

# **Status and Future Prospects of High Time Resolution Photon Counting Sensor Arrays**

**A decade of CMOS  
photon counting & single-photon imaging  
(2004-2015)**

**E. Charbon**



# 2014 Nobel Prize in Chemistry



Stefan W. Hell

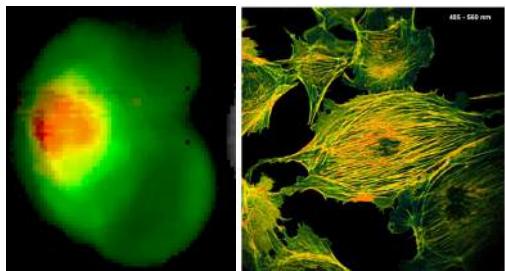
for his contributions to Super-Resolution Microscopy

Made possible, in great part, by photon counting cameras

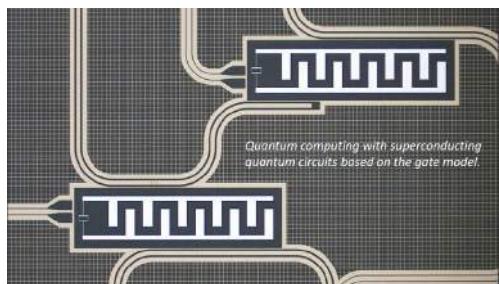
# Areas of Application



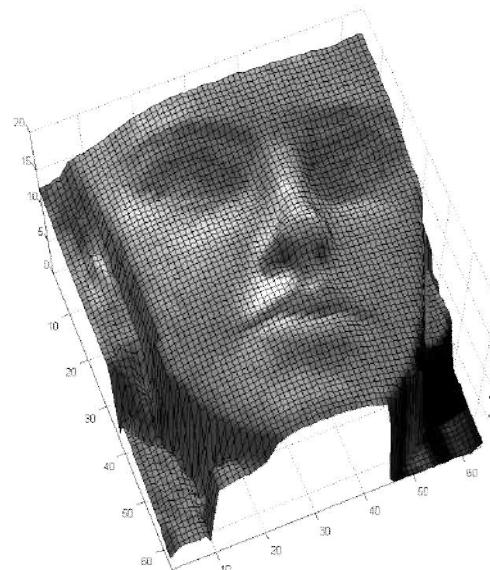
High-energy physics experiments



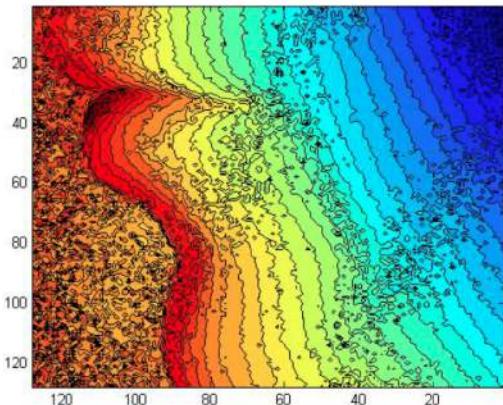
Fluorescence Lifetime Imaging Microscopy (FLIM) and super-resolution microscopy (STED, STORM, GSDIM, PALM, etc.)



Electronics for Quantum Computing



Near Infrared Imaging (NIRI)



3D Vision



Time-resolved Raman Spectroscopy



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

# Also: Quantum security, quantum information technology, etc.

## Jailbreak Imagers: Transforming a Single-Photon Image Sensor

### Heralded entanglement between solid-state qubits separated by three metres

letters to nature

( $\sigma \approx 0.003\text{--}0.015$  mag), almost any transit-like light curve can be reproduced as a blend, and only with spectroscopy can these cases be recognized. For each trial simulation, the relative brightness and velocity amplitude of the primary in the eclipsing binary can be predicted. Although a good fit to the photometry of OGLE-TR-56 can indeed be obtained for a model with a single star blended with a fainter system comprising a G star eclipsed by a late M star, the G star would be bright enough that it would introduce strong line asymmetries (which are not seen), or would be detected directly by the presence of a second set of lines in the spectrum. Careful inspection using TODCOR<sup>18</sup> rules this out as well. Therefore, based on the data available, a blend scenario seems extremely unlikely.

This is the faintest ( $V \approx 16.6$  mag) and most distant ( $\sim 1,500$  pc) star around which a planet with a known orbit has been discovered. The planet is quite similar to the only other extrasolar giant planet with a known radius, HD209458b, except for having an orbit which is almost two times smaller. Thus its substellar hemisphere can heat up to about 1,900 K. However, this is still insufficient to cause appreciable planet evaporation (with a thermal root-mean-square (r.m.s.) velocity for hydrogen of around  $7 \text{ km s}^{-1}$  compared to a surface escape velocity of around  $50 \text{ km s}^{-1}$ ). The tidal Roche lobe radius of OGLE-TR-56b at its distance from the star is about 2 planet radii. The planet's orbit is most probably circularized ( $e = 0.0$ ) and its rotation tidally locked, but the star's rotation is not synchronized ( $v \sin i \approx 3 \text{ km s}^{-1}$ ). Thus the system appears to have adequate long-term stability. Interestingly, OGLE-TR-56b is the first planet found in an orbit much shorter than the current cut-off of close-in giant planets at 3–4-day periods ( $\sim 0.04$  AU)<sup>8</sup>. This might indicate a different mechanism for halting migration in a protoplanetary disk. For example, OGLE-TR-56b may be representative of a very small population of objects—the so-called class II planets, which have lost some of their mass through Roche lobe overflow<sup>21</sup> but survived in close proximity to the star; a detailed theoretical study of OGLE-TR-56b will be presented elsewhere (D.D.S., manuscript in preparation). These observations clearly show that transit searches provide a useful tool in adding to the great diversity of extrasolar planets being discovered. □

Received 27 November; accepted 30 December 2002; doi:10.1038/nature01379.

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**Competing interests statement** The authors declare that they have no competing financial interests.

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### Long-distance teleportation of qubits at telecommunication wavelengths

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<sup>‡</sup> These authors contributed equally to this work

Matter and energy cannot be teleported (that is, transferred from one place to another without passing through intermediate locations). However, teleportation of quantum states (the ultimate structure of objects) is possible: only the structure is teleported—the matter stays at the source side and must be

olstra, M. S. Blok, L. Robledo, T. H. Taminiau, M. Markham, D.

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Print

ially separated objects is one of the most intriguing s of independent measurements on entangled objects show by classical physics. As well as being of fundamental source for quantum information processing and bits (qubits) can be used to share private information or Such capabilities are particularly useful when the entangled providing the opportunity to create highly connected quantum graphy to long distances<sup>7,8</sup>. Here we report entanglement of with a spatial separation of three metres. We establish this based on creation of spin–photon entanglement at each measurement of the photons. Detection of the photons heralds the entangled state. We verify the resulting non-local quantum of readout<sup>9</sup> on the qubits in different bases. The long-distance combined with recently achieved initialization, readout and on local long-lived nuclear spin registers, paving the way for ion, quantum repeaters and extended quantum networks.

Quantum optics   Quantum mechanics

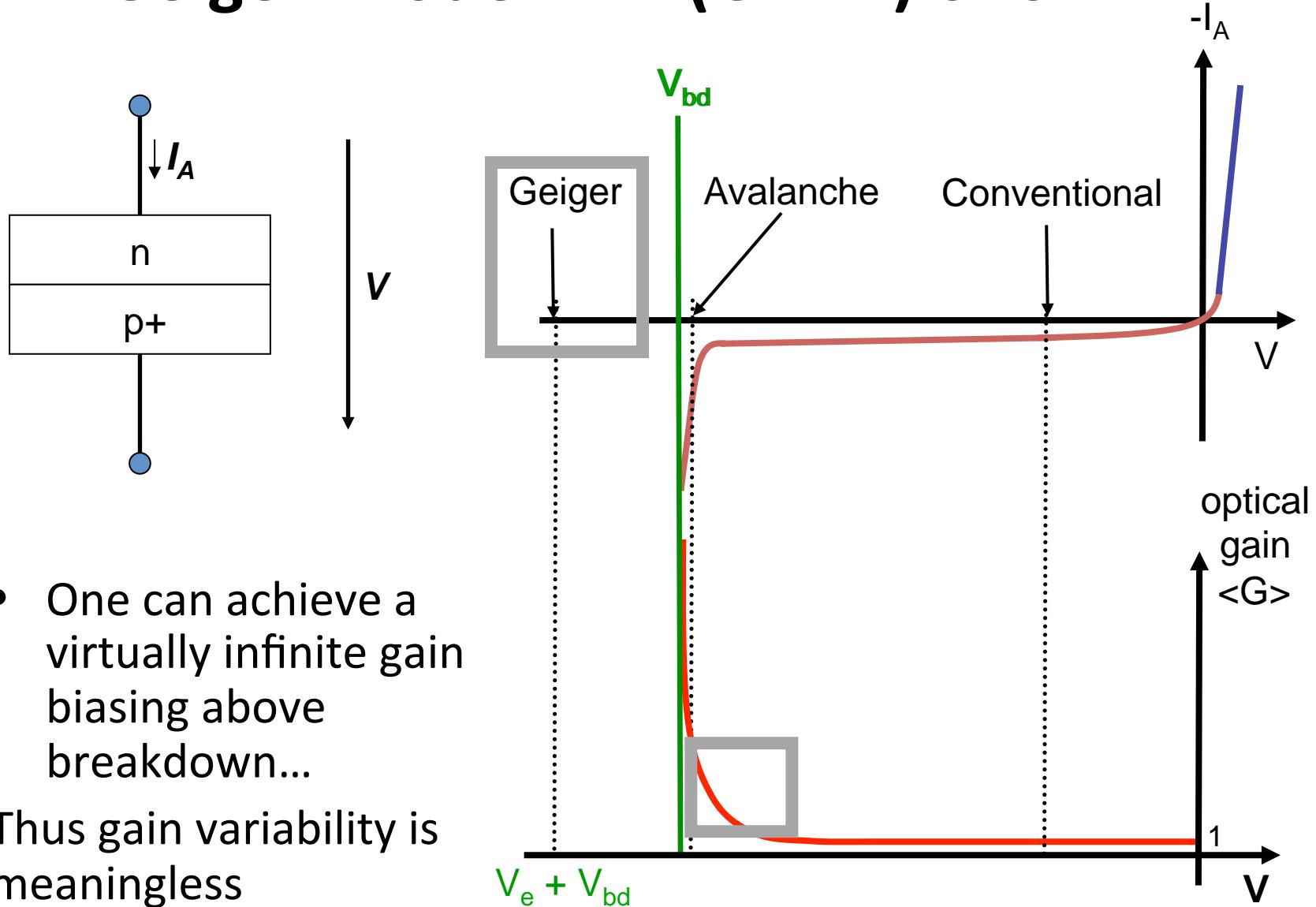
illuminate the model completely, view of 30° was installed. Fig. 12 the model as well as the picture

background photons falling on the laser emission spectral band and possible dark counts are distributed evenly over the full

of the model, captured with a standard digital camera.

**Photon Counting  
&  
Single-Photon Detection**

# Geiger-Mode APD (GAPD) or SPAD



# Third Step: Understanding & Modeling

- Seeding

$$(z_1 - z_0) \frac{dc(t)}{dt} = -2c(t)v_s + 2\bar{\alpha}v_s c(t)(z_1 - z_0)$$
$$\frac{dc(t)}{dt} = 2c(t)(v_s \bar{\alpha} - \frac{v_s}{z_d}).$$

- Build-up

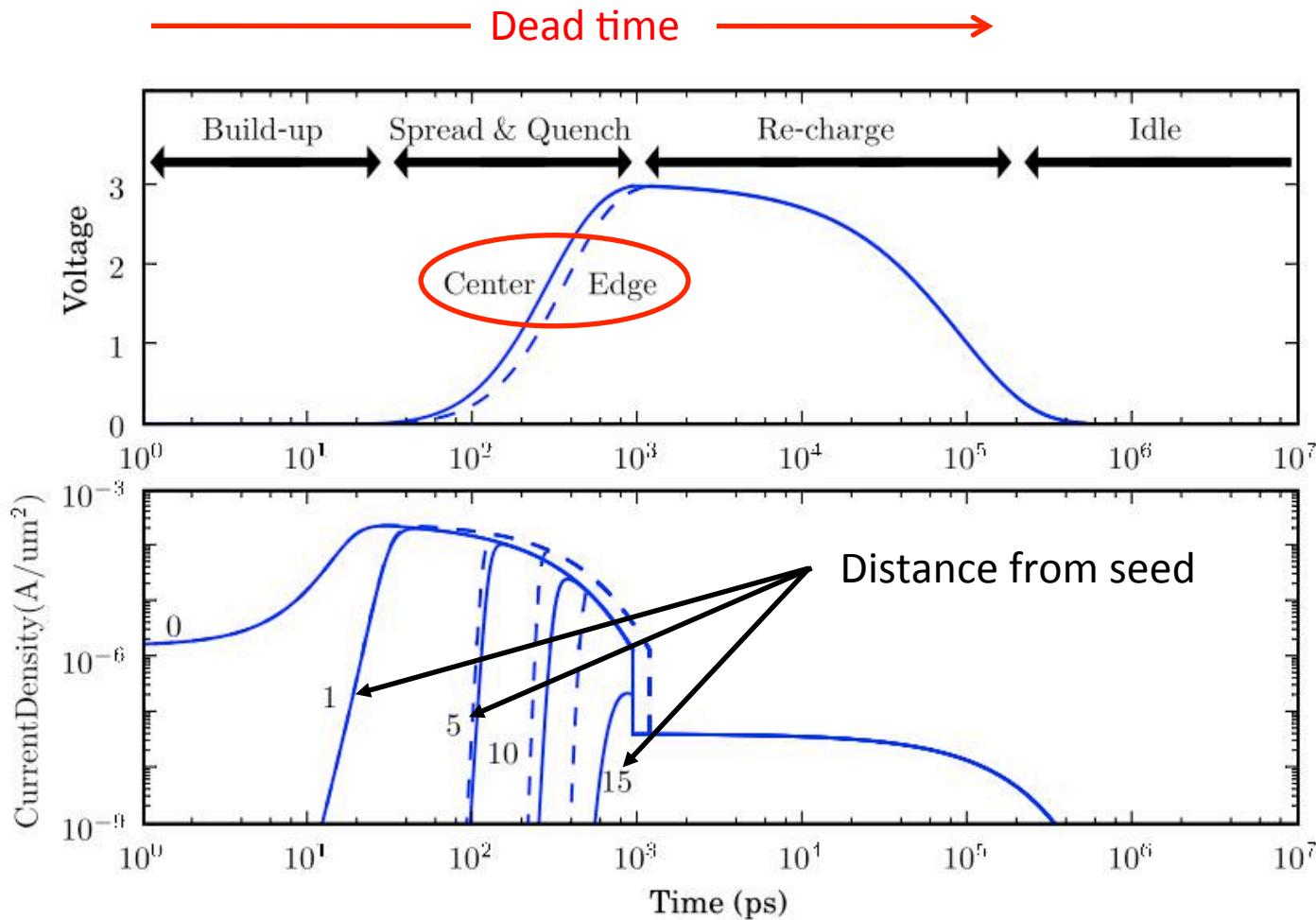
$$\frac{\partial c}{\partial t} = D_{eff} \nabla^2 c - \vec{v}_c \cdot \nabla c + \frac{c}{\tau} + \Phi.$$

- Spreading

Essentials:

- Diffusion equation
- Convection-diffusion equation  
(Fishburn, Charbon, 2011)

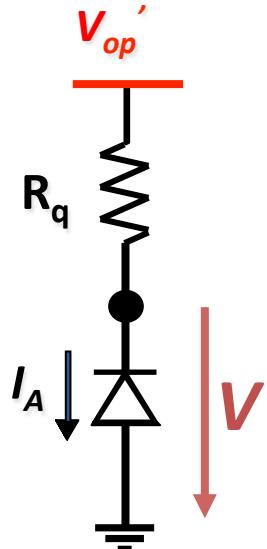
# Build-up, Propagation, Quenching Model



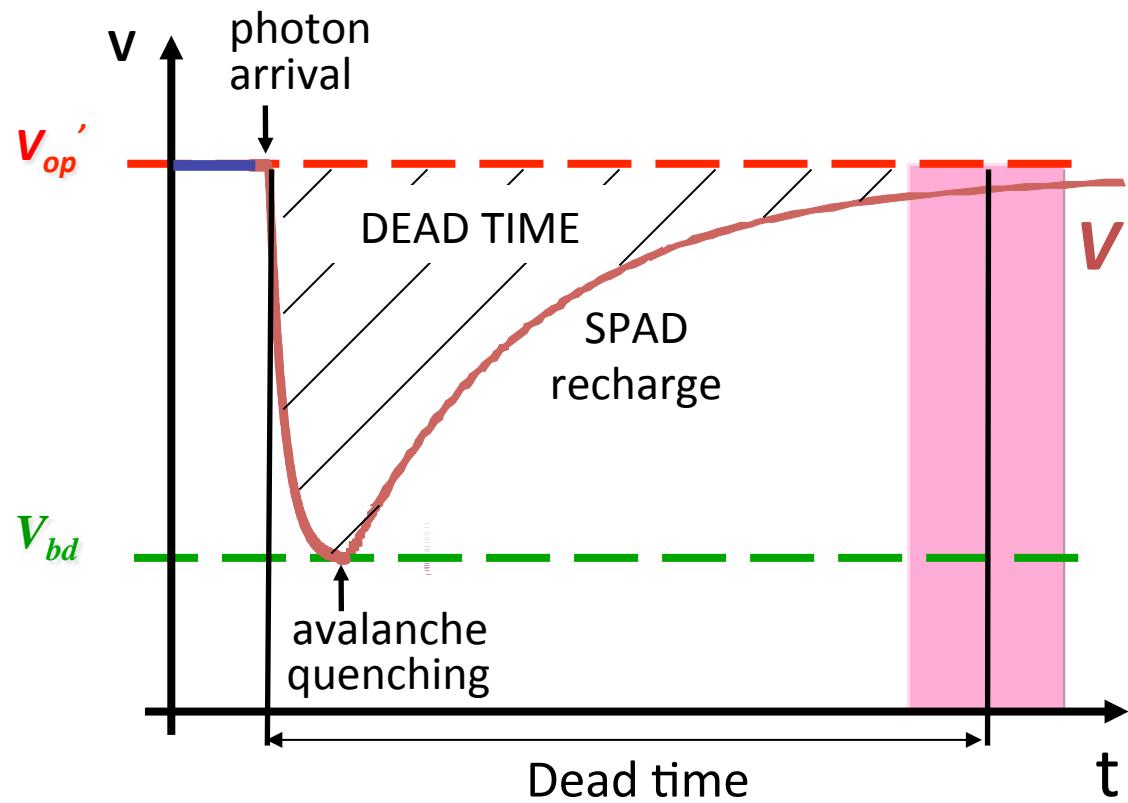
Fishburn, Charbon, *Trans. El. Dev.*, 2011

# Passive Quenching, Passive Recharge

Passive quenching:

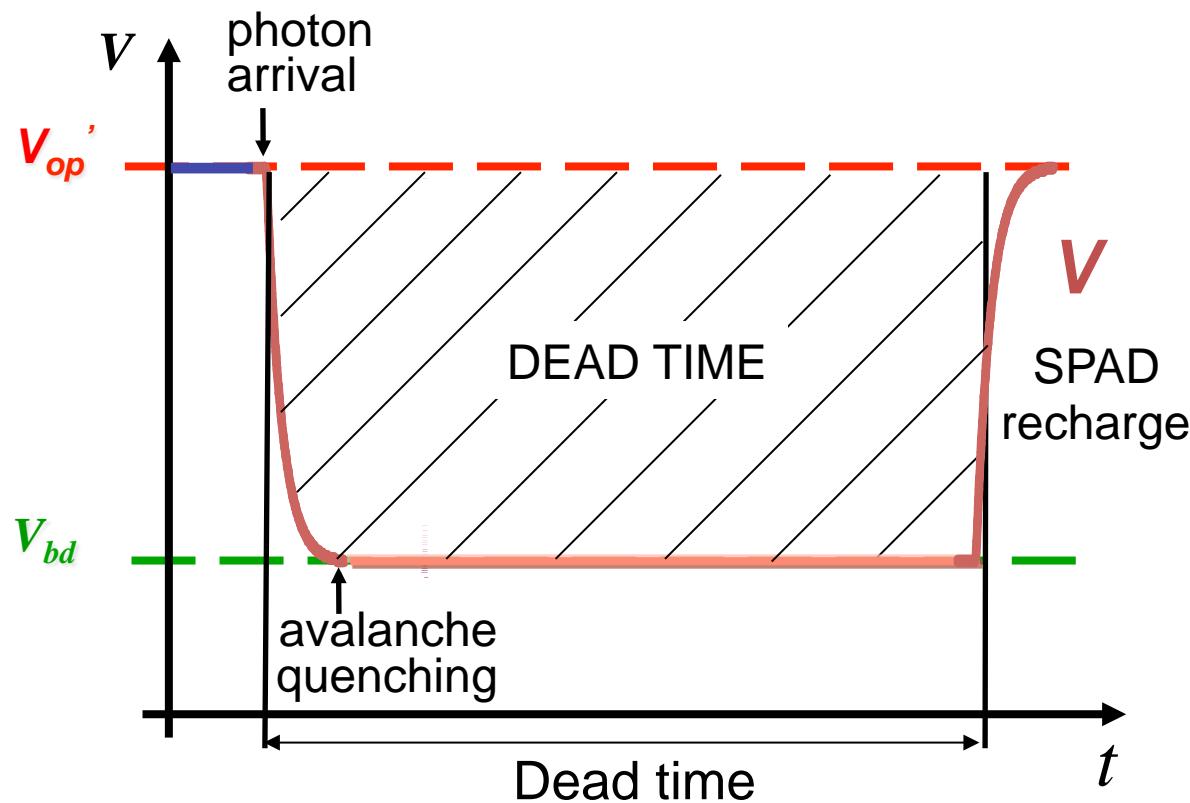


Operation cycle:

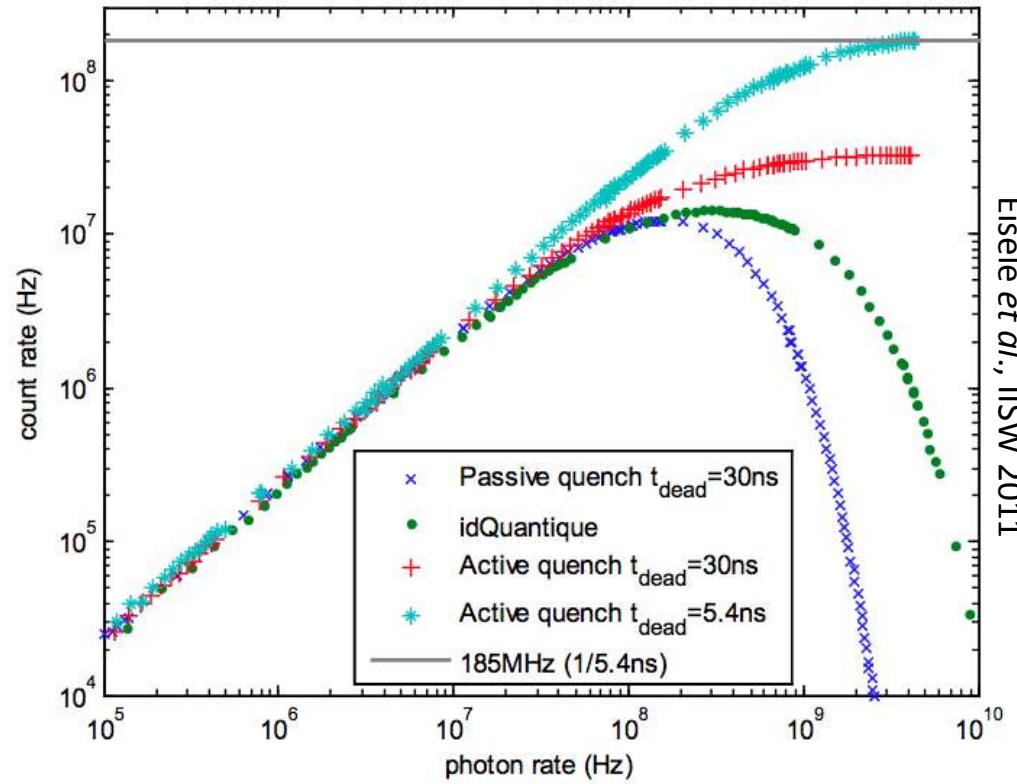


# Active Recharge: Afterpulsing

- Since afterpulsing is a function of the relaxation time left after an avalanche, it can be controlled by extending the dead time.



# Active Recharge: Detection Saturation

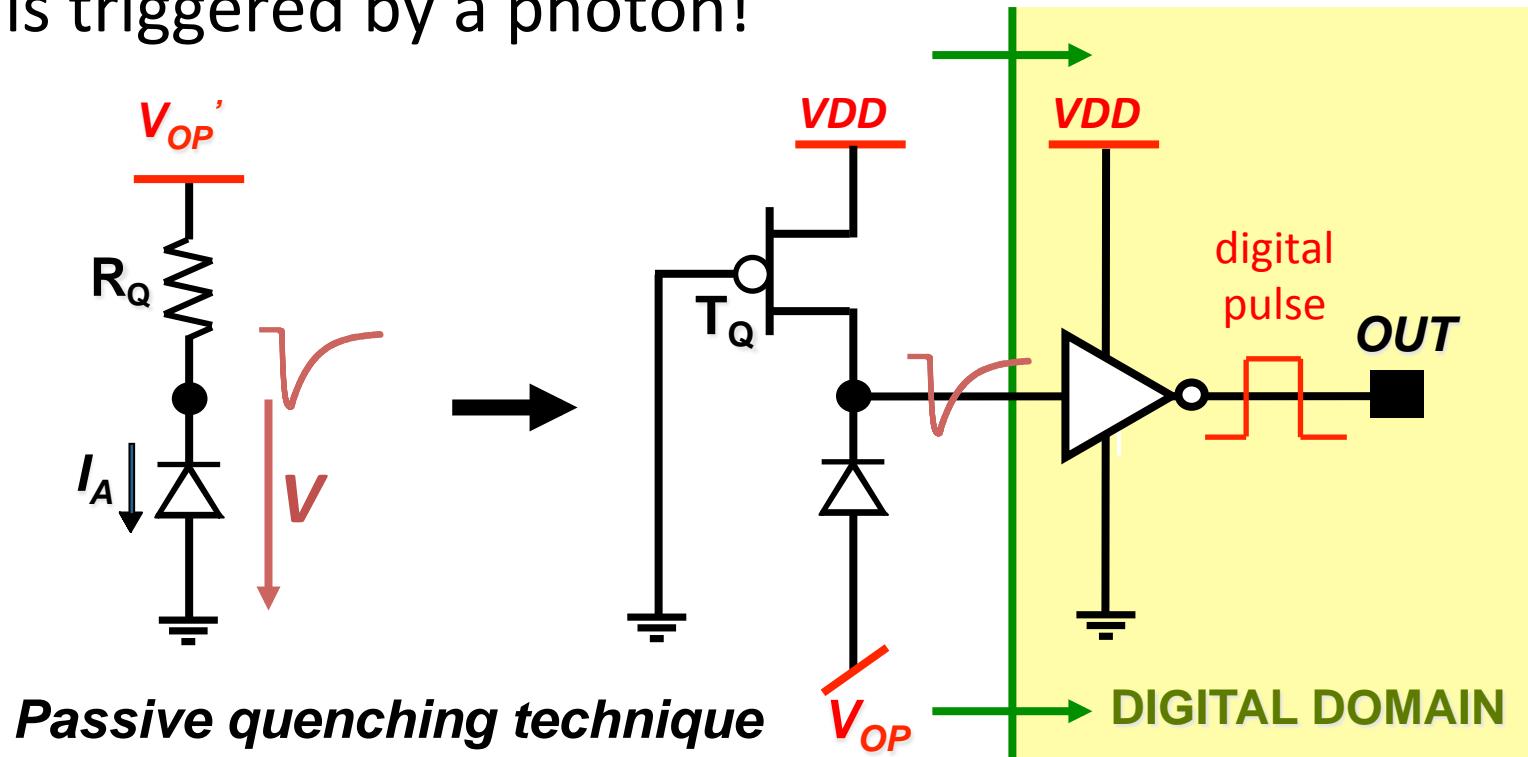


$$f_{\text{MAX}} \approx \frac{1}{t_{\text{DEAD}}} \quad \text{for active quenching}$$

