# SiPM: on the Way at Becoming an Ideal Low Light Level Sensor

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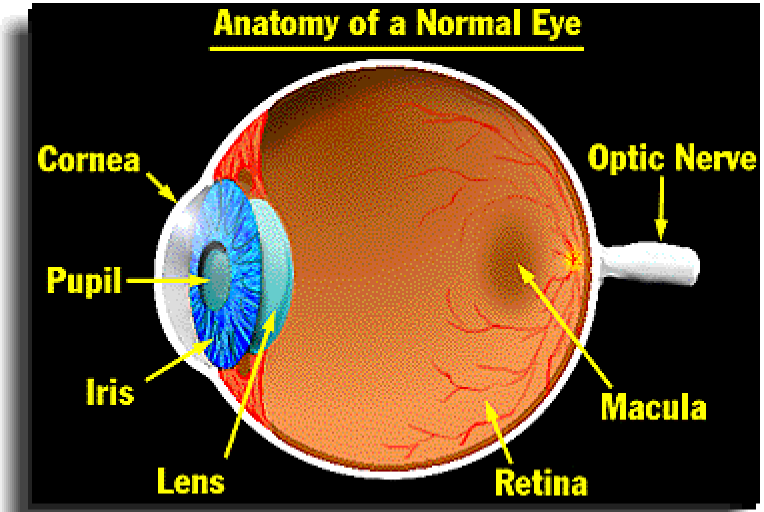
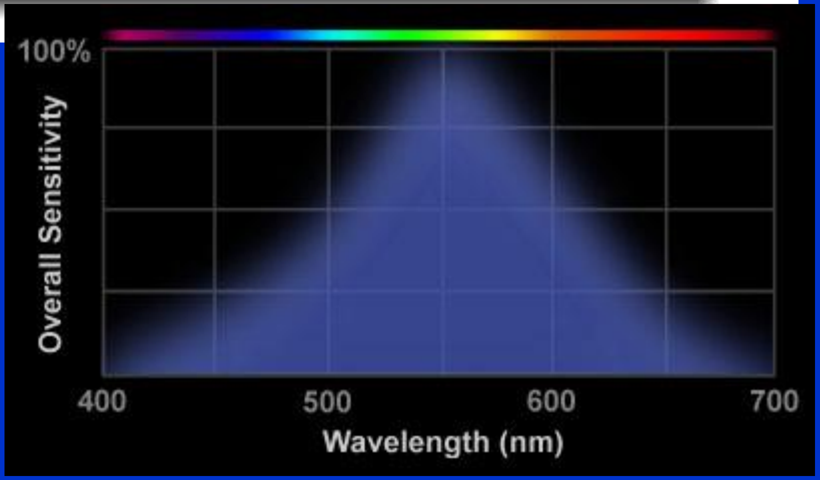
# The most complex light sensors

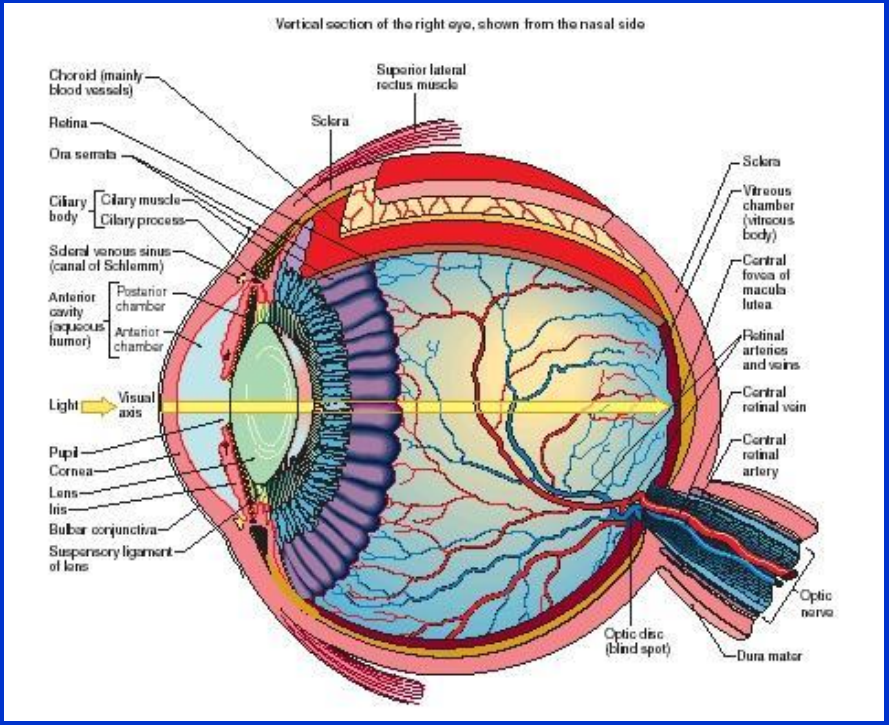
These seemingly best-known imaging light sensors measure colour in the a relatively wide band (400 – 700 nm) as well as the light intensity within a

- dynamic range of 13 orders of magnitude !
- angular resolution ~ 1‘ (oculists call it 100 % sight)
- integration time $\geq$ 30 ms,
- threshold value for signals
  - 5-7 green photons (after few hours adaptation in the darkness)
  - 30 photons on average in the dark

# Complex light sensors



# What LLL sensor can we dream about ?

- Die eierlegende Woll-Milch-Sau (german)

  (approximate english translation: all-in-one device suitable for every purpose)

# What LLL sensor can we dream about ?

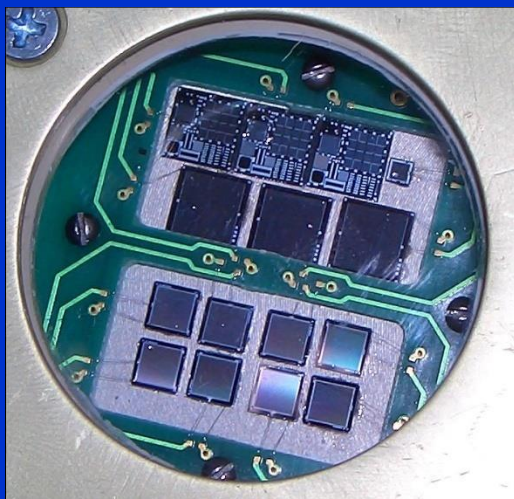
- Nearly 100 % QE and photon detection efficiency (PDE)
- Could be made in very large and in very small sizes
- Few ps fast (in air and in many materials the light speed is usually 20-30 cm/ns;  in 5 ps it will make 1-1.5 mm)
- Signal amplification x$10^6$
- Noiseless amplification: F-factor - 1.001
- Few % amplitude resolution
- No fatigue, no degradation in lifetime
- Low power consumption
- Operation at ambient temperatures
- No danger to expose to light
- Insensitive to magnetic fields
- No vacuum, no HV, lightweight,...

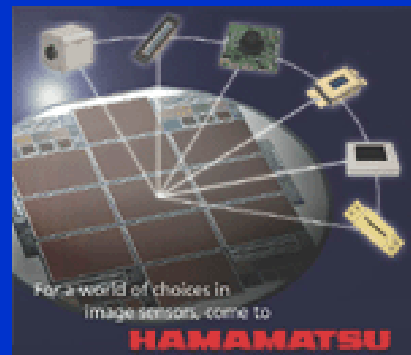
# Light conversion into a measurable

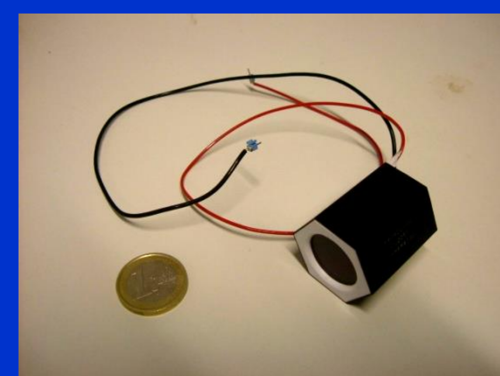
- Visible light can react and become measurable by:
  - Eye *(human: QE ~ 3 % &* animal), plants, paints,...
  - Photoemulsion *(QE ~ 0.1 – 1 %)* (photo-chemical)
  - Photodiodes (photoelectrical, evacuated)
    - Classical & hybrid photomultipliers *(QE ~ 25 %)*

      *QE ~ 45 % (HPD with GaAsP photocathode)*
  - Photodiodes *(QE ~ 70 – 80 %)* (photoelectrical)
    - PIN diodes, Avalanche diodes, SiPM,...
    - photodiode arrays like CCD, CMOS cameras,...

# The „zoo“ of LLL sensors

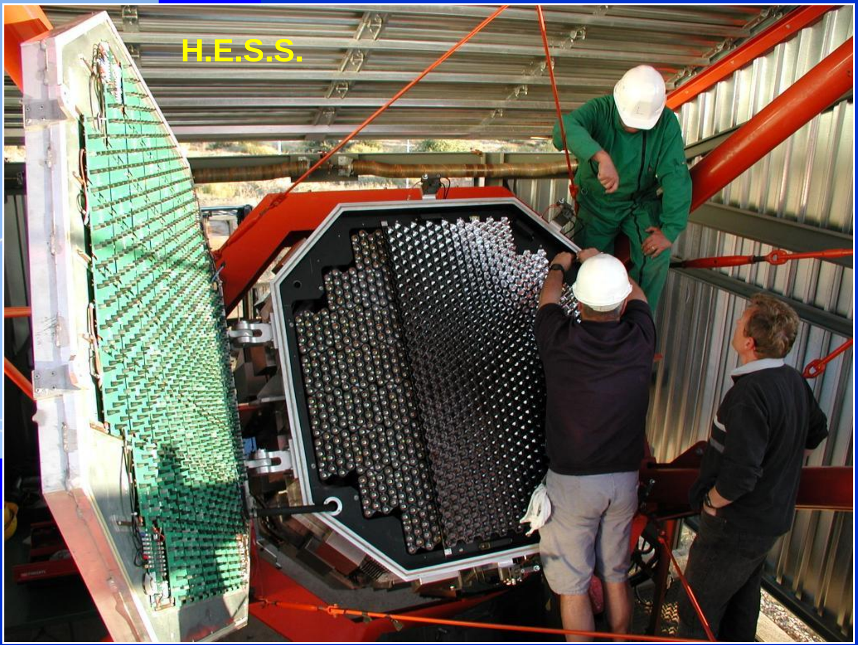




# The 17m Ø MAGIC IACT project for VHE $\gamma$ astrophysics at E~ 25 GeV - 30 TeV


Photograph of the 576-pixel imaging camera of MAGIC-I. In the central part one can see the 396 high resolution pixels of 0.10° size. Those are surrounded by 180 pixels of 0.20°.

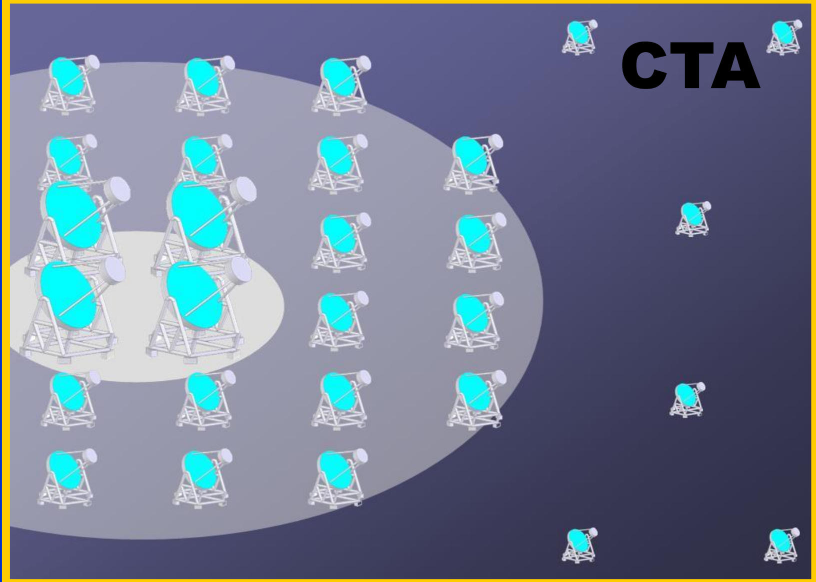



# Outlook : the next 5-7 years

## Next generation VHE γ ray Observatory: CTA

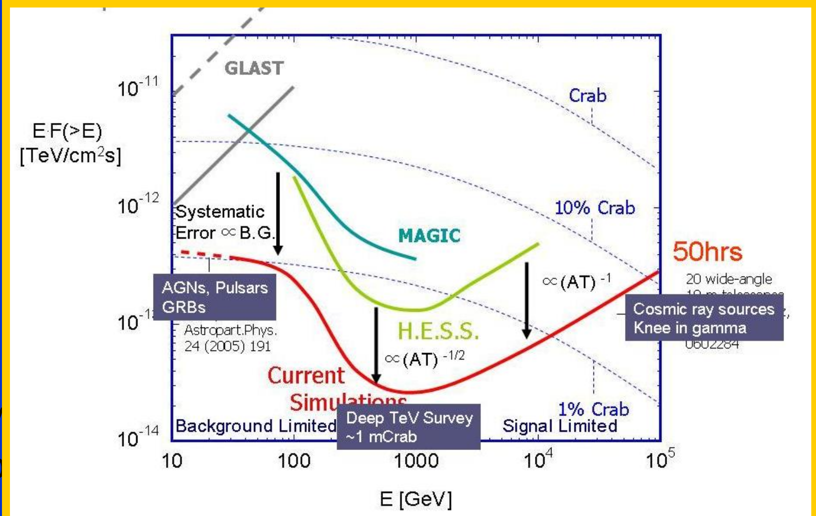
MAGIC Phase II (MAGIC-I + MAGIC-II) in 2010
~100 sources are already discovered

Cherenkov Telescope Array
1000's of sources will be discovered




~500 scientists
~50 institutions

HESS Phase II (HESS + 28m Telescope) in 2012 ?




Astronomers in EU

JAPAN, US

# Quantum Efficiency

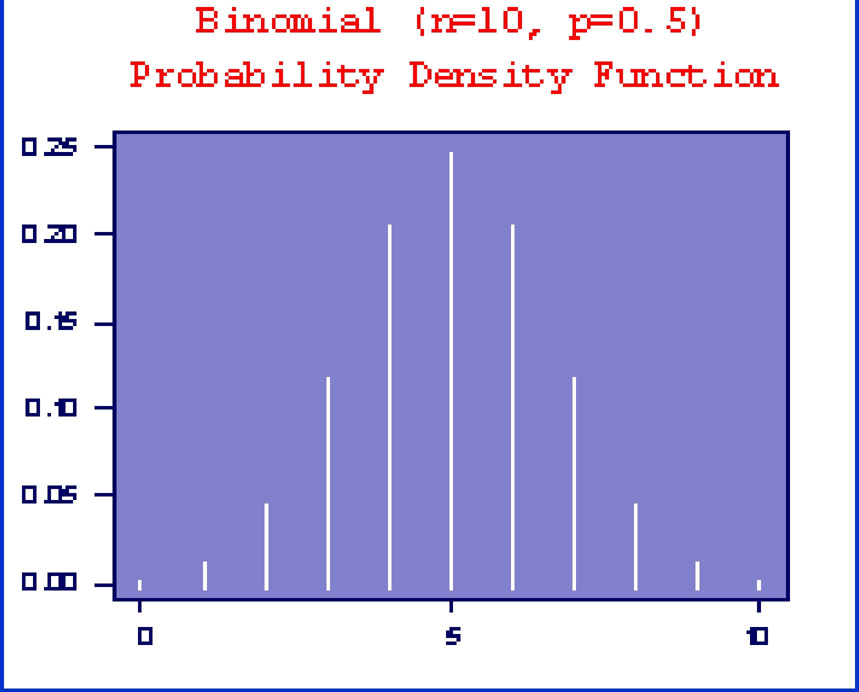
Quantum efficiency (QE) of a sensor is defined as the ratio

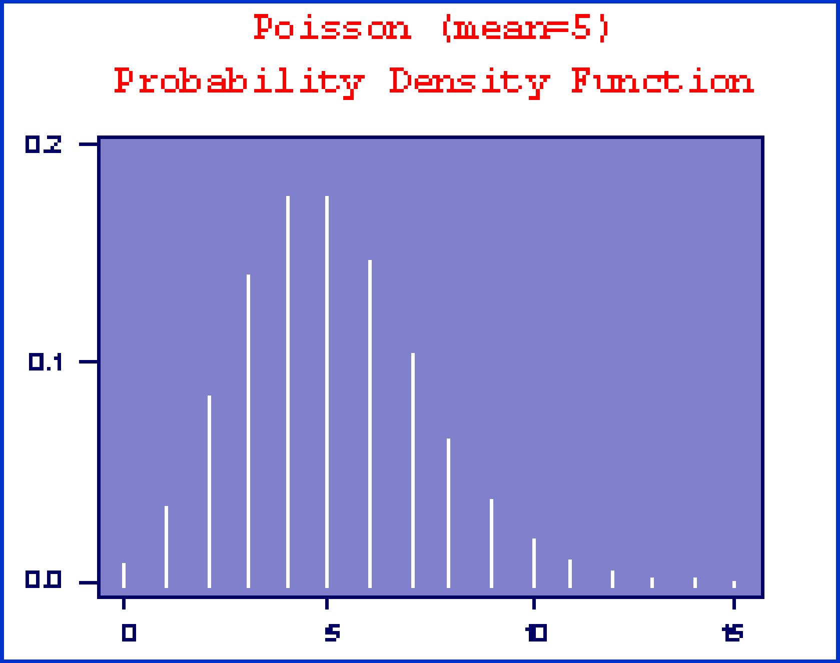
$$QE = N(ph.e.) / N(photons)$$

Conversion of a photon into ph.e. is a purely binomial process (and not poisson !)

