The Physics of Particle Detectors

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Summer Term 2017
Ruprecht-Karls-University, Heidelberg

Scintillation Detectors

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Scintillation detectors in general

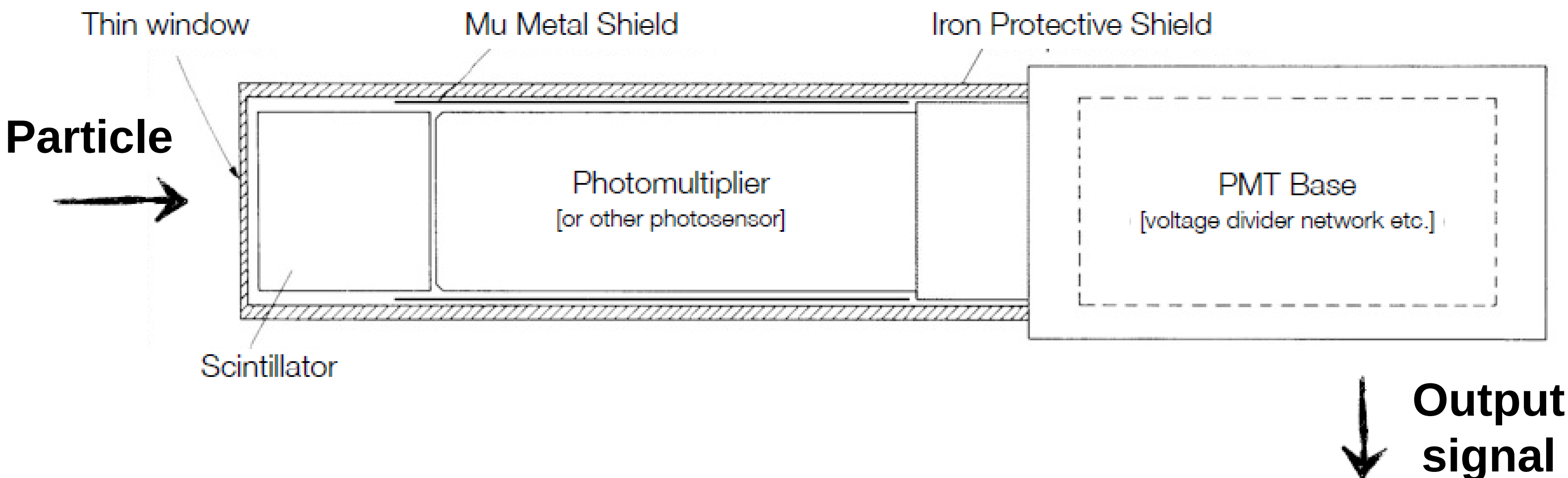
- principle of scintillation detector
  - dE/dx converted into visible light
  - detection via photo sensor (photomultiplier, human eye)
- detect radiation via scintillation
  - one of the oldest methods of particle detection
  - example: particle hits ZnS screen → flash of light
- main features
  - sensitivity to energy deposit
  - fast time response
  - pulse shape discrimination → PID

Scintillation detectors in general

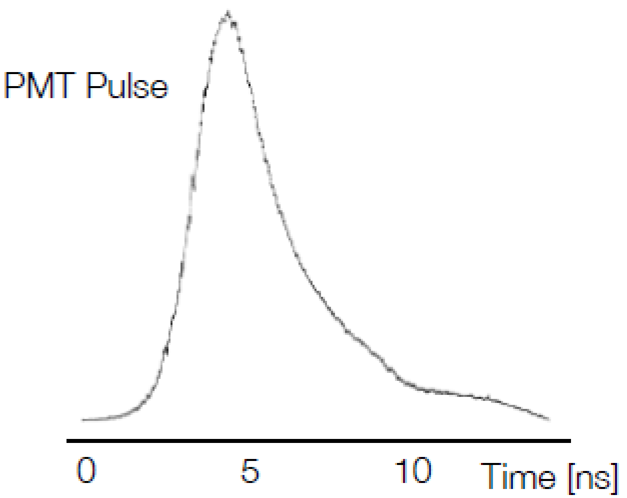
- requirements
  - high efficiency for conversion of deposited energy to fluorescent radiation
  - transparency to its fluorescent radiation to allow the transmission of light
  - emission of light in a spectral range detectable for photosensors
  - short decay time to allow fast response
- scintillating materials
  - inorganic crystals
  - organic crystals
  - polymers (plastic scintillators)

TAPS BaF_2 crystals

Basic Detector Setup



- topics
  - scintillators
  - propagation of light
  - photon detection
  - applications

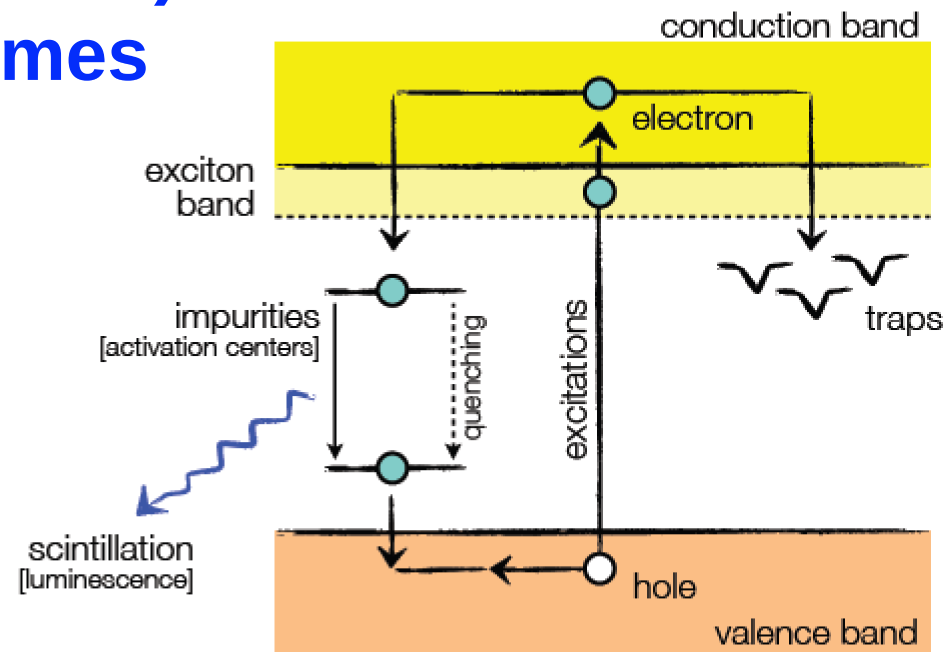


Inorganic crystals

- $PbWO_4$ crystals from the CMS electromagnetic calorimeter

Inorganic crystals

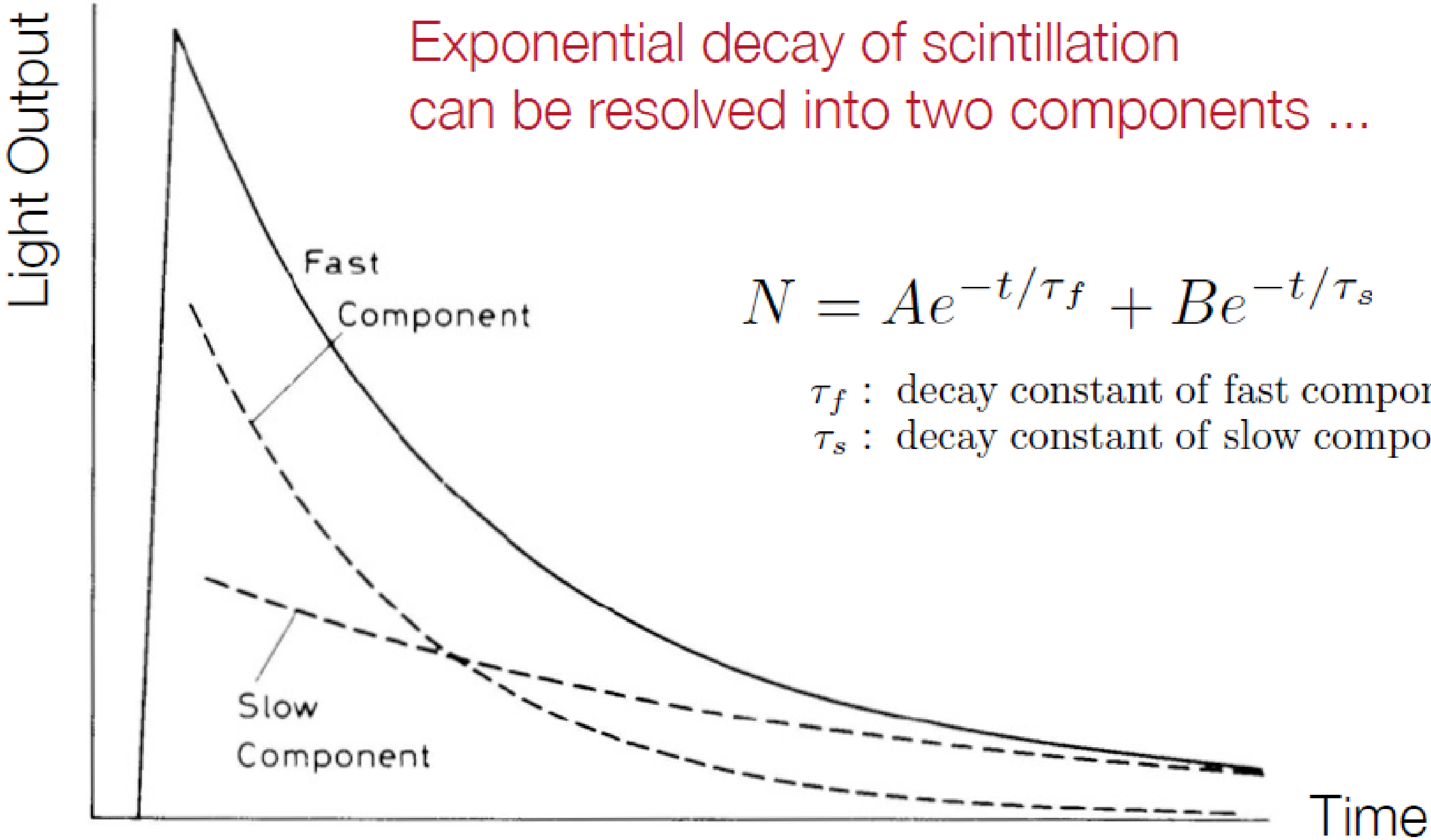
- crystals (electric insulators) with impurities (sometimes introduced via doping, e.g. NaI(Tl))
  - sodium iodide (NaI)
  - cesium iodide (CsI)
  - barium fluoride (BaF_2)
  - lead tungstate ($PbWO_4$)
- working principle
  - energy deposit via ionization
    → promote electrons into higher bands
  - energy transfer to impurities
  - emission of scinillation photons



Energy bands in impurity activated crystal
showing excitation, luminescence, quenching and trapping

Inorganic crystals: time constants

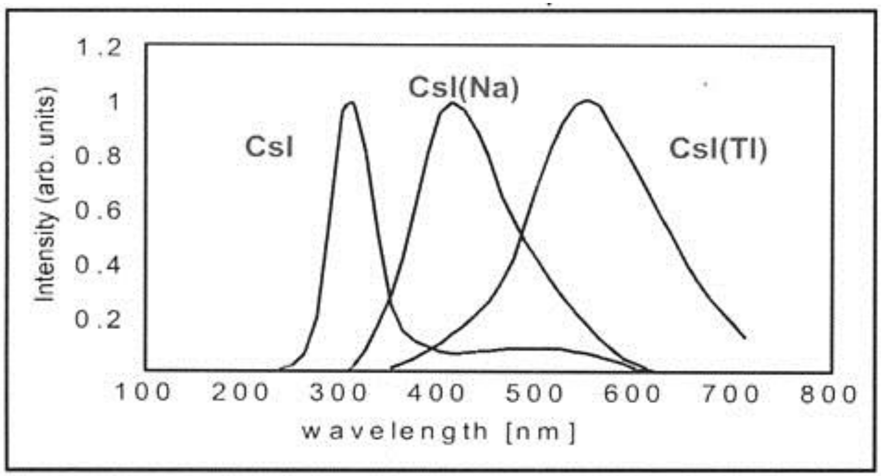
- time constants
  - fast: recombination from activation centers [ns - μs]
  - slow: recombination from traps [ms – s]

