SiPM: How to Make it an ideal LLL Sensor

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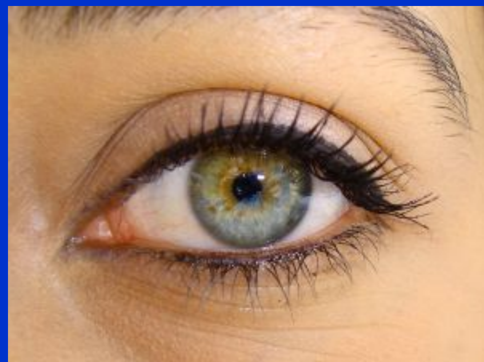
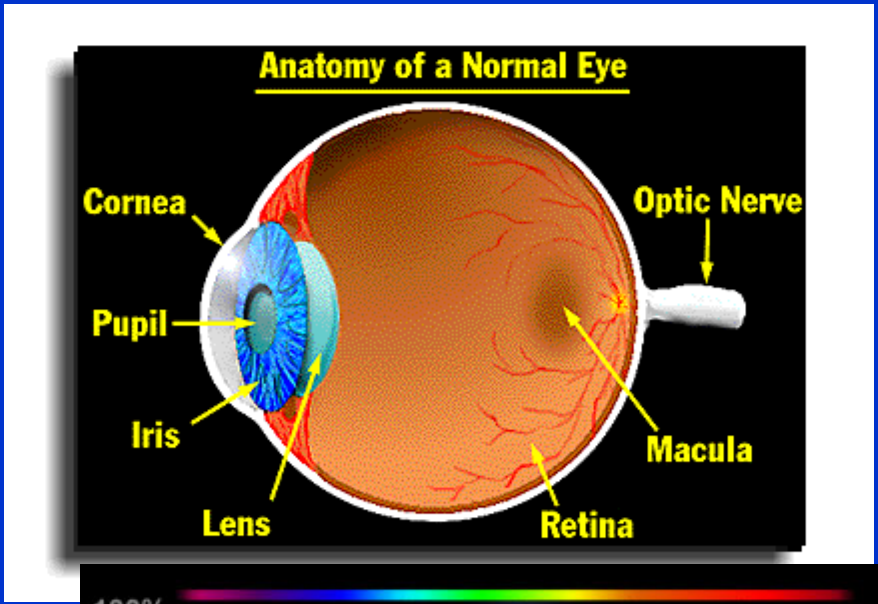
The most complex light sensors

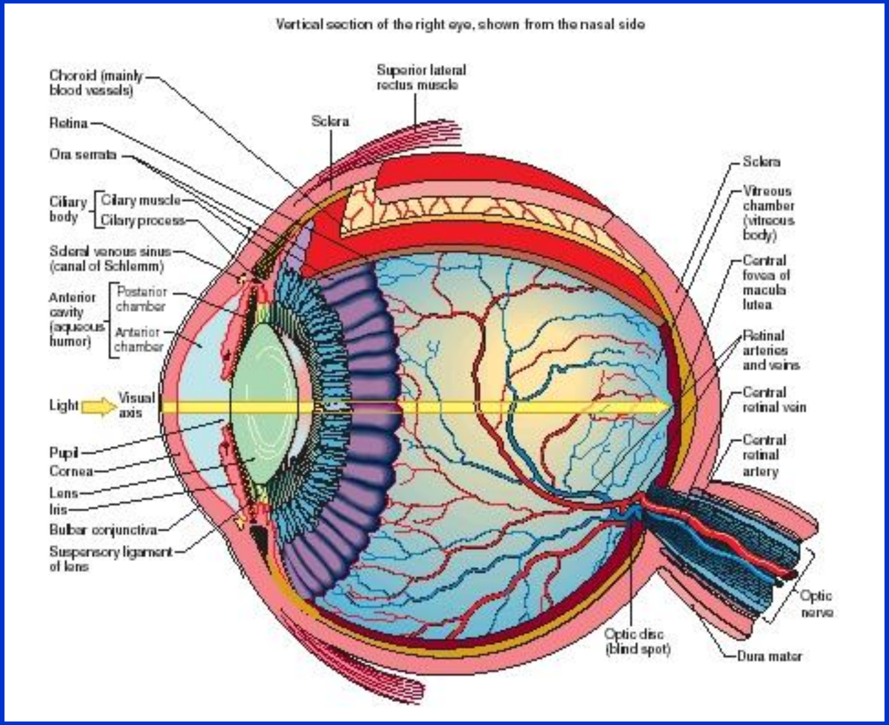


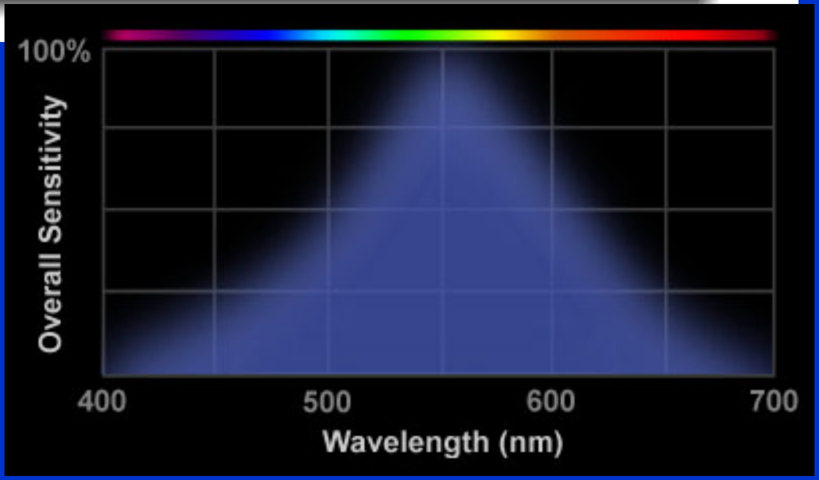
These seemingly best-known imaging light sensors measure colour in the a relatively wide band (400 – 700 nm) as well as the light intensity within a

- dynamic range of 13 orders of magnitude !
- angular resolution ~ 1‘ (oculists call it 100 % sight)
- integration time ≥ 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)

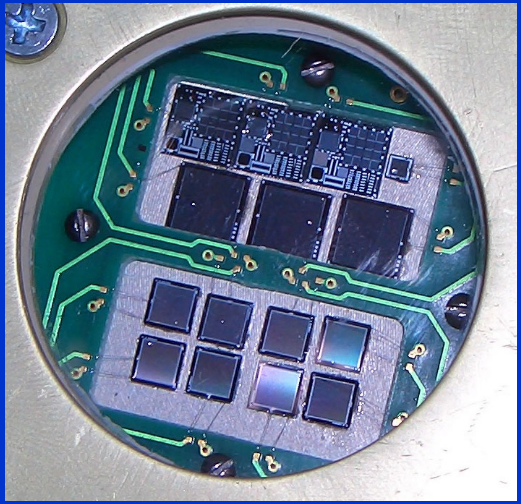
What LLL sensor can we dream about ?

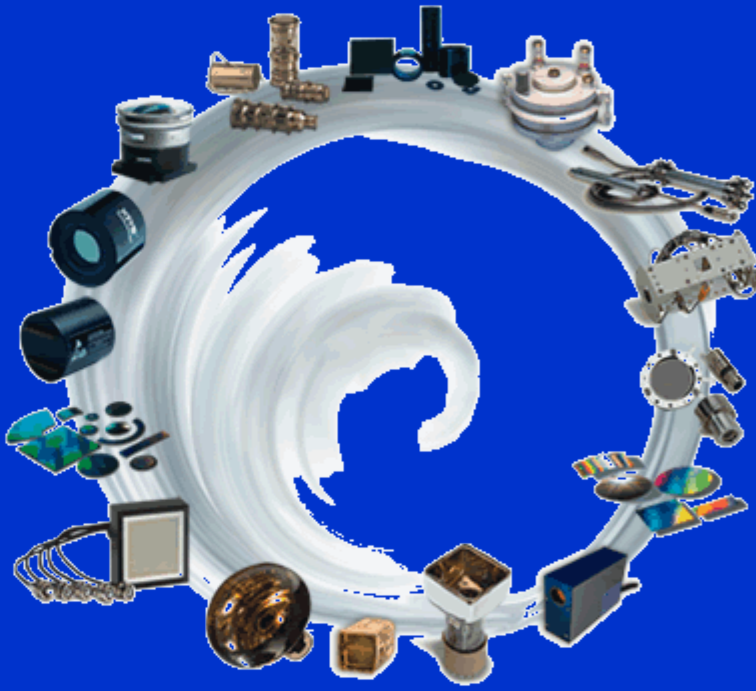
- Nearly 100 % QE and photon detection efficiency (PDE)
- Could be made in very large and in very small sizes
- Few ps fast (in air and in many materials the light speed is usually 20-30 cm/ns; in 5 ps it will make 1-1.5 mm)
- Signal amplification x10^6
- Noiseless amplification: F-factor - 1.001
- Few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

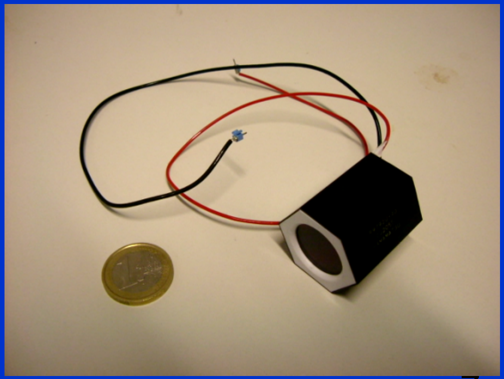
Light conversion into a measurable

- 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,...

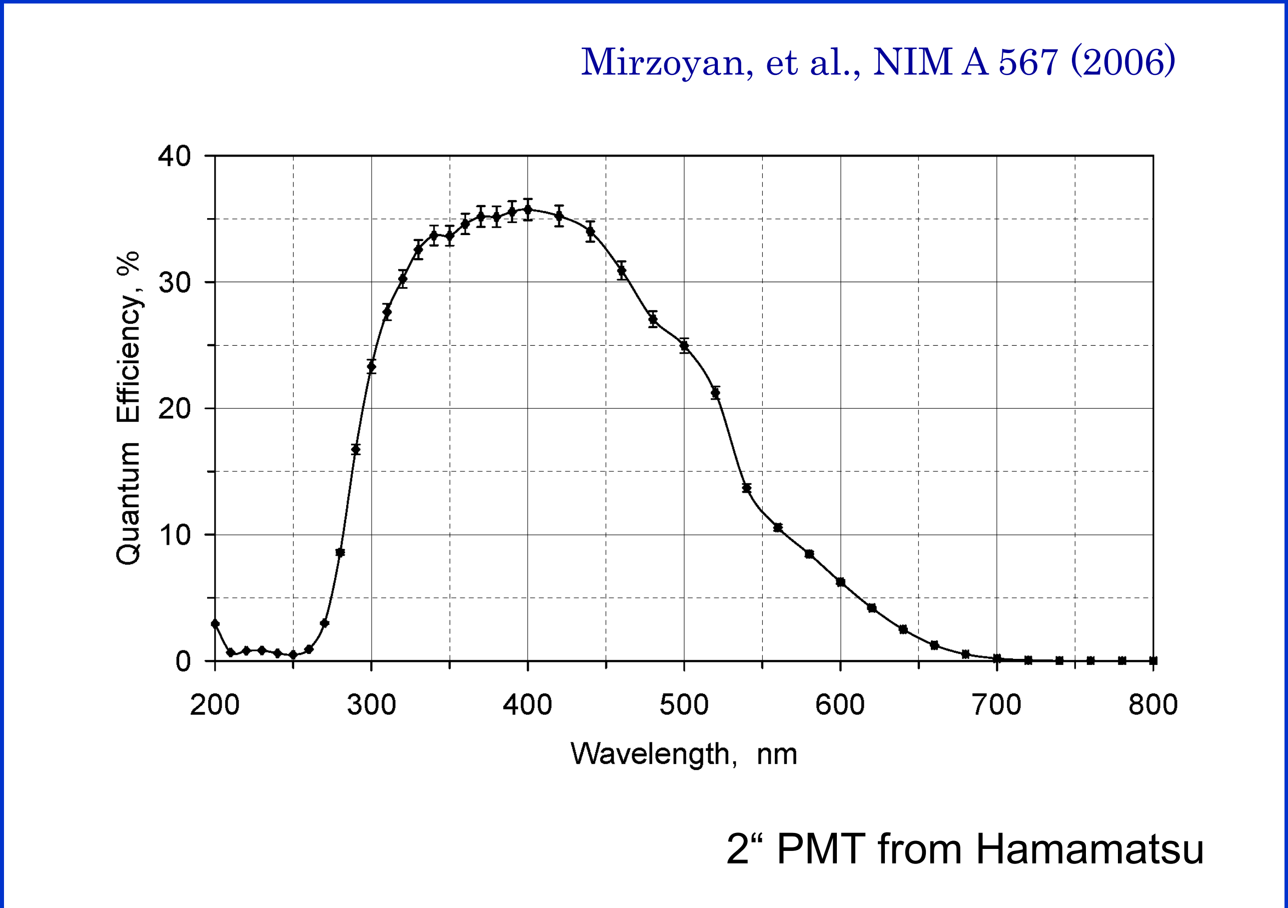
The „zoo“ of LLL sensors



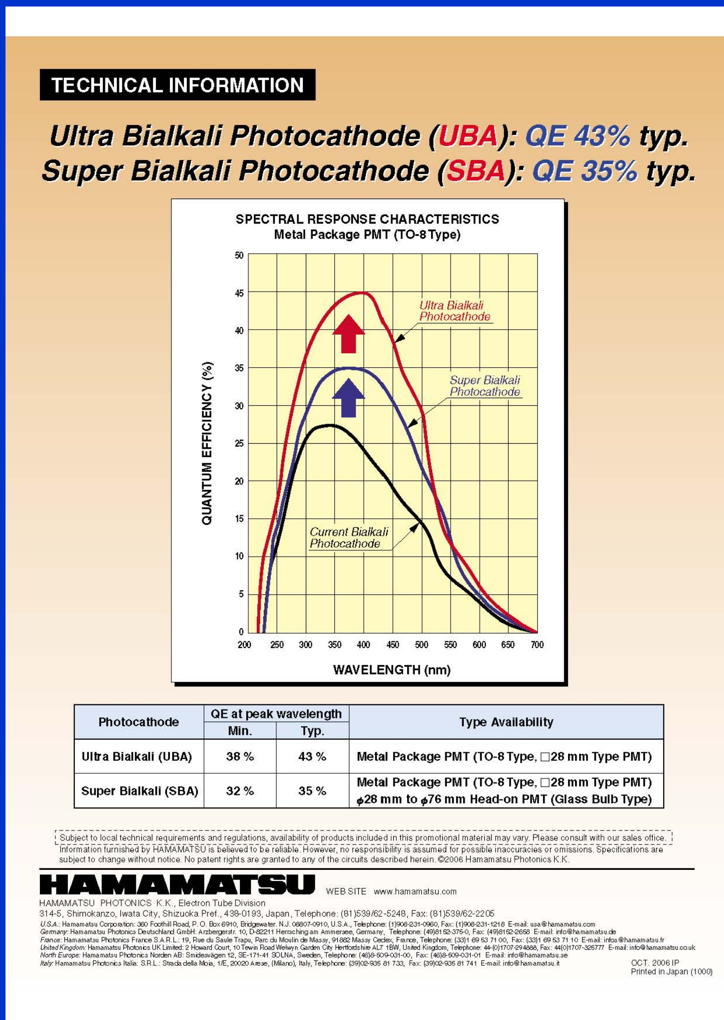




The beginning of the bialkali PMT QE enhancement program



Recent Surprises

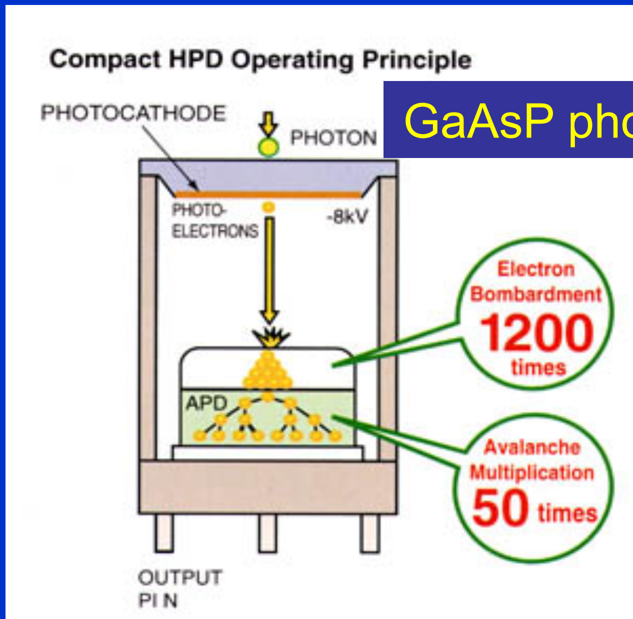


- All the 3 PMT manufacturers could report enhanced QE, the best being Hamamatsu, who gave it the name „Super-bialkali“ (QE~ 33-36 %) (Mirzoyan, et al., NIM A 572 (2007))

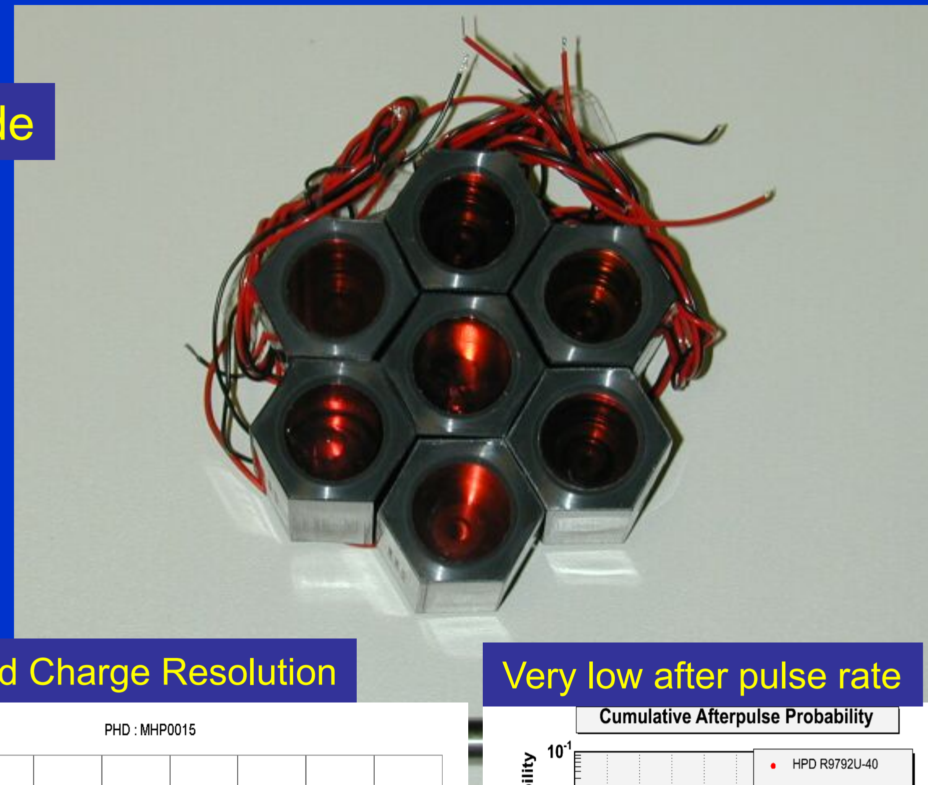
- ~2 years ago Hamamatsu claimed to produce PMTs with QE 43-45 % ! (once the *djinn* comes out of the lamp you cannot control it anymore) ;-)

- Recently also Photonis joined club of „Ultra-bialkali“. Moreover, it pushed the QE values even higher up !

