Light Sensing Detectors: Human Eyes, PMTs and SiPM

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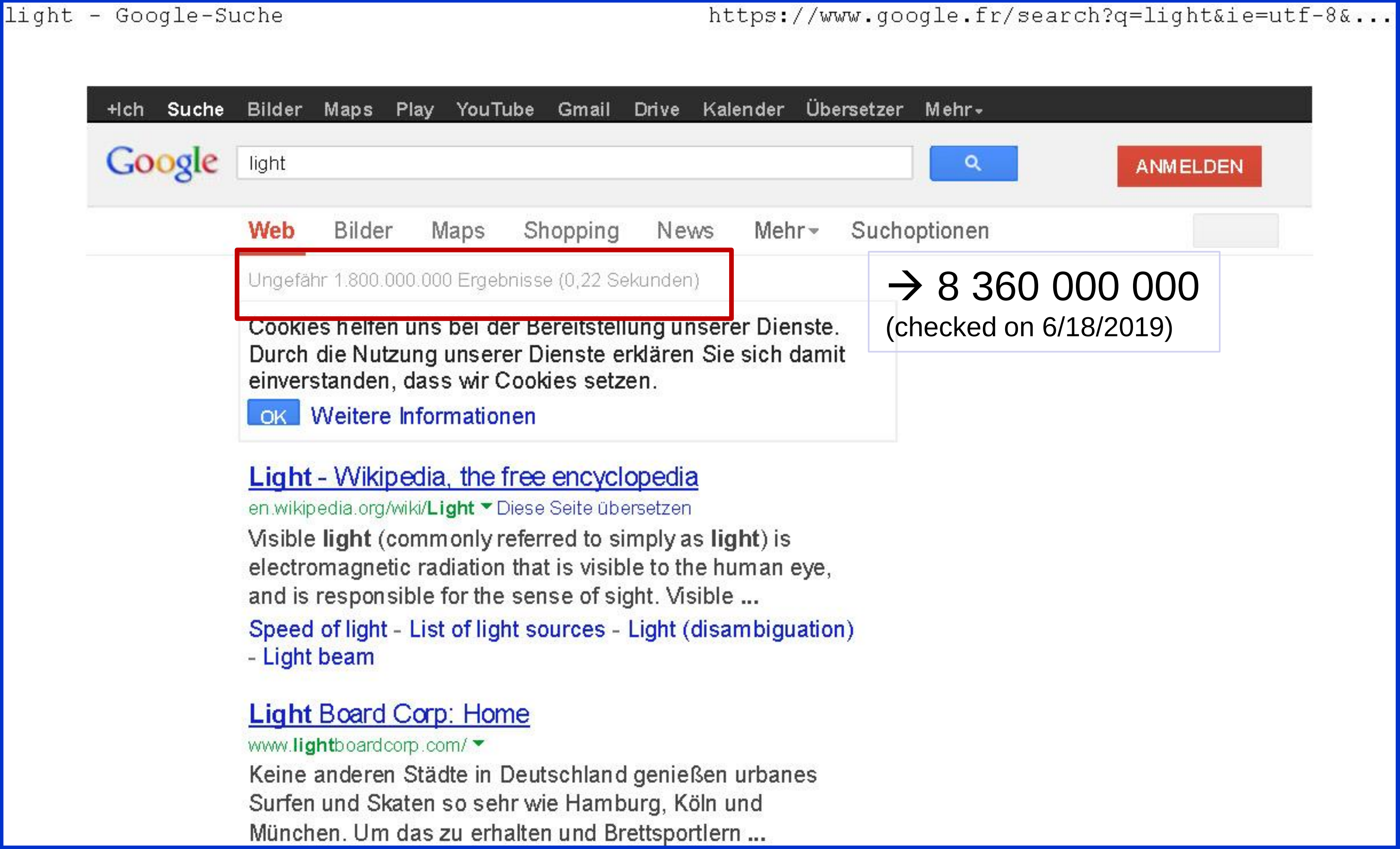
Light in web



→ 8 360 000 000
(checked on 6/18/2019)

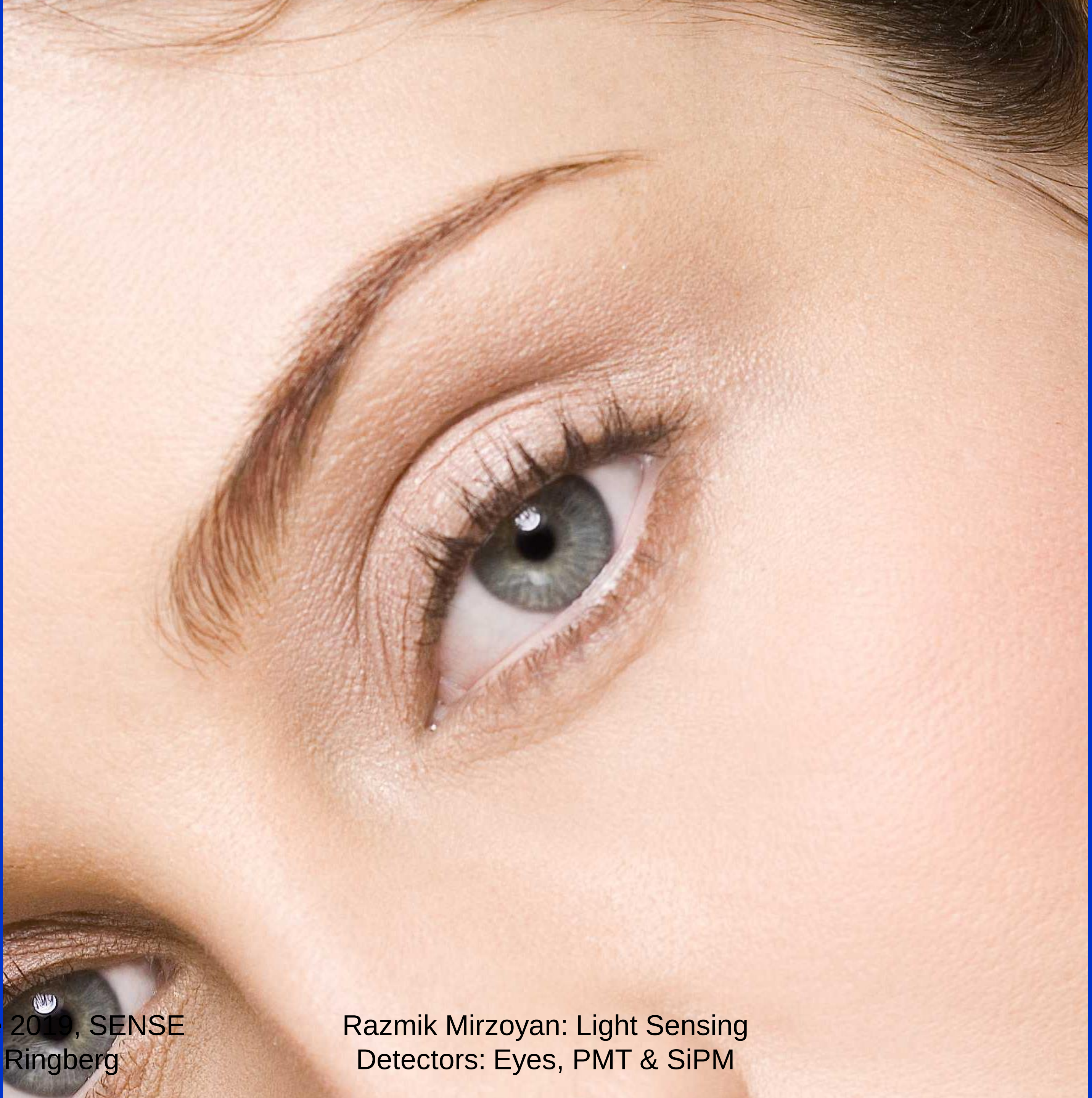
Origin of the word „Light“

- Middle English, from Old English *lēoht;* akin to Old High German *lioht* light, Latin *luc-, lux* light, *lucēre* to shine, Greek *leukos* white
- The word photography is based on the Greek *φῶς* (*photos*) "light" and *γραφή* (*graphé*) "representation by means of lines" or "drawing", together meaning "drawing with light".
- Light can be gentle, dangerous, dreamlike, bare, living, dead,
- misty, clear, hot, dark, violet, springlike, falling, straight,
- sensual, limited, poisonous, calm and soft

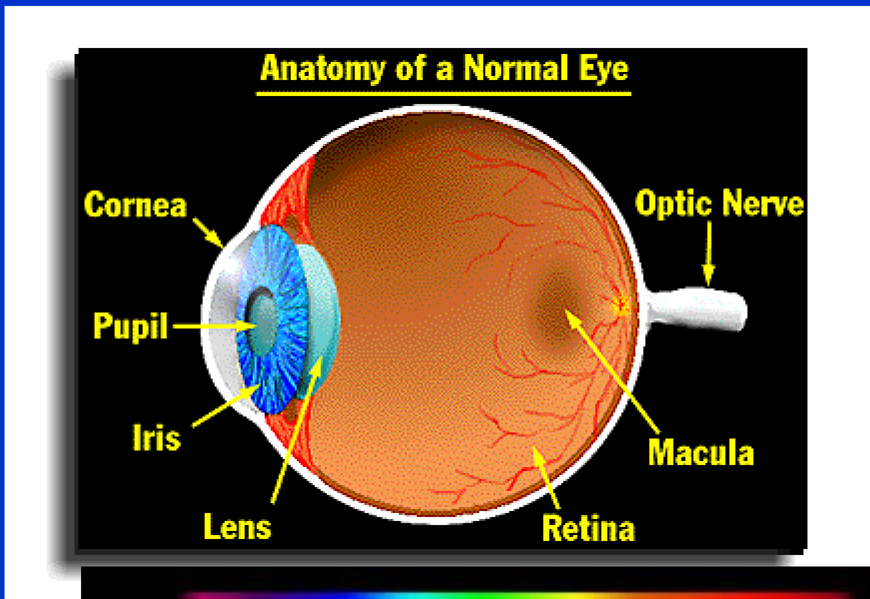
The most complex light sensors: eyes

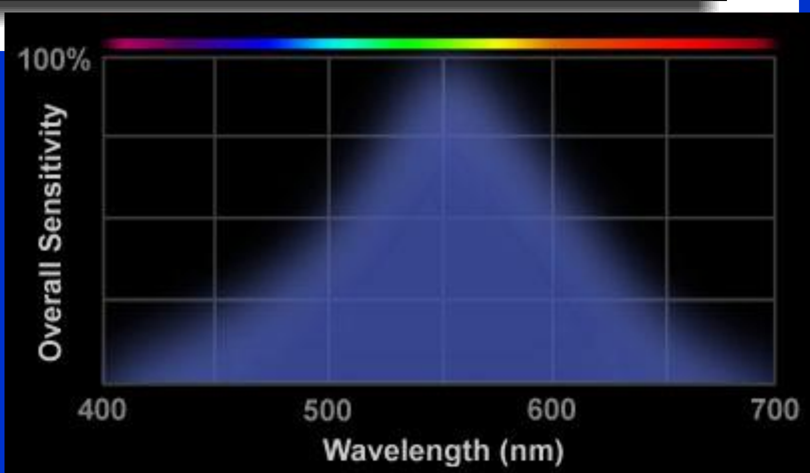
These seemingly best-known imaging light sensors measure colour in the a relatively wide band (400 – 700 nm) as well as the light intensity within a

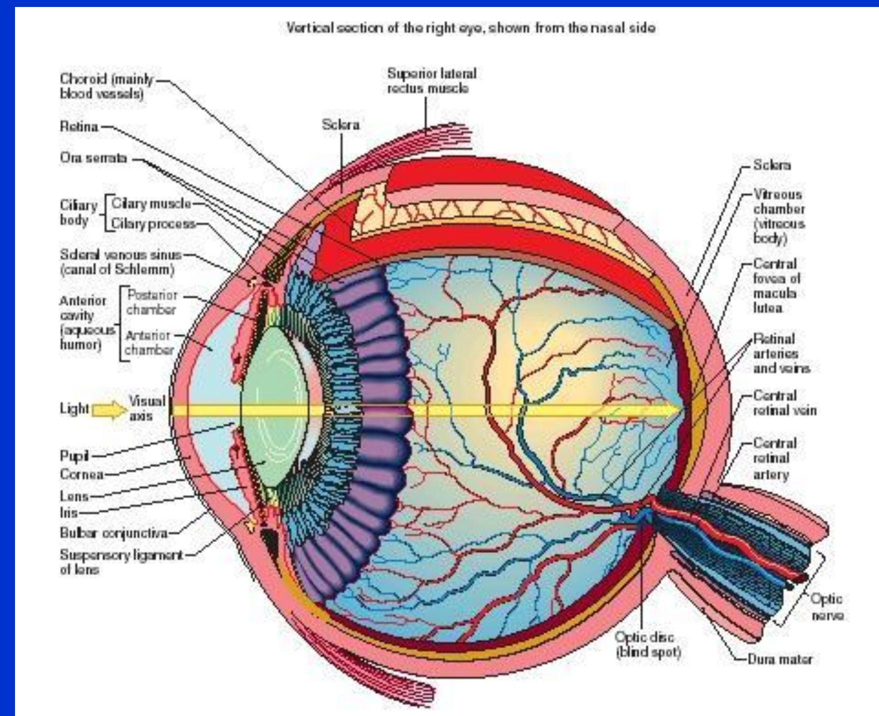
- dynamic range of 13 orders of magnitude !
- angular resolution ~ 1‘ (oculists call it 100 % sight)
- integration time $\geq$ 30 ms,
- threshold value for signals
  - 5-7 green photons (after few hours adaptation in the darkness)
  - 30 photons on average in the dark



Complex light sensors







The human way of developing light sensors

- Human eye cannot resolve in time processes that are faster than its light integration time: ~ 30ms
- Today with sensors we can easily measure processes with a time resolution $\leq 10^{-12}$ s (ps)
- We can measure images with a time resolution of ~250ps (gated image intensifiers)
- We cannot cover with a single sensor the dynamic range of a human eye of $\sim 10^{13}$ (logarithmic) but, for example, the linear dynamic range of a PIN diode couild be as high as $\sim 10^{8}$

What LLL sensor can we dream about ?

- **Die eierlegende Woll-Milch-Sau (german)**

  (approximate english translation: all-in-one device suitable for every purpose)

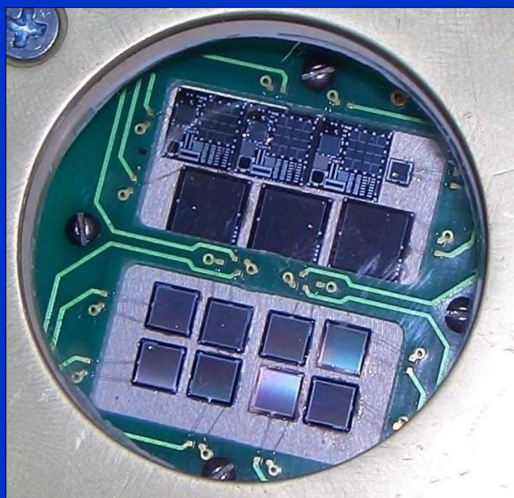
What LLL sensor can we dream about ?

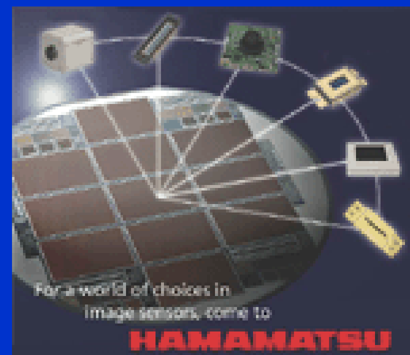
- Nearly 100 % QE and photon detection efficiency (PDE)
- Could be made in very large and in very small sizes
- Few ps fast (in air and in many materials the light speed is usually 20-30 cm/ns; in 5 ps it will make 1-1.5 mm)
- Signal amplification x10^6
- Noiseless amplification: F-factor - 1.001
- Few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

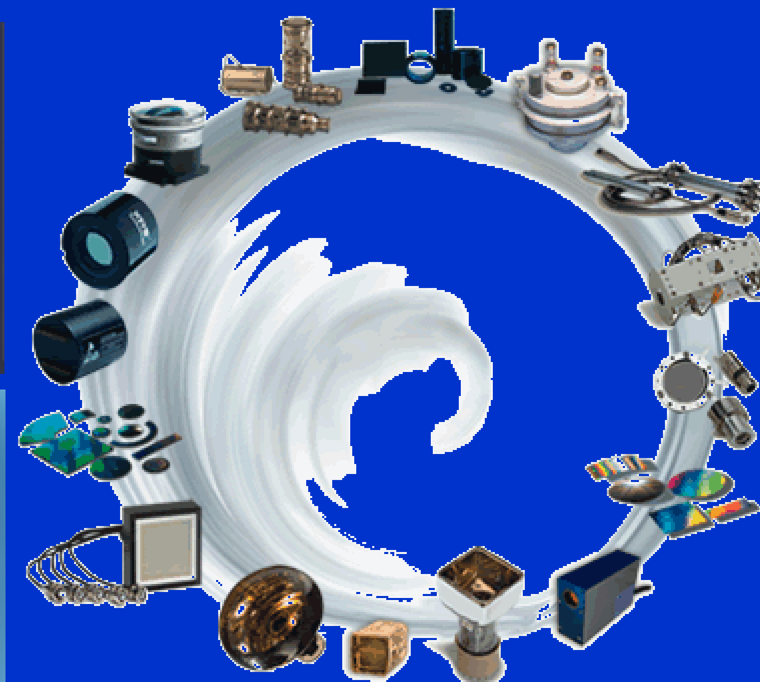
Light conversion into a measurable

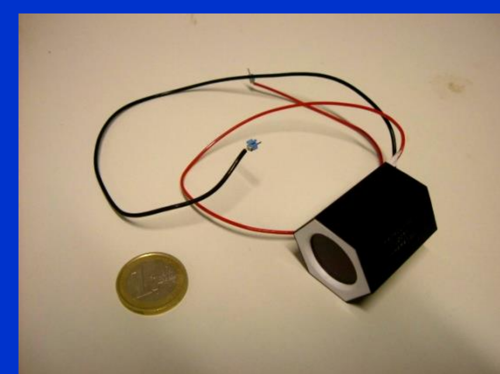
- Visible light can react and become measurable by:
  - Eye *(human: QE ~ 3 % &* animal), plants, paints,…
  - Photoemulsion *(QE ~ 0.1 – 1 %)* (photo-chemical)
  - Photodiodes (photoelectrical, evacuated)
    - Classical & hybrid photomultipliers *(QE ~ 25 %)*
    - *QE ~ 55 % (HPD with GaAsP photocathode)*
  - Photodiodes *(QE ~ 70 – 80 %)* (photoelectrical)
    - PIN diodes, Avalanche diodes, SiPM,…
    - photodiode arrays like CCD, CMOS cameras,…

The „zoo“ of LLL sensors



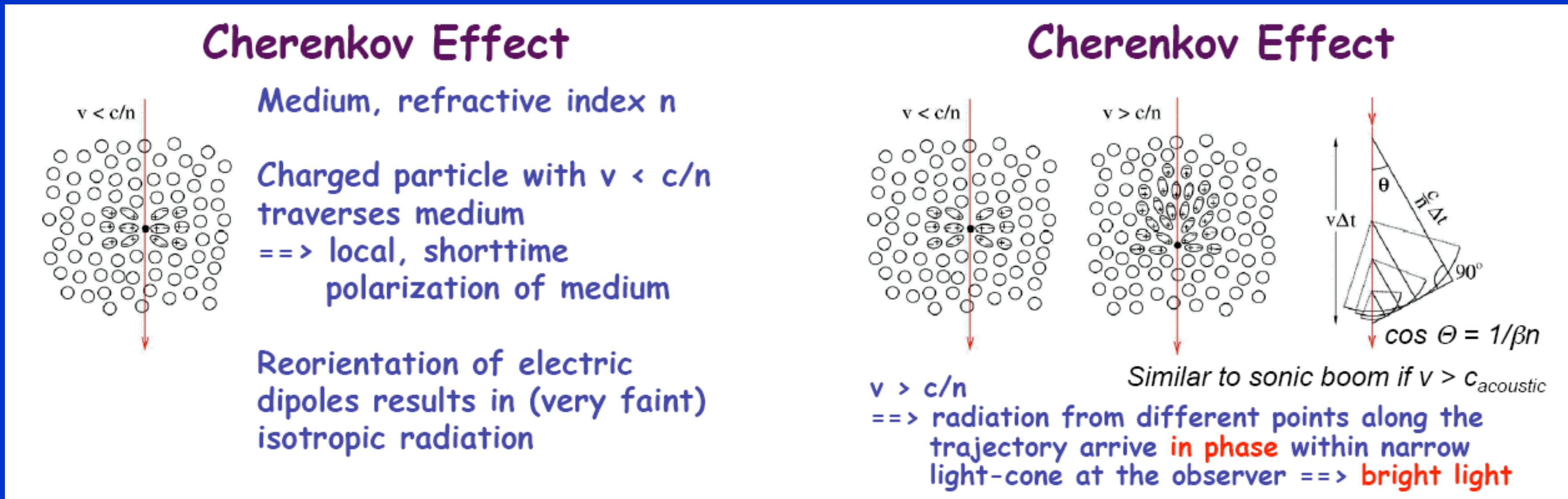




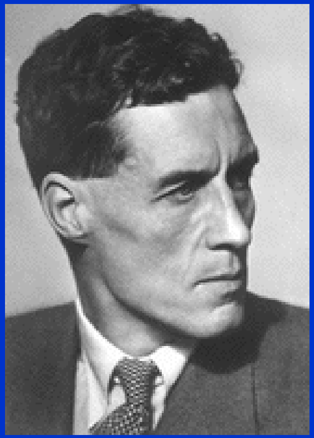


Light in Astro-Physics

- Air-Cherenkov experiments in Astro-physics use Cherenkov light emission in atmosphere
- Milagro, HAWC were/are using Cherenkov emission in water
- Neutrino experiments use Cherenkov light emission in ice (BAIKAL, AMANDA, IceCube), in water (Antares, NESTOR, Kamiokande,…)
- Air fluorescence detectors use fluorescent light emission in atmosphere (High-Res Fly's Eye, AUGER)
- Many experiments, also in high energy physics, use light emission in scintillating solid materials and liquids



- Pavel Cherenkov had to spend >1-1,5 hours in a dark, cold cellar, for accomodating his eyes to darkness for seeng the very faint bluish emission from solvents containing radioactive salts
- 1934-1938 conducted a series of brilliant expeirments.
- Obtained Nobel Prize in 1956 for the discovery



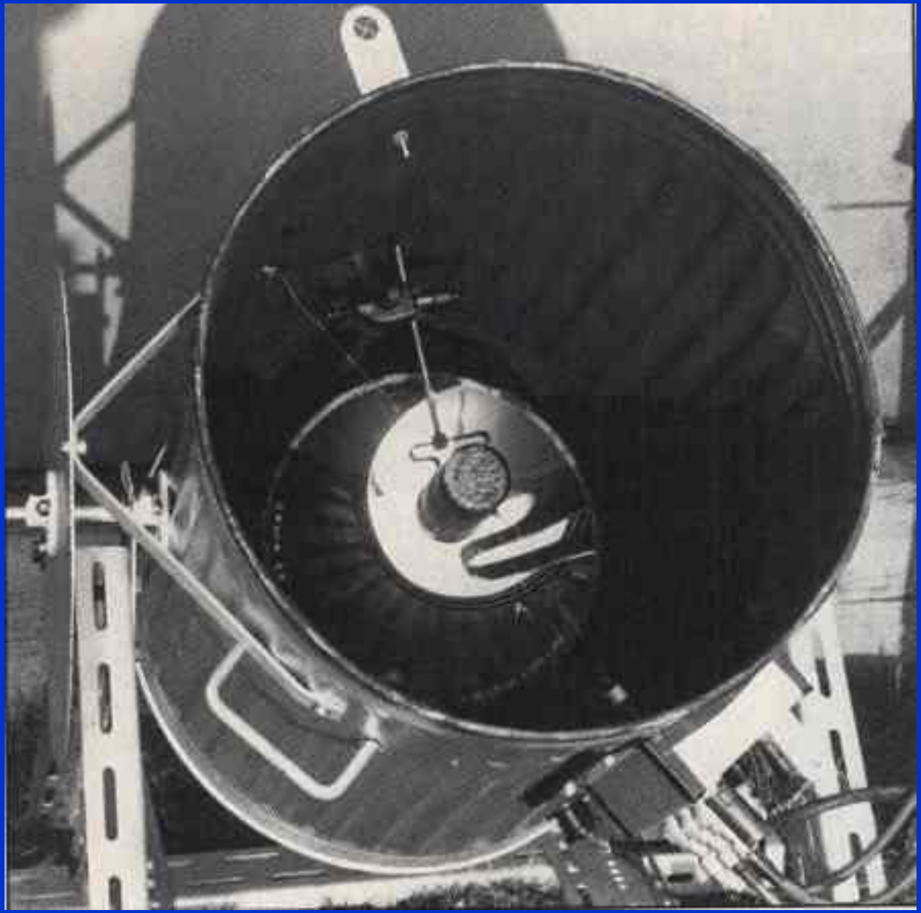
The Very Beginning of Atmospheric Air Cherenkov Telescope Technique

1948

- Patrick Blackett (Nobel prize laureate of 1948: study of cosmic rays using counter-controlled cloud chamber) was the first to mention that there shall be Cherenkov light component from relativistic particles in air showers (mostly e-, e+, μ-, μ+) marginally contributing (~ 10^{-4}) to the intensity of the light of night sky (LoNS)

- Until that the Cherenkov light has been detected only in solids and liquids

The Experimental Beginning

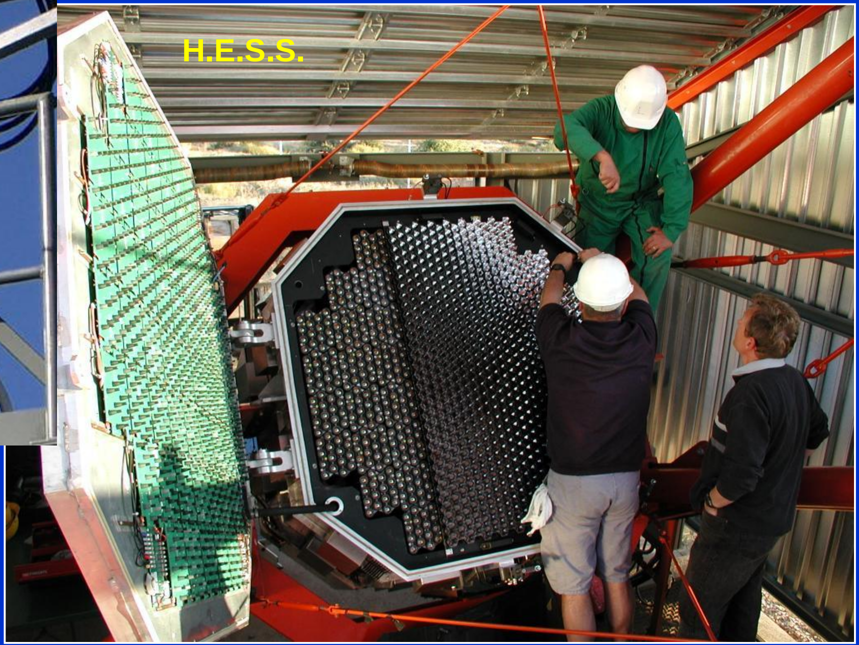


1953

By using a garbage can, a 60 cm diameter mirror in it and a PMT in its focus Galbraith and Jelly had discovered the Cherenkov light pulses from the extensive air showers.

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

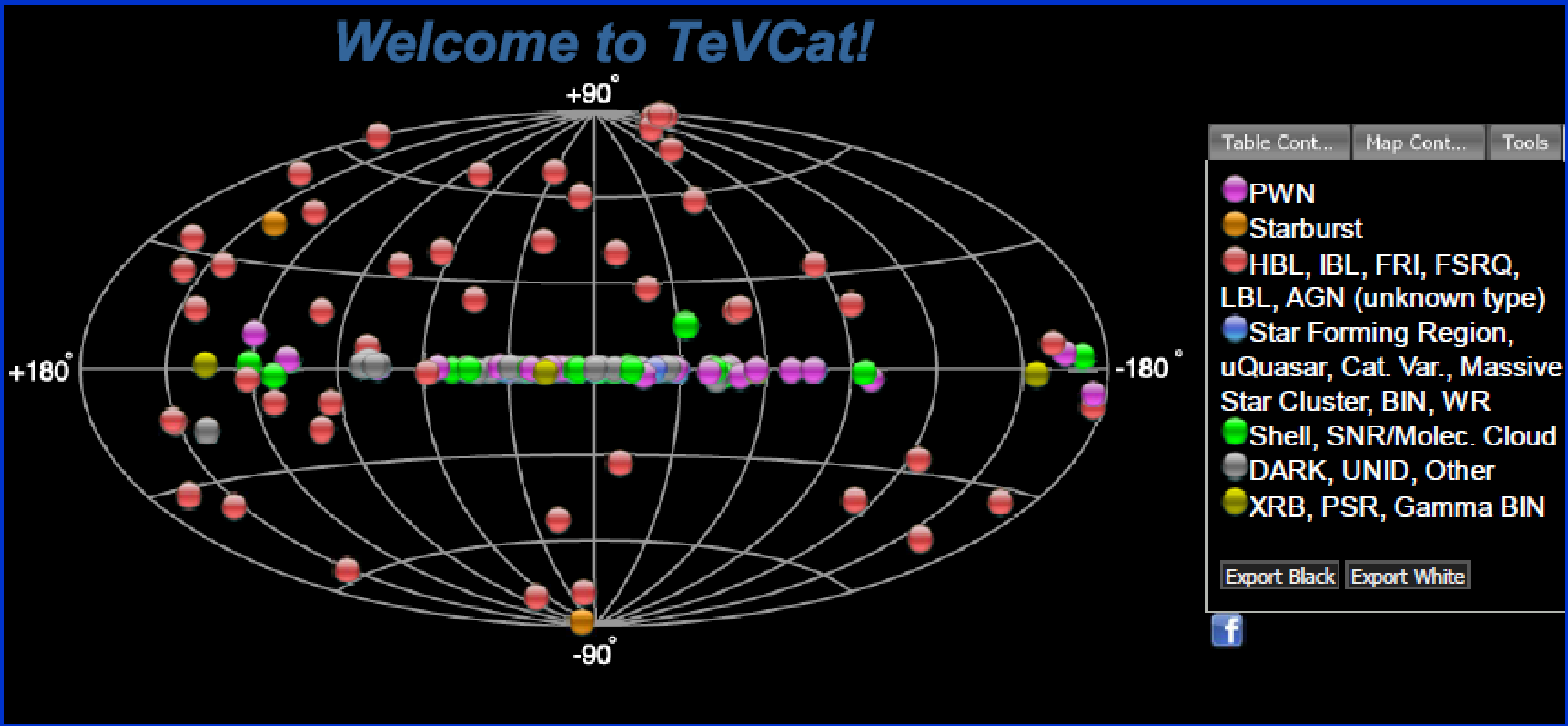
Photograph of the 1039-pixel imaging camera of MAGIC-I. Pixels are based on superbialkali PMTs each covering 0.10° in the sky.



