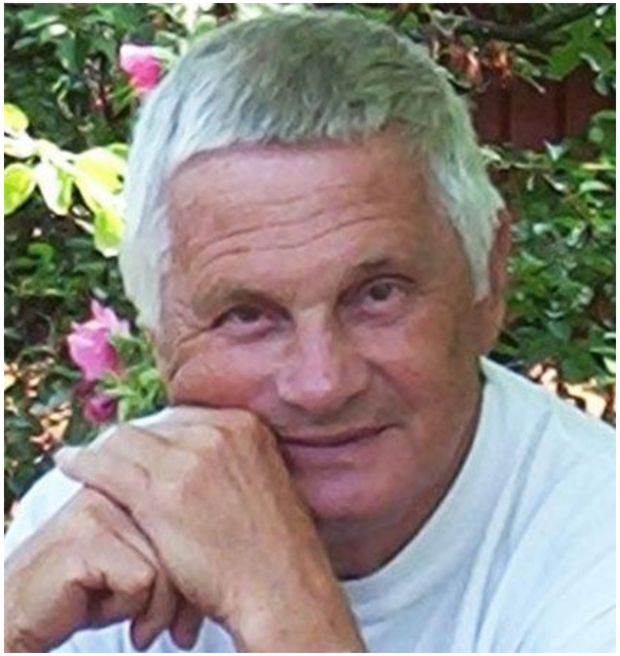
Homage to Boris Dolgoshein
(1930-2010)



Chasing the Ideal LLL Detector:

Large, UV Sensitive SiPMs with very high PDE & extremely low X-talk

Razmik Mirzoyan

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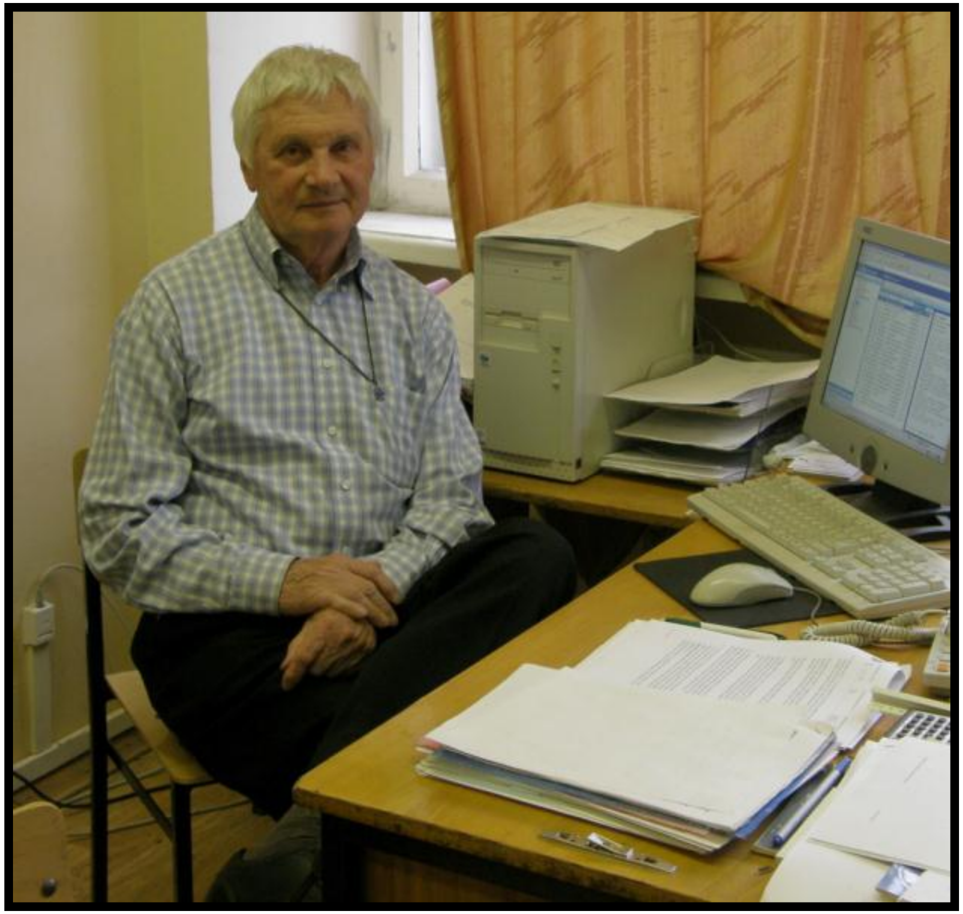
Homage to Boris Dolgoshein



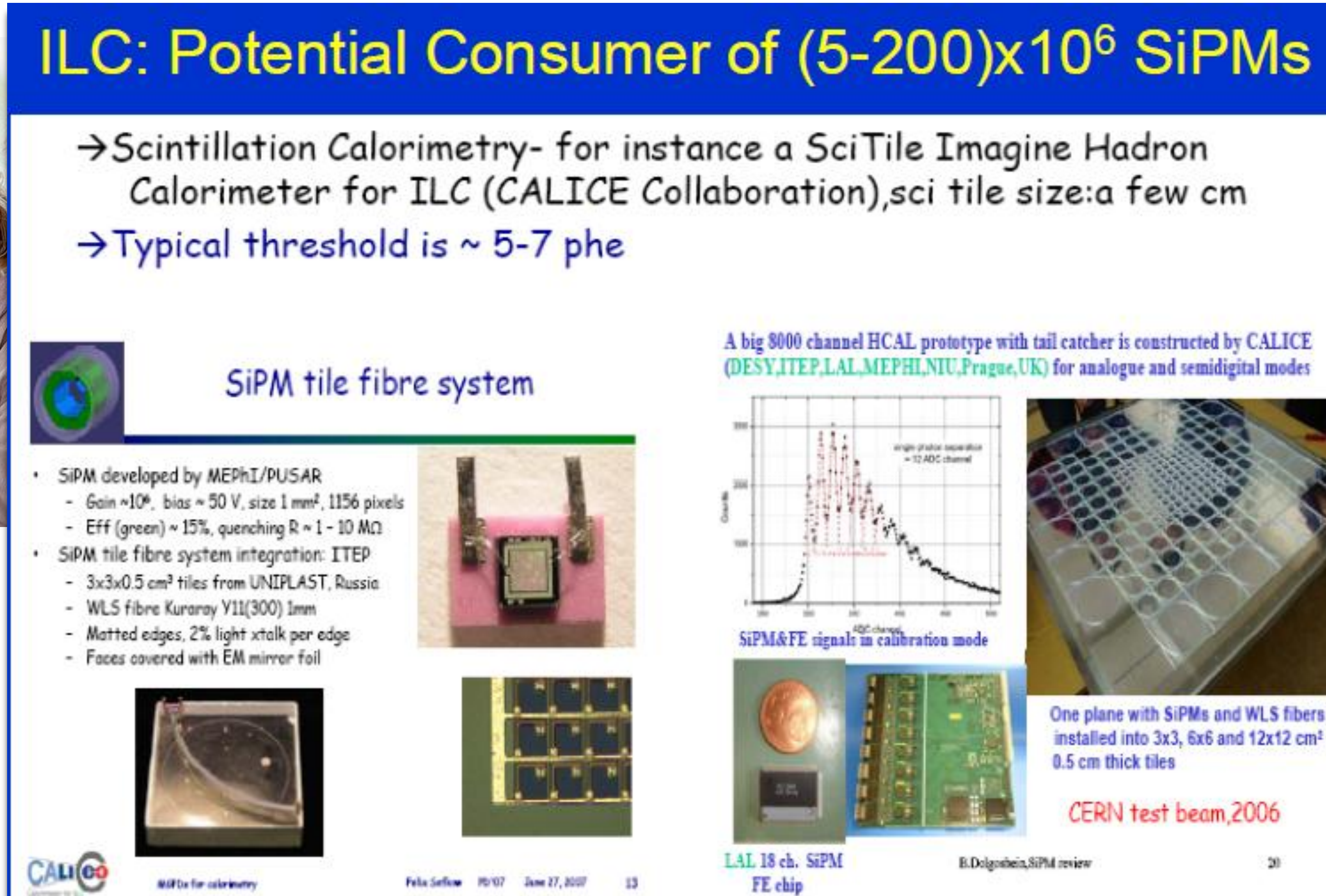
- Professor, head of the particle-physics department in MEPHI
- Inventor of streamer chamber (1962)
- Developer and pioneer of Transition Radiation Detector (TRD)
- Since 1993 developing a new photon detector which he gave the name Silicon Photo-Multiplier (SiPM).

Homage to Boris Dolgoshein

- 1st in the world large-scale SiPM application in Hadron Calorimeter prototype (~10^4 SiPM channels)
- In the beginning collaborating with DESY and then with the Max-Planck Institute for Physics in Munich on SiPM
- Developing UV sensitive SiPM with extremely low X-talk and very high PDE for the MAGIC and EUSO experiments, 2002-2010

Homage to Boris Dolgoshein

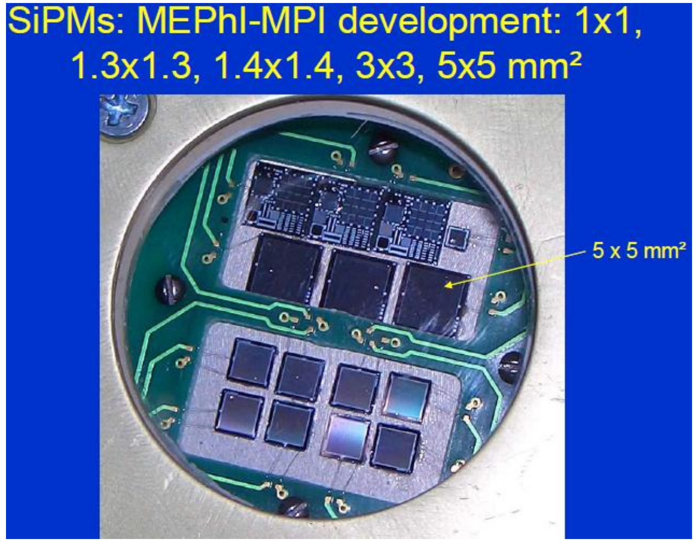
Boris at „Medical Imaging-2010“ in Stockholm, June 2010

