
Houston, we have a problem!
My AMS laser alignment system went berserk

Silizium Photomultiplier

Th. Kirn

I. Physikalisches Institut IB

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Licht-, γ-Nachweis, Spuren geladener Teilchen

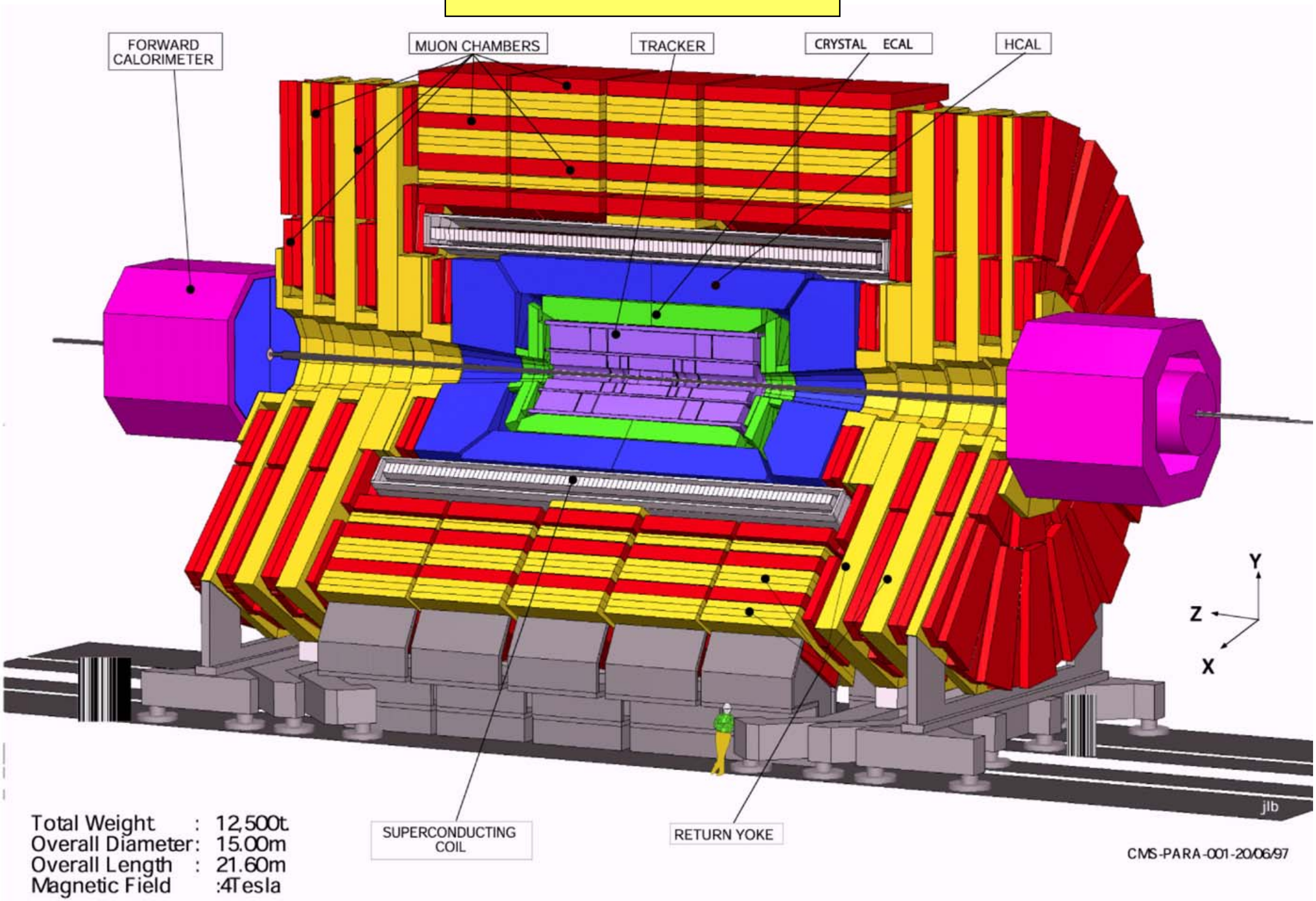
↓

Avalanche-Photodioden APD → **CMS ECAL**

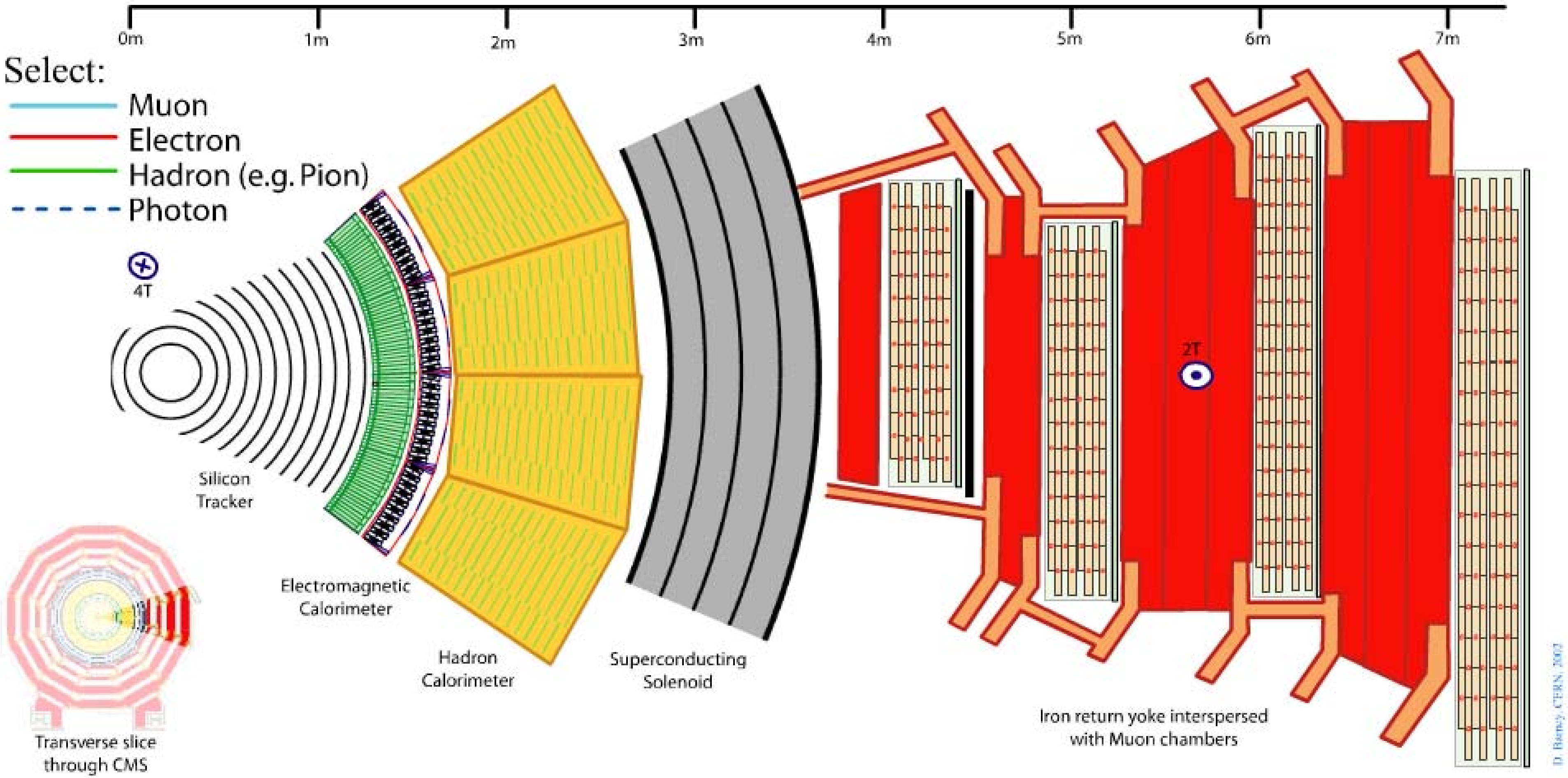
↓

Silizium Photomultiplier SiPMT → **Zukunft**

CMS Detector

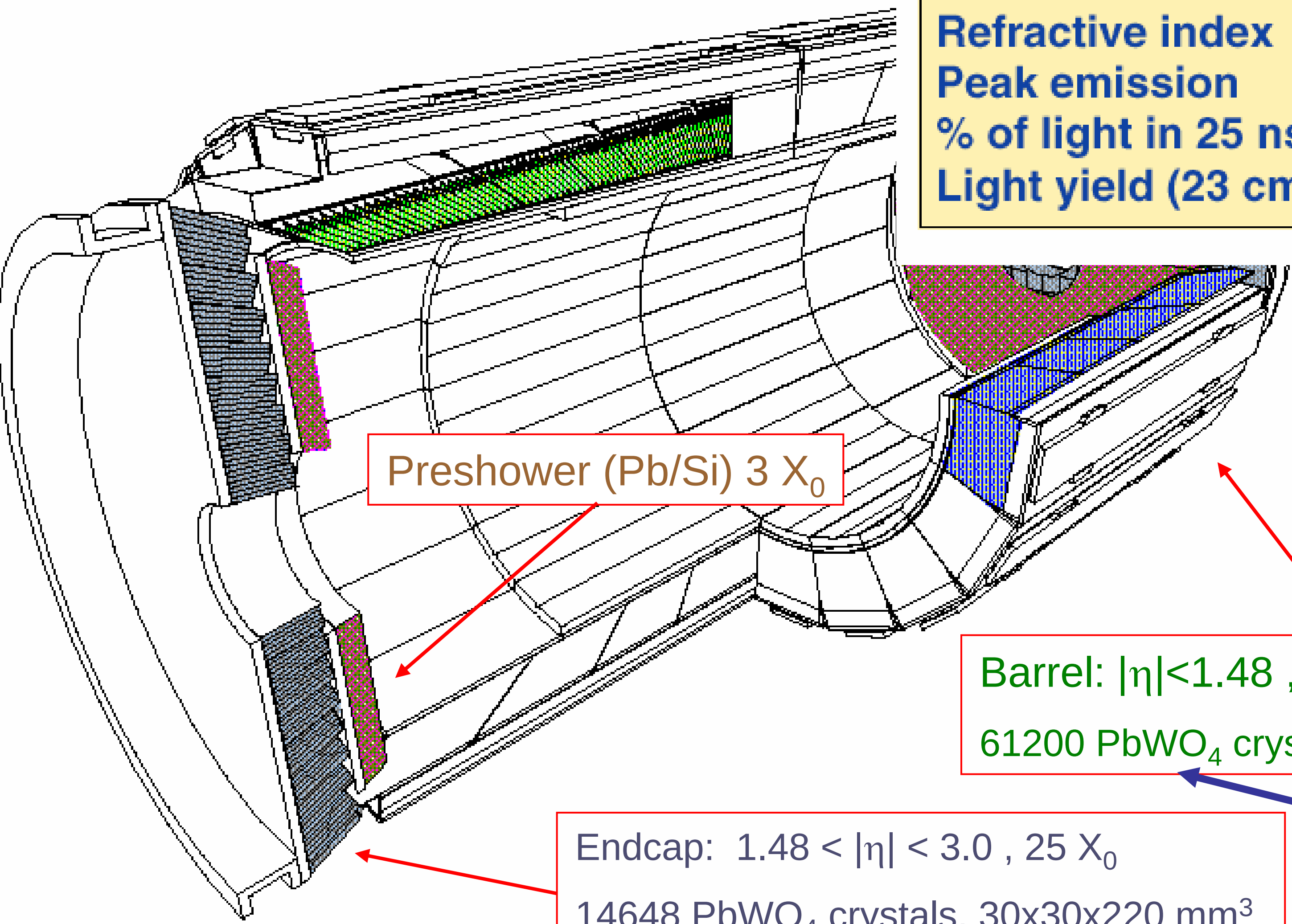


Transverse slice through CMS detector

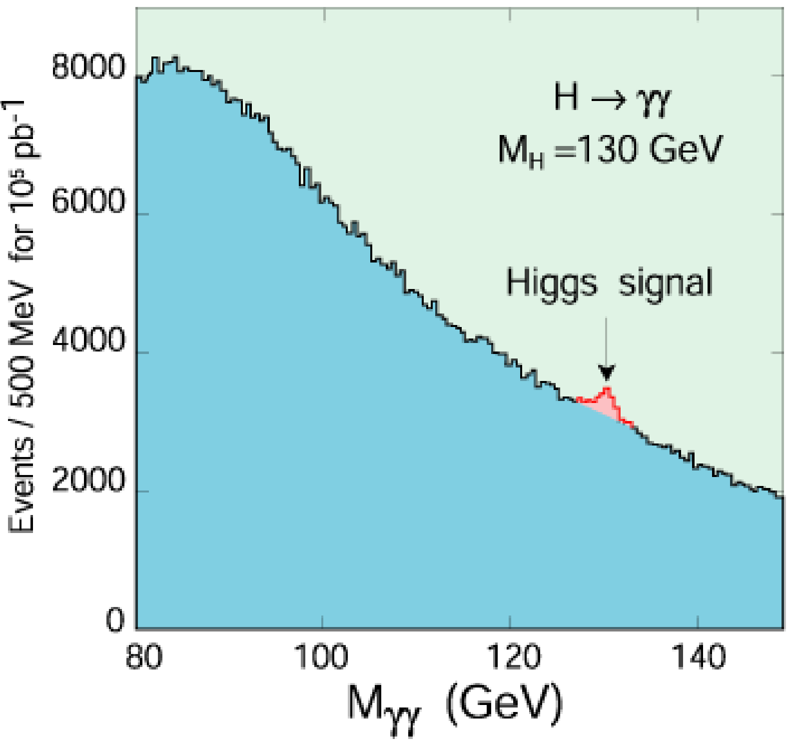


CMS ECAL Structure

Parameter		Value
Radiation length	cm	0.89
Moliere radius	cm	2.2
Hardness	Moh	4
Refractive index		2.3
Peak emission	nm	440
% of light in 25 ns		80%
Light yield (23 cm)	γ/MeV	100



The CMS Electromagnetic CALorimeter

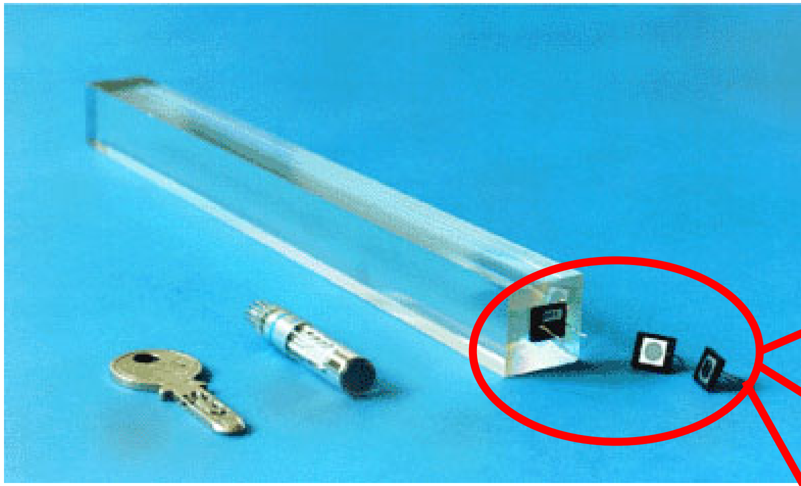


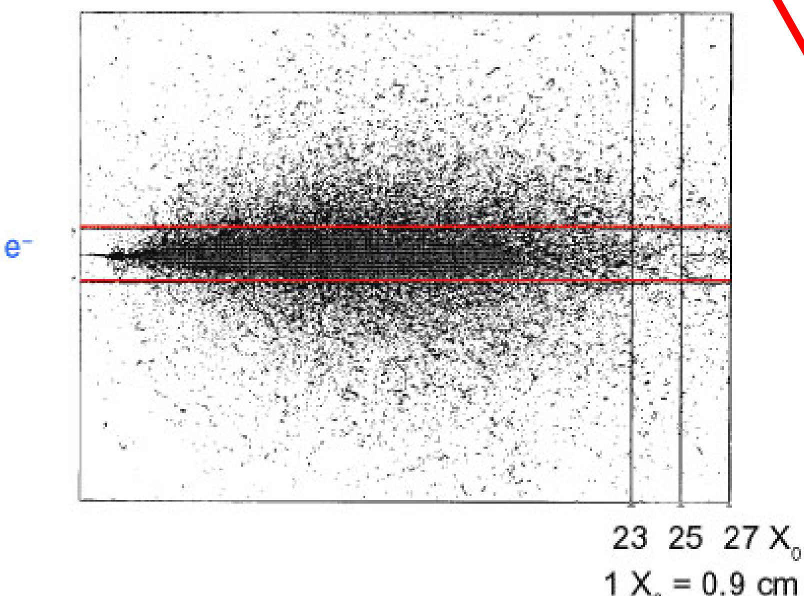
$$M_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}\cdot(1-\cos\Theta_{\gamma\gamma})}$$

$$\frac{\sigma_M}{M} = \frac{1}{2}\sqrt{\left(\frac{\sigma_{E_{\gamma 1}}}{E_{\gamma 1}}\right)^2 + \left(\frac{\sigma_{E_{\gamma 2}}}{E_{\gamma 2}}\right)^2 + \left(\frac{\sigma_{\Theta_{\gamma\gamma}}}{\tan\left(\frac{\sigma_{\gamma\gamma}}{2}\right)}\right)^2}$$

$$\frac{\sigma_{E_{\gamma 1}}}{E_{\gamma 1}} = \frac{a}{\sqrt{E_{\gamma 1}(GeV)}} \oplus \frac{b}{E_{\gamma 1}} \oplus c$$

The CMS ECAL





$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus \frac{b}{E} \oplus c$$

a : **intrinsische Schauer Fluktuationen,**
Photonstatistik (Fläche, QE, F)

b : **Elektronisches Rauschen**
Kapazität C (serielles Rauschen),
Dunkelstrom I (paralleles Rauschen)

c : **Stabilität, Kalibrationsfehler**
Verstärkungsänderungen aufgrund von Spannungs- bzw. Temperatur-schwankungen

CMS Design Goal :
a ~3%, b ~200 MeV, c ~0.5%

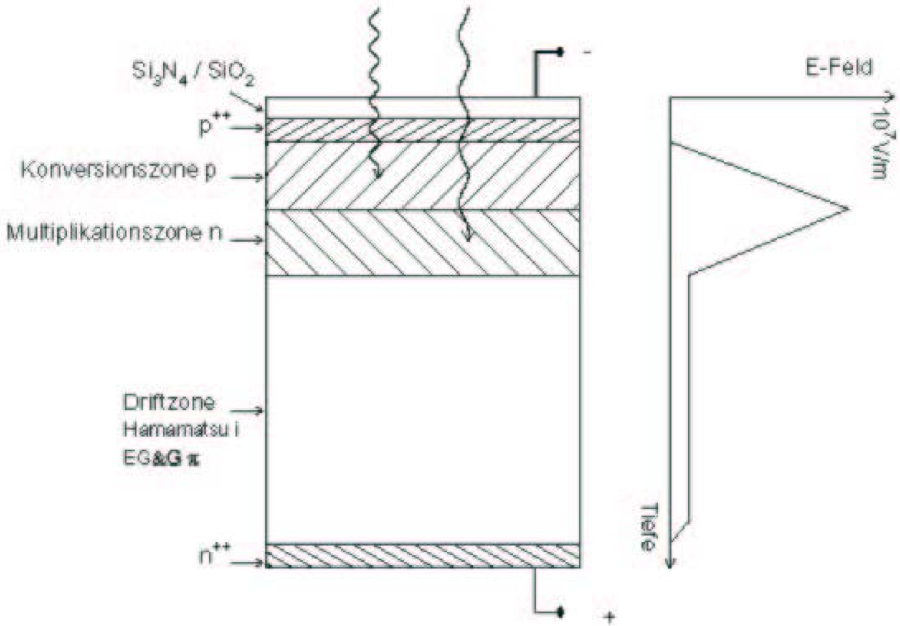
Anforderungen an Photosensoren

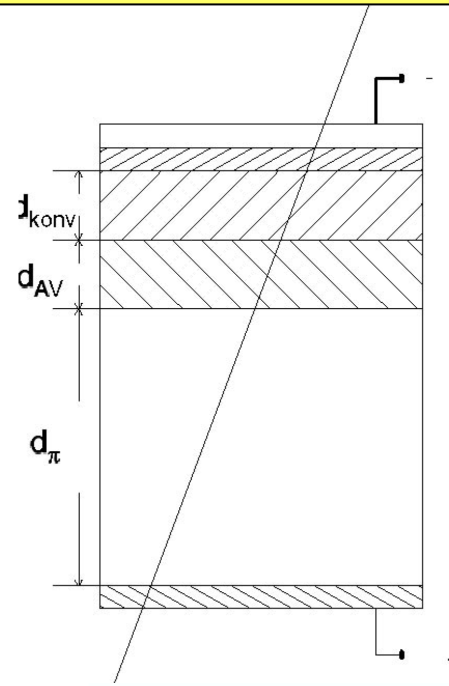
- **Strahlungshärte: $2*10^{13}$ n/cm^2 + 250 kRad (10 Jahre LHC)**
- **Einsatz in 4 Tesla Magnetfeld**
- **Nicht sensitiv auf Teilchendurchgang**
- **Schnell ($\leq$ 10 nsec)**
- **Angepaßt an PbWO4-Licht (λ=420nm)**
- **Langzeitstabil**
- **Preiswert (122400 Stücke)**