Light sources of thermal origin can be described by the poisson distribution (including LED)

# Differences between binomial and poisson distributions




SNR = 3.16

mean/σ = 2.24

# Why do we want high Quantum Efficiency

Please note that here there is no noise source, we are talking about the „noise in the signal“ because just statistically, from trial to trial, the number of detected photons vary.

# Why do we want high Quantum Efficiency

Assume <u>N photons</u> are impinging onto a sensor and every photon has the same <u>probability P</u> to kick out a ph.e..

Then the <u>mean</u> number of ph.e.s is **N x P** and

the <u>Variance</u> is equal to **<u>N x P x (1 – P)</u>**

Signal/Noise = mean/sigma =

$$NxP / \sqrt{[NxPx(1-P)]} = \sqrt{[NxP/(1-P)]}$$

# Signal to noise ratio

The signal-to noise ratio of a light sensor can be calculated as

$$\mathbf{SNR = [N \times P/(1 - P)]^{1/2}}$$

For example, if N = 1 (single impinging photon):

| | | | |
|---|---|---|---|
| P | 0.1 | 0.3 | 0.9 |
| SNR | 0.33 | 0.65 | 3 |

# Signal to noise ratio

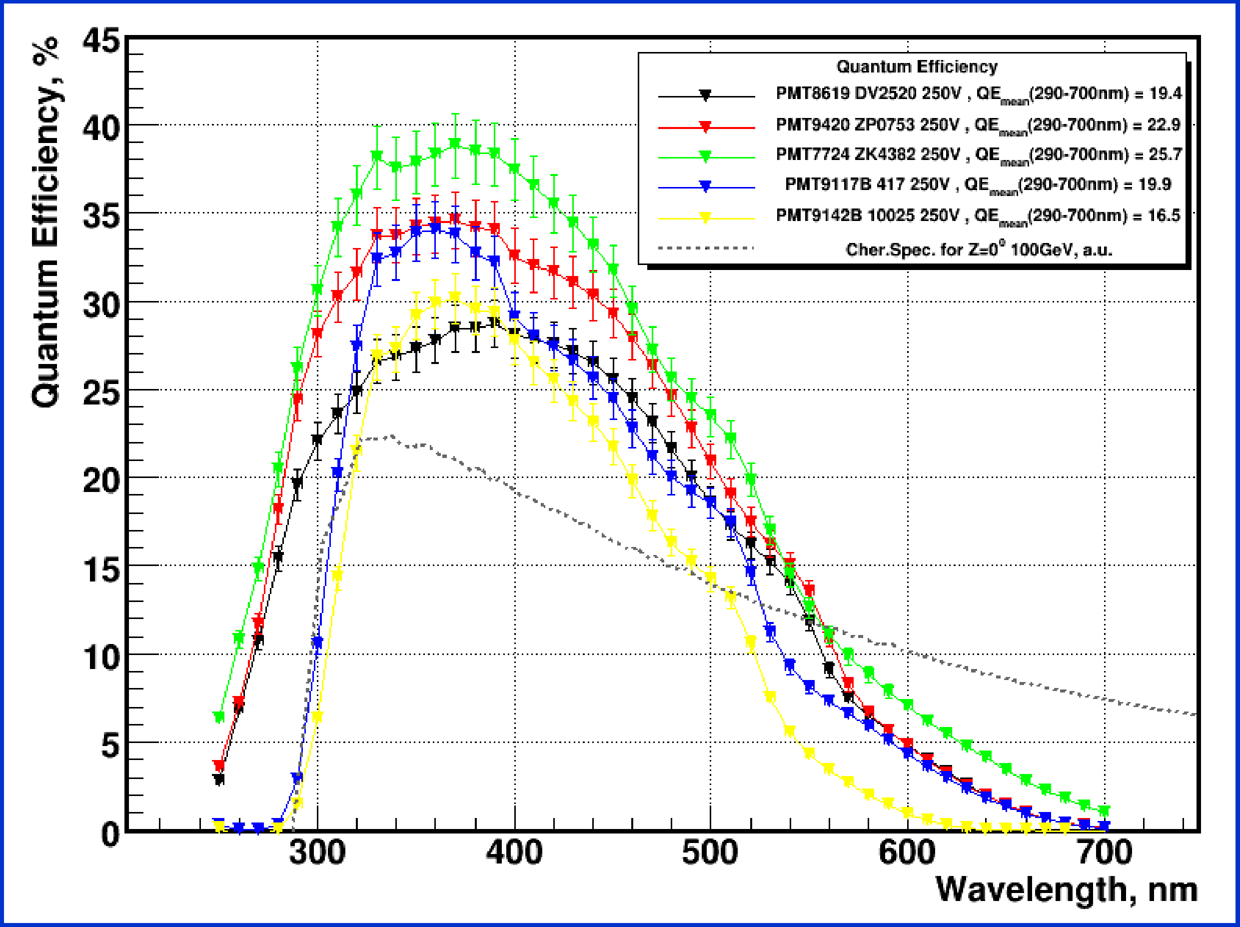
$$\mathbf{SNR = [N \times P/(1 - P)]^{1/2}}$$

For N = 20 impinging photons:

| | | | |
|---|---|---|---|
| P | 0.1 | 0.3 | 0.9 |
| SNR | 1.5 | 2.9 | 13.4 |

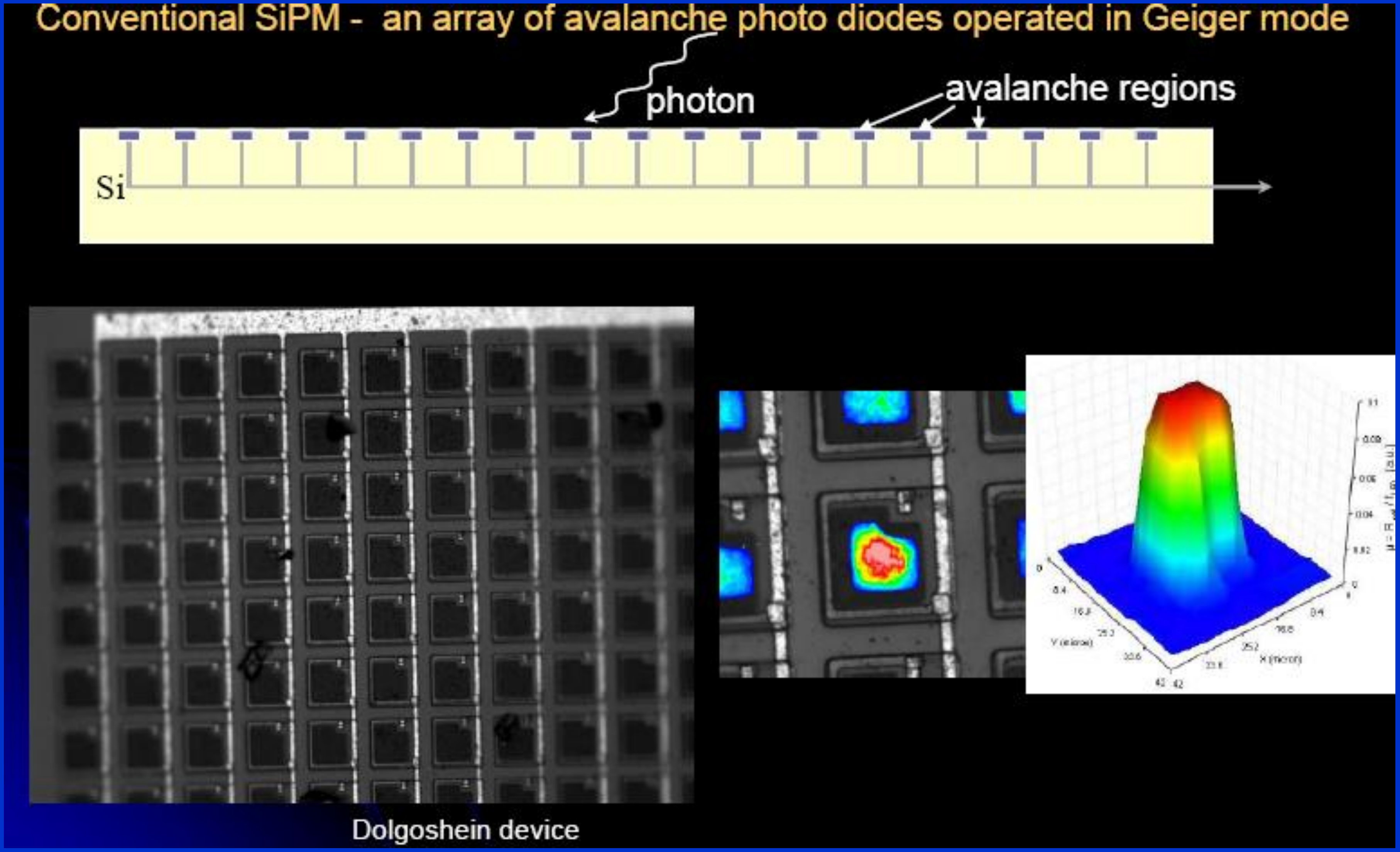
# Instrumental/technological improvements

Running target: light sensor improvements. Successfully pushing the PDE higher up. Shown for several types of PMTs

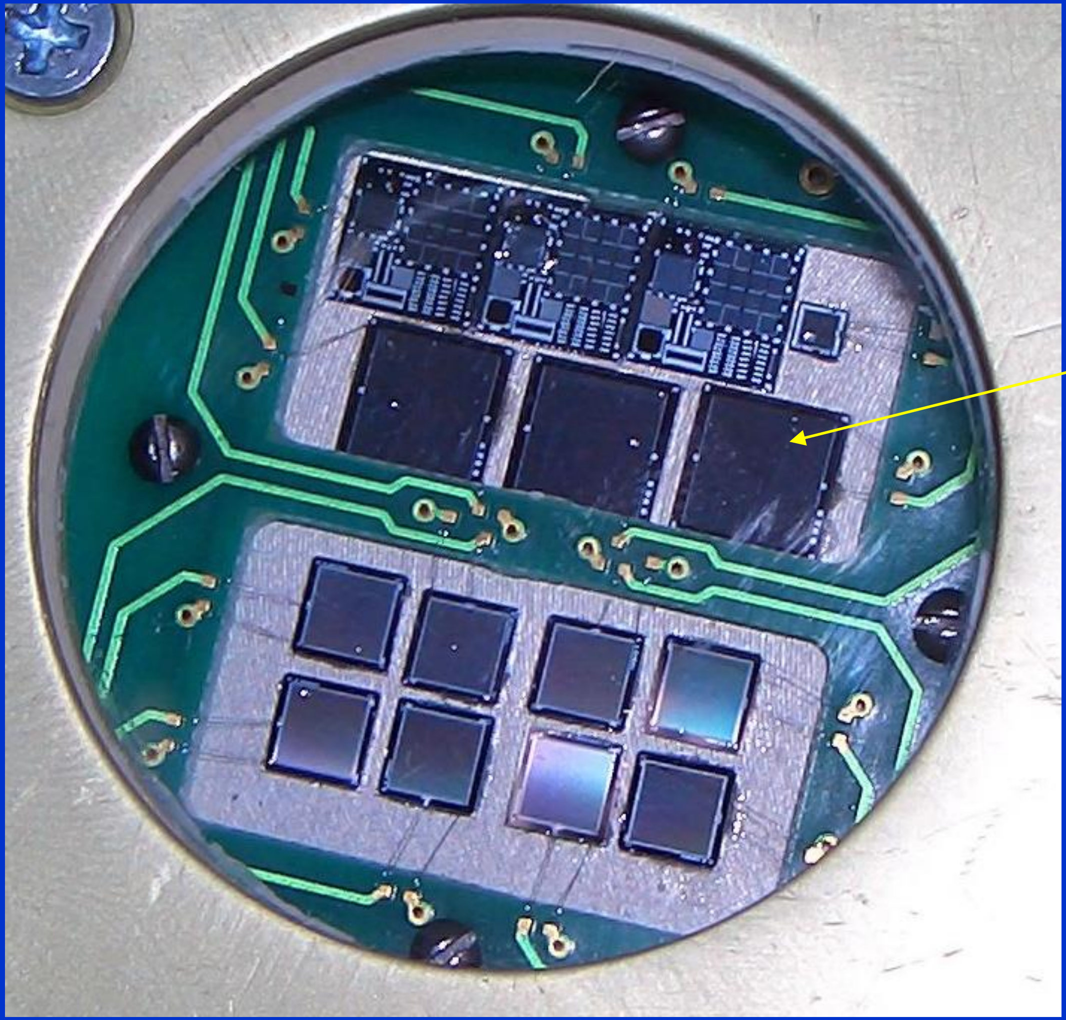



- Some 7 years ago we have launched a QE improvement program with manufacturers Hamamatsu (Japan), Photonis (France) and Electron Tubes Enterprises (England).
- The results were very encouraging
- Since about 3 years a new program has been launched for CTA; the results are shown on the left

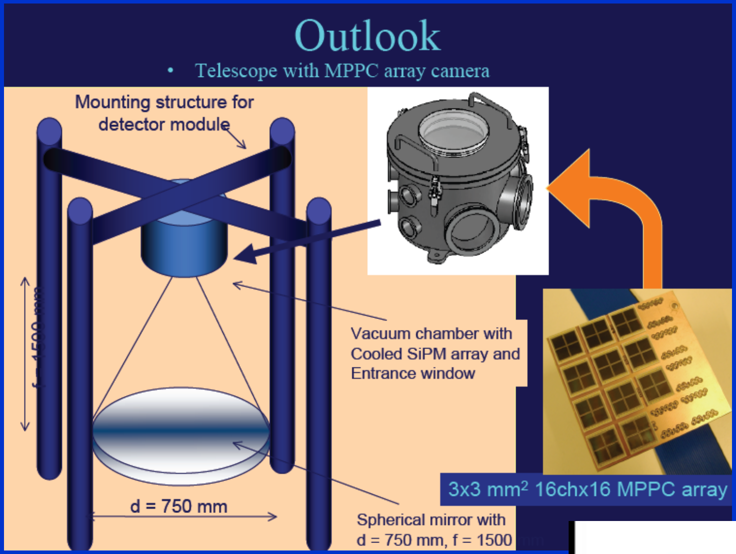
# SiPM: novel light sensors

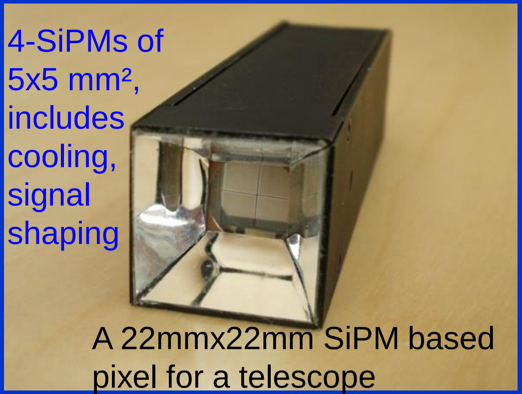


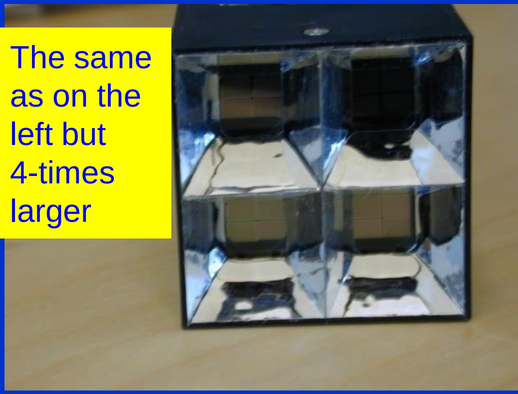
# SiPMs: MEPhI-MPI development: 1x1, 1.3x1.3, 1.4x1.4, 3x3, 5x5 mm², some 6 years ago

