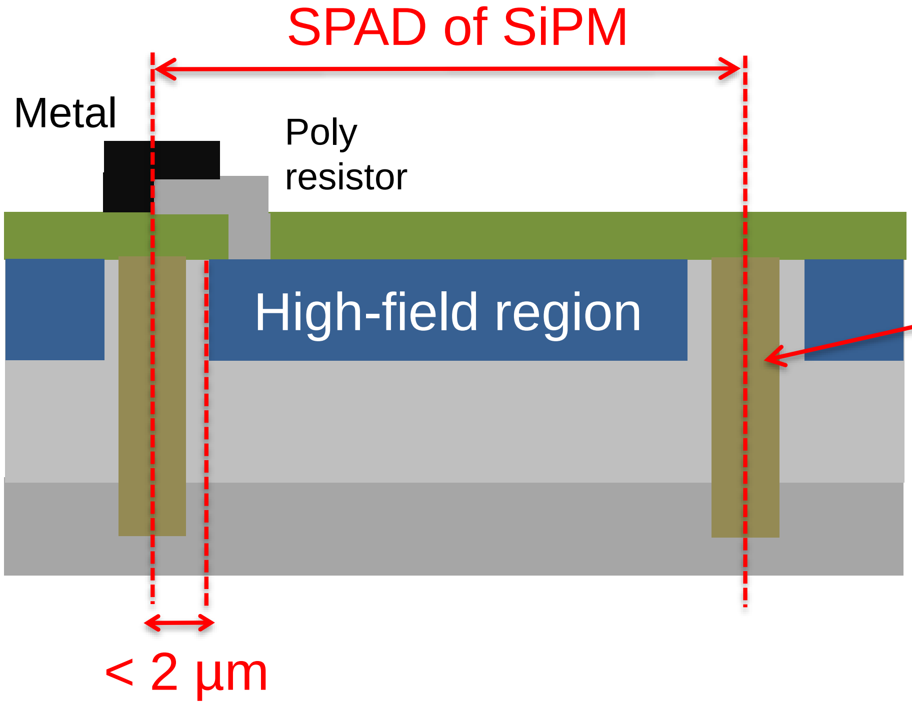
NUV-HD-LF

VUV-HD

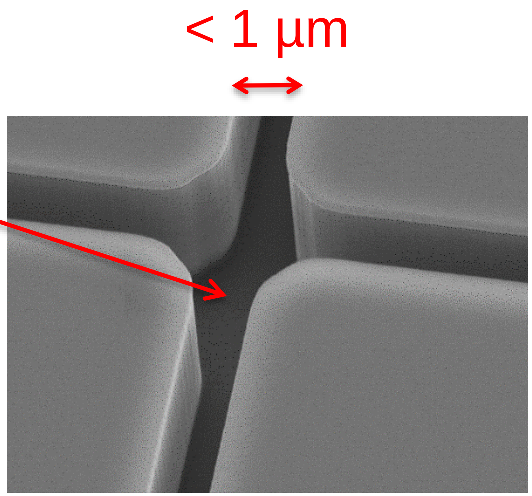
RGB-UHD

NIR

NIR-HD: technology

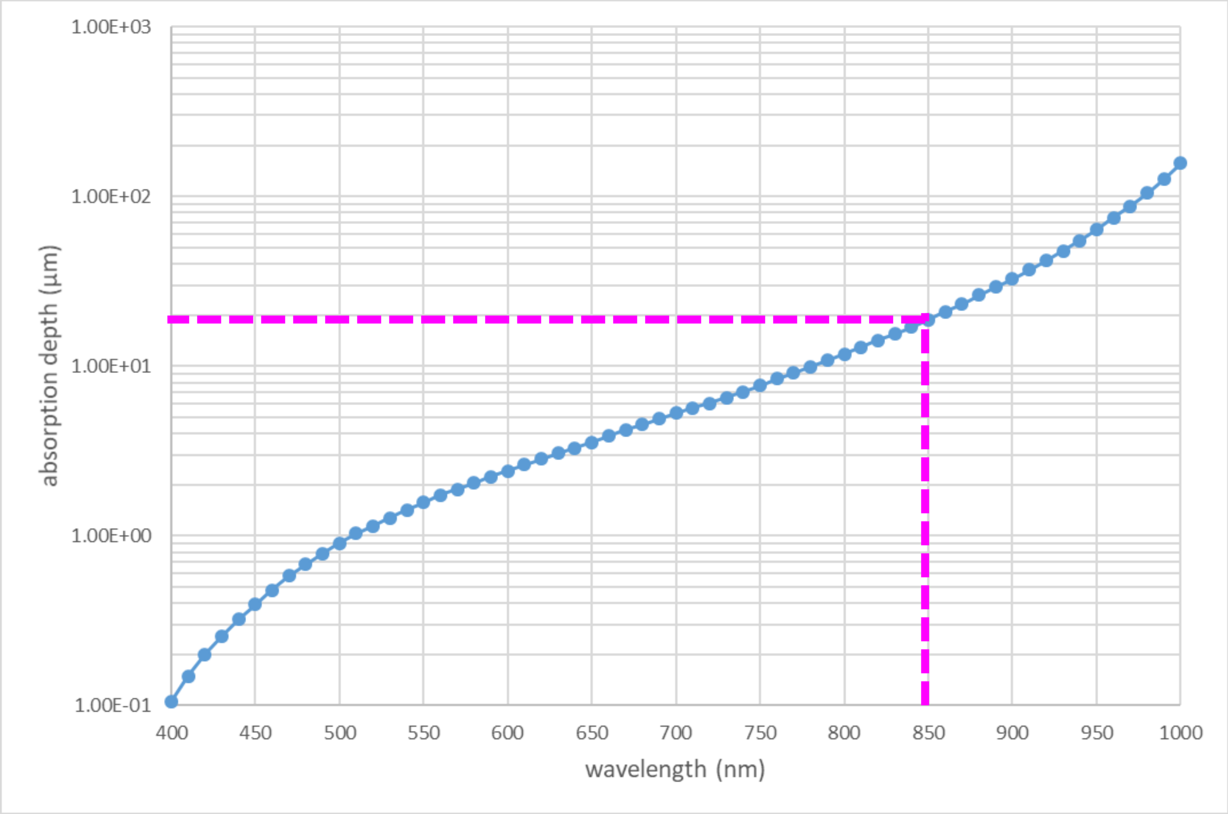


Trench



- 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

Light attenuation length in Si



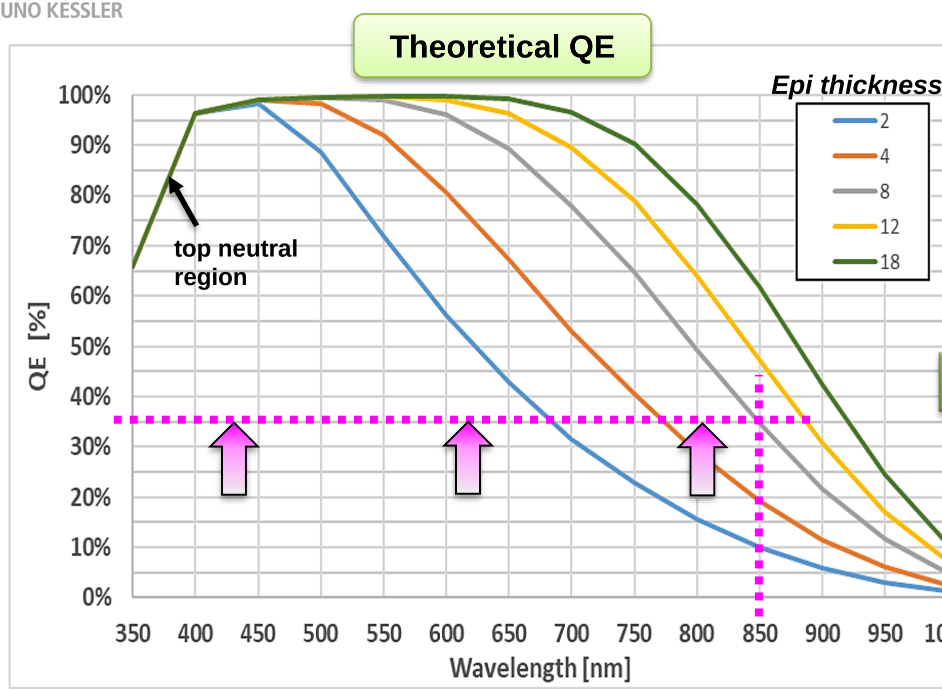
At 850nm → the silicon absorption depth is about 18µm.

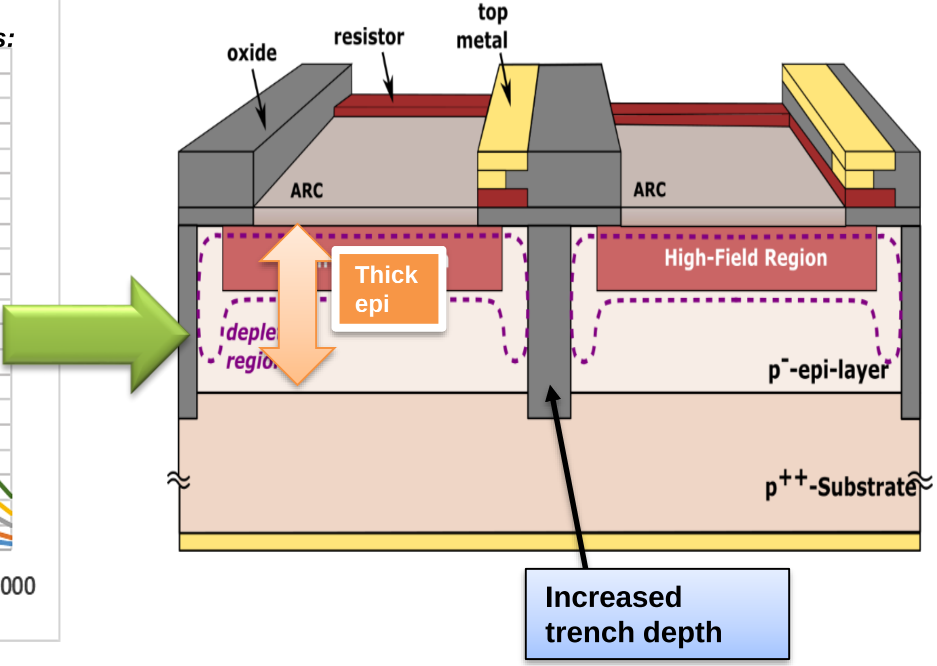
→ important to extend the collection depth (with respect to std. SiPMs)

⇩

We need to use a thicker epitaxial layer!