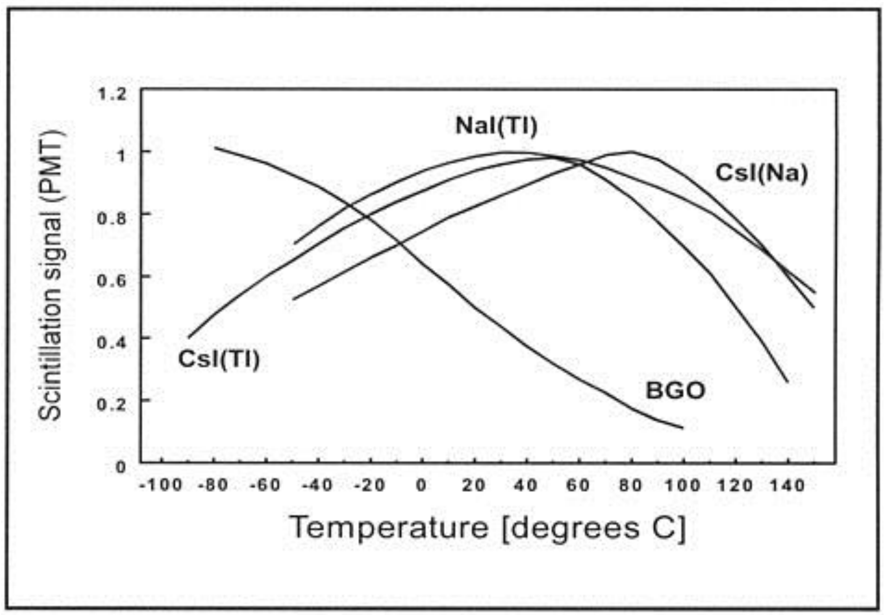


$$N = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$$

τ_f : decay constant of fast component
τ_s : decay constant of slow component

Inorganic crystals: light output

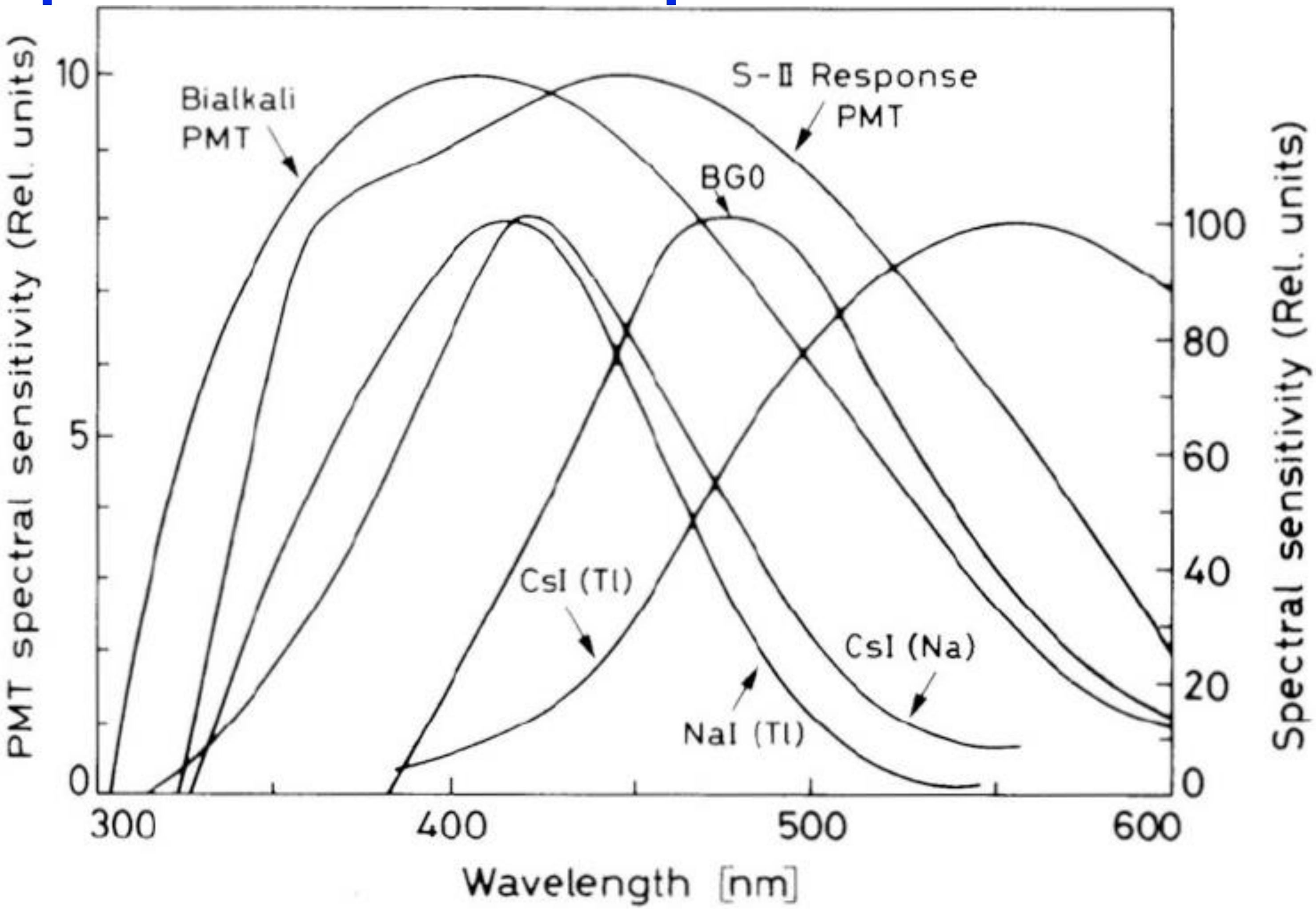




- **scintillation spectra of undoped and doped CsI crystals**
- **strong temperature dependence of light output (in contrast to organic scintillators)**

Light output & PMT sensitivity

- **spectral sensitivities of PMTs compared to emission spectra**

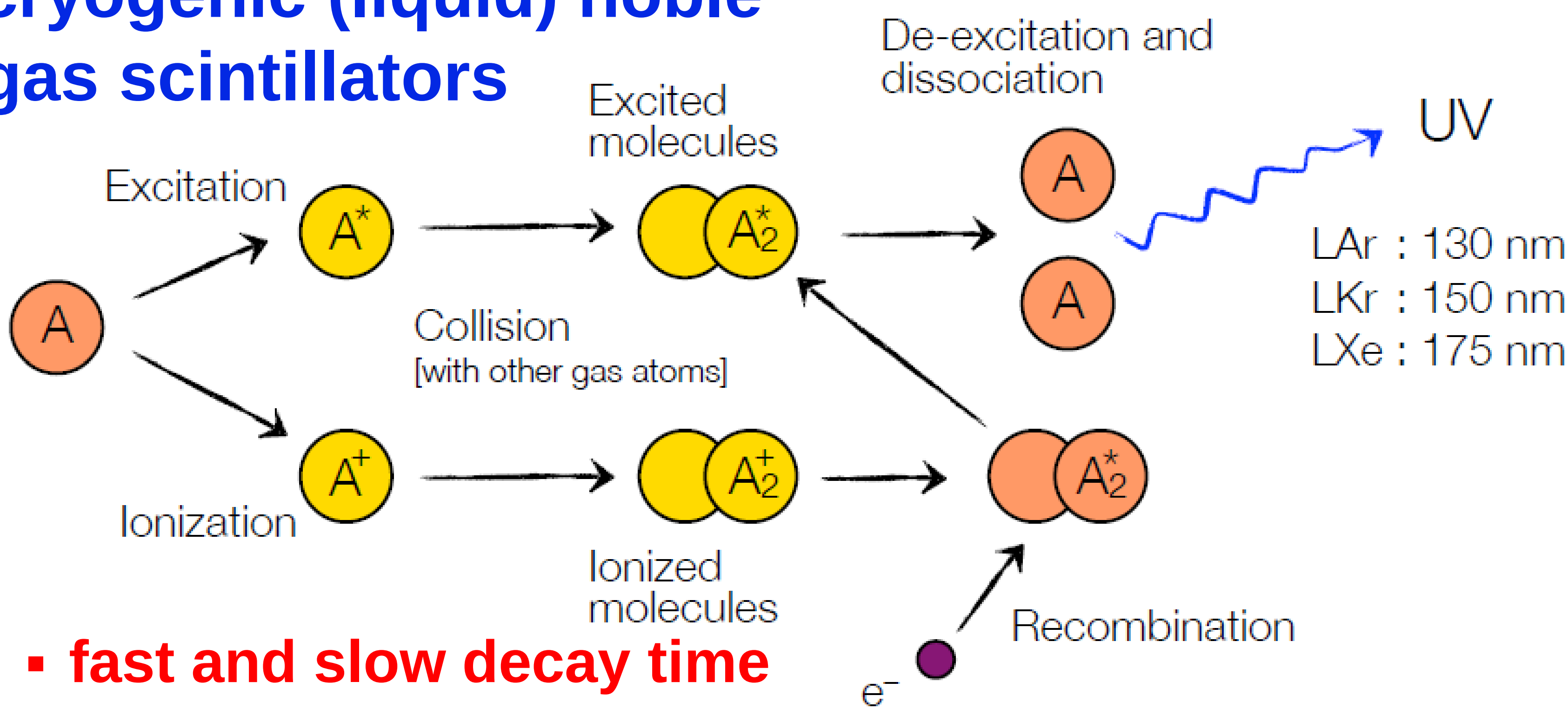


Scintillation in (noble) gases

- **many gases exhibit some degree of scintillation**
  - **response to 4.7 MeV α particles**
  - **careful in Cherenkov detectors!**

	λ_{max} [nm]	$\gamma/4.7MeV$
N_2	390	800
He	390	1100
Ar	250	1100

- **cryogenic (liquid) noble gas scintillators**



  - **fast and slow decay time constants → PID**

Inorganic scintillator properties

Scintillator material	Density [g/cm³]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29*	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60*	150	0.003/0.02	$4 \cdot 10^4$

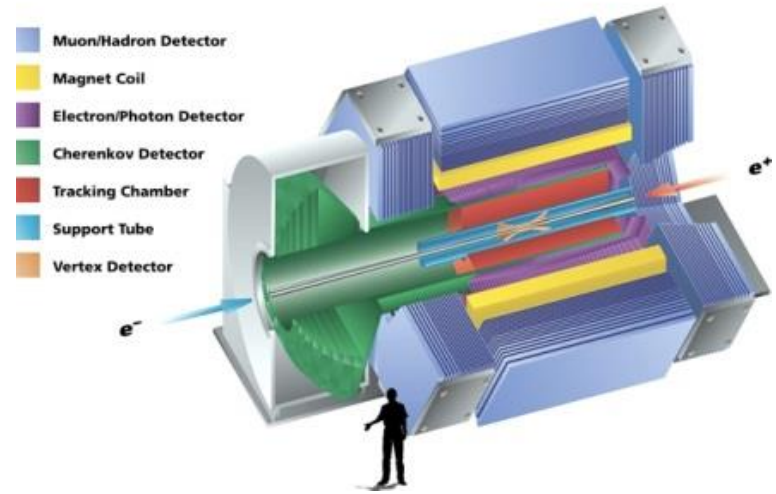
* at 170 nm

Inorganic scintillator properties

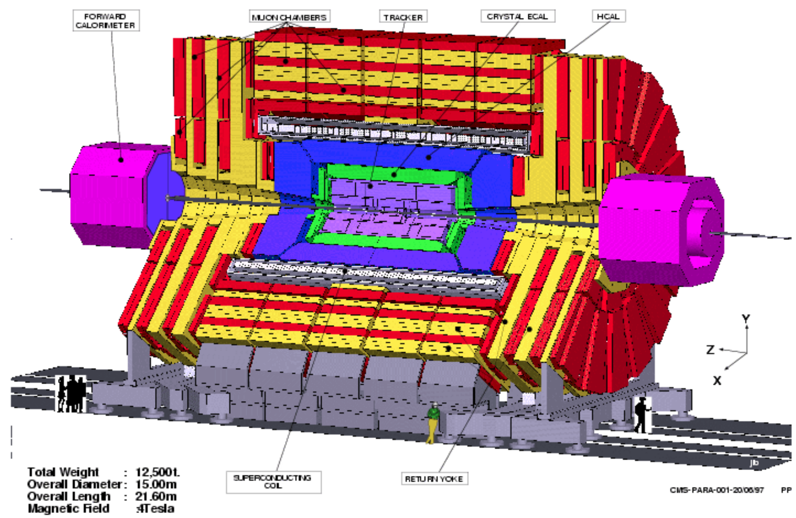
- a numerical example
  - NaI(Tl): λ_{max} = 410 nm; hν = 3 eV
    photons/MeV = 40000
    τ = 250 ns
  - $PbWO_4$: λ_{max} = 420 nm; hν = 3 eV
    photons/MeV = 200
    τ = 6 ns
- light yield ε_{SC}: fraction of energy loss going into photons
  - NaI(Tl): 40000 photons; 3 eV/photon → $\varepsilon_{sc} = 4 \cdot 10^4 \cdot 3\ \text{eV}/10^6\ \text{eV} = 11.3\%$
  - $PbWO_4$: 200 photons; 3 eV/photon → $\varepsilon_{sc} = 2 \cdot 10^2 \cdot 3\ \text{eV}/10^6\ \text{eV} = 0.06\%$

Application in large experiments

- **BaBar at SLAC**
  - **6580 CsI(Tl) crystals**
  - **depth: 17 X_0**
  - **volume: 5.9 m^3**
  - **read-out: Si-photodiode (gain = 1)**
  - **read-out noise: 0.15 MeV**
  - **dynamic range: 10^4**



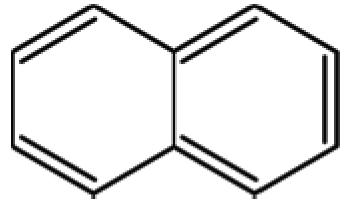
- **CMS at LHC**
  - **76150 $PbWO_4$ crystals**
  - **depth: 26 X_0**
  - **volume: 11 m^3**
  - **read-out: APD (gain = 50)**
  - **read-out noise: 30 MeV**
  - **dynamic range: 10^5**



