ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

TU Delft Delft University of Technology

(Challenges in) Time Correlated Single Photon Counting Imagers

***C. Bruschini*, E. Charbon**

SIGNAL 2016

June 26 - 30, 2016 - Lisbon, Portugal

Outline

1. (Time Correlated) Single-photon Counting & Single-photon Imaging
2. SPAD basics & SPAD imagers
3. Key SPAD Parameters, pros/cons
4. SPAD Sensor Architectures
    1. Applications & related challenges
    2. Signal processing implications, HW vs FW vs SW, embedded aspects, data management
5. Roadmap

1. (Time Correlated) Photon Counting & Single-Photon Imaging

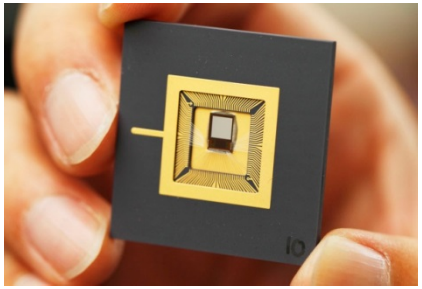
(Time correlated) Photon Counting Camera

Simple definition:

A camera where every pixel delivers a photon count and/or timestamp

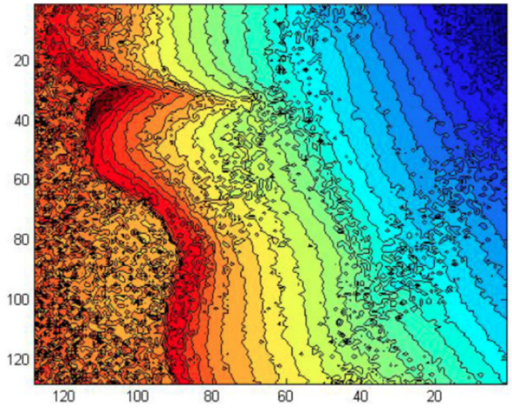
(emphasis on CMOS developments over other time-resolved approaches, e.g. MCP-PMT, ICCD, scanning systems, …)

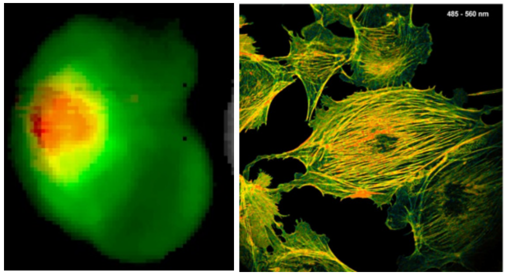
Areas of application



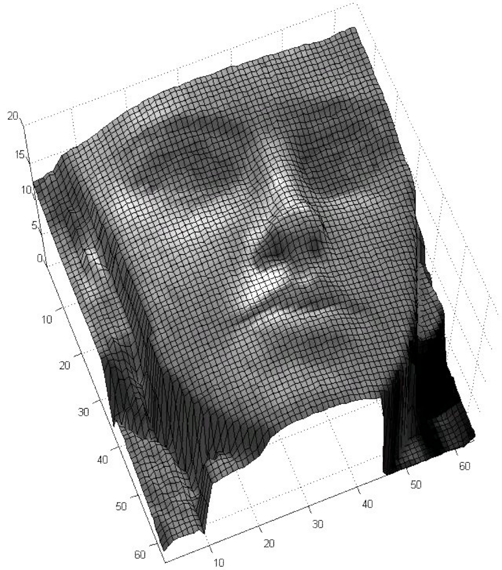
Quantum Security

Near Infrared Imaging (NIRI)



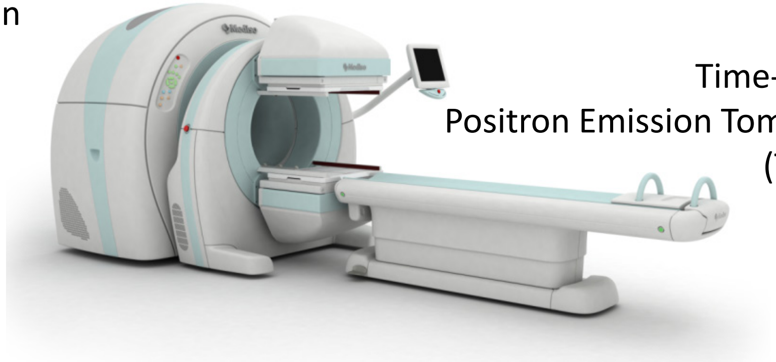


Fluorescence Lifetime Imaging Microscopy (FLIM) and super-resolution microscopy (STED, STORM, GSDIM, PALM, etc.)

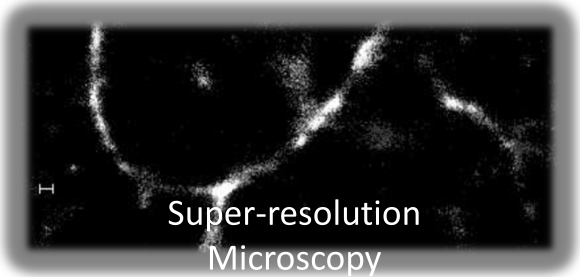


3D Vision

Time-resolved Raman Spectroscopy



Time-of-Flight Positron Emission Tomography (TOF PET)



Super-resolution Microscopy

Potentially:

single-photon granularity

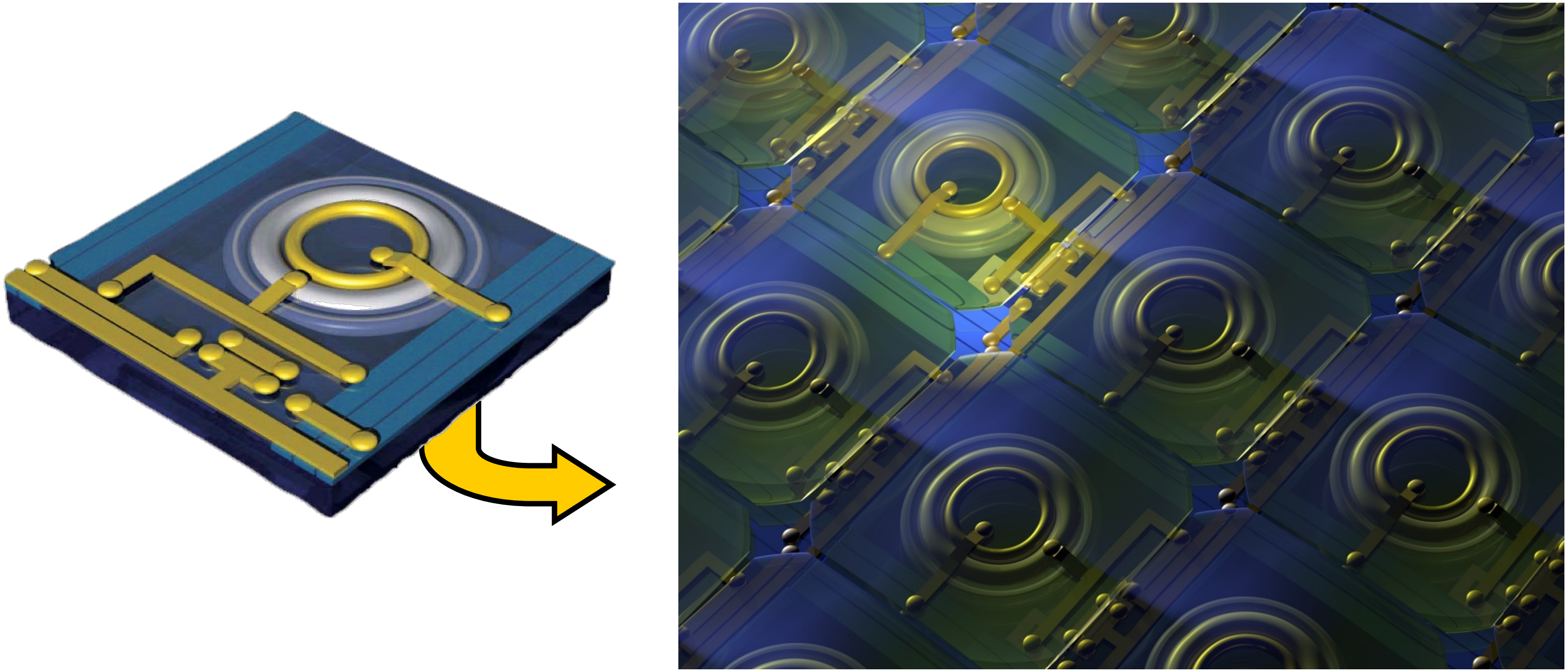
-» photon-counting imaging

picosecond granularity

-» time-resolved imaging

(CMOS) low-cost, with on-chip processing capabilities

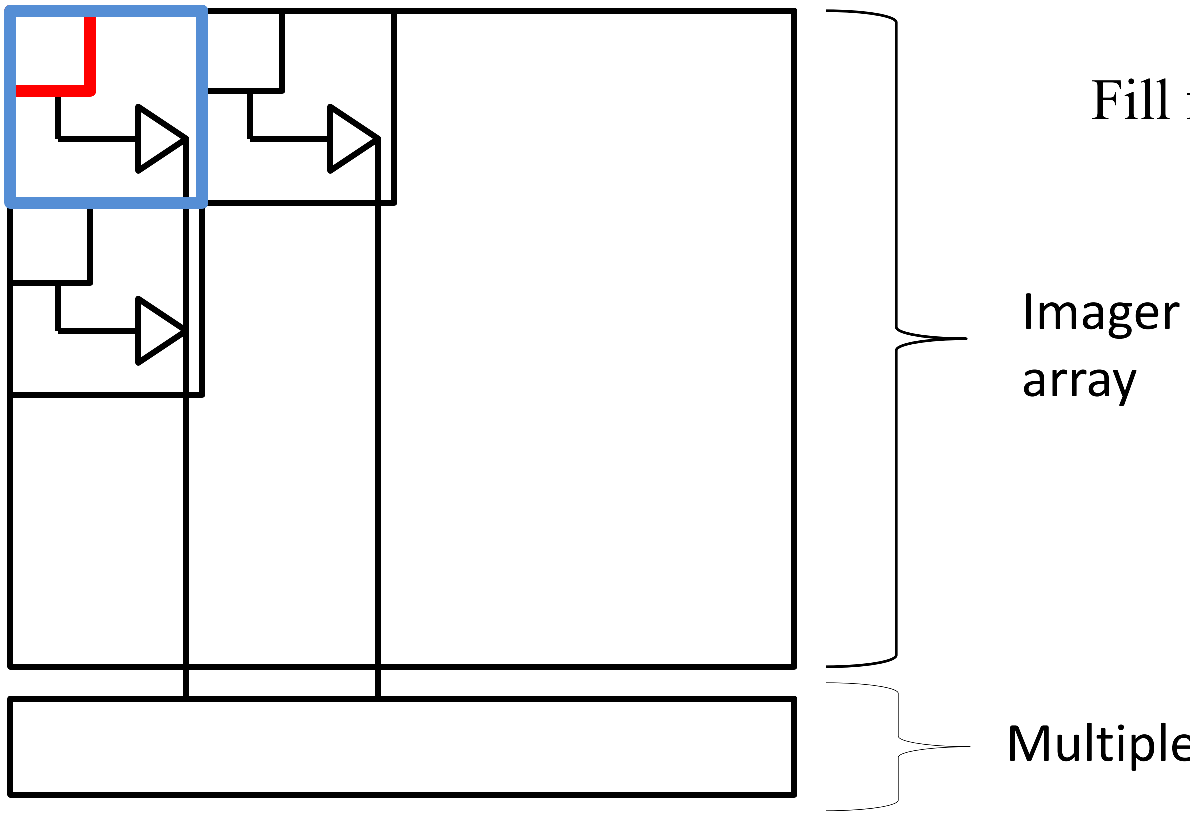
Main Challenge:
Pixel → Imager → System → «Image»



2. SPAD Basics
&
SPAD Imagers

(SPAD: Single-Photon Avalanche Diode)

SPAD imager overview



$$\text{Fill factor} = \frac{\text{active area}}{\text{pixel area}}$$

I.M. Antolovic, FOM 2015

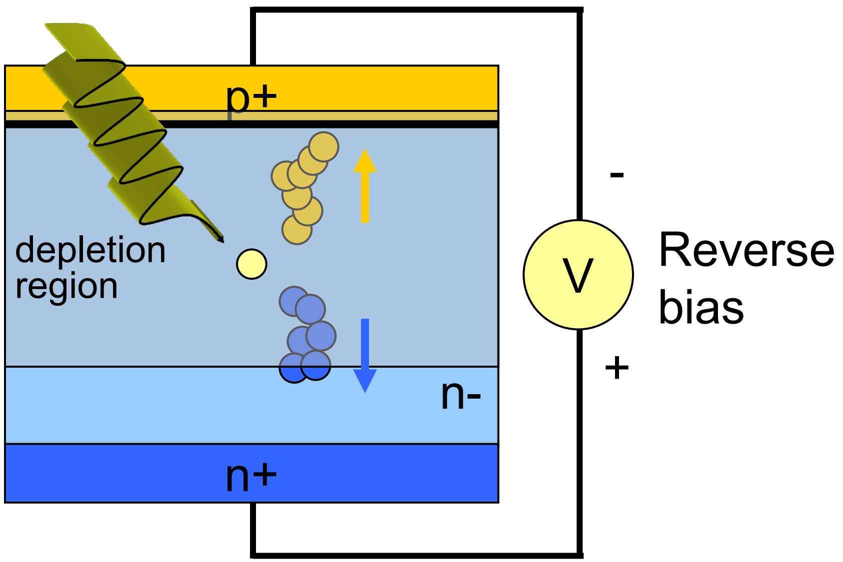
Advantages:
- Early digitalization
- Very fast
- No readout noise

Disadvantages:
- Lower fill factor
- Lower sensitivity

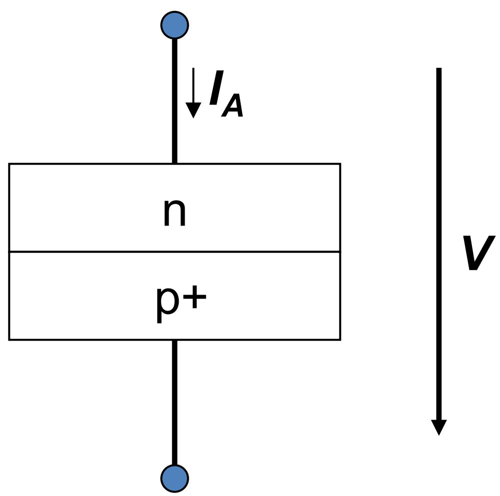
Avalanche photodiode (APD)

