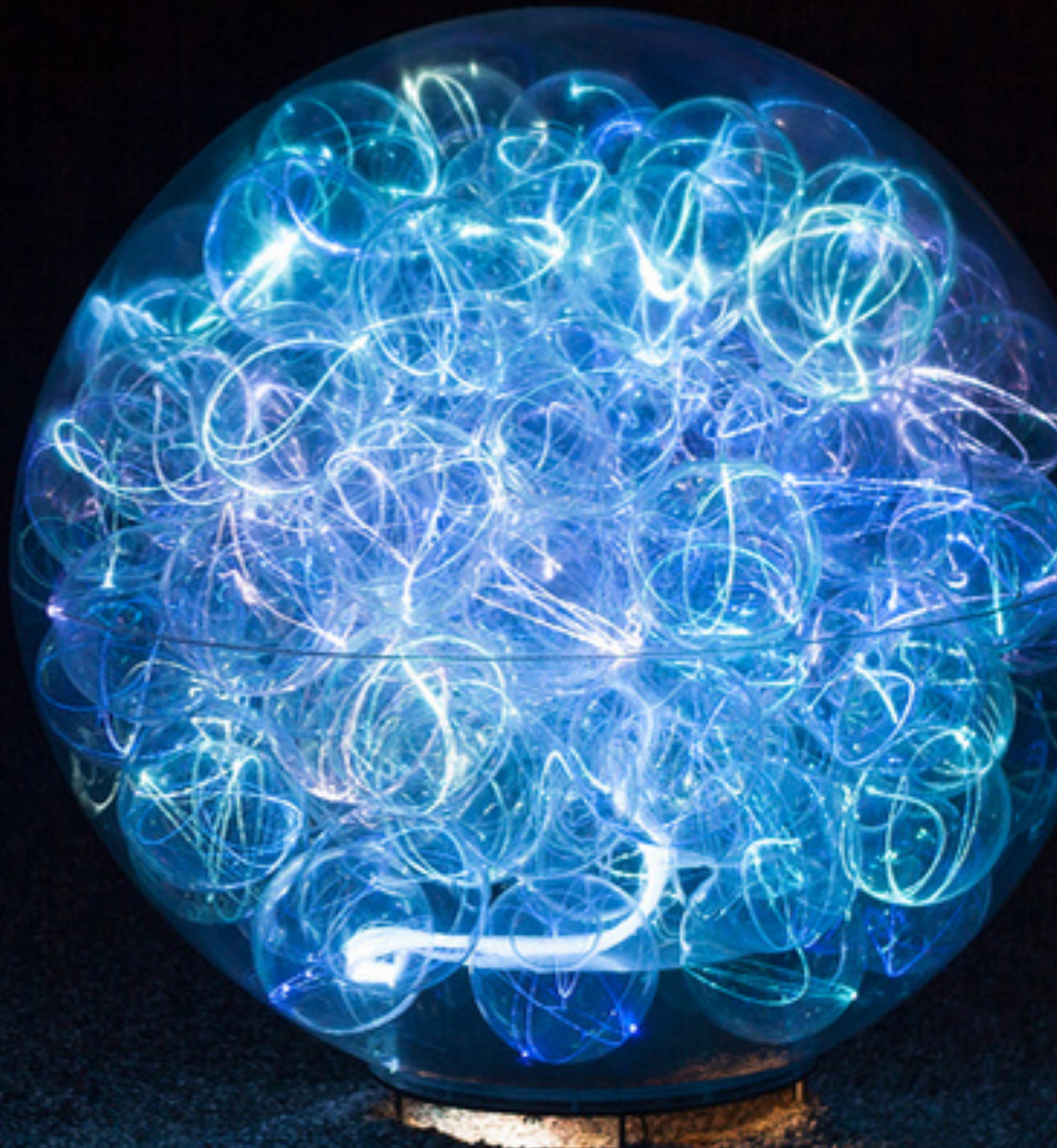
The Power of One

Part 1
Basic principles & main features

Dipartimento di Fisica
Università di Torino
May 11th, 2017

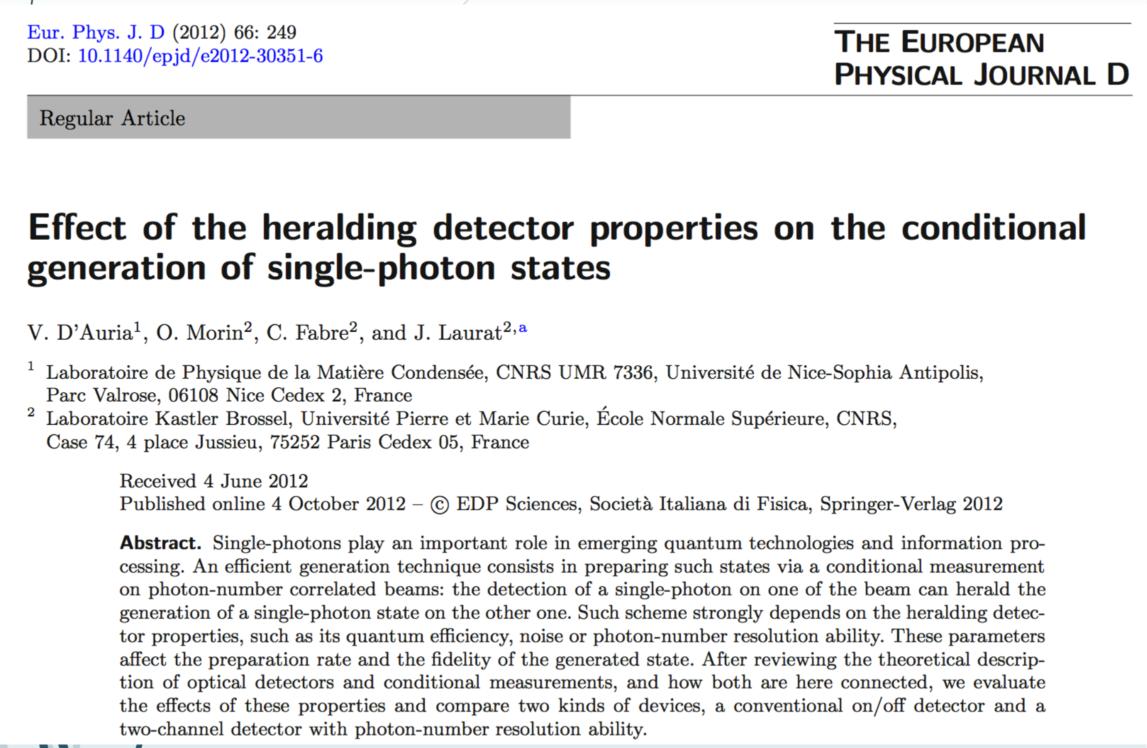
Massimo Caccia
Dipartimento di Scienza & Alta Tecnologia
Uni. Insubria @Como, Italy
Massimo.caccia@uninsubria.it



March 11th, 2017 Issue

[QuantumLeaps - March 2017]

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

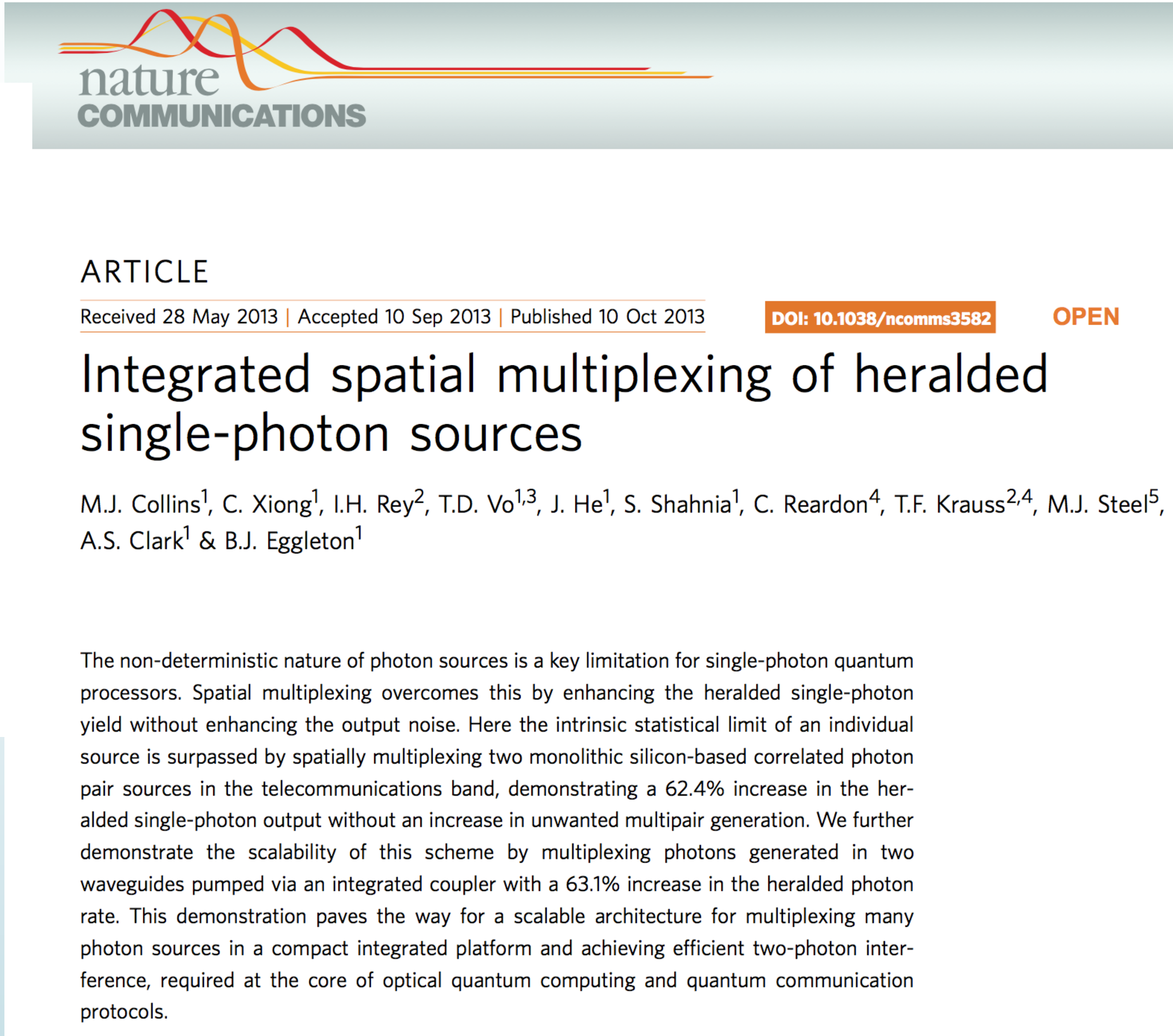
Effect of the heralding detector properties on the conditional generation of single-photon states

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.



nature COMMUNICATIONS

ARTICLE

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

DOI: 10.1038/ncomms3582

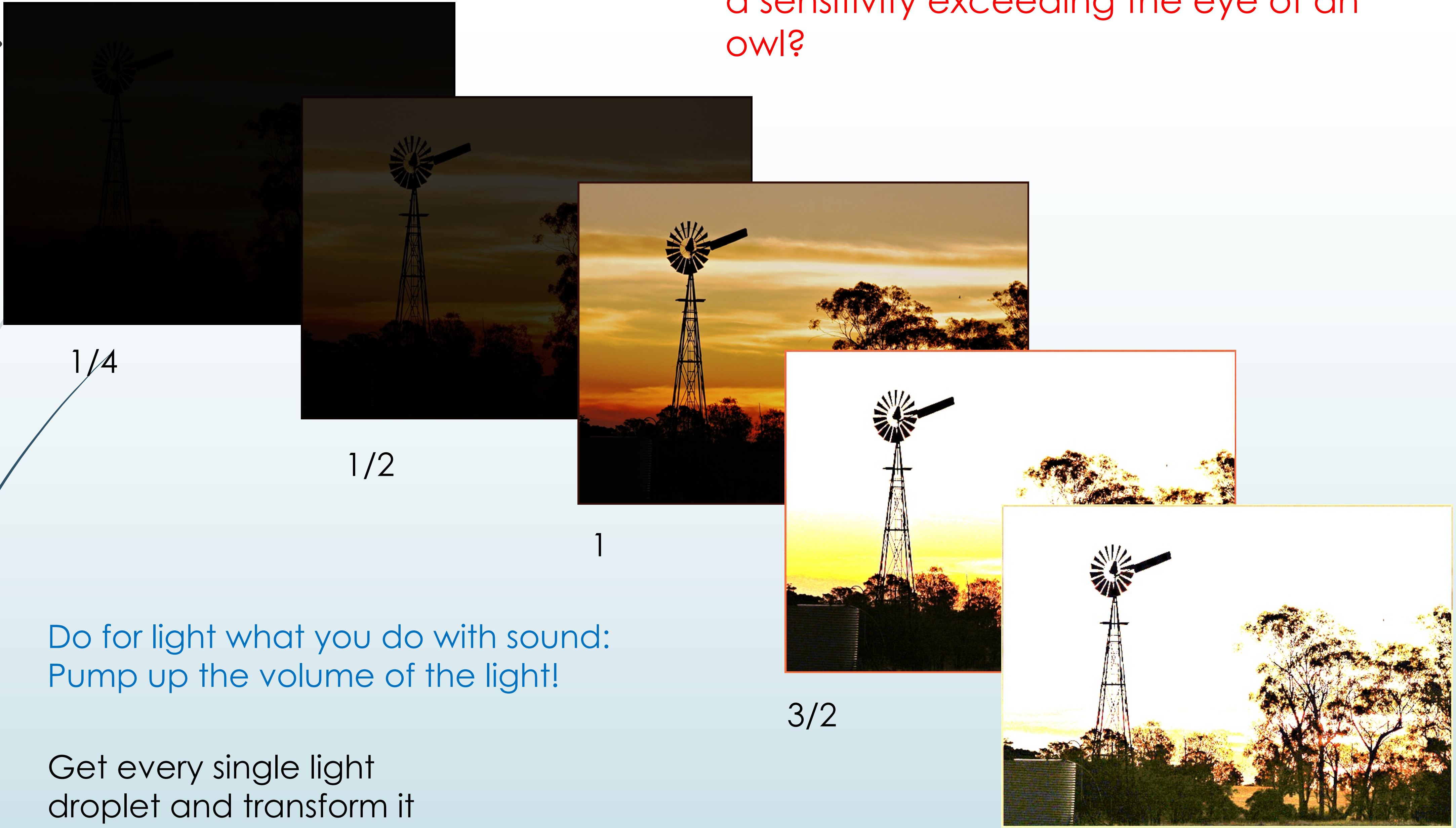
OPEN

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.

How can I see in the night and having a sensitivity exceeding the eye of an owl?



