SiPM: almost an Ideal Low Light Level Sensor for CTA SST

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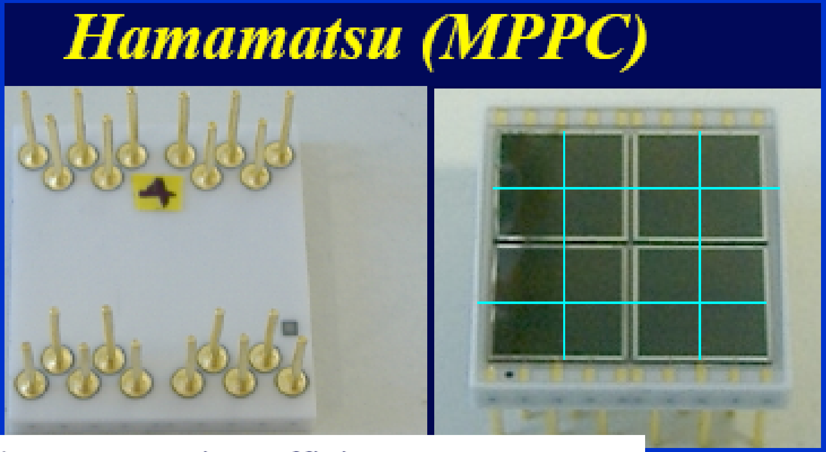
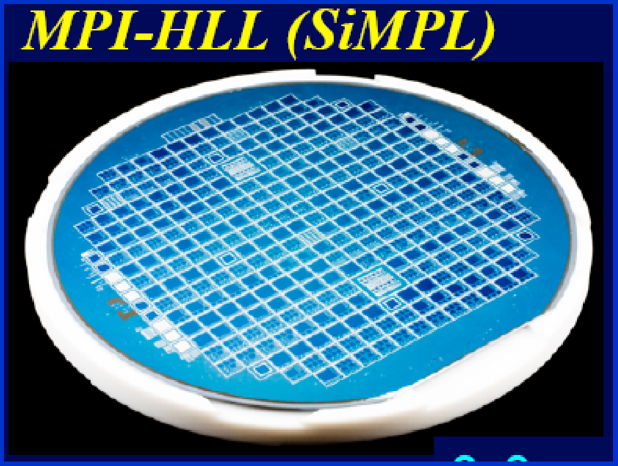
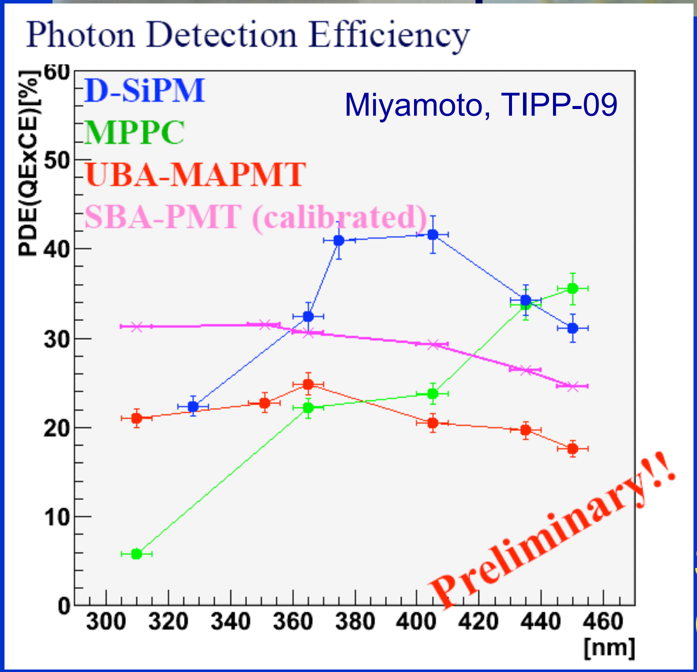
What LLL sensor can we dream about ?

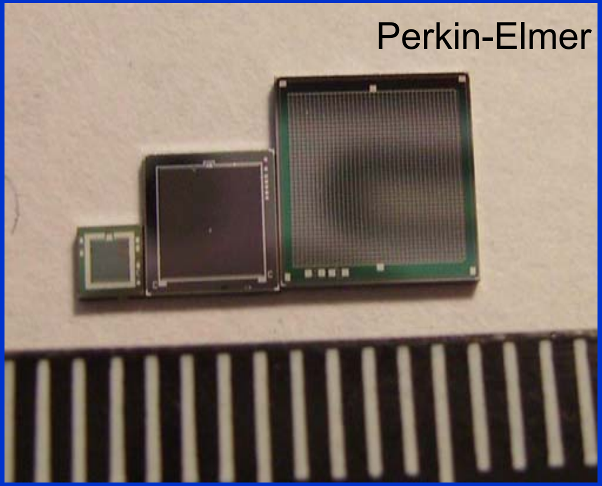
- Nearly 100 % QE and photon detection efficiency (PDE)
- Could be made in very large and in very small sizes
- Few ps fast (in air and in many materials the light speed is usually 20-30 cm/ns; in 5 ps it will make 1-1.5 mm)
- Signal amplification x10^6
- Noiseless amplification: F-factor - 1.001
- Few % 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,...

Few examples of SiPMs, still under development







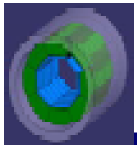


SiPMs with ~ 50-60% PDE and low cross-talk (< 1%) could be anticipated within 1-2 years

ILC: Potential Consumer of $(5\text{-}200)\times10^6$ SiPMs

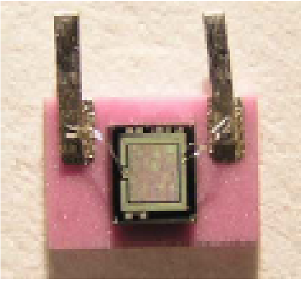
→Scintillation Calorimetry- for instance a SciTile Imagine Hadron Calorimeter for ILC (CALICE Collaboration),sci tile size:a few cm

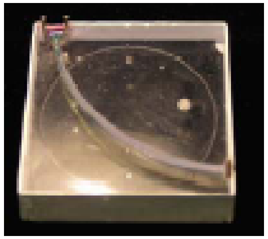
→Typical threshold is ~ 5-7 phe

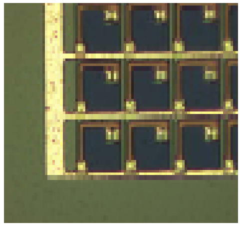


SiPM tile fibre system

- SiPM developed by MEPhI/PUSAR
  - Gain ~10^6, bias ~ 50 V, size 1 mm^2, 1156 pixels
  - Eff (green) ~ 15%, quenching R ~ 1 - 10 MΩ
- SiPM tile fibre system integration: ITEP
  - 3x3x0.5 cm^3 tiles from UNIPLAST, Russia
  - WLS fibre Kuraray Y11(300) 1mm
  - Matted edges, 2% light xtalk per edge
  - Faces covered with EM mirror foil



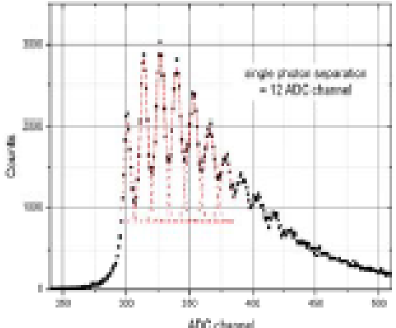




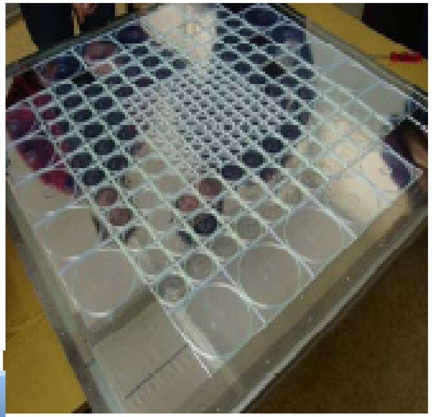
CALICE

MPPCs for calorimetry   Felix Sefkow   PD'07   June 27, 2007   13

A big 8000 channel HCAL prototype with tail catcher is constructed by CALICE (DESY,ITEP,LAL,MEPHI,NIU,Prague,UK) for analogue and semidigital modes

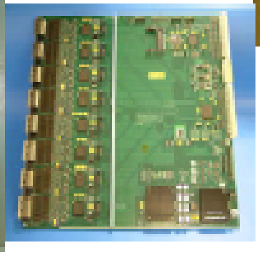


SiPM&FE signals in calibration mode



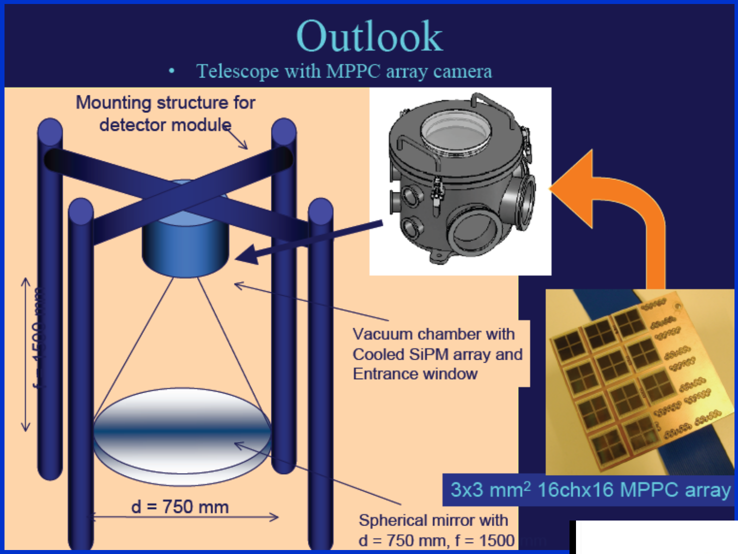
One plane with SiPMs and WLS fibers installed into 3x3, 6x6 and 12x12 cm^2 0.5 cm thick tiles

