Digital Photo-Multipliers: Design and Applications

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TU Delft

DESY, April 13, 2012

Why Photon Counting?

- Applications requiring PC
  - HEP experiments
  - Biomedical imaging
  - Neurobiology research
  - Astronomy and astrophysics observation
- Multiple detection points
  - Typically thousands
  - Possibly 100,000 or more in the near future

Photon Counters of the Future

- Solid state
- Low cost
- Low power
- Small detection cycle
- Compact

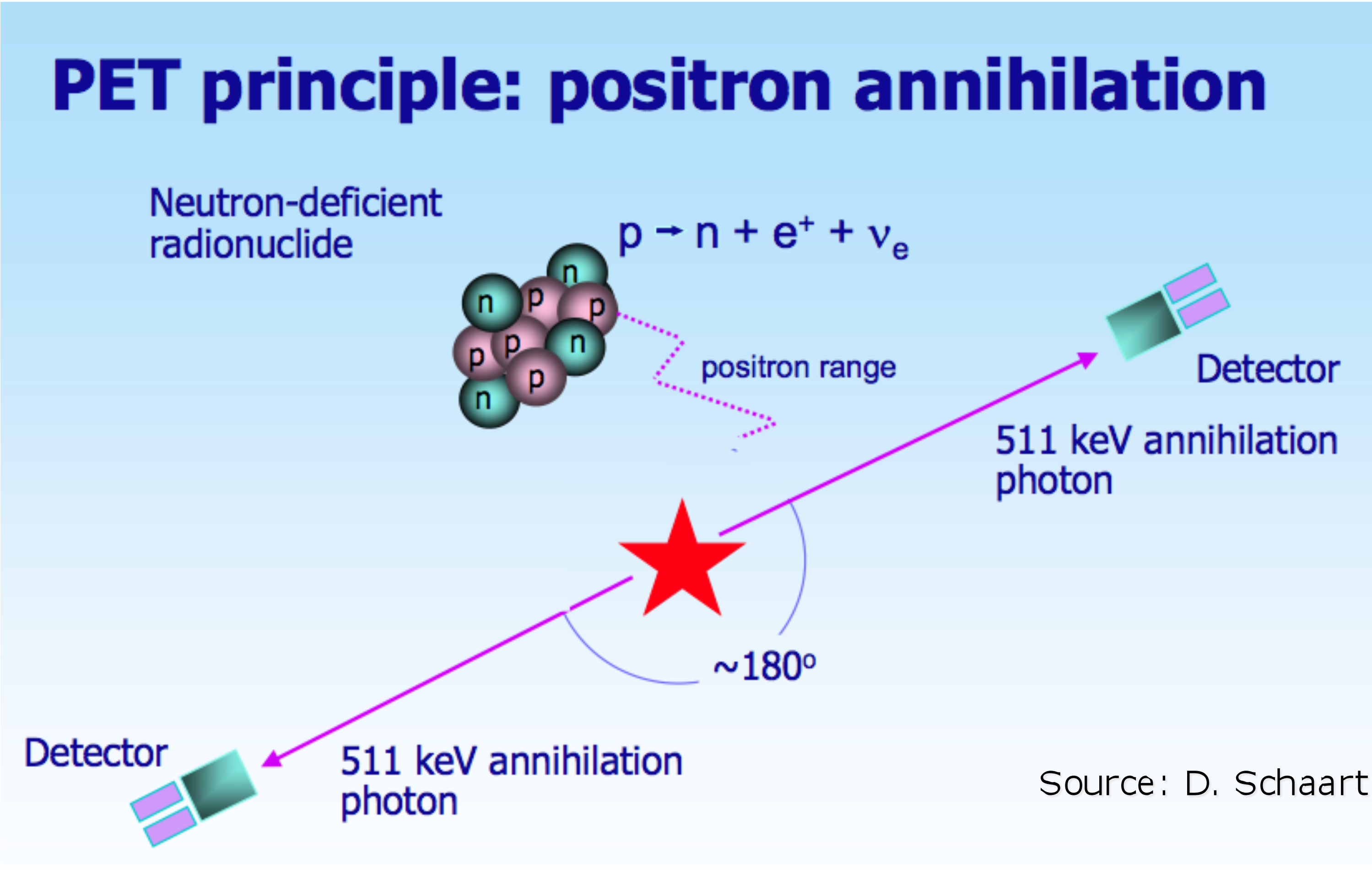
… Small design cycle!!

What About…

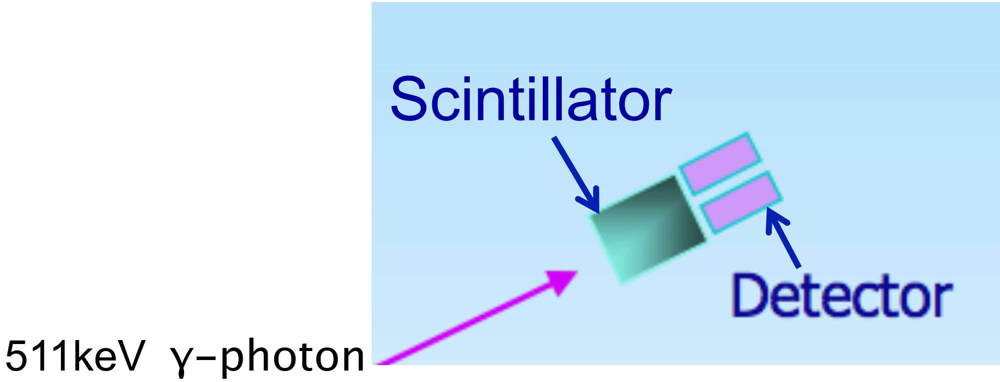
- Time resolution (Δt)
- Photon Detection Efficiency (PDE)

- Δt should be *enough*
- PDE should be, possibly, 100%

A Case for Photon Counters
Positron Emission Tomography



Coincidence Detection



- Photomultiplier tubes (still heavily used)
- Emerging technology: silicon photo-multiplier (SiPM) or simply *PM*
- SiPMs essentially *Geiger-mode avalanche photodiode* arrays

Outline

- SiPM Building Block: GAPD or SPAD
- Analog vs. Digital SiPM
- An md-SiPM based Sensor
- The Next Big Challenges
- Conclusions

Geiger-mode Avalanche Photodiode

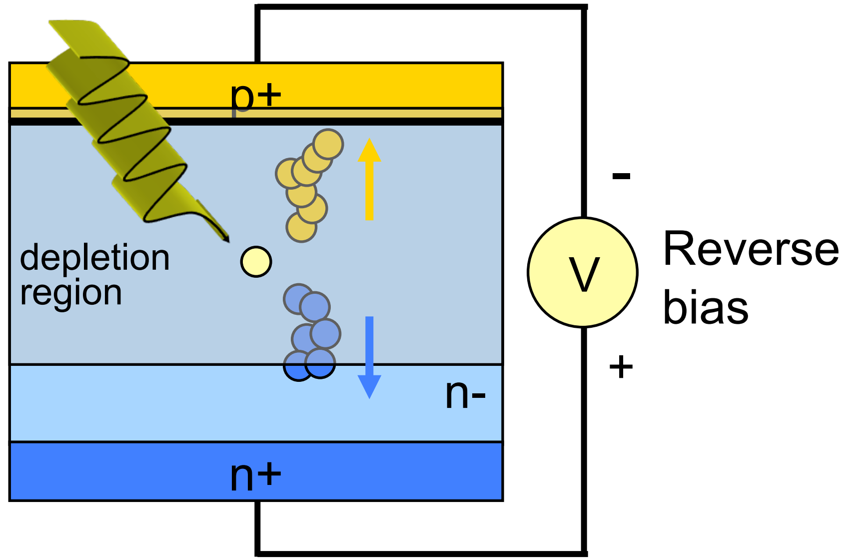
Also known as:
Single-Photon Avalanche Photodiode
(SPAD)

Multiplication in Silicon

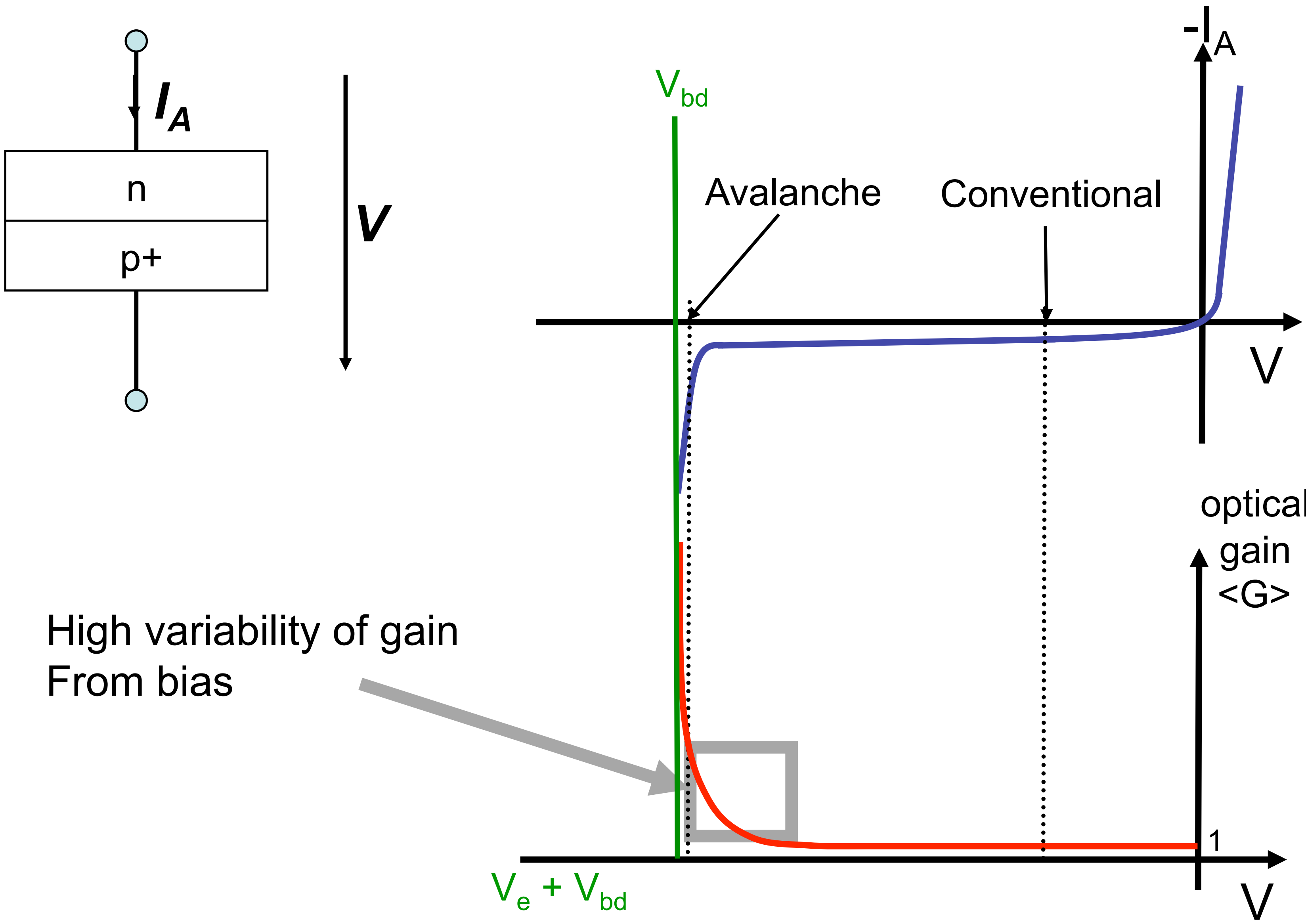
- *Review*:

  Photon to electron - Secondary electron - Multiplication

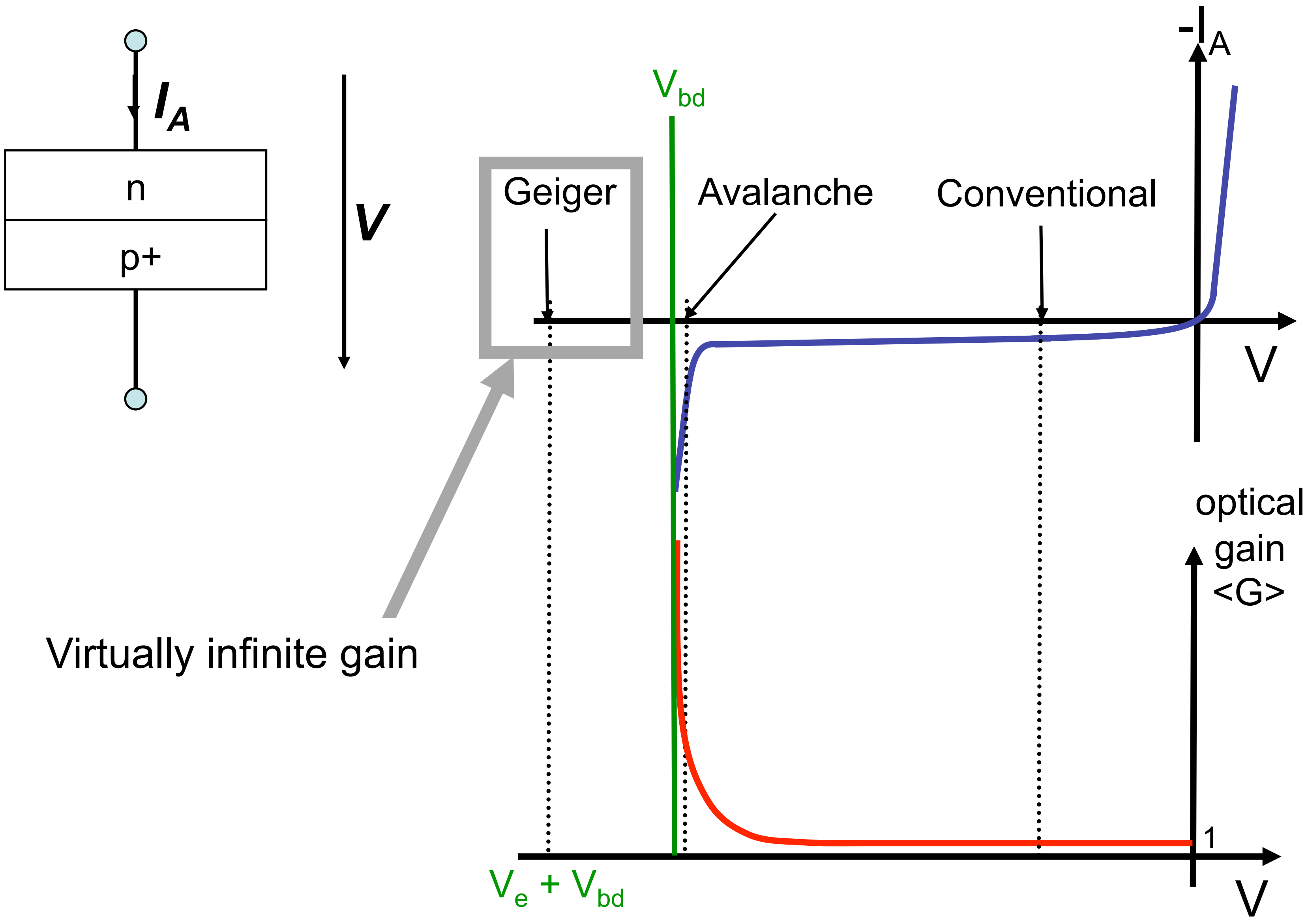
  Multiplication in depletion region by *impact ionization*



