FONDAZIONE BRUNO KESSLER

Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler

A. Gola, F. Acerbi, A. Altamura, G. Borghi, M. Capasso, A. Ficorella, A. Mazzi, S. Merzi, G. Paternoster, V. Regazzoni, N. Zorzi.

gola@fbk.eu

FONDAZIONE BRUNO KESSLER

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

450 researches working in different fields

FBK is typically interested in R&D activities, and collaborations.
Industrialization is carried out relying on partners.

LFOUNDRY Solutions for great visions

BROADCOM

FONDAZIONE BRUNO KESSLER

FBK SiPM technology roadmap

Original technology *2005*

Electric field engineering

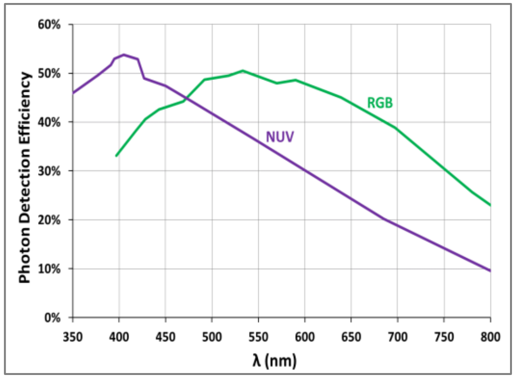
RGB *2010*

NUV *2012*

New cell border (trenches)

RGB-HD *2012*

NUV-HD *2015*

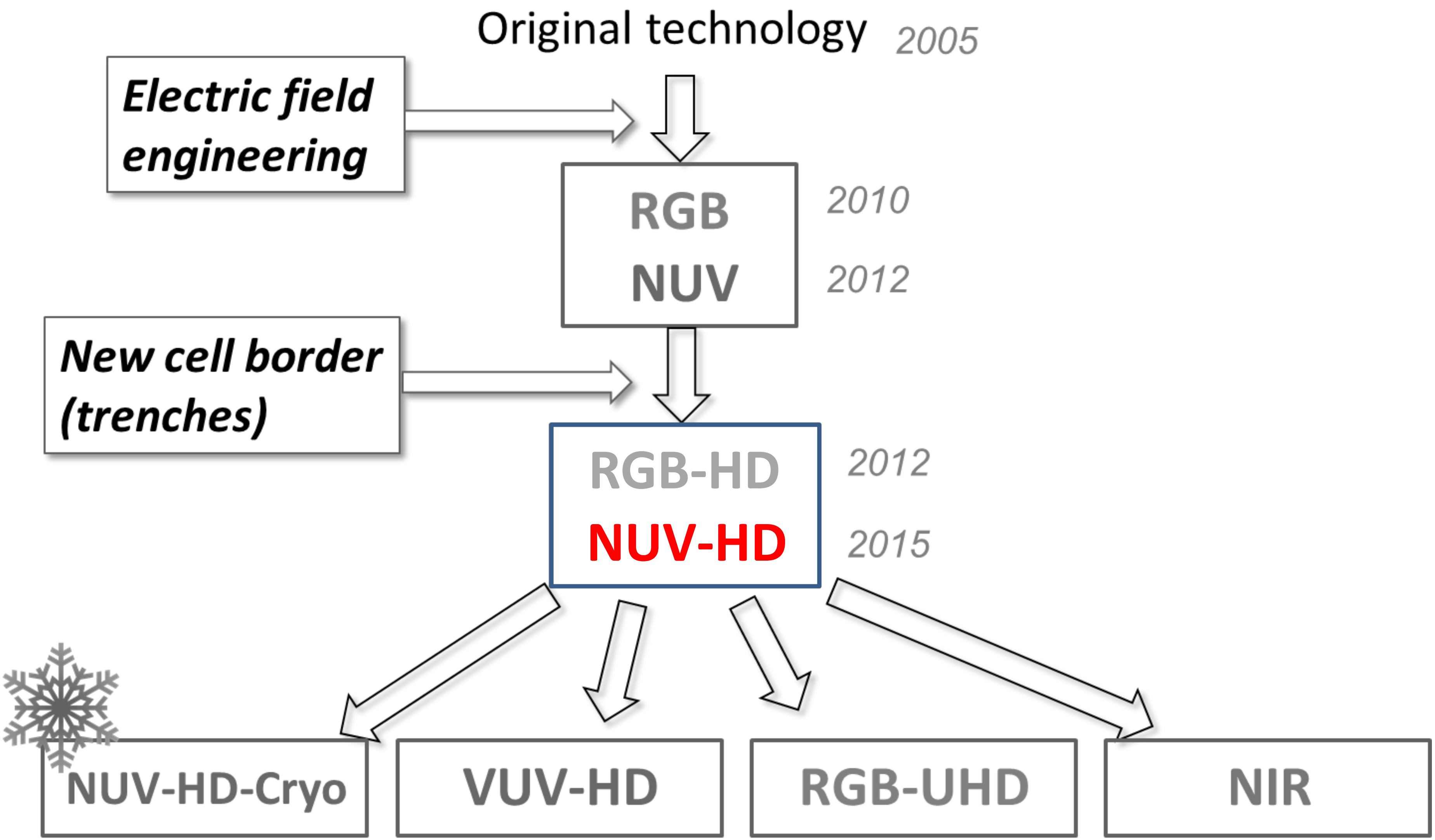


Ongoing Developments

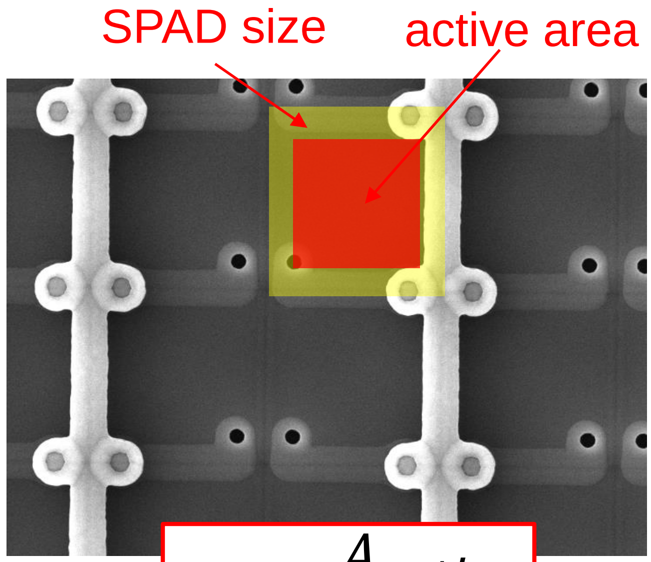
NUV-HD-Cryo | **VUV-HD** | **RGB-UHD** | **NIR**

