Single-photon Cameras for Quantum Imaging Applications

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aqualab

Phose 2023, CERN

EPFL

Acknowledgements

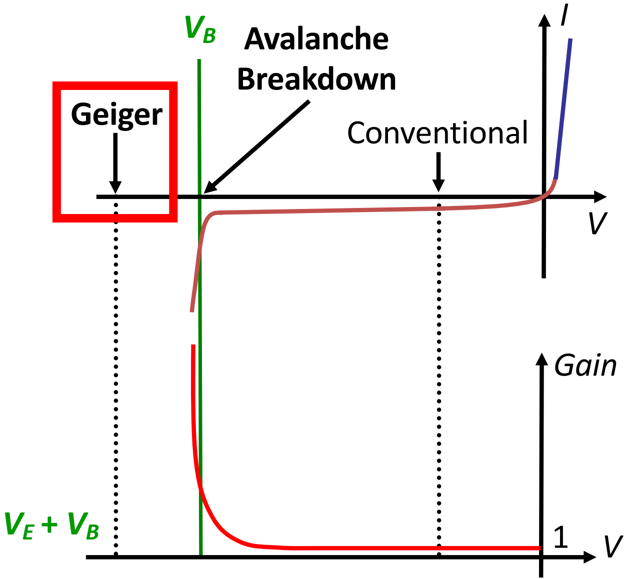
Swiss National Science Foundation
European Commission, STW/NOW

Global Foundries, Canon, and many others.

Solid-state photon counting:

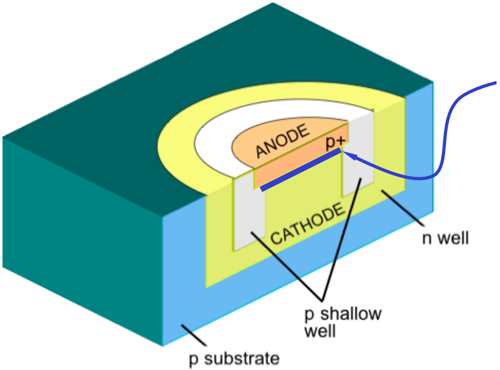
APDs and GM-APDs/SPADs

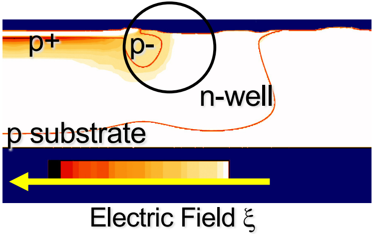
SPAD or Geiger-Mode APD



The first CMOS SPAD

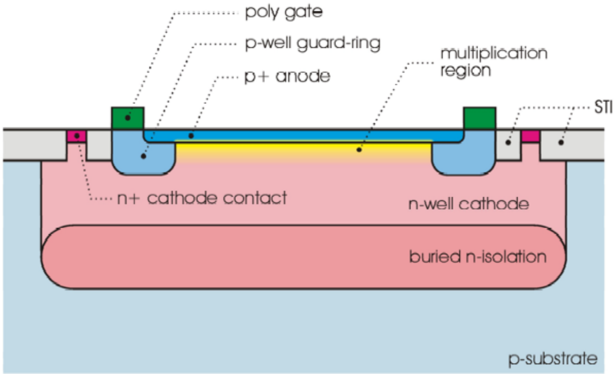
- Implemented entirely using standard layers and conventional process steps!
- Further miniaturization, thinner devices, lower voltages





Rochas *et al*.

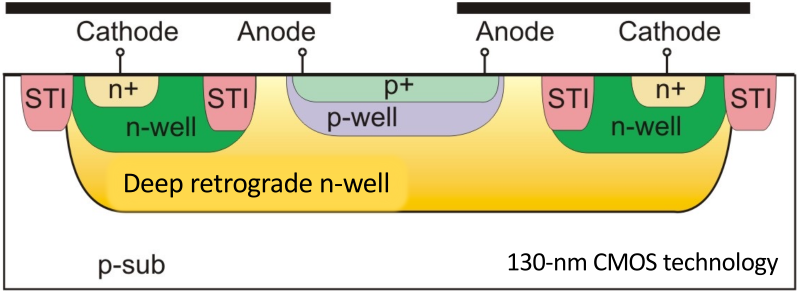
The first deep-submicron CMOS SPAD



Niclass et al. 2007

- First deep-submicron CMOS structure (130nm)
- In DSM processes, high doping and shallow implants, thus high DCR
- Quasi neutral field region at the edges, thus long diffusion tail in the time response

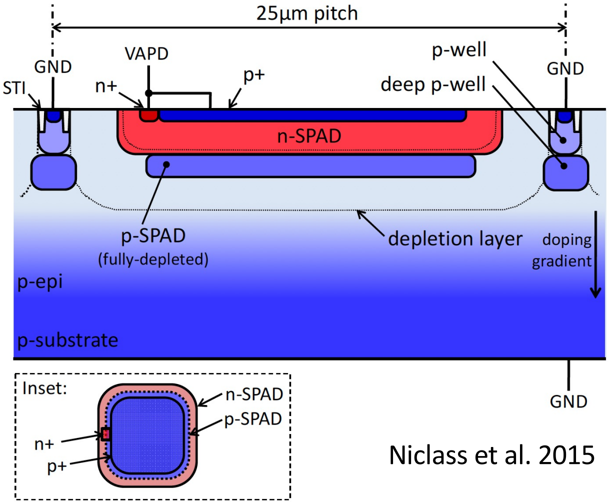
The first industrial SPAD



Niclass et al. 2007 – Richardson et al. – Pellegrini et al.

- Guard ring implicitly obtained from retrograde well
- Suitable for deep-submicron processes (in this case 130nm)
- Compatible with triple-well process
- Good DCR performance

SPAD with fully-depleted avalanche region



Niclass et al. 2015

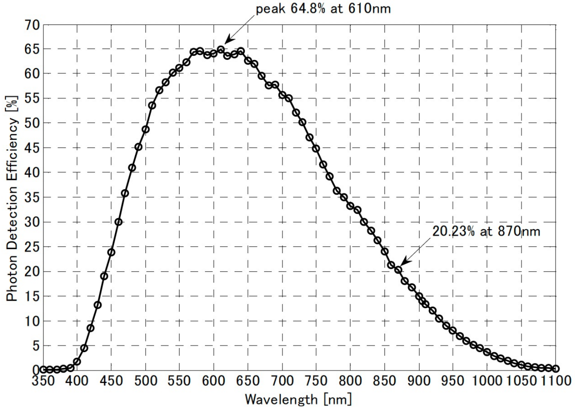


Fig. 10. Photon detection efficiency as a function of signal wavelength at an excess bias of 5V.

Recent advances

The phenomenal SPAD CIS evolution

- Timing resolution (100ps → 7.5ps)
- Sensitivity
  - Photon Detection Probability (PDP) (10% → 90%)
  - Fill-factor (1% → 80%)
- Dead time (100ns →1.5ns)
- Dark counts (kcps → cps → mcps)
- Afterpulsing (10% → 0.1%)

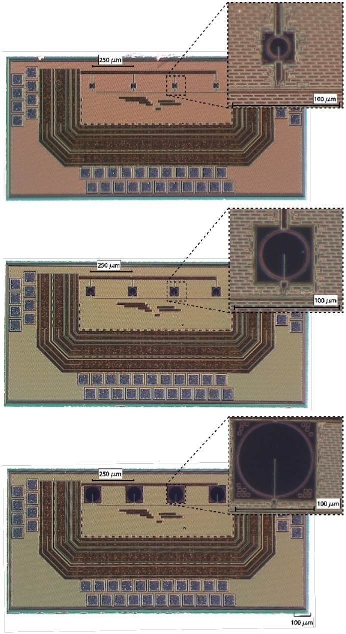
cps = counts per second
kcps = 10^3 cps
mcps = 10^{-3} cps

