Scintillation Detectors

Particle Detection via Luminescence

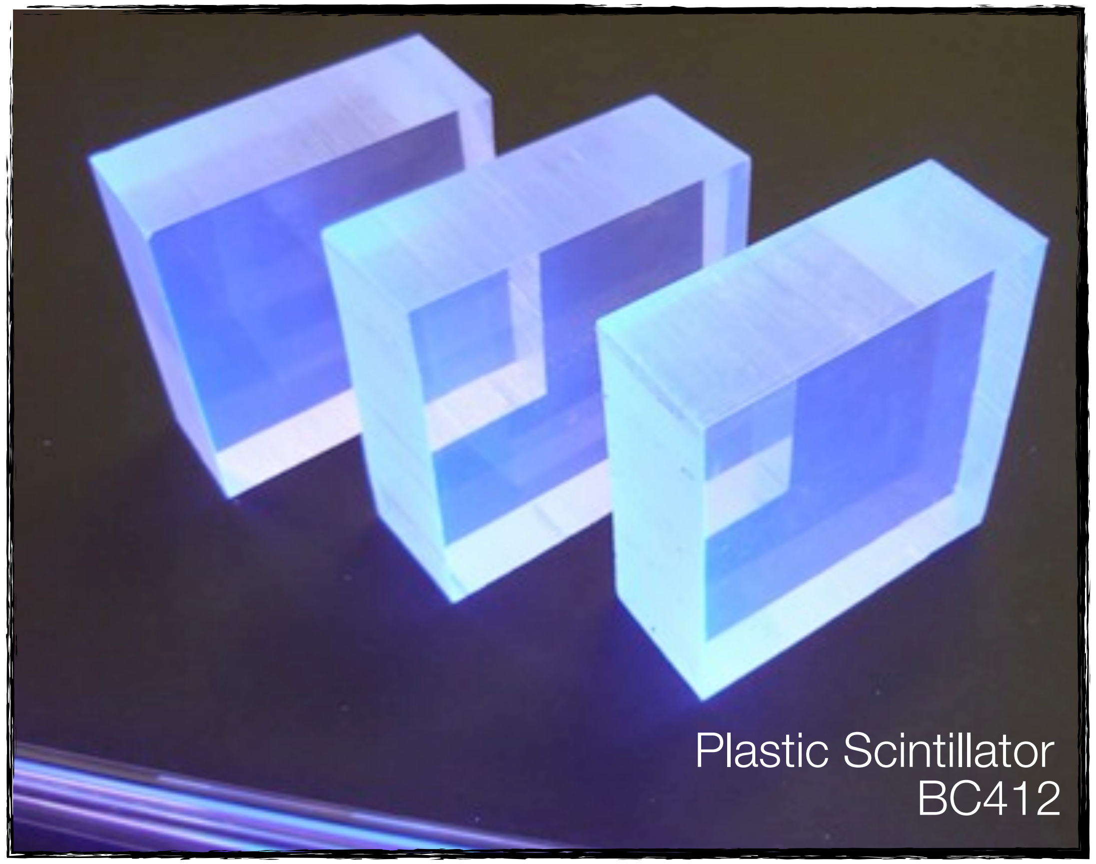
Scintillators – General Characteristics

Principle:

dE/dx converted into visible light
Detection via photosensor
[e.g. photomultiplier, human eye ...]

Main Features:

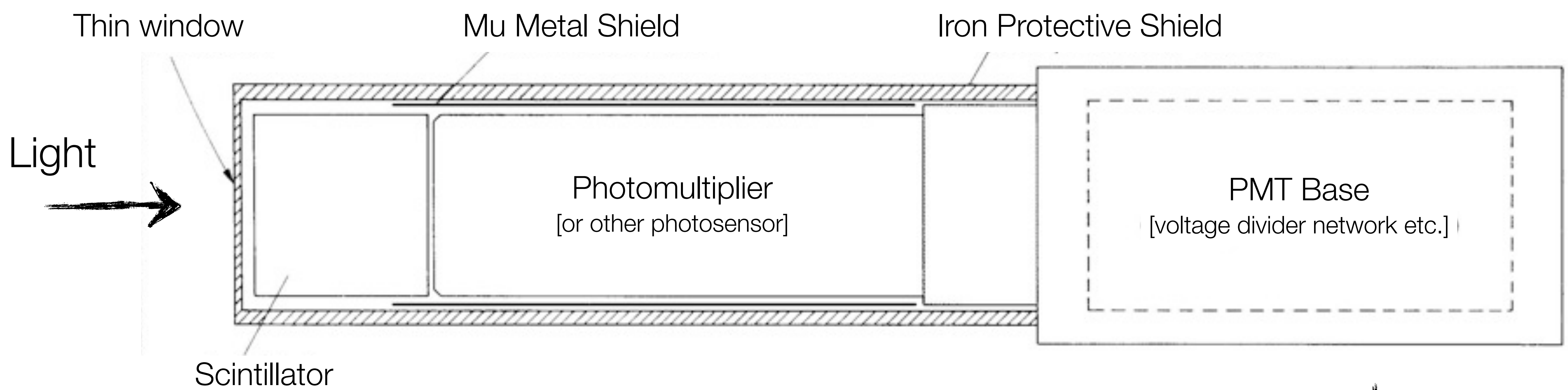
Sensitivity to energy
Fast time response
Pulse shape discrimination



Requirements

High efficiency for conversion of exciting energy to fluorescent radiation
Transparency to its fluorescent radiation to allow transmission of light
Emission of light in a spectral range detectable for photosensors
Short decay time to allow fast response

Scintillators – Basic Counter Setup

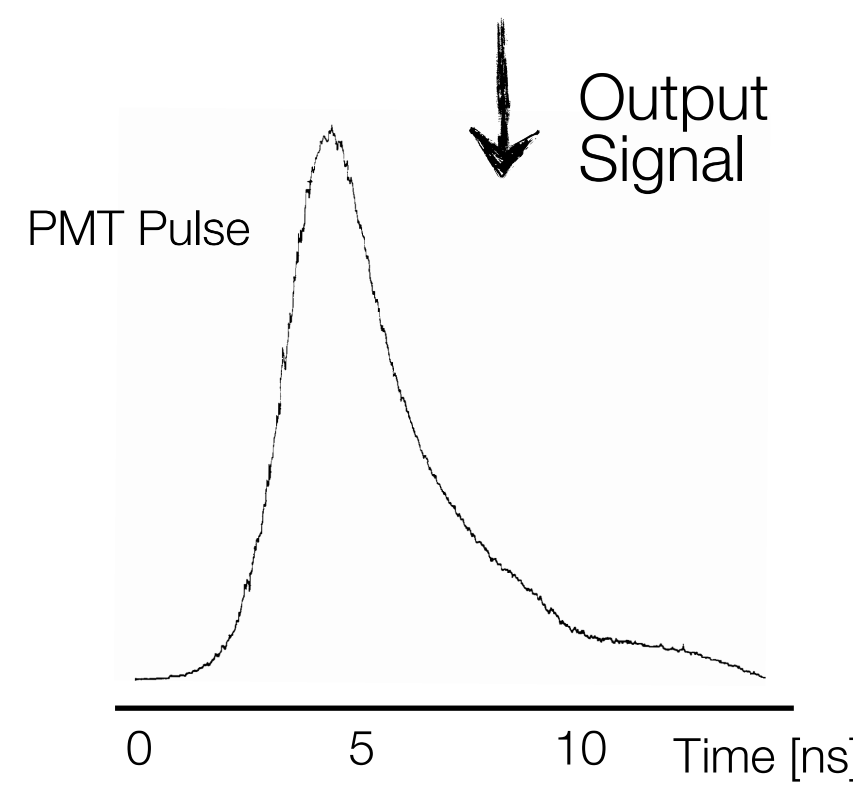


Scintillator Types:

Organic Scintillators
Inorganic Crystals
Gases

Photosensors

Photomultipliers
Micro-Channel Plates
Hybrid Photo Diodes
Visible Light Photon Counter
Silicon Photo Multipliers



Inorganic Crystals

Materials:

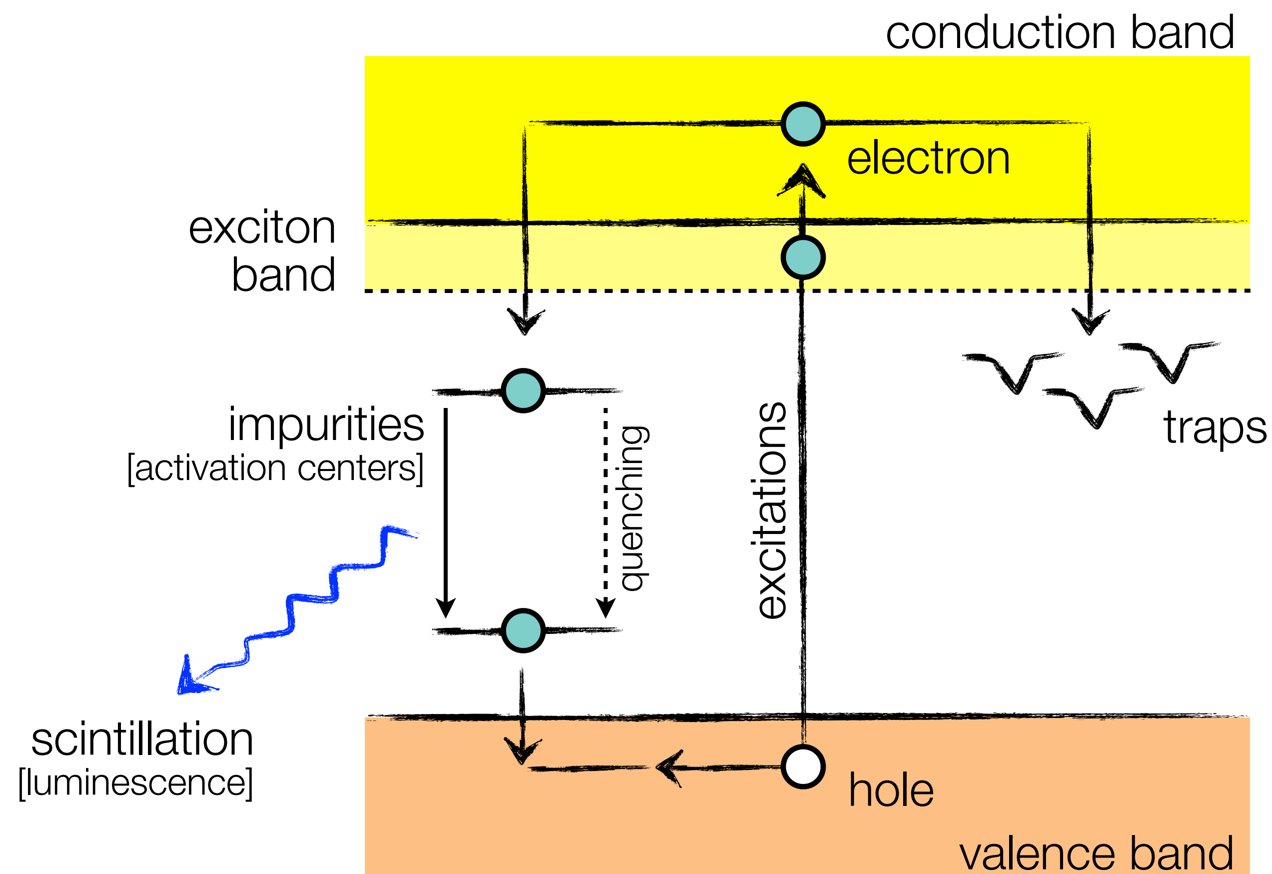
Sodium iodide (NaI)
Cesium iodide (CsI)
Barium fluoride (BaF_2)
...

