Silicon Photomultipliers:

Introducing the digital age in low light detection

Rudjer Boskovic Institute
October 24th, 2018

Massimo Caccia
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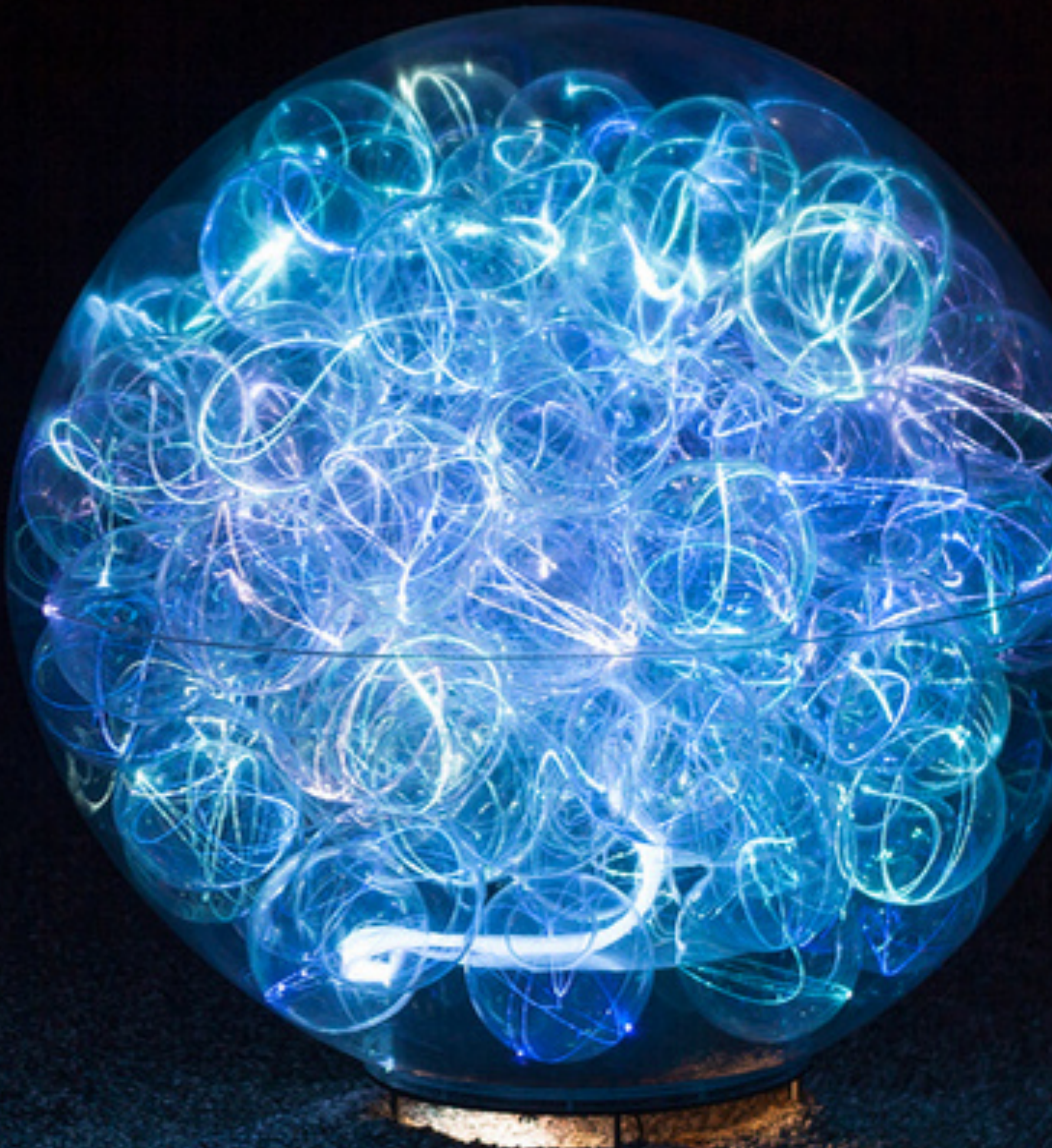

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Introducing the Silicon age in low light detection

Part 1: principles, today & tomorrow

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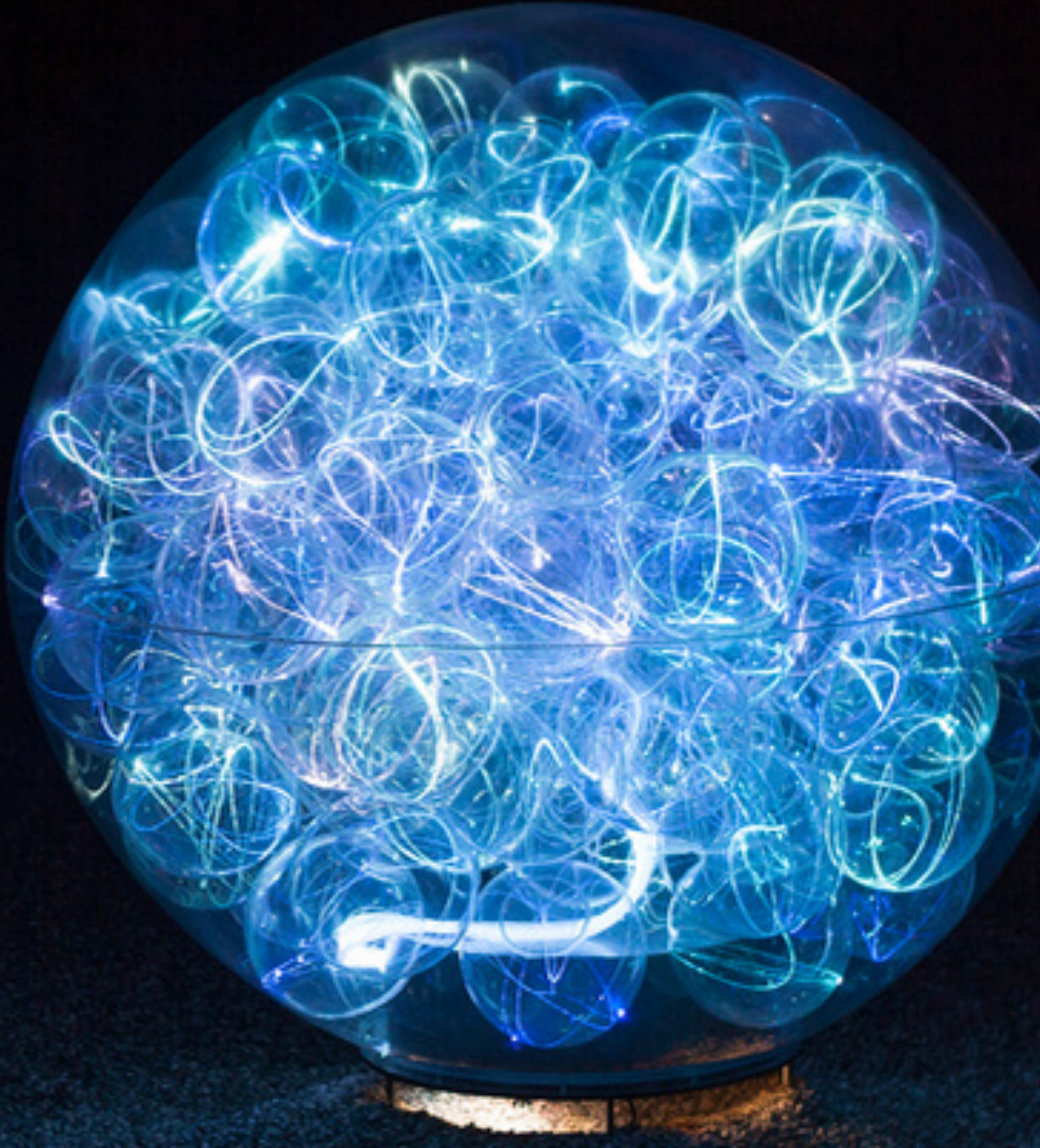
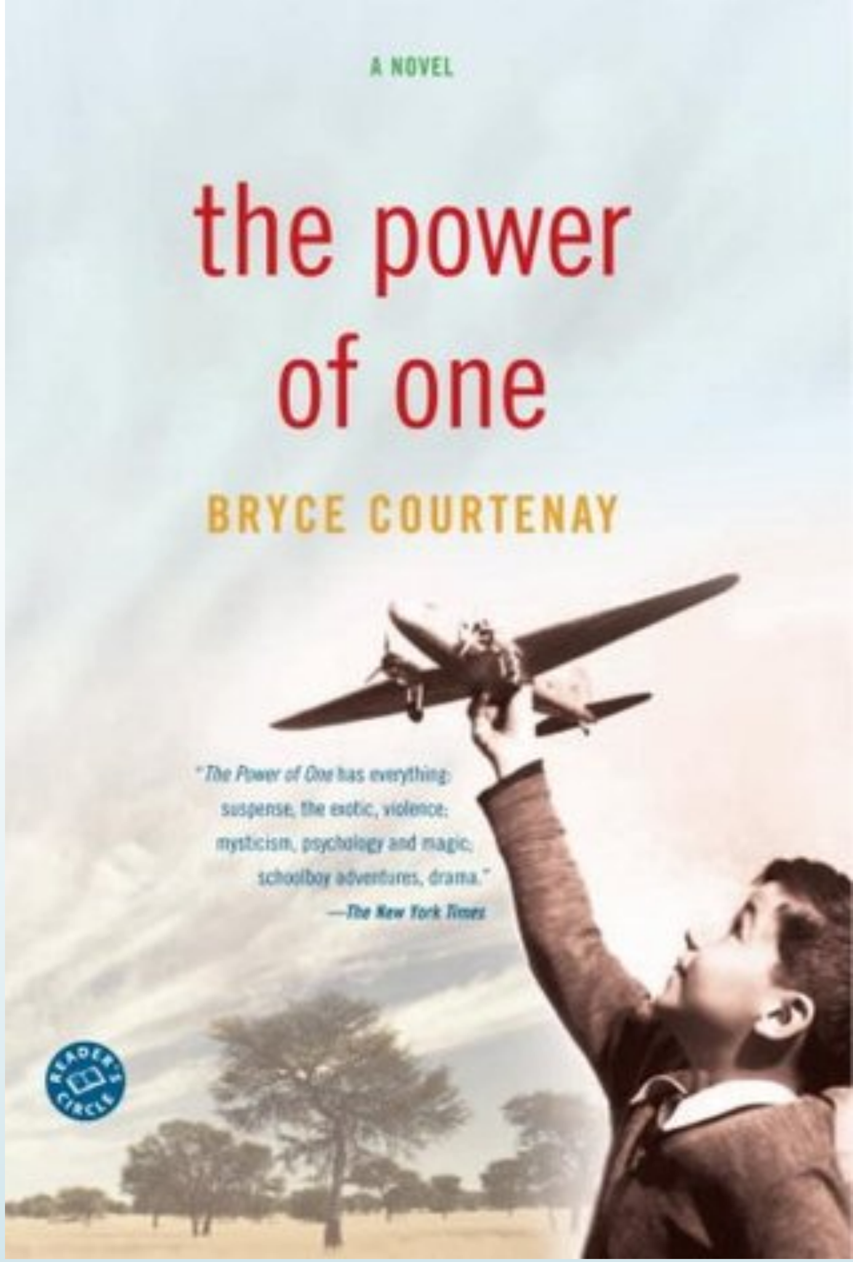


what if? *

- I had a sensor with with single photon sensitivity?



* Credits: https://what-if.xkcd.com
Randall Munroe

The book: ***What If?*** *Serious Scientific Answers to Absurd Hypothetical Questions*

what if?

- I had a sensor retaining at the same time the capability of measuring the intensity, possibly counting the photons in the light pulse illuminating the sensor (at the same time)?

1

2

4

3

Can I have a little more?*

*Credits: All together now, The Beatles, May 1967

what if?

- I had a sensor with Position Sensitivity in 4D [namely telling me where & when the photon(s) hit the detector]?

PSD11

The Position Sensitive Detector Conference
Milton Keynes, UK
September 2017

March 11th, 2017 Issue

I would probably be able to confirm what valuable people think (or presume to know):

[QuantumLeaps - March 2017]

And make them happy*

* It looks like an M&M, isn't it?

Well, maybe not all of them:

But I could anyway do a lot…

Engineering single photon (deterministic!) sources and photon number resolving sensors is actually the name of the game in "quantum" technologies [cryptography, computing, networks]

Eur. Phys. J. D (2012) 66: 249
DOI: 10.1140/epjd/e2012-30351-6

THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

Effect of the heralding detector properties on the conditional generation of single-photon states

V. D'Auria[1], O. Morin[2], C. Fabre[2], and J. Laurat[2,a]

[1] Laboratoire de Physique de la Matière Condensée, CNRS UMR 7336, Université de Nice-Sophia Antipolis, Parc Valrose, 06108 Nice Cedex 2, France
[2] Laboratoire Kastler Brossel, Université Pierre et Marie Curie, École Normale Supérieure, CNRS, Case 74, 4 place Jussieu, 75252 Paris Cedex 05, France

Received 4 June 2012
Published online 4 October 2012 – © EDP Sciences, Società Italiana di Fisica, Springer-Verlag 2012

Abstract. Single-photons play an important role in emerging quantum technologies and information processing. An efficient generation technique consists in preparing such states via a conditional measurement on photon-number correlated beams: the detection of a single-photon on one of the beam can herald the generation of a single-photon state on the other one. Such scheme strongly depends on the heralding detector properties, such as its quantum efficiency, noise or photon-number resolution ability. These parameters affect the preparation rate and the fidelity of the generated state. After reviewing the theoretical description of optical detectors and conditional measurements, and how both are here connected, we evaluate the effects of these properties and compare two kinds of devices, a conventional on/off detector and a two-channel detector with photon-number resolution ability.

The characterization of the statistics of photons emitted by a classical and quantum source is essential. This is requiring sensors with PHOTON NUMBER RESOLVING CAPABILITY.

See also: M. Ramilli, M.C. et al, J. Opt. Soc. Am. B, Vol. 27, No. 5, May 2010

nature COMMUNICATIONS

ARTICLE

Received 28 May 2013 | Accepted 10 Sep 2013 | Published 10 Oct 2013

DOI: 10.1038/ncomms3582 OPEN

Integrated spatial multiplexing of heralded single-photon sources

M.J. Collins[1], C. Xiong[1], I.H. Rey[2], T.D. Vo[1,3], J. He[1], S. Shahnia[1], C. Reardon[4], T.F. Krauss[2,4], M.J. Steel[5], A.S. Clark[1] & B.J. Eggleton[1]

The non-deterministic nature of photon sources is a key limitation for single-photon quantum processors. Spatial multiplexing overcomes this by enhancing the heralded single-photon yield without enhancing the output noise. Here the intrinsic statistical limit of an individual source is surpassed by spatially multiplexing two monolithic silicon-based correlated photon pair sources in the telecommunications band, demonstrating a 62.4% increase in the heralded single-photon output without an increase in unwanted multipair generation. We further demonstrate the scalability of this scheme by multiplexing photons generated in two waveguides pumped via an integrated coupler with a 63.1% increase in the heralded photon rate. This demonstration paves the way for a scalable architecture for multiplexing many photon sources in a compact integrated platform and achieving efficient two-photon interference, required at the core of optical quantum computing and quantum communication protocols.

KUNGL. VETENSKAPS-AKADEMIEN

THE ROYAL SWEDISH ACADEMY OF SCIENCES

8 OCTOBER 2014

Scientific Background on the Nobel Prize in Chemistry 2014

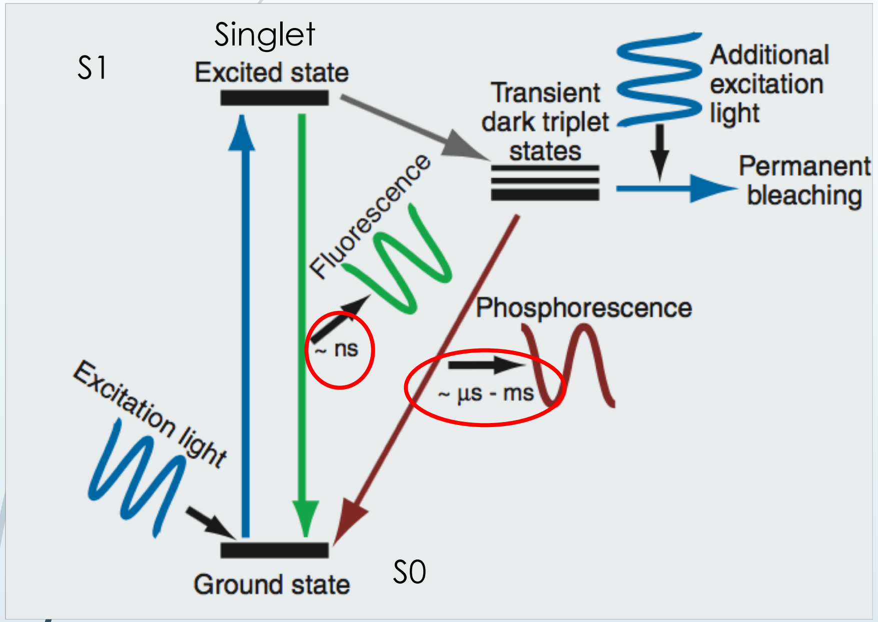
SUPER-RESOLVED FLUORESCENCE MICROSCOPY

Awarded to: Eric Betzig, Stefan W. Hell, William E. Moerner

Heralded by Nature:

Method of the Year 2008

With its tremendous potential for understanding cellular biology now poised to become a reality, super-resolution fluorescence microscopy is our choice for Method of the Year.



States and transitions of a fluorophore

Key issues:

- The lifetime of the emission from the Triplet state is $O(10^6)$ wrt Singlet
- The transition probability to the Triplet state is O(0.1%)

⇒ with a continuous excitation of intensity 1kW/cm^2 the fraction of molecules in S0 << 10%

and for every cycle you will see a subset of molecules *blinking*

- Sub-diffraction limit imaging by stochastic optical recostruction microscopy (STORM)

Rust et al., Nature Methods vol.3 NO.10 | OCTOBER 2006 | **793**

- Fluorescence Nanoscopy by ground state depletion and single molecule return (GDSIM)

Folling et al., Nature Methods vol.5 NO.11 | OCTOBER 2008 | 943

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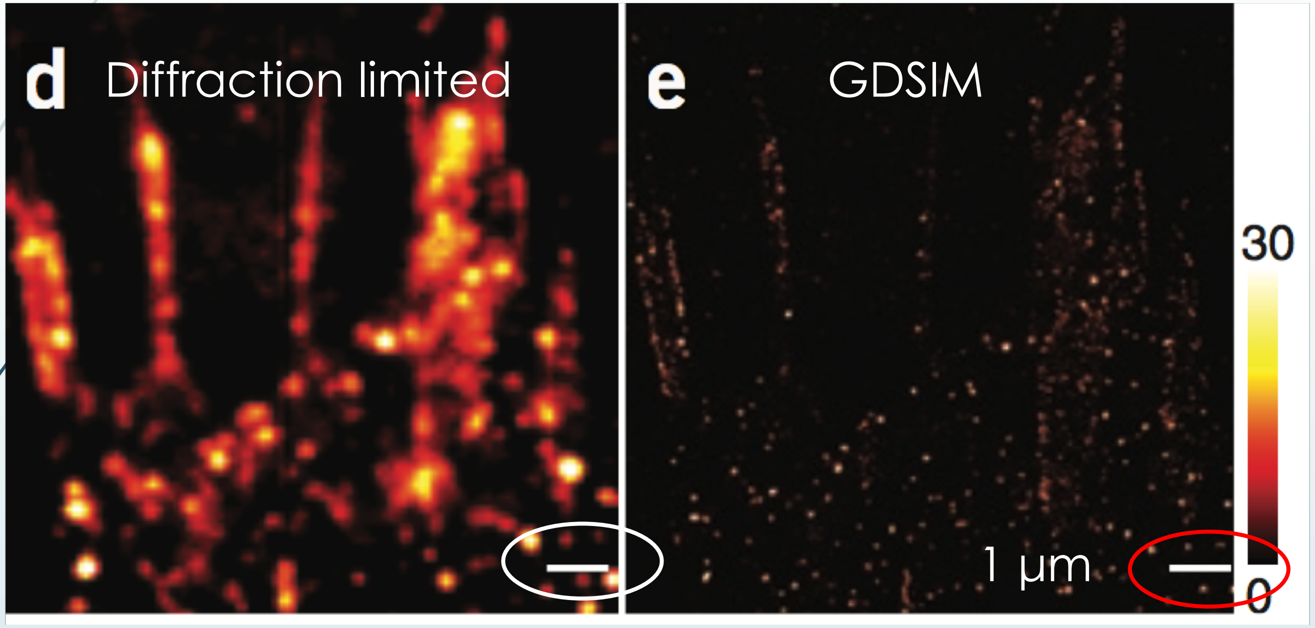

- Camera frame: 200 Hz
- No. frames: 31 000
- Laser intensity: 2.5 kW/cm^2
- Laser wavelength: 532 nm

Immunostained (Atto532) integrin-β-3 clusters of human glioma cells in a cell medium

- Fluorescence Nanoscopy by ground state depletion and single molecule return (GDSIM)

Folling et al., Nature Methods vol.5 NO.11 | OCTOBER 2008 | 943

Heralded by Nature:

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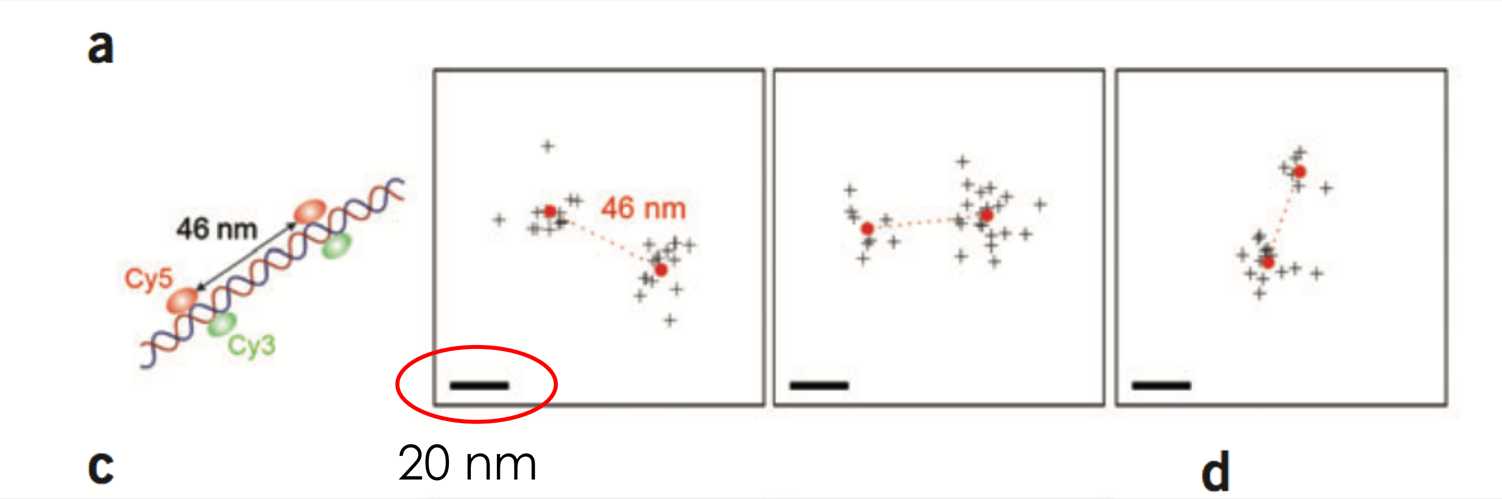


Separation between "switches" attached to a DNA molecule separated by a well known number of base pairs

- Sub-diffraction limit imaging by stochastic optical recostruction microscopy (STORM)

Rust et al., Nature Methods vol.3 NO.10 | OCTOBER 2006 | **793**

Single photon Sensitive device

biotech
- bioluminescence
- Single molecule detection
- imaging

Metrology
- Detector Calibration
- Quantum standards
- Hyper-spectral imaging
- Primary radiometric scales

Quantum info processing
- imaging
- cryptography
- computing
- Single photon sources

