Performance of FBK SiPMs in fast timing applications

Mazzi A., Acerbi F., Paternoster G., Zorzi N., Gola A.

Fondazione Bruno Kessler, Trento, Italy

https://www.fbk.eu/en/

mazzi@fbk.eu

Fondazione Bruno Kessler

Publicly funded research center

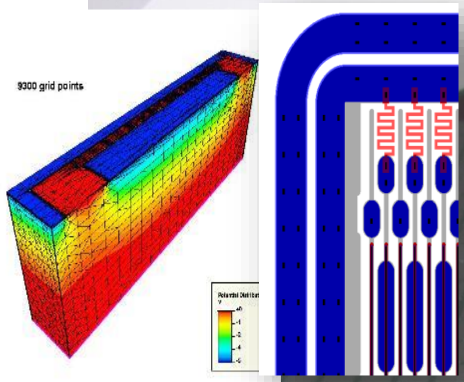
350 researchers working in different fields

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

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

FBK expertise in SiPM technology

Simulation & design → Fabrication → Device testing



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Presentation Outline

1. Introduction
    - SiPM technology in FBK
    - NUV-HD and RGB-HD: spectral sensitivity

2. Single Photon Time Resolution
    - Single cell and SiPM time resolution

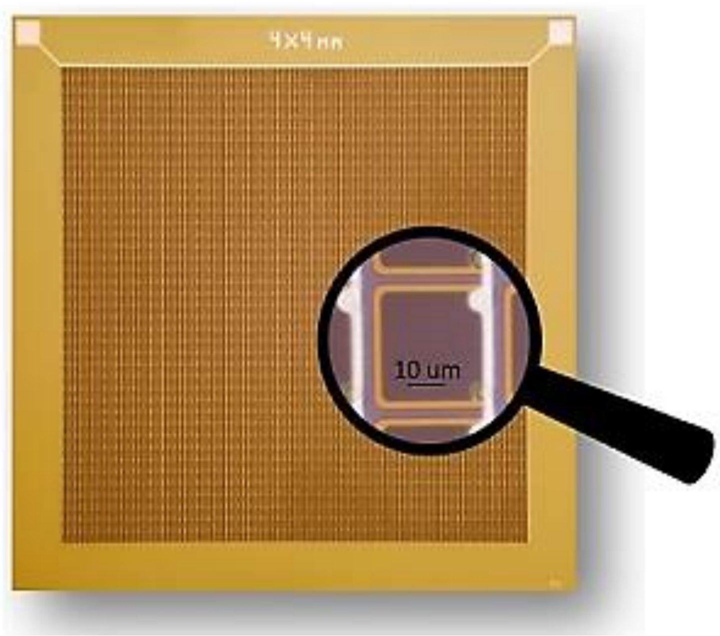
3. Coincidence time resolution results at 511 keV
    - Setup and measurement technique
    - NUV-HD + LSO, LYSO
    - RGB-HD + GAGG

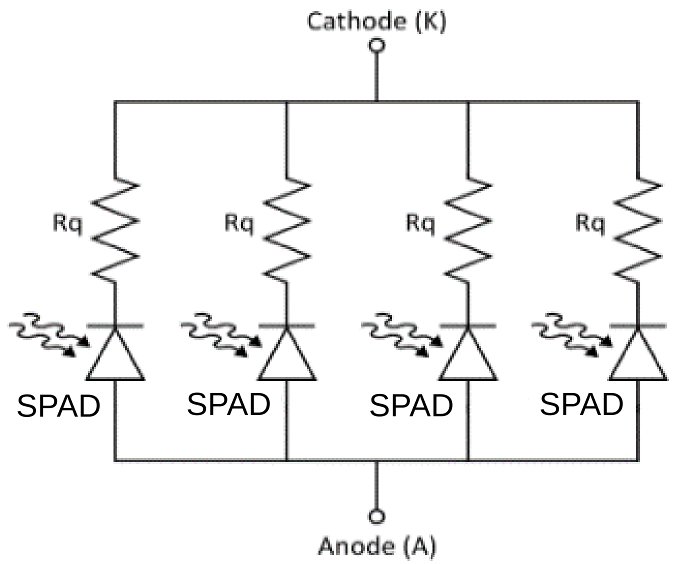
4. Summary and conclusions

The Silicon Photomultiplier (SiPM)

SiPMs are arrays of small diodes (SPADs) connected in parallel.

Each SPAD is capable generating a measurable signal after the detection of a single photon!

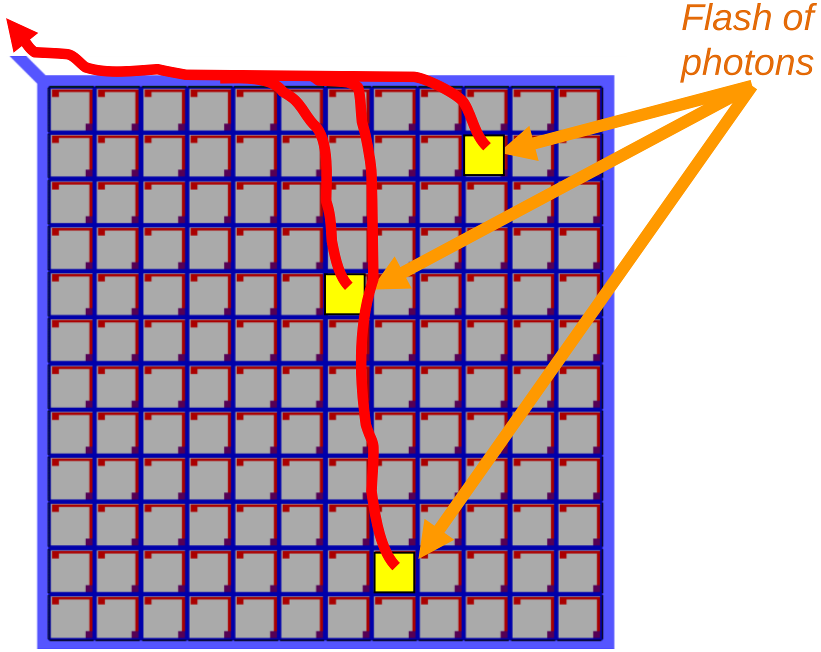


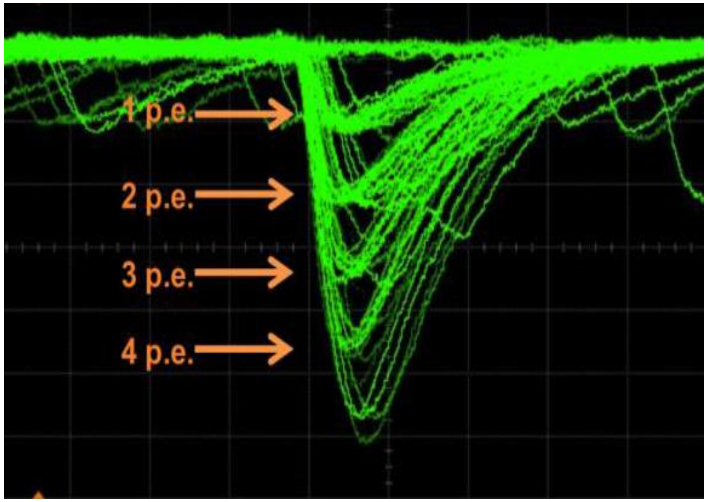


SiPM size:
1x1 mm^2 to 10x10 mm^2

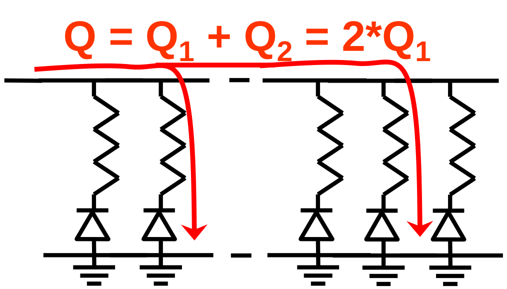
Microcell (SPAD) pitch:
12 um to 40 um
(typical)

The Silicon Photomultiplier (SiPM)



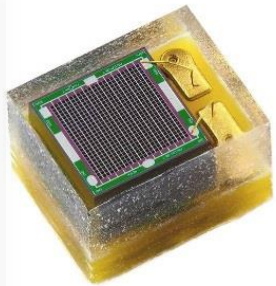


Each element is independent and gives the same signal when fired.

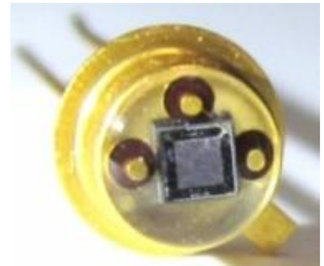


Output amplitude (and charge)
→ proportional to the number of triggered cells
→ proportional to the number of photons.

