Low Light Level Sensor Applications and Needs

Razmick Mirzoyan

Max-Planck-Institute für Physik

Munich, Germany

The most complex light sensors

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

• dynamic range of 13 orders of magnitude !

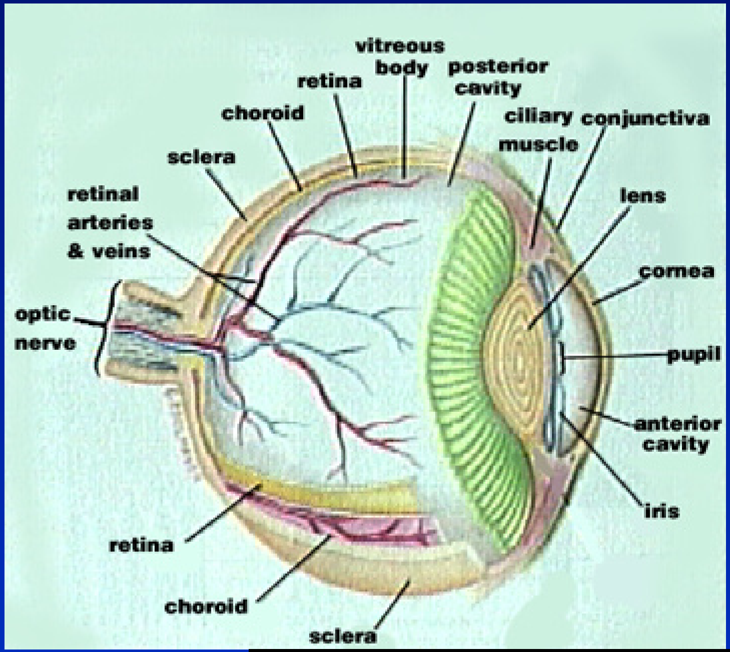
• angular resolution ~ 1‘ (oculists call it 100 % sight)

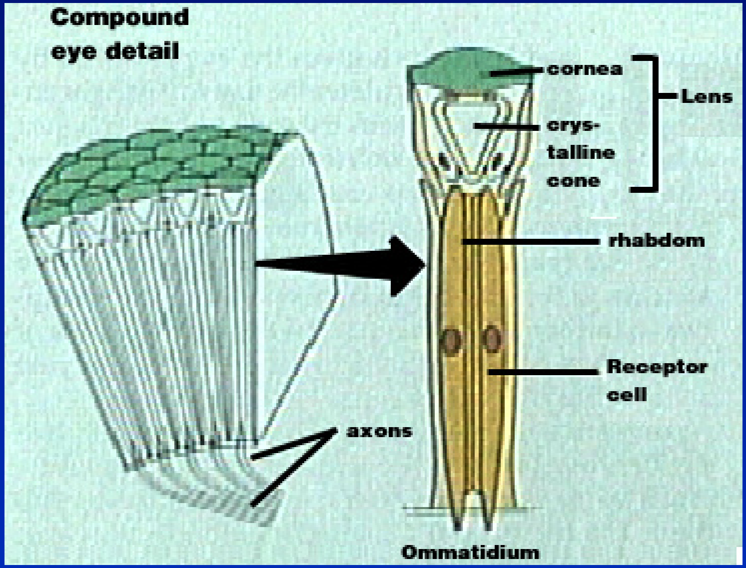
• integration time ≥ 30 ms,

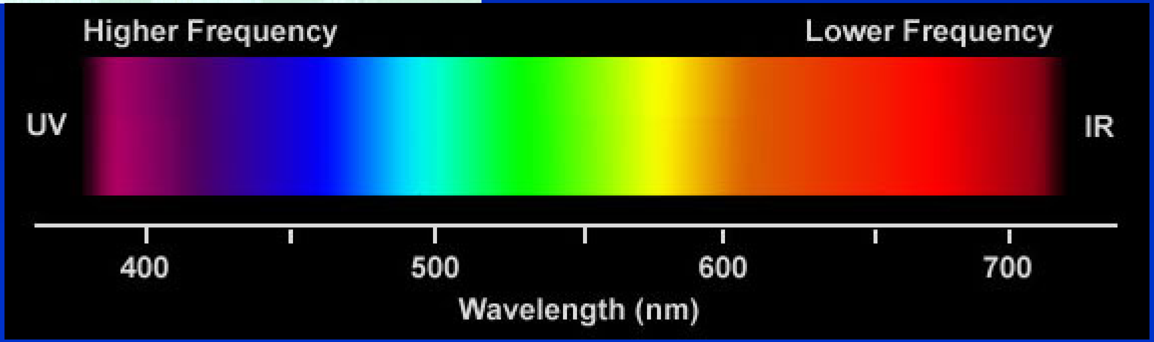
•threshold value for signals

  - 5-7 green photons (after few hours adaptation in the darkness)
  - 30 photons on average in the dark

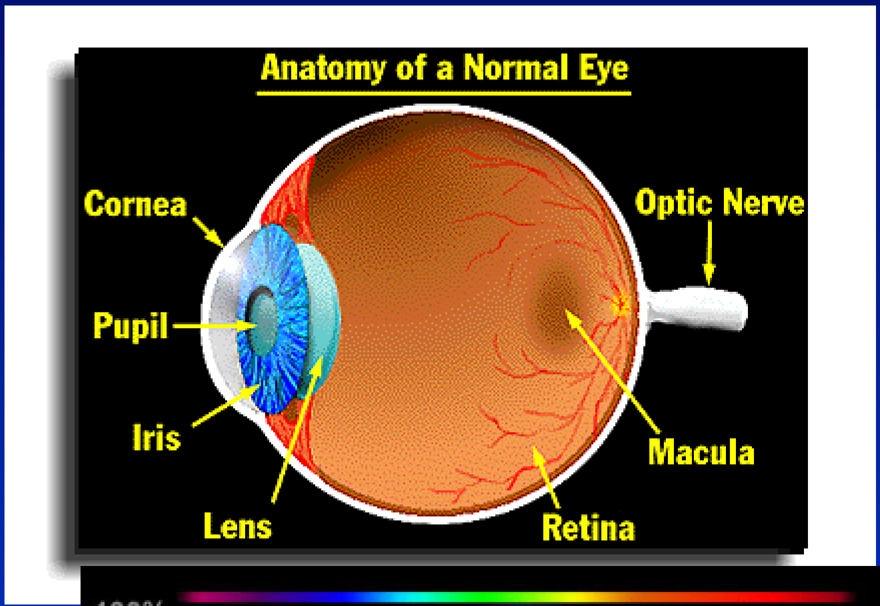
Complex light sensors, that at this very moment we are using

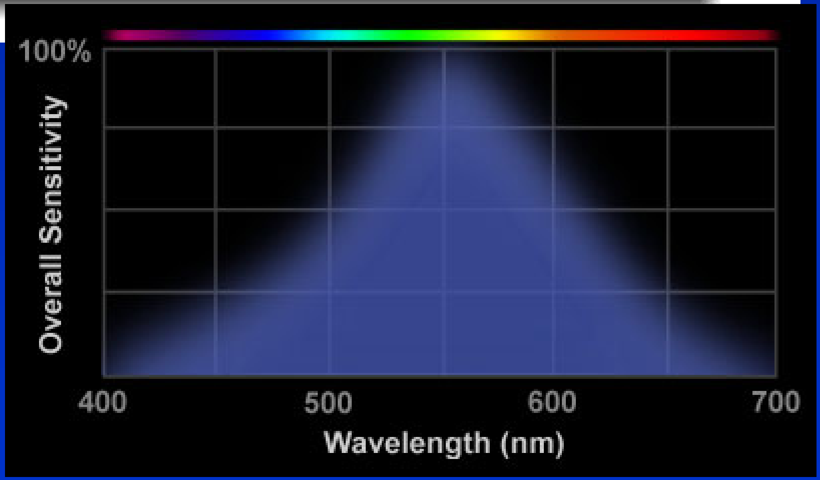


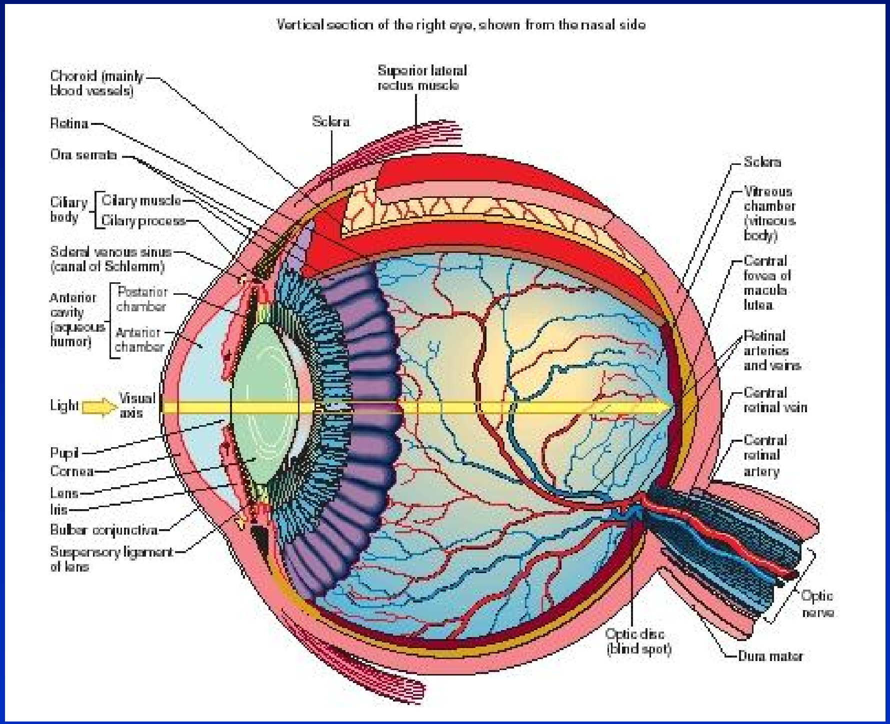




Complex light sensors







What do we know and we can do ?

- Because of the complexity of the human eye‘s operation the humans started looking into the things much simpler and easier, namely the man-made light sensors.
- Surprisingly the humans could improve strongly produced by them light sensors
  - Increasing in some cases the QE towards much higher value (for some sensors 80-95 %)
  - Making them ultra-fast

(perhaps these characteristics were/are not essential for our survival on Earth)

What LLL sensor can we dream about ?

- Die eierlegende Woll-Milch-Sau (german)

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

What LLL sensor can we dream about ?

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

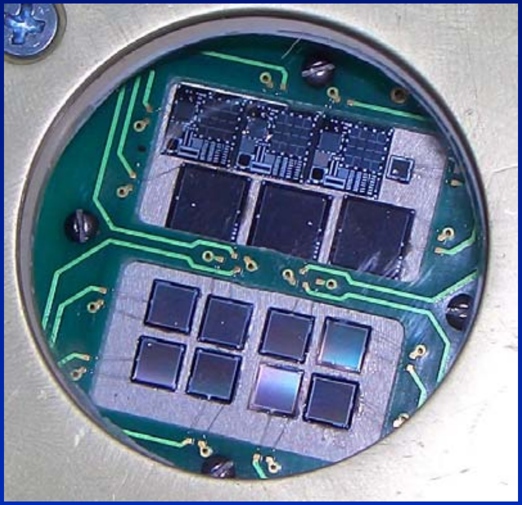
Light conversion into a measurable

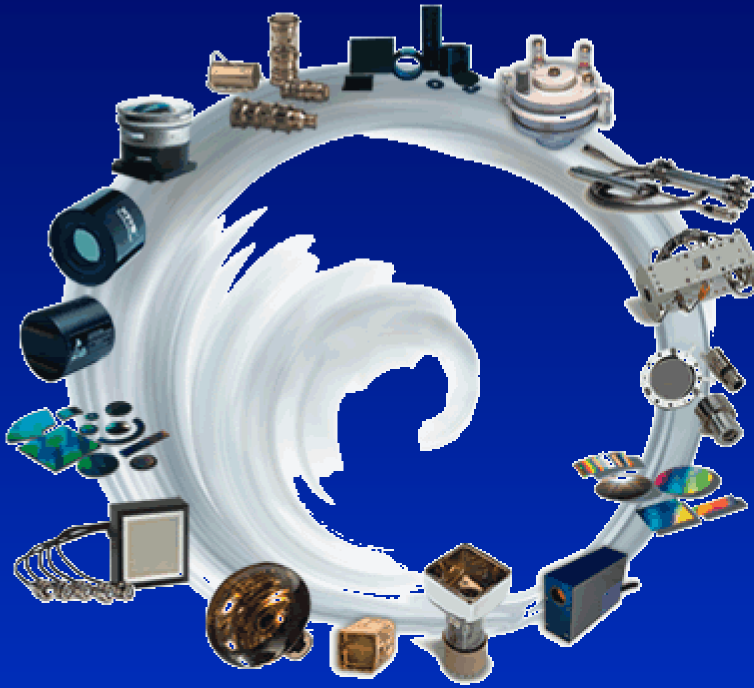
- Visible light can react and become measurable by:
  - Eye *(human: QE ~ 3 % &* animal), plants, paints,...
  - Photoemulsion *(QE ~ 0.1 – 1 %)* (photo-chemical)
  - Photodiodes (photoelectrical, evacuated)
    - Classical & hybrid photomultipliers *(QE ~ 25 %)*
      QE ~ 45 % (HPD with GaAsP photocathode)
  - Photodiodes *(QE ~ 70 – 80 %)* (photoelectrical)
    - PIN diodes, Avalanche diodes, SiPM,...
    - photodiode arrays like CCD, CMOS cameras,...

