Photon detectors 1/2

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8th Summer Topical Seminar on Frontier of Particle Physics -
- Detector and Electronics
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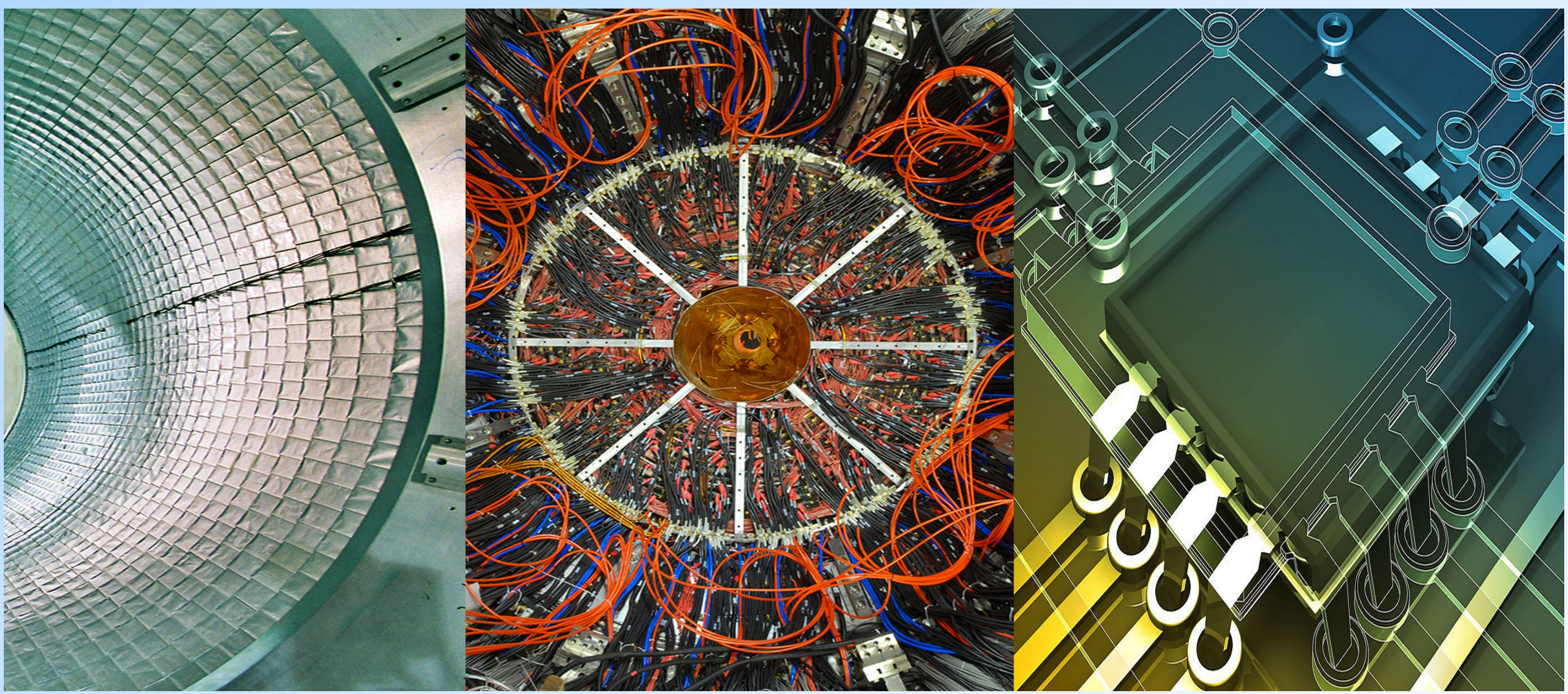

Thanks

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Outline

Outline:

- Basics
- Typical applications
- Requirements on photon detectors
- Detector types

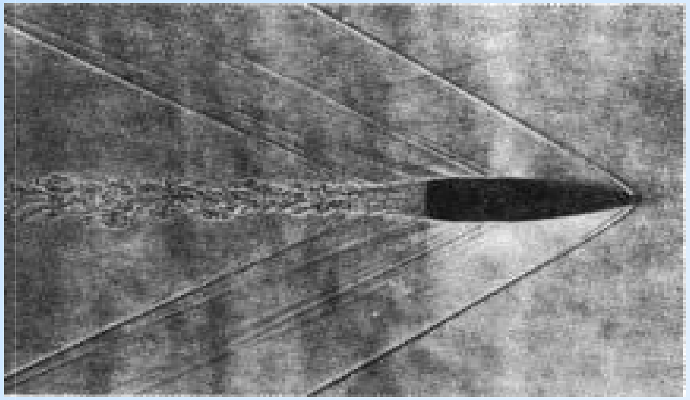
Applications

- Cherenkov light based:
  - Cherenkov threshold detectors, RICH detectors, TOF, Calorimeters ...
- Scintillator based:
  - Calorimeters, TOF, fiber trackers, medical imaging ...

Cherenkov radiation

- threshold - radiation is emitted when charged particles moves through the medium faster than the speed of light

$$\beta = \frac{v}{c} > \frac{1}{n}$$



- Cherenkov angle - angle between the particle and photon directions

$$\cos \vartheta_C = \frac{1}{\beta n}$$

- number of photons - depends on refractive index → Cherenkov angle

$$\frac{d^2 N}{dE dl} \approx \frac{370}{eV\ cm} \sin^2 \vartheta_C \qquad \left(\frac{dN}{d\lambda} = \frac{ch}{\lambda^2} \frac{dN}{dE} \right)$$

→ high sensitivity in blue to UV region

- prompt emission – no decay constant as with scintillators

→ enables precise time measurements

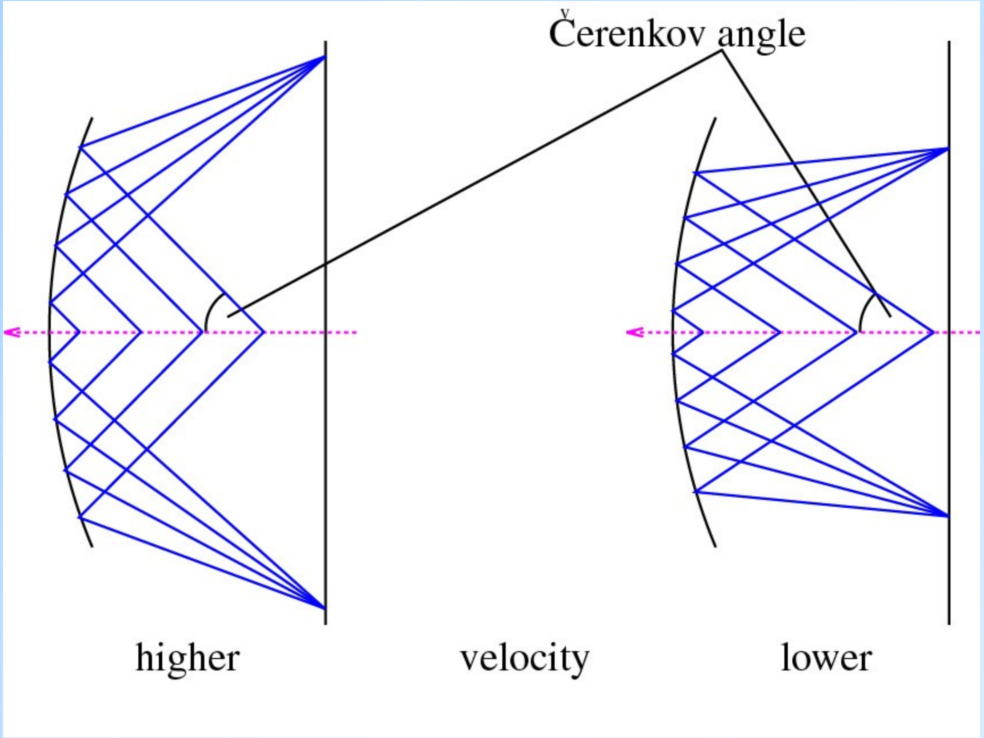
- light is polarized – E lies in the plane defined by particle and photon momenta

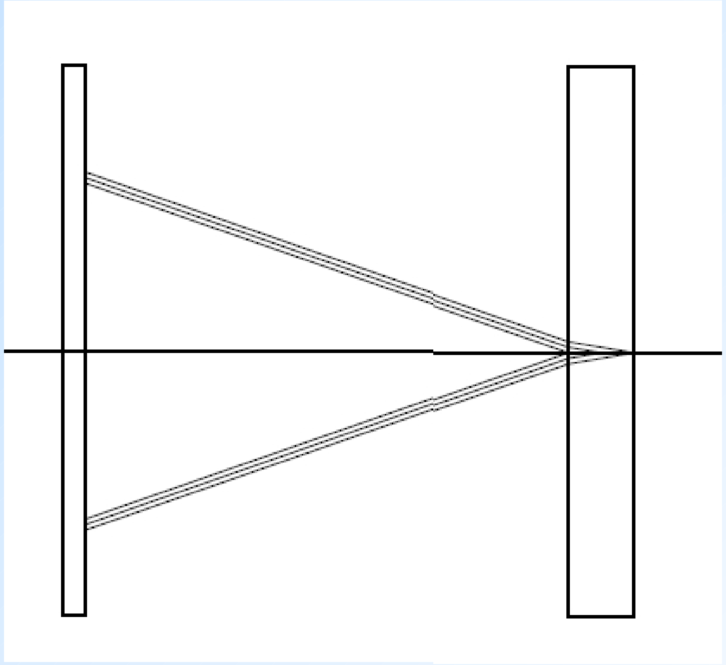
Cherencov detectors

- threshold Cherenkov counter

$$p_{thr} = \frac{mc}{\sqrt{n^2 - 1}}$$

- Ring Imaging CHerenkov counter (RICH) → measurement of Cherenkov angle → particle velocity. Base designs:

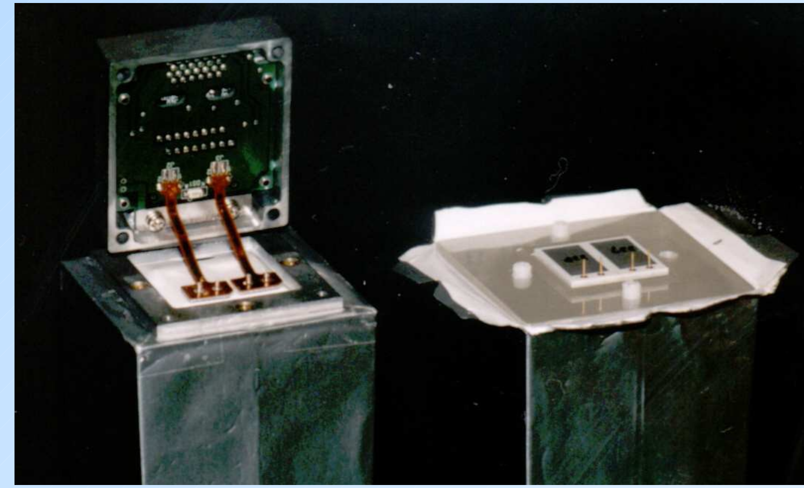




detector with focusing mirror → gas radiator

proximity focusing detector → solid or liquid radiator

Applications using scintilators

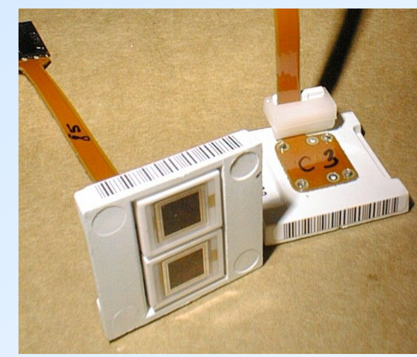


- Calorimeters:
- Belle calorimeter with CsI(TI) (λ~550 nm) and PIN photodiodes

~ 50000 photons/MeV

- CMS calorimeter with $PbWO_4$ (λ~420–430 nm) and APDs

~ 100 photons/MeV



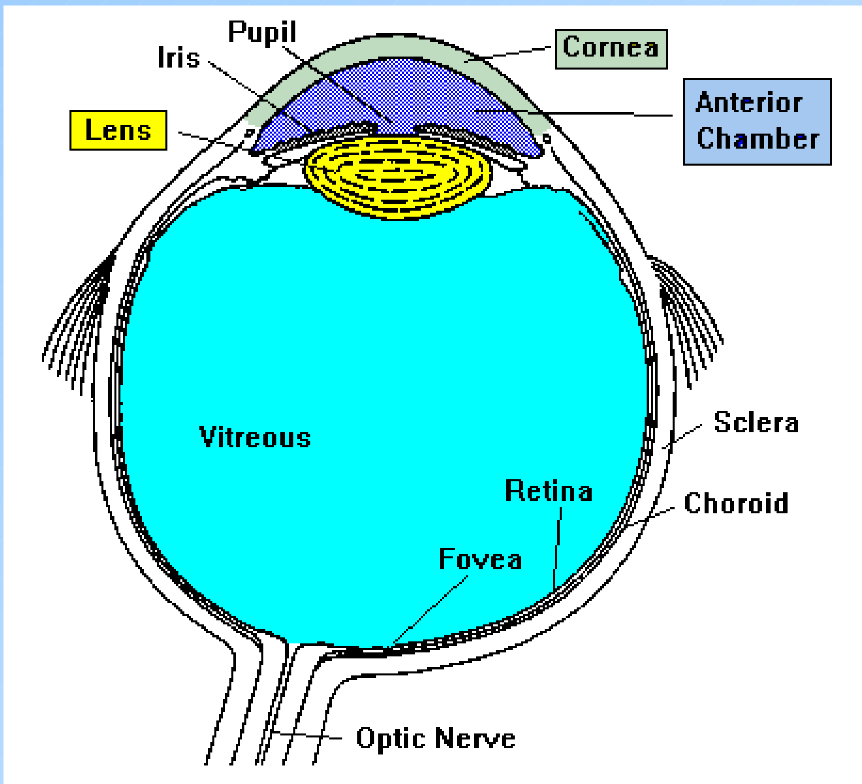
- Time-Of-Flight detectors
- Fiber trackers
- Medical imaging (PET, …)

→ high sensitivity in blue-grean region

Basics:

- The human eye as a photo-detector
- Photoelectric effect
- Photosensitive materials and windows

The human eye



- The first proto-eyes evolved among animals 540 million years ago.
- Light passes through the cornea, pupil and lens before hitting the retina. The iris controls the size of the pupil and therefore, the amount of light that enters the eye. Also, the color of your eyes is determined by the iris.
- The vitreous is a clear gel that provides constant pressure to maintain the shape of the eye.
- The retina is the area of the eye that contains the receptors (rods for low light contrast and cones for colors) that respond to light. The receptors respond to light by generating electrical impulses that travel out of the eye through the optic nerve to the brain.

The optic nerve contains 1.2 million nerve fibers. This number is low compared to the roughly 100 million photoreceptors in the retina.

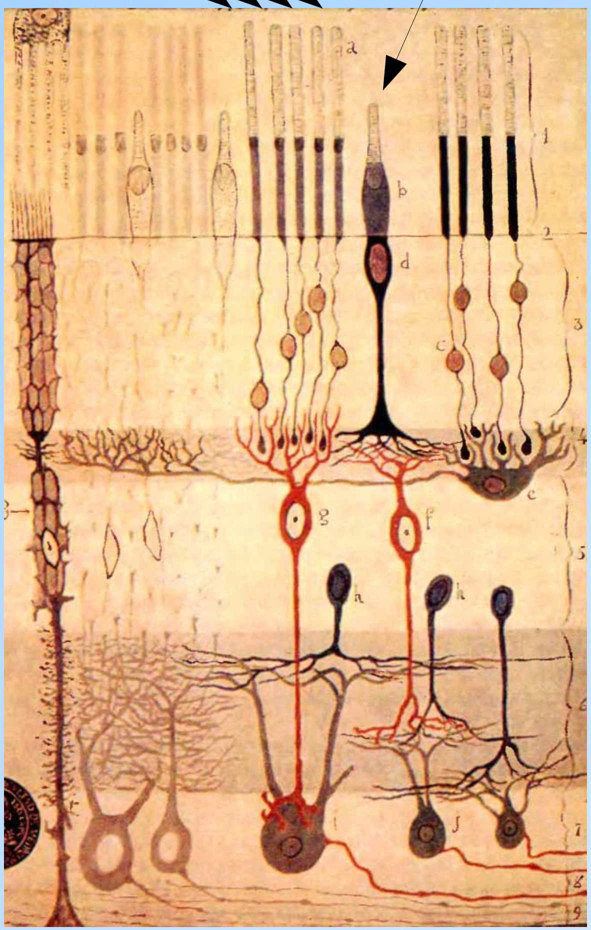
Rods and cones

rods

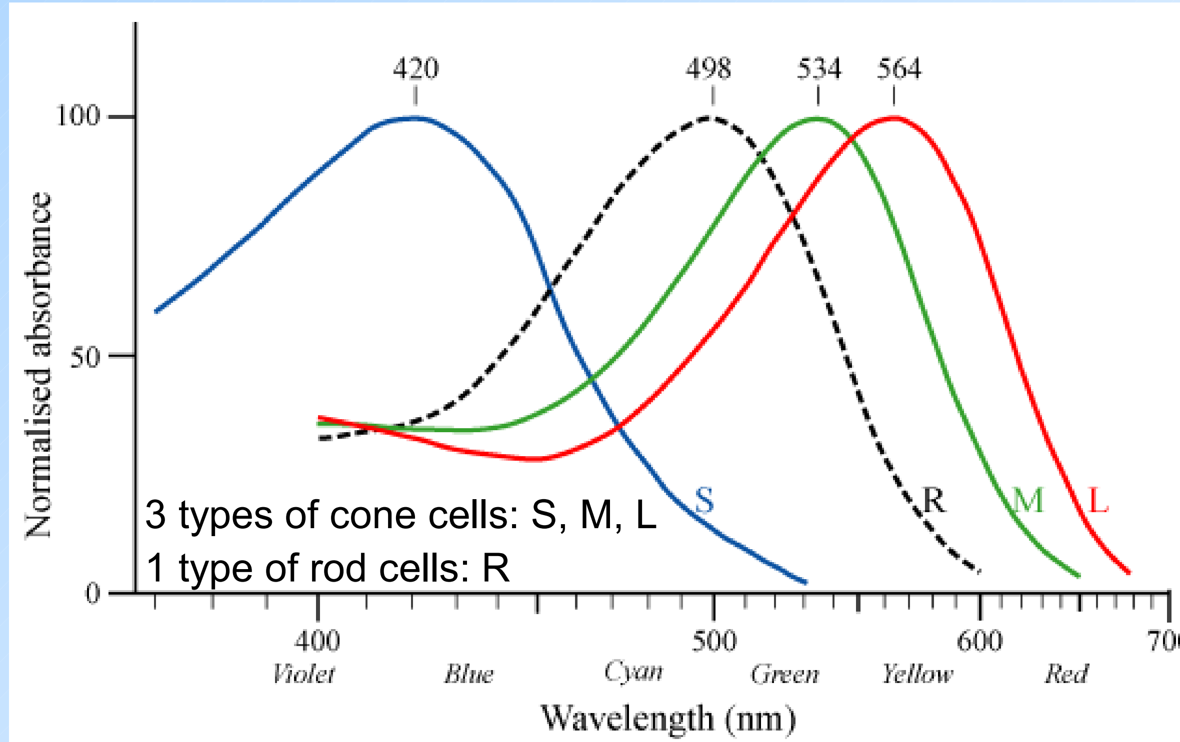
$\sim 10^8$ cells

cones

$\sim 5 \times 10^6$ cells



Spectral sensitivity rods & cones



The human eye can detect light pulse of 10-40 photons. Taking into account that absorption of light in retina is ~10-20% and transparency of vitreous is ~50%

→ ~2-8 photons give detectable signal.

Eye performance

After having been built many billion times, the eye can be considered as a very successful and reliable photo-detector.

It provides…

- Good spatial resolution. <1 mm, with certain accessories even <0.01 mm
- Very large dynamic range (1:106) + automatic threshold adaptation
- Energy (wavelength) discrimination \ colours
- Long lifetime. Performance degradation in second half of life-cycle can be easily mitigated.

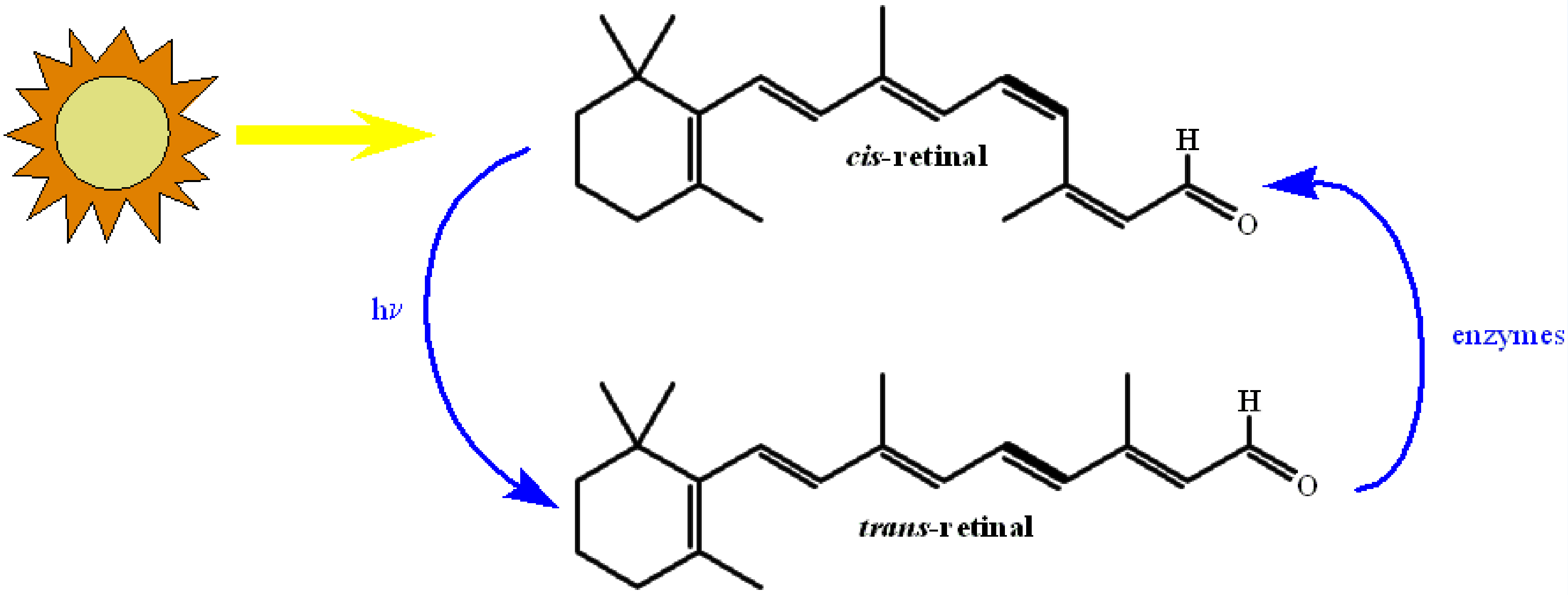
Weak points:

- Modest sensitivity: 500 to 900 photons must arrive at the eye every second for our brain to register a conscious signal
- Modest speed. Data taking rate ~ 10Hz (incl. processing)
- Trigger capability is very poor. “Look now’’ → Time jitter ~1 s.

→ There is room for improvement

Visual photo-transduction

Visual photo-transduction is a VERY COMPLEX process by which light is converted into electrical signals in the rod and cone cells of the retina of the eye.



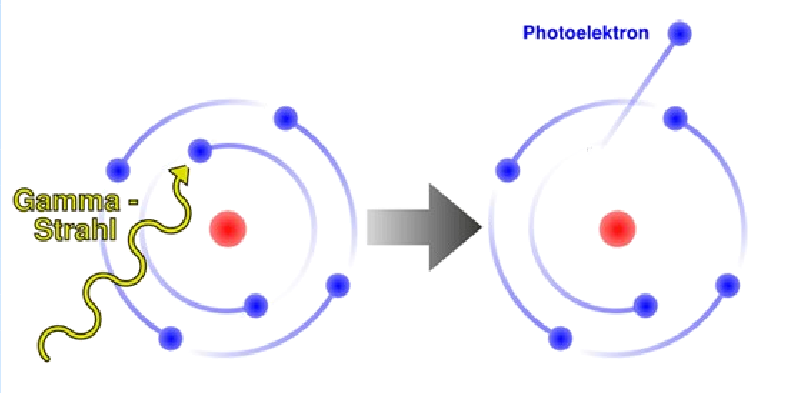
See e.g. http://en.wikipedia.org/wiki/Phototransduction

Photo-effect

First we need to convert light into detectable electronic signal

Principle:

- Use photoelectric effect to ‘convert’ photons (γ) to photoelectrons (pe)
- Details depend on the type of the photosensitive material (see below).
- Photon detection involves often materials like K, Na, Rb, Cs (alkali metals). They have the smallest electronegativity → highest tendency to release electrons.
- Most photo-detectors make use of solid or gaseous photosensitive materials.
- Photo-effect can in principle also be observed from liquids.