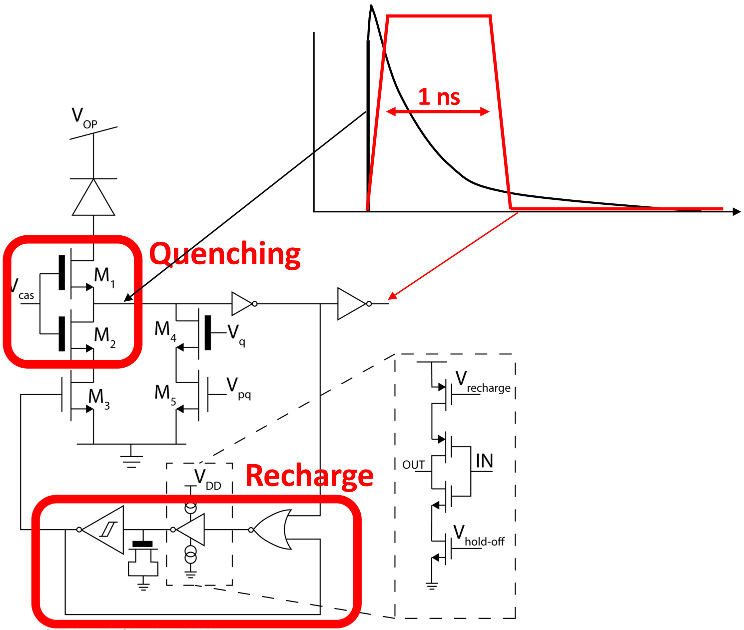
The power of integration

25µm

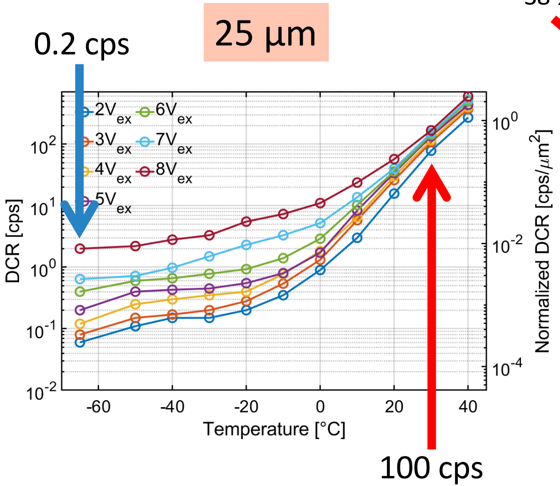
50µm

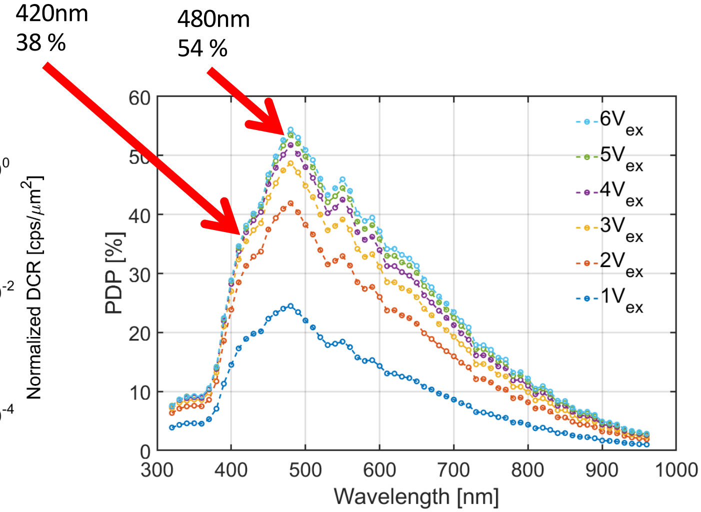
100µm





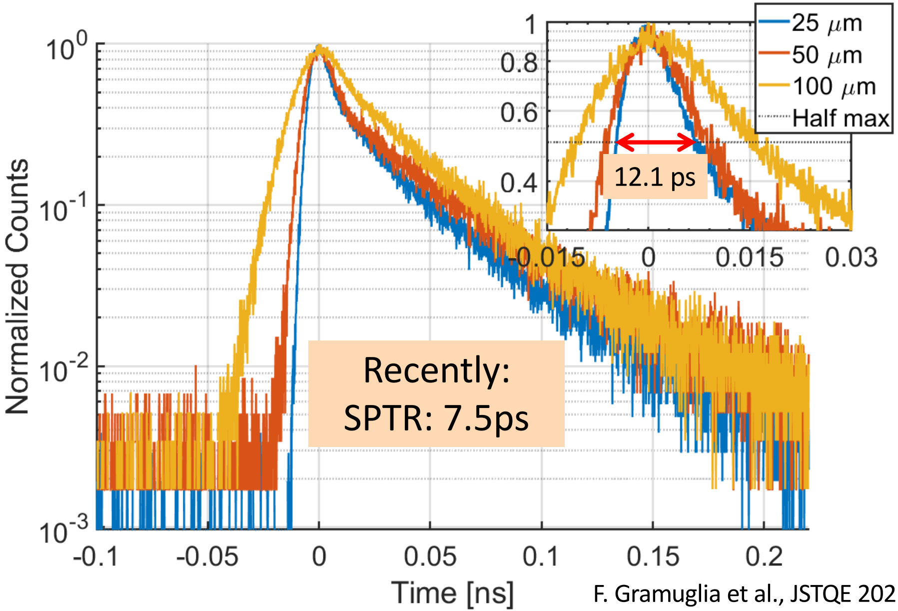
Sensitivity (PDP) and noise (DCR)





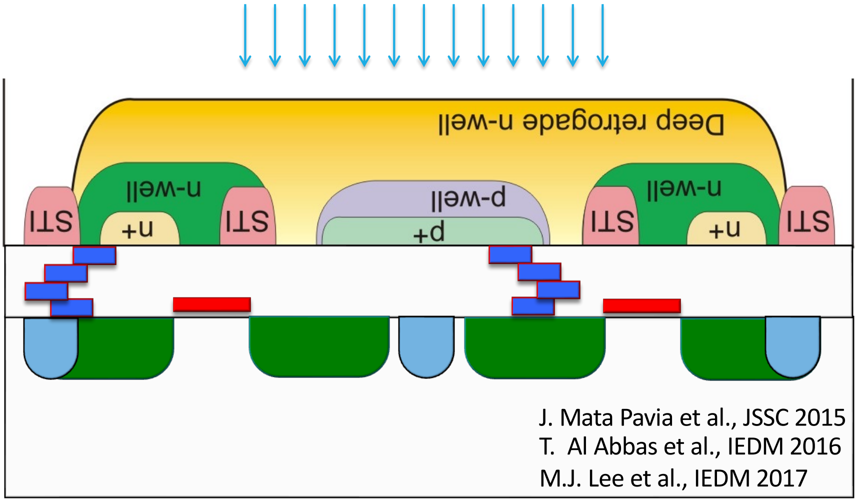
F. Gramuglia et al., JSTQE 2021

Timing resolution (SPTR)



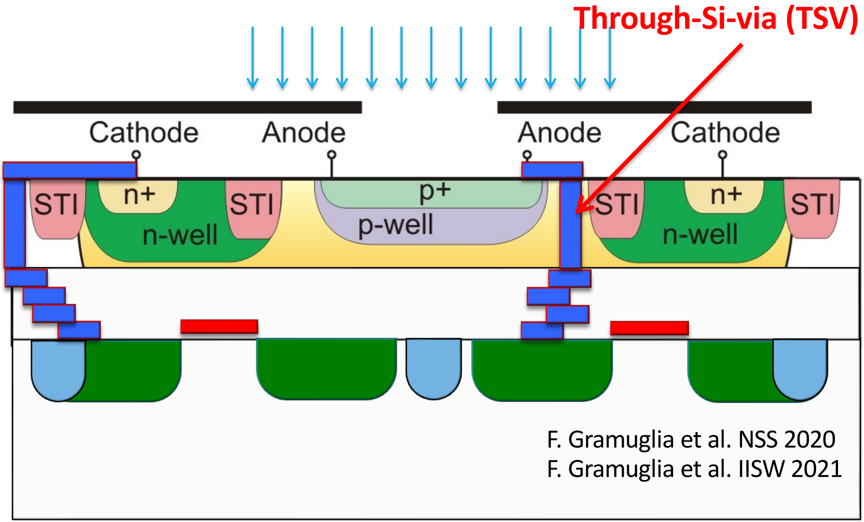
F. Gramuglia et al., JSTQE 2021
F. Gramuglia et al., Frontiers in Physics, 2022

3D stacking (backside illumination – BSI)



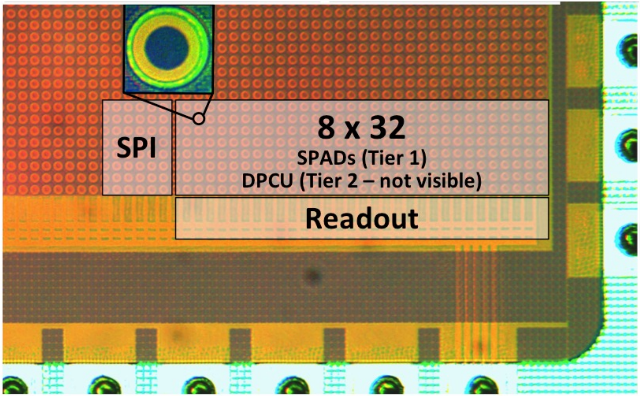
J. Mata Pavia et al., JSSC 2015
T. Al Abbas et al., IEDM 2016
M.J. Lee et al., IEDM 2017

3D stacking (frontside illumination – FSI)



