Light Sensors for the Contemporary Astro-Particle Physics Experiments; Comparative Analysis

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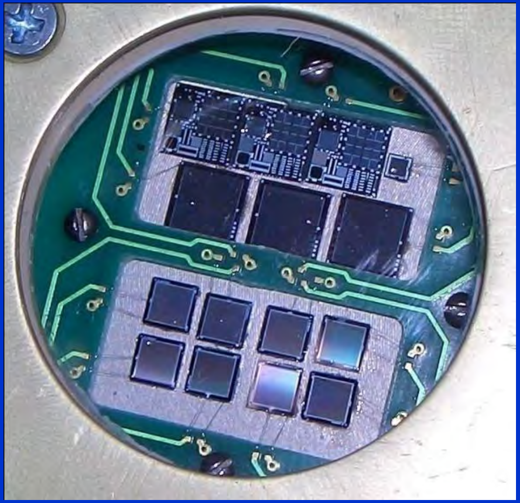
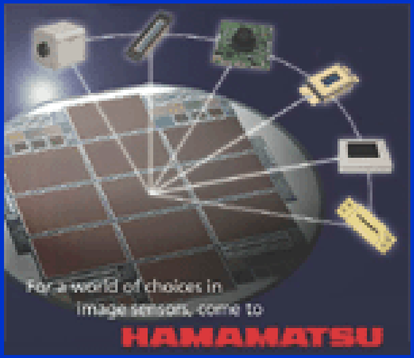
What LLL sensor can we dream about ?

- Nearly 100 % QE and photon detection efficiency (PDE)
- Could be made in very large and in very small sizes
- Few ps fast (in air and in many materials the light speed is usually 20-30 cm/ns; in 5 ps it will make 1-1.5 mm)
- Signal amplification x10^6
- Noiseless amplification: F-factor - 1.001
- Few % amplitude resolution
- No fatigue, no degradation in lifetime
- Low power consumption
- Operation at ambient temperatures
- No danger to expose to light
- Insensitive to magnetic fields
- No vacuum, no HV, lightweight,...

The „zoo“ of LLL sensors



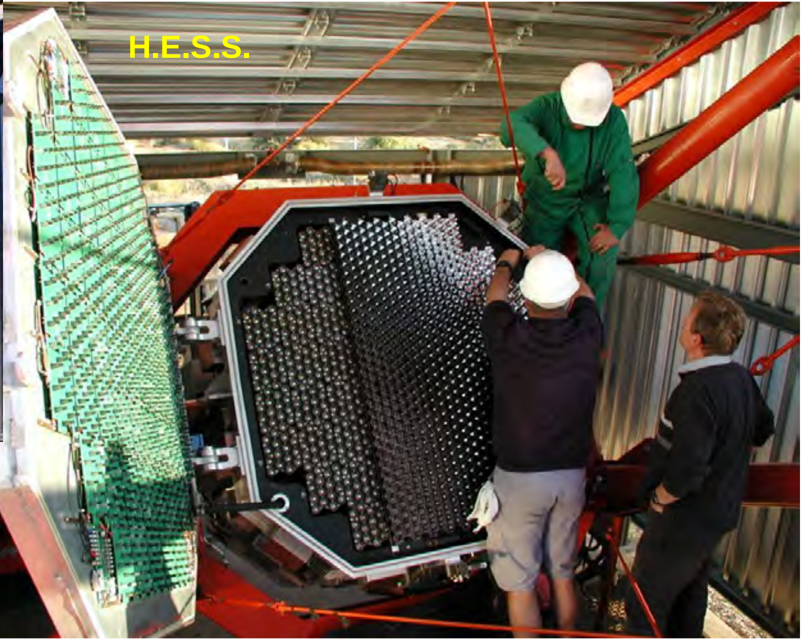


Today: the 17m Ø MAGIC IACT project for VHE γ astrophysics at E ~ 25 GeV - 30 TeV

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

Photograph of the 1039-pixel imaging camera of MAGIC-I. Pixels are based on superbialkali PMTs each covering 0.10° in the sky.

VERITAS camera

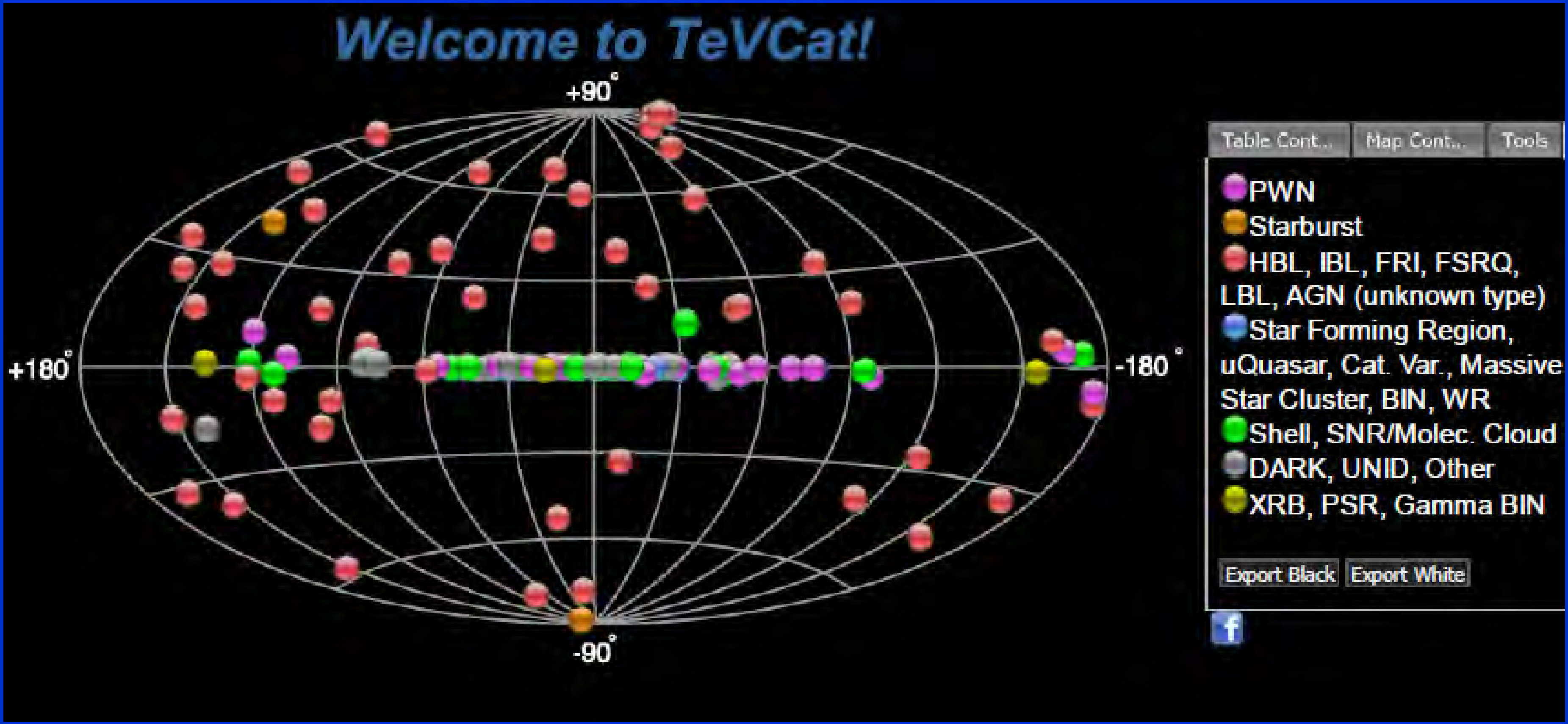


H.E.S.S.

Ground-based VHE γ Astrophysics

# of sources discovered by H.E.S.S., MAGIC, VERITAS, Milagro, Cangaroo: ~160

Also sources by Whipple, HEGRA, Durham, Crimea, Potchefstroom, Telescope Array

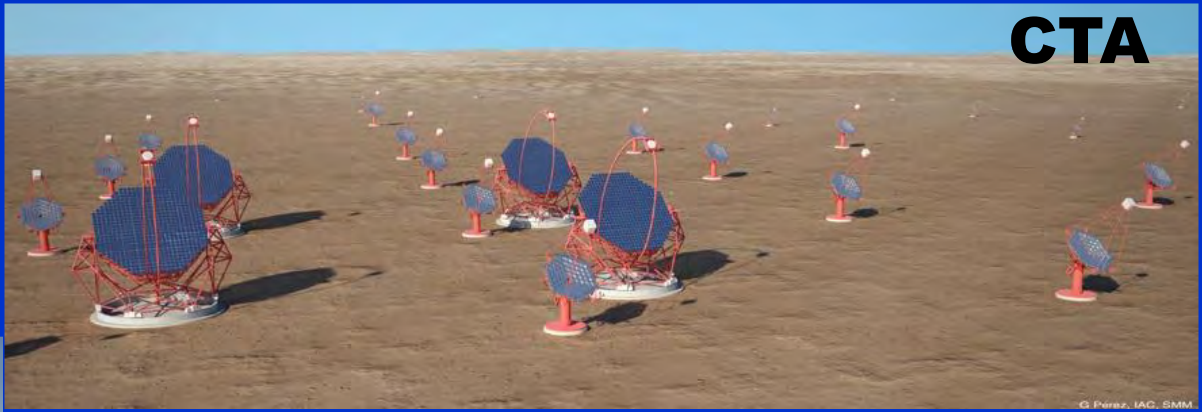


Outlook : the next 3-7 years

Next generation VHE γ ray Observatory: CTA

MAGIC

Cherenkov Telescope Array
1000’s of sources will be discovered



HESS Phase II

>1200 scientists
>130 institutions

Astronomers in EU + Japan + USA = CTA

Quantum Efficiency

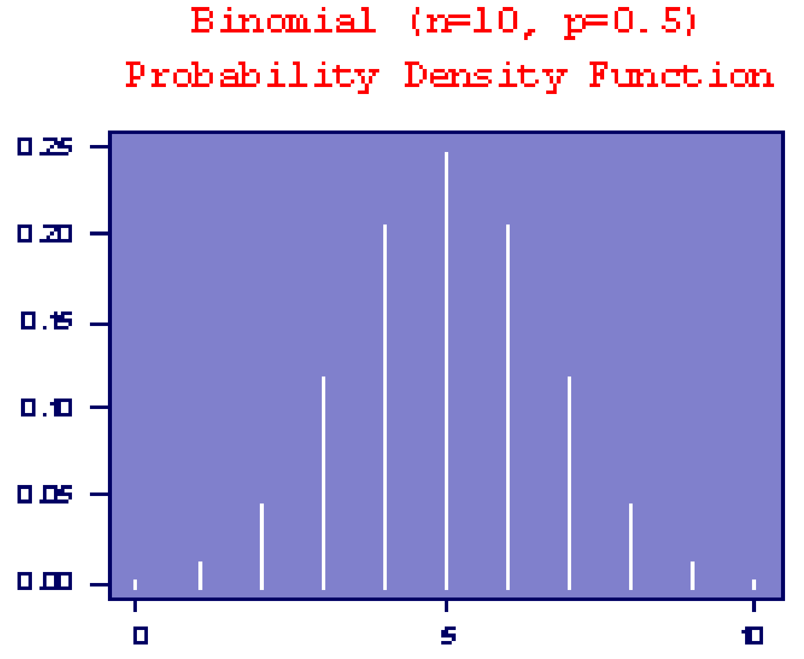
Quantum efficiency (QE) of a sensor is defined as the ratio

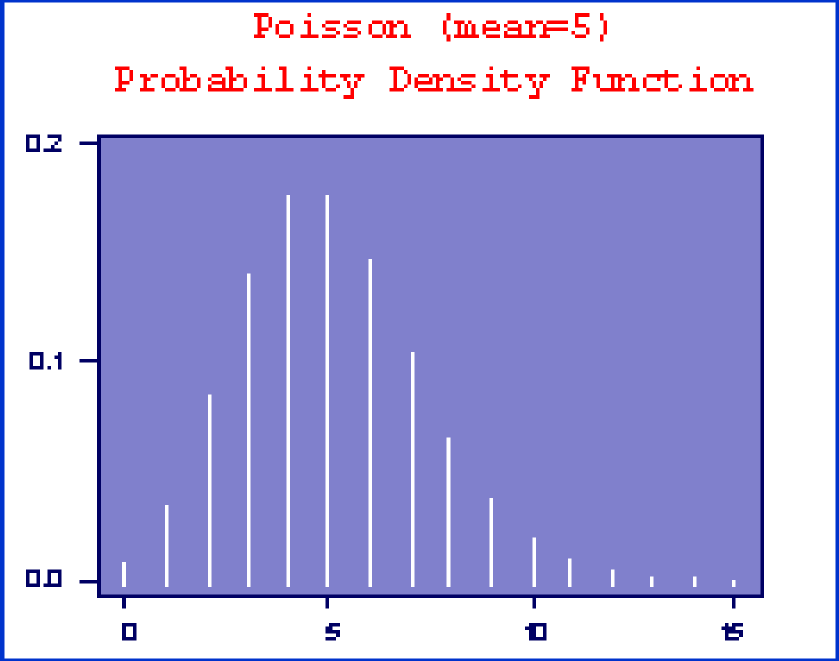
$$QE = N(\text{ph.e.}) / N(\text{photons})$$

Conversion of a photon into ph.e. is a purely binomial process (and not poisson !)

Light sources of thermal origin can be described by the poisson distribution (including LED)

Differences between binomial and poisson distributions





SNR = 3.16

mean/σ = 2.24

Why do we want high Quantum Efficiency

Please note that here there is no noise source, we are talking about the „noise in the signal“ because just statistically, from trial to trial, the number of detected photons vary.

Why do we want high Quantum Efficiency

Assume <u>N photons</u> are impinging onto a sensor and every photon has the same <u>probability P</u> to kick out a ph.e..

Then the <u>mean</u> number of ph.e.s is **N x P** and

the <u>Variance</u> is equal to **<u>N x P x (1 – P)</u>**

Signal/Noise = mean/sigma =

$$N \times P / \sqrt{[N \times P \times (1-P)]} = \sqrt{[N \times P/(1-P)]}$$

Signal to noise ratio

The signal-to noise ratio of a light sensor can be calculated as

$$SNR = [N \times P/(1 - P)]^{1/2}$$

For example, if N = 1 (single impinging photon):

P	0.1	0.3	0.9
SNR	0.33	0.65	3

Signal to noise ratio

$$SNR = [N \times P/(1 - P)]^{1/2}$$

For N = 20 impinging photons:

P	0.1	0.3	0.9
SNR	1.5	2.9	13.4

One of the best known light sensors: the classical PMT

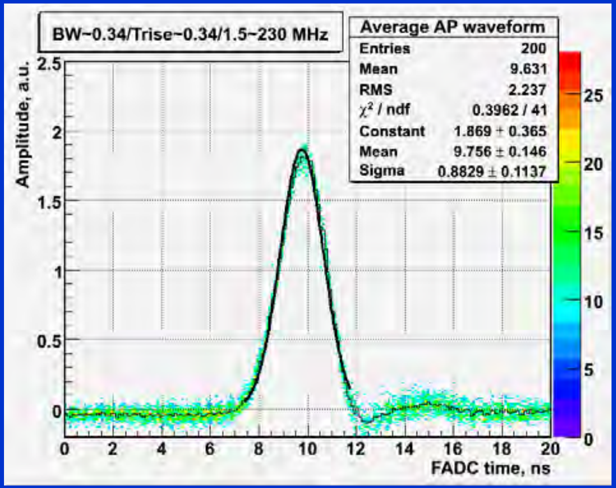
- The impinging photons kick out e- from the thin photo cathode (~25nm)
- e- are accelerated in a static electric field (~100V) and hit dynodes arranged in a sequential topology
- Every dynode enhances the number of e- by a factor 4-5
- The net gain of a PMT could be $10^5 – 10^7$
- That allows measuring single photons

PMTs for MAGIC from Electron Tubes Enterprises and from Hamamatsu

Hamamatsu R10408-01
ET 9116 A: 1.0 inch
ET 9117 A: 1.5 inch

- 1-inch were developed initially with ETE (England), initiated y Eckart Lorenz. Then continued with Hamamatsu (Japan). Also Photonis produced a hemispherical PMT for us.
- We used PMTs from ETE in MAGIC-I
- When constructing the MAGIC-II, we checked PMTs from ETE against those from Hamamatsu and finally chose the latter because of higher PDE
- Similarly we co-developed 1.5 PMTs, outer rings of the MAGIC-I camera

PMTs for MAGIC developed by ETE, Hamamatsu, Photonis

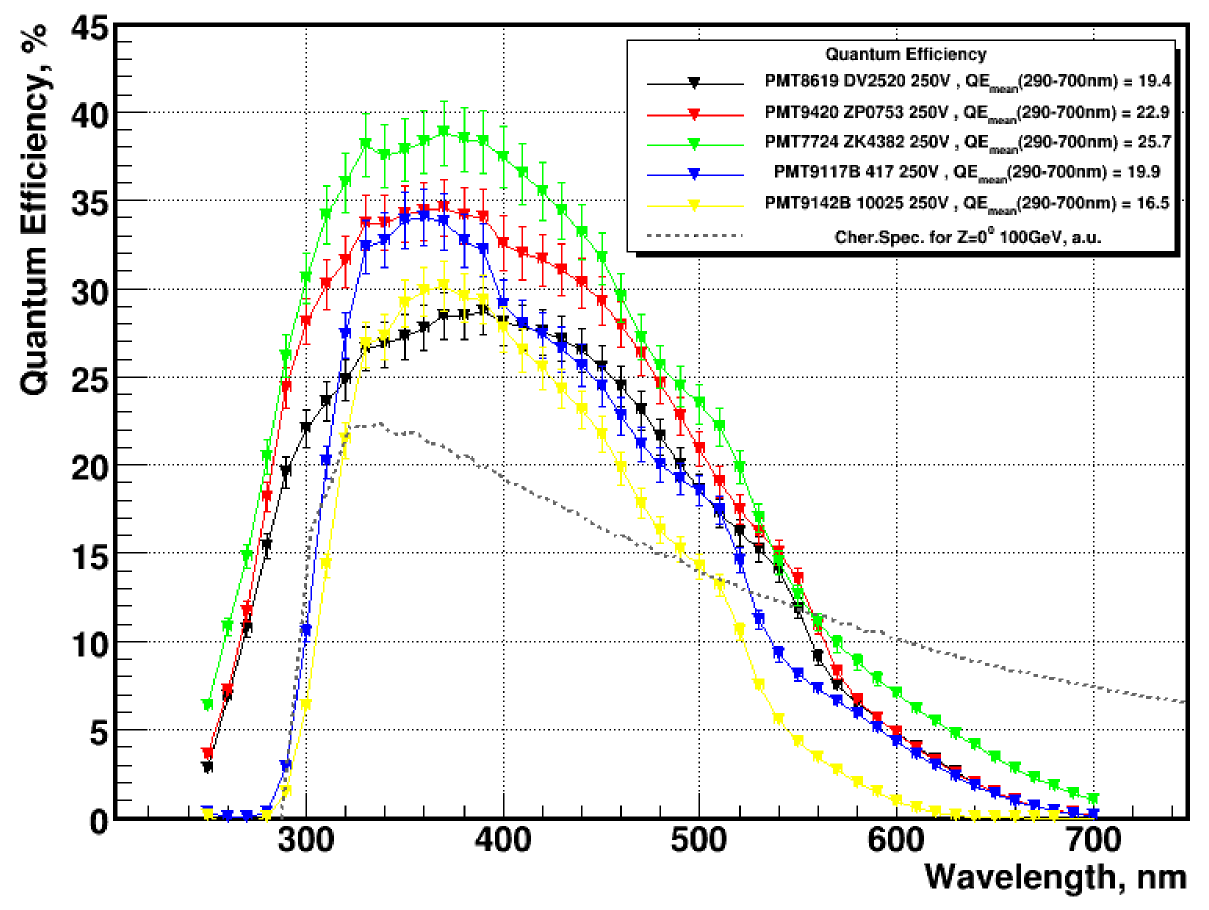


Main advantages offered by 1-inch hemispherical MAGIC-type PMTs:

- ultra-fast resonse; ETE PMT: rise tome 600ps, fall time 700ps, FWHM = 1.2ns
- possible due to 6 dynodes
- hemisperical shape photo cathode
- providing double crossing of photons (the highest probability of the semi-transparent photocathode is ~60% @ 400nm) with light guides
- low gain → slow ageing in time

Instrumental/technological improvements

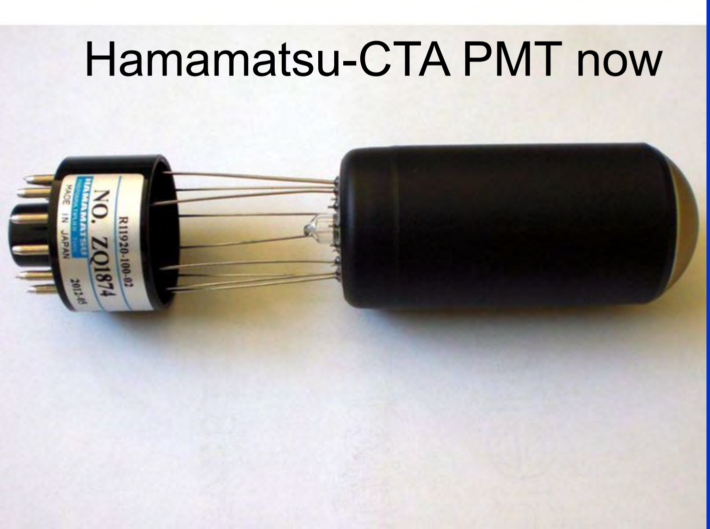
Running target: light sensor improvements. Successfully pushing the PDE higher up. Shown for several types of PMTs



- Some 9 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 4 years we launched a new improvement program for CTA PMTs

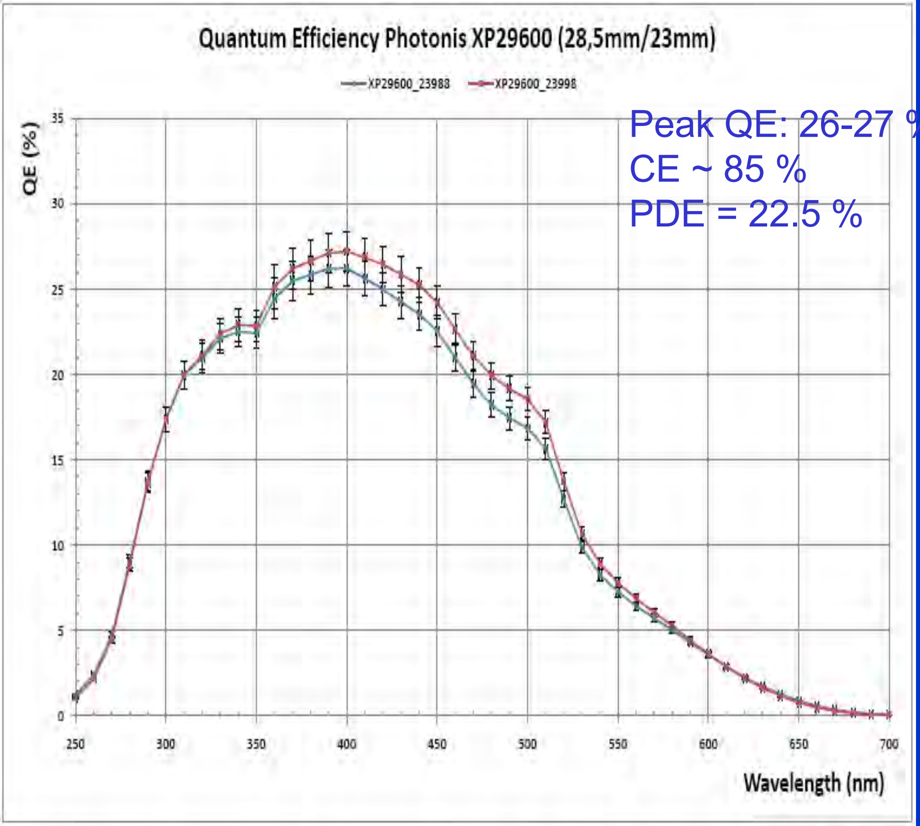
Development of PMTs for CTA


Hamamatsu 4 years ago


Hamamatsu-CTA PMT now


Electron Tubes Enterprises
CTA PMT now

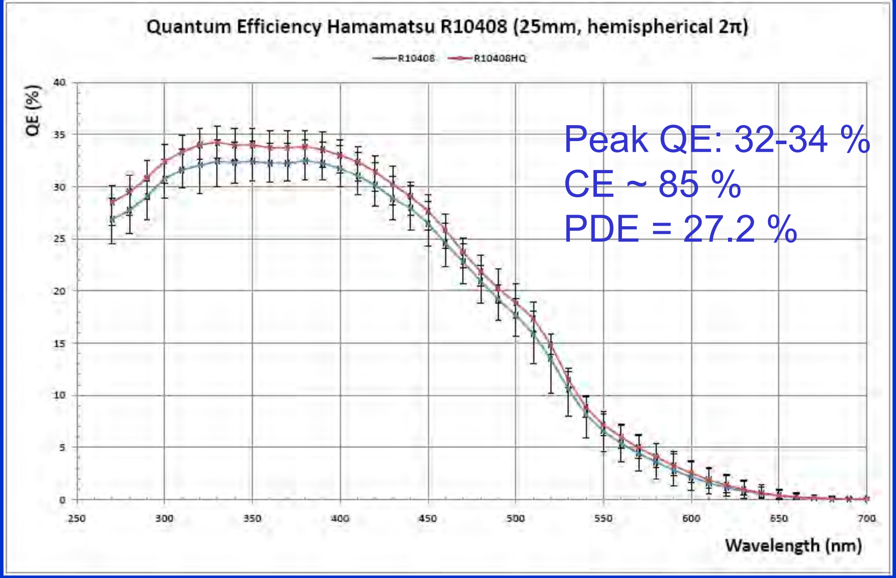
Some background information



Peak QE: 26-27 %
CE ~ 85 %
PDE = 22.5 %

- On the left one can see the typical quantum efficiency (QE) of PMTs (from Photonis) used in the H.E.S.S. project
- The peak QE is in the range of 25-27%, CE ~85%
- This was the QE level of PMTs since 1960‘s

Some background information



Peak QE: 32-34 %
CE ~ 85 %
PDE = 27.2 %

Later on these PMTs have got the name "Superbialkali"

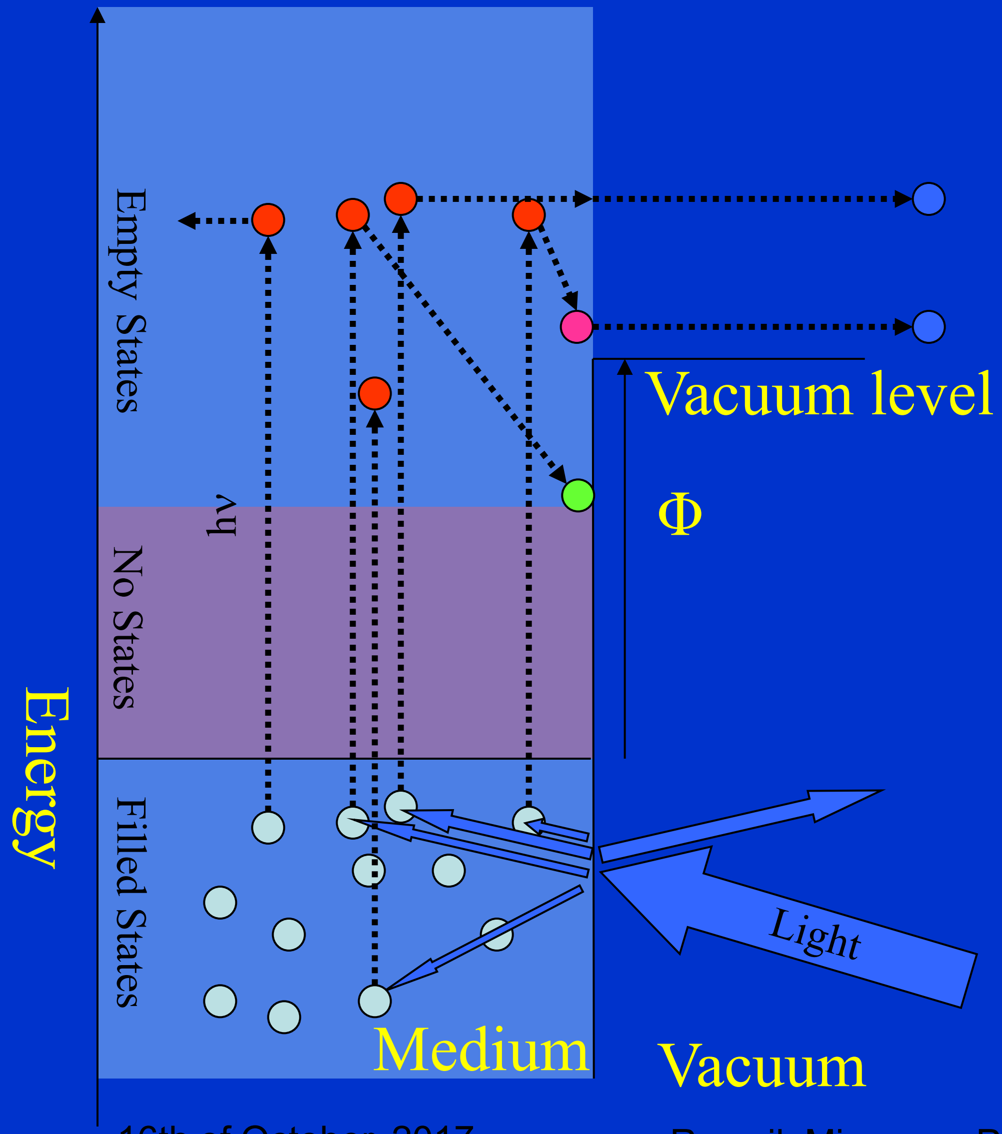
- In 2004-2008 we have developed a program for enhanicing the QE, primarily for using in the MAGIC IACTs
- Working with industrial partners *Photonis*, *Electron Tubes* and *Hamamatsu* the QE of bialkali PMTs was enhanced towards 32-34%
- Note that the collection efficiency of ph.e. was still only ~85%

Photosensors for CTA

- When the CTA project started the Focal Plane Instrumentation working group asked the consortium for some funds for further development of PMTs
- A very modest level funding became available through the Preparatory Phase funding of CTA
- About 5 years ago we launched a new program for further improving the PMTs
- Today we face an improvement of
  - ph.e. collection efficiency from 85% → 95%, as well as
  - the QE has further increased towards ~40%
  - Afterpulsing level has been reduced from a typical 0.3% → 0.02%

Three Step Model of Photoemission - Semiconductors

J.Smedley, 2nd PC Work.