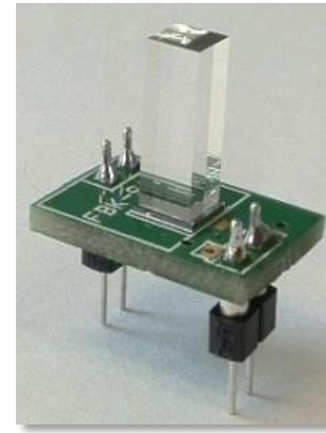
Silicon Photomultiplier (SiPM)



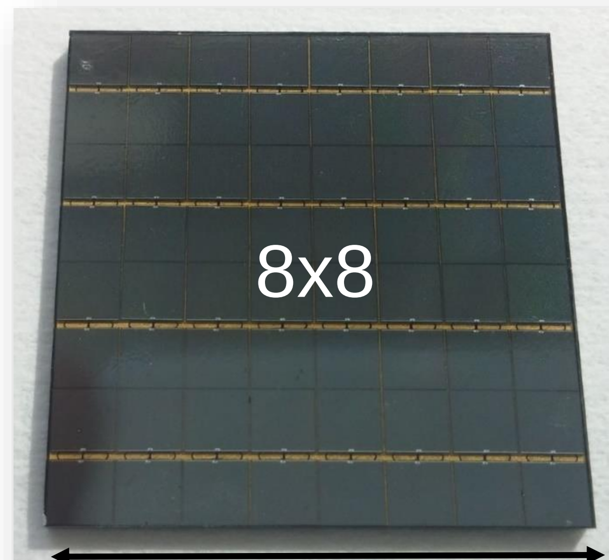
http://www.ketek.net/



http://advansid.com/

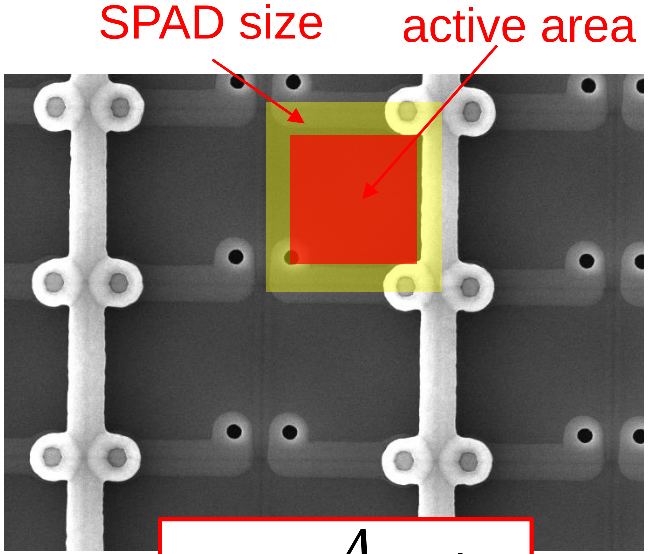


- Composed by square SPAD e.g. 50x50 μm^2
- Active area of 1x1mm^2 up to 10x10mm^2
- Different package and connections.
- **TILE of SiPMs** to cover big areas.
- Typically **coupled with scintillators** for gamma-ray detection *(e.g. medical imaging, high-energy physics)*

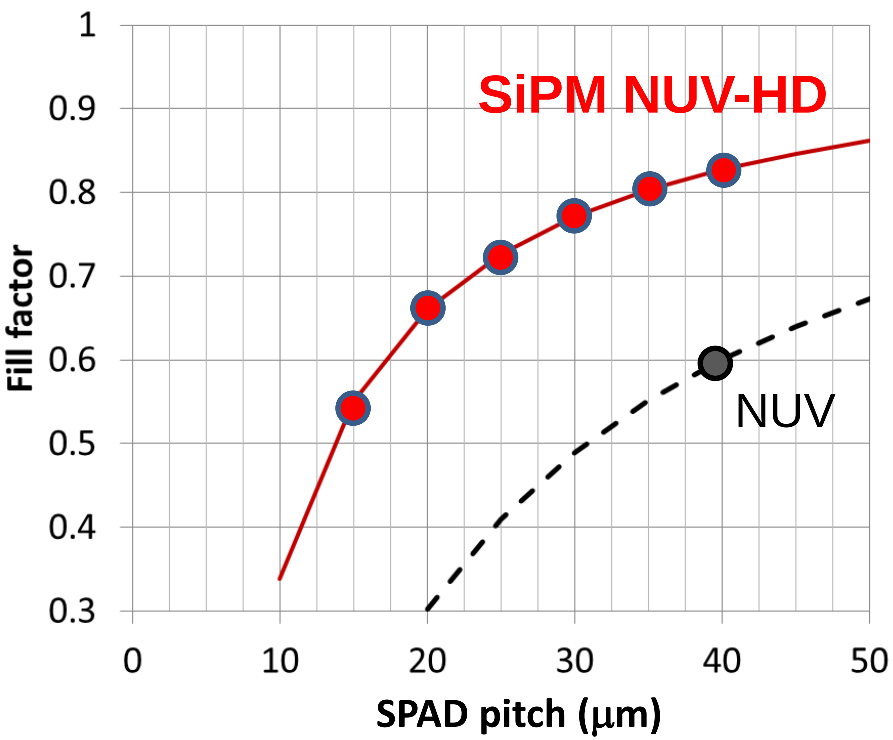


3.23 cm

High Density (HD) SiPMs: Fill Factor



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



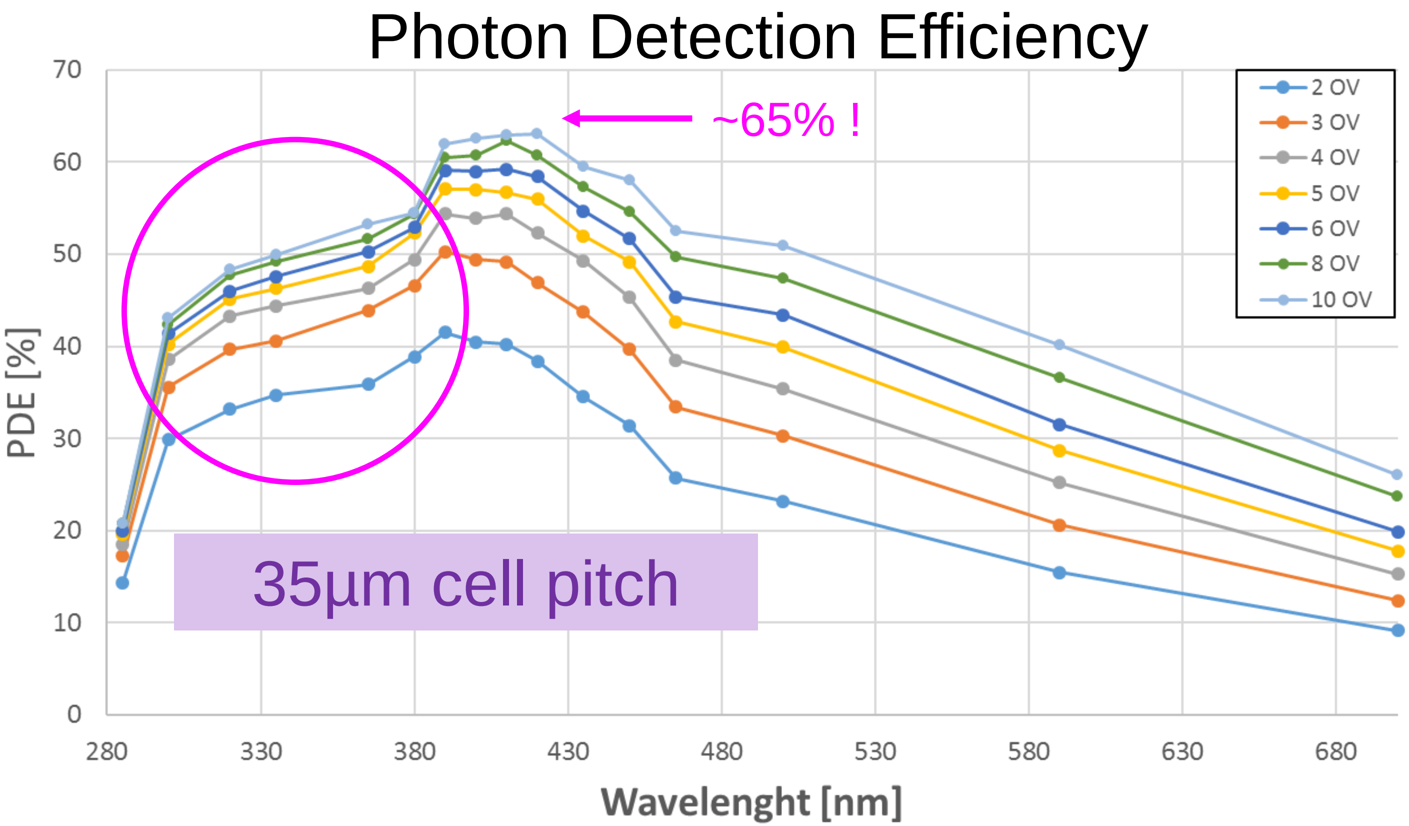
SPAD Pitch	15 μm	20 μm	25 μm	30 μm	35 μm	40 μm
Fill Factor (%)	55	66	73	77	81	83
SPAD/mm^2	4444	2500	1600	1111	816	625

High Dynamic Range, Low correlated noise

High PDE

Near-UV SiPMs: NUV-HD

- p-on-n junction → peak sensitivity at ~420 nm
- Narrow dead border region → High Fill Factor
- Trenches between cells → Lower Cross-Talk