Design: thicker epitaxial layer





We use a thick epitaxial layer

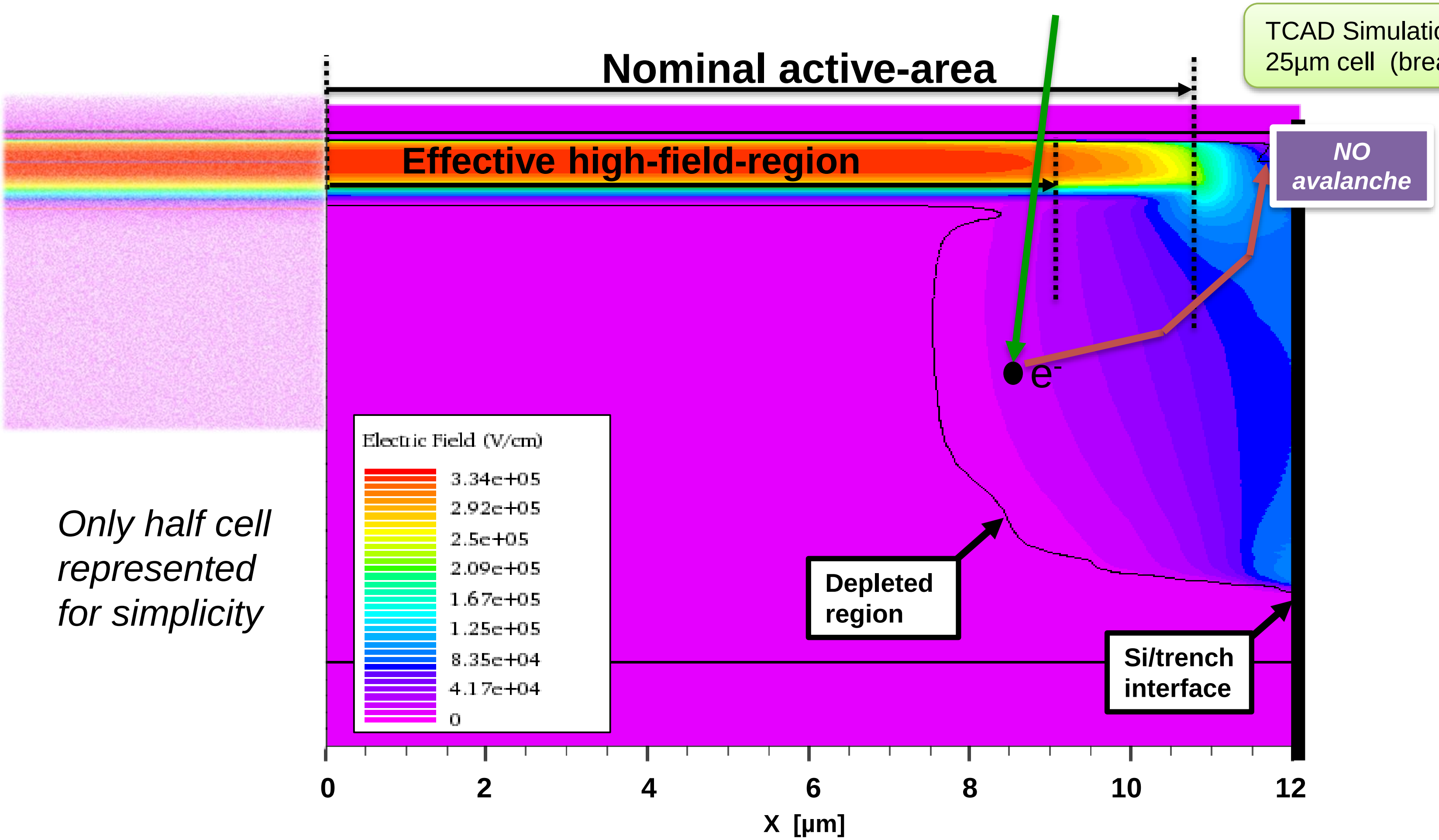
- Theoretical QE at 850 nm: about 35%
- Trench depth increased to: > 8µm

Other factors affect PDE:

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

The “Border effect”

TCAD Simulation: Electric Field
25µm cell (breakdown voltage)



Only half cell represented for simplicity

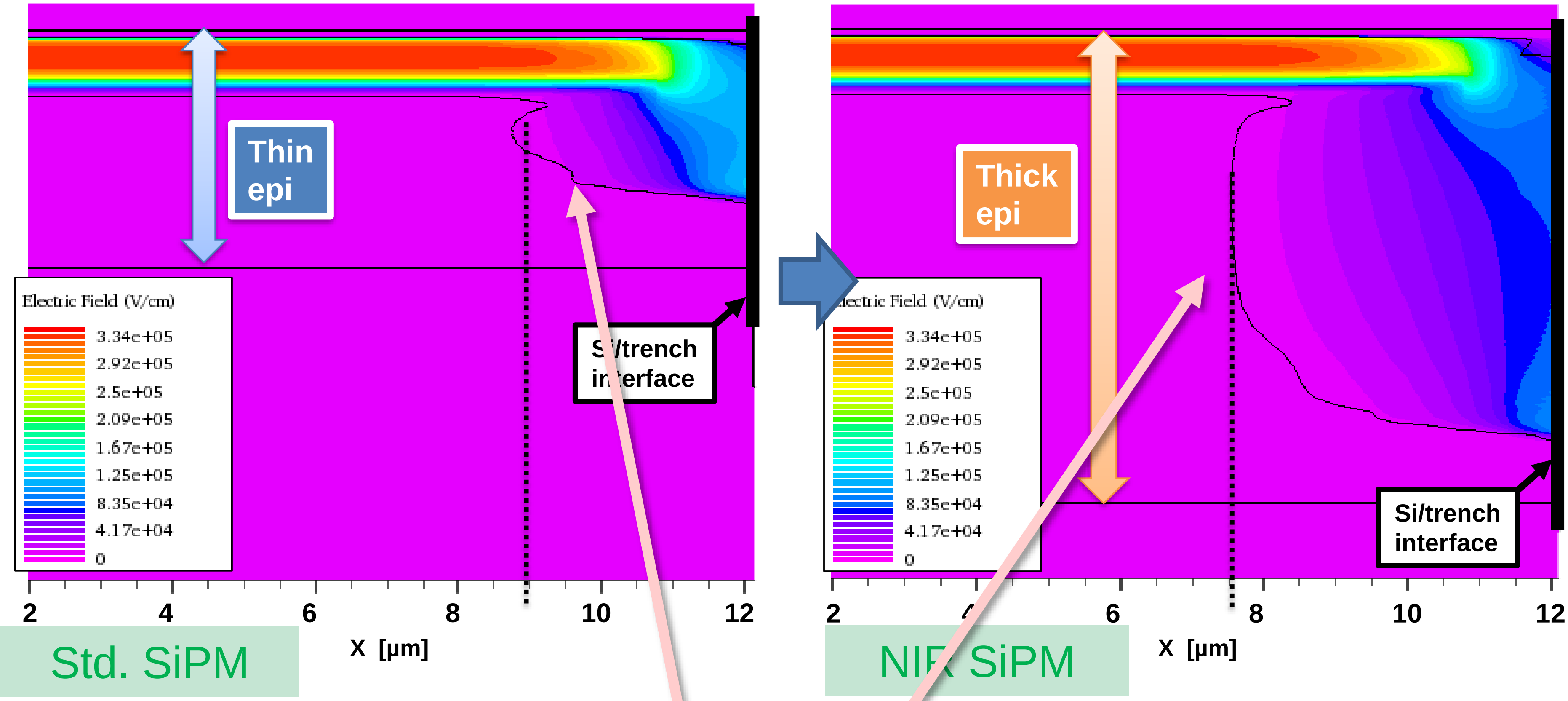
- Effective high-field region is <u>smaller than the nominal one</u>
- Lateral depletion below the high field region → <u>lateral drift</u>