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

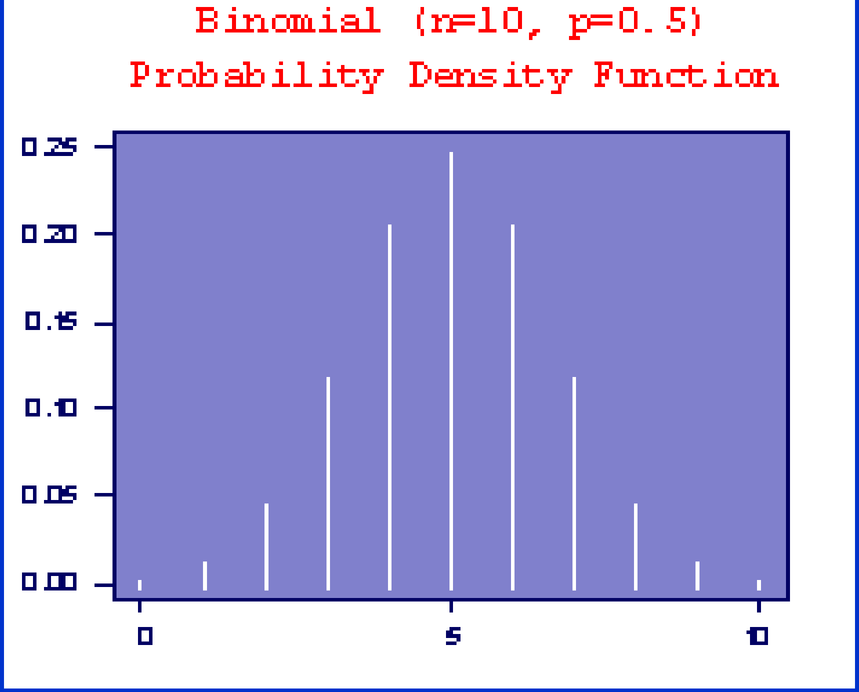
Quantum efficiency (QE) of a sensor is defined as the ratio

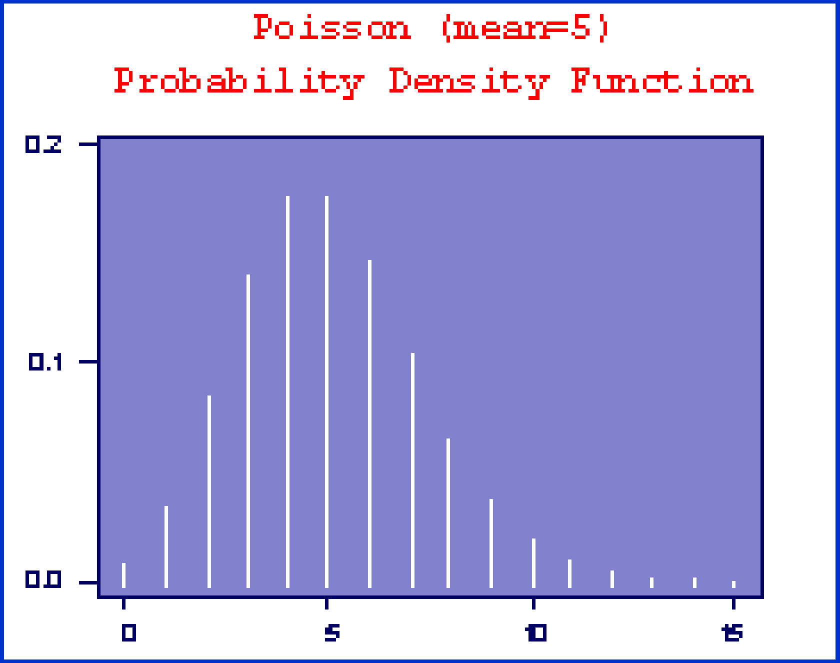
$$QE = N(\text{ph.e.}) \,/\, N(\text{photons})$$

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 =

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

Signal to noise ratio

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

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

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

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

For N = 20 impinging photons:

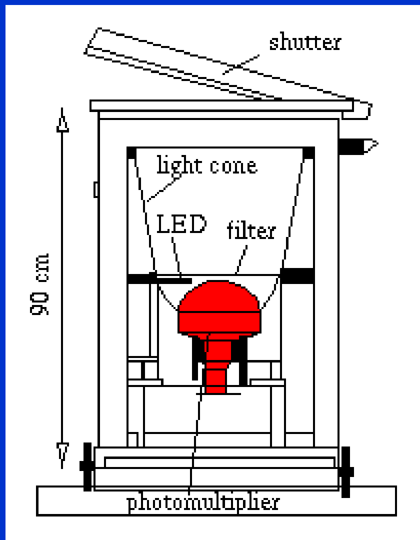
P	0.1	0.3	0.9
SNR	1.5	2.9	13.4

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

HEGRA Detector, operating 1989 - 2002

AIROBICC 8-inch Electron Tubes KB 9352



Development initiated by Eckart Lorenz for the AIROBICC detector of HEGRA

- 8-inch PMTs from Electron Tubes, England
- 6-dynodes, slow ageing
- hemispherical shape
- very fast response, 3-4ns FWHM

PMTs for MAGIC from Electron Tubes Enterprises and from Hamamatsu

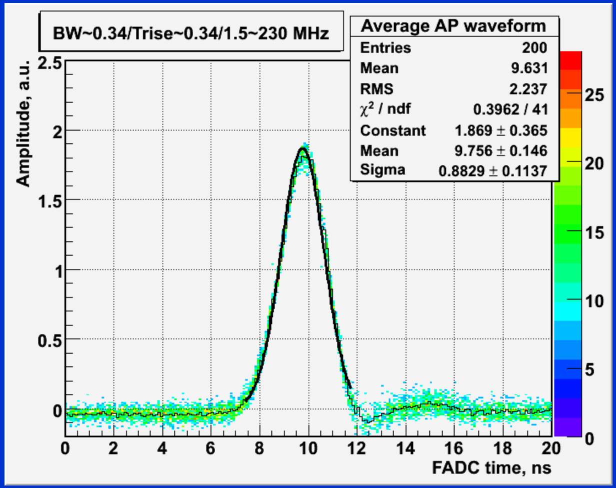
Hamamatsu R10408-01
ET 9116 A: 1.0   inch
ET 9117 A: 1.5 inch

- 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

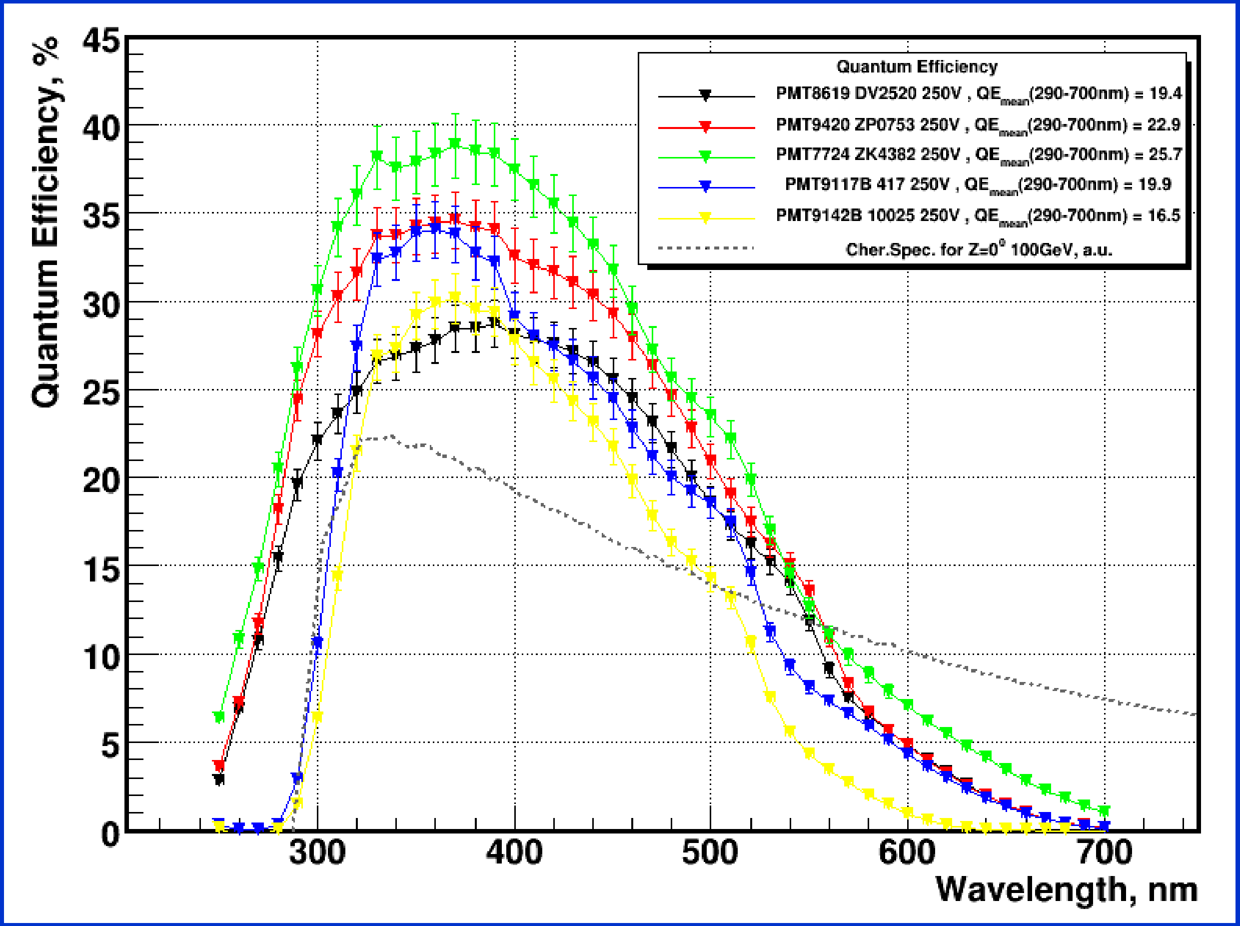
Main advantages offered by 1-inch hemispherical MAGIC-type PMTs:

- 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



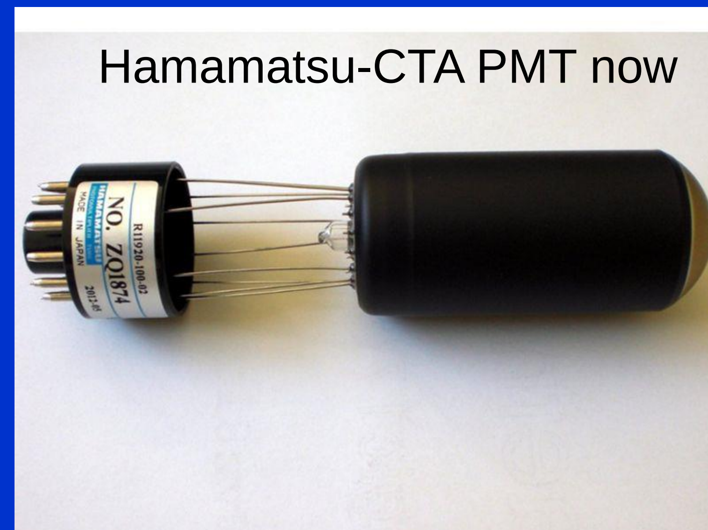
Instrumental/technological improvements

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



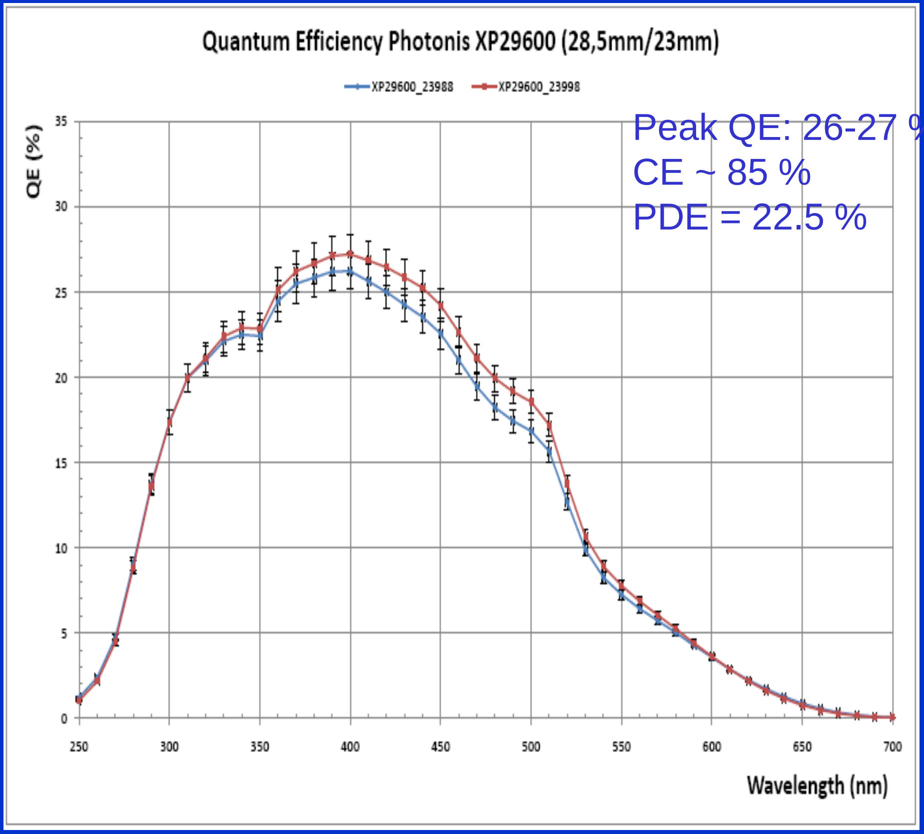
- Some 9 years ago we have launched a QE improvement program with manufacturers Hamamatsu (Japan), Photonis (France) and Electron Tubes Enterprises (England).
- The results were very encouraging
- Since about 4 years we launched a new improvement program for CTA PMTs

Development of PMTs for CTA



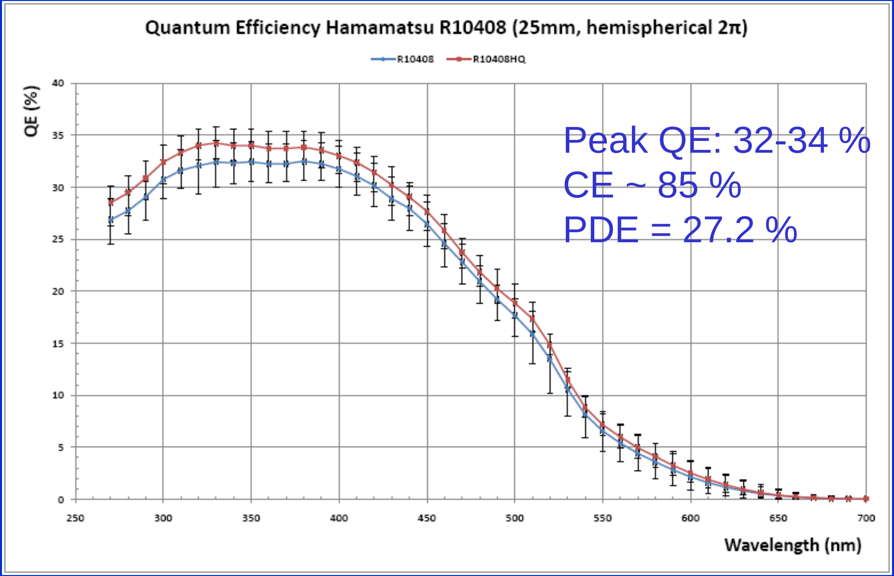
Electron Tubes Enterprises
CTA PMT now

Some background information



- 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



- 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%

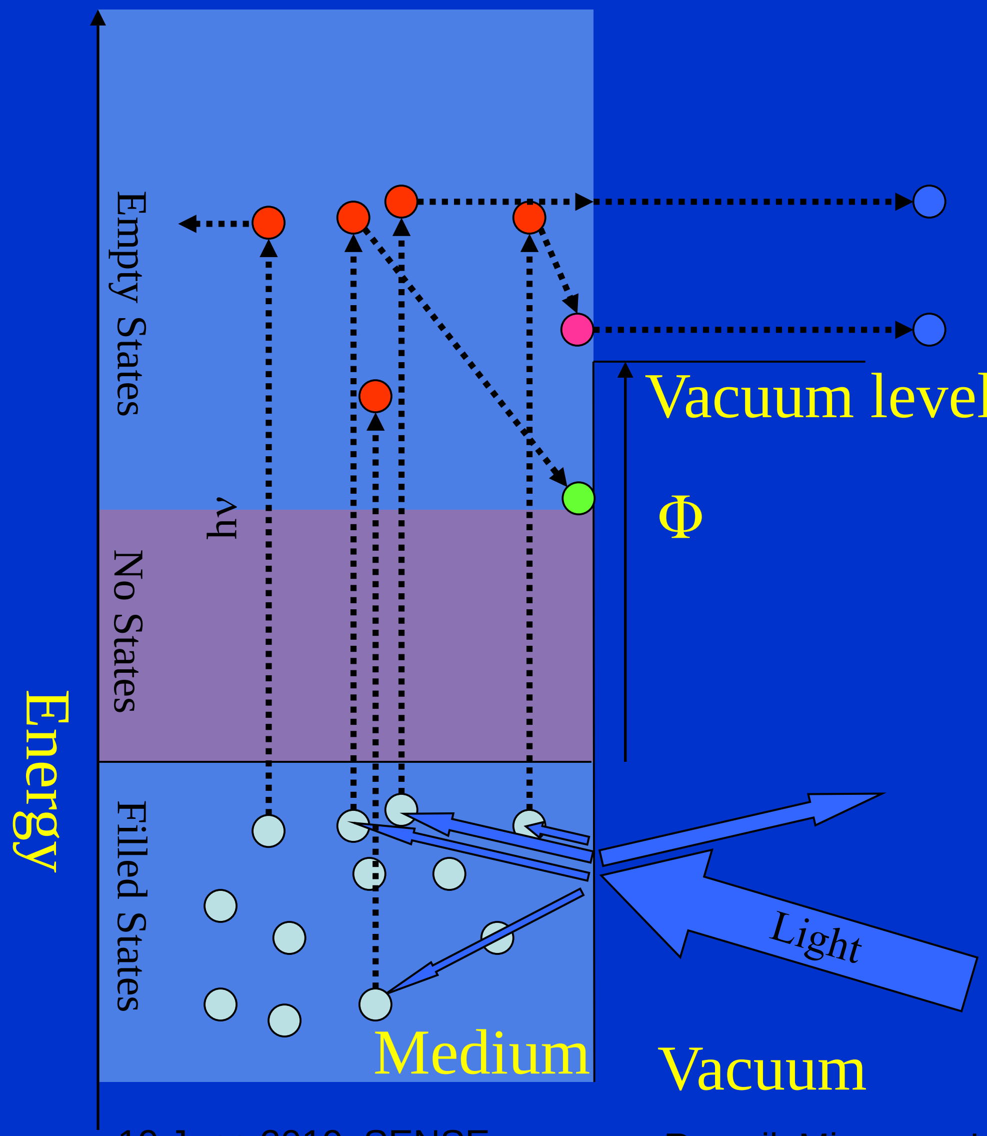
Later on these PMTs have got the name "<u>Superbialkali</u>"

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

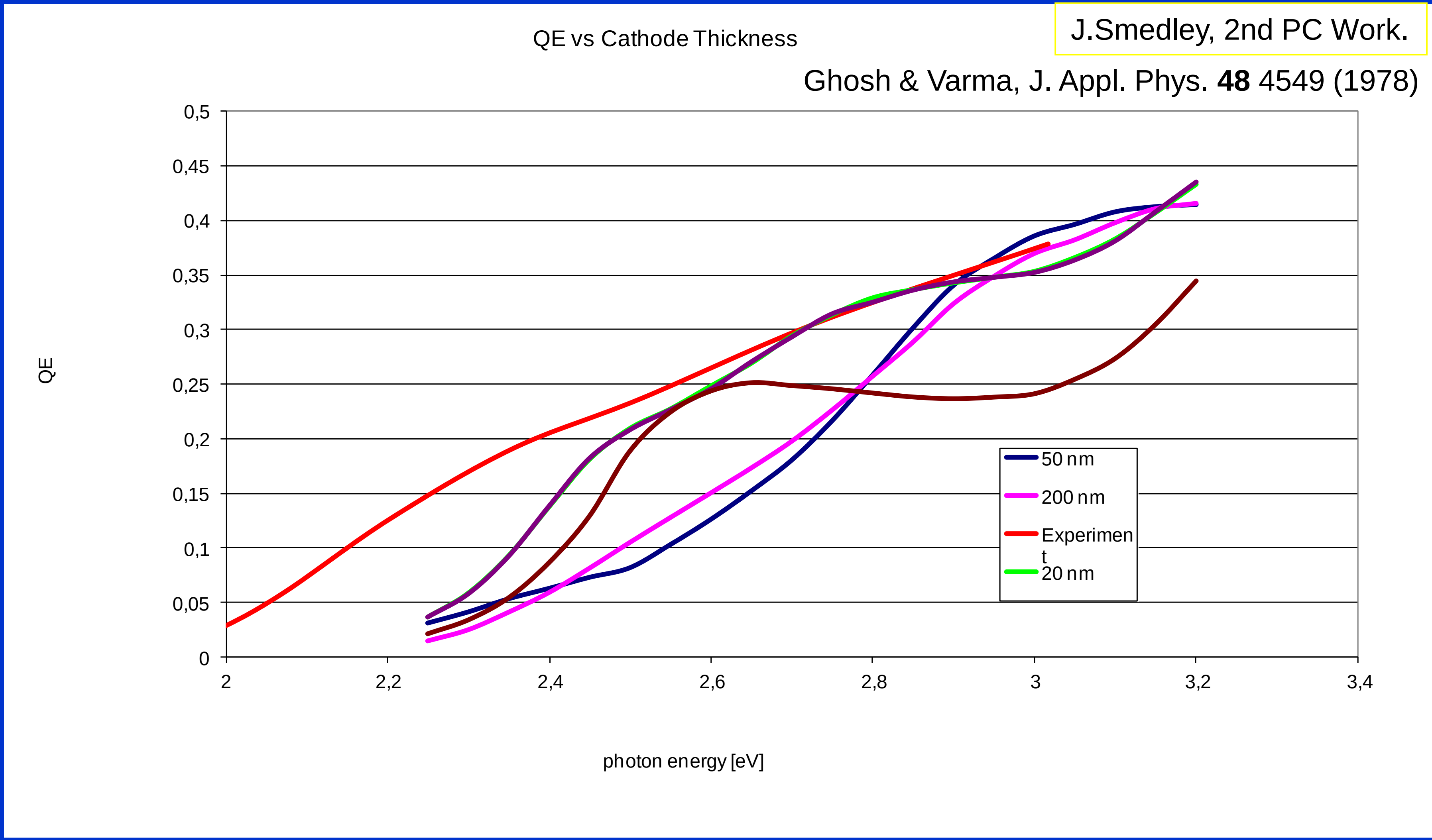
J.Smedley, 2nd PC Work.



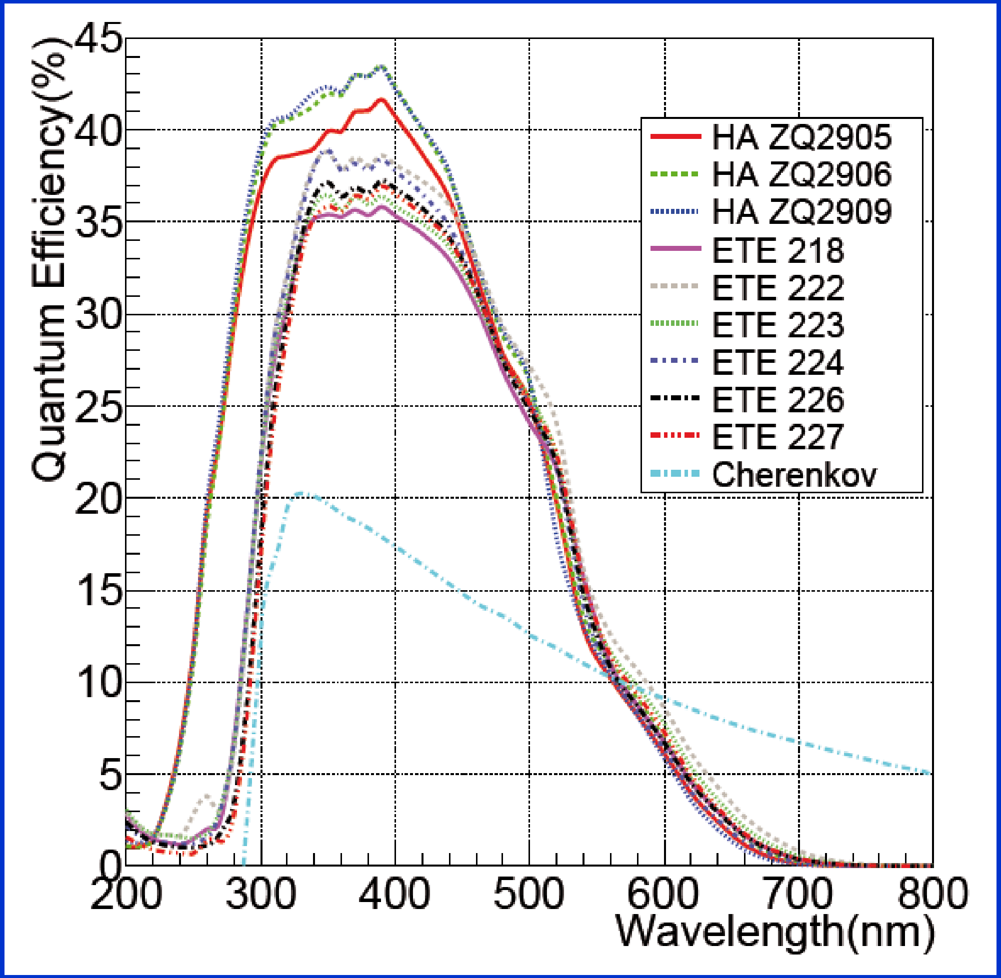
1) Excitation of e$^-$
   - Reflection, Transmission, Interference
   - Energy distribution of excited e$^-$
2) Transit to the Surface
   - e$^-$-phonon scattering
   - e$^-$-defect scattering
   - e$^-$-e$^-$ scattering
   - Random Walk
3) Escape surface
   - Overcome Workfunction
   - Multiple tries

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

Monte Carlo for K_2CsSb



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 %

HAMAMATSU
PHOTONICS OUR BUSINESS

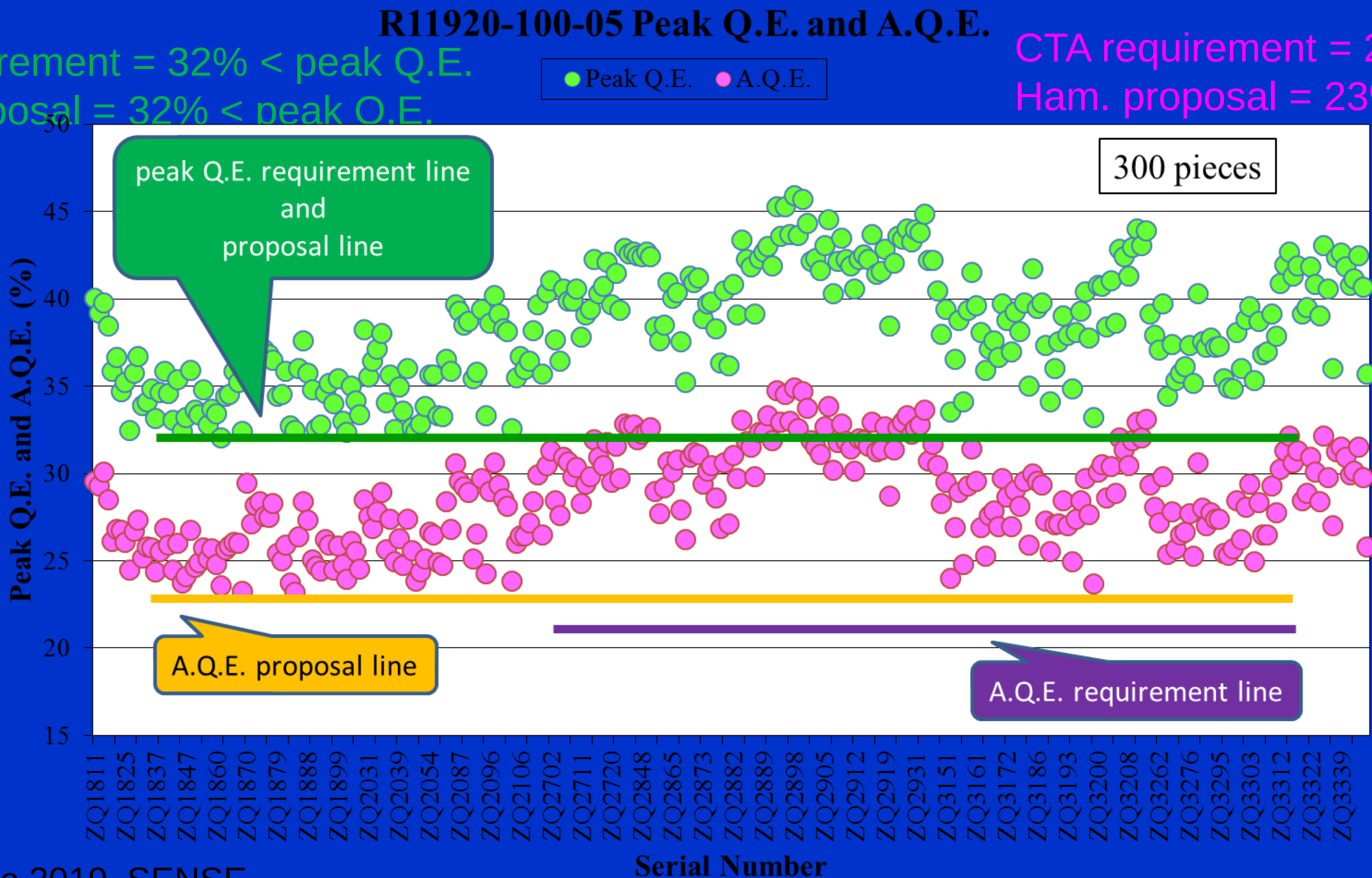
(See how the company met our request of a minimum 32% peak QE)

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.