==> 8 Jahre R&D von Hamamatsu (anfangs auch EG&G)

Mehr als 100 verschiedene Prototypen

Struktur einer Avalanche Photodiode APD





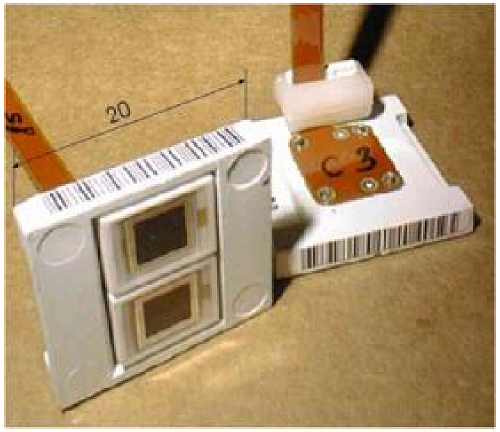
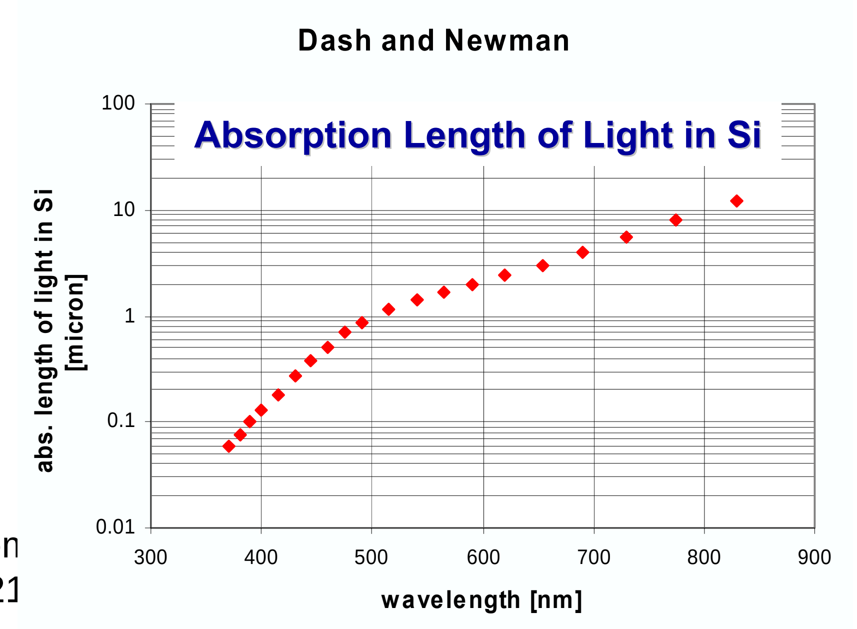
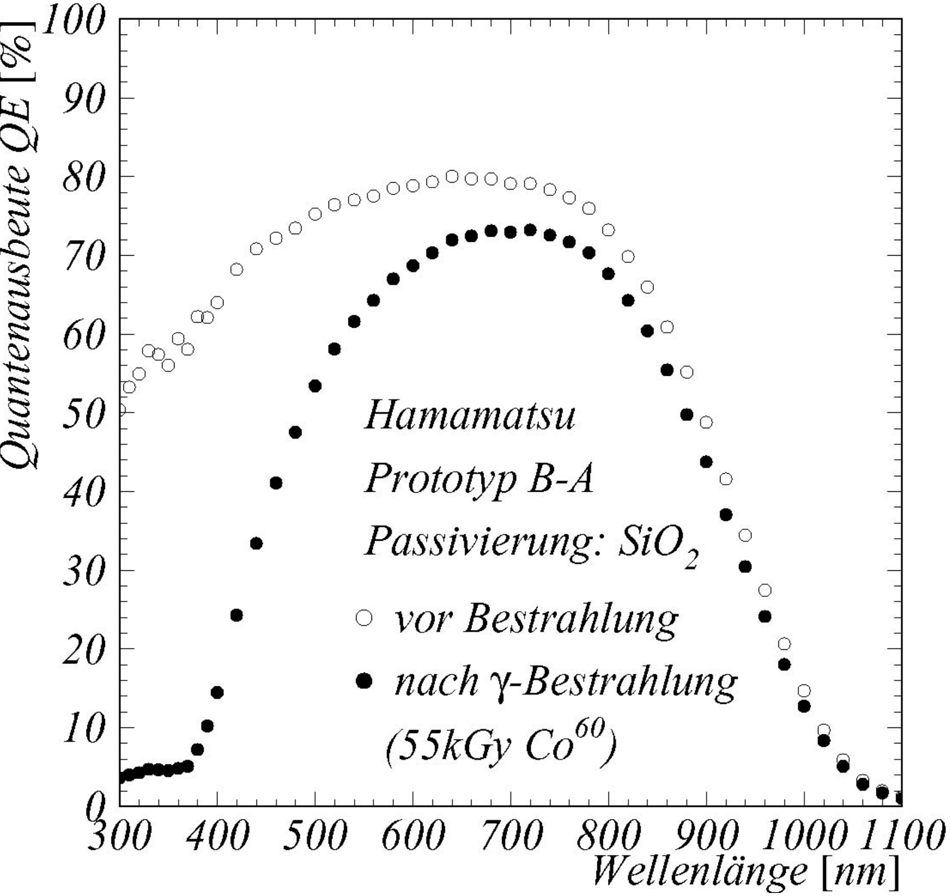


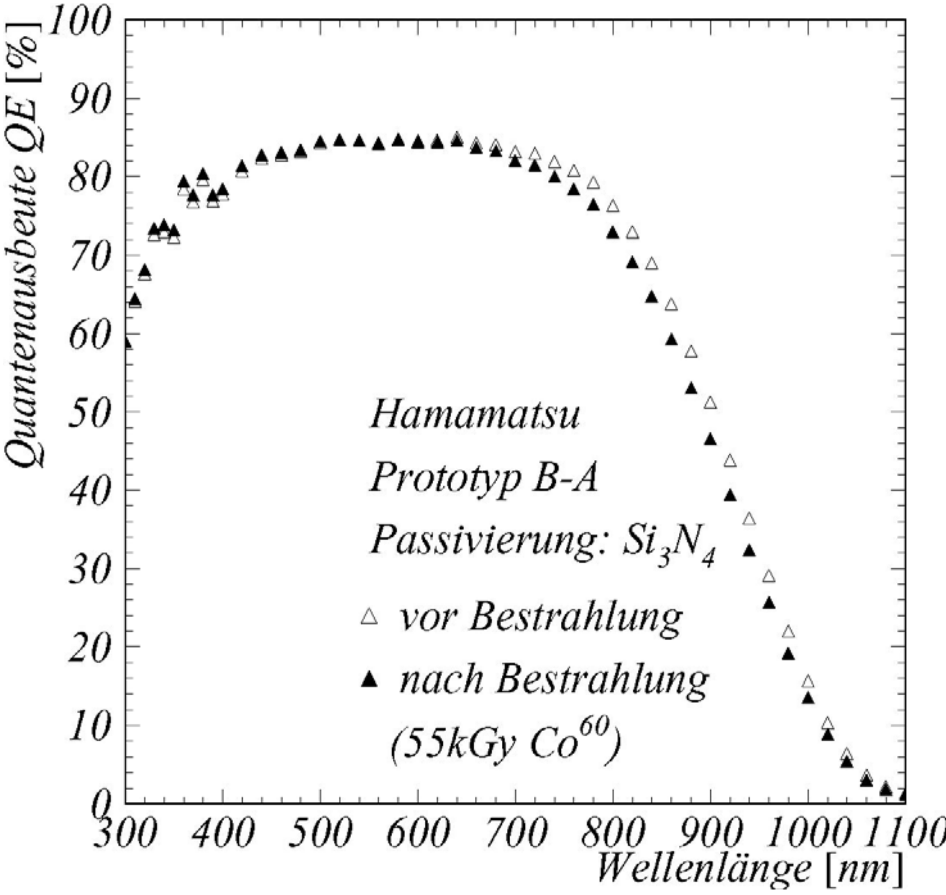
Photo-conversion electrons from the thin p-layer induce avalanche amplification at the p-n junction.

Electrons created by ionising particles traversing the bulk are not amplified.



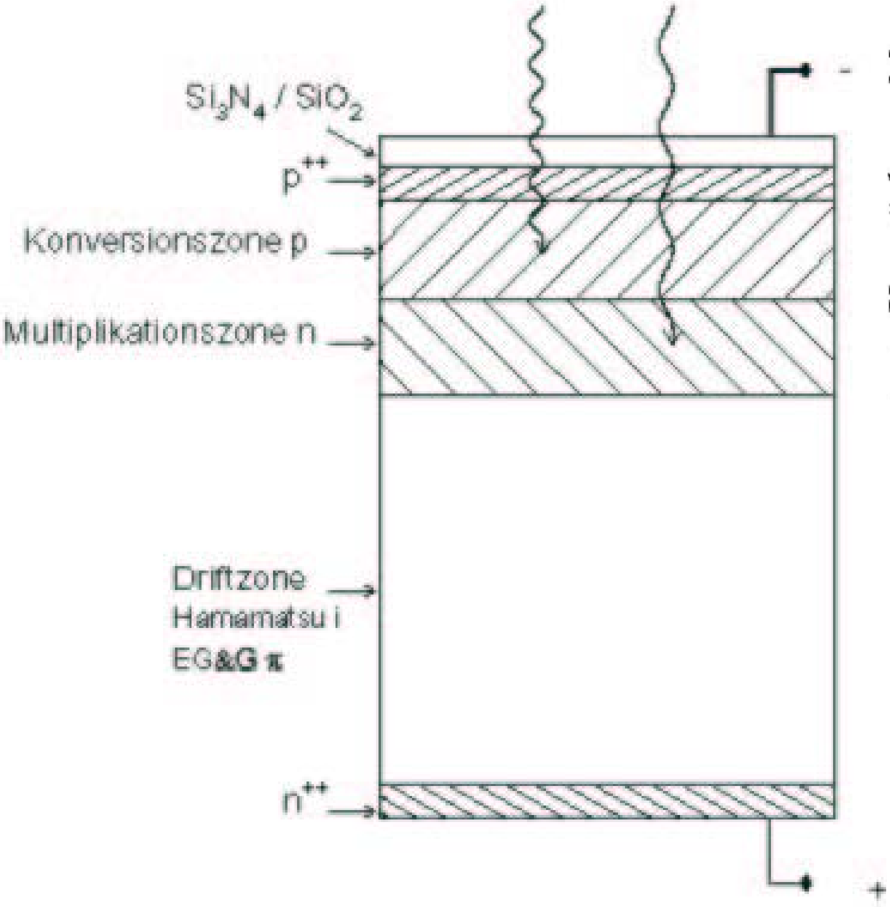
APD: Quantenausbeute

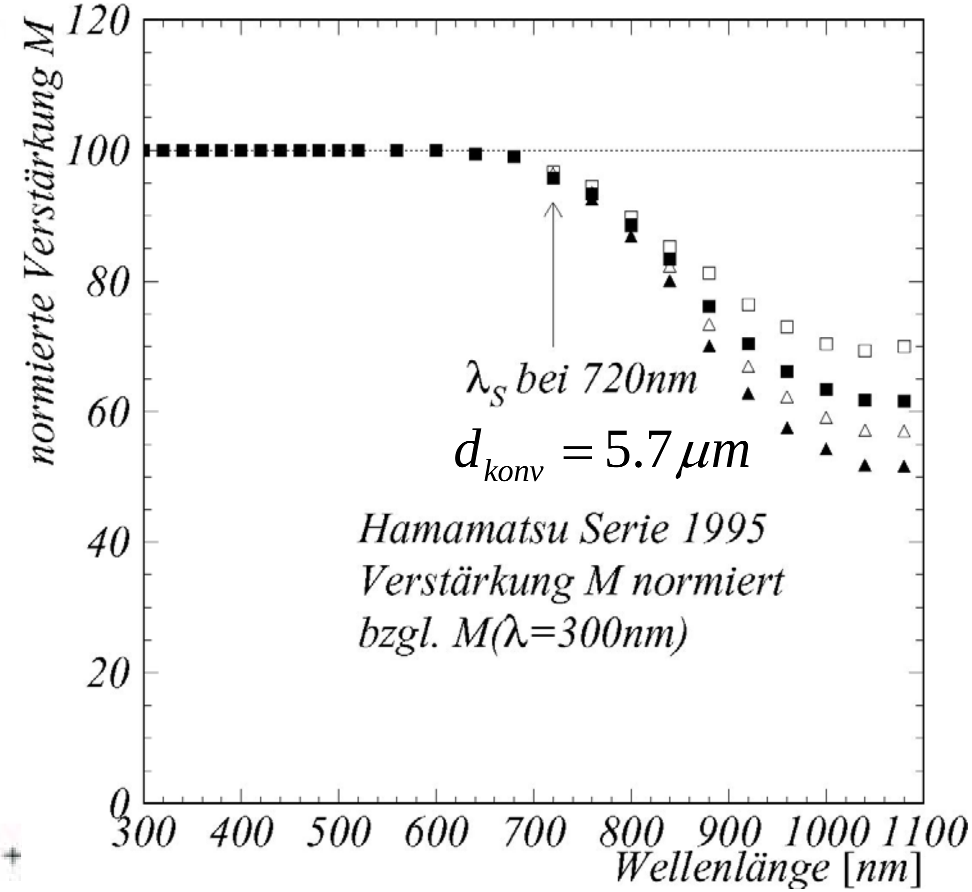




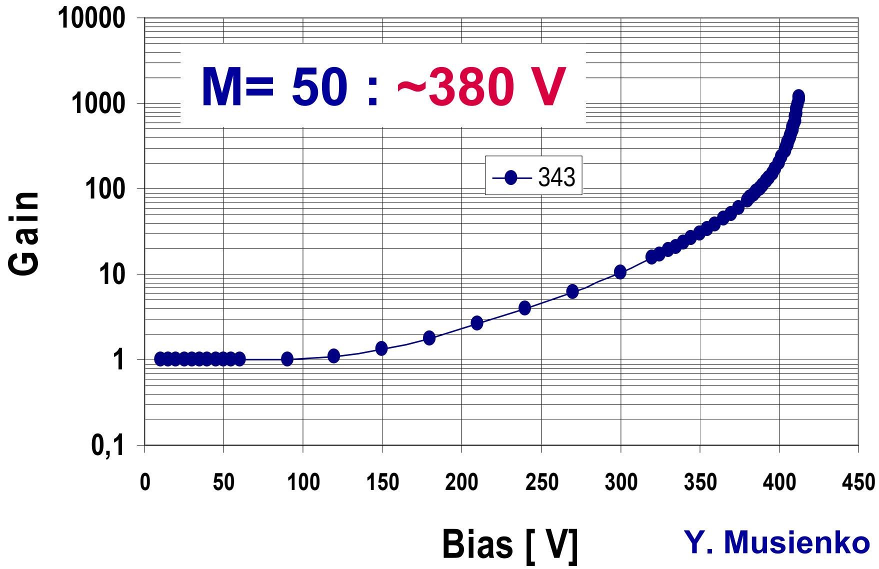
$$\left(\frac{\sigma_E}{E}\right)_\gamma = \frac{a}{\sqrt{E}} = \sqrt{\frac{F}{N_{pe^-}}} = \sqrt{\frac{F}{LY \bullet E}}$$