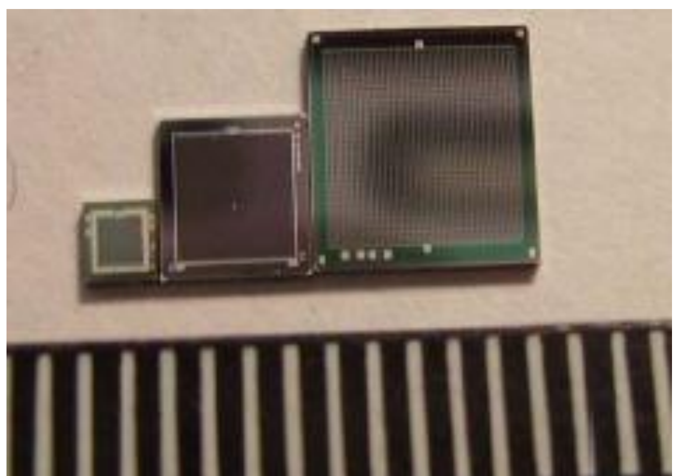


R. Mirzoyan: Dream of Boris- Large SiPMs with maximum PDE and almost no X-talk

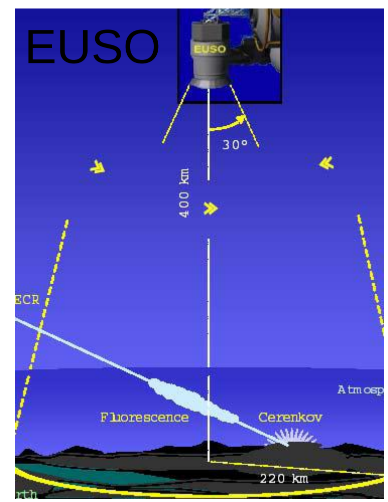
Homage to Boris Dolgoshein

5 patents on SiPM applied in many countries worldwide





R. Mirzoyan: Dream of Boris- Large SiPMs with maximum PDE and almost no X-talk



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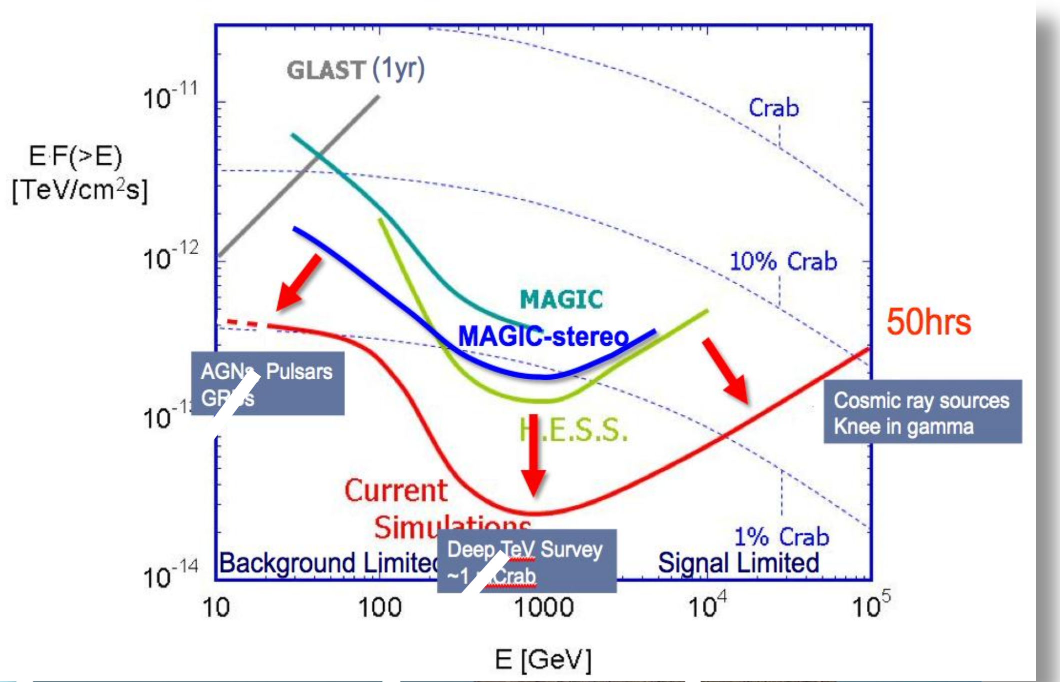
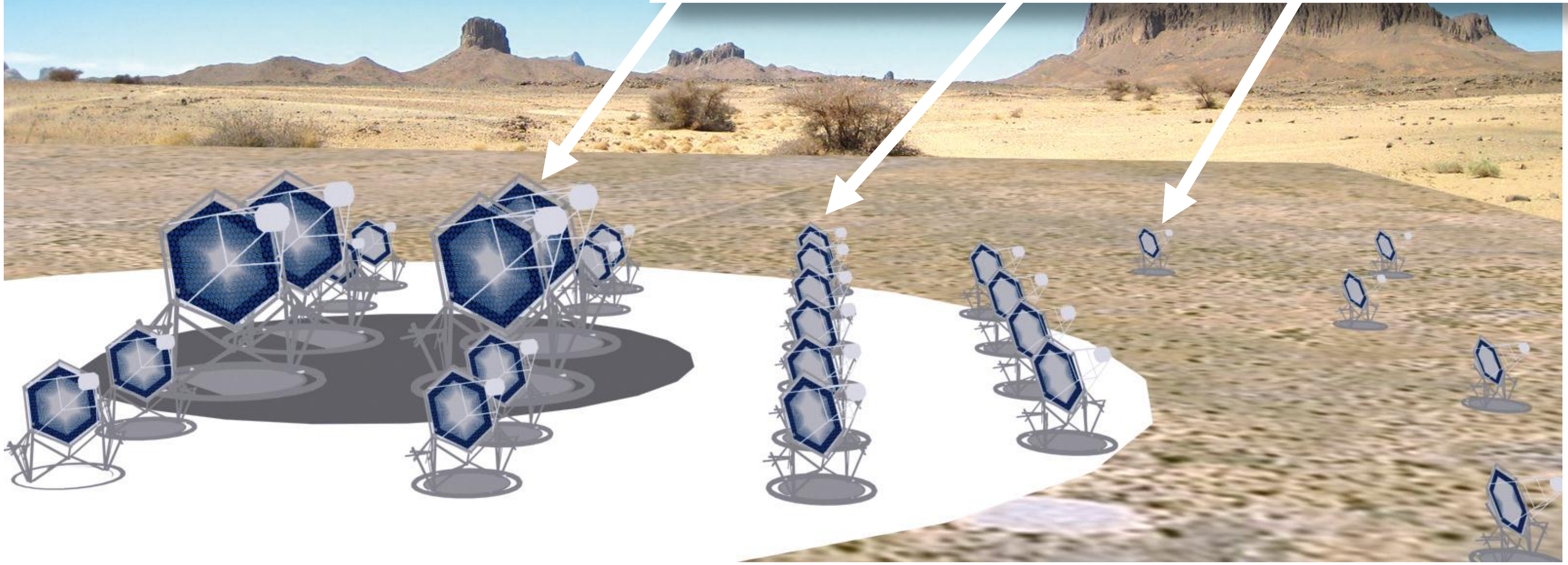
The Imaging Air Cherenkov γ-ray Telescopes employ cameras of 1-3 m in ø, covered by closely packed 1000-2000 PMTs

CTA

~840 scientists Europe, USA and Japan plan to build ~100 telescopes of 3 sizes





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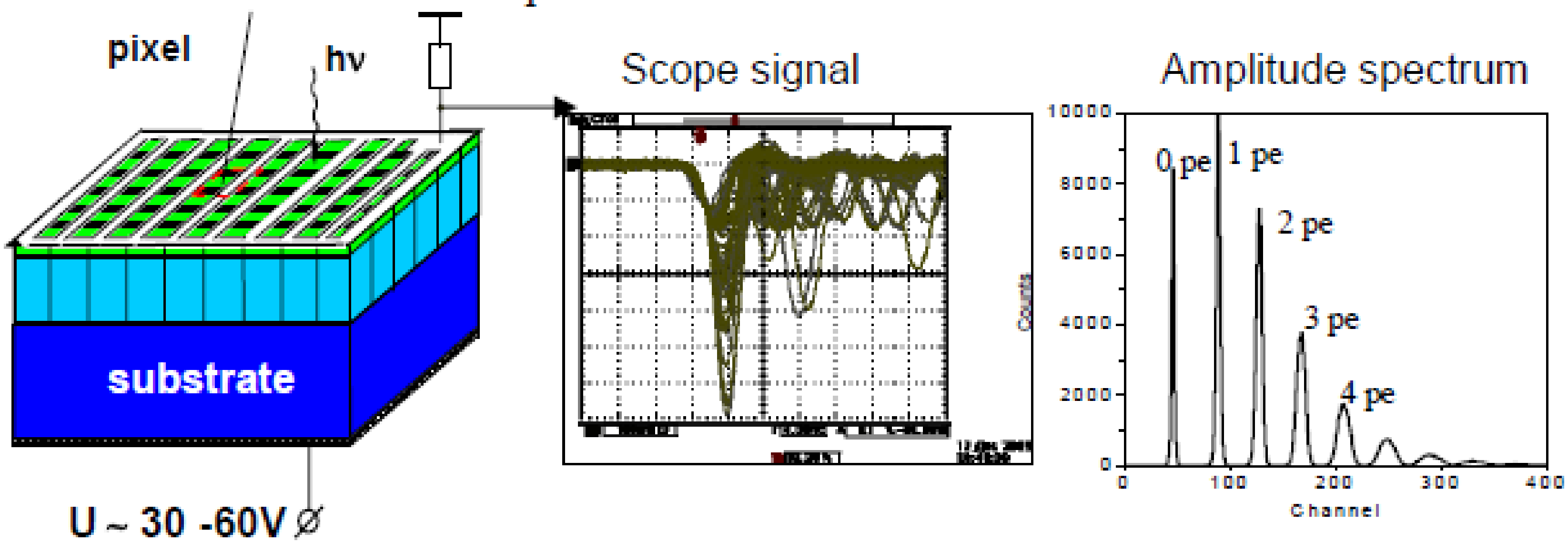
R. Mirzoyan: Dream of Boris- Large SiPMs with maximum PDE and almost no X-talk

Silicon Photomultiplier (SiPM)

The novel type of photon detector

Multipixel device with common readout



SiPM - main features:

- Each pixel – reverse biased above breakdown p-n-junction operated in selfquenching Geiger mode
- Sensitivity to single photons
- Pixel gain ~ 10^6-10^7
- Pixels number: ~ 100 - 10000/mm^2
- Pixel recovery time $R_{pixel}*C_{pixel}$~30ns ÷ 1 μs

Pixel signal - 0 or 1
But SiPM is analogue device

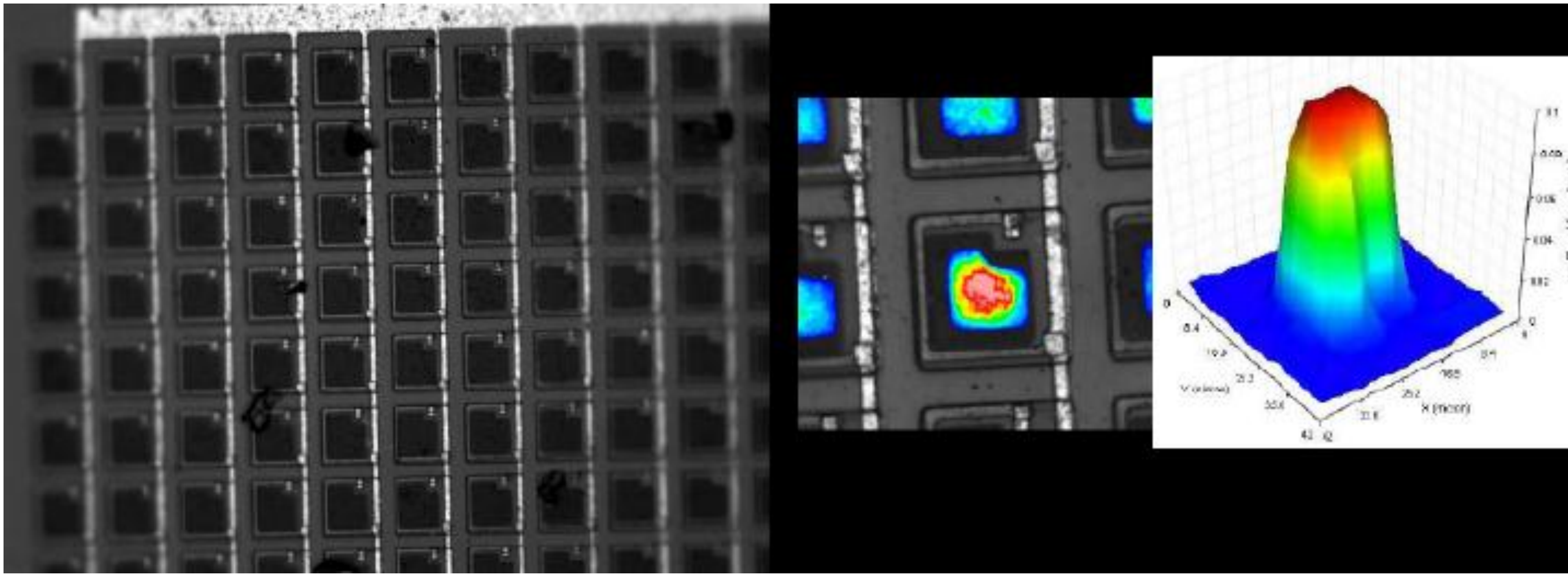
SiPM Essentials

- 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 λ, 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 $\Delta U/U \geq 12\text{-}15$ % could become ≥ 95 %

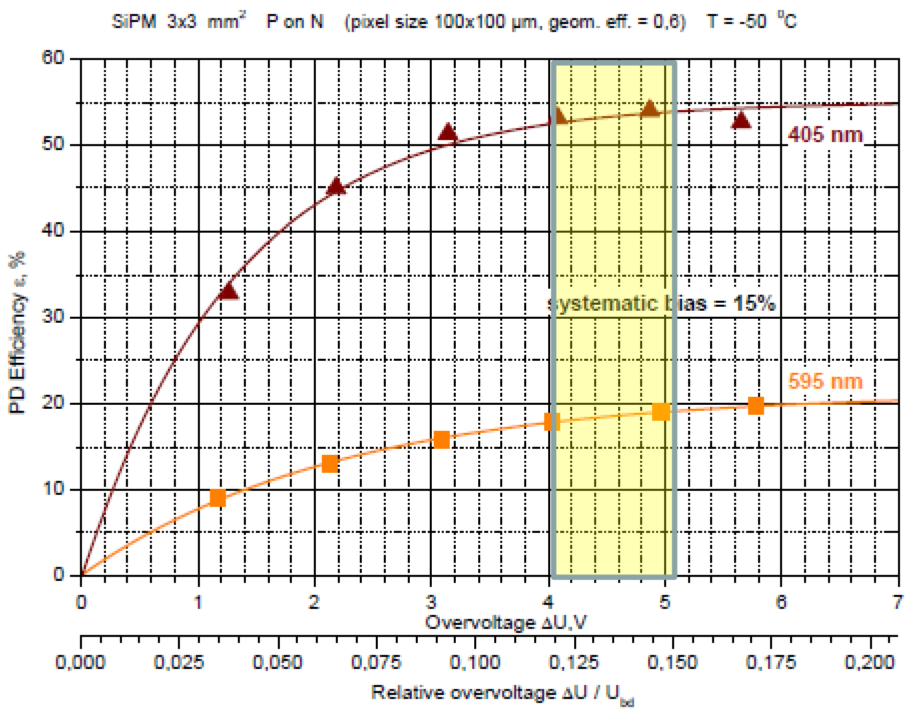
Sensitive area of a cell $A_{\text{active area}}$



Well-optimised SiPM cell topology can provide senstive area as high as ~80 %. Efficiency losses are due to power lines, polysilicon resistor, trenches and implantation profile.