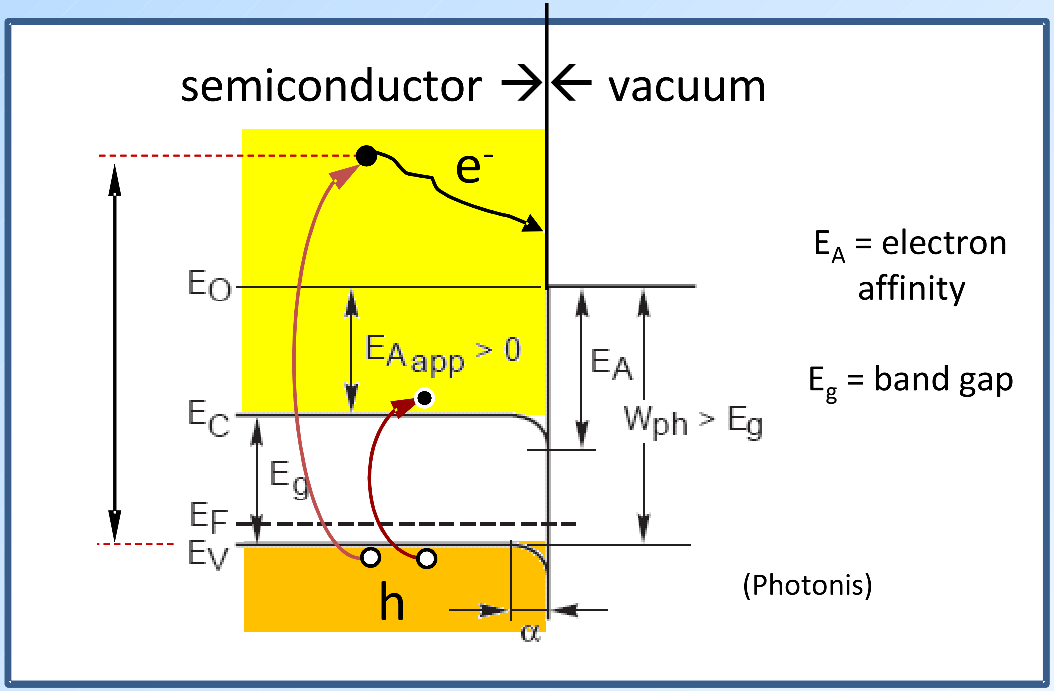


A. Einstein.
Annalen der Physik 17 (1905) 132–148.

Solid photocathode

Good materials for solid photocathode are semiconductors

• absorbed γ's impart energy to electrons (e) in the material; If $E_\gamma > E_g$, electrons are lifted to conductance band.
→ In a Si-photodiode, these electrons can create a photo-current. → Photon detected by Internal Photoeffect.



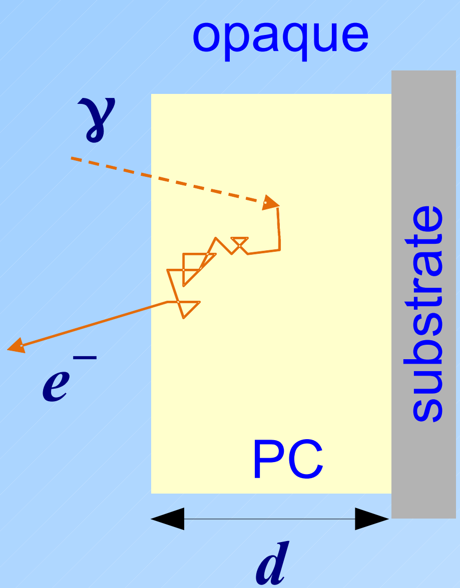
However, if the detection method requires extraction of the electron into vacuum, 2 more steps must be accomplished:

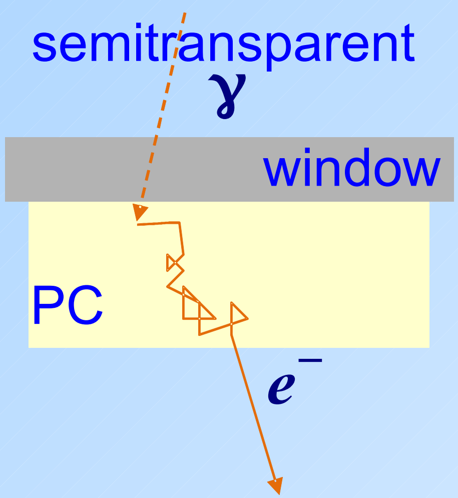
• energized e's diffuse through the material, losing part of their energy (~random walk) due to electron-phonon scattering. ΔE ~ 0.05 eV per collision. Free path between 2 collisions is ~ 2.5 - 5 nm → escape depth λ_e ~ some tens of nm.

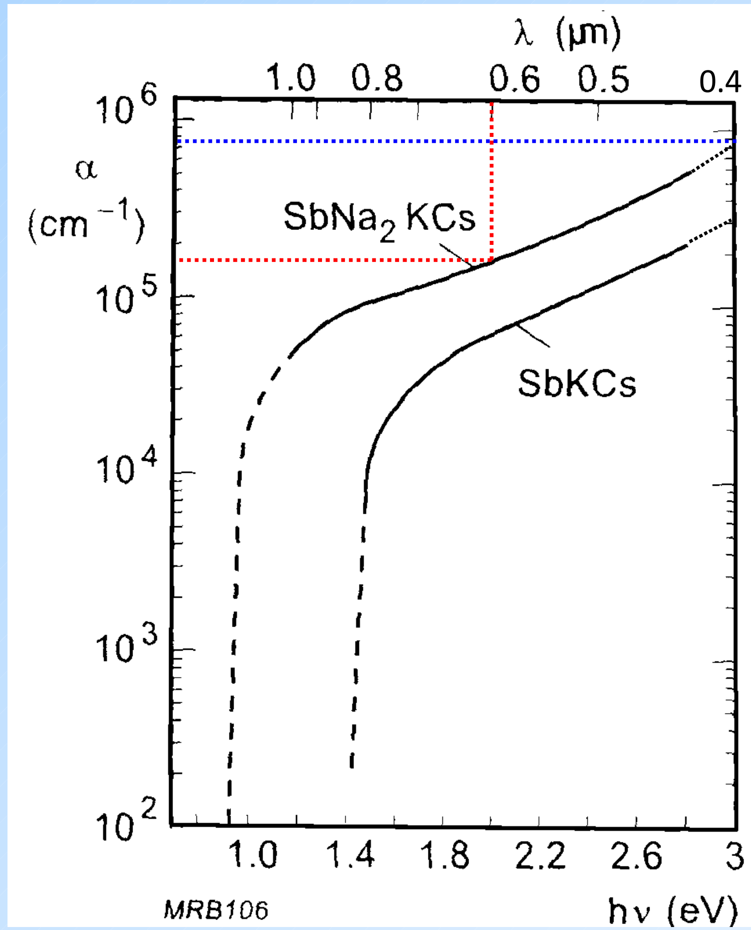
• only e's reaching the surface with sufficient excess energy escape from it
→ External Photoeffect

$$E_\gamma = h\nu > W_{ph} = E_G + E_A$$

Opaque vs semitransparent photocathode







$$N = N_0 \cdot e^{-\alpha d}$$

$$\lambda_a = \frac{1}{\alpha}$$

Red light ($\lambda \approx 600$ nm)

$\alpha \approx 1.5 \cdot 10^5$ cm^{-1}

$\lambda_a \approx 60$ nm

Blue light (l ≈ 400 nm)

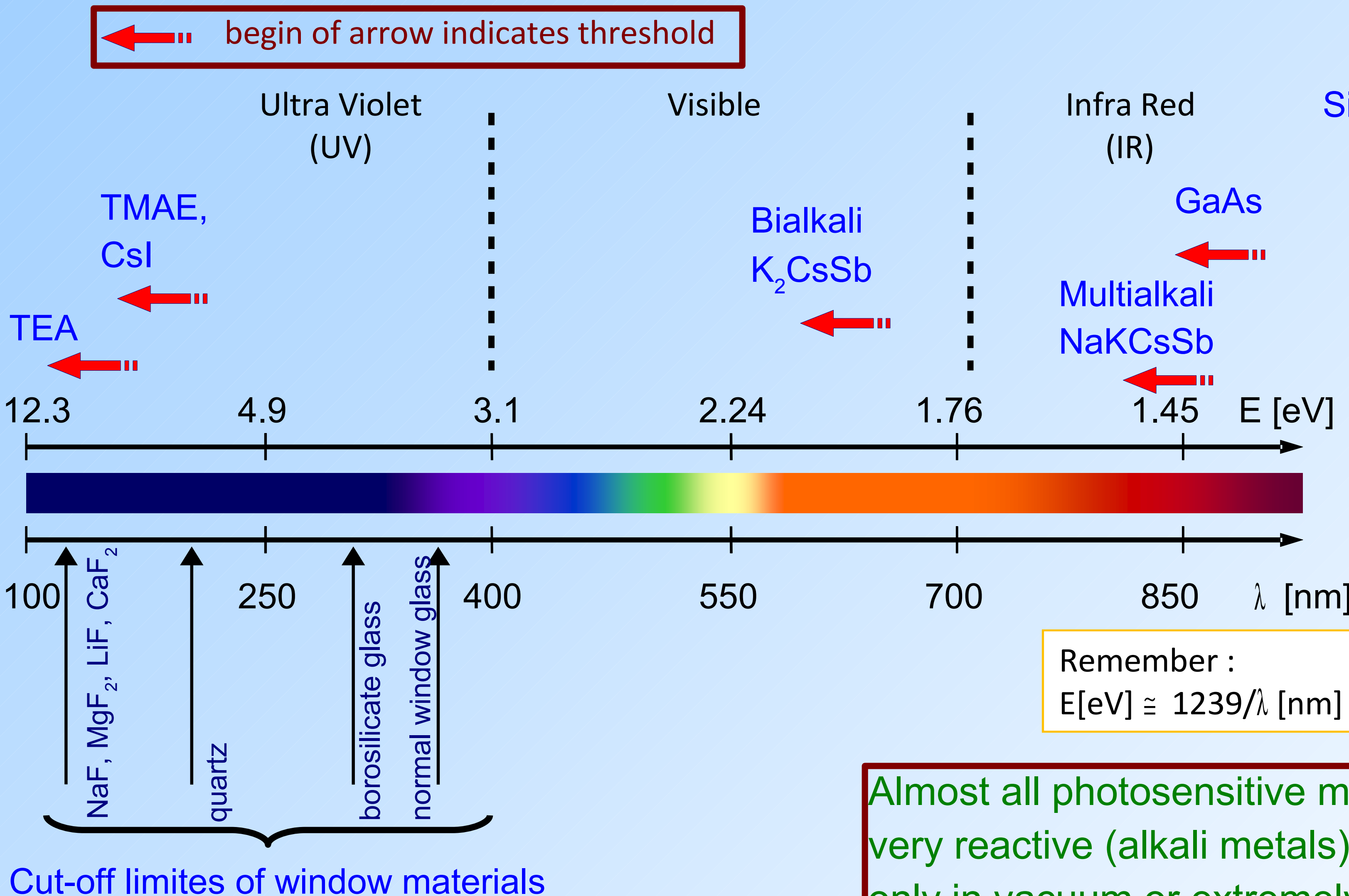
$\alpha \approx 7 \cdot 10^5$ cm^{-1}

$\lambda_a \approx 15$ nm

Blue light is more strongly absorbed than red light !

→ Make semitransparent photocathode just as thick as necessary!

Photosensitive materials - photo-cathodes

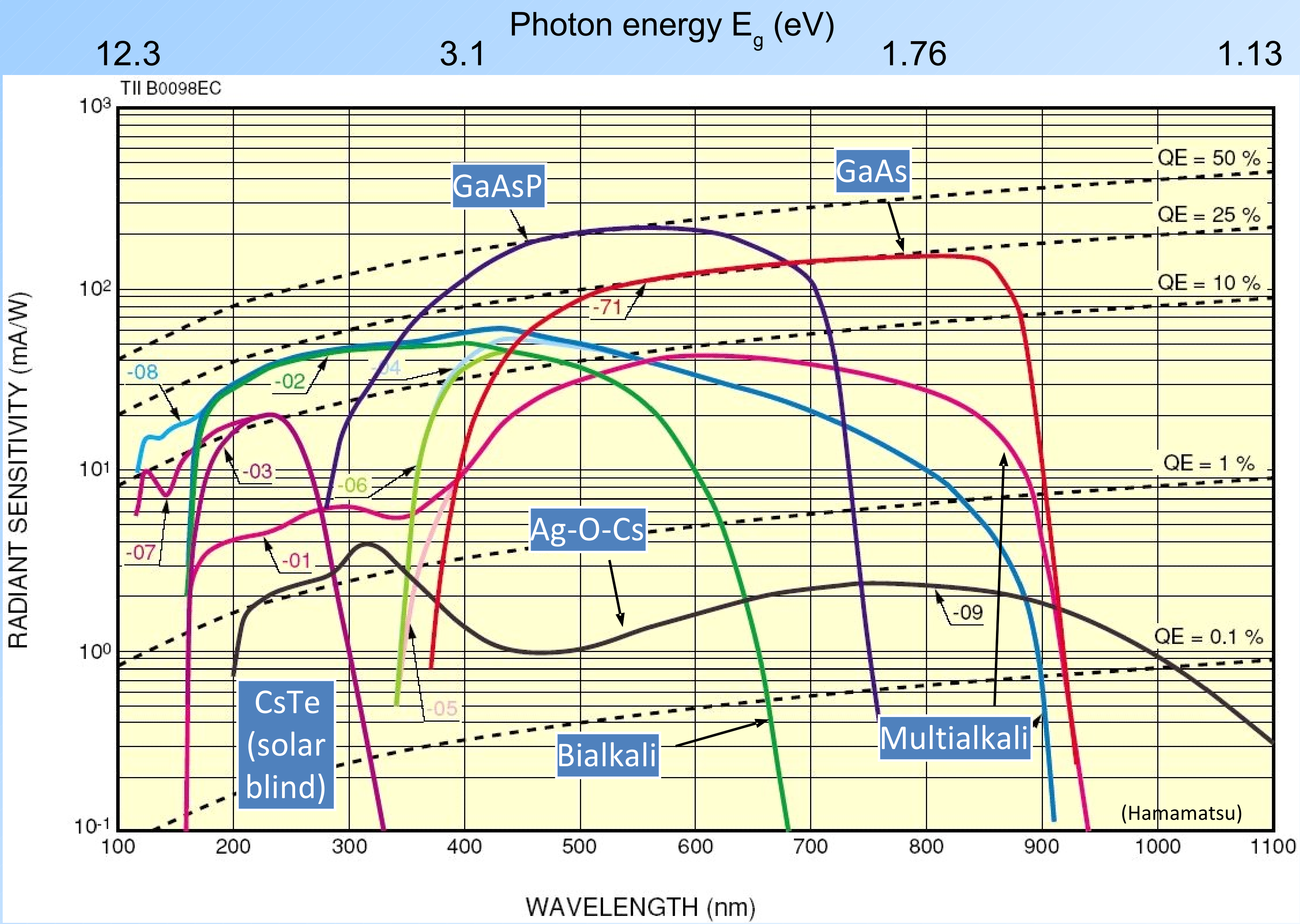


Remember :
E[eV] ≅ 1239/λ [nm]

Almost all photosensitive materials are very reactive (alkali metals). Operation only in vacuum or extremely clean gas.

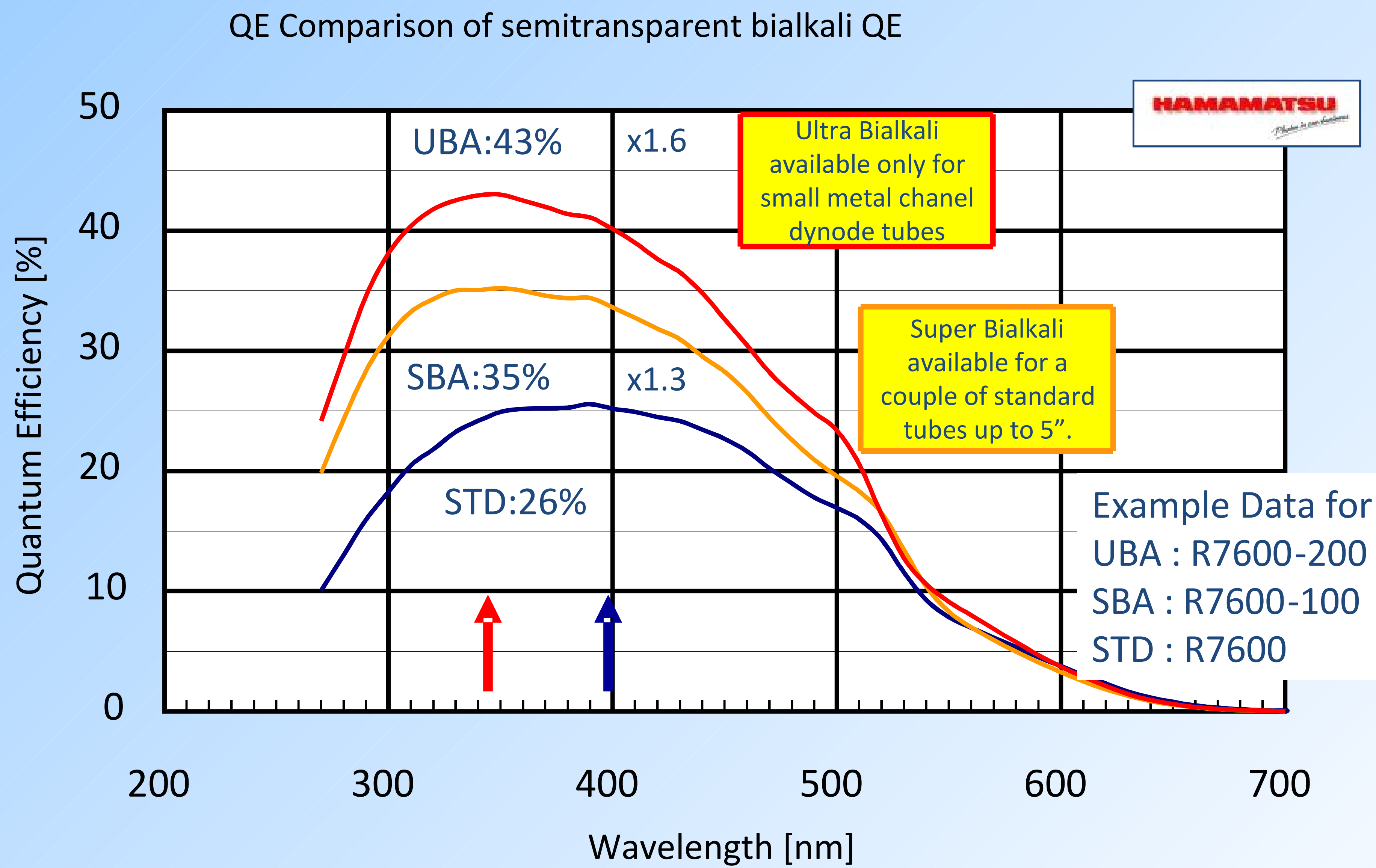
Exception: Silicon, CsI.

Semitransparent photo-cathodes

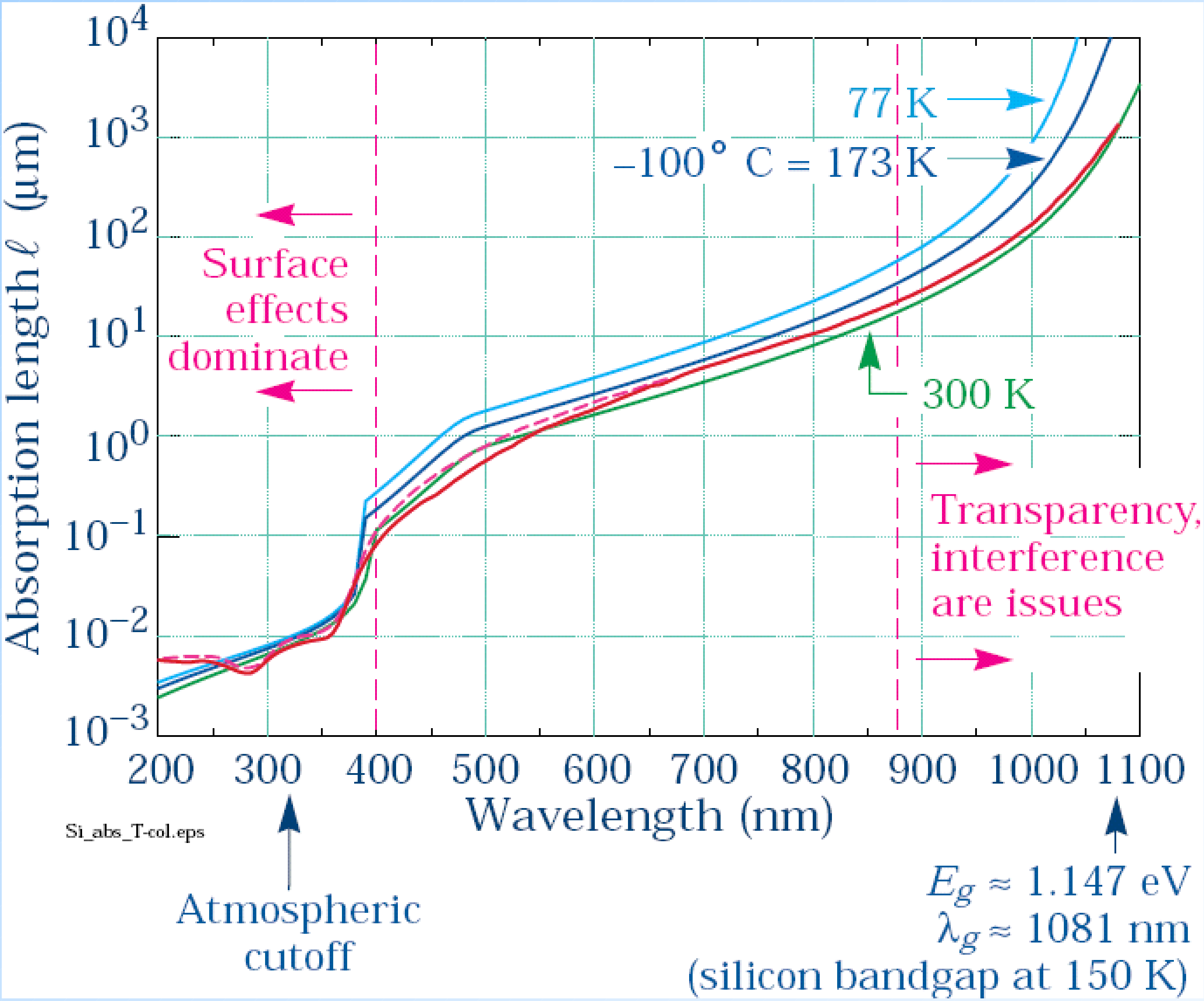


Bialkali: SbKCs, SbRbCs Multialkali: $SbNa_2KCs$ (alkali metals have low work function)

Recent improvements of photo-cathode QE

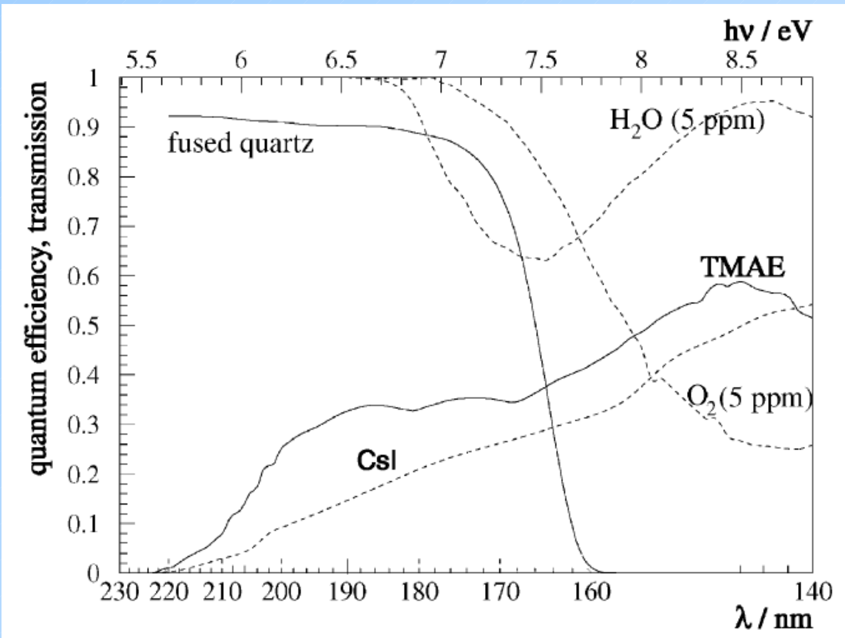


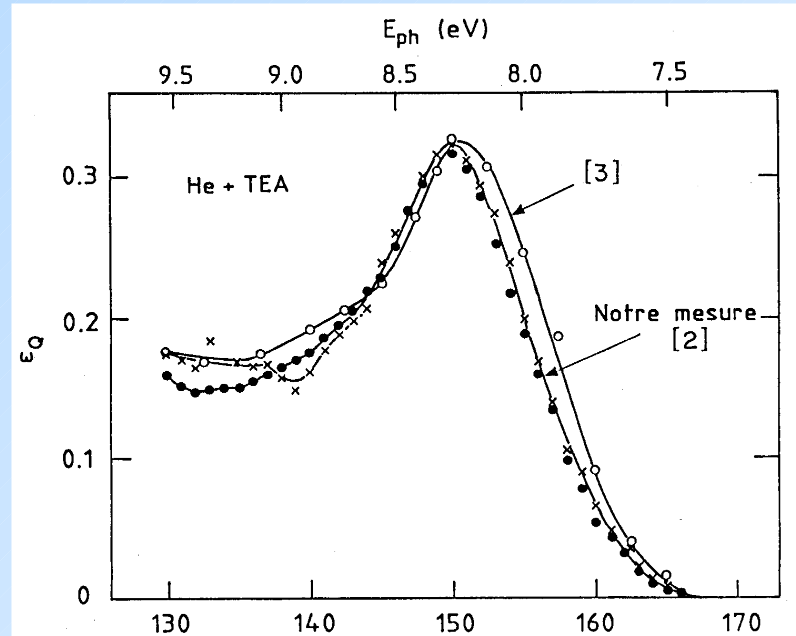
Light absorption in Silicon

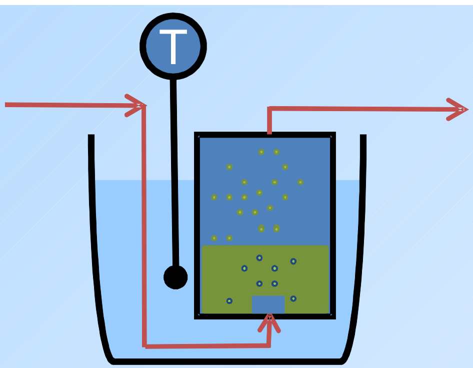


QE in gaseous detectors

Gaseous detectors (MWPCs, TPCs) use admixtures os photosensitive substances to gain photosensitivity in UV/VUV region.







molecule	formula	E_I [eV] (λ_I [nm])	max. ε_Q (E)	λ_{ph} (at 293K)
TEA	$(C_2H_5)_3N$	7.5 (164)	0.33 (8.2)	0.43 mm
TMAE	$C_2[(CH_3)_2N]_4$	5.36 (230)	0.51 (8.3)	26 mm
DMA	$(CH_3)_2NH$	8.3 (148)	0.2 (9.2)	
TMA	$(CH_3)_3N$	7.9 (156)	0.27 (8.6)	

Photosensitive agent is admixed to the counting gas of a MWPC by bubbling the gas through the liquid agent at a given temperature → concentration control.