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

# CMOS Interface

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



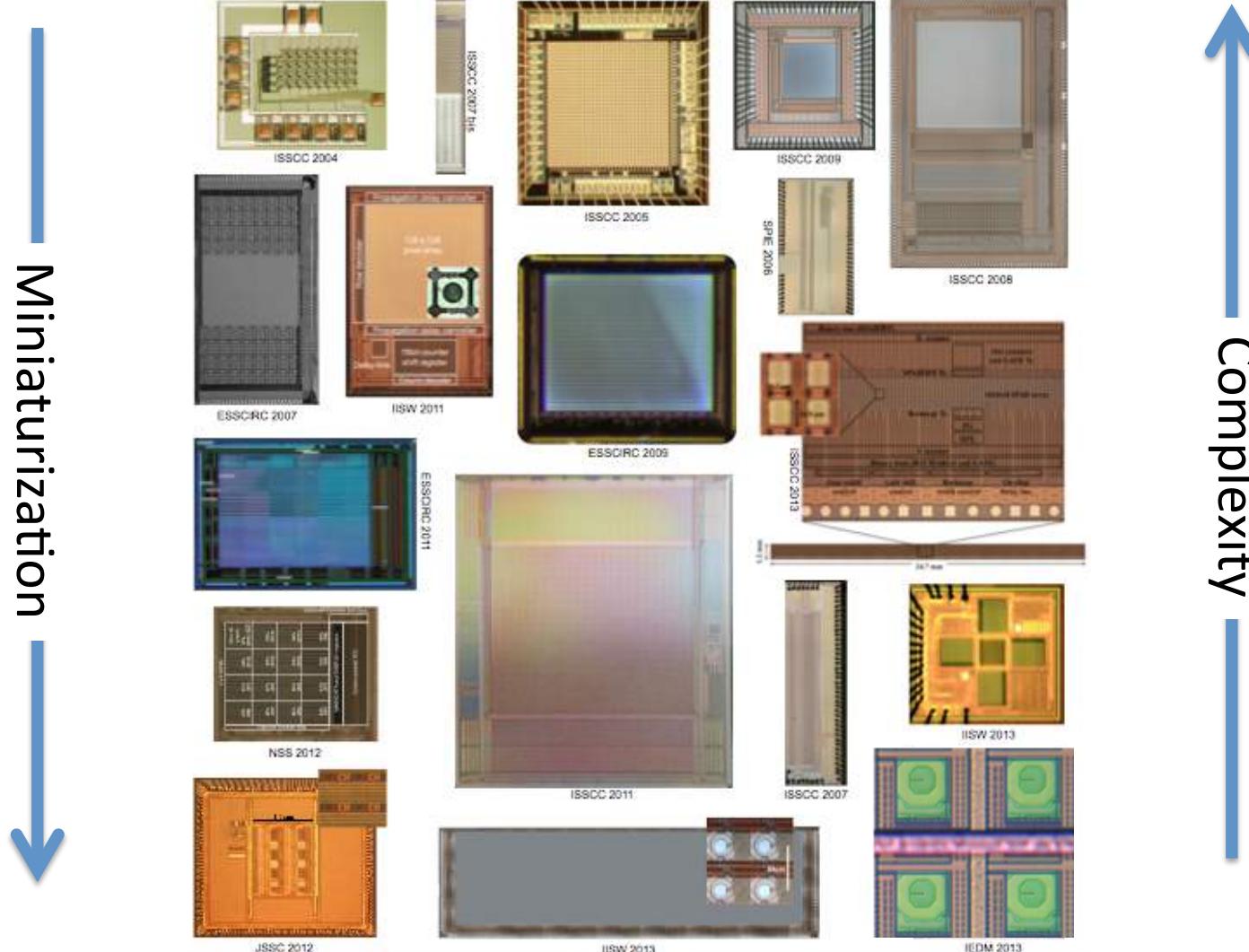
- With two more switches one can gate sensitivity

**OK...**

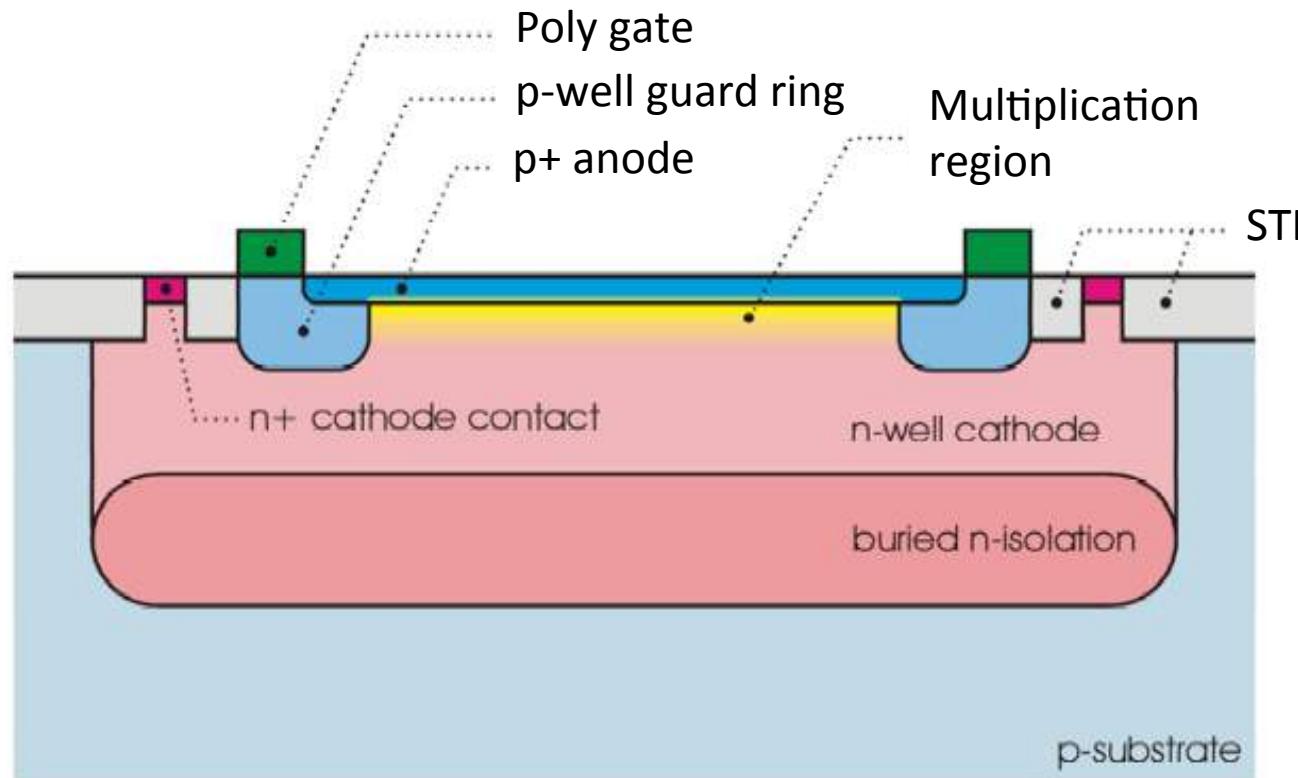
**We have built an interface between  
photons and digital electronics**

**What do we do now?**

# All-Digital Imagers based on Single-Photon Detection (2004-15)

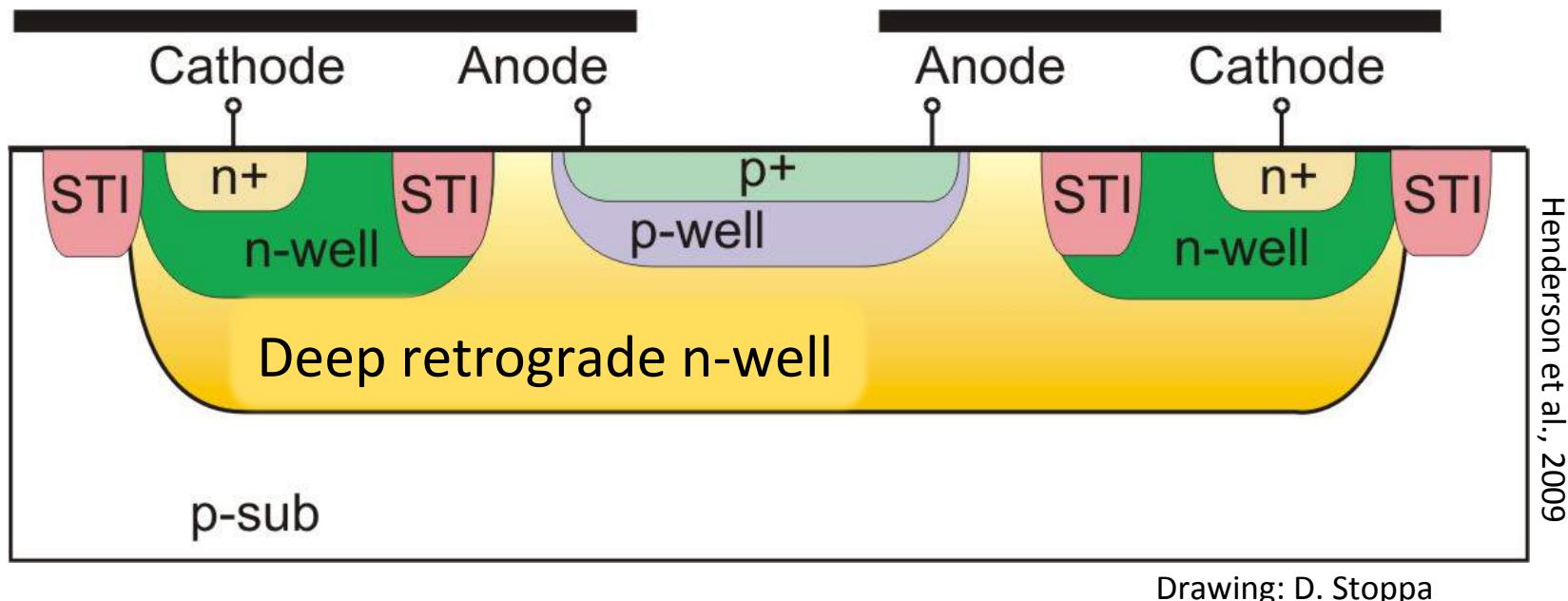


# The First Deep-submicron CMOS SPAD



Niclass *et al.*, Sel. Topics in Quantum Electronics, 2007

# Today's Industrial SPADs (STMicroelectronics)



Drawing: D. Stoppa

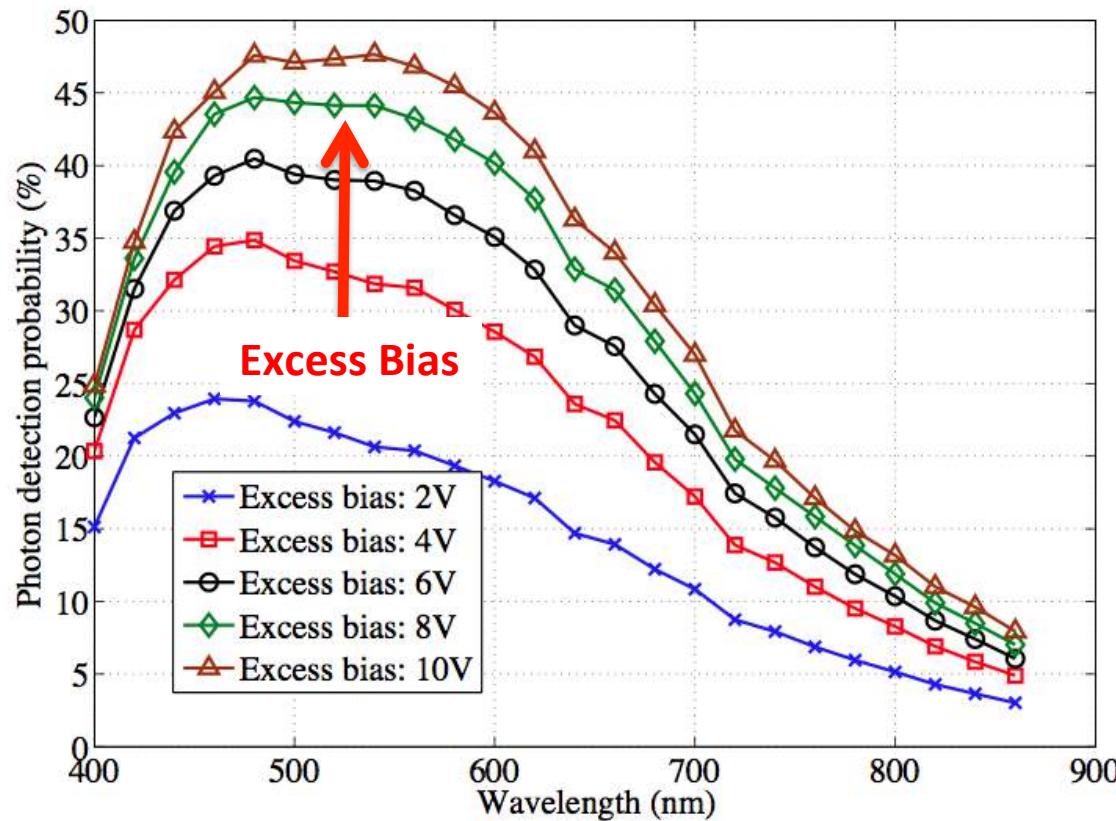
# Characterizing SPADs

- *Dead time*
- Dark counts
- Photon detection probability (PDP)
- Timing resolution
- *Afterpulsing*

... and in SPAD imagers

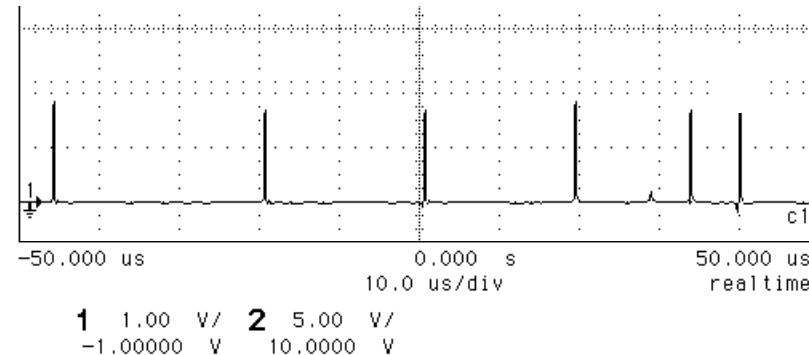
- Cross-talk
- PDP Uniformity

# Sensitivity: Photon Detection Efficiency (PDE)



C. Veerappan and E. Charbon, JSTQE 2014

# Dark Counts: Dark Count Rate



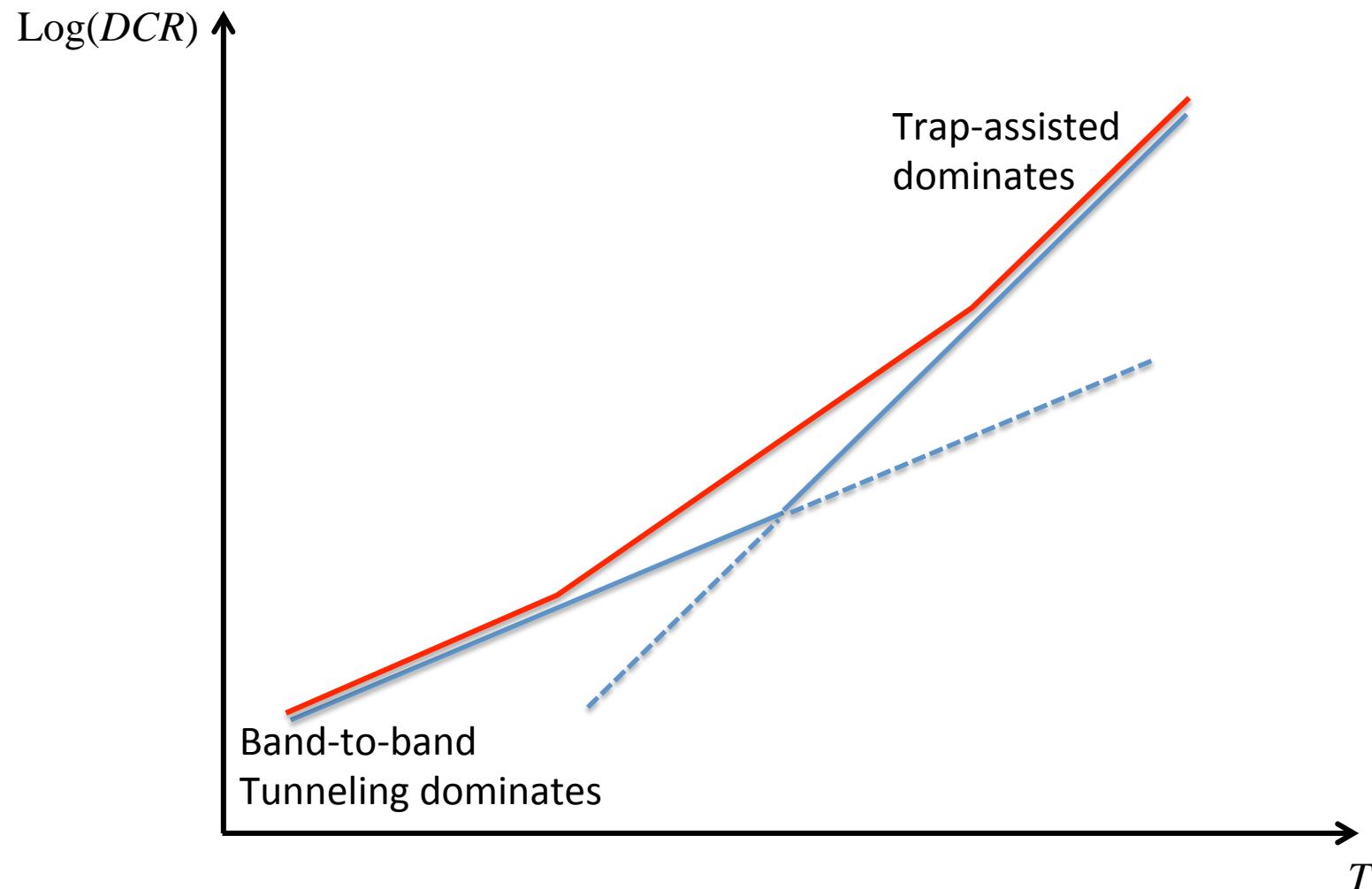
- State-of-the-art SPADs in dedicated technology:  
 $0.04\text{--}1\text{Hz}/\mu\text{m}^2$
- State-of-the-art CMOS SPADs:  
 $0.1\text{--}10\text{Hz}/\mu\text{m}^2$