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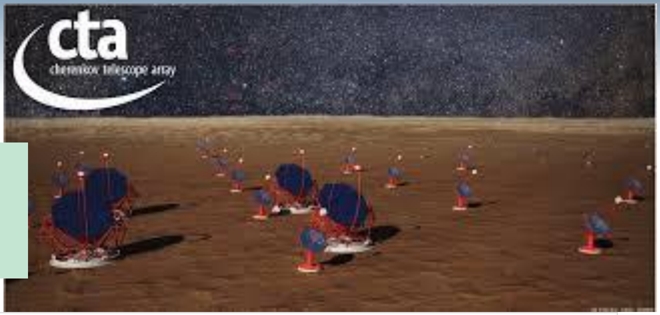
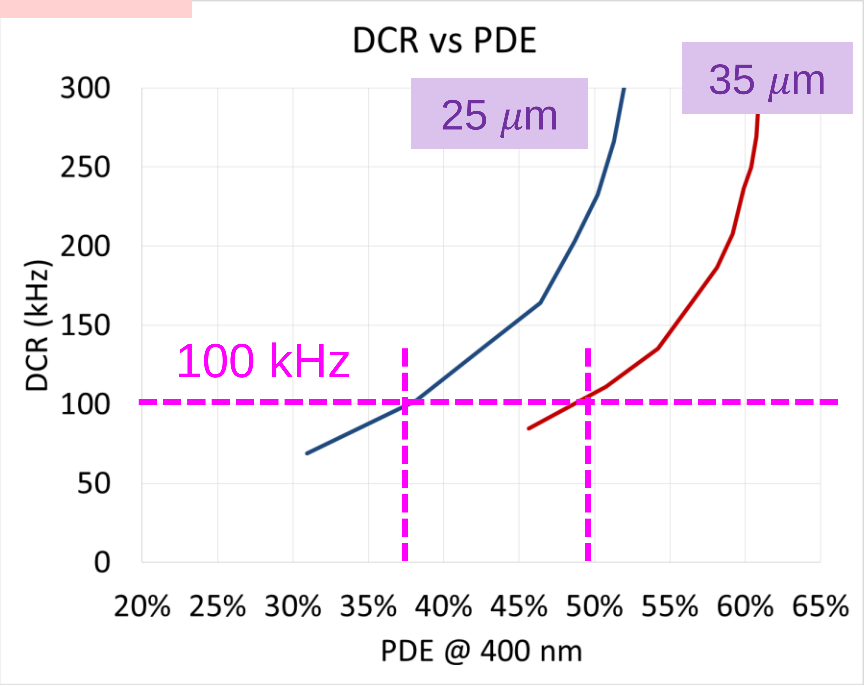
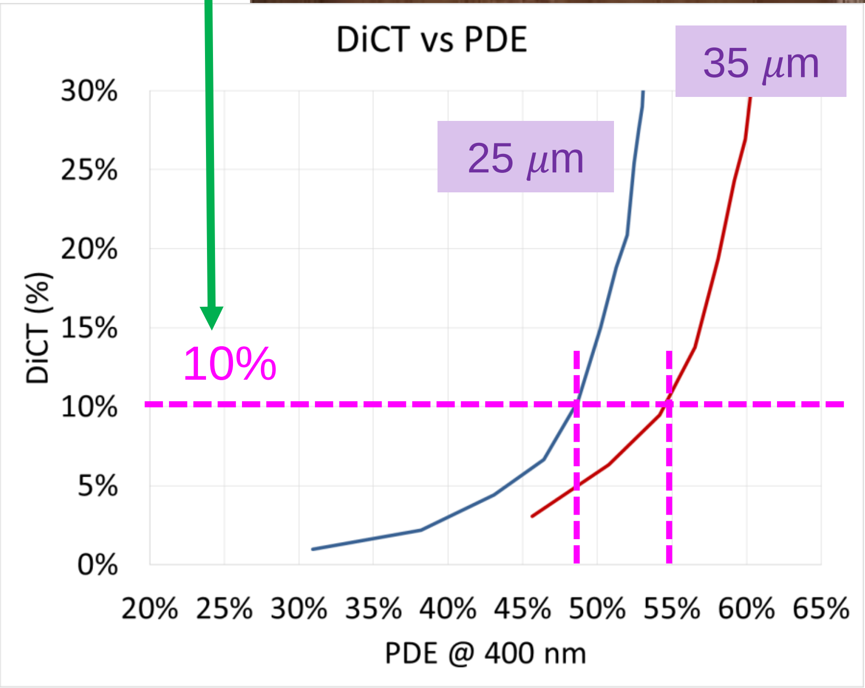
NUV-HD: Dark Count Rate



Applications such as CTA

T = 20 C



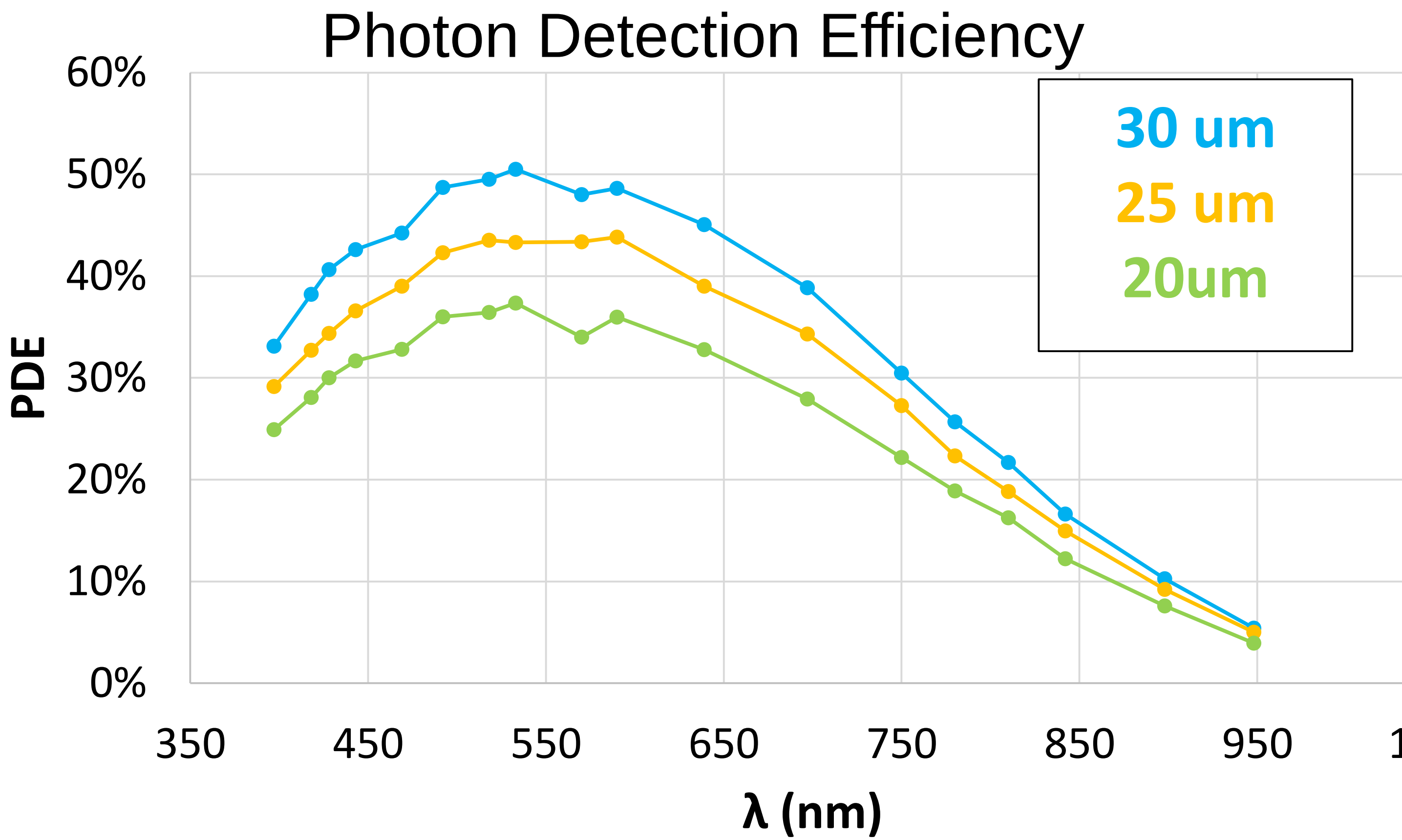


Dark Count Rate

Optical Crosstalk (Correlated Noise)

Visible light sensitive SiPMs: RGB-HD

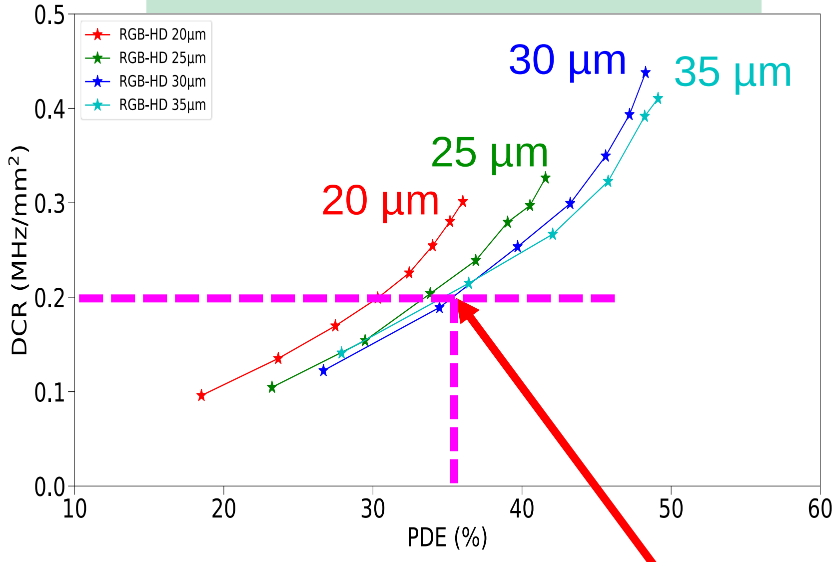
- n-on-p junction → peak sensitivity at ~550 nm
- Narrow dead border region → High Fill Factor
- Trenches between cells → Lower Cross-Talk



