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

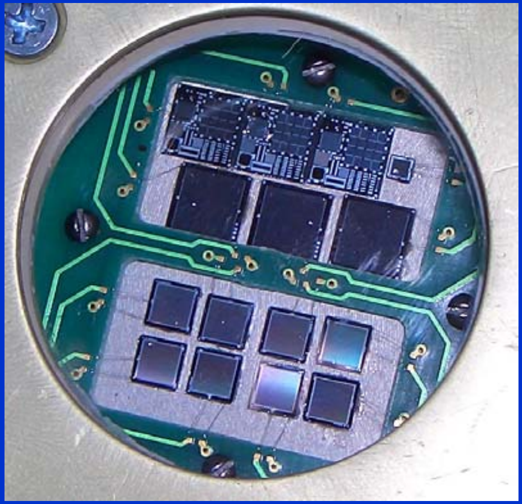
Razmik Mirzoyan

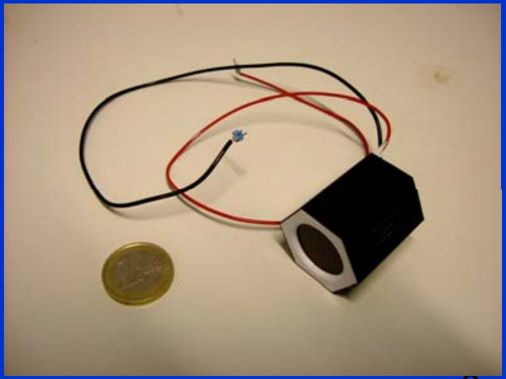
Max-Planck-Institute for Physics
(Werner-Heisenberg-Institute)
Munich, Germany

What LLL sensor can we dream about ?

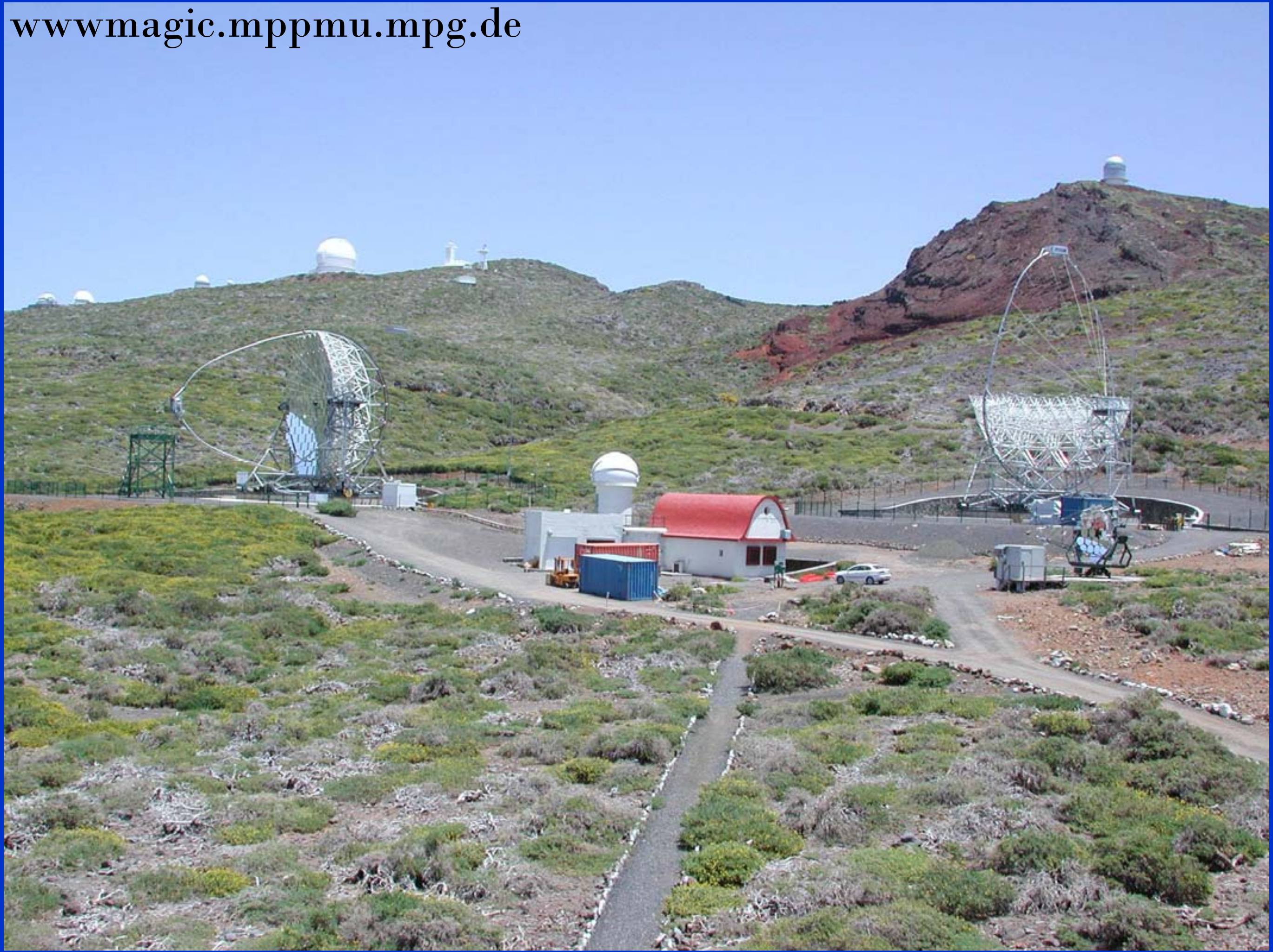
- Nearly 100 % QE and photon detection efficiency (PDE)
- Could be made in very large and in very small sizes
- Few ps fast (in air and in many materials the light speed is usually 20-30 cm/ns; in 5 ps it will make 1-1.5 mm)
- Signal amplification x10^6
- Noiseless amplification: F-factor - 1.001
- Few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

The „zoo“ of LLL sensors



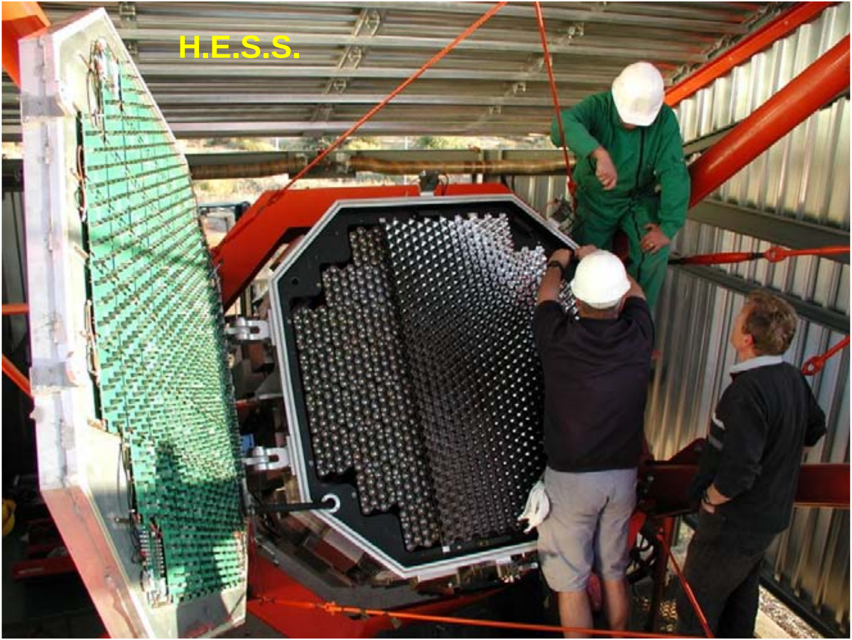


The 17m Ø MAGIC IACT project for VHE γ astrophysics at E~ 25 GeV - 30 TeV


wwwmagic.mppmu.mpg.de


Laser beams of the Active Mirror Control system become visible on foggy night

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

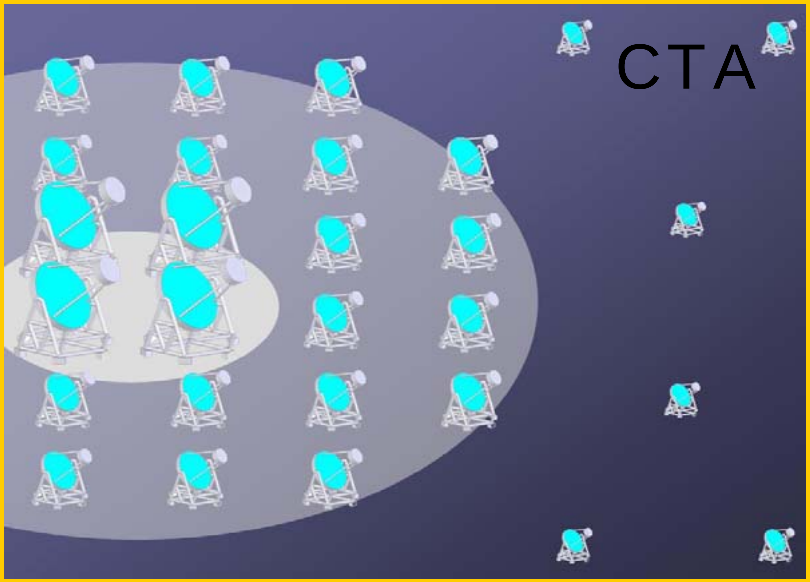
Next generation VHE γ ray Observatory: CTA

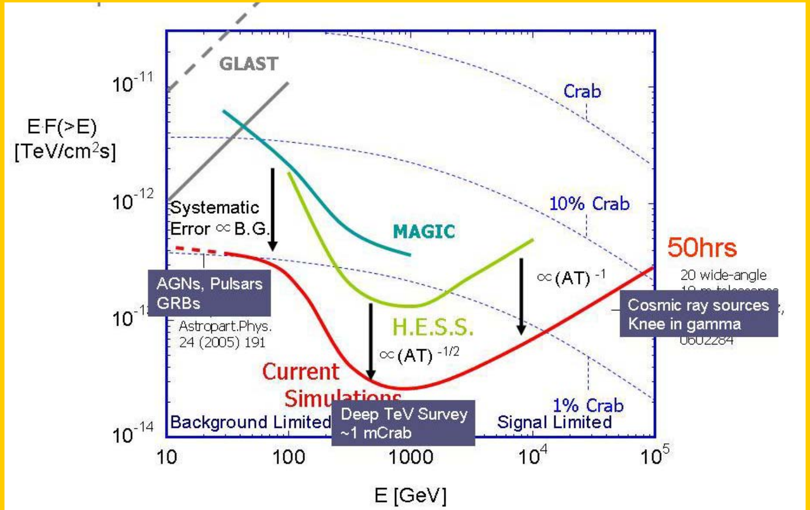
MAGIC Phase II (MAGIC-I + MAGIC-II) in 2010
~100 sources are already discovered

~500 scientists
~50 institutions

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

Cherenkov Telescope Array
1000’s of sources will be discovered



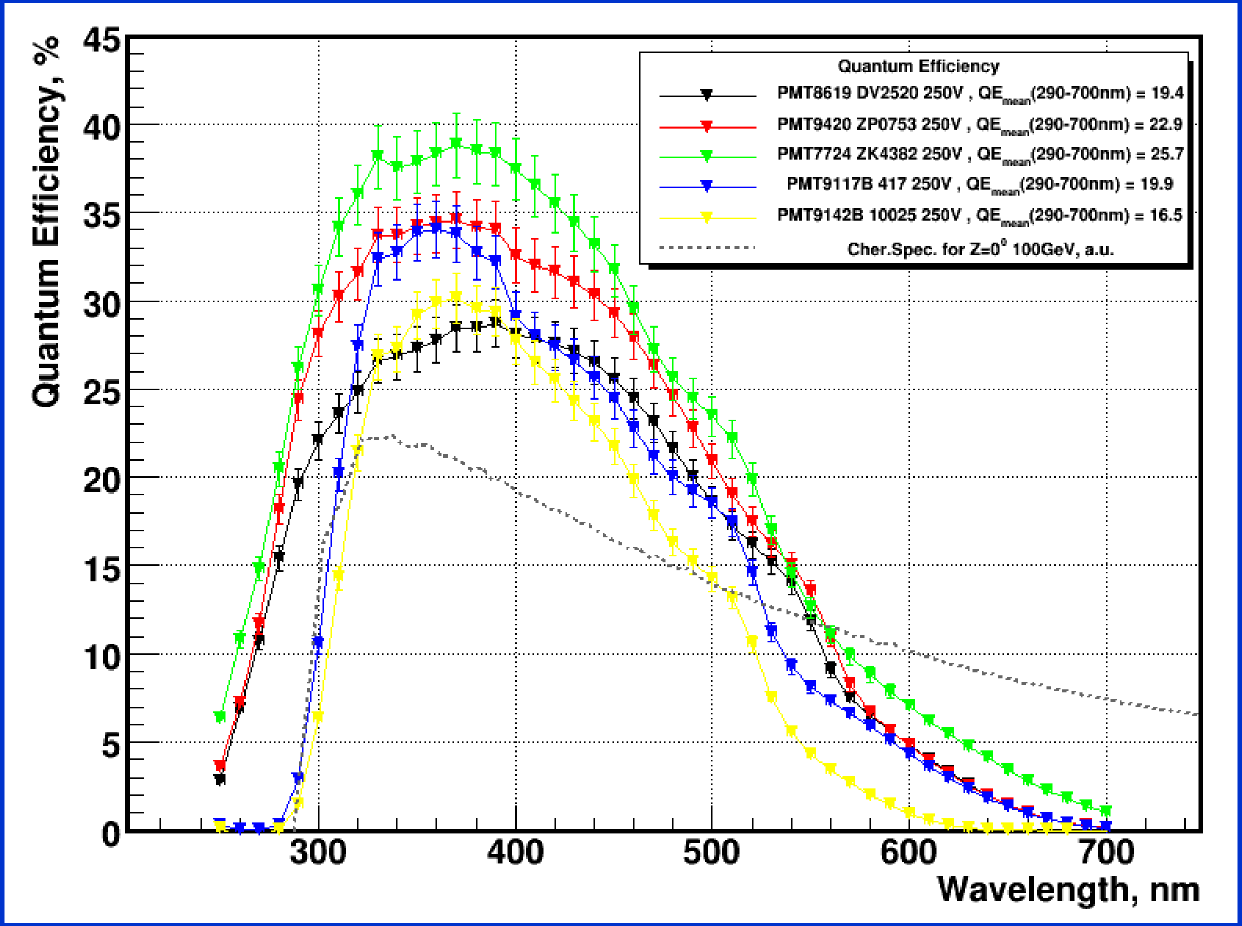


Astronomers in EU

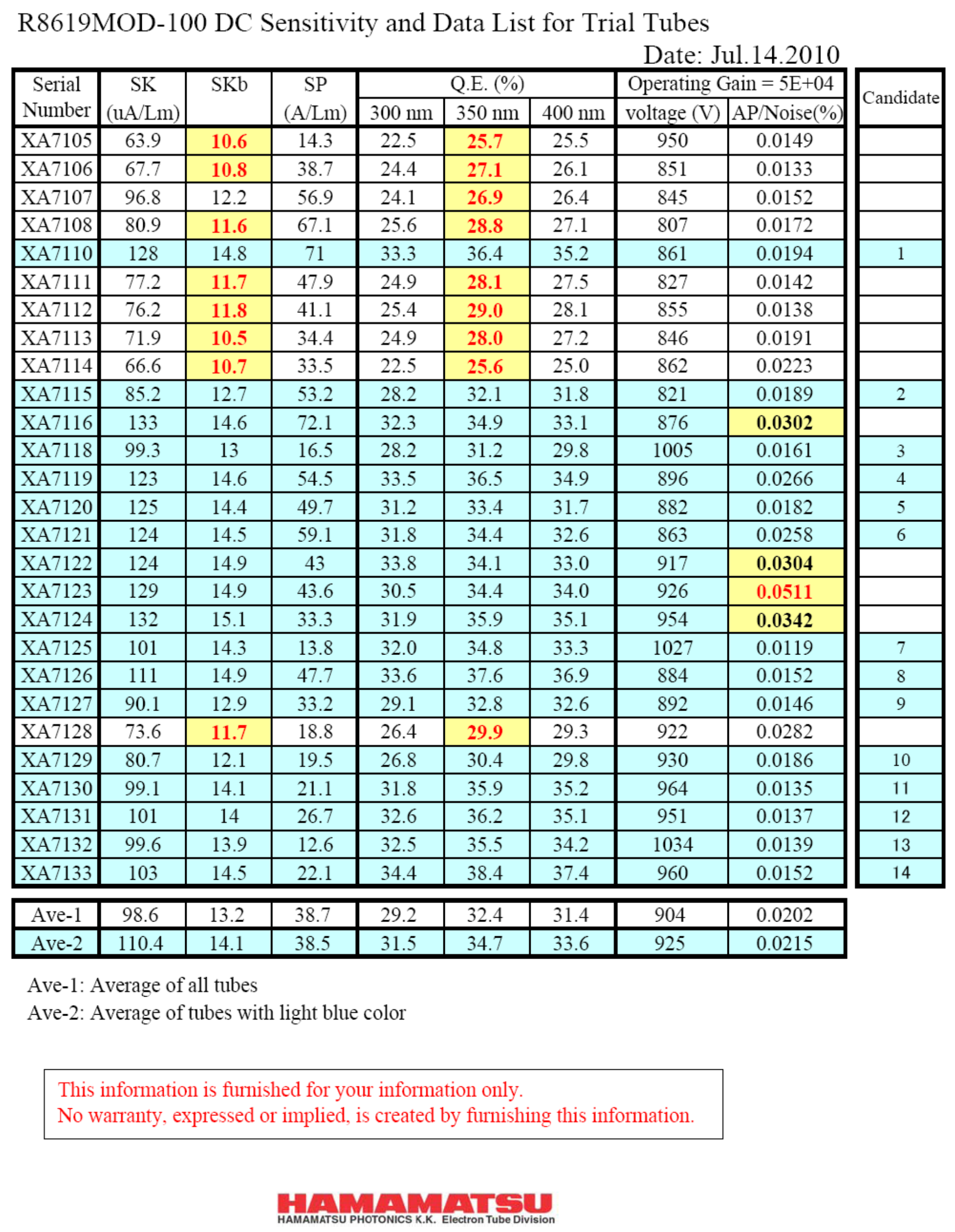
JAPAN, US

Instrumental/technological improvements

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



- Some 6 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 1.5 years a new program has been launched for CTA; the results are shown on the left



R8619MOD-100 DC Sensitivity and Data List for Trial Tubes

Date: Jul.14.2010

Serial Number	SK (uA/Lm)	SKb	SP (A/Lm)	Q.E. (%)			Operating Gain = 5E+04		Candidate
				300 nm	350 nm	400 nm	voltage (V)	AP/Noise(%)	
XA7105	63.9	**10.6**	14.3	22.5	**25.7**	25.5	950	0.0149	
XA7106	67.7	**10.8**	38.7	24.4	**27.1**	26.1	851	0.0133	
XA7107	96.8	12.2	56.9	24.1	**26.9**	26.4	845	0.0152	
XA7108	80.9	**11.6**	67.1	25.6	**28.8**	27.1	807	0.0172	
XA7110	128	14.8	71	33.3	36.4	35.2	861	0.0194	1
XA7111	77.2	**11.7**	47.9	24.9	**28.1**	27.5	827	0.0142	
XA7112	76.2	**11.8**	41.1	25.4	**29.0**	28.1	855	0.0138	
XA7113	71.9	**10.5**	34.4	24.9	**28.0**	27.2	846	0.0191	
XA7114	66.6	**10.7**	33.5	22.5	**25.6**	25.0	862	0.0223	
XA7115	85.2	12.7	53.2	28.2	32.1	31.8	821	0.0189	2
XA7116	133	14.6	72.1	32.3	34.9	33.1	876	**0.0302**	
XA7118	99.3	13	16.5	28.2	31.2	29.8	1005	0.0161	3
XA7119	123	14.6	54.5	33.5	36.5	34.9	896	0.0266	4
XA7120	125	14.4	49.7	31.2	33.4	31.7	882	0.0182	5
XA7121	124	14.5	59.1	31.8	34.4	32.6	863	0.0258	6
XA7122	124	14.9	43	33.8	34.1	33.0	917	**0.0304**	
XA7123	129	14.9	43.6	30.5	34.4	34.0	926	**0.0511**	
XA7124	132	15.1	33.3	31.9	35.9	35.1	954	**0.0342**	
XA7125	101	14.3	13.8	32.0	34.8	33.3	1027	0.0119	7
XA7126	111	14.9	47.7	33.6	37.6	36.9	884	0.0152	8
XA7127	90.1	12.9	33.2	29.1	32.8	32.6	892	0.0146	9
XA7128	73.6	**11.7**	18.8	26.4	**29.9**	29.3	922	0.0282	
XA7129	80.7	12.1	19.5	26.8	30.4	29.8	930	0.0186	10
XA7130	99.1	14.1	21.1	31.8	35.9	35.2	964	0.0135	11
XA7131	101	14	26.7	32.6	36.2	35.1	951	0.0137	12
XA7132	99.6	13.9	12.6	32.5	35.5	34.2	1034	0.0139	13
XA7133	103	14.5	22.1	34.4	38.4	37.4	960	0.0152	14

Ave-1	98.6	13.2	38.7	29.2	32.4	31.4	904	0.0202
Ave-2	110.4	14.1	38.5	31.5	34.7	33.6	925	0.0215

Ave-1: Average of all tubes
Ave-2: Average of tubes with light blue color

This information is furnished for your information only.
No warranty, expressed or implied, is created by furnishing this information.