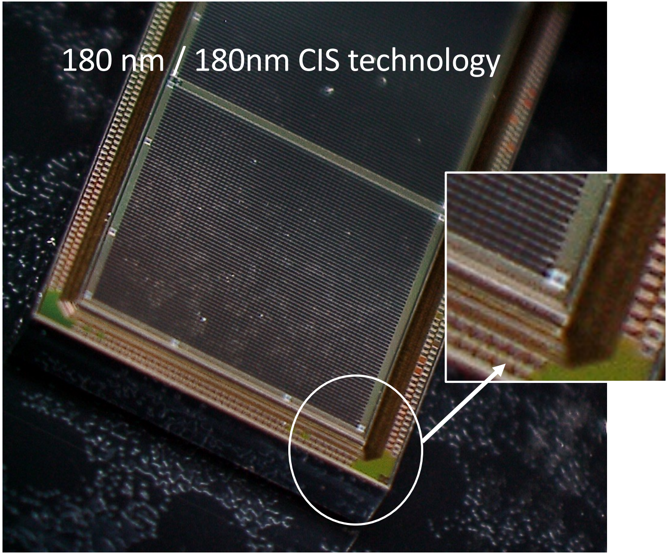
3D-stacked BSI & FSI chips

45 nm / 65nm & 22nm TSMC technology



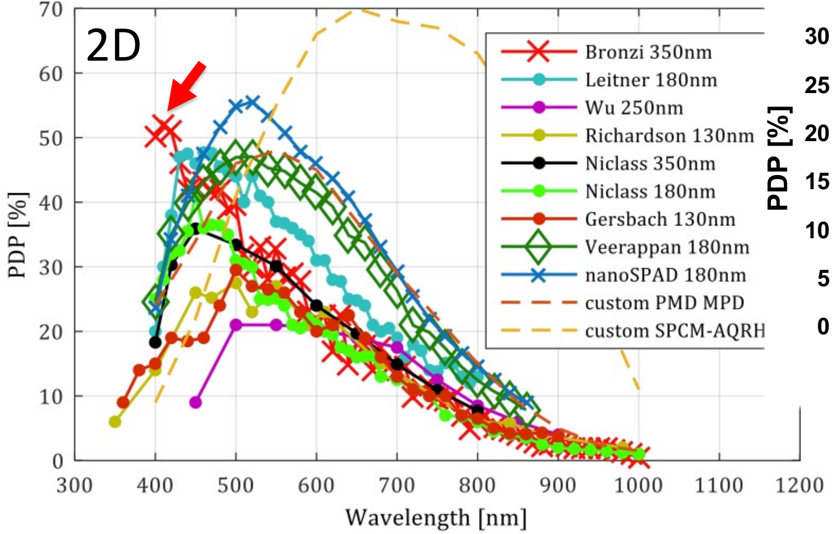
A. Ximenes et al. ISSCC 2018 / JSSC 2019
P. Padmanabhan et al. ISSCC 2021