Both these phenomena cause a “**border effect**” → reduction of effective FF

NIR-HD SiPMs: the challenge

TCAD Simulation: Electric Field
25µm cell @ breakdown voltage

Thicker epitaxial layer



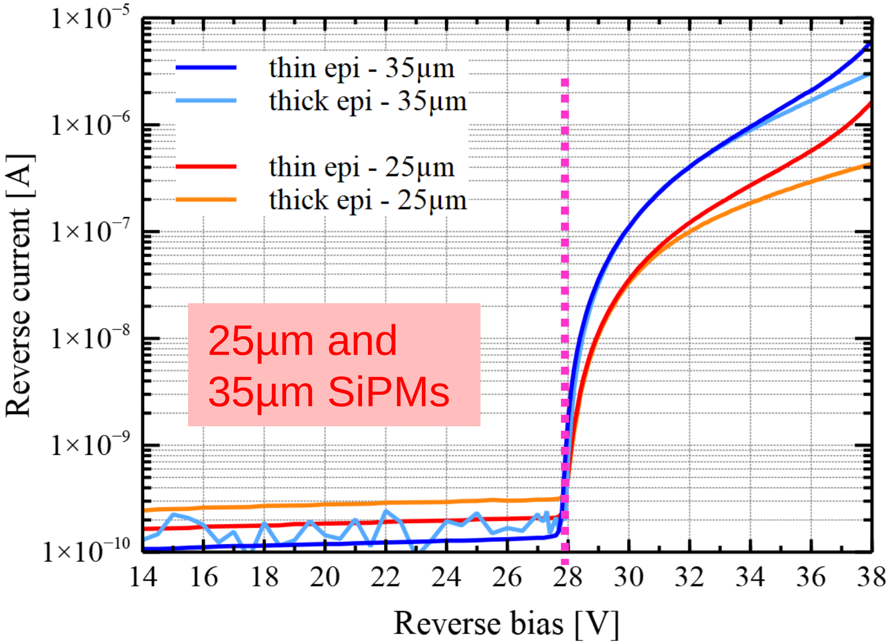
Std. SiPM

NIR SiPM

Charge collection loss at the edges:
→ Increases with thickness of epi layer

NIR-HD – I-V curve and Breakdown voltage

Breakdown Voltage

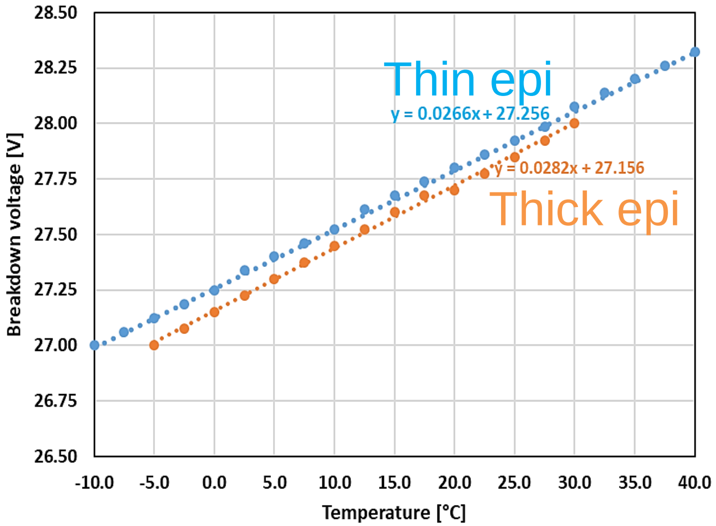


25µm and 35µm SiPMs

Thin vs. thick epitaxial layer

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

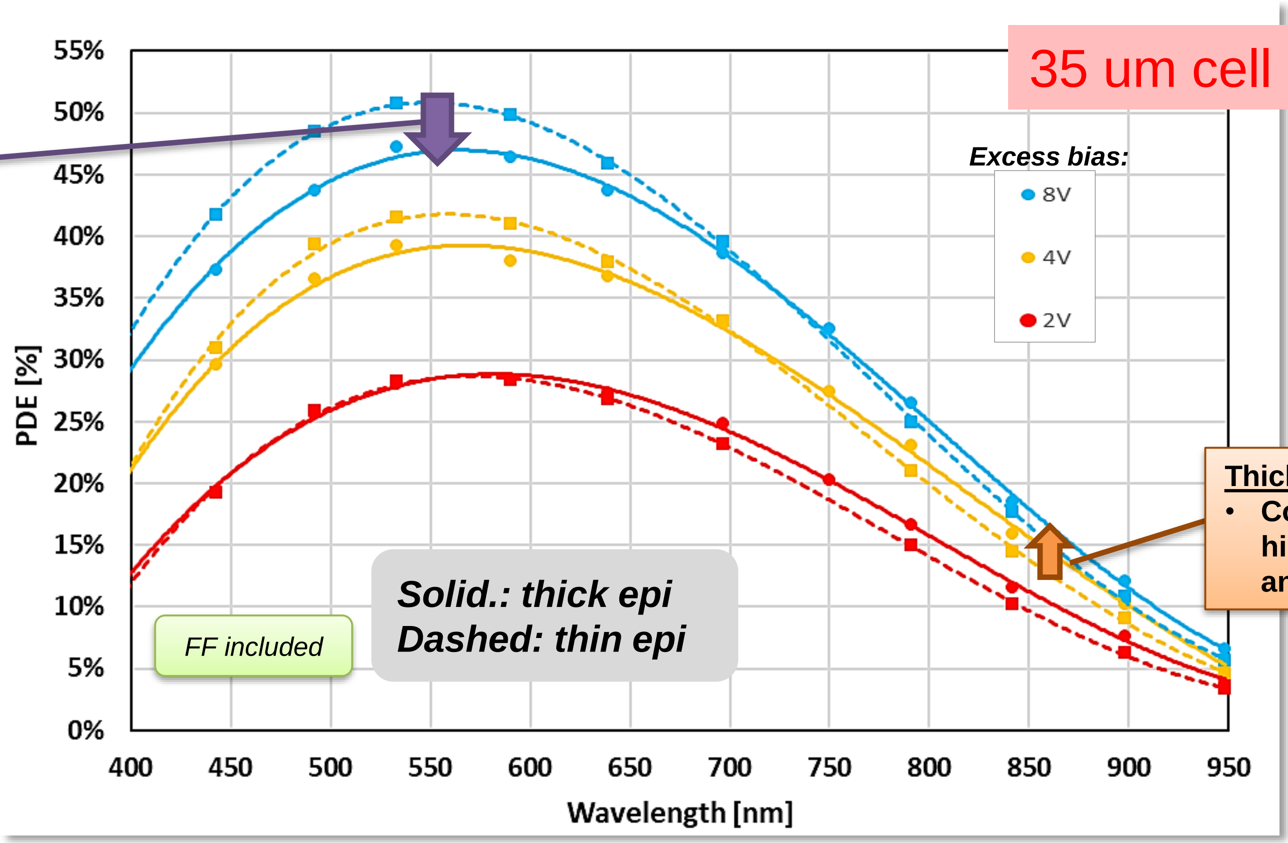
BD Temperature dependence



Small Vbd temperature dependence even with thick epitaxial layer

Approx. 28 mV/°C

NIR-HD PDE: thin vs. thick epi layer



35 um cell

Triggering probability: slower rise in thick epi

<u>Thick-epi: higher PDE !</u>

- **Compensation of the higher border effect and slower Pt rise**

FF included

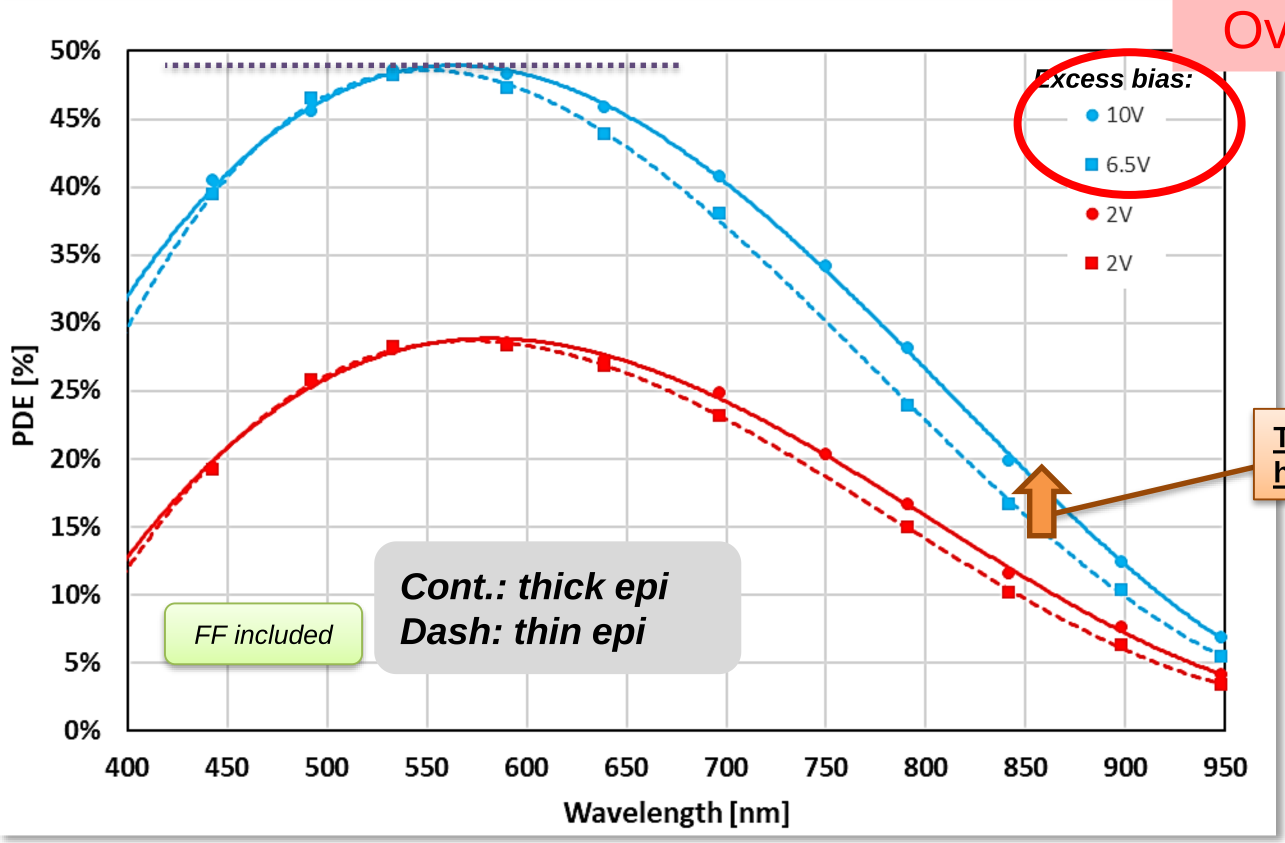
Solid.: thick epi
Dashed: thin epi

Only minor improvements!

1. Lower triggering probability: slower rise in thick epi → wider epi-layer depletion
2. Border effect: in thick epi it is larger

PDE comparison: same trig. prob.

Different Overvoltage!



FF included

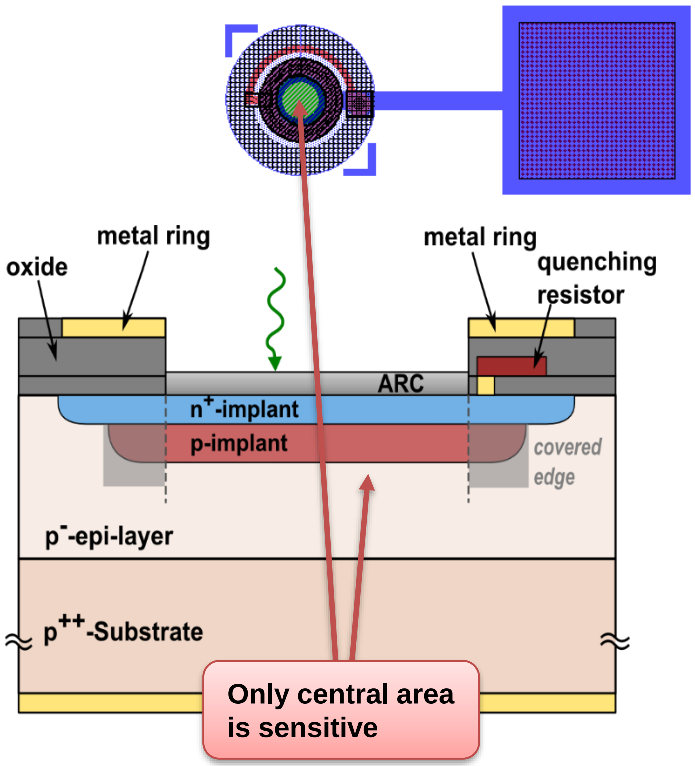
Cont.: thick epi
Dash: thin epi

Thick-epi: higher PDE !

Comparison at the same triggering probability !

- **Improvement: from ~16% to ~19% at 850nm**
- **Still border-effect higher in thick epi**

PDE without border effects: masked SPAD



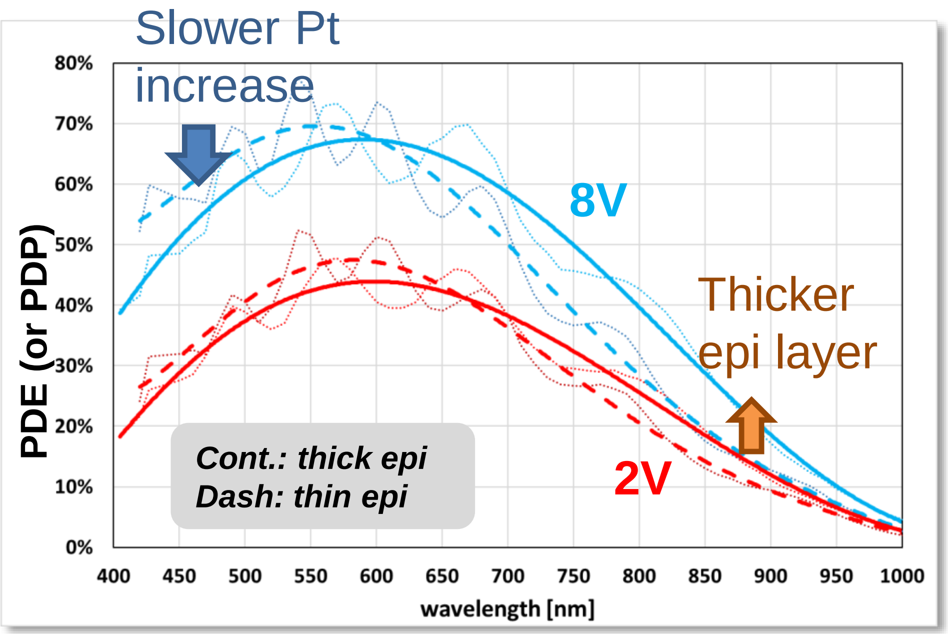
Only central area is sensitive

"Masked" SPAD

Single SPAD (circular) with covered edges

Limit of the technology
(without changing epi layer)

Masked SPAD PDE



Cont.: thick epi
Dash: thin epi

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

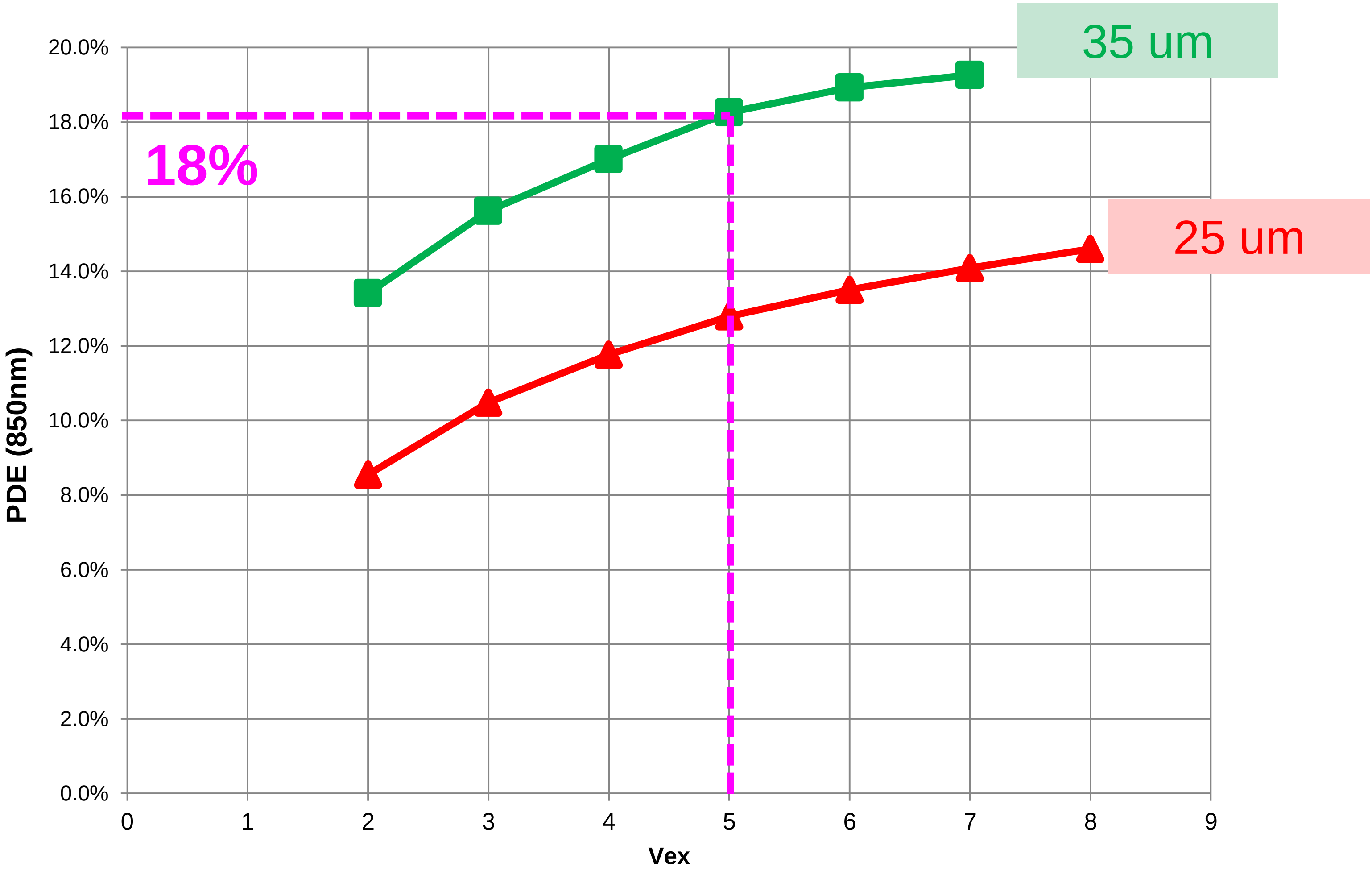
PDE: from 20% to ~ 30% at 850nm
from ~12% to ~18% at 900nm