HAMAMATSU
HAMAMATSU PHOTONICS K.K. Electron Tube Division

The most recent production of PMTs by Hamamatsu Photonics

Already now they came very close to requested parameters

The <QE> peak is approaching ~ 35 %. The ph.e. collection efficiency is 95-98 %.

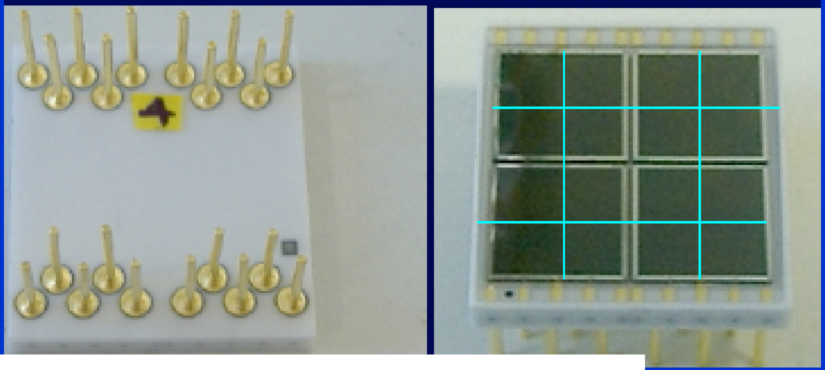
Requested afterpulsing < 0.02 %.

More improvements requested, like much lower variation in the gain of dynodes

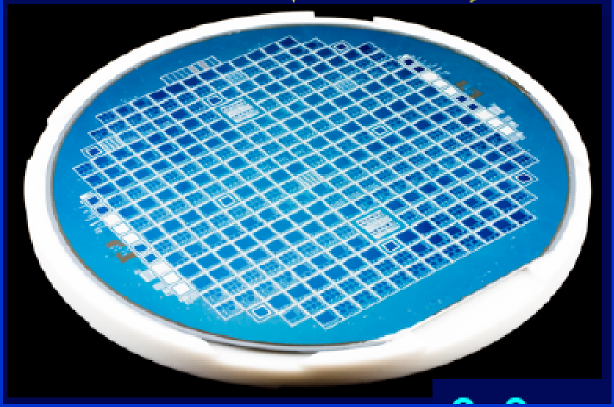
Currently launching a 2-year development contracts with Hamamatsu and ETE (England)
Financial support from CTA

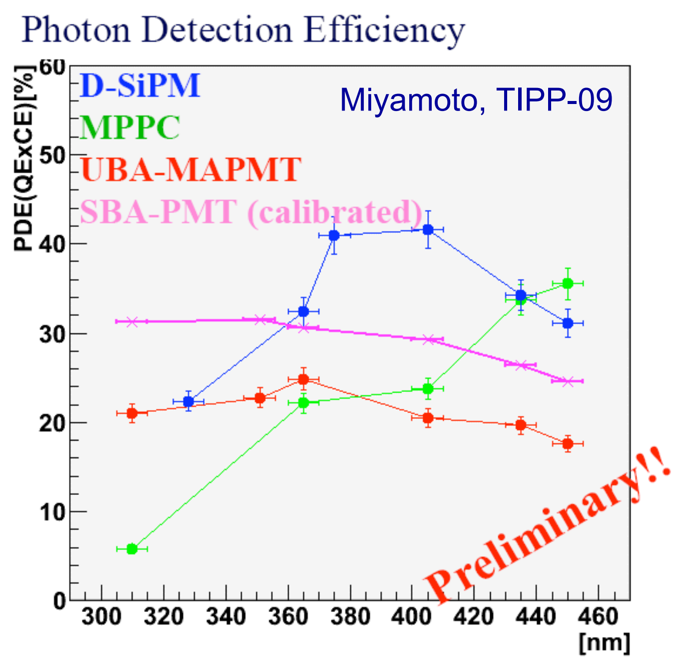
Few examples of SiPMs, still under development

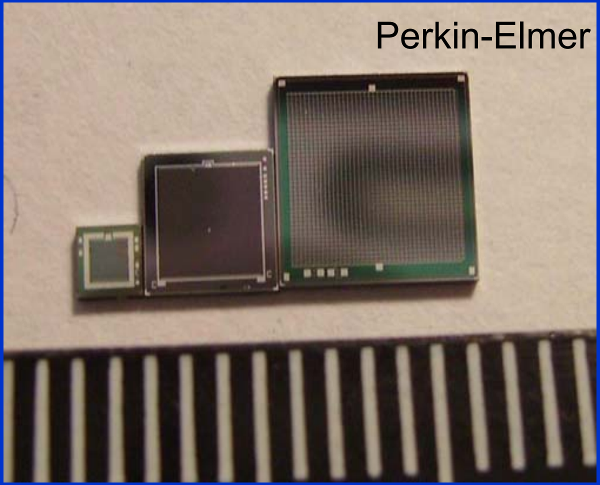
Hamamatsu (MPPC)



MPI-HLL (SiMPL)





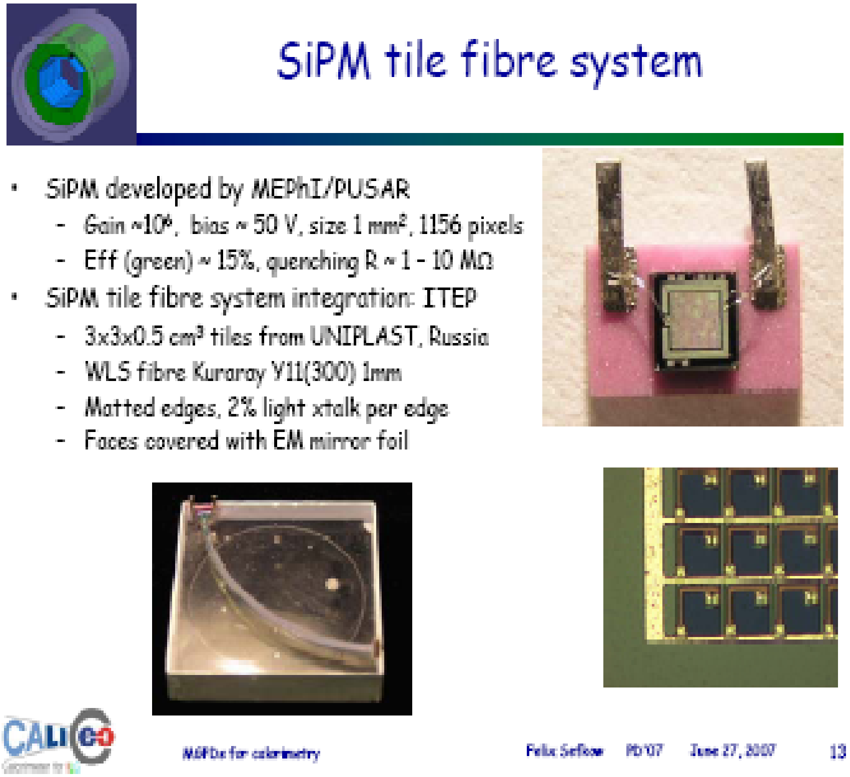


SiPMs with ~ 50-60% PDE and low cross-talk (< 1%) could be anticipated within 1-2 years

ILC: Potential Consumer of (5-200)x10^6 SiPMs

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

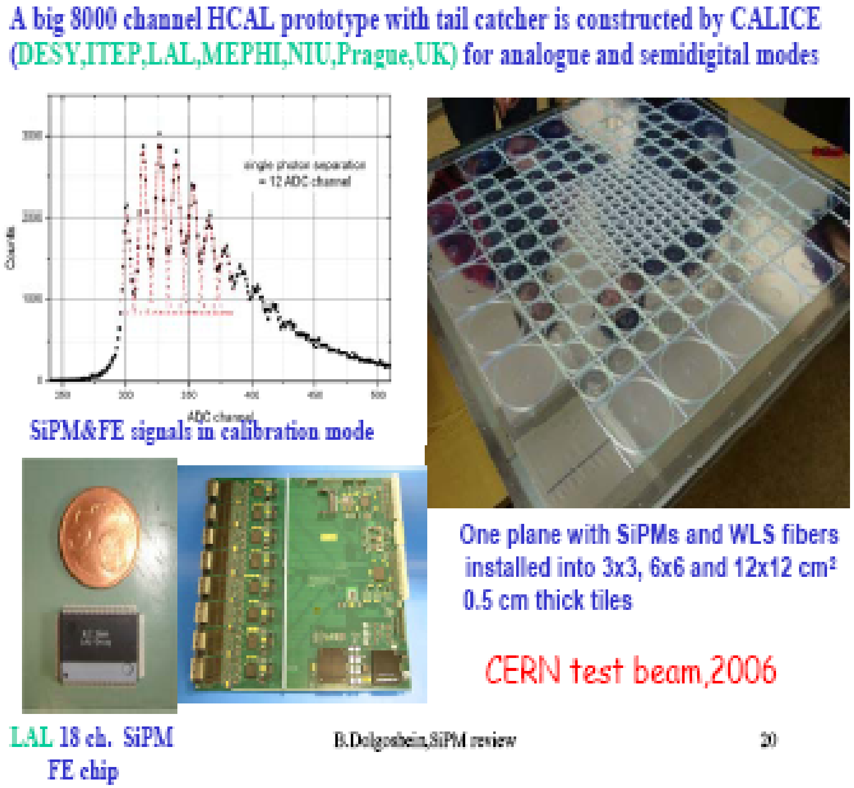
→Typical threshold is ~ 5-7 phe



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

MAPDs 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

LAL 18 ch. SiPM FE chip

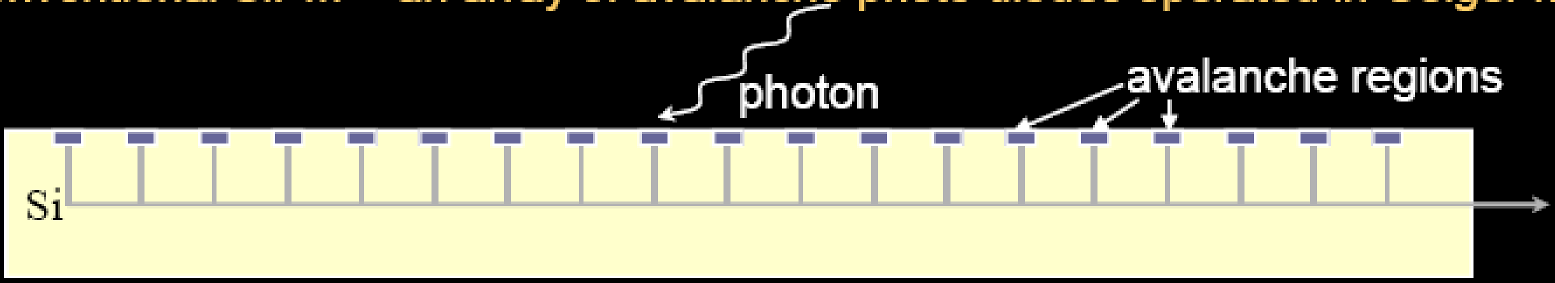
One plane with SiPMs and WLS fibers installed into 3x3, 6x6 and 12x12 cm^2 0.5 cm thick tiles

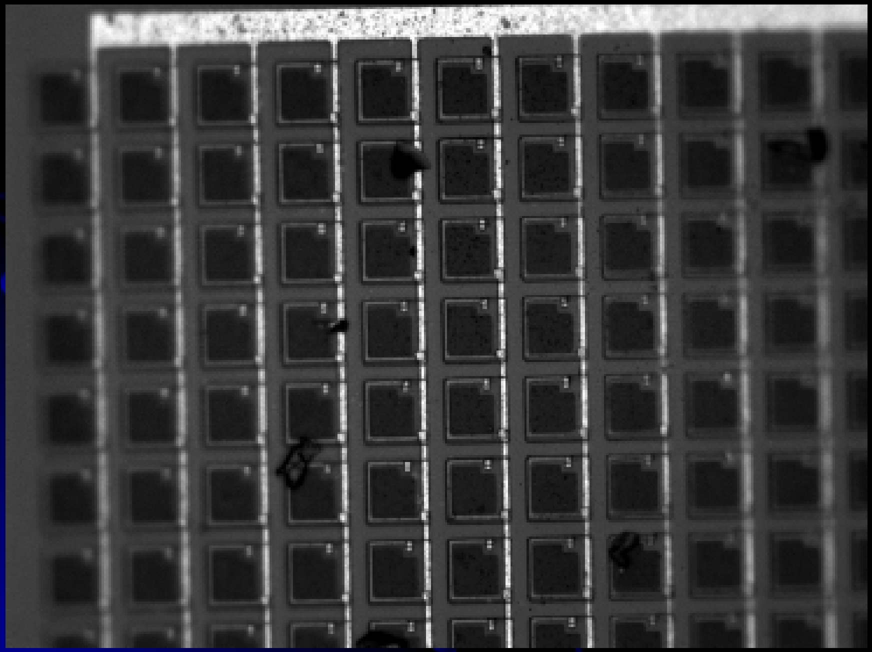
CERN test beam,2006

B.Dolgoshein,SiPM review   20

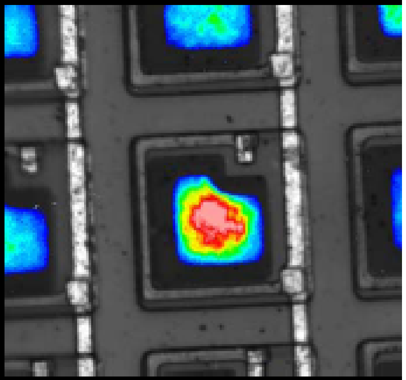
SiPM: novel light sensors

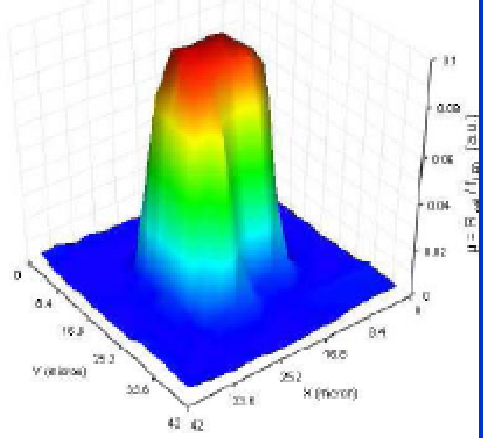
Conventional SiPM - an array of avalanche photo diodes operated in Geiger mode