FONDAZIONE BRUNO KESSLER

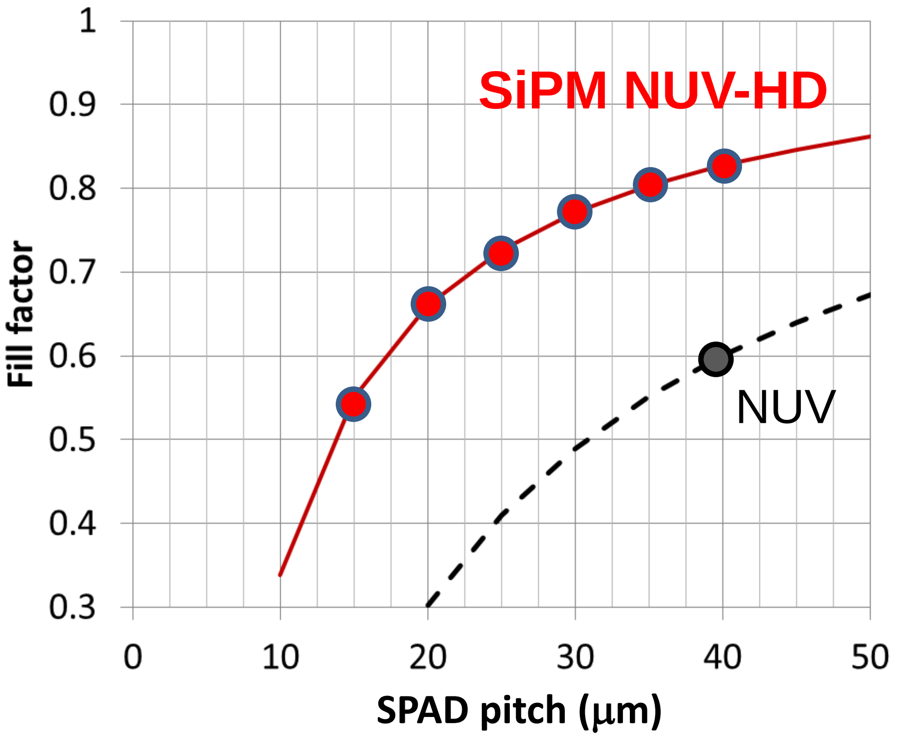
Near-UV technology: NUV-HD



NUV-HD: Fill Factor



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

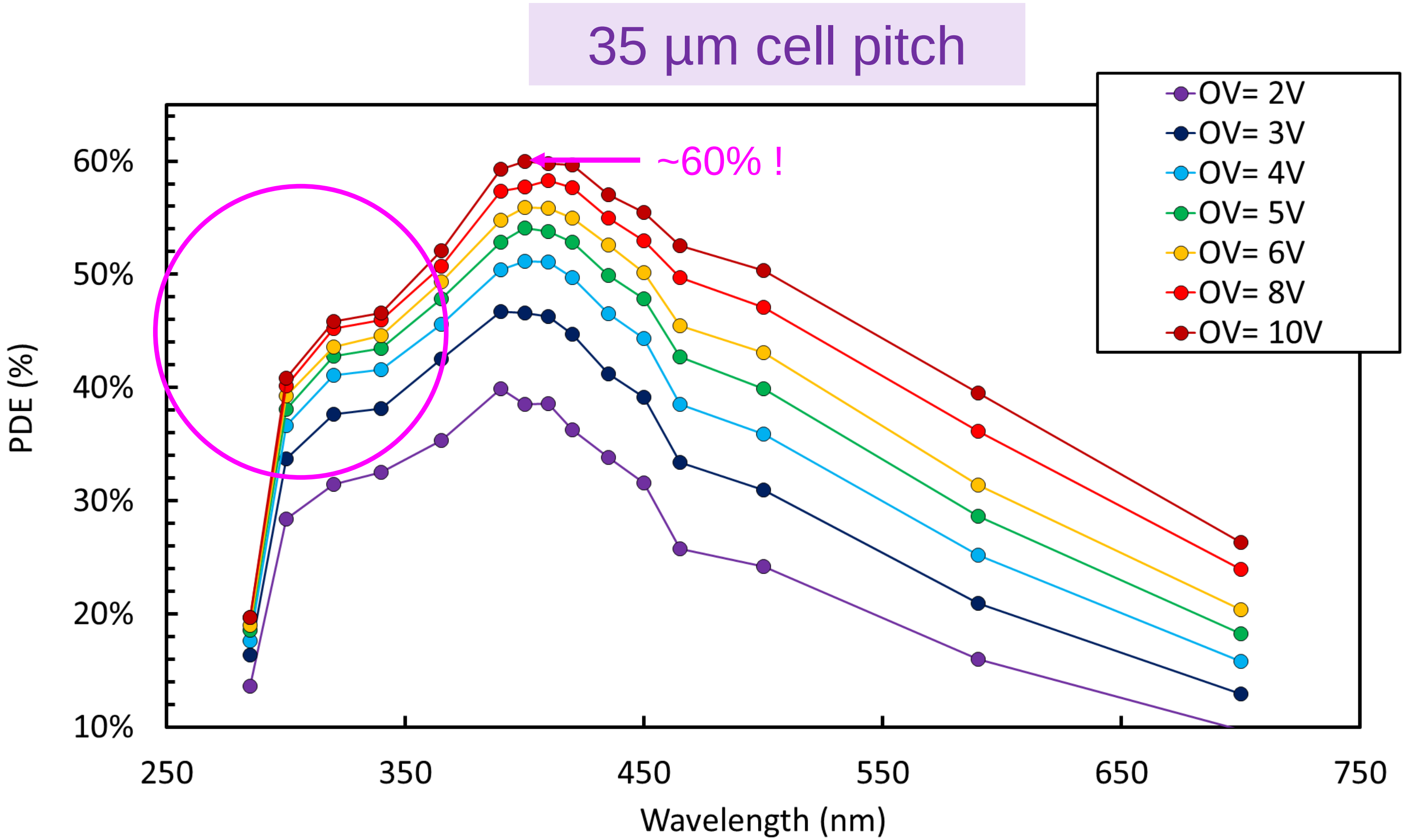


SPAD Pitch	15 μm	20 μm	25 μm	30 μm	35 μm	40 μm
Fill Factor (%)	55	66	73	77	81	83
SPAD/mm^2	4444	2500	1600	1111	816	625

High Dynamic Range, Fast recovery time

High PDE

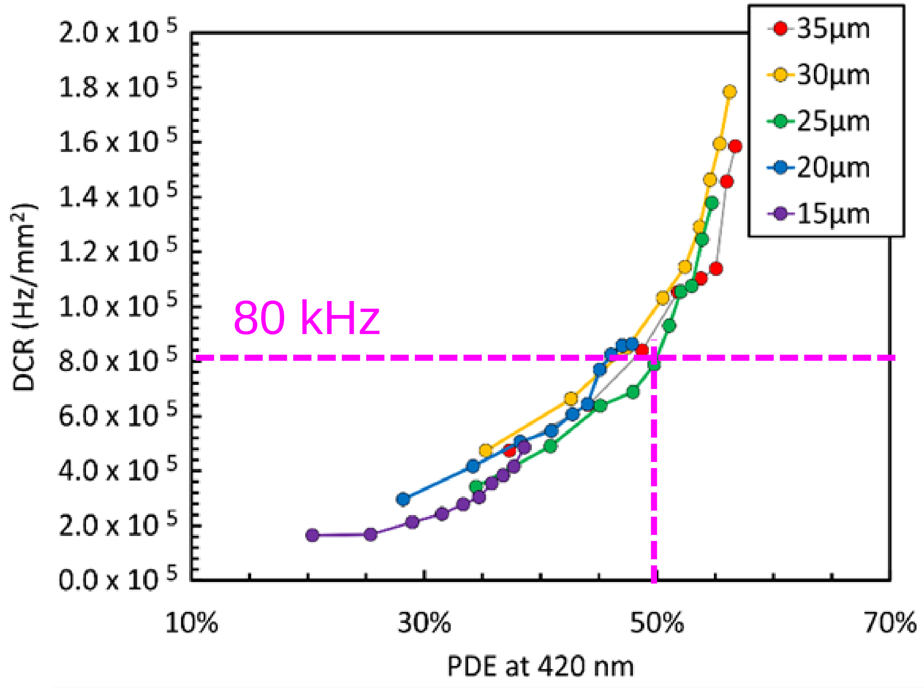
Photon detection efficiency

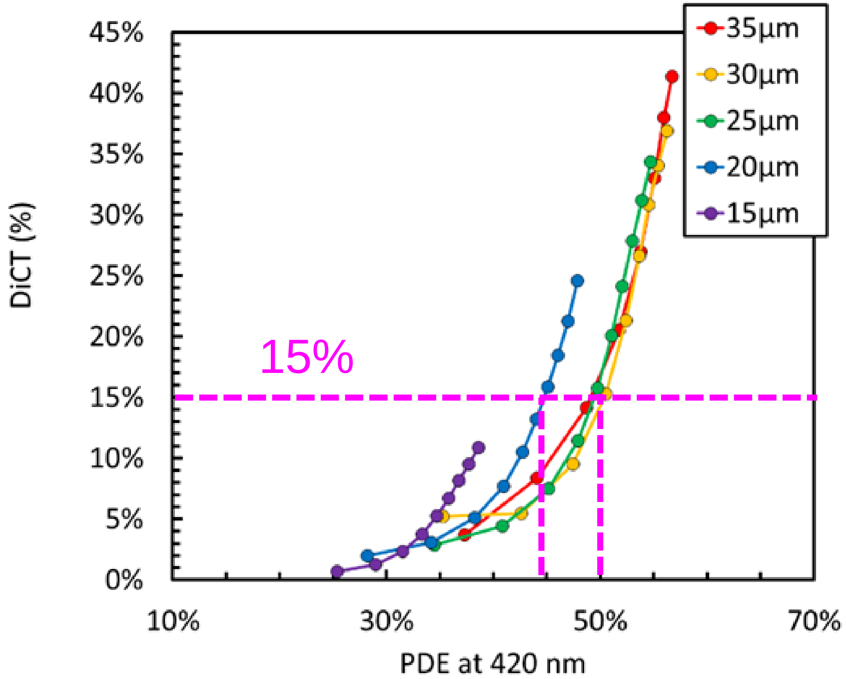


Gola, A et al. (2019). “NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler.” *Sensors*, *19*(2), 308.

SiPM noise: Dark Count Rate and Optical Crosstalk

T = 20 C





Dark Count Rate

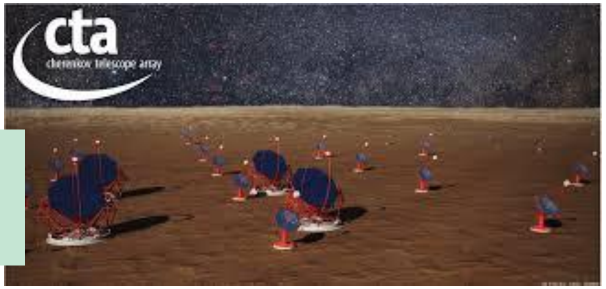
Optical Crosstalk (Correlated Noise)

