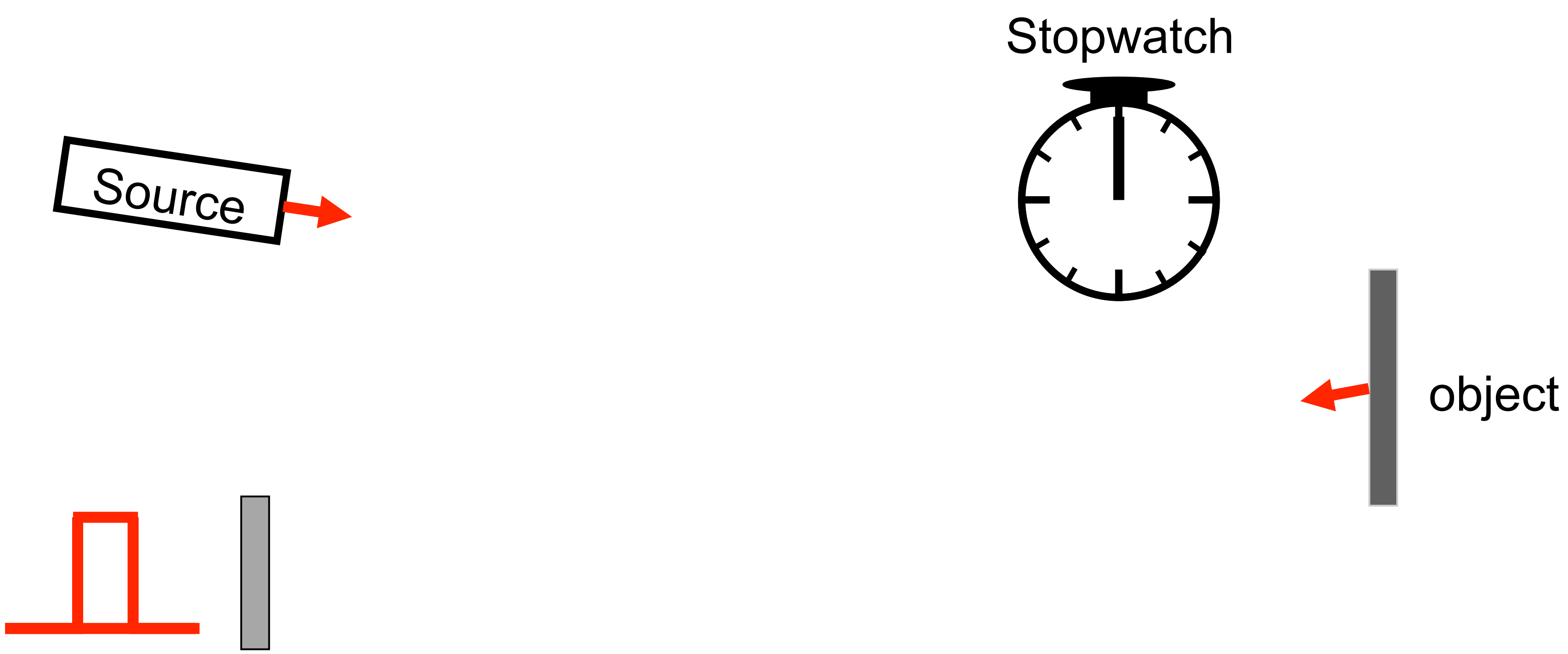
Time-of-Flight Approaches to SPAD and SiPM Imaging

E. Charbon

TU Delft

iToF Workshop

Time-of-Flight



Source: Alexis Rochas

Short burst or pulse of light; distance $d = \dfrac{c \cdot t_{TOF}}{2}$

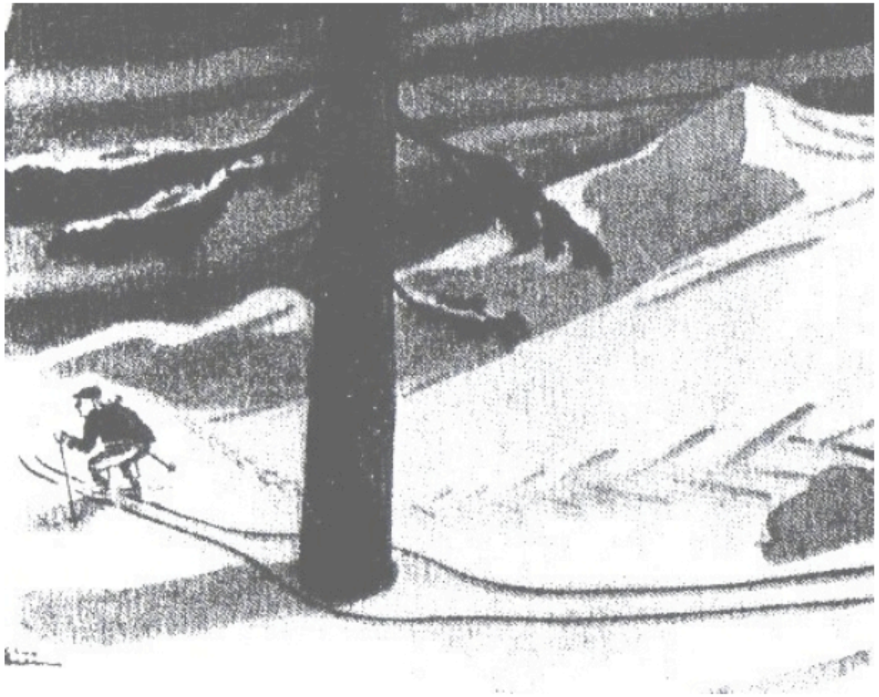
How short of a burst?

How about a single photon?

Single Photons

- Photons are indeed the smallest unit of energy defining light

… but they are strange particles or, better, quantum paths



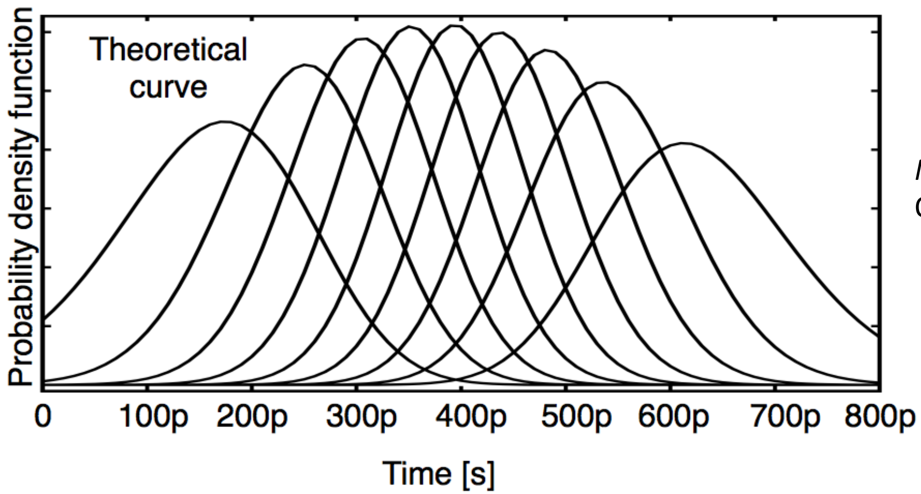
Source: Neil J. Gunther

Photons in a Laser Pulse Are <u>not</u> i.i.d.: Order Statistics

$$f_{k:n}(t) = n\binom{n-1}{k-1} f(t) F(t)^{k-1} (1 - F(t))^{n-k}$$

$f_{k:n}(t)$: k-th order statistics
$f(t)$: probability density function
$F(t)$: cumulative density function

<u>Assumptions:</u>
- Each photon is stat. independent
- The pulse has a Gaussian p.d.f.



Mandai, Charbon,
Optics Letters **39**(3), 552-554 (2014)

Photon Counting in TOF Makes Sense!

- Single-photon detection can result in better statistics

… but multiple single photons must be detected

- Photon time-of-arrival must be accurate to the picosecond (timestamping)
- For imaging many simultaneous photon detections are needed

Single-Photon Detectors

- Electron multiplication in vacuum
  - Photomultiplier tube (PMT)
  - Microchannel plate (MCP)
- CMOS APS
  - Amplifying pixel
- Electron multiplied charge-coupled device (EMCCD)
  - See lessons on CCD
- Avalanche photodiode (APD)
- Geiger-mode APD (GAPD) or Single-photon avalanche diode (SPAD)
- Silicon photomultiplier (SiPM)

Outline

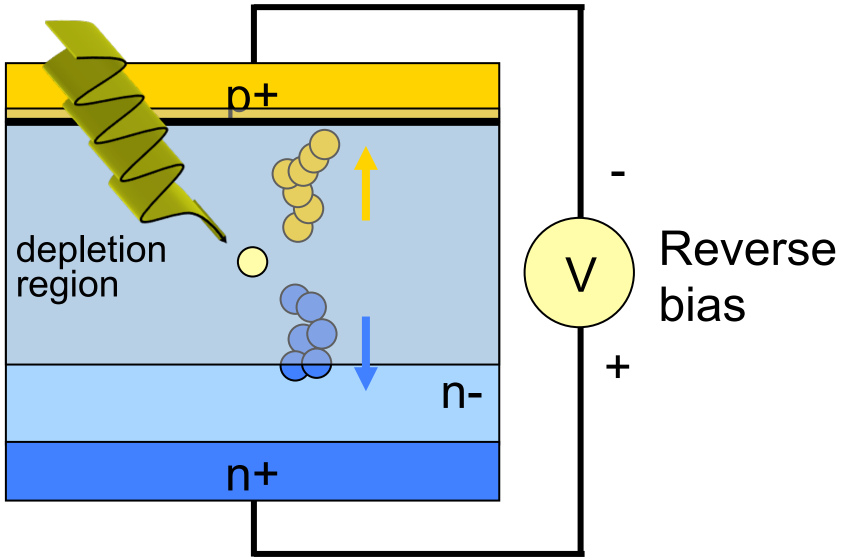
- Photon counting & single-photon detection
- SPAD image sensors for TOF
- The silicon photomultiplier
- TOF in medical imaging
- Current & future challenges

Photon Counting
&
Single-Photon Detection

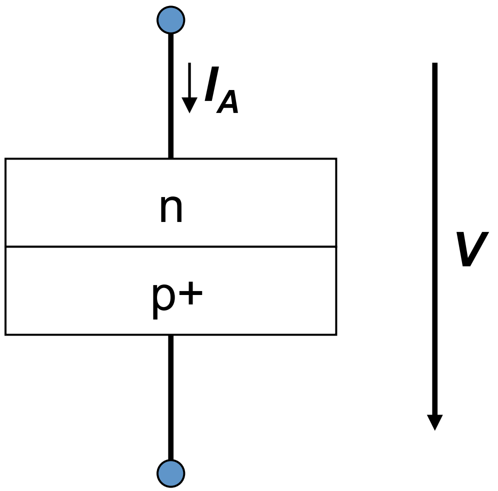
Avalanche Effect in Condensed Matter

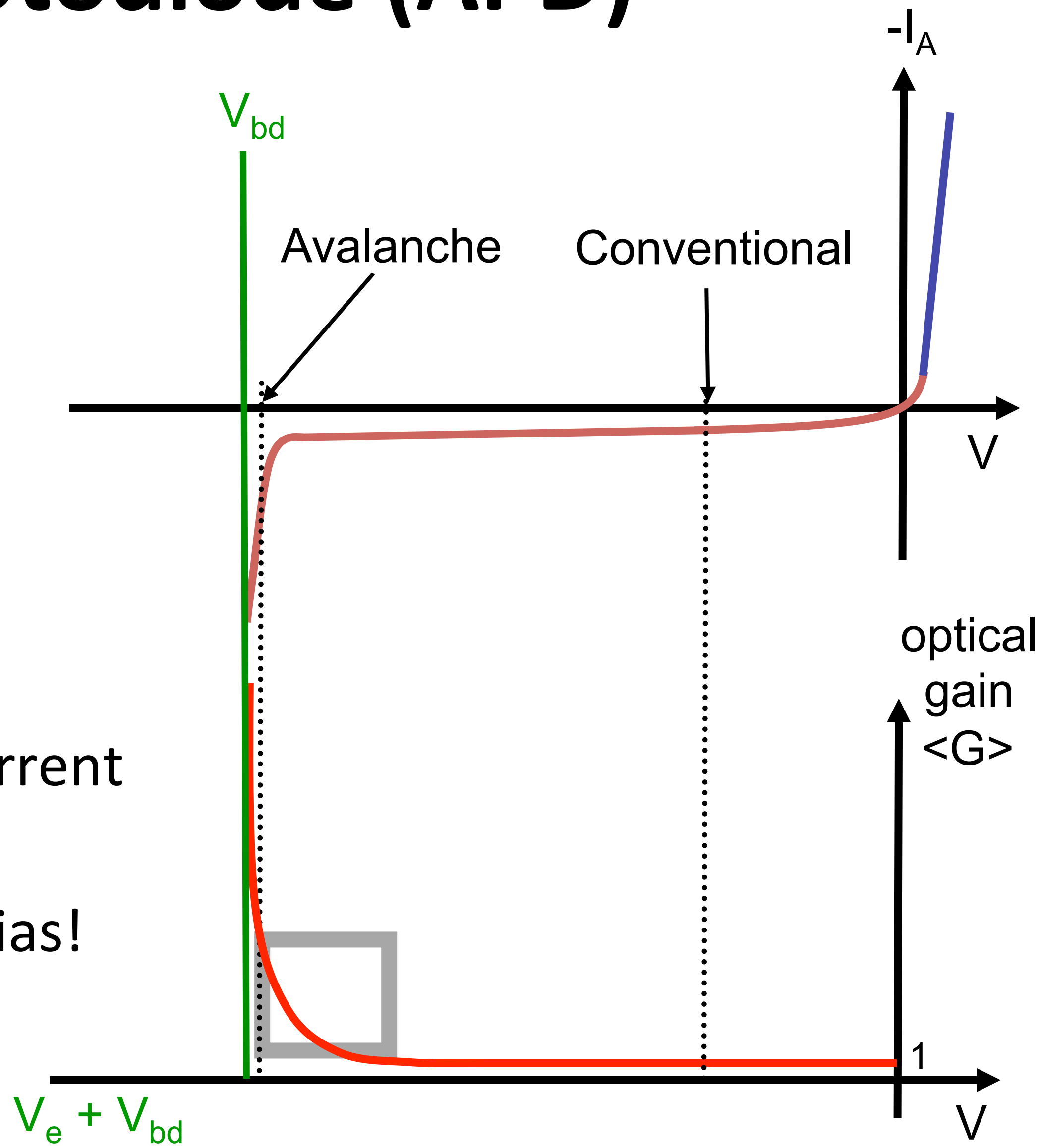
- Suppose one can perform *impact ionization* in a solid, thereby achieving *very large gain* in an area of a *few tens of μm^2* (thus at pixel level)

- This can be achieved in an abrupt one-sided junction



Avalanche Photodiode (APD)

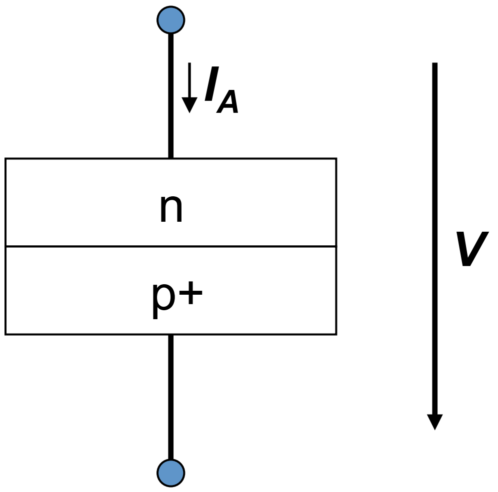


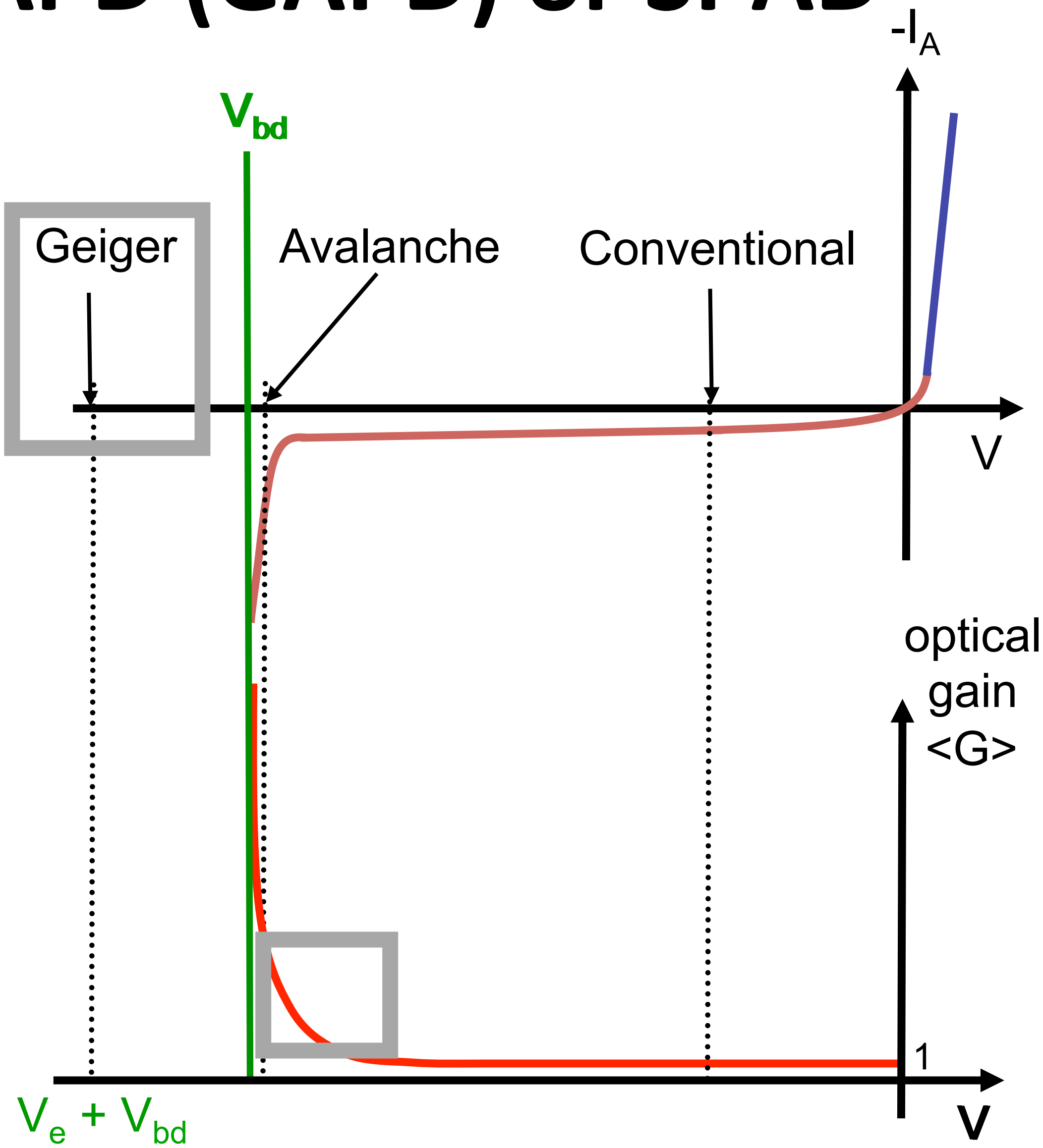


- One can achieve a current gain of 2-10,000…

but G varies exp. with bias!

Geiger-Mode APD (GAPD) or SPAD



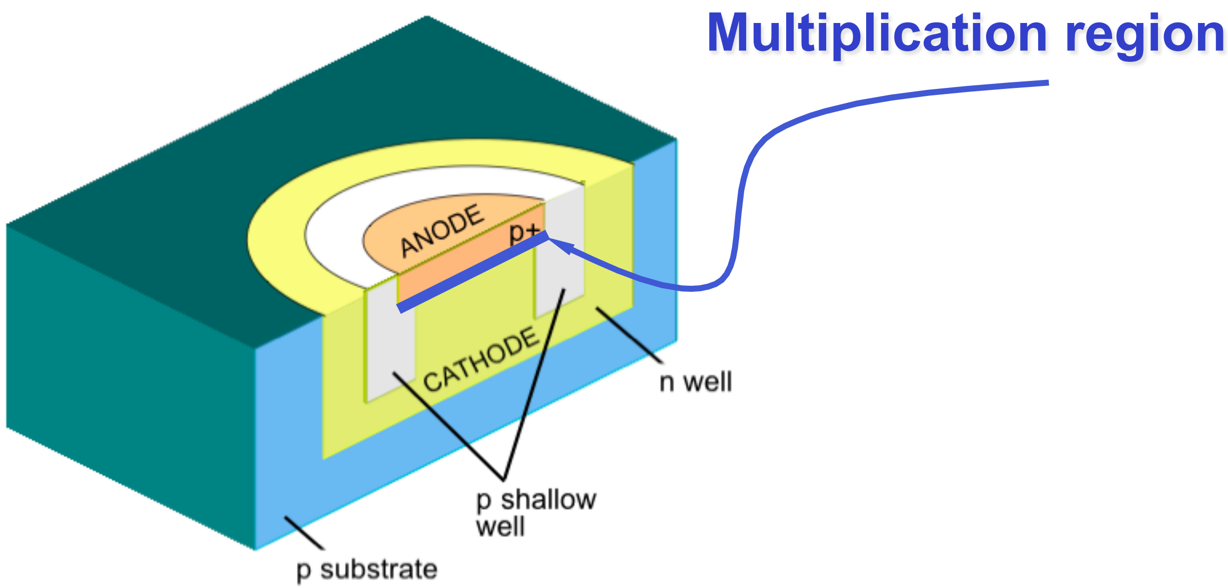


- One can achieve a virtually infinite gain biasing above breakdown…

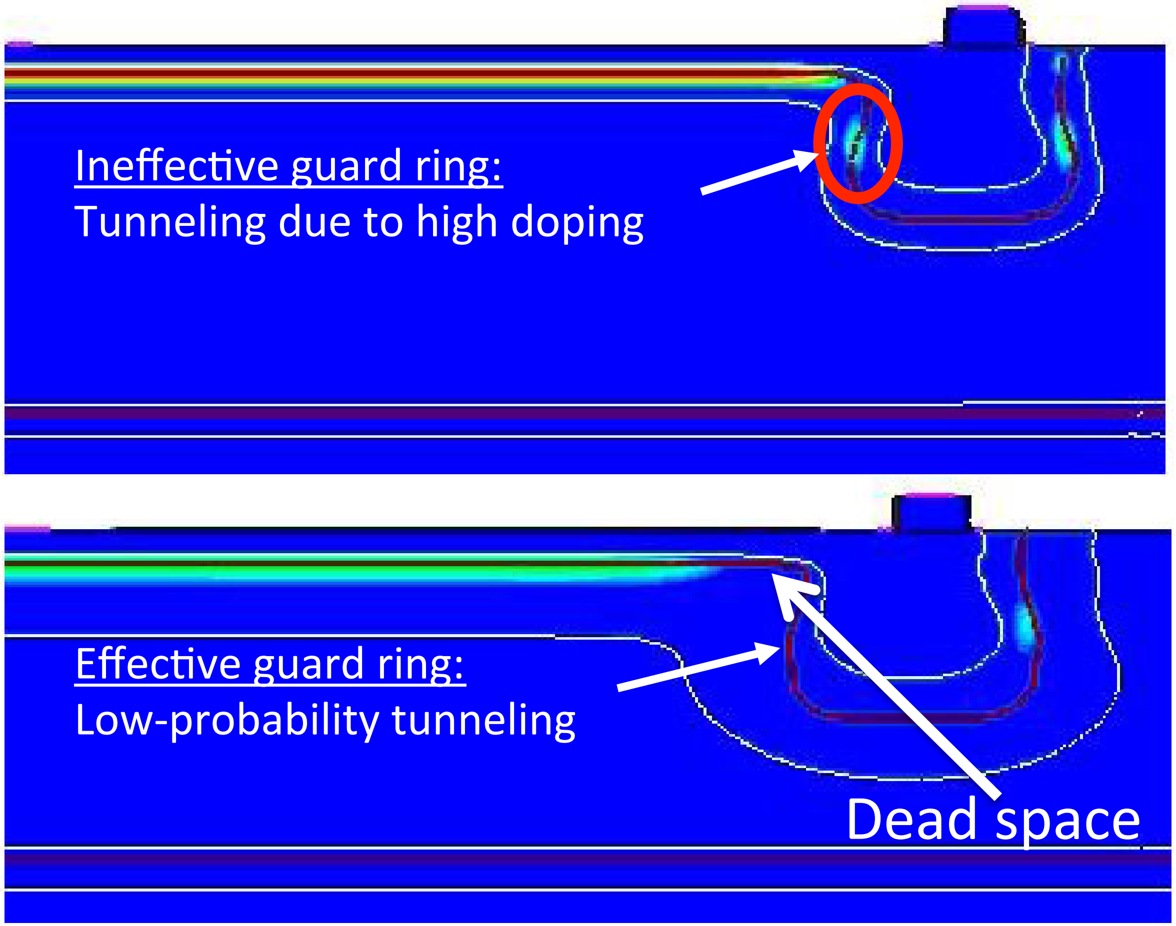
Thus gain variability is meaningless

CMOS SPAD

- Implemented entirely using standard layers and conventional process steps!
- Low breakdown voltage, low noise
- Guard rings: minimize edge breakdown, create a zone of constant electric field

