Potential of Silicon Photomultiplier

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Outline

- Introduction
- Single Photon avalanche diode (SPAD)
- From SPAD to Silicon Photomultiplier (SiPM)
- SiPM features
- Technologies available
- Application example
- Conclusion

Photomultiplier tube (PMT)

Today, it is the most used sensor
for low-level light detection.

Features:
- high gain
- single photon sensitivity
- low noise
- large sensitive area
- high frequency response
- good QE from UV to nearIR
- low cost

Issues:
- bulky and fragile
- influenced by magnetic fields
- damaged by high-level light

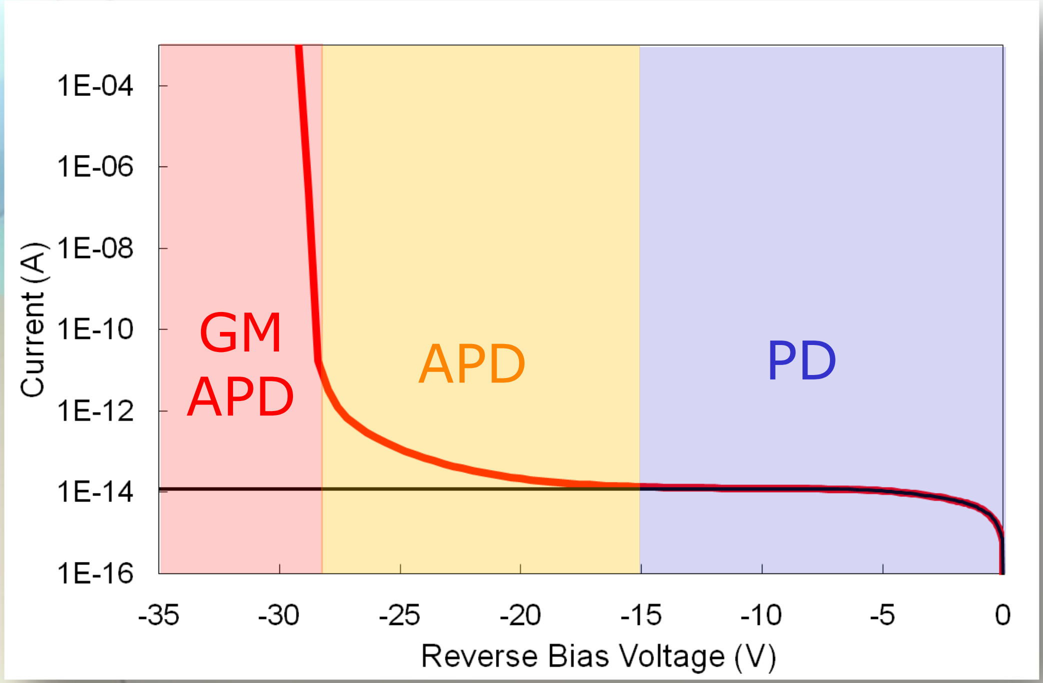
Applications:

physics experiments astronomy
medicine biology material analysis

Difficult to compete with this technology!!

Solid-state alternatives?

Devices with internal gain based on carrier multiplication via impact ionization



AVALANCHE PHOTODIODE
- Gain ~100
- Timing ~ ns/ 10ph.e.
- Bias voltage ~500V
- Sensitivity ~10 ph. e.
- QE ~ high in all spectrum

GEIGER-MODE APD
- Gain ~10^6
- Timing ~ 10ps /10ph.e.
- Bias voltage <100V
- Sensitivity ~1 ph. e.
- QE ~ medium

This is the basis to build a PMT counterpart!

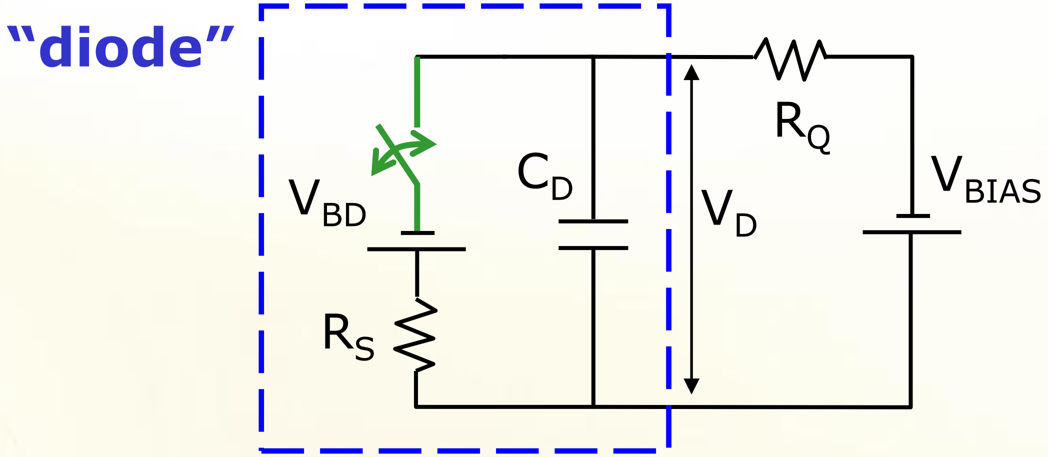
GM-APD: the beginning

Concept of self-quenching avalanche was developed in the '60s to study micro-plasma instabilities in p-n junctions
[R.J. McIntyre, JAP vol.32, n.6 **1961**;   R. Haitz, JAP vol.35, n.5 **1964**]

The micro-plasma was modeled with the following:

- $\mathbf{C_D}$ = diode capacitance
- $\mathbf{R_s}$ = series resistance (~1kΩ)
- $\mathbf{V_{BD}}$ = breakdown voltage

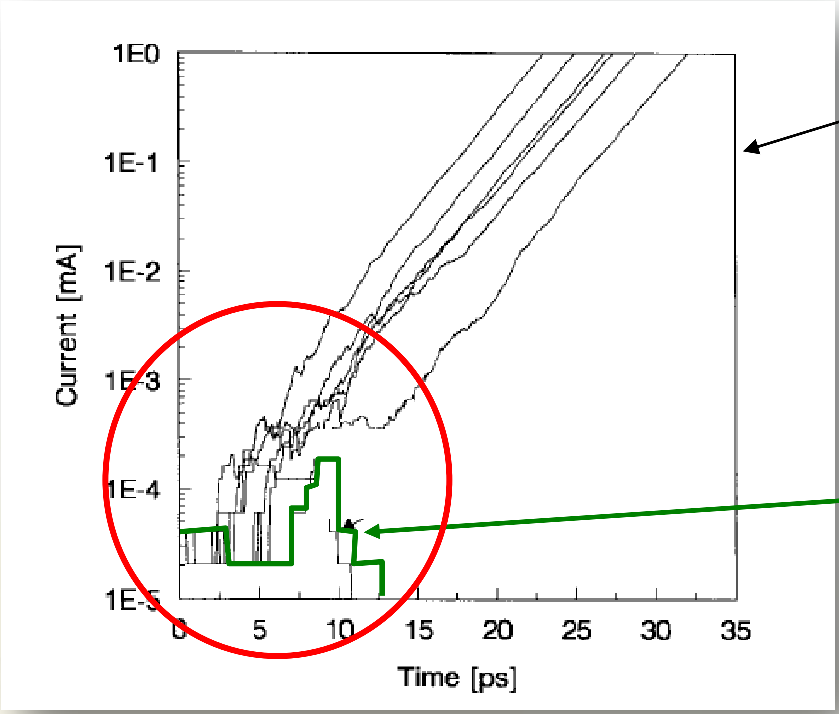
- $\mathbf{R_Q}$ = quenching resistor
- $\mathbf{V_{BIAS}} > V_{BD}$



- $\mathbf{P_{01}}$ = Triggering probability
- $\mathbf{P_{10}}$ = turn-off probability

Triggering probability

probability for a carrier traversing the high-field to trigger the avalanche.



MC simulations of the current growth during an avalanche build-up process
[Spinelli, IEEE TED, vol. 44, n. 11, 1997]

avalanche failed

First stages of the avalanche process

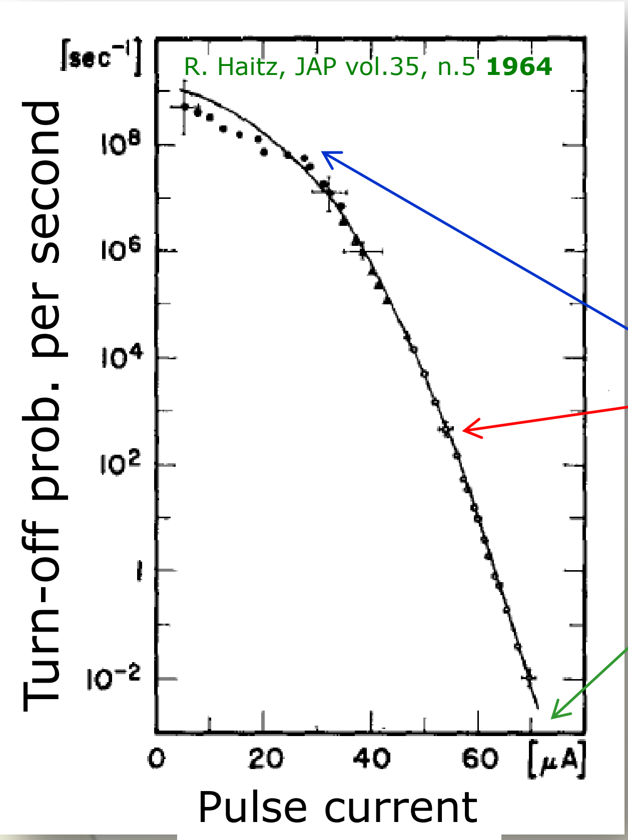
Triggering probability depends on the ionization rates.

