Very High QE bialkali PMTs

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Quantum Efficiency

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

  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)

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

Short Historical Excursion

- **1889**: Elster and Geitel discovered that in alkali metals a photo-electric effect can be induced by visible light (the existence of the e^- was yet unknown)
- **1905**: Einstein put forward the concept that photoemission is the conversion of a photon into a free e^-
- Until ~1930 QE of available materials was < 10^{-4}
- **1929**: discovered **Ag-O-Cs** photo-emitter (Koller; Campbell) improved the QE to the level of ~ 10^{-2}
- 1st important application: reproduce sound for film

Short Historical Excursion

- Improved materials were discovered later on but it was a combination of a good luck with „intelligent guessing“
- A very important step was to realize that the photocathode materials are SEMICONDUCTORS
- **Metallic** versus **Nonmetallic** materials:
  - yield of metallic photocathodes is very low because of very high reflectivity
  - semiconductors have less reflection losses
- The main loss process in metals is the e^- scattering; => e^- escape depth of only few atomic layers is possible

Short Historical Excursion

- The losses in Semiconductors because of phonon scattering (interaction with lattice) are much less, i.e. e^- from deeper layers can reach the surface

Short Historical Excursion

	Metal	Semiconductor
Photon → e- conversion	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

Short Historical Excursion

- 1910: Photoelectric effect on K-Sb compound was found (Pohl & Pringsheim).
- 1923: found that thermionic emission of W is greatly enhanced when exposed to Cs vapour (Kingdon & Langmuir).
- It was found that the work function in the above case was lower than of Cs metal in bulk.
- 1936: discovered high efficiency of Cs-Sb (Görlich).

QE of Metals

- For photon energies > 12 eV QE of 1-10 % were reported for

  Ni, Cu, Pt, Au, W, Mo, Ag and Pd (1953, Wainfan).

- 7% for Au @ 15 eV

- 2% for Al @ 17 eV

Escape Depth

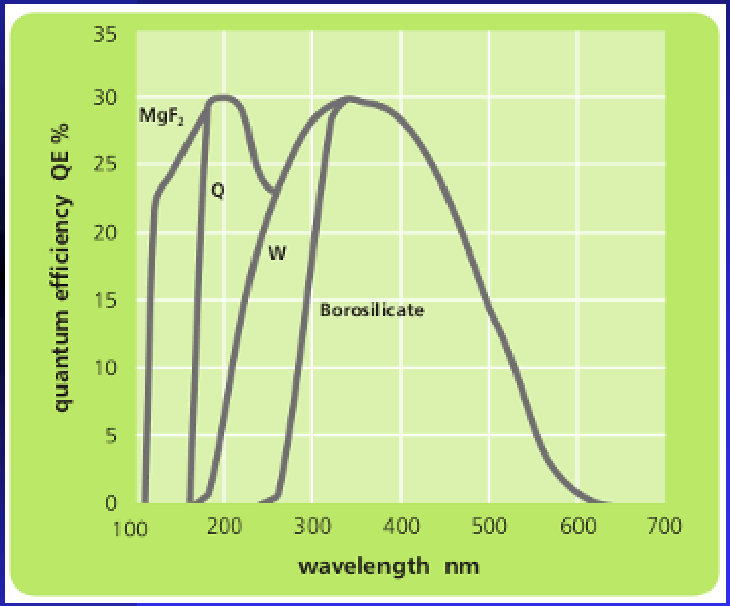
- Escape depth can be defined as the thickness above which the photoemission becomes independent on thickness (in reflective mode)

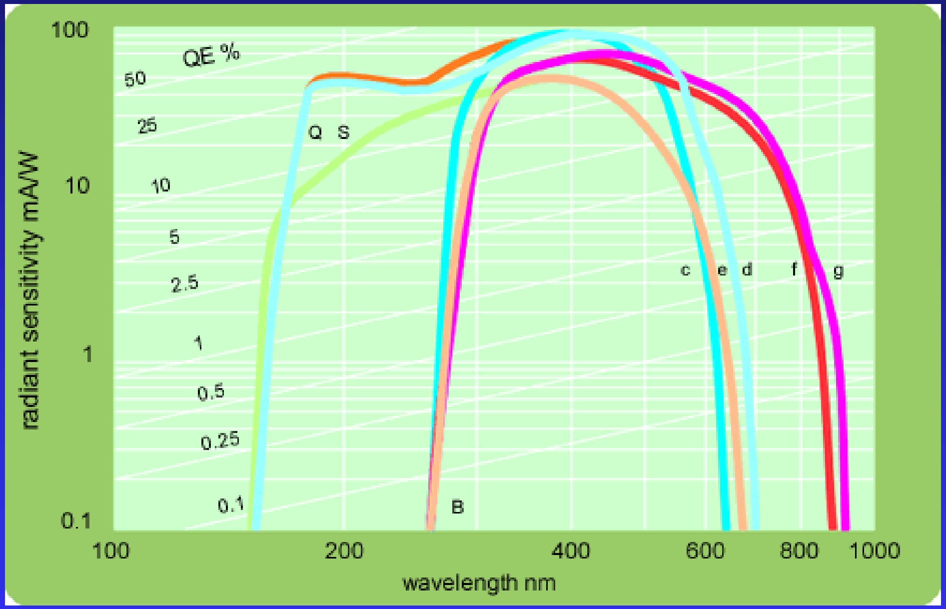
- The measured escape depth was 10-20 atomic layers for K, Rb, Cs (1932).

QE: Short Historical Excursion

- 1955-1958 Sommers found the „multialkali" effect: combination of Cs-K-Na-Sb has high QE in the visible spectrum.
- Also were discovered
  - Cs_3Sb on MnO (S11, λ_{peak} @400nm, QE ~ 20%)
  - $(Cs)Na_2KSb$ (S20, λ_{peak} @400nm, QE ~ 30%)
  - K_2CsSb (λ_{peak} @400nm, QE ~ 30%)
  - $K_2CsSb(O)$ (λ_{peak} @400nm, QE ~ 35%)