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

Nostell & Roos, Rev. Sc.Ins, 1999

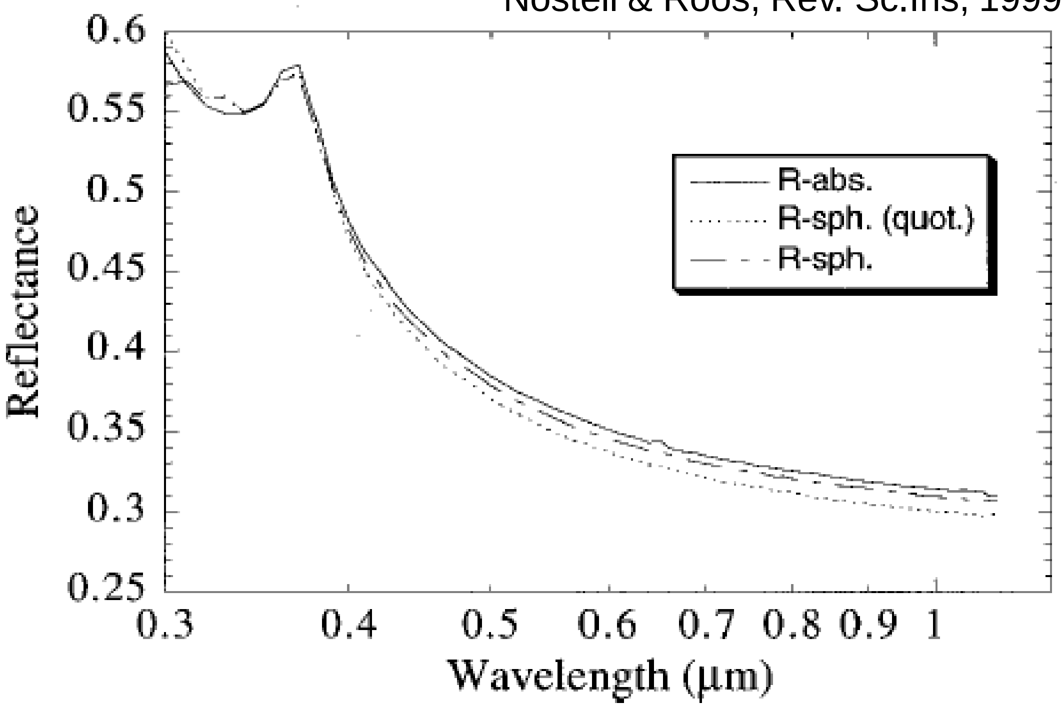
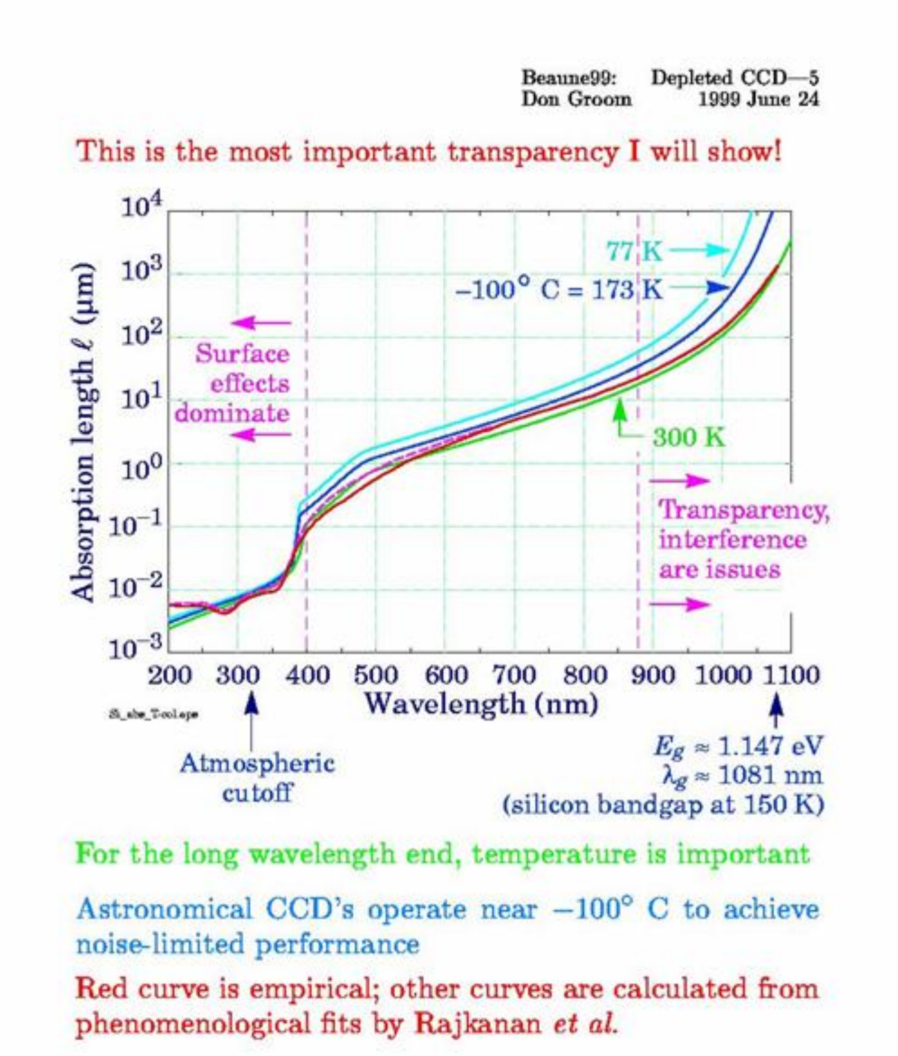


FIG. 19. Near normal reflectance spectra in the wavelength range 0.3–1.1 μm of silicon measured in the absolute spectrophotometer and the reflectance sphere. The reflectance sphere spectra consist of a corrected spectrum, R-sph, and the direct ratio between sample and reference signals, R-sph (quot.).

- Reflectivity of Si varies In the range of ~ 60 – 31 % for the wavelength range 300 – 1000 nm at normal incidence.
- It is obvious that one needs to apply anti--reflective coatings for improving the light Transmission
- Proper choice of the window coating can provide efficiency ≥ 80-90 %

Reminder: light absorption in Si



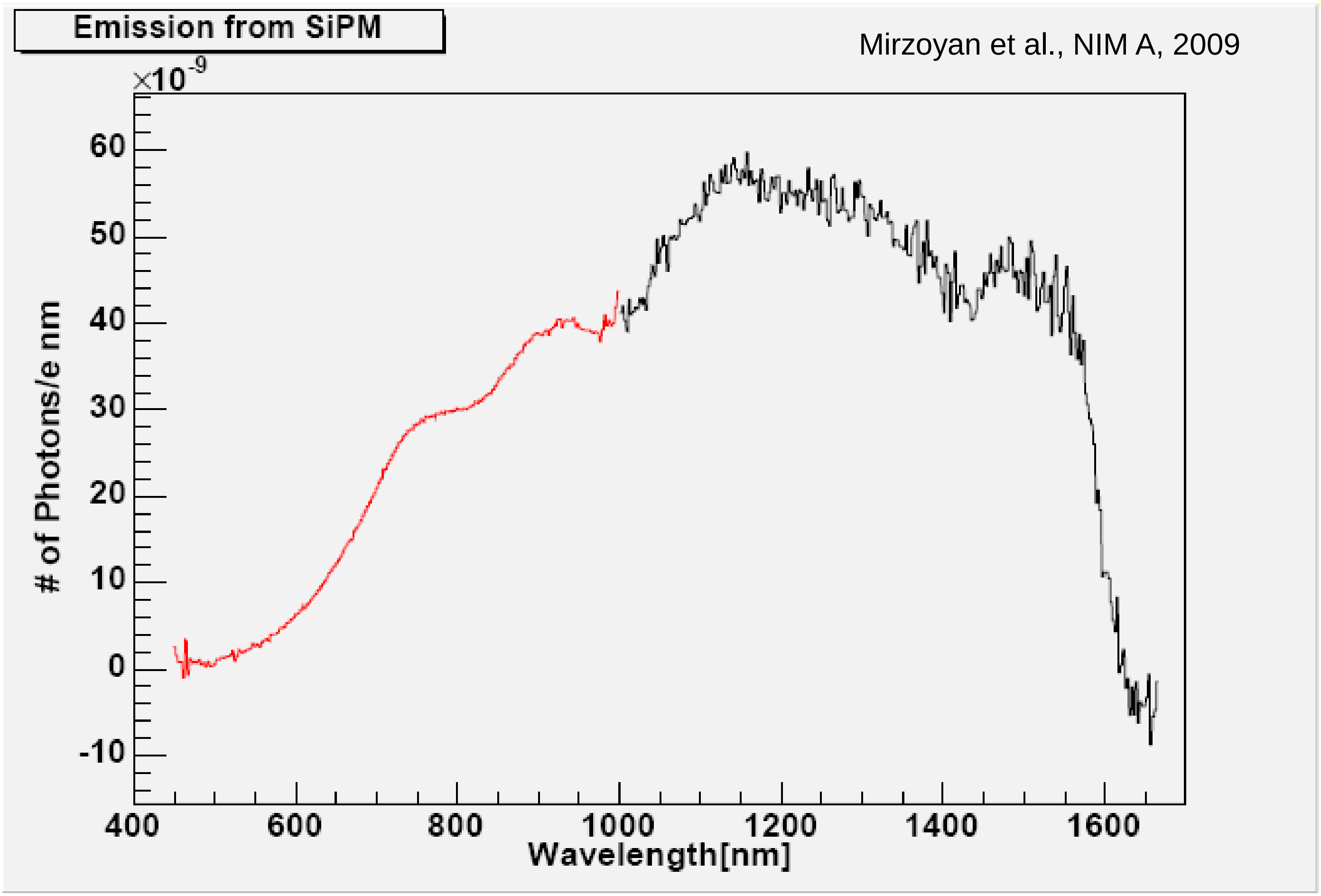
- While light of wavelength 1000nm can penetrate ~100 µm deep into Si, light of 300 nm wavelength can penetrate only 5-7 nm!

- It is a major challenge to collect produced charge carriers from the very surface of the sensor, providing blue – near UV sensitivity

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

Light emission spectrum from Si



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

The PDE and the large cell size

- For max. PDE one needs 1) a large cell size and 2) to operate the SiPM @ high Geiger efficiency
- For this one needs to apply a high over-voltage $\Delta U/U$, which means operating them under very high gain.
- Light emission in Si avalanches is ~ to the number of e^- in the discharge. A high gain means a very high-level of X-talk
- X-talk can become so intense as to simply prohibit the functionality of the sensors.
- This is becoming especially important for large cell area SiPMs.