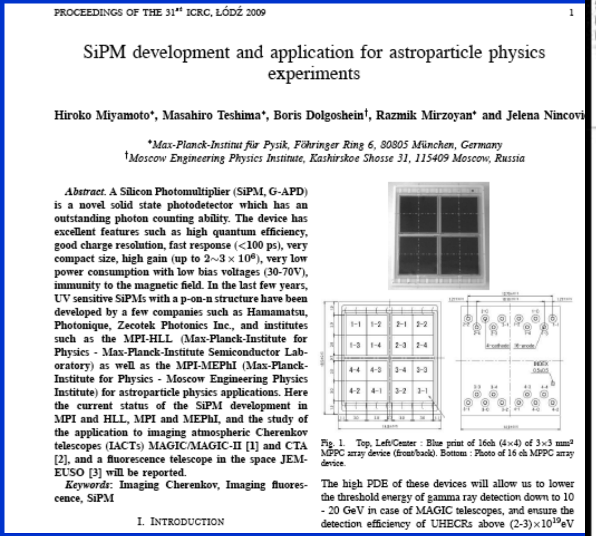


5 x 5 mm²





PROCEEDINGS OF THE 31st ICRC, ŁÓDŹ 2009 1

SiPM development and application for astroparticle physics experiments

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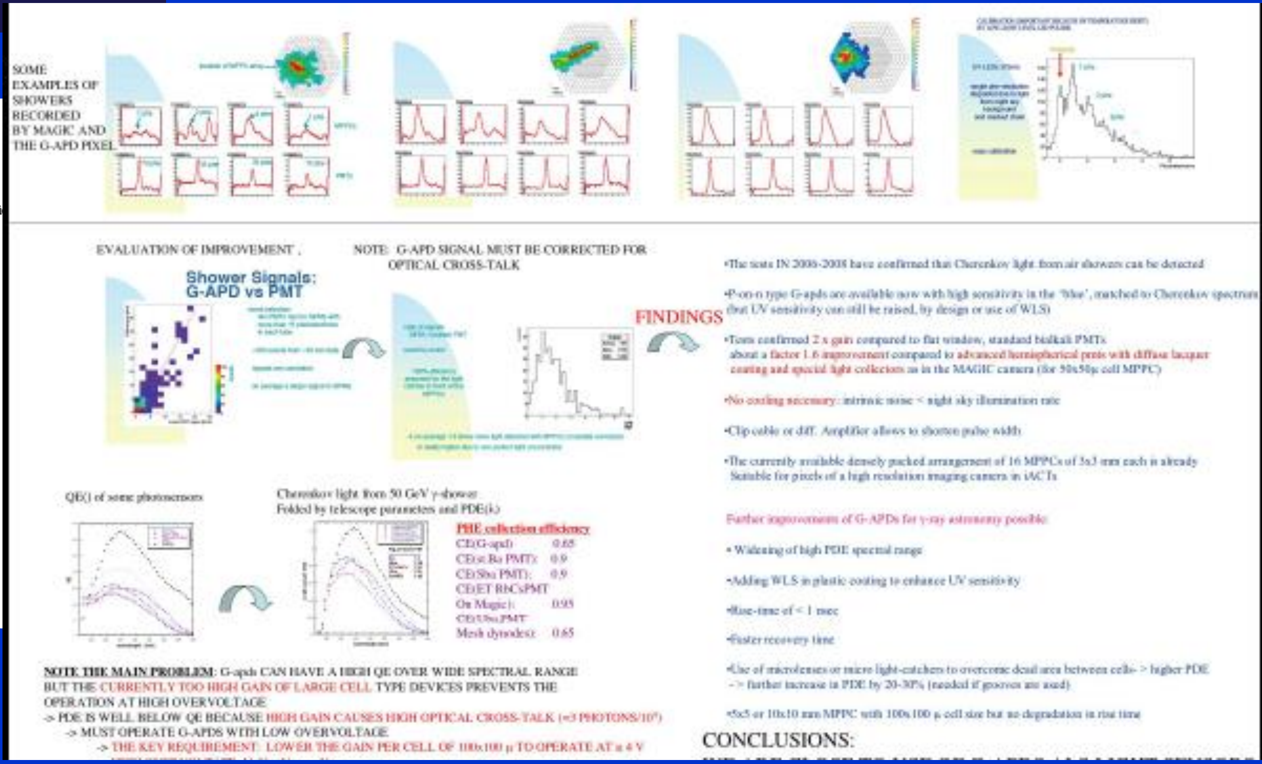
*Abstract.* A Silicon Photomultiplier (SiPM, G-APD) is a novel solid state photodetector which has an outstanding photon counting ability. The device has excellent features such as high quantum efficiency, good charge resolution, fast response (<100 ps), very compact size, high gain (up to $2\sim3\times10^6$), very low power consumption with low bias voltages (30-70V), immunity to the magnetic field. In the last few years, UV sensitive SiPMs with a p-on-n structure have been developed by a few companies such as Hamamatsu, Photonique, Zecotek Photonics Inc., and institutes such as the MPI-HLL (Max-Planck-Institute for Physics - Max-Planck-Institute Semiconductor Laboratory) as well as the MPI-MEPhI (Max-Planck-Institute for Physics - Moscow Engineering Physics Institute) for astroparticle physics applications. Here the current status of the SiPM development in MPI and HLL, MPI and MEPhI, and the study of the application to imaging atmospheric Cherenkov telescopes (IACTs) MAGIC/MAGIC-II [1] and CTA [2], and a fluorescence telescope in the space JEM-EUSO [3] will be reported.

*Keywords:* Imaging Cherenkov, Imaging fluorescence, SiPM

I. INTRODUCTION

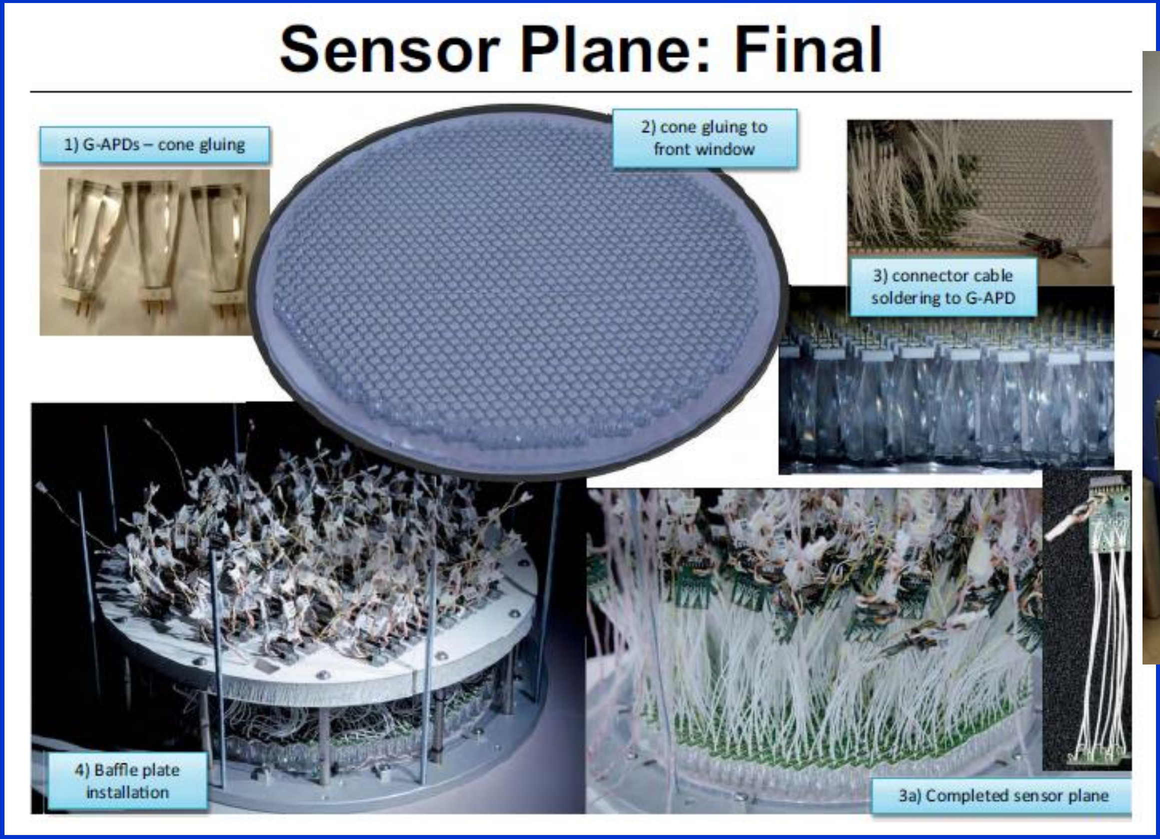
Fig. 1. Top, Left/Center : Blue print of 16ch (4×4) of 3×3 mm² MPPC array device (front/back). Bottom : Photo of 16 ch MPPC array device.

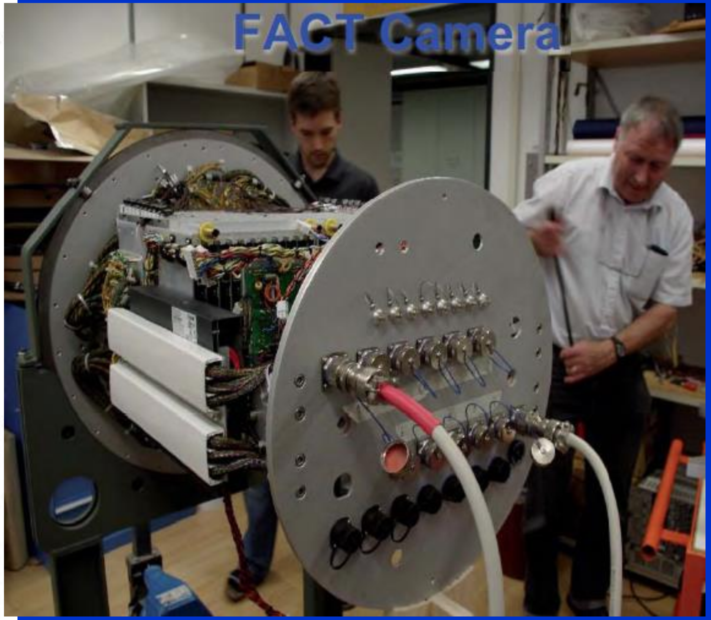
The high PDE of these devices will allow us to lower the threshold energy of gamma ray detection down to 10 - 20 GeV in case of MAGIC telescopes, and ensure the detection efficiency of UHECRs above (2-3)×10¹⁹eV



1440-pixel MPPC camera

# FACT telescope camera




This approach is probably not the one that will be followed in future

# SiPM Essentials

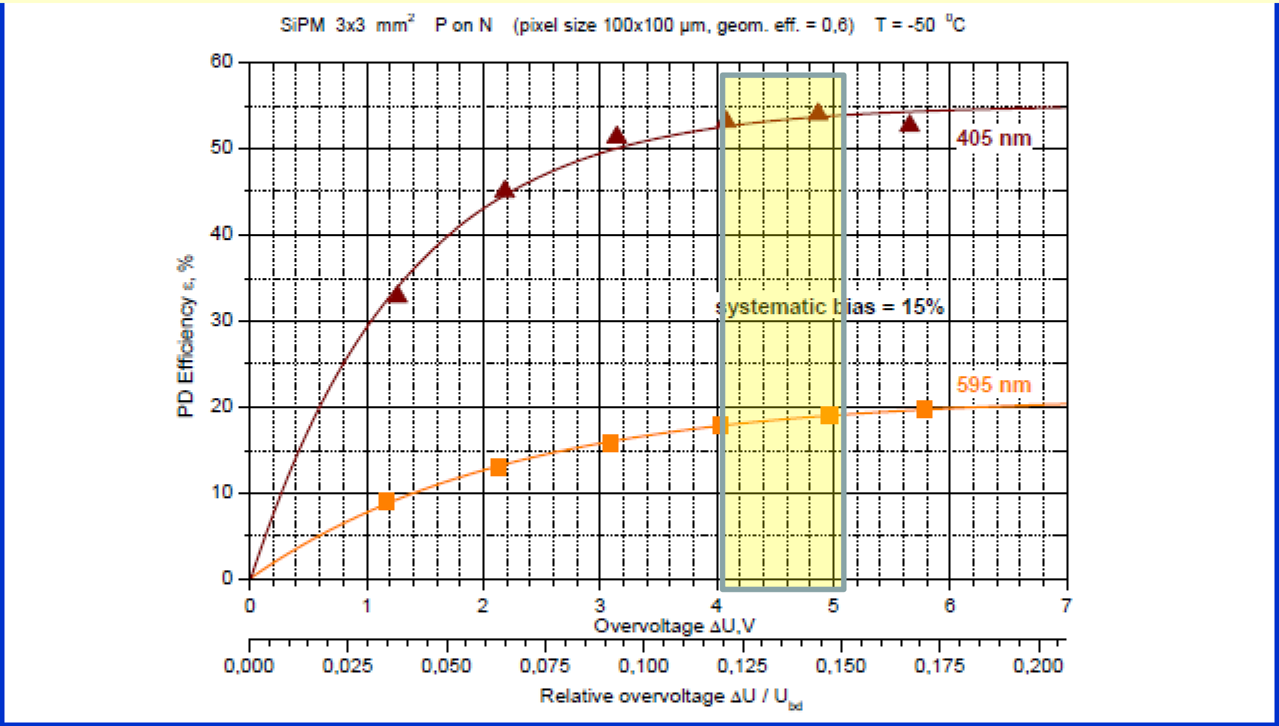
- Photon Detection Efficiency (PDE):

$$PDE(\lambda) = QE_{internal} \times T(\lambda) \times A_{active\ area} \times G_{geiger\text{-}eff.}(\lambda)$$

| | |
|---|---|
| $QE_{internal}$: | essentially 100 % |
| $T(\lambda)$ : | strongly varies with $\lambda$, could reach 80-90 % |
| $A_{active\ area}$: | some number between 20-80 % |
| $G_{geiger\text{-}eff.}(\lambda)$: | strong function of applied $\Delta U/U$, for $\Delta U/U \geq$ 12-15 % could become $\geq$ 95 % |

# Geiger Efficiency $G_{geiger\text{-}eff.}(\lambda)$

High Geiger efficiency can be achived for high Over-voltage ΔU/U:
Relative overvoltage ΔU/U ≈ 12 – 15 %



# Reflectivity of Si

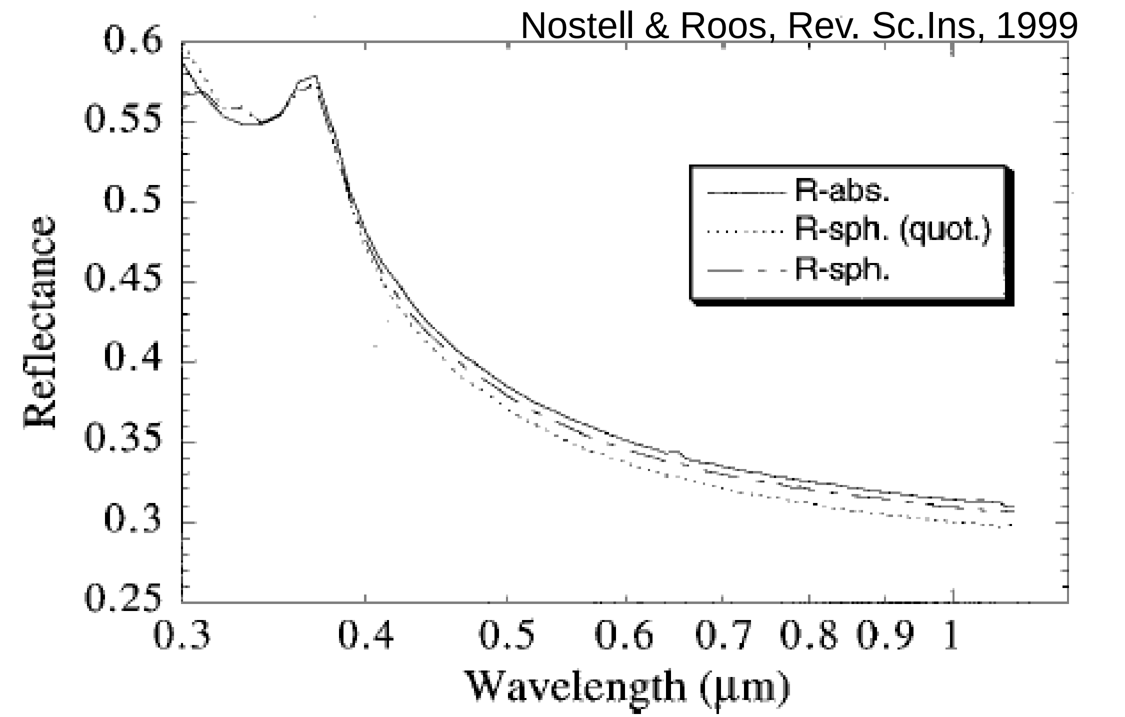
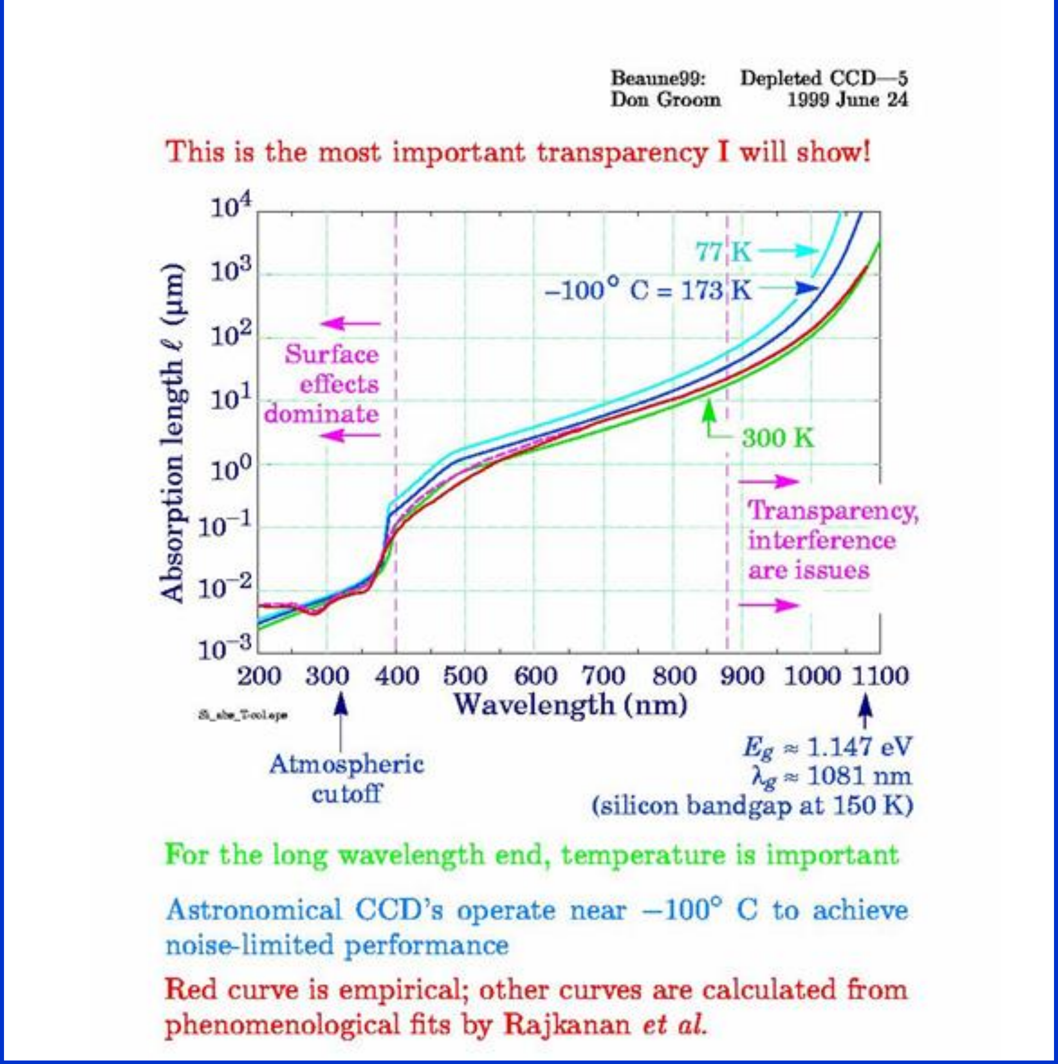



