Lecture 16

Light transmission and optical detectors

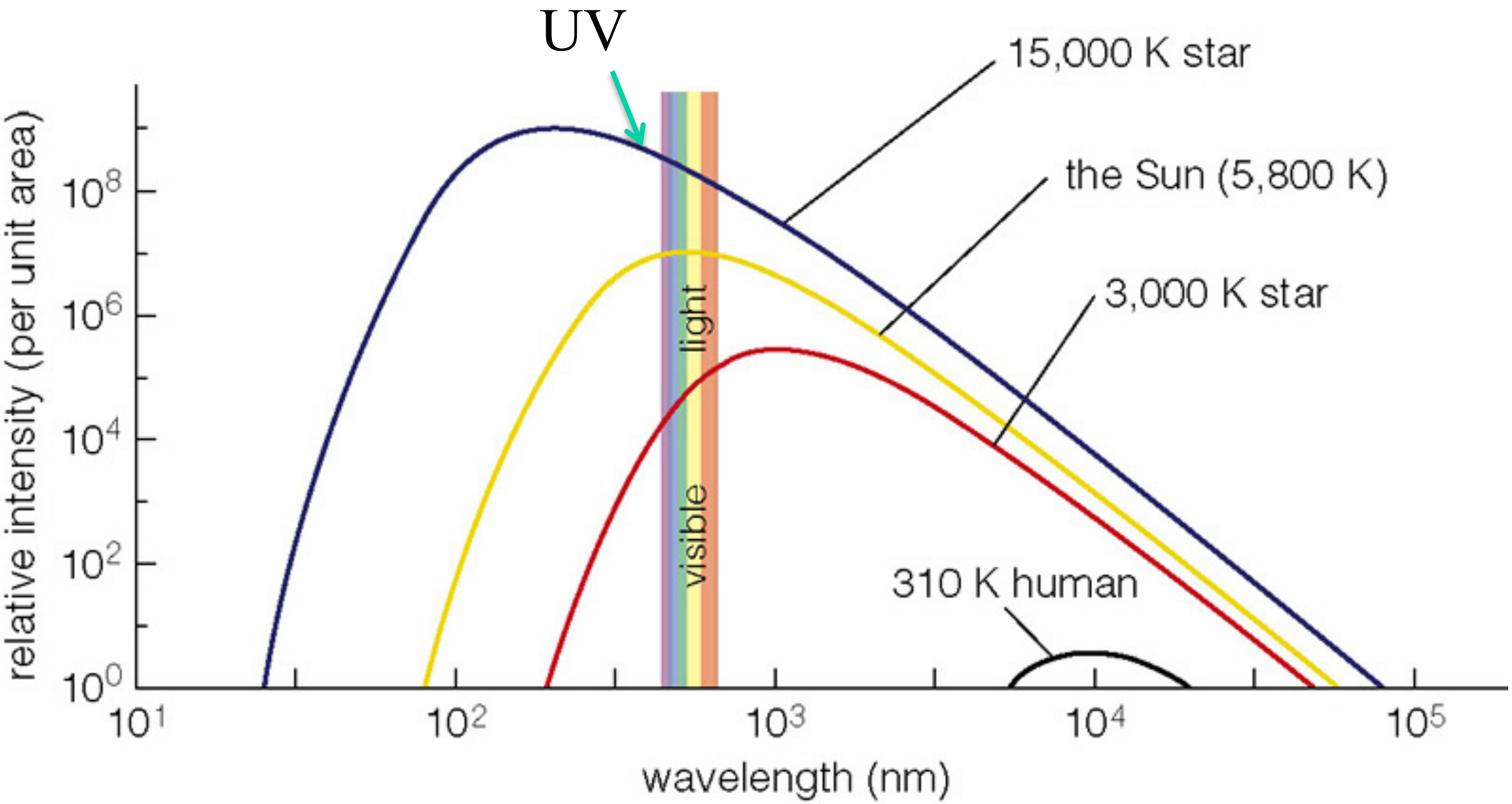
Charged particle traversing through a material can generate signal in form of light via electromagnetic interactions with orbital electrons of the atoms or molecules in the medium.

To detect a signal we need to transfer the light signal through the medium to a detector that will transform light signal into an electrical pulse.

Table 1: The electromagnetic spectrum

Radiation type	Wave length λ , (Å)	Frequency $\nu = c / \lambda$, (Hz)	Applications
radio	10^{14}	3×10^{4}	
Nuclear magnetic resonance	10^{12}	3×10^{6}	
Television	10^{10}	3×10^{8}	Spin orientation
Radar	10^{8}	3×10^{10}	
Microwave	10^{7}	3×10^{11}	Rotational
Far infrared	10^{6}	3×10^{12}	Vibrational
Near infrared	10^{4}	3×10^{14}	
Visible	8×10^{3} - 4×10^{3}	3.7×10^{14} - 7.5×10^{14}	
Ultraviolet	3×10^{3}	1×10^{15}	Electronic
X-rays	1	3×10^{18}	
Gamma rays	10^{-2}	3×10^{20}	Nuclear transitions
Cosmic rays	10^{-4}	3×10^{22}	

Radiation spectra



Light transmission through total internal reflection is known since ~1840. Initially used mostly for illumination of fountains. First famous “jet d’ eau” in Geneva was designed in 1886 with light sources.

Optical quartz fibers were originally developed for signal transmission during nuclear tests. Electrical signals were unreadable due to e-m shock wave of the explosion. Such fibers were later used for the cameras in first Moon missions and spy planes. Commercial fibers made from pure silica or various plastics were developed in late 1970ties for telecommunication.

Plastic optical fibers can be doped with scintillating compounds.