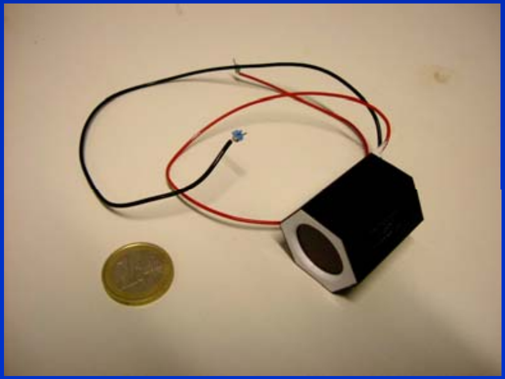
Short Reminder

	Metal	Semiconductor
Photon → e-	High reflectivity Low efficiency	Low reflectivity High efficency
e- motion	Low efficiency: e- e- scattering	High efficiency low phonon loss
Surface barrier	Work function > 2 eV	Determined by e- affinity

The „zoo“ of LLL sensors







Radiopurity

BUS 2006

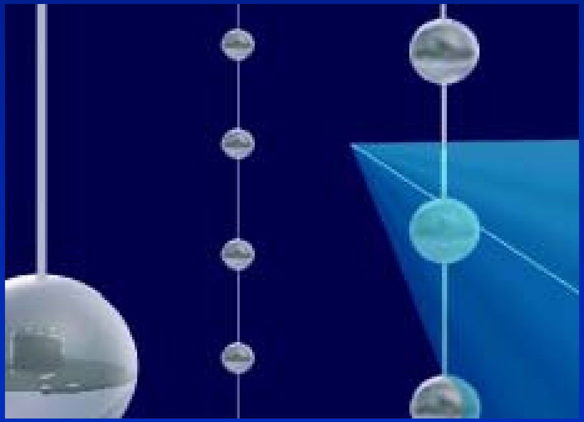
Electron Tubes Limited

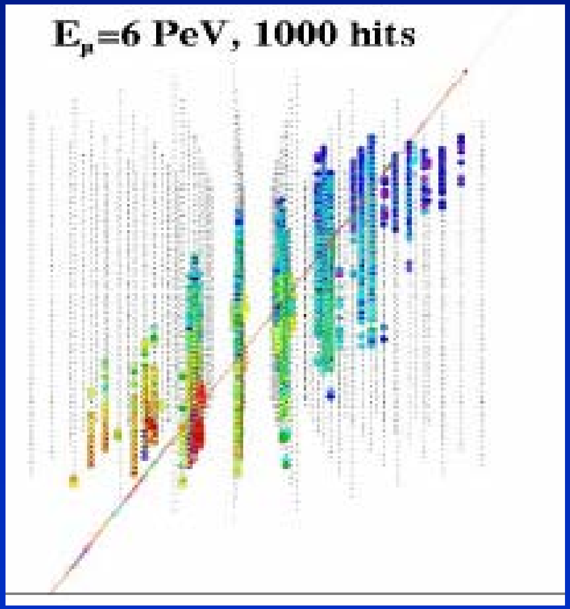
electron tubes

For example: improving radiopurity

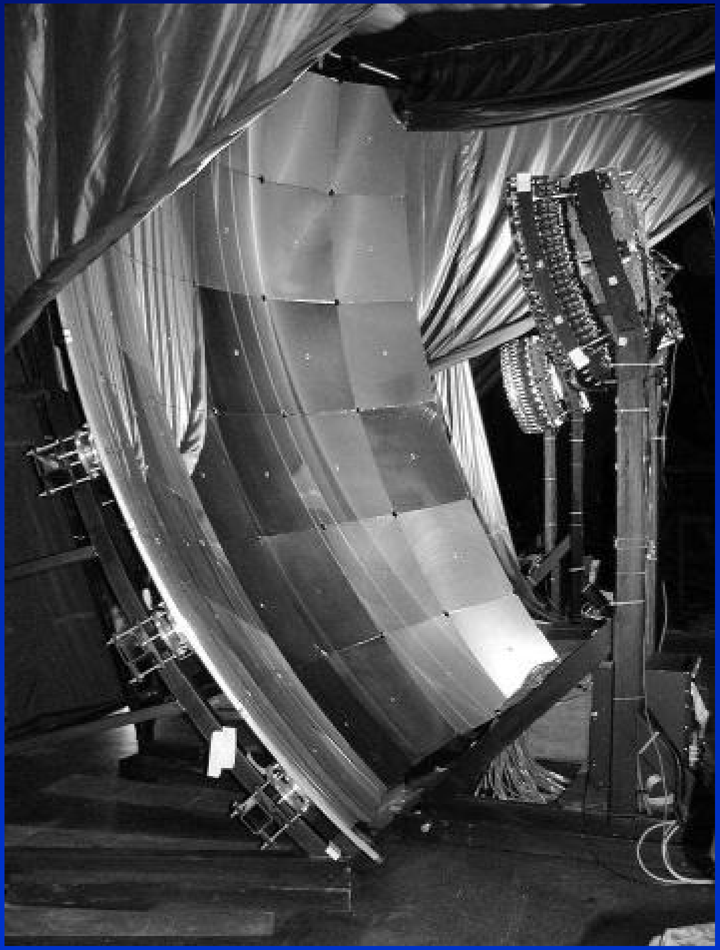
Photomultiplier Type	Potassium ppm	Thorium ppb	Uranium ppb	
Standard glass	60000	700	800	
ETL Standard glass pmt	1400	900	1100	
ETL Low background pmt	300	250	100	
ETL Ultra-low background pmt	60	30	30	
ETL Metal-sapphire pmt <0.1Bq/pmt	< 1	1	5	*NEW

The IceCube experiment

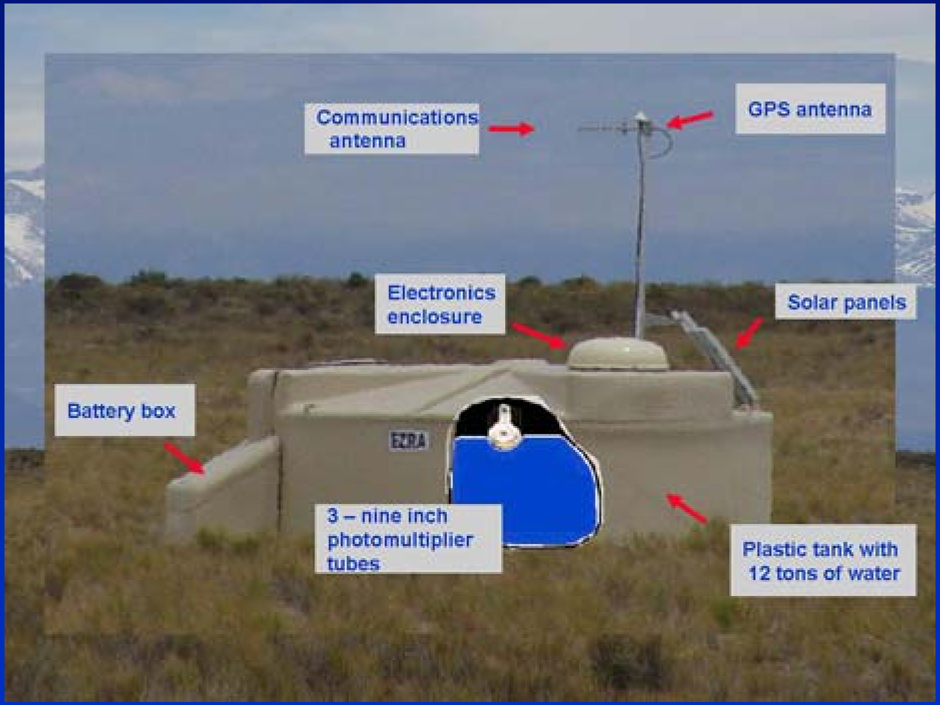


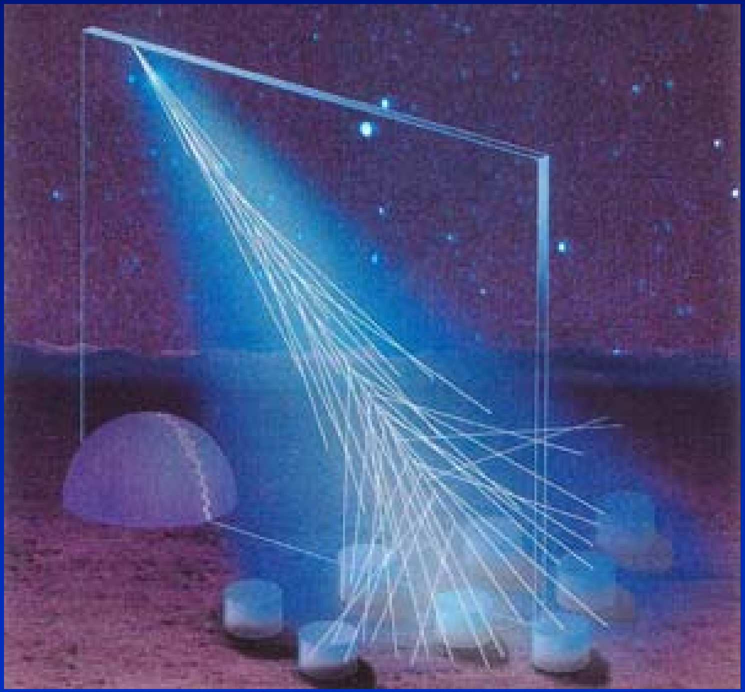


World largest cosmic ray detector: AUGER

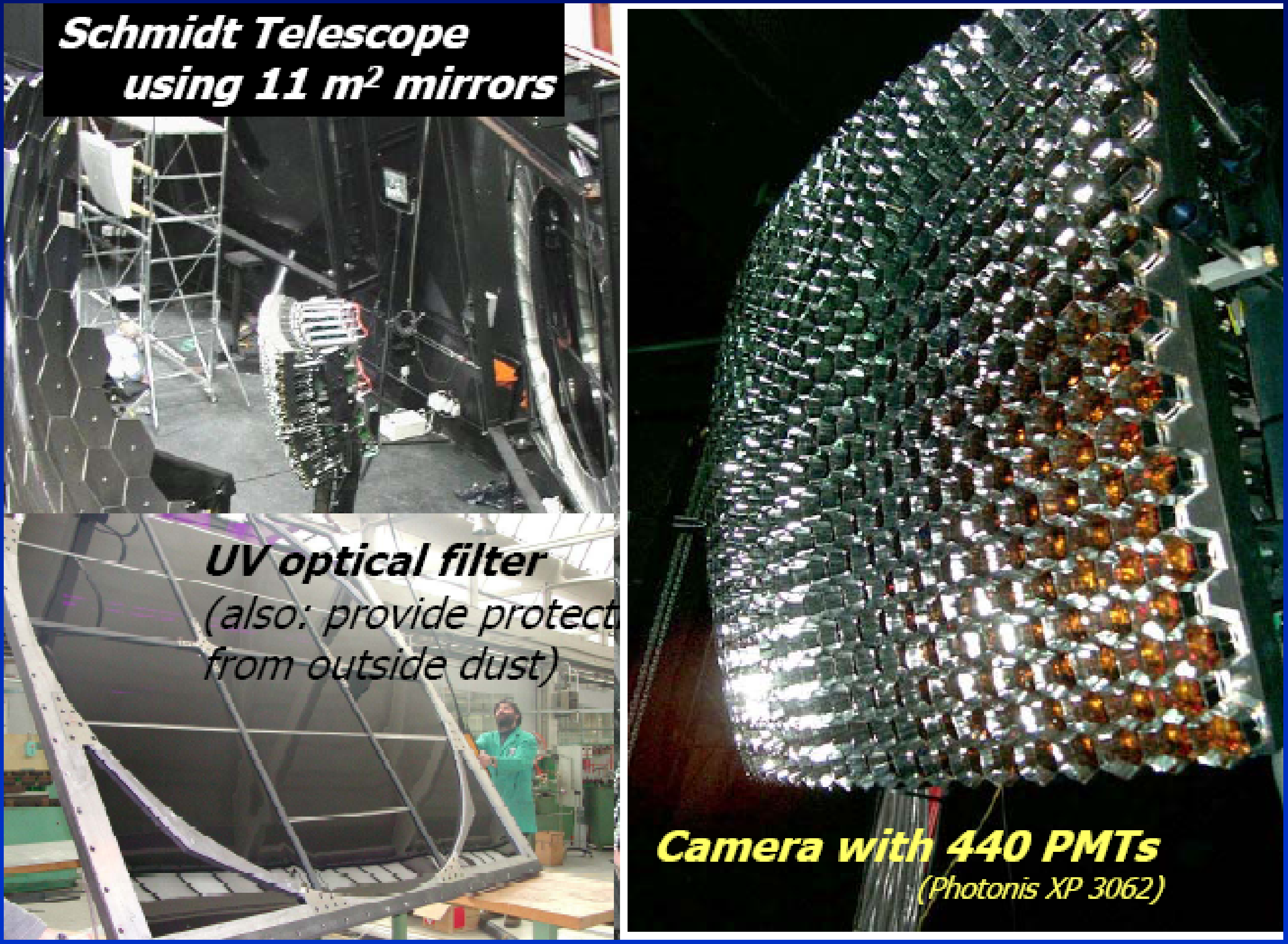


AUGER


Communications antenna
GPS antenna
Electronics enclosure
Solar panels
Battery box
EZRA
3 – nine inch photomultiplier tubes
Plastic tank with 12 tons of water