FONDAZIONE BRUNO KESSLER

NUV-HD Improvements

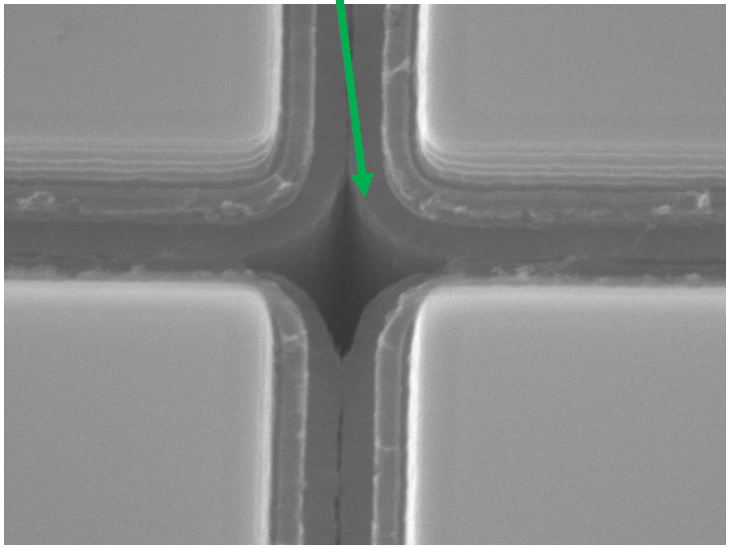
FONDAZIONE BRUNO KESSLER

NUV-HD-LowCT



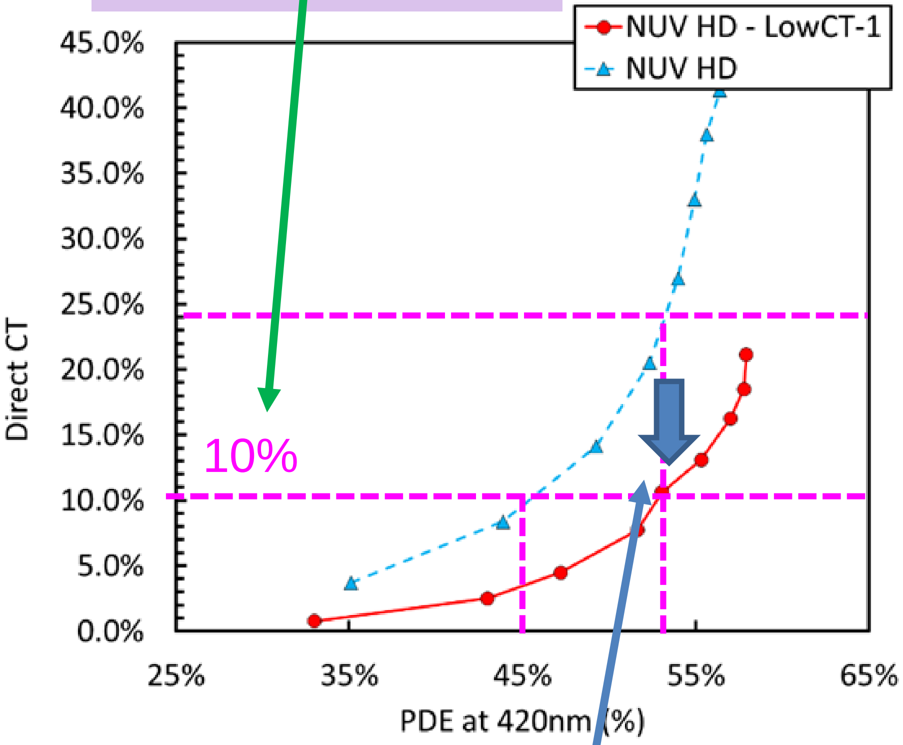
Applications such as CTA

Light absorbing material was inserted inside trenches, between adjacent microcells



SEM image of trenches, separating adjacent microcells.

35 μm cell size



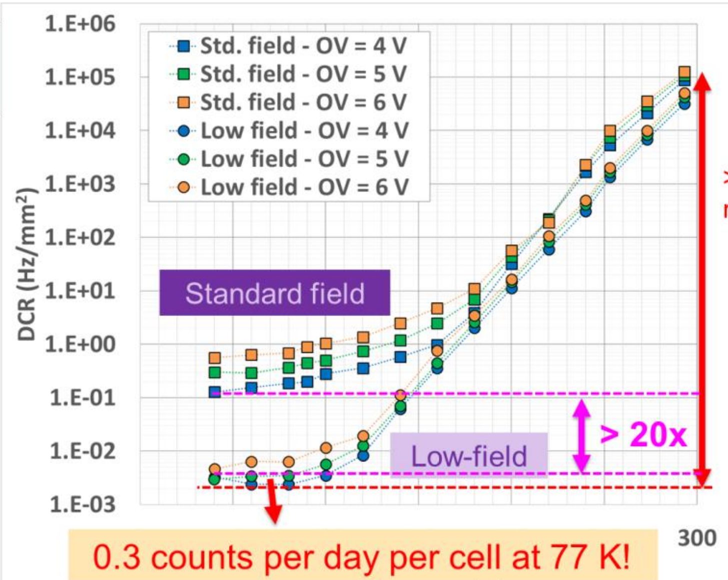
Metal in trenches is under development..

2.5x reduction of Optical Crosstalk at same PDE

FONDAZIONE BRUNO KESSLER

NUV-HD-Cryo and VUV–HD

25 um cell



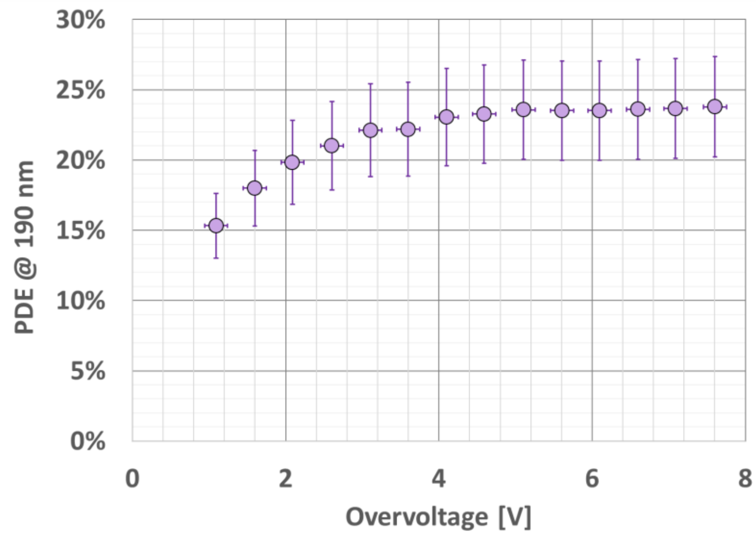
> 7 orders of magnitude !

0.3 counts per day per cell at 77 K!

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

TRIUMF

PDE vs OV (~190nm)



DARKSIDE

See A. Razeto and I. Kochanek presentations

nEXO

See F. Retière and M. Capasso presentations

FONDAZIONE BRUNO KESSLER

Radiation Damage of SiPMs

Radiation damage in SiPMs is currently a hot research topic in the SiPM field.

- Small-cell SiPMs fabricated at FBK (< 20 um cell size) with optimized electric field provide mitigation of typical effects of radiation damage.

Main effects of radiation damage in SiPMs	Mitigation of the effects of rad. damage with HD-SiPM technology:
Increase of the primary noise (DCR).	E field engineering allows a faster reduction of DCR with cooling.
Increased afterpulsing (increased number of traps).	Low gain and low E field reduce afterpulsing (for a given number of traps).
PDE loss due to cells busy triggering dark counts.	Many, smaller cells with faster recharge are less sensitive to the problem.
Increased power consumption due to higher DCR.	Lower gain allows less current (for a given value of DCR) + Low V_{BD}.