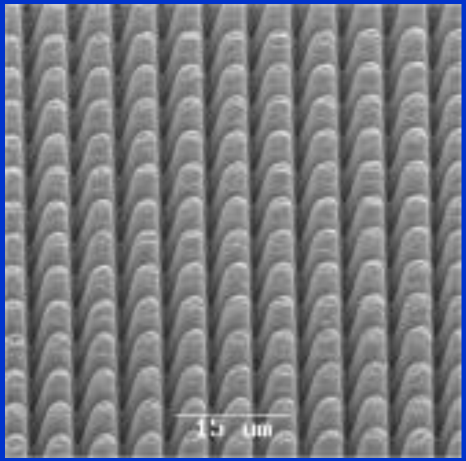


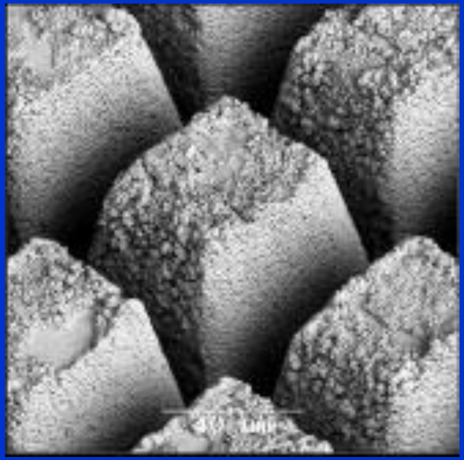
Reflectivity and QE

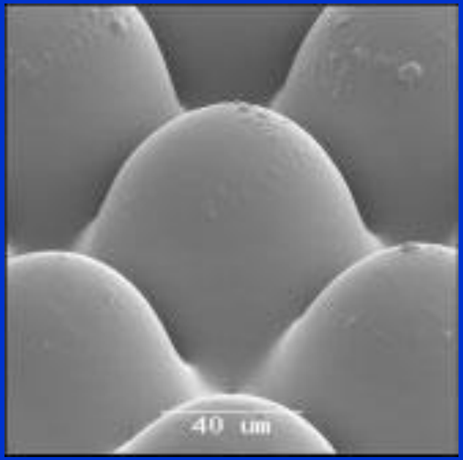
J.Smedley, 2nd PC Work.

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

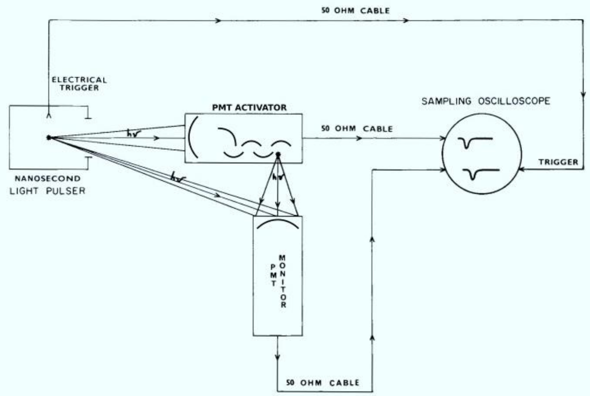
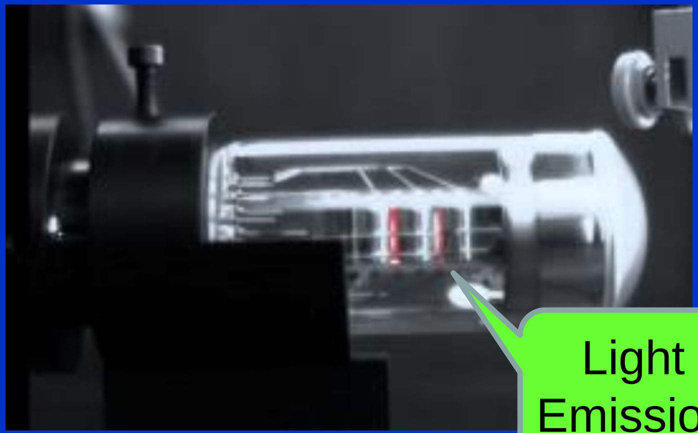


Figure 2.2: The photomultiplier dynode glow test apparatus, sketch adapted from [10]



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

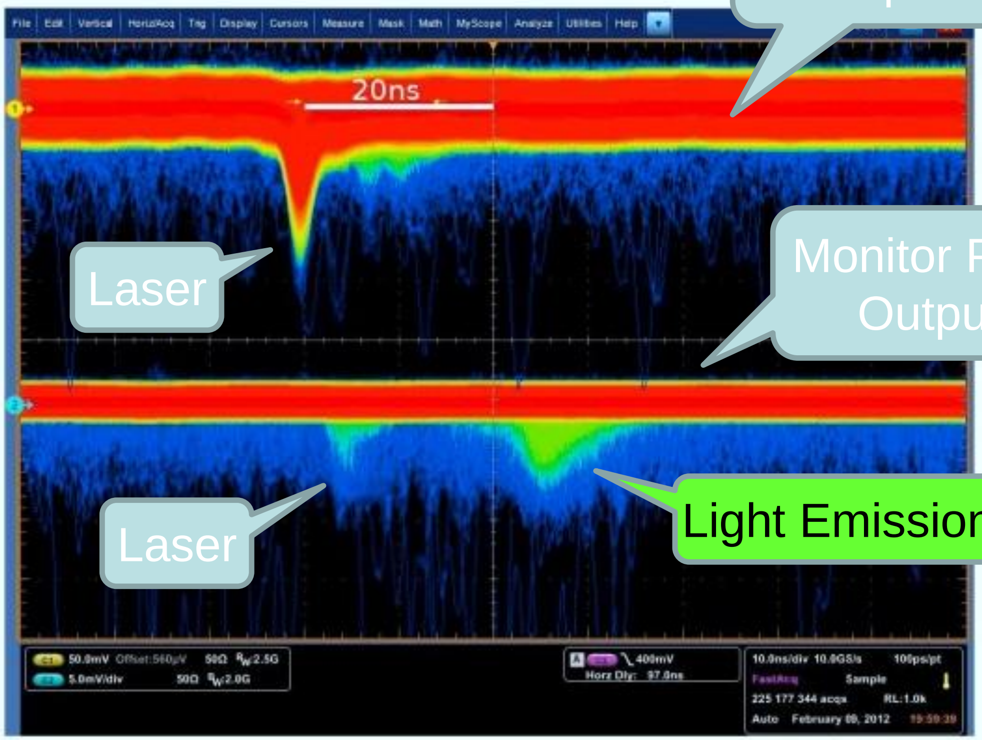
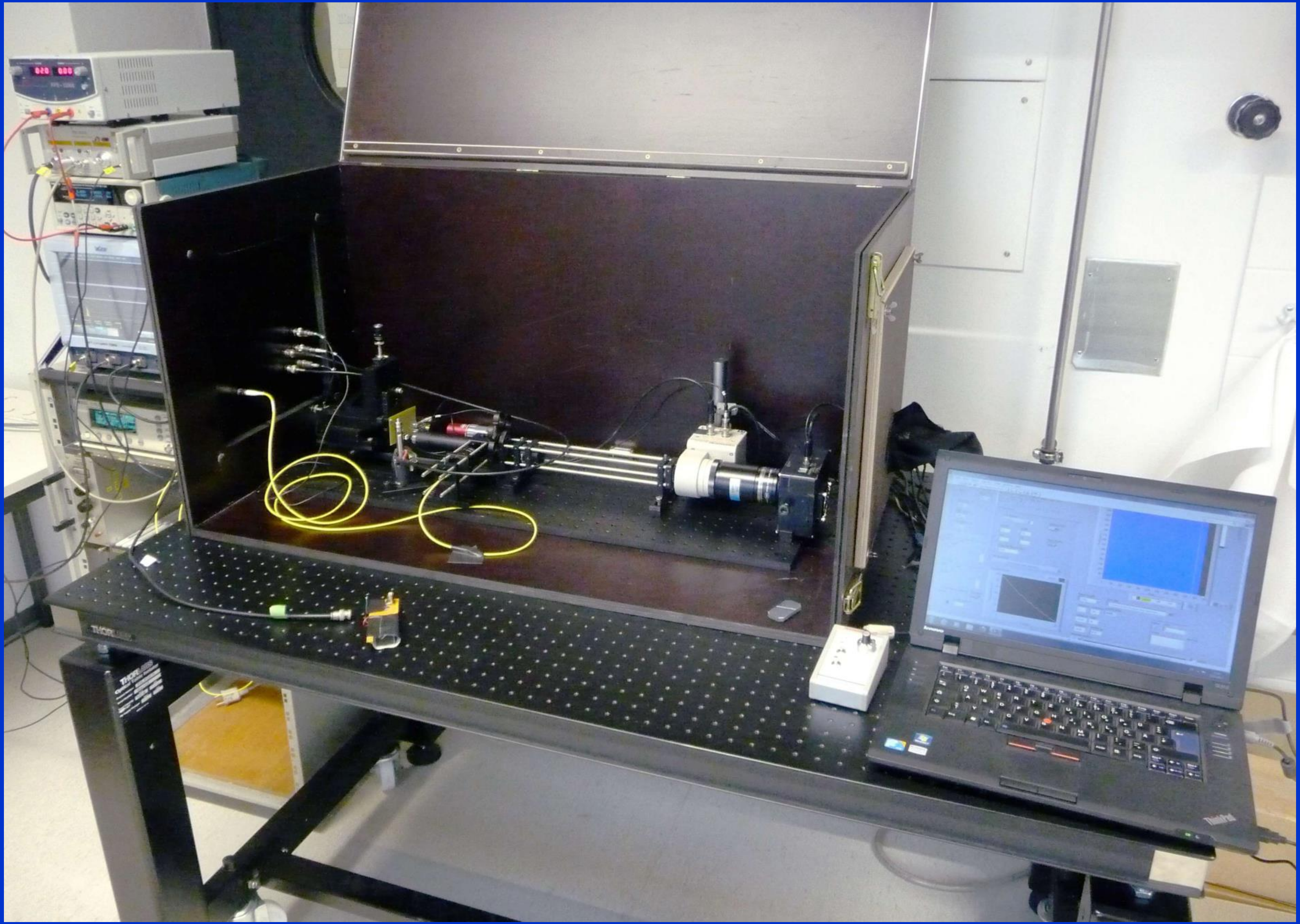
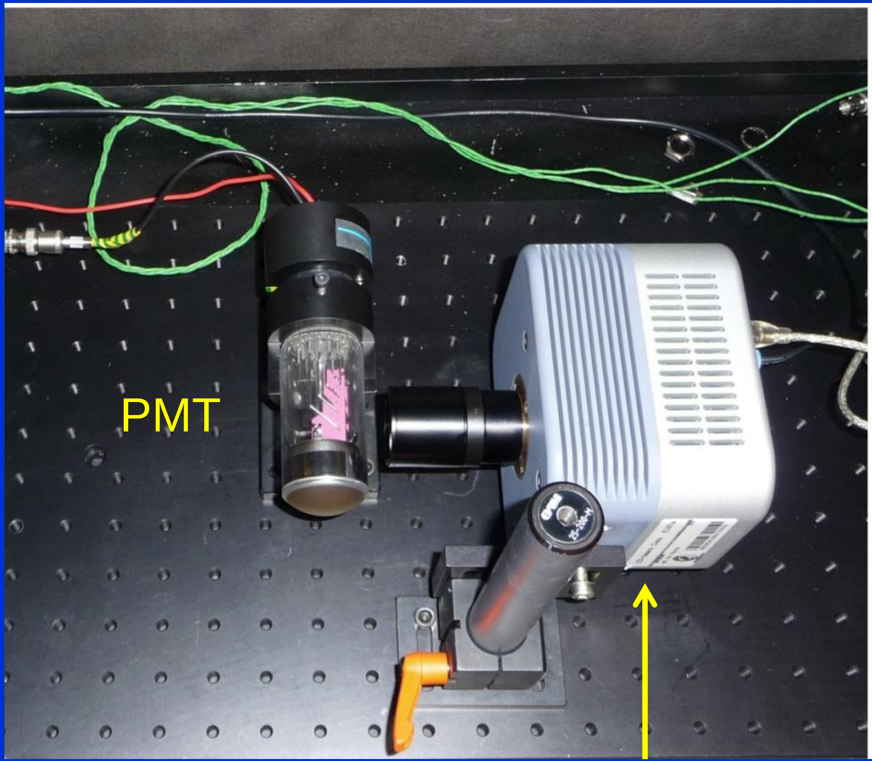


Figure 2.3: Measurement of the activator photomultiplier (top) and the monitor photomultiplier (bottom).

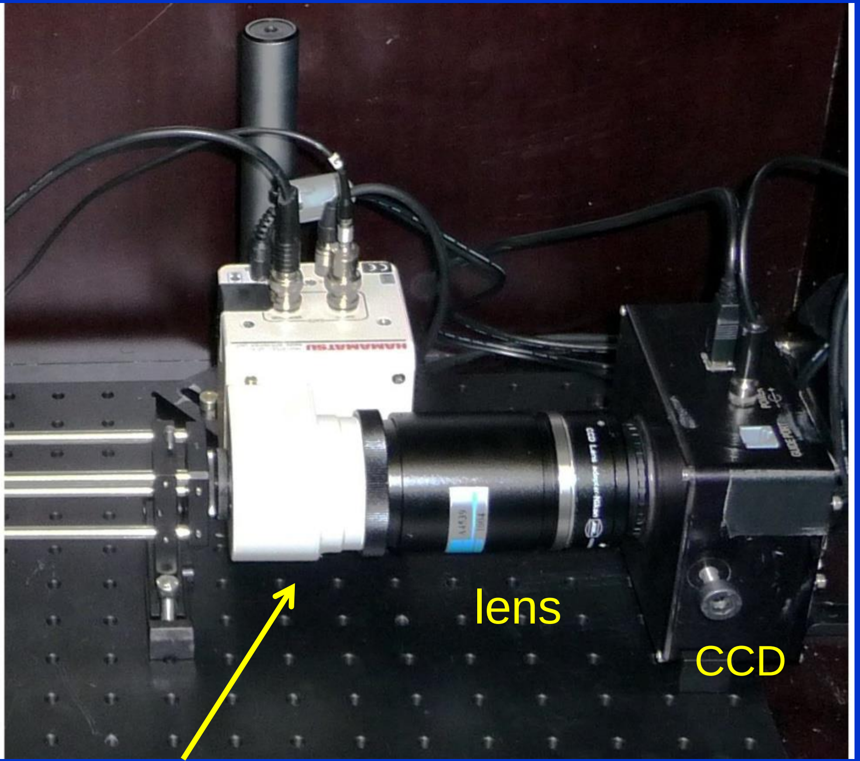
Light Emission Microscopy Setup



Light Emission Microscopy Setup

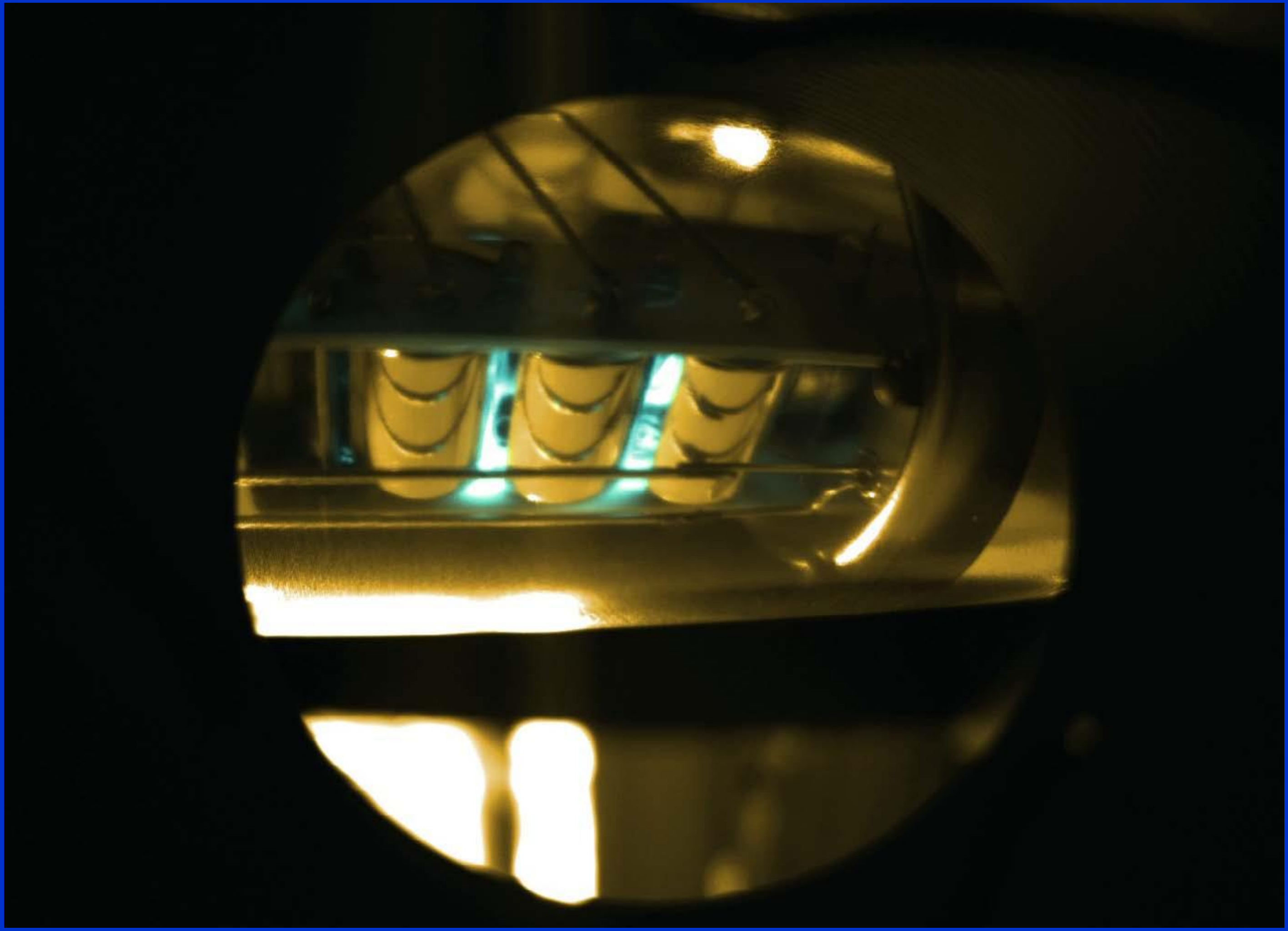


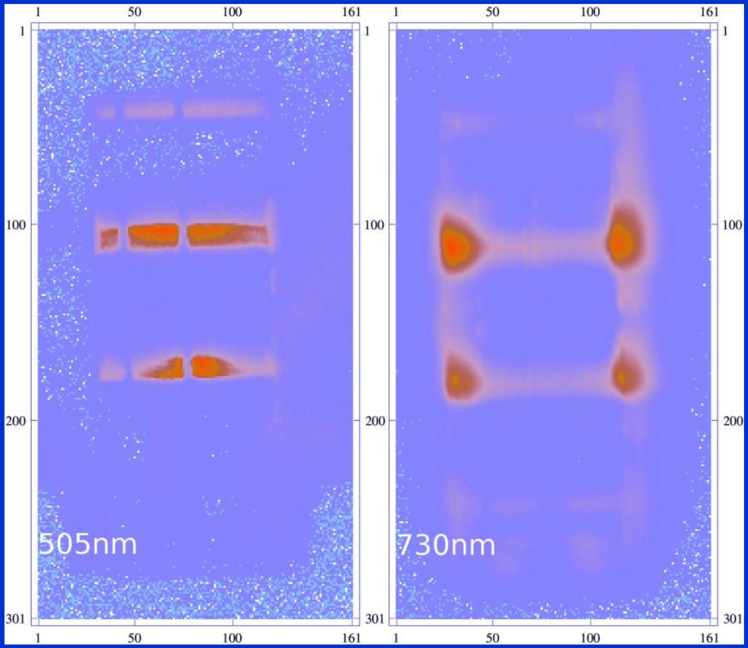
CLARA: Very sensitive CCD camera



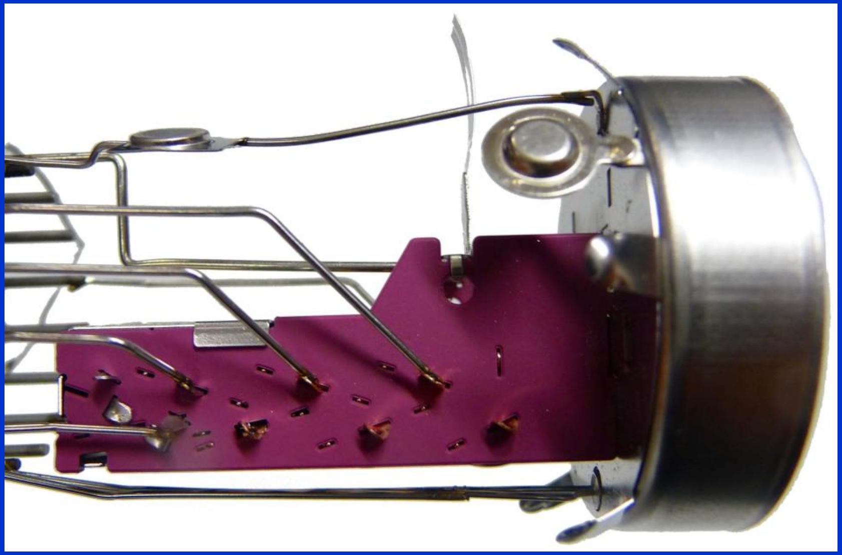
Gated (≥ 3ns) image intensifier
Coupled via a relay lense to a
CCD camera

Light emission leaking through the PMT dynodes can be see

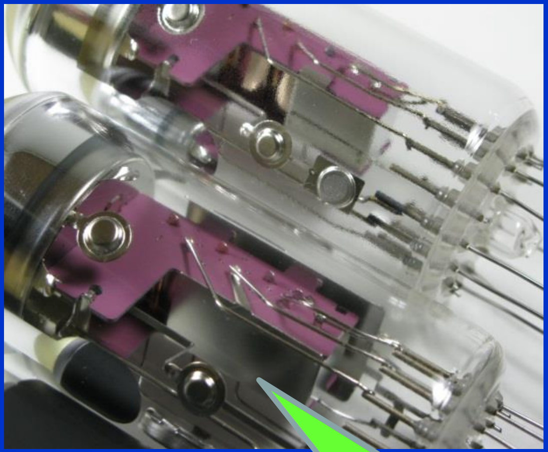




Not only the dynodes of a PMT, Bombarded by e-, are glowing, but also ist holding structure. The material of the isolating holding structure could be largely identified as corundum chromium (ruby)

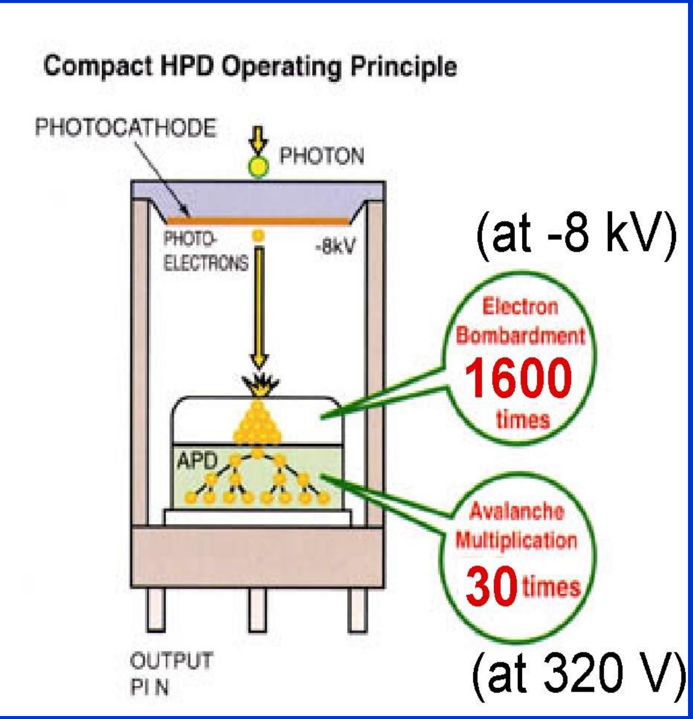


After Pulsing for threshold 4 p.e. (Light Emission)
HAMAMATSU measurement result



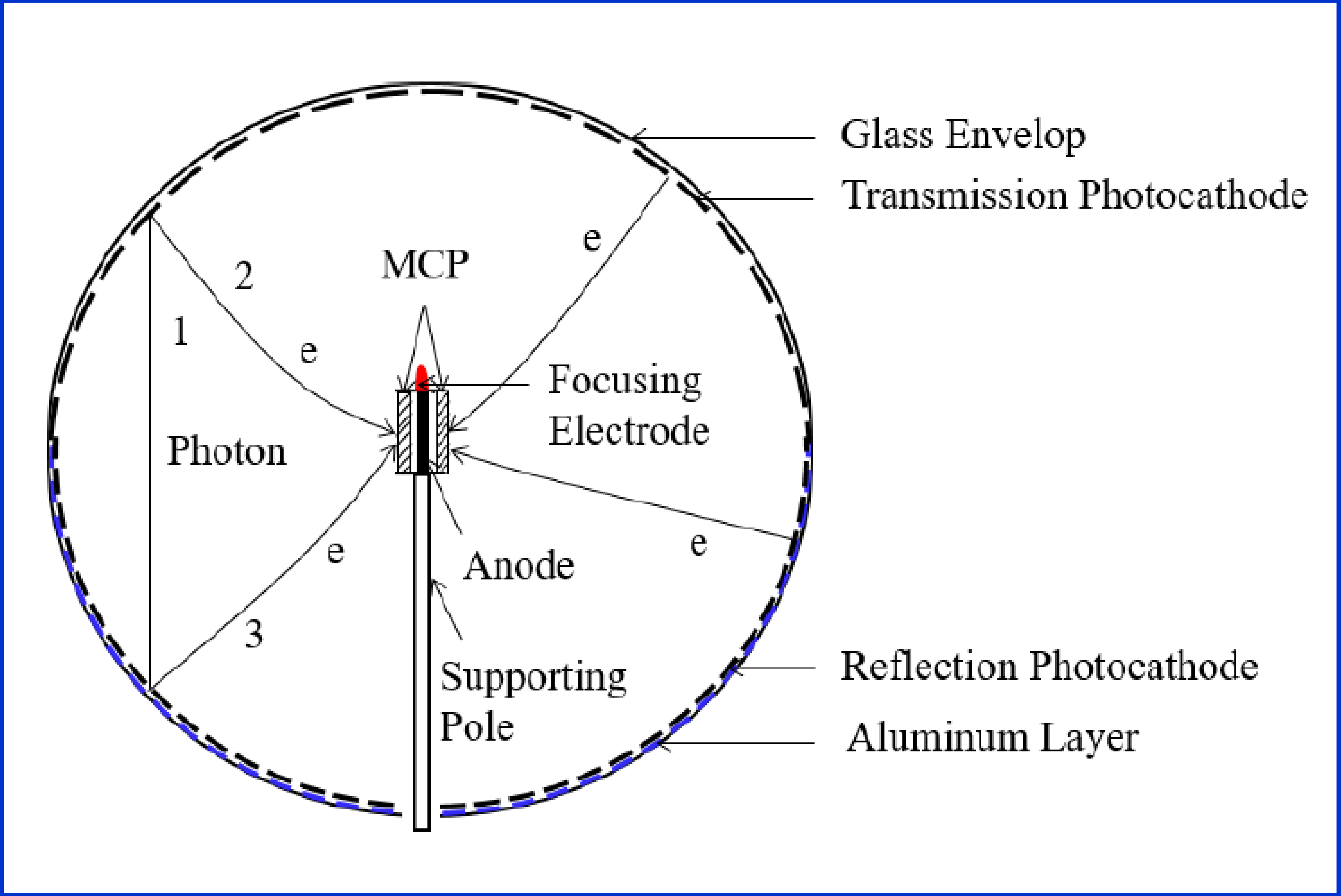
HPD Structure

- 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)

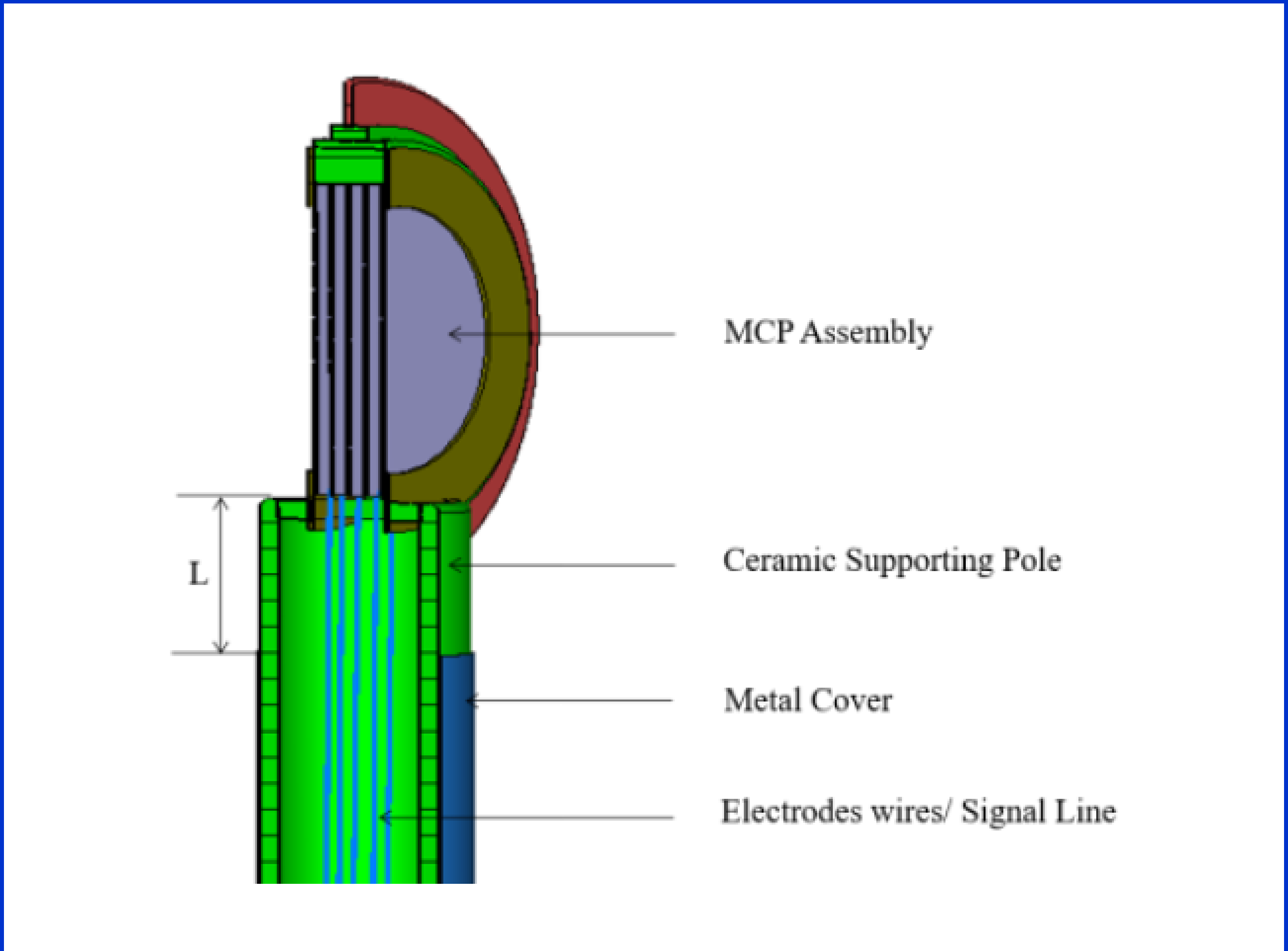


Much better pulse height resolution than PMT.