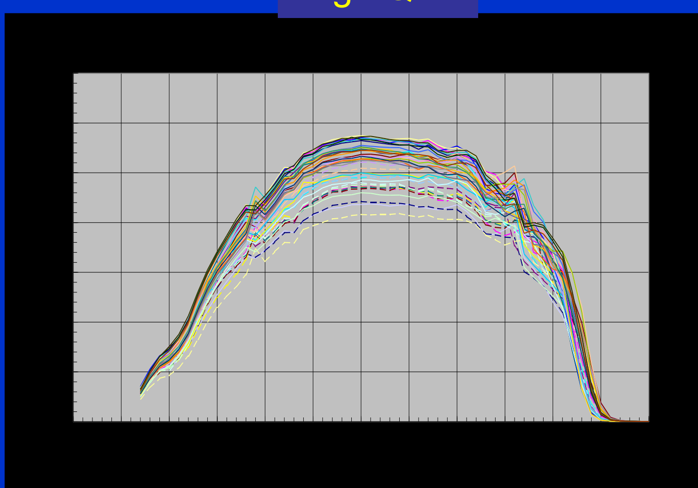
R9792U-40, 18mm GaAsP HPD by Hamamatsu for MAGIC future camera



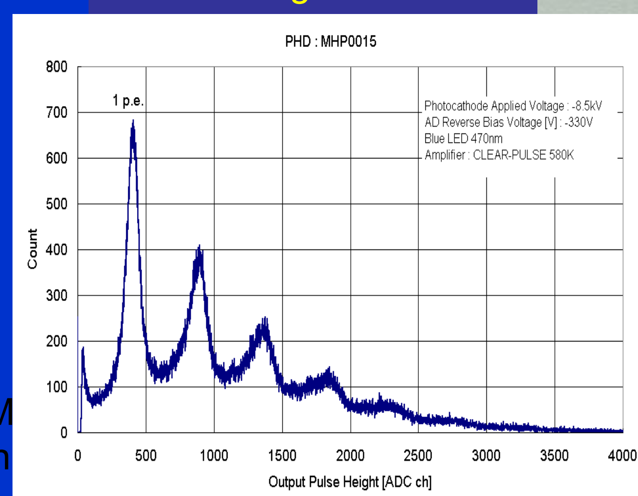
GaAsP photocathode



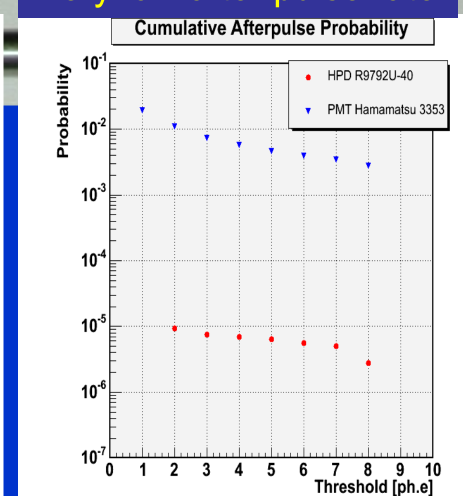
High Q.E.



Good Charge Resolution

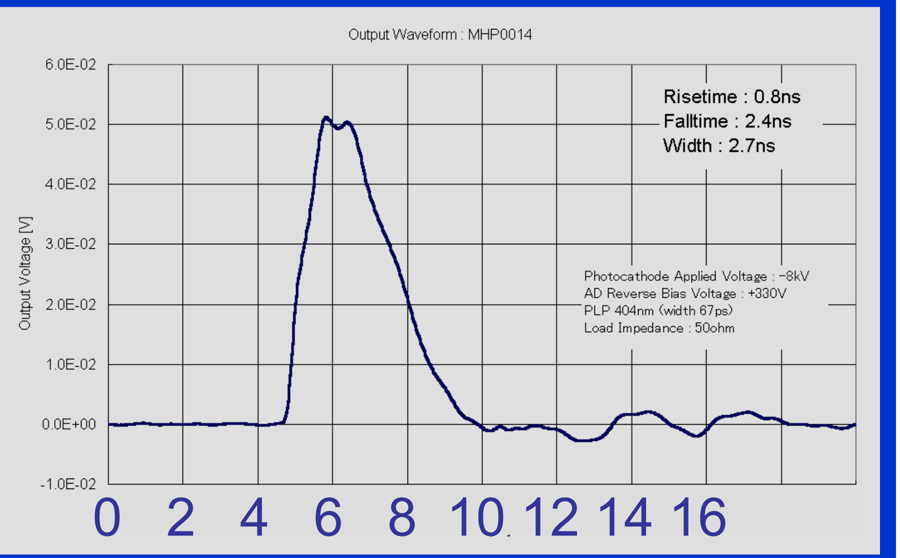


Very low after pulse rate



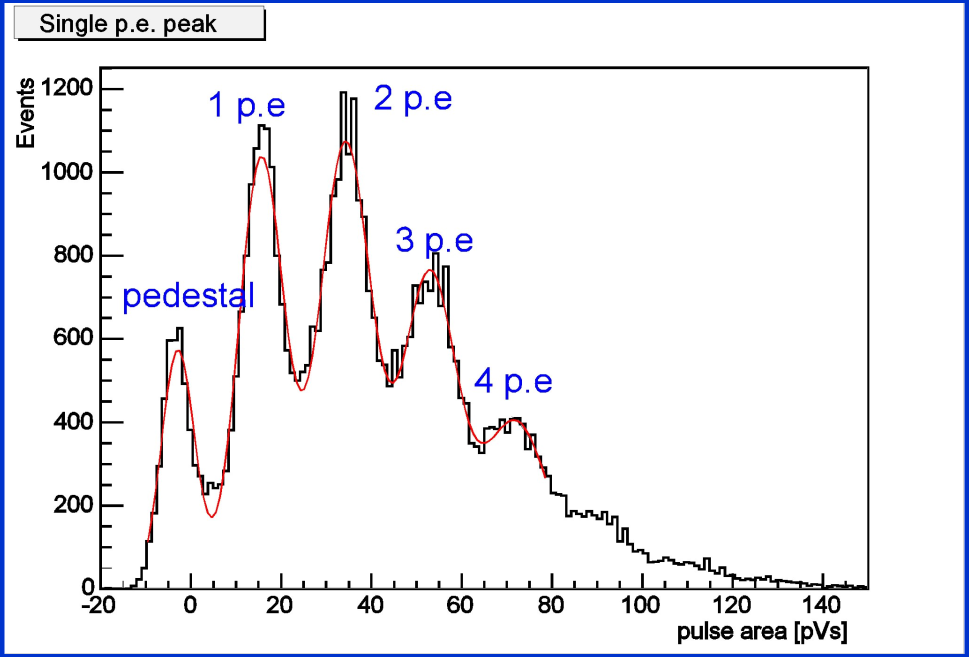
HPD Output Signal

<pulse shape>



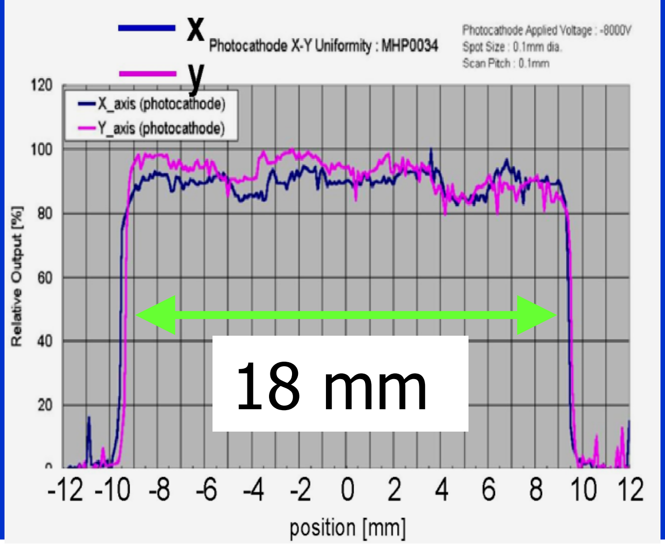
Time [ns]

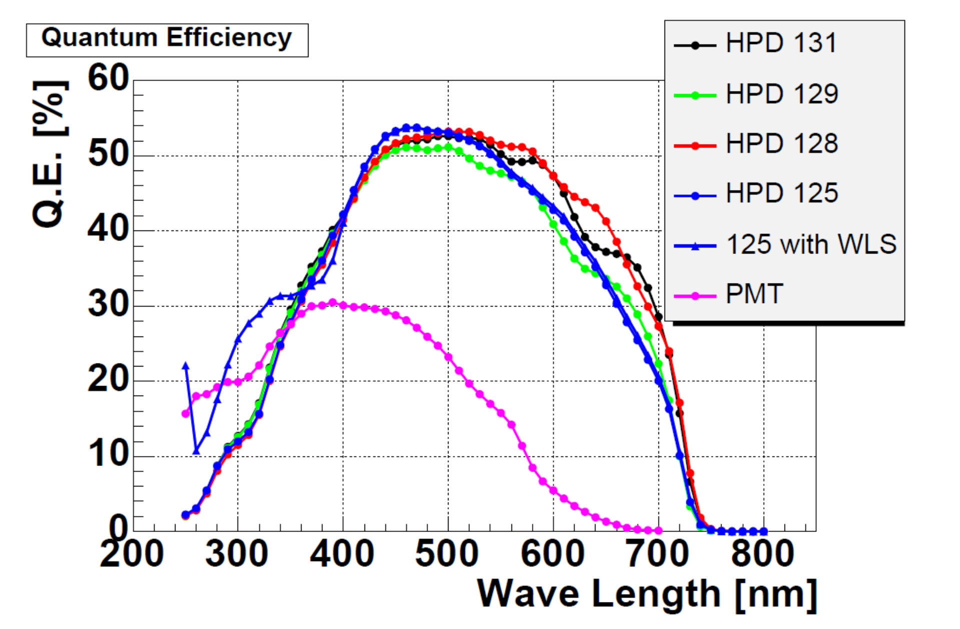
<pulse height distribution>

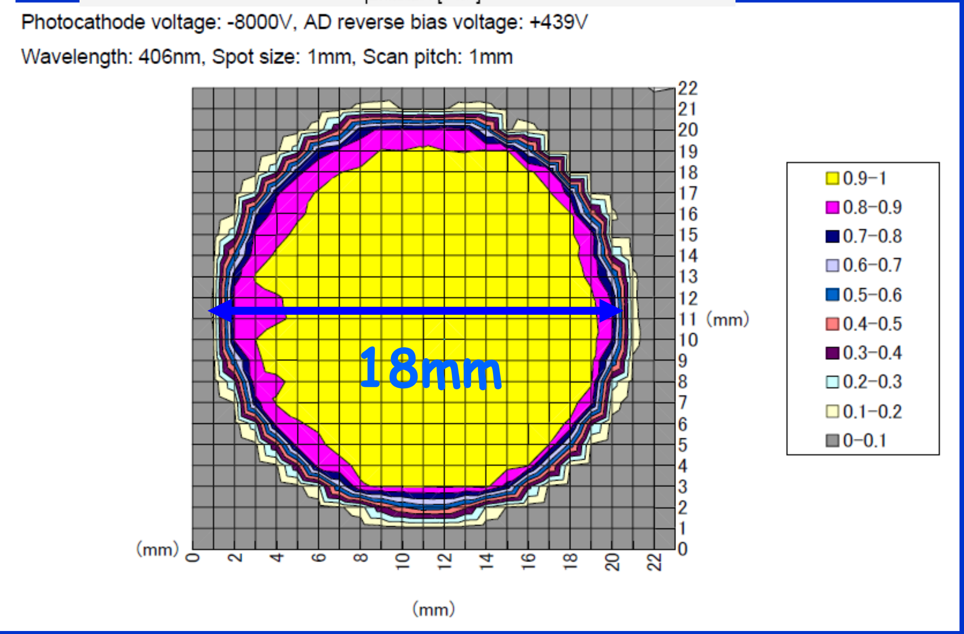


FWHM～2.7 ns

GaAsP HPD from Hamamatsu



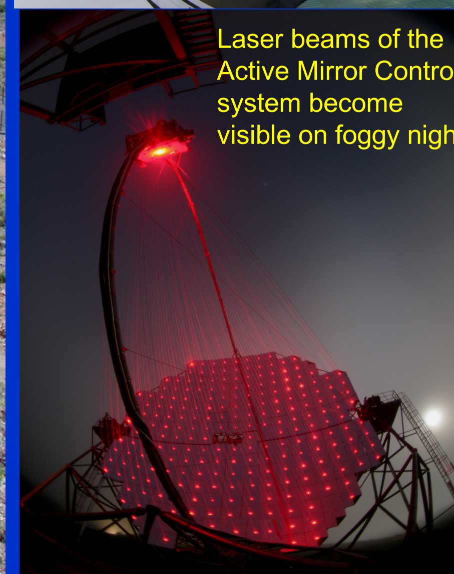




QE exceeds 50% at 450 nm
Two times higher photon detection

Good Uniformity. 18mm diameter
Within 10%.

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



The MAGIC Project

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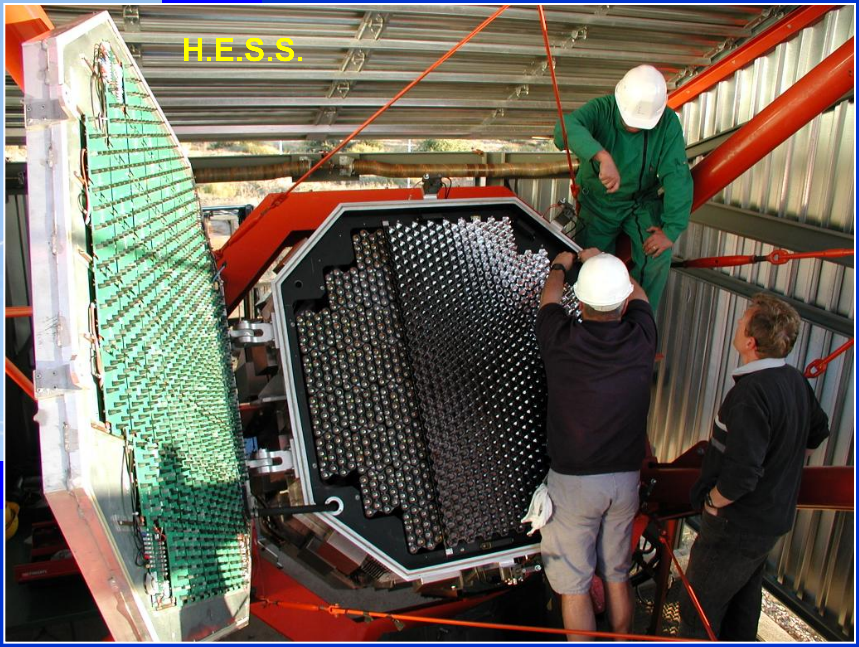
Photograph of the 576-pixel imaging camera of MAGIC-I. In the central part one can see the 396 high resolution pixels of 0.10° size. Those are surrounded by 180 pixels of 0.20°.