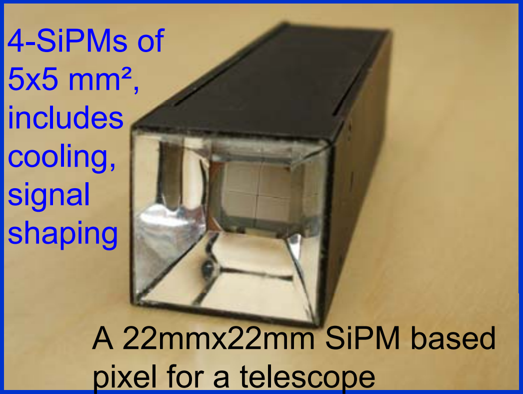
CERN test beam,2006

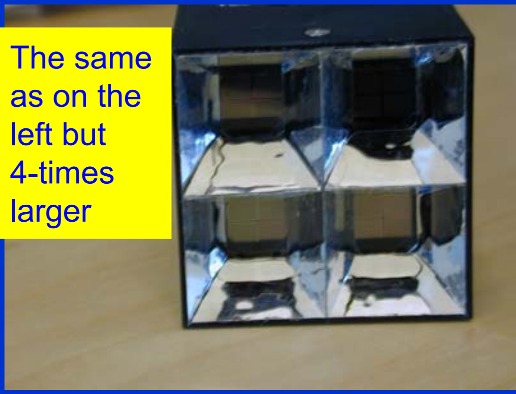


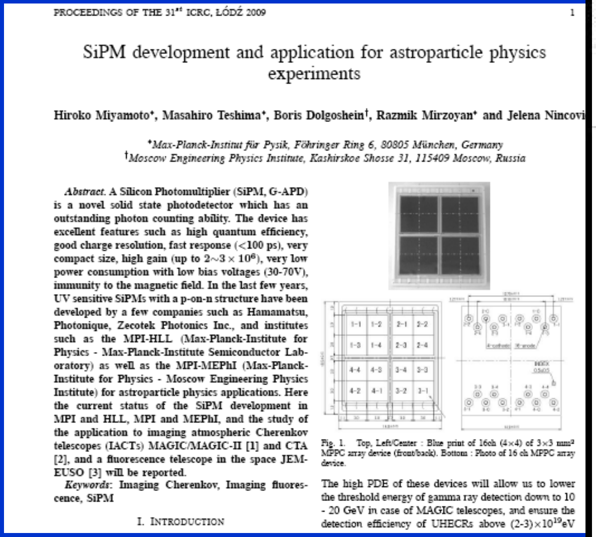
LAL 18 ch. SiPM FE chip

B.Dolgoshein,SiPM review   20









PROCEEDINGS OF THE 31st ICRC, ŁÓDŹ 2009 1

SiPM development and application for astroparticle physics experiments

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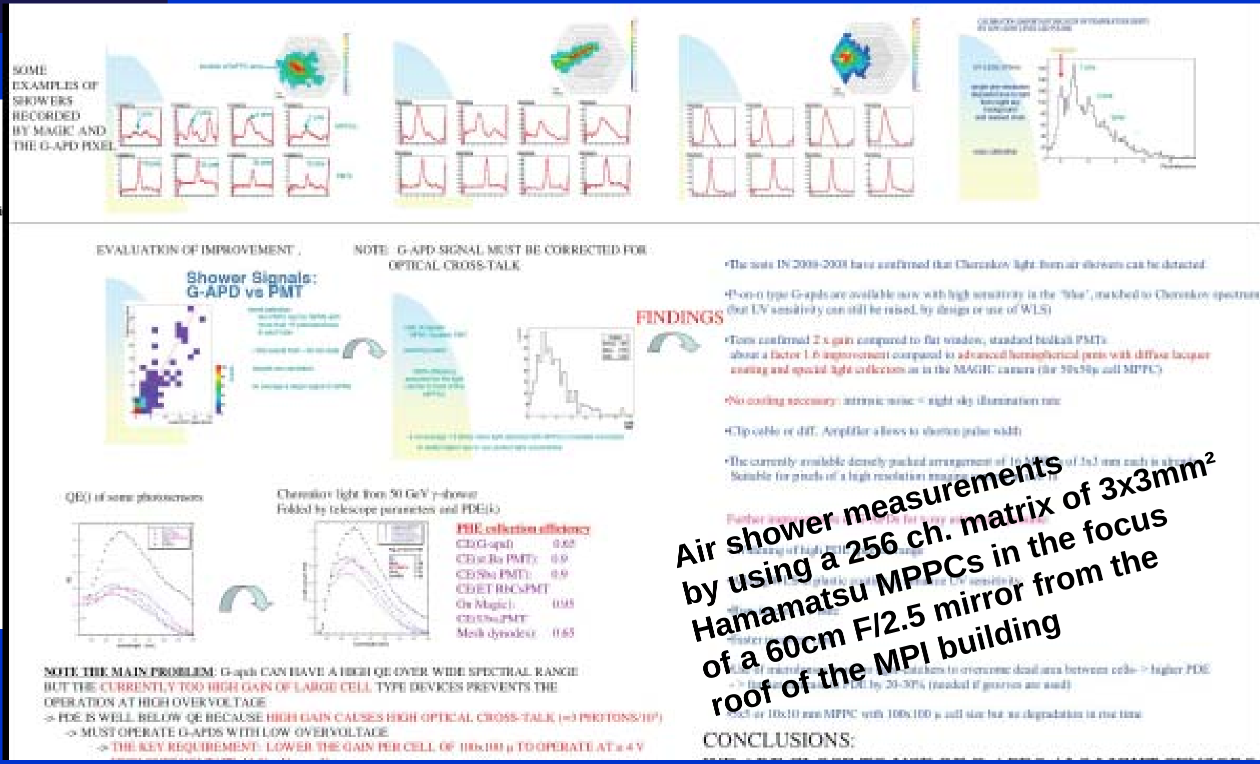
Abstract. A Silicon Photomultiplier (SiPM, G-APD) is a novel solid state photodetector which has an outstanding photon counting ability. The device has excellent features such as high quantum efficiency, good charge resolution, fast response (<100 ps), very compact size, high gain (up to $2\sim3\times10^6$), 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

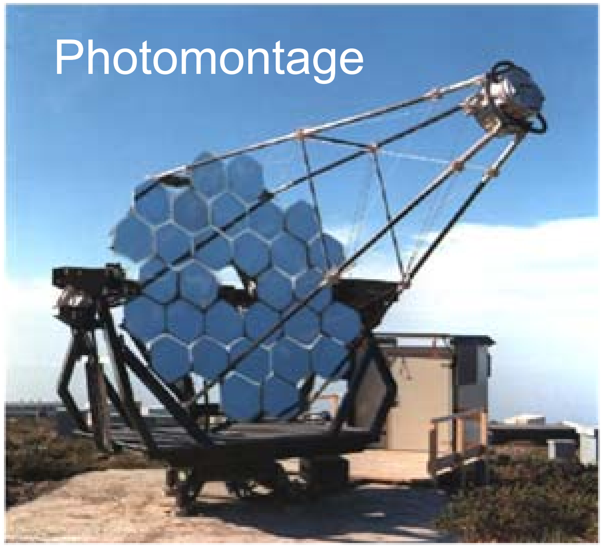
Fig. 1. Top, Left/Center : Blue print of 16ch (4×4) of 3×3 mm² MPPC array device (front/back). Bottom : Photo of 16 ch MPPC array device.

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 $(2\text{-}3)\times10^{19}$eV

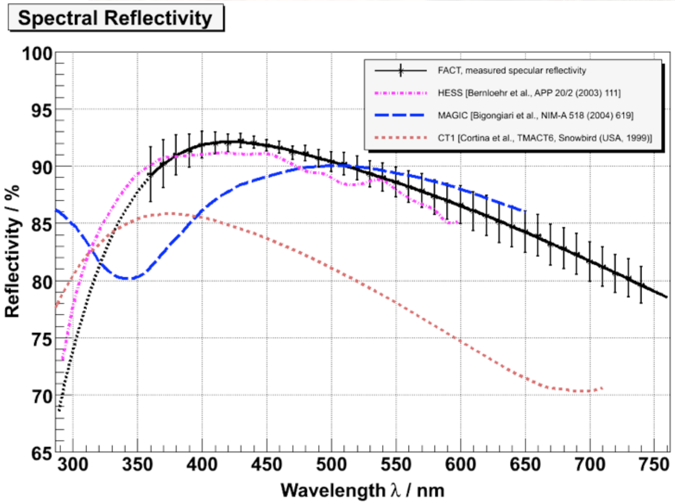


FACT = First G-APD Cherenkov Telescope for TeV Gamma Astronomy

TU Dortmund, EPF Lausanne, U Würzburg, ETH Zürich



- **Goal:**
  - **Crab**-observations in the coming period
  - Test the technology (**CTA, AGIS, MAGIC**, ...)
  - Will be operated for the DWARF-projects physics program !
- **Ready availability**
  - HEGRA-3 Telescope-Mount (La Palma):
  - 8.5 m^2 mirror of good reflectivity
  - Microcontroller-based Drive system
  - Experience with 36 Pixel-Test camera M0