180 nm / 180nm CIS technology

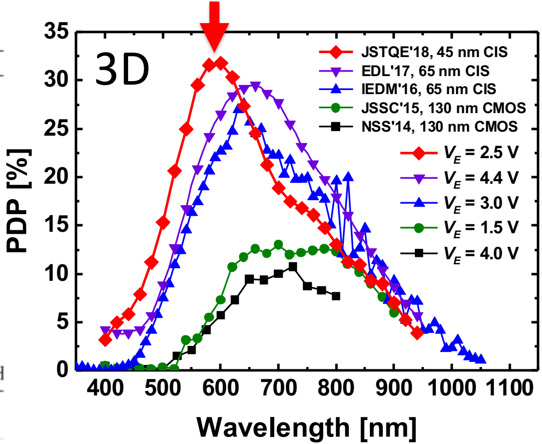


F. Gramuglia et al. NSS 2020 / IISW 2021

FSI vs. BSI



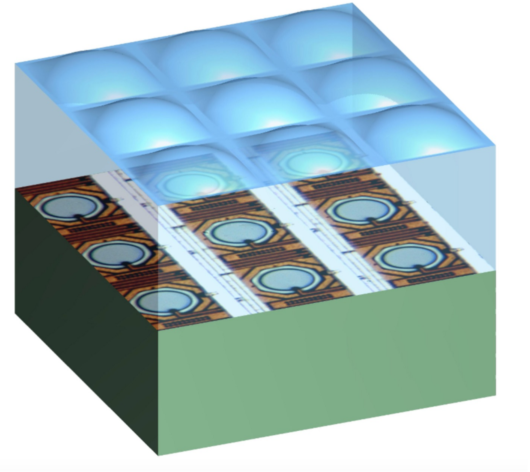
C. Veerappan & E. Charbon, TED 2016

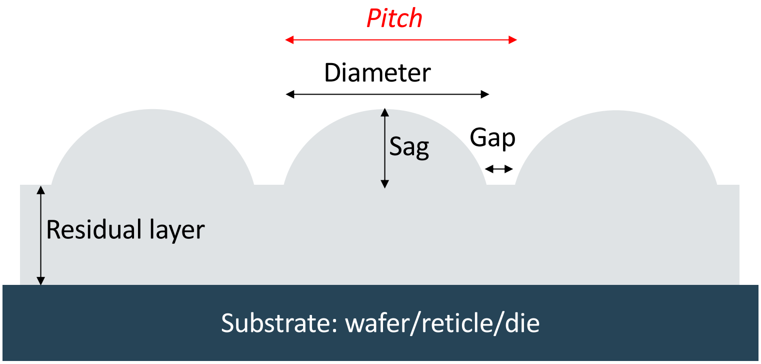


M.-J. Lee *et al.*, Jpn. J. Appl. Phys'18

Optical interfaces

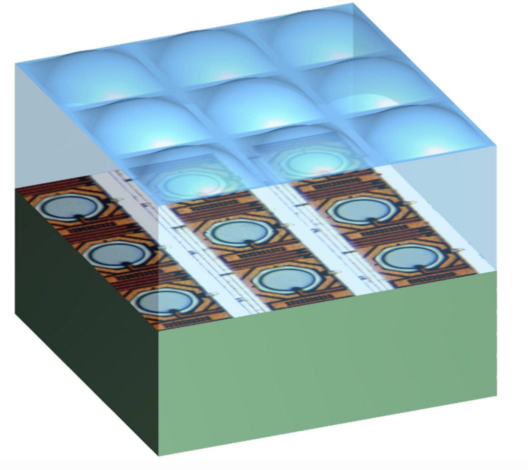
Optical microlenses

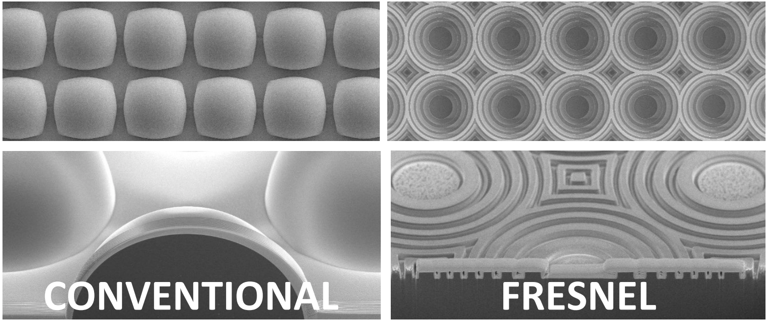




Mata Pavia et al. 2014 – Ximenes et al. 2018 – Bruschini et al. 2023

Optical microlenses

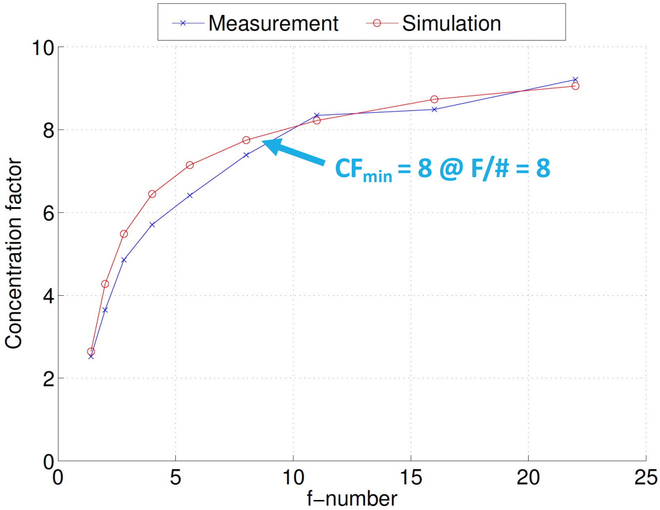




Ximenes et al. 2018

Mata Pavia et al. 2014 – Ximenes et al. 2018 – Bruschini et al. 2023

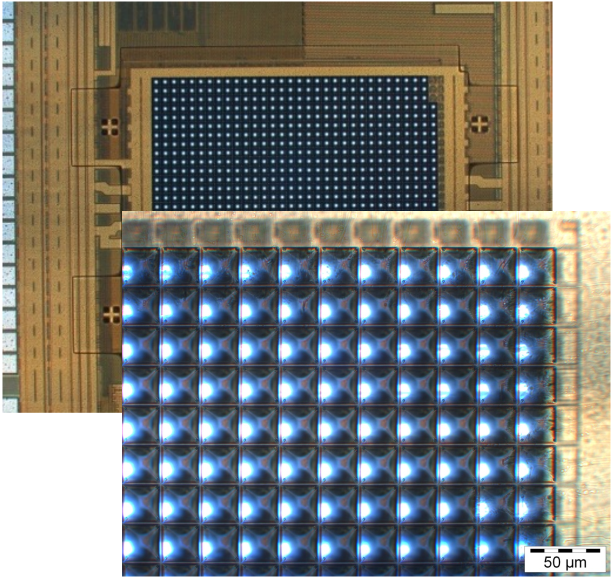
Concentration factor

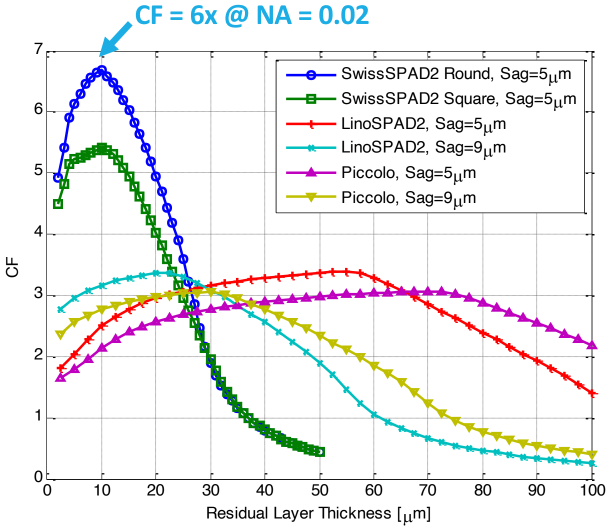


Mata Pavia et al. 2014

CF = concentration factor

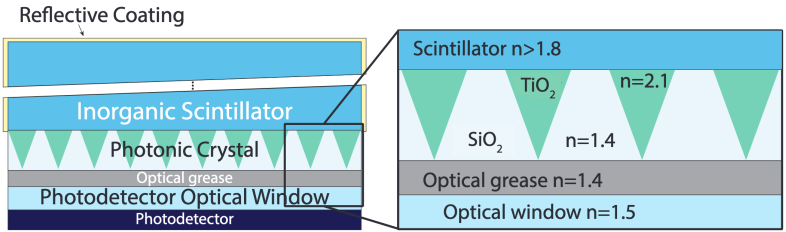
CF for different SPADs



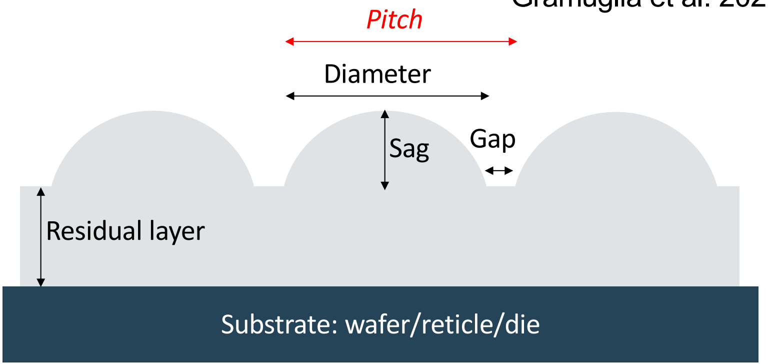


Bruschini et al. 2023

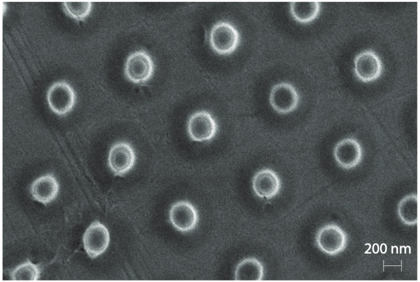
Optimizing microlens-scintillator interfaces

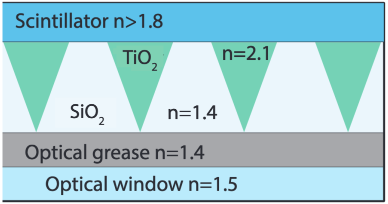


Gramuglia et al. 2021



Optimizing microlens-scintillator interfaces





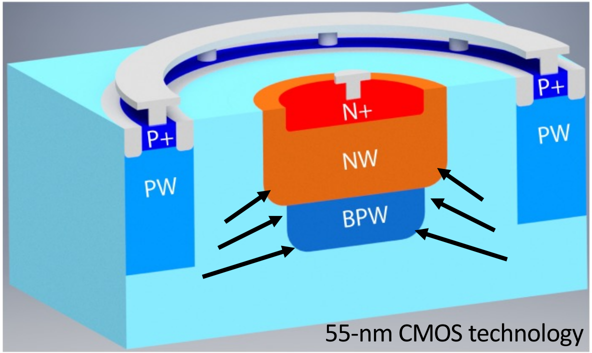
Gramuglia et al. 2021

Comparison of Experimental Results

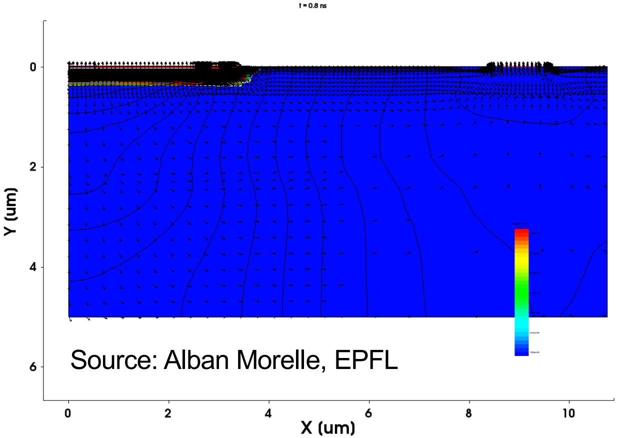
ID	Crystal	Configuration	Light Gain	Energy Resolution (%)	Energy Resolution Improvement
1	BGO	Bare crystal & Opt. Grease	0.55	20.8 ± 0.48	0.74
2	BGO	Bare crystal & Opt. Grease & DBR (top)	0.64	19.3 ± 0.26	0.80
3	BGO	ESR & Opt. Grease	0.98	15.6 ± 0.29	0.99
4	BGO	Teflon & Opt. Grease	1.00	15.4 ± 0.19	1.00
5	BGO	PhC Pattern & Opt. Grease	0.80	17.2 ± 0.58	0.90
6	BGO	PhC Pattern, Teflon & Opt. Grease	1.41	12.7 ± 0.36	1.21
7	BGO	PhC Pattern & Opt. Grease & DBR (top)	0.88	16.4 ± 0.57	0.94
1	LYSO	Bare crystal & Opt. Grease	0.74	12.2 ± 0.32	0.85
2	LYSO	Bare crystal & Opt. Grease & DBR (top)	0.79	11.8 ± 0.36	0.88
3	LYSO	ESR & Opt. Grease	1.00	10.4 ± 0.12	1.00
4	LYSO	Teflon & Opt. Grease	1.00	10.4 ± 0.15	1.00
5	LYSO	PhC Pattern & Opt. Grease	0.85	11.4 ± 0.33	0.91
6	LYSO	PhC Pattern, Teflon & Opt. Grease	1.10	10.0 ± 0.24	1.04
7	LYSO	PhC Pattern & Opt. Grease & DBR (top)	0.86	11.3 ± 0.34	0.92

Electrical microlenses

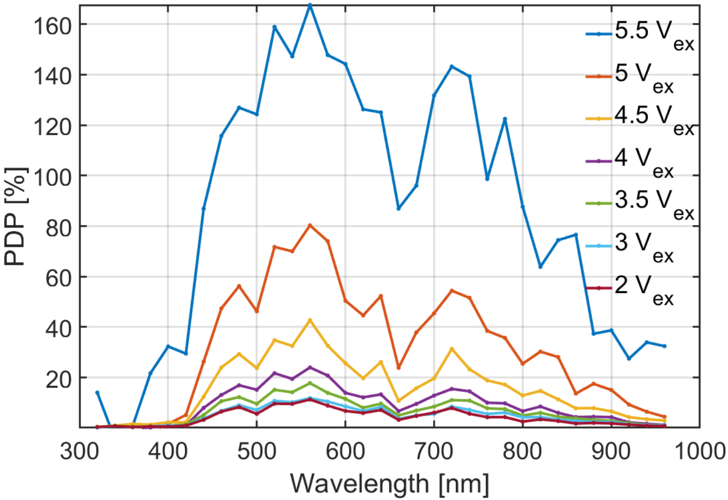
- Innovative use of horizontal E-field
- Multiplication region is reduced, while sensitive region is augmented
- Lateral electric field is used to sweep carriers towards multiplication region



Original idea: Veerappan & Charbon, IISW 2013
Rediscovered by Canon, who names it 'charge focusing'

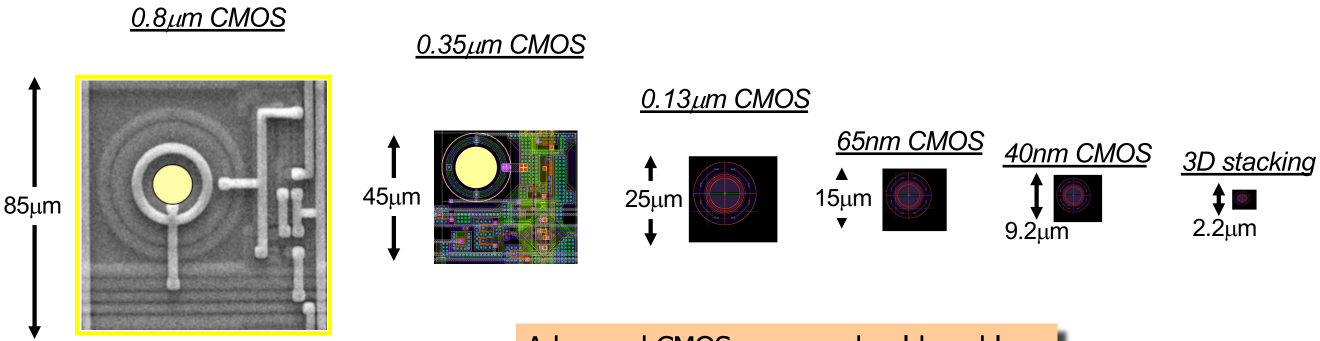


Electrical microlenses (2)