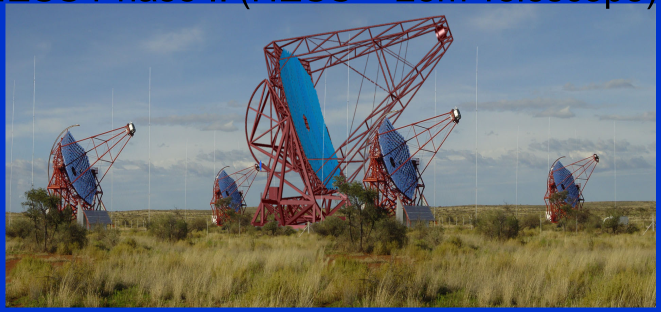
Outlook : the next 5-7 years

Next generation VHE γ ray Observatory: CTA

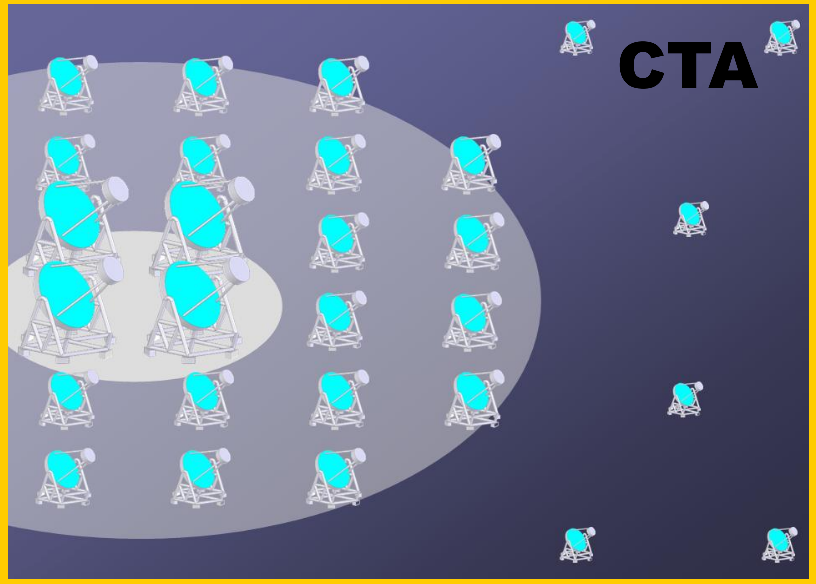
MAGIC Phase II (MAGIC-I + MAGIC-II) in 2008
50-100 sources will be discovered

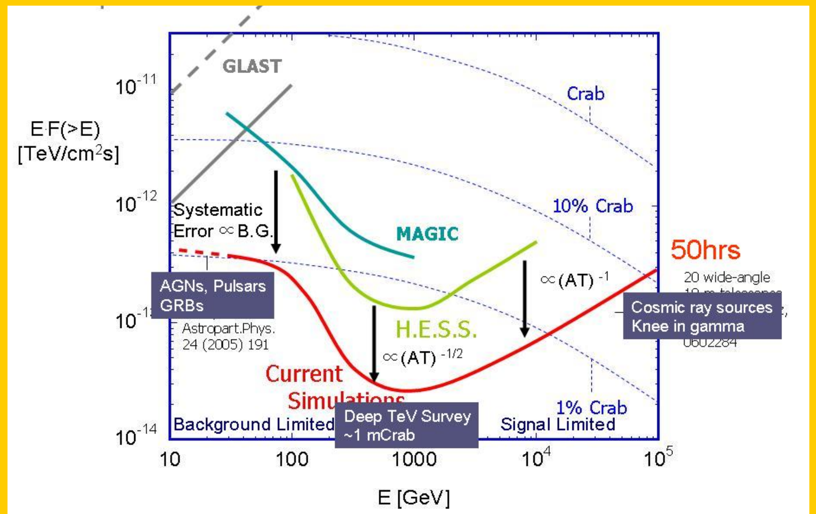
~400 scientists
~50 institutions

HESS Phase II (HESS + 28m Telescope) in 2009



Cherenkov Telescope Array
1000's of sources will be discovered





Astronomers in EU

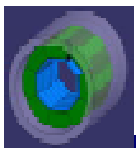
JAPAN, US

R. Mirzoyan: SiPM: Hov
Ideal LLL Sensor;

A Potential Sensor for ILC: (5-200)x10^6 SiPMs

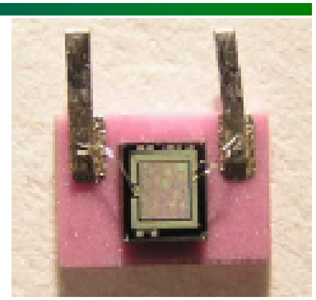
→Scintillation Calorimetry- for instance a SciTile Imagine Hadron Calorimeter for ILC (CALICE Collaboration),sci tile size:a few cm

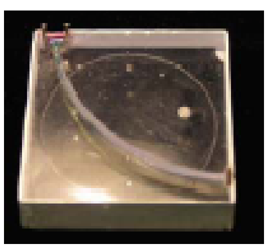
→Typical threshold is ~ 5-7 phe

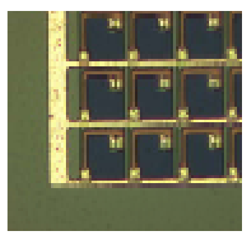


SiPM tile fibre system

- SiPM developed by MEPhI/PUSAR
  - Gain ~10^6, bias ~ 50 V, size 1 mm², 1156 pixels
  - Eff (green) ~ 15%, quenching R ~ 1 - 10 MΩ
- SiPM tile fibre system integration: ITEP
  - 3x3x0.5 cm³ tiles from UNIPLAST, Russia
  - WLS fibre Kuraray Y11(300) 1mm
  - Matted edges, 2% light xtalk per edge
  - Faces covered with EM mirror foil

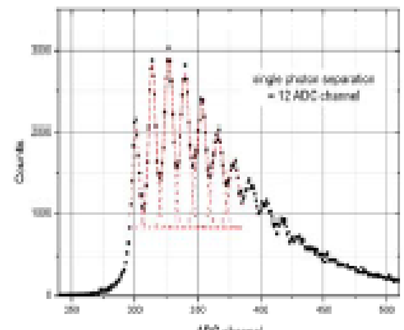






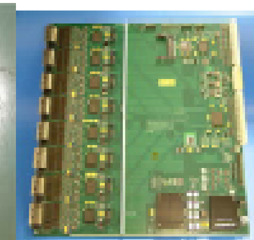
CALICE   MPPDs for calorimetry   Felix Sefkow   PD'07   June 27, 2007   13

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 cm² 0.5 cm thick tiles



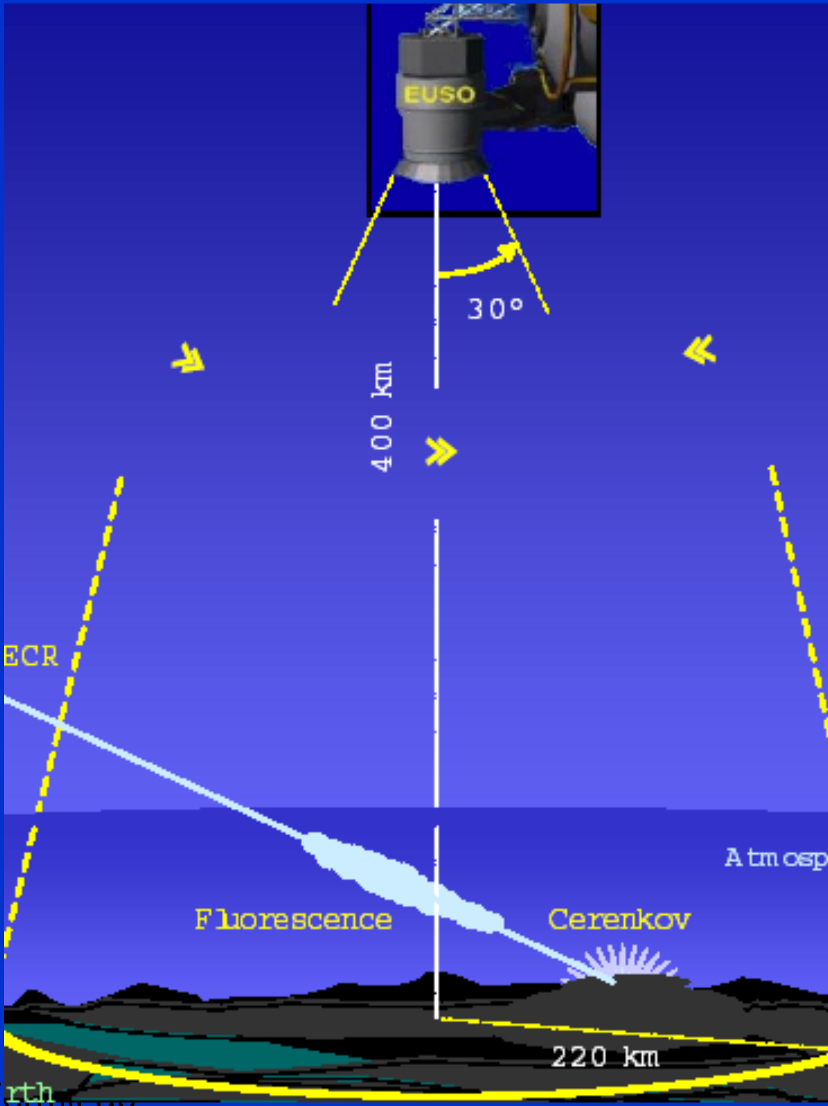
CERN test beam,2006

LAL 18 ch. SiPM FE chip

B.Dolgoshein,SiPM review   20

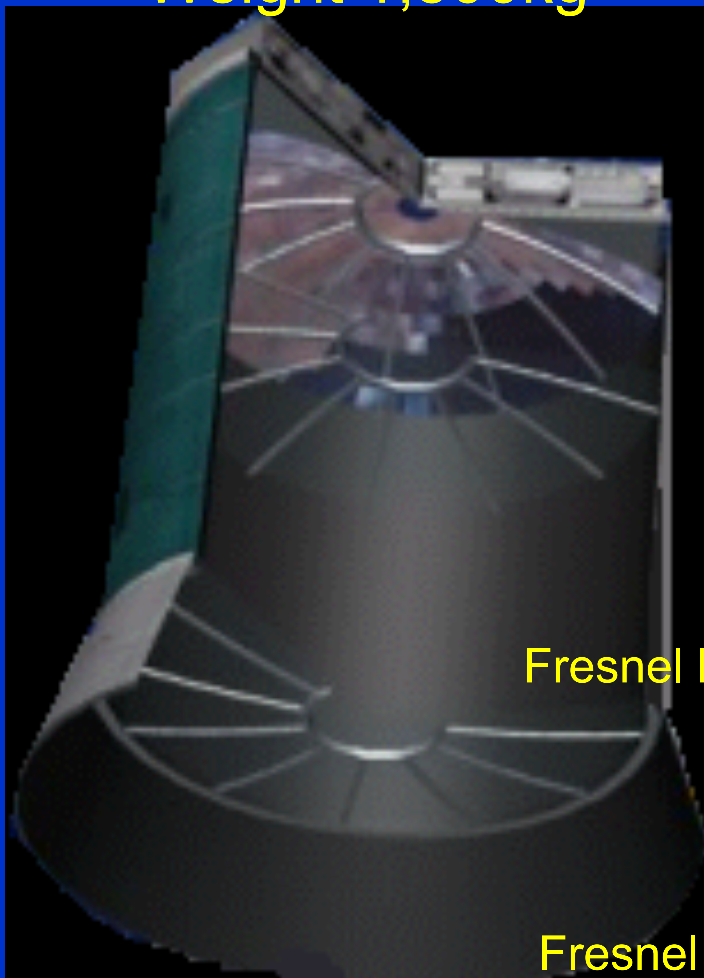
(JEM)EUSO Concept

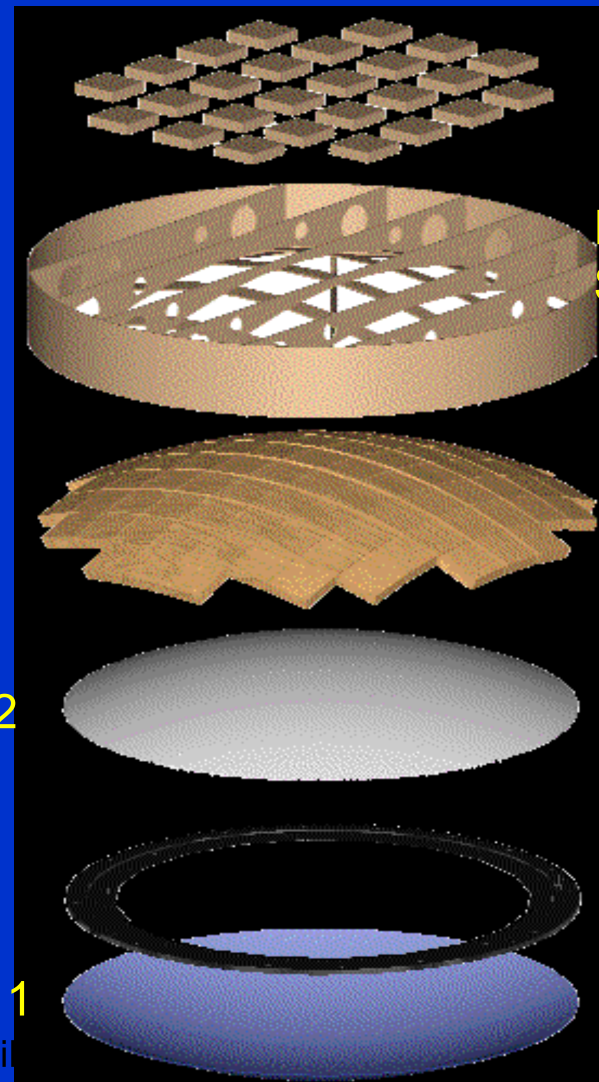
- Large Distance and Large F.O.V. → Large Aperture
  - ~4.5x10^5 km2 sr
    - Good Cosmic Ray detector
    - 3000 times sensitive to C.R. bursts
  - 1500 Giga-ton atmosphere
    - Good neutrino detector
- All Sky coverage
  - North and south sky covered
- Complementary to the observation from the ground
  - Different energy scale
  - Different systematic errors
- Shower Geometry is well defined



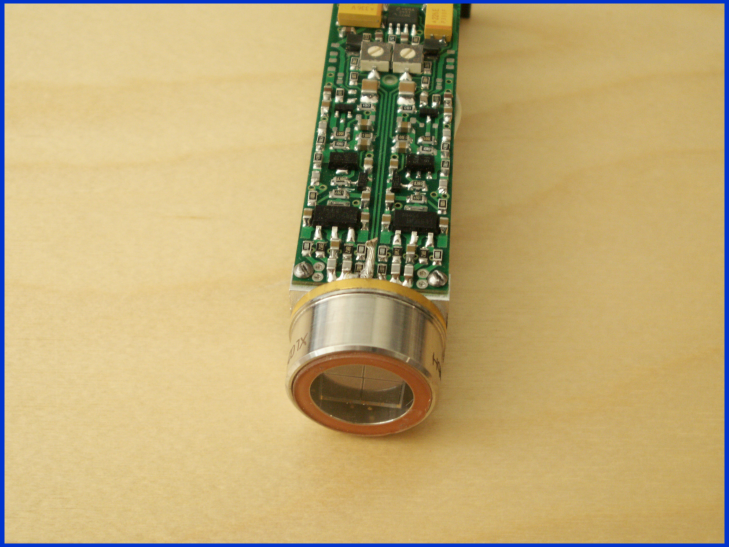
Detector Element

Power 1,060W
Weight 1,500kg

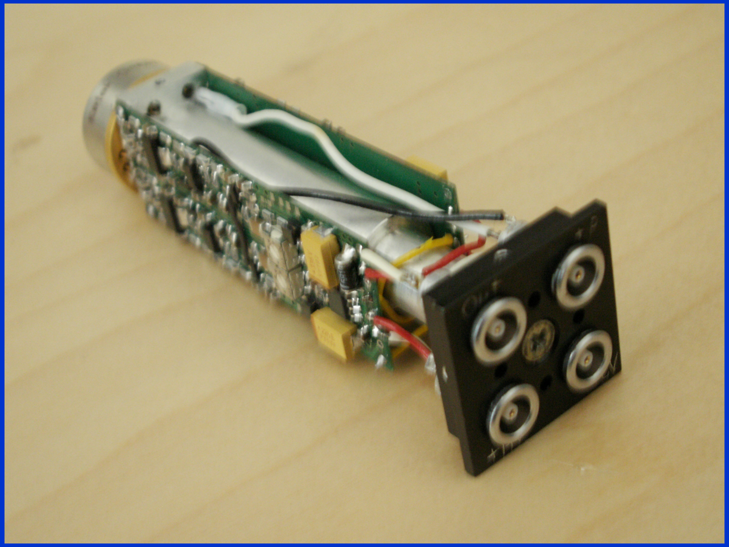


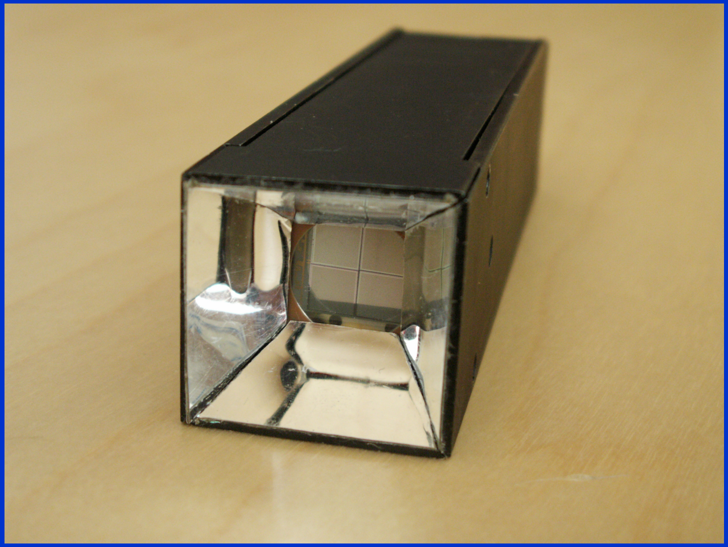


A „pixel“ for MAGIC; 4 SiPMs of 5x5mm² size

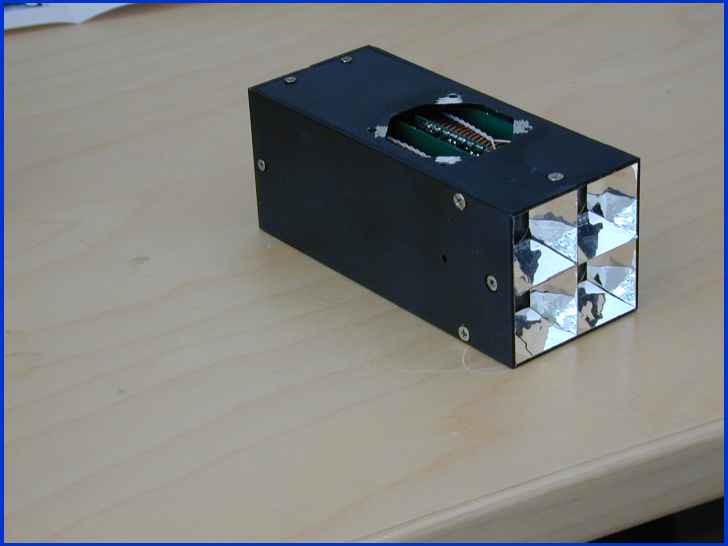


The pixel includes:
- 4 SiPMs of 5mm x 5mm size in an evacuated encasing
- signal amplifier-shaper
- 2-stage Peltier cooling system
- Winston cone type light concentrator
- metallic encasing with lemo connectors