1) Excitation of e$^-$
   - Reflection, Transmission, Interference
   - Energy distribution of excited e$^-$

2) Transit to the Surface
   - e$^-$-phonon scattering
   - e$^-$-defect scattering
   - e$^-$-e$^-$ scattering
   - Random Walk

3) Escape surface
   - Overcome Workfunction
   - Multiple tries

Need to account for Random Walk in cathode suggests Monte Carlo modeling

Parameters, and how to affect them

J. Smedley, MPP, 2016

- Increasing the electron MFP will improve the QE. Phonon scattering cannot be removed, but a more perfect crystal can reduce defect and impurity scattering

$$\frac{1}{\lambda_{MFP}} = \frac{1}{\lambda_{el\ el}} + \frac{1}{\lambda_{ap}} + \frac{1}{\lambda_{op,ems}} + \frac{1}{\lambda_{op,abs}} + \frac{1}{\lambda_{impurity}} + \frac{1}{\lambda_{defect}} + \frac{1}{\lambda_{boundary}}$$

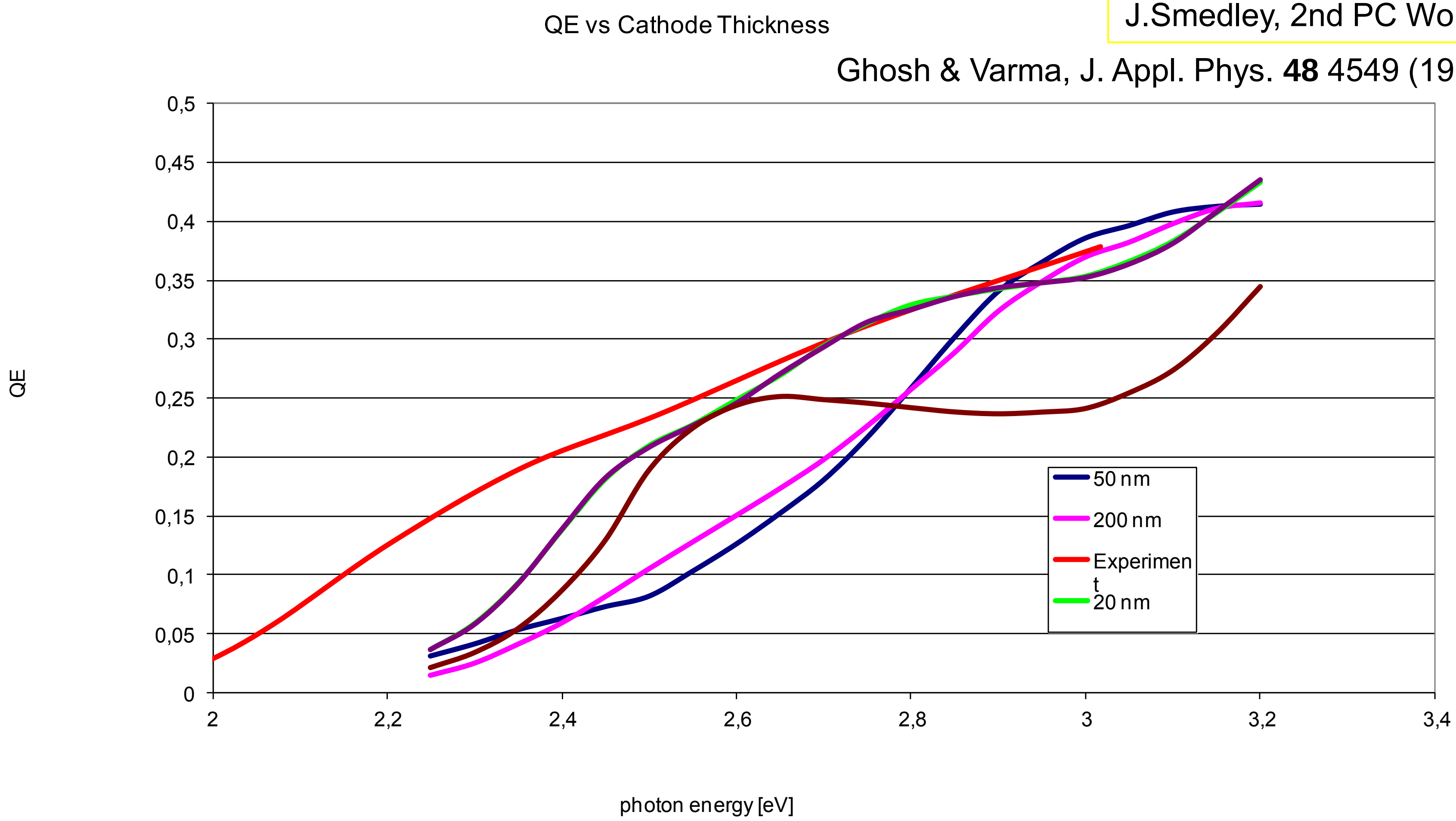
- Control of surface roughness is critical to minimizing the intrinsic emittance – epitaxial growth?
- A question to consider: Why can CsI (another ionic crystal, PEA cathode) achieve QE>80%?
- Large band gap and small electron affinity play a role, but, so does crystal quality. T.H. Di Stefano and W.E. Spicer,

Phys. Rev. B **7**, 1554 (1973)

Monte Carlo for K_2CsSb

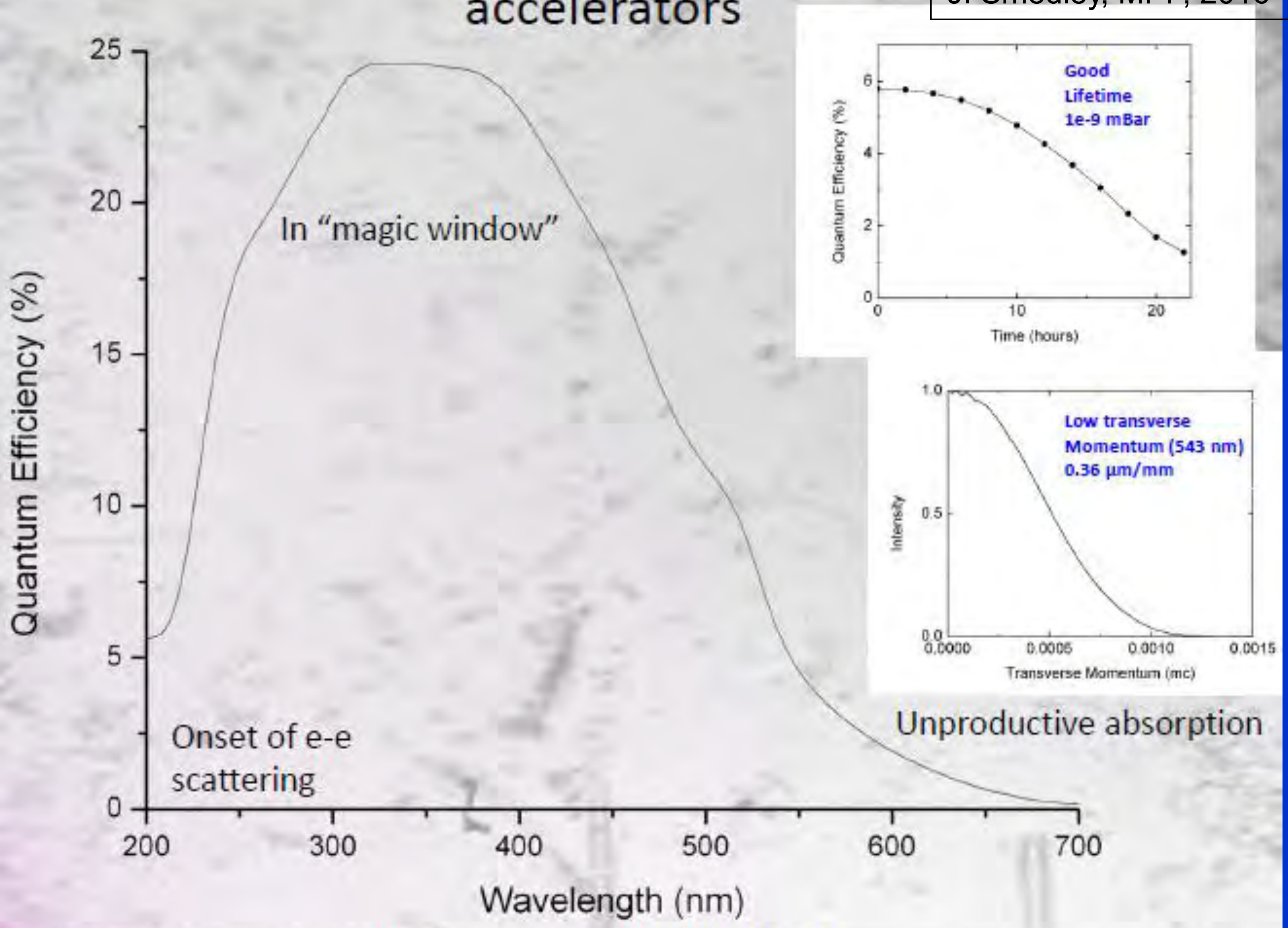
J.Smedley, 2nd PC Work.

Ghosh & Varma, J. Appl. Phys. **48** 4549 (1978)



K_2CsSb: A cathode with excellent characteristics for accelerators

J. Smedley, MPP, 2016



In “magic window”

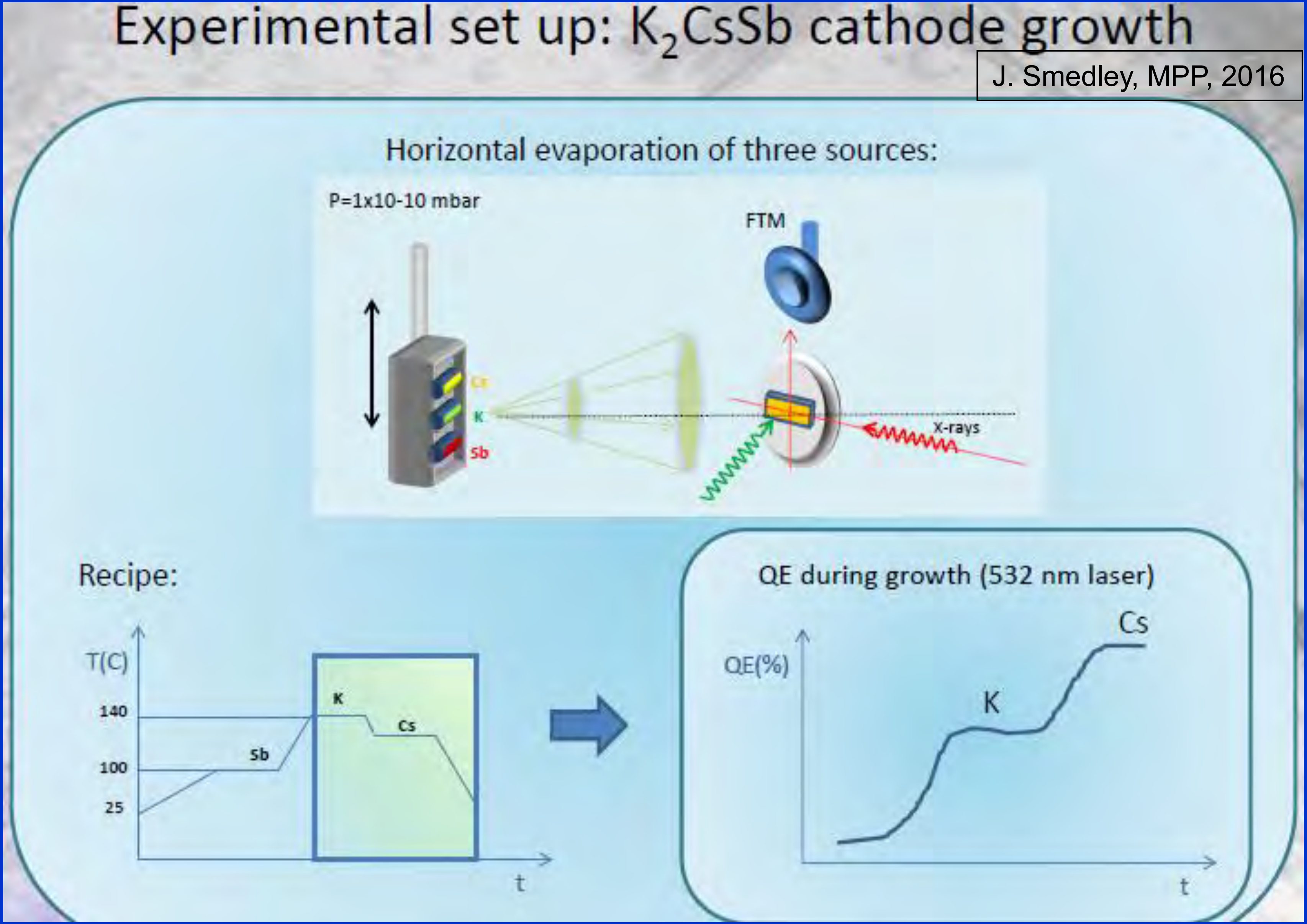
Onset of e-e scattering

Unproductive absorption

Good Lifetime 1e-9 mBar

Low transverse Momentum (543 nm) 0.36 µm/mm

T. Vecchione et al., *Appl. Phys. Lett.* **99**, 034103 (2011)



Experimental set up: K_2CsSb cathode growth

J. Smedley, MPP, 2016

Horizontal evaporation of three sources:

Recipe:

QE during growth (532 nm laser)

X-ray reflectometry (XRR) provides in-situ thickness monitoring

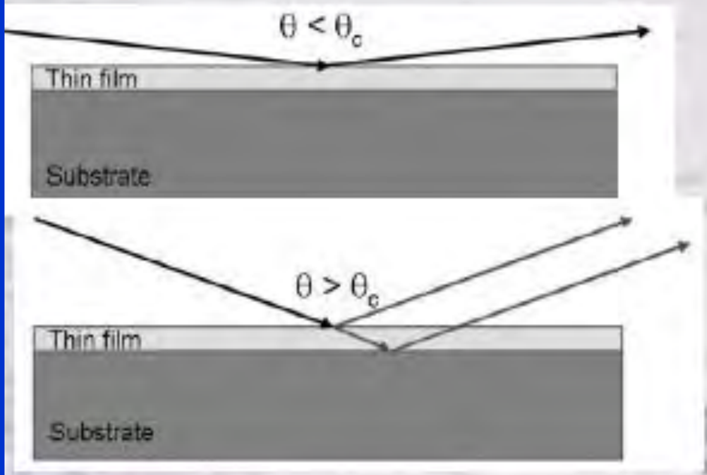
J. Smedley, MPP, 2016

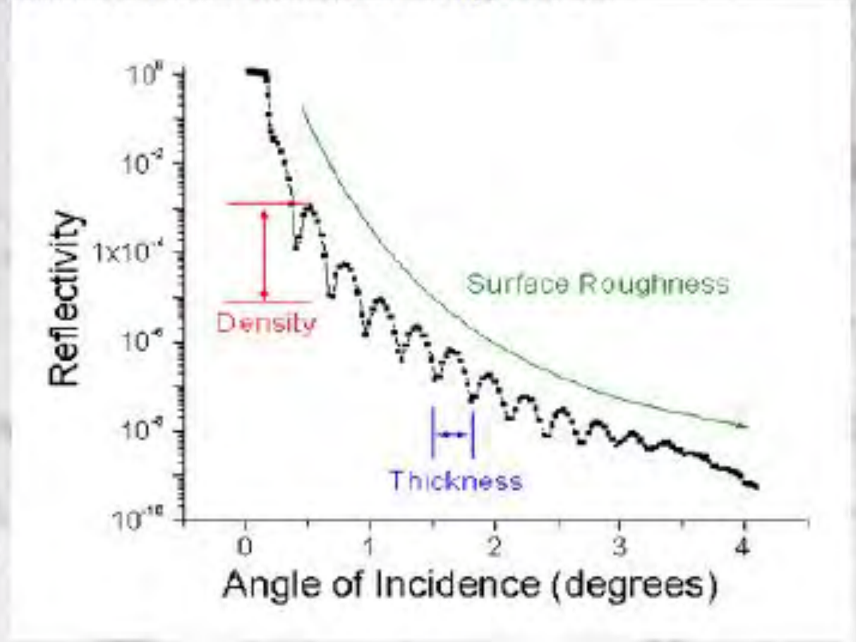
Understand ‘sticking’ coefficient of materials to substrates at various temperatures

Observe the intermixing vs layering of materials

Observe the onset of roughness

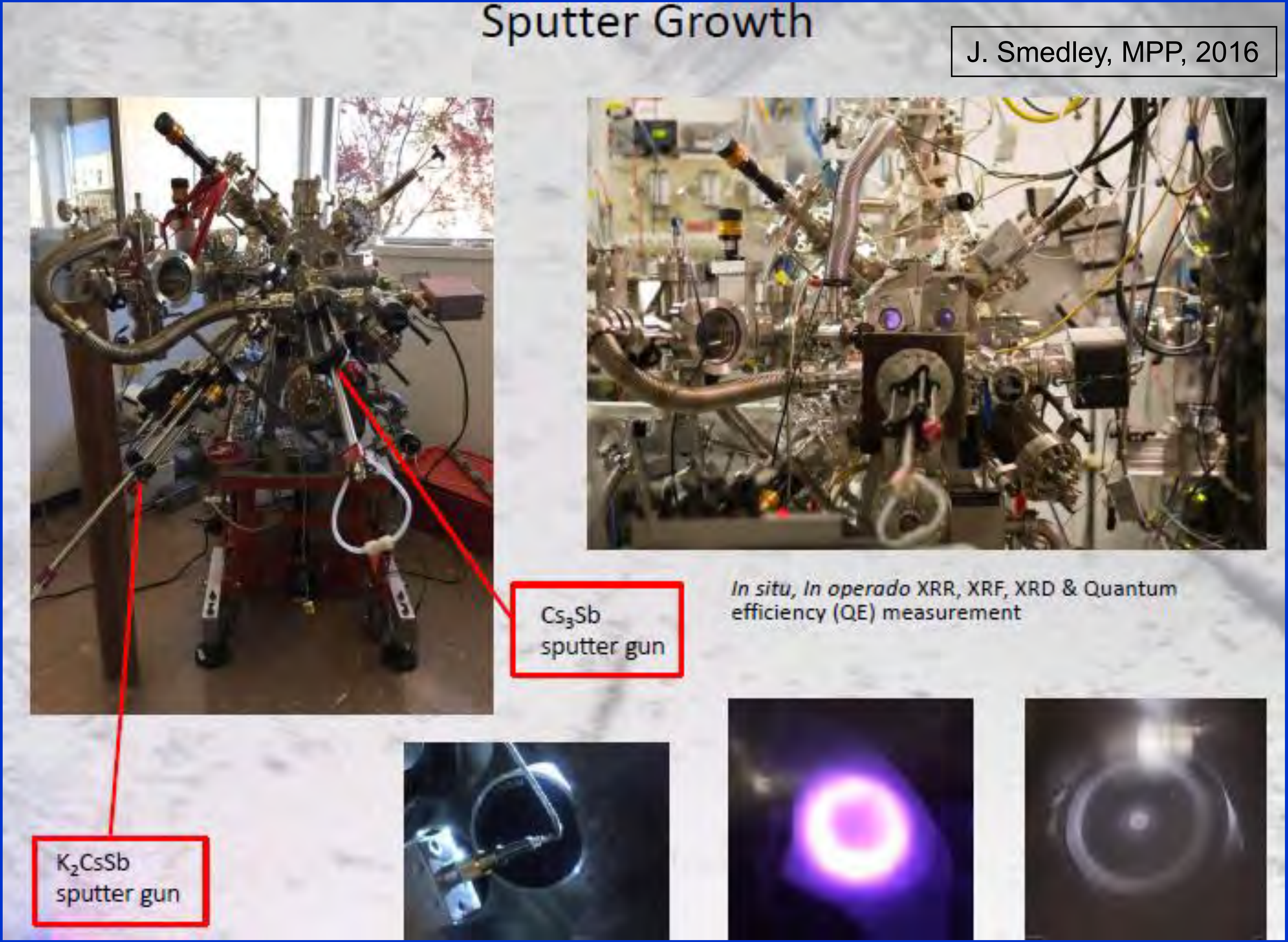
$$\theta_c = \arccos(n_{medium} / n_{air})$$





16th of October, 2017,
Light-2017, Ringberg

Razmik Mirzoyan: PMT & SiPM



Sputter Growth

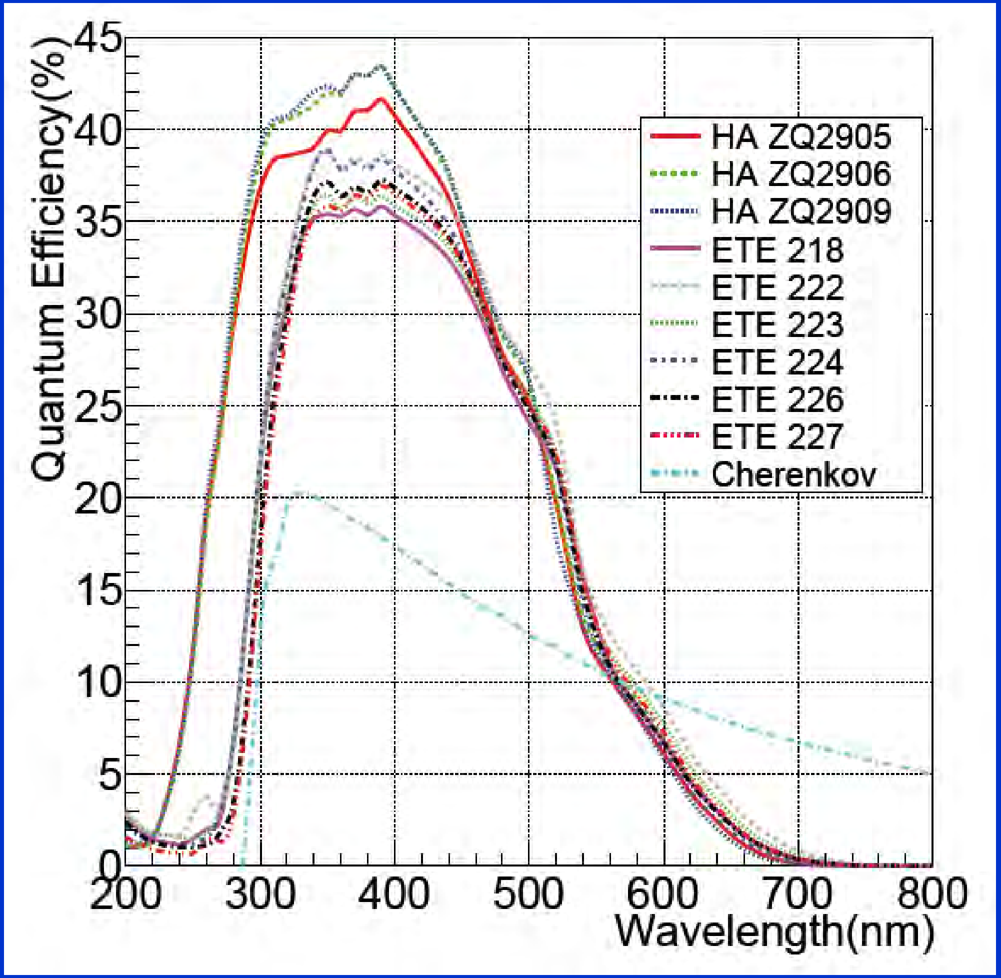
J. Smedley, MPP, 2016

Cs_3Sb
sputter gun

In situ, In operado XRR, XRF, XRD & Quantum efficiency (QE) measurement

K_2CsSb
sputter gun

PMT candidates for the CTA



- Both *Electron Tubes Enterprises* (England) and *Hamamatsu* (Japan) have made a big progress.
- The average QE level moved towards 40%
- The ph.e. CE moved towards 95-98%
- Compared to H.E.S.S. already with these tubes one gets +60% enhancement

Recent strong boost of QE → 45 %

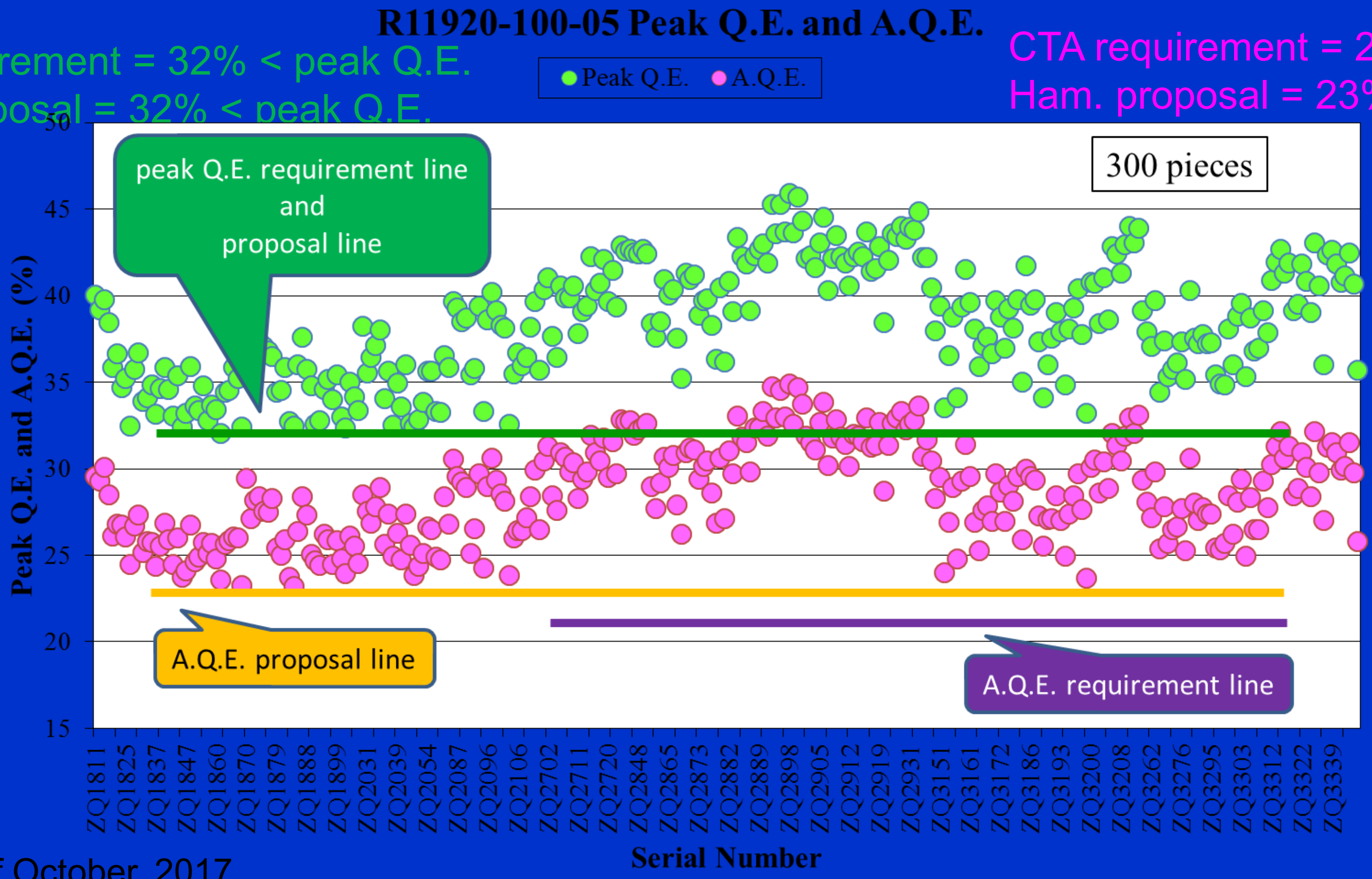
(See how the company met our request of a minimum 32% peak QE)

Peak Q.E.

Average QE over Cherenkov spectrum (290nm-600nm)

CTA requirement = 32% < peak Q.E.
Ham. proposal = 32% < peak Q.E.

CTA requirement = 21% < A.Q.E.
Ham. proposal = 23% < A.Q.E.

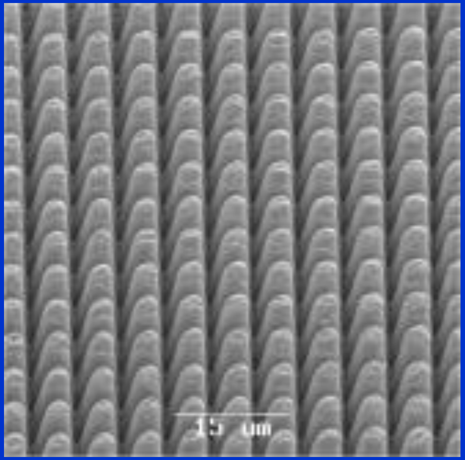


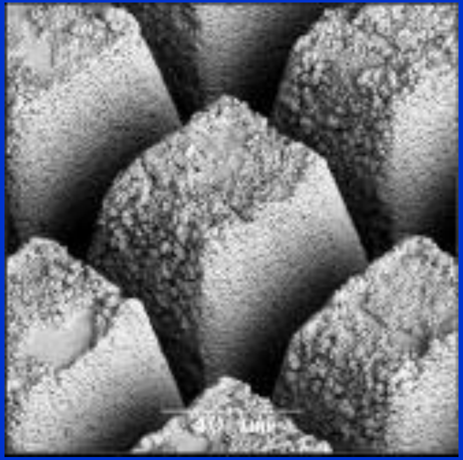
Reflectivity and QE

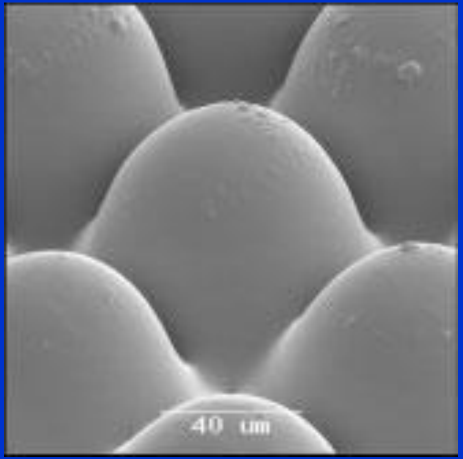
J.Smedley, 2nd PC Work.