Typical Quantum Efficiencies





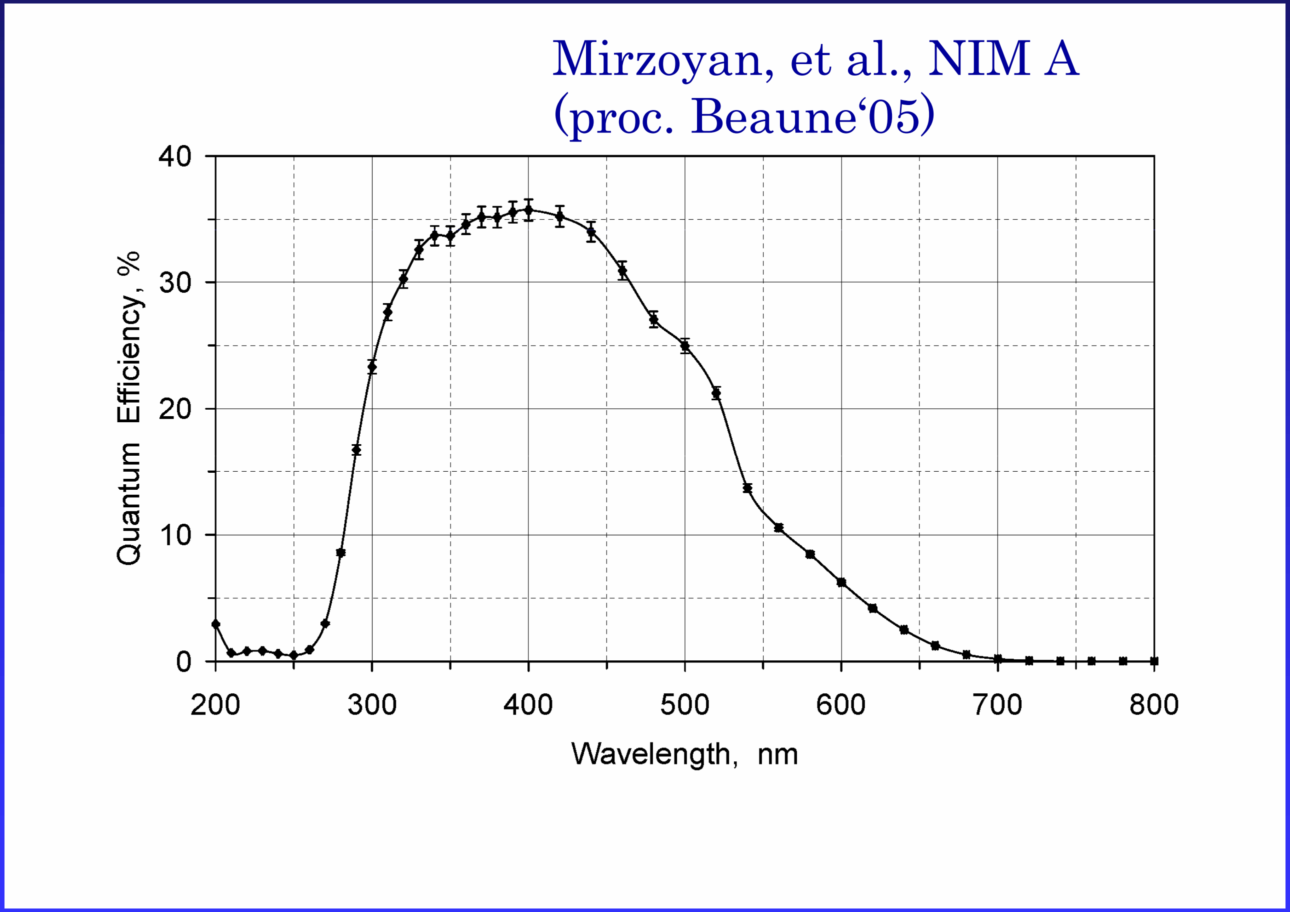
Boost of the QE of Bialkali PMTs

- In recent few years we were intensively 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 success could be reported.
  - Already 2 years ago PMTs with peak QE values in the range of 32-35 % became available.
  - These QE boosted PMTs are used in the imaging camera of the MAGIC-II telescope, that shall be completed in 2007-2008.

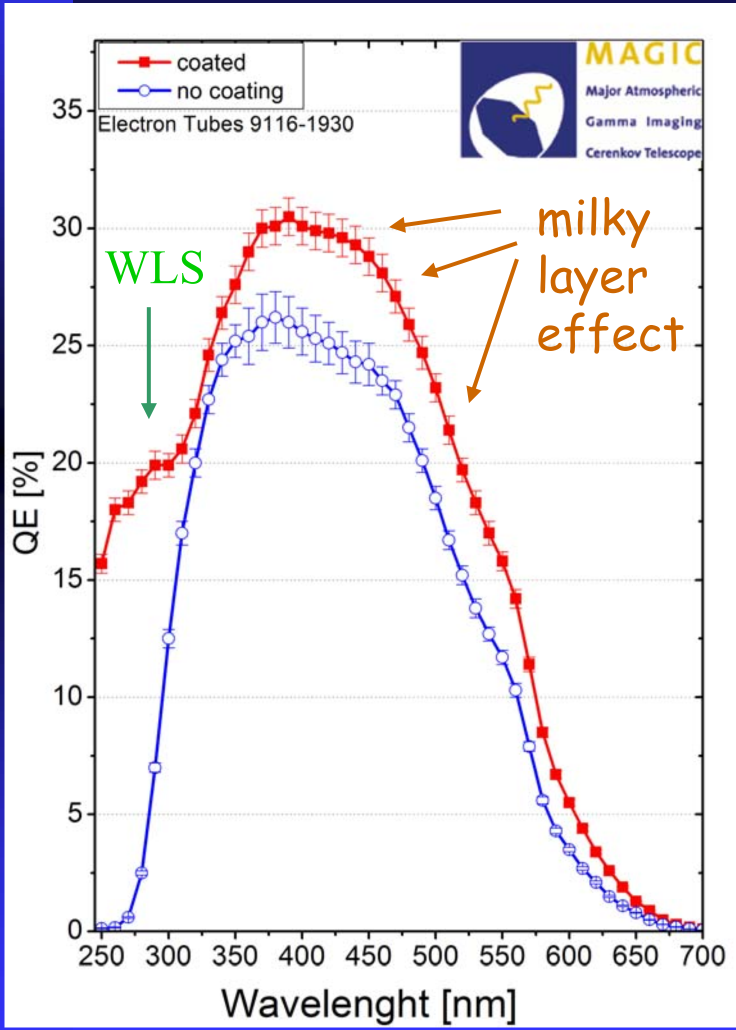
How it shall be possible to boost the QE and who is interested in it ?