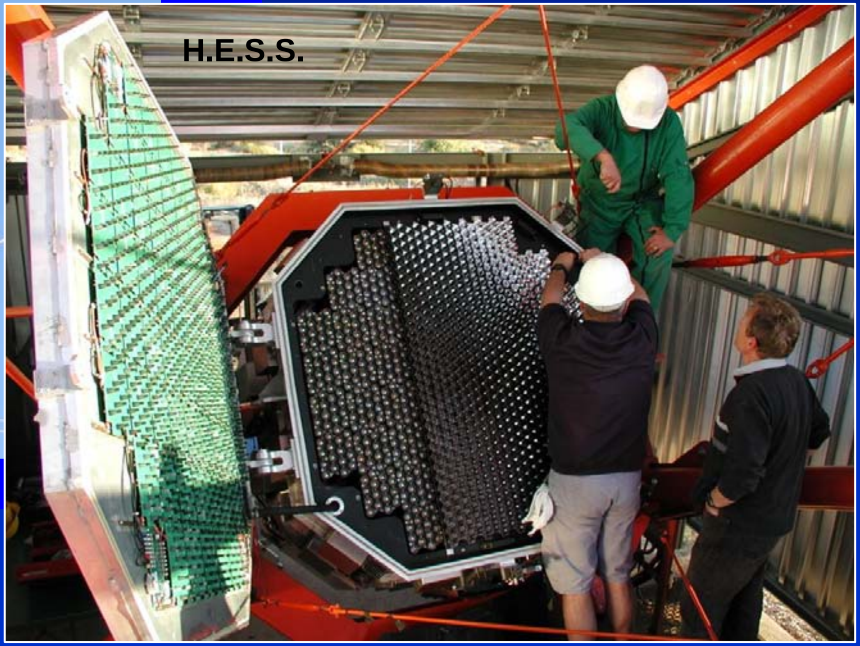


AUGER

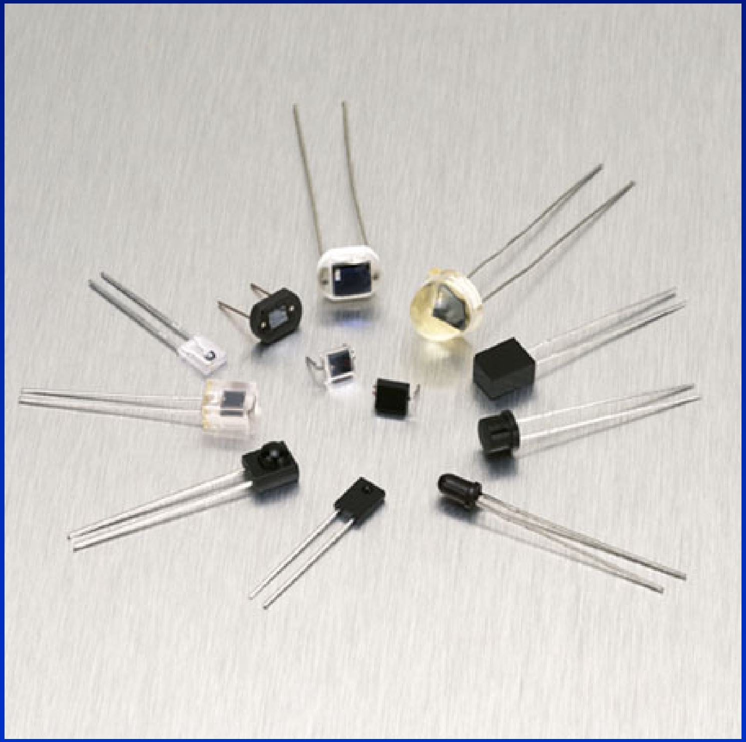


Schmidt Telescope
using 11 m² mirrors
UV optical filter
(also: provide protect
from outside dust)
Camera with 440 PMTs
(Photonis XP 3062)

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



APD



Quantum Efficiency

- Quantum efficiency (QE) of a sensor is defined as

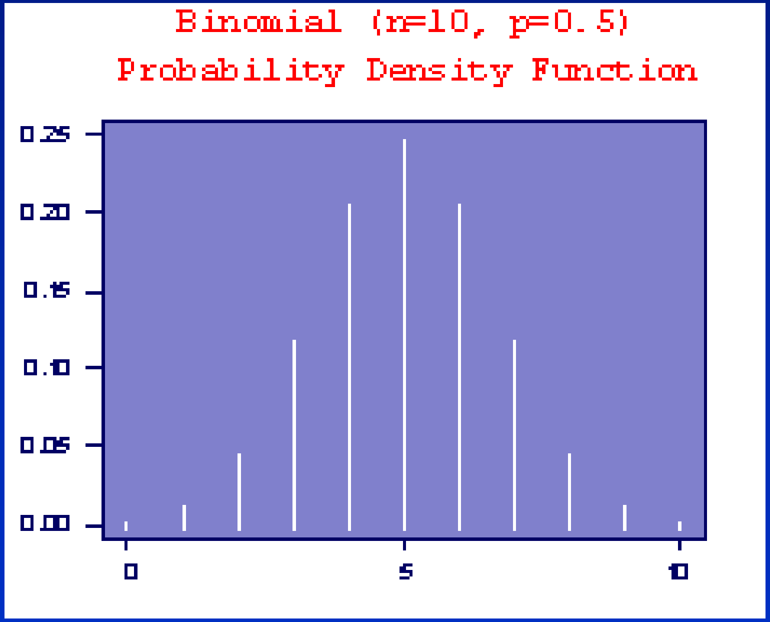
  QE = N(ph.e.) : N(photons)

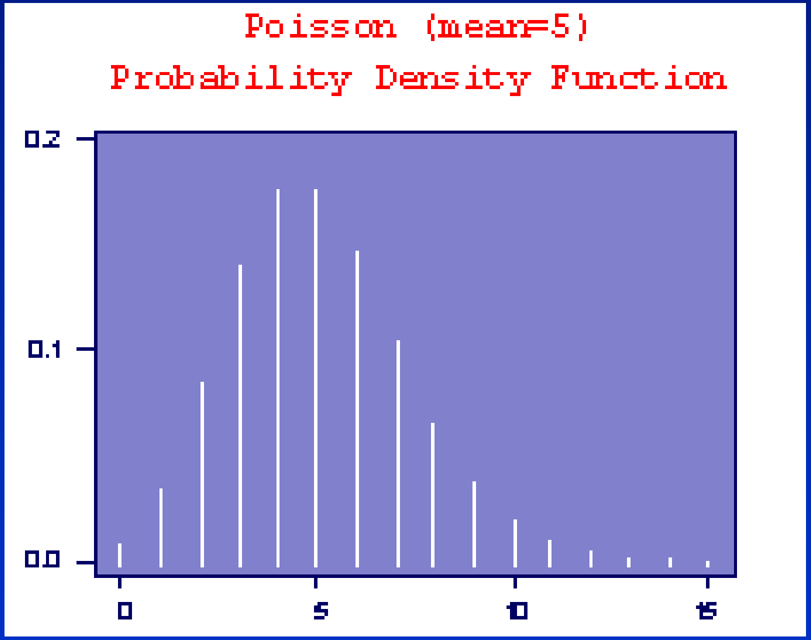
- Conversion of a photon into ph.e. is a purely binomial process (and not poisson !)
  - Assume **N photons** are impinging onto a photocathode and every photon has the same **probability P** to kick out a ph.e..

    Then the

    mean number of ph.e.s is **N x P** and the **Variance** is equal to **N x P x (1 – P)**

Differences between binomial and poisson distributions





Signal to noise ratio

The signal-to noise ratio (SNR) of a given photocathode with QE=P can be calculated as

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

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

P	0.1	0.3	0.9	0.95	0.99
SNR	0.33	0.65	3	4.4	9.9

Often we need not only high QE but also very fast detectors

- In *1J* optical energy, for example of wavelength of λ, there are

$$N(\text{photons}) = \lambda(\mu m) \times 5.03 \times 10^{18}$$

For λ=0.4μm (blue) N(photons)=2×10^{18}

Only ~ 10^{-5} part of the energy of an air shower goes into the emission of fluorescence light and a 10^{-4} part into the emission of Cherenkov light. So for a 10^{18} eV shower (*E ~ 1J shower*) one has 10^{13} fluorescence photons (distributed isotropically, or roughly 8000 ph/m² on a 10 km distance, arriving within ~50μs) and 10^{14} Cherenkov photons (distributed essentially within a cone of ~1° opening angle, arriving within ~5-10 ns).

Real LLL Sensors

	PMT	APD	SiPM	HPD	CCD
QE, %	25-27 (35)	60-80	~ 60 ?	25-50	50-80
Time response	> 1 ns	> 1 ns	~ 1 ns	> 1 ns	--------- (gated ?)
Single ph.e.	Yes	No	Yes	Yes	No
Gain	10^4-10^9	50-100	10^5-10^6	> $5x10^4$	---------
Cost	Ok	Ok	Ok ?	Expens.	Expens. depends

Best LLL Sensor Candidates

	PMT	APD	SiPM	HPD	CCD
QE, %	25-27 (35)	60-80	~ 60 ?	25-55	50-80
Time response	> 1 ns	> 1 ns	~ 1 ns	> 1 ns	--------- (gated ?)
Single ph.e.	Yes	No	Yes	Yes	No
Gain	10^4-10^9	30-300	10^5-10^6	> $5x10^4$	---------
Cost	Ok	Ok	Ok ?	Expens.	Expens., depends

Very Fast Detectors for Ultrafast Light Flashes

- Only a few light sensor types can measure very fast signals. If one will require to detect just few ten‘s of photons then one is essentially left with PMTs (also hybrid ones with Avalanche Diode readout) and APDs (or variations of it).
- PIN diode readout is relatively slow, allowing one to work in the regime of ~100 ns pulses.
- In the moment when one starts to search for ns fast detectors, measuring single photons, then there is almost no alternative to classical PMTs.

Why Gaseous Photomultiplier (GPM) ?

Breskin, Light06

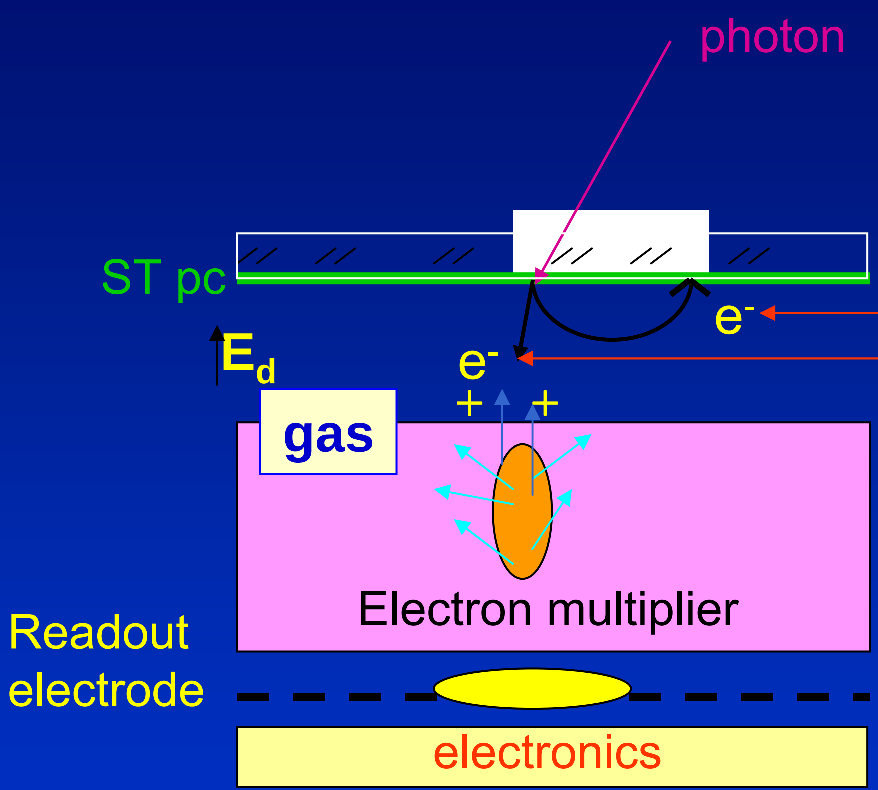
- large area
- flat geometry
- Moderate cost
- Operation in **high magnetic fields**
- Operation at **very low temperatures**
- Sensitivity to **single photons**
- Spectral range from UV to visible
- Fast (sub-ns range)
- High localization accuracy (sub-mm)

Applications:
RICH, scintillators, calorimetry, astroparticle physics, medical, plasma, atomic…etc.

