



Very High QE bialkali PMTs

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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 !)

- 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 $N \times P$ and the Variance is equal to $N \times P \times (1 - P)$



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 $\sim 10^{-2}$
- 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; \Rightarrow 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 \rightarrow e^- conversion	High reflectivity Low efficiency	Low reflectivity High efficiency
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).

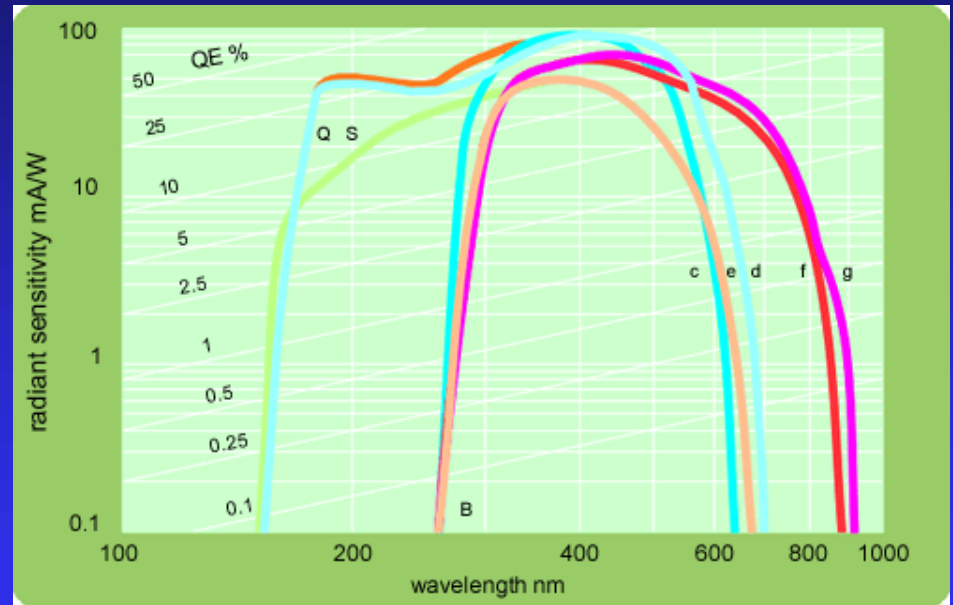
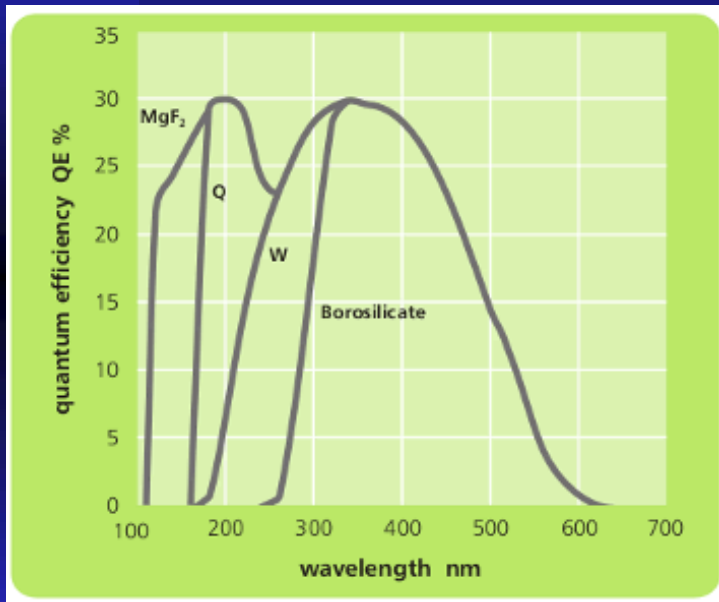


QE: Short Historical Excursion

- 1955-1958 Sommers found the „multialkali“ effect: combination of **Cs-K-Na-Sb** has high QE in the visible spectrum.
- Also were discovered
 - ◆ **Cs₃Sb** on MnO (S11, λ_{peak} @400nm, QE ~ 20%)
 - ◆ **(Cs)Na₂KSb** (S20, λ_{peak} @400nm, QE ~ 30%)
 - ◆ **K₂CsSb** (λ_{peak} @400nm, QE ~ 30%)
 - ◆ **K₂CsSb(O)** (λ_{peak} @400nm, QE ~ 35%)



Typical Quantum Efficiencies



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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 progress 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.