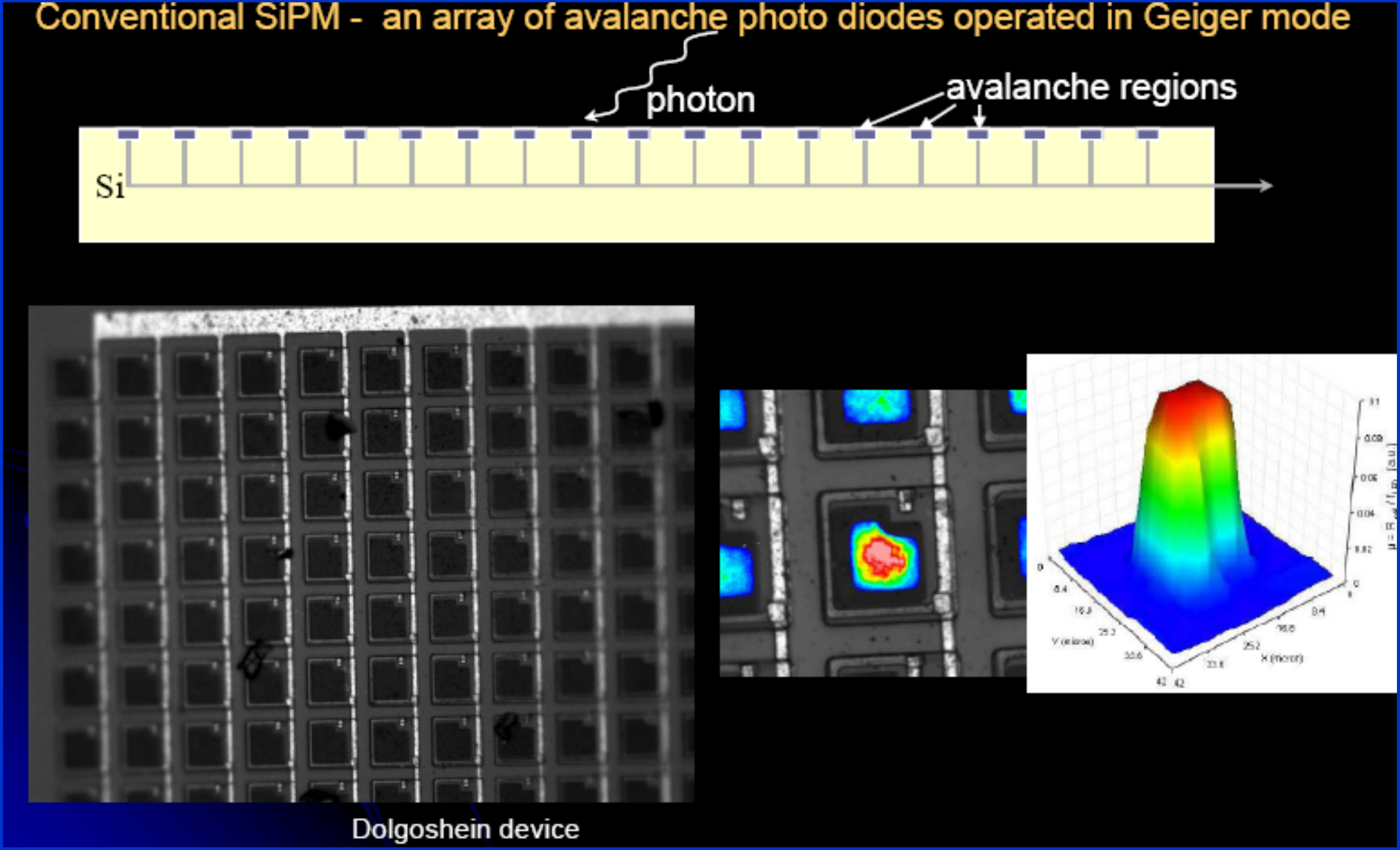


The next step: 4-pixel unit each consisting of 4 SiPMs of 5mm x 5mm size

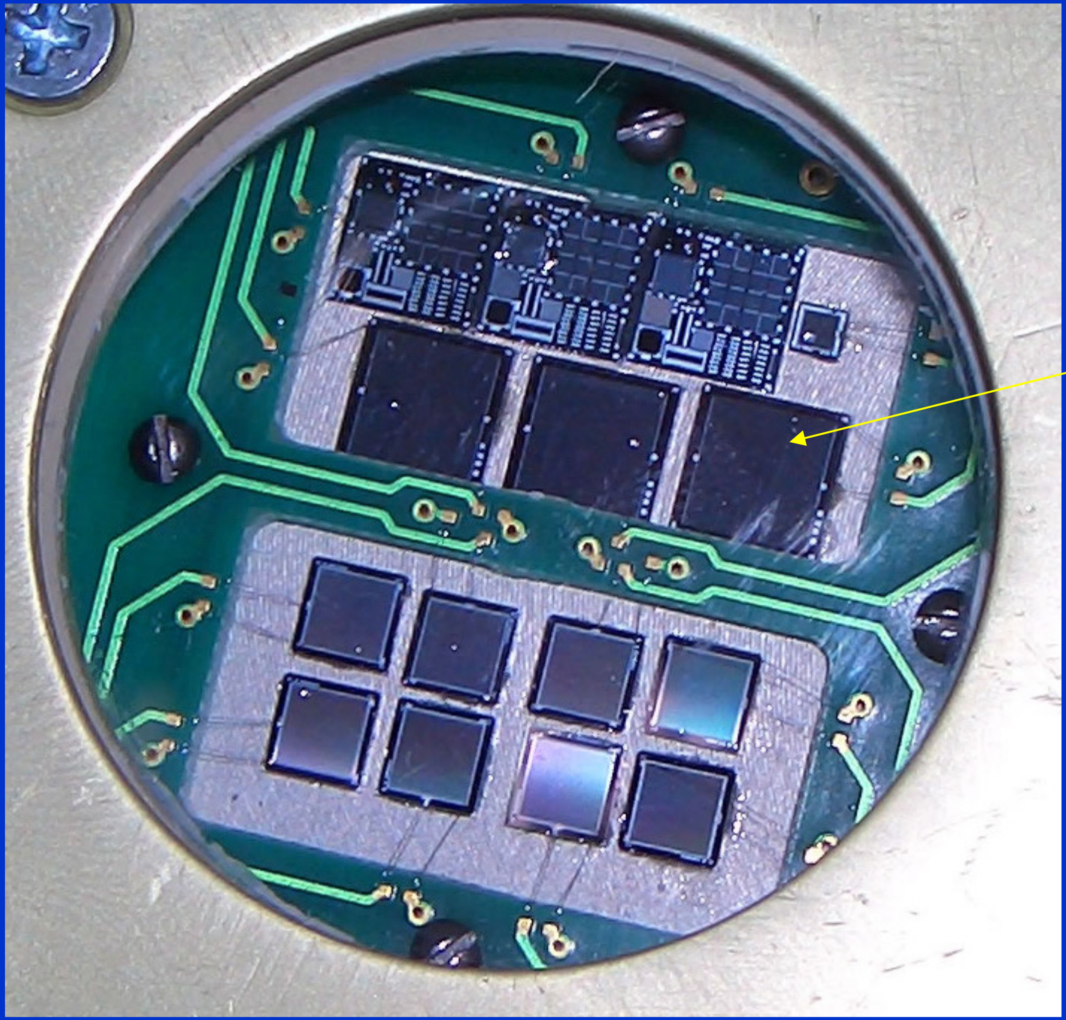


- This „autonomous“ unit needs just to get the necessary power connections and is fully operational
- It is rather starightforward to constrcut an imaging camera from such modules

SiPM: novel light sensors



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



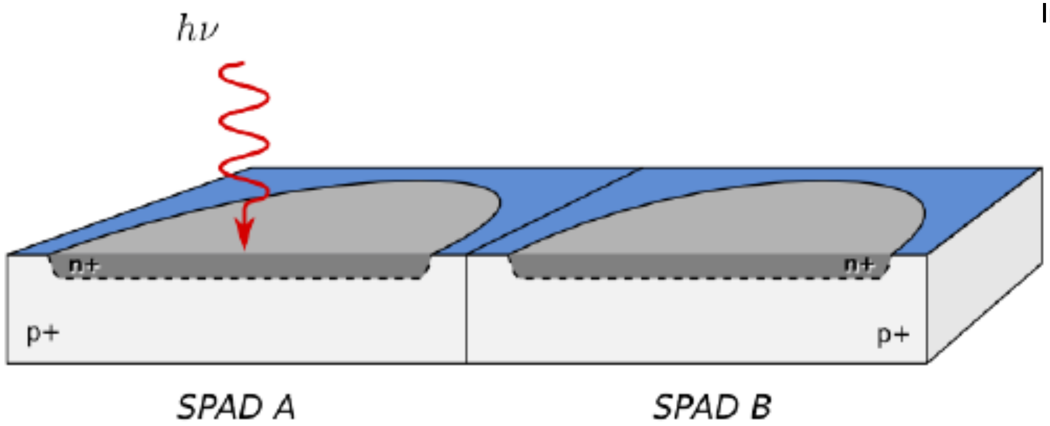
5 x 5 mm²

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

Ingargiola NDIP-08

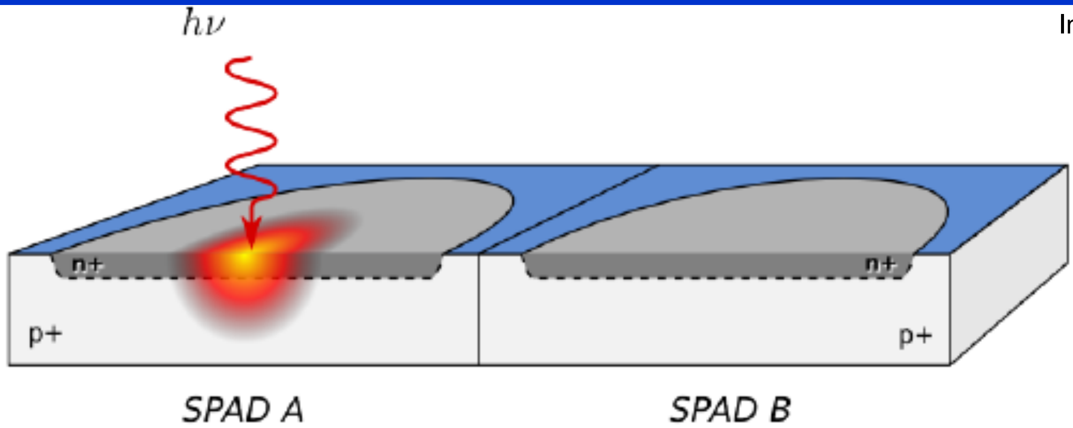


When an avalanche is triggered in one SPAD we have:

- 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:

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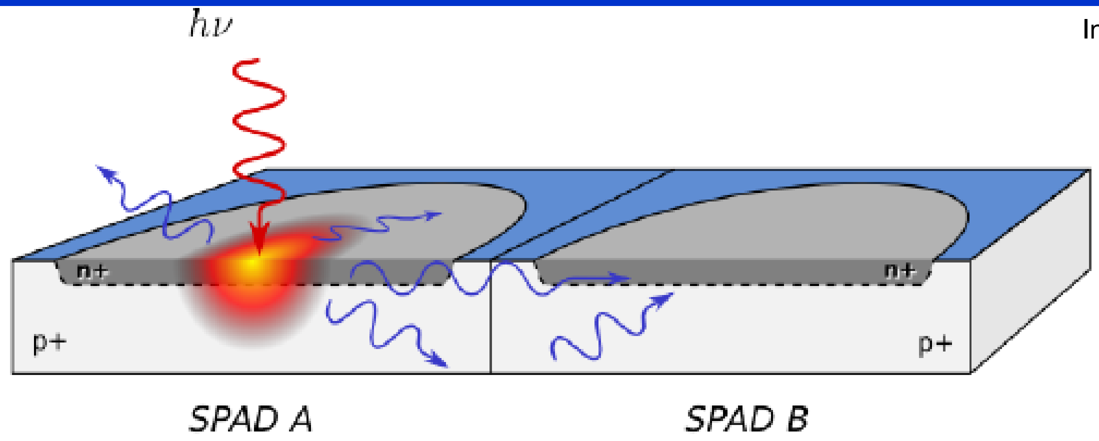
- Photons propagation throughout the chip
- Secondary photon detection by a nearby detector

Cross-Talk



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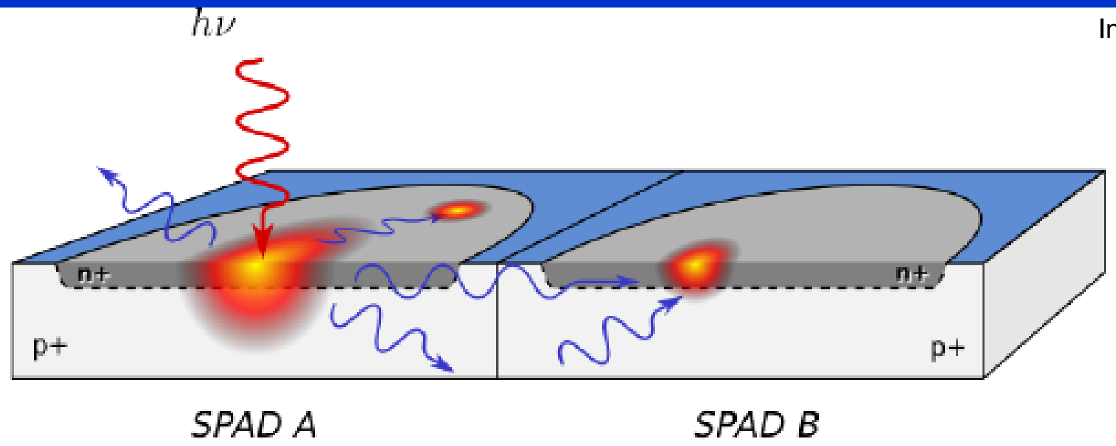