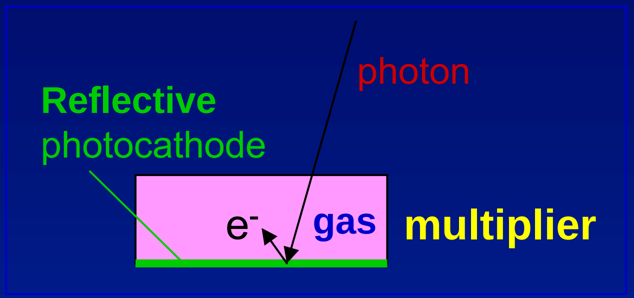
GPM: Physical processes

Breskin, Light06

SEMI-TRANSPARENT GPM



REFLECTIVE GPM

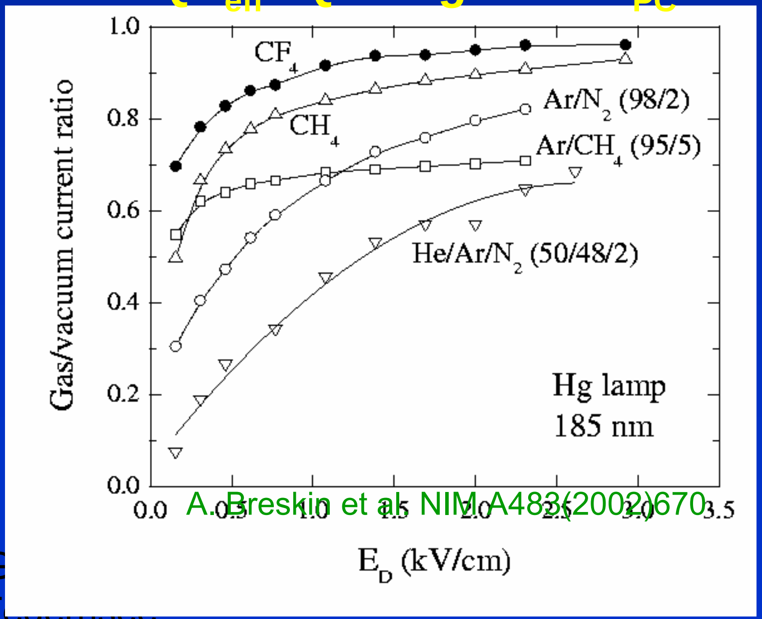


- e^- backscattering in gas (**QE_{eff}<QE**)
- e^- transport (diffusion, collection)

CRUCIAL for single photons

Gas-compatible photocathodes:
UV: CsI, CsBr, CsTe, CVD-diamond…
Visivle: Cs_3Sb, K-Cs-Sb…

QE_{eff} / QE in gas vs E_{PC}



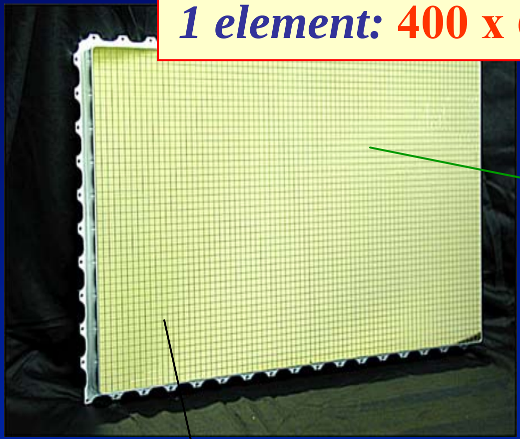
A. Breskin et al. NIM A483(2002)670

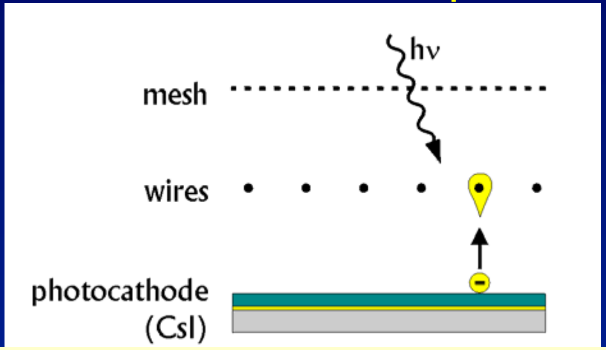
The CERN-ALICE CsI-RICH detector

RICH: Ring Imaging Cherenkov UV-detectors for particle identification

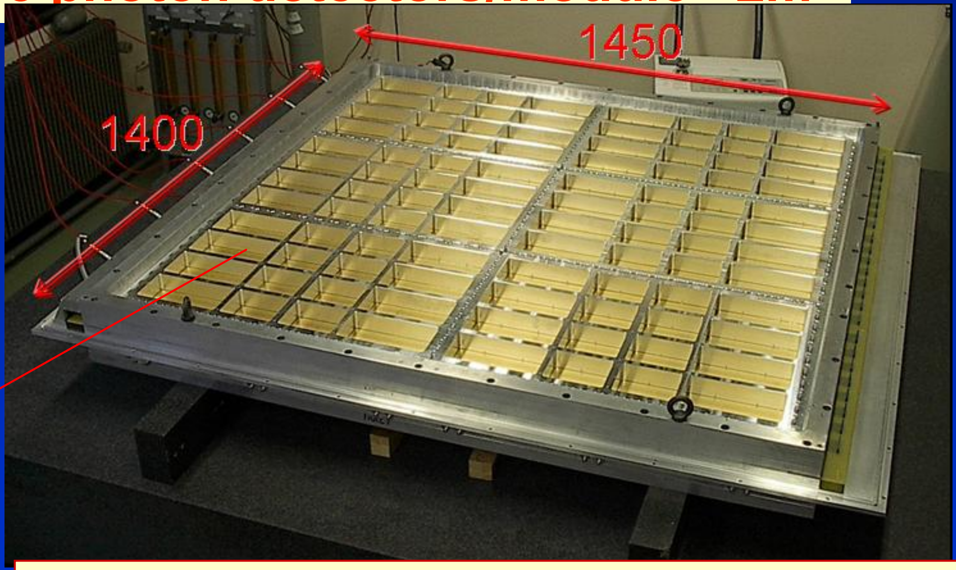
F.Piuz et al. ALICE

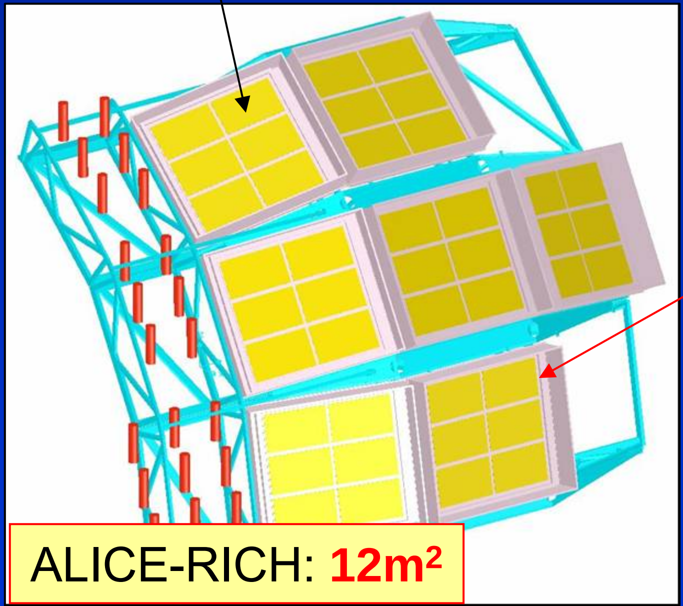
1 element: **400 x 600 mm^2**





6 photon detectors/module ~2m^2





ALICE-RICH: **12m^2**

CsI-MWPC UV-RICH:

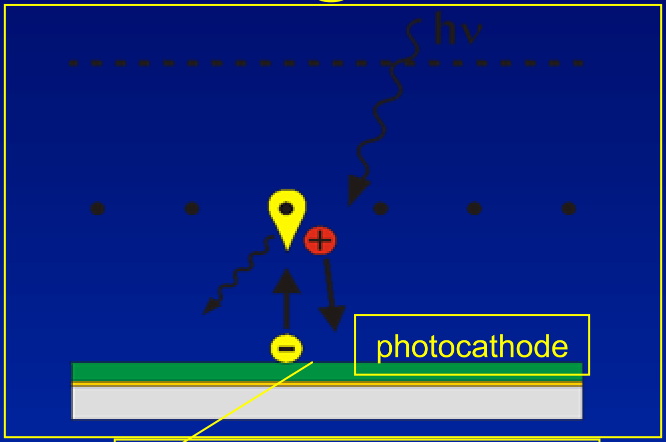
ALICE, HADES, COMPASS, J-LAB….

The e-multiplier: “open” vs “closed” geometry

Breskin, Light06

Wire-chamber GPM

VISIBLE: no way!



CsI on readout pads

open geometry

Photocathode “sees” the avalanche:

Photon-feedback &

Ion-feedback →

-Gain limitations:~**$5\ 10^4$ (UV)**

-Localization problems

-Photocathode damage

closed geometry

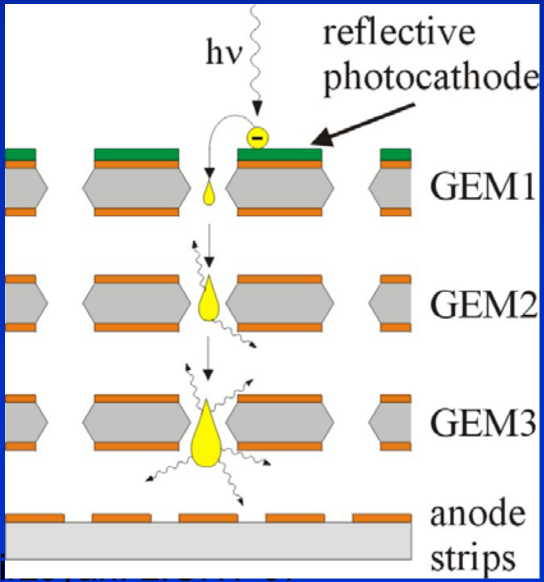
Photocathode “does not see” the avalanche:

No photon-feedback

Low ion-feedback →

-High gain: $\geq 10^6$

-Longer photocathode lifetime



Multi-GEM GPM

VISIBLE: possible!

GPM for visible light

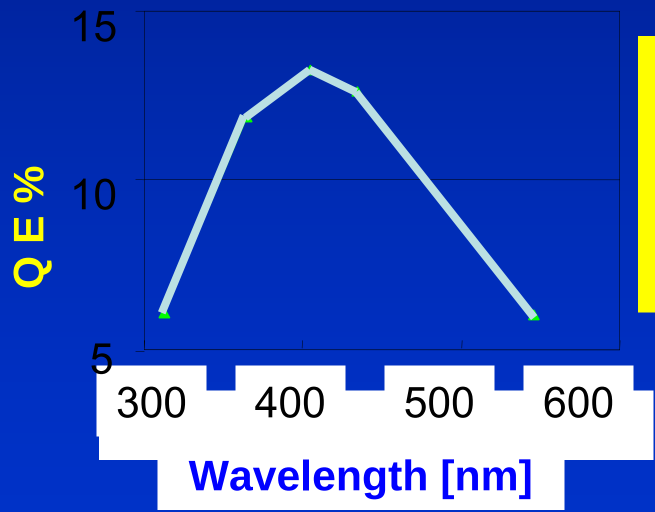
Breskin, Light06

UV: MATURE TECHNIQUE
VISIBLE: Reactive photocathodes, secondary effects ➔ real challenge!

sealed 3 Kapton-GEMs & KCsSb PC

Sealing in gas: In/Sn; 130-150^{0}C

QEeff in Ar/CH4 (95/5) ~ 70% of QEvac ➔ best expected ~20% @360-400 nm



13% = best QE measured after sealing. 2 weeks stability

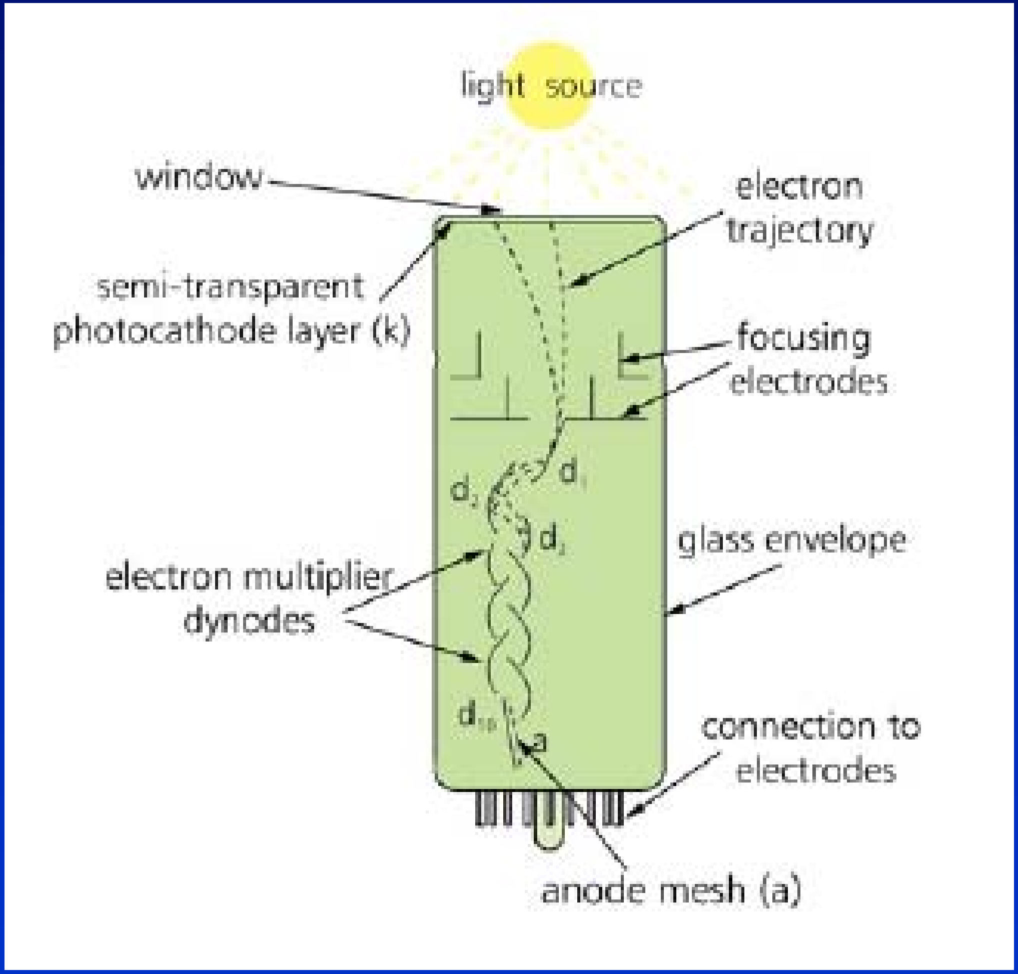
Sealed detector package with semitransparent K-Cs-Sb PC