- Use of highly purified materials for the photo cathode (change from 99.999 → 99.9999 or even of higher purity; will provide less scattering length for e^- (low recombination probability)
  - → e- kicked out from deeper (top) layers can reach photo cathode-vacuum junction ¬_ and „jump“ into it (→ thicker cathode is possible).
- Optimal tuning of the photo cathode thickness
- Optimal tuning of the material composition
- Optimal tuning of the anti-reflective layer
- Optimal tuning of the Cs layer thickness

QE of our „old champion“ 2‘ PMT from Hamamatsu



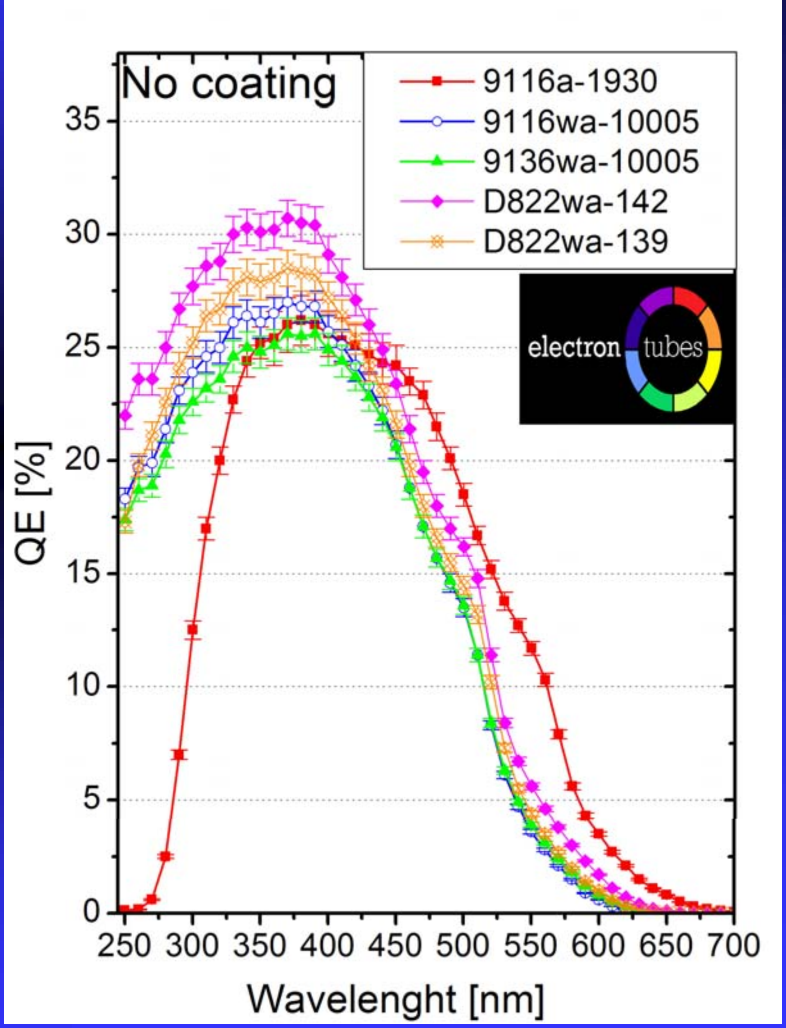
PMTs of MAGIC-I →



QE ↑ by a diffuse scattering coating, +WLS

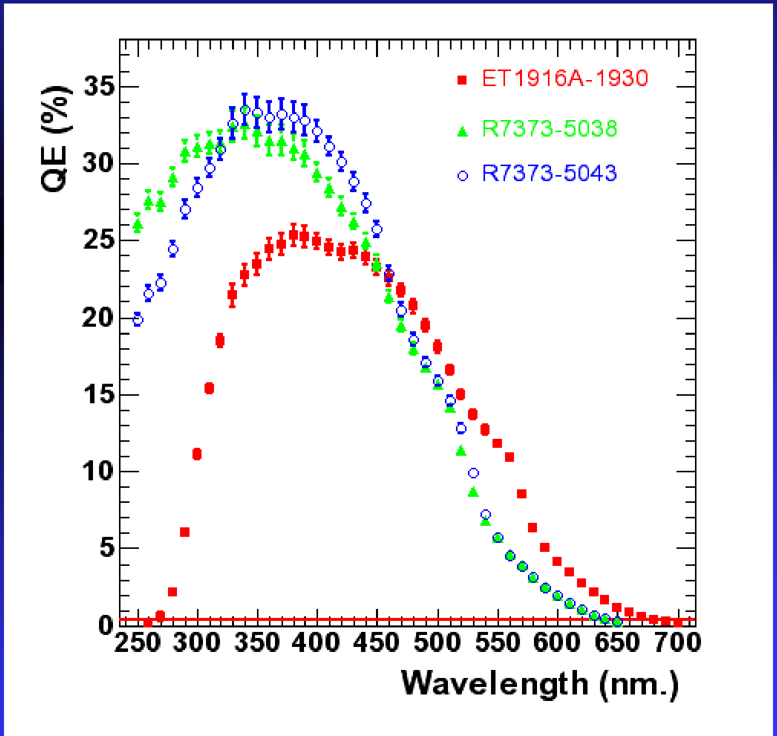
Effective QE ↑ ~ 15 %

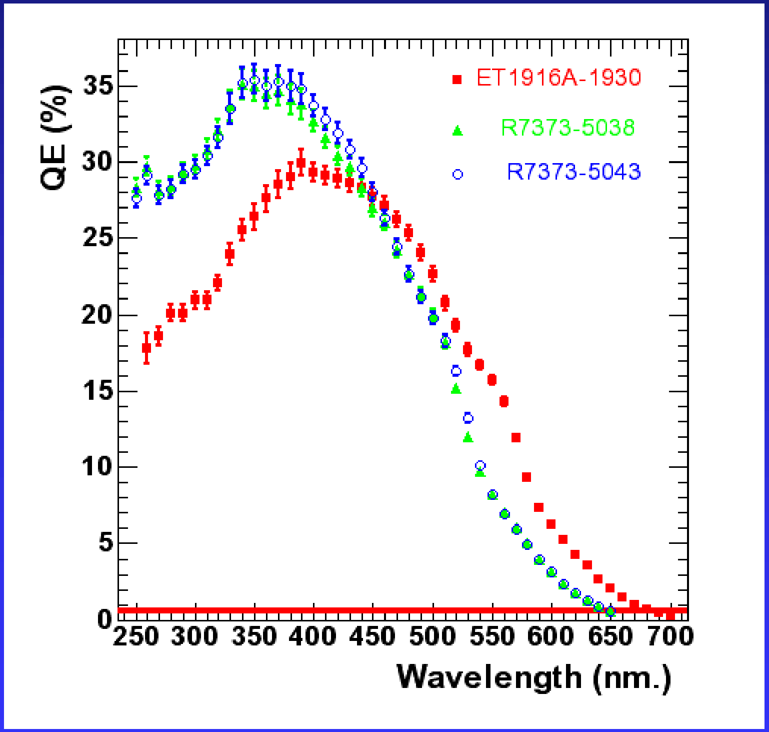
Recent PMTs → Electron Tubes



- Different batches show different behaviour
- QE is high (~30% !!)
- Peak @ ~ 350 nm
- Low QE at long λ (> 450 nm)