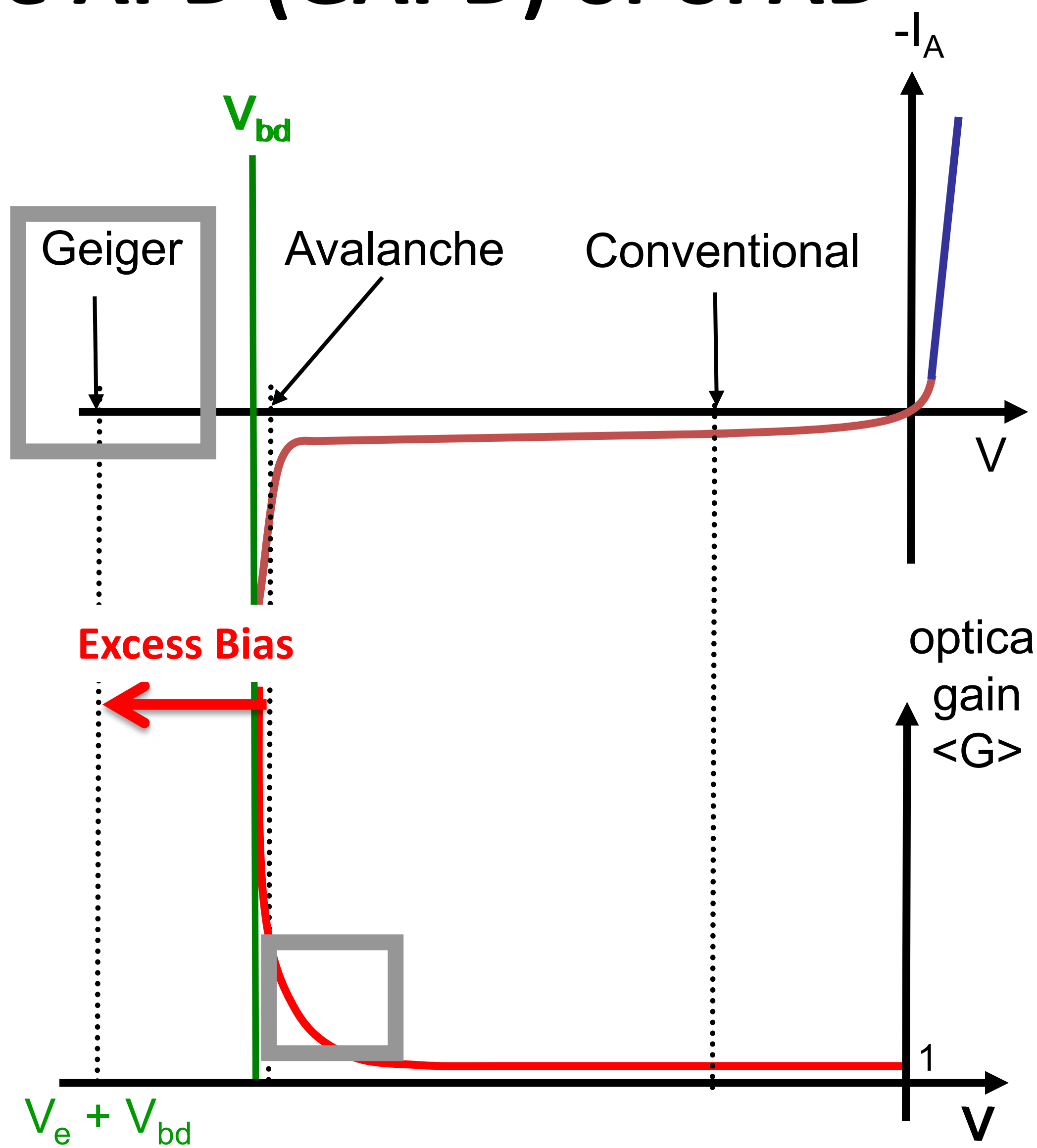
- Suppose one can perform *impact ionization* in a solid, thereby achieving *very large gain* in an area of a *few tens of μm²* (thus at pixel level)

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



Geiger-mode APD (GAPD) or SPAD



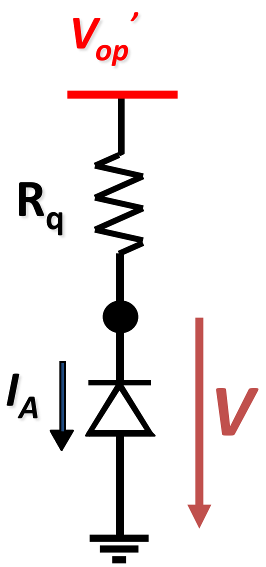


- One can achieve a virtually infinite gain biasing above breakdown…

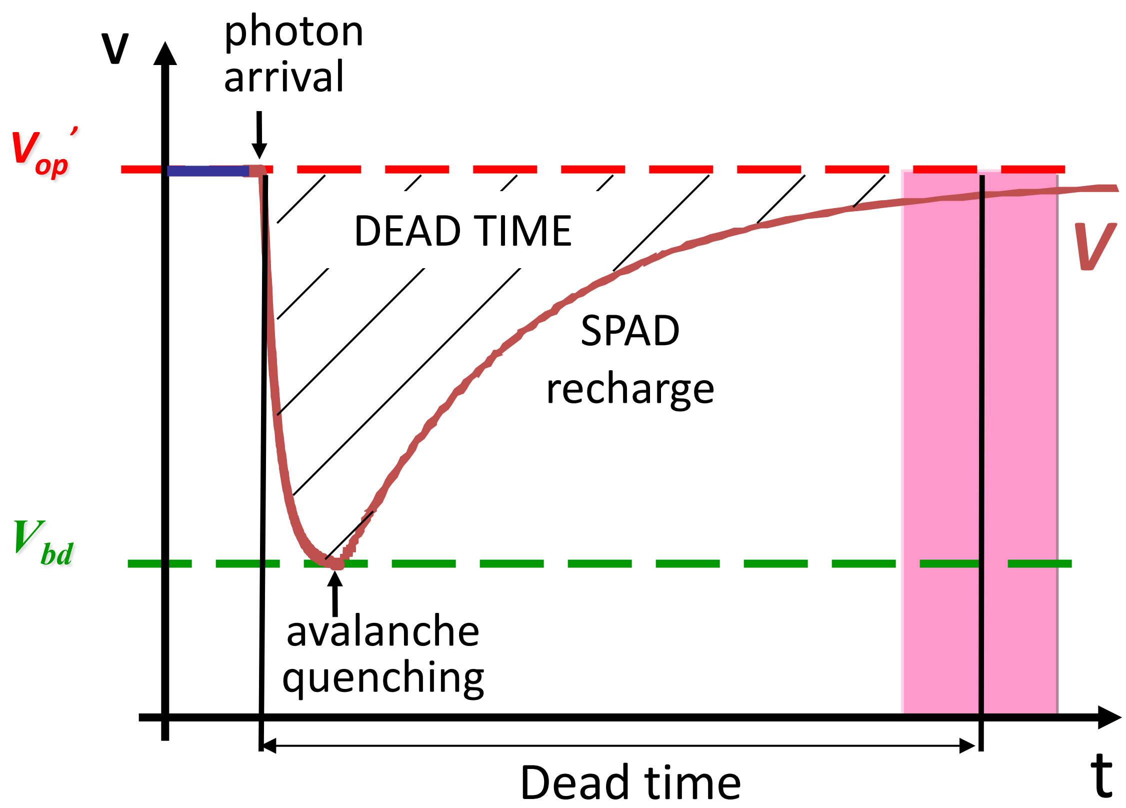
Thus gain variability is meaningless

Quenching

Passive quenching:

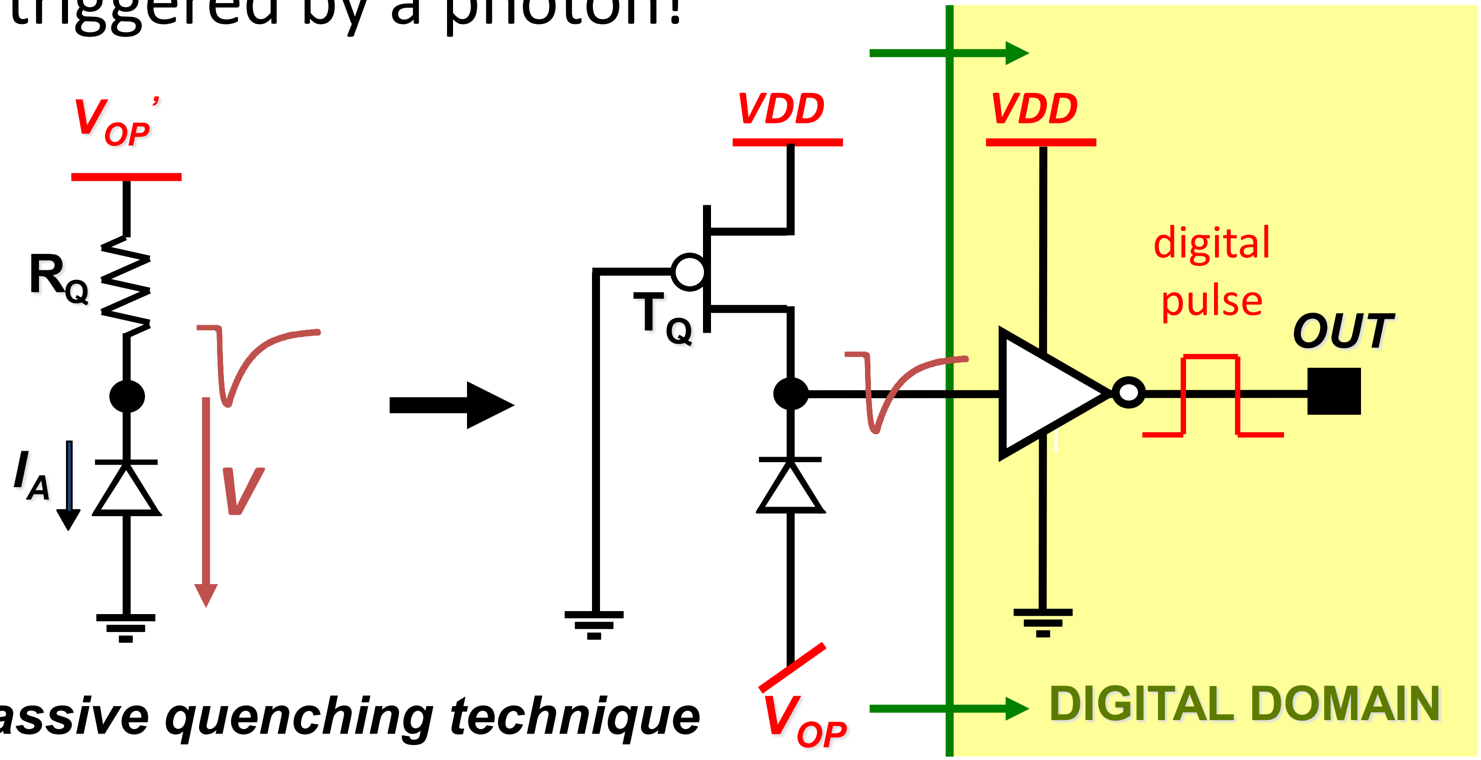


Operation cycle:



Quenching (and gating) a SPAD in CMOS

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



Passive quenching technique

- With two more switches one can <u>gate</u> sensitivity

3. Key SPAD Parameters

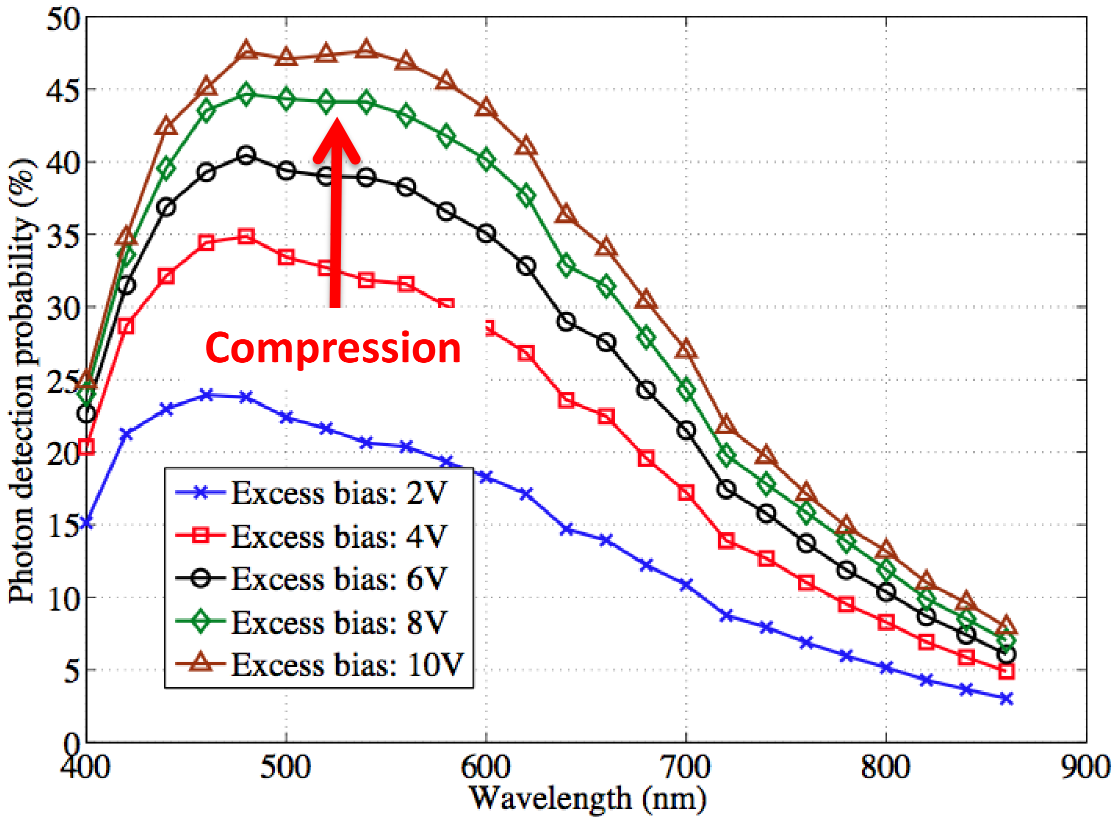
Characterizing SPADs for imaging

- *Dead time* (10-100ns)
- Dark counts (Hz-kHz)
- Sensitivity
  - Photon Detection Probability (PDP) (1-50%)
  - Fill-factor (1-50%)
- Timing resolution (~10-100ps)
- *Afterpulsing* (0.1-10%)