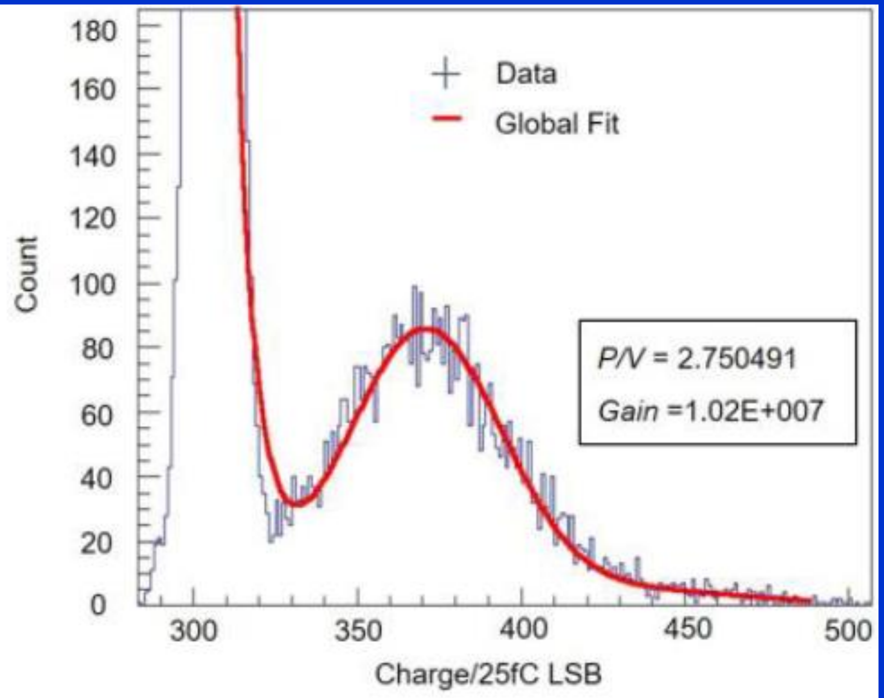
8-inch spherical MCP-PMT from China



The MCP assembly with the supporting pole

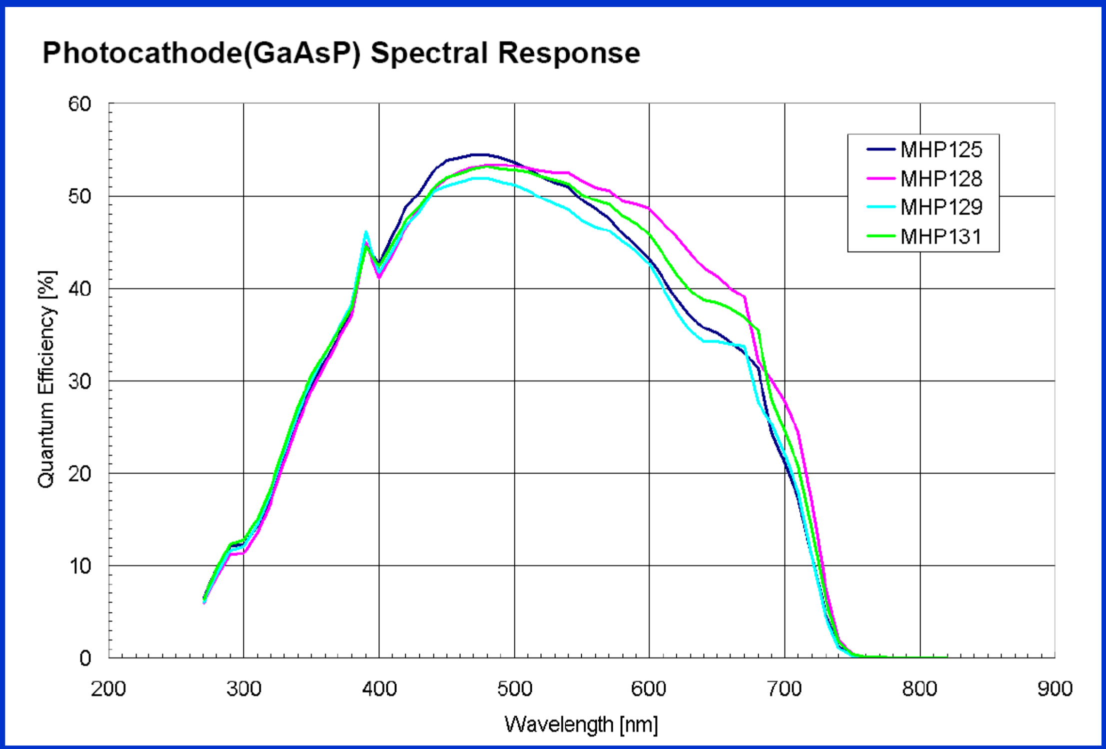


Picture of the 8-inch spherical MCP-PMT prototype

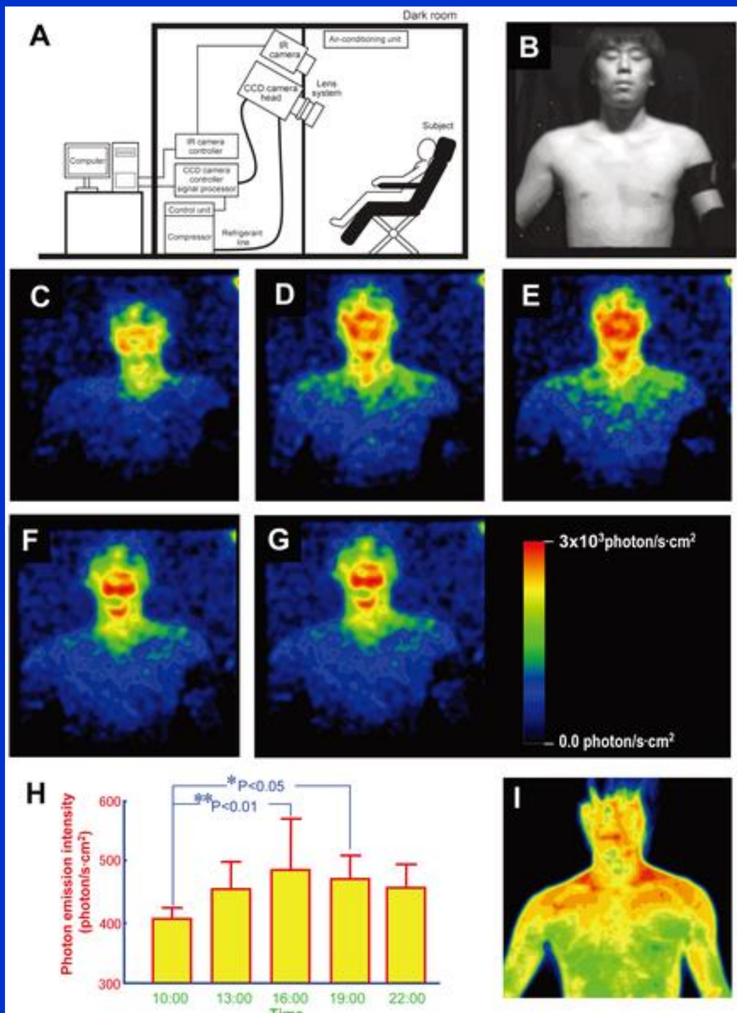


18-mm GaAsP HPD (R9792U-40) (development started ~15 years ago)

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



Human body light emission



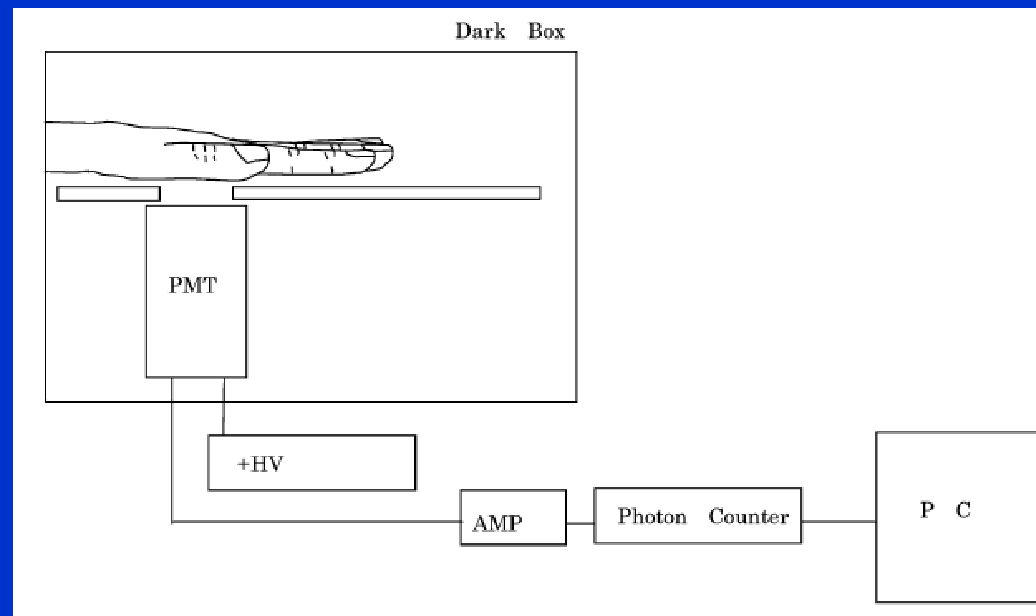
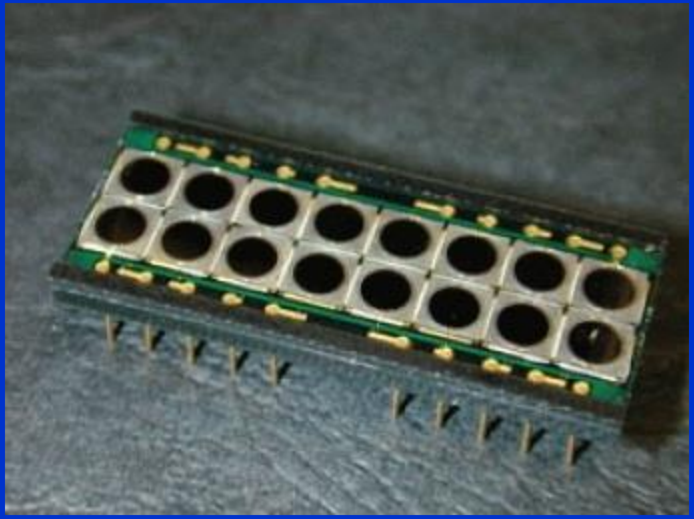
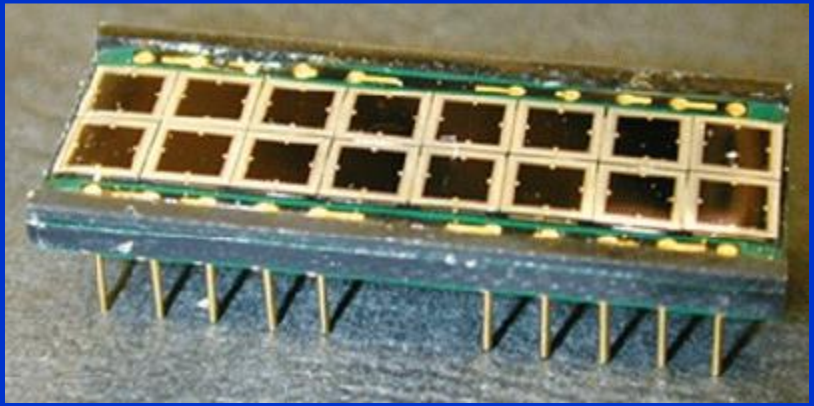


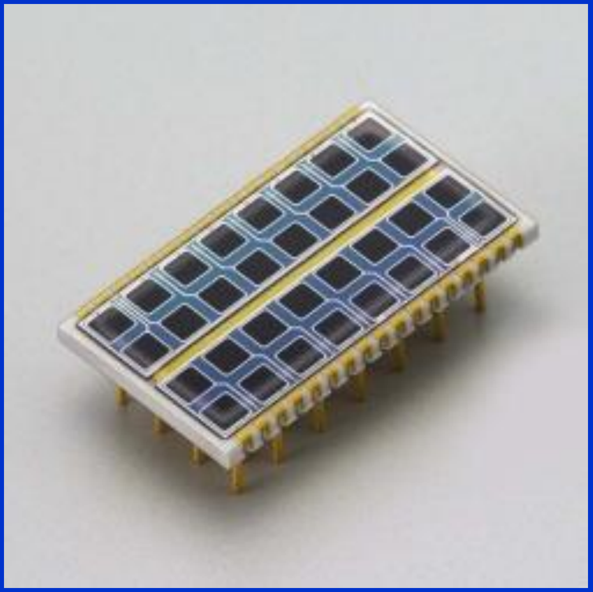
Fig. 1. Schematic drawing for measuring ultra-weak luminescence from human hand.

APD Matrixes for pioneering small animal PET constructed at MPI

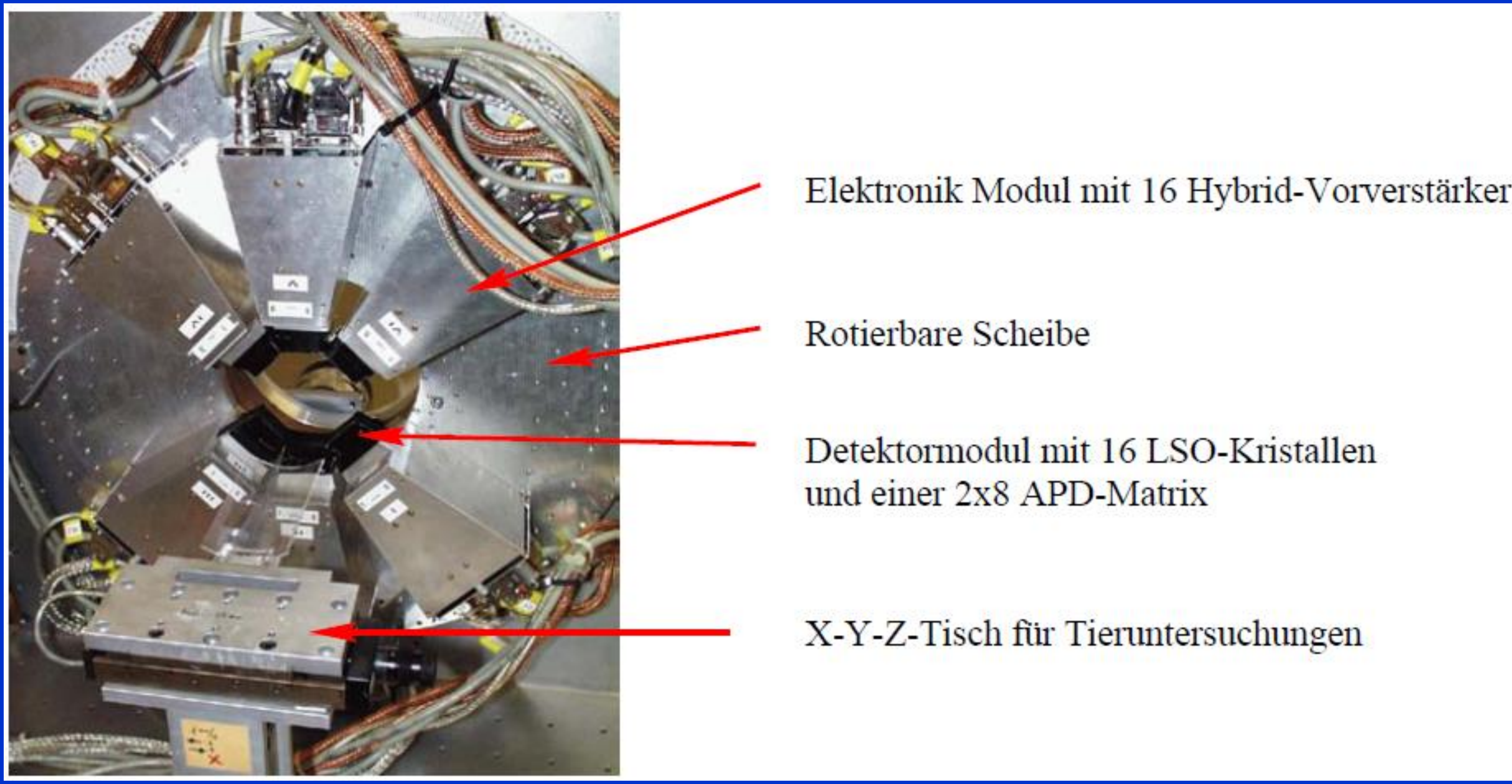




Hamamatsu S8550-02
4 x 8 array of 1.6 x 1.6 mm²



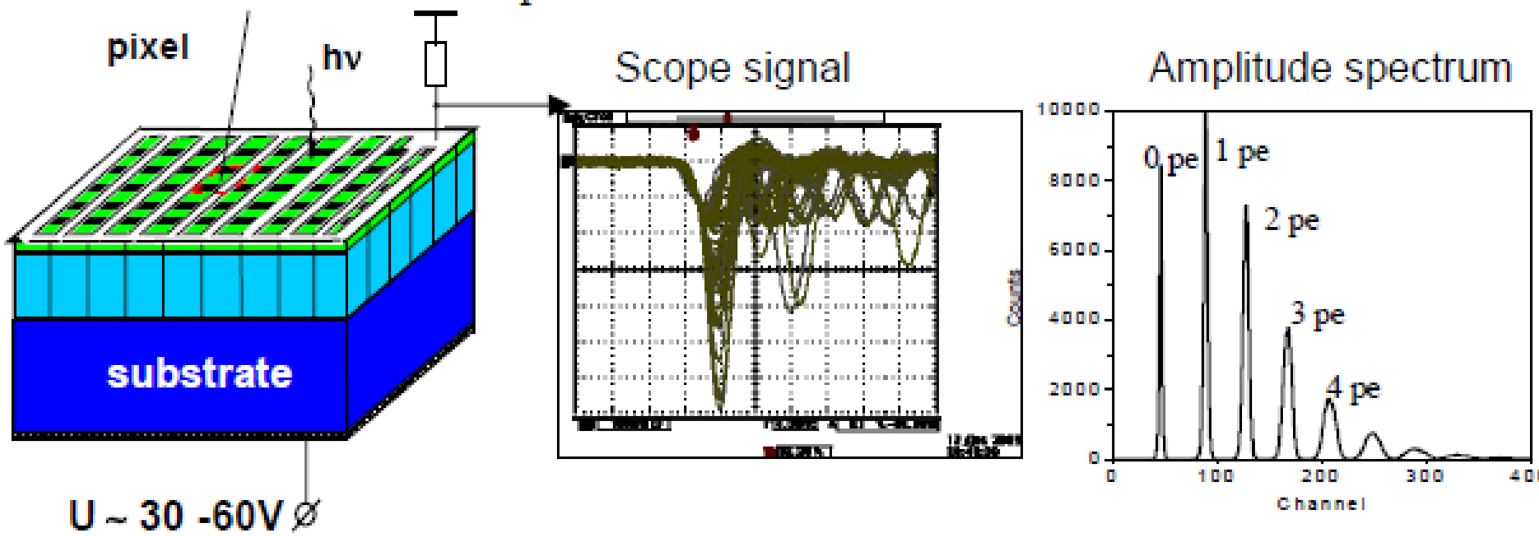
APD-Based Small Animal PET built in MPI



Silicon Photomultiplier (SiPM)

The novel type of photon detector

Multipixel device with common readout



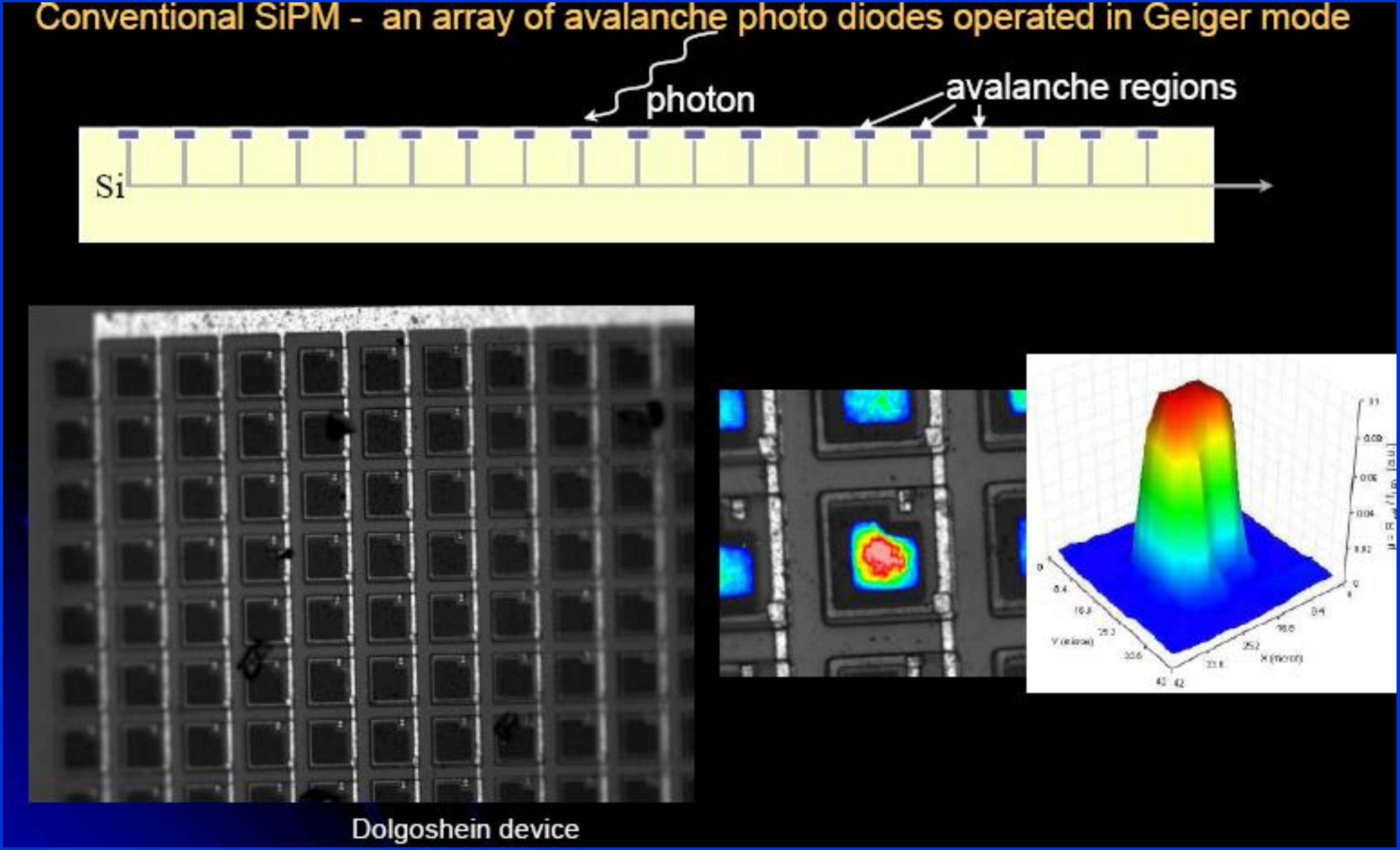
SiPM - main features:

- 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

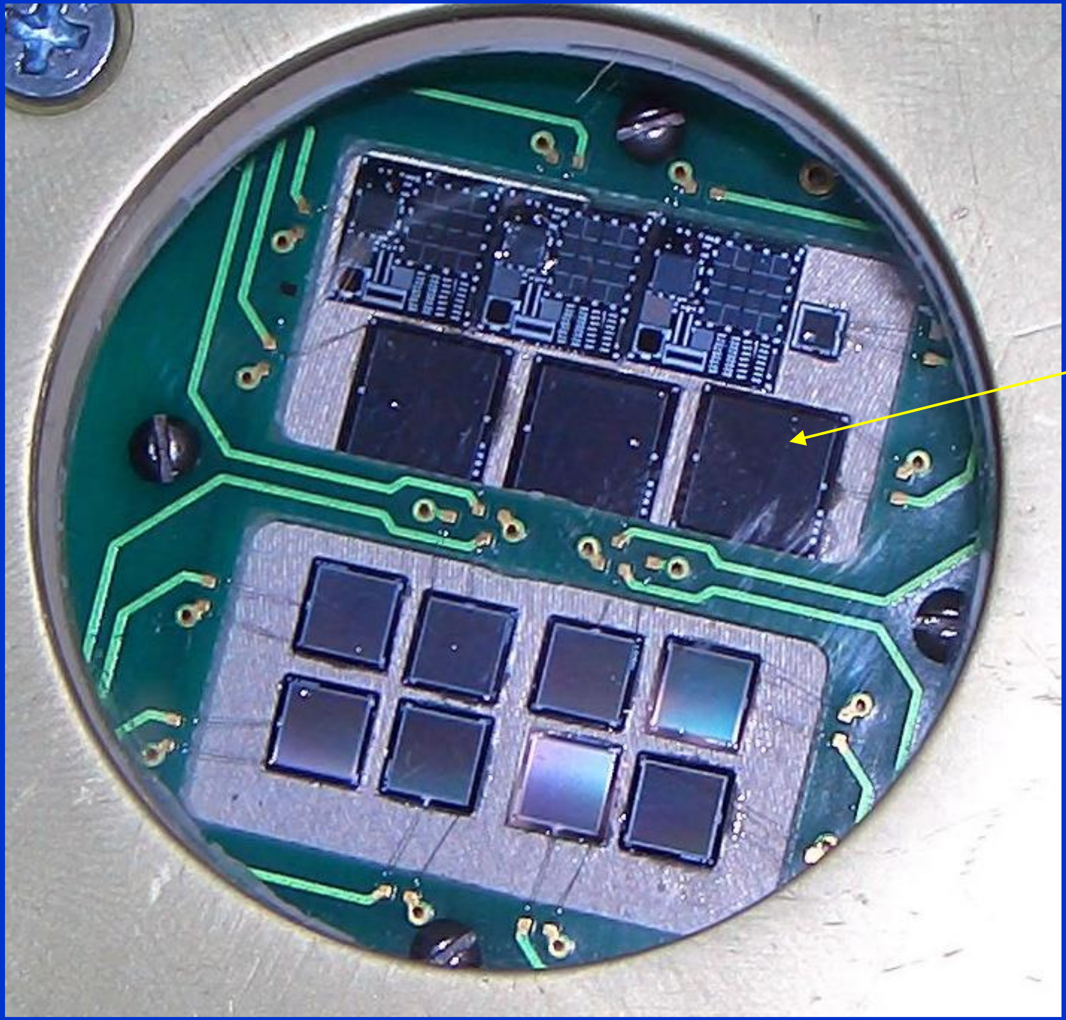
Pixel signal - 0 or 1

But SiPM is analogue device

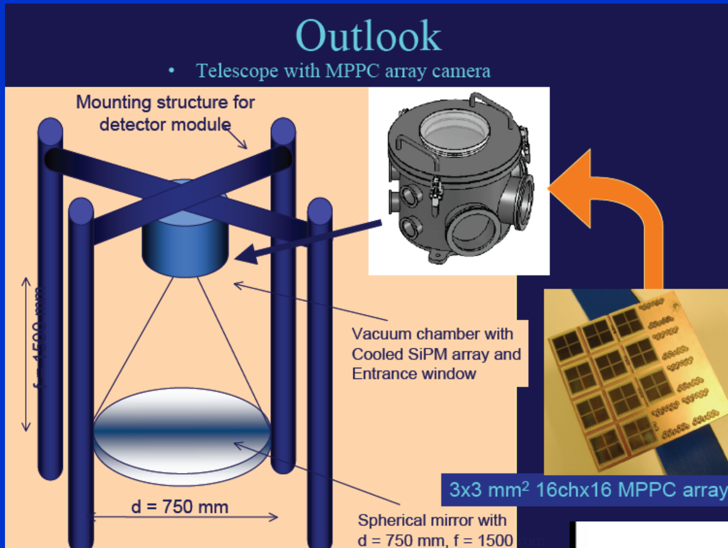
SiPM: novel light sensors

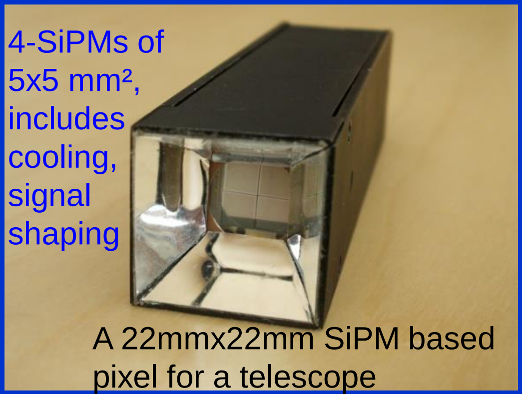


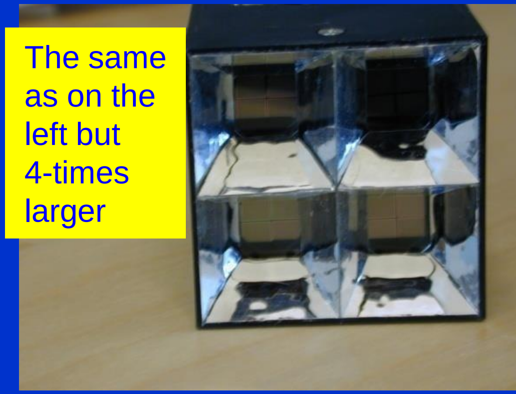
SiPMs: MEPhI-MPP development: 1x1, 1.3x1.3, 1.4x1.4, 3x3, 5x5 mm², some 8 years ago