1  
1Hz

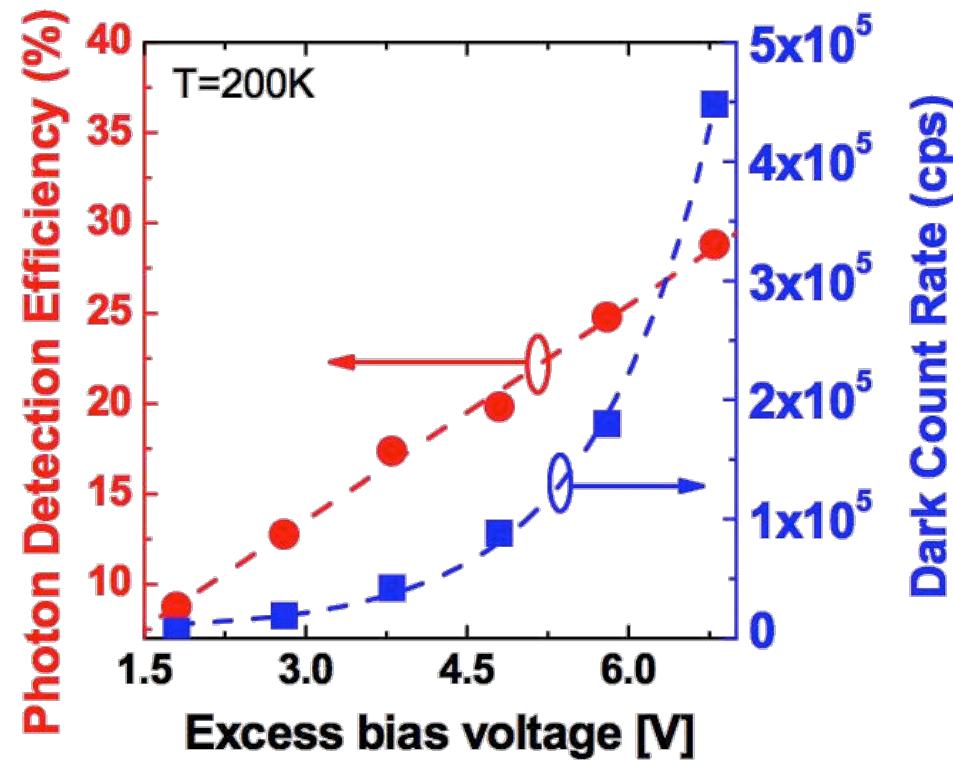
15x15  
250Hz

50x50  
3kHz vs. 60Hz

# Temperature Dependence of DCR

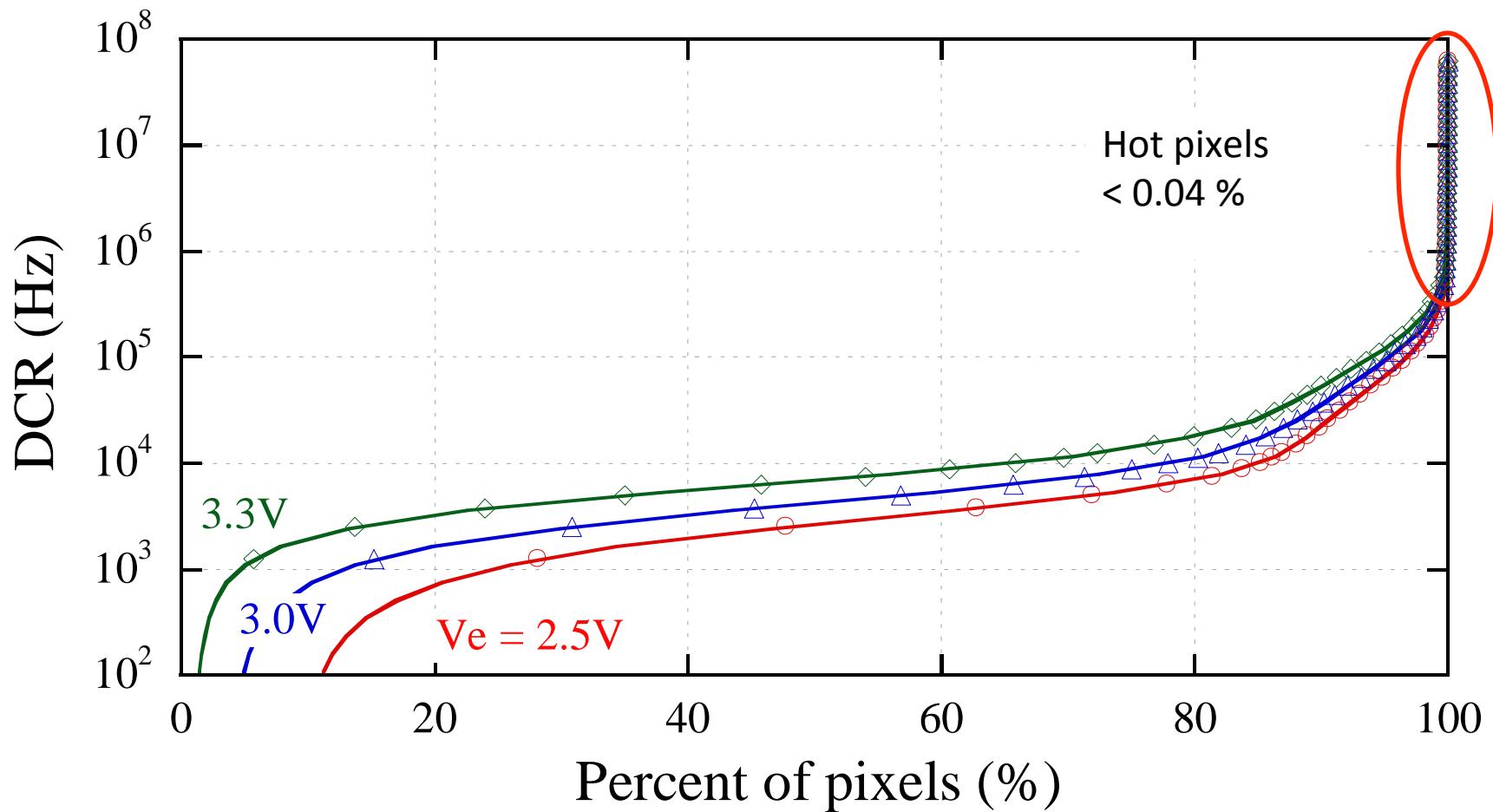


# PDE vs. DCR

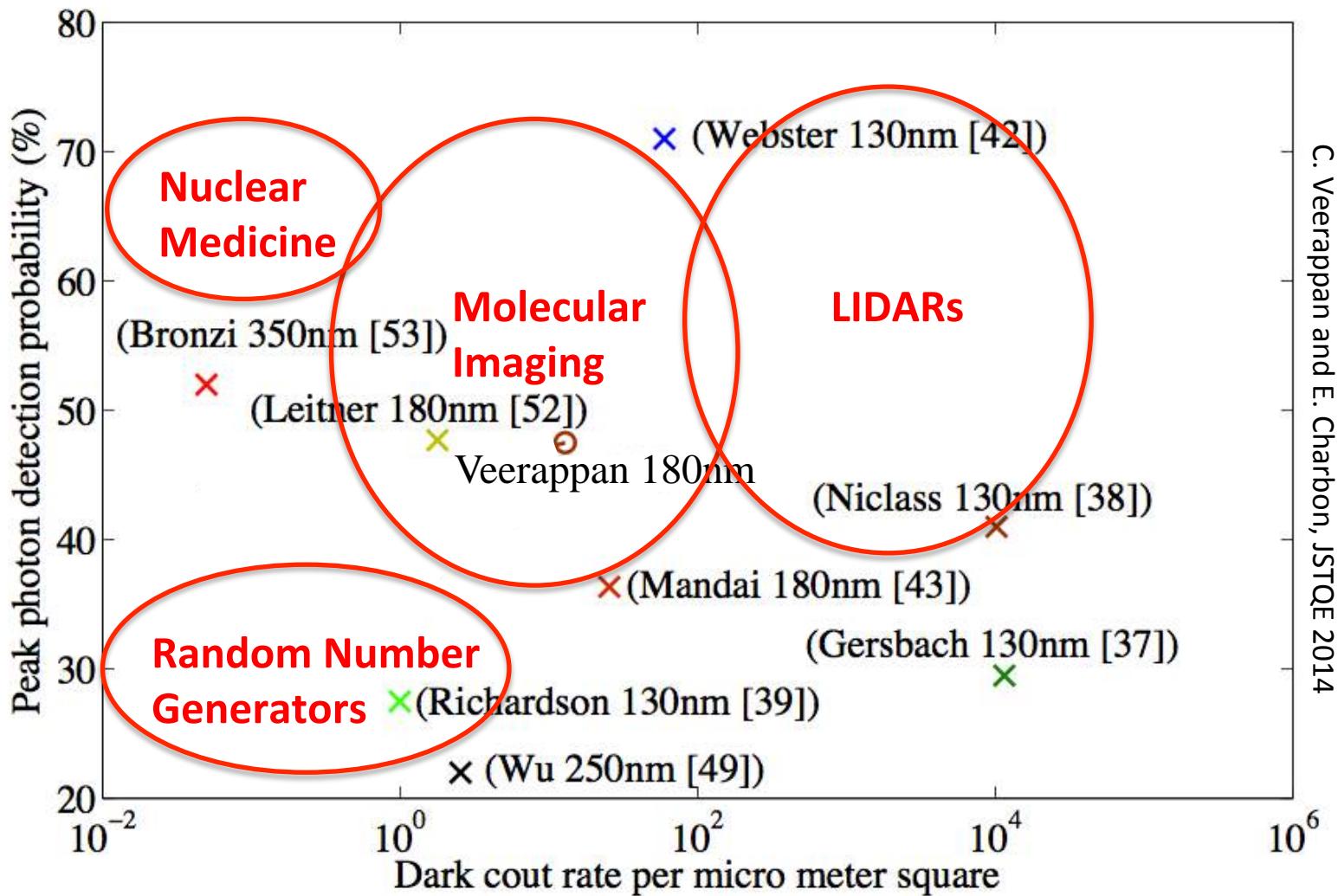


Tosi *et al.*, 2009

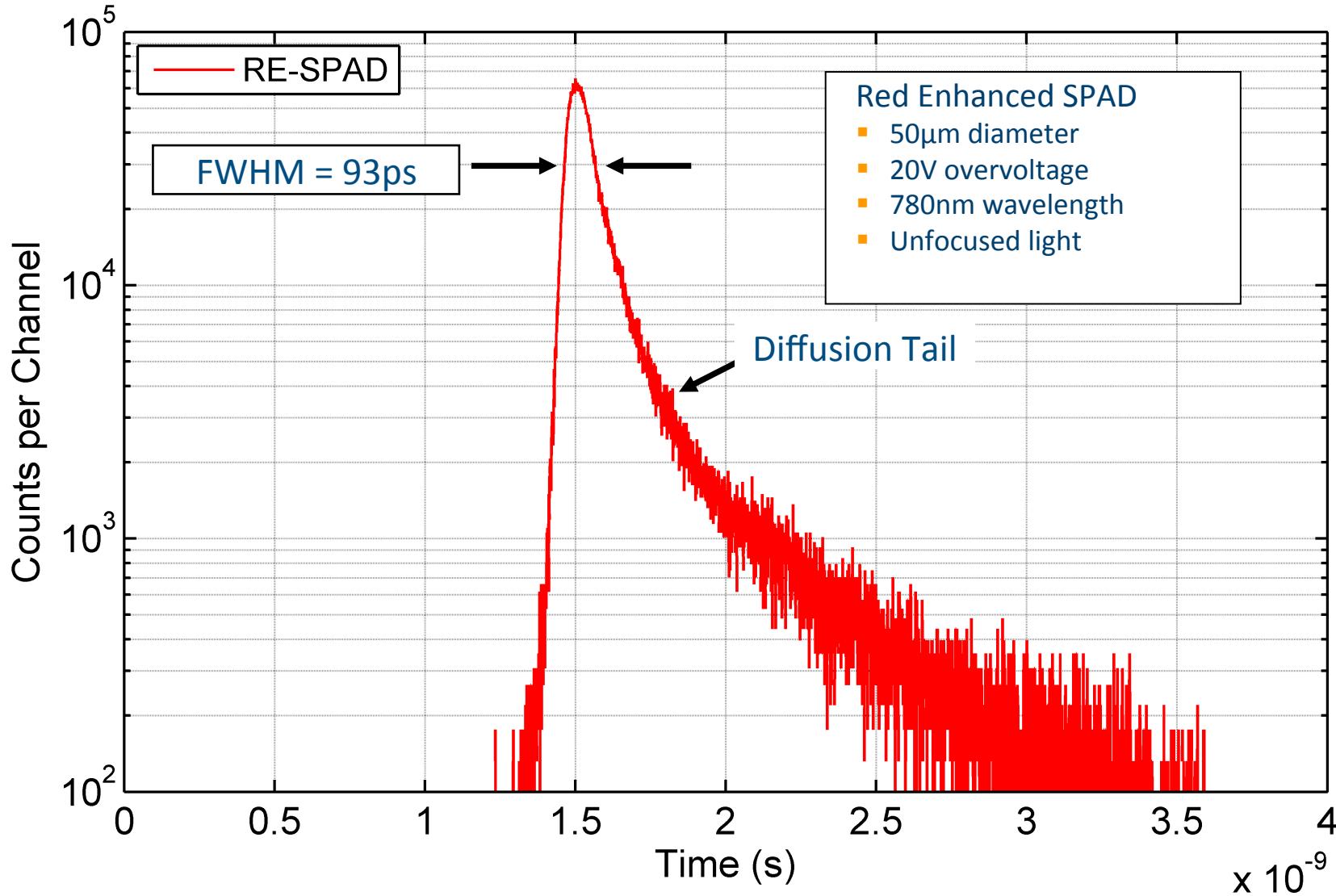
# DCR by Population



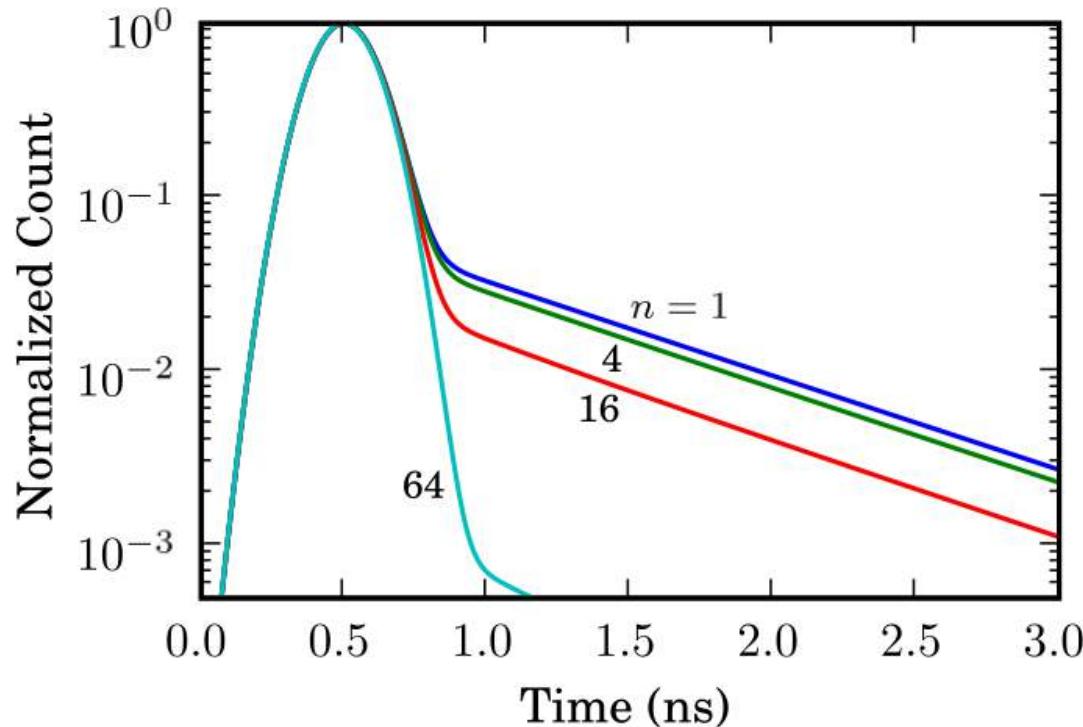
# PDE vs. DCR in Applications



# Timing Resolution vs. Thickness



# Diffusion Tail vs. # Photons



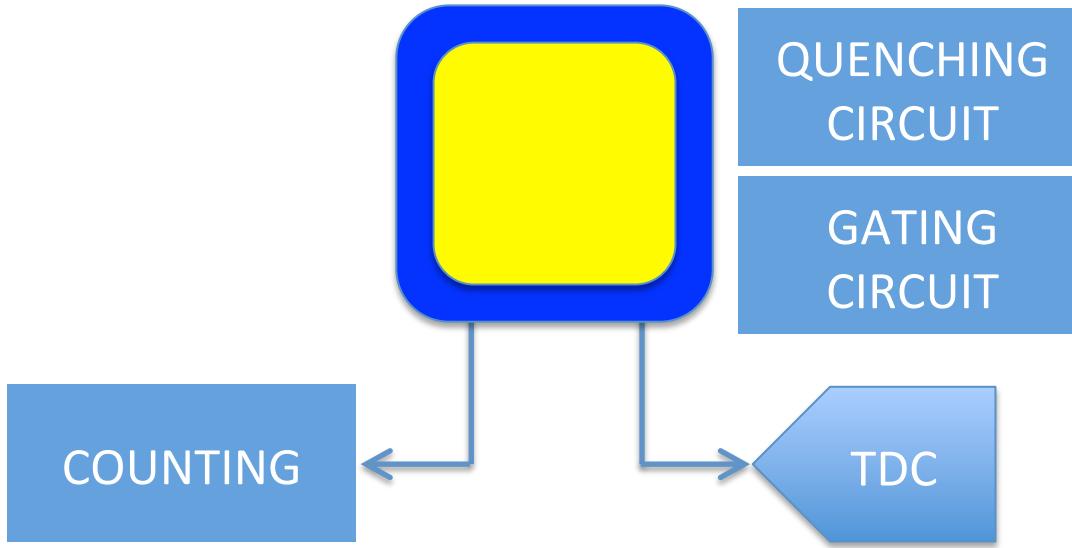
Fishburn, *Ph.D. Thesis*, Delft, 2012

**1<sup>st</sup> Take-Home Message:**

**SPAD imaging is now an established technology, supported by CMOS single-photon detection**

# **Single-Photon Imagers**

# First, the Pixel



*Another Tradeoff:*  
Functionality vs. Fill Factor

# Then, the Architecture

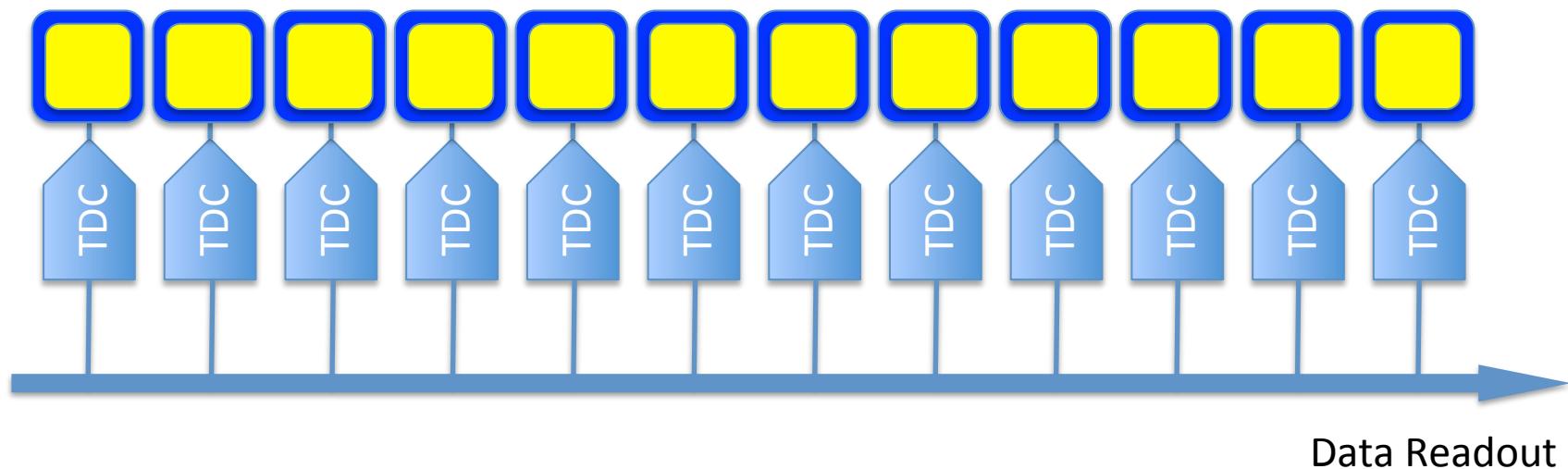
- Single-pixel

- 1D array

- 2D array

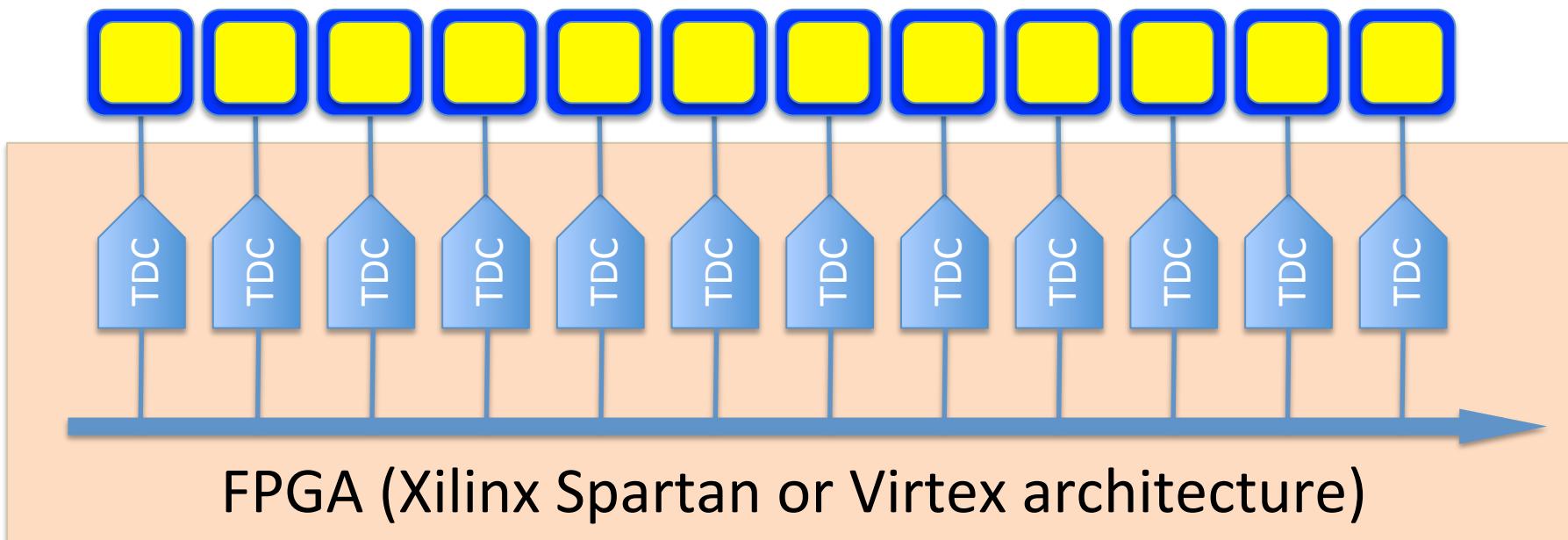
# 1D Array

- No sharing of resources
- High fill factor

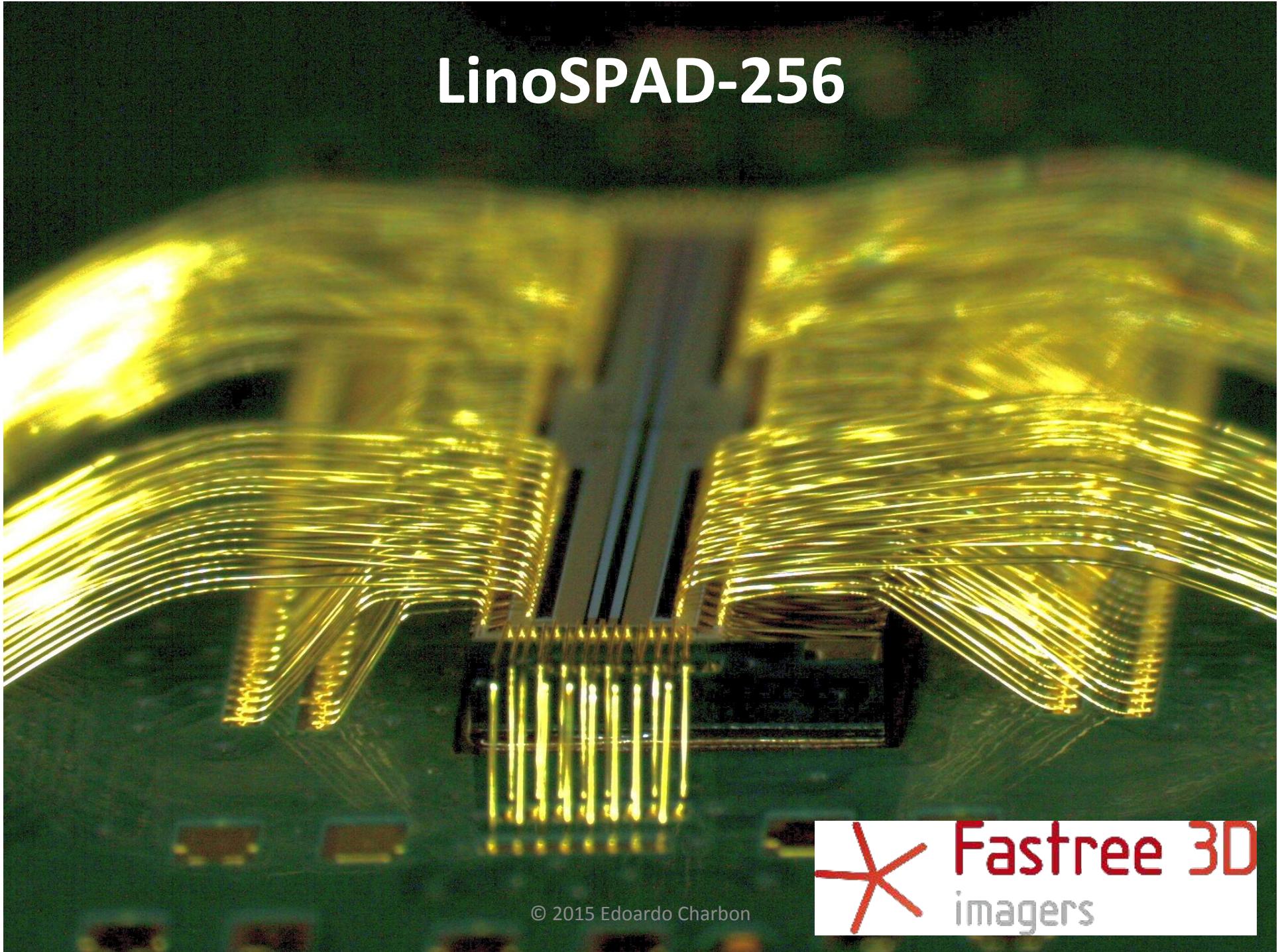


# The LinoSPAD Project

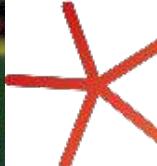
- Only SPAD integrated, fully parallel TDC array
- TDCs can use the best technology (e.g. 28nm)
- Medium fill factor (43%)
- Resolution on-demand (e.g. 9ps)
- Readout on-demand



# LinoSPAD-256



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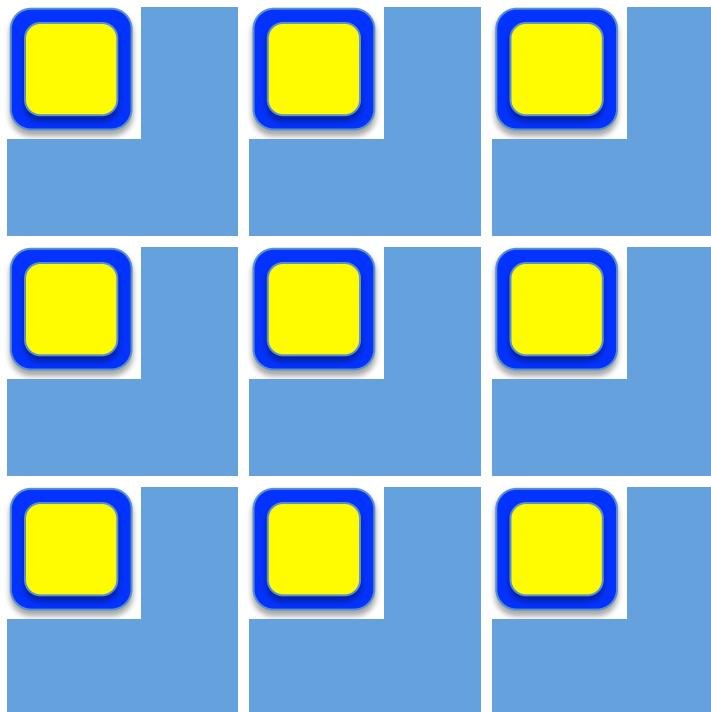
 **Fastree 3D**  
**imagers**

# Uses and Performance of LinoSPAD

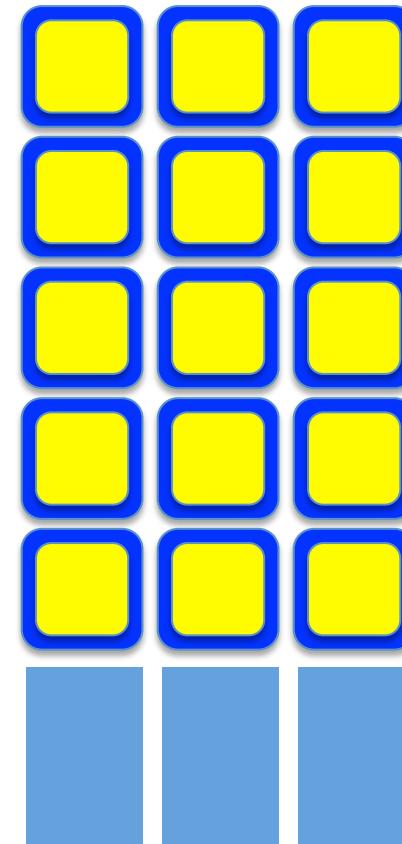
- Single-photon scanning
- Time-of-flight imaging
- Fluorescence Correlation Spectroscopy (FCS)

# 2D Array

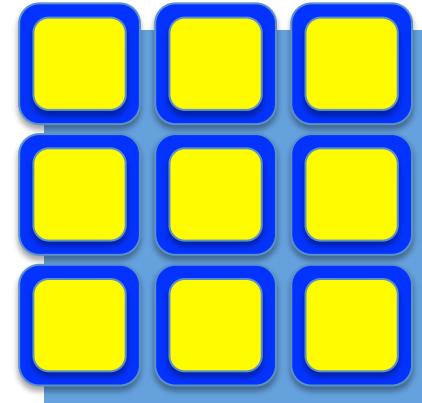
Fully parallel



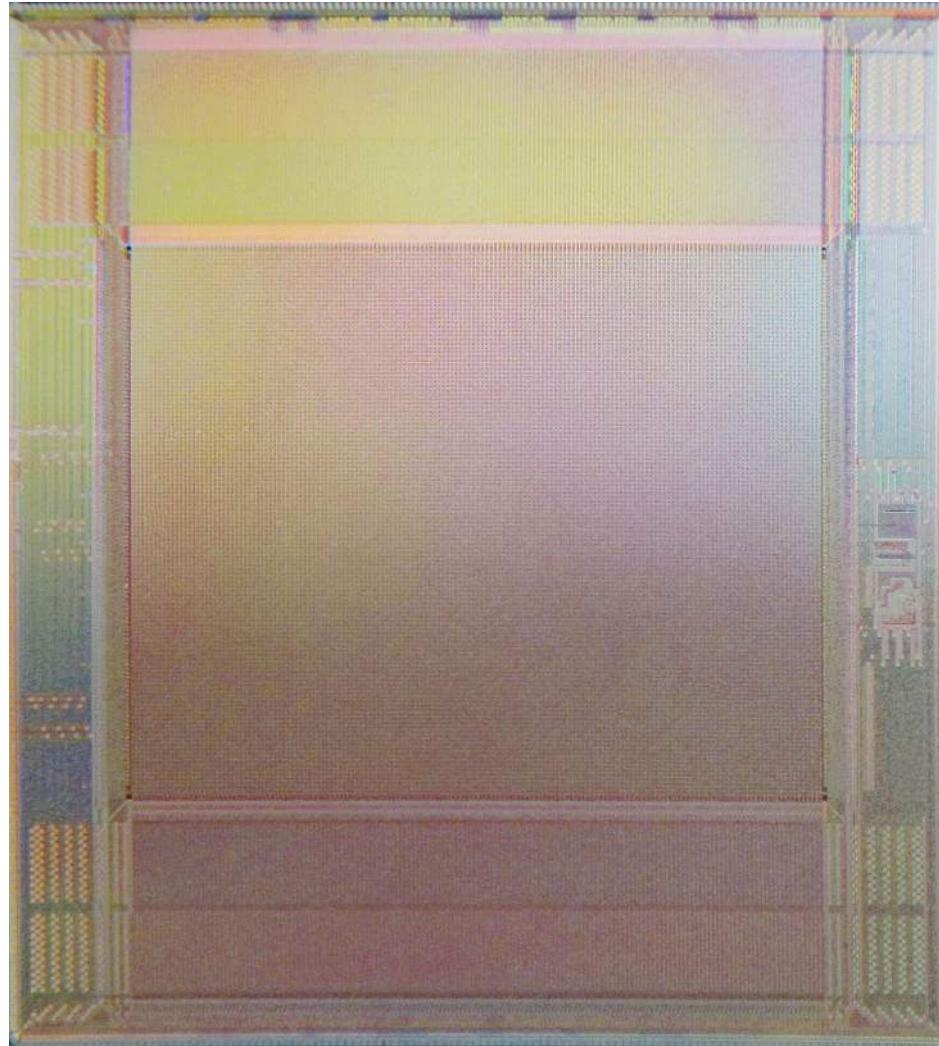
Column-Parallel



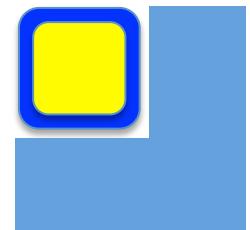
3D Integration



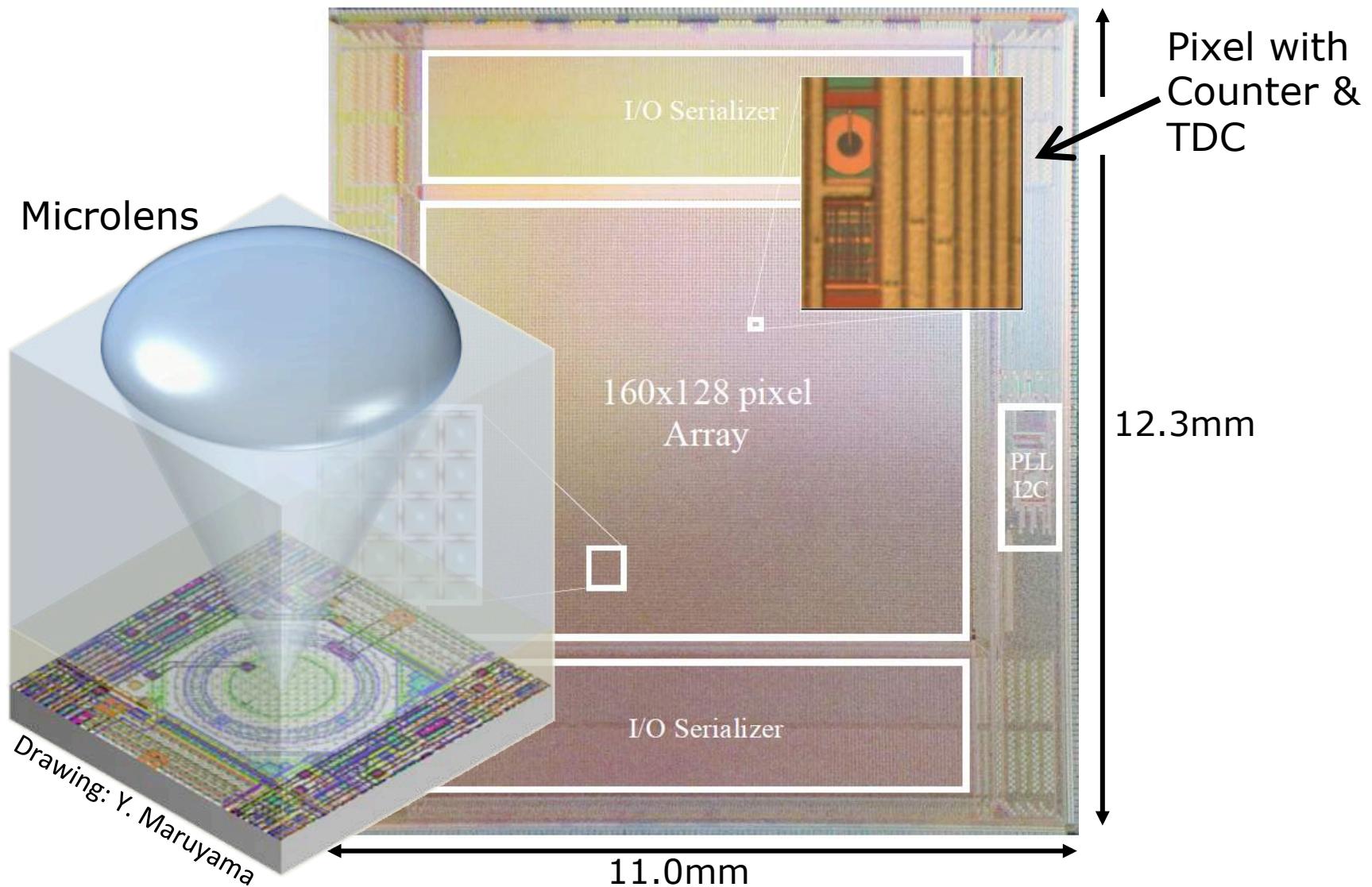
# The Megaframe Project



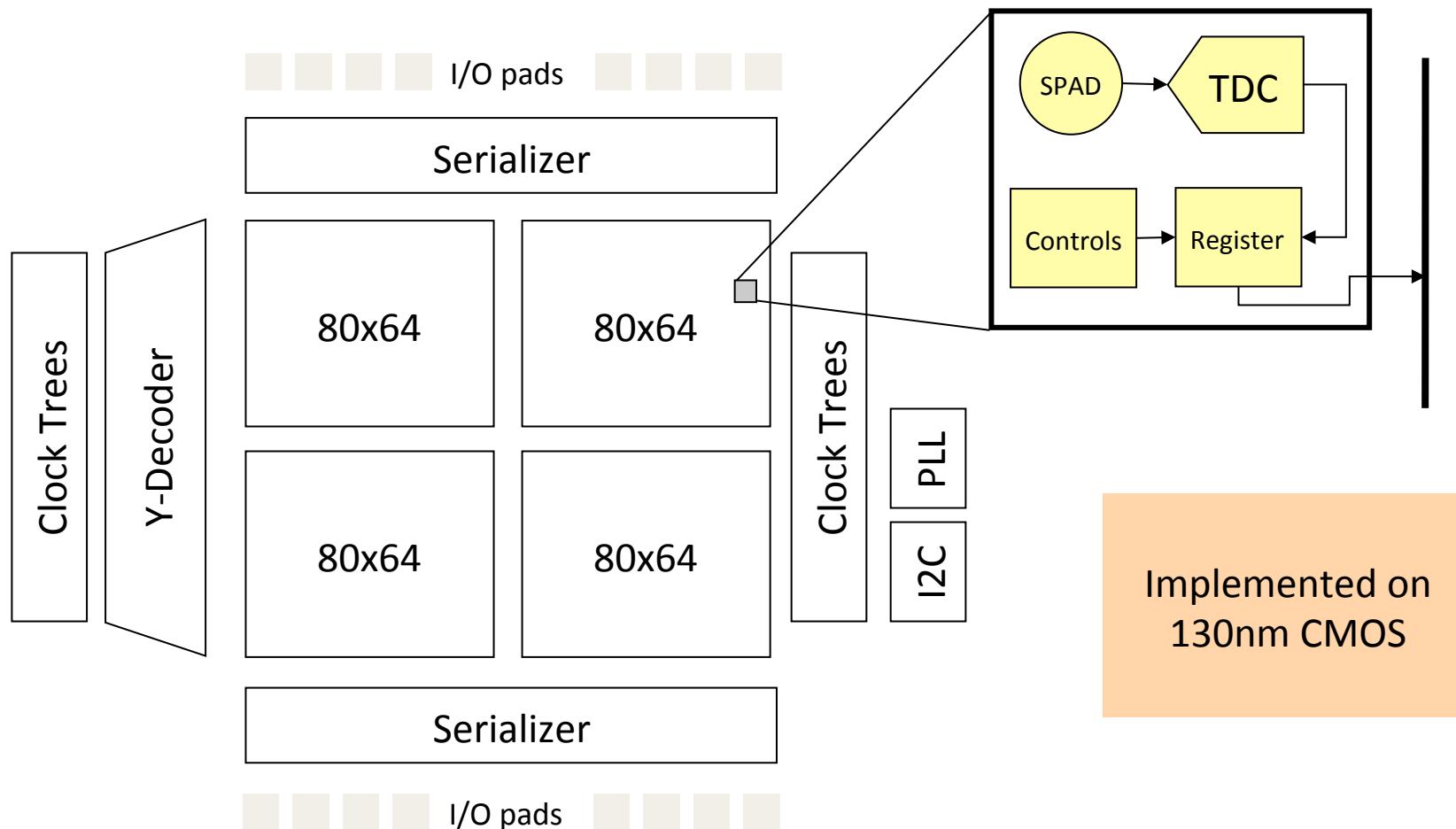
Veerappan, Richardson, Walker, Li, Fishburn, Maruyama, Stoppa,  
Borghetti, Gersbach, Henderson, Charbon, *ISSCC2011*



