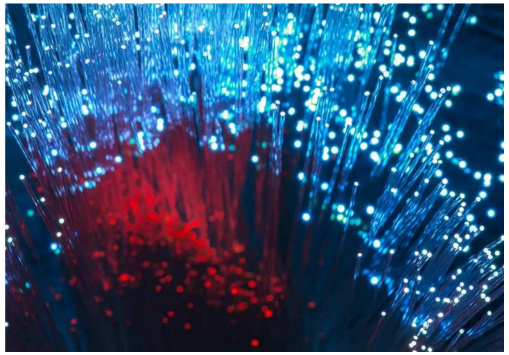
Heidelberg University, SS 2026

The Physics of Particle Detectors



Scintillator counters and photon detectors

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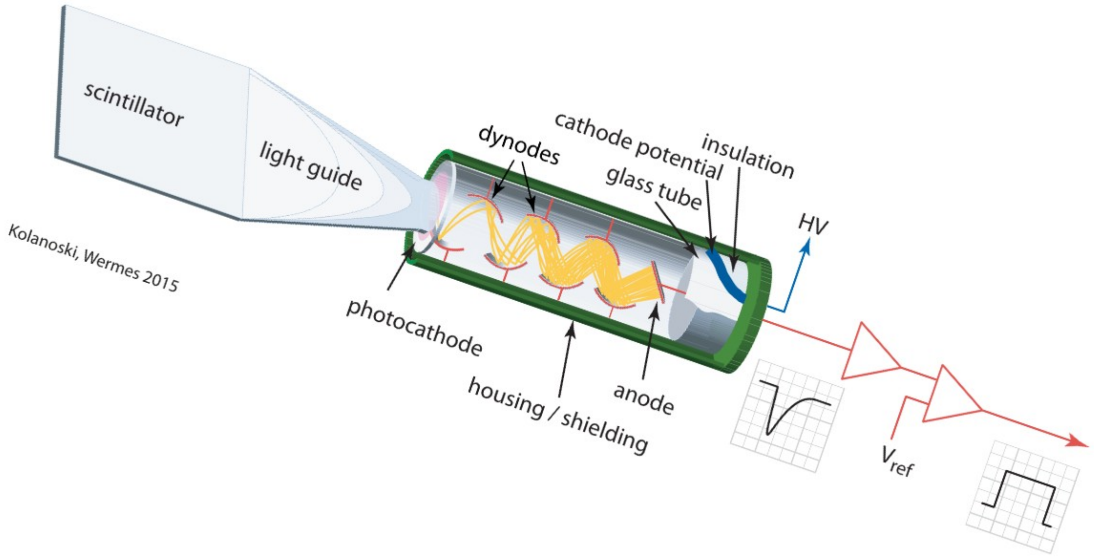
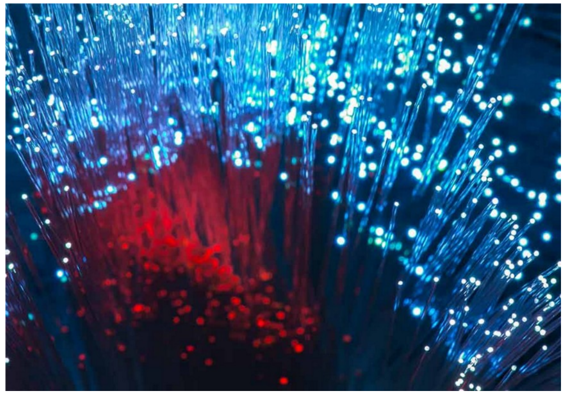
June 15, 2026

Outline: scintillation counters

- **Scintillators**
  - The detection principle
    Energy loss -> light emission
  - Inorganic scintillators
  - Organic scintillators
- **Transmission of light**
- **Light detection**
  - Photomultipliers
  - (Avalanche) photo-diodes
  - Hybrid photon detectors
- **Applications of scintillation detectors**

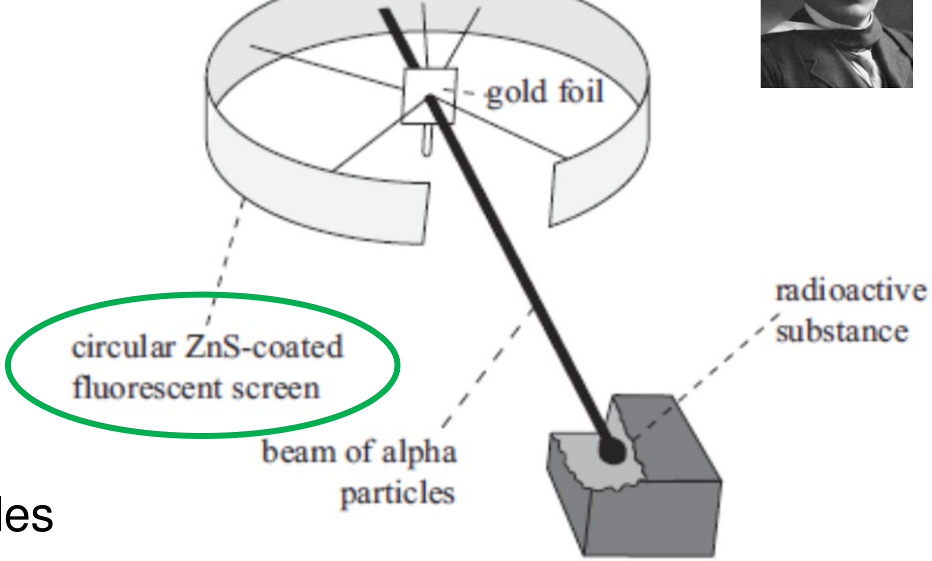


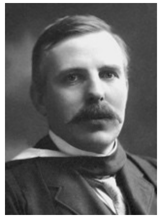


Scintillation counters

Radiation detection by scintillation is one of the oldest detection methods
Rutherford, 1910

Alpha particles hit a zinc sulfide screen
⟶ emit a flash of light





General properties:

- Energy loss by traversing particles ⟶ excitation of atoms/molecules ⟶ de-excitation by **EMISSION OF VISIBLE LIGHT**
- Photons must be transmitted efficiently to …
  … a photon detector

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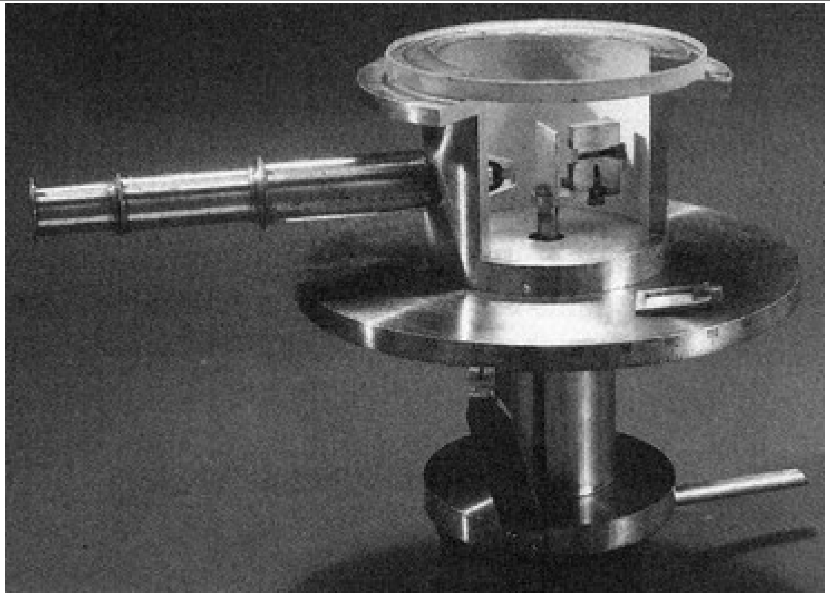


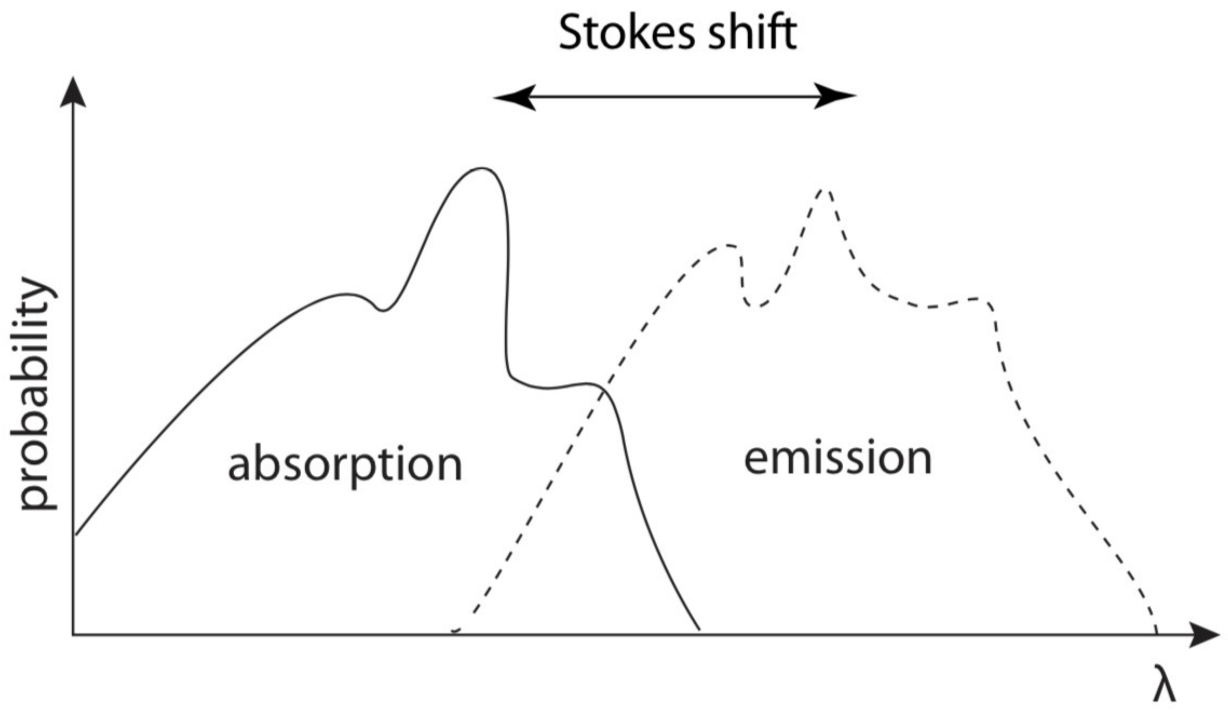
A replica of an apparatus used by Geiger and Marsden to measure alpha particle scattering in a 1913 experiment. Source: Wikipedia

General properties:

- Energy loss by traversing particles ⟶ excitation of atoms/molecules
  ⟶ de-excitation by **EMISSION OF VISIBLE LIGHT**
- Photons must be transmitted efficiently to …
  … a photon detector
- The scintillating material should be transparent for the wavelength of the scintillation light ⟶ next slide

Scintillation counters

The scintillating material should be transparent for the wavelength of the scintillation light to avoid re-absorption in the scintillator



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Scintillation counters

Scintillating materials

Luminescence: light emission with a characteristic spectrum caused by certain inherent molecular or crystalline properties of materials.

- Inorganic crystals
- Organic scintillators
  - Organic crystals
  - Plastic scintillators

Scintillation counters

Scintillating materials

Luminescence: light emission with a characteristic spectrum caused by certain inherent molecular or crystalline properties of materials.

- Inorganic crystals
- Organic scintillators
  - Organic crystals
  - Plastic scintillators

- Different mechanisms of light emission
- Different time scales involved
- Different applications:
  - Timing, trigger, veto counters
  - Time-of-flight measurements
  - Energy measurement (calorimeters)
  - Tracking detectors

Scintillation counters

What are the most important properties for a good scintillator material?

Scintillation counters

Qualities of a scintillator:

- The fraction of energy loss going into photons should be as high as possible: conversion into light should be as efficient as possible (**light yield**)
- The number of photons per deposited energy should be proportional to the energy released (**linearity**)
- The material must be transparent for the scintillation light (**large absorption length**)
- The decay time of the luminescence (duration of the excitation and light emission processes) should be as short as possible (**fast signals**)

- **Scintillators**
  - **Organic scintillators**
  - Inorganic scintillators

- Transmission of light

- Light detection
  - Photomultipliers
  - (Avalanche) photo-diodes
  - Hybrid photon detectors

- Applications of scintillation detectors

Organic scintillators

Different scintillation mechanism, largely based on the electronic structure of the carbon atom.

Often very fast light emission
- well suited for **fast timing** applications

Possible forms:

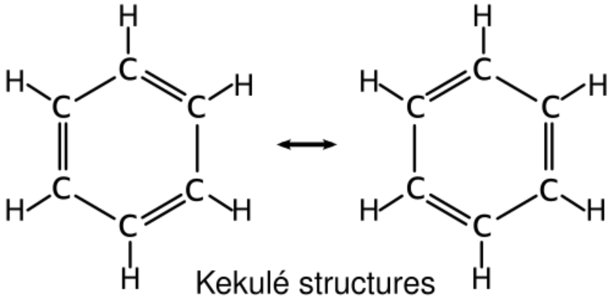
- **Crystals** (like anthracene or stilbene)
  largest light yields, but brittle and difficult to handle. Crystal axis dependence.
- **Liquids** (like xylene or benzene)
  low light yield, few photons at detectable wavelengths and in fast time.
  Materials dissolved in liquids (e.g. p-terphenyl $C_{18}H_{14}$ dissolved in benzene C_6H_6)
  sometimes also with the addition of a *wavelength shifter* (like POPOP).
- **Plastic scintillators** (e.g. Polystrene or Polyvinyl as base material -> next slide)
  By polimerisation of the base material, liquid scintillators can be solidified and can be formed in *any shape*

Organic scintillators: scintillation mechanism

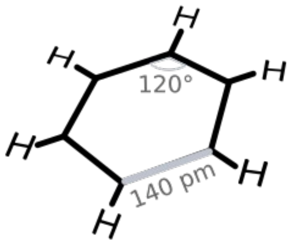
Carbon: 6 electrons in K-shell (1s) and L-shell (2s, 2p)
Electron orbitals different depending on the shell occupation in compounds

C_6H_6

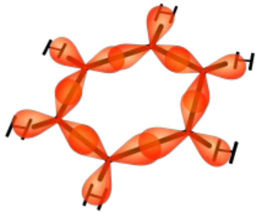
Benzene
molecular formula



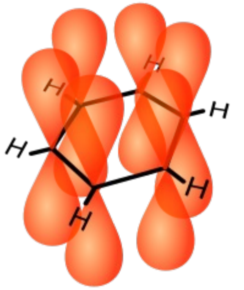
Kekulé structures
(resonance forms)



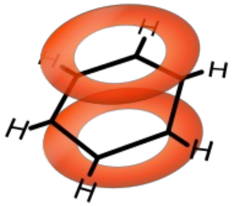
Planar hexagon
bond length 140 pm



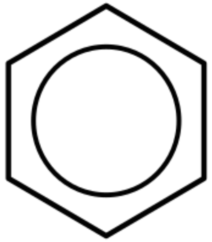
Sigma bonds
sp[2] hybridized orbitals



$6p_z$ orbitals



Delocalized pi
system



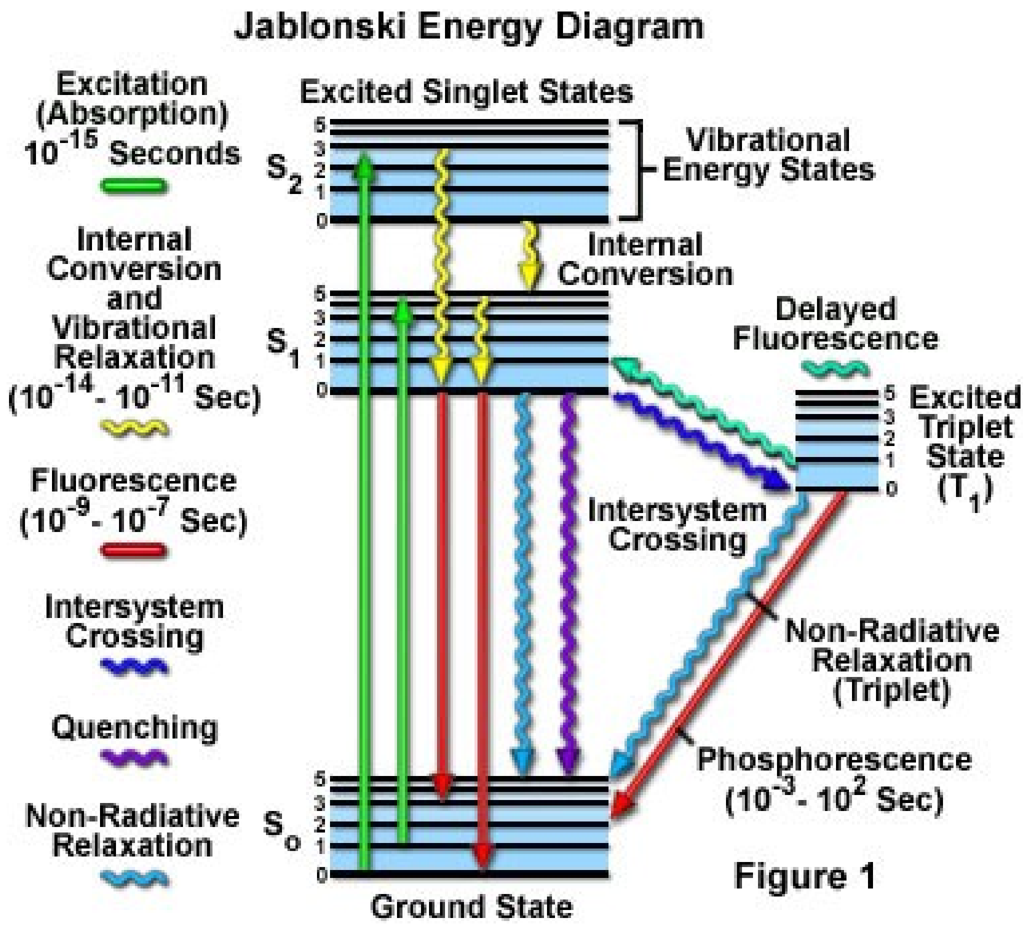
Benzene ring
simplified depiction

Organic scintillators : scintillation mechanism

Luminescence from transitions between the molecular π electron levels

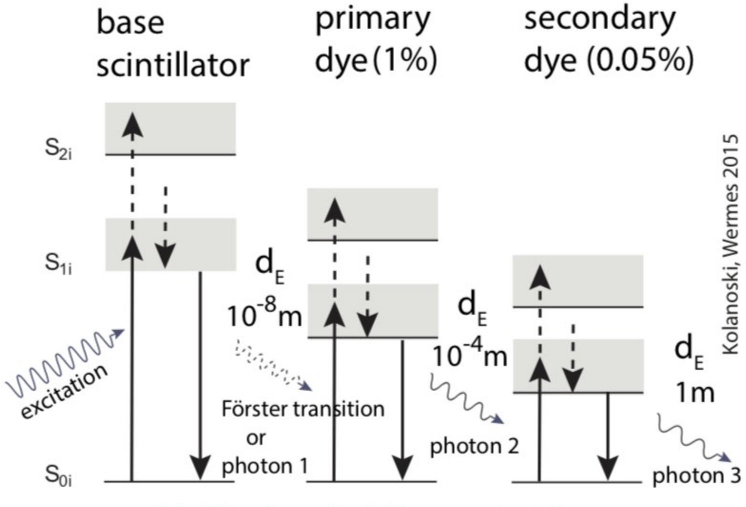
Following excitation (10^{-14} s):