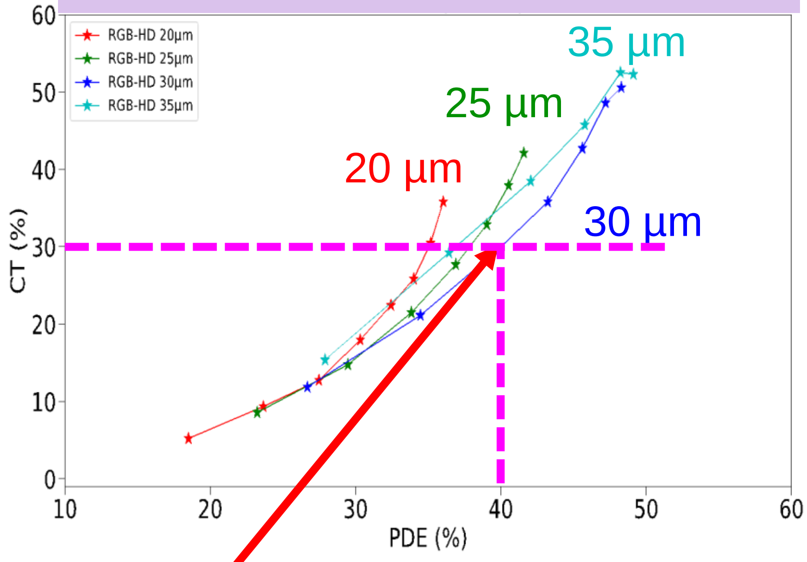
RGB-HD: dark characterization

A. Gola et al. talk at NSS2017

DCR vs. PDE at 545 nm



Crosstalk vs. PDE at 545 nm



Larger cells provide higher PDE for the same level of DCR or CT.

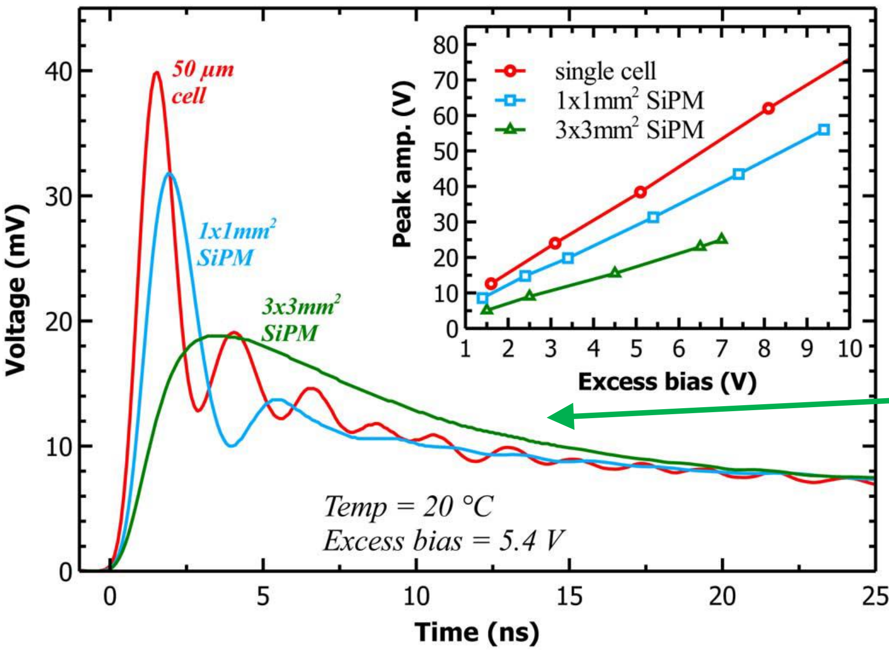
Different cell sizes provide very different PDE at the same over-voltage.

All SiPM noise measurements were carried out with scintillator:

- Increased optical crosstalk caused by the scintillator.

Single Photon Time Resolution (SPTR)