Mechanism:

Energy deposition by ionization
Energy transfer to impurities
Radiation of scintillation photons

Time constants:

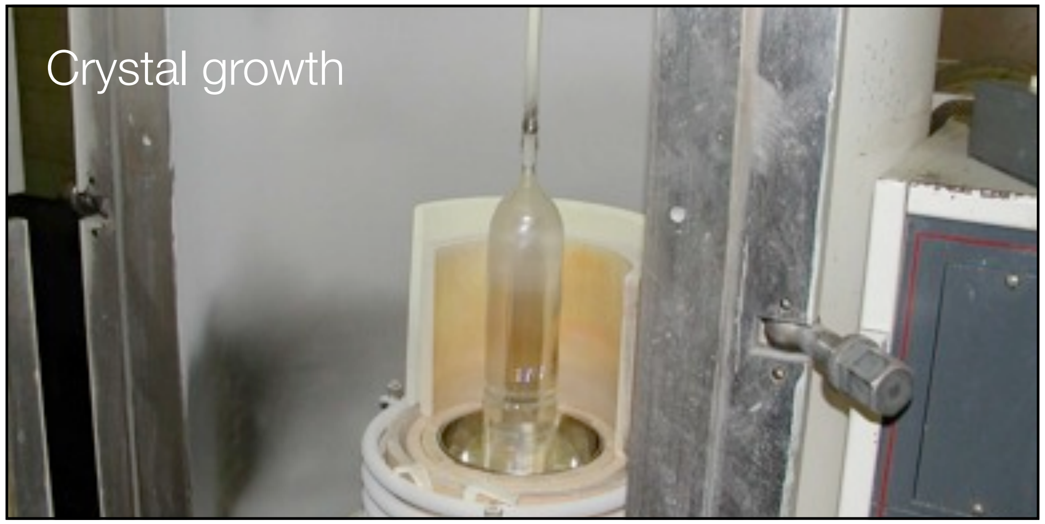
Fast: recombination from activation centers [ns ... µs]
Slow: recombination due to trapping [ms ... s]



Energy bands in impurity activated crystal

showing excitation, luminescence, quenching and trapping

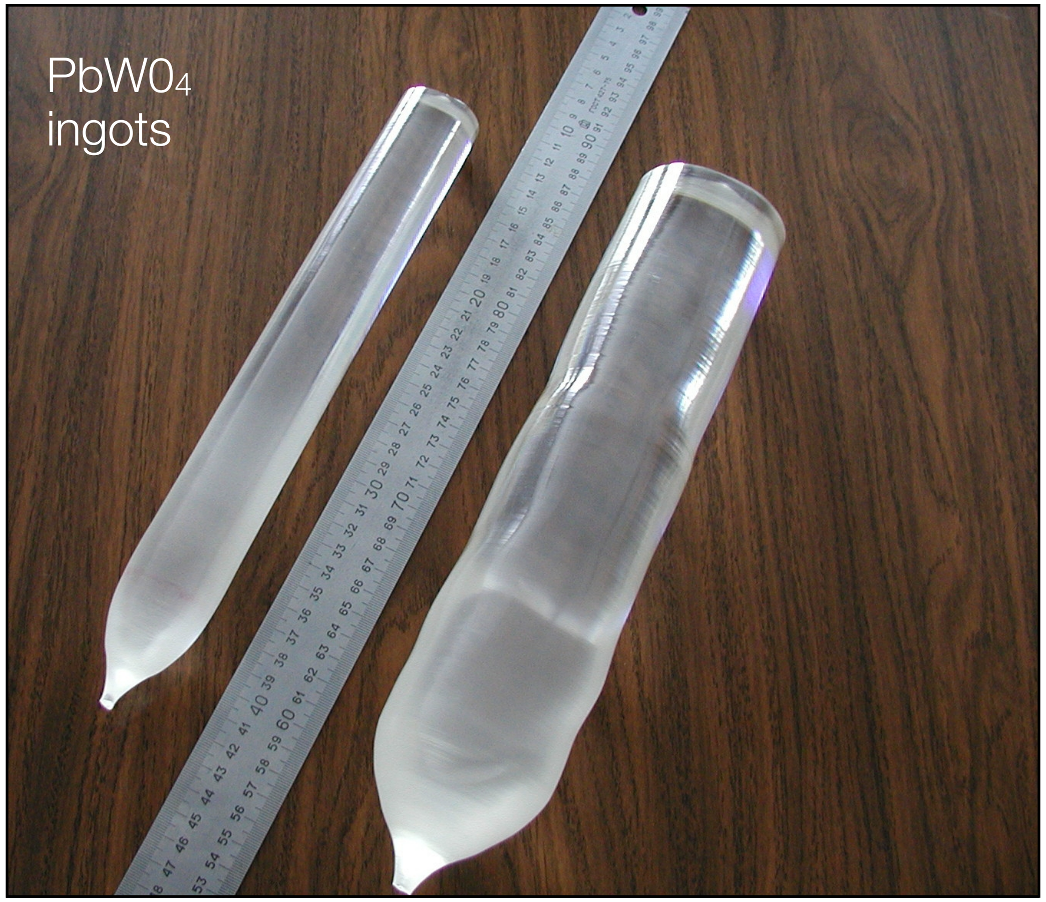
Inorganic Crystals



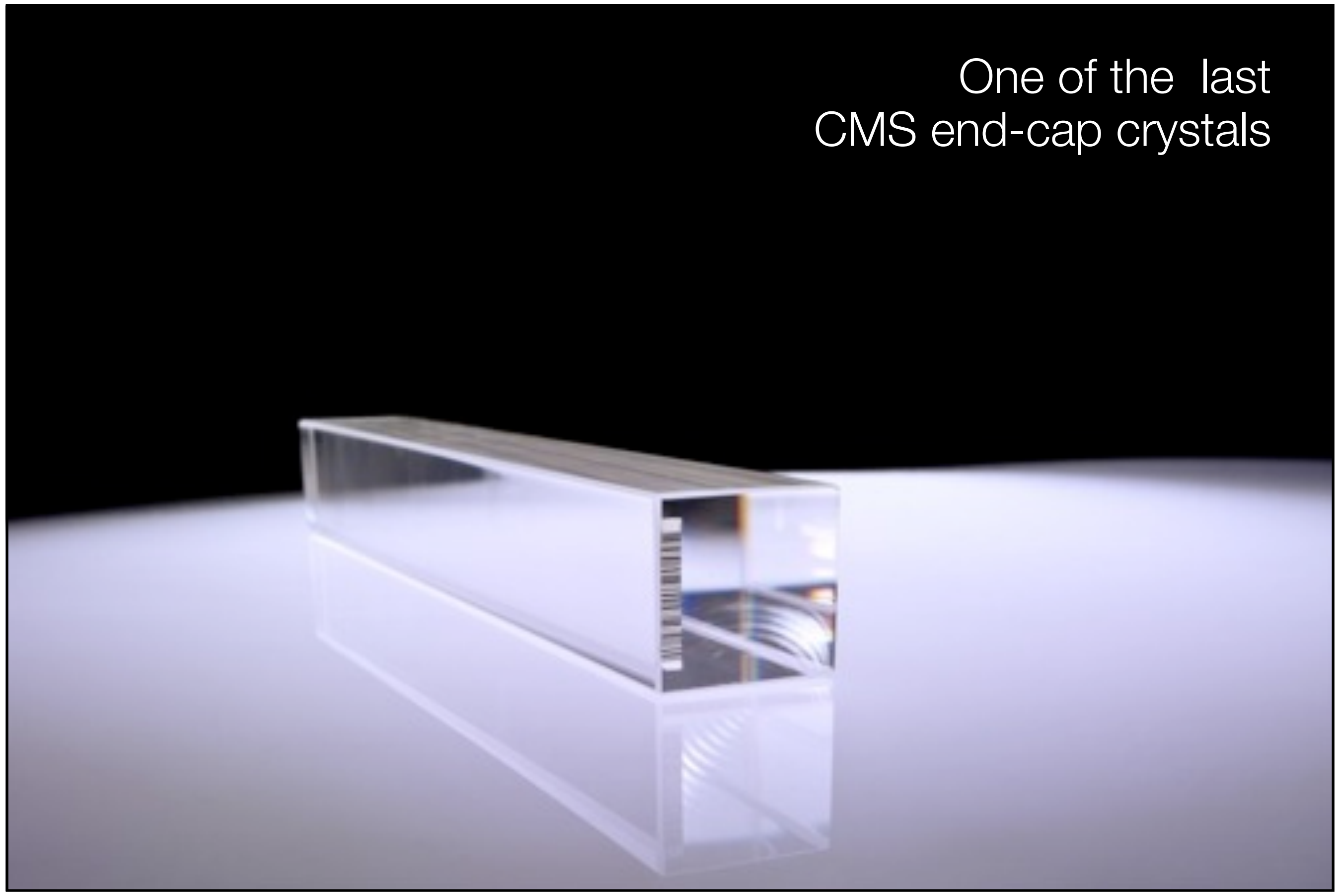
Crystal growth

Example CMS

Electromagnetic Calorimeter



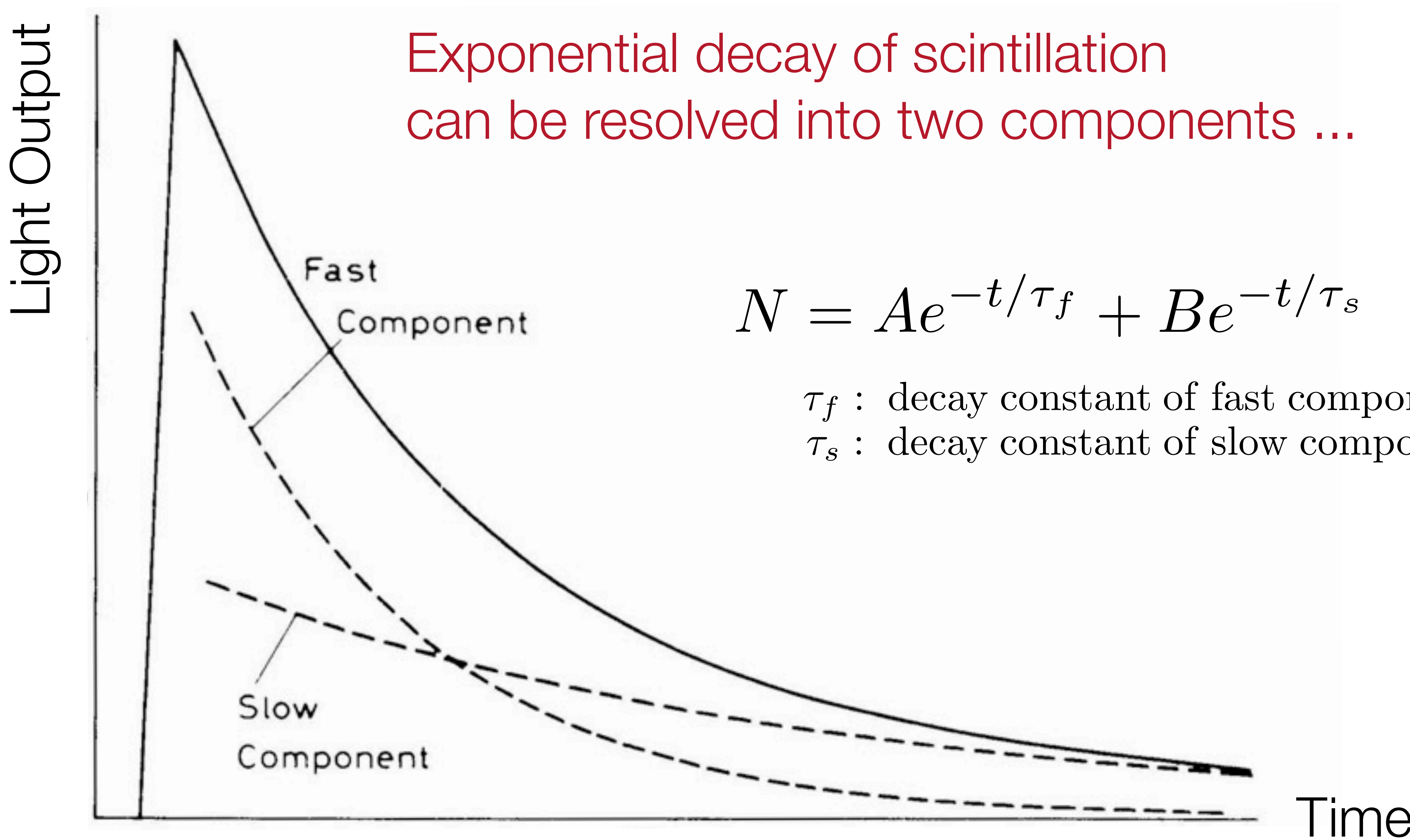
$PbWO_4$ ingots



One of the last CMS end-cap crystals

Inorganic Crystals – Time Constants

Exponential decay of scintillation
can be resolved into two components ...