1/4

1/2

1

3/2

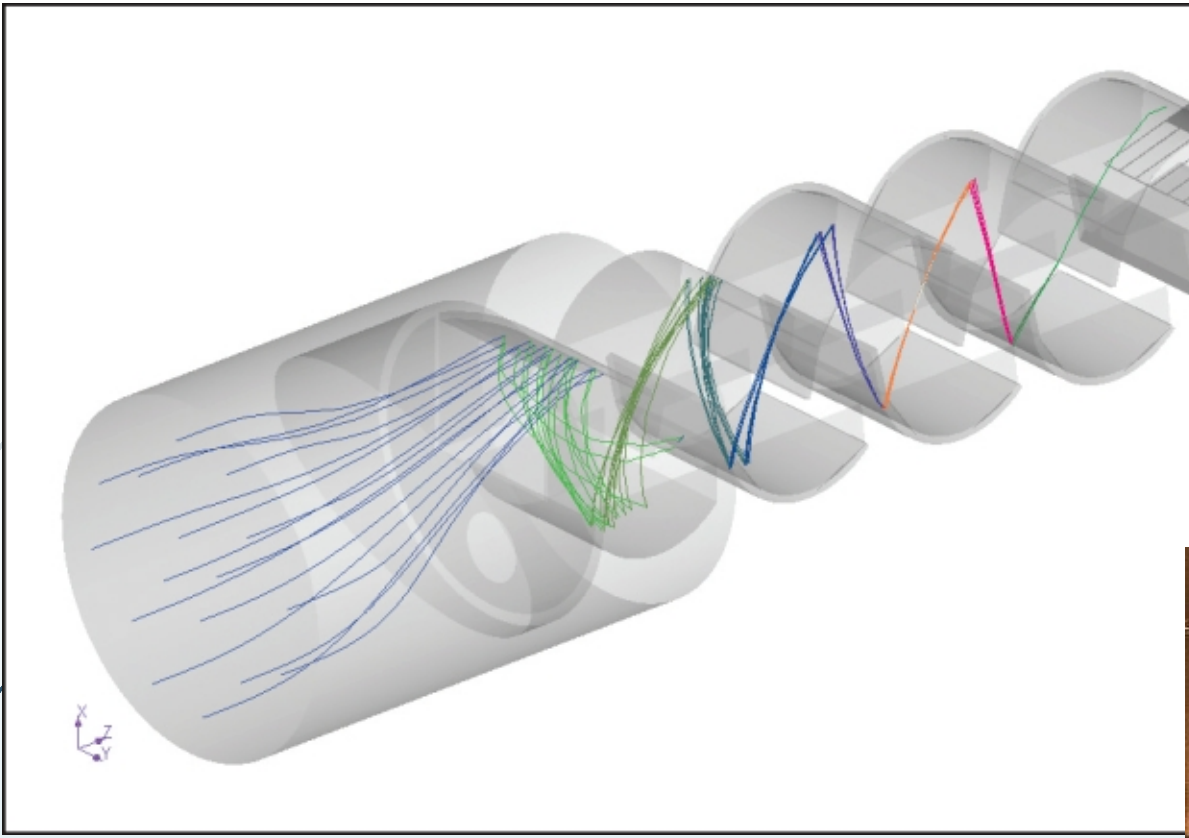
7/4

Do for light what you do with sound:
Pump up the volume of the light!

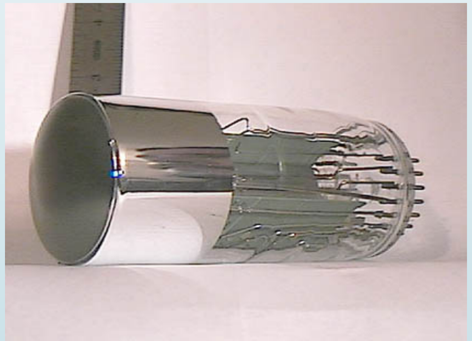
Get every single light droplet and transform it into a heavy shower…

The pre-Silicon age:

the photomultiplier, a solid rock technology since 1934

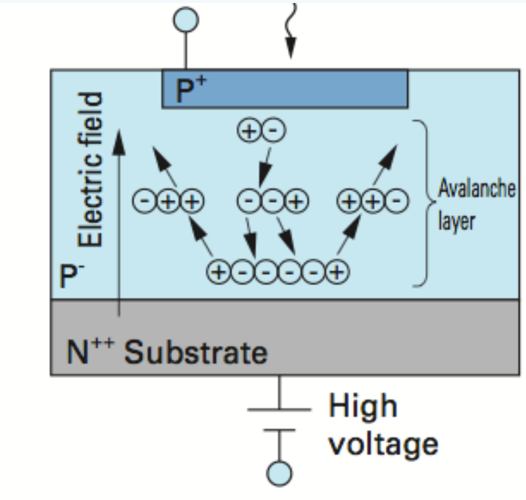


The ENIAC



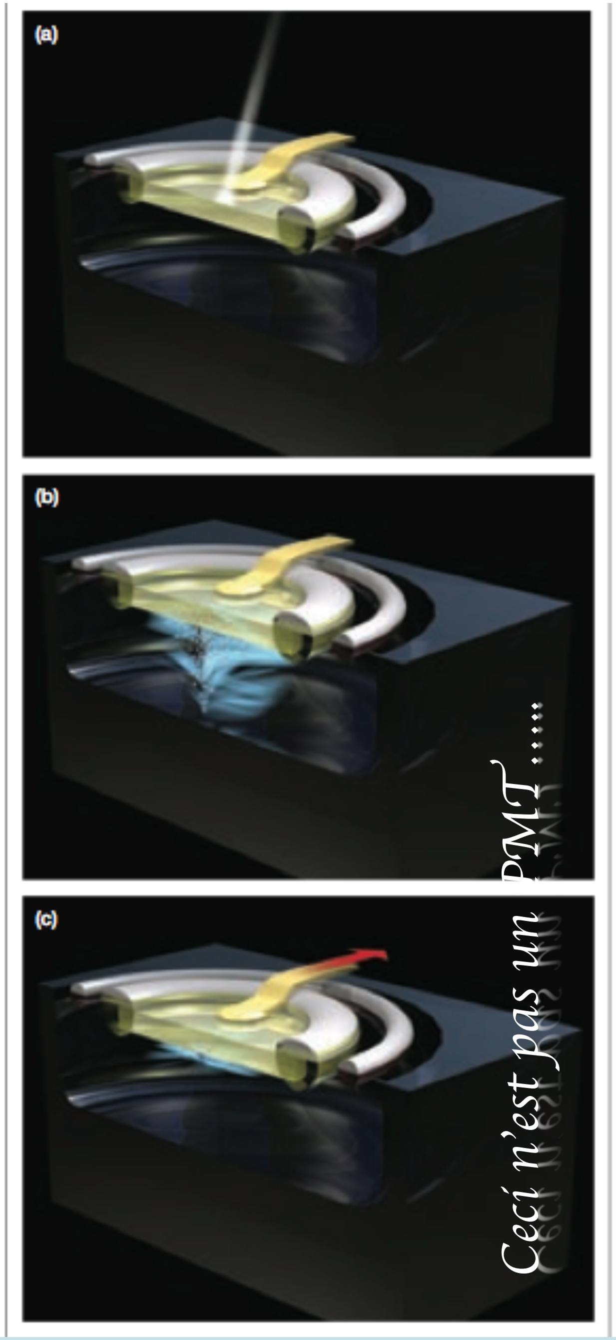
Photon absorption and avalanche ignition in a Single Photon Avalanche Photodiode (SPAD)

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



Mean free path
≈ 0.01 μm

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

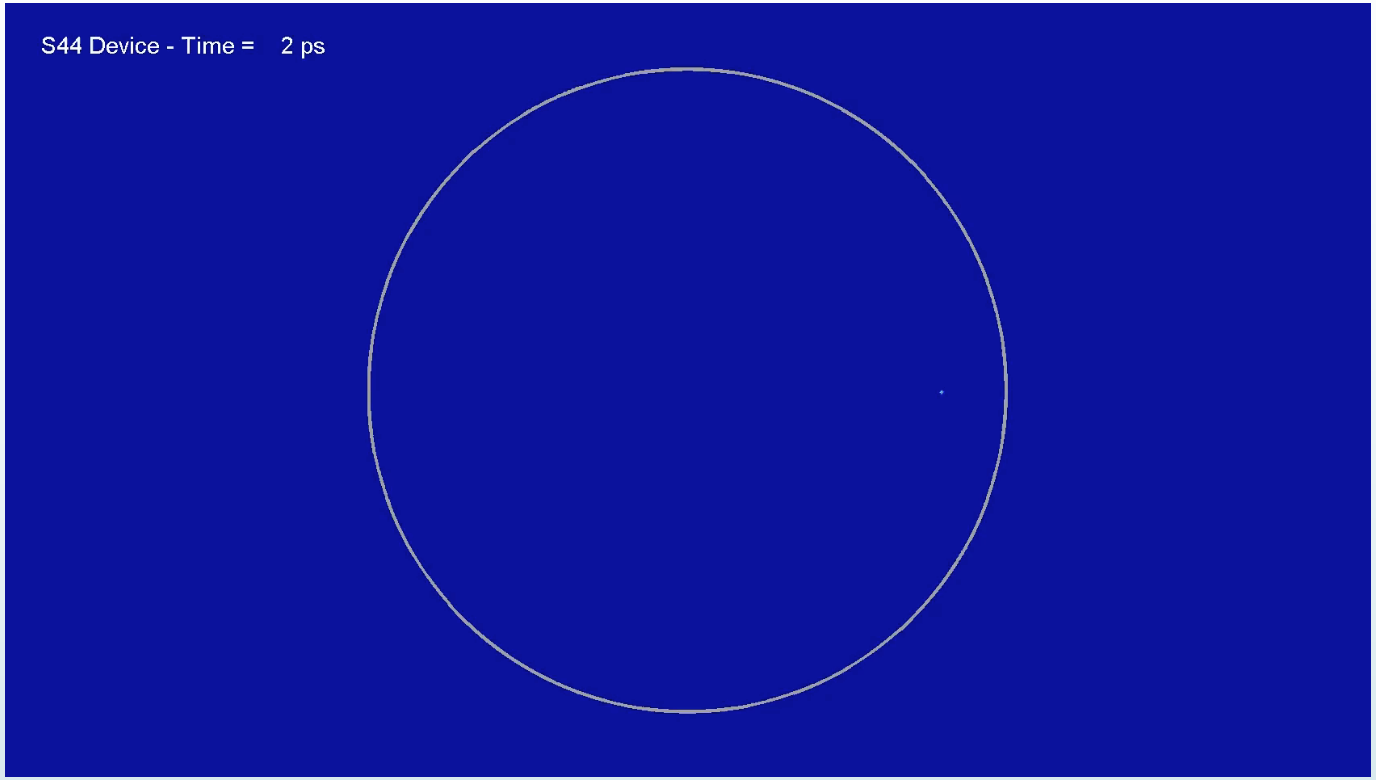


Ceci n'est pas un PMT …..

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

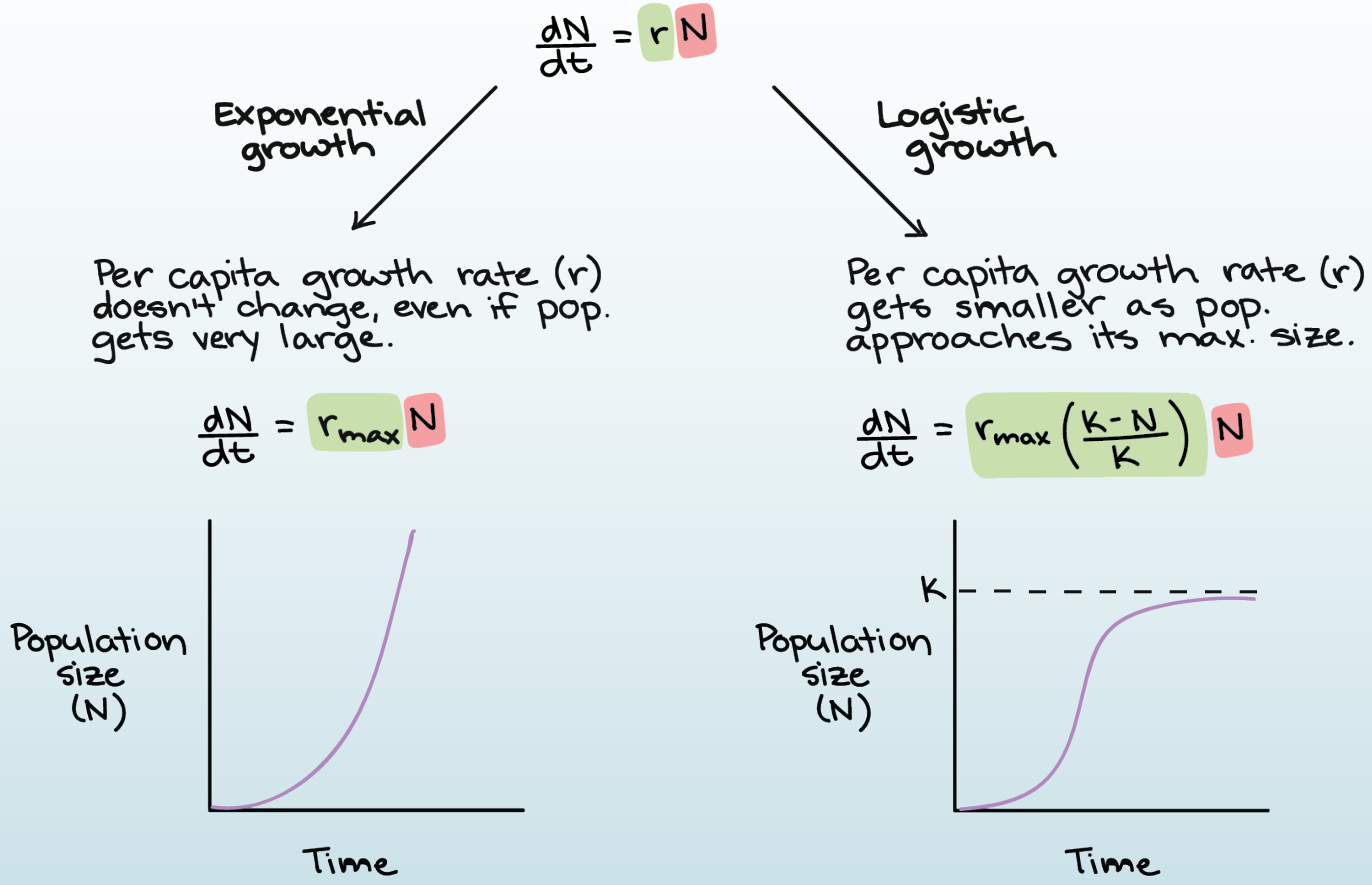
A multiplication game in Silico

Courtesy Ivan Rech, Politecnico di Milano



- 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
- 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

Exponential growth, logistic curves & more



$$\frac{dN}{dt} = rN$$

Exponential growth

Per capita growth rate (r) doesn't change, even if pop. gets very large.

$$\frac{dN}{dt} = r_{max}N$$

Logistic growth

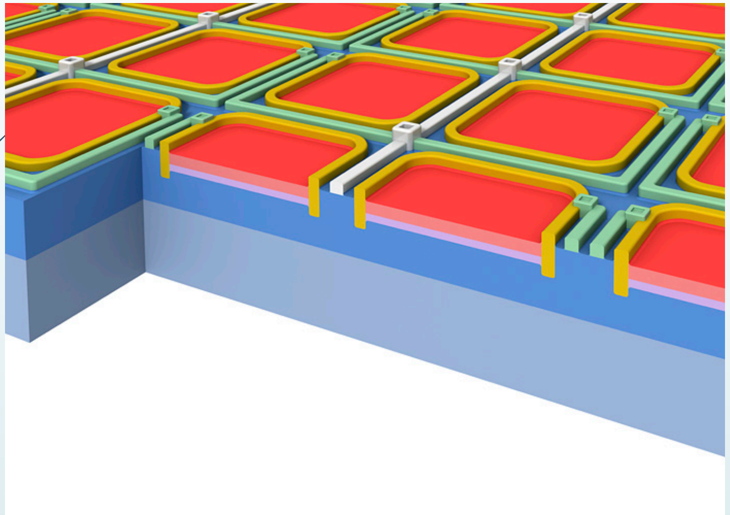
Per capita growth rate (r) gets smaller as pop. approaches its max. size.

$$\frac{dN}{dt} = r_{max}\left(\frac{K-N}{K}\right)N$$

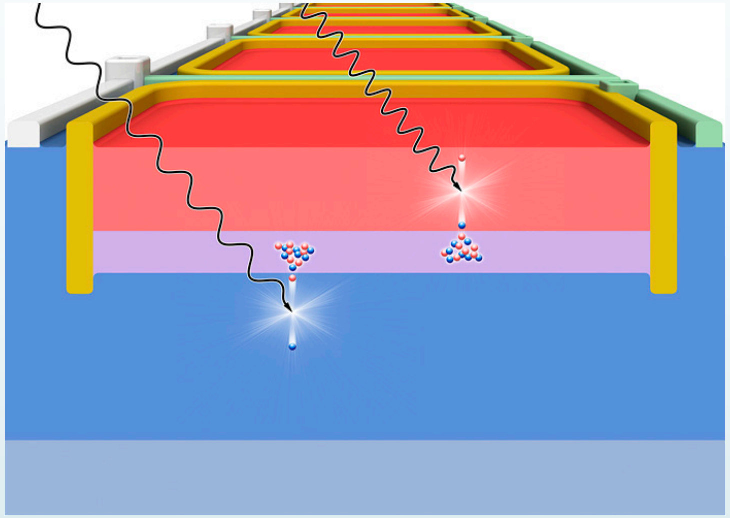
https://www.khanacademy.org/science/biology/ecology/population-growth-and-regulation/a/exponential-logistic-growth