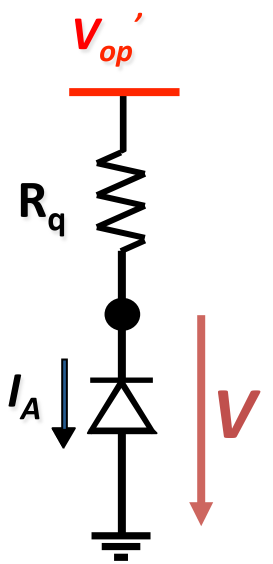


Minimizing Edge Breakdown

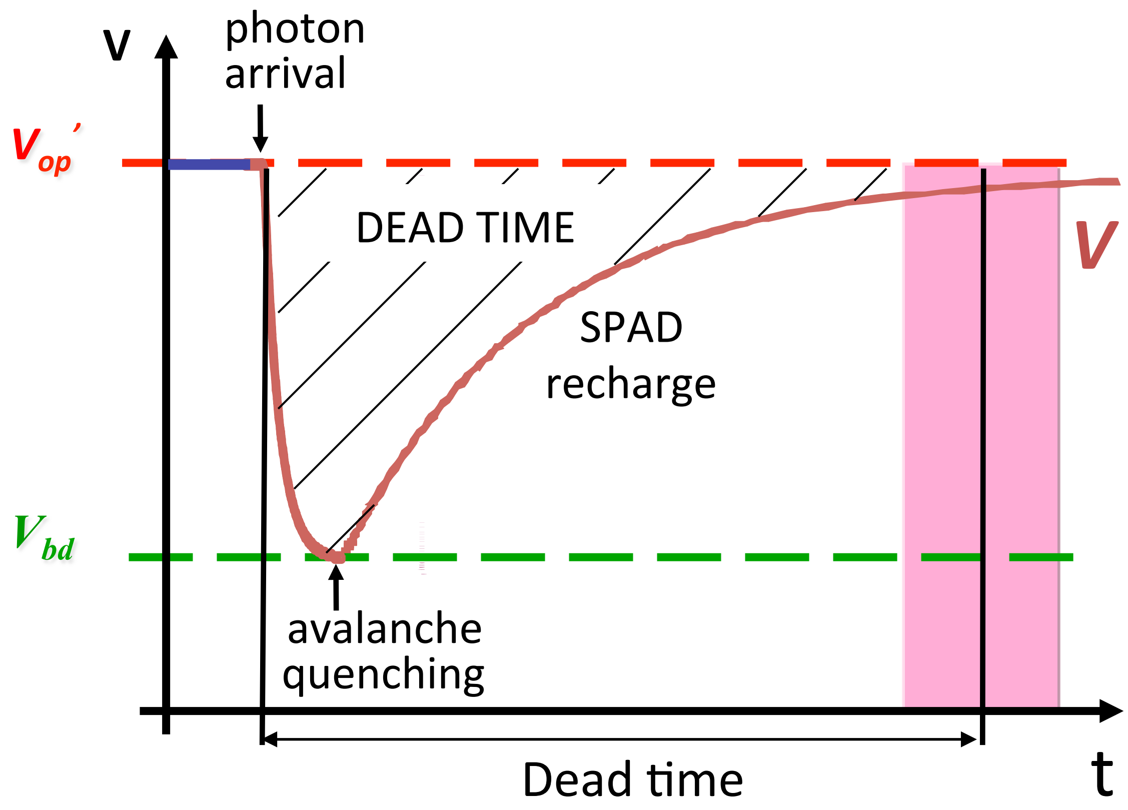


Quenching

Passive quenching:

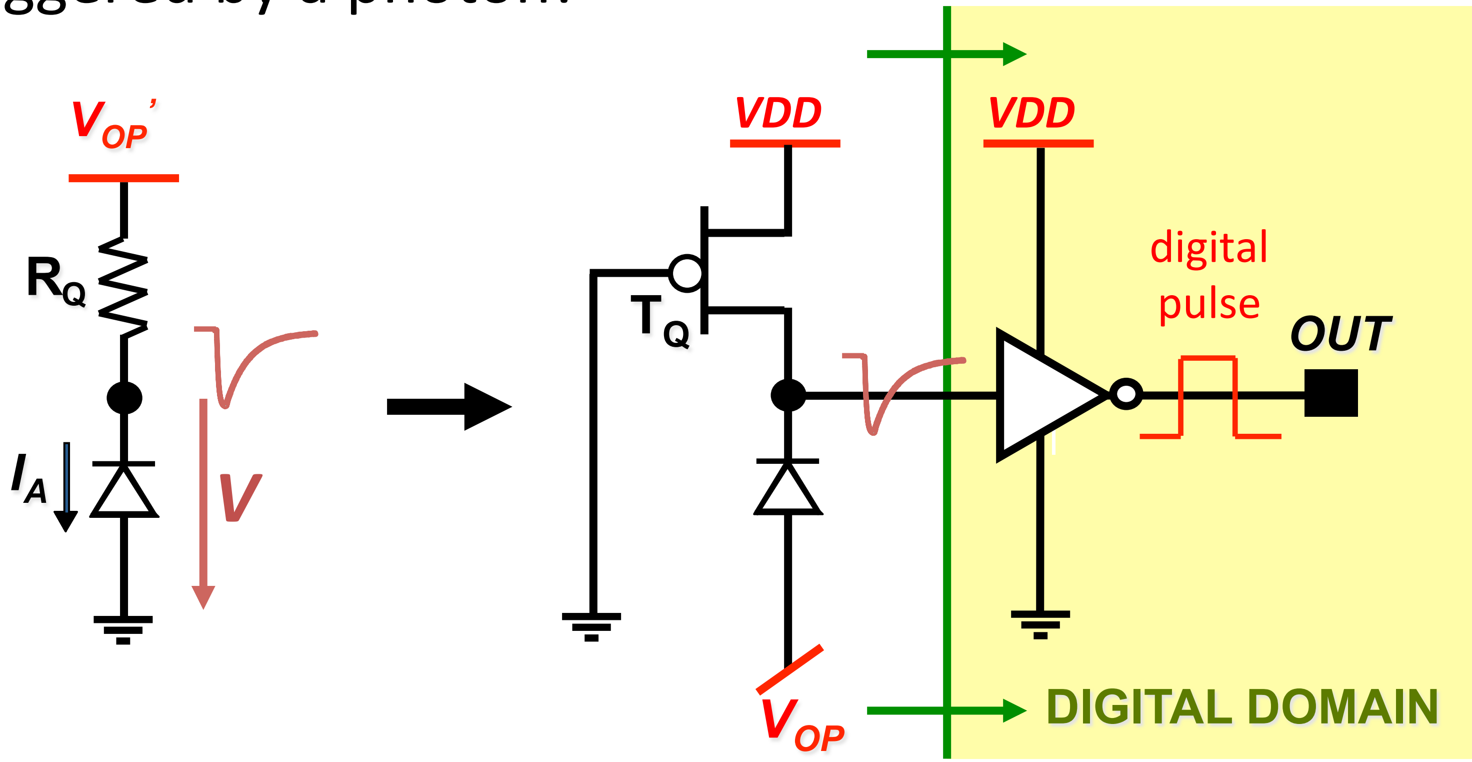


Operation cycle:



Quenching a SPAD in CMOS

- The SPAD becomes like any other digital device but it is triggered by a photon!



Passive quenching technique

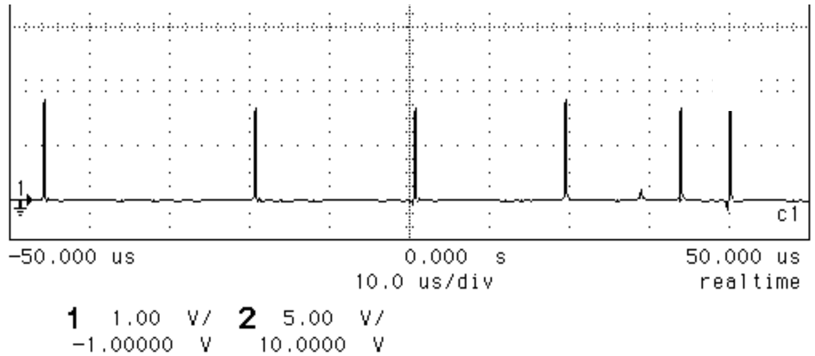
SPAD Non-Idealities

- *Dead time*
- Dark counts
- Photon detection efficiency (PDE)
- Timing resolution
- *Afterpulsing*

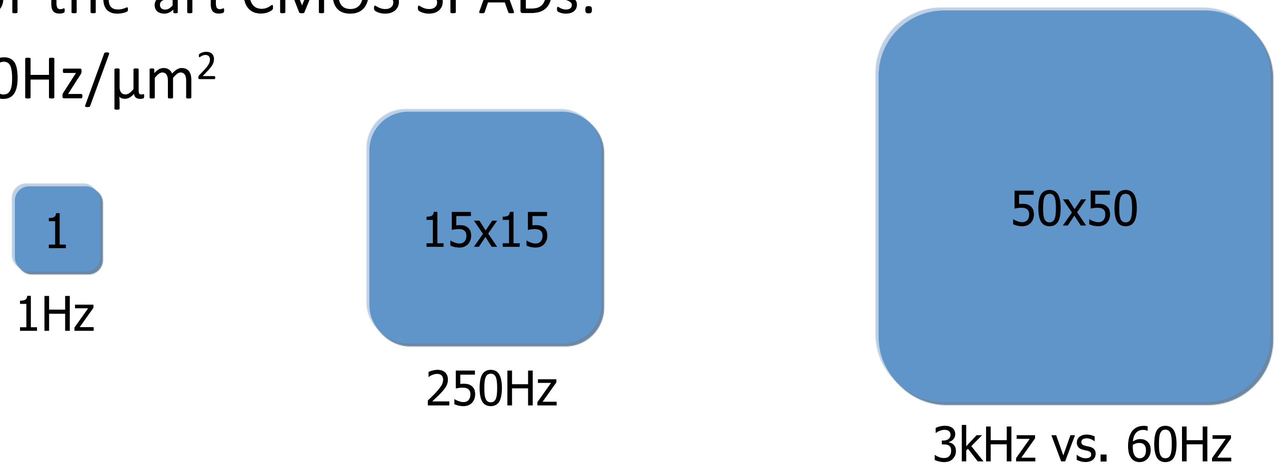
… and in SPAD matrices

- Cross-talk
- PDE Uniformity

Dark Counts: Dark Count Rate

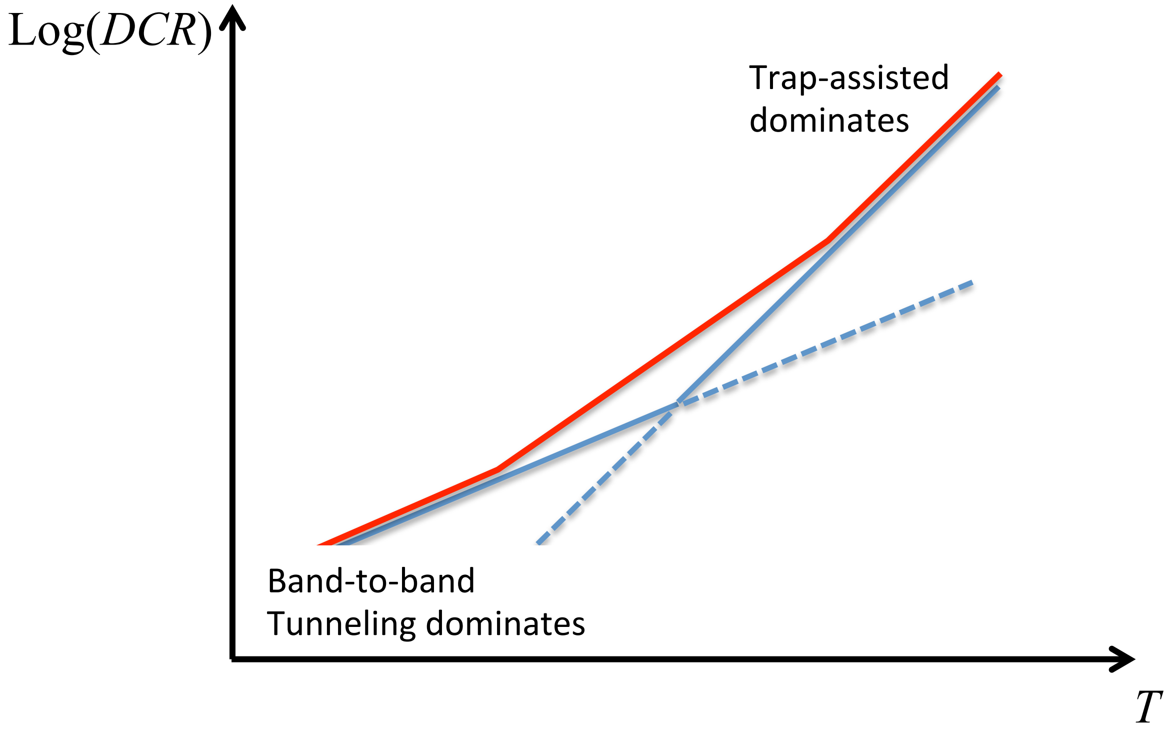


- State-of-the-art SPADs in dedicated technology:
  $0.02 \sim 1\text{Hz}/\mu\text{m}^2$
- State-of-the-art CMOS SPADs:
  $0.1 \sim 10\text{Hz}/\mu\text{m}^2$

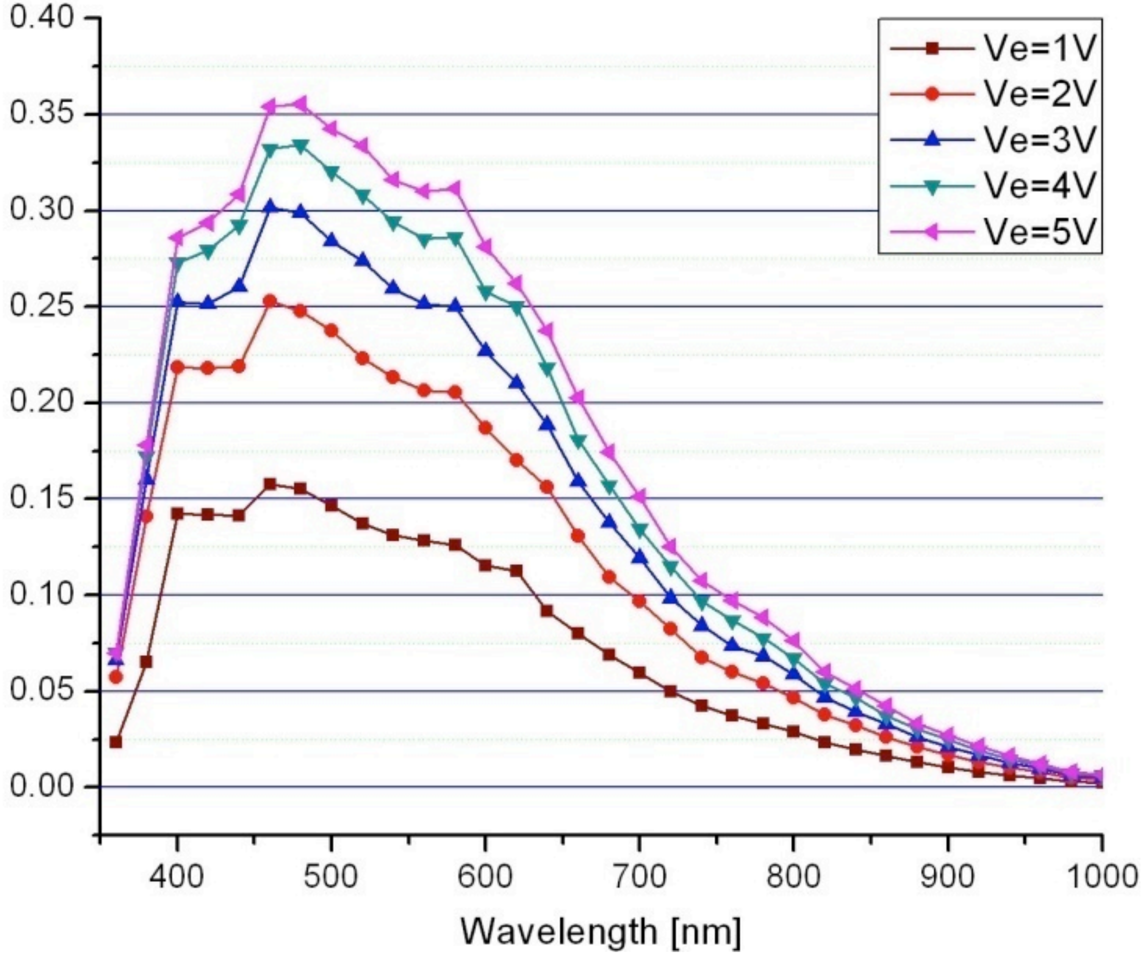


DCR Mechanisms

- Band-to-band tunneling generation
- Trap-assisted thermal generation
- Trap/tunneling assisted generation

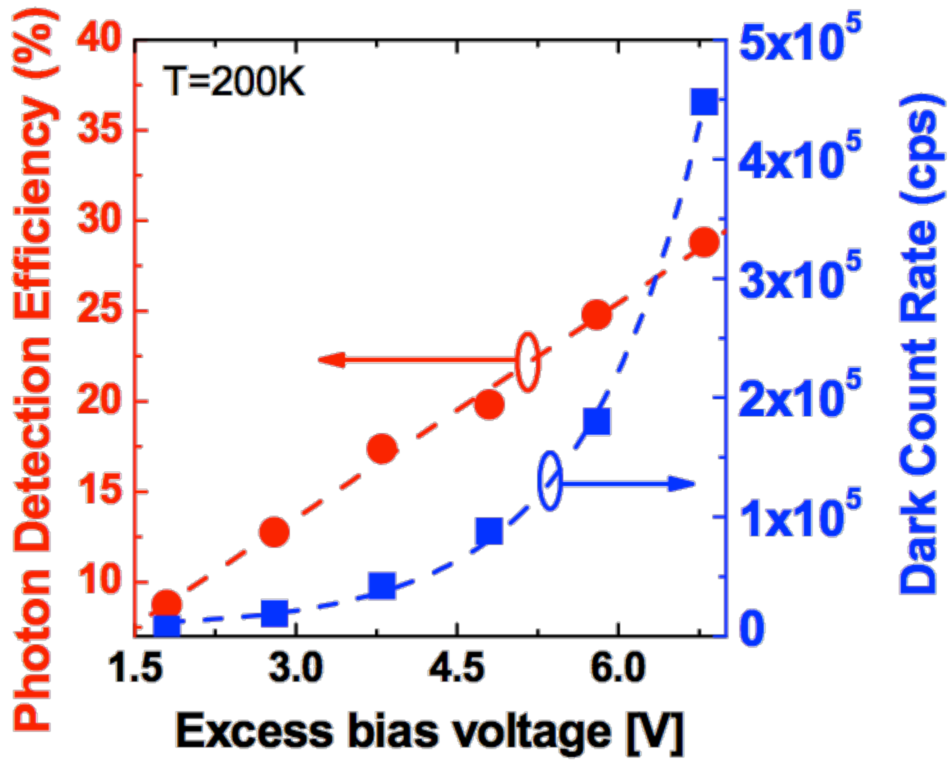


Photon Detection Efficiency



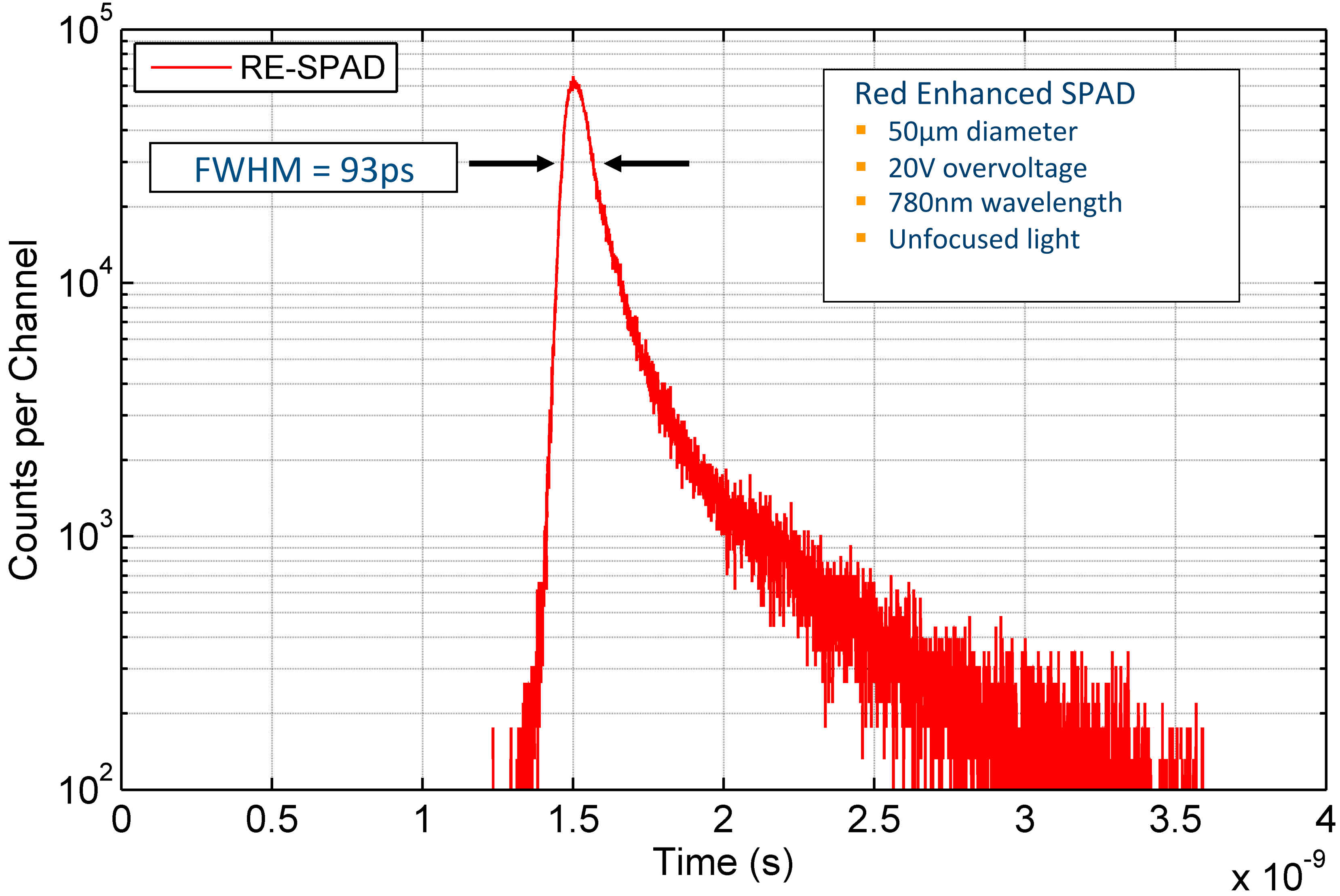
Gersbach, Charbon, *et al. SS Sensors* 2009

PDE vs. Excess Bias



Tosi *et al.*, 2009

Timing Resolution

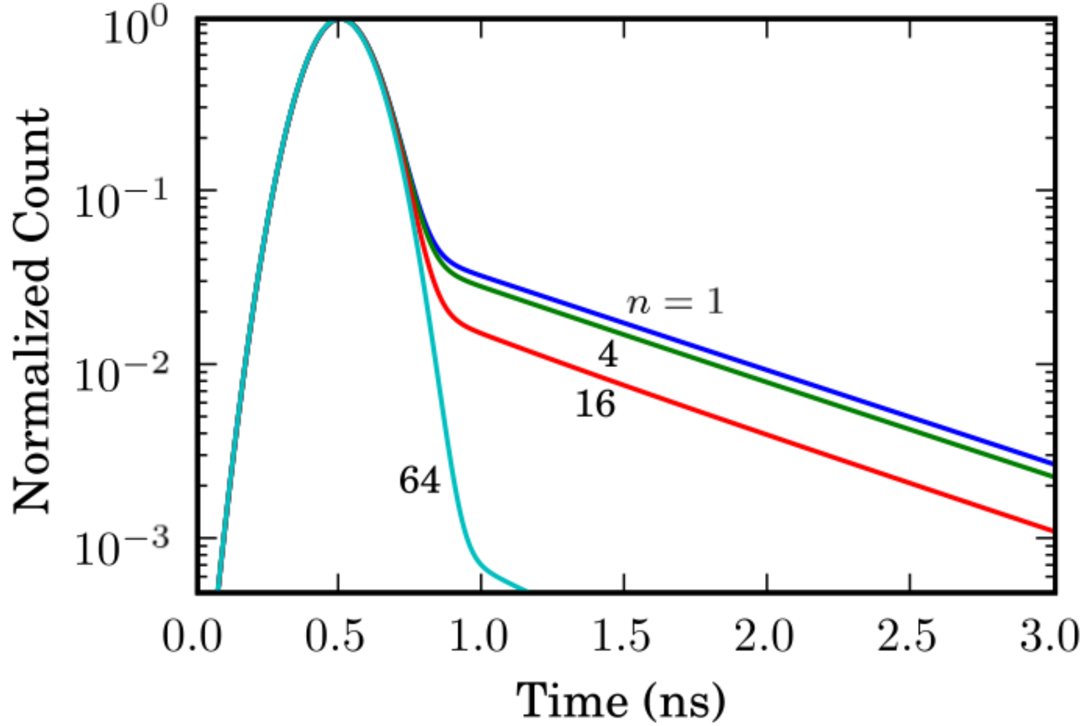


Courtesy: Sergio Cova

Timing Resolution vs. Wavelength

- The depth of interaction (and thus wavelength) determines the presence of a tail in the response
- The width of the multiplication region also determines the tail