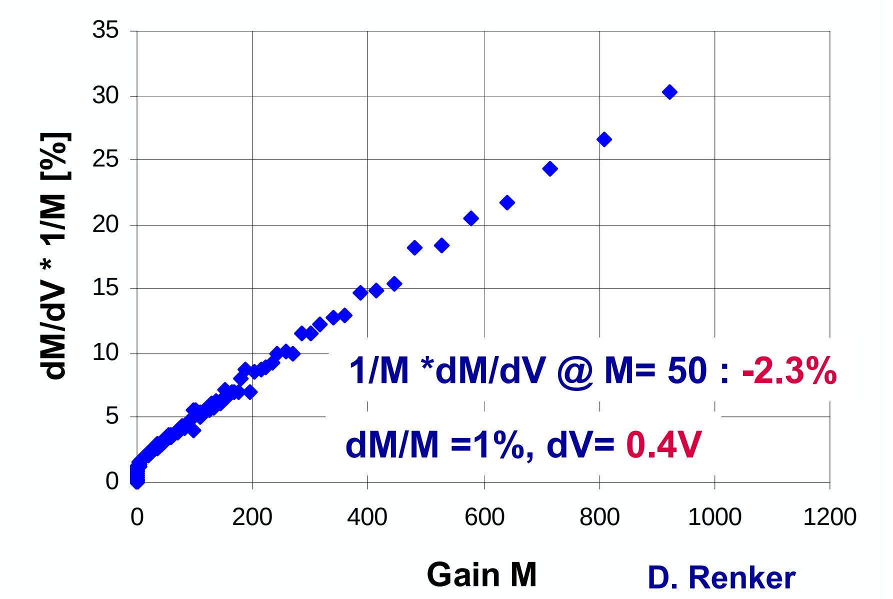
APD: Verstärkung M



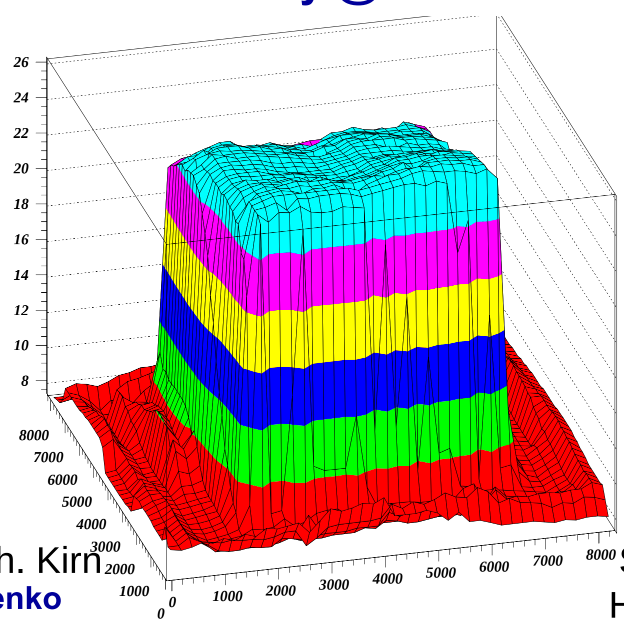


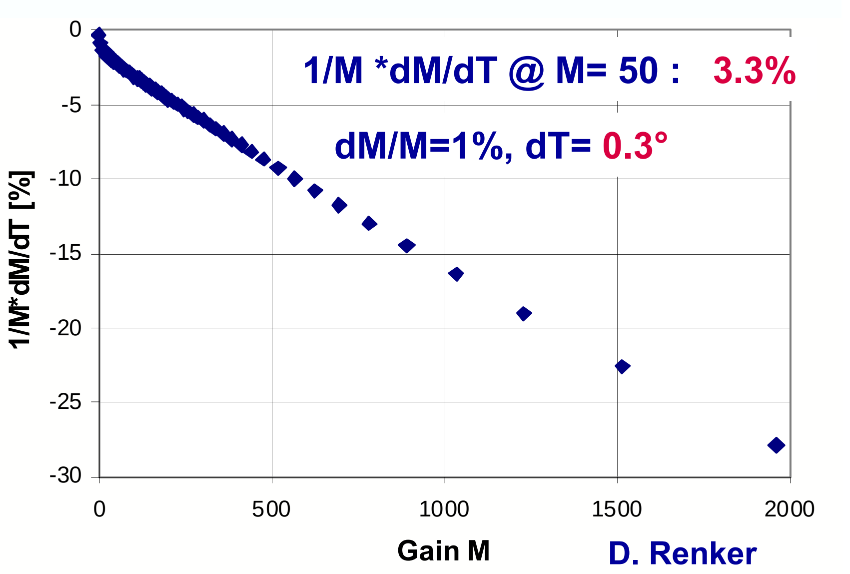
APD: Verstärkung M





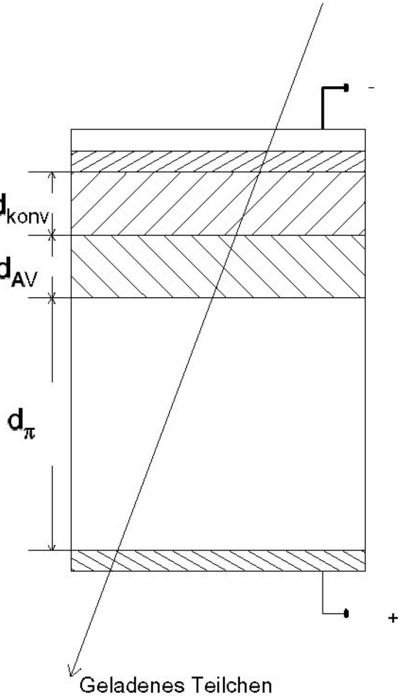
Gain Uniformity @ M=100

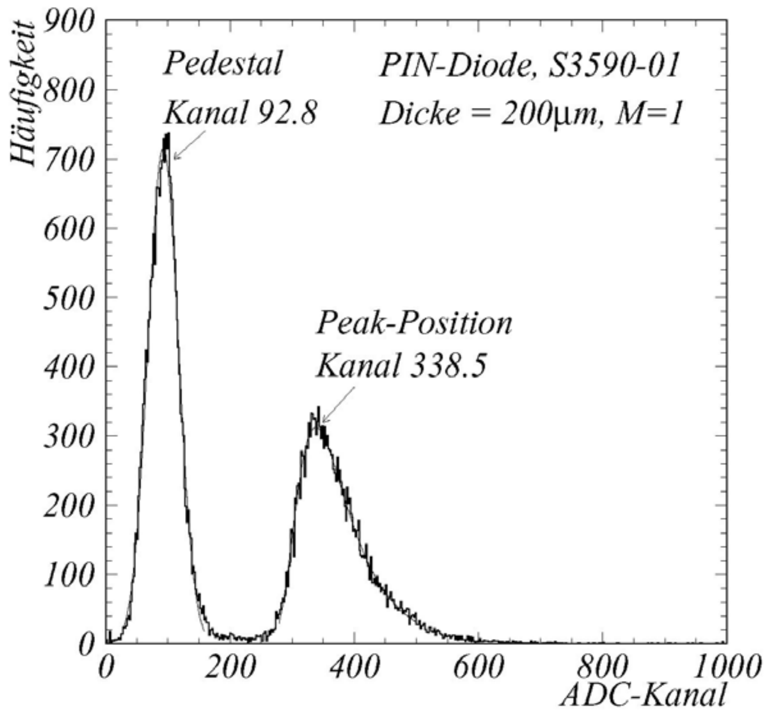


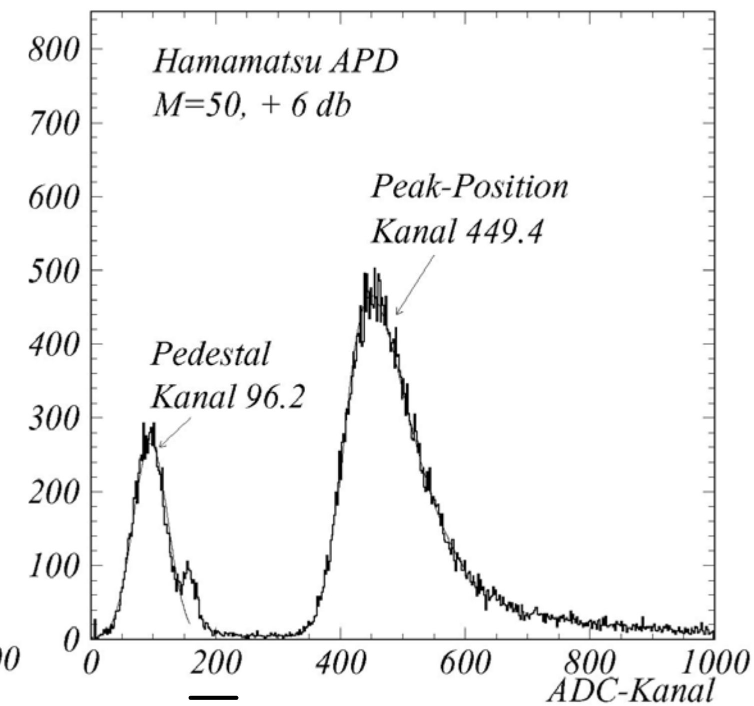


Y. Musienko

APD: Nuclear Counter Effect





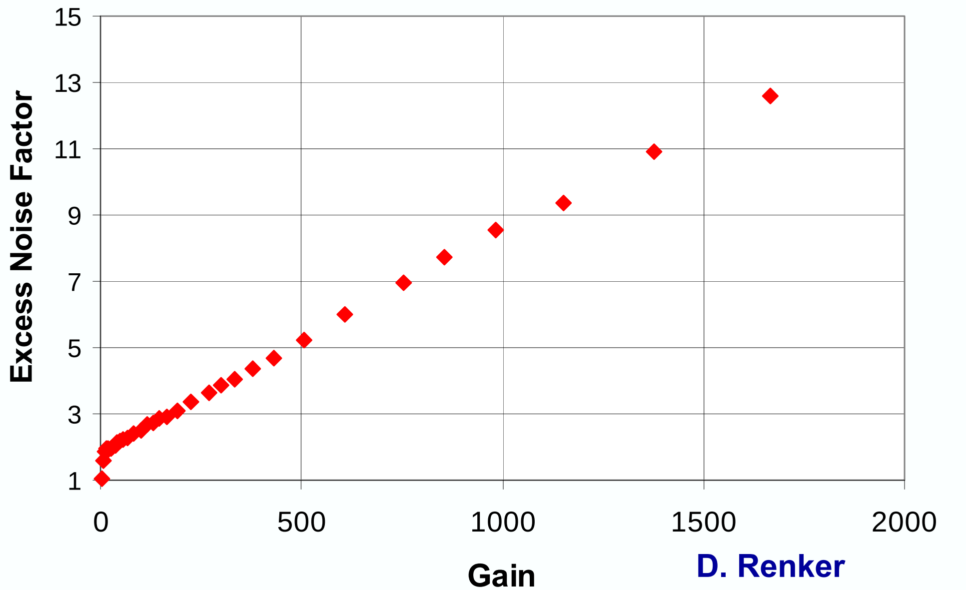


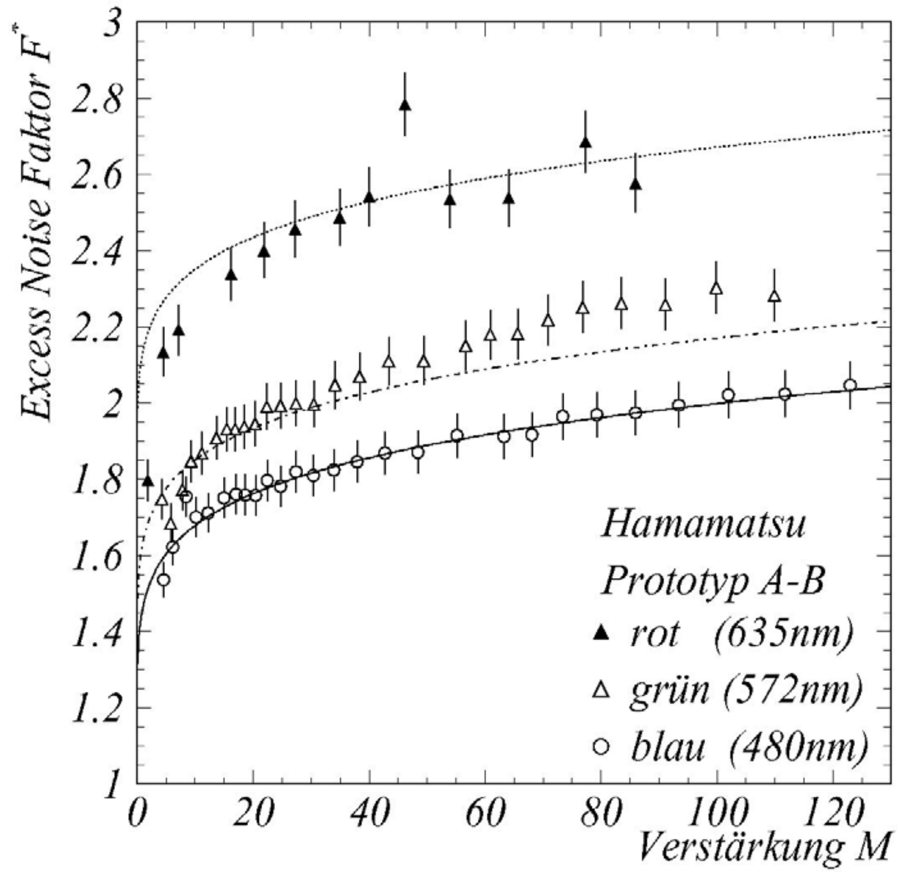
$$S' = M \bullet \frac{dN_e}{dx} \bullet \left[d_{konv} + \frac{M'}{M} \bullet d_{AV} + \frac{1}{M} d_\pi \right] \longrightarrow d_{eff} = \frac{200}{50} \bullet \frac{\overline{S}_{APD}}{\overline{S}_{PIN}} = 11{,}5\mu m \quad (CMS: 6\mu m)$$

$$S'' = \frac{\frac{dN_e}{dx}}{LY} \bullet d_{eff} \xrightarrow{\text{MIP: 76 e-h/µm}} S'' = 400 MeV \xrightarrow{E=100\,GeV} \frac{\sigma_E}{E}_{NUC} \approx 0{,}1\% \longrightarrow \frac{\sigma_E}{E}_{NUC} = \frac{a}{\sqrt{E}} \oplus c$$

$$LY = 2 \frac{pe^-}{MeV}$$

APD: Excess Noise Factor F





F ($\langle M \rangle$) = $\langle M^2 \rangle / \langle M \rangle^2$

F = k_{eff} • M + (2-1/M) • (1-k_{eff})

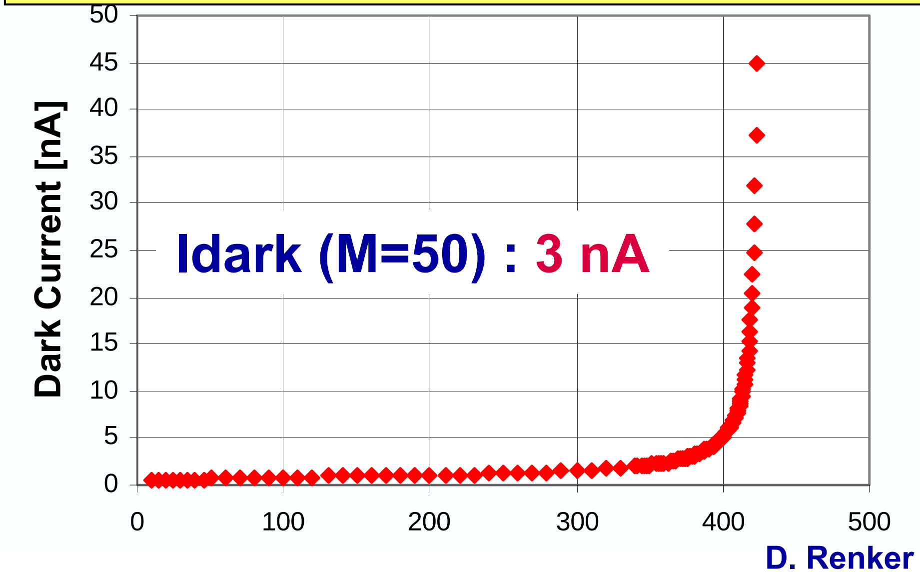
for M > 10: F = 2 + k_{eff} • M

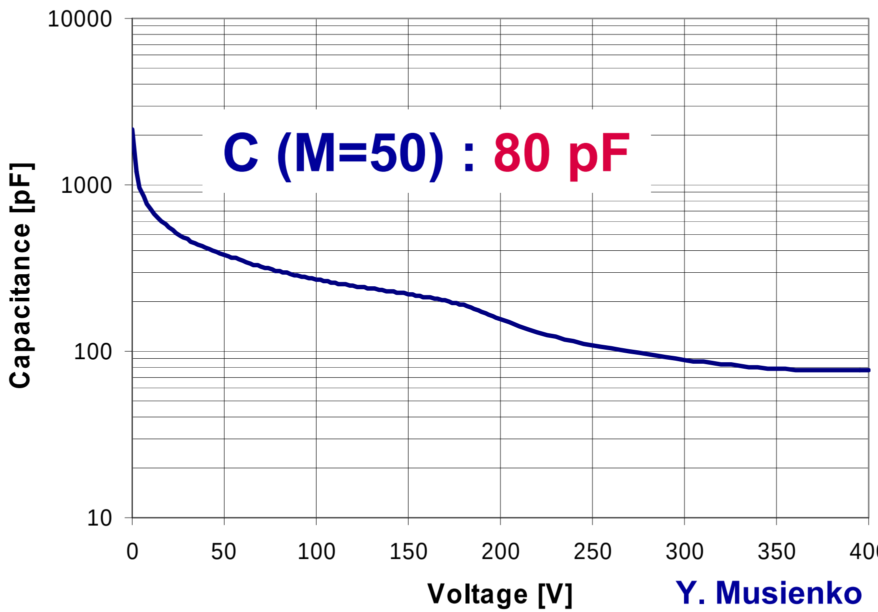
$k_{eff} \approx$ k = β/α

α and β are the ionization coefficients for electrons and holes   α >> β

$$\left(\frac{\sigma_E}{E}\right)_\gamma = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} = \sqrt{\frac{F}{N_{pe^-}}} \oplus \frac{b}{E}$$

APD: Noise





$$\sigma_{total} = \sqrt{\sigma^2_{parallel} + \sigma^2_{series}}$$

$$\sigma_{parallel} = \sqrt{\left(I_{ds} + I_{db} M^2 F\right) \cdot q\tau}$$

$$\sigma_{series} = \sqrt{\frac{4kT \cdot C^2}{2\tau}\left(R + \frac{1}{g}\right)}$$

M = APD gain
F = excess noise factor
τ = shaping time constant
q = electron charge
I_{ds}= dark surface current
I_{db}= dark bulk current
R = series resistance of APD and amplifier
C = capacitance of APD and amplifier
k = Boltzmann constant
T = absolute temperature
g = transconductance of amplifier first stage

$$\left(\frac{\sigma_E}{E}\right)_{Noise} = \frac{b}{E}$$

APD: Radiation Hardness

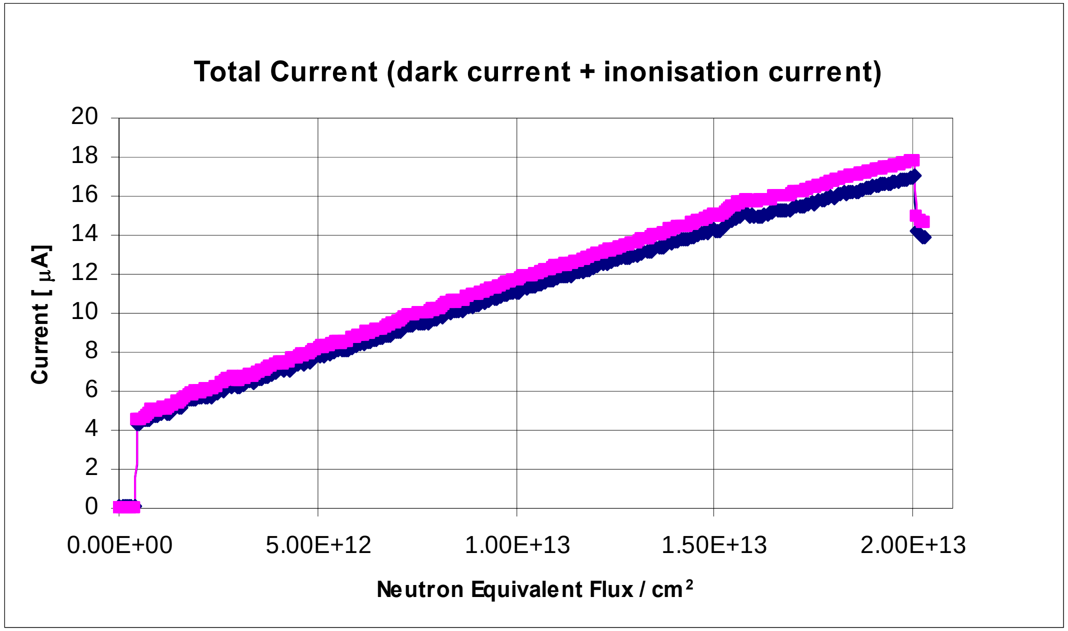
APD's irradiated at PSI

70 MeV proton beam for 105 minutes

9×10^{12} protons/cm^2

⇨ 2×10^{13} 1MeV neutrons/ cm^2

⇨ 10 years CMS barrel



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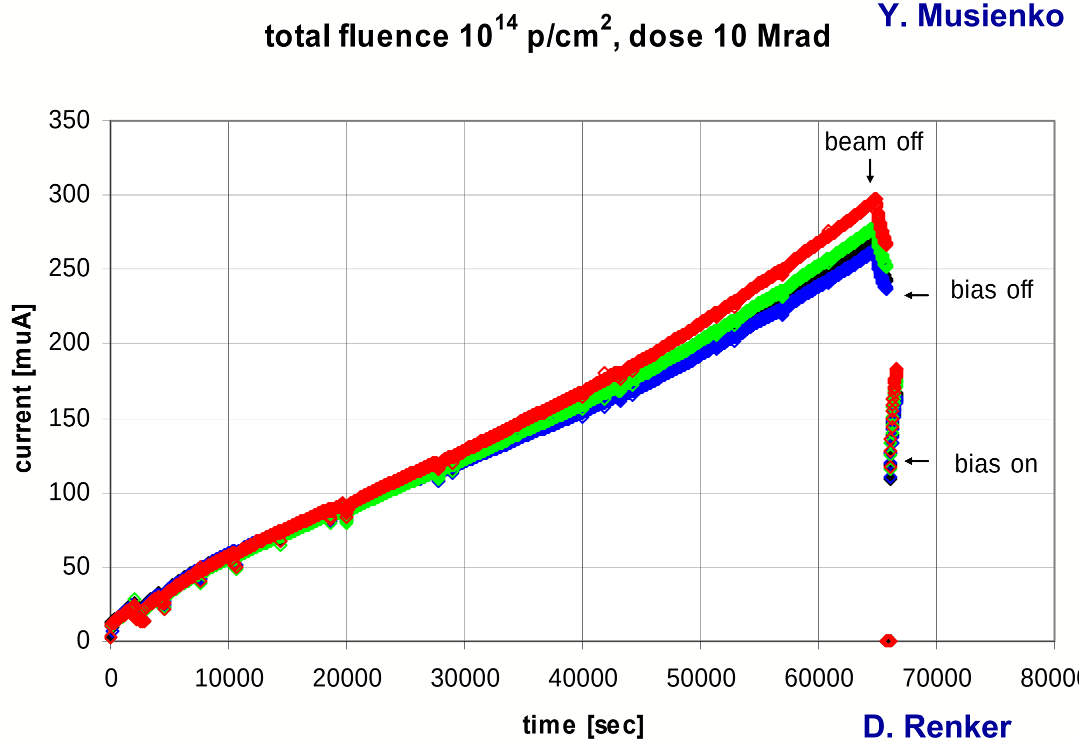
4 APDs were irradiated with 10x 10 years of LHC operation