Silicon PhotoMultiplies (someone still calls them MultiPixel Photon Counters, MPPC): in essence, an array of SPADs

Principle



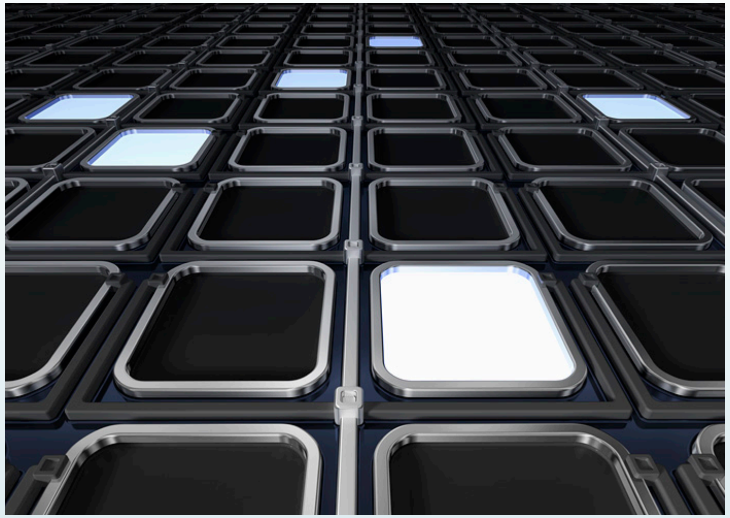
SiPM = High density (~10^4/mm^2) matrix of diodes with a common output, reverse biased, working in Geiger-Müller regime



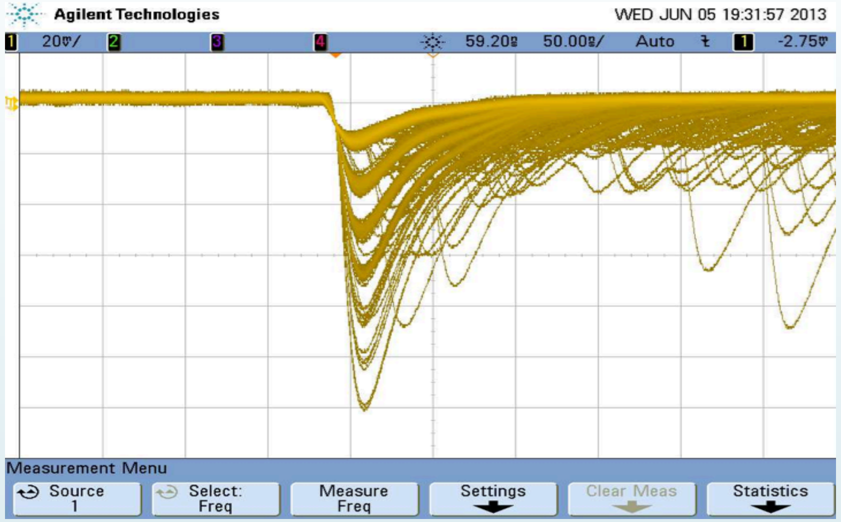
When a photon hits a cell, the generated charge carrier triggers an avalanche multiplication in the junction by impact ionization, with gain at the 10^6 level

Silicon PhotoMultipliers: genuine Photon Number Resolving detectors

Operation



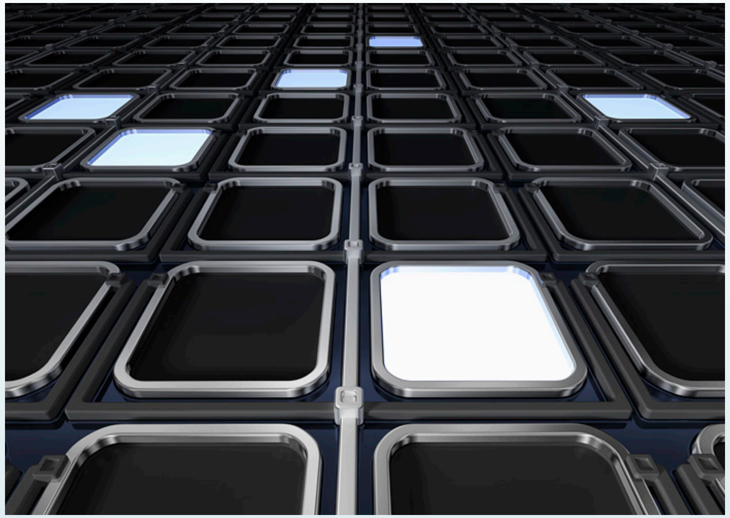
- SiPM may be seen as a collection of binary cells, fired when a photon in absorbed



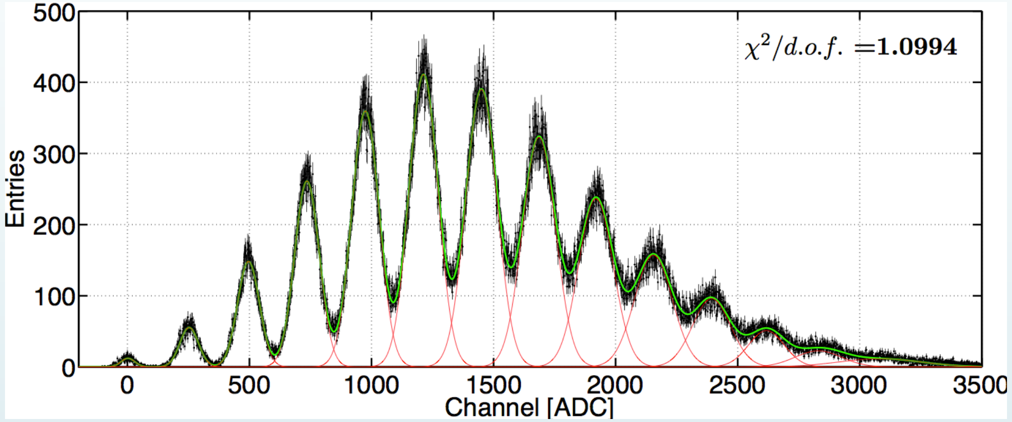
- “counting” cells provides an information about the intensity of the incoming light:

Silicon PhotoMultipliers: genuine 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:

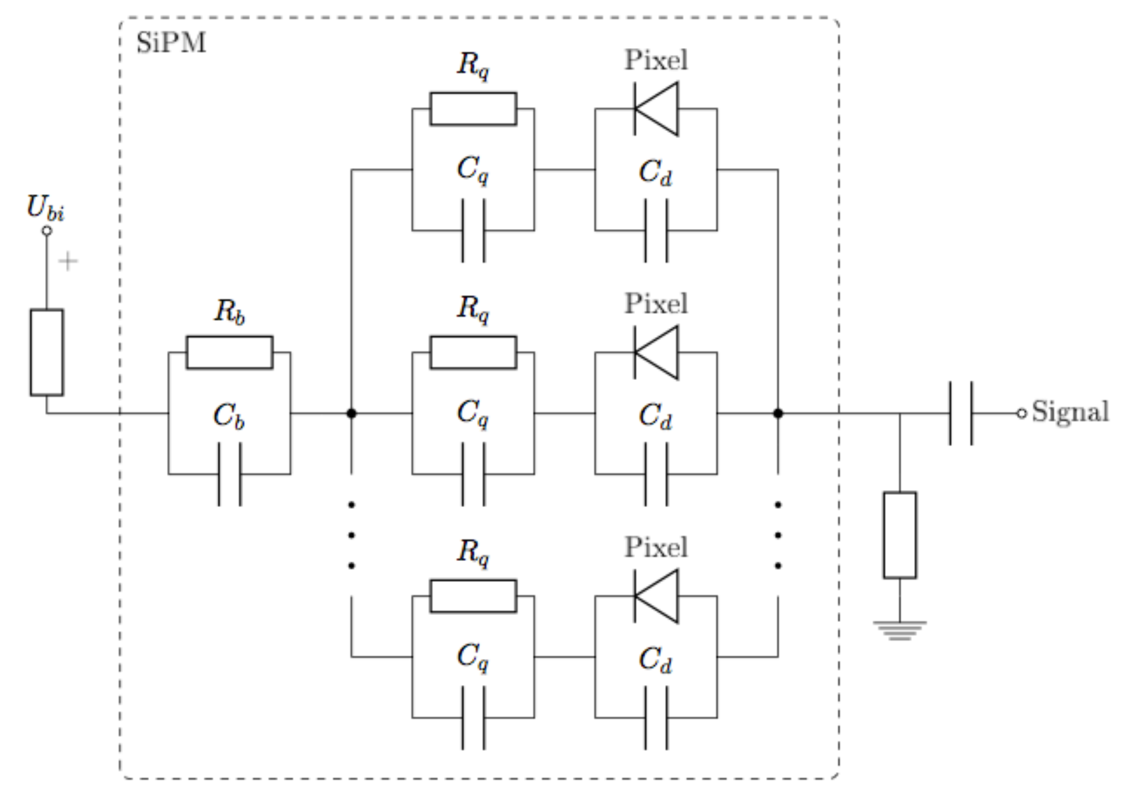
Is the world interested in these little toys?

No. of papers in Google Scholar with the exact match of "silicon photomultiplier" in the title/abstract/body

Year	# papers
2000-2001	11
2002-2003	31
2004-2005	82
2006-2007	211
2008-2009	366
2010-2011	603
2012-2103	1117
2014-2015	1320
2016-Feb-2017	772

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



- exponential pulse with

$$\tau = R_q C_D$$

- Gain:

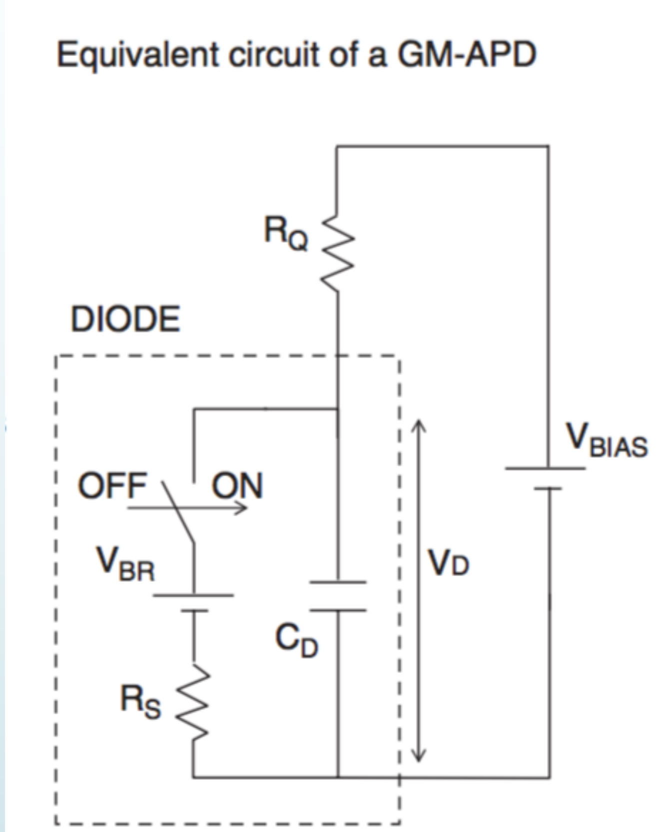
$$G = \frac{\left(V_{bias} - V_{Breakdown}\right) C_D}{e}$$

Typical values:

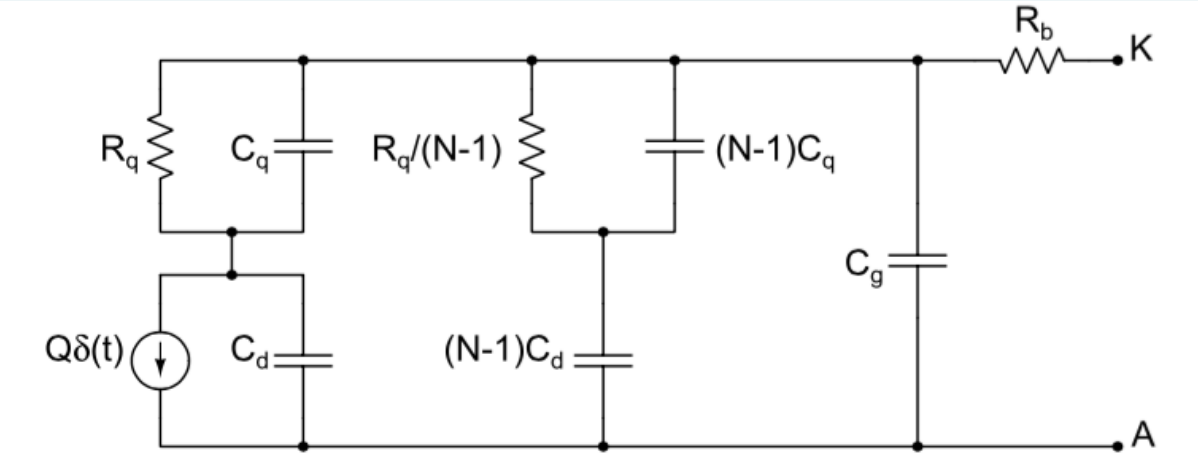
- R_q ~ 200 kΩ
- C_D ~ 100 fF (30x30 μm^2)
- τ ~ 20 ns
- $V_{breakdown}$ ~ 50-70V
- G ~ 10^6

SiPM electrical model: a closer look

- 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

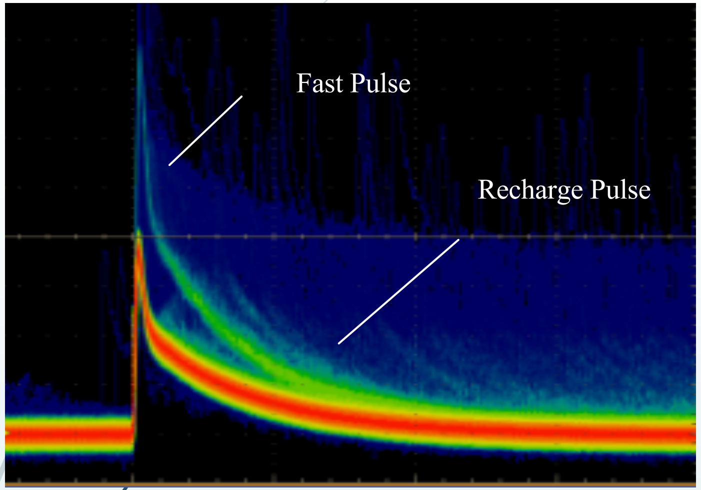


For a single cell (ref. 2, 2006)

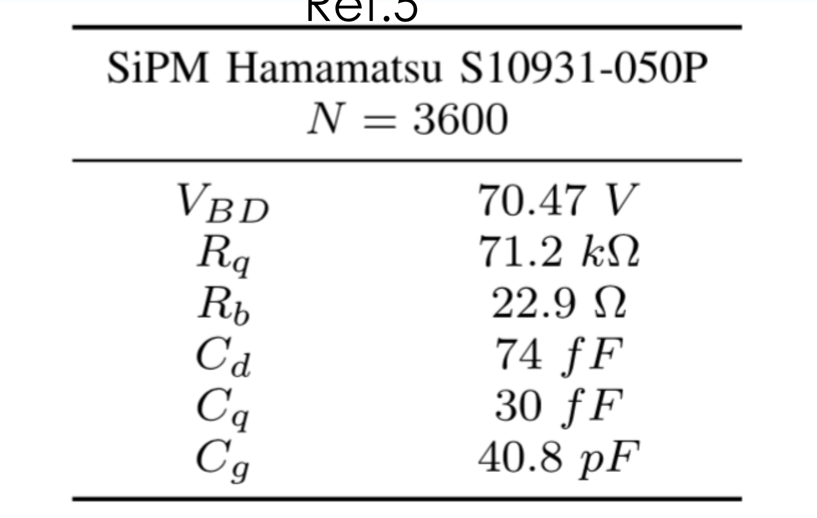


For the full array (ref. 5, 2016), one cell "triggering"
(fast response made easy as a "Dirac delta" of current)