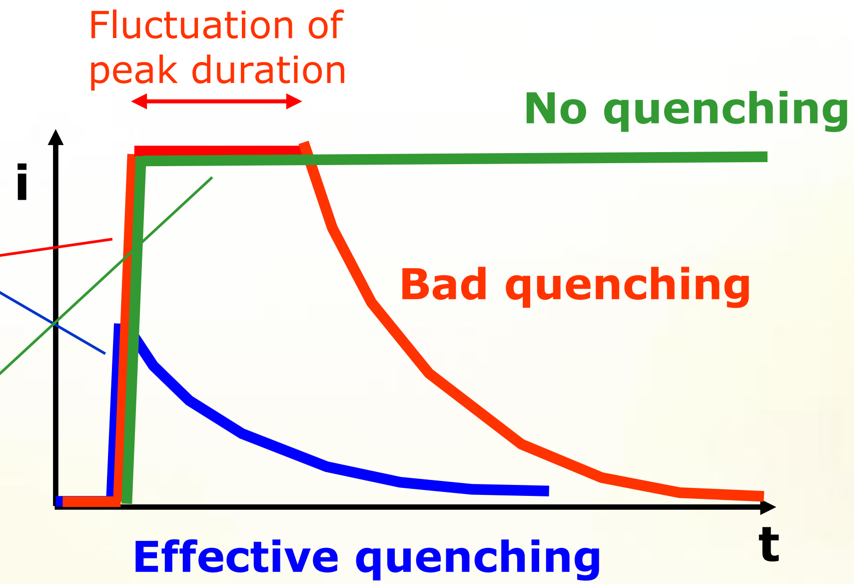
=> Important factor in the photo-detection efficiency.

Turn-off probability

avalanche quenching probability

due to a fluctuation to zero of the number of carriers traversing the high-field region



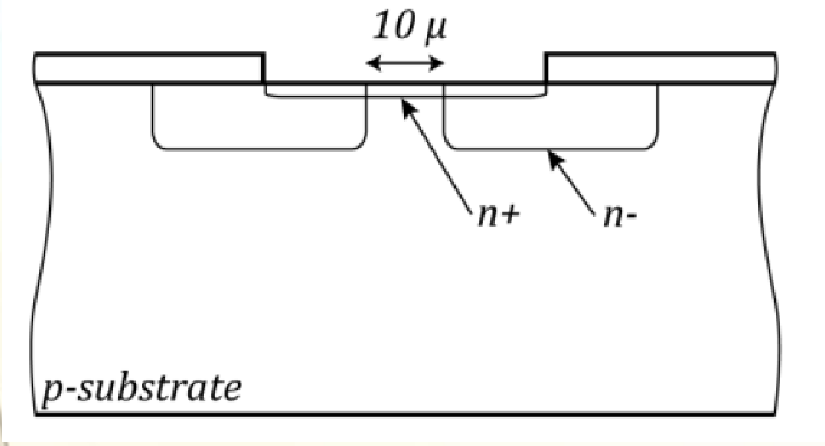


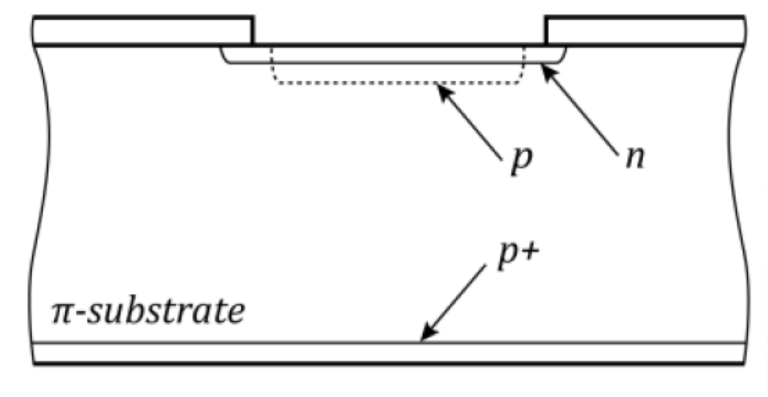
Impact on the quenching resistor value

GM-APD/SPAD: a light detector

Very soon it appeared a very sensitive photo-detector could be built extending the micro-plasma behavior to an entire junction

Small structures were built to test and control the Geiger behavior



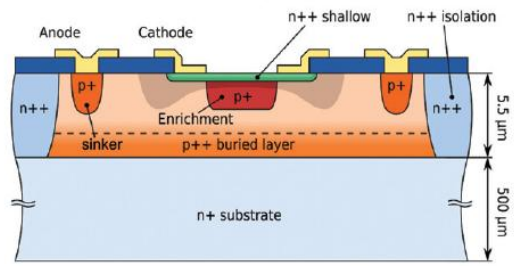


From that point, few groups started real development of SPADs mainly to timing measurements.

GM-APD/SPAD: technology trends

- **Full custom process**

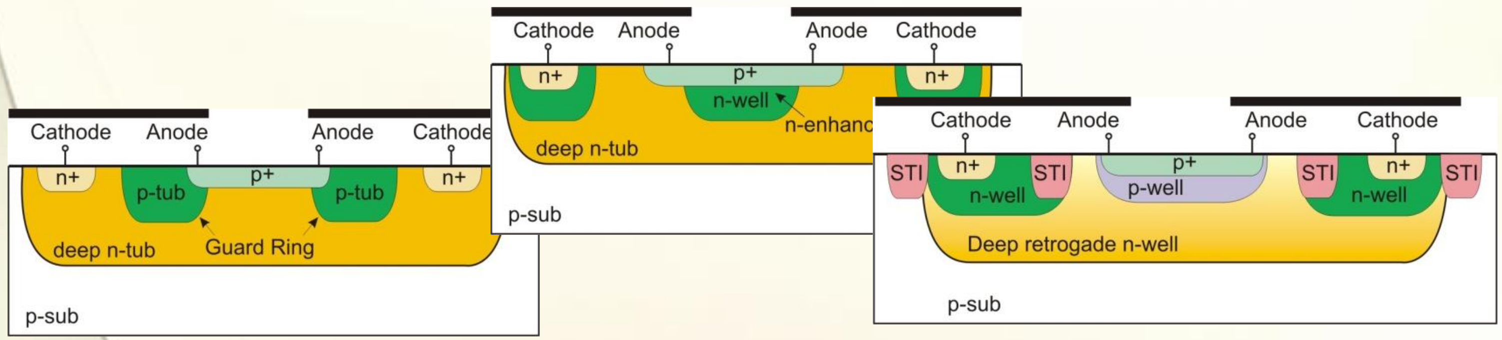
  development of optimized SPAD technology to be coupled to external electronics



I. Rech,
Journal of Modern Optics
Vol. 58, Nos. 3–4, 10–20
February 2011, 233–243

- **CMOS implementation**

  use of standard technology to create SPAD with integrated circuitry (active quenching, read-out ….)

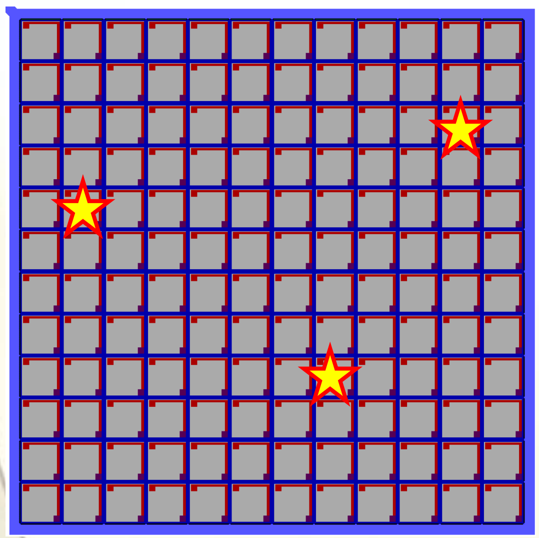


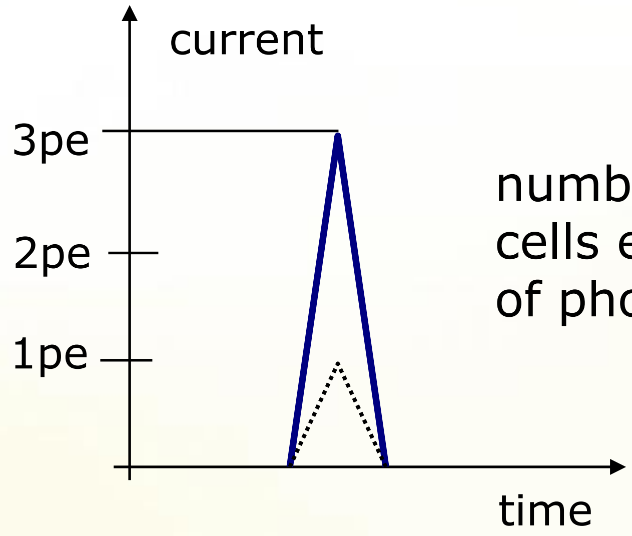
…and many others

From SPAD to SiPM

When the application requires (also) the estimation of the number of photons in a short light flash SPADs are not useful.