Medical Physics
- Imaging
- radioactivity
- Nuclear Medicine

Military
- Night Vision
- Security
- Chem-Bio Threat

Electronics
- Lighting
- Displays
- Entertainement

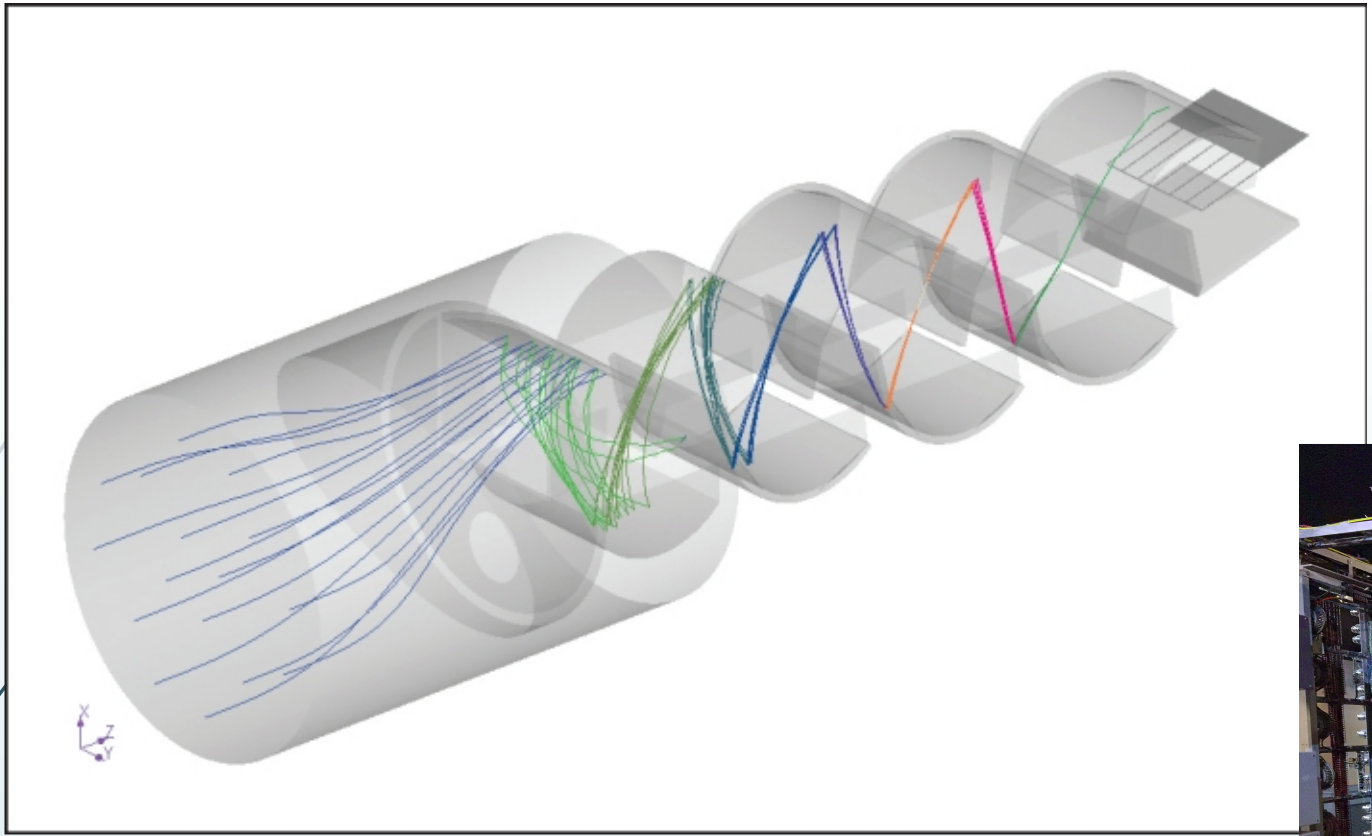
Space
- Ch. Telescope Array
- IR detectors
- Robust imaging devices

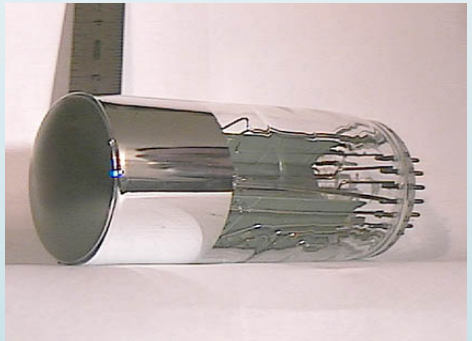
Meteorology
- Remote Sensing
- Lidar
- Environmental monitoring

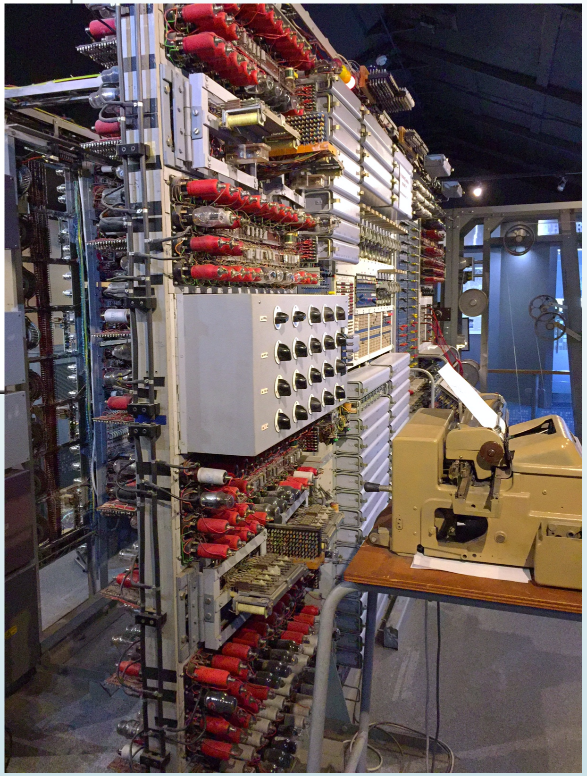
Summary Table from http://www.photoncount.org

The pre-Silicon age:

the photomultiplier, a solid rock technology since 1934





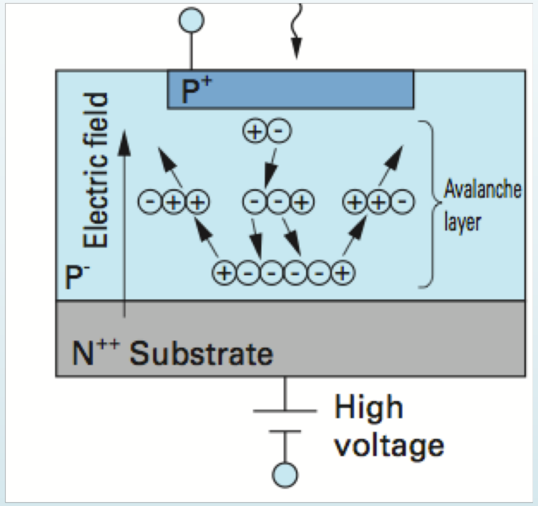


The Colossus (1944), containing on 1700 thermoionic valves

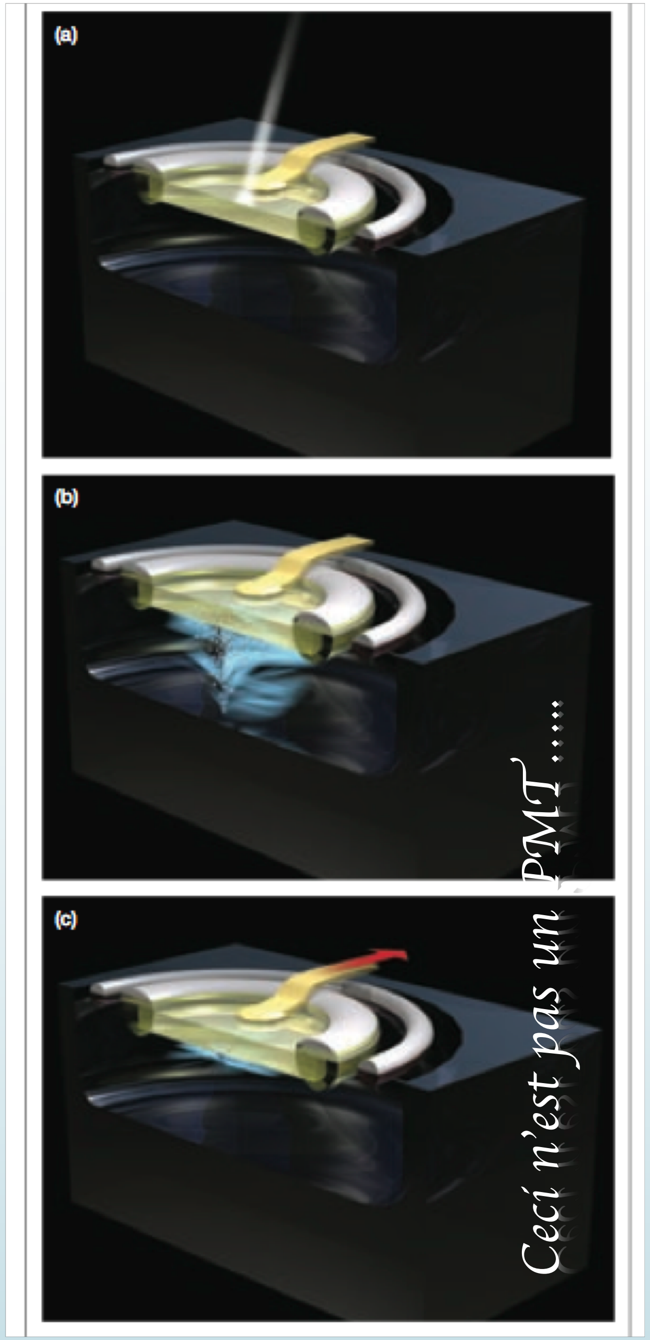
Photon absorption and avalanche ignition in a Single Photon Avalanche Photodiode (SPAD)

A pioneering development by Prof. S. Cova at Politecnico di Milano

Cova, S., Ghioni, M., Lacaita, A. L., Samori, C., and Zappa, F. "Avalanche photodiodes and quenching circuits for single-photon detection", Applied Optics, 35(12), 1956—1976 (1996)



- Very shallow p-n junction
  ➔ ~ 1 µm
- High electric field
  ➔ > 3 x 10^5 V/cm
- Mean free path
  ≈ 0.01 µm

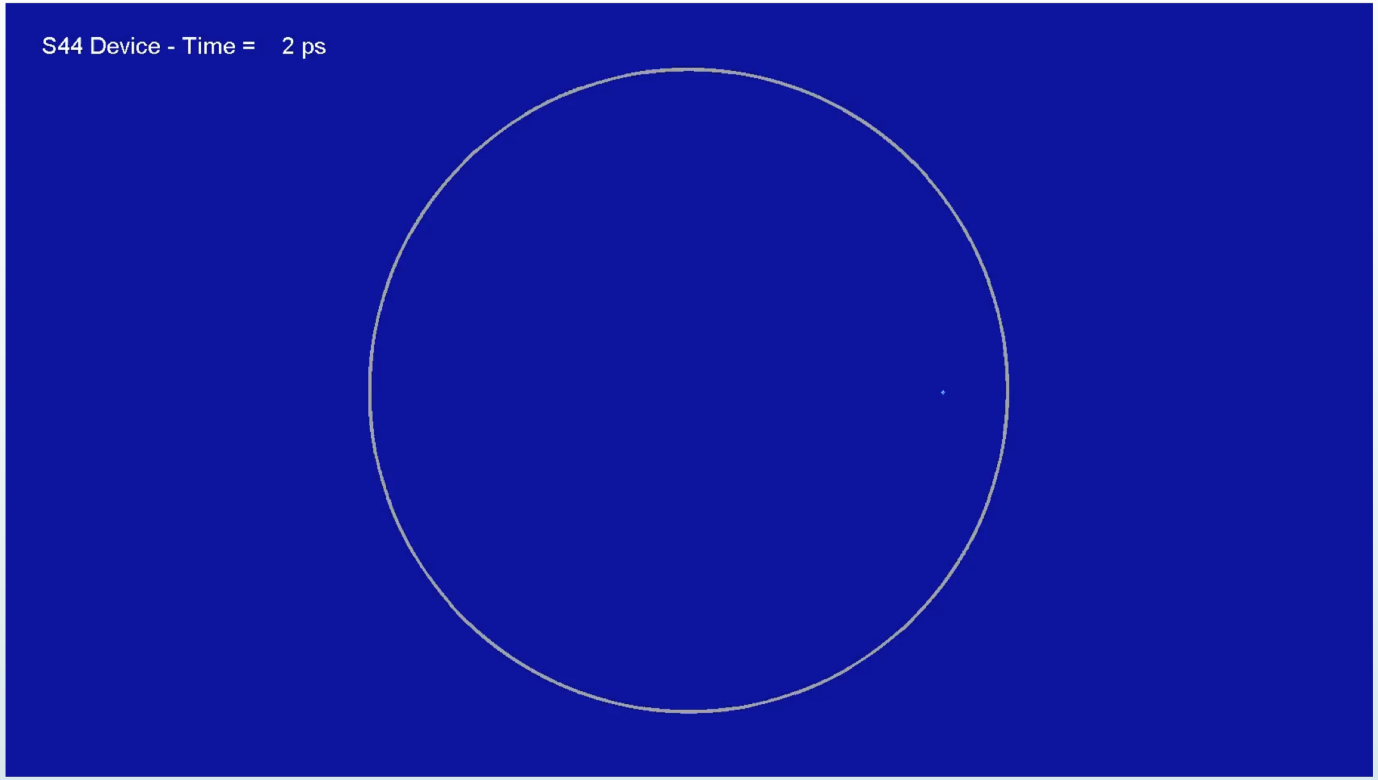


E. Charbon & S. Donati, OPN Optics & Photonics News, February 2010

… and when you get to an array, a matrix of SPAD, you get to the main subject of this talk

A multiplication game in Silico

Courtesy Ivan Rech, Politecnico di Milano

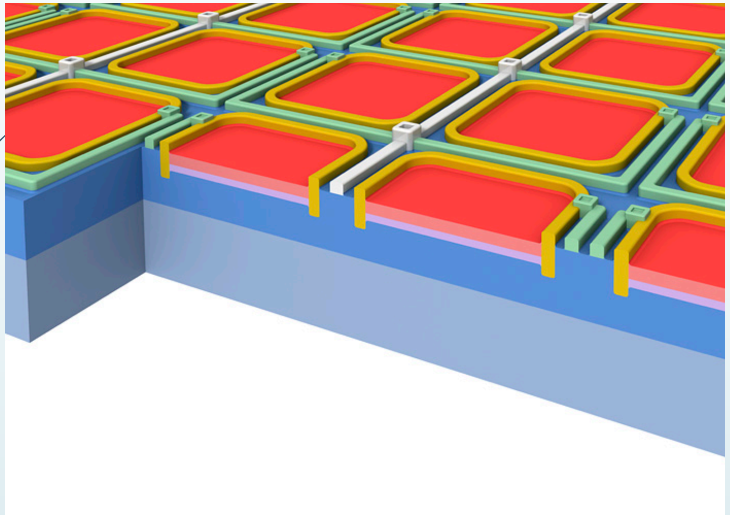


- ❖ Spread of the avalanche essentially diffusion assisted (with minor contributions from photons)
- ❖ Speed 10-20 µm/ns (this cell has a diameter of 50 µm)

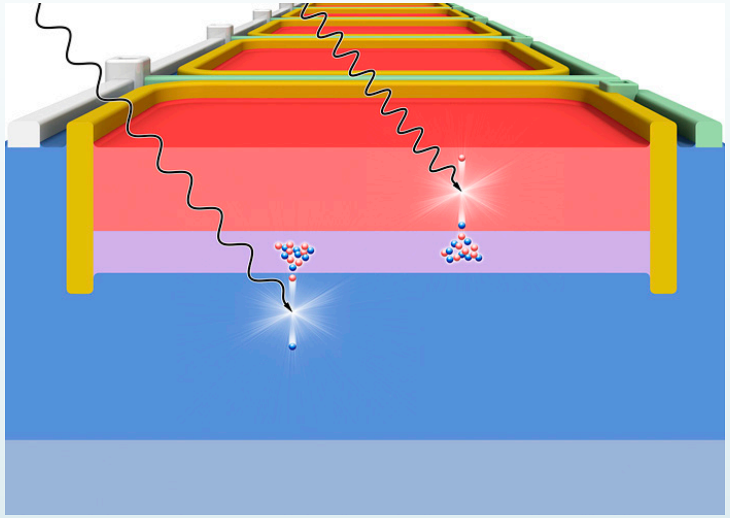
1. A. Gulinatti , I. Rech , M. Assanelli , M. Ghioni & S. Cova (2011) A physically based model for evaluating the photon detection efficiency and the temporal response of SPAD detectors, Journal of Modern Optics, 58:3-4, 210-224, DOI: 10.1080/09500340.2010.536590
2. A. Gulinatti, I. rech et al., Modeling photon detection efficiency and temporal response of single photon avalanche diodes , Proc. of SPIE Vol. 7355 73550X-1
3. Spinelli, A. and Lacaita, A. L. "Physics and numerical simulation of single photon avalanche diodes", IEEE Transactions on Electron Devices, 44(11), 1931—1943 (1997).

Silicon PhotoMultipliers(a.k.a. as MPPC, for MultiPixel Photon Counters): in essence, an array of SPADs

Principle



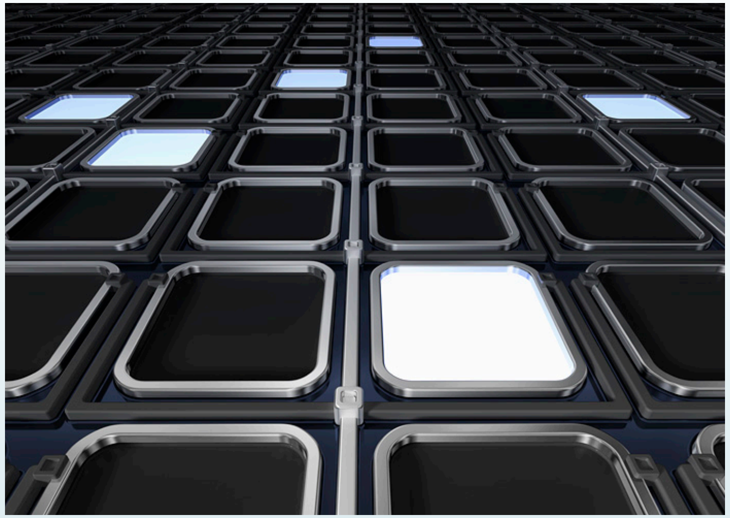
SiPM = High density (~10^4/mm^2) matrix of diodes with a common output, reverse biased, working in Geiger-Müller regime

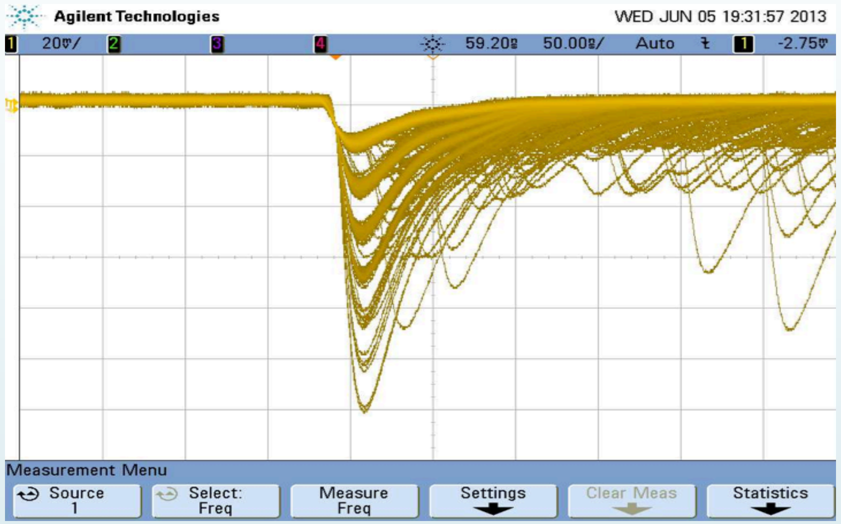


When a photon hits a cell, the generated charge carrier triggers an avalanche multiplication in the junction by impact ionization, with gain at the 10^6 level

Silicon Photomultipliers: genuine digital Photon Number Resolving detectors

Operation





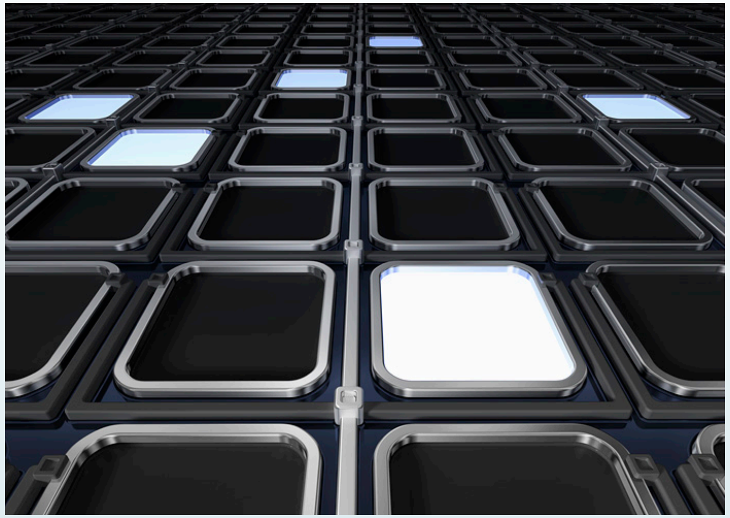
- SiPM may be seen as a collection of binary cells, fired when a photon in absorbed

[in principle, a NATIVE DIGITAL DEVICE]

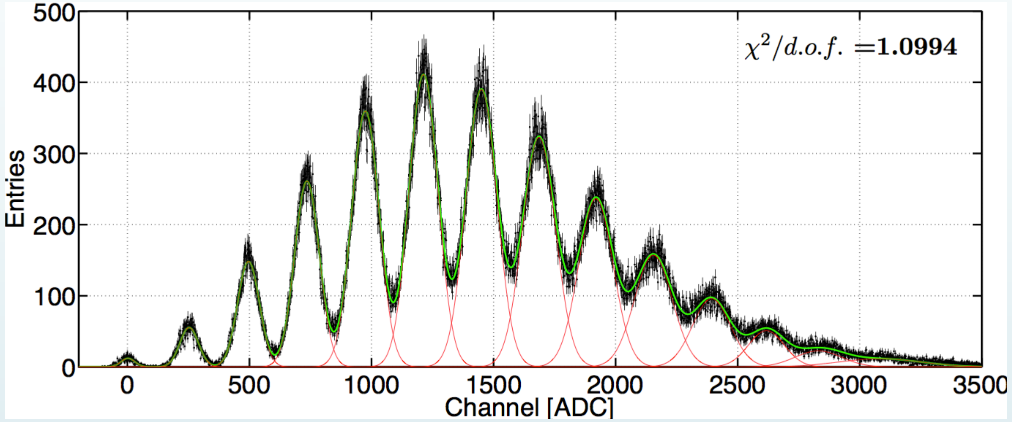
- "counting" cells provides an information about the intensity of the incoming light:

Silicon Photomultipliers: genuine digital Photon Number Resolving detectors

Operation



➢ SiPM may be seen as a collection of binary cells, fired when a photon in absorbed



➢ "counting" cells provides an information about the intensity of the incoming light:

There's a lot of  behind the SiPM concept and technology

With reference to the paper:
A. Gasanov, V. Golovin, Z. Sadigov, N. Yusipov, Avalanche photodetector on base metal-resistor-semiconductor structure, Microelectronics, 1989

ELSEVIER
Nuclear Instruments and Methods in Physics Research A 442 (2000) 223–229
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.nl/locate/nima

Silicon avalanche photodiodes on the base of metal-resistor-semiconductor (MRS) structures

V. Saveliev[a],*, V. Golovin[b]

[a]*Moscow Engineering and Physics Institute, Kashirskoe Shosse 31, 115409 Moscow, Russia*
[b]*Center of Perspective Technology and Apparatus, Moscow, Russia*

ELSEVIER
Nuclear Physics B (Proc. Suppl.) 61B (1998) 347–352
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

Limited Geiger-mode silicon photodiode with very high gain

G.Bondarenko[a], B.Dolgoshein[a], V.Golovin[b], A.Ilyin[a], R.Klanner[c], E.Popova[a]

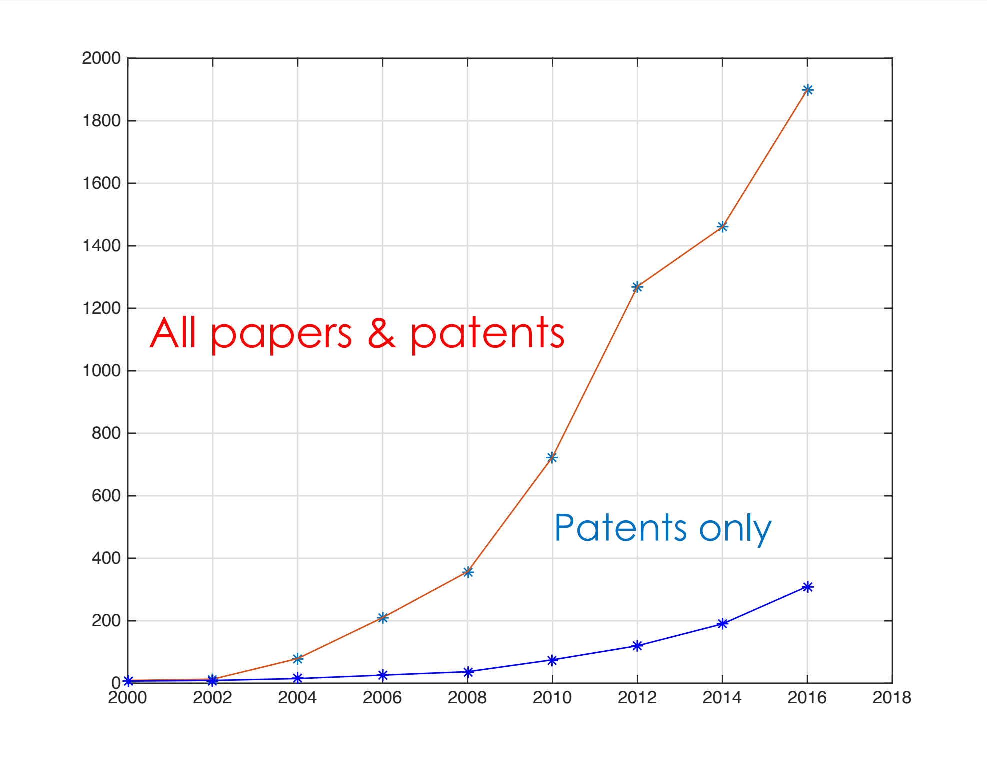
[a]Moscow Engineering and Physics Institute (MEPHI), Russia
[b]Centre of Perspective Technology and Apparatus (CPTA), Moscow, Russia
[c]DESY, Hamburg, Germany

The novel type of the Silicon Photodiode – Limited Geiger-mode Photodiode (LGP) has been produced and studied. The device consists of many $\approx 10^4$ mm^{-2} independent cells $\approx$10 mkm size around n^+ -"pins" located between p-substrate and thin SiC layer. Very high gain more than 10^4 for 0.67 mkm wave length light source and up to $6{\cdot}10^5$ for single electron have been achieved. The LGP photon detection efficiency at the level of one percent has been measured.