Window transmission

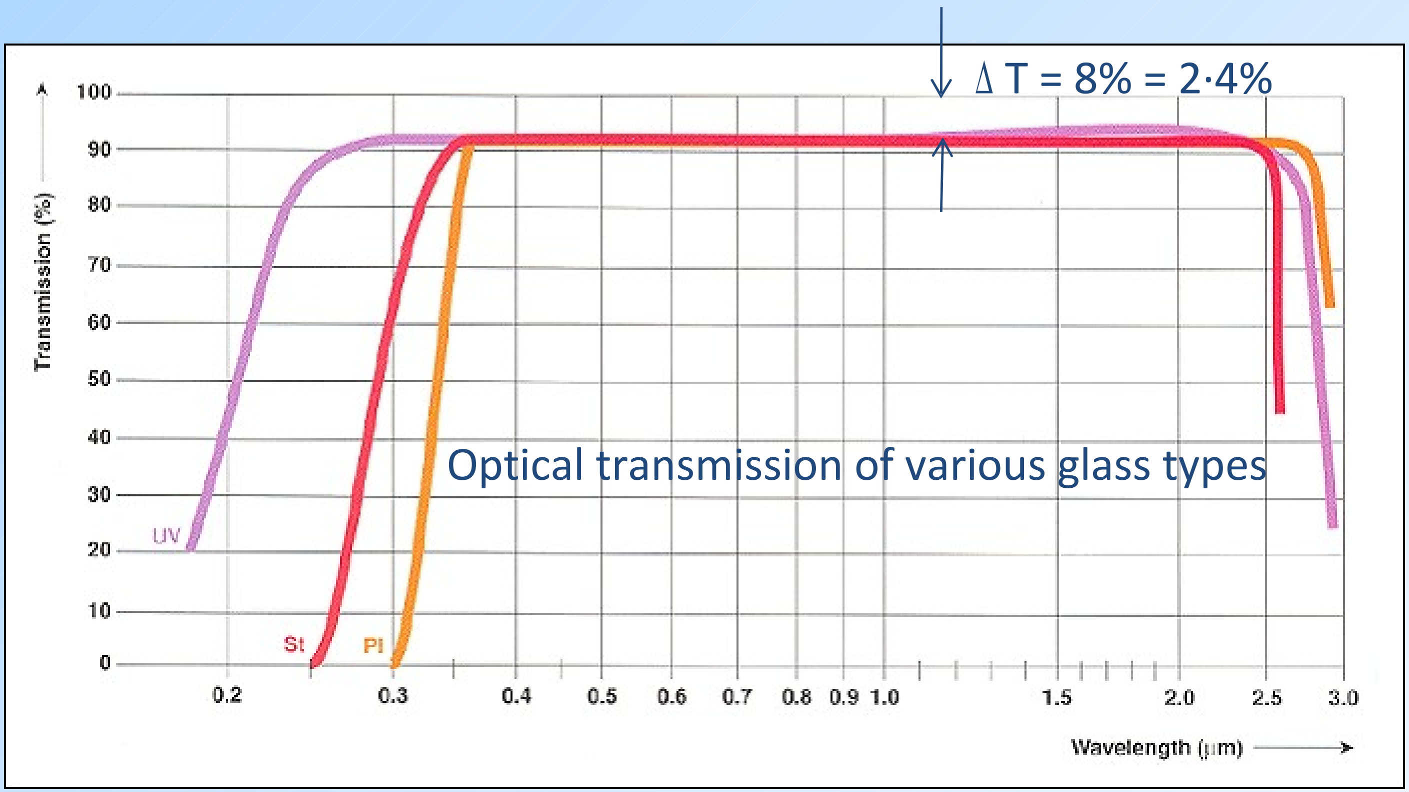
2 types of losses:

- Fresnel reflection at interface air/window and window/photocathode

  $R_{Fresnel} = (n-1)^2 / (n+1)^2$ n = refractive index (wavelength dependent!)

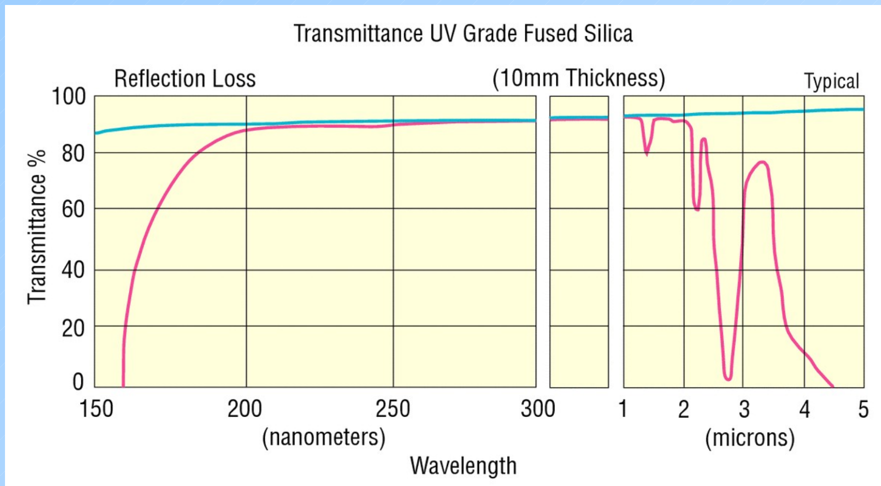
  $N_{glass} \sim 1.5$, $R_{Fresnel} = 0.04$ (per interface)

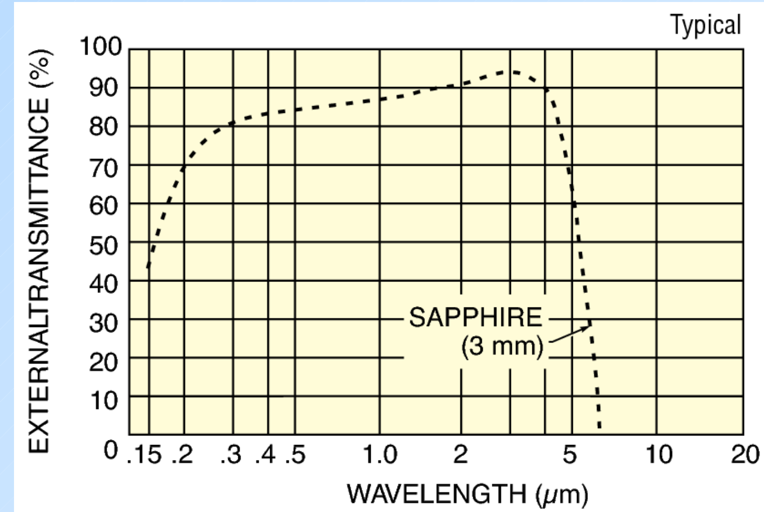
- Bulk absorption due to impurities or intrinsic cut-off limit. Absorption is proportional to window thickness (for low absorption)

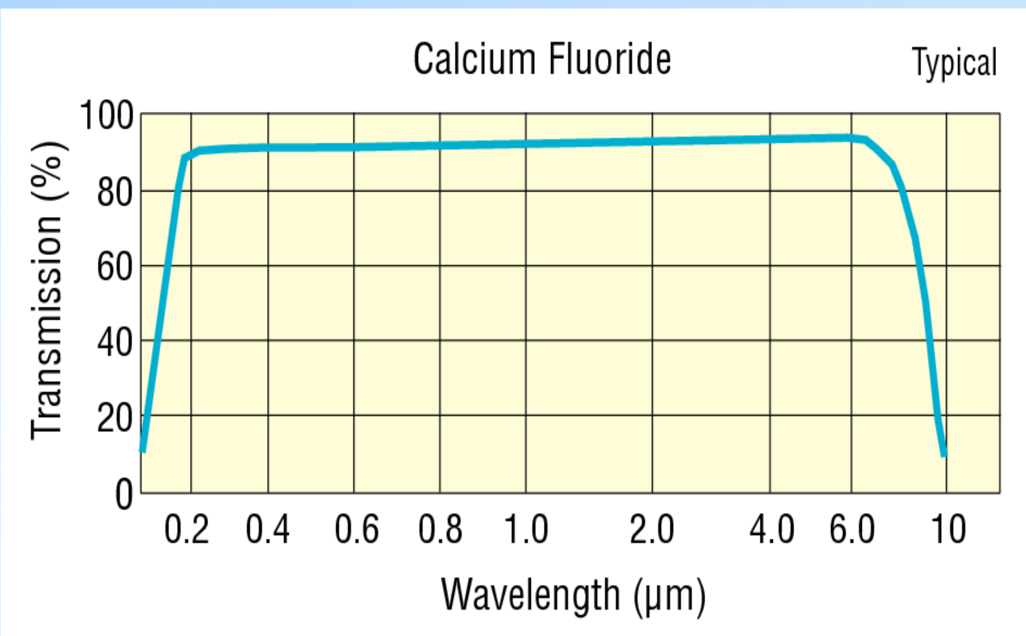


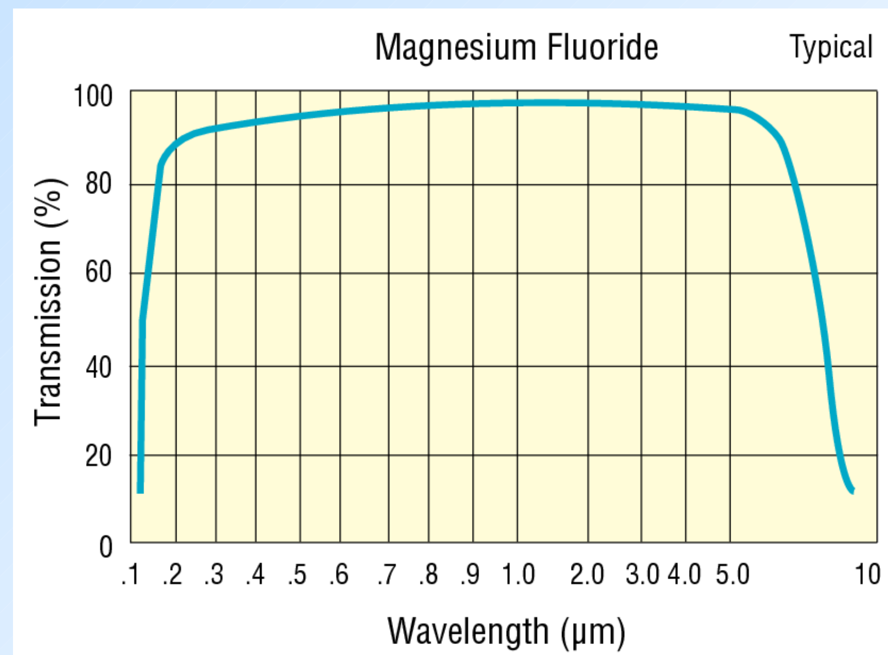
Schott

Exotic windows









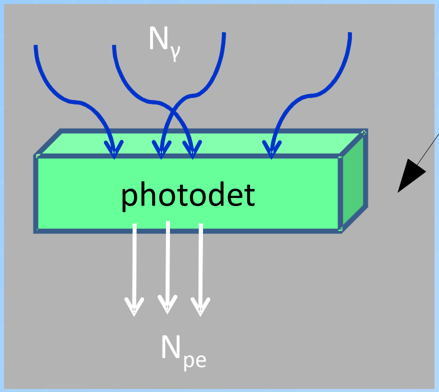
Newport

Requirements on photo-detectors

Basic properties of photo-detectors and Requirements:

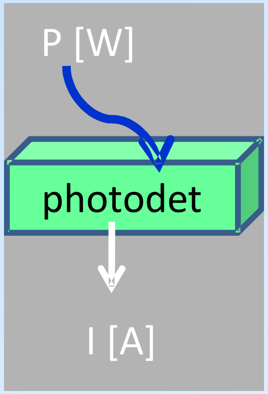
- Sensitivity
- Linearity
- Signal fluctuations
- Time response
- Rate capability / aging
- Dark count rate
- Operation in magnetic fields
- Radiation tolerance

Sensitivity



Quantum Efficiency (QE) is the number of emitted photoelectrons divided by number of incident photons.

$$QE = \frac{N_{pe}}{N_\gamma}$$



Radiant sensitivity (S) is photoelectric current divided by incident radiation power at certain wavelength

$$S = \frac{I}{P} = \frac{QE \cdot \lambda \cdot e_0}{hc} \approx \frac{QE \cdot \lambda}{1239\, nm\, W/A}$$

Photo Detection Efficiency (PDE):

combined probability to produce a photoelectron and to detect its signal

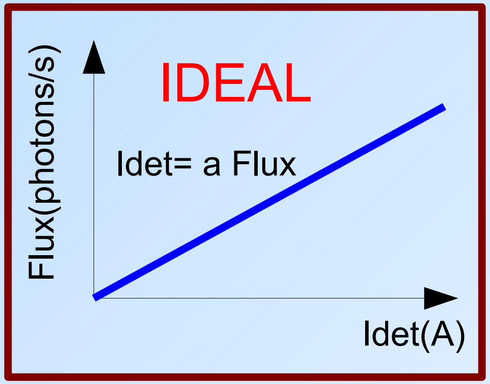
$$PDE = \epsilon_{geom} \cdot QE \cdot P_{trig}$$ For a SiPM (ϵ_{geom}: geometrical eff., P_{trig} breakdown prob.)

$$PDE = QE \cdot CE \cdot P_{mult}$$ For a PMT (CE: collection eff., P_{mult} multiplication prob.)

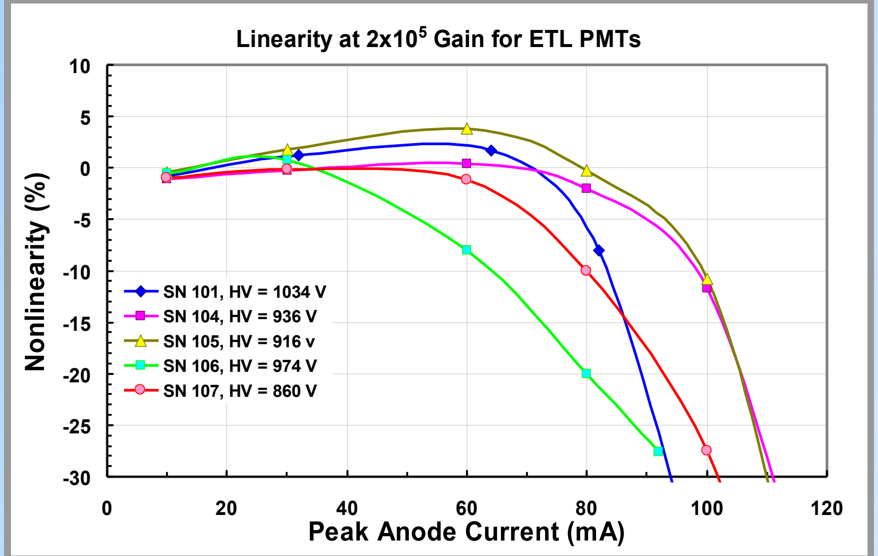
- UV-blue sensitivity is required for detectors based on Cherenkov light (RICH, water Cherenkov telescope, Imaging Atmospheric Cherenkov Telescopes (HES II, CTA …)).
- Blue-green sensitivity is required for calorimeters (CMS, ILC HCAL …), TOF detectors, fiber trackers detecting scintillation light.

Linearity

<u>Requirement</u>: Photo-current response of the photo-detector is linear with incident radiation over a wide range. Any variation in response with incident radiation represents a variation in the linearity of the detector.

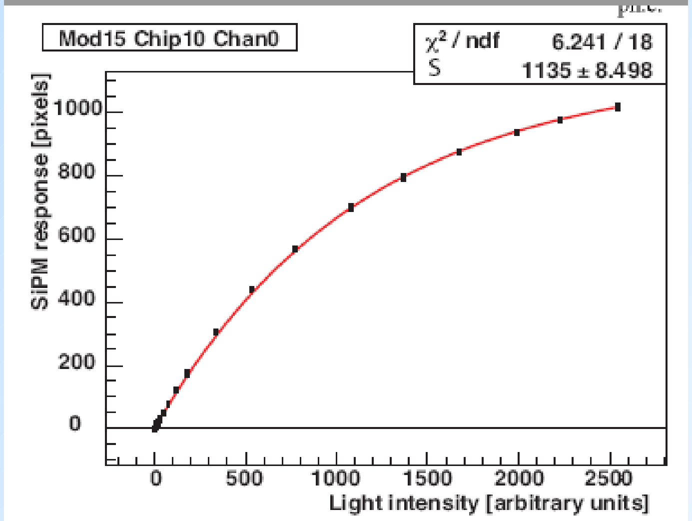


Example for PMT : non linearity curves



at UCLA PMT Test Facility

Example for SiPM



arXiv:0902.2848v1 [physics.ins-det] 17 Feb 2009

	PMT	HPD	MCP-PMT	APD	SiPM
Dynamic range (p.e.)	10^6	10^7	10^7	10^7	10^3

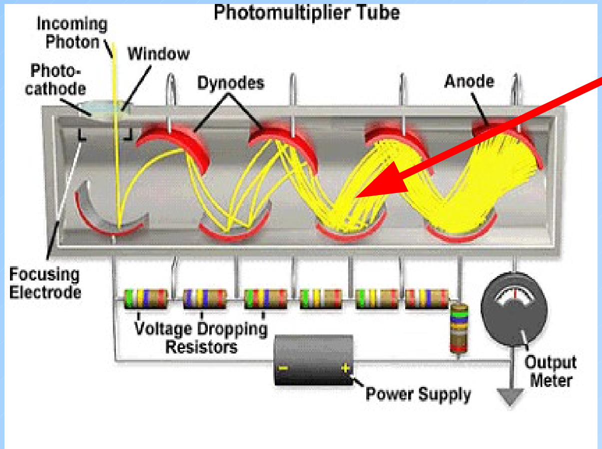
Example of dynamic range required : HCAL of ILC

Min: 20 photons/mm² (μ for calibration)

Max: 5×10^3 photons/mm² (high-energy jet)

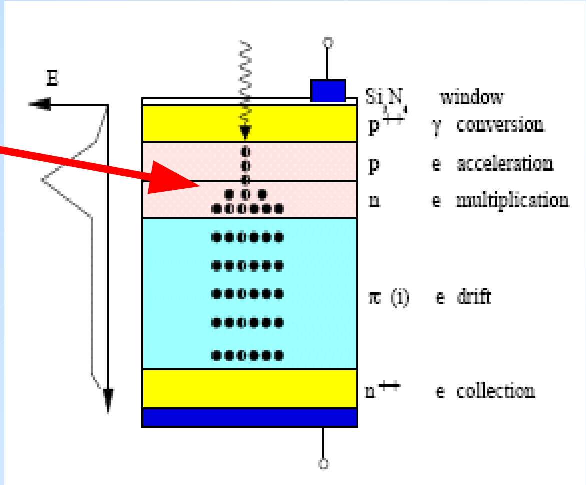
(C. Cheshkov et al., NIM A440(2000)38)

Signal fluctuations



PMT

Statistical fluctuation of the avalanche multiplication widen the response of a photo-detector to a given photon signal beyond what would be expected from simple photoelectron statistics (Poissonian distribution)



APD

→ **multiplication fluctuations are characterized by Excess Noise Factor - ENF**

$$ENF = \frac{\sigma^2_{out}/N^2_{out}}{\sigma^2_{pe}/N^2_{pe}}$$ definition

$$ENF = 1 + \frac{\sigma^2_M}{M^2}$$ M - multiplication $(N_{out} = M \cdot N_{pe})$

$$\frac{\sigma_E}{E} = \sqrt{\frac{ENF}{N_{pe}}}$$ Energy resolution

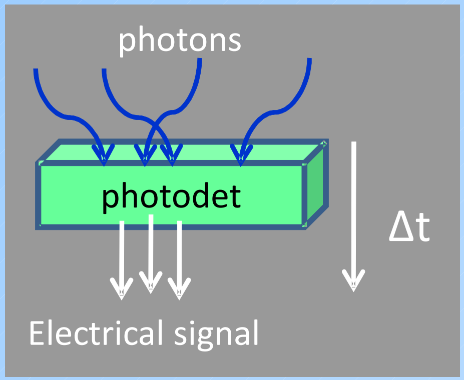
Typical ENF values for different sensors

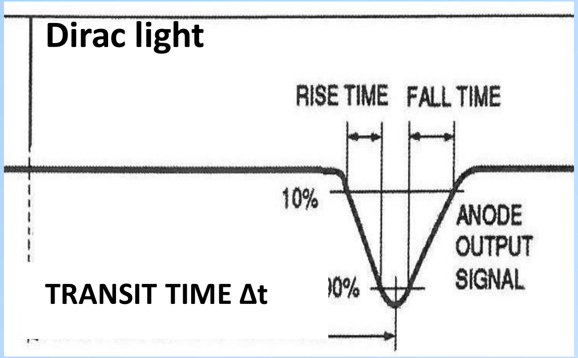
sensor	ENF
PMT	1-1.5
APD	2 @ gain=50
HPD, HAPD	~1
SiPM	1-1.5
MCP-PMT	1-1,5

- Impacts photon counting capability at low light levels
- Deteriorates energy resolution of the calorimeters

Time response

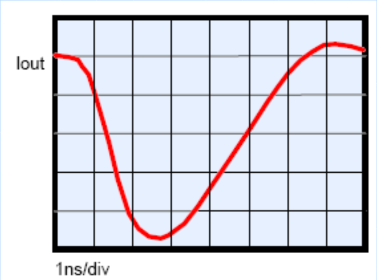
• Light travels 3 mm in 10ps (vakuum)



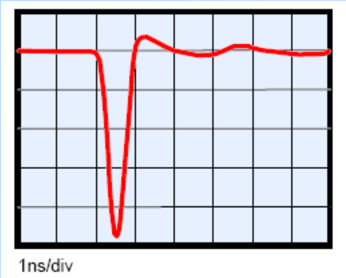


- Rise time, fall time (or decay time)
- Duration
- Transit time (Δt): time between the arrival of the photon and the electrical signal → trigger decision time
- Transit time spread (TTS): transit time variation between different events → timing resolution