Best sealed GPMT: stable for 1 month

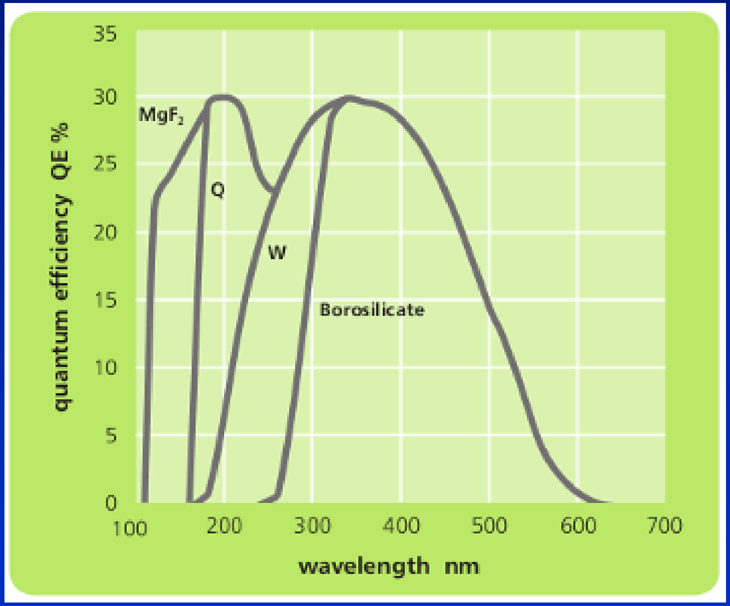
D. Mörmann et al. NIM A504 (2003) 93
M. Balcerzyk et al. IEEE TNS 50 (2003) 847

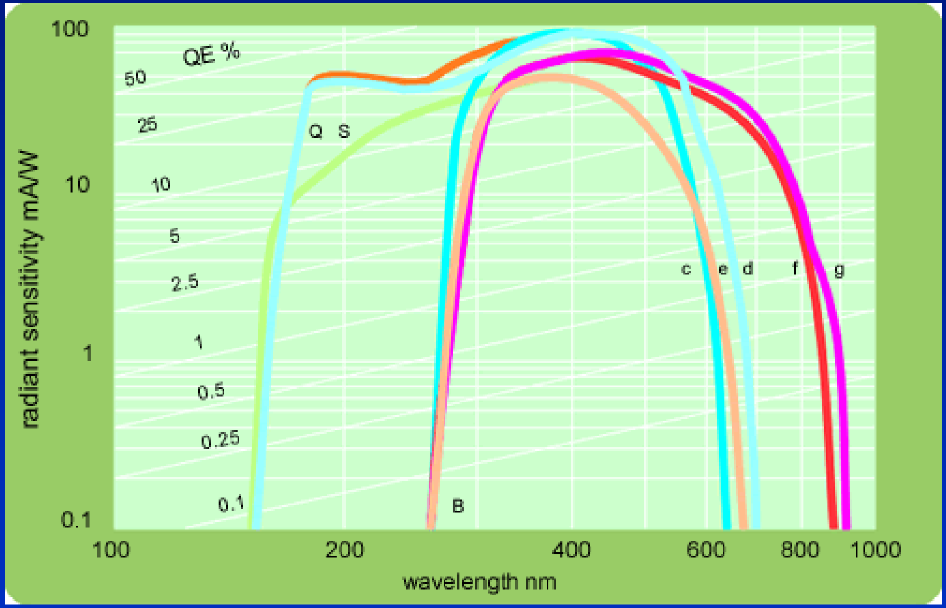
- **Gaseous photomultipliers (GPM)**:
- - many techniques: wire chambers, RPC, MICROMEGAS, &
- **hole-multipliers:**
- **CPs, GEM,, optimized GEM, MHSP, R-MHSP, THGEM…**
- **UV**: **Mature** concepts & **large-area** devices (wire chambers, multi- GEM)
- **Single-photon sensitivity, sub-ns response, 0.1mm localization,**
- **high rate, operation in magnetic fields**
- **GEM & THGEM: Atm pressure ➔ simple manufacture, flat geometry**
- **visible:** Important progress: gain 10^6 in **gated mode**; sealed GPMs;
- Good prospects for avalanche-ion blocking in **DC mode**:
- Cascaded GEM/MHSP/R-MHSP, MICROMEGAS, Inclined CPs & MICROMEGAS in magnetic fields, etc.
- e.g.: GEM/MHSP/RMHSP: **IBF = 10-3**
- **Low IBF**→ high gains and long photocathode lifetime!
- (>10y @ gain 10^5 & KHz/mm2)
- Good results in cryogenic conditions, down to 4K
- GEM/THGEM from UHV-compatible materials: in progress
- Applications: **large-area photon detectors** & others

How a classical PMT is operating



Typical Quantum Efficiencies





amplification factor of a given dynode. The average gain $\overline{G}$ of the PMT, according to equation (5), can be written as:

$$\overline{G} = \overline{g_1} \cdot \overline{g_2} \cdots \overline{g_n} \qquad (7)$$

and its fractional variance, according to equation (6), as:

$$v(G) = v(g_1) + \frac{v(g_2)}{\overline{g_1}} + \cdots + \frac{v(g_n)}{\overline{g_1} \cdot \overline{g_2} \cdots \overline{g_{n-1}}} \qquad (8)$$

One can see that the first dynode has a dominant contribution into the total fractional variance $v(G)$ and all the other dynodes contribute much less (usually in order to provide peaked single *phe* distribution at the output one selects PMTs for which the gain of the first dynode $\overline{g_1}$ at the specified voltage is ≥ 6, so already the second term in (8) is 6 times less than the first one if the fractional variances are comparable). This should be one of the reasons why the PMT manufacturers measure the gain g_1 of the first dynode and show its value on the PMT data tickets. If we assume that all the PMT dynodes operate at the same mean gain $\overline{g}$ and have the same variance $v(g)$ then one can simplify the equation (8):

$$v(G) = v(g) \cdot \frac{\overline{g}^n - 1}{(\overline{g} - 1) \cdot \overline{g}^{n-1}} \qquad (9)$$

Because of $\overline{g}^n \gg 1$, one can further simplify the equation (9) and obtain

$$v(G) = v(g) \cdot \frac{\overline{g}}{\overline{g} - 1} \qquad (10)$$

Note that $v(G)$ in equation (10) is independent on the number of dynodes n. One can see from equation (10) that the total fractional variance of the PMT gain (under the assumption of identical dynodes and potential differencies) is essentially equal to the fractional variance of a single dynode; the rest of the dynode system enhances the fractional variance by $\frac{\overline{g}}{\overline{g}-1}$ times which, for example, is equal to 1.25 for a dynode gain of 5. If we assume now, as a *Gedanken experiment*, that the dynode gain has a Poisson variance (which is not true, in reality the gain has always larger than Poisson variance), i.e. $v(g) = \frac{1}{g}$ then

$$v(G) = \left(\frac{\sigma_G^2}{\overline{G}^2}\right) = \frac{1}{\overline{g} - 1} \qquad (11)$$

(Mirzoyan, 2000)

4

The relative variation (amplitude resolution) of the PMT signal can be written as

$$\sqrt{1/(g-1)}$$

where g is the gain of the 1st dynode. Easy to calculate The theoretically possible amplitude resolution for Several values of gain

g	10	100	1000
σ/A, %	33	10	3

Degradation of the amplitude resolution because of the back-scattering effect

- Unfortunately the backscattering of accelerated e- from the dynodes is rather spoiling the amplitude resolution of PMTs.

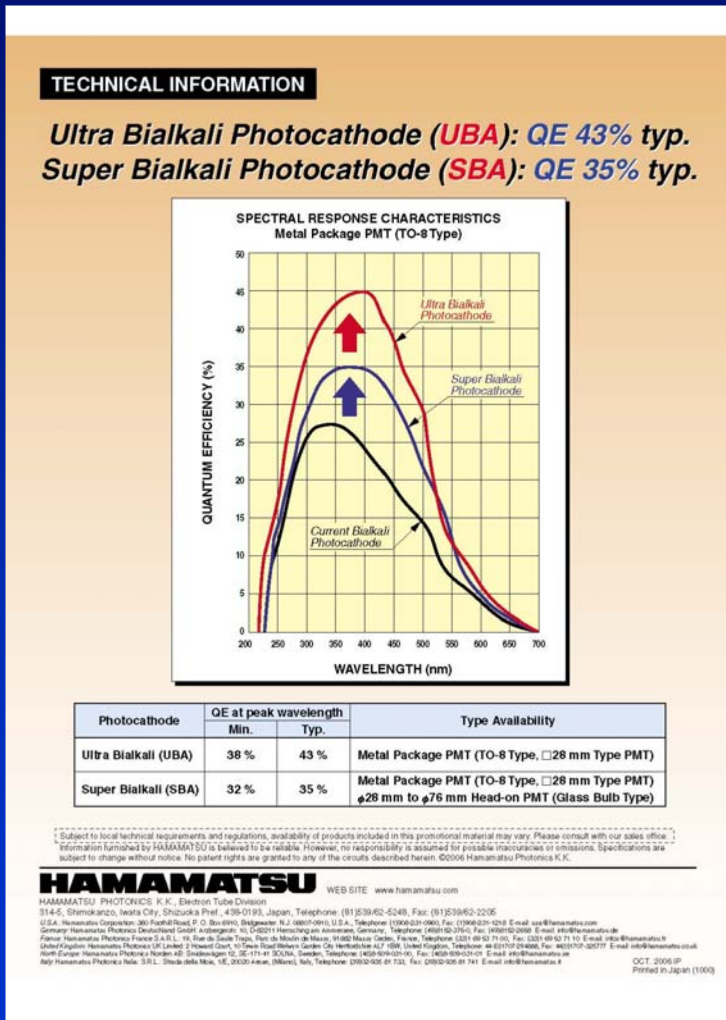
- The back-scattering probability is proportional to Z of the dynode material.

- The only remedy could be the use of dynode materials with low Z.

Boost of the QE of Bialkali PMTs

- Some 5 years ago we started working with the well-known PMT manufacturers looking into the business of boosting the QE of bialkali PMTs. Over past 40 years there was no progres reported.
- After several iterations real success could be reported.
  - Already 2 years ago PMTs with peak QE values in the range of 33-35 % became available.
  - These QE boosted PMTs are planned to be used in the imaging camera of the MAGIC-II telescope, that shall be completed in 2007/2008.

Recent Surprises


TECHNICAL INFORMATION

Ultra Bialkali Photocathode (UBA): QE 43% typ.
Super Bialkali Photocathode (SBA): QE 35% typ.

Photocathode	QE at peak wavelength		Type Availability
	Min.	Typ.	
Ultra Bialkali (UBA)	38 %	43 %	Metal Package PMT (TO-8 Type, □28 mm Type PMT)
Super Bialkali (SBA)	32 %	35 %	Metal Package PMT (TO-8 Type, □28 mm Type PMT) ϕ28 mm to ϕ76 mm Head-on PMT (Glass Bulb Type)

HAMAMATSU WEB SITE www.hamamatsu.com

HAMAMATSU PHOTONICS K.K., Electron Tube Division
314-5, Shimokanzo, Iwata City, Shizuoka Pref., 438-0193, Japan, Telephone: (81)539/62-5248, Fax: (81)539/62-2205

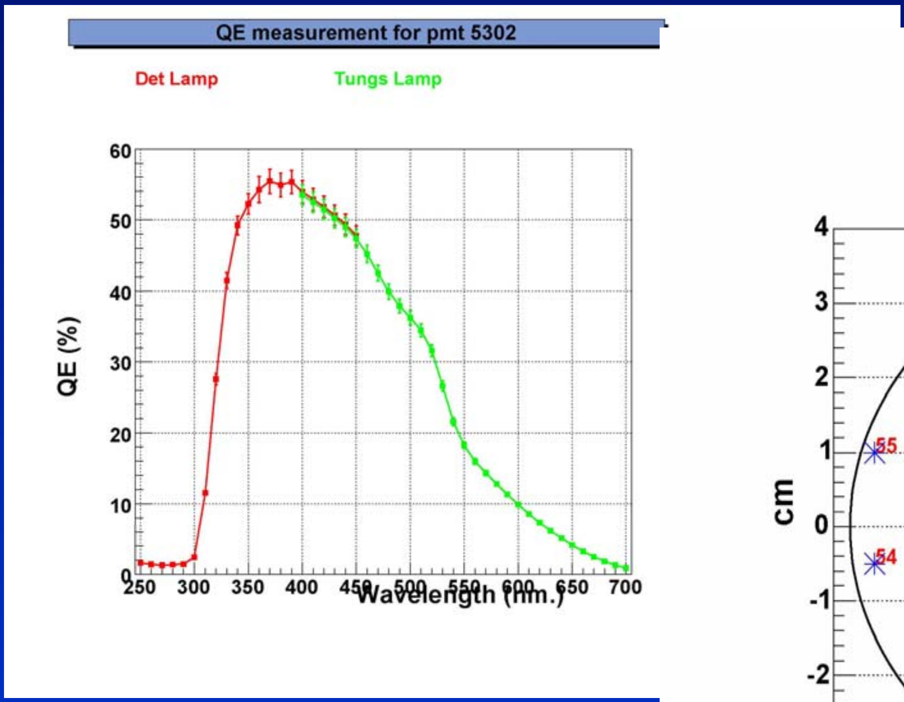
OCT. 2006 IP
Printed in Japan (1000)