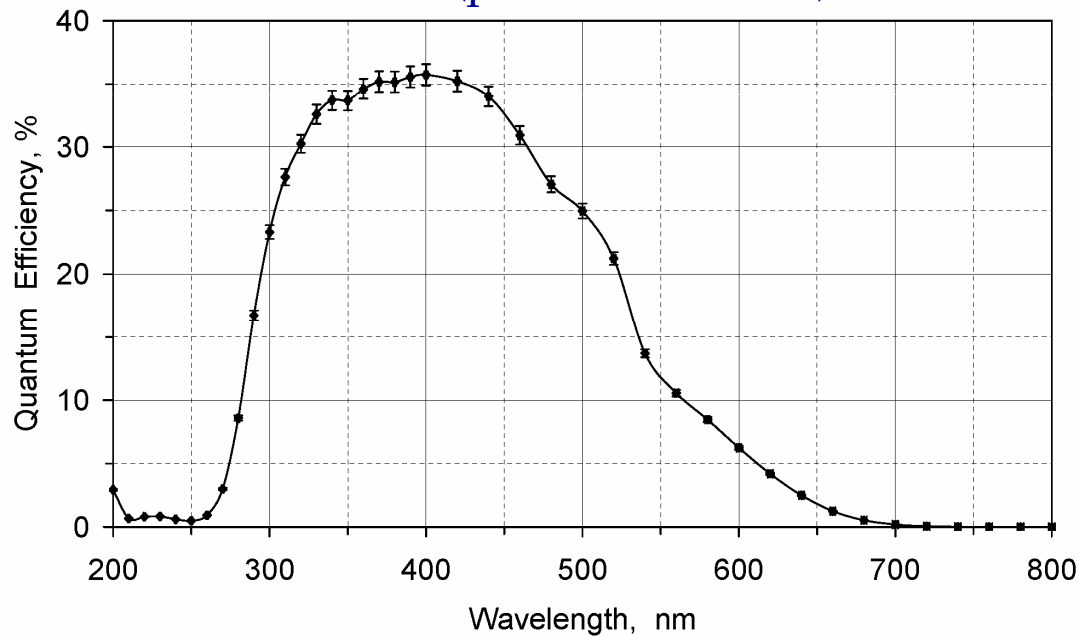
How it shall be possible to boost the QE and who is interested in it ?

- 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 \neg 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



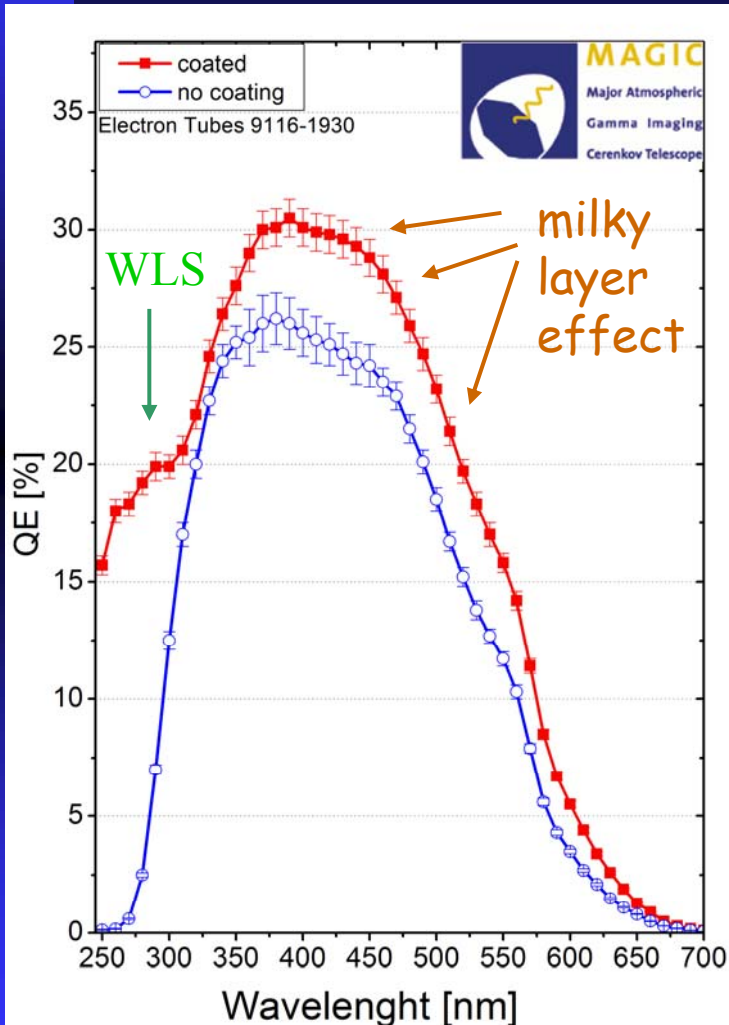
QE of our „old champion“ 2‘ PMT from Hamamatsu

Mirzoyan, et al., NIM A
(proc. Beaune'05)





PMTs of MAGIC-I →



QE ↑ by a diffuse scattering coating, +WLS

(D. Paneque, et al., 2002)