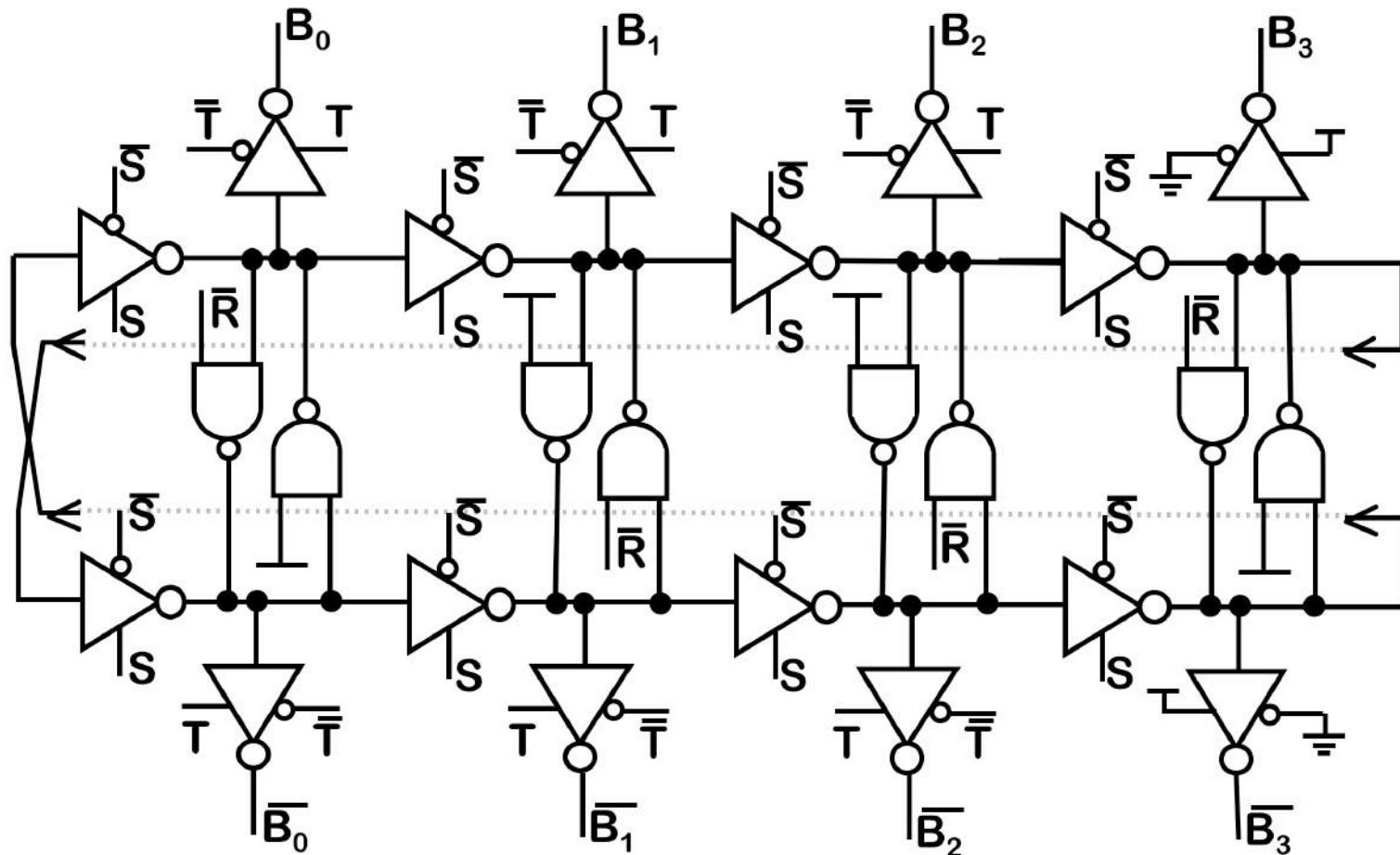
# The Megaframe-128 Chip



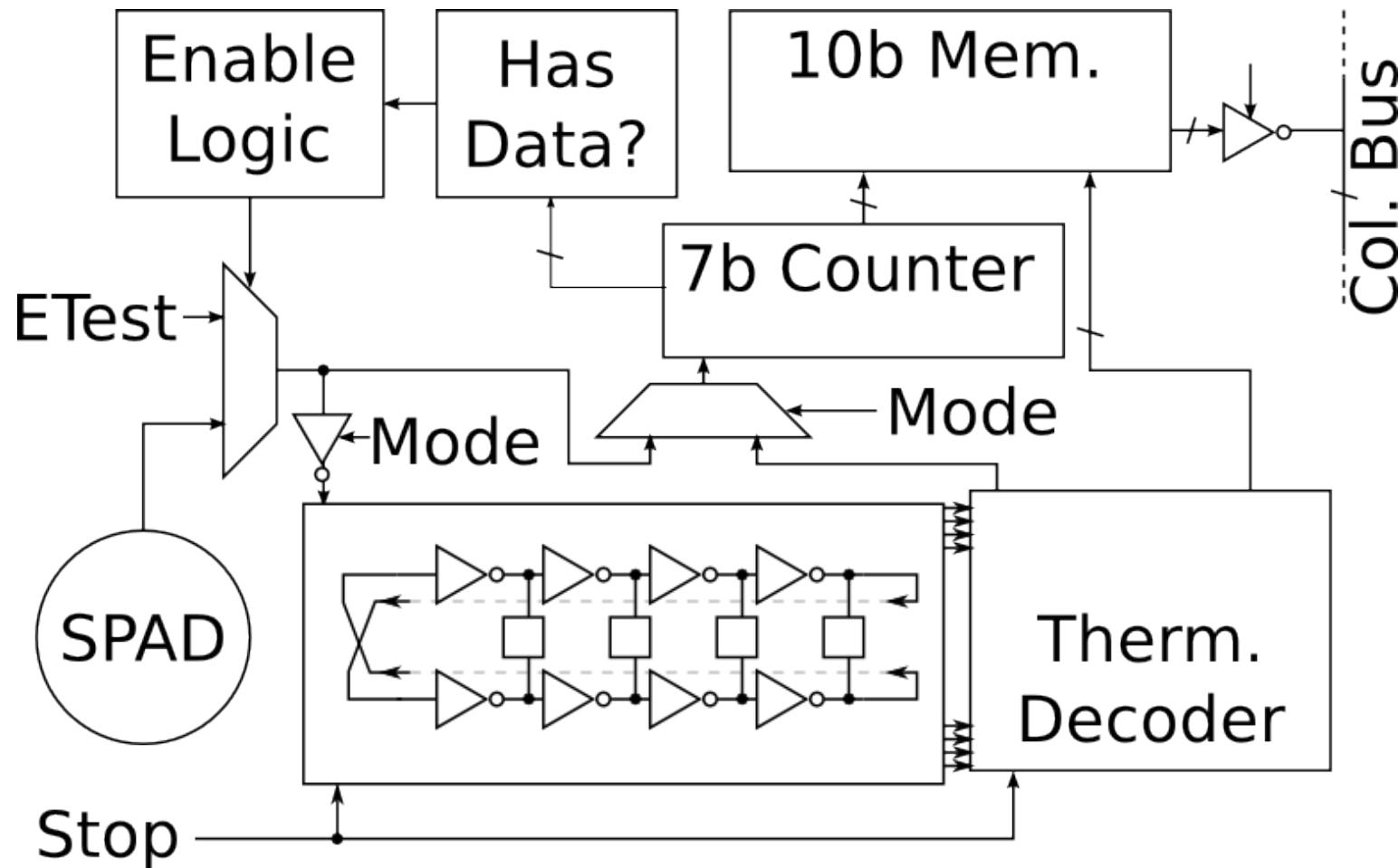
# The Megaframe-128 Chip



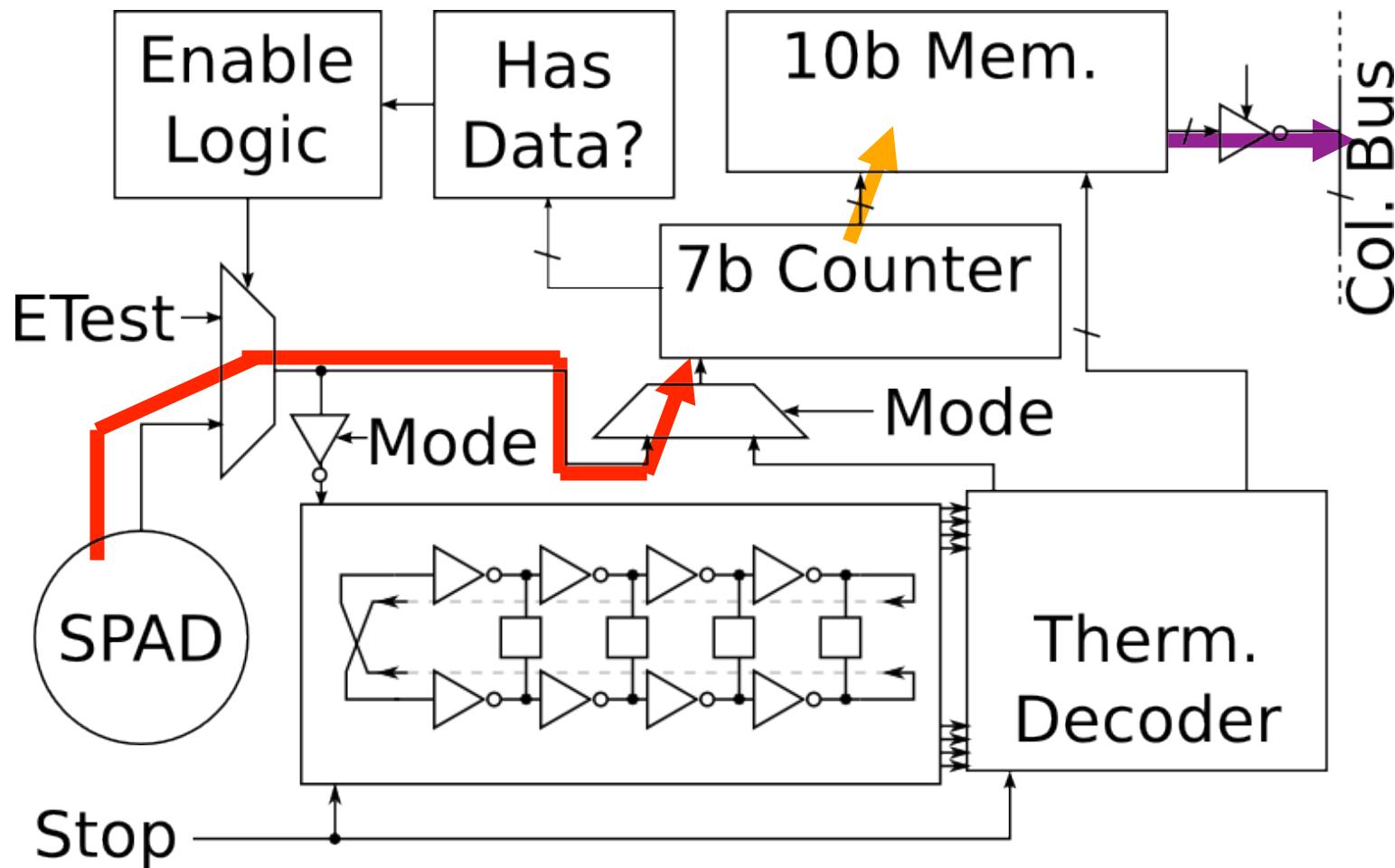
# TDC Core: the Ring Oscillator



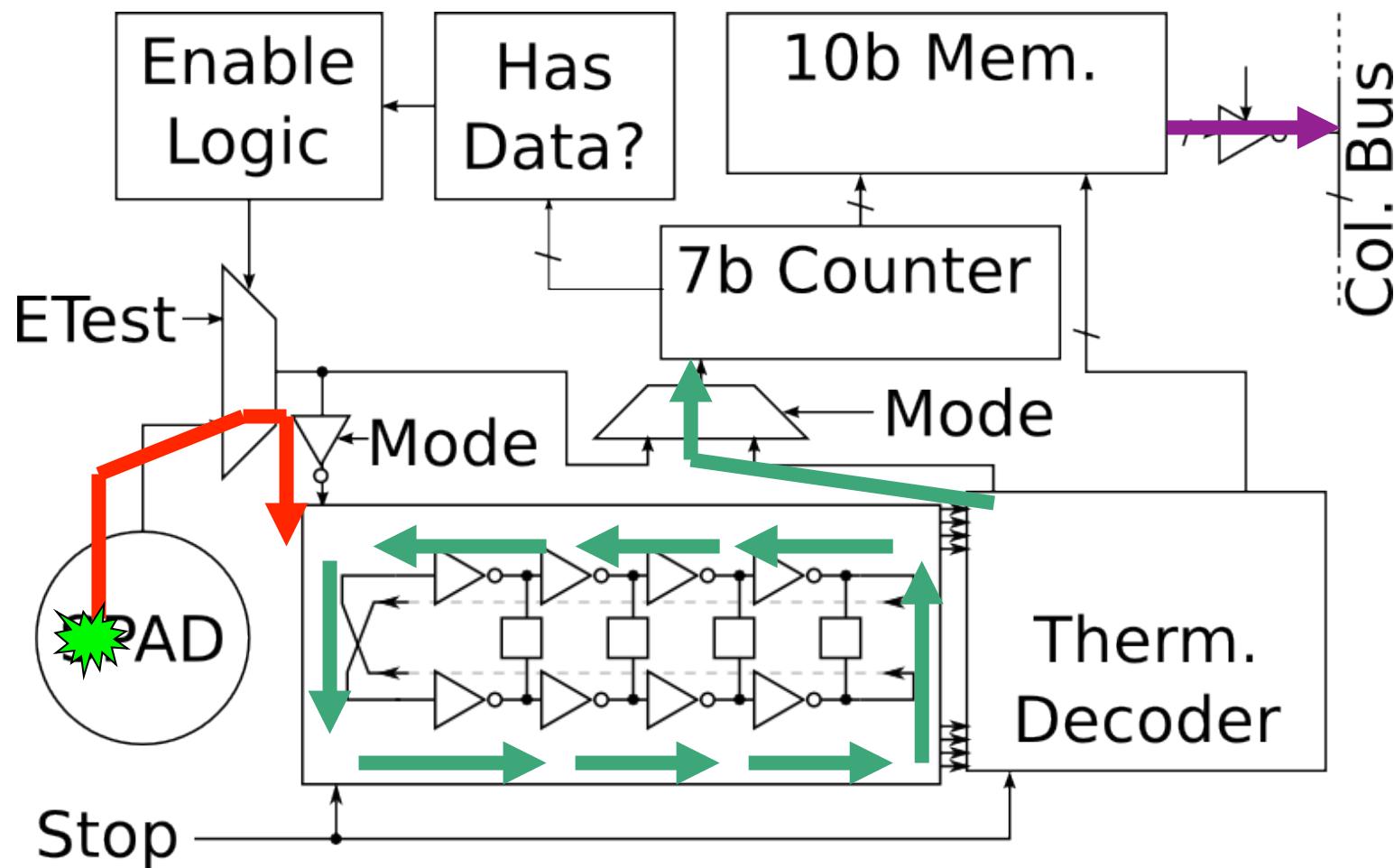
# Overall Pixel Schematic



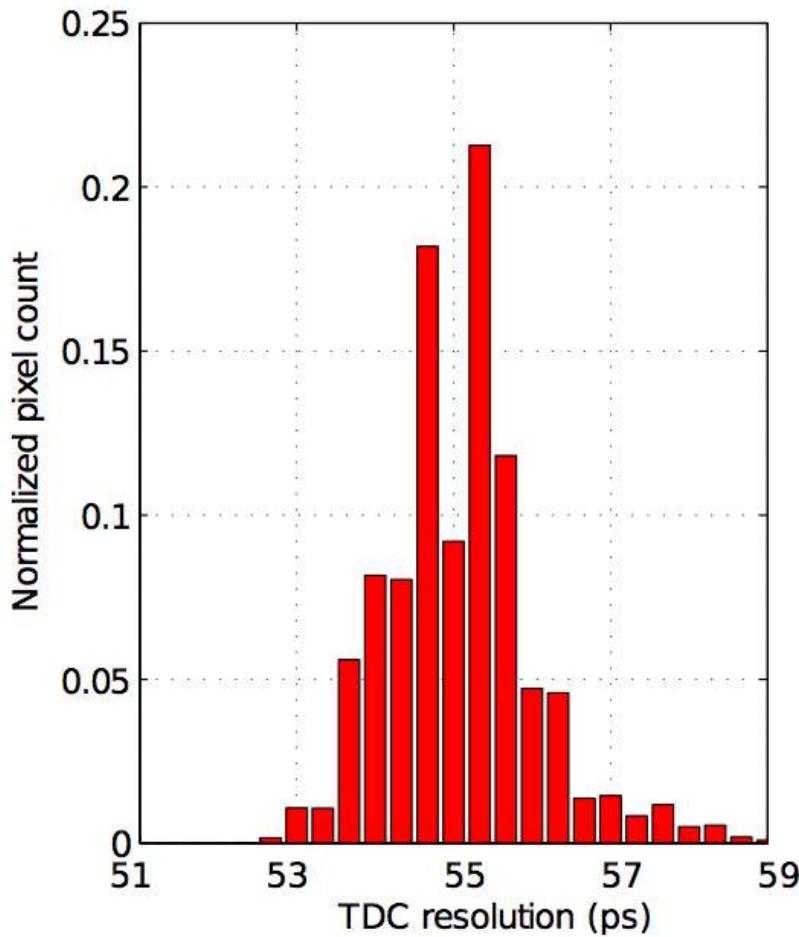
# Mode 1: Photon Counting



## Mode 2: Time stamping

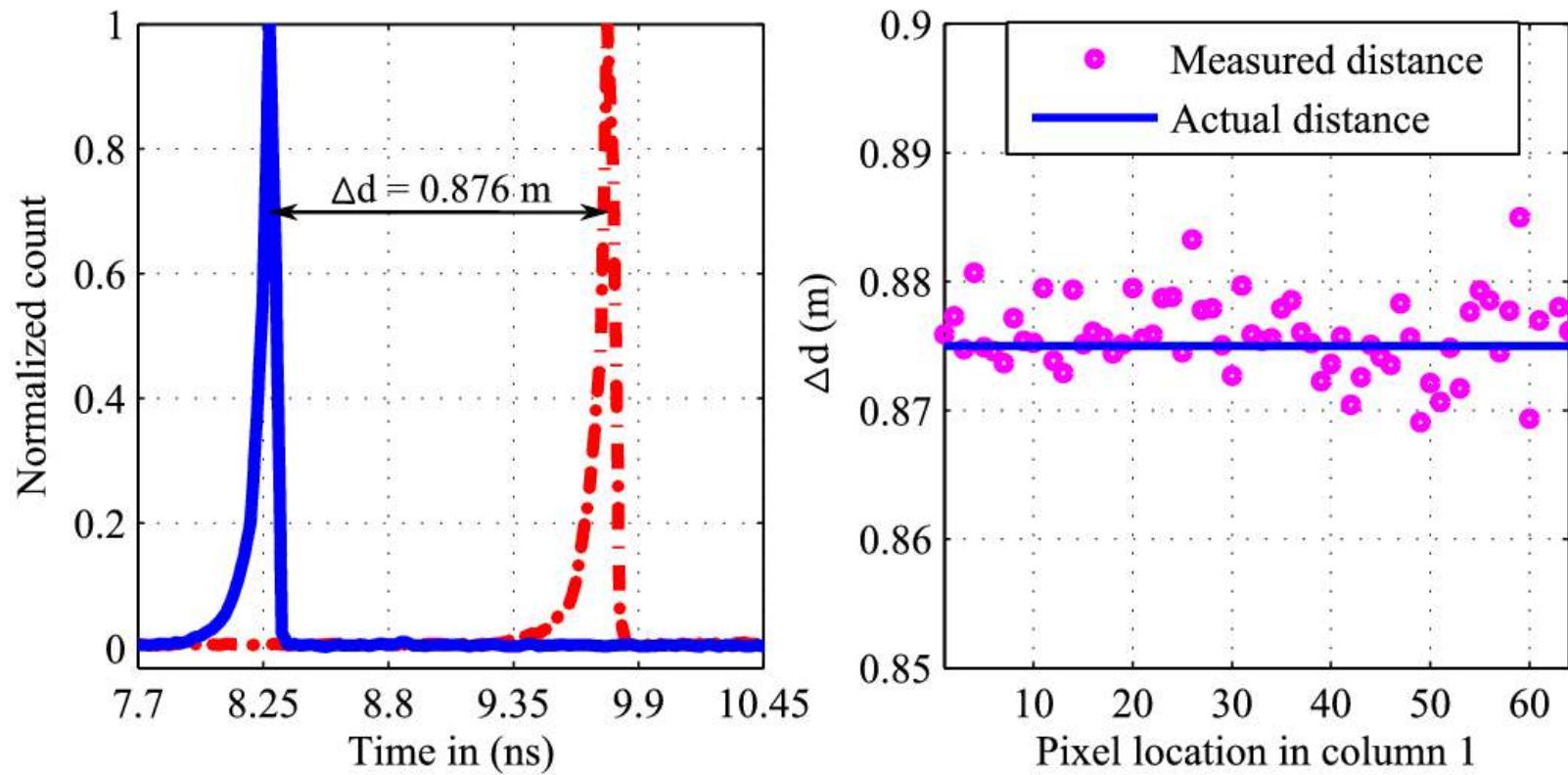


# TDC Resolution Spread (Non-Deterministic)



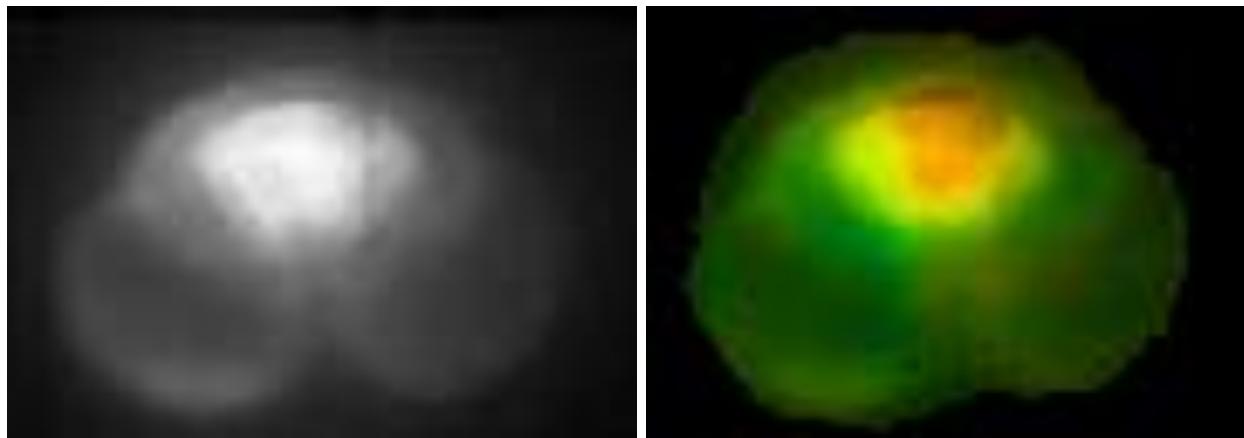
C. Veerappan et al., *ESSDERC*, 2011

# Jitter Uniformity



# Uses for Megaframe

- Fluorescence Lifetime Imaging Microscopy (FLIM)
- Förster Resonance Energy Transfer (FRET)
- Super resolution imaging
- Time-of-flight imaging
- Quantum Random Number Generators (QRNG)



Bisaccate Pine pollen

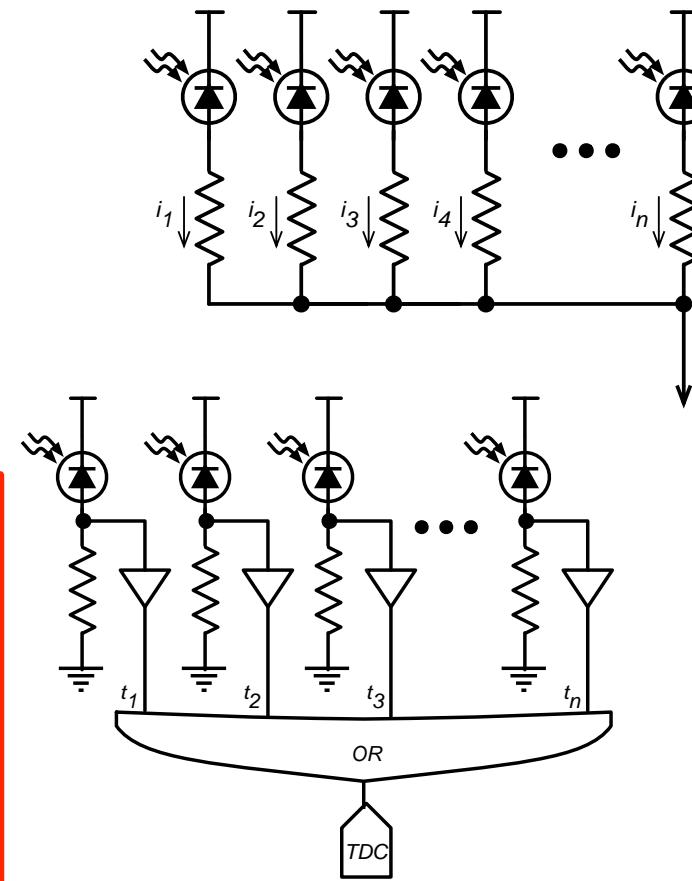
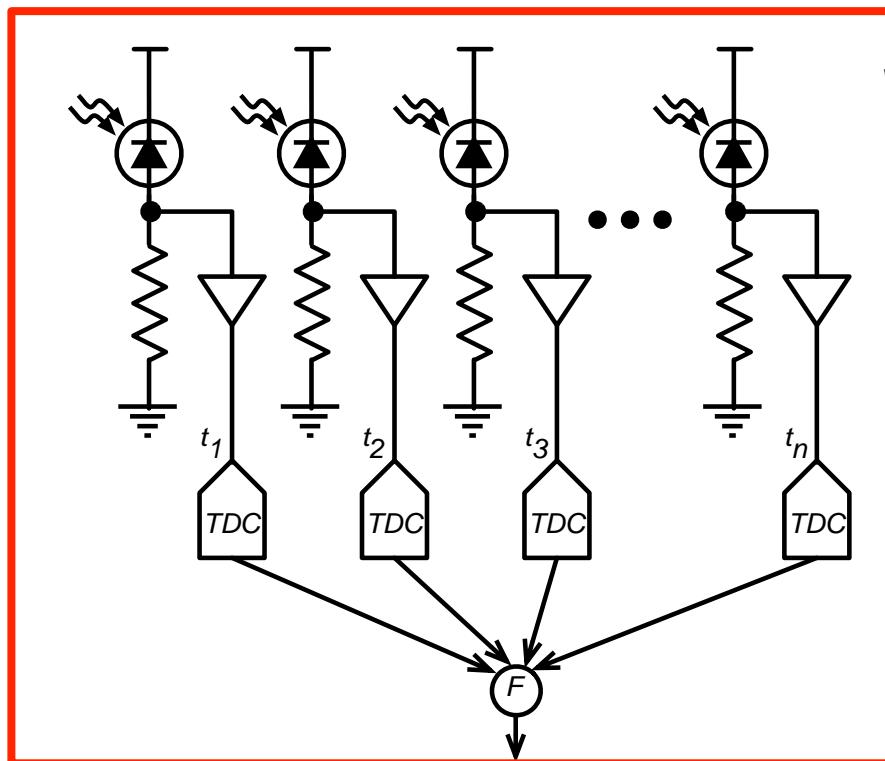
# Megaframe Legacy