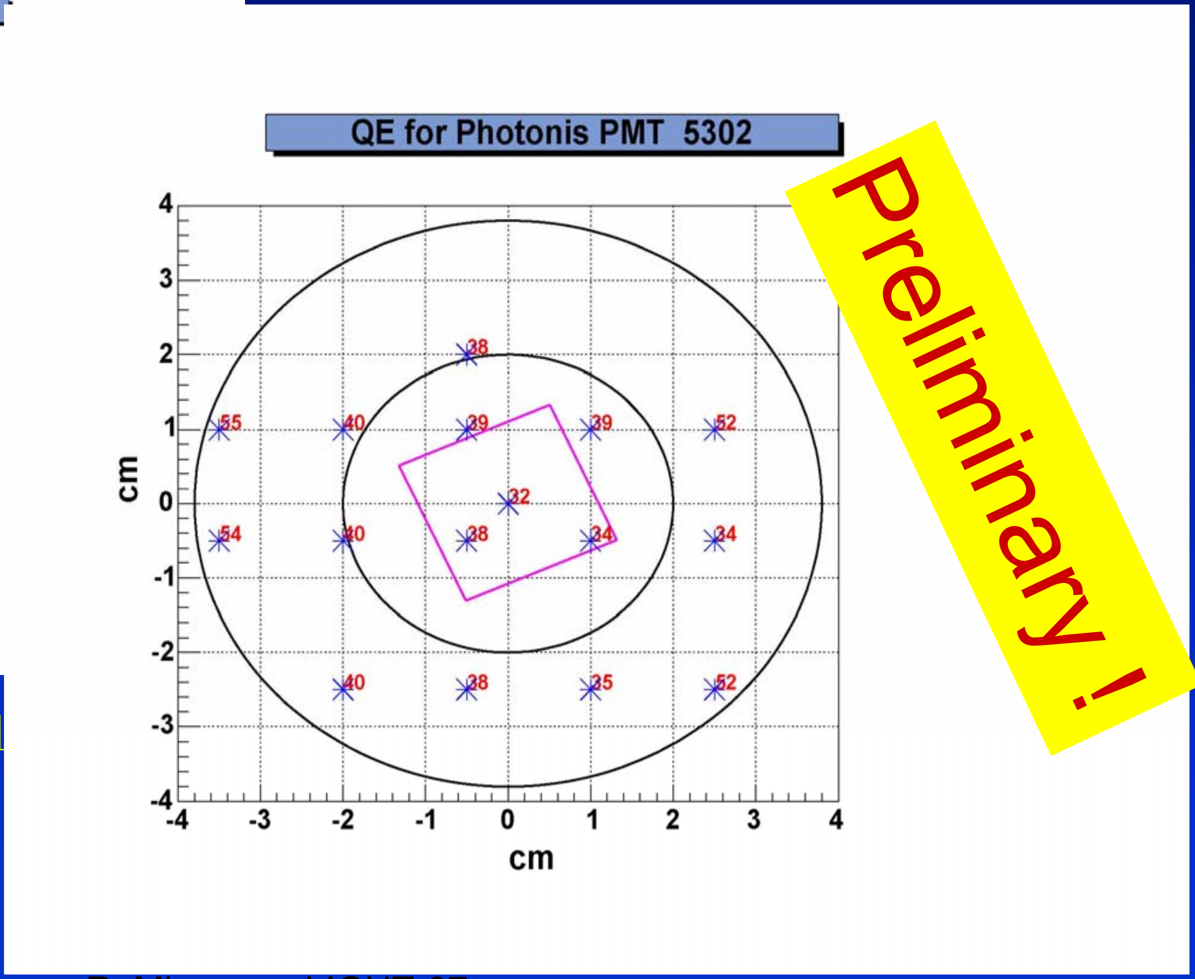
• All the 3 PMT manufacturers could report enhanced QE values, the best being Hamamatsu, who gave it the name „Super-bialkali“ (QE~ 33-36 %).

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

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

The very recent 3‘ Photonis PMTs: QE peak values in excess 50 % !



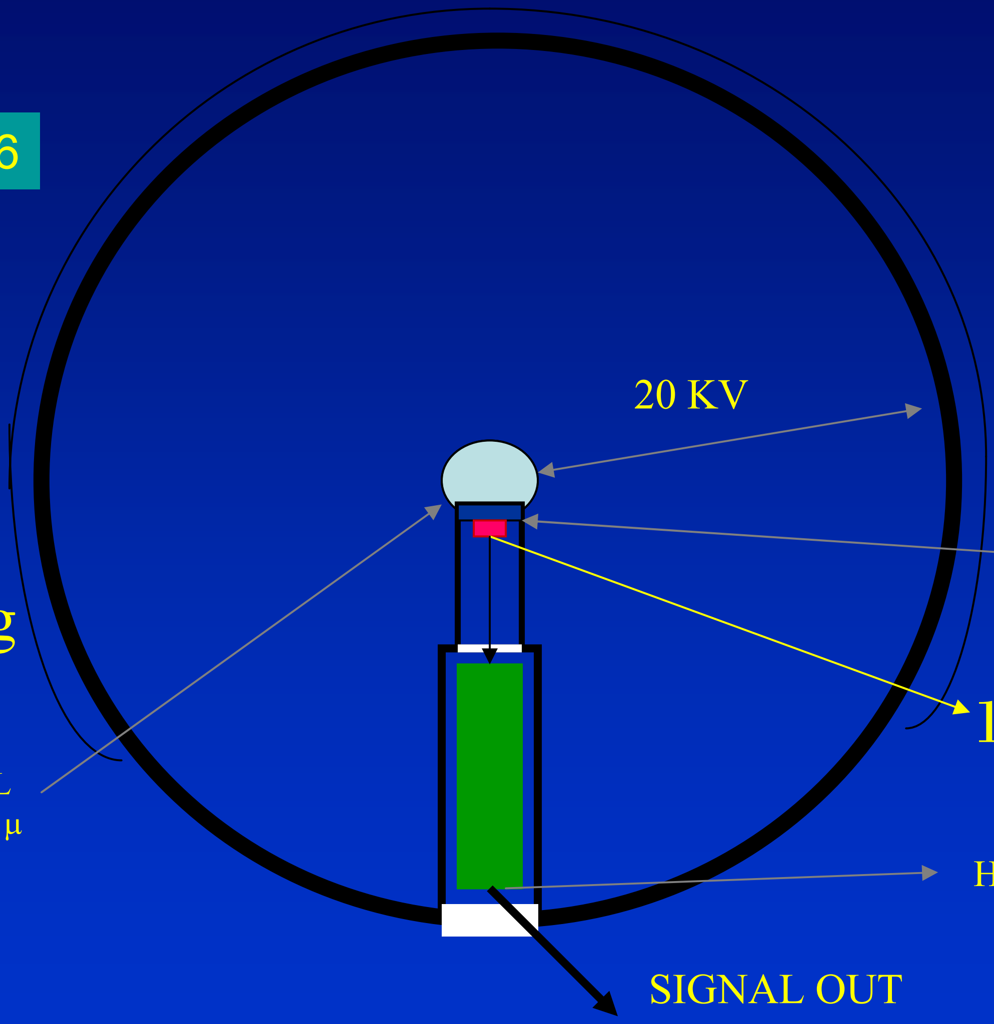


I am curious if Photonis could reproduce this results, what name are they going to give that type (Extreme-bialkali)?

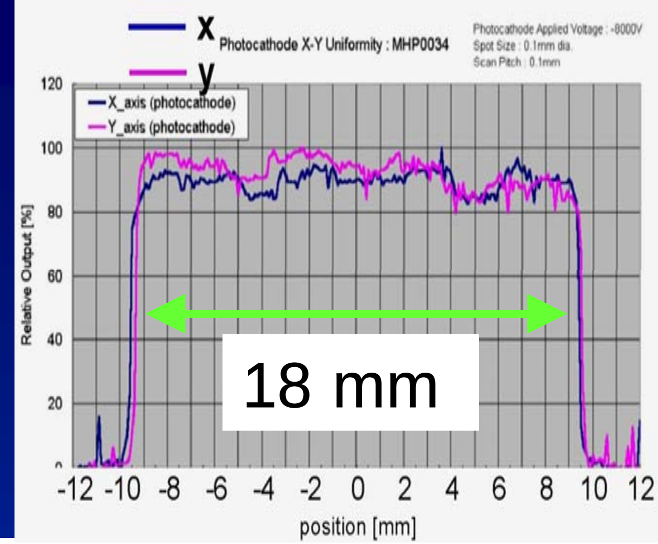
Reviving the idea of the „Smart“ PMT

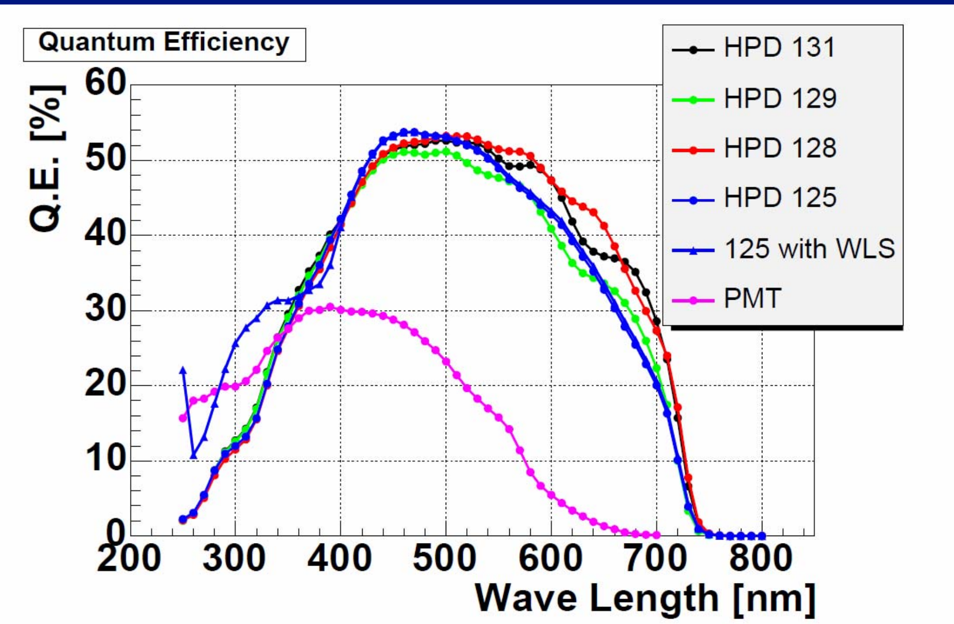
Lorenz, Light-06

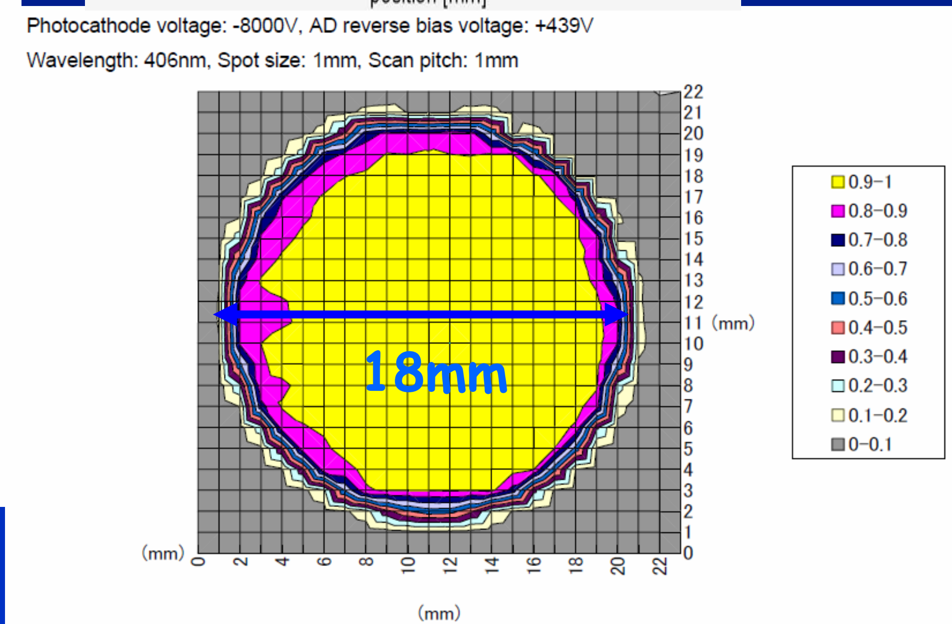
A SPHERICAL SOLUTION WITH SPHERICAL SCINTILLATOR, SIMPLE PRODUCTION, MINIMAL TIME JITTER



GaAsP HPD from Hamamatsu







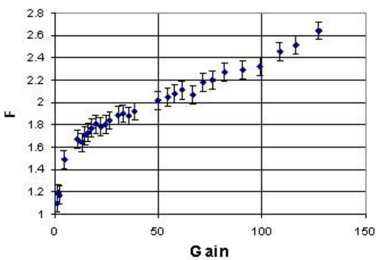
QE exceeds 50% at 450 nm

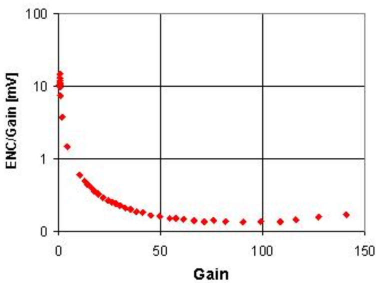
Two times more photon detection

See talk of Takayuki Saito

Good Uniformity. 18mm diameter Within 10%.