SiPM: array of SPADs tightly packed and connected in parallel.
(first proposed by Golovin and Sadygov in the '90s)





number of activated cells equal to number of photons (PDE=1)

In principle it can fully replace a PMT

From SPAD to SiPM

The transition from SPAD to SiPMs is not just design.

New issues are:

- a third factor enters in the photo-detection efficiency: the **fill factor** that for small cell size can be quite low

- to **control the dark rate** because
  - limited space for gettering techniques
  - high probability to include noisy cells in a device

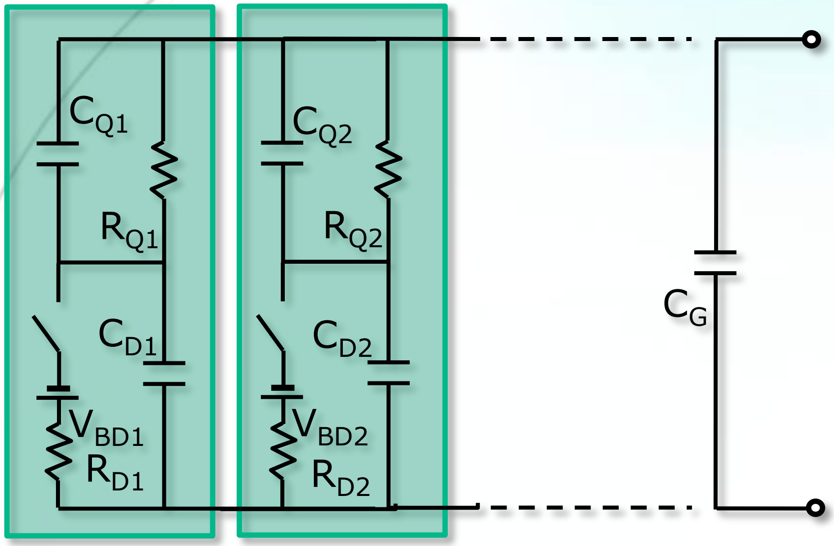
- direct **optical-cross talk** can be quite strong

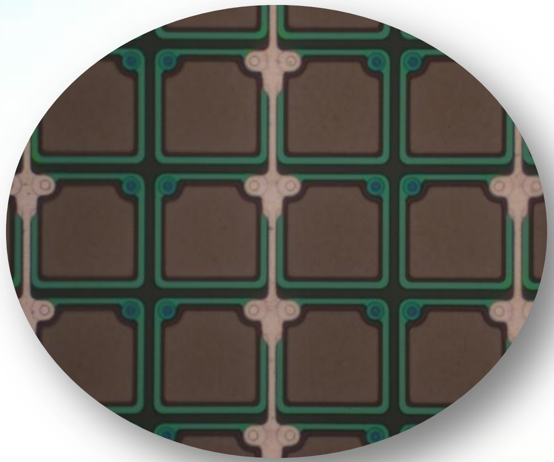
- …

Fundamental SiPM parameters

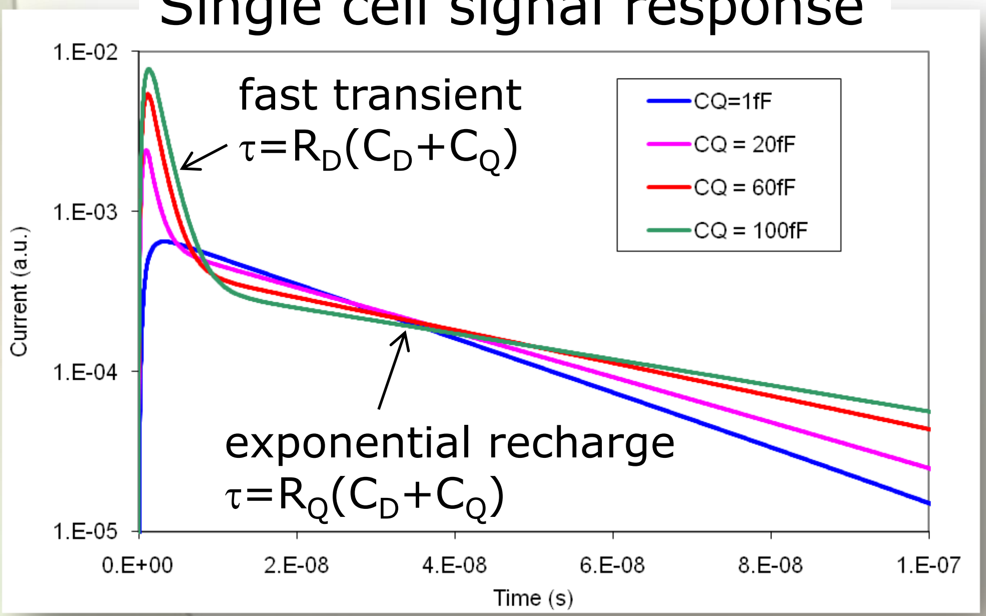
- Gain
  - Number of electrons per detected photon
- Noise (Dark event, Afterpulse, Crosstalk)
  - Pulses not directly generated by incoming light
- Photodetection efficiency (PDE)
  - Number of detected photons over total incident photons
- Dynamic range
  - Linearity of response
- Time resolution
  - Precision in the determination of photon arrival time

Equivalent circuit





Single cell signal response

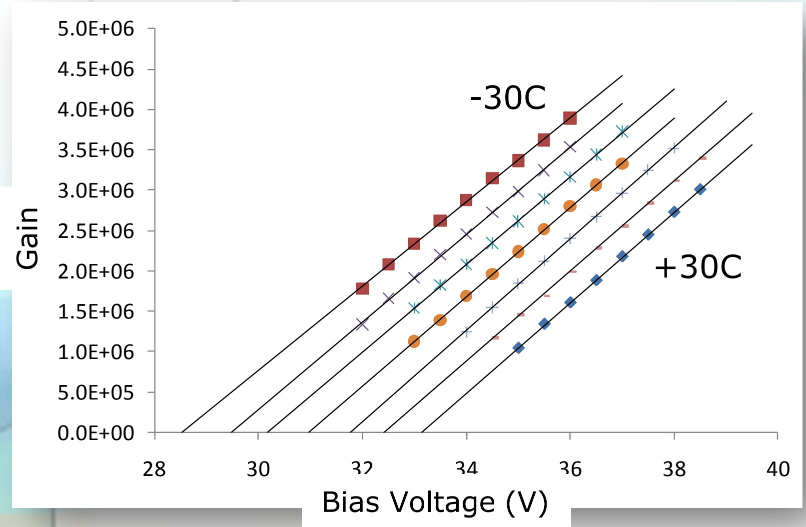


Cell Layout, SiPM size affect the pusle shape

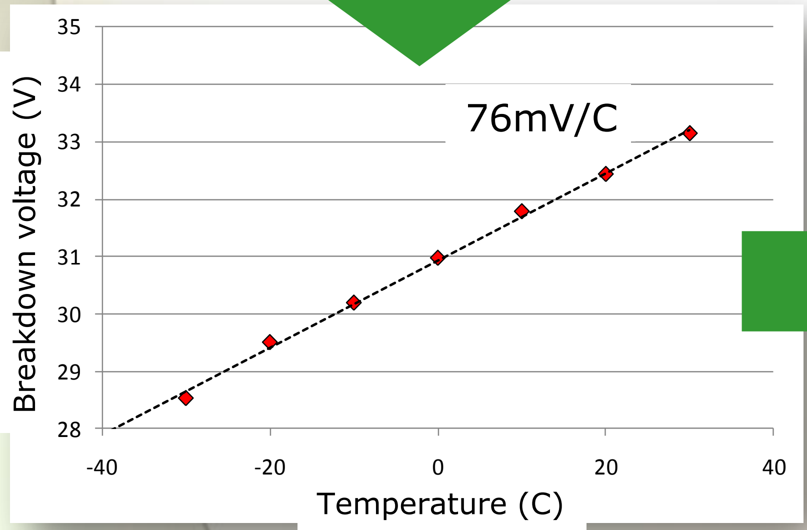
Gain = pulse area
$$= (C_D+C_Q)(V_{BIAS}-V_{BD})$$