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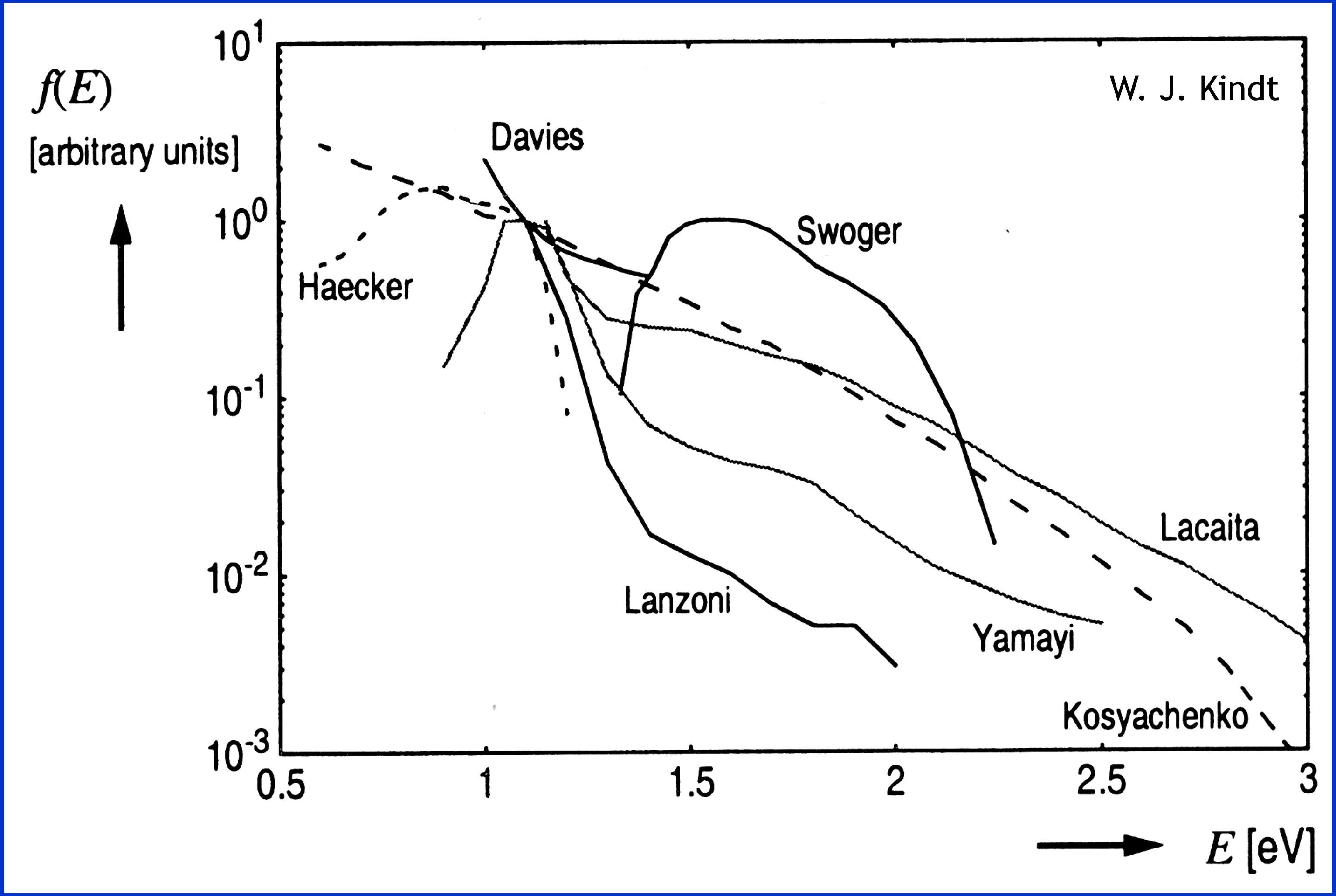
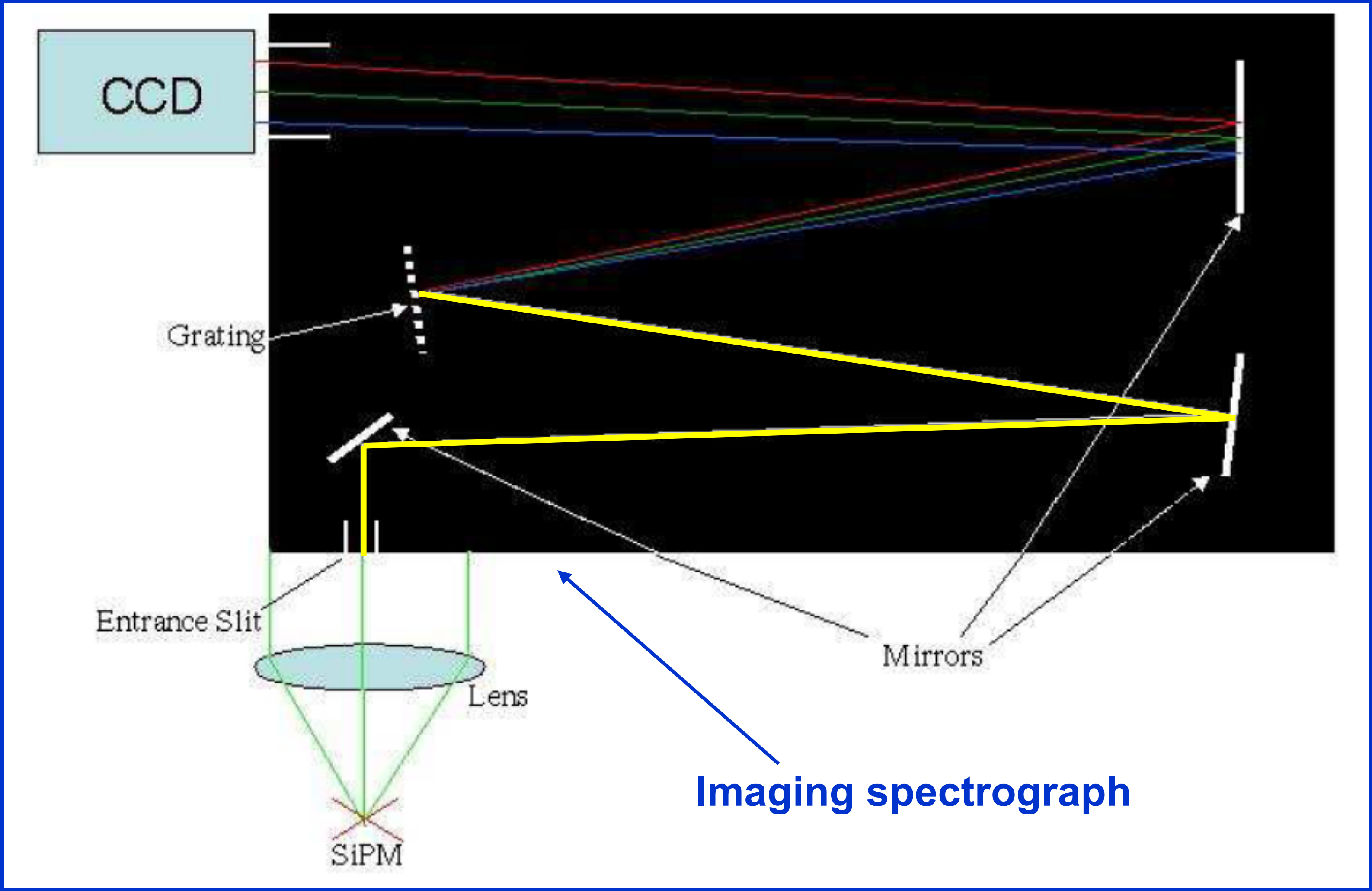
Light Emission in Si Avalanches: collection of different measurements



The Setup

- List of the 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 the experimental setup



Parameters of the setup

CCD pixels (row x column)	1024 x 256 (VIS) 512 x 1 (NIR)
Preamplifier gain CCD	14 e/count (VIS) 300 e/count (NIR)
Grating, lines/mm	150
Blase wavelength of grating	800nm
Slit size	2.5mm
Focal lenth of lens	50mm
Used gain of MPPC	1.56 x 10^6
Calibrated diodes	Si PIN and GaAs diodes
Number of used calib. LEDs	14 (470 – 1700)nm

The Absolute Calibration

- 14 different LEDs were used for the absolute calibration. They were grinded flat, polished and installed in the same position as the SiPM, in the focus of the lens. The CCD had absolute calibration. Then 2 measurements were done:

1- the LED light was measured by the CCD

2- the same light was measured by a calibrated PIN diode just behind the slit

The amount of light emitted by the SiPM was measured from the known geometry. The tabulated values of the refraction index in Si and SiO_2 were used in order to calculate the emission solid angle.

The Absolute Calibration

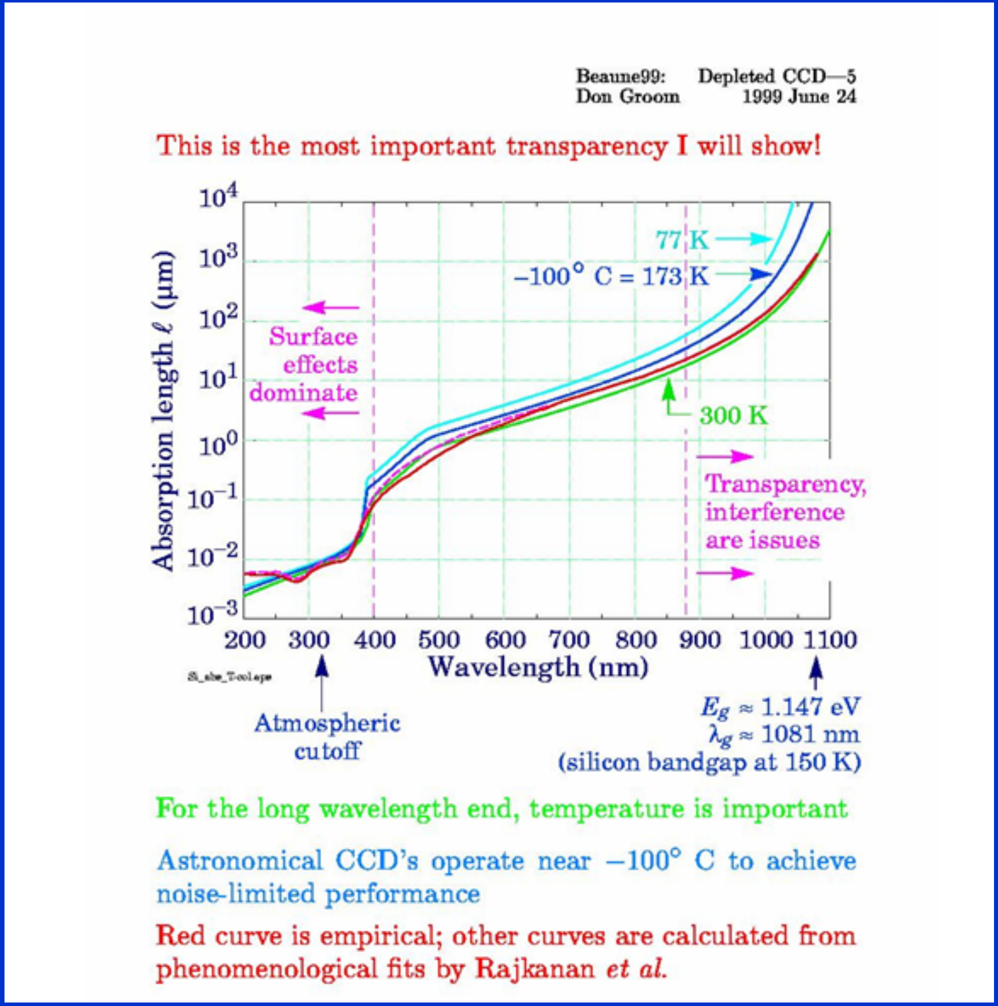
It was assumed that the used type of MPPC from Hamamatsu had an active zone of 1.8 μm in depth.

- 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 for this calculation.
- Light reflection on the interface Si-SiO_2-air has been taken into account

The calibration LEDs

VIS LED, nm	470	520	621	700	750	810	910	102 0
NIR LED, nm	910	1020	1200	1300	1450	1550	1600	170 0

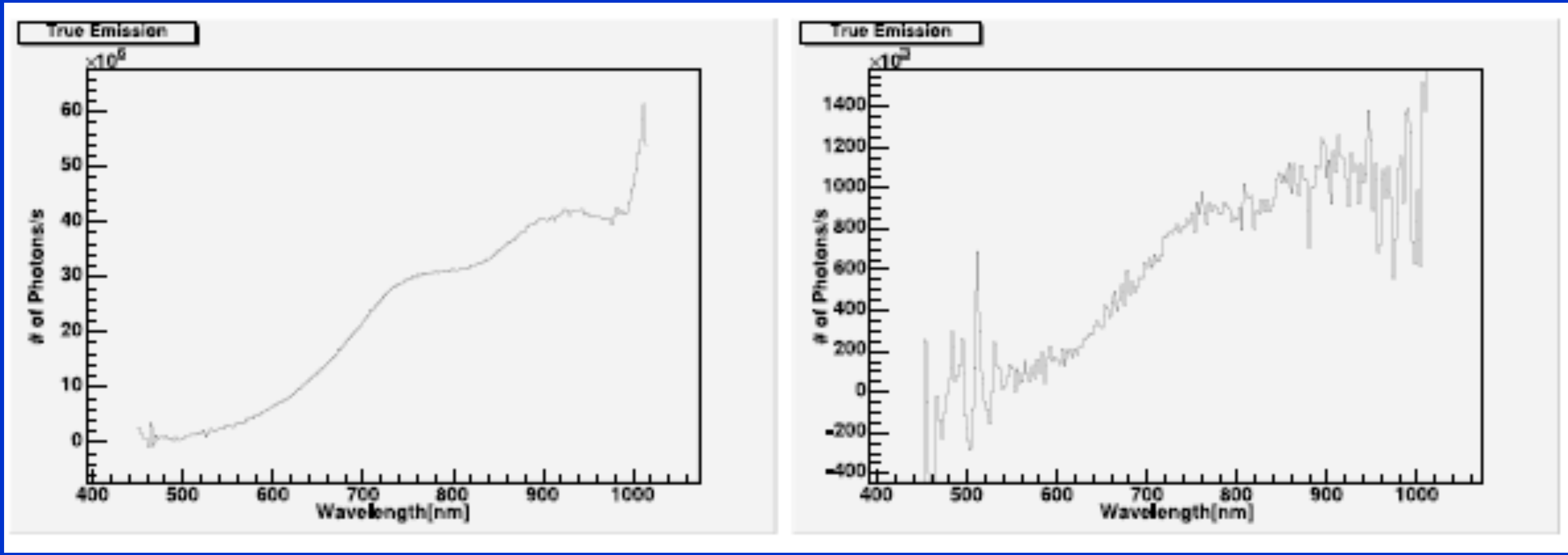
Reminder: light absorption in Si



- 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

Measured spectrum in visible



It was difficult to measure the light emission signal in the NIR because of a) high noise level, b) the InGaAs CCD had only 512x1 pixels. To overcome this at 1st the signal in the VIS was measured directly by integrating the signal from 256 rows operating the MPPC under the gain of 1.56x106.

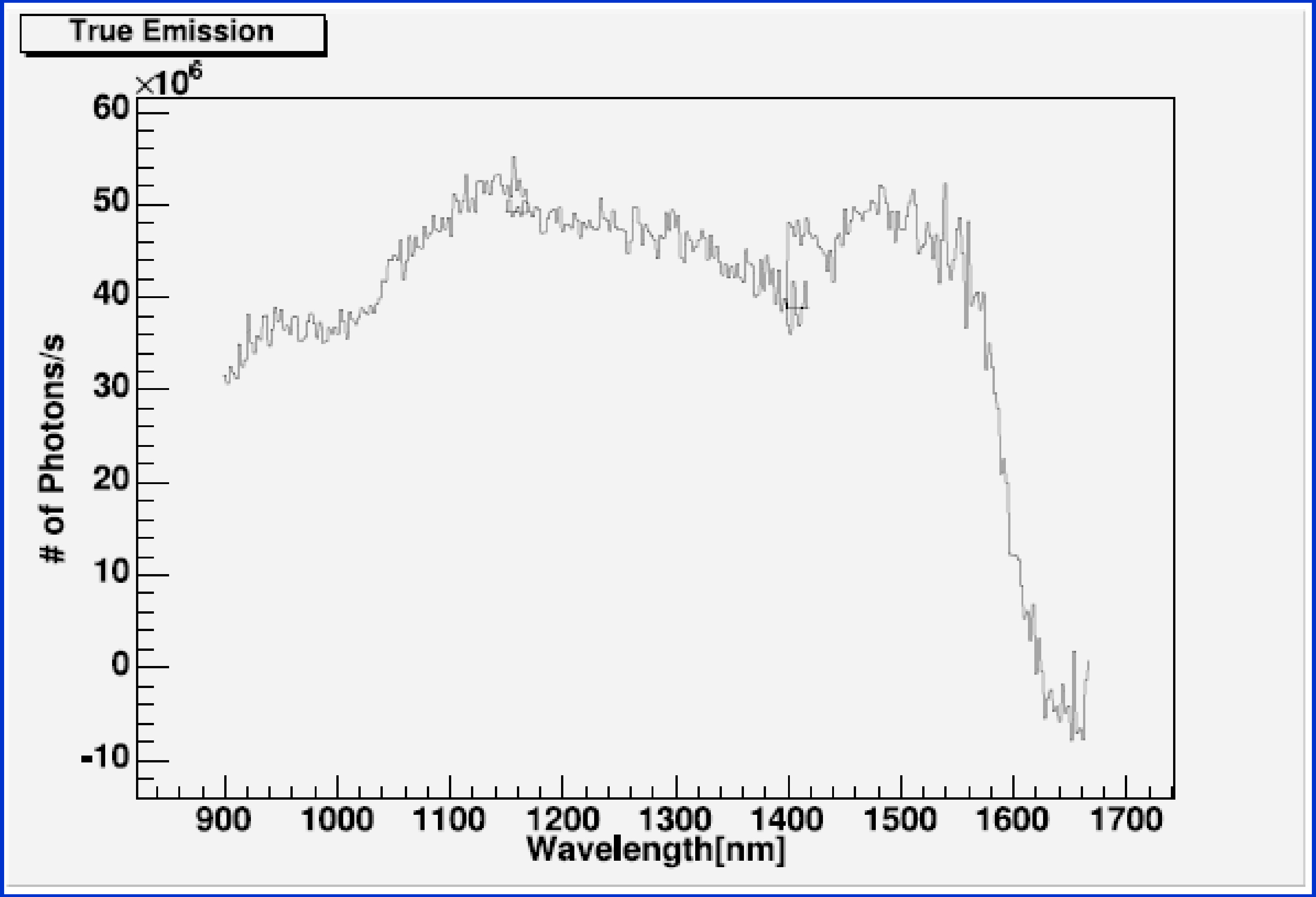
Controlled increase of the light emission in NIR

In order to amplify the light emission the MPPC was illuminated by an ultra-fast semiconductor laser (λ=440nm, τ=80 ps) at 2.5 MHz, producing an average amplitude of 13 ph.e. in the matrix of 100 pixels (the dark rate was about 0.6-0.7 MHz). In this way we achieved an emitted light amplification of ~50 times.