Avalanche photo diodes





Excess Noise Factor

The avalanche multiplication is a random process leading to additional fluctuations in the collected charge. These fluctuations are characterised by the excess noise factor F. At high gain F can be approximated by the expression:

$$F = k \times M + \left(2 - \frac{1}{M}\right) \times (1 - k)$$

where k is the ration of the ionisation coefficients for holes and electrons and M is the gain.

The energy resolution then becomes:

$$\frac{\sigma(E)}{E} = \frac{A}{\sqrt{E}} \oplus \sqrt{\frac{F}{N_{pe} \cdot E}} \oplus \frac{Noise}{N_{pe} \cdot E} \oplus Const$$

Some critical issues:

- Usually gain G is a function of temperature and applied voltage :
  G ~ 2.2 %/°C
  G ~ 3.3 %/V
- The APDs of moderate size (few mm ∅) have a relatively high noise level, $\sigma \approx$ few x 10 e^-

Avalanche photo diodes

- It is important to underline:

Because of the x2 amplification at each stage of the avalanche (an e^-/hole pair), and because of the statistical nature of the avalanche, one may obtain, under certain circumstances, a single ph.e. response, but not a single ph.e. resolution ! (One more or one less stage of the avalanche changes the gain by 2 times on both sides).

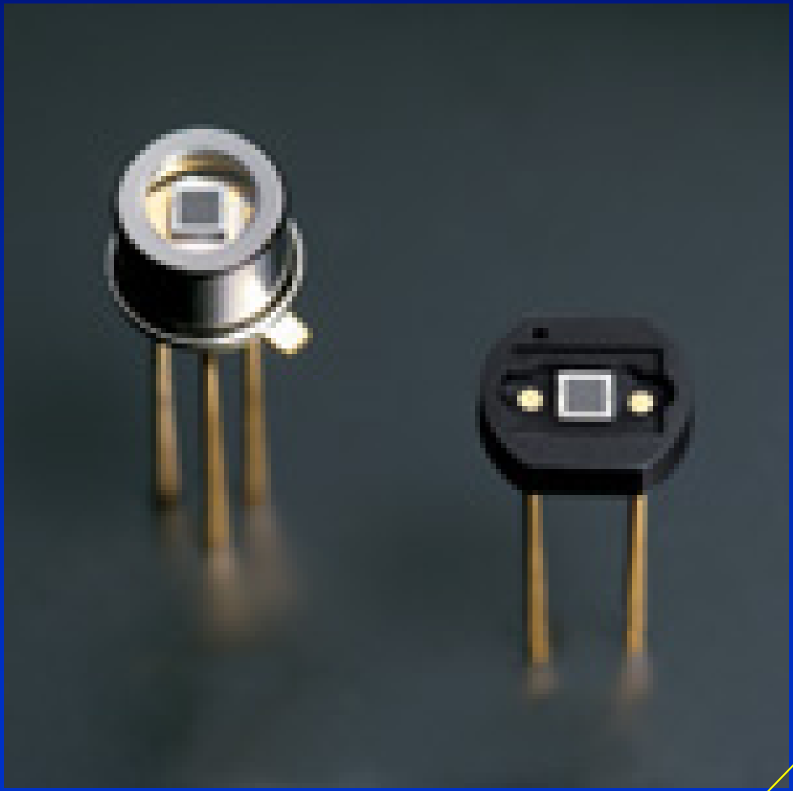
- One can compare an APD with a „bad“ PMT that has a 1st dynode gain of „only“ x2: in both cases one expects the so-called exponential amplitude distribution.
- These features are reflected in the F-factor studies.

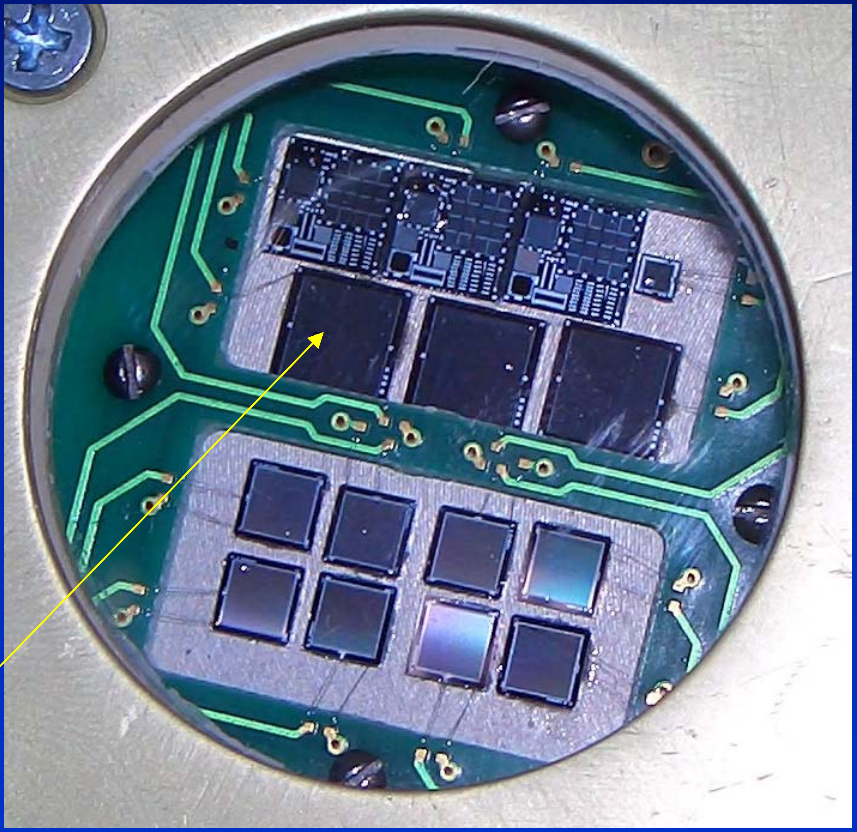
Avalanche photo diodes

- An APD could be a good choice for moderaely strong input light (to avoid the usual noise problems one needs to work at roughly 5 times higher signal levels than the noise: 5σ. For noise level of σ = 20 ph.e. one will need a

  signal of 5x20 = 100 ph.e. ($\geq$ 120 photons)
- Because of the relatively low gain (30-300) one needs
  - To filter out the signal (limit the bandwidth by integrating and differentiating the signal)
  - Match the follow-up amplifier to the capacitance of the APD
  - Pay attention to the special low noise performance of the amplifier, usually of charge sensitive type
  - Often to sacrifice the rate that one can measure

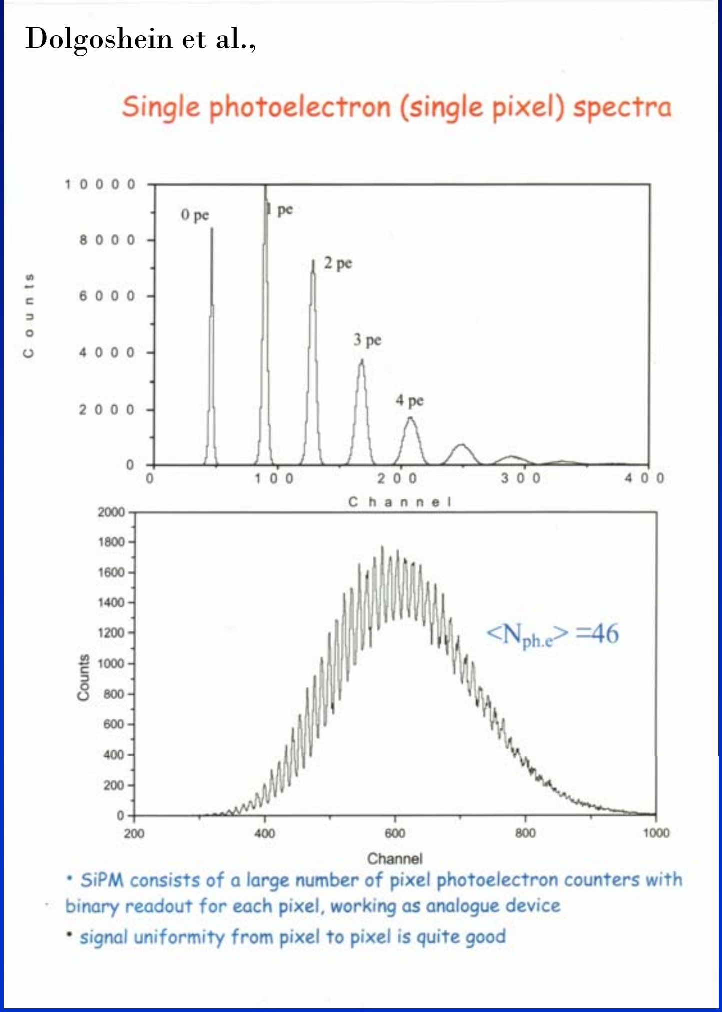
SiPM, GAPD, MPPC,...
Wonderful, one major step towards the ideal light sensor !

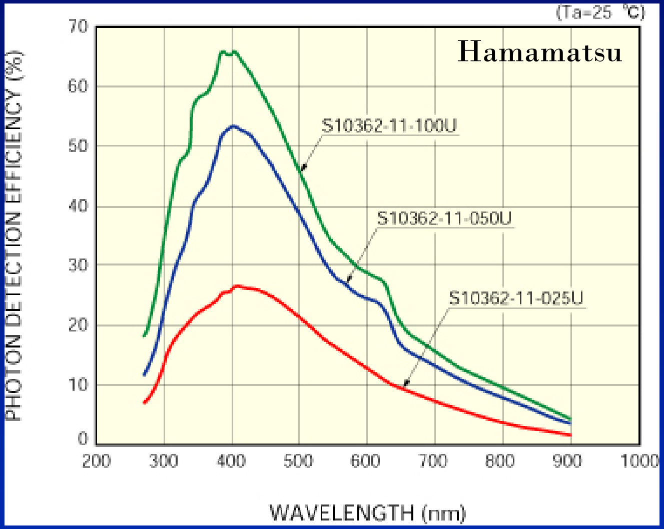




Still the size is limited to ≤ $5x5mm^2$; soon probably $8x8mm^2$ are available

SiPM, GAPD, MPPC,...

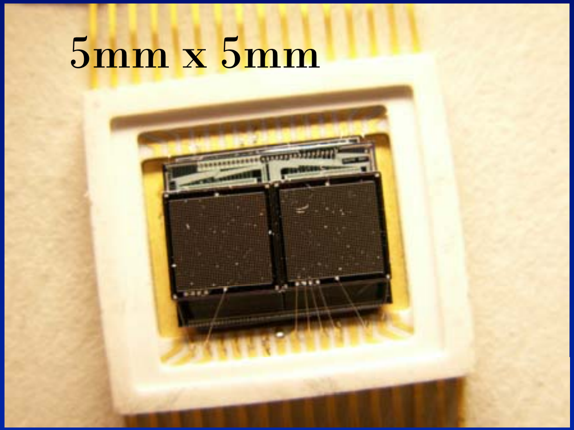




Almost ideal
light sensor !

Unique spectrum, no other device can provide this high resolution !

SiPM, GAPD, MPPC,...



- Main drawbacks:
  - relatively high dark rate
  - cross-talk (now 10 – 30 %) => poor F-factor
  - amplitude temperature dependence
    - Hamamatsu devices: 10 % /°C
    - Dolgoshein et al.: 4.3 % /°C
  - amplitude applied voltage dependence: ~ 7 % / °C
  - low near UV sensitivity, especially for $\lambda \leq 370$ nm
  - QE still below what is theoretically possible:

PDE(λ) = GEOM-active-area x Geiger-efficiency x Transmit-efficiency(λ) x QE-intrinsic

(the 1st and the 3rd terms above can still be optimised)

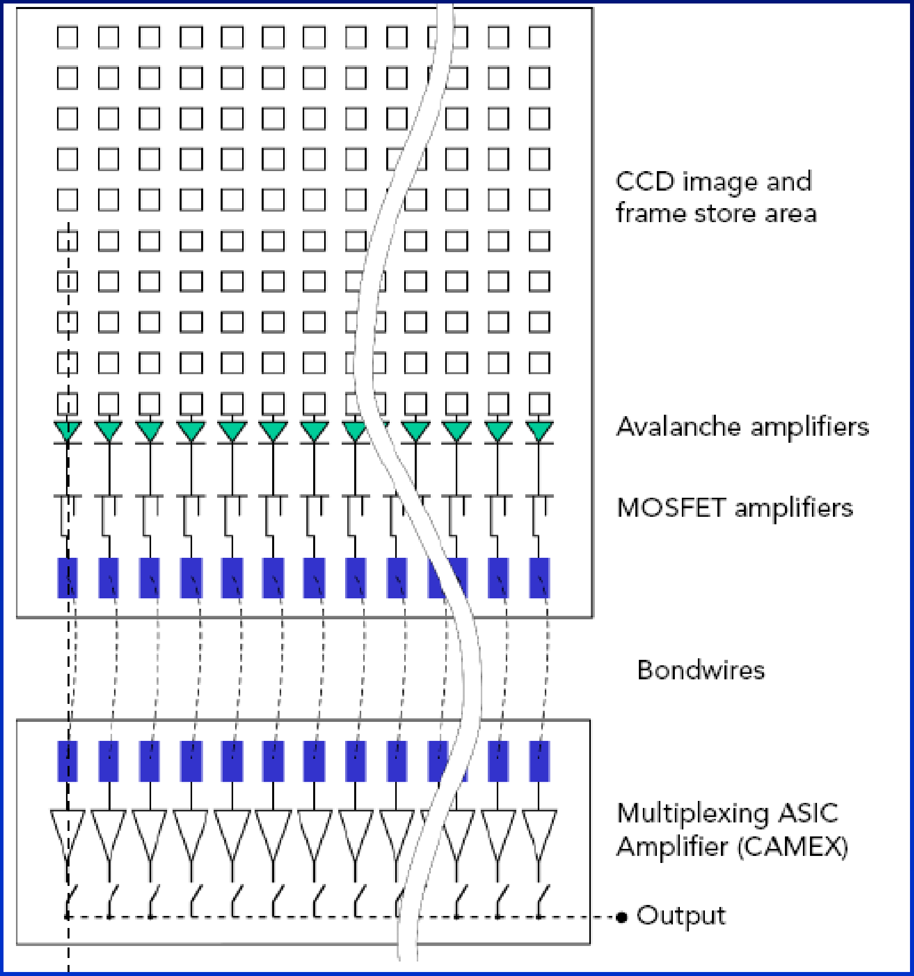
SiPM, GAPD, MPPC,...