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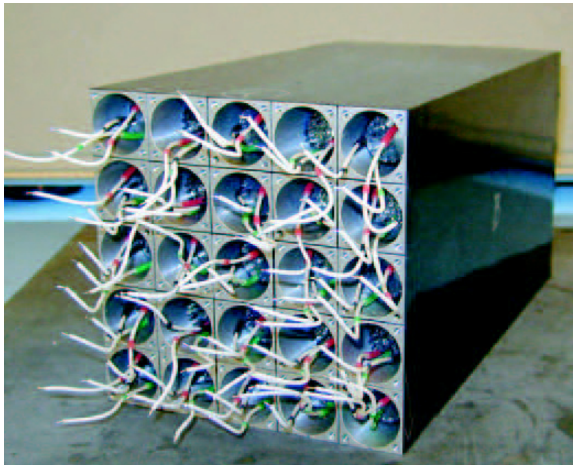
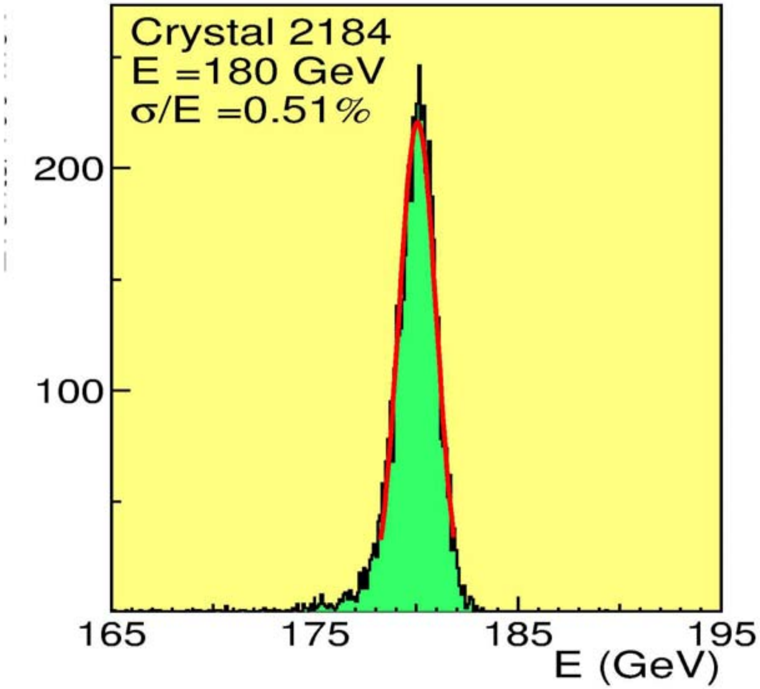
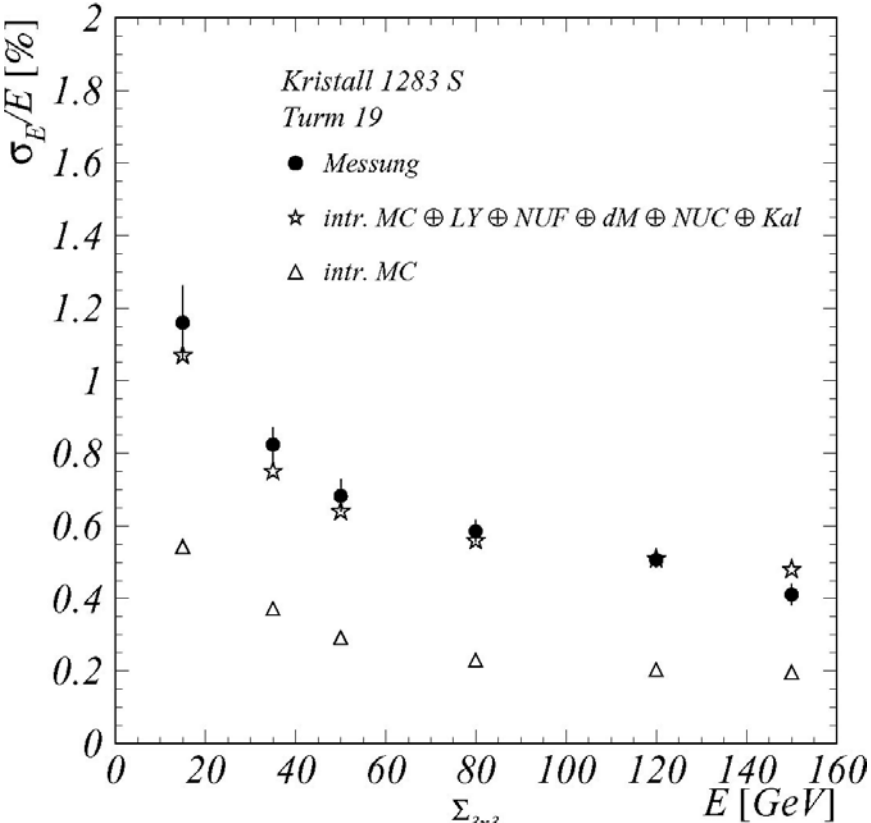
Testbeam Results

Barrel - 3x3 crystals

$$\frac{\sigma_E}{E} = \frac{2.7\,\%}{\sqrt{E}} \oplus \frac{140\ \text{MeV}}{E} \oplus 0.4\,\%$$



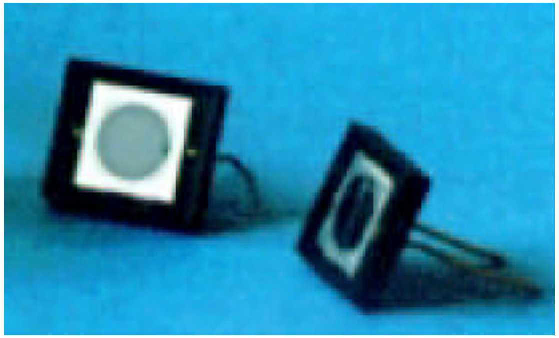




Barrel specifications: $\frac{\sigma_E}{E} = \frac{2.7\,\%}{\sqrt{E}} \oplus \frac{155\ \text{MeV}}{E} \oplus 0.55\,\%$

CMS-APD Properties

Active area	5x5 mm^2
Operating voltage (Vr)	~ 380 V
Capacitance	80 pF
Serial resistance	< 10 Ω
Dark Current (M=50)	~ 3 nA
Quantum efficiency	~ 75% @ 430 nm
1/M*dM/dV (M=50)	3.3 %
1/M*dM/dT (M=50)	- 2.3 %
Excess Noise Factor (M=50)	2
Distance to breakdown (Vb-Vr)	> 40V
Effective Thickness	~ 6 μm
Maximum Gain	> 1000



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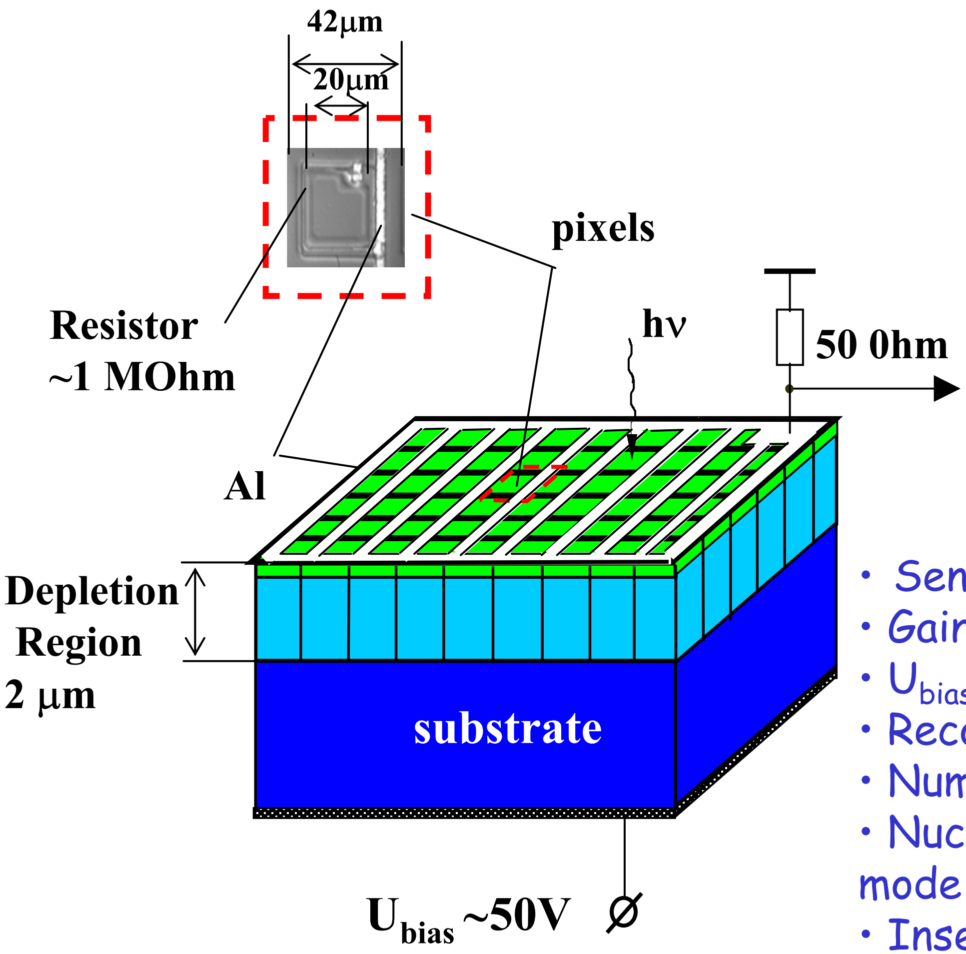
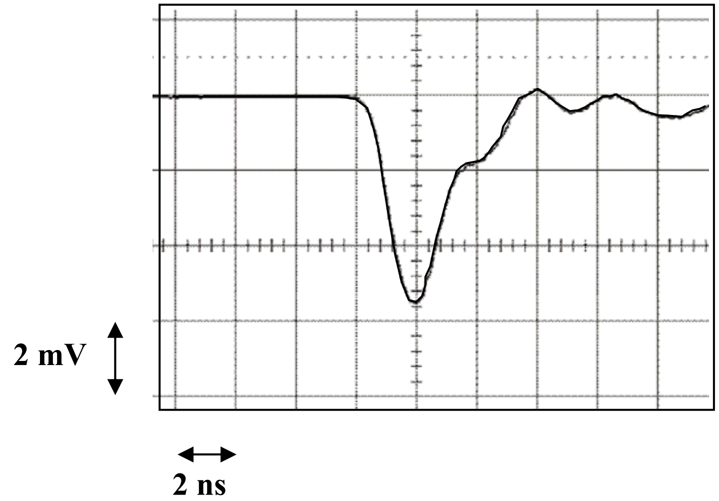
Struktur eines SiPM (Pulsar)





SiPM main features:

- Sensitive size 1x1mm^2 on chip 1.5x1.5 mm^2
- Gain $2 \cdot 10^6$
- U_{bias}~50V
- Recovery time < 100 ns/pixel
- Number of pixels: ~ 1000/mm^2
- Nuclear counter effect: negligible (due to Geiger mode
- Insensitive to magnetic field
- Dynamic range ~10^3/mm^2

B. Dolgoshein: "SiPM in particle physics", Bari

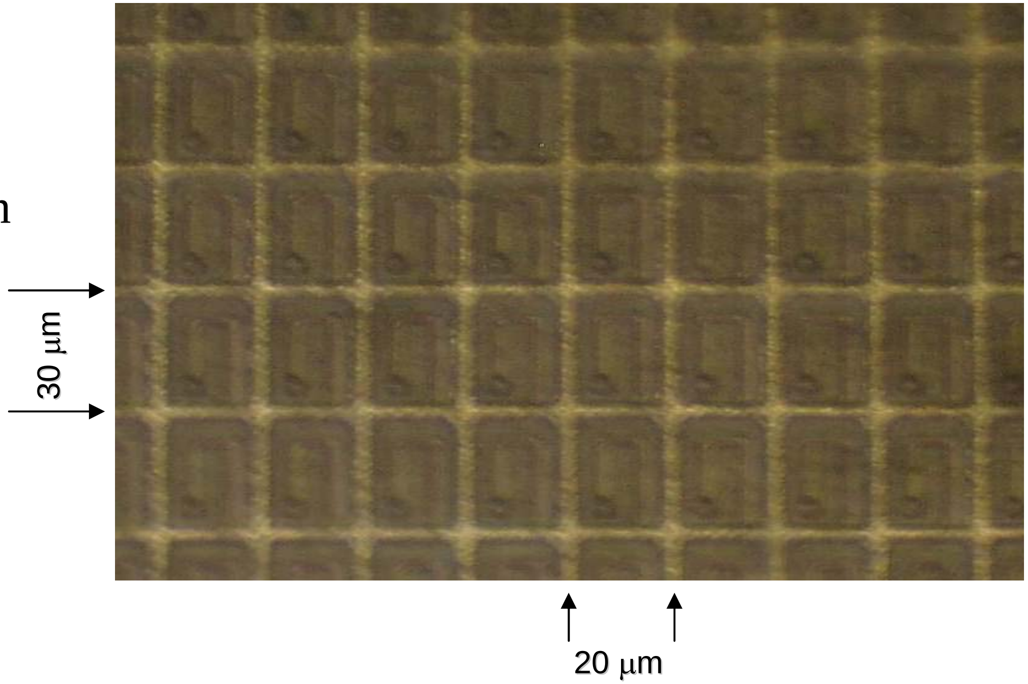
for details: NIMA 504(2003)48

Geiger Mode PhotoDiode GMPD (SiPM)

- Number of Pixels ~ 1500/mm²
- Each Pixel has its own voltage connection via resistor >100 kOhm
- Operating voltage Vbr+10V
- A single photon hitting one of the pixels triggers a breakdown and an output signal of ~10^6 electrons
- Due to the individual resistivity the bias voltage of the pixel drops, the breakdown is quenched and after ~100 ns the pixel is armed again.

Unfortunately a thermally liberated electron has the same effect and is undistinguishable.

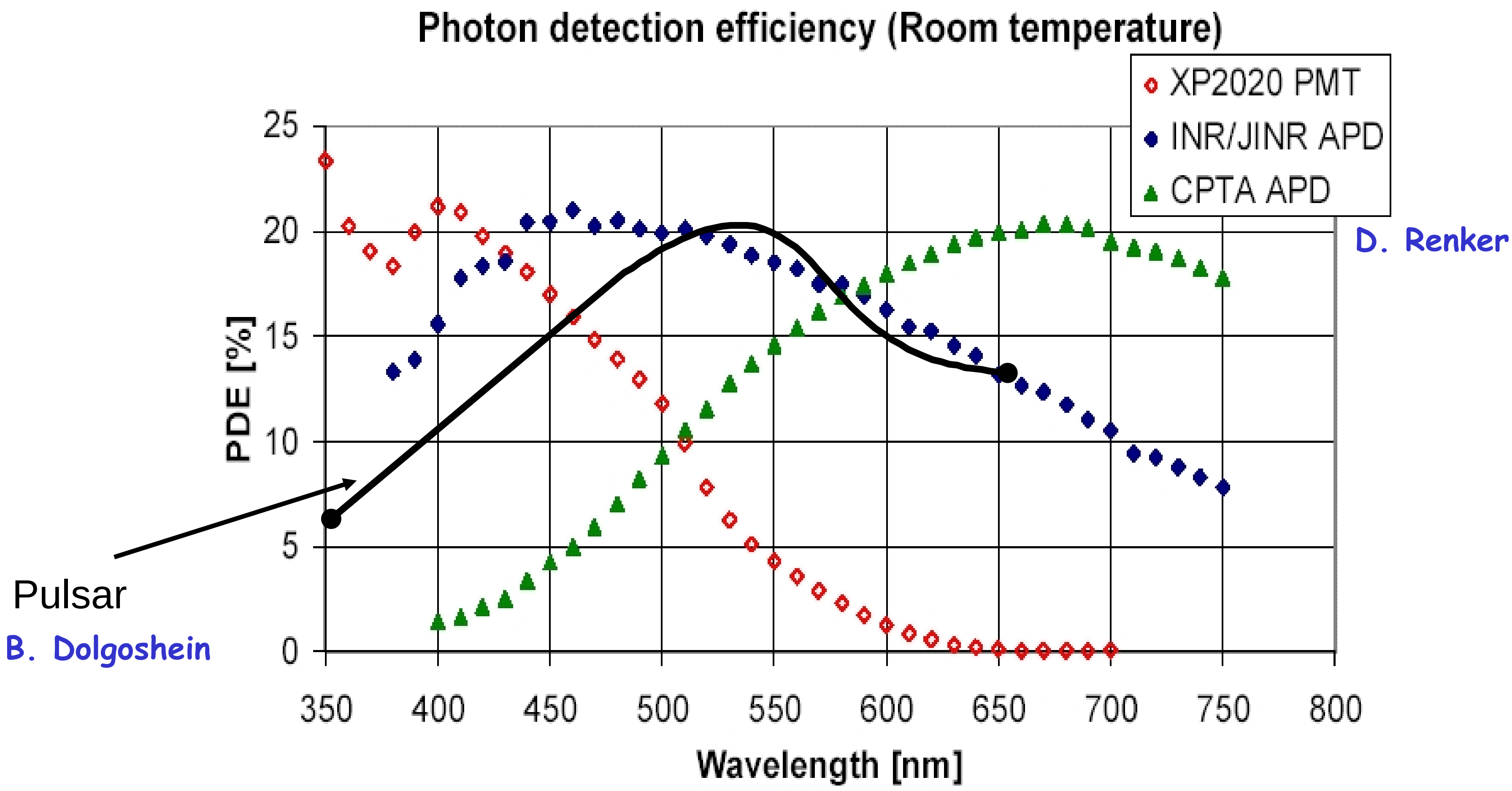
Crosstalk due to UV-photons



SiPM produced by CPTA in Moscow
(Center of Perspective Technology and Apparatus)

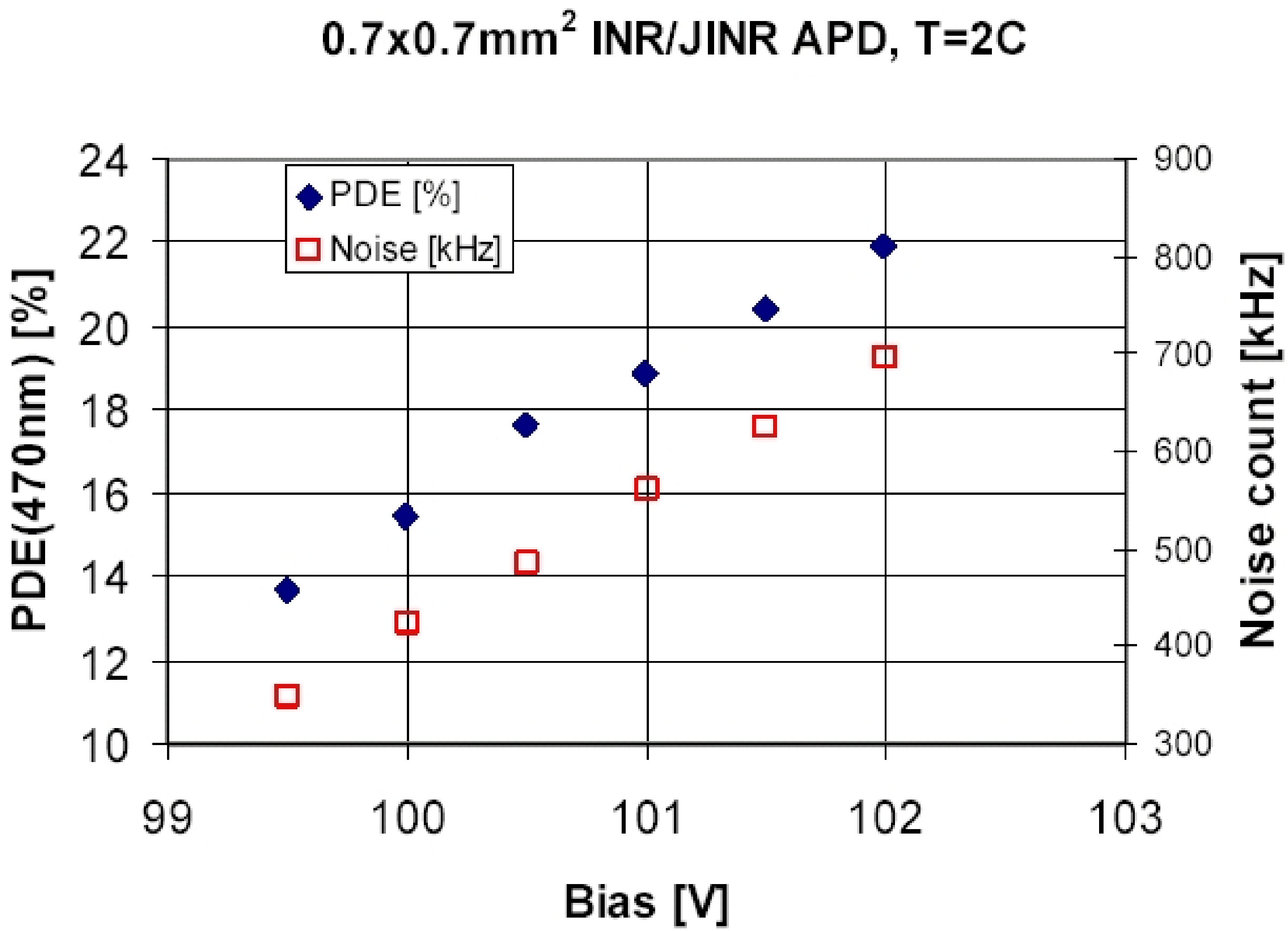
SiPM produced by INR/JINR
(Institute of Nuclear Research/Joint Institute of Nuclear Research)

SiPM: Photon detection efficiency



SiPM: $\varepsilon = QE \cdot \varepsilon_{geom}$, $\varepsilon_{geom} \sim 0.3$ (possible improvement up to ~ 0.7)