QE of 3 PMTs (2 *Hamamatsu* + 1 *ET*) before and after coating with milky layer

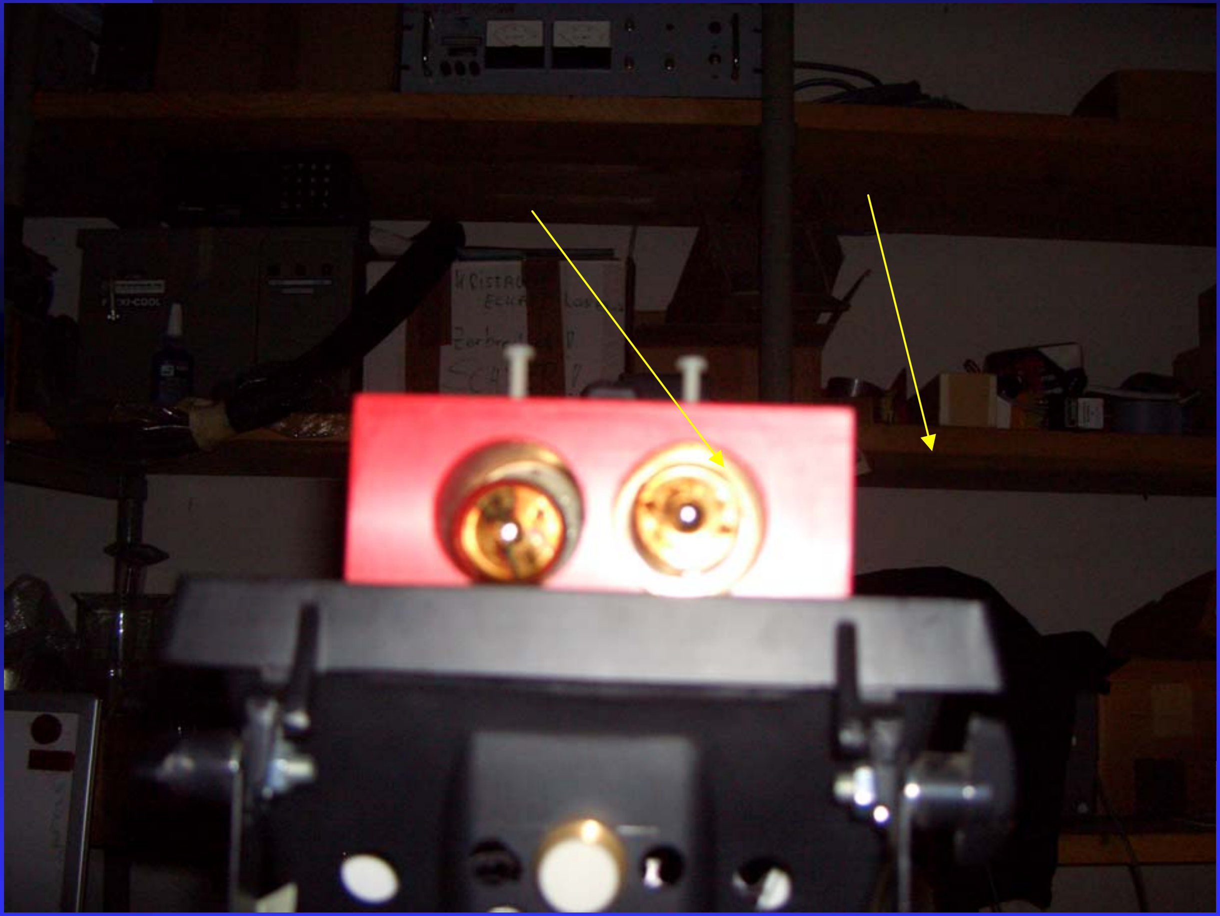




Charge collection efficiency

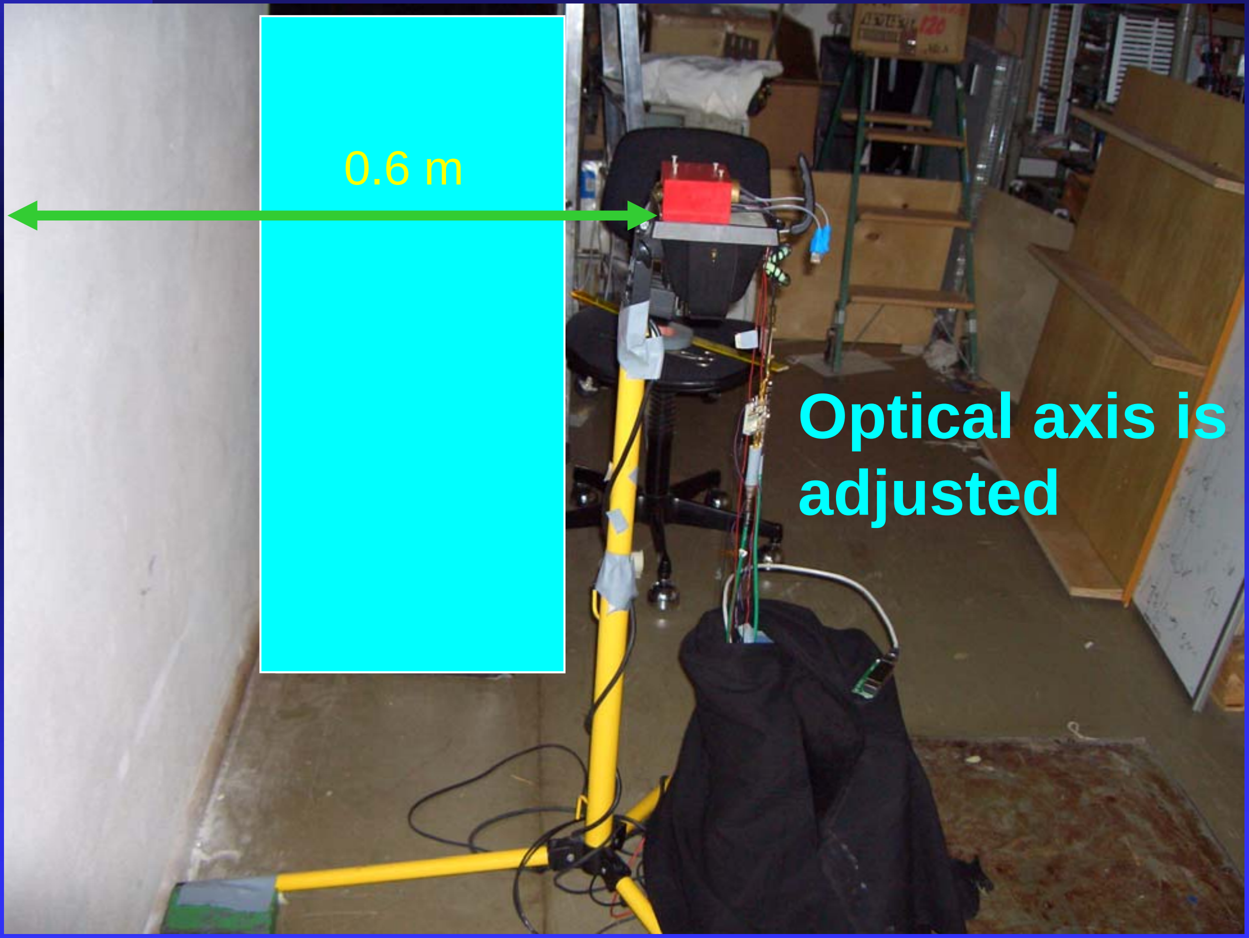
- QE alone is not a very meaningful parameter for a PMT. The charge collection efficiency (CE) is an equally important parameter.
- The convolution of the QE with the CE is the real important parameter. This is what one needs to measure
- While an absolute measurement is not easy, a comparative, relative measurement can be easily performed.