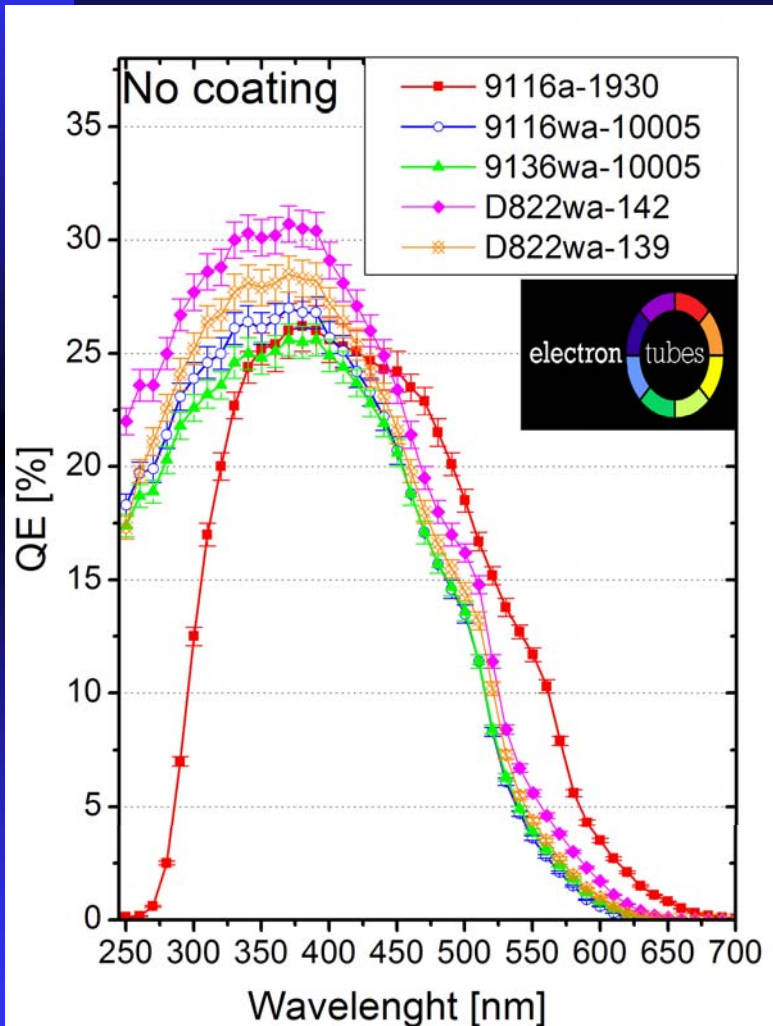
Effective QE ↑ ~ 15 %

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Recent PMTs → Electron Tubes



- Different batches show different behaviour

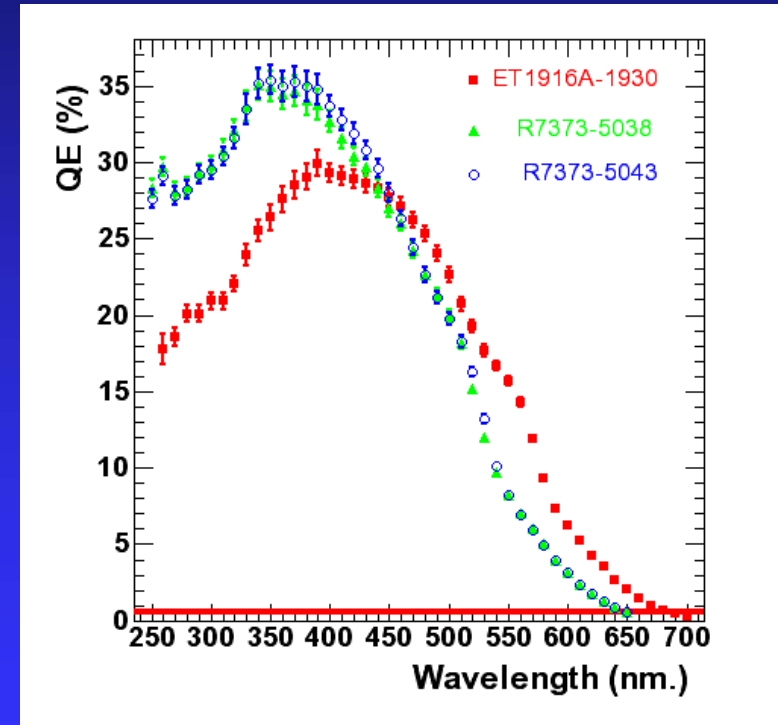
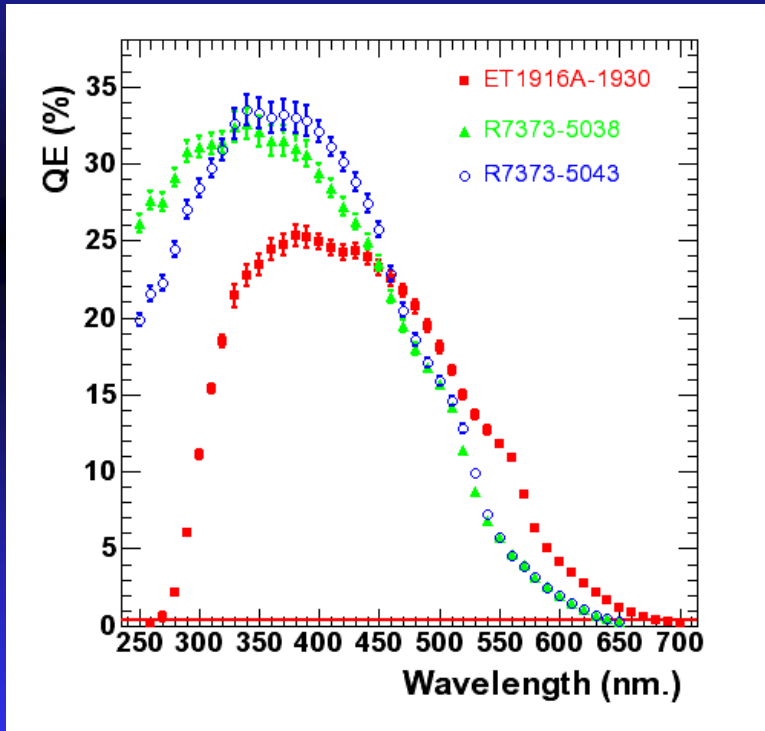
- QE is high (~30% !!)