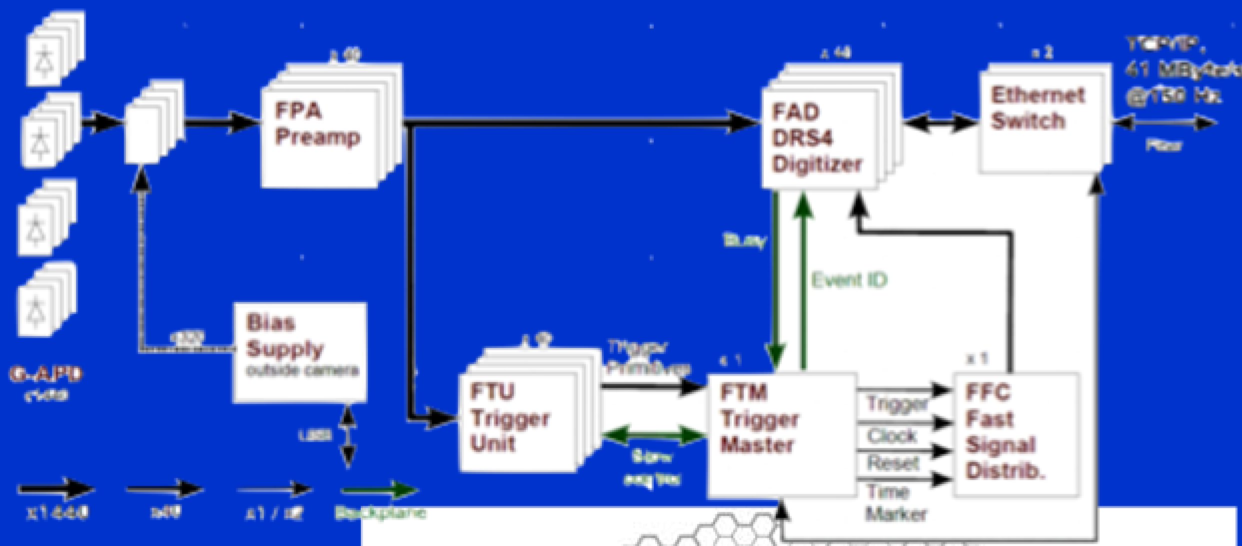


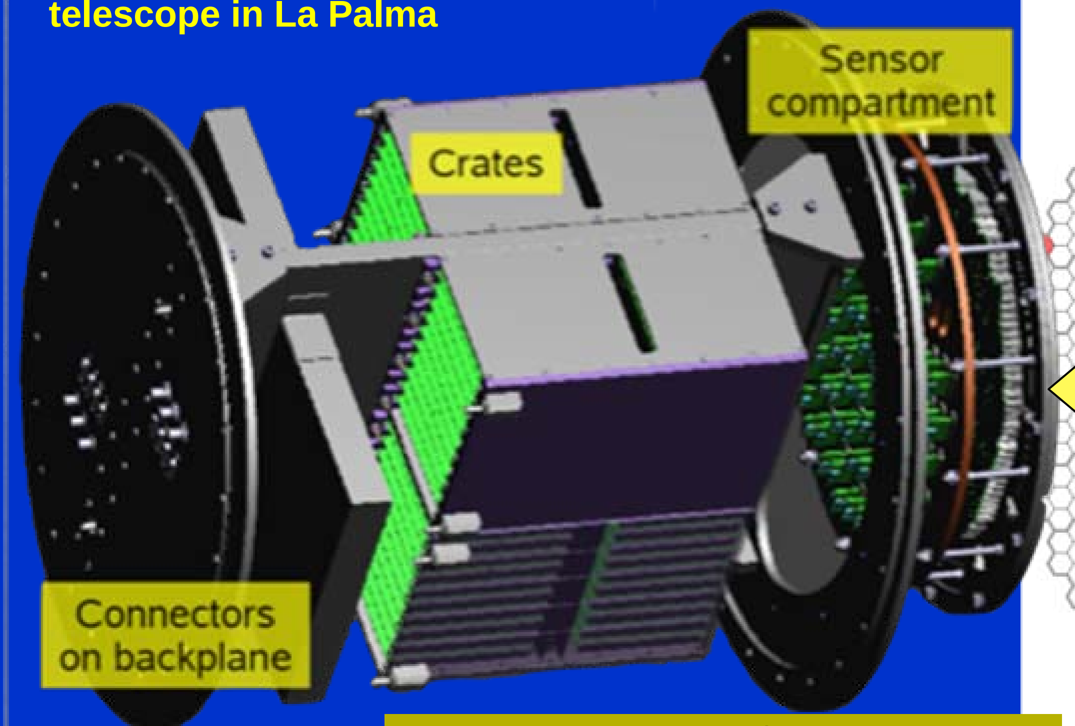
2010: 1440-Pixel G-APD-Kamera

DAQ in Kamera integriert

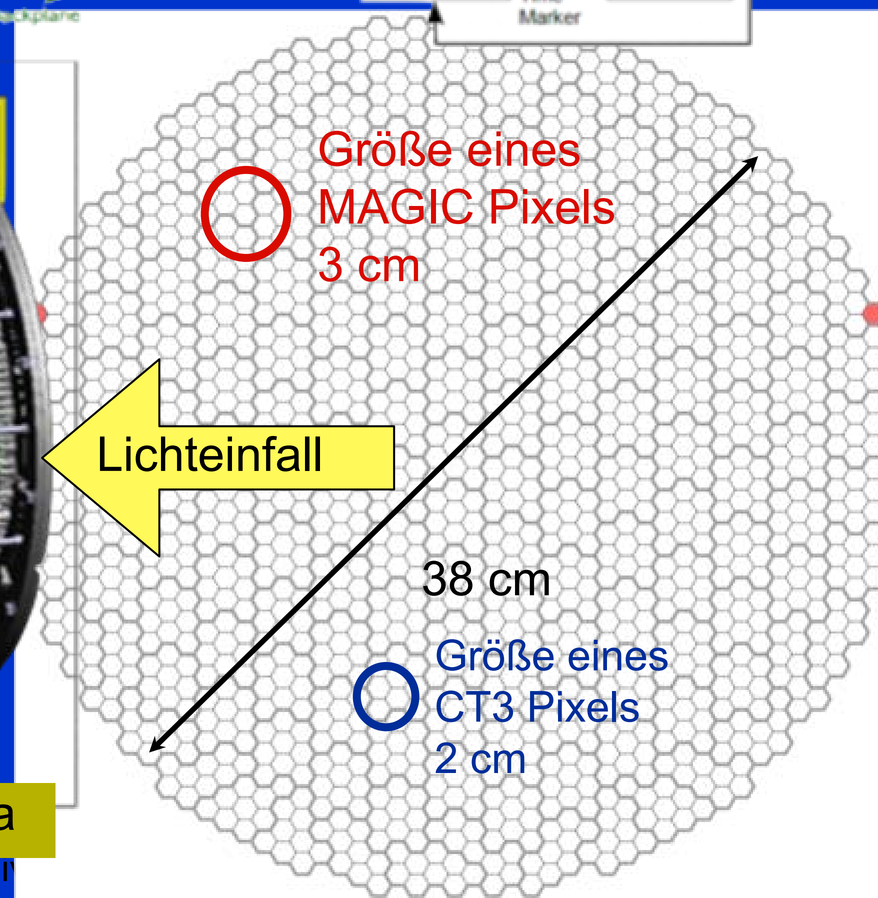
Produced in Zurich

In fall 2010 will be installed in the Focus of the 4.2m HEGRA 3 telescope in La Palma





Detail structure of the camera

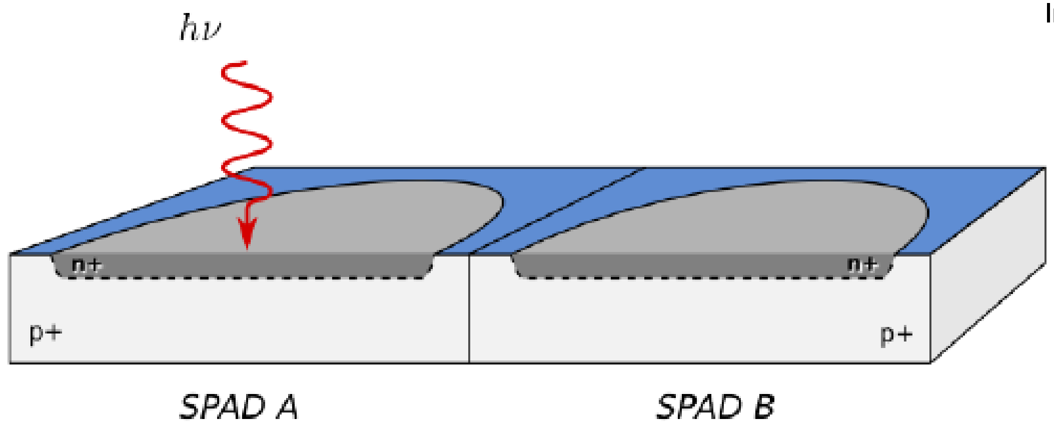


Why the light emission from Si avalanches is so important

- 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

Ingargiola NDIP-08

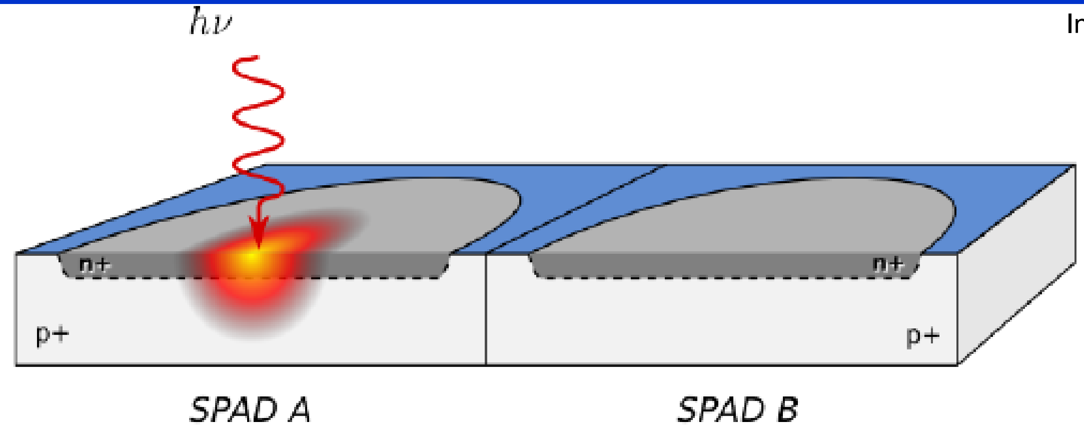


When an avalanche is triggered in one SPAD we have:

- Secondary photons emission due to the avalanche current
- Photons propagation throughout the chip
- Secondary photon detection by a nearby detector