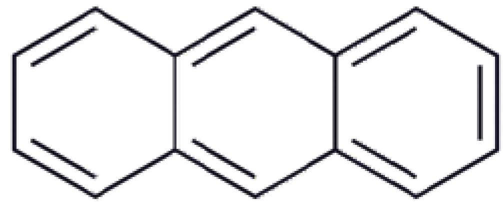
Organic scintillators

- **aromatic hydrocarbon compounds**
  - **naphtalene: $C_{10}H_8$**
  - **antracene: $C_{14}H_{10}$**

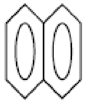
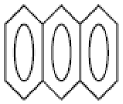
Naphtalene

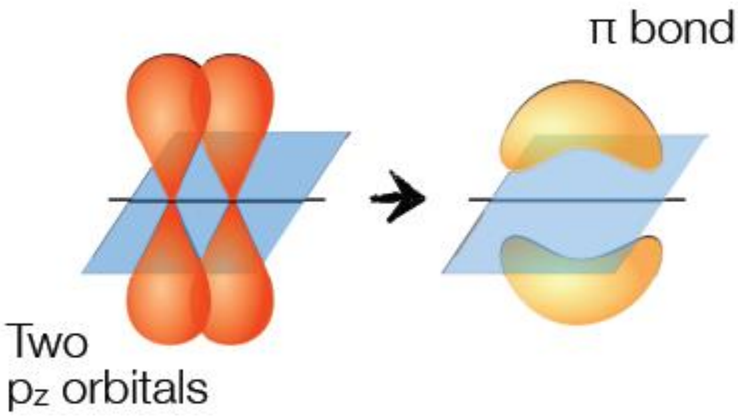


Antracene



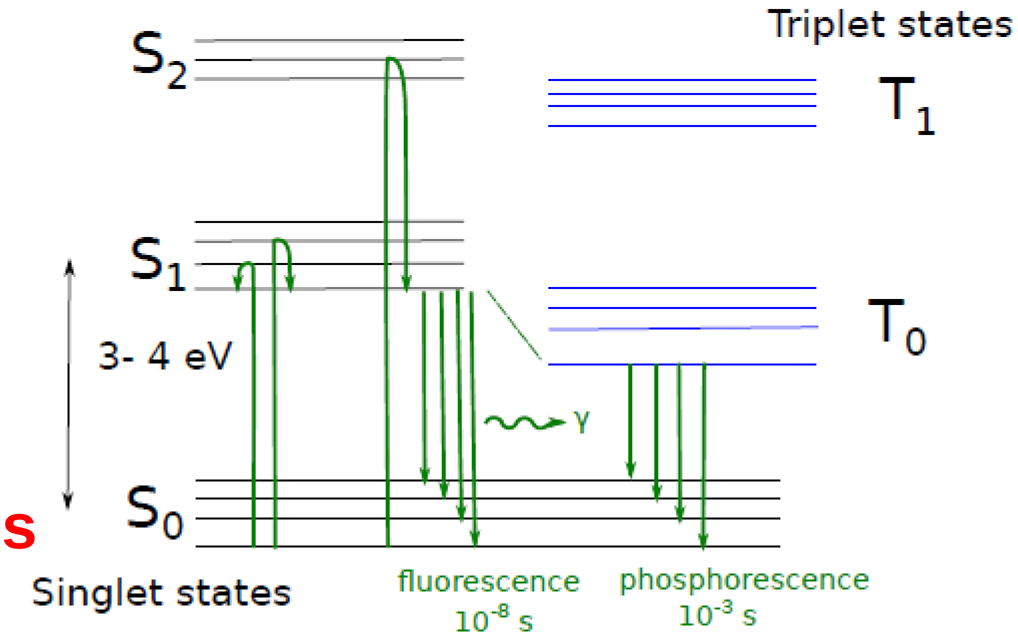
- **scintillation**
  - **based on electrons of the C=C bond**
  - **light arises from delocalized electrons in π orbitals**
  - **transitions of ‘free’ electrons**

		$\lambda_{max} [nm]$	$\tau [ns]$	light yield rel. to NaI
naphtalene		348	96	12%
anthracene		440	30	50%



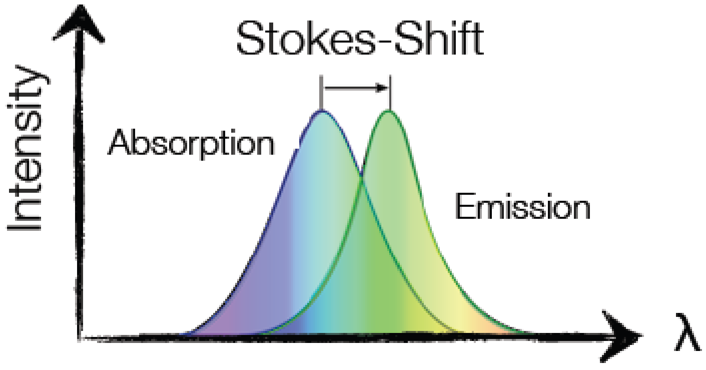
Organic scintillators

- principle of operation of organic scintillators
  - valence electrons pair wise in π states
  - molecular level scheme
    - singlet states
    - triplet states
  - energy absorption → excitation of π electrons
  - fluorescence: $S_1 \rightarrow S_0$ (in UV range → wavelength shifters!)
  - ionization followed by recombination populates T states
  - phosphorescence: $T \rightarrow S_0$
  - excitation of δ electrons → thermal deexcitation
  - other ionization → radiation damage!

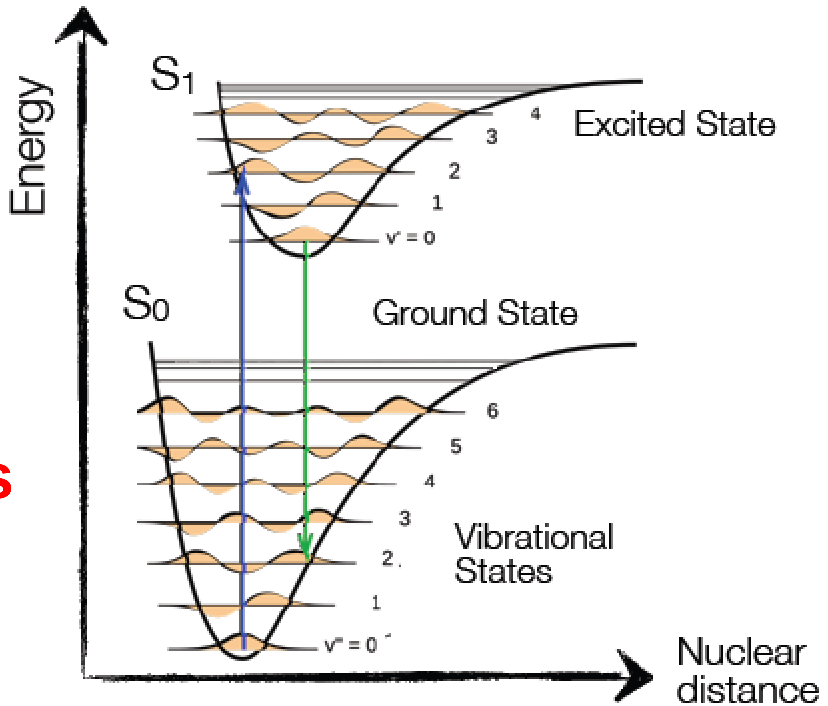


Organic scintillators

- **material should be transparent for radiation → shift of emission and absorption spectra**

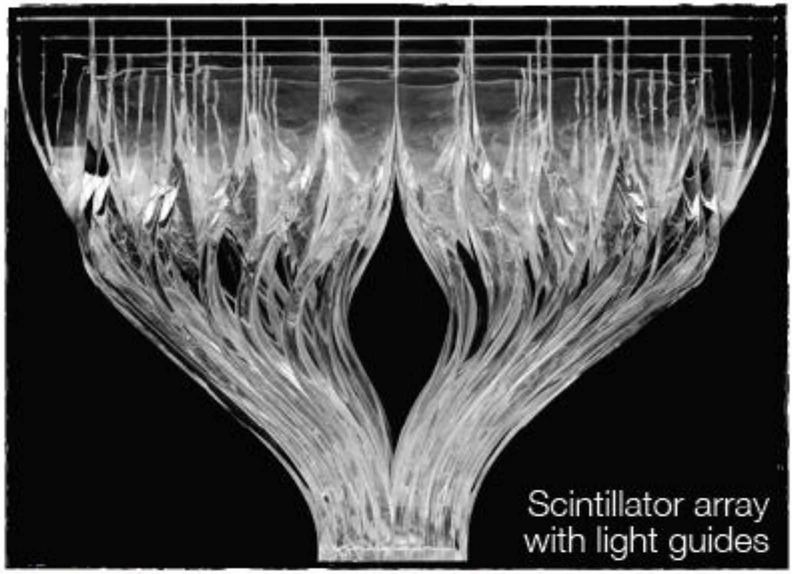


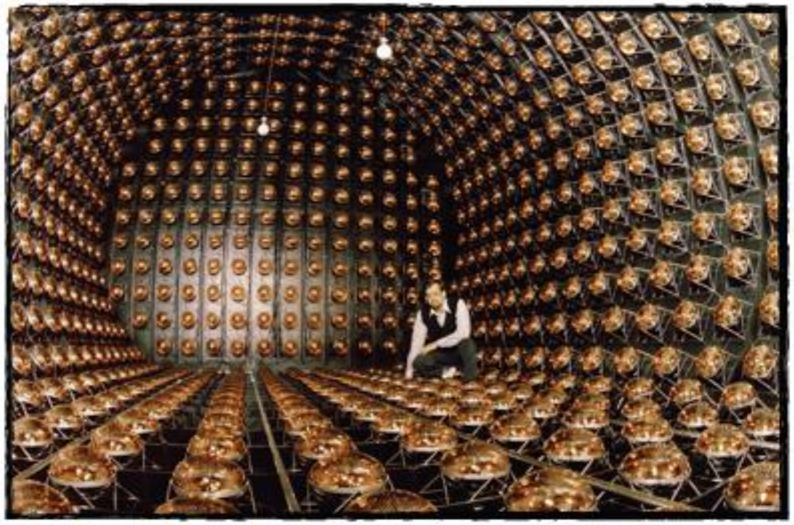
- **Stokes shift due to Franck-Condon principle**
  - **excitation into higher vibrational states on a time scale of 10^{-14} s**
  - **vibrational time scale: 10^{-12} s**
  - **deexcitation from lowest vibrational state (S_1 lifetime: 10^{-8} s)**



Plastic or liquid scintillators

- **organic scintillator material in practice**
  - **solution of organic scintillators (solved in plastic or liquid)**
  - **+ large concentration of primary ‘fluor’**
  - **+ smaller concentration of secondary ‘fluor’ (wavelength shifter)**





LSND experiment

Plastic or liquid scintillators

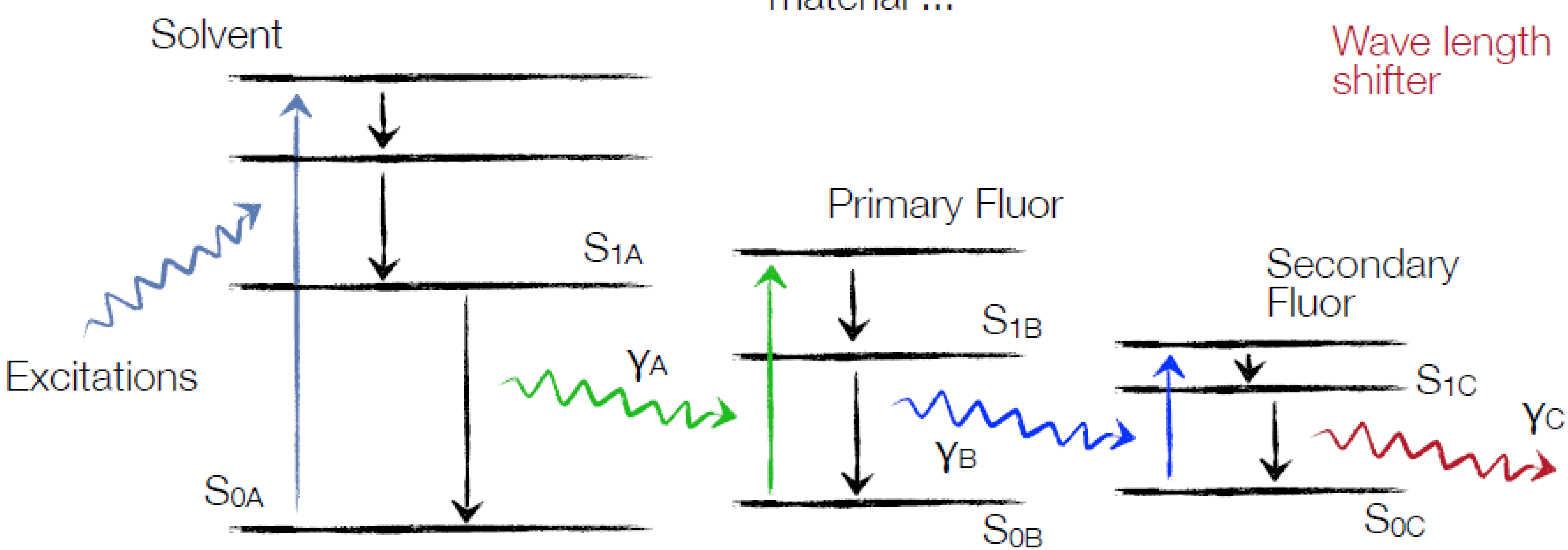
A

Energy deposit in base material → excitation

Primary fluorescent B
- Good light yield ...
- Absorption spectrum matched to excited states in base material ...