Large-format cameras

SPAD scaling

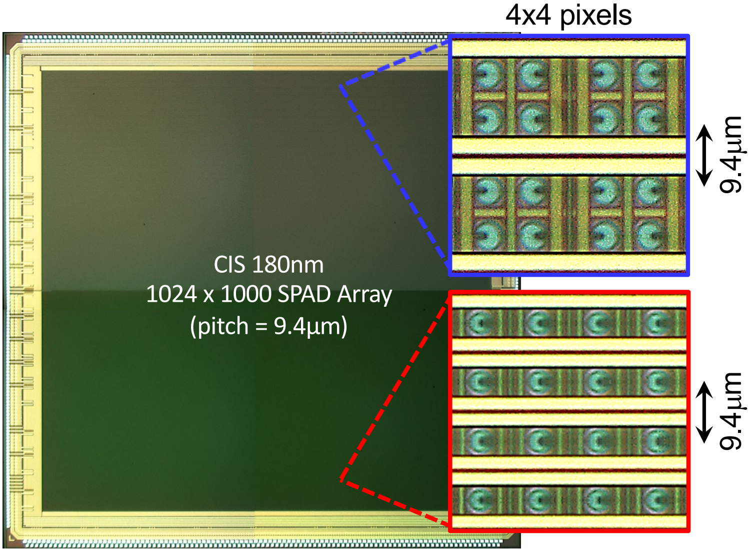


Advanced CMOS process should enable:
- low pitch
- high performance
- high fill factor

MegaX: the first SPAD megapixel camera

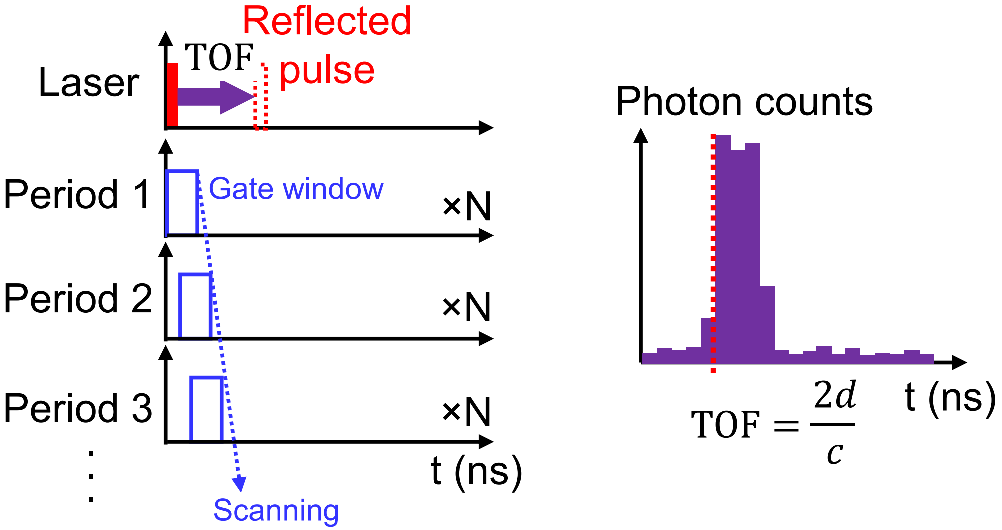
Features

- 1024 x 1000 pixels
- 9.4µm pitch
- 3.8ns gating
- 24,000 fps
- 24.5Gb/s
- VDD: 1.8V
- VBD: 24.7V



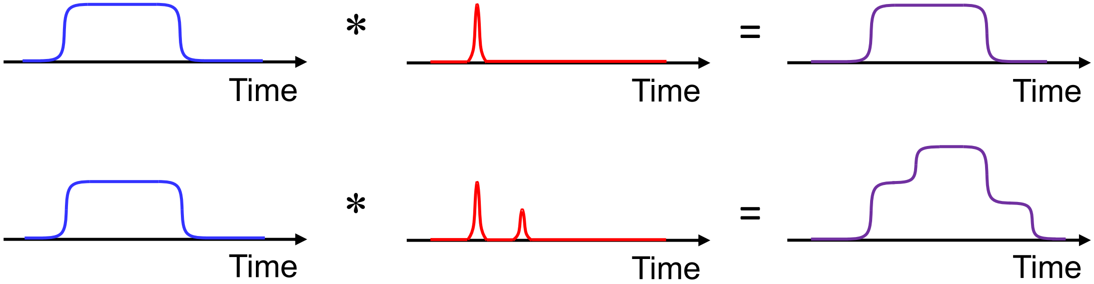
K. Morimoto et al., Optica 2020

To keep pixels small: time gating

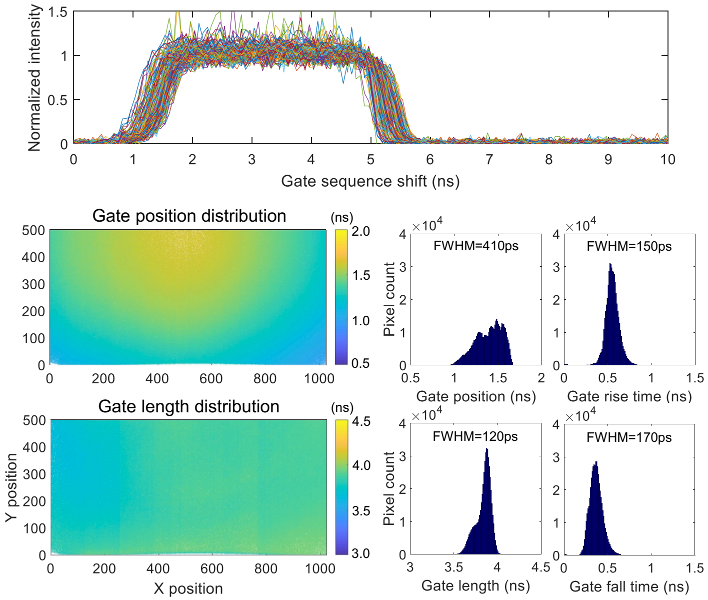


Multiple reflections

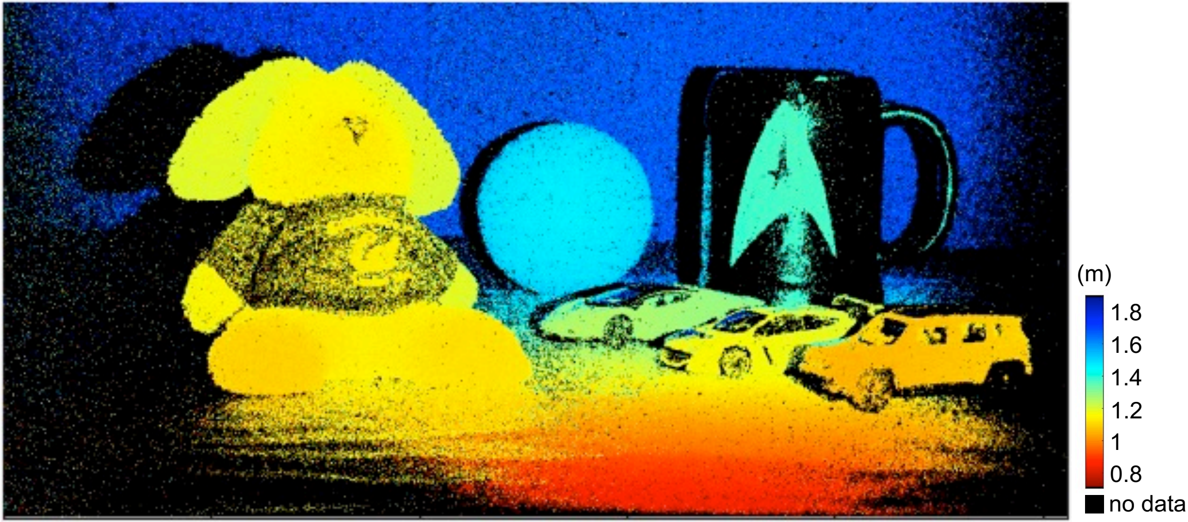
Gating window profile: $f(t)$ Photon distribution: $g(t)$ Detected intensity: $h(t)$