Gain vs temperature

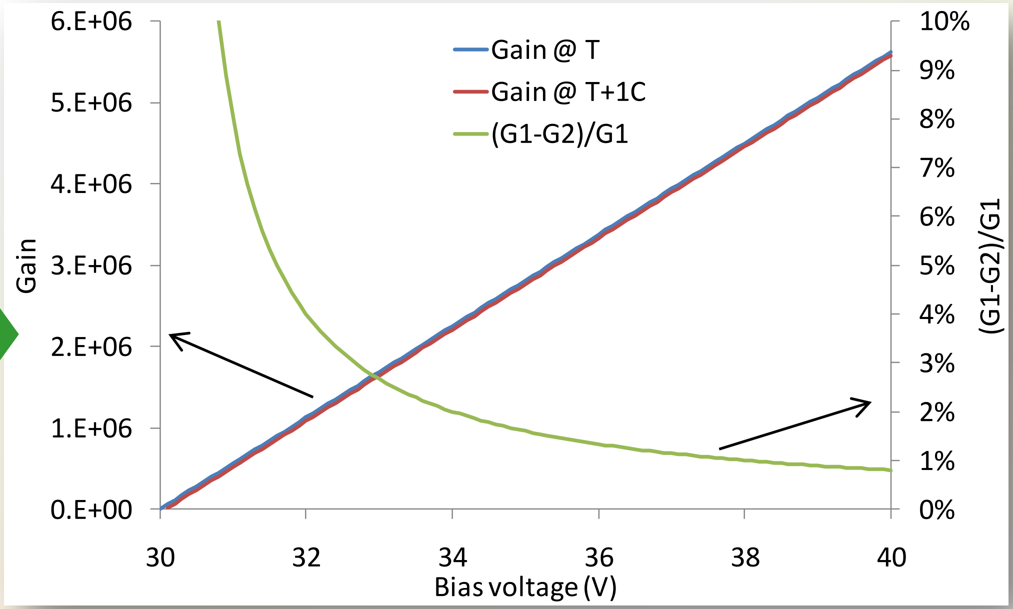
Data from FBK SiPMs



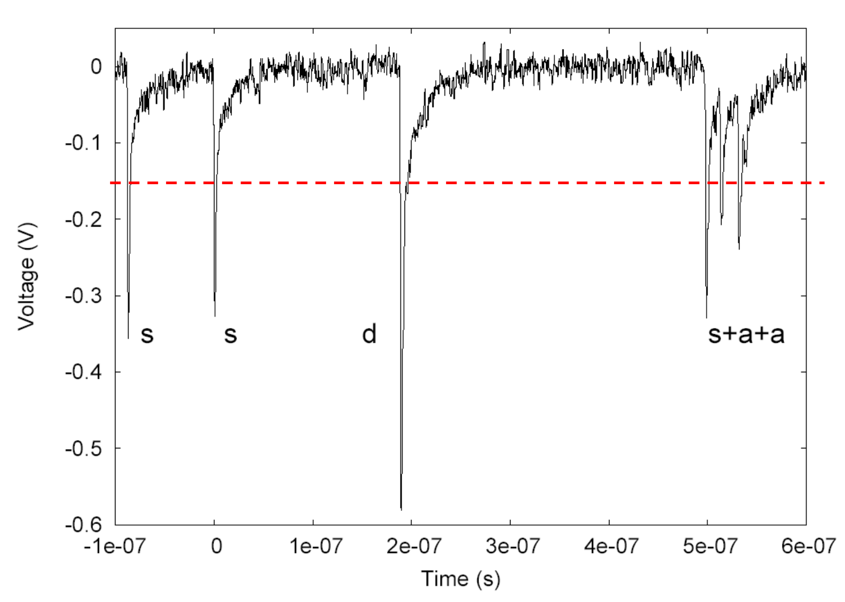
- Gain proportional to Vov
- Vbd increases with T



- **Good to operate at high OV**



Noise



Origin of pulses:

s = dark noise

- Carriers thermally generated in depleted region
- tunneling

a = Afterpulse

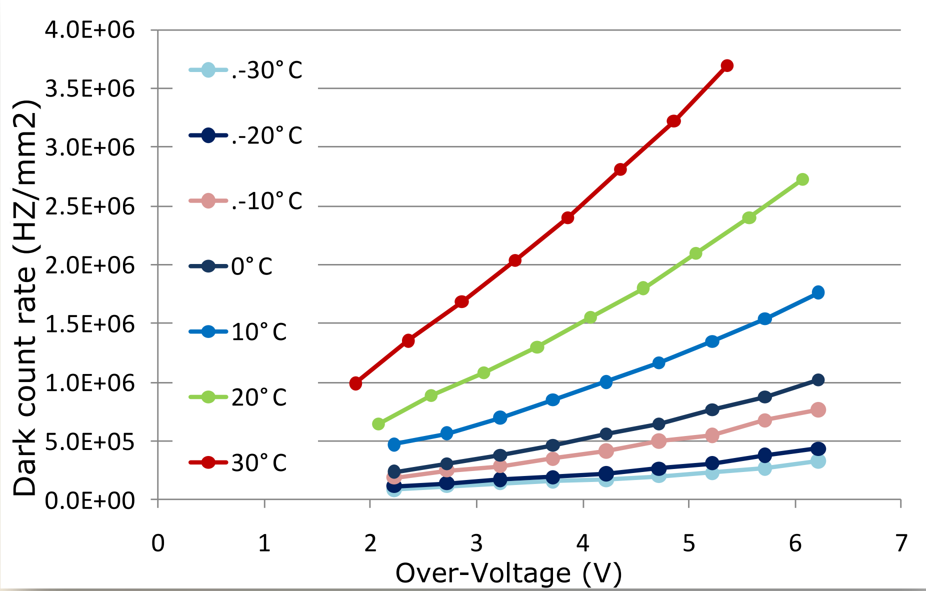
Carriers trapped and released later

d = Crosstalk

Optical coupling between cells

Dark rate (0.5 pe level)

- Doubles every 10C T increment
- Increases with Vov



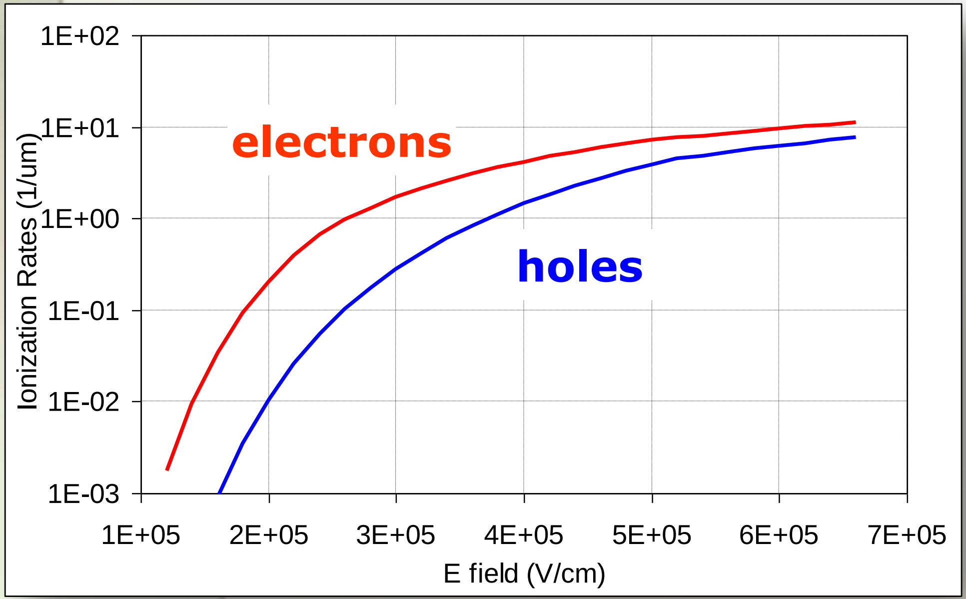
Photon-Detection Efficiency

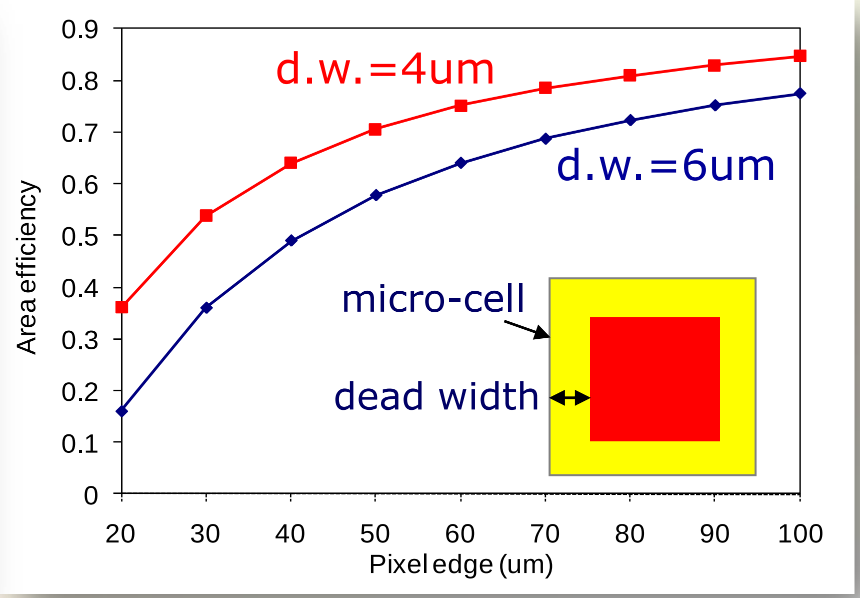
$$\mathbf{PDE} = N_{pulses} / N_{photons} = \mathbf{QE \times P_{01} \times FF}$$

QE Quantum efficiency is the probability for a photon to generate a carrier that reaches the high-field region.