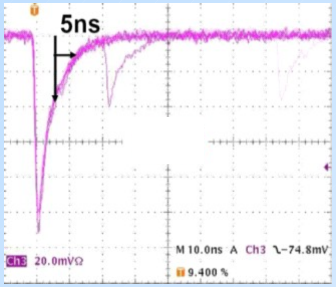
Some typical signals:



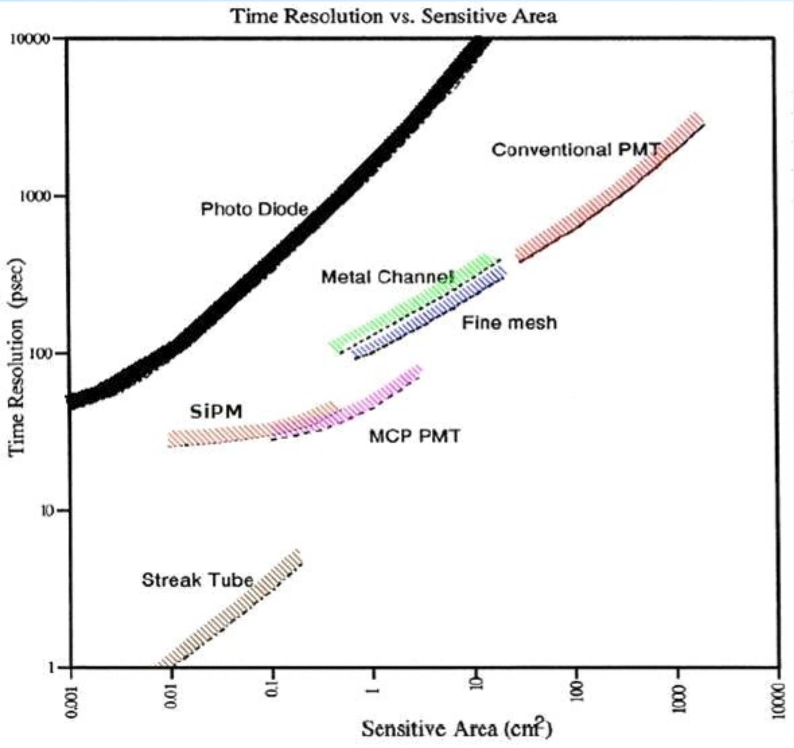
PMT



MCP-PMT



SiPM



Adopted from K. Arisaka, NIM A 442 (2000) 80

Applications requiring good timing:

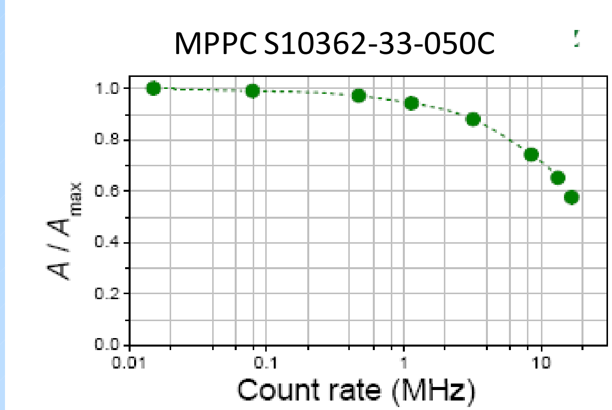
- Cherenkov light based TOF systems
- Time-Of-Propagation counter (Belle II)
- Focusing DIRC with chromatic correction (SuperB)

High rate operation, aging

Rate capability: inversely proportional to the time needed, after the arrival of one photon, to get ready to receive the next

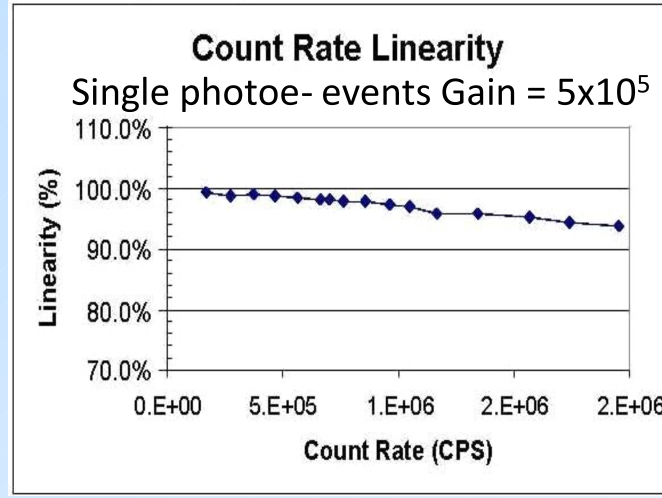
Requirements in calorimeters:
100 kHz → few MHz

SiPM

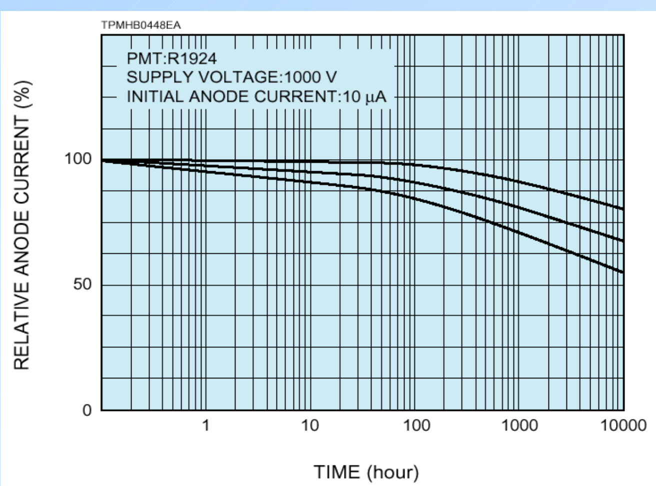


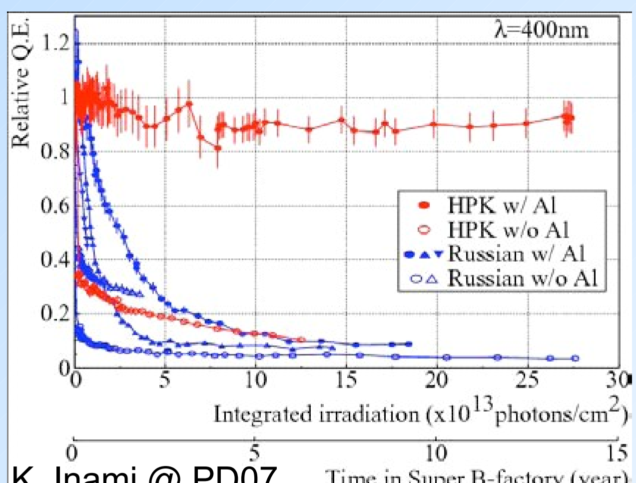
A. Stoykov, μSR at PSI

MCP-PMT



Aging (long-term operation at high counting rates): how is the photo-detector behavior changed when operated at high counting rate during several years ?





Parameter affected (generally in a negative way):

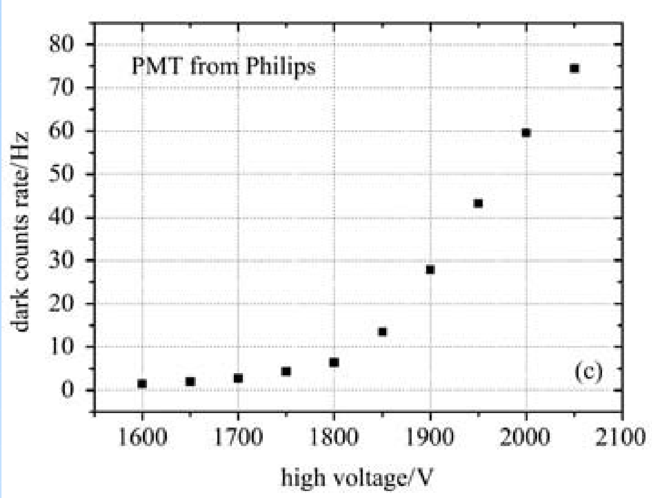
- gain
- quantum efficiency
- dark current

Dark count rate (DCR)

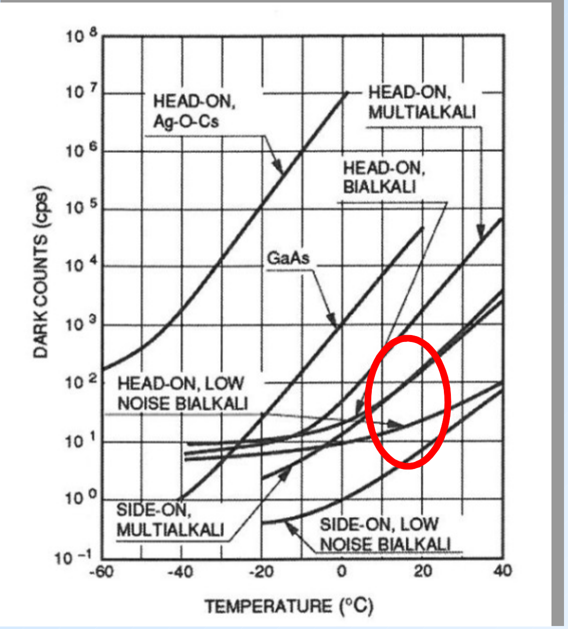
Sensors produce signals even in total darkness!

DCR of PMTs:

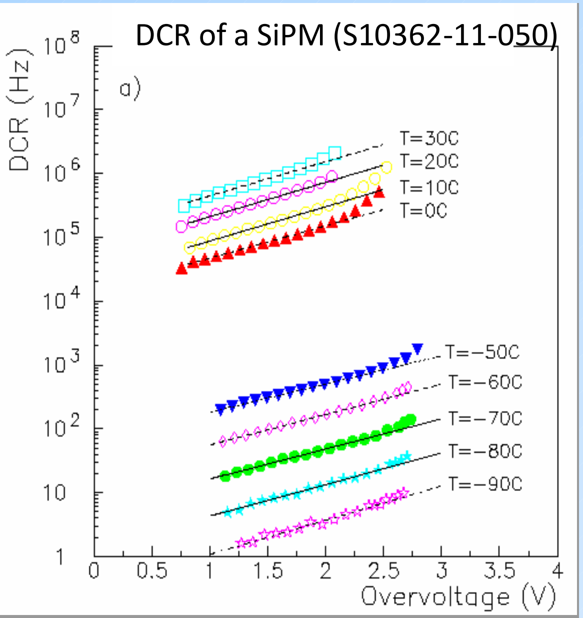
- depends on the cathode type, the cathode area, and the temperature.
- few kHz (threshold = 1 p.e.)
- is highest for cathodes with high sensitivity at long wavelengths.
- Temporarily increases considerably after exposure to daylight



DCR of different photocathodes



DCR of a SiPM (S10362-11-050)



N. Dinu, IEEE NSS 2010

DCR of SiPMs:

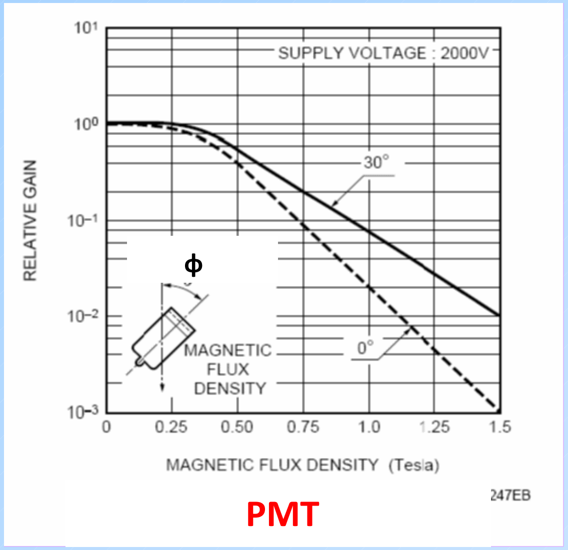
- depends on the pixel size, the bias voltage, the temperature
- quite high (0.3–2MHz/mm² at room temp, threshold = 1 p.e.)

DCR depends strongly on the threshold level → not a problem for detection of many photon signals (threshold > 10).

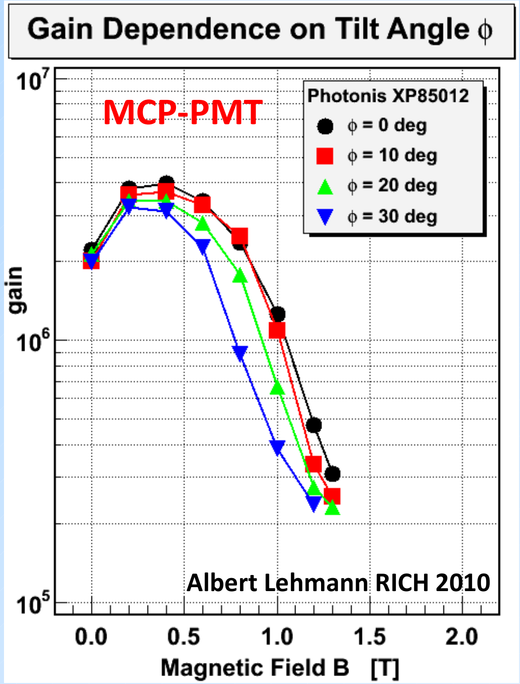
Can be efficiently reduced by lowering the temperature.

Magnetic field tolerance

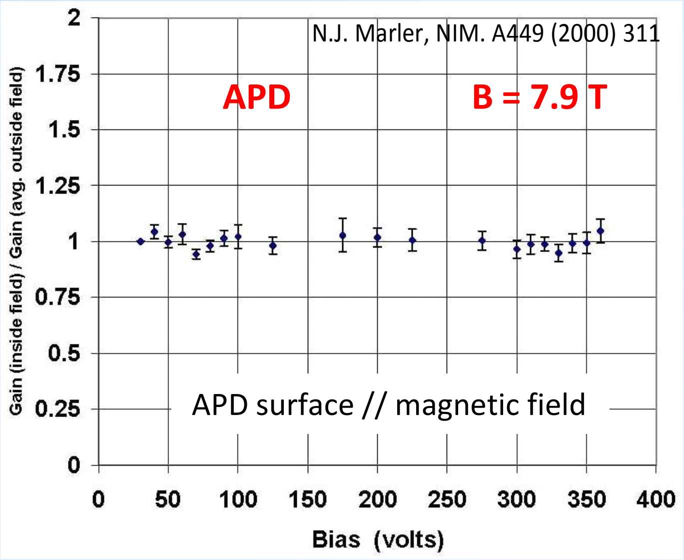
• Earth's magnetic field = 30-60 μT



PMT very sensitive to magnetic Field → shielding required (μ metal)



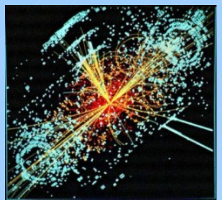
MCP-PMT tolerant to magnetic field up to ~ 2T (6 μm pores).



PD, APD, SiPM insensitive to magnetic field

Typical requirements 1.5T @ Belle II, 2T @ PANDA, SuperB, 4T CMS, ILC ...

Radiation tolerance

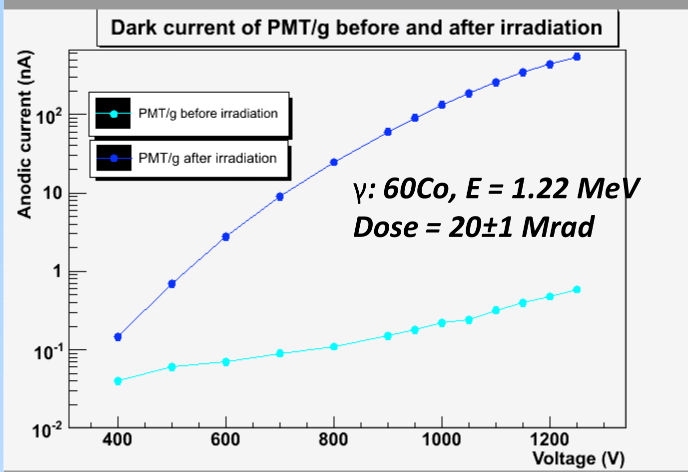


Damages caused by:

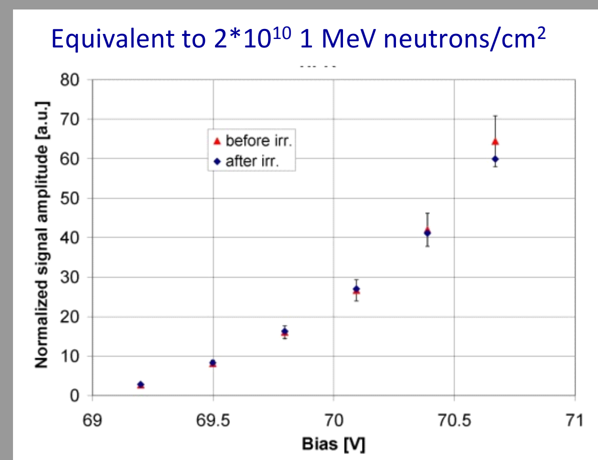
- ionizing radiation: energy deposited in the detector material by particles and by photons from electromagnetic showers
(the unit of absorbed dose is Gray [Gy] → 1 Gy = 1 J/kg = 100 rad).
- neutrons created in hadronic shower, also in the forward shielding of the detectors and in beam collimators

→ **Result is degradation of DRC, gain QE ...**

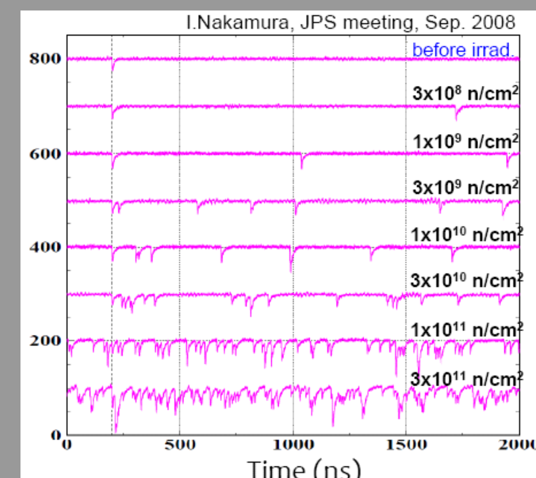
Dark current of PMT



SiPM amplitude proton irradiation



DCR of SiPM neutron irradiation



A. Sbrizzi LUCID in ATLAS

Y. Musienko, AMPDs for Frontier Detector Systems

- Belle II ARICH photon detector 10^{12} n/cm^2 + 100 krad
- At LHC, the ionizing dose is ~ 2×10^6 Gy / r_T^2 / year (r_T = transverse distance to the beam)

→ CMS ECAL (10 years) 2×10^{13} n/cm^2 + 250 krad

Pphoto-detectors

Detector types

- PMT
- MAPMT, Flat-panel PMT
- MCP-PMT
- Photosensitive gas detectors (MWPC / MPGD)
- PIN diode
- APD
- HPD, HAPD
- G-APD / SiPM

'Family tree' of photo-detectors

Photo-detectors

Gas
External photoeffect

- TMAE
- TEA
- CsI

\+ MWPC, GEM, …

Vacuum
External photoeffect

Avalanche gain Process

Dynodes → PMT

Continuous dynode
→Channeltron, MCP

Multi-Anode devices

Other gain process = Hybrid tubes

Silicon	Luminescent anodes
HPD	SMART/Quasar
HAPD	X-HPD
G-APD-HPD	

Solid state
Internal photoeffect

- PIN-diode
- APD
- SiPM
- CMOS
- CCD

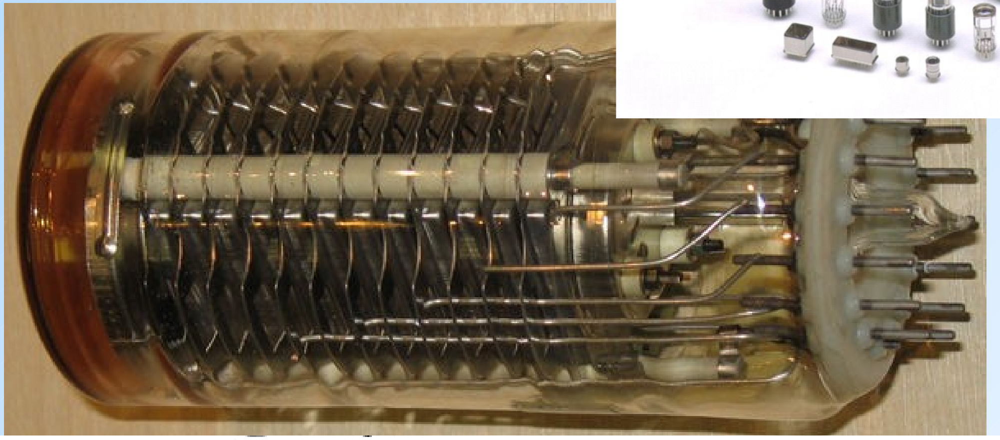
Photo-multiplier tubes (PMT's)

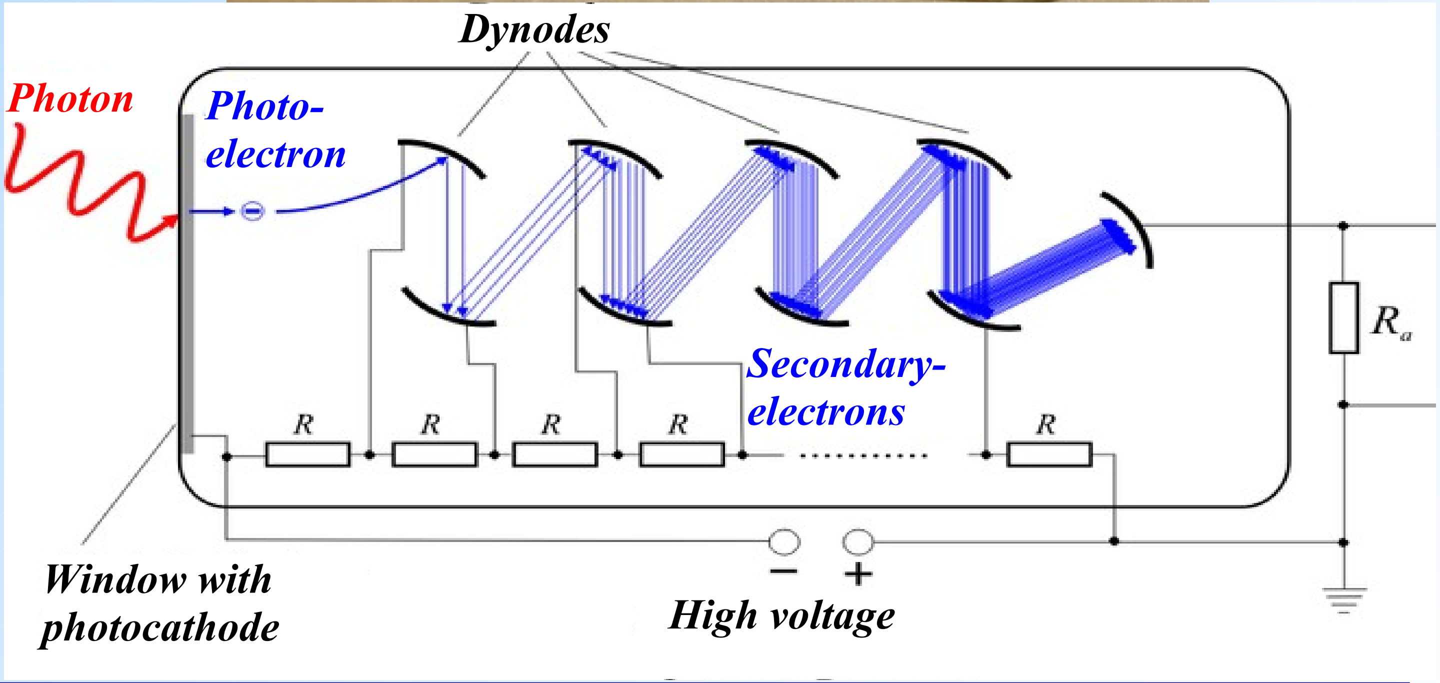
Principle of operation:

- Photo-emission from photo-cathode
- Secondary emission (SE) from N dynodes:
  - dynode gain g ~ 3-50 (function off incoming electron energy E);
  - total gain M:

$$M = \prod_{i=1}^{N} g_i$$

- Example:
  - 10 dynodes with g = 4
  - M = 4^{10} ~ 10^{6}





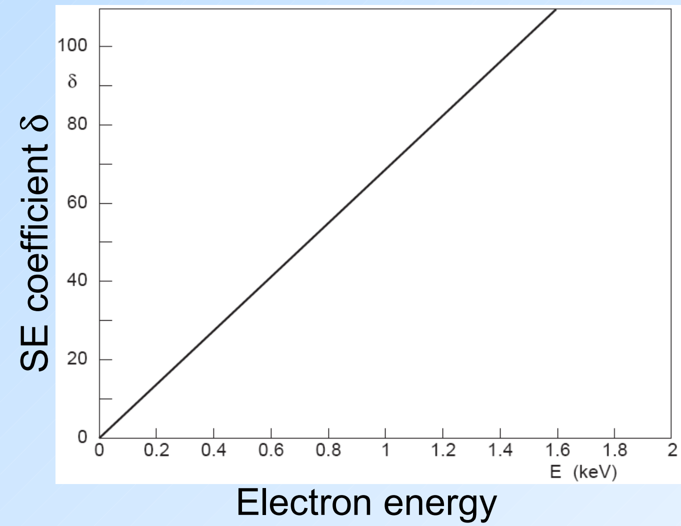
PMT: gain fluctuations (ENF)

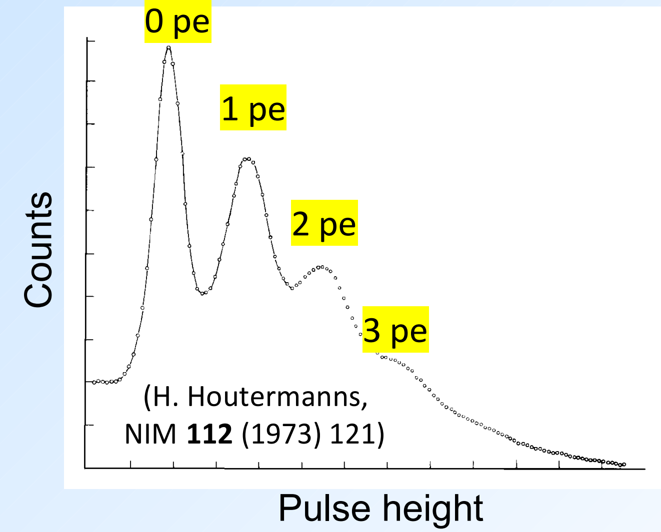
Mainly determined by the fluctuations of the number of secondary electrons emitted from the dynodes;

- Poisson distribution: $P_i(m;\delta_i) = \dfrac{\delta_i^m e^{-\delta_i}}{m!}$
- Standard deviation: $\dfrac{\sigma_m}{\delta} = \dfrac{\sqrt{\delta}}{\delta} = \dfrac{1}{\sqrt{\delta}}$
- $ENF = \dfrac{1}{\delta_1} + \dfrac{1}{\delta_1\delta_2} + \dfrac{1}{\delta_1\delta_2\delta_3}\ldots \quad \left(= \dfrac{1-\frac{1}{\delta^{N+1}}}{1-\frac{1}{\delta}} \approx \dfrac{\delta}{\delta-1}\right)$

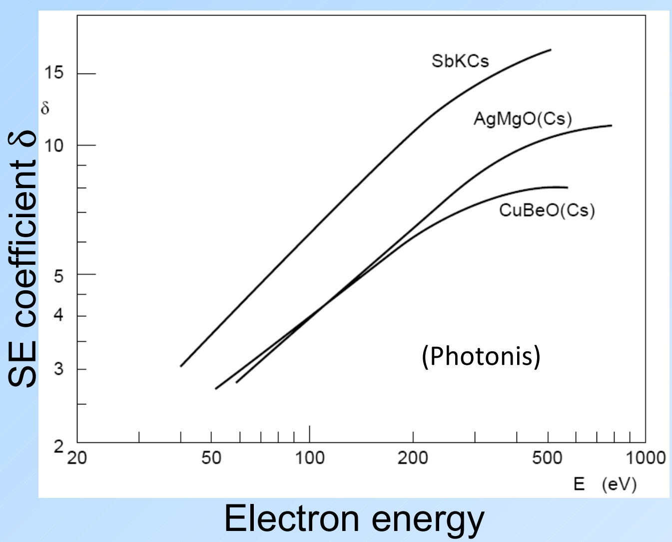
→ fluctuations dominated by 1st dynode gain

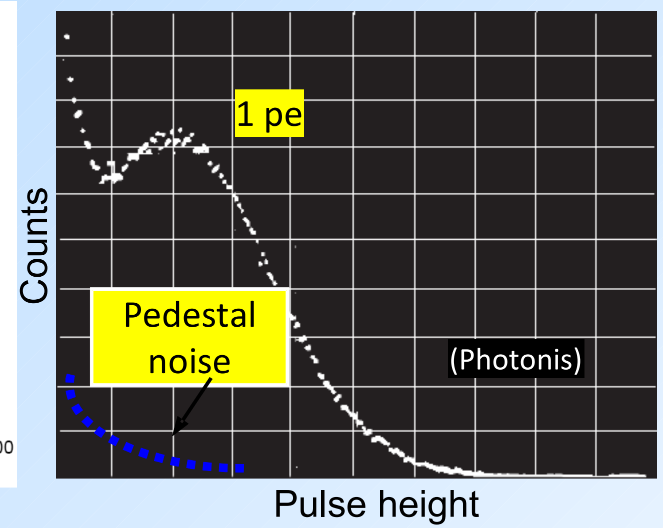
GaP(Cs) dynodes EA<0





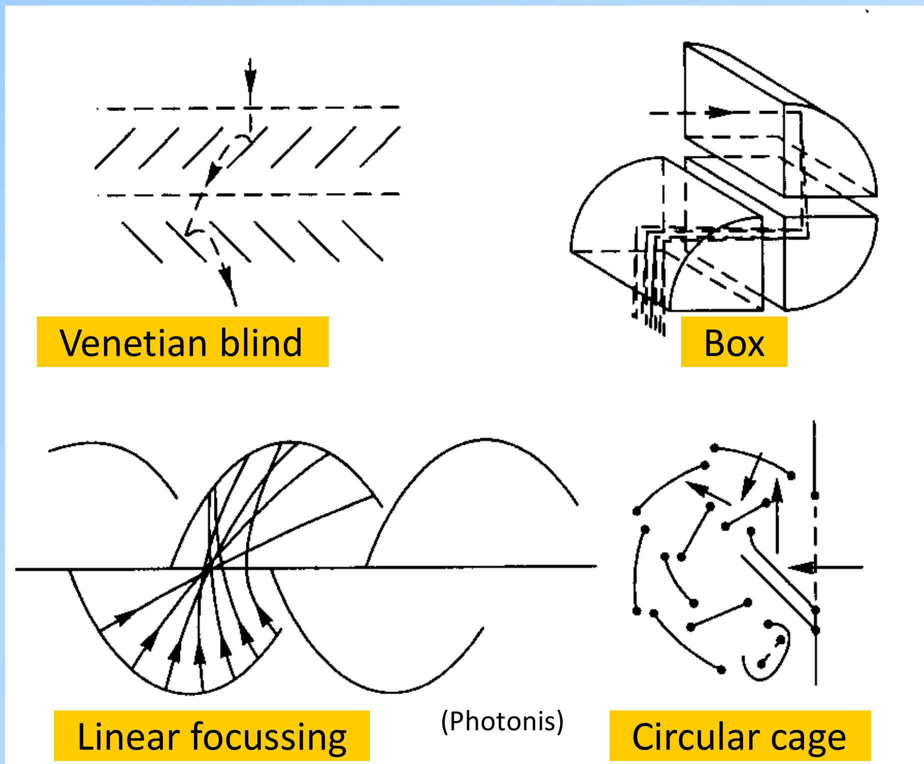
CuBe dynodes EA>0



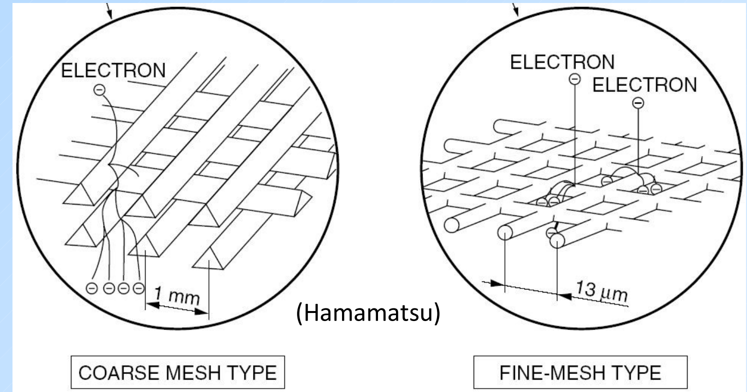


PMT: different dynode structures

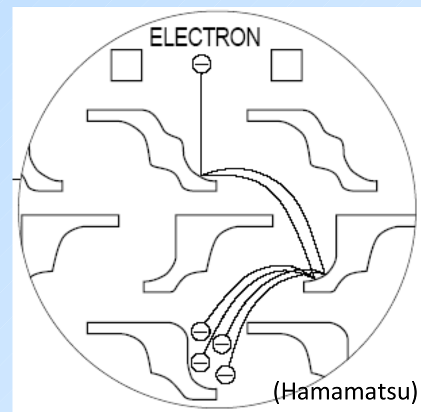
Traditional types



Position sensitive types



Mesh



Metal-channel (fine-machining techniques)

Modern micro-machining techniques allow fabricating fine dynode structures. Avalanche is confined in a narrow channel.
→ Multi-anode designs
→ some tolerance to modest magnetic field

The design of a dynode structure is a compromise between:

- collection efficiency (input optics: from cathode to first dynode)
- gain (minimize losses of electrons during passage through structure)
- transit time and transit time spread (minimize length of path and deviations)
- immunity to magnetic field

PMT: timing and magnetic field

Rough estimation of transit time: $t \approx N \cdot \sqrt{\frac{2l}{a}} = \frac{N \cdot l}{\sqrt{\frac{eU}{2m_e}}} = \frac{0.1\text{m}}{\sqrt{\frac{e \cdot 100\text{V}}{2 \cdot 0.5\, MeV / c^2}}} = \frac{0.1\text{m}}{0.01 \cdot c} \approx 33\, ns$

To optimize TTS:

- Compact construction (short distances between dynodes) keeps the overall transit time small (~10 ns).
- "Fast" PMT's require well-designed input electron optics to equalize travel times of photoelectrons → transit time spread < 100 ps;

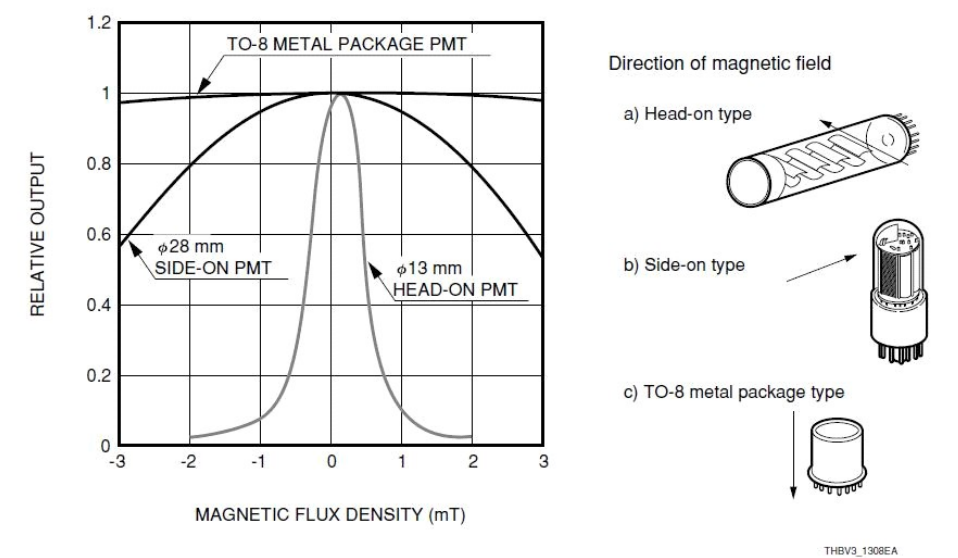
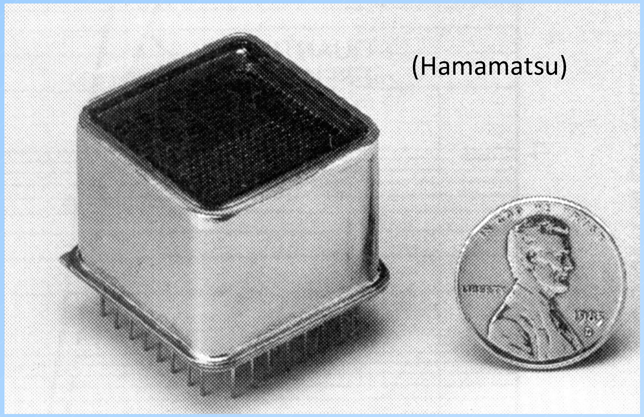
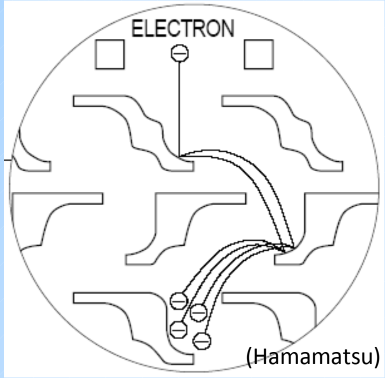


Figure 13-8: Magnetic characteristics of typical photomultiplier tubes

- PMT's are in general very sensitive to magnetic fields, even to earth field (30-60 mT = 0.3-0.6 Gauss).
- Magnetic shielding required.

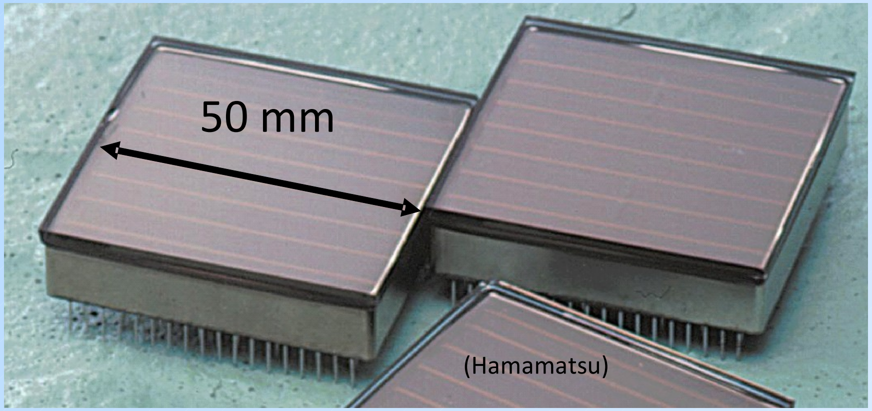
PMT: multi-anode and flat-panel





Multi-anode (Hamamatsu H7546):

- Up to 8 x 8 channels (2 x 2 mm^2 each);
- Size: 28 x 28 mm^2;
- Active area 18.1 x 18.1 mm^2 (41%);
- Bialkali PC: QE ≈ 25 - 45% @ λ_{max} = 400 nm;
- Gain ≈ 3×10^5;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. < 2%

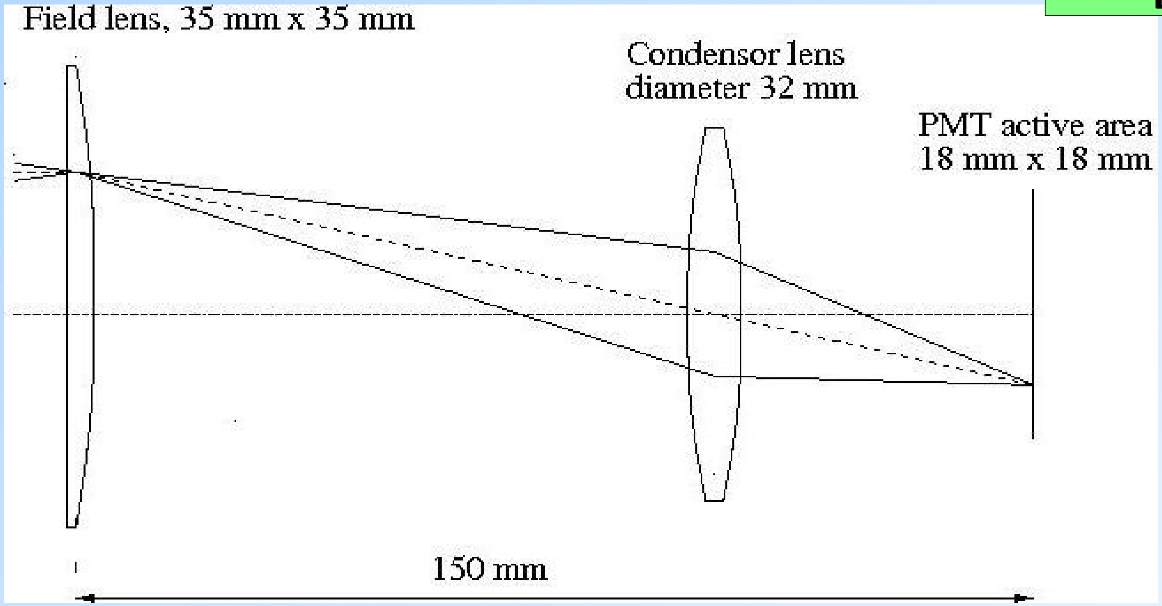


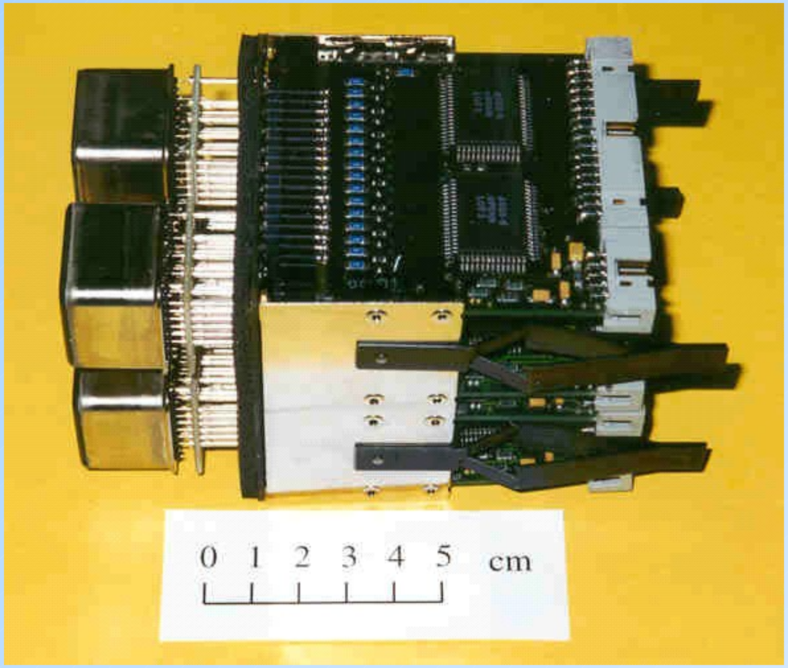
Flat-panel (Hamamatsu H8500):

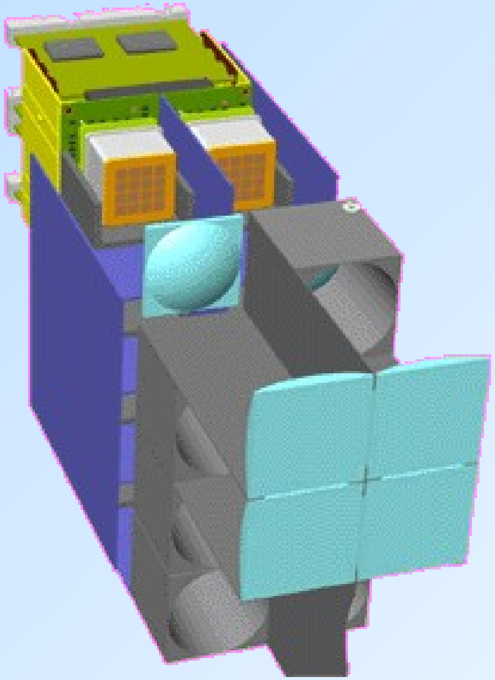
- 8 x 8 channels (5.8 x 5.8 mm^2 each)
- Excellent active area coverage (89%)