  A 100µm x 100µm size cell has 16-times larger area and capacitance C than a 25µm x25µm cell. Correspondingly it has 16-times higher gain: $Q = C \times \Delta U$. ➔ 16-times higher light emission → 16-times higher X-talk
- The X-talk in SiPM is one of the main problems limiting the PDE

Cross-Talk: X-talk

X-talk has (at least) 2 components:

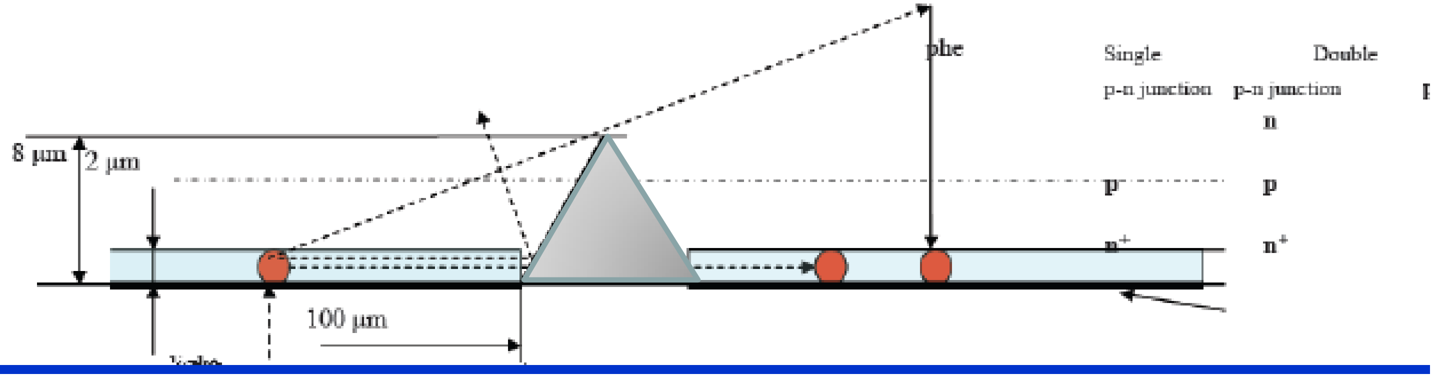
P. Buzhan, B. Dolgoshein, et al., 2009

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

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

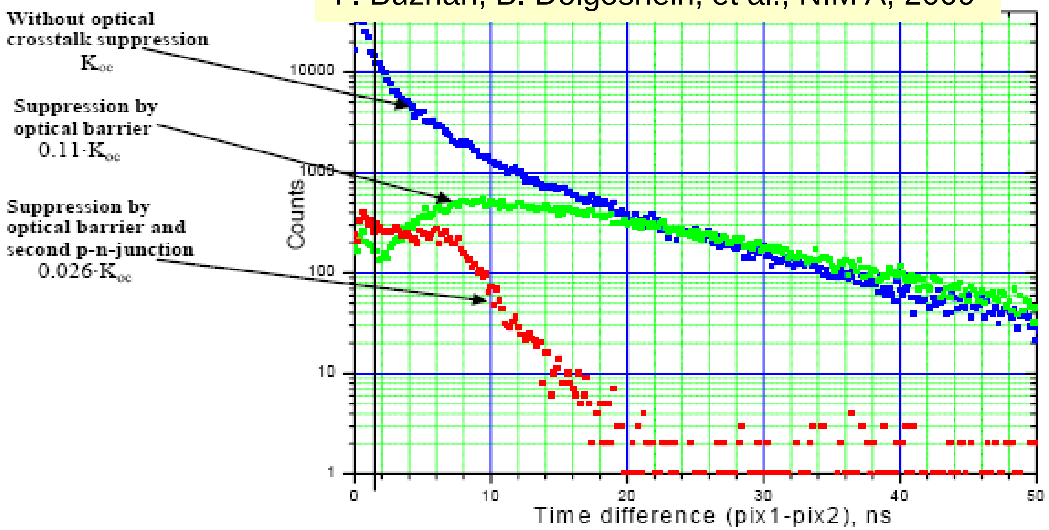
SECOND :The same in undepleted region and then the diffusion(or drift)to high electric field Geiger region of neibouring pixels

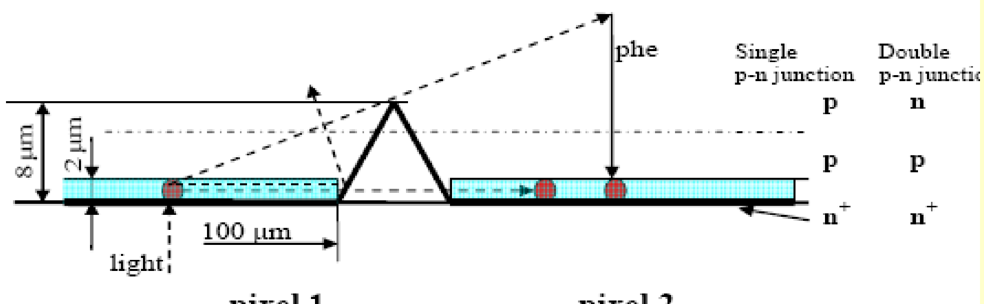
→this process is delayed: later than 1ns



Optical Crosstalk studies

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





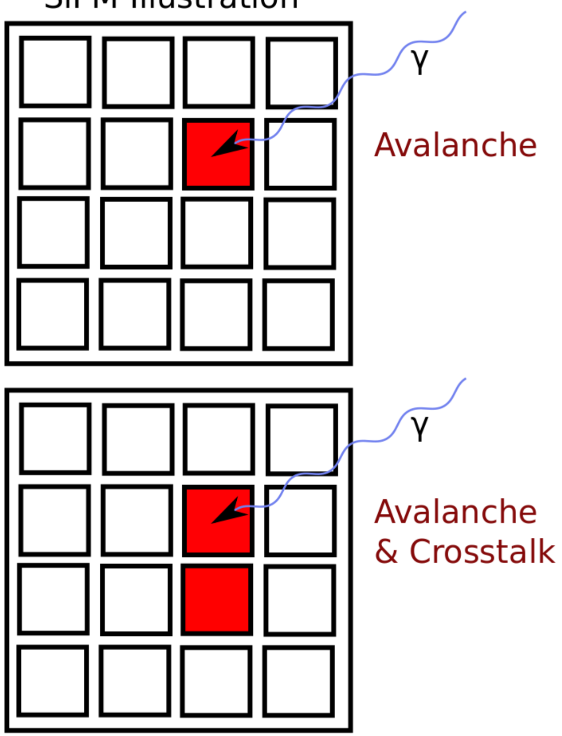
Optical crosstalk between two separate pixels

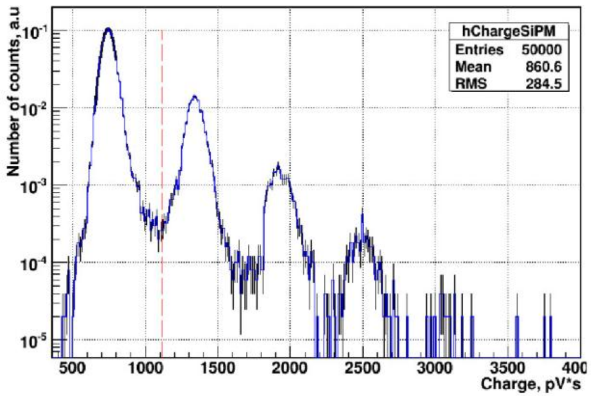
- Only much later on we, people working next to Boris, could (again) fully appreciate the deep insight and vision of SiPM by Boris.
- He understood very early that only strong suppression of the X-talk can allow one to operate them at full efficiency.
- ~6 years ago during 2 years different recepies were tried in ***4-production batches*** for suppressing the X-talk
- That was successful