P_{01} Triggering probability

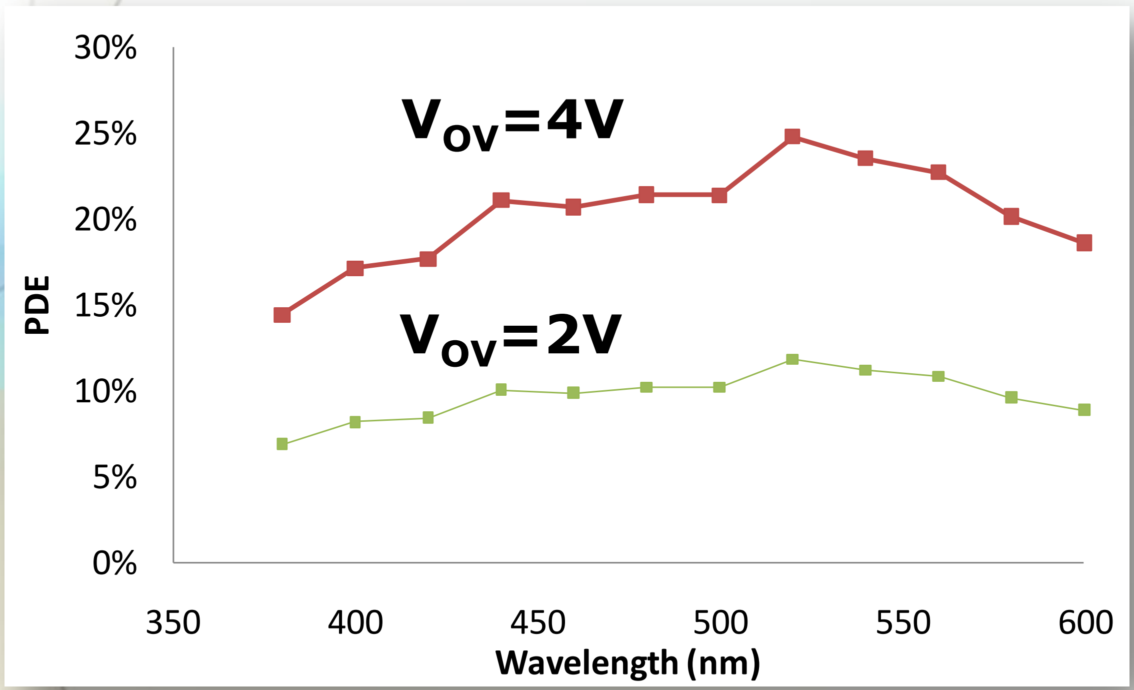
FF Fill factor





PhotoDetection Efficiency

Data from FBK SiPMs



- ~ 50% fill factor
- after-pulses not counted

PDE

- Increases with Vov
- λ - dependent

Shape of the PDE can be changed using different doping configurations

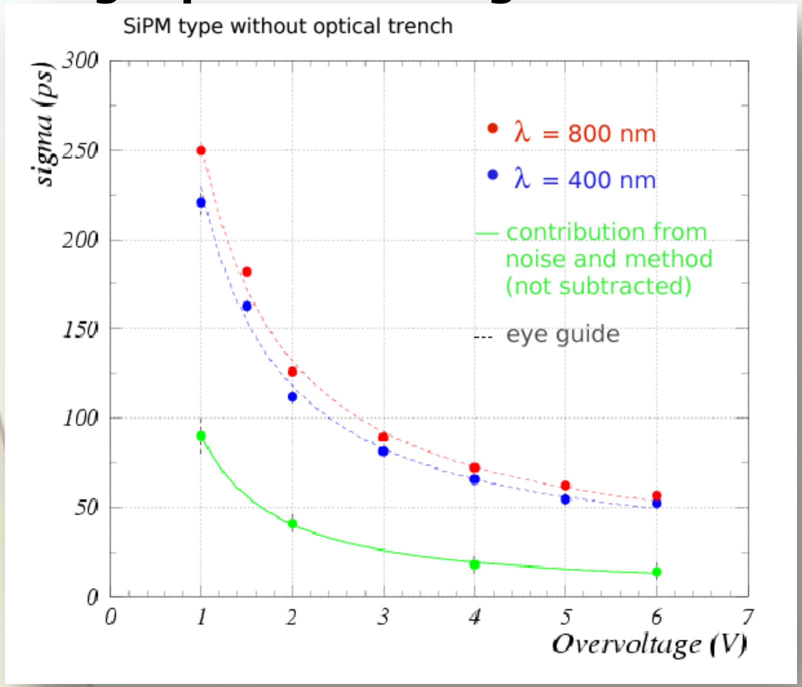
Timing capability

Data from FBK SiPMs

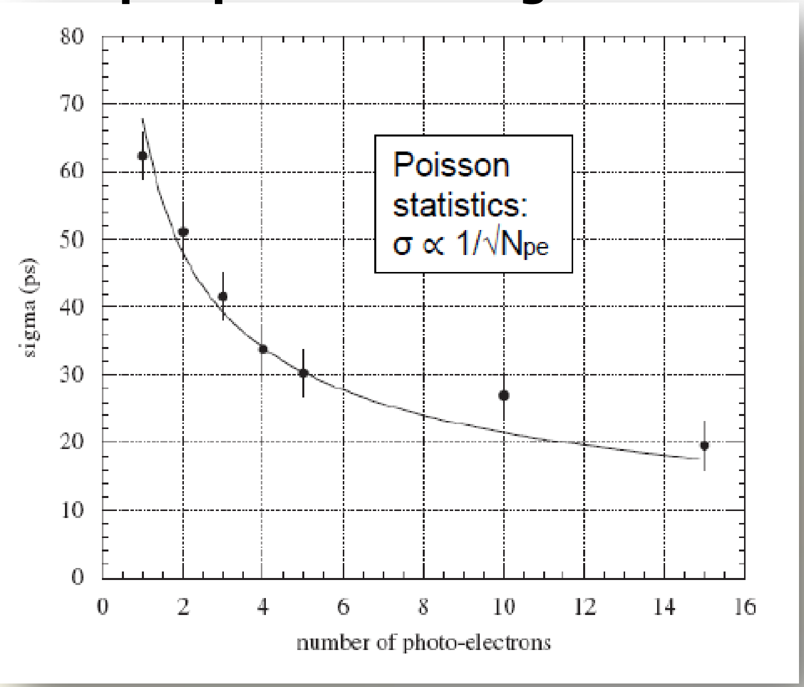
Statistical Fluctuations in the current growth:

- 1. Photo-**conversion depth**
- 2. ***Vertical*** Build-up at the very beginning of the avalanche
- 3. ***Lateral*** Propagation

single photon timing resolution



multiple-photon timing resolution



$1mm^2$ device, $50x50um^2$ cell size

Technologies around the world

Pioneering work in the 90's by russian institutes

- JINR, Dubna
- Obninsk/CPTA, Moscow
- Mephi/PULSAR, Moscow

Metal-Resistive-Semiconductor

→ polysilicon resistor

Recently, more institutes/companies involved in SiPM production:

- Hamamatsu, Japan
- SensL, Ireland
- FBK/AdvanSiD, Italy
- Ketek, Germany
- RMD inc., USA
- Excelitas Technologies

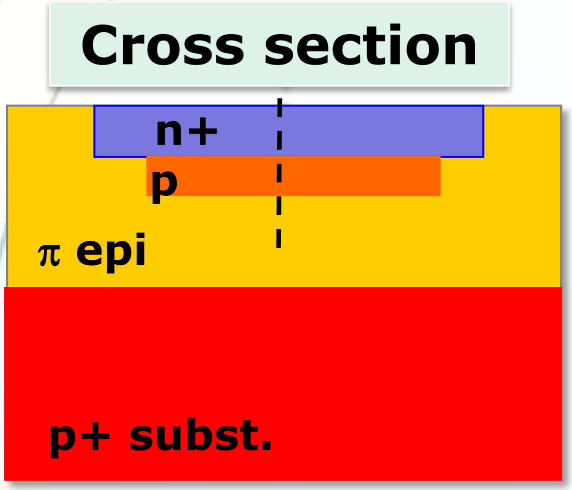
→ polysilicon resistor

- Zecotek, USA → quenching with floating wells
- MPI, Germany → resistor embedded in the bulk
- Philips → Digital SiPM
- …