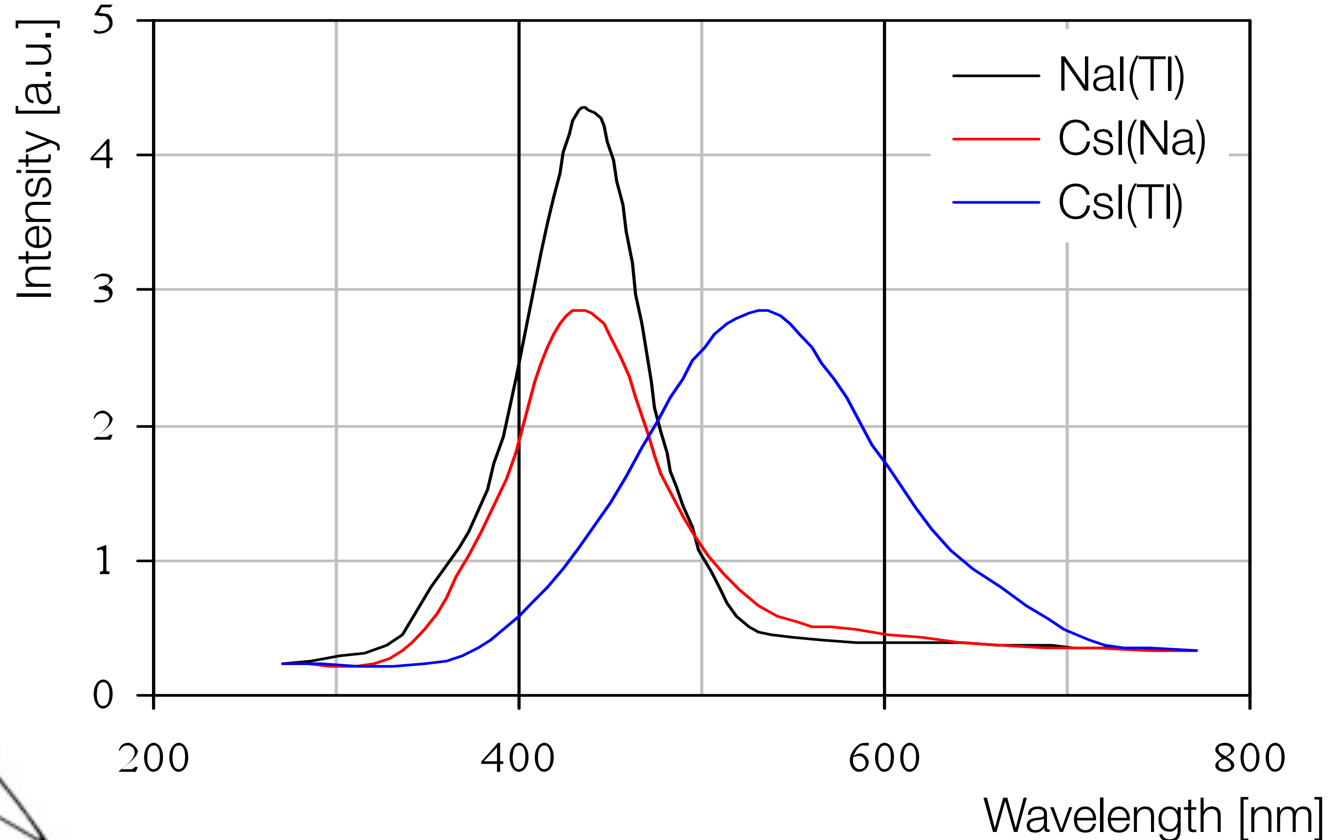


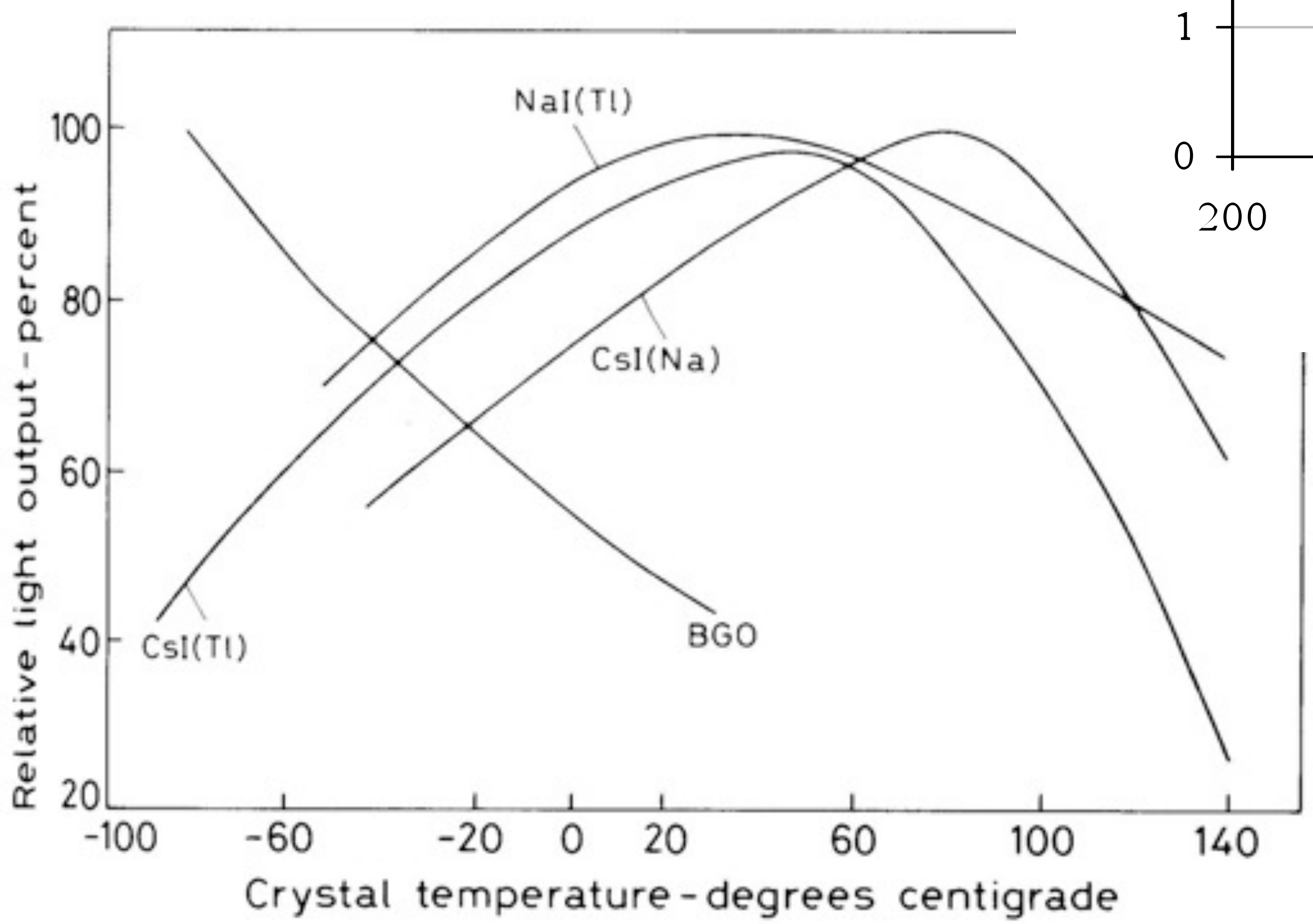
$$N = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$$

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

Inorganic Crystals – Light Output

Scintillation Spectrum
for NaI and CsI

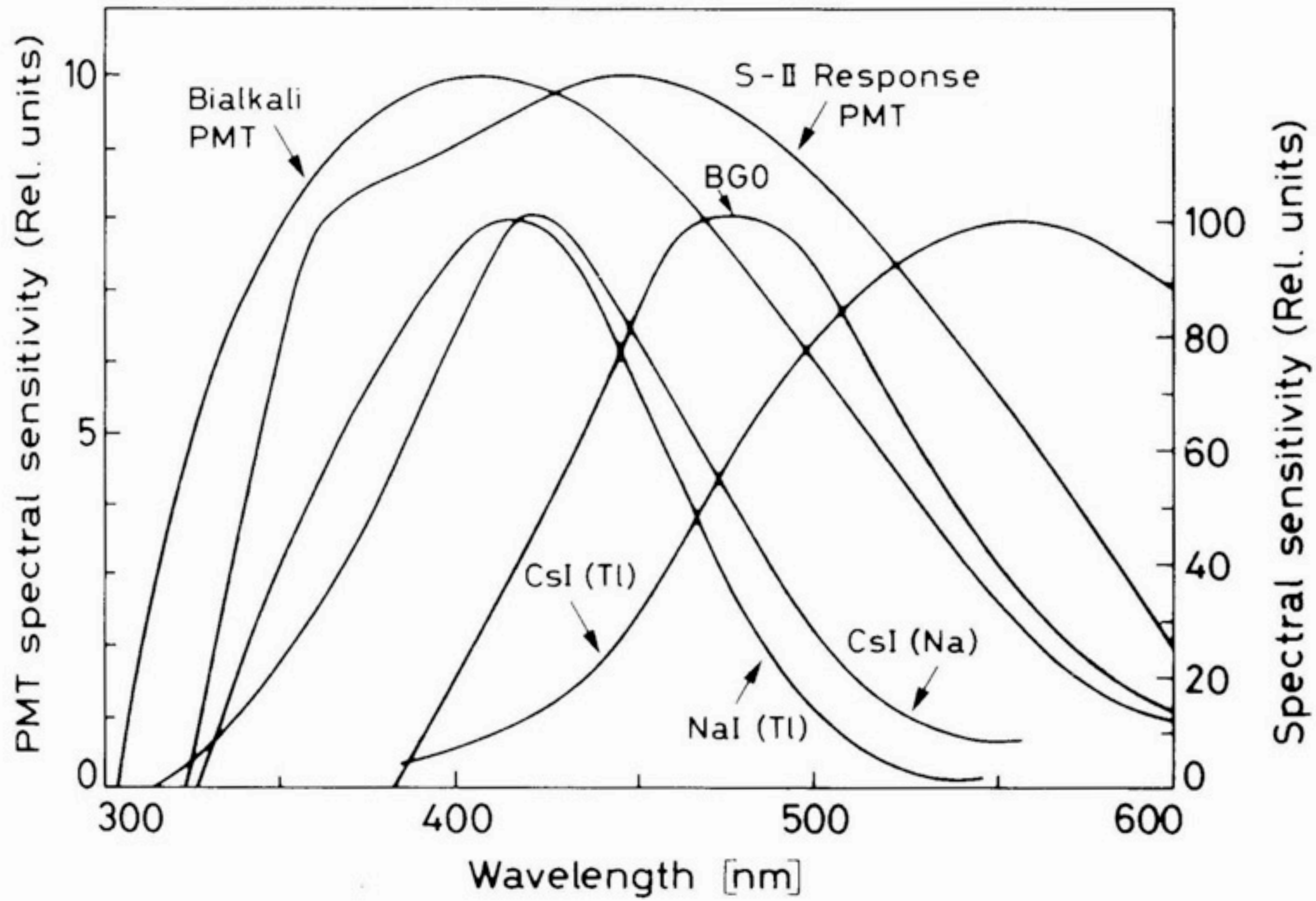




Strong
Temperature Dependence
[in contrast to organic scintillators]

