FBK SiPM technology

F. Acerbi, G. Borghi, M. Capasso, A. Gola, A. Mazzi, G. Paternoster

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JENNIFER2

IRIS INTEGRATED RADIATION AND IMAGE SENSORS

Fondazione Bruno Kessler

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

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

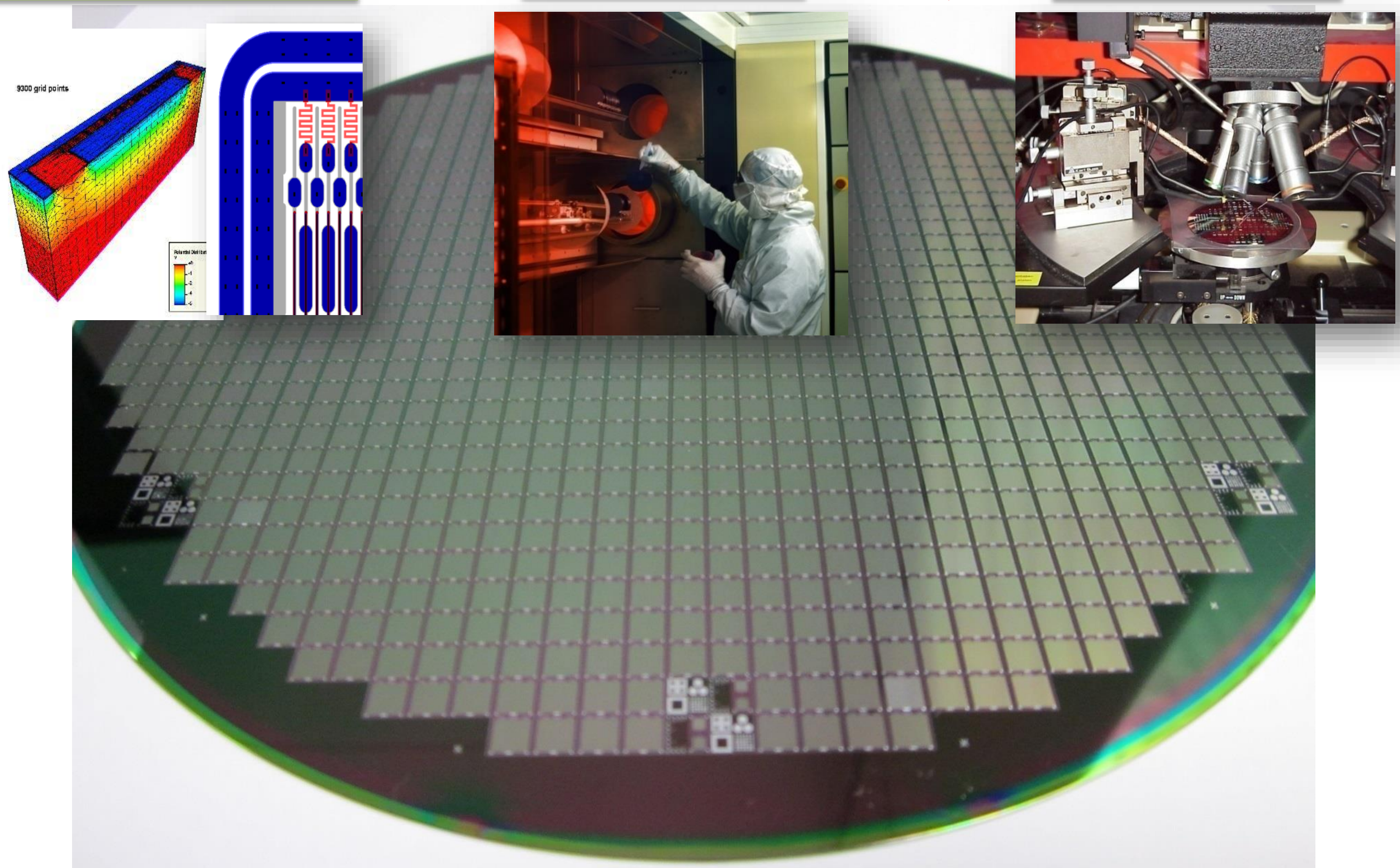
Publicly funded research center

350 researches working in different fields

In addition, we have proven experience (e.g. with CERN) in Strip Detectors, Pixel Detectors and Silicon Drift Detectors (state of the art)

FBK expertise

Simulation & design → Fabrication → Device testing



Outline

- SiPM technology at FBK
  - NUV-HD technology
  - Performance improvements
  - Crosstalk reduction
  - Primary DCR reduction
  - VUV-HD
  - Position sensitive SiPMs
  - Radiation hardness of SiPMs
- Single photon time resolution
  - SPTR: factors affecting single SPAD performance
  - SPTR: factors affecting SiPM performance

FBK SiPM technology roadmap

Original technology

Electric field engineering

2005

RGB *2010*

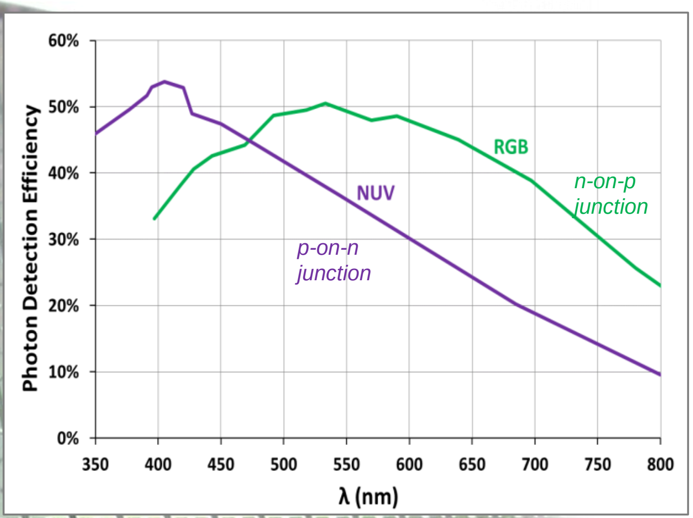
NUV *2012*

New cell border (trenches)

RGB-HD *2012*

NUV-HD *2015*

Position sensitive SiPMs



Ongoing Developments

NUV-HD-Cryo

Optimized for cryogenic applications

VUV-HD

For detection in VUV (e.g. 175nm)

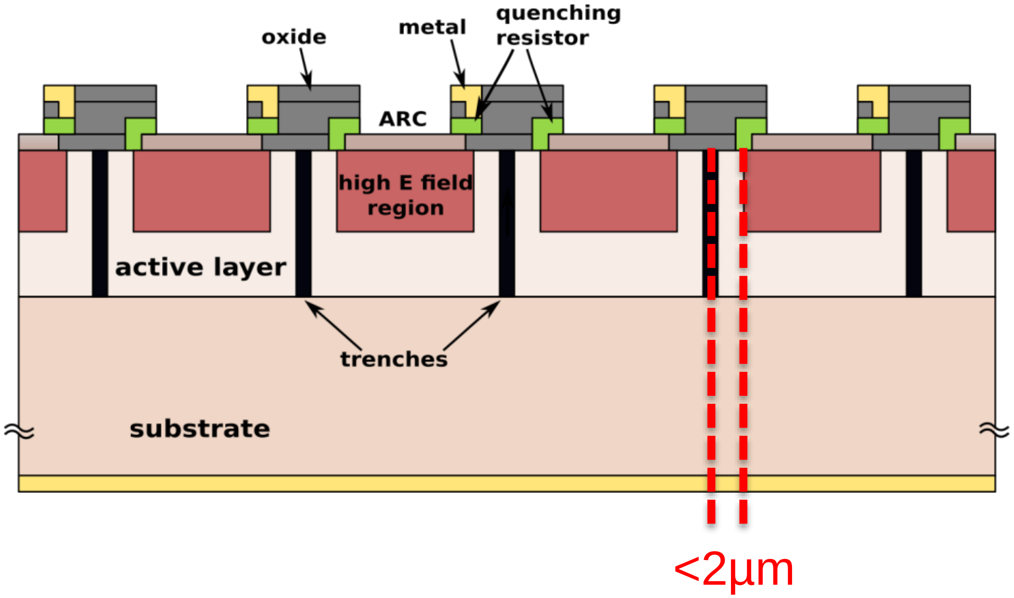
RGB-UHD

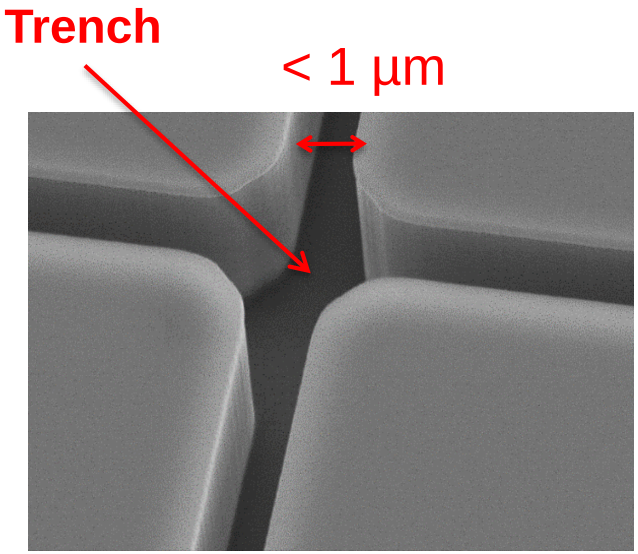
Ultra high cell density (Very small cells)