Cross-Talk

Ingargiola NDIP-08



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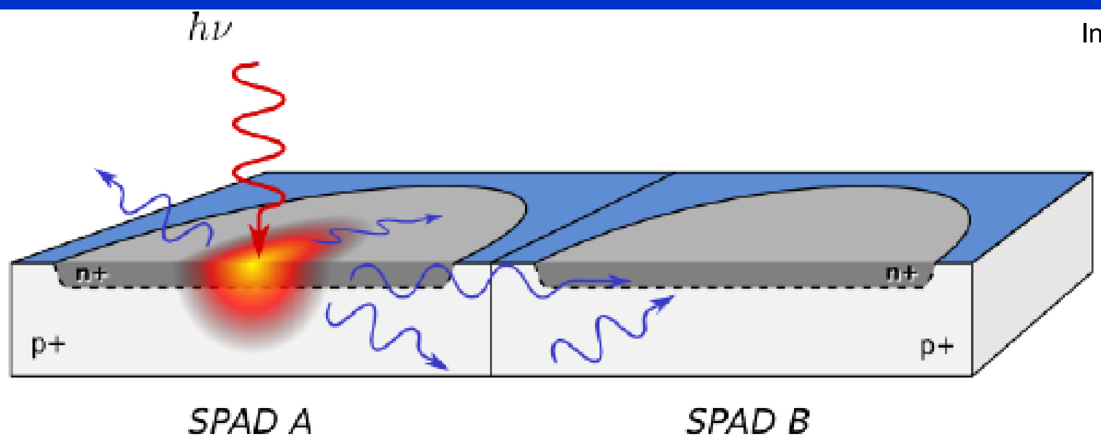

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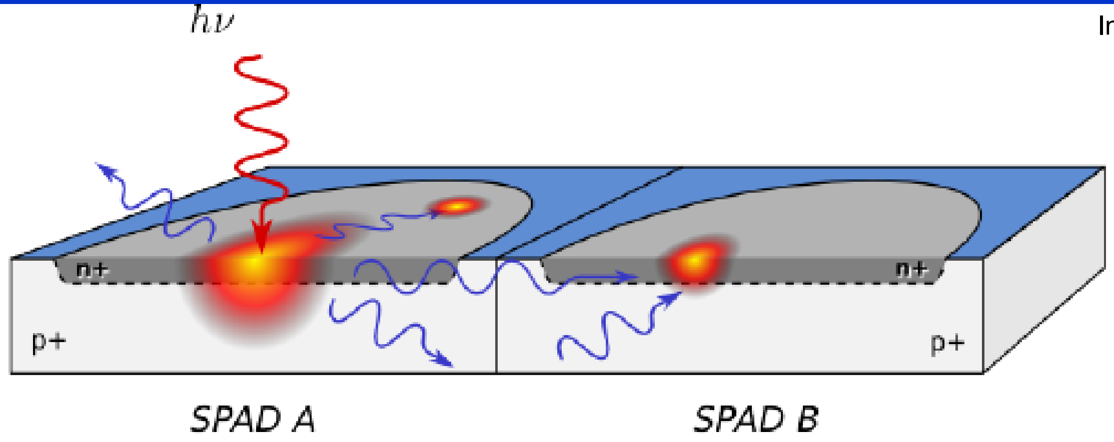

Ingargiola NDIP-08

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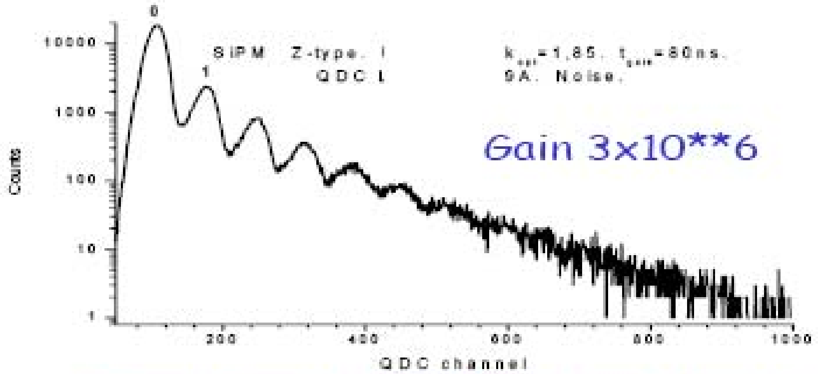
Current status of SiPM and the prospects

- Currently there is a lot of enthusiasm about the new devices but the deep understanding is not simple, it comes only slowly
- One of the main problems of SiPMs is the low PDE, that is not easy to measure. It shall be disentangled from the cross-talk and afterpulsing.
- The afterpulsing in PMTs is a ~1% effect on single ph.e. level, while for example, for currently existing MPPC's from Hamamatsu it is a 20-30 % effect. This shall strongly manifest itself in self-trigger mode
- Usually the real value of PDE is much lower than the claimed (advertised) one. The reason is the low applied overvoltage.
- For ~100 % Geiger efficiency and a high PDE one needs to apply an overvoltage that is 15-20 % higher than the breakdown one. The commercially available devices cannot do this yet (because of their design they do not quench above an applied overvoltage of 2.5 %).
- Already during this year some type of SiPMs with good UV response and a low cross-talk level could become available.
- Hamamatsu, Philips, Perkin-Elmer and some other companies are working on it.

→ Long tail in SiPM pulse hight distribution vs threshold

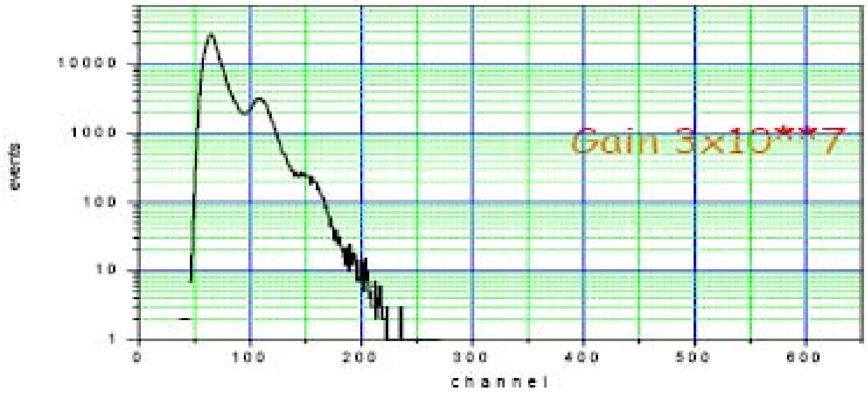
Optical crosstalk,SiPM 1x1 mm2,dark noise



Crosstalk→non-Poissonian distribution:

pixel fired/phe=1.7

ENF=1.6



Crosstalk suppression by special SiPM topology:

Poisson distribution:

pixel fired/phe= ~1

ENF= ~1

Optical Crosstalk OC

P. Buzhan, B. Dolgoshein, et al., 2009

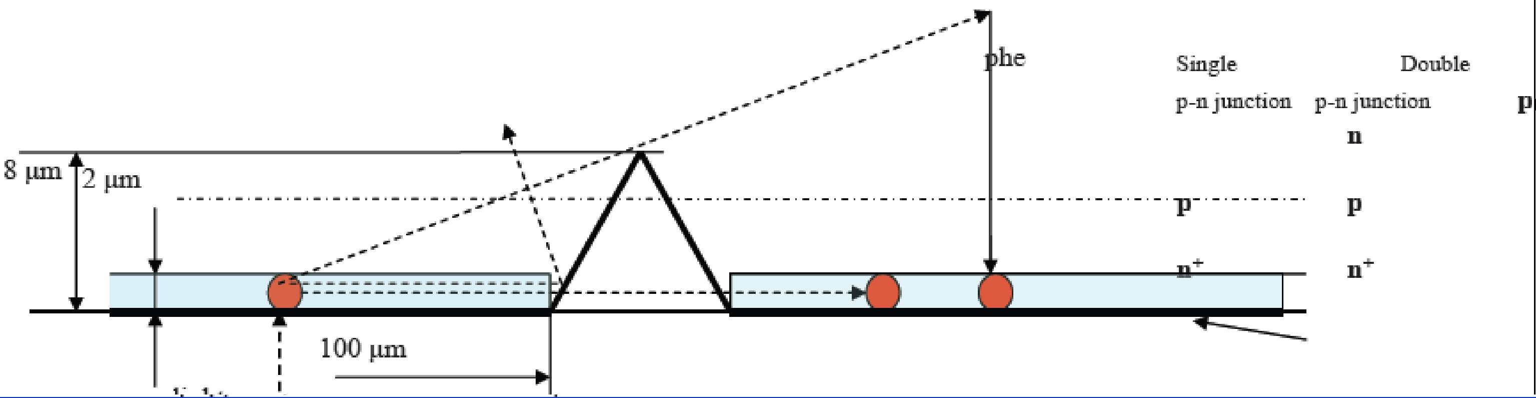
OC has two components

FIRST:phe's are induced in high electric field depletion region of neibouring pixels