NIR-HD run @ FBK

End of 2017

Functional characterization

PDE vs. Over-voltage at 850 nm



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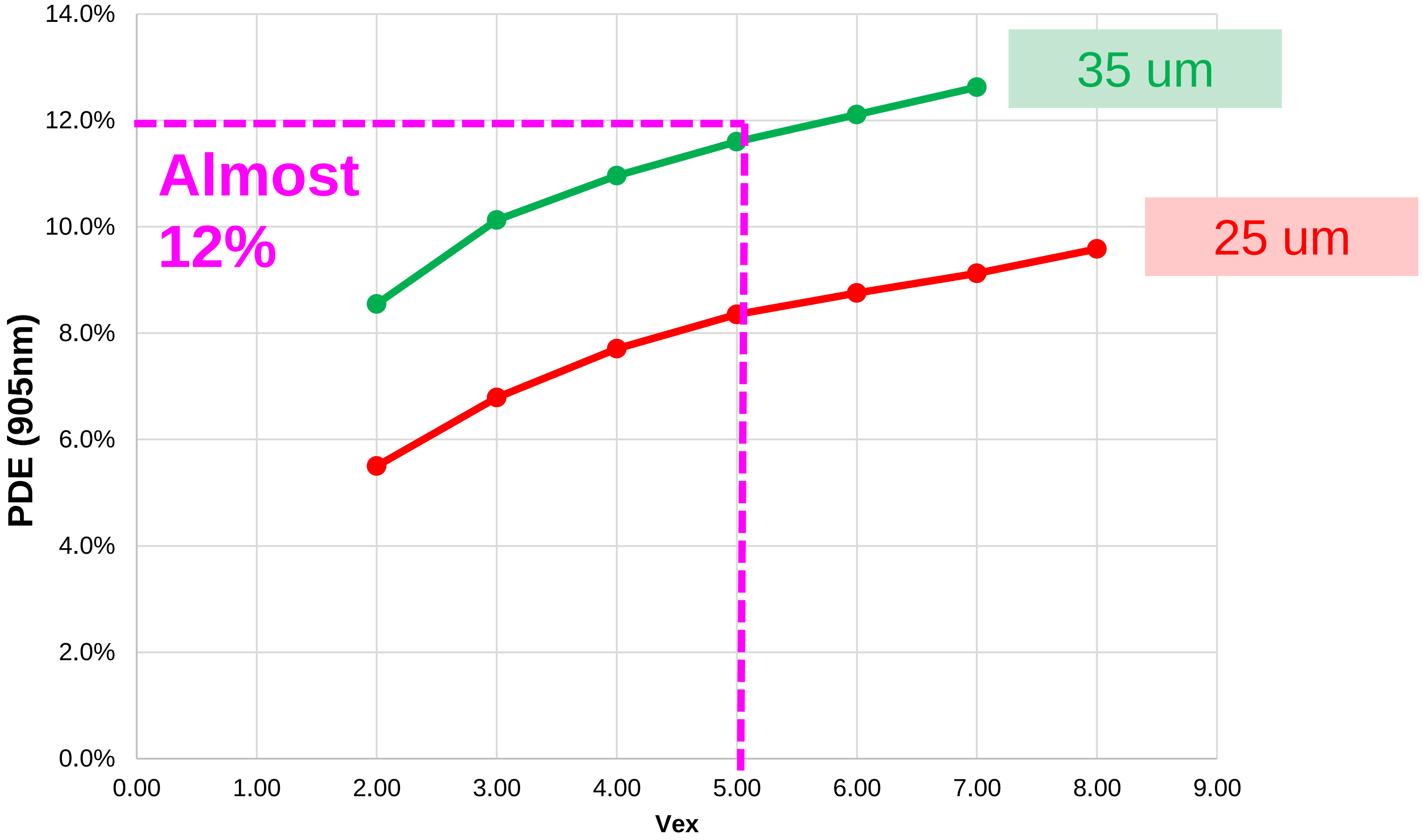
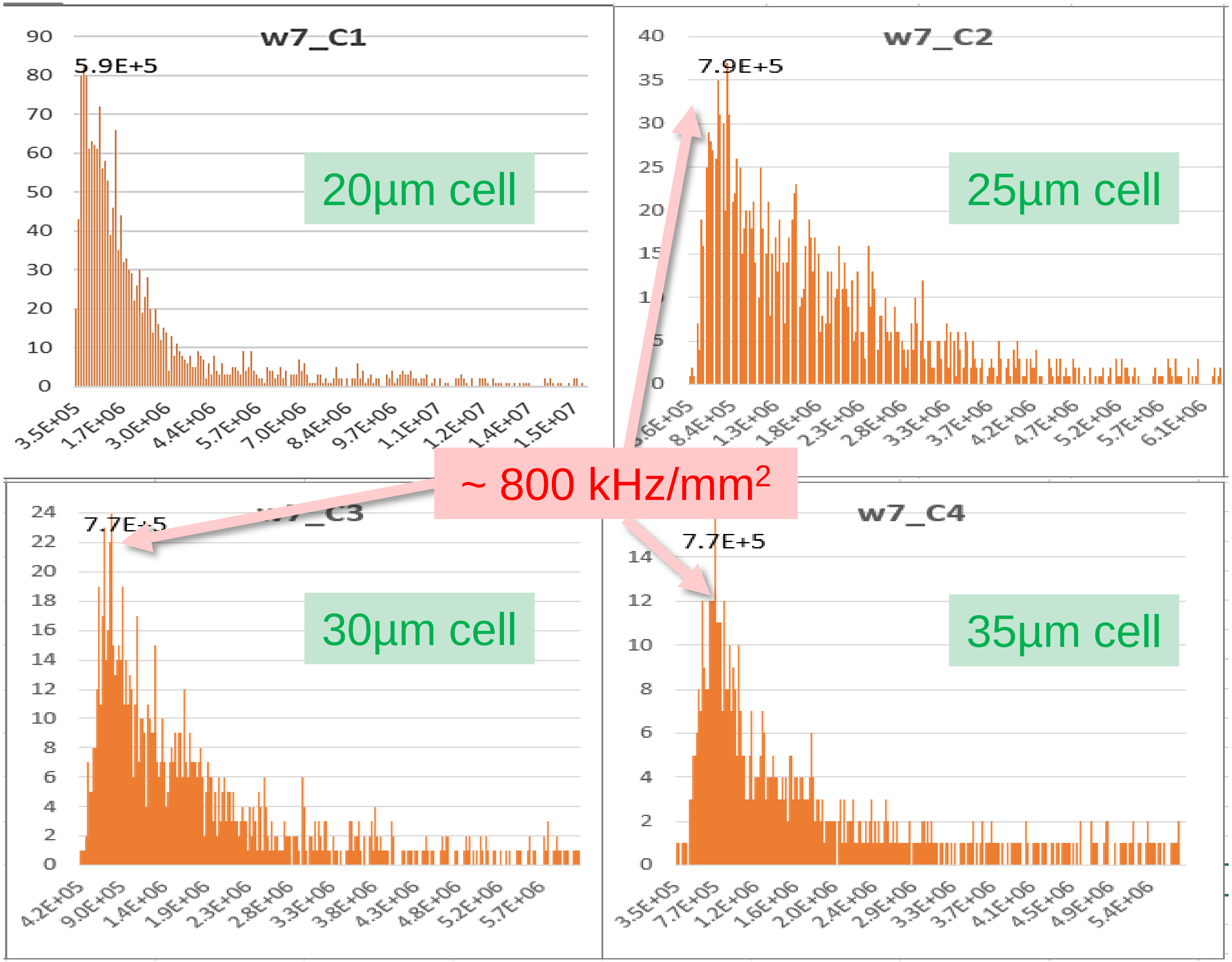
PDE vs. Over-voltage at 905 nm



Statistics on DCR @ Vex=5V



20µm cell

25µm cell

30µm cell

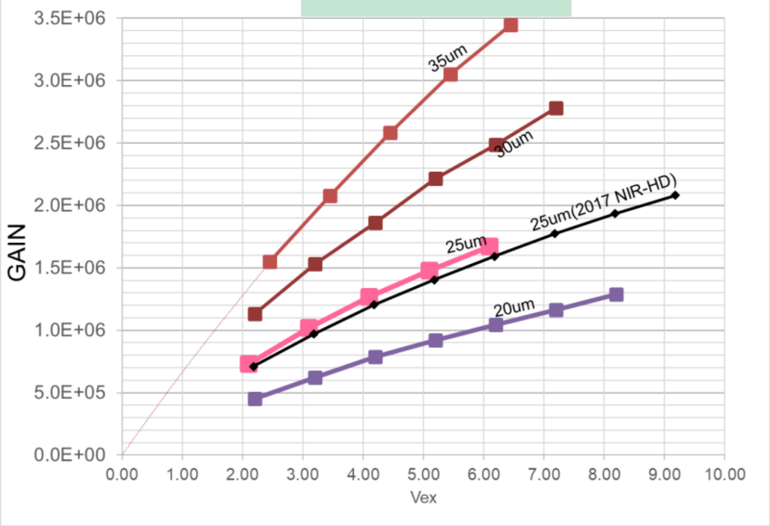
35µm cell

~ 800 kHz/mm^2

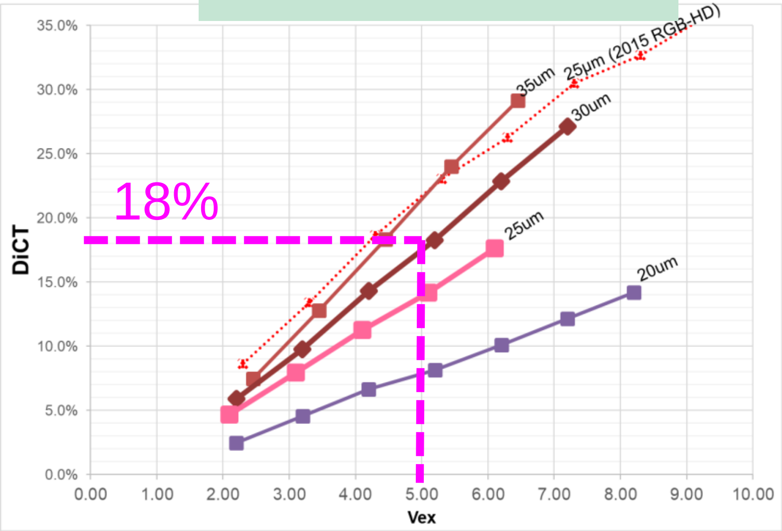
- Extrapolated from the hist. of reverse I-V curve → converted in primary DCR (DCR are for 1mm2)