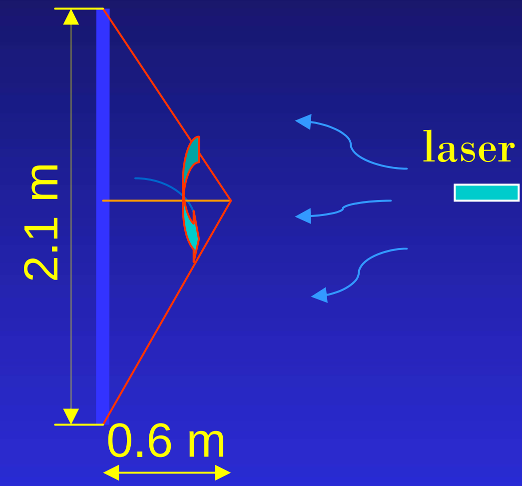
PDE measurements



We performed PDE measurements for Hamamatsu and ET PMTs. 80 ps flashes from a laser @ 400 nm were illuminating a white wall in a storage room.

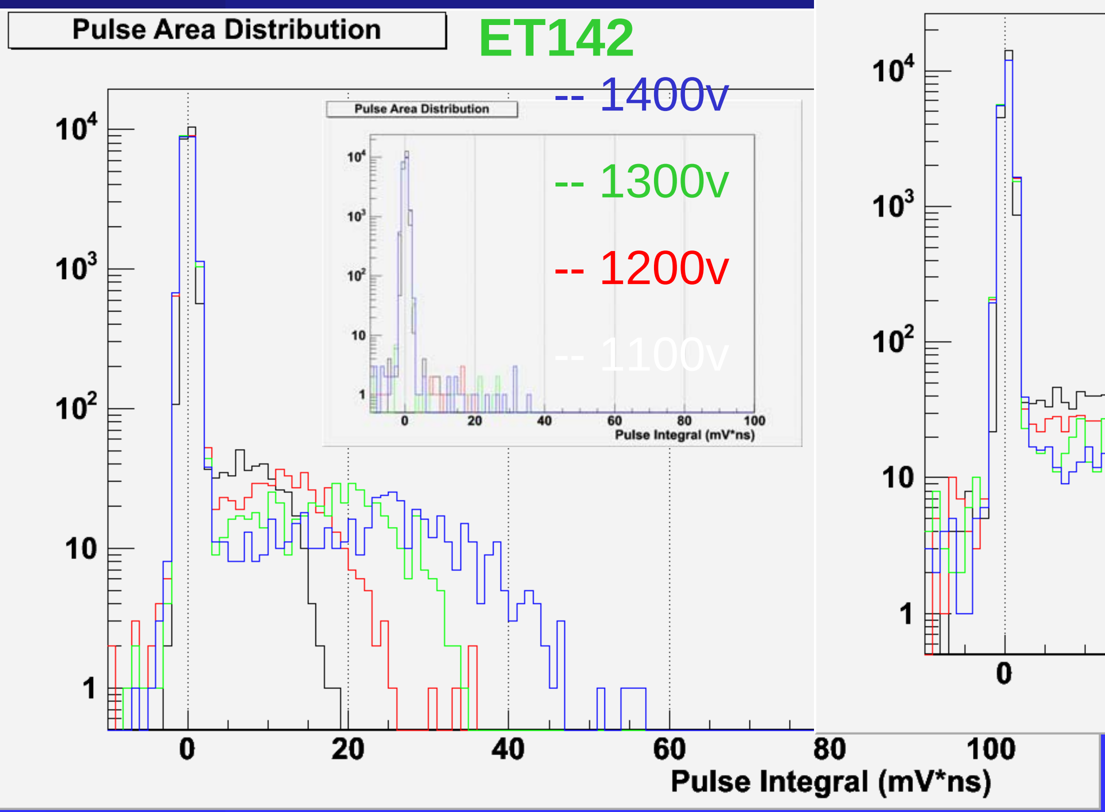
PDE measurements

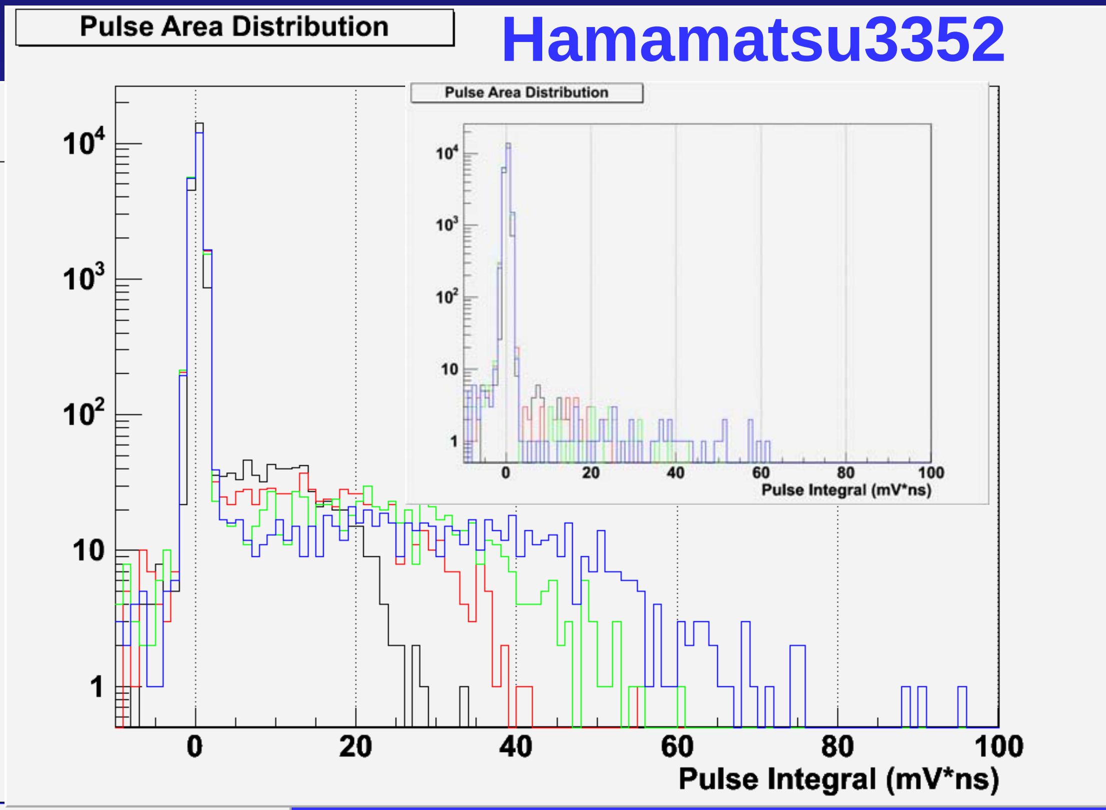




PMTs were observing a piece of white wall of 2.1 m size. The full observing angle was set to 120°.

PDE measurements

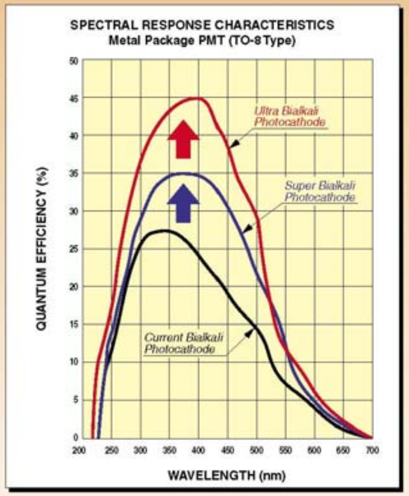




Final PMT selection

- Our measurements have shown that the PMTs from Hamamatsu have on average 20 % higher photon detection efficiency (PDE) than the PMTs from ET (this essentially reflects the existing differences between the QE's).
- The QE of a not coated PMT from Hamamatsu is comparable to the QE of a milky coated ET.
- The coating of Hamamatsu PMT is increasing its effective QE by ~10 %. => select Hamamatsu PMTs for the M-II camera.
- Short before we were going to put the order for the selected PMTs for the M-II camera to Hamamatsu, they released news on their very recent developments, Ultrabialkali PMTs:

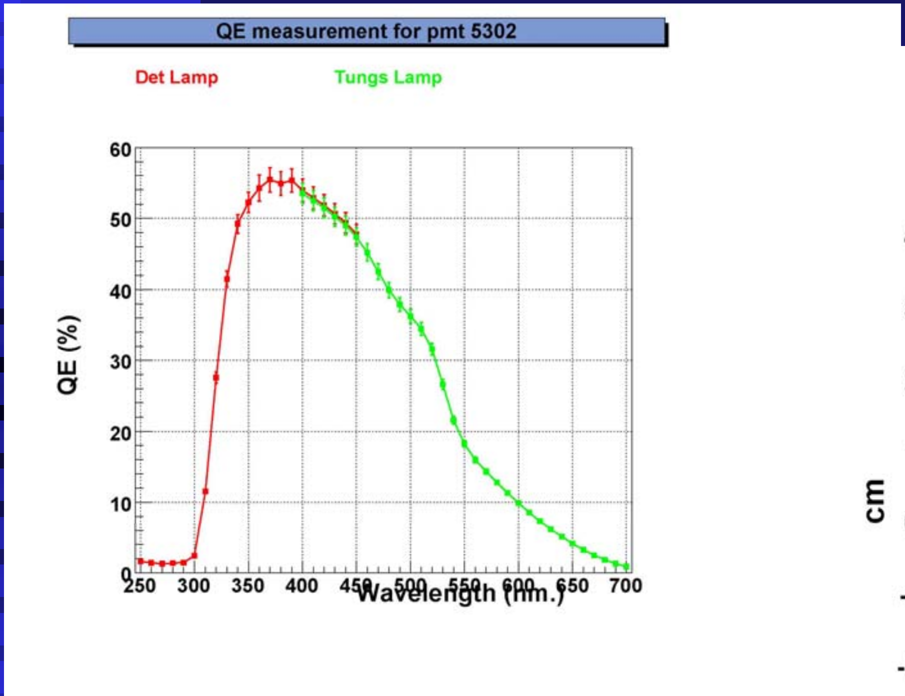
Recent Surprises

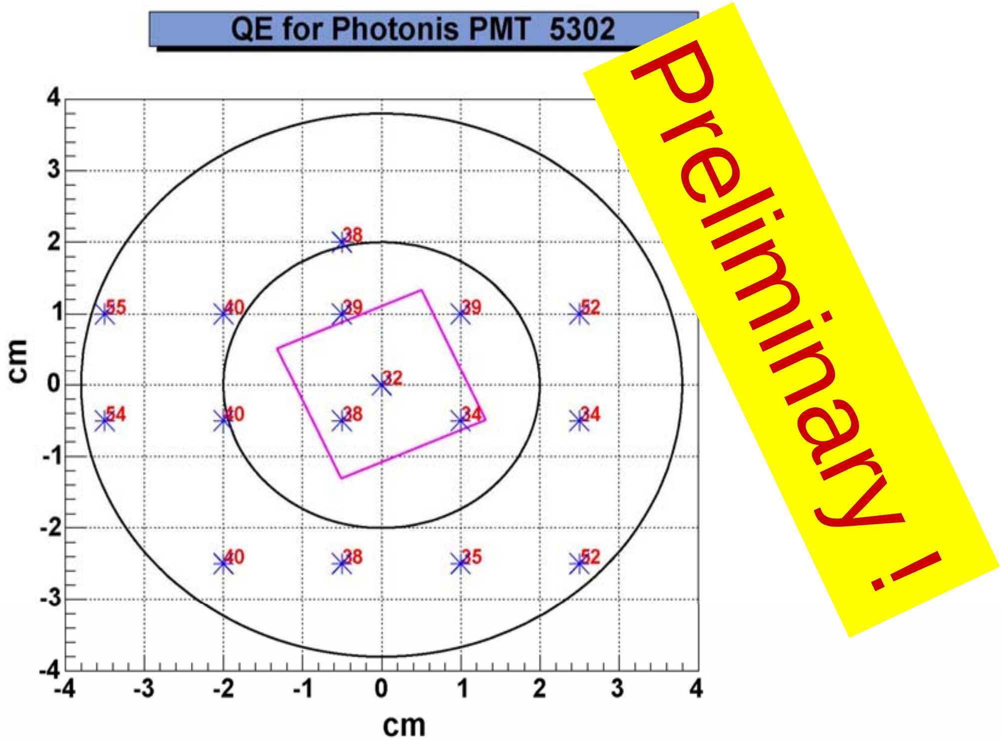


Photocathode	QE at peak wavelength		Type Availability
	Min.	Typ.	
Ultra Bialkali (UBA)	38 %	43 %	Metal Package PMT (TO-8 Type, □28 mm Type PMT)
Super Bialkali (SBA)	32 %	35 %	Metal Package PMT (TO-8 Type, □28 mm Type PMT) ϕ28 mm to ϕ76 mm Head-on PMT (Glass Bulb Type)

- 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)?

Other strongly competing ultra-fast, LLL sensors with single ph.e. resolution

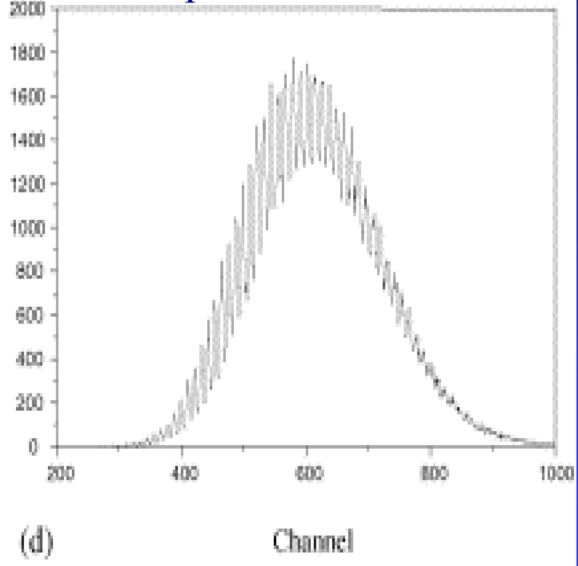
- In recent times two more types of ultra-fast response LLL sensors, providing good single ph.e. resolution, start to strongly compete with the classical PMTs.