SiPM electrical model: time development of the signal & parameters

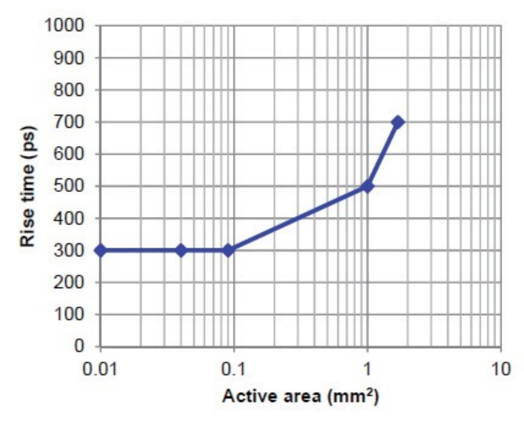


Ref.5



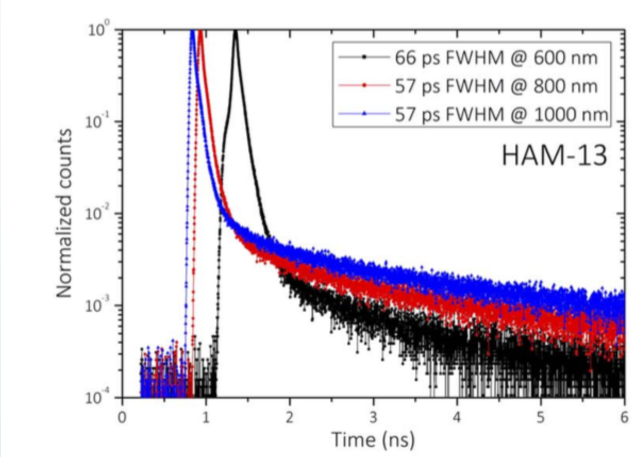
SiPM Hamamatsu S10931-050P $N = 3600$	
V_{BD}	$70.47\ V$
R_q	$71.2\ k\Omega$
R_b	$22.9\ \Omega$
C_d	$74\ fF$
C_q	$30\ fF$
C_g	$40.8\ pF$

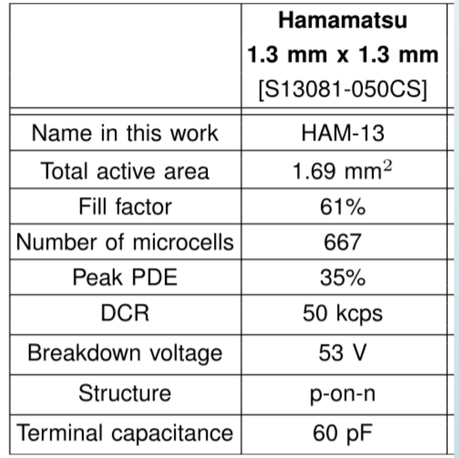
- ❖ Fast Pulse:
  $\tau_{FP} = R_S \times (C_D+C_Q)$
- ❖ Recharge Pulse:
  $\tau_{RP} = R_Q \times (C_D+C_Q)$



Courtesy of HAMAMATSU Photonics

The little secret behind this astonishing result: a Single Photon Timing resolution at the 60 ps level

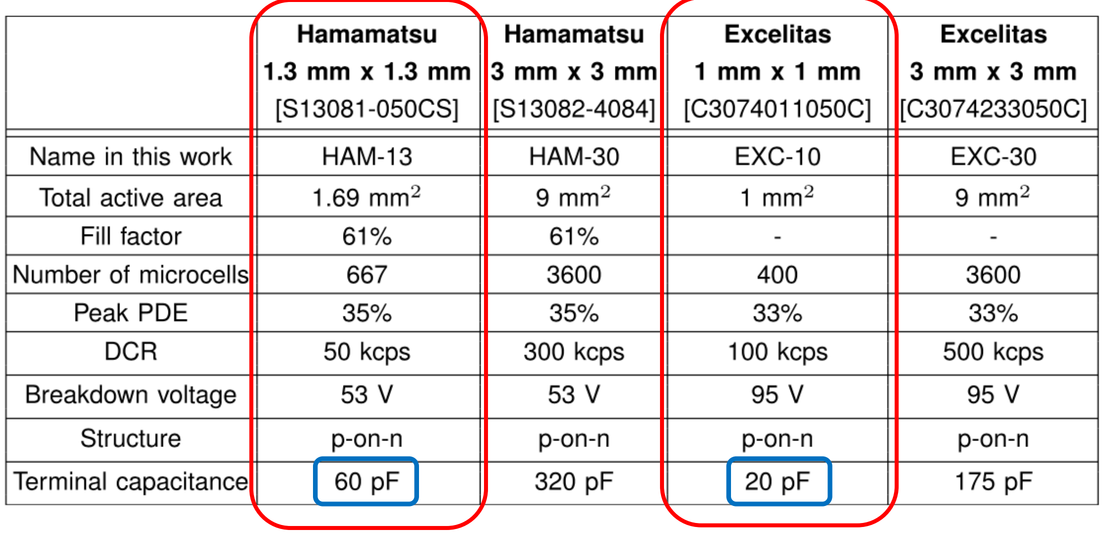




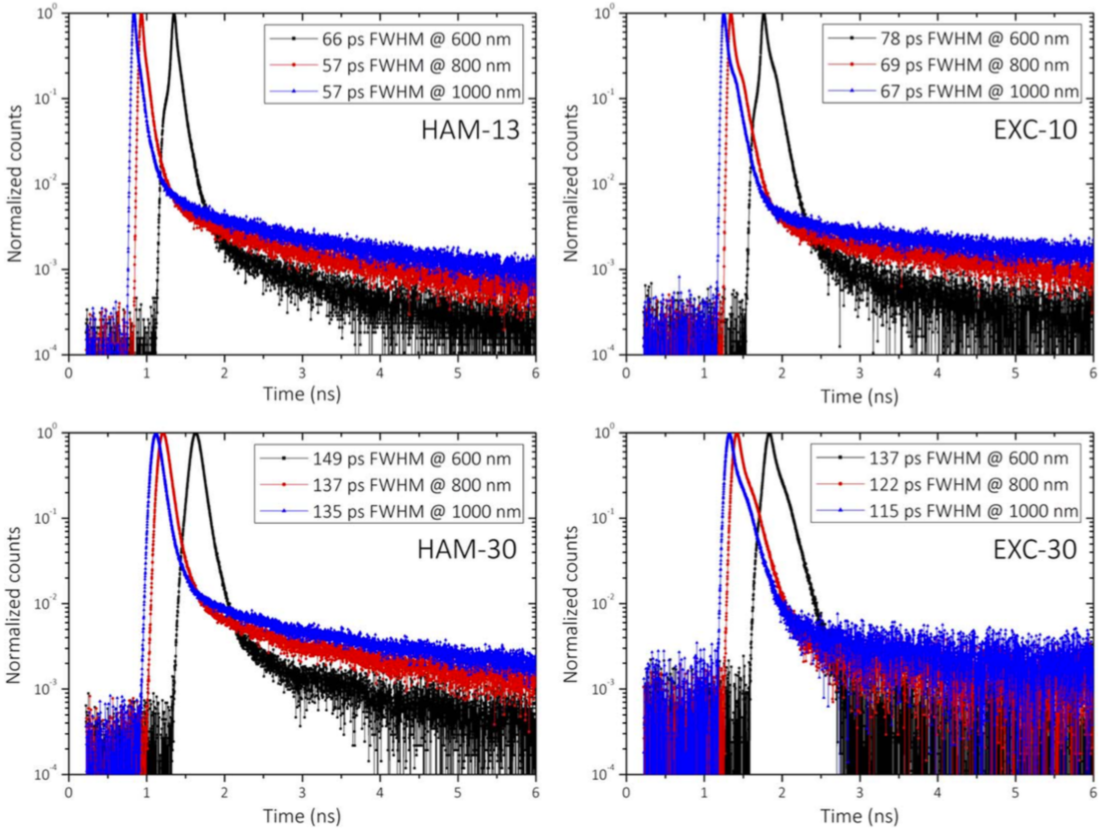
	Hamamatsu 1.3 mm x 1.3 mm [S13081-050CS]
Name in this work	HAM-13
Total active area	1.69 mm^2
Fill factor	61%
Number of microcells	667
Peak PDE	35%
DCR	50 kcps
Breakdown voltage	53 V
Structure	p-on-n
Terminal capacitance	60 pF

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

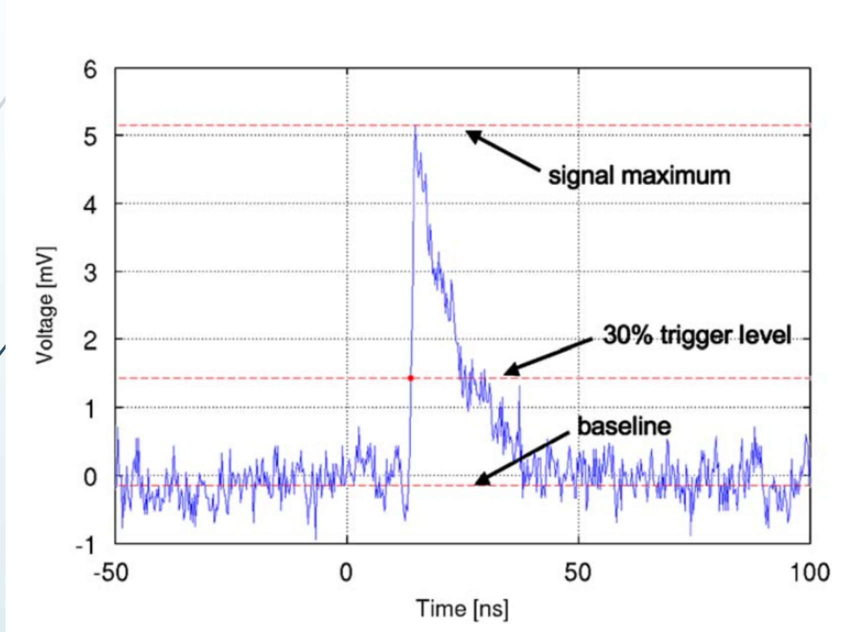
If the winner is clear, who were the competitors?



	Hamamatsu 1.3 mm x 1.3 mm [S13081-050CS]	**Hamamatsu 3 mm x 3 mm** [S13082-4084]	**Excelitas 1 mm x 1 mm** [C3074011050C]	**Excelitas 3 mm x 3 mm** [C3074233050C]
Name in this work	HAM-13	HAM-30	EXC-10	EXC-30
Total active area	1.69 mm^2	9 mm^2	1 mm^2	9 mm^2
Fill factor	61%	61%	-	-
Number of microcells	667	3600	400	3600
Peak PDE	35%	35%	33%	33%
DCR	50 kcps	300 kcps	100 kcps	500 kcps
Breakdown voltage	53 V	53 V	95 V	95 V
Structure	p-on-n	p-on-n	p-on-n	p-on-n
Terminal capacitance	60 pF	320 pF	20 pF	175 pF



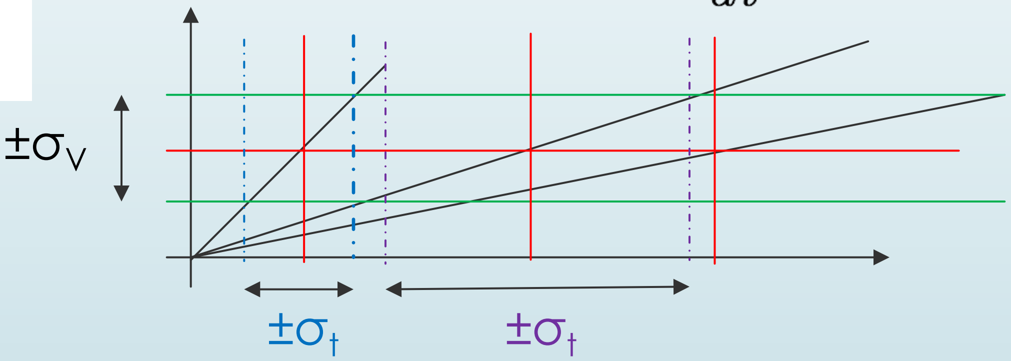
More about timing: impact of the shape of the signal and the number of photons (presuming they all come at once! It does not apply to timing with scintillation light) on time resolution



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

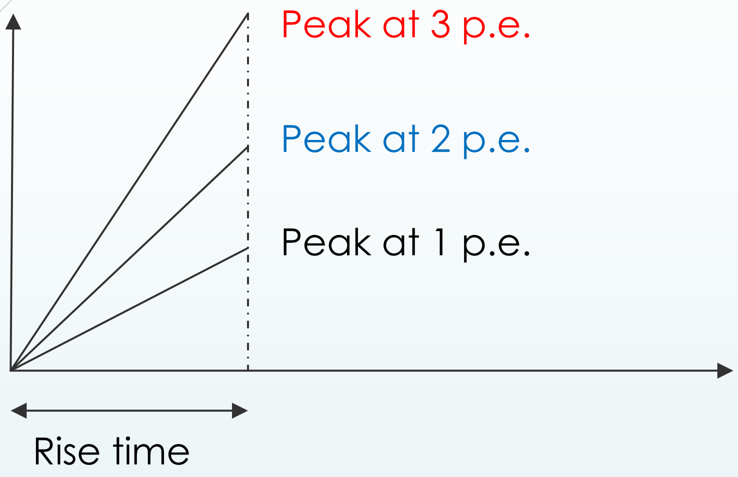
$$V = m \times t = \frac{dV}{dt} \times t$$

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



* 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

$$N \times \left.\frac{dV}{dt}\right|_{N=1}$$

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

- 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 $\sqrt{N}$, namely:

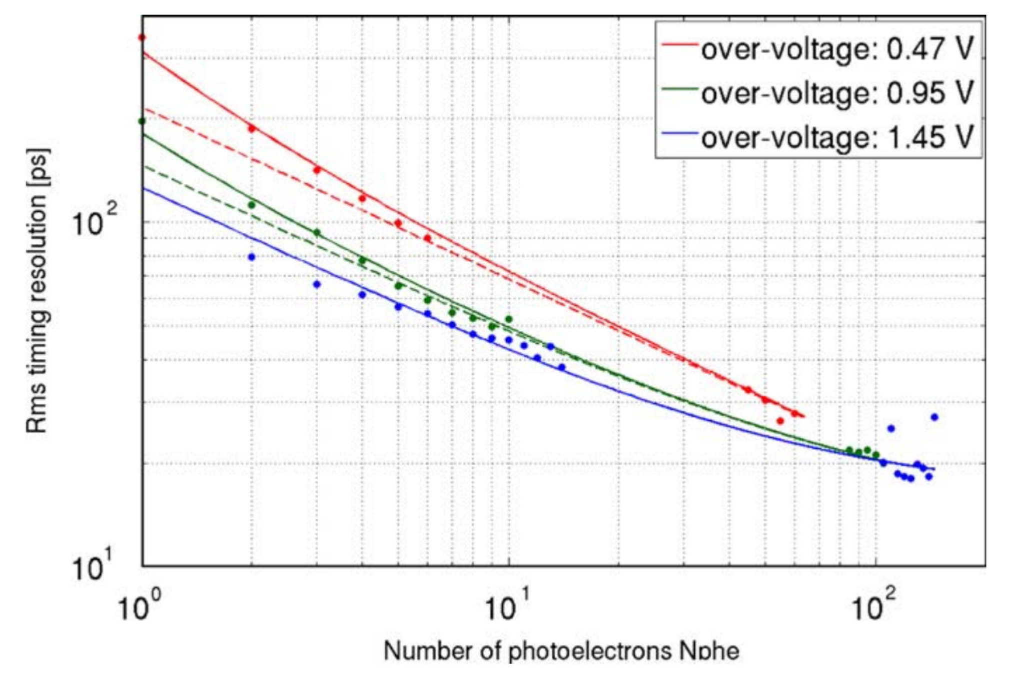
$$\Longrightarrow \quad \sigma_{N,arrival} = \frac{\sigma_{1,arrival}}{\sqrt{N}}$$