NIR-HD

Improved PDE in NIR (at 800÷1000nm)

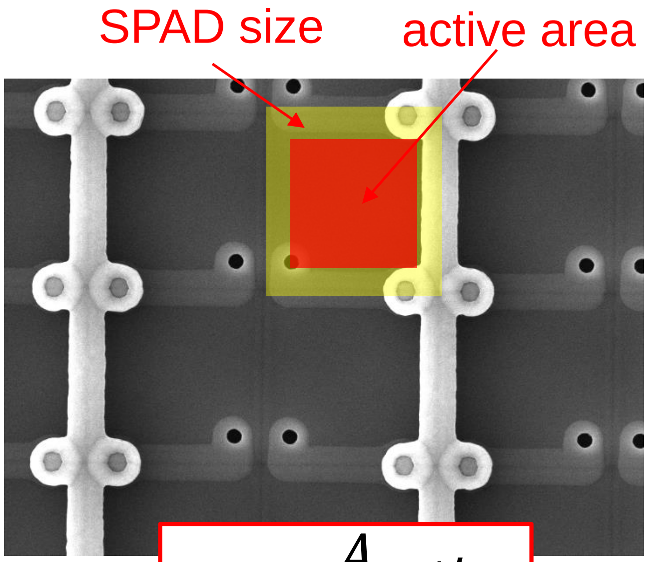
NUV-HD Technology



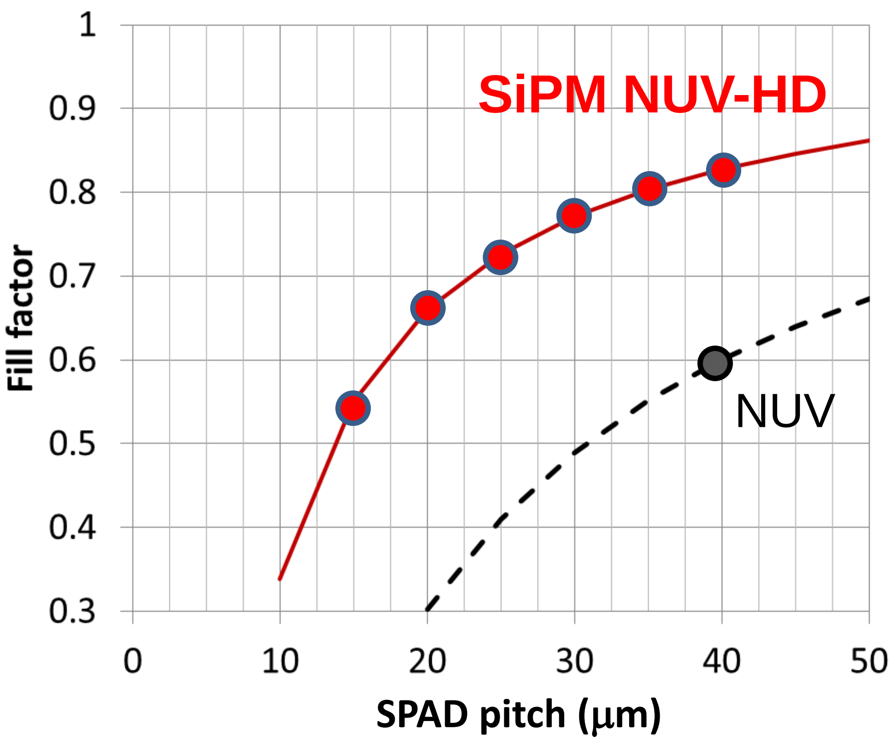


- p-on-n junction → Higher trigger probability for NUV light
- Narrow dead border region (< 2 µm) → Higher Fill Factor
- Trenches between cells → Lower Cross-Talk

NUV-HD: Fill Factor



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

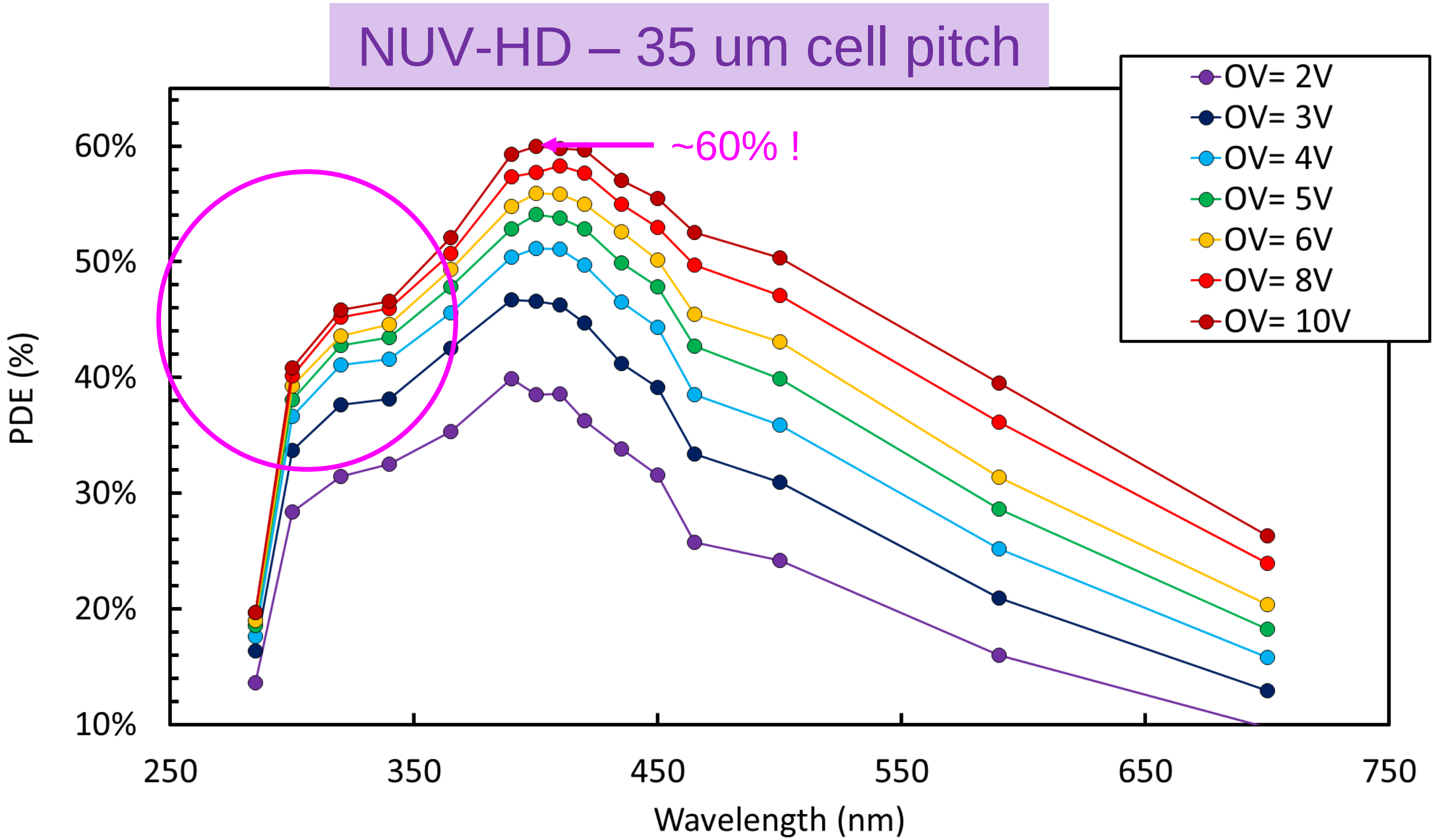


SPAD Pitch	15 µm	20 µm	25 µm	30 µm	35 µm	40 µm
Fill Factor (%)	55	66	73	77	81	83
SPAD/mm^2	4444	2500	1600	1111	816	625