Timing Resolution vs. # Photons



Fishburn, *Ph.D. Thesis*, Delft, 2012

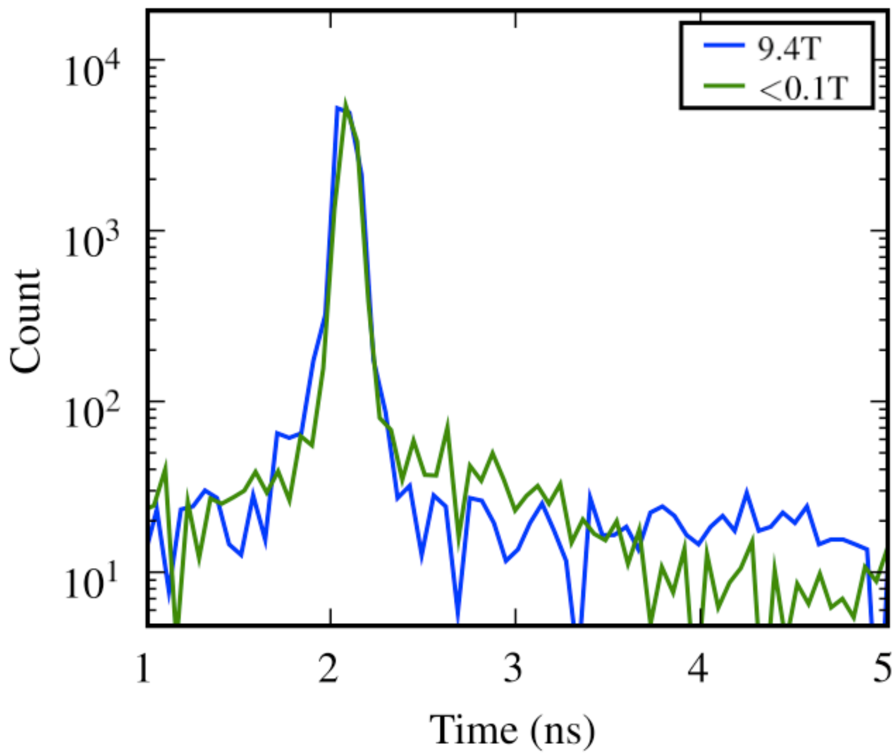
Timing Resolution vs. B-Fields

Time resolution in 9.4T

Delta FWHM < 10ps:

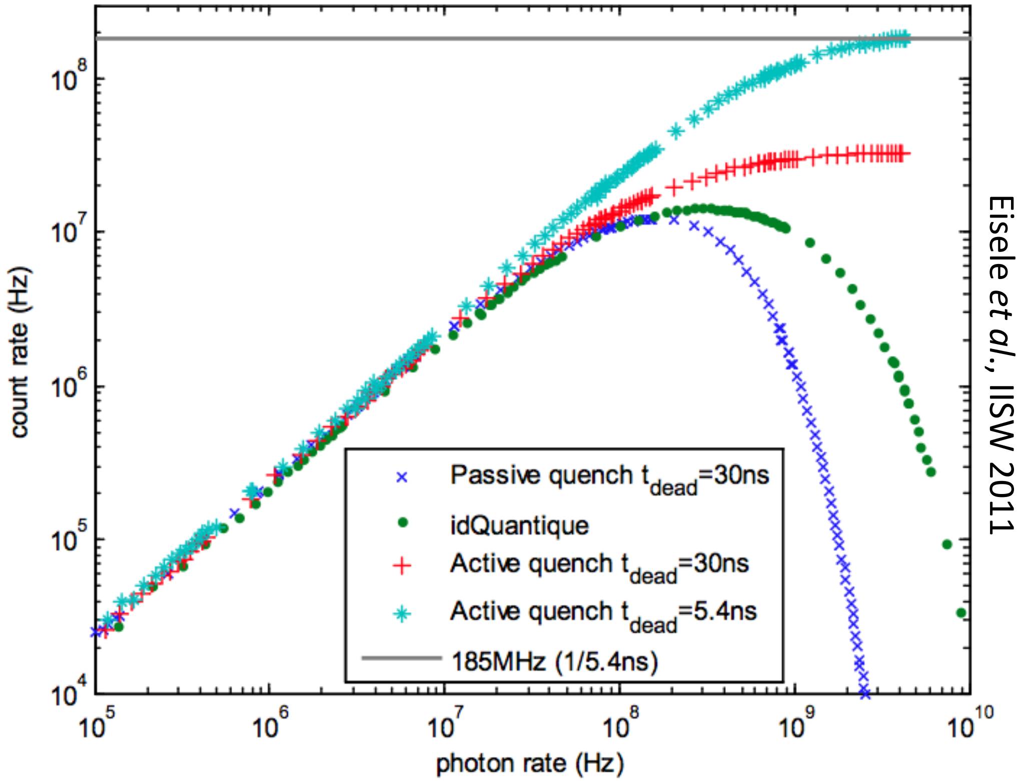
Test conditions:

- External laser source
- Internal TDC
- Integrated TDC



Fishburn and Charbon, *EEE Nuc. Sci Symp* (NSS), *2011*

Active vs. Passive Recharge



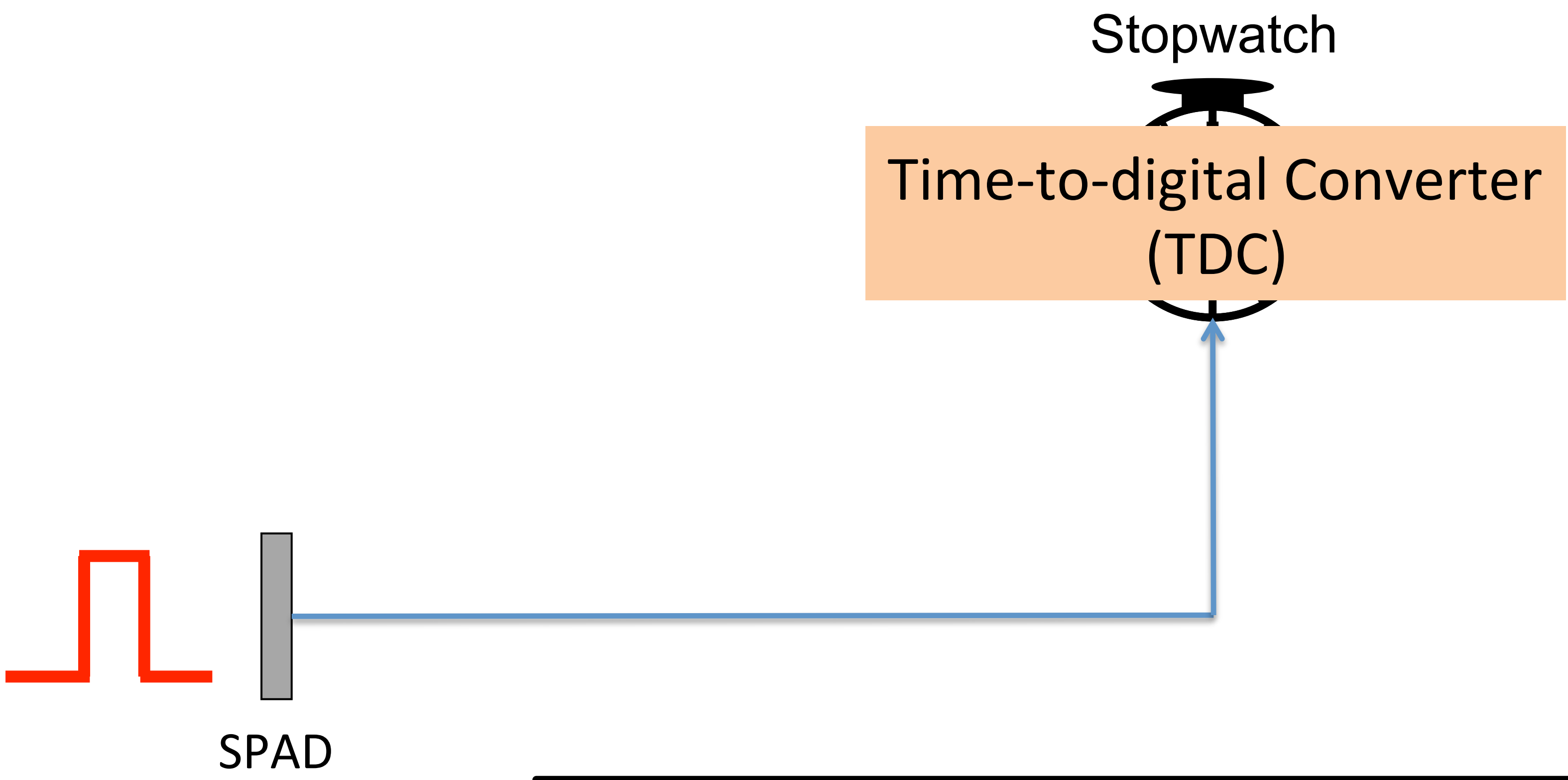
Eisele *et al.*, IISW 2011

$$f_{MAX} \cong \frac{1}{t_{DEAD}} \quad \text{for active quenching}$$

$$f_{MAX} \cong \frac{1/e}{t_{DEAD}} \quad \text{for passive quenching}$$

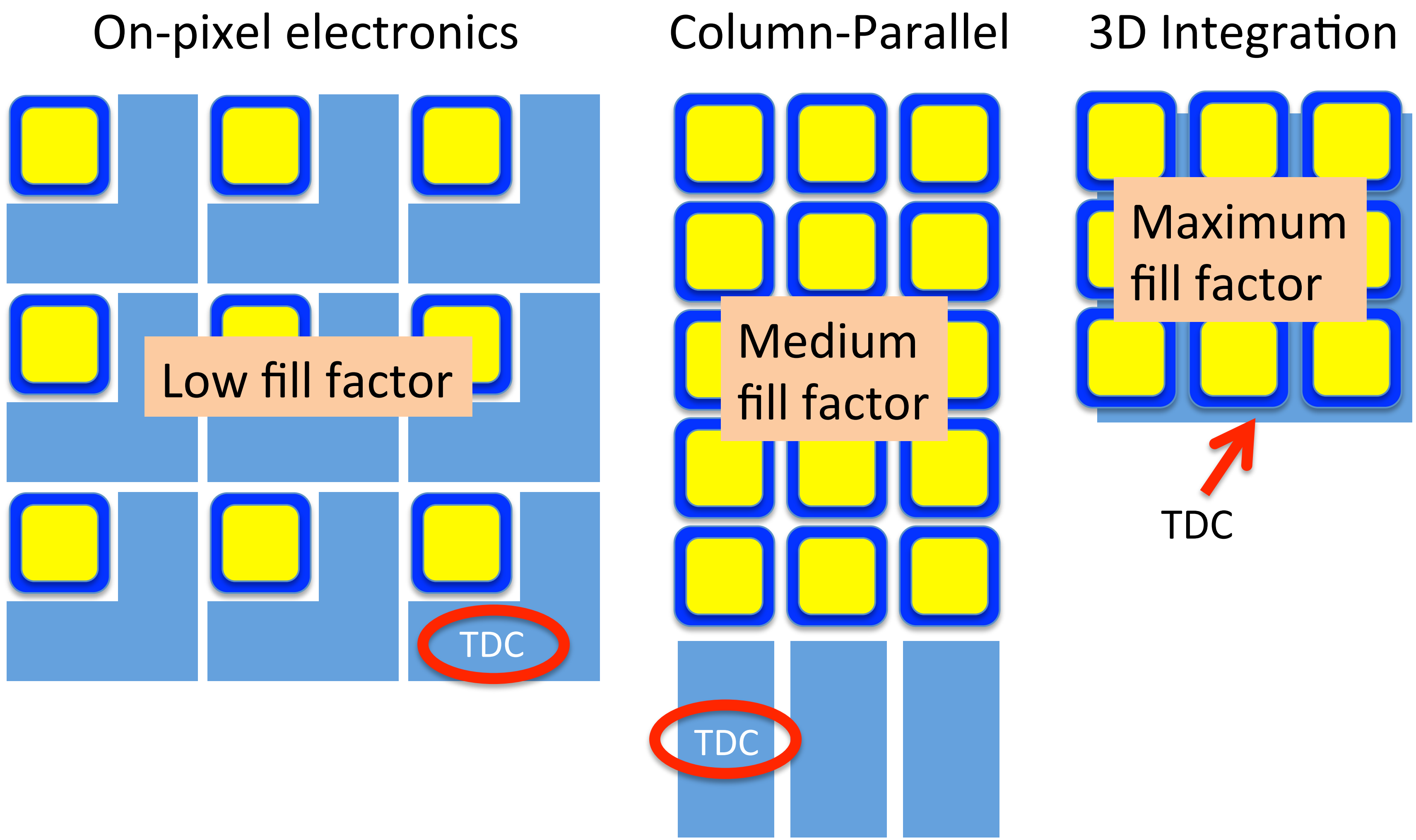
SPAD Image Sensors for TOF

Direct Method for Measuring TOF

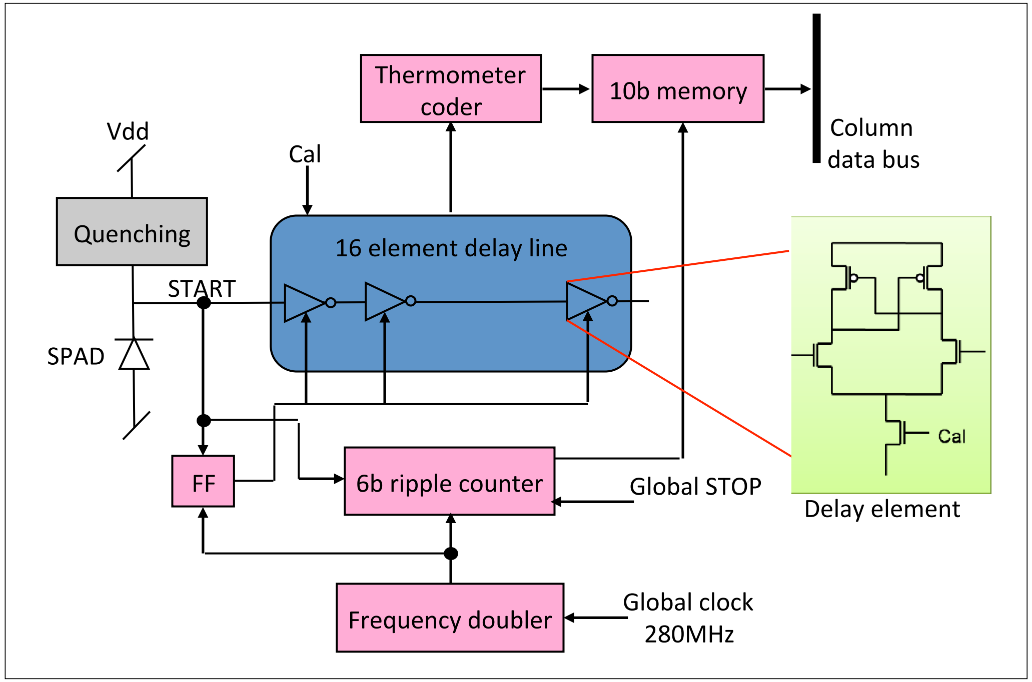


Time-correlated Single-Photon Counting
(TCSPC)

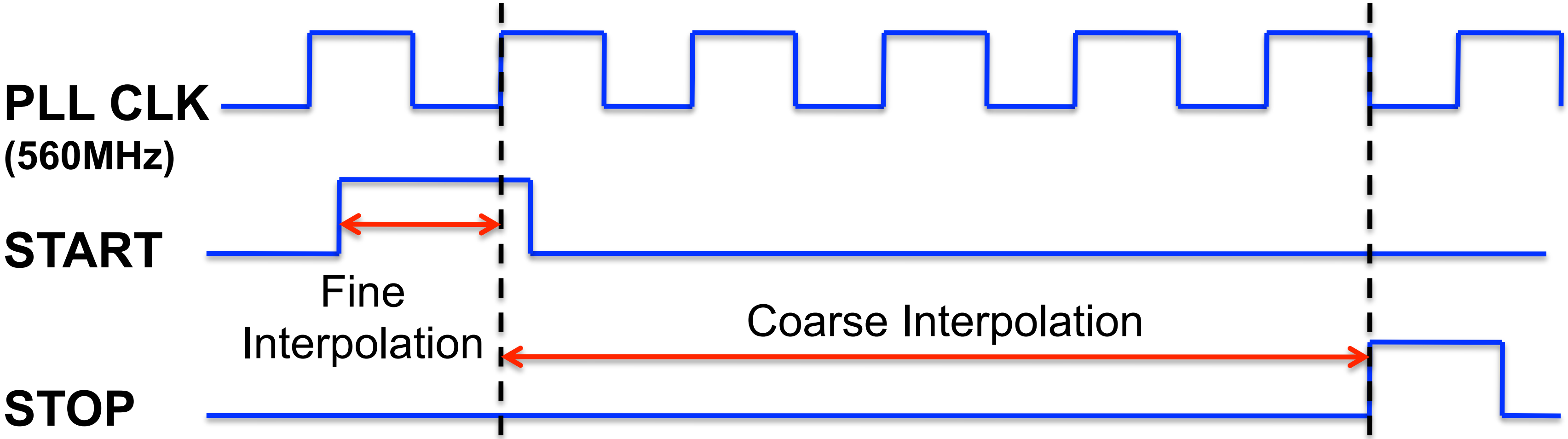
Measuring TOF in Many Pixels



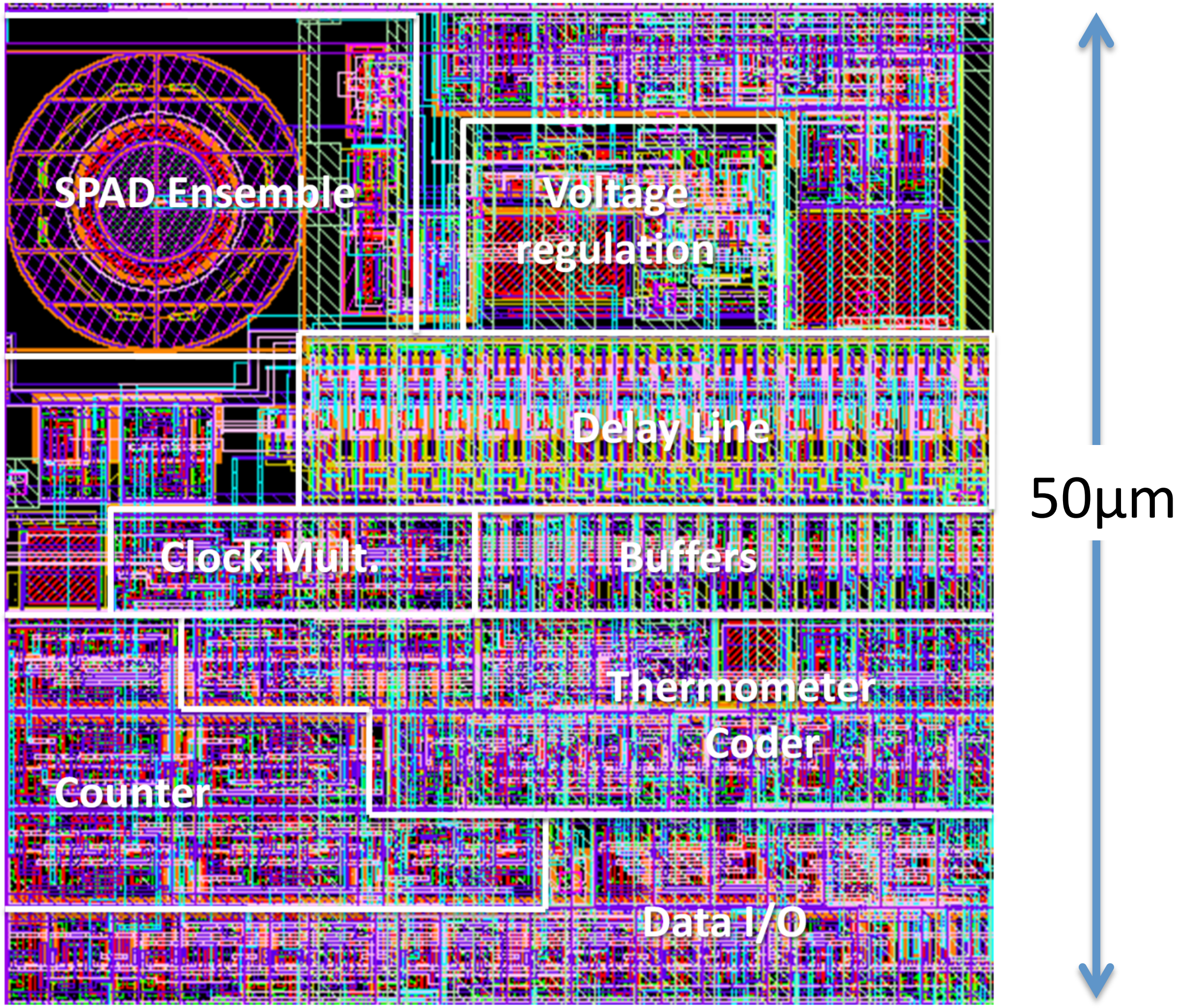
On-pixel Electronics: MEGAFRAME



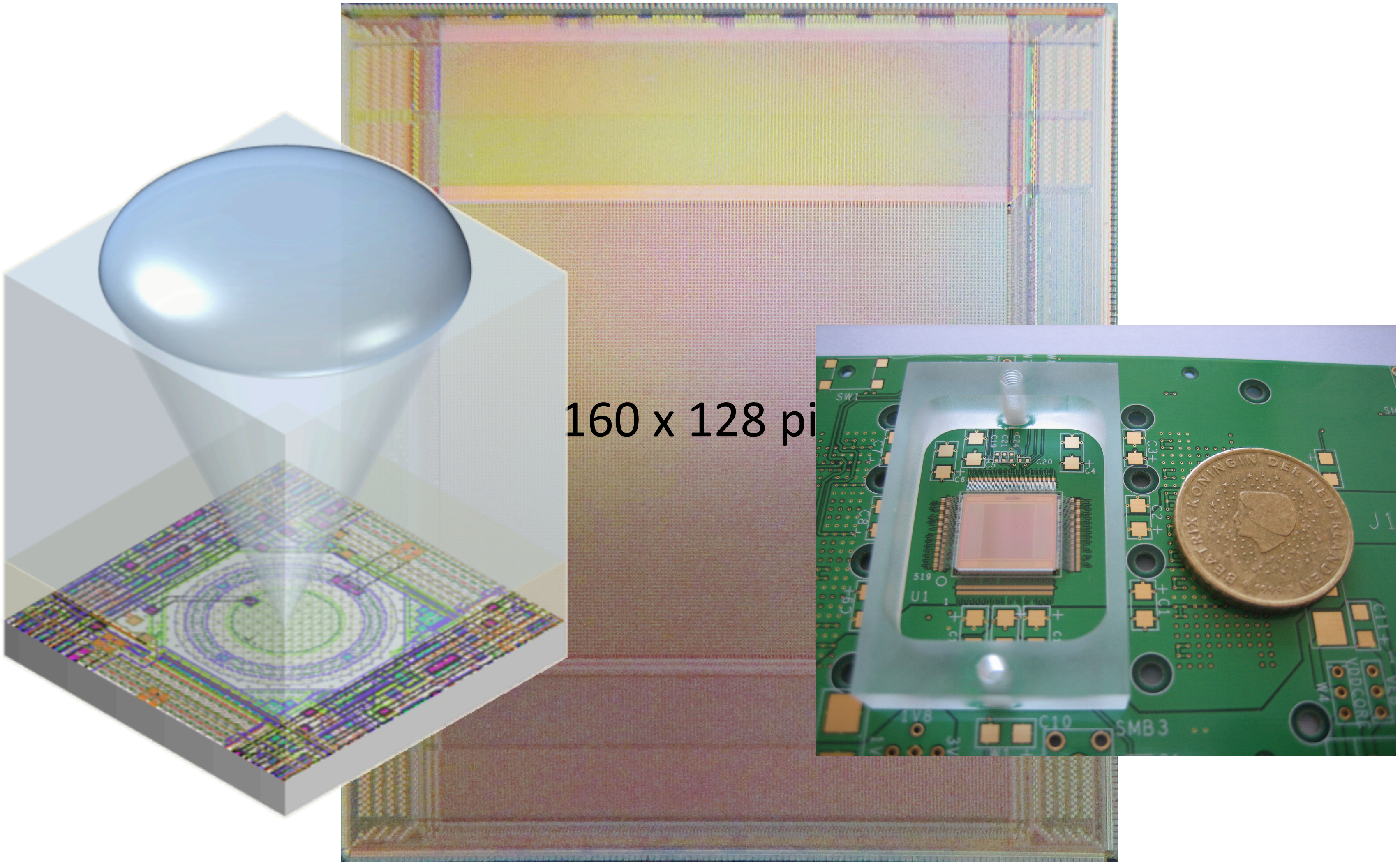
Gersbach, *et al.*, *IEEE ESSCIRC*, 2009.
Same authors, *JSSC* 2012.