R. Downey, P.D. Townsend, and L. Valberg, phys. stat. sol. (c) **2**, 645 (2005)

Reflectivity depends on incidence angle of light and the thickness of PC. Possiility to pass a structure to the PC can reduce losses due to reflection and increase QE







In a huge number of processes and phenomenae light is emitted

- Also light sensors are not an exception from this „rule“
- The majority of known light sensors not only detect light, but also emit light
- This can be used for diagnostic purposes

After Pulsing for threshold 4 p.e. (Light Emission)

MPI measurement result

2.3.1 Set-Up

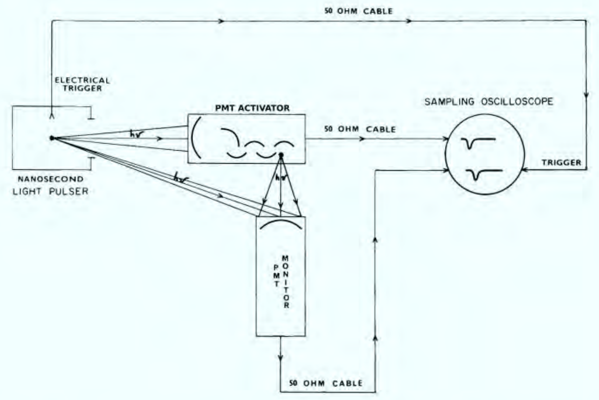


Figure 2.2: The photomultiplier dynode glow test apparatus, sketch adapted from [10]

2.3.3 Results

A screen capture of the oscilloscope with more than 200 million
Fig.2.3. The individual peaks on the activator photomultiplier are

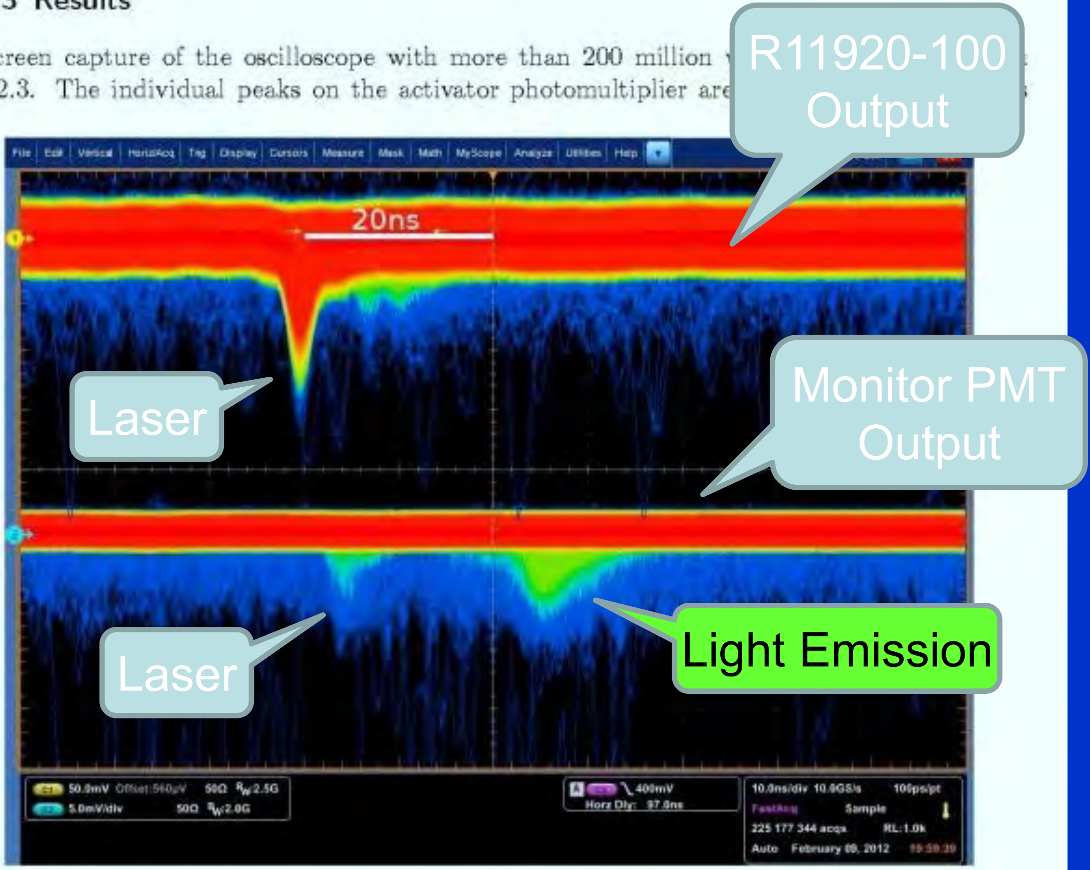
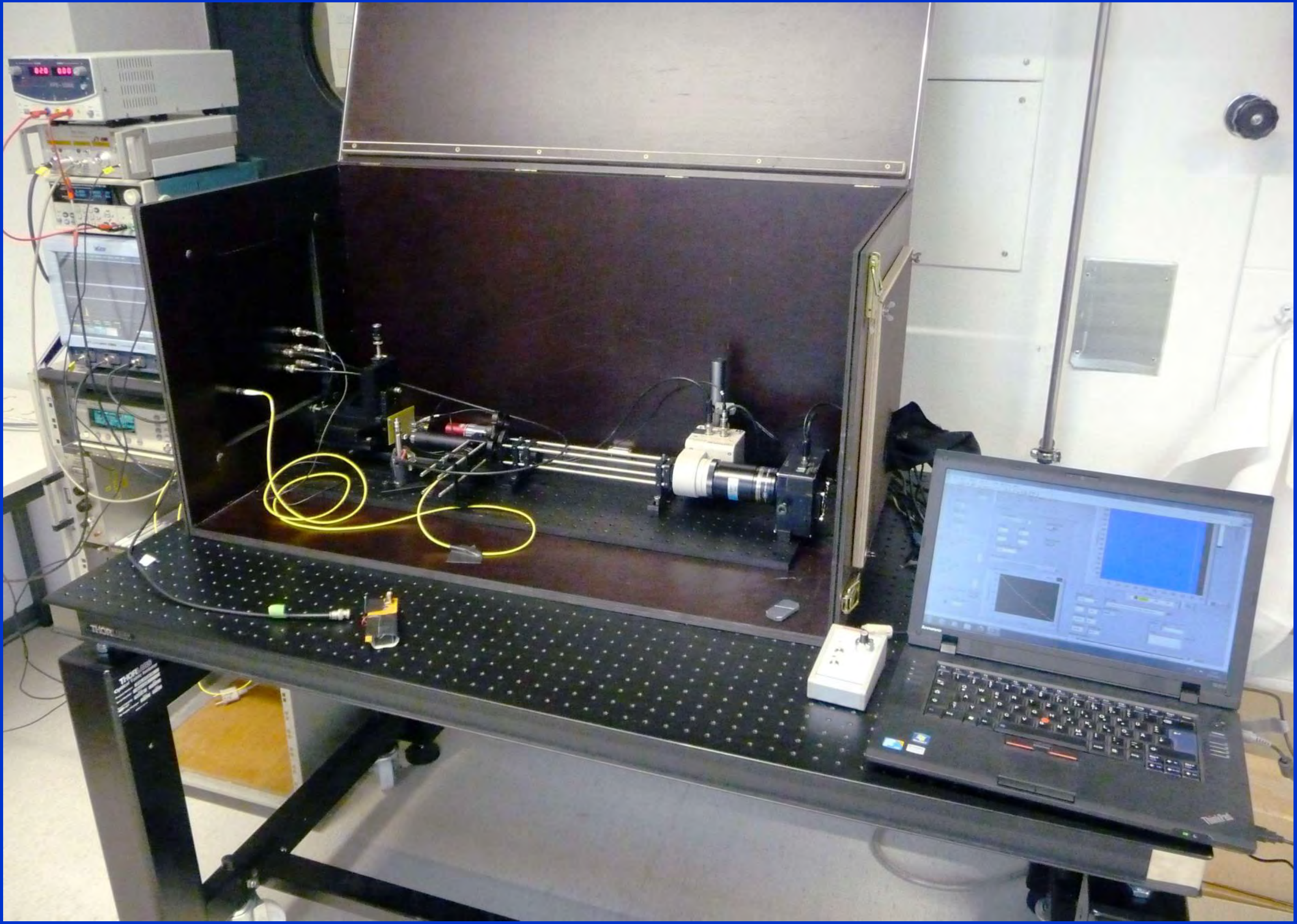
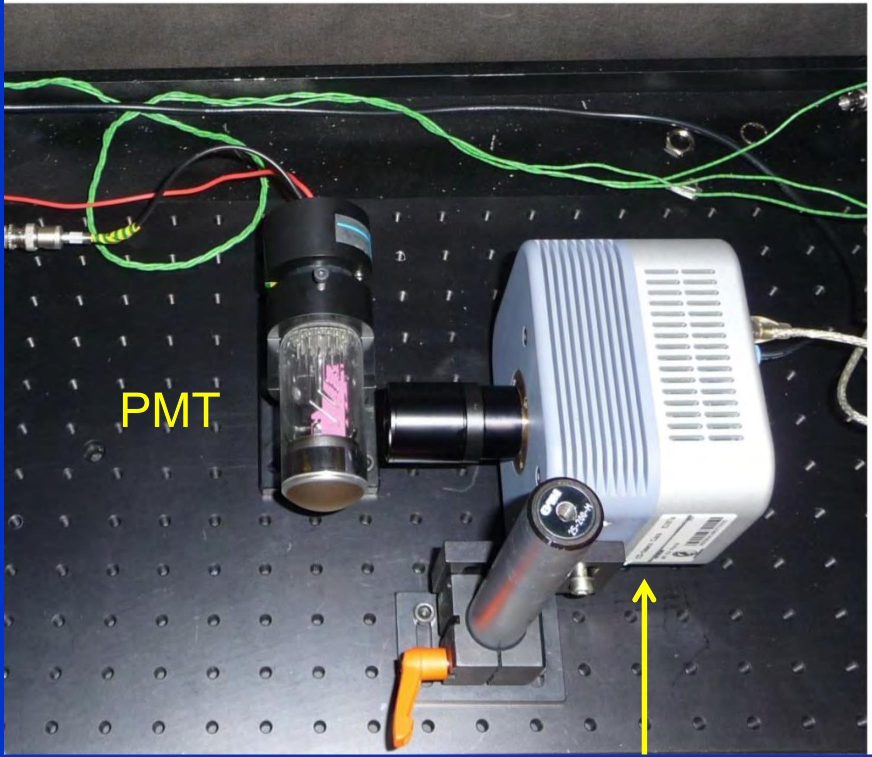


Figure 2.3: Measurement of the activator photomultiplier (top) and the monitor photomultiplier (bottom).

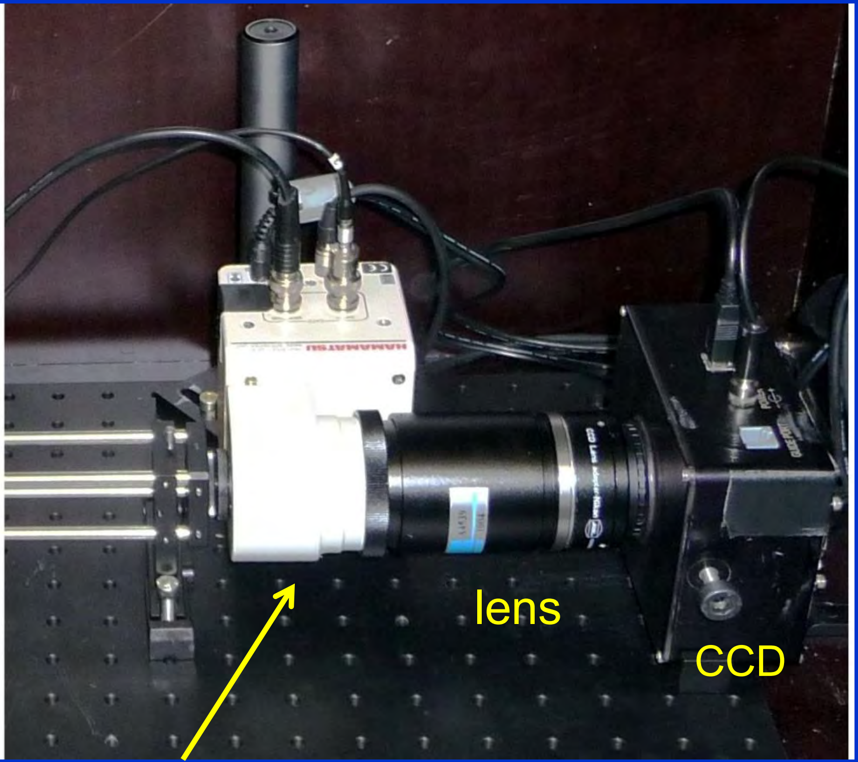
Light Emission Microscopy Setup



Light Emission Microscopy Setup

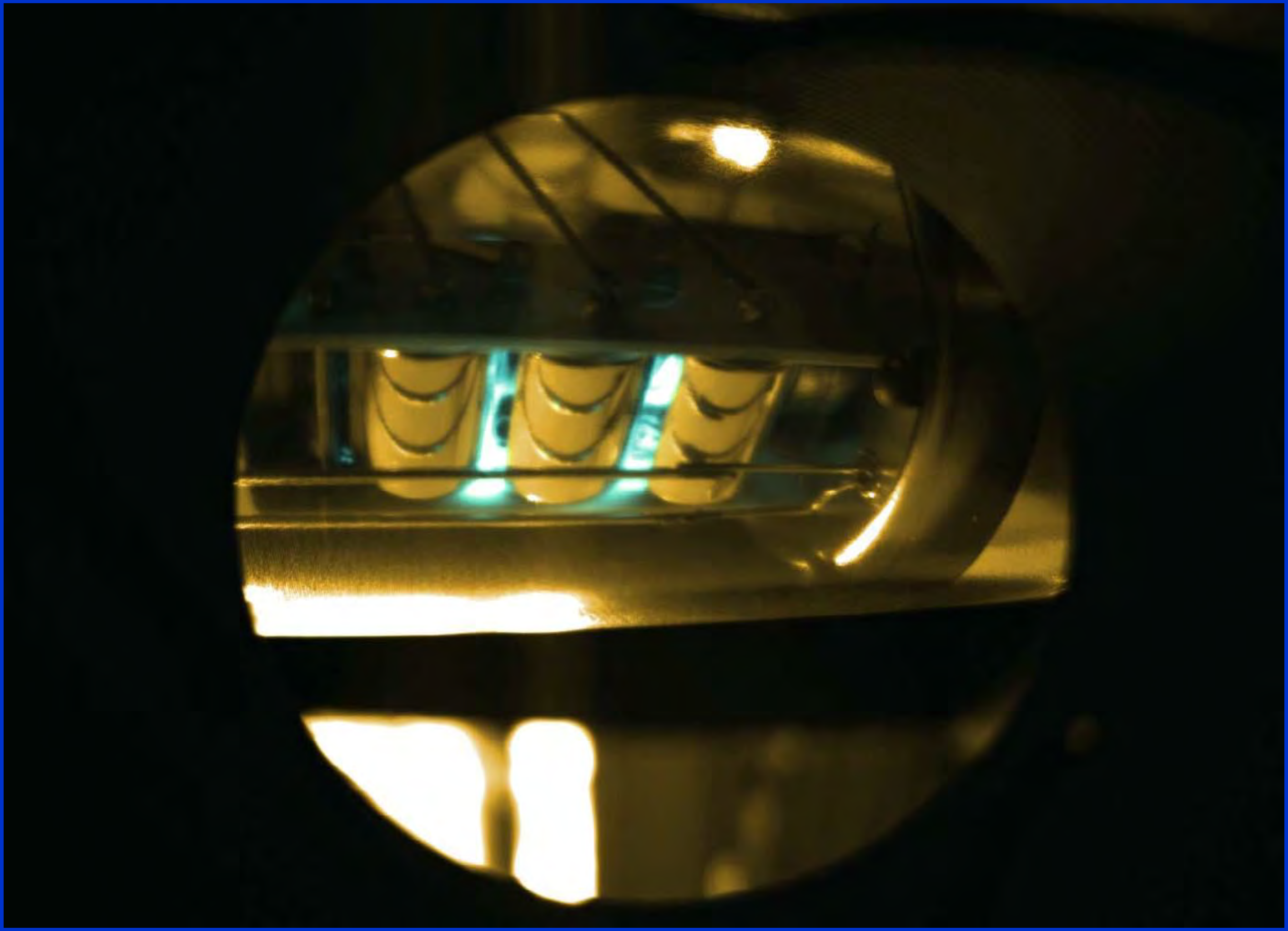


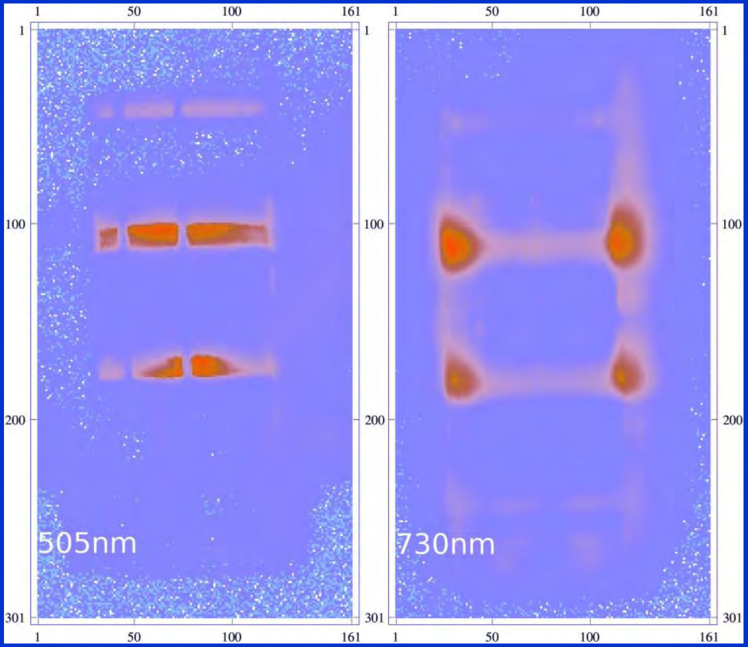
CLARA: Very sensitive CCD camera



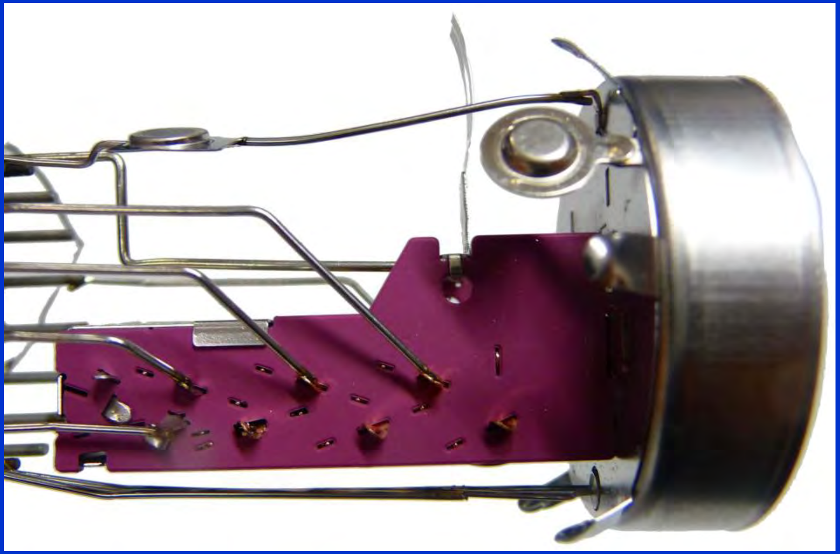
Gated (≥ 3ns) image intensifier
Coupled via a relay lense to a
CCD camera

Light emission leaking through the PMT dynodes can be see





Not only the dynodes of a PMT, Bombarded by e-, are glowing, but also ist holding structure. The material of the isolating holding structure could be largely identified as corundum chromium (ruby)



After Pulsing for threshold 4 p.e. (Light Emission)

HAMAMATSU measurement result

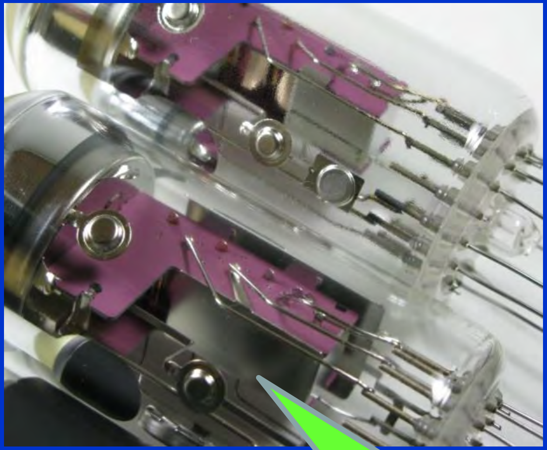
HAMAMATSU
PHOTON IS OUR BUSINESS

R11920-100

R11920-100
Shield Type

Light Shield

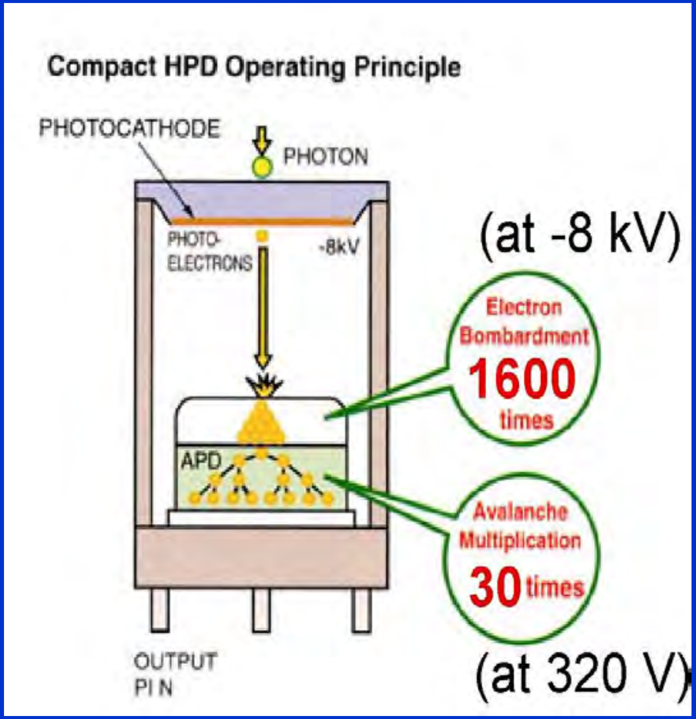
R11920-100-05 Shield type
(HA Treatment, Magnetic Shield
and Heat Shrinkable Tube)



Light Shield

HPD Structure

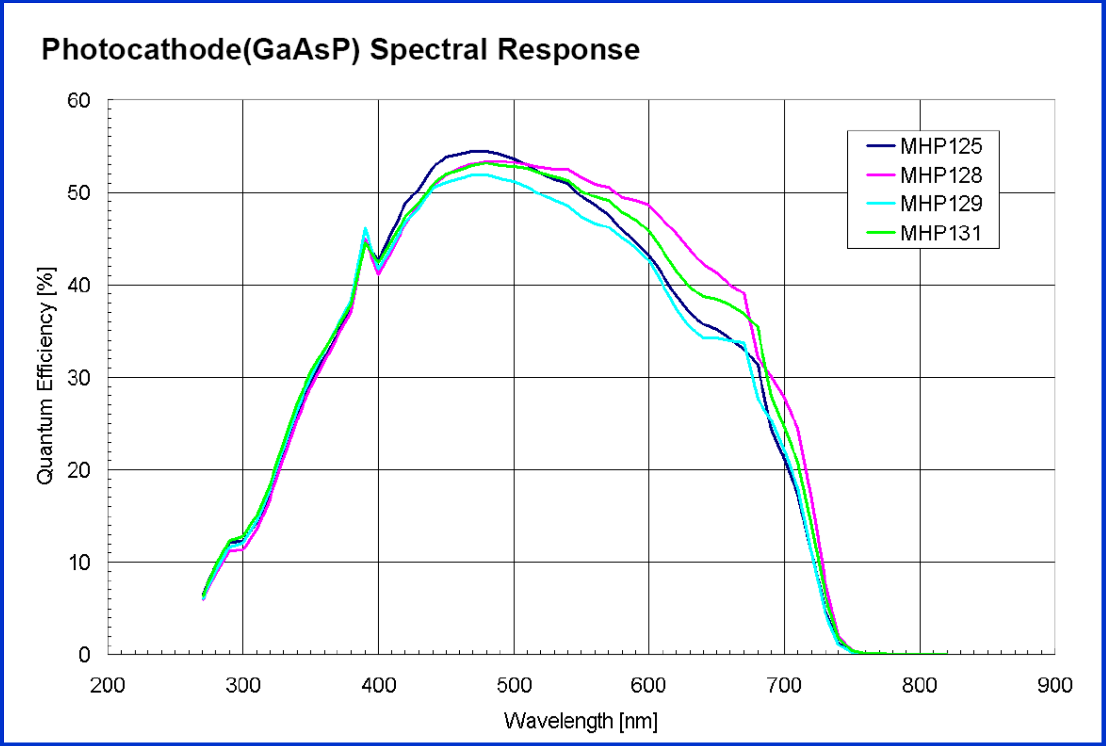
- HPD (Hybrid Photo Diode).
- Structure
  - Photo cathode
  - Avalanche diode as anode.
  - High vacuum tube (～10^{-7} Pa)
- Gain mechanism (2 stages)
  - Electron bombardment ~(x 1600)
  - Avalanche effect ~(x 30-50)



Much better pulse height resolution than PMT.

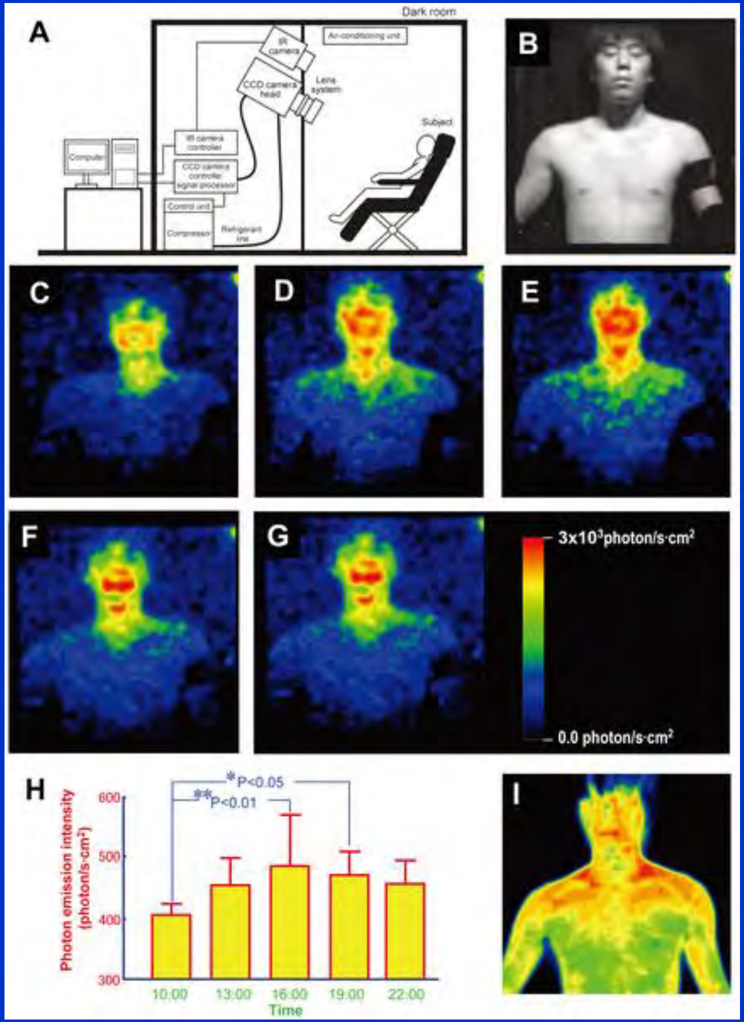
18-mm GaAsP HPD (R9792U-40) (development started ~15 years ago)

Designed for MAGIC-II telescope camera;
(developed with *Hamamatsu Photonics*)



(expensive)

Human body light emission



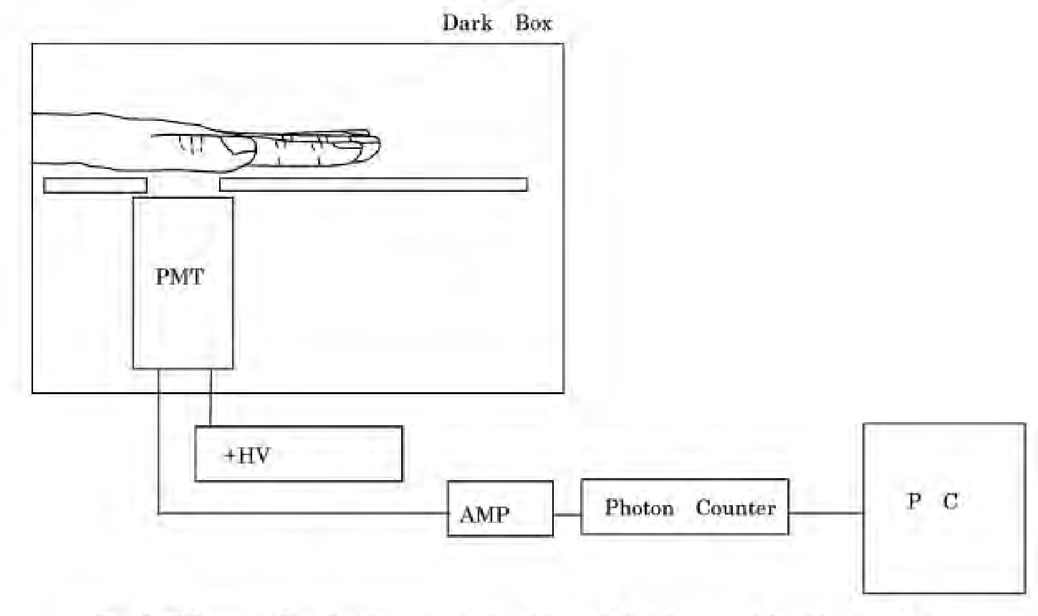
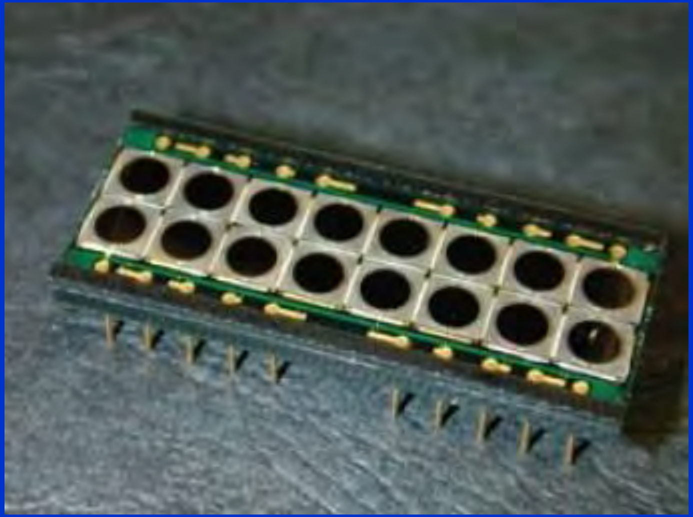
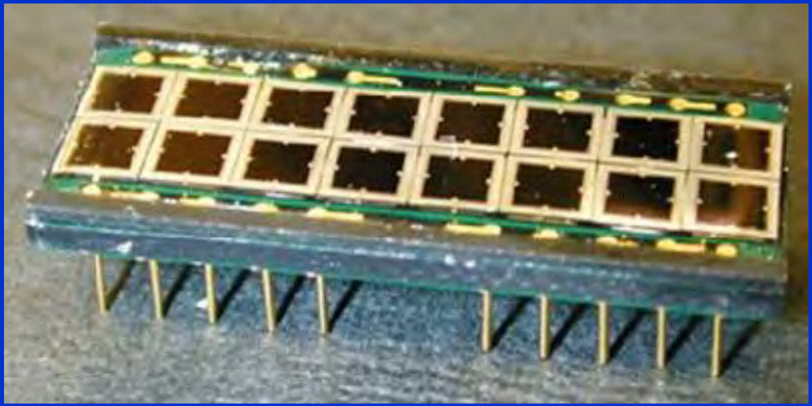


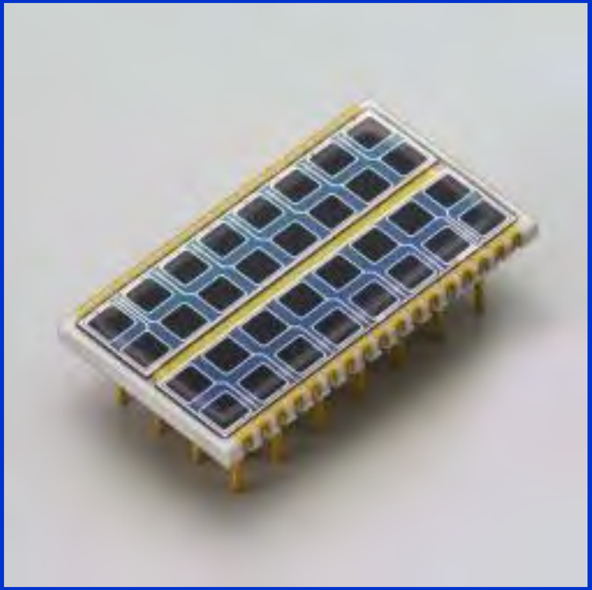
Fig. 1. Schematic drawing for measuring ultra-weak luminescence from human hand.