High Dynamic Range, Fast recovery time (15 µm – 20 µm)

High PDE (35 µm – 40 µm)

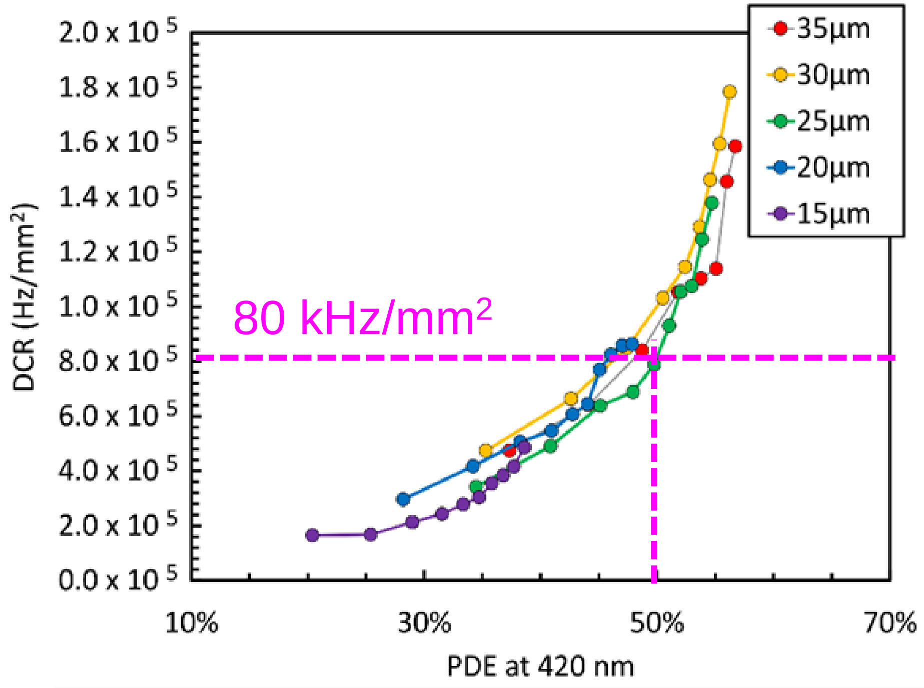
Photon Detection Efficiency

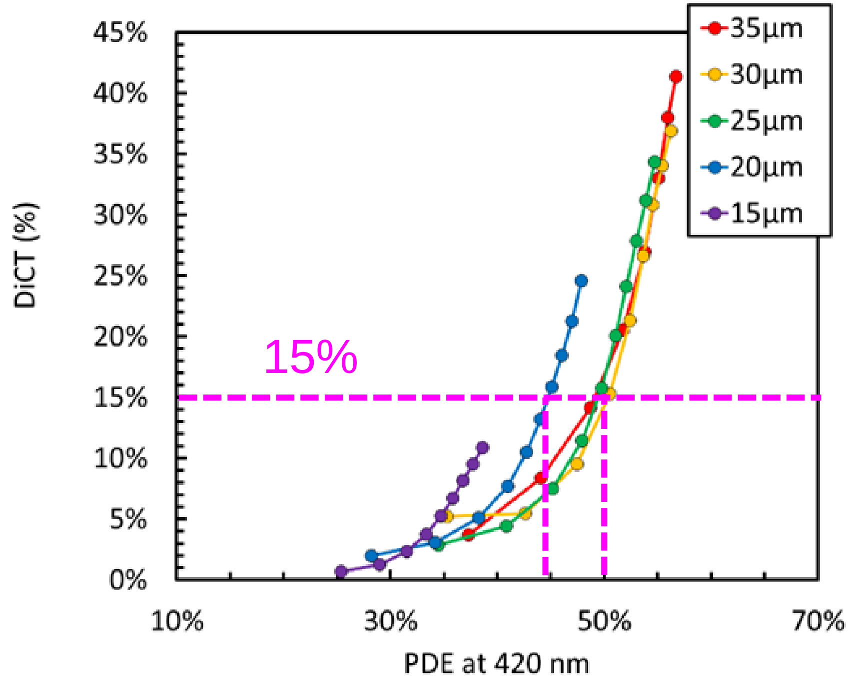


Gola, A et al. (2019). "NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler." *Sensors*, *19*(2), 308.

Dark Count Rate and Direct Cross Talk

T = 20 C





Dark Count Rate

Optical Crosstalk (Correlated Noise)

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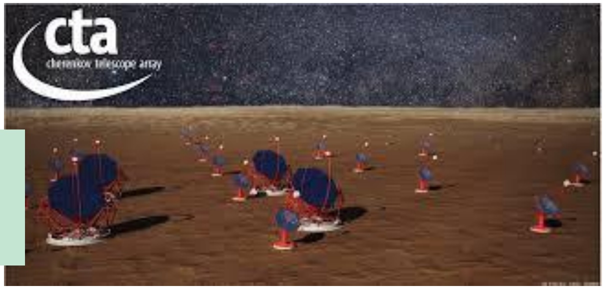
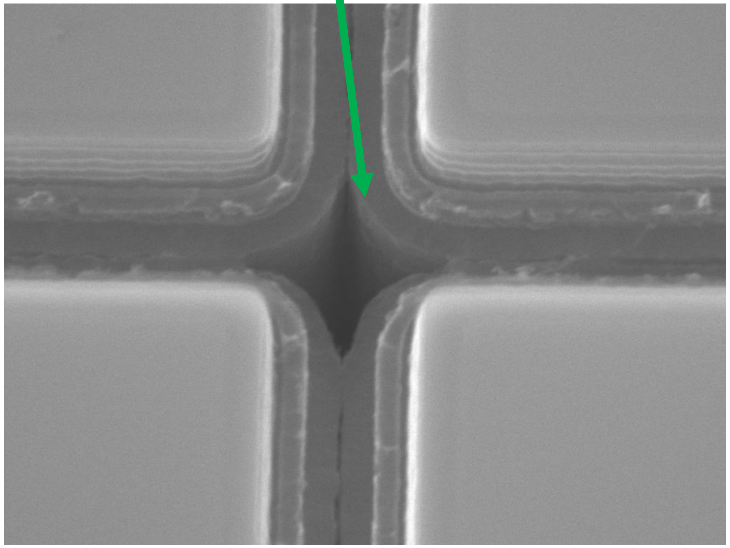
NUV-HD Improvements

NUV-HD-LowCT



Applications such as CTA

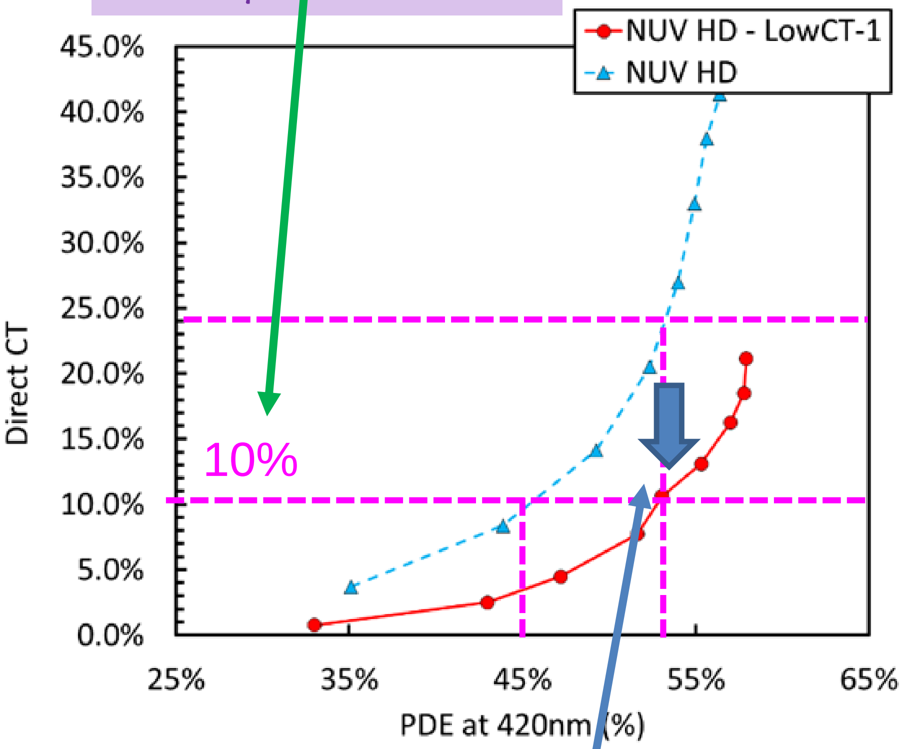
Light absorbing material was inserted inside trenches, between adjacent microcells



SEM image of trenches, separating adjacent microcells.