- Radiationless transitions $S_{1i} \rightarrow S_{10}$ in **ps** time (10^{-12} s)
- *From S_{10} to S_{0i}: prompt fluorescence in **ns** scintillation light (10^{-9}-10^{-8} s)*
- Singlet $\rightarrow$ triplet transitions suppressed: triplet states metastable: phosphorescence in **ms**
- If electrons jump back from triplet to singlet states, the de-excite immediately: delayed fluorescence (μ**s to ms**)

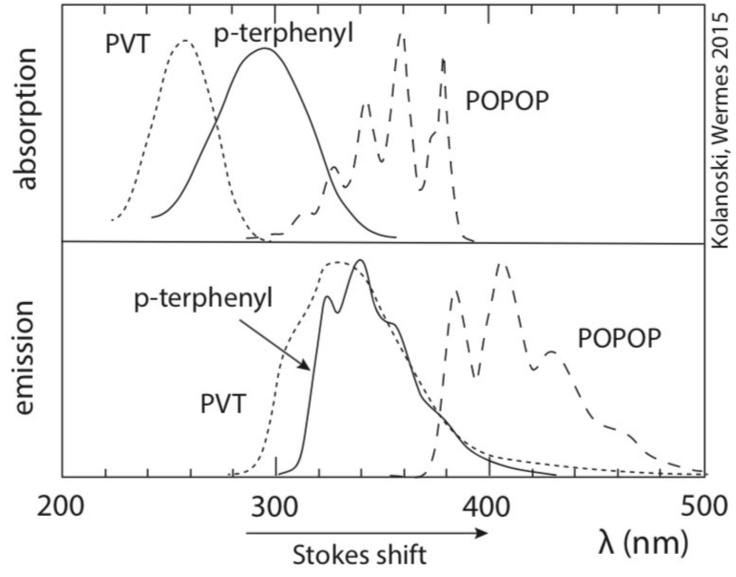


http://micro.magnet.fsu.edu/primer/techniques/fluorescence/fluorescenceintro.html

Organic plastic scintillators



(a) Wavelength shifting: principle.



(b) Absorption and emission spectra.

Typically: achieve large Stokes shifts by having

1. base material: initial energy absorber (e.g. PVT, PS, etc.)
2. first agent: large light yield, good spectra conformity to base solvent (e.g. p-terphenyl)
3. second agent, acting as **wavelength-shifter** for light **transparency** (e.g. POPOP) and to **match photon detector** sensitivity

Scintillator	Base	Primary additive	Secondary additive
liquid	benzene	*p*-terphenyl	POPOP
	toluene	DPO	BBO
	xylene	PBD	BPO
plastic	polyvinyl benzene (PVB)	*p*-terphenyl	POPOP
	polyvinyl toluene (PVT)	DPO	TBP
	polystyrene (PS)	PBD	BBO/DPS

Abbreviations are as follows: PBD = $C_{24}H_{22}N_2O$; DPO = $C_{15}H_{11}NO$; BPO = $C_{21}H_{15}NO$; TBP = $C_{12}H_{27}O_4P$; BBO = $C_{27}H_{19}NO$; POPOP ($C_{24}H_{16}N_2O_2$); DPS = diphenylstilbene.

Organic plastic scintillators: applications

ADVANTAGES:

+ Simple handling to realize any shape
+ Cheap fabrication
+ Robustness and reliability
+ Good spatial resolution with scintillating fibers
+ Fast timing

DISADVANTAGES:

- Low light yield (1 photon per 100 eV energy loss)
- Sensitivity to solvents and greases
- Sensitivity to high temperatures
- Aging effects and limited radiation hardness: decrease of light yield and attenuation length for light transmission

Organic scintillators: signal shape

Time response of scintillating organic molecules:

- Prompt fluorescence: decay time constant τ_f
- Gaussian g(t) to account for excitation and rise time
- Additional component from delayed fluorescence (slow, several hundred ns): decay time constant τ_s

Light intensity:

$$I(t) = I_1\ g(t)\ \mathrm{e}^{-\frac{t}{\tau_f}} + I_2\ \mathrm{e}^{-\frac{t}{\tau_s}}$$

Generally $I_1 > I_2$
Details depend on the scintillating material

But also on the impinging radiation: p, α, n, γ

Note: neutrons detected by (n,p) reactions

Organic scintillators: signal shape

Signal time shape depend on the impinging radiation:
p, α, n, γ

Reason: their different ionisation densities

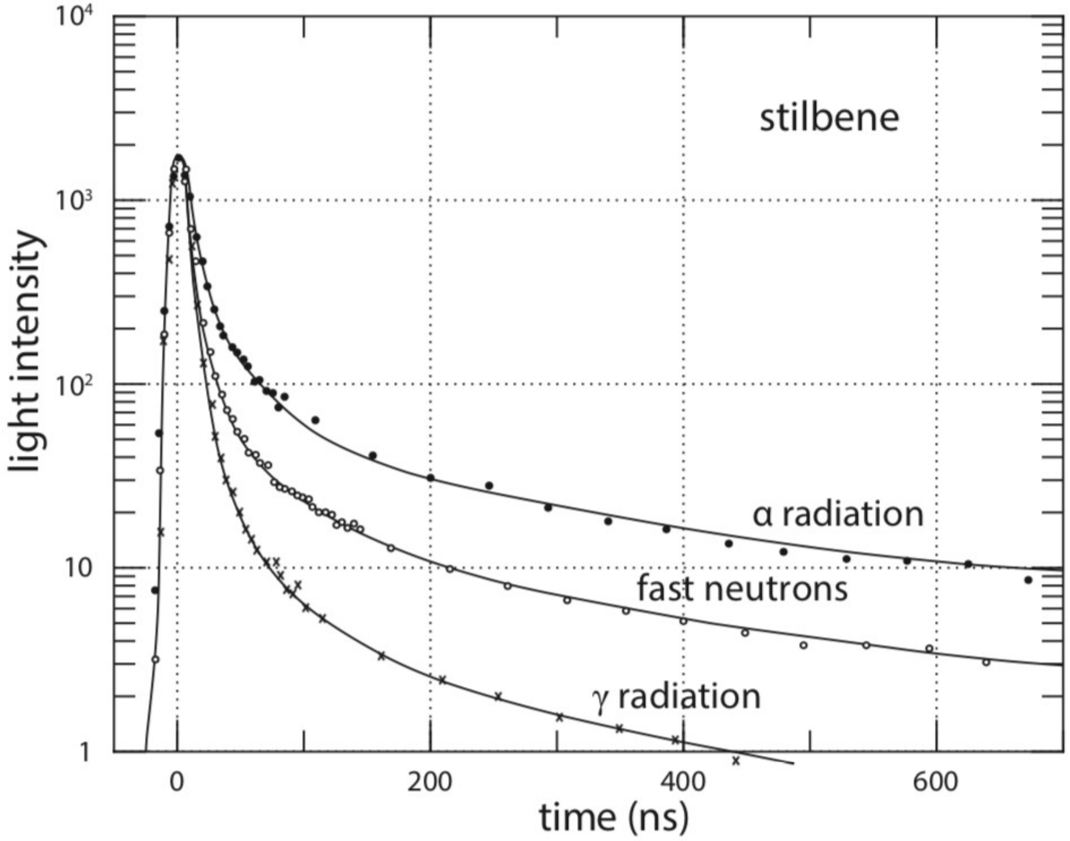
Ionisation processes are considered the reason for transitions between the singlet and triplet energy levels

→ With larger dE/dx deposit by ionisation, the transitions to triplet states and back to singlet become more probable

→ The delayed fluorescence component becomes more important

Particle identification
by pulse shape discrimination

$$I(t) = I_1\ g(t)\ \mathrm{e}^{-\frac{t}{\tau_f}} + I_2\ \mathrm{e}^{-\frac{t}{\tau_s}}$$



- **Scintillators**
  - Organic scintillators
  - **Inorganic scintillators**

- Transmission of light

- Light detection
  - Photomultipliers
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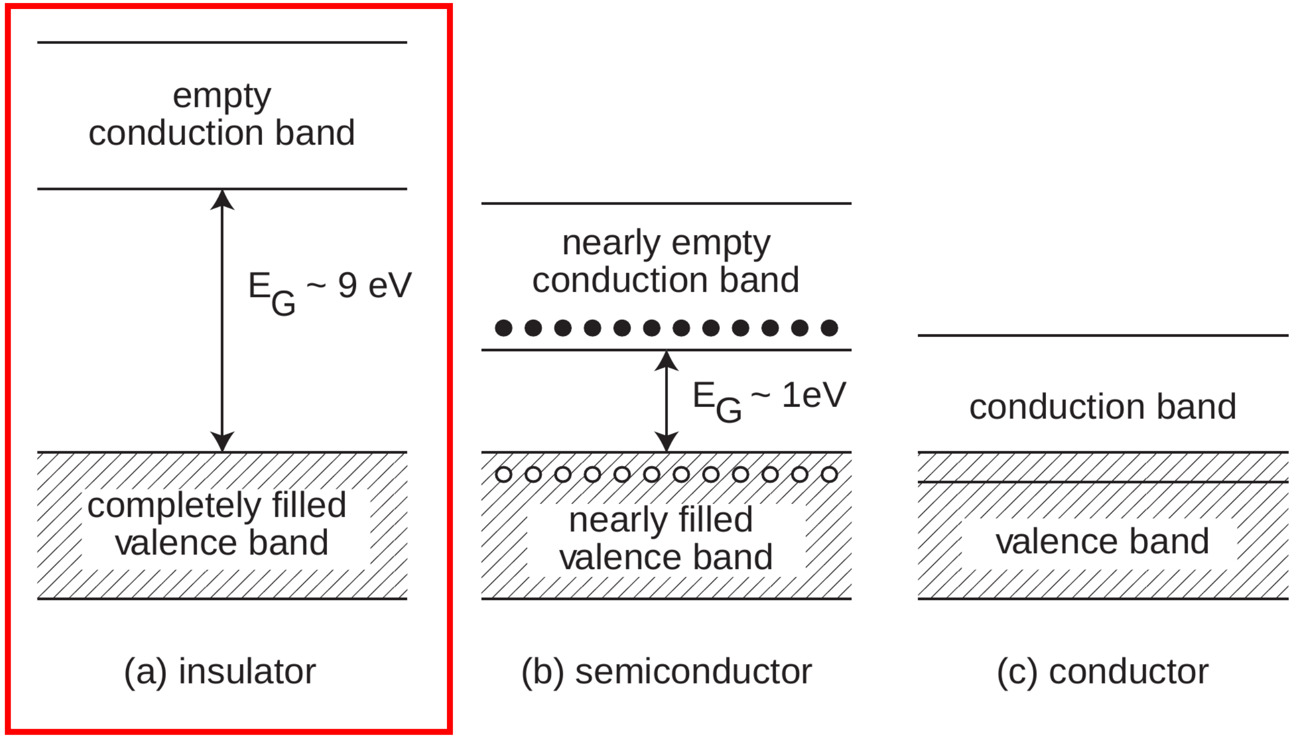
- Applications of scintillation detectors

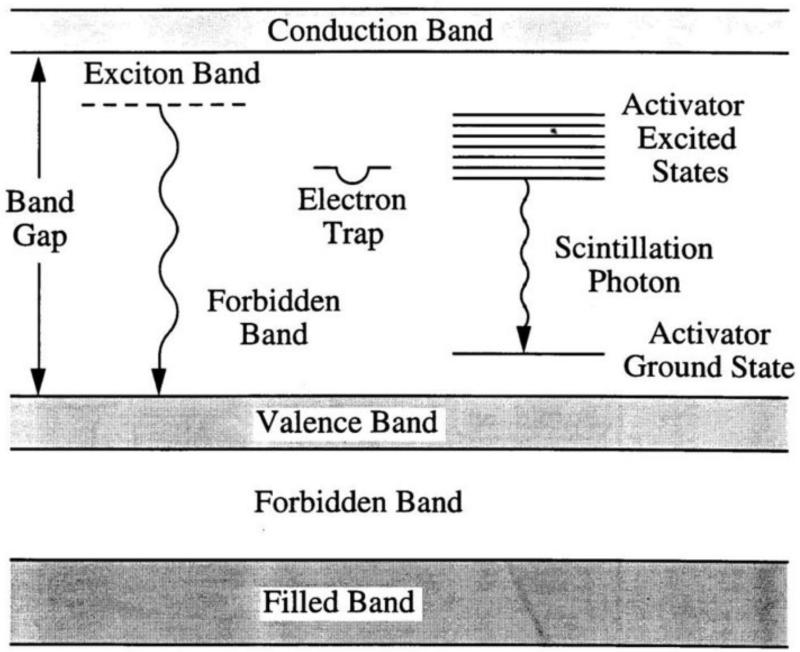
Inorganic crystals



Crystal lattice → energy bands

- Excitation brings electrons to the conduction band
- Direct de-excitation (recombination) produces photons of inconvenient λ
- They might get trapped → delayed fluorescence or phosphorescence
- Electrons can also reach lower energy levels (in the band gap, from dopants) from which that can return to a lower level by emitting a scintillation photon or lattice vibrations

Inorganic crystals



S.E. Derenzo, *Scintillation Counters, Photodetectors and Radiation Spectroscopy*, IEEE Short Course *Radiation Detection and Measurement* 1997 Nuclear Science Symp.

8/2/201

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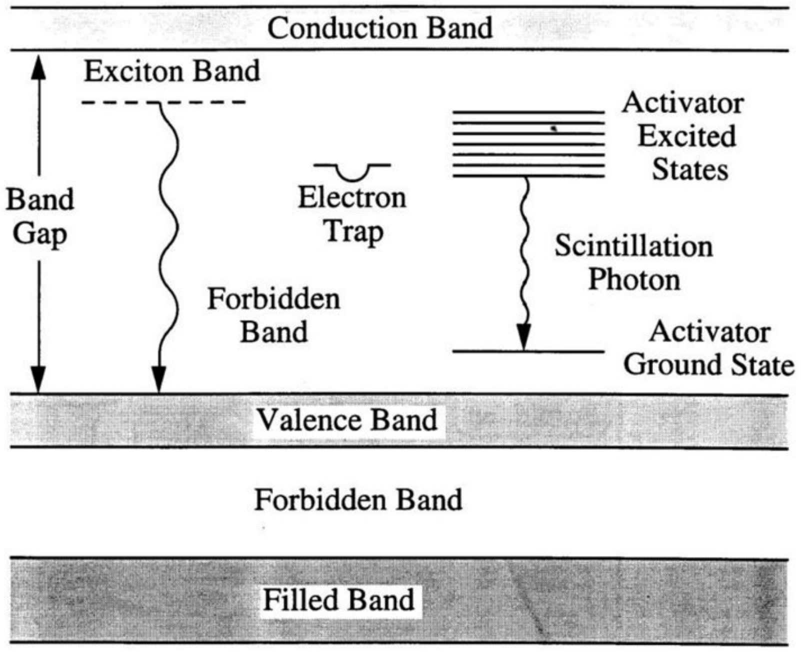
Inorganic crystals

Crystals of electric-insulator type (energy gap ~ 4-12 eV)

with energy levels which enable radiative transitions in optical region = Luminescence centers



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Extrinsic luminescence centers:

Introduced via doping of ions as activators(e.g. Tl in NaI(Tl)).

Intrinsic luminescence centers:

Present as intrinsic property of the scintillator. Different processes possible, e.g.