APD Matrixes for pioneering small animal PET constructed at MPI

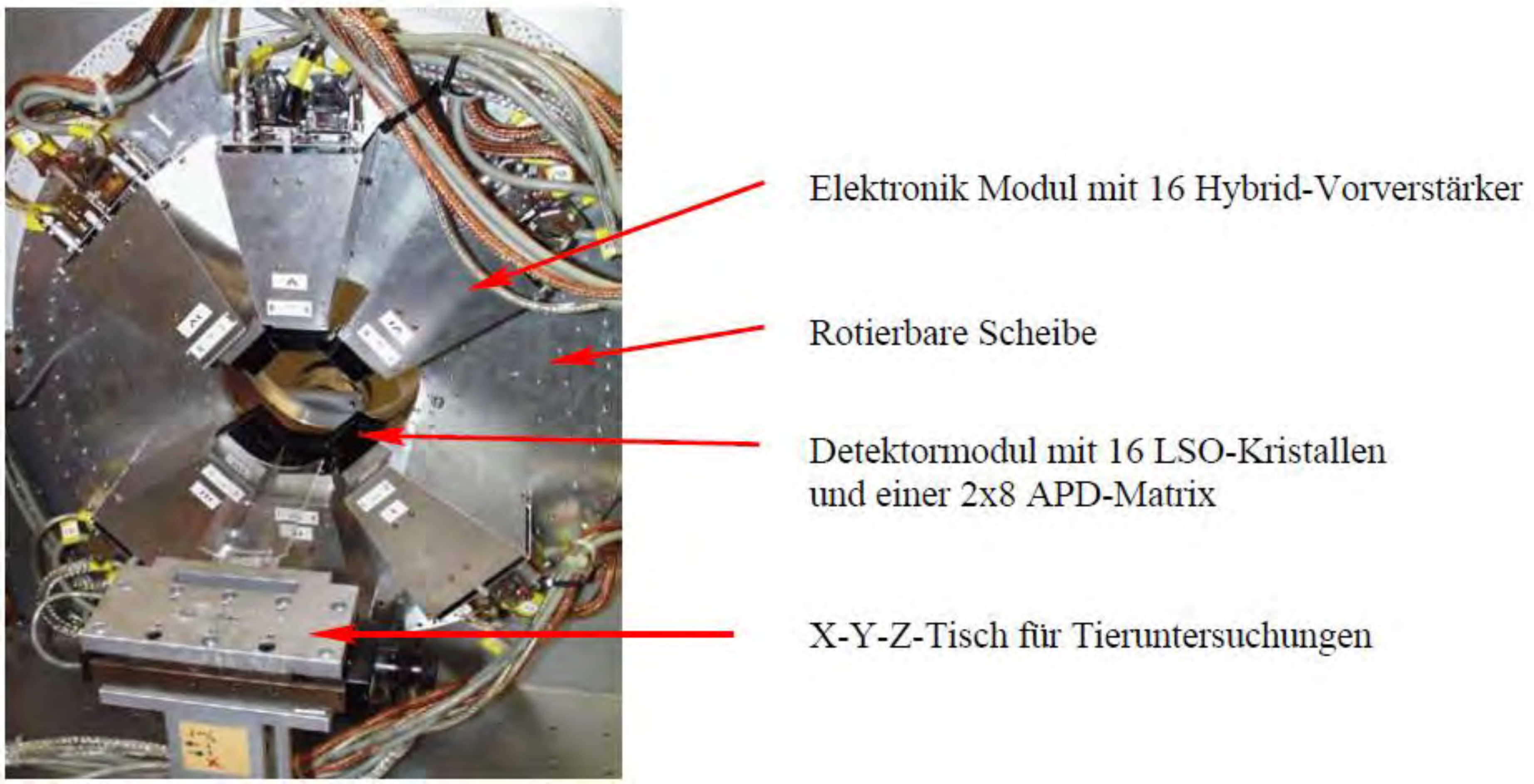




Hamamatsu S8550-02
4 x 8 array of 1.6 x 1.6 mm^2



APD-Based Small Animal PET built in MPI

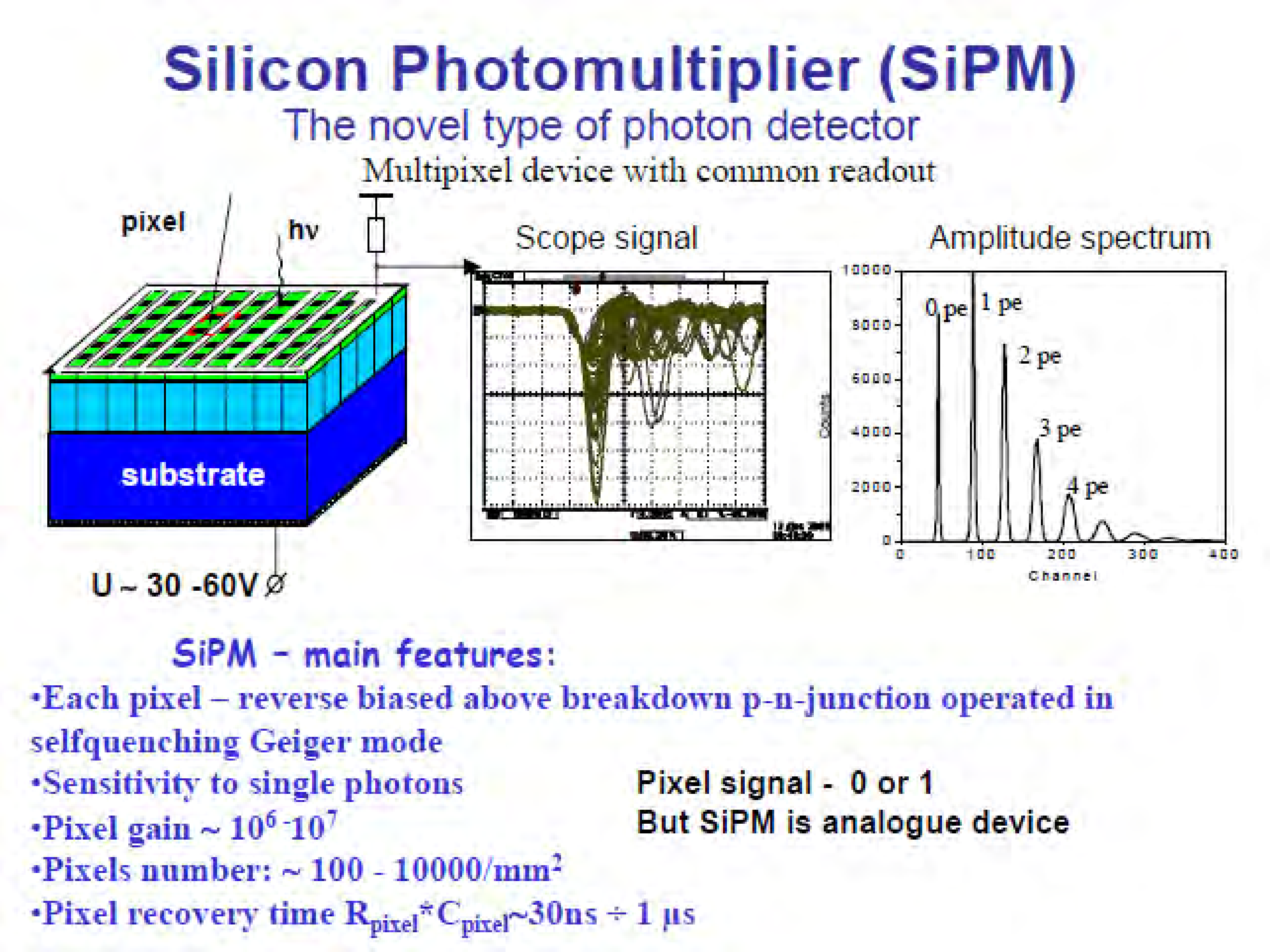


Elektronik Modul mit 16 Hybrid-Vorverstärker

Rotierbare Scheibe

Detektormodul mit 16 LSO-Kristallen
und einer 2x8 APD-Matrix

X-Y-Z-Tisch für Tieruntersuchungen



Silicon Photomultiplier (SiPM)

The novel type of photon detector

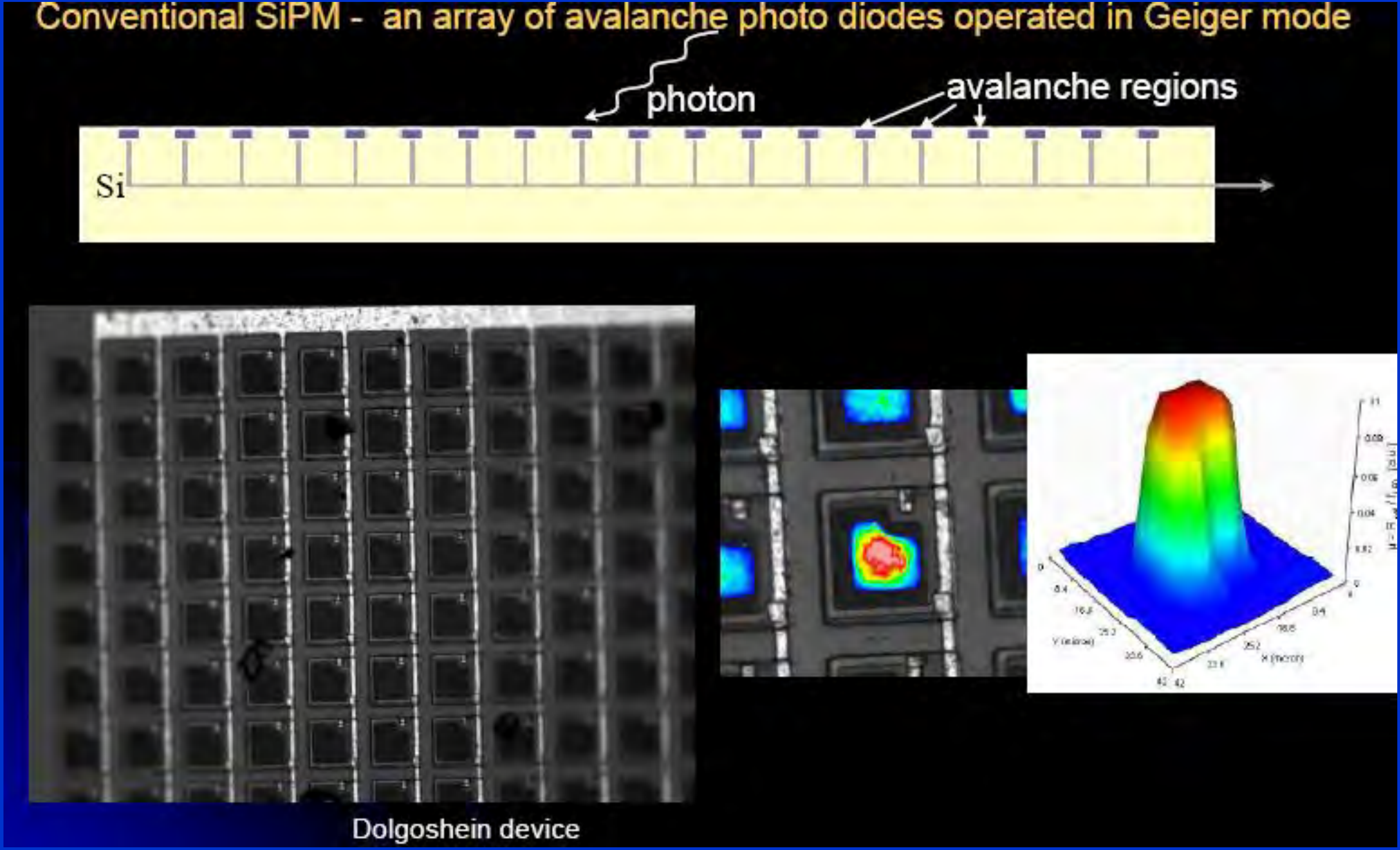
Multipixel device with common readout

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

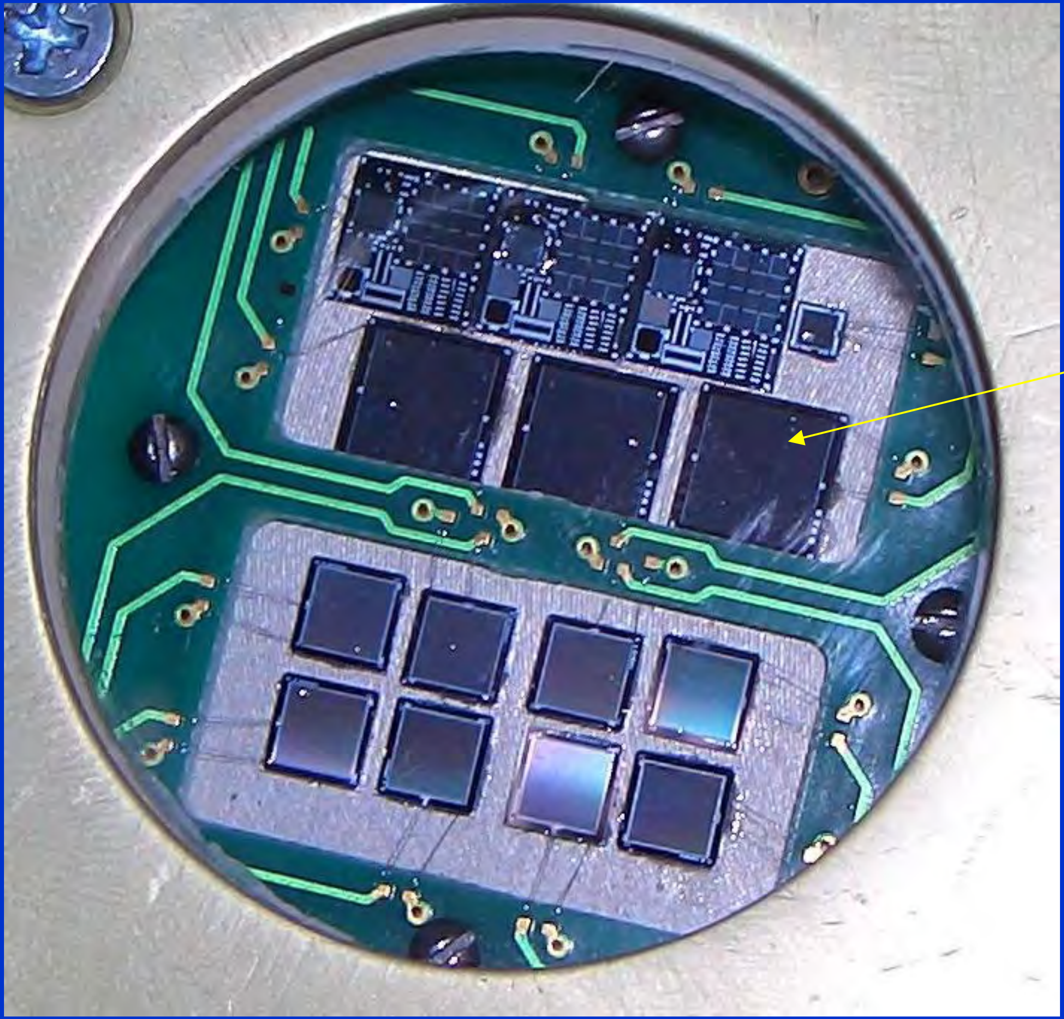
SiPM: novel light sensors



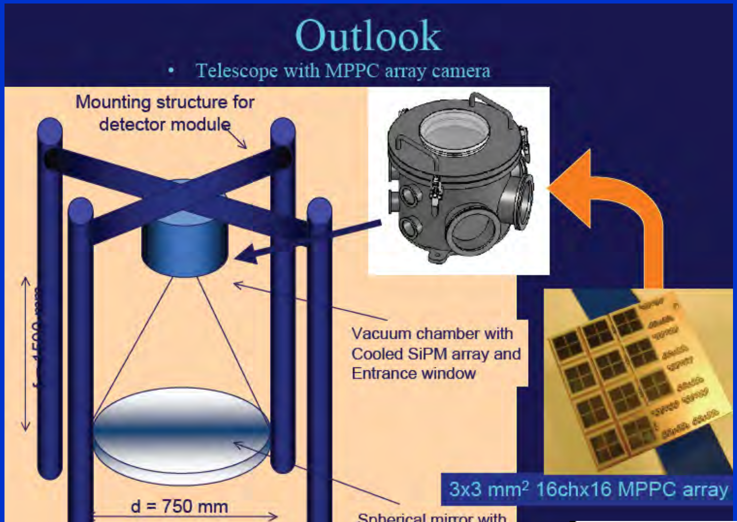
Conventional SiPM - an array of avalanche photo diodes operated in Geiger mode

Dolgoshein device

SiPMs: MEPhI-MPP development: 1x1, 1.3x1.3, 1.4x1.4, 3x3, 5x5 mm², some 8 years ago

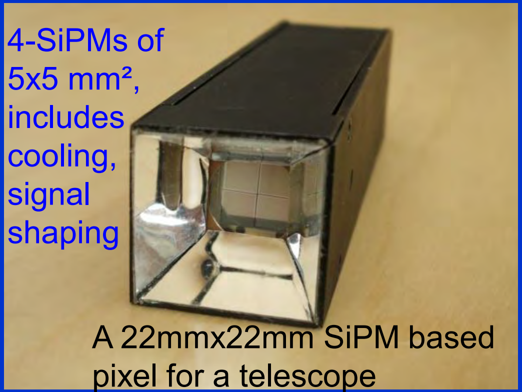


5 x 5 mm²



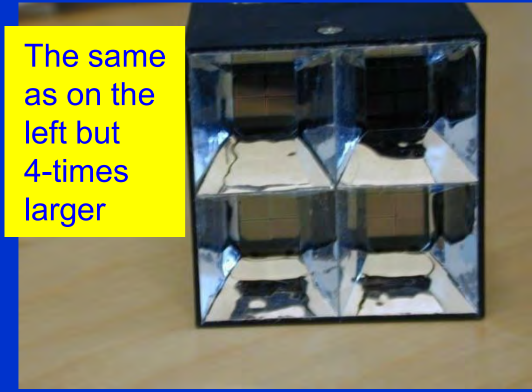
Outlook

- Telescope with MPPC array camera

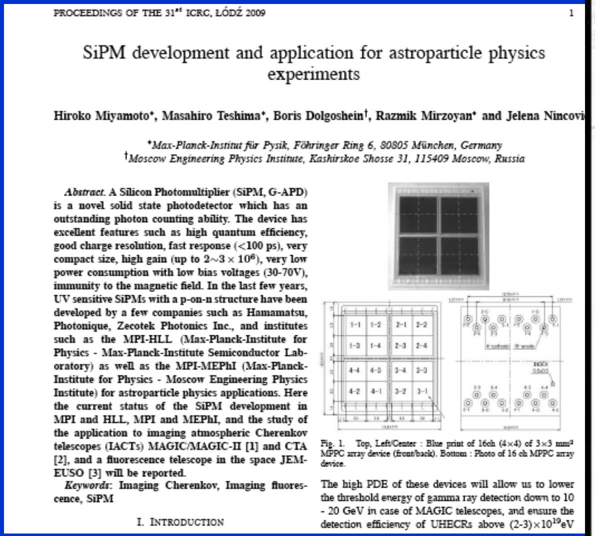


4-SiPMs of 5x5 mm², includes cooling, signal shaping

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

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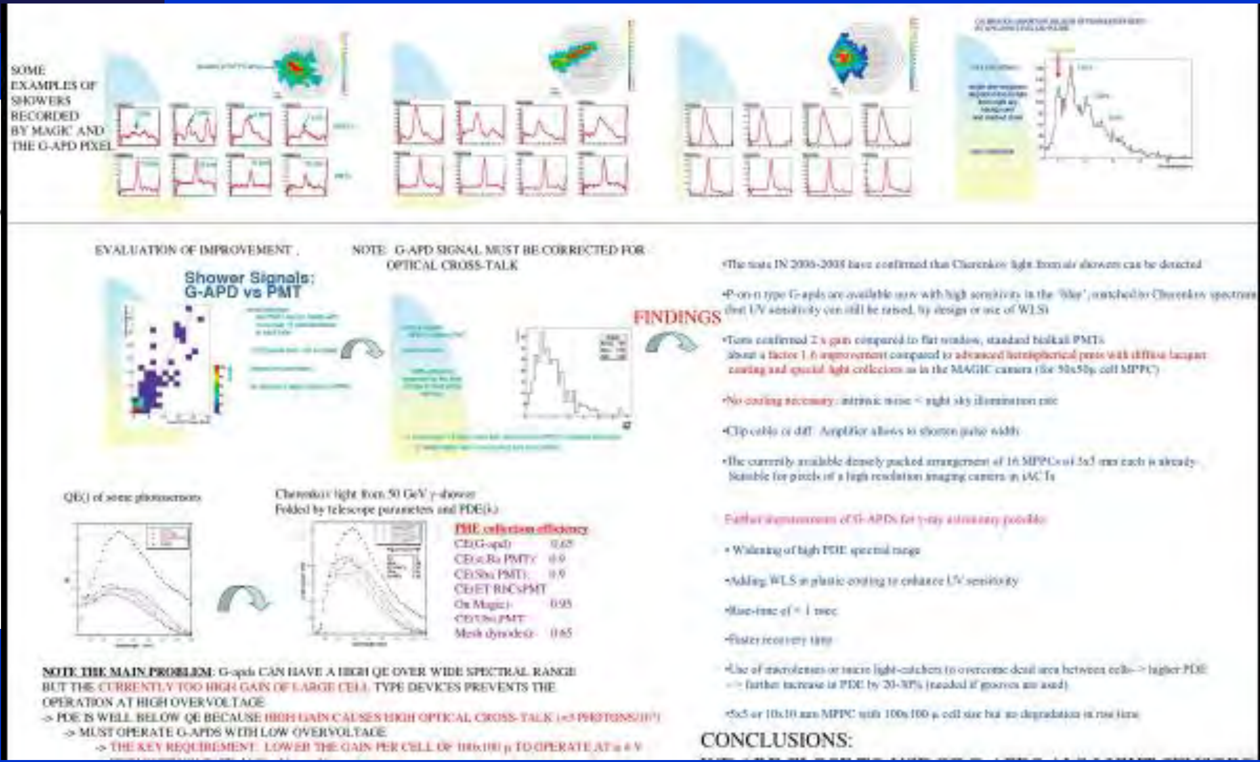
Abstract. A Silicon Photomultiplier (SiPM, G-APD) is a novel solid state photodetector which has an outstanding photon counting ability. The device has excellent features such as high quantum efficiency, good charge resolution, fast response (<100 ps), very compact size, high gain (up to 2∼3 × 10^6), 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 (2-3)×10^{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

Shower Signals: G-APD vs PMT

FINDINGS

QE(λ) of some photosensors

Cherenkov light from 50 GeV γ-shower
Folded by telescope parameters and PDE(λ)

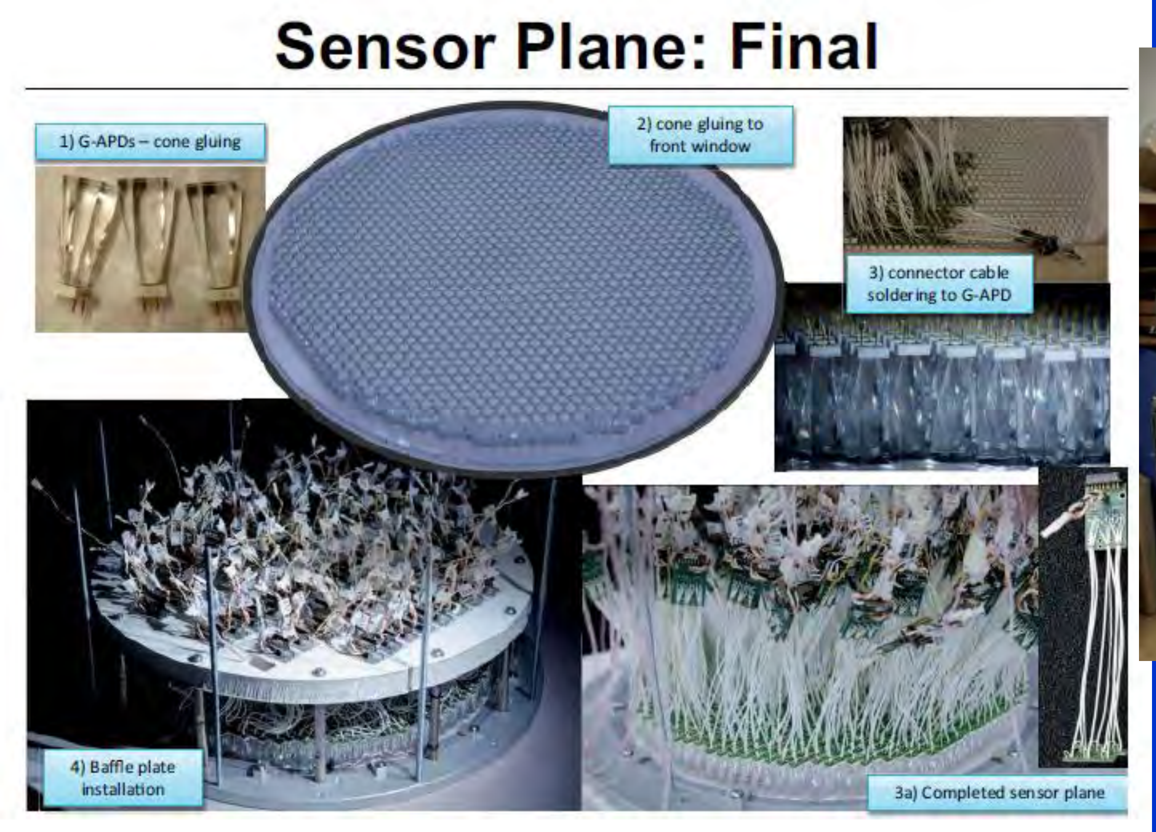
PDE collection efficiency

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 [illegible]
-> MUST OPERATE G-APDS WITH LOW OVERVOLTAGE
-> THE KEY REQUIREMENT: LOWER THE GAIN PER CELL OF 100x100 μ TO OPERATE AT [illegible]

CONCLUSIONS:

1440-pixel MPPC camera

FACT telescope camera



Sensor Plane: Final

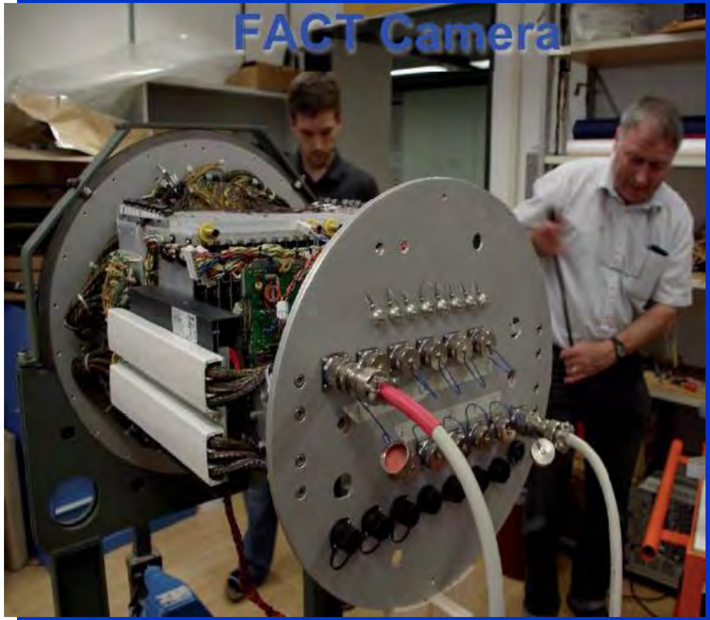
1) G-APDs – cone gluing

2) cone gluing to front window

3) connector cable soldering to G-APD

3a) Completed sensor plane

4) Baffle plate installation



SiPM Essentials

- Photon Detection Efficiency (PDE):