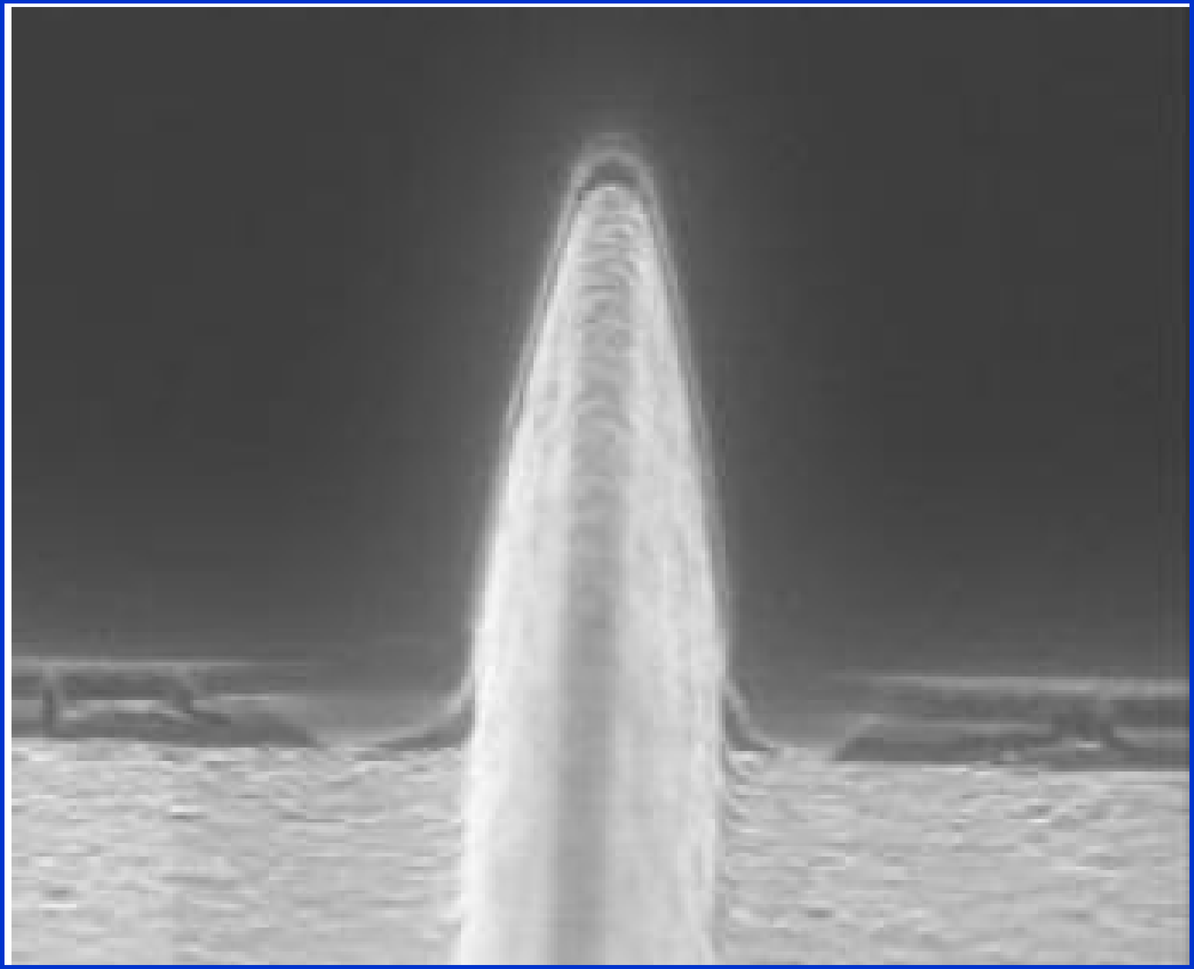
→this mechanism is very fast: ~1ns(prompt OC)

SECOND :The same in undepleted region and then the diffusion(or drift)to high electric field Geiger region of neibouring pixels

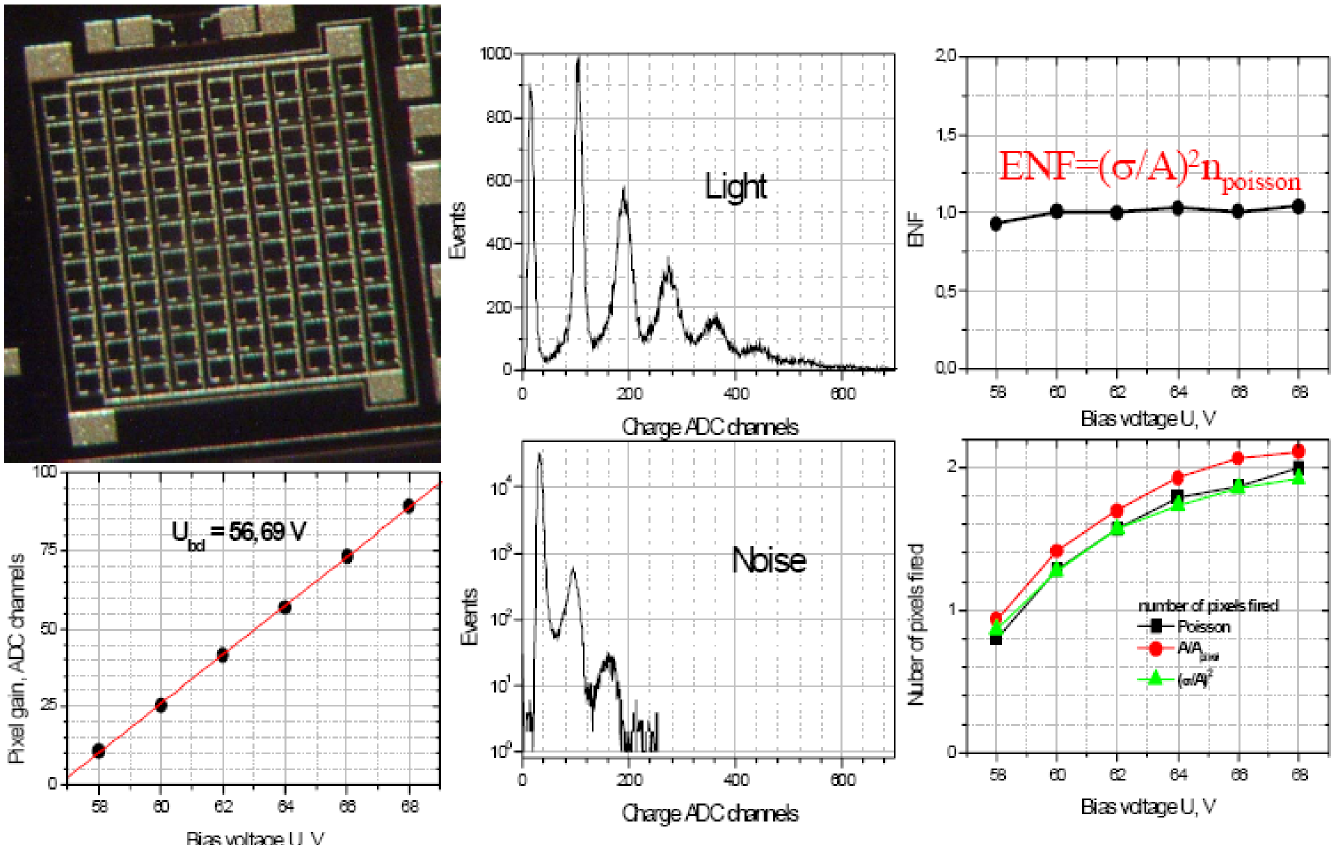
→this process is delayed: later than 1ns



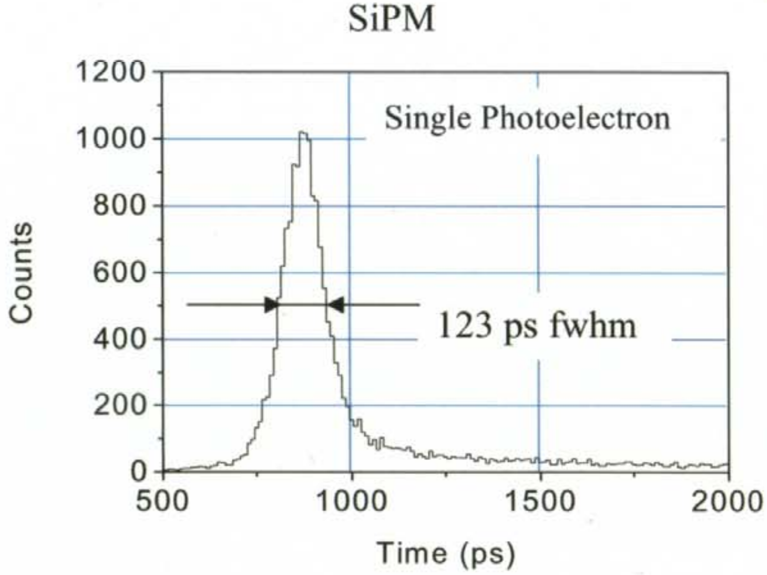
A filled in trench

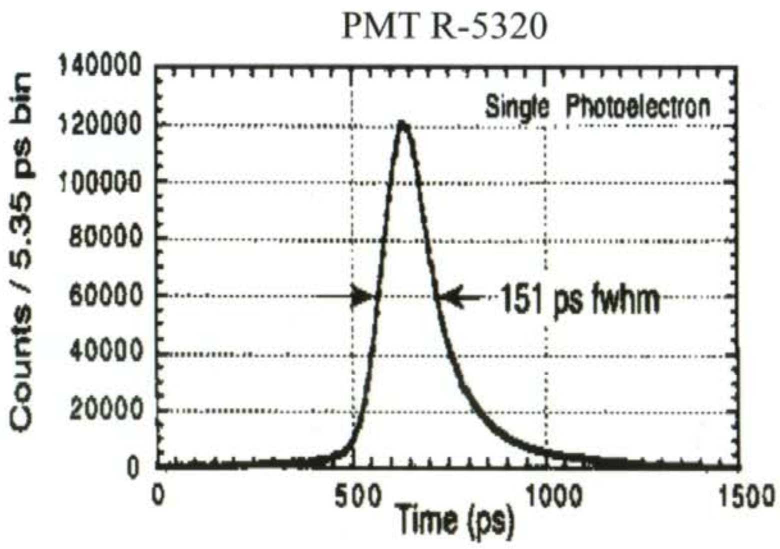


First step: SiPM 1.4x1.4 mm2 with OC suppression topology



Timing by SiPM: possible application for Cherenkov Imaging Counters





SiPM:

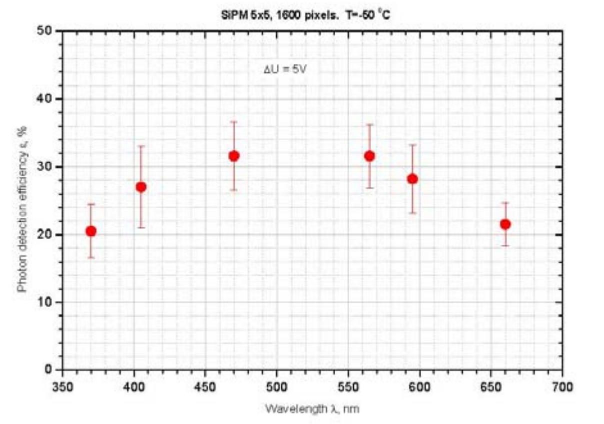
- position sensitive (~1 mm^2)
- a single photon detection capability with background hits density : $2 \cdot 10^{-3}$ 1/ns·mm^2 (room temperature)
  $3 \cdot 10^{-4}$ 1/ns·mm^2 (-50°C)
- insensitive to magnetic field
- good time resolution (~50 ns rms)