- 5d-4f transition from Ce^{3+} in CeF3
- electrons transfer between metal and ligand orbitals (e.g., $Bi^{3+} \leftrightarrow O^{2-}$ in BGO or $W^{6+} \leftrightarrow O^{2-}$ in PbWO4)
- processes that involve excitons, i.e. loosely bound (0.01 eV) e-h pairs that can move within the crystal e.g.CsI, NaI, BaF_2

Inorganic crystals

An example: NaI(Tl)   thallium doped sodium iodide

- **Light production:**
  - Wavelength: λ_{max} = 410 nm (~ 3 eV)
  - Decay time: τ = 250 ns

- Radiation length: X_0 = 2.6 cm

- **Fraction of energy going into photons:**
  light yield: ε_{sc} ~ 11.3 % good!
  38,000 photons with 3 eV per MeV energy loss

Inorganic crystals

ADVANTAGES:

- High light yield
- High density

→ **Good energy resolution for compact detectors**

DISADVANTAGES:

Complex crystal growth

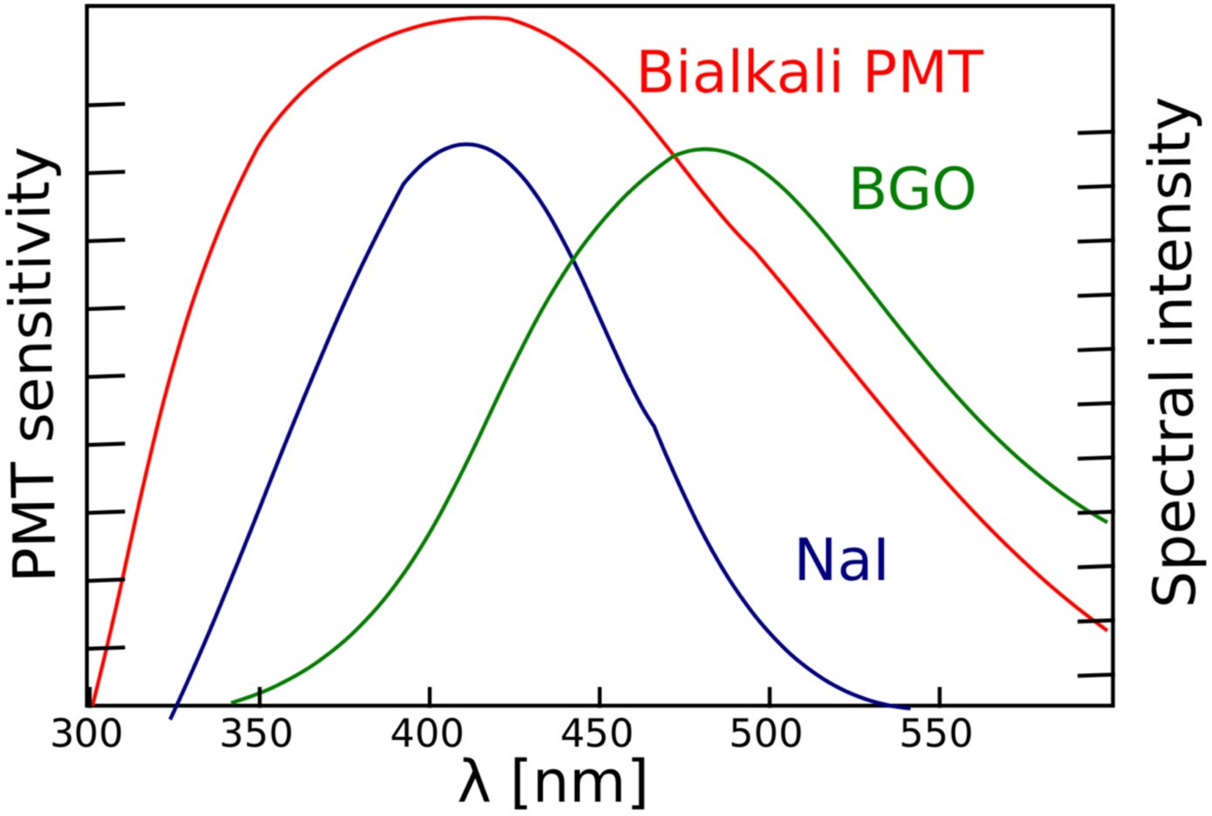
→ **Very expensive detectors**

	type	λ_{max}[nm]	$\tau[\mu s]$	photons per MeV	X_0[cm]
Sodium iodide	NaI(Tl)	410	0.23	38000	2.6
Cesium iodide	CsI(Tl)	565	1.0	52000	1.9
Bismuth germanate	BGO (bismuth germanate)	480	0.35	2800	1.1
Barium fluoride	BaF_2 slow component	310	0.62	6300	2.1
	BaF_2 fast component	220	0.0007	2000	2.1
Cerium fluoride	CeF_3	330	0.03	5000	1.7
Lead tungstate	$PbWO_4$	430	0.01	100	0.9

Inorganic crystals

To be kept in mind: the spectral distribution of the light emission must match the absorption and sensitivity of the photon detector

The light output strongly depends on the **TEMPERATURE!** (differently from organic scintillators)



Inorganic crystals: radiation damage

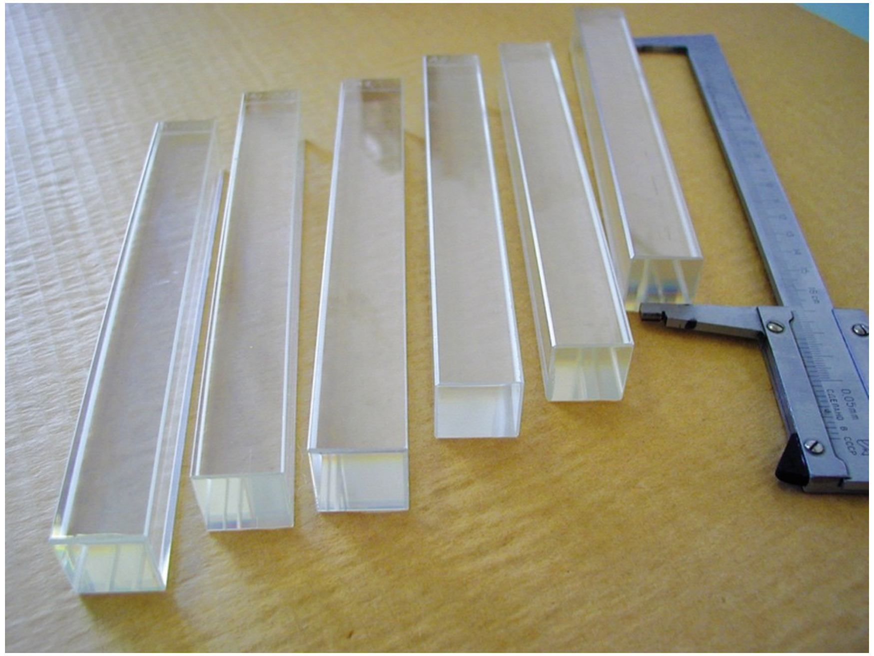
High radiation fluxes can damage the inorganic crystals.

Consequences:

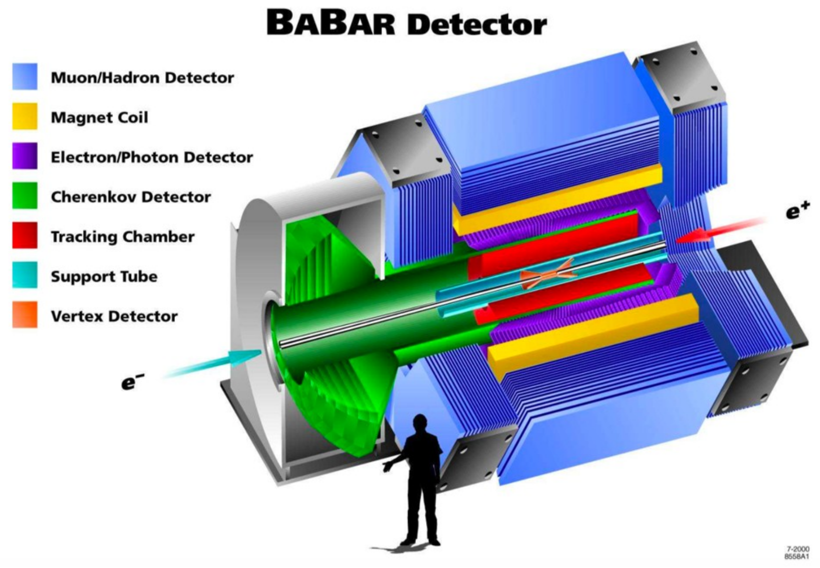
1. Influence on the scintillation mechanism (light creation)
2. Radiation-induced phosphorescence (afterglow)
3. Absorption of light by radiation-induced defects (color-centers)

Inorganic crystals very good for
electro-magnetic calorimeters:
at high rate experiments (e.g. LHC)
→ radiation hardness is an issue!

$PbW0_4$
e.g. CMS,
ALICE PHOS



Inorganic crystals: calorimeters



BaBar (SLAC)

- 6580 CsI(Tl) crystals
- Depth 17 X_0
- Total 5.9 m^3
- Readout: Si photodiodes (gain=1)
- Noise: 0.15 MeV
- Dynamic range: 10^4

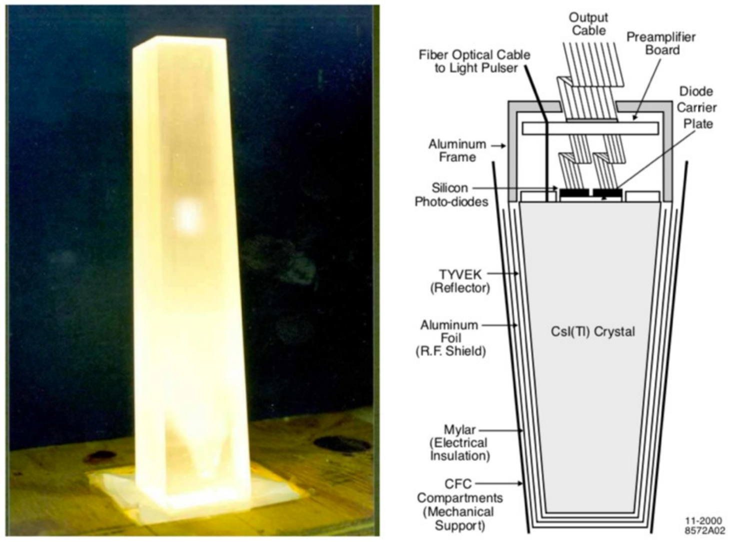
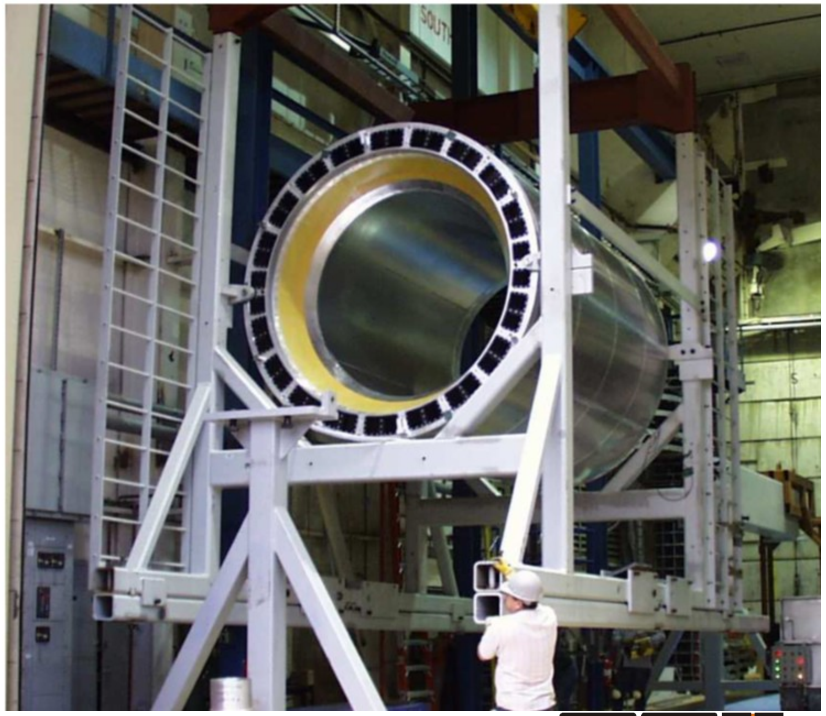
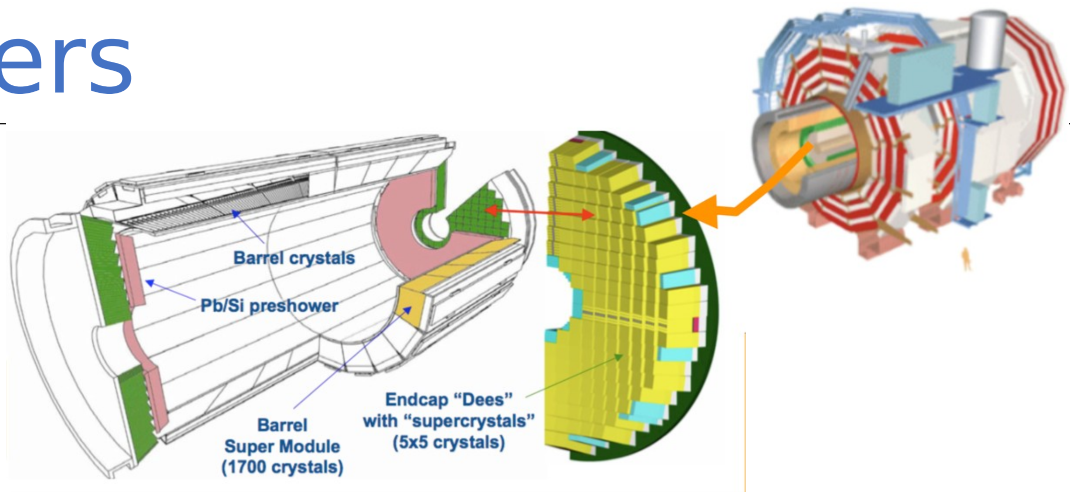


Fig. 3. Left: Photograph of a CsI(Tl) crystal lit from the bottom by a light bulb. Right: Schematic drawing (not to scale) of a crystal with attached electronics.

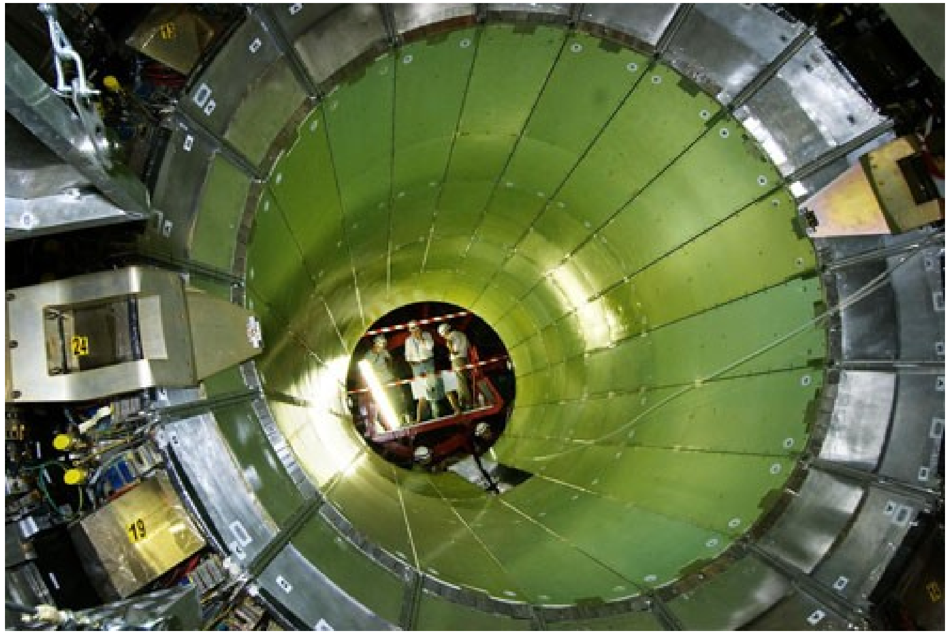


Inorganic crystals: calorimeters



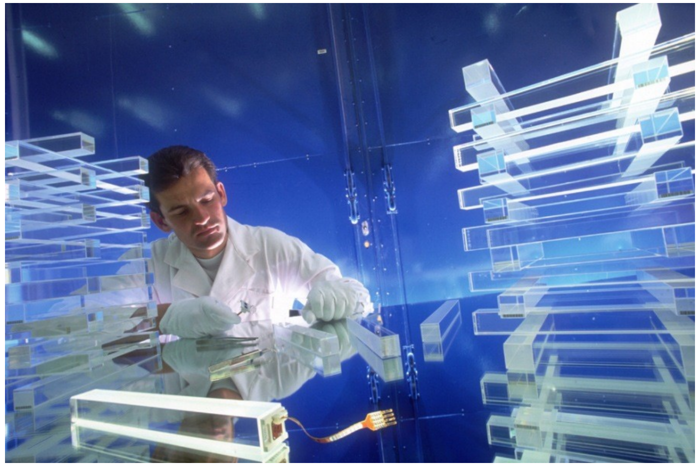
CMS at the LHC (CERN)

- 76150 $PbWO_4$ crystals
- Depth 26 X_0
- Total 11 m^3
- Readout: avalanche photodiodes (gain=50)
- Noise: 30 MeV
- Dynamic range: 10^5



$PbW0_4$

+ Fast
+ Small radiation length
+ Good radiation hardness
- Few photons
  ~100-200 photons per MeV



Scintillation counters: overview

Inorganic

- High light yield (ε_{sc} ~ 0.13)
- High density
- **Good energy resolution for compact detectors (calorimetry)**
- Moderate timing
- **Large temperature dependence**
- Elaborate handling
- Complex crystal growth
- **Very expensive detectors**
- (can be) **Radiation hard** (high rate applications)

Organic

- **Low light yield** (ε_{sc} ~ 0.03)
- **Fast timing (trigger, time-of-flight, PID)**
- Simple handling to realize any shape, robust
- Small temperature dependence
- Cheap fabrication
- **Good spatial resolution with scintillating fibers**
- Sensitivity to solvents and greases
- Sensitivity to high temperatures
- **Aging effects and limited radiation hardness**

Quiz: Assign the best scintillator for the given applications

Application A:
calorimeter@e+e- collider
max. particle flux: 100 Hz/cm²
Energy range: 50MeV - 5GeV

Application B:
calorimeter@hadron collider
max. particle flux: 10 kHz/cm²
Energy range: 500MeV - 100GeV

Application C:
Particle ID with ToF method
max. particle flux: 1kHz/cm²
Energy range: 50MeV - 1GeV

Application D:
measure α's & suppress γ's
max. particle flux: 100Hz/cm²
Energy range: 500keV - 5MeV

Material 1:	Organic Scintillator
Photon yield:	1.5 photons / keV
Decay constant:	3ns & 450ns
Radiation tolerance:	reasonable
Material 2:	Inorganic scintillator
Photon yield:	12 photons / keV
Decay constant:	1.8 ns & 630 ns
Radiation tolerance:	excellent
Material 3:	Organic Scintillator
Photon yield:	2 photons / keV
Decay constant:	0.8ns
Radiation tolerance:	good
Material 4:	Inorganic Scintillaor
Photon yield:	8 photons / keV
Decay constant:	3 ns
Radiation tolerance:	excellent
Material 5:	Inorganic Scintillator
Photon yield:	41 photons / keV
Decay constant:	2.3 ns
Radiation tolerance:	good

- Scintillators
  - Inorganic scintillators
  - Organic scintillators

- **Transmission of light**

- Light detection
  - Photomultipliers
  - (Avalanche) photo-diodes
  - Hybrid photon detectors