RGB SPAD/SiPM – SPTR

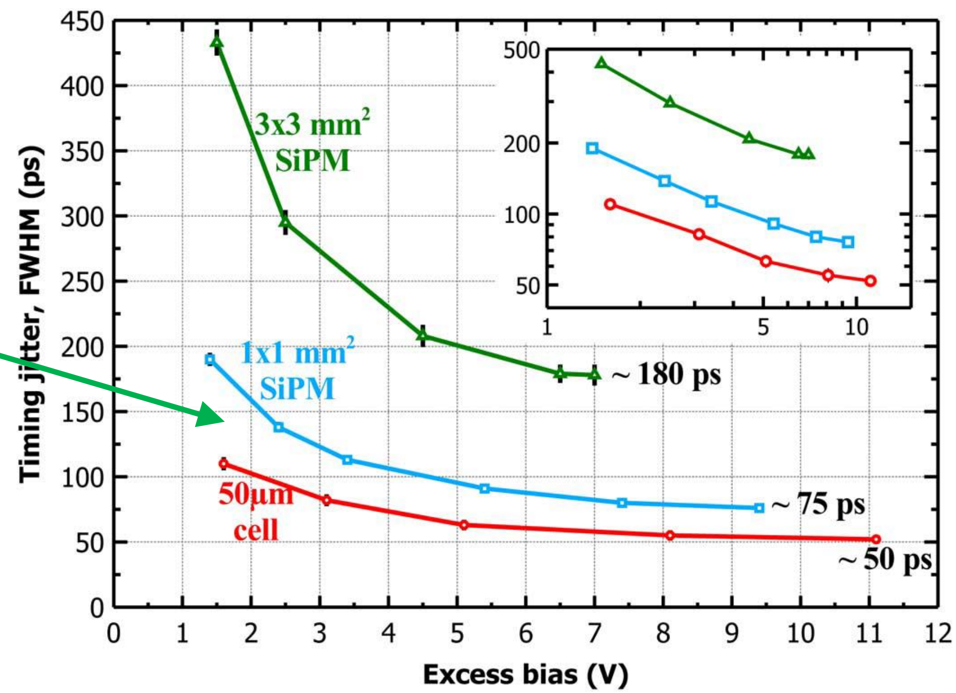


Measurements with pulsed laser light
λ = 425 nm, 2 ps pulses
kHz repetition rate

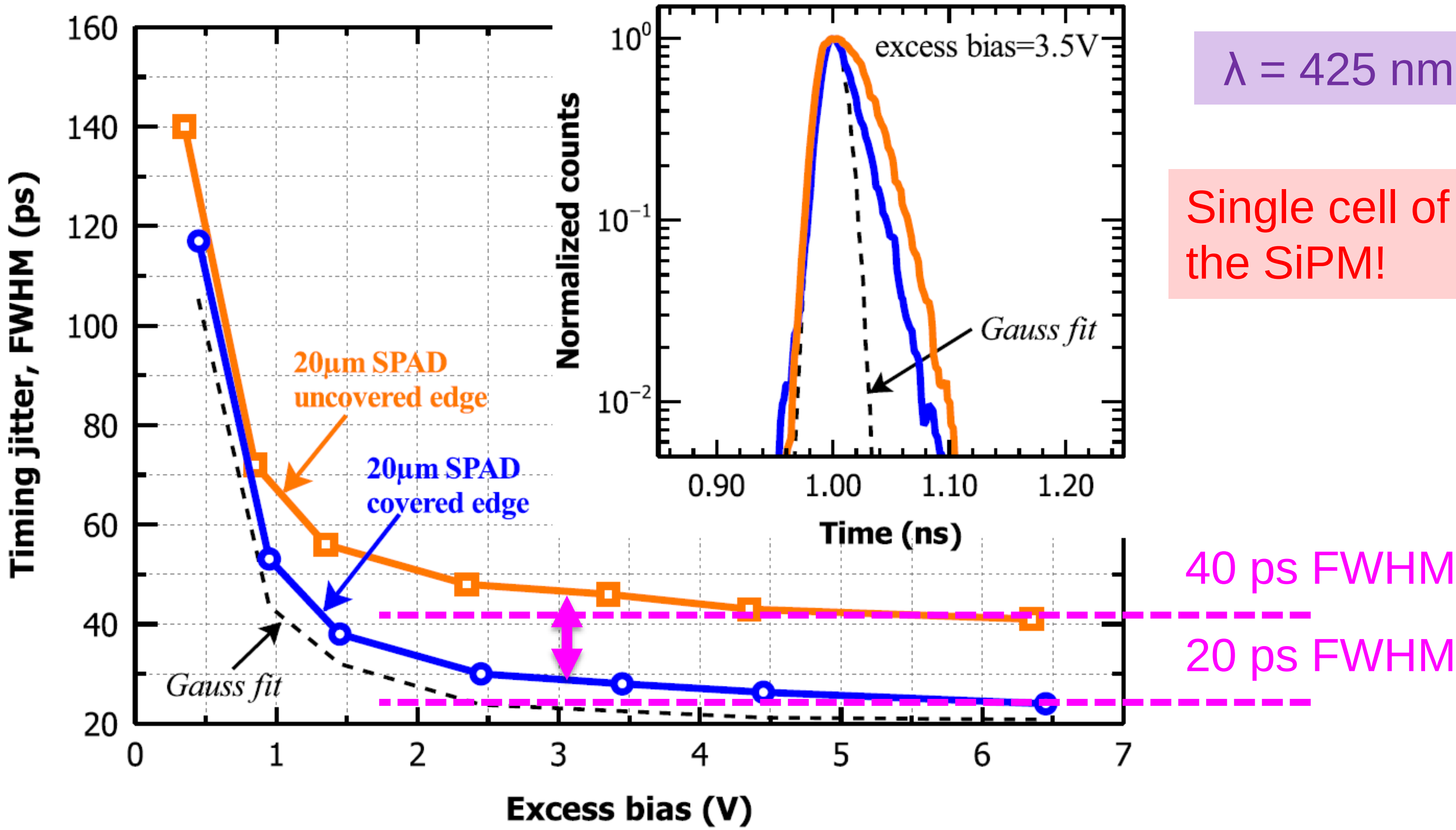
Single SPAD to full SiPM response

Single photon timing jitter
With increasing photodetector size

Single SPAD time resolution 50 ps



NUV SPAD – SPTR



λ = 425 nm

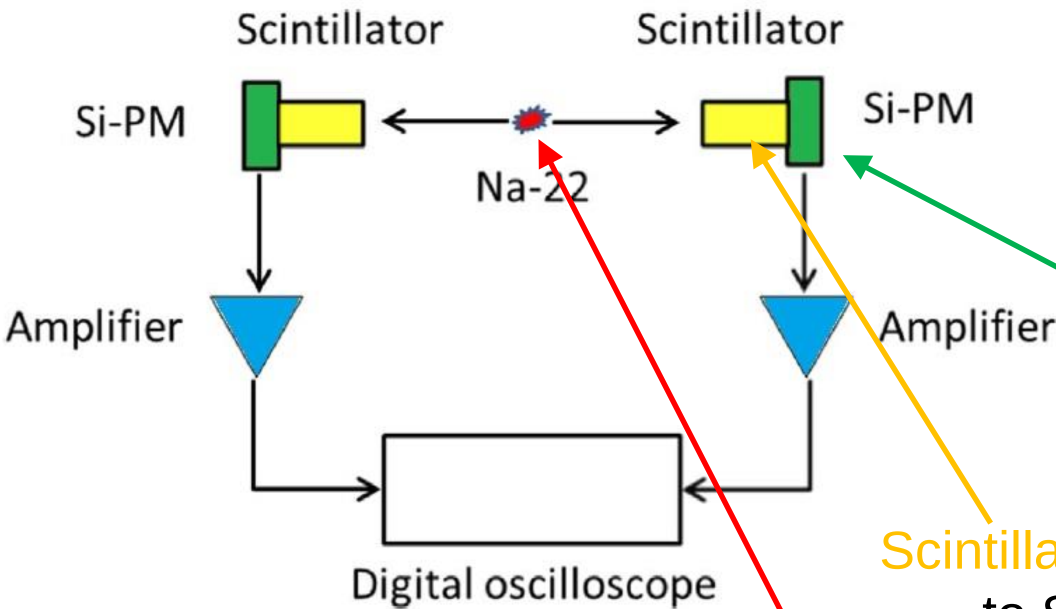
Single cell of the SiPM!

Worse charge collection at SPAD edges

Covering the SPAD edges reduces the SPTR by 20 ps

Coincidence Time Resolution

Coincidence time resolution (CTR) setup



FBK SiPMs

Scintillation crystals optically coupled to SiPMs with optical grease

Crystals wrapped with Teflon tape

^{22}Na as source of coincidence events
511 keV gamma rays

Controlled temperature:
Climatic chamber -70°C / +80°C

Coincidence time resolution (CTR) setup

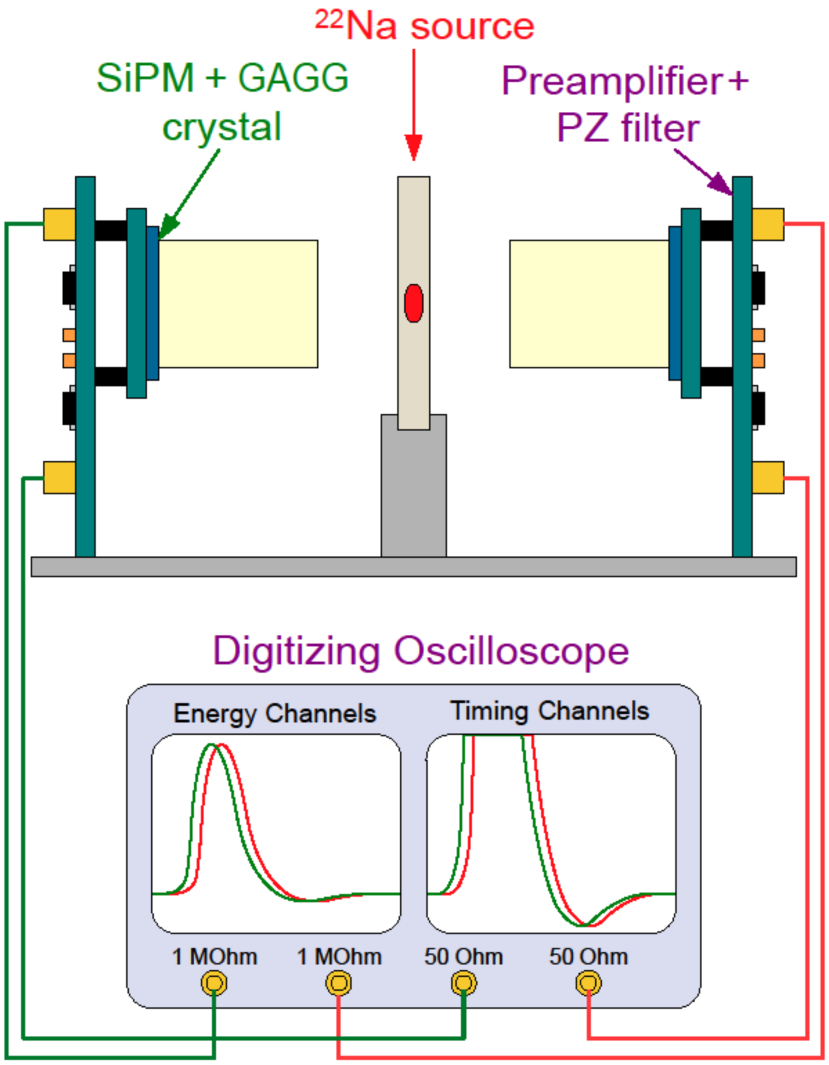
Two identical scintillation detectors
Same distance, same axis

Double stage amplifier:

- 1st stage: **γ-ray energy** (charge integration)
- 2nd stage: PZ compensation **low-noise LED technique**

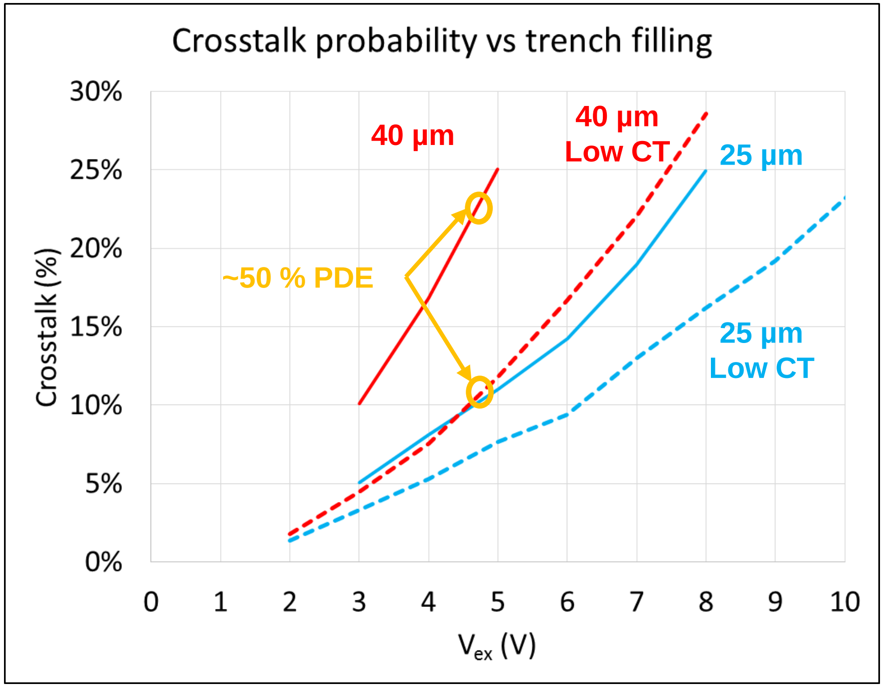
A. Gola et al., *IEEE Trans. Nucl. Sci.* **60** (2013) 1296-1302