MEGAFRAME Pixel: 500 Transistors

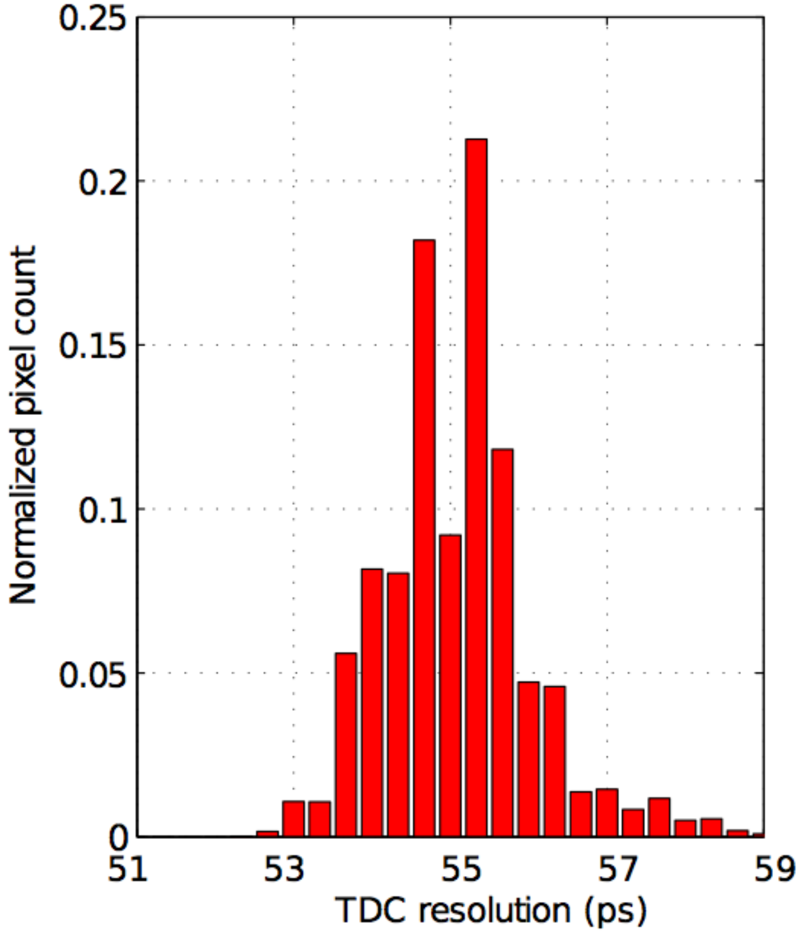


The Megaframe-128 Chip



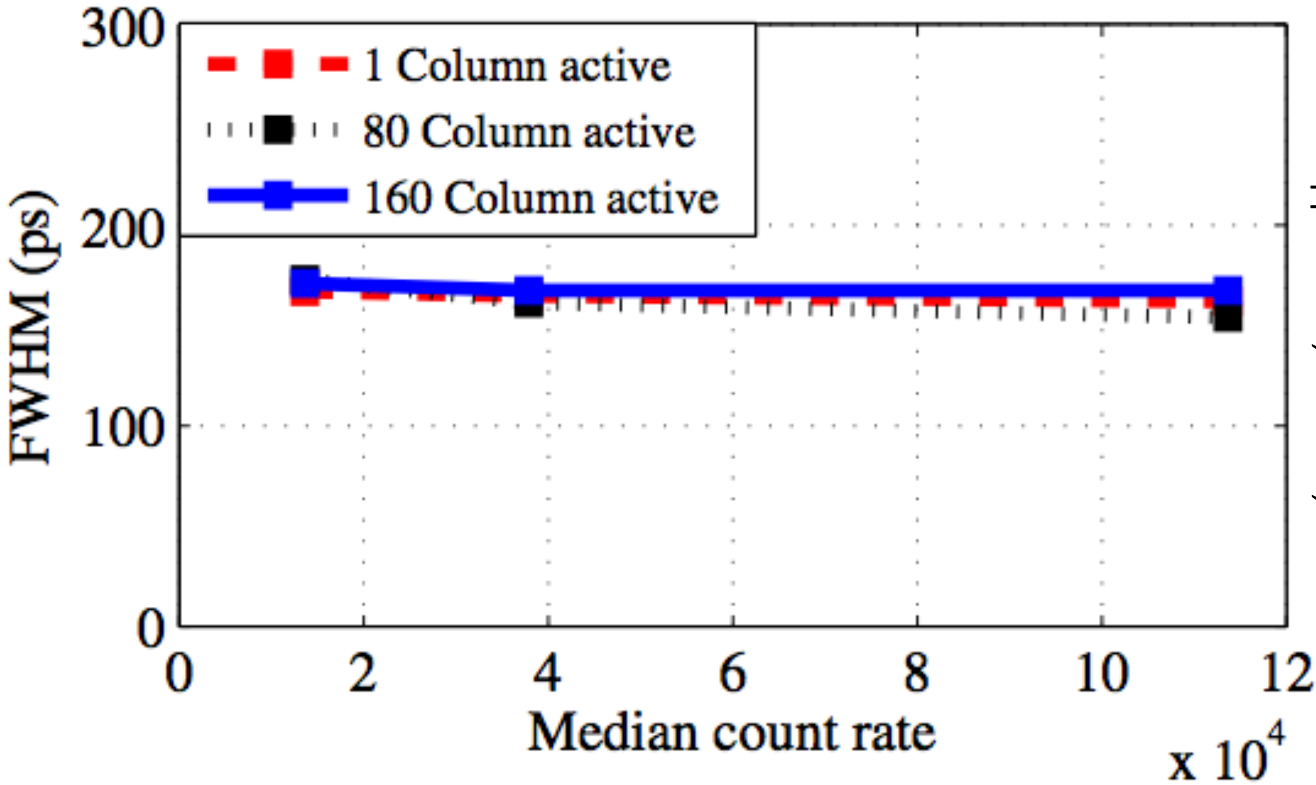
C. Veerappan, J. Richardson, R. Walker, D.-U. Li, M. W. Fishburn, Y. Maruyama, D. Stoppa, F. Borghetti, M. Gersbach, R.K. Henderson, E. Charbon, *ISSCC,* 2011

Non-Deterministic Resolution Spread



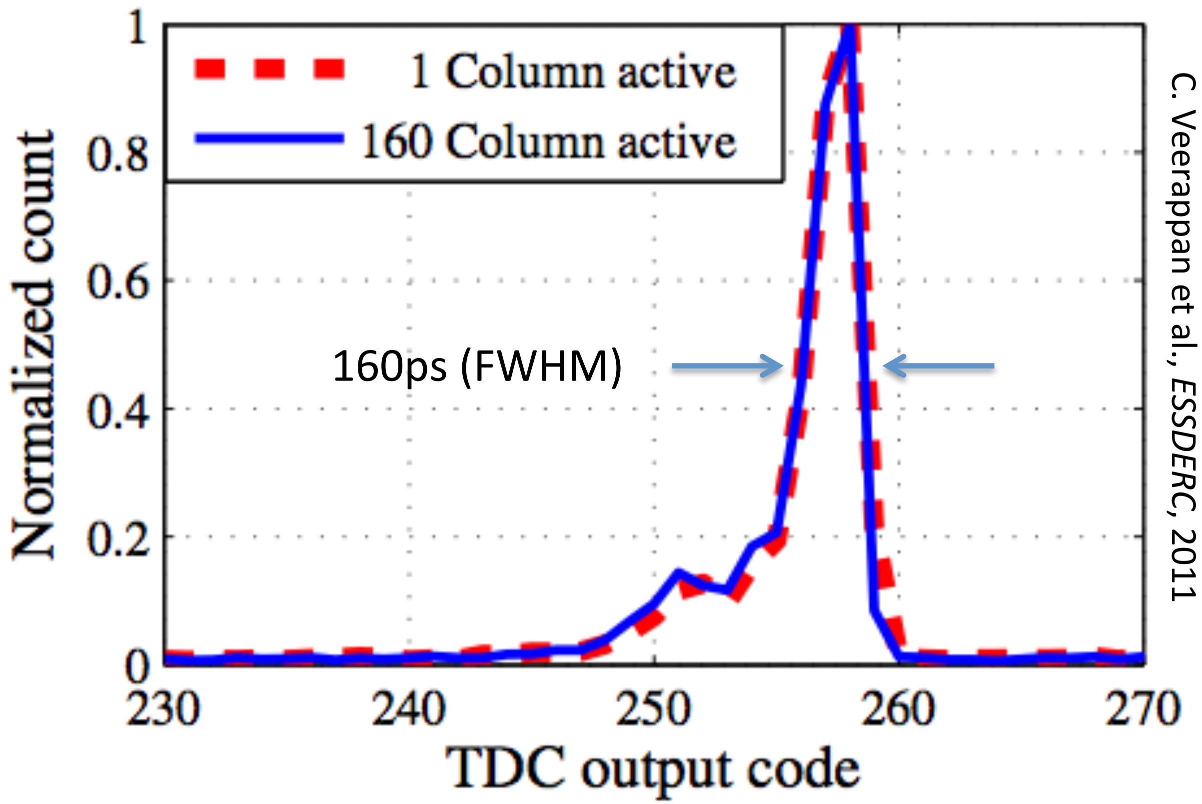
C. Veerappan et al., *ESSDERC*, 2011

Timing Jitter vs. Light Brightness (Compensated)



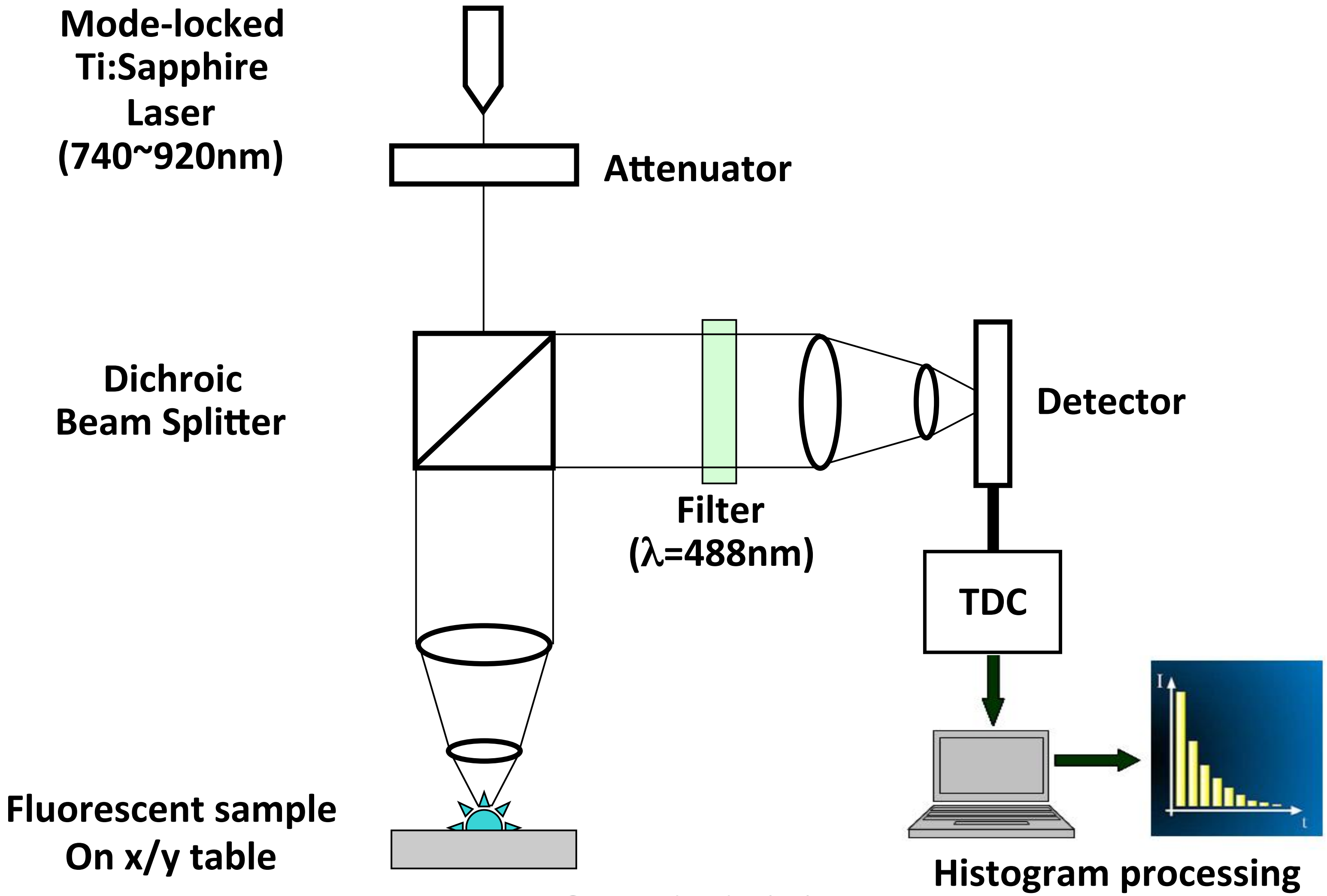
C. Veerappan et al., *ESSDERC*, 2011

Single-Shot TOF Measurement (Compensated)



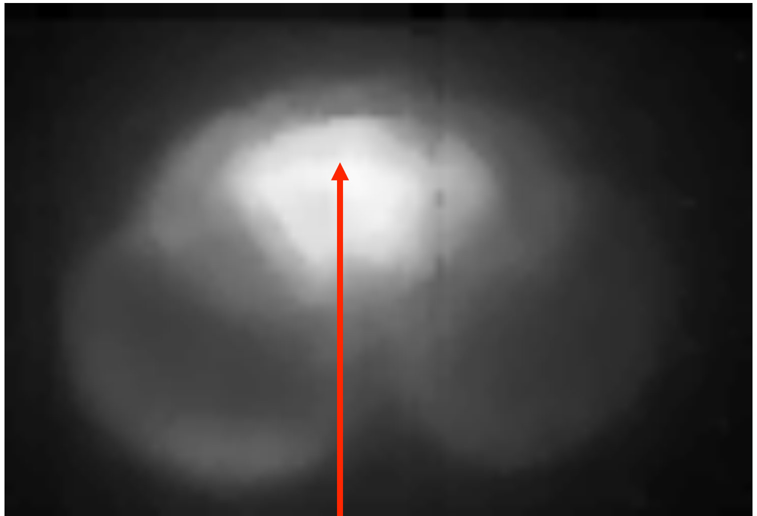
C. Veerapan et al., *ESSDERC*, 2011

Fluorescence Lifetime Imaging Microscopy (FLIM)



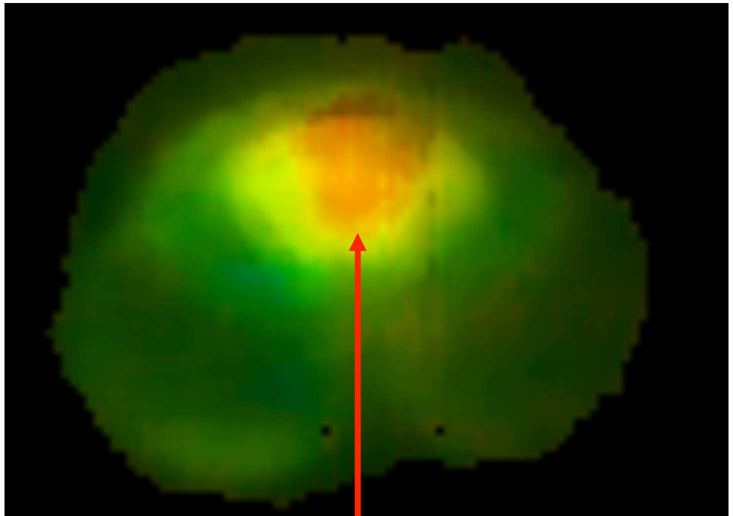
FLIM Images

Intensity Image



Seed makeup is
unclear, spot
caused by intensity
variations

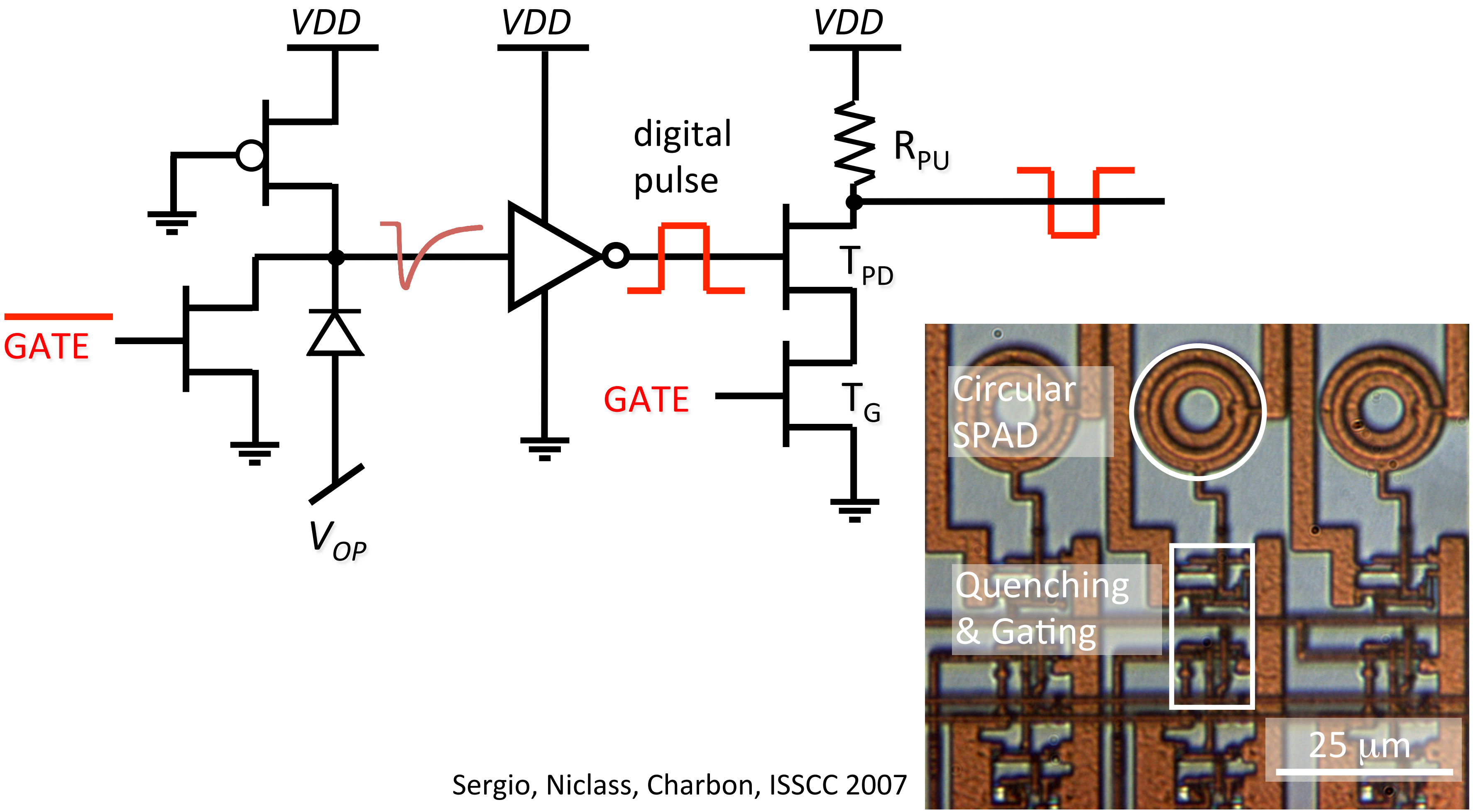
Lifetime Image



Nutrients in seed
occupy a limited
portion

C. Veerappan et al., *ISSCC*, 2011

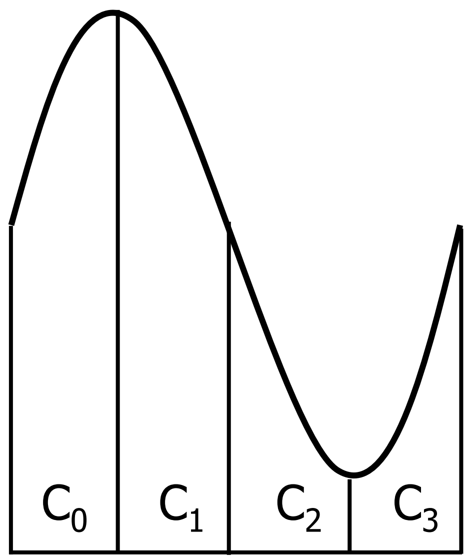
On-Pixel Electronics: SPAD Gating

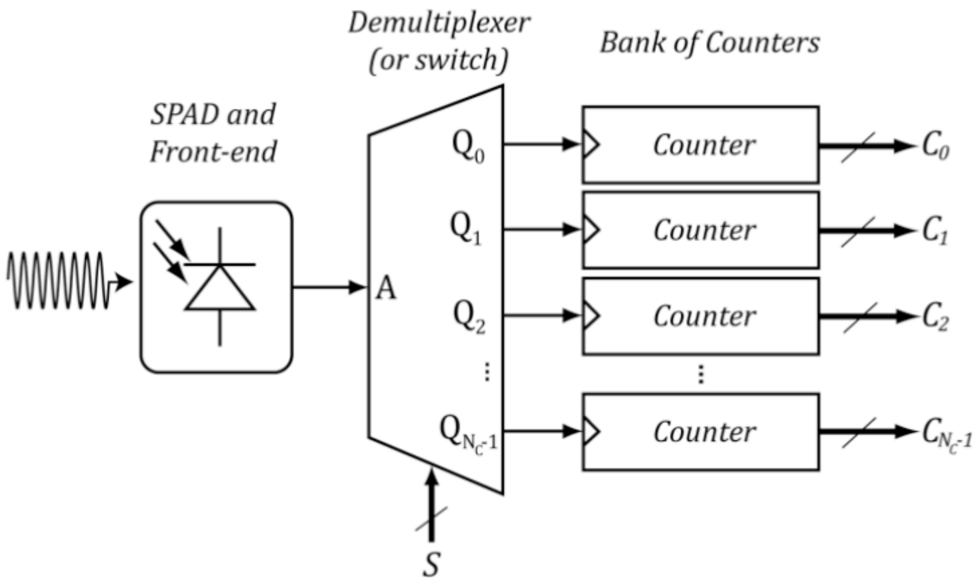


Sergio, Niclass, Charbon, ISSCC 2007

Indirect Method to Measure TOF: Single-Photon Synchronous Detection

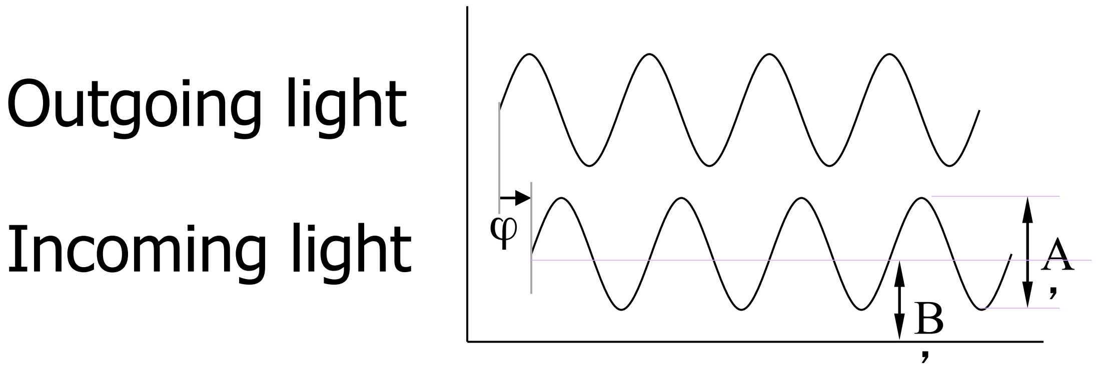
- Digital equivalent of lock-in method
- Continuously modulated illumination
- Gated SPAD with counters





Niclass, Charbon, *et al*., "Single-Photon Synchronous Detection", *IEEE Journal of Solid-State Circuits* (JSSC), **44**(7), pp. 1977-1989, July 2009

SPSD Method



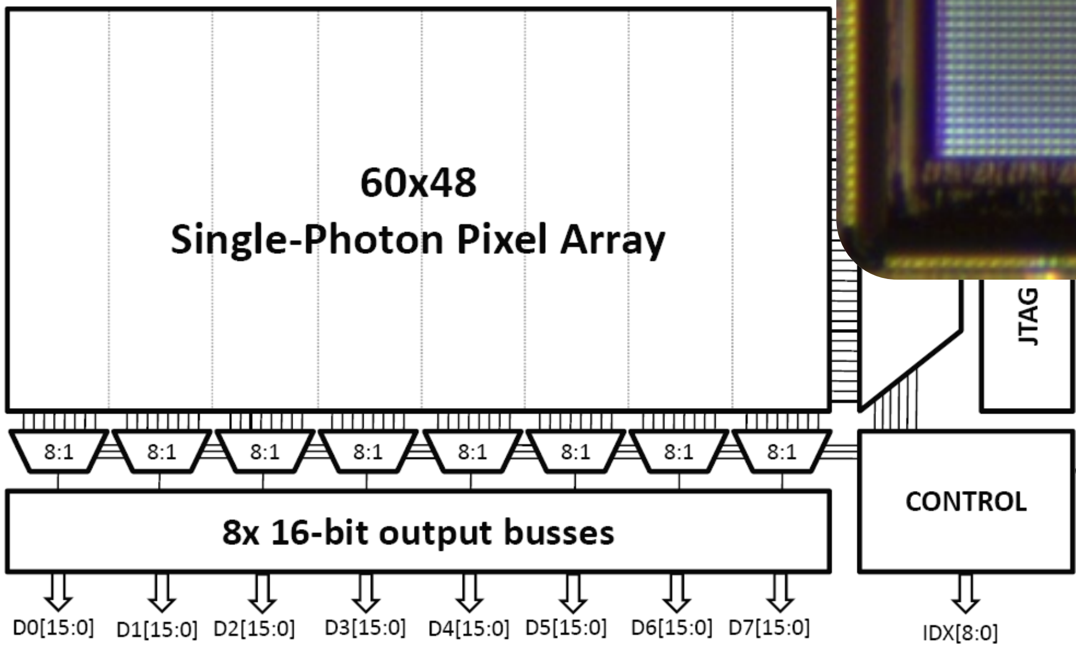
$$A' = \frac{\sqrt{(C_3 - C_1)^2 + (C_0 - C_2)^2}}{2}$$