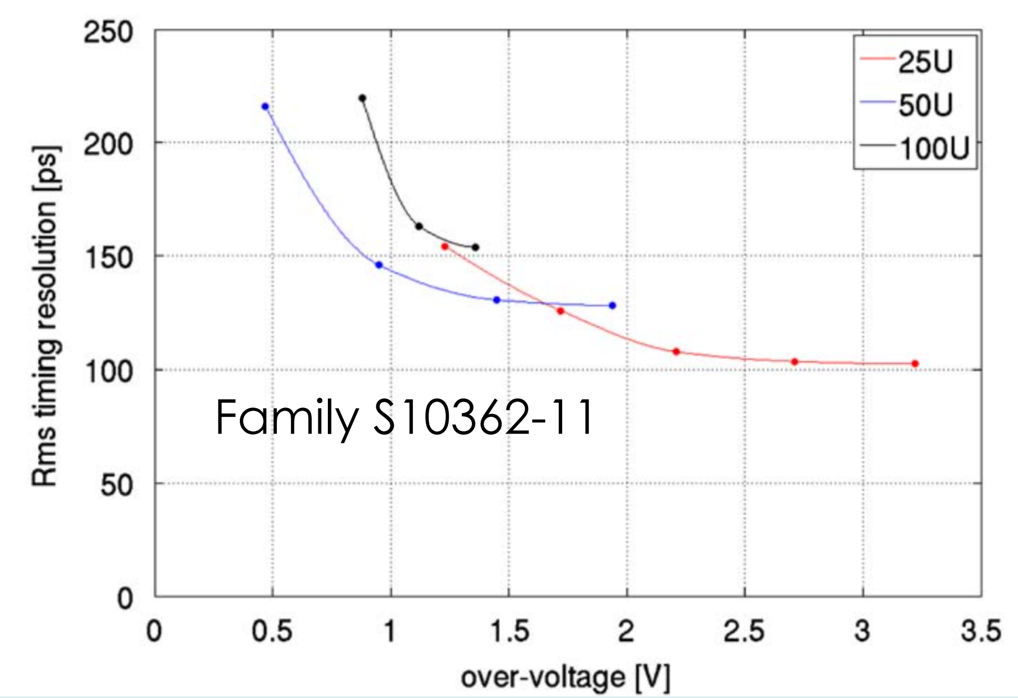
for a very nice analysis of the question see:

- F. Acerbi et al. Characterization of Single-Photon Time Resolution: From Single SPAD to Silicon Photomultiplier, IEEE TNS – for technology issues
- S. Mandai et al., Timing optimization utilizing order statistics and multichannel digital silicon photomultipliers, OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014 - for methodology

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

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





Family S10362-11

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

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

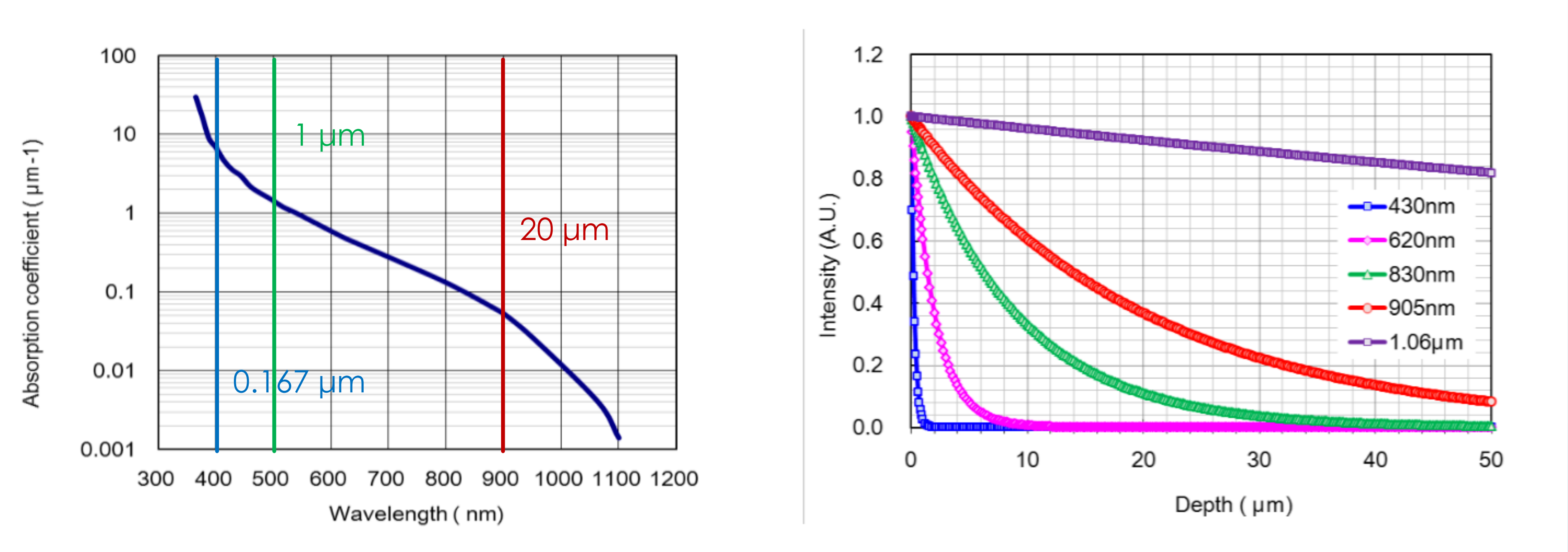
SiPM technology: what’s behind the spectral response

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:

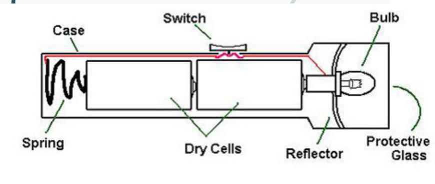
(ref.2)



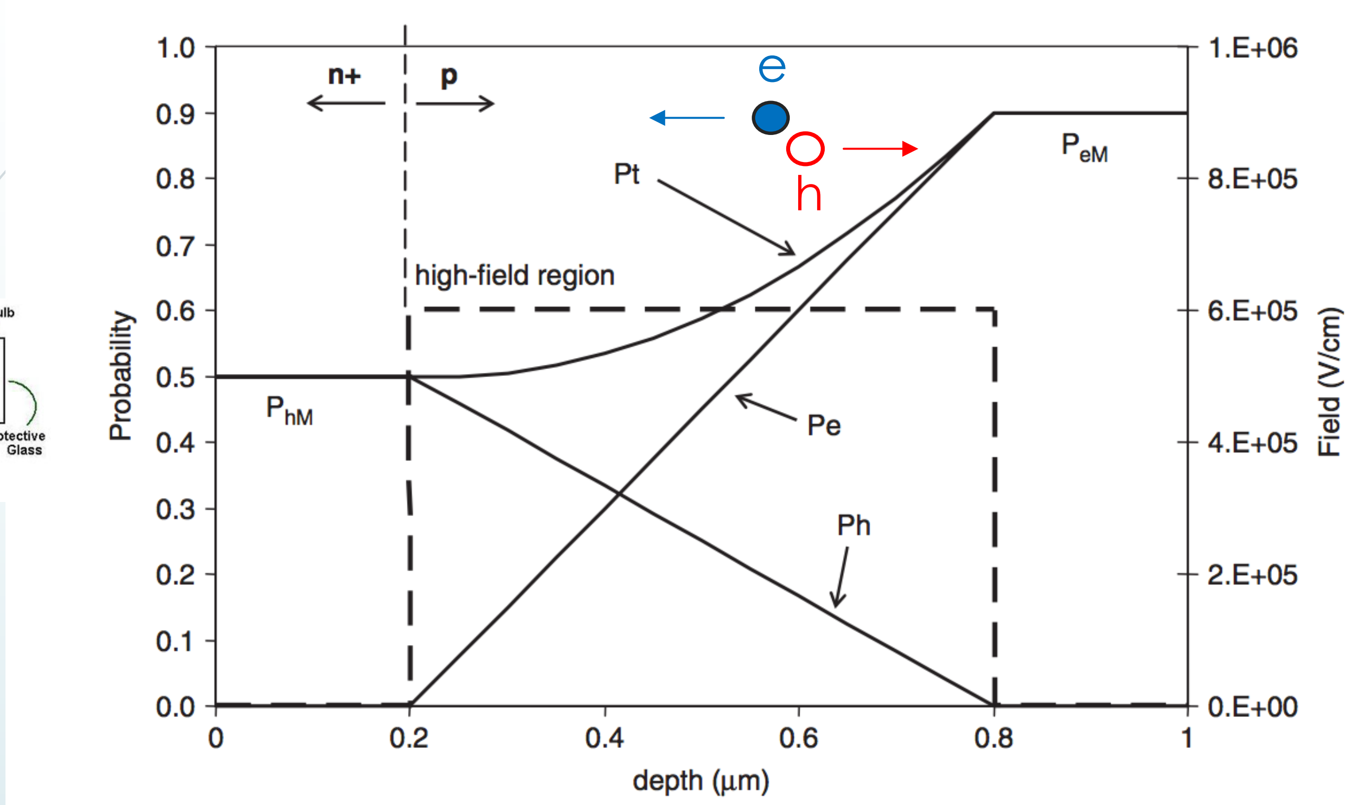
Absorption coefficient (µ) in [μm^{-1}] vs λ [nm]

Light attenuation vs depth [µm]

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



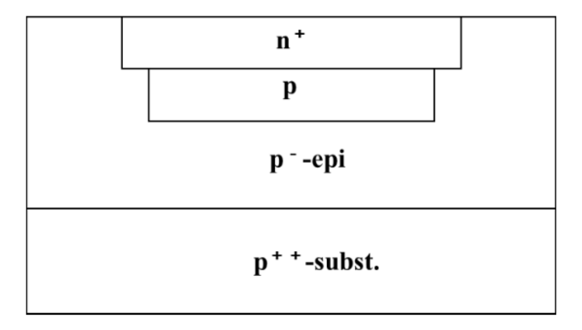
Light in



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

n-on-p junction:

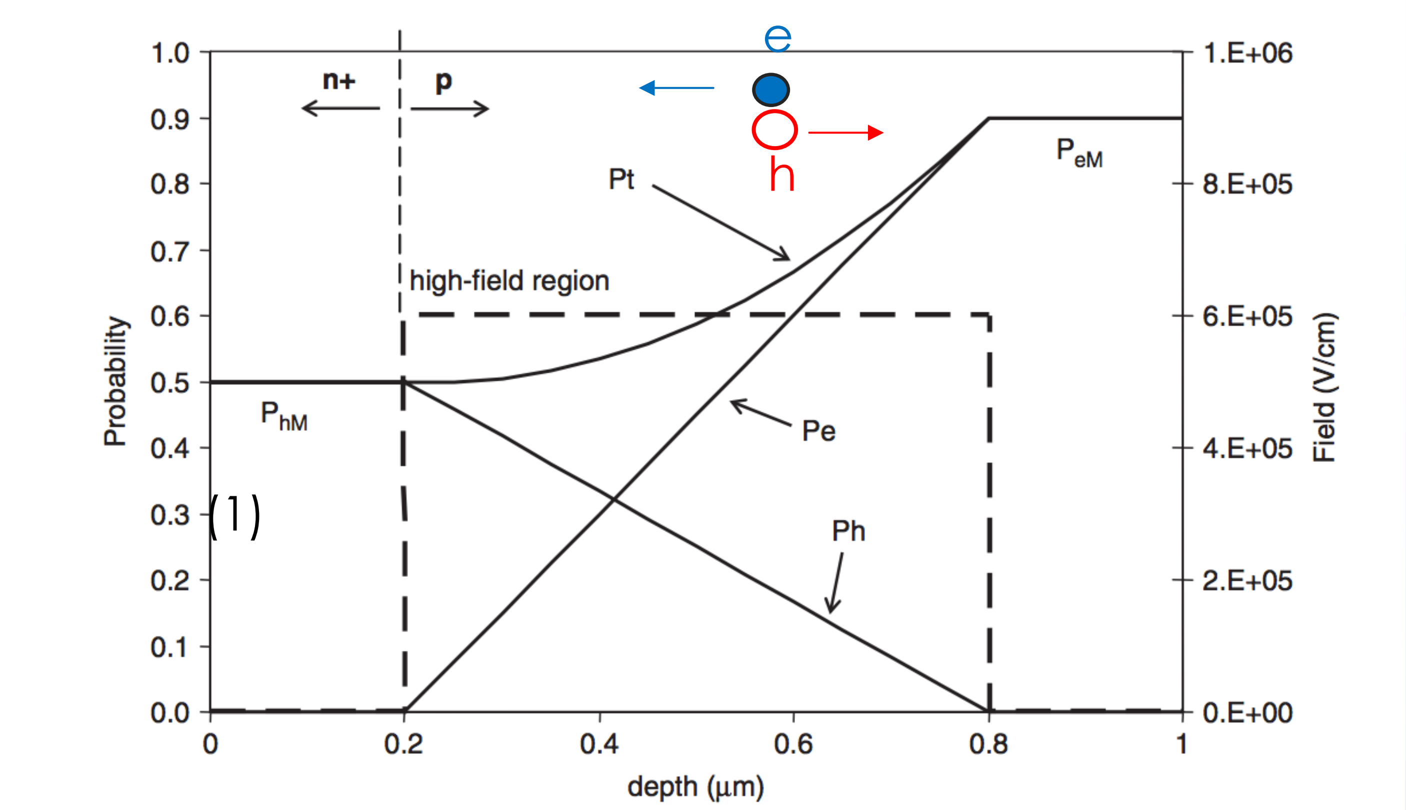
- Not ideal for blue
- Good enough for green
- Bad for red



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

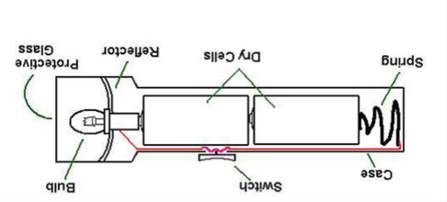
P_t = total triggering probability
P_e= electron triggering probability
P_h= hole triggering probability

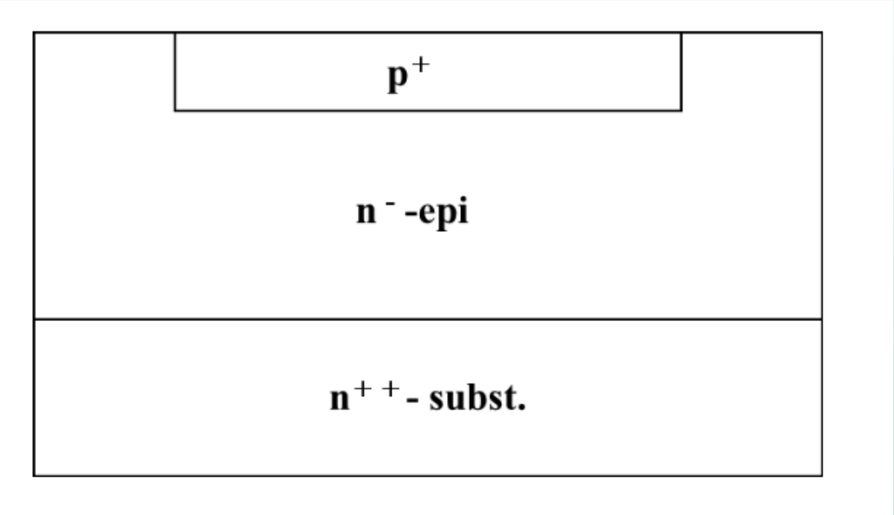
I have to tailor my junction to maximize the probability to trigger an avalanche:



p-on- junction:

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





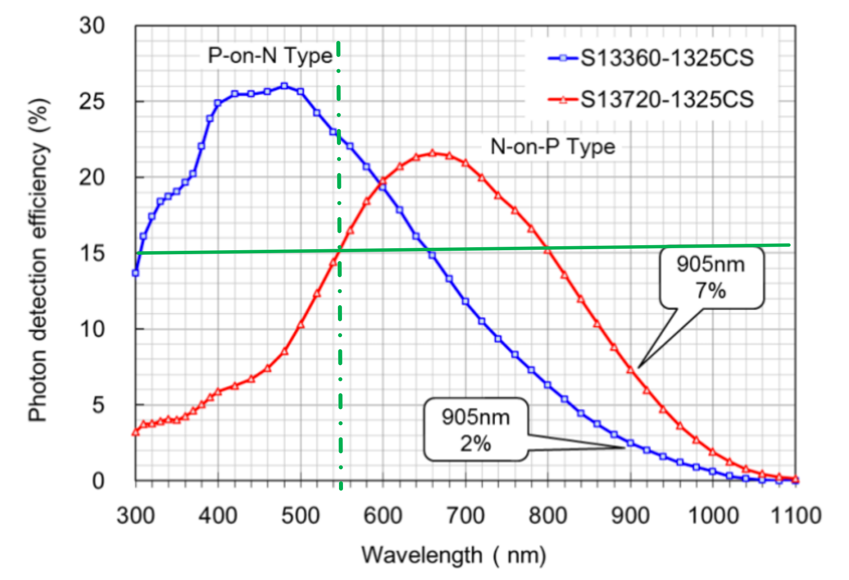
Holes & electrons were not born equal and the ionization rate of “e” is about double wrt “h”

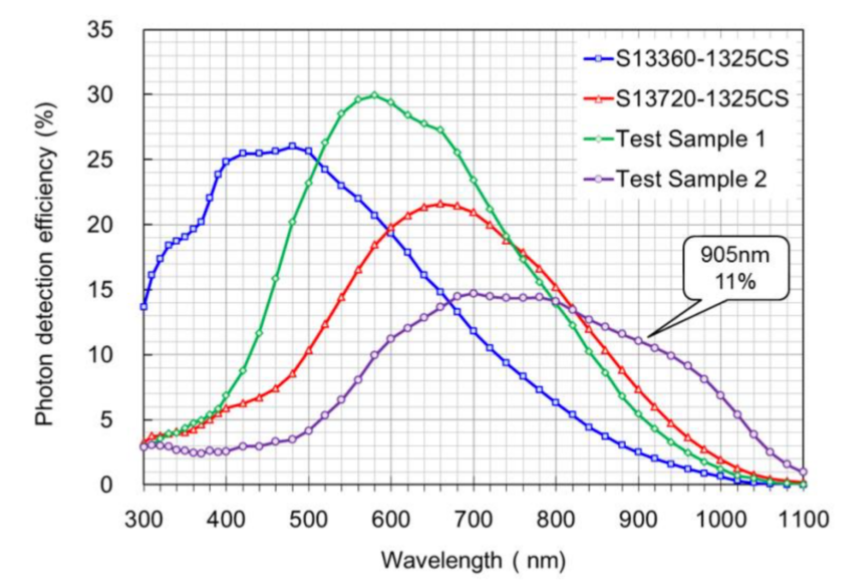
⇒ if I go to p-on-n and I have a shallow junction, I maximize the triggering probability also for blue light

Where are we today (2017)?