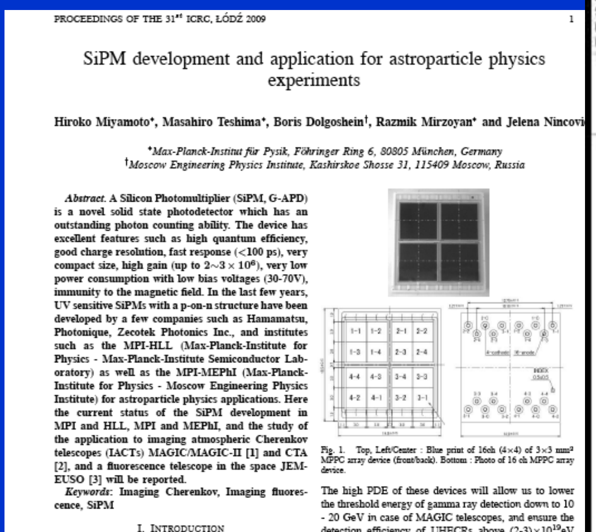


5 x 5 mm²









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SiPM development and application for astroparticle physics experiments

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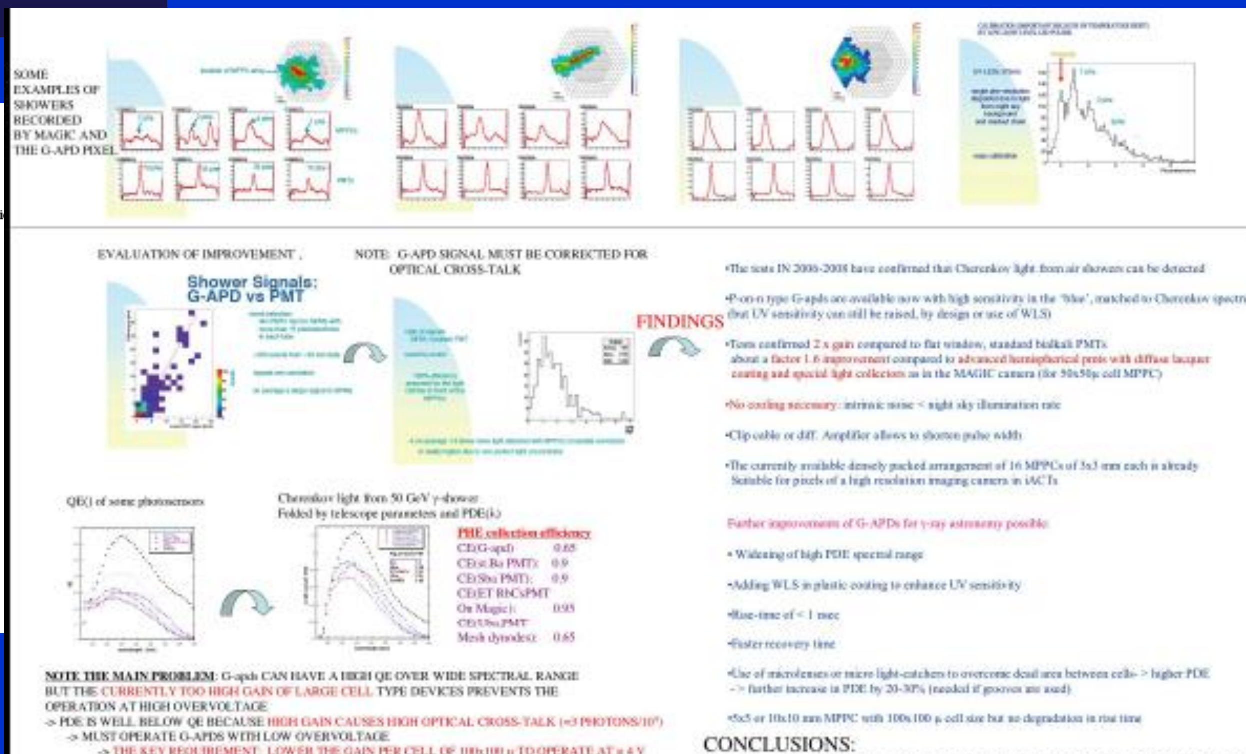
Abstract. A Silicon Photomultiplier (SiPM, G-APD) is a novel solid state photodetector which has an outstanding photon counting ability. The device has excellent features such as high quantum efficiency, good charge resolution, fast response (<100 ps), very compact size, high gain (up to $2\sim3\times10^6$), very low power consumption with low bias voltages (30-70V), immunity to the magnetic field. In the last few years, UV sensitive SiPMs with a p-on-n structure have been developed by a few companies such as Hamamatsu, Photonique, Zecotek Photonics Inc., and institutes such as the MPI-HLL (Max-Planck-Institute for Physics - Max-Planck-Institute Semiconductor Laboratory) as well as the MPI-MEPhI (Max-Planck-Institute for Physics - Moscow Engineering Physics Institute) for astroparticle physics applications. Here the current status of the SiPM development in MPI and HLL, MPI and MEPhI, and the study of the application to imaging atmospheric Cherenkov telescopes (IACTs) MAGIC/MAGIC-II [1] and CTA [2], and a fluorescence telescope in the space JEM-EUSO [3] will be reported.

Keywords: Imaging Cherenkov, Imaging fluorescence, SiPM

I. INTRODUCTION

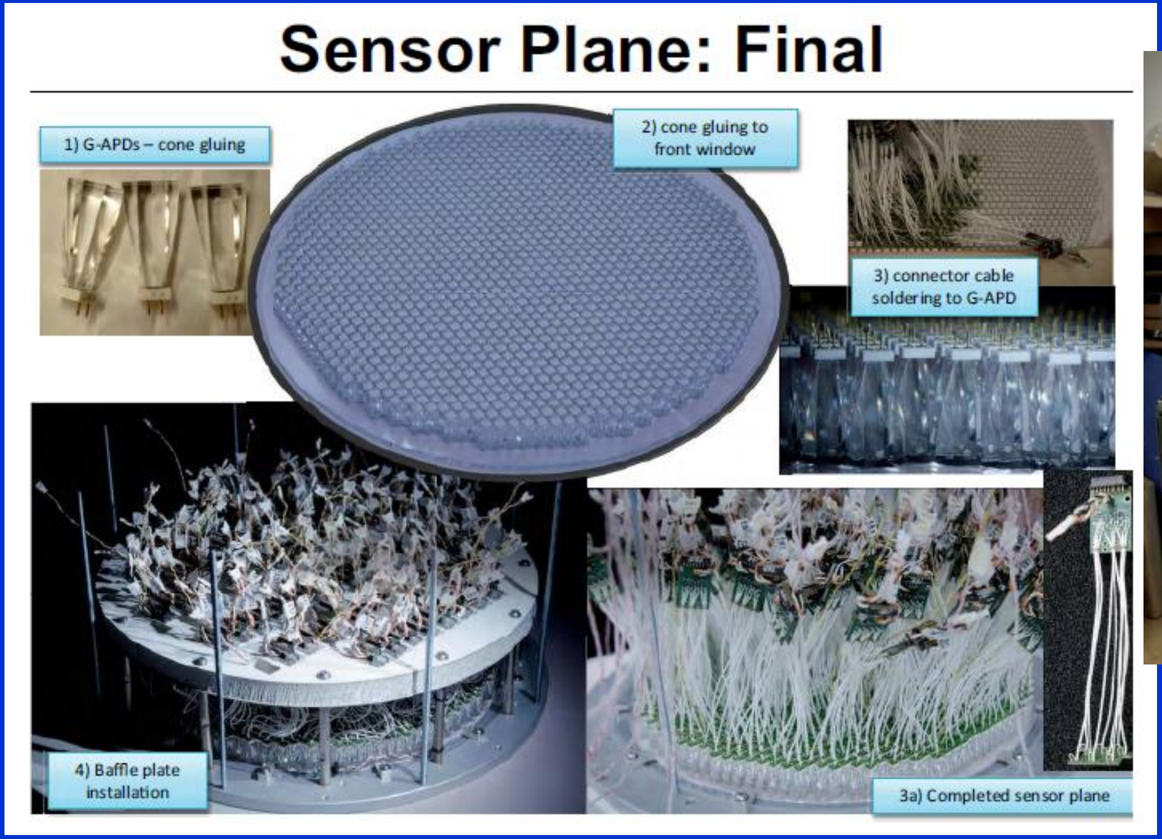
Fig. 1. Top, Left/Center : Blue print of 16ch (4×4) of 3×3 mm² MPPC array device (front/back). Bottom : Photo of 16 ch MPPC array device.

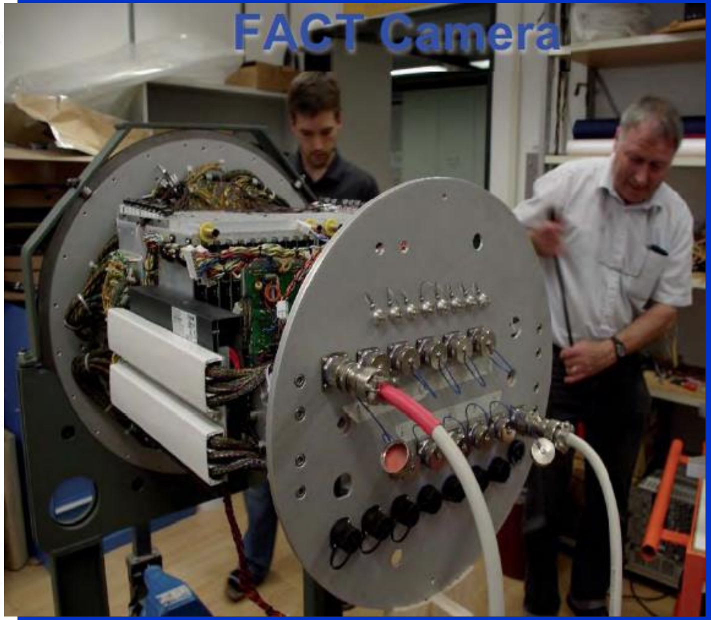
The high PDE of these devices will allow us to lower the threshold energy of gamma ray detection down to 10 - 20 GeV in case of MAGIC telescopes, and ensure the detection efficiency of UHECRs above $(2\text{-}3)\times10^{19}$eV



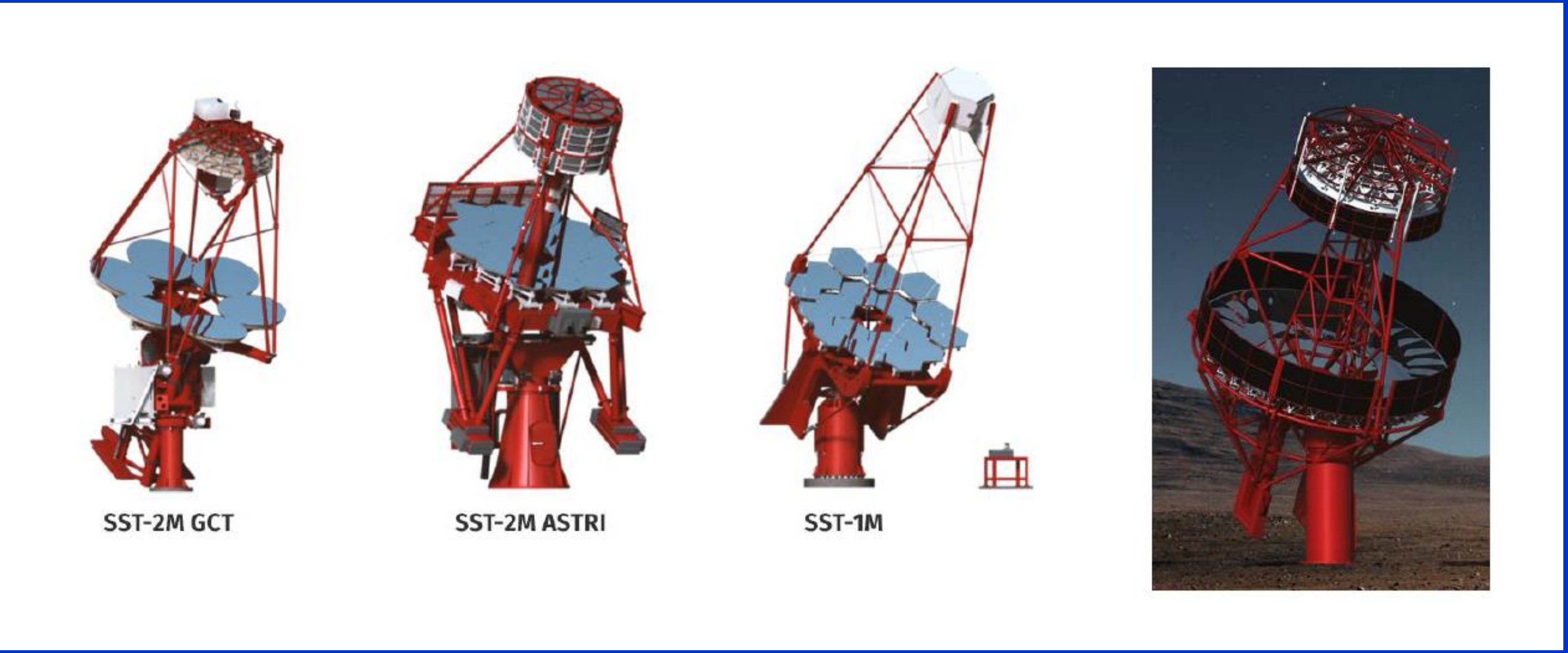
1440-pixel MPPC camera

FACT telescope camera





3-different types of CTA SST Telescopes + the 9m diameter SCT



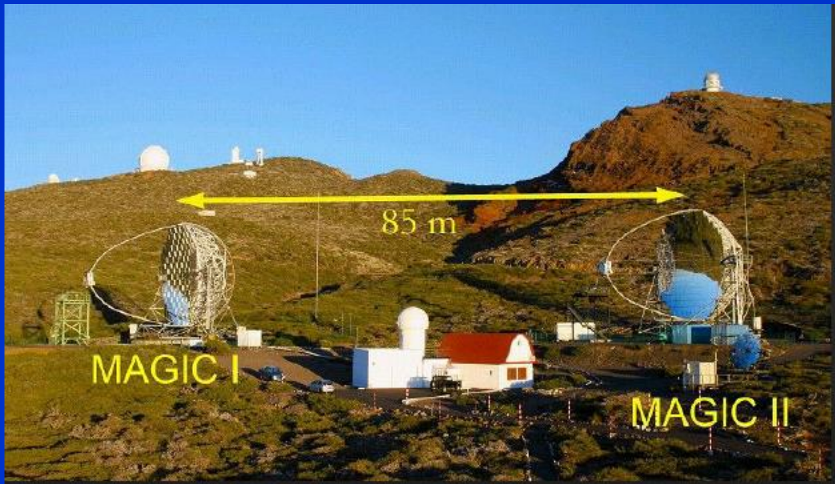
The main parameters of the CTA telescopes which employ SiPM in the imaging camera

Summary of the main parameters of the SST and SCT telescopes of the CTA collaboration, using SiPM-based imaging cameras

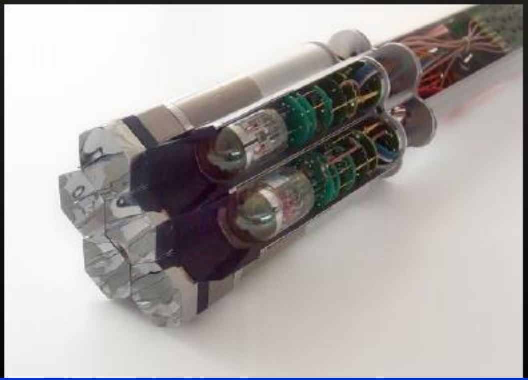
Telescope name and reflecting surface	Reflector eff. Ø, eff. area	Reflector design	*Focus*	# of SiPMs in the final stage	*pixel aperture*	Camera FoV
SST-1M Prime focus	4m, 6.5m²	Davies-Cotton	5.6m	1296	0.24°	9°
ASTRI, dual	4.3m, 8m²	SC*	2.15m	2368	0.19°	8.3°
GCT, dual	4m, 8.9m²	SC	2.28m	2048	0.17°/6mm	(8-9)°
SCT, dual	9.7m, 41m²	SC	5.6m	11328	0.067°/6mm	7.6°

*SC stands for Schwarzschild-Couder

The MAGIC telescopes and the imaging camera based on PMT clusters



- Canary island of La Palma
- 2200 m above see level
- Two imaging atmospheric Cherenkov telescopes (IACTs)
- Each camera equipped with 1039 PMTs
- Up to 7 pixels partitioned in 169 clusters plus 6 open corner locations



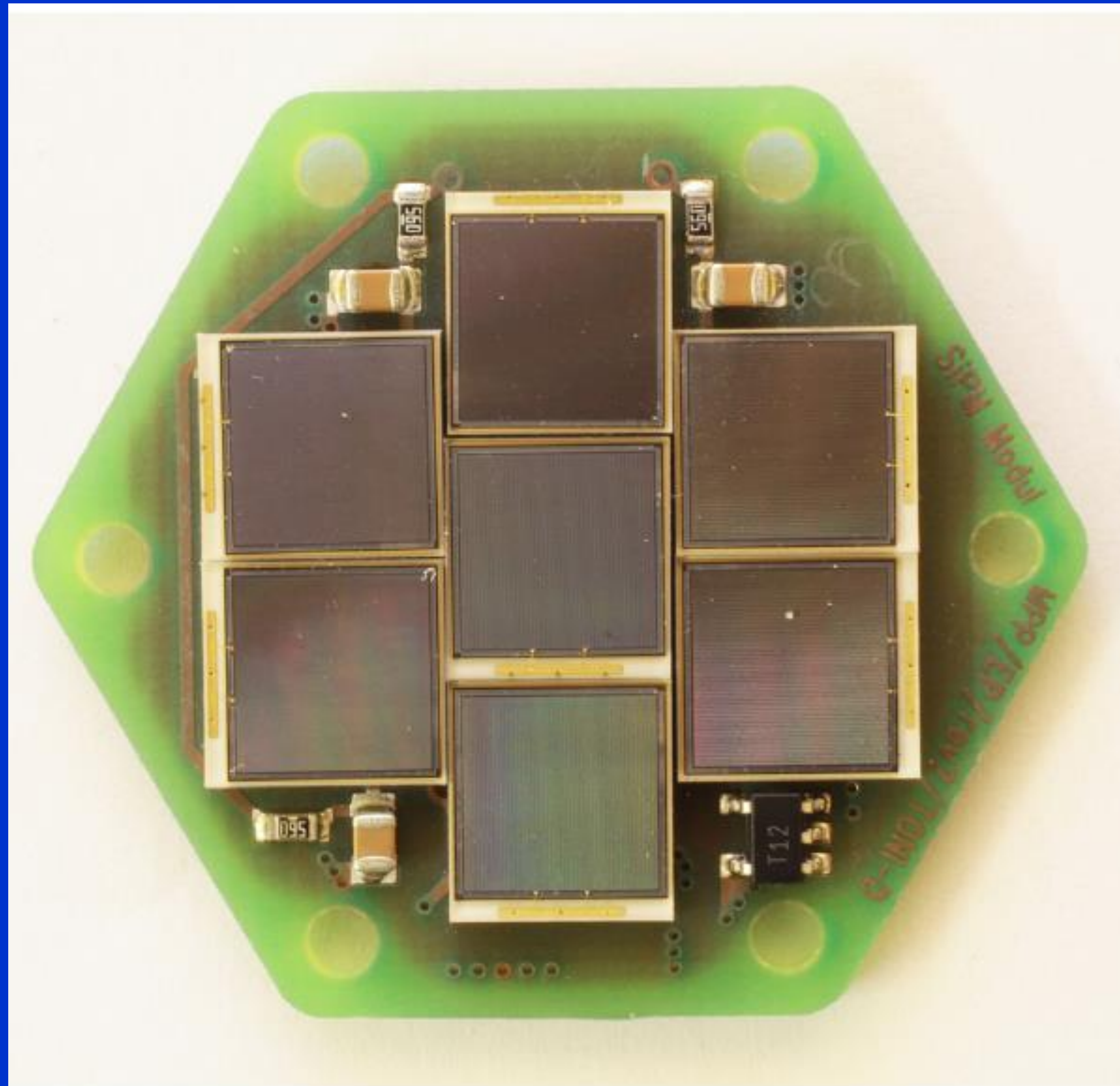
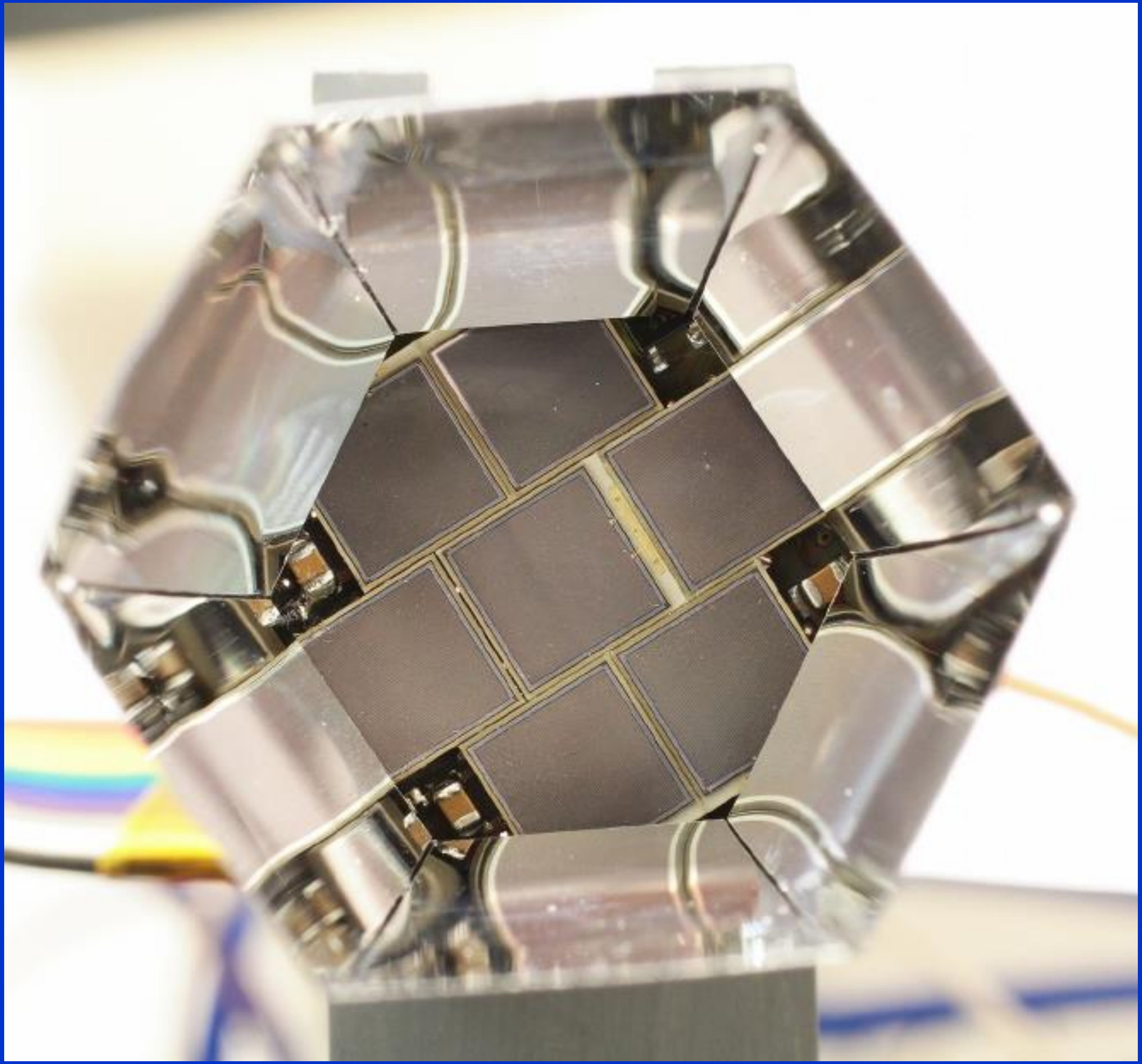


Fig. 1. First generation pixel equipped with seven Excelitas SiPMs.

The same cluster with the light guide



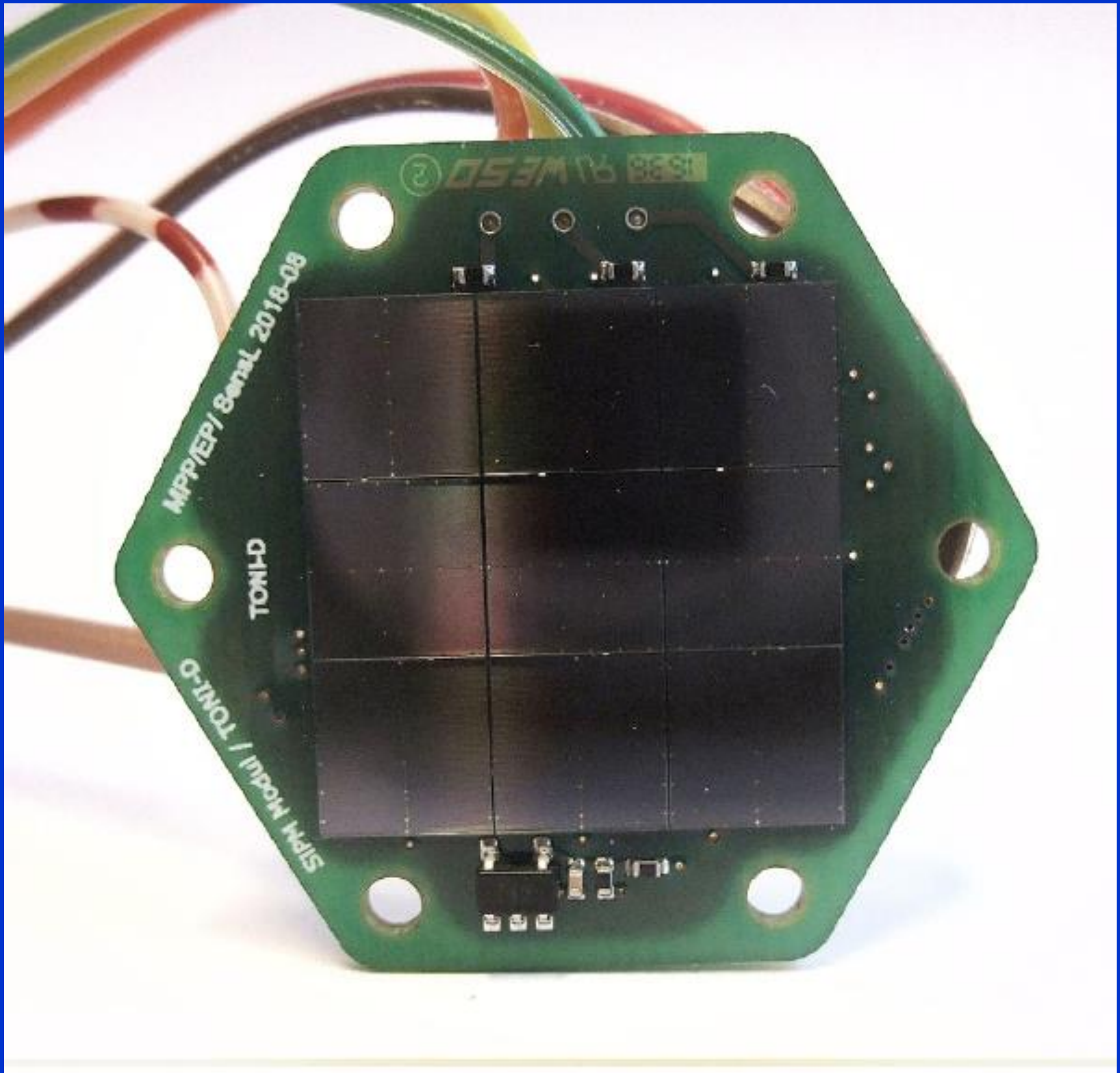


Fig. 3. Second generation pixel equipped with nine SensL SiPMs.