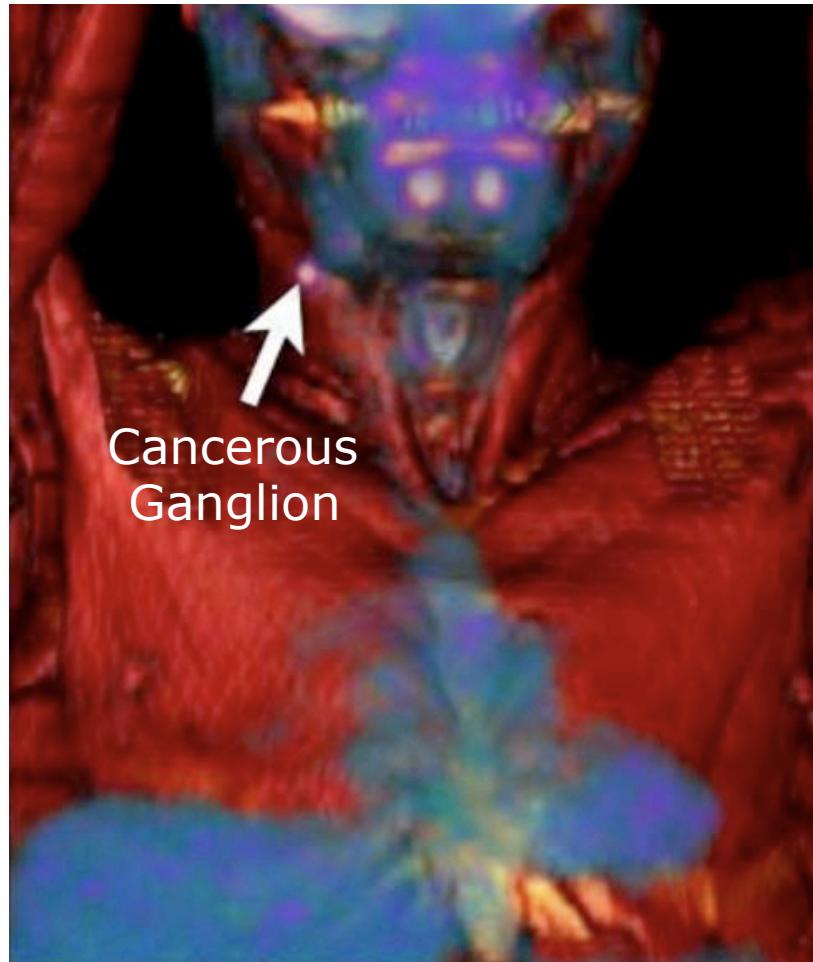
# Silicon Photomultipliers

# SiPM Architectures

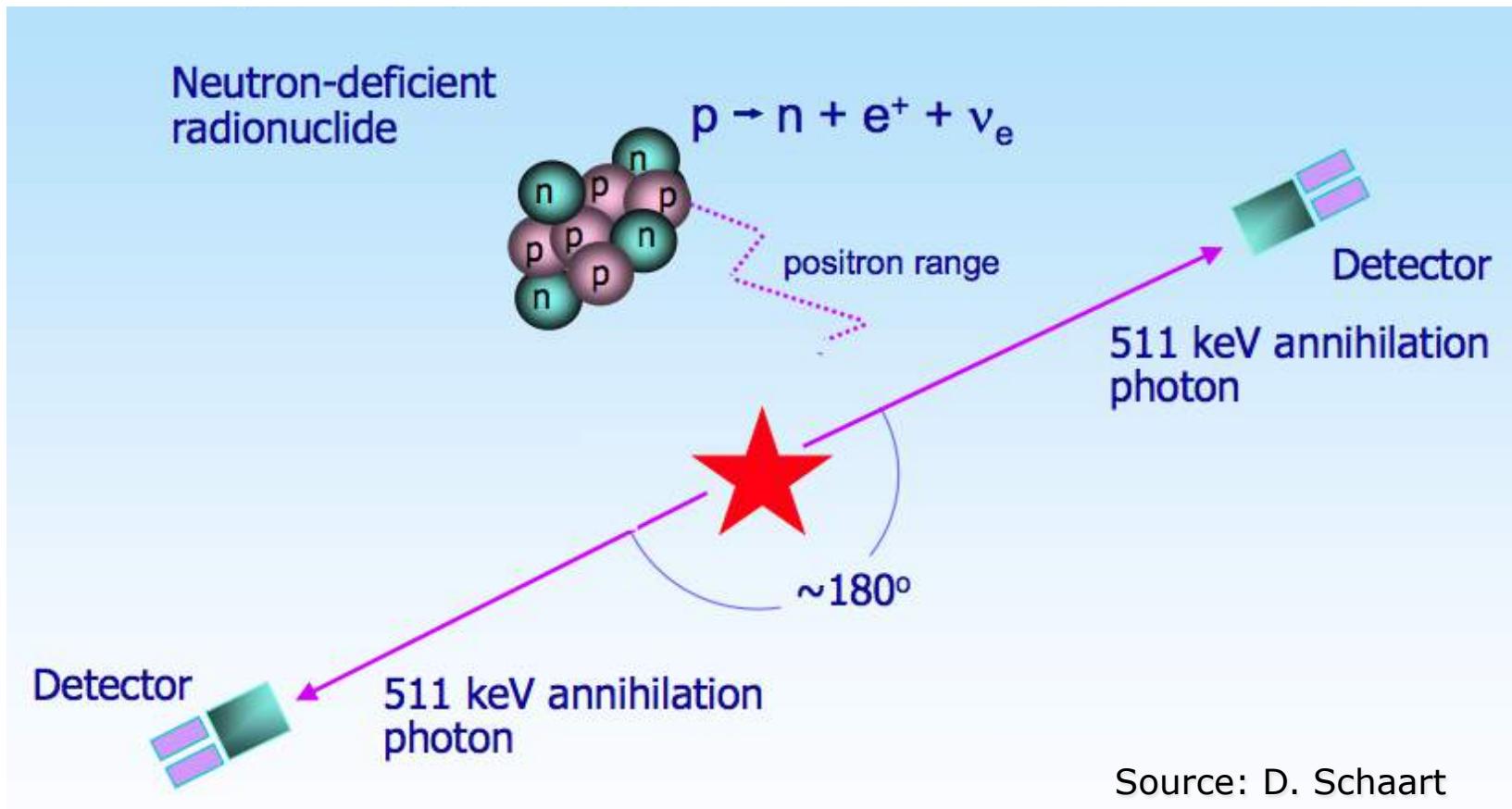
- Analog SiPMs
- Digital SiPMs
- Multi-channel digital SiPMs (MD-SiPMs)



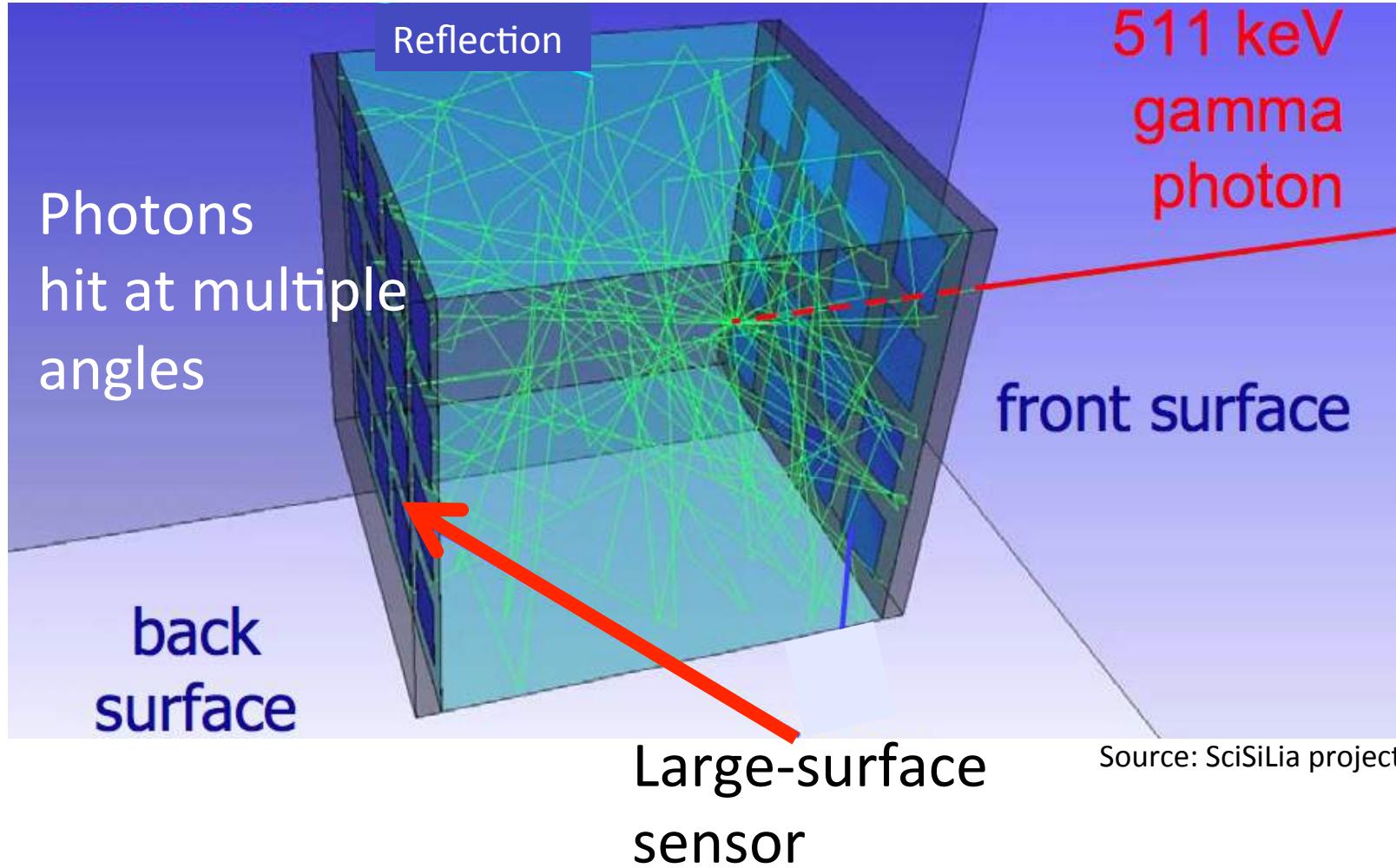
# Positron Emission Tomography (PET)



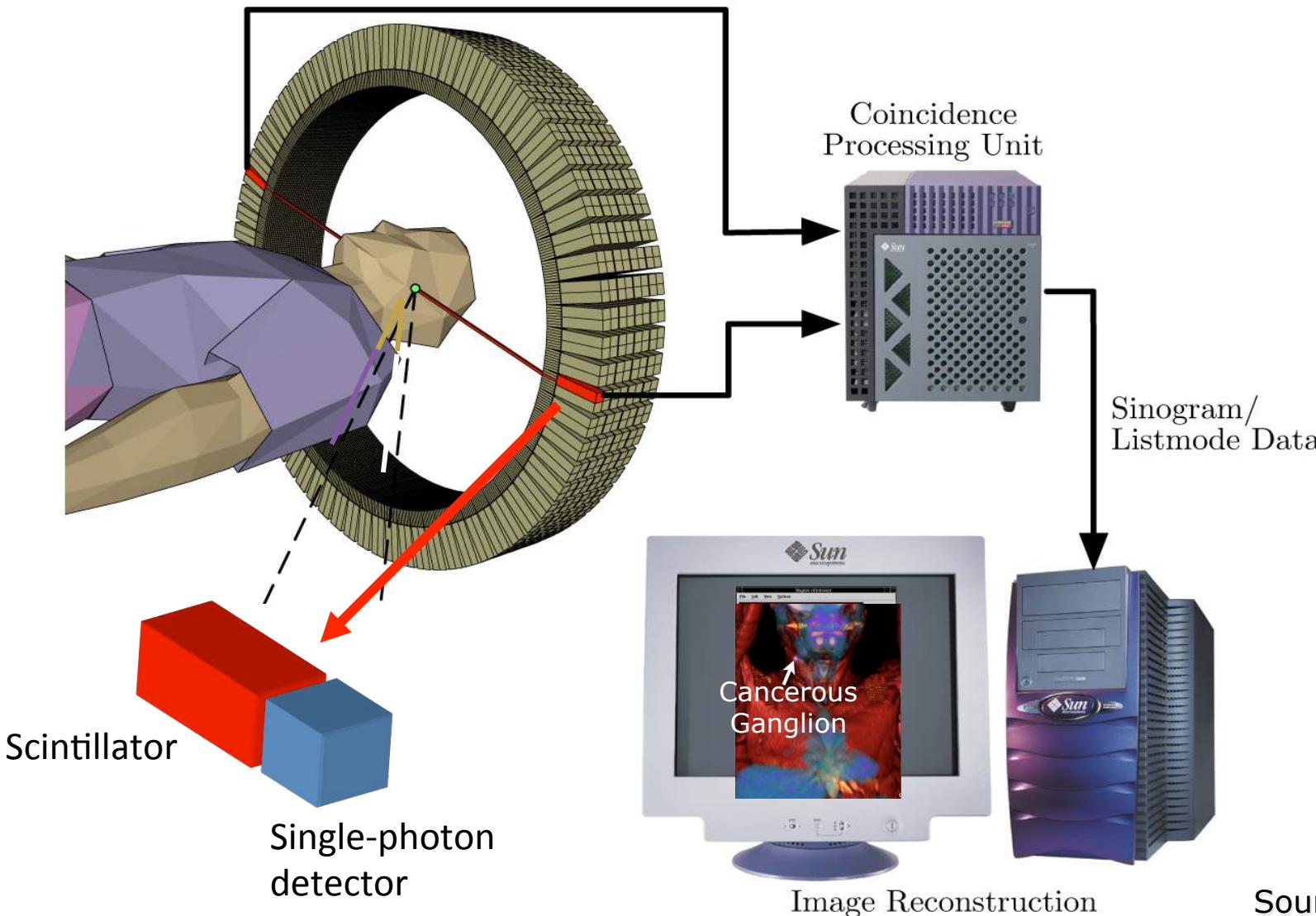
# PET Principle



# Scintillations Also Follow Order-Statistics

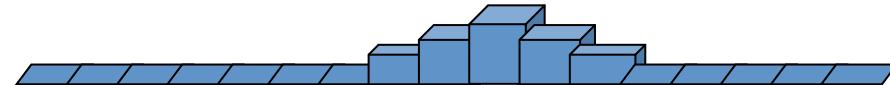


# 3D Reconstruction in PET



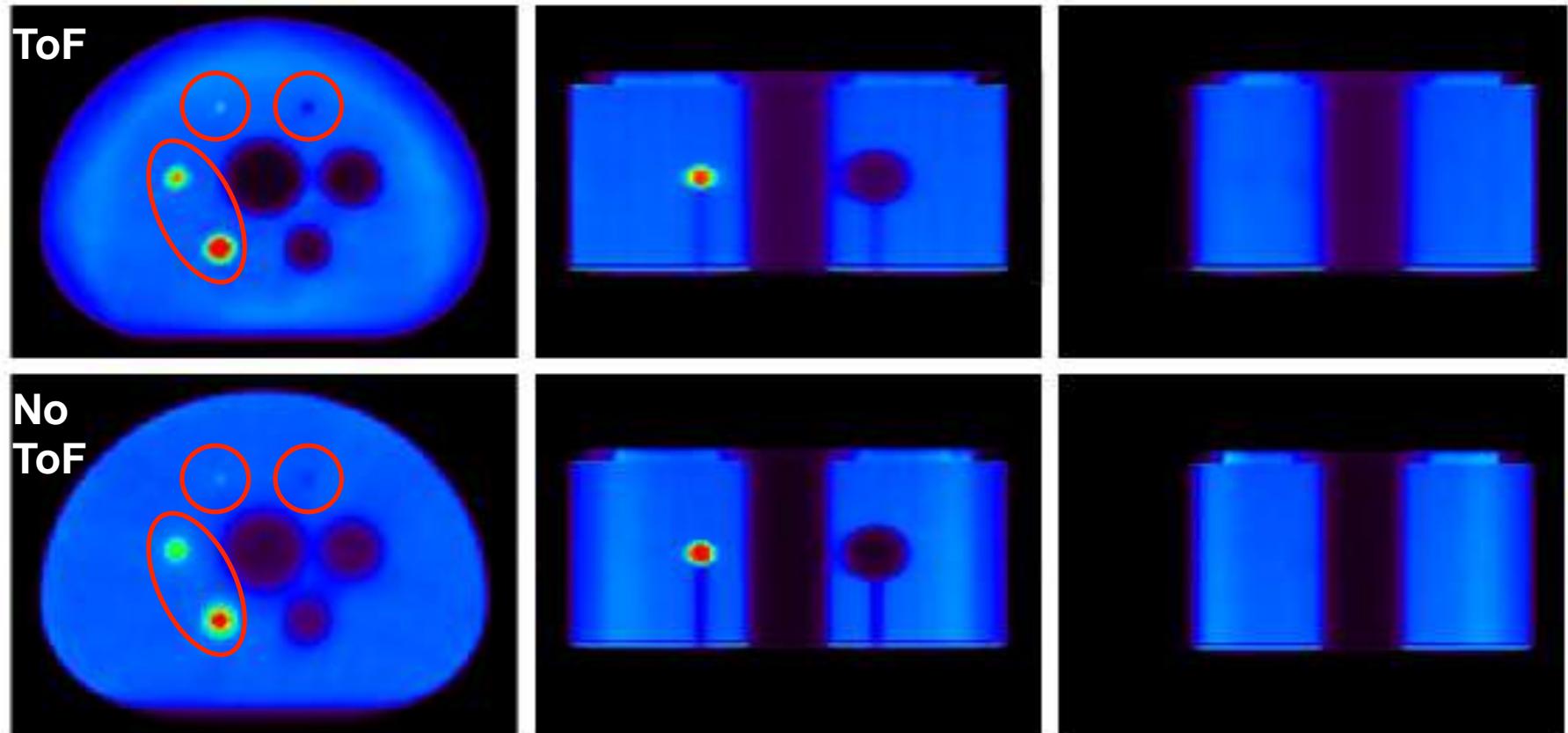
# Time-of-flight PET

Line of response  
sinogram weighting



Time of flight  
sinogram weighting

# The Advantages of TOF PET



Source: G. Nemeth

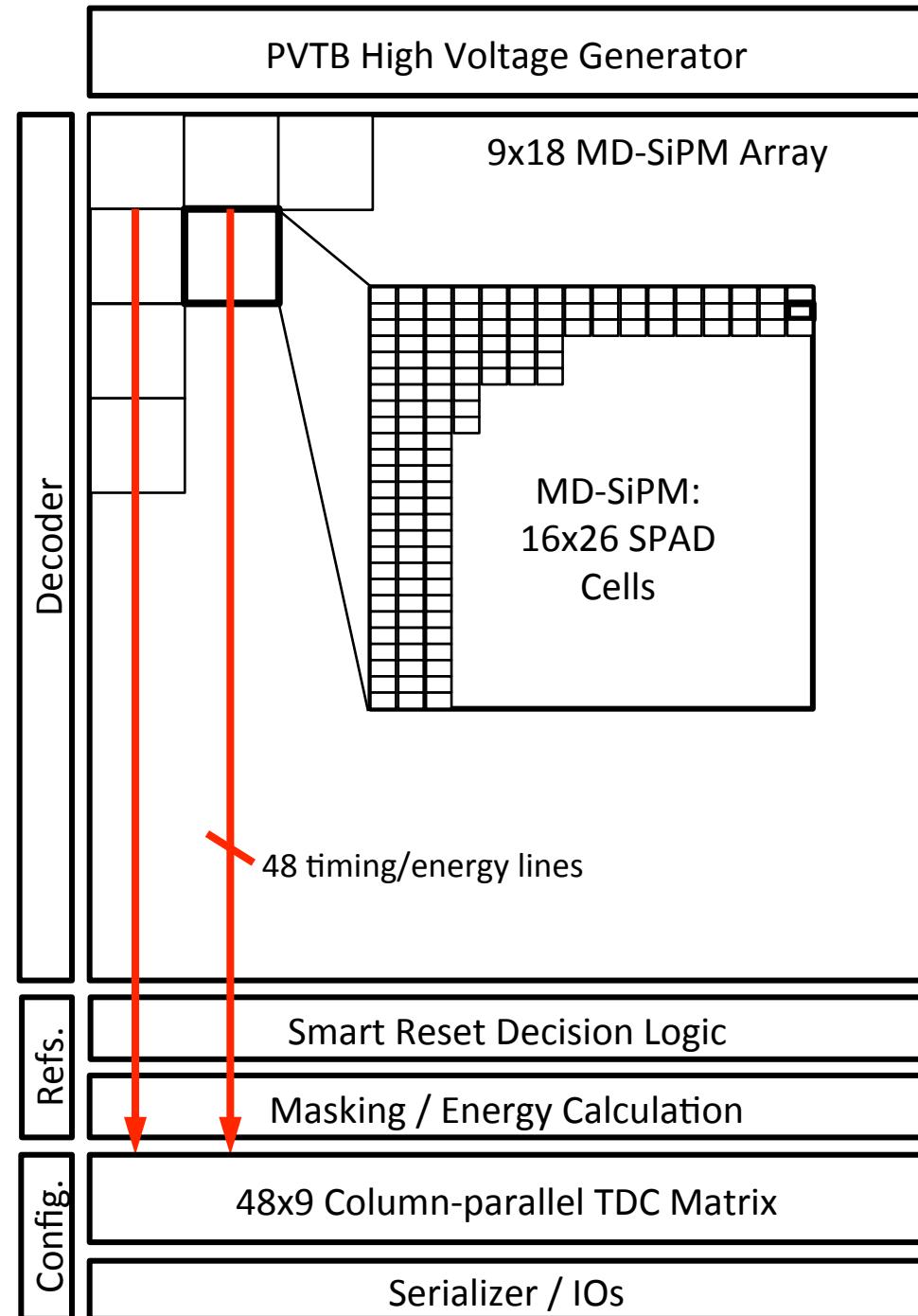
# EndoTOFPET US Concept



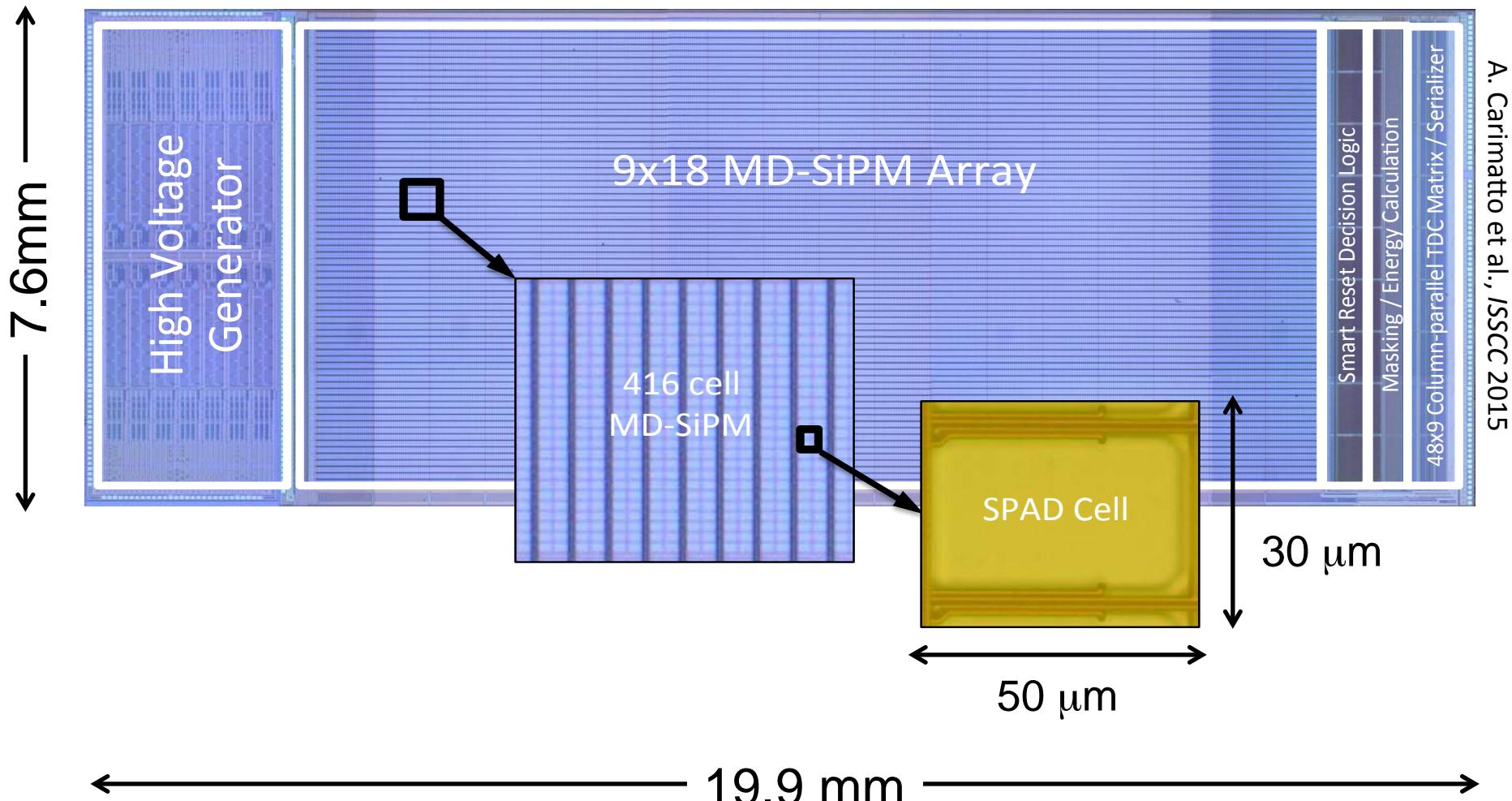
- **Endoscopic probe:**
  - design of mechanics / cooling - system integration test
- **External plate:**
  - MPPC characterization
  - MPPC + crystals characterization
  - design of mechanics / cooling
  - system integration test

# The EndoTOFPET US Probe MD- SiPM

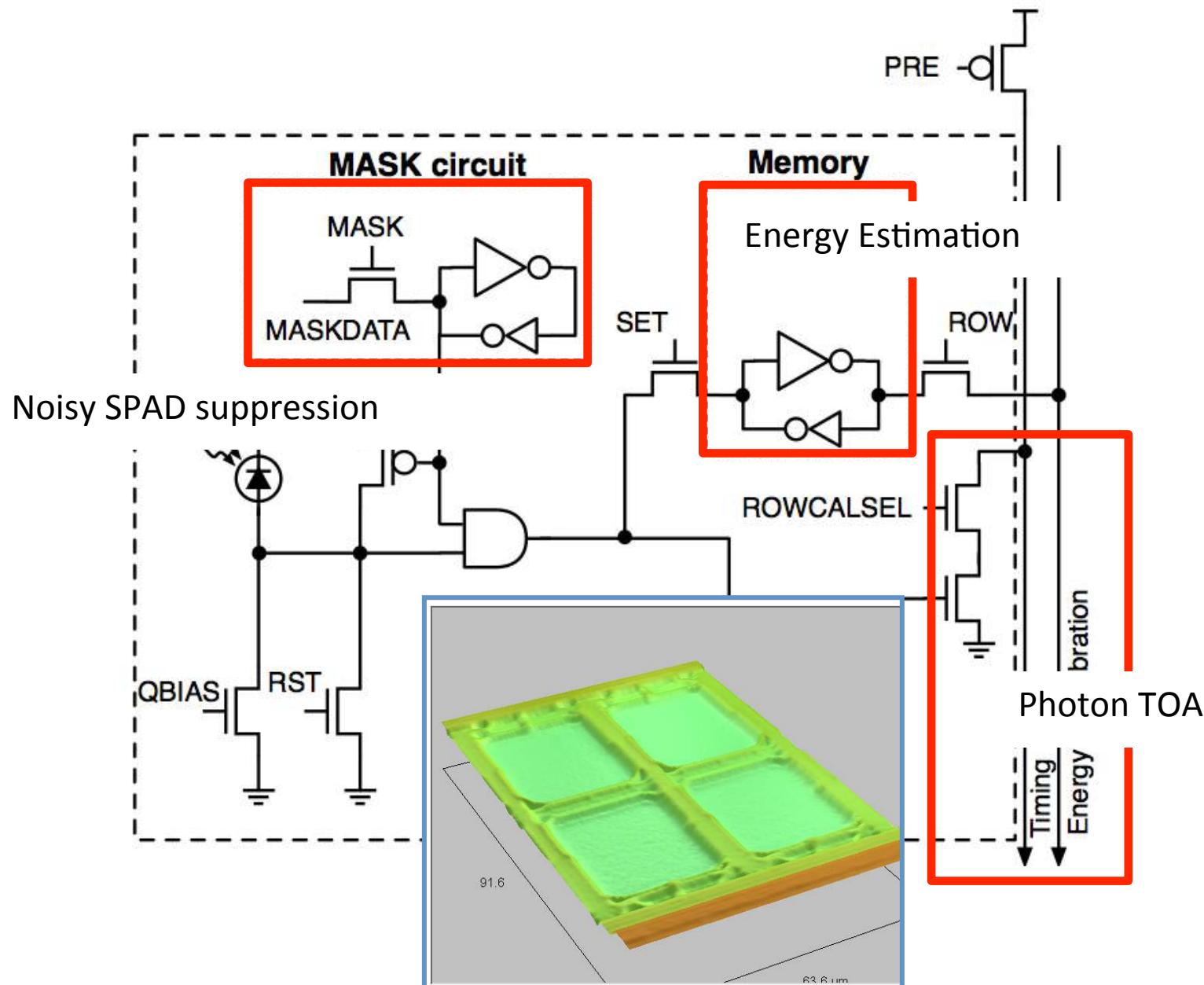
- 9x18 multi-channel digital SiPMs
- 432 TDCs (50ps)
- High voltage generator (PVT-B controlled)
- 57% FF
- <50ps LSB
- 179ps SPTR