GMPD from INR/JINR: Dark Count Rate



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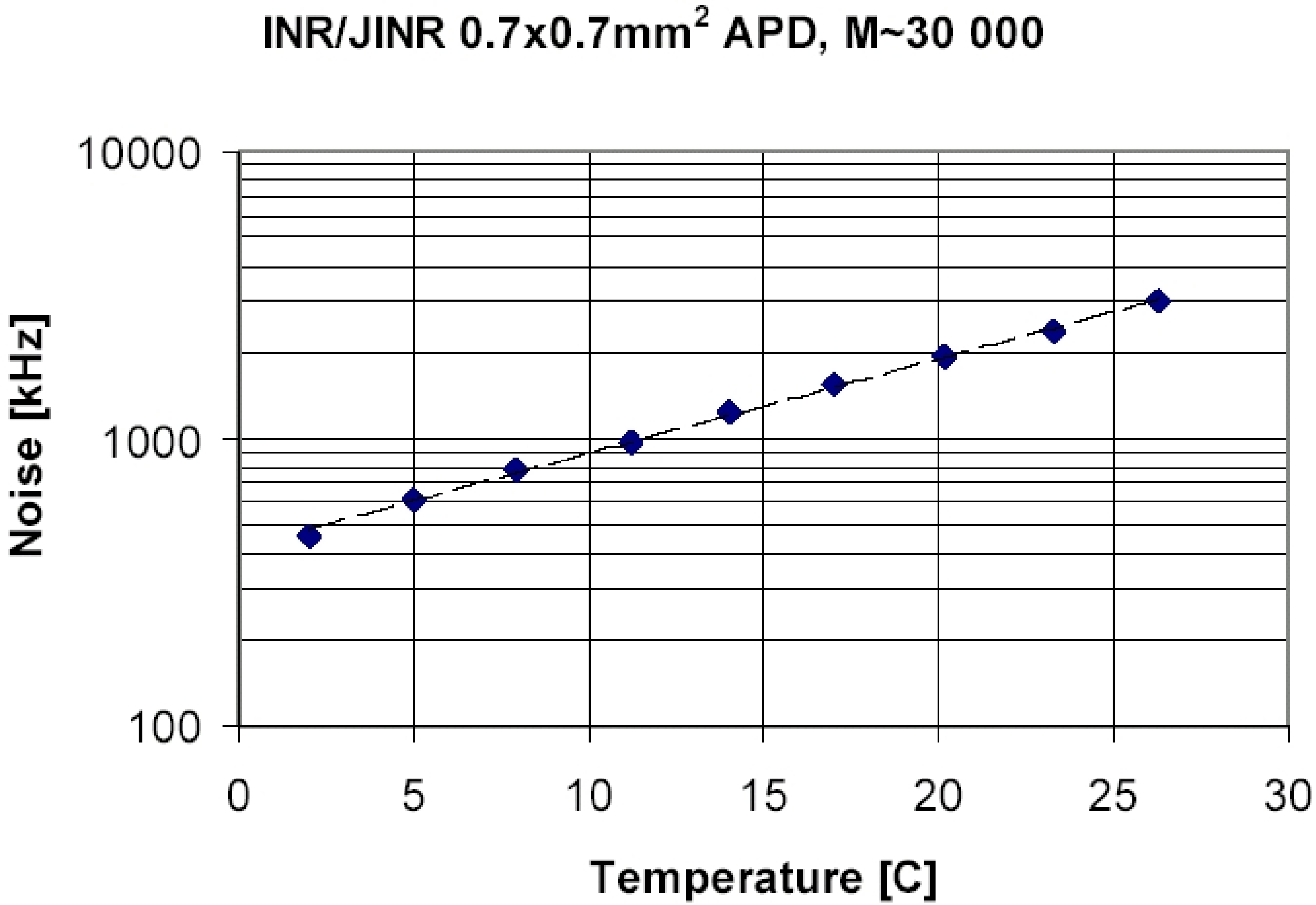
GMPD from INR/JINR: Dark Count Rate



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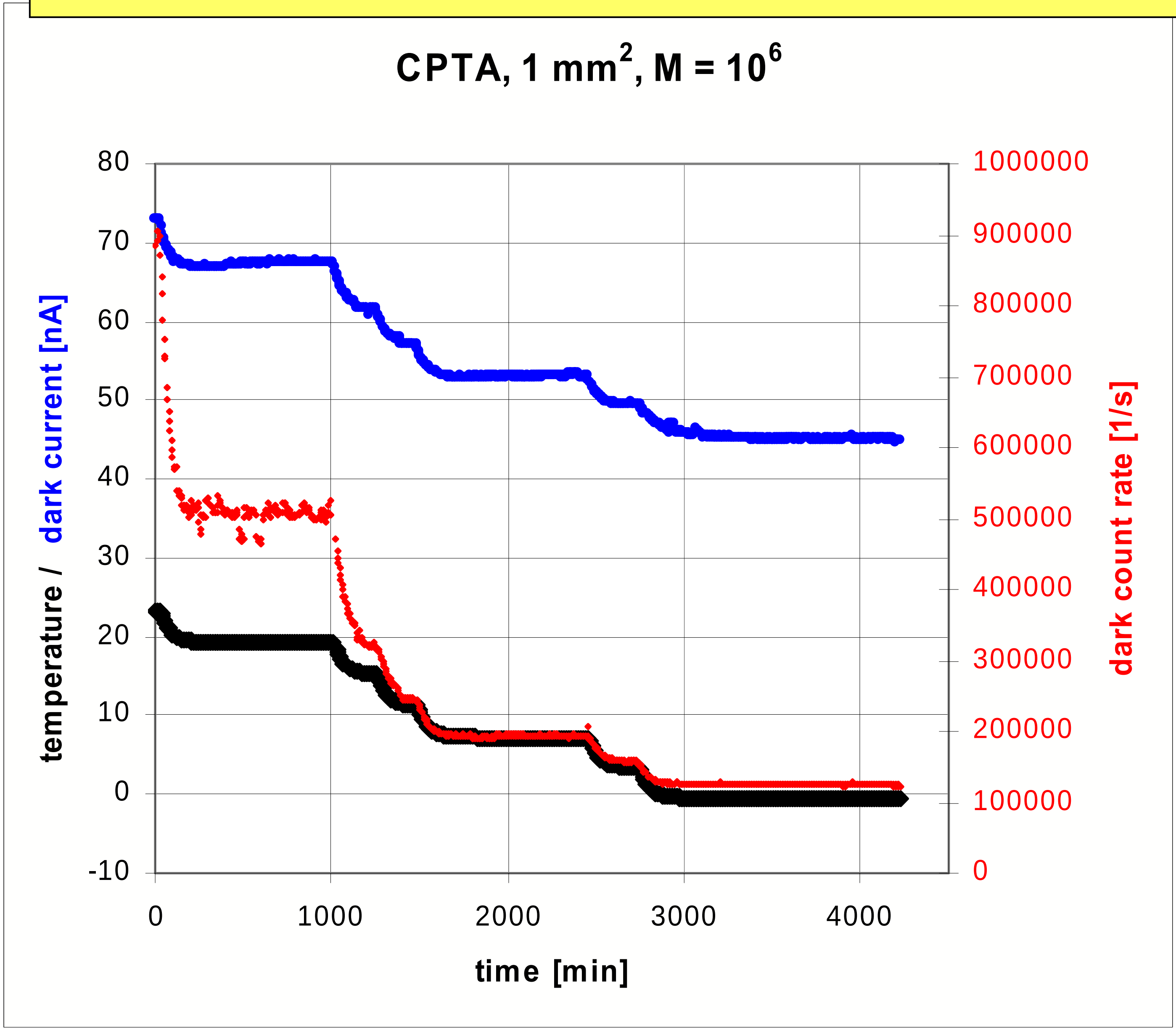
GMPD from CPTA: Dark Count Rate



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Photon Detection Efficiency and Dark Rate

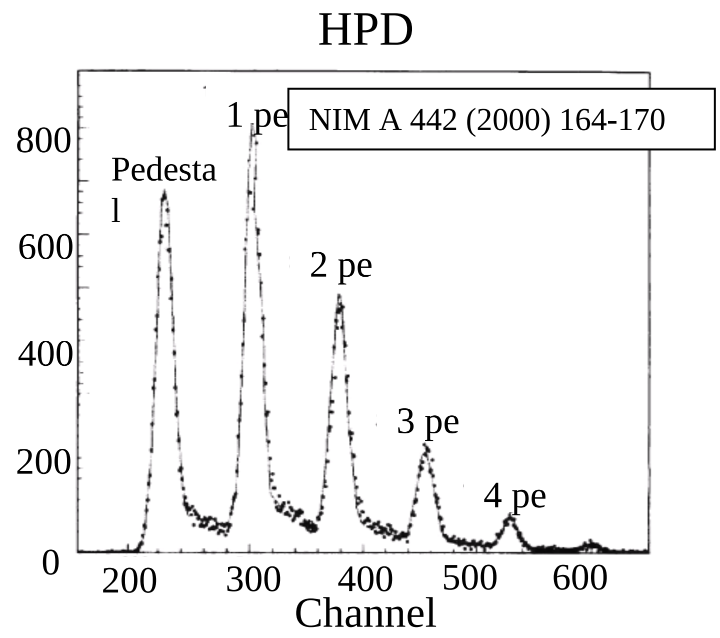
- Photon Detection Efficiency or Probability of Detection is:
  - Geometry Efficiency (technology)
  - Quantum Efficiency (wavelength dependent)
  - Probability that the photoelectron will trigger an avalanche (bias voltage dependent)

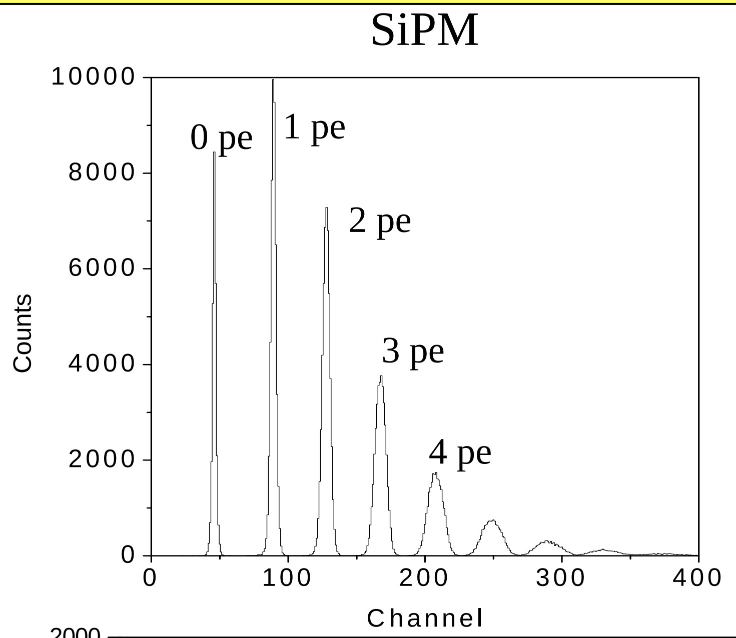
- Dark Count Rate (background signals)
  - Probability that the bulk thermal electron will trigger an avalanche (bias voltage dependent)

The tradeoff is between Single Photon Detection Efficiency and Dark Rate:
While a large bias voltage will increase the detection efficiency, so it will increase the background rate

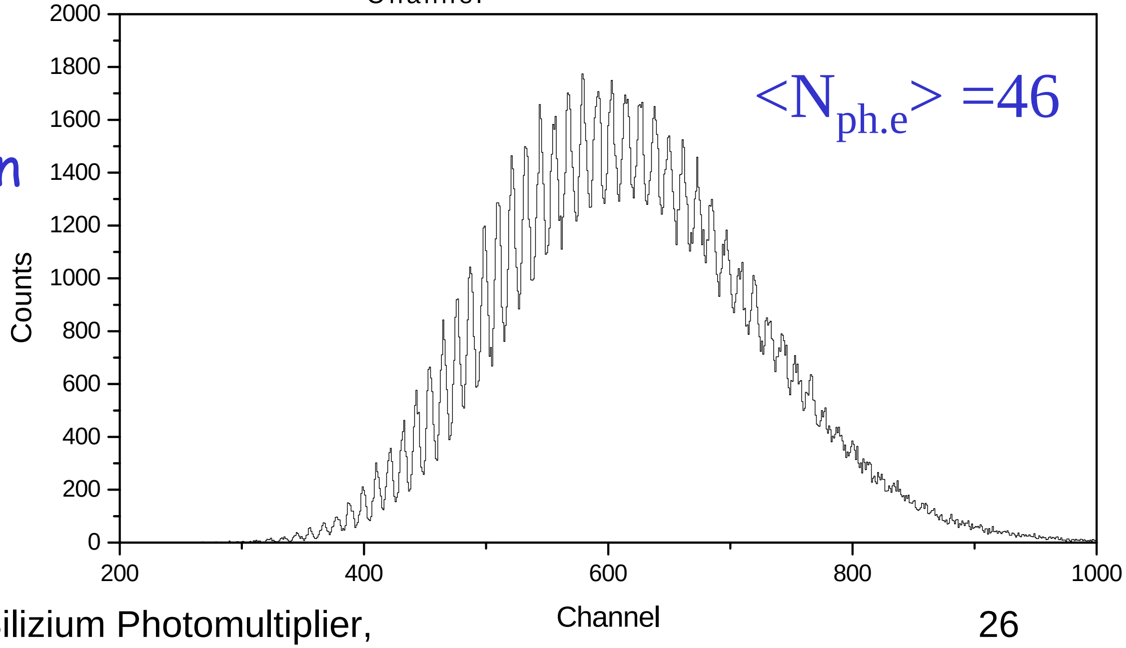
V. Saveliev

SiPM: Single Photoelectron (single pixel) Spectra



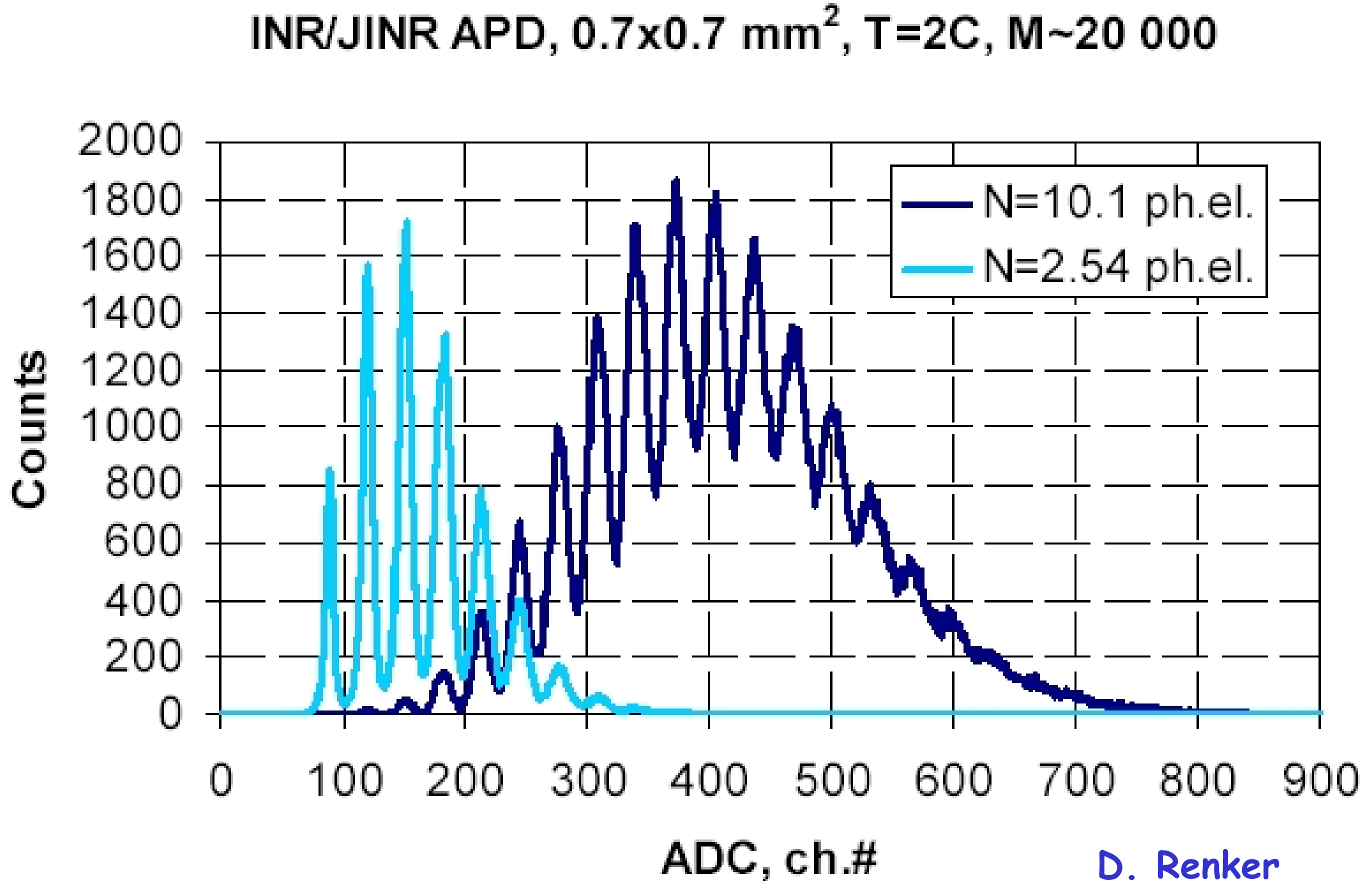


B. Dolgoshein



SiPM:
- excellent single photoelectron resolution
- consists of a large number of pixel photoelectron counters with binary readout for each pixel, working as analogue device

SiPM: Single Photoelectron (single pixel) Spectra



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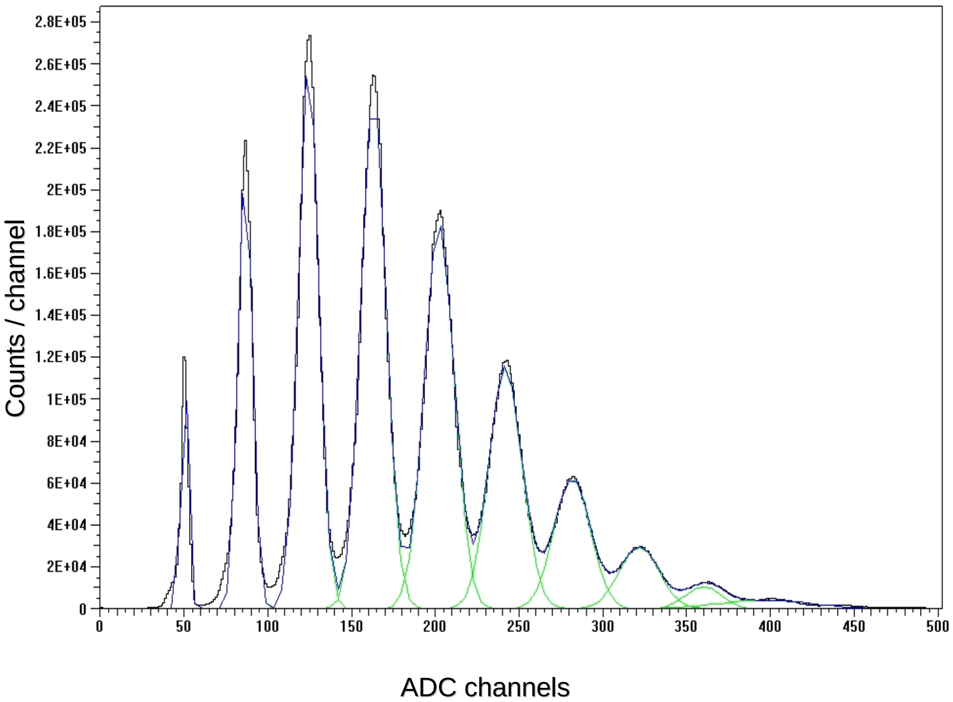
SiPM:
- excellent single photoelectron resolution
- consists of a large number of pixel photoelectron counters with binary readout for each pixel, working as analogue device

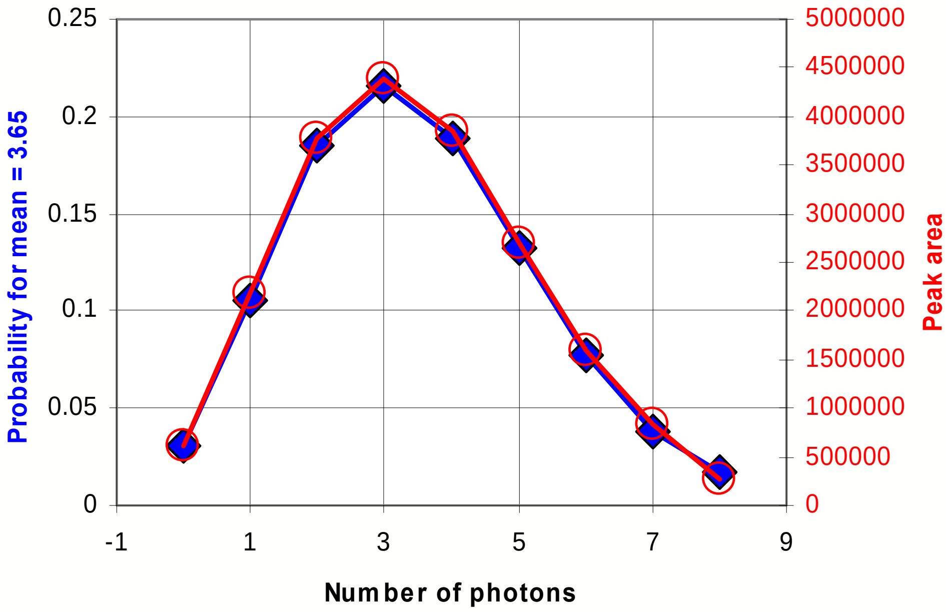
GMPD from JINR: Crosstalk

A GMPD was illuminated with a small number of photons and a pulse height spectrum was recorded.