… and in SPAD imagers

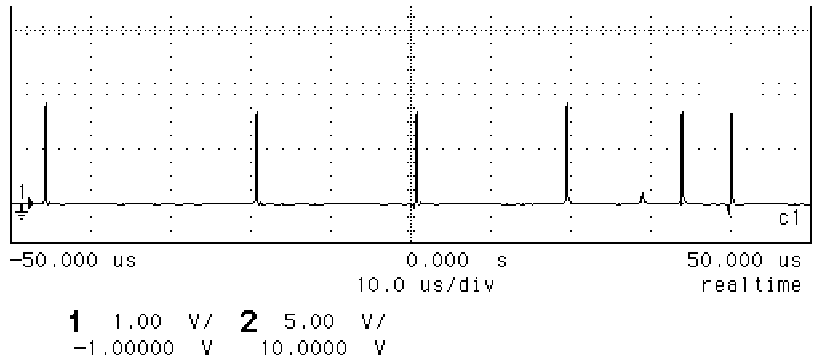
- Cross-talk
- Sensitivity Uniformity
- Noise Uniformity

Sensitivity: Photon Detection Efficiency (PDE)

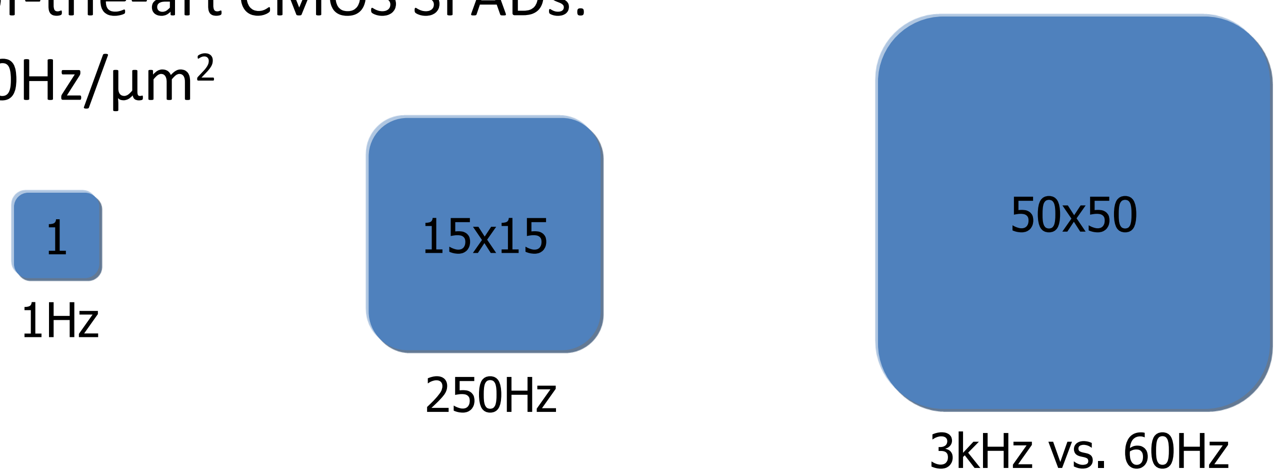


C. Veerappan and E. Charbon, JSTQE 2014

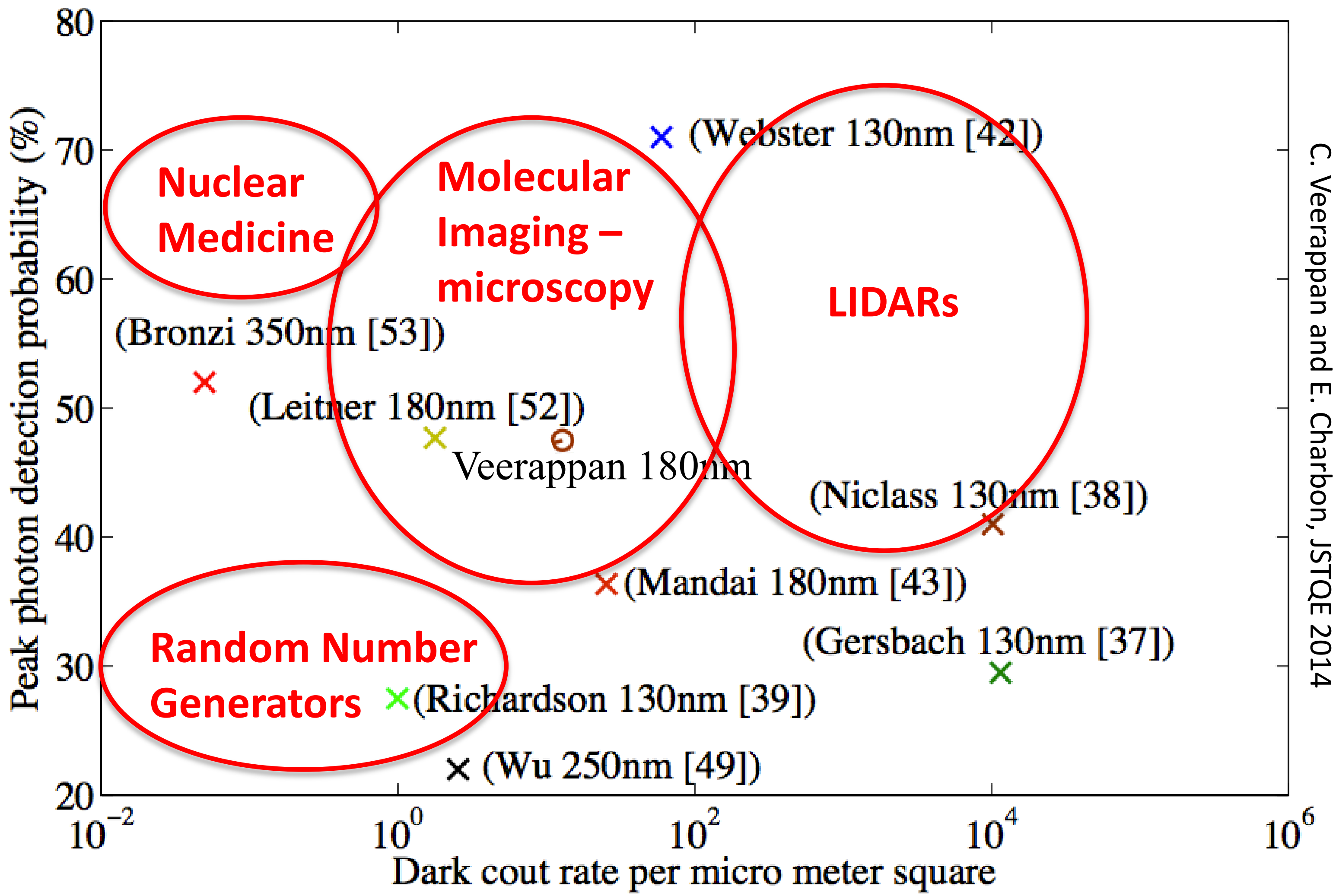
Dark Counts: Dark Count Rate (DCR)



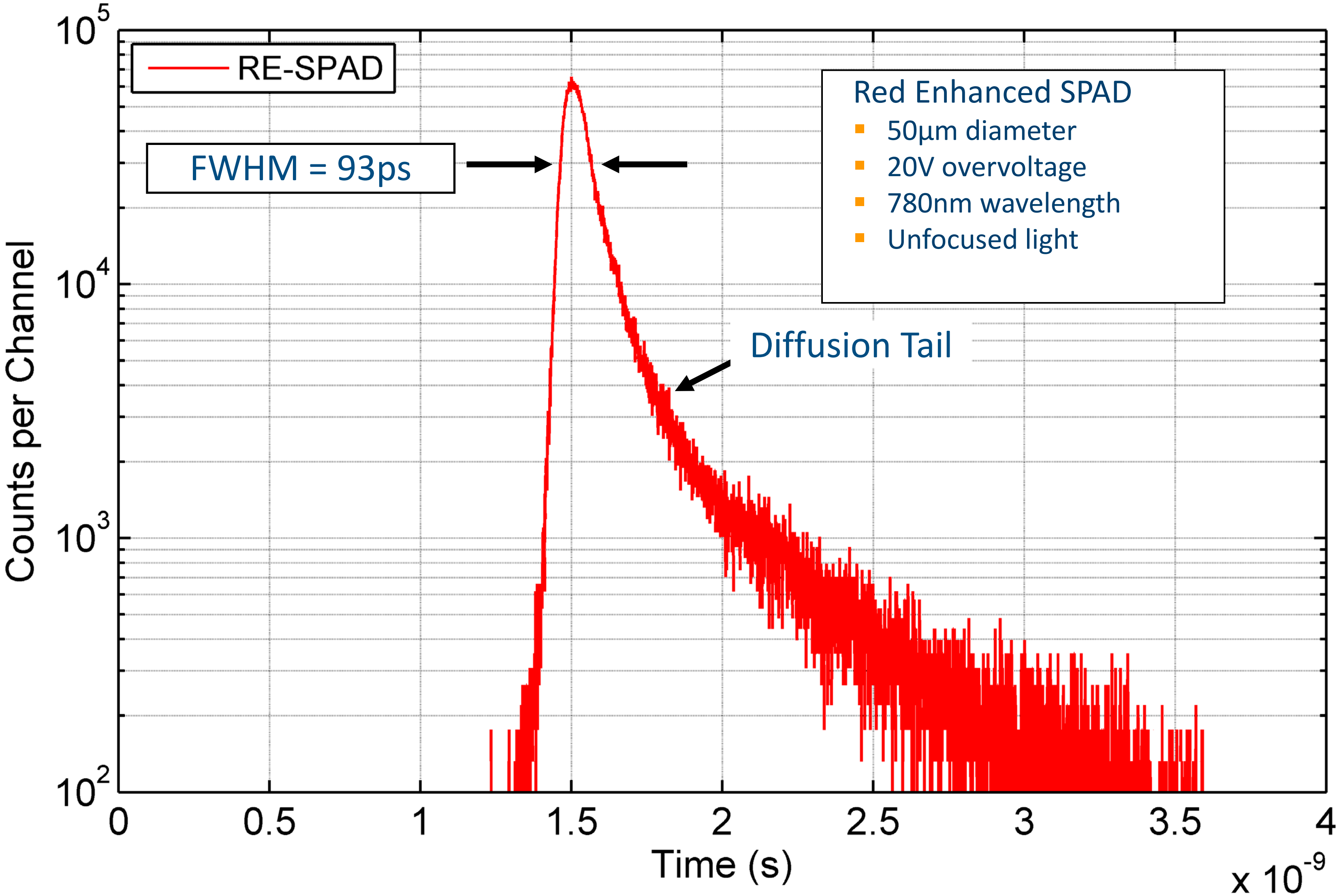
- State-of-the-art SPADs in dedicated technology: 0.04~1Hz/µm^2
- State-of-the-art CMOS SPADs: 0.1~10Hz/µm^2



DCR vs. Applications



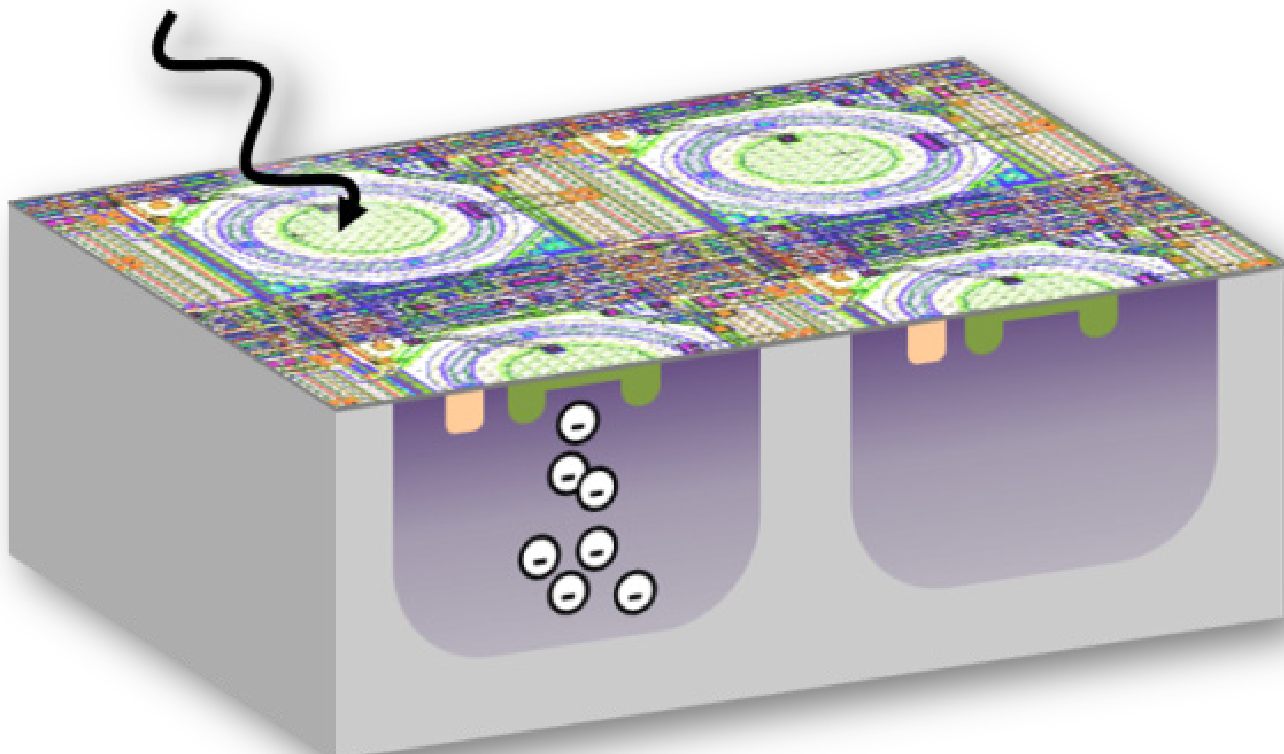
Timing resolution



Courtesy: Sergio Cova

Crosstalk

- Optical and electrical interference
- Measured by avalanche cross-inter-arrival
- Similar to afterpulsing acting between pixels



Take-Home Message – Uniformity:

Uniformity of sensitivity
Uniformity of noise
Uniformity of xtalk, afterpulsing (~0)

Take-Home Message – Tradeoffs:

PDE vs. DCR

Wavelength vs. Timing

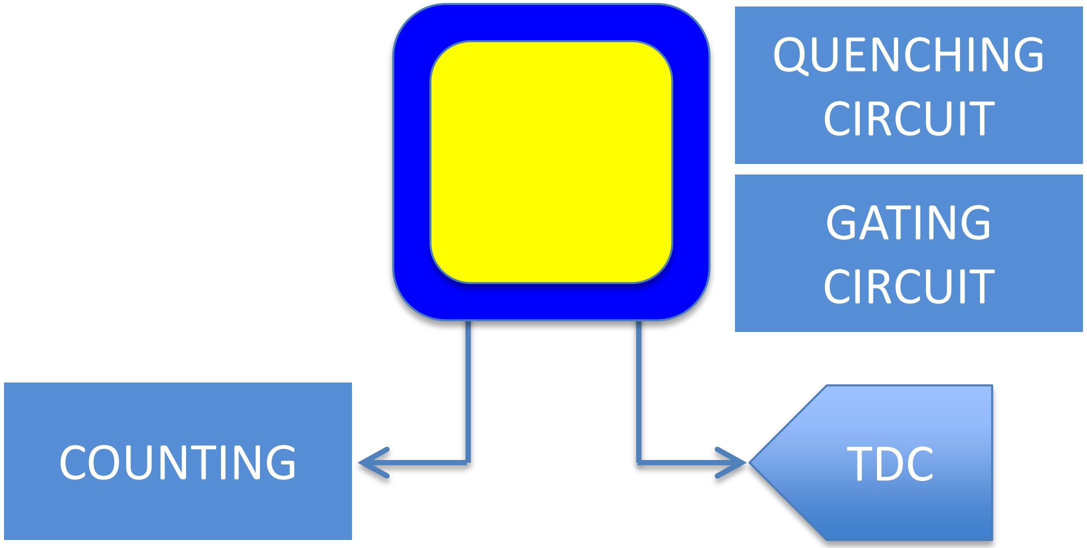
Dead Time vs. Dynamic Range

…For imaging…

Uniformity, Uniformity, Uniformity

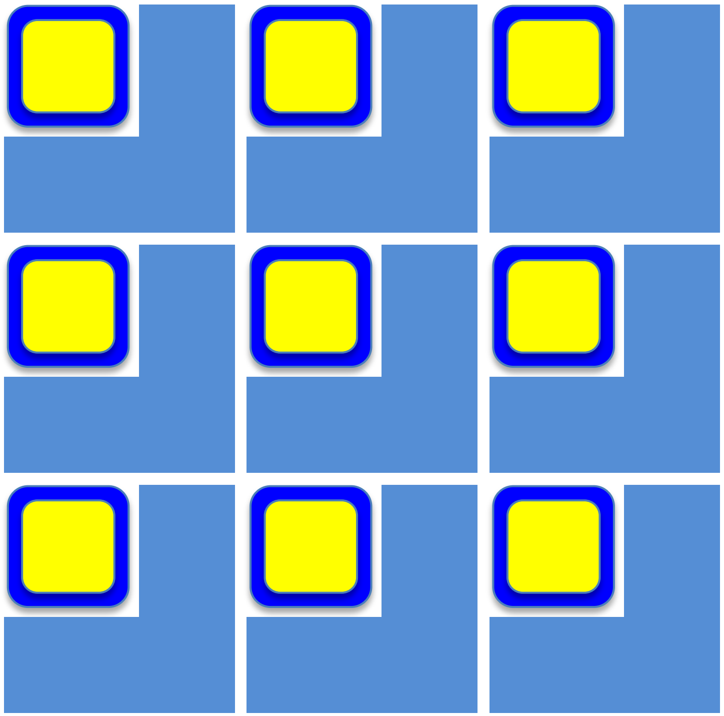
4. SPAD Sensor Architectures & Applications

Generic pixel

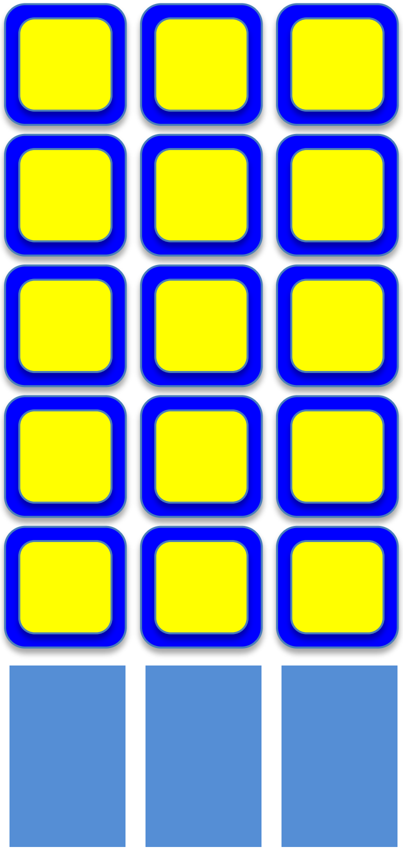


2D array

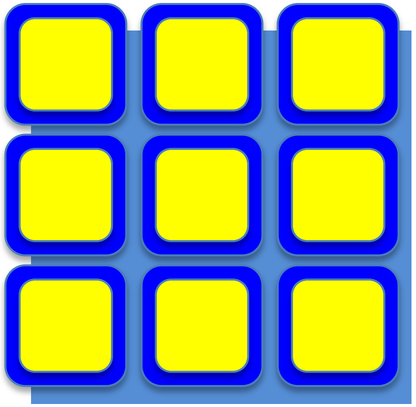
Fully parallel



Column-Parallel

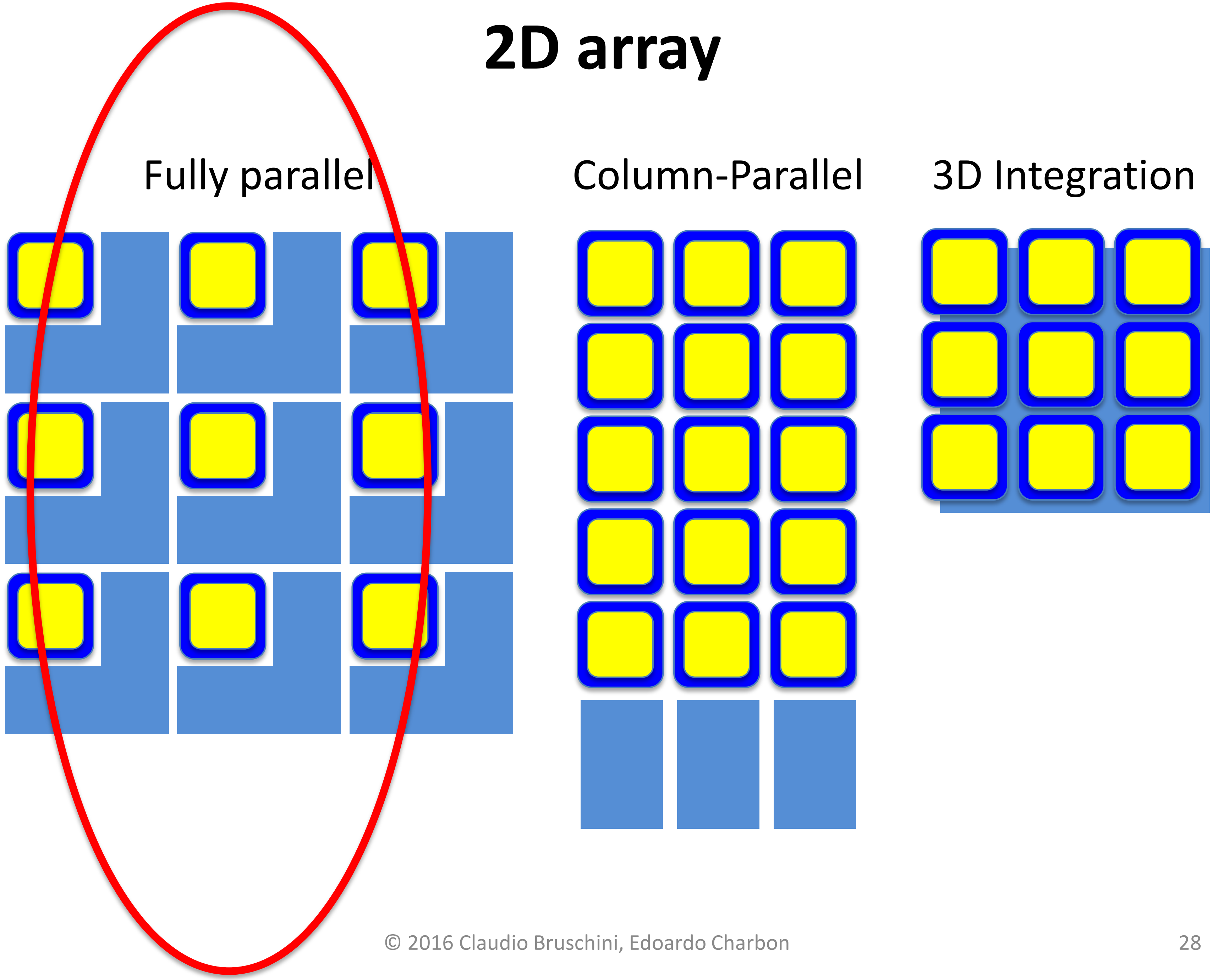


3D Integration

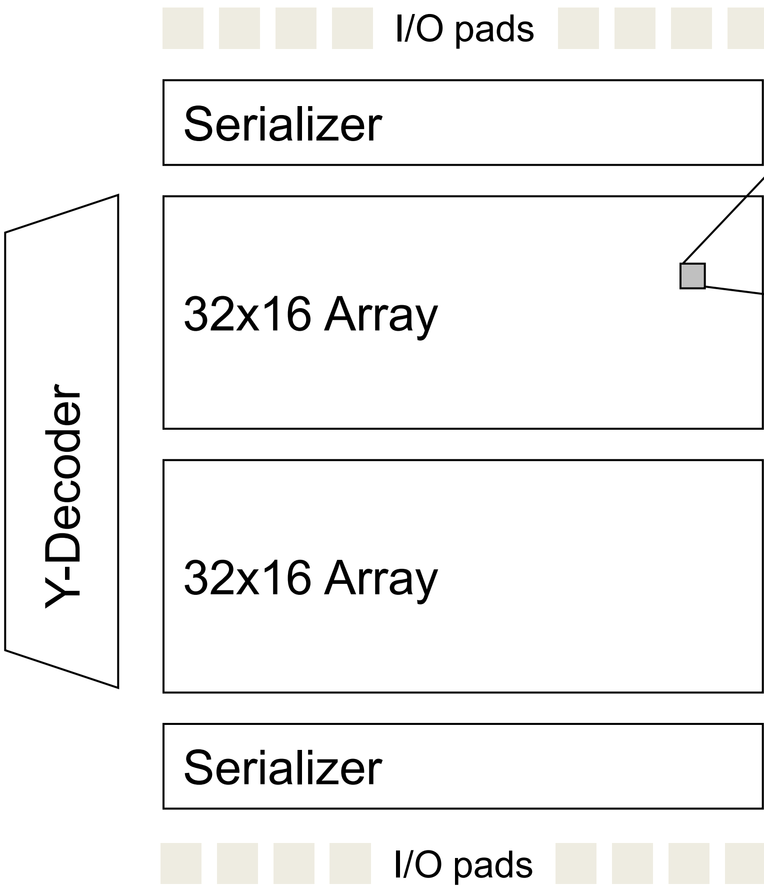


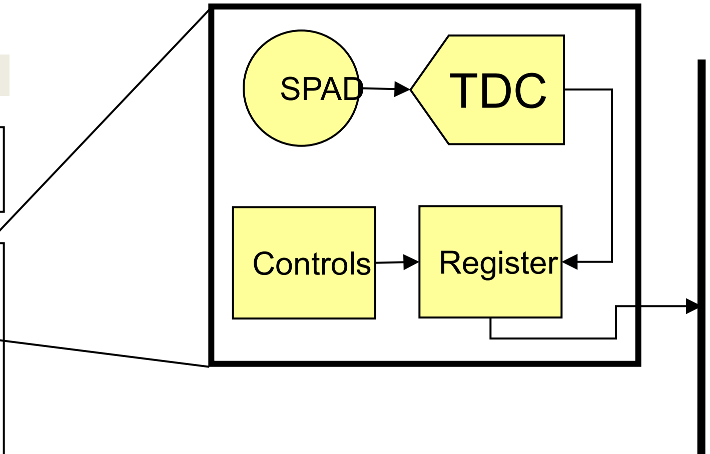
4.1 MEGAFRAME – 32×32 & 128×160 Fully Integrated TCSPC Matrix