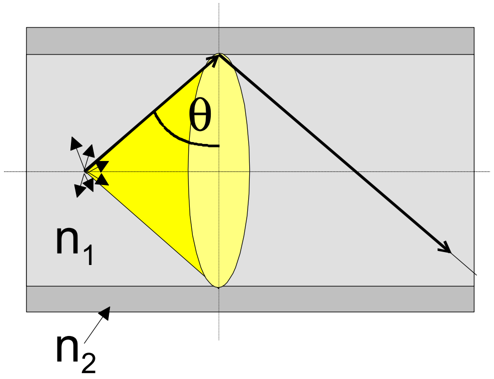
There are also capillary tubes filled with liquid scintillator.

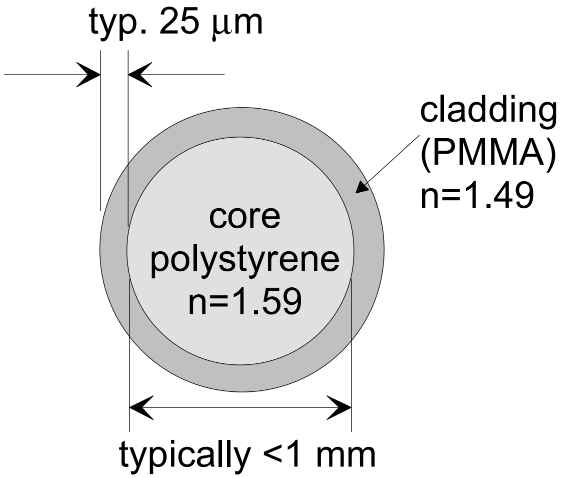
They can be used for construction of fiber tracking devices.

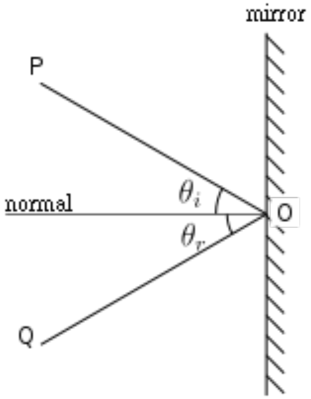
Since there is no “cross-talk” effect – optical fibers provide flexible solutions for difficult geometries of the detector.

Jet d’eau, Geneve
300 ft

Optical fibers as light guides







light transport by total internal reflection

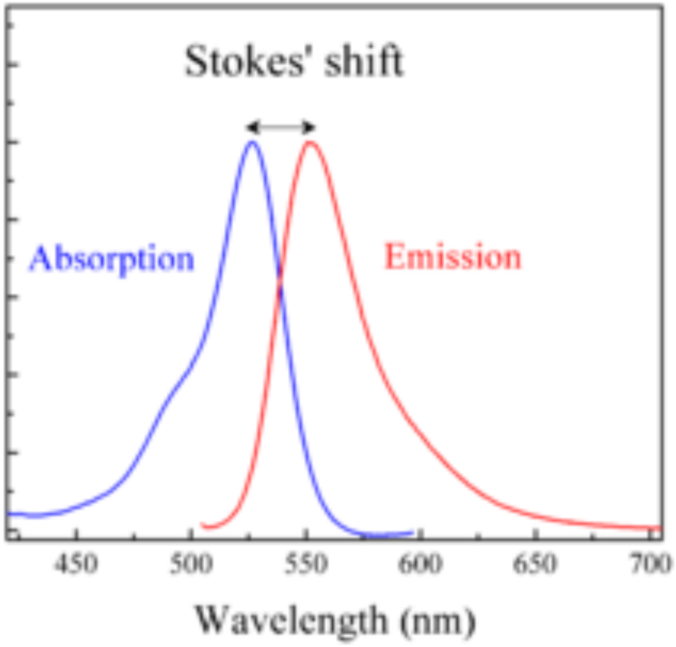
Idealized (wrong) estimate

$\theta \geq \arcsin n_2/n_1 \sim 69.6^{o}$

Light is generated mostly away from fiber axis.

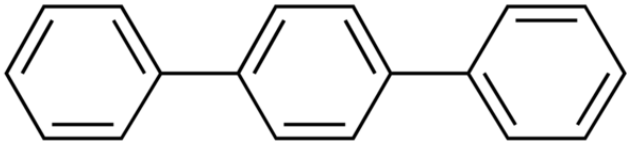
Light transport is mostly away from the cross-sectional plane