Metal in trenches is under development..

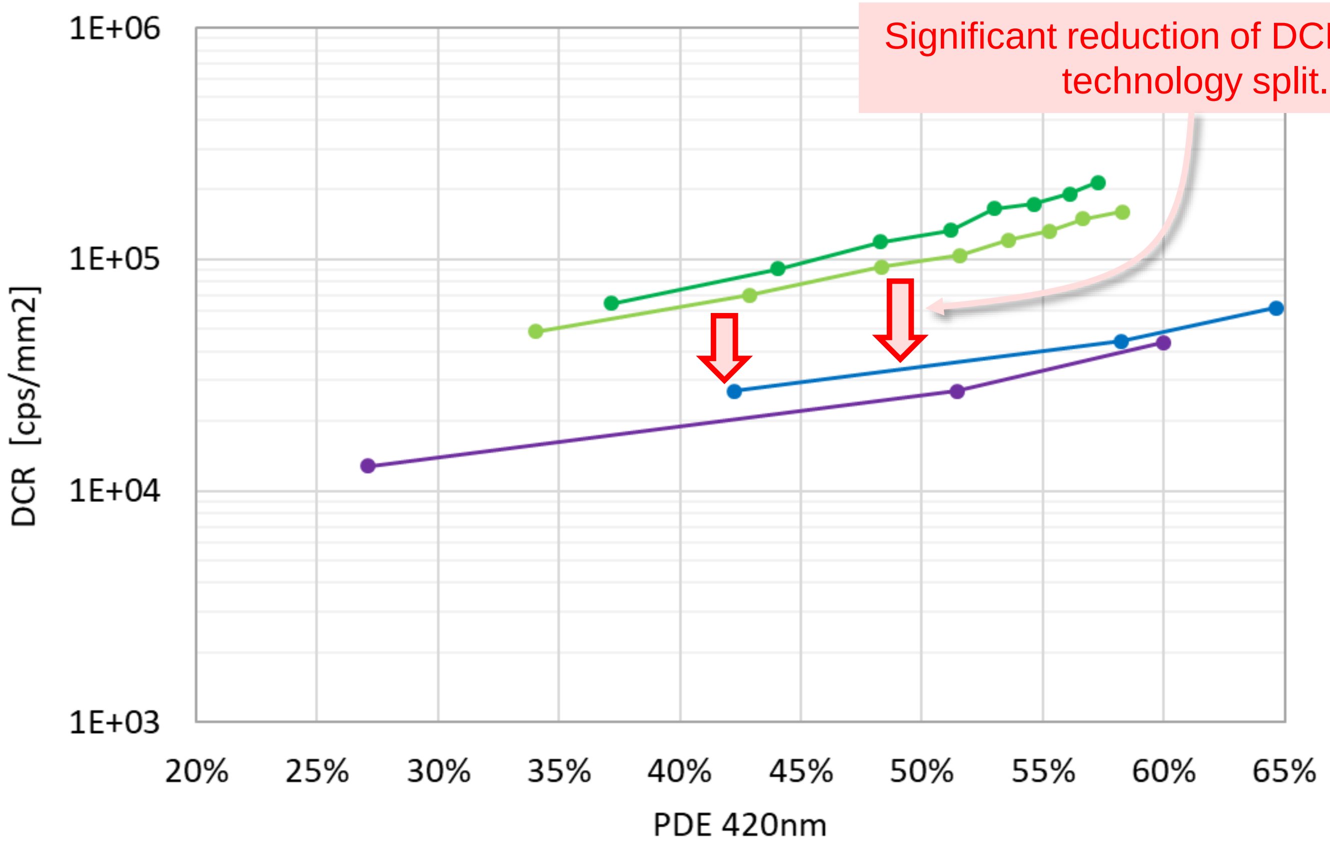
35 μm cell size



2.5x reduction of Optical Crosstalk at same PDE

NUV-HD – Reduction of DCR

We are experimenting with technology splits to further reduce the noise (DCR).



New NUV-HD & VUV-HD SiPMs: 35µm and 40µm cell pitch

VUV-HD

In some specific applications direct detection of VUV light is required → NUV-HD technologies have 2 main limiting factors

Typical ARC is a multi-layer stack of SiO_2(absorbs λ<150nm), Si_3N_4(absorbs λ<250nm) → external QE is affected

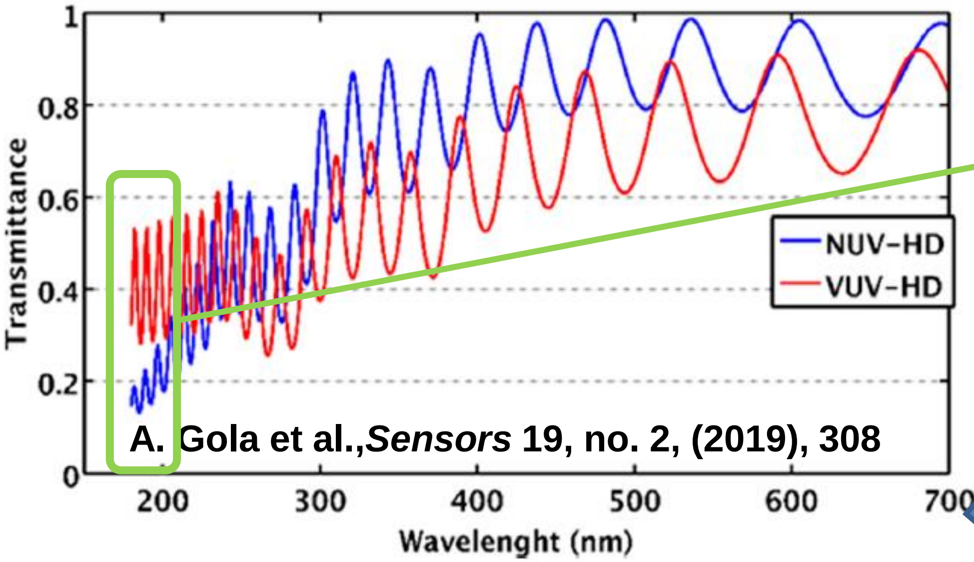
Ultra-shallow absorption of UV light in silicon: λ_{abs}<10nm at λ=300nm → generated e-h pairs have high recombination probability due to defects → internal QE is affected

R&D focused on ARC optimization:

- Si_3N_4 removal
- Preservation of surface passivation quality

Current R&D has been conducted in collaboration with TRIUMF

VUV-HD

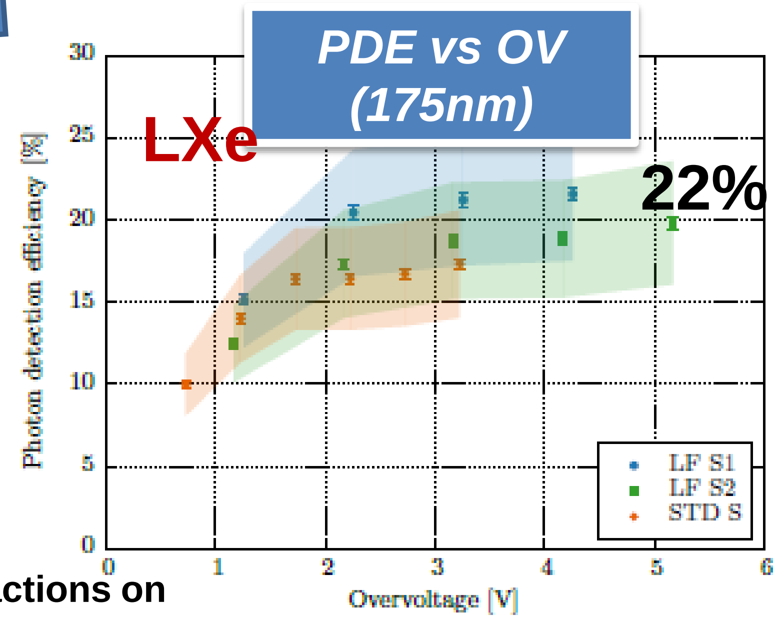


A. Gola et al.,*Sensors* 19, no. 2, (2019), 308

Transmittance below 200nm stays between 30%-50%

Normal ARC (NUV) and modified (VUV) ARC under the hypothesis of normal incident light. Air is assumed to be the surrounding medium.