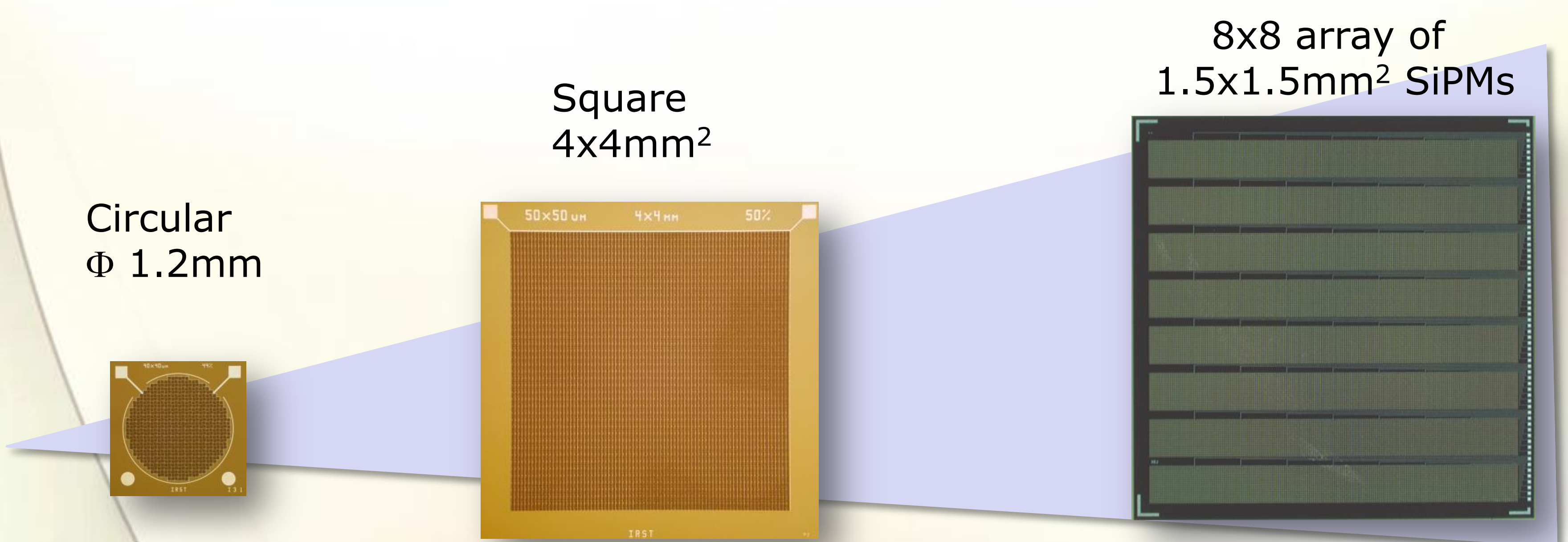
Some are commercially available, some only prototypes

Technologies around the world: **3 examples**

FBK, commercialized by AdvanSiD

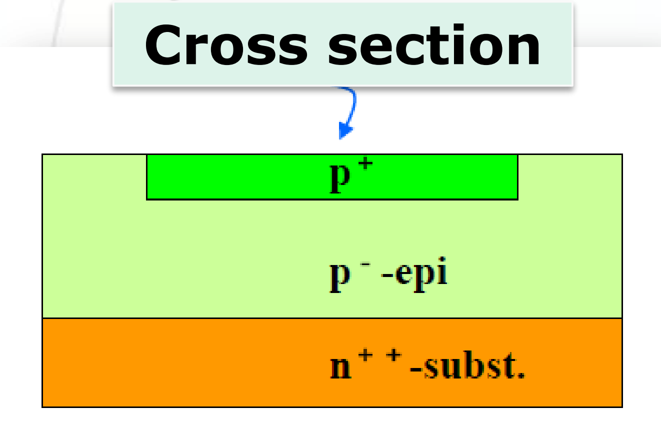


- PDE peaked at 450-550nm
  Good PDE also in UV-BLUE region
- can be operated at high over-voltages
- V_{BD} ~35V
- cell size: from 25x25 to 100x100um^2

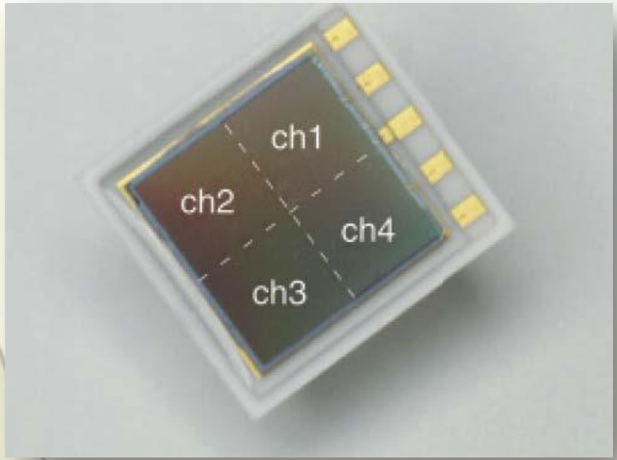


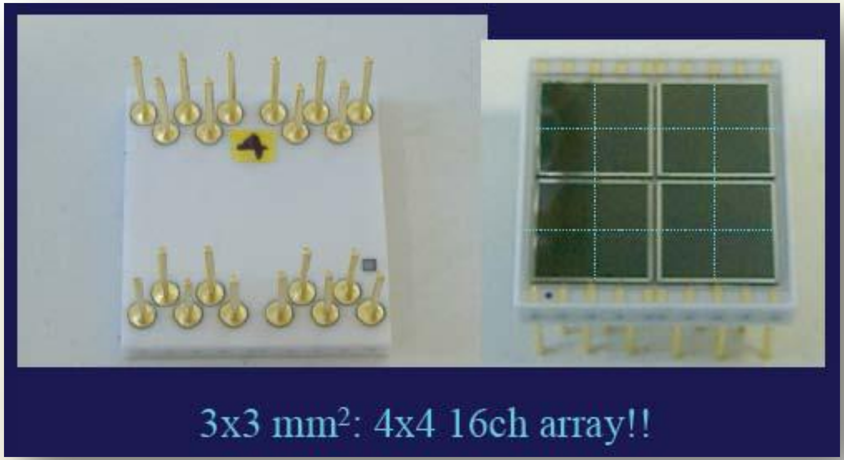
Technologies around the world: **3 examples**

Hamamatsu



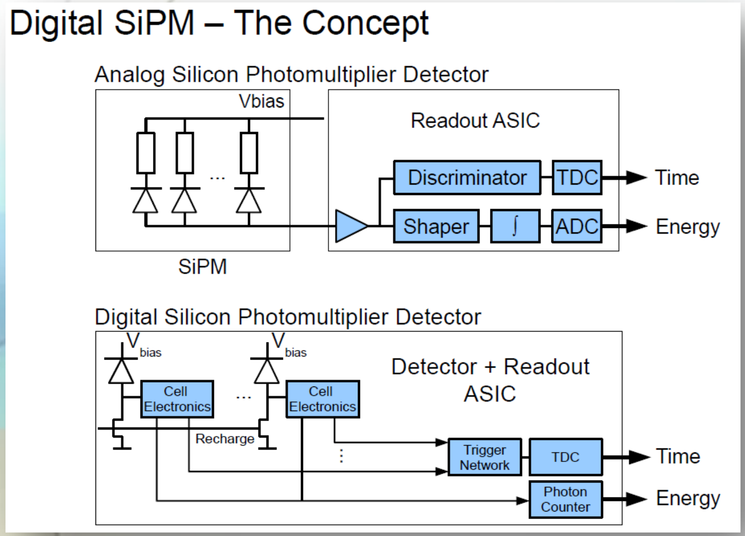
- **PDE peaked at 400-450nm**
- V_{BD} ~70V
- very narrow operation voltage range
- very low noise (down to 100kHz/mm^2)



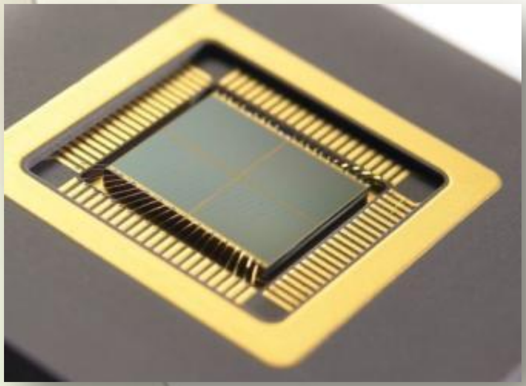


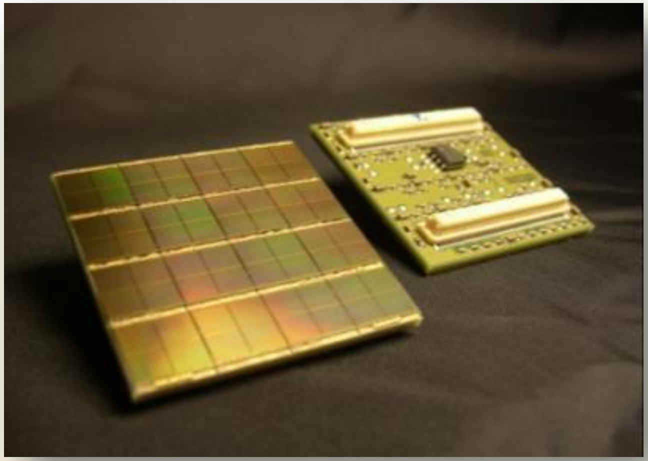
Technologies around the world: **3 examples**

Philips digital Silicon Photomultiplier



- **electronics integrated in the sensor**
- digital output with timing and number of photons information
- possibility to switch off noisy cells
- low temperature sensitivity
- PDE peaked at 420nm