FIG. 19. Near normal reflectance spectra in the wavelength range 0.3–1.1 $\mu$m of silicon measured in the absolute spectrophotometer and the reflectance sphere. The reflectance sphere spectra consist of a corrected spectrum, R-sph, and the direct ratio between sample and reference signals, R-sph (quot.).

- Reflectivity of Si varies ~ 60 – 31 % for 300 – 1000 nm at normal incidence.
- antireflective coatings can help
- Proper choice of window coating can provide efficiency ≥ 80-90 %

# Reminder: light absorption in Si

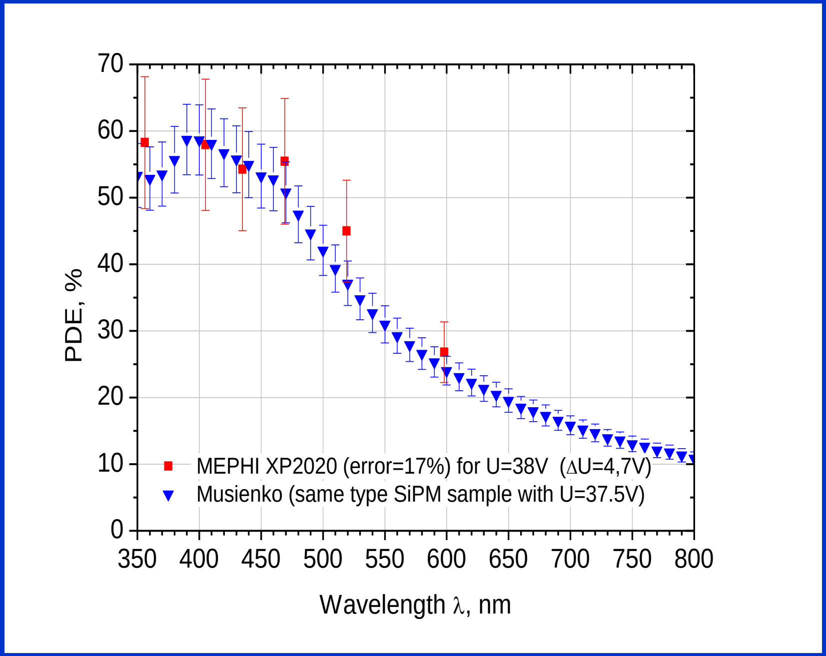



- While 1000nm light can penetrate ~100 µm deep into Si, light of 300 nm can penetrate only 5-7 nm!
- It is a major challenge to collect produced charge carriers from the very surface of the sensor, providing blue – near UV sensitivity

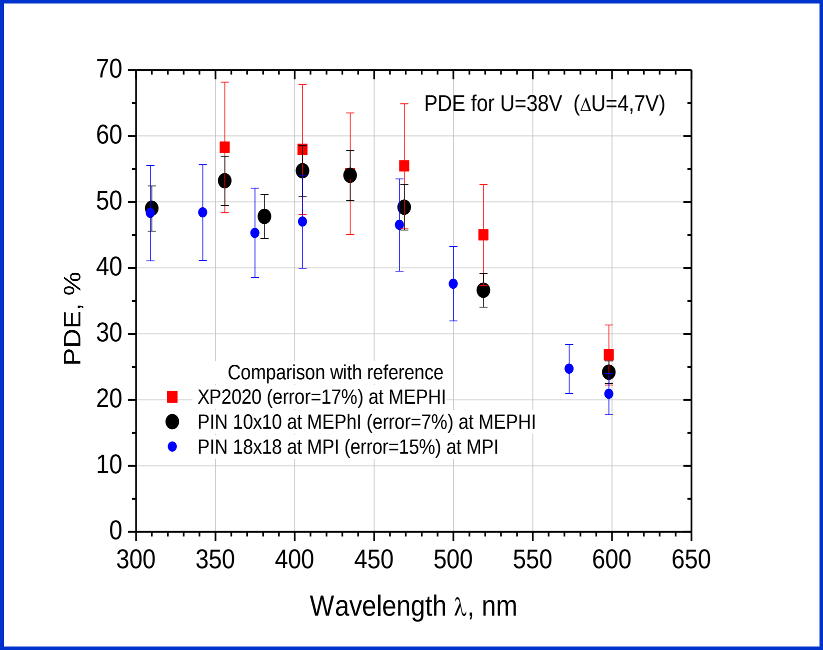
# Record high PDE (pulsed mode LED, 100B type SiPM, 1x1 mm²)

Measurements at MEPHI and

at CERN (Y.Musienko)

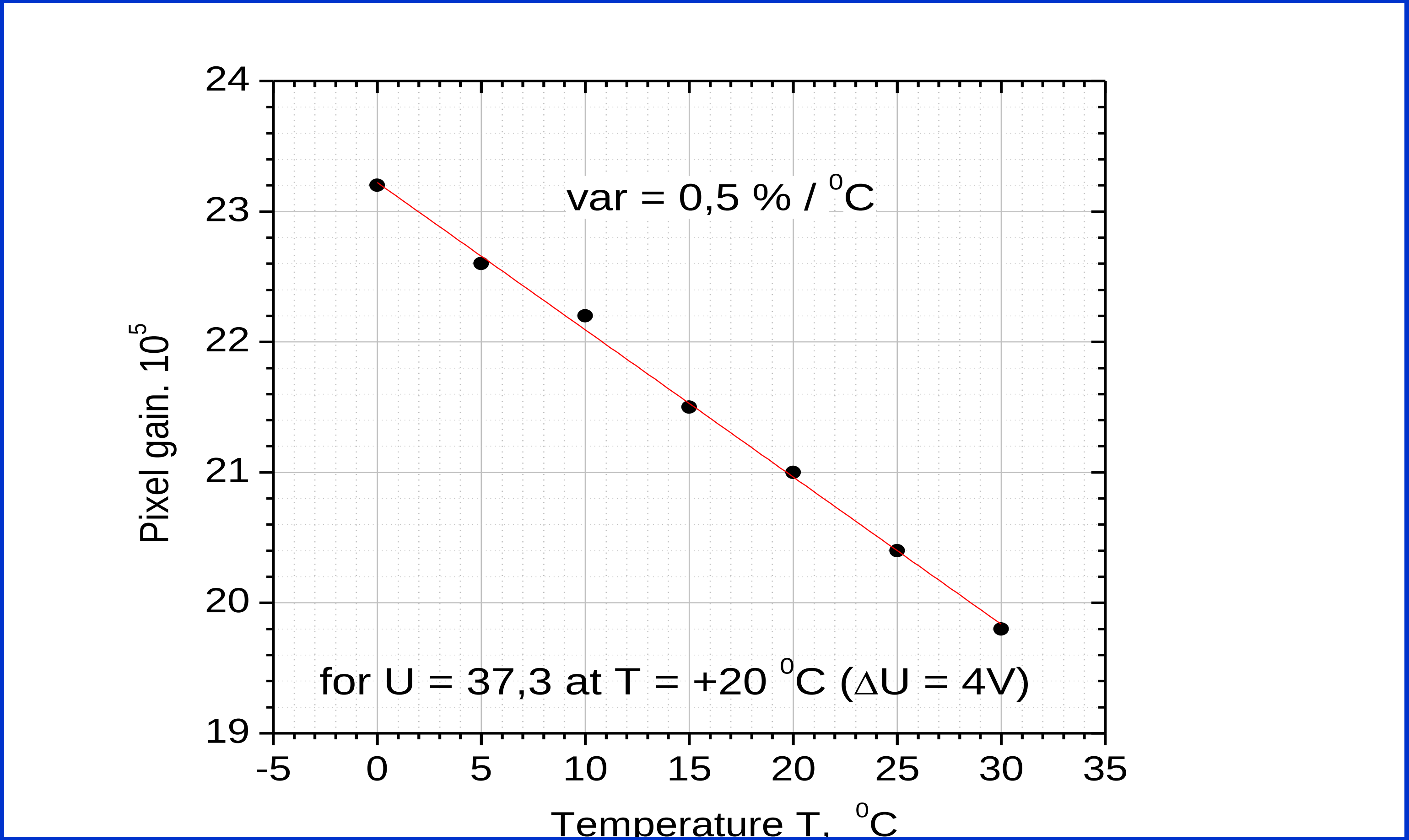



Measurements at MEPHI and at MPI

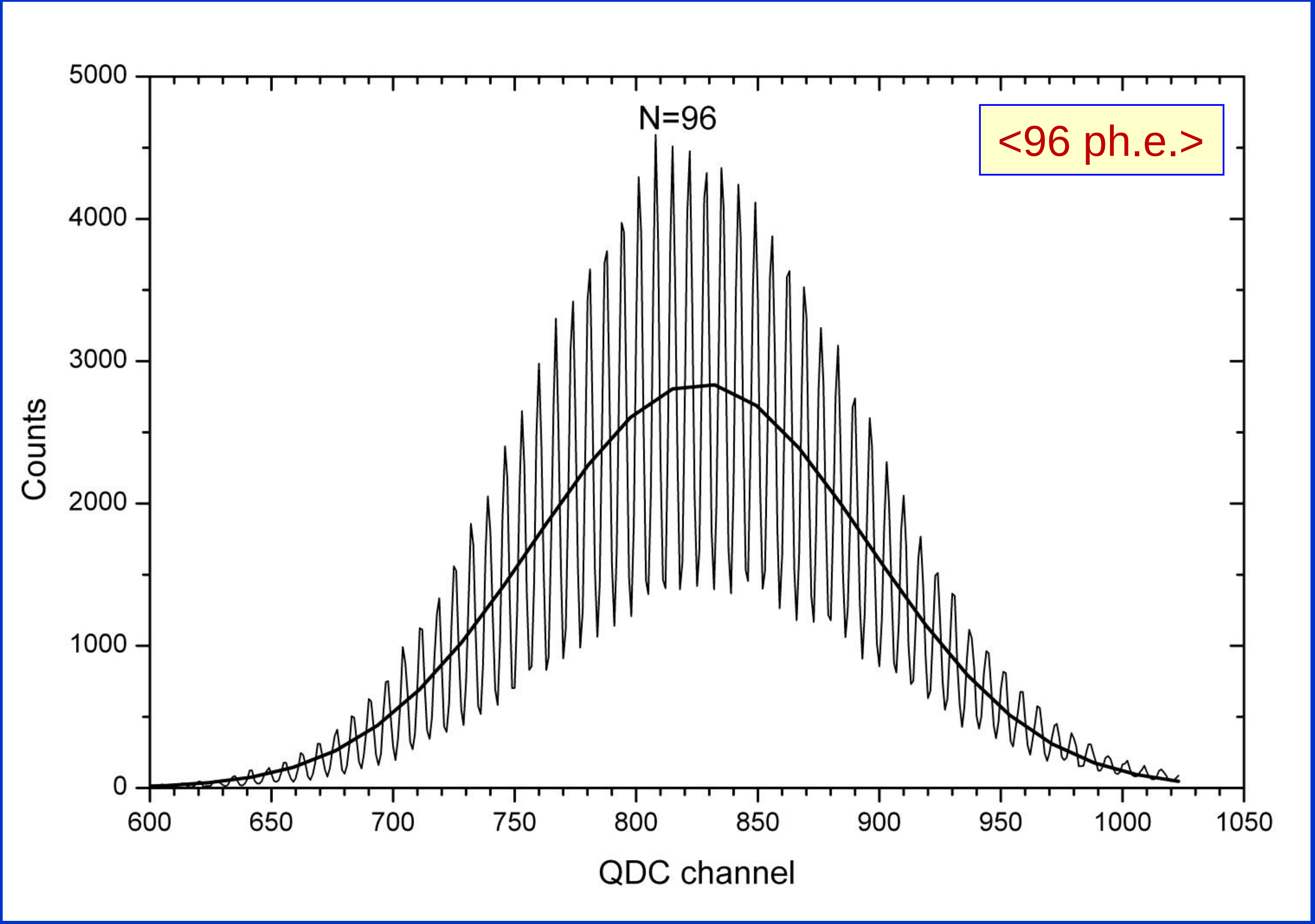



All results are consistent within experimental errors

# Extremely low temperature dependence



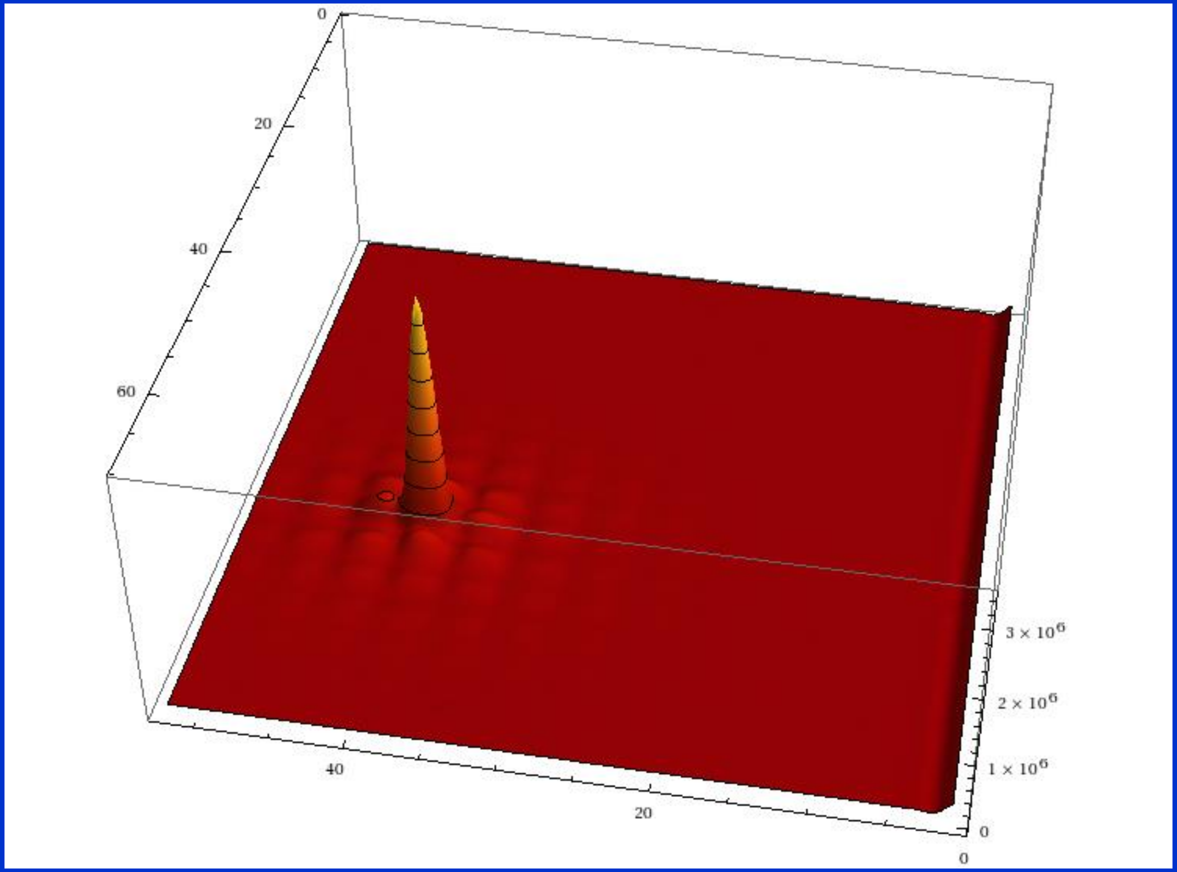
# SiPM with X-talk suppression: World record of ultra-fast light sensors in amplitude resolution