TRIUMF



Jamil, A. et al. (2018). IEEE Transactions on Nuclear Science. PP.11.10.1109/TNS.2018.2875668.

Linearly-Graded SiPM (LG-SiPM)

- Linearly-Graded Silicon Photomultiplier
  - A type of position-sensitive silicon photomultipliers (PS-SiPM).
  - 4 cathode signals (position information) and 1 anode signal.
- The currents of the 4 cathode signals change linearly according to the position of the fired microcell.
- Position

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

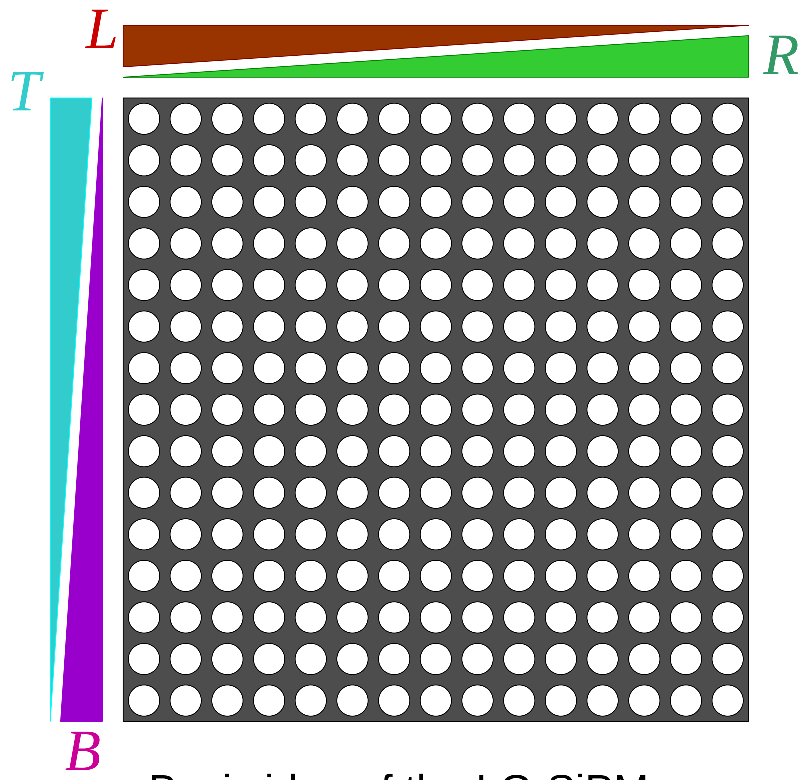
- Energy

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

Several microcells triggered

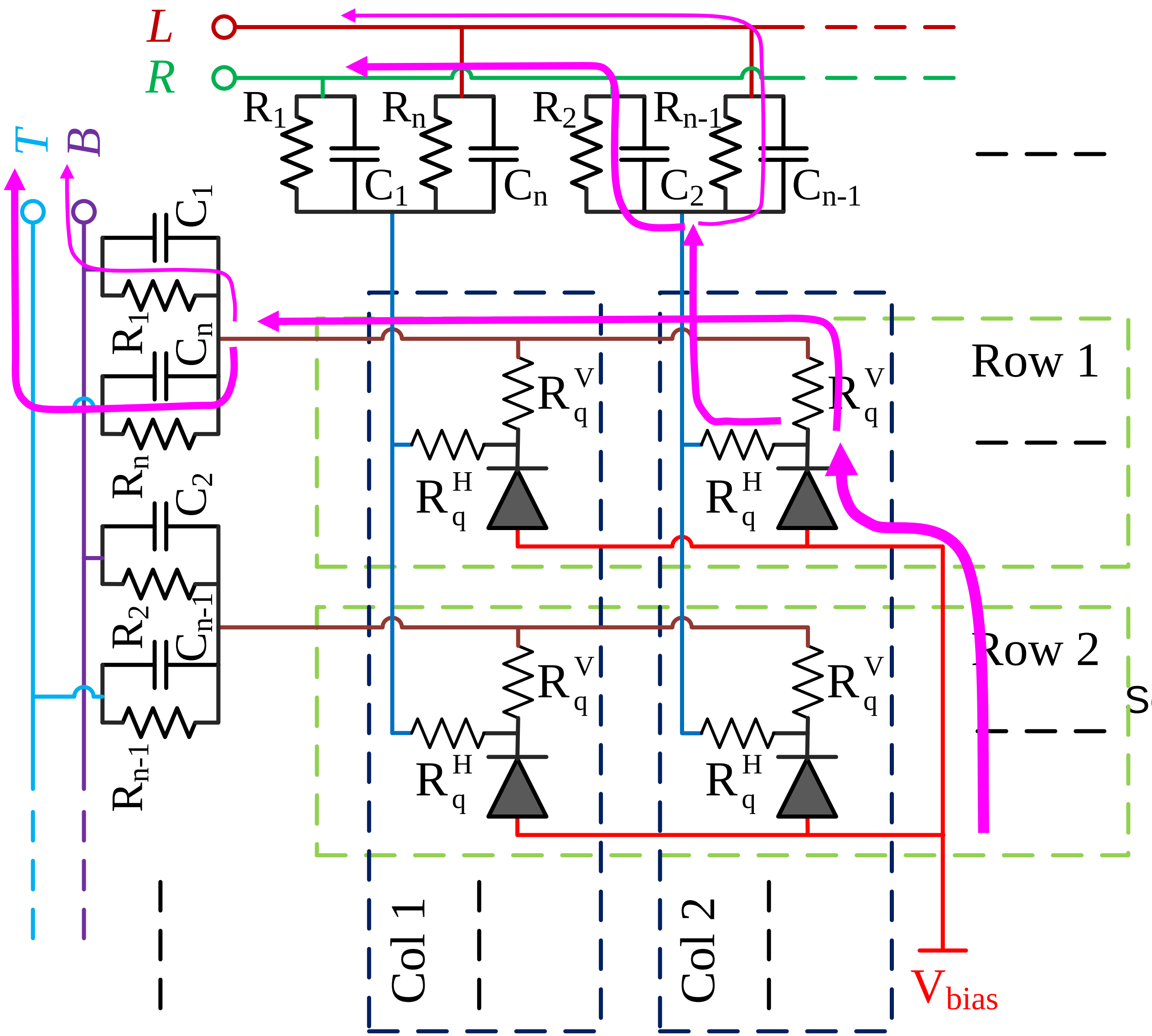
⇓

Implements the Center of Gravity



Basic idea of the LG-SiPM.

LG-SiPM

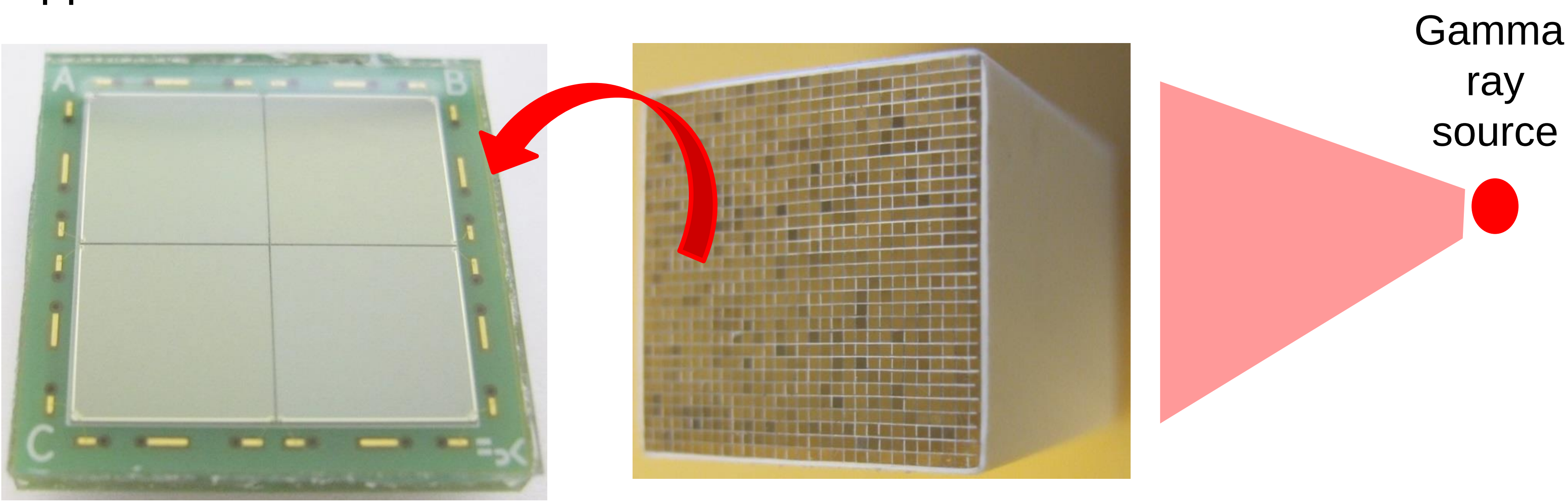


Schematic of the 2D position encoding method

2 x 2 array of LG-SiPMs

- 2 x 2 array of 7.75 x 7.75 mm^2 LG-SiPMs
- Microcell size: 20 μm (square cells).
- Gap between LG-SiPMs is 0.2 mm.
- Application: small-animal PET