Wavelength shifters



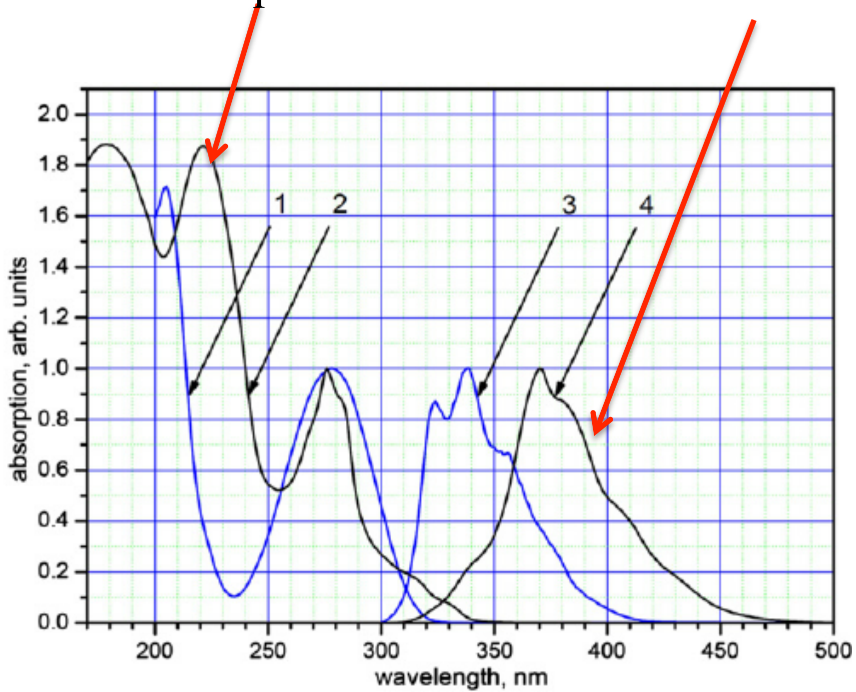
p-terphenyl

$C_6H_5C_6H_4C_6H_5$



absorption

emission



Fibers doped with scintillators

Total internal reflection in a fiber

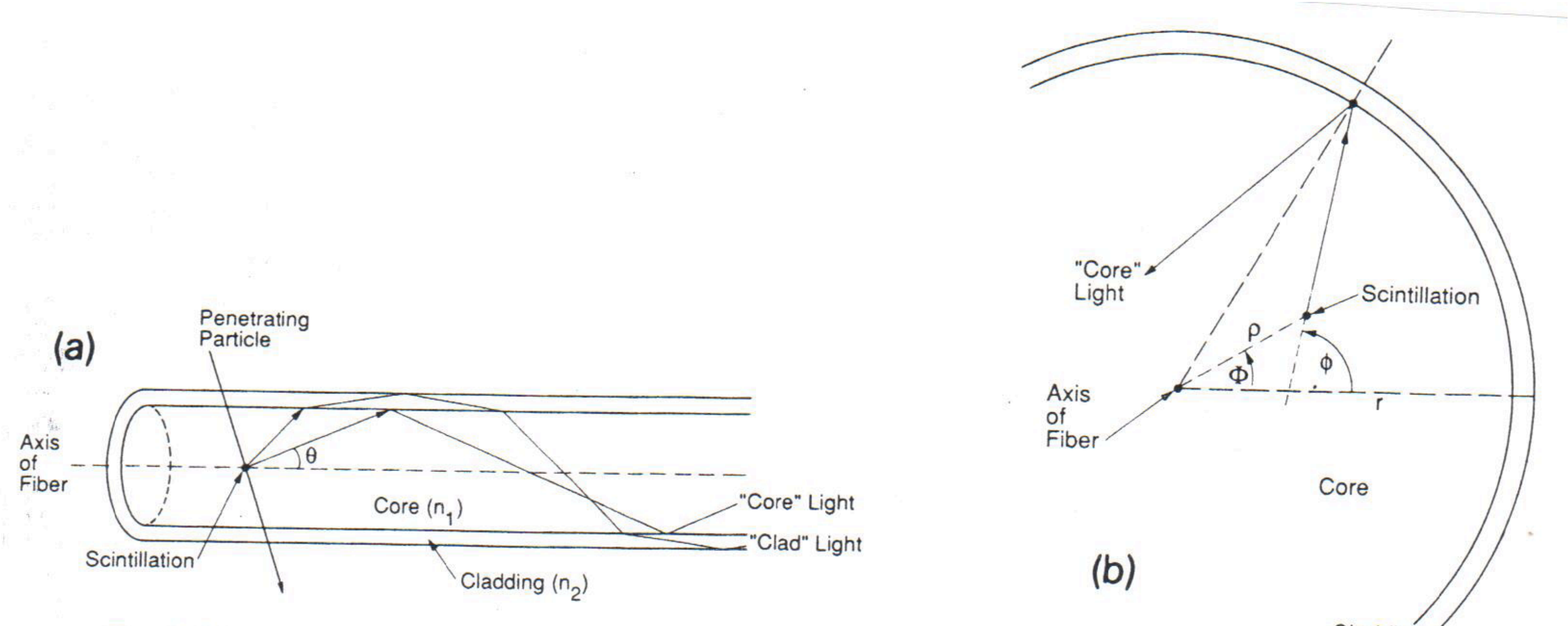
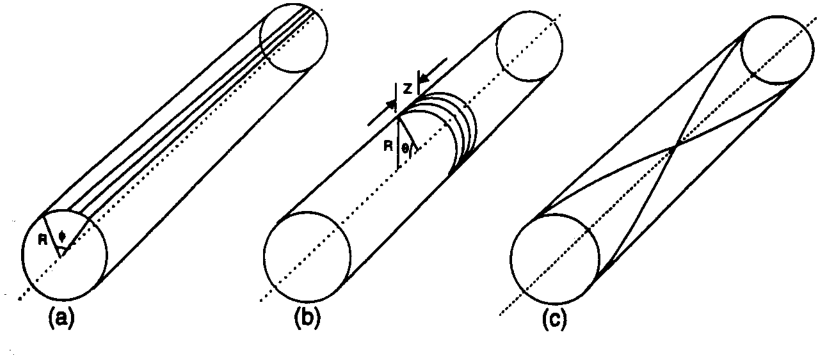


Fig. 1. Light propagation in a scintillating fiber for light rays emitted (a) on-axis and (b) off-axis.

Condition for trapping

$$\sin\theta\sqrt{1-\left(\frac{\rho}{r}\sin(\varphi-\Phi)\right)^2}\leq\sin\theta_{tr}$$