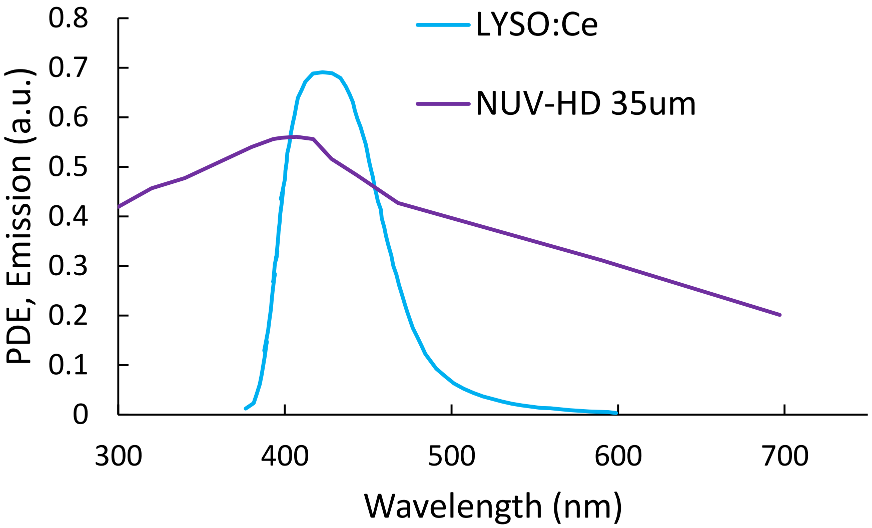
Digitizing oscilloscope with 10 GS/s sampling rate and 1 GHz analog bandwidth



State of the art:
top performing NUV-HD SiPMs

- **NUV-HD Peak PDE @ 400 nm**
- Successful strategy to reduce crosstalk





- High PDE at peak scintillation
- Low crosstalk

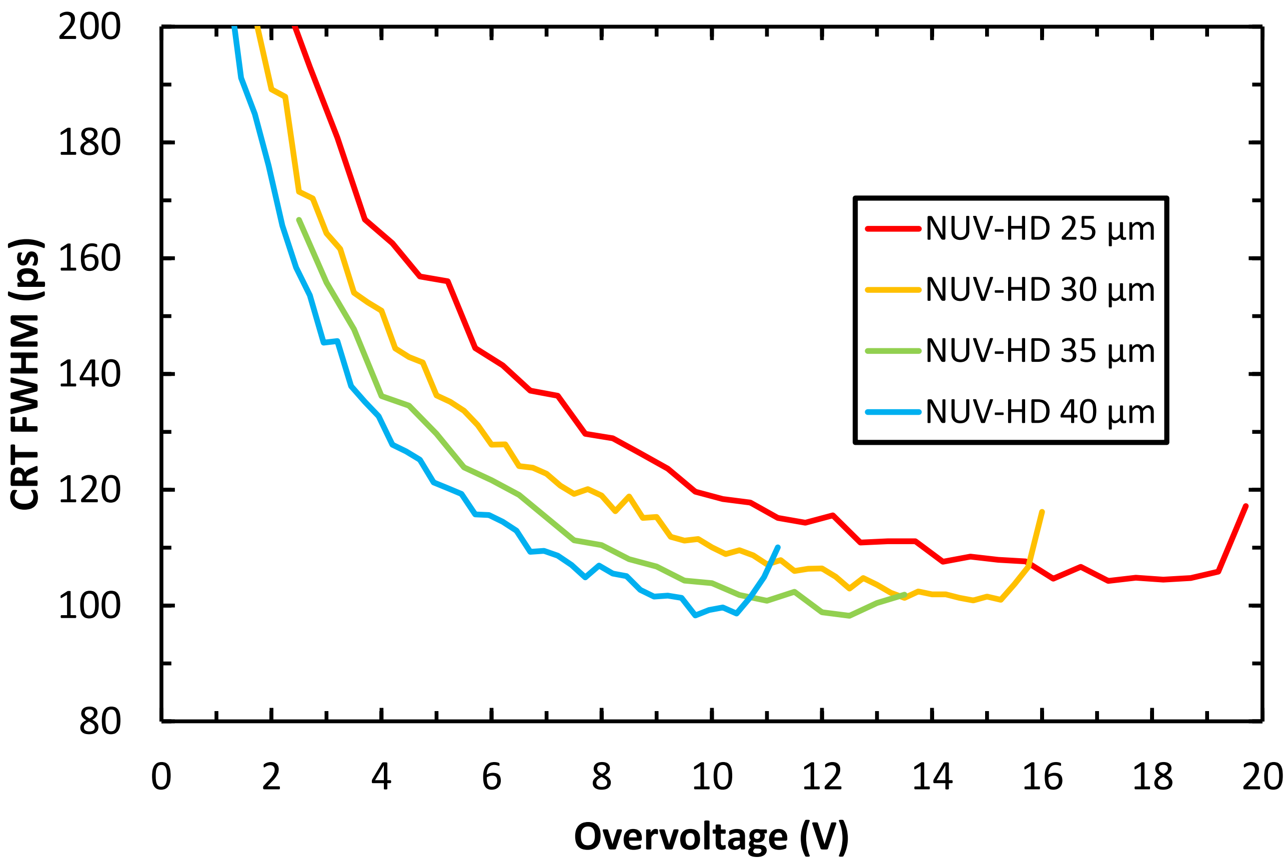
↓

Optimal conditions to maximize SNR at high operating overvoltage

CTR NUV-HD + LYSO 3x3x5 mm^3

NUV-HD SiPMs 4x4mm^2 low crosstalk
Maximum excess bias 20 V for 20 µm cell pitch

CTR FWHM 98±2 ps with LYSO 3x3x5 mm3
Single detector time resolution 70 ps FWHM (σ = 30 ps) at 511 keV



State of the art: coincidence time resolution

Current best performance reported for SiPM based TOF-PET detectors

Lu-based orthosilicates coupled to NUV-HD SiPMs

Crystal	Size (mm^3)	CRT FWHM (ps)	Reference
LYSO:Ce	2×2×3	87 ± 3	S. Gundacker et al., *J. Inst.* **11** (2016) P08008
	3×3×20	137 ± 3	
LSO:Ce,Ca	2×2×3	75 ± 3	
	3×3×20	126 ± 2	

State of the art:
GAGG:Ce for fast coincidence timing

<table>
<tr><th>Scintillator</th><th>ρ (g/cm³)</th><th>Z_{eff}</th><th>LY (ph./MeV)</th><th>τ_r (ps)</th><th>τ_d (ps)</th><th>λ_{max} (nm)</th></tr>
<tr><td>LSO:Ce,Ca</td><td>7.4</td><td>66</td><td>27 k</td><td>9</td><td>33</td><td>420</td></tr>
<tr><td>LYSO:Ce</td><td>7</td><td>60</td><td>30 k</td><td>80</td><td>38</td><td>420</td></tr>
<tr><td>GAGG:Ce</td><td rowspan="2">6.67</td><td rowspan="2">50.6</td><td>46 k</td><td>497</td><td>89</td><td rowspan="2">520</td></tr>
<tr><td>GAGG:Ce,Mg</td><td>35 k</td><td>72</td><td>60</td></tr>
</table>

P. Lecoq et al., *Inorganic Scintillators for Detector Systems*. Springer 2017
S. Gundacker et al., *NIM-A* **891** (2018) 42-52

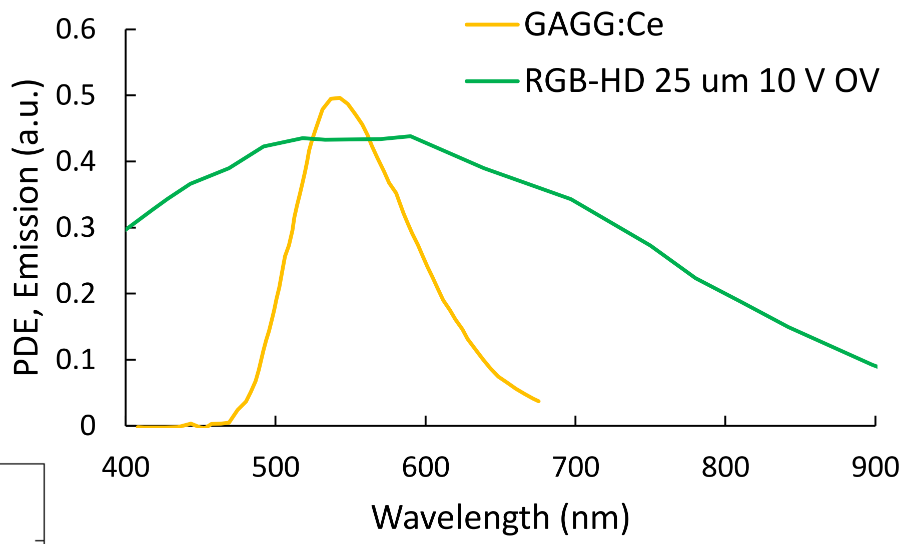
GAGG has interesting properties for fast timing scintillation detectors