Then Gaussian distributions were fitted to the peaks and the resulting areas were compared to a Poisson distribution with a mean of 3.65.

From the good agreement we conclude that the crosstalk between pixels is no more than few percent.





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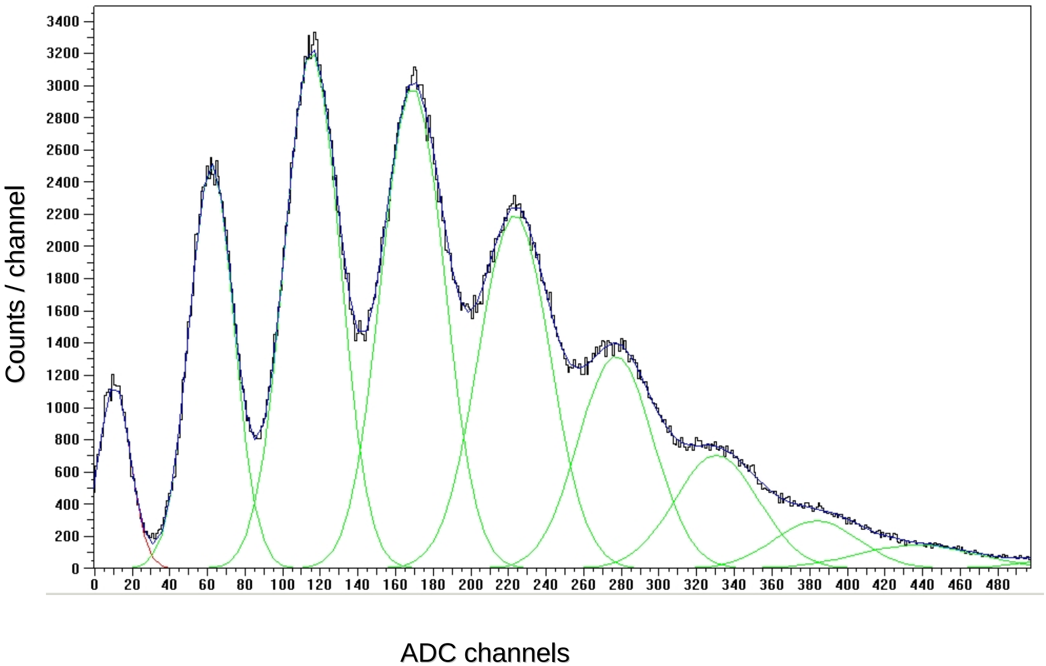
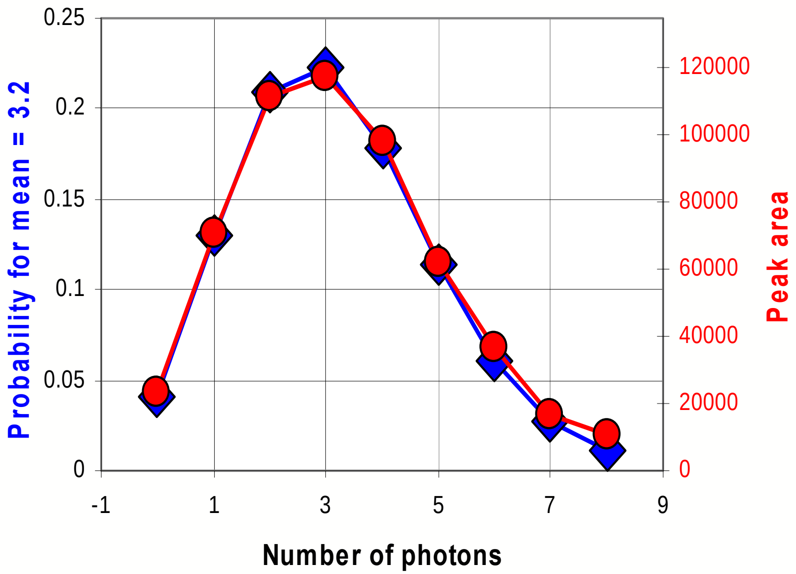
GMPD from CPTA: Crosstalk

A GMPD was illuminated with a small number of photons and a pulse height spectrum was recorded.

Then Gaussian distributions were fitted to the peaks and the resulting areas were compared to a Poisson distribution with a mean of 3.2.

From the good agreement we conclude that the crosstalk between pixels is no more than few percent.





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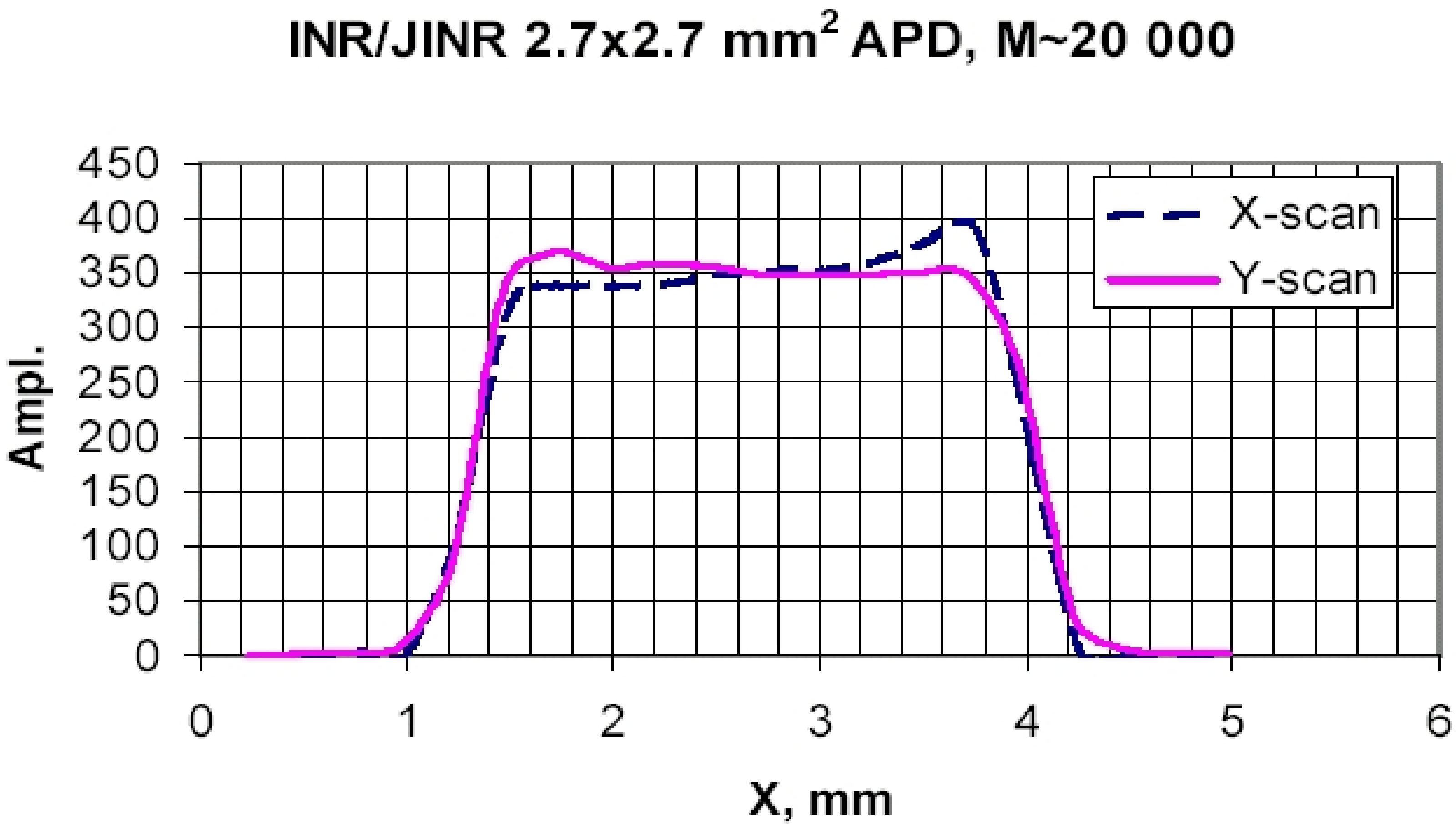
GMPD from JINR: Uniformity



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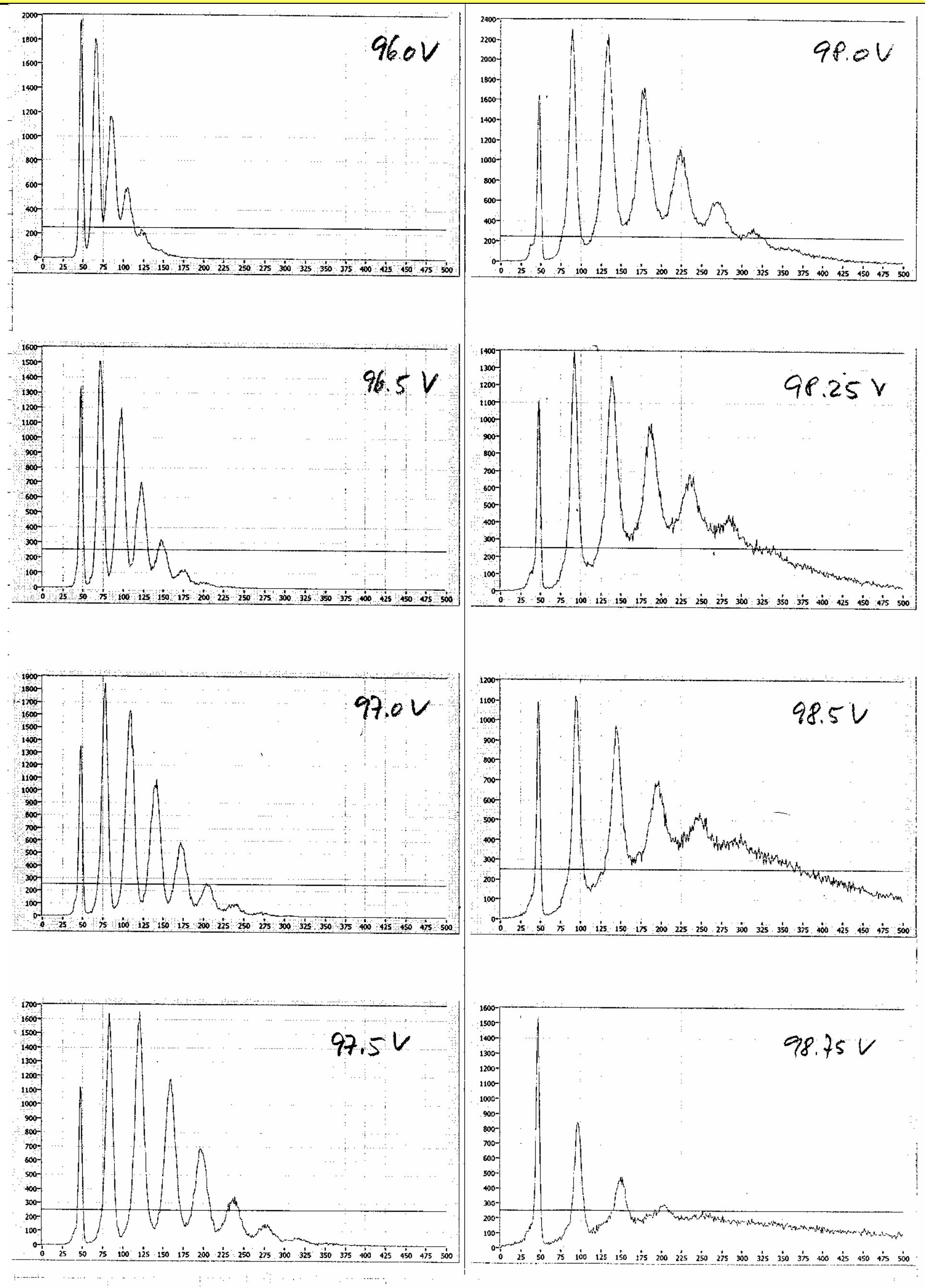
GMPD from JINR: Voltage dependence



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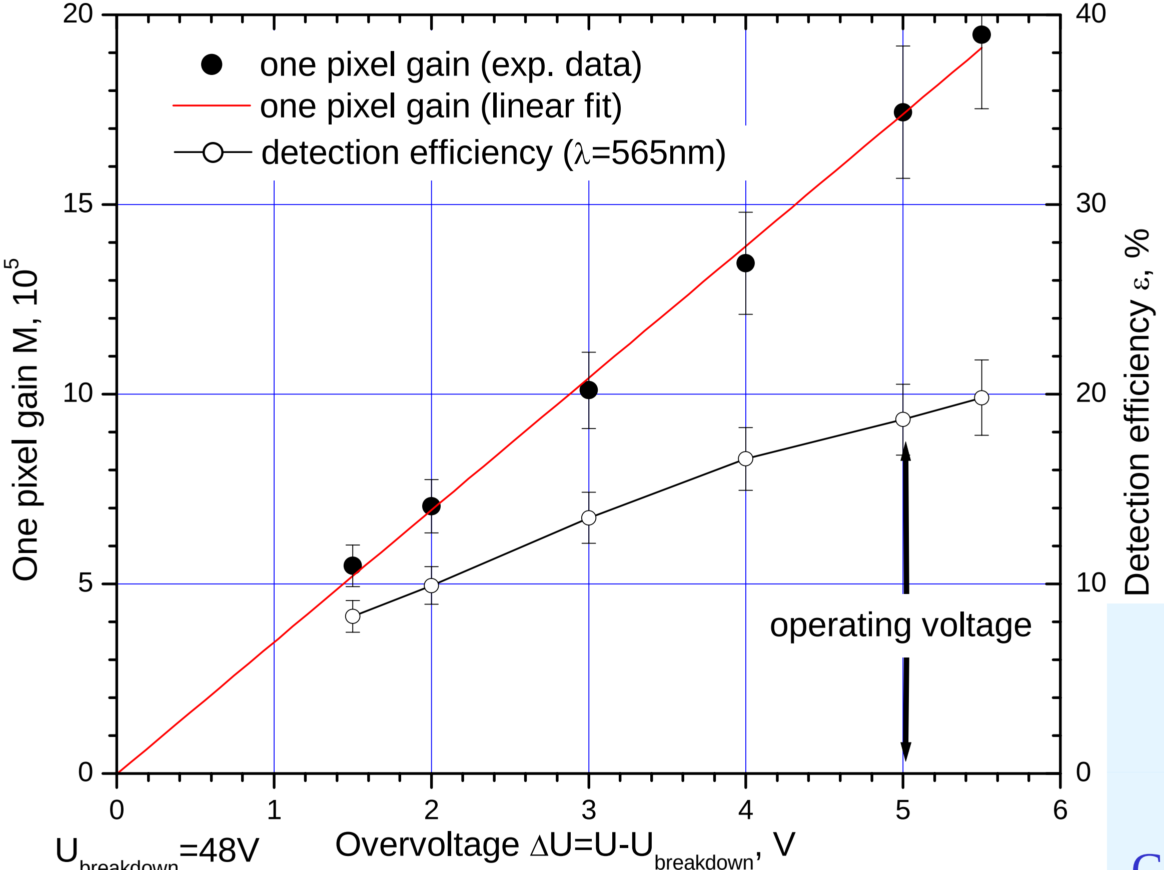
SiPM Pulsar: Single pixel gain



$U_{breakdown}$=48V

B. Dolgoshein

Photon detection efficiency $\varepsilon = QE \cdot \varepsilon_{geom}$

Photo-detector	ΔT for ΔM/M=1%	$\Delta V/V_0$ for ΔM/M=1%
CMS APD (M=50)	0.3°	0.4V/380V $=1.1\cdot10^{-3}$
SiPM ($M=2\cdot10^6$)	2.0°	0.05V/50V $=1.0\cdot10^{-3}$

SiPM Signal

SiPM signal

- The output SiPM signal is proportional to the number of pixels fired N

$$S \approx N_{pixel\_fired} = m \cdot (1 - e^{-\frac{N_{ph} \cdot \varepsilon}{m}})$$

where m- total number of pixels

N_{ph}- number of photons

ε - photon detection efficiency

⇨ saturation of the signal

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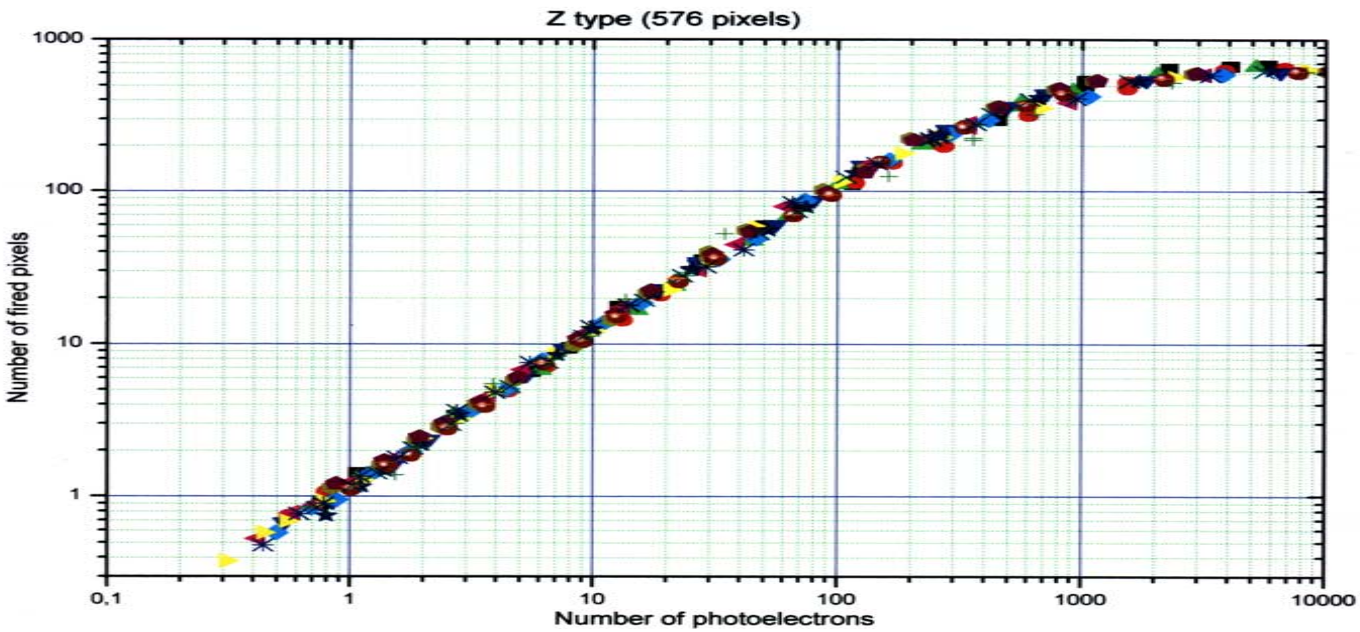
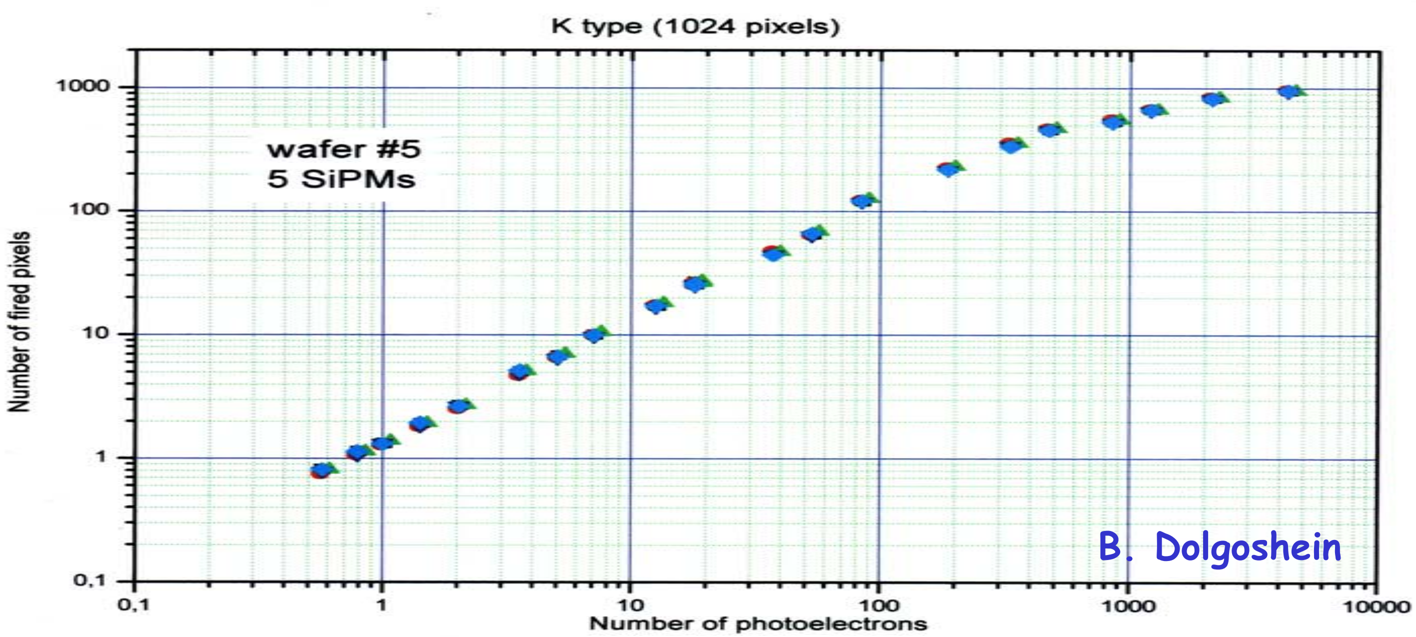