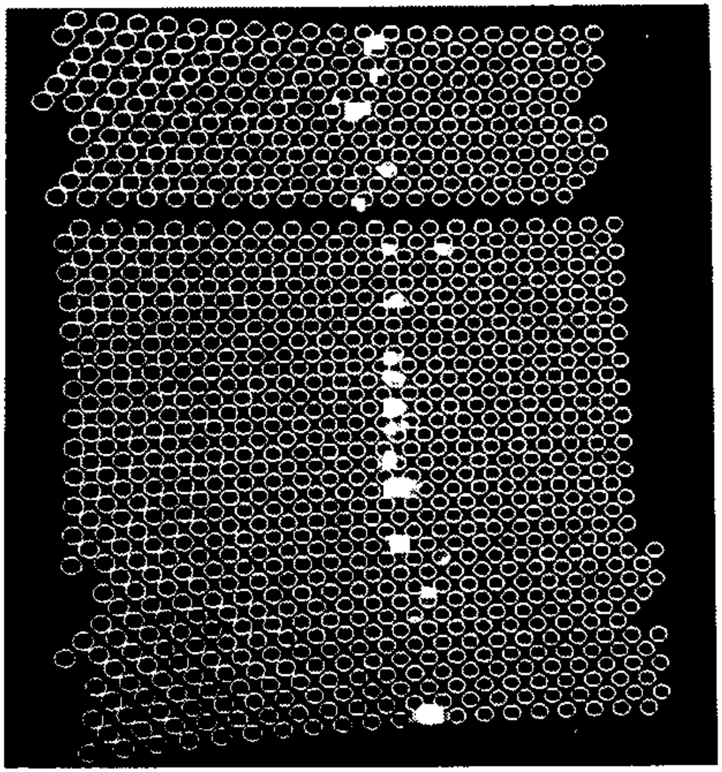
Fiber tracking arrangements



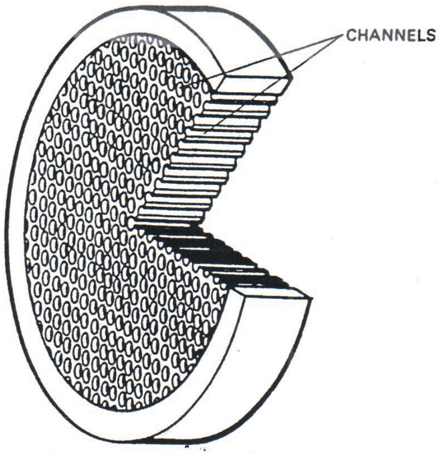
a) axial
b) circumferential
c) helical

Advantages: low mass, fine granularity, fast readout

Charged particle passing through a stack of scintillating fibers with 1 mm diameter



Time resolution improvement - Multichannel plate MCP



(a) Schematic construction of MCP

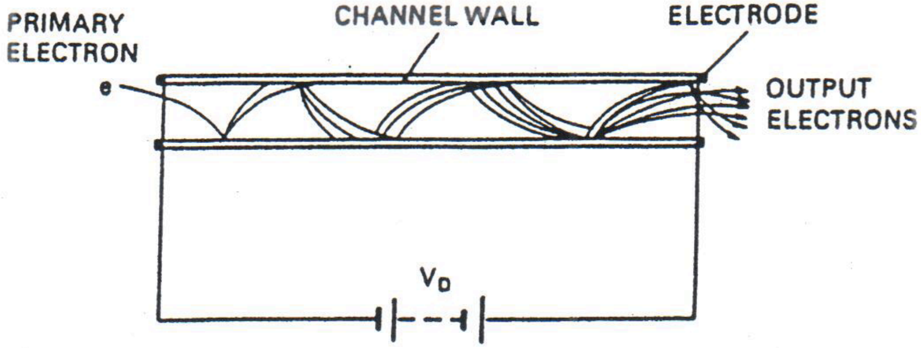


Fig. 1-(b) Operation of electron amplification

Photo detectors

Use photoelectric effect to convert light into electrical signals
Sensitivity usually expressed as quantum efficiency

$$QE = N_{photoelectrons}/N_{photons}$$

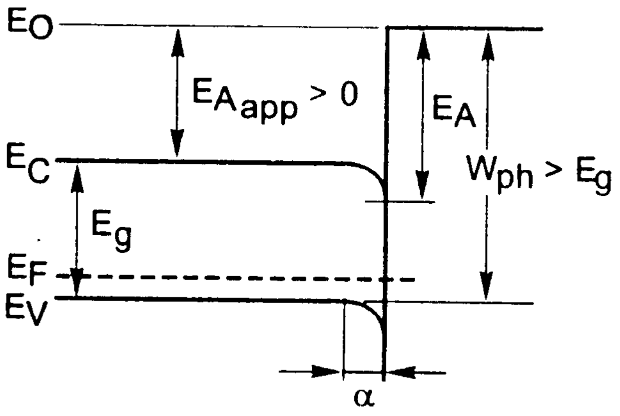
Photomultipliers

3-step process in the photocathodes

- photo ionization of molecule
- electron propagation through photocathode
- escape of the electron into vacuum

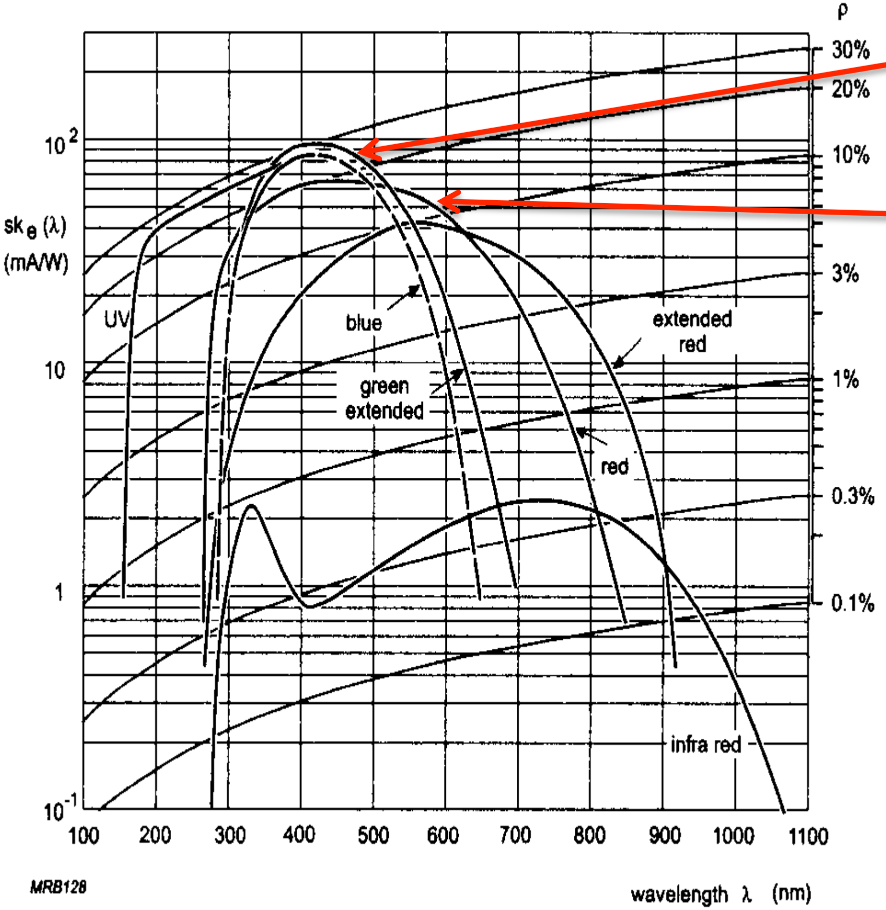
Typical photocathodes are semiconductors

Photon energy has to be sufficient to bridge the band gap E_g, but also to overcome the electron affinity E_A, so that the electron can be released into the vacuum.