- Applications of scintillation detectors

Propagation of light

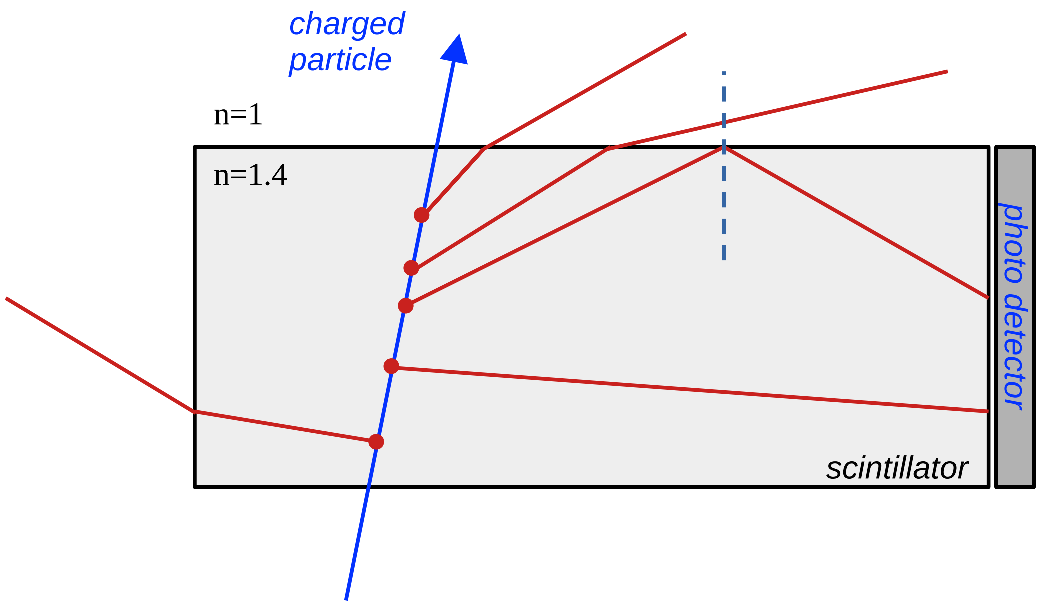
In the scintillator:

- Absorption: $N_\gamma = N_0 \exp(-x/L)$
  L = absorption length

- Reflection at the edges
  total reflection for $\Theta > \Theta_{tot} = \arcsin(n_0/n_s)$

  Typically: n ~ 1.4 → Θ_{tot} = 45°

  It can be helped, by wrapping the scintillator in material with the proper refraction index



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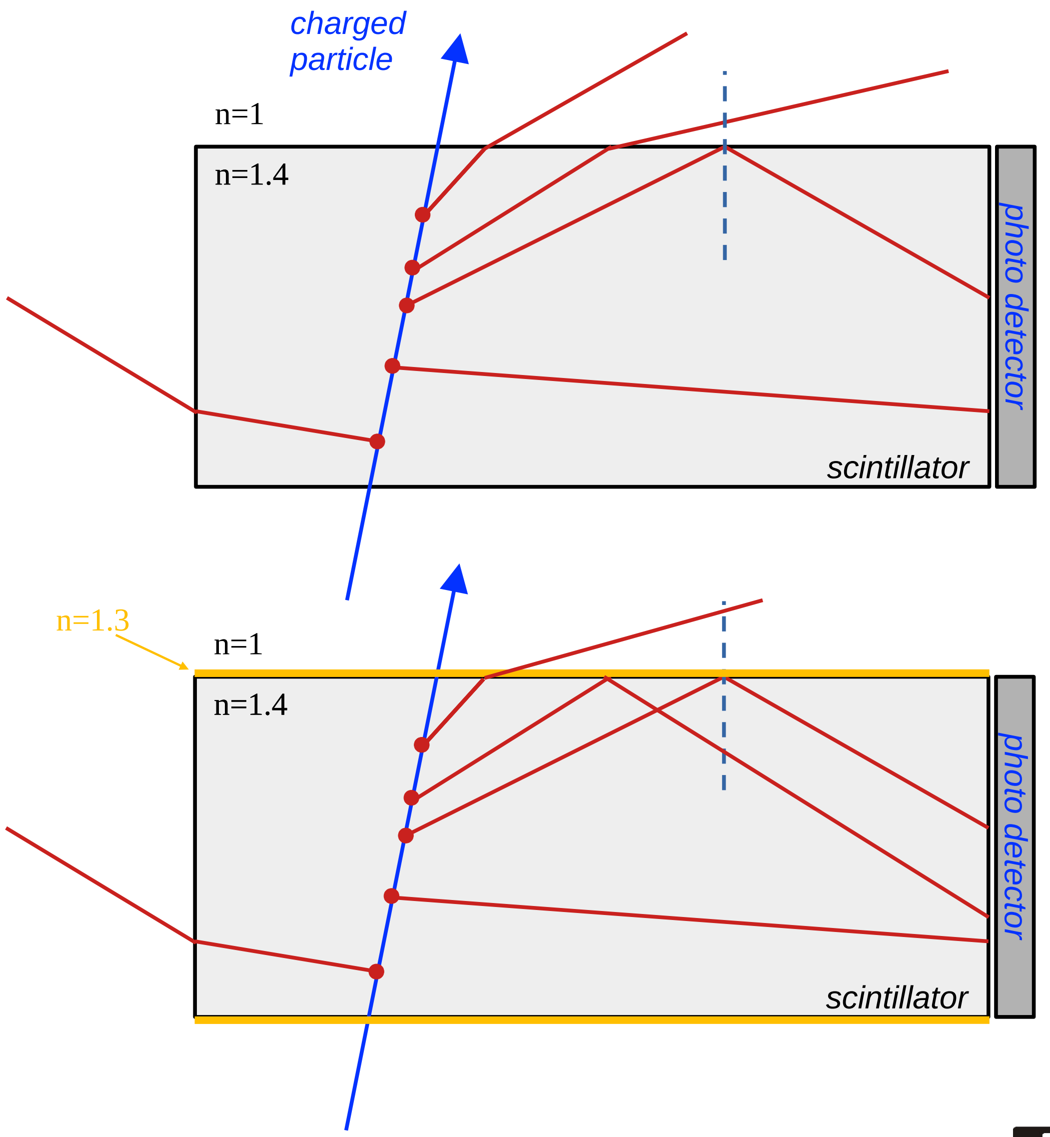

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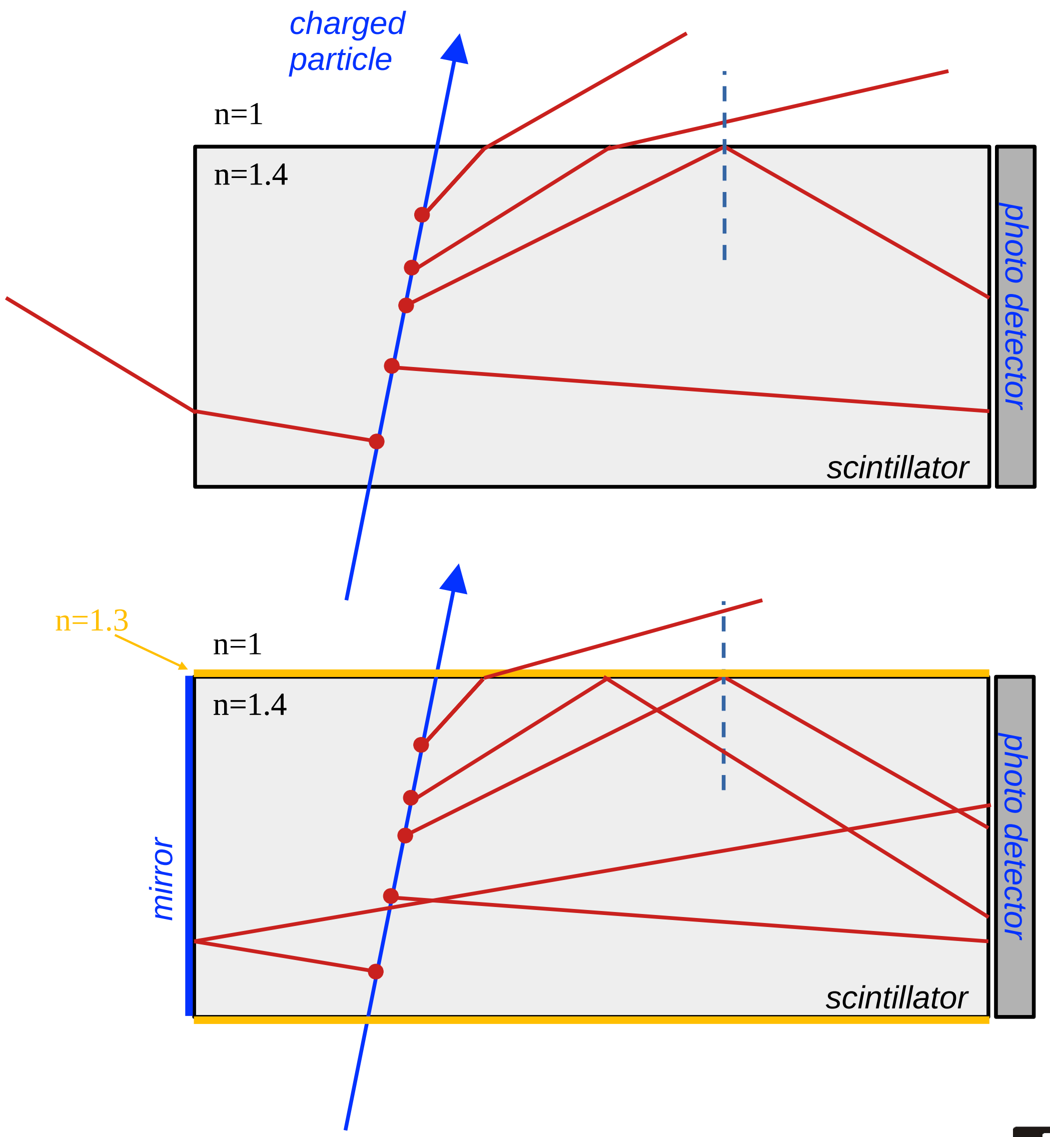
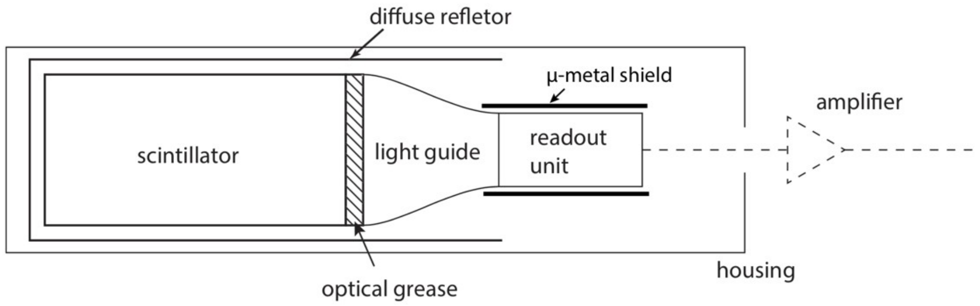


Light collection and transmission



Scintillator producing light → LIGHT GUIDE → Photon detectors (photomultipliers, photo-diodes)

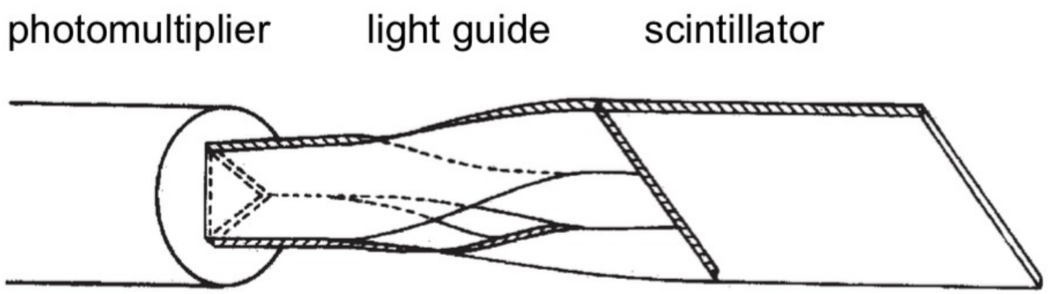
The light guide
- Provides the coupling to the photon detector and readout system
- With as little light loss as possible

It might be mandatory to:
- Connect the scintillator and the photon detector *geometrically* (matching of shapes)
- Transport the light further away from the scintillator, if e.g. the PMT needs to be further away from a high magnetic field region

System with a photomultiplier

- Scintillator and light guide are wrapped by a reflector foil, to limit light losses at the walls

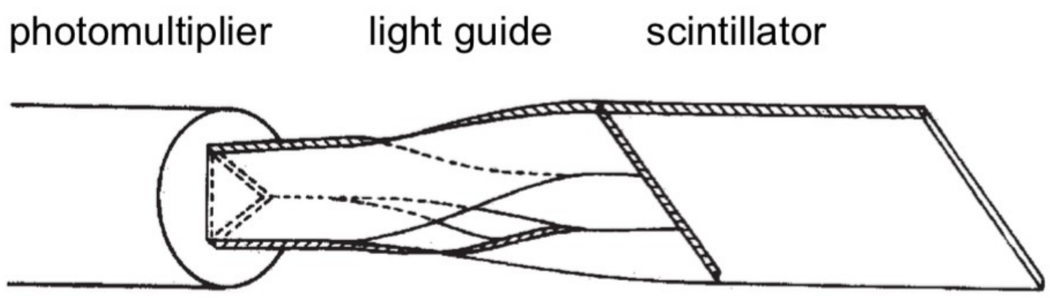
- At the interfaces scintillator-light guide, and light guide-PMT: use optical grease or optical glue, for better contact



(a) Scintillator–light guide–PMT system.

(b) Components and complete assembly.

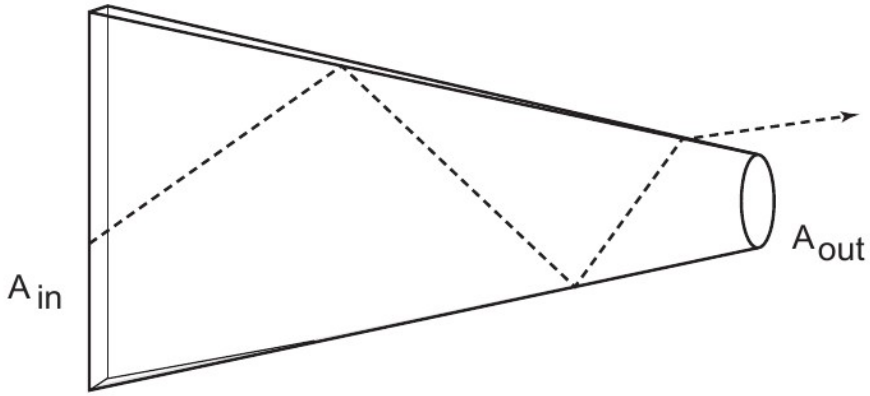
Example: Fish tail light guide



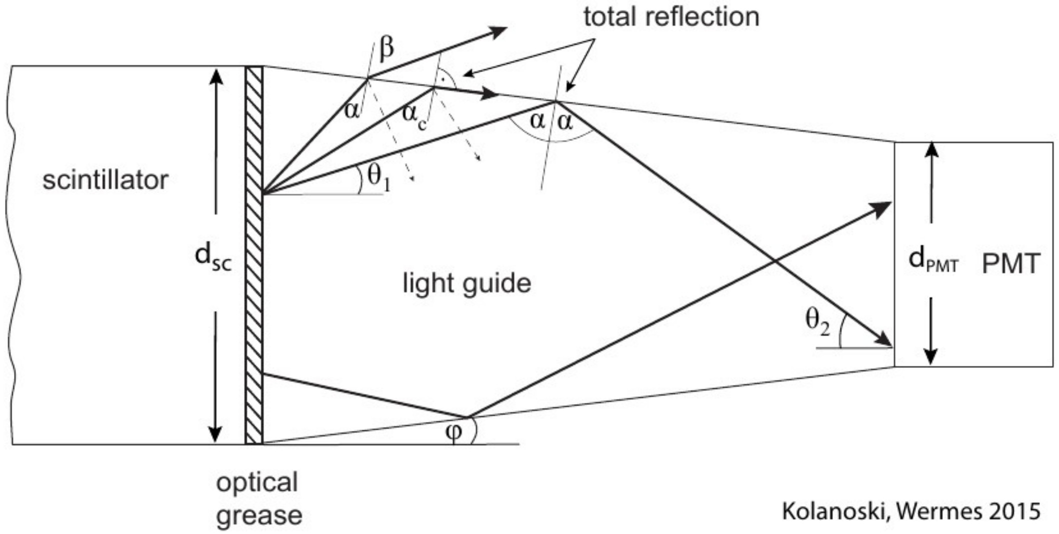
- In light guides the fraction of detected light is limited by Liouville's theorem (product of width and divergence is constant).

$$f_{\text{det}} \leq \frac{A_{out}}{A_{in}}$$

- This does not include losses from photons emitted outside the cone of total reflection.
- Optimization of light collection efficiency includes
  - using 'adiabatic light guiding', i.e. avoiding sharp bends or kinks and large angle changes.
  - wrapping of light guide to improve relection



(a) Light guide in the form of a *fish tail*.



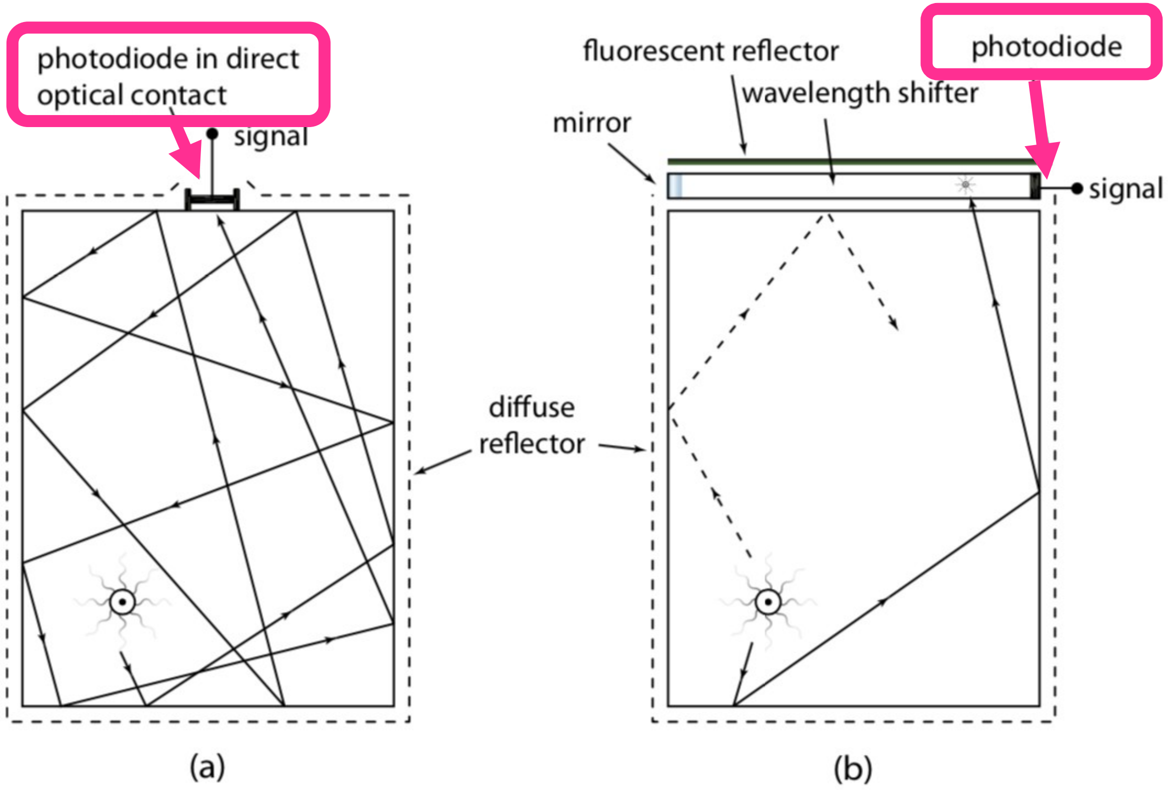
(b) Light guiding by total reflection.