Linear (or Proportional) Mode

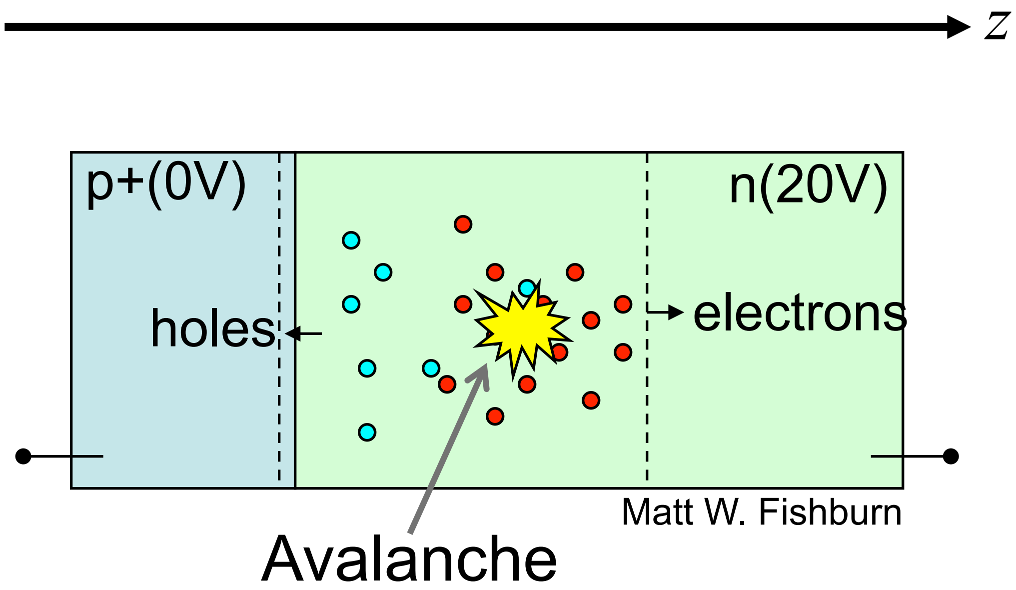


Geiger Mode (SPAD)

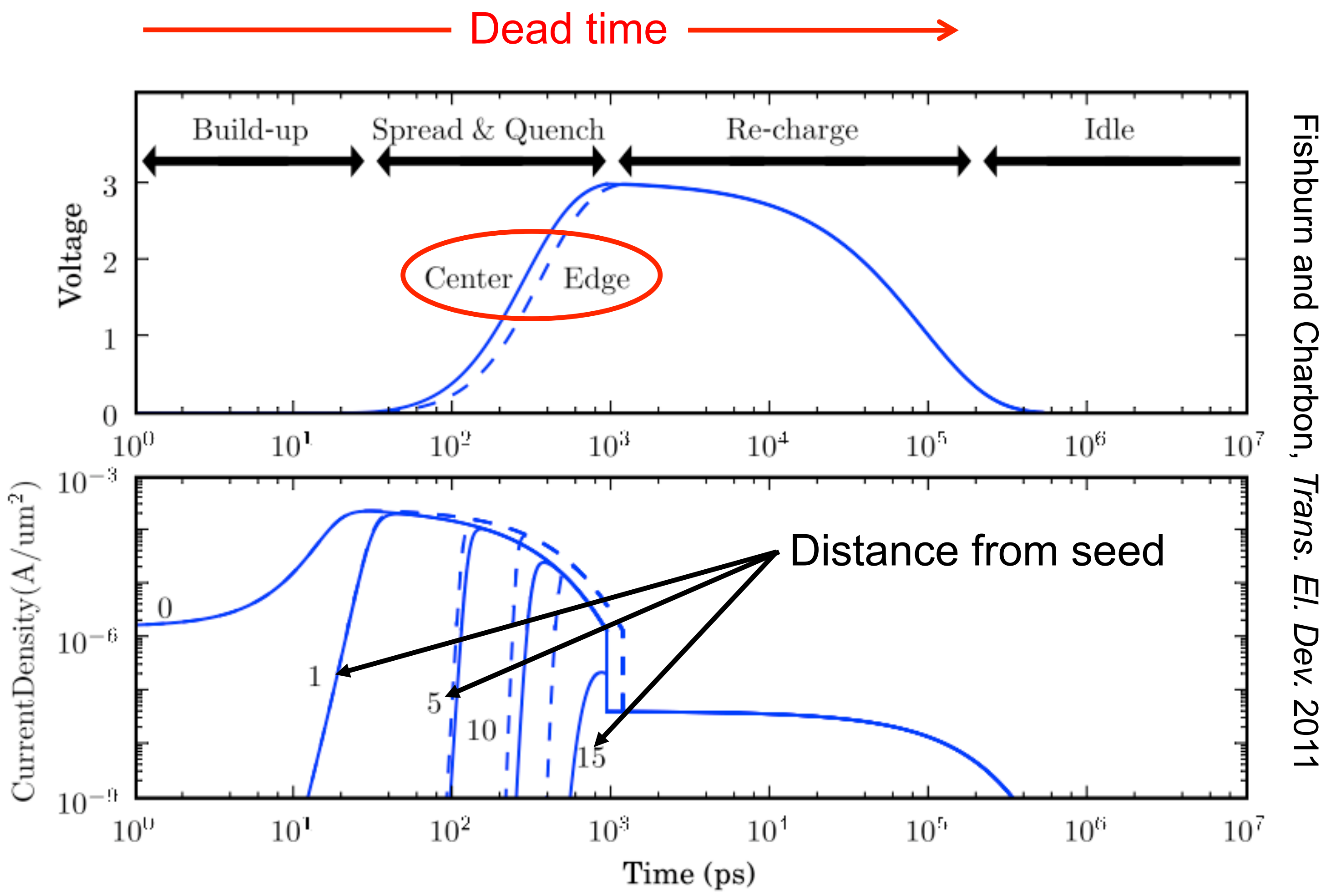


Under the Hood of a SPAD

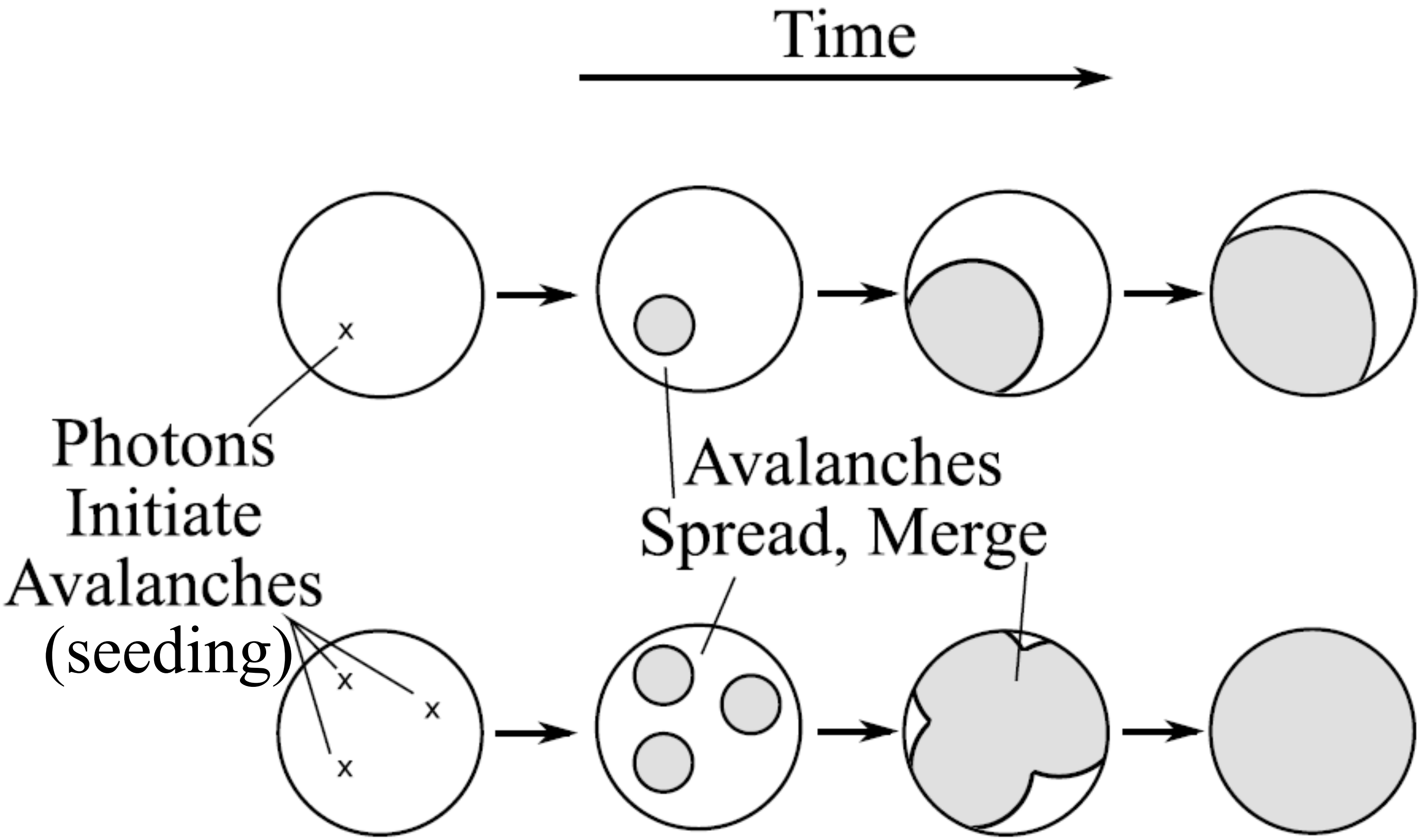
- Seeding
- Build-up
- Spreading
- Quenching
- Recharge



Avalanche Phases

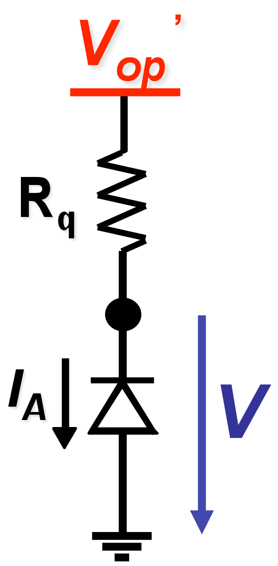


Spreading from Multiple Locations

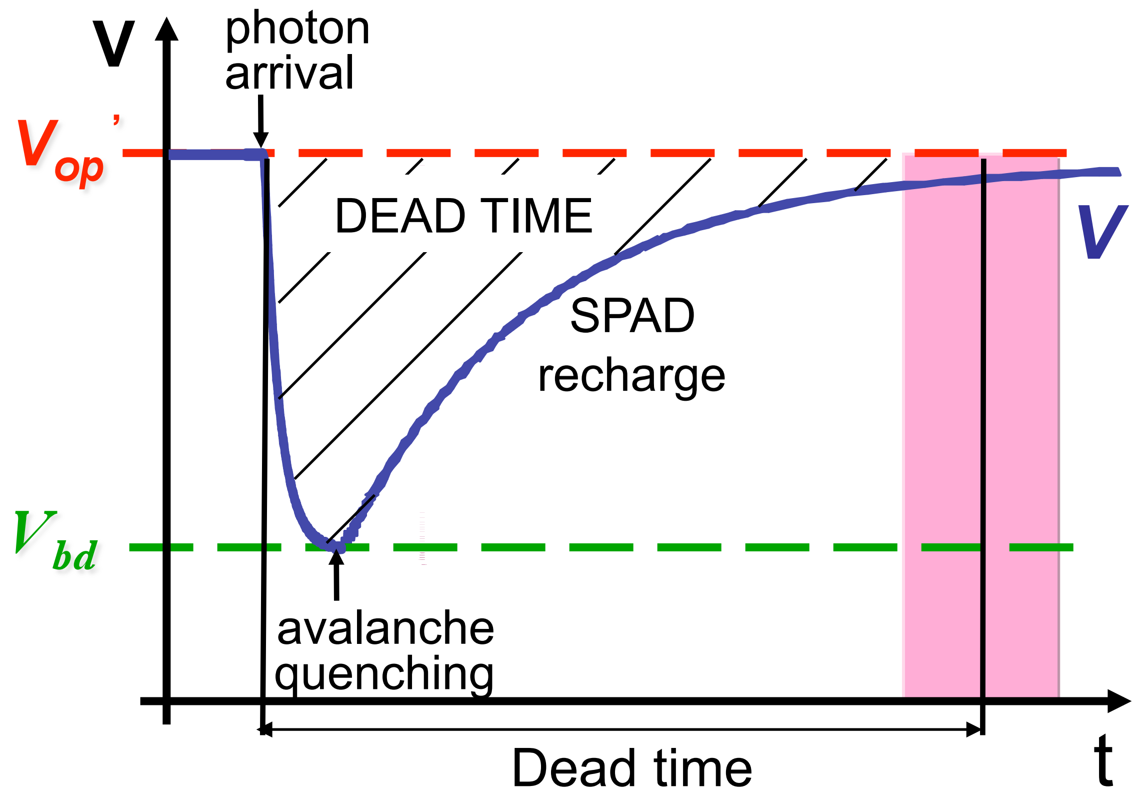


Quenching

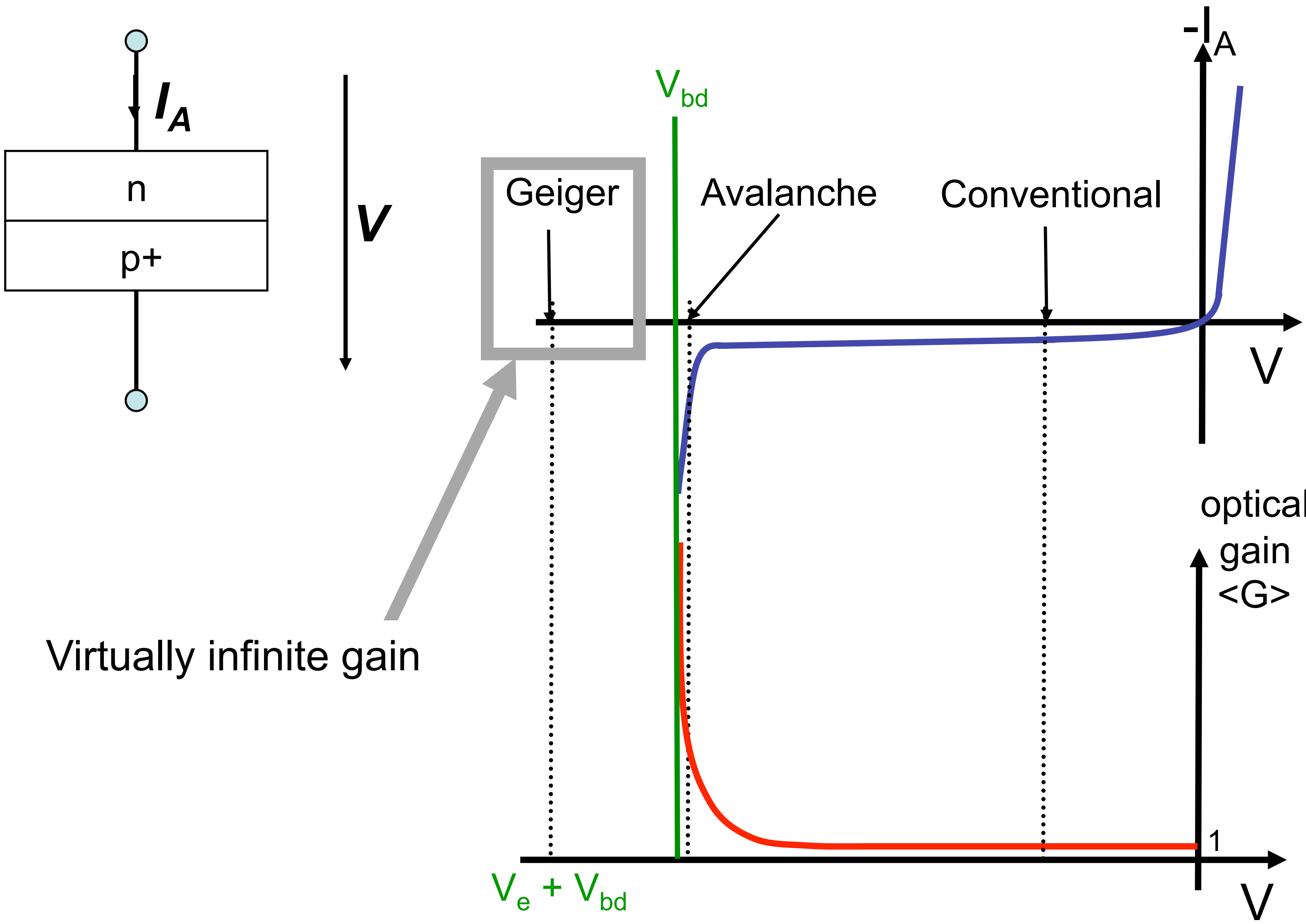
Passive quenching:



Operation cycle:



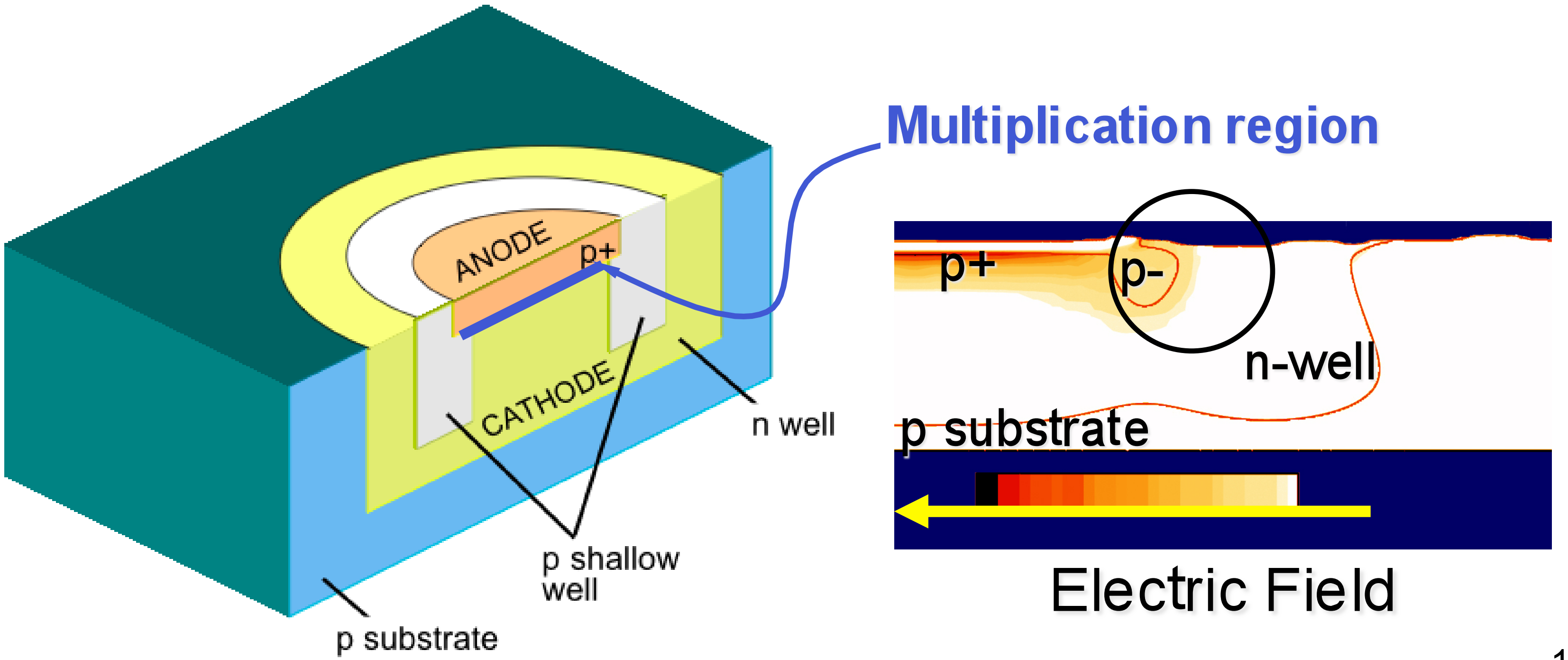
P^+-N Junction



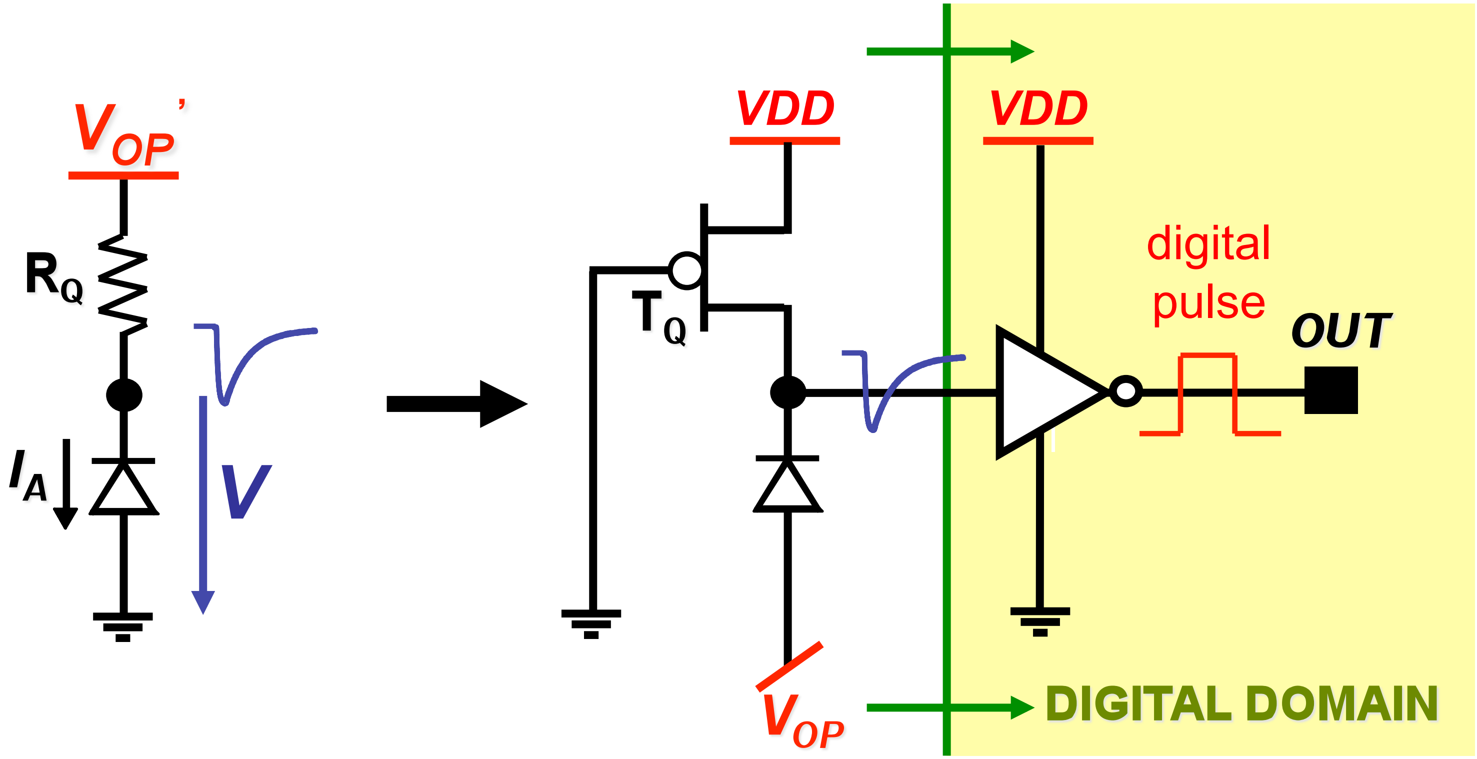
I_A
n
p+
V
V_{bd}
Geiger
Avalanche
Conventional
$-I_A$
V
optical gain <G>
1
V
$V_e + V_{bd}$
Virtually infinite gain

SPAD Implementation

- p- guard ring for electric field reduction in edges
- Prevention of premature edge breakdown
- Creation of zone with constant electric field



SPAD in CMOS



Passive quenching technique

SPAD Non-Idealities

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

… and in SPAD matrices

- **Cross-talk**
- **PDP Uniformity**

Dark Counts: Dark Count Rate

Mechanisms:

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

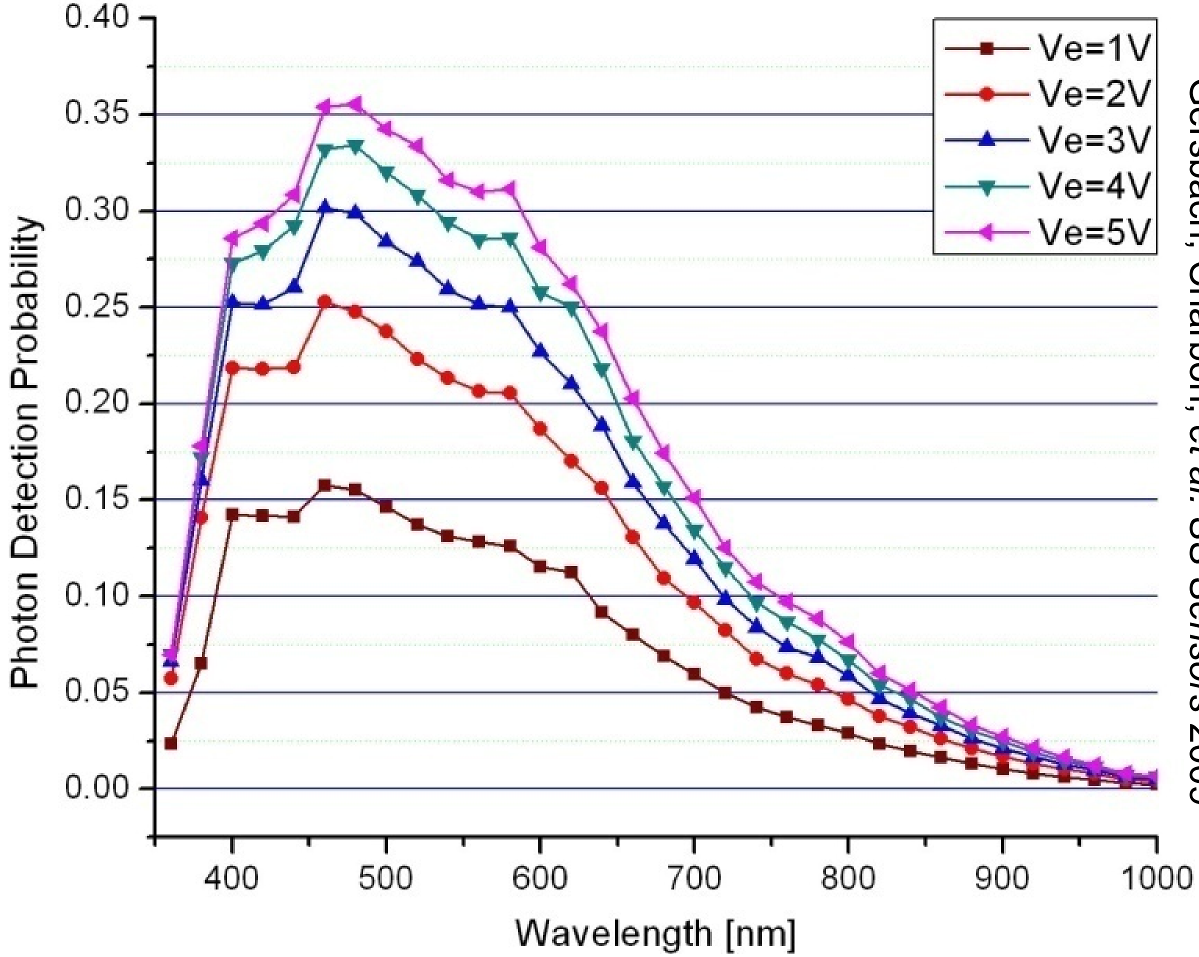
- State-of-the-art SPADs in dedicated technology:
  0.04~1Hz/μm^2
- State-of-the-art CMOS SPADs:
  1~10Hz/μm^2

1	15x15	50x50
1Hz	250Hz	3kHz vs. 60Hz

DCR Characterization

- Due to statistical behavior we use:
  - Mean
  - Median
  - Cumulative
- Proportionalities
  - Linear (active area)
  - Non-linear (excess bias voltage, temperature)

Photon Detection Probability (PDP)



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

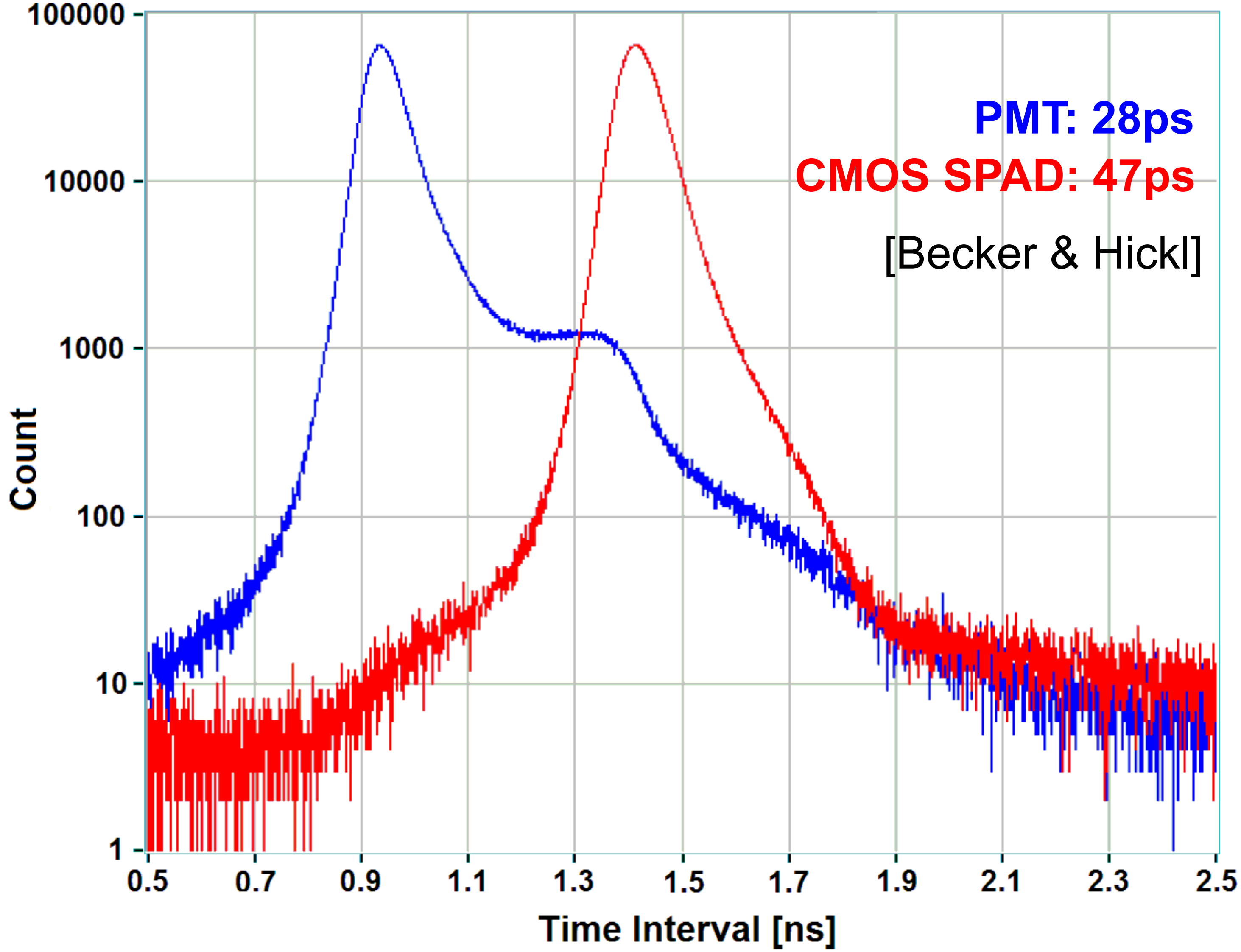
Photon Detection Efficiency

$$PDE = FF \cdot PDP$$

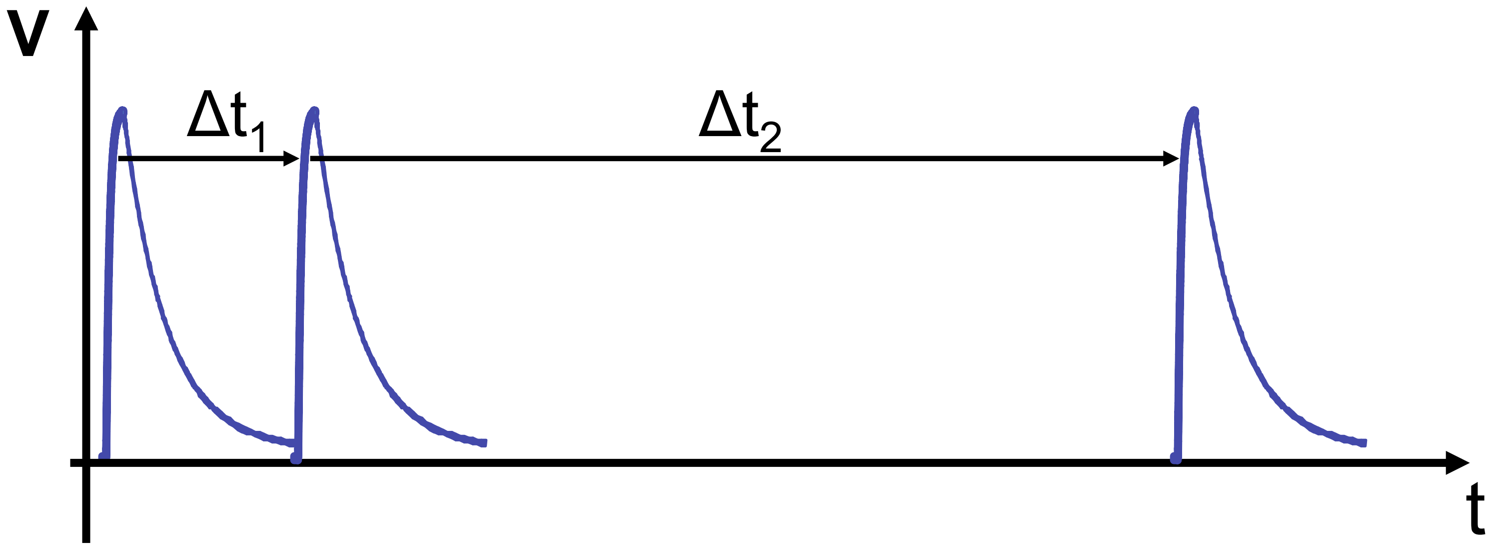
where

$$FF \text{ : fill factor} = \frac{\text{Active Area}}{\text{Total Sensor Area}}$$