- These are
  - HPDs with GaAsP photocathode
  - SiPM (and its variations)

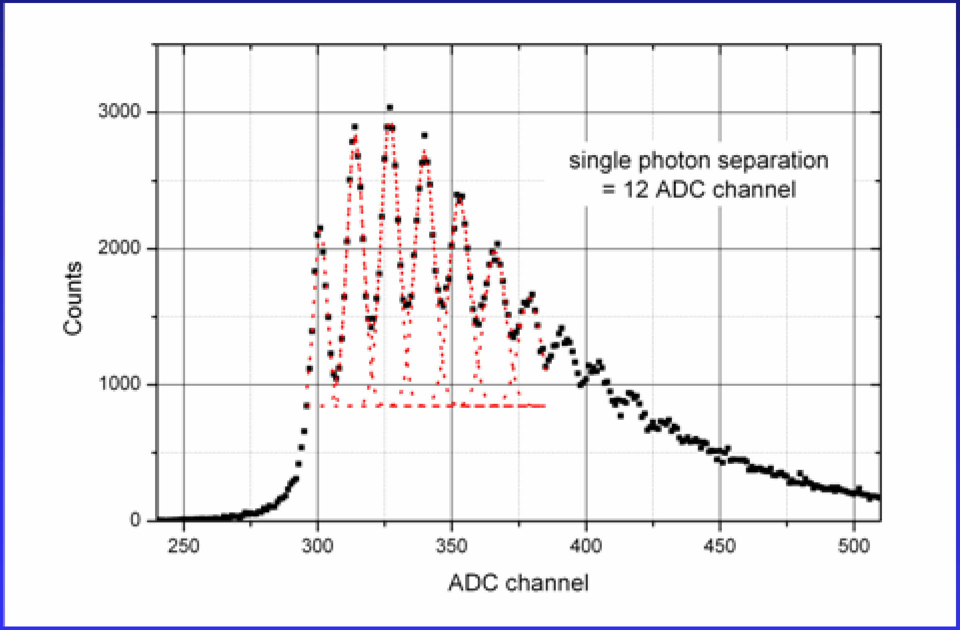
Conclusions

- In recent few years on our request the main PMT manufacturers were working on boosting the QE of classical PMTs
- As a result bialkali PMTs of 1-3´´ size with 32-35 % peak QE will become commercially available already in 2006 (~ 35% boost!)(they got the name super-bialkali)
- In autumn 2006 we learned from Hamamatsu about the so-called ultra-bialkali PMTs with 43-45 % peak QE
- Now also Photonis could demonstrate on the example of 3‘ PMT peak QE values scattered in the range 35-55 %.
- Together with SiPM the new bialkali PMTs will dominate the market very soon !