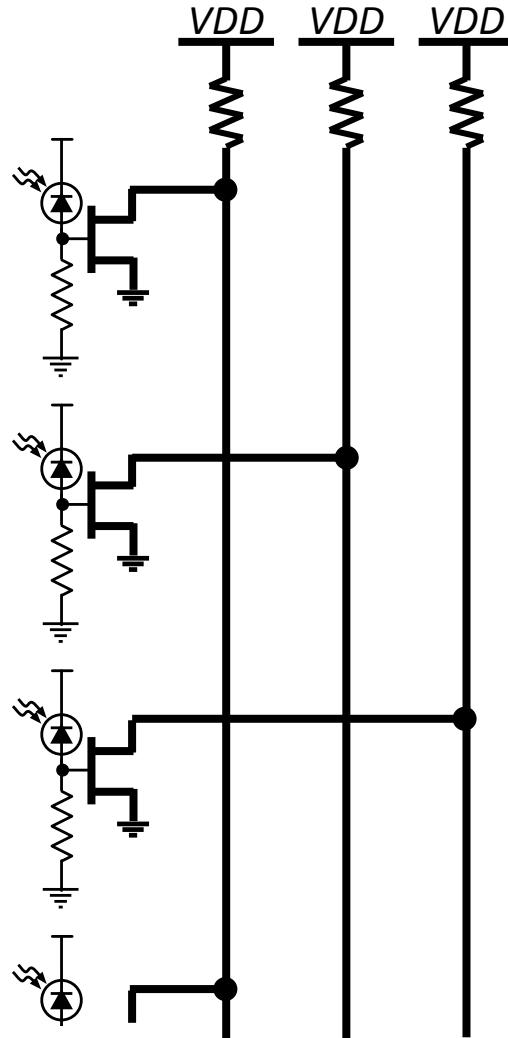
# The EndoTOFPET US Chip



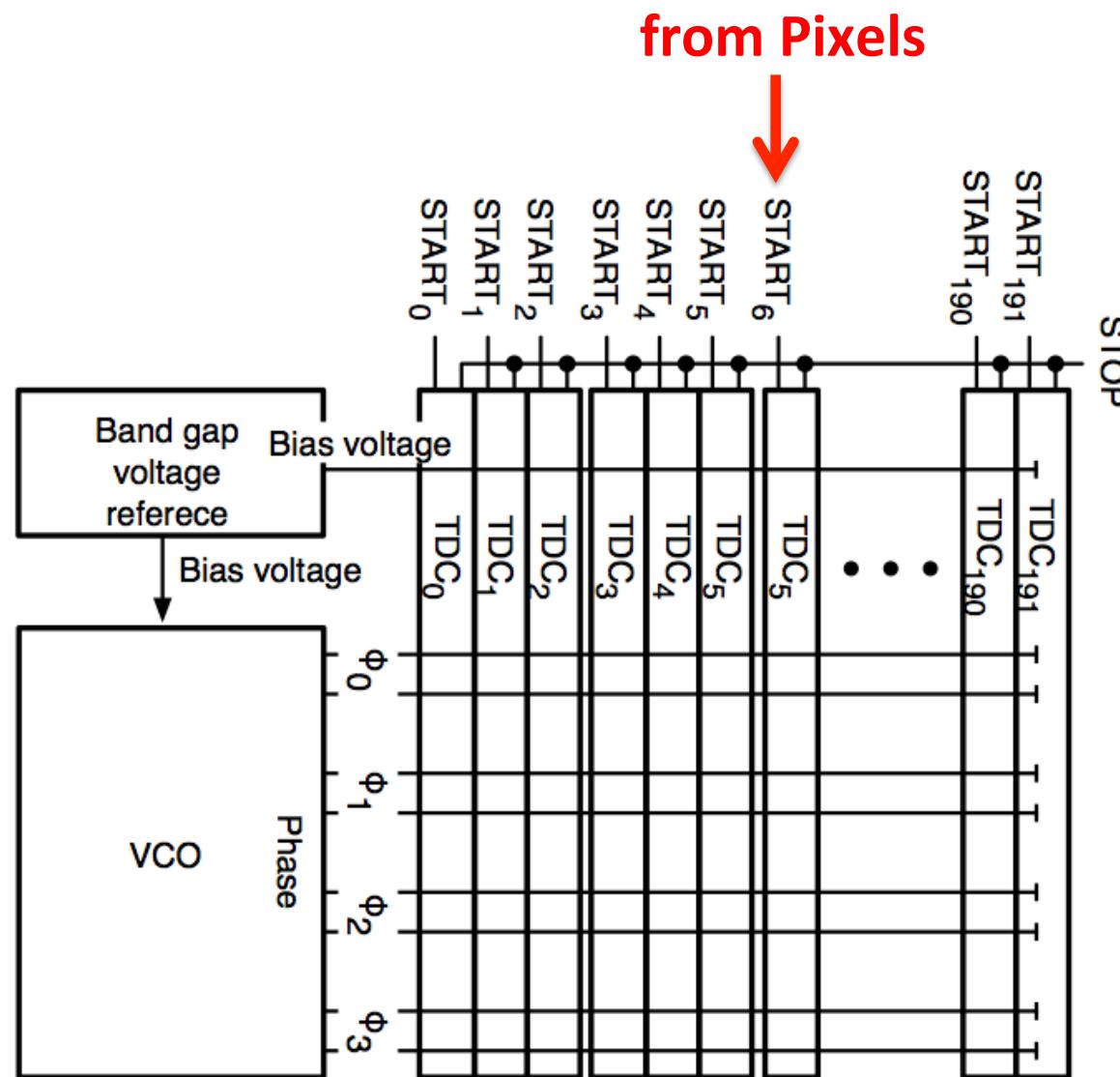
# Pixel Architecture



# MD-SiPM Arch: Column-Parallel

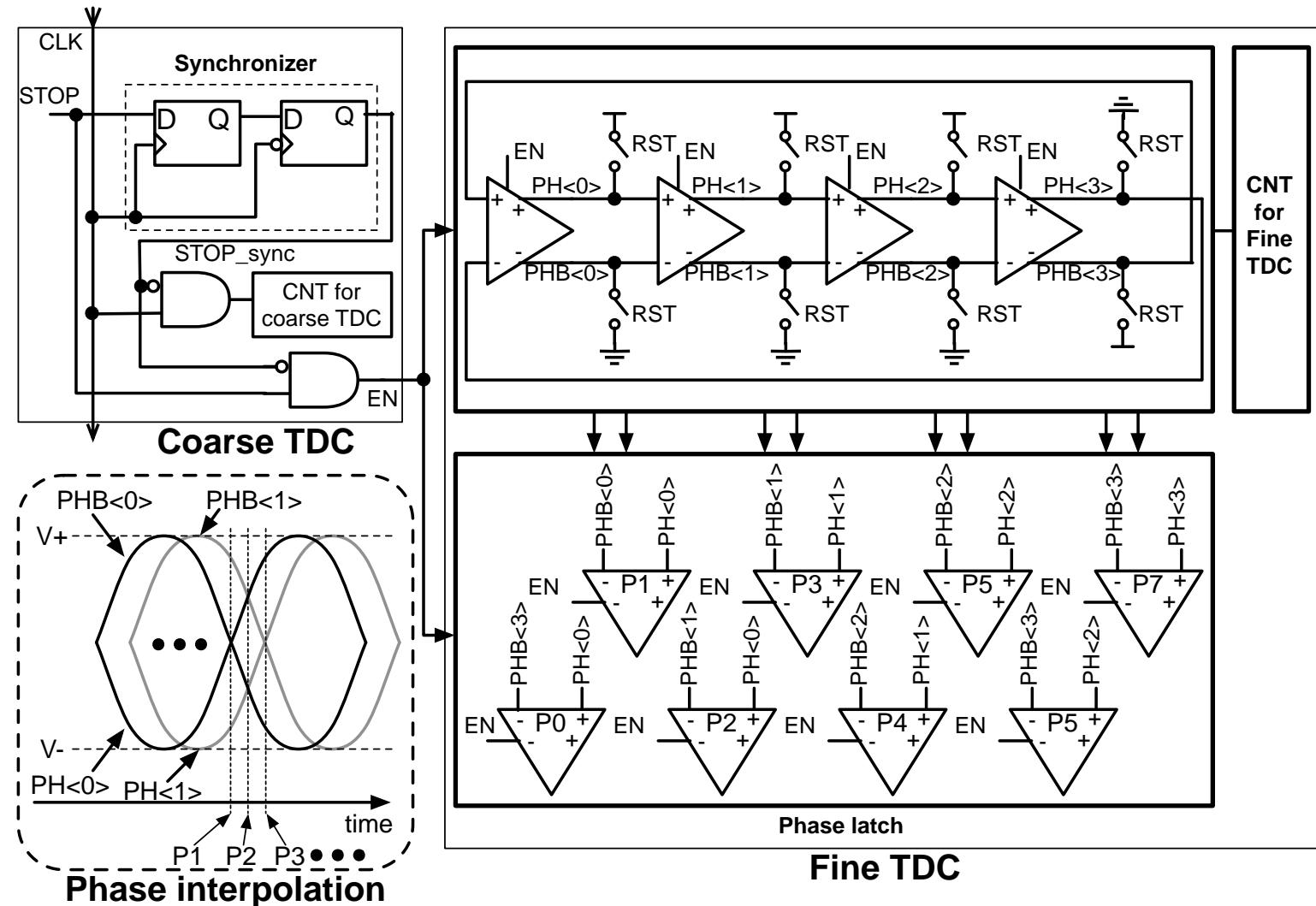


# Column-Parallel Pixel-TDCs

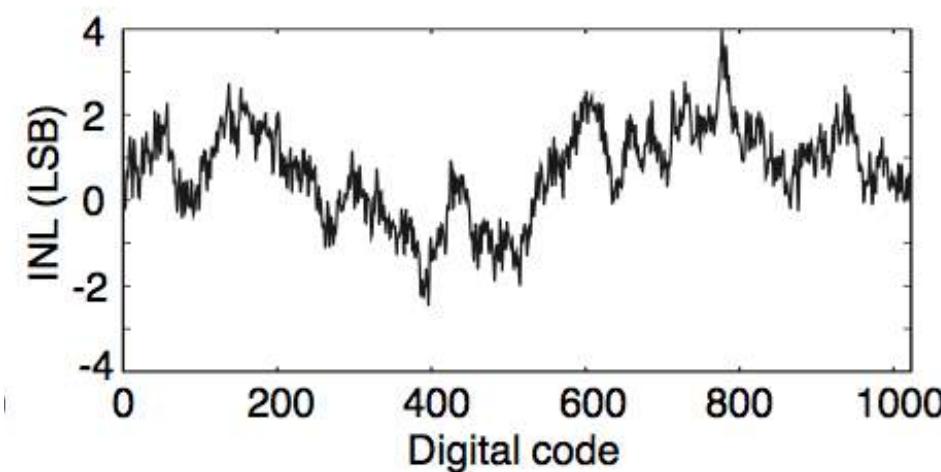
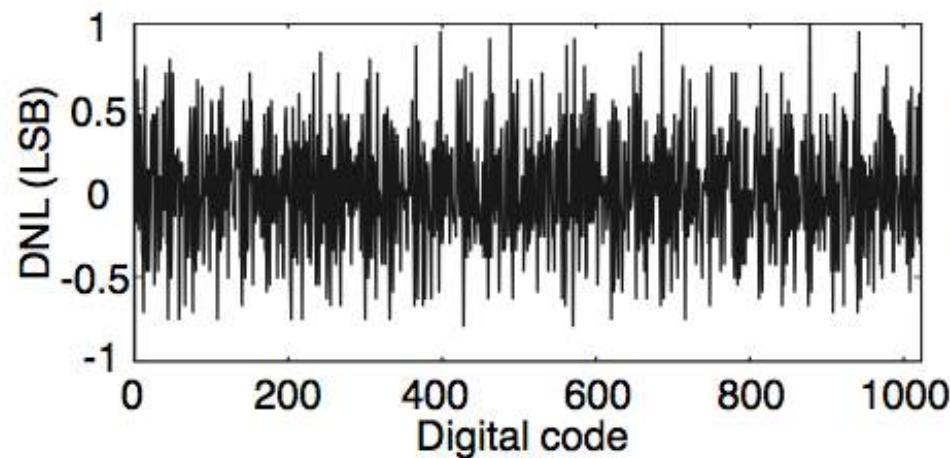


S. Mandai and E. Charbon, IEEE Nuc. Sci Symp. (NSS) 2012

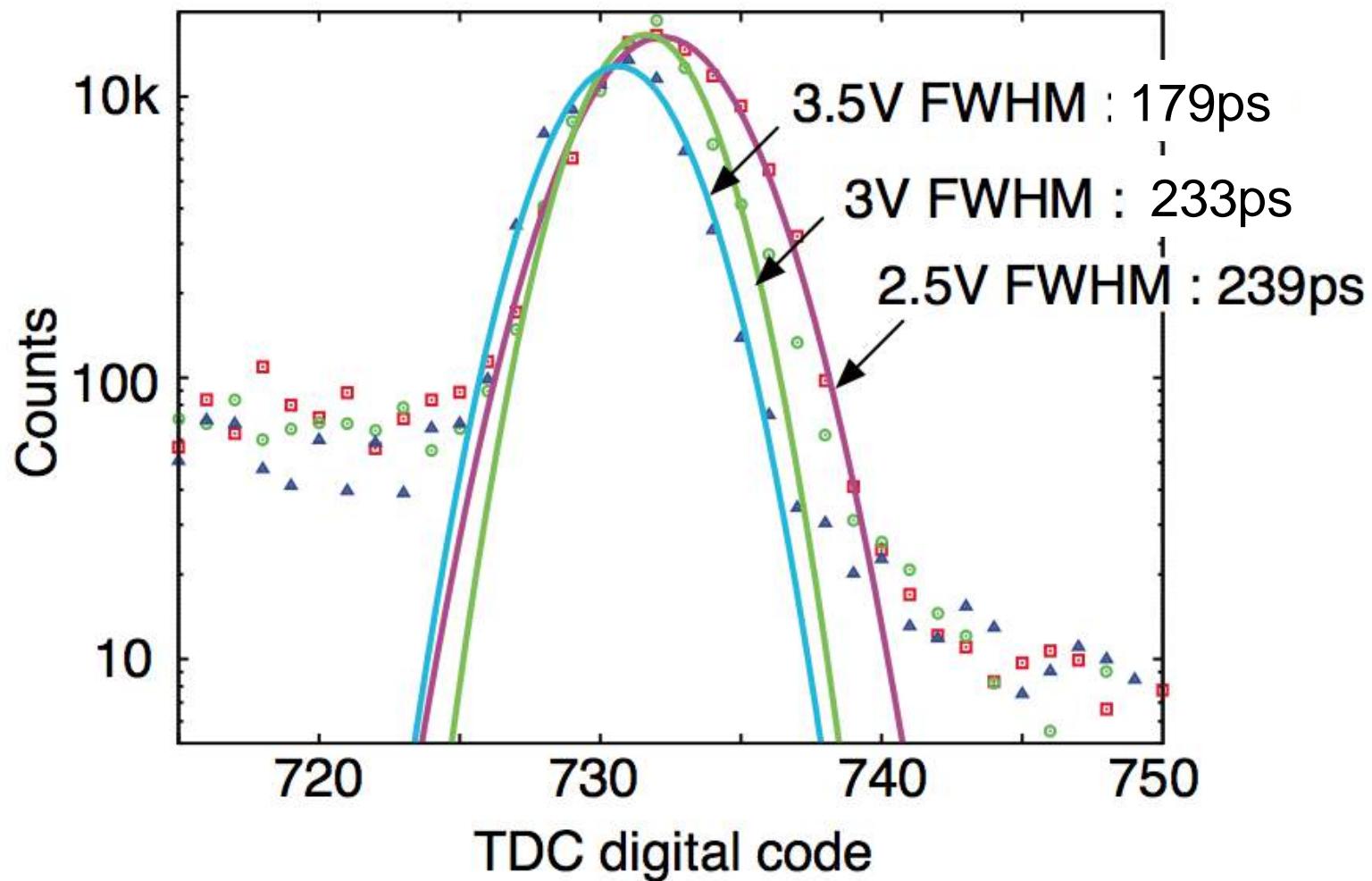
# Time-to-Digital Converter (TDC)



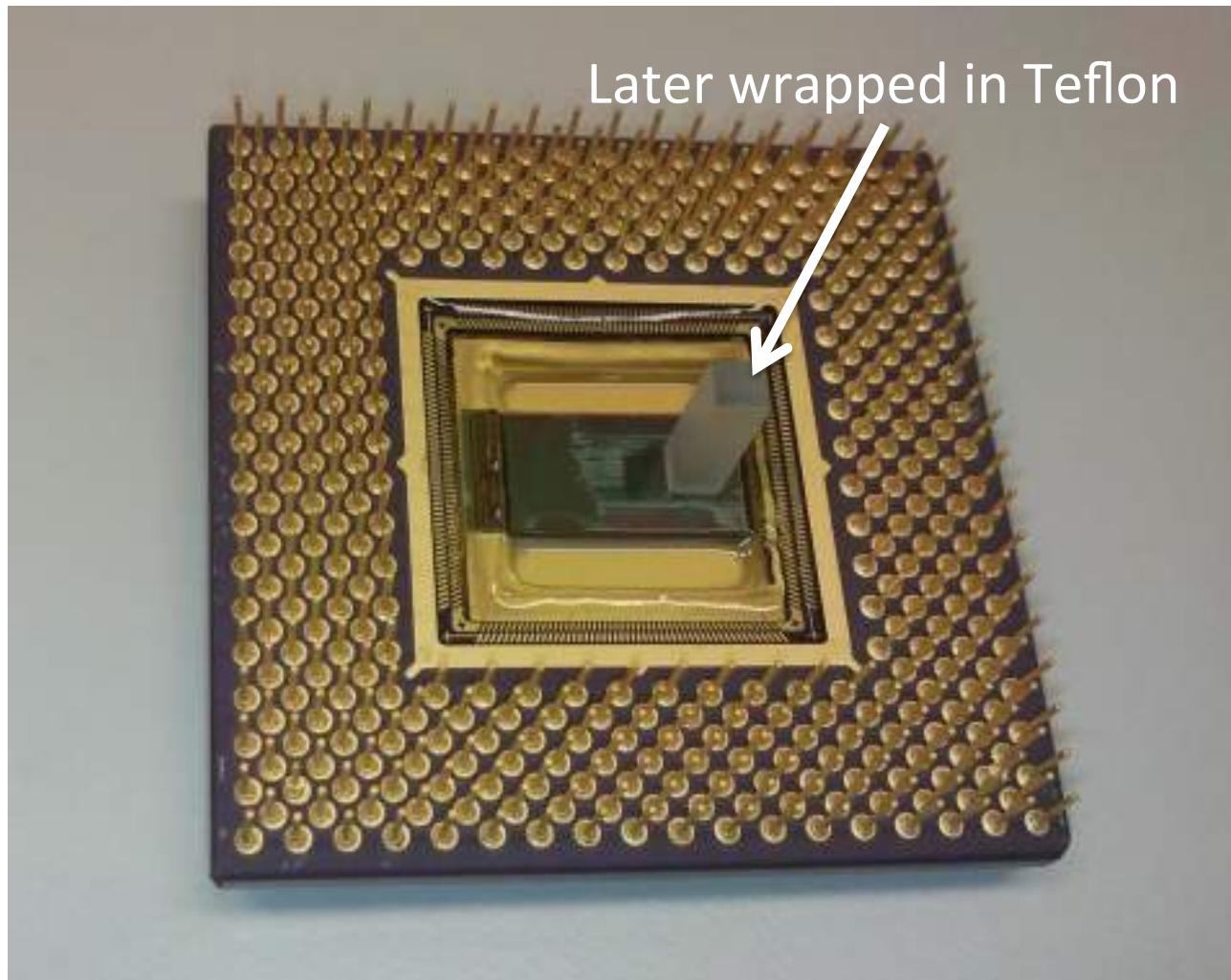
# Integral/Differential Non-Linearity



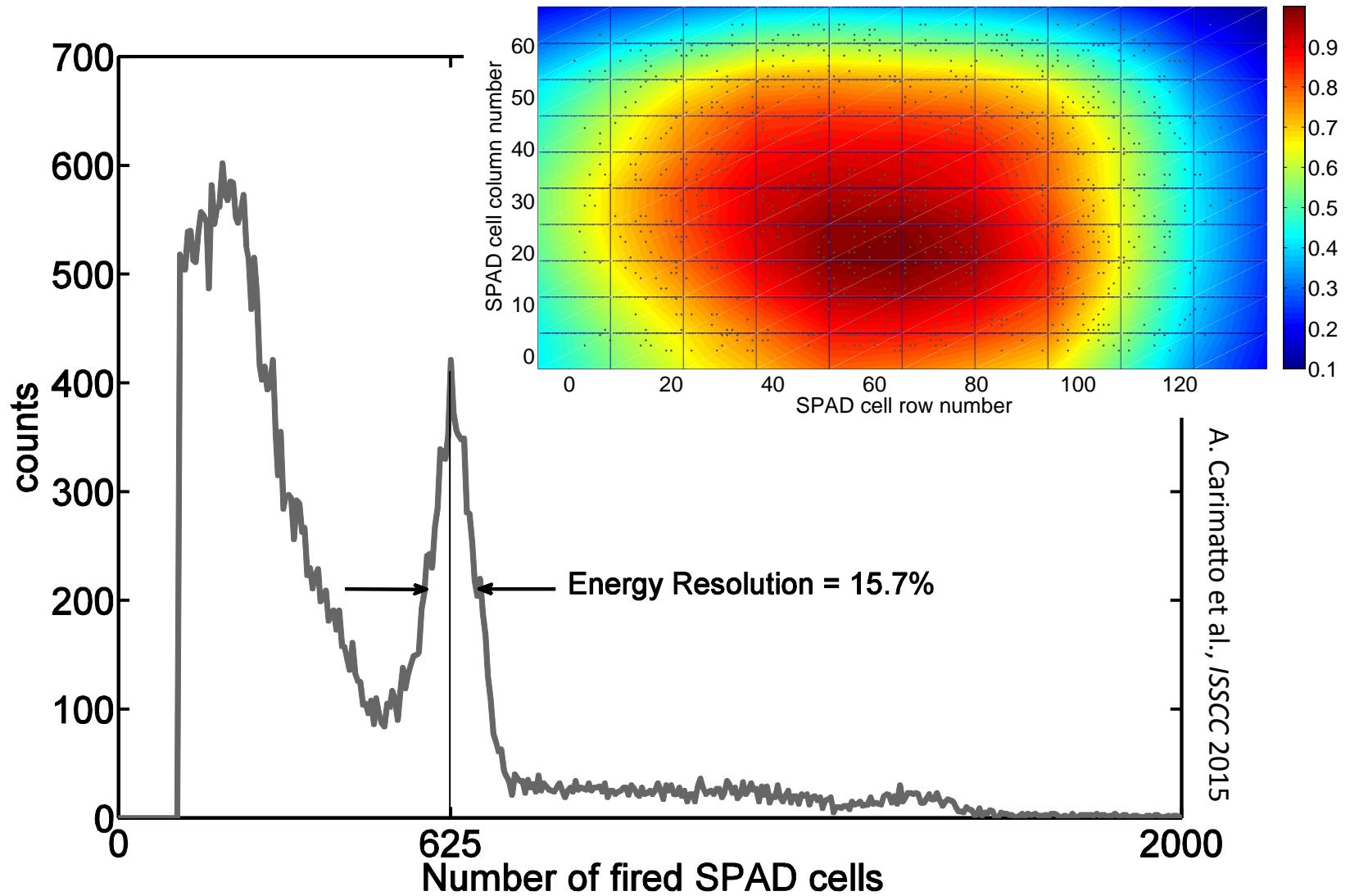
# Single-Photon Timing Resolution



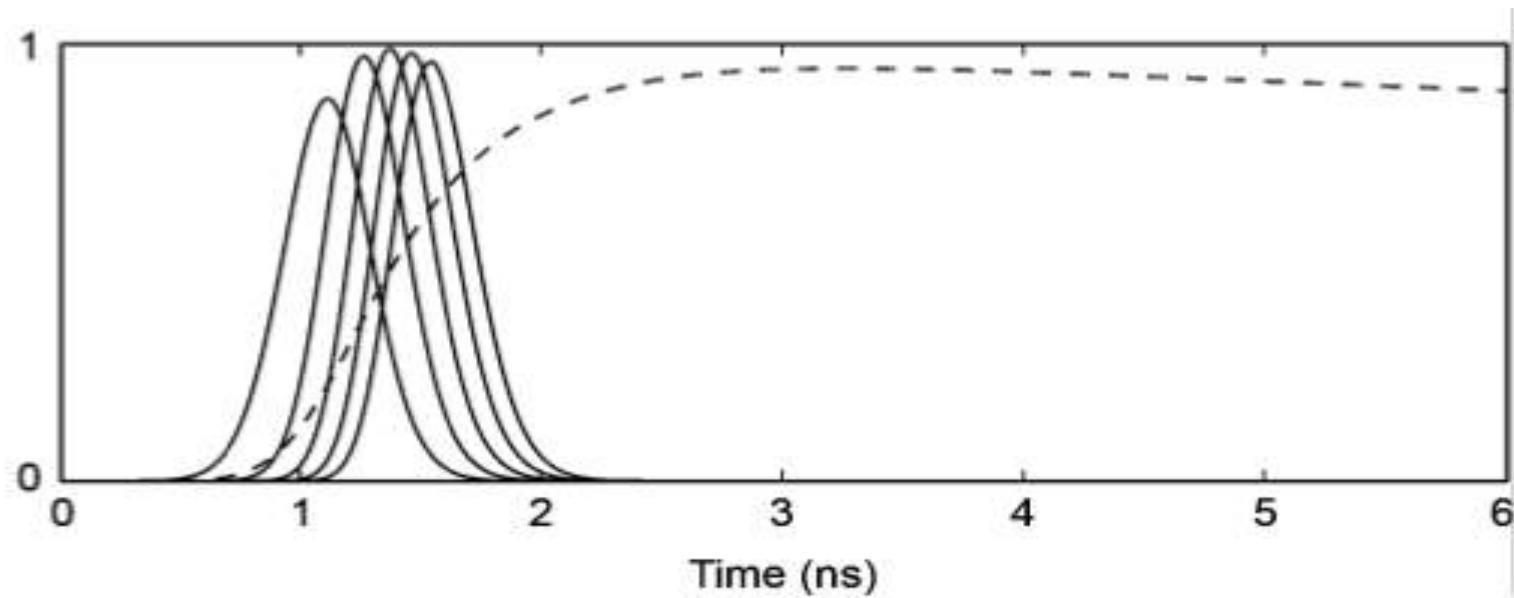
# **3x3x10mm<sup>3</sup> LYSO**



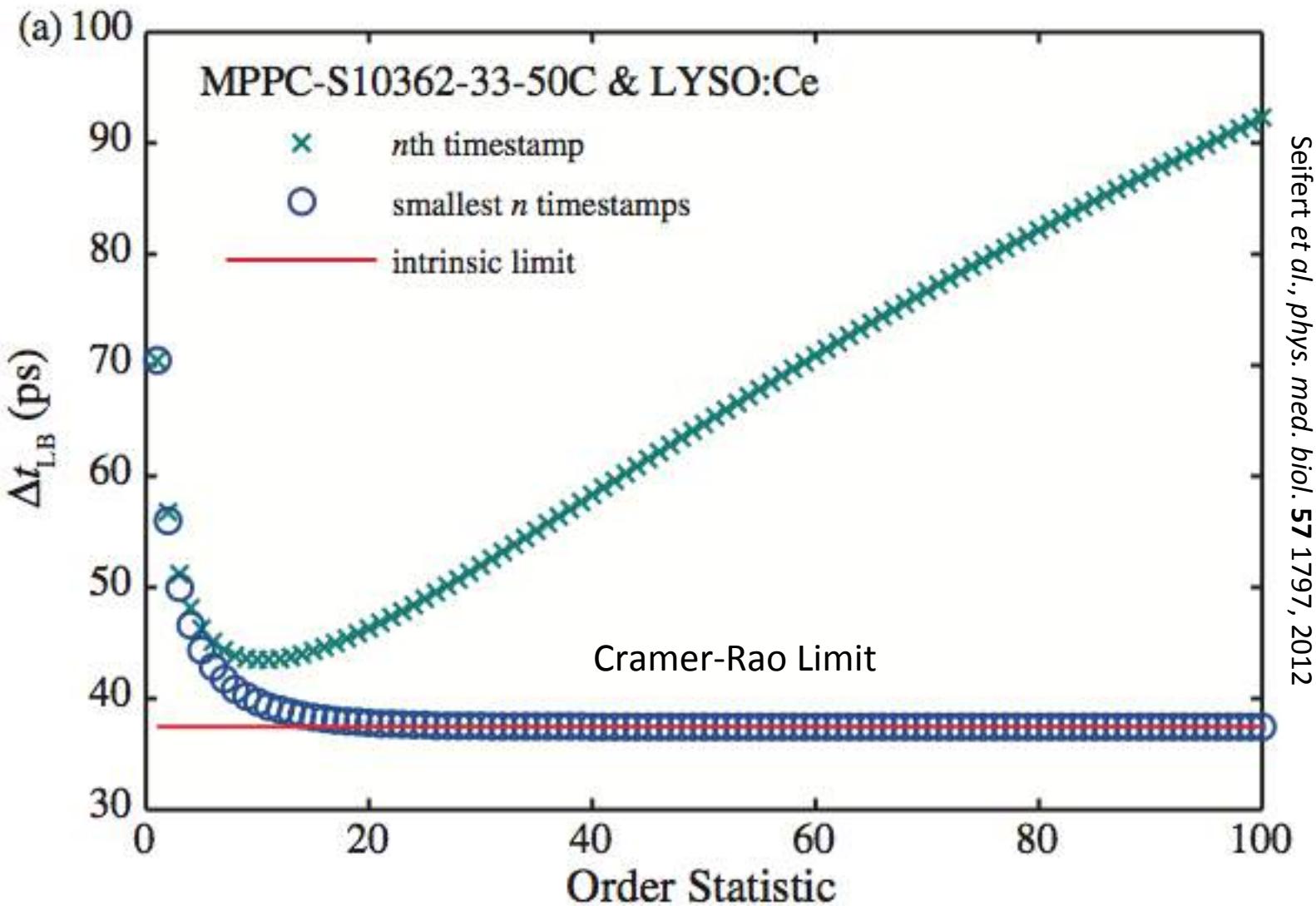
# Energy Spectrum



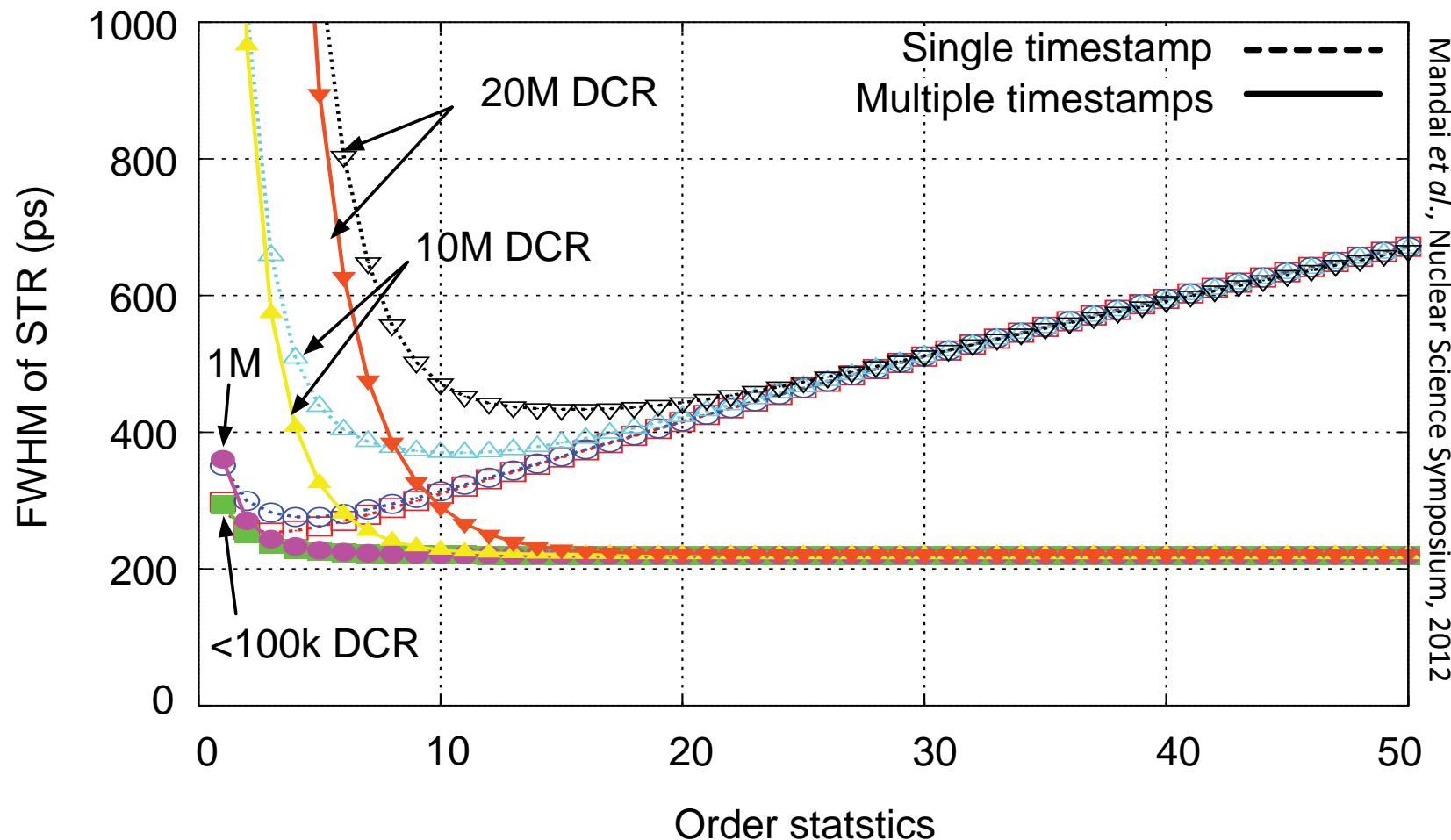
# Photons in a Scintillation are not i.i.d.