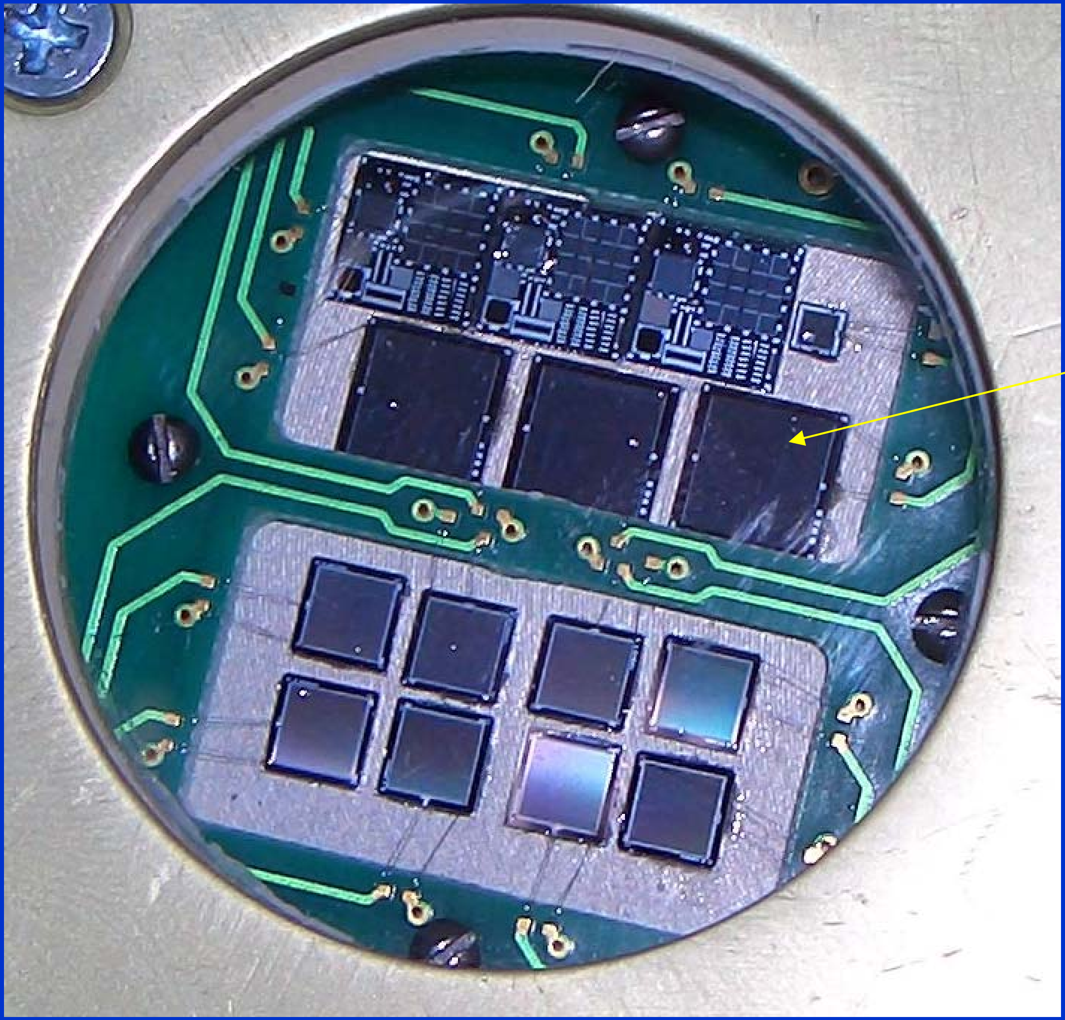


Dolgoshein device

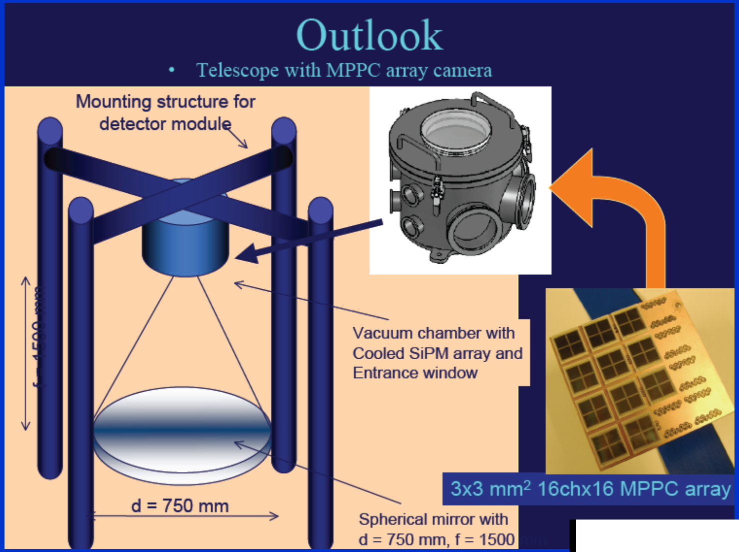




SiPMs: MEPhI-MPI development: 1x1, 1.3x1.3, 1.4x1.4, 3x3, 5x5 mm²

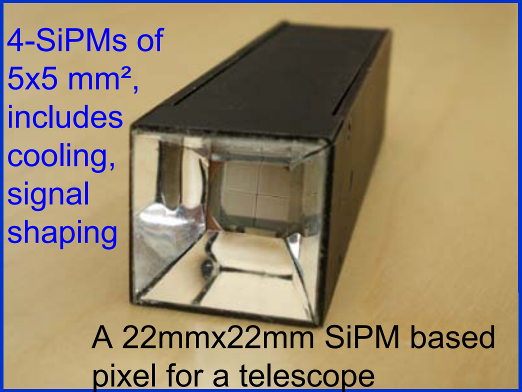


5 x 5 mm²



Outlook

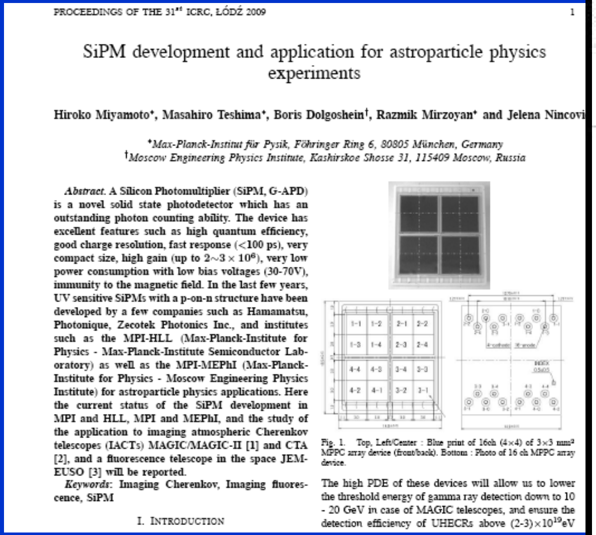
- Telescope with MPPC array camera



4-SiPMs of 5x5 mm², includes cooling, signal shaping

A 22mmx22mm SiPM based pixel for a telescope

The same as on the left but 4-times larger



PROCEEDINGS OF THE 31st ICRC, ŁÓDŹ 2009 1

SiPM development and application for astroparticle physics experiments

Hiroko Miyamoto*, Masahiro Teshima*, Boris Dolgoshein†, Razmik Mirzoyan* and Jelena Nincovi

**Max-Planck-Institut für Pysik, Föhringer Ring 6, 80805 München, Germany*
†Moscow Engineering Physics Institute, Kashirskoe Shosse 31, 115409 Moscow, Russia

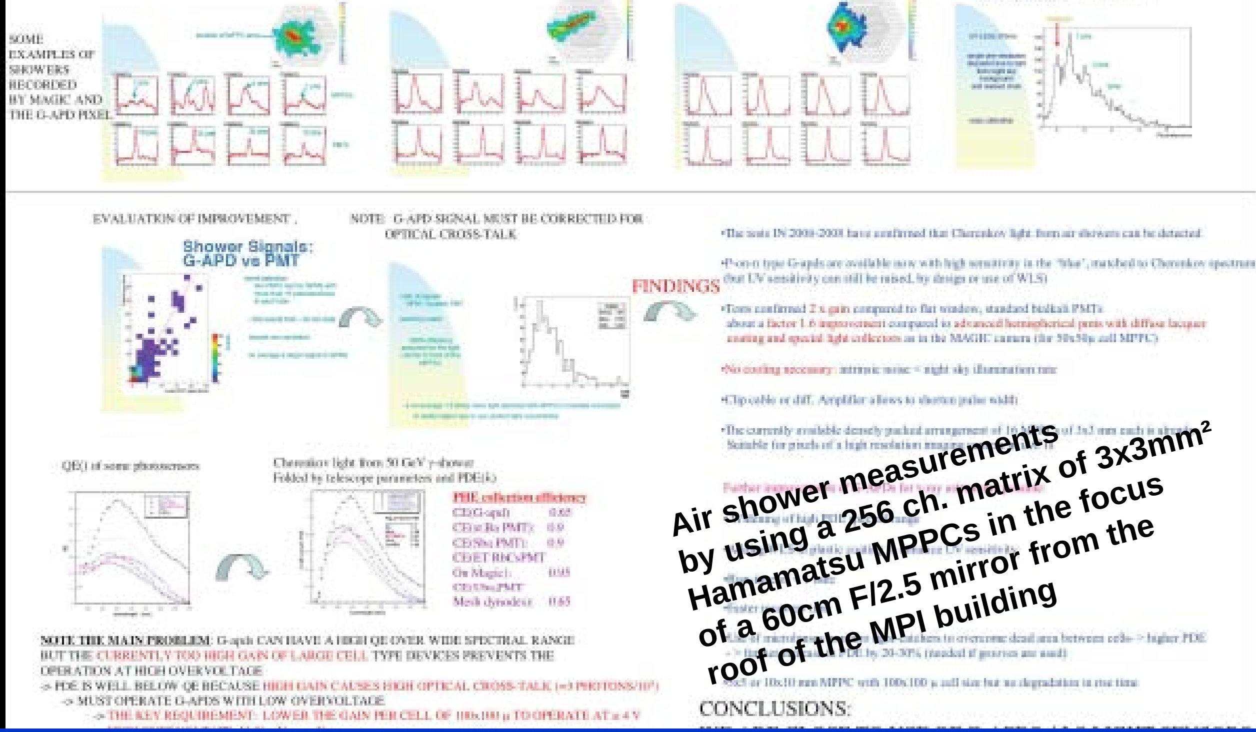
Abstract. A Silicon Photomultiplier (SiPM, G-APD) is a novel solid state photodetector which has an outstanding photon counting ability. The device has excellent features such as high quantum efficiency, good charge resolution, fast response (<100 ps), very compact size, high gain (up to $2\sim3\times10^6$),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



SOME EXAMPLES OF SHOWERS RECORDED BY MAGIC AND THE G-APD PIXEL

EVALUATION OF IMPROVEMENT

NOTE: G-APD SIGNAL MUST BE CORRECTED FOR OPTICAL CROSS-TALK

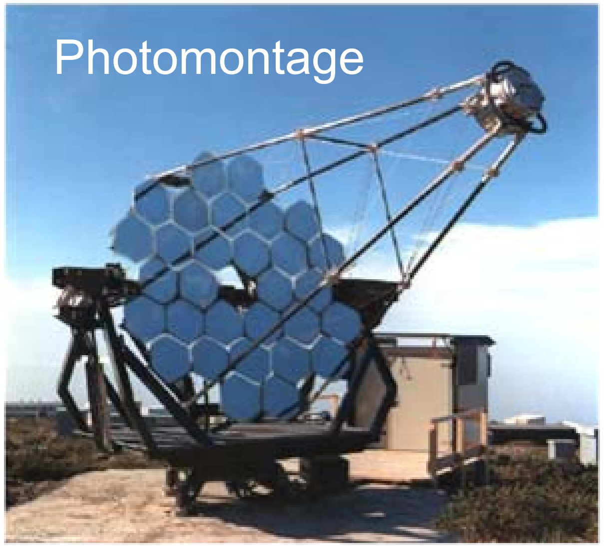
NOTE THE MAIN PROBLEM: G-apds CAN HAVE A HIGH QE OVER WIDE SPECTRAL RANGE BUT THE CURRENTLY TOO HIGH GAIN OF LARGE CELL TYPE DEVICES PREVENTS THE OPERATION AT HIGH OVERVOLTAGE
-> PDE IS WELL BELOW QE BECAUSE HIGH GAIN CAUSES HIGH OPTICAL CROSS-TALK
-> MUST OPERATE G-APDS WITH LOW OVERVOLTAGE
-> THE KEY REQUIREMENT: LOWER THE GAIN PER CELL

CONCLUSIONS:

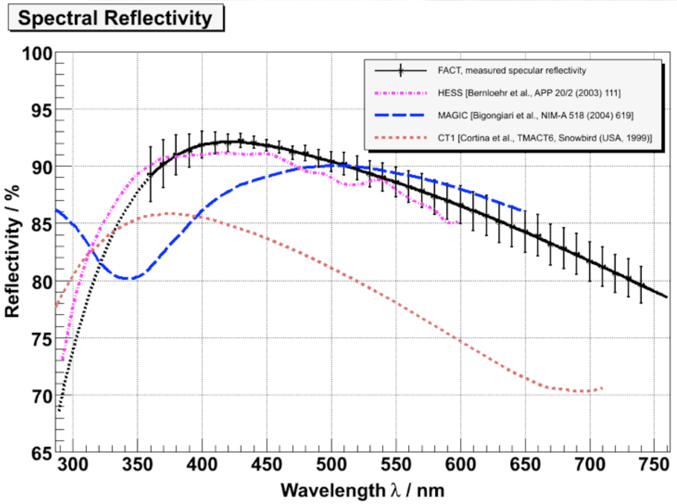
Air shower measurements by using a 256 ch. matrix of 3x3mm² Hamamatsu MPPCs in the focus of a 60cm F/2.5 mirror from the roof of the MPI building