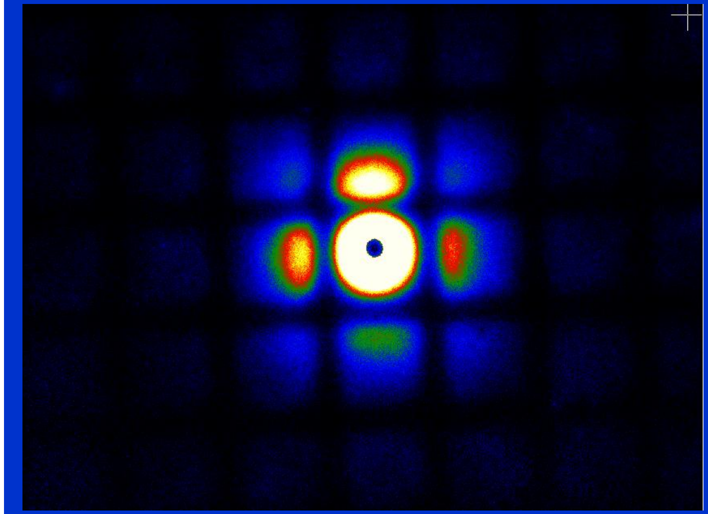


# Why the light emission from Si avalanches is important

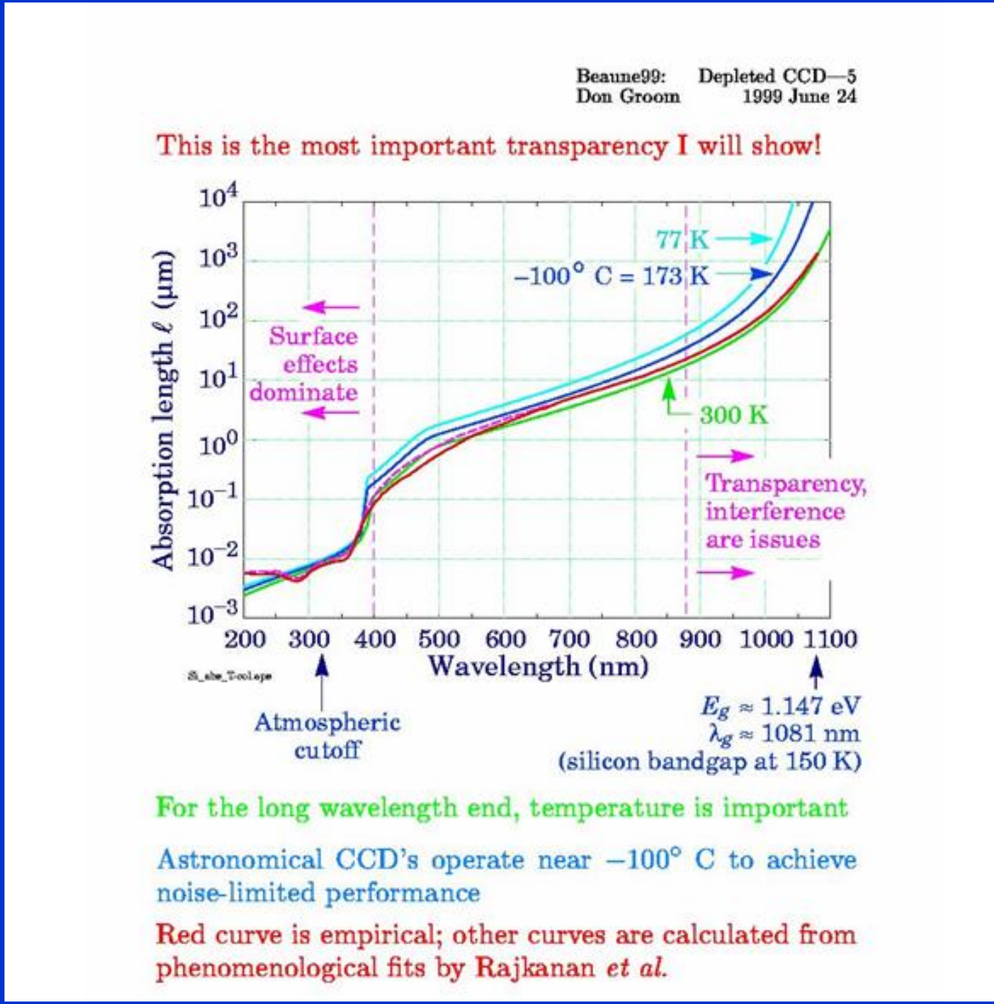
- First observation of the light emission from reversed-biased Si p-n junction in 1955 (Newman)
- Revived interest about the effect in recent years because of:
- Cross-talk in SiPMs (GAPD, MPPC, micro-channel APD,…) spoils the amplitude resolution
- The light emission is proportional to the number of e- in the avalanche. This puts a limit to the maximum gain under which one can operate the SiPMs
- If no measures are taken against the cross-talk, then the F-factor is worse than in classical PMTs
- As a consequence one encounters major problems in self-trigger schemes when measuring very low light level signals

# Cross-Talk



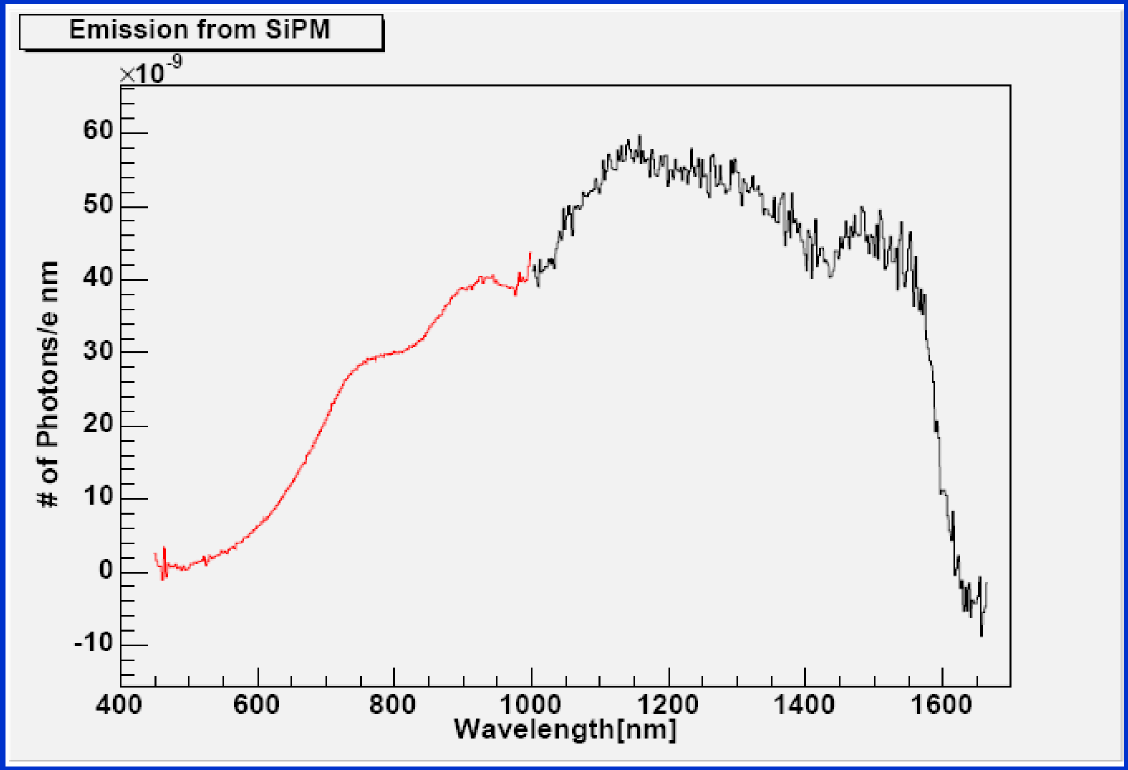



# Reminder: light absorption in Si




- The related to absorption effects in Si were taken into account in our measurements
- Already from this graph one can get an impression about the relevant for the cross-talk effect wavelength range

# Light emission spectrum

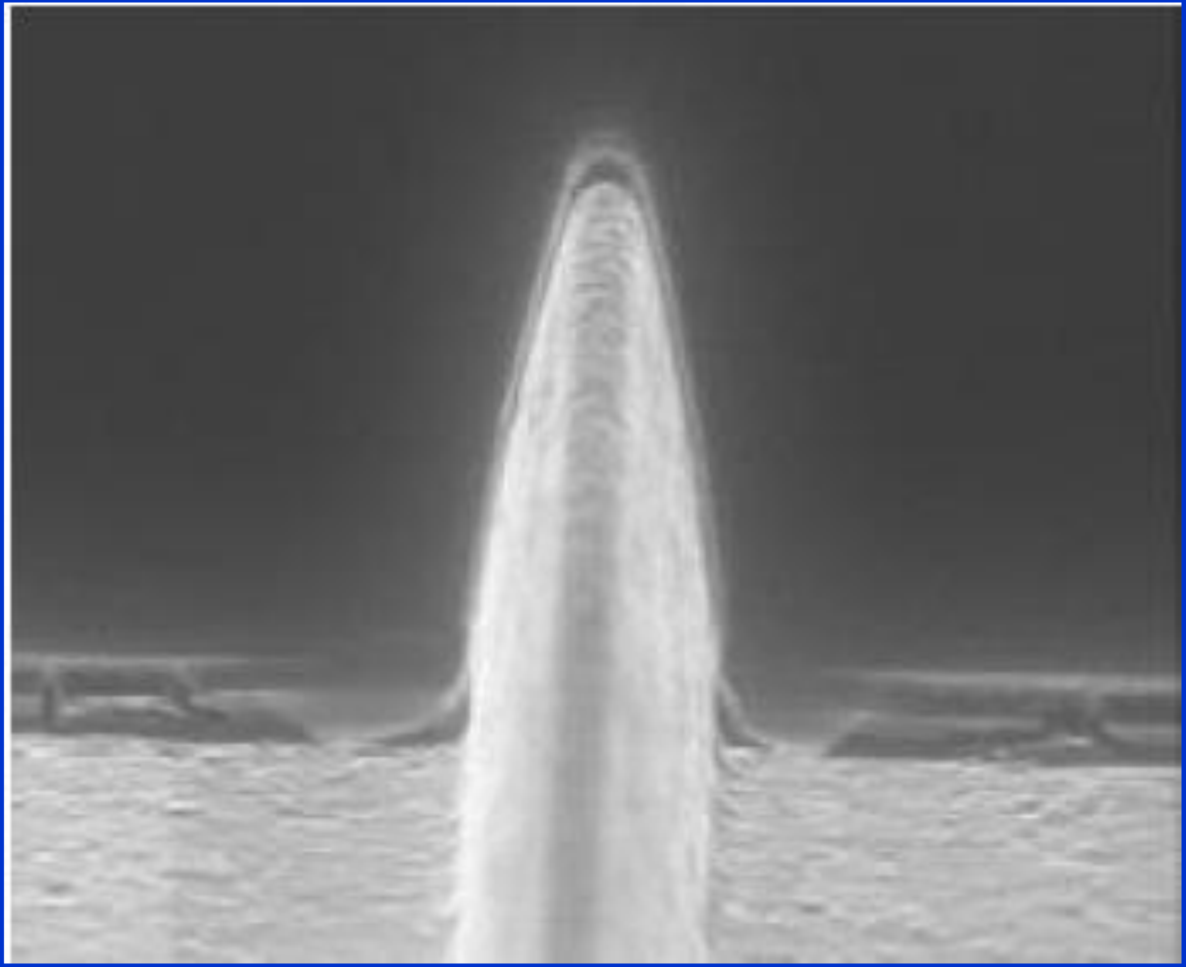



| | | |
|---|---|---|
| Wavelength range | 450 – 1600 nm | < 1117 nm |
| This measurement | 3.86 x $10^{-5}$ ph/e | 1.69 x $10^{-5}$ ph/e |
| Lacaita, et al., 93 | | 2.9 x $10^{-5}$ ph/e |

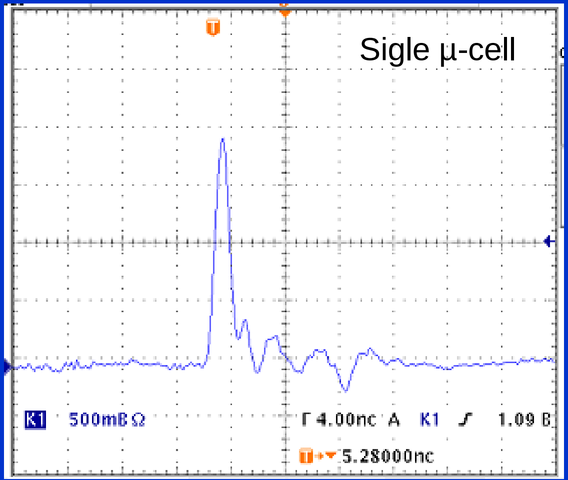
Imagine a SiPM operating ata gain of $10^6$.
It will emit ~17 (39) photons.
The total internal reflection angle in Si is ~16°, ➔ only light within 0.24 srad can leave the SiPM
(only $0.24/4\pi = 0.02$)

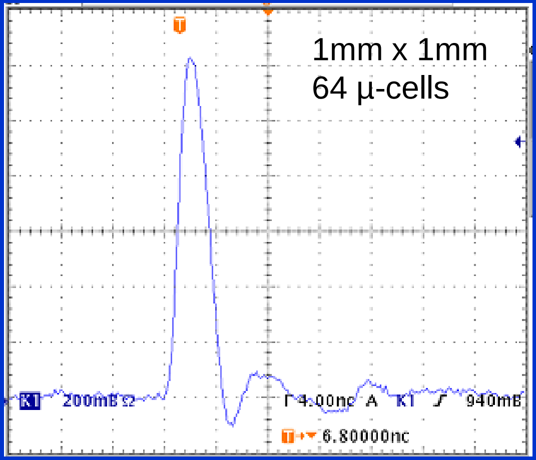
➔Only ~2 % of produced light comes out

# A filled in trench



# Pulse width depends on the SiPM chip size

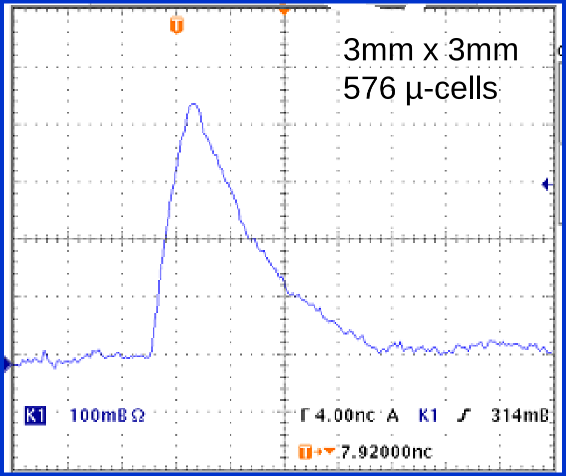


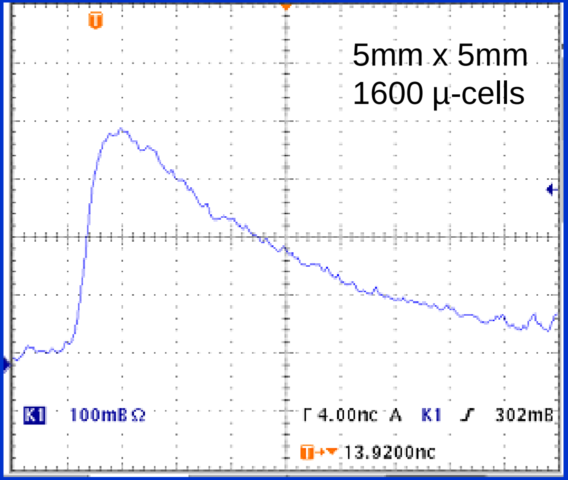




A single ph.e. pulse shape for different SiPMs

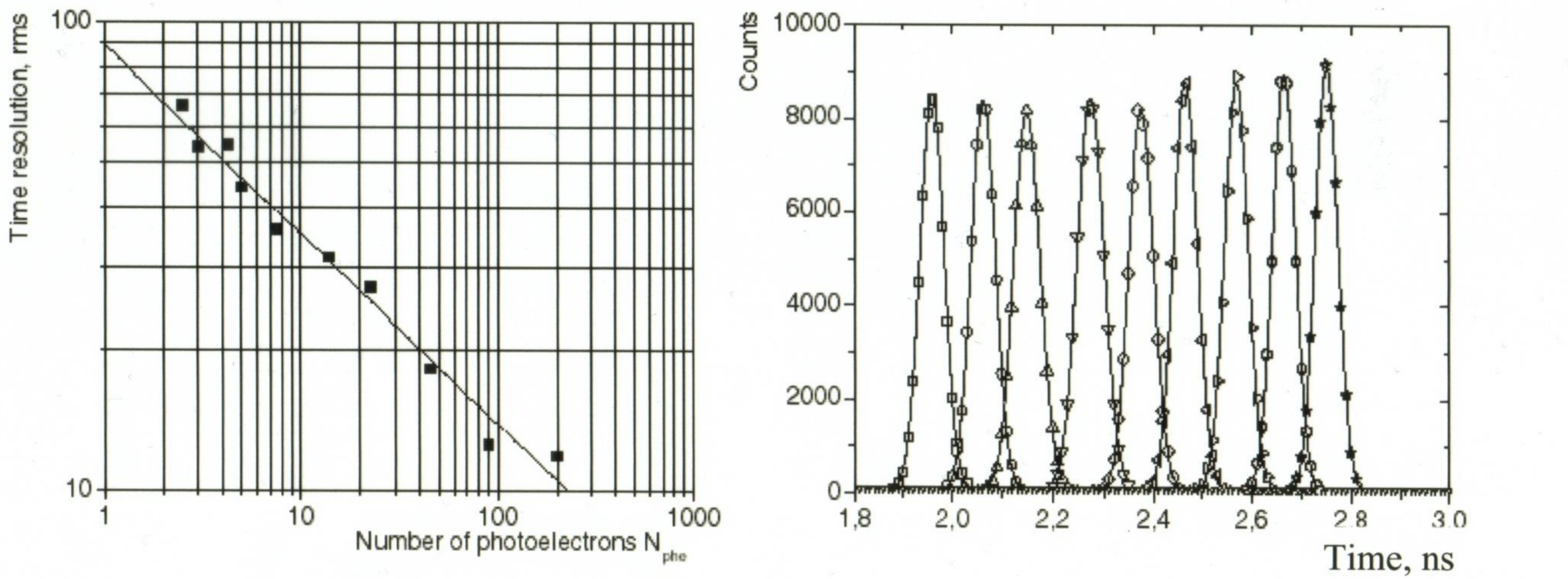
All tested devices had µ-cell size of 100µm x 100µm