2D array

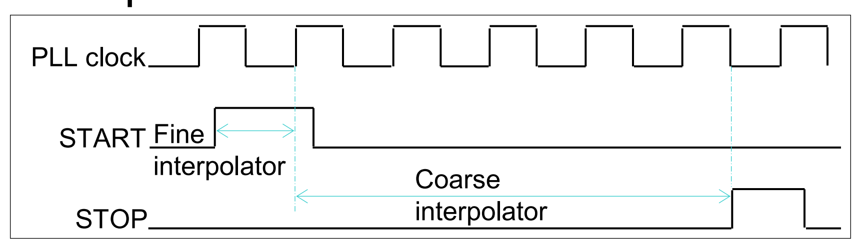


MEGAFRAME:
Massive Integration in DSM



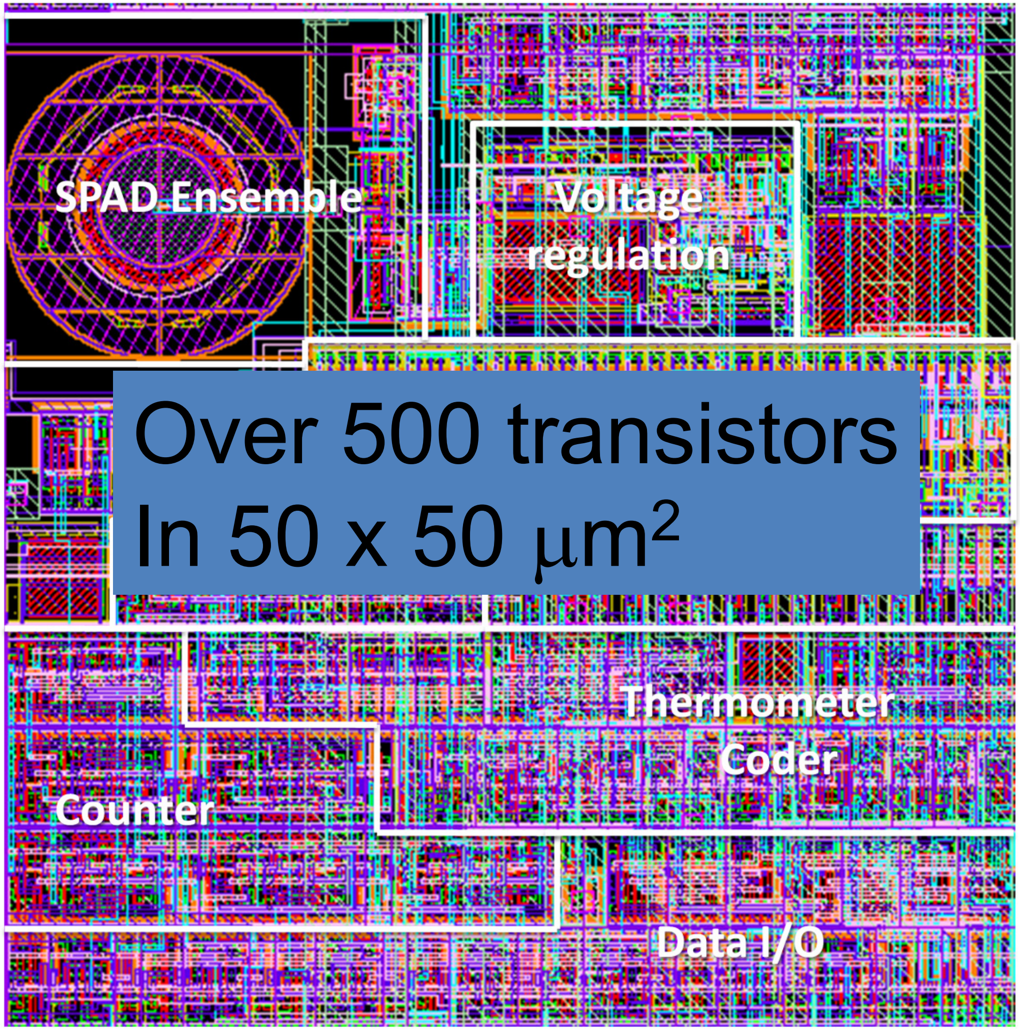


Principle of TDC



Implemented on 130nm CMOS

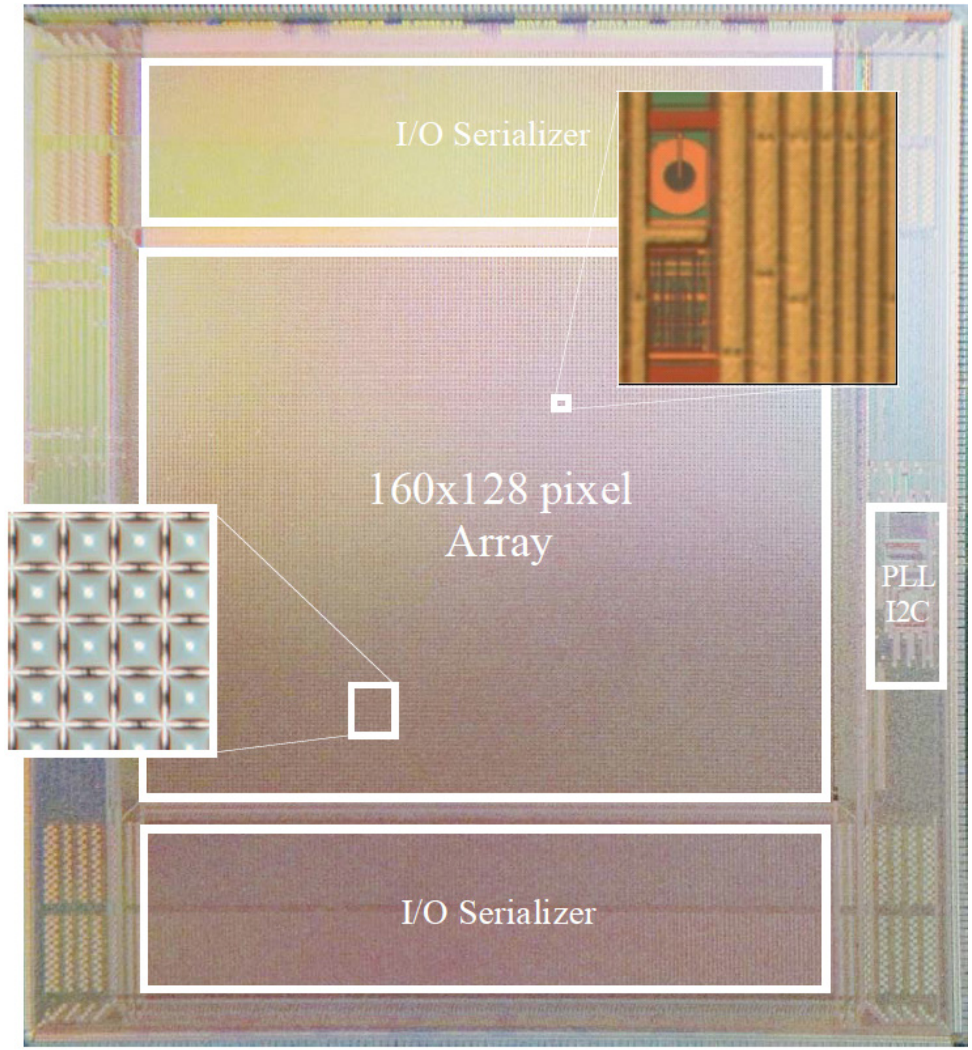
MEGAFRAME
Pixel Layout



Pitch: 50um
Max. Resolution: 119ps
Bandwidth: 1MS/s
Accuracy: 1.2LSB (INL)
Timing jitter: 128ps (FWHM)
Timing uniformity: < 2LSB

The MEGRAME128 Chip

50um pitch

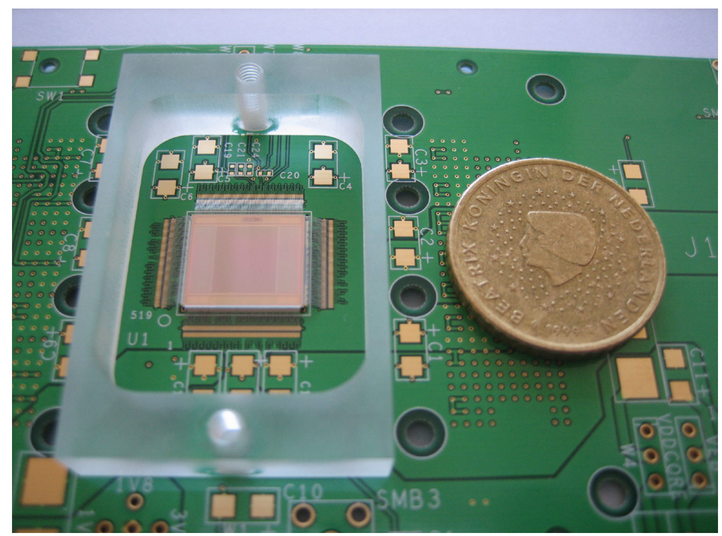


12.3mm

11.0mm

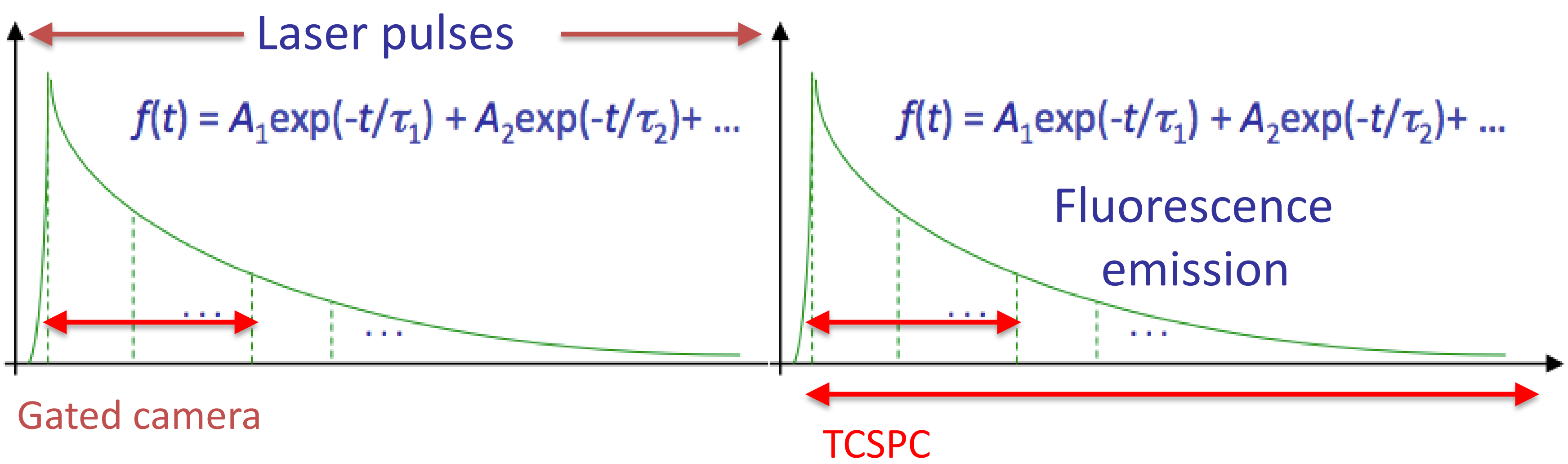
MEGAFRAME Summary

- Format: 160x128 pixels
- Timing resolution: 55ps
- Impulse resp. fun.: 140ps
- DCR (median): 50Hz
- R/O speed: 250kfps
- Size: 11.0 x 12.3 mm^2



4.1 MEGAFRAME - Applications

Fluorescence Intensity vs Lifetime Images

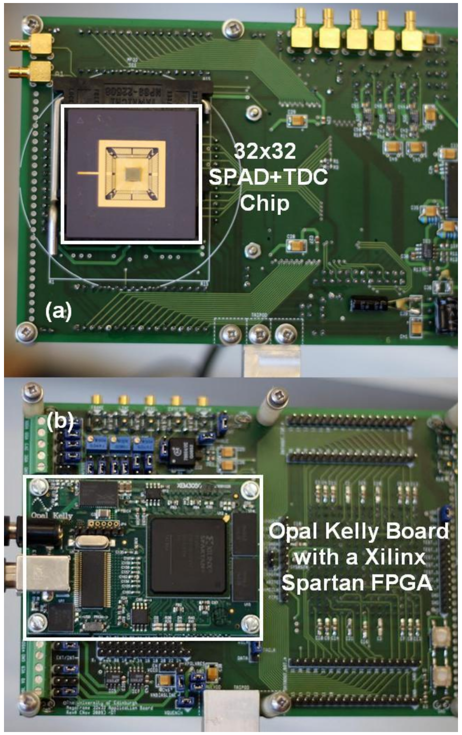


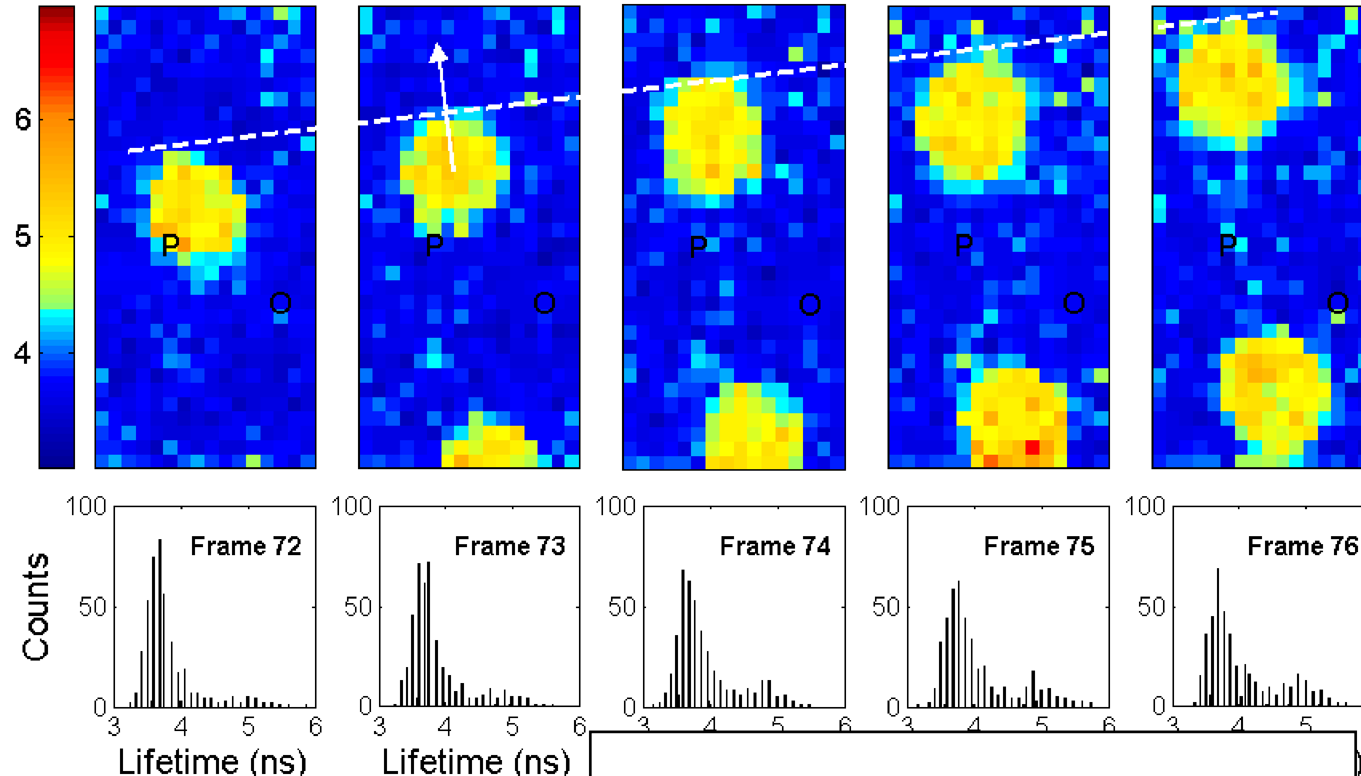
- Intensity images: the pixel measures the intensity in the gated window: $I(t) \propto \int_w f(t)\,dt$, $f(t)$ is the fluorescence density.
- Lifetime images: the pixel time-tags all photons and calculates parameters τ_1, τ_2, A_1, A_2, etc.