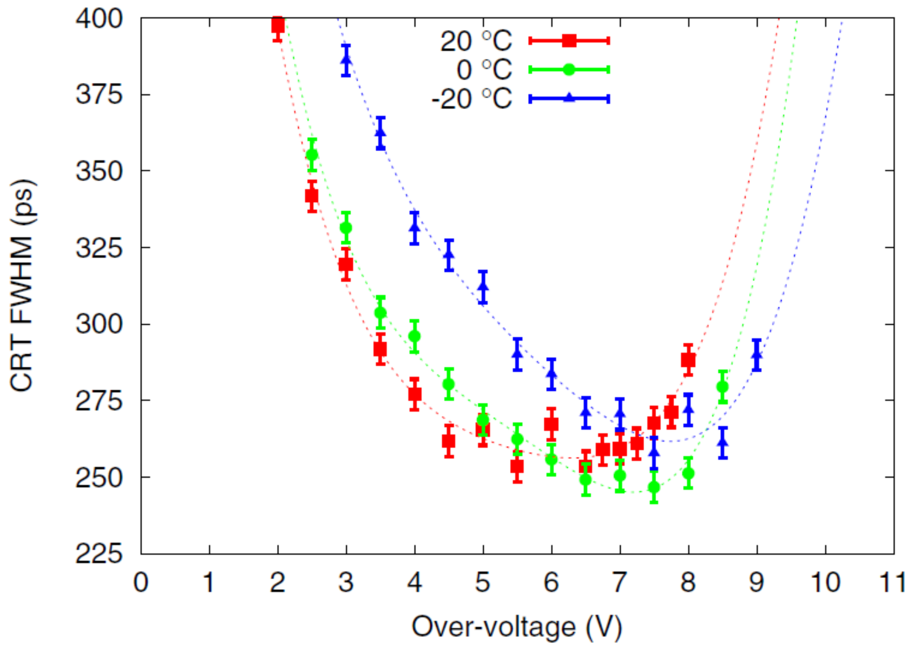
- High light yield
- High density
- Non-radioactive

But needs doping optimization to improve scintillation rise time

State of the art: GAGG:Ce for fast coincidence timing

Good matching of the peak PDE of RGB-HD with the scintillation spectrum of GAGG:Ce at 520 nm





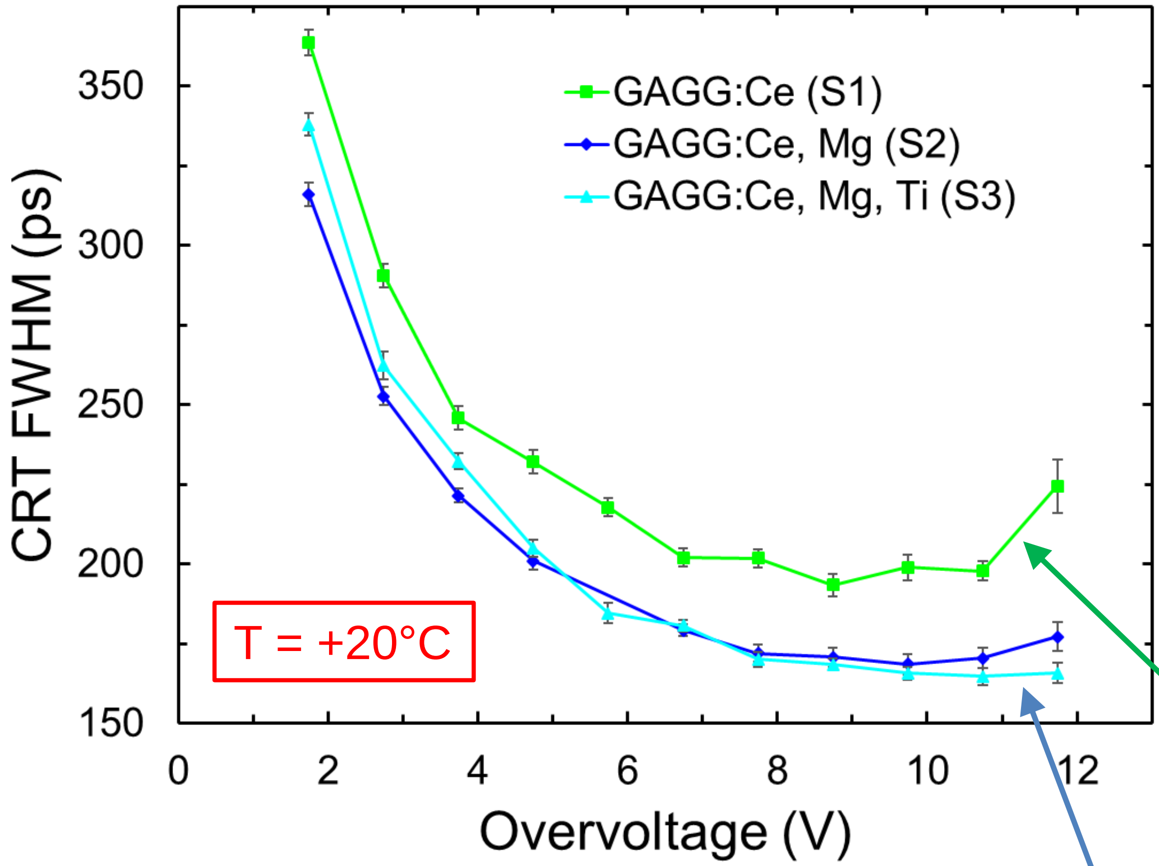
But, up to now, not excellent timing performance from RGB-HD/GAGG scintillation detectors

A. Ferri et al. Phys. Med. Biol. 59 (2014) 869

CTR RGB-HD + GAGG 3x3x5 mm^3

RGB-HD SiPMs 4x4mm^2

GAGG with different dopant concentrations to improve scintillation timing



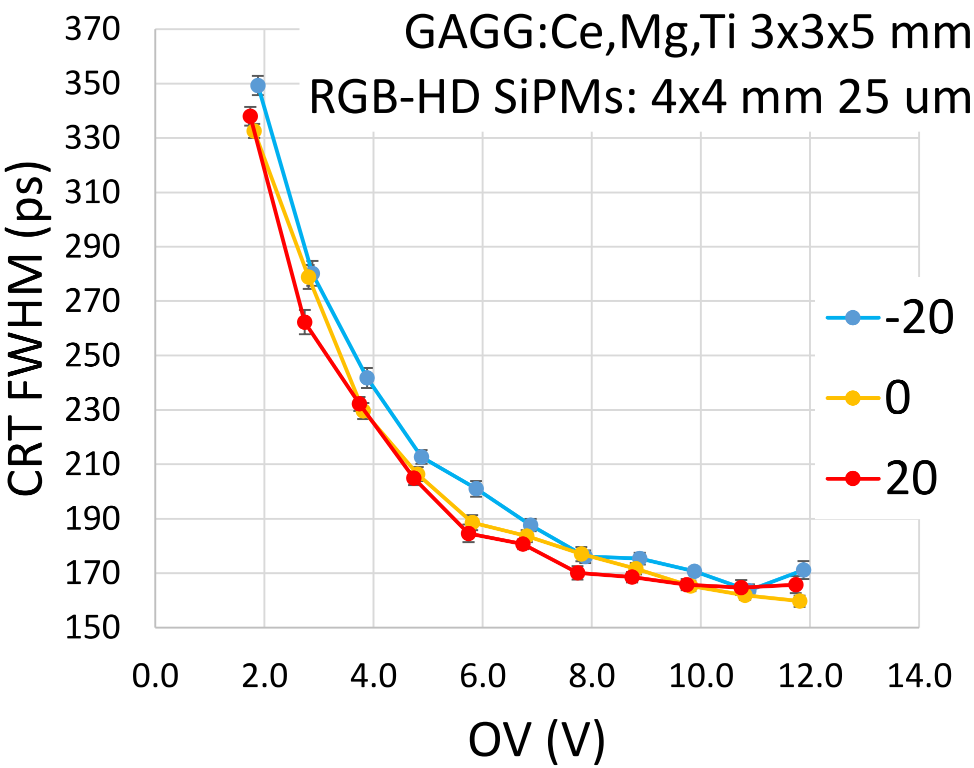
	Ce (ppm)	Mg (ppm)	Ti (ppm)
S1	550		
S2	530	10	
S3	800	50	20

CTR FWHM 193±4 ps with GAGG:Ce 3x3x5 mm^3

CTR FWHM 165±3 ps with GAGG:Ce,Mg,Ti 3x3x5 mm^3

G. Tamulaitis et al. “Improvement of response time in GAGG:Ce scintillation crystals by magnesium cooping” (submitted article)