Timing Resolution



Afterpulsing

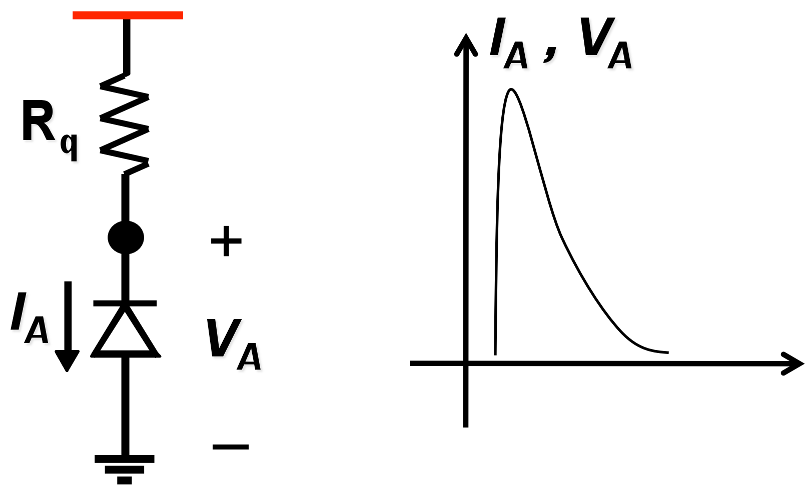


Generally exponential due to Poissonian nature of pulses

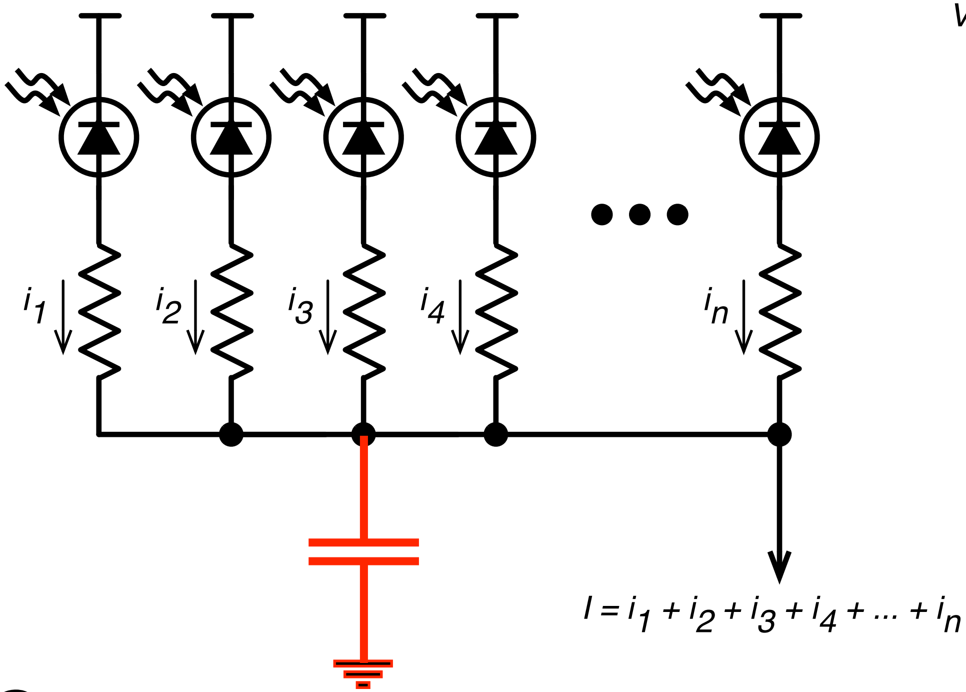
Analog vs. Digital SiPM

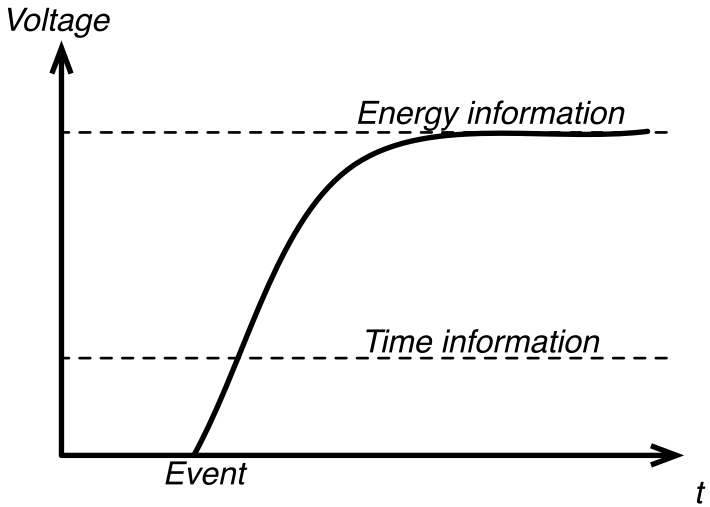
Two Flavors of SiPMs

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



a-SiPMs



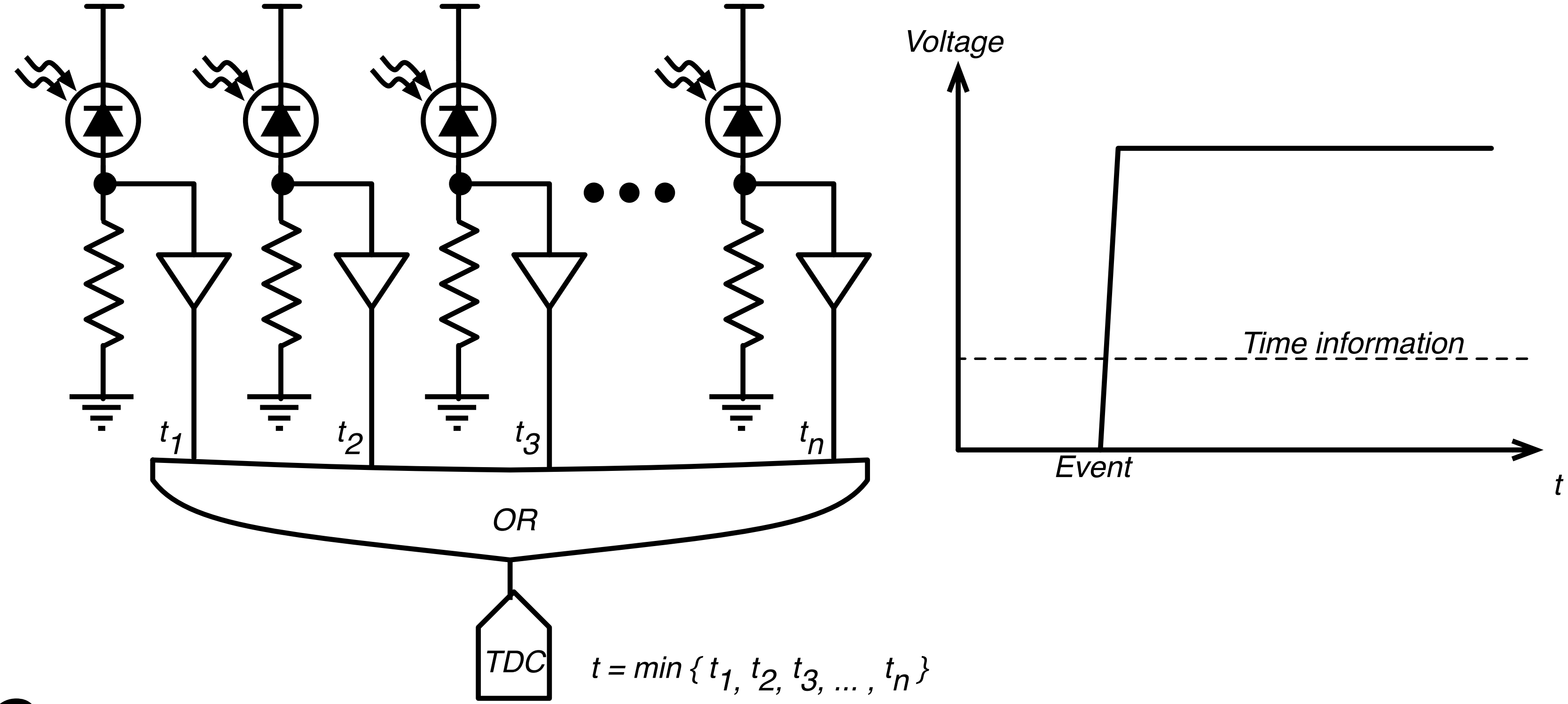


Cons:

– Cannot remove noisy SPADs

– Relative slow rise time due to loading (if no differentiation/delay techniques are used)

d-SiPMs

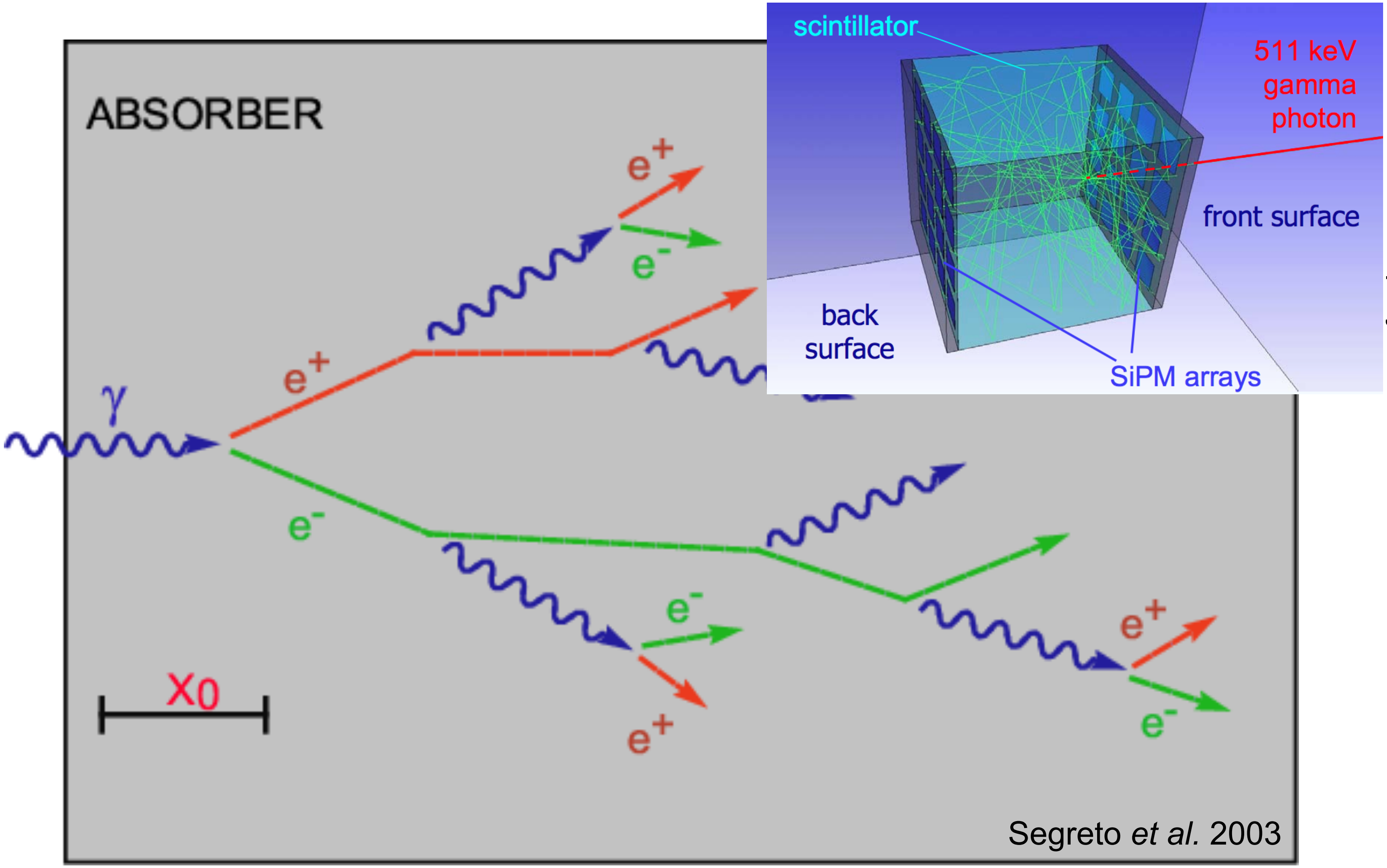


Cons:

– No energy estimation

– Only first photon detected

Energy Estimation



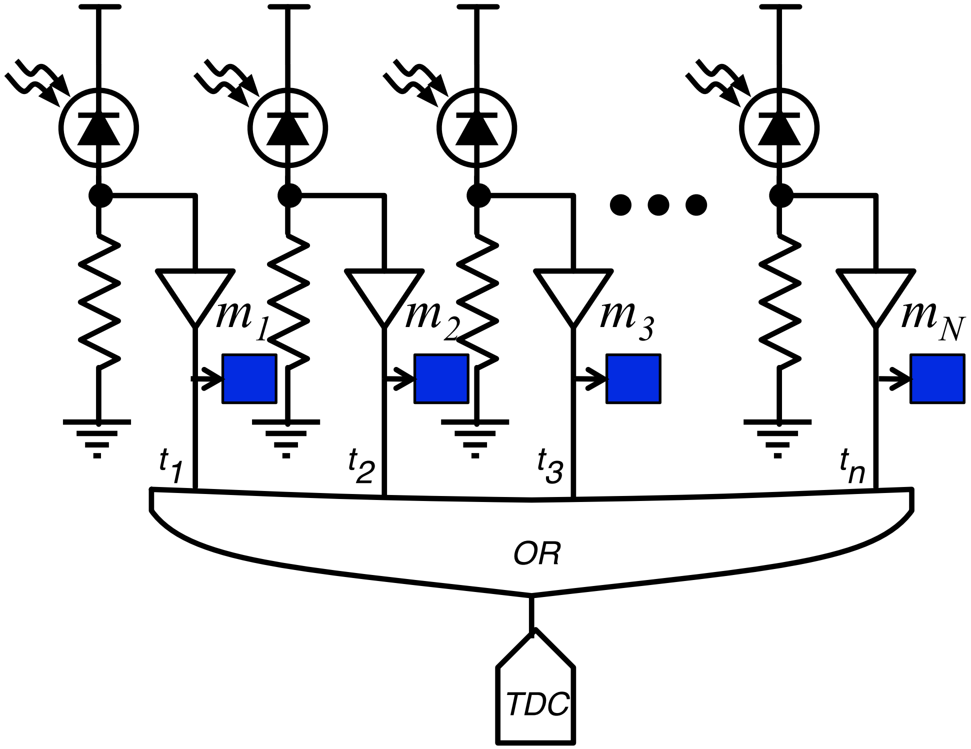
Source: SciSiLia project

Good estimate of energy

=

Mitigation of the effects of Compton and Scattering effects

Solving Shortcomings of d-SiPM



Energy

■ : 1-bit memory

$$E \propto \sum_j m_j$$

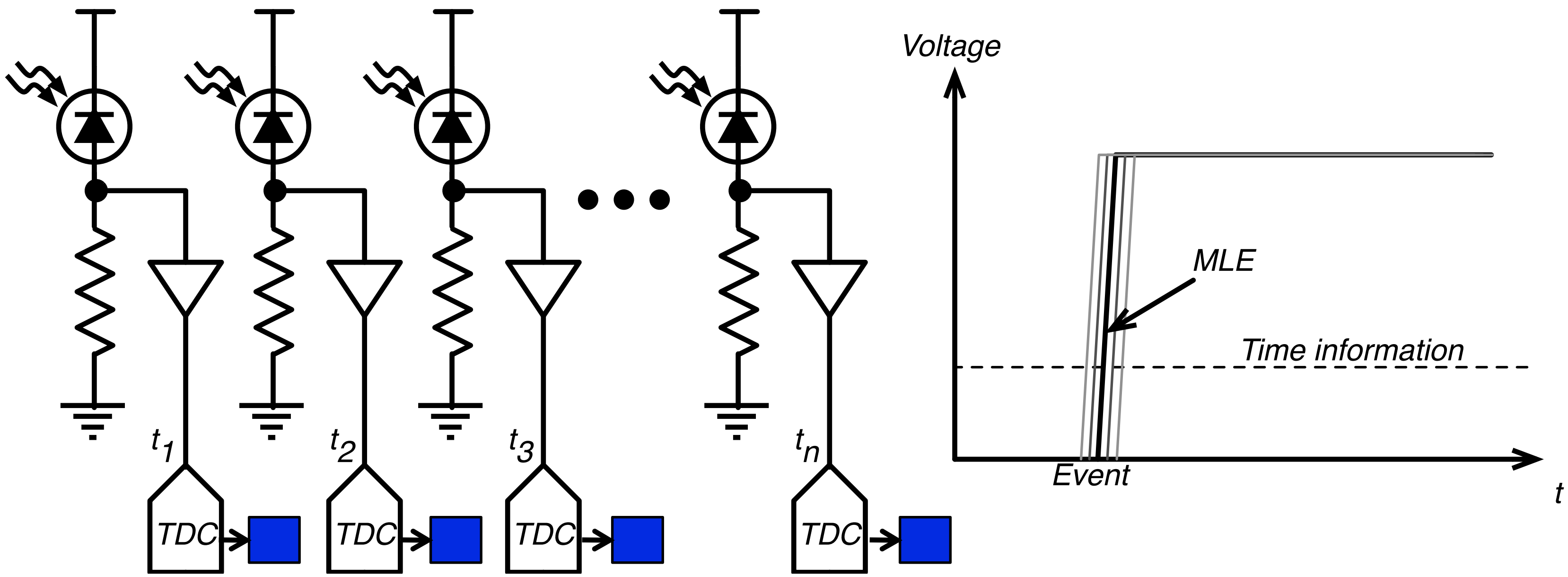
First photon issue

1st or 2nd or 3rd or 4th photon detected

In Summary

- a-SiPM
  - + Simple, High FF (~100%), thus high PDE
  - – Sensitivity to threshold, rel. slow rise time
- Modified d-SiPM
  - + Fast rise time
  - + Can remove noisy SPADs
  - + Robust to thermal noise
  - – Lower FF (77%, Frach *et al.* NSS2011)
  - – Only first n=4 photons individually detected

Introducing: md-SiPMs



- Pros:
  - Independent detection of n>>4 photons
  - Integrated time-to-digital converters (TDCs)

Why Detect Many Photons Individually?

- 1st reason
  - If a Compton or scattering photon or dark count is detected before the Gamma event, it does not block the whole SiPM
  - *A posteriori* snooping can remove spurious events
- 2nd reason (and even more important)
  - We get much better statistics of the Gamma event

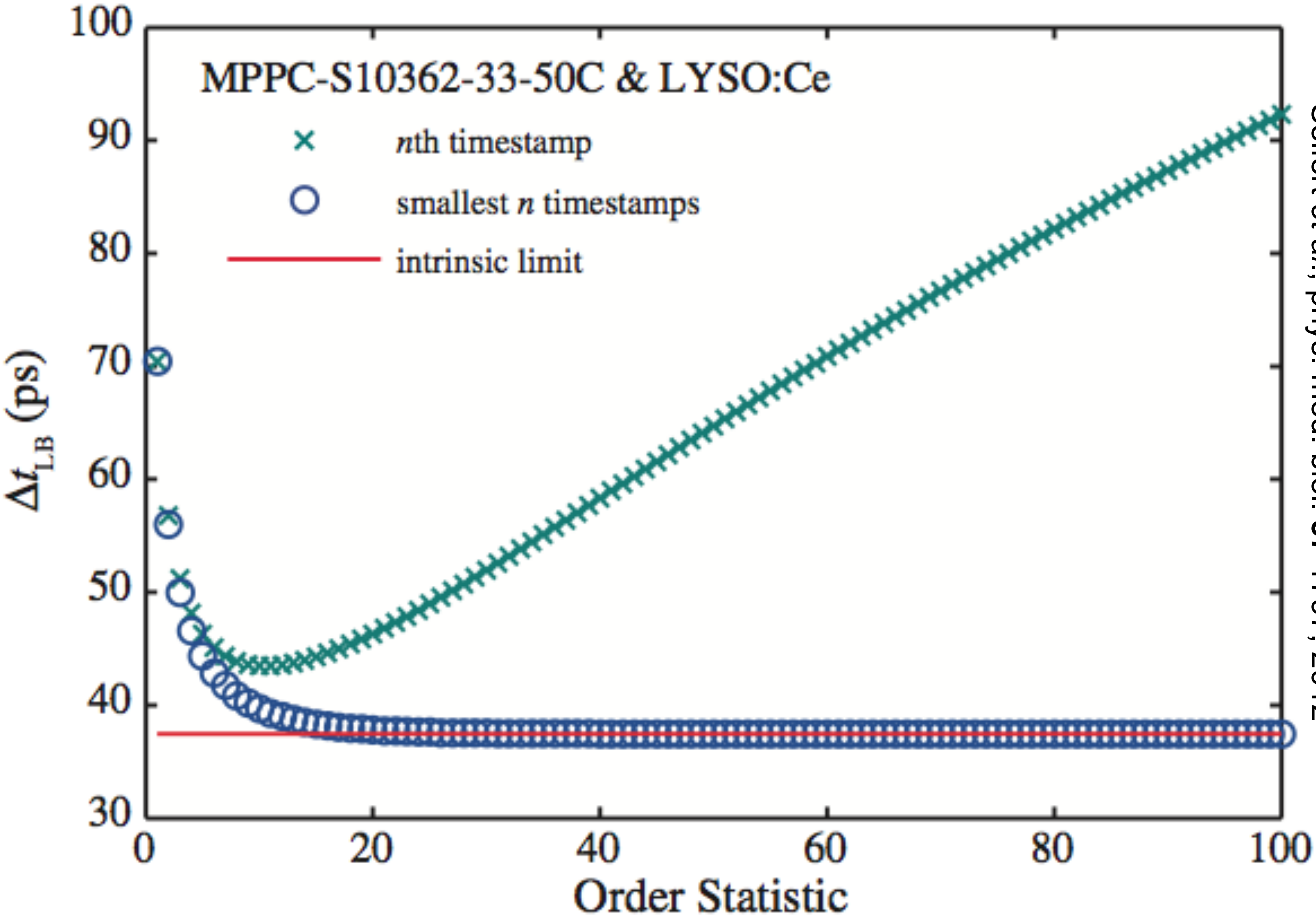
Rationale – Statistics

- Assume standard model of scintillator response at time Θ

$$\frac{1}{\tau_d - \tau_r}\left[e^{-\frac{t-\Theta}{\tau_d}} - e^{-\frac{t-\Theta}{\tau_r}} \right]$$

- Then, a lowerbound on the variance of the estimator exists that satisfies Cramér-Rao's inequality
- The uncertainty of the estimator is lower if the previous n-1 measurements are taken into account vs. only the n^{th} order statistic

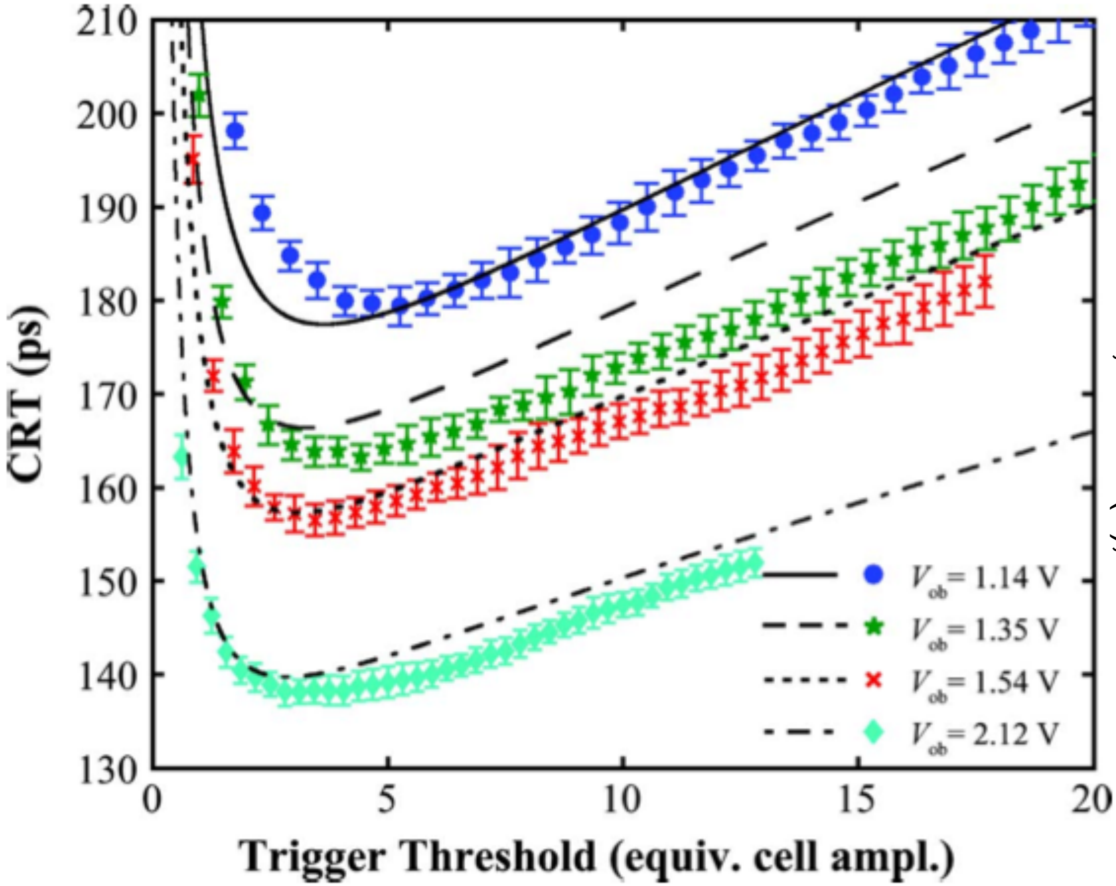
Rationale – Statistics(2)



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

Rationale – Statistics(3)

- A a-SiPM exhibits a coincidence resolving time (CRT) following the <u>*same*</u> behavior



Seifert *et al.*, TNS **59**(1), 2012

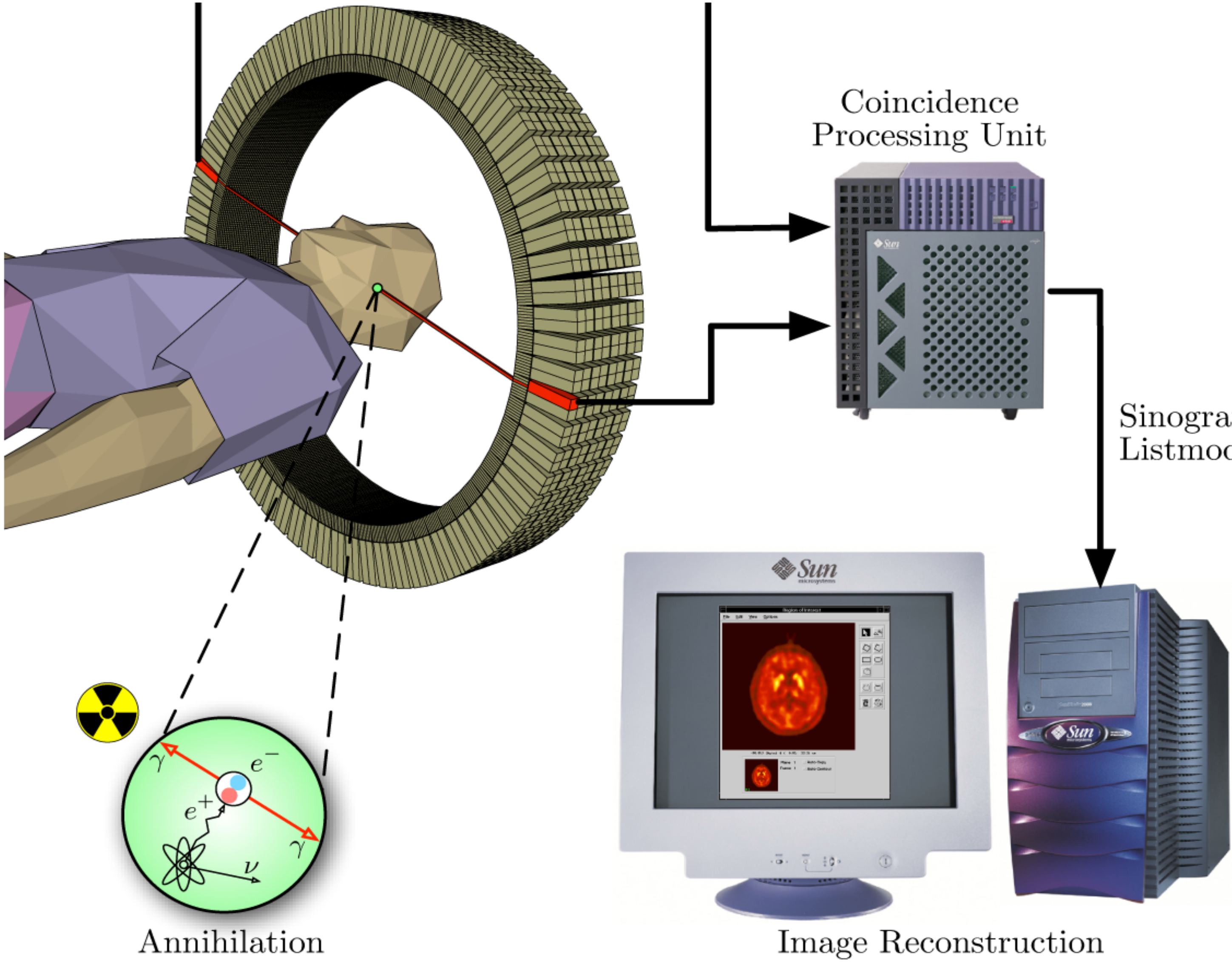
Rationale – Statistics(4)

- A a-SiPM will achieve the lowerbound of CRT but *only* at a given threshold that is often unknown *a priori* and somewhat unstable
- A md-SiPM will guarantee to *always* find that lowerbound provided a sufficient number n is used
- PROVIDED that

  The number of photons is not reduced significantly, i.e. the FF is not drastically lower!