Courtesy David Li, Strathclyde Univ., 2016

Courtesy David Li, Strathclyde Univ., 2016

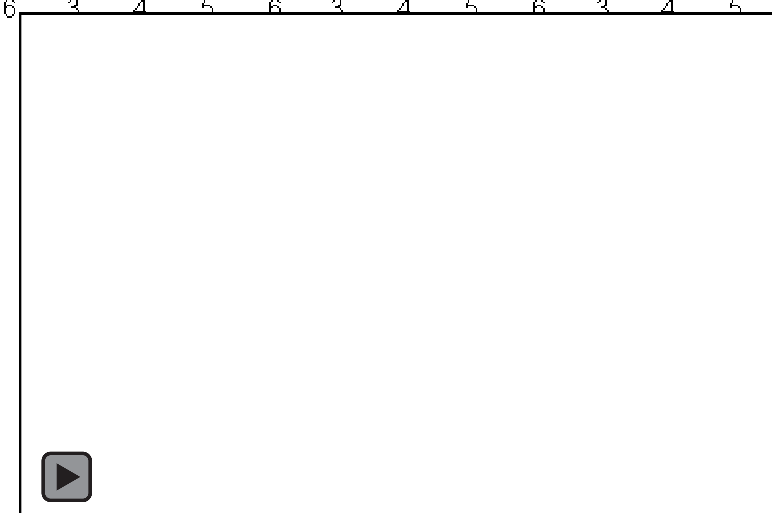
Video-rate FLIM (> 100fps)





Li et al., 2011, 2012
Arlt et al., 2013

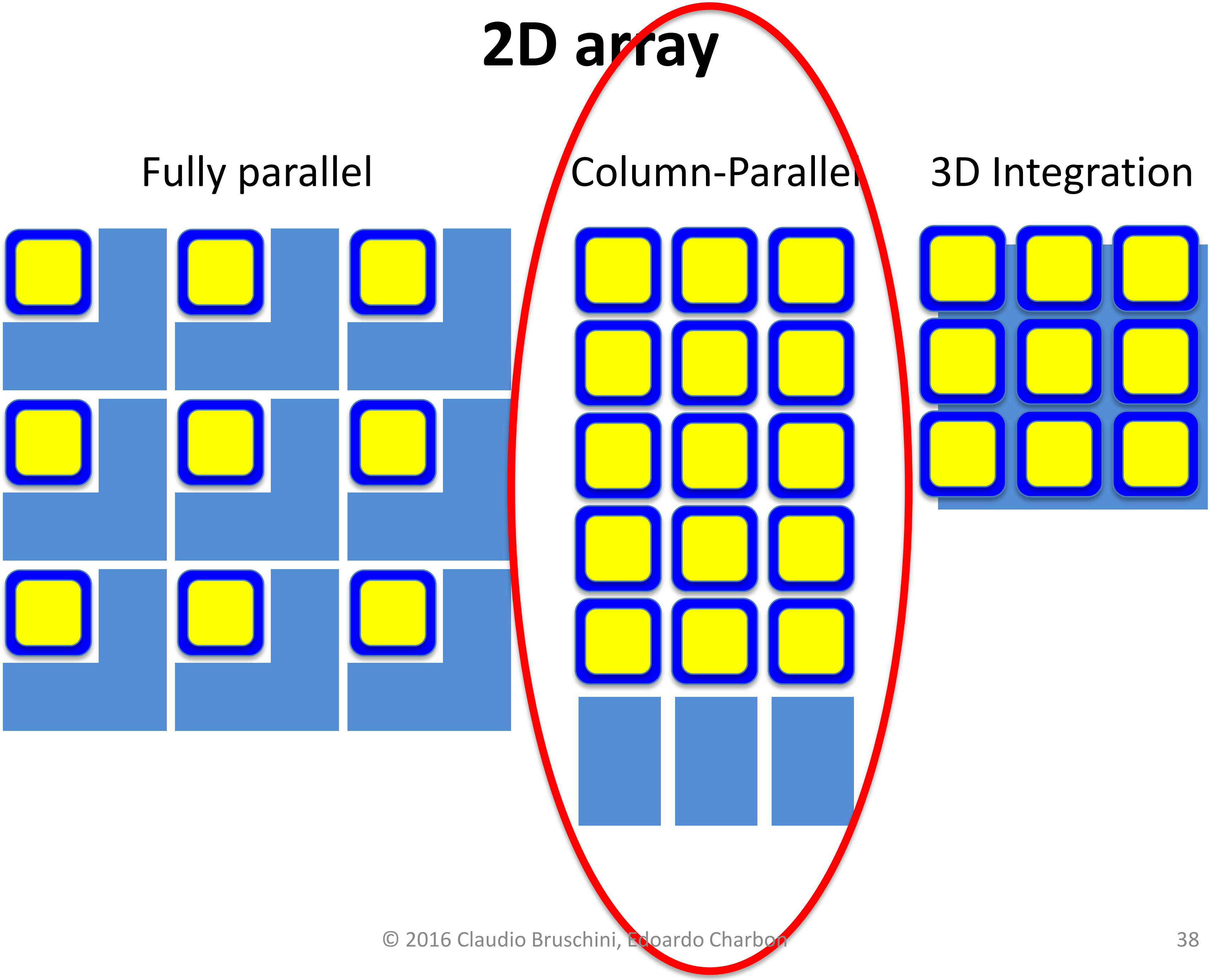
Fast FLIM:
$$\tau = \frac{\sum_{i=1}^{N_C} t_i}{N_C}, N_C = \sum_{j=1}^{M} N_j$$



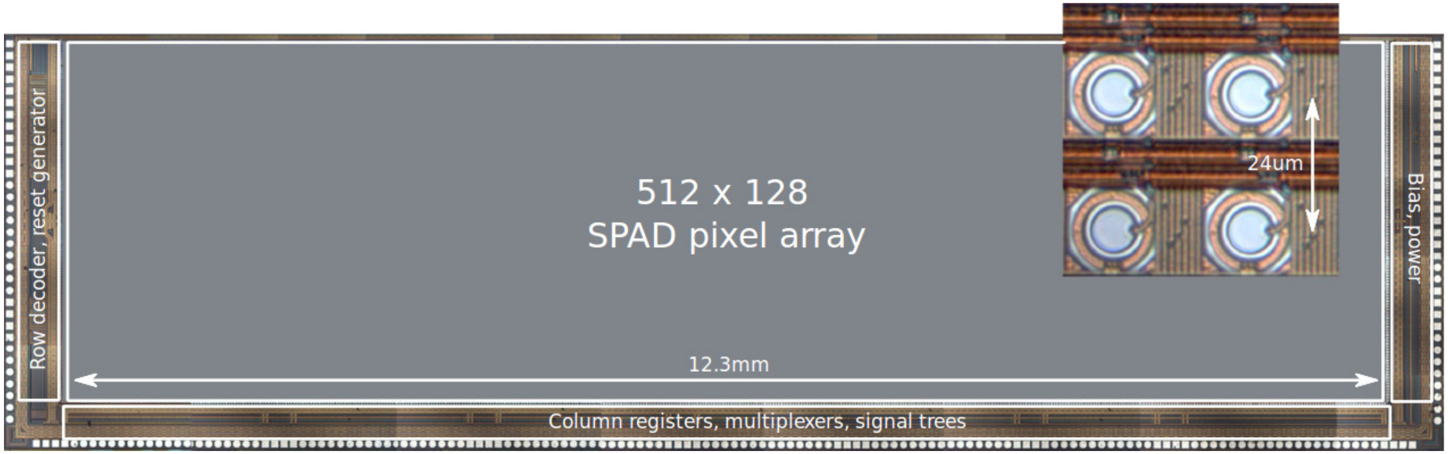
Raw TCSPC data: 640Mb/s
FLIM data: 20Mb/s, No FLIM software.

4.2 SwissSPAD - 512×128 single-bit time-gated matrix

2D array



SwissSPAD

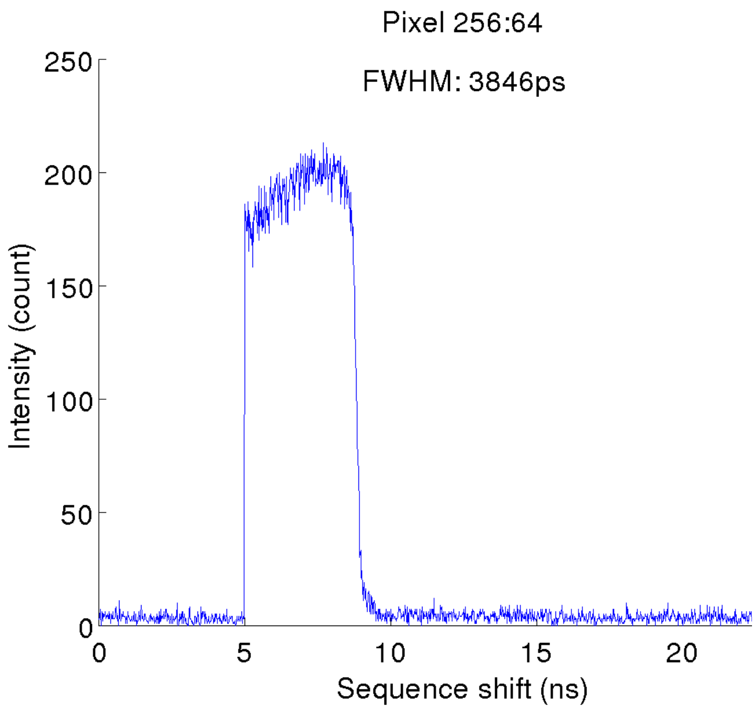


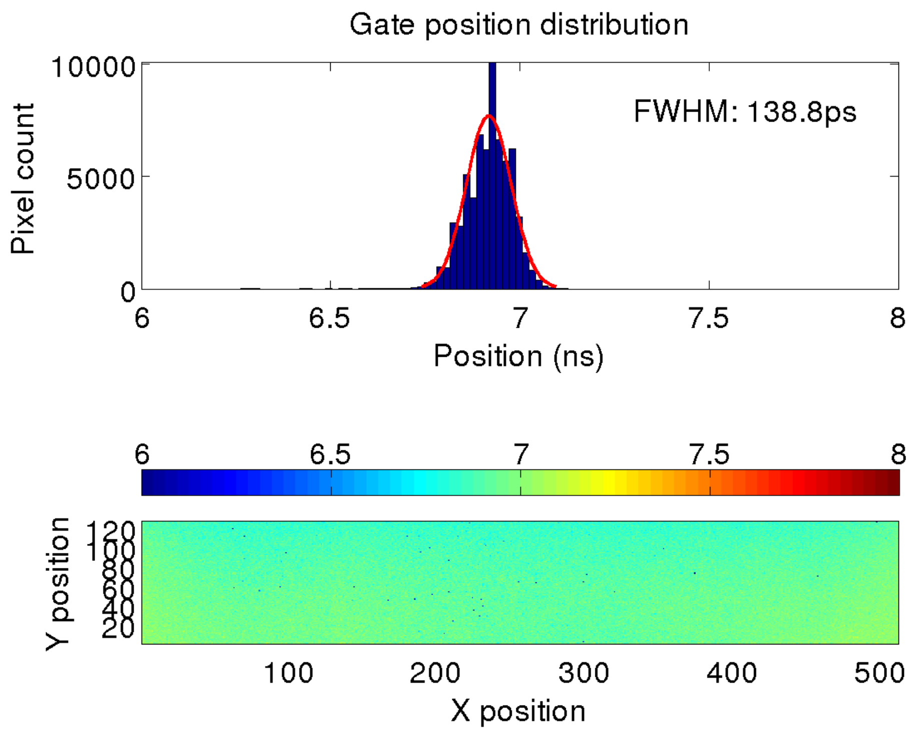
Burri et al., Optics Express 2014

Peak PDE	~20% at 450 nm
Min. frame time	6.4 µs, 512×128 pixels, 1 bit
Readout noise	0 counts
Dark counts	~200 cps at 25 ℃
Pixel pitch	24 µm
Imager size	12.3×3.1 mm^2
Operating temperature	25 ℃
Afterpulsing	<0.3%
Crosstalk	<0.3%
PRNU	<1.8%