System with photodiodes

Photodiodes and avalanche photodiodes good, when the input light intensity is sufficiently high (e.g. from high energy photons)

Coupling to scintillators can be:
- (a) direct
- (b) via a wavelength shifter

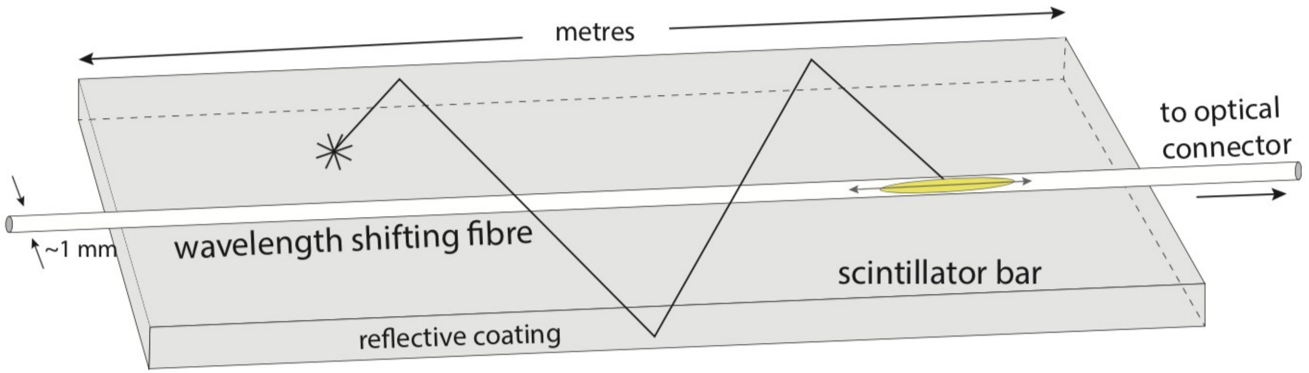
Consider:
- Collection area of photodiode best small (smaller noise, lower cost)
- WLS collects larger amount of light (even with small losses at the internal reflection)



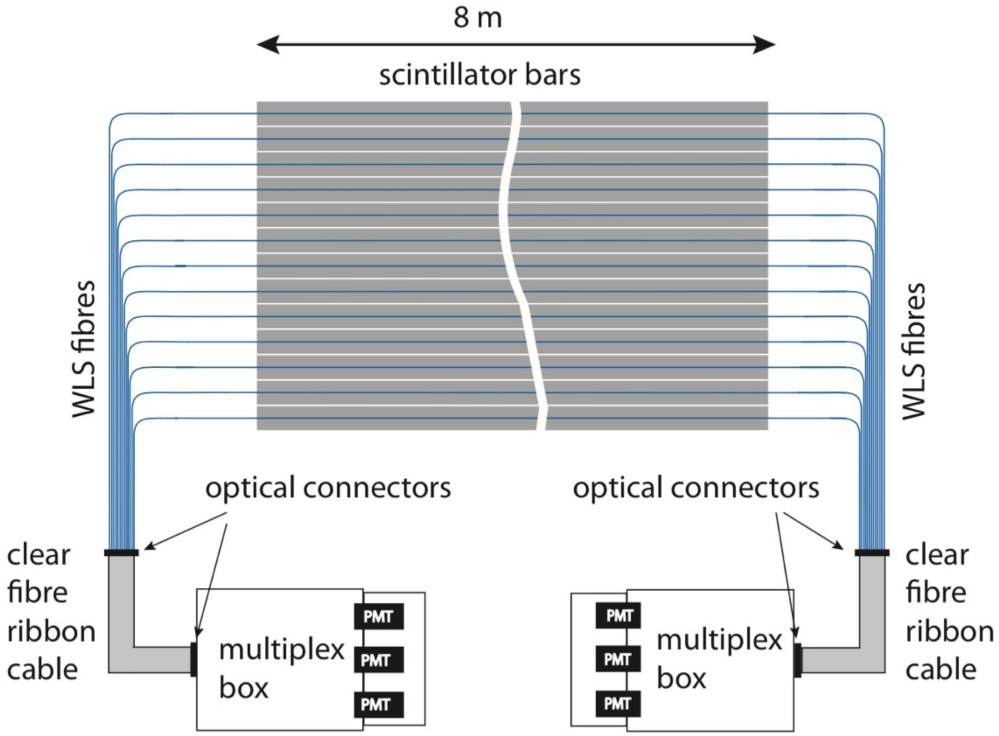
System with wavelength-shifting fibers

For large timing or calorimetric applications, using e.g. plastic scintillator bars:
Wavelength-shifting fibers are embedded in scintillating elements:

- 1-3 mm diameter
- Up to several meters long
- Fed to multichannel PMTs or SiPMs



(a) WLS fibre readout of a scintillator bar.



(b) Scintillator array with WLS fibre readout.

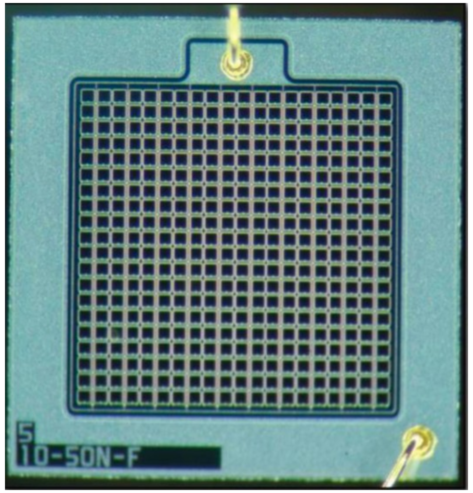
From neutrino oscillation experiment MINOS

- Scintillators
  - Inorganic scintillators
  - Organic scintillators
- Transmission of light
- **Light detection**
  - **Photomultipliers**
  - **(Avalanche) photo-diodes**
  - **Hybrid photon detectors**
- Applications of scintillation detectors

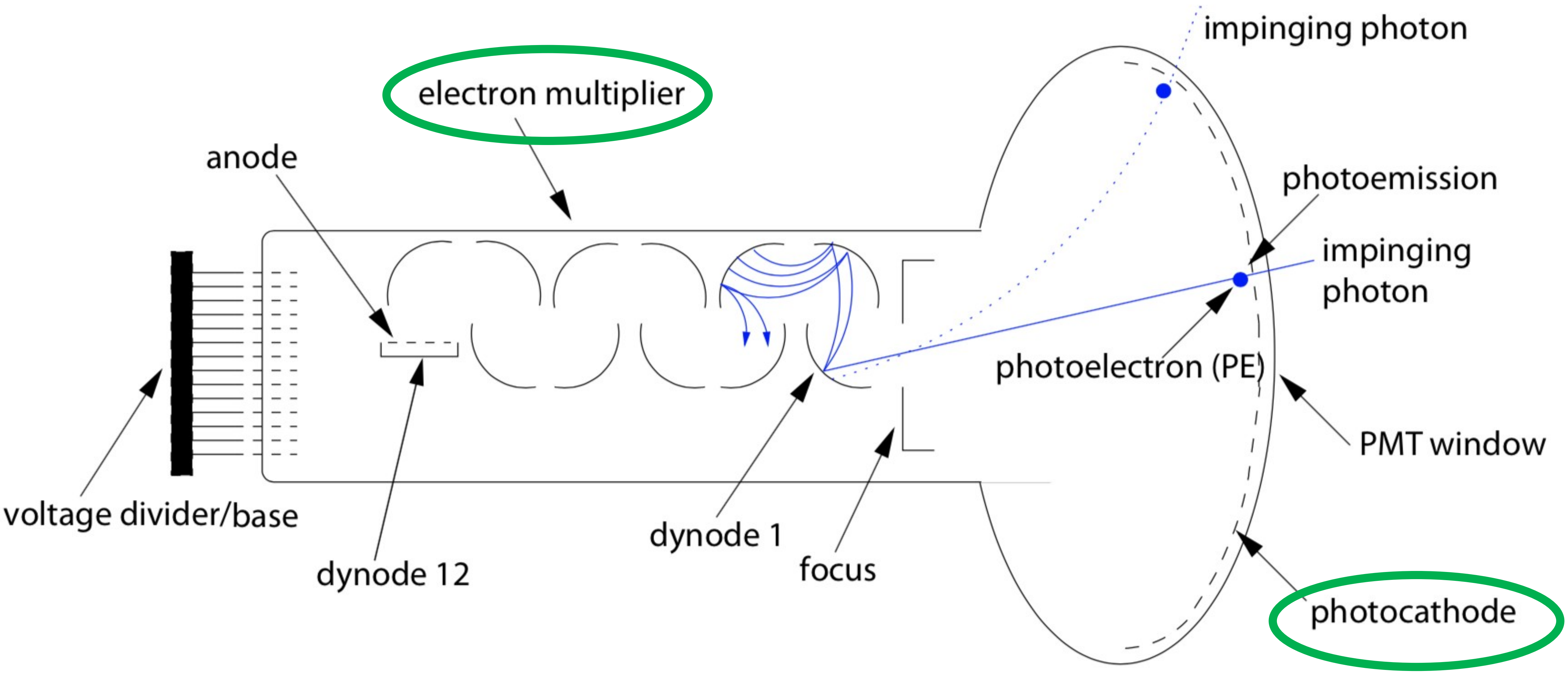
Photon detection

Conversion of light into an electronic signal

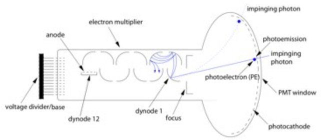
- **Photomultipliers:**
  systems with photo-cathode and electron amplification
  - Dynode system
  - Micro channel plate
- **Semiconductor-based photon detectors:**
  - Photo-diodes
  - Avalanche photo-diodes
- **Hybrid systems:**
  - Hybrid (avalanche) photo-diodes
- **Silicon photomultipliers (SiPM)**



Photomultiplier tube (PMT)



Photomultipliers



Operation principle:

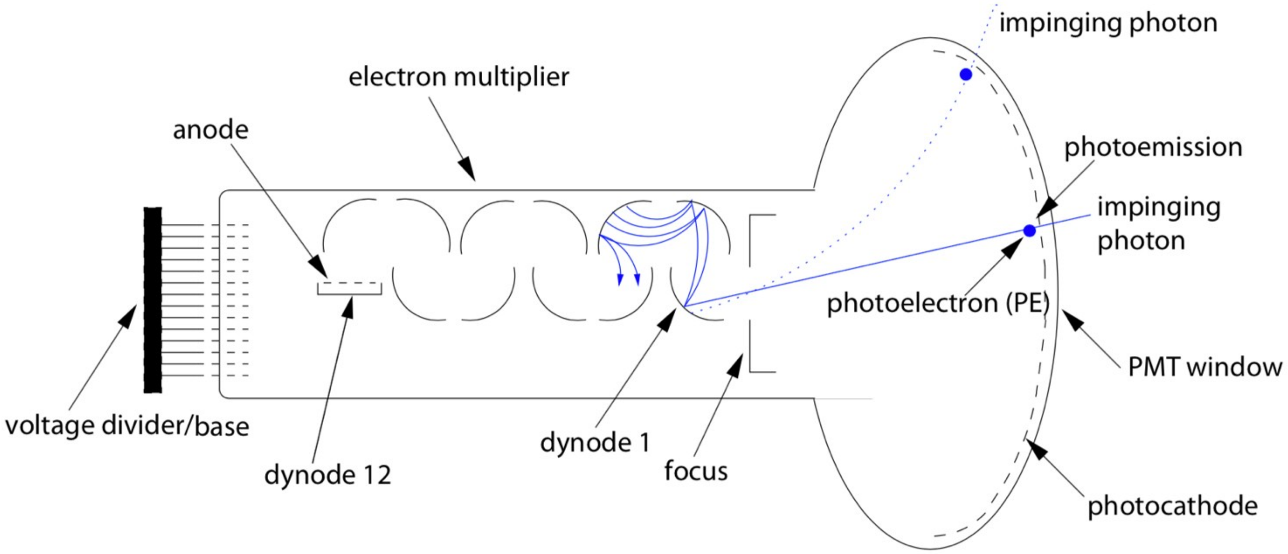
- Photo-electric effect in the **photocathode**

  γ + atom → atom$^+$ + e$^-$

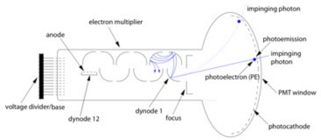
- **Electron amplification** in an electrode system in an evacuated glass tube: dynodes
  - Electrons are accelerated towards dynodes
  - Knock out further electrons in dynode
  - Secondary emission coefficient δ

$$\delta = \frac{\#\ \text{leaving}\ e^-}{\#\ \text{incident}\ e^-}$$

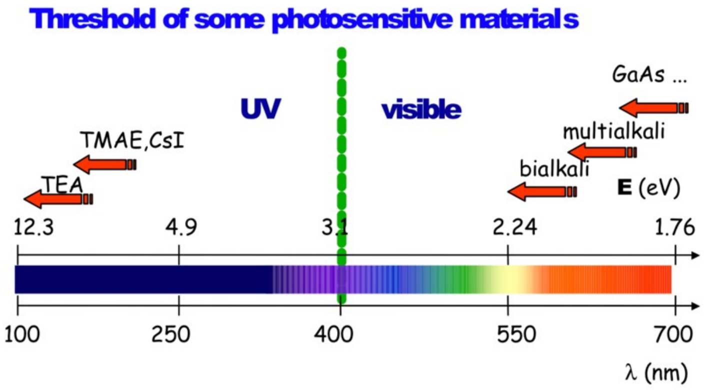
- Amplified signal **readout** at anode



Photomultipliers



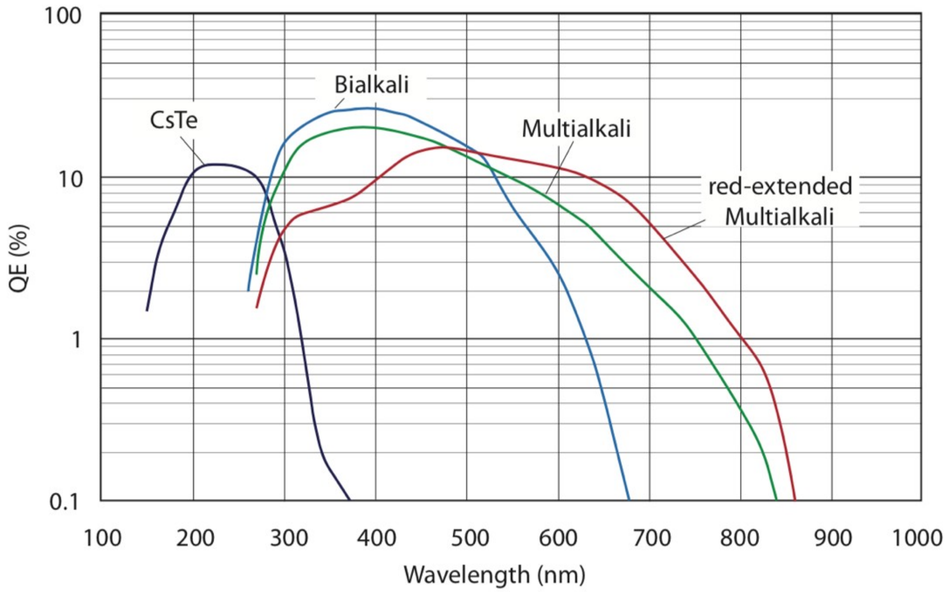
- **Entrance window:**
  - Typically thin glass: imposes cut-off at low wavelengths
  - Sometimes replaced by quarz (lower λ)



- **Photocathode:**
  Quantum yield:

$$Q = \frac{\#\text{photoelectrons}}{\#\text{photons}} \cong 10 - 30\%$$

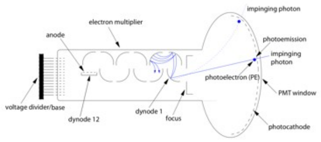
  - Special materials to optimize quantum yield
  - $T_e = h\nu - W$
    W = work function
    in metals: 3-4 eV (too high! as photon energy)
    special alloys: bialkali, multialkali W = 1.5-2 eV

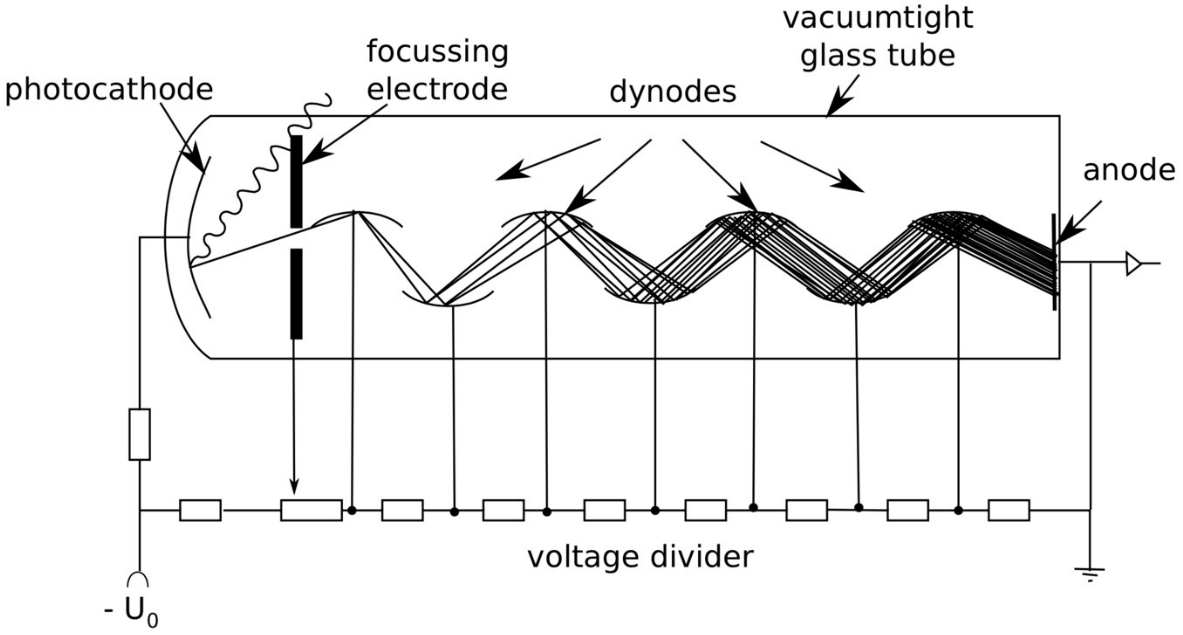


Number of photo-electrons:

$$n_e = \frac{dE}{dx} \times \frac{\text{photons}}{\text{MeV}} \times \text{light collection efficiency} \times \text{quantum efficiency}$$