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

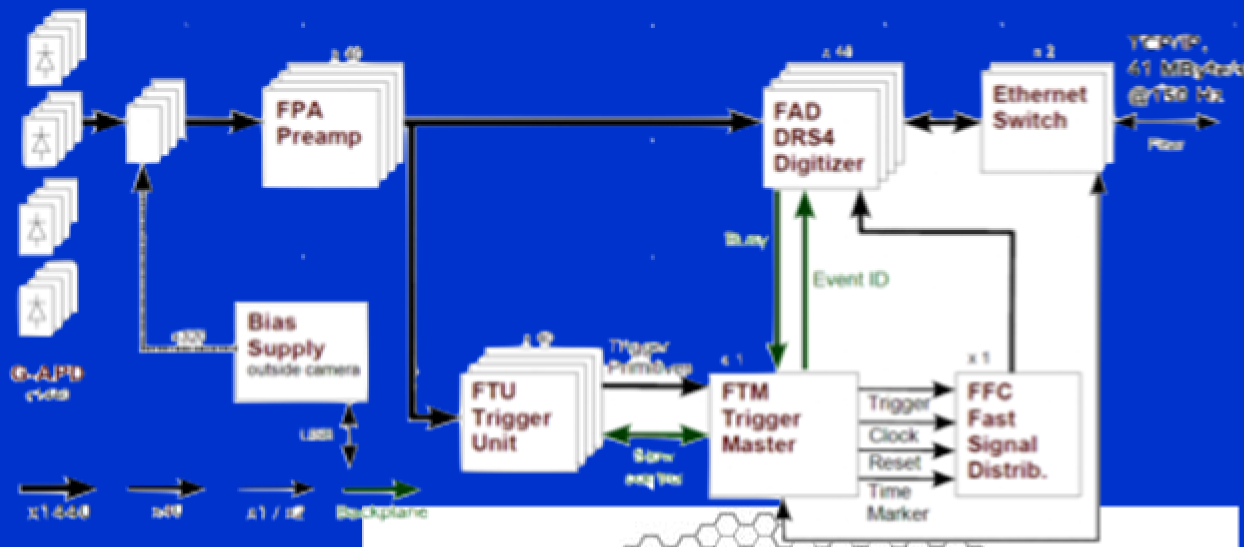


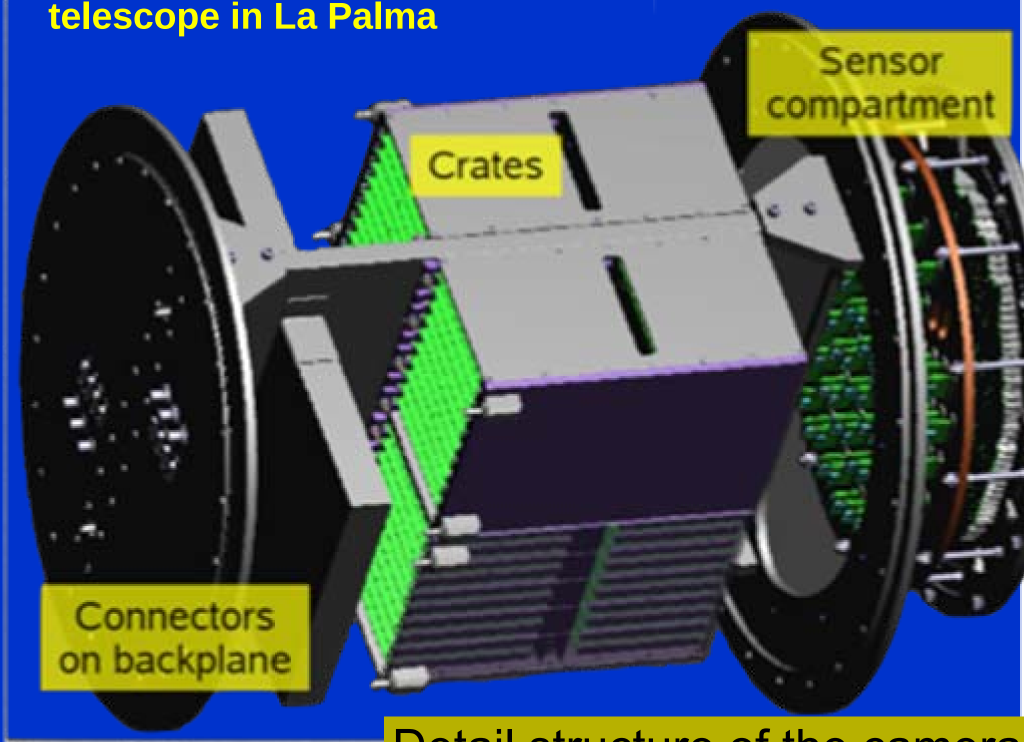
2010: 1440-Pixel G-APD-Kamera

DAQ in Kamera integriert

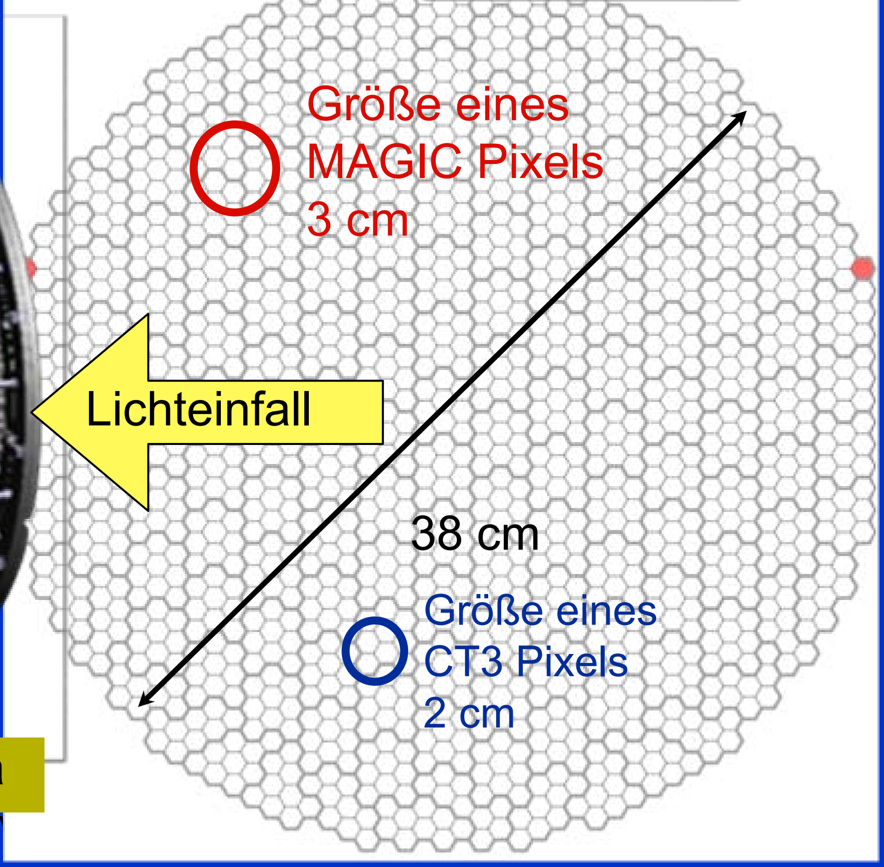
Produced in Zurich

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





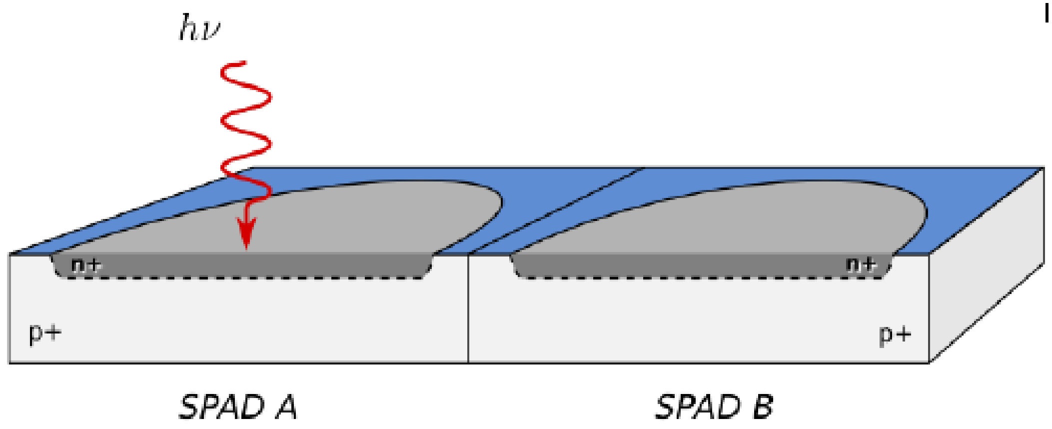
Detail structure of the camera



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

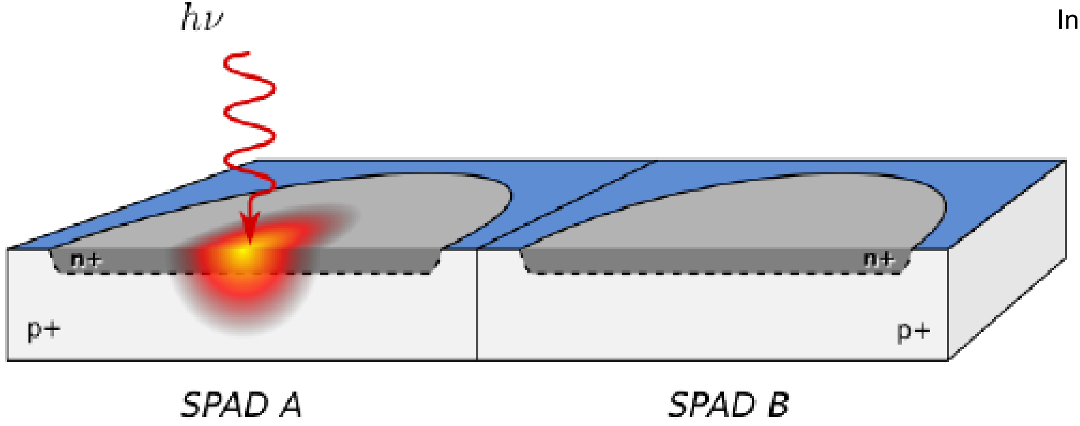


Ingargiola NDIP-08

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

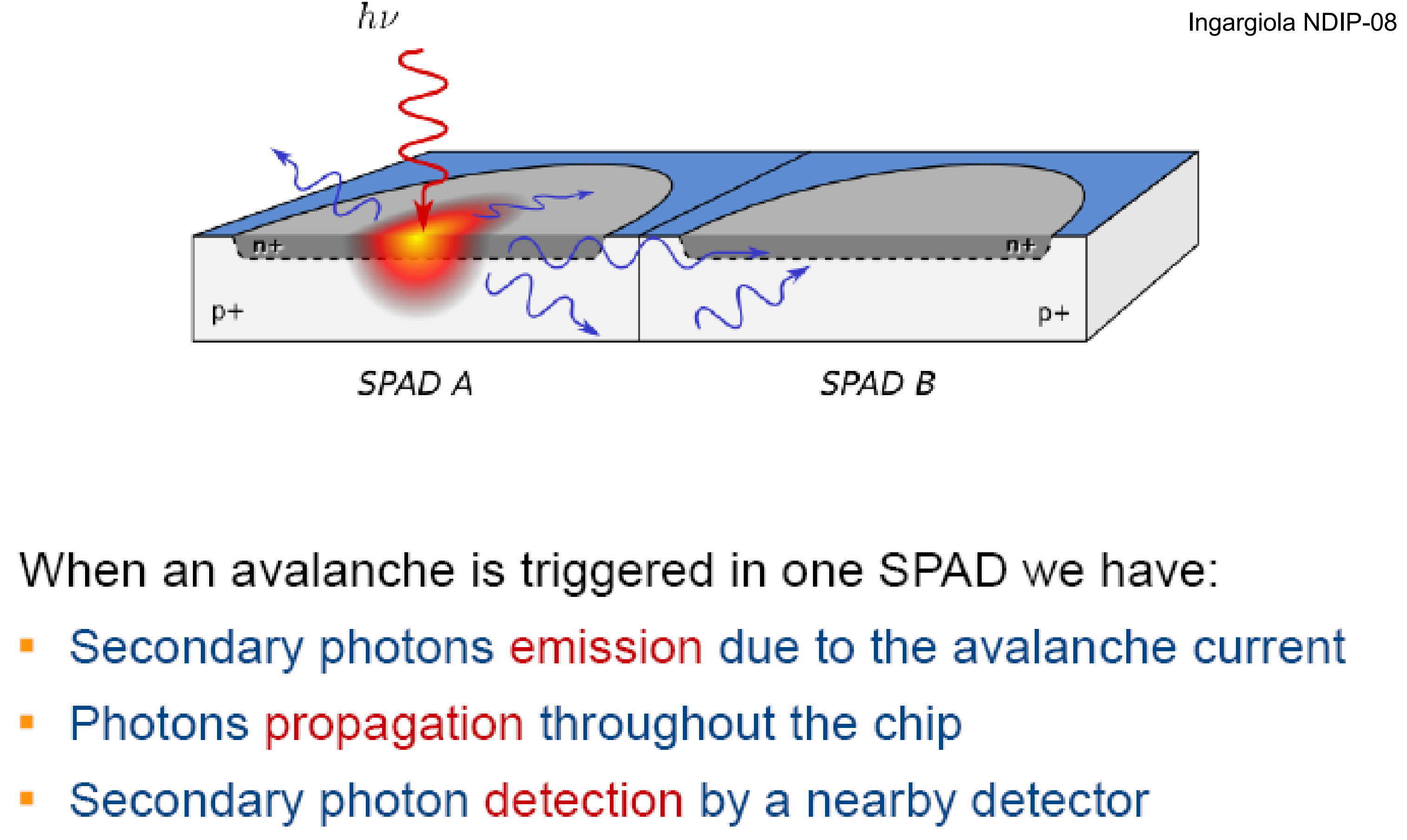


Ingargiola NDIP-08

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

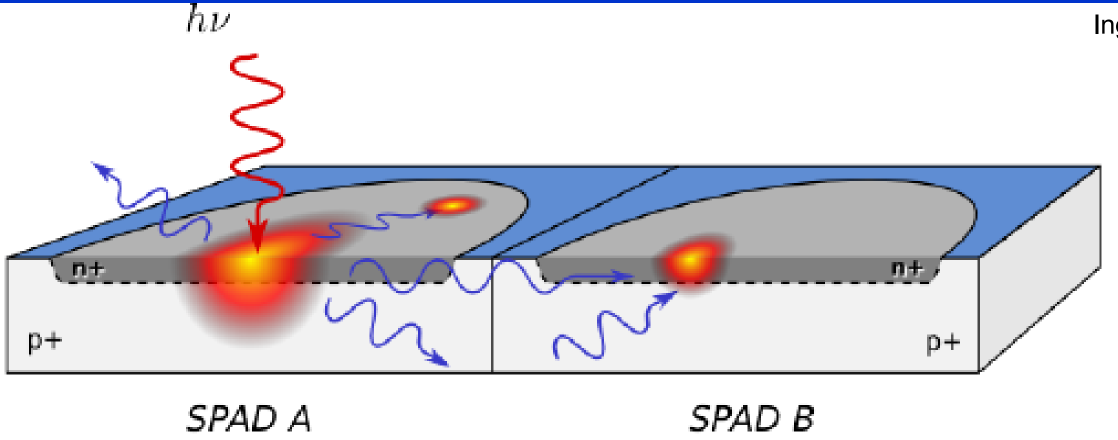


Ingargiola NDIP-08

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

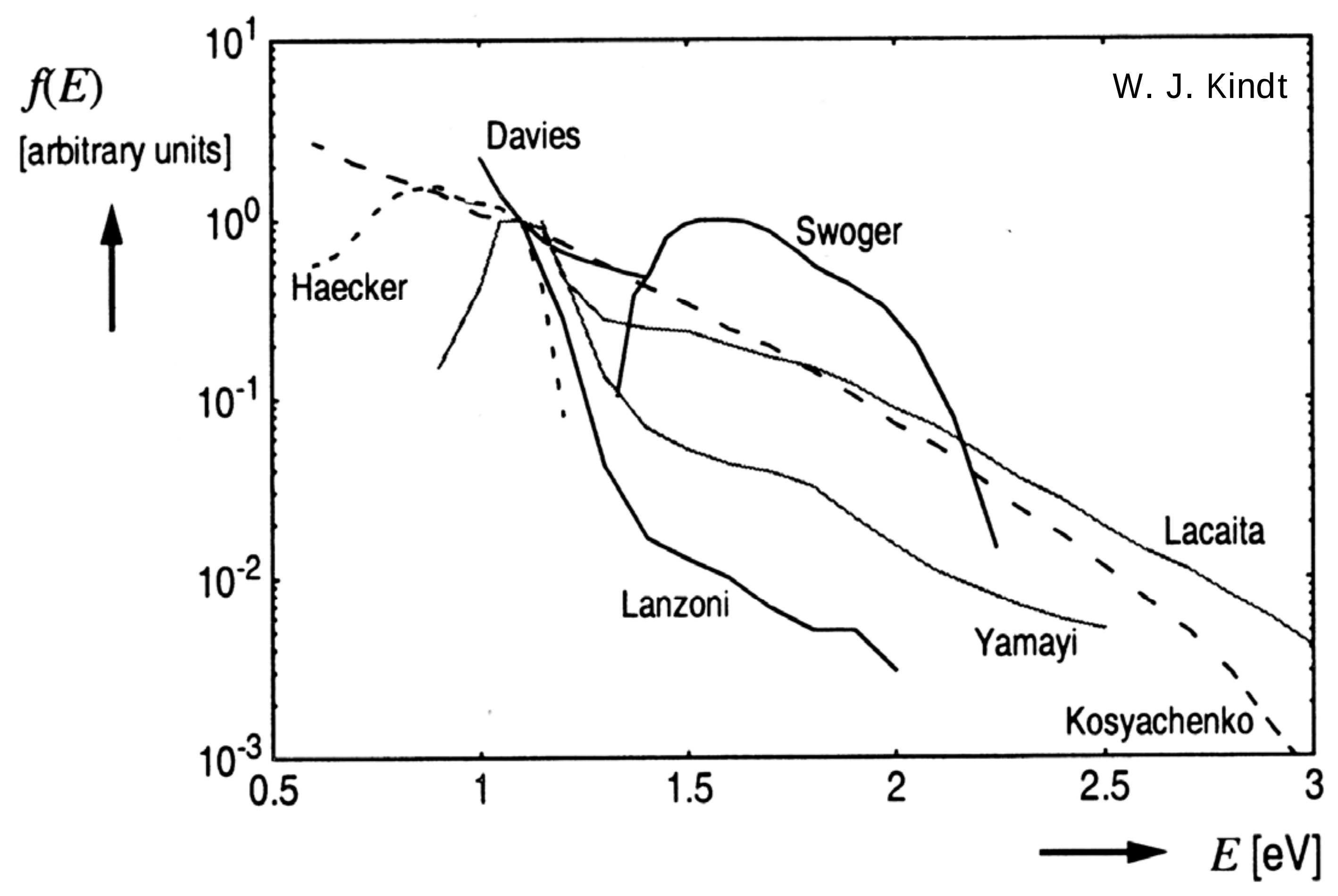


Ingargiola NDIP-08

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

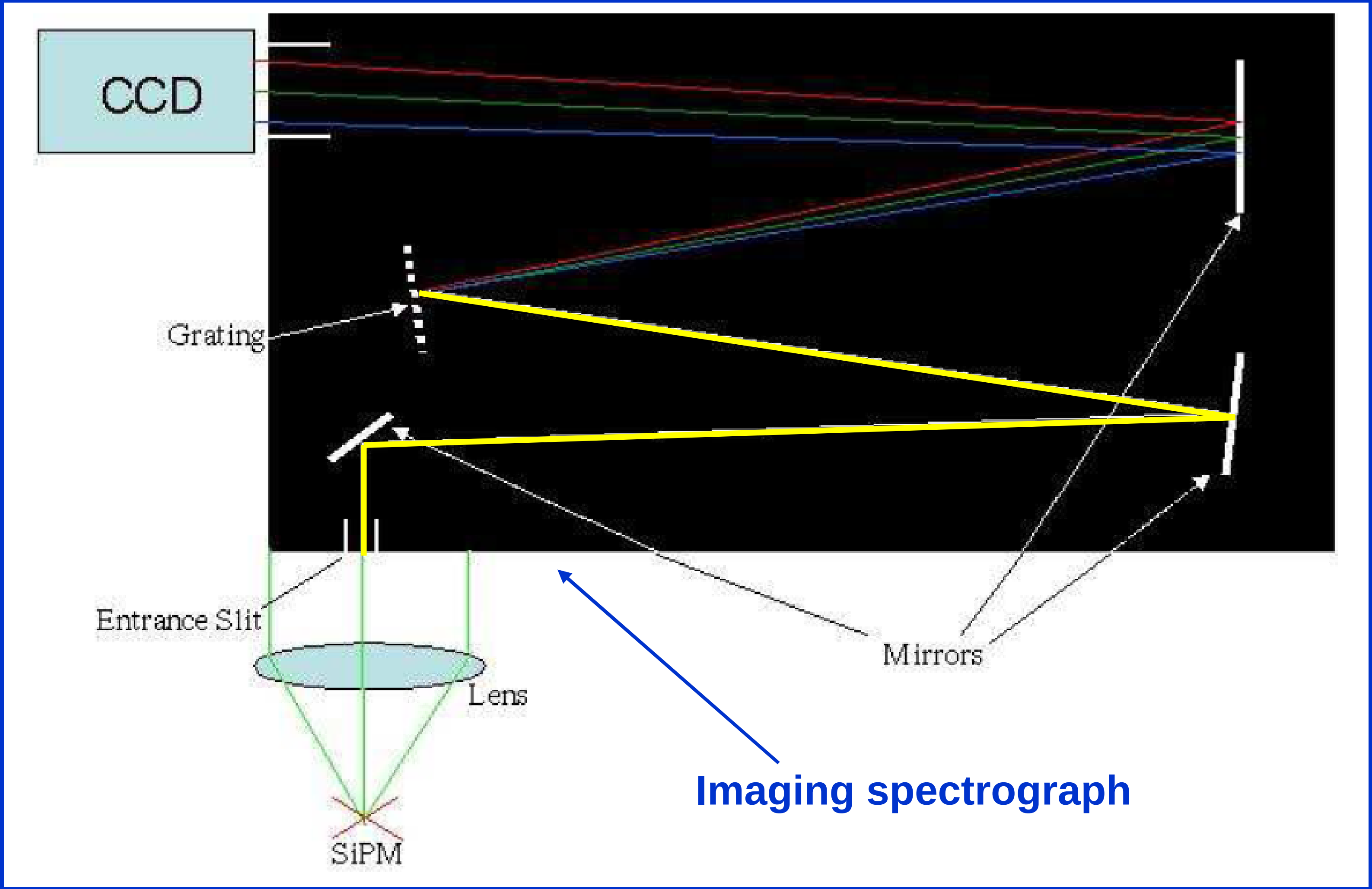
Light Emission in Si Avalanches: collection of different measurements



Our own measurements: the setup

- Components used in our setup:
  - (SiPM) MPPC *S0362-11-100U* from Hamamatsu
  - Imaging Single ph.e. Sensitive Spectrograph *Shamrock 303i* from Andor
  - CCD-camera *Idus 420 OE* for optical spectrum 450-1000nm
  - InGaAs –camera *DU490 A-1.7* from Andor for NIR spectrum 900-1700nm

Sketch of our experimental setup



Imaging spectrograph

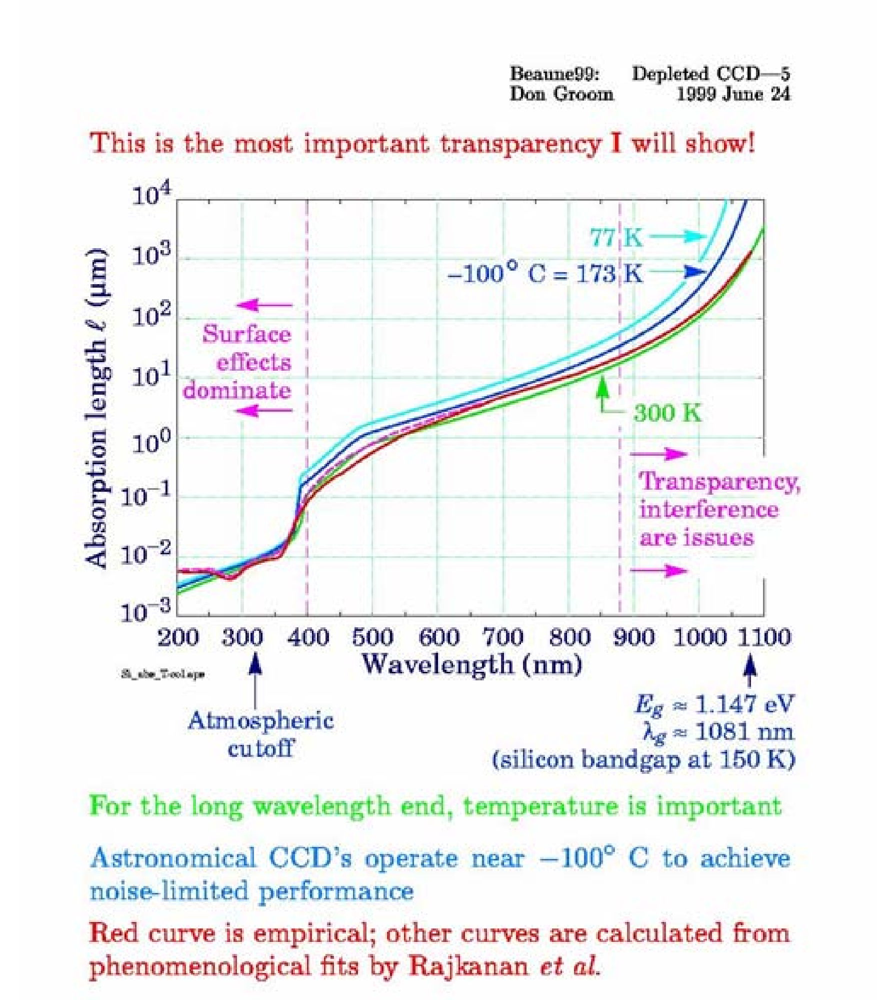
The Absolute Calibration

- It was assumed that the used MPPC had an active depth of 1.8 µm.
- The emitted light absorption in Si was simulated by using a simple Monte Carlo with a step size of 0.1 µm in depth.
- Tabulated values of the light absorption in Si were used.
- Light reflection on the interface Si-SiO_2-air taken into account.
- One-by-one LEDs were inserted in the place of the MPPC
- A calibrated PIN photo diode was inserted just behind the gap of the spectograph. The CCD calibration by the manufacturer was used.

The used for calibration LEDs

VIS LED, nm	470	520	621	700	750	810	910	1020
NIR LED, nm	910	1020	1200	1300	1450	1550	1600	1700

Reminder: light absorption in Si



Beaune99: Don Groom

Depleted CCD—5
1999 June 24

This is the most important transparency I will show!