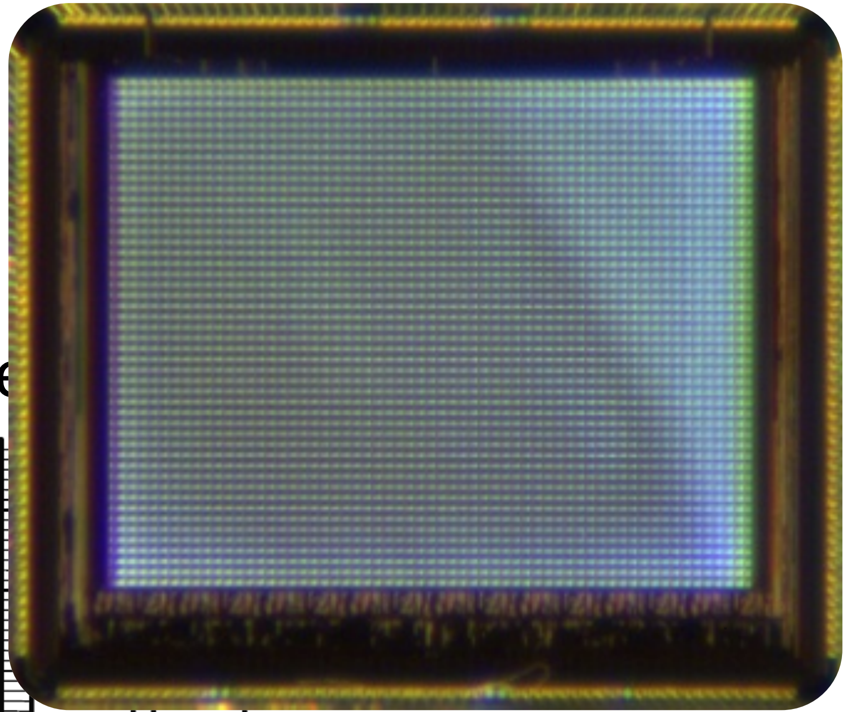
$$B' = \frac{C_0 + C_1 + C_2 + C_3}{4}$$

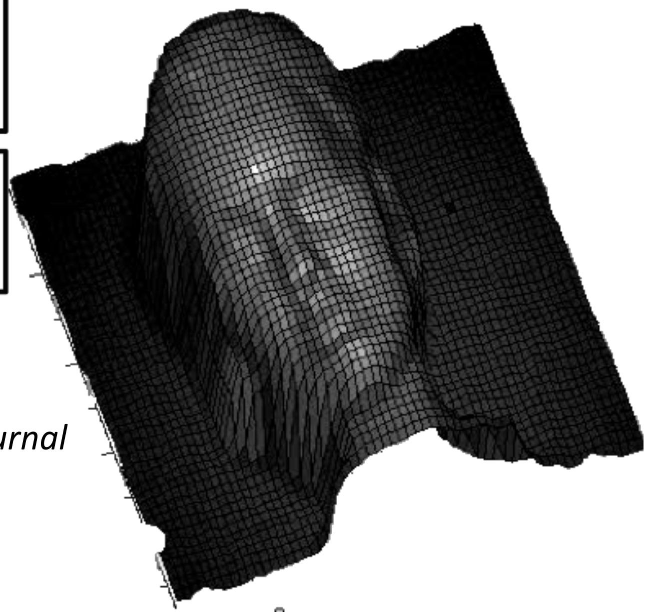
$$\varphi' = \arctan\left(\frac{C_3 - C_1}{C_0 - C_2}\right)$$

SPSD Camera

- System: fully digital
- Pixel: SPAD + mux + 2 counte



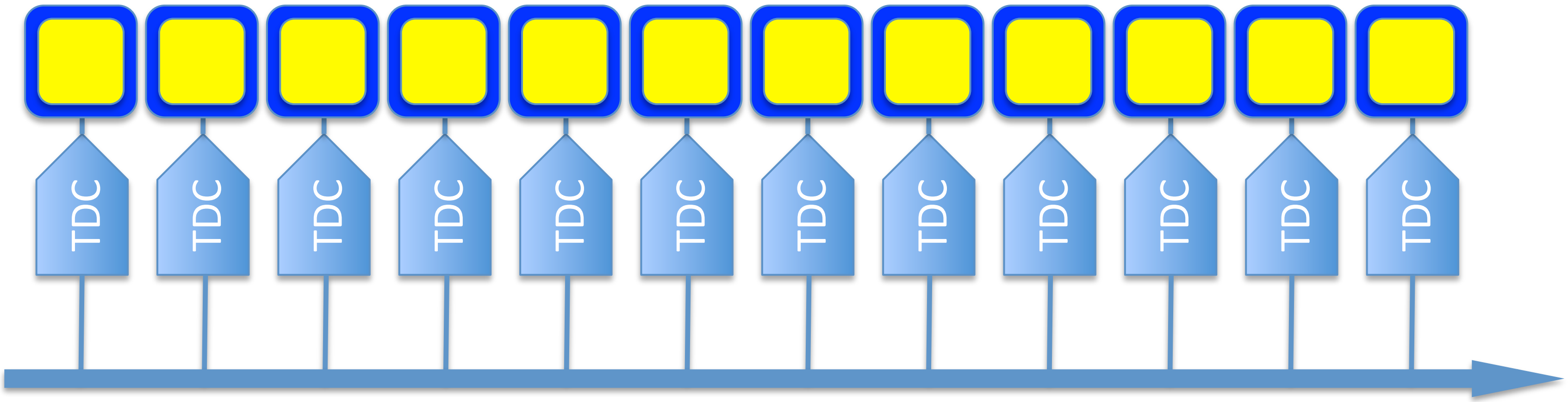




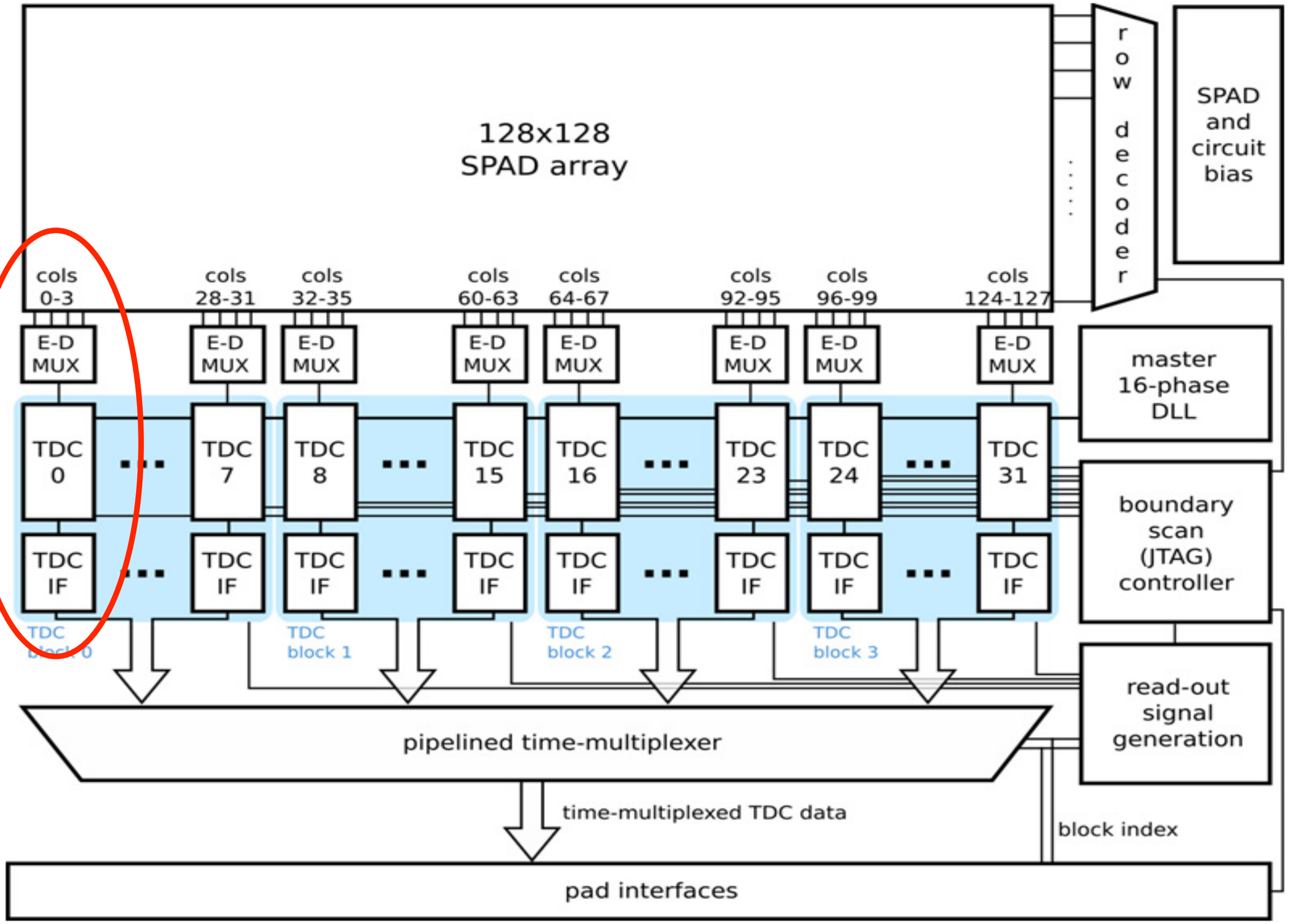
Niclass, Charbon, *et al.*, "Single-Photon Synchronous Detection", *IEEE Journal of Solid-State Circuits* (JSSC), **44**(7), pp. 1977-1989, July 2009

Improving Fill Factor

- Place complex electronics outside sensitive are
- Limited to line-pixel sensors
- 2D arrays require scanning

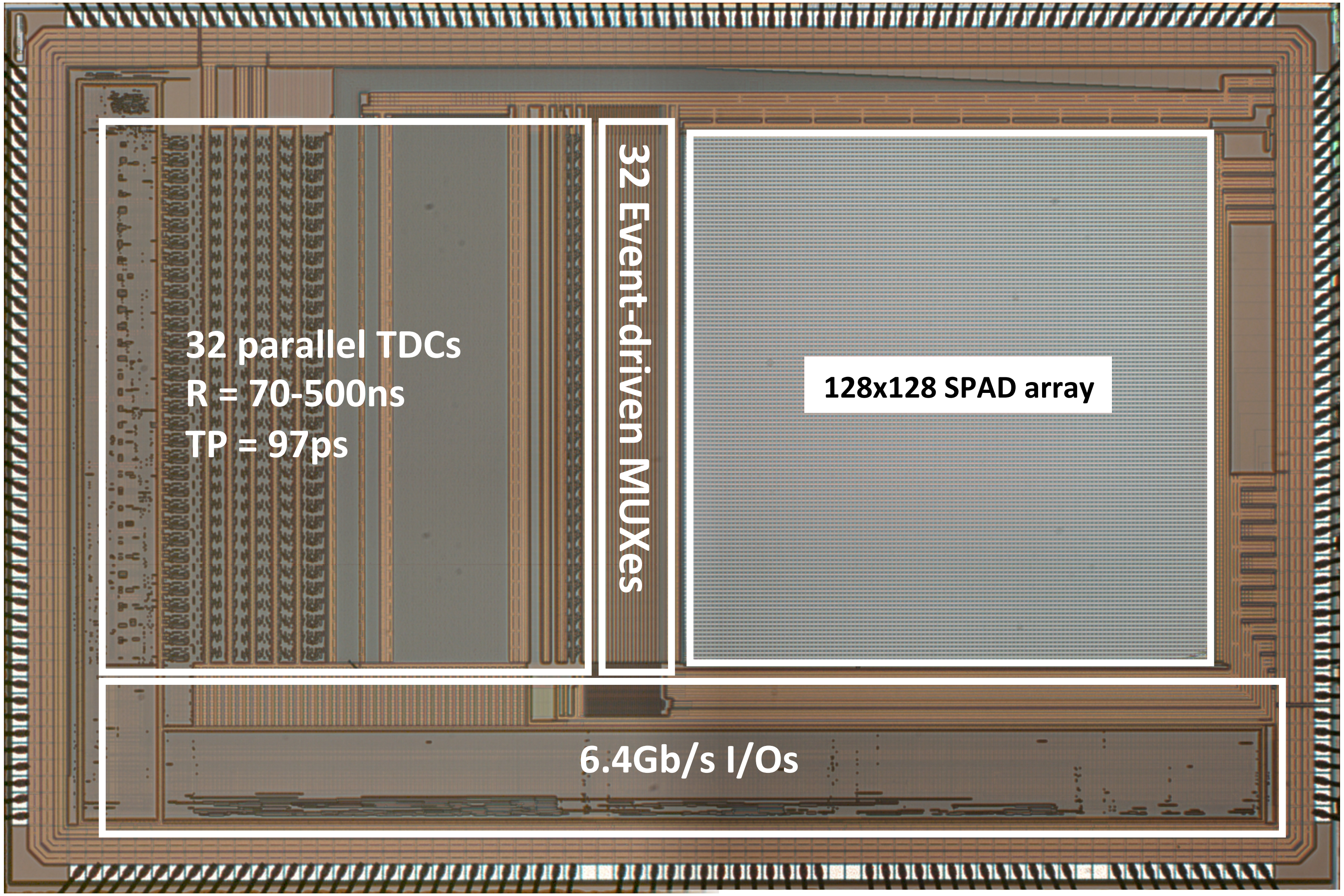


Column-Parallel Approach: LASP



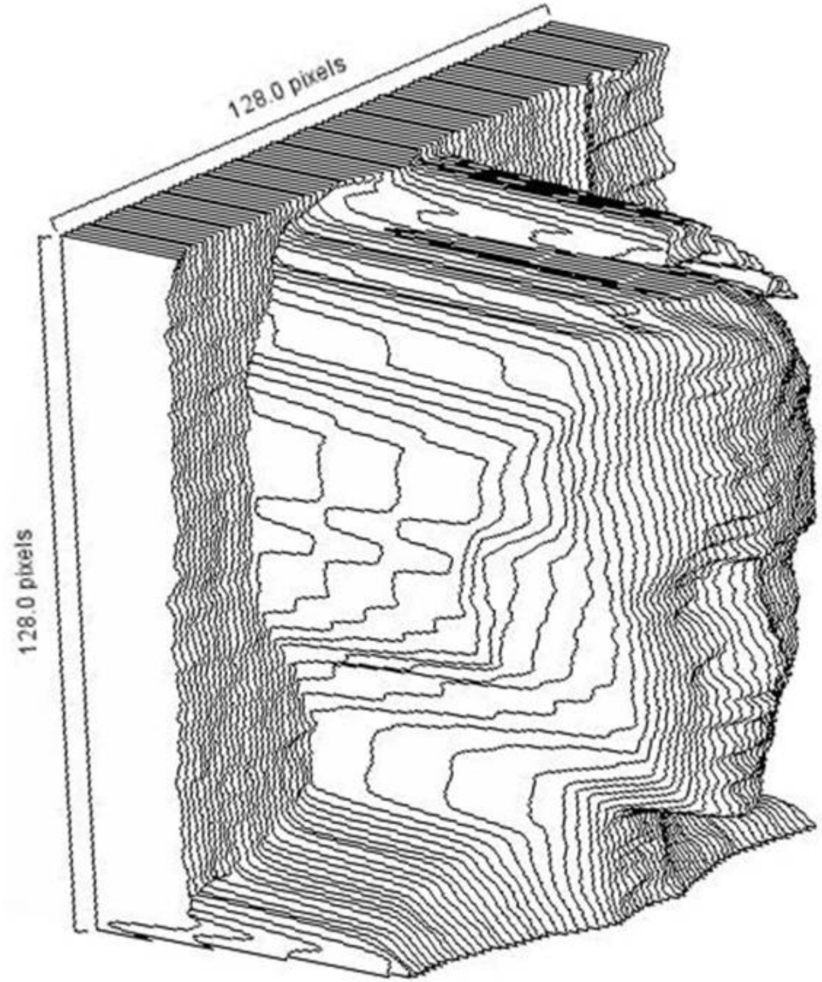
Niclass, Favi, Kluter, Gersbach, Charbon, *ISSCC2008, JSSC* 2008

LASP: First Fully Integrated Sensor



Niclass, Favi, Kluter, Gersbach, Charbon, *ISSCC* 2008, *JSSC* 2008

TCSPC Method for 3D Reconstruction



SPAD Arrays

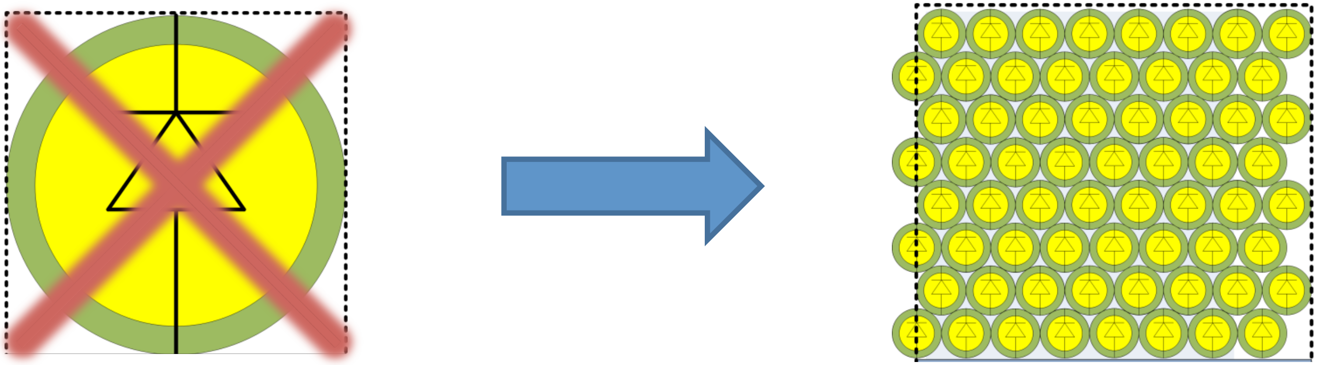
Let us fast-rewind and go back to basics!

SPADs are the interface between photons and the digital world

Why not combine them into a single pixel and use scanning or coded-aperture?

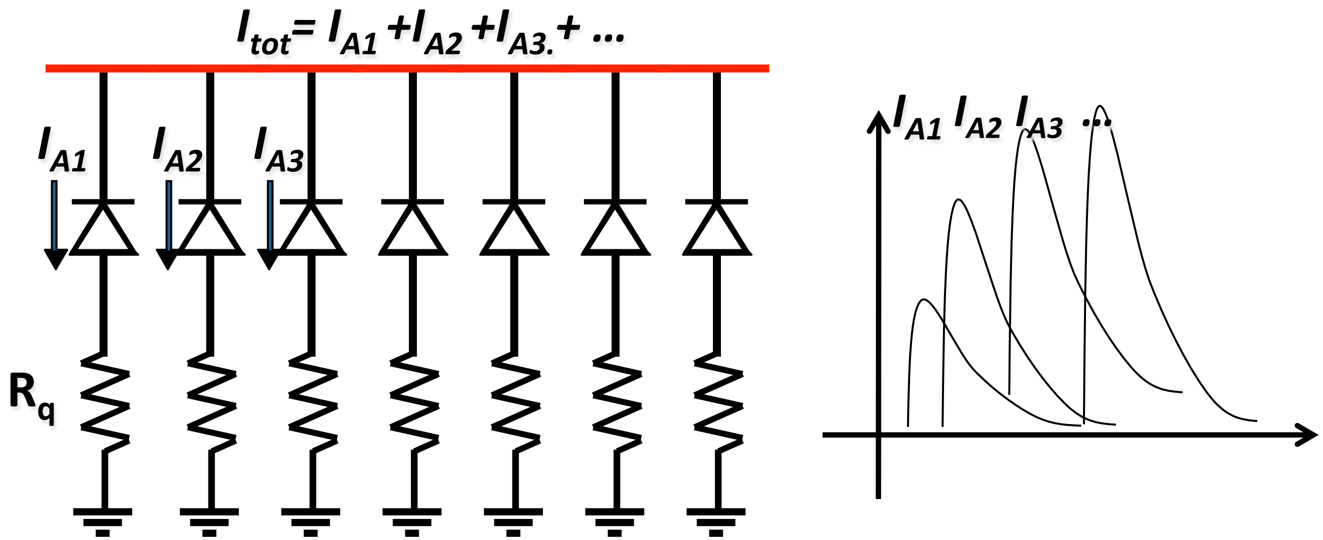
The Silicon Photomultiplier (SiPM)

SiPM Concept



- Single- and multi-photon detectability
- Better fill factor
- Defect-driven noise can be isolated and eliminated
- Each diode is a SPAD

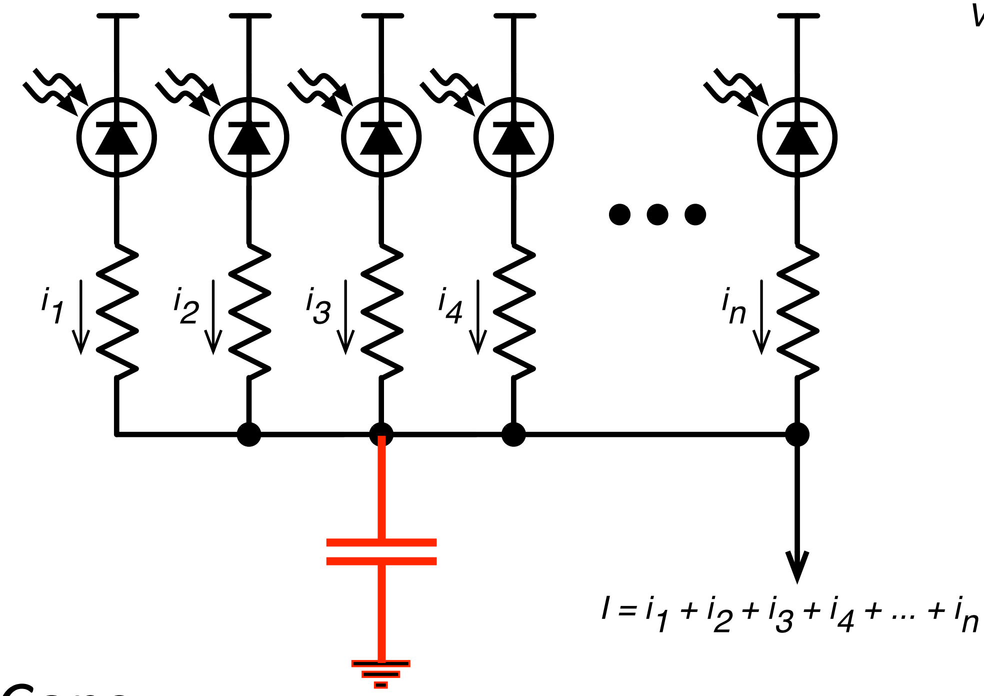
SiPM Concept

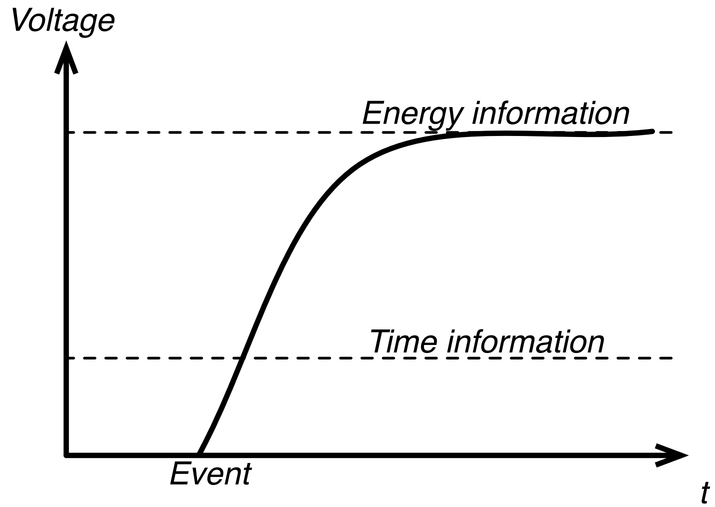


Two Flavors of SiPMs

- Analog silicon photo-multiplier (a-SiPM)
- Digital silicon photo-multiplier (d-SiPM)

a-SiPMs

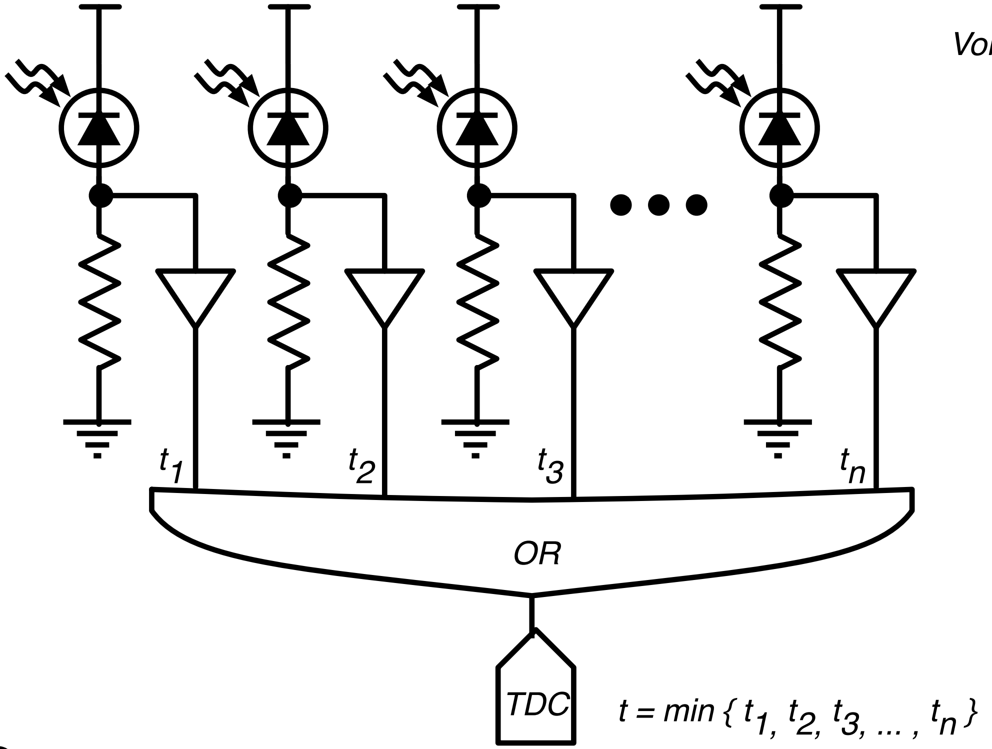


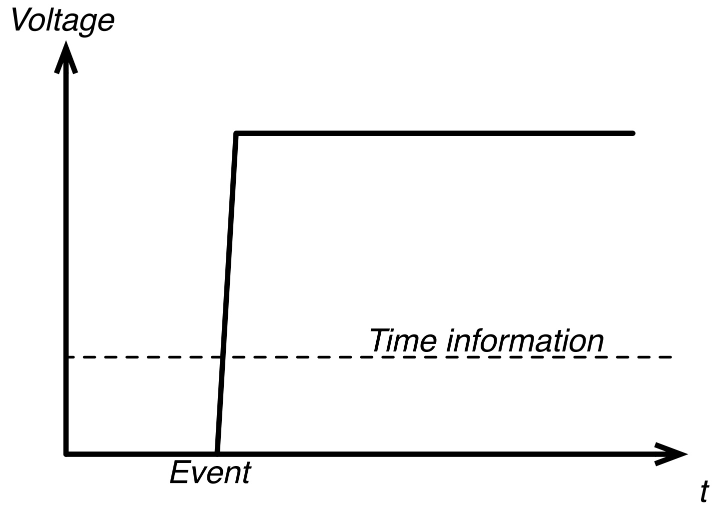


Cons

- Cannot remove noisy SPADs
- Relative slow rise time due to loading (no differentiation/delay techniques)