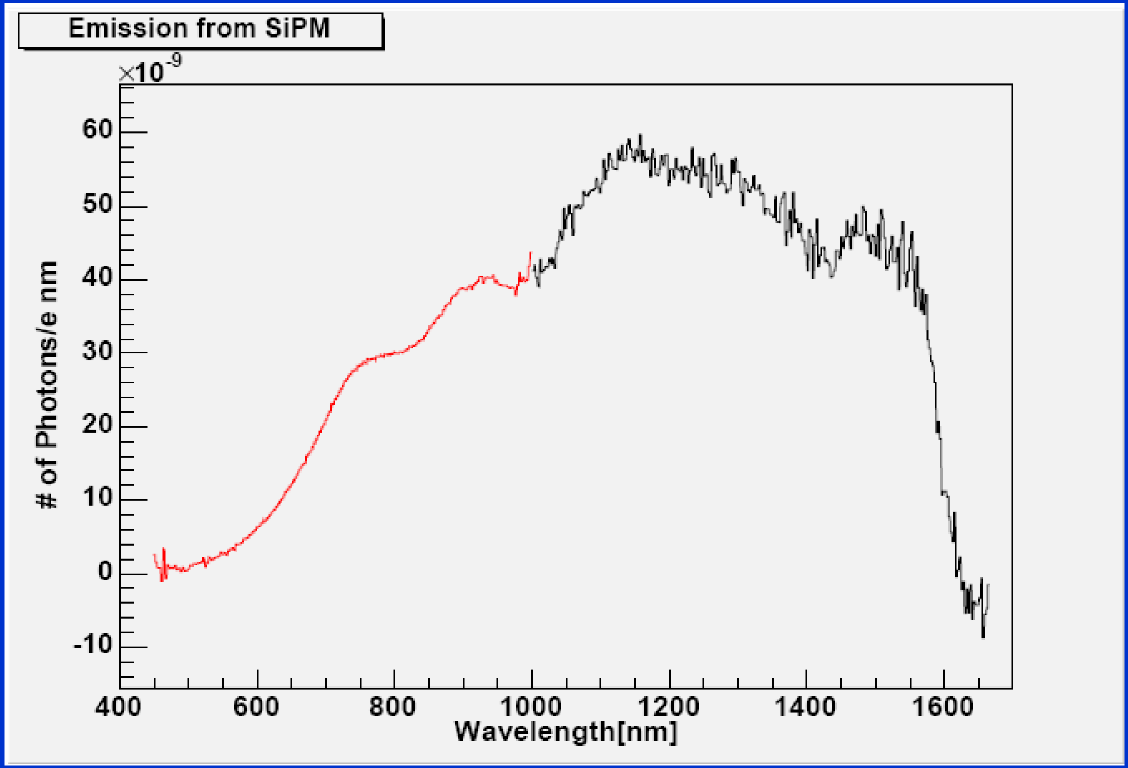
After that the applied voltage of the MPPC was increased putting it into a continuous trigger mode (no quenching) and the emitted light was again measured. By taking the ratio of the two measurements a scaling factor of 36.82 has been measured.

That factor was used to scale down the NIR emission to find out the emission rate at the used gain of 1.56×10^6.

Measured spectrum in infrared



Entire emission spectrum



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

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

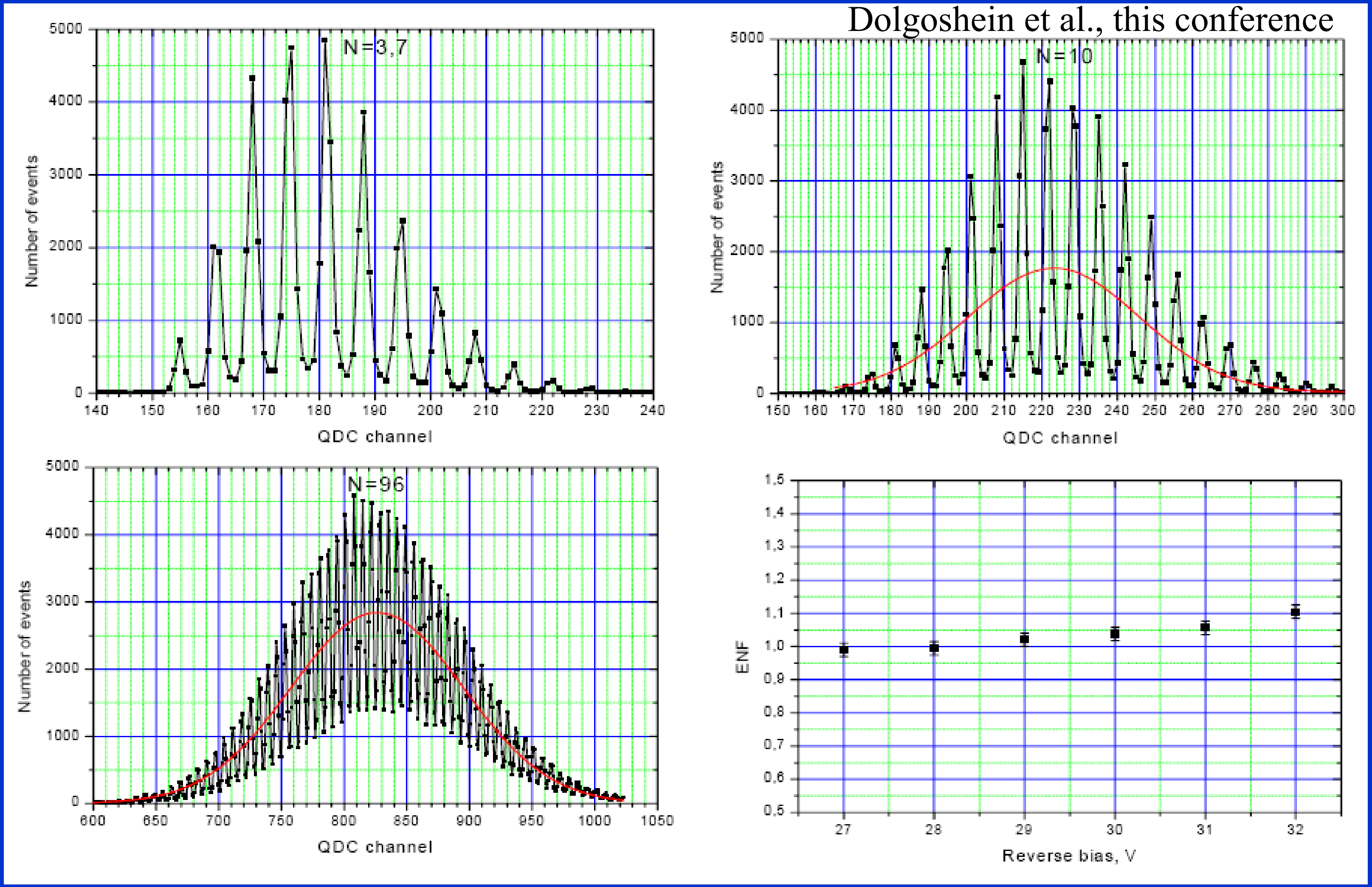
Possible emission mechanisms

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

What can happen when the cross-talk is much suppressed

Dolgoshein et al., this conference

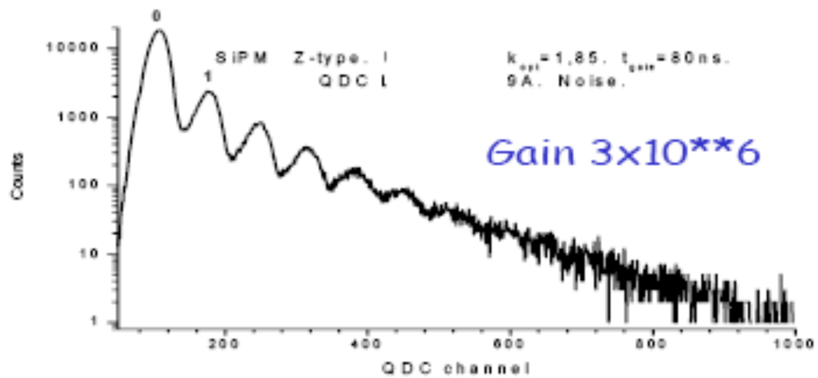


Short Summary

- In the 1st time we have measured the absolute light emission from an avalanche process in Si in the entire wavelength range 450-1600 nm.
- The measured value in the optical is in agreement with some selected measurements within factor of 2
- This measurement may help researchers in modeling the theory aspects of the light emission in Si avalanches
- This measurement may help researchers to better the design of SiPM matrixes as well as of (SiPM + scintillator) detectors

→ Long tail in SiPM pulse hight distribution vs threshold

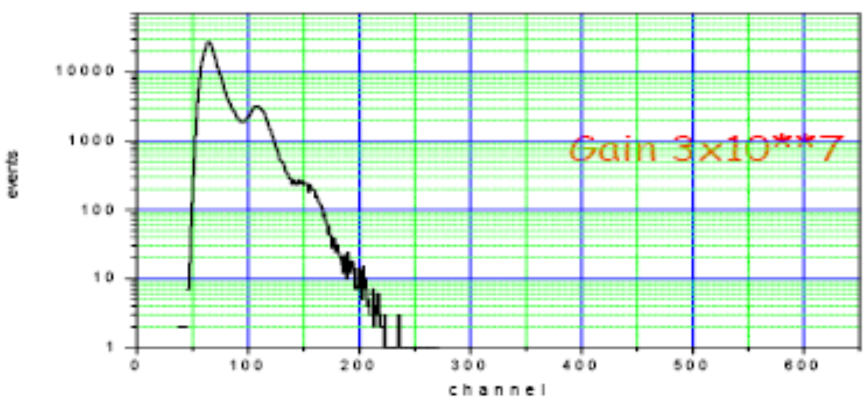
Optical crosstalk,SiPM 1x1 mm2,dark noise



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

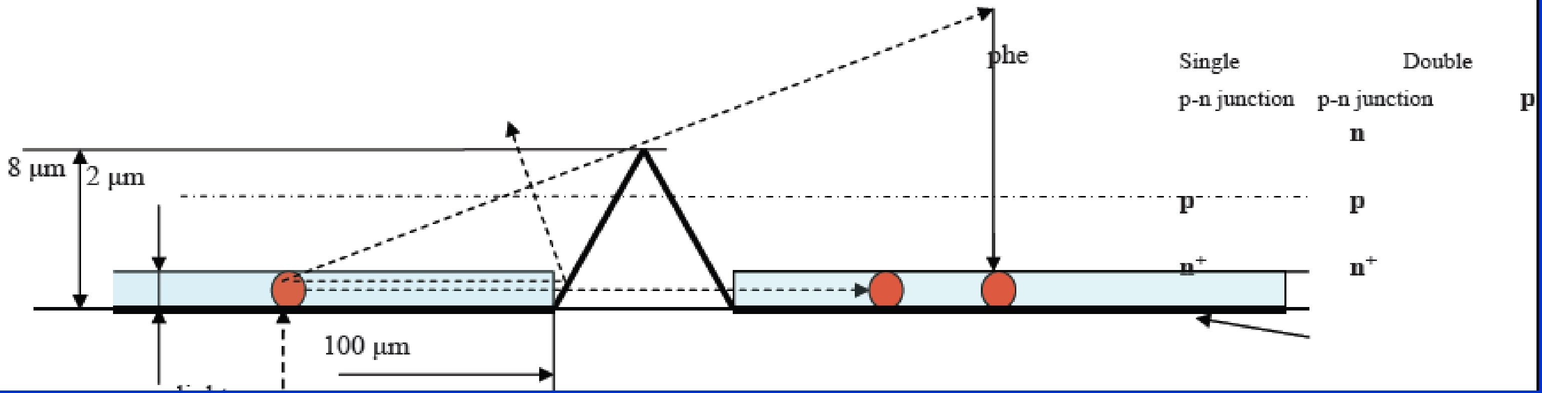
OC has two components

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

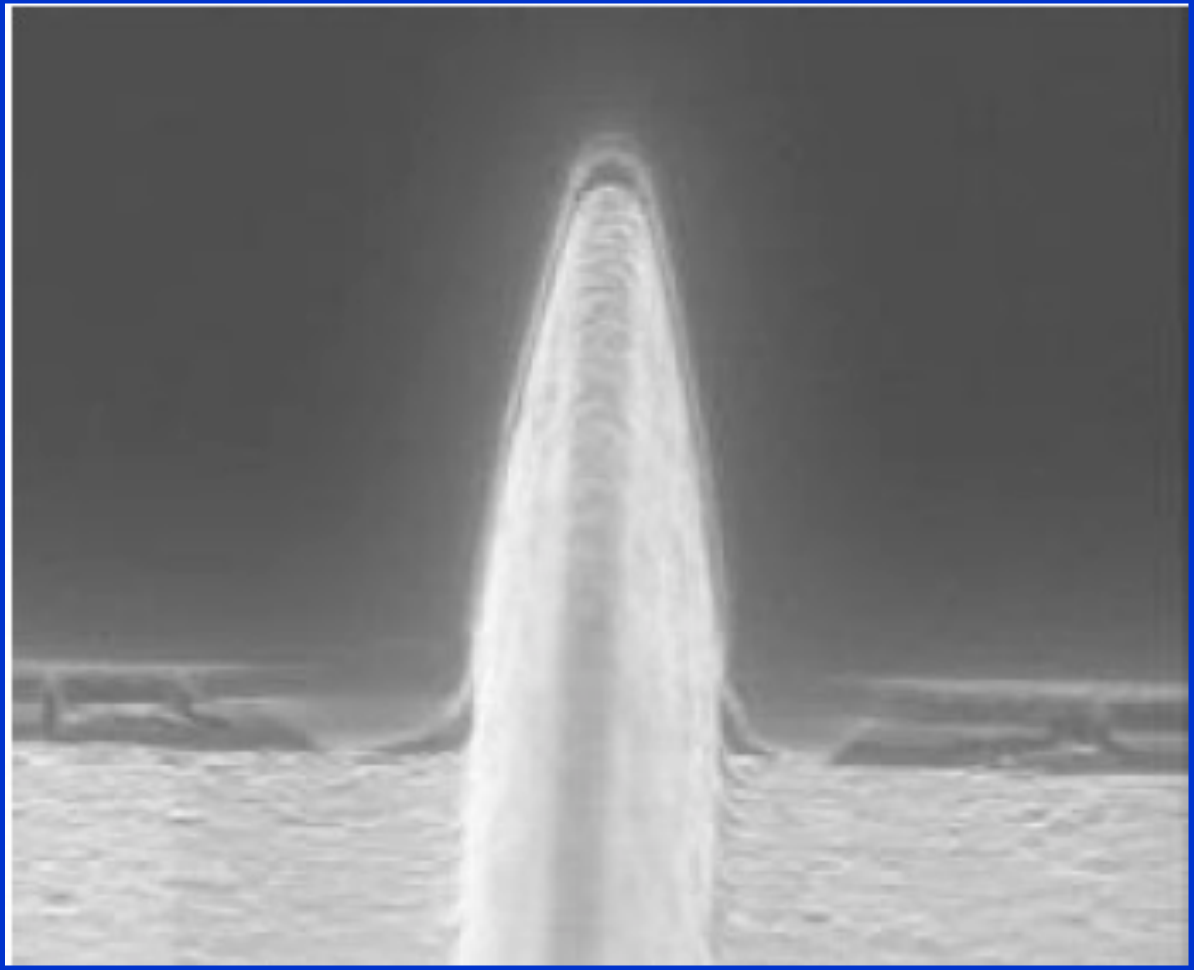
→this mechanism is very fast: ~1ns(prompt OC)

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

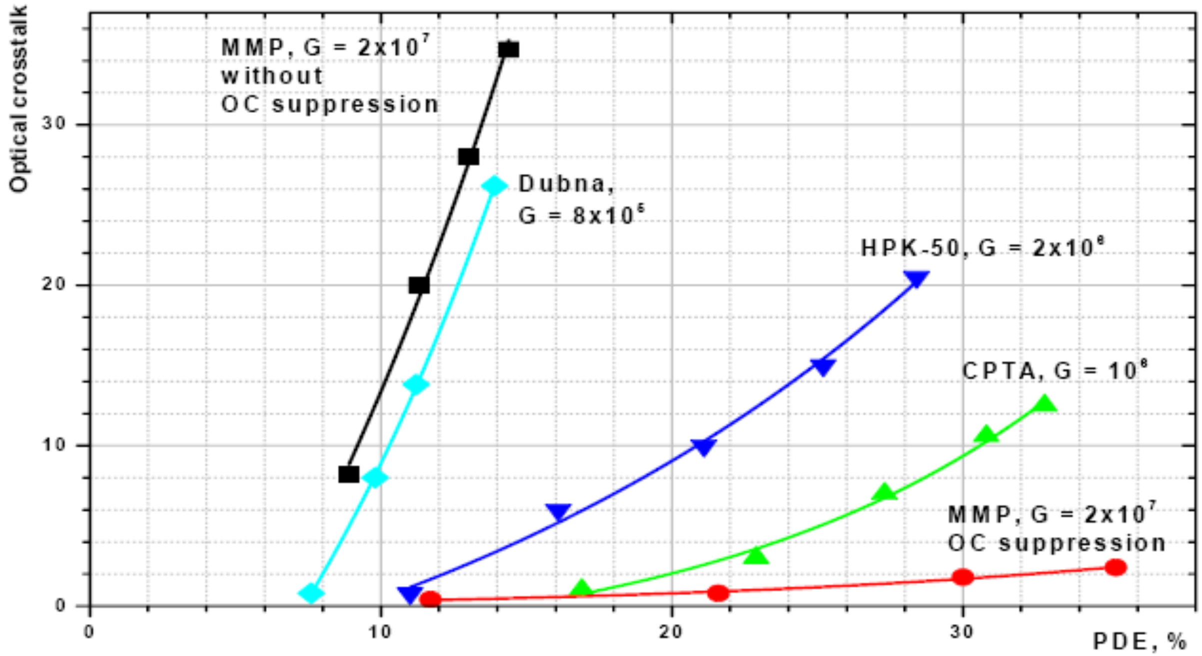


Comparison with other producers devices

-extracted from measurements made by Yu.Musienko,PD07,Kobe,2007

➔ Let's define the Optical Crosstalk as

OC = N(threshold > .5 phe) / N(threshold > 1.5 phe)