CTR RGB-HD GAGG:Ce,Mg,Ti 3x3x5 mm^3

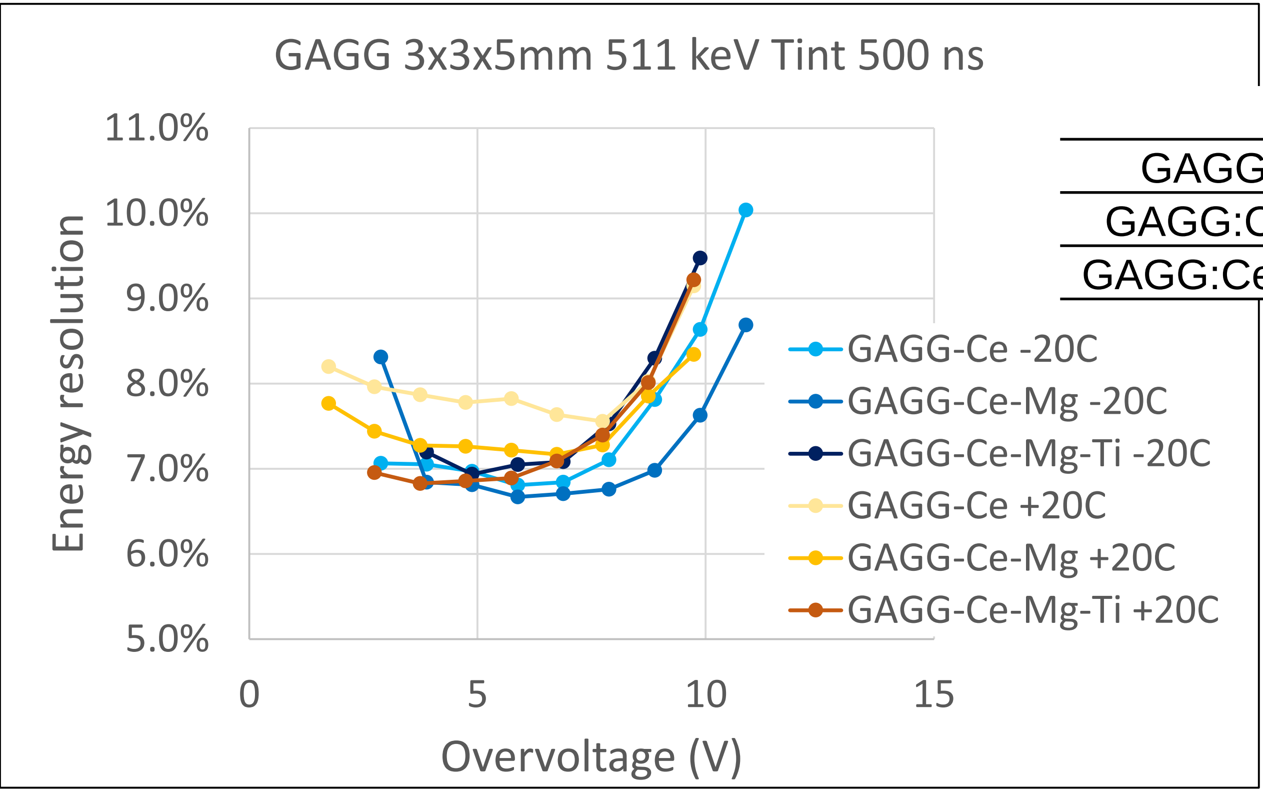


CTR @ +20°C	165±3 ps
CTR @ 0°C	160±2 ps
CTR @ -20°C	164±2 ps
Optimal overvoltage	~10 V
Optimal threshold	~8 mV
Crystals	GAGG-42 3x3x5
Detectors	RGB-HD SiPMs 4x4 mm, 25 um cells
Analysis method	Pole zero compensation

No significant differences for all the investigated temperatures: -20°C ÷ 20°C

Energy resolution RGB-HD/GAGG 3x3x5 mm^3

Energy resolution measurements obtained by charge integration
Correction for SiPM non-linearity



	-20 C	+20 C
GAGG:Ce	6.8%	7.5%
GAGG:Ce,Mg	6.7%	7.2%
GAGG:Ce,Mg,Ti	6.9%	6.8%

Optimal SiPM conditions:
Overvoltage ~6 V
Integr. time 500 ns

Good energy resolution
Small Temp variations

Energy resolution of RGB-HD/**LYSO** detector
9.0 – 9.5% at 511 keV
A. Ferri et al. *Phys. Med. Biol.* **59** (2014) 869

CRT results: final comparison

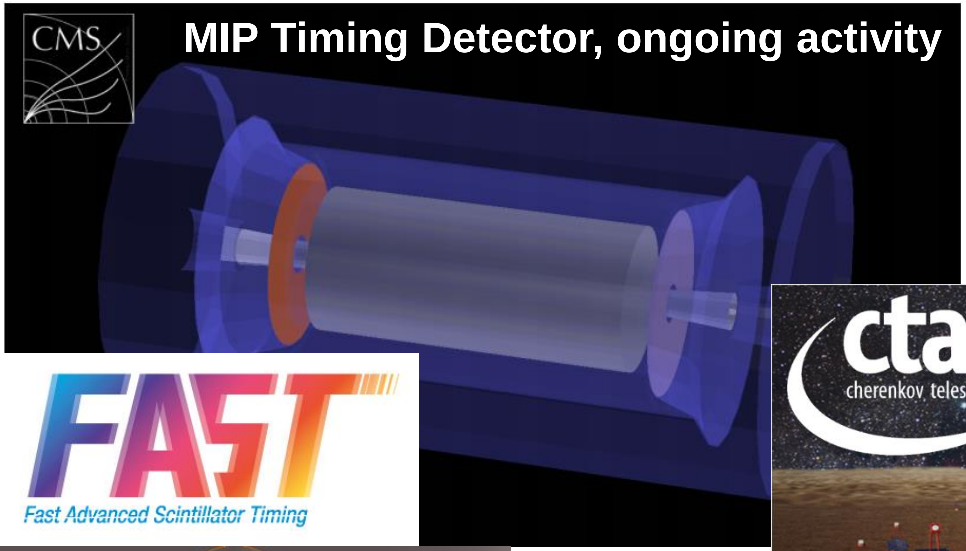
State of the art CTR measurements with different scintillation crystals
Coupled to FBK SiPMs (4x4 mm^2, single channel)

Crystal	size (mm^3)	SiPM	CRT (ps)	Reference
LSO:Ce,Ca	2x2x3	NUV-HD 25 um	75 ± 3	S. Gundacker et al., *J. Inst.* **11** (2016) P08008
LYSO:Ce	2x2x3	NUV-HD 25 um	87 ± 3	S. Gundacker et al., *J. Inst.* **11** (2016) P08008
	3x3x5	NUV-HD 35 um	98 ± 2	
GAGG:Ce	3x3x5	RGB-HD 25 um	193 ± 4	
Ce,Mg	3x3x5	RGB-HD 25 um	169 ± 3	
Ce,Mg,Ti	3x3x5	RGB-HD 25 um	165 ± 3	
YAP:Ce	3x3x5	NUV-HD 35 um	239 ± 6	
LuYAP:Ce	2x2x8	NUV-HD 35 um	405 ± 6	

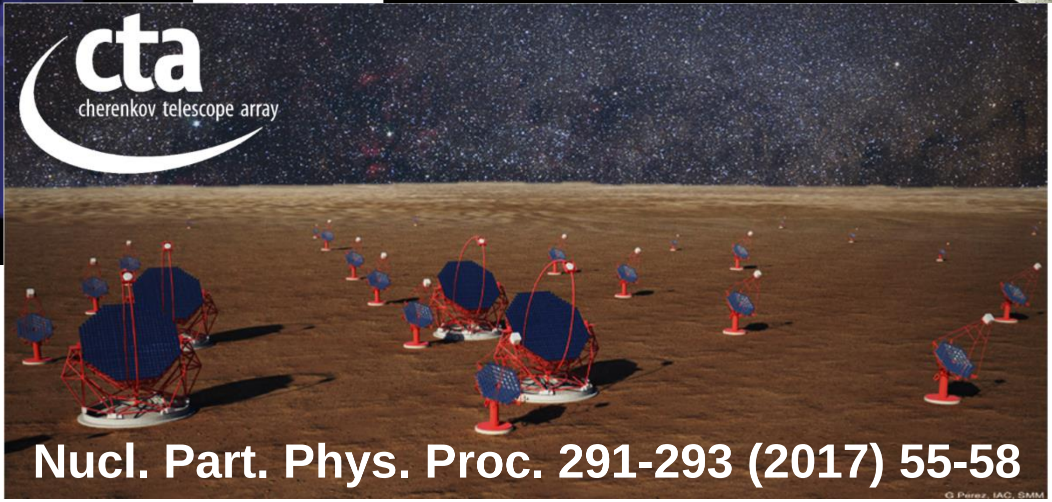
Final remarks

- Expertise in SiPM simulation, desing, production and testing
- Development of NUV-HD and RGB-HD SiPM technology
- Measurements setups and techniques for SiPM characterization
- Top state-of-the-art timing results with SiPMs / scintillators
  <100 ps CTR FWHM at 511 keV

FBK SiPMs scientific collaborations



FAST
Fast Advanced Scintillator Timing



- UHD technology development
  F. Acerbi et al. IEEE J. Sel. Top. Quantum Electron. 24 (2017) 3800608
- Position sensitive SiPMs (LG-SiPMs)
  A. Ferri et al. IEEE TNS 62 (2015) 688 – 693
- Near-IR (NIR) SiPMs
  F. Acerbi et al. NIM-A (2017) in press

FBK SiPMs research group

Visit us at the industrial exhibition… and in Trento, Italy

iris.fbk.eu

Thank you

for your attention!