Photomultipliers



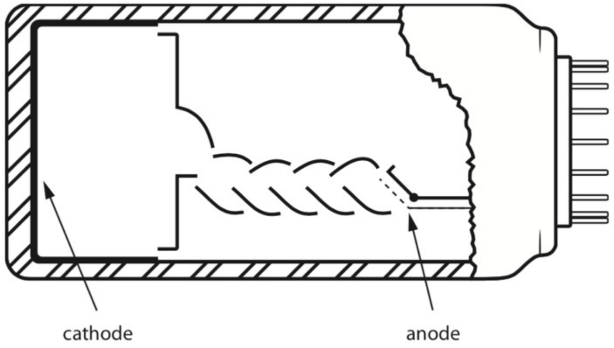


- **Dynode system:**
  Secondary Electron Multiplication (SEM)

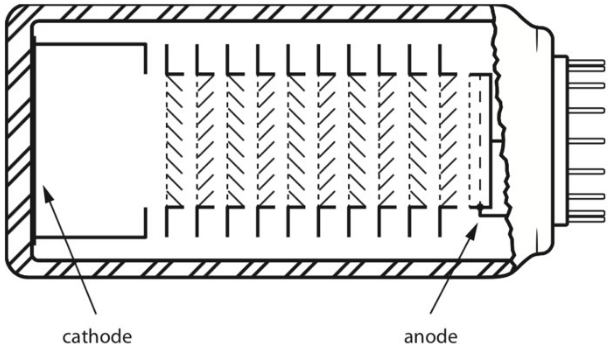
  Very sensitive to magnetic fields:
  - Housing in shielding material (mu-metal)
  - Place them further away from scintillator, where B field lower or absent

  Gain:
  \# dynodes   n = 8-15
  typically δ = 2-10
  → $G = \delta^n = 10^6 - 10^8$

  Limitations to energy measurements:
  - Linearity of PMT can be limited by saturation effects due to space charge
  - Fluctuation of SEM, first stage dominates



(a) Linearly focusing dynodes.



(b) Photomultiplier with slit-like dynodes.

Micro channel plate

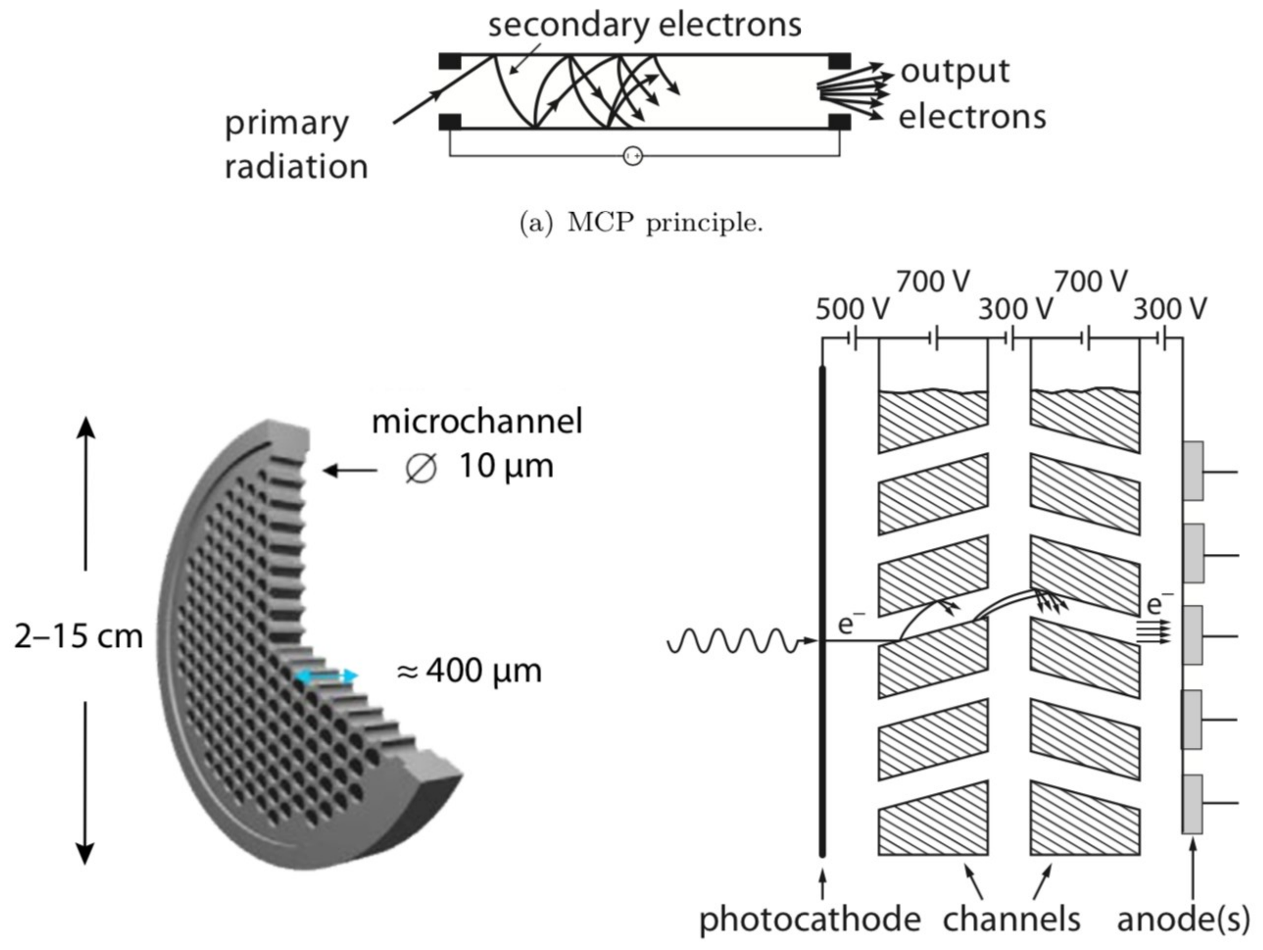
10^4 -10^7 parallel channels (glas tubes) of 10-50 μm diameter, 5-10 mm length

Channels coated inside with resistive layer acting as continuous dynode

Electric field applied between the two ends

Advantages:

- Can be operated inside a magnetic field
- Good for timing applications, reduces the dependence on path length of photoelectons in normal PMTs



(a) MCP principle.

(b) MPC cutout.

(c) Chevron-channel structure.

Fig. 10.15 Microchannel plate photomultiplier (MCP). (Figure (c) adapted from [350] with kind permission, © 1977 IEEE).

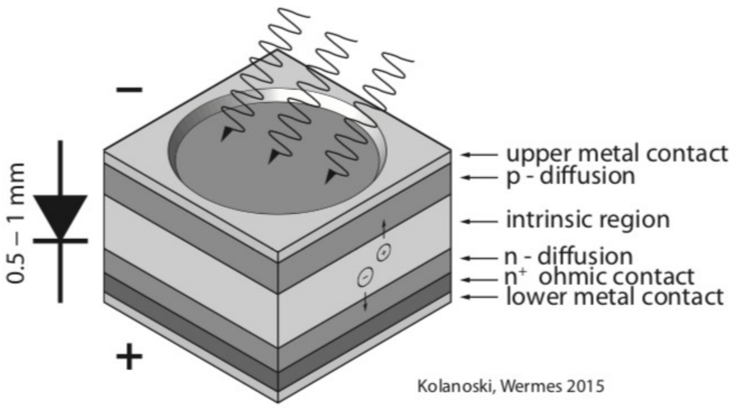
Photodiodes

Photoelectric effect in diode itself (intrinsic region)

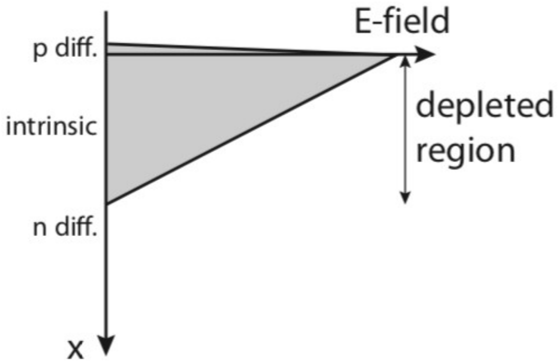
Gain = 1

With respect to PMTs:
+ much larger quantum efficiency over a larger wavelength range
+ cheaper
+ more compact
+ low voltage needed
+ can be operated in magnetic fields

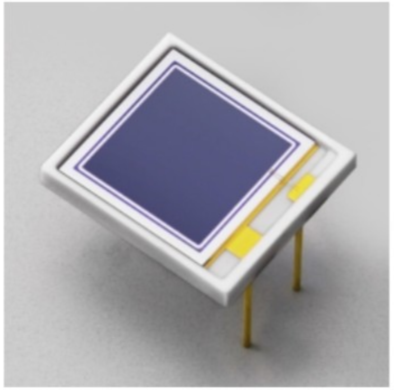
- Small sensitivity at low light intensity
- Worse time resolution
- Small sensitive area



(a) Principle.



(b) Electric field.


(c) Photograph.

Avalanche photodiodes (APD)

Amplification achieved with an additional buried pn-junction, called *metallurgical junction* (high doping and equal in concentration, of both p and n type)

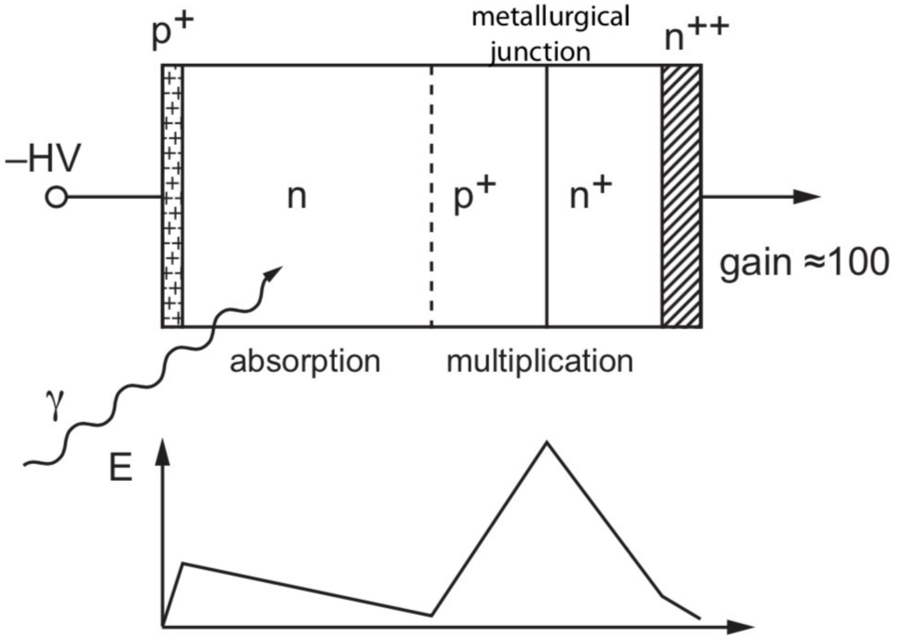
- Very high electric field
- Amplification of charges: gain ~ 10 – 1000 (creates *excess noise*, in addition to the one from leakage current)

Photons absorbed in n-type thicker substrate

Diameters from 100 μm to 1.5 cm

Example: readout of CMS $PbWO_4$ calorimeter

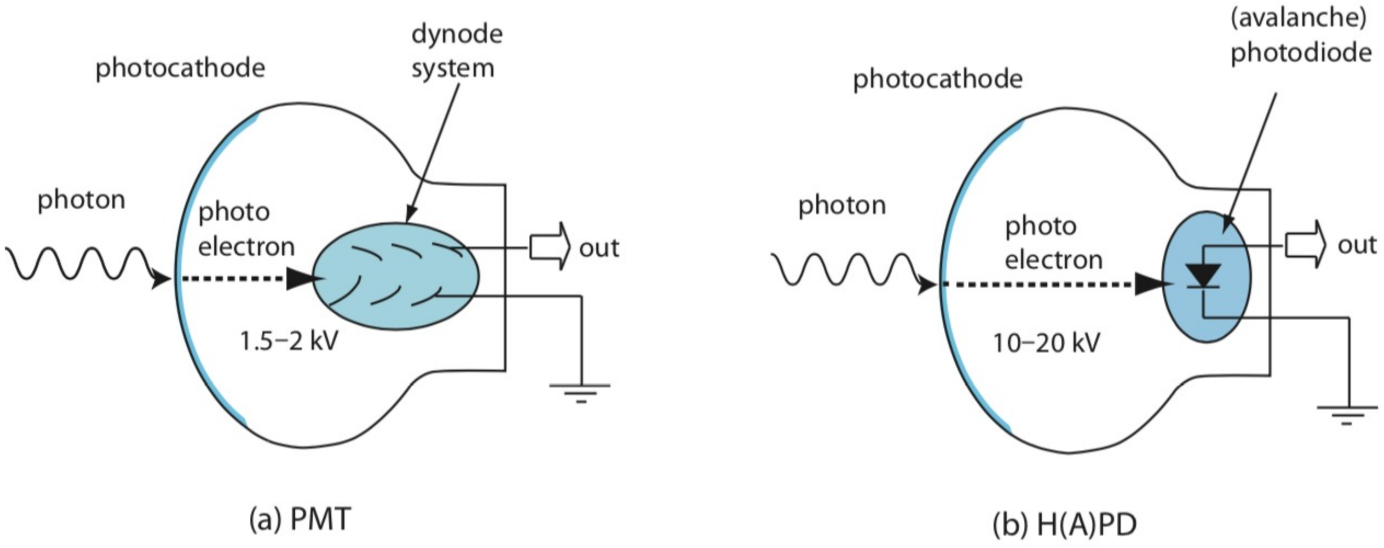
Not to scale



Kolanoski, Wermes 2015

Can be operated in Geiger mode: → **Single Photon Avalanche Diode (SPAD)**

Hybrid photon detectors



Combine photocathode with semiconductor photon detector: Hybrid (Avalanche) Photo Diode

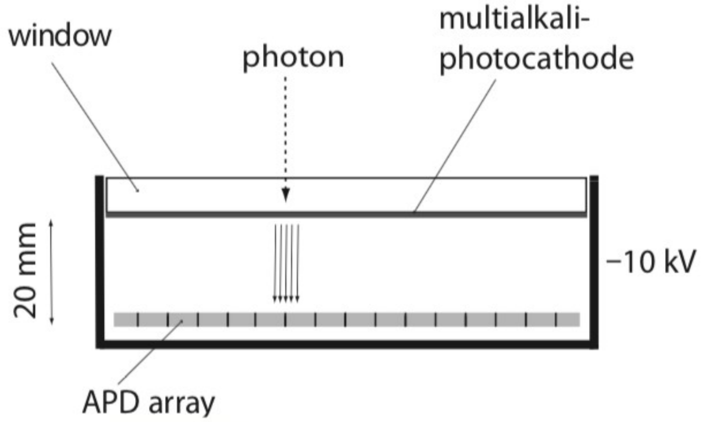
- Use of photocathode extends the wavelength range of photodiodes to short wavelengths
- Using the (Avalanche)PhotoDiode instead of the dynodes removes the problem of operating in a magnetic field
- Semiconductor diodes can be structured, to create anodes with spatially resolving pad or pixel structures

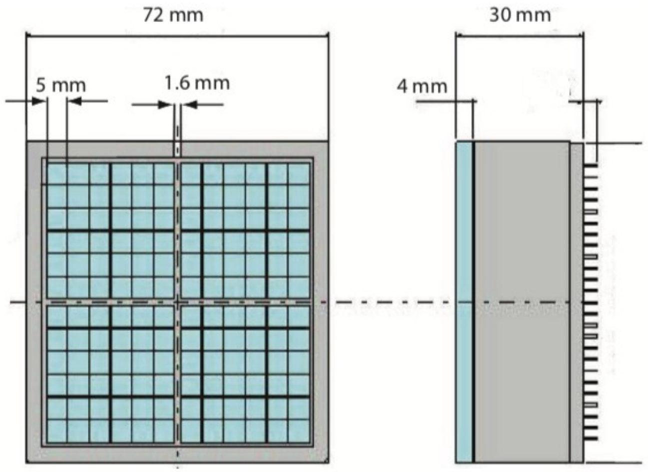
Hybrid Avalanche Photodiode (HAPD)

Photosensitive photodiode
+
Array (e.g. 12x12) of avalanche photodiodes

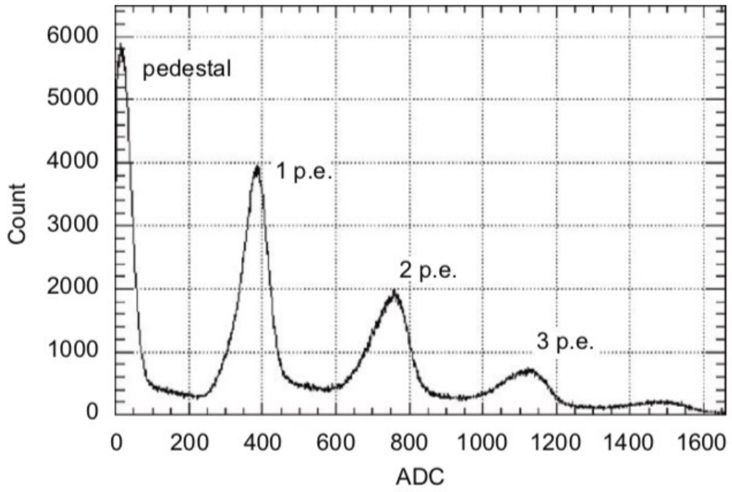
- Photoelectrons are accelerated to produce up to 10^3 e/h pairs in the silicon
- APD further gain of 40-50

→ Excellent Signal/Noise
→ High energy resolution (first stage crucial)
→ Excellent timing resolution
→ Operate well up to B = 1 T





(a) Composition.