# Cramer-Rao Limit in Scintillators



# Robustness to Noise



# Laser Photon Bunch Analysis

Photon distribution in a laser bunch follows order-statistics

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

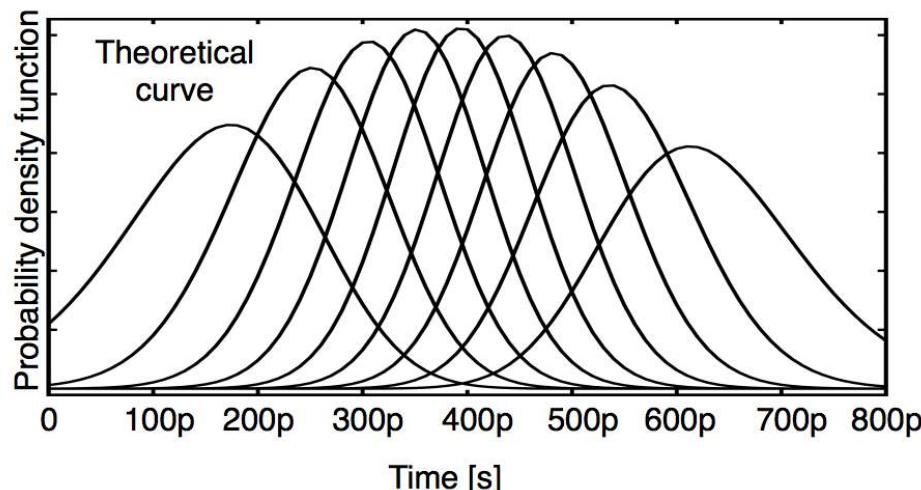
$f_{k:n}(t)$ : k-th order statistics

$f(t)$ : probability density function

$F(t)$ : cumulative density function

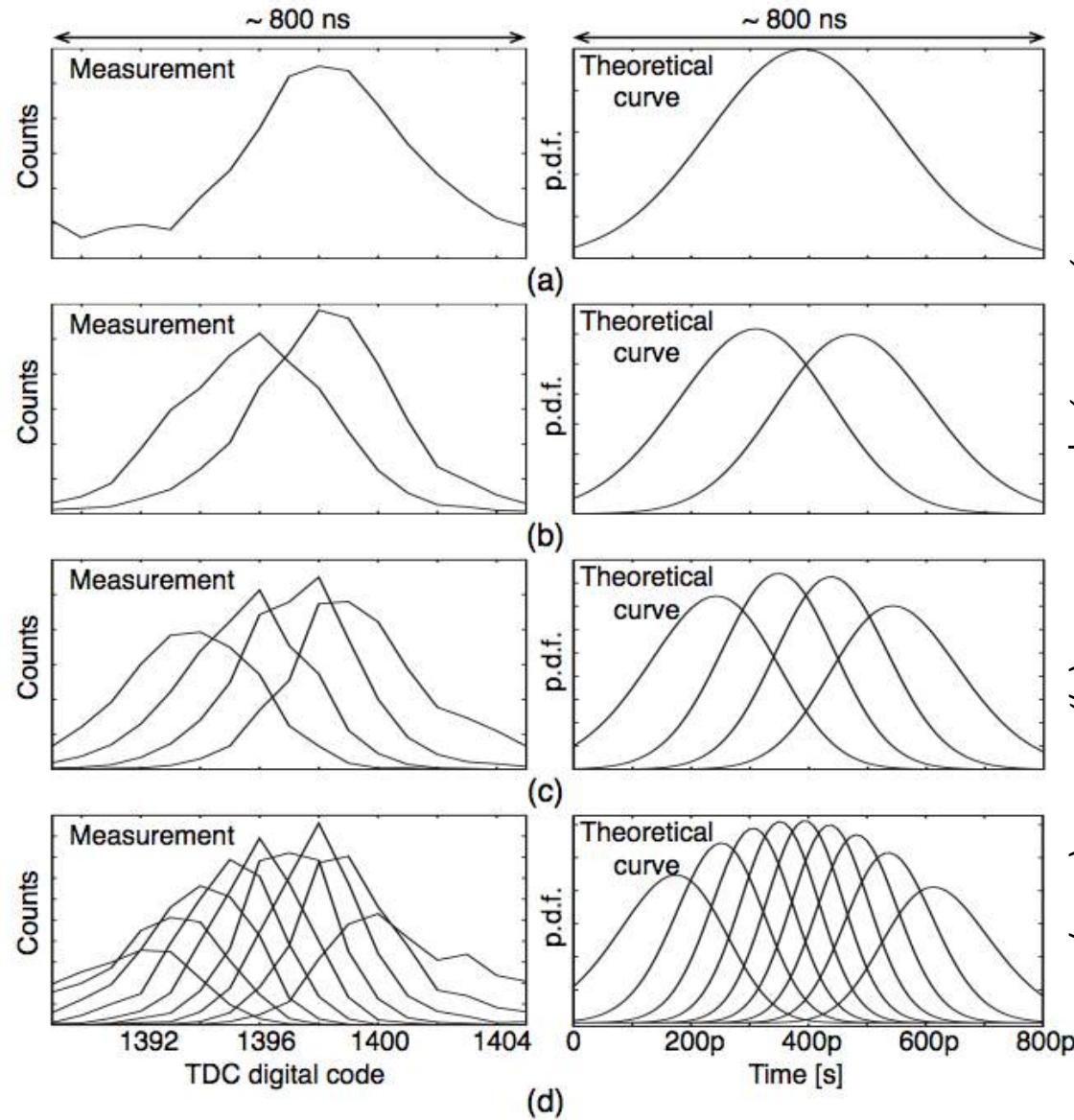
Assumptions:

- Each photon is stat. independent
- The pulse has a Gaussian p.d.f.



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

# Laser Photon Bunch Analysis



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

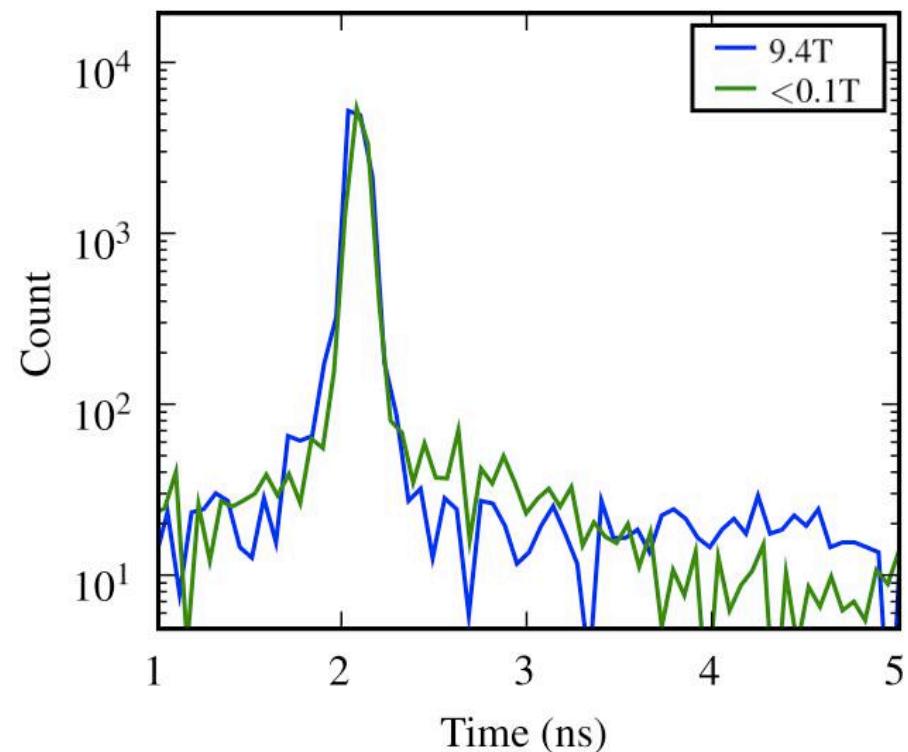
# Robustness to B-Fields

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*

## **2<sup>nd</sup> Take-Home Message:**

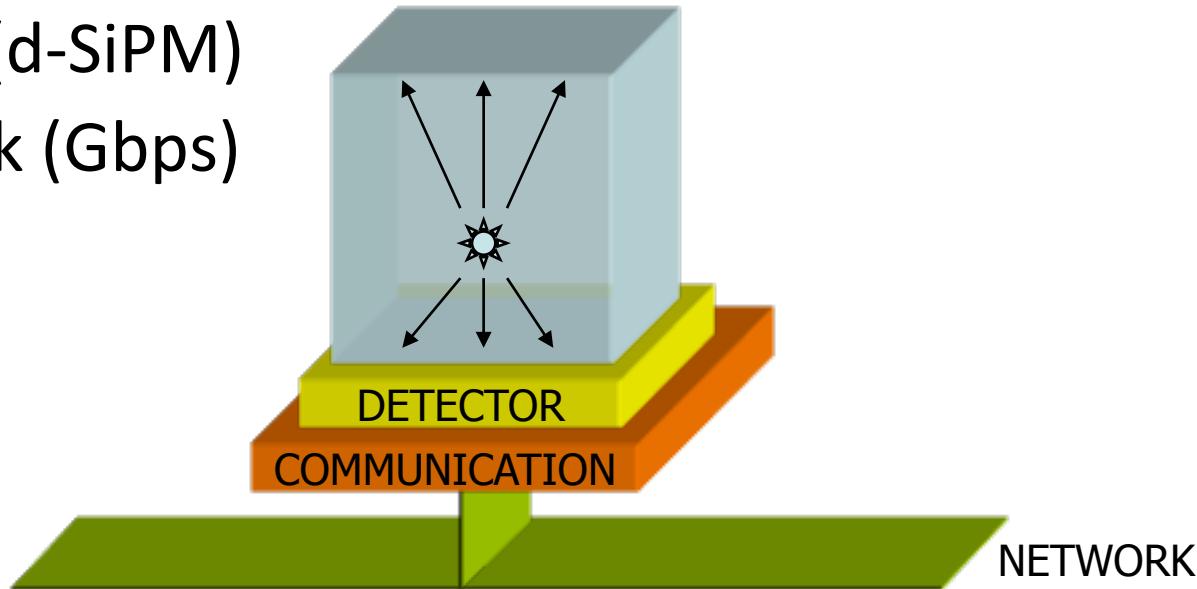
**Order-statistics with single-photon  
timestamping can improve  
fundamental understanding at  
quantum level**

# The SPADnet Concept



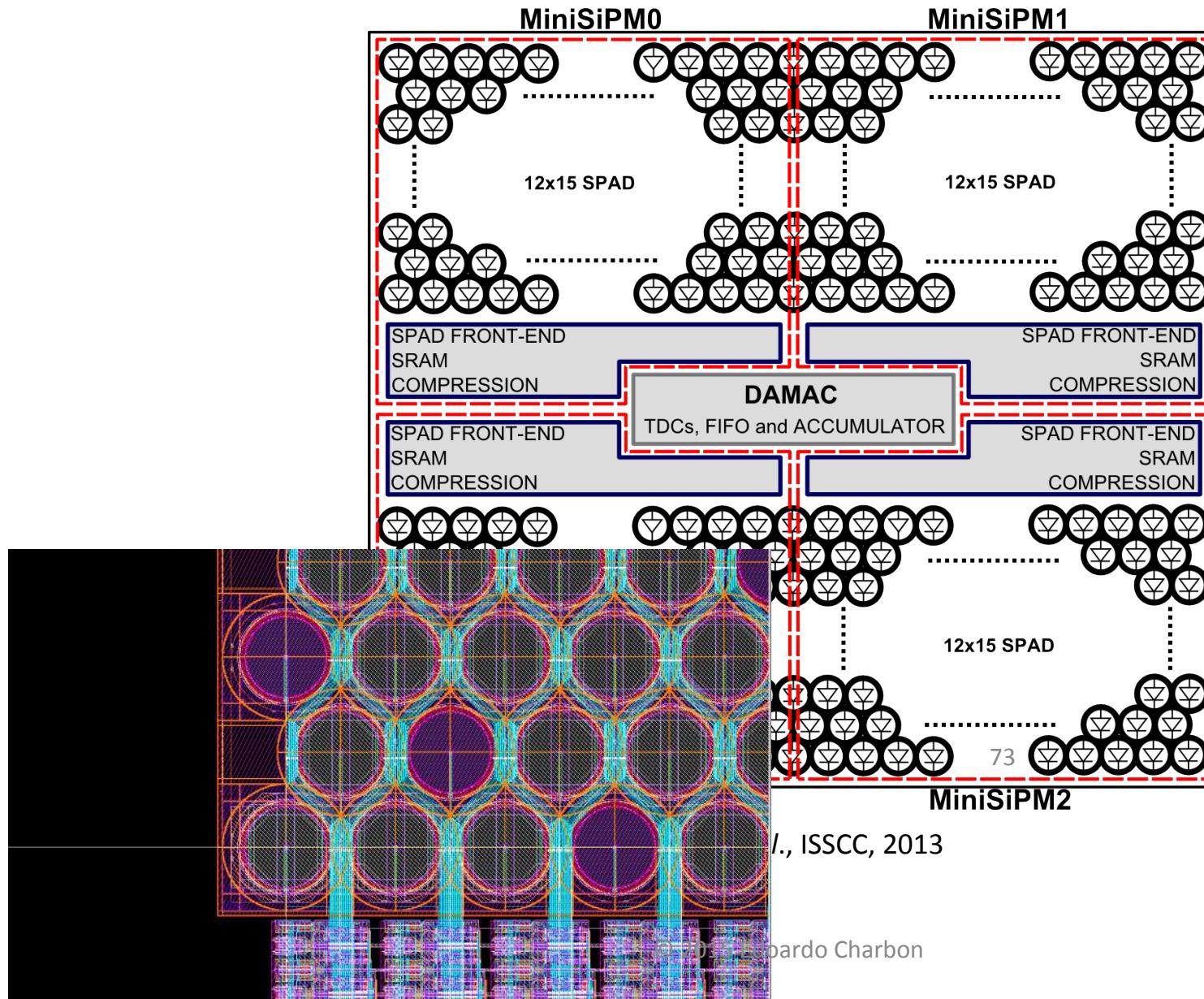
**Photonic Module**, comprising:

- Scintillator (LYSO)
- Sensor (d-SiPM)
- Network (Gbps)



Digital, scalable, networked Photonic Module

# SPADnet Sensor

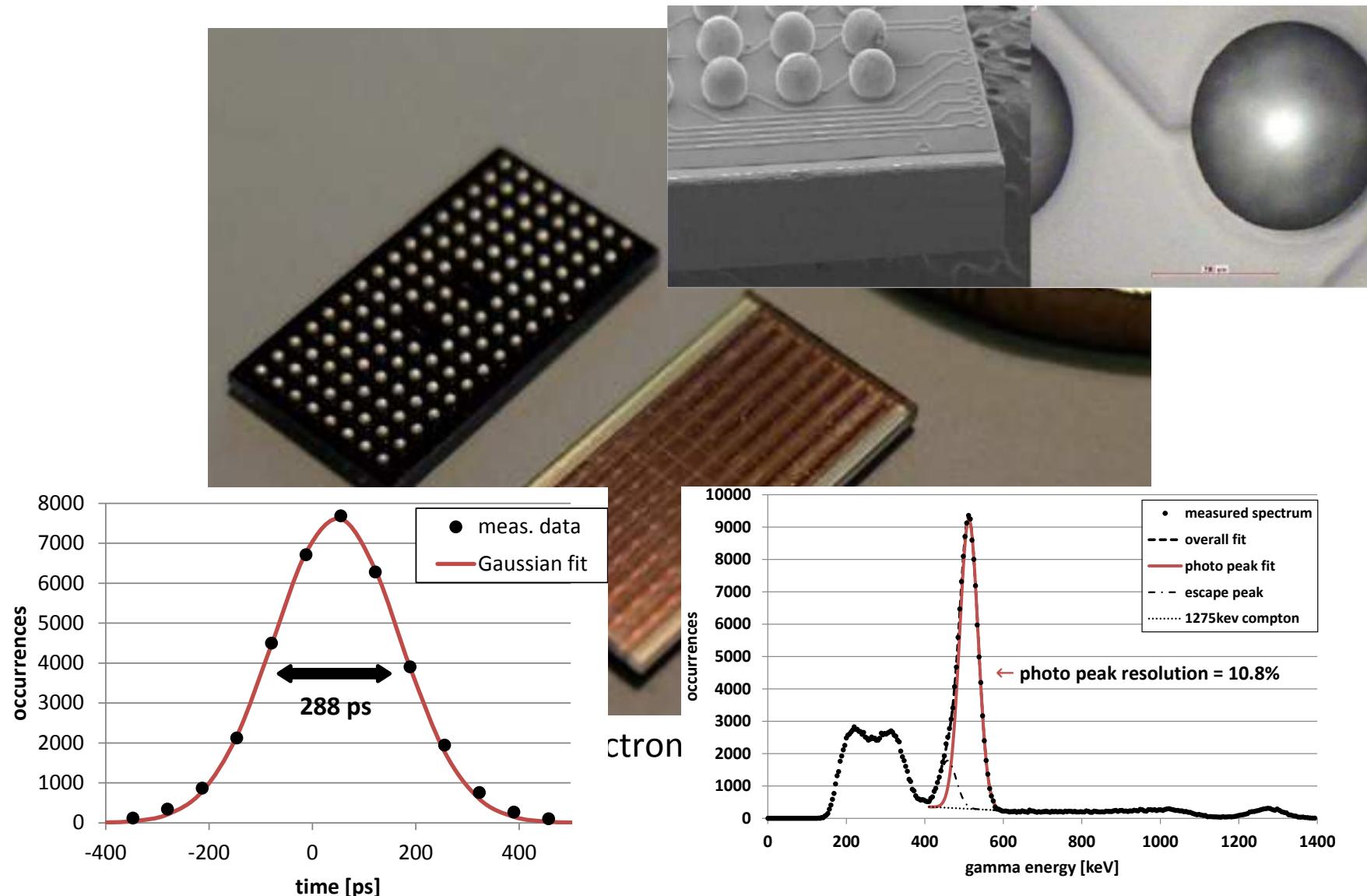


# SPADnet Sensor Chip



Braga *et al.*, ISSCC, 2013

# SPADnet Sensor Chip

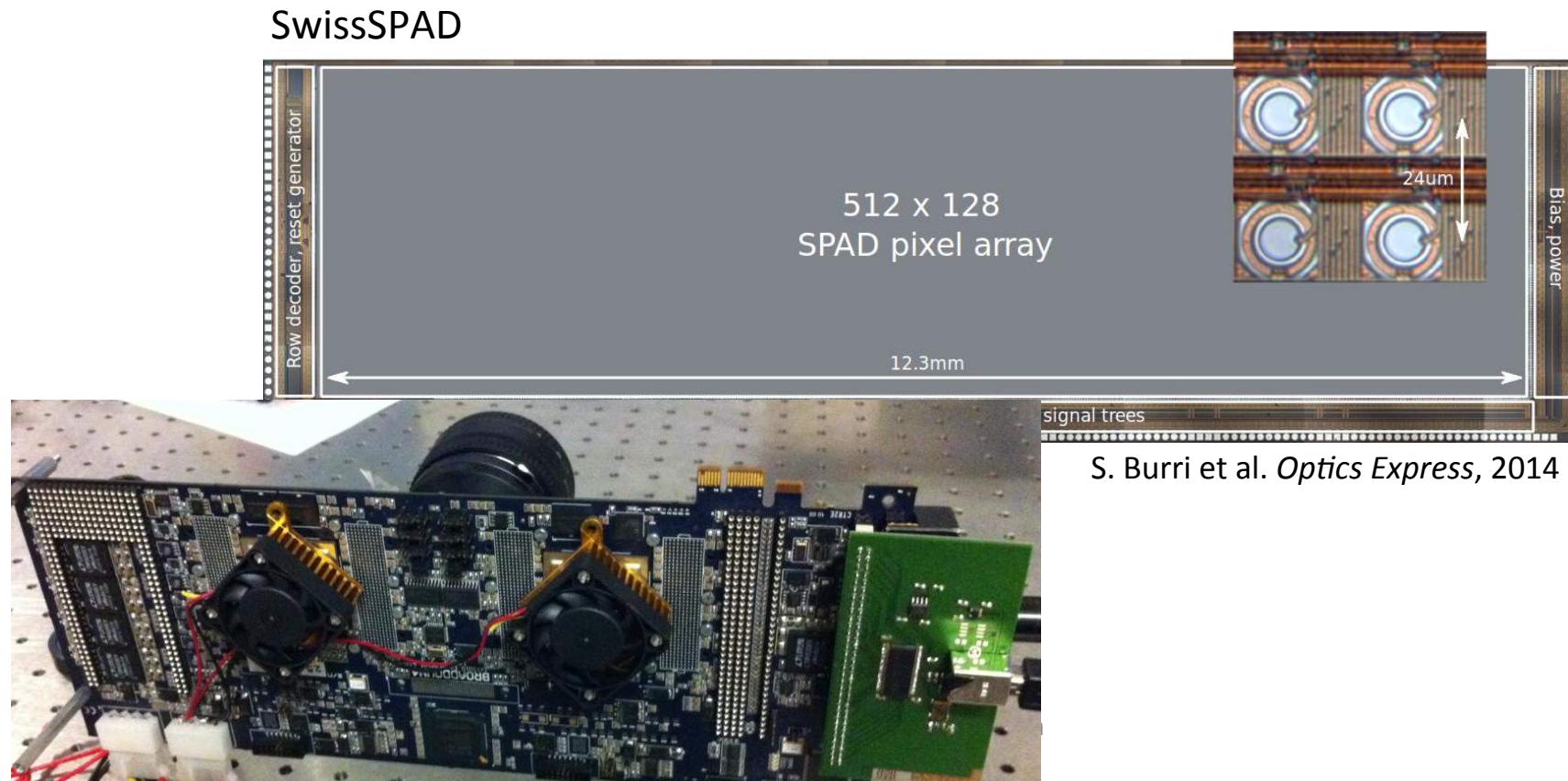


### *3<sup>rd</sup> Take-Home Message:*

**CMOS ensures scalability and thus  
multiplies applications with  
unprecedented accuracy**

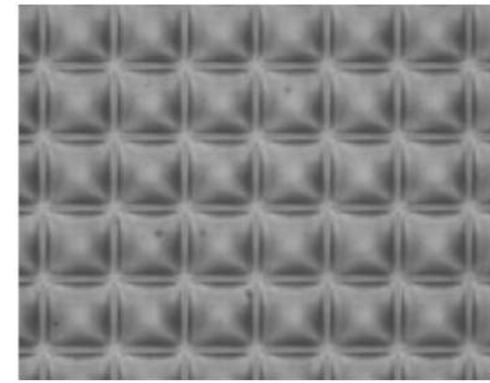
# SwissSPAD: Towards 1Megapixel SPAD

- Ground State Depletion Imaging Microscopy (GSDIM) requires ultra-fast single-photon imagers
- Compact, solid-state cameras are sought after

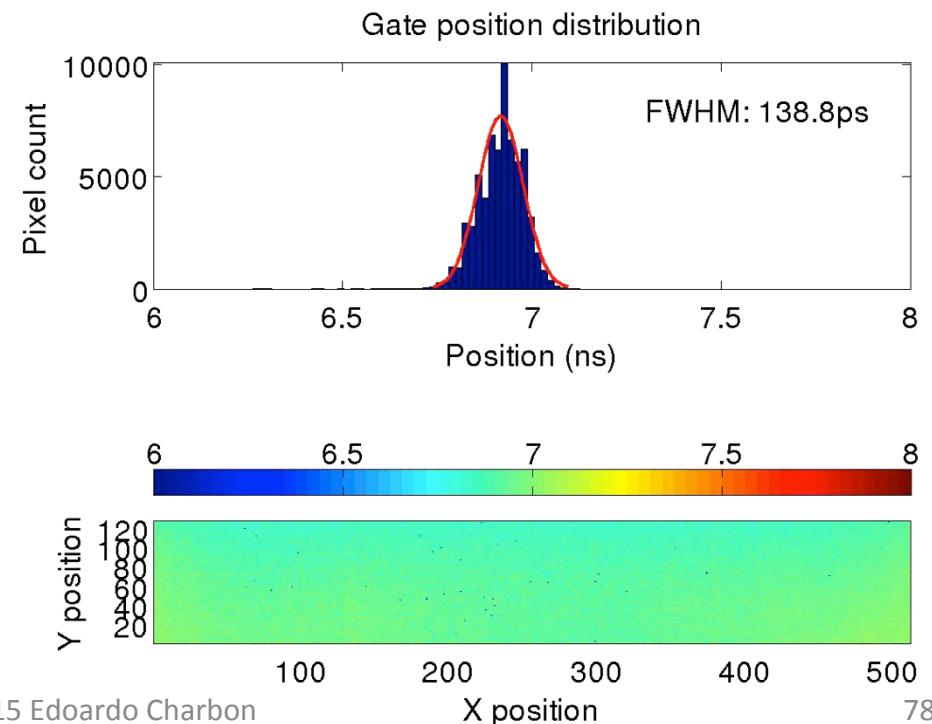
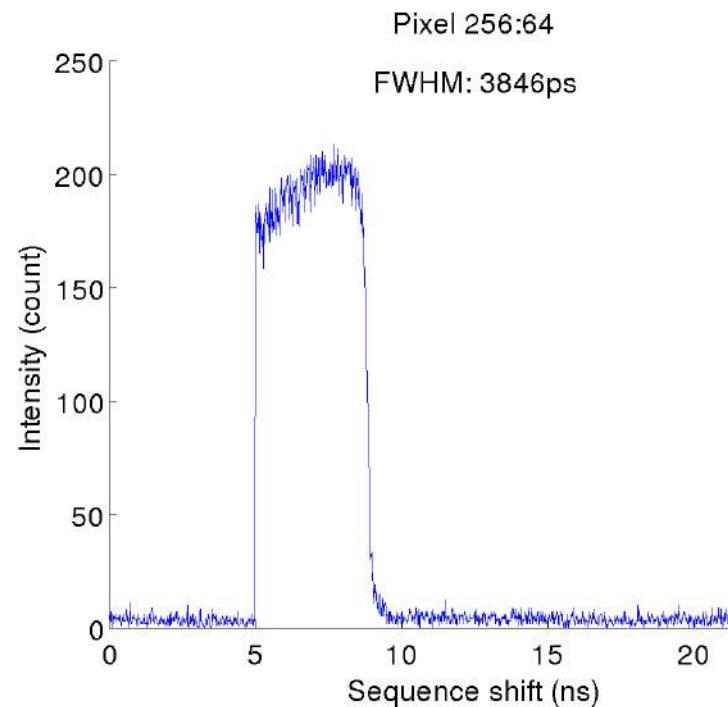