Secondary fluorescent C

Wave length shifter

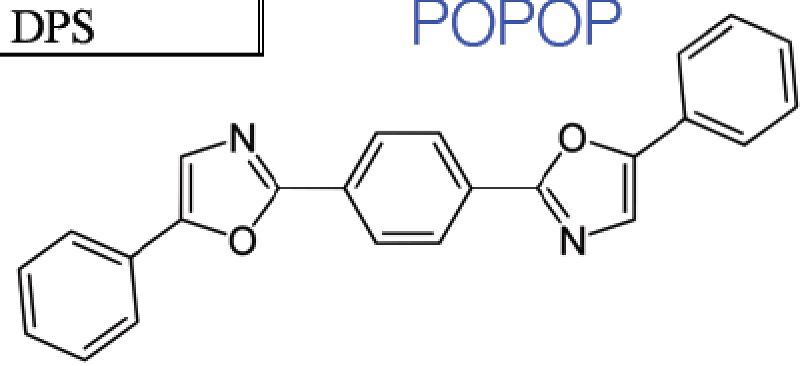


Plastic or liquid scintillators

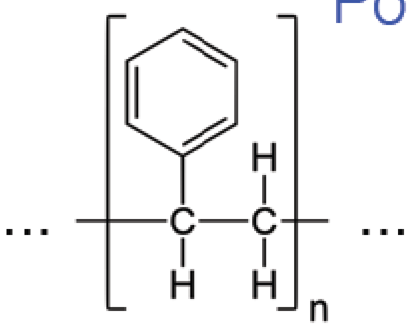
Some widely used solvents and solutes

	solvent	secondary fluor	tertiary fluor
Liquid scintillators	Benzene Toluene Xylene	p-terphenyl DPO PBD	POPOP BBO BPO
Plastic scintillators	Polyvinylbenzene Polyvinyltoluene Polystyrene	p-terphenyl DPO PBD	POPOP TBP BBO DPS

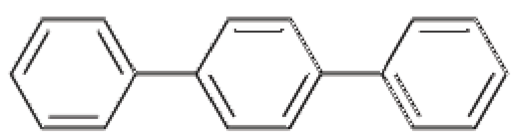
POPOP



Polystyrene

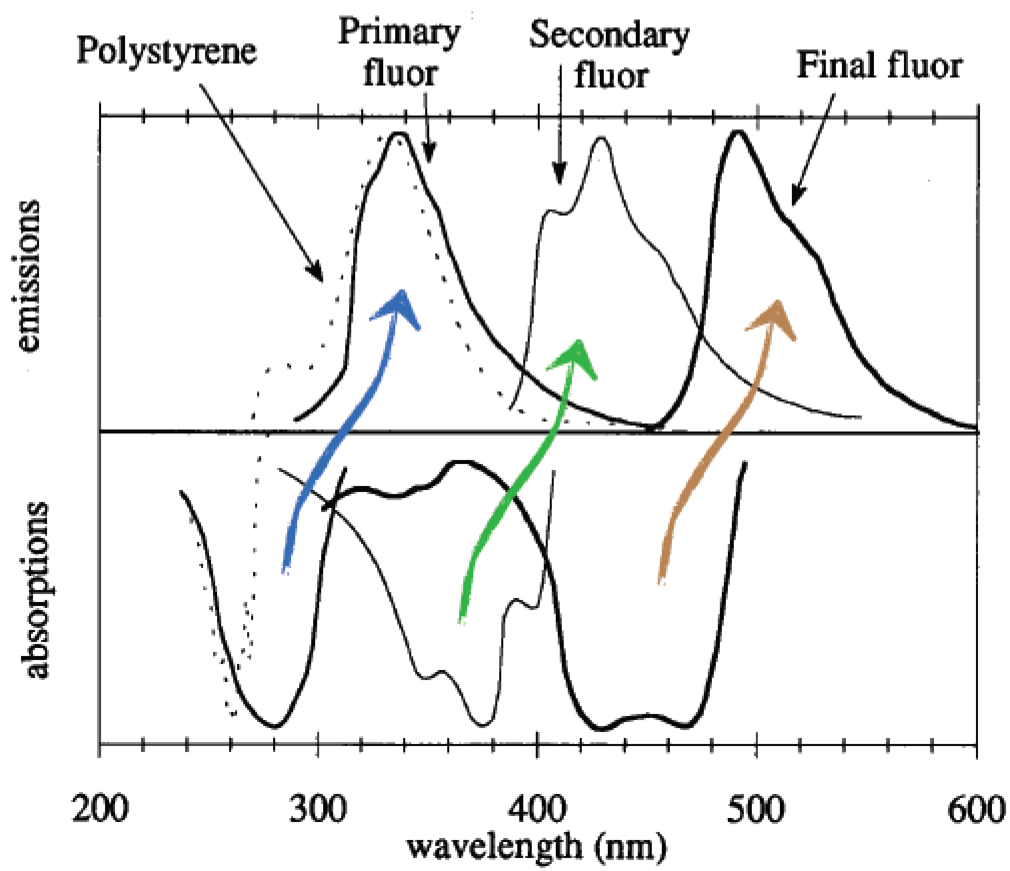


p-Terphenyl



Wavelength shifting

- working principle
  - absorption of primary scintillation light
  - re-emission at longer wavelength
- adapts light to spectral sensitivity of photo sensor
- requirement: good transparency for emitted light



Organic scintillator properties

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Organic scintillator properties

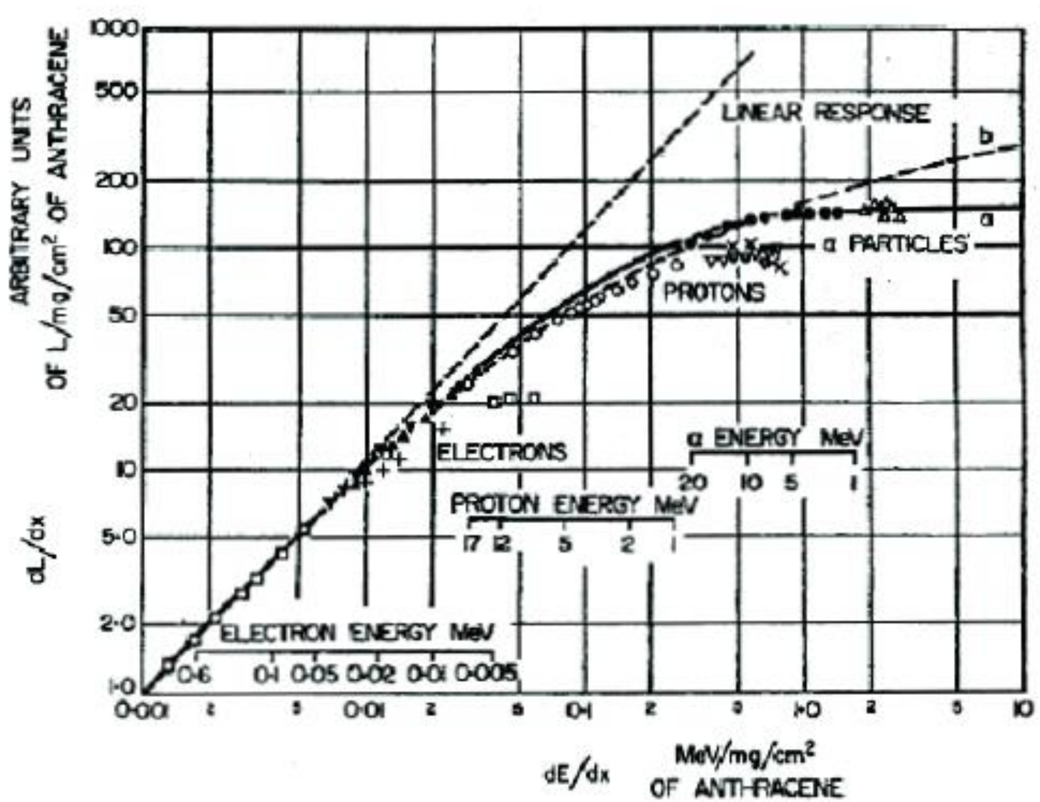
- **light yield**
  - **without quenching**

$$\frac{dL}{dx} = L_0 \frac{dE}{dx}$$

  - **with quenching (non-linear response due to saturation of available states): Birk's law**

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

  - **where kB is a parameter that needs to be measured**



Scintillators: comparison

Inorganic Scintillators

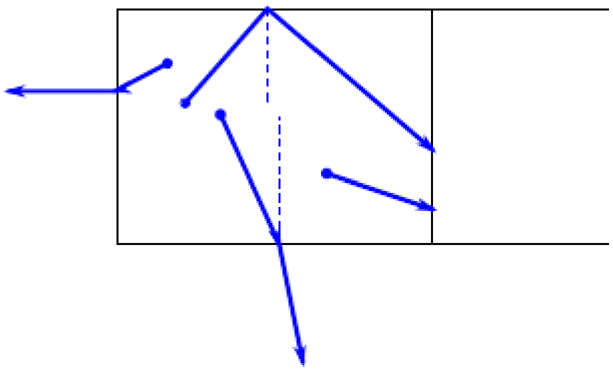
Advantages	high light yield [typical; $\varepsilon_{sc} \approx 0.13$] high density [e.g. $PBWO_4$: 8.3 g/cm^3] good energy resolution	
Disadvantages	complicated crystal growth large temperature dependence	Expensive

Organic Scintillators

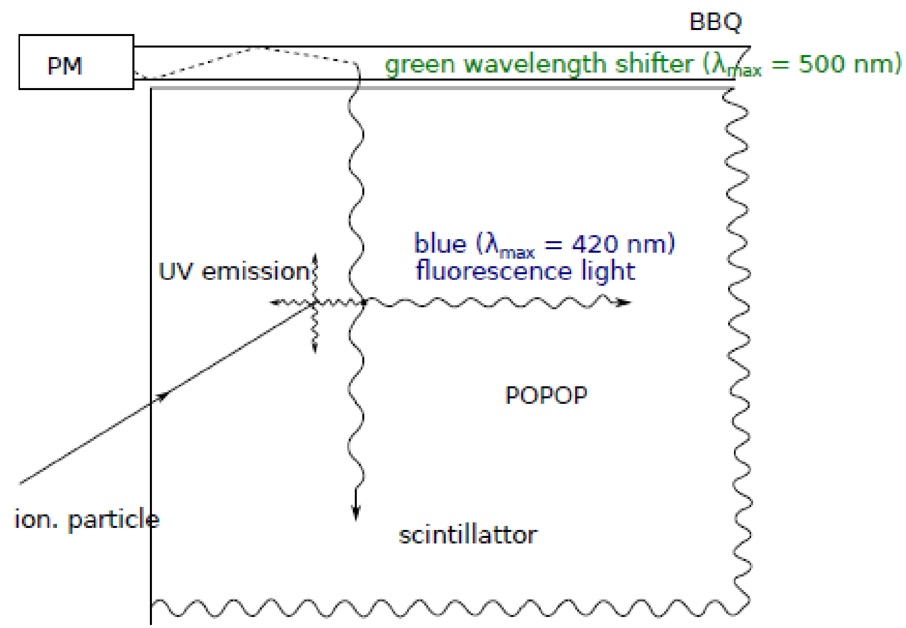
Advantages	very fast easily shaped small temperature dependence pulse shape discrimination possible	
Disadvantages	lower light yield [typical; $\varepsilon_{sc} \approx 0.03$] radiation damage	Cheap

Propagation of light

- in the scintillator itself
  - absorption $N_\gamma = N_0 \exp\left(-\frac{x}{L}\right)$ with L : absorption length
  - reflection at the edge, total reflection for $\theta > \theta_B = \sin^{-1}(n_e/n_s)$
    typical scintillator: $n_s \sim 1.4$, $\theta_B \sim 45^o$



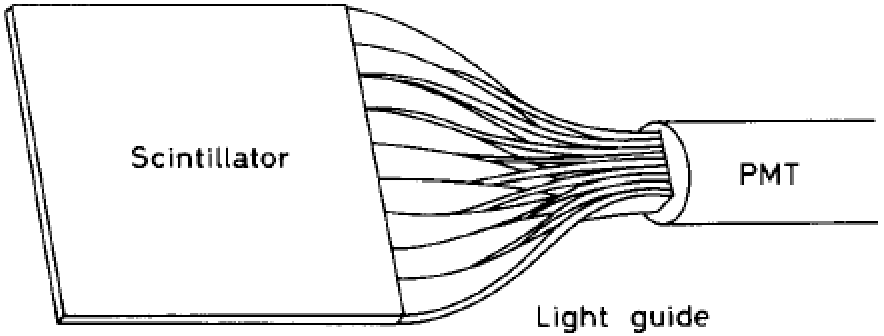
- careful shaping needed in order not to lose too much light