FWHM: Laser (40 ps) + electronics (60 ps) => SiPM (100 ps)

Second step: 5x5mm2 SiPM with OC and AP suppression

SiPM parameters:

→ size	5x5mm2
→ double junction structure with optical barriers 6mkm	
→ number of pixels	1600
→ pixel size	100mkm
→ gain	2x10*7
→ geometrical eff.(filling factor)	64%
→ pixel capacitance	~1pF
→ output SiPM capacitance	~160pF
→ antireflection entrance window	
→ single pixel recovery time	~ .5mks



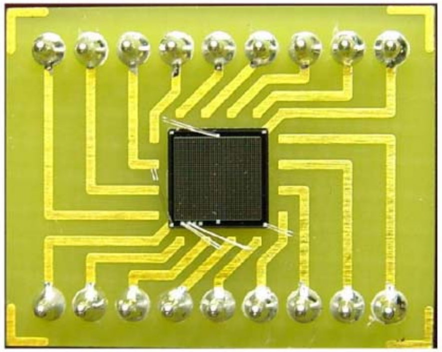


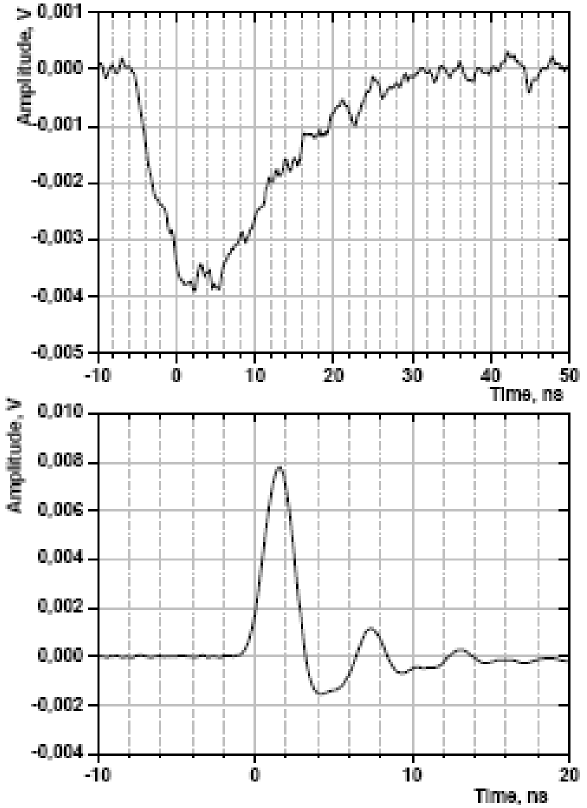
Figure 3: $25 (5 \times 5) mm^2$ SiPM. It consists of the array of $1600 (40 \times 40)$ micropixels with $100 \times 100 \mu m^2$ size.

Timing by 5x5mm2 SiPM: signal shape

➔ Because high SiPM output capacitance (~160pF)

a special FE electronics has been developed:

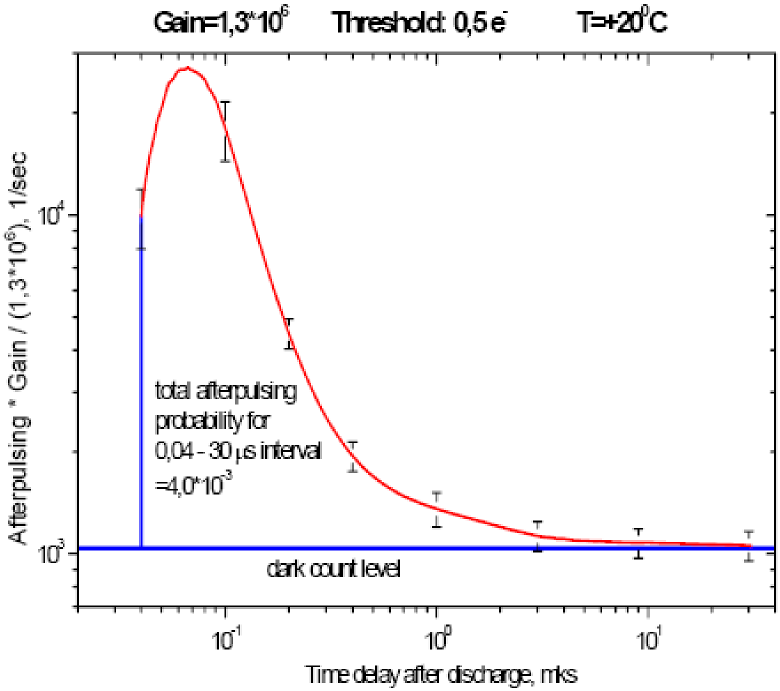
low imput impedance(a few Ohm) current amplifier+shaper