Inorganic Crystals – Light Output

Spectral sensitivity



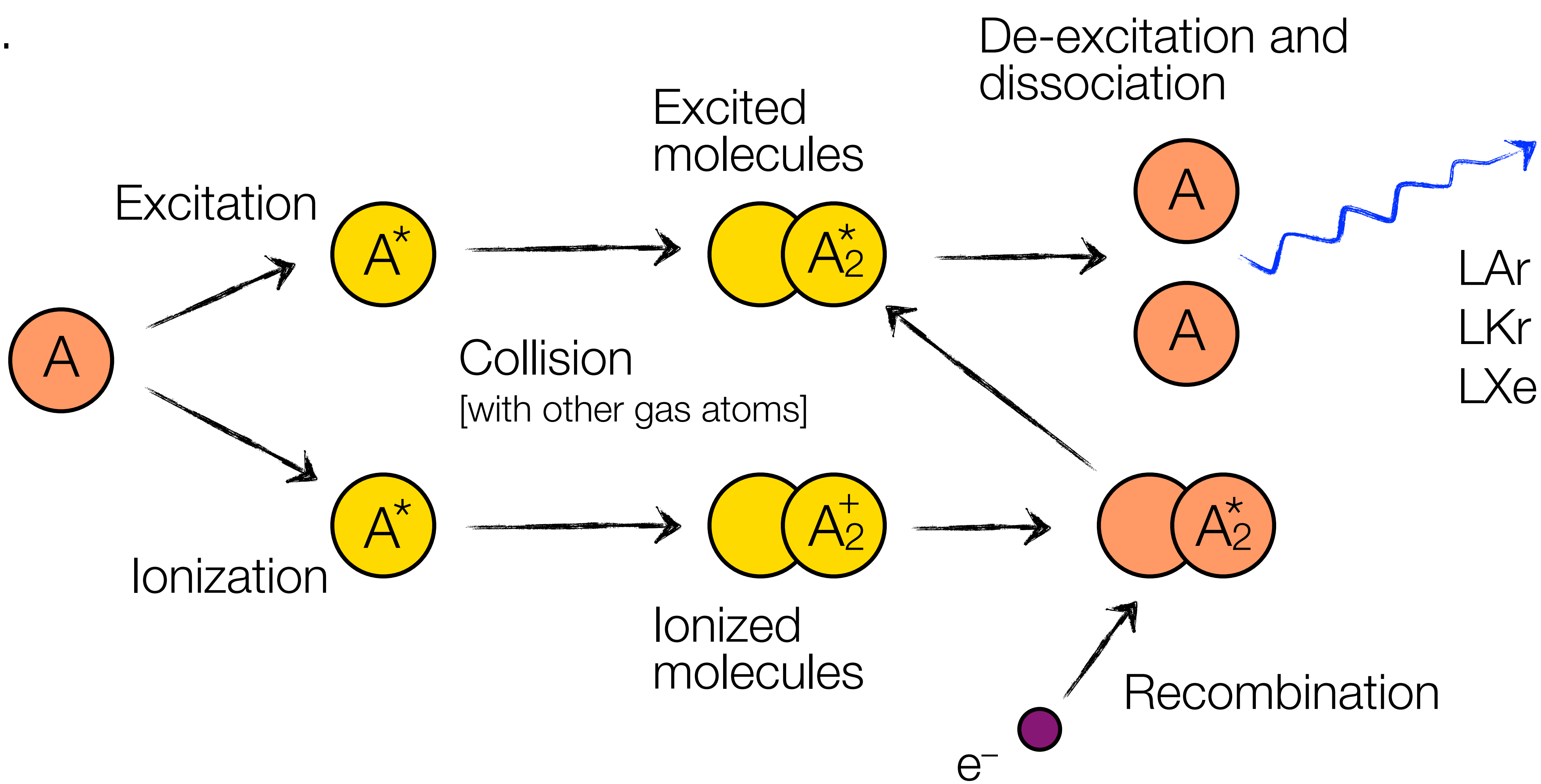
Scintillation in Liquid Nobel Gases

Materials:

Helium (He)
Liquid Argon (LAr)
Liquid Xenon (LXe)
...

Decay time constants:

Helium : $\tau_1 = .02\ \mu s$, $\tau_2 = 3\ \mu s$
Argon : $\tau_1 \leq .02\ \mu s$



LAr : 130 nm
LKr : 150 nm
LXe : 175 nm

Inorganic Scintillators – Properties

Scintillator material	Density [g/cm^3]	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 Scintillators – Properties

Numerical examples:

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

Scintillator quality:

Light yield – ε_{SC} ≡ fraction of energy loss going into photons

e.g. NaI(Tl) : 40000 photons; 3 eV/photon ➛ $\varepsilon_{SC} = 4 \cdot 10^4 \cdot 3$ eV$/10^6$ eV = 11.3%
PBWO$_4$: 200 photons; 3 eV/photon ➛ $\varepsilon_{SC} = 2 \cdot 10^2 \cdot 3$ eV$/10^6$ eV = 0.06%

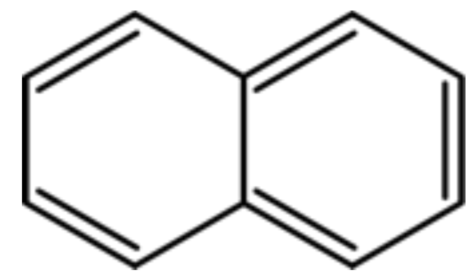
[for 1 MeV particle]

Organic Scintillators

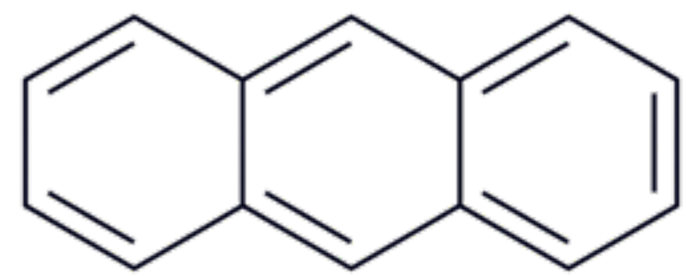
Aromatic hydrocarbon compounds:

e.g. Naphtalene [$C_{10}H_8$]
Antracene [$C_{14}H_{10}$]
Stilbene [$C_{14}H_{12}$]
...

Naphtalene

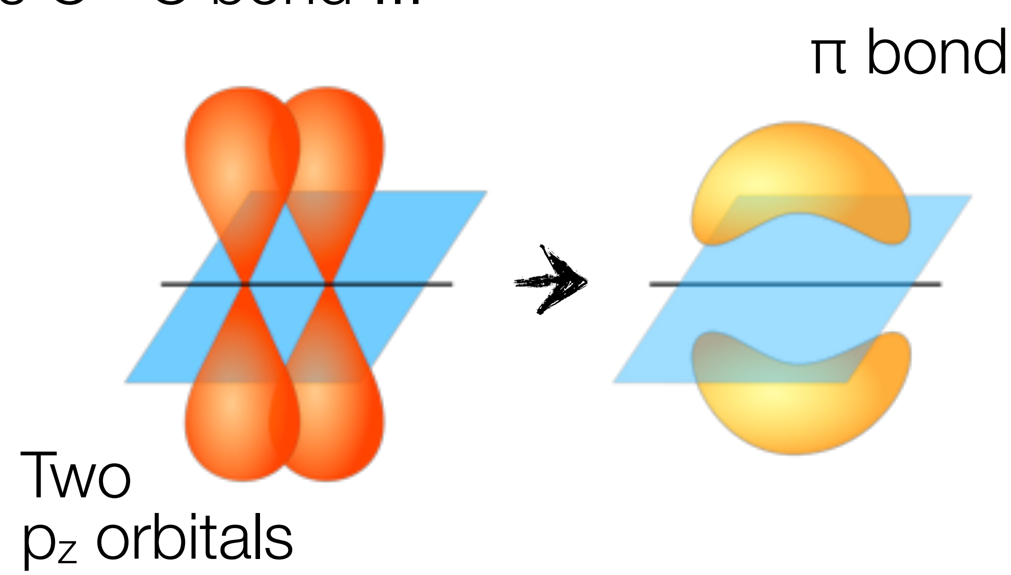


Antracene



Very fast!
[Decay times of O(ns)]

Scintillation is based on electrons of the C = C bond ...



Scintillation light arises from
delocalized electrons in π-orbitals ...

Transitions of 'free' electrons ...

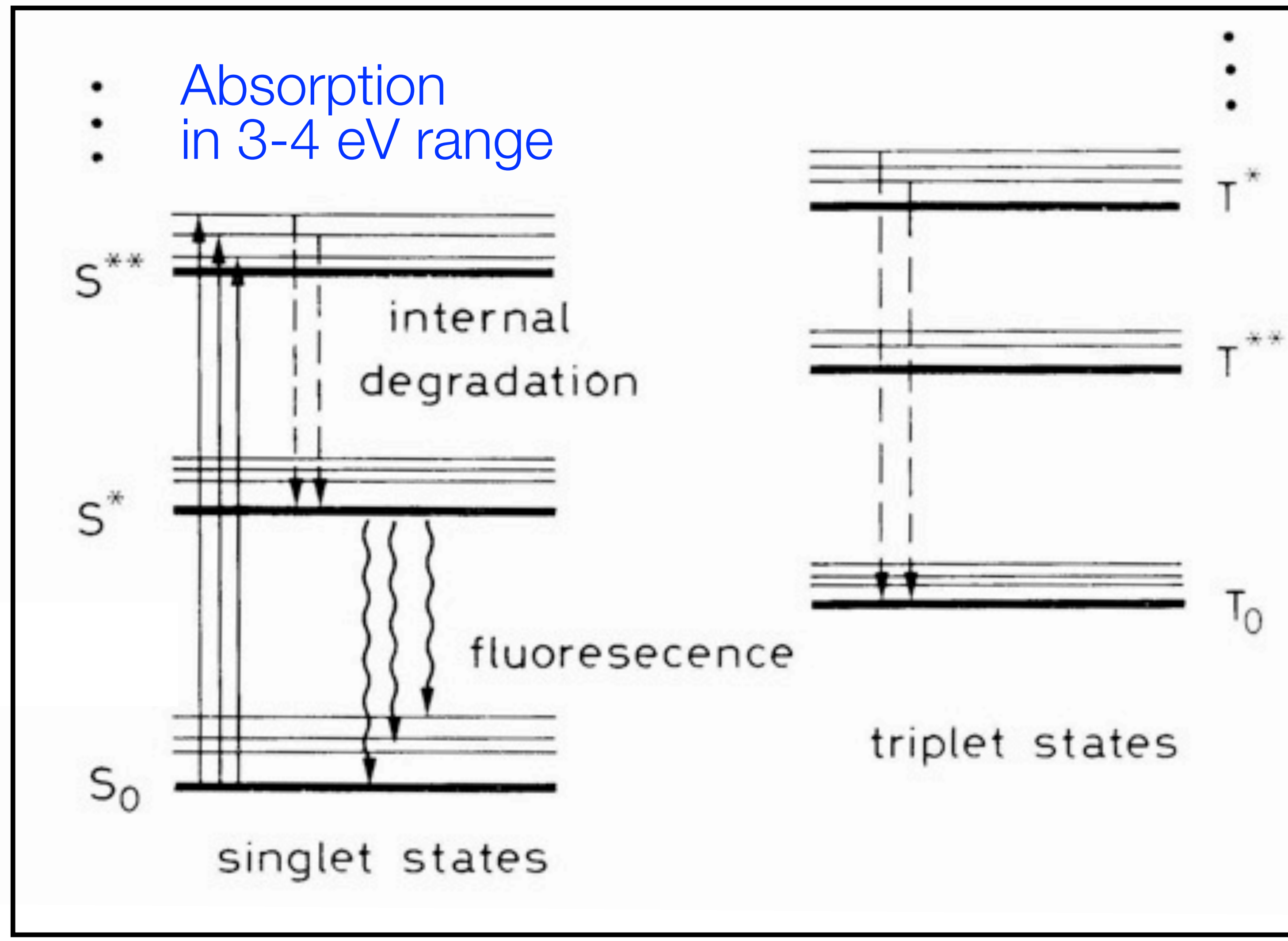
Organic Scintillators

Molecular states:

Singlet states
Triplet states

Fluorescence in UV range
[~ 320 nm]

➡ usage of
wavelength shifters



Fluorescence : $S_1 \rightarrow S_0$ [$< 10^{-8}$ s]
Phosphorescence : $T_0 \rightarrow S_0$ [$> 10^{-4}$ s]

Organic Scintillators

Transparency requires:

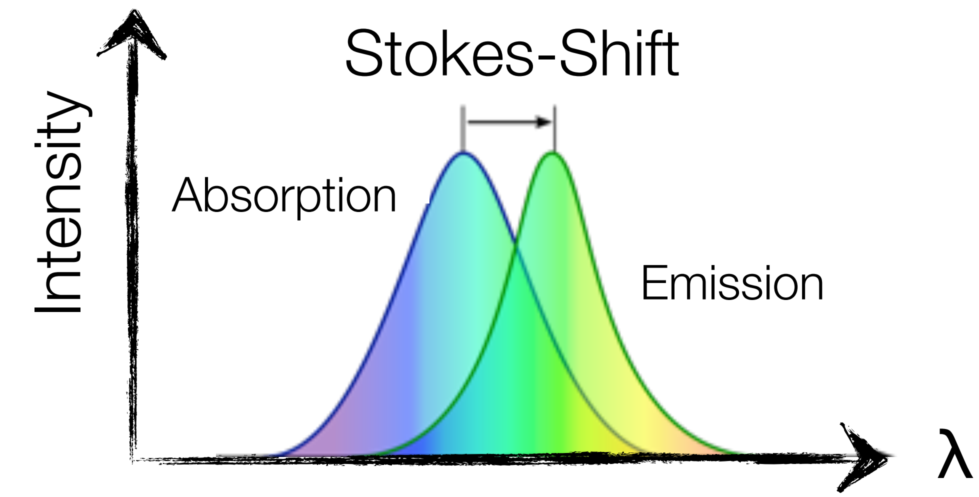
Shift of absorption and emission spectra ...