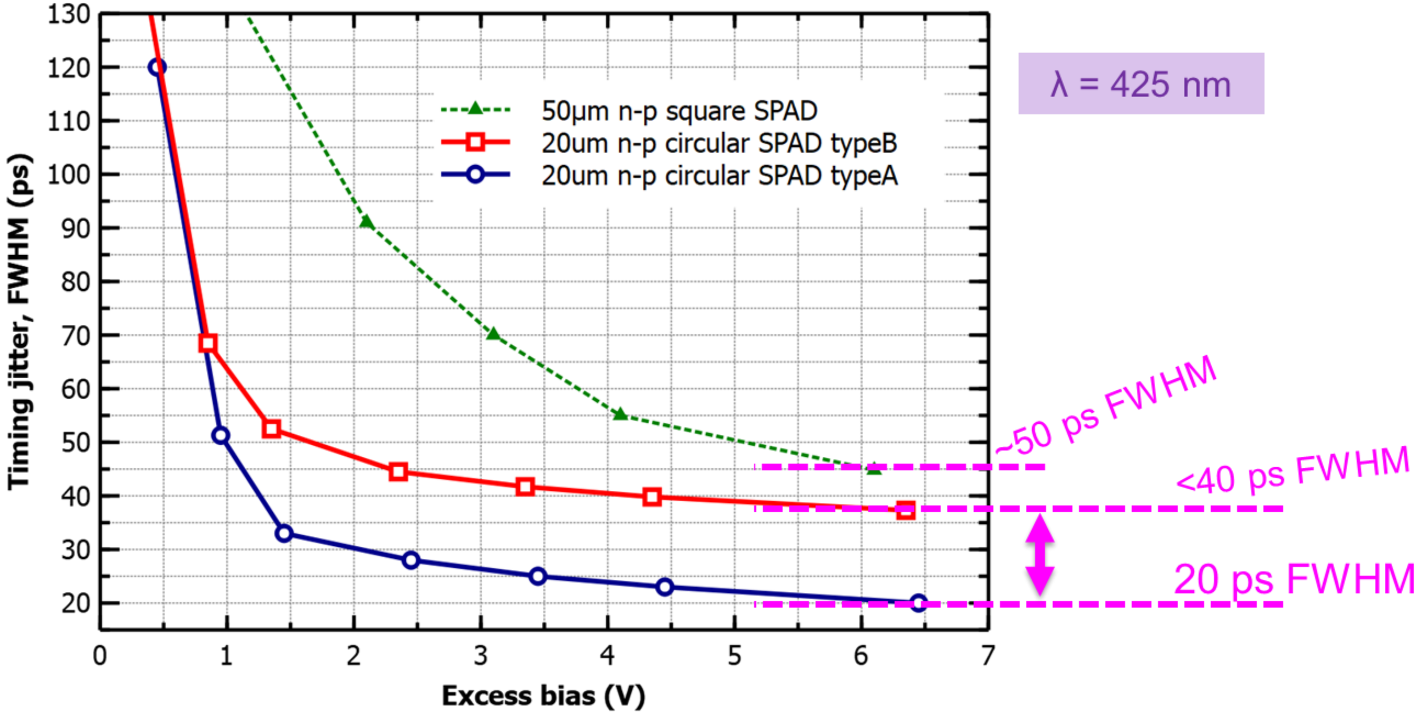
FONDAZIONE BRUNO KESSLER

NUV-HD-LF with small cells

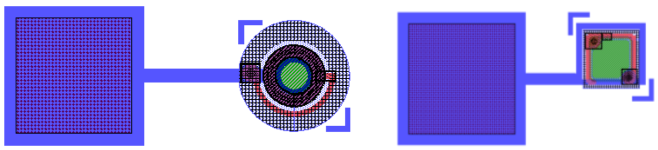
FONDAZIONE BRUNO KESSLER

Single Photon Time Resolution

NUV SPAD – SPTR



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 also very important

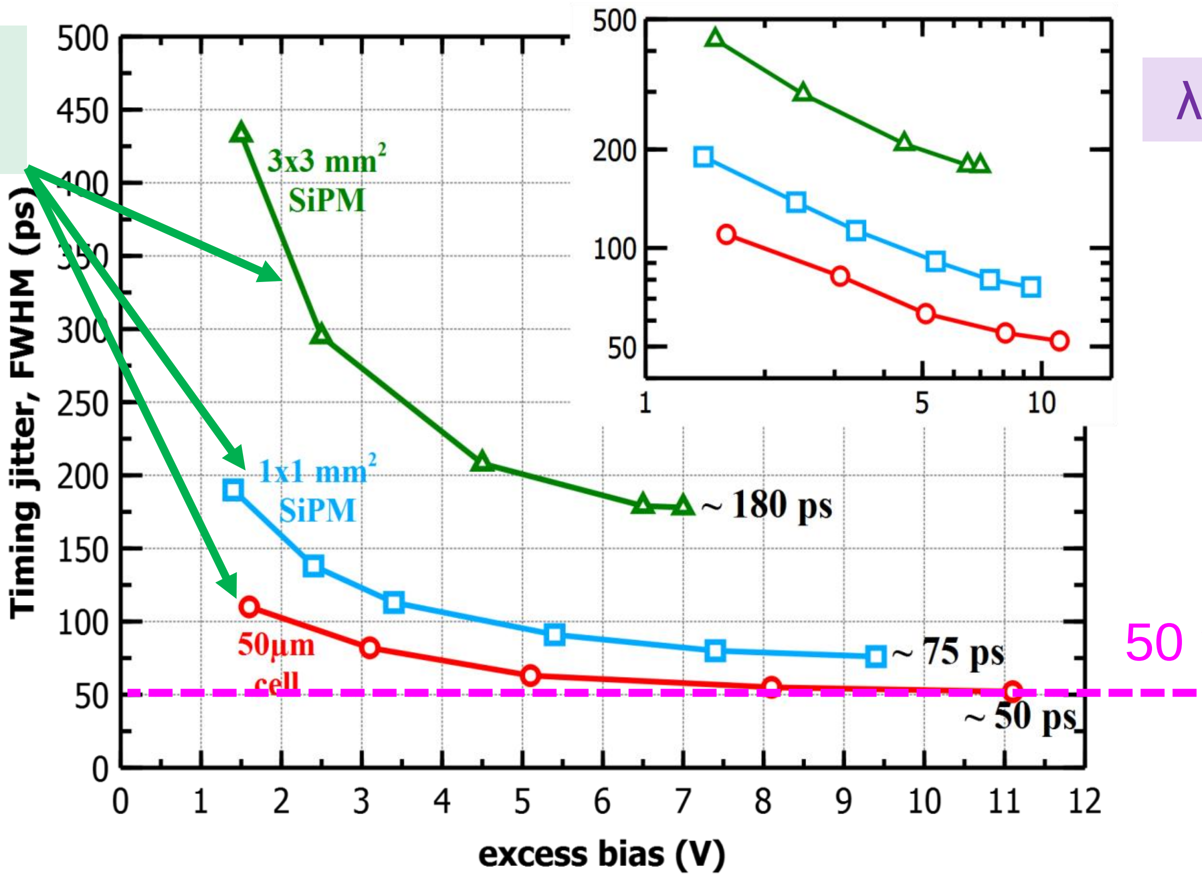
Covering the SPAD edges with metal *reduces the SPTR to 20 ps*

FONDAZIONE BRUNO KESSLER

NUV SiPM – SPTR

Different SiPM sizes

λ = 425 nm



50 ps FWHM!

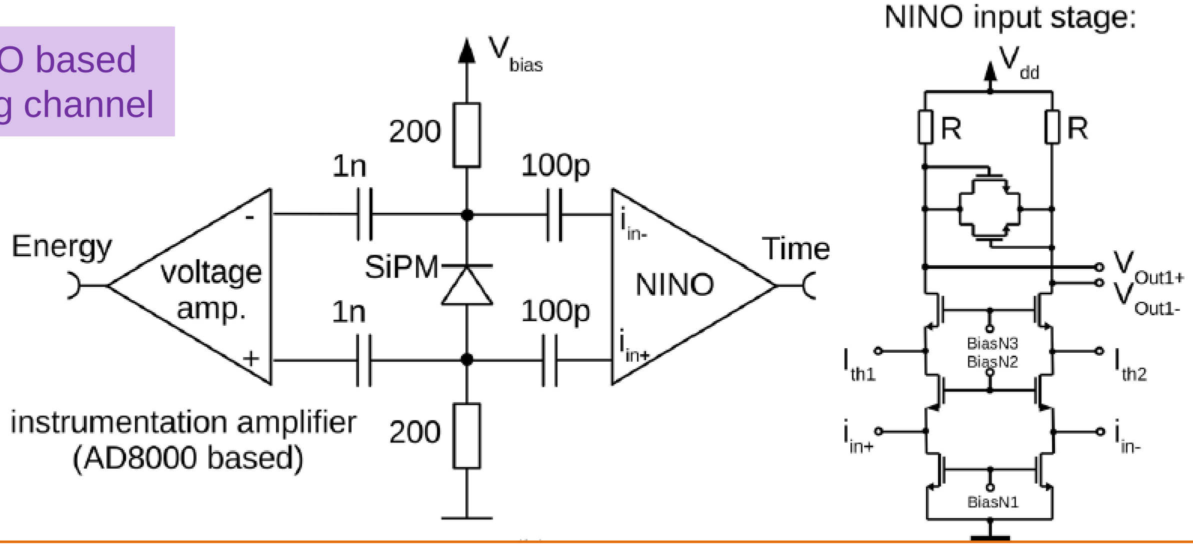
Larger active are → larger SiPM capacitance → more LP filtering → smaller signal