Dynode gain ~4, so a PMT with 10 dynodes has a gain $4^{10} \sim 10^6$

Quantum efficiency of typical photo cathodes



Bialkali
SbK_2Cs

Multialkali
$SbNa_2KCs$

Energy resolution of a PMT is determined by the fluctuations of the number of secondary electrons emitted from dynodes.

Poisson fluctuations

$$P(\bar{n},m)=\frac{\bar{n}^{m}e^{-m}}{m!}$$

Relative fluctuations $$\frac{\sigma_n}{\bar{n}}=\frac{\sqrt{\bar{n}}}{\bar{n}}=\frac{1}{\sqrt{\bar{n}}}$$

Dominated by the fluctuations when the numbers are small i.e., at the first dynode.

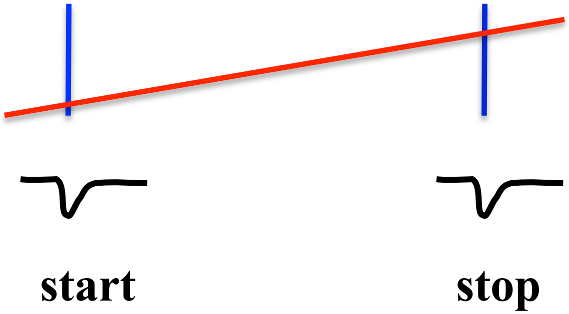
PMT's are in general very sensitive to B-fields, even to earth field (30-60 mT) -> μ-metal shielding required.

Solid state photo detectors

PiN diodes:
- thin p layer to avoid light absorption by silicon
- high quantum efficiency (~80% at 700 nm)
- no gain – used for high light yield readouts

APD avalanche photo diodes:
- high reverse bias voltage ~100-200 V
- high internal field -> avalanche multiplication
- gain ~100

Time of Flight



$$t = \frac{L}{\beta c}$$

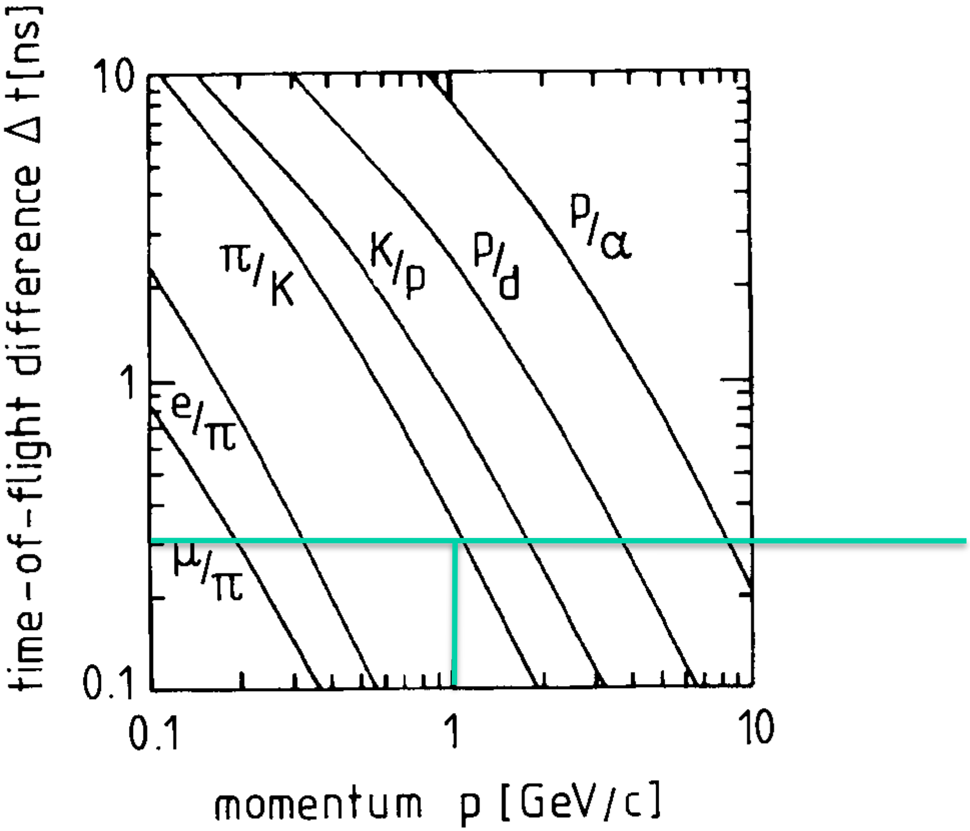
$$(p = m_0 \beta \gamma)$$

$$m = p\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

Mass resolution $$\frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right)$$