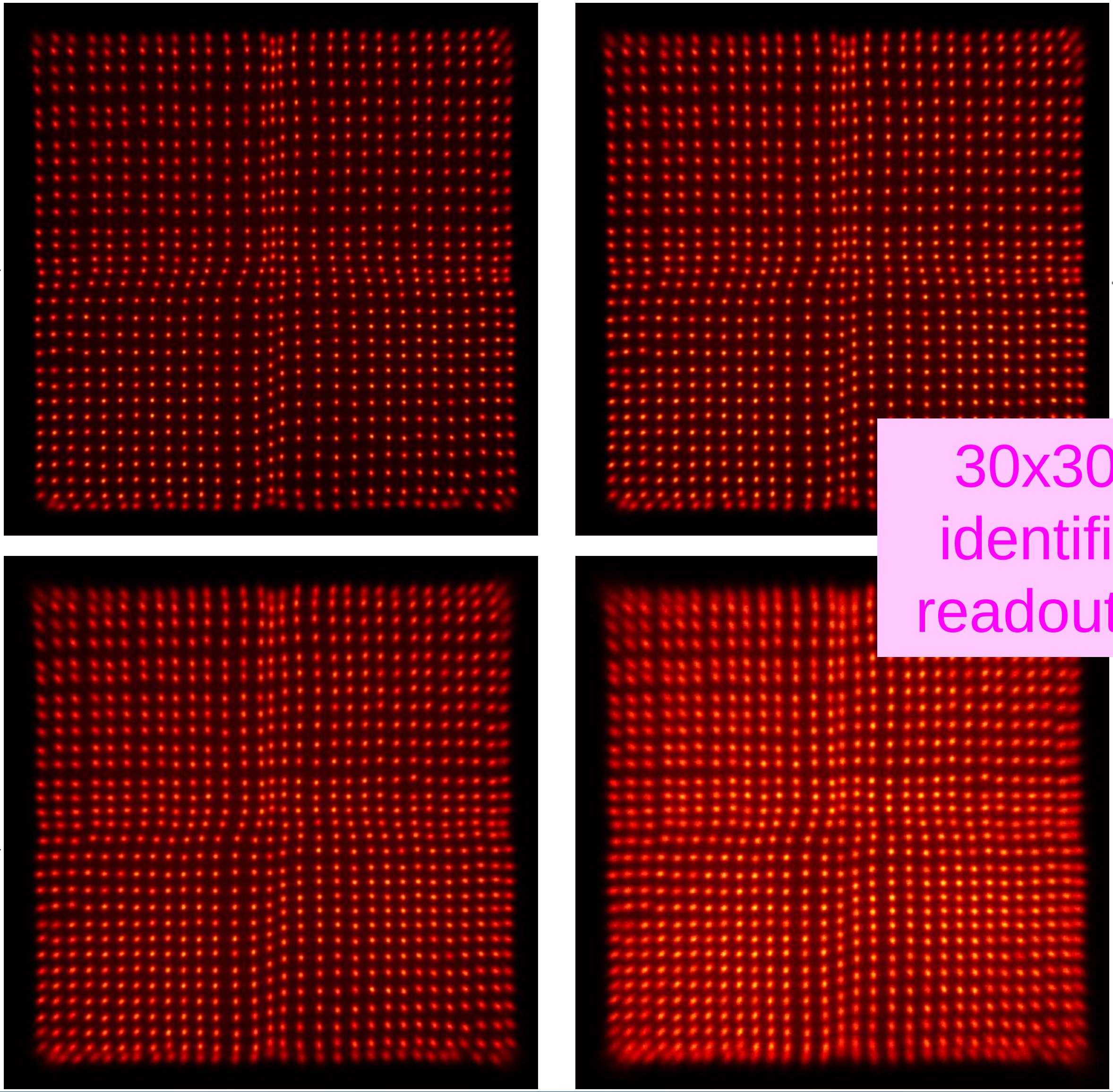
Collaboration with UCDavis: Junwei Du and Simon Cherry



1.5 x 1.5 cm^2
4 readout
channels only

LYSO array
30 x 30 array of 0.445 x 0.445 x 20 mm^3
Pitch size is 0.5 mm.

Are we able to identify all crystals?



-10 ºC

0 ºC

10 ºC

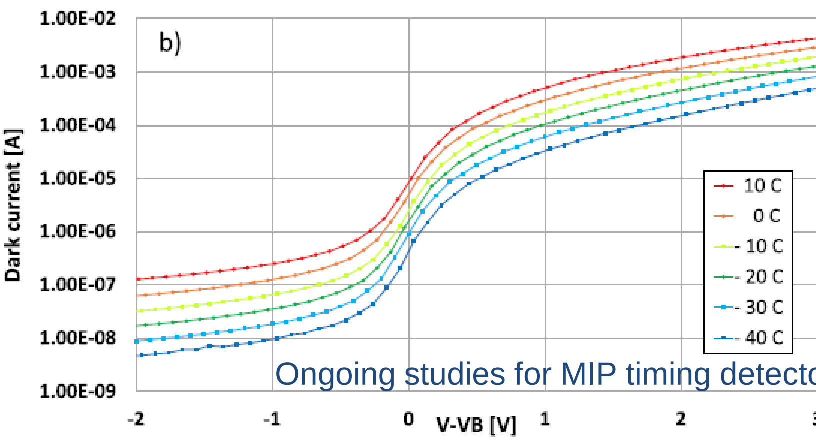
20 ºC

30x30 crystals identified with 4 readout channels

SiPM Radiation Hardness

At FBK we are developing radiation hard SiPMs for HEP and spatial applications.

Effects of Radiation Damage	Mitigation techniques
Increased Primary Dark Count Rate	Electric field engineering
Increased Afterpulsing	Electric field engineering Process adjustments
Efficiency loss (due to cells busy at triggering dark noise)	Very high cell density Ultra-fast recharge time



Ongoing studies for MIP timing detector of CMS

Low Field NUV-HD SiPMs, 15 µm cell irradiated at 5x10^{13} 1 MeV eq n/cm^2
Dark current per mm^2 at variable temperature

FBK SiPMs already demonstrated capability of surviving > 5e13 1 MeV neq/cm2 irradiation dose.

More and more demanding specifications form HEP experiments required development of single-photon detectors with next-generation radiation hardness.

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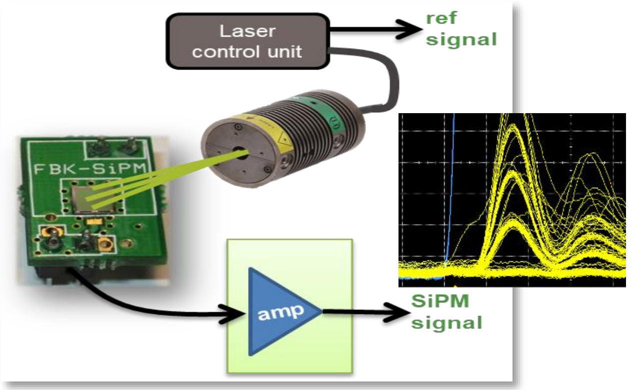
Thank you!
Any question?