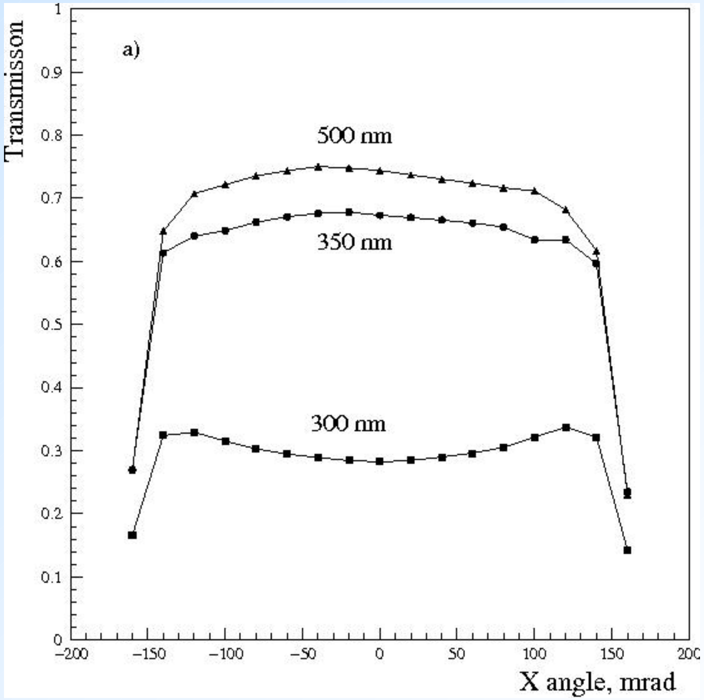
HERA-B RICH MAPMT module

- First detector with MAPMTs
- Lens system used to eliminate dead space

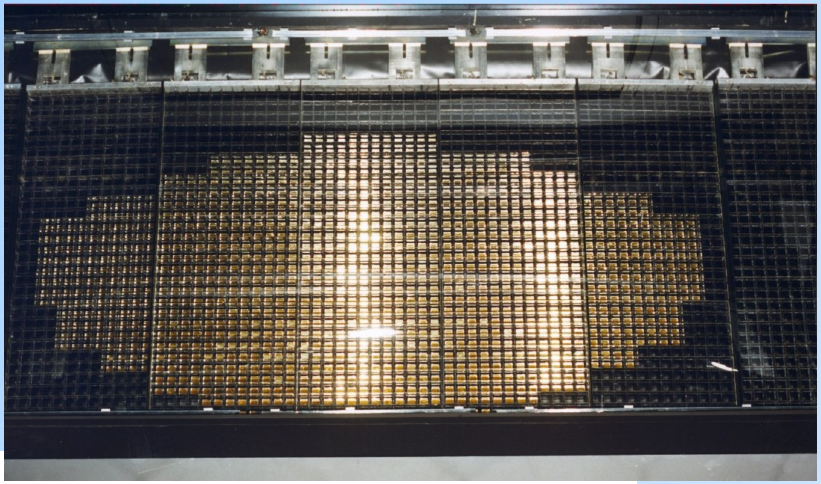


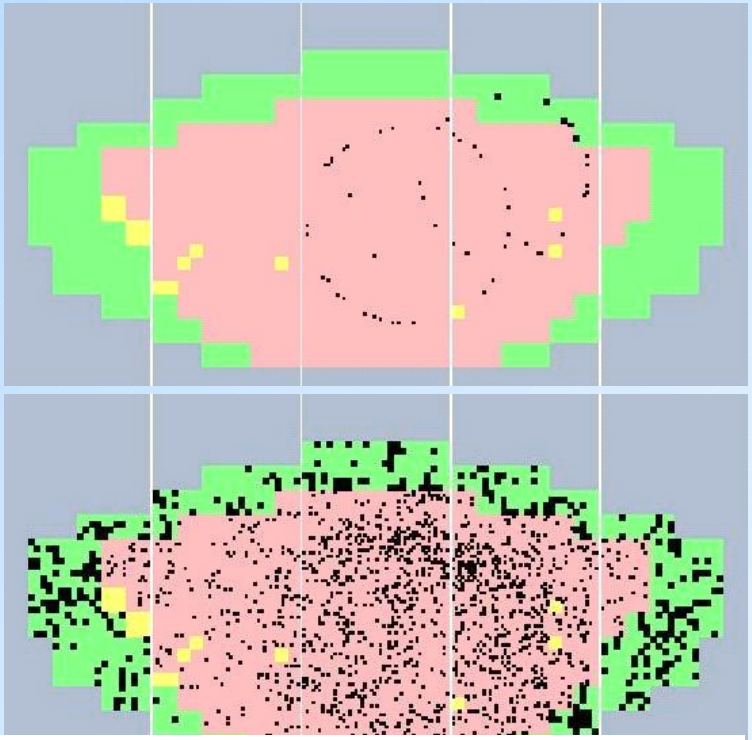


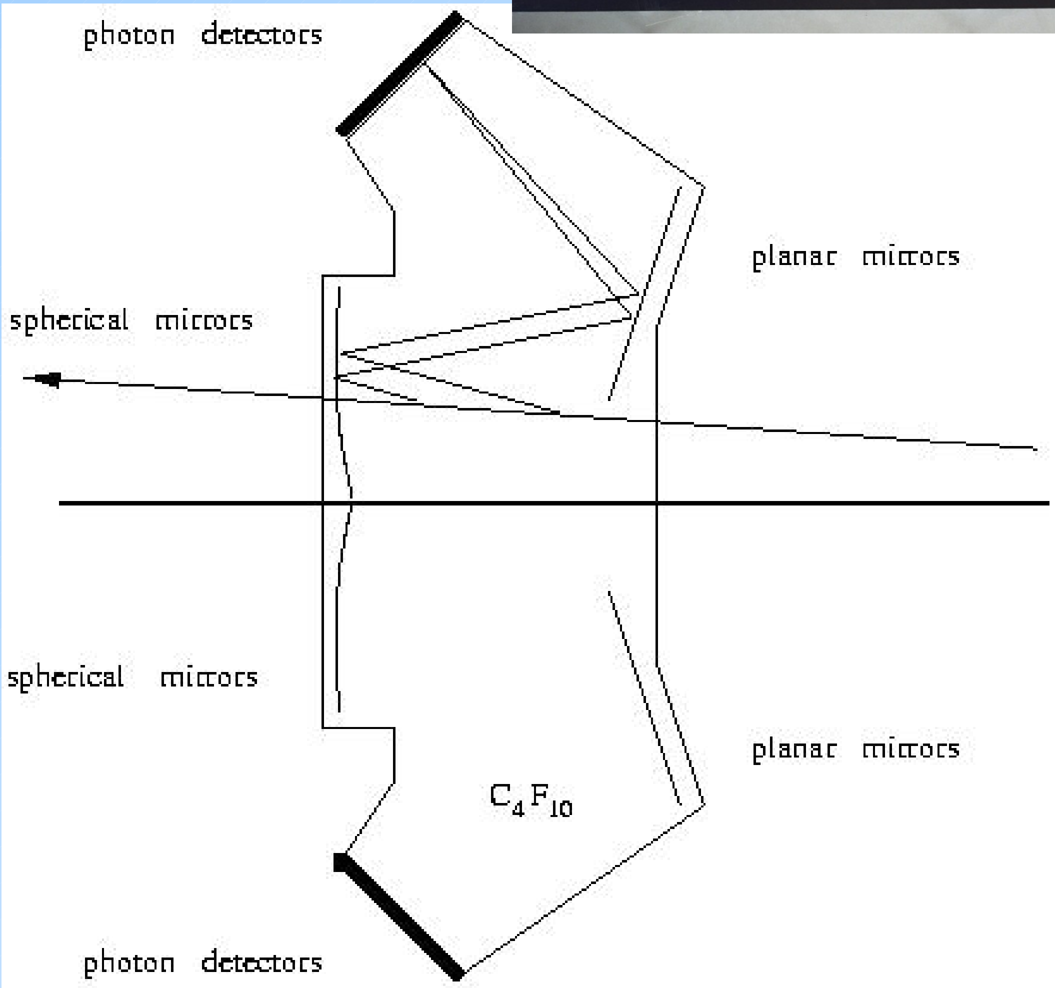




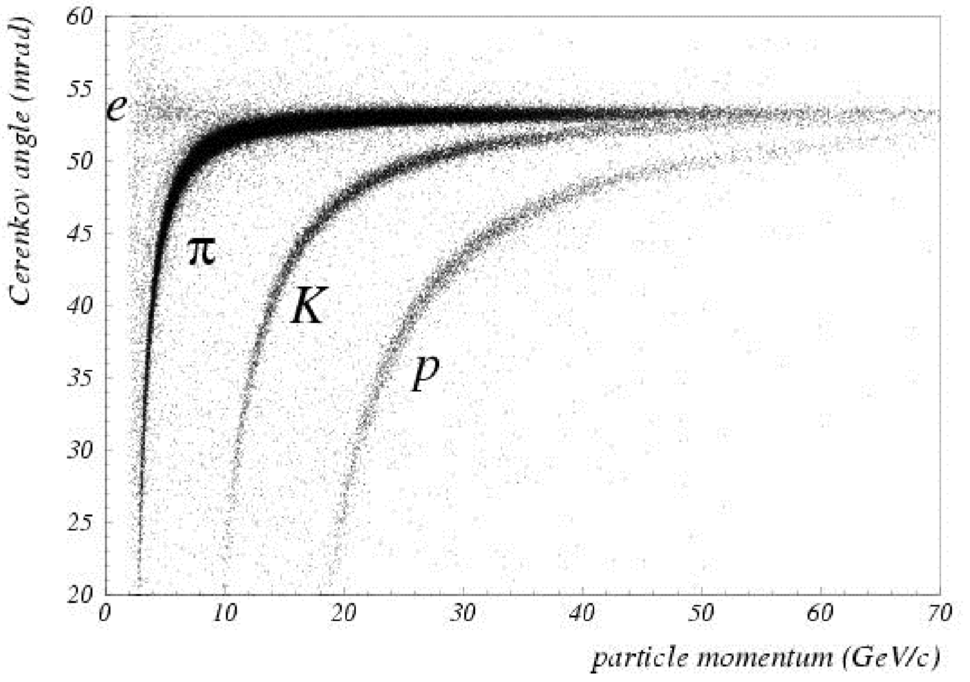
HERA-B RICH







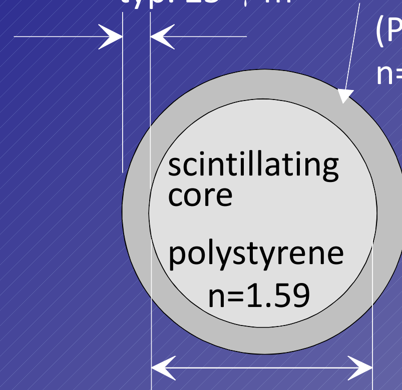
photon detectors
planar mirrors
spherical mirrors
spherical mirrors
planar mirrors
C_4F_{10}
photon detectors



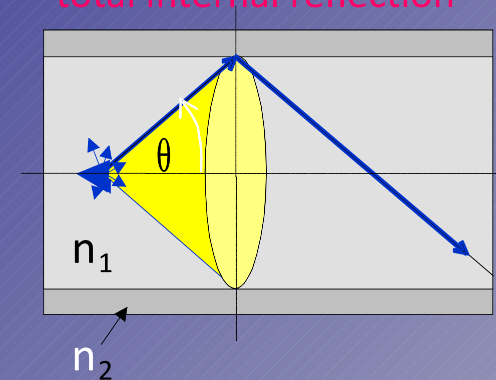
Cerenkov angle (mrad)
particle momentum (GeV/c)
e
π
K
p
60
55
50
45
40
35
30
25
20
0
10
20
30
40
50
60
70

PMT: scintillating fiber tracker with MAPMTs

Working principle of scintillating plastic fibres :



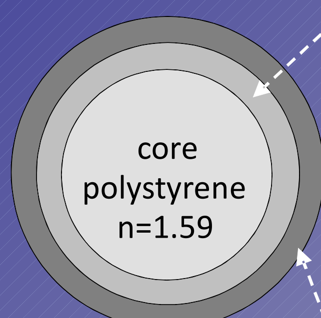
light transport by
total internal reflection



$$\theta \leq \arccos \frac{n_2}{n_1} \approx 20.4^\circ$$

$$\frac{d\Omega}{4\pi} = 0.5\,(1 - \cos\theta\,) = 3\%$$ (per side)

Double cladding system
(developed by CERN RD7)



$$\frac{d\Omega}{4\pi} = 0.5\,(1 - \cos\theta\,) \approx 5.3\%$$

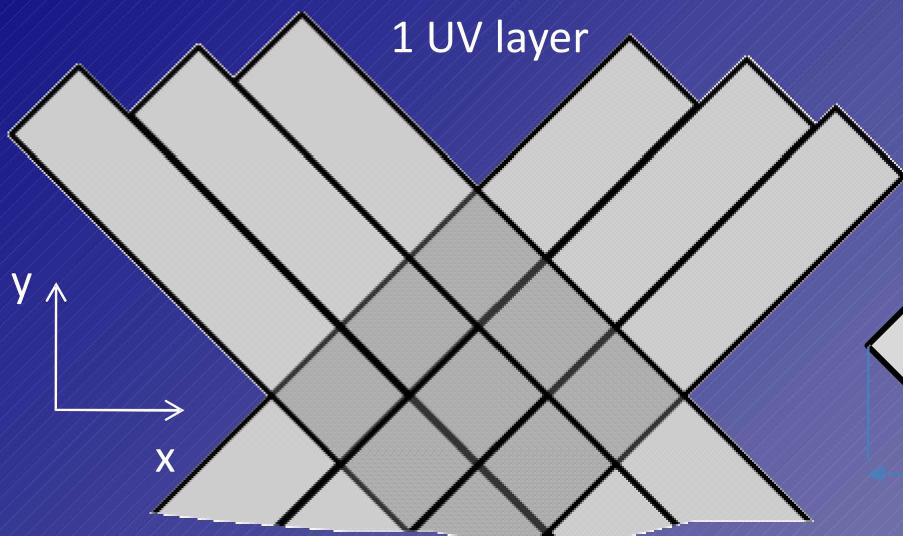
Samo Korpar
University of Maribor and Jožef Stefan Institute

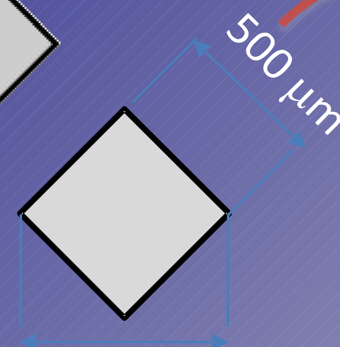
PMT: ATLAS ALFA fibre tracker

- Technology: Scintillating plastic fibres, square cross-section, 500 μ m overall width, single cladded (10 μ m). Type: Kuraray SCSF-78.

- Geometry: UV (45°)

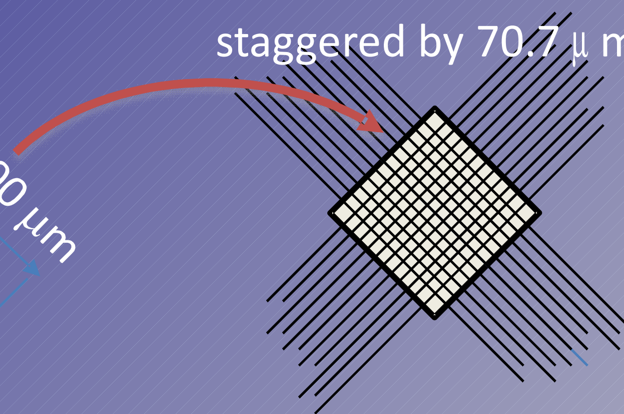
1 UV layer

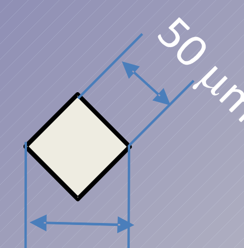




707 μ m

10 UV layers,
staggered by 70.7 μ m





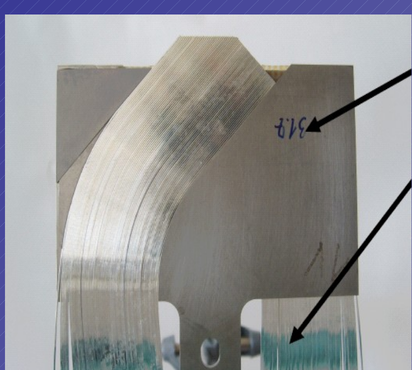
70.7 μ m

ultimately: $\sigma_x = \sigma_y \sim 70.7/\sqrt{24}$ μ m = 14.4 μ m

Expect:

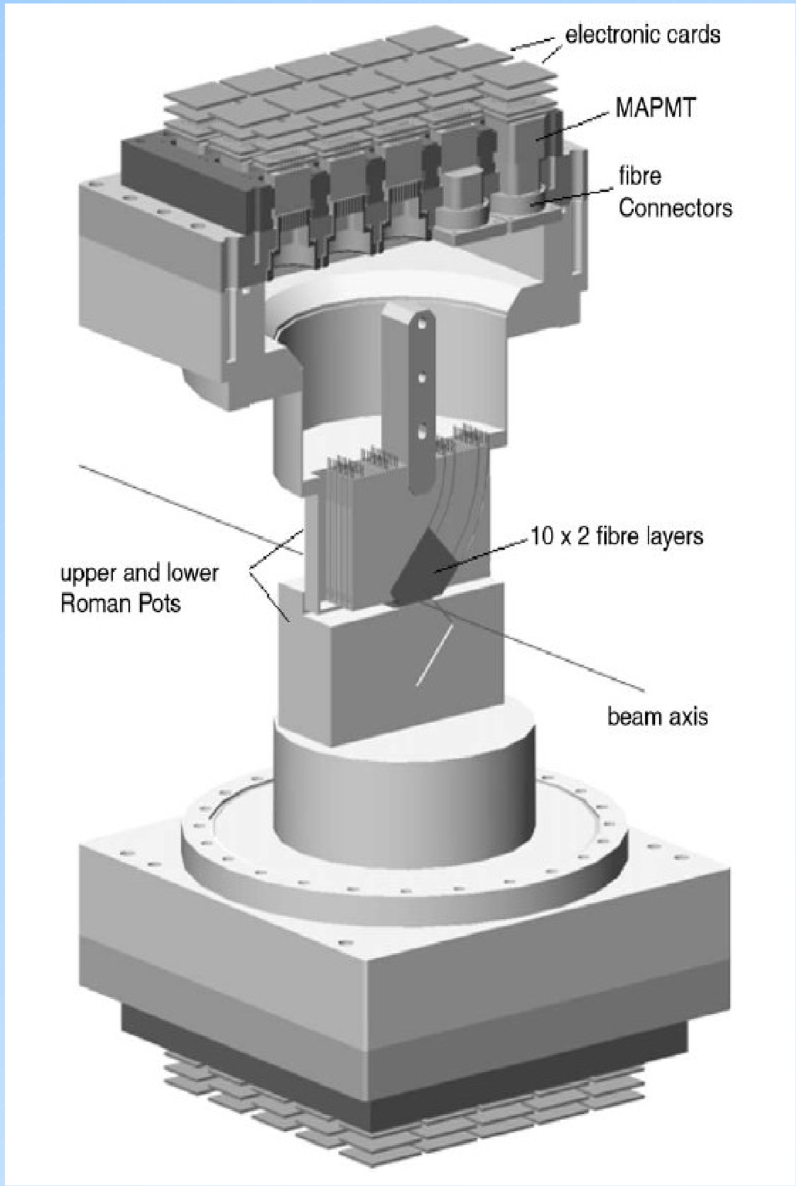
$\sigma_x = \sigma_y \sim 707 / \sqrt{24}$ μ m = 144 μ m

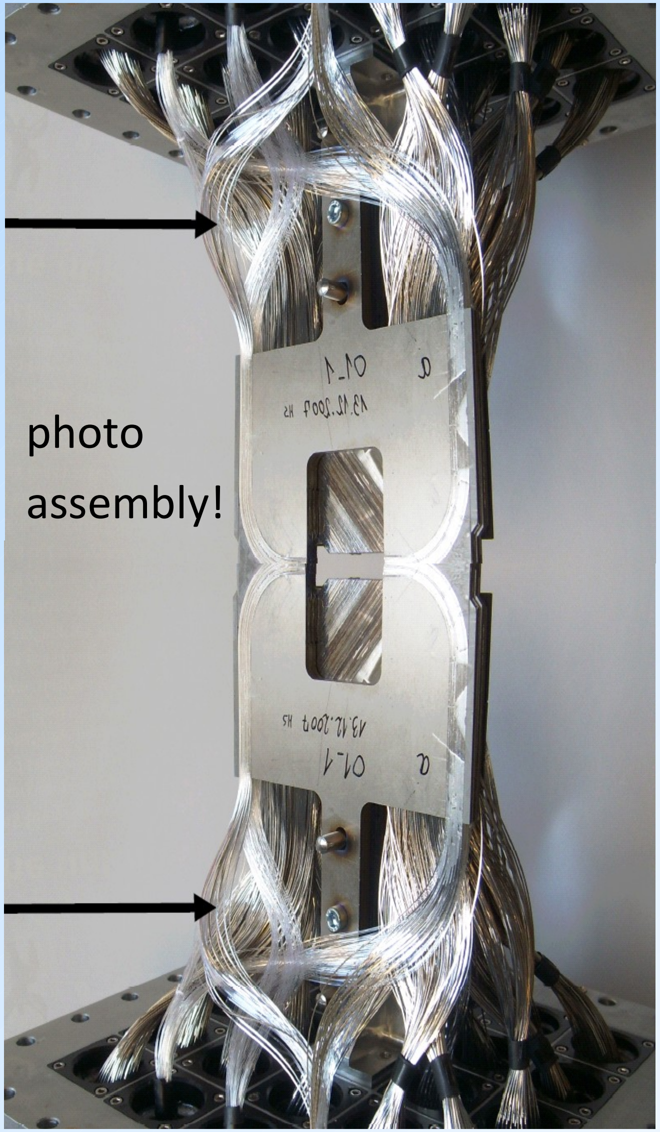
remember: triangular distribution function



Samo Korpar
University of Maribor and Jožef Stefan Institute

PMT: ATLAS ALFA fibre tracker



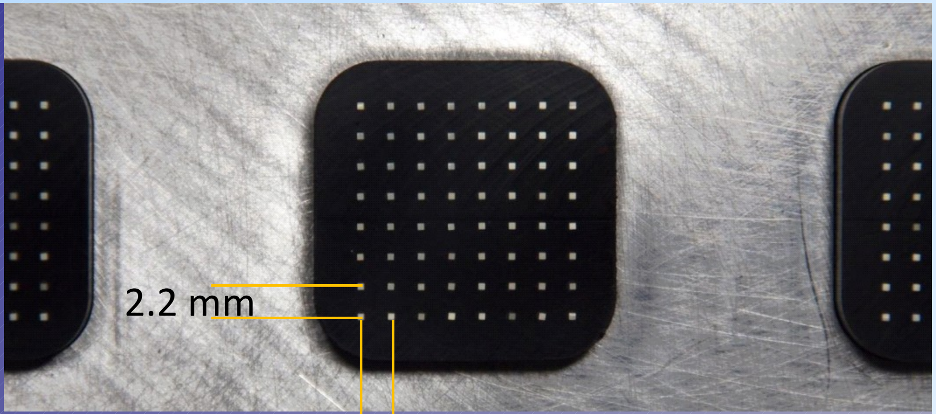


~2x1400 fibres

Samo Korpar
University of Maribor and Jožef Stefan Institute

PMT: ATLAS ALFA fibre tracker

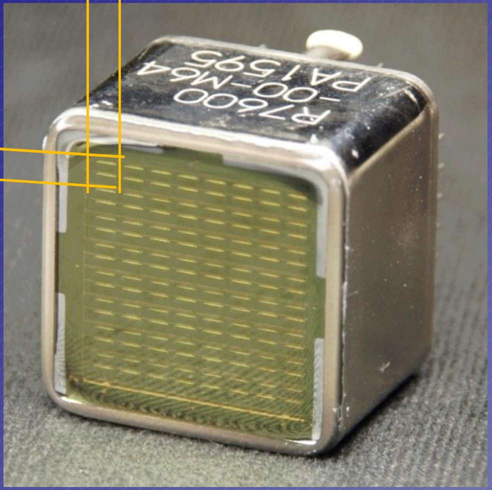
64 Fibres are glued in a 8x8 matrix ‘connector’ . The pitch of 2.2 mm corresponds exactly to the one of the MAPMT.



2.2 mm

2.2 mm

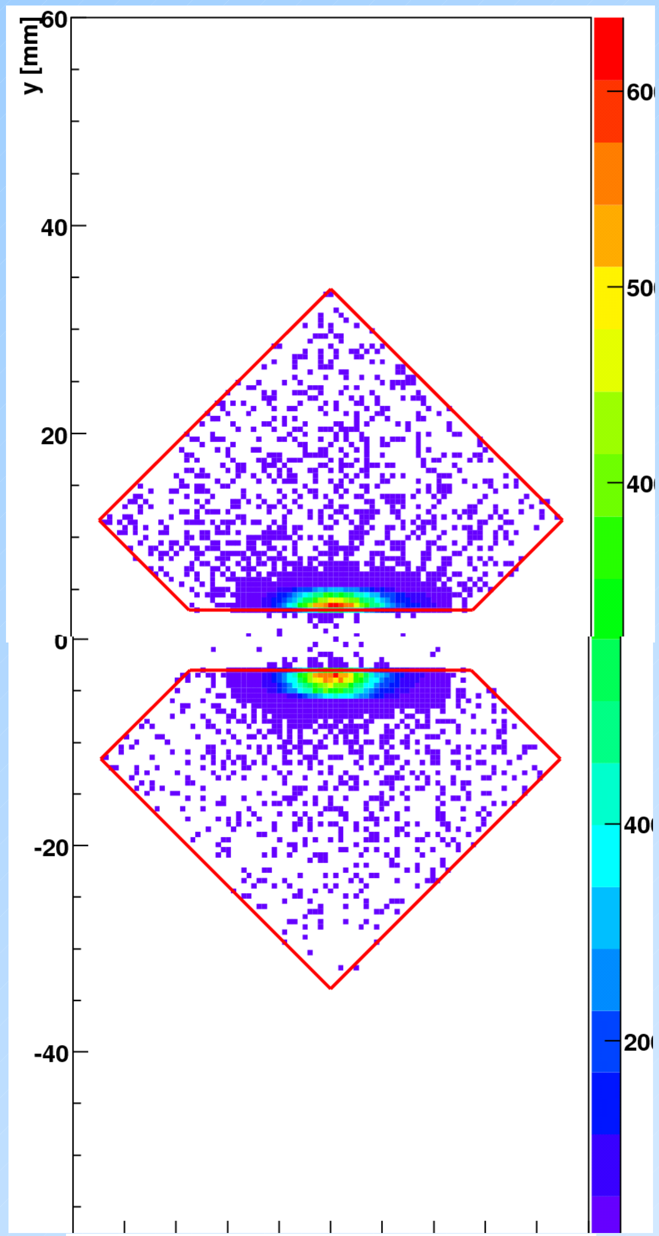
2.2 mm

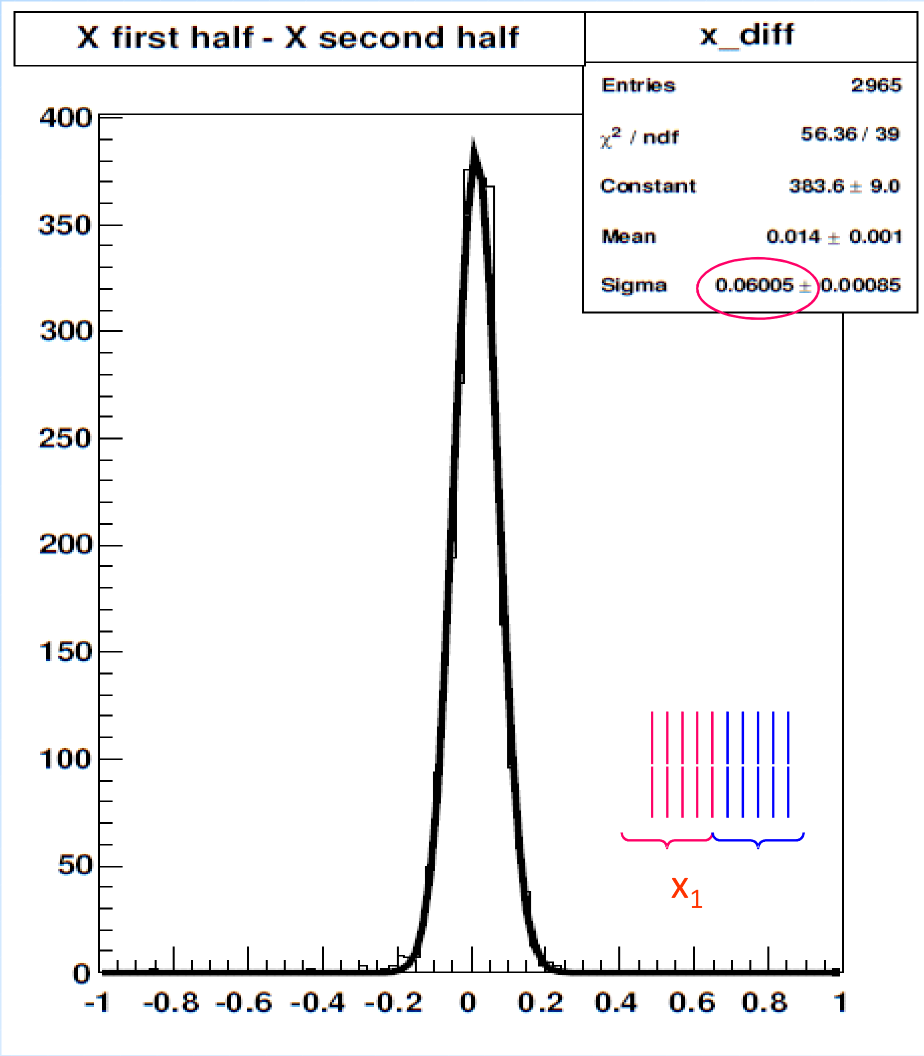


2.2 mm

4 shims centre the MAPMT w.r.t. the fibre connector → Maximize light coupling and minimize cross-talk!