An md-SiPM Based Sensor

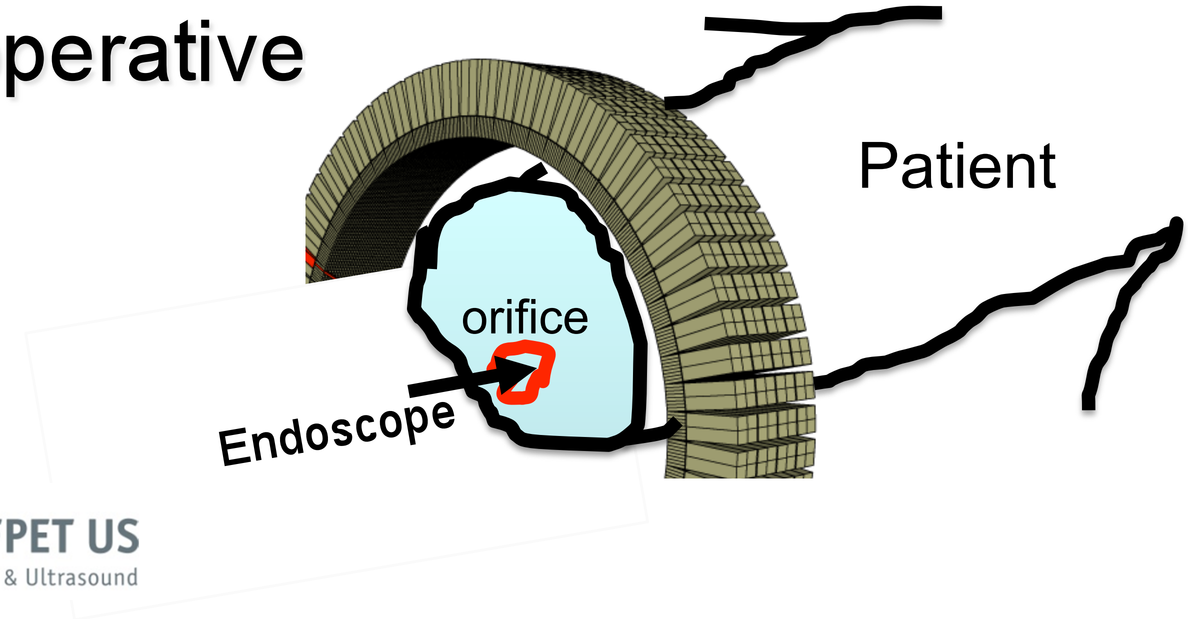
Positron Emission Tomography



Source: Sun

The EndoTOFPET-US Project

- Asymmetrical PET
  - Endoscope (intra-orifice detection)
  - Belt (external detection)
- Adjacency improves resolution
- Intra-operative

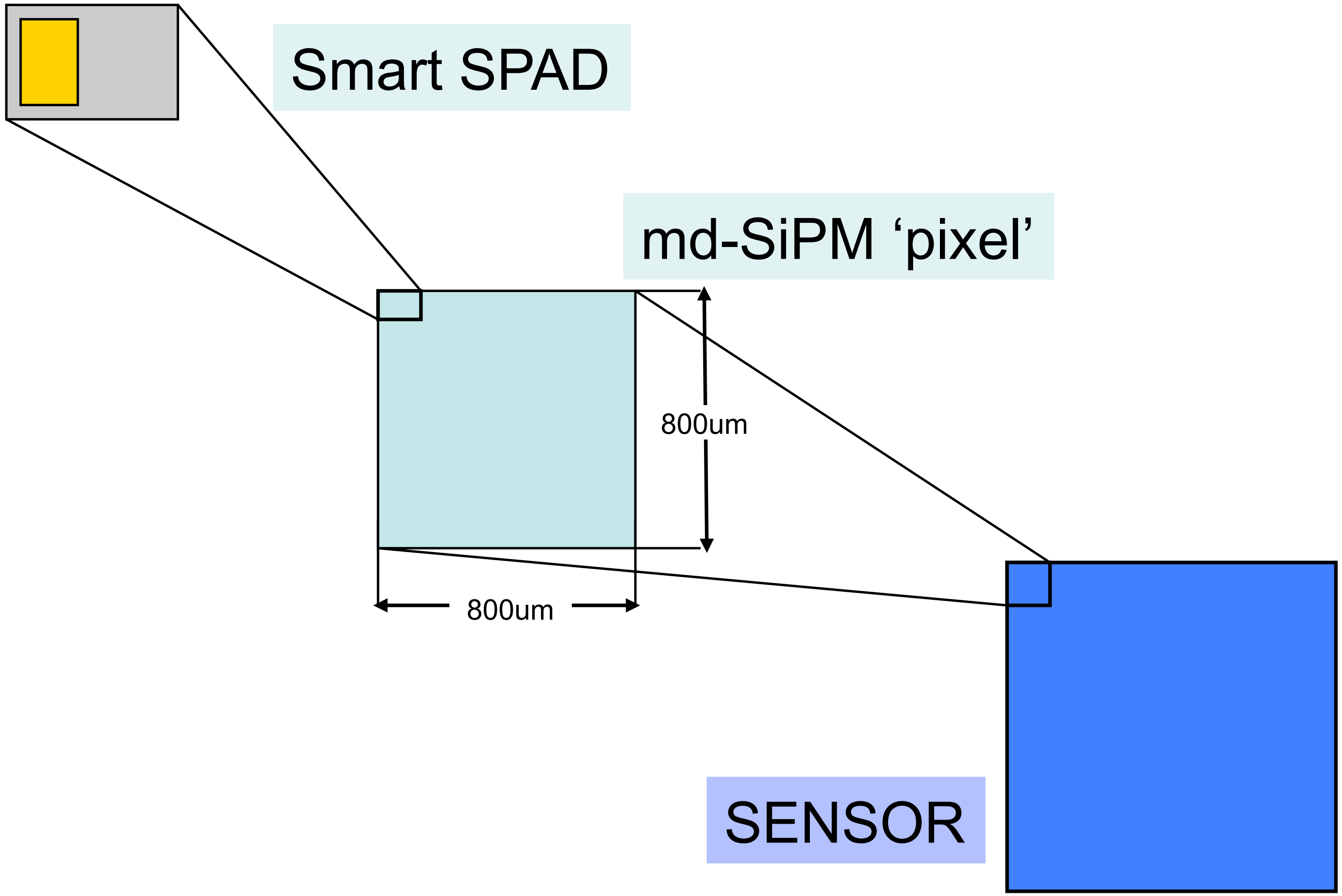


ENDO TOFPET US
Endoscopic TOFPET & Ultrasound

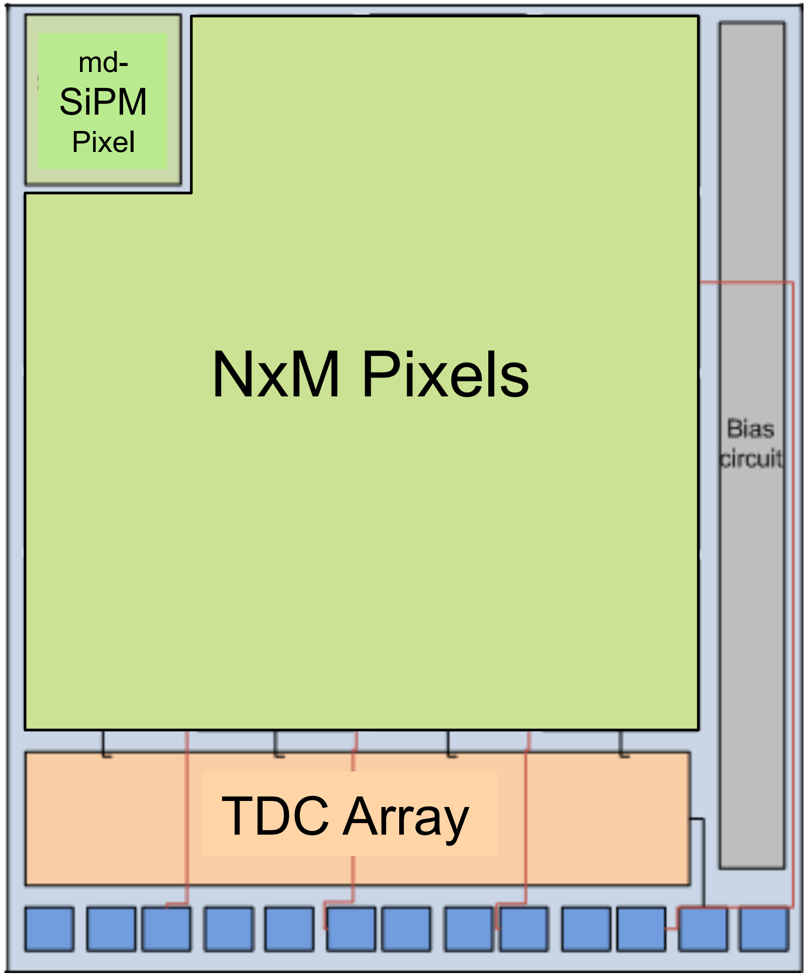
Endoscope Sensor

Parameter	**EndoTOFPET-US**
Number of “Pixels”	See Upcoming Publications
“Pixel” Pitch (μm)	800
Max. PDE (%)	See Upcoming Publications
Max. Fill Factor (%)	>40
# of First Photons Detected	See Upcoming Publications
Timing resolution or LSB (ps)	<100
Max. Conv. rate (MS/s)	See Upcoming Publications

Solution



Sensor Floorplan



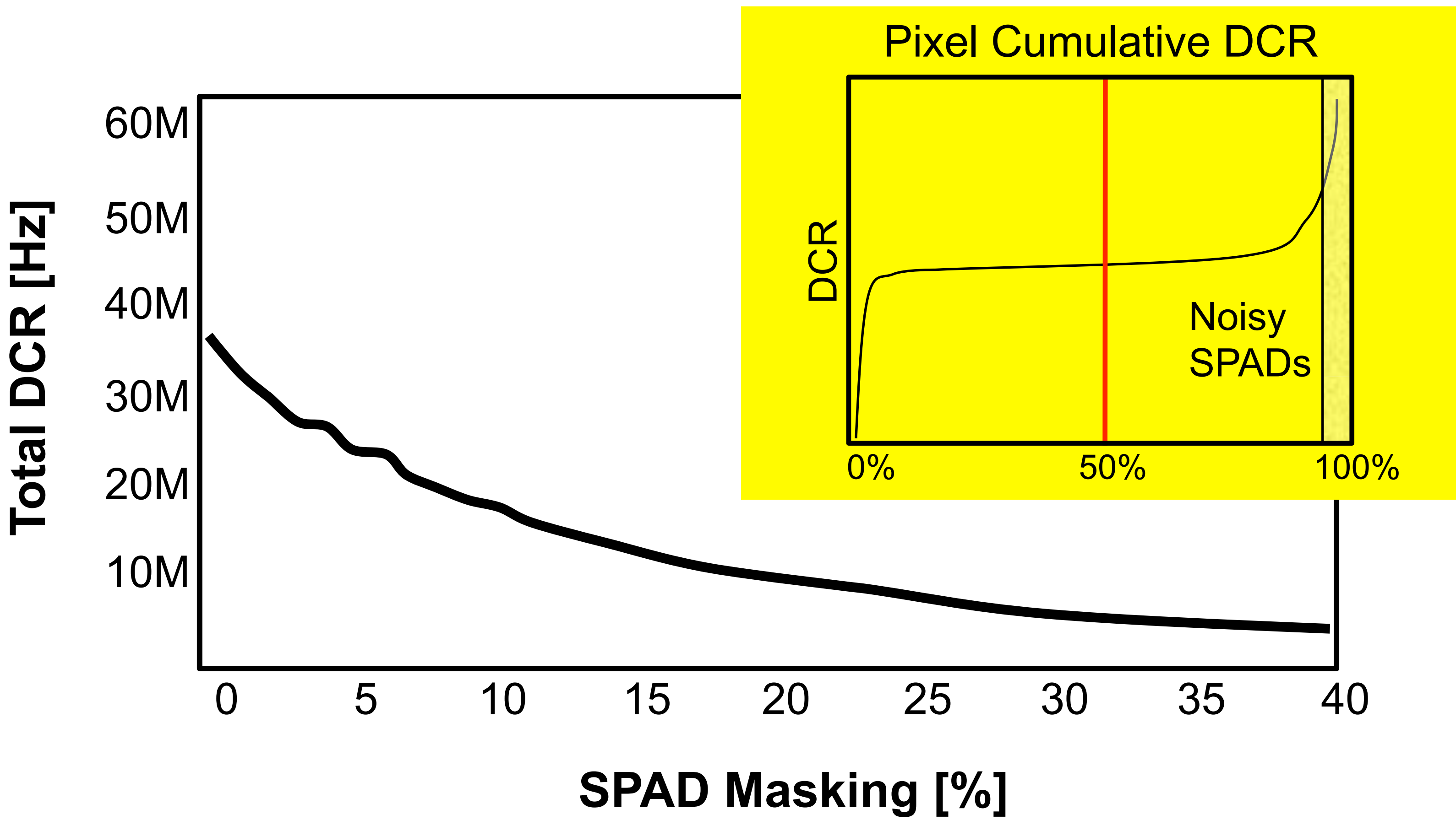
Sensor Architecture Highlights

- Careful balance FF vs. functionality
  - Column-parallel TDCs
  - Noisy SPAD suppression
  - Optical concentrators
- Smart reset mechanism
- Column-parallel TDCs

Smart SPAD

- Noisy SPAD suppression (‘masking’)
- Internal counter (for energy determination)
- Fast & accurate photon pulse shaping
- Low power
- High FF