d-SiPMs

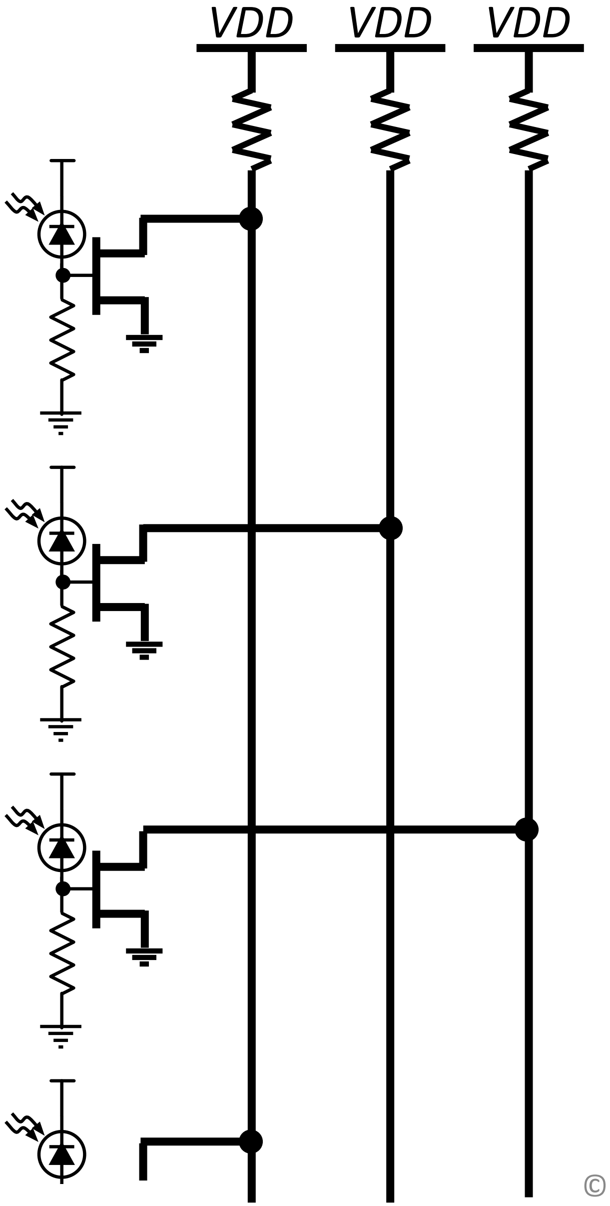


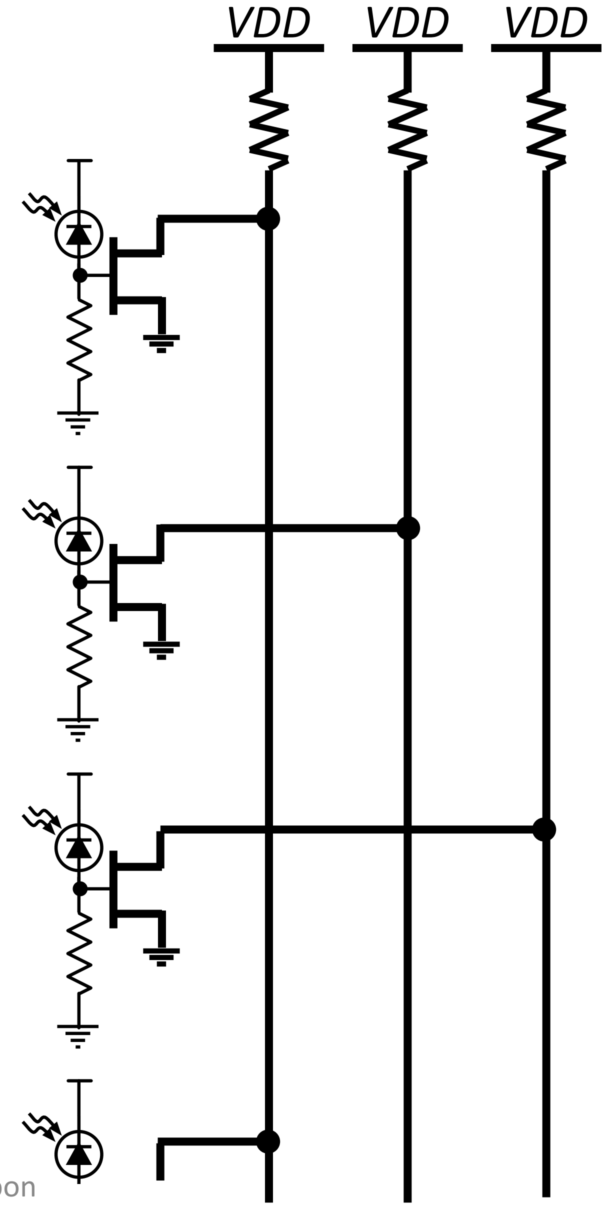


<u>*Cons*</u>

– Only first photon detected

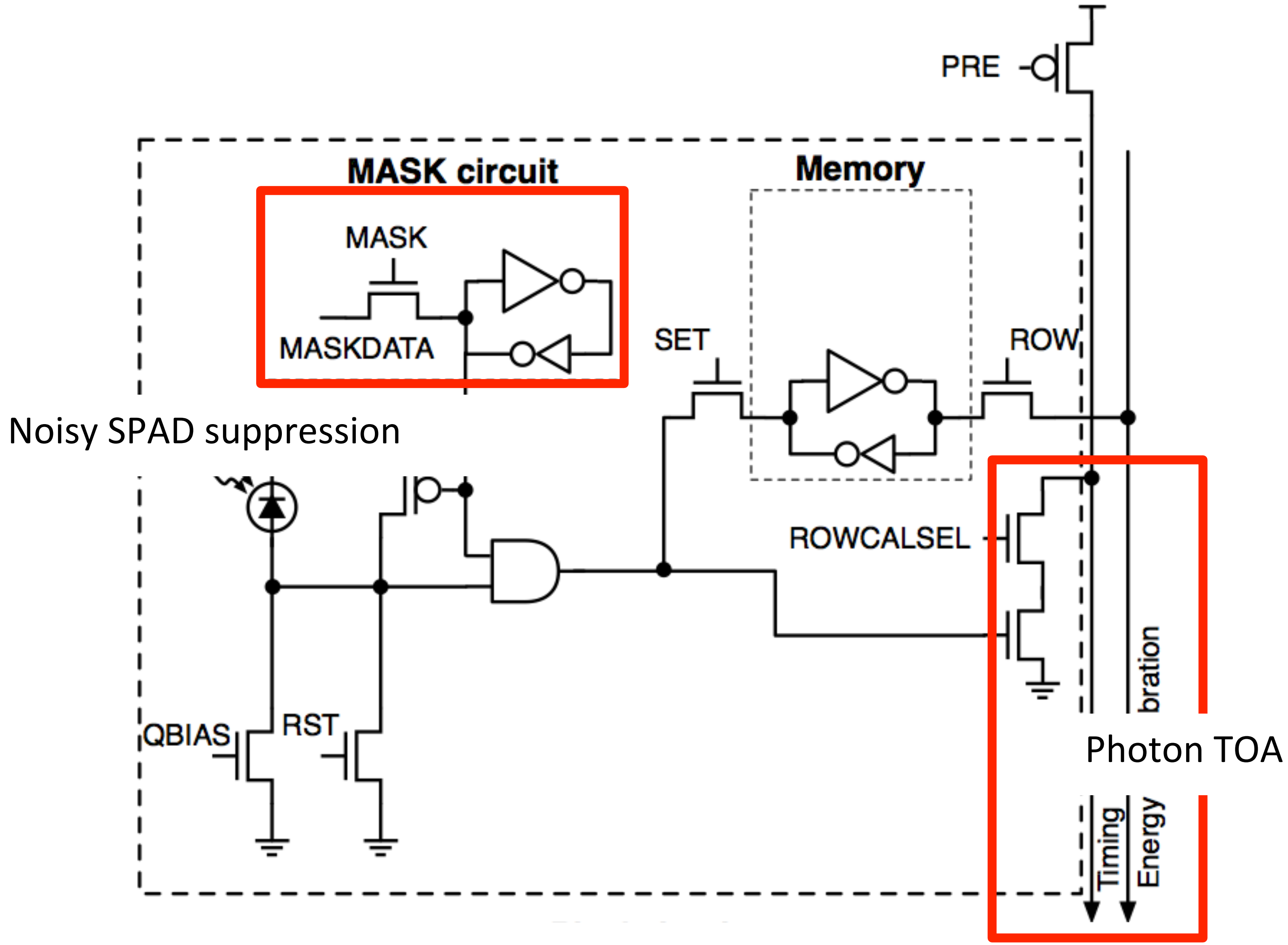
Column-Parallel Approach to d-SiPM



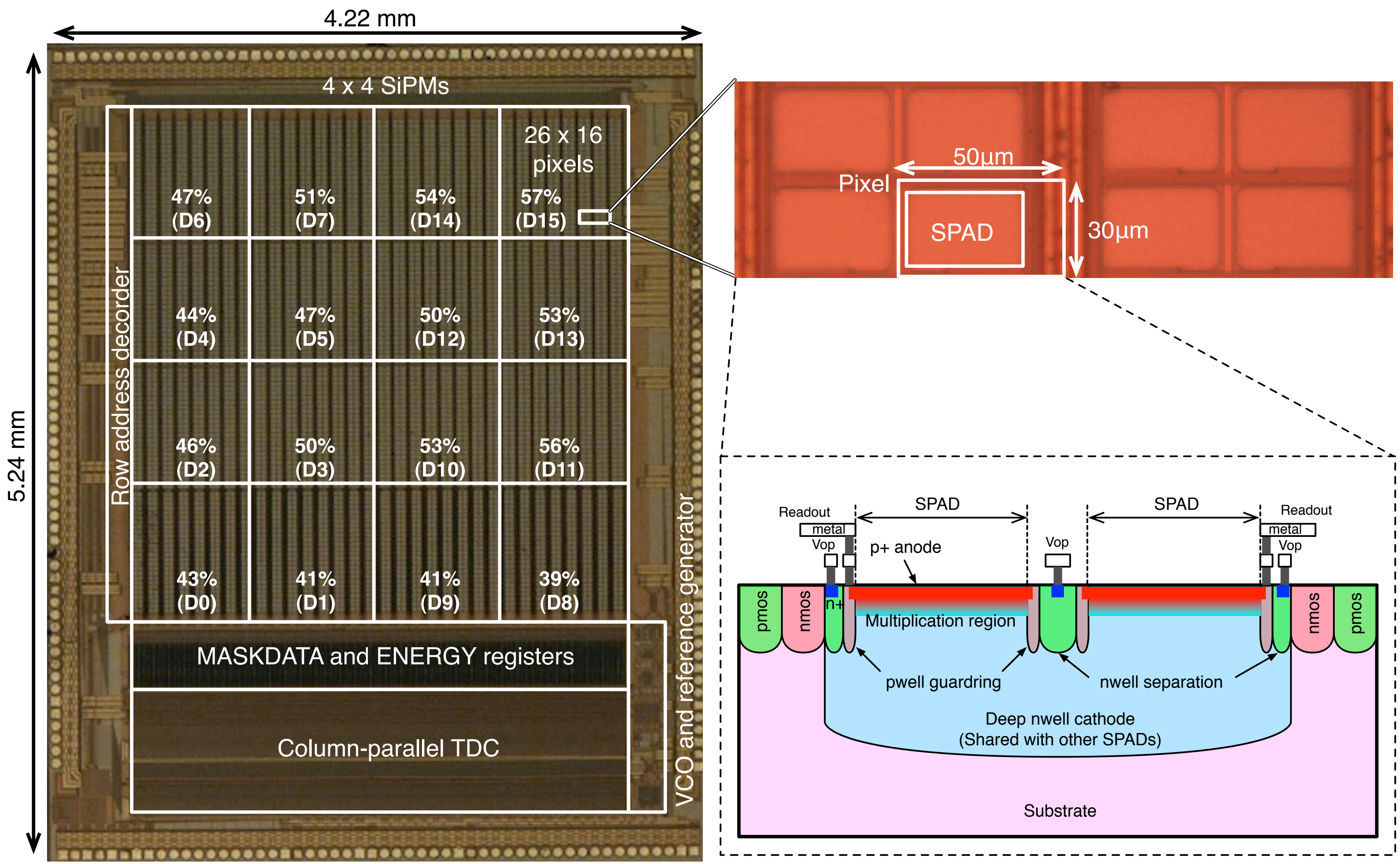


S. Mandai and E. Charbon, IEEE *Nuc. Sci Symp.* (NSS) 2012

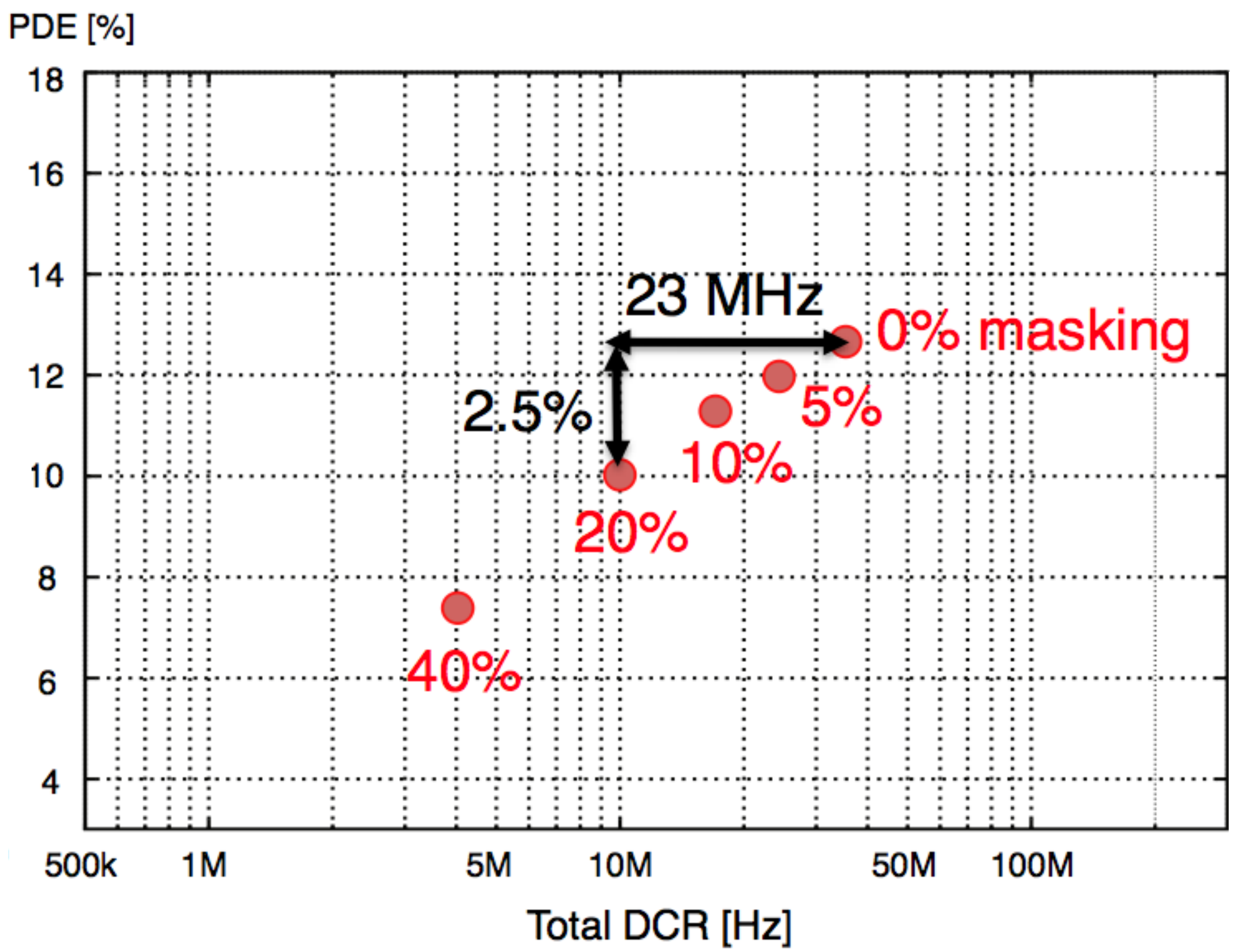
Column-Parallel or Multichannel d-SiPM



Multichannel d-SiPM: EndoTOFPET

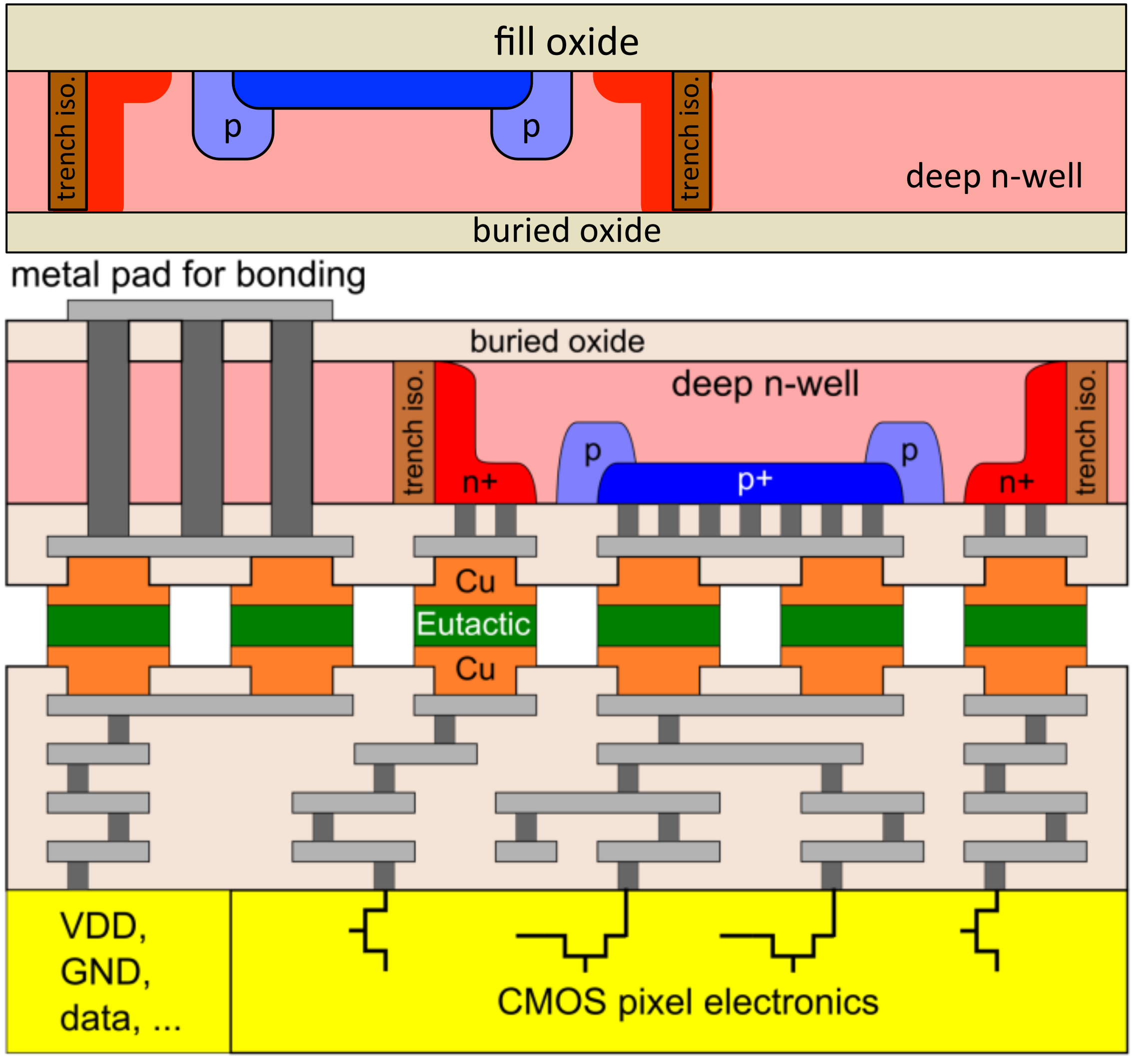


Hot Pixel Suppression



Mandai, Charbon, *IEEE Nuc. Sci Symp. (NSS)*, 2012

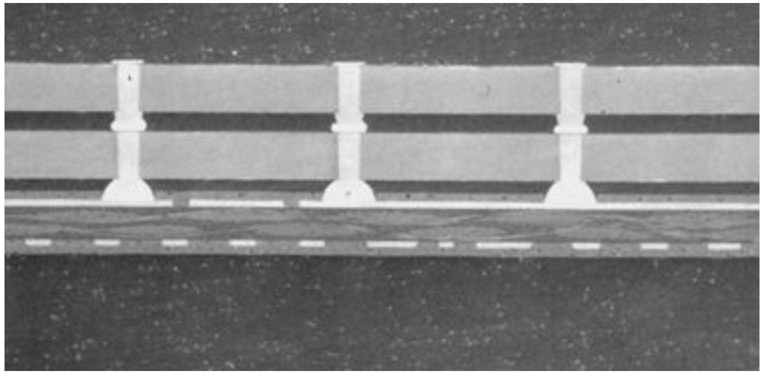
3D Integration: Flip-Chip

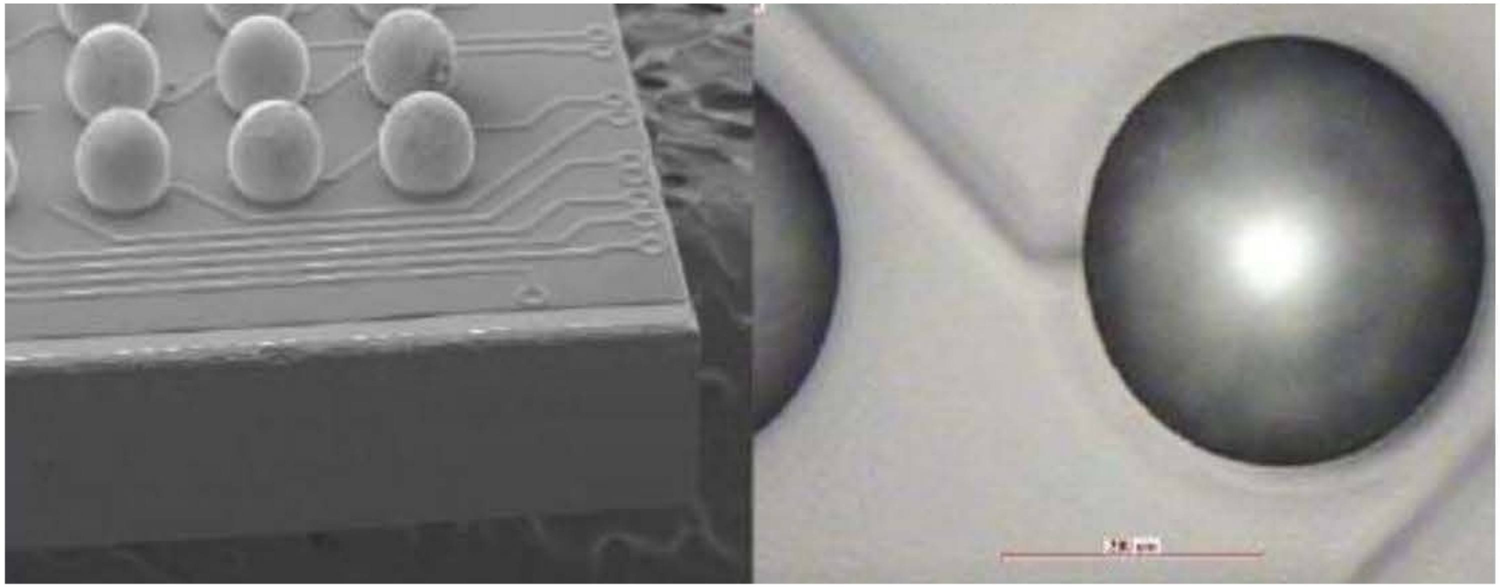


Durini *et al., IEEE Nuc. Sci. Symp.* (NSS), 2012

Courtesy: Franco Zappa

3D Integration: Through-Silicon Via



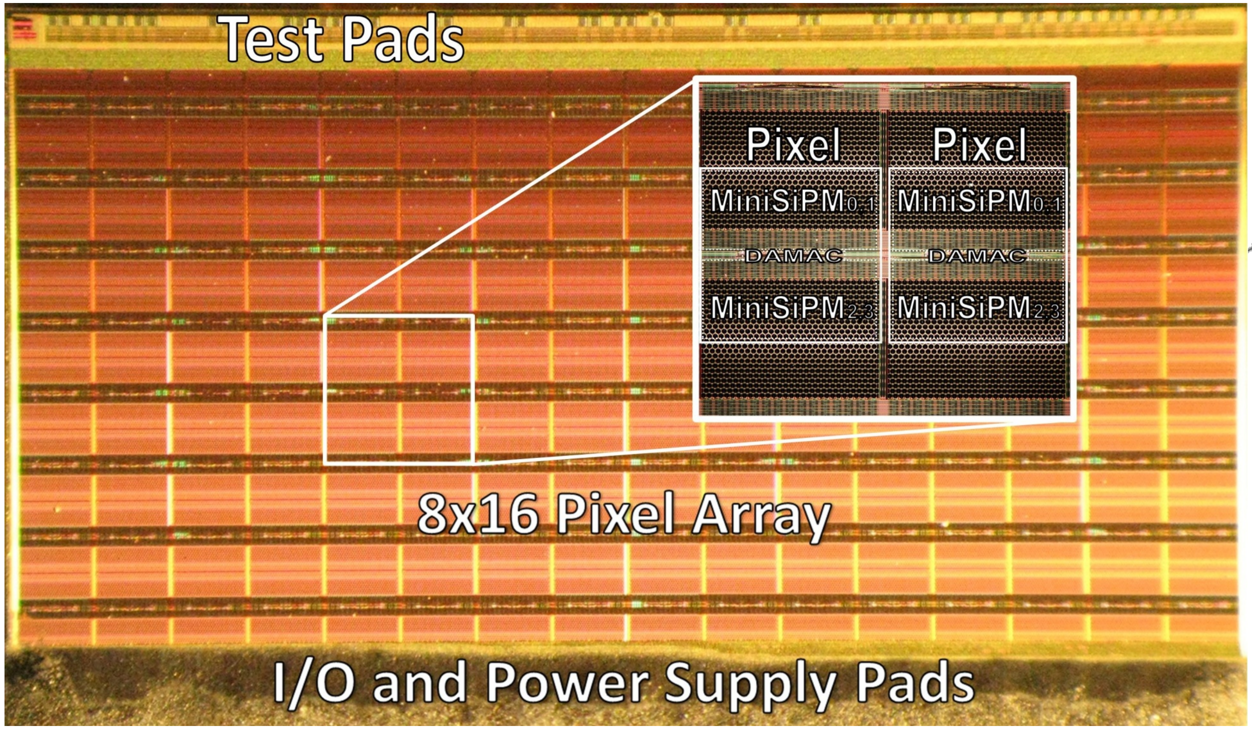


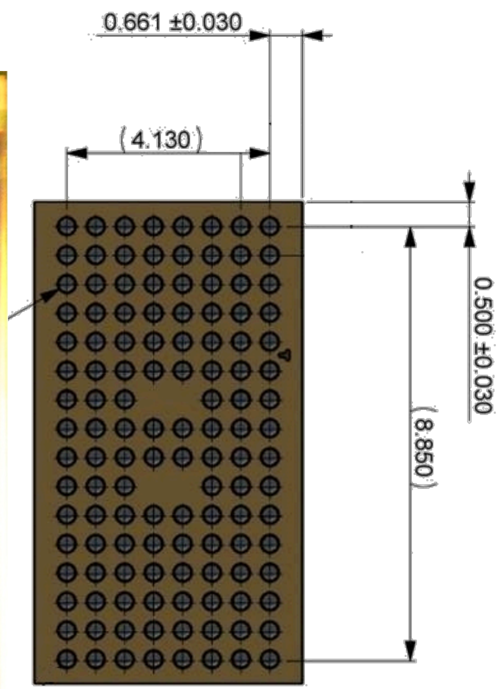