Correlated noise, Gain and recharge time

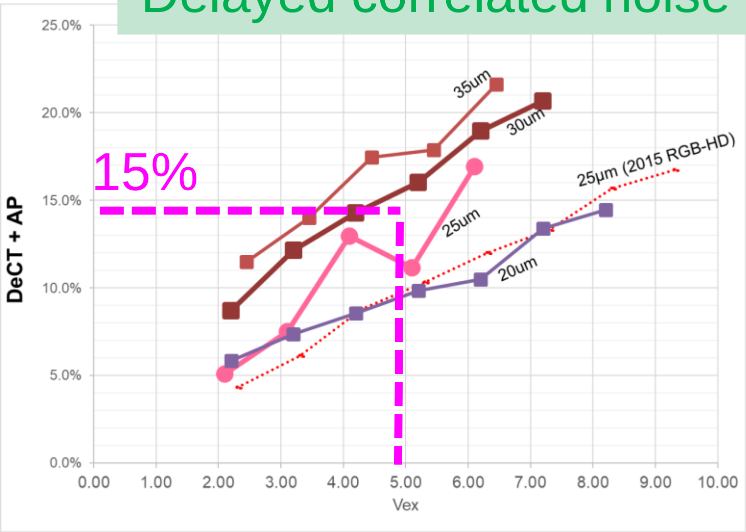
Gain



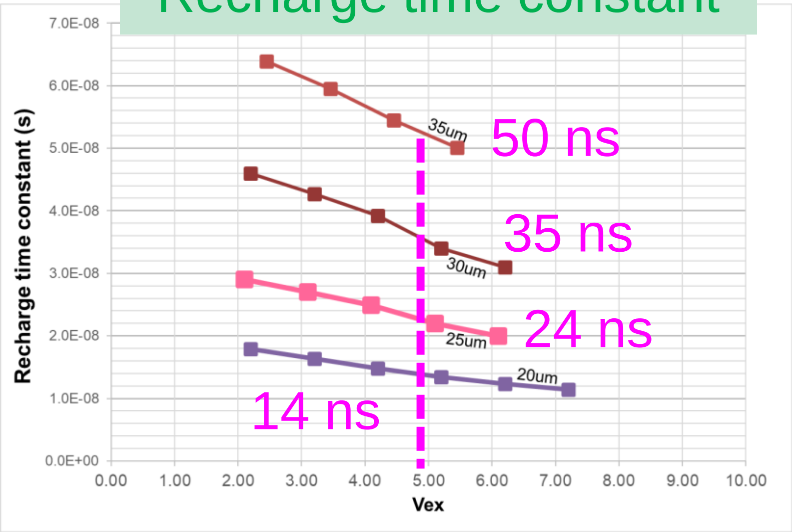
Direct Crosstalk



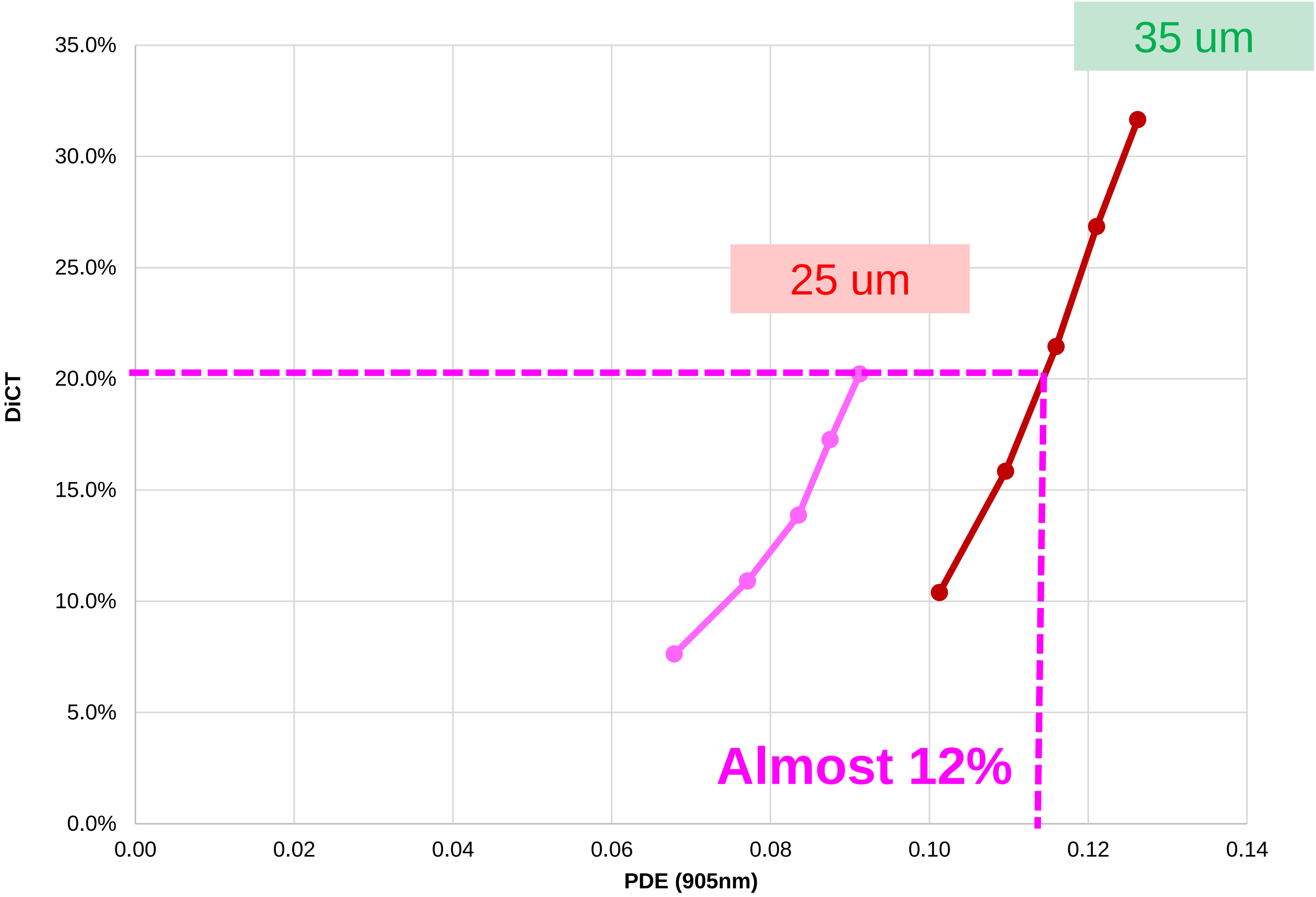
Delayed correlated noise



Recharge time constant

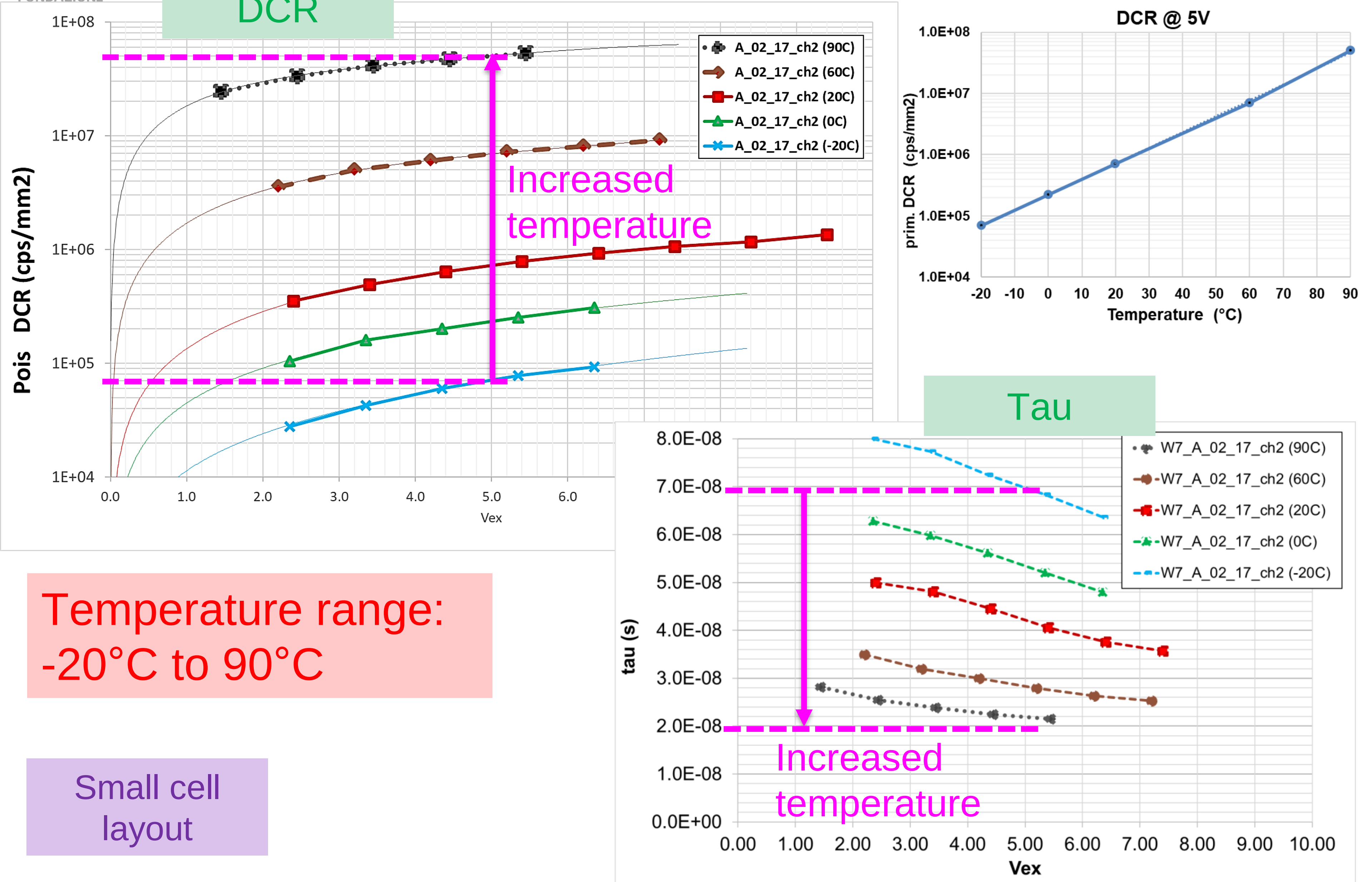


Direct Crosstalk vs. PDE



DCR and Tau vs. Temp

DCR



Tau

Temperature range:
-20°C to 90°C

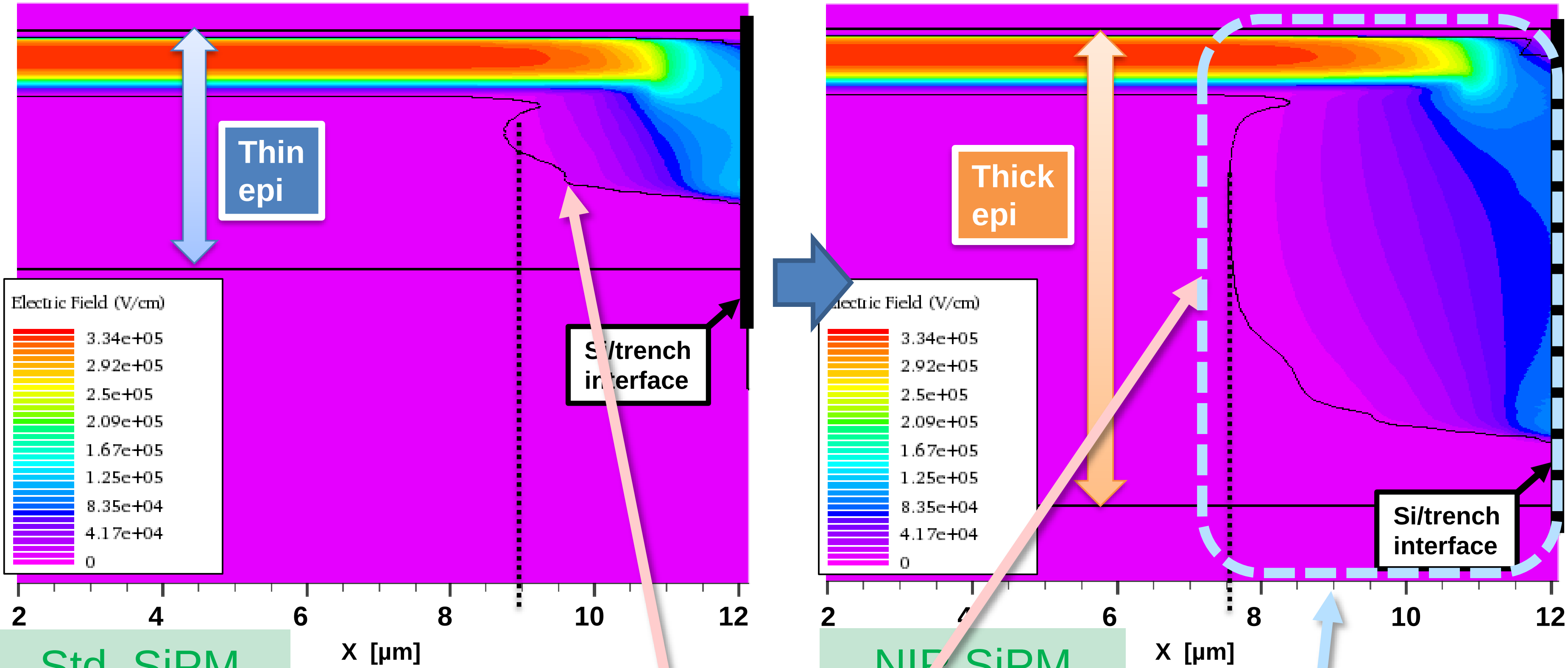
Small cell layout

NIR-HD – new developments

Ongoing Developments: new border

TCAD Simulation: Electric Field
25µm cell @ breakdown voltage

Thicker epitaxial layer



Std. SiPM