$E_g \approx 1.147$ eV
$\lambda_g \approx 1081$ nm
(silicon bandgap at 150 K)

For the long wavelength end, temperature is important

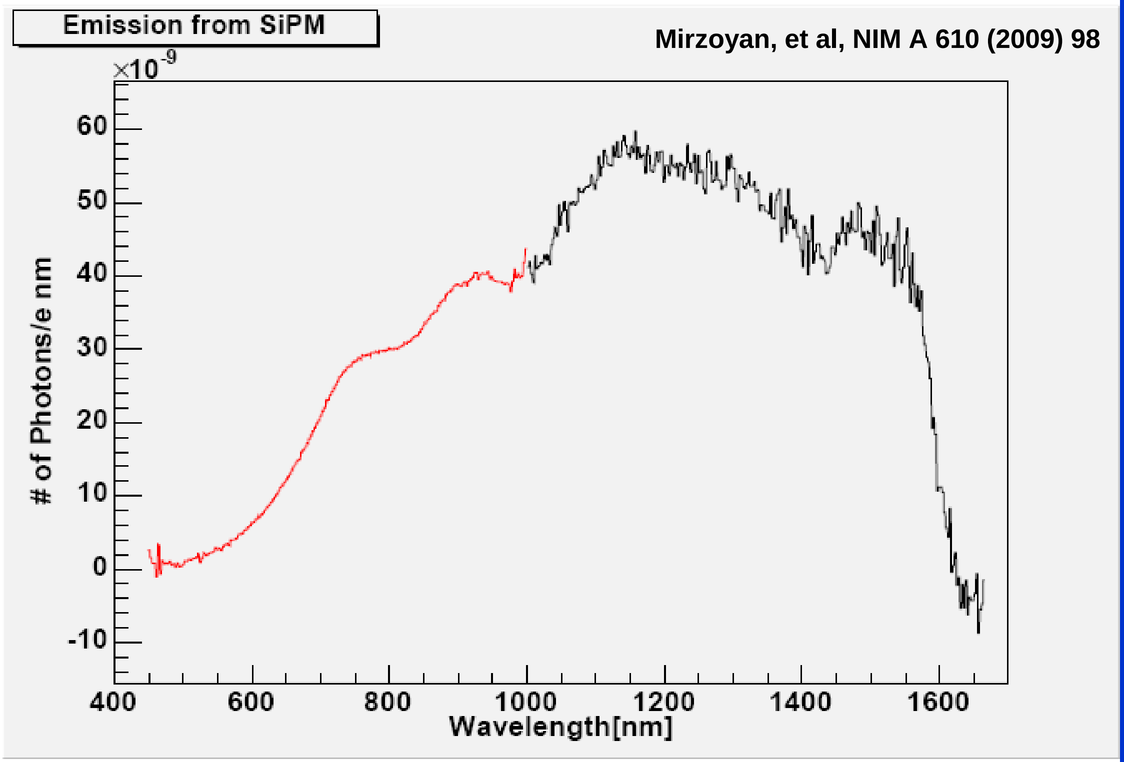
Astronomical CCD's operate near −100° C to achieve noise-limited performance

Red curve is empirical; other curves are calculated from phenomenological fits by Rajkanan *et al.*

- 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 (>700 nm)

Measured differential emission spectrum



The largest error is ≤ 19.7 % for the „worst“ wavelength range < 600 nm

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

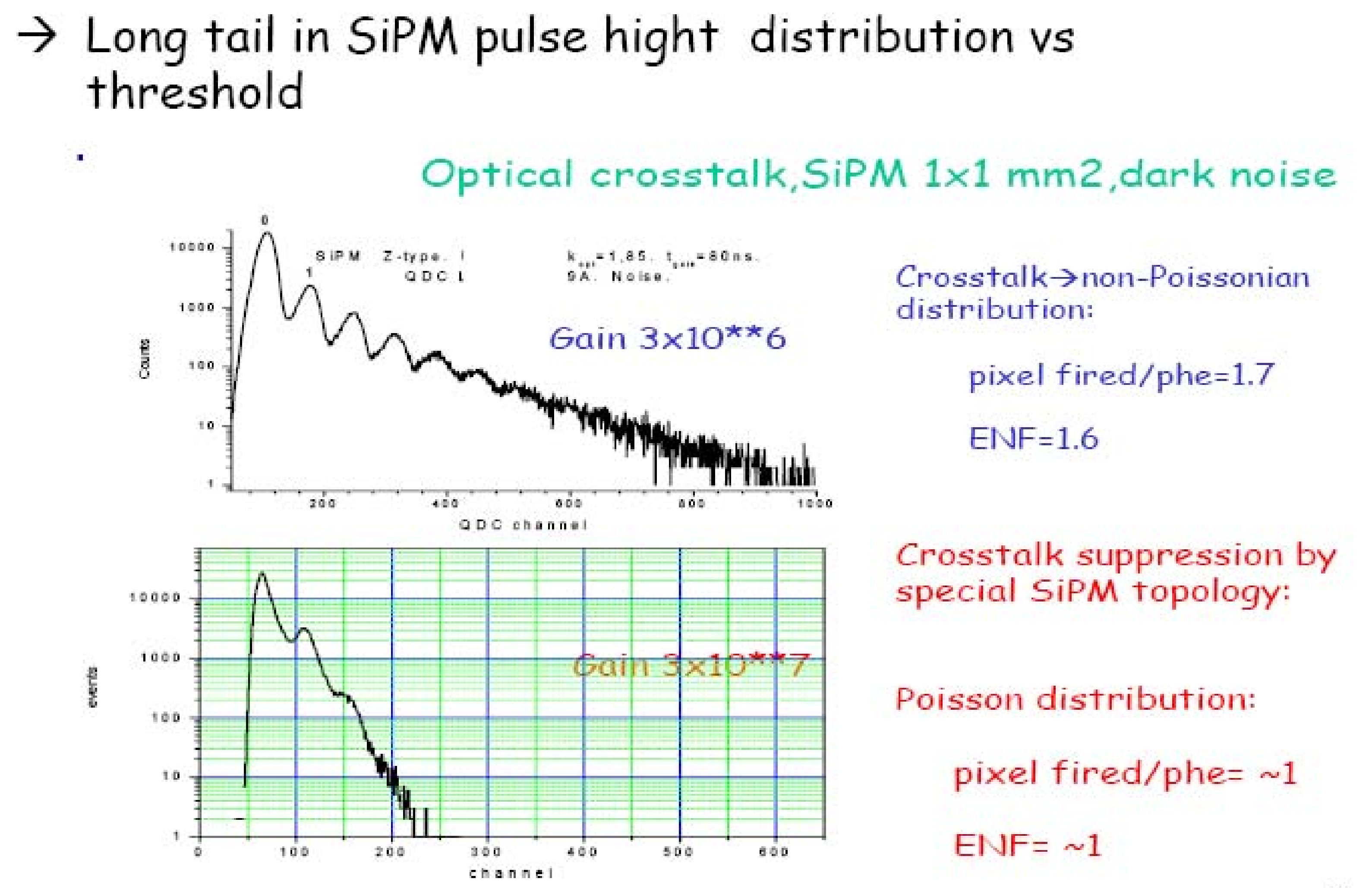
Possible emission mechanisms

Akil et al., 1999, Villa et al., 1995, Bude et al., 1992, …

- Interband transitions between hot e- and holes
- Direct intraband e- transitions, Bremsstrahlung radiation from hot e- scattered by charged coulombic centers, and phonon-assisted e- transitions
- Ionization and indirect interband recombination of e- and holes under high-field conditions
- Intraband transitions of hot holes between the light and heavy-mass valence bands

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

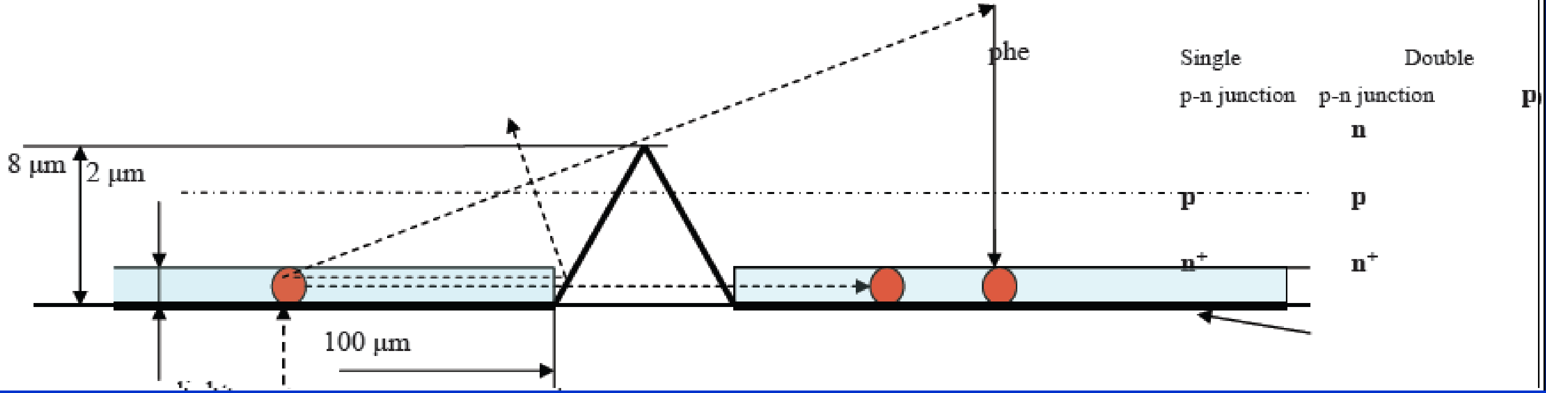
OC has two components

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

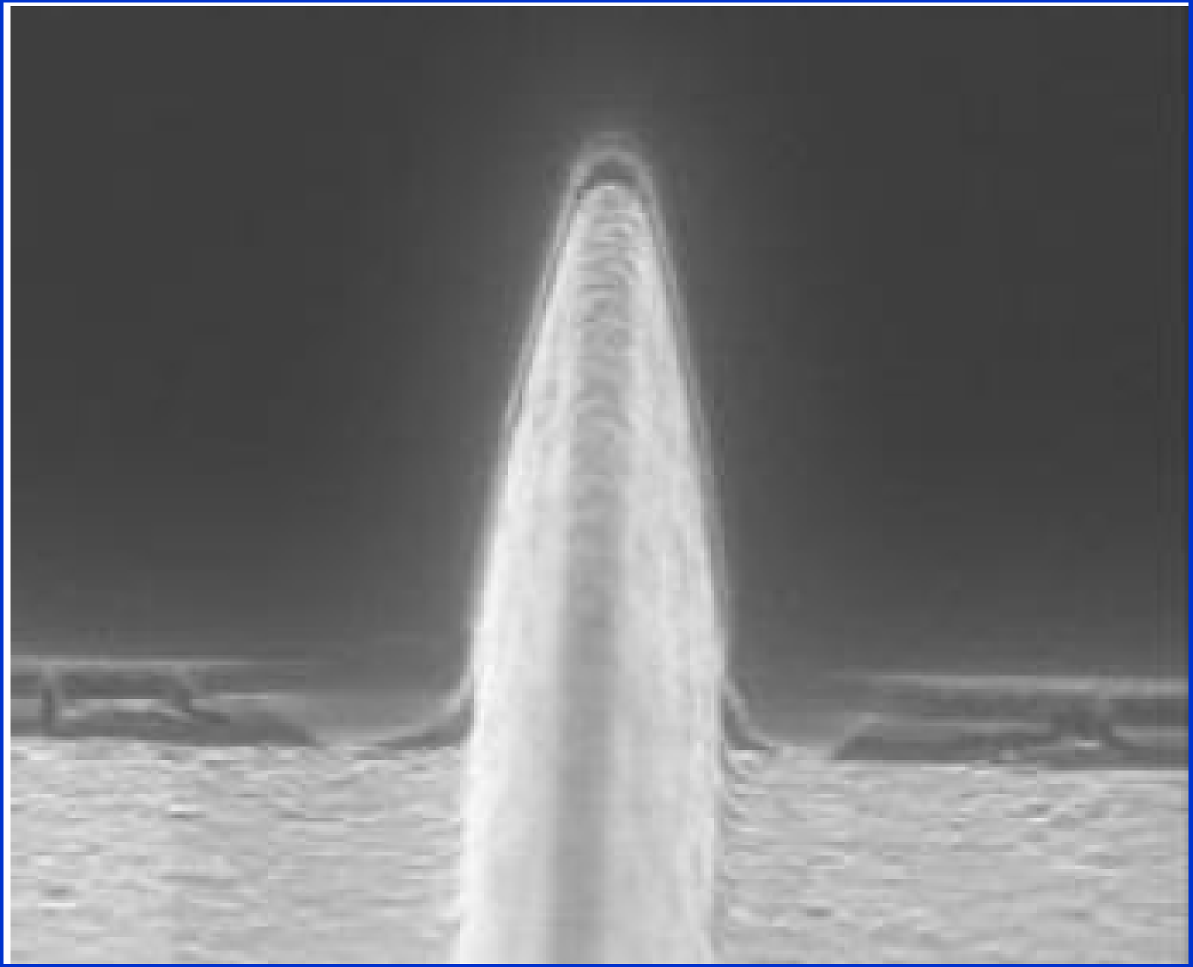
→this mechanism is very fast: ~1ns(prompt OC)

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

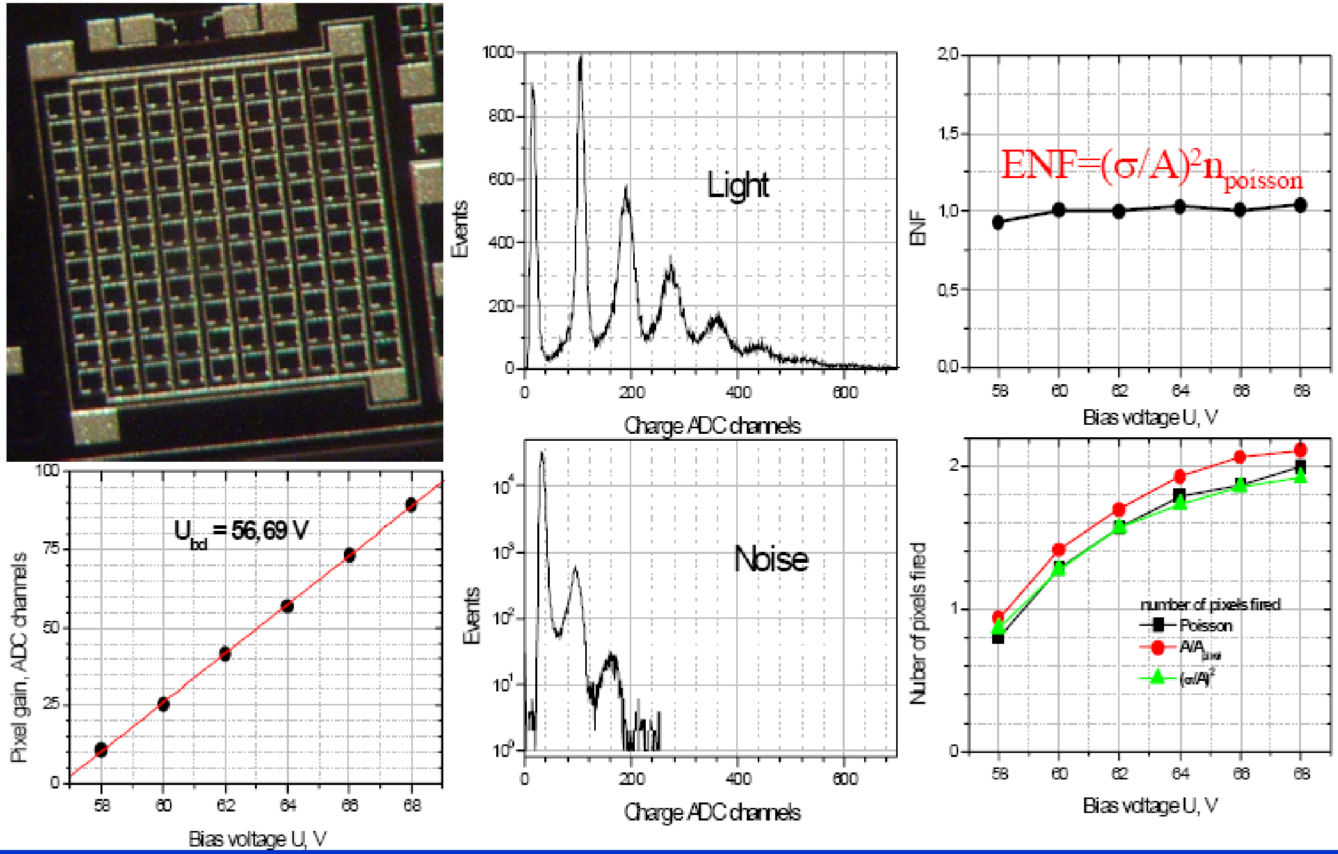
→this process is delayed: later than 1ns



A filled in trench

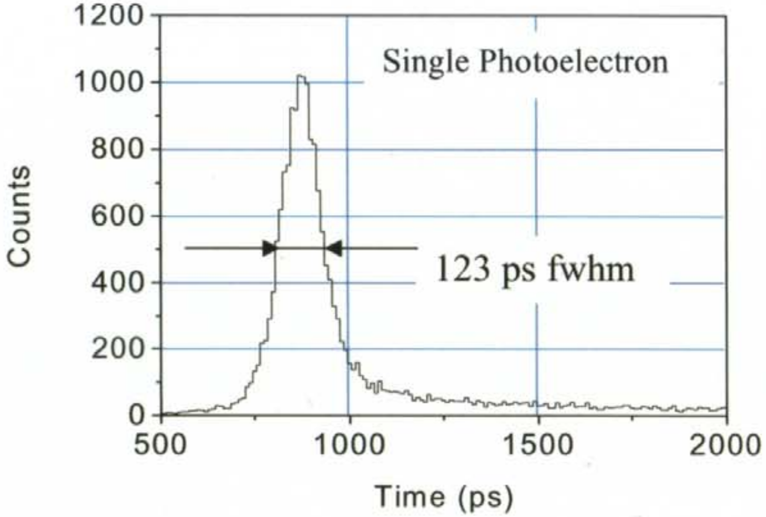


First step: SiPM 1.4x1.4 mm2 with OC suppression topology

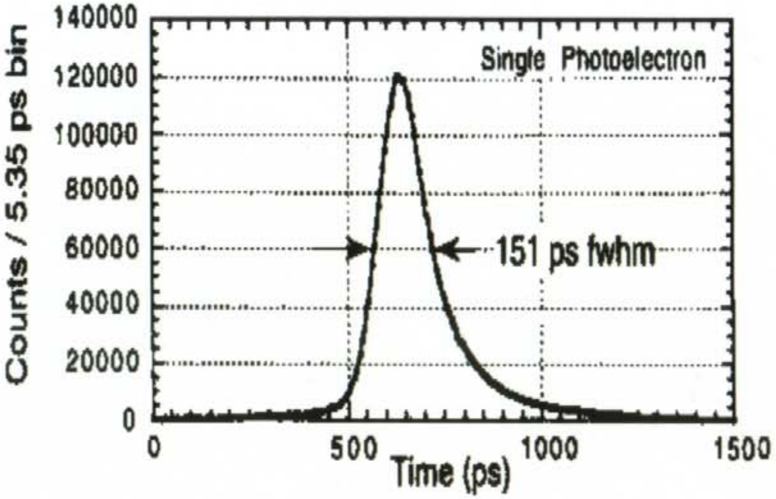


Timing by SiPM: possible application for Cherenkov Imaging Counters

SiPM



PMT R-5320

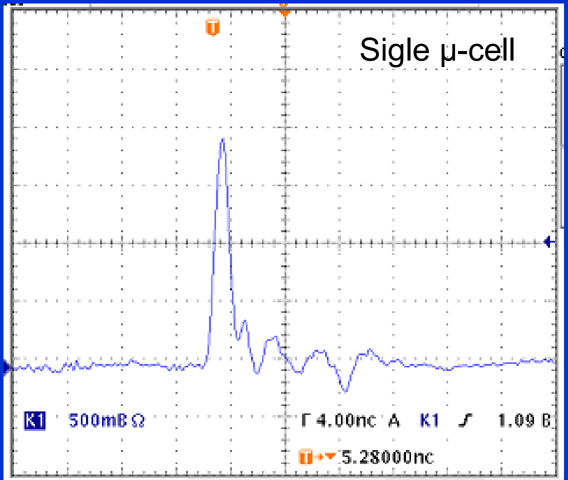


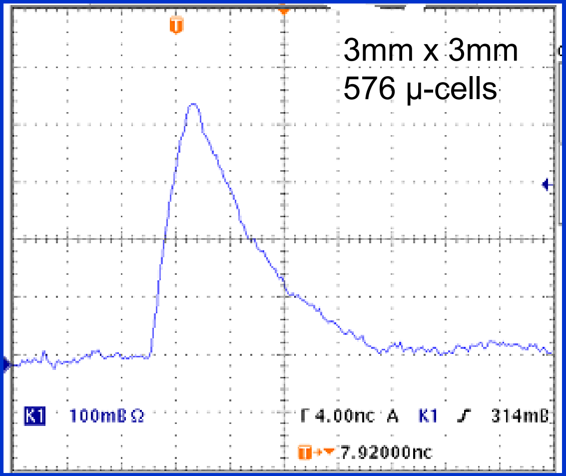
SiPM:

- 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)

Pulse width depends on the SiPM chip size

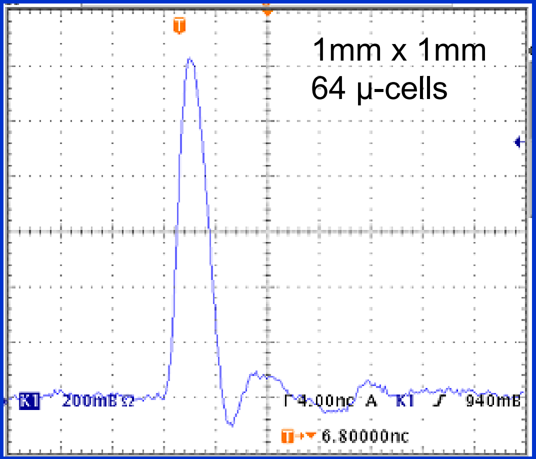

Sigle μ-cell

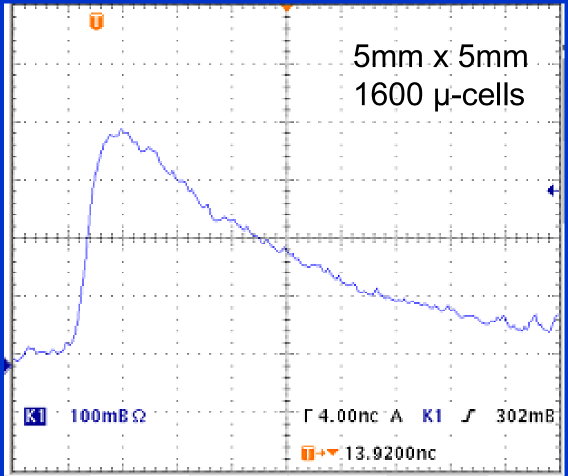

3mm x 3mm
576 μ-cells

A single ph.e. pulse shape for different SiPMs

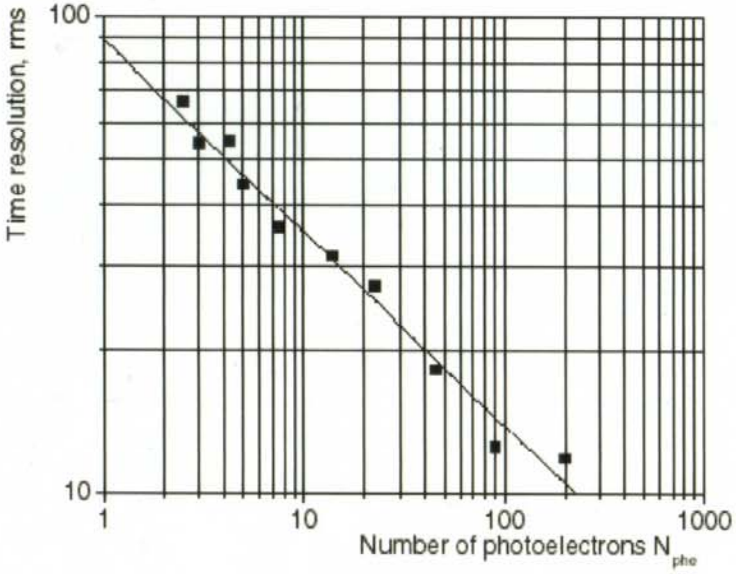
All tested devices had μ-cell size of 100μm x 100μm

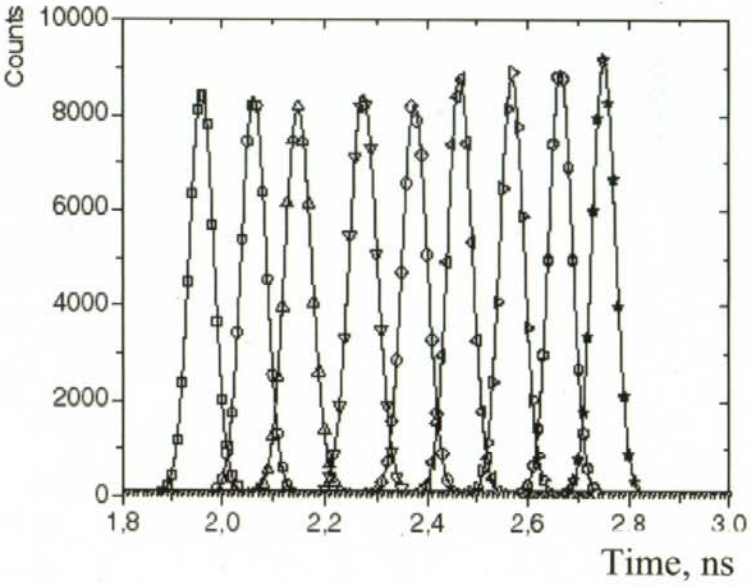
Operated under gain: 10^7


1mm x 1mm
64 μ-cells


5mm x 5mm
1600 μ-cells

SiPM time resolution

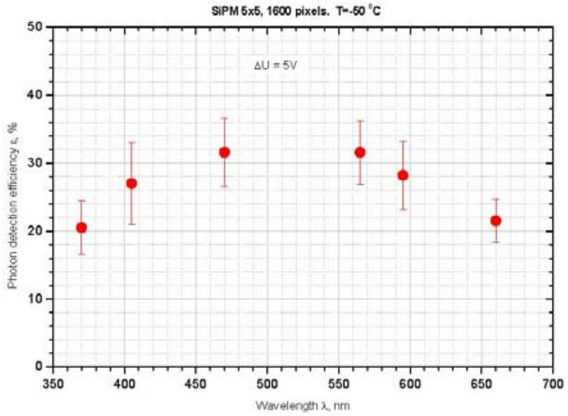




Second step: 5x5mm2 SiPM with OC and AP suppression

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



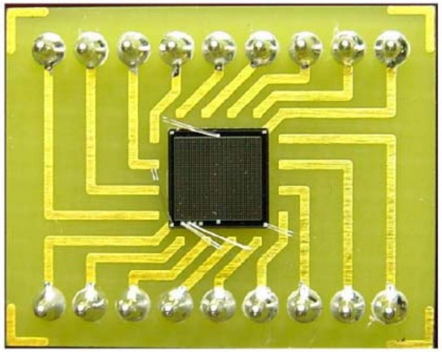


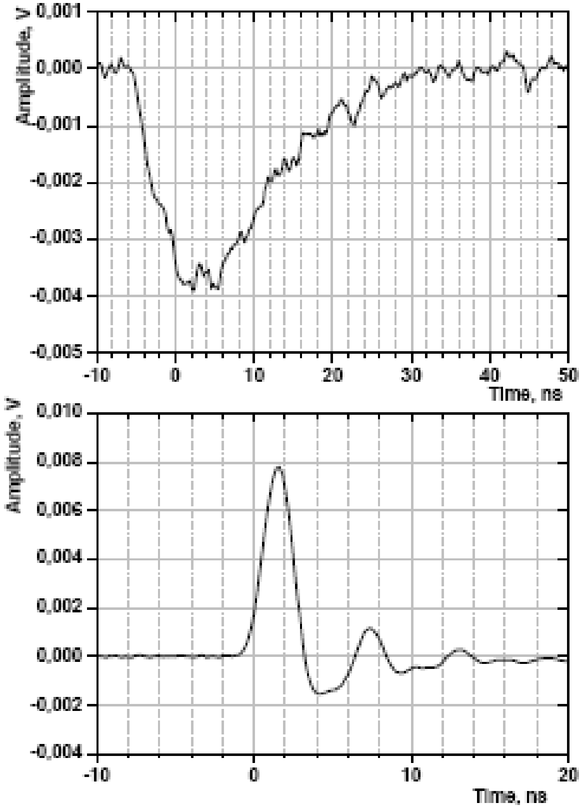
Figure 3: $25(5 \times 5)mm^2$ SiPM. It consists of the array of $1600(40 \times 40)$ micropixels with $100 \times 100\mu m^2$ size.

Timing by 5x5mm2 SiPM: signal shape

➔ Because high SiPM output capacitance (~160pF)

a special FE electronics has been developed:

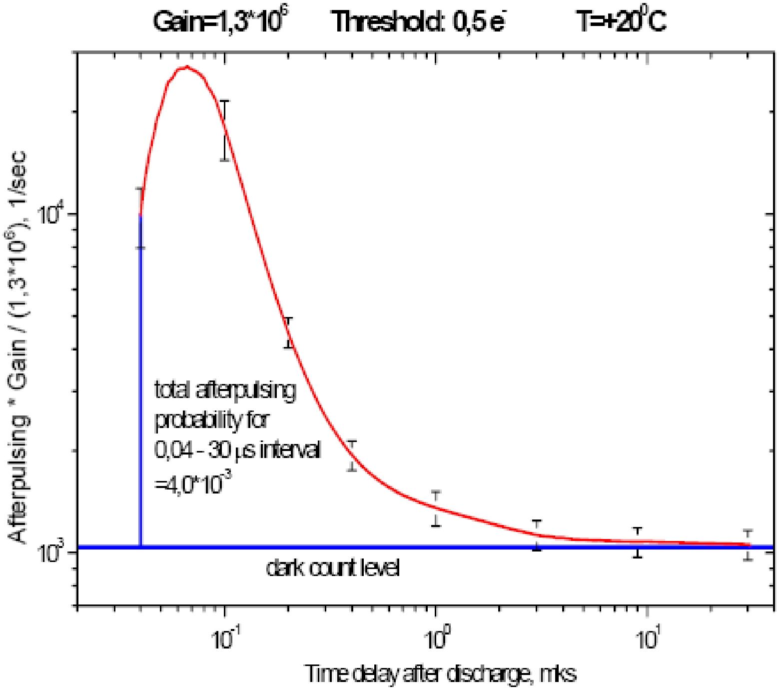
low imput impedance(a few Ohm) current amplifier+shaper



50 Ohm
FWHM
15ns

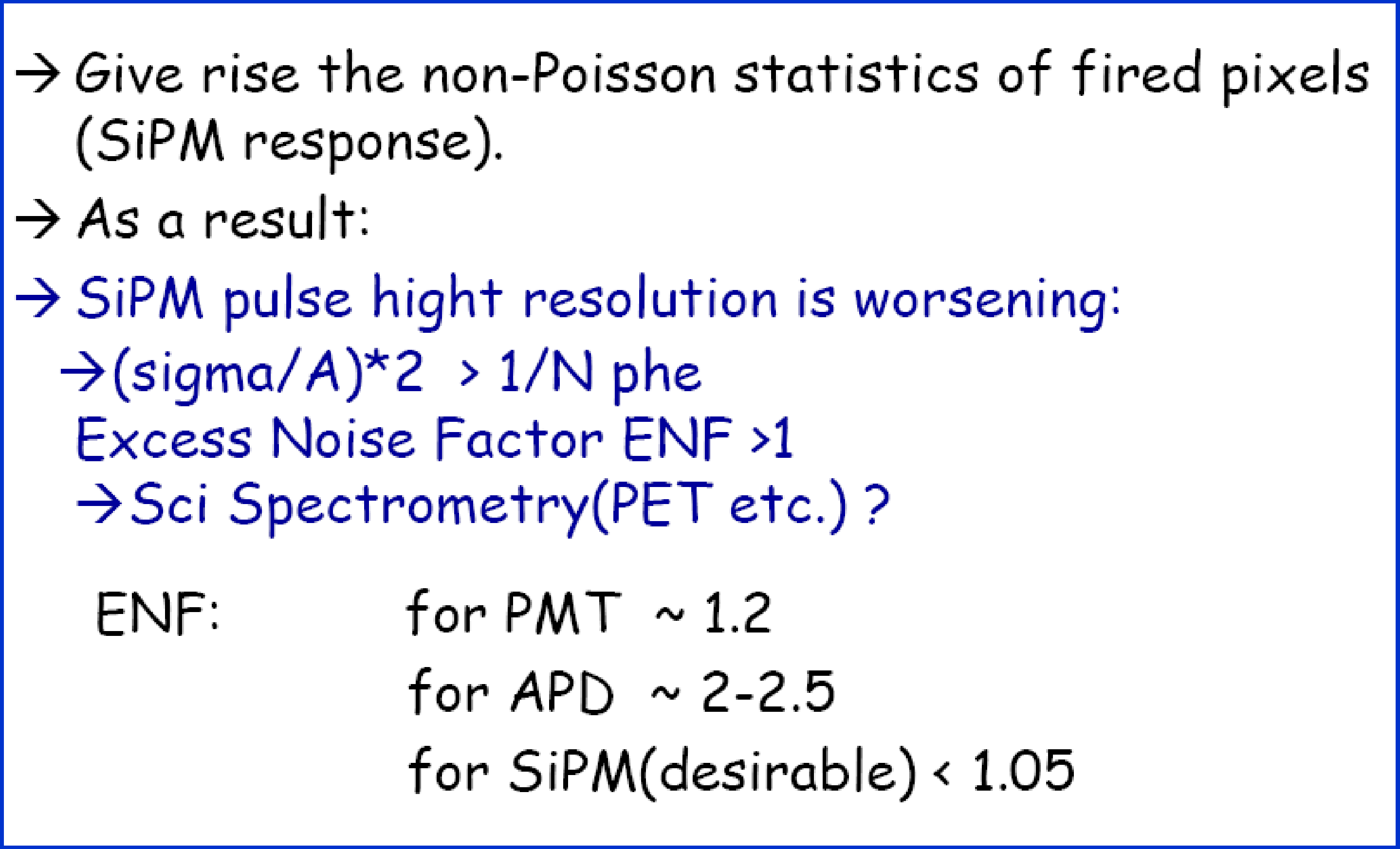
~ 7 Ohm
+shaper
FWHM
2,5ns

→ 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



→ 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

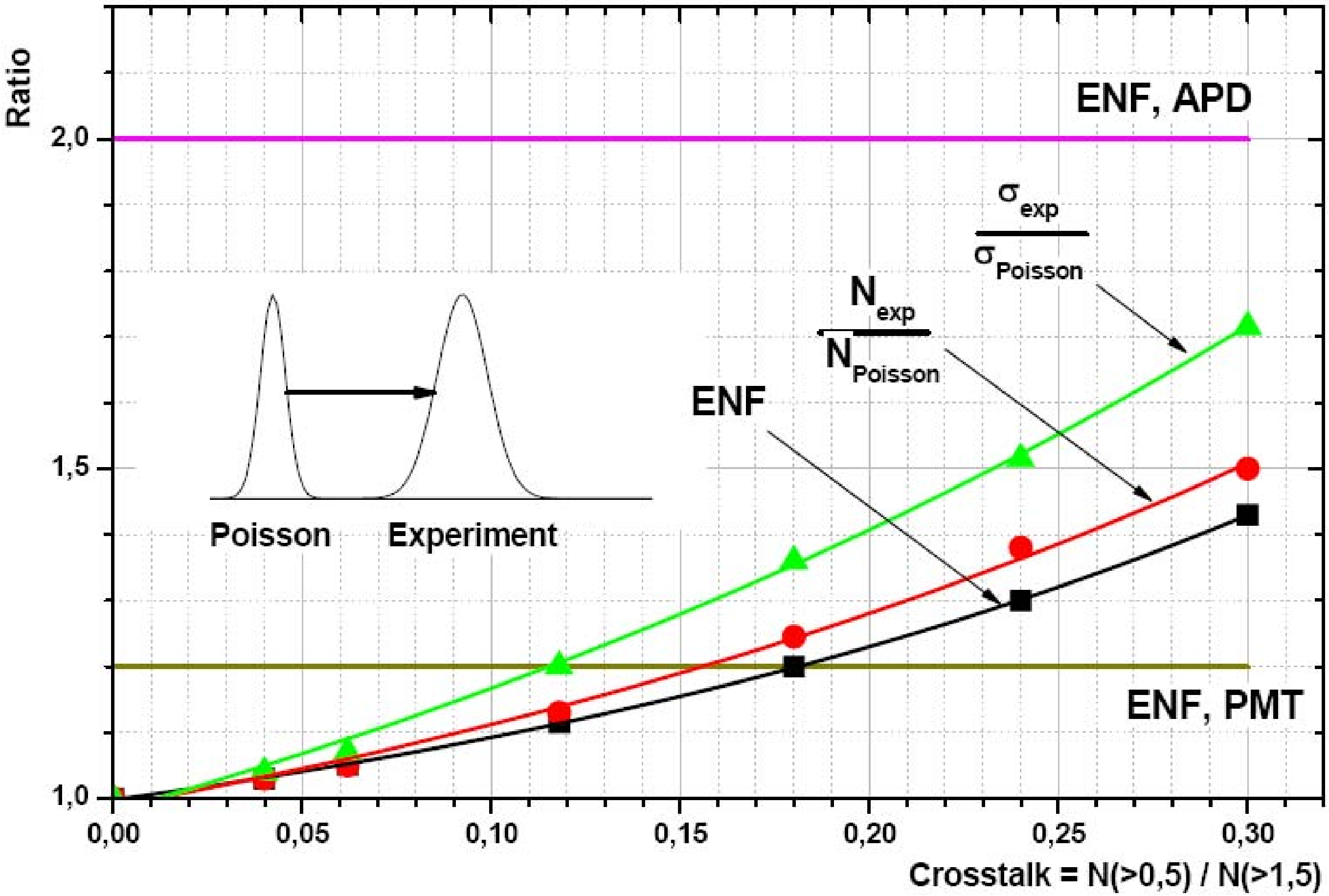
Excess Noise Factor ENF >1

→Sci Spectrometry(PET etc.) ?