- 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



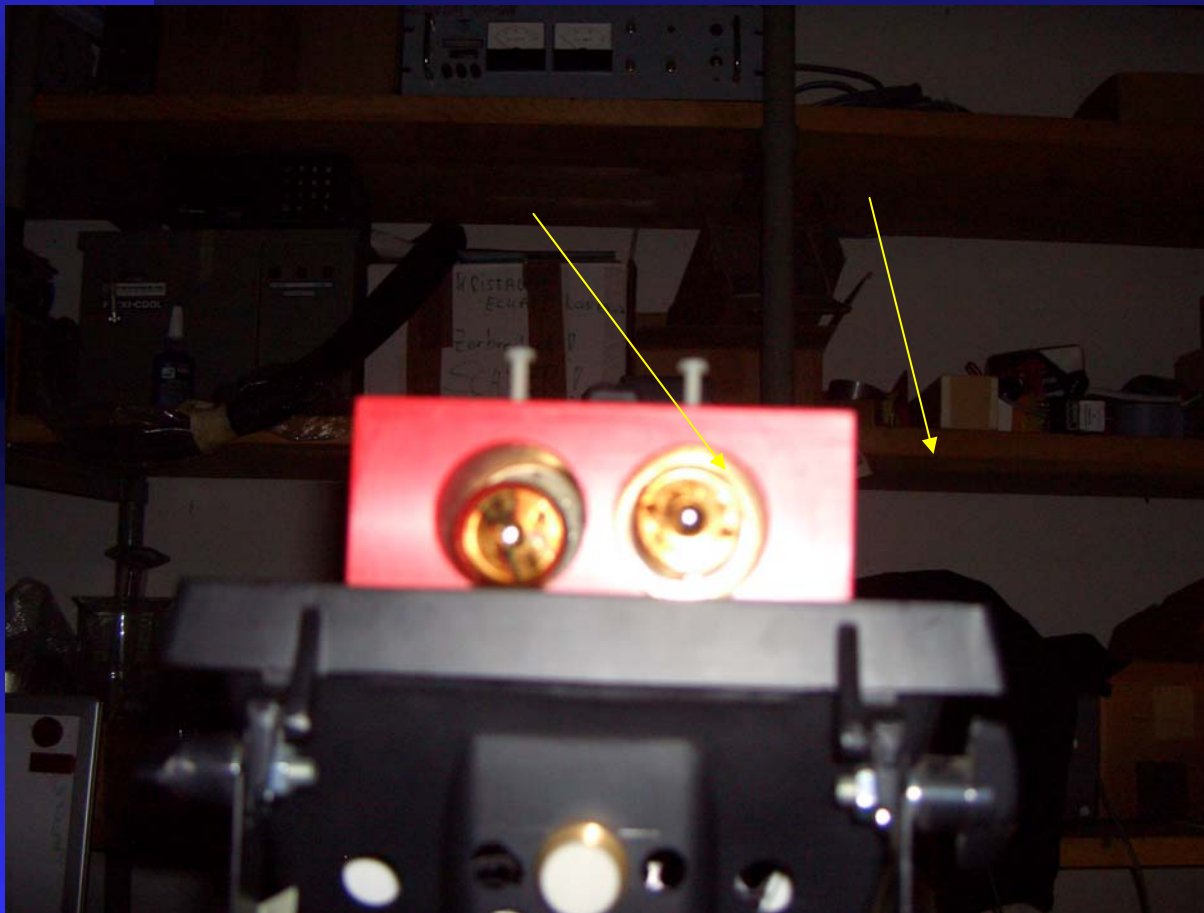


Charge collection efficiency

- 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



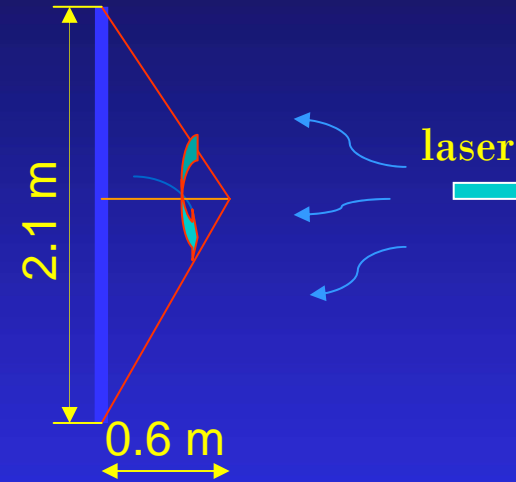
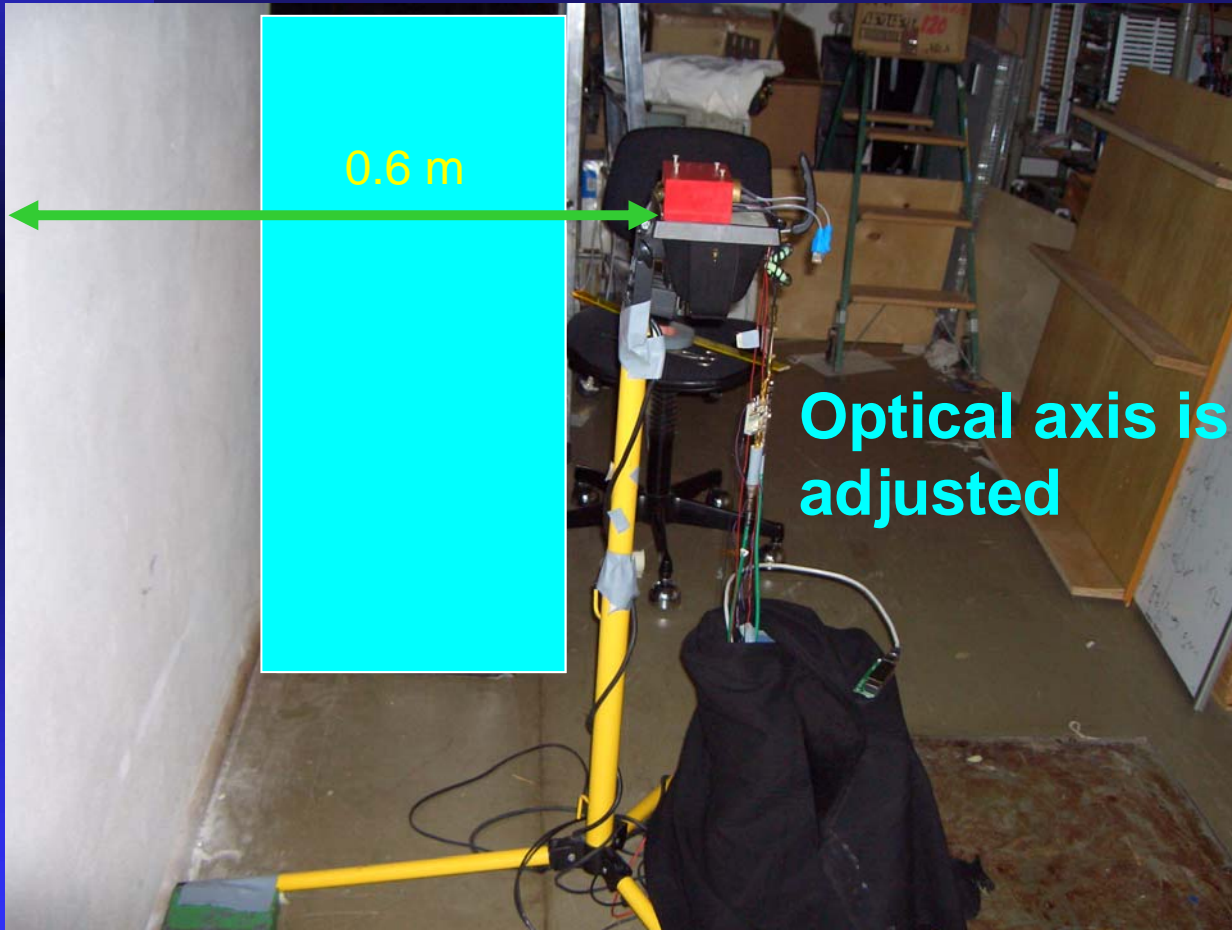
We performed PDE measurements for Hamamatsu and ET PMTs. 80 ps flashes from a laser @ 400 nm were illuminating a white wall in a storage room.

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PDE measurements



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

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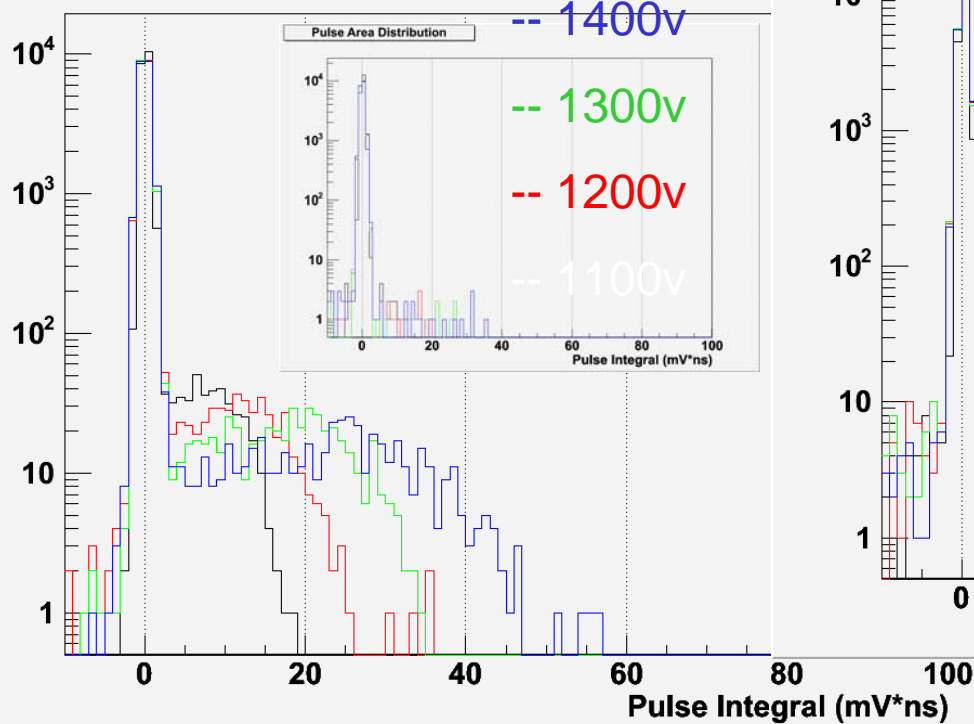
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PDE measurements