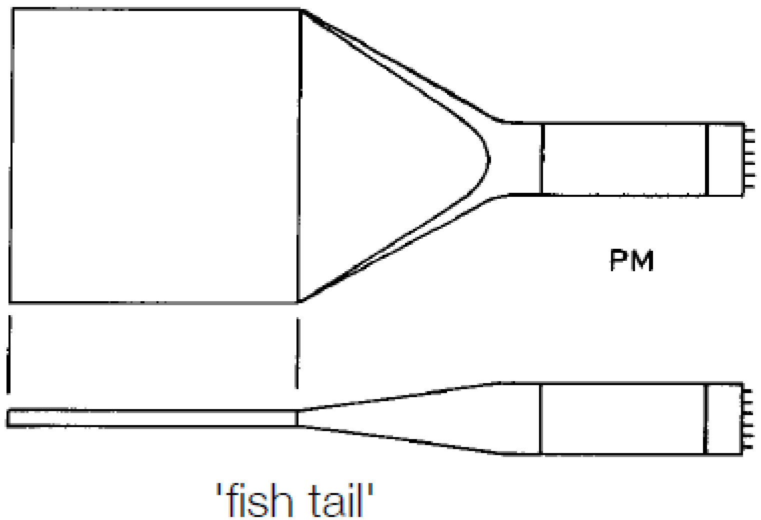
- alternative: light collection via 2nd wavelength shifter along the edge of the scintillator

Light guides

- scintillator light to be guided to the photo sensor
  - light guide (plexiglas, optical fibers)
  - light transfer by total internal reflection (maybe wavelength shifter in addition)



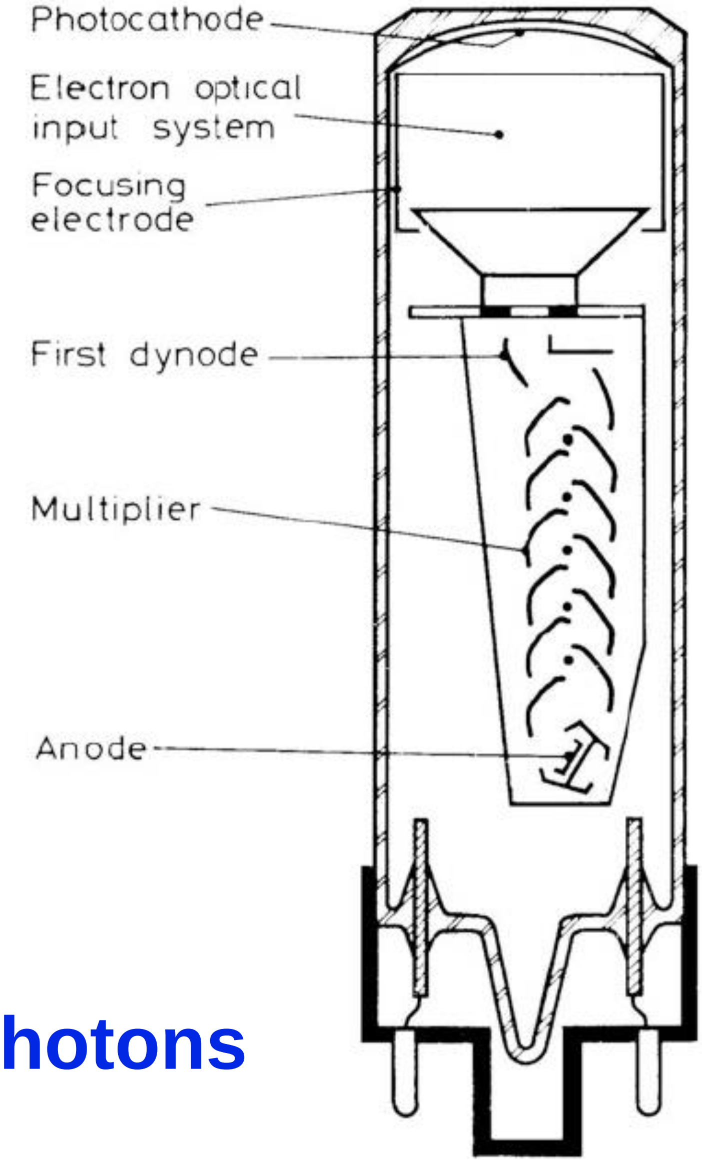
- Liouville's theorem
  - $\Delta x\ \Delta\theta_x$ = const. → keep area constant since divergence is constant when guiding light
  - use small curvatures to maintain total reflection for photons captured once → adiabatic light guides (e.g. 'fish tail')



Photon detection

- goal: convert light into detectable electronic signal
- principle: use photo-electric effect to convert photons into photo-electrons (p.e.)
- what is needed?
  - high photon detection efficiency (PDE) or
  - quantum efficiency: $QE = N_{p.e.}/N_{photons}$
- (some) available devices
  - photomultipliers (PMT)
  - silicon photomultipliers (SiPM)
  - micro channel plates (MCP)
  - photo diodes (PD)
  - ....

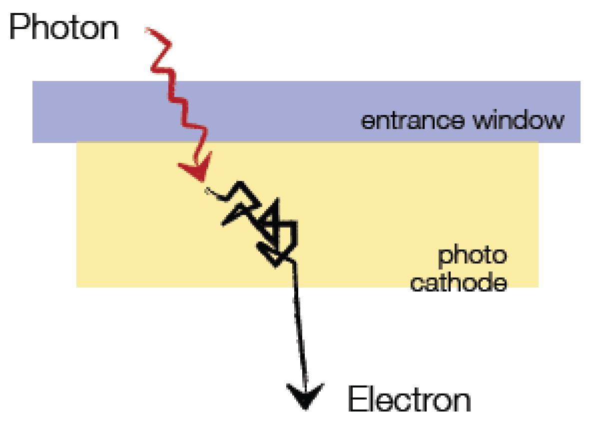
Photomultipliers (PMT)



- **principle:**
  - **electron emission from photo cathode**
  - **secondary emission from dynodes (gain: 3-50)**
- **typical PMT gain: > 10^6**
  → PMTs can count single photons

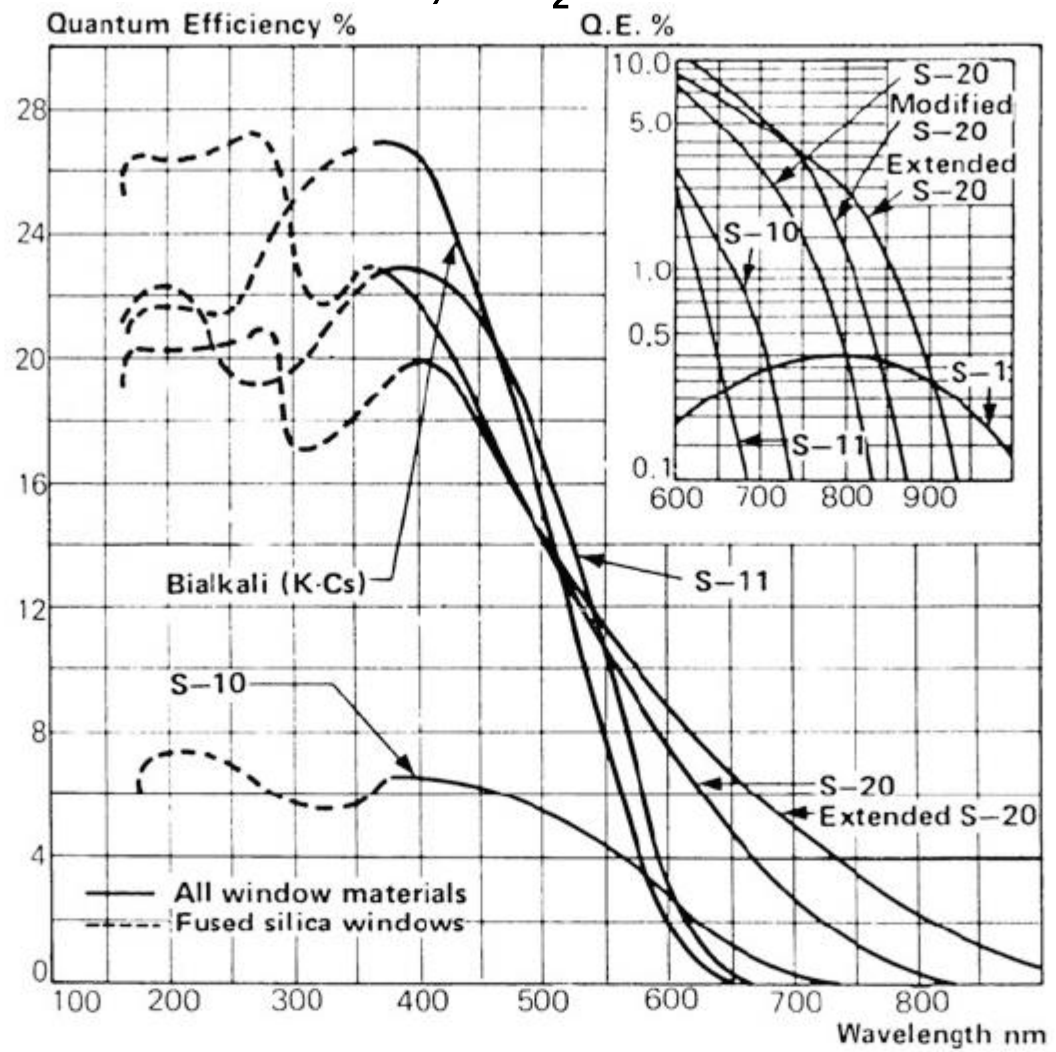
PMTs: photocathode

- γ conversion via photo effect



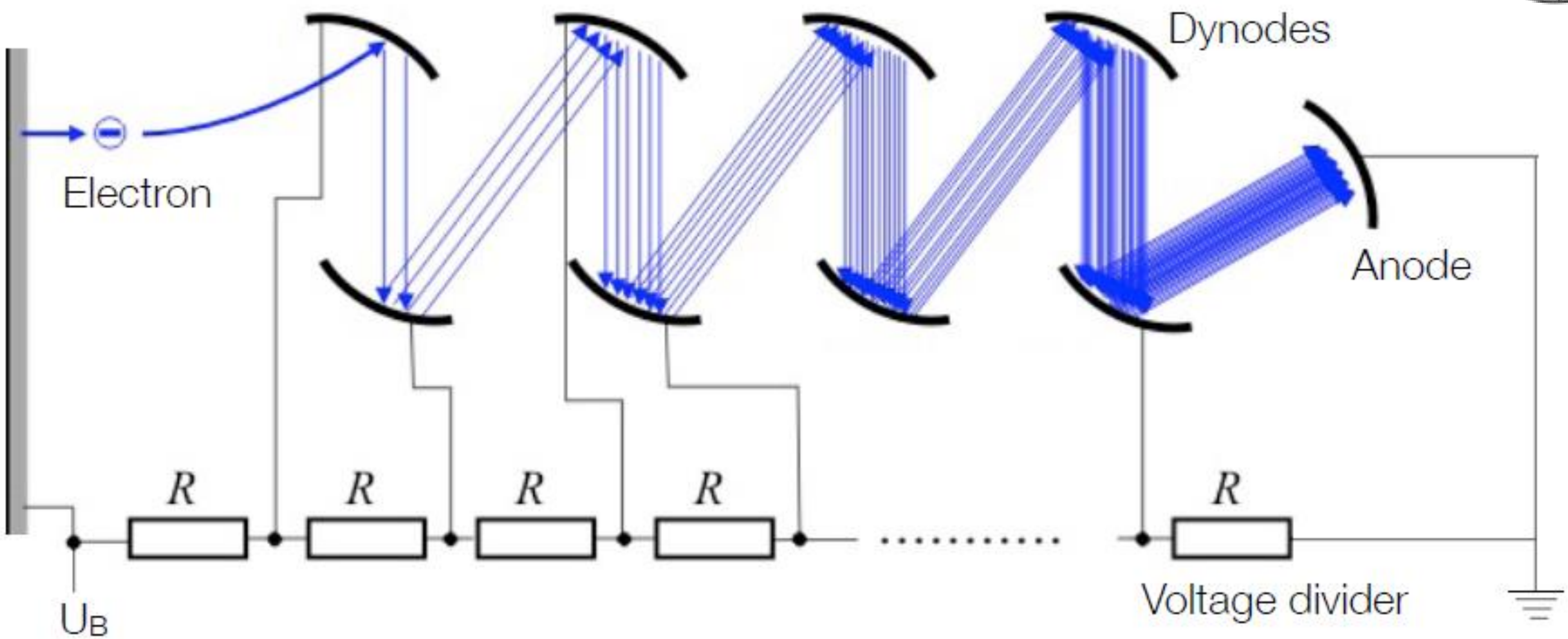
  - **3-step process**
    - electron generation via ionization
    - propagation through cathode
    - escape of electron into vacuum

Bialkali: SbRbCs, SbK_2Cs



- Q.E. ~10-30% (with specifically developed alloys)

PMTs: dynode chain



- **multiplication process**
  - **e^- accelerated towards dynode**
  - **further e^- produced → avalanche**
- **secondary emission coeff.**
  $\delta = \#(e^-_{produced}) / \#(e^-_{incoming})$
- **typical values**
  - **δ = 2-10; n = 8-15**
    → gain $G = \delta^n = 10^6 - 10^8$
- **gain fluctuations**
  - **$\delta = kU_D$; $G = a_0(kU_D)^n$**
    $dG/G = n\, dU_D/U_D = n\, dU_B/U_B$

PMTs: energy resolution

- energy resolution is influenced by
  - linearity of PMT: high dynode currents can lead to saturation by space charge effects; $I_A \propto n_\gamma$ possible over 3 orders of magnitude
  - photo electron statistics as given by Poisson statistics:

$$P_n(n_e) = \frac{n_e^n \, e^{-n_e}}{n!}$$

$$\sigma_n / \langle n \rangle = 1/\sqrt{n_e}$$

with n_e given by dE/dx ...

$$n_e = \frac{dE}{dx} \times \frac{\text{Photons}}{\text{MeV}} \times \eta \times \text{Q.E.}$$

For NaI(Tl) and 10 MeV photon;
photons/MeV = 40000;
η = 0.2; Q.E. =0.25

$$n_e = 20000$$

$$\sigma_n / \langle n \rangle = 0.7\%$$

  - secondary electron fluctuations:

$$P_n(\delta) = \frac{\delta^n \, e^{-\delta}}{n!}$$

$$\sigma_n / \langle n \rangle = 1/\sqrt{\delta}$$

with dynode gain δ;
and with N dynodes ...