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

Fabio Acerbi
Anna Rita Altamura
Giacomo Borghi
Massimo Capasso
Andrea Ficorella
Nicola Furlan
Alberto Gola
Stefano Merzi
Vladimir Mozharov
Giovanni Paternoster
Veronica Regazzoni
Nicola Zorzi

"Time Resolution" Using SiPMs

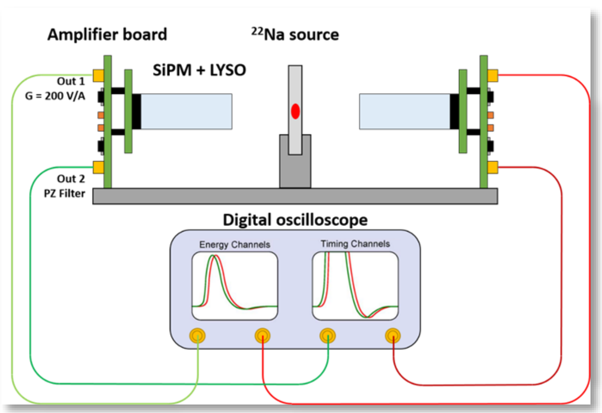


1) Single-photon time resolution (SPTR)

- LASER excitation; 1-photon triggers the SiPM
- Very important: SPAD internal structure!
  Signal amplitude! Noise of front-end electronics!

2) Time resolution for few-photon signals

- Applications like Cherenkov detection, LIDAR
- Important: Noise of detector! Crosstalk between SPADs!

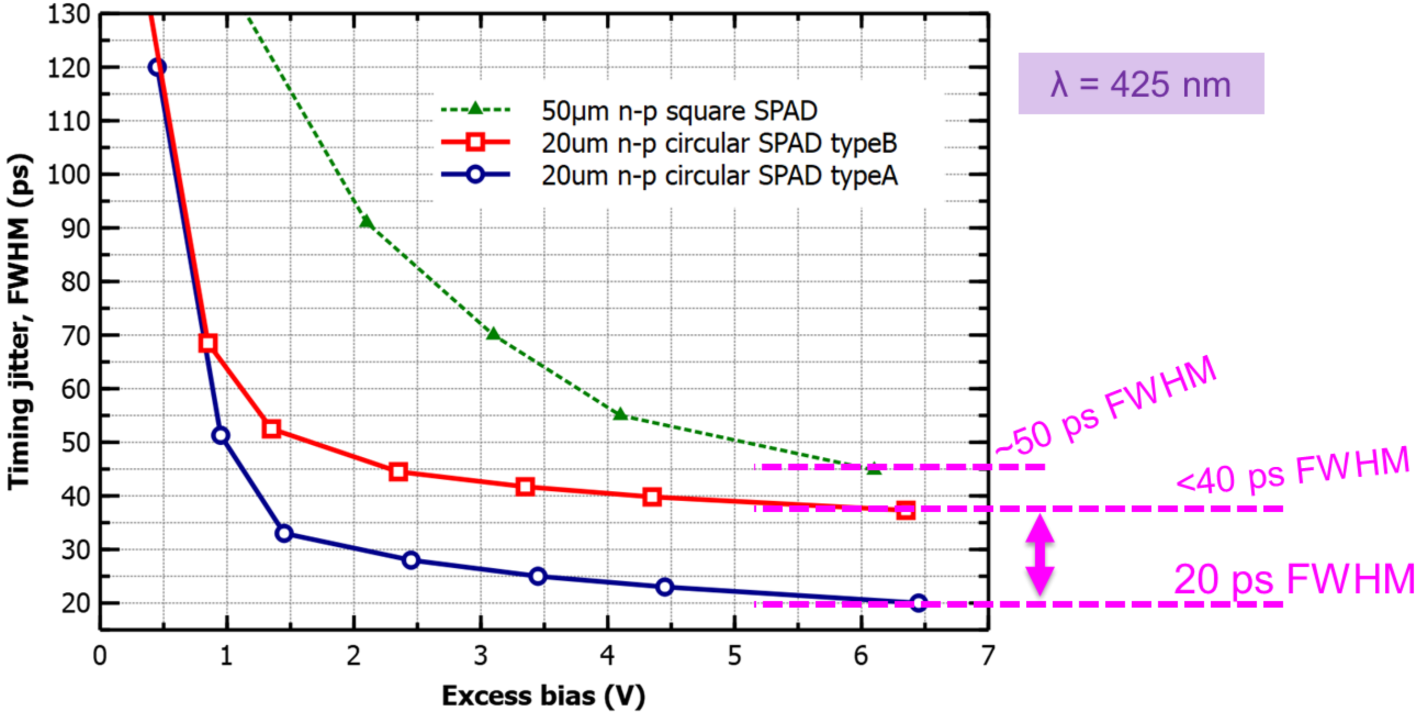


3) Time of arrival of high-energy gamma rays

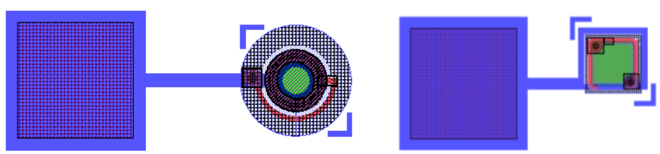
- Resolving the time-of-arrival of 1 gamma ray or 2 simultaneous gamma rays (coincidence resolving time, CRT)
- Many photons: large signals but threshold few ph. level.
- SiPM is coupled with scintillator → PDE important !
- Applications: ToF-PET / timing in HEP experiments

Single Photon Time Resolution

SPTR of Single SPADs



ACTIVE AREA LAYOUT	Diameter / side (μm)	Metallization
circular	20	Covered edges (A) with metal
circular	20	uncovered edges (B)
square	50	uncovered edges



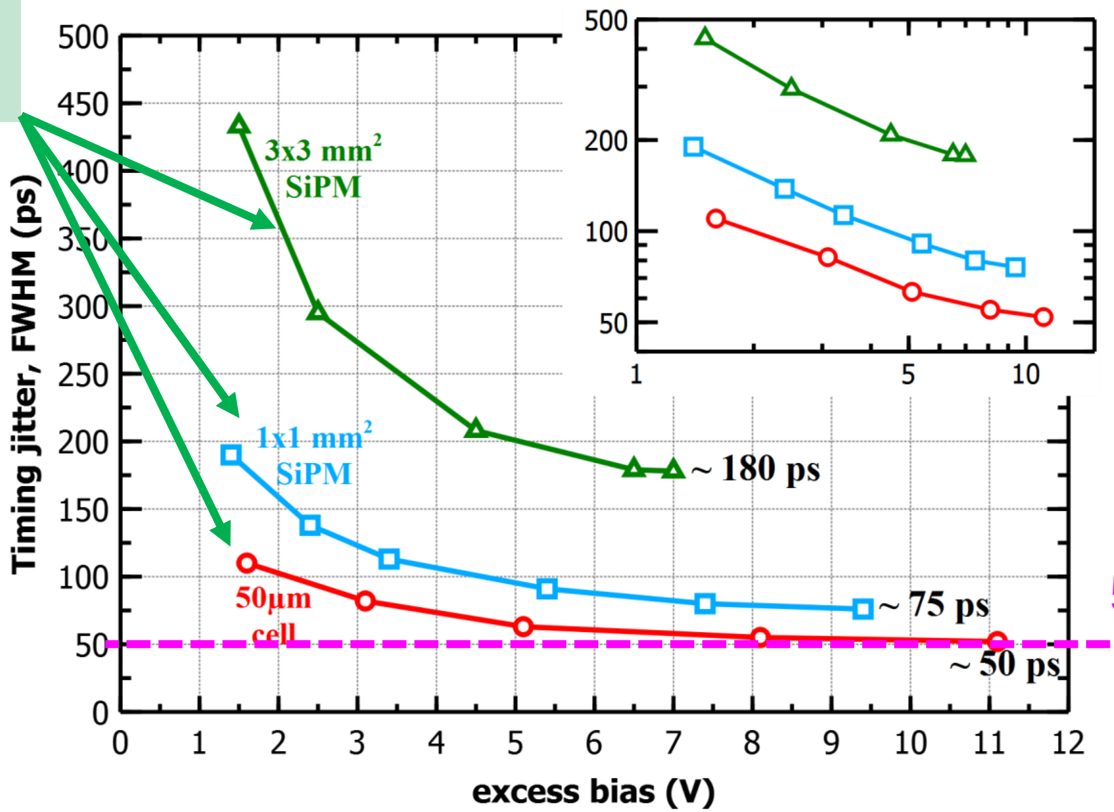
1) *Worse charge collection at SPAD edges*
2) Signal pick-up is very important