Operated under gain: $10^7$

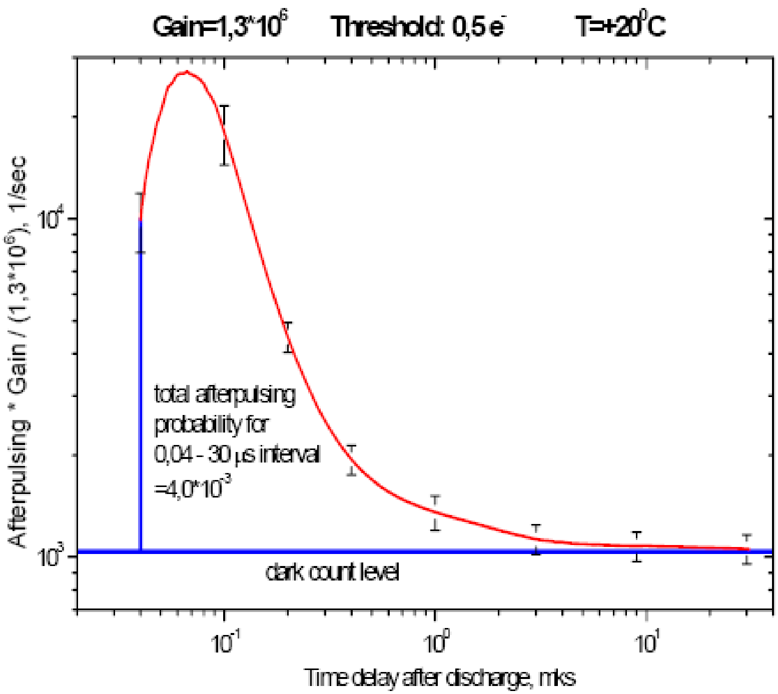


# SiPM time resolution



→ The lifetimes of trapped electron are mostly rather small:
less than ~100 ns




Therefore a single pixel recovery time Rquench x Cpixel sould not be not very small and recommended at level of .5-1 mks

→Even for high Gain x PDE the Afterpusing has to be small enough:
AP(Gain=10*7)=~1%
for recovery time of >500ns

→ Give rise the non-Poisson statistics of fired pixels (SiPM response).

→ As a result:

→ SiPM pulse hight resolution is worsening:

→(sigma/A)*2 > 1/N phe

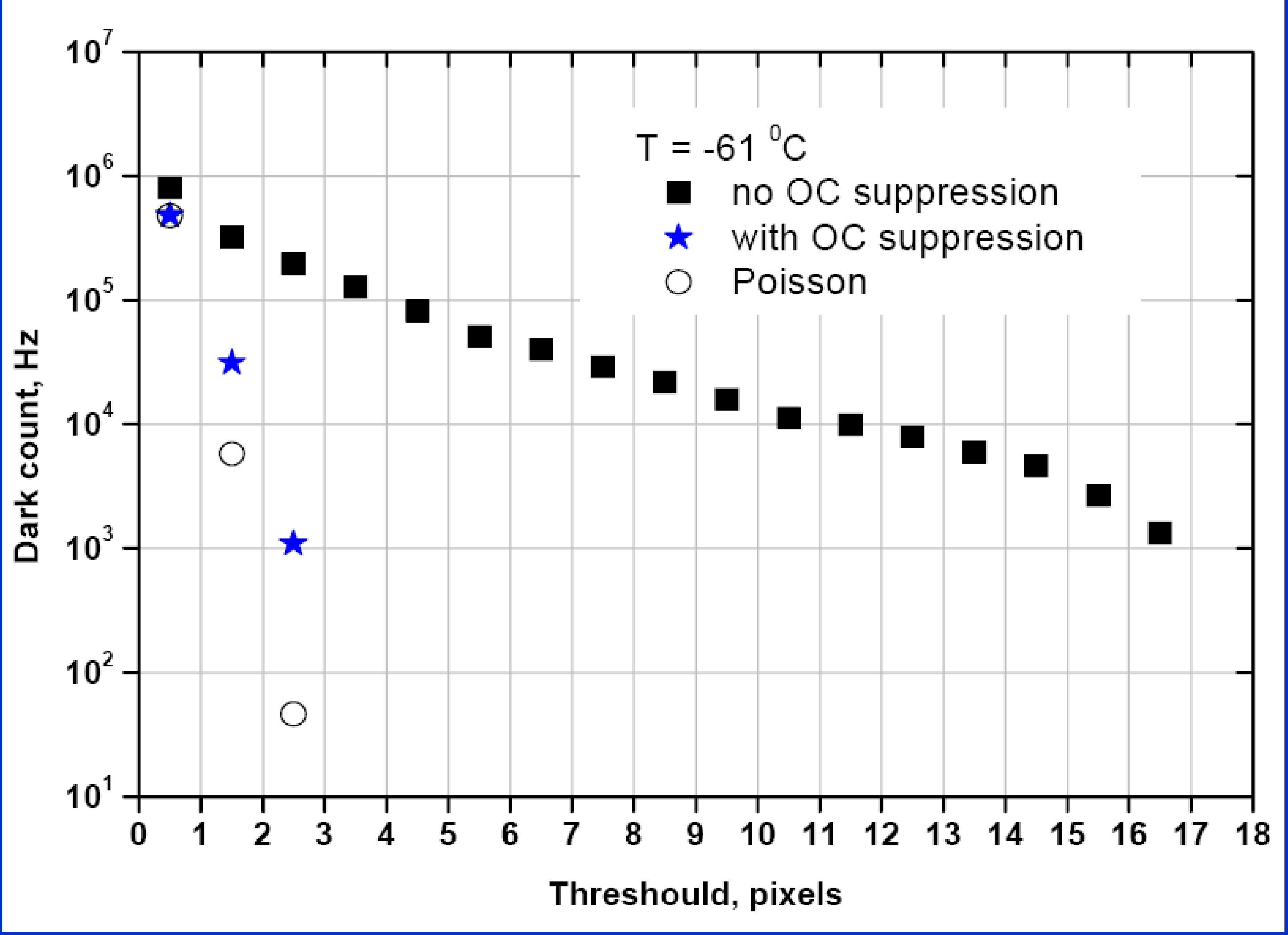
Excess Noise Factor ENF >1

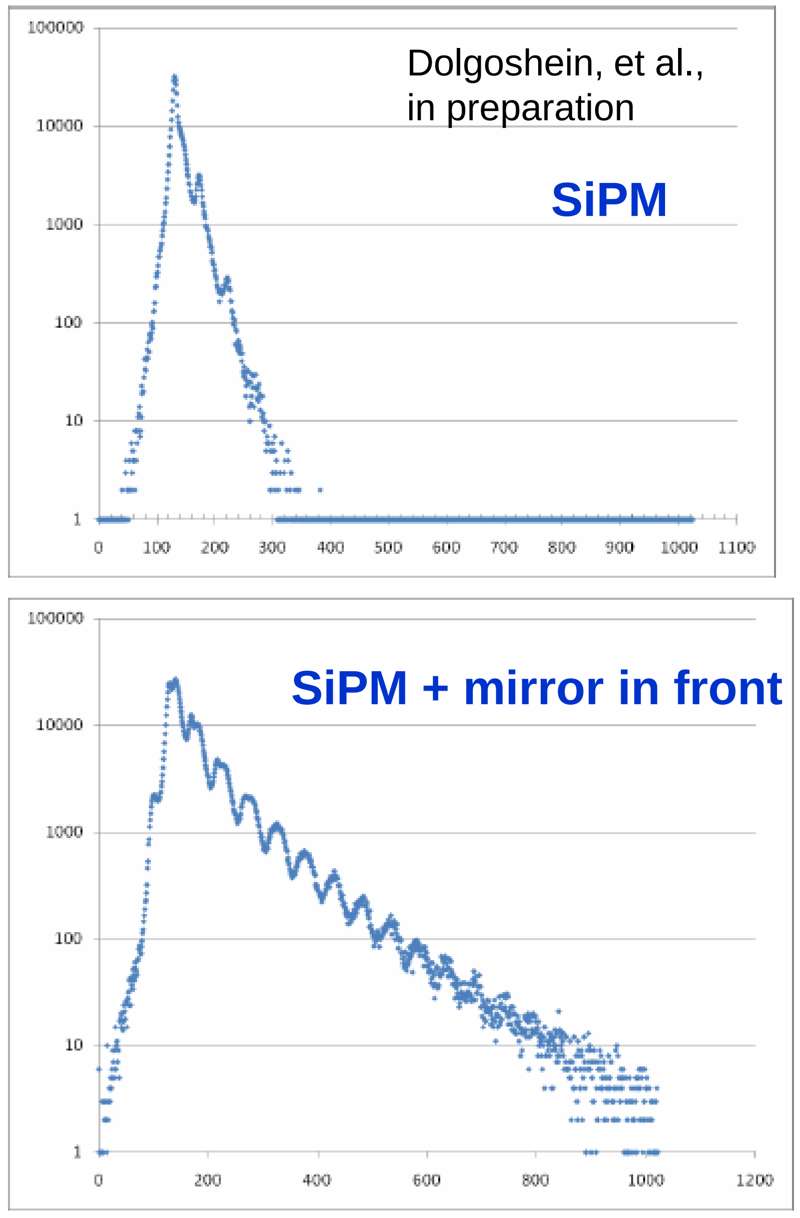
→Sci Spectrometry(PET etc.) ?

ENF: for PMT ~ 1.2

for APD ~ 2-2.5

for SiPM(desirable) < 1.05


T = -61 $^0$C
no OC suppression
with OC suppression
Poisson
Dark count, Hz
Threshould, pixels
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18



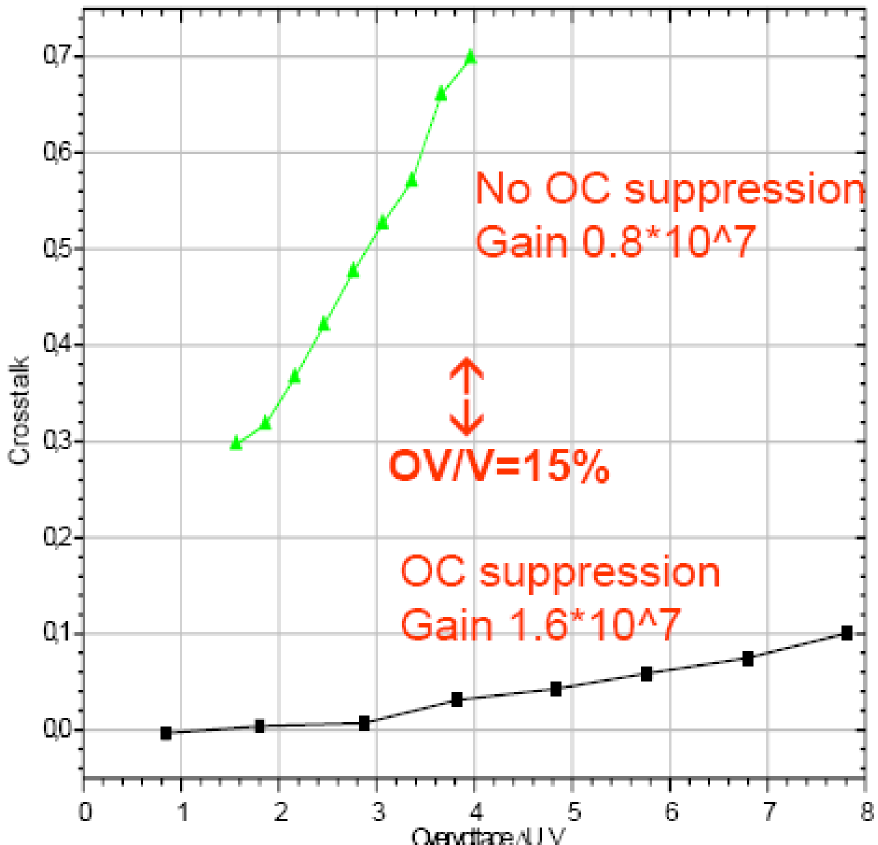

- A curious experiment: what will happens if one will hold a mirror in front of a SiPM ?

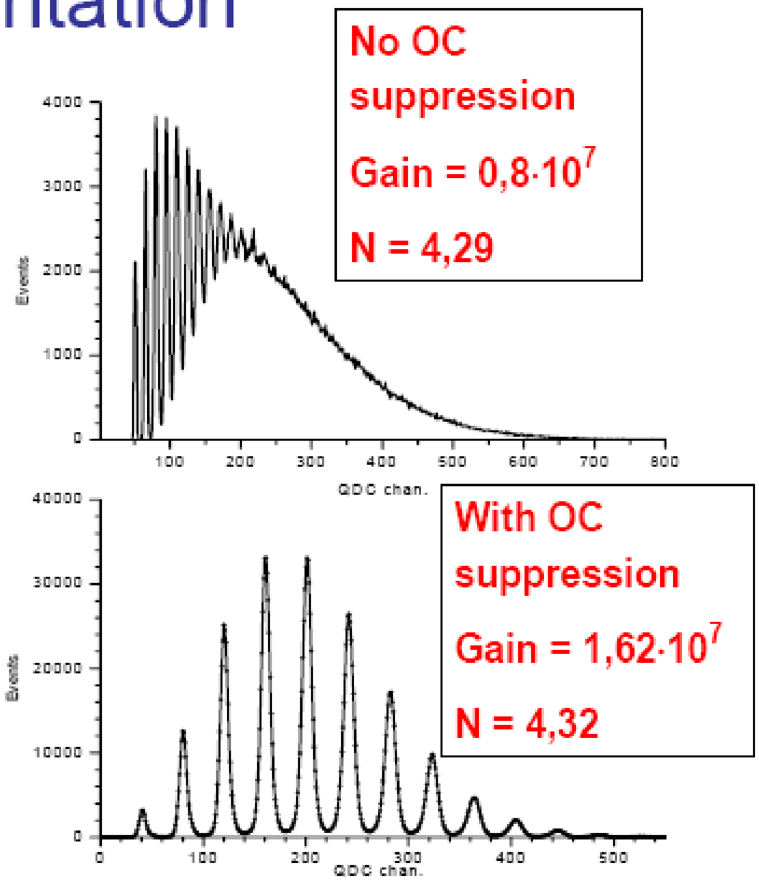
- The emiited light bounces back strongly amplifying the cross-talk effect

- Similarly the amplitude resolution shall degrade when SiPMs are coupled to scintillators (Dolgoshein et al., under preparation)