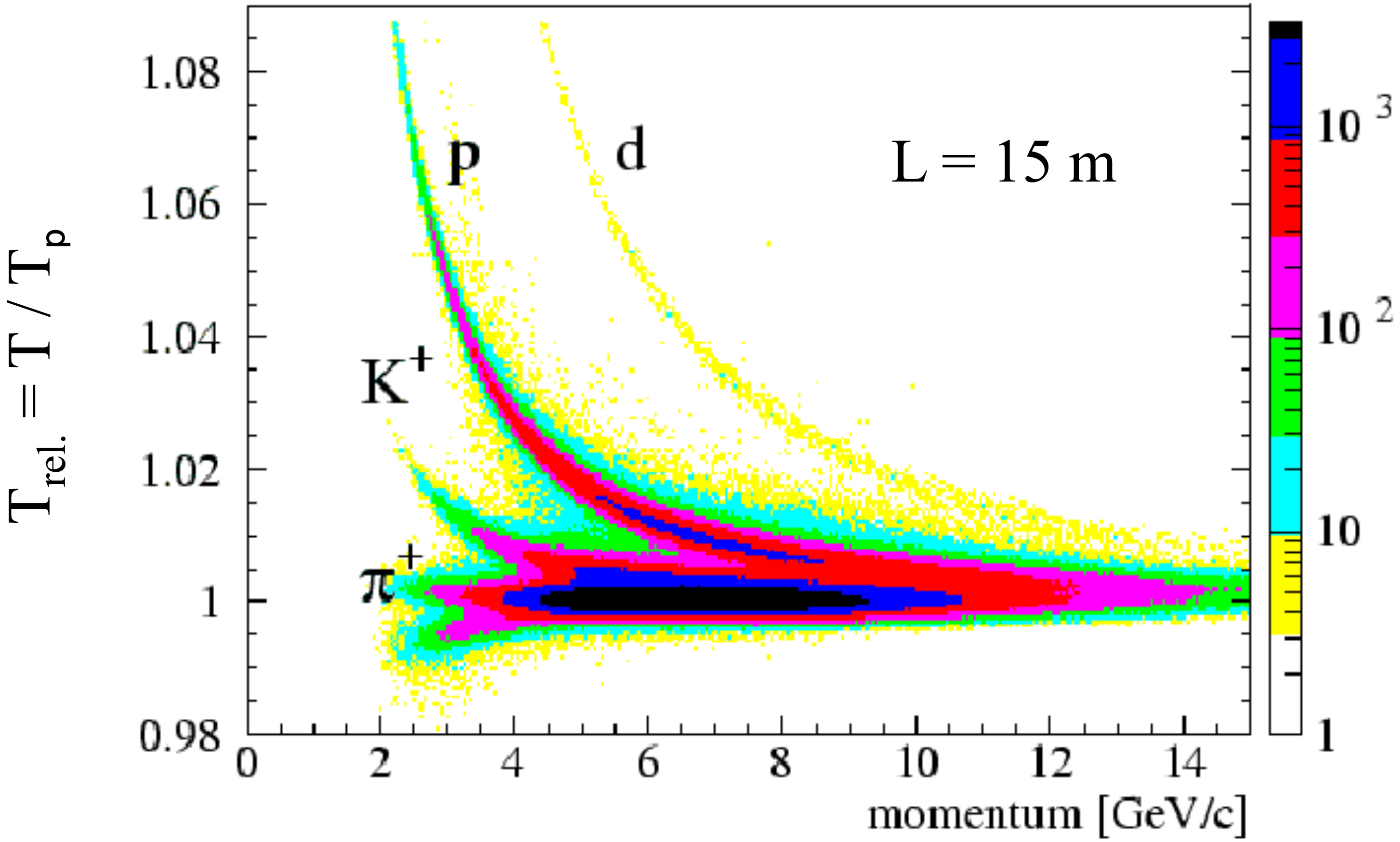
TOF difference of 2 particles at a given momentum

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1 + m_1^2 c^2 / p^2} - \sqrt{1 + m_2^2 c^2 / p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$



For σ_t = 300 ps
π/K separation up to
~ 1 GeV/c

NA49 experiment



Cherenkov radiation

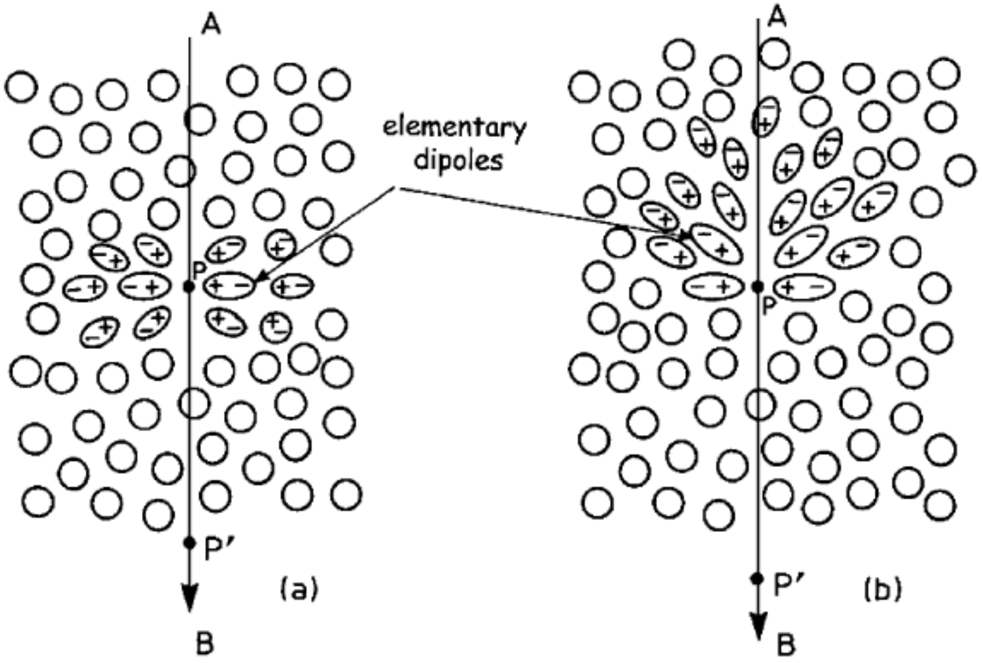
Speed of light in vacuum - c

Speed of light in a material - $c/n(\lambda)$

n - index of refraction, λ - wavelength

If the velocity of a particle is such that $\beta = v_p/c > c/n(\lambda)$, a pulse of light is emitted around the particle direction with an opening angle ($\boldsymbol{\theta}_c$)