PMT: ATLAS ALFA fibre tracker



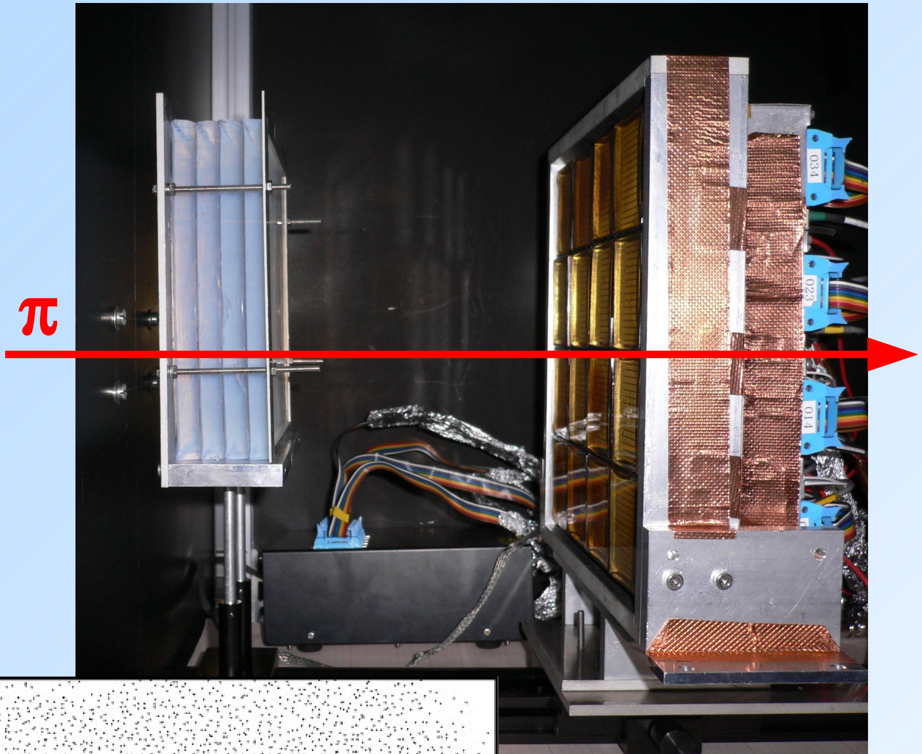


Expected σ_{ALFA}~32 μm

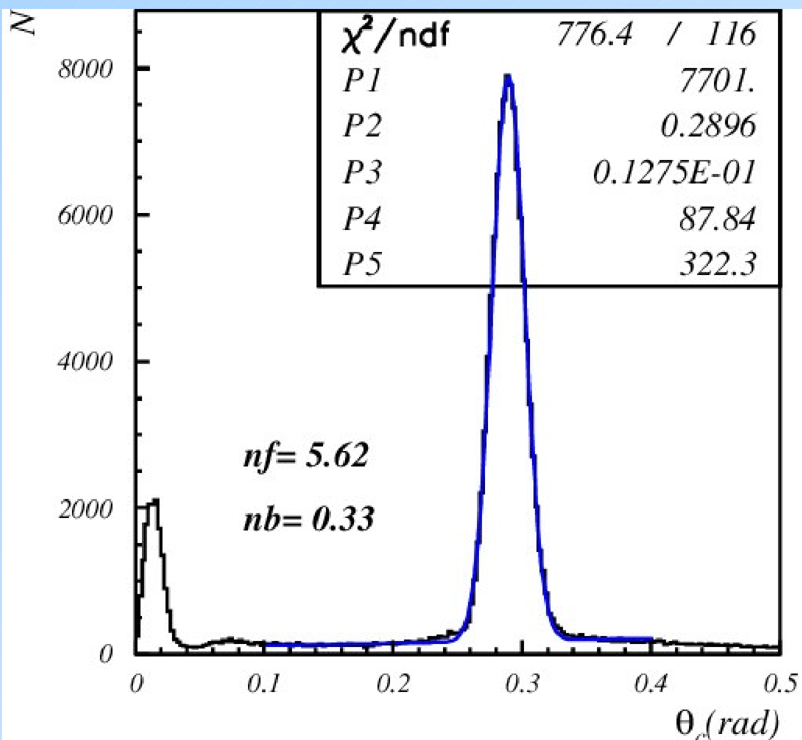
Belle II ARICH prototype

Photon detector

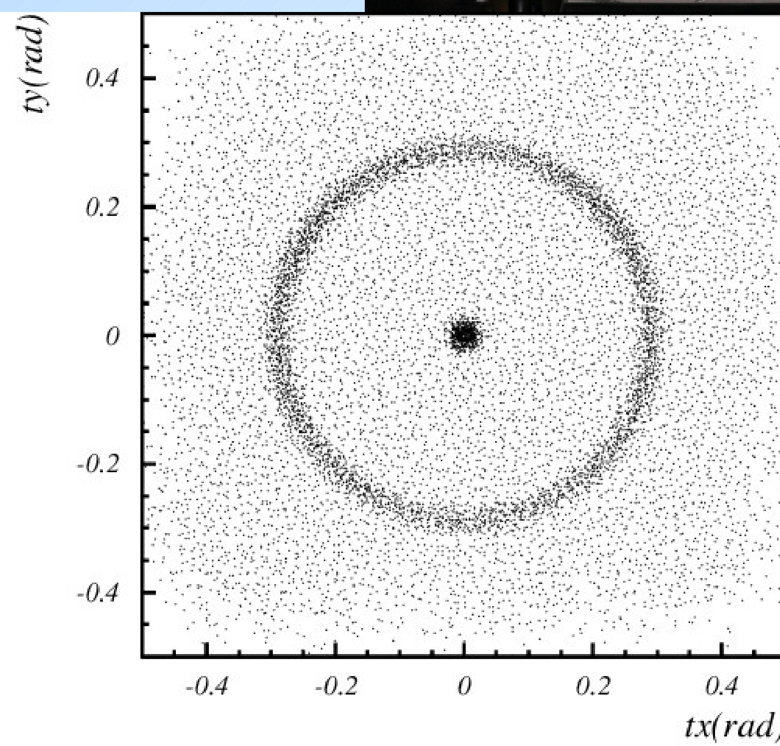
- 4x4 array Hamamatsu H8500
- 1024 channels
- 52.5 mm pitch (84% eff. Area)
- does not work in magnetic field



- 2cm thick aerogel sample, n=~1.04



theta cerenkov



ring in cerenkov space

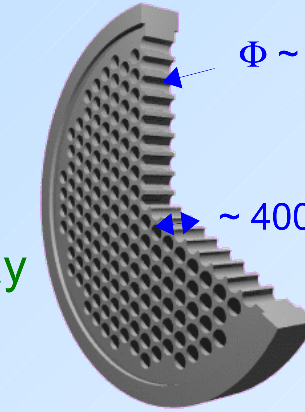
Micro Channel plate PMT (MCP-PMT)

Similar to ordinary PMT – dynode structure is replaced by MCP.

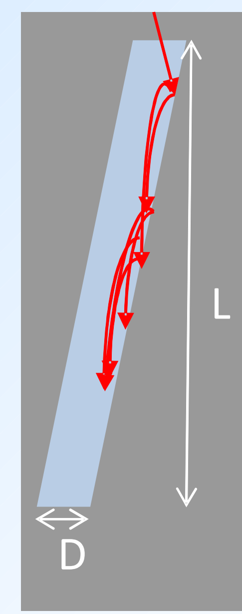
Basic characteristics:

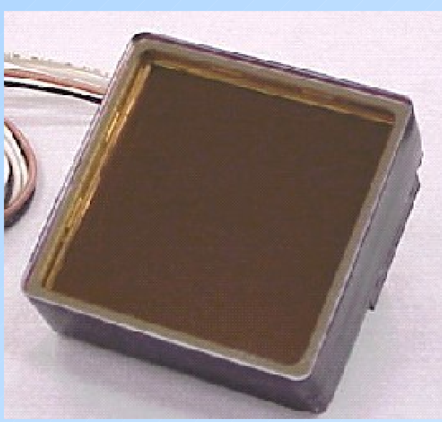
- Gain ~ 10^6 → single photon
- Collection efficiency ~ 60%
- Small thickness, high field → small TTS
- Works in magnetic field
- Segmented anode → position sensitive

MCP is a thin glass plate with an array of holes (<10-100 μm diameter) - continuous dynode structure



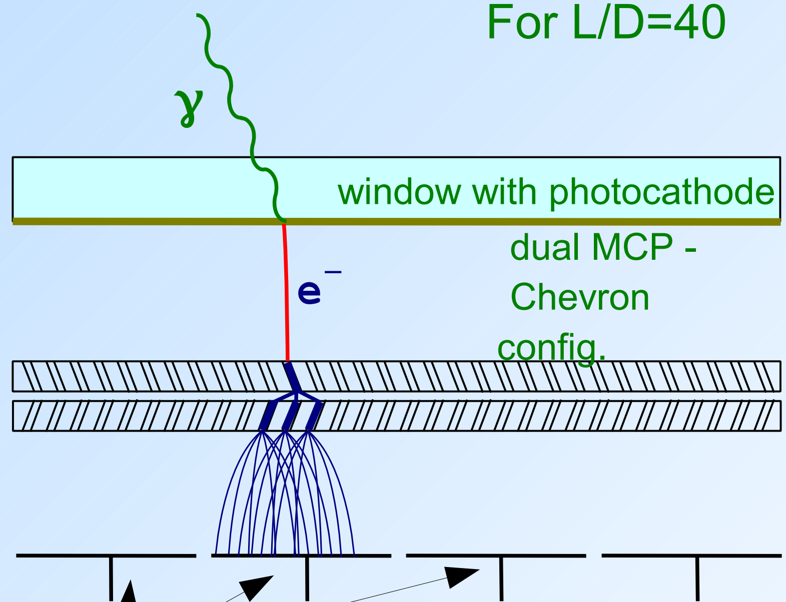
MCP gain depends on L/D ratio – typically 1000 For L/D=40





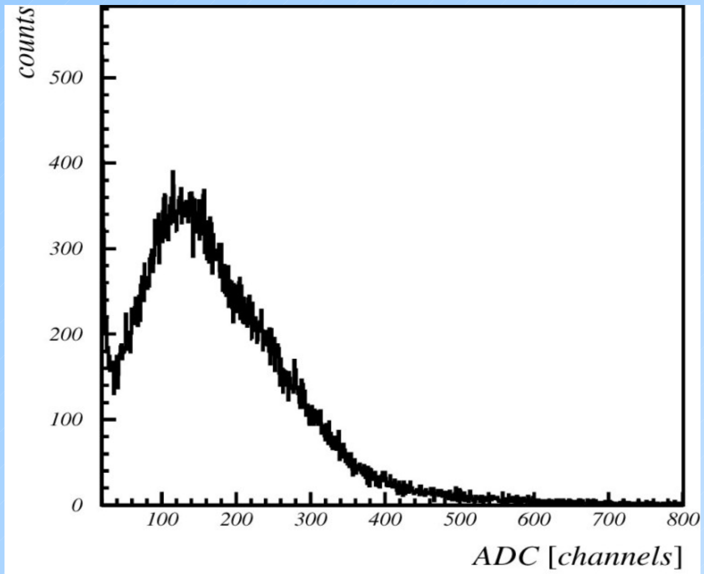
PHOTONIS

HAMAMATSU



Anodes → can be segmented according to application needs

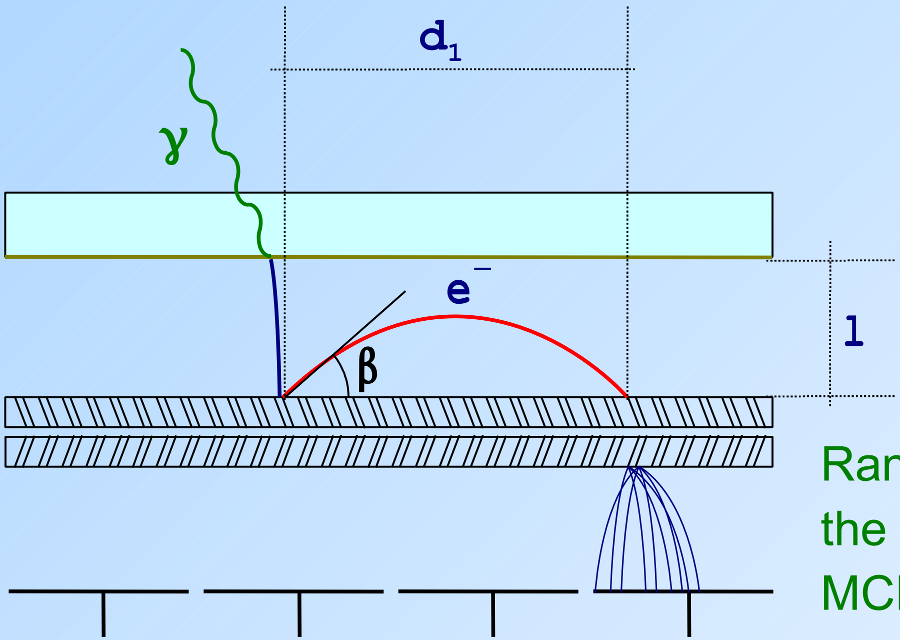
MCP-PMT: single photon pulse height and timing



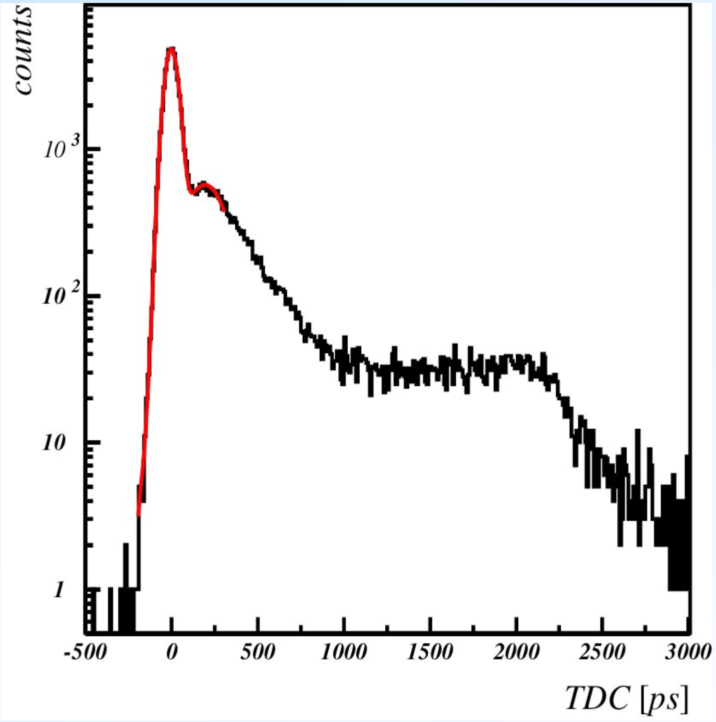
Gain in a single channel saturates at high gains due to space charge effect → peaking distribution for single photoelectron

Typical single photon timing distribution with narrow main peak (σ ~ 40 ps) and contribution from photoelectron back-scattering.

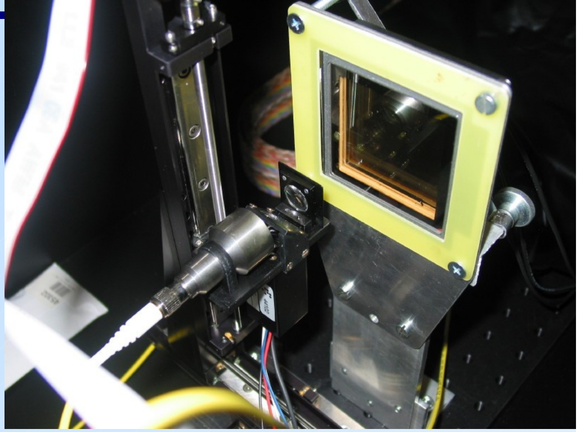
Photoelectron back-scattering produces rather long tail in timing distribution and position resolution.



Range equals twice the photocathode-MCP distance (2l).



MCP-PMT: photoelectron timing and position



Photoelectron travel time and range:

$$t_0 \approx l \sqrt{\frac{2 m_e}{U e_0}}$$

$$d_0 \approx 2 l \sqrt{\frac{E_0}{U e_0}} \sin(\alpha)$$

Backscatering delay and range:

$$t_1 = 2 t_0 \sin(\beta) \quad d_1 = 2 l \sin(2\beta)$$

Parameters used:

- $U = 200$ V
- $l = 6$ mm
- $E_0 = 1$ eV
- $m_e = 511$ keV/c^2
- $e_0 = 1.6\ 10^{-19}$ As

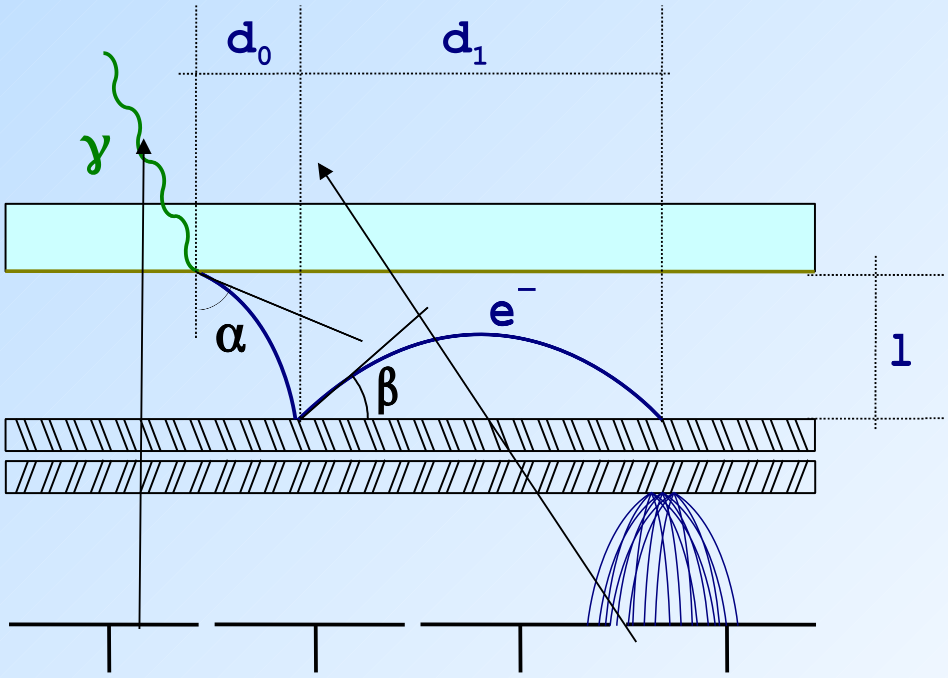


Photo-electron:

- $d_{0,max} \sim 0.8$ mm
- $t_0 \sim 1.4$ ns
- $\Delta t_0 \sim 100$ ps

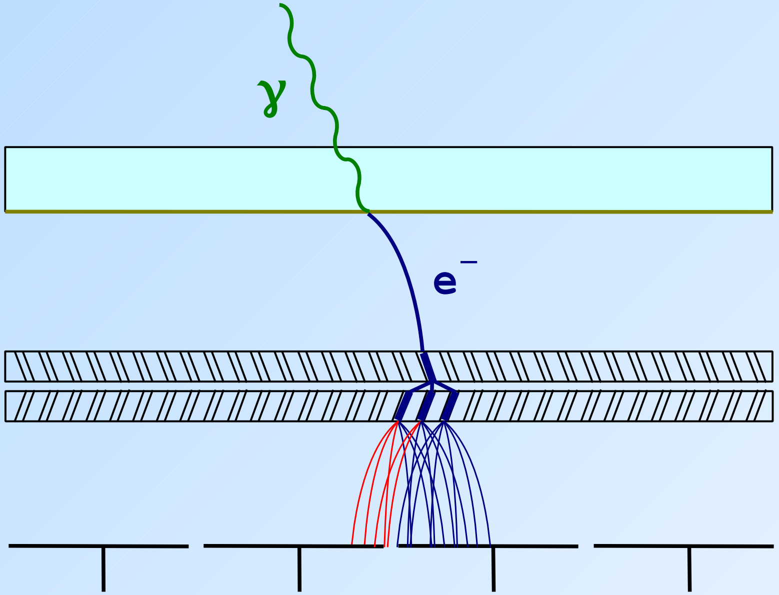
Backscattering:

- $d_{1,max} \sim 12$ mm
- $t_{1,max} \sim 2.8$ ns

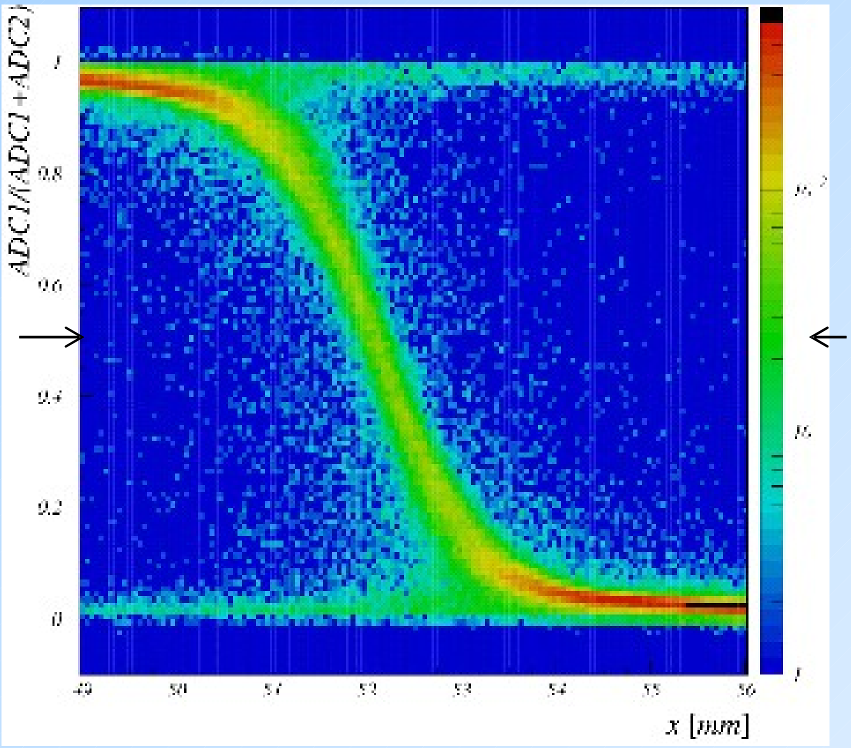
MCP-PMT: charge sharing

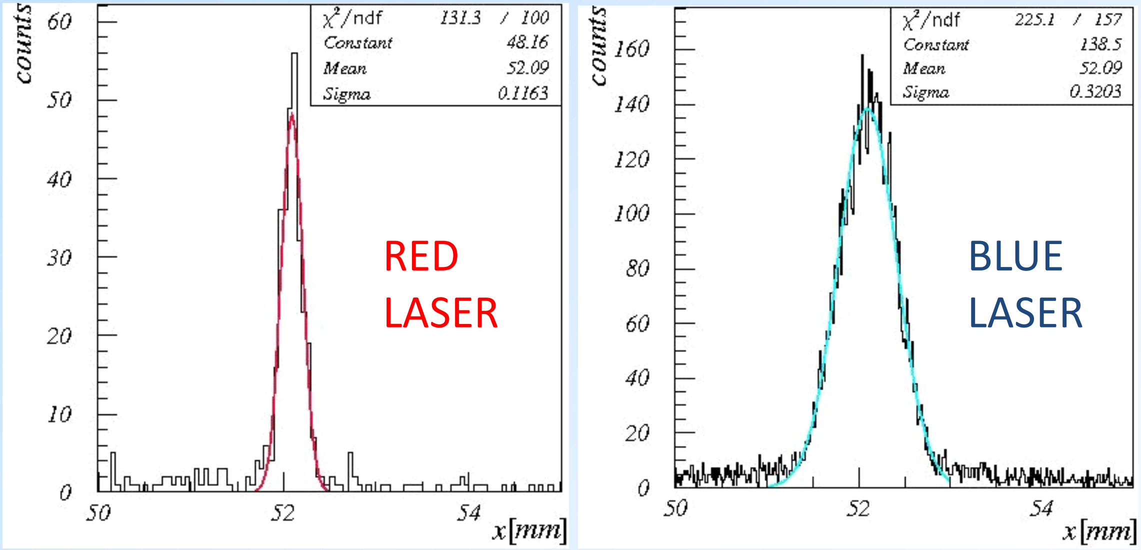
Secondary electrons spread when traveling from MCP out electrode to anode and can hit more than one anode → Charge sharing

Can be used to improve spatial resolution.