With a series of early patents also assigned to Russian inventors

Is the world interested in these little toys?

No. of papers in Google Scholar with the exact match of “silicon photomultipliers” in the title/abstract/body

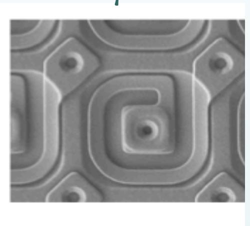
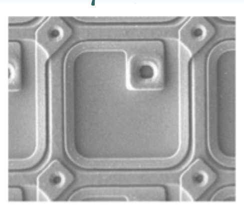


Year	# papers	Excluding patents
2000-2001	9	2
2002-2003	13	4
2004-2005	79	64
2006-2007	210	184
2008-2009	357	320
2010-2011	724	649
2012-2103	1270	1150
2014-2015	1460	1270
2016-2017	1900	1590

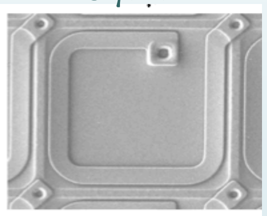
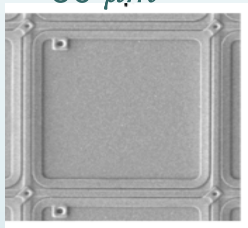
What is being offered on the “Menù à la carte?”

➢ In terms of pixel pitch:

10 μm | 15 μm

25 μm | 50 μm

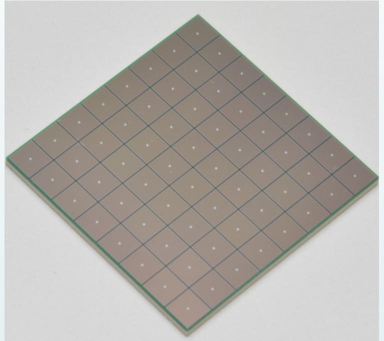



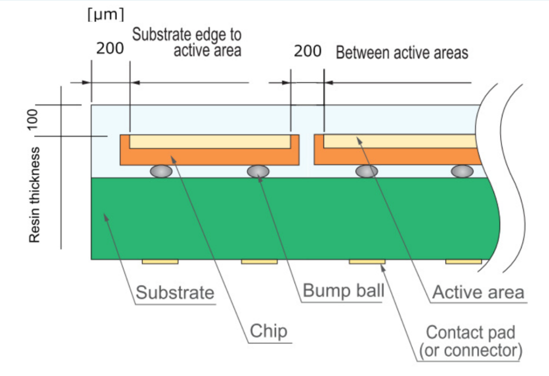
75 & 100 μm *are available as well*

Not to mention the variety of available options for the front-end, the **packaging** and the near future integration with the read-out electronics

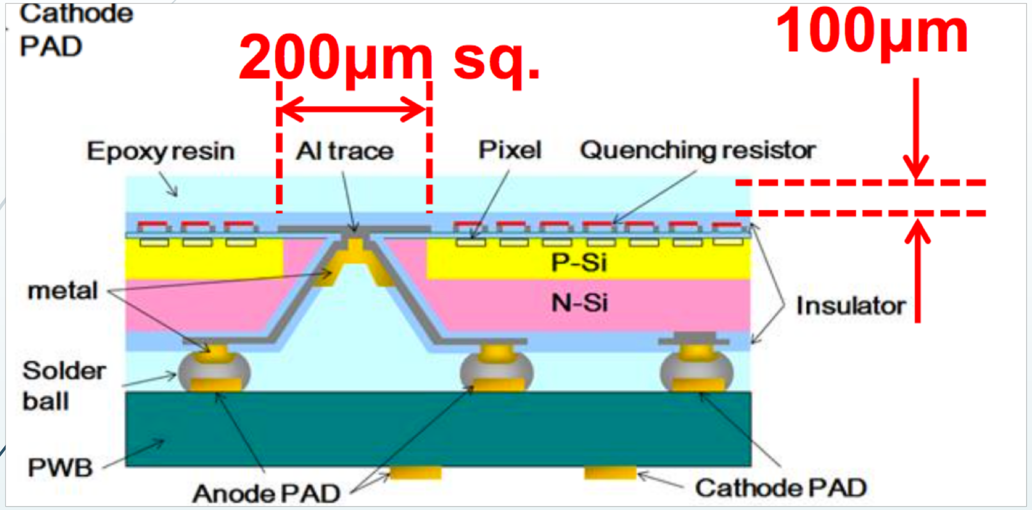
➢ In terms of sensor area:

- 1x1 mm^2
- 3x3 mm^2
- 6x6 mm^2
-
- 1x4 mm^2
- 12x12 mm^2
- 24x24 mm^2



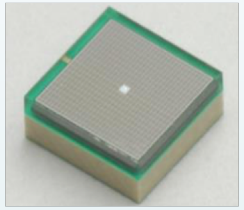


Talking about packaging, it is worth focusing on the "little white dot" in the middle of the array:

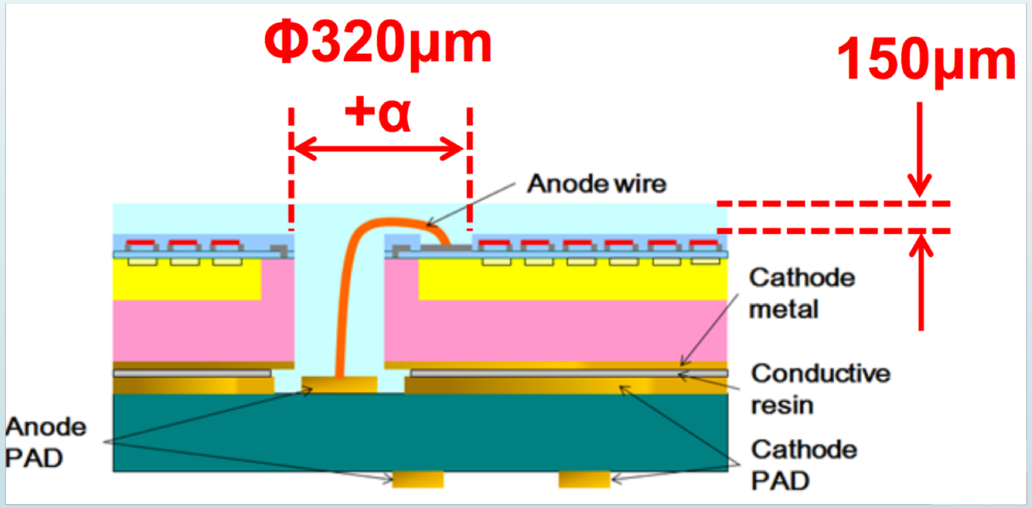


Through-Silicon Vias

- Makoto Motoyoshi, Proceedings of the IEEE, **DOI:** 10.1109/JPROC.2008.2007462, 2009
- Gambino et al., Microelectronic Engineering 135 (2015) 73–106



S13360 series



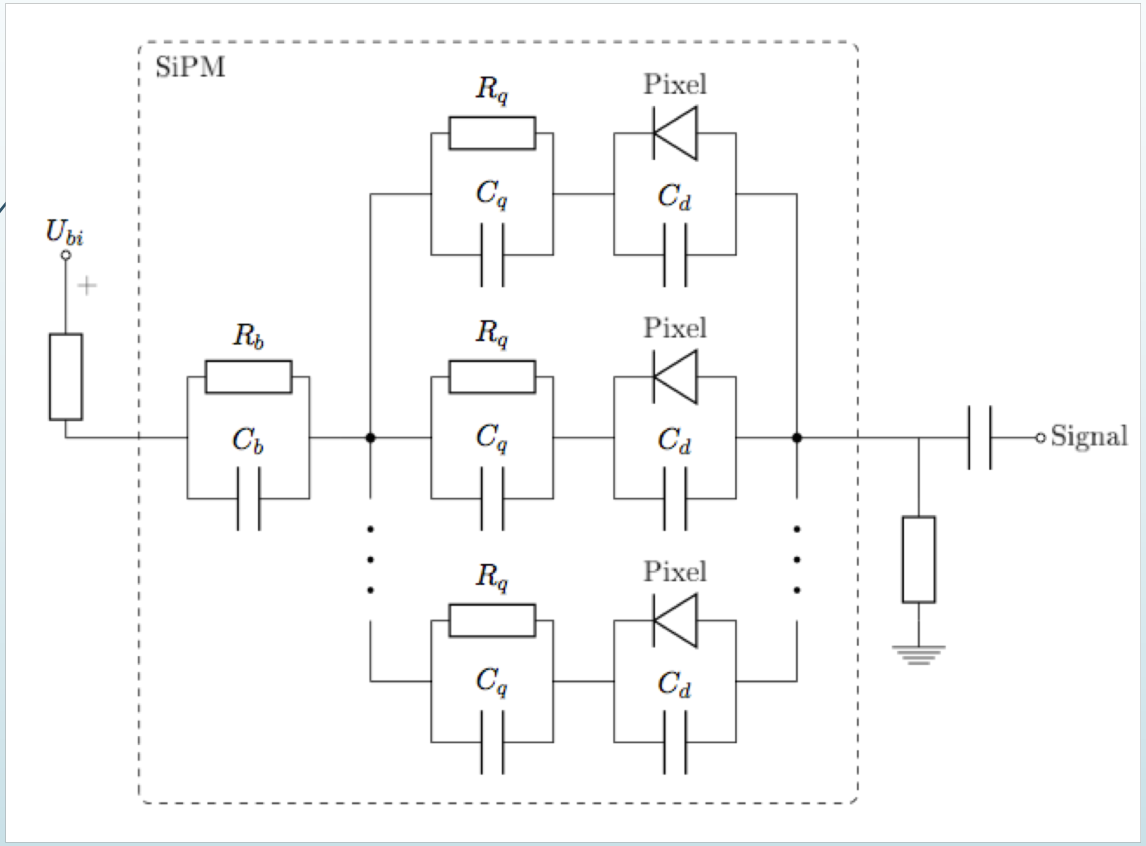
Hole-Wire bonding (patent pending)

S1416X series (X = 0,1)

LOWER COST, comparable specs

SiPM: electrical model(s)

1. Roland Heitz, Journal of Applied Physics **35**, 1370 (1964)
2. C. Piemonte, NIM A 568 (2006) 224–232
3. S. Seifert et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 4, 2010
4. P. Hallen, bachelor thesis, Aachen University, 2011
5. F.Licciulli, C.Marzocca, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 5, 2016
6. D. Marano eta al., Improved SPICE electrical model of SiPM, NIM A726, 1-7, 2013
7. F. Villa et al., Spice electrical models and simualtions of Silicon Photomultipliers, IEEE-TNS October 2015



- exponential pulse with

$$\tau = R_q C_D$$

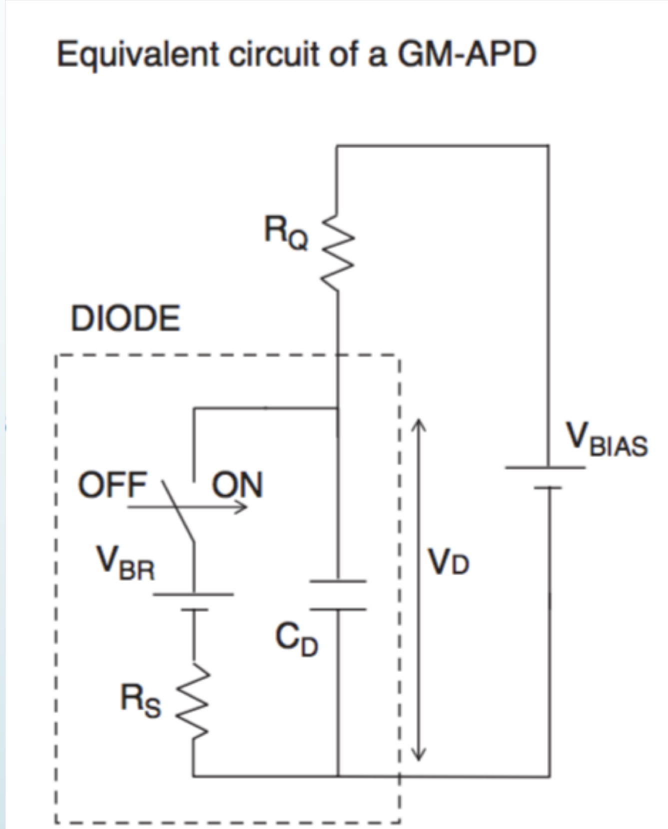
- Gain:

$$G = \frac{(V_{bias} - V_{Breakdown})C_D}{e}$$

Typical values:

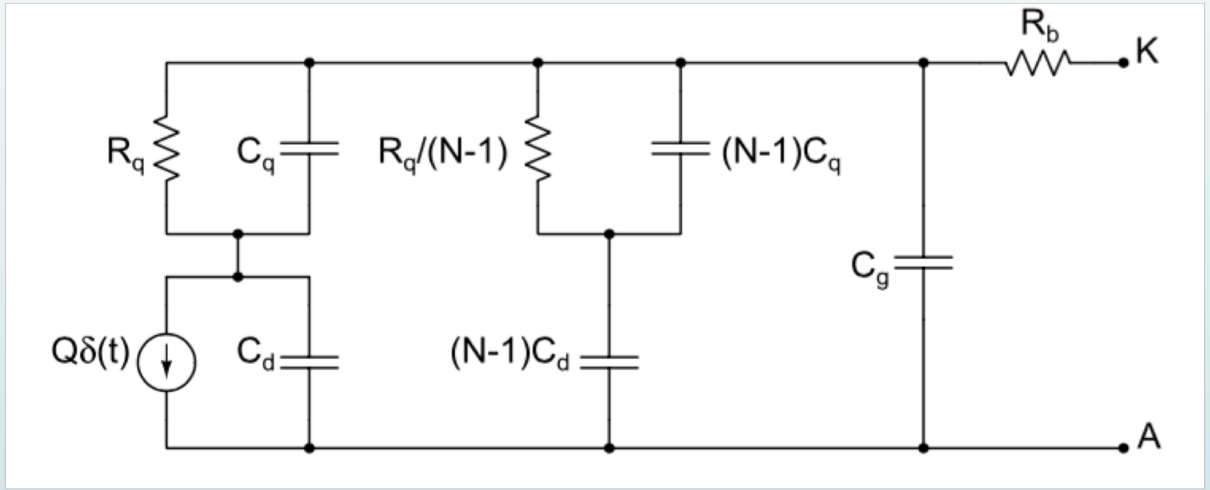
- R_q ~ 200 kΩ
- C_D ~ 100 fF (30x30 μm^2)
- τ ~ 20 ns
- $V_{breakdown}$ ~ 50-70V
- G ~ 10^6

SiPM electrical model: a closer look



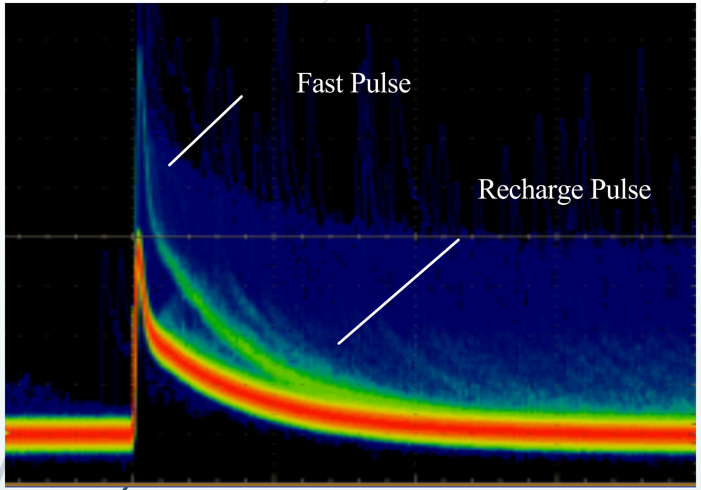
For a single cell (ref. 2, 2006)

- C_D = cell capacitance
- R_Q = quenching resistor
- C_q = stray capacitance of the quenching resistor
- R_S = space charge resistance + neutral regions (≈ 1 kΩ
- R_b = substrate ohmic resistance
- C_g = stray capacitance of the cell grid to the substrate



For the full array (ref. 5, 2016), one cell "triggering"
(fast response made easy as a "Dirac delta" of current)

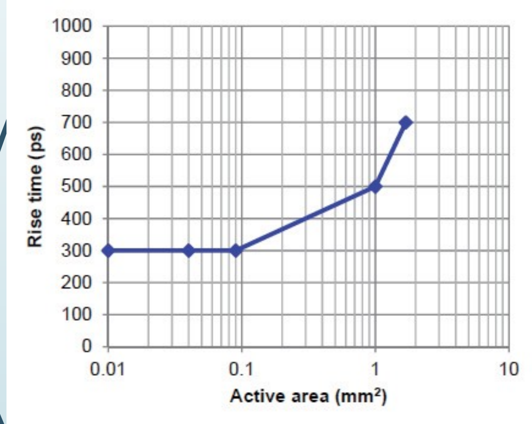
SiPM electrical model: time development of the signal & parameters



Ref.5

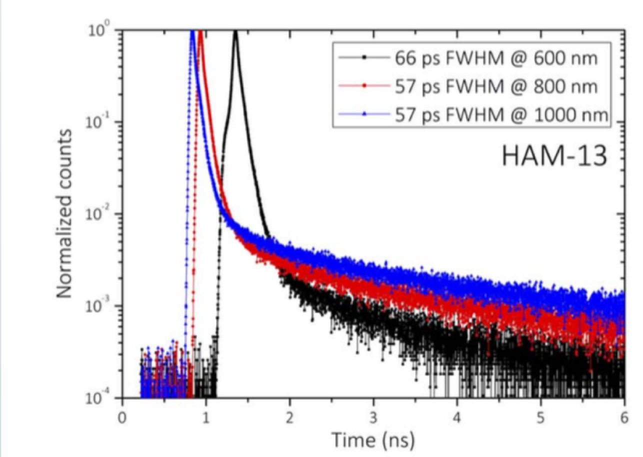
SiPM Hamamatsu S10931-050P $N = 3600$	
V_{BD}	$70.47\ V$
R_q	$71.2\ k\Omega$
R_b	$22.9\ \Omega$
C_d	$74\ fF$
C_q	$30\ fF$
C_g	$40.8\ pF$

- Fast Pulse:
  $\tau_{FP} = R_S \times (C_D + C_Q) \approx$
- Recharge Pulse:
  $\tau_{RP} = R_Q \times (C_D + C_Q) \approx$



Courtesy of HAMAMATSU Photonics

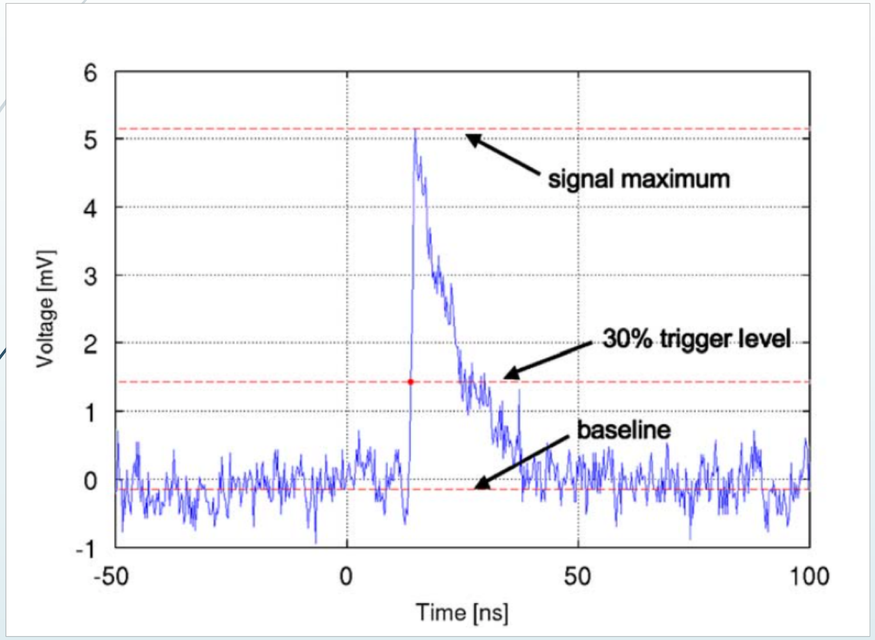
This is leading to an astonishing result: a Single Photon Timing resolution at the 60 ps level



	Hamamatsu 1.3 mm x 1.3 mm [S13081-050CS]
Name in this work	HAM-13
Total active area	1.69 mm^2
Fill factor	61%
Number of microcells	667
Peak PDE	35%
DCR	50 kcps
Breakdown voltage	53 V
Structure	p-on-n
Terminal capacitance	60 pF

E. Martinenghi et al., IEEE Photonics Journal, 7, 4, 2015, DOI: 10.1109/JPHOT.2015.2456070

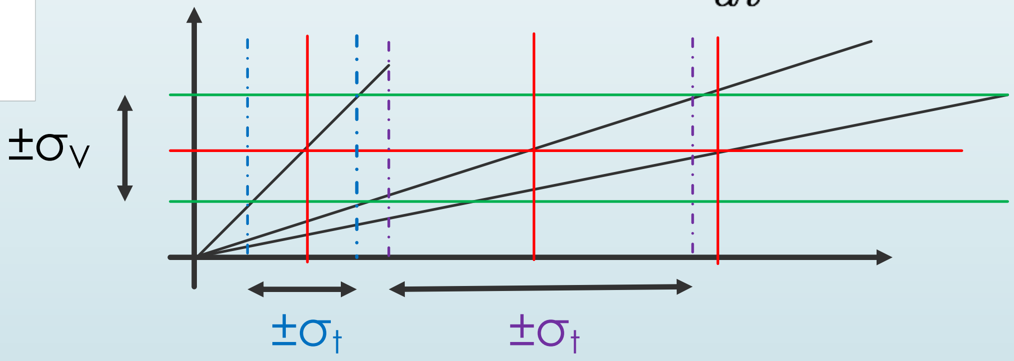
More about timing: impact of the shape of the signal and the number of photons (presuming they all come at once! It does not apply to timing with scintillation light) on time resolution



- The rise time of the signal obviously has an impact! Presuming a local linear dependence of the output voltage with time, you have:

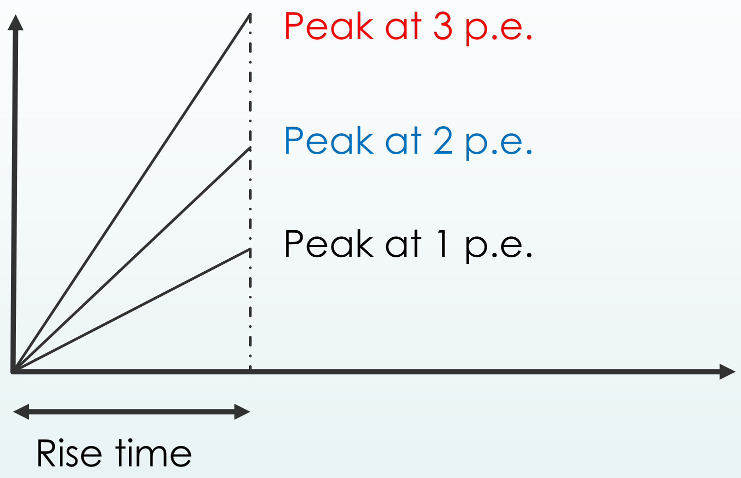
$$V = m \times t = \frac{dV}{dt} \times t$$

$$\Longrightarrow \sigma_t = \frac{\sigma_V}{\frac{dV}{dt}}$$



* R. Vinke et al, Optimizing the timing resolution of SiPM sensors for use in TOF-PET detectors, Nuclear Instruments and Methods in Physics Research A 610 (2009) 188–191

❖ Presuming the rise time is defined by the sensor characteristics & front-end electronics and it is independent from the signal amplitude, it is clear that the LARGER the signal, the higher the slope:



The slope for N photo.electrons is

$$N \times \frac{dV}{dt}\Big|_{N=1}$$

$$\Longrightarrow \sigma_N = \frac{\sigma_{1,slope}}{N}$$

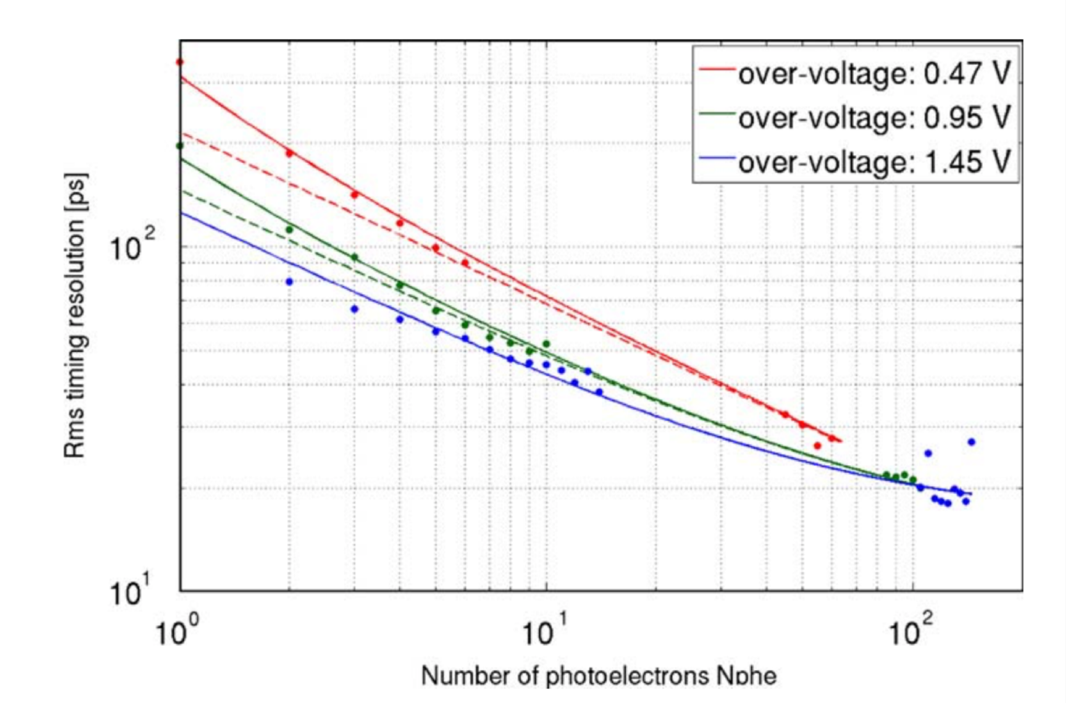
❖ Assuming to have N photo-electrons, the intrinsic fluctuation of the arrival time can be referred to the "mean photon". And the spread of the mean of a series of N random variables is smaller than the spread of a single one by √N, namely:

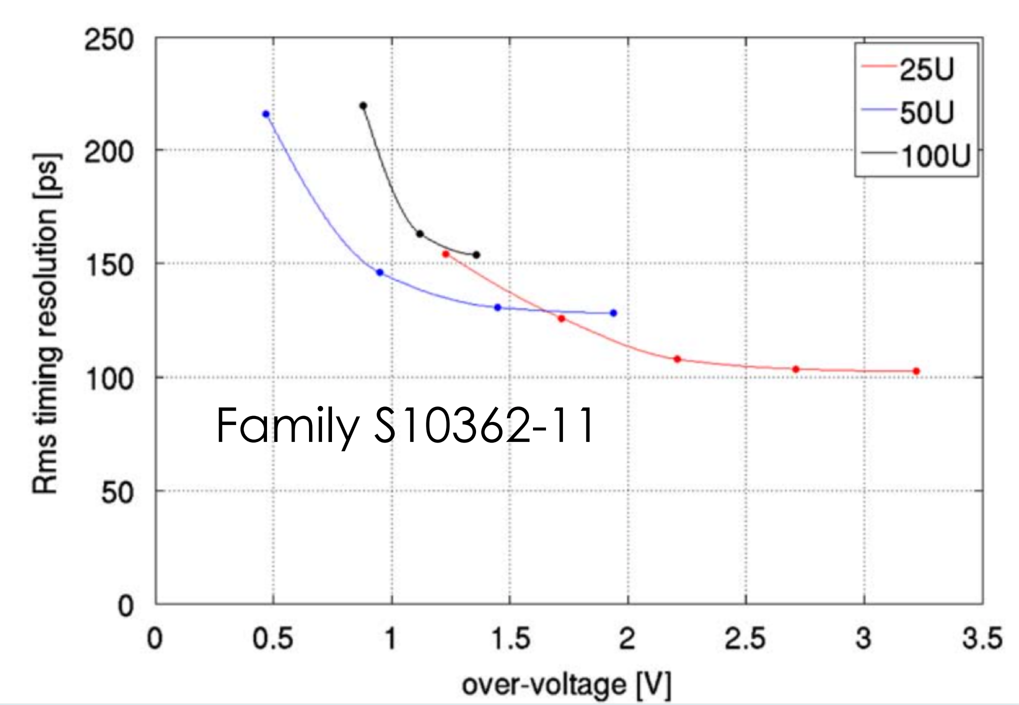
$$\Longrightarrow \sigma_{N,arrival} = \frac{\sigma_{1,arrival}}{\sqrt{N}}$$

[a bit like saying that I time stamp every photon and I take the average..]

Summing (in quadrature) the different contributions, I have:

$$\sigma_{t,N}^2 = \sigma_0^2 + \frac{\sigma^2{}_{1,slope}}{N^2} + \frac{\sigma_{1,arrival}^2}{N}$$





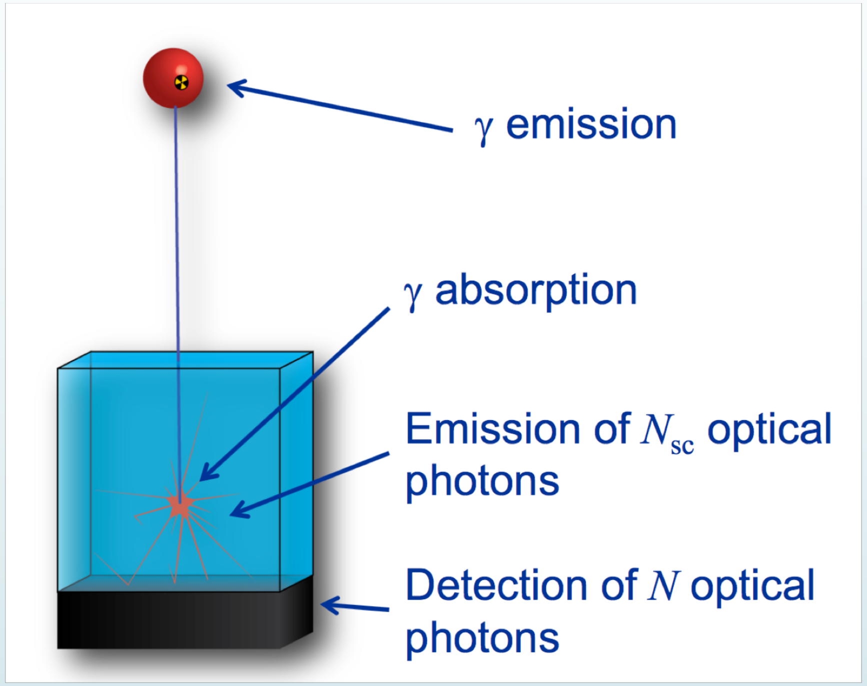
Resolution vs. number of p.e.
(AfterVinke et al.)

Intrinsic resolution for N=1
(After Vinke et al.)

Timing is actually a very serious topics and many bright minds devoted their time to it

A number of stochastics effects enter the game:

- ❖ The number of photons/event (particle interaction or light source pulse)
- ❖ The time distribution of the photons
- ❖ The optical photon dispersion in the crystal
- ❖ The spatial distribution of the photons on the sensor surface
- ❖ The time response of the sensor
- ❖ The shape of the signal
- ❖ The layout of the sensor
- ❖ The Time Stamping machine
- ❖ The “system noise”
- ❖ The algorithm (possibly not stochastics)

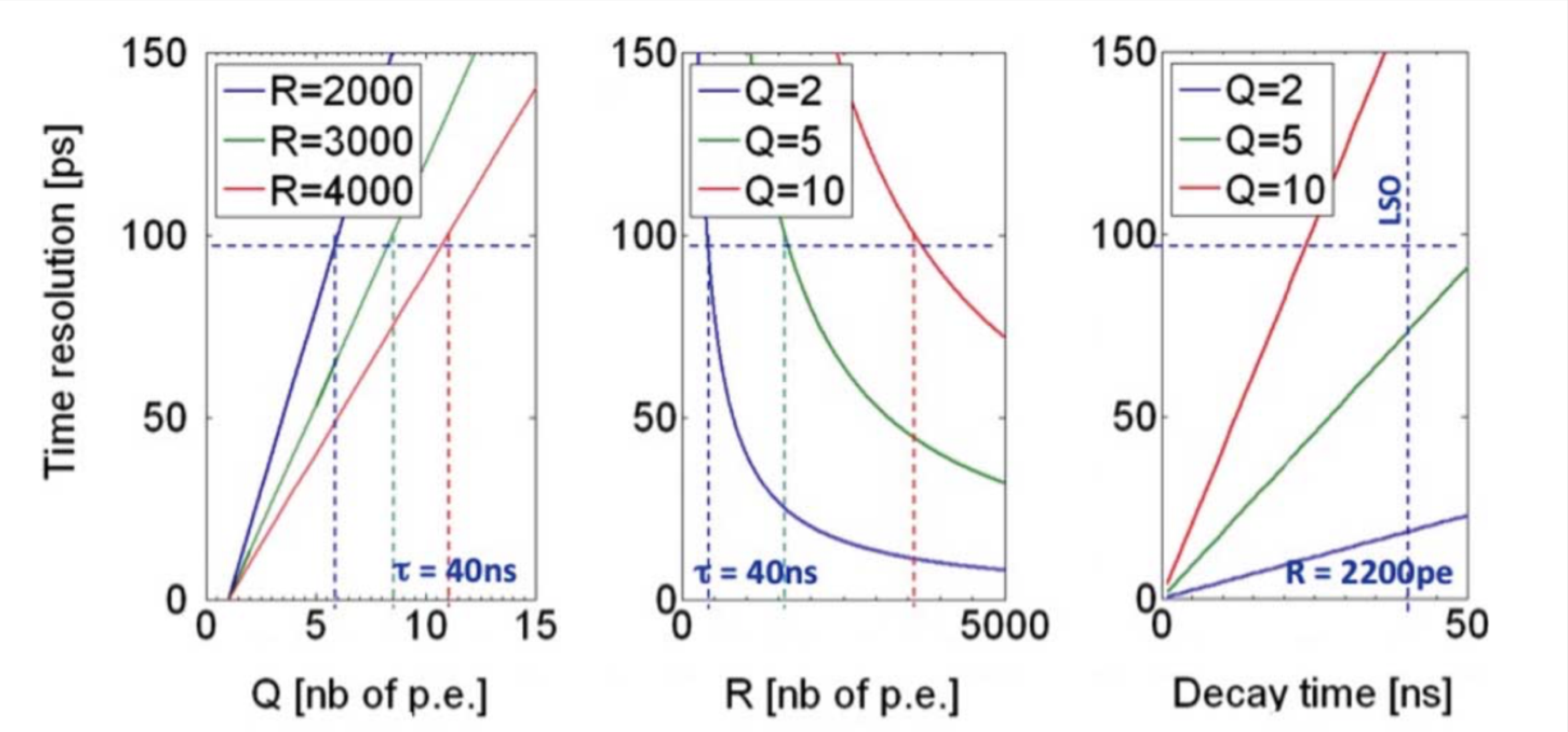


[credits for the drawing: Dennis Schaart, TU Delft]

It looks like the ideal situation for a Monte Carlo simulation but actually someone was so brave to tackle the problem analytically:

1. F. Acerbi et al. Characterization of Single-Photon Time Resolution: From Single SPAD to Silicon Photomultiplier, IEEE TNS – for technology/layout issues
2. R.F. Post & L.I. Schiff, Statistical limitations on the resolving time of a Scintillator counter, Physical Review, vol. 80, Issue 6, pp. 1113-1113 – a seminal paper (with unresolved doubts on my side)
3. S. Seifert, HT. Van Dam, D. Schaart, The lower bound on the timing resolution of scintillation detectors, Phys. Med. Biol. 57 (2012) 1797–1814 – an excellent paper! Formally correct, clear and useful
4. Leo H. C. Braga et al., A Time of Arrival Estimator Based on Multiple Timestamps for Digital PET Detectors, IEEE Nuclear Science Symposiun and Medical Imaging Conference Record (NSS/MIC), 2012 – nice, even if the initial hp. could be discussed
5. S. Mandai et al., Timing optimization utilizing order statistics and multichannel digital silicon photomultipliers, OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014 - it shows the benefit of using multi-tagged photons
6. P. Lecoq et al., Factors Influencing Time Resolution of Scintillators and Ways to Improve Them Nuclear Science Symposium Conference Record (NSS/MIC), 2009 IEEE, DOI: 10.1109/NSSMIC.2009.5402178 – it nicely addresses also the question of the light transport in crystals
7. Stephen Derenzo et al., Fundamental limits of scintillation detector timing precision, Phys. Med. Biol. 59 (2014) 3261–3286 – A Monte Carlo simulation ending up with a heuristic (horrible) formula
8. S. Vinogradov, Analytical model of SiPM time resolution and order statistics with crosstalk, Nucl. Instr. Methods A (2015), pp. 229-233 [http://dx.doi.org/10.1016/j.nima.2014.12.010]. A very good paper!

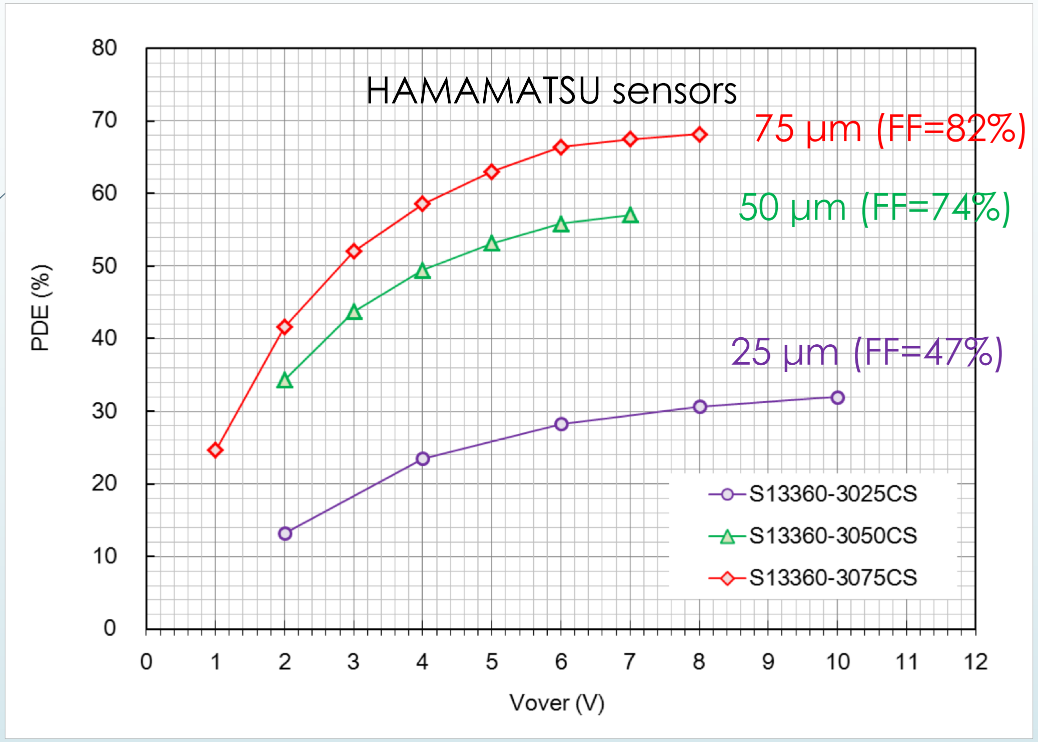
Three nice plots from ref. 6:



- R is the total light output
- Q is the threshold I set in photoelectrons ⇒ the LOWEST, the BEST

Photon Detection Efficiency: PDE = n $_{p.e.}$/$n_{photons}$

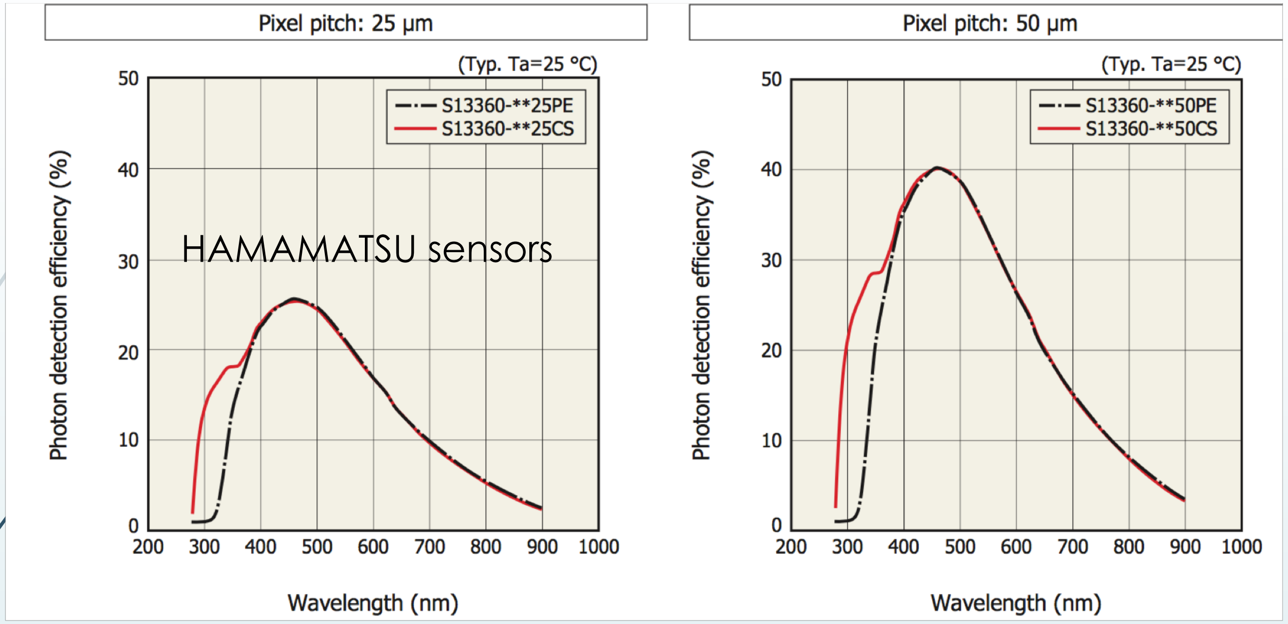
$$n_{p.e.} = n_{photons} \times [QE][FillFactor][P_{GM}]$$



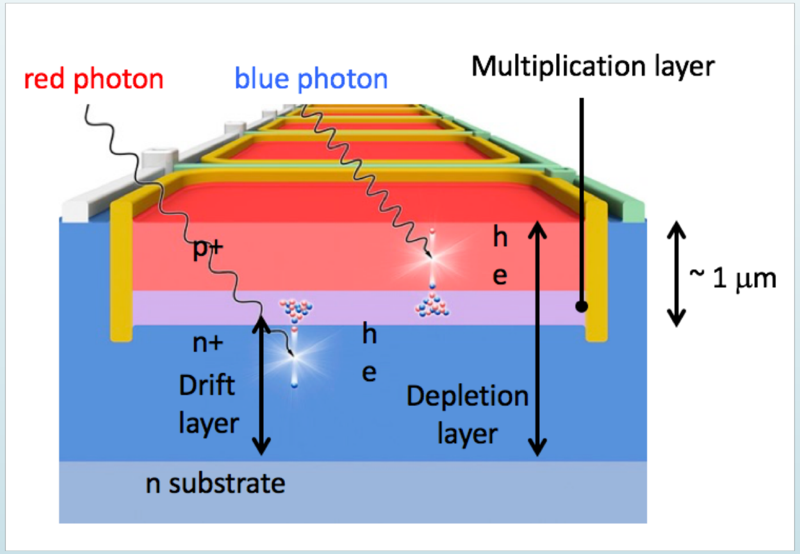
- QE = Quantum Efficiency (material properties)
- Fill Factor (FF) = fraction of sensitive area within the cell (technology)
- P_{GM} = triggering probability (physics, design and technology)

The variation of the ionization coefficients vs. over-voltage is the reason for the trend of the Photon Detection Efficiency (PDE)

Spectral response:



The variation vs wavelength results by the absorption properties of Silicon and the junction technology



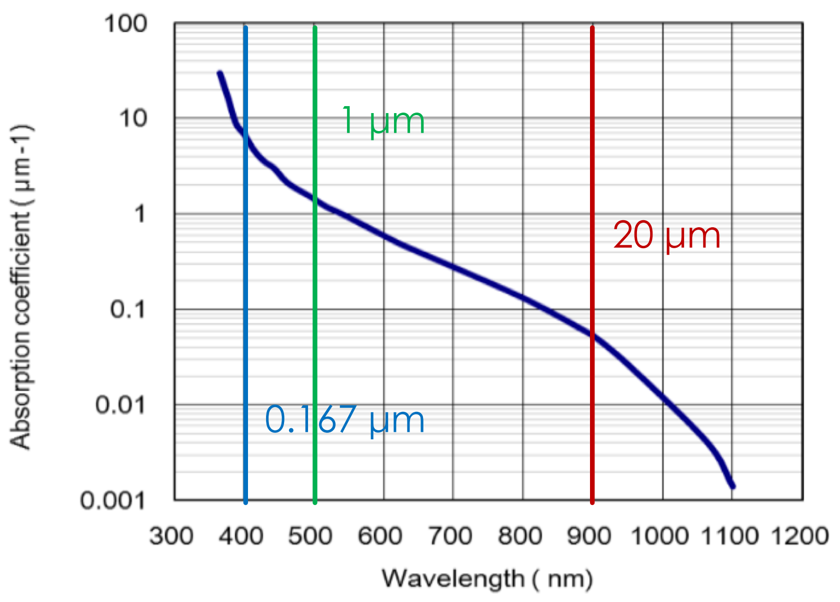
SiPM technology: what's behind the spectral response

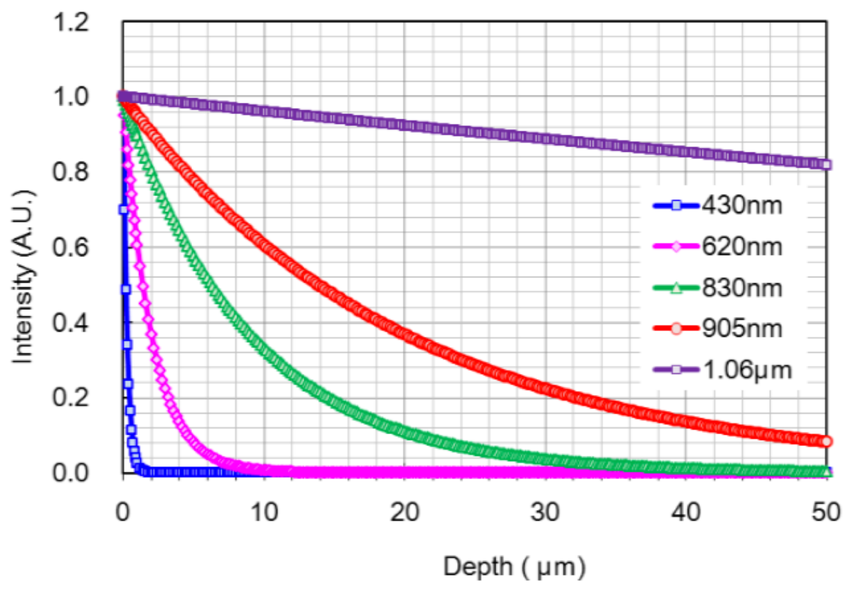
1. Claudio Piemonte, Nuclear Instruments and Methods in Physics Research A 568 (2006) 224–232
2. Nagano et al., Development of new MPPC with higher NIR sensitivity and wider dynamic range, Internal note 2017
3. Oldham et al, IEEE 'TRANSACTIONS ON ELECTRON DEVICES, **VOL.**ED-19, NO. 9,SEPTEMBER 1972
4. McKay, Physical Review 94 (4) 877-884 (1954)

Light intensity in a medium drops exponentially: $$I(x) = I_0 \times e^{-\mu x}$$

1/e reduction (0.37) in:

(ref.2)