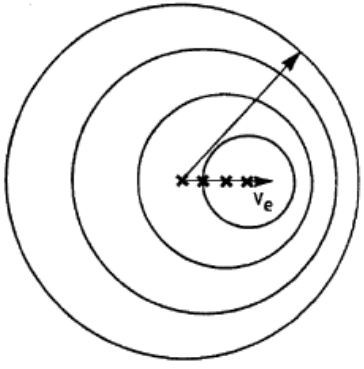
$v_p/c < c/n(\lambda)$
symmetric
dipoles



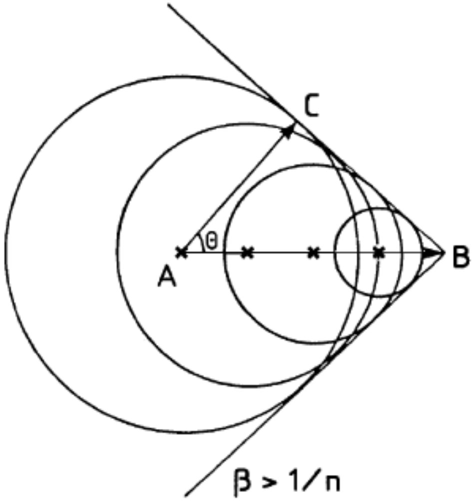
$v_p/c > c/n(\lambda)$
coherent
wavefront

dielectric, polarizable medium

- The threshold velocity is $\beta_c = 1/n$
- At velocity below β_c no light is emitted
- If velocity exceed phase velocity of light (rather than group velocity) there is a Cherenkov light emission

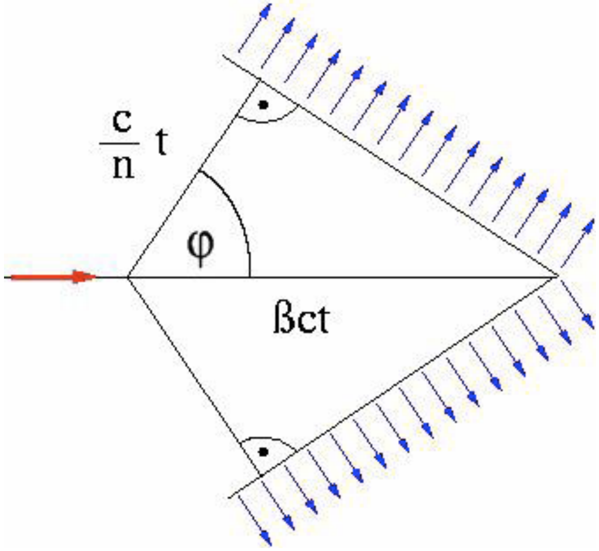


$\beta < 1/n$



$\beta > 1/n$

Cherenkov angle

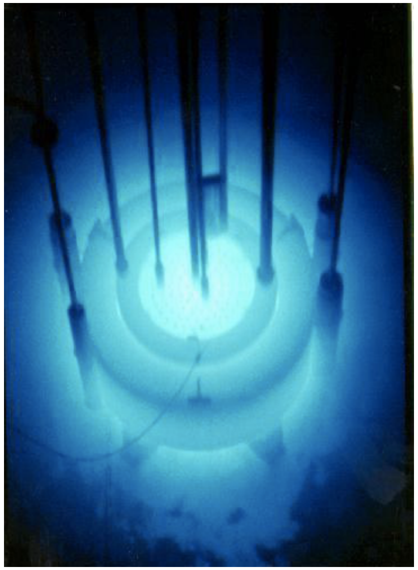


Cherenkov photon emission – cone around particle direction

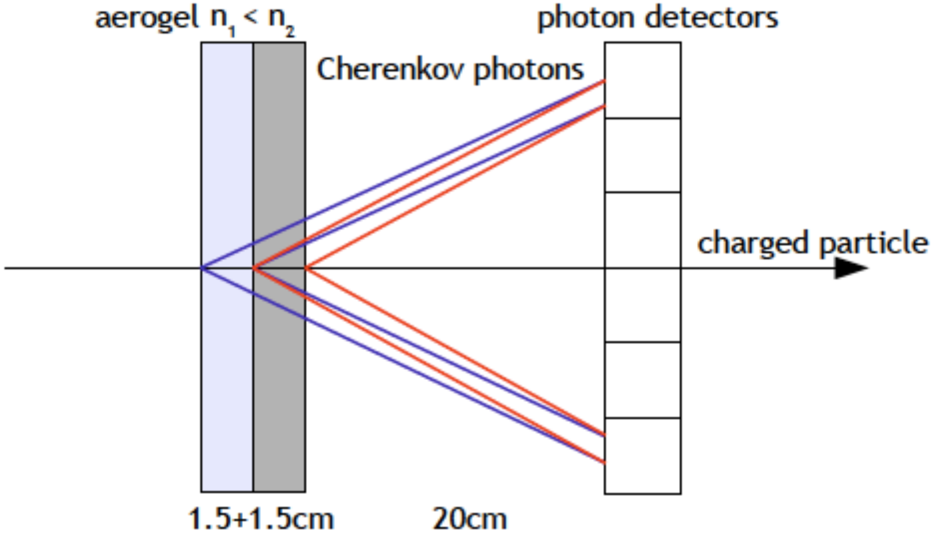
- Typical intersection of cone with a photon detection plane – ring

  RICH – ring imaging detector counter
- Weak effect, causes no significant energy loss (<1%)
- It takes place only if the track L of the particle in the radiating medium is longer than the wavelength λ of the radiated photons.