50 Ohm
FWHM
15ns

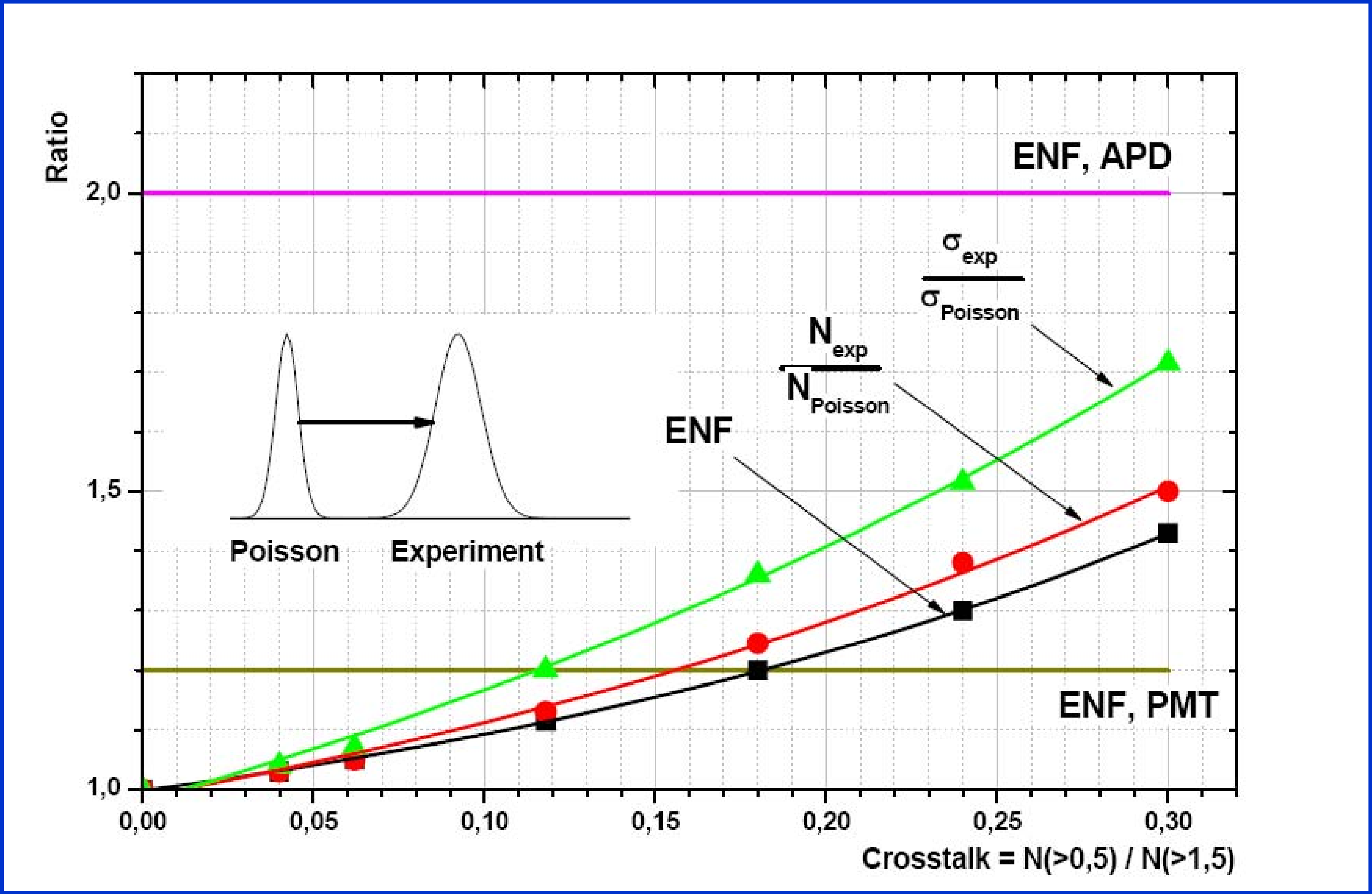
~ 7 Ohm
+shaper
FWHM
2,5ns

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

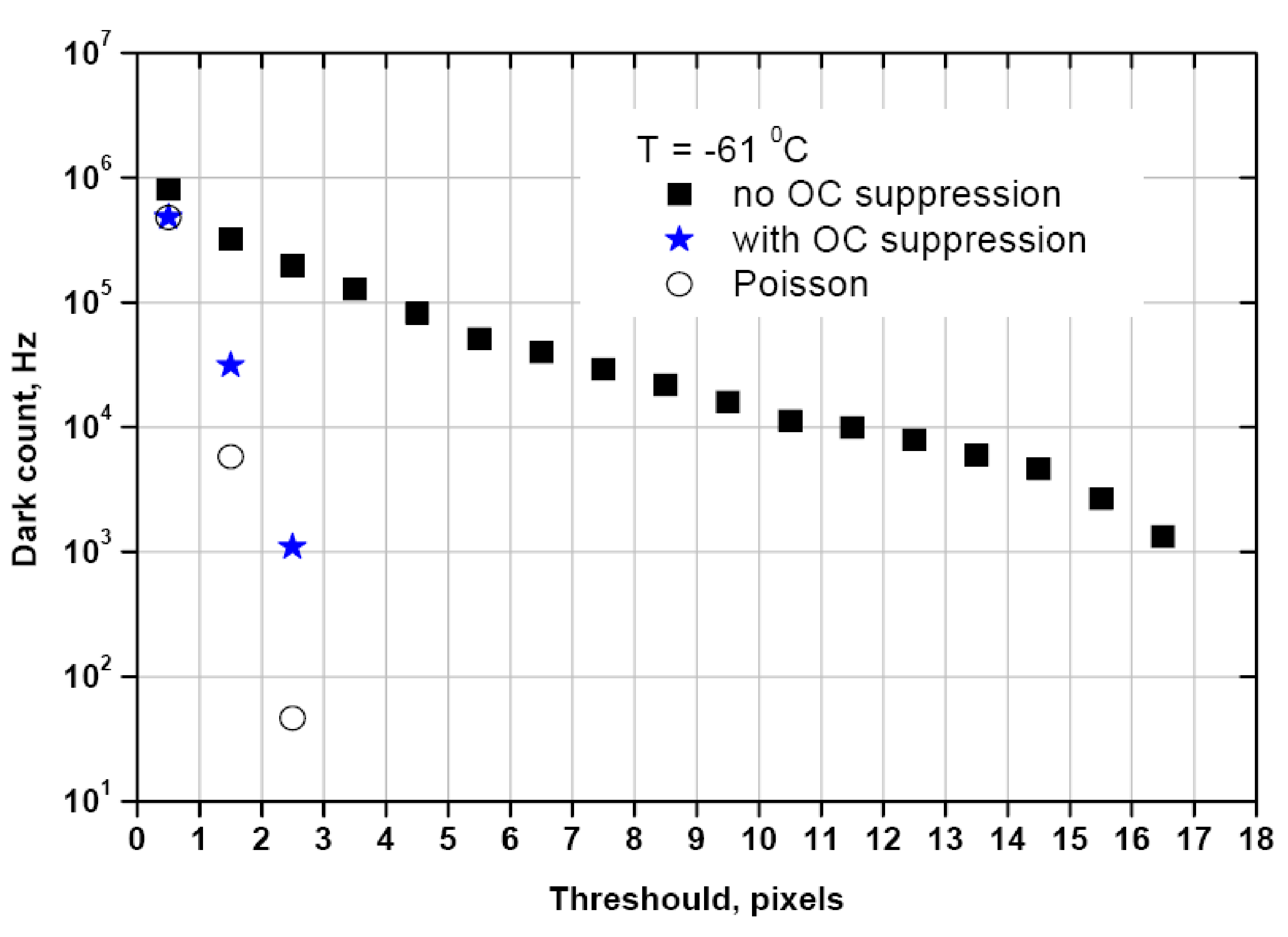


Therefore a single pixel recovery time Rquench x Cpixel sould not be not very small and recommended at level of .5-1 mks

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

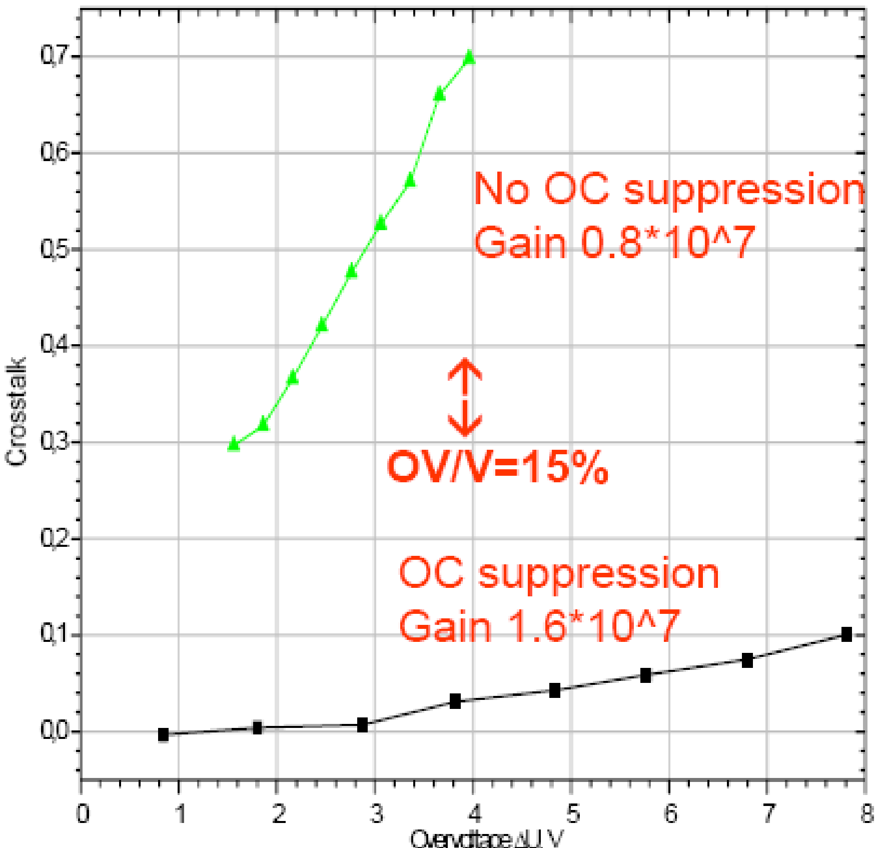

Ratio
2,0
1,5
1,0
ENF, APD
σ exp
σ Poisson
N exp
N Poisson
ENF
Poisson
Experiment
ENF, PMT
0,00
0,05
0,10
0,15
0,20
0,25
0,30
Crosstalk = N(>0,5) / N(>1,5)

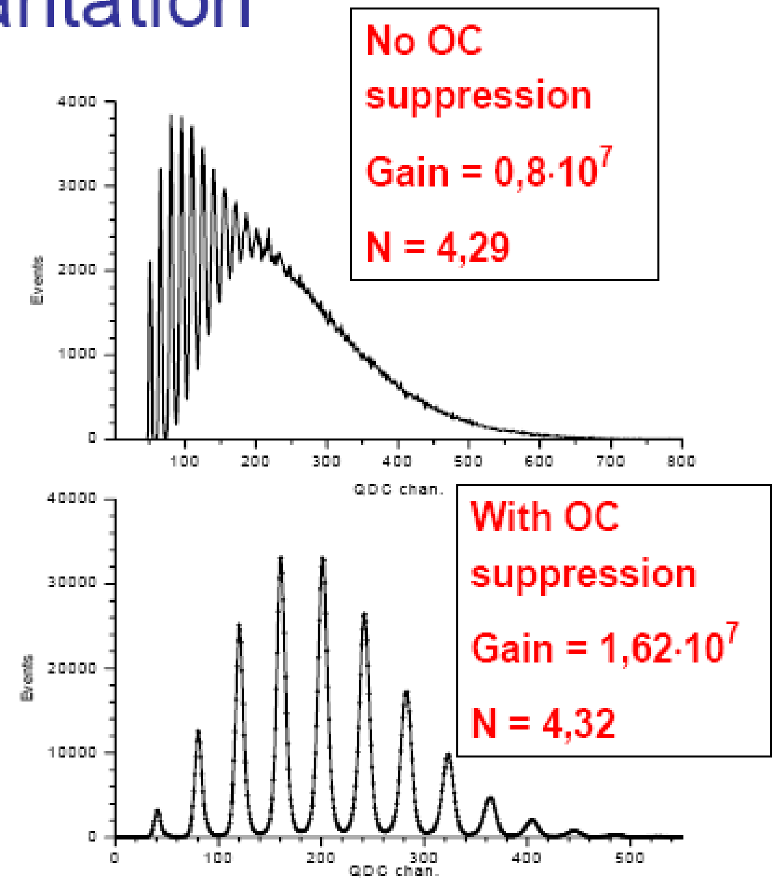
The cross-talk effect (optical coupling: OC) has a major impact in self-trigger schemes, it can prohibit obtaining a low threshold setting



Prompt OC suppression using Si damaged by ion implantation

(Patent pending)