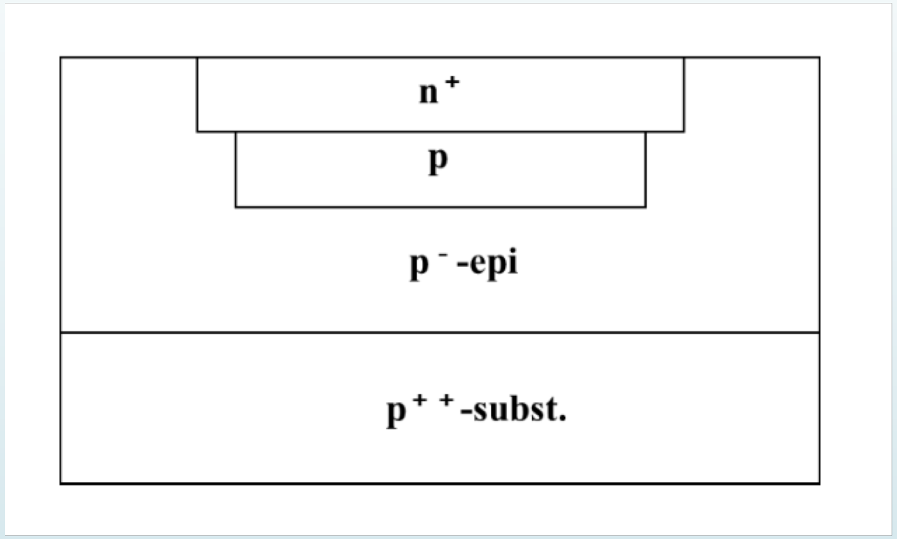
Absorption coefficient (µ) in [µm^{-1}] vs λ [nm]

Light attenuation vs depth [µm]

I have to tailor my junction to maximize the probability to trigger an avalanche:

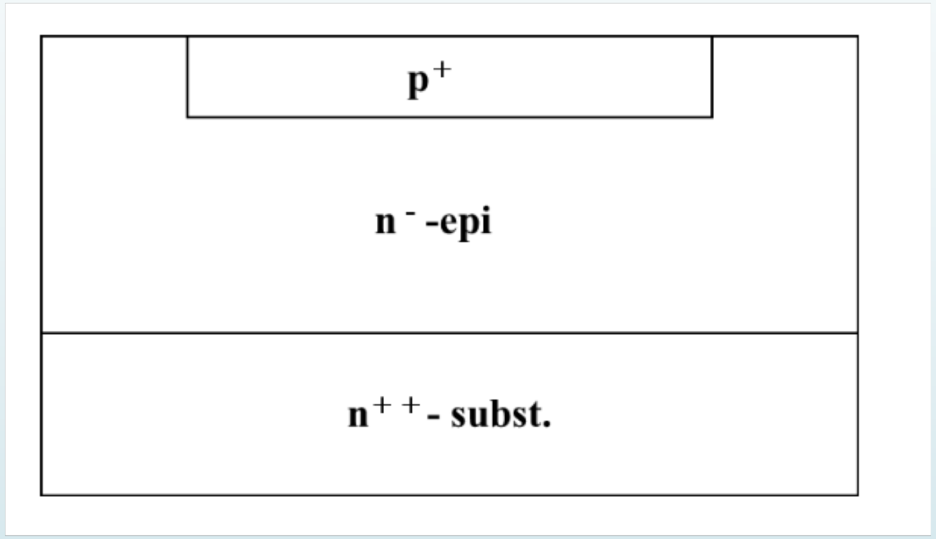
n-on-p junction:

- ❖ Not ideal for blue
- ❖ Good enough for green
- ❖ Bad for red



p-on- junction:

- ❖ Optimized for blue
- ❖ Fair enough for green
- ❖ Worse for red

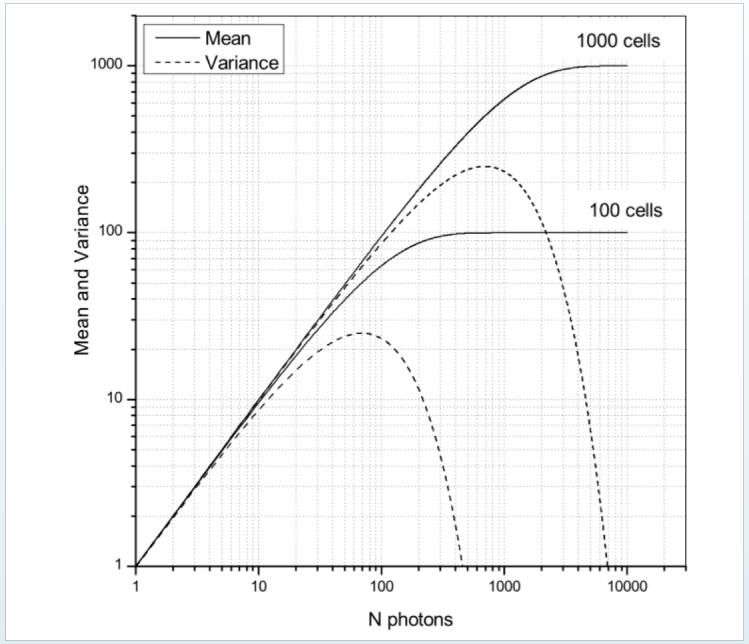


Stochastics effects affecting the sensor response
[actually introducing non-linarities]:

❖ Saturation [⬇]:

$$N_{fired} = N_{cells} \times \left[1 - e^{\frac{-N_{photons} \times PDE}{N_{cells}}}\right]$$

K.E. Kuper et al. 2017 *JINST* **12** P01001



How do I get to this magic formula? In essence, it is a problem related to the finite number of cells & Geiger-Mueller process: as long as the probability of having more than one photo-electron (i.e. photon induced avalanche) in a single cell is not negligible, I can expect a deviation from the linearity in the response.

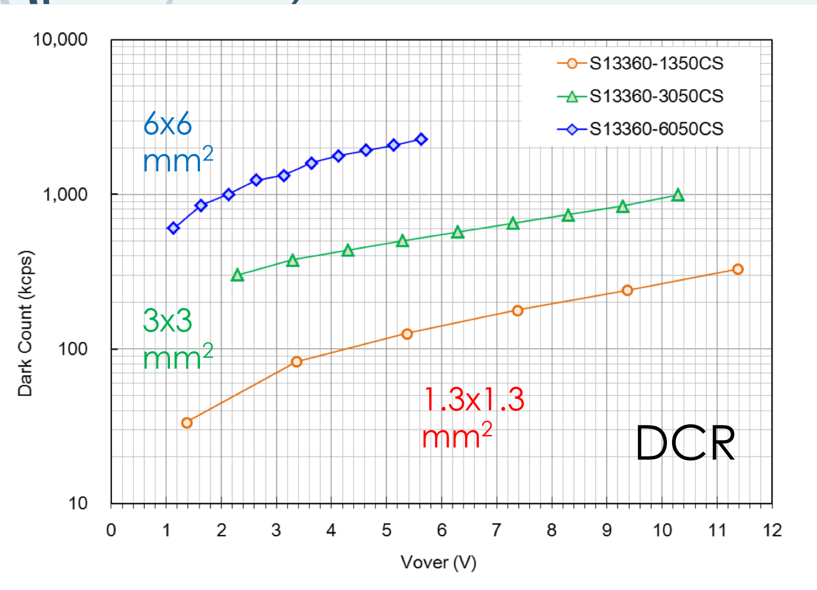
[look at the supplementary slides for a simple statistical exercise based on balls & baskets]

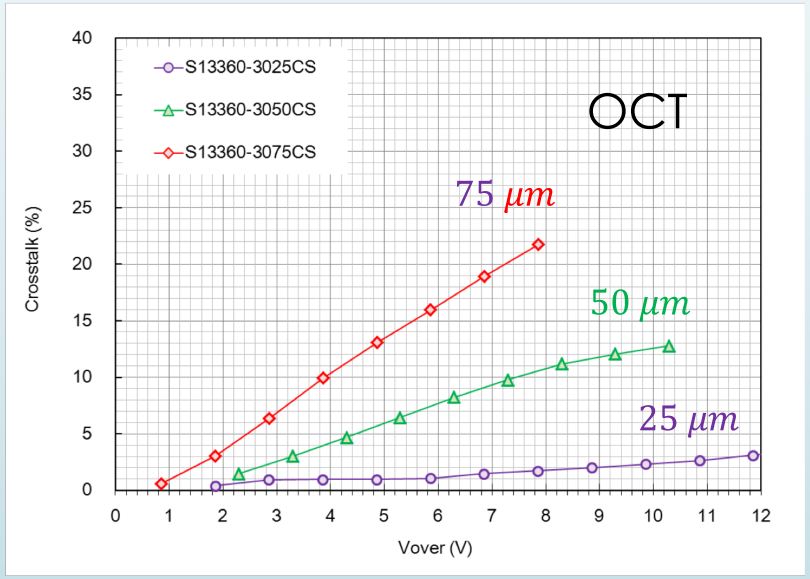
More Stochastic effects affecting the sensor response [actually introducing non-linarities]:

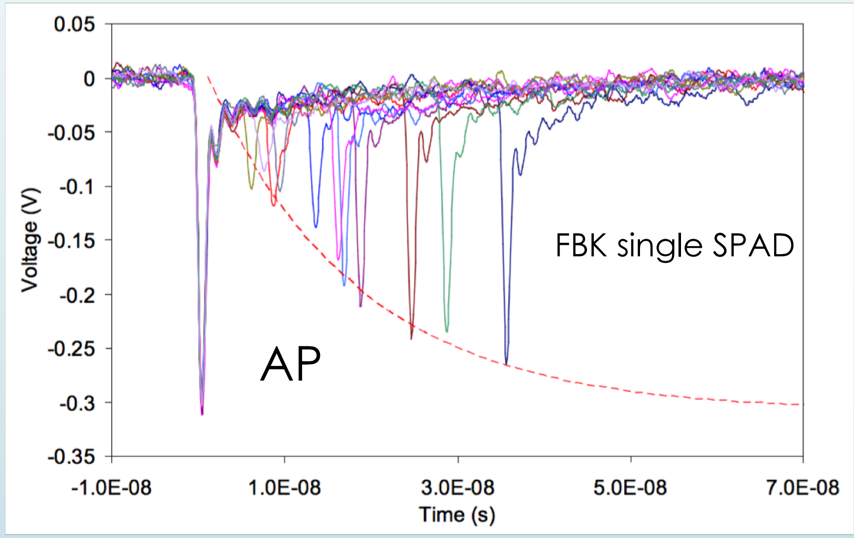
- Dark Count Rate[⬆] (rate of avalanches randomly initiated by thermal generation of carriers): currently at the 60 kHz/mm^2 level

- Optical Cross Talk [⬆] (secondary avalanches triggered by photons emitted during the primary event): currently < 10% at operating voltages

- After-pulsing [⬆] (Delayed avalanches triggered by the release of a charge carriers that has been produced in the original avalanche and trapped on an impurity): ≈ 1% at operating voltages



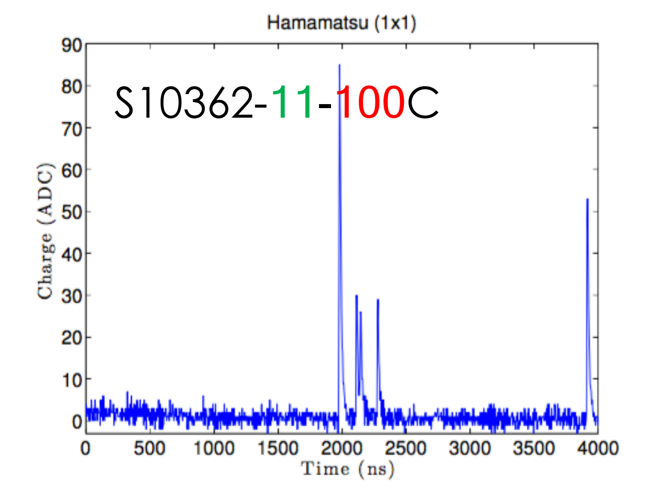




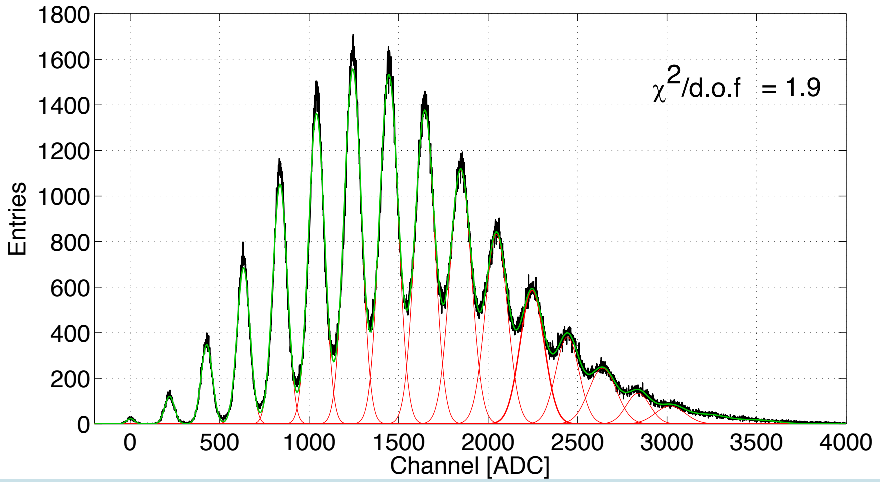
C. Piemonte, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 54, NO. 1, 2007

Since a picture is worth a thousand words:

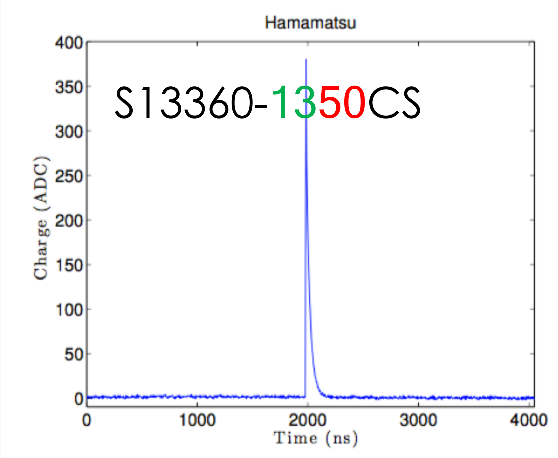
An old sensor by HAMAMATSU (2008)



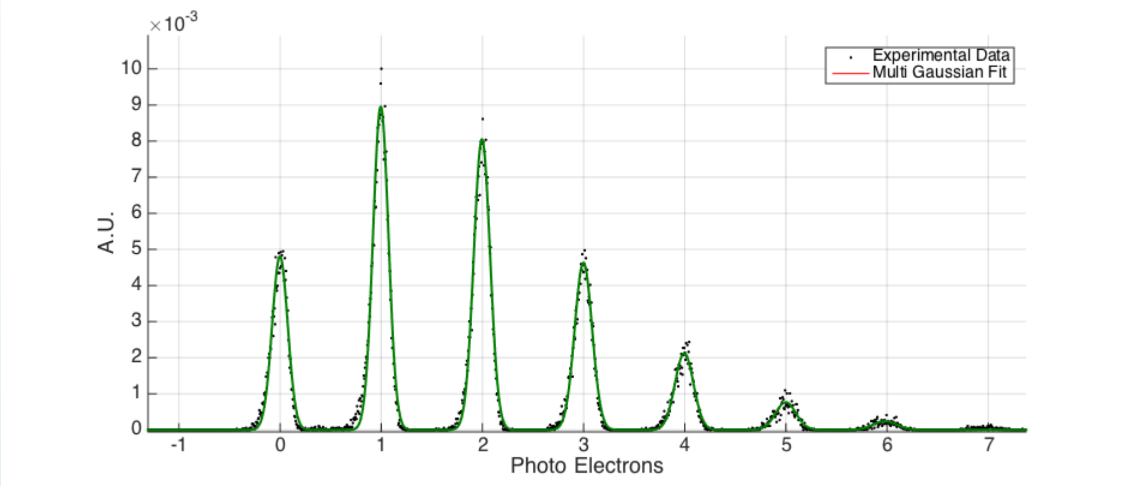
(a) Hamamatsu (1x1)



A new sensor by HAMAMATSU (2016)



(b) Hamamatsu (1.3x1.3)

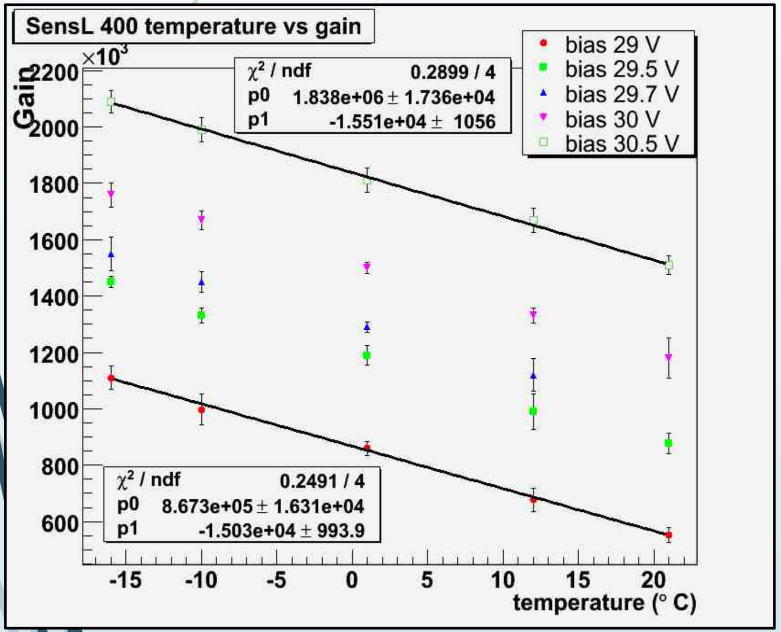


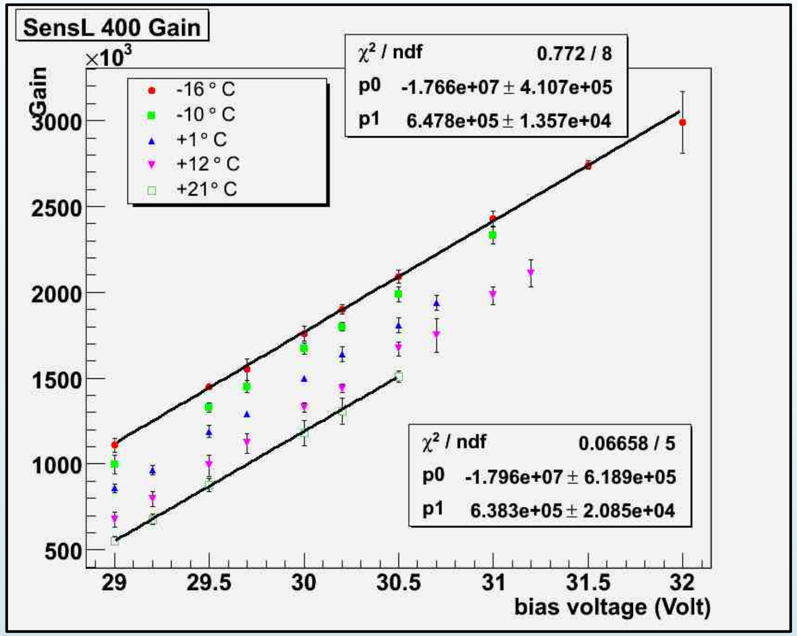
One more point: make it stable (against temperature stability)!

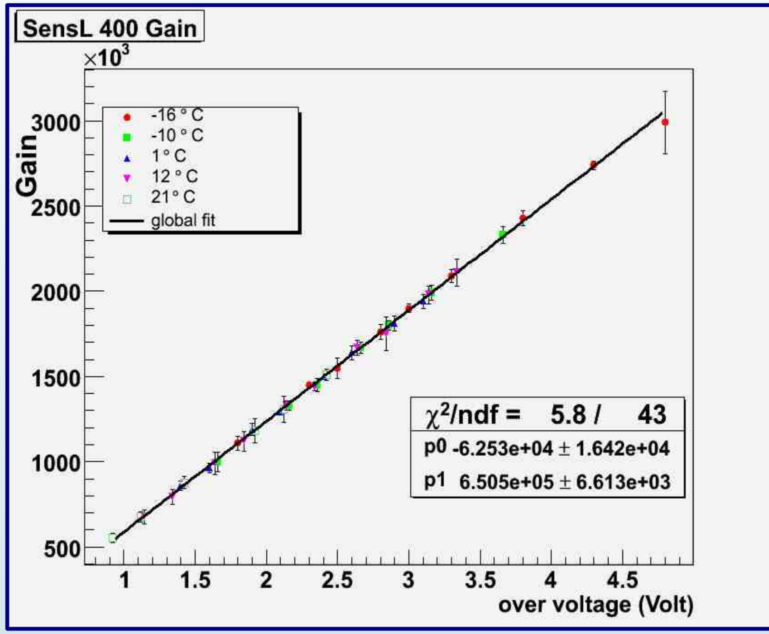
- C.R. Crowell, S.M.Sze, "TEMPERATURE DEPENDENCE OF IN SEMICONDUCTORS", APPLIED PHYSICS LETTERS 9, pag. 242, 1966
- C. Y. Chang, S. S. Chiu, and L. P. Hsu, "Temperature dependence of breakdown voltage in silicon abrupt P-N junctions," IEEE Trans. Elec- tron Devices, vol. 18, no. 6, pp. 391–393, 1971

$$V_{Br}(T) = V_{Br}(T_o) \times \left[1 - \beta(T - T_o)\right]$$

22 mV/°K < β < 55 mV/°K







$$\frac{dV}{dT} = -\frac{dG}{dT}\frac{1}{\frac{dG}{dV}}$$

M. Ramilli, Characterization of SiPM: temperature dependencies, Nuclear Science Symposium Conference Record, 2008. NSS '08. IEEE

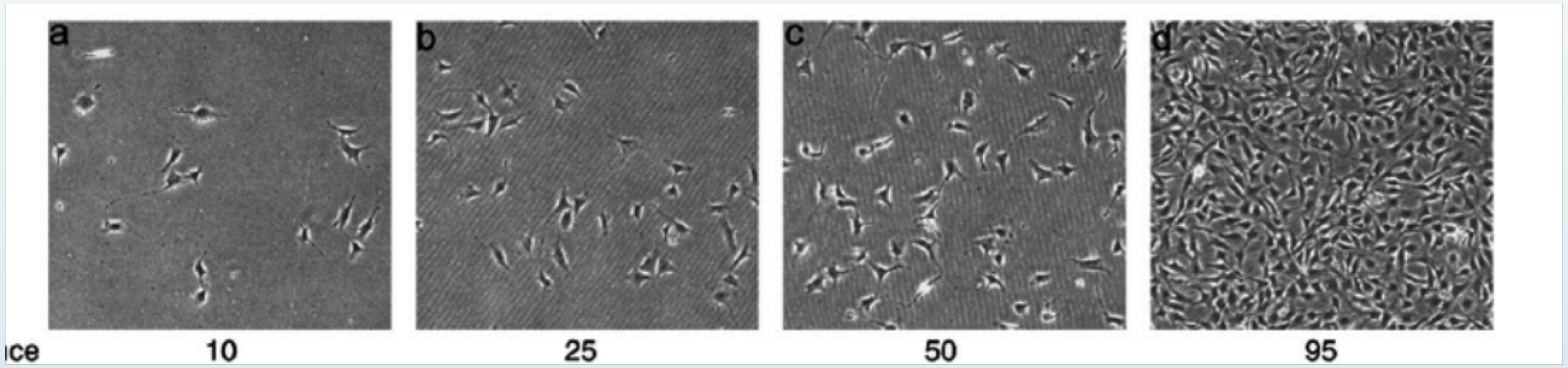
What's Next?