X-talk in SiPM

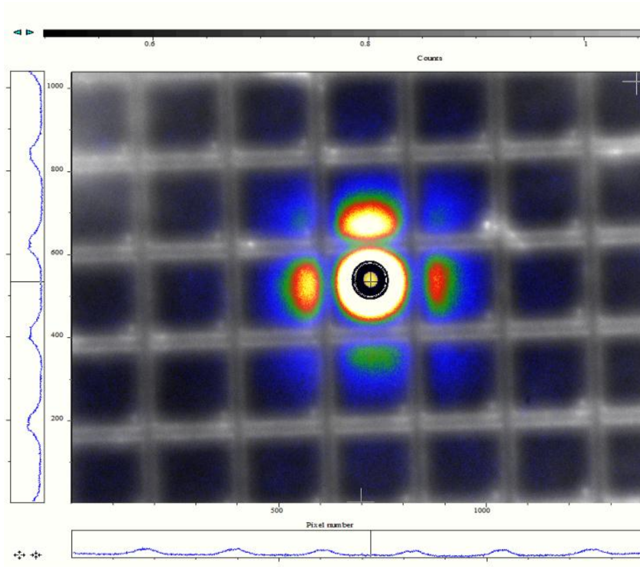
SiPM cross-talk

SiPM Illustration



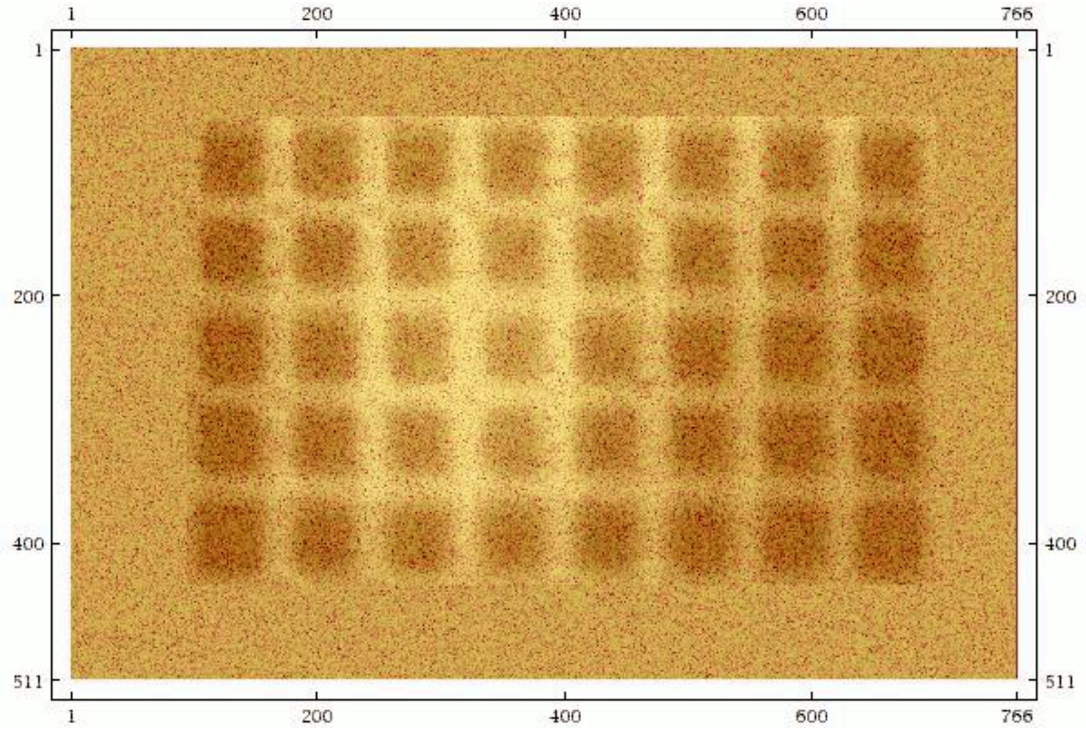


Charge spectrum



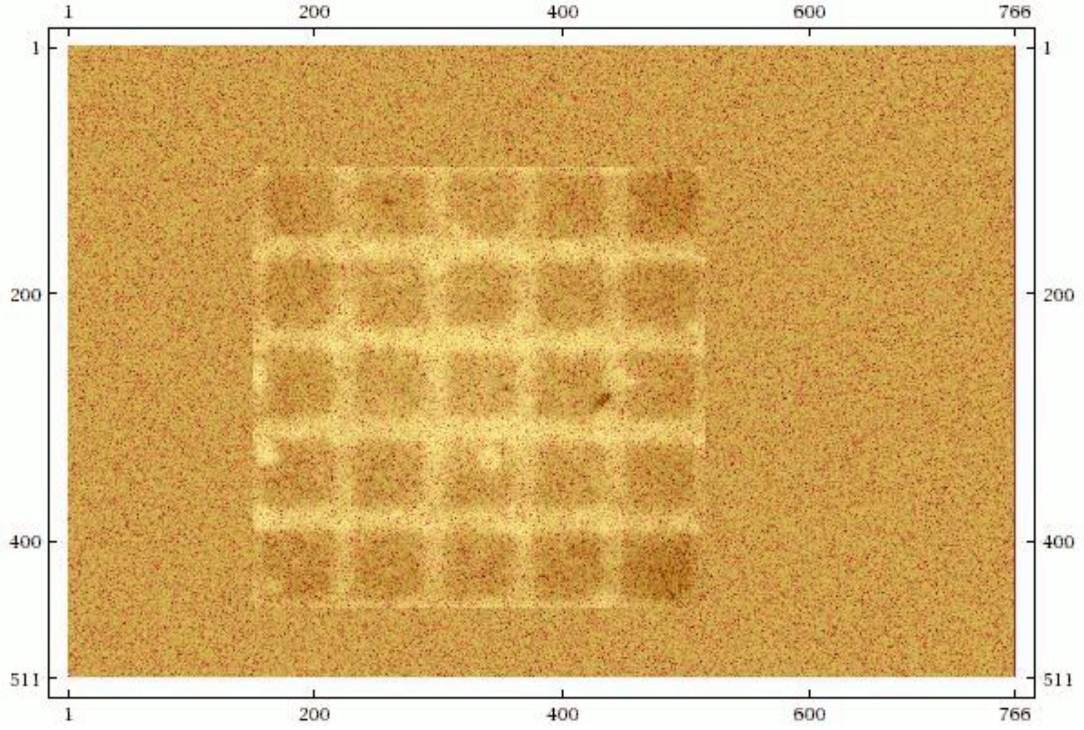
cross-talk morphology

Time Resolved imaging of cross-talk



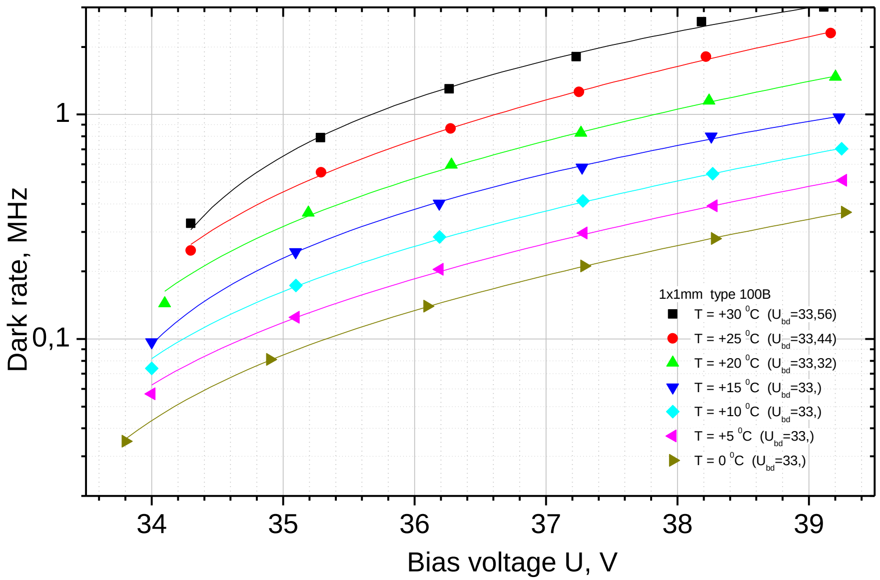
MPPC 33-050-UVE-SIRESIN

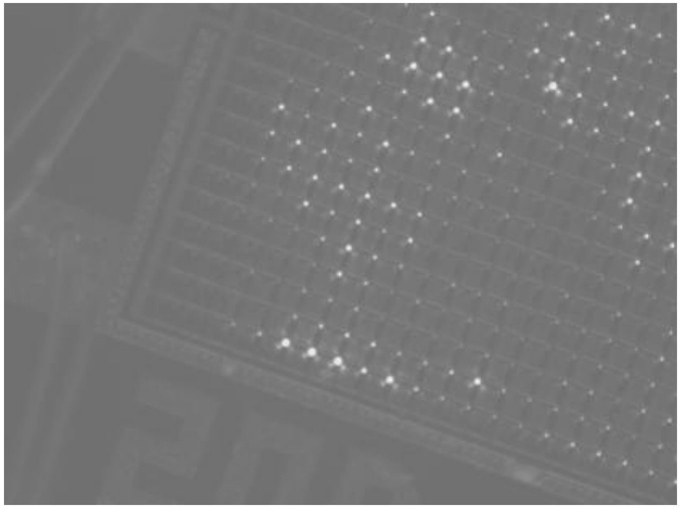
Time Resolved imaging of cross-talk

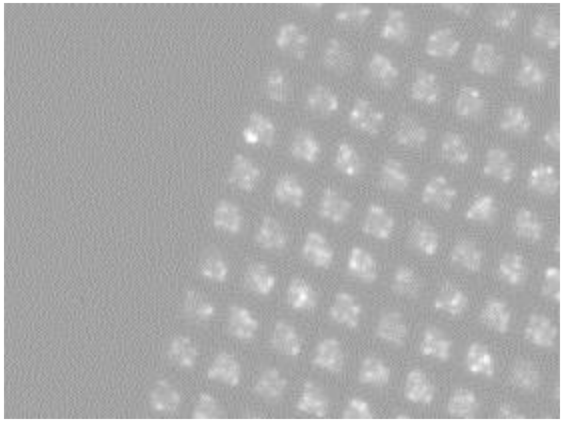


100a – trenches

SiPM Dark Noise







Frequently technical problems during production of SiPM (sharp edges in the high field region) cause excessive light emission (see above)
This heavily contributes into the dark rate, although it is not genuine noise and can be successfully removed in the next production batch.

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R. Mirzoyan: Dream of Boris- Large SiPMs with maximum PDE and almost no X-talk

MEPhI - MPI for Physics R&D collaboration and cooperation with EXCELITAS (former PerkinElmer)

A test batch produced in December 2010

- SiPM Sizes

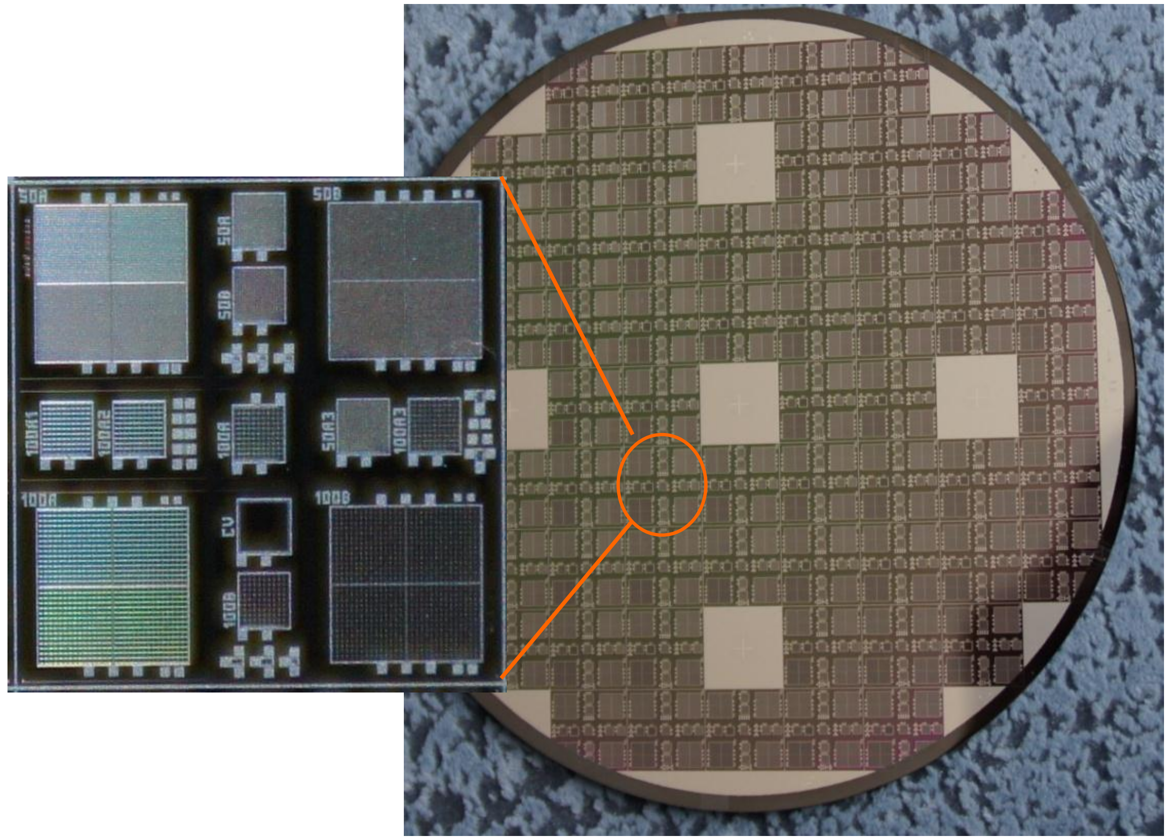
1x1 and 3x3 mm²

- µ-cell pitch

50 and 100 µm

- Geom. Eff.

40-80%



18 different modifications

Main features

X-talk suppression:

1. Isolating trenches
   by total internal reflec.

New ways:

2. 2nd p-n junction
   for isolating the
   bulk from the
   active region

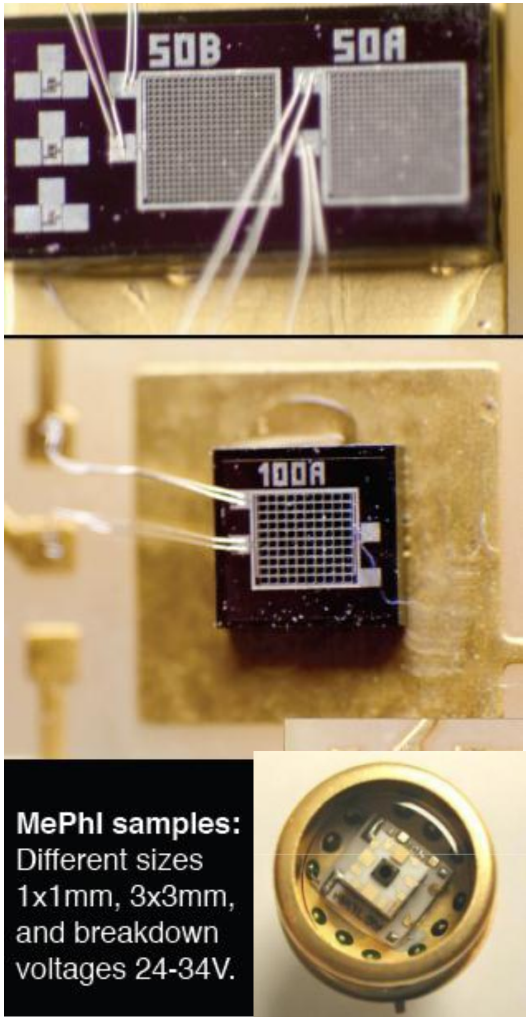
3. OC suppression
   by ion implantation