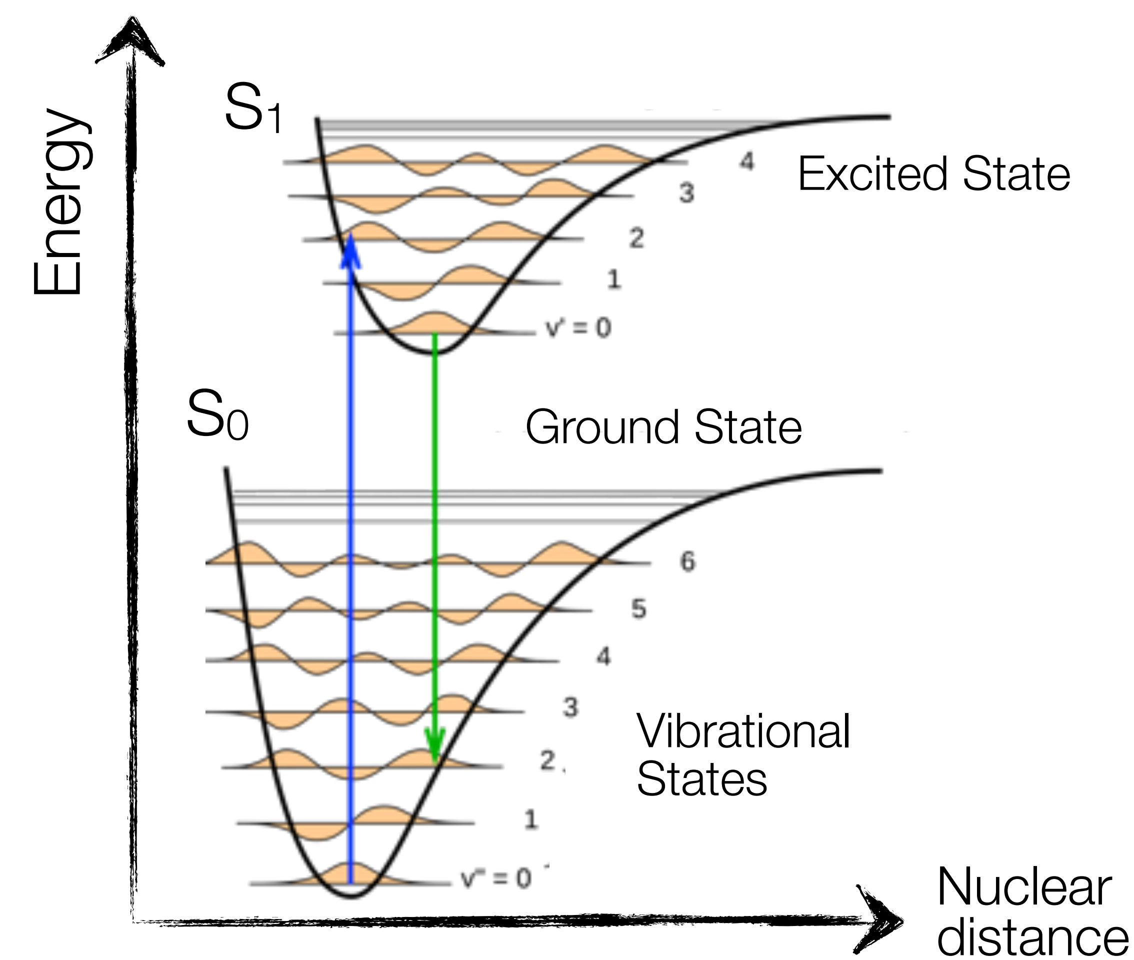
Shift due to

Franck-Condon Principle

Excitation into higher vibrational states
De-excitation from lowest vibrational state

Excitation time scale : 10^{-14} s
Vibrational time scale : 10^{-12} s
S_1 lifetime : 10^{-8} s



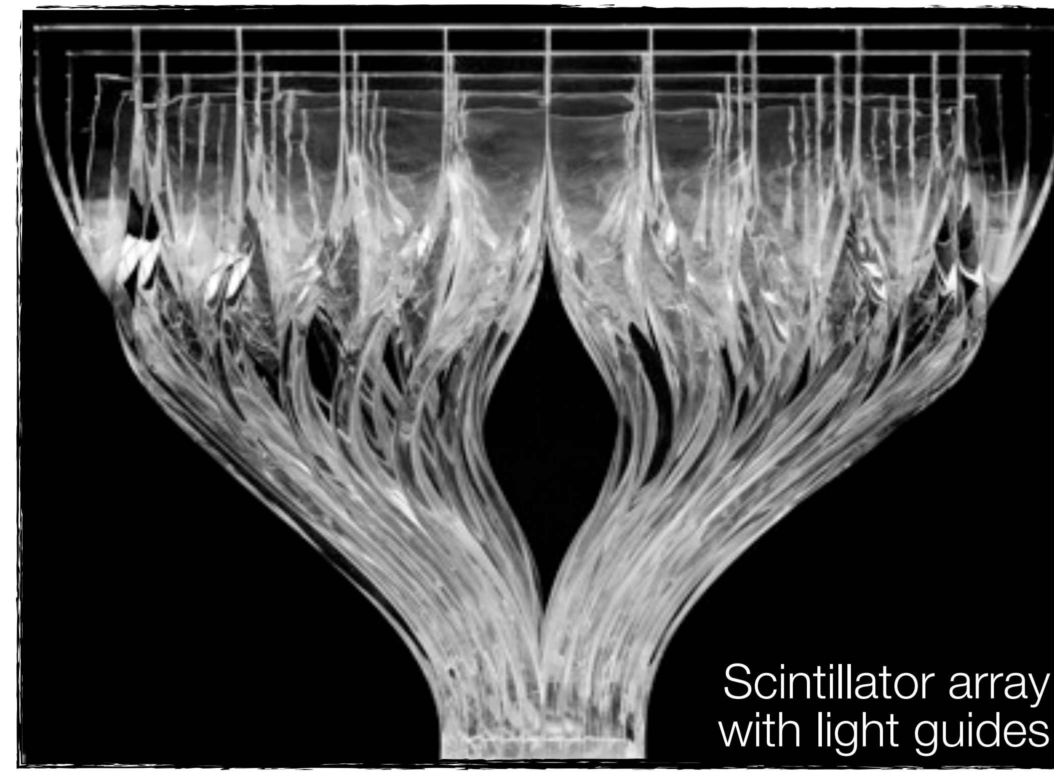


Plastic and Liquid Scintillators

In practice use ...

solution of organic scintillators
[solved in plastic or liquid]

+ large concentration of primary fluor
+ smaller concentration of secondary fluor
+ ...



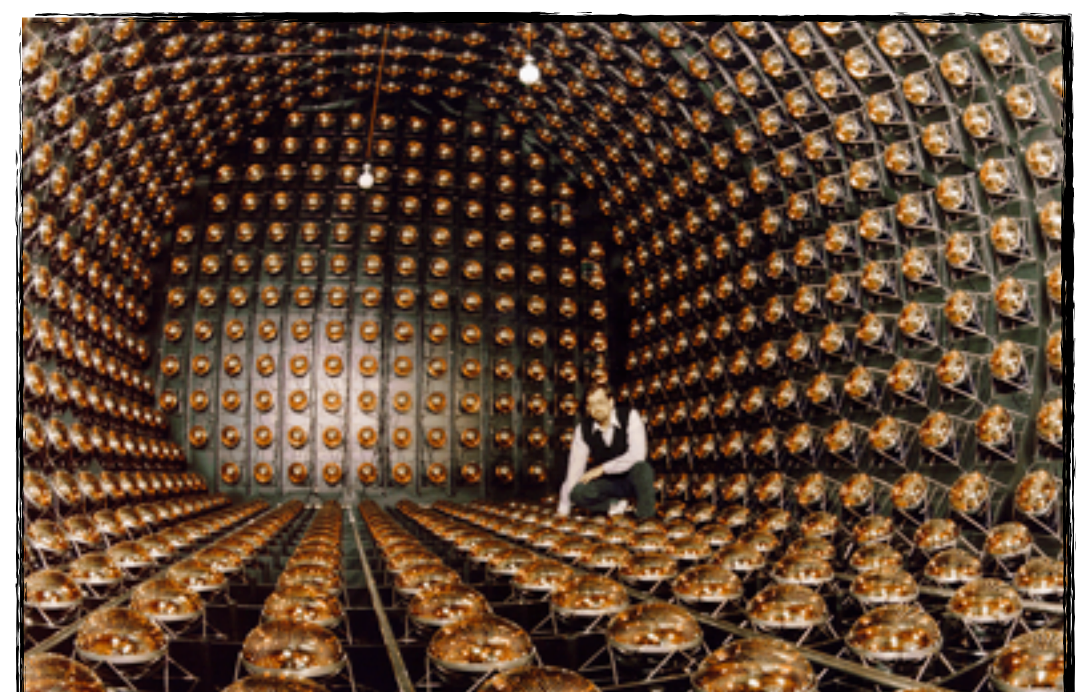
Scintillator array
with light guides

Scintillator requirements:

Solvable in base material

High fluorescence yield

Absorption spectrum must overlap
with emission spectrum of base material



LSND experiment

Plastic and Liquid Scintillators

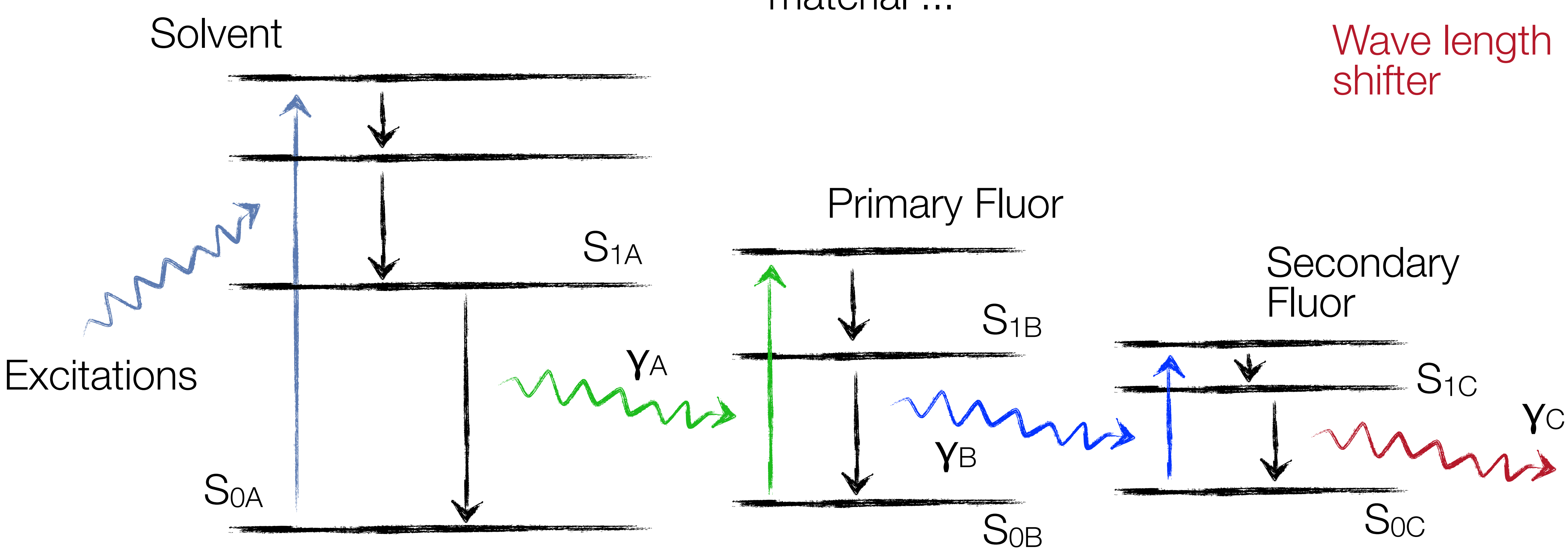
A

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

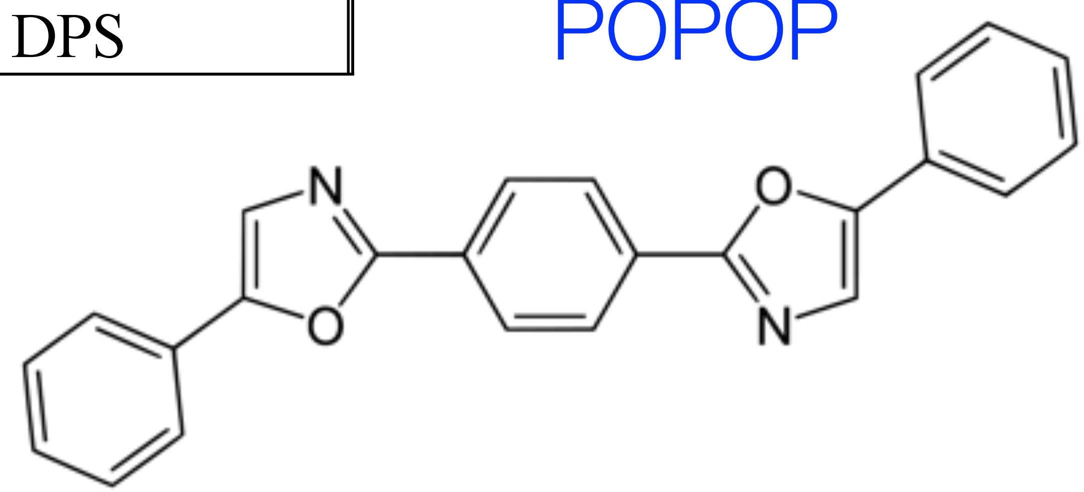


Plastic and Liquid Scintillators

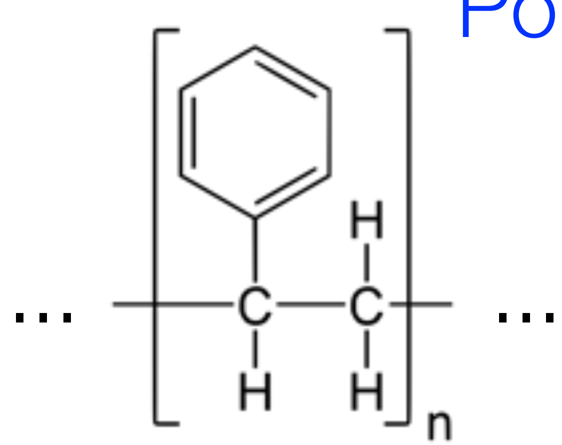
Some widely used solvents and solutes

	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

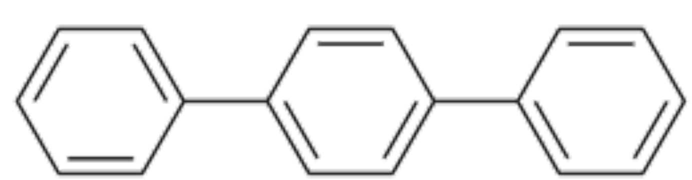
POPOP



Polystyrene



p-Terphenyl



Wavelength Shifting

Principle:

Absorption of
primary scintillation light

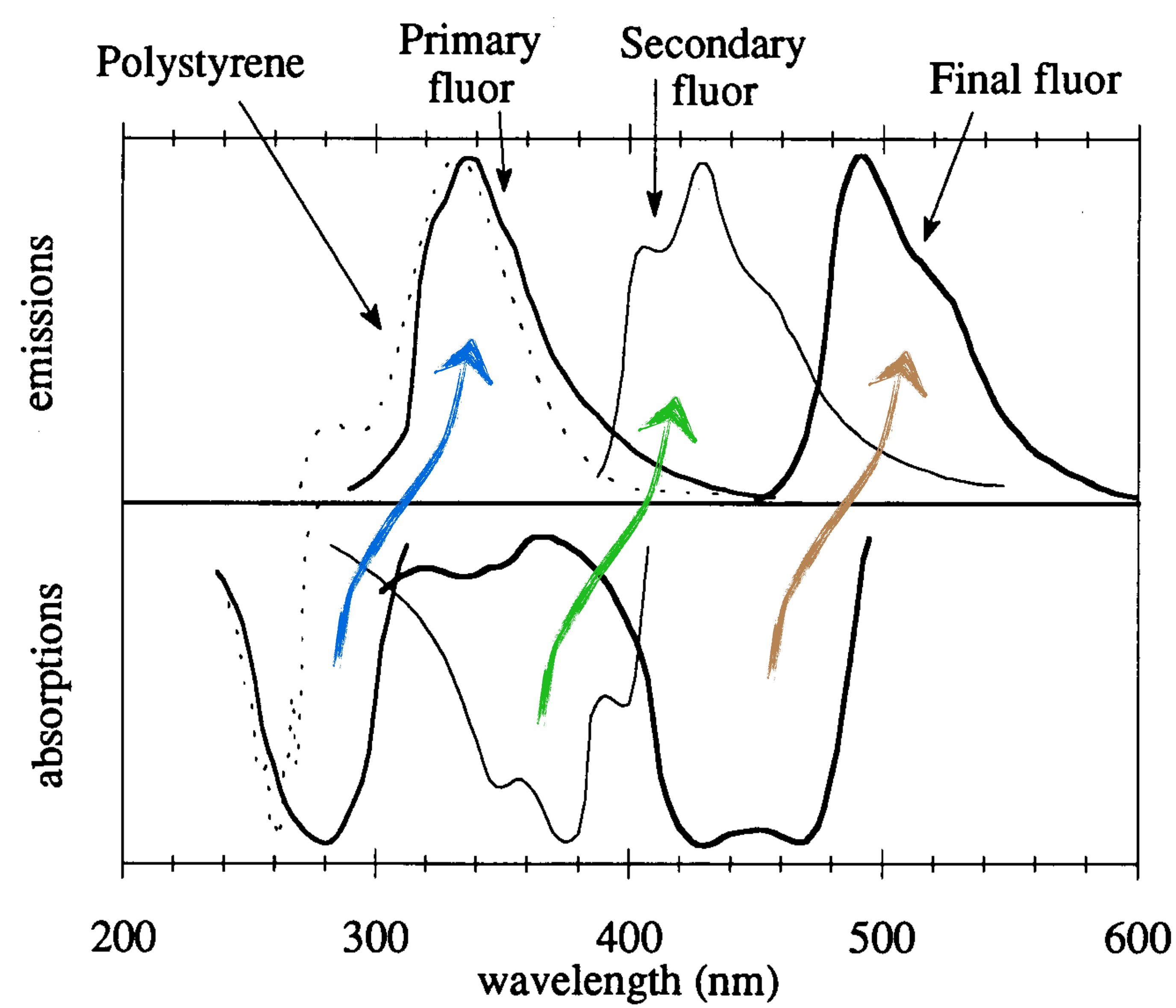
Re-emission at
longer wavelength

Adapts light to spectral
sensitivity of photosensor

Requirement:

Good transparency
for emitted light

Schematics of
wavelength shifting principle

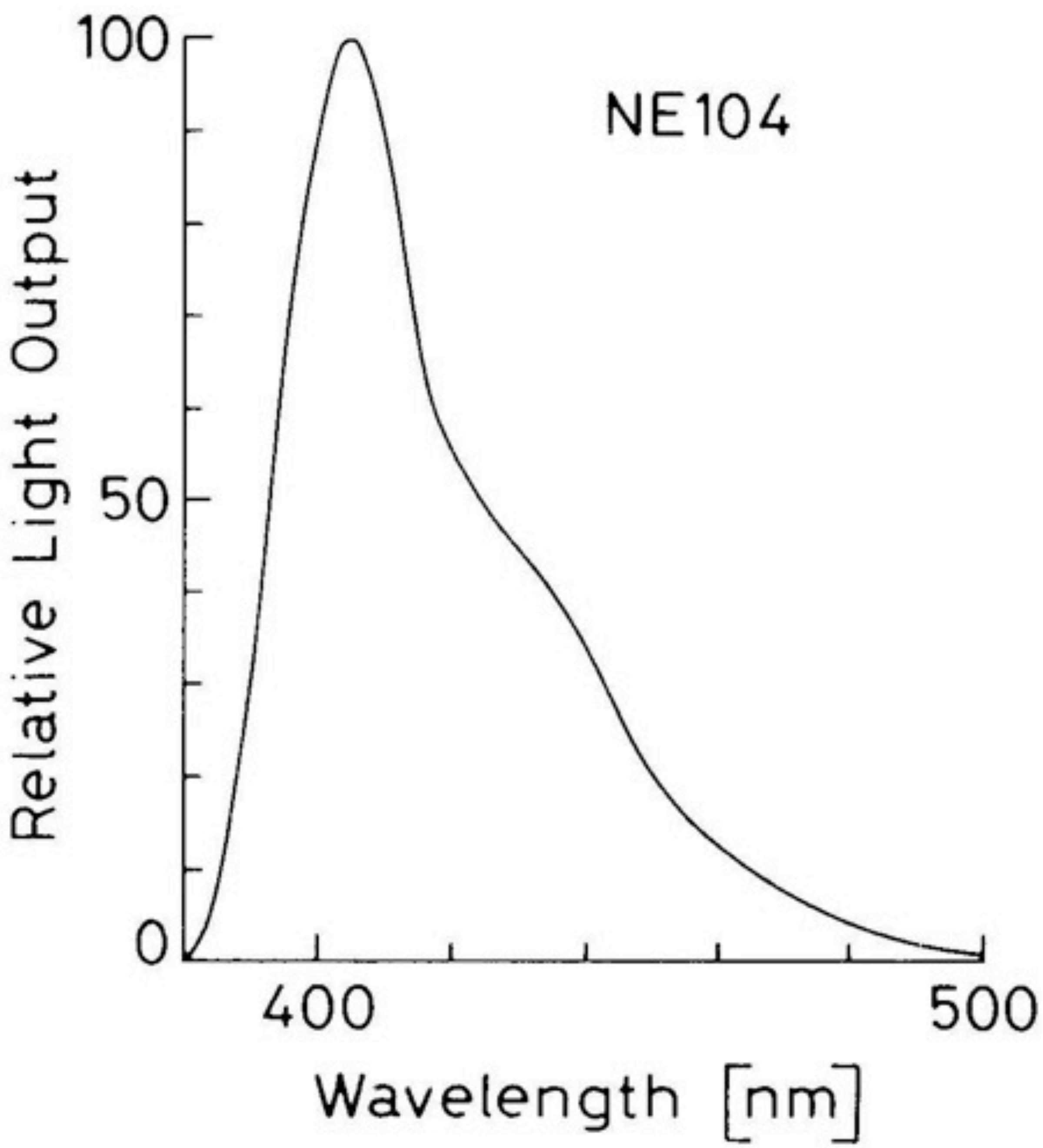


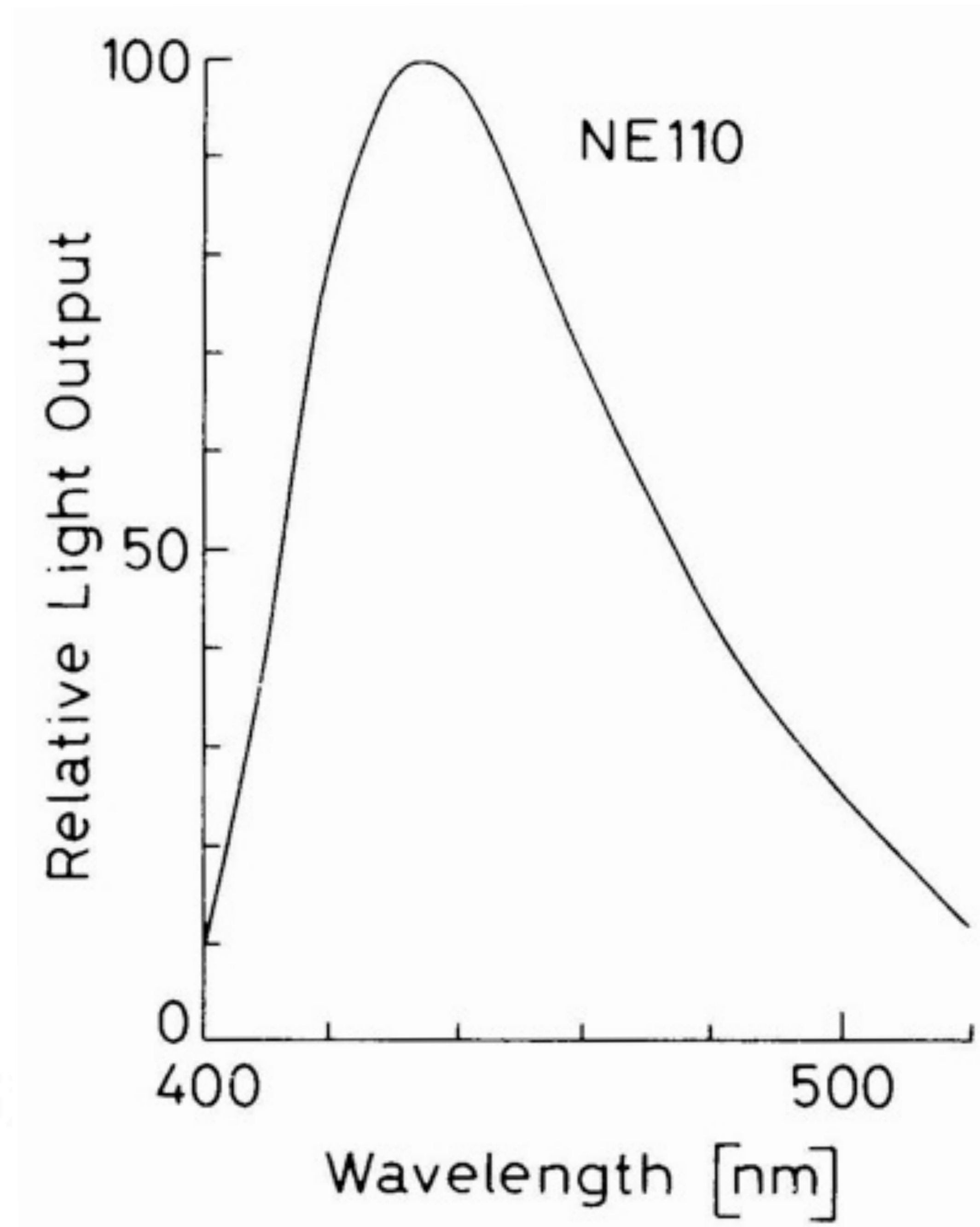
Organic Scintillators – Properties

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 Scintillators – Properties





Organic Scintillators – Properties

Light yield:
[without quenching]

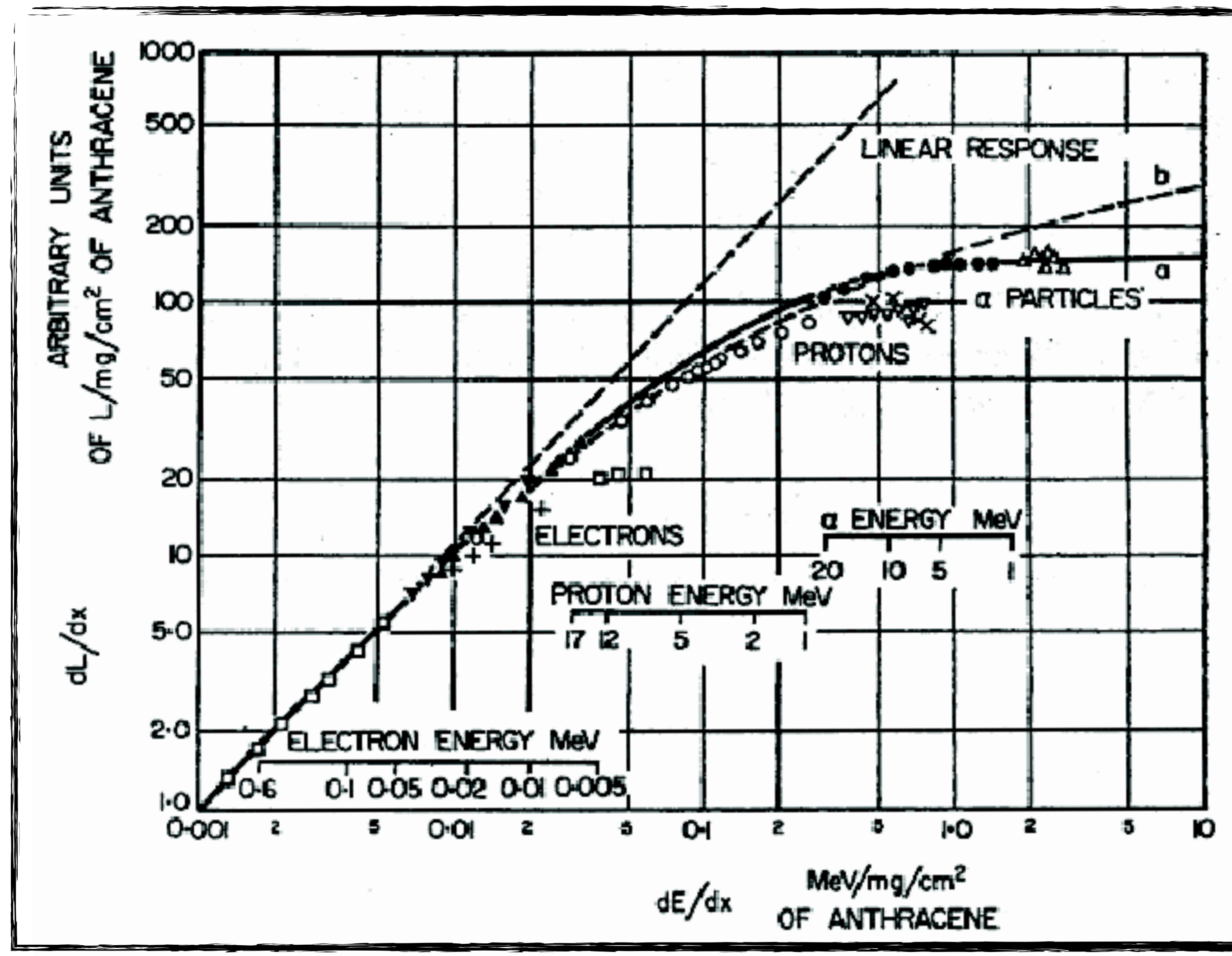
$$\frac{dL}{dx} = L_0 \frac{dE}{dx}$$

Quenching:
non-linear response due to
saturation of available states

Birk's law:

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

[kB needs to be determined experimentally]



Also other
parameterizations ...

Response different
for different particle types ...

Scintillators – Comparison

Inorganic Scintillators

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

Organic Scintillators

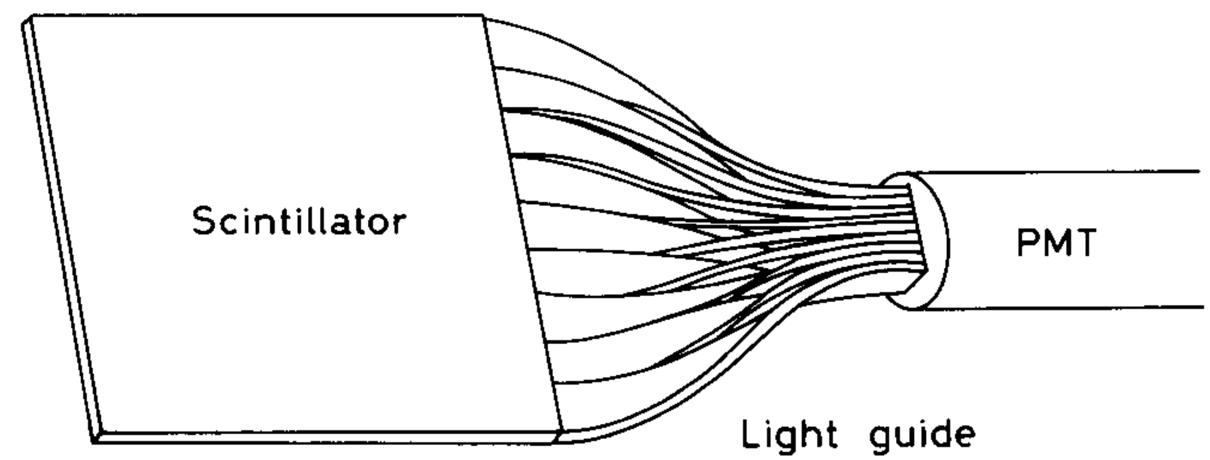
Advantages	very fast easily shaped small temperature dependence pulse shape discrimination possible	
Disadvantages	lower light yield [typical; $\boldsymbol{\varepsilon}_{SC} \approx 0.03$] radiation damage	Cheap

Scintillation Counters – Setup

Scintillator light to be guided to photosensor

➛ Light guide
[Plexiglas; optical fibers]

Light transfer by total internal reflection
[maybe combined with wavelength shifting]

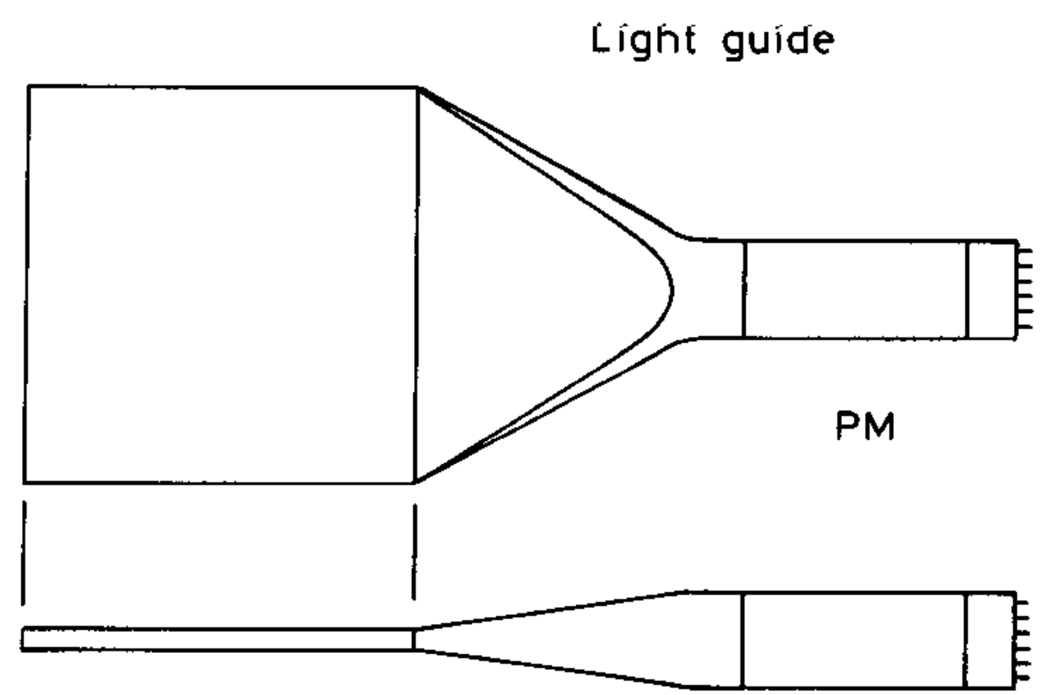


Liouville's Theorem:

Complete light transfer impossible as $\Delta x\ \Delta\theta$ = const.
[limits acceptance angle]