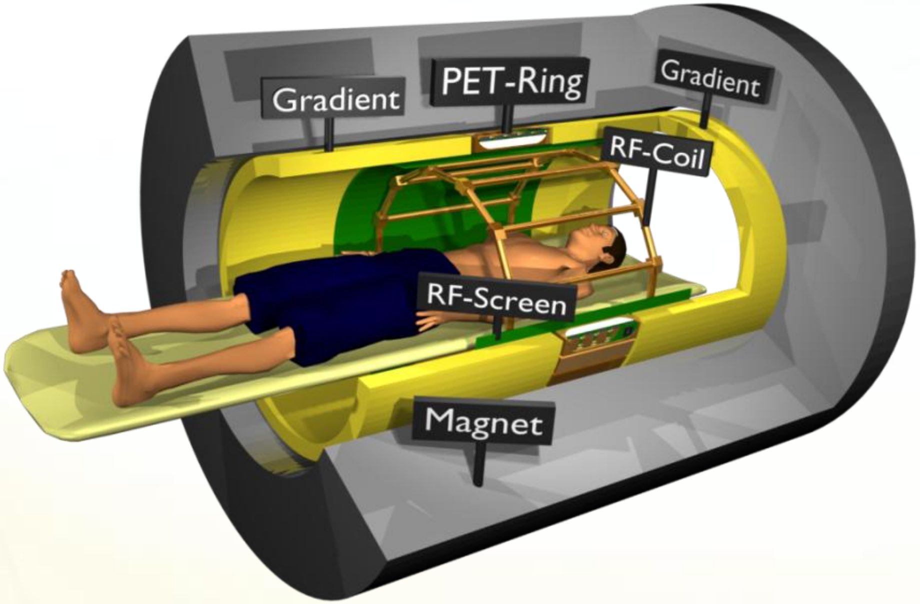




Very encouraging results obtained for first TOF-PET modules
(dE/E~11%,
CRT ~320ps, LYSO)

Application-oriented development

Development of an integrated TOF-PET/MR system

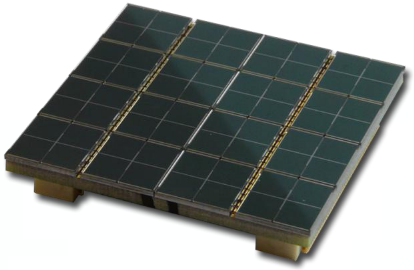


Picture of the system under development by **HyperImage/SUBLIMA** EU funded projects

Type	PMT	APD	SiPM
MR compliant	no	yes	yes
ToF compliant	yes	no	yes

Photosensor development

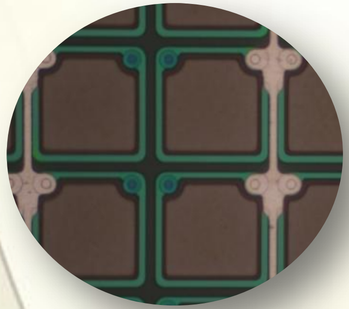
Sensor tiles production to equip a machine



- geometry definition
- integration scheme definition
- device production

some results presented @ IEEE NSS/MIC 2009

Development of improved SiPMs



Tuning of both technology as well as design

↓ (technology)
- PDE
- Vbd uniformity
- Temperature dep.

↓ (design)
- signal shape
- cells density

some results presented @ IEEE NSS/MIC 2010

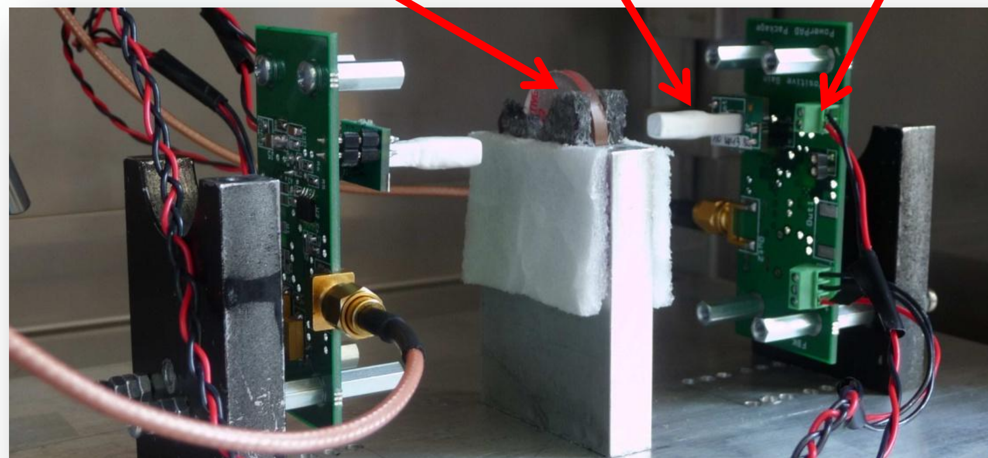
Testing SiPM building block

Thermostatic chamber

Na^{22} radiation source

SiPM + LYSO

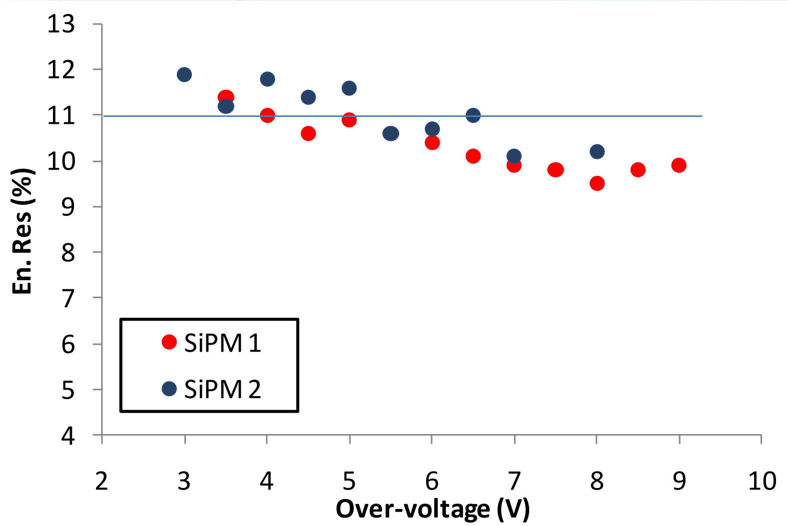
amplifier



- SiPMs: 4x4mm^2, produced @ FBK, n-on-p technology
- LYSO crystals: 3.8x3.8x22mm^3, teflon-wrapped
  slightly smaller section than SiPM for easier alignment
- voltage amplifiers: R_{in}=20ohm; G=2.5