Covering the SPAD edges with metal *reduces the SPTR to 20 ps*

SPTR of SiPMs: Effect of Dimension

Different SiPM sizes

λ = 425 nm



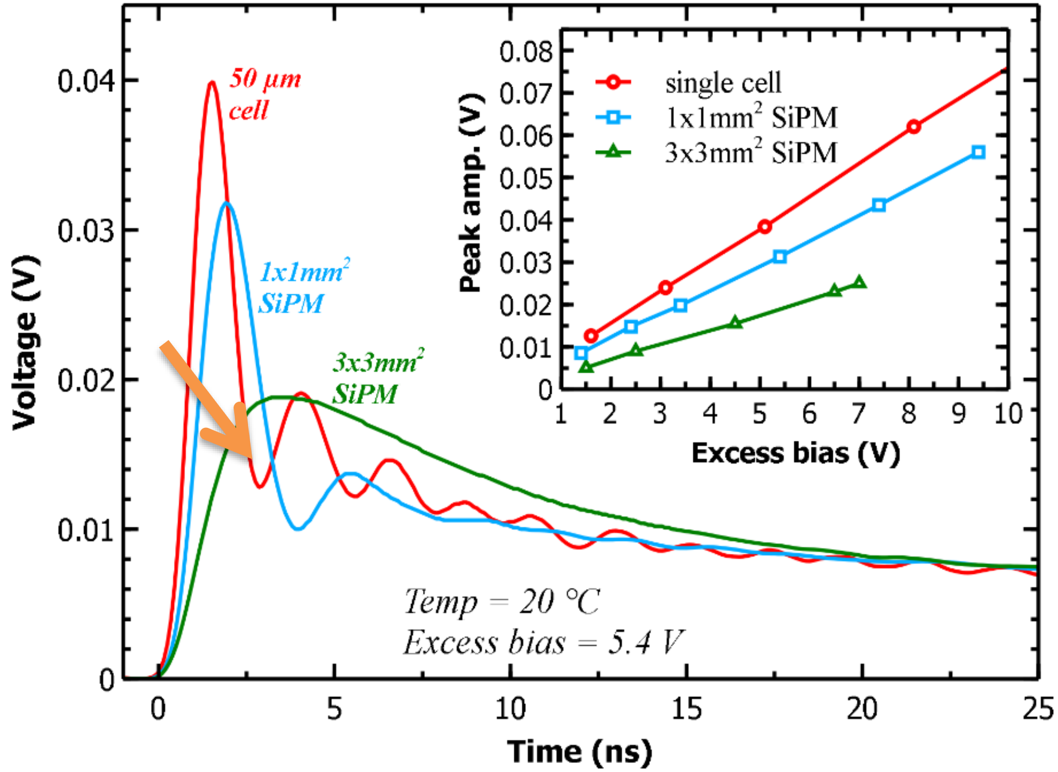
50 ps FWHM

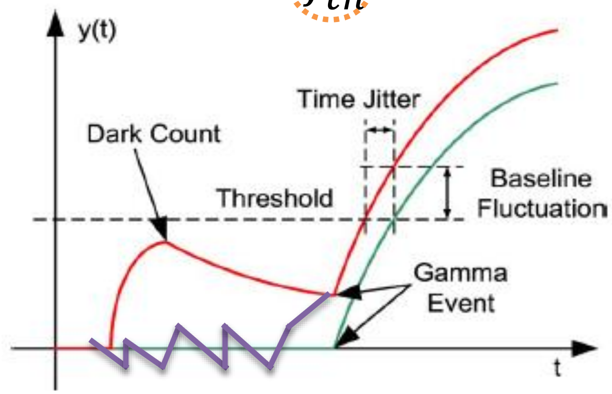
Larger active area
→ larger SiPM metal capacitance

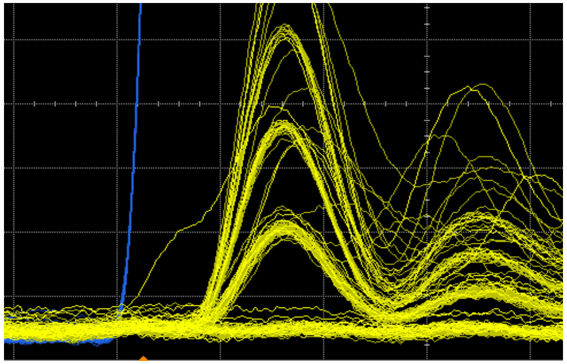
Electronic noise effect on SPTR very important on med/big area SiPMs

SPTR of SiPMs: Effect of Dimension

$$\sigma_n \propto \frac{\sigma_a}{f'_{th}}$$



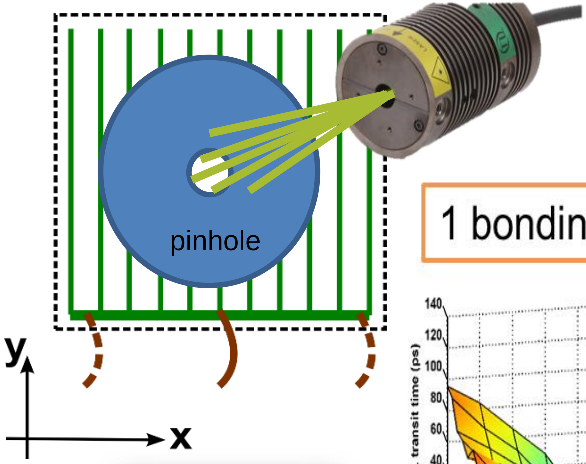


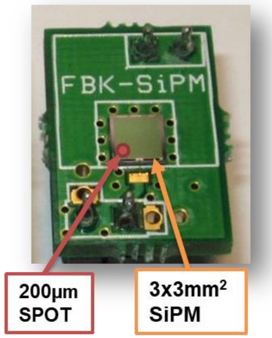


Larger active area
→ larger SiPM metal capacitance

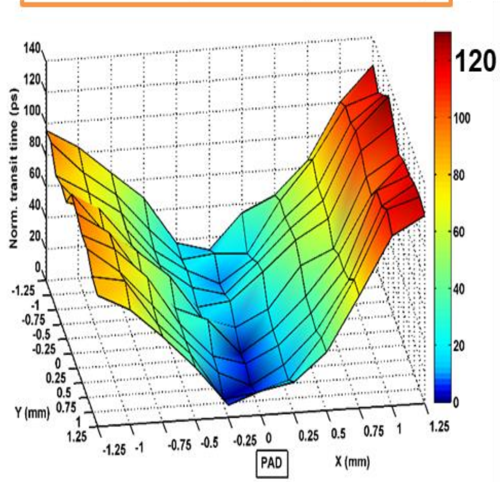
Electronic noise effect on SPTR very important on med/big area SiPMs

SPTR of SiPMs: Transit Time Skew

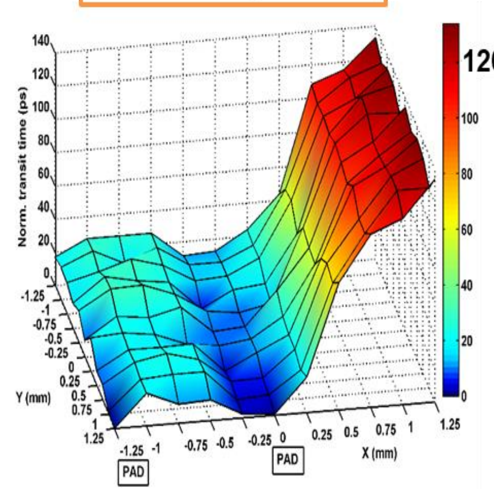




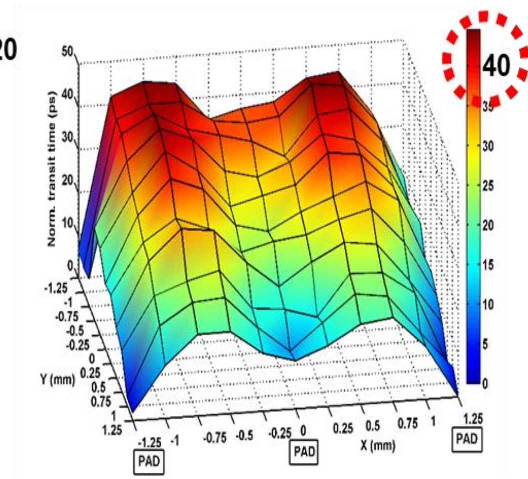
1 bonding wire (center)



2 bonding wires



3 bonding wires



With med./large area SiPMs
→ important also the effect of transit time skew
→ depend on metal grid and bonding pads

Efficient signal pick-up and improved metal grid layout needed.