@HAMAMATSU:

(Ref.2)



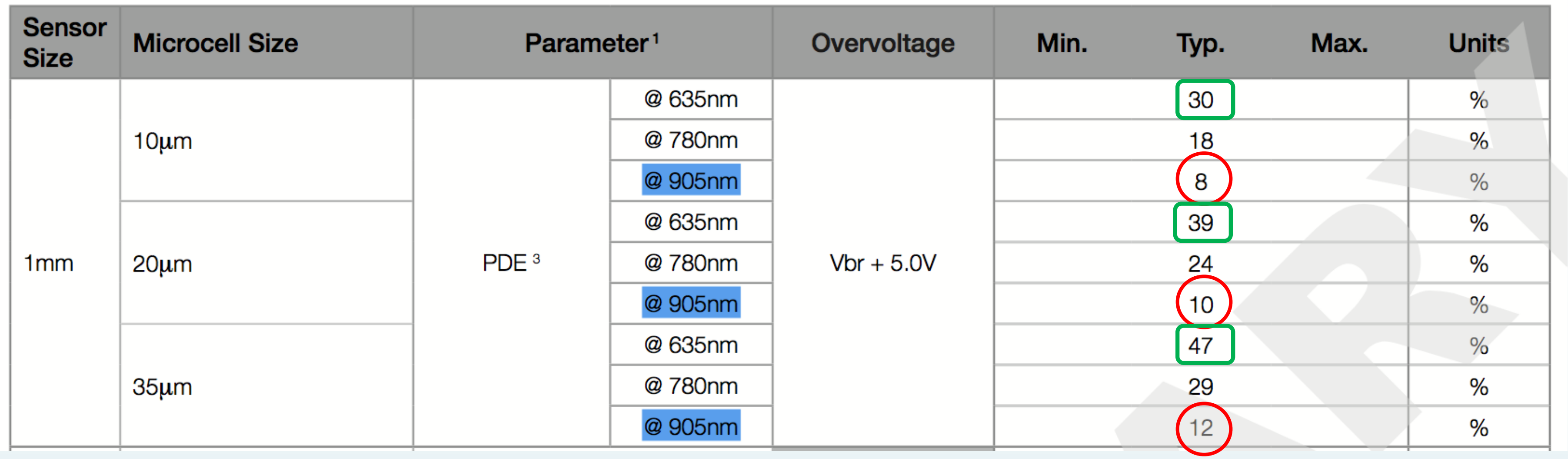


Available products

Under test

Where are we today (2017)?

@SensL:

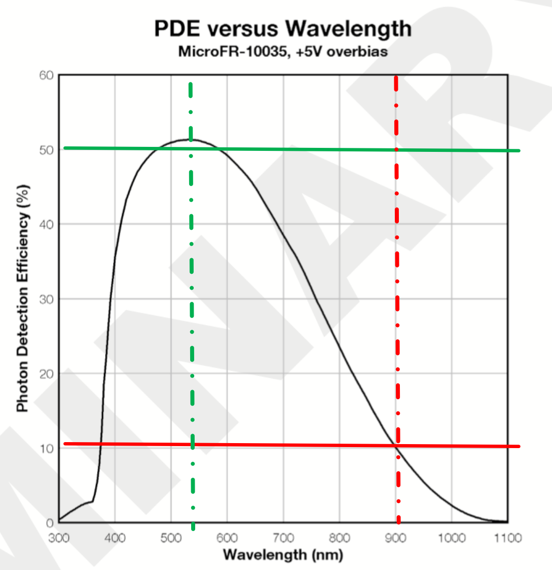


Sensor Size	Microcell Size	Parameter[1]		Overvoltage	Min.	Typ.	Max.	Units
1mm	10µm	PDE[3]	@ 635nm	Vbr + 5.0V		30		%
			@ 780nm			18		%
			@ 905nm			8		%
	20µm		@ 635nm			39		%
			@ 780nm			24		%
			@ 905nm			10		%
	35µm		@ 635nm			47		%
			@ 780nm			29		%
			@ 905nm			12		%

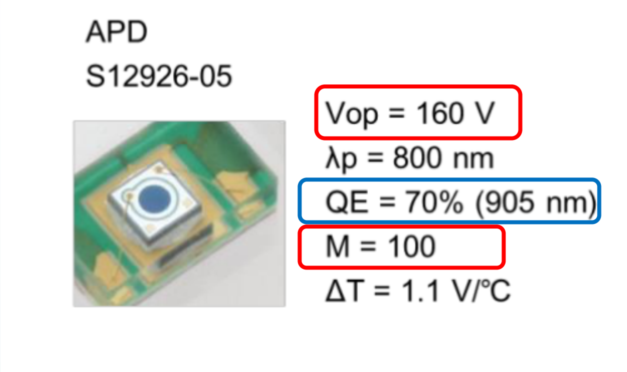
Available products (R series)

DCR ≈ 70 kHz / mm^2 @5V$_{over}$

50%

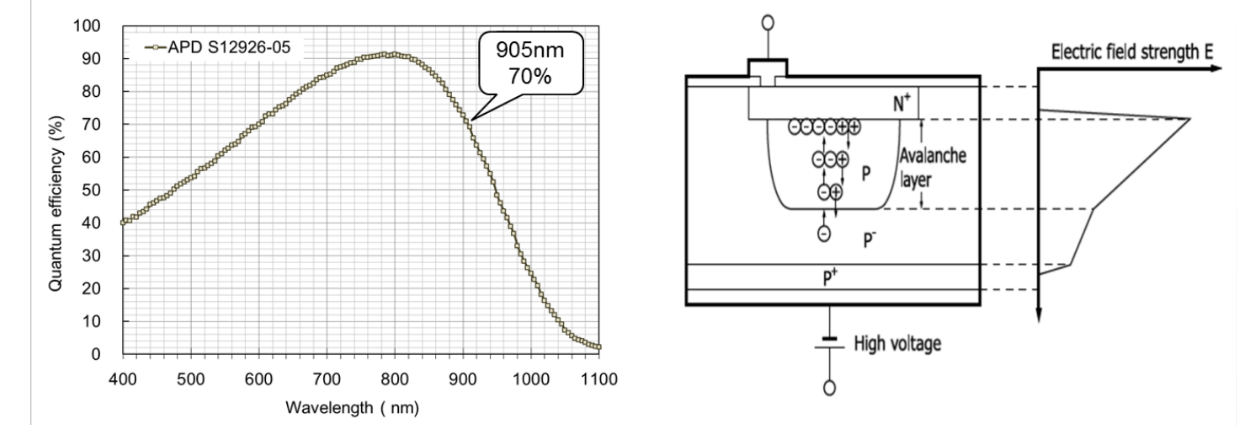


Worth fighting against APD?



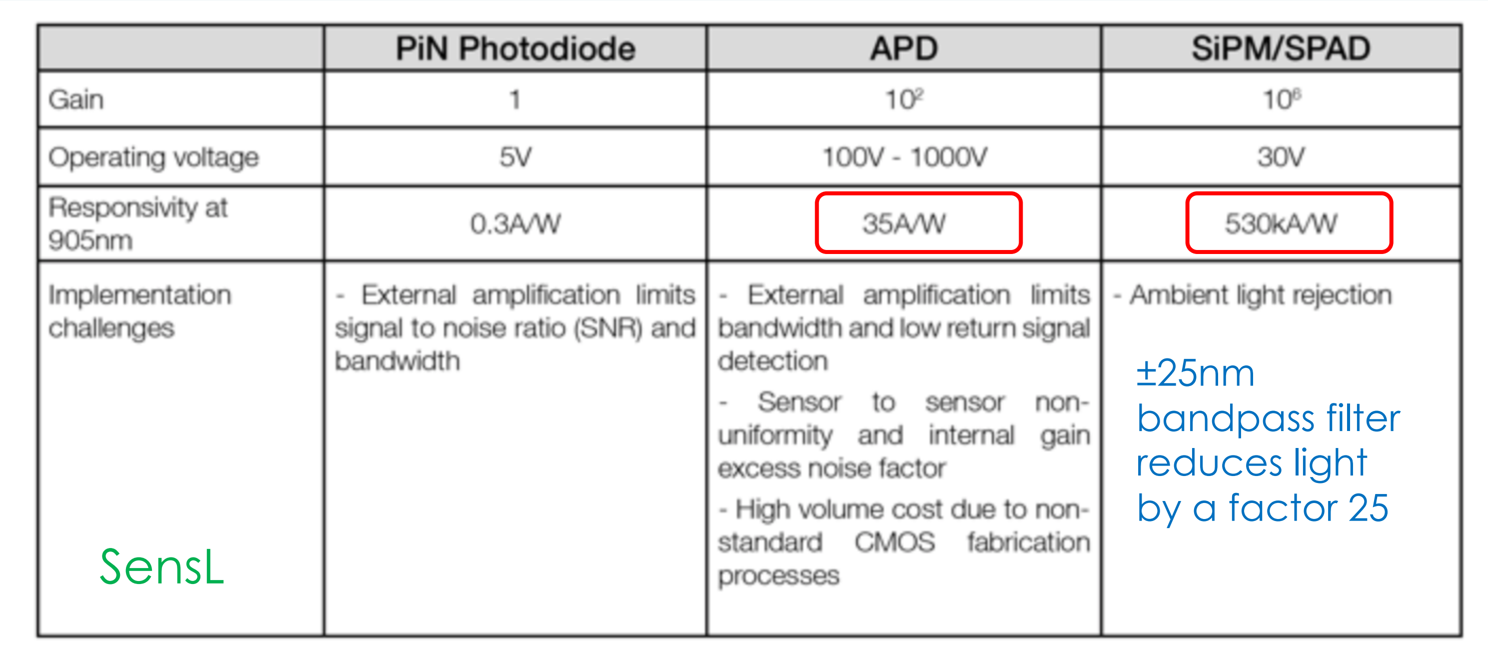
APD
S12926-05

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.
p.s. I could not get the figures for your device…

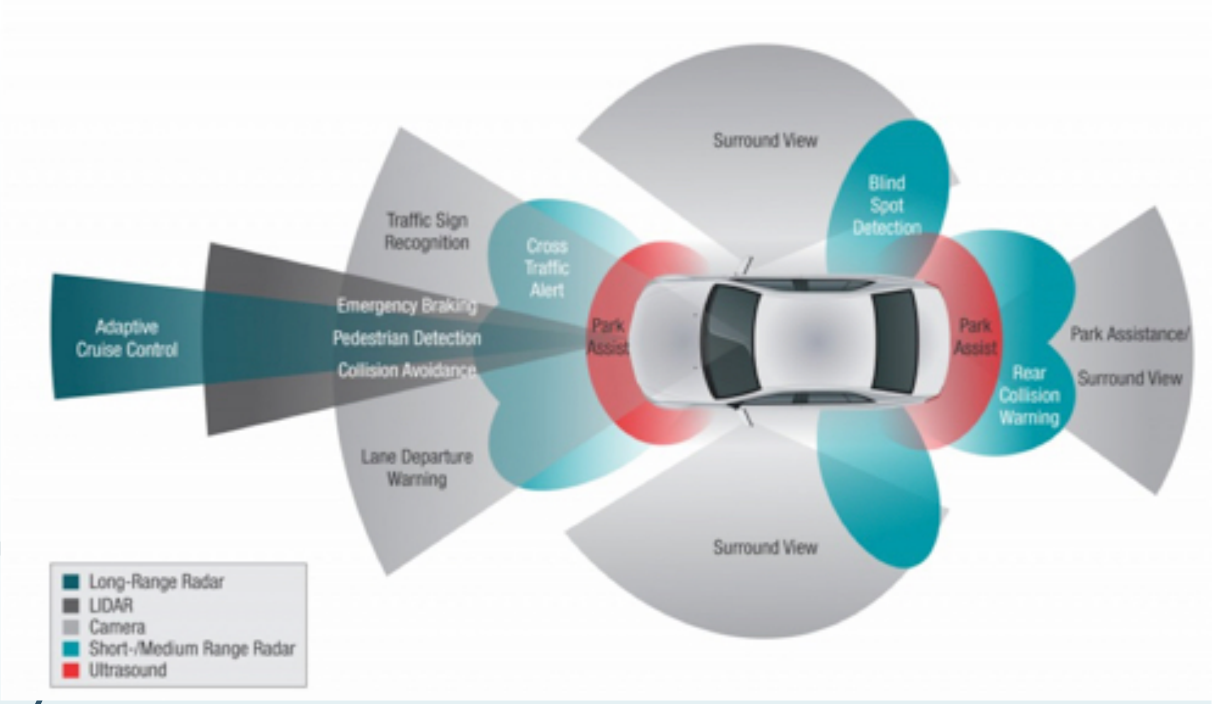


	PiN Photodiode	APD	SiPM/SPAD
Gain	1	10^2	10^6
Operating voltage	5V	100V - 1000V	30V
Responsivity at 905nm	0.3A/W	35A/W	530kA/W
Implementation challenges	- External amplification limits signal to noise ratio (SNR) and bandwidth	- External amplification limits bandwidth and low return signal detection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

SensL

±25nm bandpass filter reduces light by a factor 25

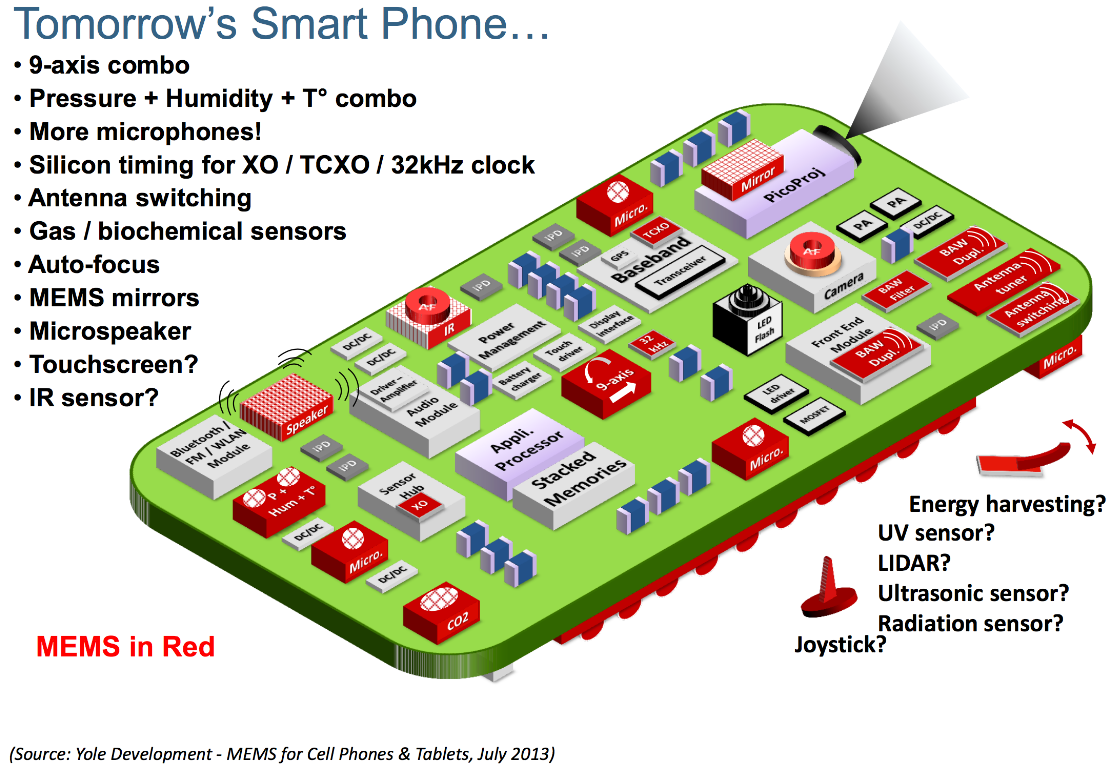
Certainly YES!