C. Piemonte, NSS Conference 2010

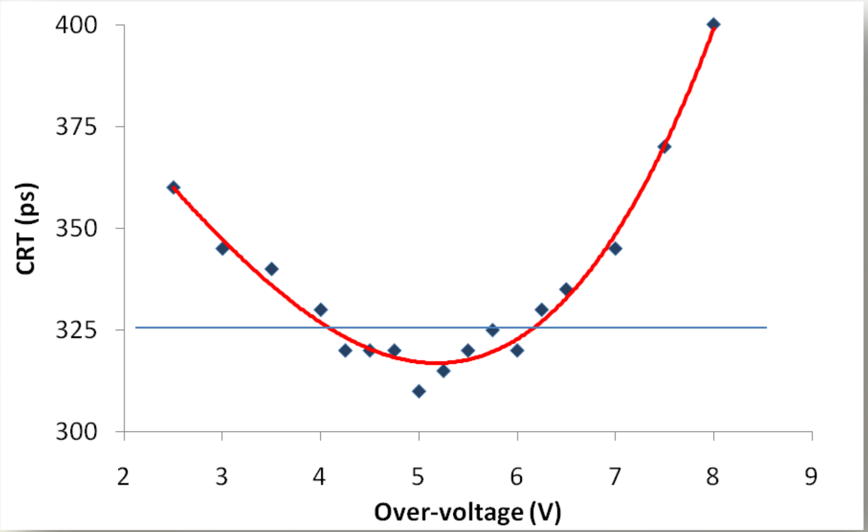
Testing SiPM building block



dE/E < 11% corrected for non-linearity

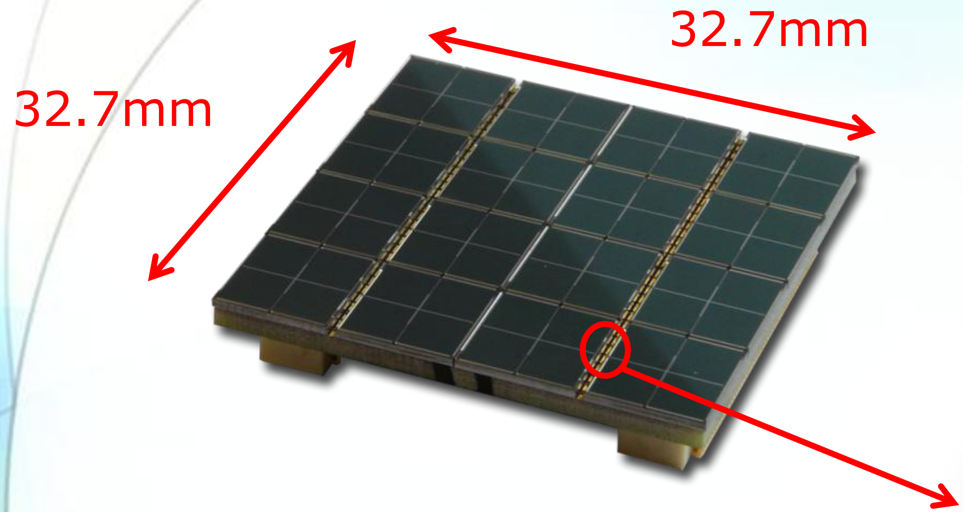
C. Piemonte, NSS Conference 2010

CRT<325ps @ 4-6V
⇒ detector time res.<230ps

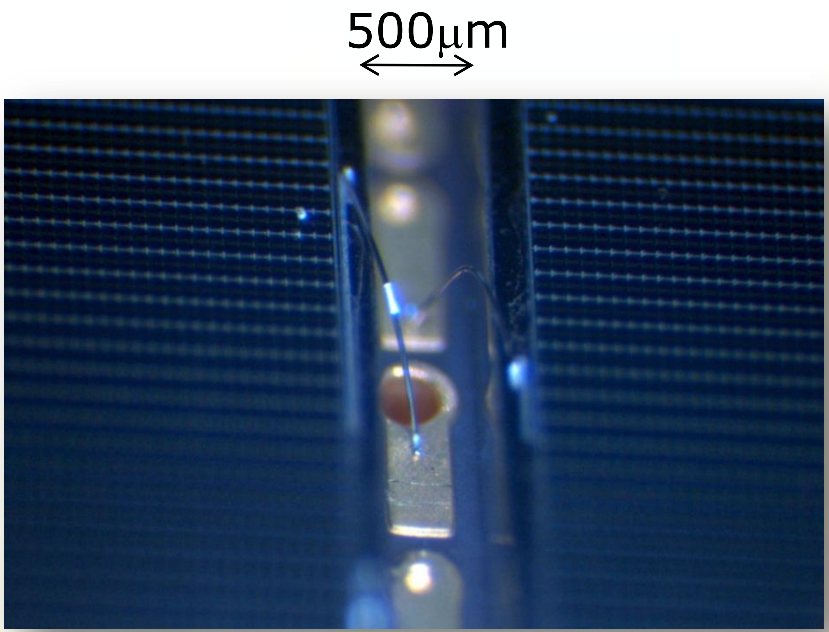


This proves timing capability of large area SiPMs!
New results will be presented at NSS (if accepted!): CRT~260ps!!!

The SiPM tile

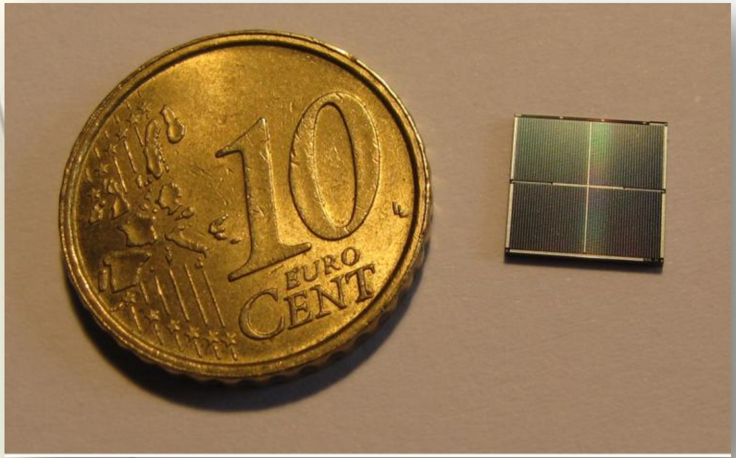


- **Fill factor ~ 84%** (not including SiPM FF)
- **Flat surface for crystal mounting**



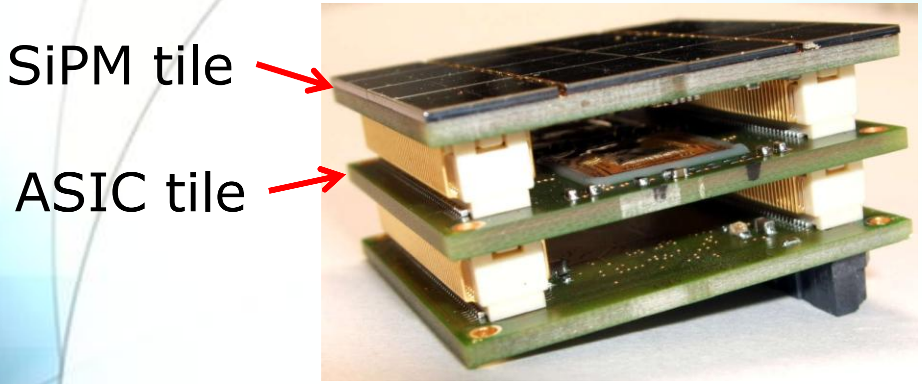
PCB design and mounting at Uni. Heidelberg and Philips

2x2 array of ~4x4mm² SiPMs
3600 cells per element

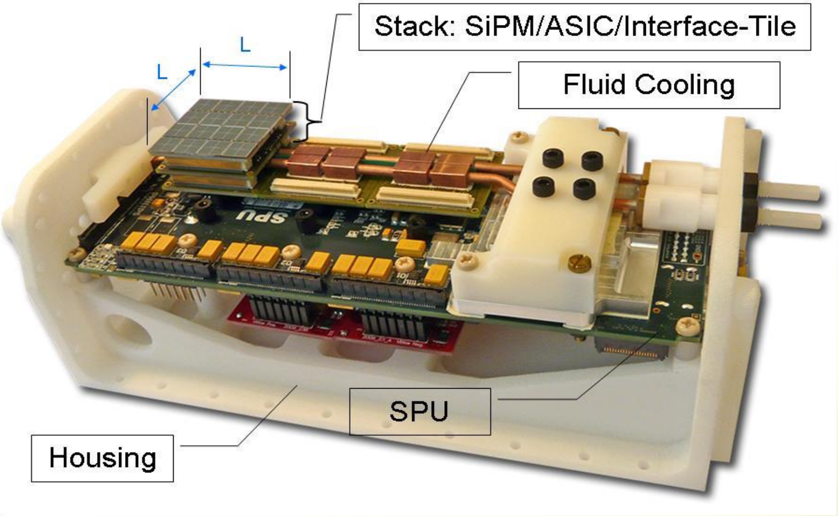


The preclinical system

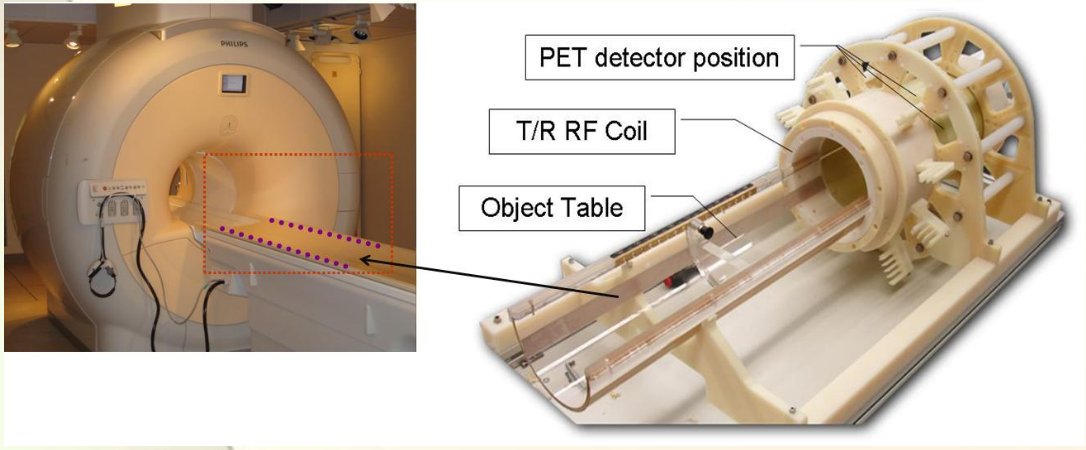
The stack



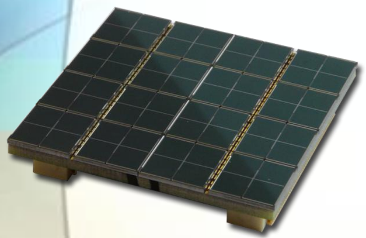
The module



Mechanics



SiPM *vs* PMT (today)



	Parameter	
✓ ✓	single photon sensitivity	✓
x x	noise per unit area	✓
✓ ✓	timing performance	✓
✓	good QE from UV to nearIR	✓
x	price per unit area	✓
✓	Fine segmentation	x
✓	low thickness	x
✓	magnetic fields insensitiveness	x
✓	high-level light tolerance	x
✓	robustness	x
✓	customization level	x
✓ x	temperature dependence	✓
✓ x	bias reproducibility	x ✓

Conclusion

- Results show that SiPM is competitive against PMT.

- Different products are appearing on the market: good competition for price and performance

- It is a relatively new technology,
  $\Rightarrow$ improvements can be expected in:
    - noise
    - PDE
    - interconnectivity