Bigger effect of the electronic noise on SPTR

FONDAZIONE BRUNO KESSLER

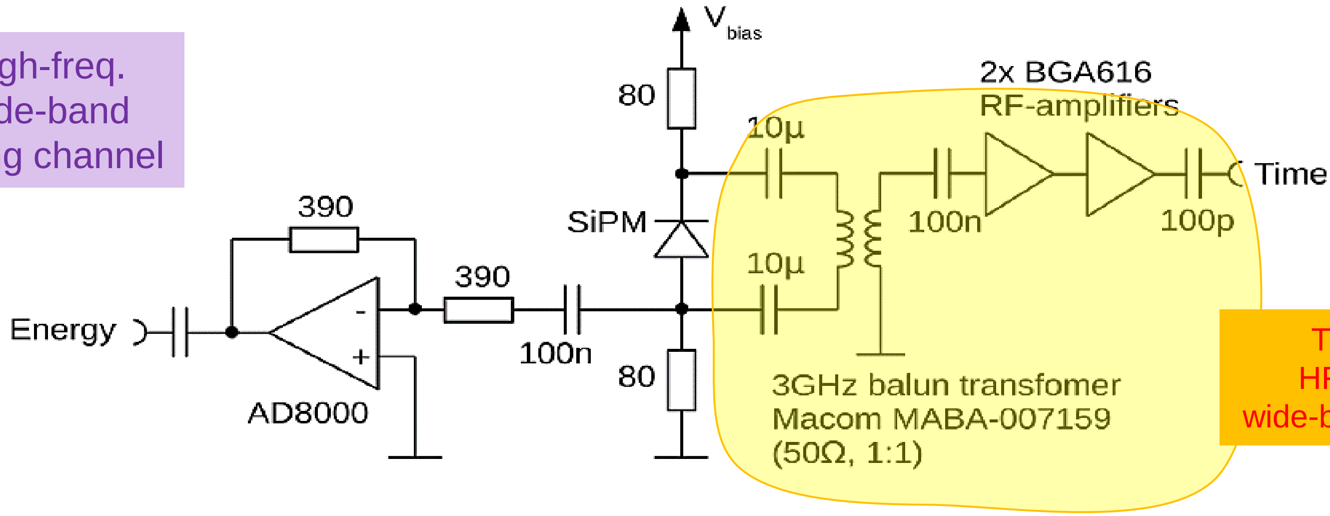
High-frequency SiPM readout

NINO based timing channel



CERN

High-freq. wide-band timing channel



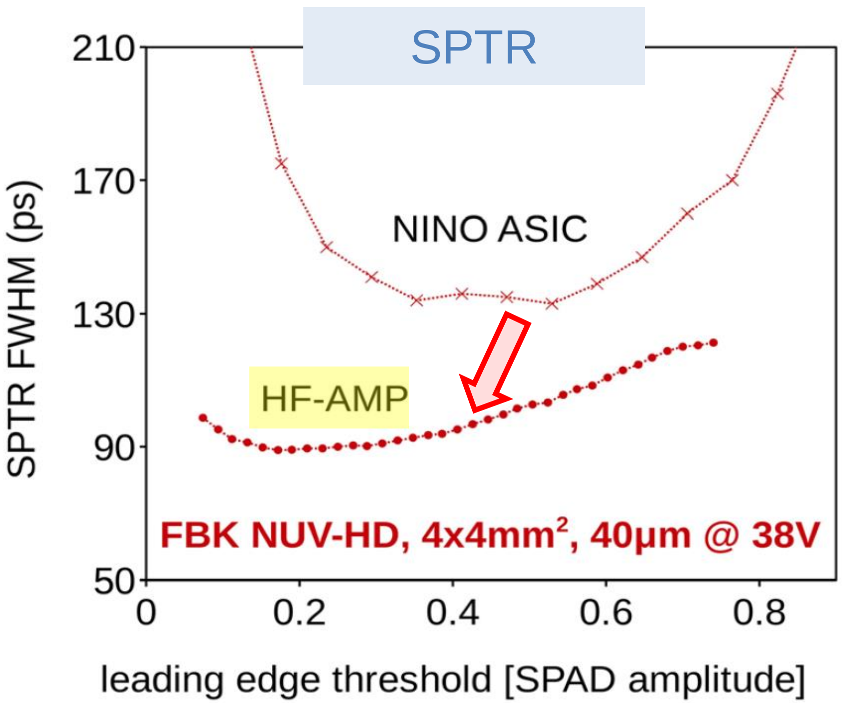
Stanford University

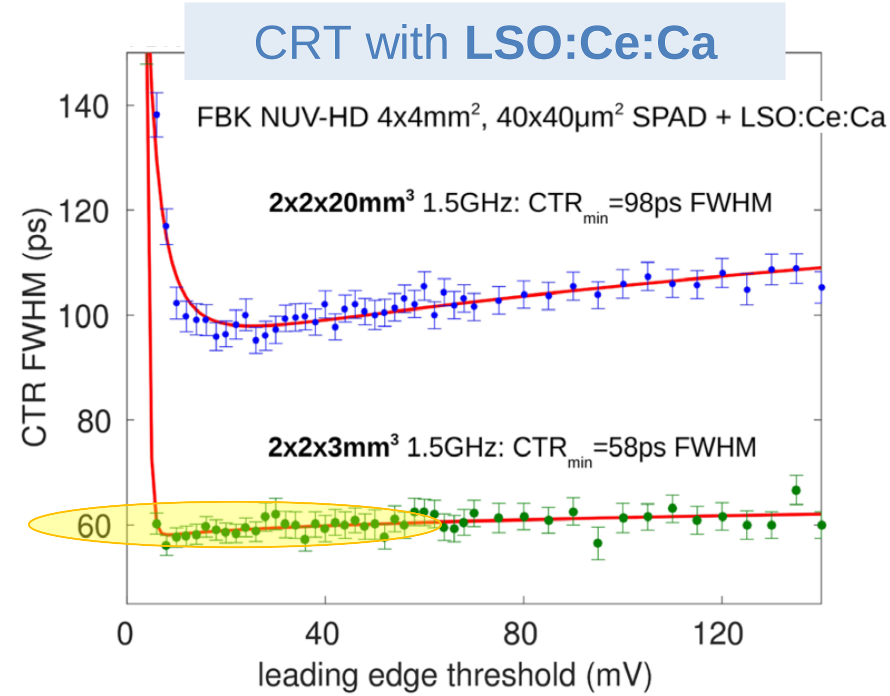
Timing signal: HF readout and wide-band amplification

S Gundacker et al, "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET"

FONDAZIONE BRUNO KESSLER

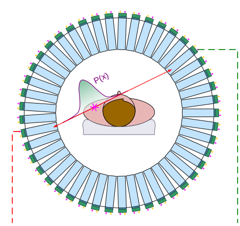
HF SiPM readout – SPTR and CRT with LSO

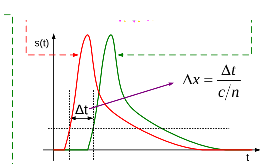




Significant reduction of SPTR with improved electronics
(but high power consumption)

Work carried out in collaboration with S. Gundacker (P. Lecoq)

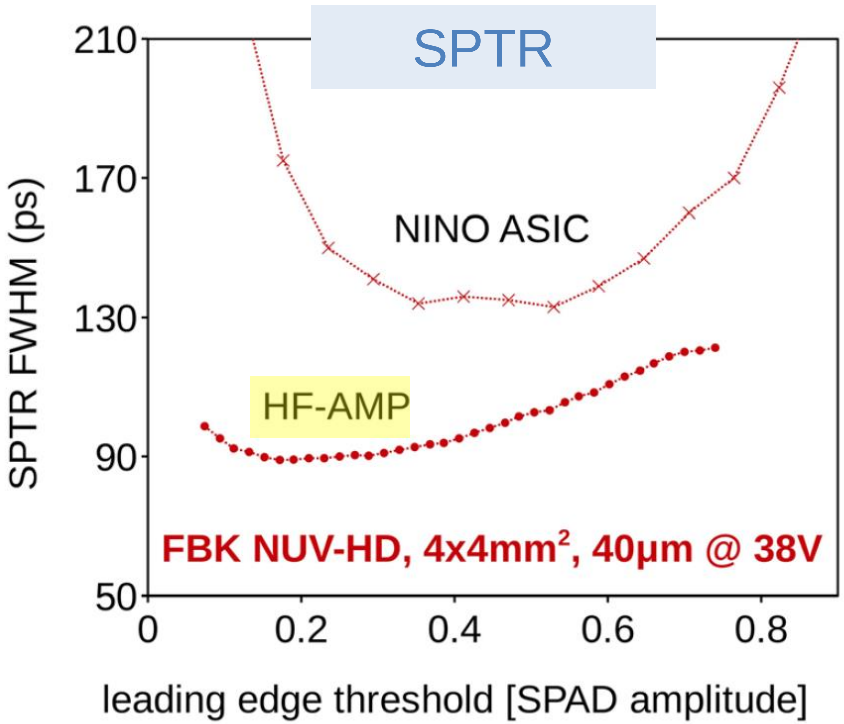


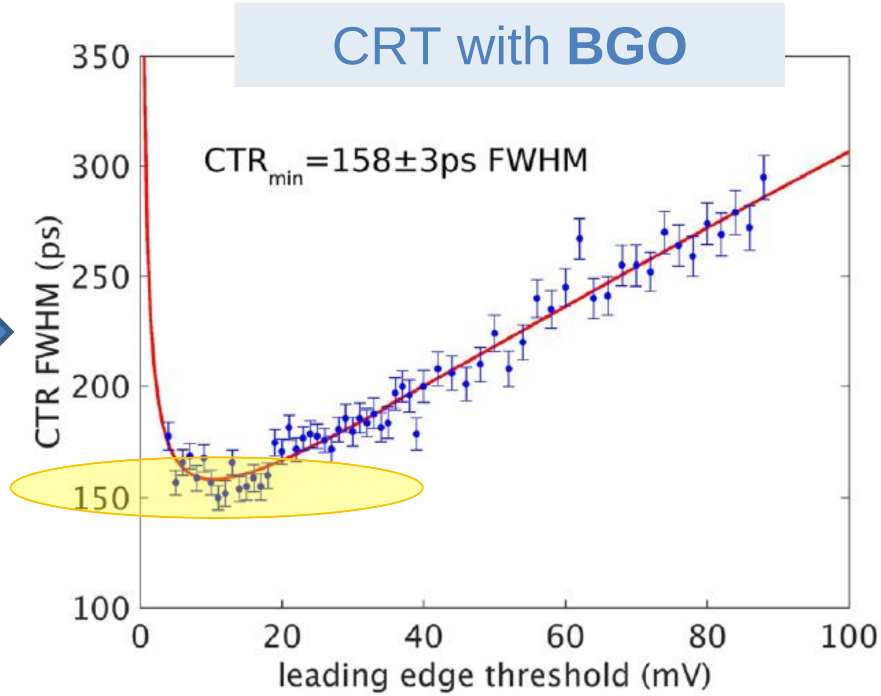


CERN

CRYSTAL CLEAR

HF SiPM readout – SPTR and CRT with BGO



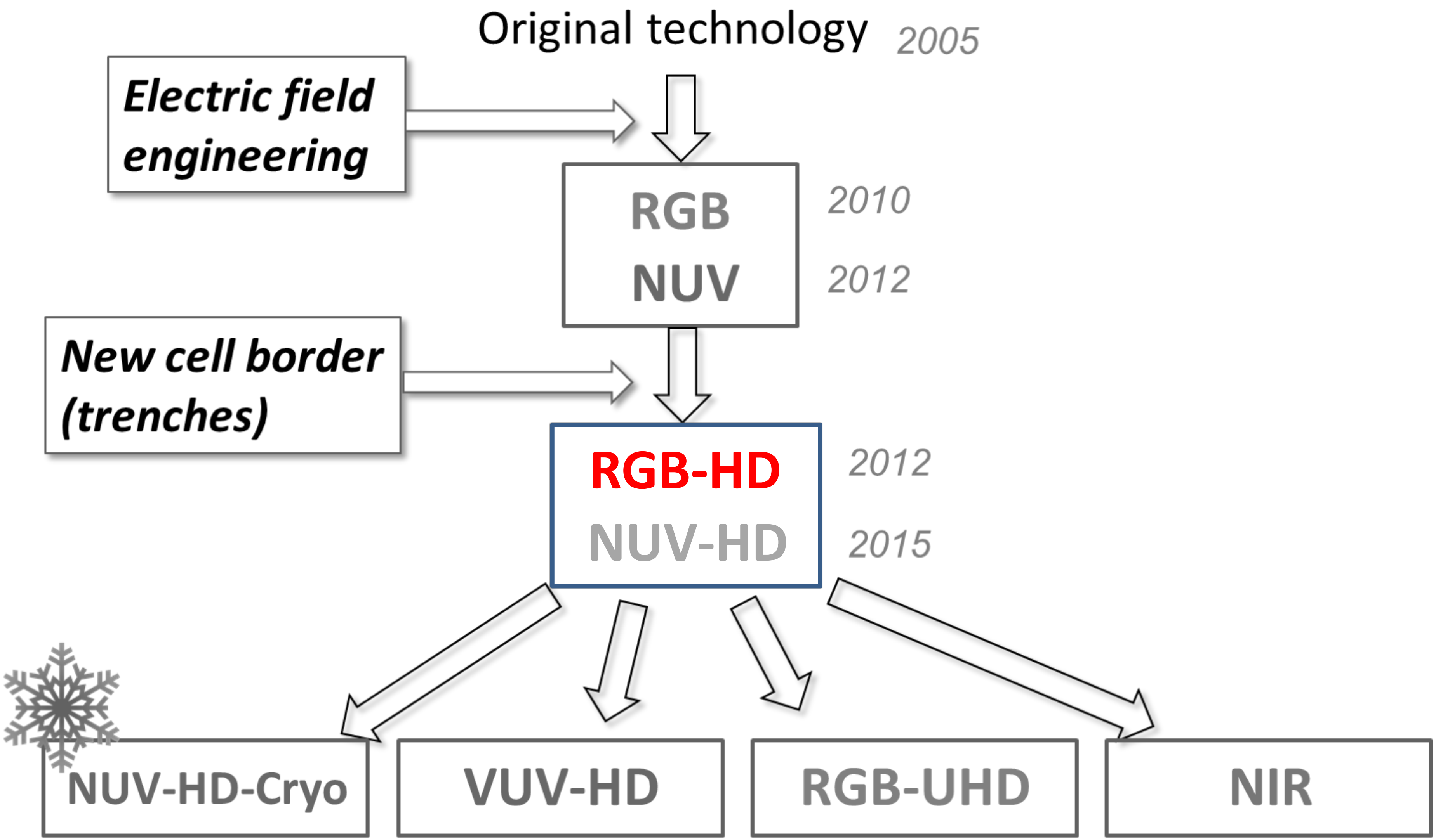


Improvement of SPTR is, possibly, even more important for BGO readout:

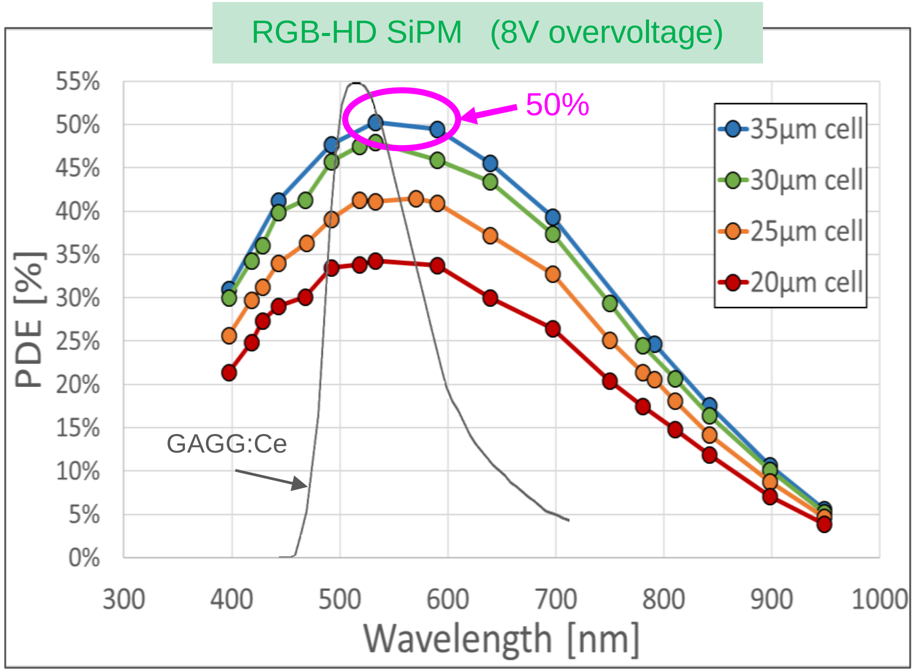
- Timing is improved with Cherenkov light detection

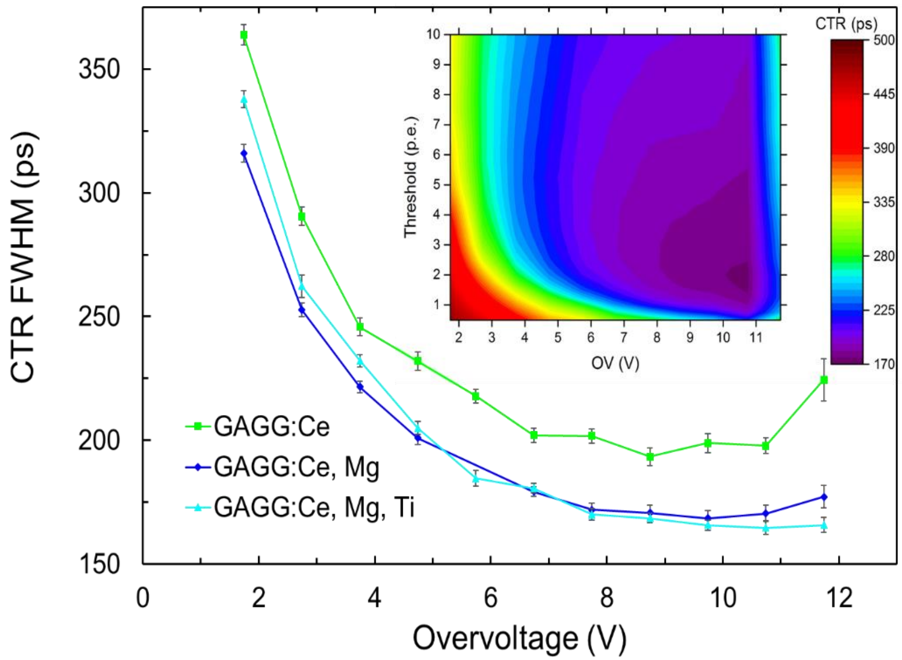
FONDAZIONE BRUNO KESSLER

RGB-HD technology



Timing with RGB-HD SiPMs coupled to GAGG





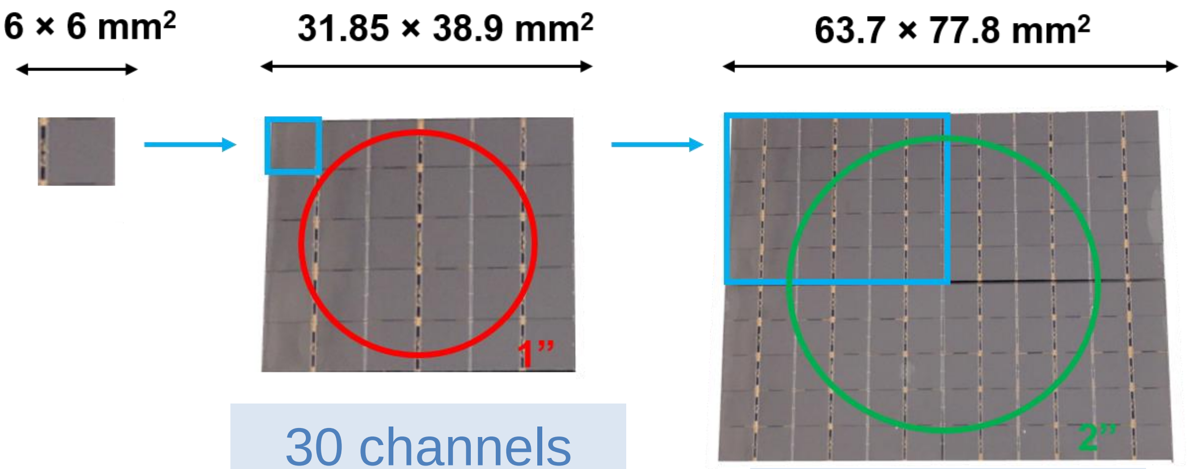
Tumulatis, et. al., "Improvement of response time in GAGG:Ce scintillation crystals by magnesium Codoping" DOI: 10.1063/1.5064434

- RGB-HD technology: optimized for green wavelength detection
- Good for CsI and GAGG scintillators

CTR with GAGG: Ce,Mg,Ti: ~170ps FWHM

Gamma-ray spectroscopy with NUV-HD SiPMs

LaBr$_3$ readout by SiPMs



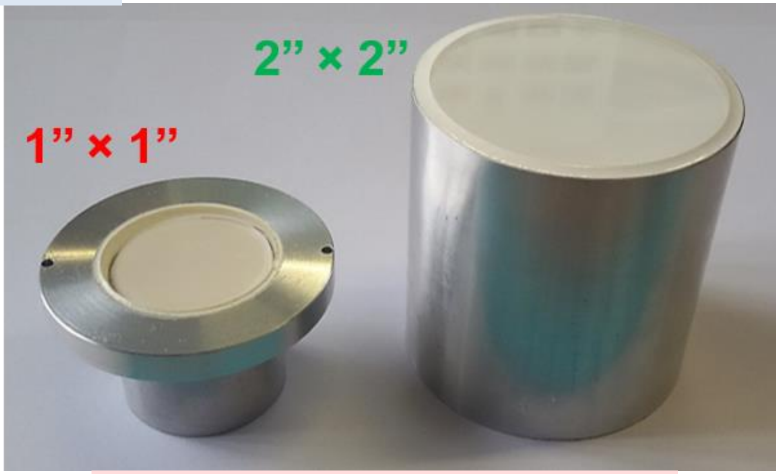
30 channels

120 channels

New prototype of 3x3 arrays with 4x4 SiPMs was developed for the readout of **3" × 3" LaBr3:Ce crystal.**

SiPM: basic unit is NUV-HD SiPM (FBK)

- 6 × 6 mm^2 active area
- 30 × 30 µm^2 microcells
- Peak efficiency of 45% at 380 nm
- DCR < 100 kcps/mm^2
- ASIC readout