3+. Special absorbing
   coating

- Thin entrance window, high UV sensitivity

- Very low temperature dependence

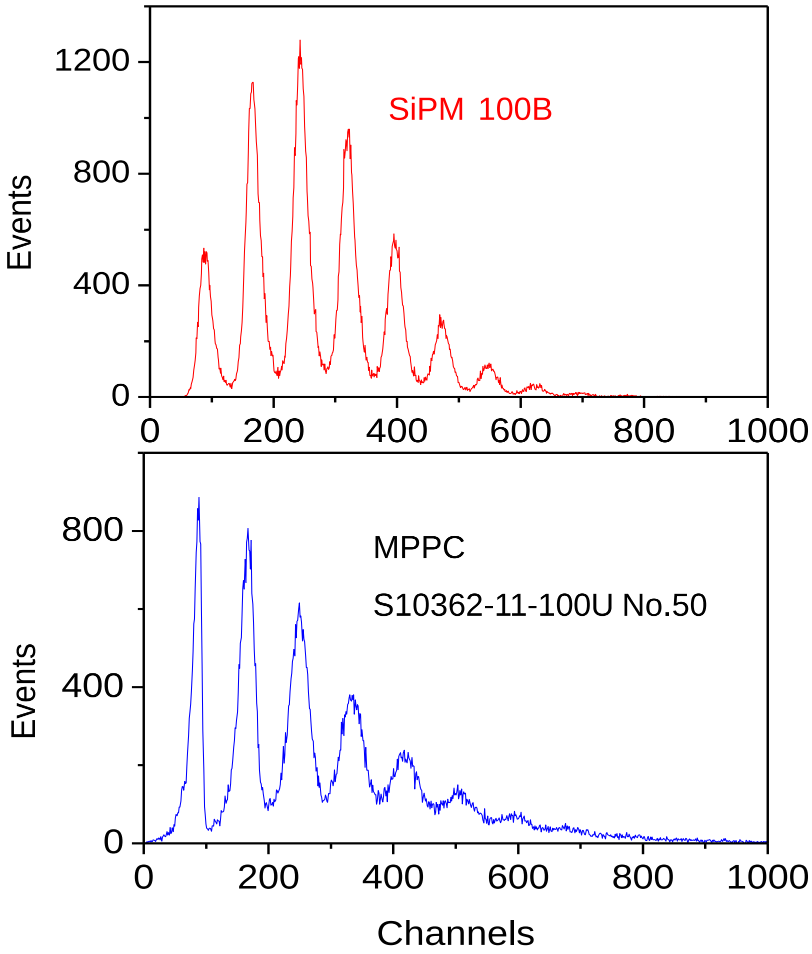
- Low noise

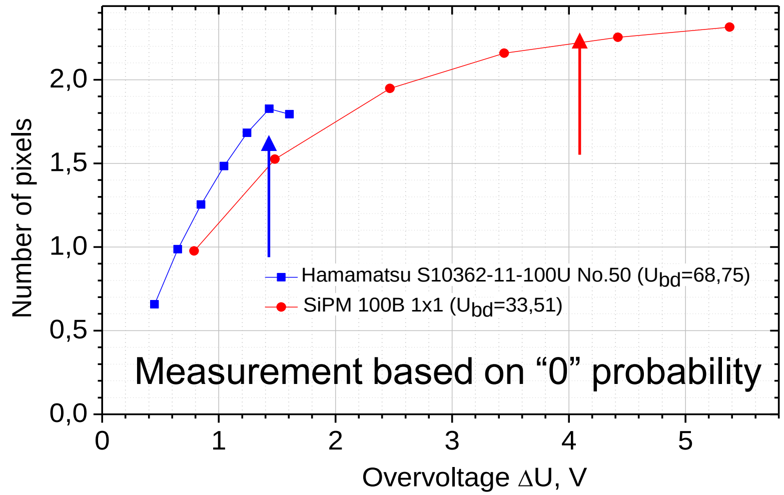


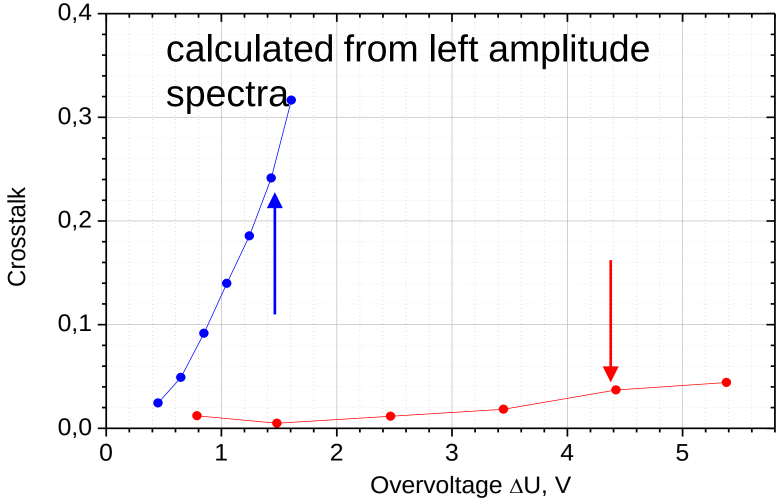
SiPM vs. MPPC

SiPM: 1x1 mm², 100x100 µm², Geometrical Efficiency ~80%, T=+25°C, λ = 435 nm

Same light impinging on both sensors







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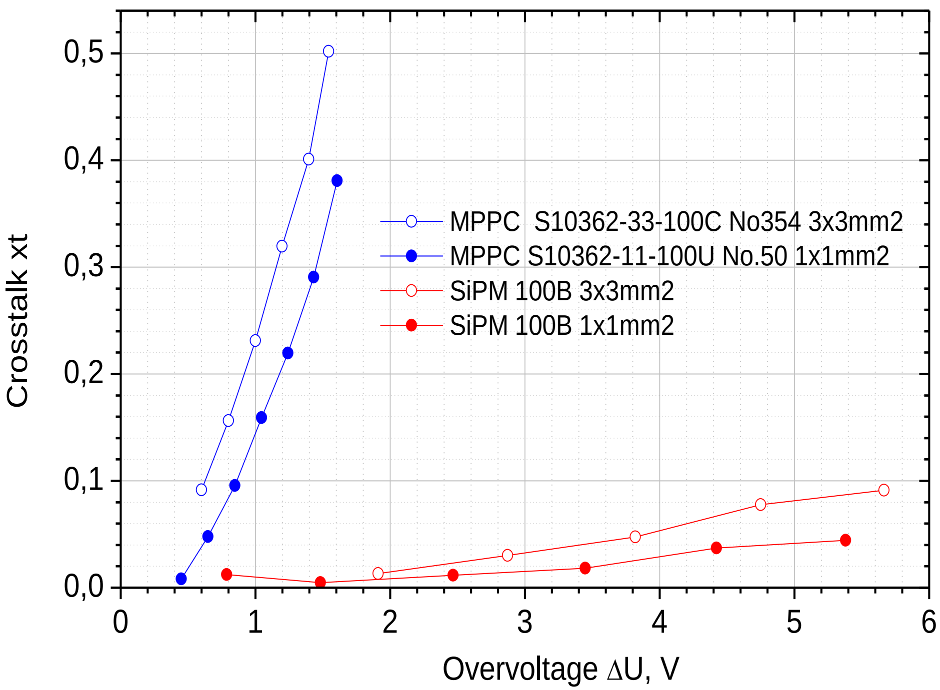
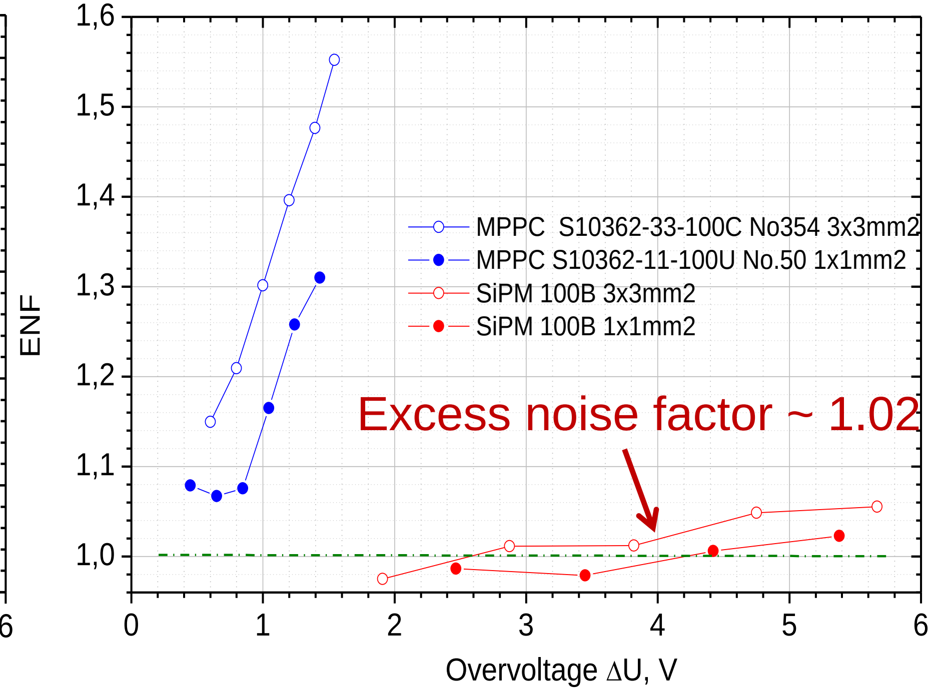
X-talk and Excess Noise Factor

Light source variation according Poisson law





$$N_{fired\_pixels} = \frac{<Mean>}{A_{1e}} \qquad N_{fired\_pixels} = \frac{N_0}{1-Xt} \qquad \left(\frac{\sigma}{<Mean>}\right)^2_{\exp} = \frac{ENF}{N_0}$$

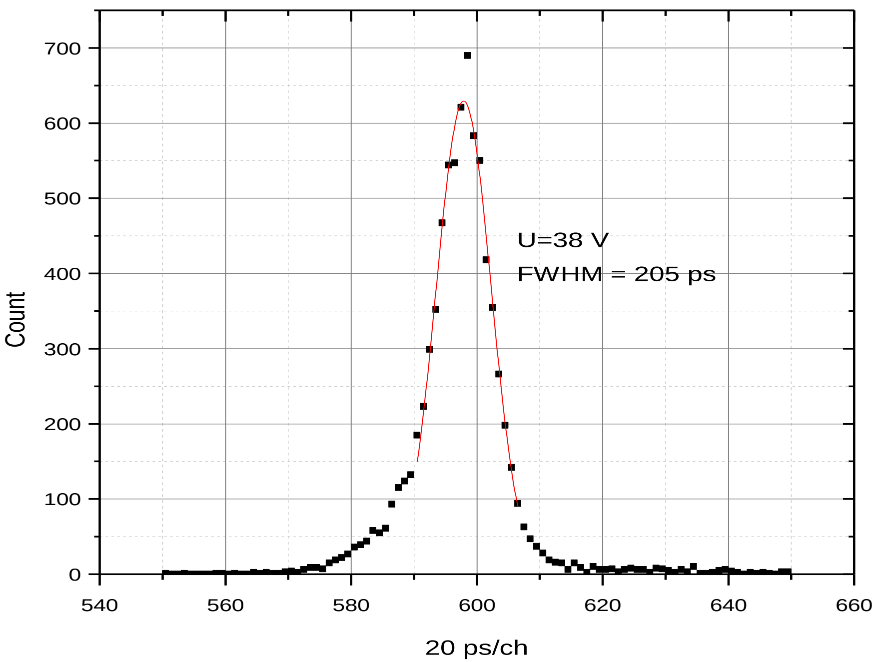
N_0 : number of fired pixels calculated from “0” probability