Pixel DCR with Masking



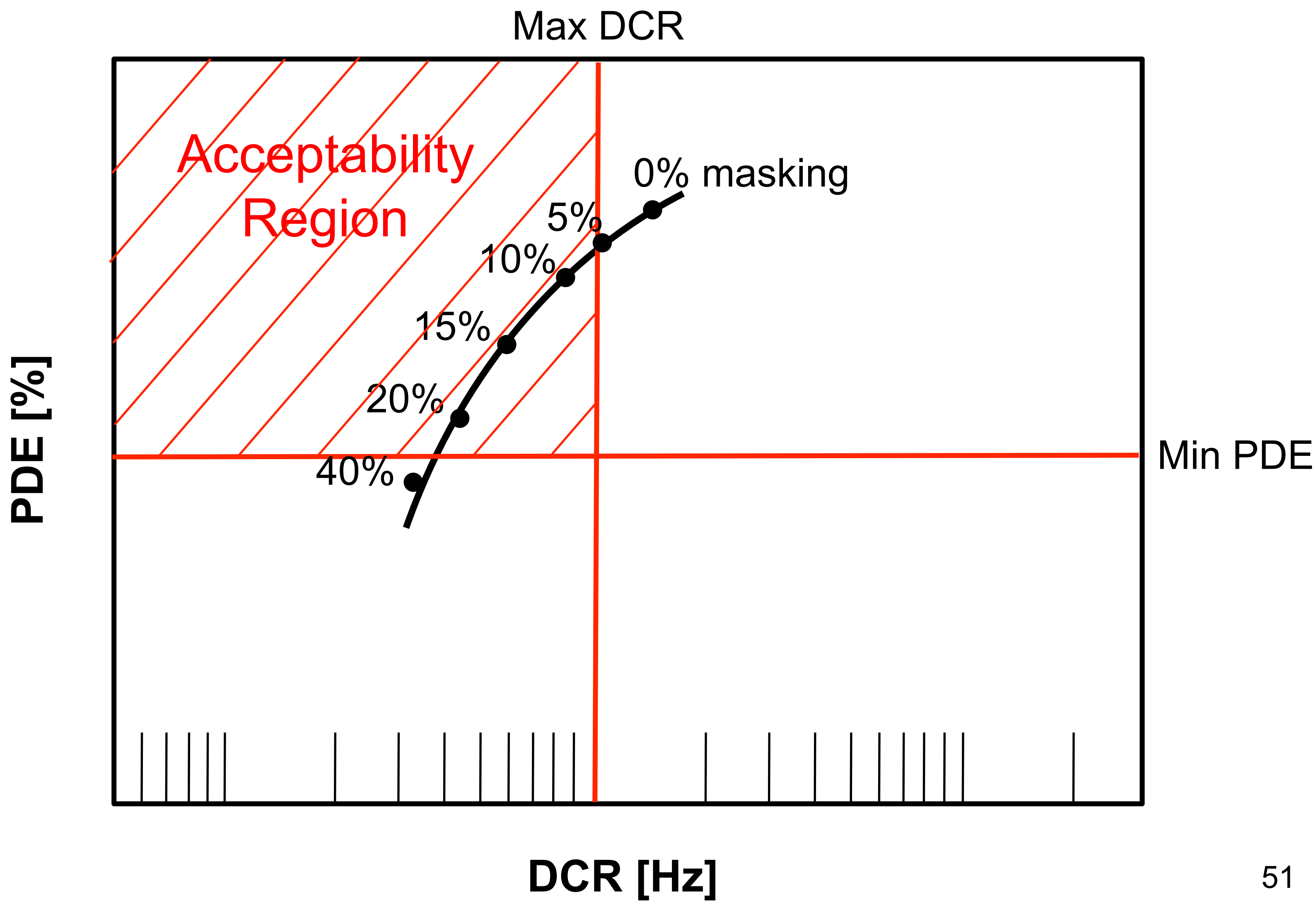
Masking vs. Fill Factor

- Masking reduces FF by the same amount
- Example

  5% masking reduces FF by 5%

  20% masking reduces FF by 20%

Masking vs. PDE



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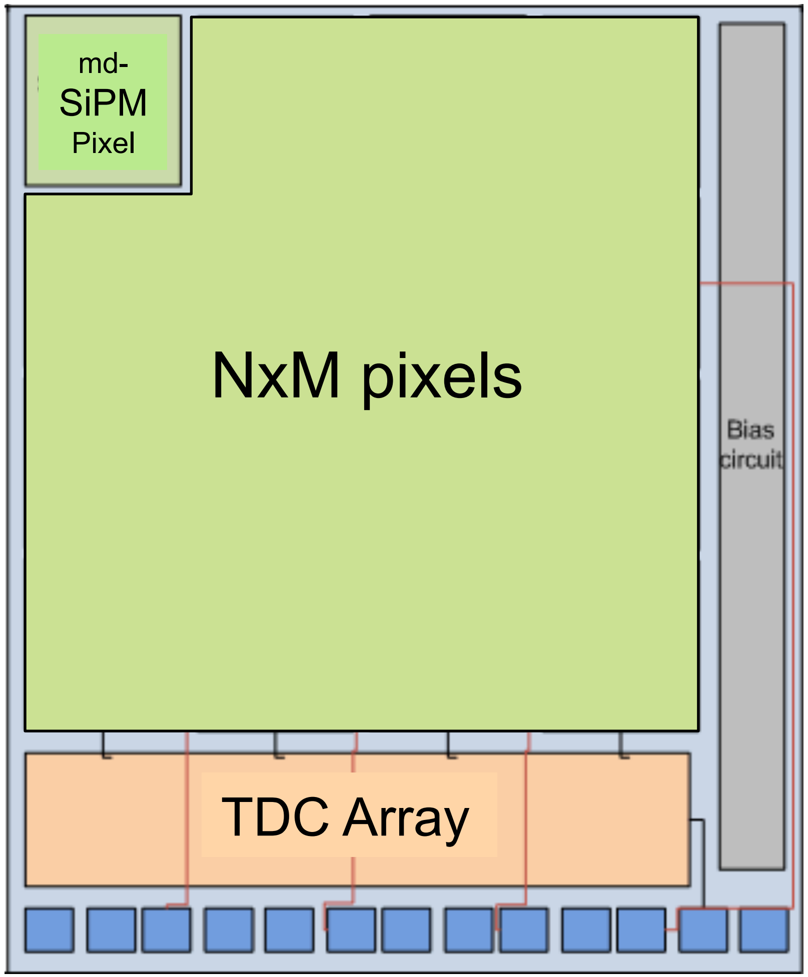
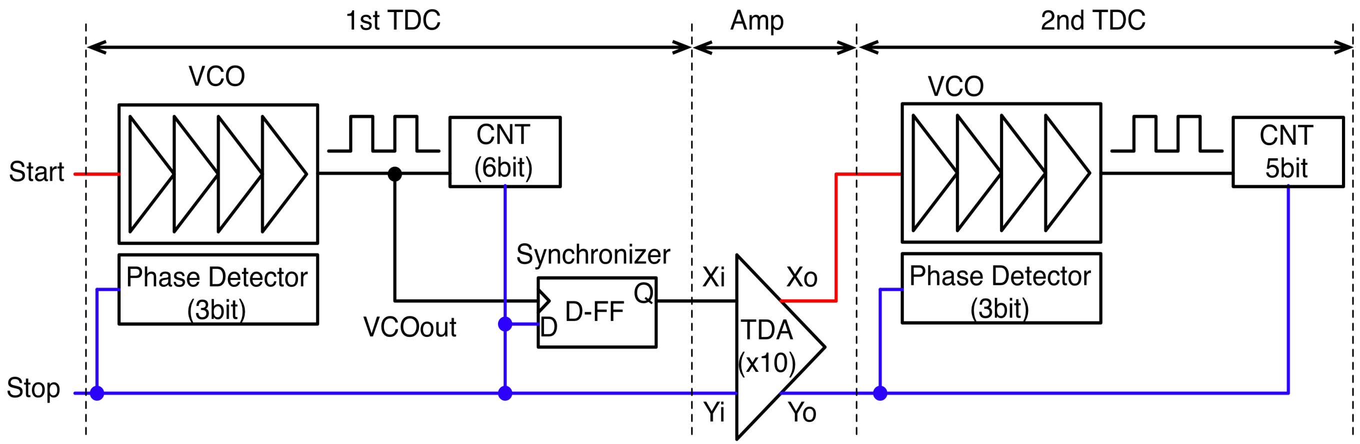
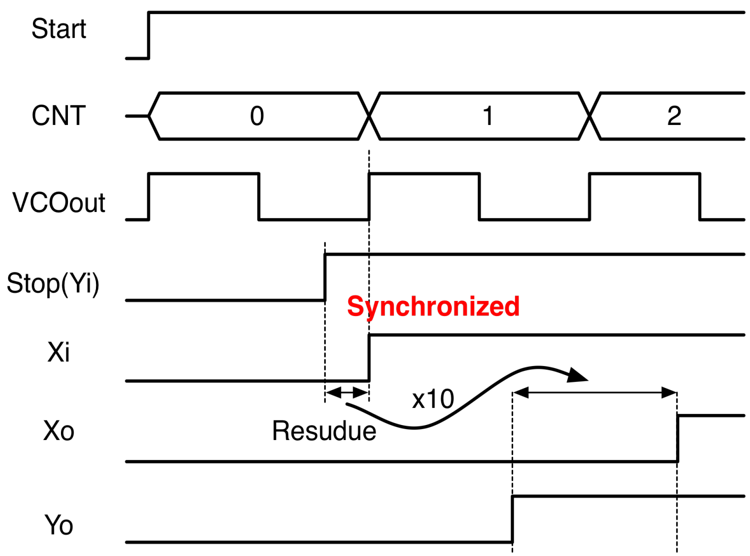
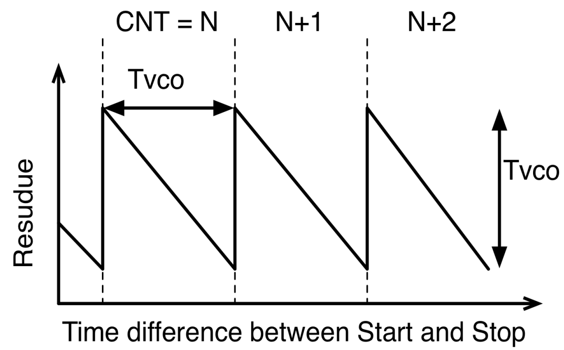


Time-to-Digital Converter (TDC)

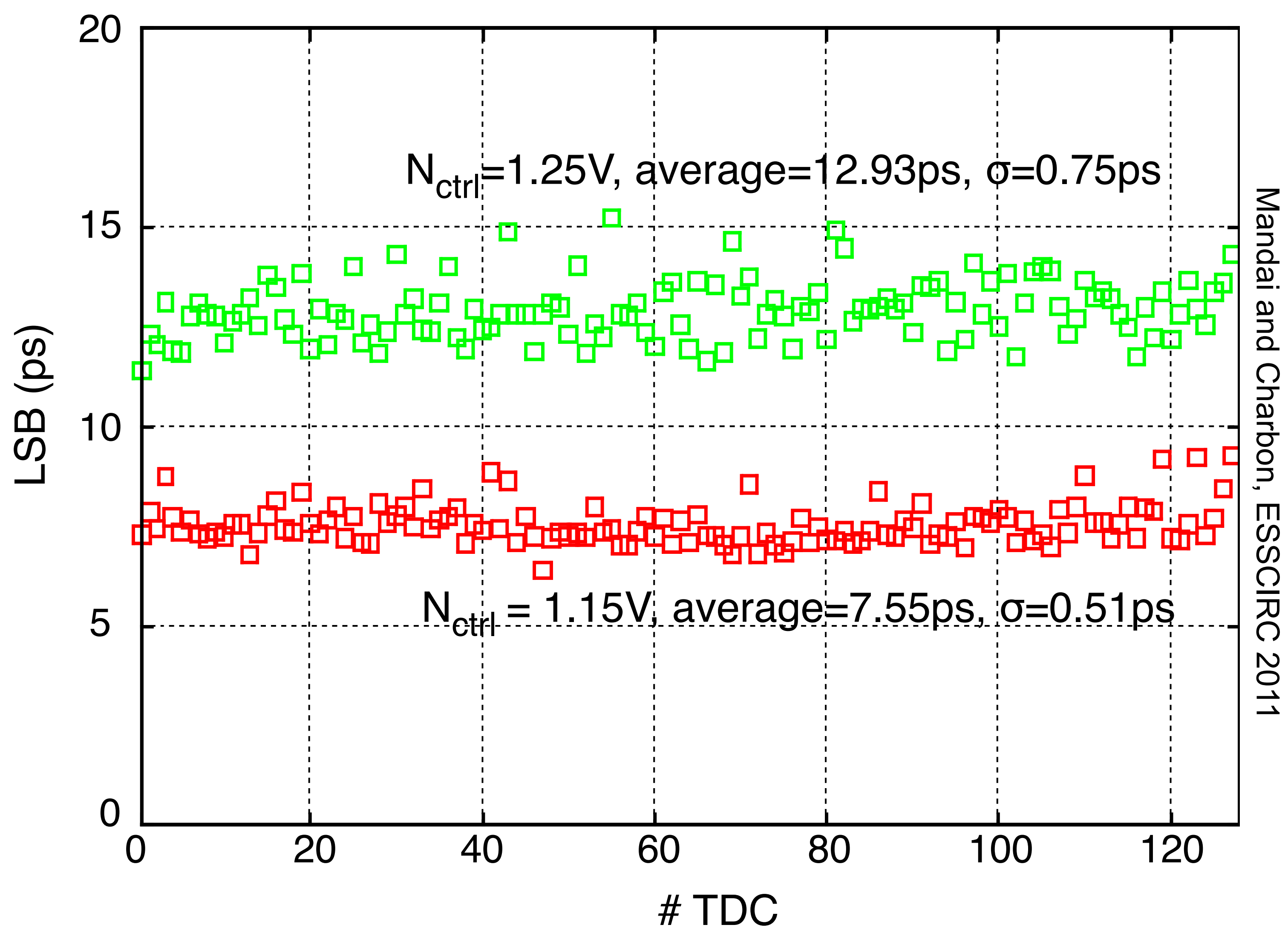






Mandai and Charbon, ESSCIRC 2011

LSB Uniformity, Equivalent TDC



a-SiPM vs. d-SiPM: the Myths

- a-SiPMs are simpler to build
- a-SiPMs have a better fill factor
- a-SiPMs have better sensitivity

* * *

- d-SiPMs have better rise time
- d-SiPMs have better noise performance
- d-SiPMs are more versatile

True or False ?

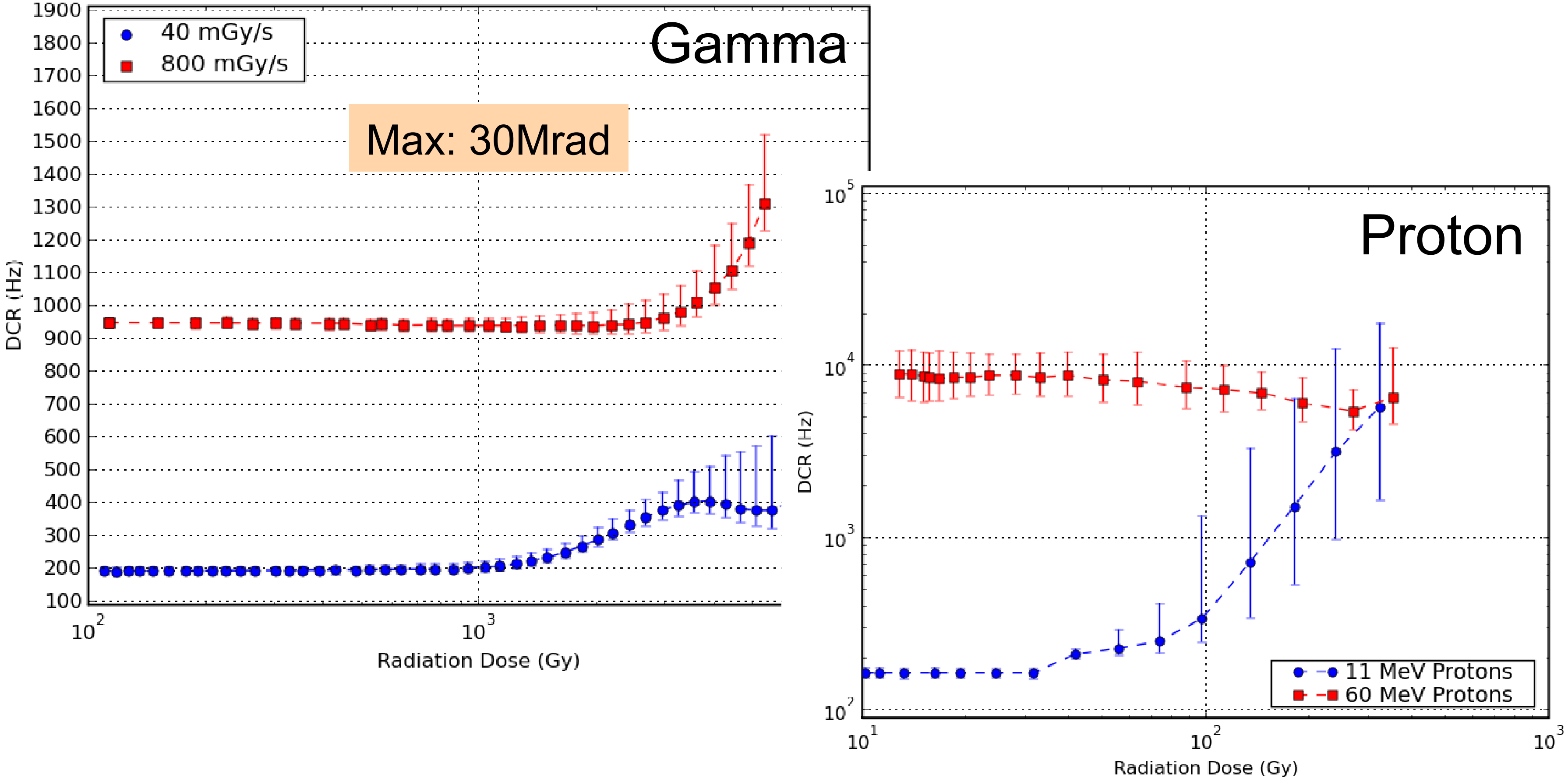
md-SiPM?

- Like a d-SiPM but much more powerful and robust!