5x5 mm2 SiPM: OC+AP(RquenchxCpix = .5mks) =~2.5%,
for PDE=36%,Gain+2x10*7

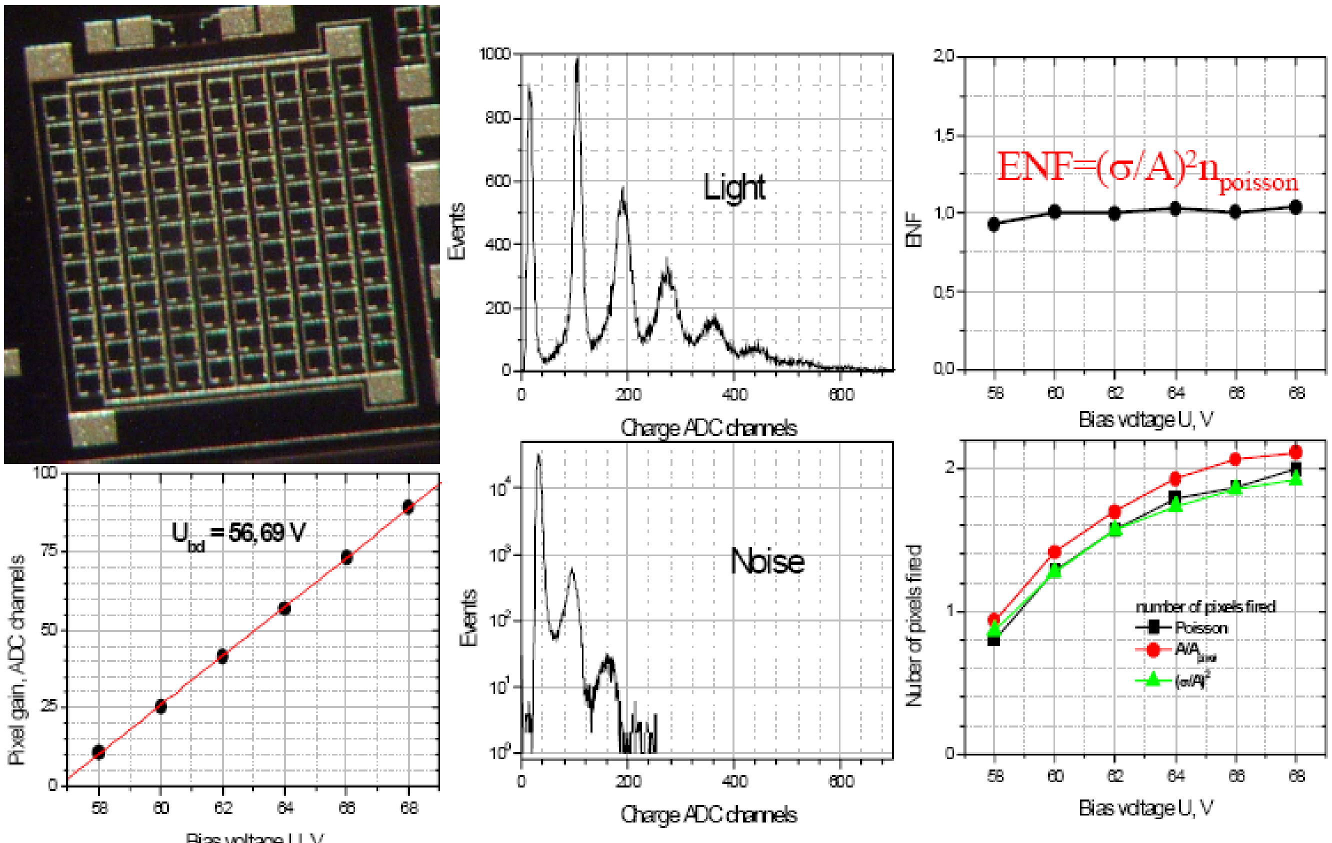
Production and performance of 5x5mm2 SiPM for MAGIC telescope
with suppression of OC and AP

MAGIC requirements discussed:

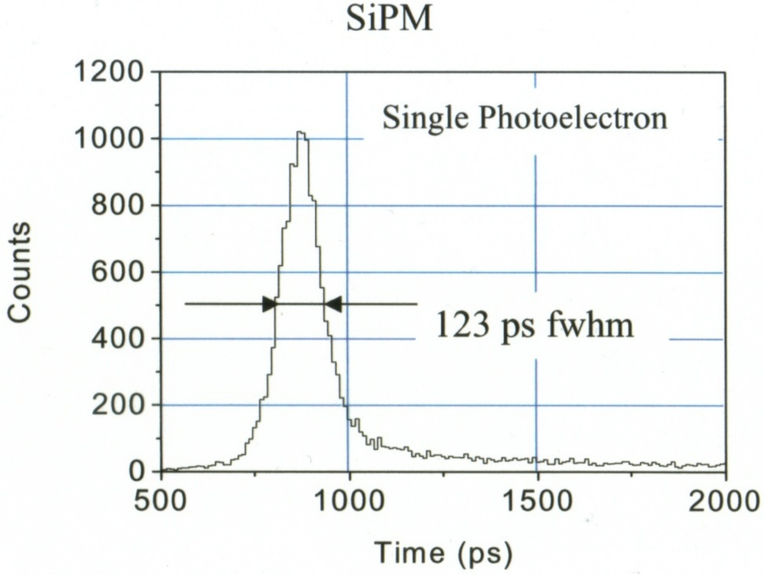
→ one cell of photodetector plane	2 cm2
with a photosensor	1 cm2
matrix	of 4(5x5mm2) SiPMs
→ spectral response	~350-650 nm
→ PDE:	as much as possible(compared to PMT)
→ Afterpulsing	<1-2%
→ Optical Crosstalk	<5%
→ single phe pulse width	~2ns
→ dark rate:	less than Light Of Night Sky(LONS) =~600 kHz/mm2

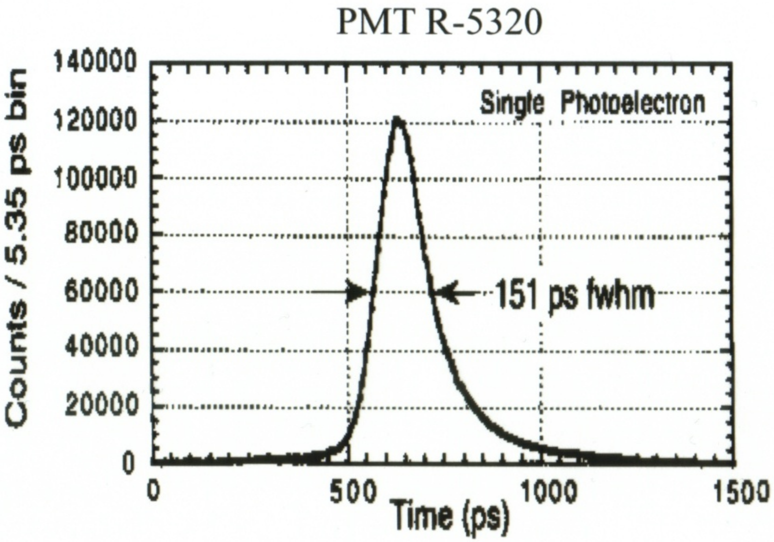
→ ~300 KHz/mm2 or ~8 MHz/5x5mm2

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



Timing by SiPM: possible application for Cherenkov Imaging Counters



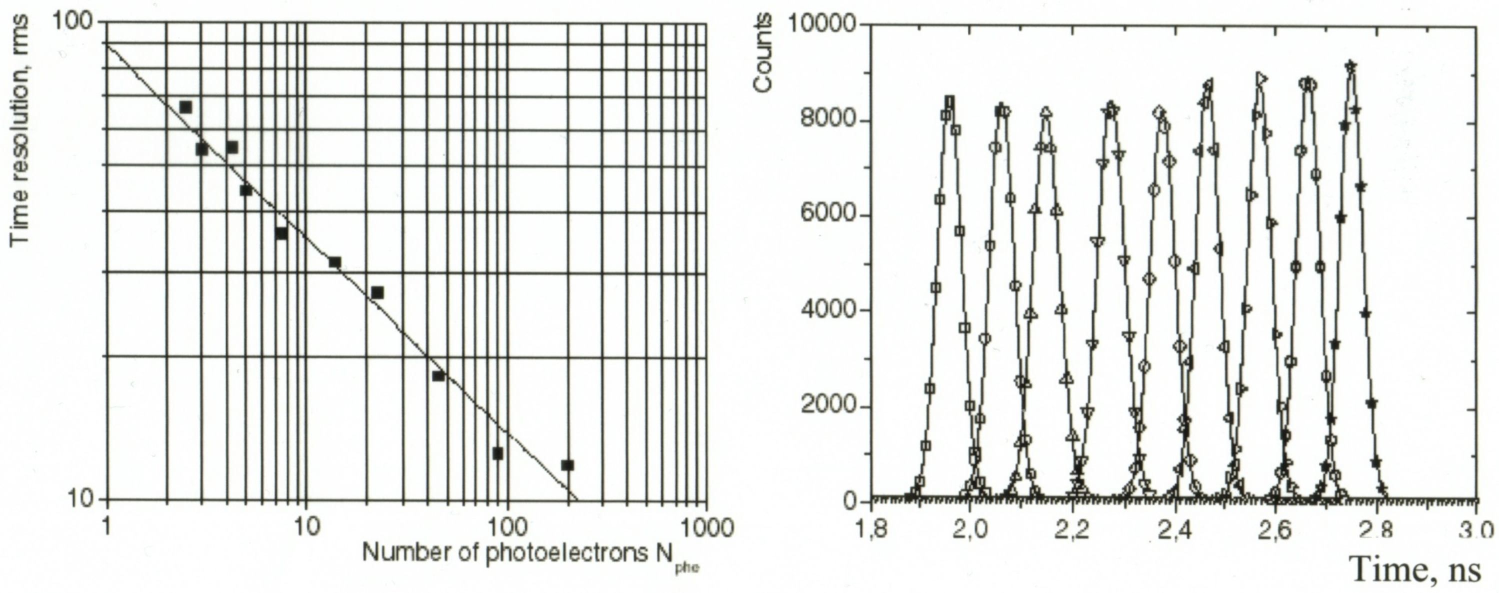


SiPM:

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

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

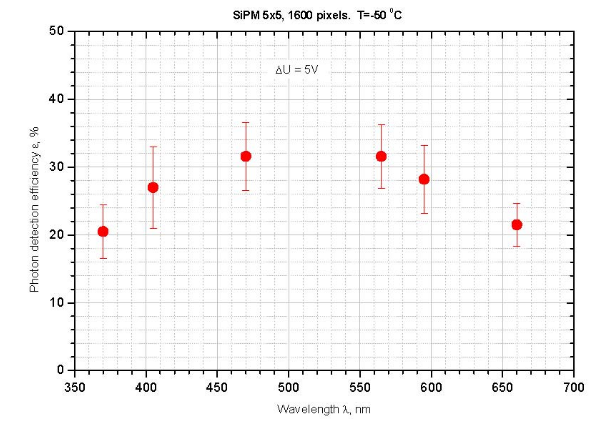
SiPM time resolution



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



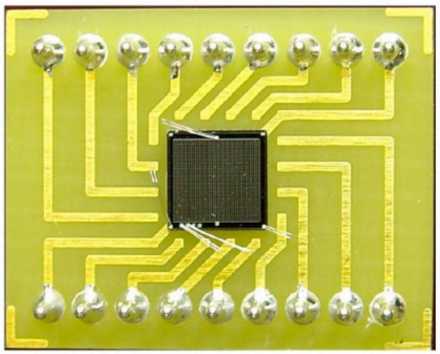


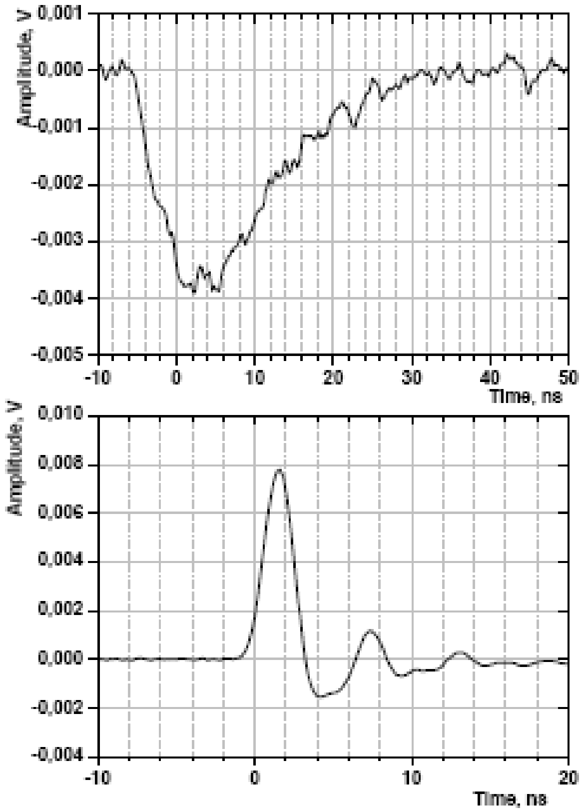
Figure 3: $25(5 \times 5)mm^2$ SiPM. It consists of the array of $1600(40 \times 40)$ micropixels with $100 \times 100\mu m^2$ size.

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

Optical crosstalk OC

One phe gives rise more than one pixel fired due to secondary photons
~ 3x 10*5 photons(~1000nm) per one electron in Geiger discharge

OC

-- does not depend on temperature
-- proportional to
Gain x Photon Detection Efficiency

The larger PDE
→ the larger pixel size
→ The larger Gain

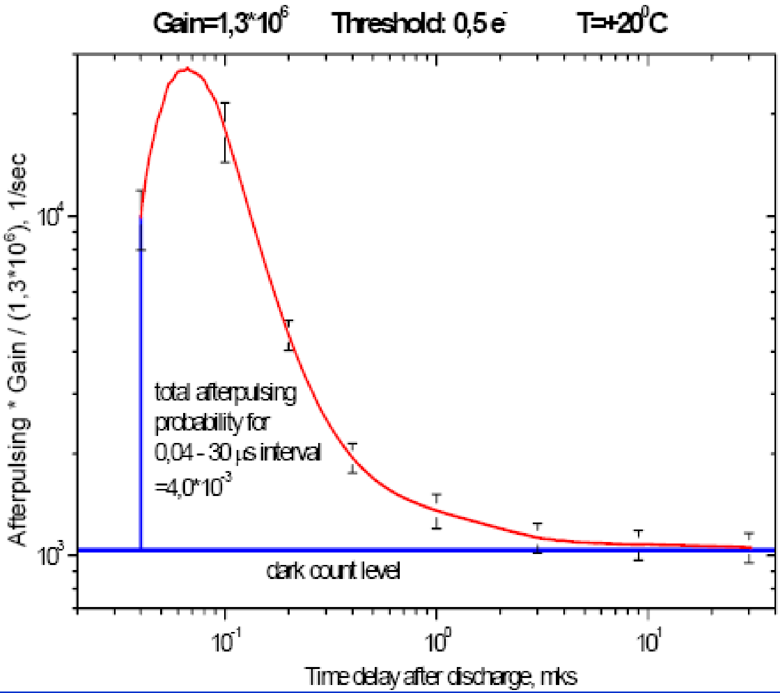
Afterpulsing AP

Capture of avalanche electron by traps and its delayed release giving the secondary Geiger discharge in the same pixel

AP

-- proportional to
Gain x PDE
-- increases for low temperature the same recovery time because trap lifetime increase

→ 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:

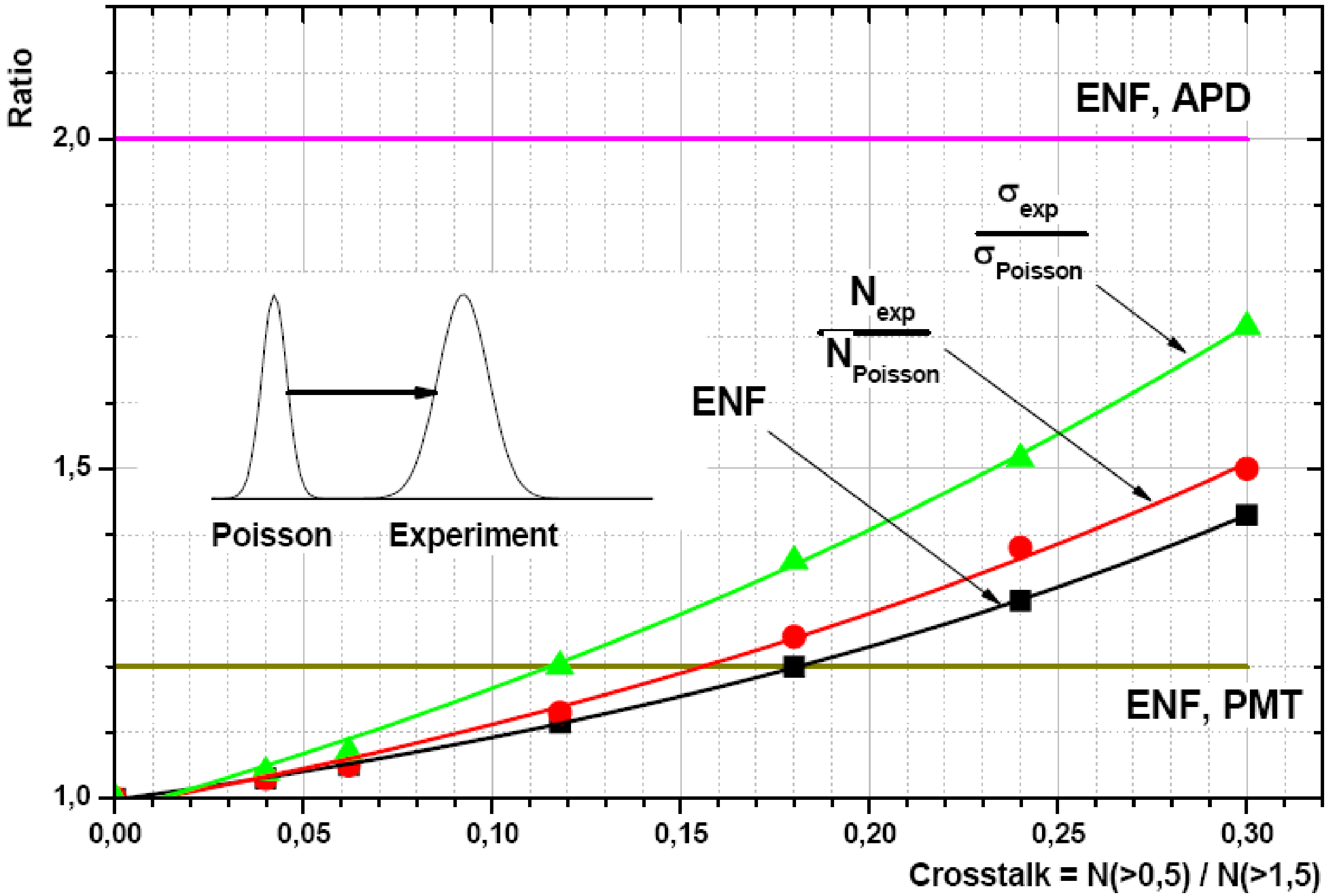
→ SiPM pulse hight resolution is worsening:

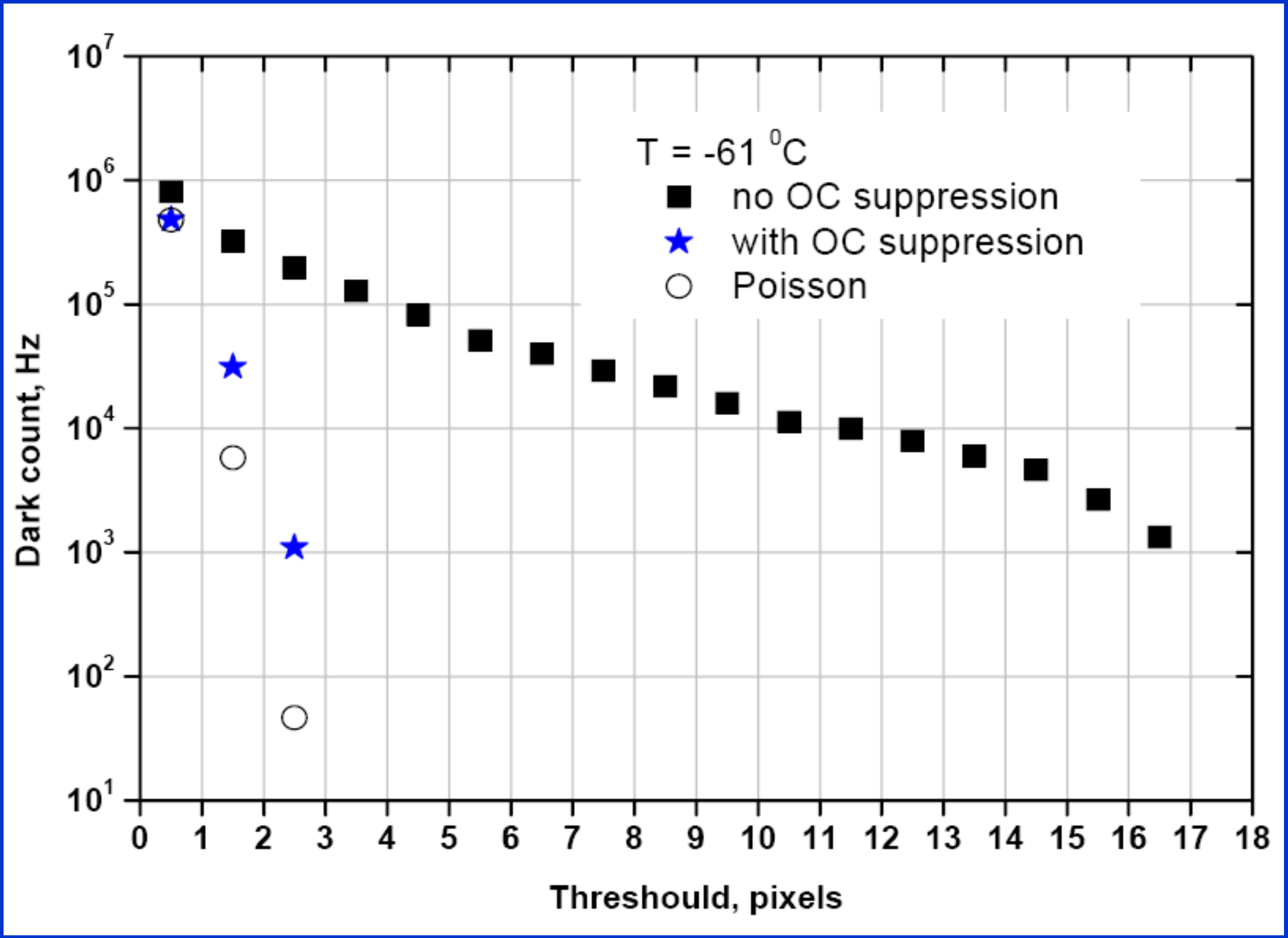
→(sigma/A)*2 > 1/N phe

Excess Noise Factor ENF >1

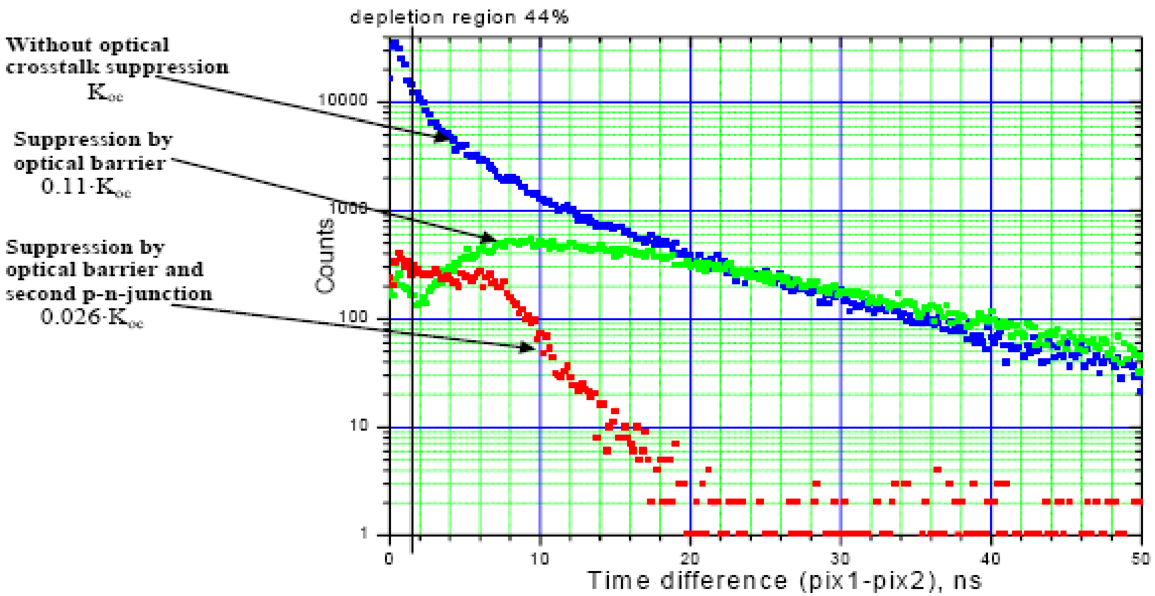
→Sci Spectrometry(PET etc.) ?

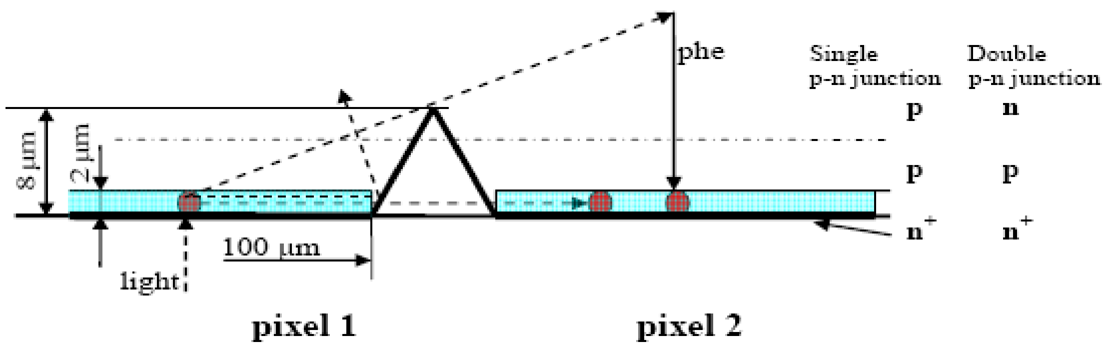
ENF:	for PMT ~ 1.2
	for APD ~ 2-2.5
	for SiPM(desirable) < 1.05


Ratio
2,0
1,5
1,0
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)


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

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%

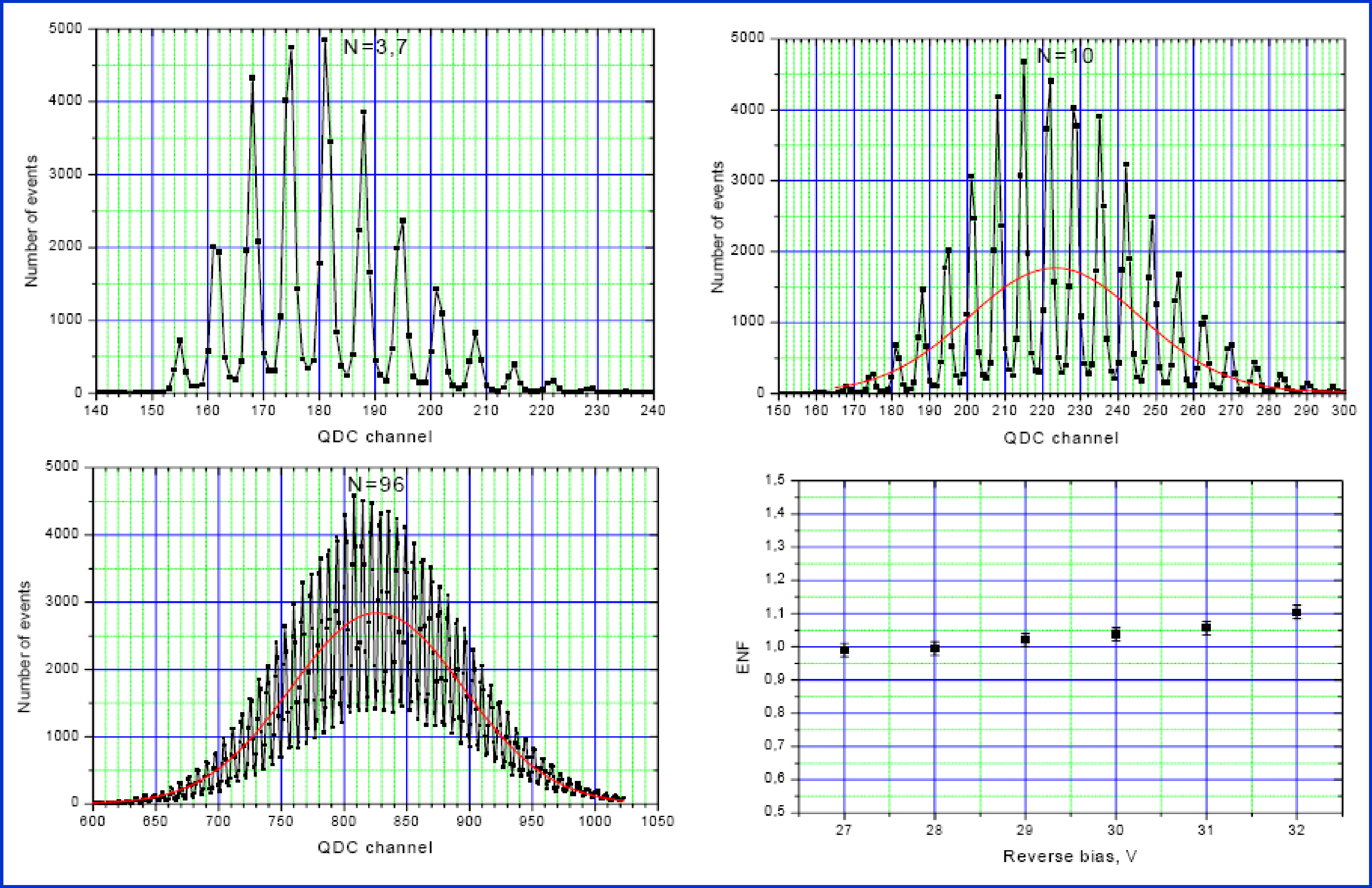
OPTICAL CROSSTALK SUPPRESSION FACTOR:

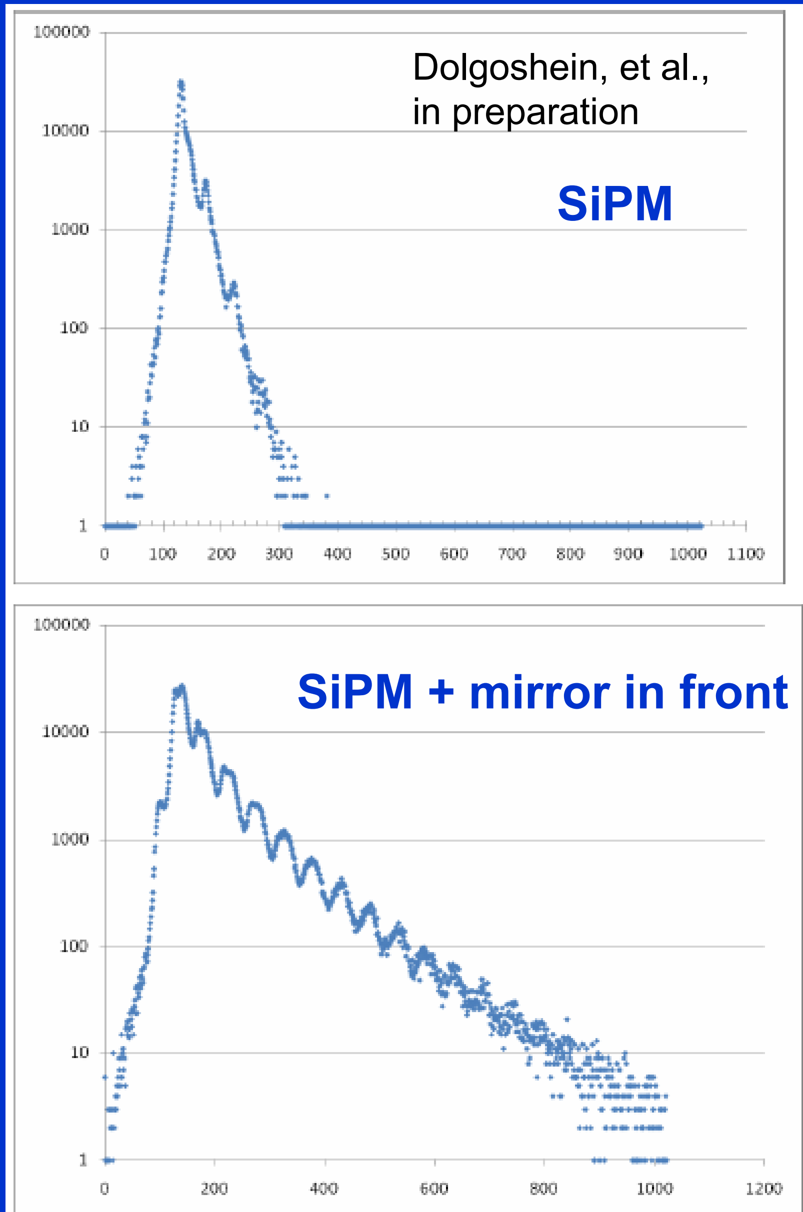
→ with optical barriers(tranches,8mkm deep) ~9

→ 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)

Conclusions

- The optical cross-talk has strong impact on SiPM seriously degrading its performance
- We have developed successful measures against it (trenches + double junction)
- The SiPM is on the way of becoming (almost) an ideal LLL sensor within next 2-3 years
- Within the next several years we will observe how they will replace the APDs and the PMTs from many „classical“ applications, including those in life sciences and probably, also in medicine
- Still they are expensive because of the monopoly of essentially one big producer