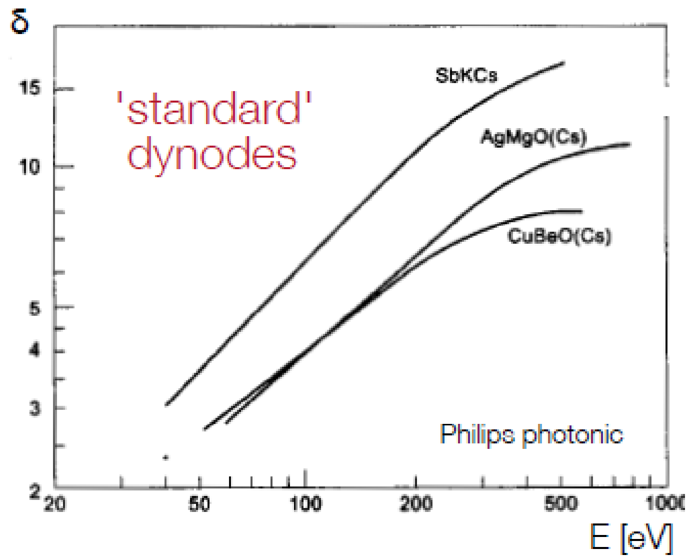
σ_n/<n> dominated by first dynode stage ...

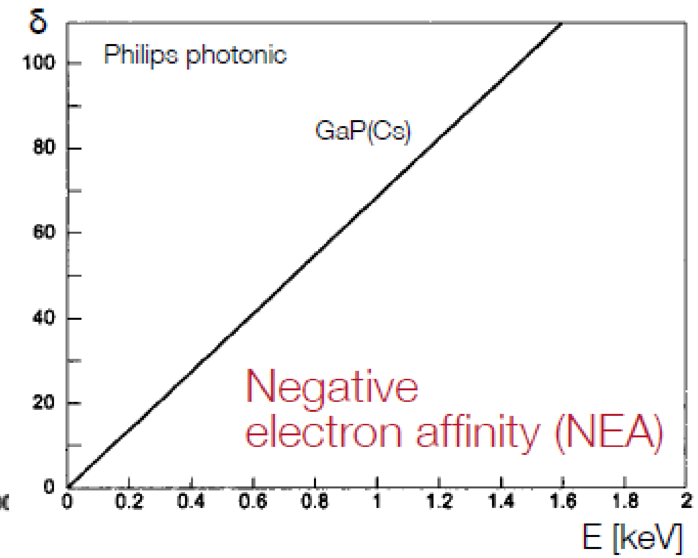
$$\left(\frac{\sigma_n}{\langle n \rangle}\right)^2 = \frac{1}{\delta} + \ldots + \frac{1}{\delta^N} \approx \frac{1}{\delta - 1}$$

... important for single photon detection

PMTs: energy resolution

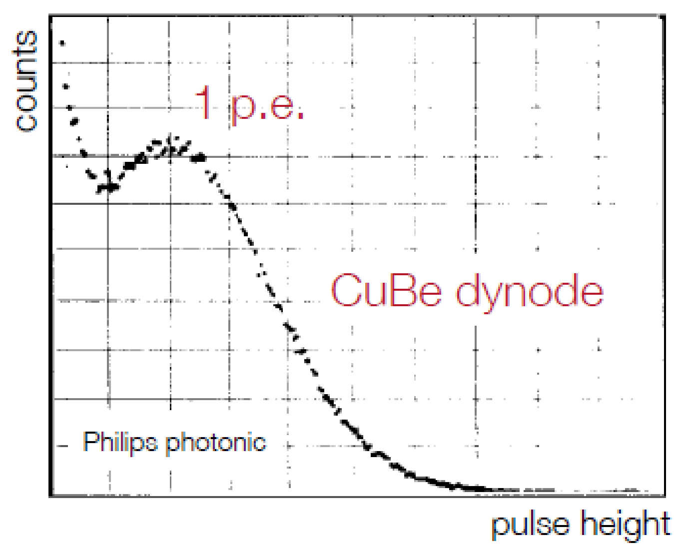
For detection of single photons

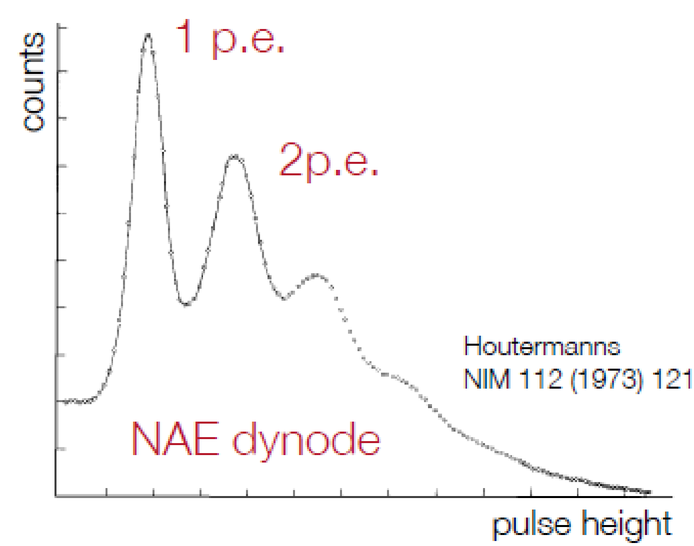




Large δ !

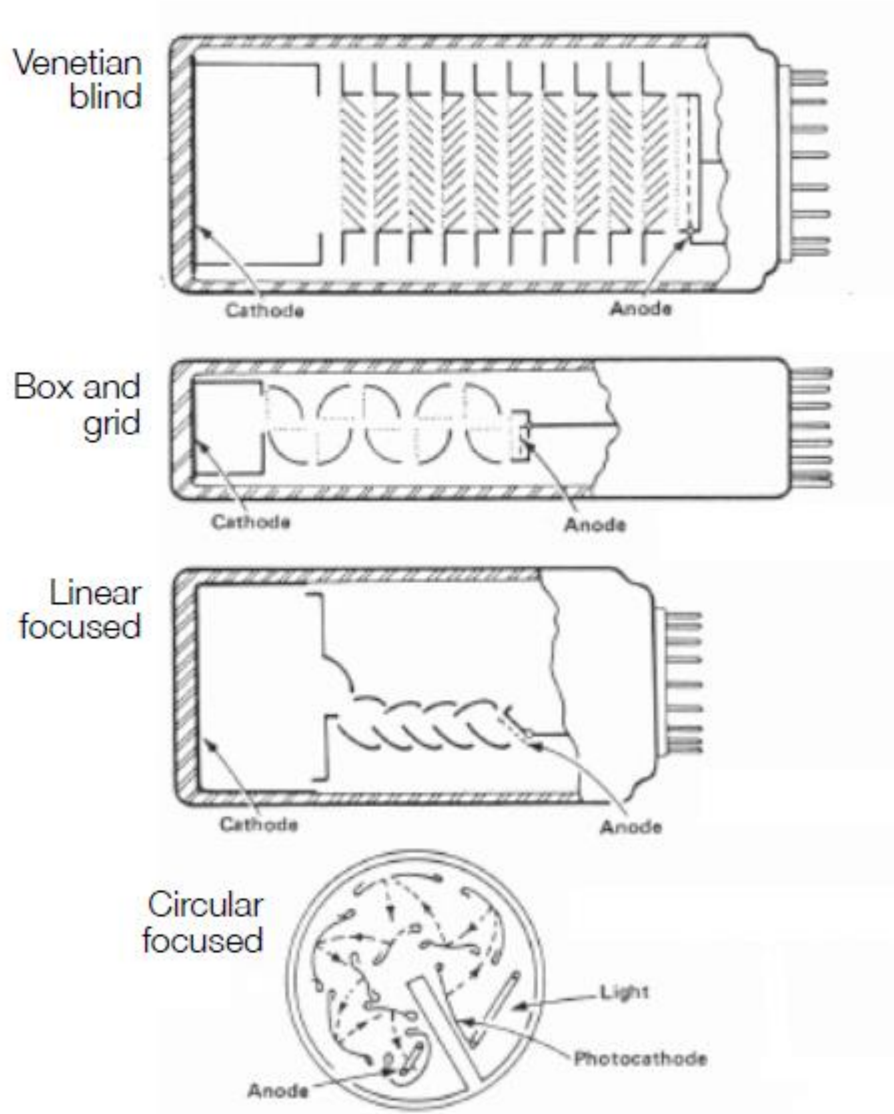
... yields better energy resolution





PMTs: dynode chain

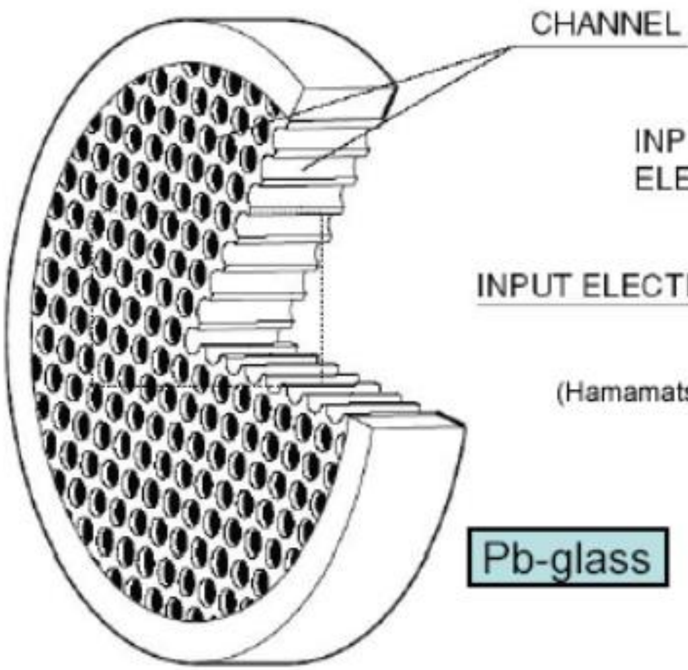
- **optimization of**
  - **PMT gain**
  - **anode isolation**
  - **linearity**
  - **transit time**
- **PMTs in general very sensitive to magnetic fields**
  - **shielding is even required for earth field (30-60 μT)**

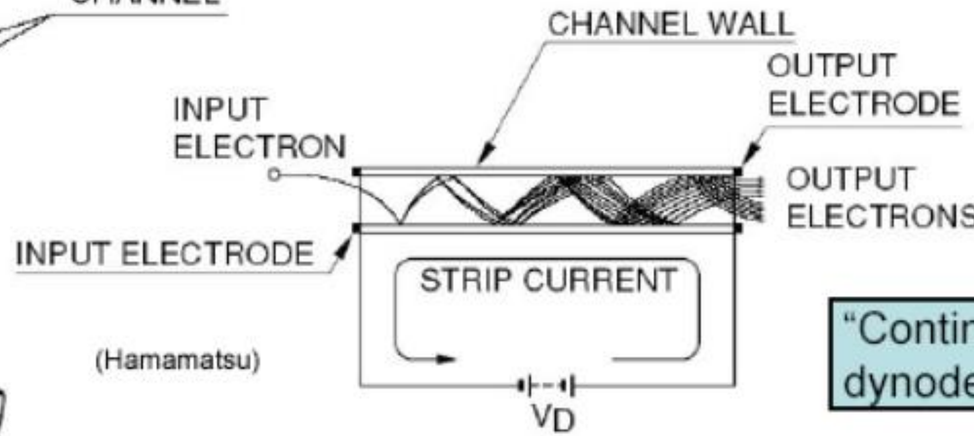


PMT in magnetic field

- **B field disturbs focusing of photo electrons and secondary electrons (typical kinetic energies ≤ 200 eV)**
- **requirement in region of dynodes: B ≤ 10^{-4} T**
- **typical effect: current decreases by factor 2 if B field increases from 0 to 0.15 x 10^{-4} T**
- **possible solutions**
  - **shield small field by so-called μ-metal**
  - **use of ‘mesh type’ dynodes**
  - **use of micro channel plate or photo diodes**