Cherenkov radiation glowing in the core of a reactor



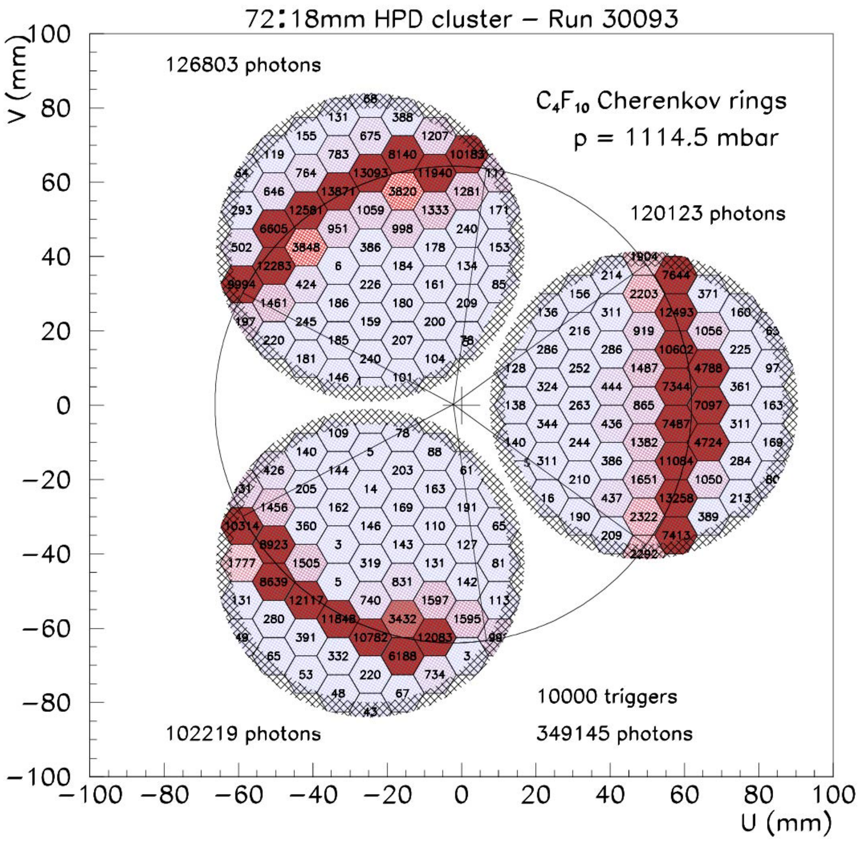
Particle physics detector



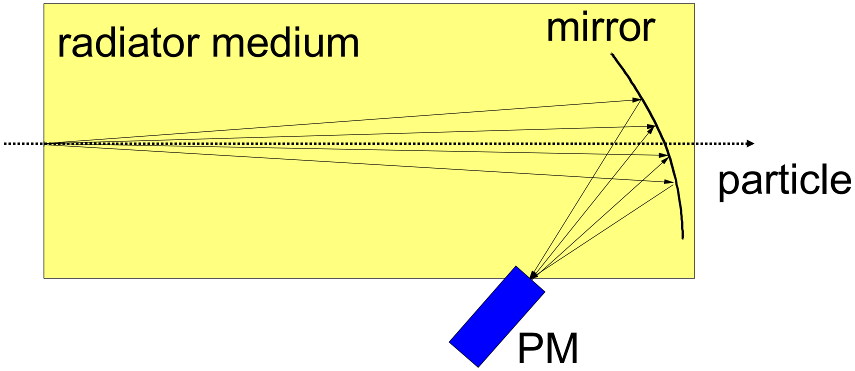
Momentum measurement + velocity threshold -> **particle mass identification** (at fixed momentum **p=m×v** particle with larger mass will have lower velocity and may be below threshold for production of Cherenkov light)

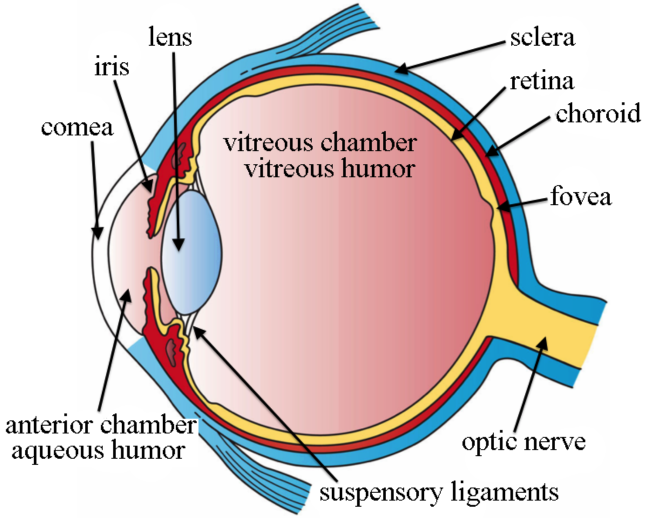
Angle + momentum measurement: $\cos\theta_c = 1/(n\beta)$ -> **mass**

ring



threshold

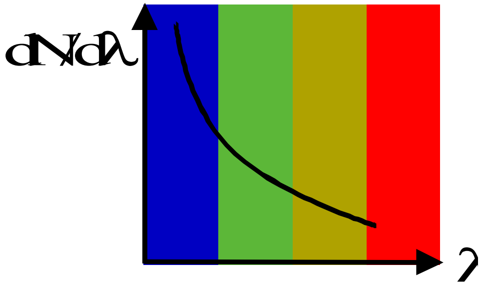




Number of emitted Cherenkov photons per unit path length and unit wavelength interval (emission spectrum)

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2\alpha}{\lambda^2}\sin^2\theta_C$$

$$\frac{d^2N}{dx\,d\lambda} \propto \frac{1}{\lambda^2} \quad \text{with} \quad \lambda = \frac{c}{\nu} = \frac{hc}{E} \qquad \frac{d^2N}{dx\,dE} = const.$$



Most at short wavelength – deep UV

Number of photons detected

$$N_{p.e.} = L\sin^2\theta\,\frac{\alpha}{\hbar c}\int_{E_1}^{E_2}\underbrace{\varepsilon_Q(E)}_{\text{Photo detector sensitivity}}\underbrace{\prod_i \varepsilon_i(E)\,dE}_{\text{Emission spectrum}}$$

Use wavelength shifters !