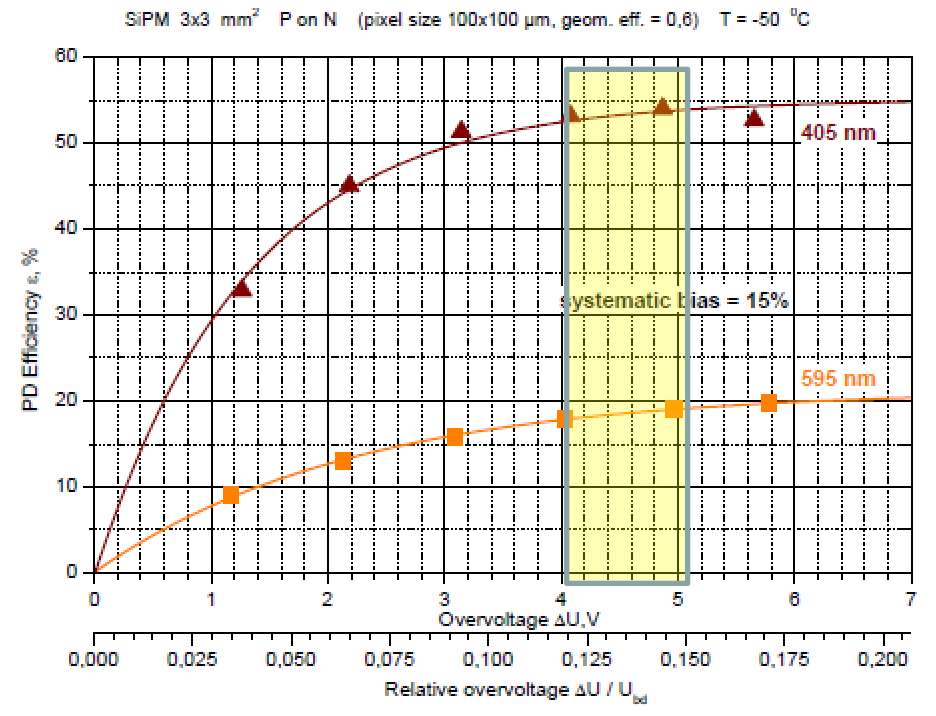
$$PDE(\lambda) = QE_{\text{internal}} \times T(\lambda) \times A_{\text{active area}} \times G_{\text{geiger-eff.}}(\lambda)$$

QE_{internal}:	essentially 100 %
$T(\lambda)$:	strongly varies with λ, could reach 80-90 %
$A_{\text{active area}}$:	some number between 20-80 %
$G_{\text{geiger-eff.}}(\lambda)$:	strong function of applied $\Delta U/U$, for $\Delta U/U \geq 12\text{-}15$ % could become ≥ 95 %

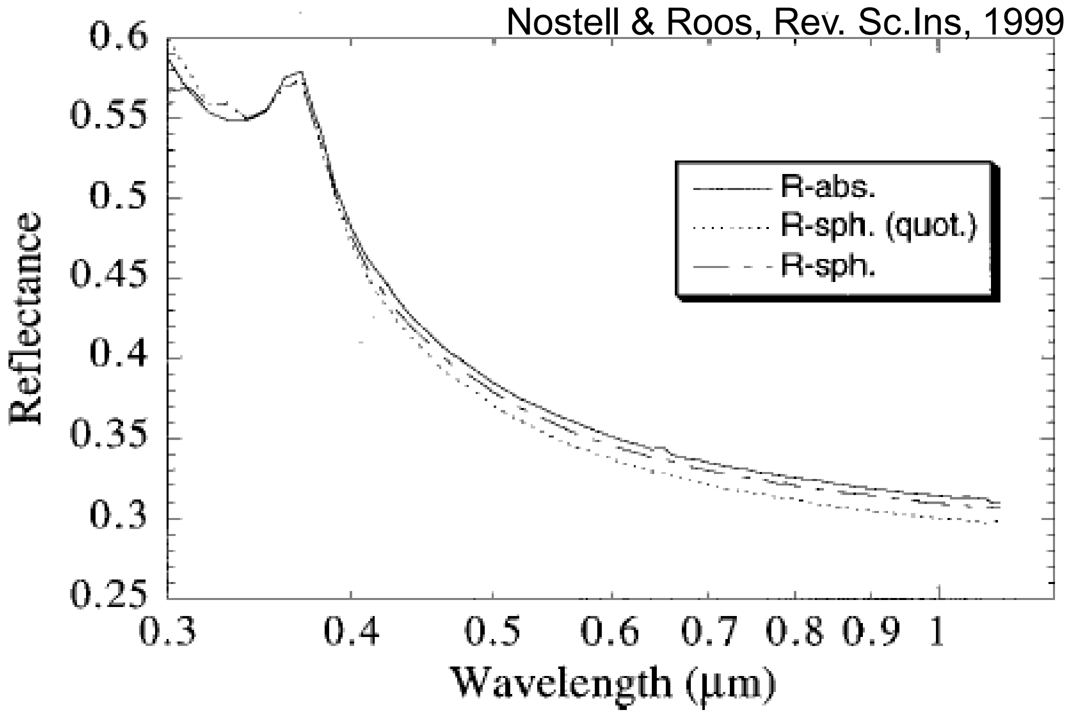
Geiger Efficiency $G_{geiger\text{-}eff.}(\lambda)$

High Geiger efficiency can be achived for high Over-voltage ΔU/U:

Relative overvoltage ΔU/U ≈ 12 – 15 %



Reflectivity of Si

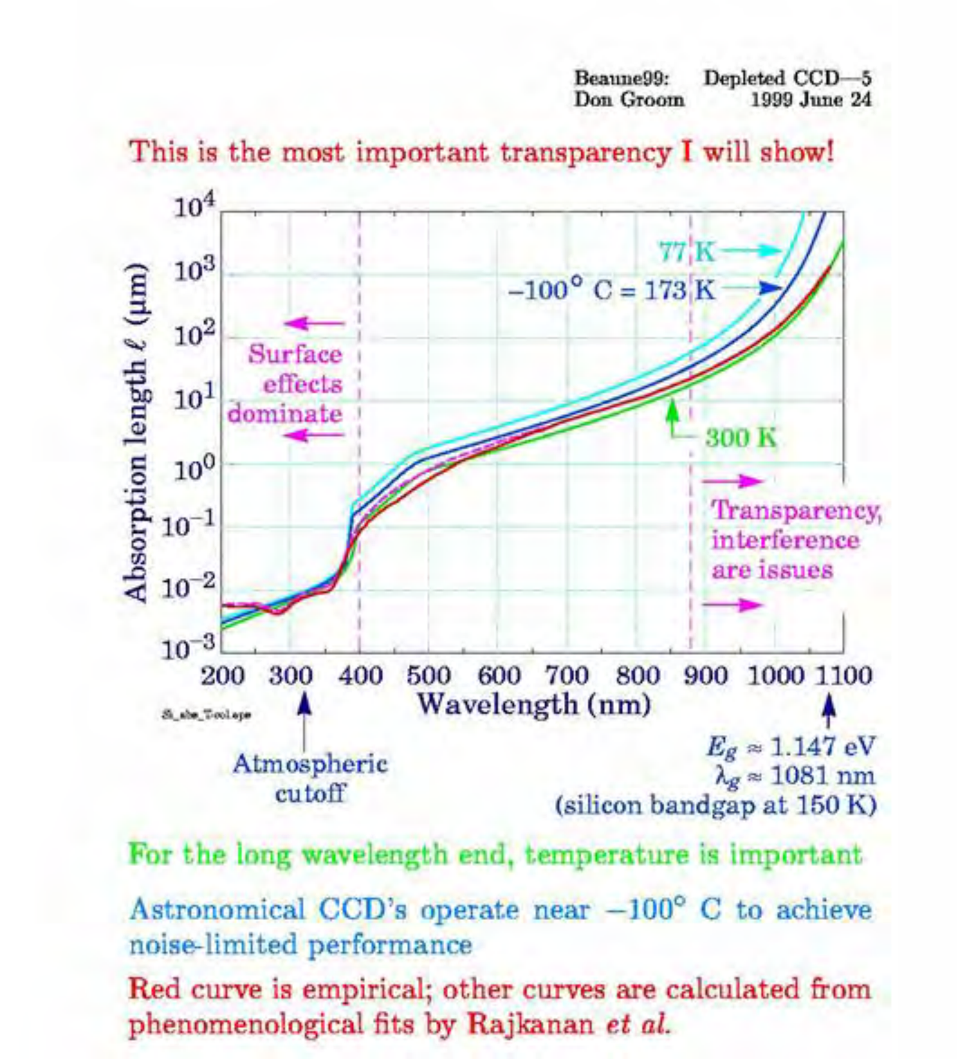


Nostell & Roos, Rev. Sc.Ins, 1999

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 ~ 60 – 31 % for 300 – 1000 nm at normal incidence.
- antireflective coatings can help
- Proper choice of window coating can provide efficiency ≥ 80-90 %

Reminder: light absorption in Si



Beaune99: Depleted CCD—5
Don Groom 1999 June 24

This is the most important transparency I will show!

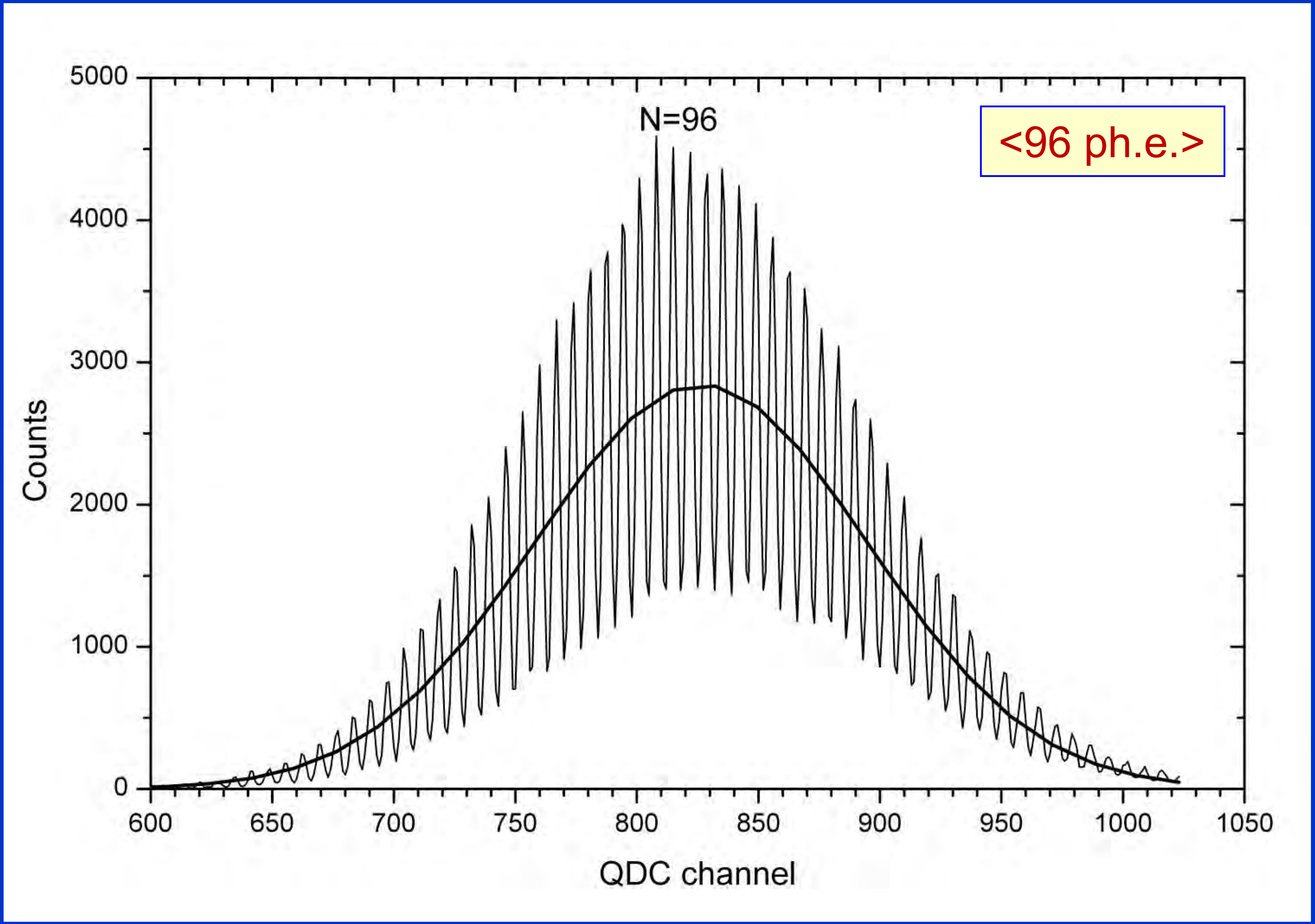
For the long wavelength end, temperature is important

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.*

- While 1000nm light can penetrate ~100 µm deep into Si, light of 300 nm 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

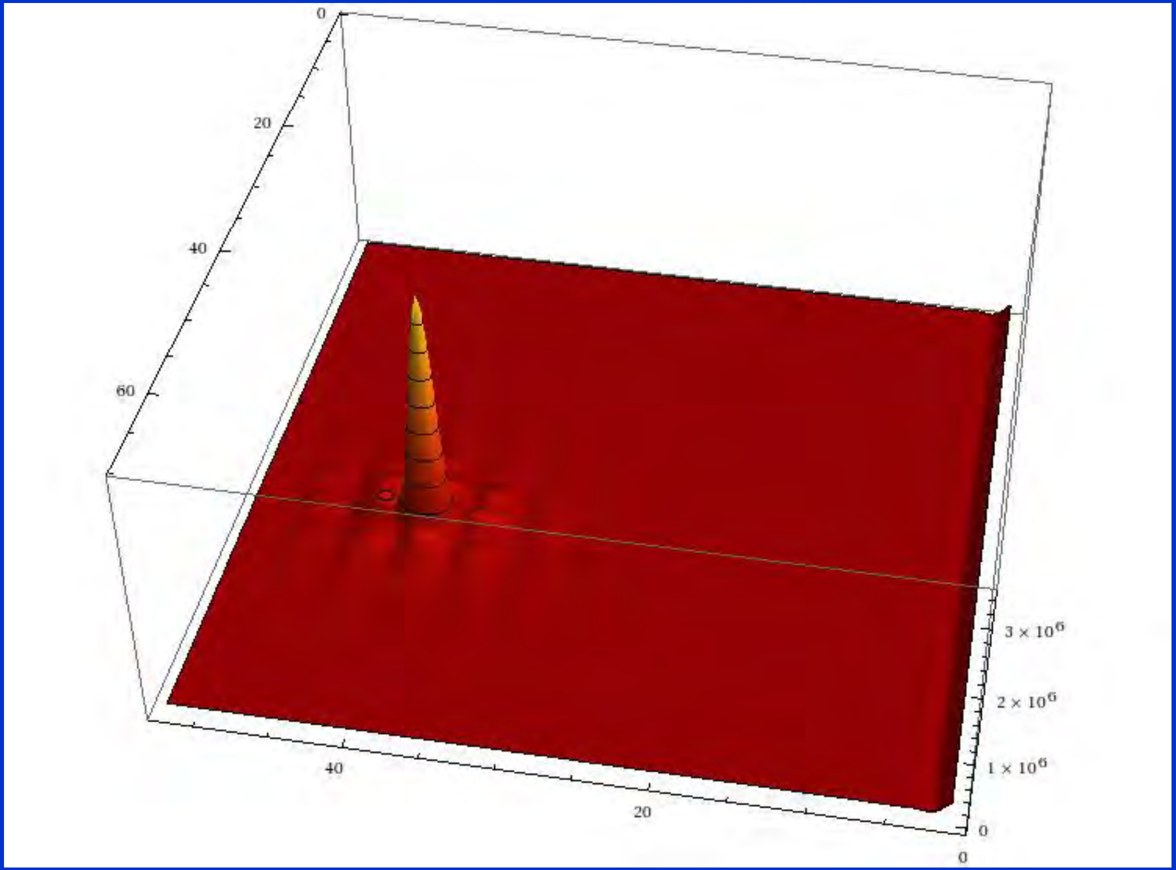
SiPM with X-talk suppression: World record of ultra-fast light sensors in amplitude resolution

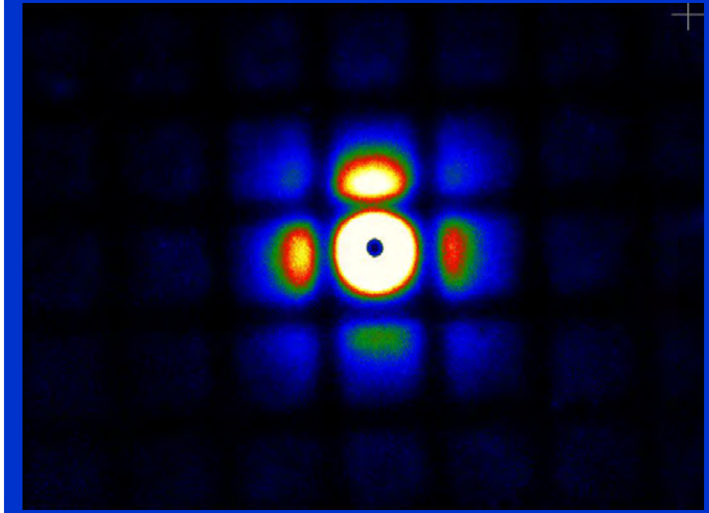


Why the light emission from Si avalanches is important

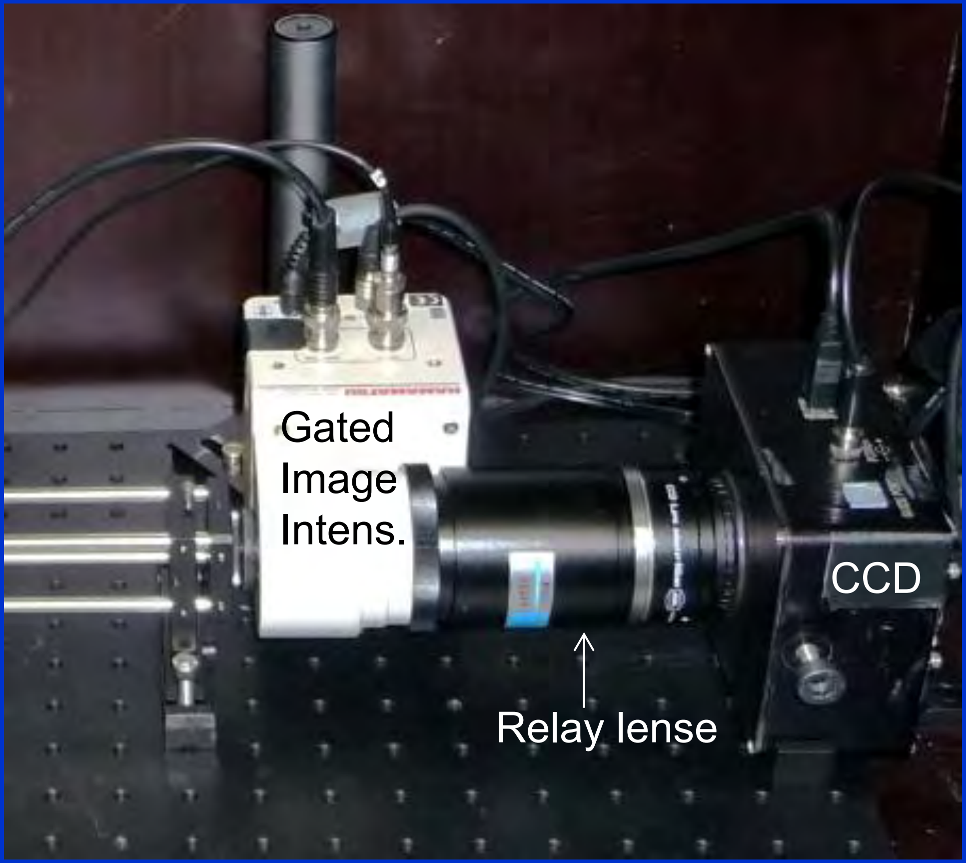
- First observation of the light emission from reversed-biased Si p-n junction in 1955 (Newman)
- Revived interest about the effect in recent years because of:
- Cross-talk in SiPMs (GAPD, MPPC, micro-channel APD,…) spoils the amplitude resolution
- The light emission is proportional to the number of 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

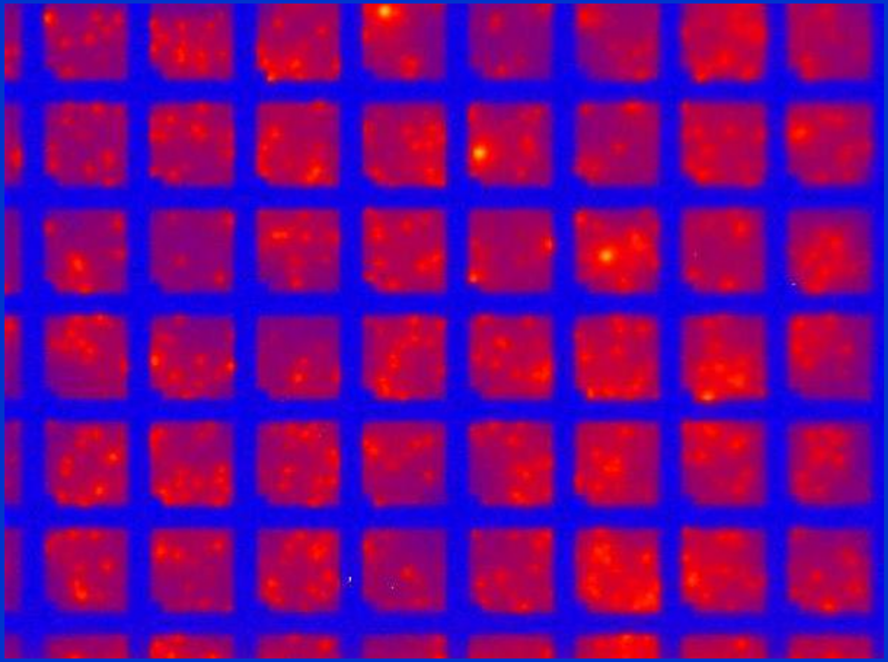
Cross-Talk

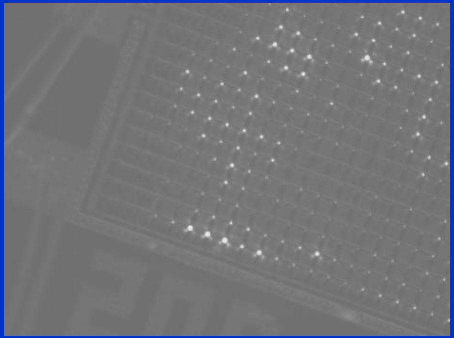




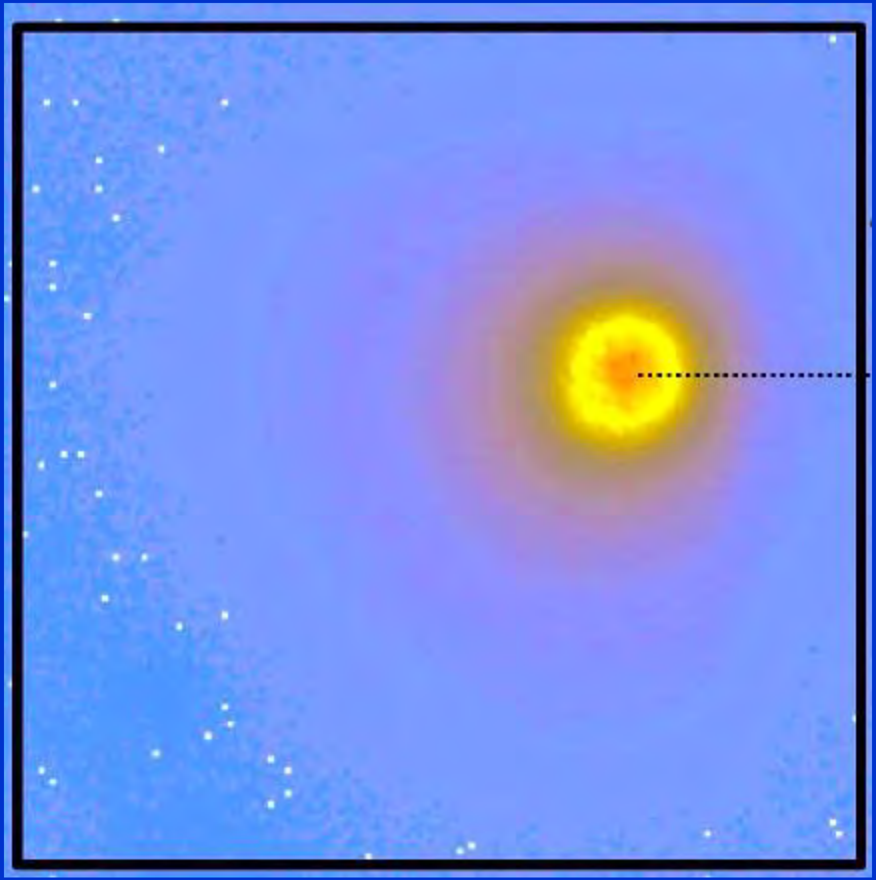
LEM is a powerful diagnostic method, revealing cell-substructures and many hidden details





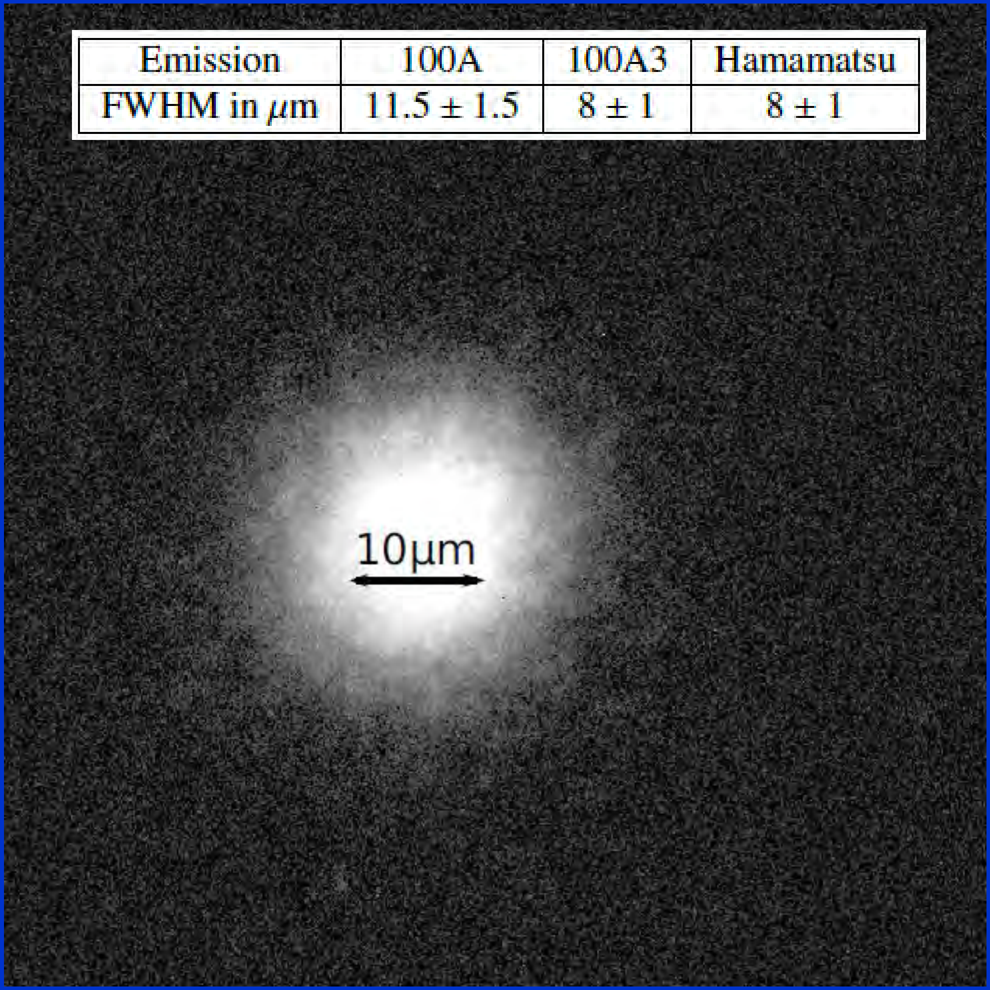


LEM Applied to Single SiPM Cell



- Shooting with laser to a cell of 100x100µm² size
- The laser light is focused to a spot size of ~2µm
- Observing that the avalanche occupies only a small part of the cell