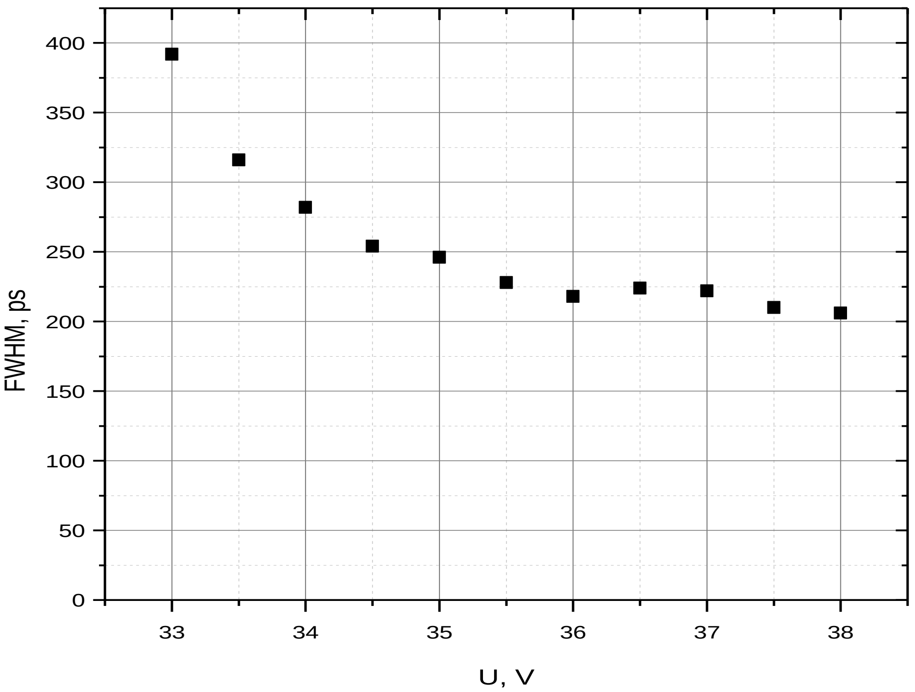
Xt: crosstalk

A_{1e} : single cell amplitude

Timing with 3x3mm^2, type 100B SiPM

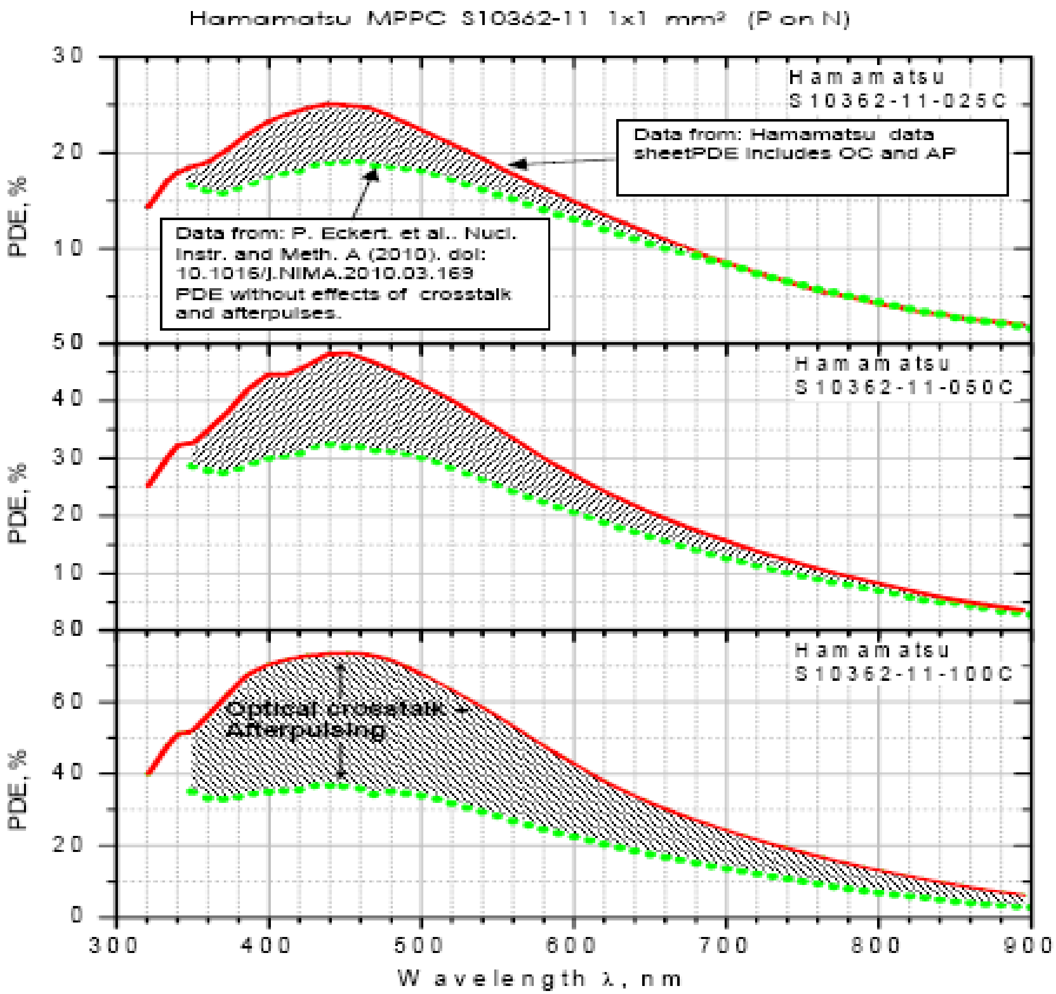
40ps laser, 405nm, single photon mode, T= -40°C





Best value measured for 3x3 mm^2 100B SiPM is **205 ps**

Real and advertised PDE measurements for Hamamatsu MPPCs

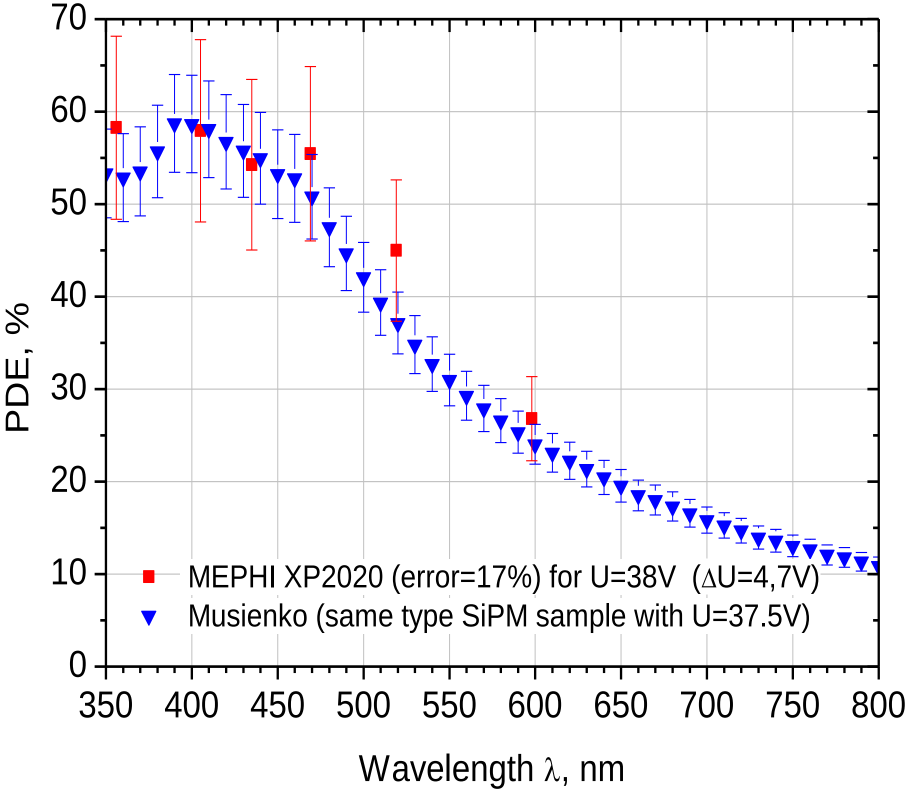


- Until very recently many researchers and companies had serious problems in measuring the real PDE: one needs to disentangle the X-talk and the afterpulsing from genuine efficiency (see left:
red line- claimed,
green line- in fact measured).

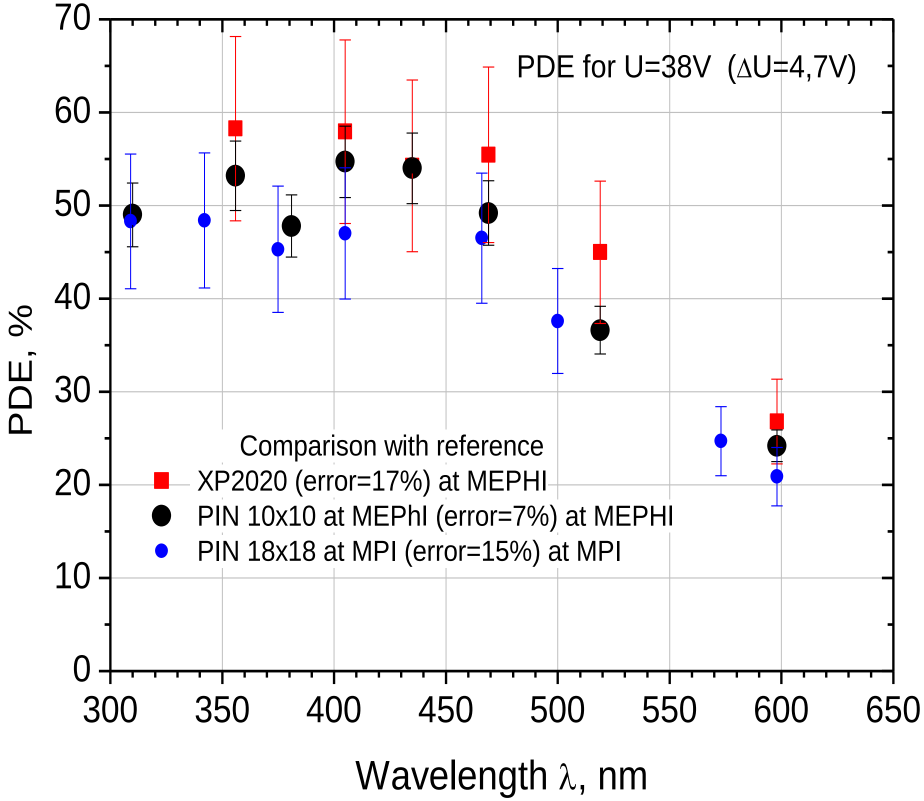
- Thanks to few publications the situation has improved.

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

Measurements at MEPHI and at CERN (thanks to Y.Musienko)

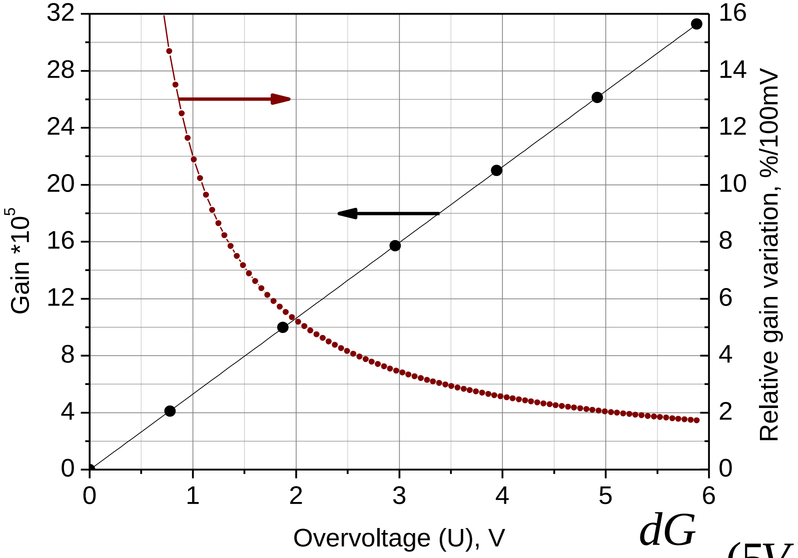


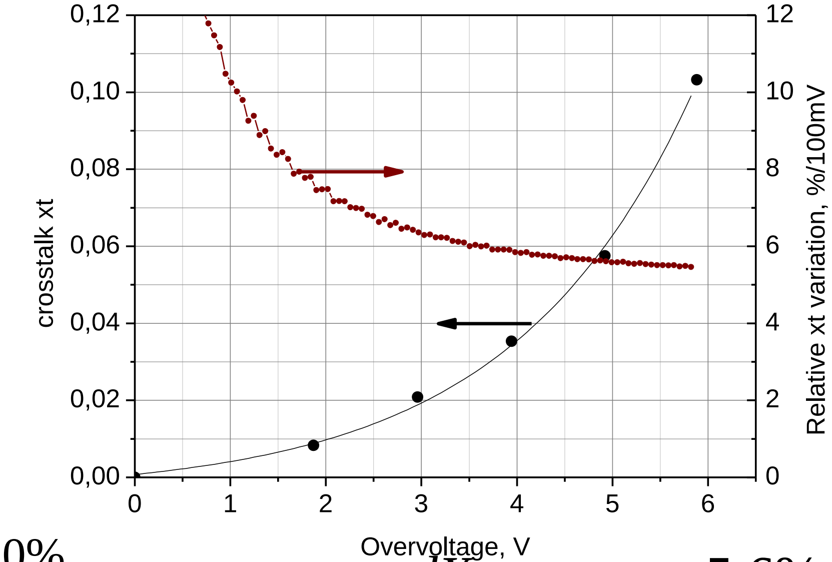
Measurements at MEPHI and at MPI



- The PDE measured with reference calibrated PIN-diodes is slightly lower than with the reference calibrated PMT
- All results are consistent within experimental errors

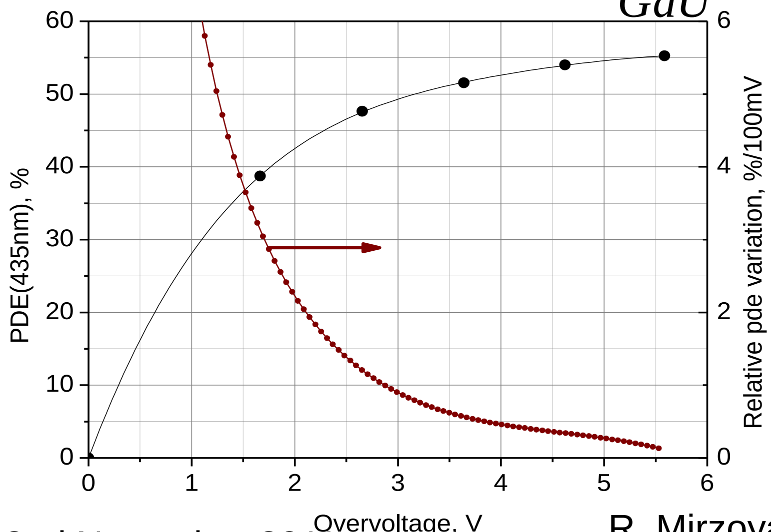
Voltage stability SiPM 100B for 5V (15%) overvoltage