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



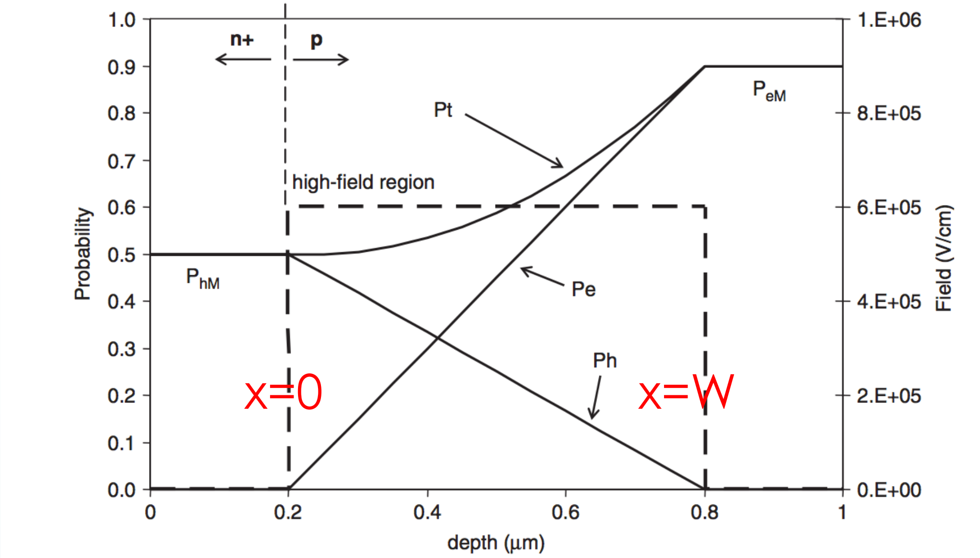
Tomorrow's Smart Phone…

- **9-axis combo**
- **Pressure + Humidity + T° combo**
- **More microphones!**
- **Silicon timing for XO / TCXO / 32kHz clock**
- **Antenna switching**
- **Gas / biochemical sensors**
- **Auto-focus**
- **MEMS mirrors**
- **Microspeaker**
- **Touchscreen?**
- **IR sensor?**

MEMS in Red

(Source: Yole Development - MEMS for Cell Phones & Tablets, July 2013)

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:

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

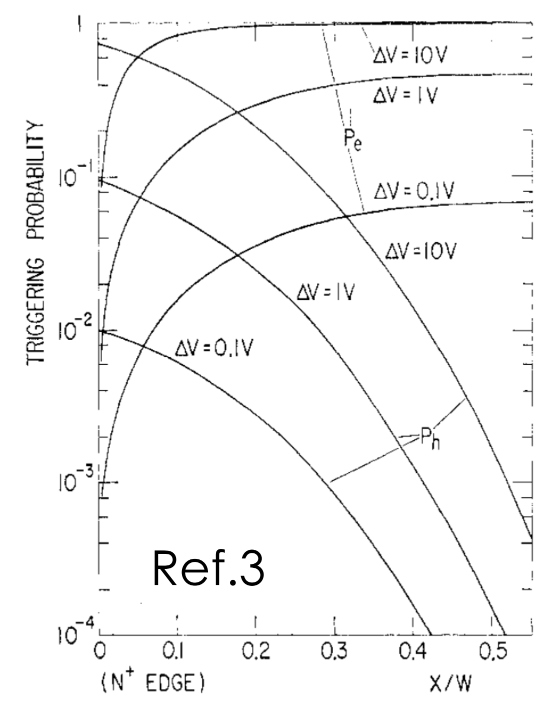
$$\frac{dP_h}{dx} = -(1 - P_h)\alpha_h[P_e + P_h - P_e P_h]$$

$$P_e(0) = 0$$

$$P_h(W) = 0.$$

Boundary conditions

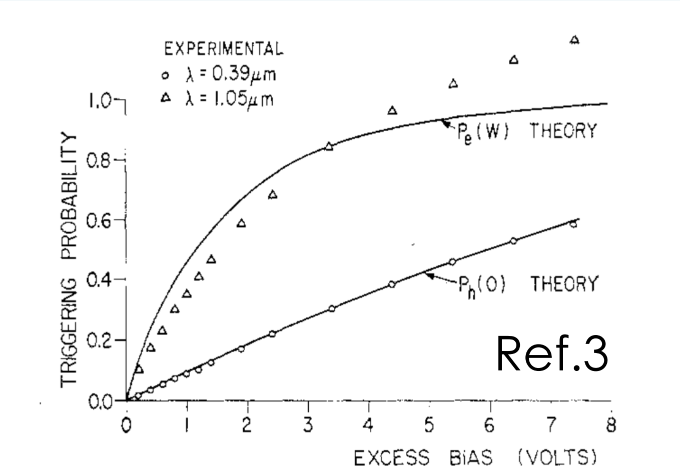
Where α_e, α_h, the IONIZATION COEFFICIENTS, depend on the electric field (i.e. the bias) as



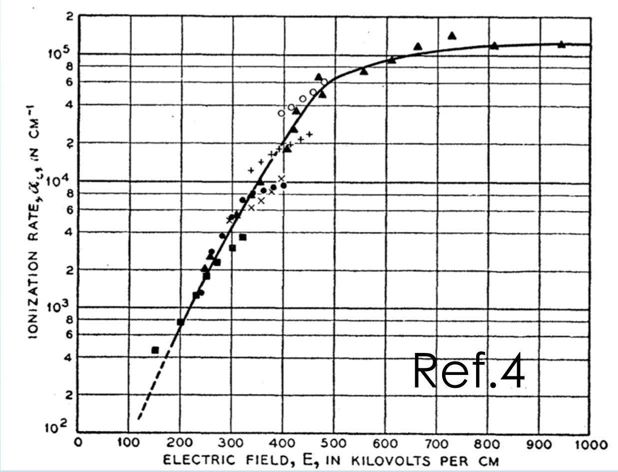
Ref.3

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

Where a ≈ 10^6, b ≈ 2×10^6

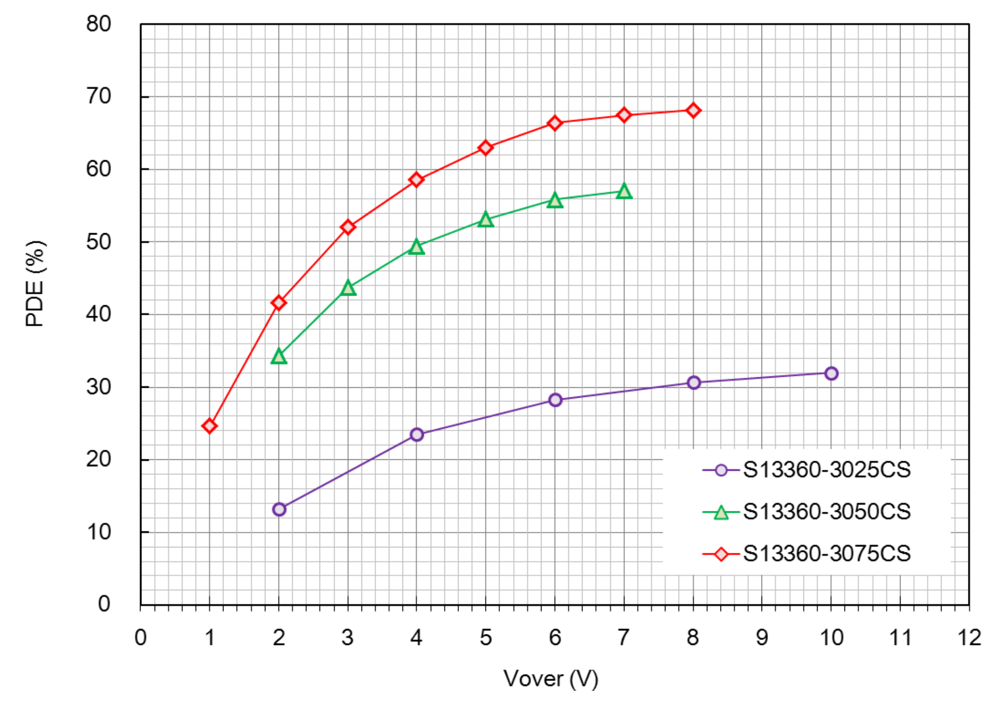


Ref.3



Ref.4

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



$PDE = n_{p.e.}/n_{photons}$

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

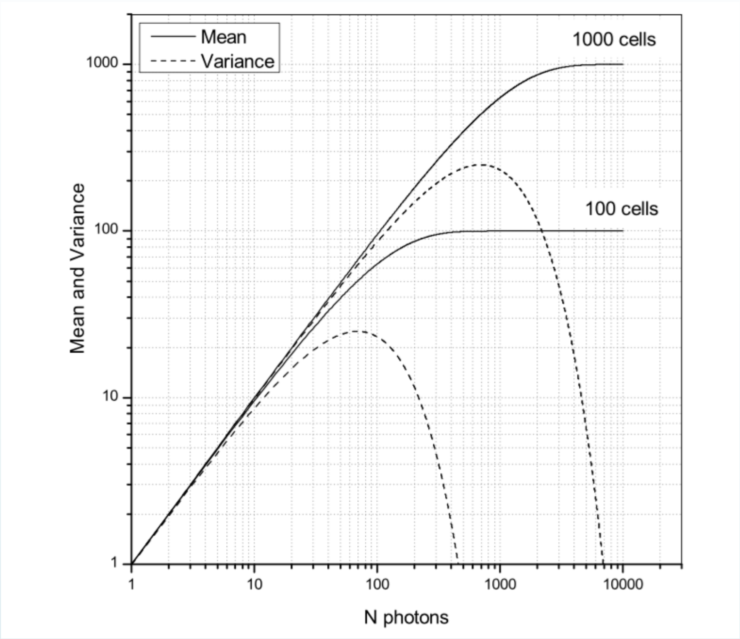
Stochastics effects affecting the sensor response

[actually introducing non-linarities]:

- ❖ Saturation [⬇]:

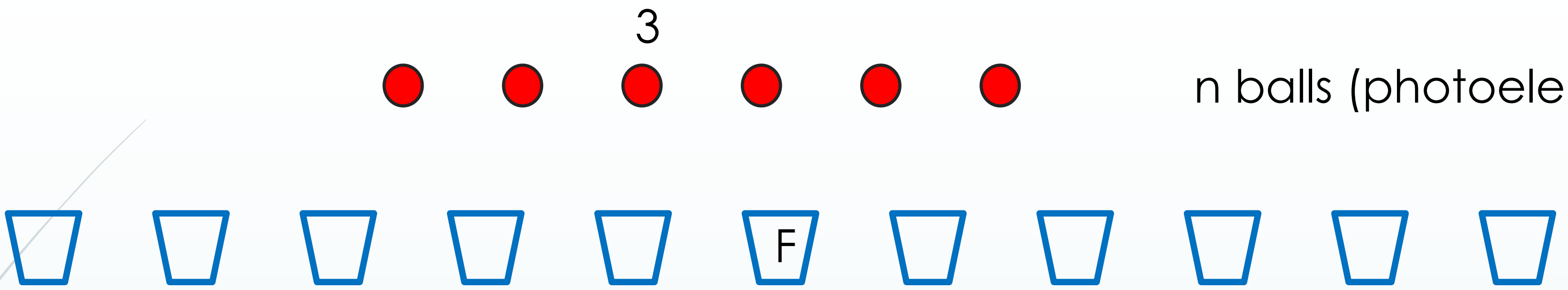
$$N_{fired} = N_{cells} \times \left[1 - e^{\frac{-N_{photons} \times PDE}{N_{cells}}}\right]$$

K.E. Kuper et al. JINST – in press



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.

About balls & baskets [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,

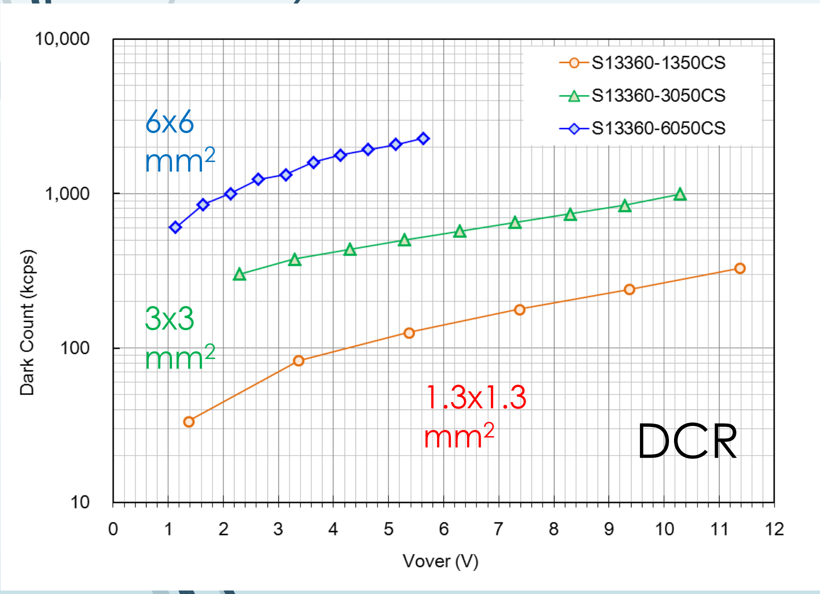
$$1 - m^{-1} \simeq e^{-\frac{1}{m}}$$

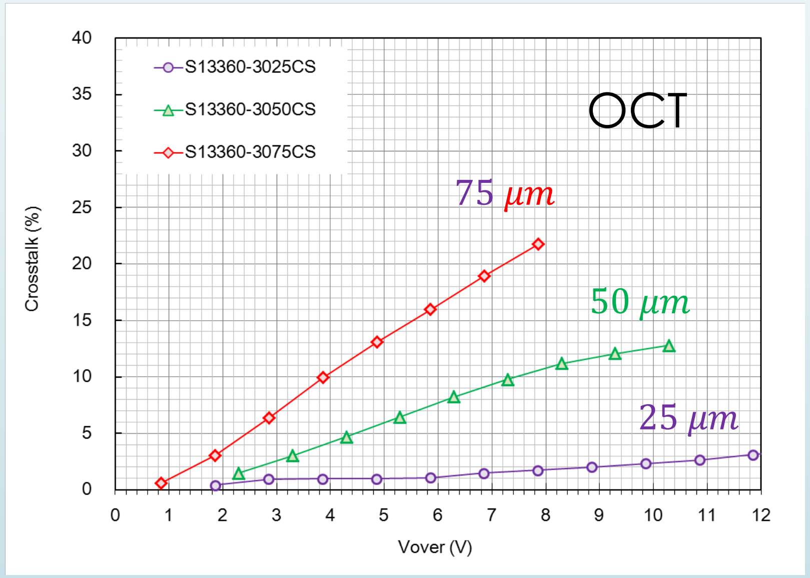
$$p \simeq 1 - e^{-\frac{n}{m}} = 1 - e^{-\frac{N_{photons} \times PDE}{N_{cells}}}$$