Fraction of the charge detected by left pad as a function of light spot position (red laser)

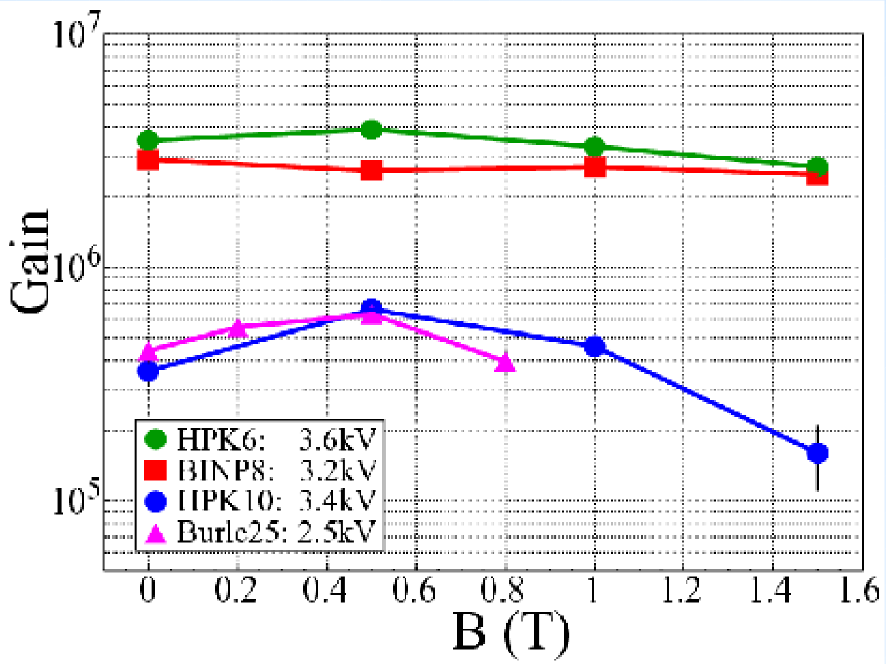




Slices at equal charge sharing for red and blue laser) – pad boundary. Resolution limited by photoelectron energy.

MCP-PMT: operation in magnetic field

- Narrow amplification channel and proximity focusing electron optics allow operation in magnetic field (~ axial direction).
- Amplification depends on magnetic field strength and direction.
- Effects of charge sharing and photoelectron backscattering on position resolution are strongly reduced while effects on timing remain



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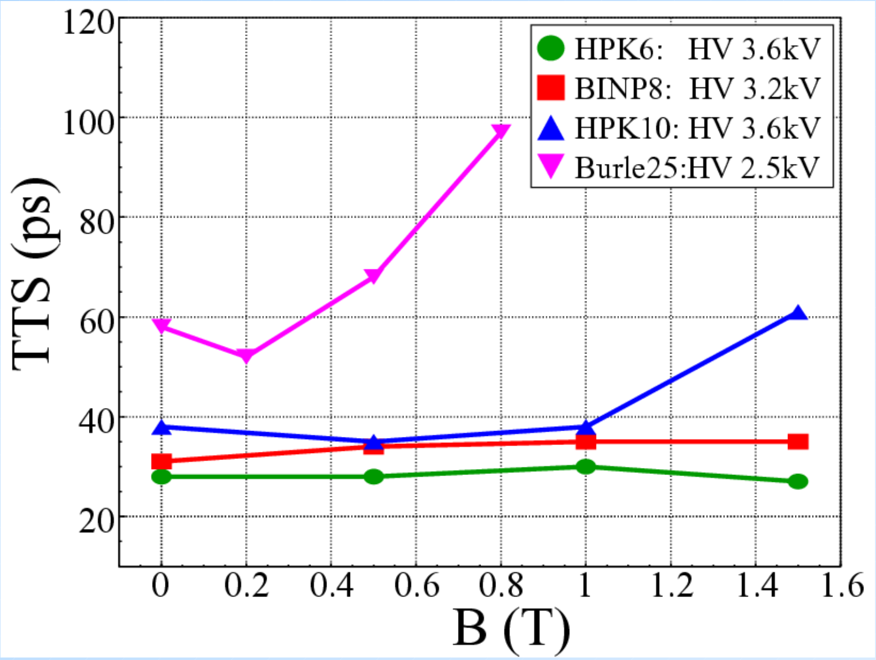
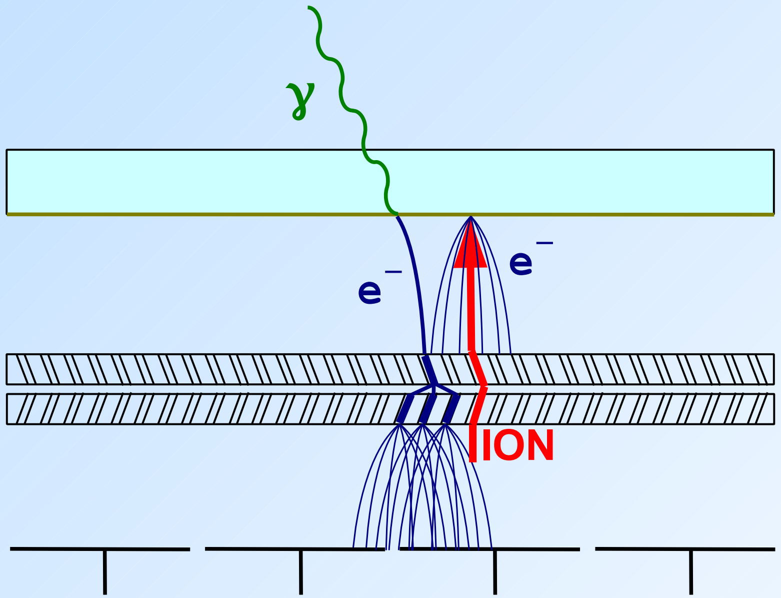
Gain vs. Magnetic field for MCP-PMT samples with different pore diameter.

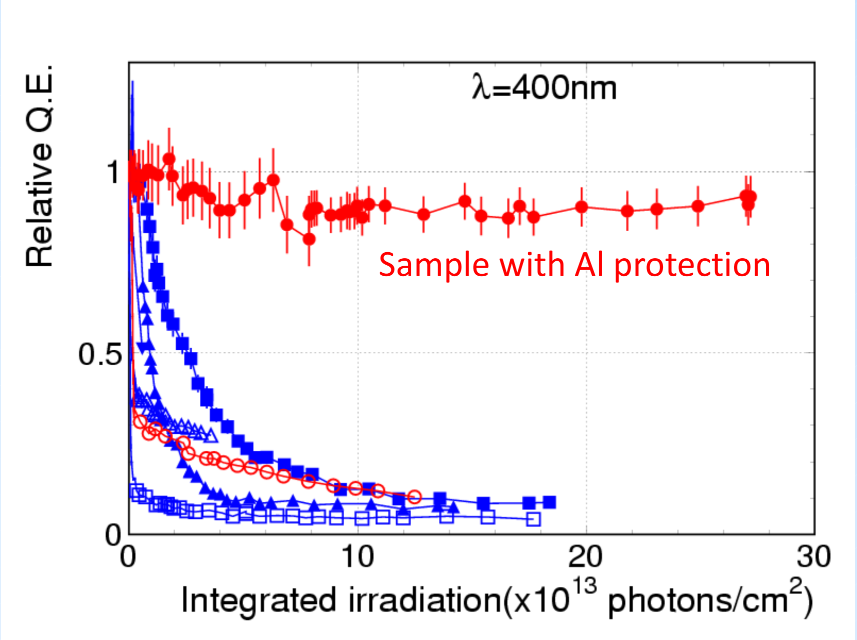


TTS vs. Magnetic field for MCP-PMT samples with different pore diameter.

MCP-PMT: Ion feedback and aging

- During the amplification process atoms of residual gas get ionized → travel back toward the photocathode and produce secondary pulse
- Ion bombardment damages the photocathode reducing QE
- Thin Al foil (few mm) blocks ion feedback but also about half of the electrons → placed between the MCPs





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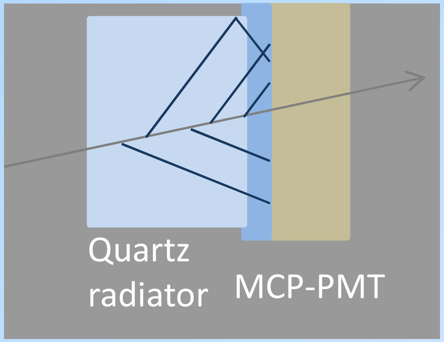
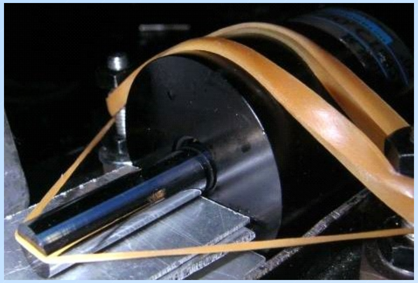
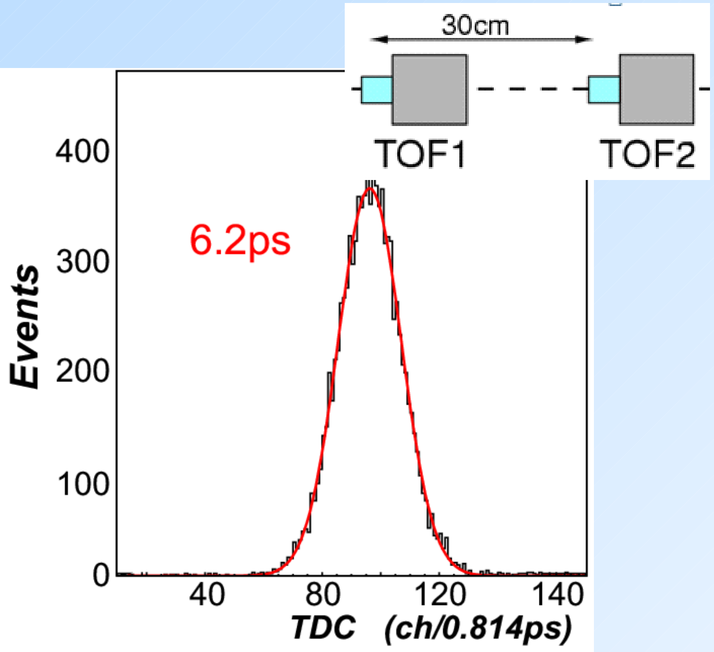
Change of relative QE during the typical aging test. MCP-PMTs without Al protection show rapid reduction of QE.

MCP-PMT: TOF applications

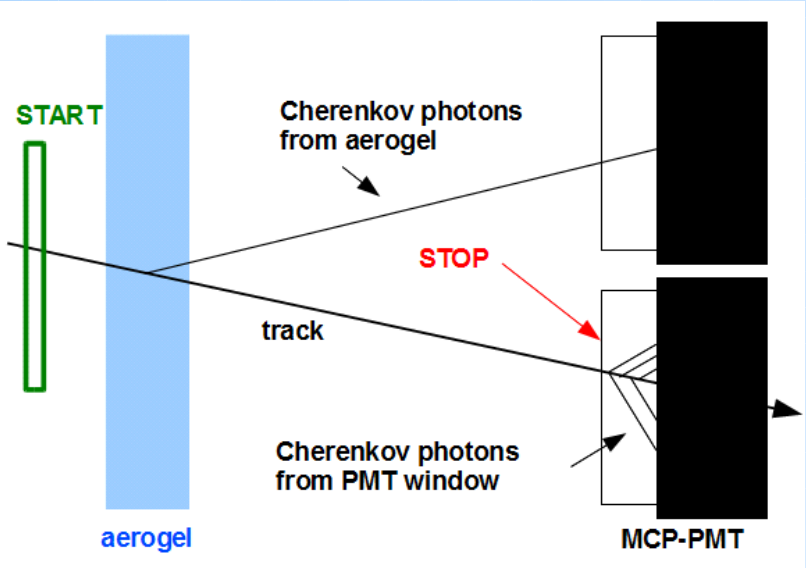
- Excellent timing properties require fast light source → Cherenkov radiator directly attached to the MCP-PMT
- Can be used as dedicated TOF (SuperB end-cap PID option) or as part of the proximity focusing RICH (Belle-II end-cap PID option)





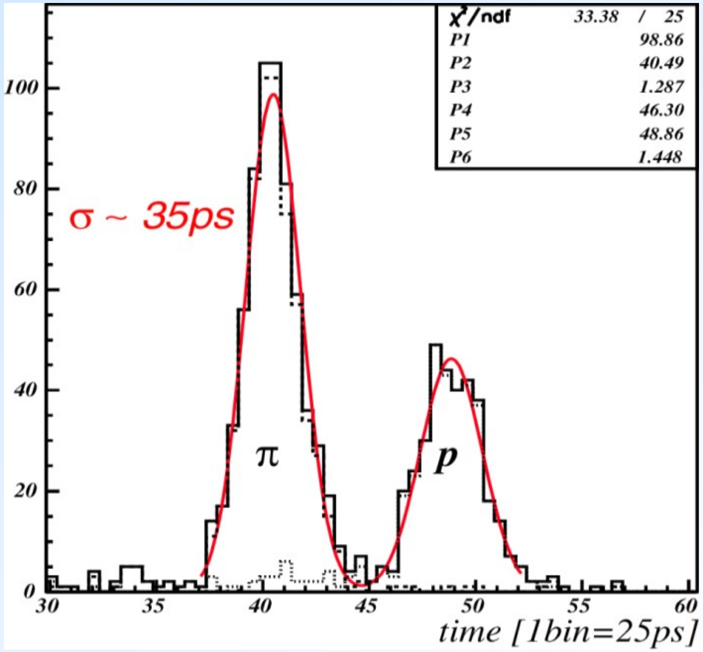


K. Inami @ PD07



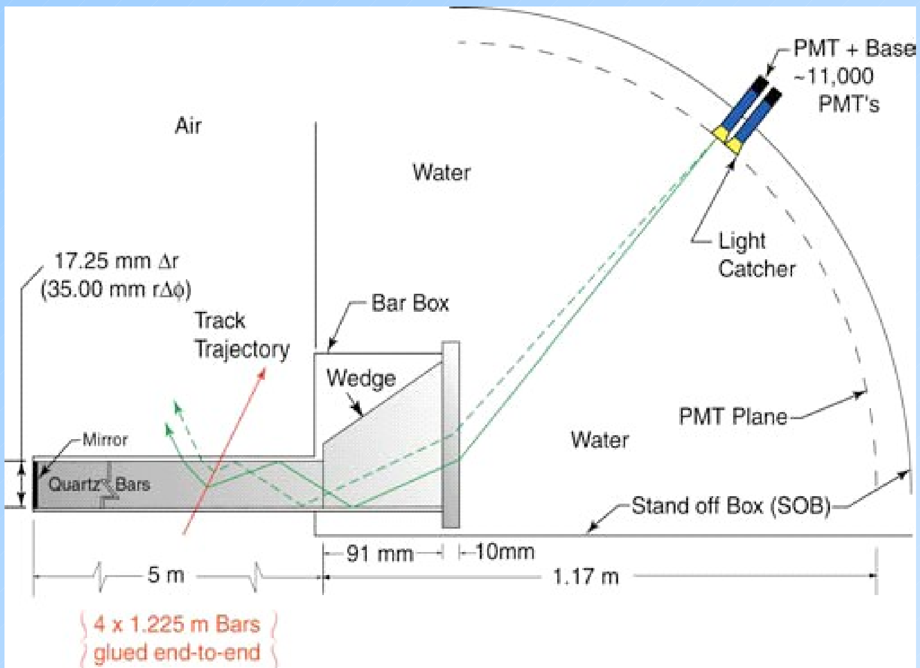
Proximity focusing aerogel RICH with TOF capability

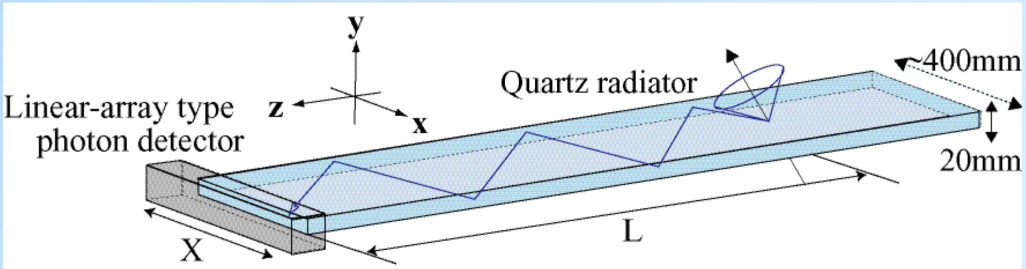
Separation of 2 GeV pions and protons with 0.6 m flight length (start counter s ~ 15 ps).

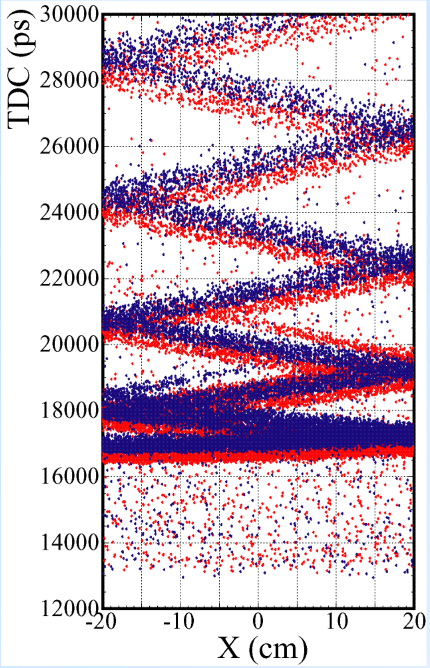


MCP-PMT: RICH with timing information

DIRC concept (BaBar) – 2D imaging







TOP (Time-Of-Propagation) counter based on DIRC concept (Belle-II). Using linear array of MCP-PMTs to measure one coordinate and time of propagation (length of photon path) to obtain 2D image → compact detector.

(pion, kaon)

Focusing DIRC with chromatic correction (SuperB) uses measured time of propagation to correct chromatic error.

$$t_p = \frac{L_{path}}{v_g} \qquad v_g = \frac{c}{n(\lambda) - \lambda \frac{dn}{d\lambda}} \text{ (group velocity)}$$

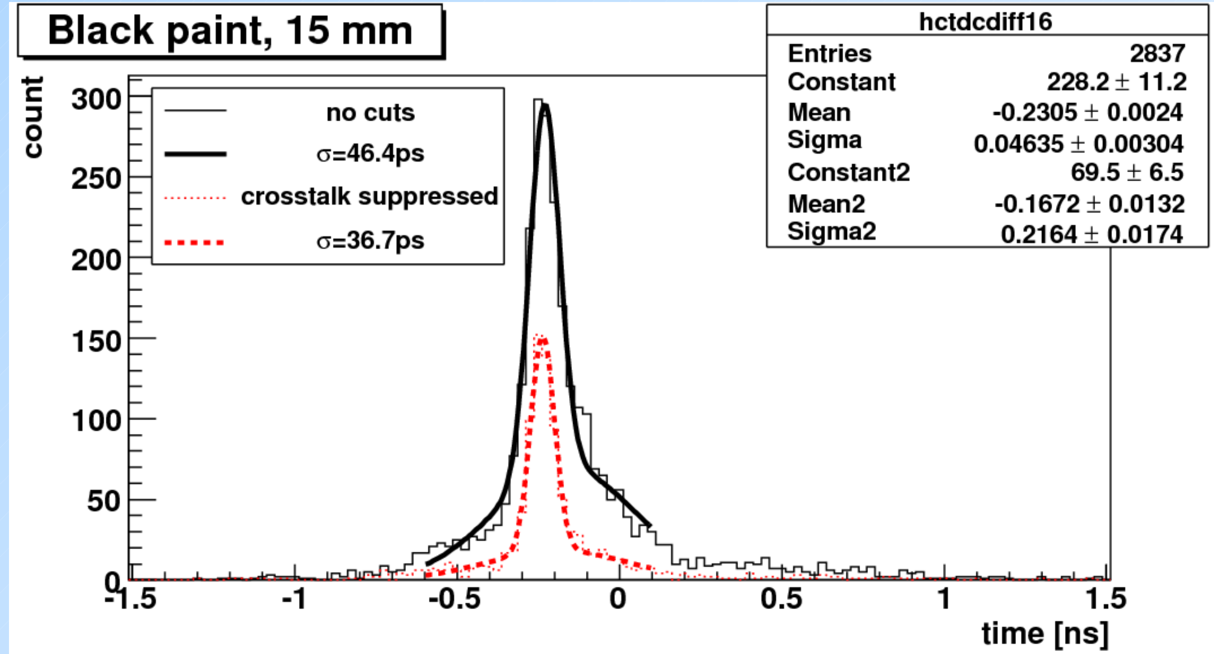
MCP-PMT TOF PET

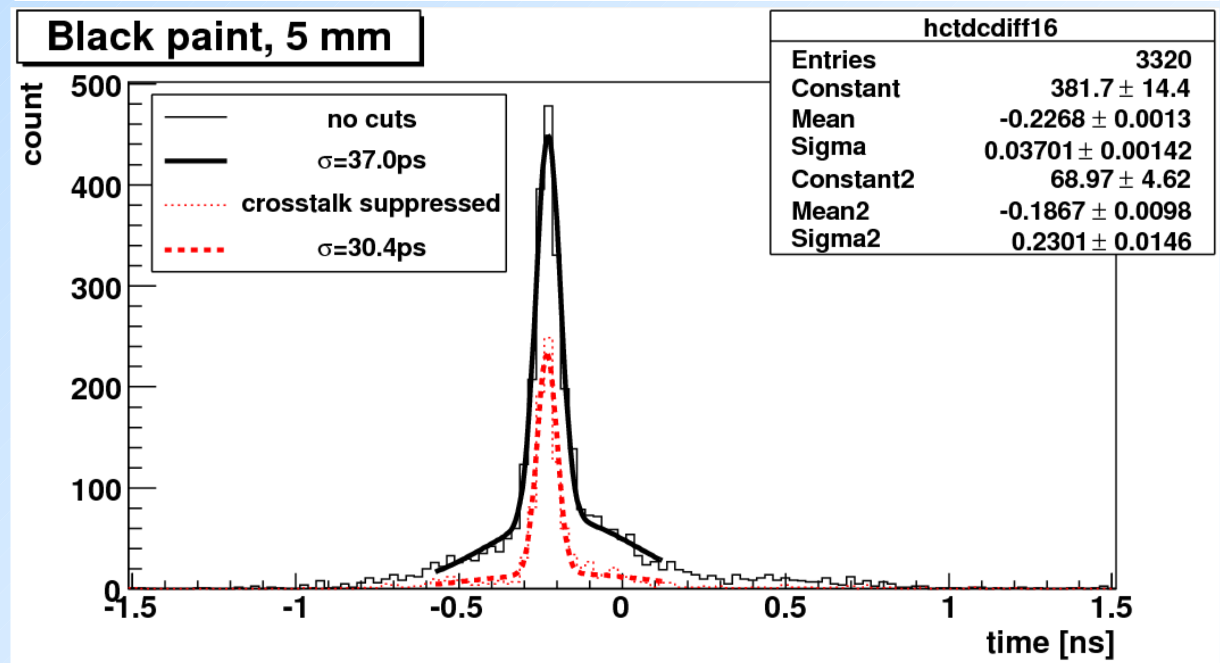
PET based on Cherenkov light

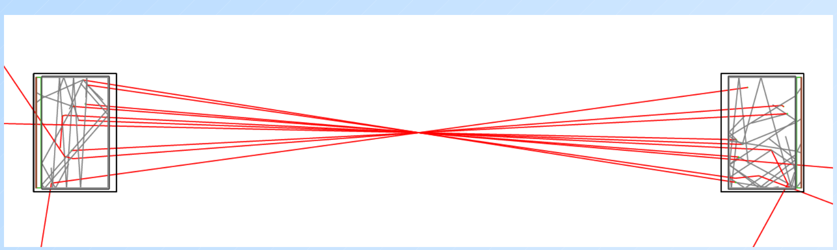
Data taken with black painted PbF_2 crystals:

- 15 mm: r.m.s. ~ 37 ps
  FWHM ~ 95 ps

- 5 mm: r.m.s. ~ 30 ps
  FWHM ~ 70 ps







MCP-PMT TOF PET

Data taken at three different point source positions spaced by 20 mm:

- average time shift 125 ps
- timing resolution ~ 40 ps
- position resolution ~ 6 mm RMS, ~ 14 mm FWHM

Black painted 15 mm PbF_2 crystals.