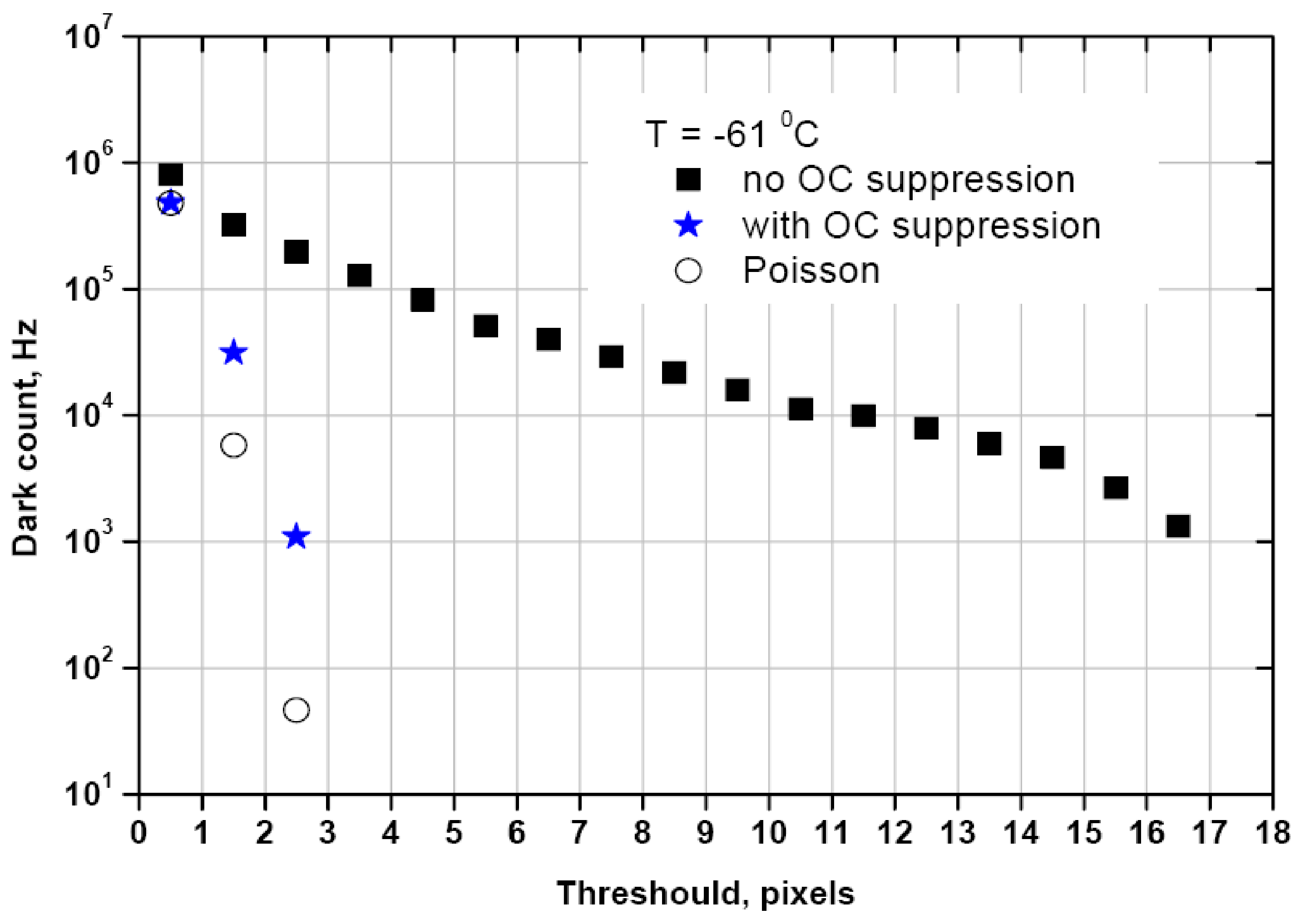
ENF: for PMT ~ 1.2

for APD ~ 2-2.5

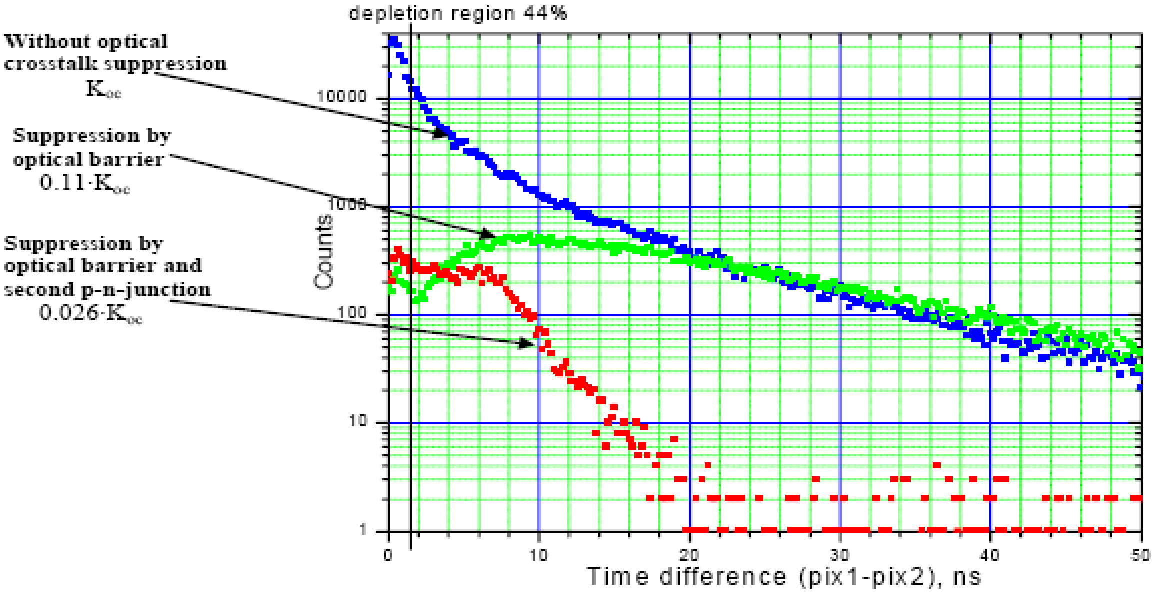
for SiPM(desirable) < 1.05

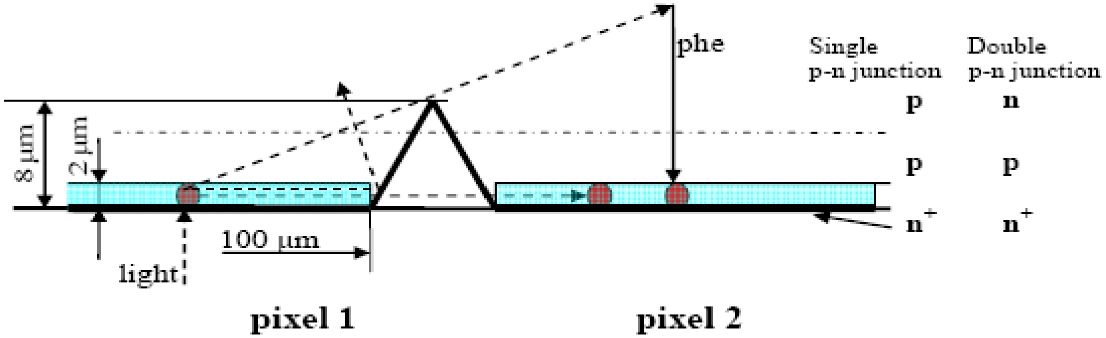

Ratio
2,0
1,5
1,0
0,00
0,05
0,10
0,15
0,20
0,25
0,30
Crosstalk = N(>0,5) / N(>1,5)
ENF, APD
$\frac{\sigma_{exp}}{\sigma_{Poisson}}$
$\frac{N_{exp}}{N_{Poisson}}$
ENF
ENF, PMT
Poisson
Experiment

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

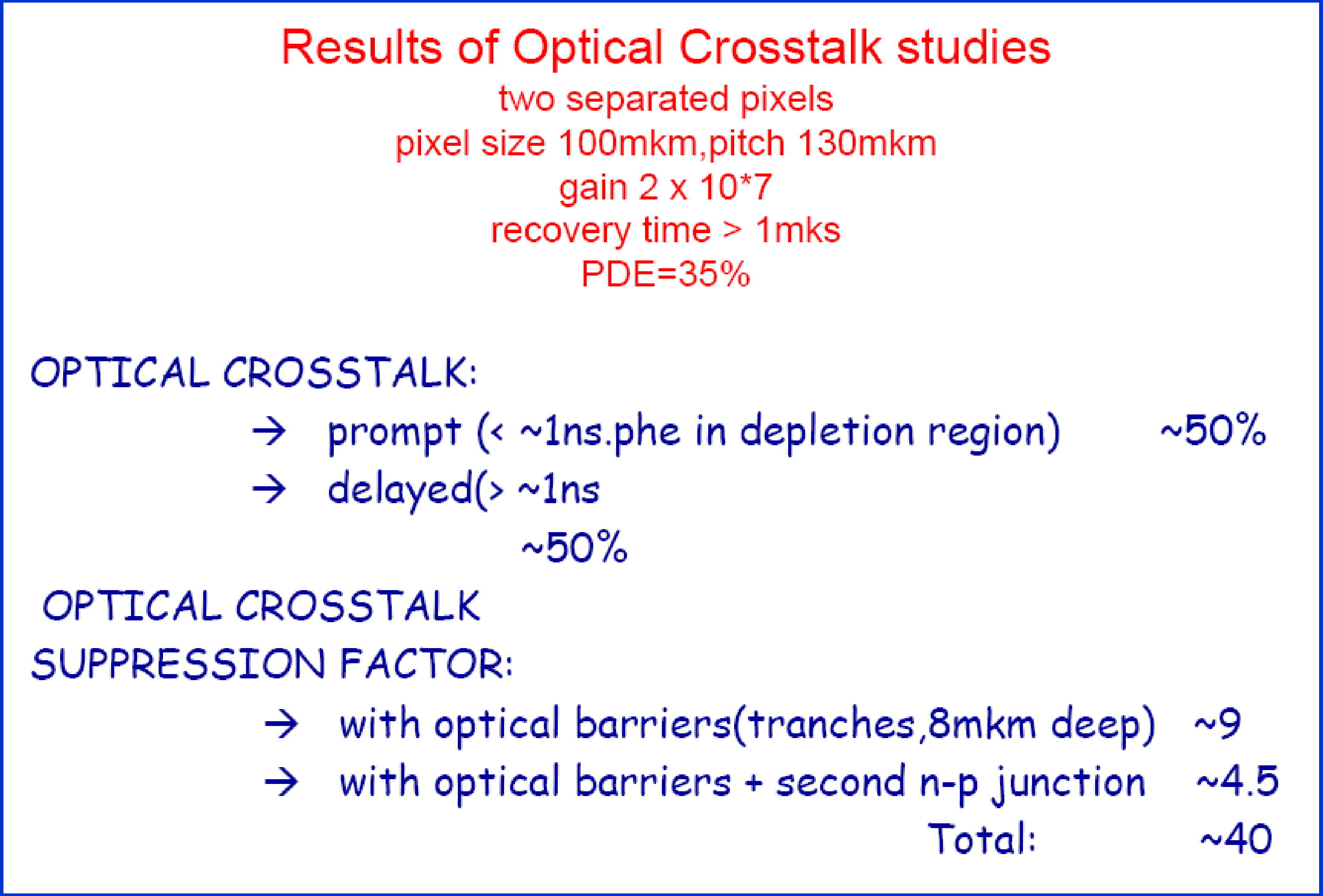


Optical Crosstalk studies





Optical crosstalk between two separate pixels



Results of Optical Crosstalk studies

two separated pixels
pixel size 100mkm,pitch 130mkm
gain 2 x 10*7
recovery time > 1mks
PDE=35%

OPTICAL CROSSTALK:

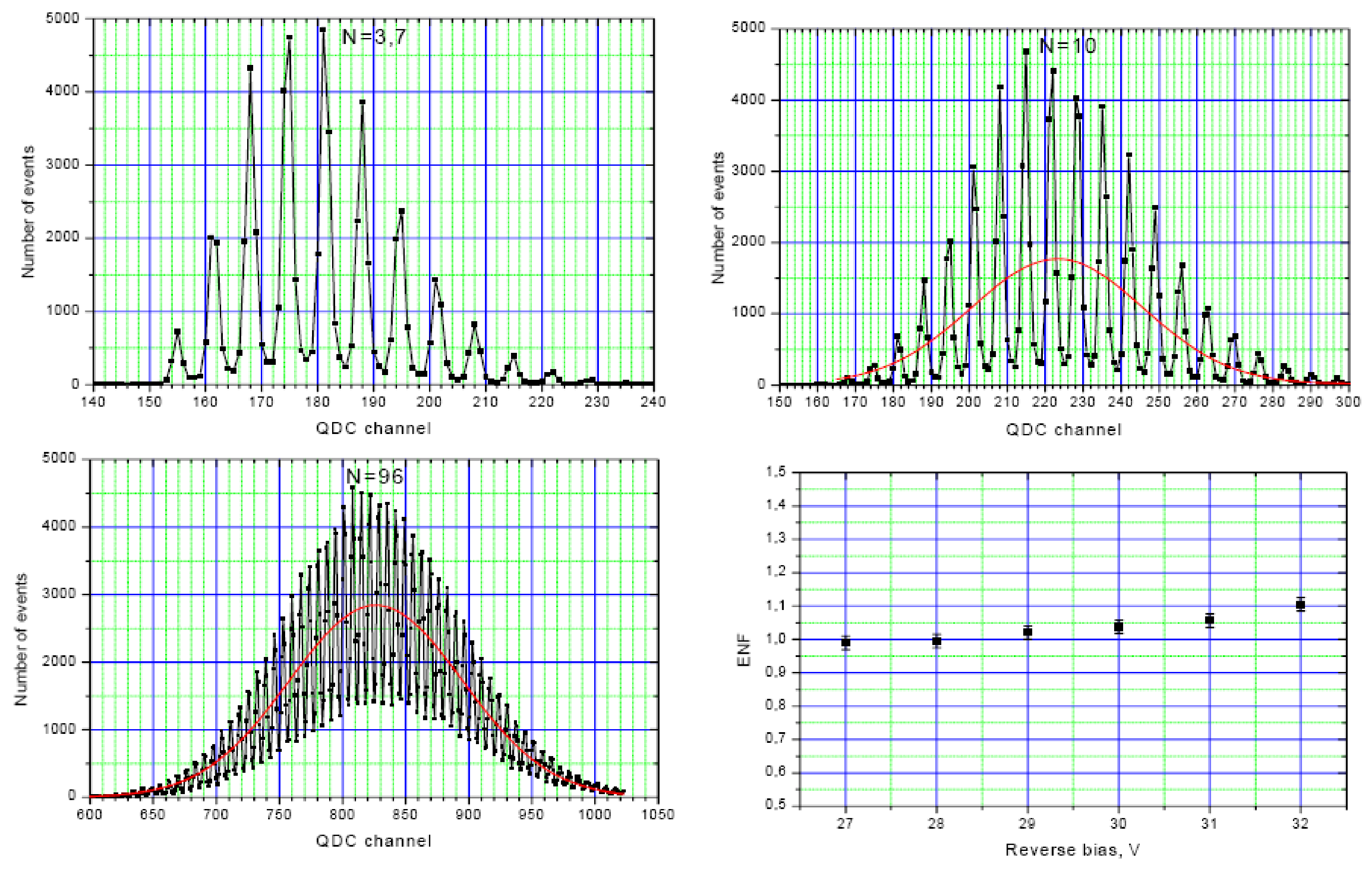
- → prompt (< ~1ns.phe in depletion region) ~50%
- → delayed(> ~1ns
  ~50%

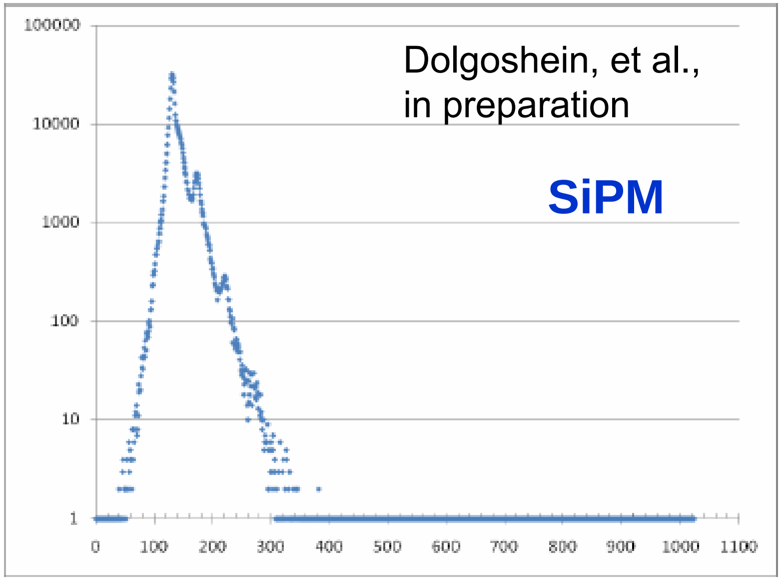
OPTICAL CROSSTALK
SUPPRESSION FACTOR:

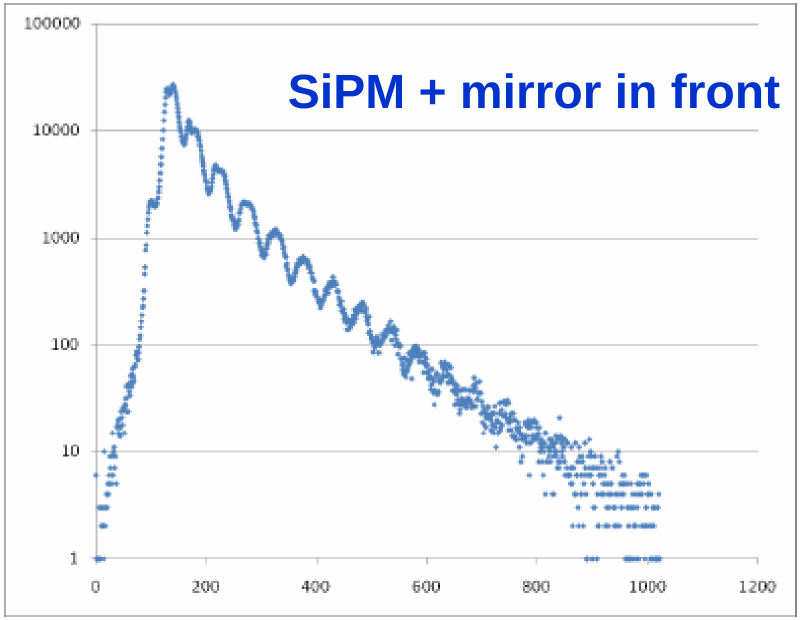
- → with optical barriers(tranches,8mkm deep) ~9
- → with optical barriers + second n-p junction ~4.5

Total: ~40

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





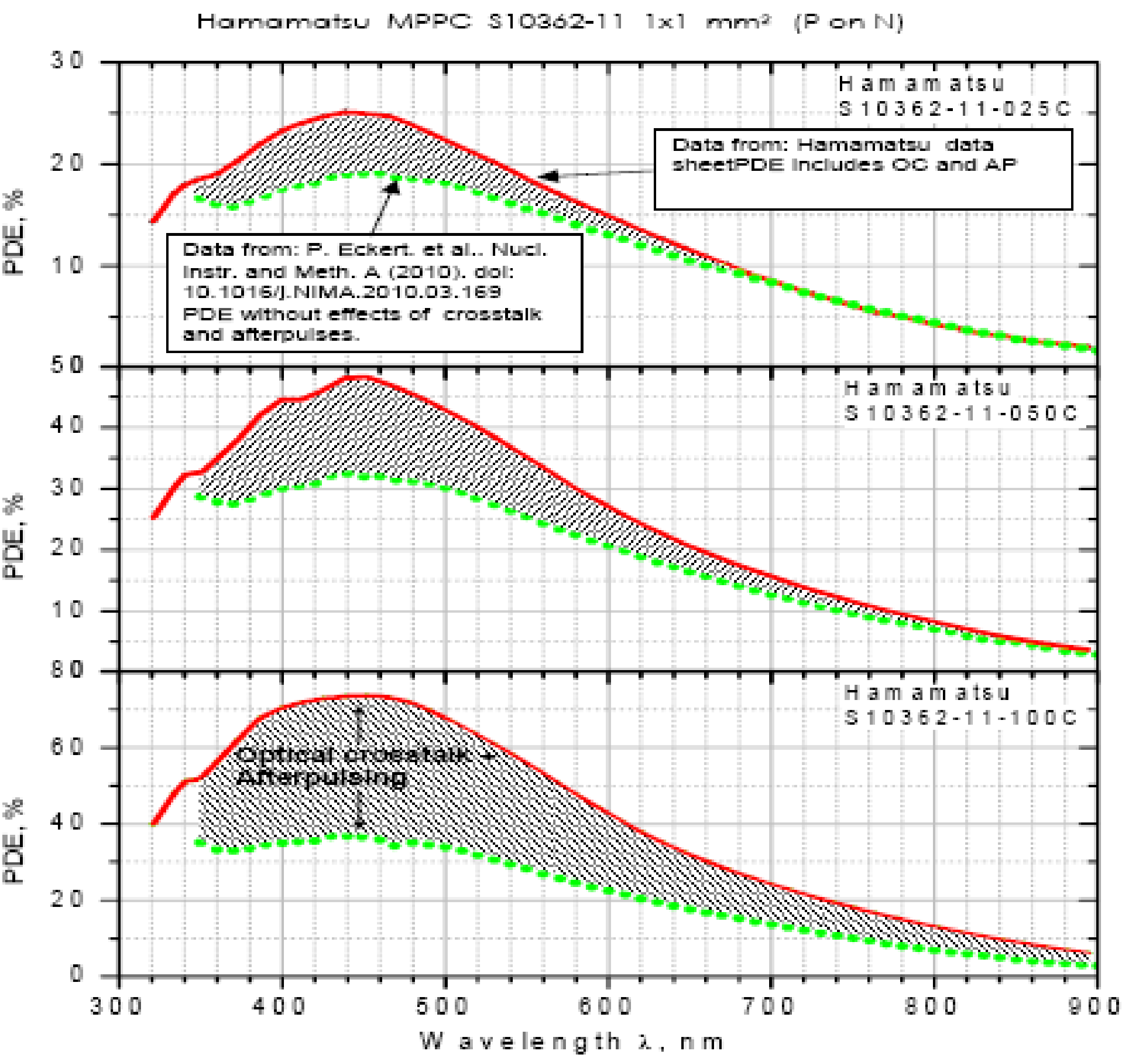


- A curious experiment: what will happens if one will hold a mirror in front of a SiPM ?