# Prompt OC suppression using Si damaged by ion implantation

**(Patent pending)**




**SiPM 1x1 mm^2**

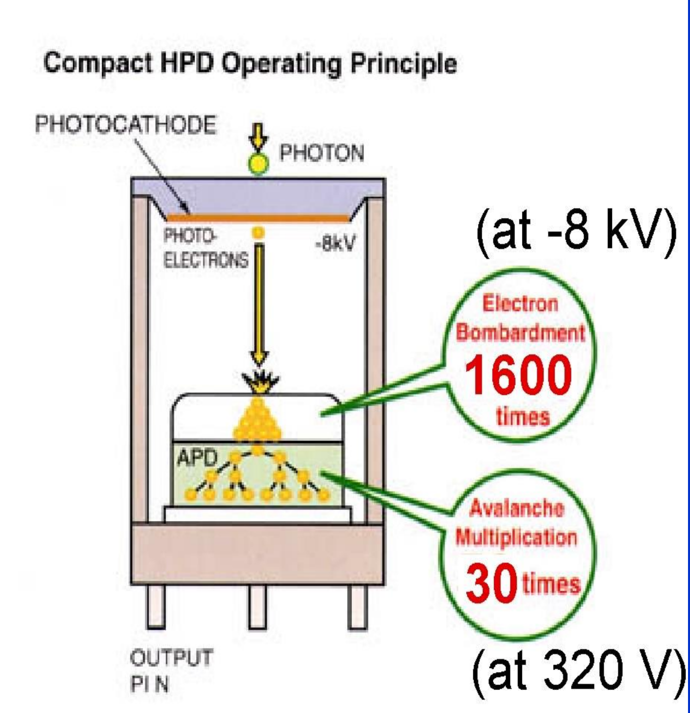
10-Jun-2010 B.Dolgoshein Silicon PM 27

# Ultra-fast, LLL sensors with single ph.e. resolution

- In recent times two types of ultra-fast response LLL sensors, providing good single ph.e. resolution, start to strongly compete with the classical PMTs.
- These are
  - HPDs with GaAsP photocathode
  - SiPM (and its variations)

# HPD Structure

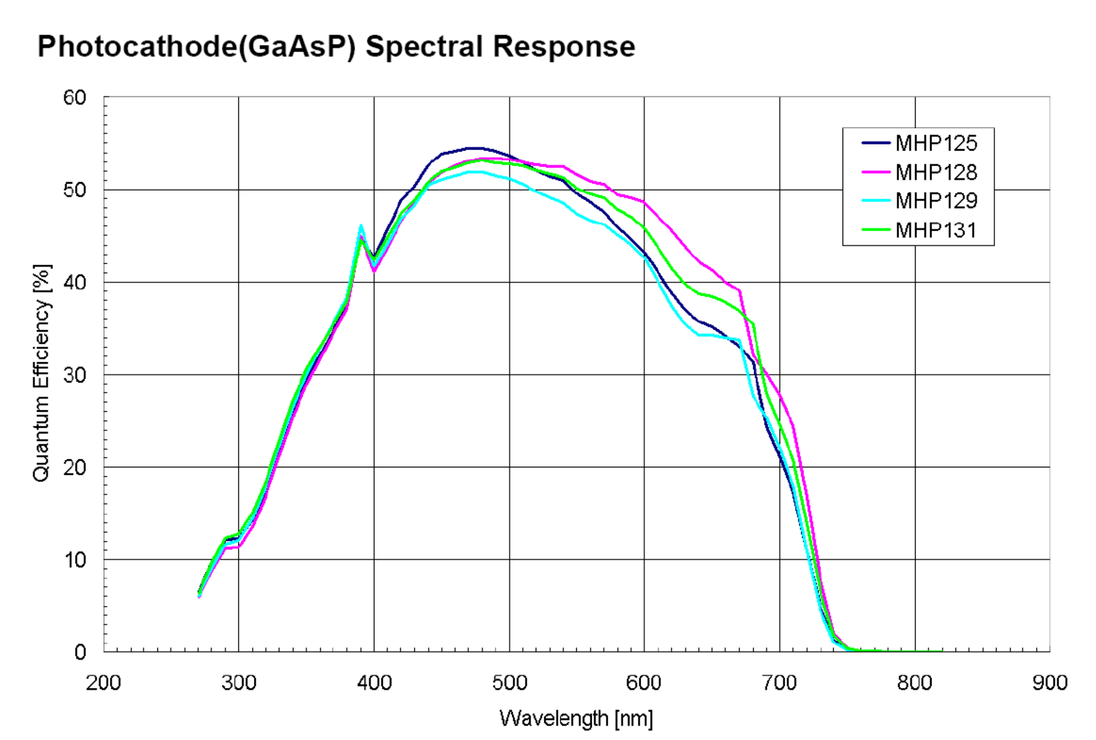
- HPD (Hybrid Photo Diode).
- Structure
  - Photo cathode
  - Avalanche diode as anode.
  - High vacuum tube ($\sim 10^{-7}$ Pa)
- Gain mechanism (2 stages)
  - Electron bombardment ~( x 1600 )
  - Avalanche effect ~( x 30-50)



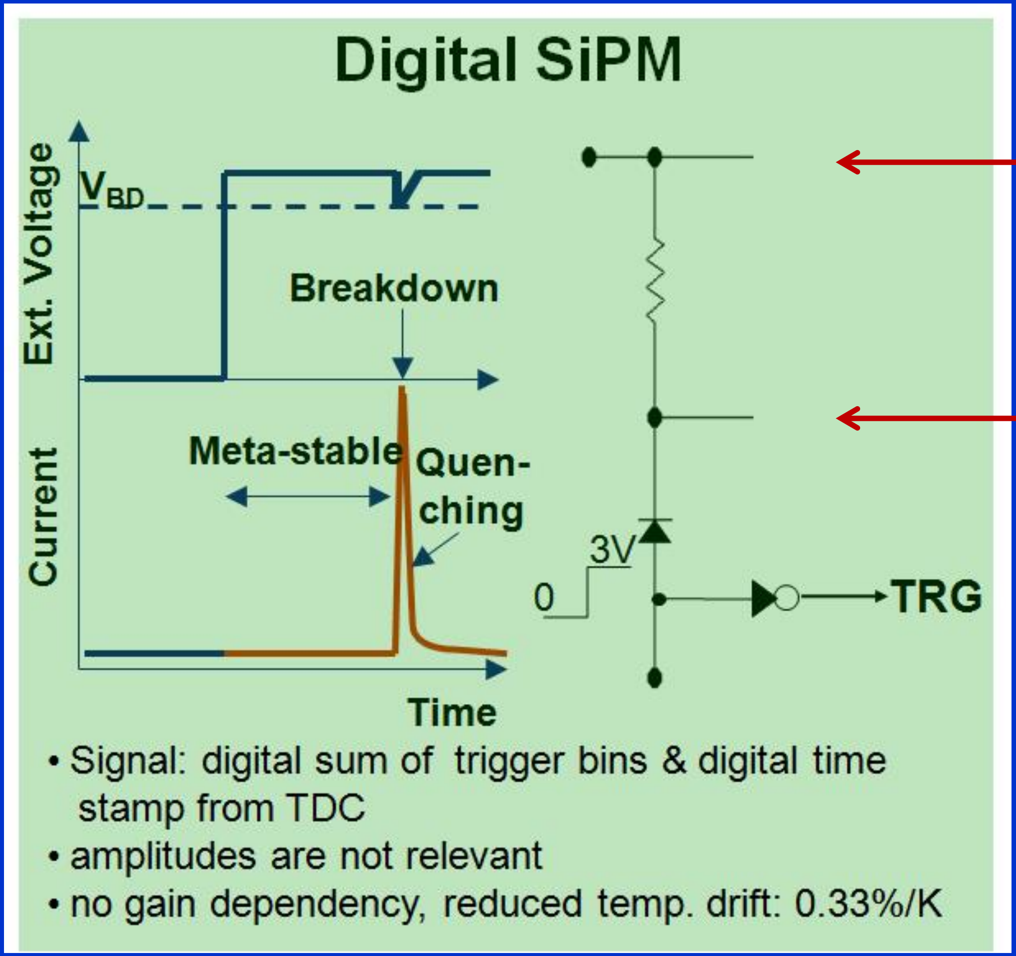

Much better pulse height resolution than PMT.

# 18-mm GaAsP HPD (R9792U-40) (development started ~15 years ago)

Designed for MAGIC-II telescope camera; (developed with *Hamamatsu Photonics* )




# DSiPM from Philips: changed priciple: no common anode anymore



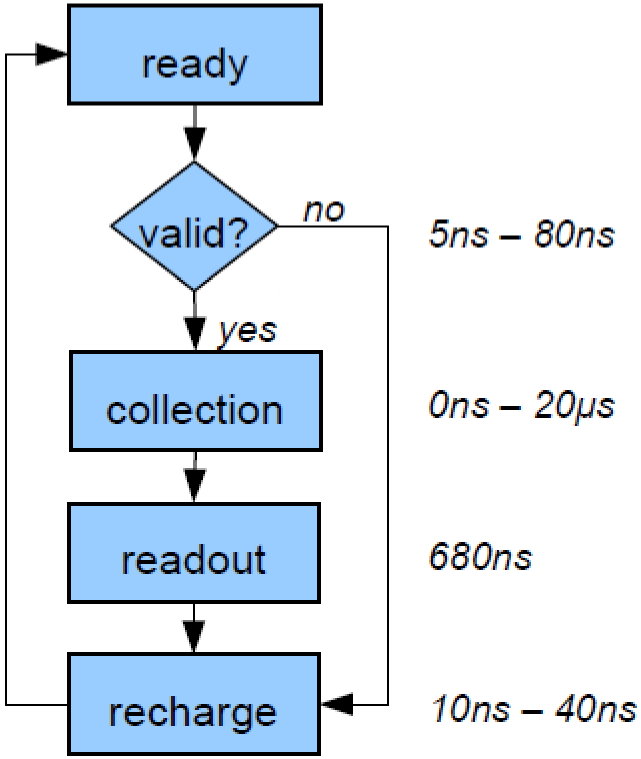

„classical readout point“
~few mV/ph.e.

„dSiPM readout point“
~3 V/ph.e.

# Event timing of dSiPM

PHILIPS

## DLS – State Machine

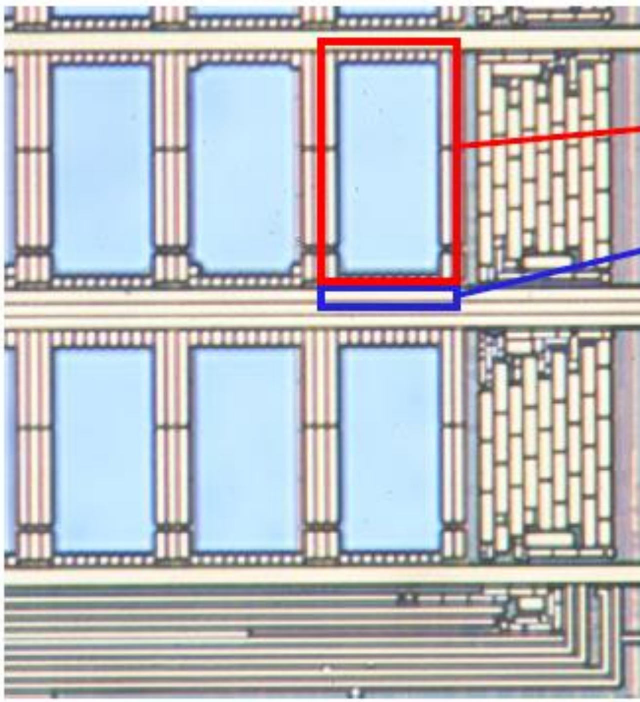


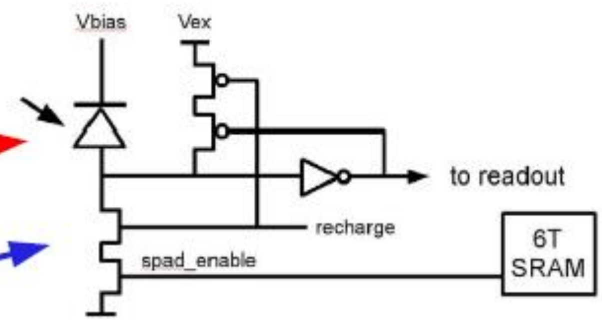

- *200MHz (5ns) system clock*
- *Variable light collection time 0 - 20µs*
- *20ns min. dark count recovery*
- *dark counts => sensor dead-time*
- *data output parallel to the acquisition of the next event (no dead time)*
- *Trigger at 1, ≥2, ≥3 and ≥4 photons*
- *Validate at ≥4 ... ≥64 photons (possible to bypass event validation)*

# dSiPM scetch of the design

PHILIPS

## Digital SiPM – Cell Electronics





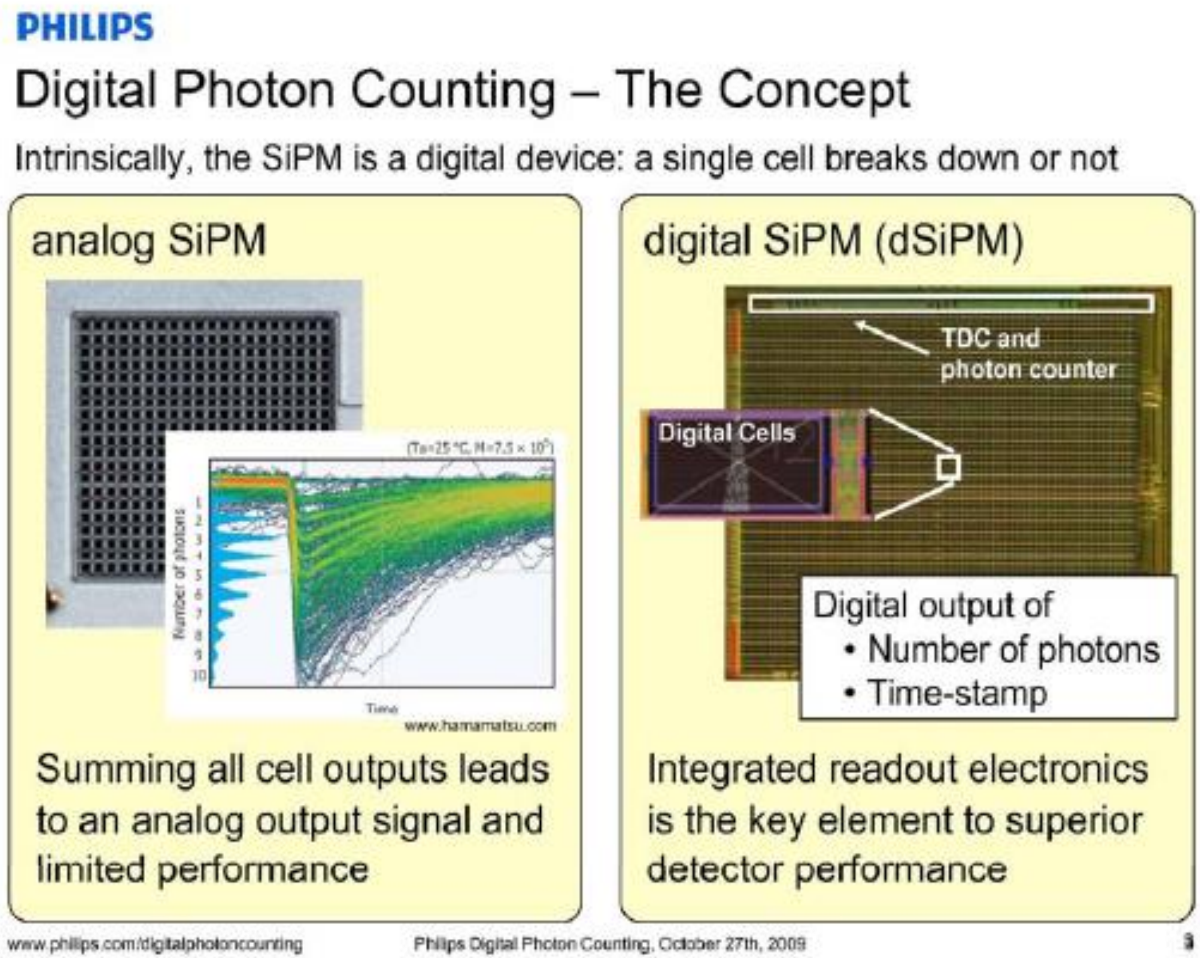

- Cell electronics area: 120µm²
- 25 transistors including 6T SRAM
- ~6% of total cell area
- Modified 0.18µm 5M CMOS
- Foundry: NXP Nijmegen

# Digital SiPM

→single pixel dark count rate is lower by factor of 1.5-2 (~physical limit)
→digital output is more convenient for system integration

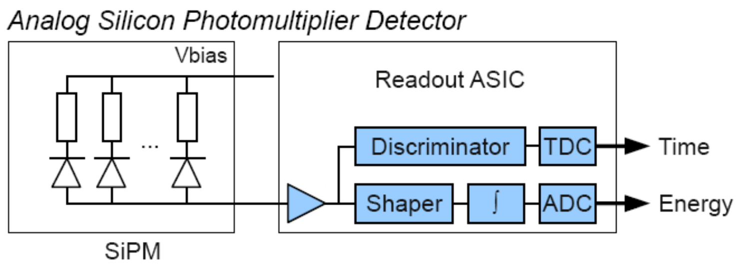
→PDE loss ( filling factor is less due to electronics on chip)
→problems with Optical Crosstalk and Afterpulsing have to be solved

**Fabrication cost?**



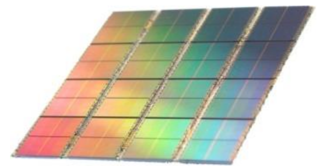
# The dSiPM is an Integrated, Scalable Solution