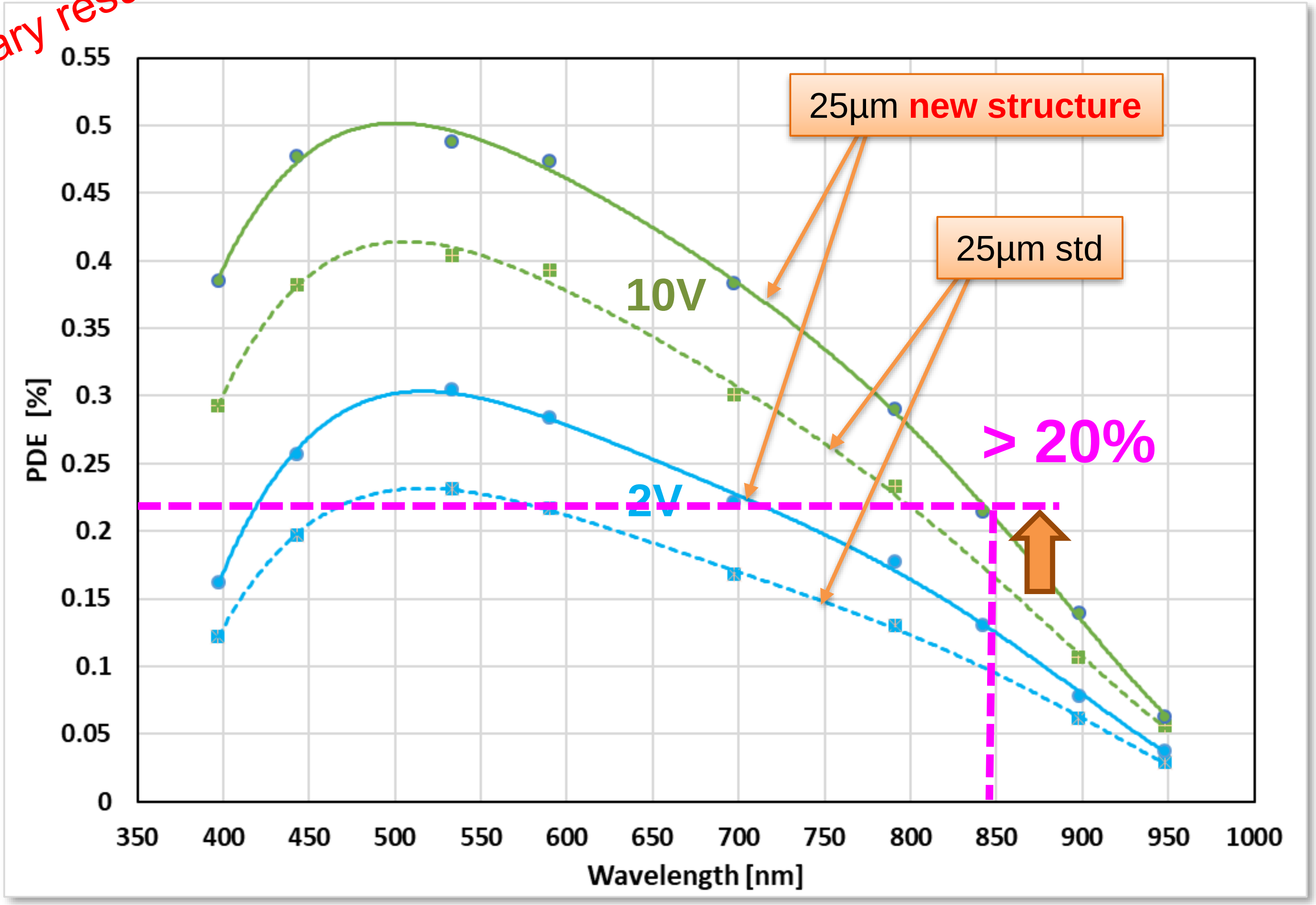
NIR SiPM

Charge collection loss at the edges:
→ Increases with thickness of epi layer

Optimization done in this region

NIR-HD_2 SiPMs PDE

Preliminary results



With new border, PDE is significantly improved in almost all the spectrum

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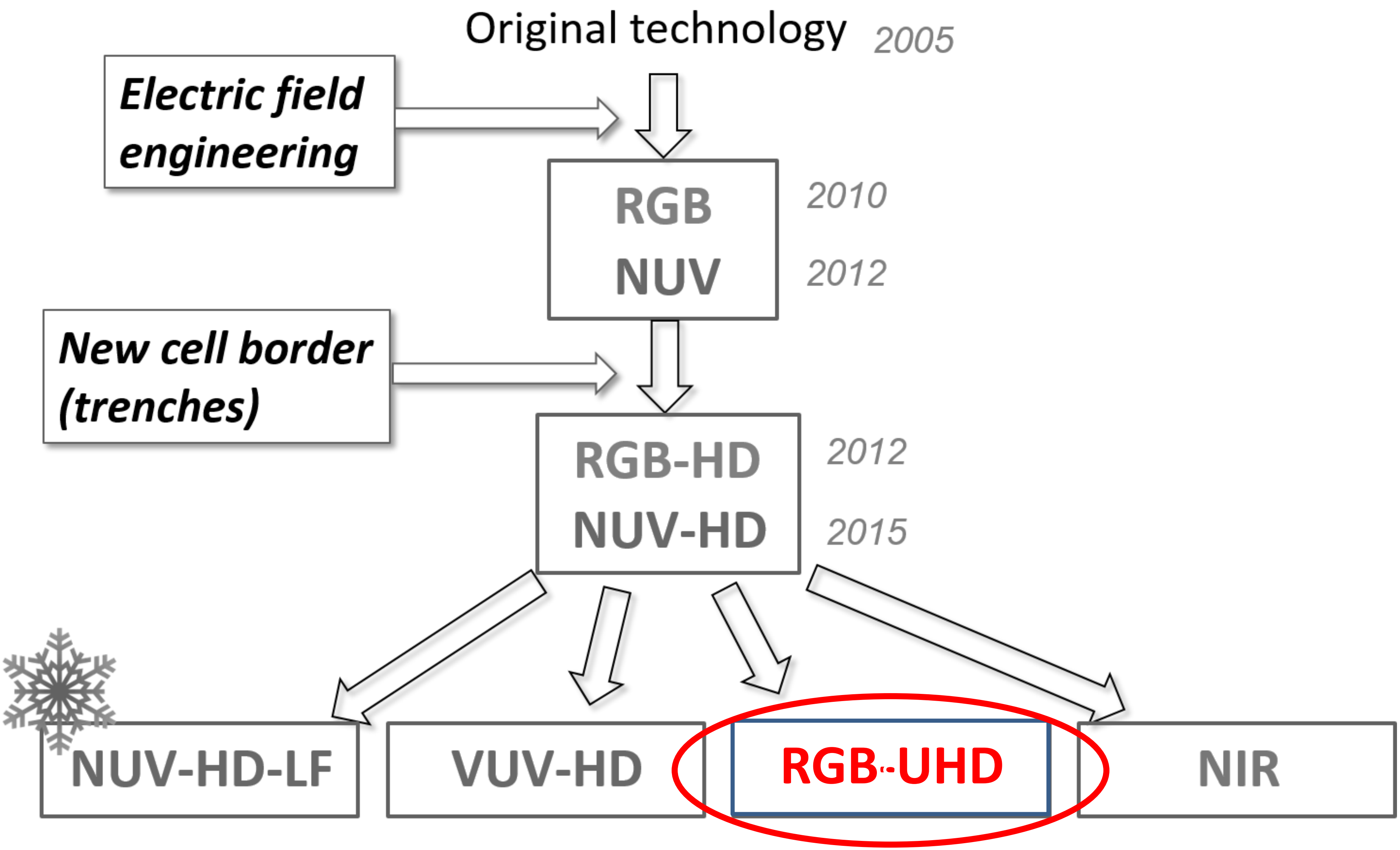
Thank you!

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

Backup slides

Ultra high-density technology RGB-UHD



Original technology 2005

Electric field engineering

RGB 2010

NUV 2012

New cell border (trenches)