SwissSPAD Gate accuracy and uniformity

- 4ns gating (138ps FWHM)
- 156kfps frame rate





Burri et al., Optics Express 2014

4.2 SwissSPAD - Applications

SwissSPAD Frame rate vs. data rate

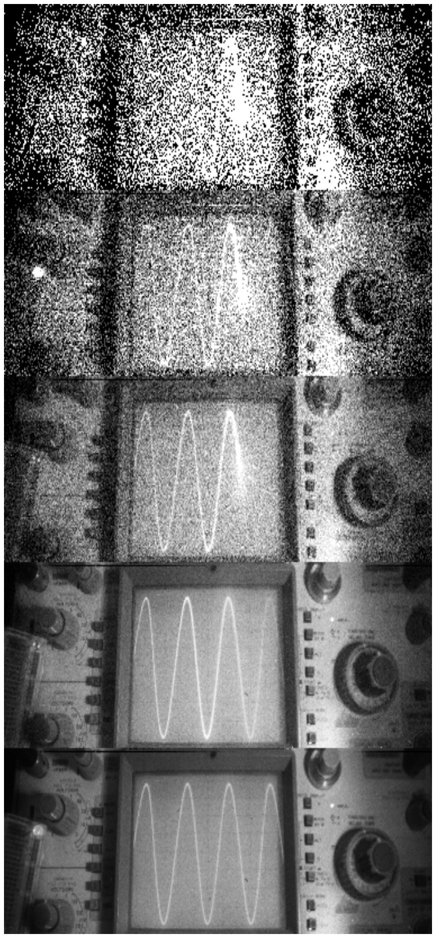
156kfps, 1 bit

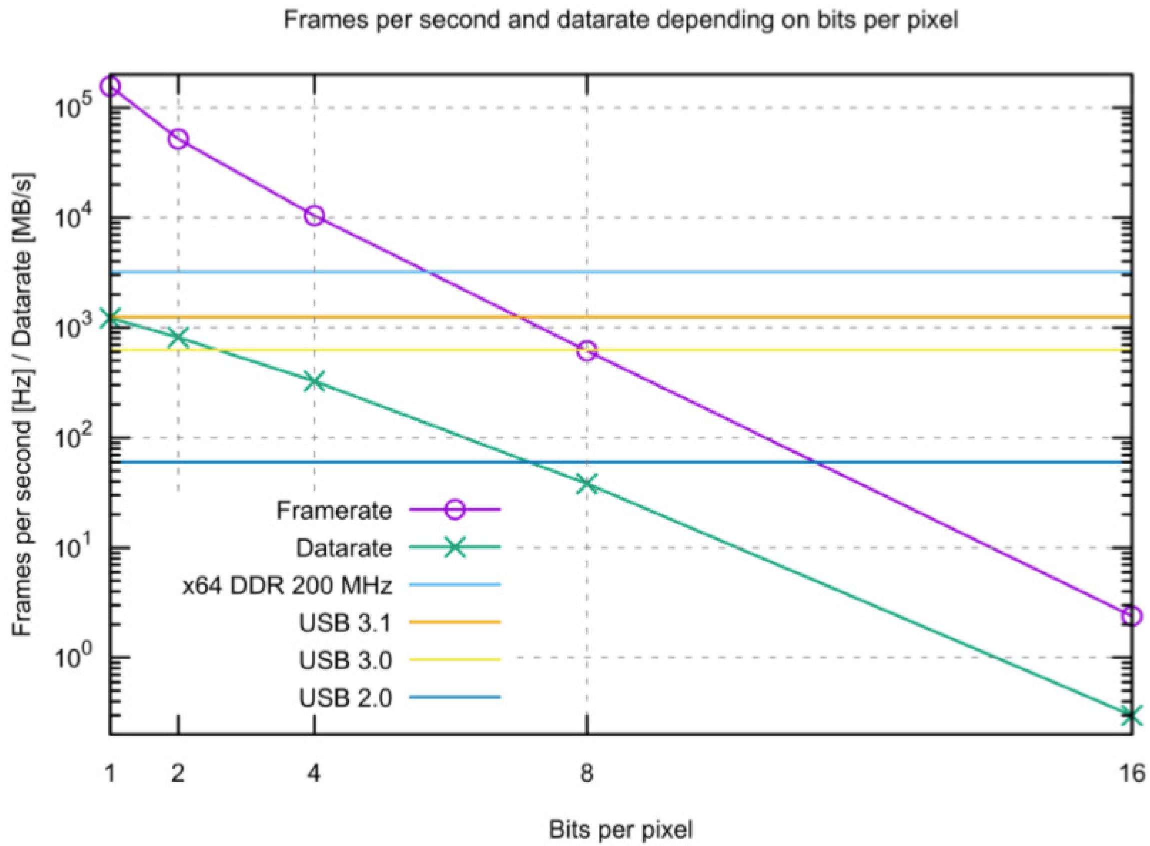
39kfps, 2 bit

10kfps, 4 bit

600fps, 8 bit

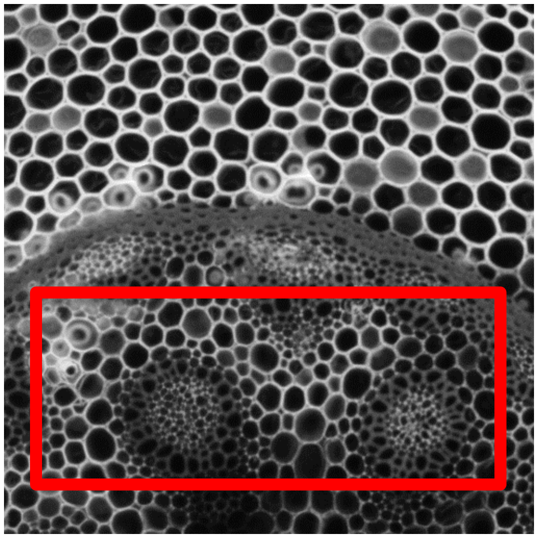
152fps, 16 bit



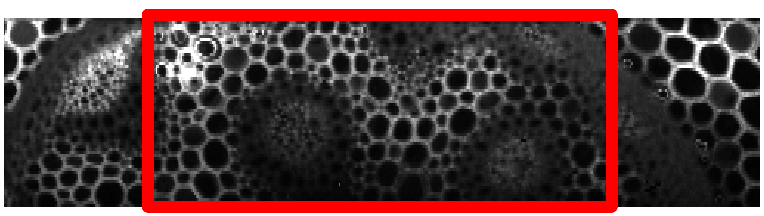


Burri et al., Optics Express 2014

EMCCD vs SwissSPAD Intensity Fluor.



EMCCD

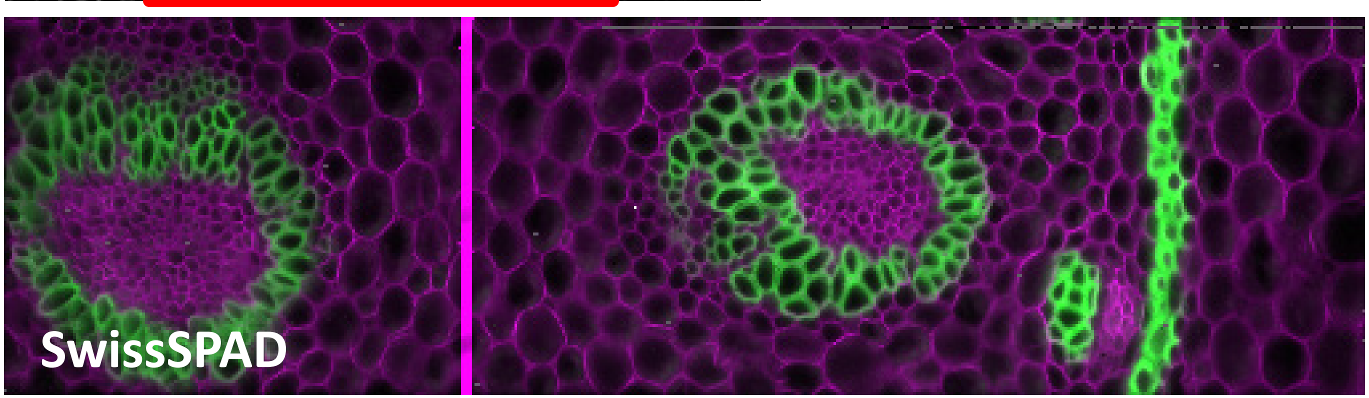


SwissSPAD

Slice of plant root stained with a mixture of dyes

Intensity per area ratio is found to be **12%**

I.M. Antolovic et al., *Sensors,* 2016



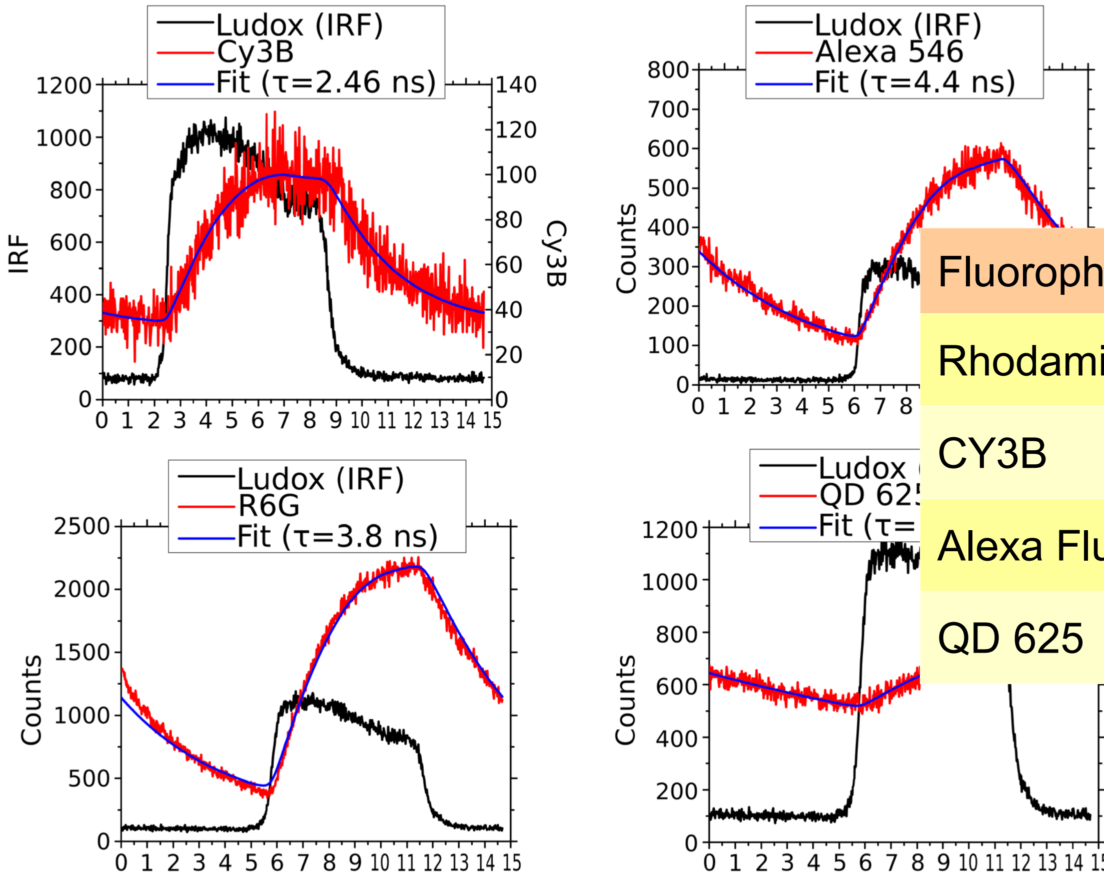
SwissSPAD: Superresolution

- First super resolution images with a SPAD imager – 30 nm localization uncertainty, 100 nm resolution
- SPAD imagers don’t change their performance when changing the frame rate 1 bit frame time of 6.4 μs
- Optimal frame time depends on the blinking parameter, emission and background intensity
- *On* and *off* lifetimes could be used for fluorophore separation – multichannel imaging

SwissSPAD FLIM

532nm, 8ps pulse, 68MHz

IRF convoluted with fluorescence decay



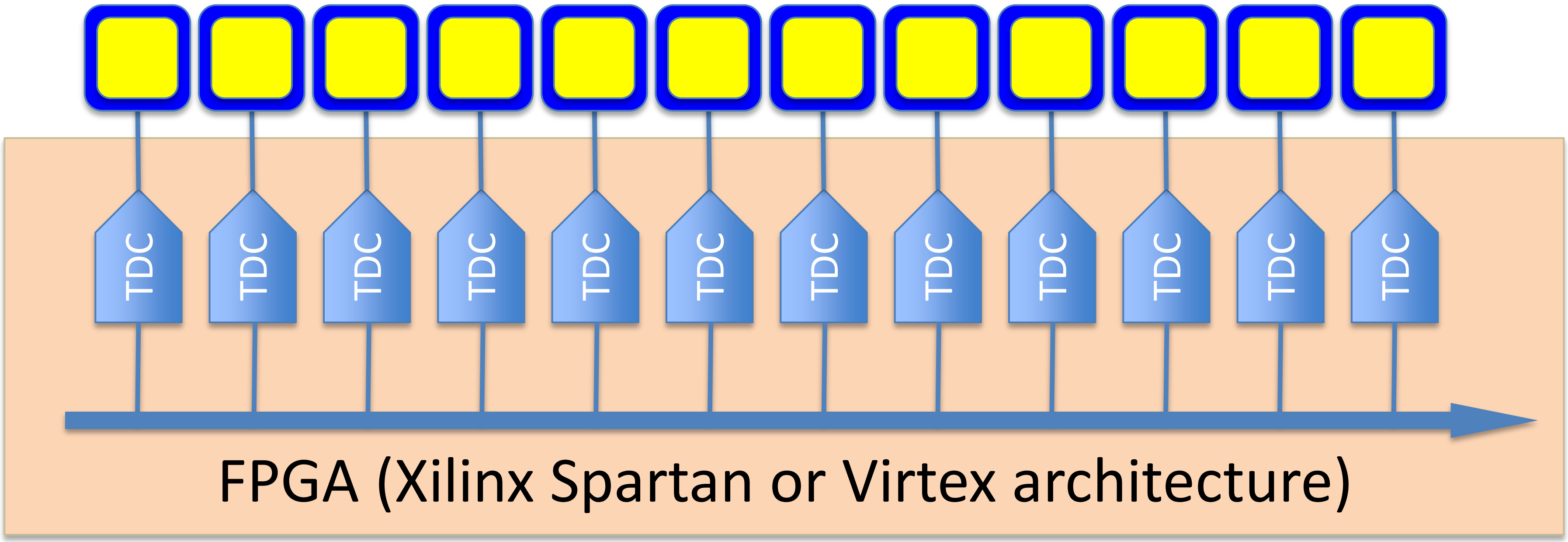
Fluorophore	Fit (ns)	Reference (ns)
Rhodamine 6G	3.8	4.08
CY3B	2.4-2.5	2.8
Alexa Fluor 546	4.2-4.4	4.1
QD 625	12.7	N/A

4.3 LinoSPAD – 256×1 Linear Reconfigurable Array

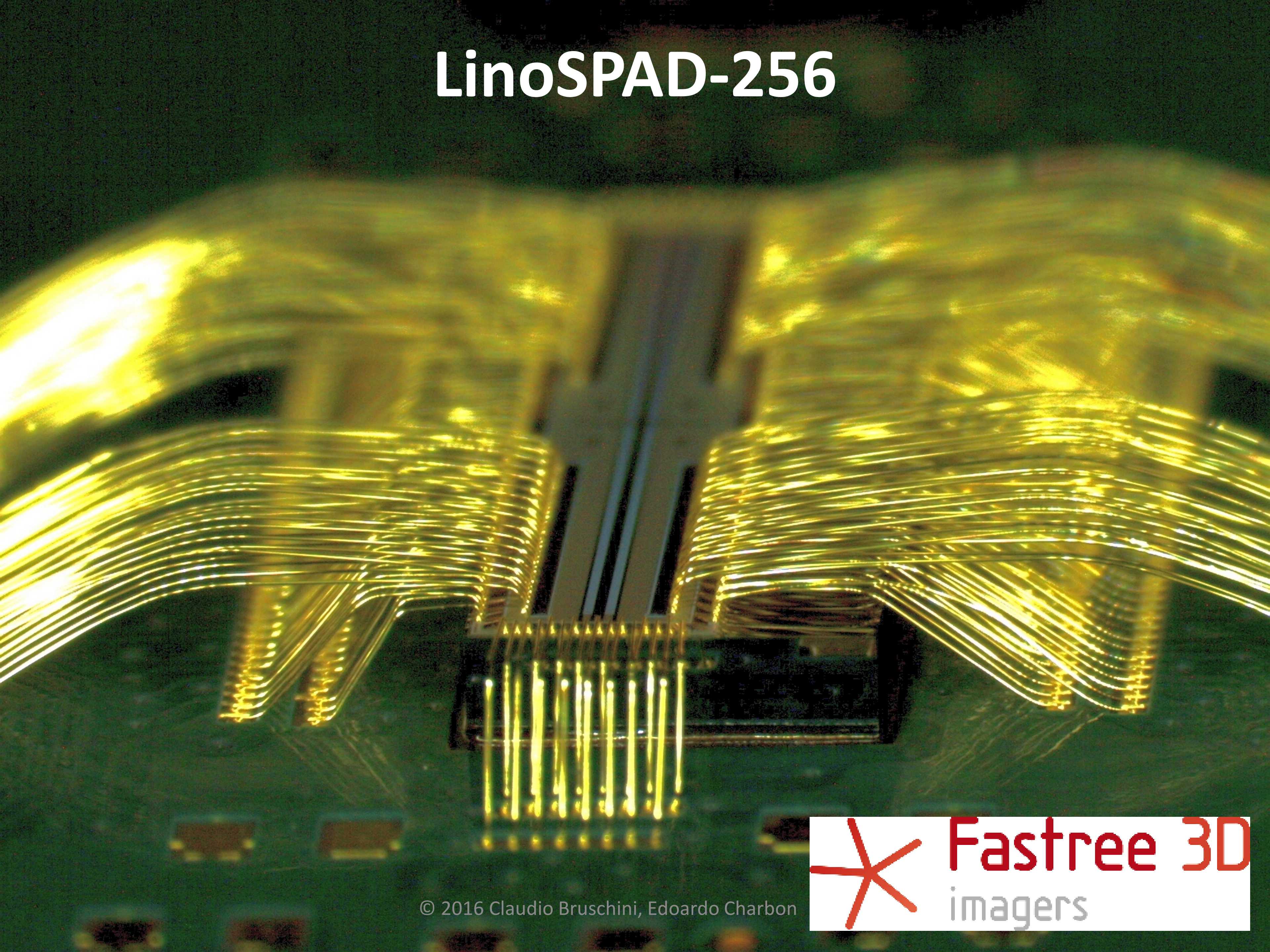
(SPAD array & FPGA-based TCSPC)