LaBr$_3$ crystals

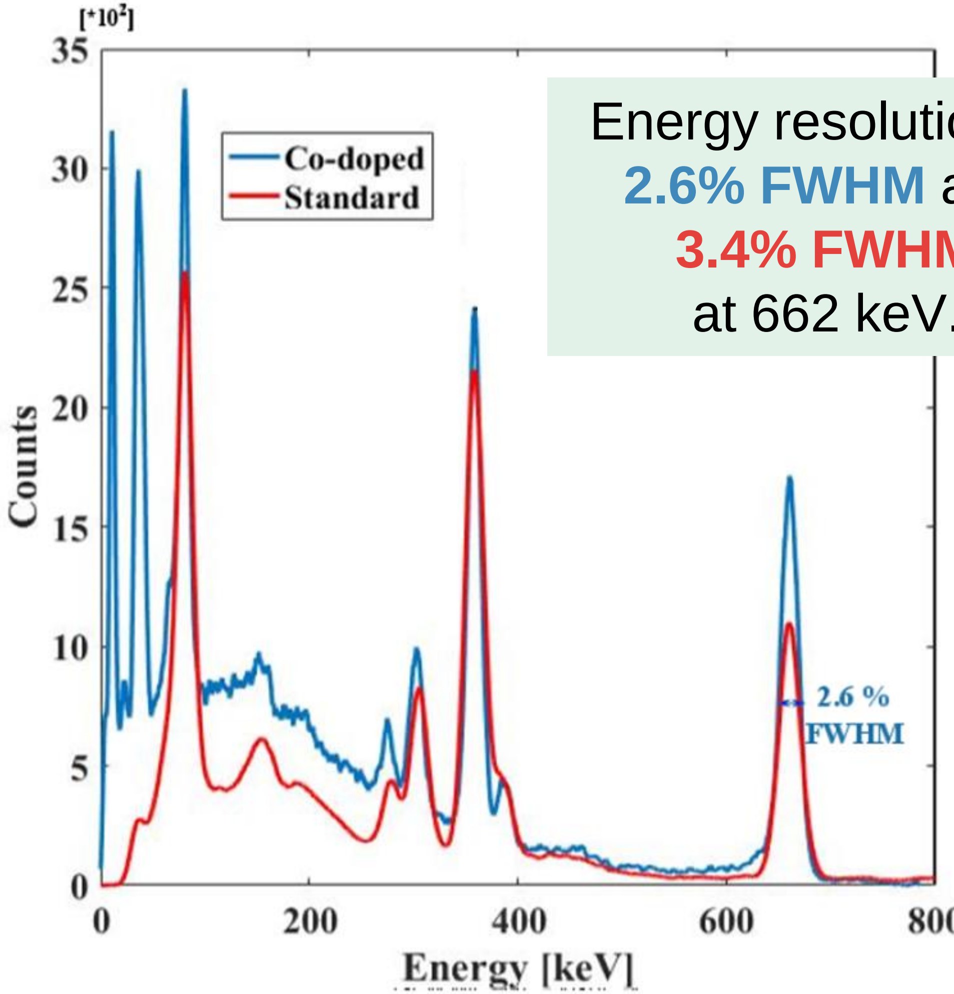
$LaBr_3$ spectroscopy results

3” $LaBr_3$:Ce
3” $LaBr_3$:Ce,Sr^{2+}

Multi-source
(^{133}Ba and ^{137}Cs sources)

No collimator

Measured at Politecnico di Milano



Energy resolution of **2.6% FWHM** and **3.4% FWHM** at 662 keV.

Montagnani et al., 2019, **Spectroscopic performance of a Sr co-doped 3” LaBr3 scintillator read by a SiPM array,** Nuclear Instruments and Methods in Physics Research Section A

FONDAZIONE BRUNO KESSLER

Thank you!

For any question:
gola@fbk.eu

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

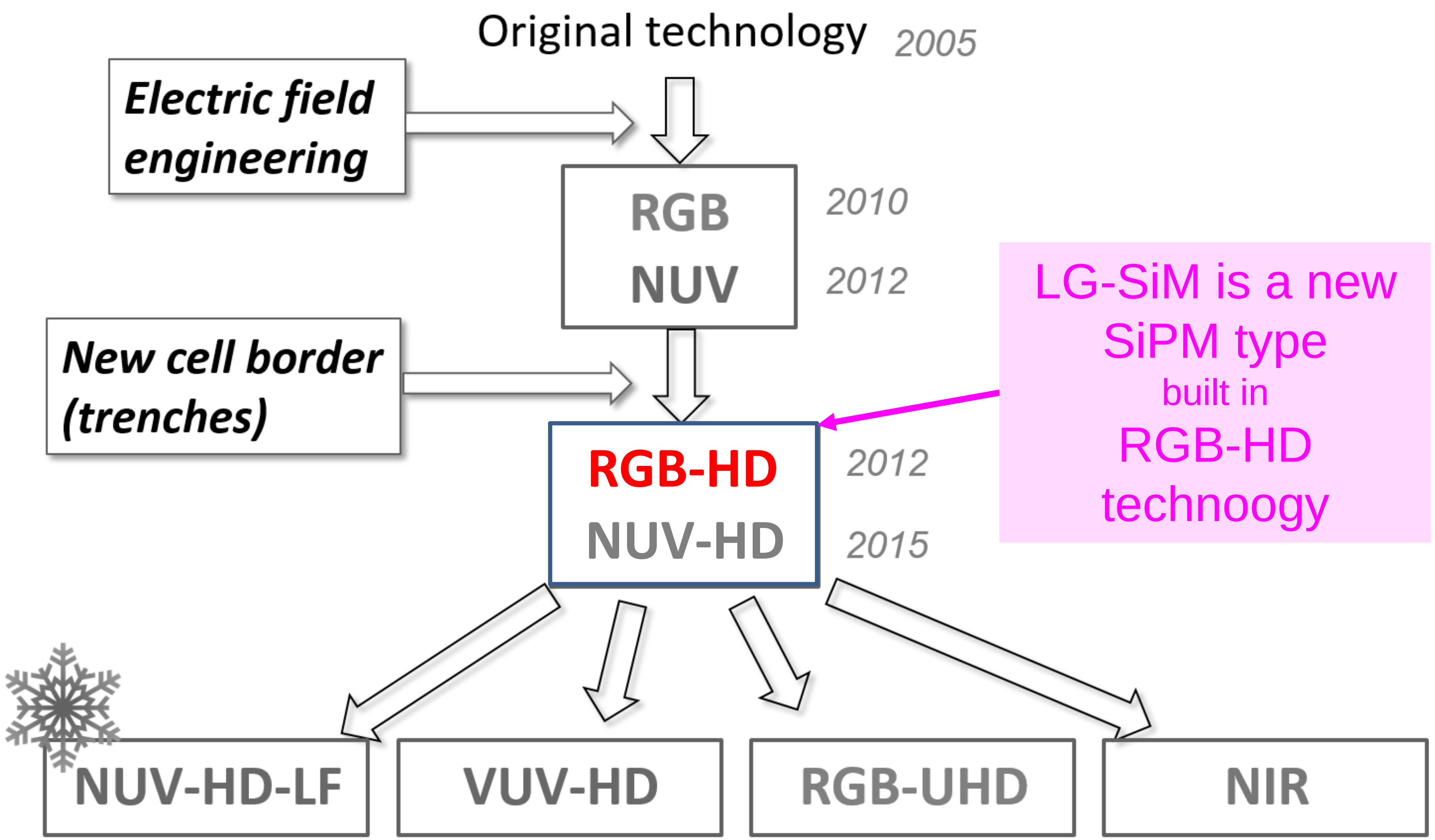
Fabio Acerbi
Anna Rita Altamura
Giacomo Borghi
Massimo Capasso
Andrea Ficorella
Nicola Furlan
Alberto Mazzi
Stefano Merzi
Vladimir Mozharov
Giovanni Paternoster
Veronica Regazzoni
Nicola Zorzi