Trends in the R&D (user's driven, steered by the companies):

- Make it (more) quiet (decrease the stochastic terms)

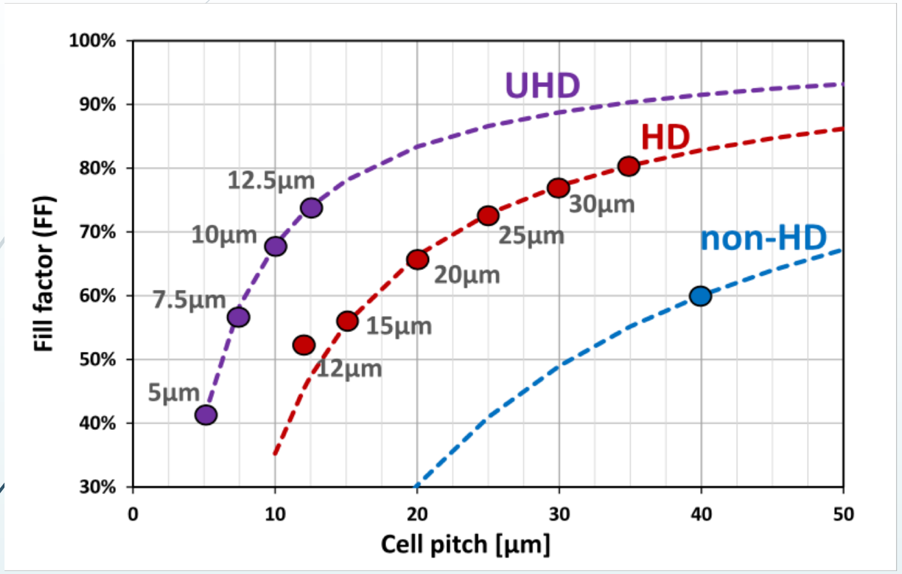
Trends in the R&D (user's driven, steered by the companies):

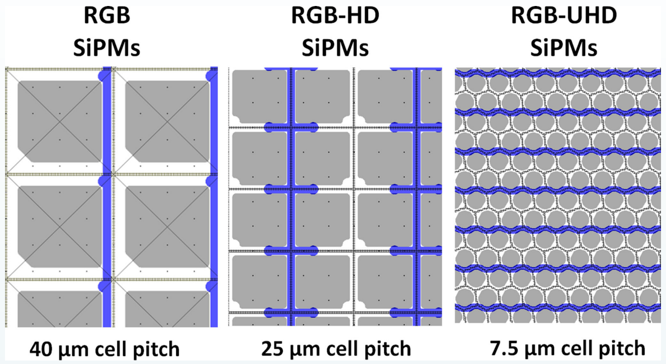
- Increase the cell densities (extend the dynamic range)



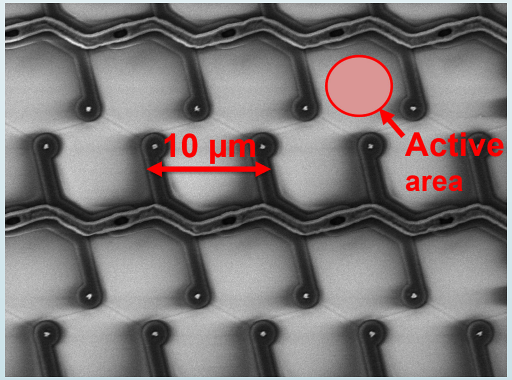
Latest from Fondazione Bruno Kessler in Trento (Italy)

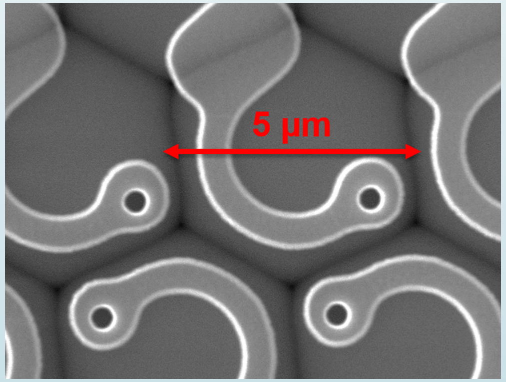
F. Acerbi et al., IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 24, NO. 2, MARCH/APRIL 2018

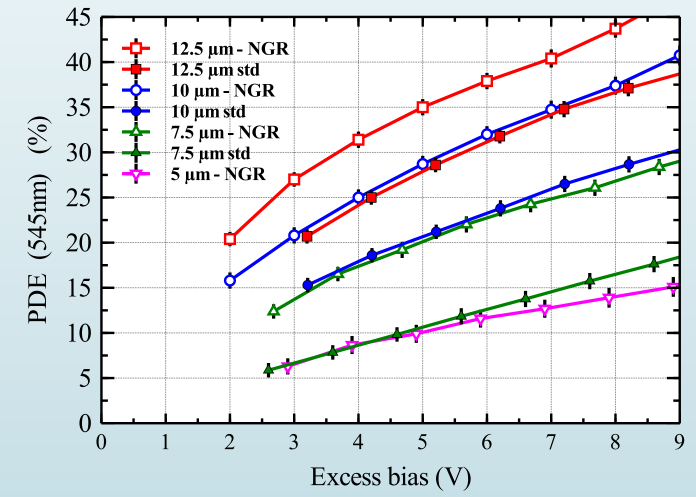




Cell pitch	5 μm	7.5 μm	10 μm	12.5 μm
Cell area [μm^2]	21.6	48.7	86.6	135
Cell density [cells/mm^2]	46190	20500	11500	7400
Cell Fill Factor	40.9%	57%	68%	75%





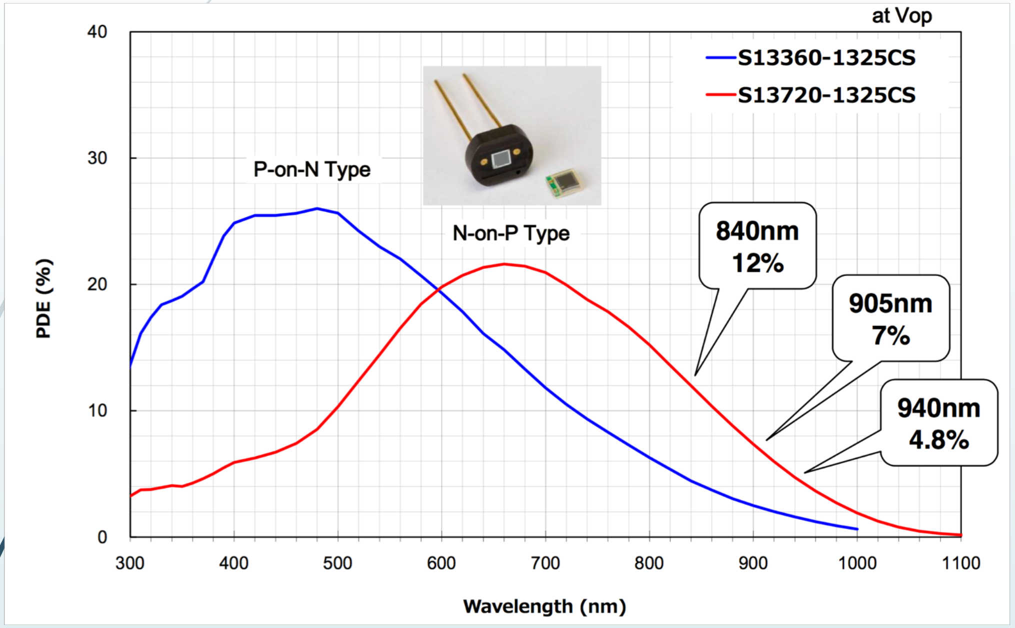


Trends in the R&D (user's driven, steered by the companies):

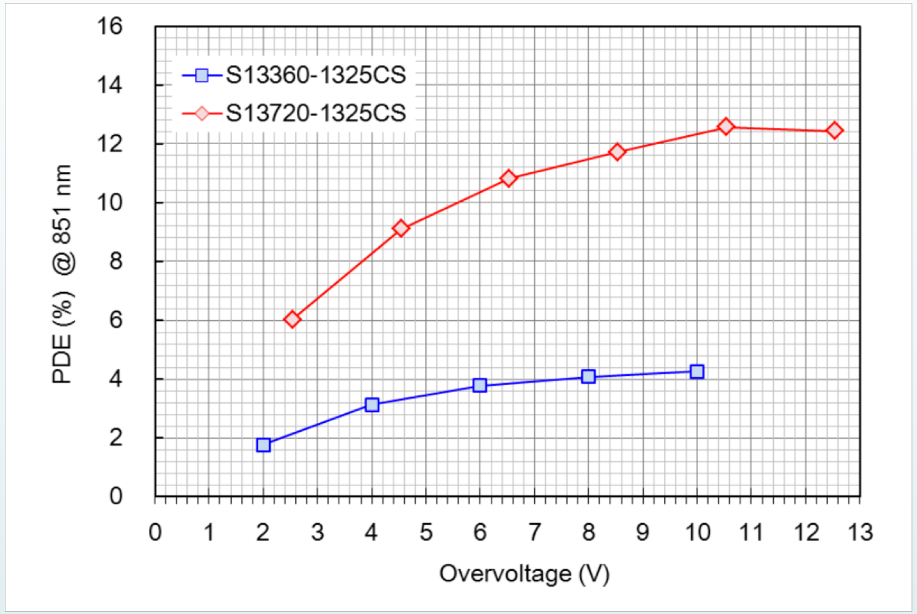
- Push the sensitivity a bit to the right (NIR)

- … and to the left (NUV)

Where are we today (2018)? The latest from HPK on the IR side



Photon Detection Efficiency vs wavelength



PDE vs overvoltage

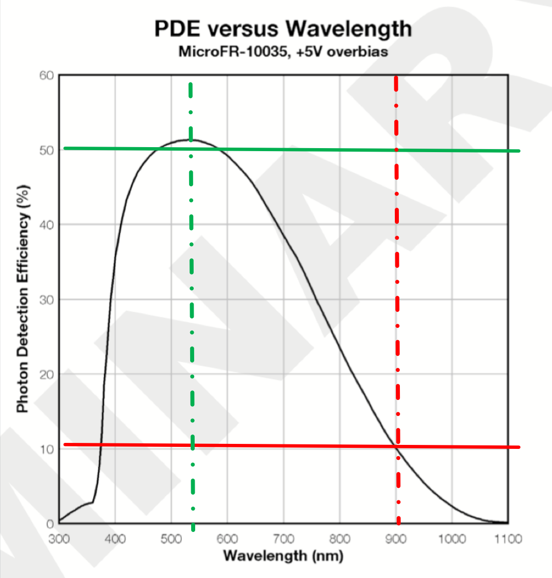
Where are we today (2018)? @SensL:

Sensor Size	Microcell Size	Parameter[1]		Overvoltage	Min.	Typ.	Max.	Units
1mm	10µm	PDE[3]	@ 635nm	Vbr + 5.0V		30		%
			@ 780nm			18		%
			@ 905nm			8		%
	20µm		@ 635nm			39		%
			@ 780nm			24		%
			@ 905nm			10		%
	35µm		@ 635nm			47		%
			@ 780nm			29		%
			@ 905nm			12		%

Available products (R series)

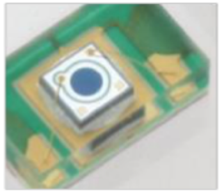
DCR ≈ 70 kHz / mm^2 @5V_{over}

50%

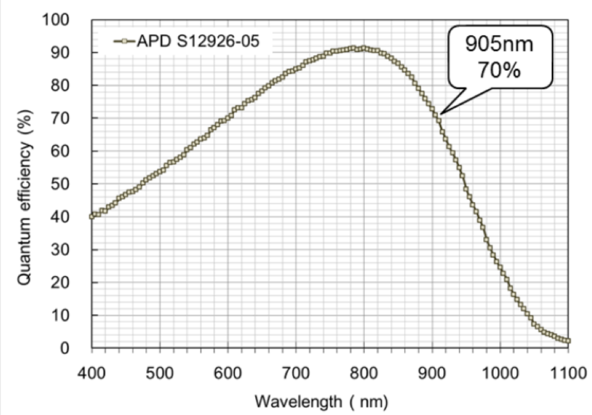


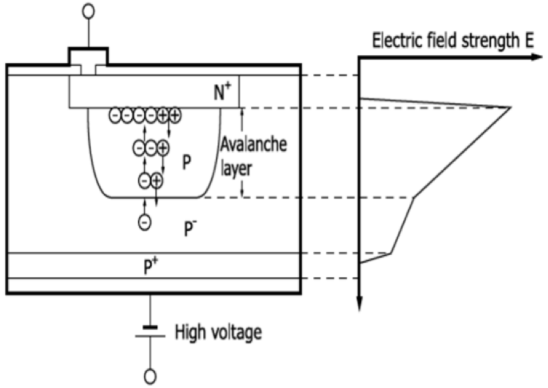
Worth fighting against APD?

APD
S12926-05



Vop = 160 V
λp = 800 nm
QE = 70% (905 nm)
M = 100
ΔT = 1.1 V/°C





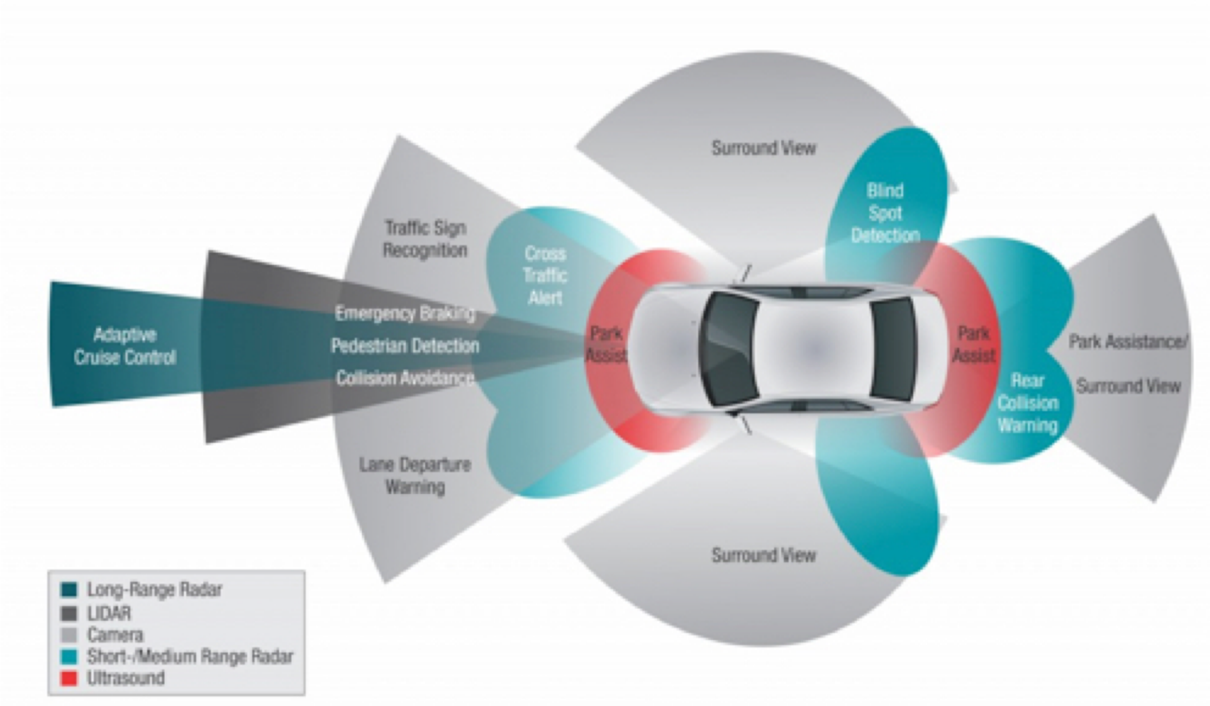
- M is the multiplication factor, 10^{-4} lower than SiPM
- The QE is 6 times higher than the PDE in SiPM
- The biasing voltage is ≈ 5 times higher than SiPM
- the sensitivity is at the 100 photon level ("*range extender*")

MindTheNumbers: if I scale down 35W/A by a factor 6 and I scale it up by a factor 10 000, I get 60kA/W, even if Sensl claims these are measured figures.

	PiN Photodiode	APD	SiPM/SPAD
Gain	1	10^2	10^6
Operating voltage	5V	100V - 1000V	30V
Responsivity at 905nm	0.3A/W	35A/W	530kA/W
Implementation challenges	- External amplification limits signal to noise ratio (SNR) and bandwidth	- External amplification limits bandwidth and low return signal detection - Sensor to sensor non-uniformity and internal gain excess noise factor - High volume cost due to non-standard CMOS fabrication processes	- Ambient light rejection ±25nm bandpass filter reduces light by a factor 25

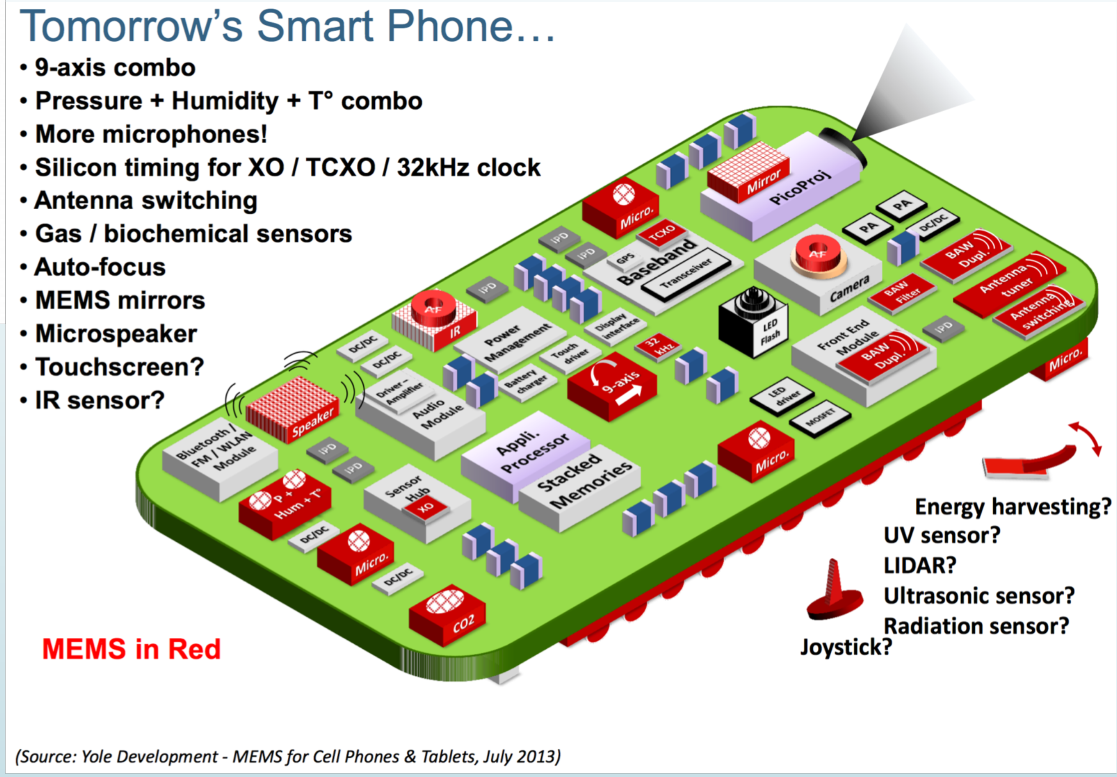
SensL

Certainly YES!



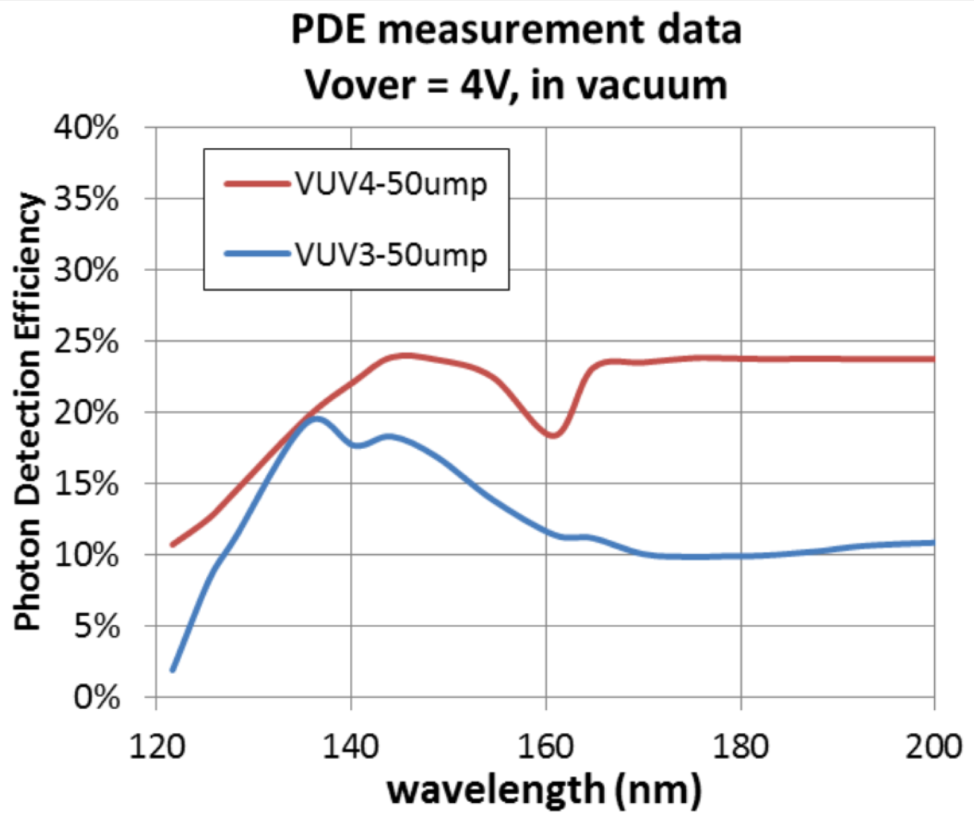
But do not forget ranging is also important for other markets:

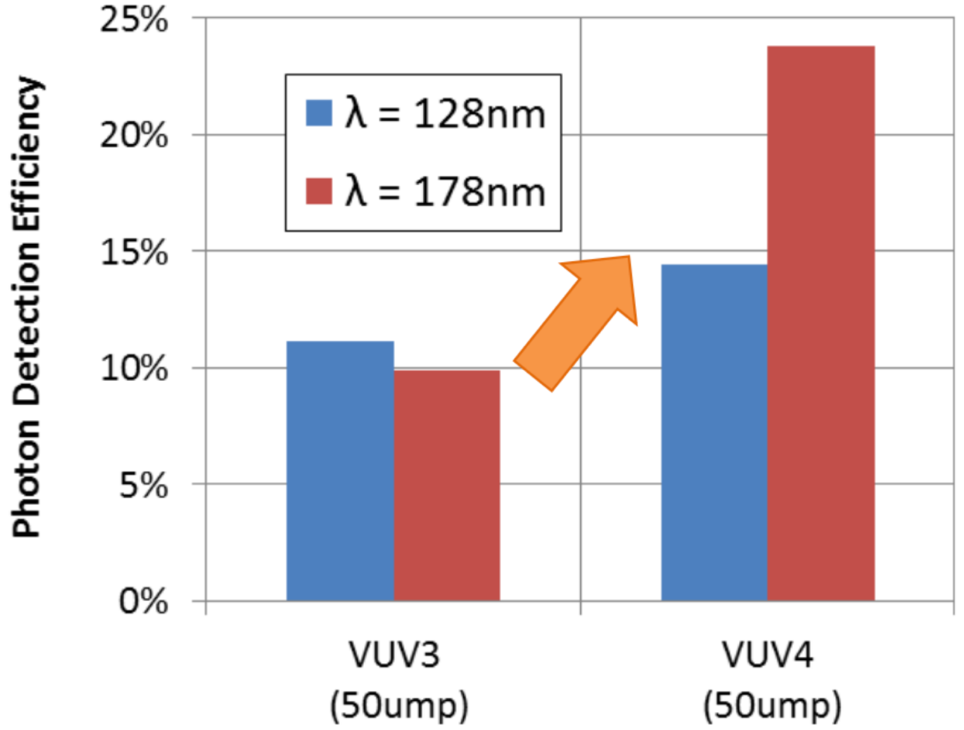
- ❖ Landscape topography
- ❖ Industrial applications
- ❖ Military



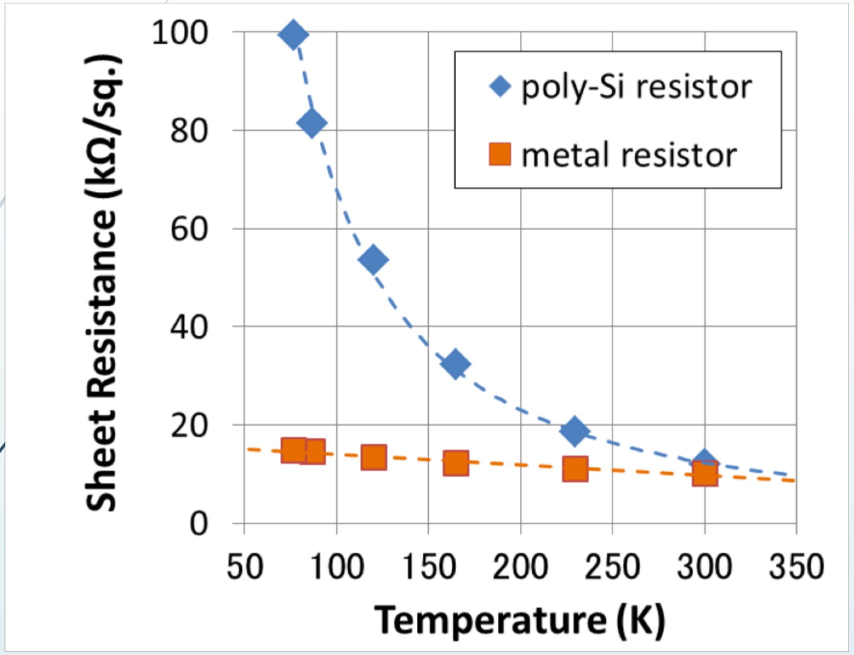
Look at the INSPEX H2020 project on obstacle detection to see what's going on at EU level

The latest from HPK: on the UV side

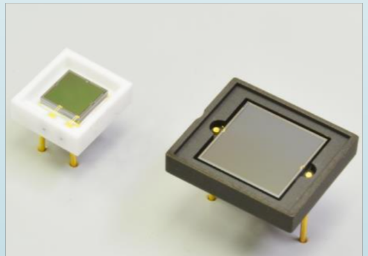


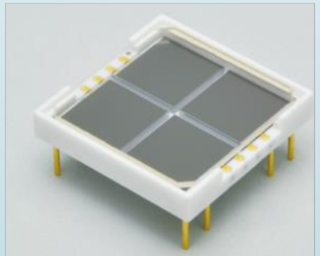


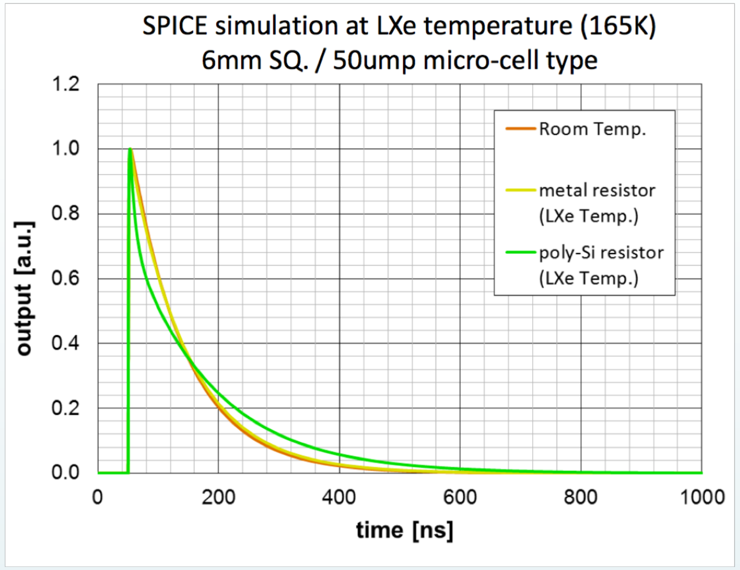
VUV enhanced sensitivity goes along with good functionality at cryo-T:

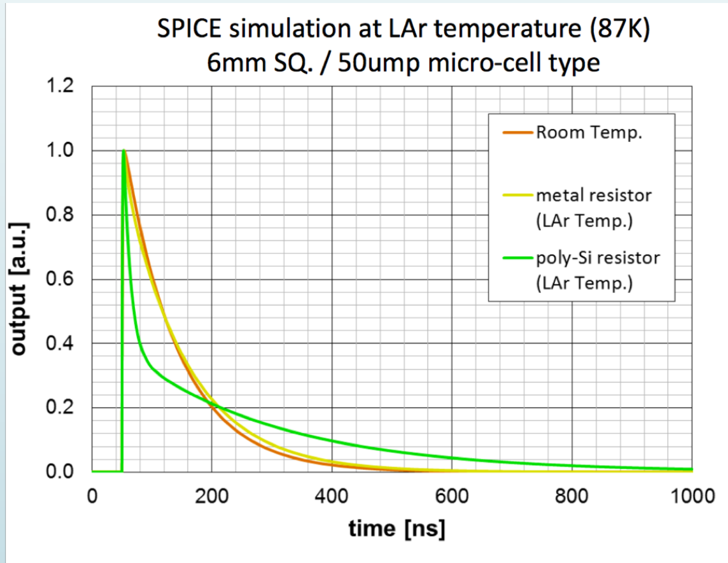


S13370 and S13361 series, available in ceramic package with high radio purity









Trends in the R&D (user’s driven, steered by the companies):

- Integrate a bit of intelligence on board

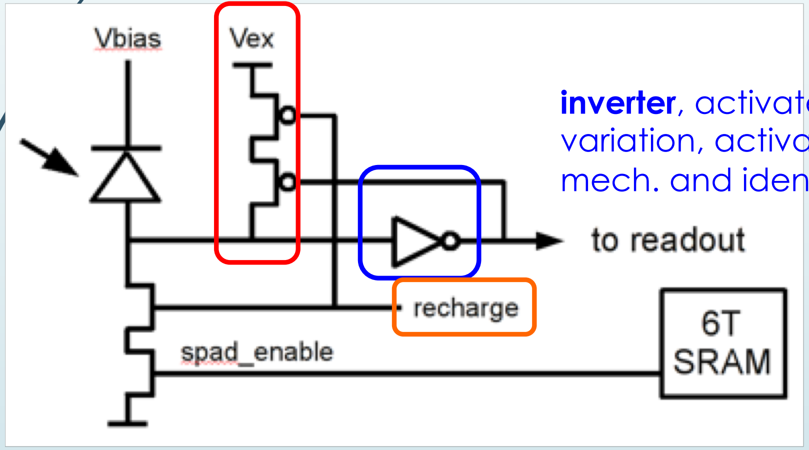
Philips Digital Photon Counting

http://www.digitalphotoncounting.com

- IEEE-NSS Conference record 2009 & 2010 (Thomas Frach)
- JINST 7 (2012) C01112
- D. Schaart et al., NIM A 809 (2016) 31-52

Put a bit of intelligence on board and turn the SiPM into a genuine DIGITAL device:

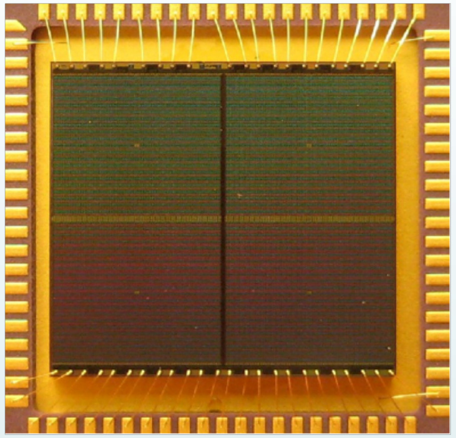
Active quenching, forcing the anode to the breakdown voltage



inverter, activated by the anode voltage variation, activating the the quenching mech. and identifying the cell was hit

Quick recharge transistor

The 2009 chip



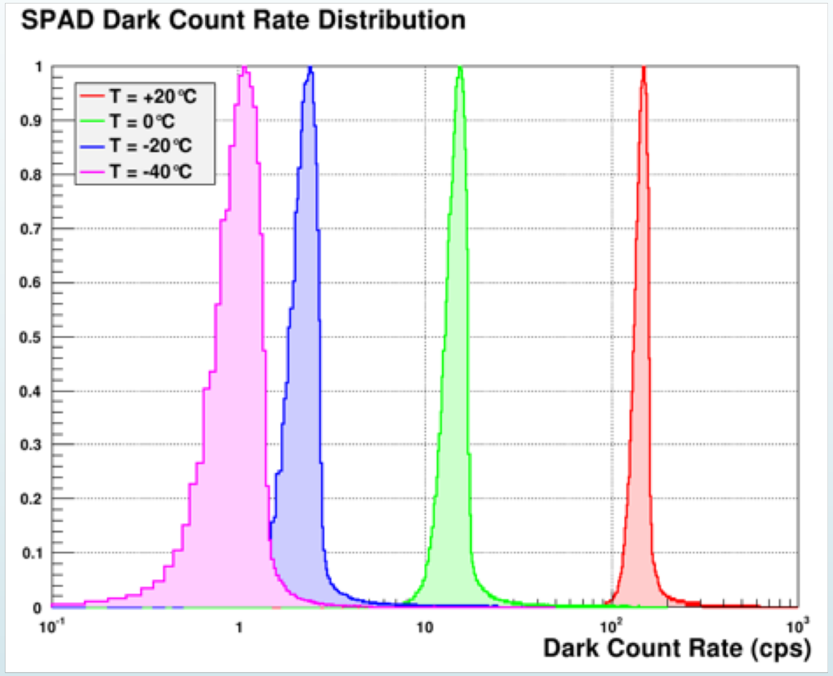
- ❖ 2 x 2 array of sensors
- ❖ 6396 cells/sensor
- ❖ 60 x 40 μm^2 cells
- ❖ chip size 7.8 x 7.2 mm^2
- ❖ peak PDE ~ 30% @430 nm
- ❖ modified 0.18 μm 5M CMOS

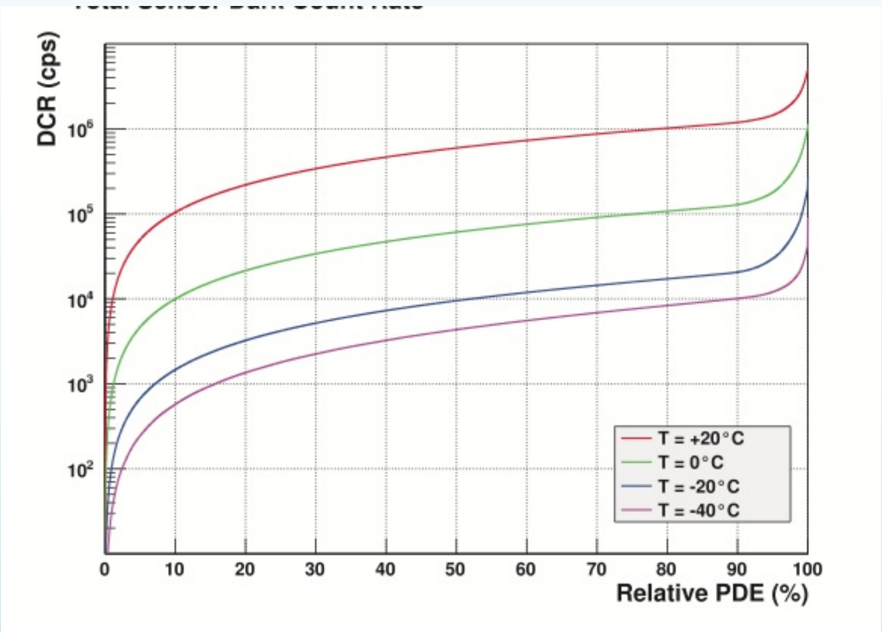
On ACTIVE QUENCHING, see for instance Gallivanoni et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 6, DECEMBER 2010

Exemplary illustrations of the advantages of this design:

1. Spotting hot cells and disabling their output

Since individual pixels may be enabled/disabled, the DCR of every cell can be measured, possibly identifying the HOT cells:



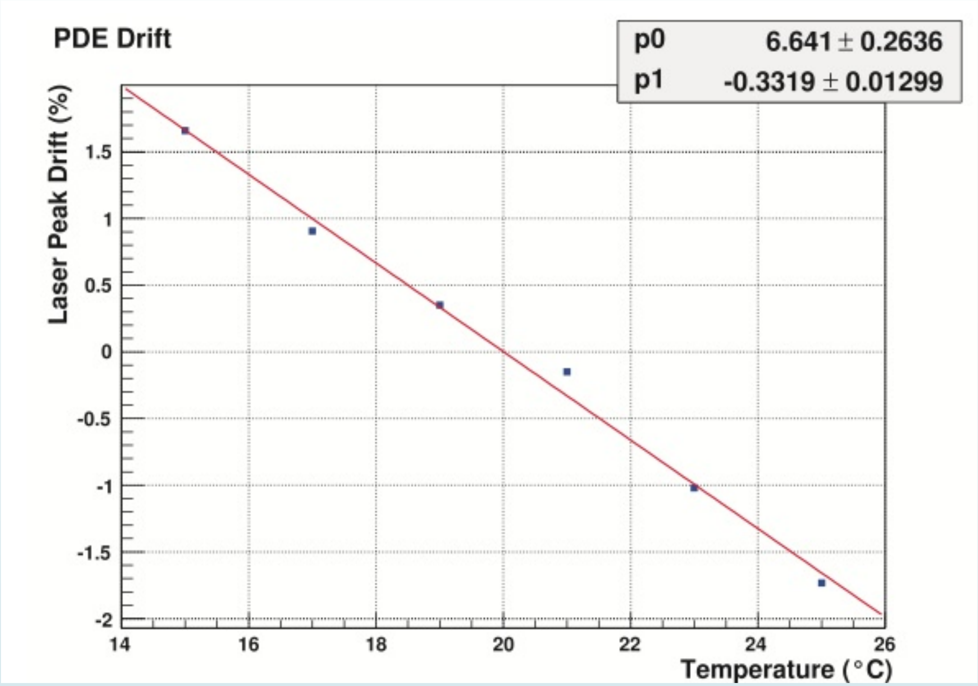


Typical dark count rate at 20°C and 3.3V excess voltage: ~150cps / diode

Exemplary illustrations of the advantages of this design:

2. Reduced temperature sensitivity

Digital SiPM are insensitive to any change in the breakdown voltage as long as the switching threshold of the gate is reached.



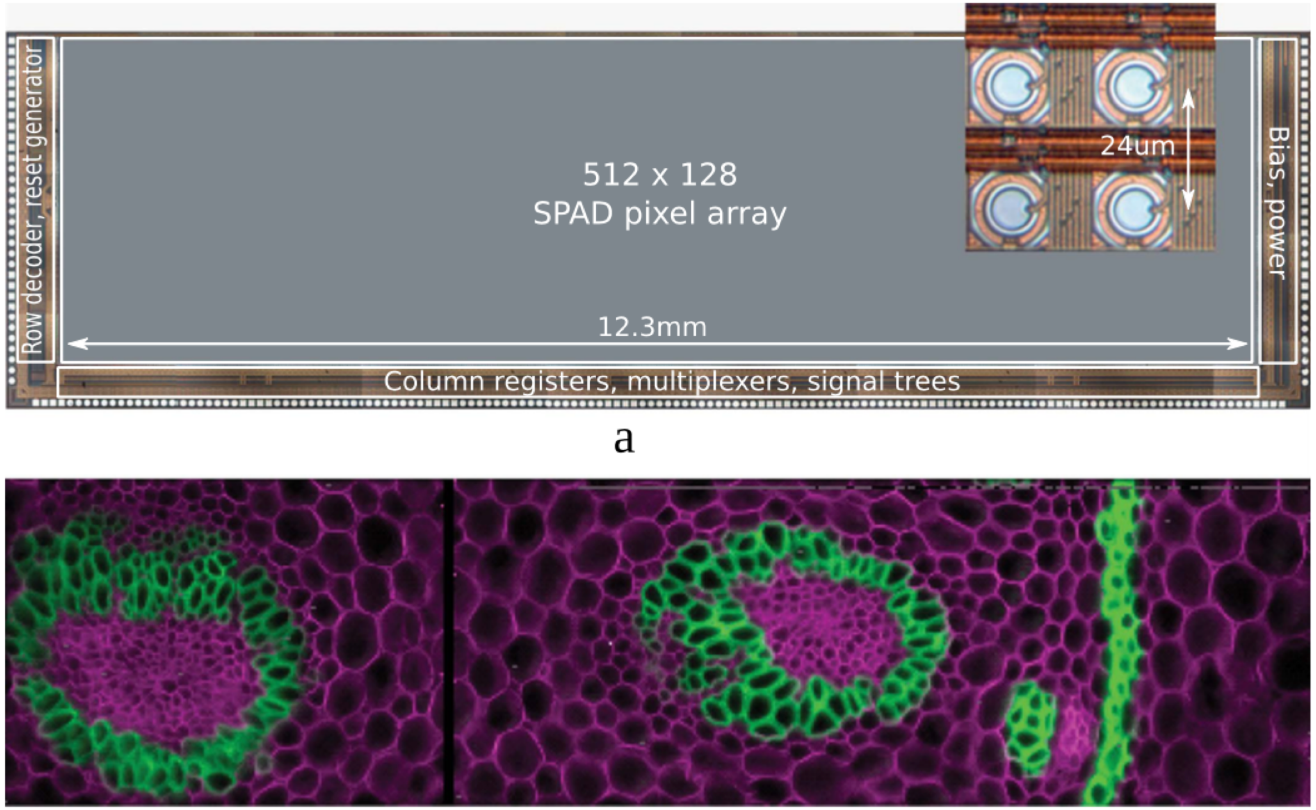
O(0.3%/C)
Vs
0.5-1%/C in standard SiPM
(operated at +5V)

The remaining drift observed in the digital SiPM is due to the change in the photon detection efficiency, caused by the temperature-dependent avalanche initiation probability.

Is it a successful device?

- 23040 detectors
- 325 ps resolution

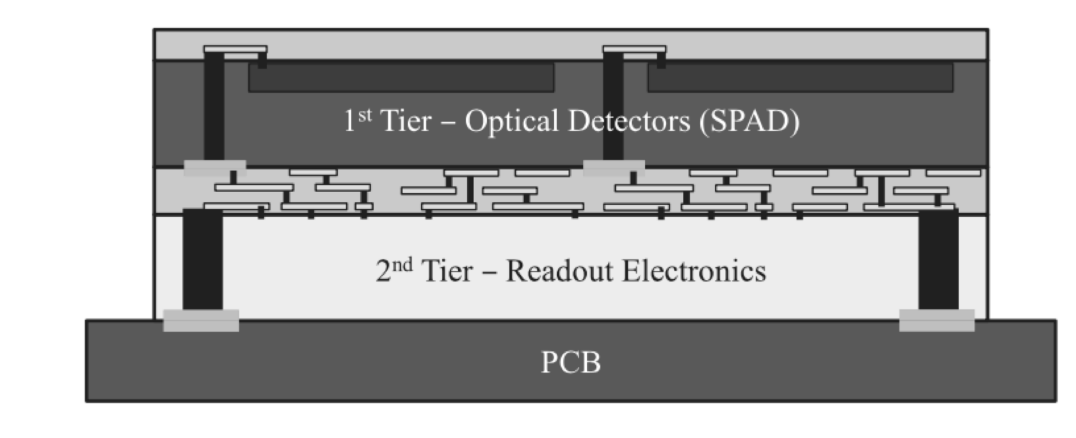
The SwissSPAD (Edoardo Charbon et al, SPAD imagers for super resolution localization microscopy enable analysis of fast fluorophore blinking, Nature Scientific RepoRts | 7:44108 | DOI: 10.1038/srep44108, 2017)



- 24 µm pixel pitch
- Rolling shutter readout (6.4 µs frame period)
- Native Fill Factor (FF) 5%
- FF enhancement by micro-lensing: 12
- Achieved super-resolution: 80 nm

multicolor fuorescence image of a thin slice of a plant root stained with a mixture of fluorescent dyes

The next frontier:
3D vertical integration, to turn a sensor into a SMART sensor, with intelligence on board



Silicon hybrid SPAD with high-NIR-sensitivity for TOF applications

Takashi Baba*[a], Terumasa Nagano[a], Atsushi Ishida[a], Shunsuke Adachi[a], Shigeyuki Nakamura[a], Koei Yamamoto[a]
[a]Hamamatsu Photonics K.K., 1126-1, Ichino-cho, Higashi-ku, Hamamatsu City, Shizuoka Pref., Japan, 433-8558

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 4, AUGUST 2016

A 2D Proof of Principle Towards a 3D Digital SiPM in HV CMOS With Low Output Capacitance

Frédéric Nolet, Vincent-Philippe Rhéaume, Samuel Parent, Serge A. Charlebois, *Member, IEEE*, Réjean Fontaine, *Senior Member, IEEE*, and Jean-François Pratte, *Member, IEEE*

One of the latest HAMAMATSU developments


Thank you for listening!

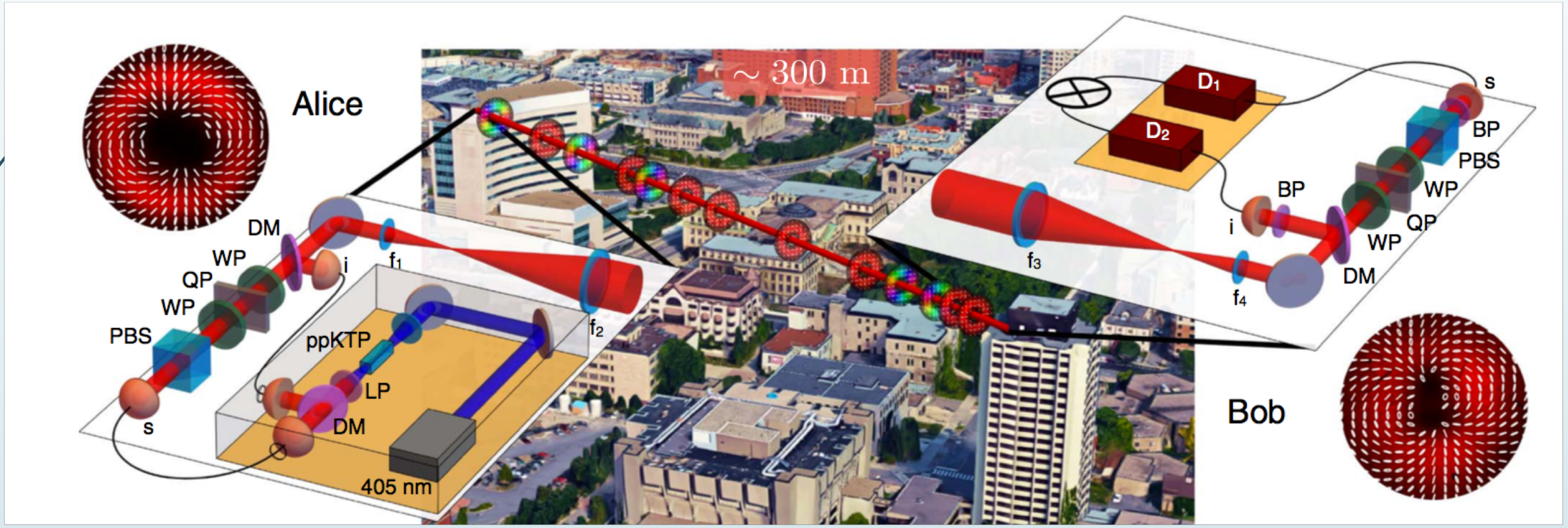
Supplementary Slides

Research Article Vol. 4, No. 9 / September 2017 / *Optica* 1006

optica

High-dimensional intracity quantum cryptography with structured photons

Alicia Sit,[1] Frédéric Bouchard,[1] Robert Fickler,[1] Jérémie Gagnon-Bischoff,[1] Hugo Larocque,[1] Khabat Heshami,[2] Dominique Elser,[3,4] Christian Peuntinger,[3,4] Kevin Günthner,[3,4] Bettina Heim,[3,4] Christoph Marquardt,[3,4] Gerd Leuchs,[1,3,4] Robert W. Boyd,[1,5] and Ebrahim Karimi[1,6,*]



Ottawa intracity communication link

The OTTAWA experiment

Research Article Vol. 4, No. 9 / September 2017 / *Optica* 1009

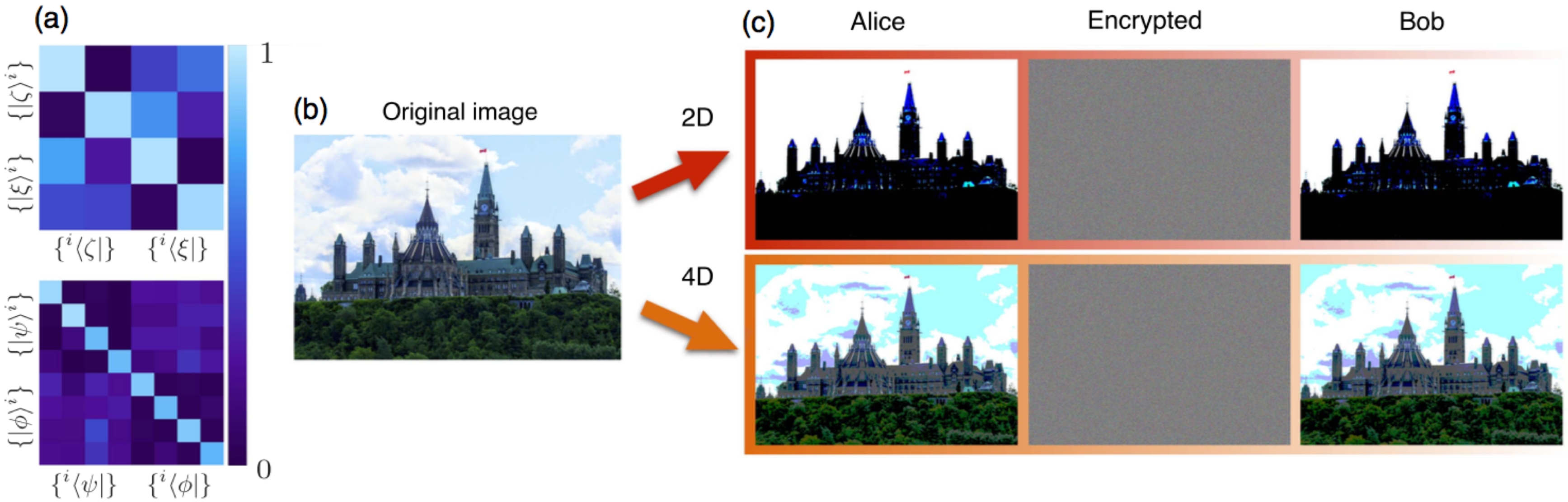
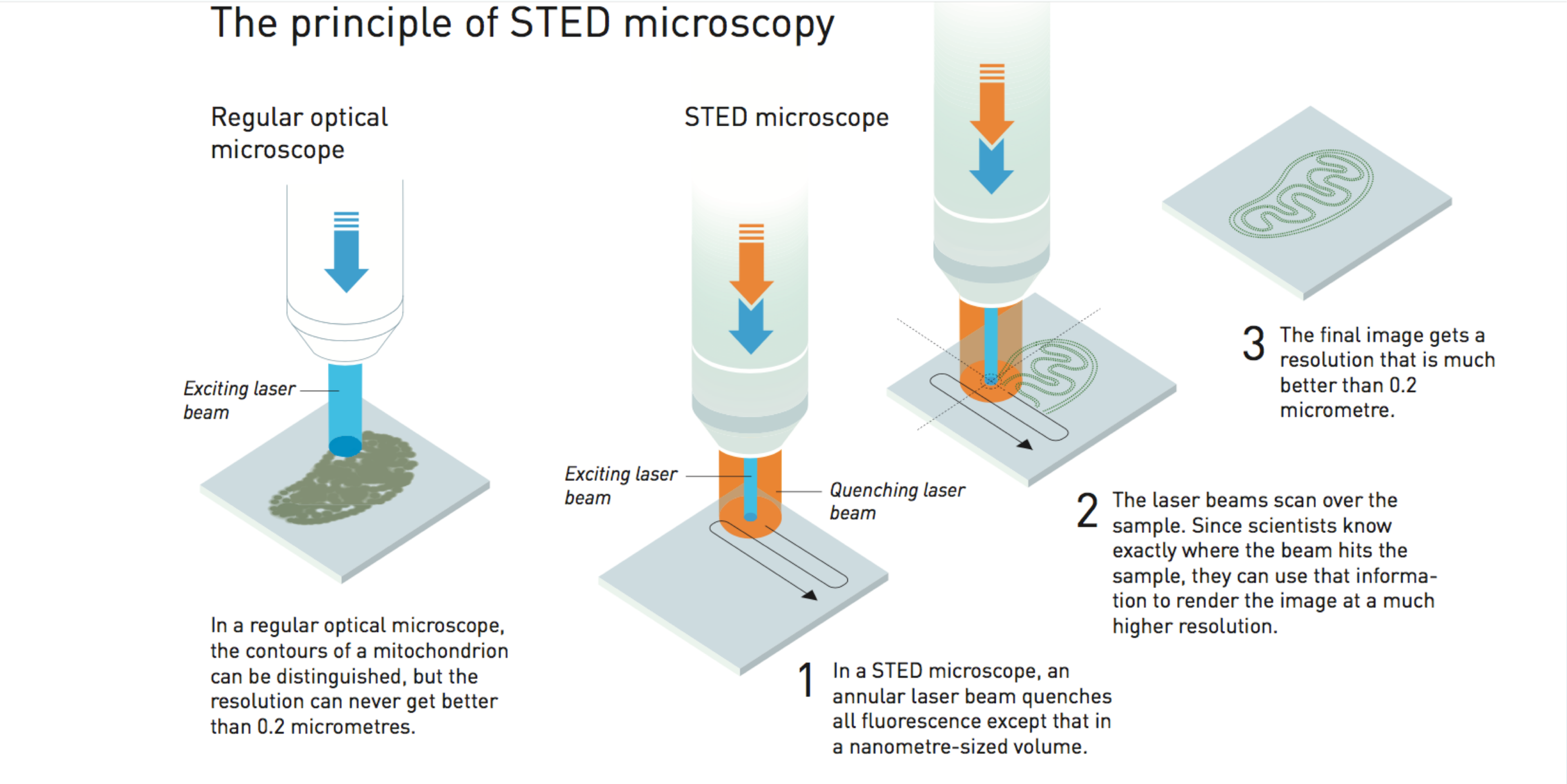
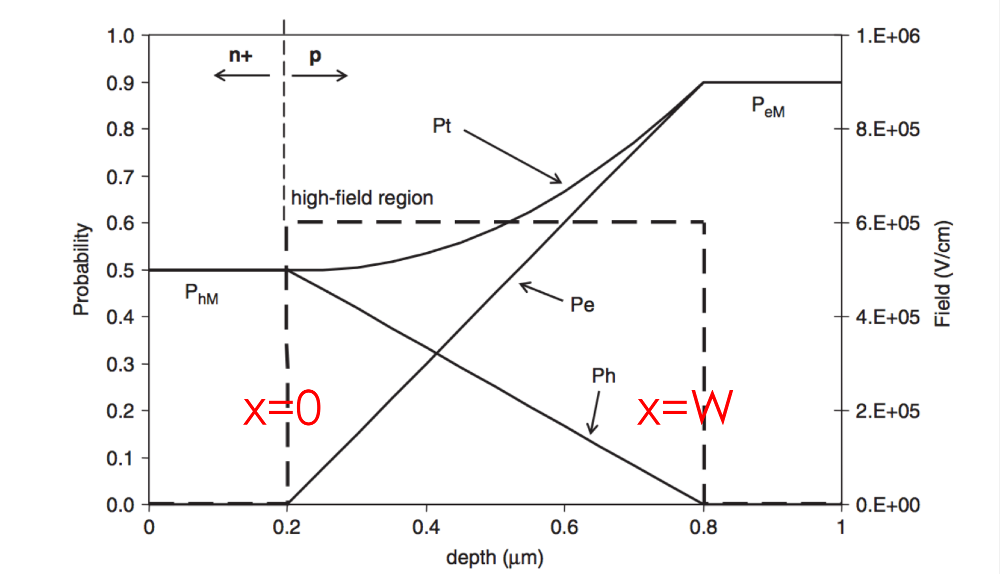