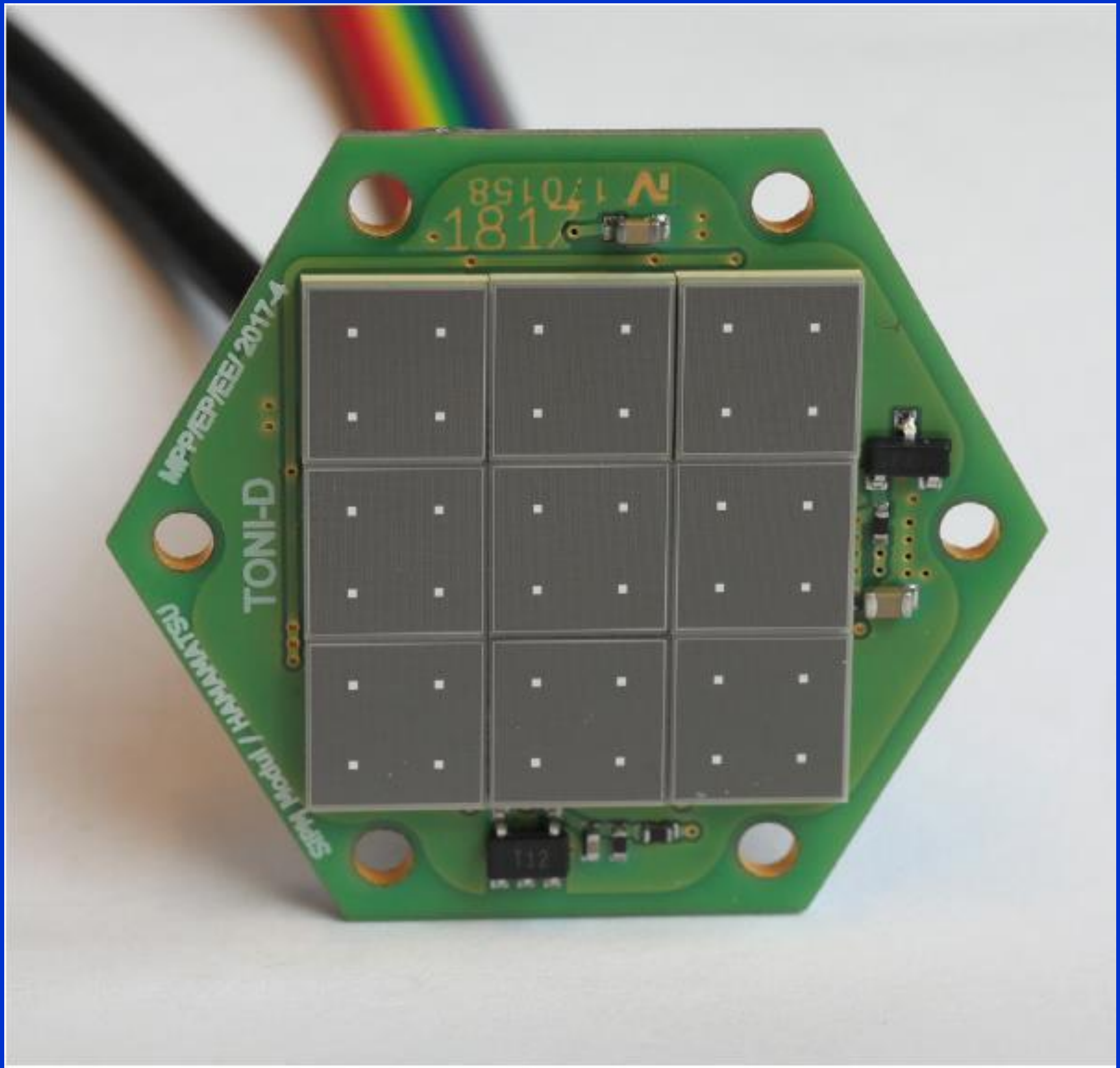
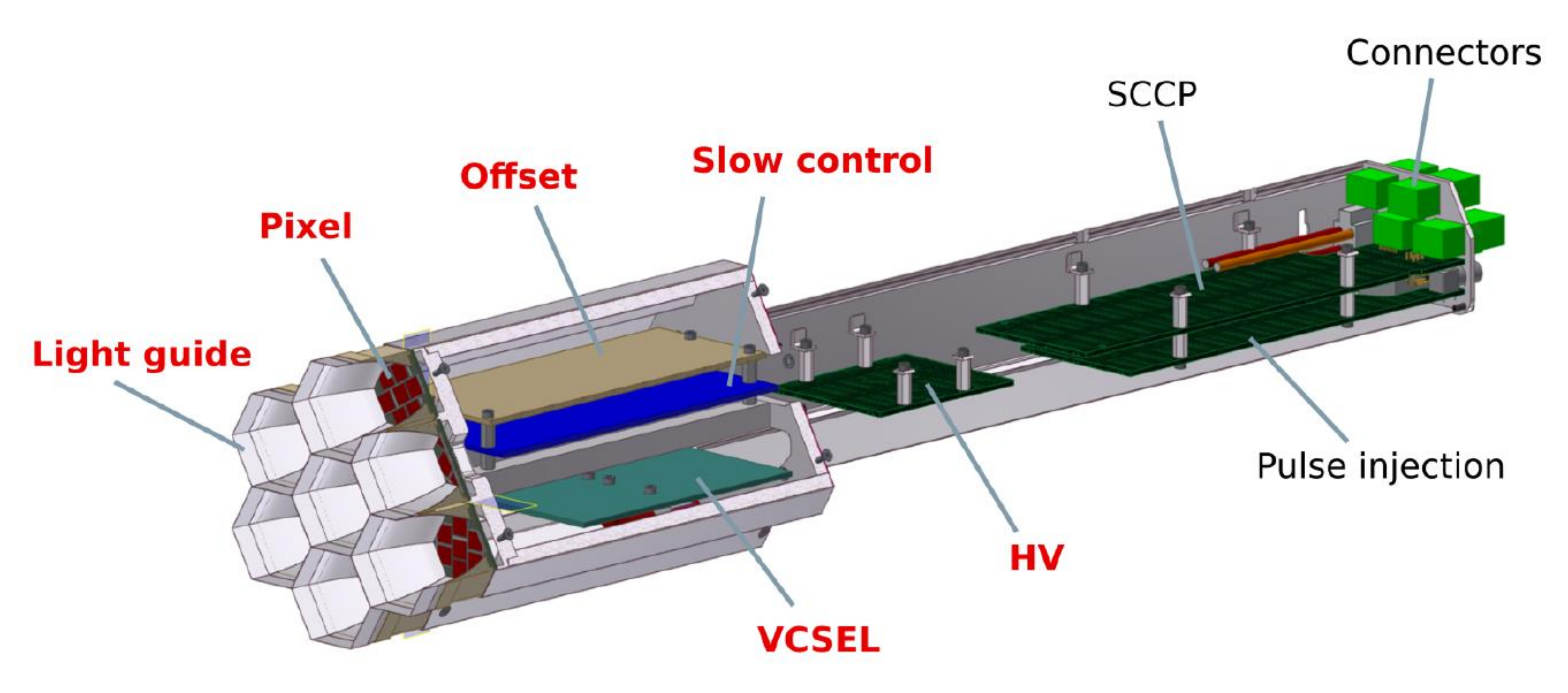


Fig. 2. Second generation pixel equipped with nine Hamamatsu SiPMs.

Design of a cluster used in the MAGIC imaging camera



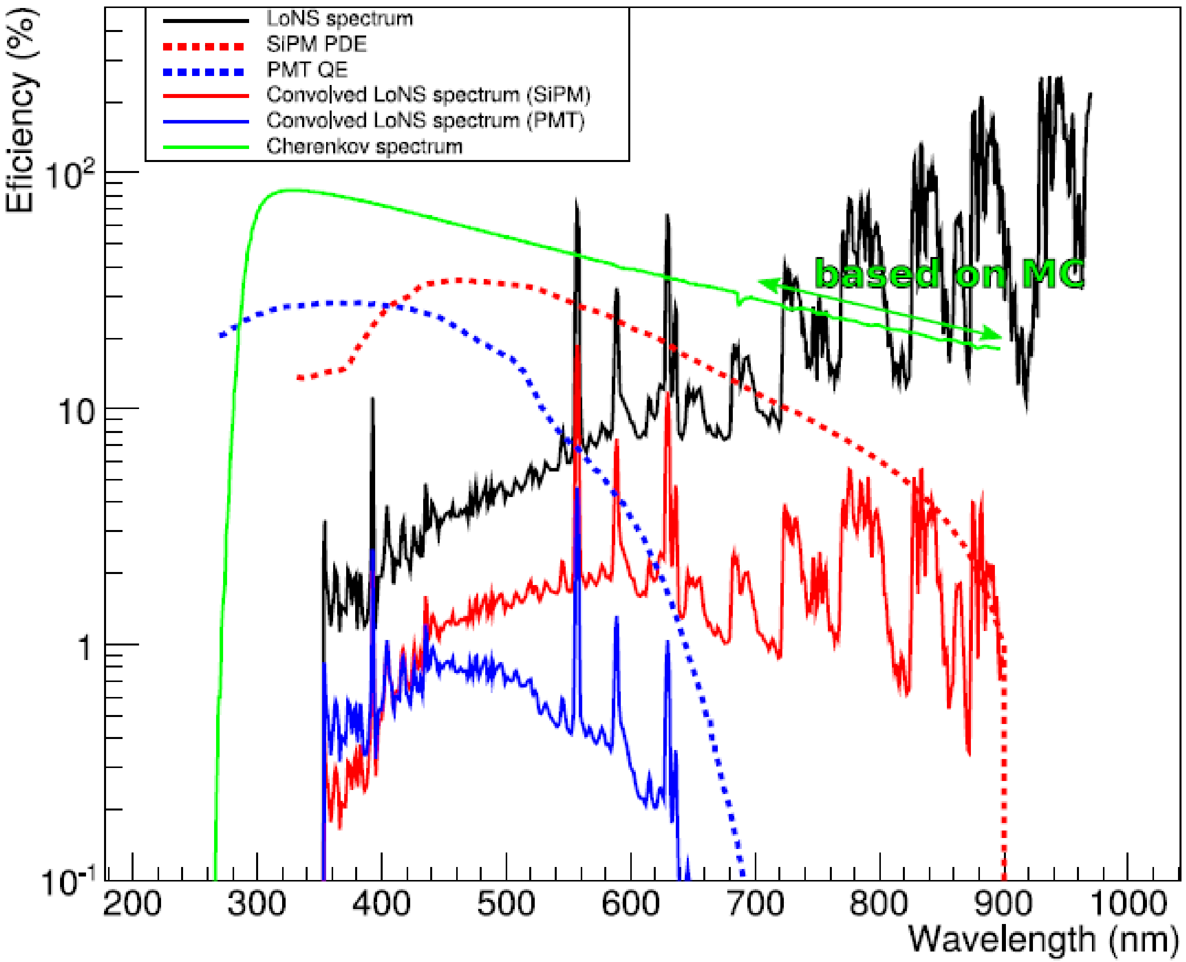
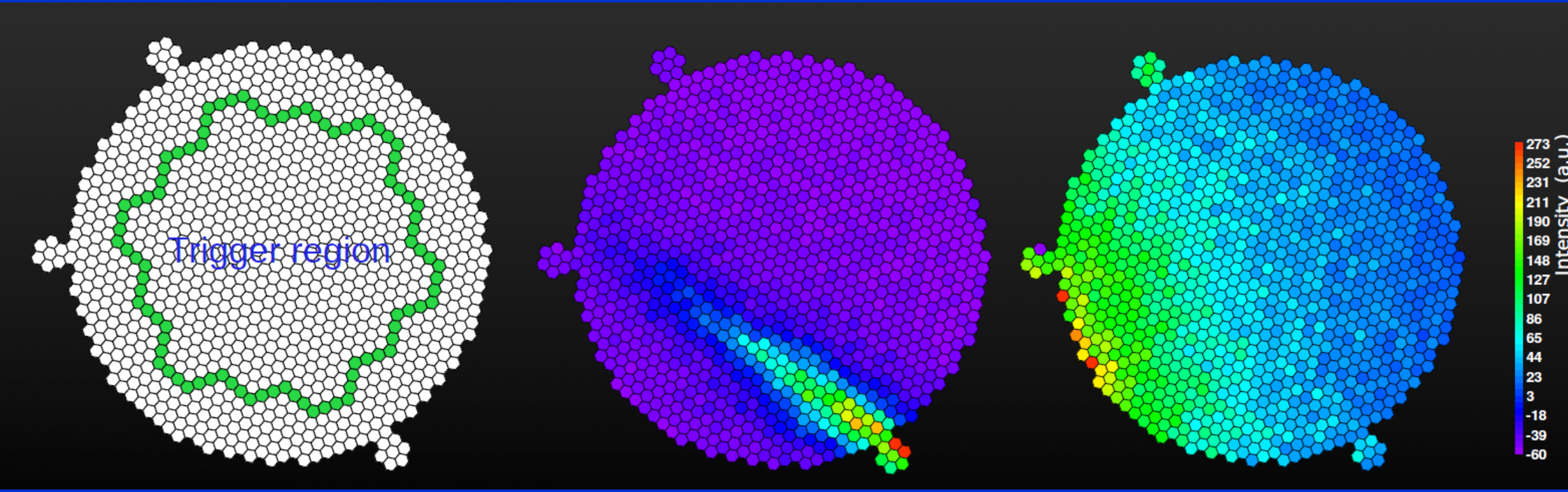
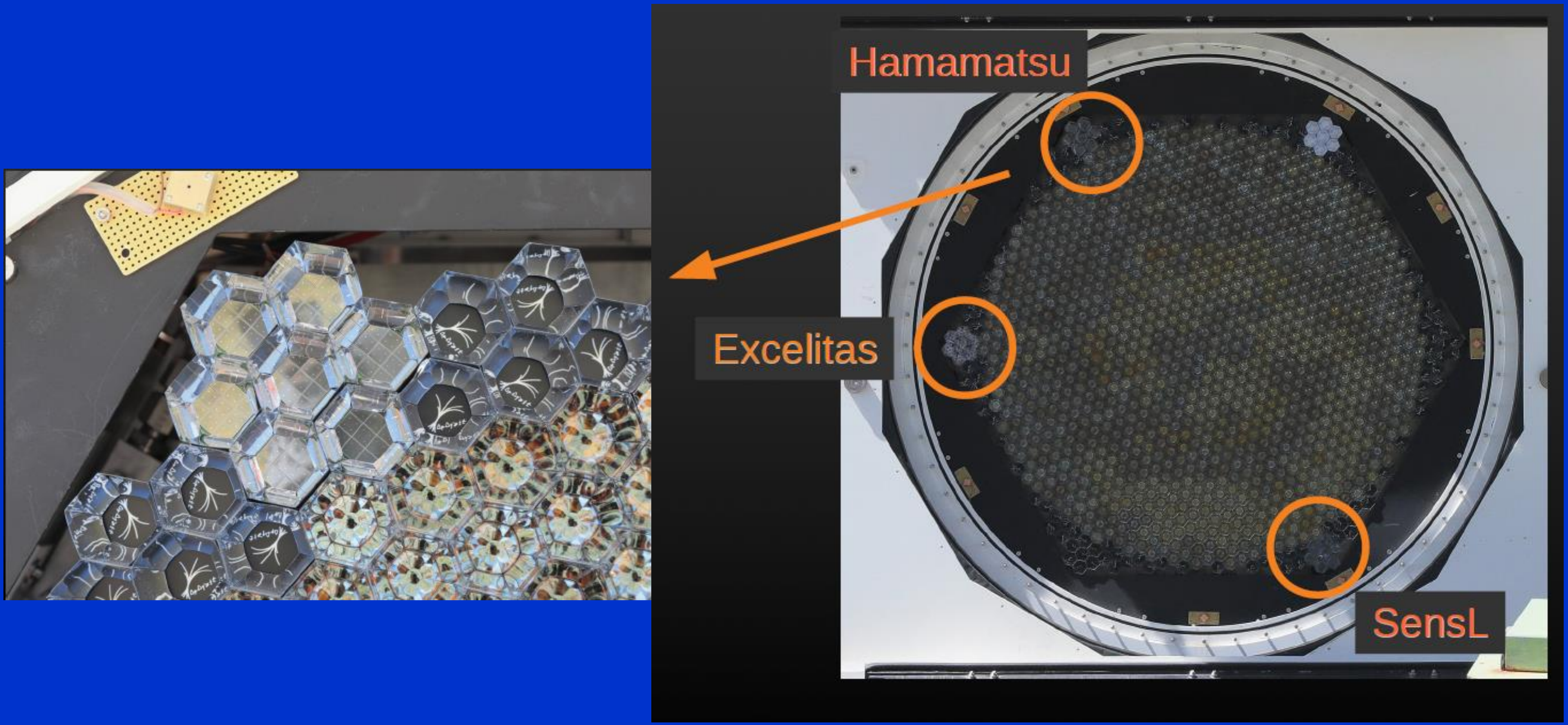


Fig. 4. LoNS spectrum at the MAGIC telescopes site and efficiencies of the Excelitas SiPM and the Hamamatsu PMTs of the MAGIC-1 camera [7]. The photo-detectors responses is calculated as the pointwise multiplication of the sensors efficiency with the LoNs spectrum. The spectrum of an extensive air shower at low zenith observations is plotted in addition. The Cherenkov spectrum is based on measurements by [8] and on monte carlo simulation for the range from 700 nm to 900 nm. The LoNS spectrum is taken from [9].

Cherenkov events detected by the imaging camera




Hamamatsu
Excelitas
SensL

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 %

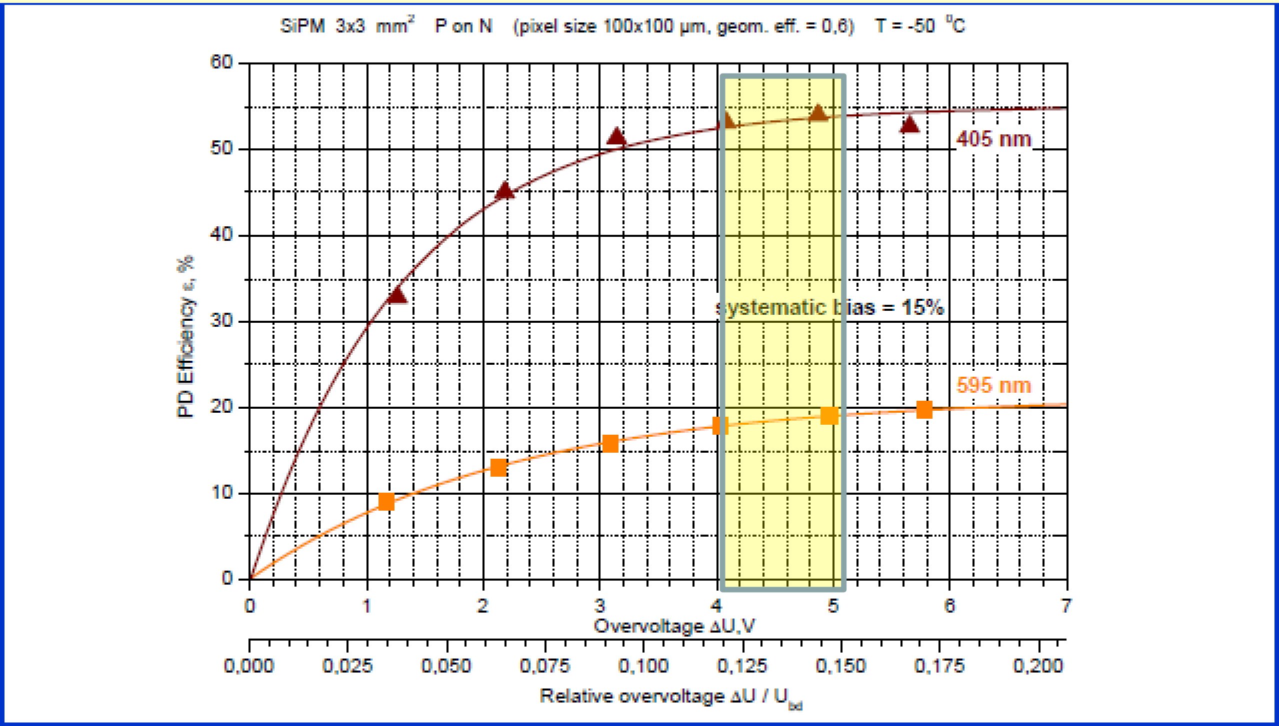
$T(\lambda)$: strongly varies with λ, could reach 80-90 %

$A_{active\ area}$: some number between 20-80 %

$G_{geiger\text{-}eff.}(\lambda)$: strong function of applied $\Delta U/U$, for $\Delta U/U \geq$ 12-15 % could become $\geq$ 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

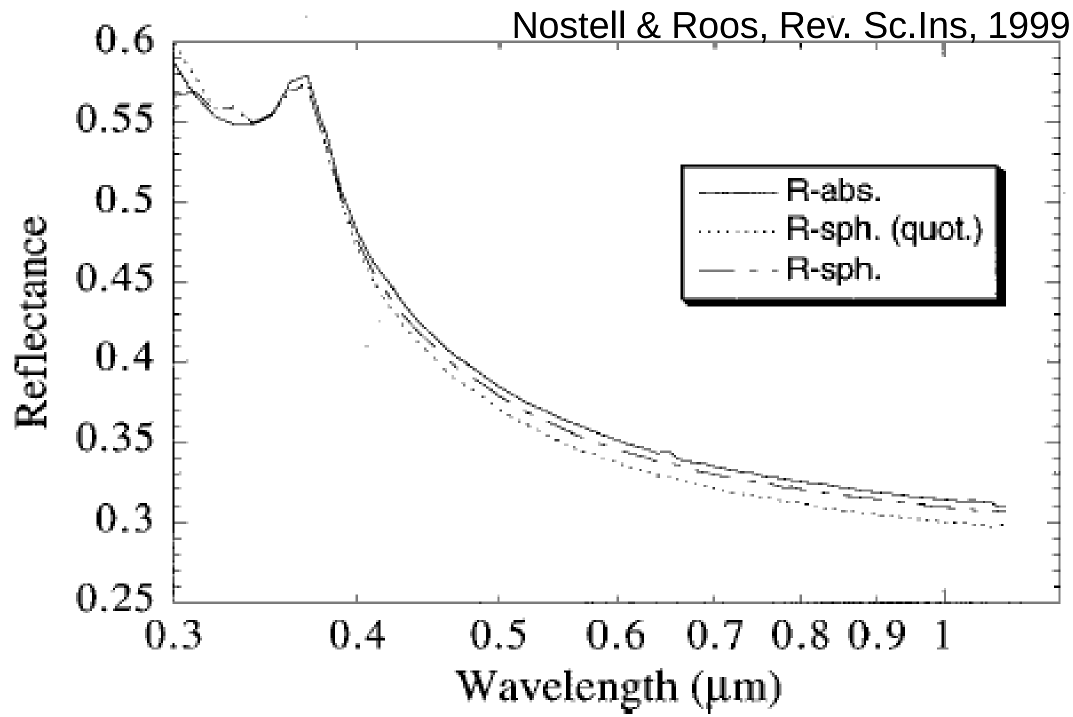
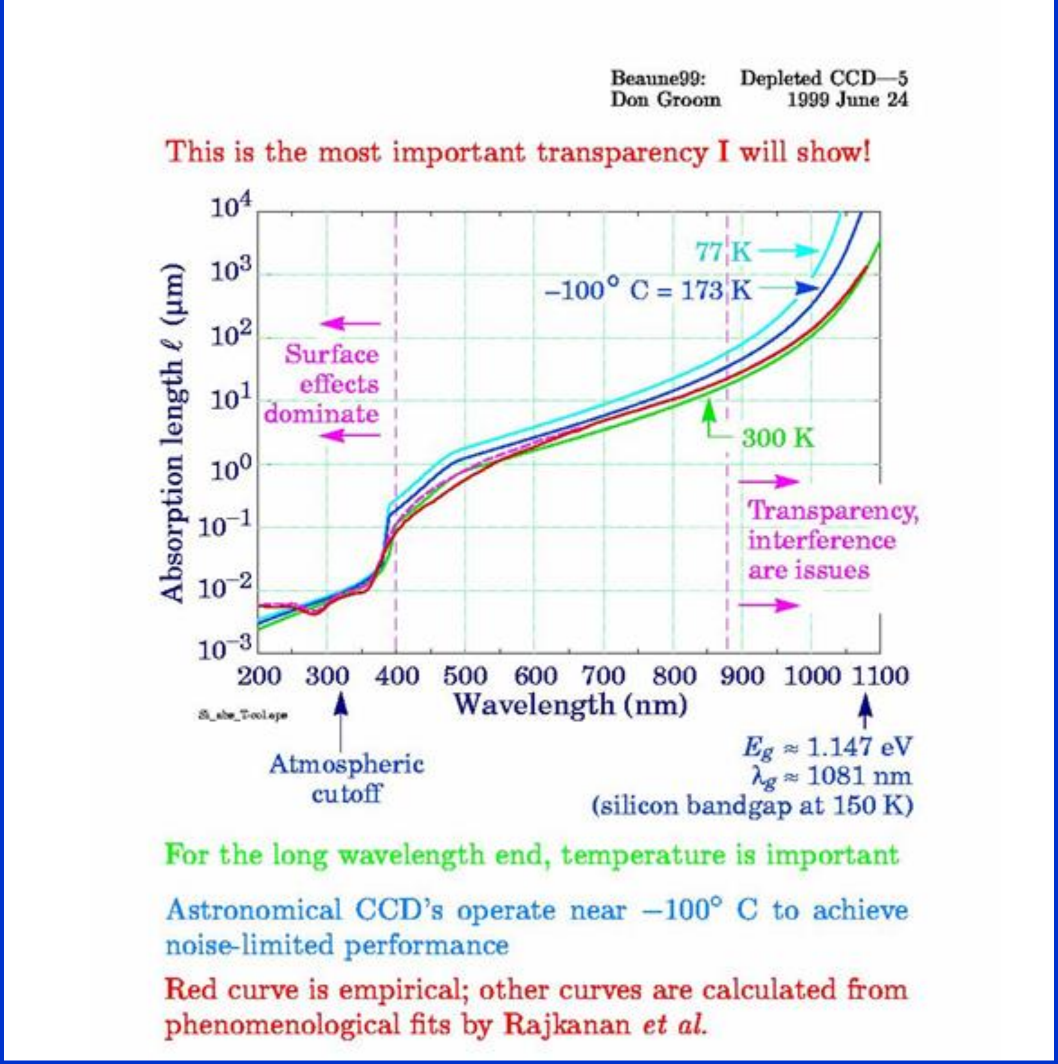


FIG. 19. Near normal reflectance spectra in the wavelength range 0.3–1.1 μm of silicon measured in the absolute spectrophotometer and the reflectance sphere. The reflectance sphere spectra consist of a corrected spectrum, R-sph, and the direct ratio between sample and reference signals, R-sph (quot.).