Z type (576 pixels)
Number of fired pixels
Number of photoelectrons
1000
100
10
1
0,1
1
10
100
1000
10000


K type (1024 pixels)
wafer #5
5 SiPMs
Number of fired pixels
Number of photoelectrons
B. Dolgoshein
1000
100
10
1
0,1
0,1
1
10
100
1000
10000

Th

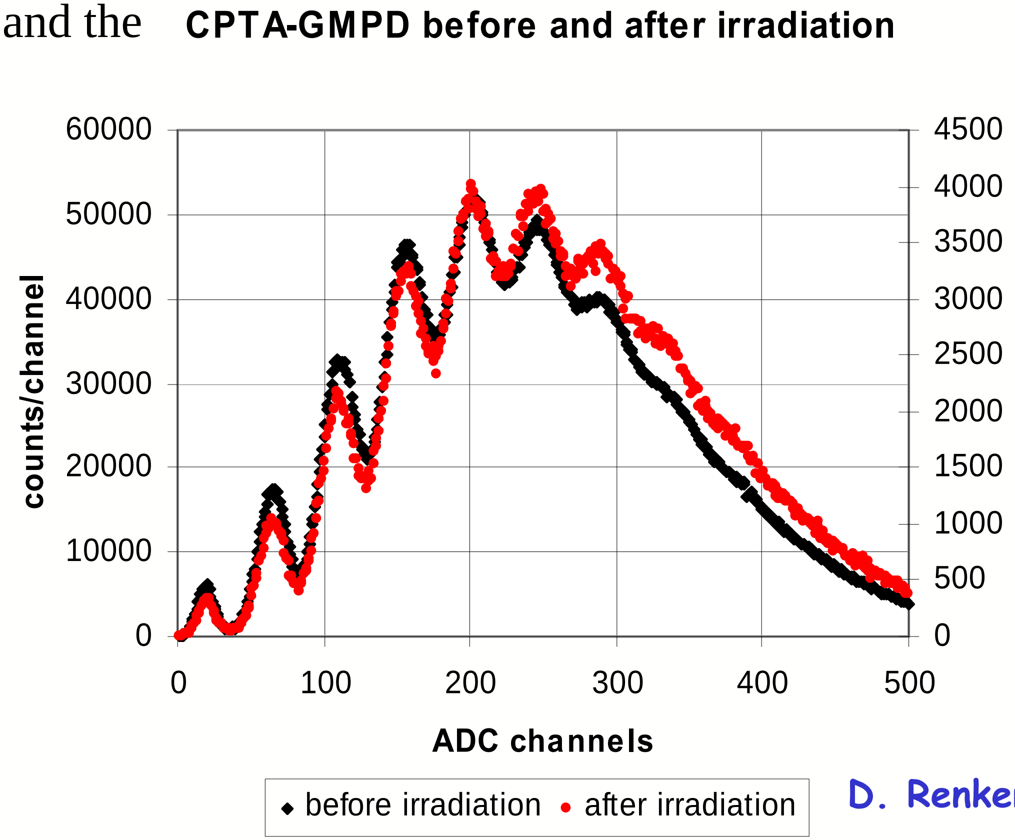
GMPD from CPTA: Irradiation 0.5 Mrad

A GMPD with an area of 1 mm^2 from CPTA has been irradiated with 5 kGy (0.5 Mrad) from a ^{60}Co source and measured one day after the irradiation.

It was not biased during the irradiation.

No change of the gain (~10^6) has been seen.

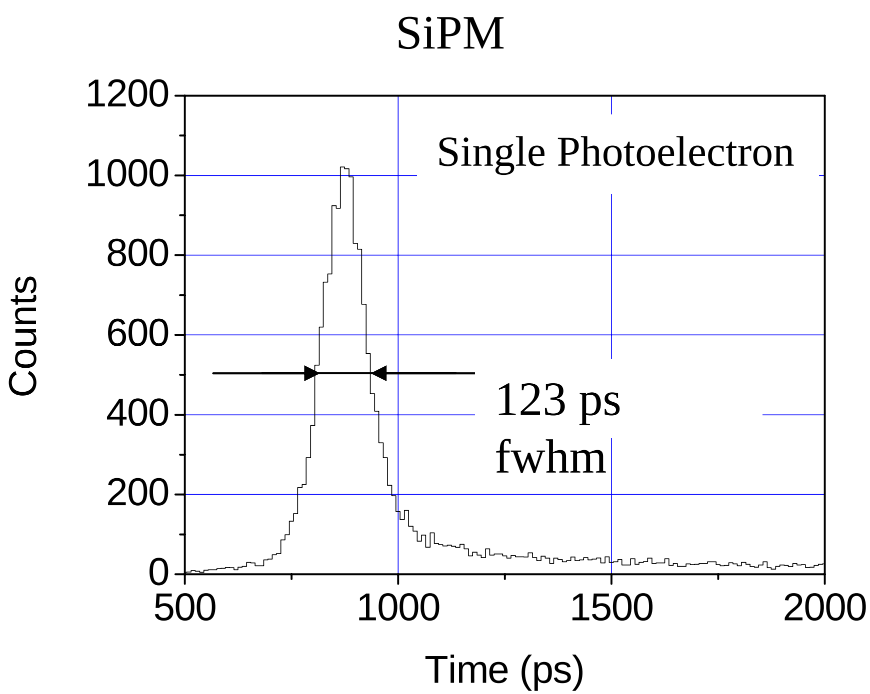
A change – if any - of the dark current and the dark count rate is below 10%.

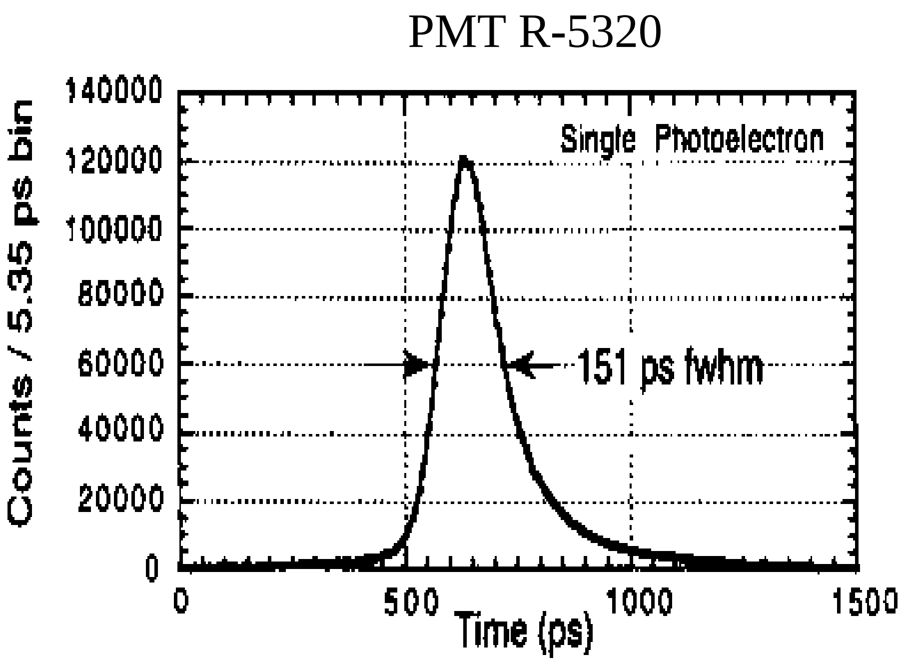


D. Renker

SiPM: Timing

- Discharge time is ~500 ps,
- Rise time ~ 1ns,
- Single pixel recovery time < 100 ns (R_{pixel} x C_{pixel} ~30 ns),
- Timing studied using very fast laser (FWHM = 40 ps)





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

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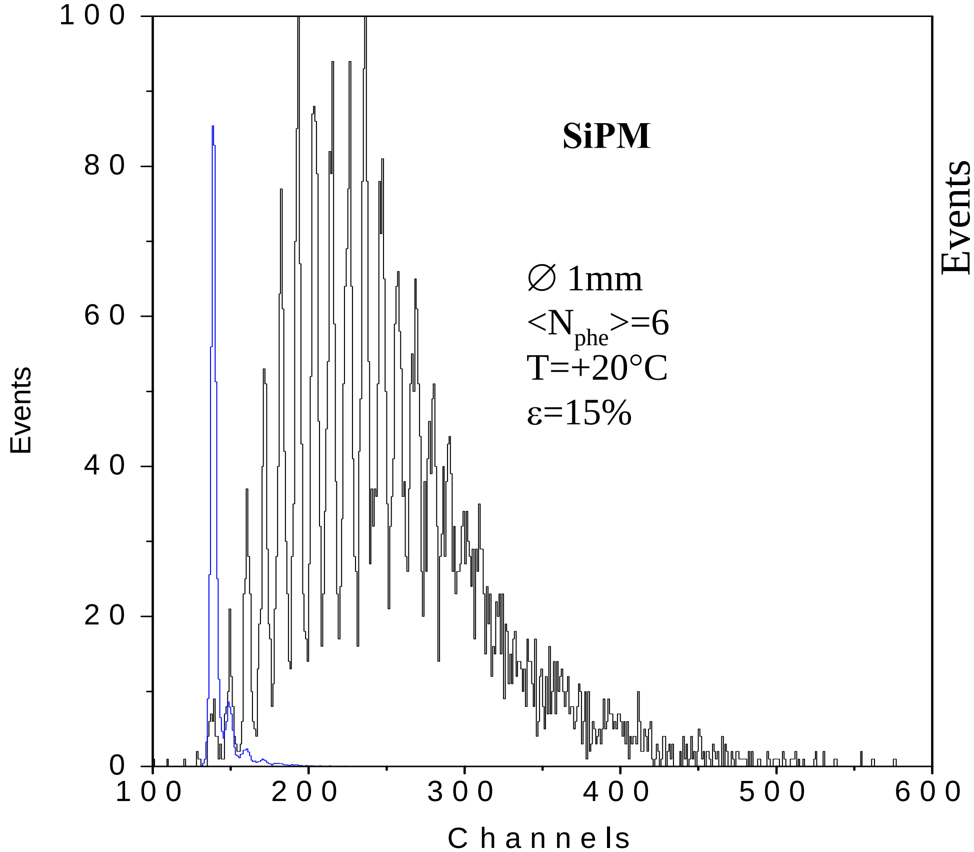
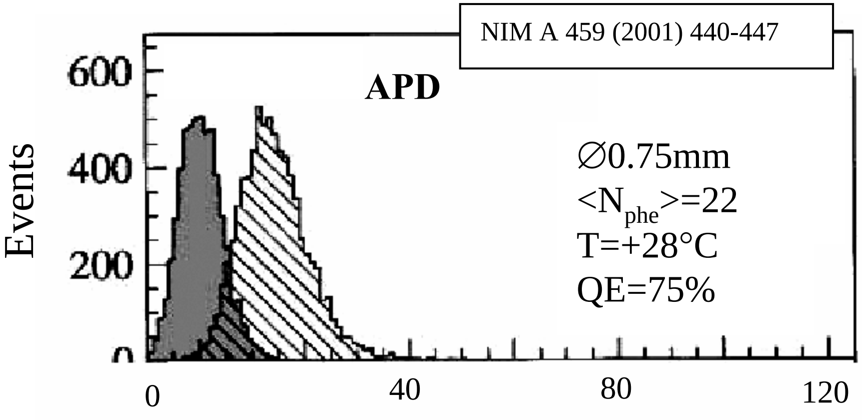
SiPM application for scintillating fiber MIP detection

Kuraray SCSF-3HF(1500)M





- SiPM is better than APD for room temperature
- Limitation: Higher PDE (30-40%) is desirable

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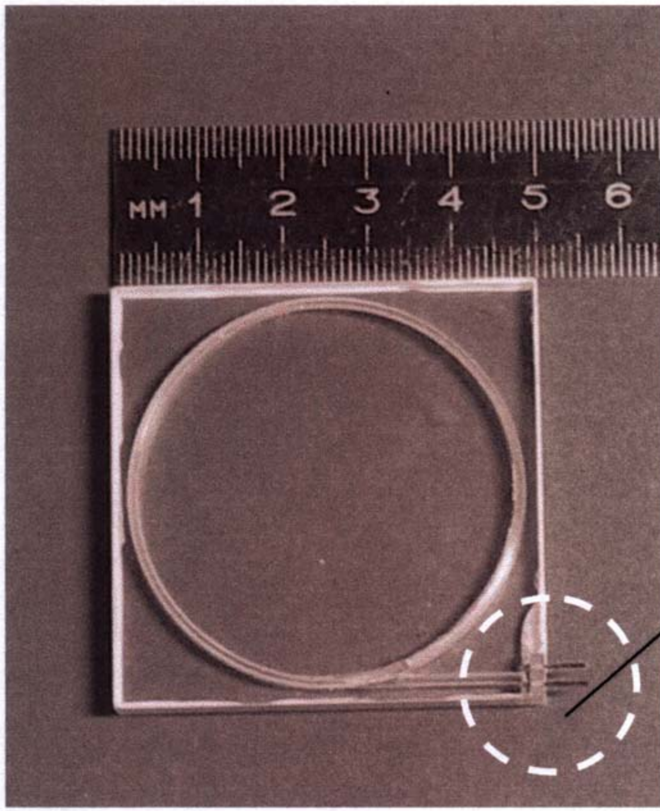
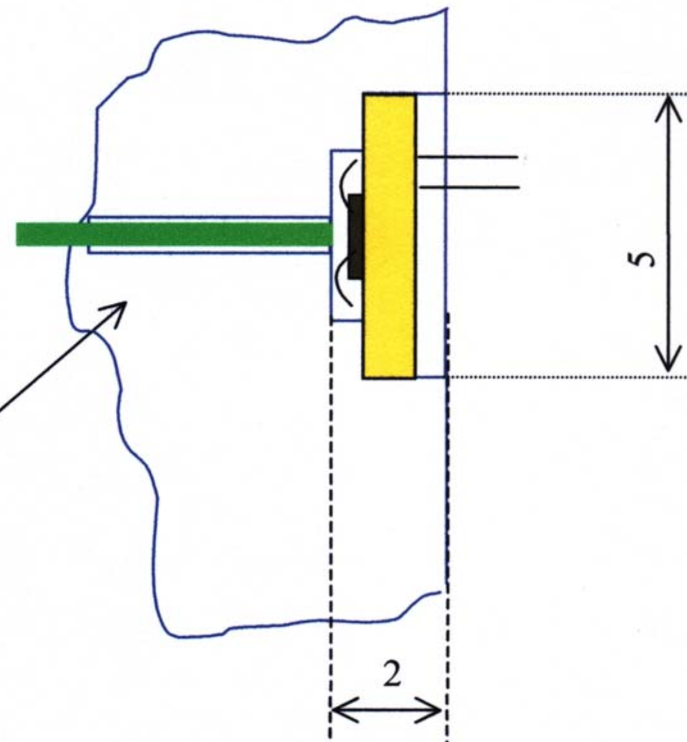
SiPM application for Hadron Tile Calorimeter: Scintillator Tile + WLS fiber readout

TESLA HCAL-scintillator tiles 50x50x5mm interlayered by 2 cm Fe

Bicron BC 404 50x50x5 mm^3
WLS fiber Kuraray Y-11; 1mm
Reflector 3M
SiPM 1x1mm,1024 pixels





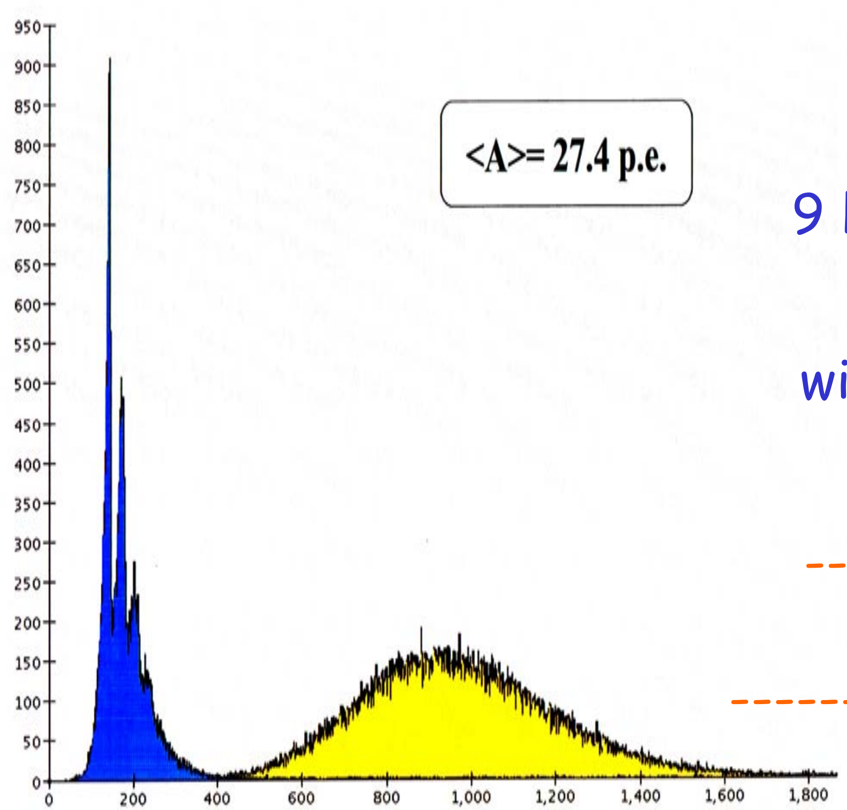
B. Dolgoshein

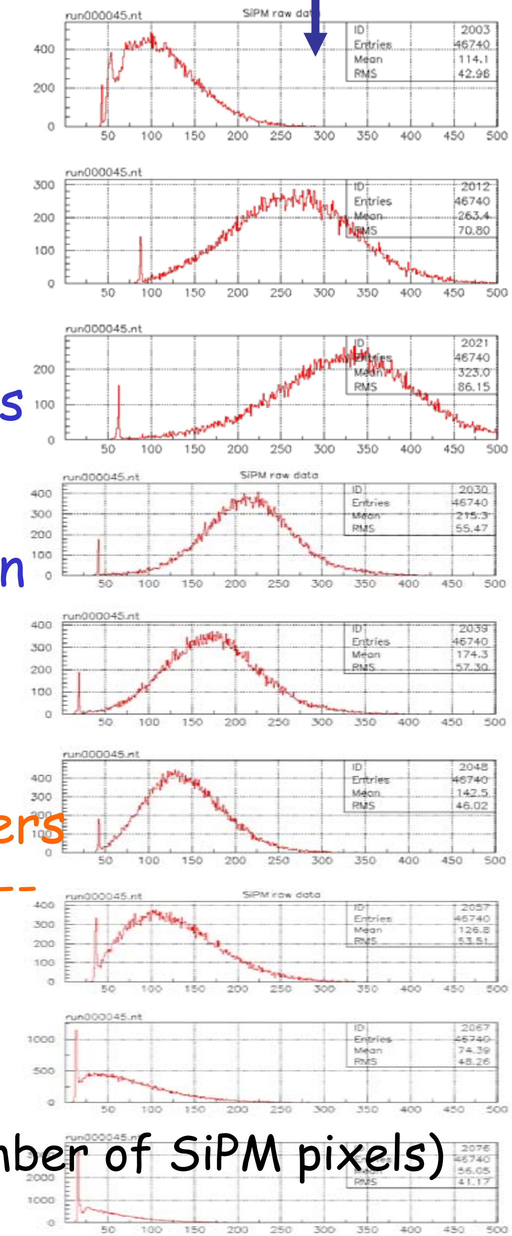
V. Saveliev

SiPM application for Hadron Tile Calorimeter: Scintillator Tile + WLS fiber readout