FONDAZIONE BRUNO KESSLER

Linearly-Graded SiPM

LG-SiPM

Linearly-Graded SiPM – LG-SiPM



FONDAZIONE BRUNO KESSLER

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

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

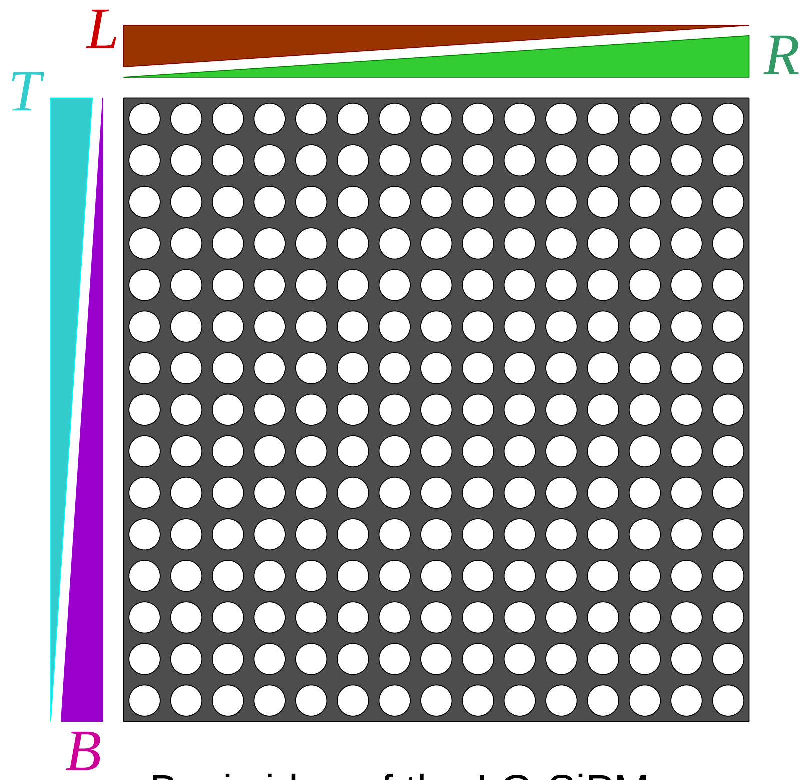
- Energy

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

Several microcells triggered

⇩

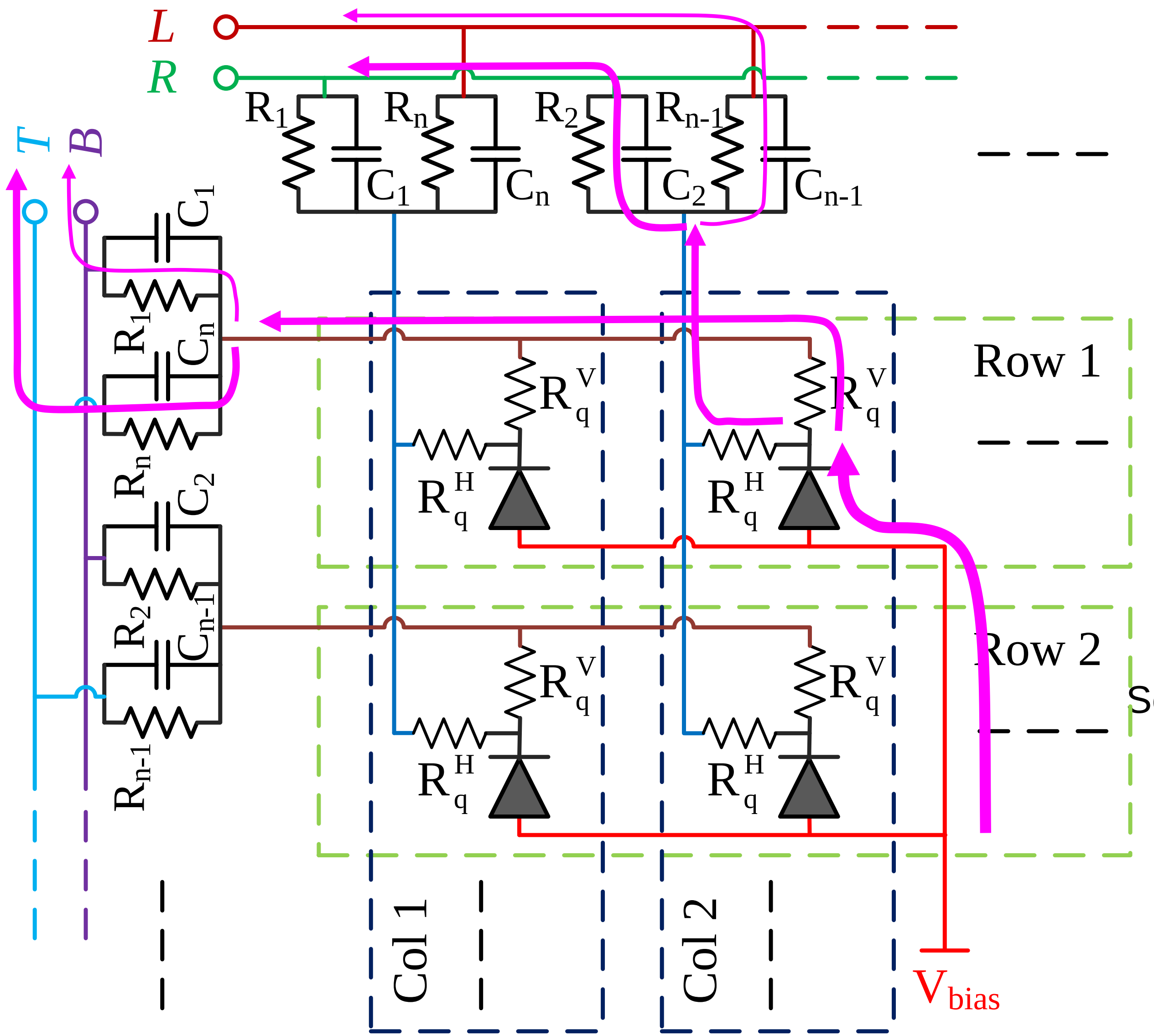
Implements the Center of Gravity



Basic idea of the LG-SiPM.

FONDAZIONE BRUNO KESSLER

LG-SiPM

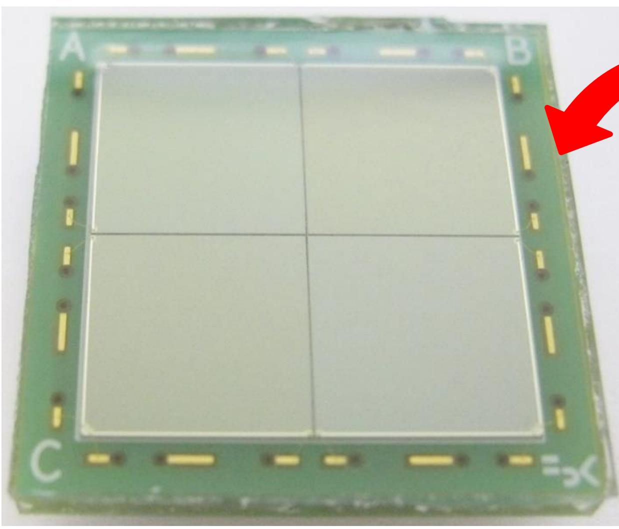


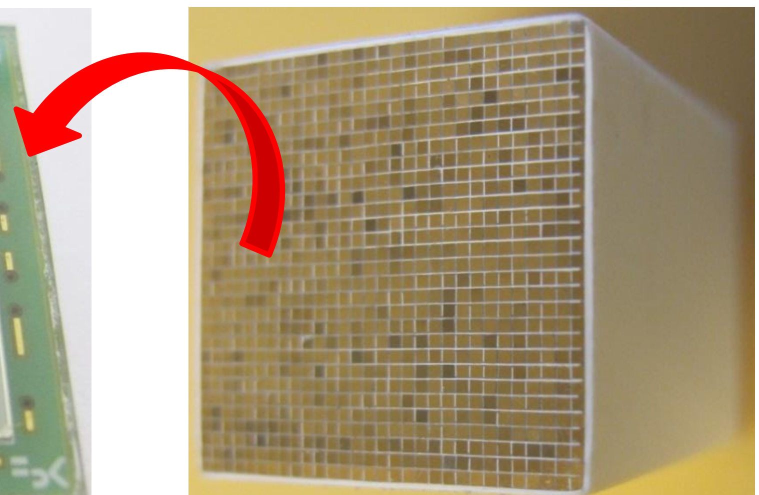
Schematic of the 2D position encoding method

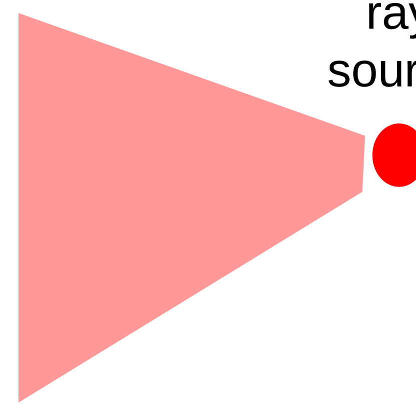
2 x 2 array of LG-SiPMs

- 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.

FONDAZIONE BRUNO KESSLER

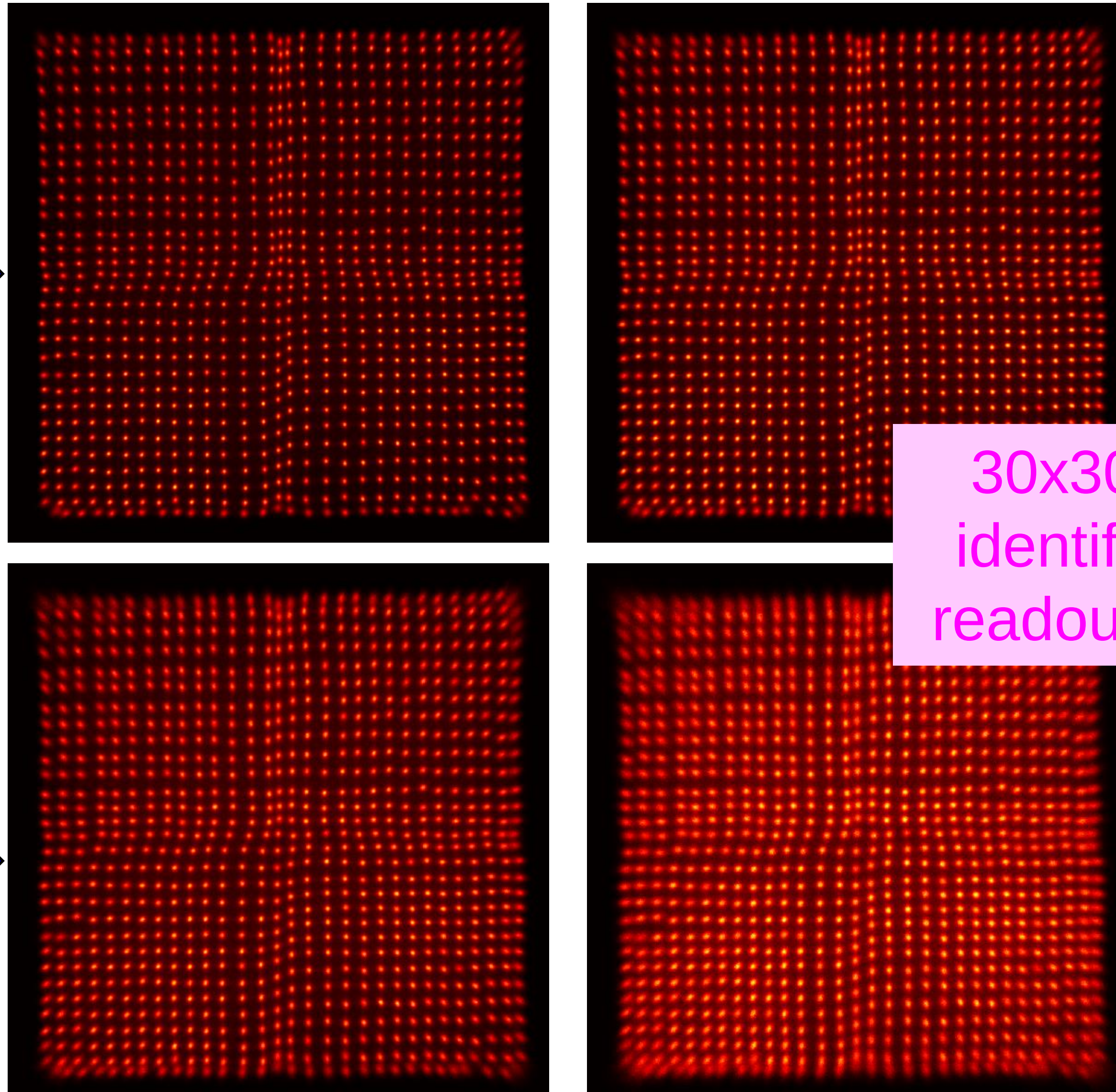
Are we able to identify all crystals?

-10 ^{o}C

0 ^{o}C

10 ^{o}C

20 ^{o}C



30x30 crystals identified with 4 readout channels