The LinoSPAD Project: Reconfigurable Pixel

- Only SPAD integrated, fully parallel TDC array
- TDCs can use the best technology (e.g. 28nm)
- Medium fill factor (43%)
- Resolution on-demand (e.g. 9ps)
- Readout on-demand



LinoSPAD-256

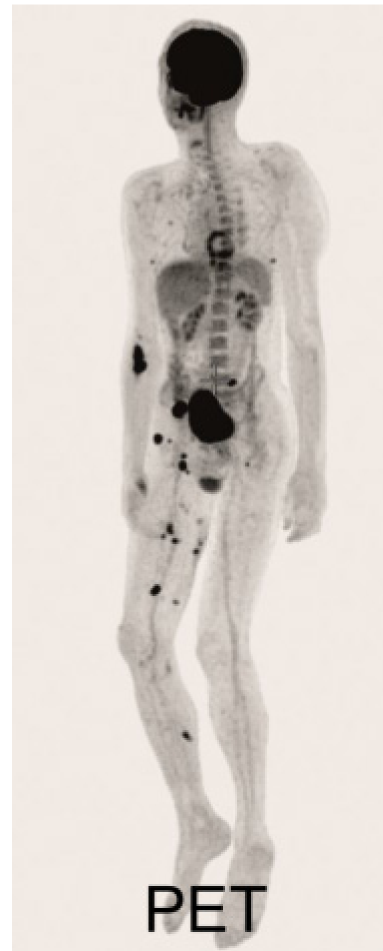


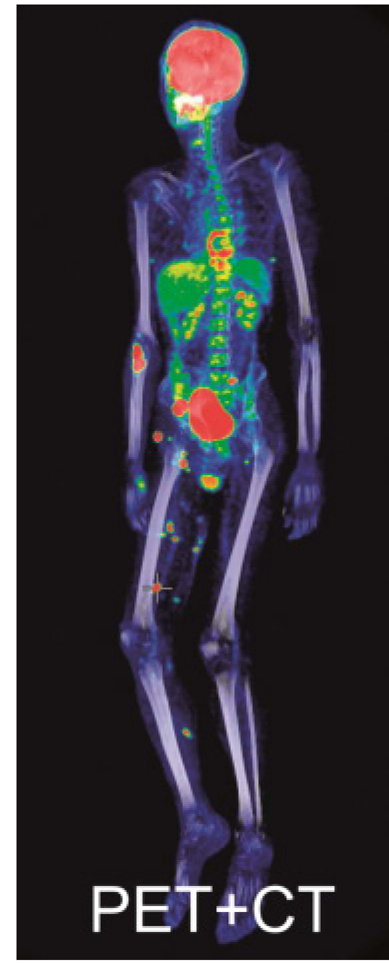
Fastree 3D imagers

4.4 SPADnet – 16x8 (x720) event-driven for Positron Emission Tomography (PET)

PET Imaging Background

- MRI/CT:
  - Provide *structural* information
- PET:
  - Provides *functional* information
  - Patient administered with radiotracer
  - Areas of high metabolic activity visible: applications in oncology & neurology etc.
- Goal:
  - Enabler for multi-modal imaging

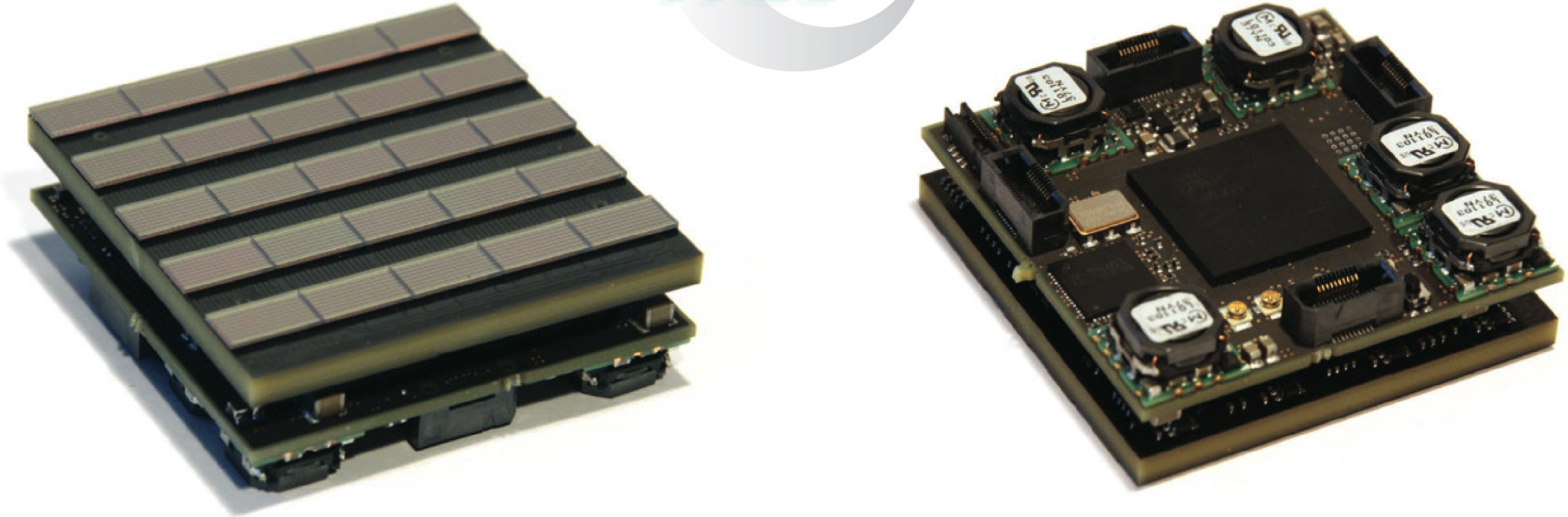




R. Walker, IISW 2013

SPADnet photonic module

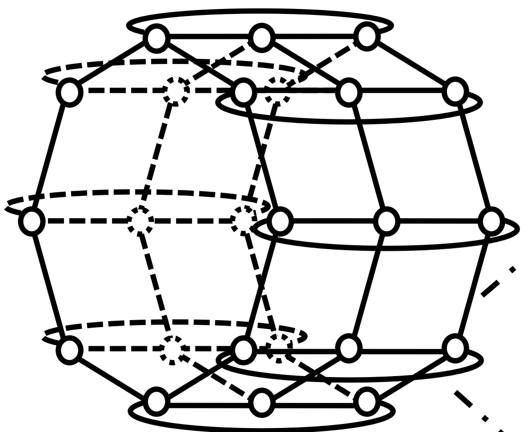
SPAD net
SINGLE PHOTON AVALANCHE DIODE NETWORK

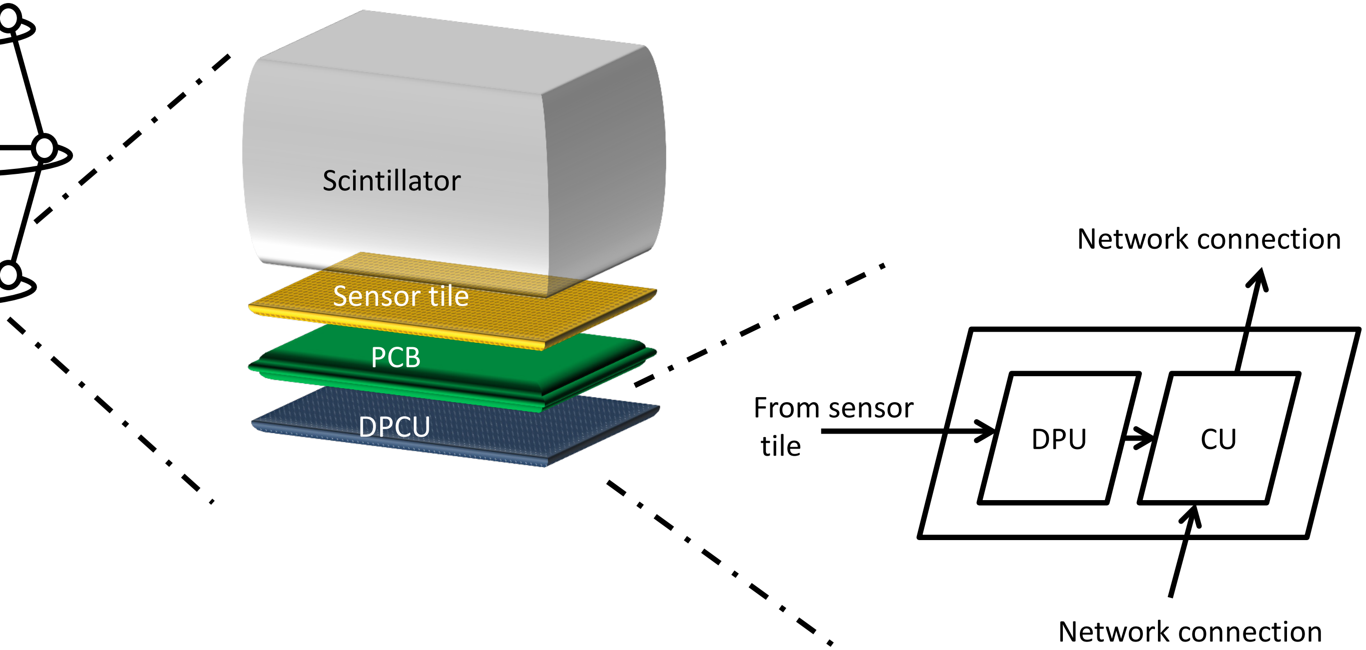


SPADnet sensor network

Sensor networks enables distributed parallel processing realizing a flexible and a scalable data acquisition system for multi-ring based PET systems.

DPCU: Data Processing and Communication Unit
DPU : Data Processing Unit
CU : Communication Unit

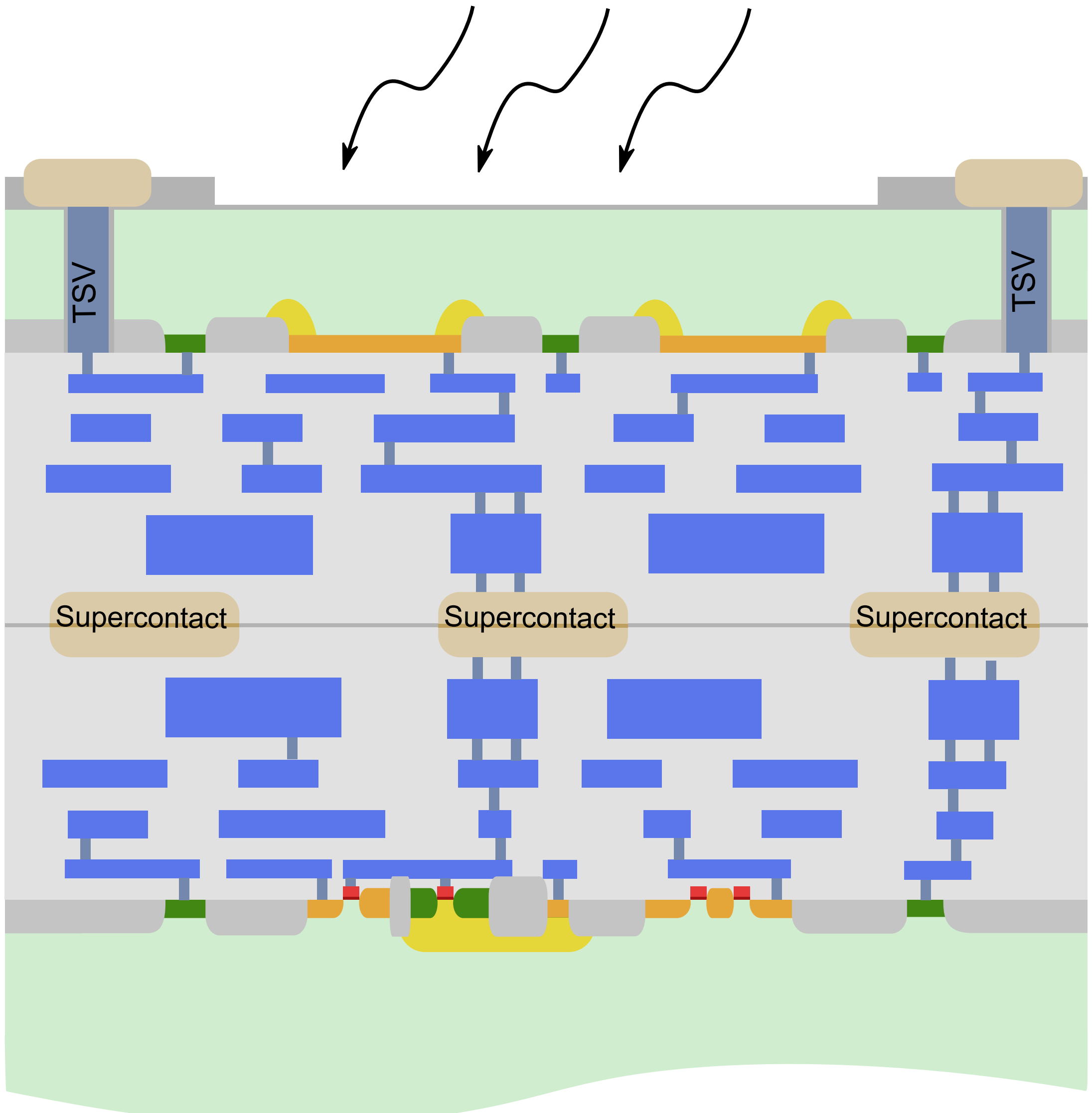




C. Veerappan, RTS 2014

5. Roadmap

3D Integrated Sensors



Acknowledgements

- AQUA groups in NL (cas.et.tudelft.nl) and CH (aqua.epfl.ch), Swiss National Science Foundation, NCCR-MICS (CH), STW (NL)
- European Space Agency
- European: FP6 (MEGAFRAME-www.megaframe.eu) and FP7 (SPADnet-www.spadnet.eu) & respective partners
- Robert Henderson (University of Edinburgh)
- David Li (Strathclyde University)
- Jörg Langowski (DKFZ Heidelberg)
- Paulien Stegehuis, Jouke Dijkstra, Boudewijn Lelieveldt (Leiden University Medical Centre - LUMC)
- Fastree3D SA (CH)
- Many, many others…