# SwissSPAD

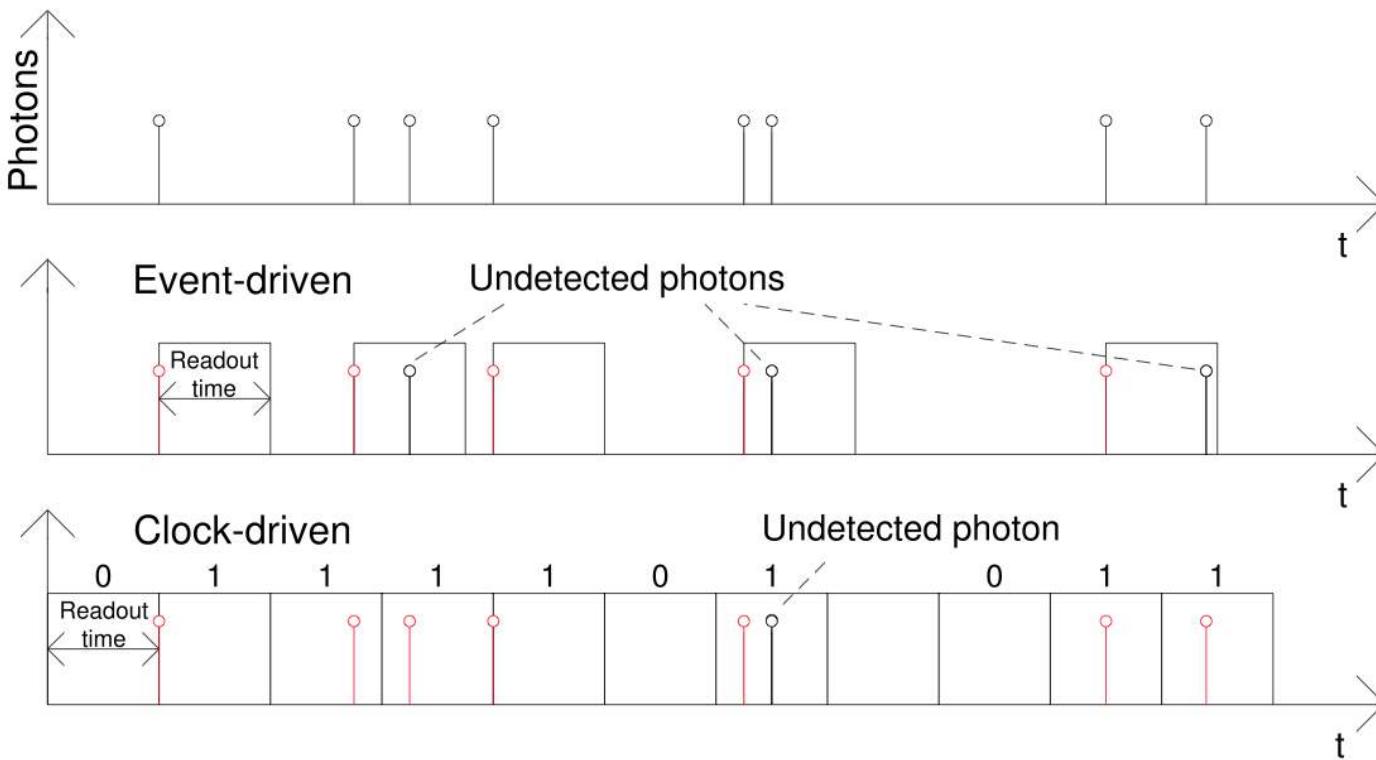
- Microlenses (CF: 6.5 @ F/8)
- 4ns gating (138ps FWHM)
- 156kfps frame rate



S. Burri et al., *Optics Express*, 2014



# Photon Statistics

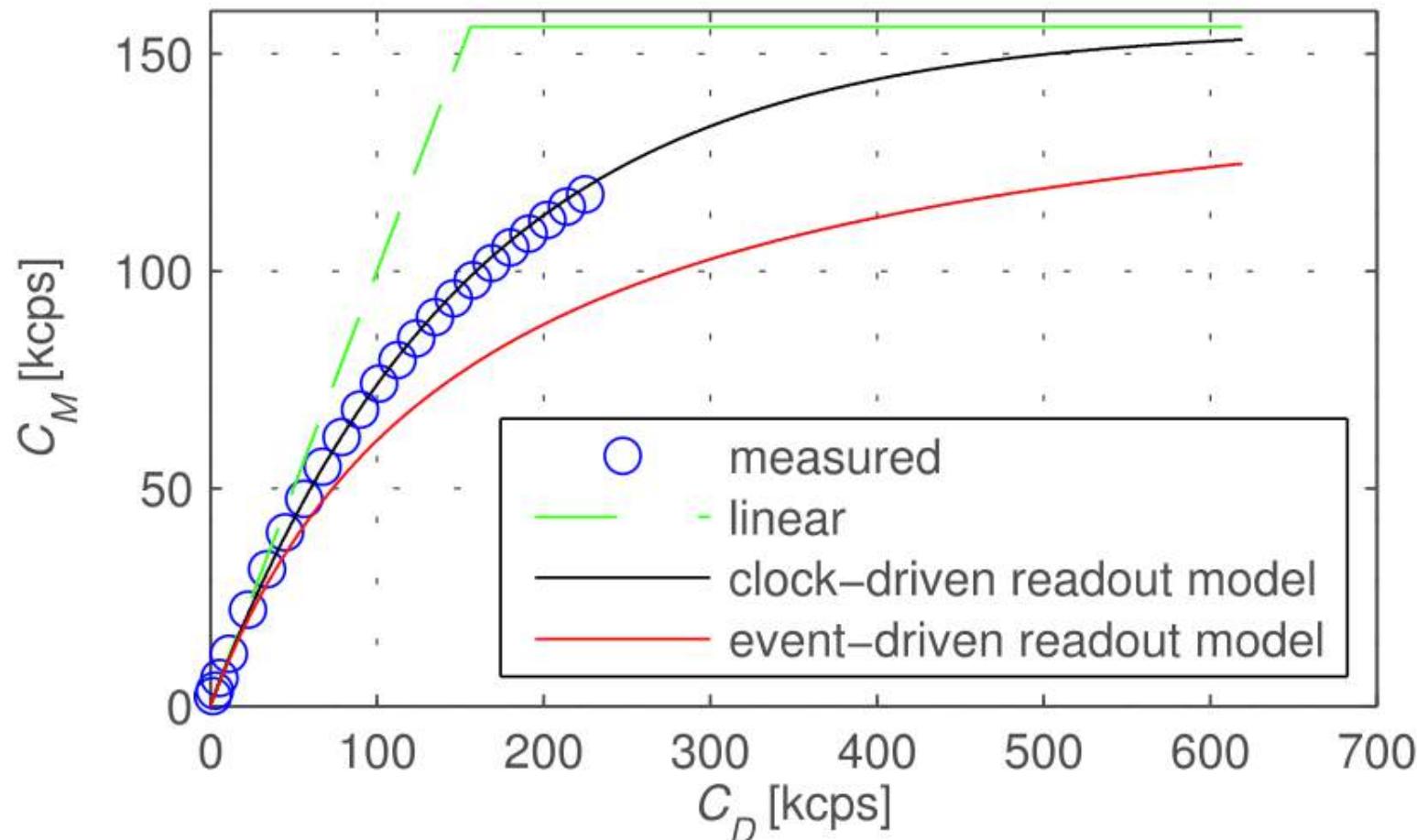


$$\Pr(\text{counts} = k) = \frac{\lambda^k e^{-\lambda}}{k!} \Rightarrow \Pr(\text{counts} \geq 1) = 1 - e^{-\lambda}$$

$$\Pr(\Delta t) = e^{-\alpha t}$$

I.M. Antolovic et al., *Trans. Electron Dev.*, 2015

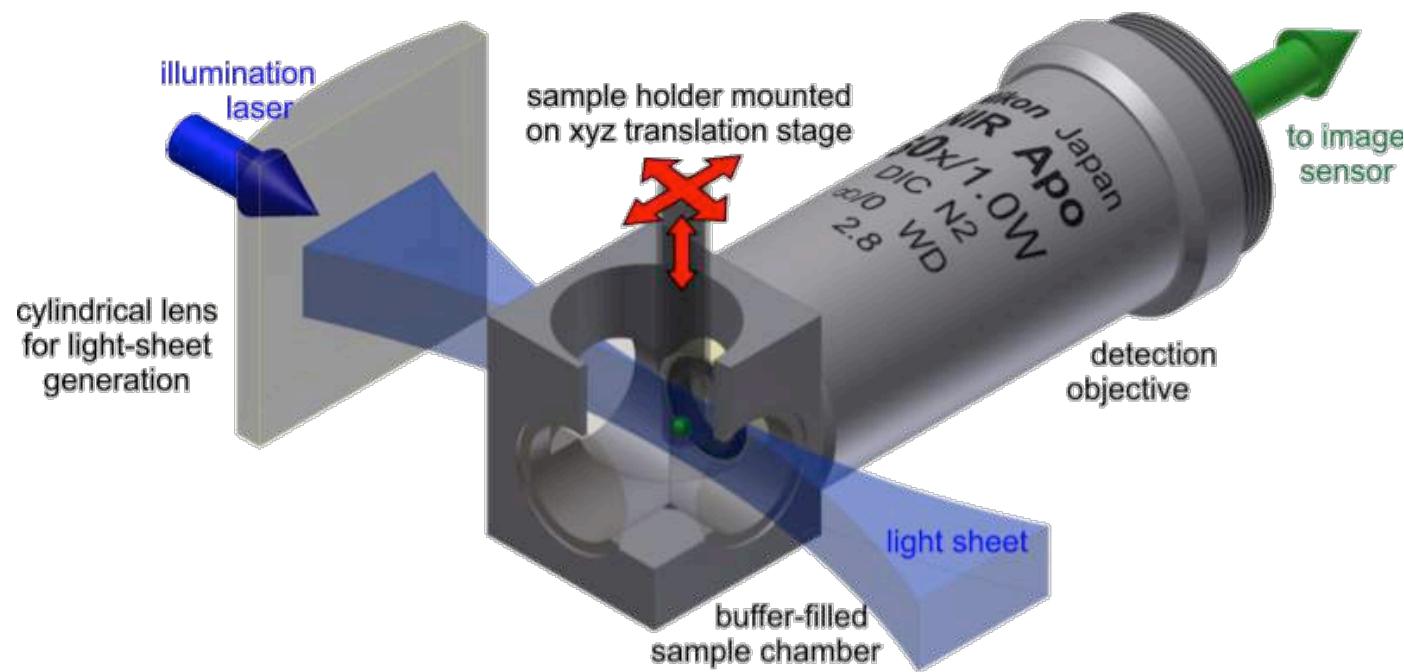
# Photon Statistics (2)



I.M. Antolovic et al., *Trans. Electron Dev.*, 2015

# Fluorescence Correlation Spectroscopy (FCS)

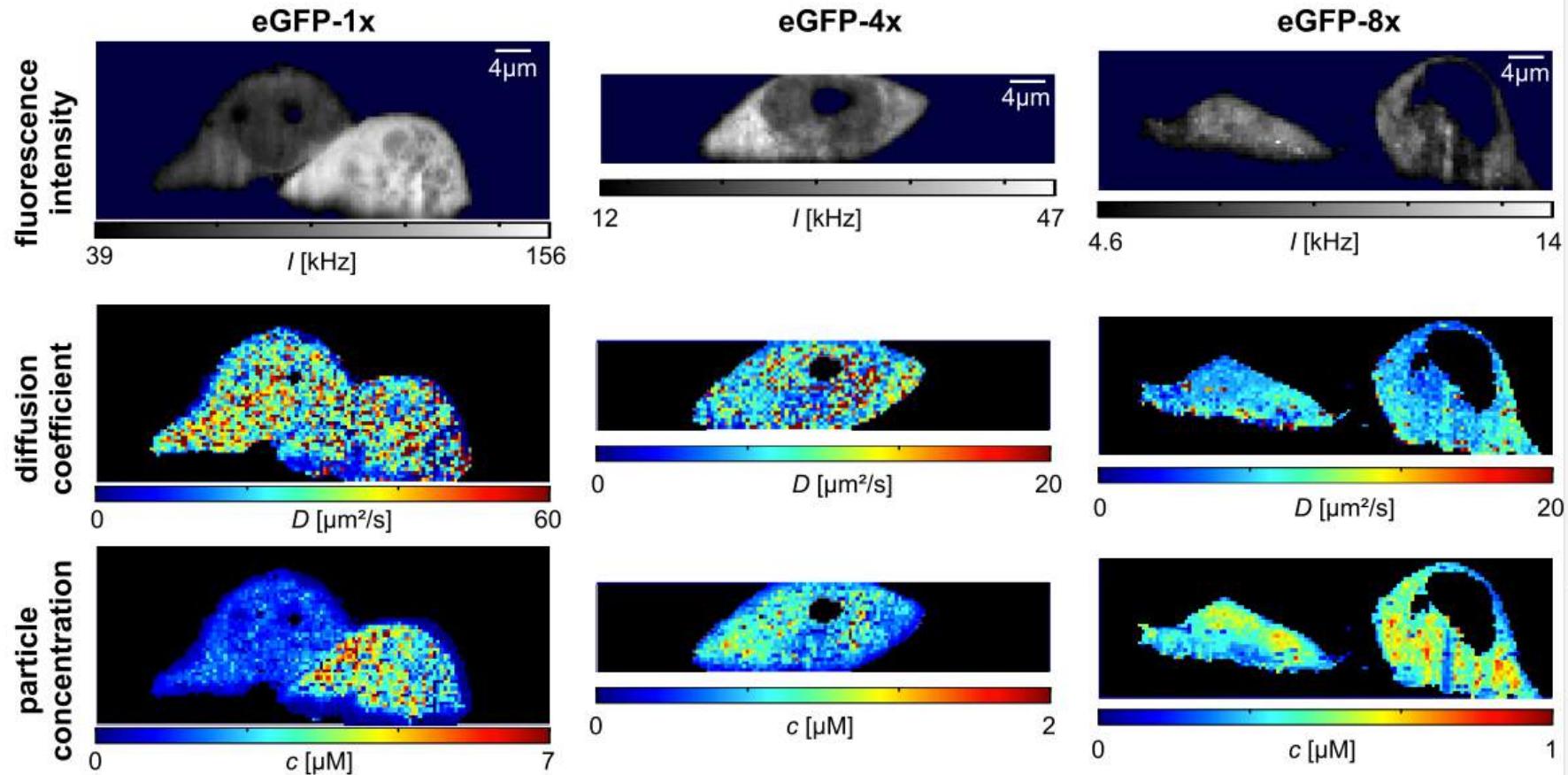
- Use of selective plane illumination microscopy (SPIM)
- Frame rate: 156kfps



Krieger et al., FOM 2015

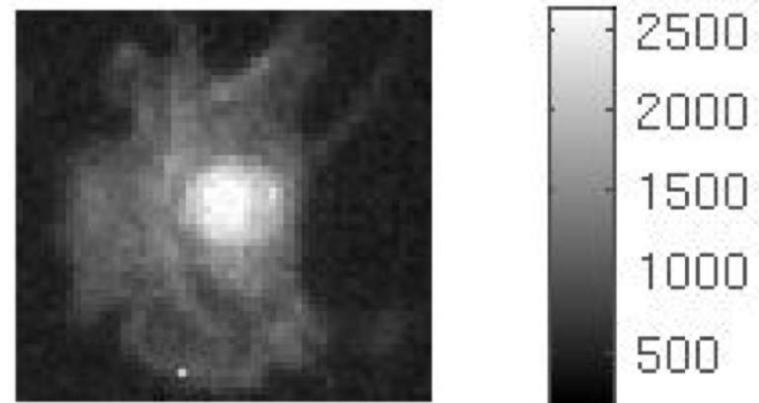
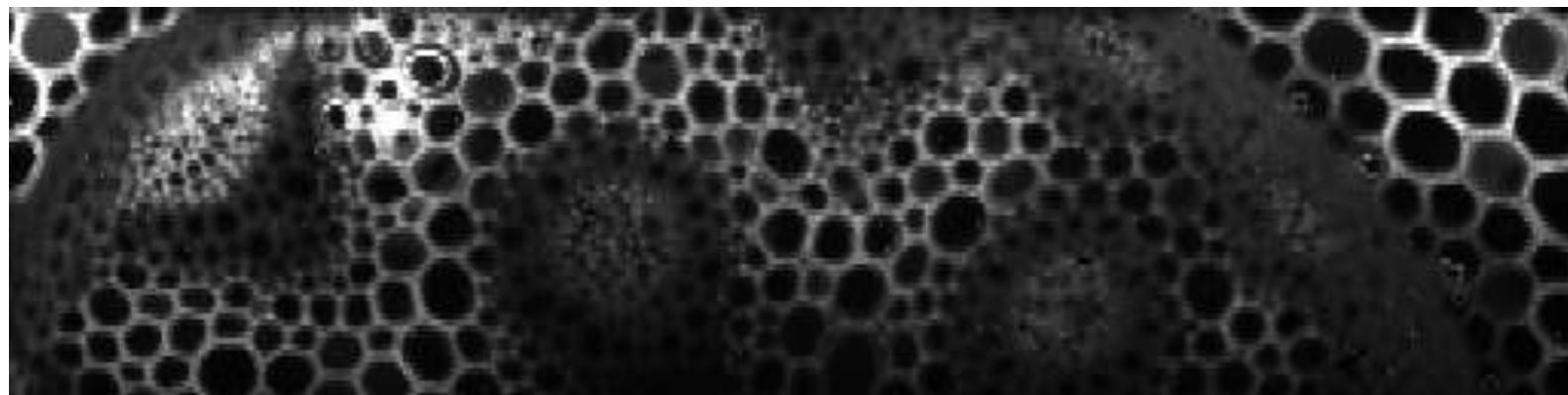
# Fluorescence Correlation Spectroscopy (FCS)

## In Vivo SPAD Array Measurements of eGFP-Oligomers in HeLa Cells



Krieger et al., FOM 2015

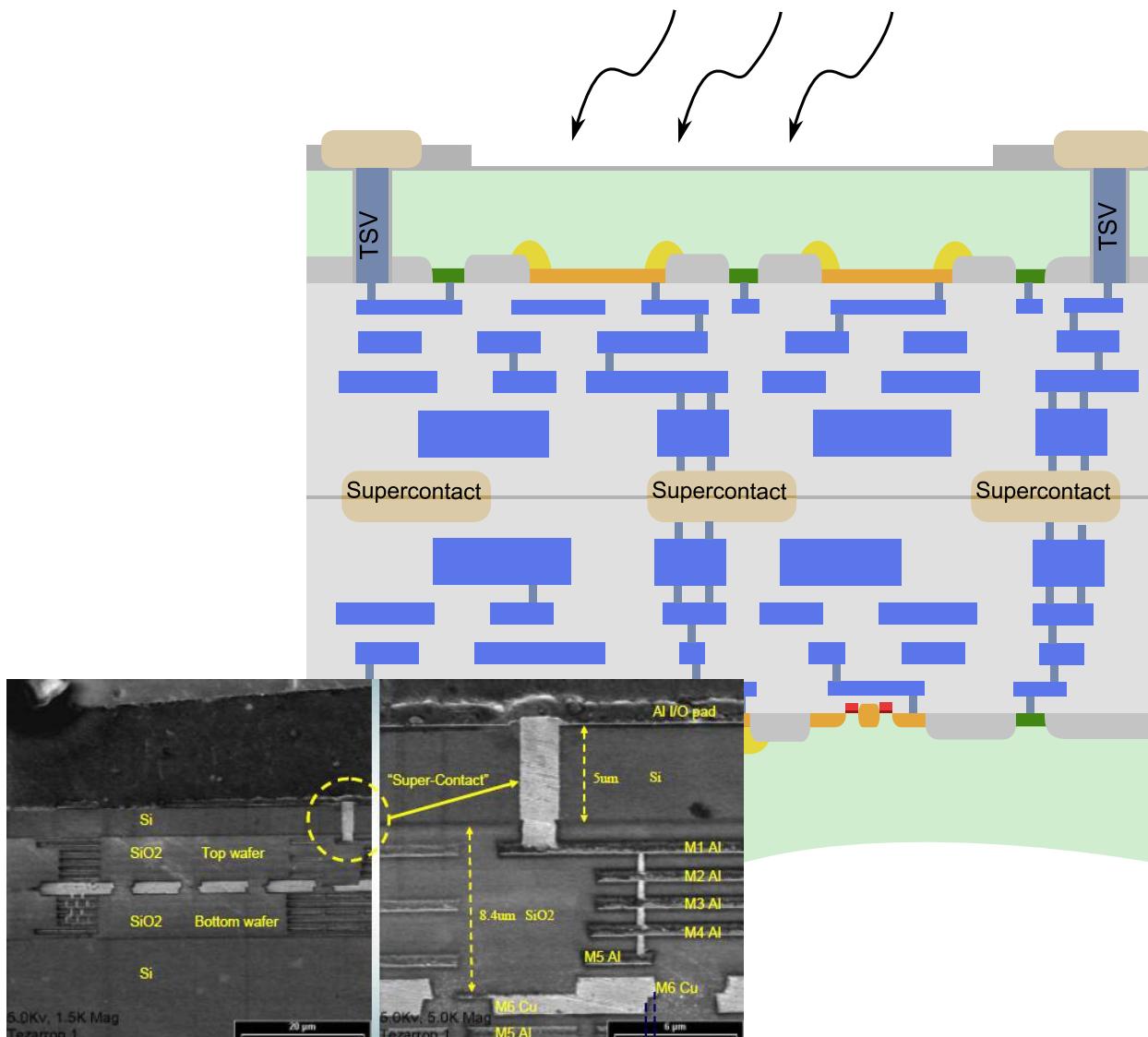
# Super-Resolution Microscopy: GSDIM



I.M. Antolovic et al., *Trans. Electron Dev.*, 2015

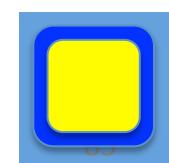
# **Summary, Current & Future Challenges**

# 3D Integration: Flip-Chip

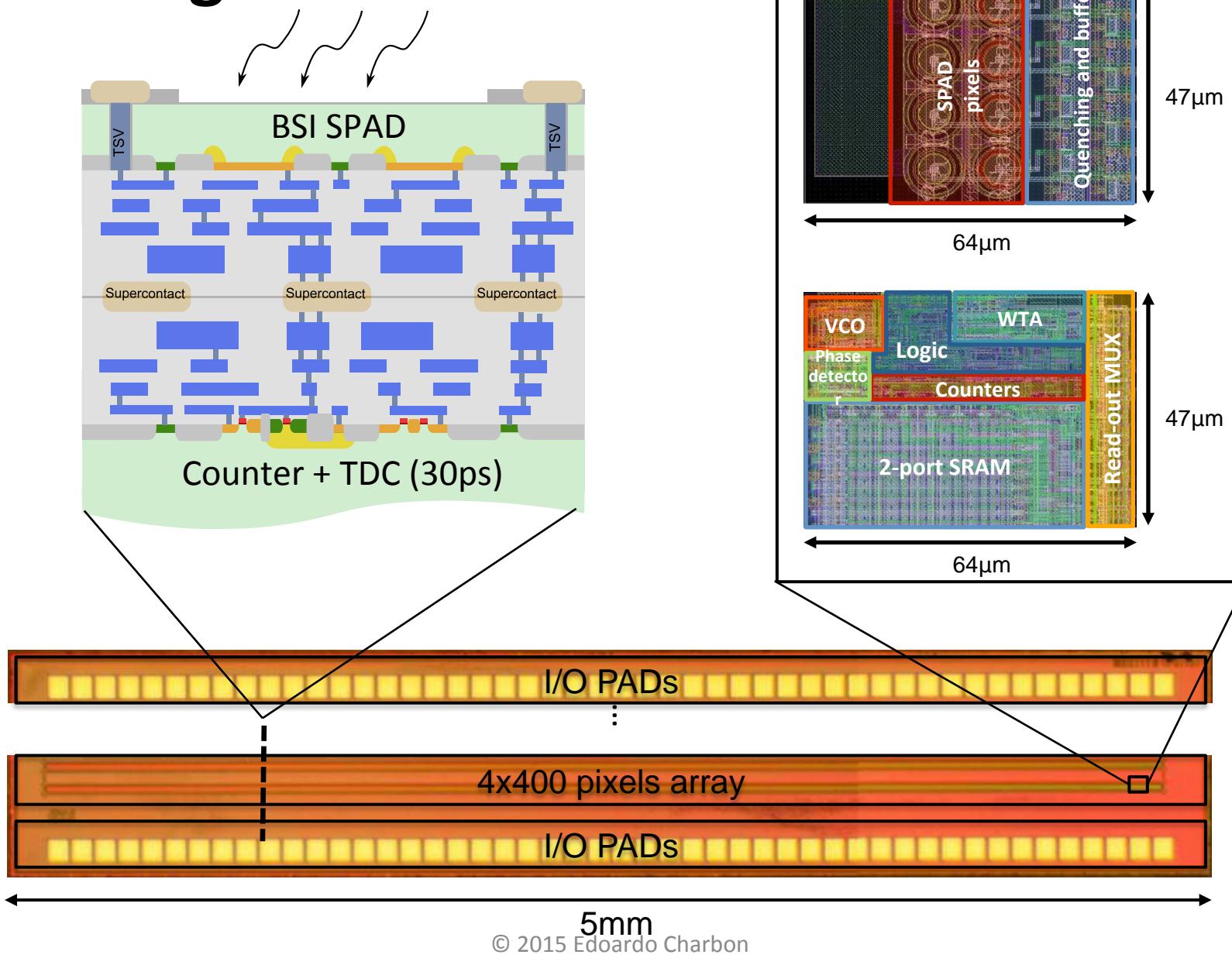


Source: Tezzaron

© 2015 Edoardo Charbon

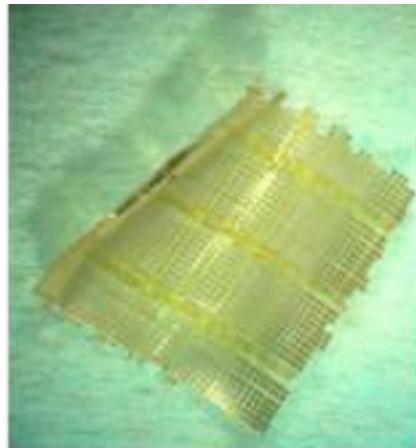


# 3D Integration: CMOS



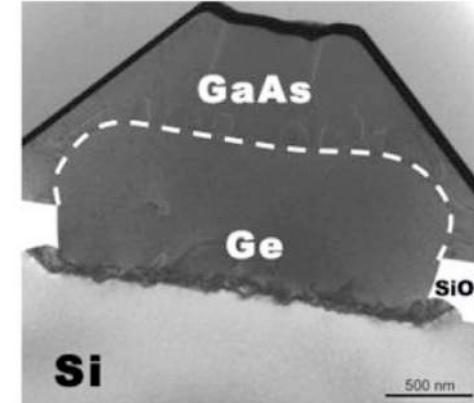
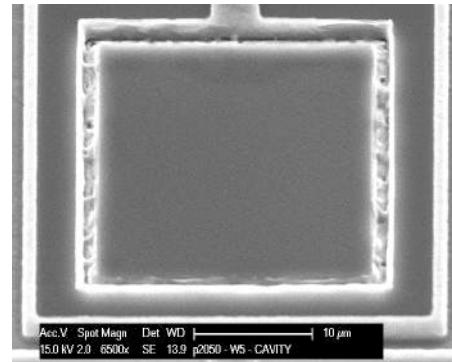
# Important Trends

- Sub-65nm CMOS
- SOI
- p-i-n structures
- New Materials (incl. polymers)
- Electrical microlenses
- Low temperatures

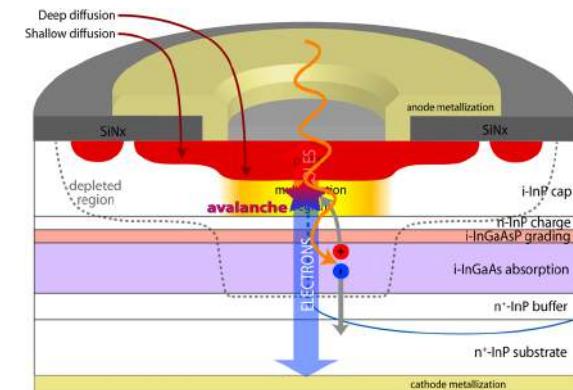


Sun, Ishihara, Charbon,  
JSTQE, 2014

Sammak, Aminian, Charbon,  
Nanver ECS14



Sammak, Aminian, Charbon,  
Nanver, IEDM11



Cova et al, 2012

# SPAD Technology Inside



**forimtech**  
fiber optic radiation imaging tech



**Mediso**



# Take-Home Messages

- SPAD imaging is now an established technology, supported by CMOS single-photon detection
- Order-statistics with single-photon timestamping can improve fundamental understanding at quantum level
- CMOS ensures scalability and thus multiplies applications with unprecedented accuracy

# Acknowledgements

- Swiss National Science Foundation
- European Space Agency
- FP6 and FP7
- NCCR-MICS
- STW



<http://cas.et.tudelft.nl>

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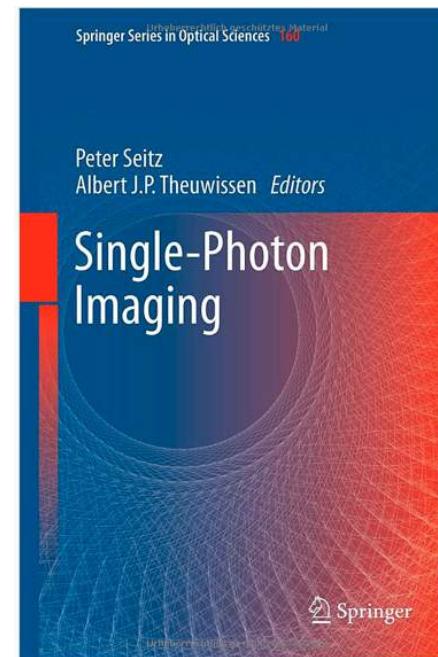
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