Shooting to different type and cell size SiPMs



Emission	100A	100A3	Hamamatsu
FWHM in μm	11.5 ± 1.5	8 ± 1	8 ± 1

Shooting to SiPM (MPPC) of Hamamatsu type

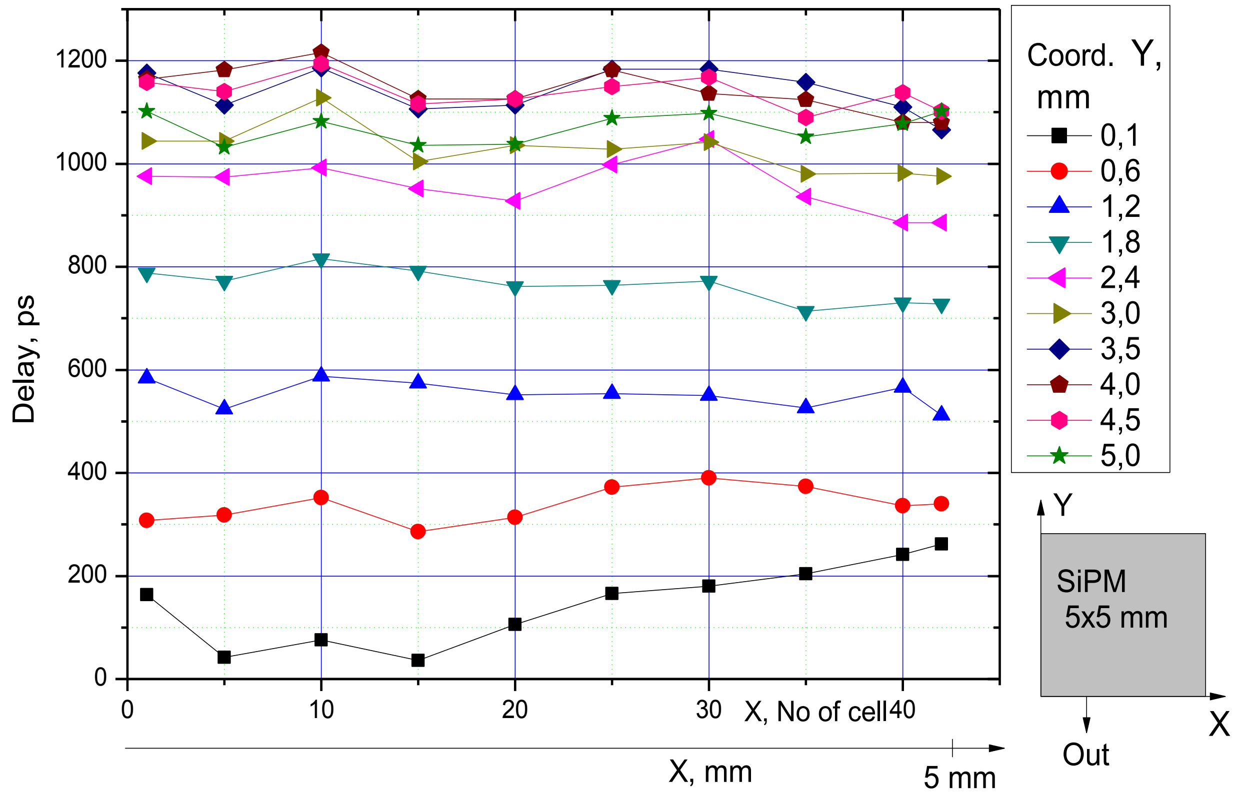
- 33-050-UVE-SIRESIN and
- MEPhI production type 100A (*with* trenches) and
- 100A3 (*no* trenches) show essentially the same results:

- FWHM size of the avalanche is 8-12 µm

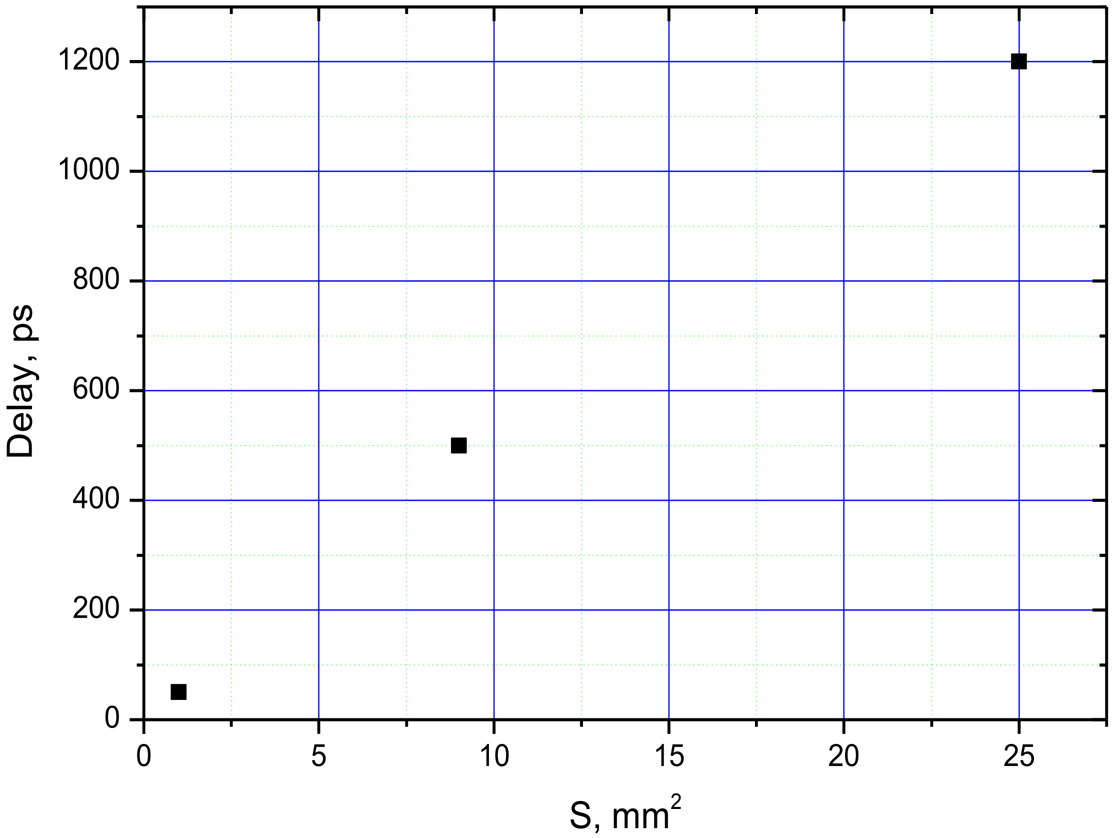
Implications of 8-12µm Transverse Size of Geiger Avalanches

- The transverse spread of an avalanche in SiPM is NOT due to photon-assisted process (that should make the entire cell glow)
- The transverse spread of an avalanche is due to a „diffusion“ process
- Cell size of a SiPM should be larger than the transverse size of avalanche (8-12 µm); this could be considered as a lower limit
- When the cell size will be comparable to or less than the transverse size of the avalanche, the latter may become truncated. This should produce additional amplitude variation
- The small stransverse size of the of the avalanches should be responsible for the frequently observed in LEM darker edges of SiPM cells at their boundaries

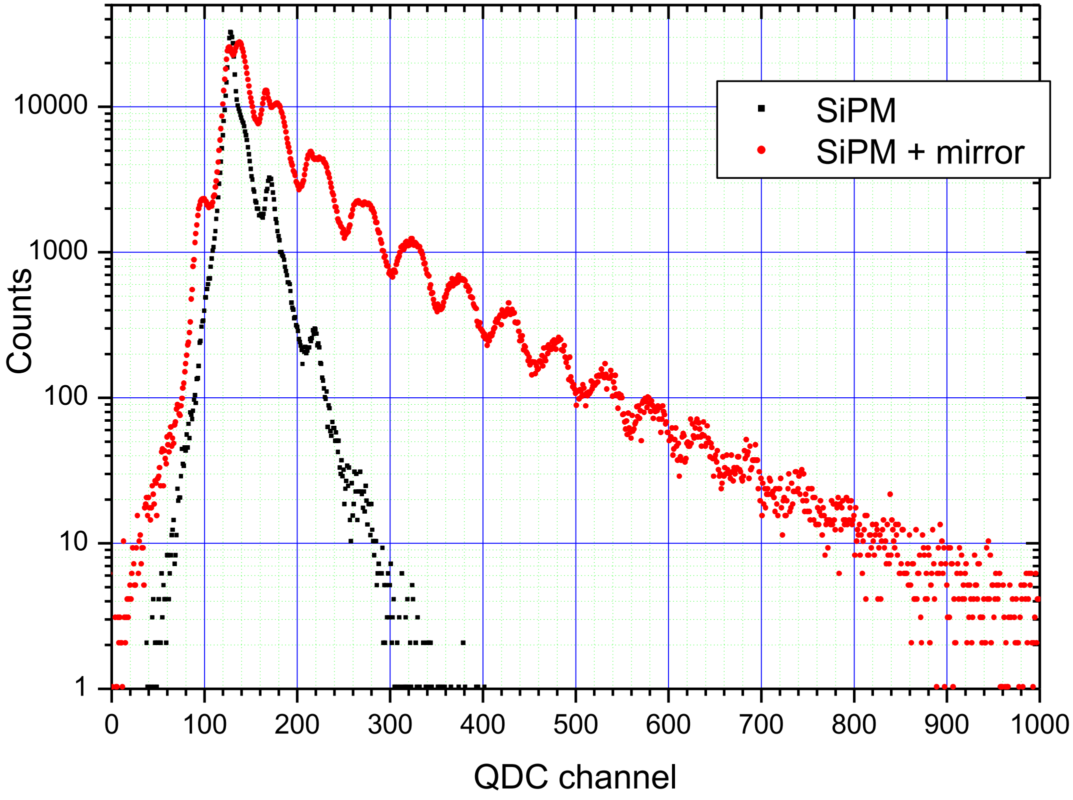
SiPM signal delay dependence on illuminated μ-cell location; ultra-fast laser pulse was used



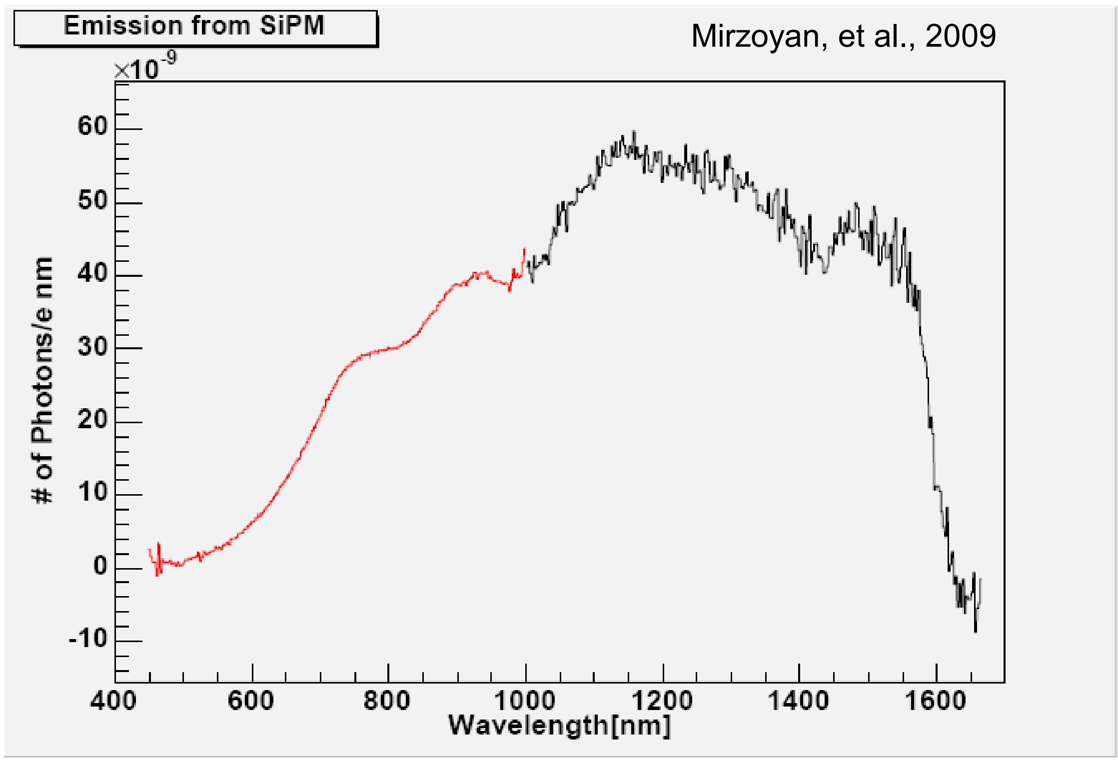
SiPM signal delay dependence on the SiPM chip area



Amplitude spectrum from a SiPM and a SiPM + mirror at 1mm distance



Light emission spectrum



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

Imagine a SiPM operating ata gain of 10^6.
It will emit ~17 (39) photons.
The total internal reflection angle in Si is ~16°, ➔ only light within 0.24 srad can leave the SiPM
(only $0.24/4\pi = 0.02$)

➔Only ~2 % of produced light comes out

MEPhI – MPI Physics cooperation

A test batch produced in December 2010

- SiPM Sizes

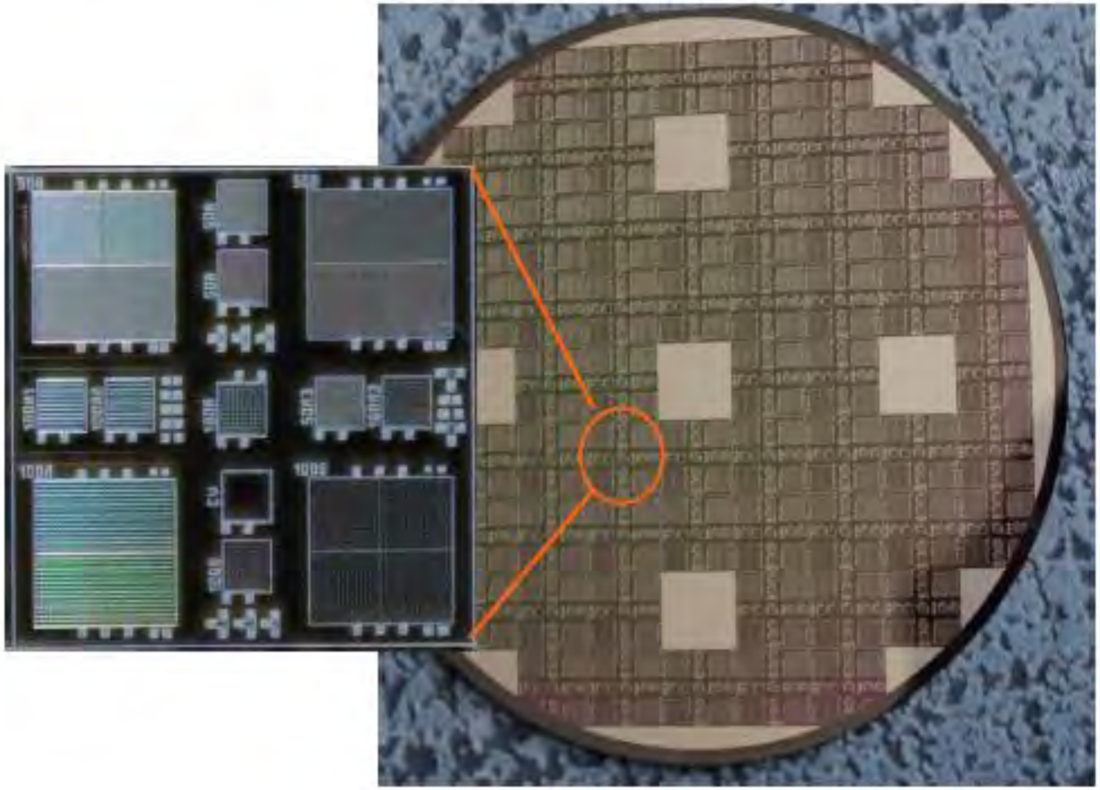
1x1 and 3x3 mm²

- µ-cell pitch

50 and 100 µm

- Geom. Eff.

40-80%



18 different modifications

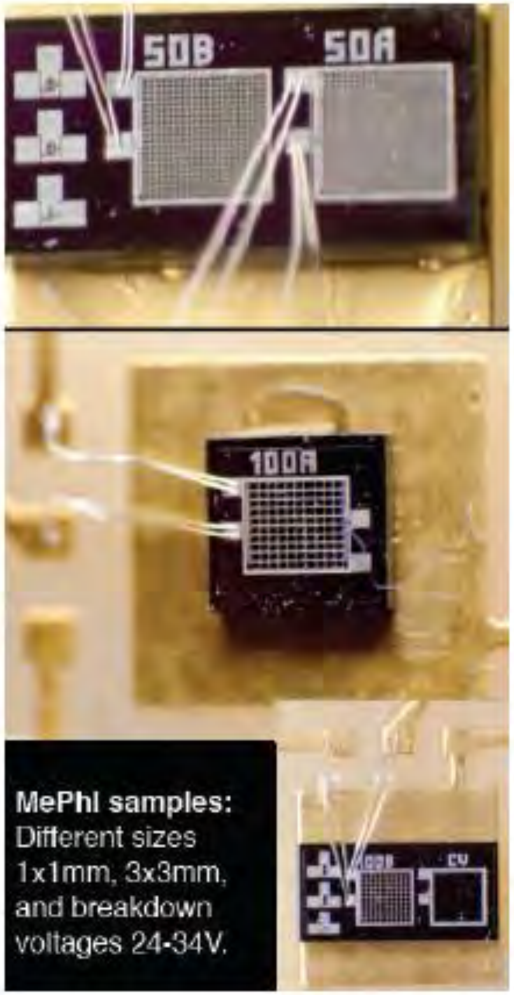
Special Features

Very high UV sensitivity

Record high PDE

Geometrical efficiency 80%

Very low temperature dependence

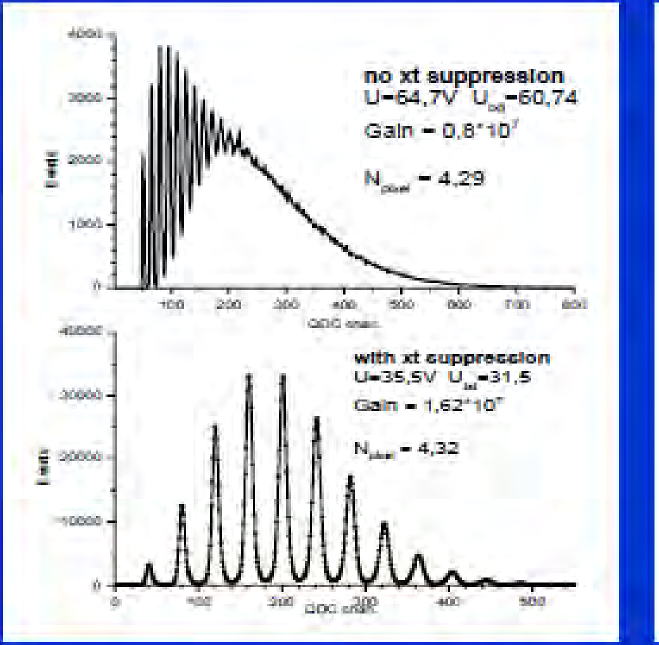


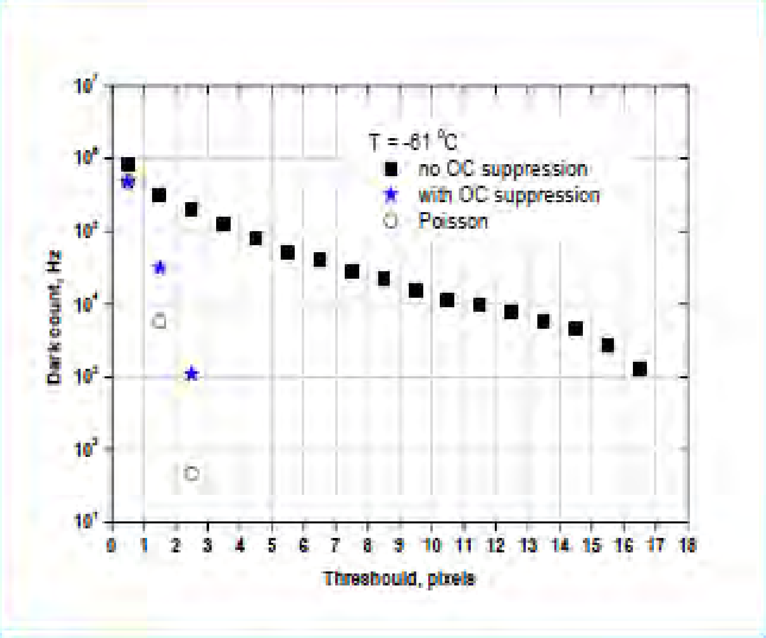
MePhI samples: Different sizes 1x1mm, 3x3mm, and breakdown voltages 24-34V.

X-talk suppression is improving the performance

Known ways to suppress X-talk:

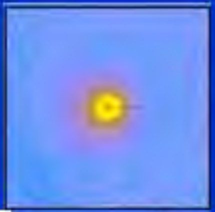
a) trenches
б) 2nd junction for isolating the bulk from the active region
c) Radiation damage
d) Special coating





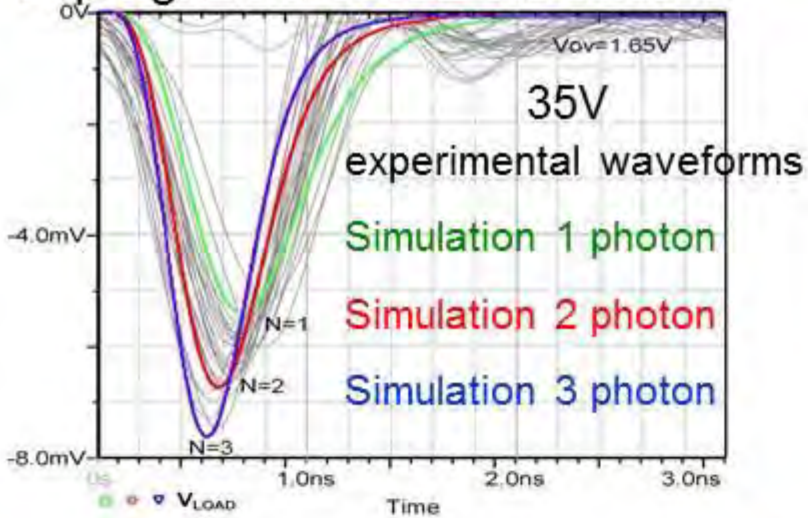
e) Ultra-thin SiPM: expected reduction by a very large number

Signal amplitude from a stand alone cell

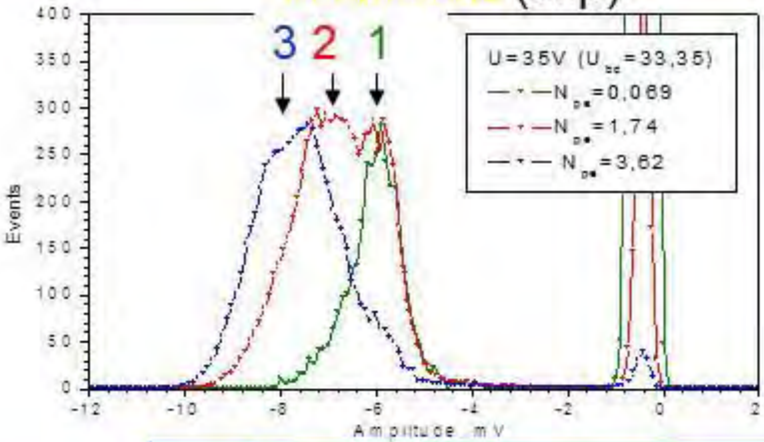


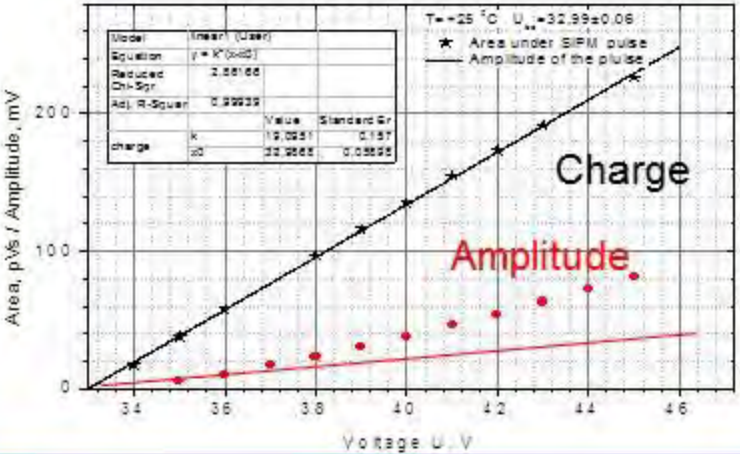
Fixed overvoltage ΔU=1.65V, different light intensity

Exp signals & SPICE simulations

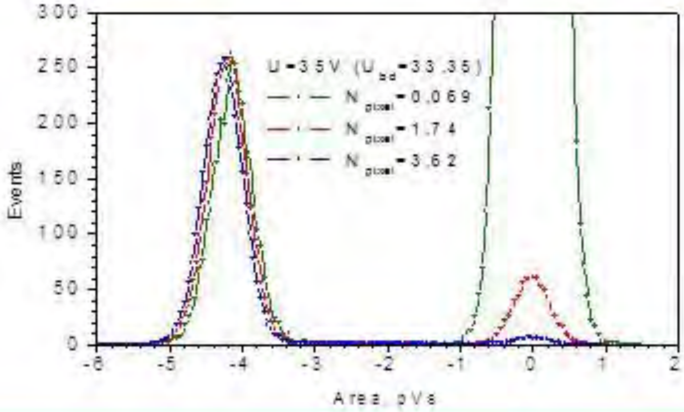


Amplitude (exp)





Charge (exp)



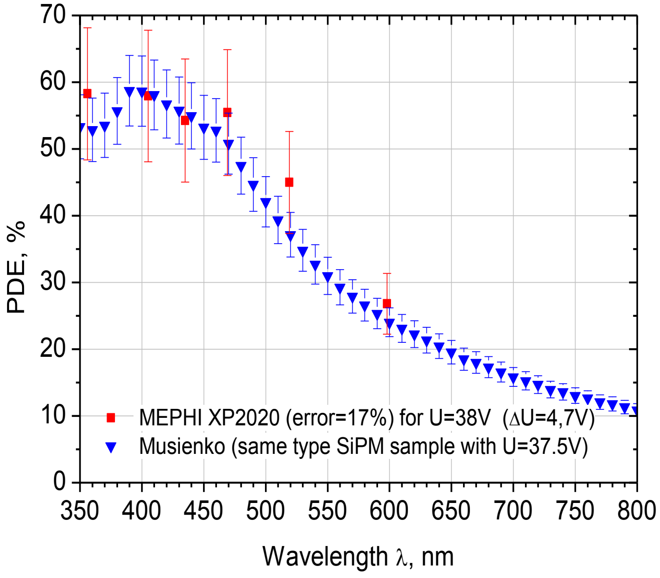
Razmik Mirzoyan: PMT & SiPM

4+ Fold X-talk suppression pursued by MEPhI – MPP researchers

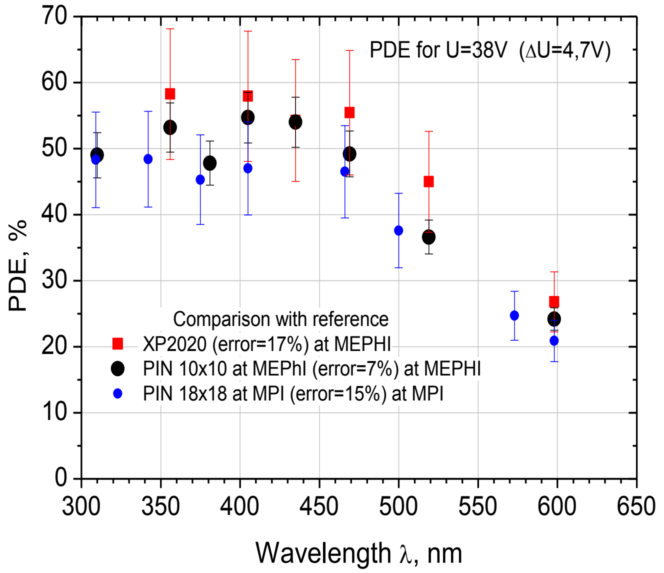
- Ways to suppress the X-talk:
  - Isolating trenches, total internal reflection: reduction 8-9 times; (intelectual property)
  - 2nd p-n junction for isolating the bulk from the active region: reduction 4-5 times; (intelectual property)
  - High-energy ion implantation: reduction ≥ 2-times (Intelectual property)
  - Special absorbing coating of the chip: ≥ 2-times (Intelectual property)
  - Ultra-thin SiPM: expected reduction by a very large number (intelectual property)

Record high PDE (pulsed mode LED, 100B type SiPM, 1x1 mm^2)

Measurements at MEPHI and at CERN (Y.Musienko)