Calibration with SiPM:

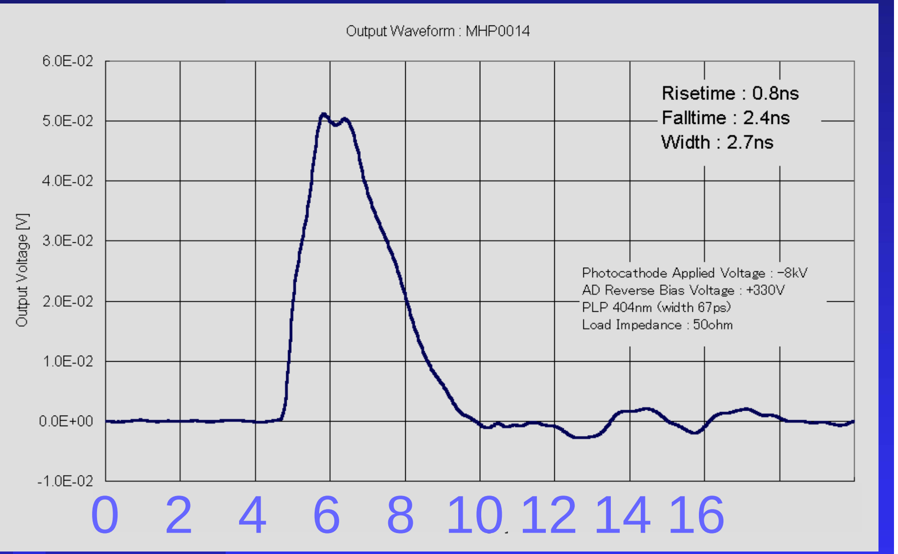
<46> ph.e. are measured





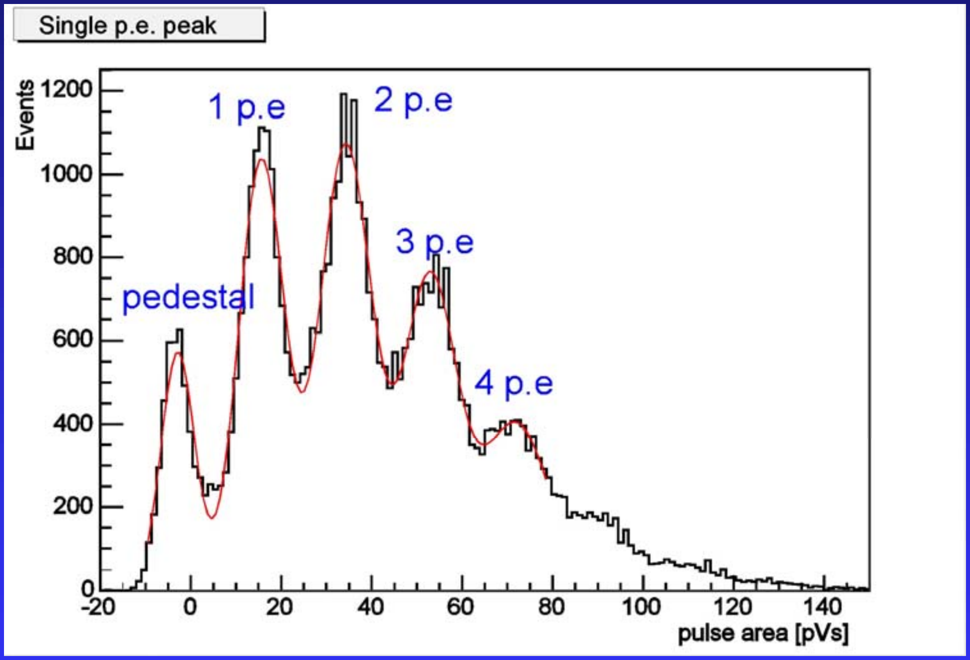
HPD Output Signal

<pulse shape>

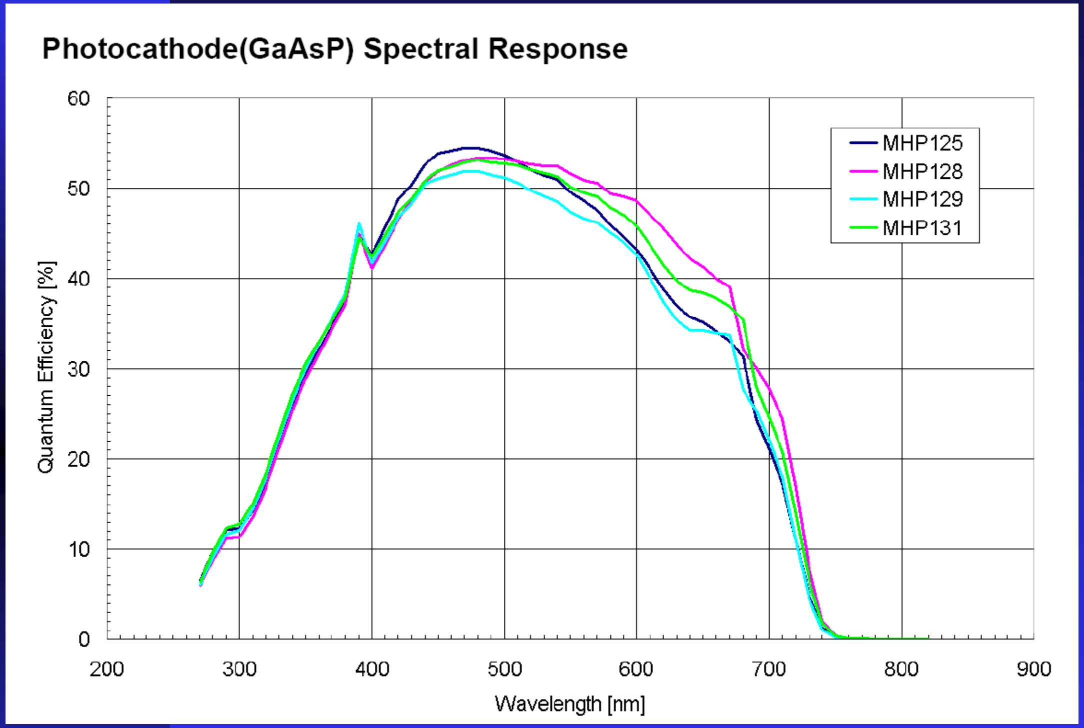


Time [ns]

<pulse height distribution>



QE boost with Wavelength Shifter



- WLS
  - Butyl- PBD (260-340 to 360-460 nm)
  - POPOP (300-400 to 400-500 nm)
  - Paraloid B72 (n = 1.4)

  in Toluene

On the Input window

$$PE = \int QE(\lambda) \times Ch(\lambda) d\lambda$$