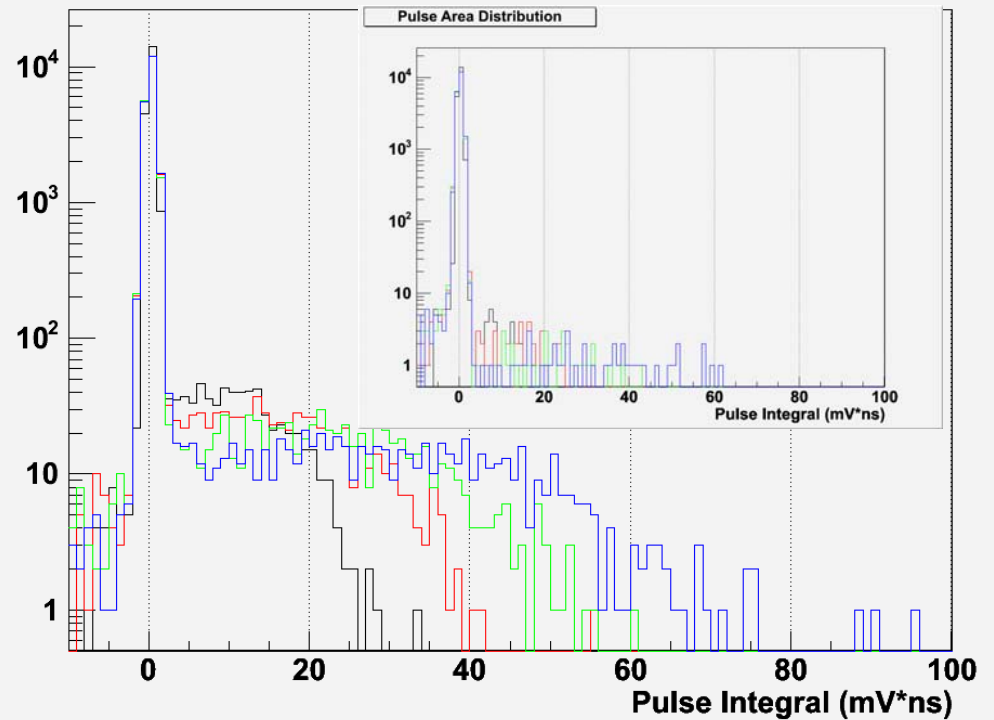
Pulse Area Distribution

ET142



Pulse Area Distribution

Hamamatsu3352





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:**

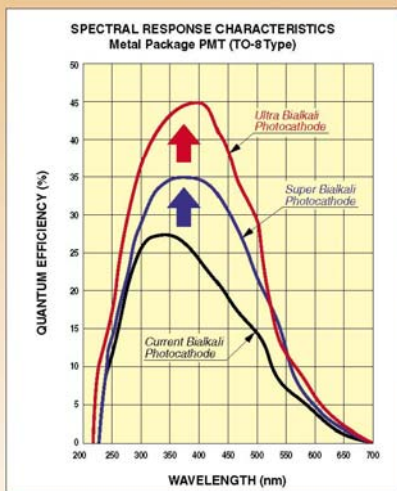
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Recent Surprises

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)

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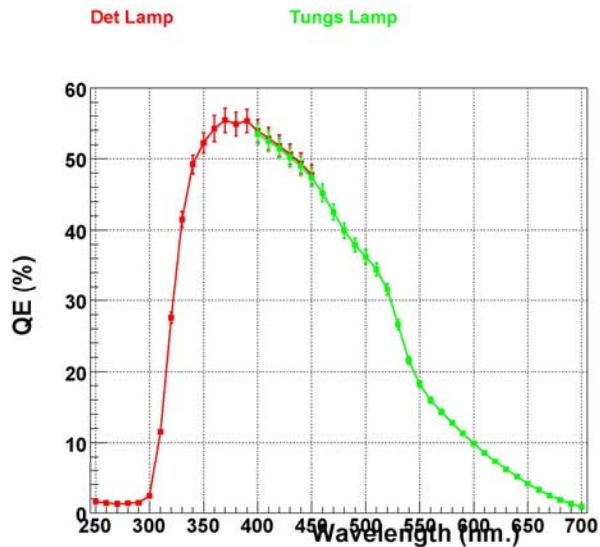
- All the 3 PMT manufacturers could report enhanced QE values, the best being Hamamatsu, who gave it the name „Super-bialkali“ (QE~ 33-36 %).
- One year ago Hamamatsu claimed to produce PMTs with peak QE of 43-45 % !
 (once the *djinn* comes out of the lamp you cannot control it anymore) ;-)
- Recently also Photonis joined club of „Ultra-bialkali“. Moreover, it pushed the QE values even higher up !

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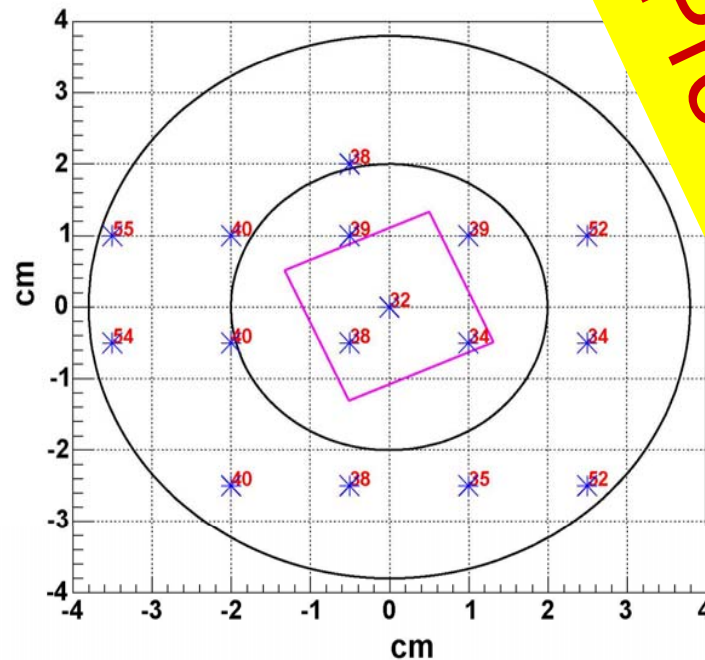
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The very recent 3' Photonis PMTs: QE peak values in excess 50 % !