- In many applications these sensors can substitute the classical PMTs and APDs.
- Big potential for medical applications (small animal PET, SPECT, ...)

Also:

- LIDAR
- laser range-meters
- coarse imaging and guidance systems (based on SiPM matrixes)
- barcode reading elements
- radiometers
- security/safety systems as ultra-sensitive sensors
- quantum cryptography
- ...
- During this workshop we will learn more

HLL: High Speed, Single Photon Imaging CCD for the Optical



This device has image store and frame store area of typically 256x256 pixels each as well as parallel column readout. The APDs are connected to on-chip MOSFETs. Thsi additional gain allows one to work with a relatively low avalanche gain and thus limit the cross--talk. The statistics of the avalanche does not allow to distinguish if 1 or more photons hit. To compensate this the device is optimised to work under 1kHz frame rate in order to limit the pile-up. Intensity measurement can be performed by measuring the rates above given thresholds.

HLL (MPI Semiconductor lab): Single Photon Imaging CCD for the Optical

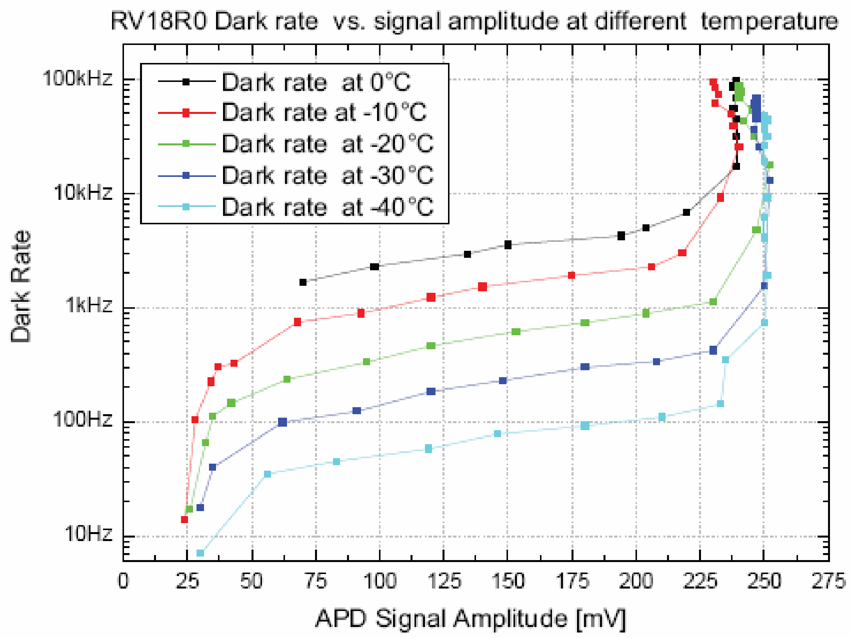


Figure 8: Dark rate as function of the output signal amplitude for various temperatures. A 36 μm diameter avalanche cell was read out

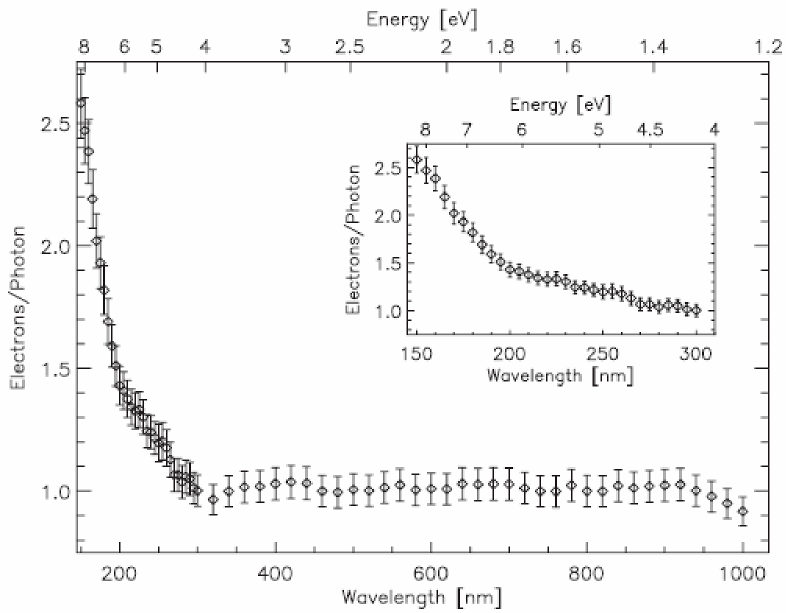


Figure 5a: Internal quantum efficiency in the wavelength range from 150 nm to 1000 nm. Below 300 nm a quantum yield above unity is achieved, i.e. more than one electron-hole pair is generated per incident photon. The drop beyond 950 nm is due to the beginning transparency of silicon in the infrared. The detector thickness for these measurements was 300 μm (from [5]).

HLL (MPI Semiconductor lab): Single Photon Imaging CCD for the Optical

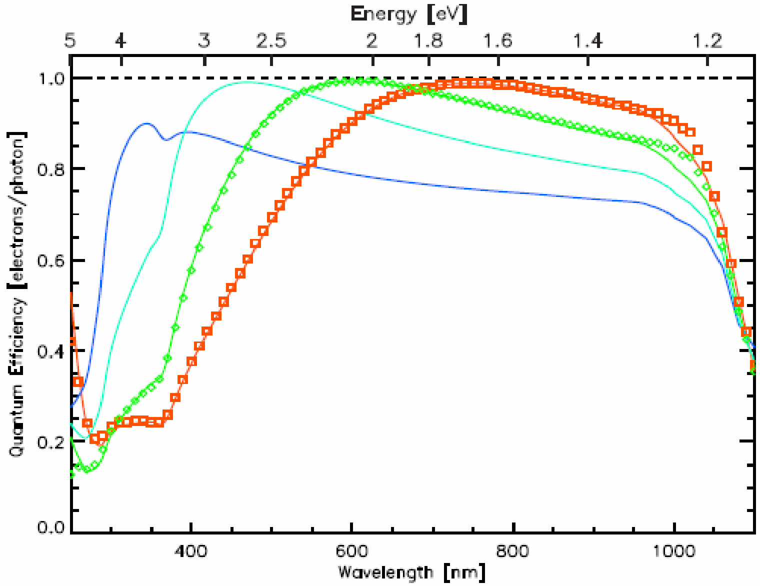


Figure 5b: Measured and calculated quantum efficiencies in the optical and NIR region for different kinds of anti-reflective-coatings [6]. The diamonds represent measurements of a detector, whose sensitivity was optimized for a detection of the sodium line at 580 nm, while the squares represent a device with a maximum quantum efficiency in the red and near infrared. Using the same model but adjusting the layer stack of the coating, detectors with optimized quantum efficiencies at shorter wavelengths might be build as well (dark and light blue lines).

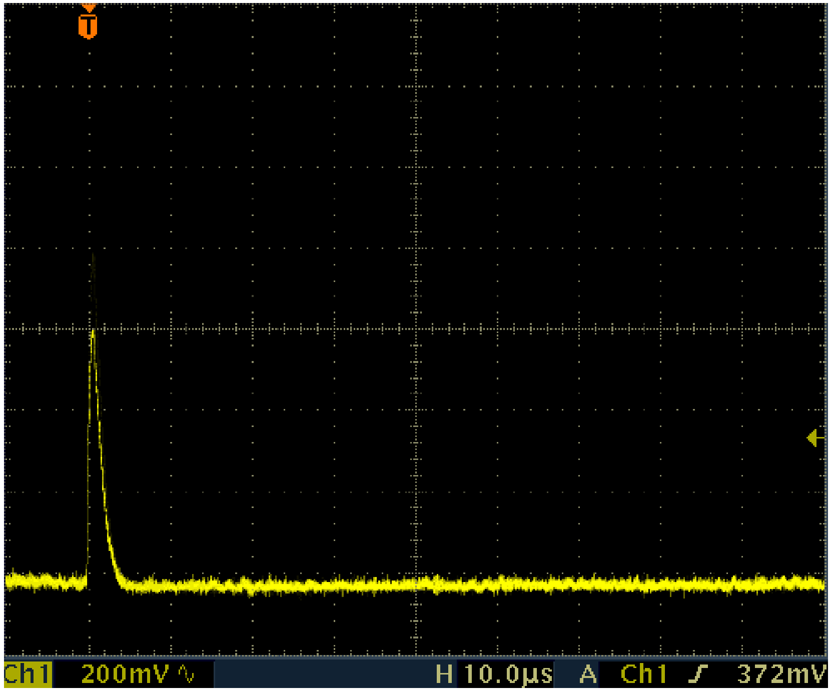
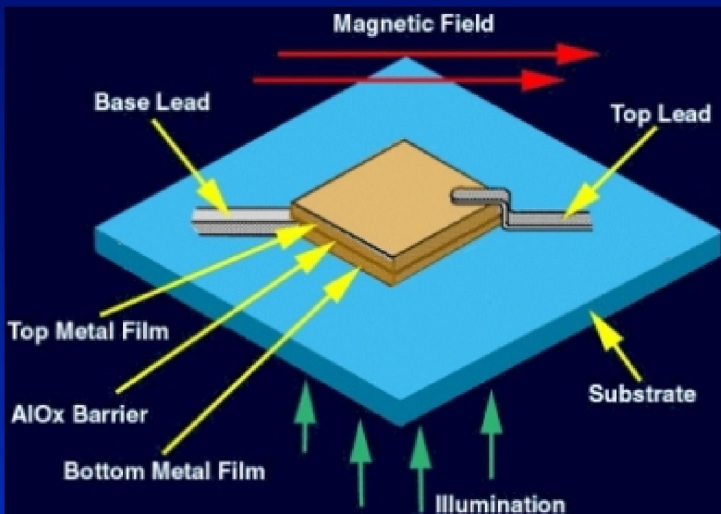
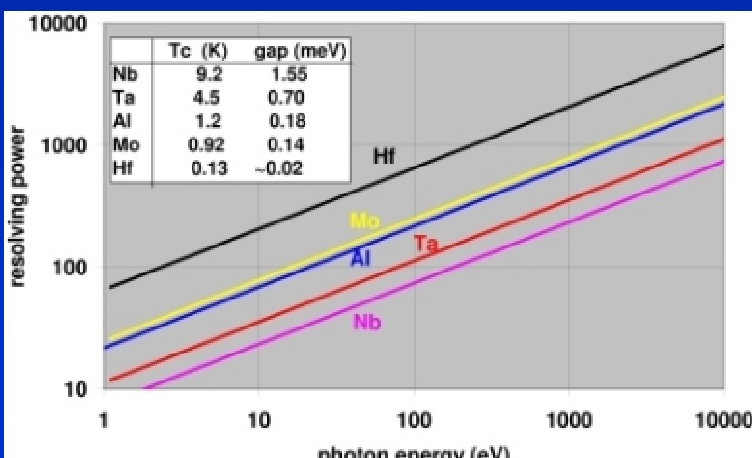


Figure 12: The signal read after the amplifier board (AMP) for APD bias at -37.2 V. Capacitive loads and coupling of the source follower output to the AMPTEK A250 preamplifier on the amplifier board (AMP) are responsible for the slow signal rise time.

Superconducting tunnel junction (STJ) device and matrixes





Intrinsic determination of individual photon energies in optical range was 1st reported in 1993 (Perryman et al.,). At temperatures typically below 1 K incident photons break Cooper pairs responsible for superconducting state. The energy gap between the ground state and excited state is only few meV, therefore each photon creates a large number of free electrons, that is proportional to incident photon energy. The amount of charge carriers N(E) generated by an absorbed photon is proportional to the energy E of the absorbed photon: N(E) = E/1.74D

(D is the energy gap of the semicunductor)

STJ in Science Program of ESA

- Typical QE ~ 70 % (limited by geometry)
- Count rate ~ 1 kHz (although the Ta relaxation time is only ~ 10μs)
- Wavelength resolution: ~100nm in 500nm (limited by electronics and residual thermal background); the intrinsic response is ~ 5 times better.
- Typical size: 25 x 25 μm^2
- Wavelength response: 300-700 nm (intrinsically possible 300-1000 nm)
- Already in 1999 a matrix of 6x6 pixels was used on William Herschell telescope in La Palma to detect the Crab pulsar.
- By arranging a number of STJ devices into a two dimensional matrix, a true „3 dimensional" detector can be constructed (the 3rd dimension is the individual photon energy; no spectrograph is necessary anymore).
- A „super STJ CCD“ at a cryogenic technology price.

Conclusions

- Many interesting new developments
- SiPM (GAPD, MPPC,...) make strong progress, parameters are still improving, 2-3 more years and we are „there“
- Even such classical devices as the PMTs and HPDs continue making progress
- Imaging devices enter the zone of single photon imaging
- Welcome and enjoy this workshop !