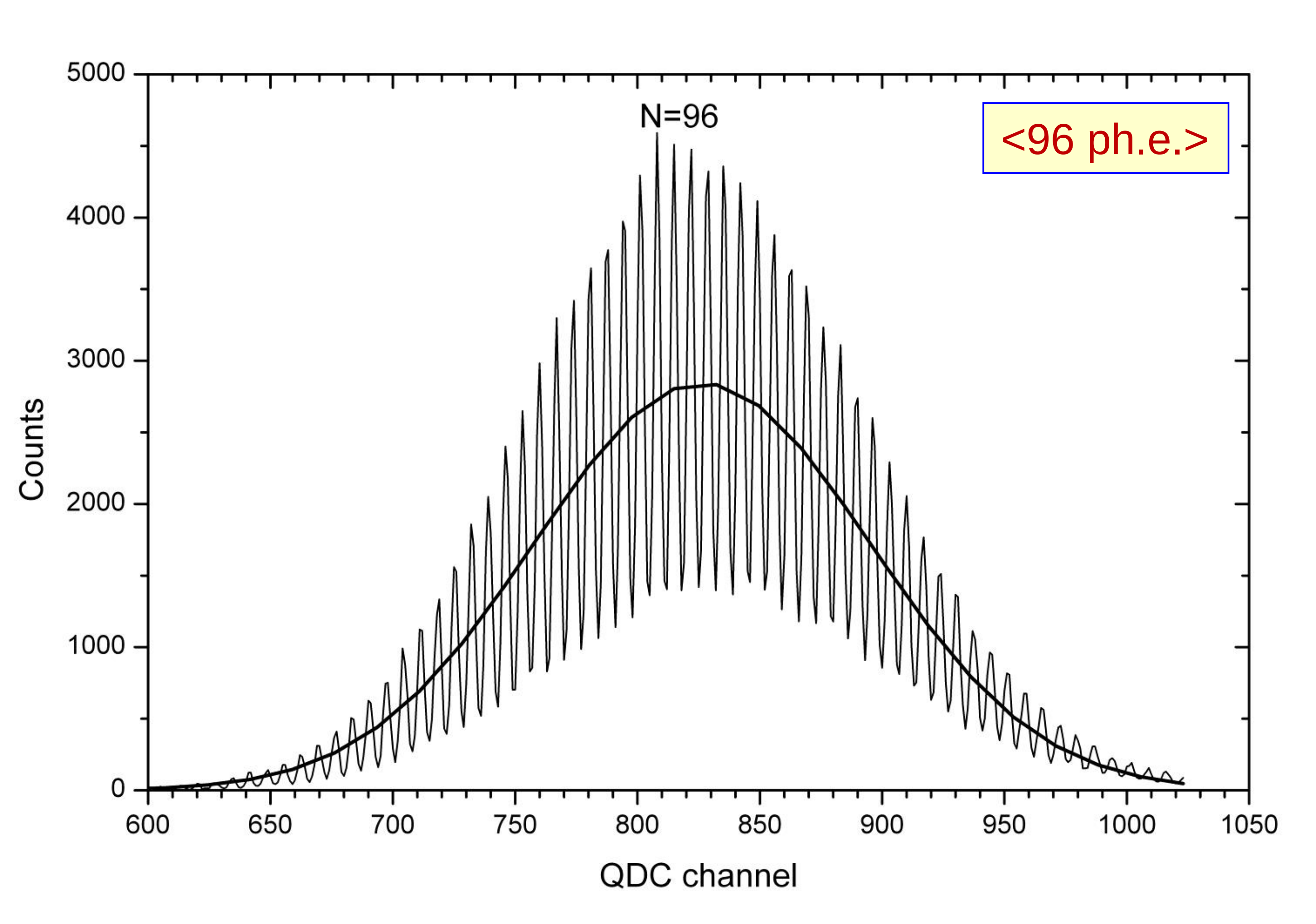
- Reflectivity of Si varies ~ 60 – 31 % for 300 – 1000 nm at normal incidence.
- antireflective coatings can help
- Proper choice of window coating can provide efficiency ≥ 80-90 %

Reminder: light absorption in Si



- 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

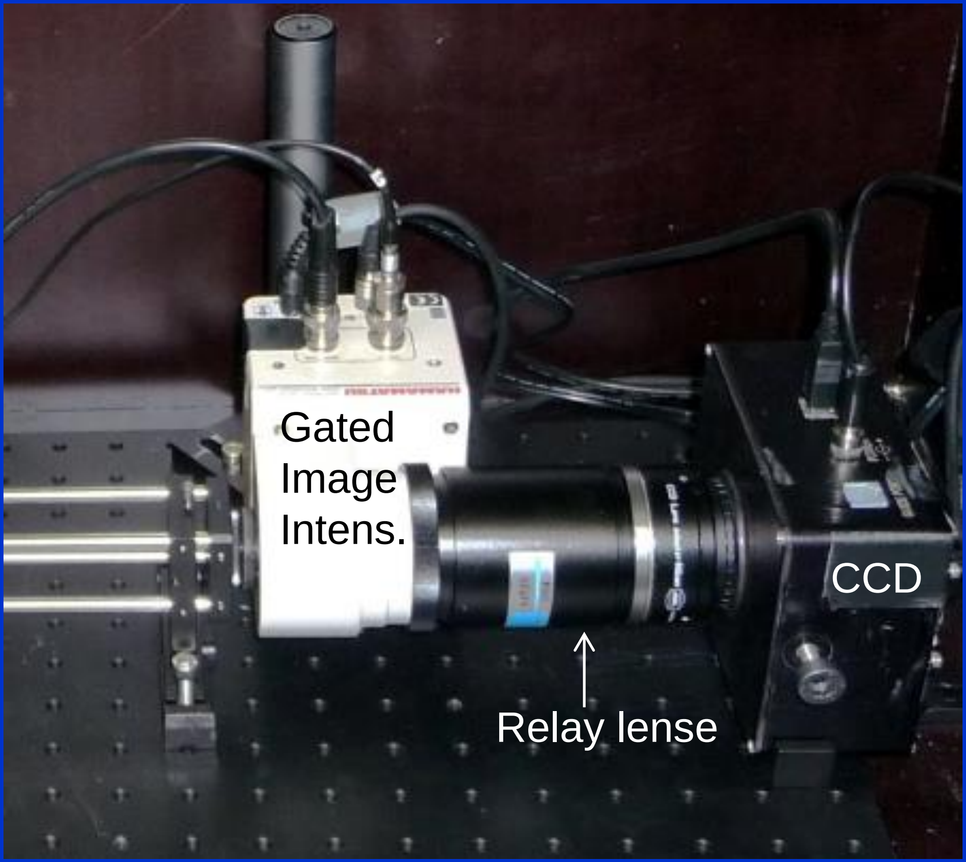
SiPM with X-talk suppression: World record of ultra-fast light sensors in amplitude resolution

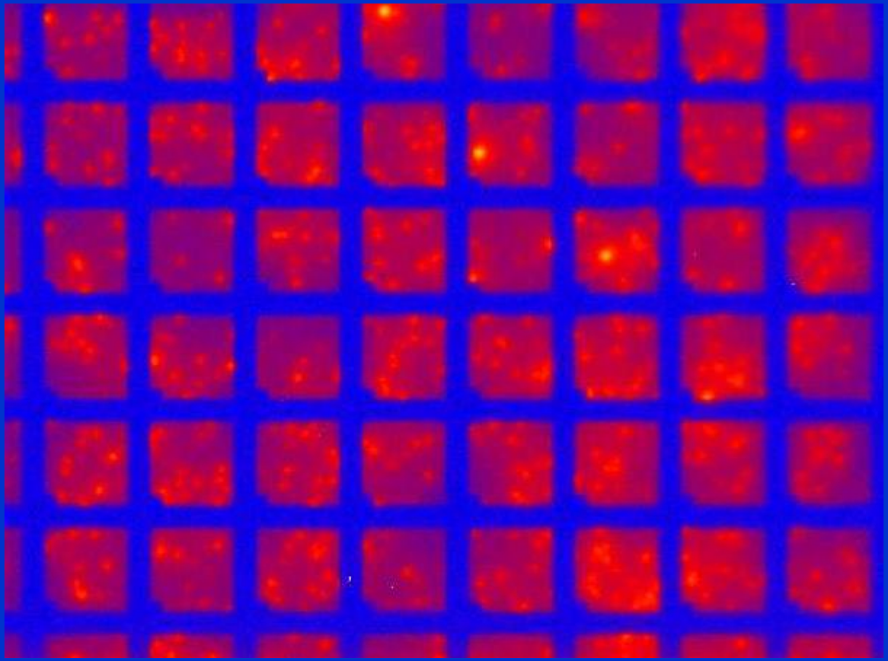


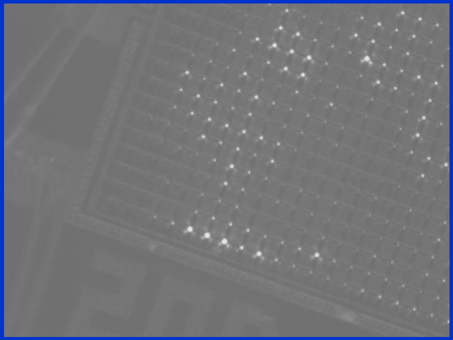
Why the light emission from Si avalanches is important

- 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

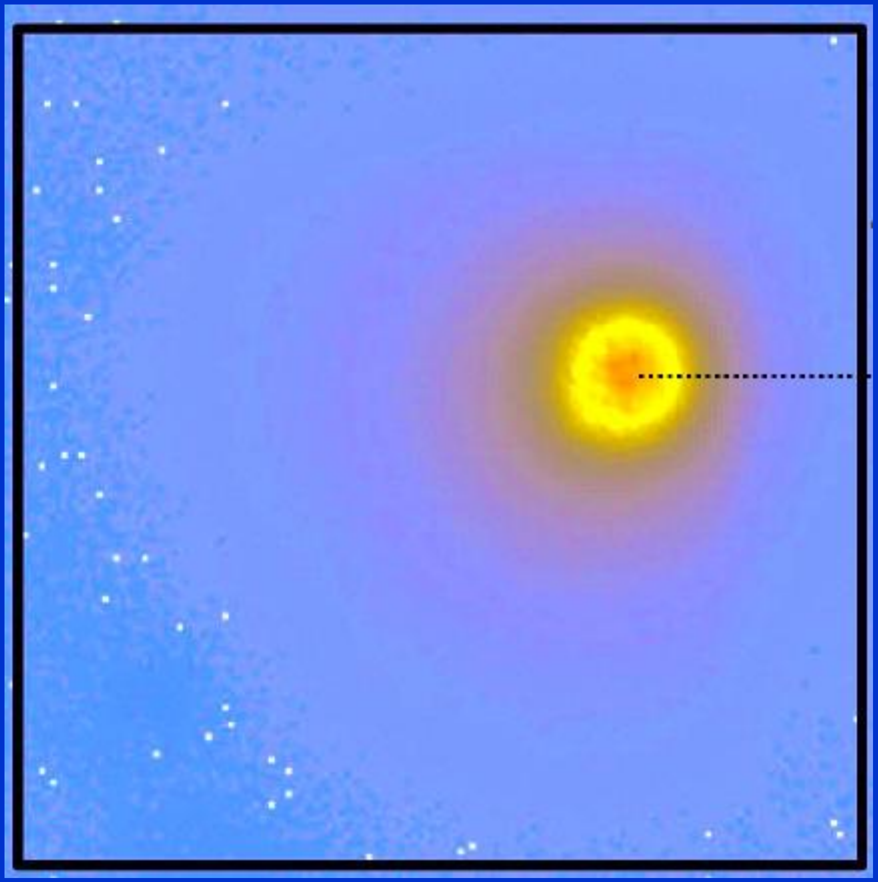
LEM is a powerful diagnostic method, revealing cell-substructures and many hidden details





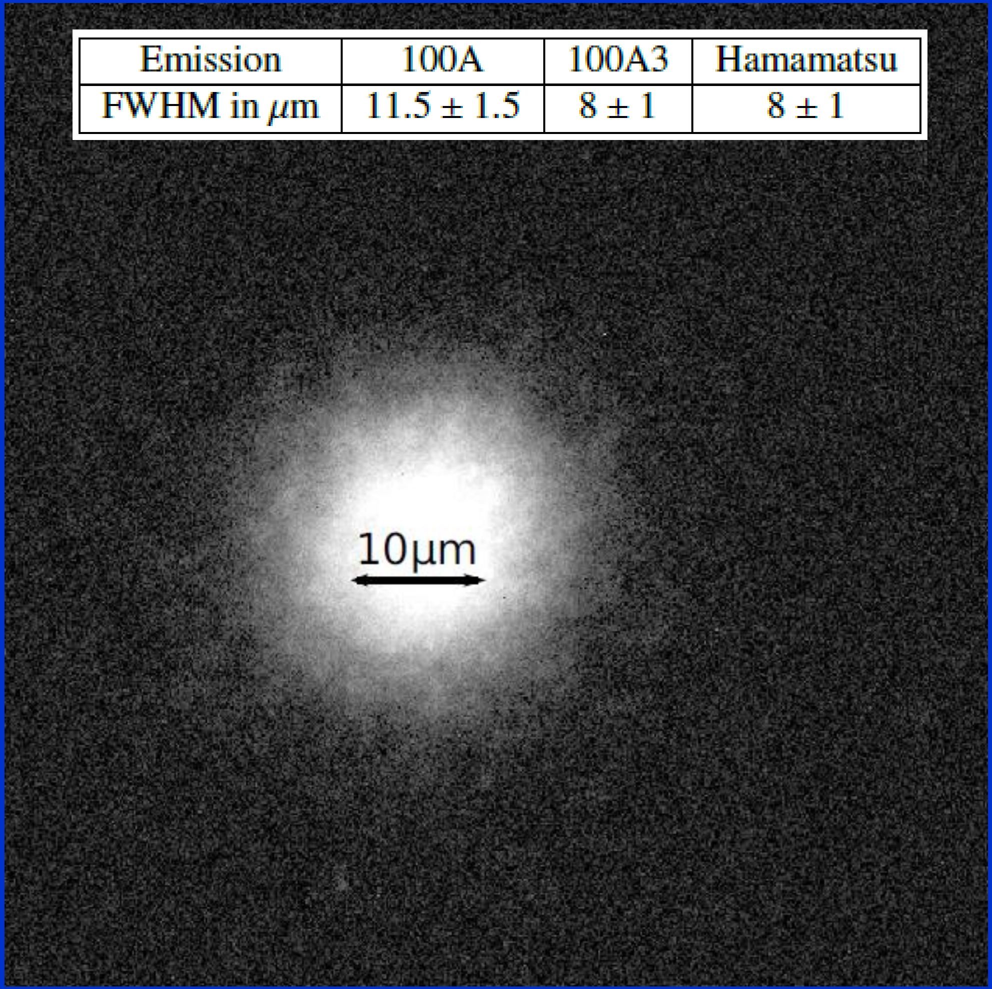


LEM Applied to Single SiPM Cell



- Shooting with laser to a cell of 100x100μm^2 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

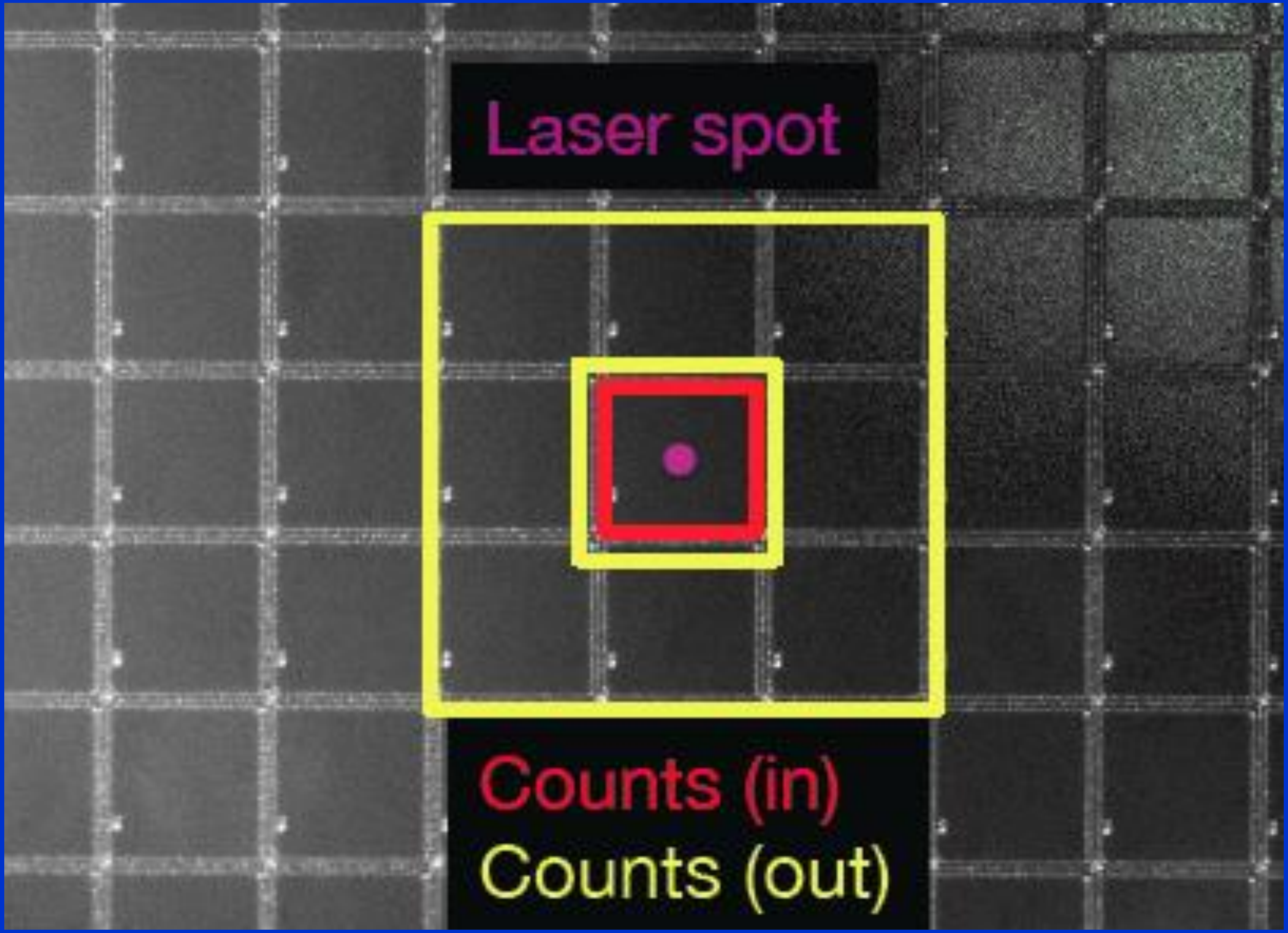
Shooting to SiPM (MPPC) of Hamamatsu type

- 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

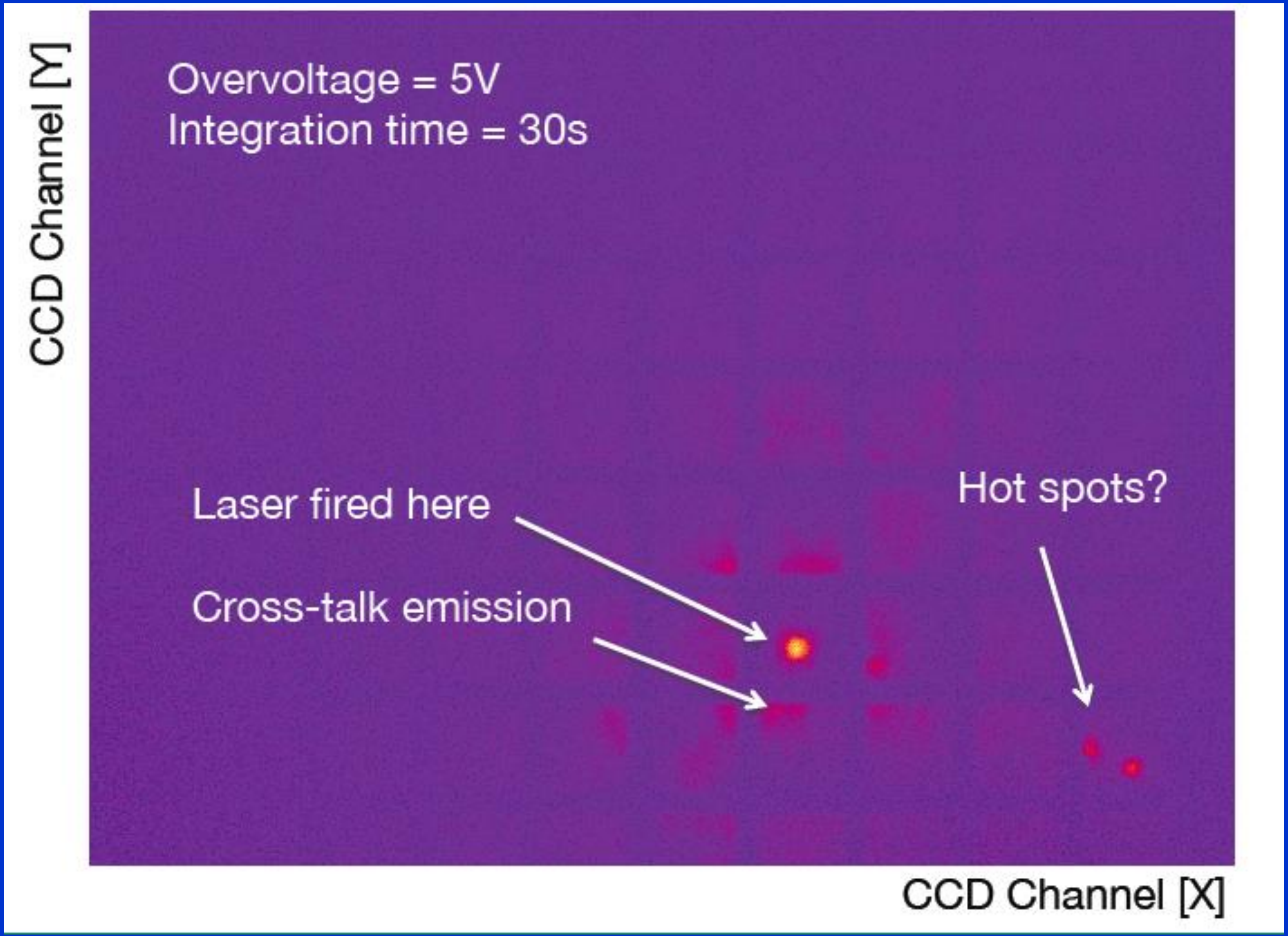
Cross-talk measurement

Strom, et al, ICASiPM, 2018



Cross-talk measurement

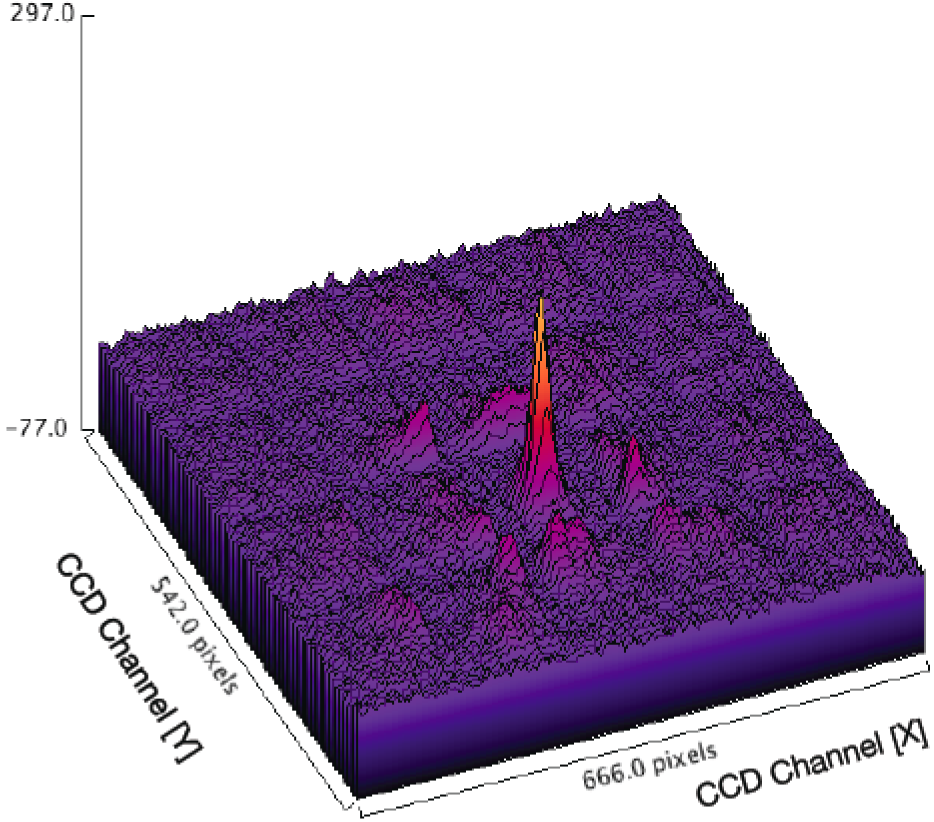
Strom, et al, ICASiPM, 2018

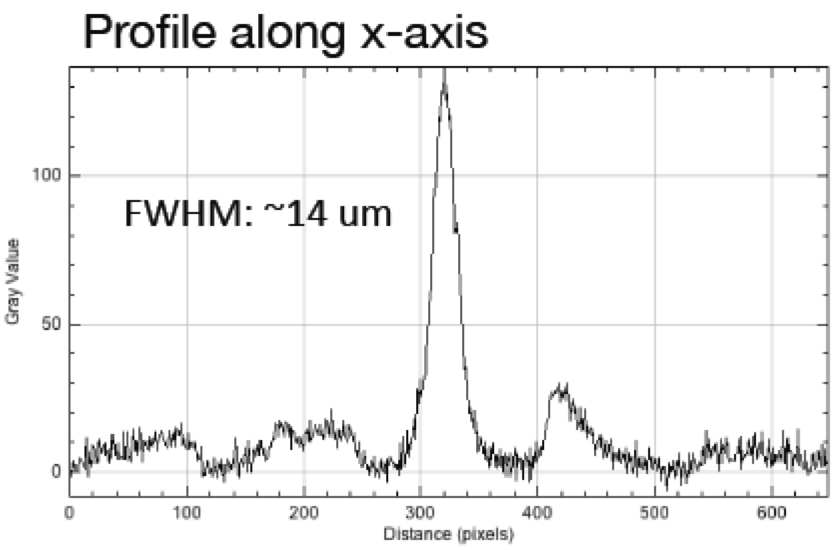


X-talk visualized

Strom, et al, ICASiPM, 2018

- The laser light is focused on a single cell.
- Emission is observed from the central cell and also neighboring cells.

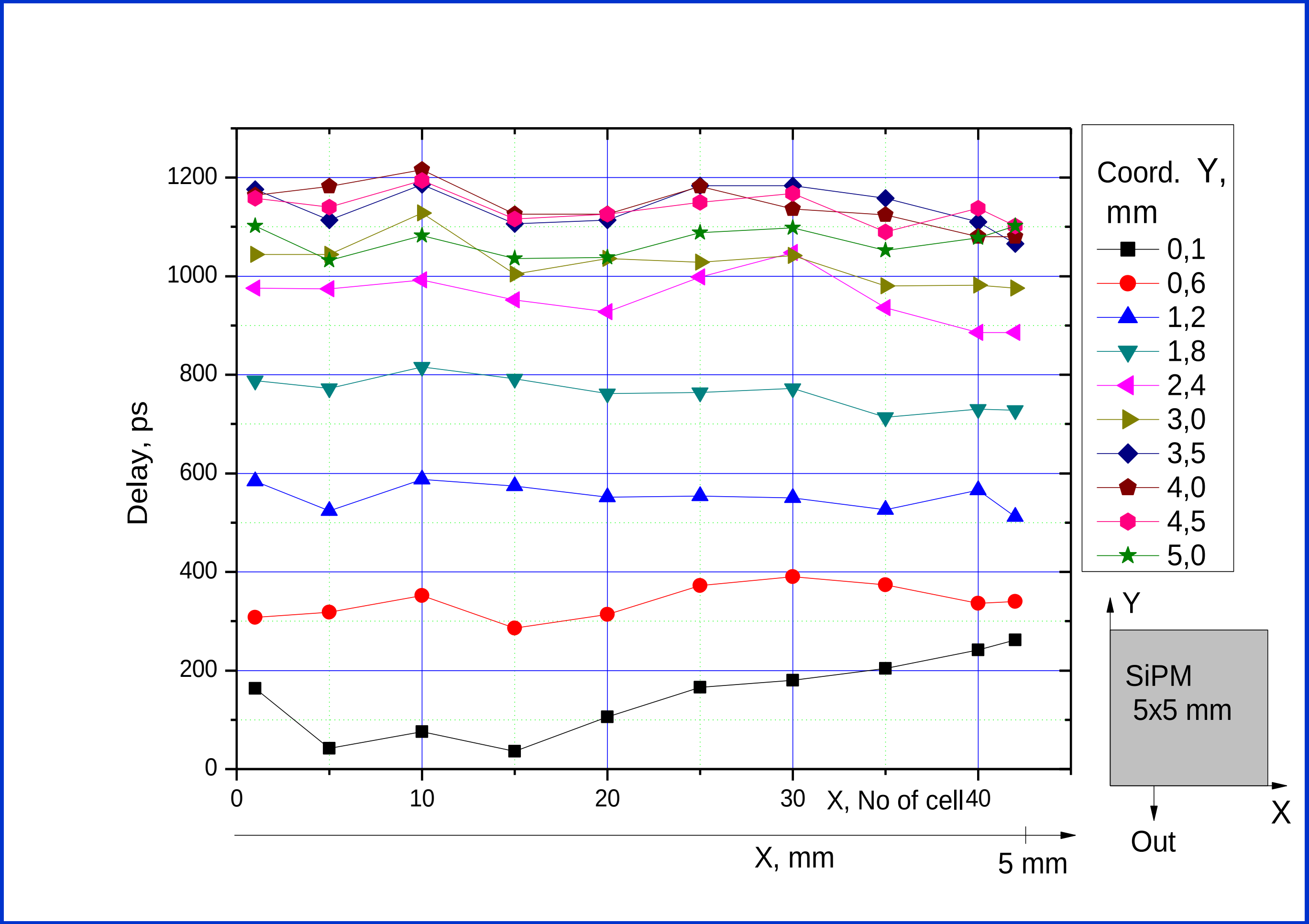




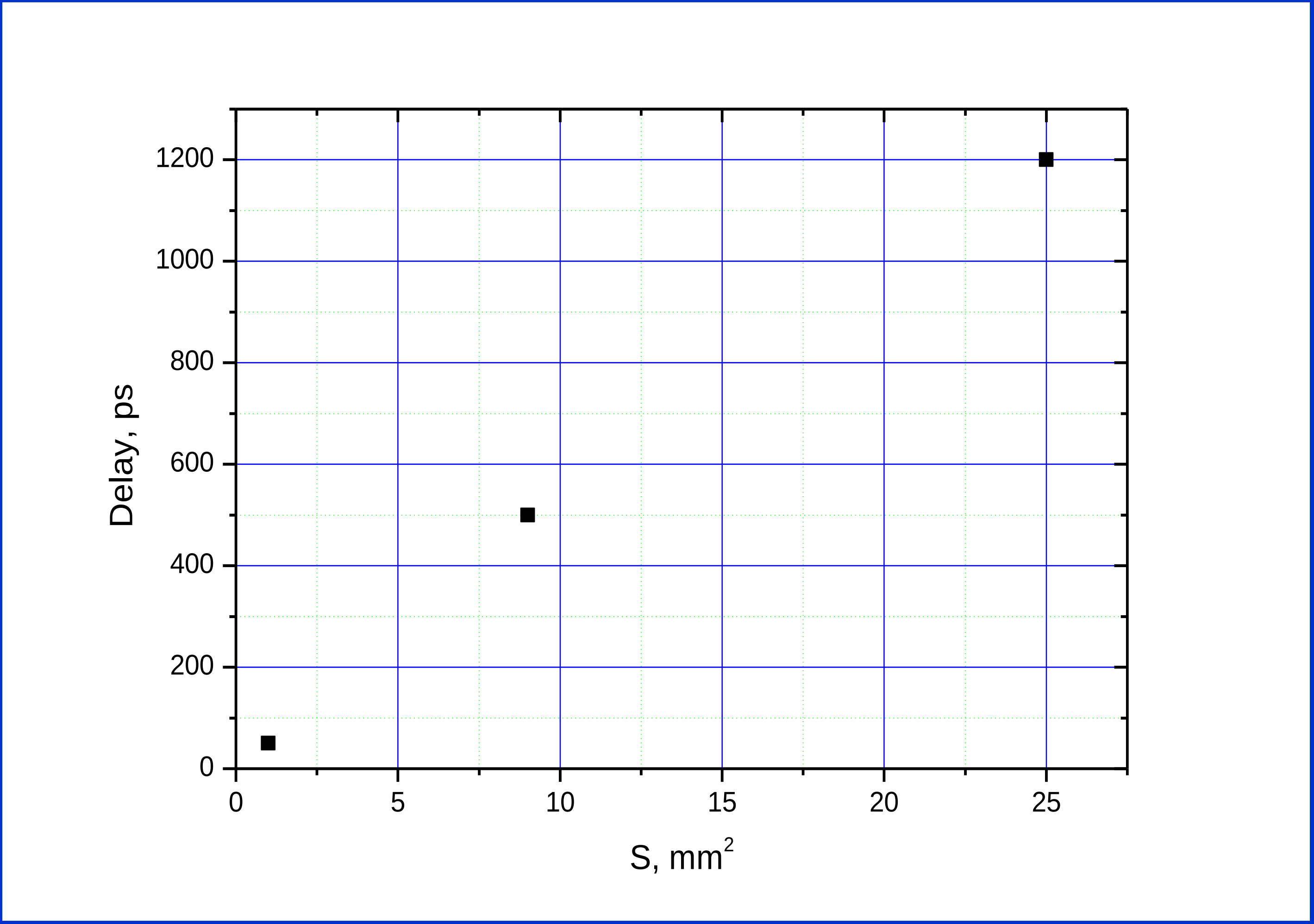
Implications of 8-12µm Transverse Size of Geiger Avalanches