Source: STMicroelectronics

3D Integration: Through-Silicon Via

- SPADnet
  - Front-side illuminated 8x16 mini SiPM matrix
  - On-pixel TDC
  - TSV to reduce gap

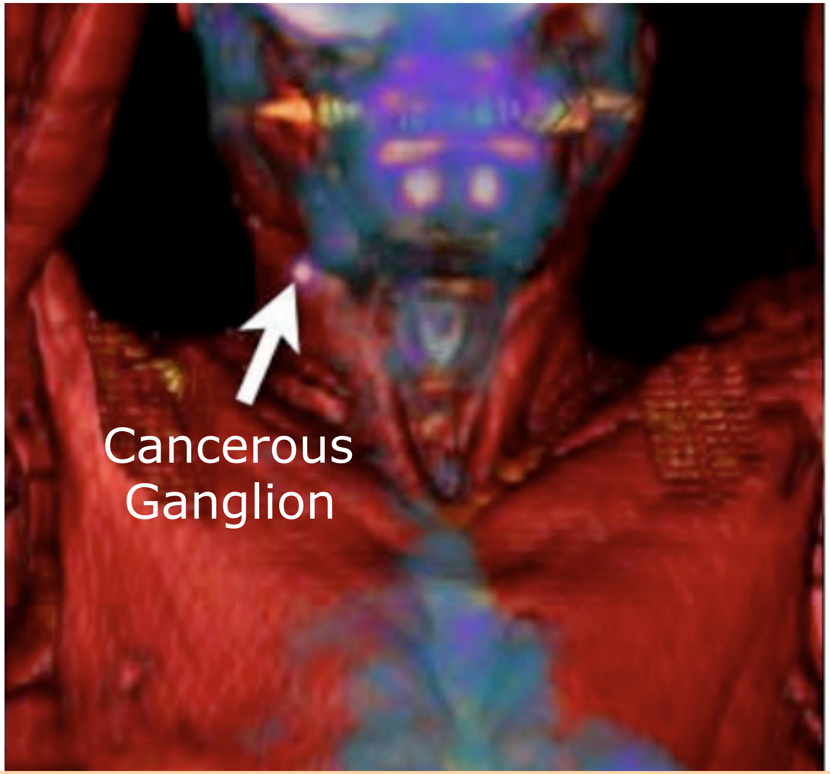
L.H. Braga et al., *ISSCC*, 2013





TOF in
Medical Imaging

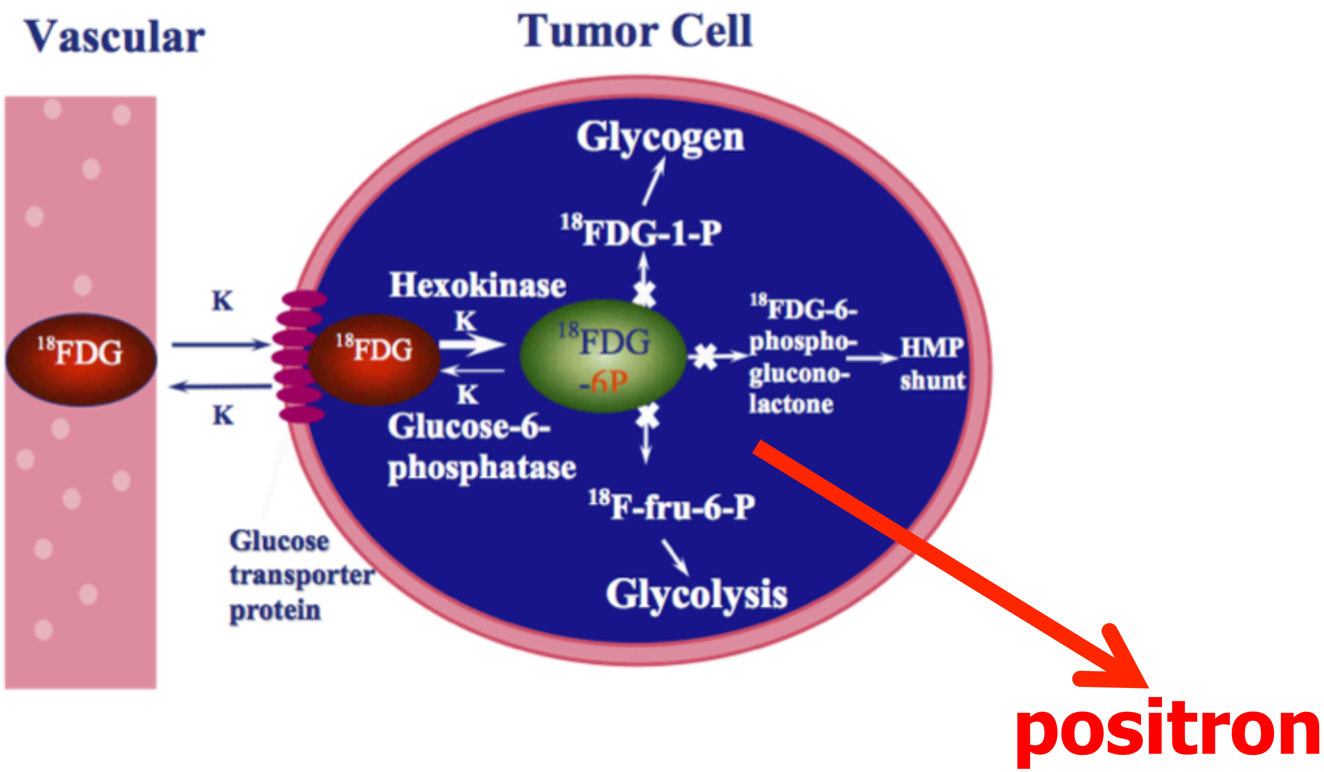
Positron Emission Tomography (PET)



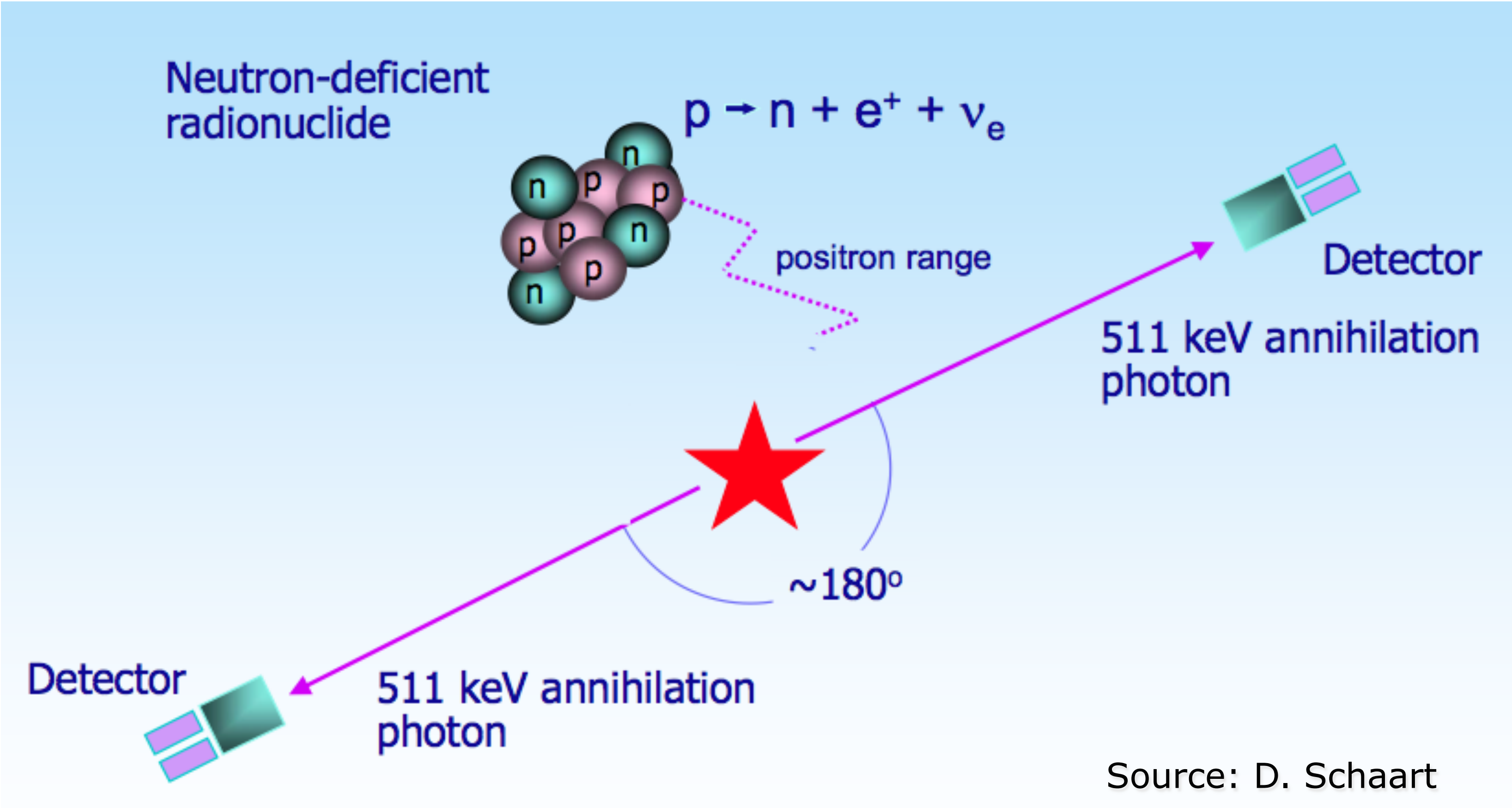
PET visualizes β+ emission from ^{18}FDG metabolized by cancer cells…

in 3D!

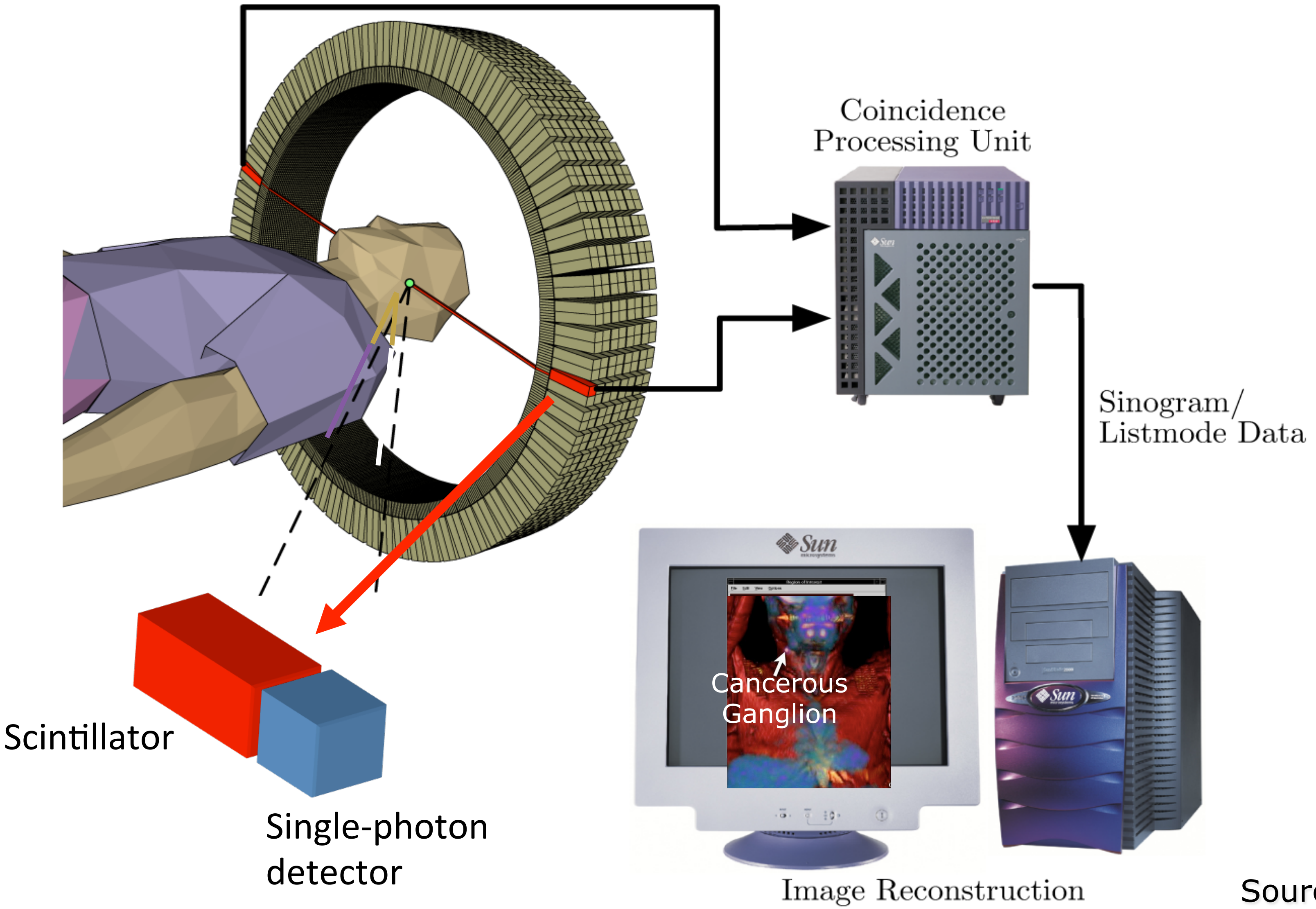
Fluorodeoxyglucose (FDG)



Positron-Electron Annihilation

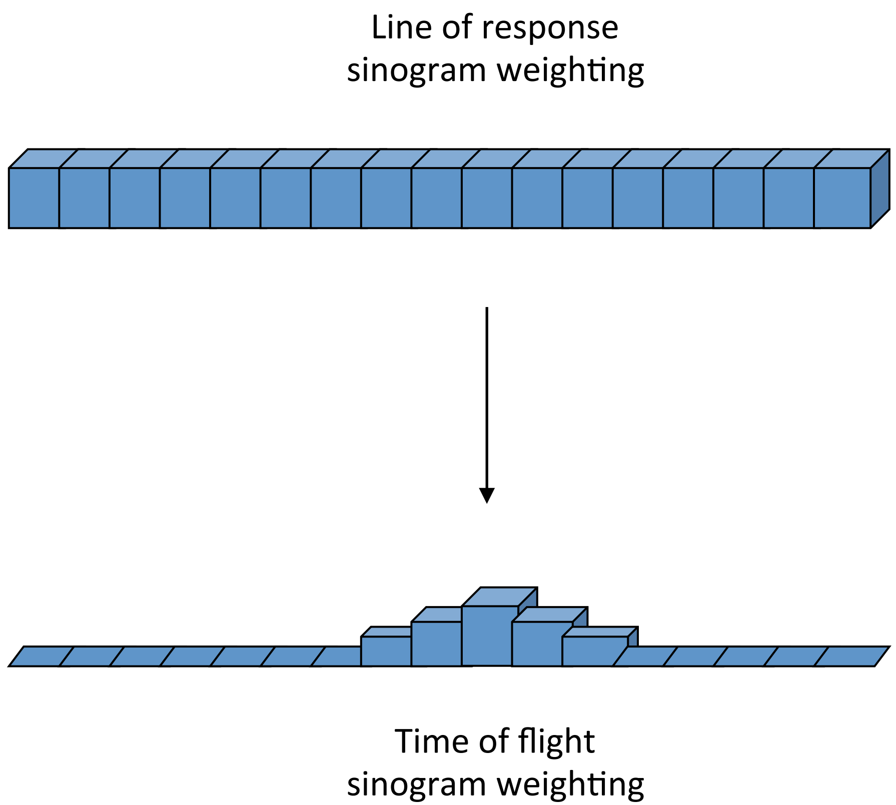


3D Reconstruction in PET



Source: Sun

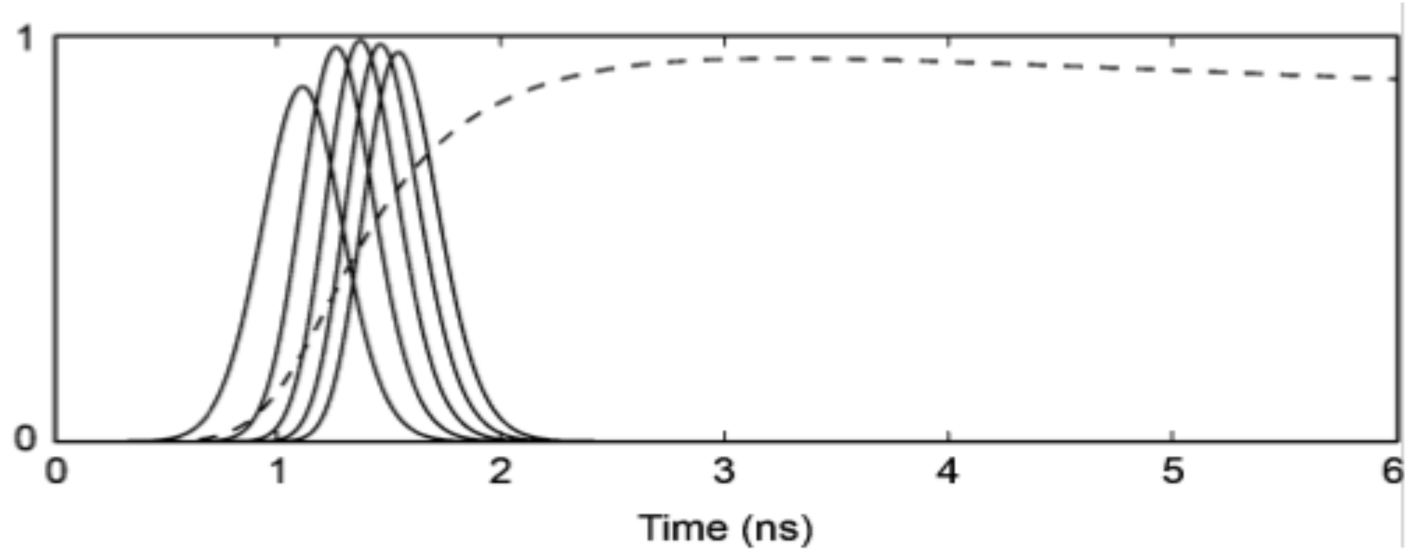
Time-of-flight PET



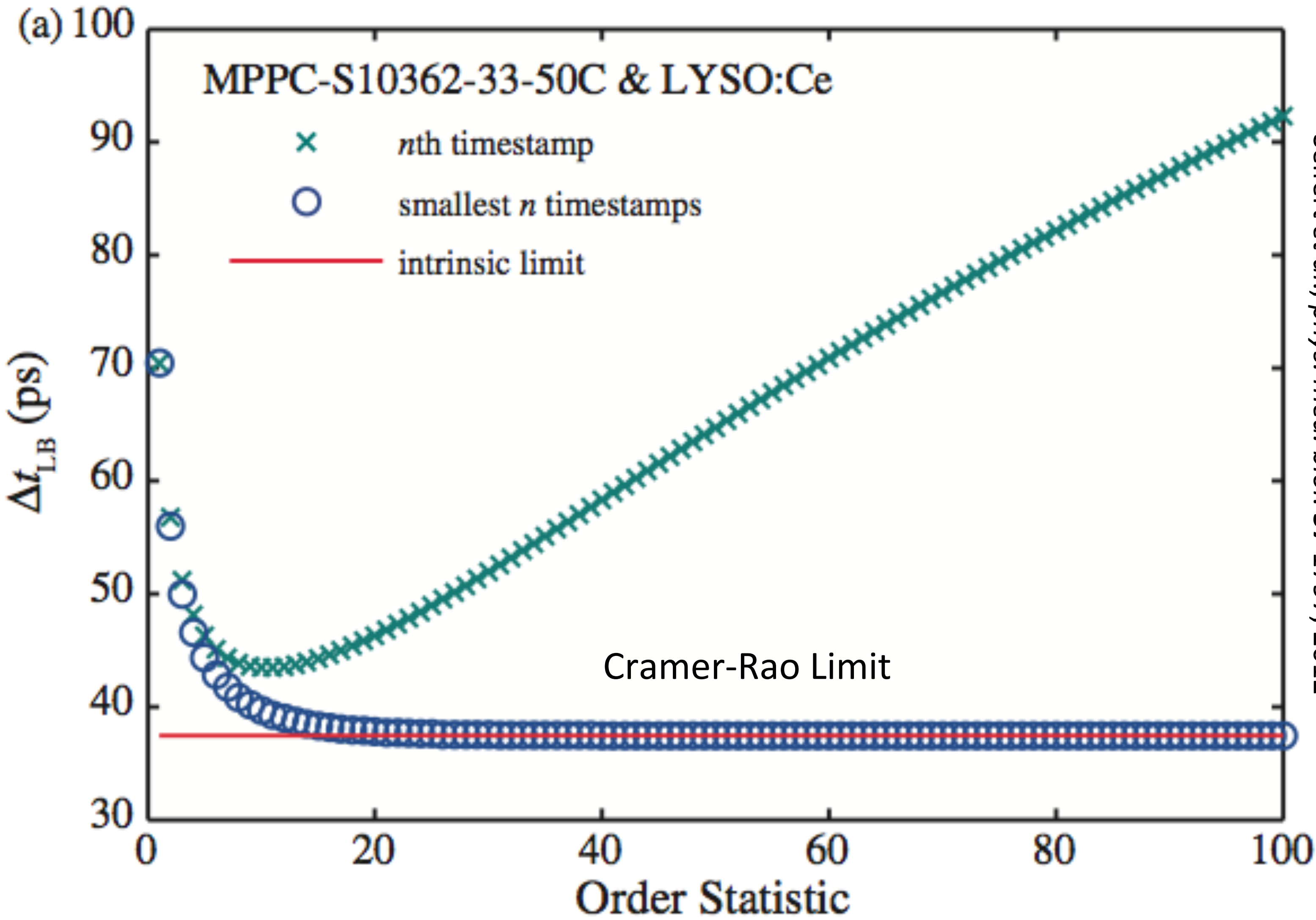
What about the multichannel d-SiPM?

Why should we keep single-photon statistics?