Fig. 3. Simulated encryption of an image with structured photons. (a) Experimentally measured probability-of-detection matrices, $P^{i,j} = |^{i}\langle\alpha|\beta\rangle^{j}|^2$, where $\alpha, \beta = \{\psi, \varphi\}$, for 2D (top row) and 4D (bottom row) structured photons with turbulence. These matrices have the corresponding bit error rates of $Q^{2D} = 5\%$ and $Q^{4D} = 11\%$, respectively. (b) Image of the Parliament of Canada that Alice encrypts and sends to Bob through a classical channel using their shared secret key. (c) Alice discretizes her intended image (left column) with d levels, where d is the encryption dimension, such that each pixel corresponds to three single photons (RGB values, leading to d^3 colors per pixel) that she sends to Bob. Using the experimentally measured probability-of-detection matrices (a), Alice then adds the shared secret key, generated from a BB84 protocol, on top of her discretized image to encrypt it (middle column). Bob decrypts Alice's sent image with his shared key to recover the image (right column). Implementing a 4-dimensional state clearly allows the ability to send more information per photon, where, in the ideal case, Alice can send twice the amount of information with respect to 2-dimensional states. However, due to noise present in the channel, we experimentally obtain an increase of 1.51 in the amount of information sent by Alice with respect to the case of 2-dimensional states. Image credit: Norman Bouchard.

The principle of the Noble prize technique (supplementary material on the Nobel academy web site)



On triggering probability and bias voltage (ref.3)



$$P_t(x) = 1 - (1 - P_e(x)) \times (1 - P_h(x)) = P_e(x) + P_h(x) - P_e(x)P_h(x)$$

How is P_e changing when I move from x to x+Δx?

1. Probability that the electron triggers an avalanche in x

$$P_e(x)$$

2. Probability that the electron induces an ionization in ΔX and either the pair triggers an avalanche in x

$$\alpha_e \Delta X \times P_t(x)$$

$$P_e(x) \times \alpha_e \Delta X \times P_t(x)$$

3. Joint probability

Working out the math, you get the equations defining the trends with x of P_e and P_h:

$$\frac{dP_e}{dx} = (1 - P_e)\alpha_e[P_e + P_h - P_eP_h]$$

$$\frac{dP_h}{dx} = -(1 - P_h)\alpha_h[P_e + P_h - P_eP_h]$$

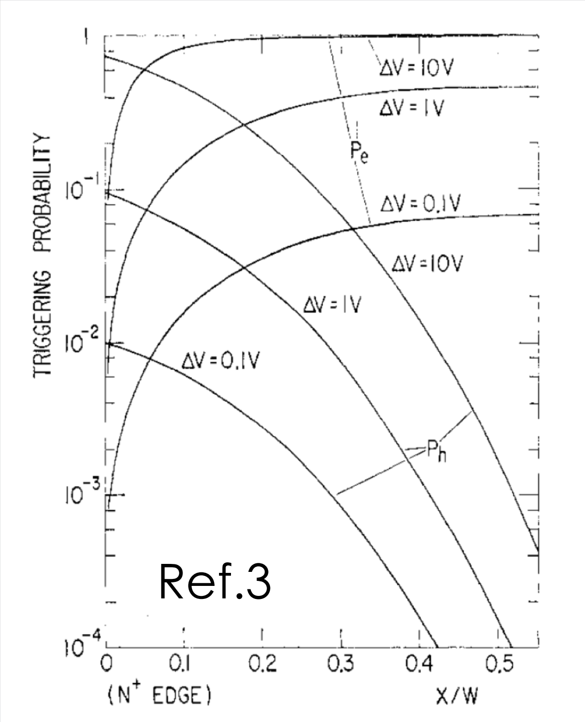
$$P_e(0) = 0$$
$$P_h(W) = 0.$$

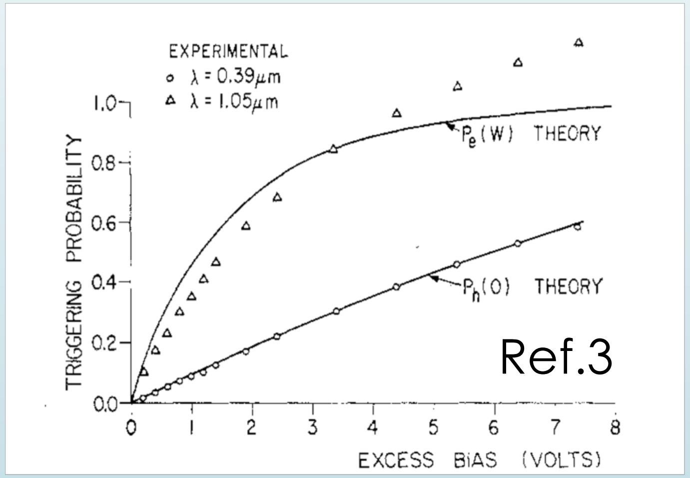
Boundary conditions

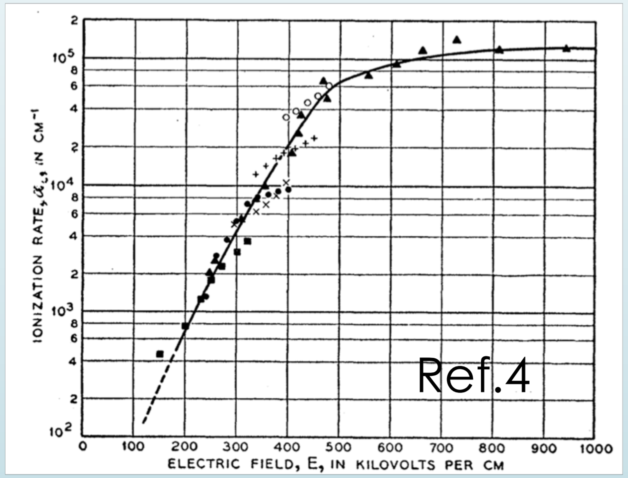
Where α_e, α_h, the IONIZATION COEFFICIENTS, depend on the electric field (i.e. the bias) as

$$\alpha = a \times e^{\frac{-b}{E}}$$

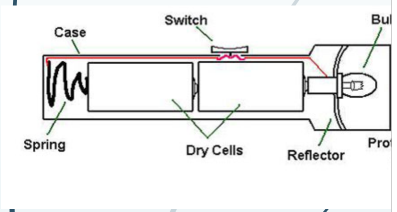
Where a ≈ 10^6, b ≈ $2x10^6$



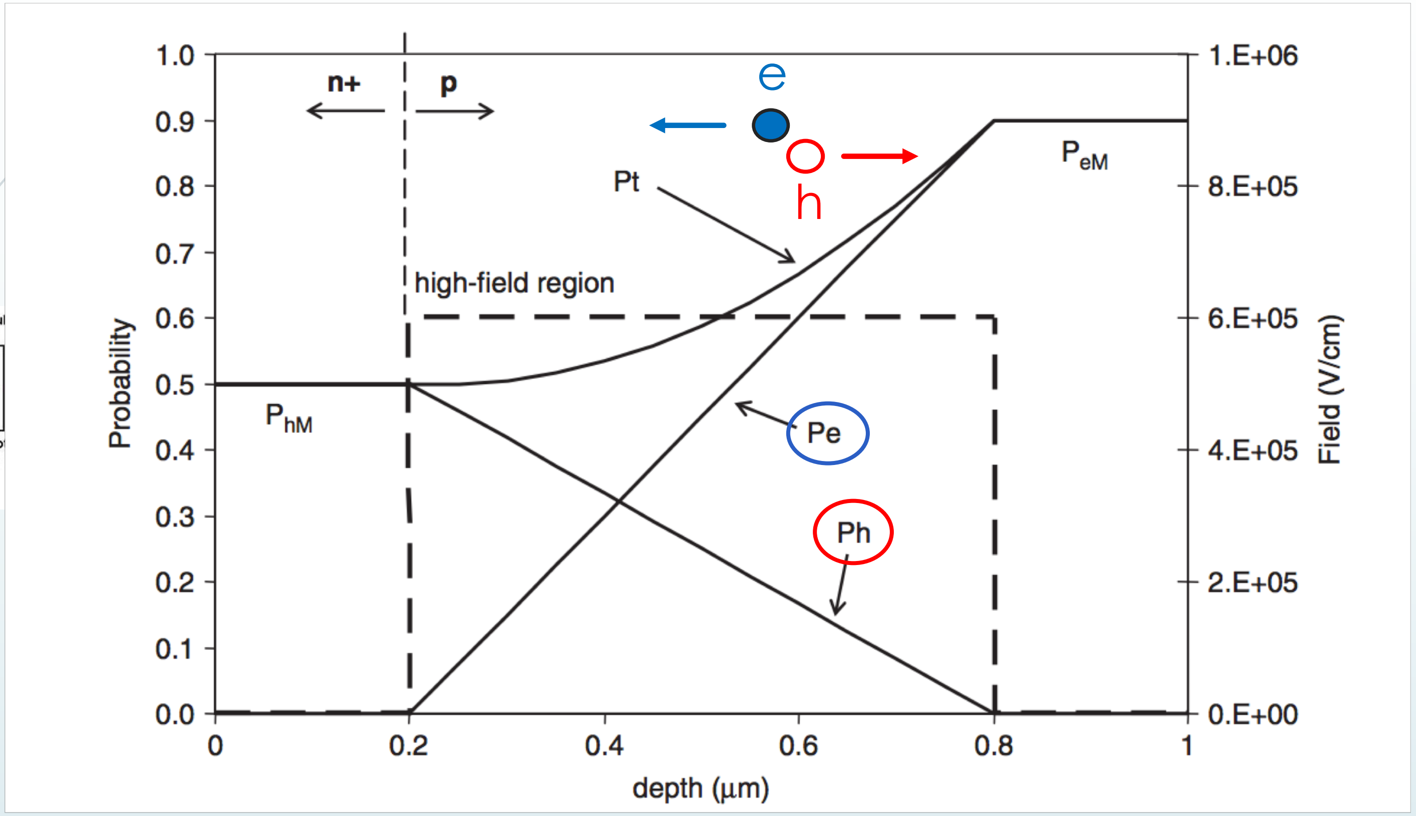




Spectral Response: I have to tailor my junction to maximize the probability to trigger an avalanche:

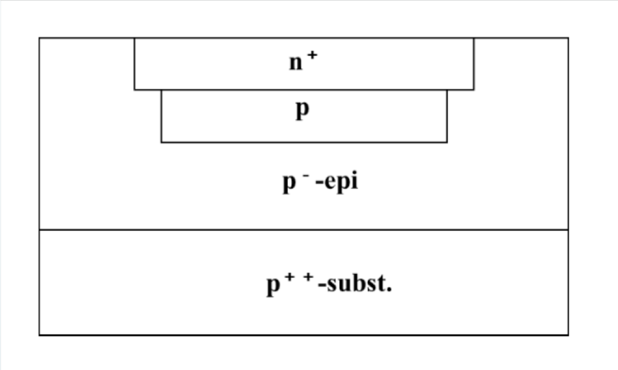


Light in



n-on-p junction:

- Not ideal for blue
- Good enough for green
- Bad for red

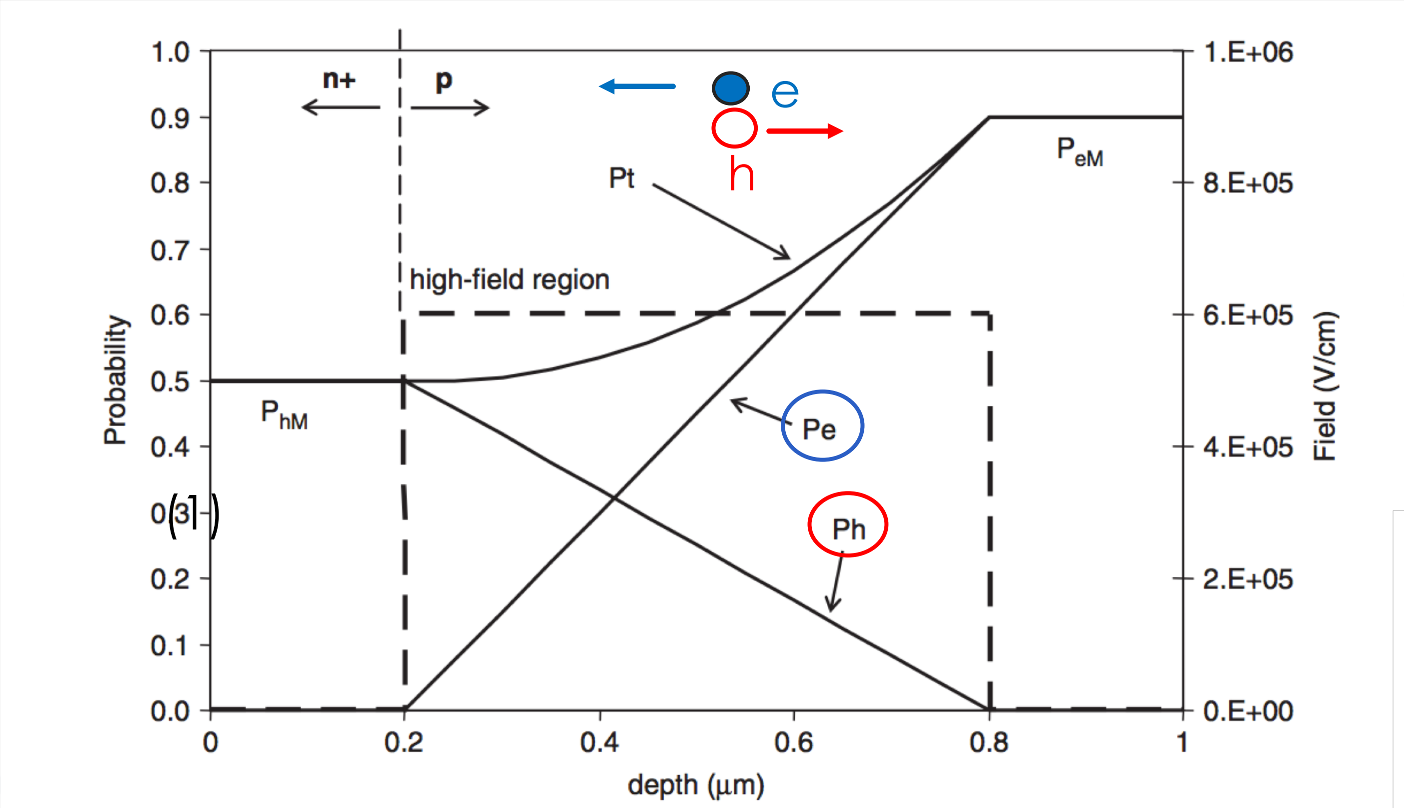


Avalanche triggering probability vs photo-absorption position (ref. 1)

$$P_t = 1 - (1 - P_e) \times (1 - P_h) = P_e + P_h - P_e P_h$$

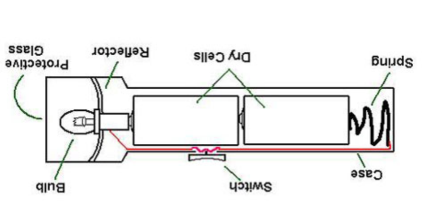
P_t = total triggering probability
P_e= electron triggering probability
P_h= hole triggering probability

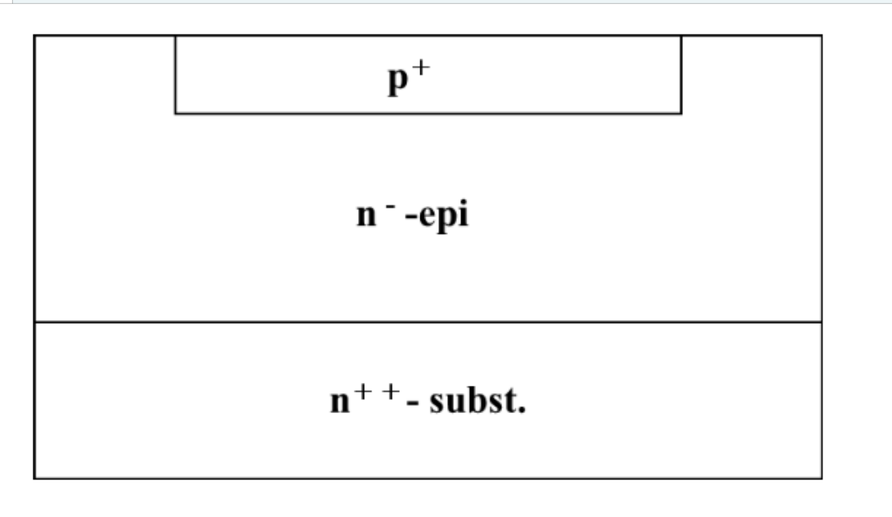
I have to tailor my junction to maximize the probability to trigger an avalanche:



p-on- junction:

- Optimizedfor blue
- Fair enough for green
- Worse for red

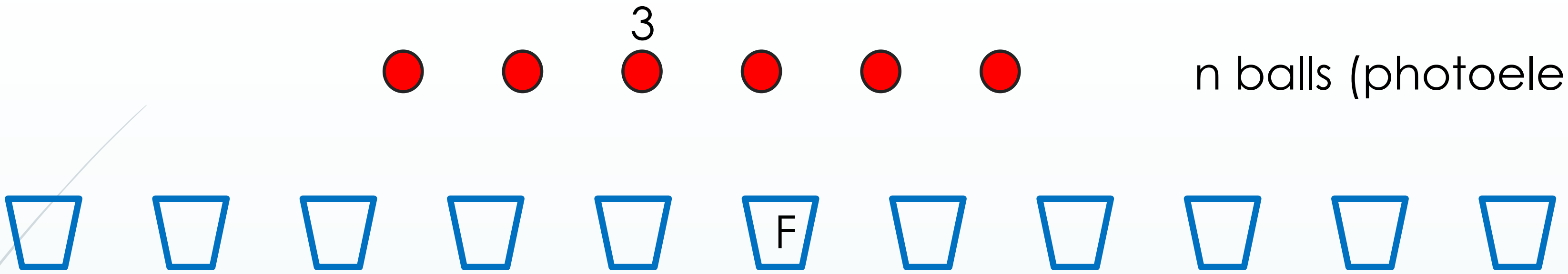




Holes & electrons were not born equal and the ionization rate of "e" is about double wrt "h"

⇒ if I go to p-on-n and I have a shallow junction, I maximize the triggering probability also for blue light

About balls & baskets [see also Stoykov et al., 2007 JINST 2 P06005]



n balls (photoelectrons)

m baskets (cells)

Presume that the balls are randomly thrown into the baskets. Then:

❖ The probability of a ball (say 3) to get into a specific basket (say F) is $1/m = m^{-1}$

⇒ The probability of NOT being hit is $(1-m^{-1})$

⇒ The probability that NONE of the n balls enters F is $(1-m^{-1})^n$
(assuming the events to be uncorrelated)

⇒ The probability to have ONE OR MORE balls in F is $p=(1-(1-m^{-1})^n)$)

❖ But F is like any other basket ⇒ I can turn the problem in the same category of the "coin toss" statistics (Bernoullian or Binomial), where the coin is not a fair coin but the probability to get "head" is p:

⇒ The mean number of baskets having at least one ball is $\bar{N} = m \times p$

⇒ The standard deviation in the number of cells having at least one ball is $\sigma = \sqrt{m \times p \times (1-p)}$

As long as the number of baskets (cells) is large,

$$1 - m^{-1} \simeq e^{-\frac{1}{m}}$$

$$p \simeq 1 - e^{-\frac{n}{m}} = 1 - e^{-\frac{N_{photons} \times PDE}{N_{cells}}}$$

And I get the magic formula (together with the fact that the standard deviation in the response, i.e. the fluctuations, do increase since the response is affected by the randomness of the detection process)

About the ENF: formulas can help you in a very effective way to perform a comparison between different solutions/technologies

Referring again to APD, another relevant figure of merit is the Excess Noise Factor (ENF), essentially measuring the fluctuations due to the multiplication process:

$$ENF = \left(\frac{SNR_{in}}{SNR_{out}}\right)^2$$

where $$SNR = \frac{Signal}{Noise}$$

and $$SNR_{in} = \sqrt{N}$$

Being N the number of photo-electrons and presuming Poissonian fluctuations

Since*:

$$ENF_{SiPM} = \frac{1+P_{AP}}{1+ln(1-P_{Xtalk})}$$

- P_{AP} = After-pulsing probability
- P_{xtalk} = Cross-talk probability

*Sergey Vinogradov, Advanced Photon Counting Techniques VI, edited by Mark A. Itzler, Joe C. Campbell, Proc. of SPIE Vol. 8375, 83750S, 2012

Assuming 5% after-pulsing and 10% Optical cross talk, I have $ENF_{SiPM} = 1.17$,
To be compared to these exemplary figures for APD:

Typical values of k, X and F for Si, Ge and InGaAs

Detector Type	Ionization Ratio	X-Factor	Typical Gain	Excess Noise Factor (at typical gain)
	(k)	-	(M)	(F)
Silicon ("reach-through" structure)	0.02	0.3	150	4.9
Silicon Epitaxial APDs	0.06	0.45	100	7.9
Silicon (SLiK™ low-k structure)	0.002	0.17	500	3.0
Germanium	0.9	0.95	10	9.2
InGaAs	0.45	0.7- 0.75	10	5.5

EXCELITAS TECHNOLOGIES

Avalanche Photodiodes: a user's guide