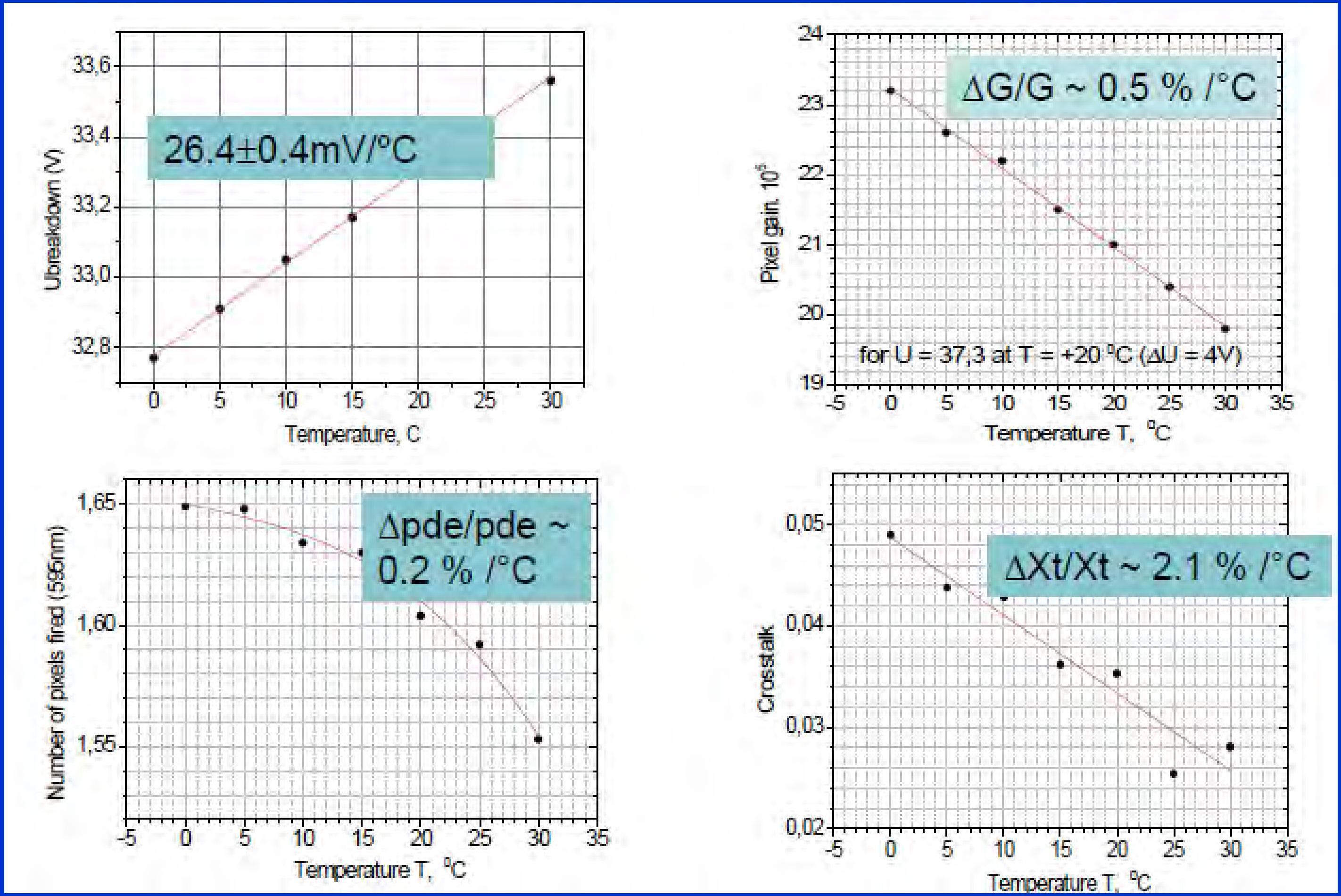


Measurements at MEPHI and at MPI



All results are consistent within experimental errors

Achieved T° dependence: 0.5 % /°C



26.4±0.4mV/°C

ΔG/G ~ 0.5 % /°C

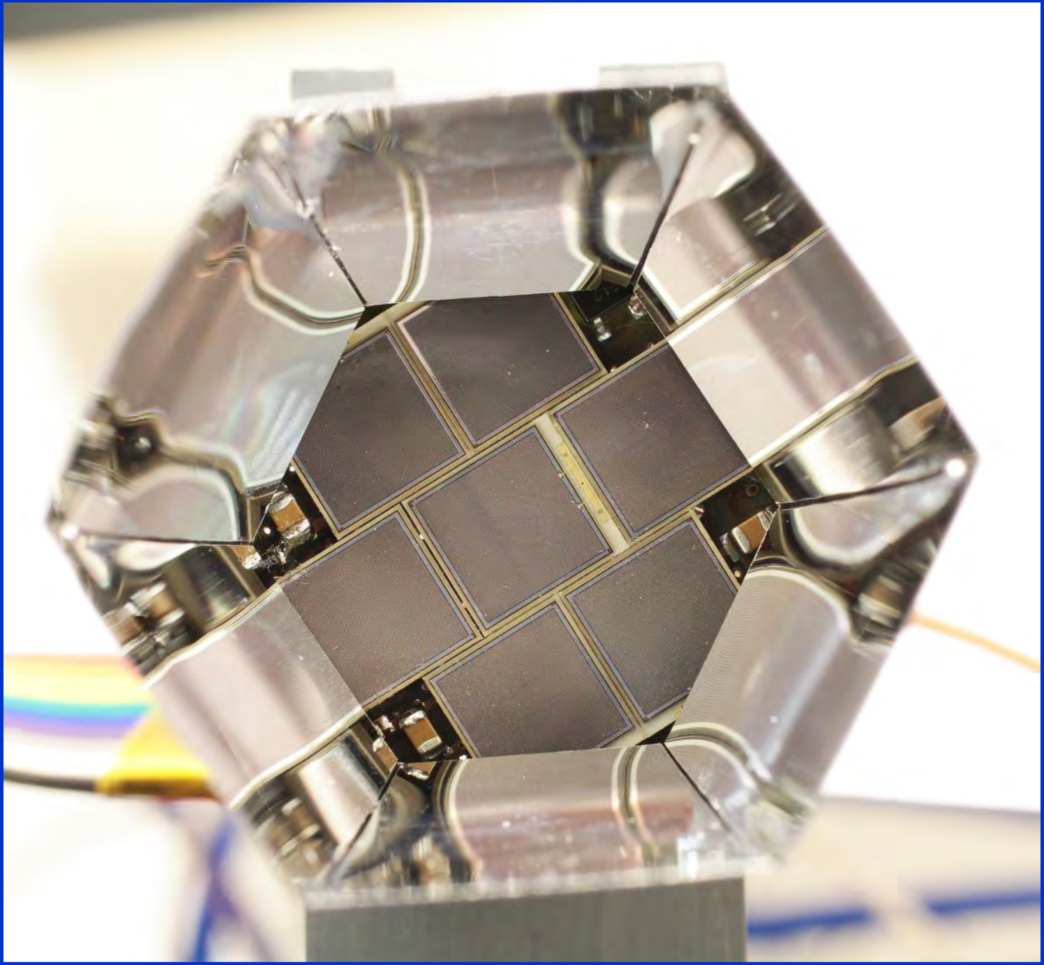
for U = 37,3 at T = +20 °C (ΔU = 4V)

Δpde/pde ~ 0.2 % /°C

ΔXt/Xt ~ 2.1 % /°C

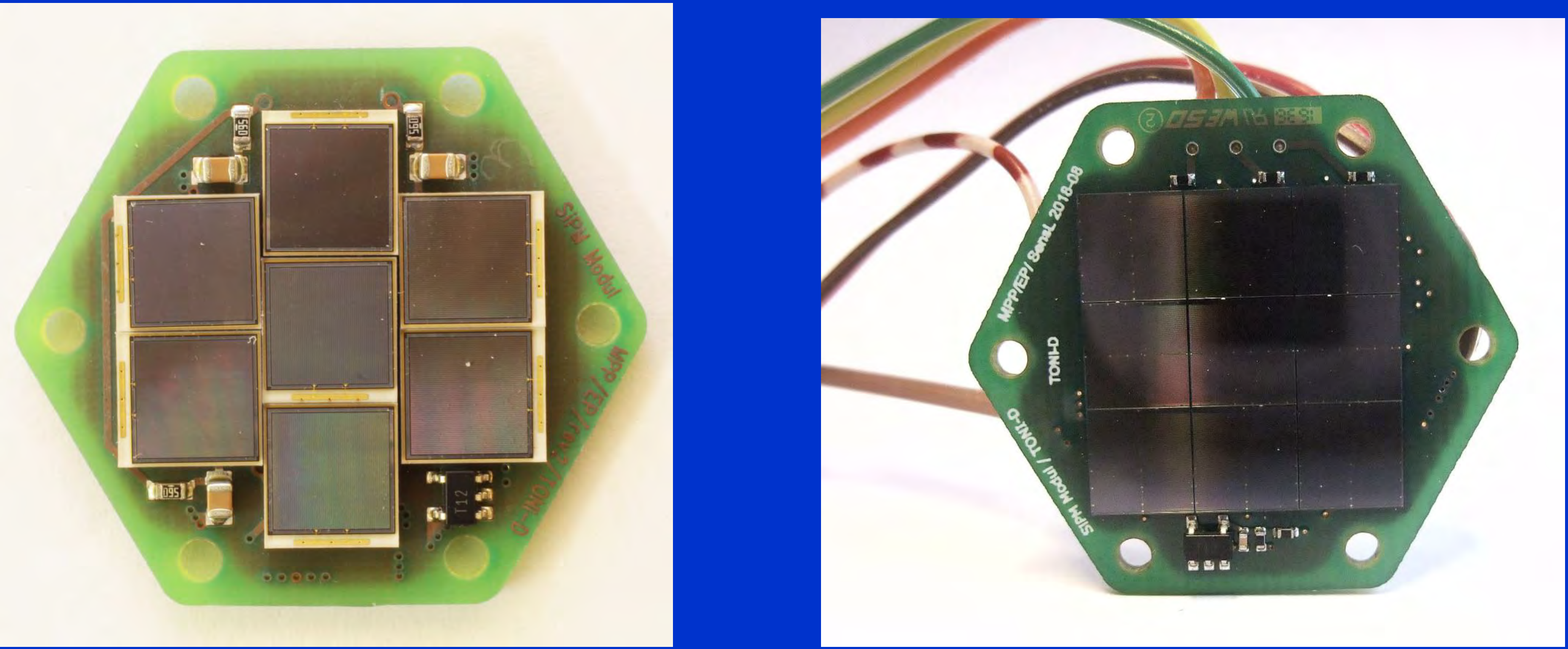
7-pixel SiPM-based sensor cluster for the MAGIC imaging camera

A composite SiPM pixel, based on summing up 7 SiPM chips



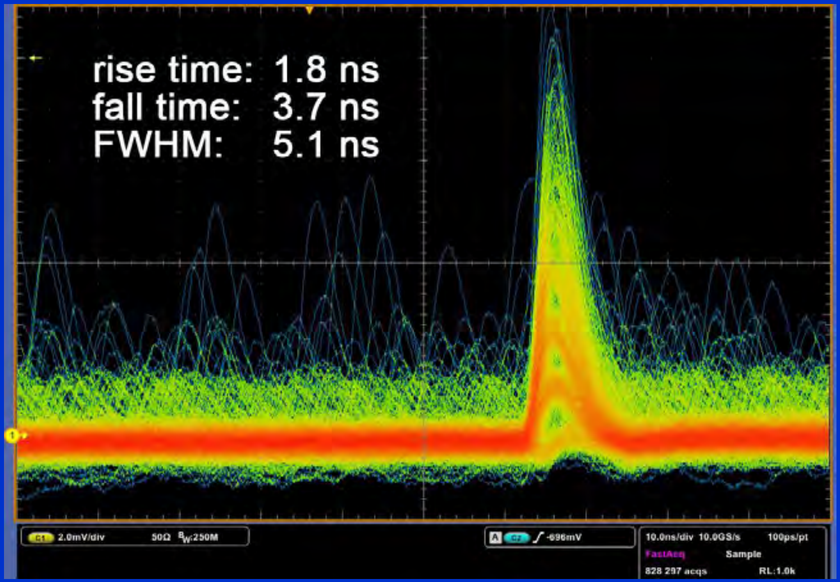
Composite SiPM pixel, based on chips from Excelitas (left) and from SensL (right)

Details will be shown in the presentation of A. Hahn on Thursday



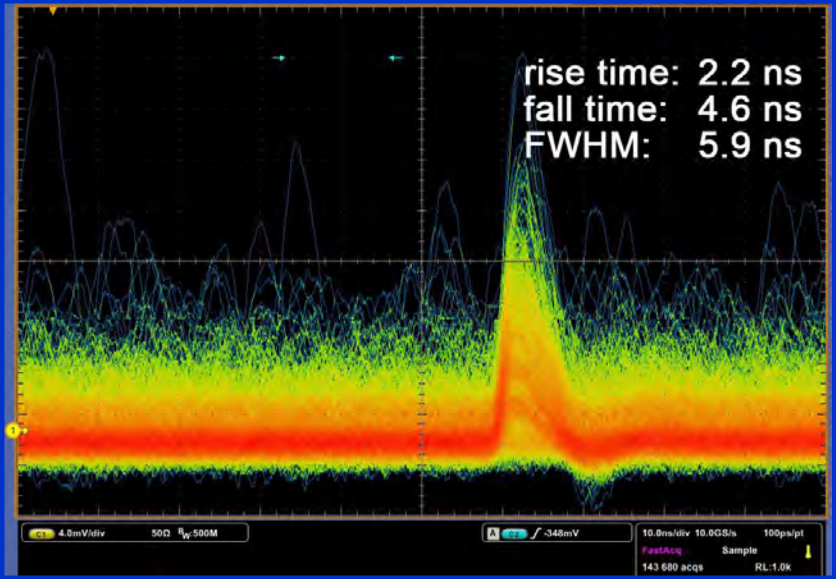
Pulse shapes

1 SiPM chip



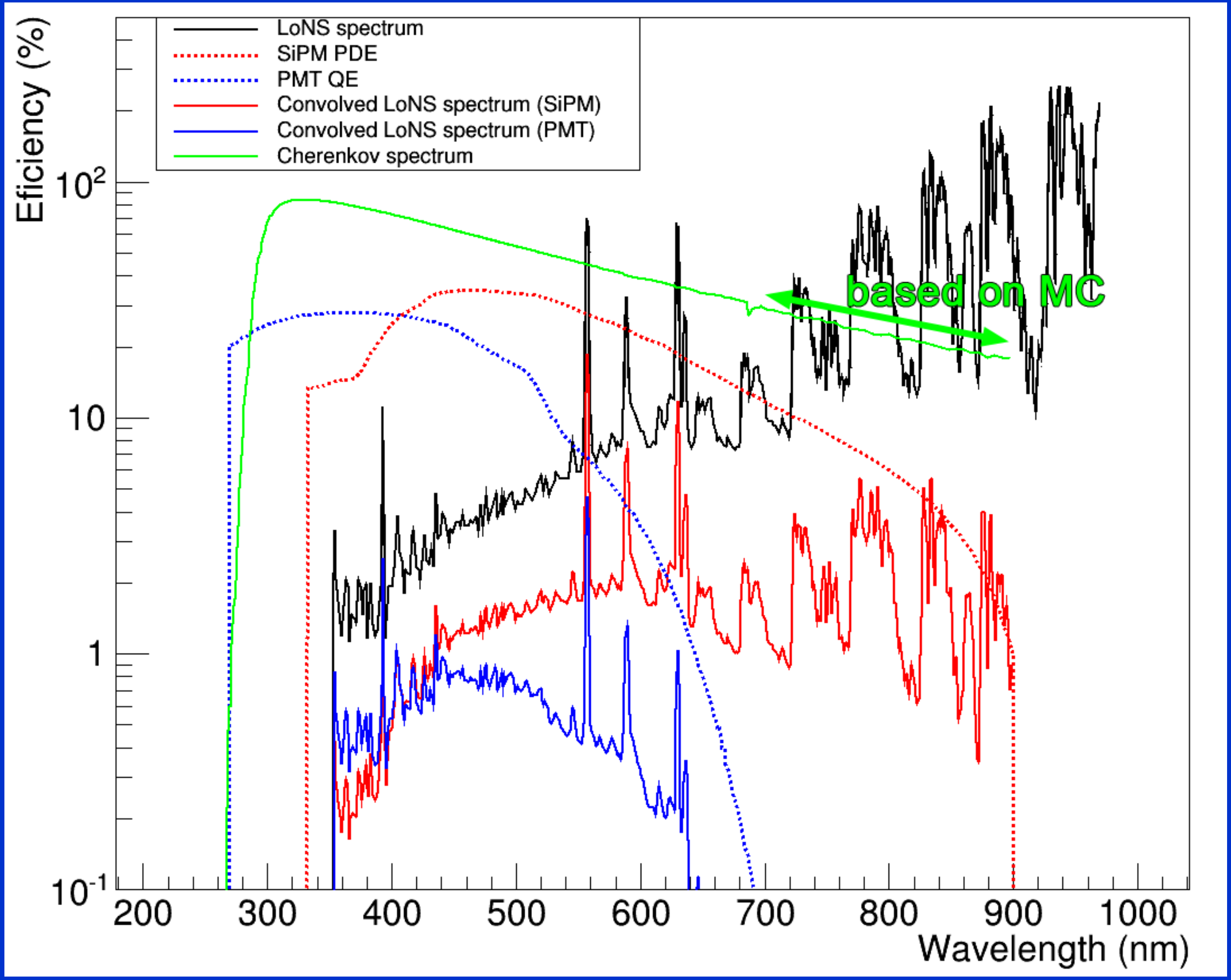
rise time: 1.8 ns
fall time: 3.7 ns
FWHM: 5.1 ns

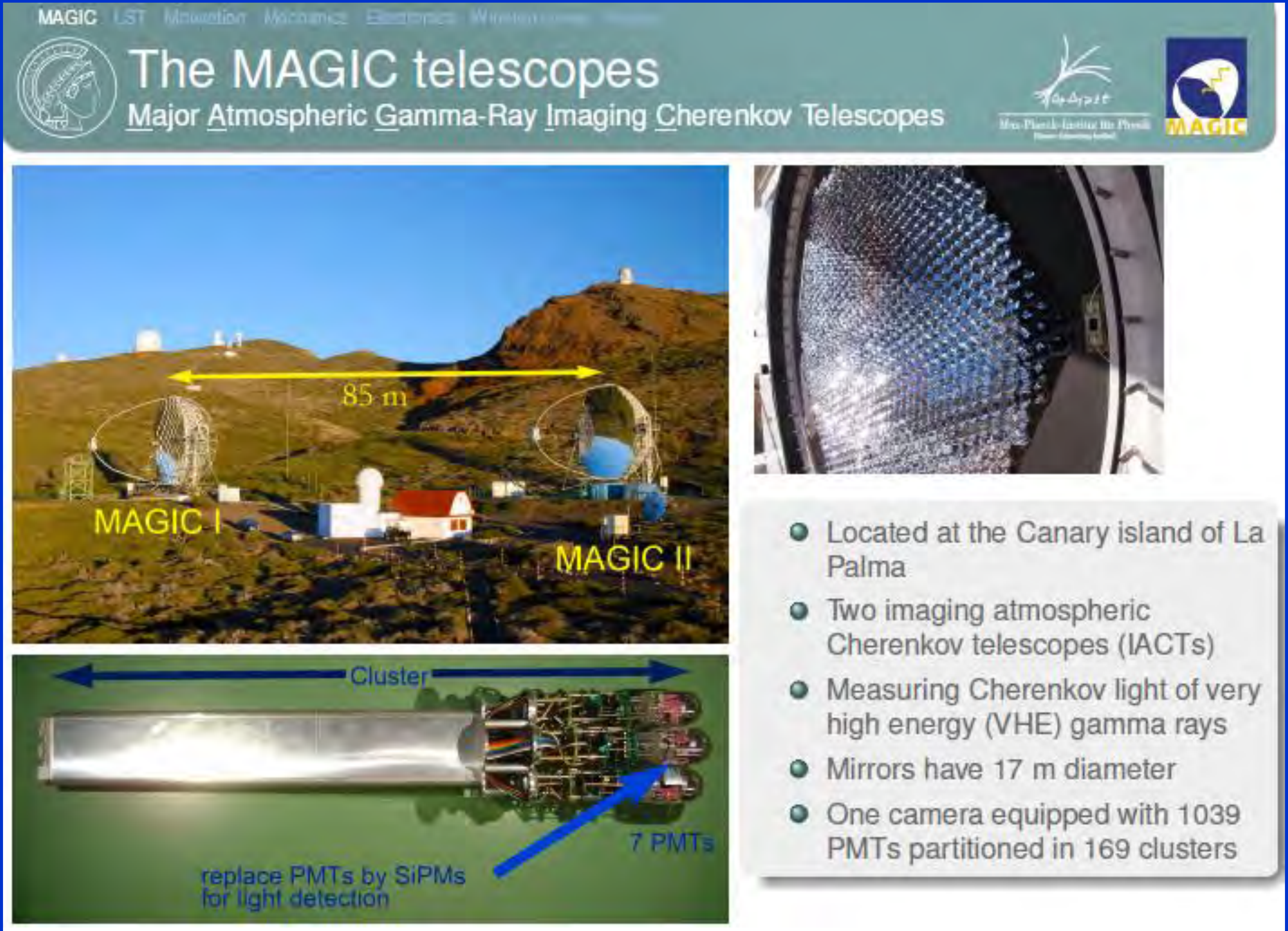
7 SiPM chips summed up



rise time: 2.2 ns
fall time: 4.6 ns
FWHM: 5.9 ns

Comparison of PMT and SiPM performances





The MAGIC telescopes

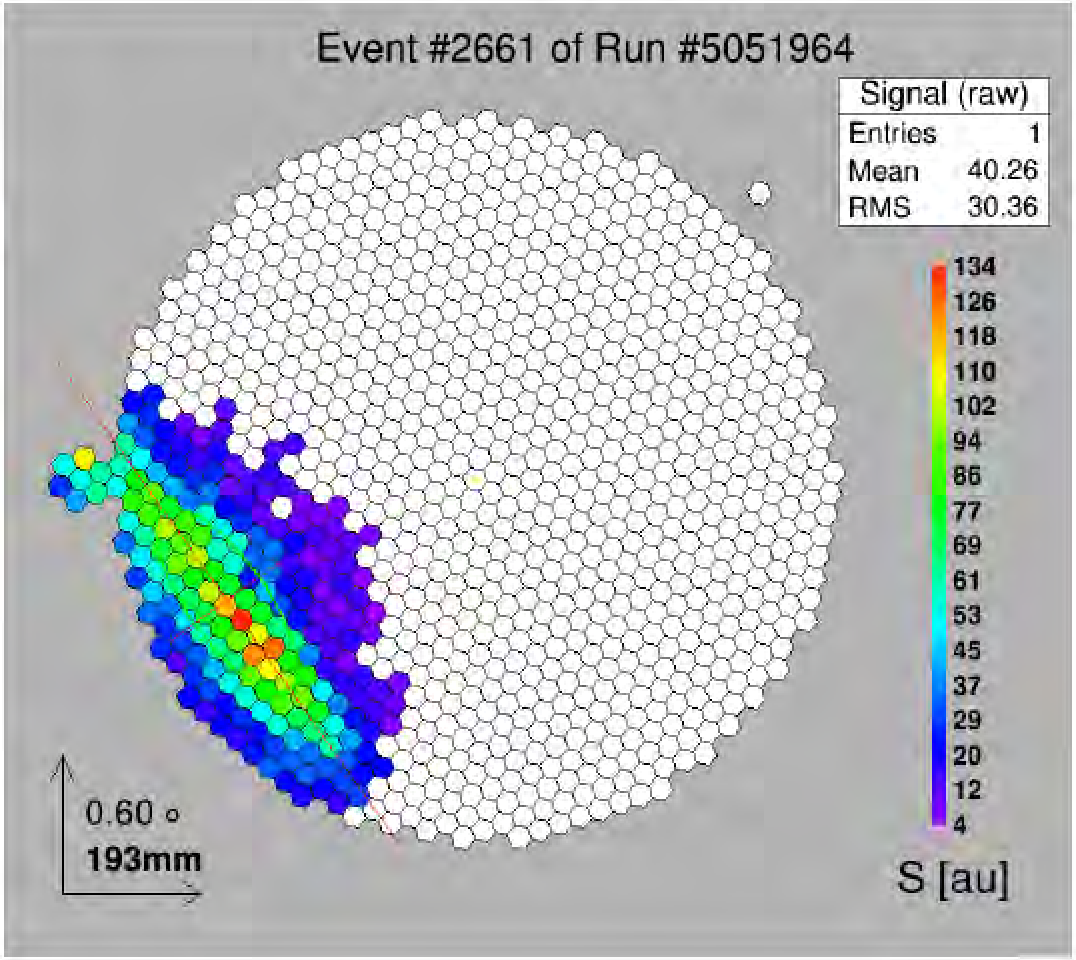
Major Atmospheric Gamma-Ray Imaging Cherenkov Telescopes

- Located at the Canary island of La Palma
- Two imaging atmospheric Cherenkov telescopes (IACTs)
- Measuring Cherenkov light of very high energy (VHE) gamma rays
- Mirrors have 17 m diameter
- One camera equipped with 1039 PMTs partitioned in 169 clusters

Installing a SiPM-based cluster inside the MAGIC imaging camera

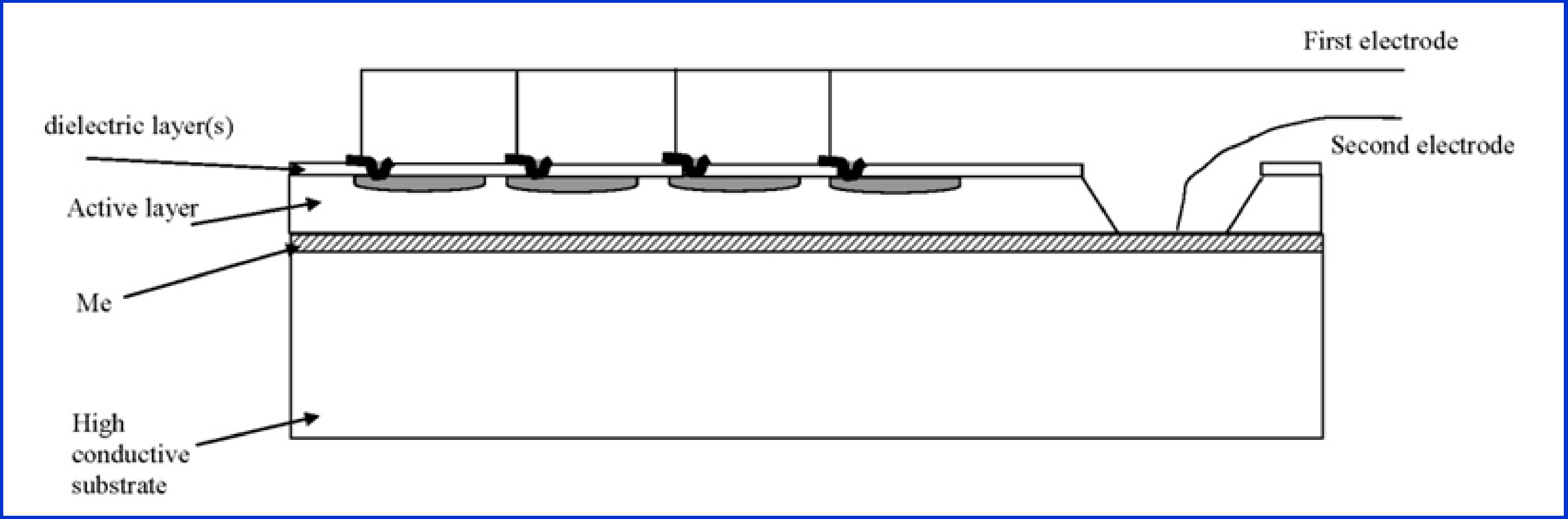
Example of an air shower measured by the standard PMT camera; in the left corner one can see the SiPM cluster

- SiPM pixel signal needs do be scaled with active area



The structural concept of the epitaxial SiPM

Me stands for the special layer(s) above which the SiPM is grown by the epitaxial method and below which the substrate material is shown



Light Sensors for astro-particle physics

- Different types of advanced light sensors are used in Astro-particle and astro-physics experiments for measuring light
- Even the classical light sensors such as the photo-multiplier tubes, are continueing to strongly improve in performance
- The number and types of SiPM matrixes from different manufacturers is increasing, the parameters are steadily And really fast improving

- Sometime soon, in a time scale of 2-3 years, we should be able to buy Si-based matrixes from several manufacturers with complete readout. We could then assemble large coordinate-sensitive imaging cameras like a lego

CTA SSTs are using SiPM

Small size telescopes

SST 1M

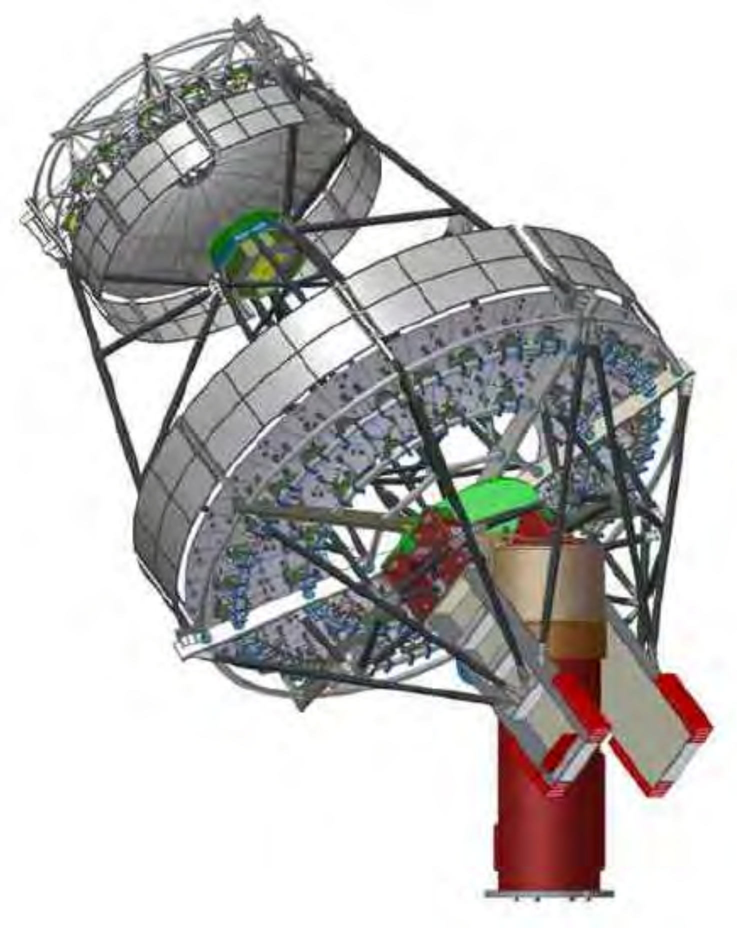
ASTRI

GCT

Science drivers
Highest energies (> 5 TeV)
Galactic science, PeVatrons

Array layout
South site: 70 SST
North site: -

Schwarzschild-Couder (SSC) telescope



- 9.7 m primary mirror
- 5.4 m secondary
- 5.6 m focal length,
- F/0.58
- 50 m² reflector area
- PSF ≤ 4.5' @ 8° FoV
- 11328 SiPM
- 0.06° pixels
- Target readout