- 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)

High optical cross-talk and afterpulsing: that’s why the advertised by Hamamatsu PDE for MPPCs (red) differ from measured ones (green)


Hamamatsu MPPC S10362-11 1x1 mm² (P on N)

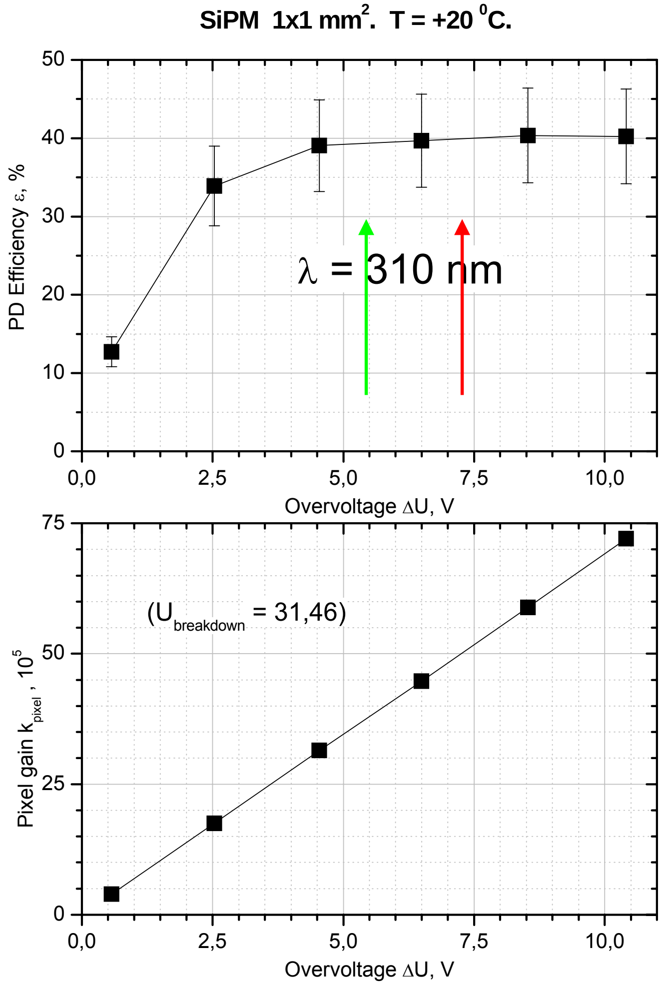
Data from: Hamamatsu data sheetPDE includes OC and AP

Data from: P. Eckert. et al.. Nucl. Instr. and Meth. A (2010). doi: 10.1016/J.NIMA.2010.03.169 PDE without effects of crosstalk and afterpulses.

Optical crosstalk + Afterpulsing

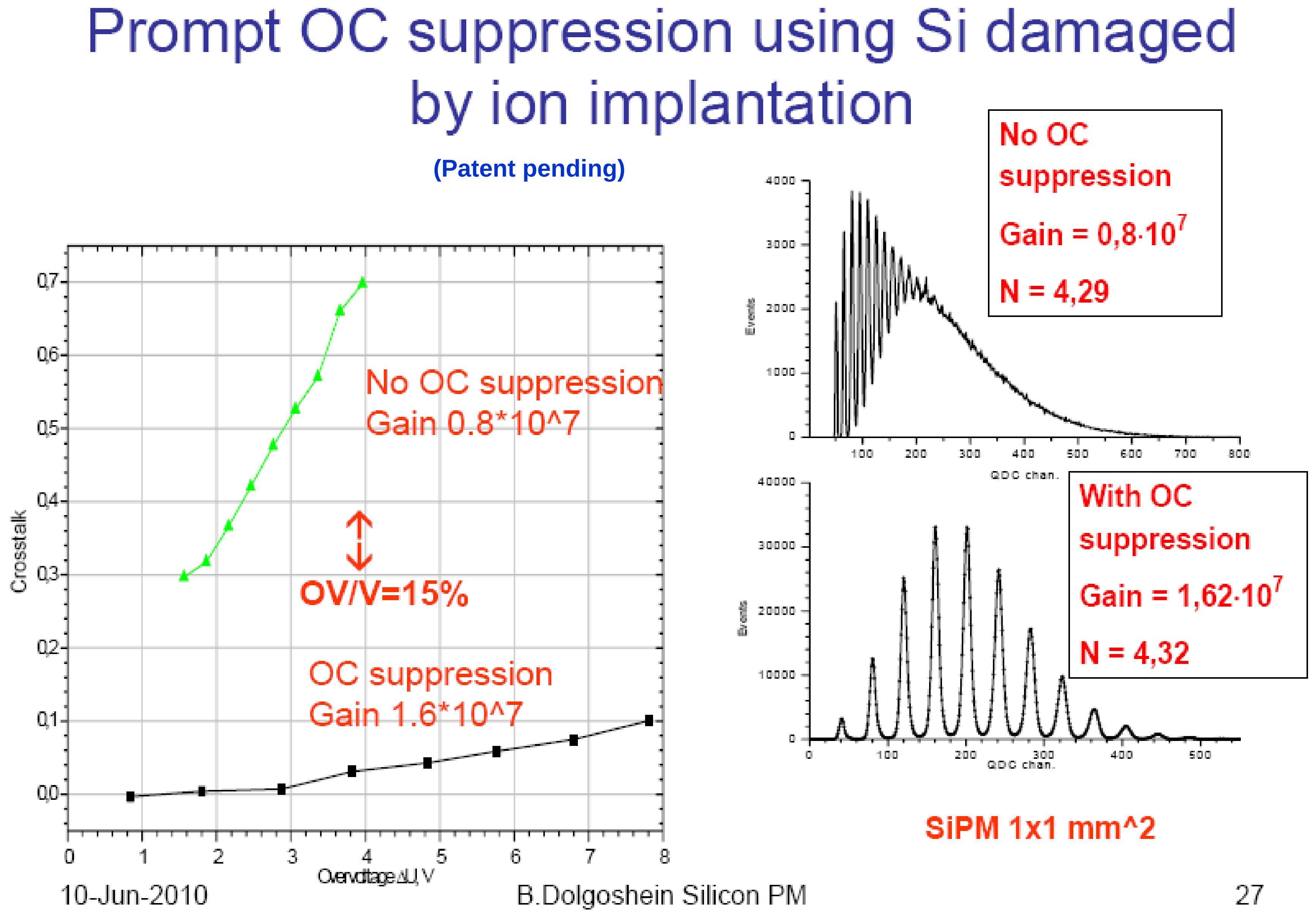
A PDE and gain of a 1x1 mm² SiPM produced by PEI measured at +20°C

Overvoltage = operational voltage – breakdown voltage



→ Overvoltage +15%

→ Overvoltage +20%



Prompt OC suppression using Si damaged by ion implantation

(Patent pending)

No OC suppression
Gain 0.8*10^7

OV/V=15%

OC suppression
Gain 1.6*10^7

No OC suppression

Gain = $0{,}8\cdot10^7$

N = 4,29

With OC suppression

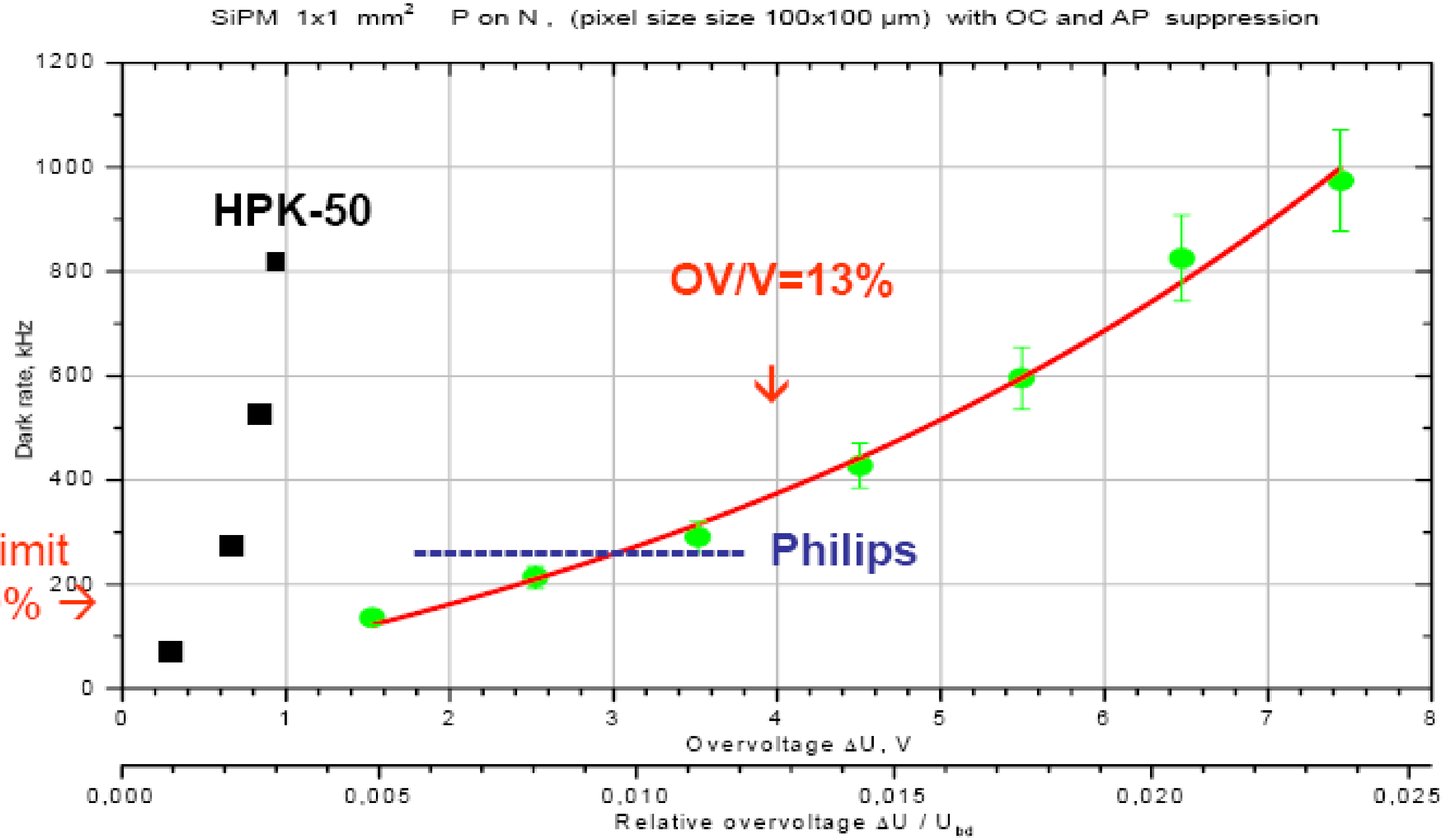
Gain = $1{,}62\cdot10^7$

N = 4,32

SiPM 1x1 mm^2

10-Jun-2010 B.Dolgoshein Silicon PM 27

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



Physical limit
PDE=100% →
Room T

OV/V x 0.1

Digital SiPM

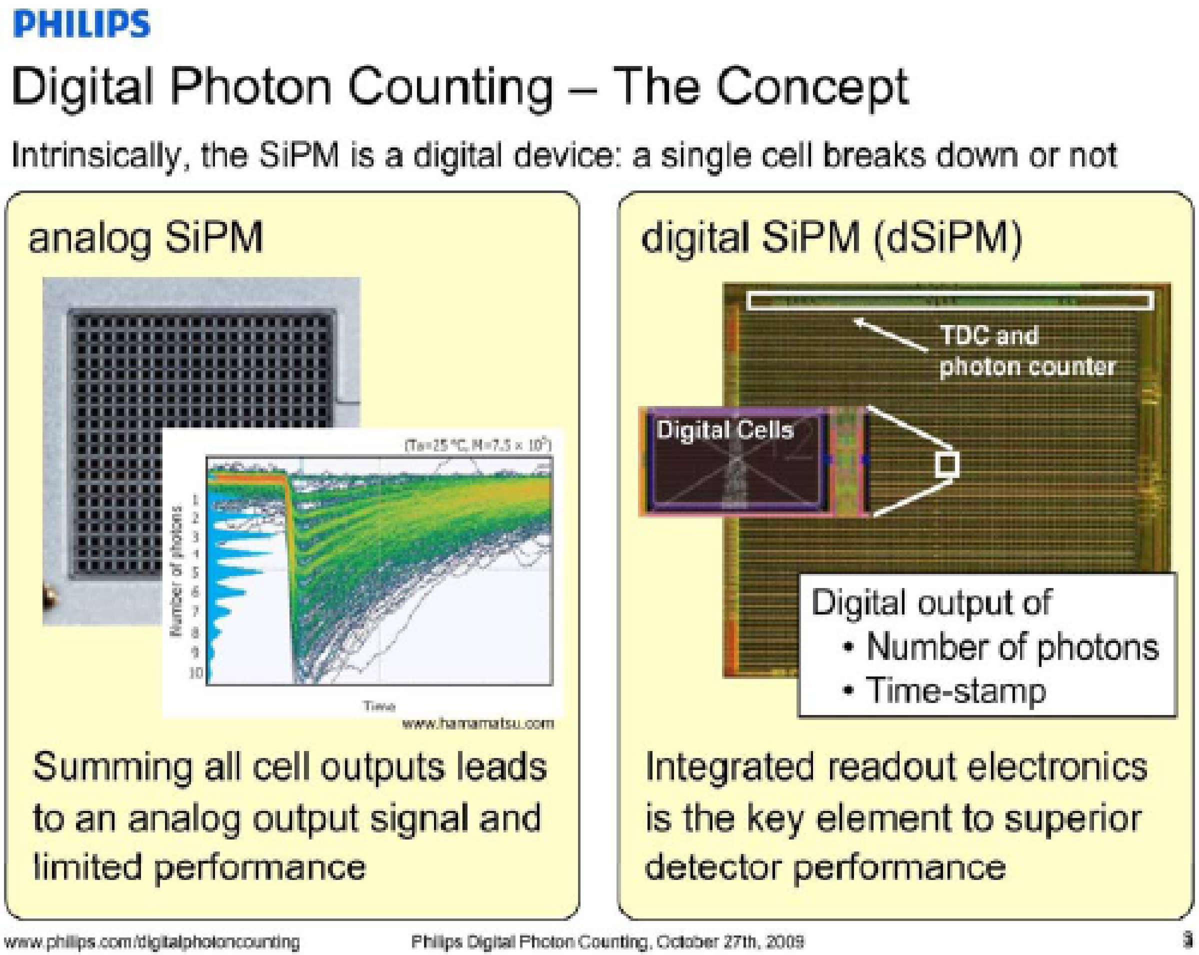
→single pixel dark count rate is lower by factor of 1.5-2 (~physical limit)

→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?



PHILIPS

Digital Photon Counting – The Concept

Intrinsically, the SiPM is a digital device: a single cell breaks down or not

analog SiPM

Summing all cell outputs leads to an analog output signal and limited performance

digital SiPM (dSiPM)

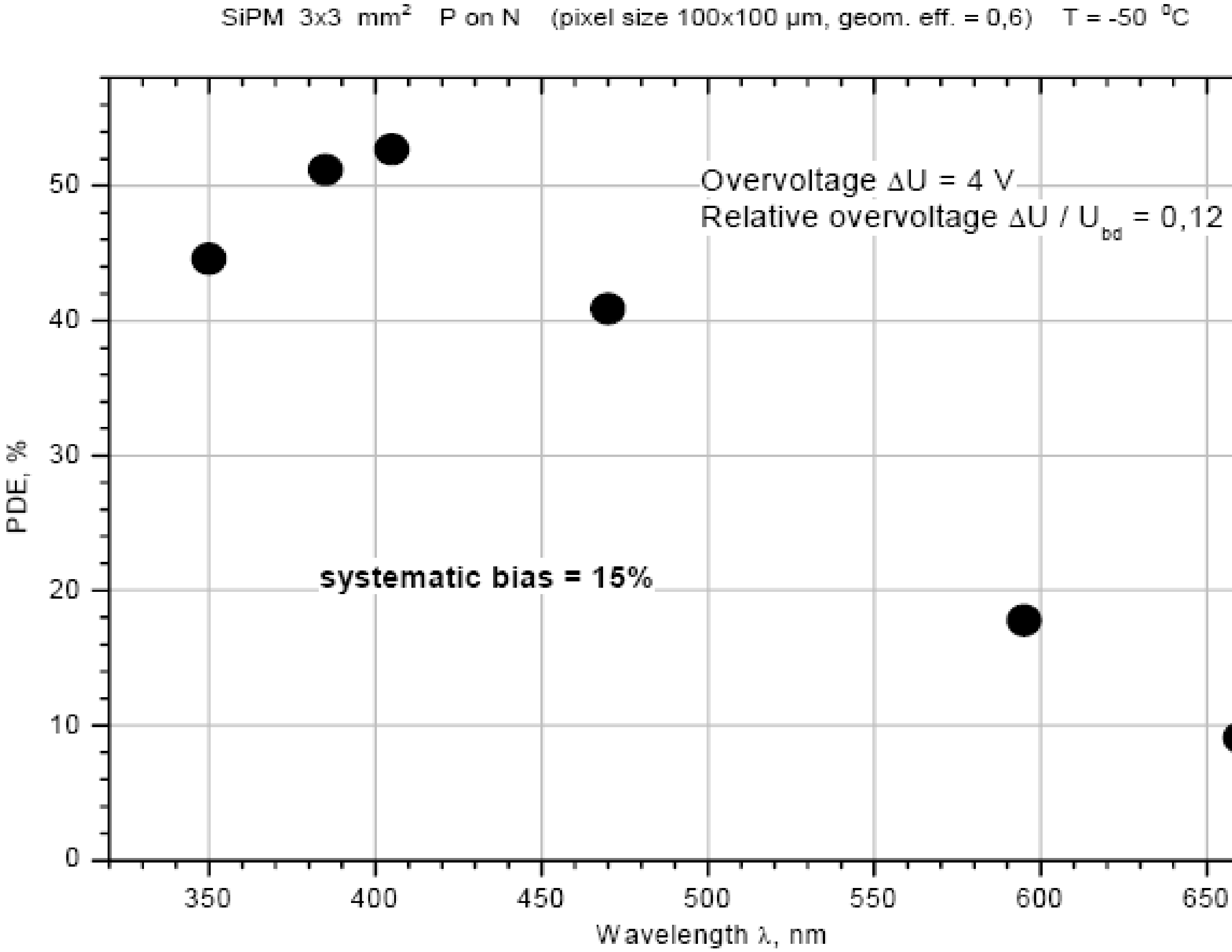
Digital output of
- Number of photons
- Time-stamp

Integrated readout electronics is the key element to superior detector performance

www.philips.com/digitalphotoncounting Philips Digital Photon Counting, October 27th, 2009 3

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