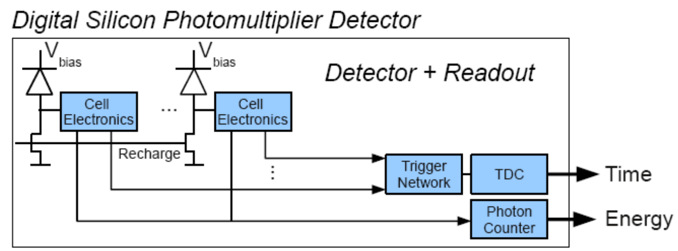
## Analog SiPM




- discrete, limited integration
- analog signals to be digitized
- dedicated ASIC needed

## Digital SiPM

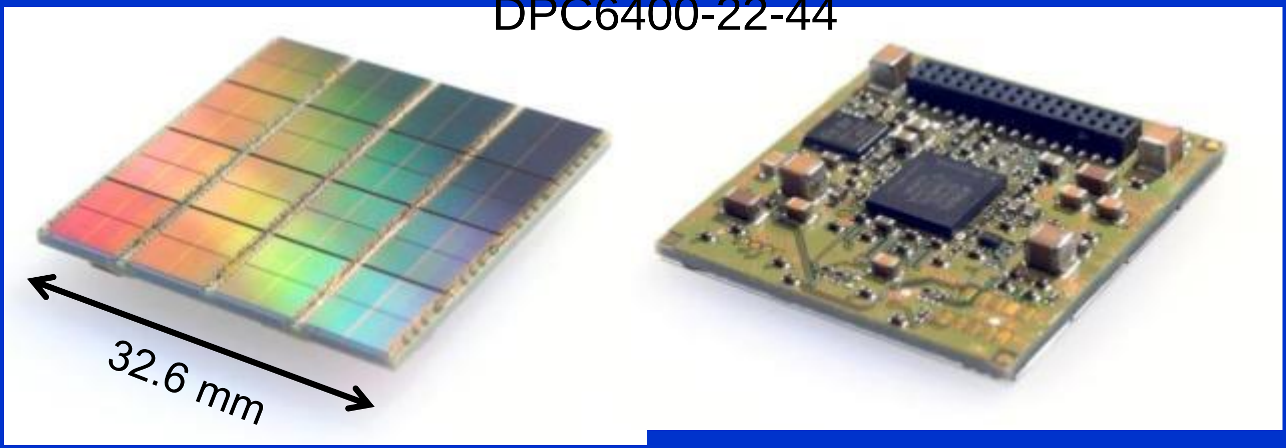





- fully integrated
- fully digital signals
- no ASIC needed

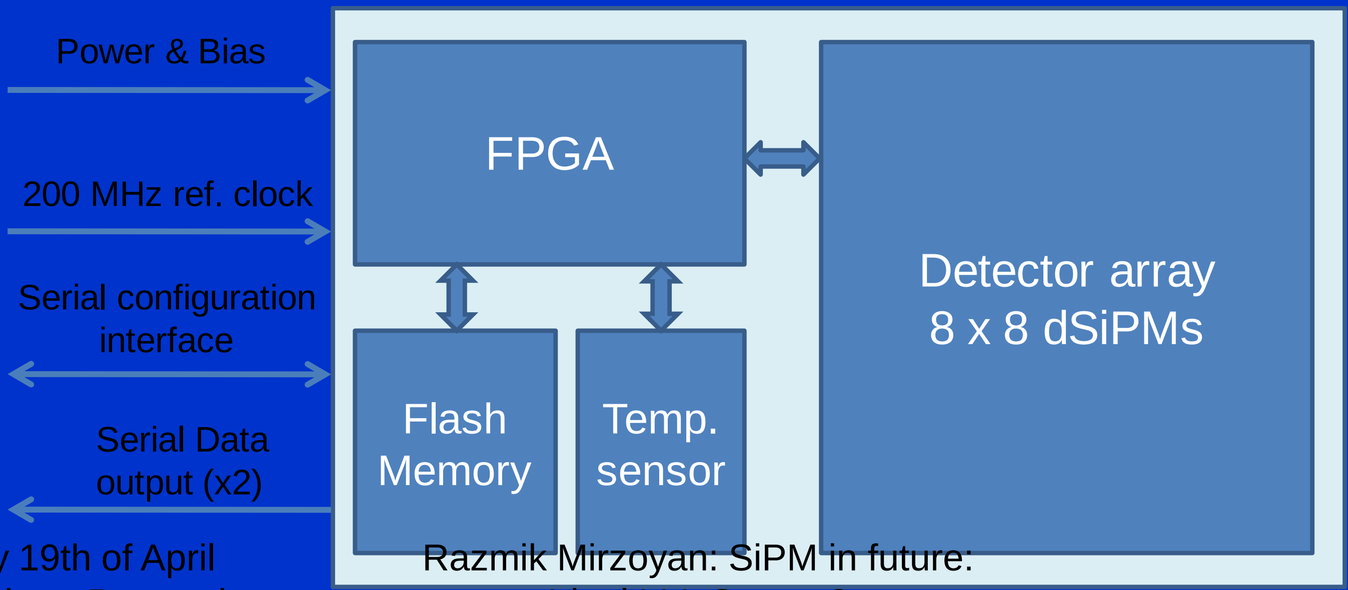
# …to Highly Integrated "Intelligent" Sensors

DPC3200-22-44
DPC6400-22-44

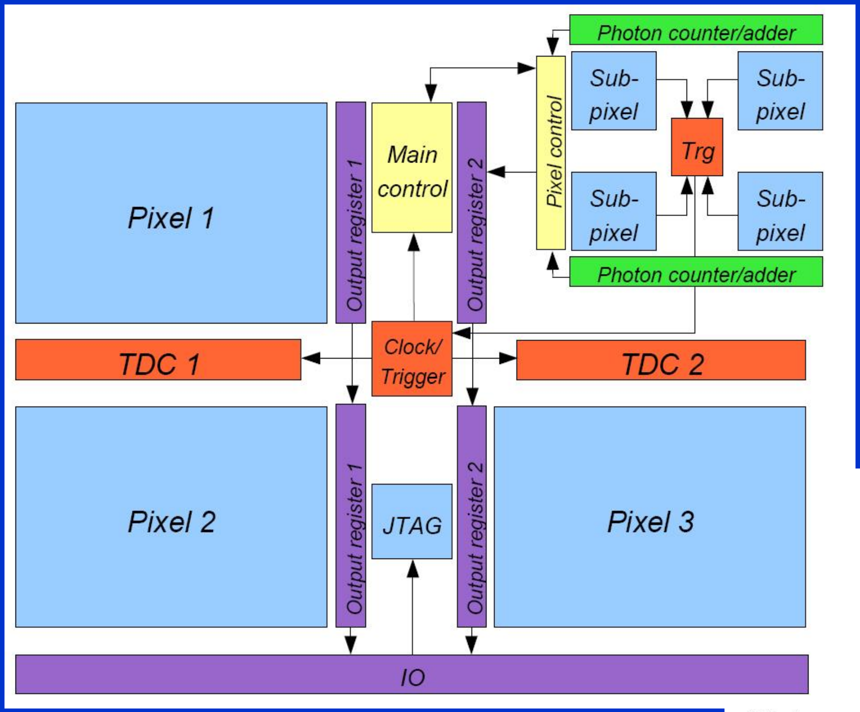


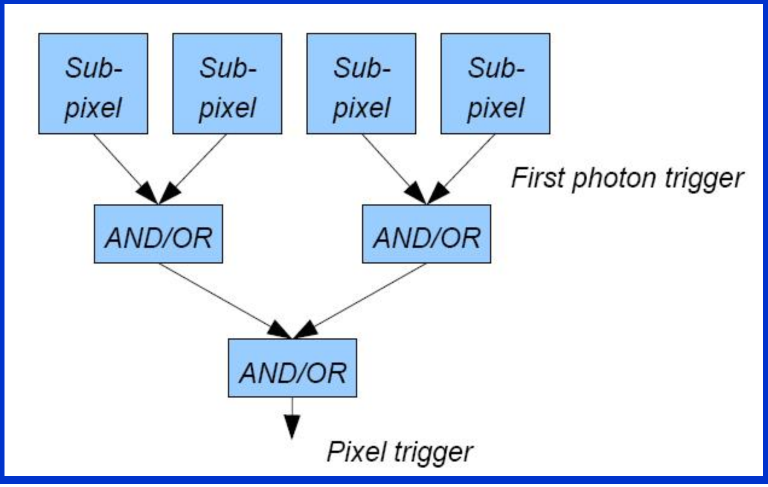

**FPGA**
- Clock distribution
- Data collection/concentration
- TDC linearization
- Saturation correction
- Skew correction

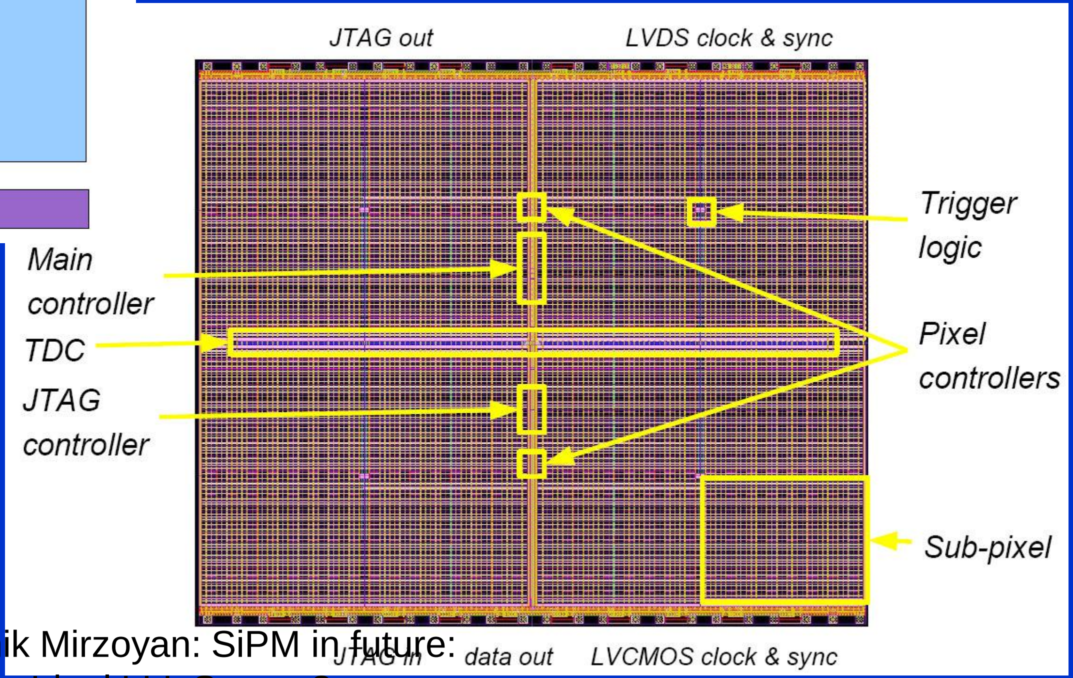
**Flash**
- FPGA firmware
- Configuration
- Inhibit memory maps



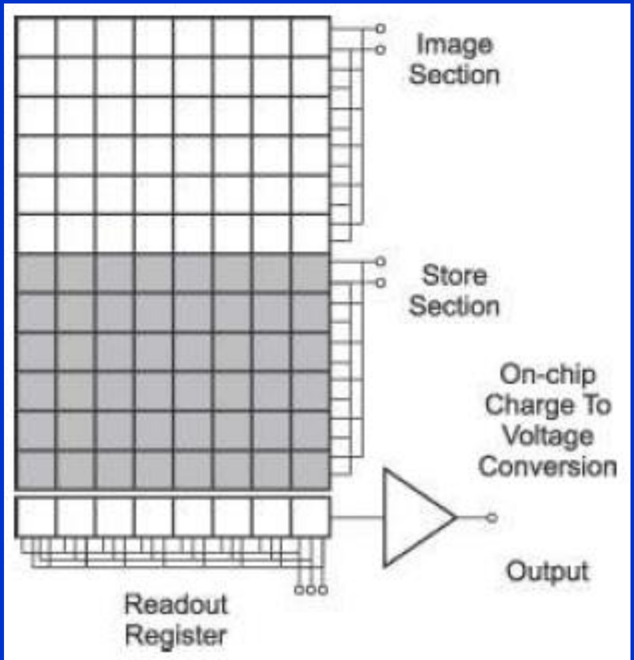
# dSiPM: From Die Architecture….

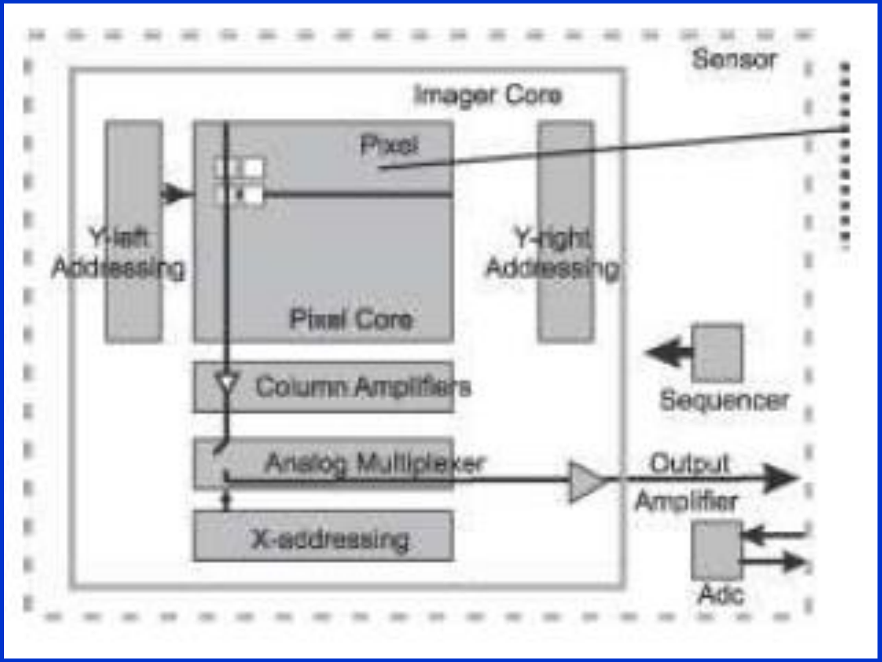


# CCD versus CMOS camera




CCD: single readout
Amplifier: $\Delta U = Q/C$
~ common anode

Independent readout of pixels
$\Delta U = Q/(C + n * C_{parasitic})$
n: number of pixels in a raw
➔ Lower amplitude

# CCD versus CMOS camera

As one can see above the same geometry CCD camera can provide a much better signal/noise ratio than CMOS

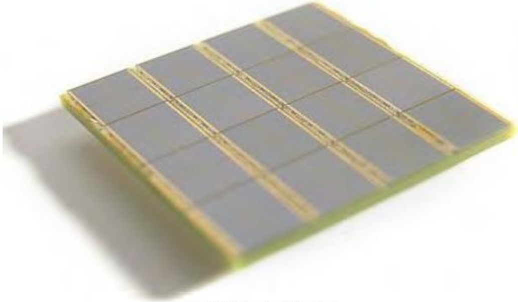
# PDPC Technology Evaluation Kit (TEK)



Very recent offer: 26300.-€ + TAX for the above kit
~5k€/cm²

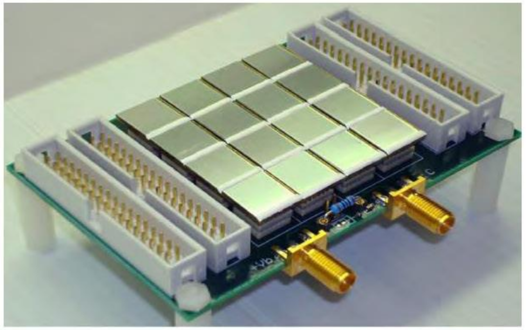
# Large Variety of SiPM Arrays Available

**Philips**



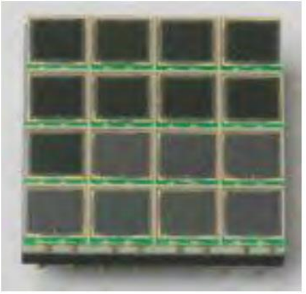
**dSiPM**

**RMD**



**SSPM**

**Hamamatsu**

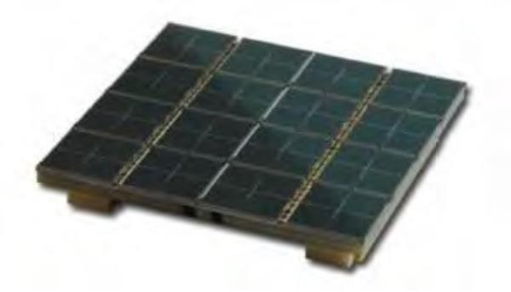


**MPPC**

**SensL**

**SPM**

**FBK**



**SiPM**

- **Very Attractive for PET**
- **Properties Vary (20 pF – 900 pF, $\propto$Pixel Area)**

# Visions of a great scientist and friend are becoming true

SiPM is becoming THE DETECTOR of future

The number and types of matrixes from different manufacturers is increasing, the parameters are steadily improving

Sometime soon in future, in a time scale of 5-10 years, we should be able to buy matrixes from several manufacturers with complete readout. We could assemble large coordinate-sensitive imaging cameras like lego