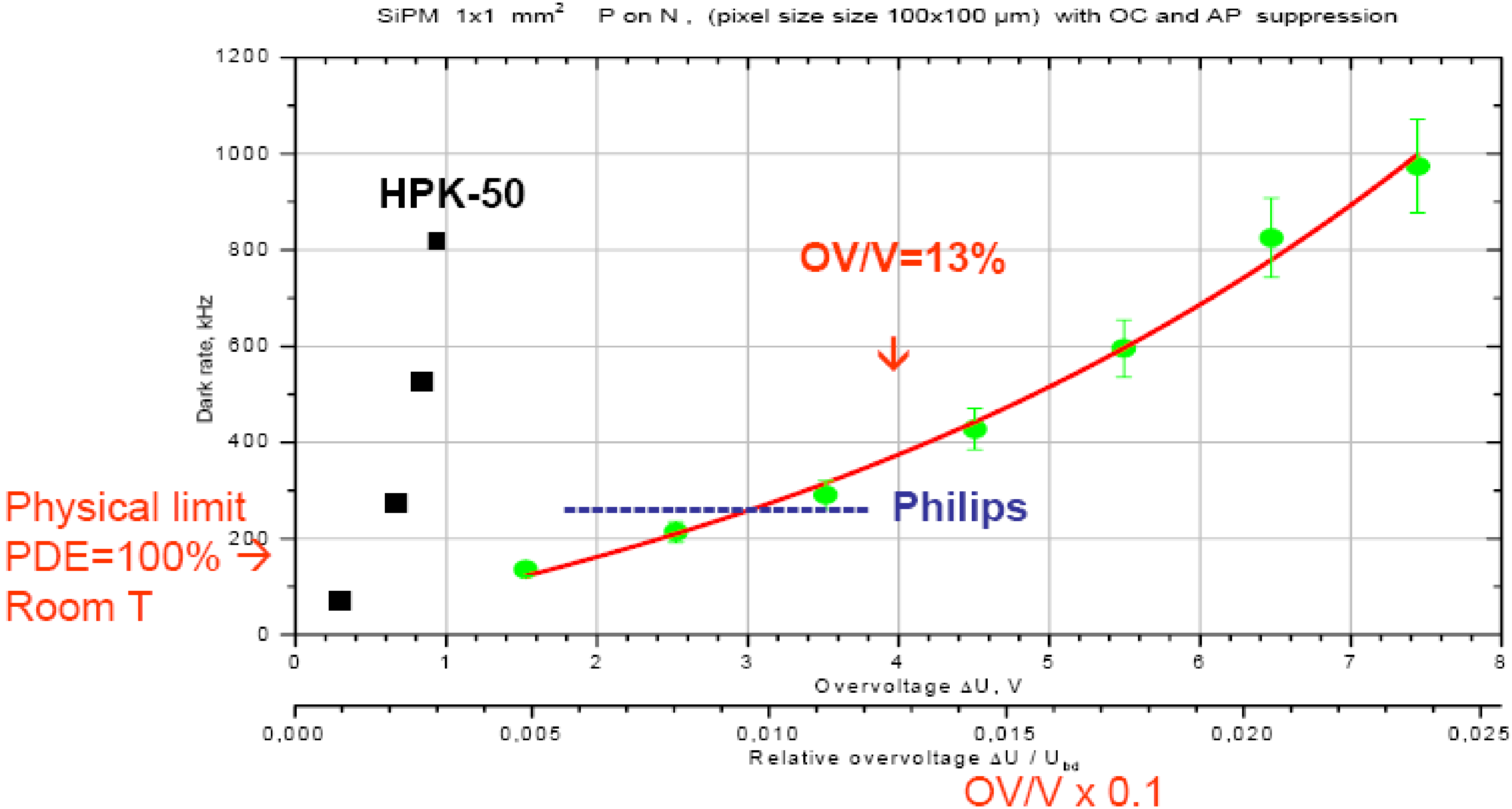




SiPM 1x1 mm^2

Dark count rate: SiPM 1x1mm^2, OC=4%,AP=1%

room temperature

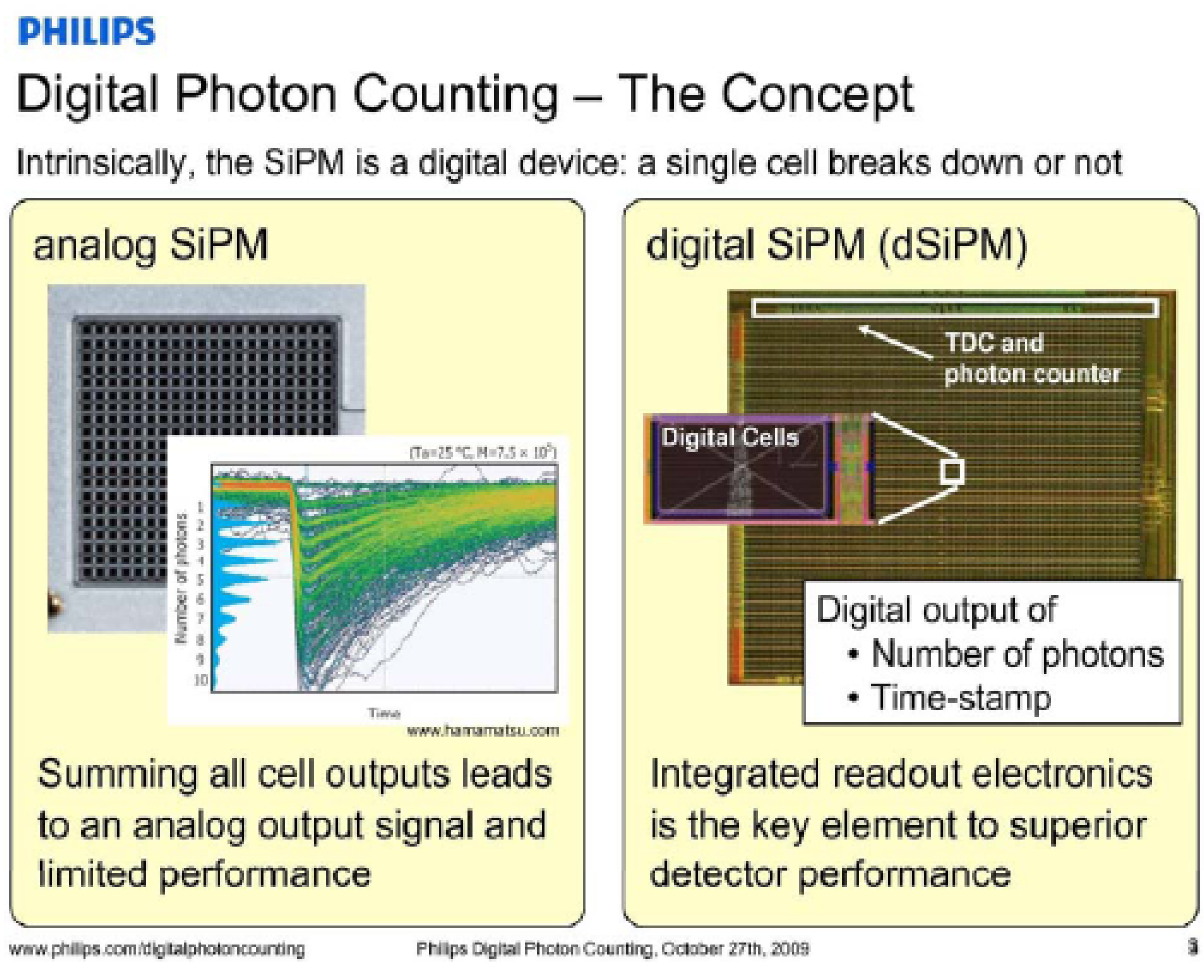


Digital SiPM

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

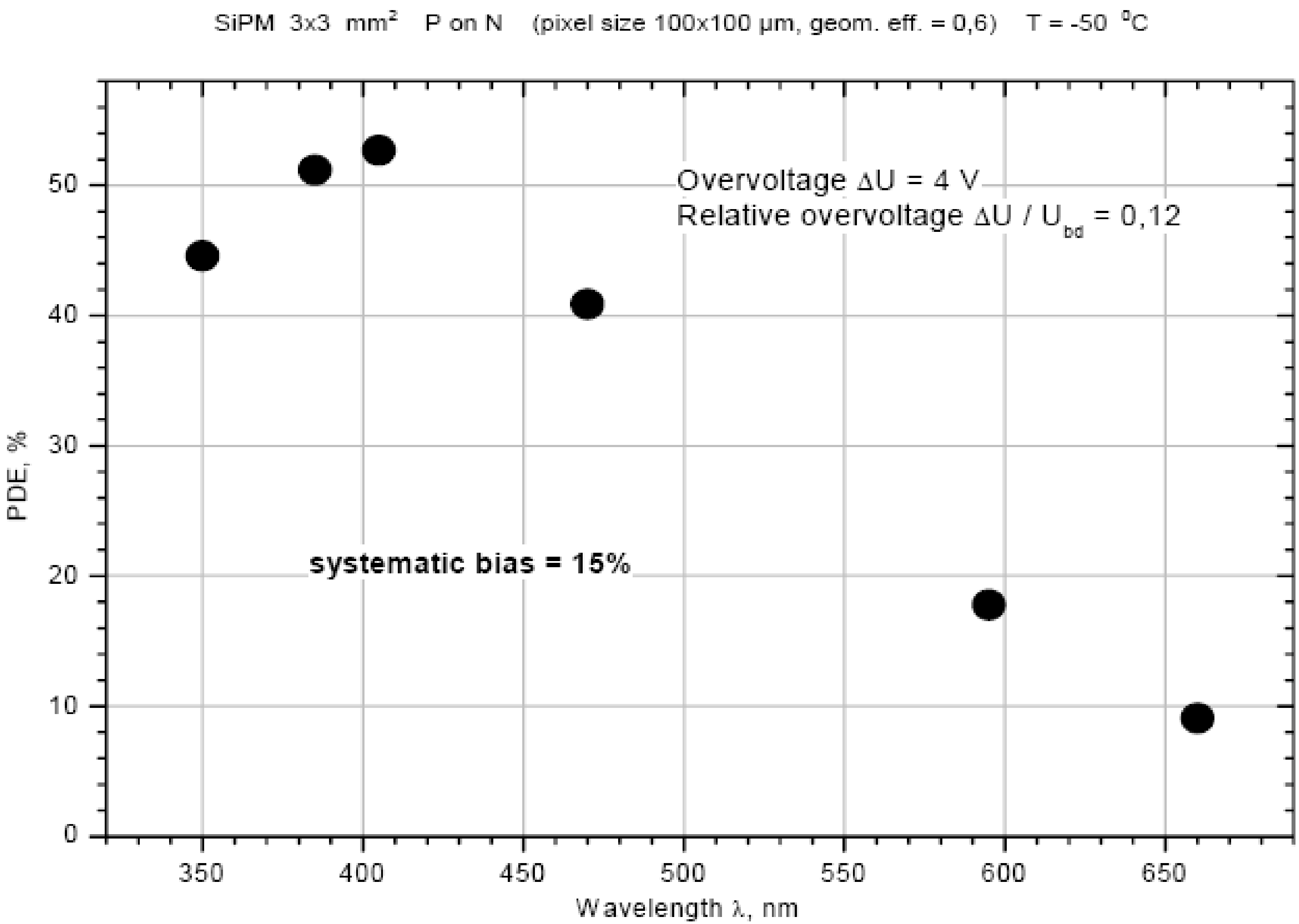
→PDE loss (filling factor is less due to electronics on chip)
→problems with Optical Crosstalk and Afterpulsing have to be solved

Fabrication cost?



PDE ,SiPM p on n,3x3 mm^2, OV/V=12% +OC suppression

Test-product of PEI, to become soon commercial product



Conclusions

- In a time scale 1-2 years from now one can buy SiPMs with outstanding characteristics, probably from several manufacturers.
- Their sizes could span 1-10 mm.
- SiPM cost will be reduced due to the availability of full CMOS designs. Several USD per mm^2 is not unrealistic.
- They could offer PDE of 60-65 %, x-talk < 1% and low temperature and voltage dependences.
- These devices are going to substitute classical PMTs and APD in many applications, including those in physics instrumentation in, for example, nuclear medicine (time-of-flight PET,…).
- Realistic candidates for SST telescopes, especially for 2-optical element designs