(b) Photoelectron spectrum.

Silicon Photomultiplier (SiPM)

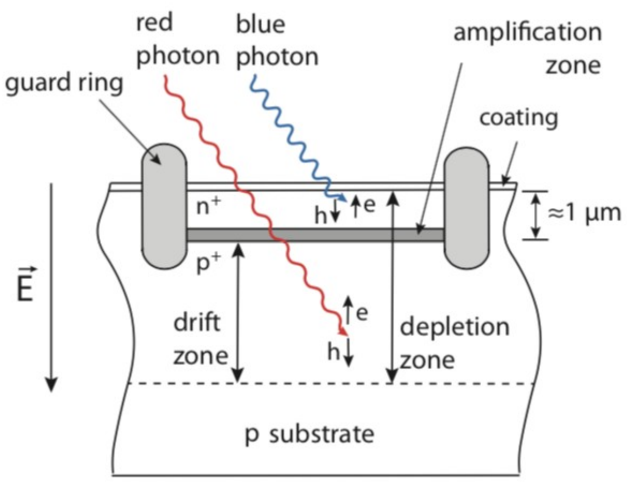
(no photocathode)

G-APDs: APD pixel array operated in limited Geiger mode
→ Sensitivity to single photons

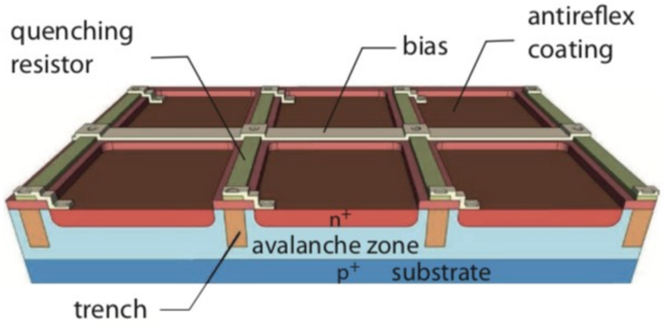
- Small pixels (15-70 μm)
- Gain ~ 10^6
- Digital pixel response
- Breakdown quenched via resistors

Assuming a photon hits one cell
→ signal intensity is given by the number of pixels firing

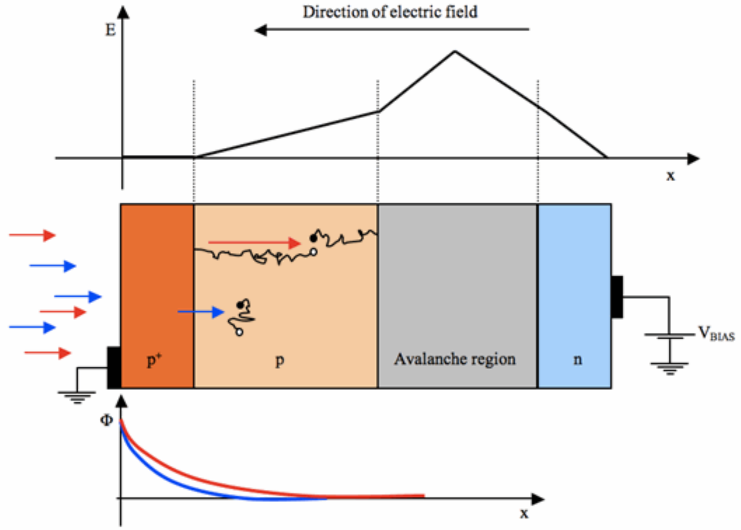
Source: Kolanoski/Wermes 2015



(a) SiPM cell.



(b) SiPM array.



Source: Hamamatsu.com

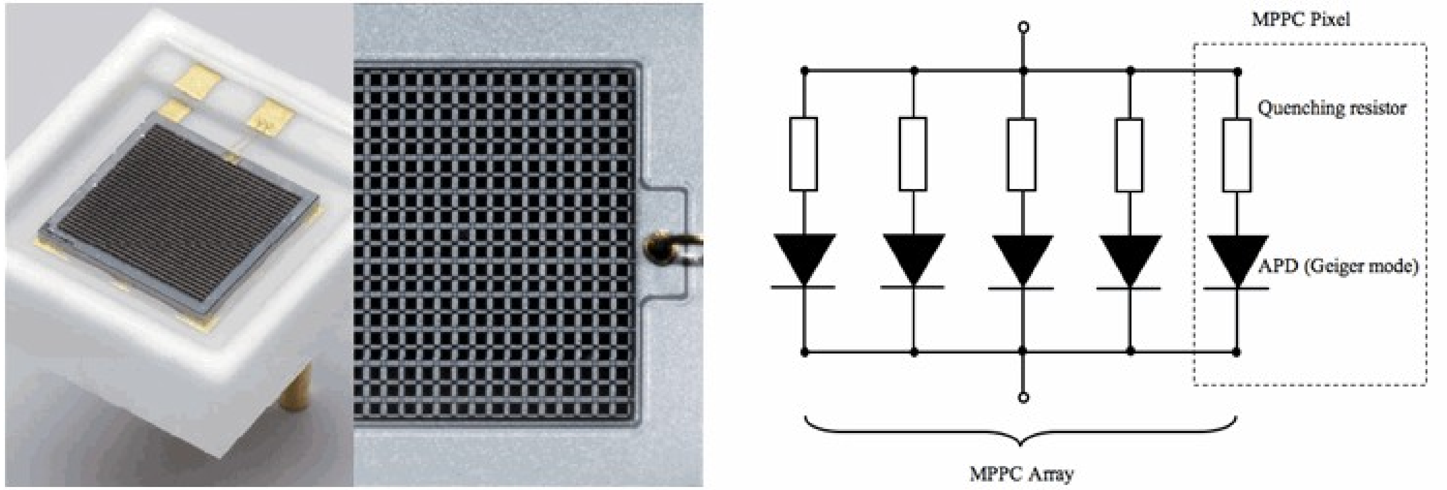
Silicon Photomultiplier (SiPM)

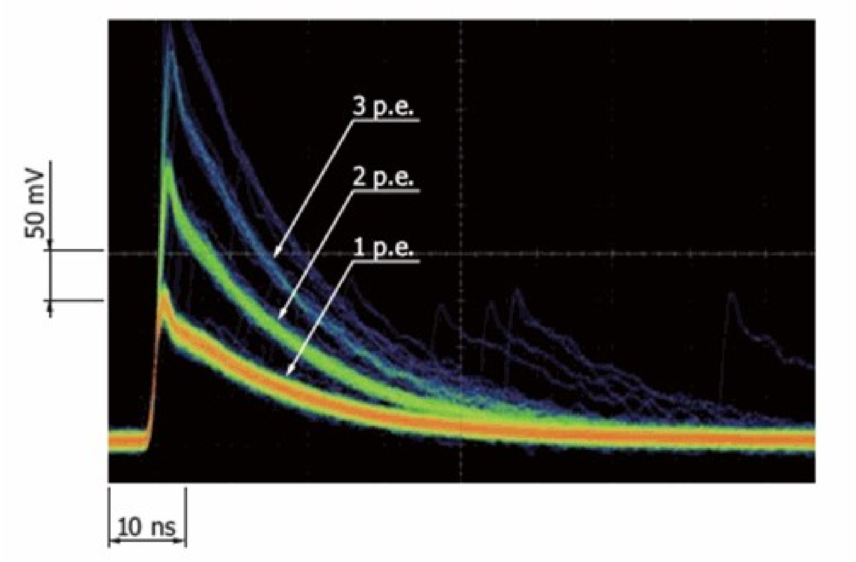
(no photocathode)

G-APDs: APD pixel array operated in limited Geiger mode
→ Sensitivity to single photons

- Small pixels (15-70 μm)
- Gain ~ 10^6
- Digital pixel response
- Breakdown quenched via resistors

Assuming a photon hits one cell
→ signal intensity is given by the number of pixels firing





- Scintillators
  - Inorganic scintillators
  - Organic scintillators

- Transmission of light

- Light detection
  - Photomultipliers
  - (Avalanche) photo-diodes
  - Hybrid photon detectors

- **Applications of scintillation detectors**

Applications

Energy measurement, calorimetry

Inorganic crystals + PMT or APDs

Sampling calorimeters: absorber (Fe, W, U) + scintillator + wavelength-shifting fibers

Time-of-flight detector for particle identification

Scintillating fibers for tracking

LHCb SciFi tracker

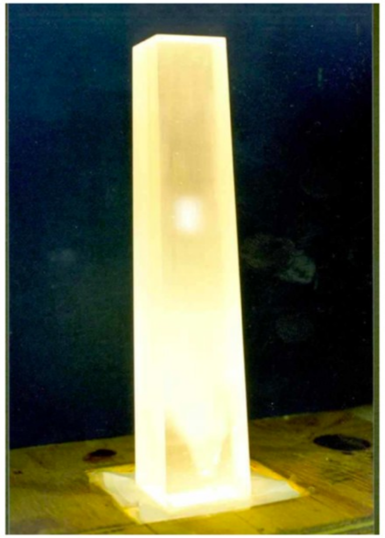
Nobel gas scintillators

Xenon1T experiment, Dark Matter searches

Applications: (homogeneous) calorimeters with inorganic crystals

BaBar (SLAC)

- 6580 CsI(Tl) crystals, 5.9 m^3
- Readout: Si photodiodes (gain=1)



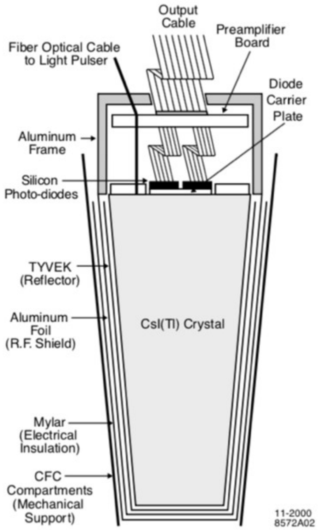


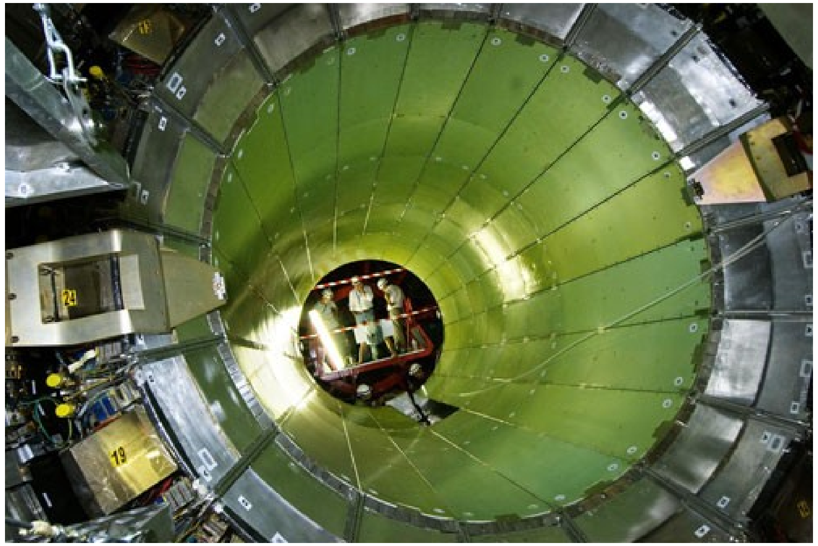
Fig. 3. Left: Photograph of a CsI(Tl) crystal lit from the bottom by a light bulb. Right: Schematic drawing (not to scale) of a crystal with attached electronics.

CMS at the LHC (CERN)

- 76150 $PbWO_4$ crystals, 11 m^3
- Readout: avalanche photodiodes (gain=50)

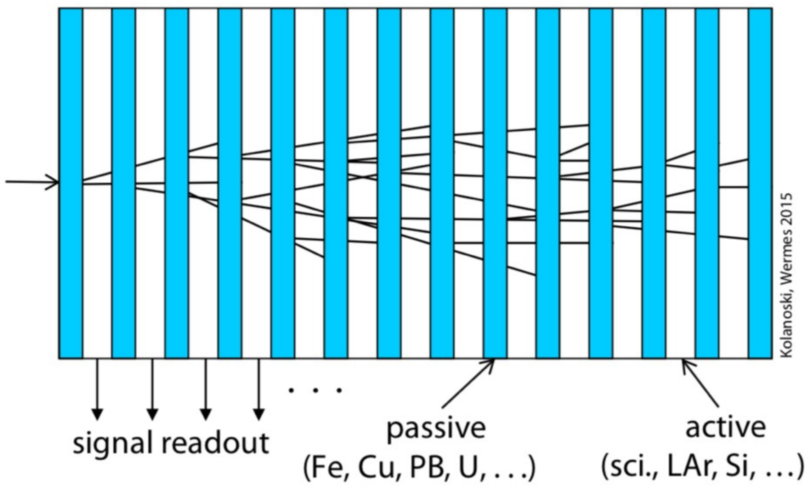
$PbW0_4$

+ Fast
+ Small radiation length
+ Good radiation hardness
- ~100-200 photons/MeV



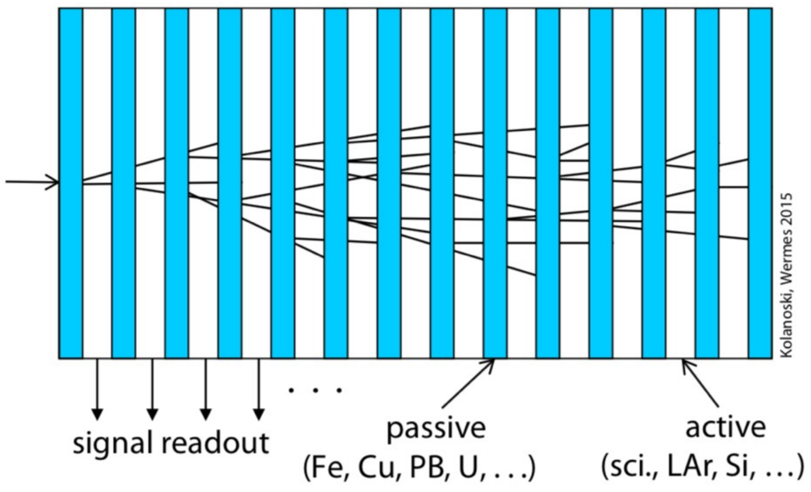
Applications: sampling calorimeters

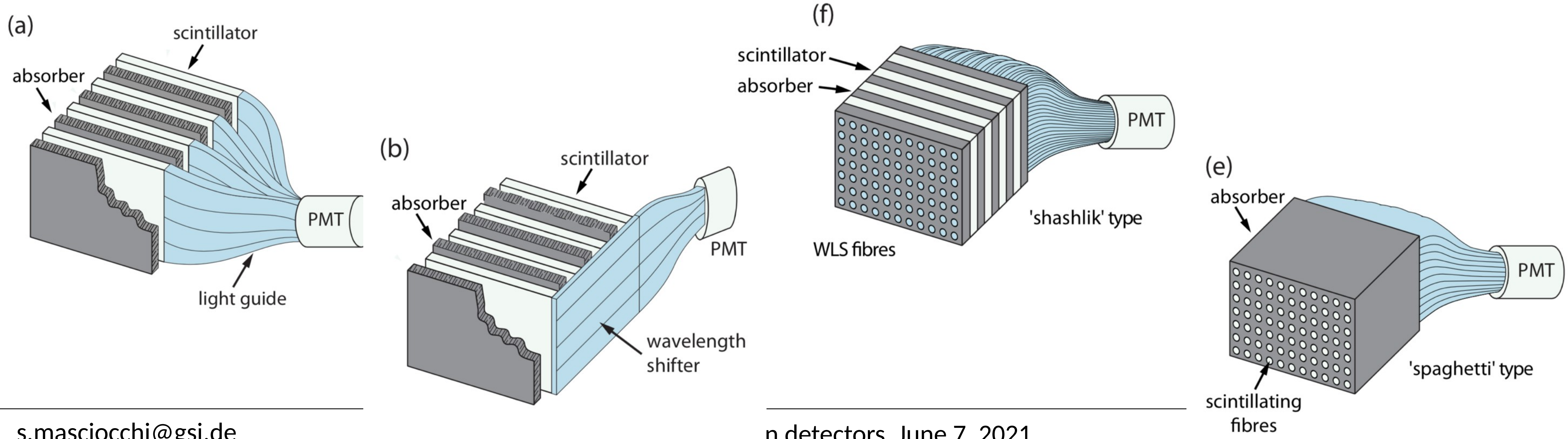
Calorimeters realized alternating:
- Passive, heavy materials (Fe, W, U)
- Sensitive material scintillator



Applications: sampling calorimeters

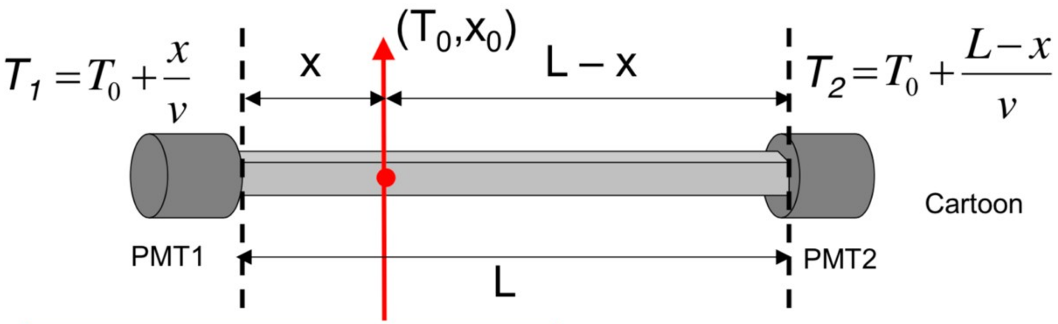
Calorimeters realized alternating:
- Passive, heavy materials (Fe, W, U)
- Sensitive material scintillator
  - (a) connected via light guide to PMTs
  - (b) and (f) with embedded wavelength-shifter, leading to PMTs, APDs or SiPMs
  - (e) scintillating fibers act as active medium (spaghetti calorimeter)





Applications: TOF detector

Scintillator bars, in PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL)