Hostile Environments

- Gamma radiation
- B-fields
- Proton irradiation
- High temperatures

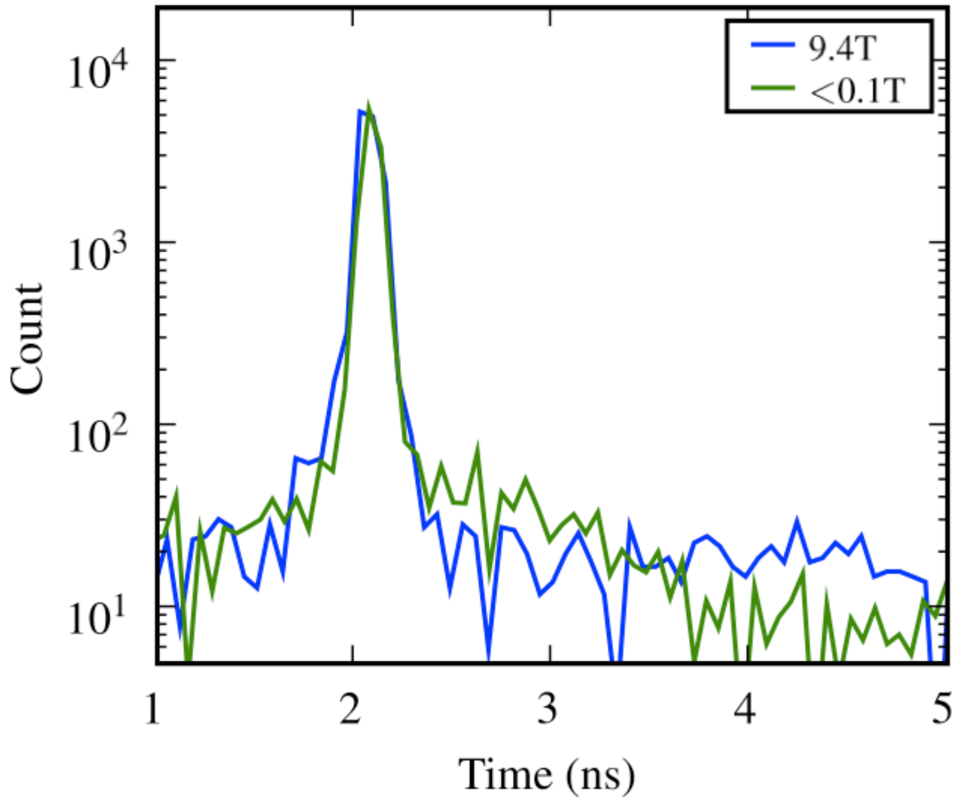
Radhardness



Charbon, Carrara *et al.*, 2010

B-Fields

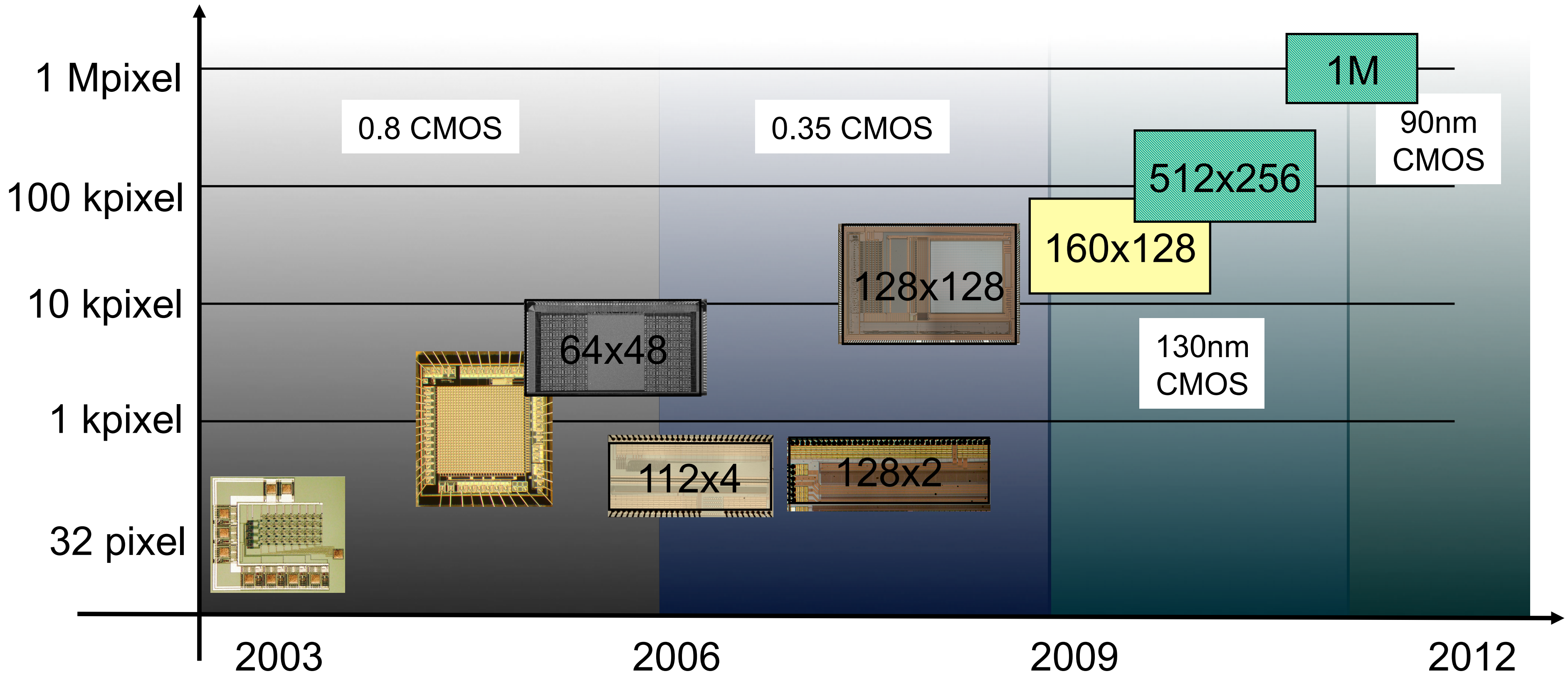
- Timing resolution insensitive due to dominating avalanche force over Lorentz forces



Fishburn and Charbon, *NSS*, 2011

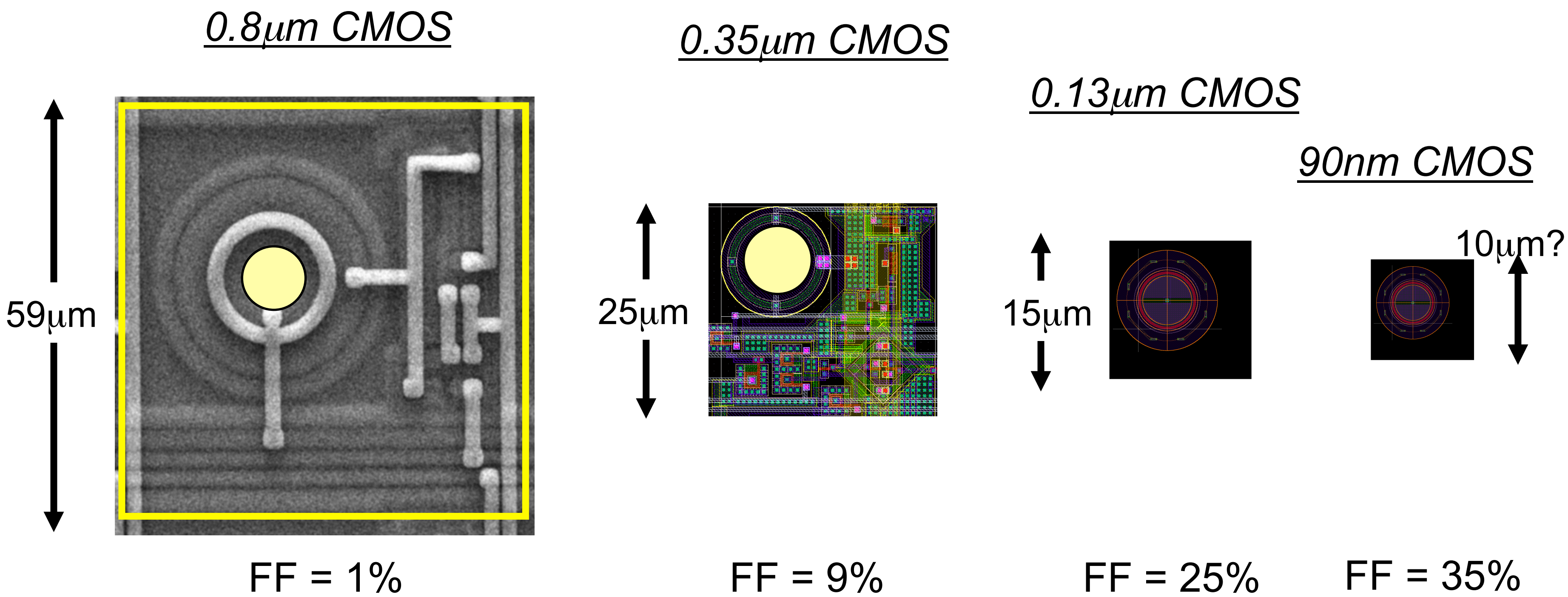
The Next Big Challenges

Moore's Law for SPADs



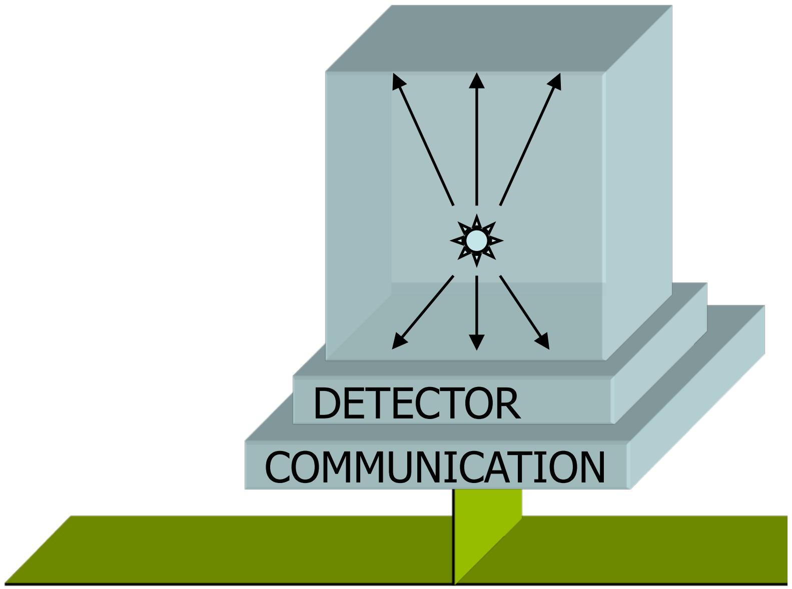
Fill Factor

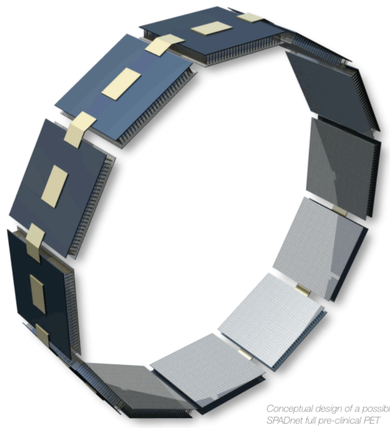
Guard rings, design rules, on-pixel processing



The SPADnet Project

<u>*Objective:*</u>
Fully digital, scalable <u>*photonic component*</u> capable of detecting single and multi-photon bursts, their time-of-arrival and intensity

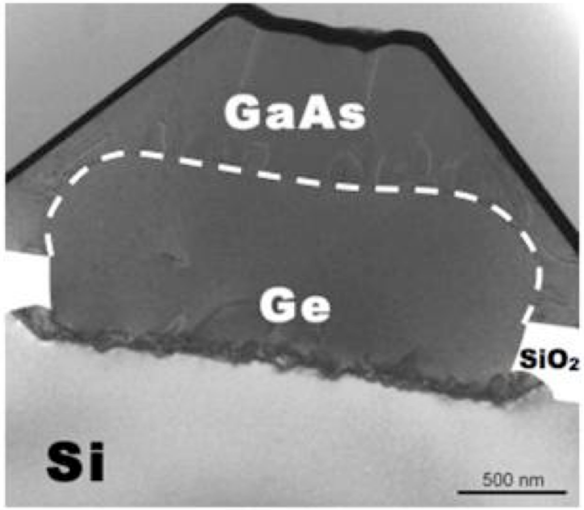




Conceptual design of a possible SPADnet full pre-clinical PET implementation.

Important Trends

- Sub-90nm CMOS
- 3D integration
- Backside illumination (BSI)
- Near IR
- Near and deep UV
- Soft and hard X-ray
- Larger formats



Sammak, Aminian, Nanver, Charbon, IEDM11

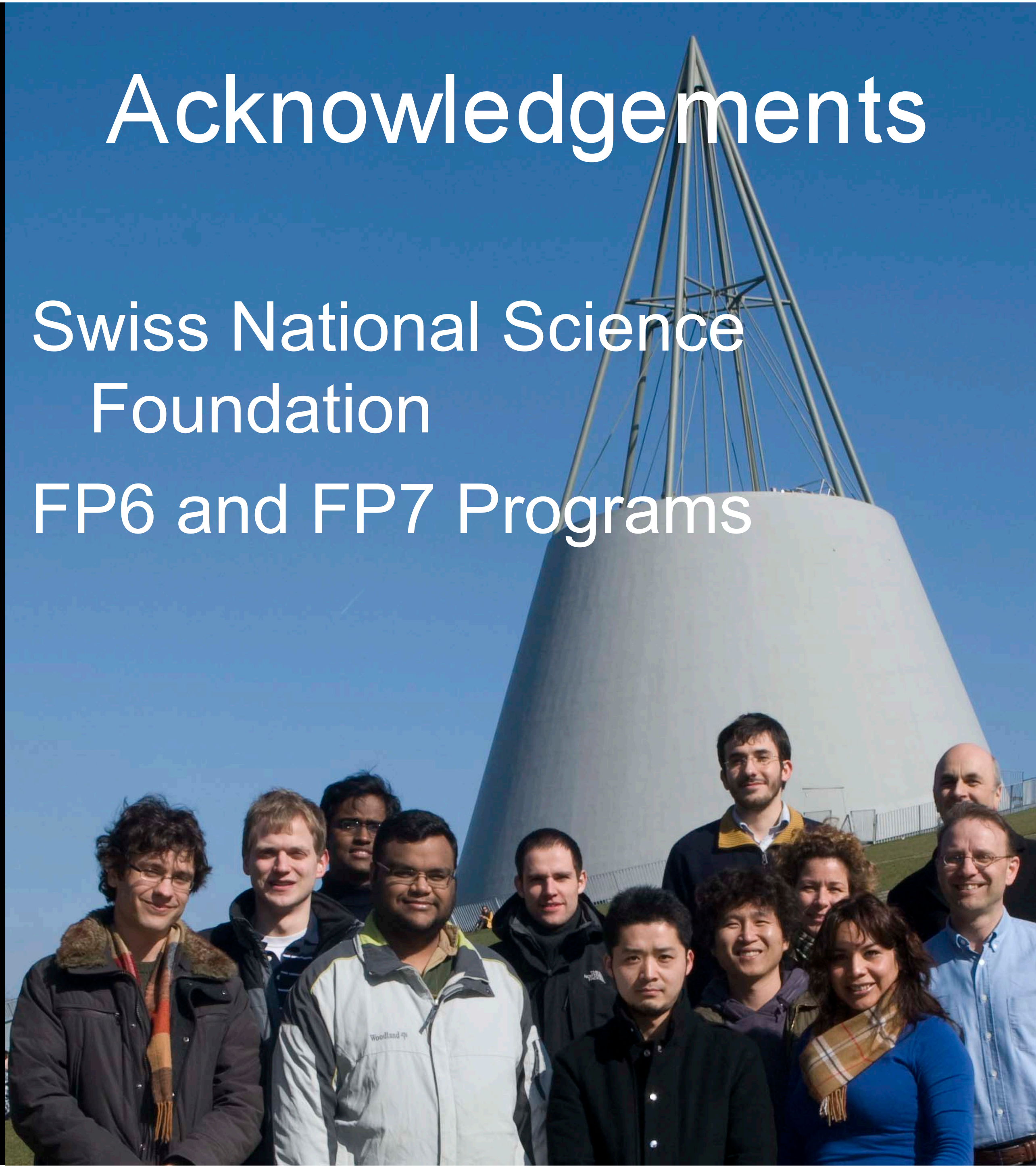
Conclusions

- Photon-counting imagers are here to stay
- New and old apps enabled
- Next challenges
  – More miniaturization
  – More parallelization
  – More flexibility
  – Novel imaging paradigms

Acknowledgements

Swiss National Science Foundation

FP6 and FP7 Programs



http://cas.et.tudelft.nl