Time gating profile

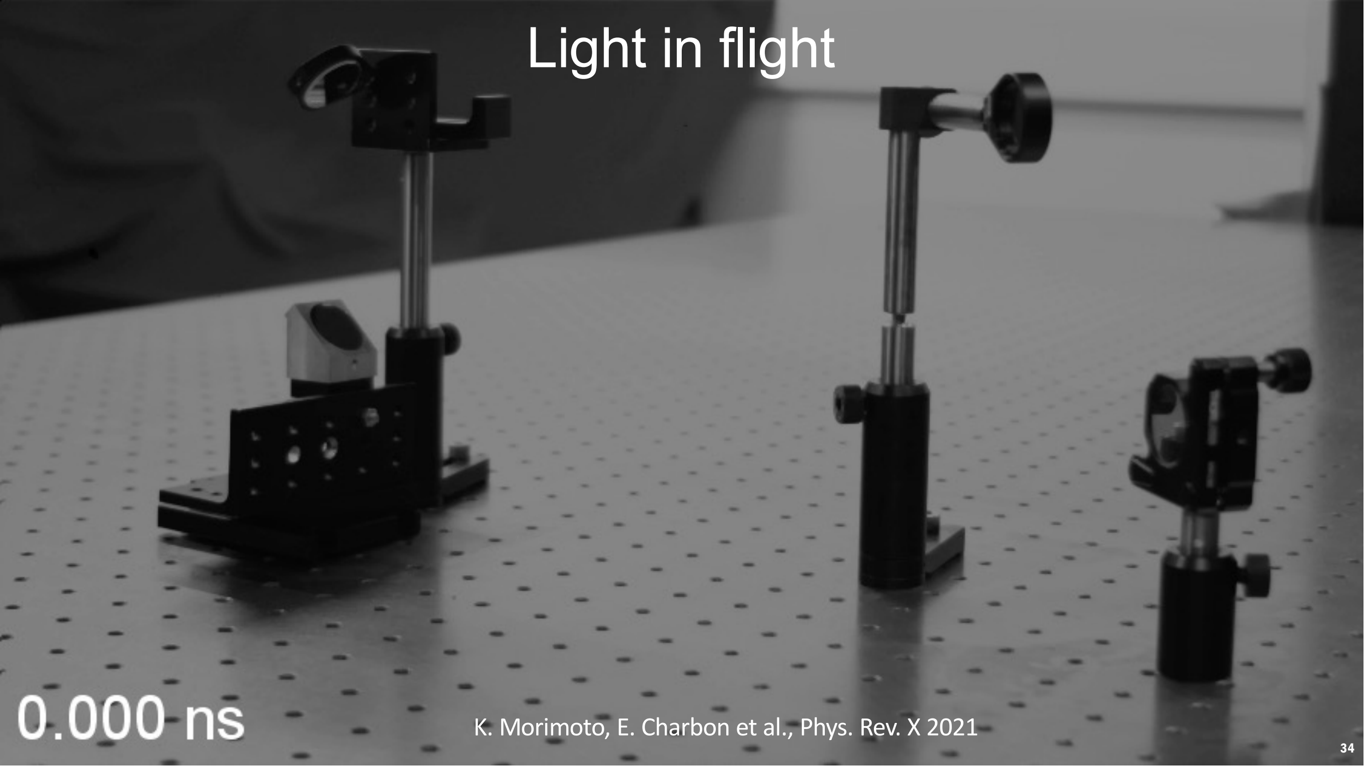


MegaX 2D/3D imaging



K. Morimoto et al., Optica 2020

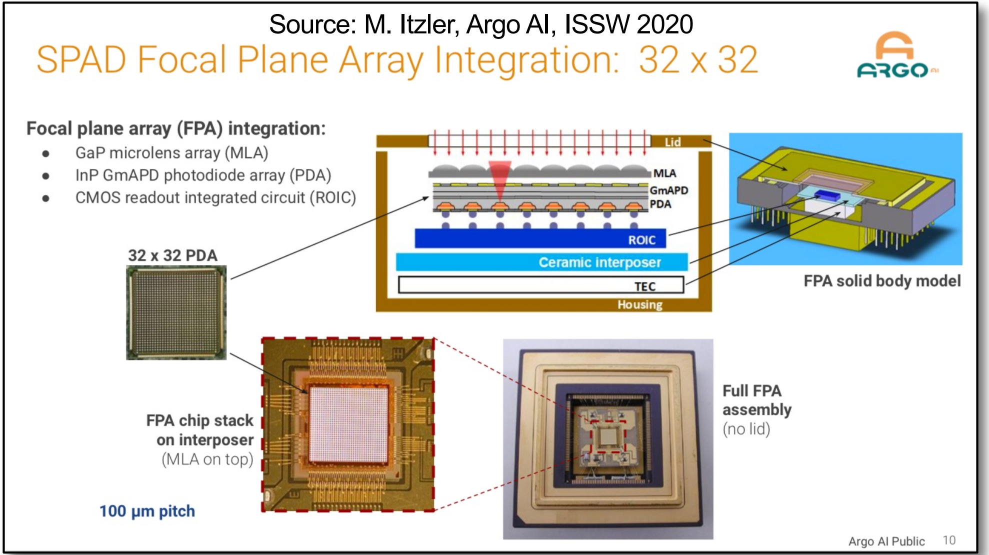
Light in flight

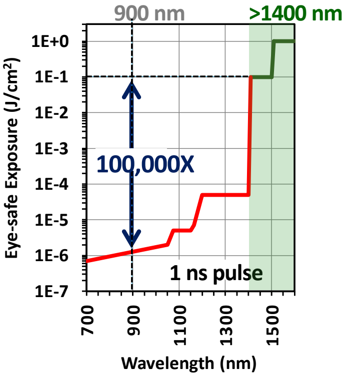


K. Morimoto, E. Charbon et al., Phys. Rev. X 2021

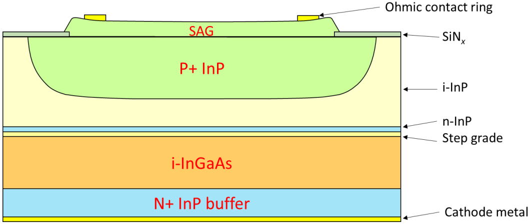
Trends

Hybrid 3D integration



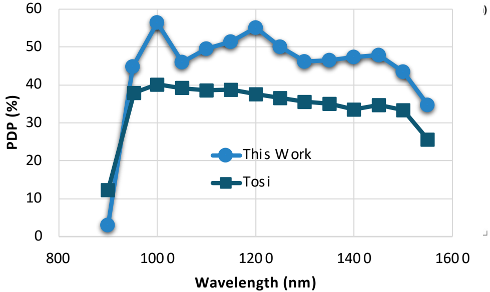


InGaAs-InP SPADs

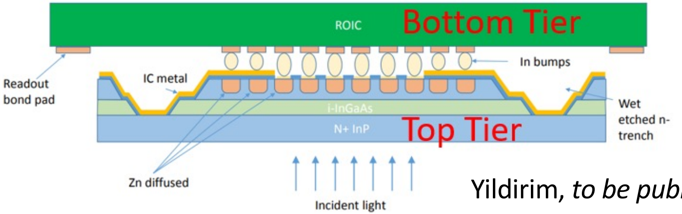


SAG = Selective area growth

Ekin Kizilkan et al., JSTQE, 2022

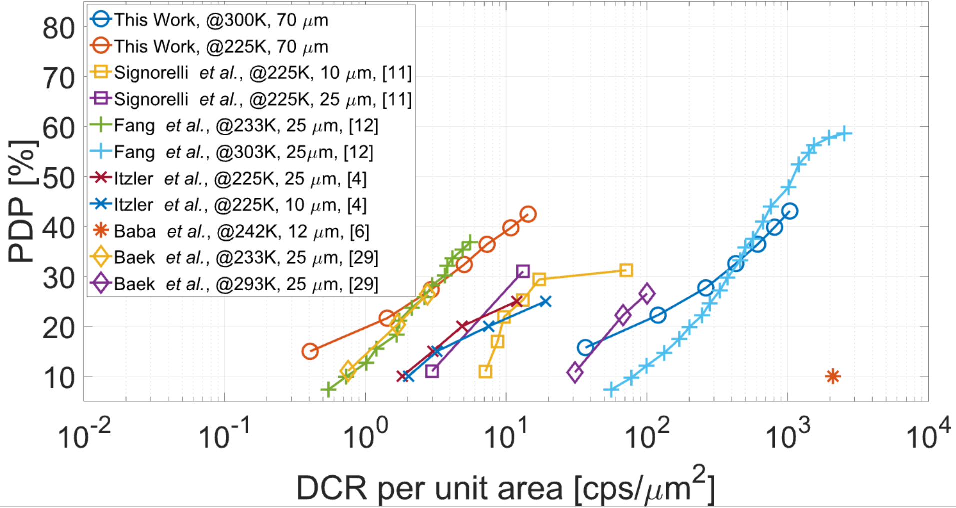


96 x 96 InGaAs SPAD pixel array

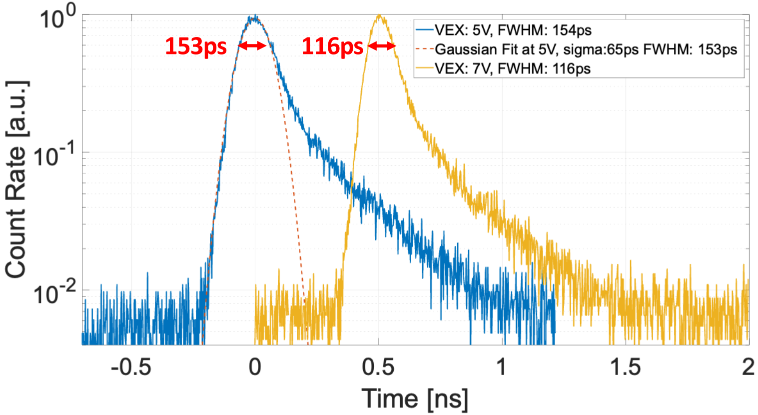


Yildirim, *to be published*, 2024

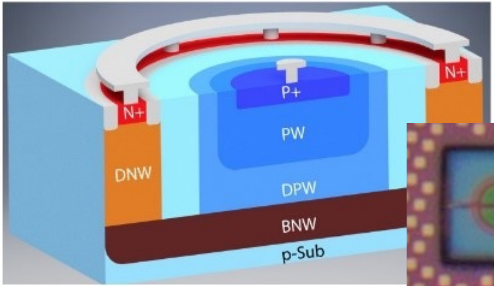
InGaAs-InP sensitivity vs. noise

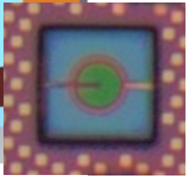


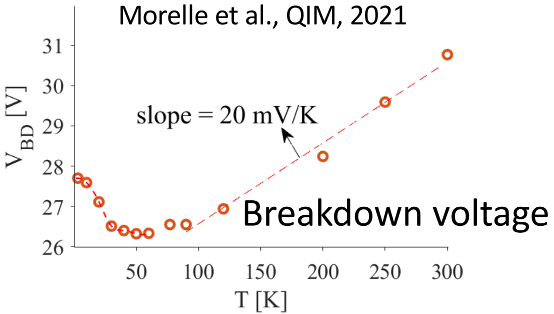
InGaAs-InP jitter

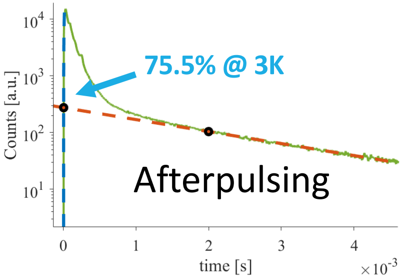


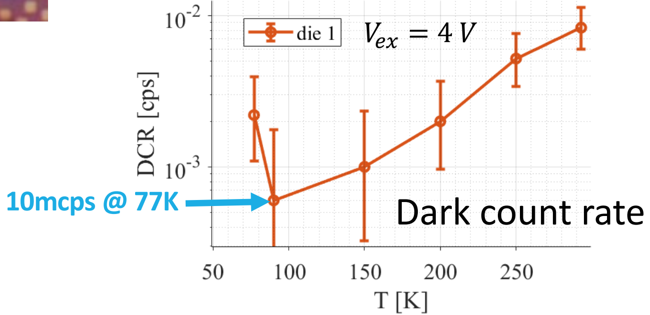
Deep-cryogenic 55-nm BSD SPAD/SiPM



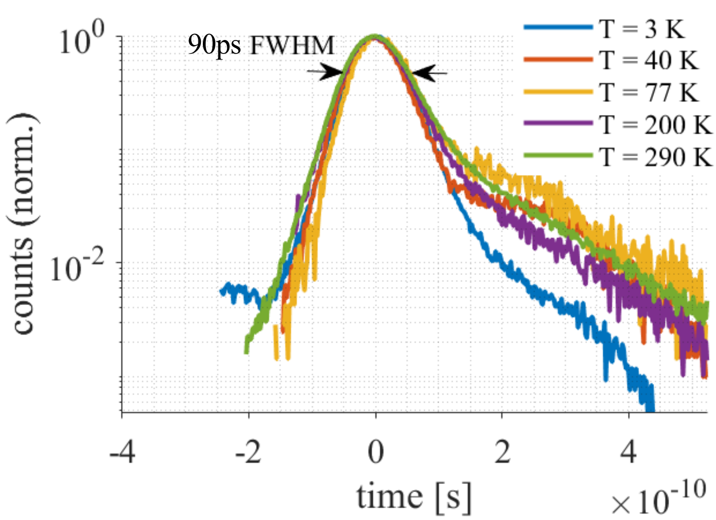