RGB-HD 2012

NUV-HD 2015

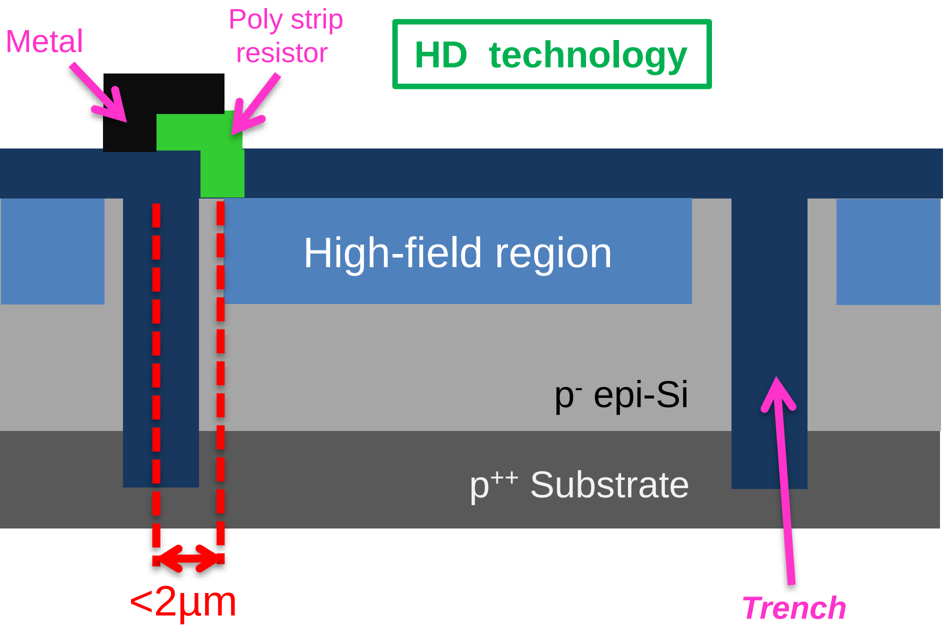
NUV-HD-LF

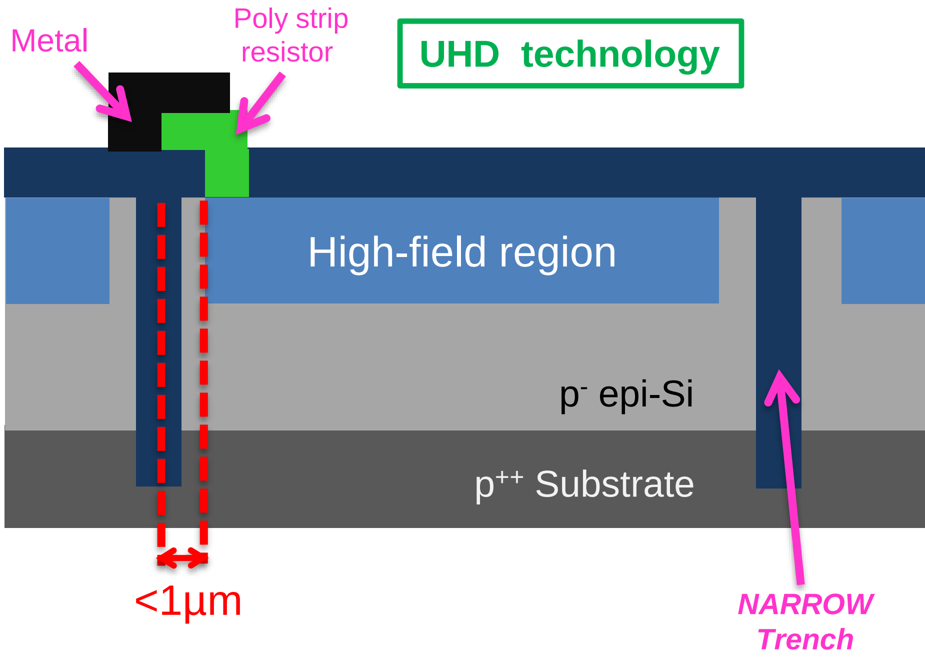
VUV-HD

RGB-UHD

NIR

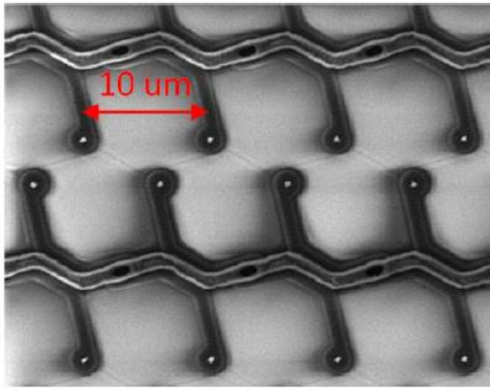
HD and UHD technologies



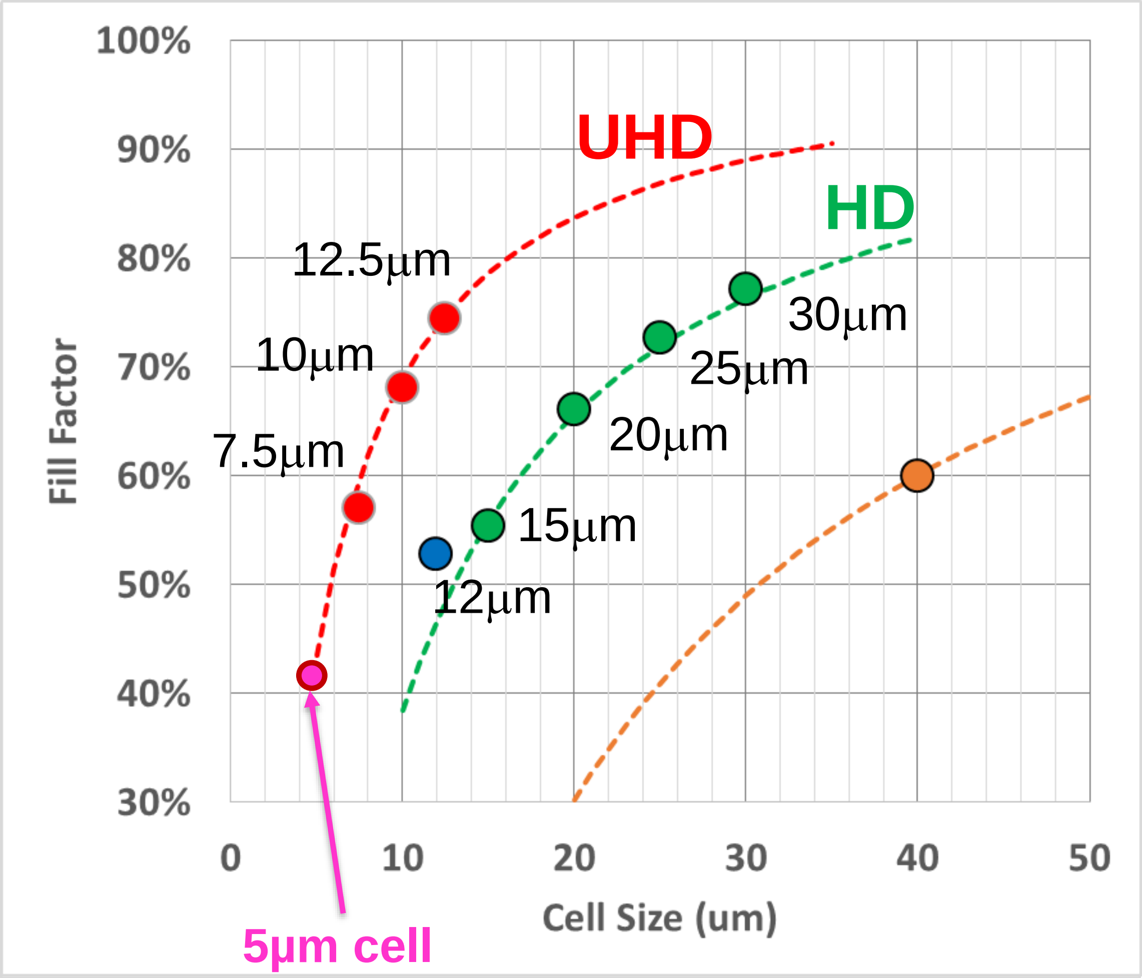


We reduced as much as possible the dead region around the cell

- **Smaller** cells
  - Gain reduction → Afterpulsing and CT reduction.
  - Faster cell recharge
  - Higher Dynamic Range
- **But we also need HIGH FF → HIGH PDE !**



UHD technology: produced SiPMs



RGB-HD

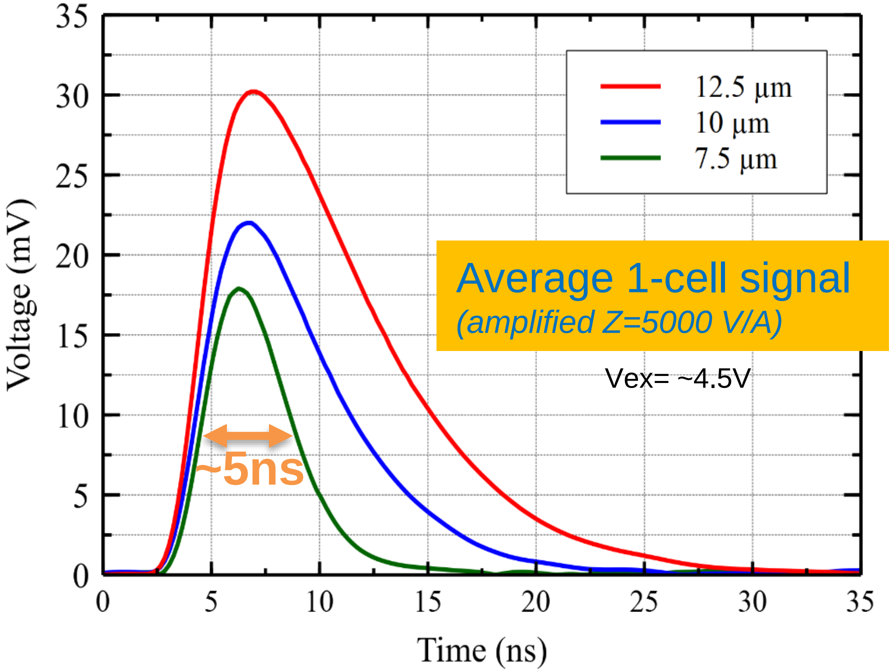
cell size (µm)	cells/mm²
30	1100
25	1600
20	2500
15	4500
12	7000

RGB-UHD

cell size (µm)	cells/mm²
12	7400
10	11550
7.5	20530
5	*46190*

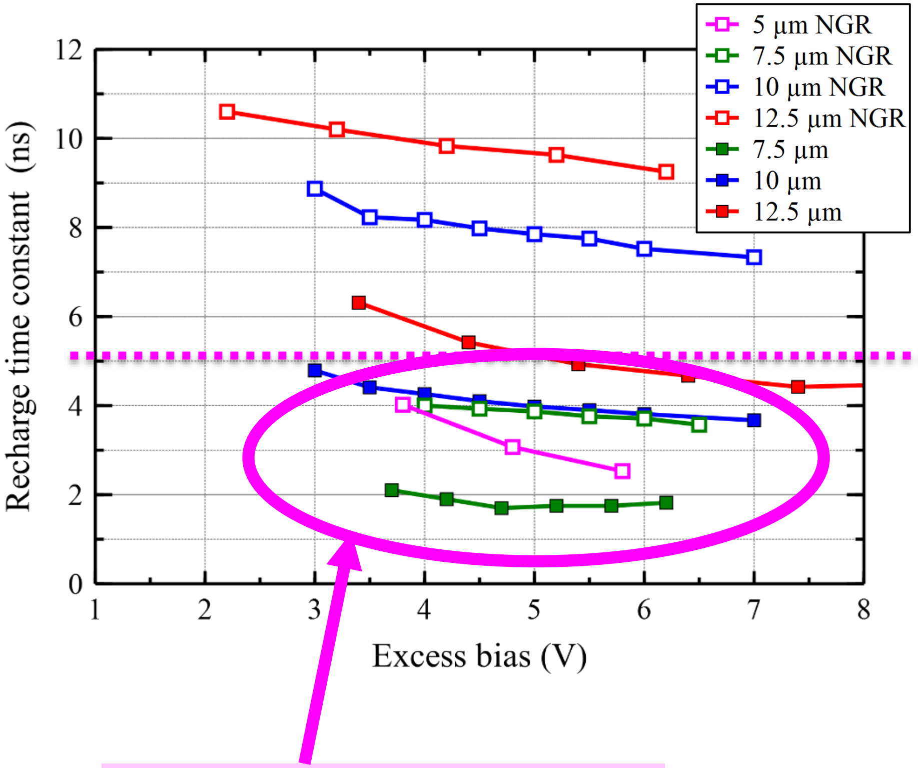
Optimization of UHD-SiPM
New Guard Ring (NGR)

Fast cell recharge – short signals

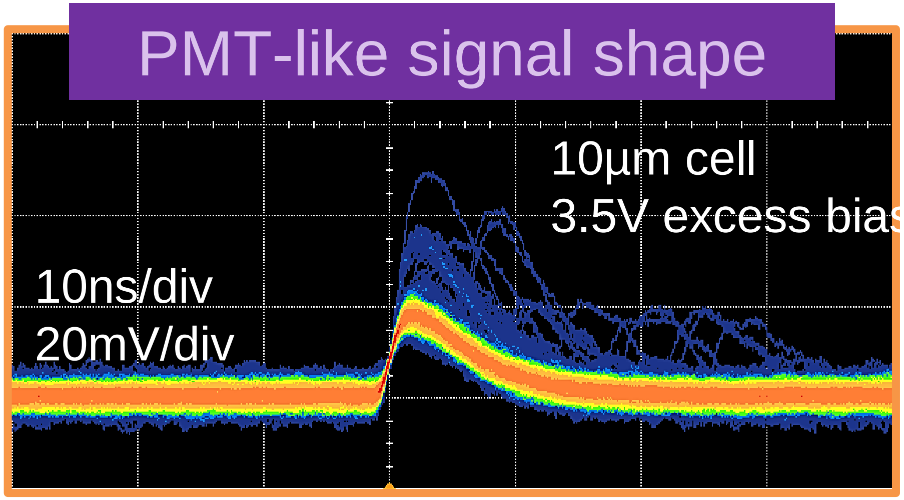


Average 1-cell signal
(amplified Z=5000 V/A)