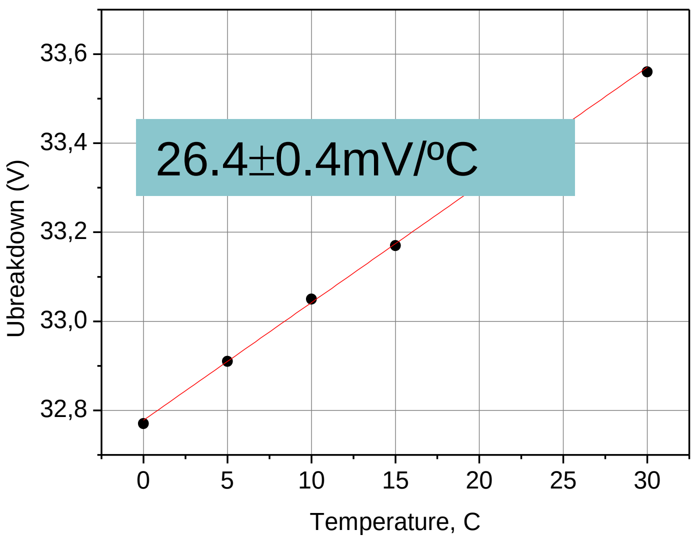
$$\frac{dG}{GdU}(5V) = \frac{2.0\%}{100mV}$$

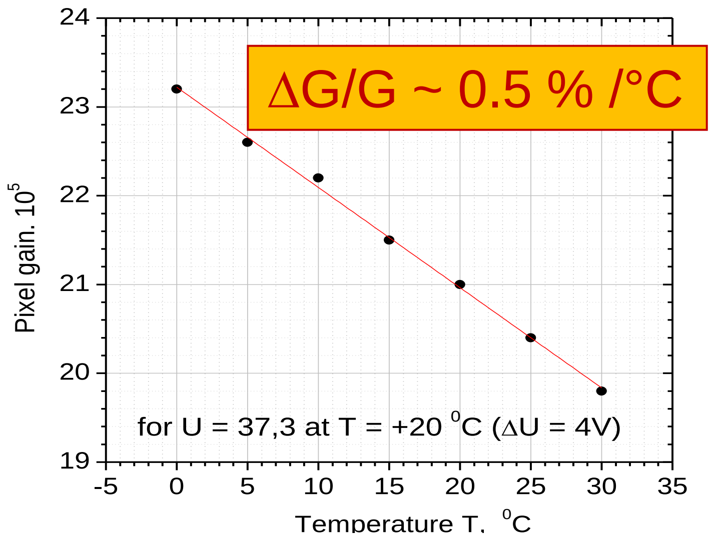
$$\frac{dXt}{XtdU}(5V) = \frac{5.6\%}{100mV}$$

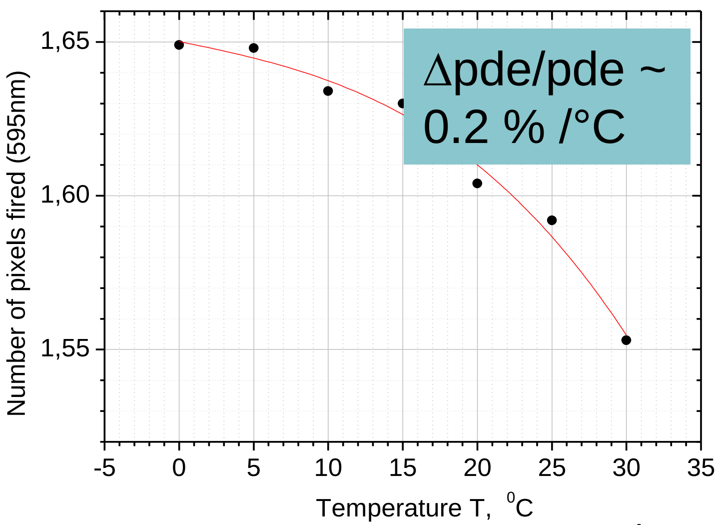


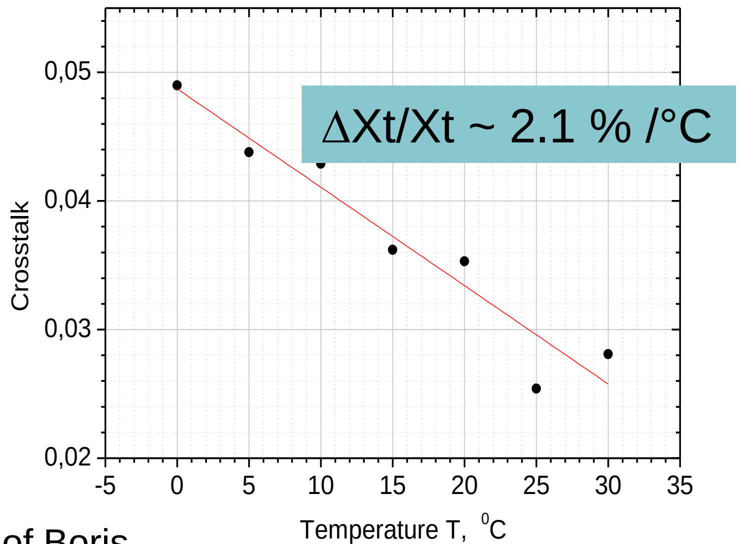
$$\frac{d\varepsilon}{\varepsilon dU}(5V) = \frac{0.25\%}{100mV}$$

Temperature dependence type 100B SiPM

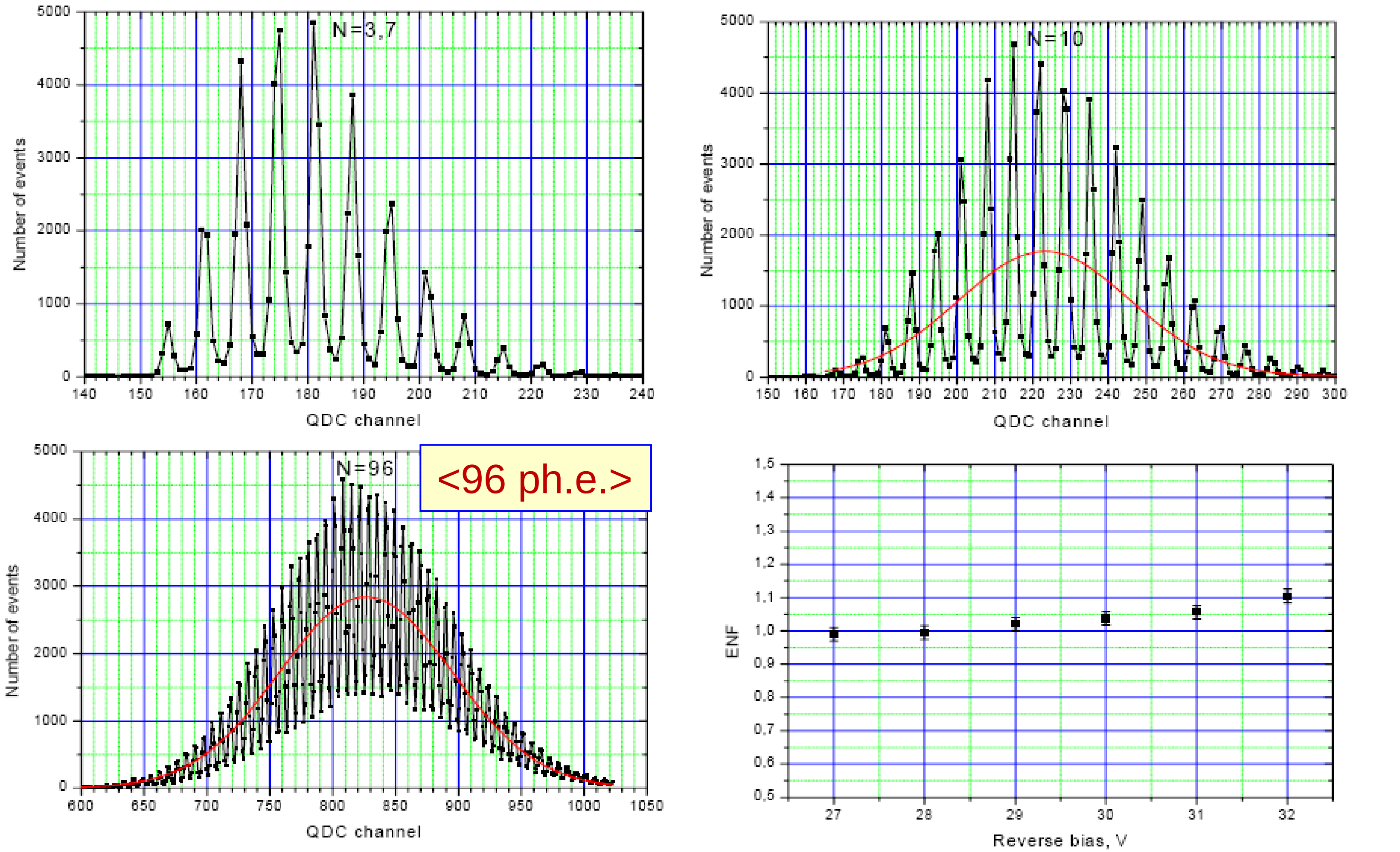








SiPM with X-talk suppression: World record of ultra-fast light sensors in amplitude resolution



We have lost a great scientists, a pioneer in many disciplines, a promoter, a senior friend, a very kind character, a gentlman. He pushed the SiPM to become almost an ideal LLL sensor. This is the beginning of a new revolutionary era for Si sensors.

2nd November 2011, Light-11, Rinberg, Germany

R. Mirzoyan: Dream of Boris- Large SiPMs with maximum PDE and almost no X-talk

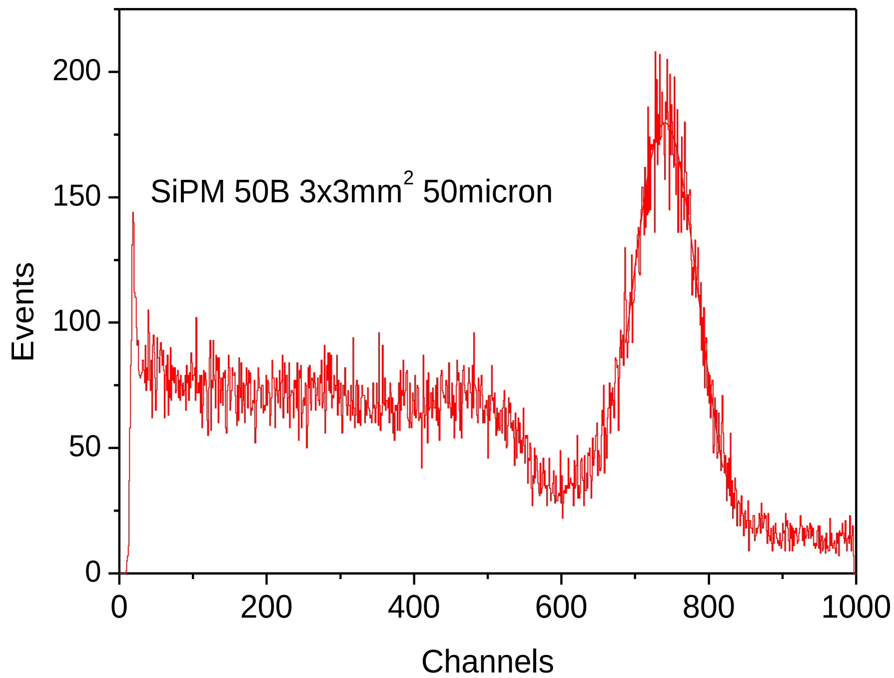
Summary

- MEPHI & MPI, with support of Excelitas, have produced SiPMs of 1x1 and 3x3 mm^2 sizes with extremely high PDE (≥ 50%) in the UV-blue region
- The X-talk is ~ 3-5 % for saturated PDE (ΔU/U ~12-15 %)
- ENF is ~ 1.02 (due to 4-fold X-talk suppression)
- T° sensitivity: PDE ~0.2 %/°C; Gain ~0.5 %/°C
- Time jitter (FWHM) (3x3mm^2) (100µm pitch) ~ 200-300 ps
- Dark rate ~ 1MHz/mm^2
- The dream of Boris became true; it's a pity that after so many years and efforts he is not with us to see it
- On the way of becoming commercial product of Excelitas

PET Spectrometry with LYSO and Na^{22}

Preliminary. Setup is not yet optimized

Self triggering mode
Amplitude spectra Integration time 1μs
LYSO 3x3x5 mm^3
Without collimator



Energy Resolution (FWHM) ~14%