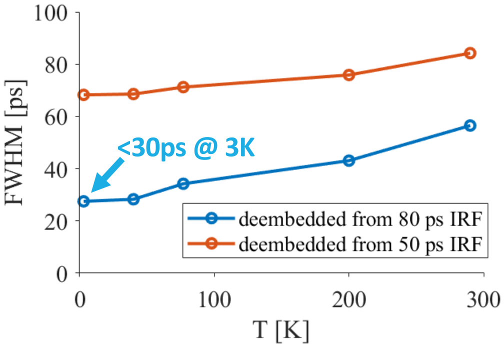






Deep-cryogenic 55-nm BSD SPAD/SiPM

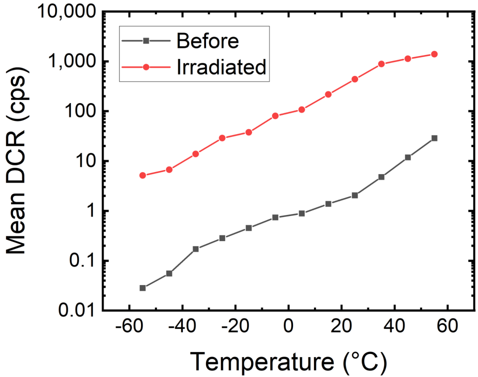


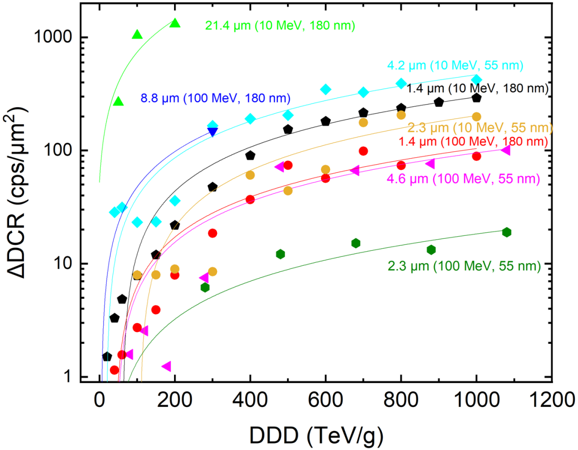


Morelle et al., QIM, 2022

Radiation testing of SPADs

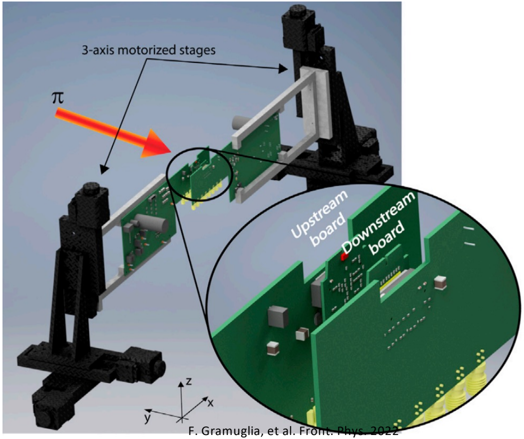
- Proton irradiation with variable fluencies
- 10/100MeV energy
- Different sizes, active areas, temperature

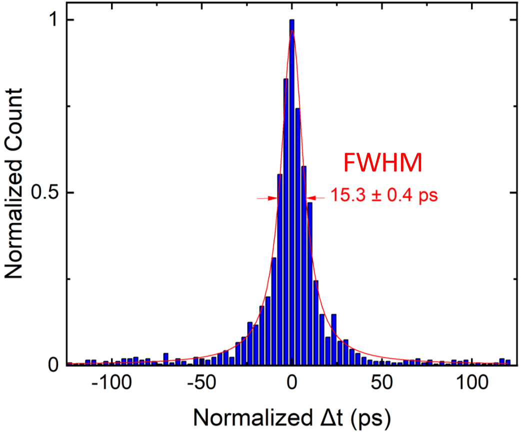




Wu, EPFL Thesis, 2023
Wu et al., EUROCON 2023

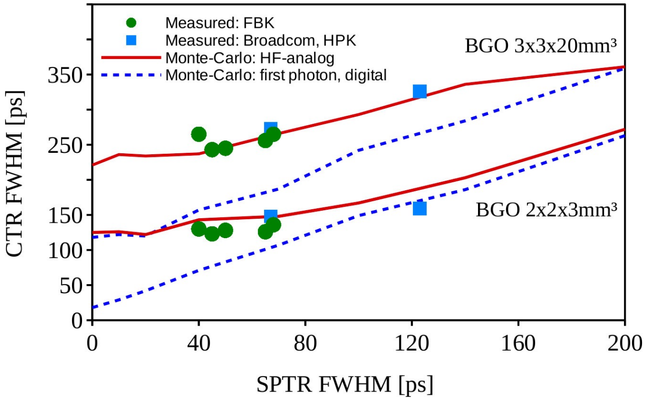
Direct MIP detection

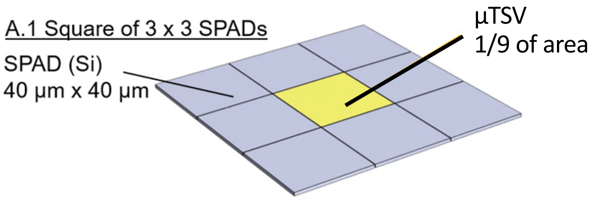




Detectors	**Resolution$_{best}$ (ps)**	**Time walk**	**Efficiency**	
PicoAD	σ = 17.3	yes	>99%	G. Iacobucci et al. 2022
UFSD	σ = 16[a]	yes	>99%	N. Cartiglia et al. 2017
TIMESPOT	σ = 11.5	yes	~99%	A. Lampis et al. 2023
This work	σ = 6.5	no	>99%	M.-L. Wu et al. 2023

The DIGILOG project: high-granularity SiPMs





- µSiPMs with µTSVs
- µASICs with *in situ* TDCs
- Embedded ANNs
- **Distributed computing**