QE measurement for pmt 5302



QE for Photonis PMT 5302



Preliminary !

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

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

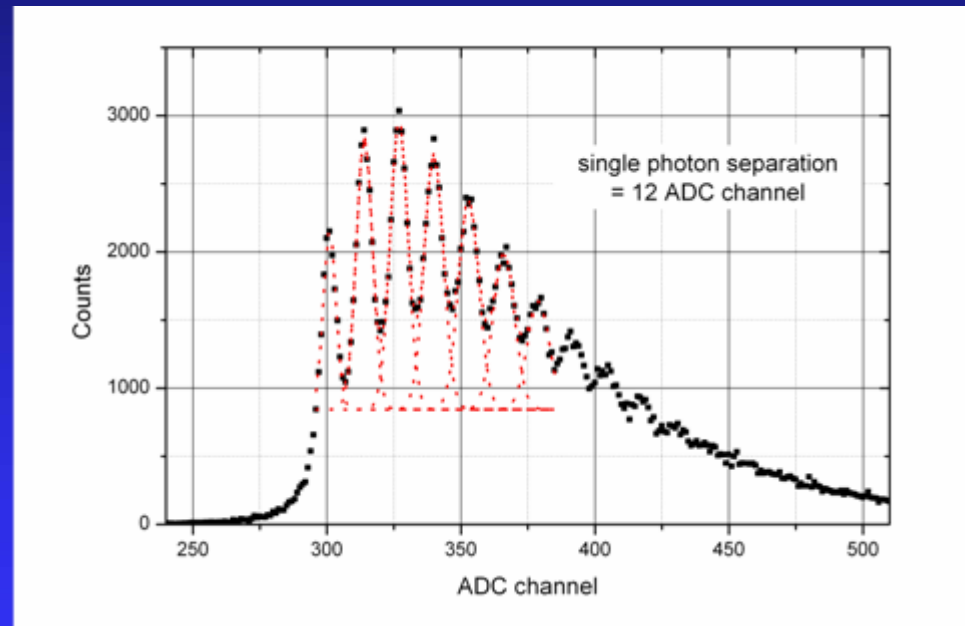
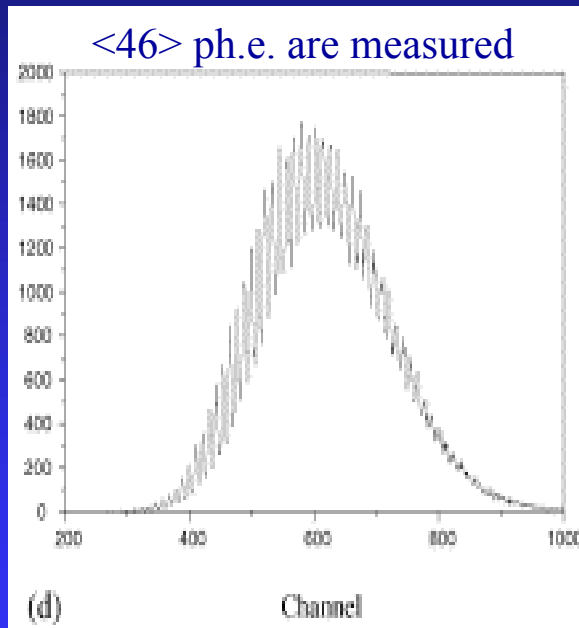
- In recent times two more types of ultra-fast response LLL sensors, providing good single ph.e. resolution, start to strongly compete with the classical PMTs.
- These are
 - ◆ HPDs with GaAsP photocathode
 - ◆ SiPM (and its variations)



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:



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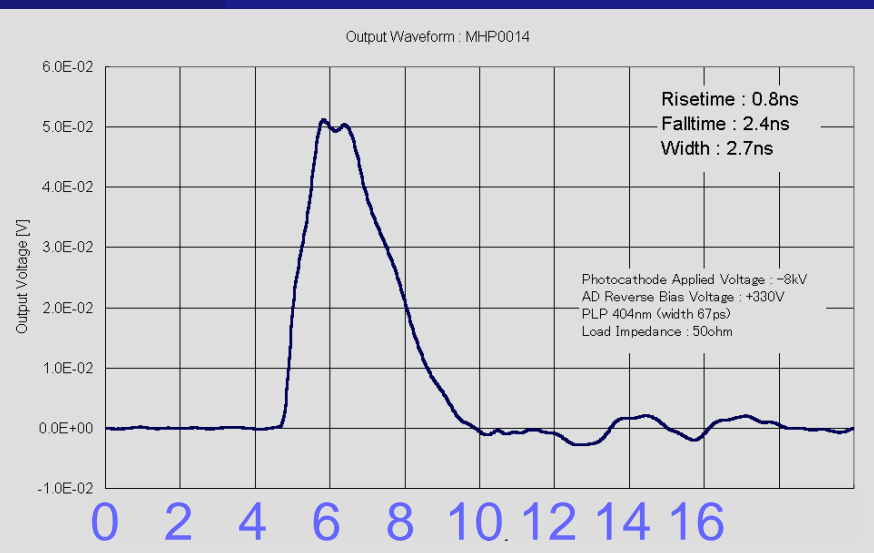
MAX-PLANCK-GESELLSCHAFT