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

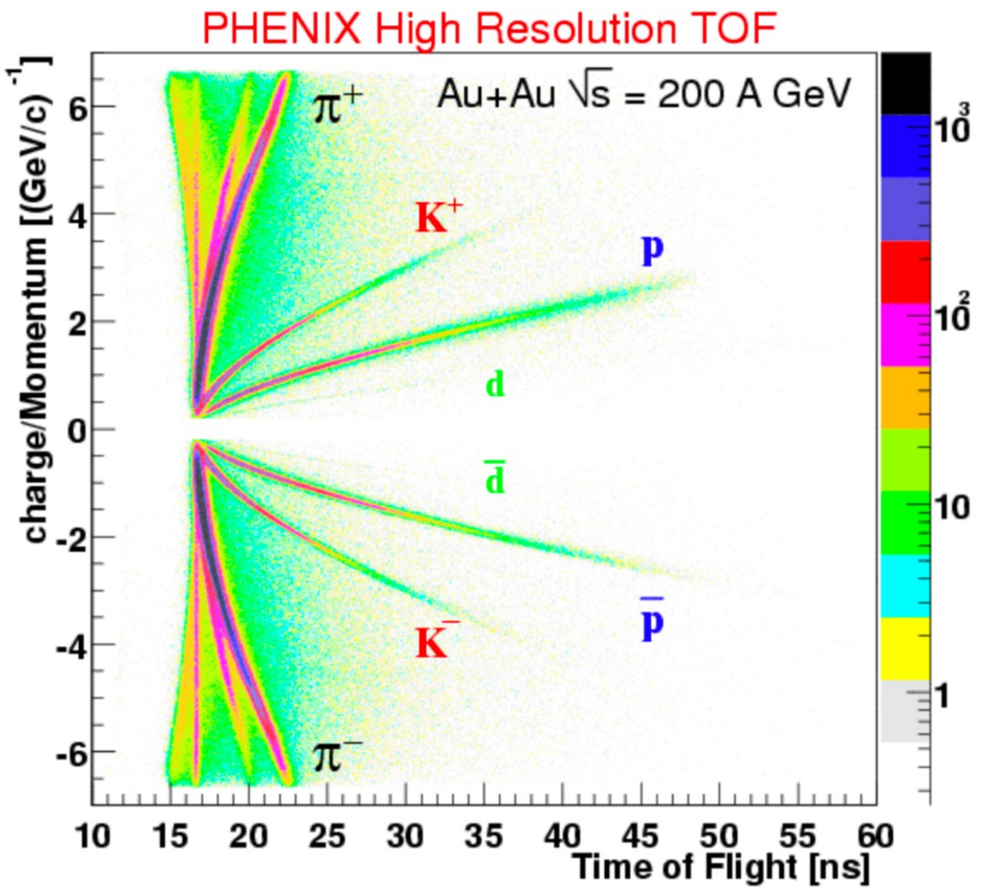
$$Y\ position = \frac{T_1 - T_2}{2} v$$

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

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

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

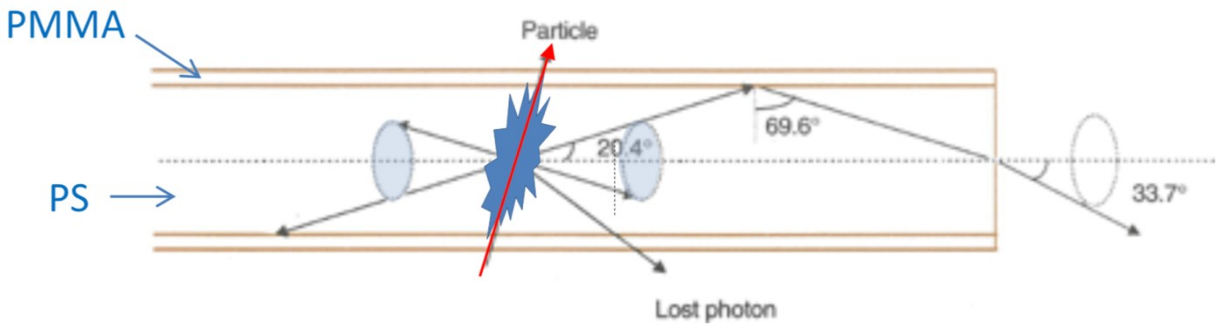
Time resolution ~ 100 ps



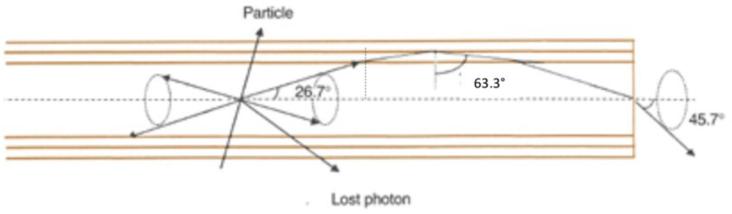
Courtesy of Ralf Averbeck (GSI)

Applications: scintillating fibers

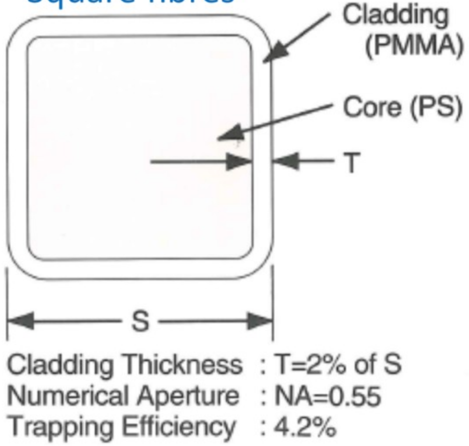
Scintillating fiber: Polysteren (PS) core (n~1.59) + plexiglass (PMMA) cladding (n~1.49)



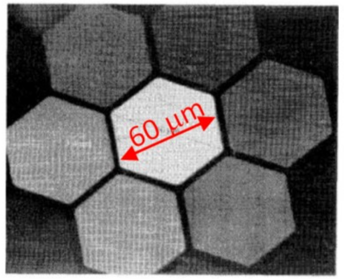
Even double cladding for better light reflection



Square fibres

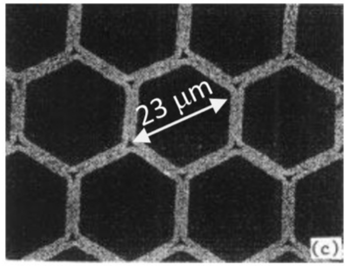


hexagonal fibres



C.D. Ambrosio et al., NIM A 325 (1993), 161

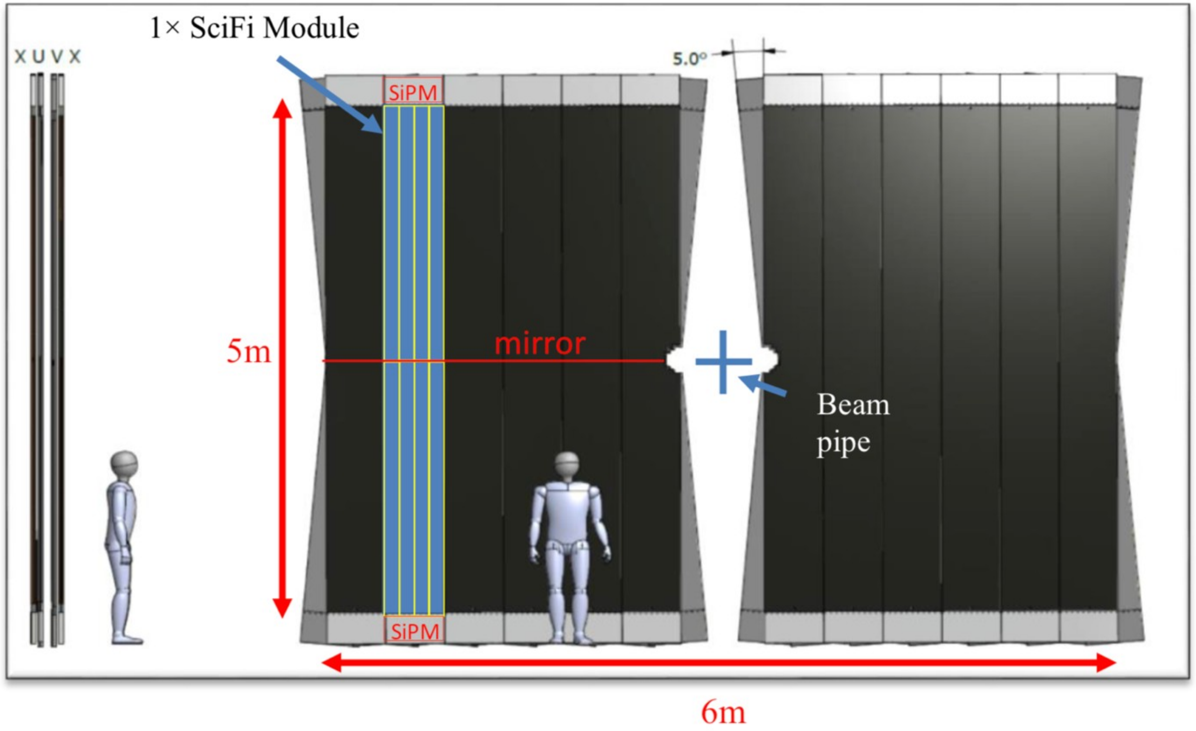
glass capillaries with liquid scintillator



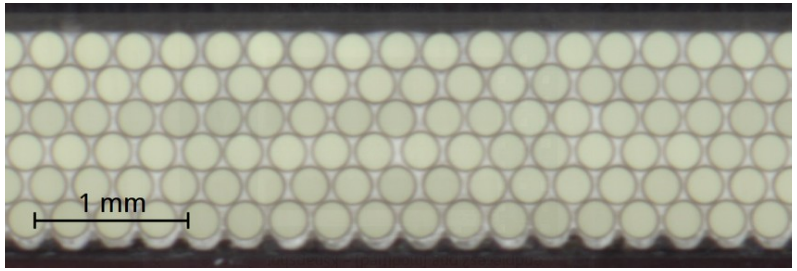
Annis P, et al. NIM A367 (1995) 377

Courtesy of Christian Joram (CERN)

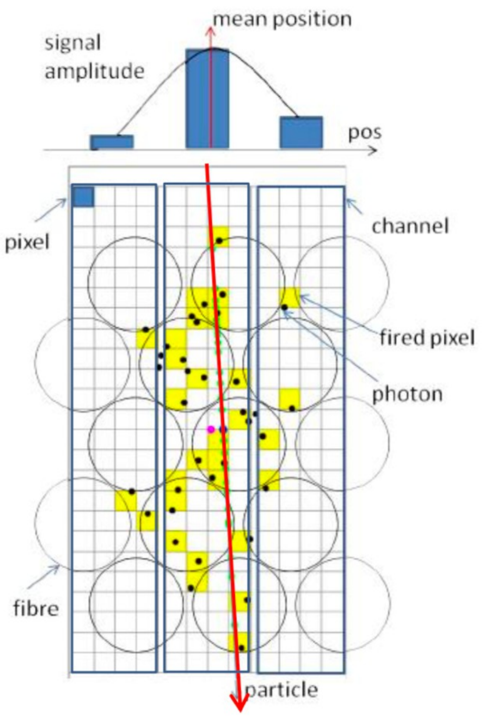
Applications: scintillating fibers for LHCb

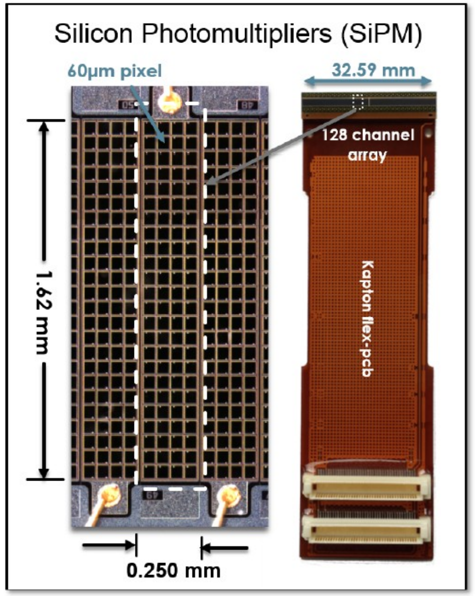


Scintillating fibre mat:
6 layers + epoxy glue



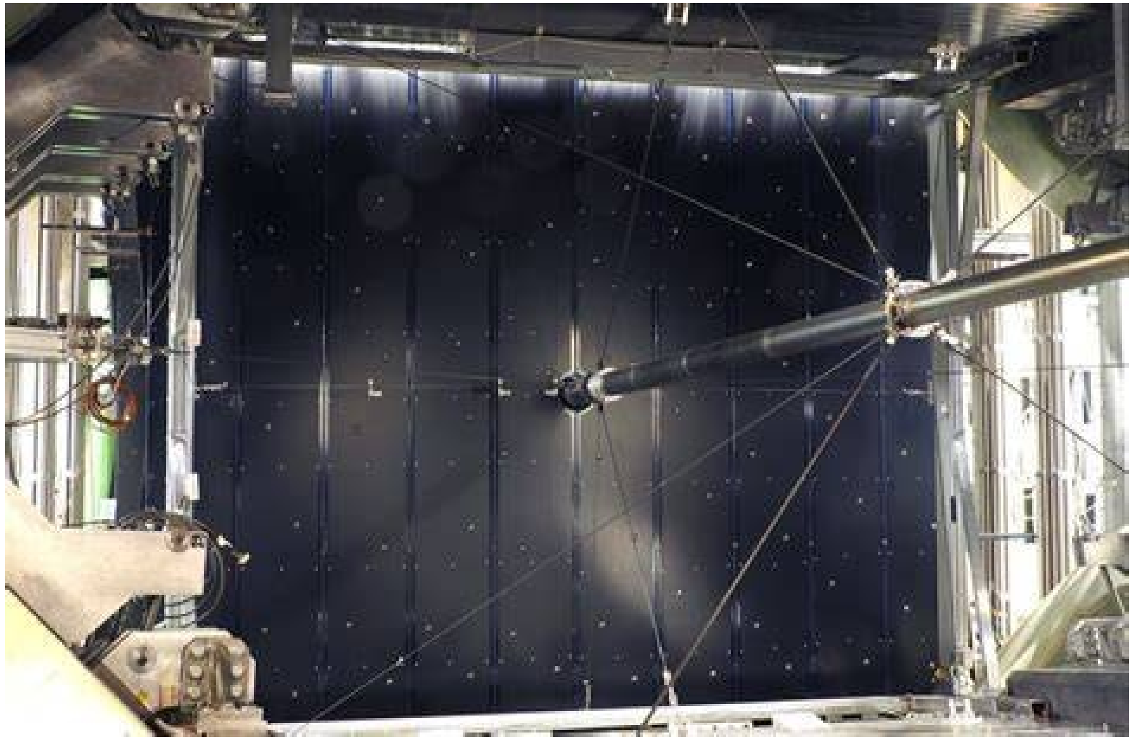
- 1024 mats, 128 modules
- 340 m^2 total area
- ~ 11,000 km of fiber
- 4096 SiPM arrays → 525,000 SiPM channels
  1 channel = 96 pixels (62x57 μm^2)



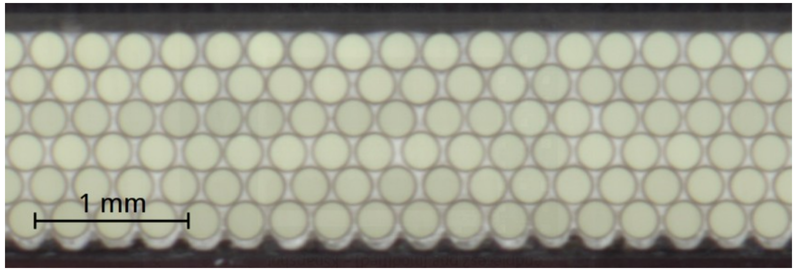


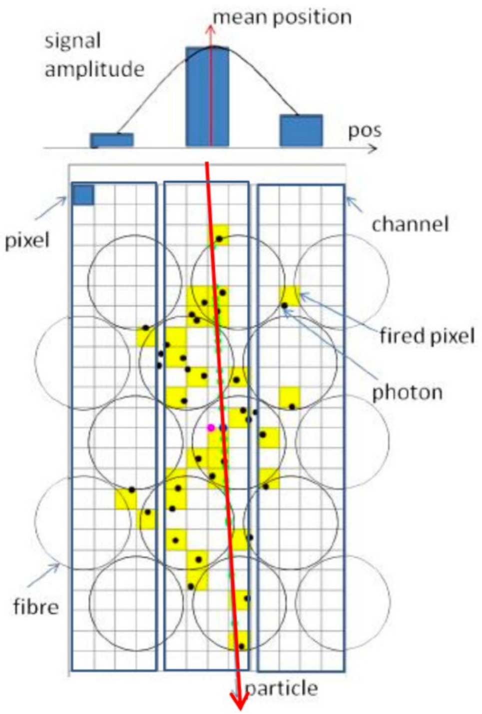
Courtesy of Christian Joram (CERN)

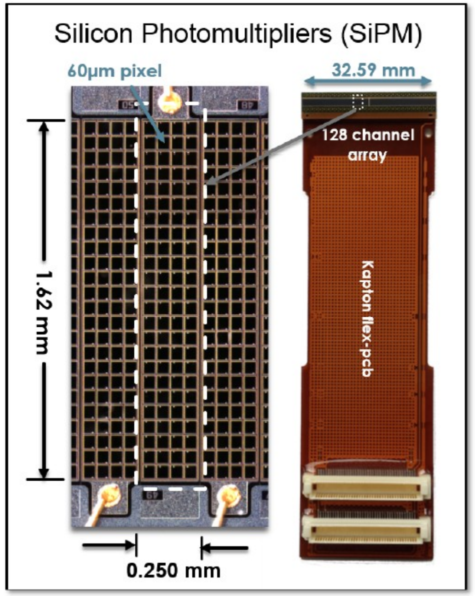
Applications: scintillating fibers for LHCb



Scintillating fibre mat:
6 layers + epoxy glue







- 1024 mats, 128 modules
- 340 m^2 total area
- ~ 11,000 km of fiber
- 4096 SiPM arrays → 525,000 SiPM channels
  1 channel = 96 pixels (62x57 μm^2)

Courtesy of Christian Joram (CERN)

Applications: Xenon1T dark matter experiment

Nobel gases exhibit some degree of scintillation

Cryogenic liquid gases: LAr, LKr, LXe produce photons in the UV region (130-175 nm)

Xenon1T experiment, Gran Sasso

Search for WIMPs

Dual phase TPC:
Scintillation light produced both in the liquid Xe and in the gaseous Xe

Photons are **readout out by PMTs**:
248 (127 top, 121 bottom)
low-radioactivity PMTs

- 76.2 mm diameter
- Bialkali-LT photocathode: 34.5% quantum efficiency at 178 nm
- 12 dynodes
- Gain > 3×10^6