S. Gundacker, et al., E. Charbon, V. Schultz *NSS* 2023
S. Gundacker, et al., *to be published* 2023

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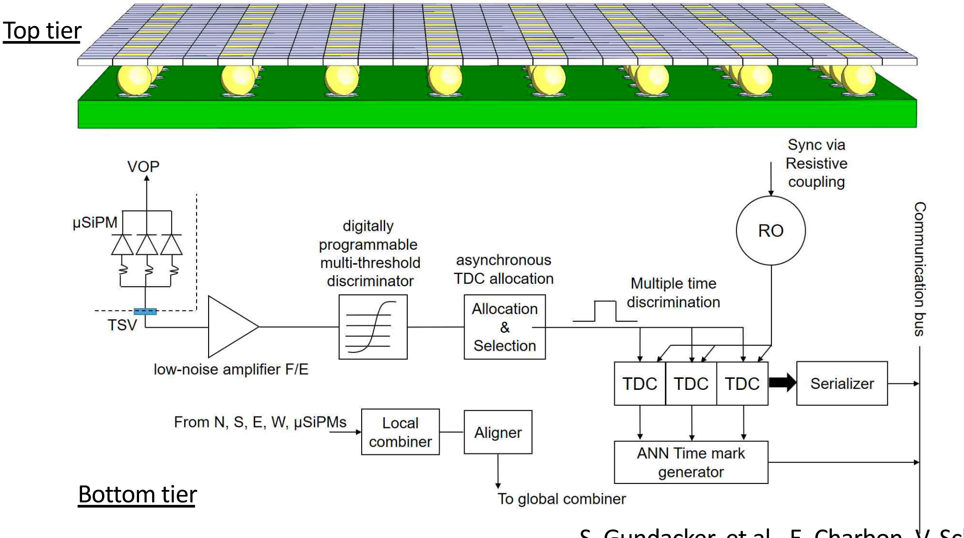
The DIGILOG project: high-granularity SiPMs (2)



S. Gundacker, et al., E. Charbon, V. Schultz *NSS* 2023
S. Gundacker, et al., *to be published* 2023

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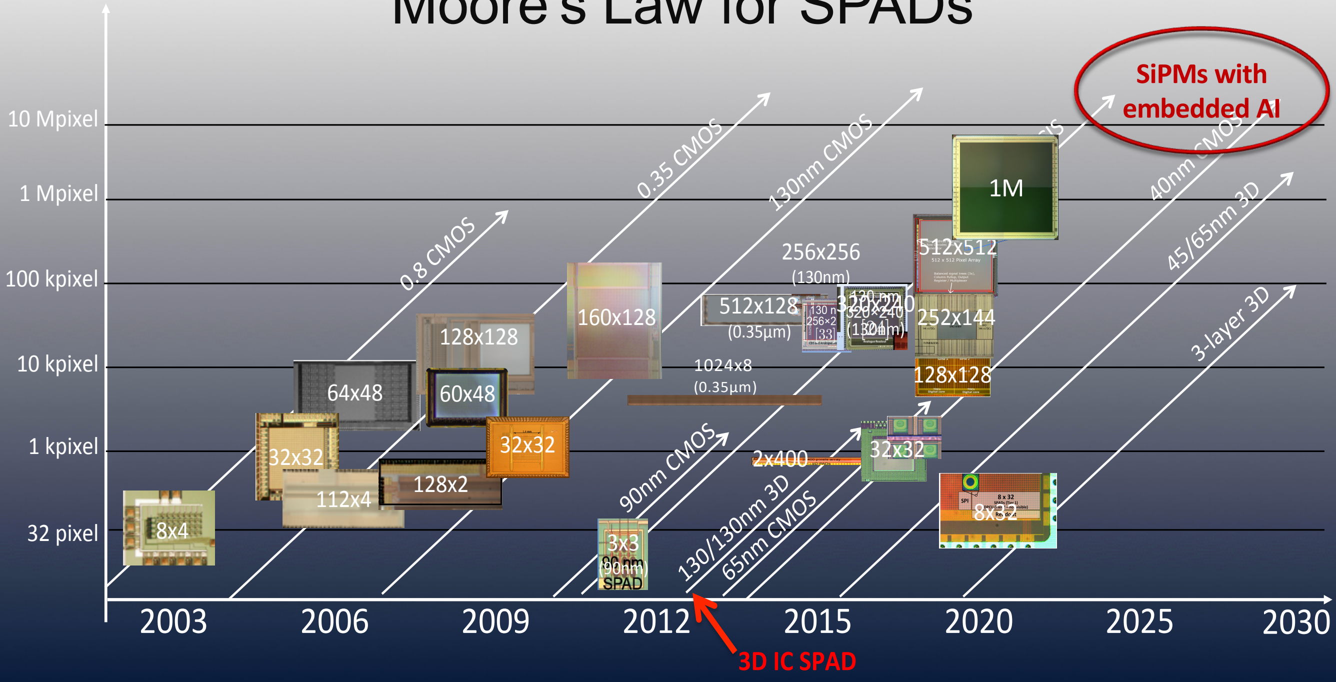
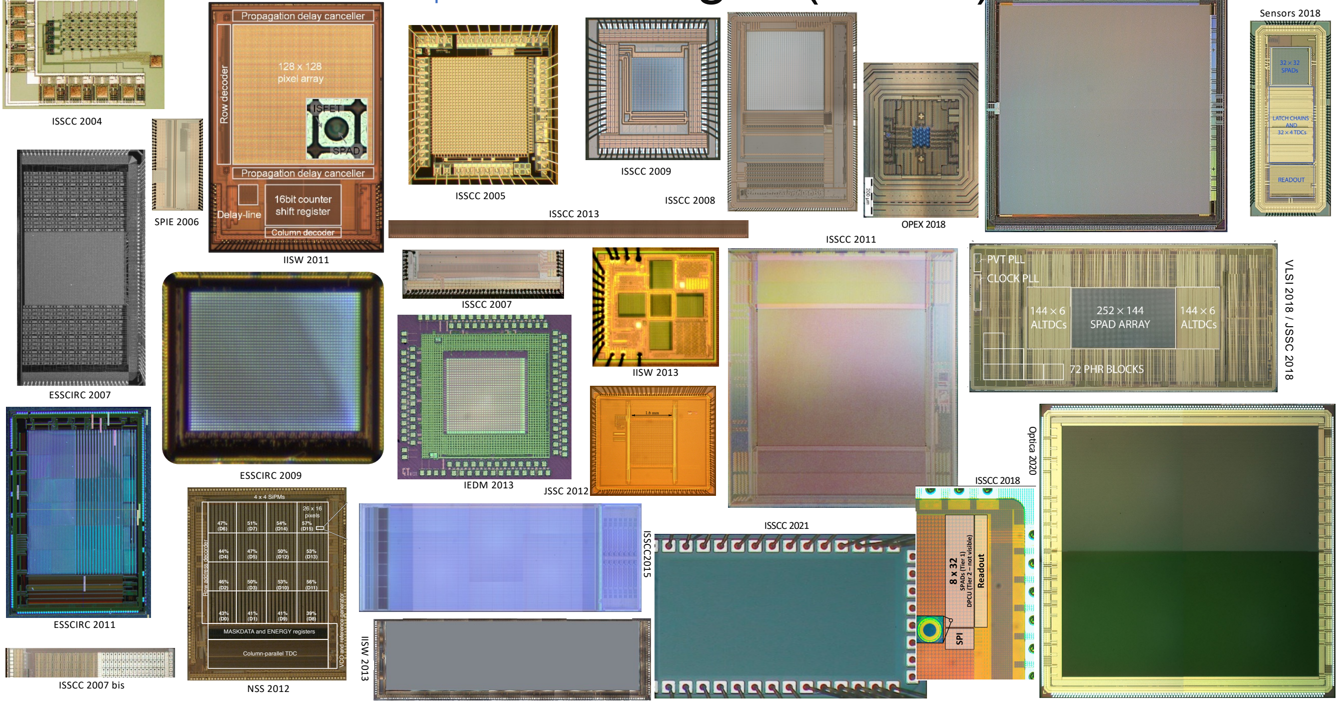
Conclusions

Moore's Law for SPADs



aqualab designs (2004–)



ISSCC 2004, SPIE 2006, IISW 2011, ISSCC 2005, ISSCC 2009, ISSCC 2008, OPEX 2018, JSTQE 2019, Sensors 2018, ISSCC 2013, ESSCIRC 2007, ISSCC 2007, IISW 2013, ISSCC 2011, VLSI 2018 / JSSC 2018, ESSCIRC 2009, IEDM 2013, JSSC 2012, Optica 2020, ESSCIRC 2011, ISSCC2015, ISSCC 2018, ISSCC 2021, IISW 2013, NSS 2012, ISSCC 2007 bis

Quantum imaging

- Quantum LiDAR
- Ghost imaging
- Quantum (ultra-fast) spectroscopy
- Quantum Raman spectroscopy
- Quantum distillation
- Quantum state tomography
- Quantum holography
- Quantum super-resolution
- Quantum plenoptic cameras
- Quanta burst photography

Take-home messages

- SPAD has emerged as the technology of choice for PET and many other applications, including quantum imaging
- Several technologies, custom and CMOS or CIS have been used to build SiPMs with low noise and high PDE
- 3D-stacking could multiply the impact of these detectors with parallelism and machine learning in the forefront

Thank You

http://aqua.epfl.ch

1st User Group Meeting, Les Diablerets, 2022
Next UGM: April 2024