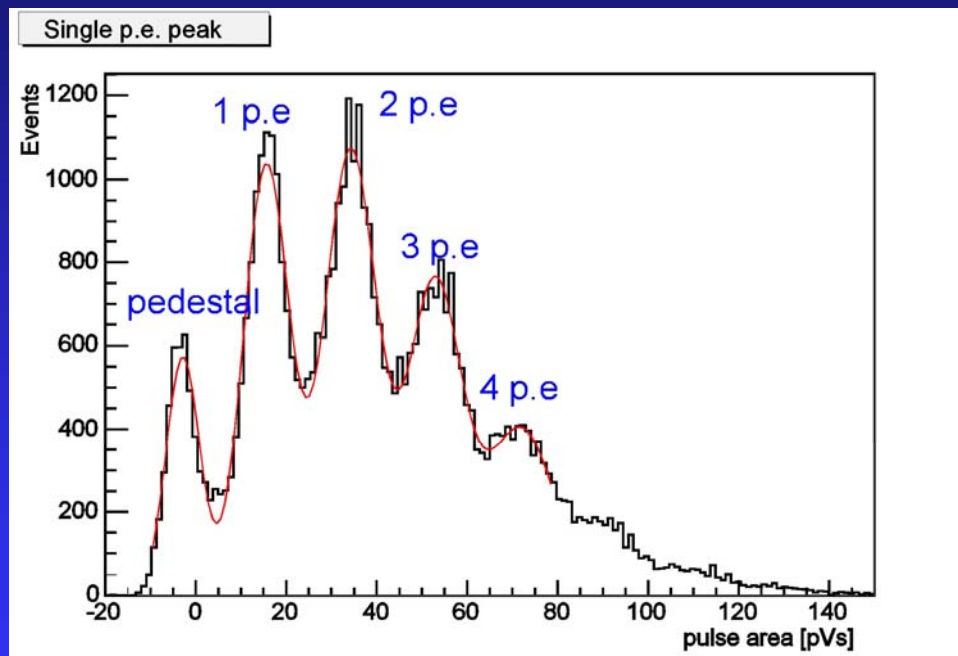
HPD Output Signal

<pulse shape>

<pulse height distribution>



Time [ns]

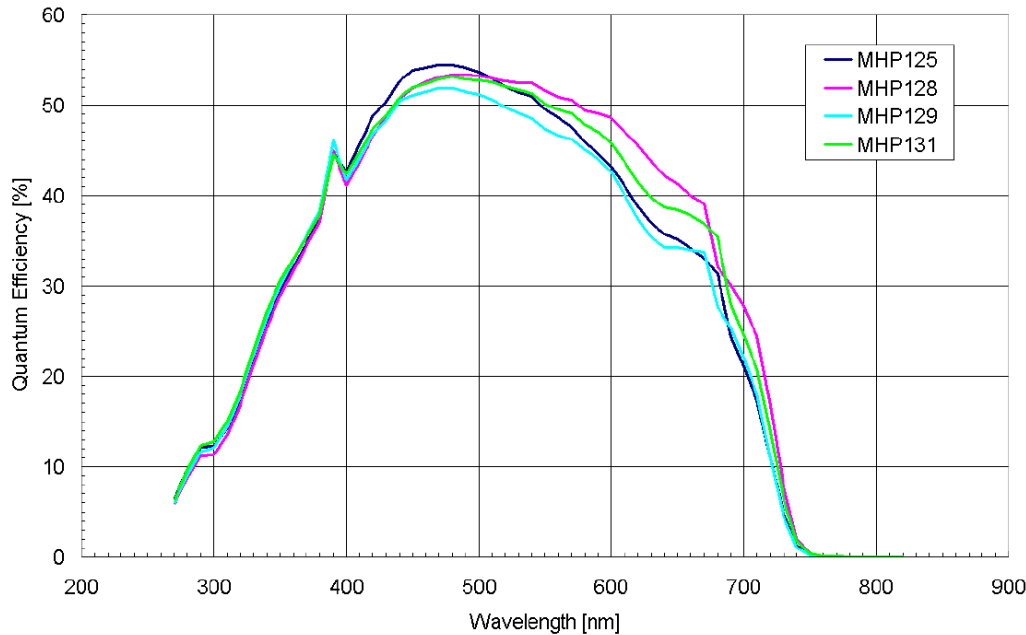


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QE boost with Wavelength Shifter

Photocathode(GaAsP) Spectral Response



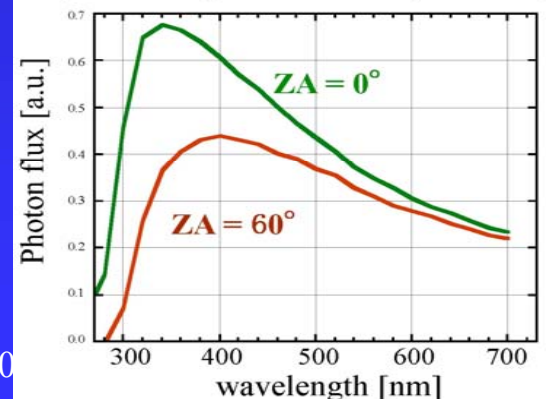
- WLS

- 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

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

Cherenkov photon spectra (from 40 GeV gamma at La Palma [a.s.l. 2200 m])



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