Hamamatsu LVR-6050CN-SMP

PDE vs. Bias

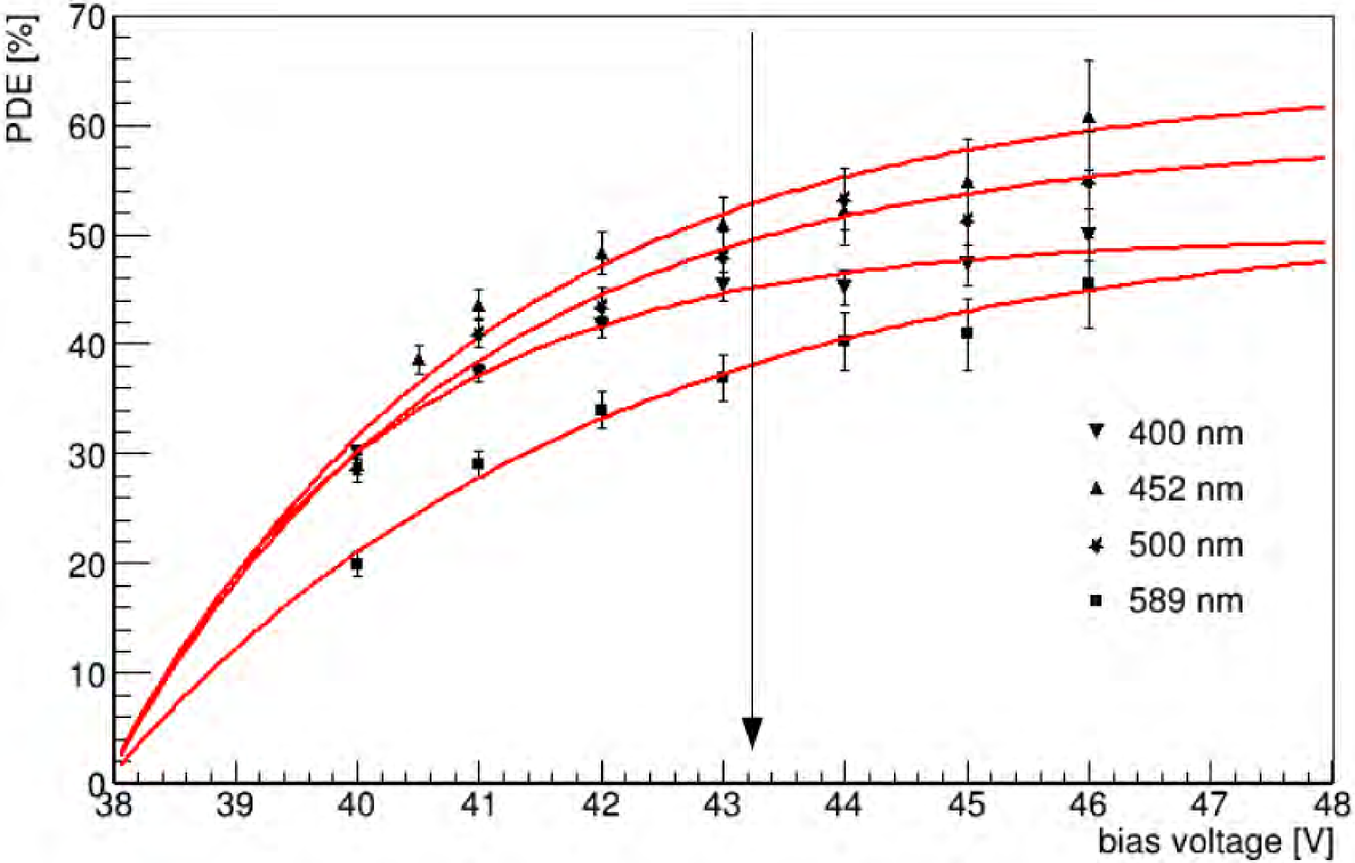
N. Otte, et al

Arrow indicates bias where breakdown probability is 90% at 400 nm

14% above breakdown

Compare to

9% above breakdown
In LCT5



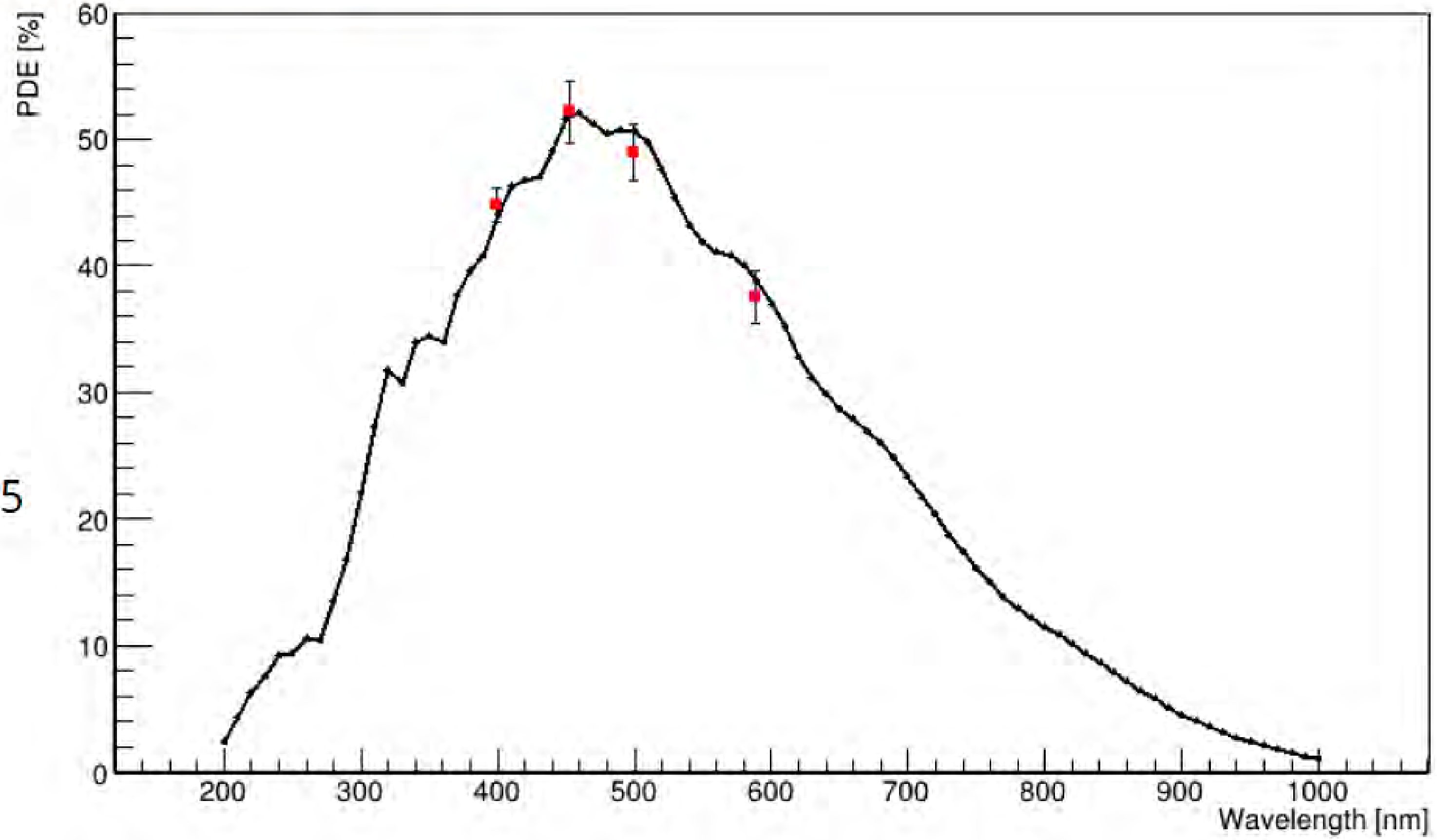
Hamamatsu LVR-6050CN-SMP

PDE vs. Wavelength

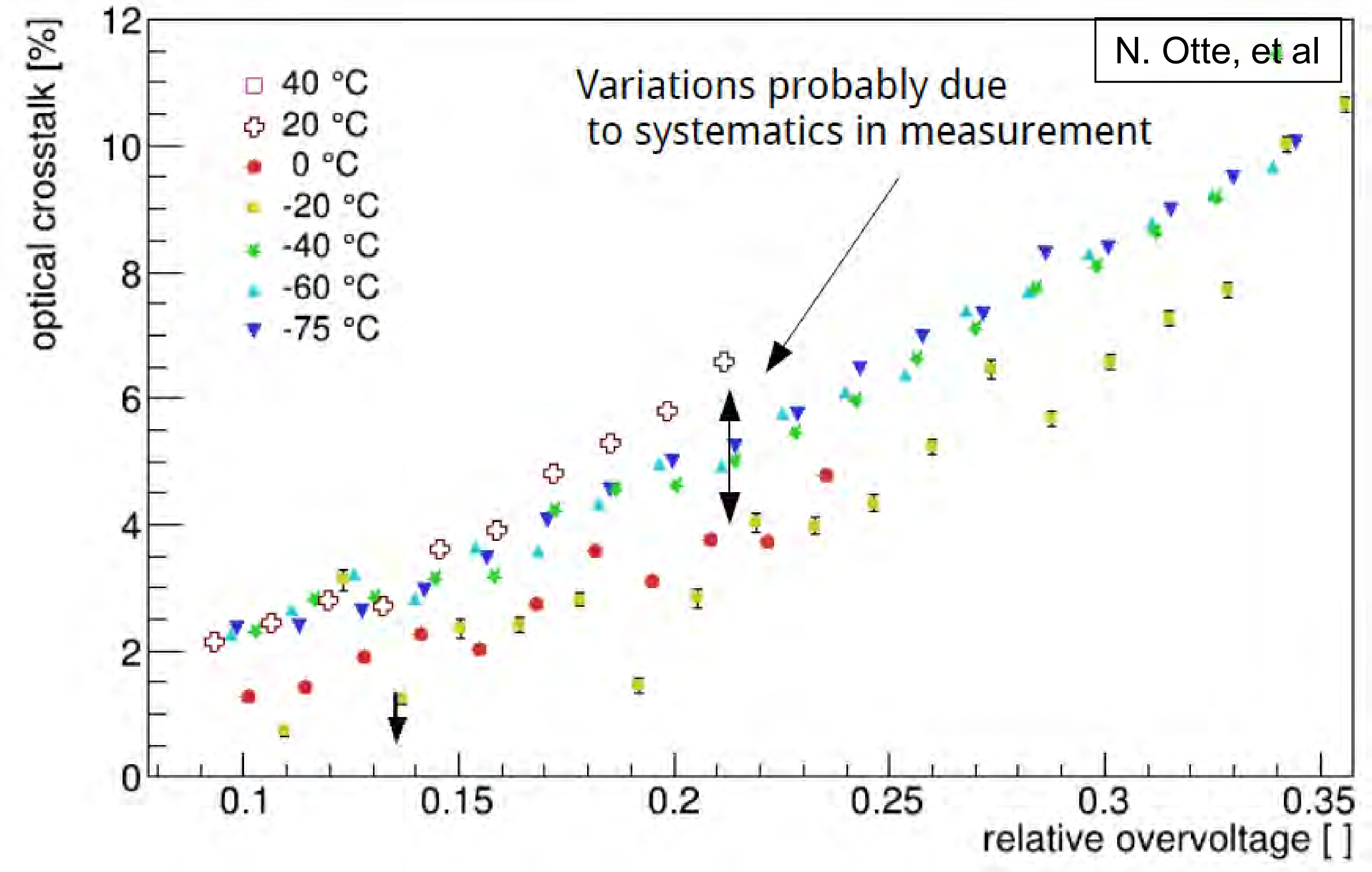
N. Otte, et al

At 25°C and
90% breakdown
probability
@ 400 nm

Same PDE like LCT5

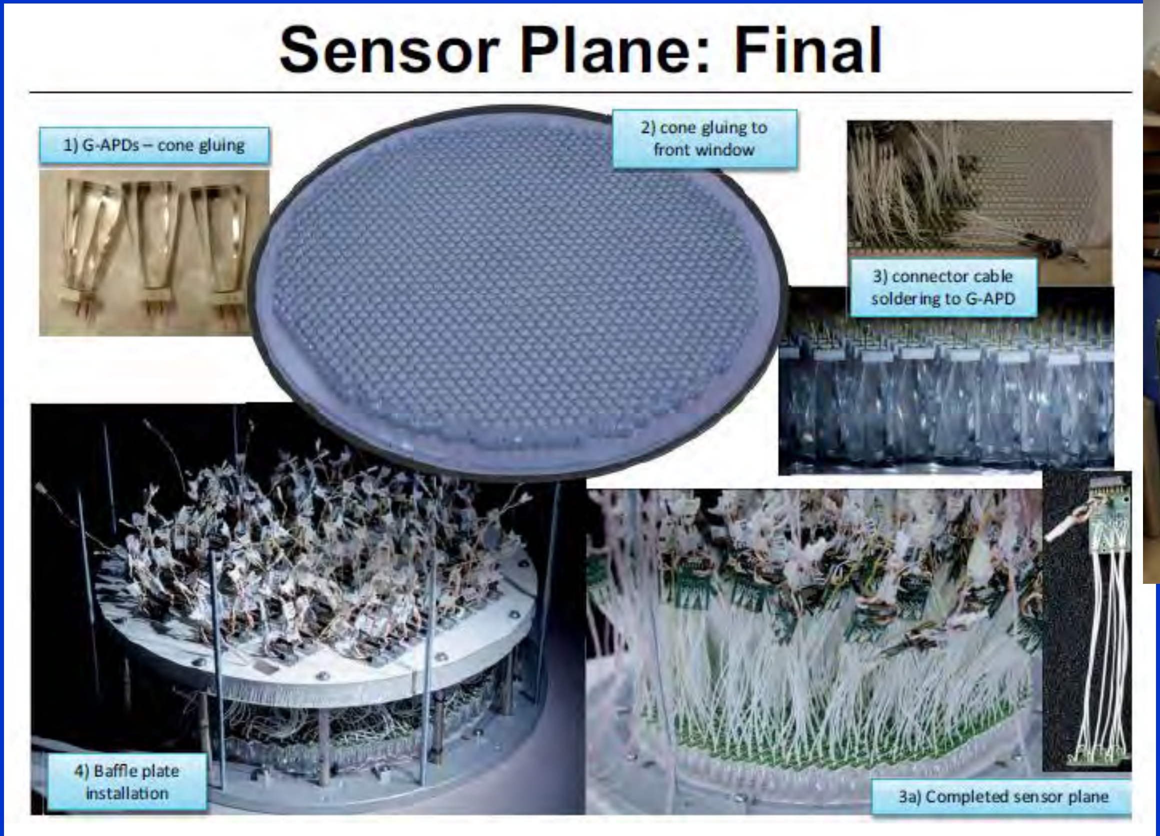


Hamamatsu LVR-6050CN-SMP Optical X-talk



1440-pixel MPPC camera

FACT telescope camera



Sensor Plane: Final

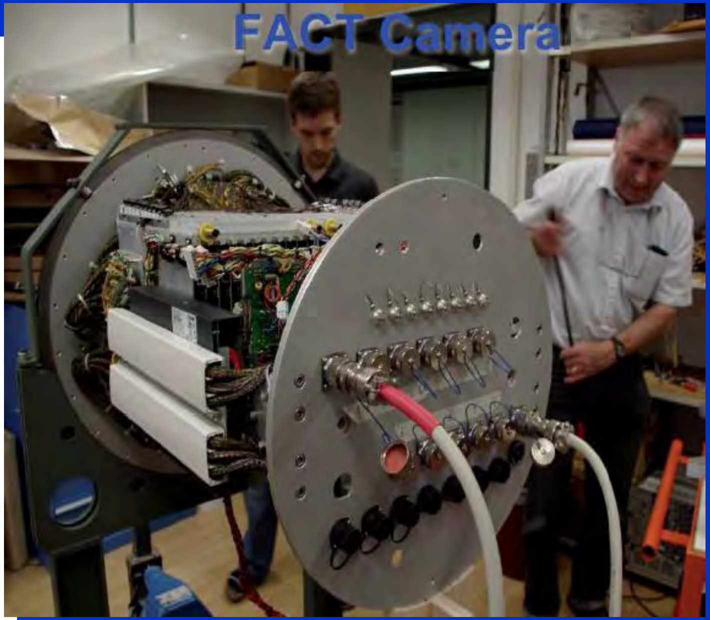
1) G-APDs – cone gluing

2) cone gluing to front window

3) connector cable soldering to G-APD

4) Baffle plate installation

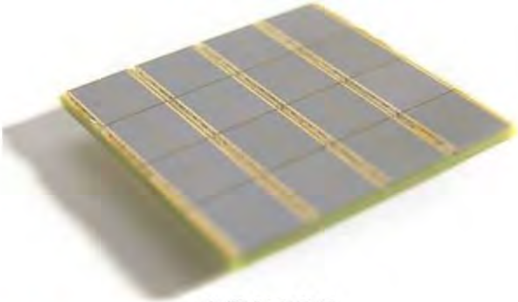
3a) Completed sensor plane



Man-power hungry; extensive manual work was needed

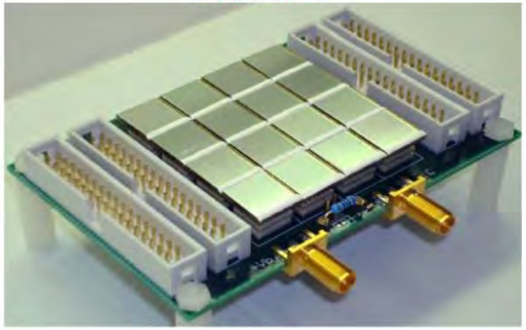
Large Variety of SiPM Arrays Available

Philips



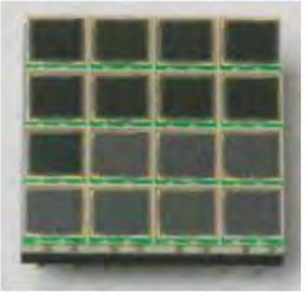
dSiPM

RMD



SSPM

Hamamatsu

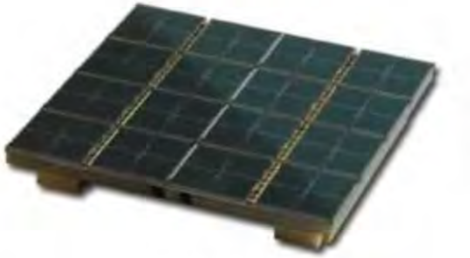


MPPC

SensL

SPM

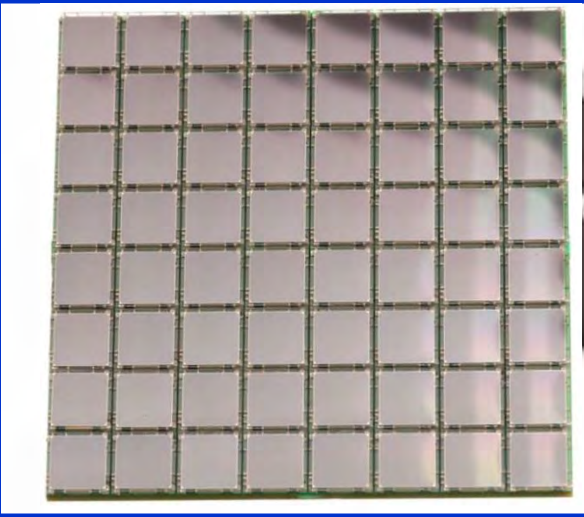
FBK

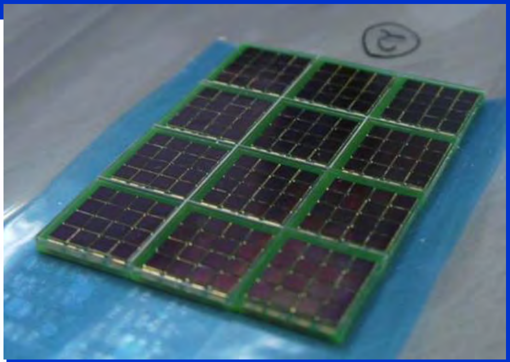


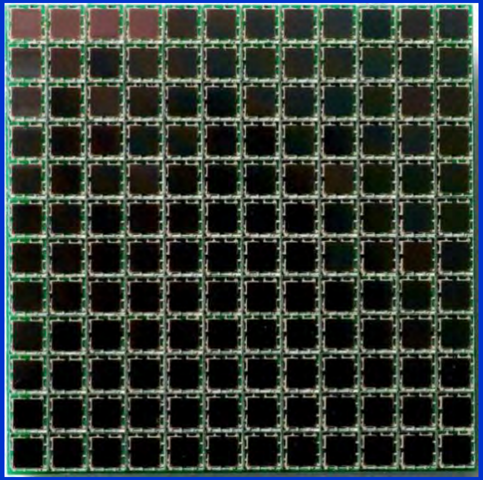
SiPM

- Very Attractive for PET
- Properties Vary (20 pF – 900 pF, ∝Pixel Area)

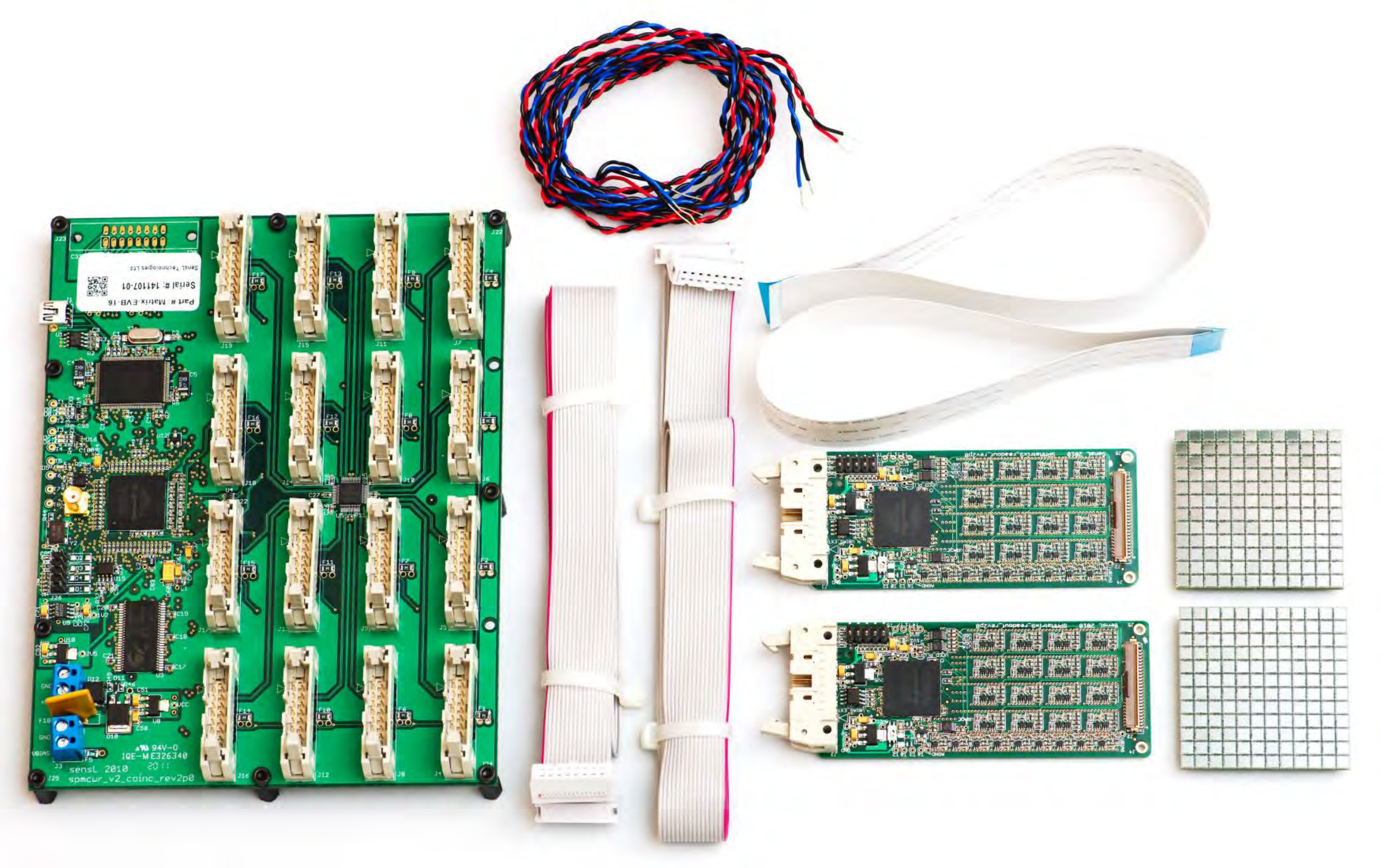
SiPM matrixes







Matrixes and readout solutions



Camera Technological Solutions

FRONT END ASIC: EASIROC

ESAIROC

a fully-analogue front-end ASIC designed to directly interface SiPM detectors

EASIROC channels are based on a shaper!

Technology :

AMS 0,35µm SiGe

Die size : 16.6mm²

4.157 x 4.013 mm²

Package :

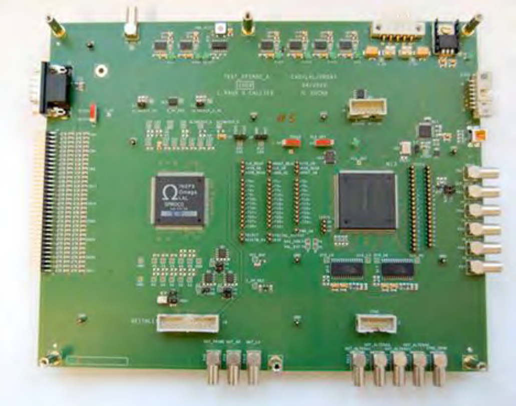
Naked (PEBS) ;TQFP160

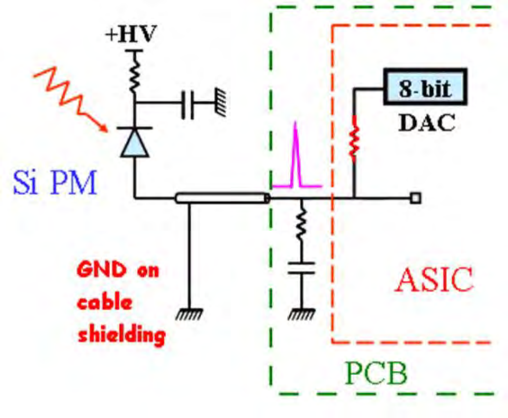
Ωmega

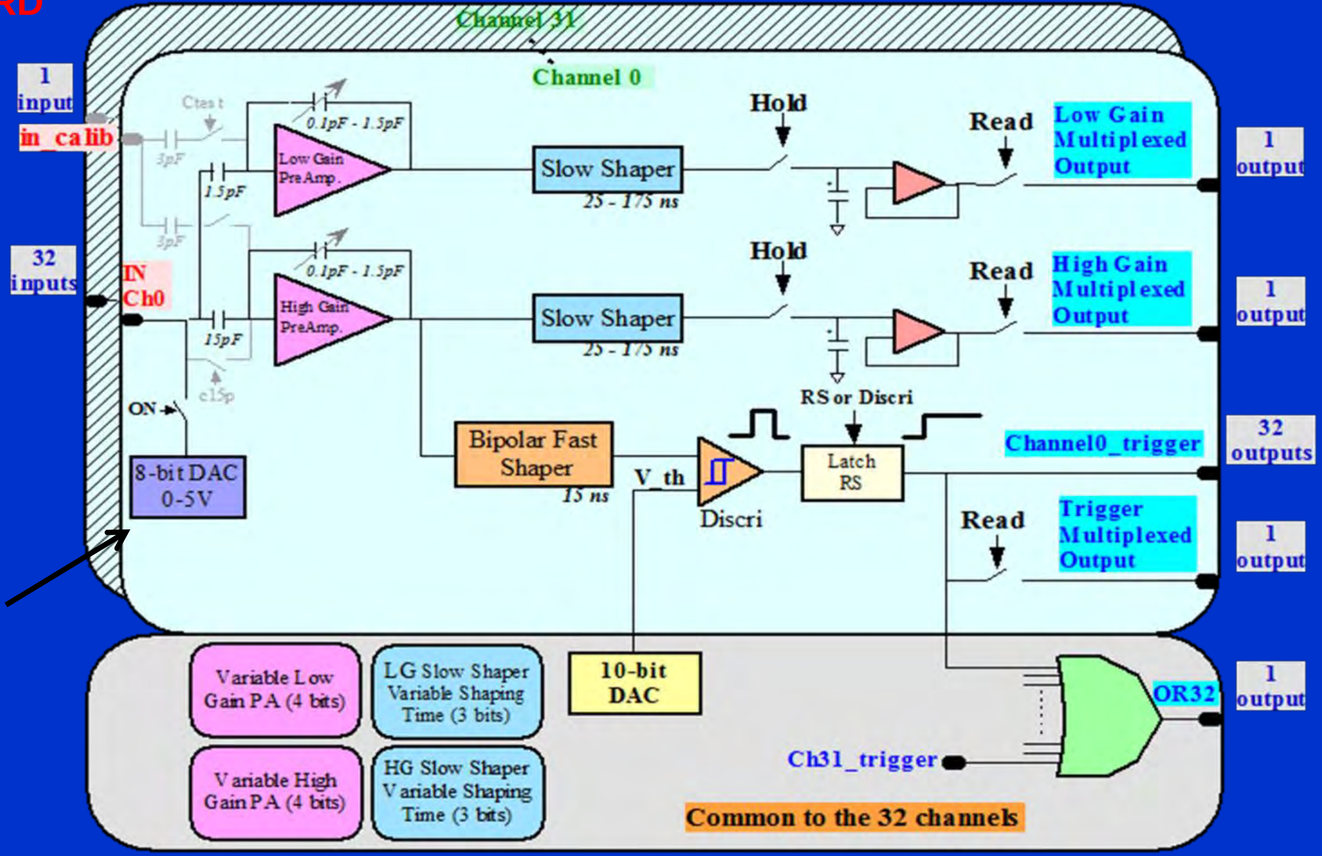
Camera Technological Solutions

FRONT END ELECTRONICS

EASIROC EVALUATION BOARD





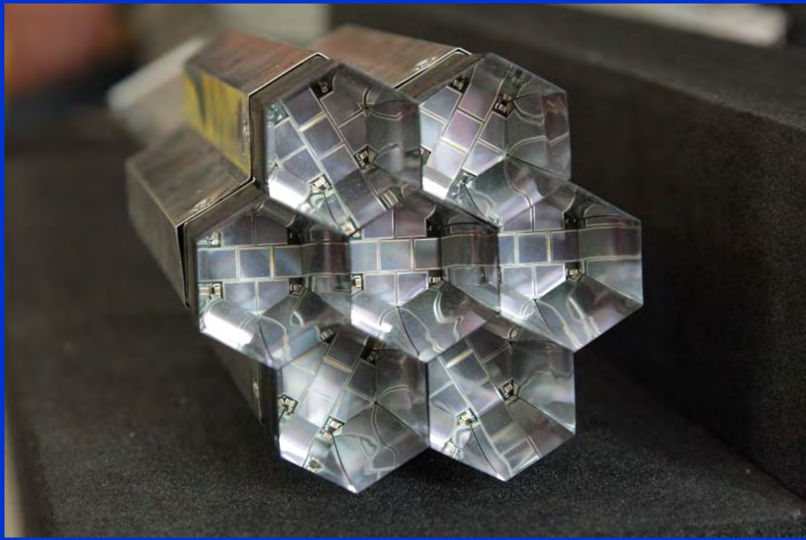


The input DACs allow to adjust HV (by slow control) on each single SiPM pixel

Large size SiPM ?

- Required fast timing limits the size of largest SiPM to several mm
- With increasing size of a SiPM cell its ***C*** ↑ and the gain ↑
  → also the X-talk is ↑ with size
- → good for “slow” applications, but need strong suppression of X-talk
- → R_{input} ***x C*** ↑
  → pulse becomes slow:

SiPM-based sensor cluster for MAGIC



Near future

- The PMTs as classical light sensors have made a big step forward, most parameters strongly improved in performance.
- The number and types of SiPM matrixes from different manufacturers is increasing, the parameters are steadily Improving
- Every 6-8 months some new, interesting integrated solutions and products are appearing
- Physicists would like to buy Si-based matrixes with complete readout.
- We could assemble arbitrary shape, large coordinate-sensitive imaging cameras like a lego