Micro Channel Plate

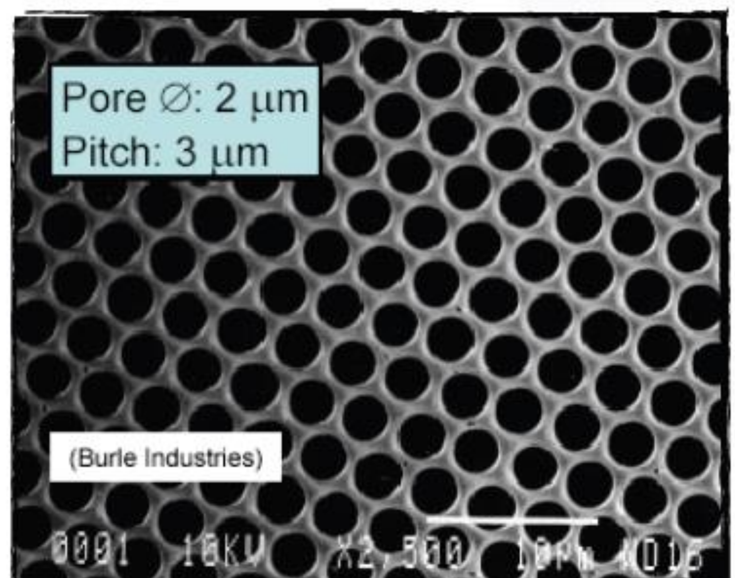




(Hamamatsu)

Pb-glass

"Continuous" dynode chain



"2D Photomultiplier"

Gain: $5 \cdot 10^4$

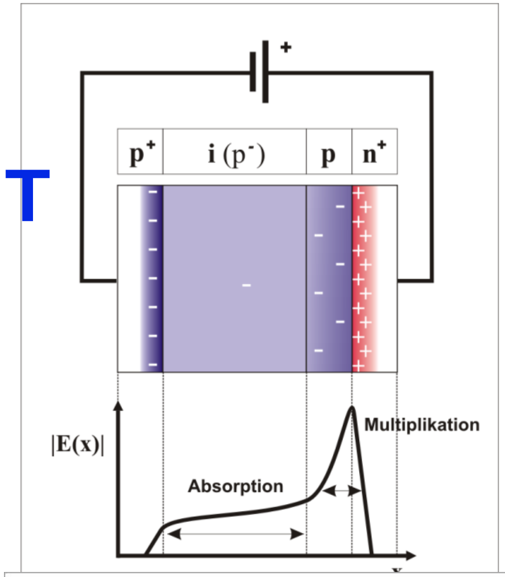
Fast signal [time spread ~ 50 ps]

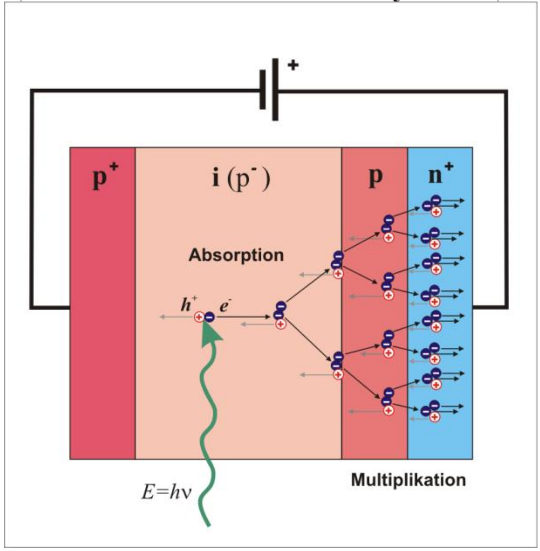
B-Field tolerant [up to 0.1T]

But: limited life time/rate capability

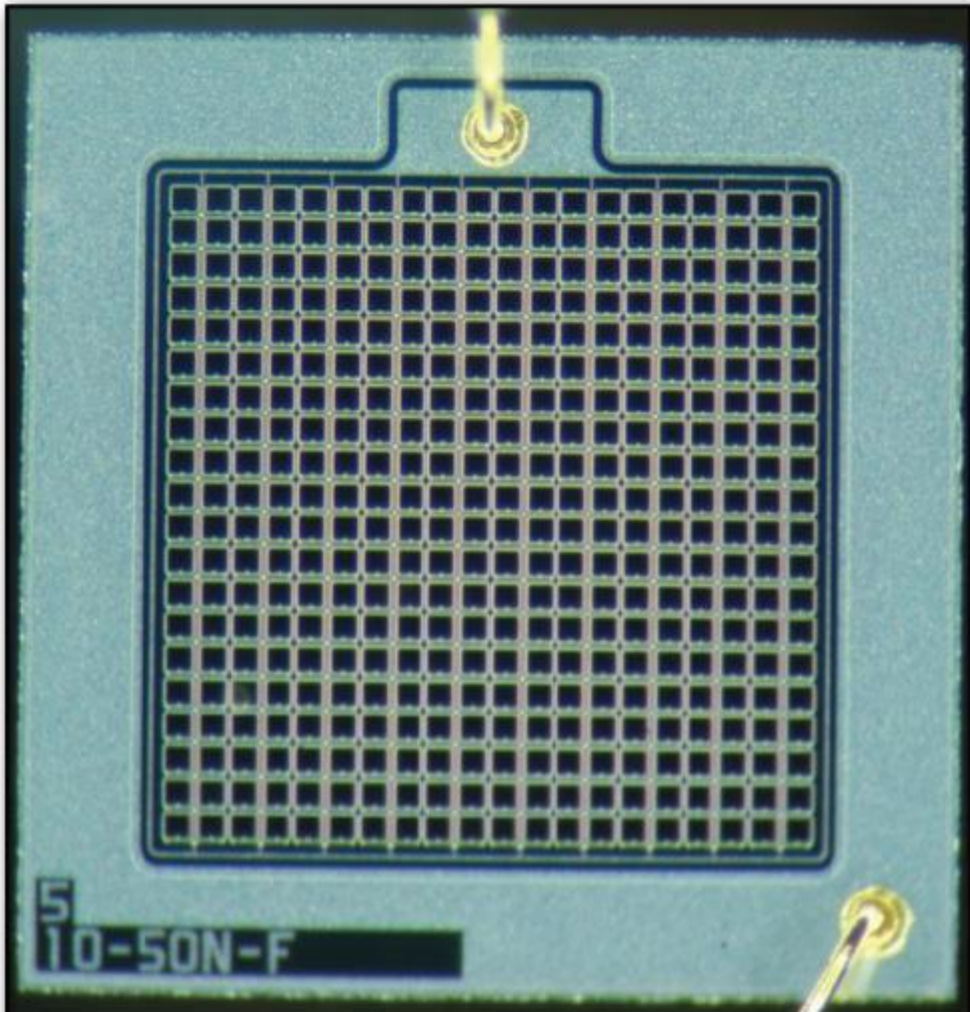
Photodiodes

- photo diode: gain = 1 (see Chapter on semiconductor detectors)
- avalanche photo diode → silicon PMT
  - pixelized photo diodes operated in Geiger mode
  - energy: #photons seen in all pixels
  - granularity: 10^3 pixels/mm^2
  - gain: 10^6
  - bias voltage: < 100 V
  - efficiency: ~30 %
  - insensitive to magnetic fields
  - works at room temperature



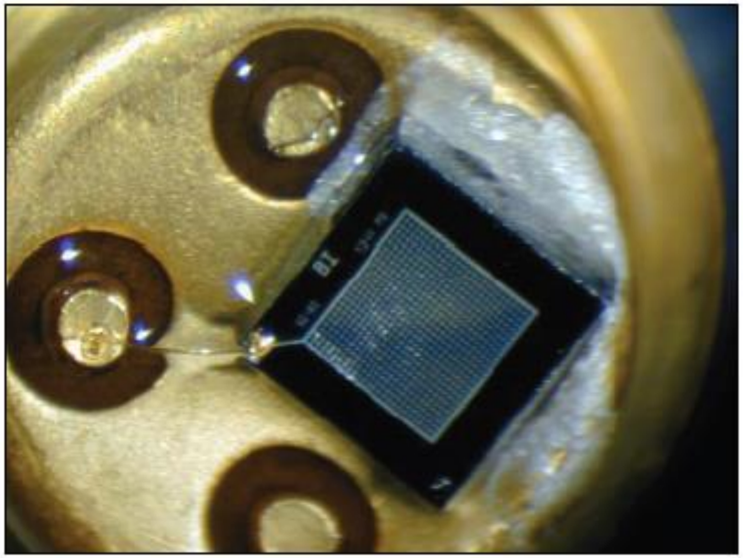


Silicon photodiodes



HAMAMATSU
MPPC 400Pixels

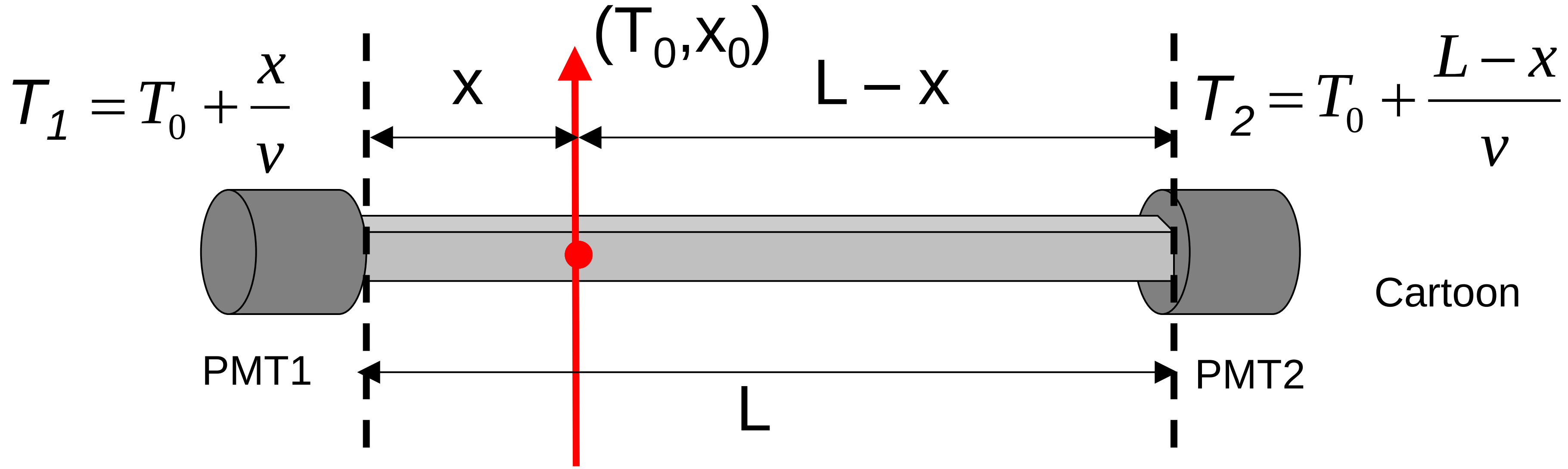
One of the first SiPM
Pulsar, Moscow



Applications

- fast signals → time of flight (TOF) measurements
- energy measurements
  - crystal calorimeter
    → precise electron/photon energy
  - sampling calorimeter: alternating layers of absorber (Fe, W, U) and scintillator with wavelength shifters and PMTs
    → electromagnetic & hadronic calorimetry
- fast tracking/vertexing
  - scintillating fibre hodoscopes

TOF (and position) with scintillators



$$TOF = \frac{(T_1 + T_2) - L/v}{2}$$

$$Y\ position = \frac{T_1 - T_2}{2} v$$

T_1, T_2 : Timing measured by PMT1,2
L : slat length
v : light velocity in scintillator

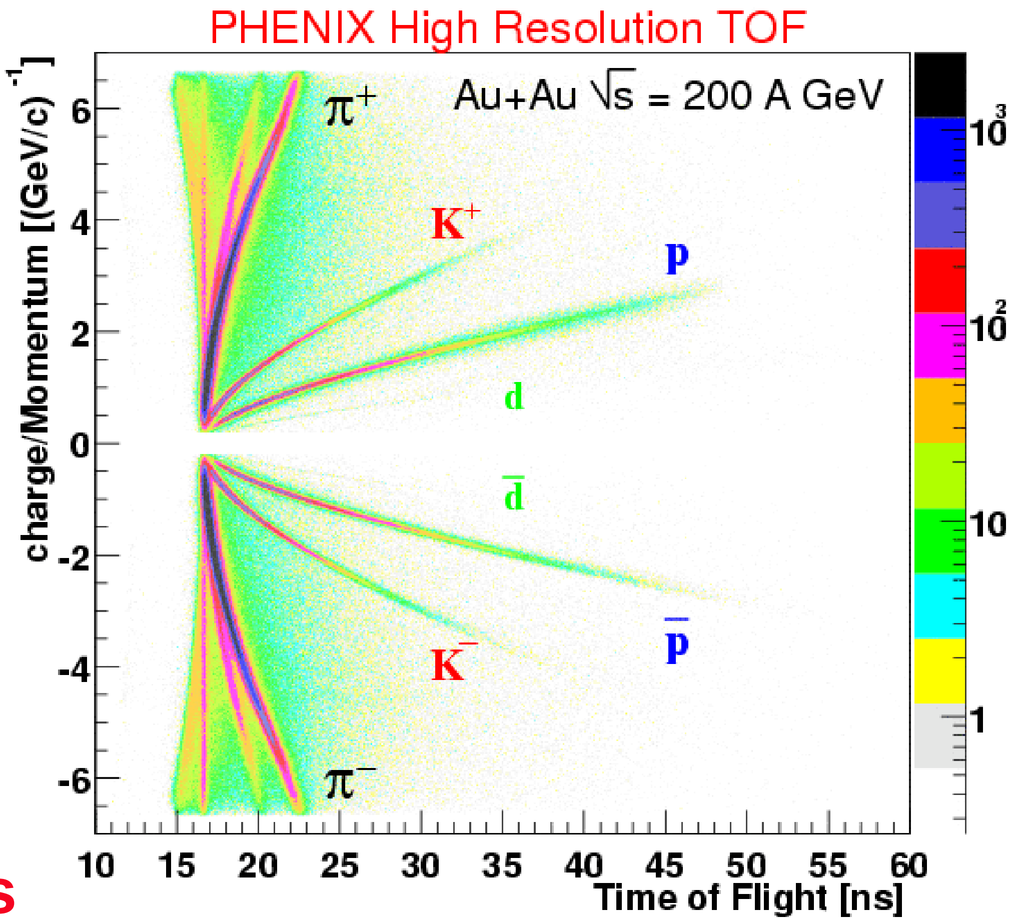
TOF example

- TOF measurement of charged particles with scintillators

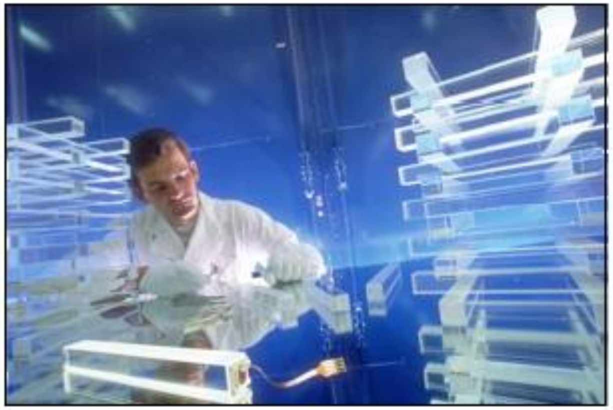
$$t = \frac{L}{c\beta} = \frac{L}{c}\frac{\sqrt{p^2+m^2}}{p}$$

$$1/p = 1/m \sqrt{\left(\frac{t}{L}\right)^2 - 1}$$

- example: PHENIX experiment at RHIC
- time resolution ~ 100 ps
- pion/kaon separation up to p = 2.4 GeV/c