Photons from a Scintillator Are <u>not</u> i.i.d.: Order Statistics

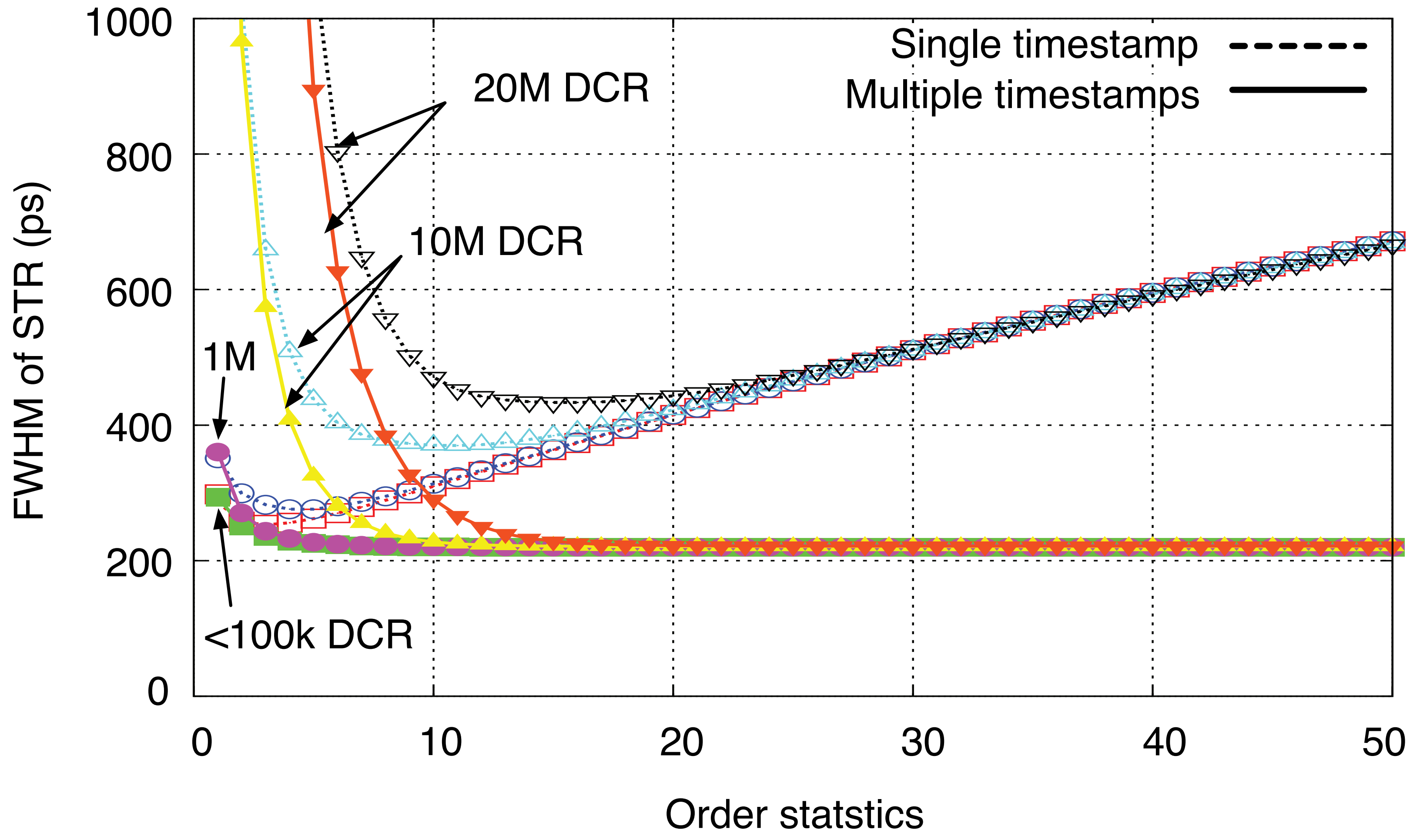


Cramer-Rao Limit



Seifert *et al., phys. med. biol.* **57** 1797, 2012

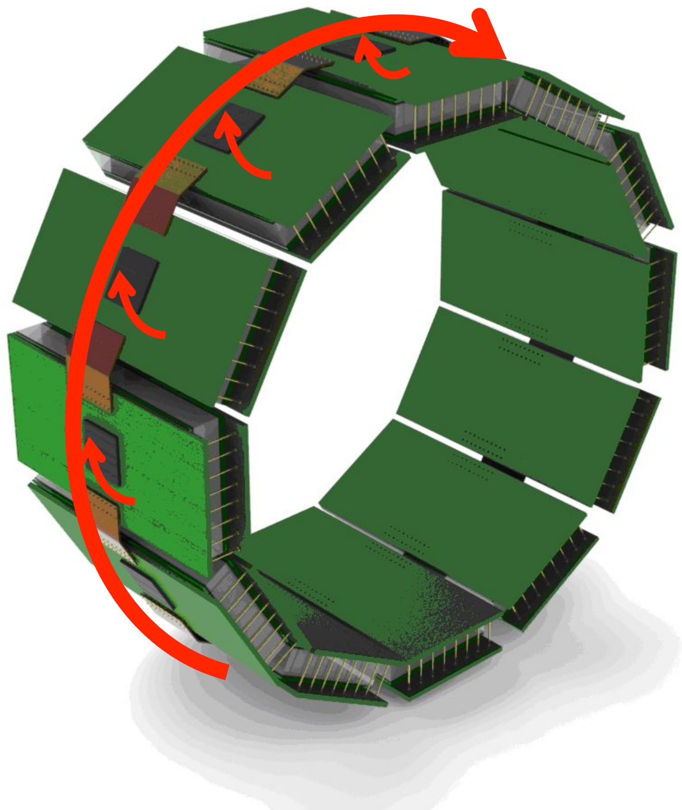
Robustness to Noise



Another Major Advantage: Coincidence Deferred to Network

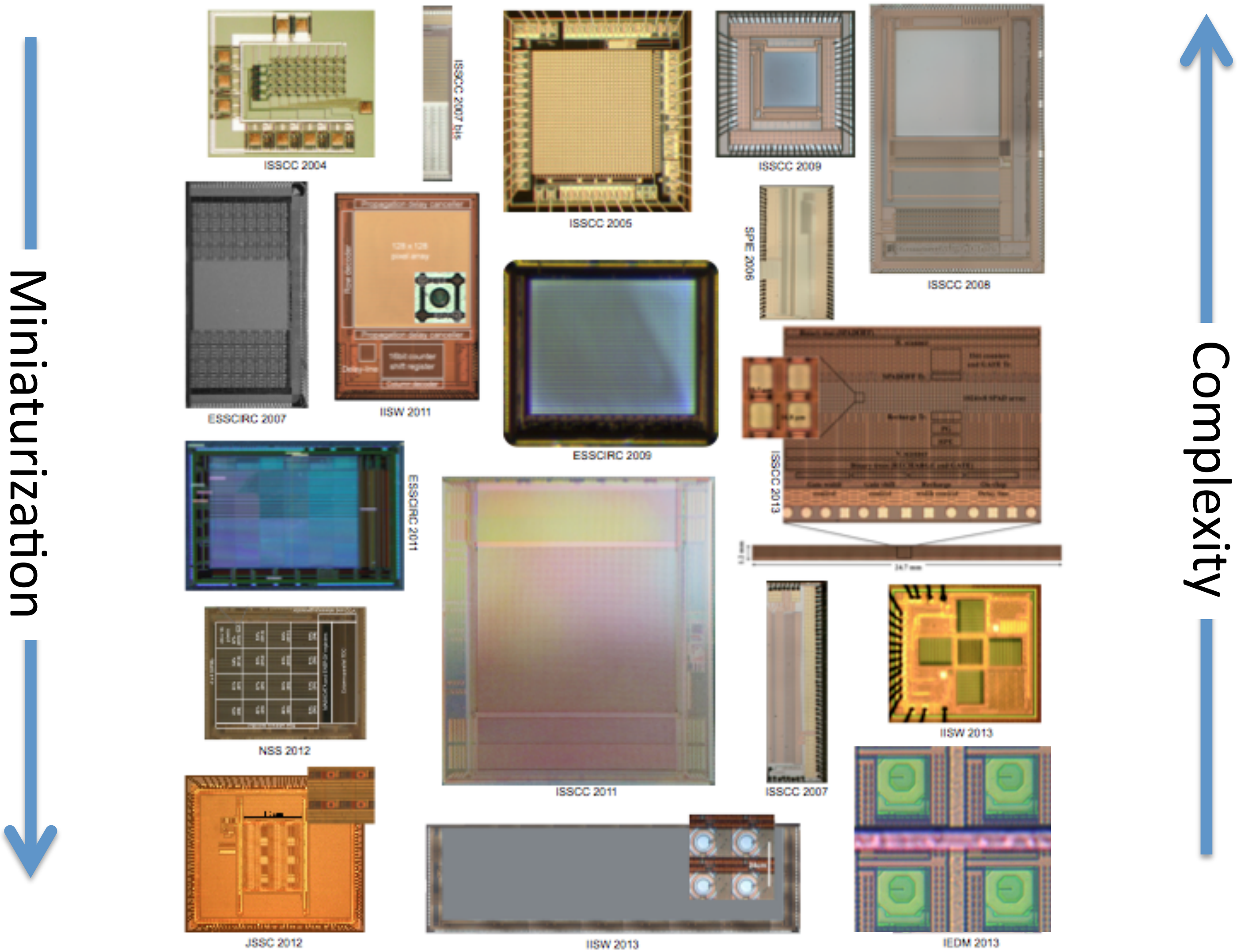
- Scalability
- Multi-ring
- Simplicity
- Cost reduction

More details in Charbon et al., IEEE NSS/MIC paper (2013)

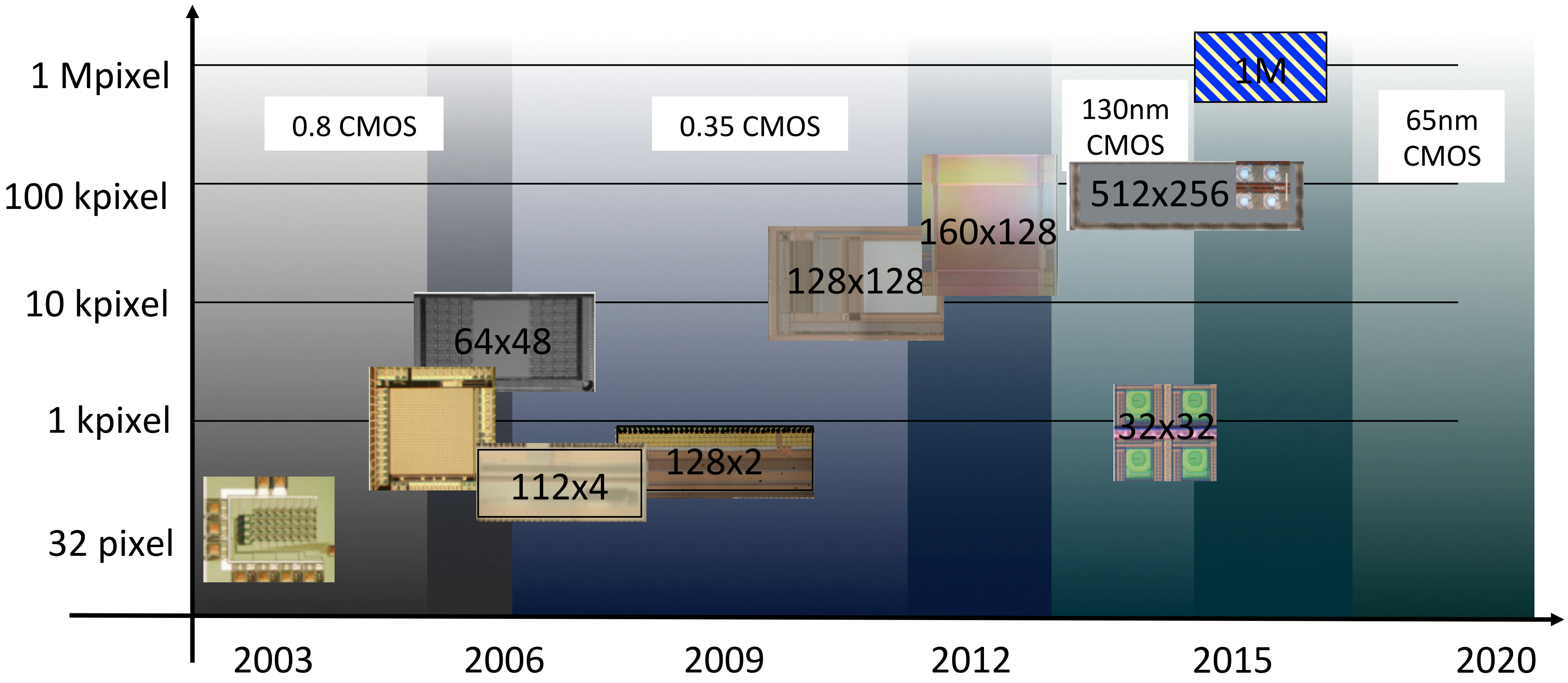


Current & Future Challenges

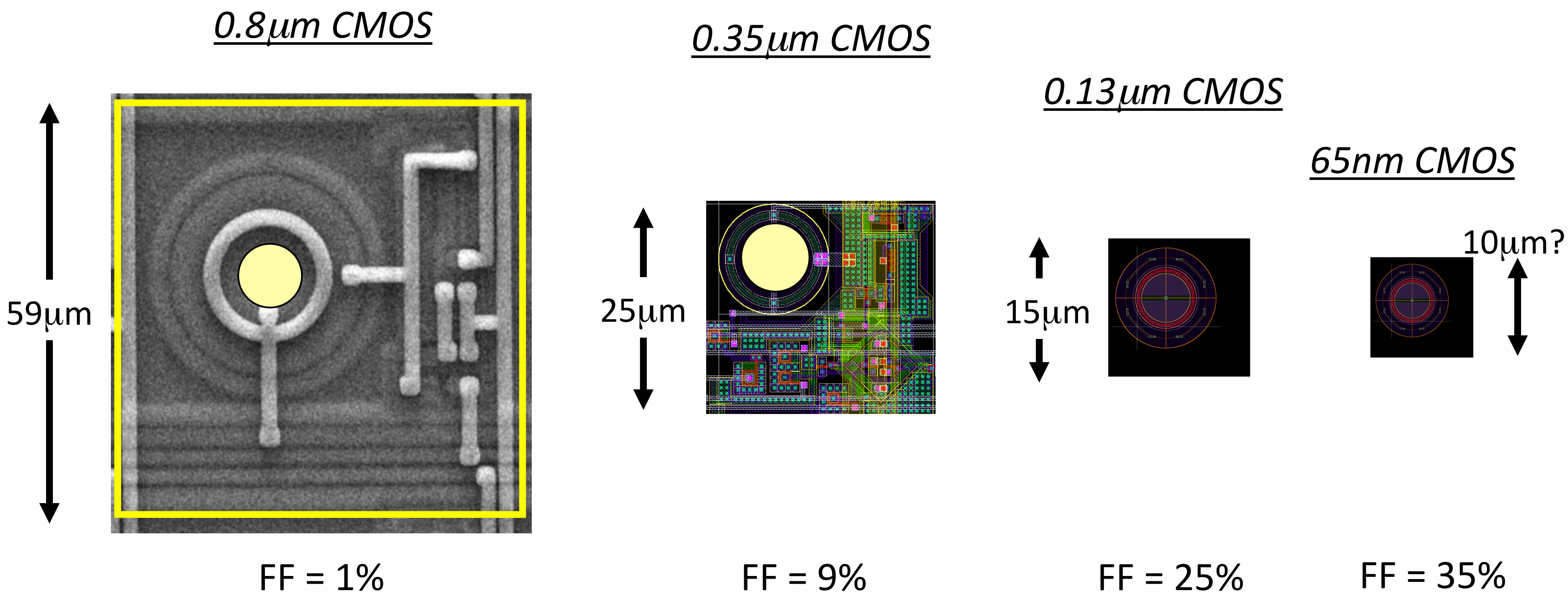
Delft/EPFL SPAD and SiPM Image Sensors (2003-13)



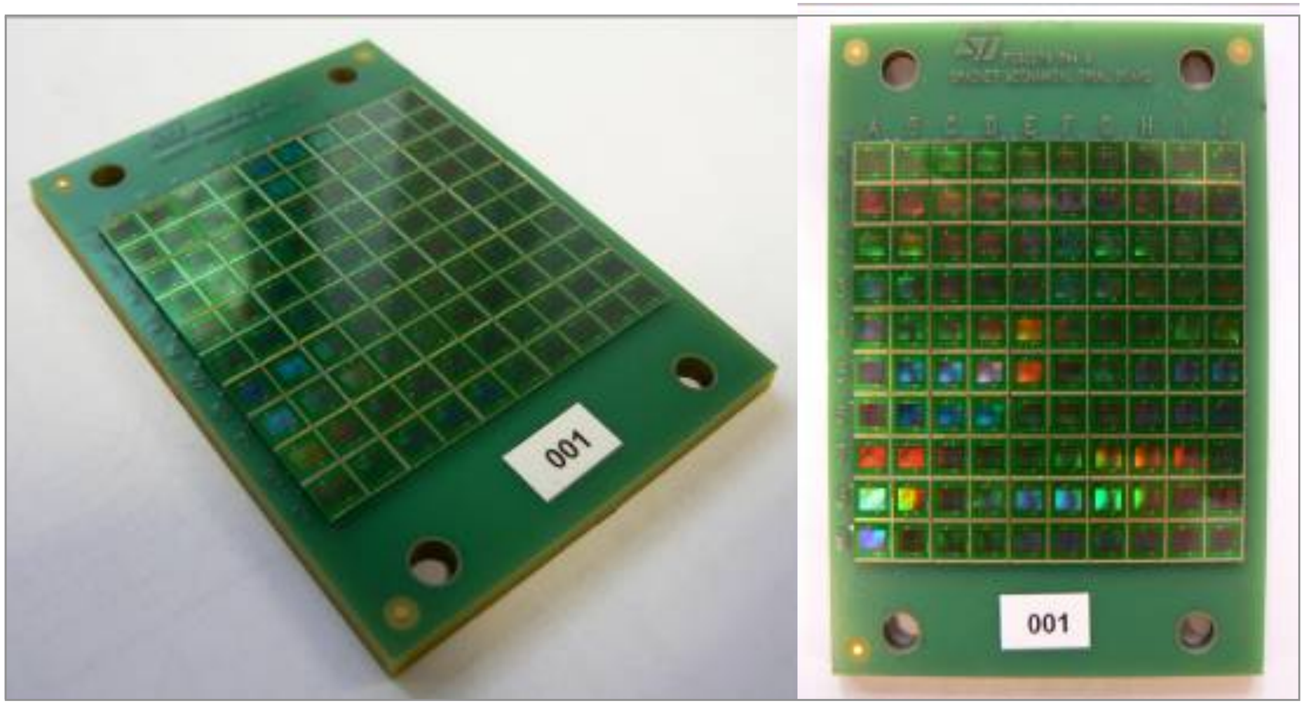
Moore's Law for SPADs



Miniaturization vs. Complexity



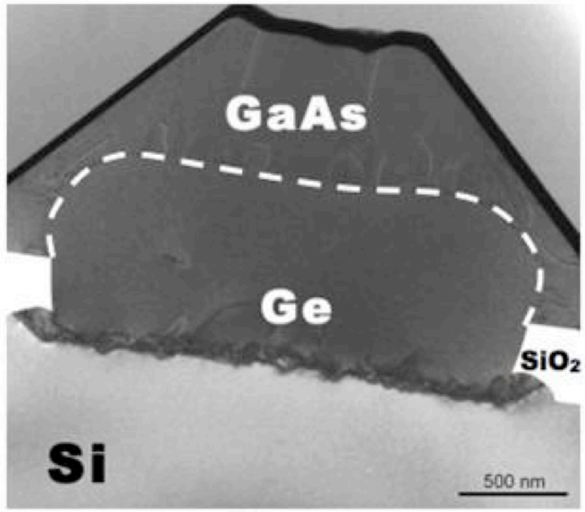
Large Format Scalability



Assembly with similar TSV chips (Courtesy: STMicroelectronics)

Ge-on-Si SPADs

- CMOS compatible
- APD / SPAD functionality
- 3D integration compatible
- Backside illumination (BSI)
- Telecom wavelengths



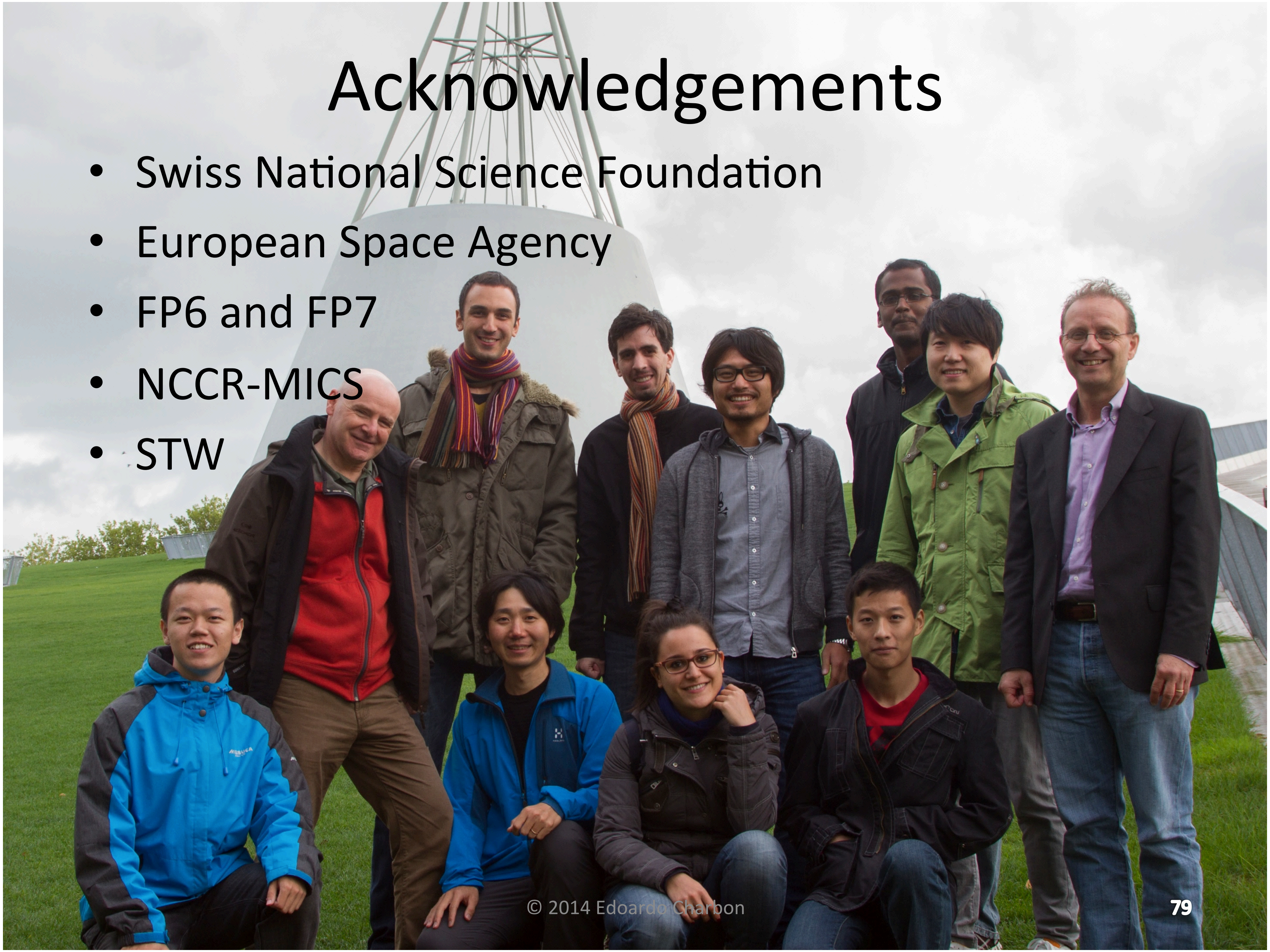
Sammak, Aminian, Nanver, Charbon, IEDM11

New Applications

- TOF PET
- Fluorescence lifetime imaging microscopy (FLIM)
- Super-resolution microscopy
- Nuclear/fluorescent cancer tracers
- Förster resonance energy transfer (FRET)
- Fluorescence correlation spectroscopy (FCS)
- Selective plane illumination microscopy (SPIM)

Conclusions: 3 Take-Home Messages

- TOF is not only for 3D vision!
- Most photon bursts have complex statistics, the mathematical tools are well developed!
- Multiphoton detection, in combination with picosecond resolution and order-statistical tools, can yield far superior timing resolutions... robustly!


Acknowledgements
• Swiss National Science Foundation
• European Space Agency
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• NCCR-MICS
• STW
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79

http://cas.et.tudelft.nl

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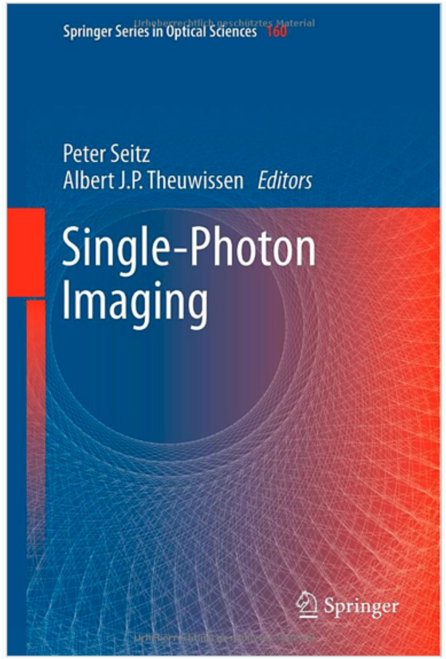

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