Electron 4 GeV

Picture from PC screen: LED and electron spectra





Test beam DESY

MiniHCAL TESLA

9 layers of 3x3 sci tiles + WLS+SiPM's

with 2cm Fe in between

Readout by SiPM's

Without any amplifiers

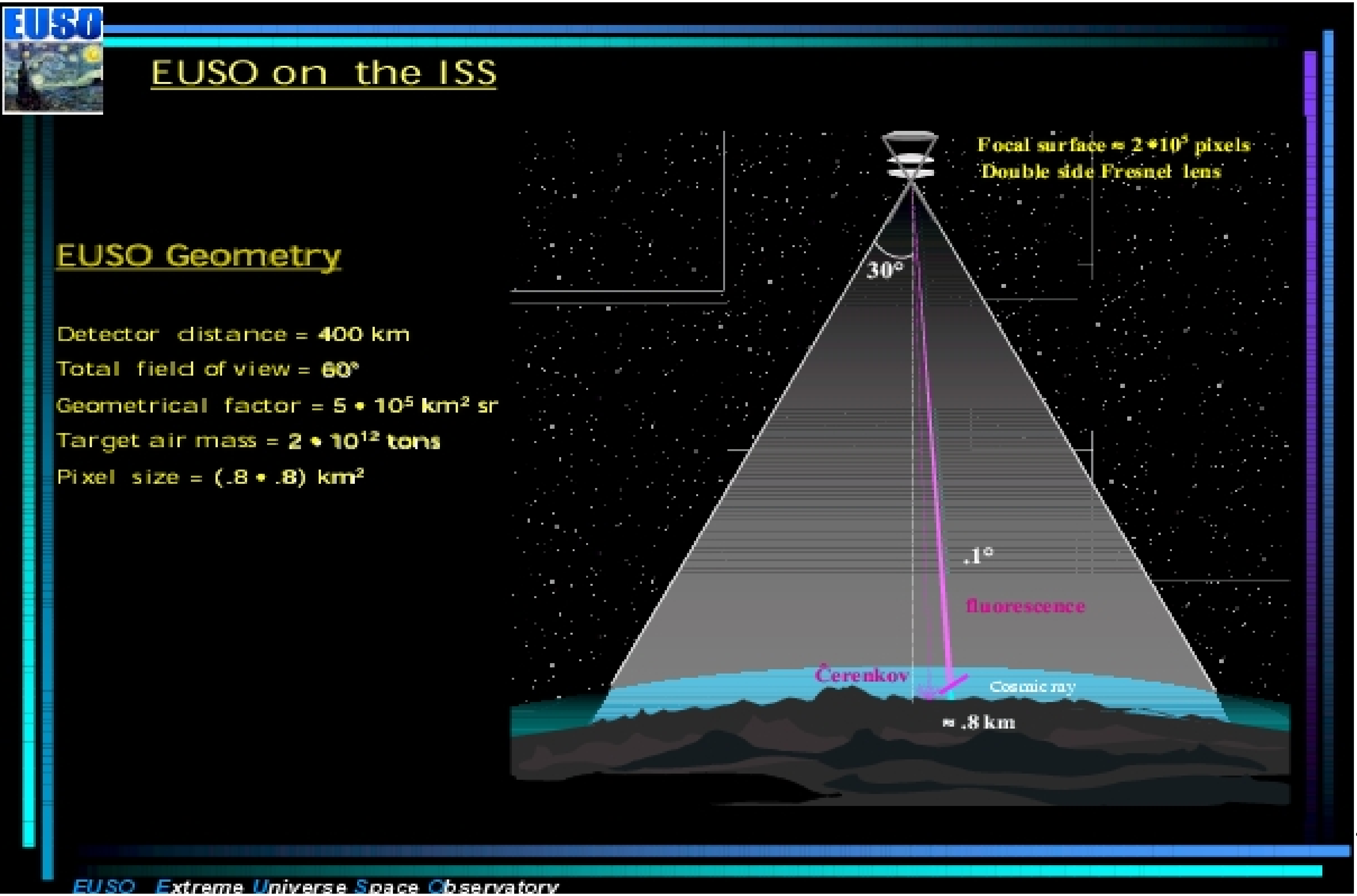
B. Dolgoshein

Limitations for Sci+WLS fiber+SiPM readout

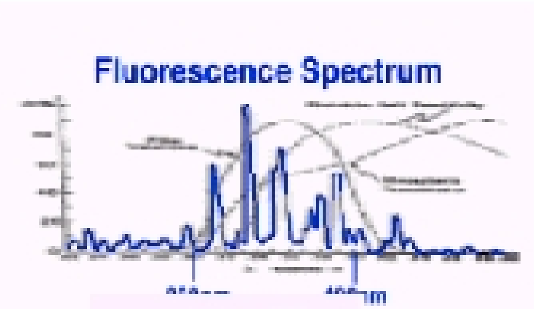
1. Limited dynamic range (number of photoelectrons/tile < number of SiPM pixels)

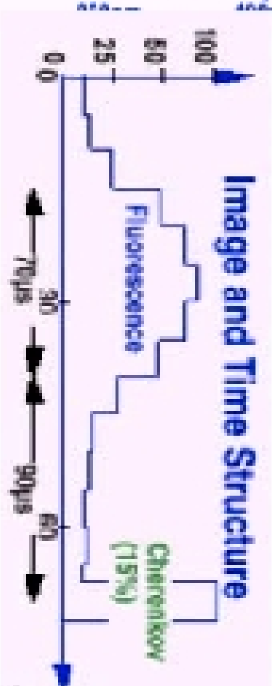
2. Optical cross-talk between the pixels

SiPM for Single Photon Counting: Possible Application for Extrem Universe Space Observatory EUSO experiment



SiPM for Single Photon Counting: Possible Application for Extrem Universe Space Observatory EUSO experiment



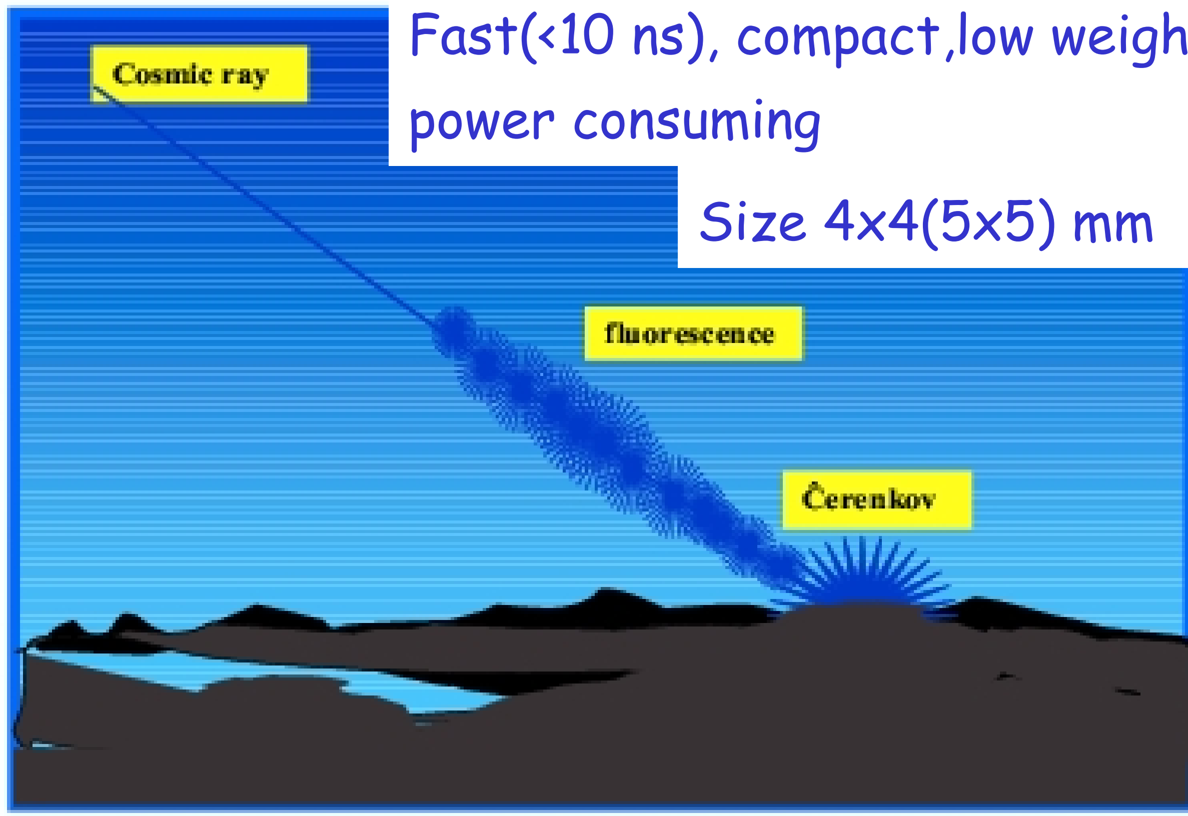


300000 Photodetectors,working in a single photon counting mode

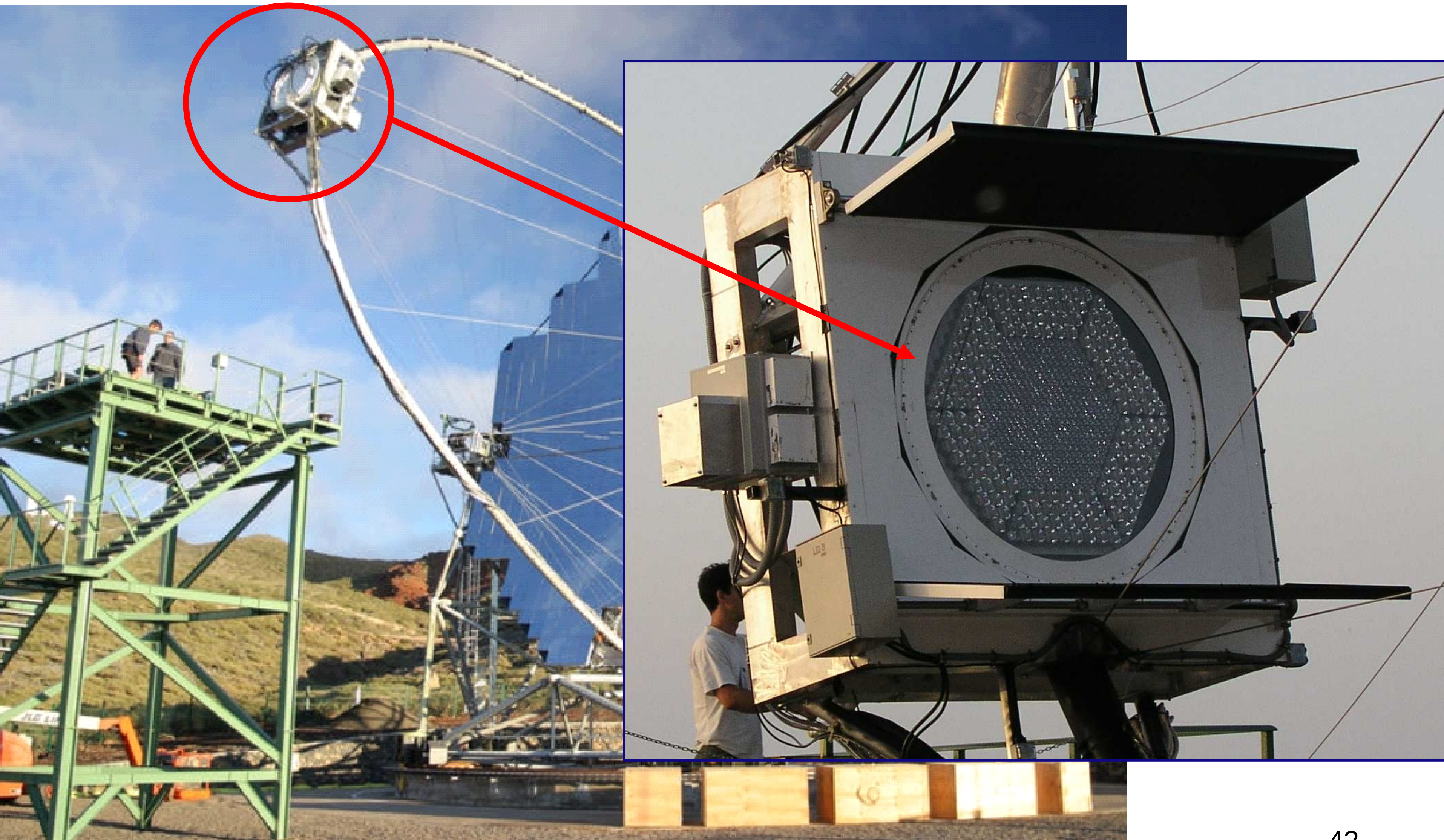
Sensitivity in 300-400 nm range,PDE 30-40%

Fast(<10 ns), compact,low weight,low power consuming

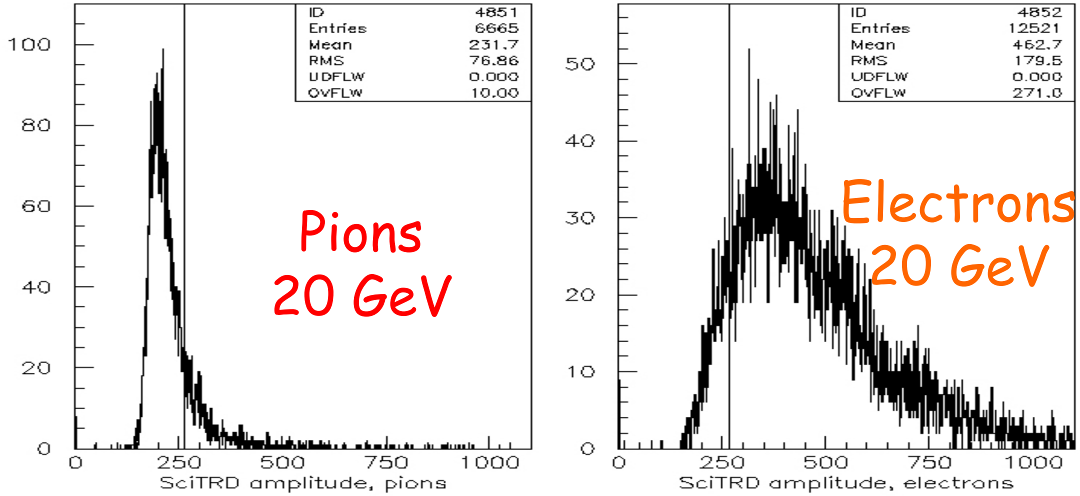
Size 4x4(5x5) mm



SiPM: Possible Application for Magic Čerenkov Telescope



SiPM: TRD based on thin scintillator



V.Sosnovtsev Bari talk
SciTRD: Radiator 40 cm
+ 30 mkm CsI(Na)+PMT

Advantages compared to Xe based TRD:

- No gas-> inportant for space experiments
- No dE/dX relativistic rise for hadrons→ better rejection power expected for 30 <E/mc< 300

Multiset radiator-detector TRD is possible only with small amount of the photodetector material → SiPM(< 0.5%X_0)

Limitation: need to have SiPM size ~5x5 mm

B. Dolgoshein

SiPM - Example of superfast timing:
Time Of Flight Positron Electron Tomography with 3D-reconstruction of each event

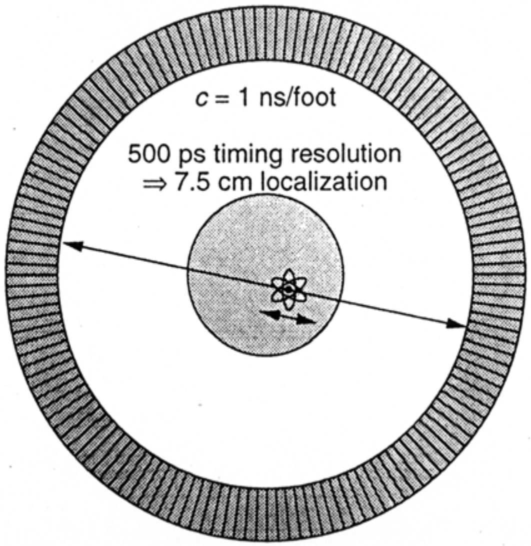
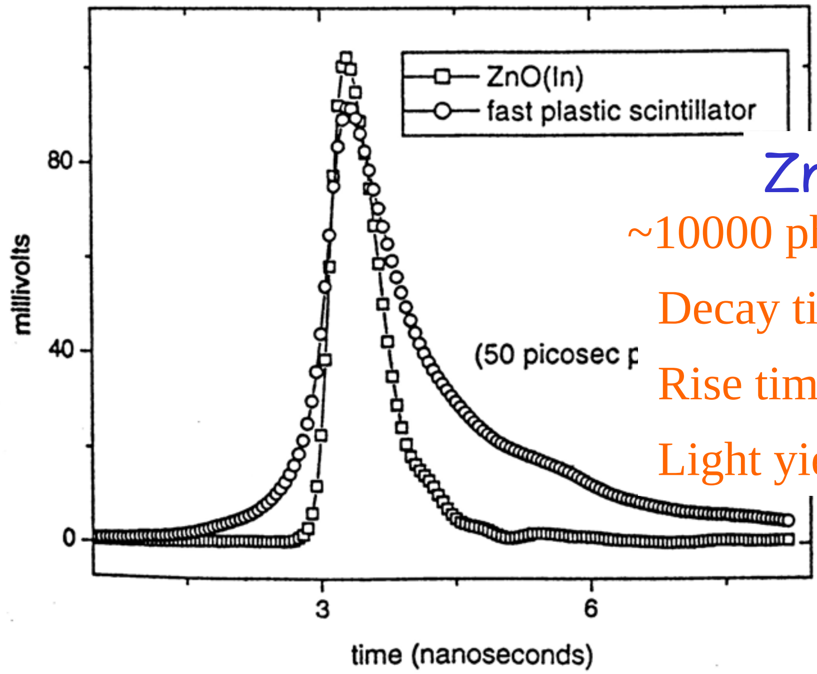


Figure 1. Time-of-Flight PET Camera. Annihilation phot
detected by a ring of scintillation crystals. With a conv
PET camera, this localizes the position of the positron to
segment joining the two crystals. With a TOF PET cam
arrival time difference is used to further restrict the positio



ZnO(In):

~10000 photons/MeV/ns

Decay time 650 ps

Rise time <100 ps

Light yield ~ Plastic Sc

400-600 nm

GEANT based simulation gives for:

ZnO(In) crystal size (4.5 mm)

SiPM size 4.5x4.5 mm

Sigma of SiPM 50 ps

Sigma electronics 5 ps

Photon Detection eff. 30%

→ 3D TOF PET resolution of 2 mm(sigma) can be achieved

Limitations: * Size 4.5x4.5mm, * PD efficiency 30%

B. Dolgoshein

SiPM for Single Photon Counting: Calibration of AMS-02 ACC @ PSI

Silicon Photomultiplier Summary: Arguments in favour

- ✓ Low noise,high gain
- ✓ Good single electron resolution
- ✓ Very good timing
- ✓ Small recovery time
- ✓ Low charge particle/photon sensitivity
- ✓ Insensitivity to B
- ✓ Low bias voltage
- ✓ Low power consumption
- ✓ Compactness
- ✓ Room temperature operation
- ✓ Good temperature and voltage stability
- ✓ Simplest electronics
- ✓ Relatively low cost(low resistivity Si,simple technology)

B. Dolgoshein

Silicon Photomultiplier Summary: Drawbacks/Limitations

- Small size (only 1x1 mm is carefully studied)
- The photon detection efficiency is not high enough(<20%)
- High dark rate
- Optical cross-talk between pixels (20 (2) % for gain 10^6)
- Limited dynamic range(1000/mm)

B. Dolgoshein

Very promising are the Geiger mode photodiodes with new structures. We are at the beginning of the development and big progress can be expected within one or two years.

D. Renker