CMS: crystal calorimeter (ECAL)

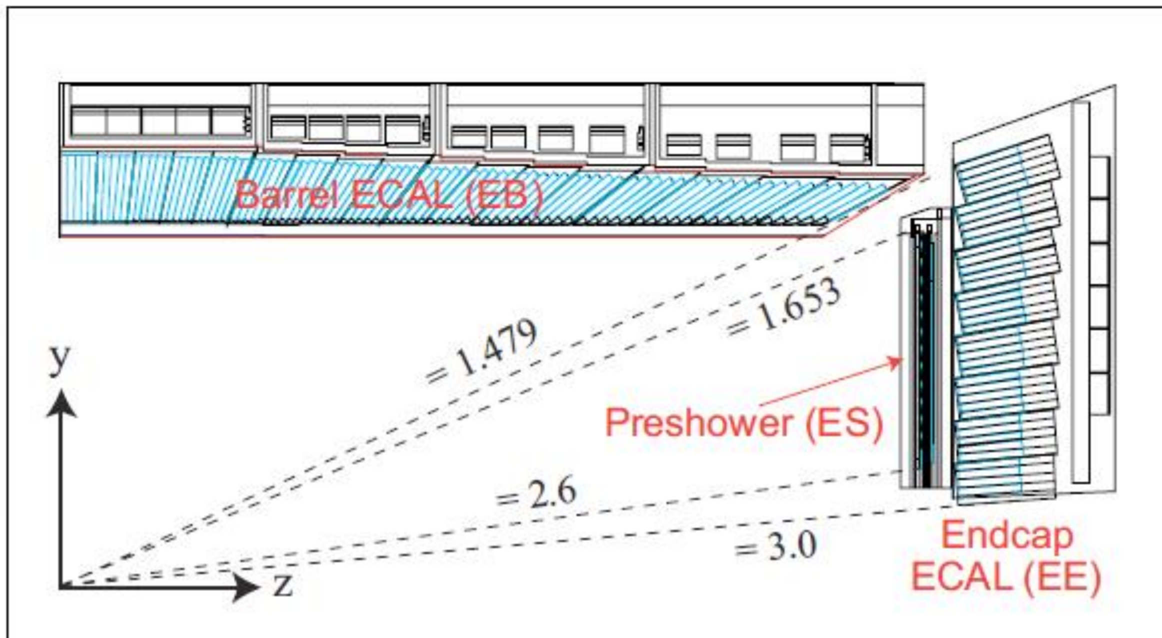


Scintillator : $PBWO_4$ [Lead Tungsten]

Photosensor : APDs [Avalanche Photodiodes]

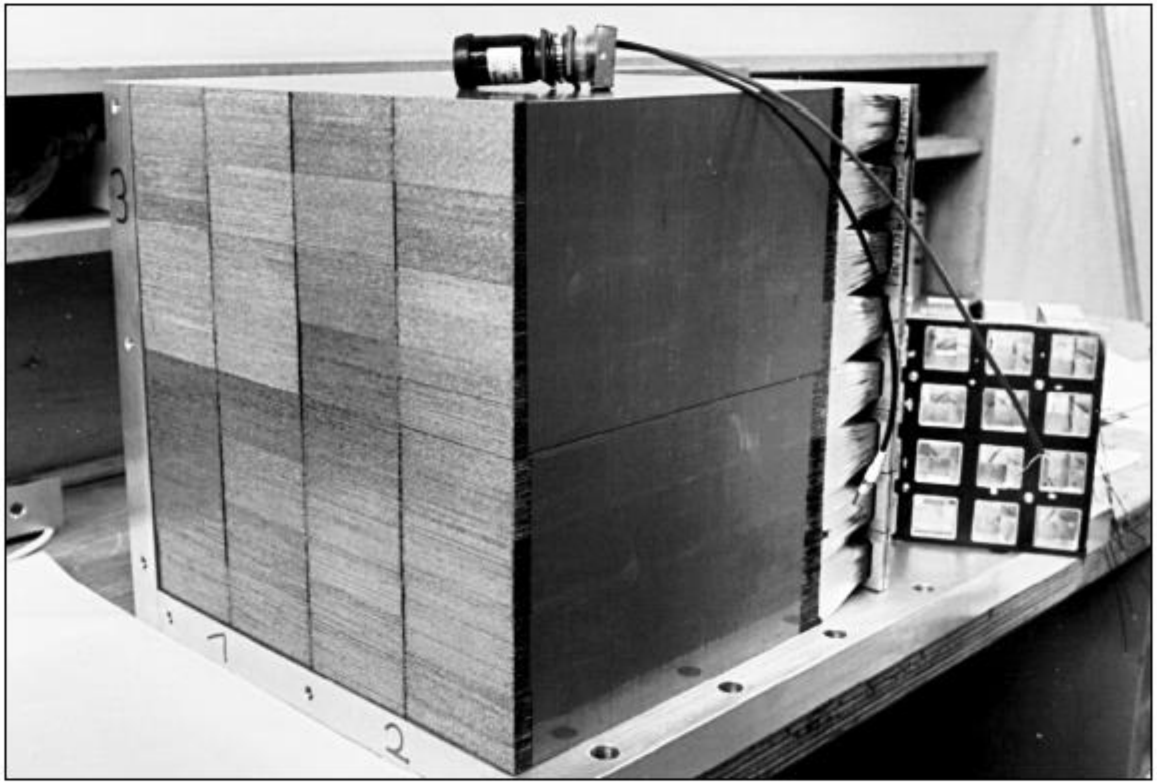
Number of crystals: ~ 70000

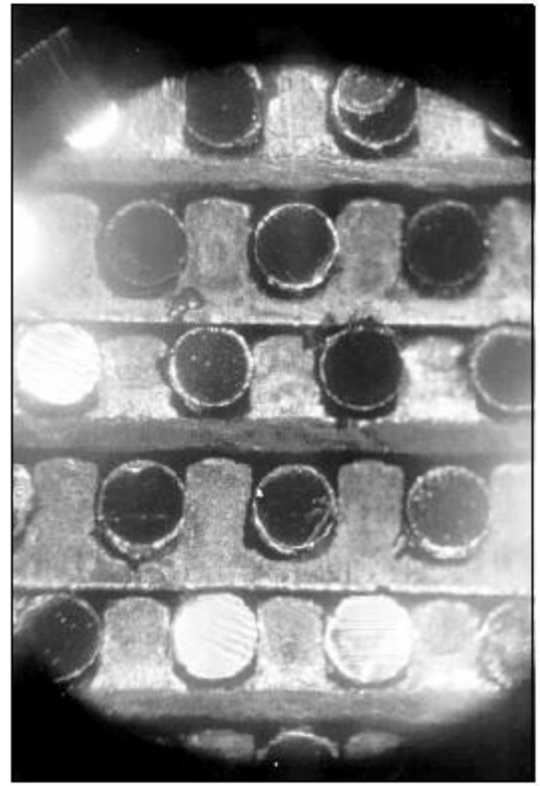
Light output: 4.5 photons/MeV



H1: spaghetti calorimeter

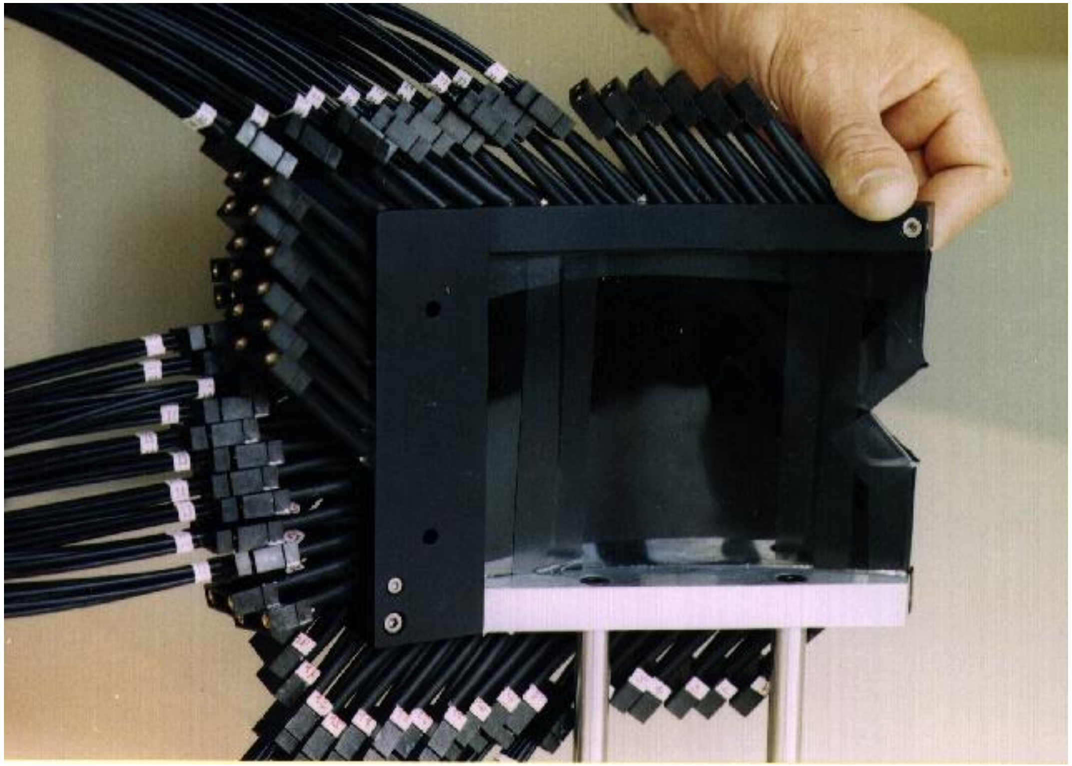
Scintillator : BICRON BCF-12
Photosensor : Photomultipliers





Scintillating fibre hodoscopes

- **scintillating fibres: diameter ~1 mm (or less)**
  → fast vertexing



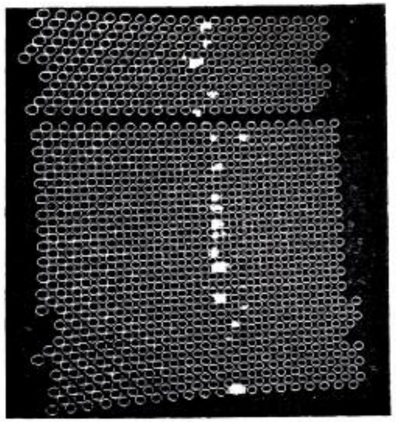


Figure: Track in scint. fibre array, fibre diameter 1 mm.

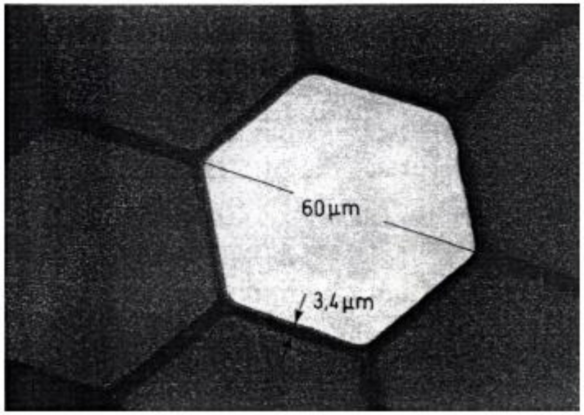


Figure: 60 μm fibre in a fibre bundle covered with cladding of lower n, single track resolution few tens of μm.