Vex= ~4.5V



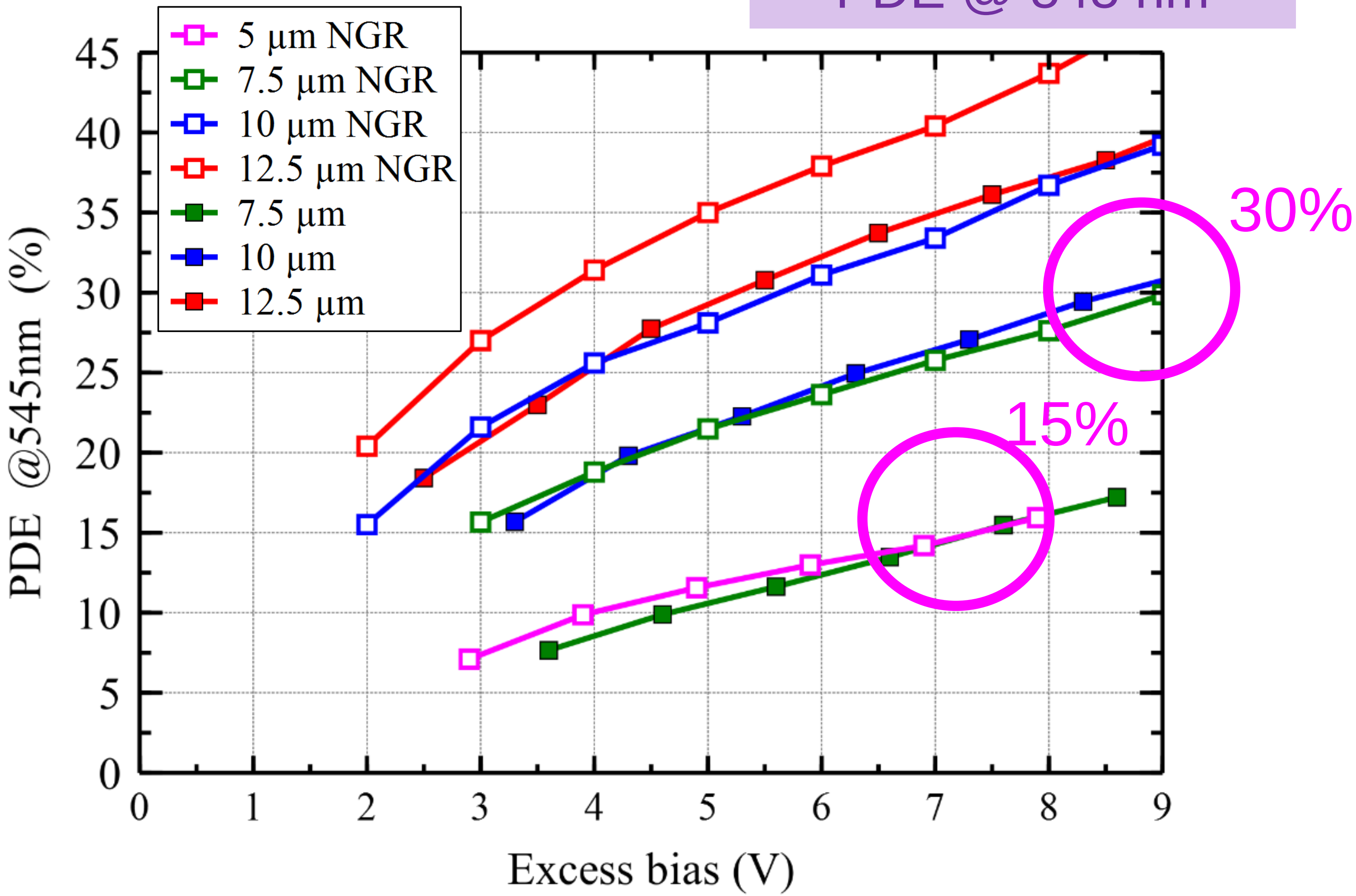
PMT-like signal shape



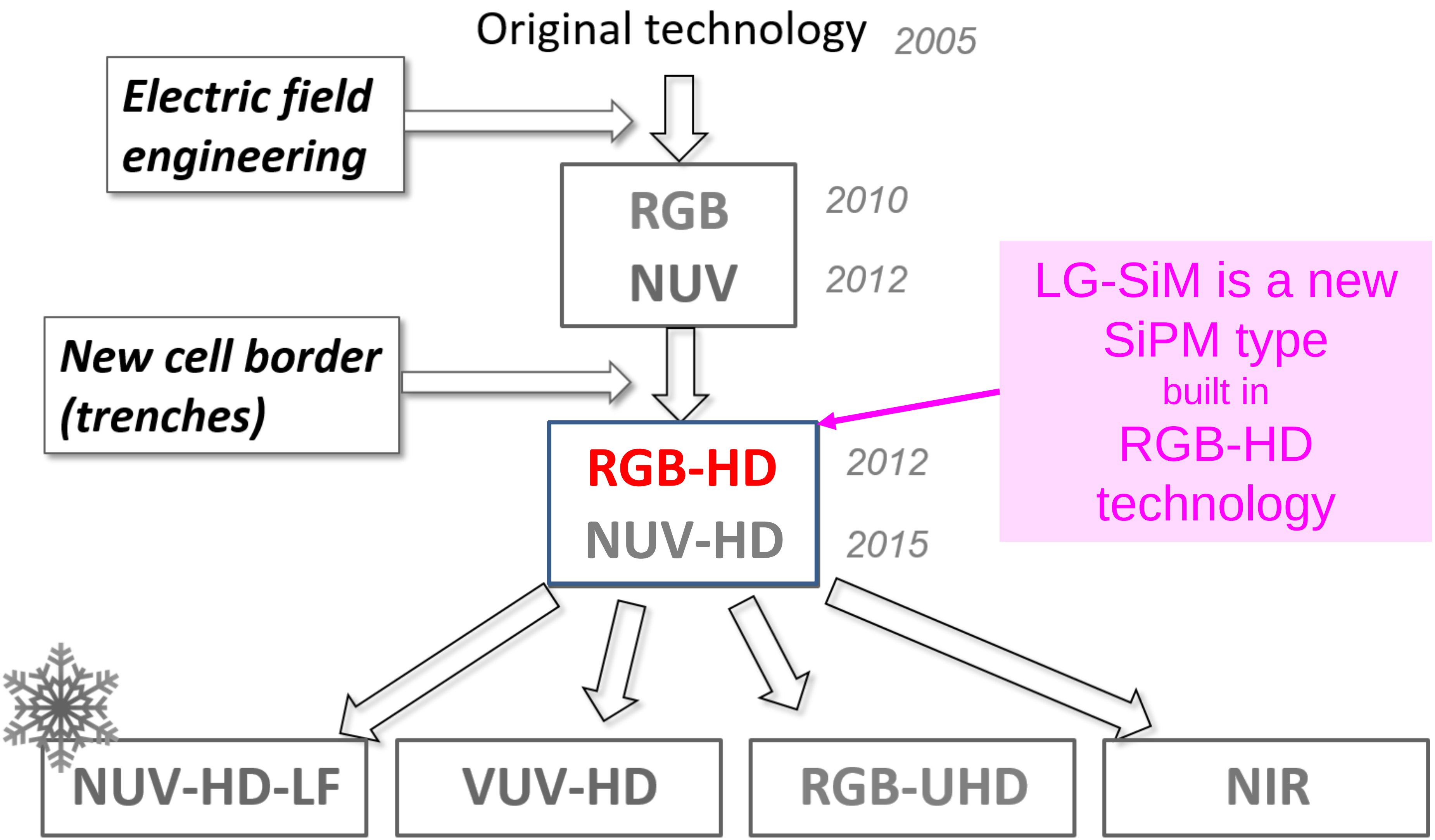
Tau < 5 ns with:
- 5 um cell
- 7.5 um cell
- 10 um cell

Detection efficiency

PDE @ 545 nm



Linearly-Graded SiPM – LG-SiPM



Original technology 2005

Electric field engineering

RGB 2010

NUV 2012

New cell border (trenches)

RGB-HD 2012

NUV-HD 2015

LG-SiM is a new SiPM type built in RGB-HD technology

NUV-HD-LF

VUV-HD

RGB-UHD

NIR

LG-SiPM

Position sensitive SiPM with four readout pads. From the combination of the four signals we can get:

Position

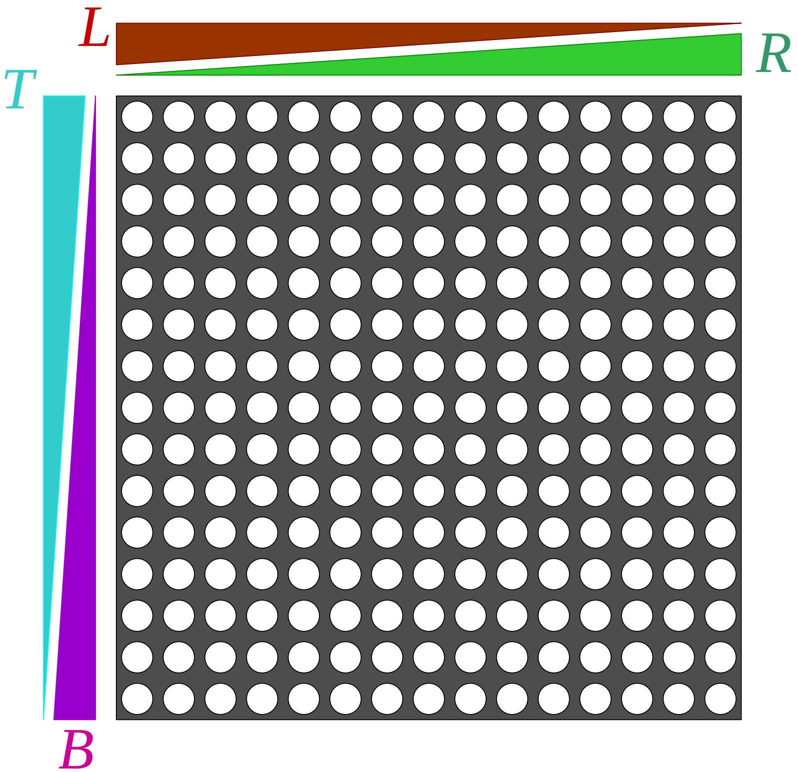
$$x = \frac{L - R}{L + R} \qquad y = \frac{T - B}{T + B}$$

Energy

$$E = L + R + T + B$$

Position sensitivity theoretically down to the single microcell level

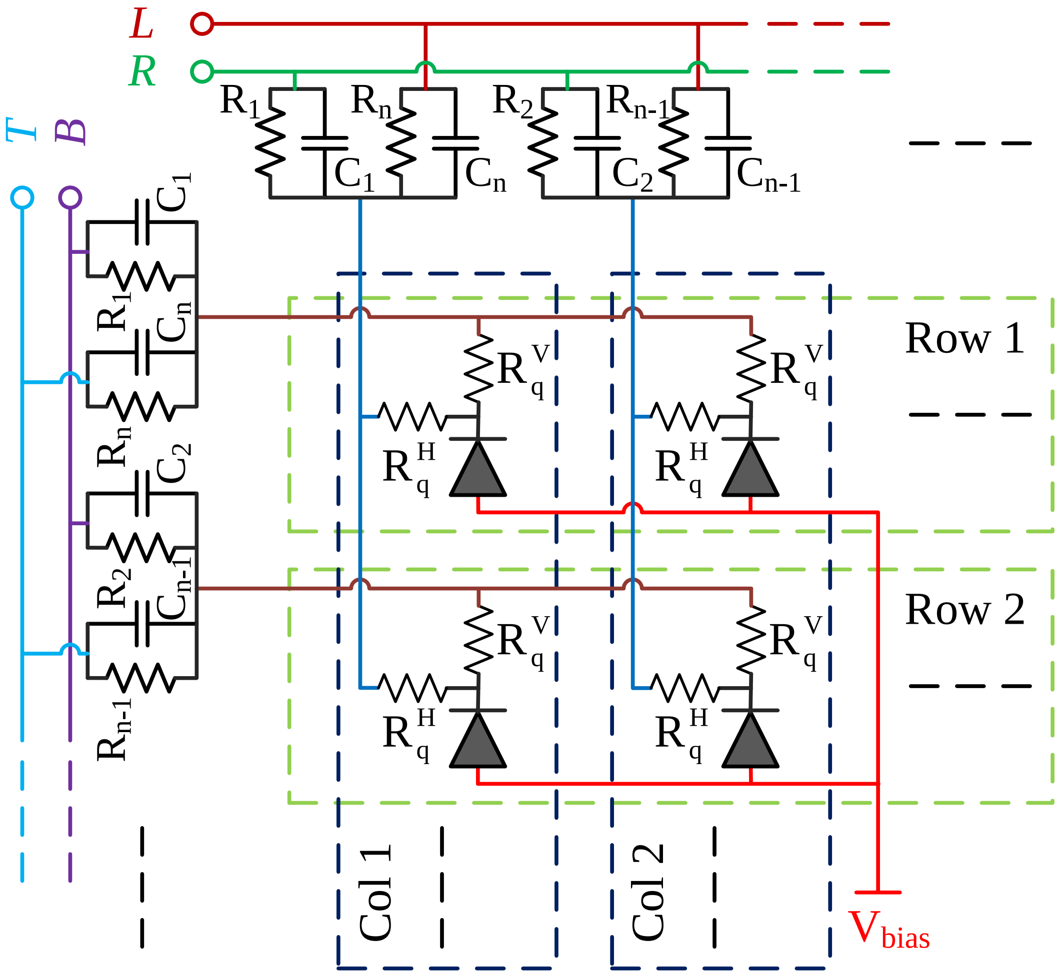
Limited by electronic noise and DCR.



Basic idea of the LG-SiPM.

Typical die size: 8x8 mm^2

LG-SiPM - implementation



Single-photon imaging should be possible with 4 readout channels.