- 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

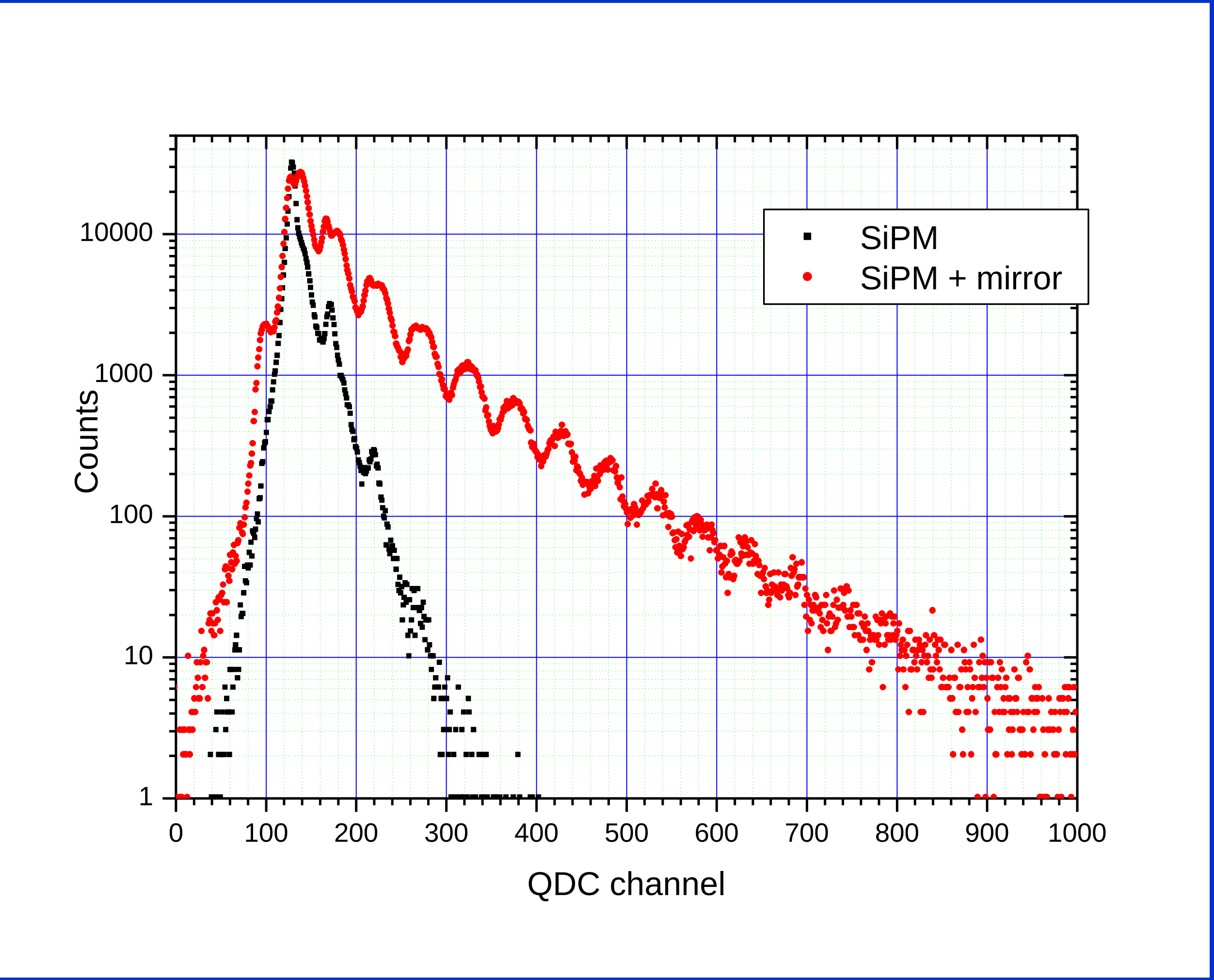
SiPM signal delay dependence on illuminated μ-cell location; ultra-fast laser pulse was used



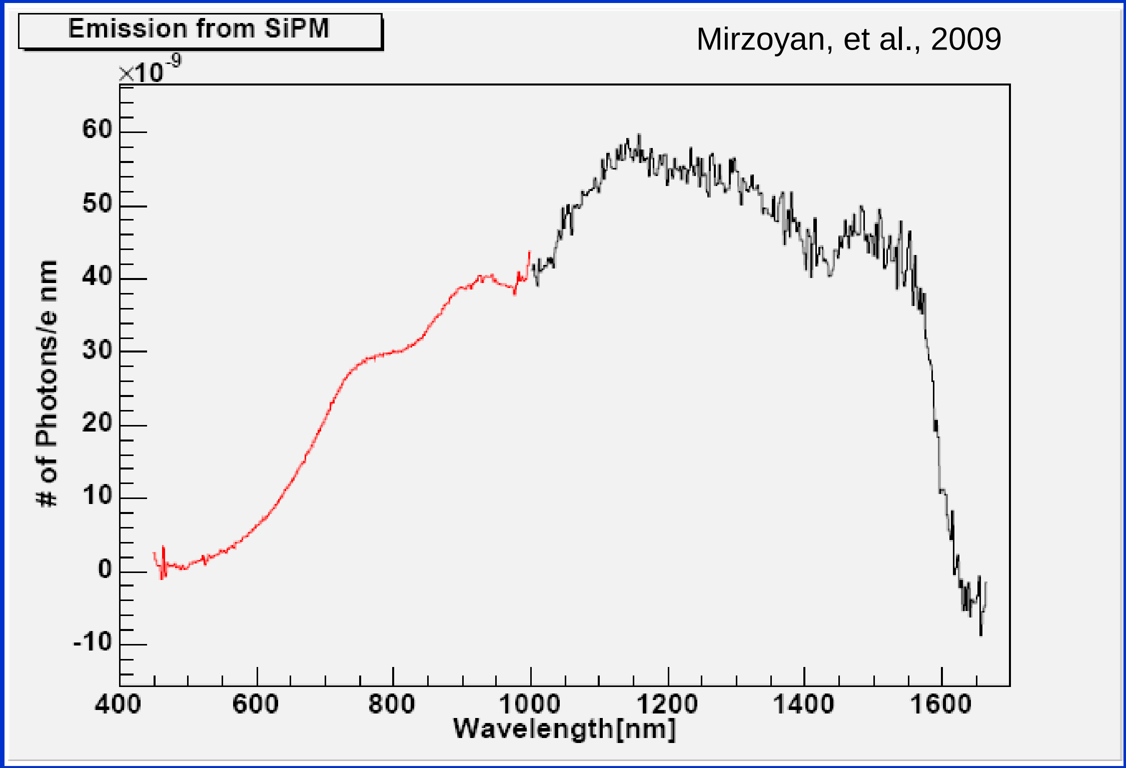
SiPM signal delay dependence on the SiPM chip area



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

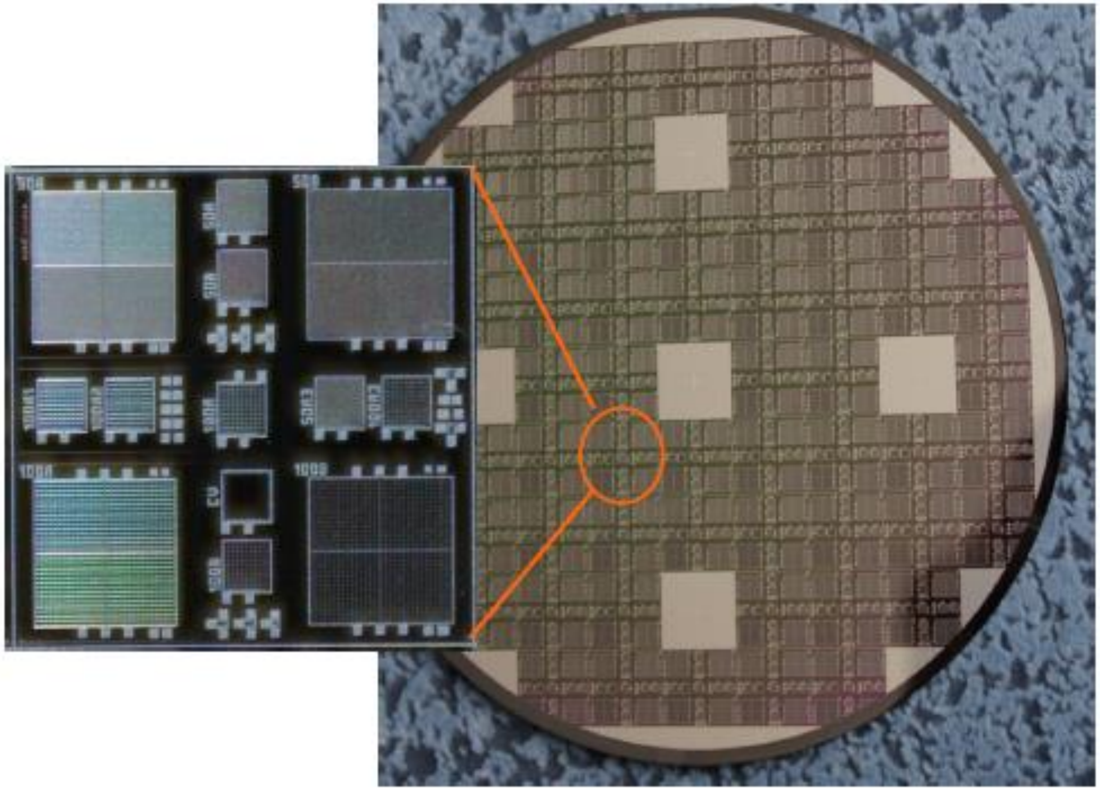
1x1 and 3x3 mm²

- μ-cell pitch

50 and 100 μm

- Geom. Eff.

40-80%



18 different modifications

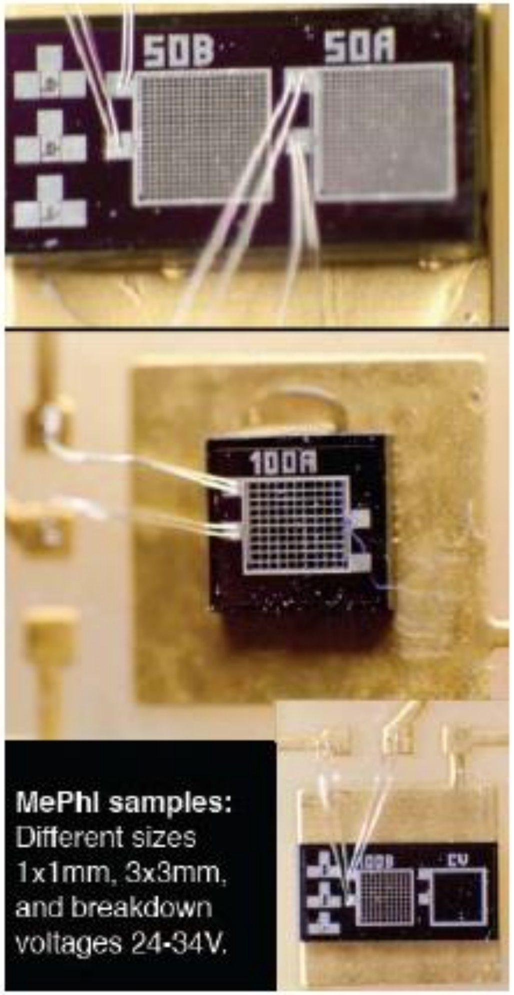
Special Features

Very high UV sensitivity

Record high PDE

Geometrical efficiency 80%

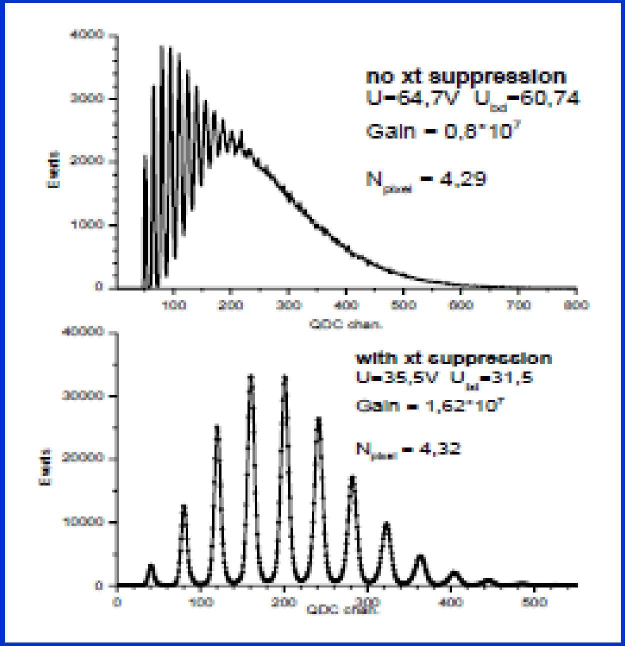
Very low temperature dependence

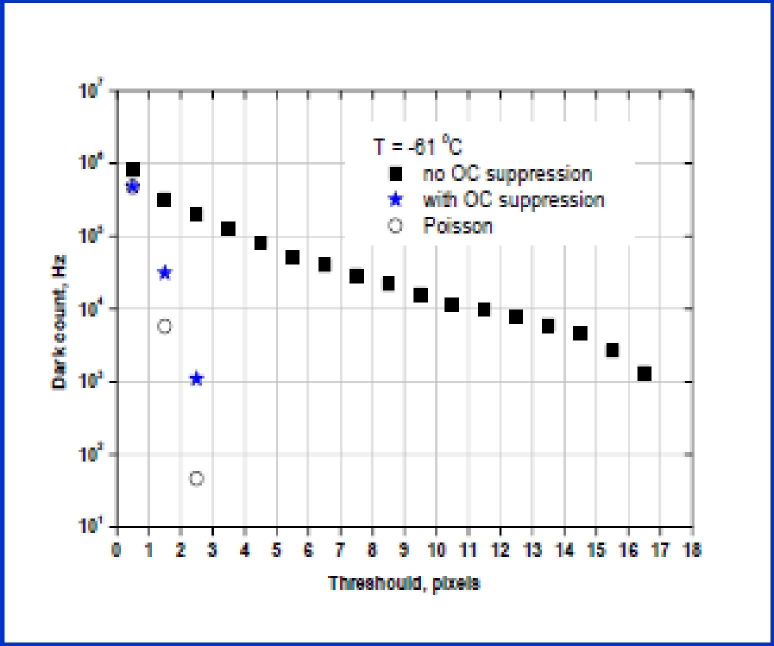


X-talk suppression is improving the performance

Known ways to suppress X-talk:

a) trenches
b) 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

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

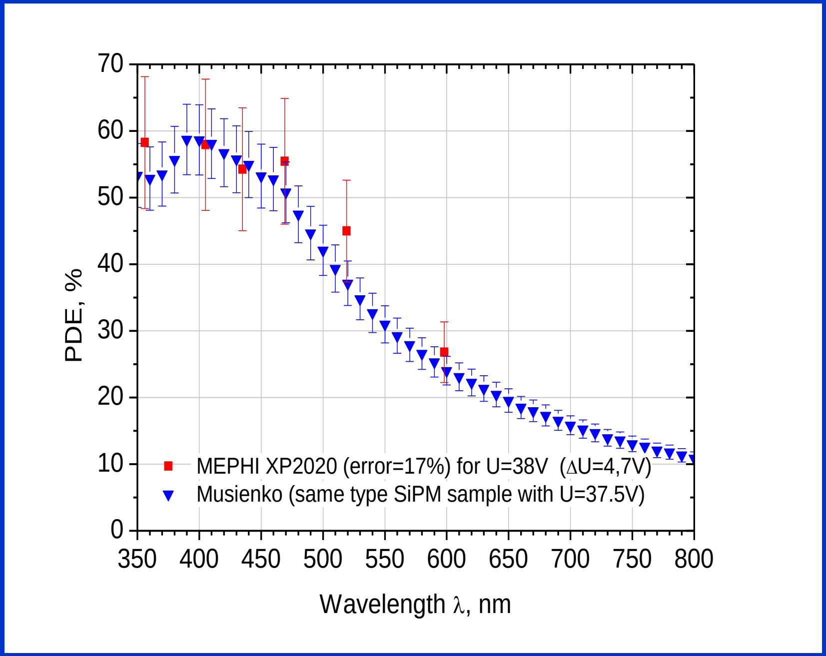
- Ways to suppress the X-talk:
  - Isolating trenches, total internal reflection: reduction 8-9 times;
    (intelectual property)
  - 2nd p-n junction for isolating the bulk from the active region: reduction 4-5 times;
    (intelectual property)
  - High-energy ion implantation: reduction ≥ 2-times
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

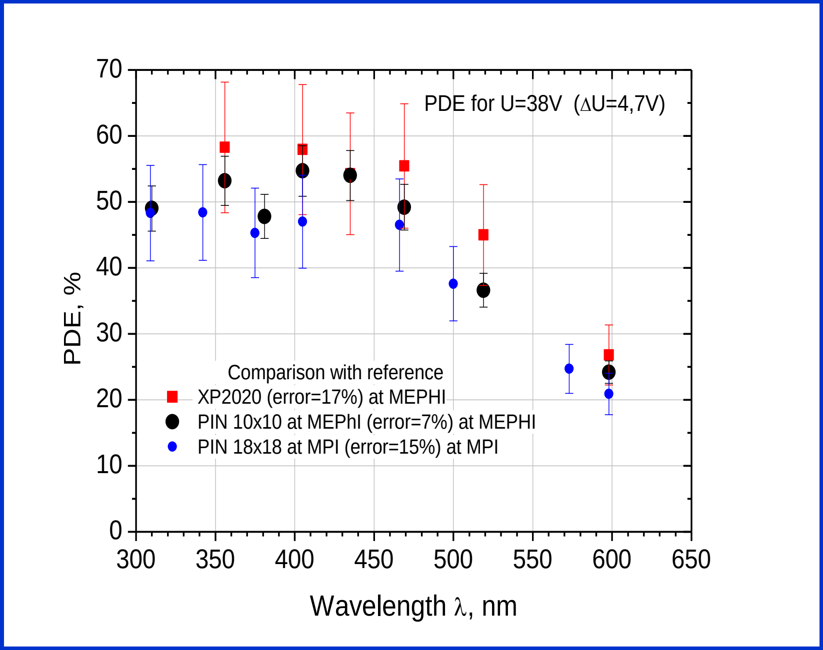
Record high PDE (pulsed mode LED, 100B type SiPM, 1x1 mm²)

Measurements at MEPHI and at CERN (Y.Musienko)

Dolgoshein, et al, 2012

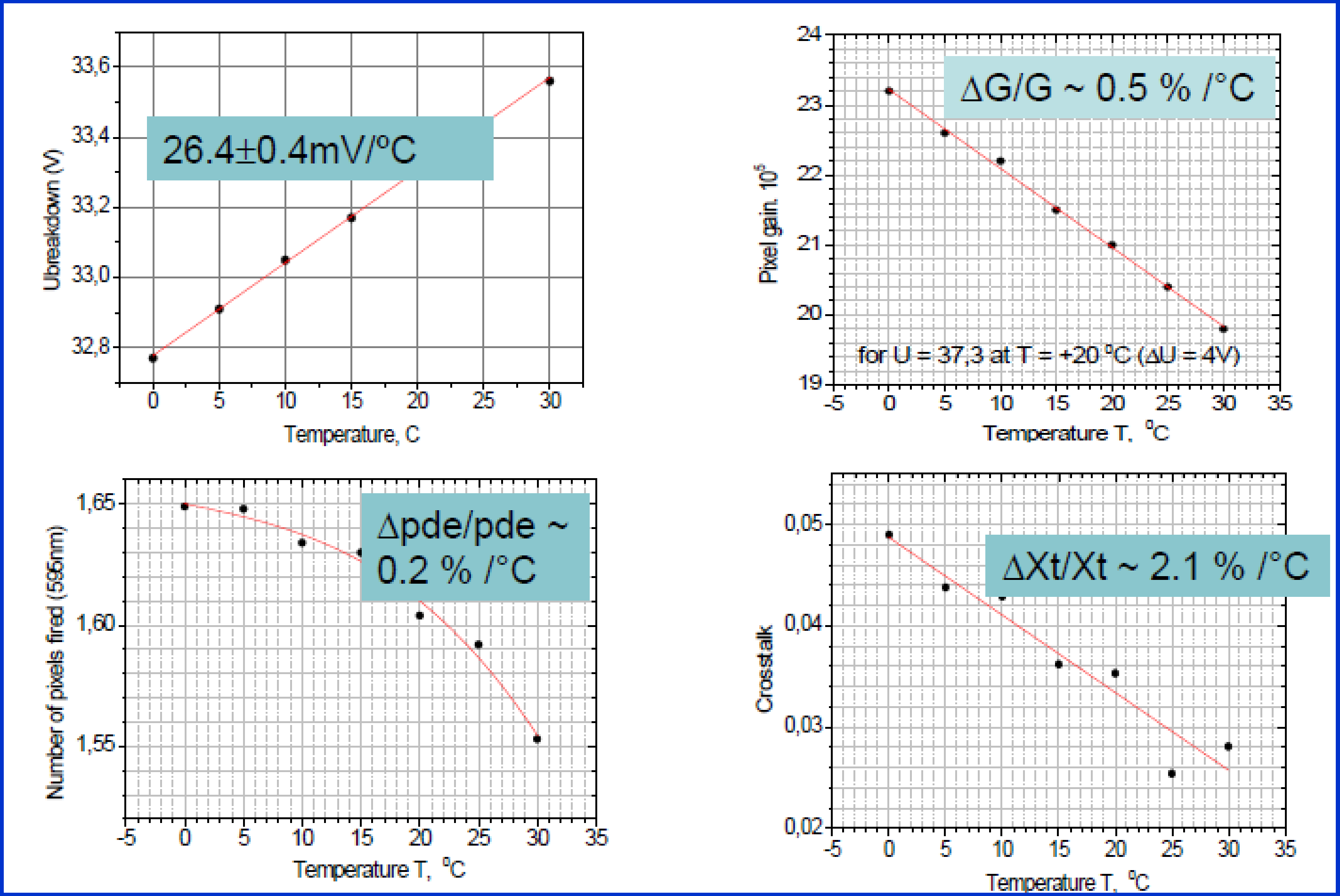
Measurements at MEPHI and at MPI





All results are consistent within experimental errors

Achieved T° dependence: 0.5 % /°C



Hamamatsu LVR2 series of SiPM

Romeo, et al, 2018

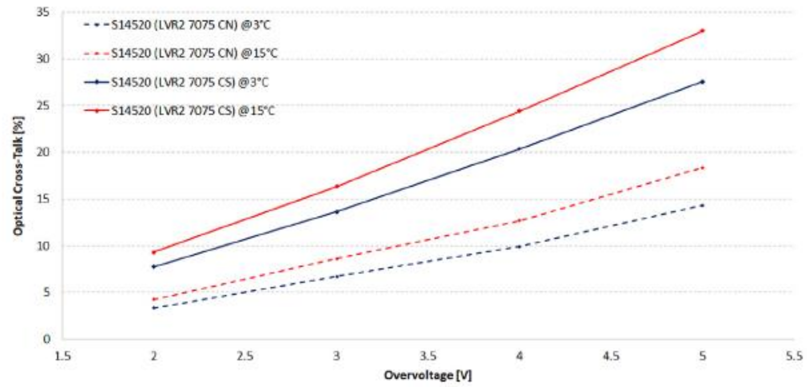


Fig. 9. OCT versus over-voltage at 3 °C and at 15 °C. The CN series shows a lower OCT compared to the CS series because of the protective coating in the CS series. The electronics is responsible for the different behaviour at the two temperatures.

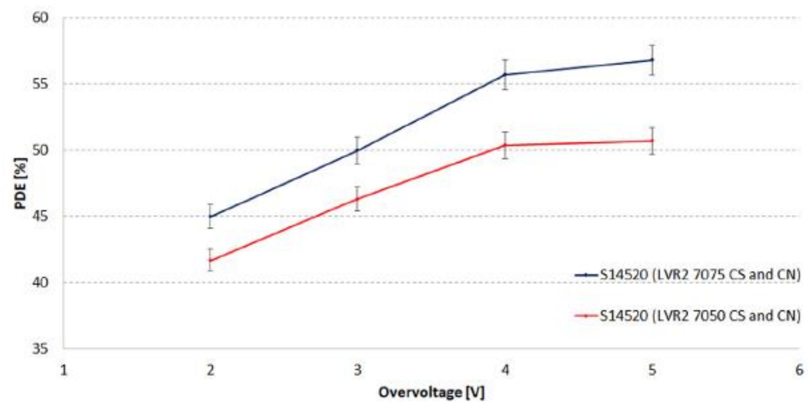


Fig. 10. PDE versus over-voltage at 405 nm. LVR2 7075 CS and CN are compared to LVR2 7050 CS and CN.

Hamamatsu LVR2 series of SiPM

Romeo, et al, 2018

G. Romeo et al.   *Nuclear Inst. and Methods in Physics Research, A 908 (2018) 117–127*

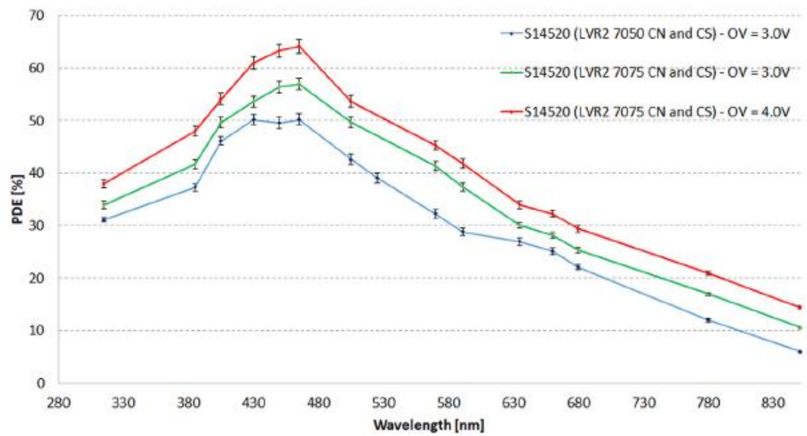
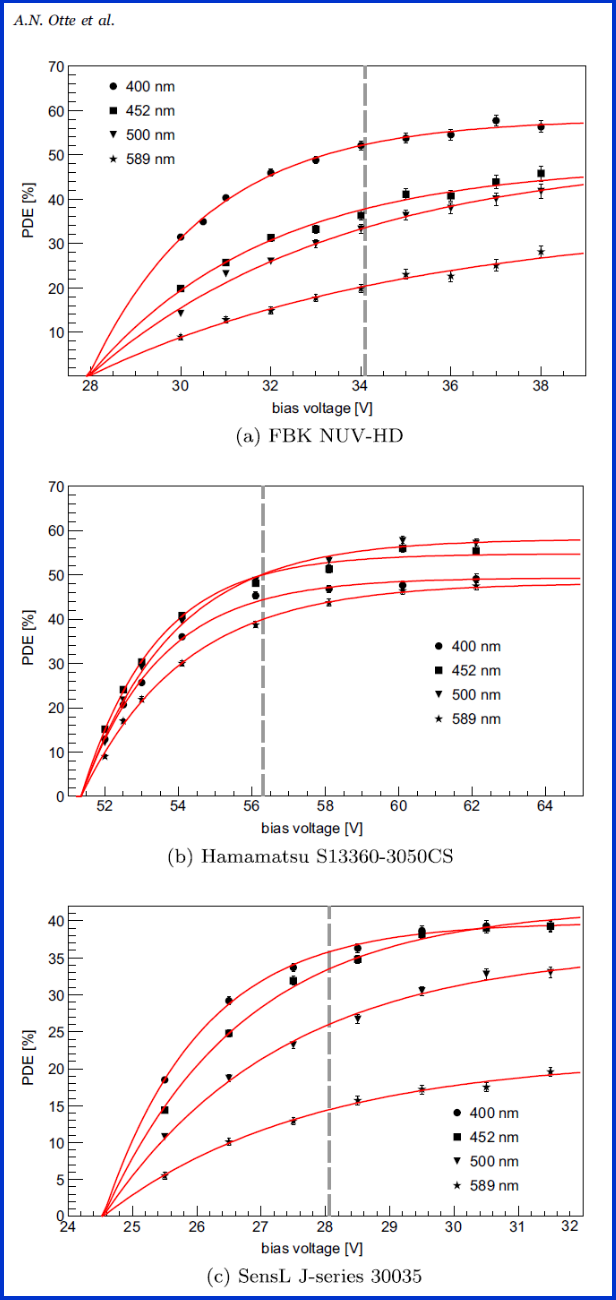


Fig. 11. *PDE* measurements of the characterized LVR2 7075 CS and LVR2 7075 CN detectors at an over-voltage of 3.0 V and 4.0 V are carried out in the 310–850 nm spectral range. The PDE of LVR2 7050 CS and CN at an over-voltage of 3.0 V is also added for comparison. A PDE of 57% at an over-voltage of 3.0 V is achieved at wave-lengths in the range 450–470 nm. A PDE of 64% at an over-voltage of 4.0 V, where a reasonable OCT is measured.



(a) FBK NUV-HD
(b) Hamamatsu S13360-3050CS
(c) SensL J-series 30035

PDE of SiPM from different manufacturers

Otte, et al, 2017

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