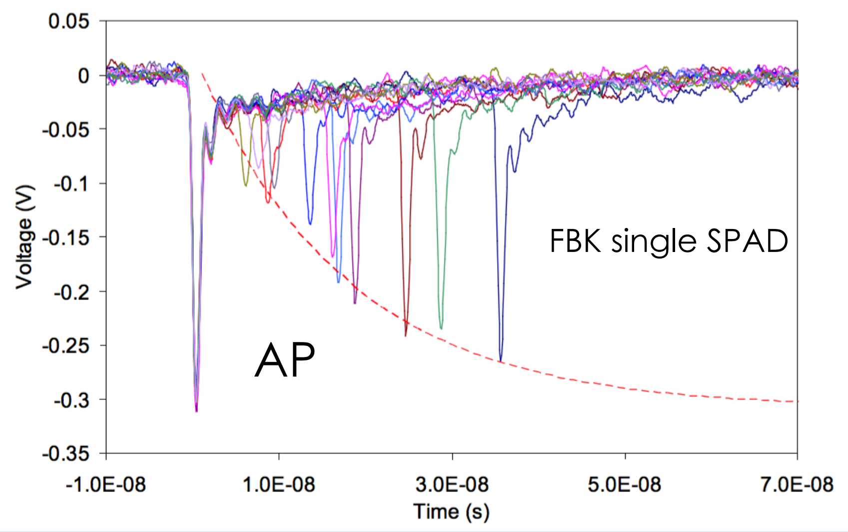
And I get the magic formula (together with the fact that the standard deviation in the response, i.e. the fluctuations, do increase since the response is affected by the randomness of the detection process)

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

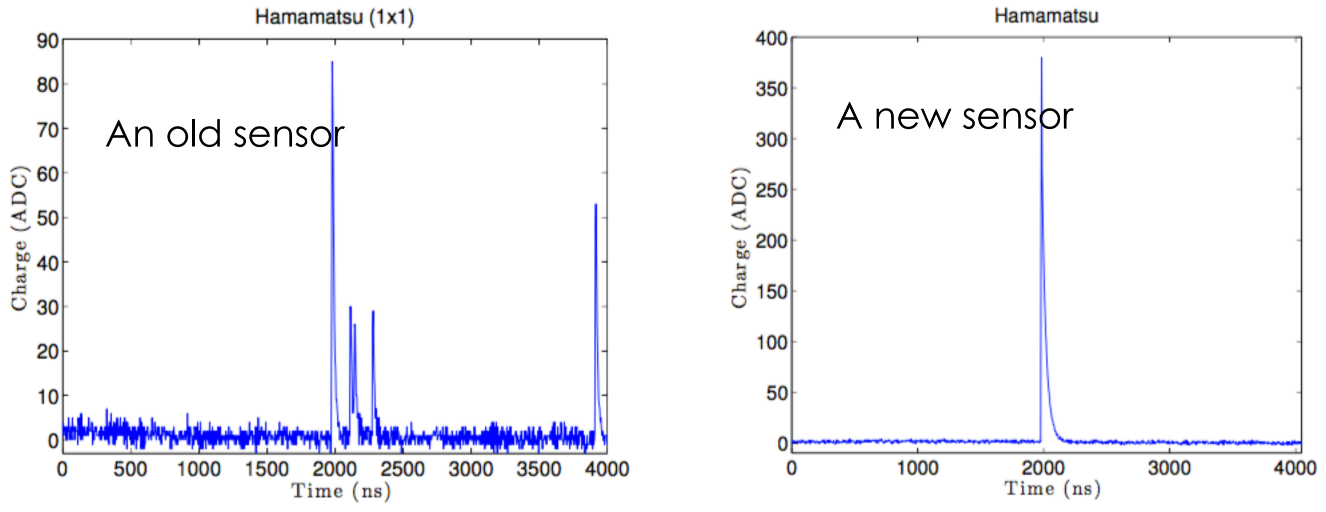






C. Piemonte, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 54, NO. 1, 2007

Since a picture is worth a thousand formulas:

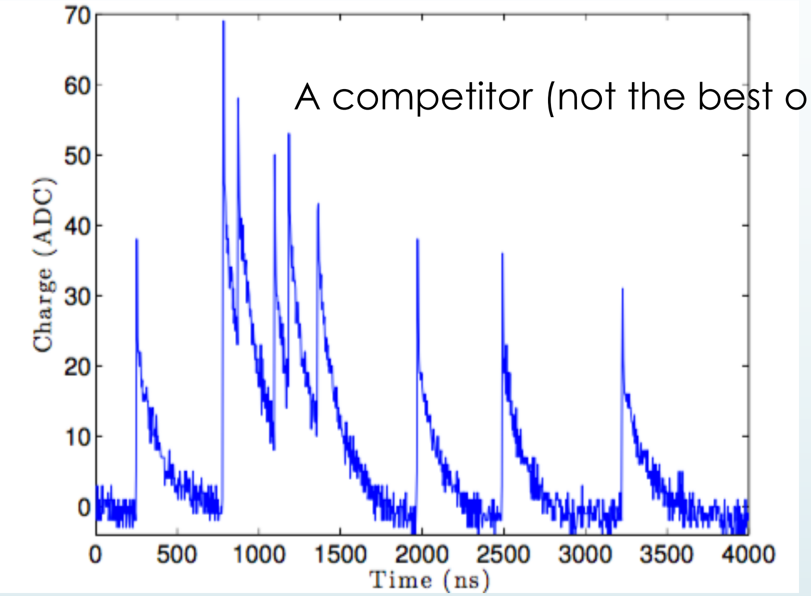


An old sensor

A new sensor

(a) Hamamatsu (1x1)

(b) Hamamatsu (1.3x1.3)



A competitor (not the best one!)

But 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

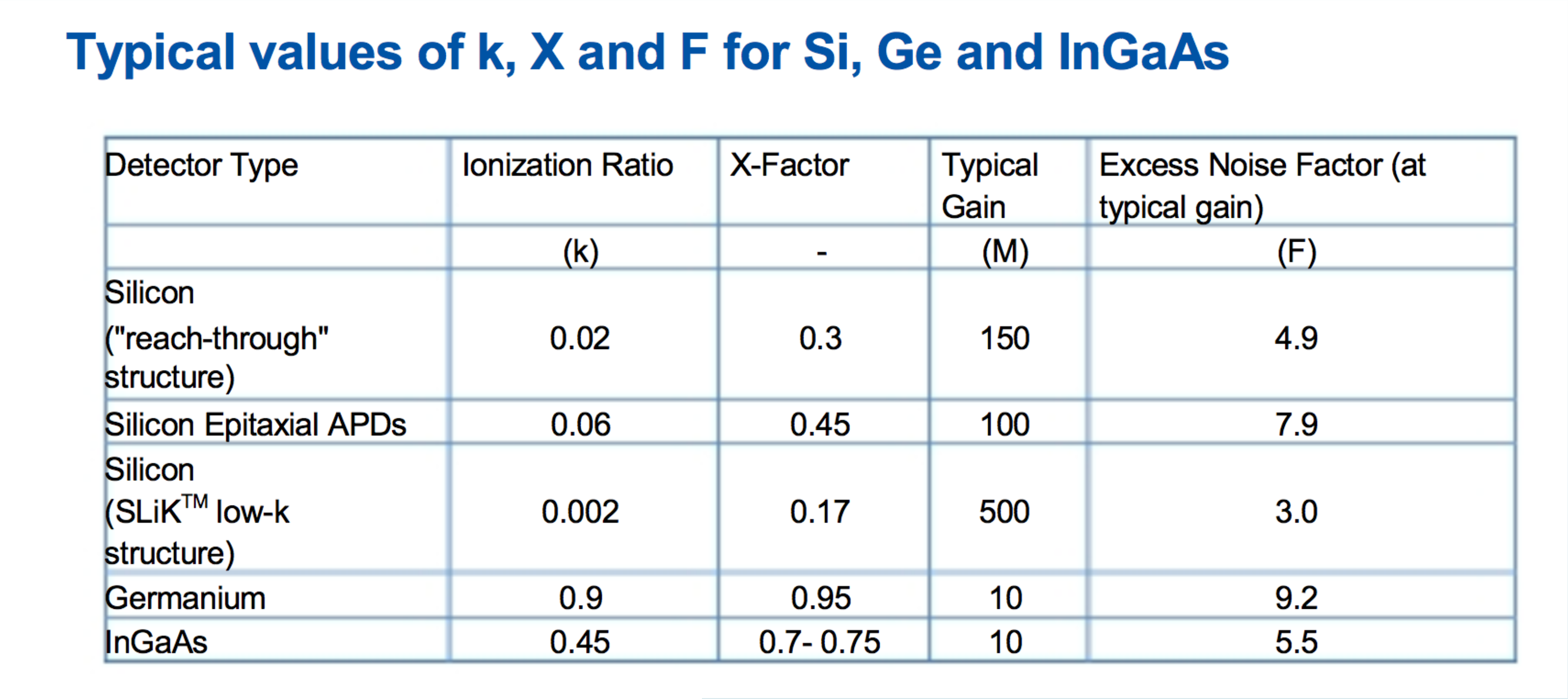
Since*:

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

- ❖ 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

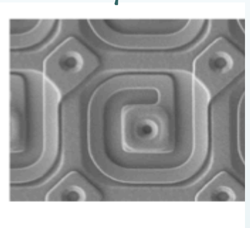
Avalanche Photodiodes: a user's guide

What can you find in the box?

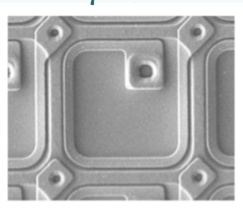
Over 15 years, the SiPM technology achieved its maturity and today a wide variety of continuously improving sensors is offered, so that users have a real “Menu à la Carte” to choose the “*best fit*” device for their application:

➢ In terms of pixel pitch:

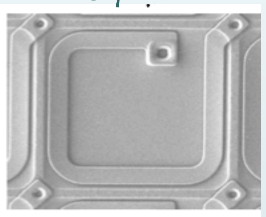
10 μm



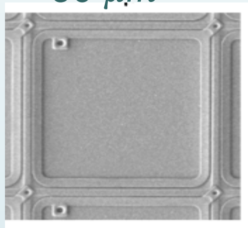
15 μm



25 μm



50 μm

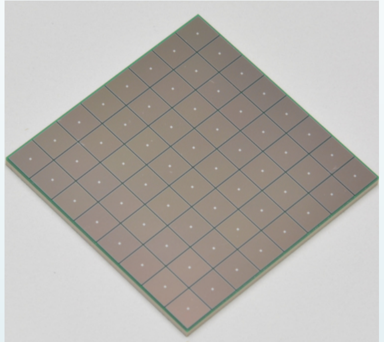


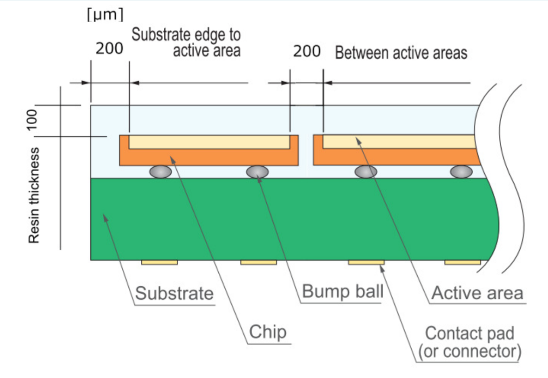
75 & 100 μm *are available as well*

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:

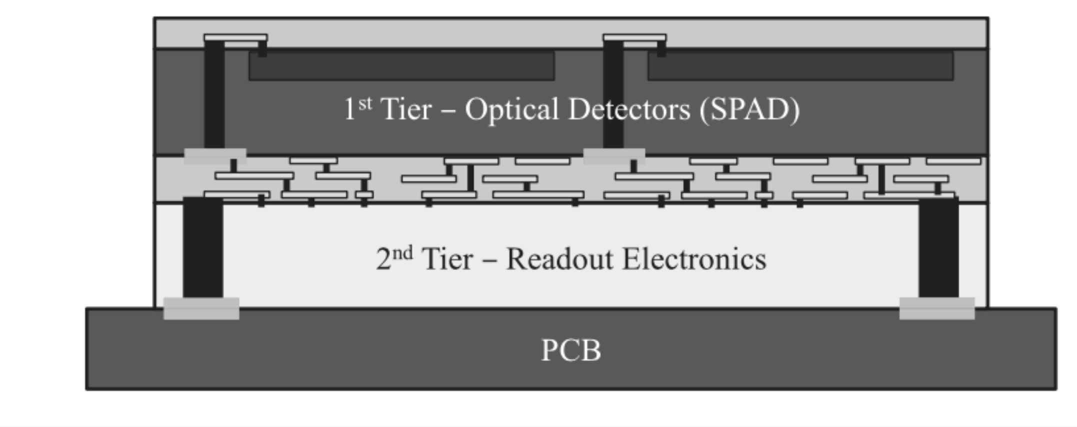
- 1x1 mm^2
- 3x3 mm^2
- 6x6 mm^2
-
- 1x4 mm^2
- 12x12 mm^2
- 24x24 mm^2

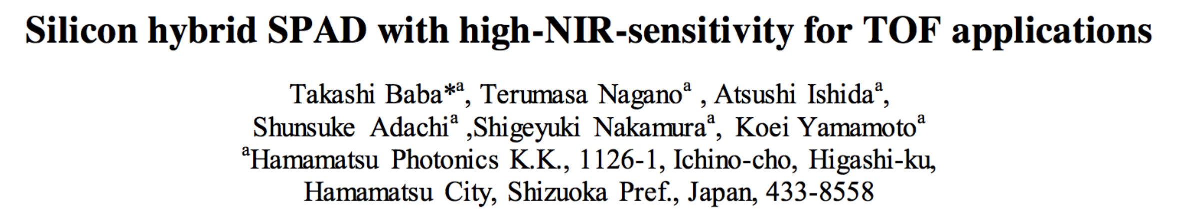




What’s Next?

3D vertical integration, to turn a sensor into a SMART sensor, with intelligence on board

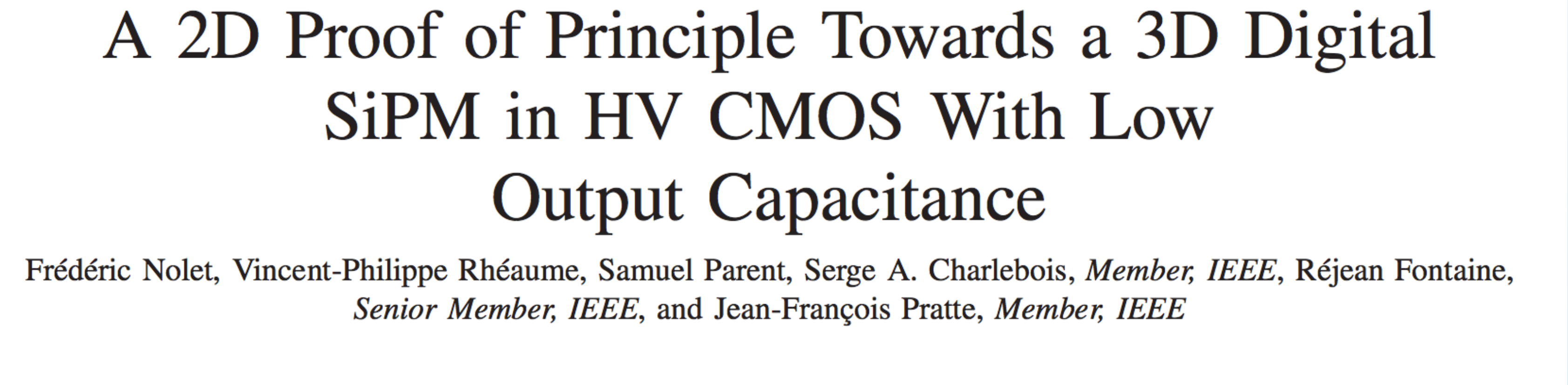




Silicon hybrid SPAD with high-NIR-sensitivity for TOF applications

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*

Thank you for listening!