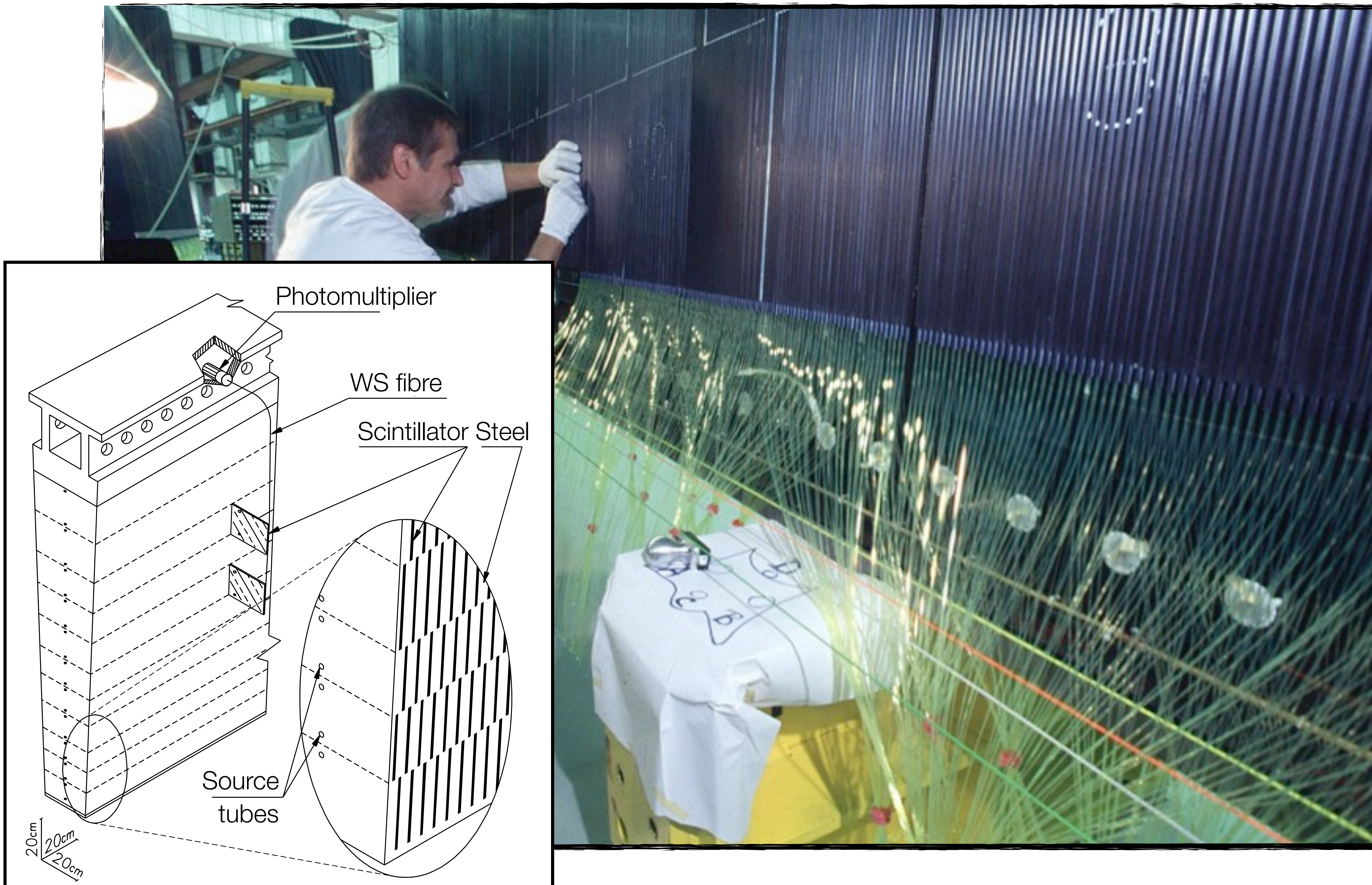
Use adiabatic light guide like 'fish tail';

➛ appreciable energy loss



'fish tail'

Scintillation Counters – Setup



ATLAS Tile Calorimeter

Photon Detection

Purpose : Convert light into a detectable electronic signal
Principle : Use photo-electric effect to convert photons to photo-electrons (p.e.)

Requirement :

High Photon Detection Efficiency (PDE) or
Quantum Efficiency; Q.E. = $N_{p.e.}/N_{photons}$

Available devices [Examples]:

- Photomultipliers [PMT]
- Micro Channel Plates [MCP]
- Photo Diodes [PD]
- HybridPhoto Diodes [HPD]
- Visible Light Photon Counters [VLPC]
- Silicon Photomultipliers [SiPM]

Photomultipliers

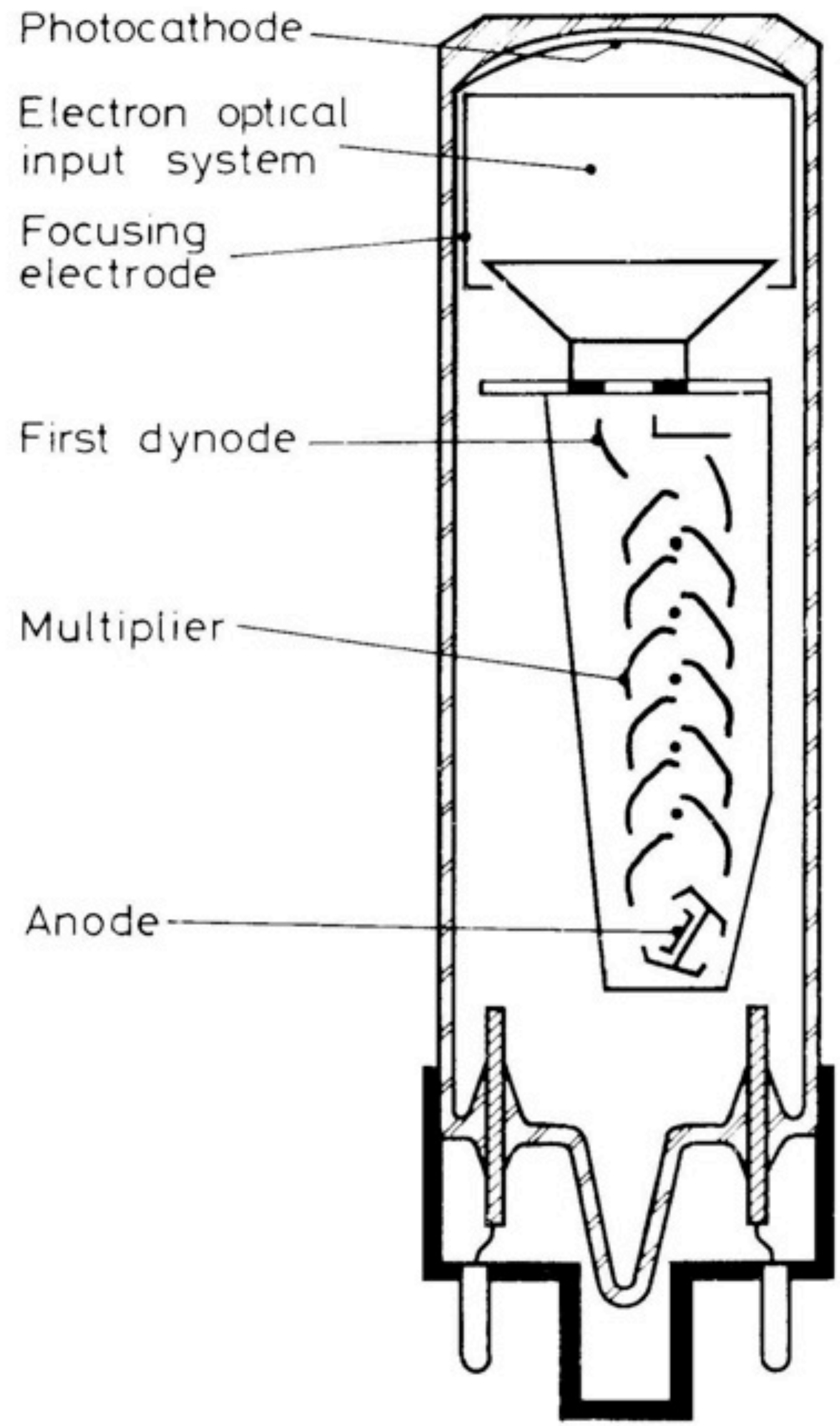
Principle:

Electron emission
from photo cathode

Secondary emission
from dynodes; dynode gain: 3-50 [f(E)]

Typical PMT Gain: > 10^6
[PMT can see single photons ...]

PMT Collection

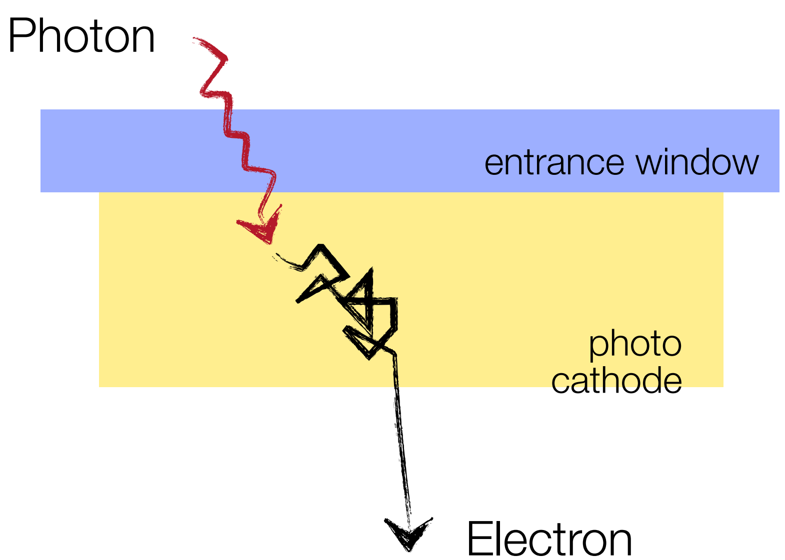


Photomultipliers – Photocathode

Bialkali: SbRbCs; SbK_2Cs

γ-conversion

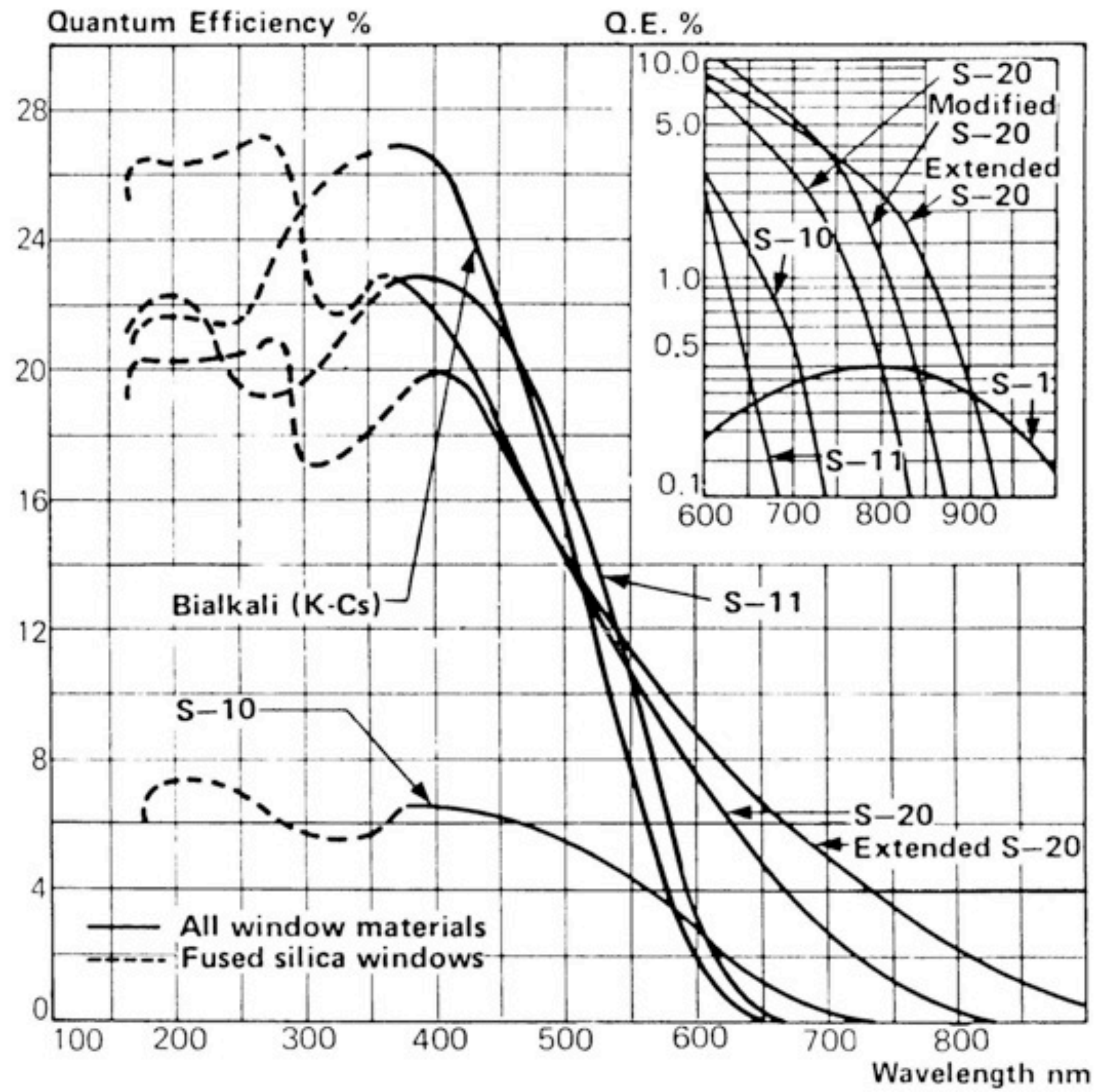
via photo effect ...



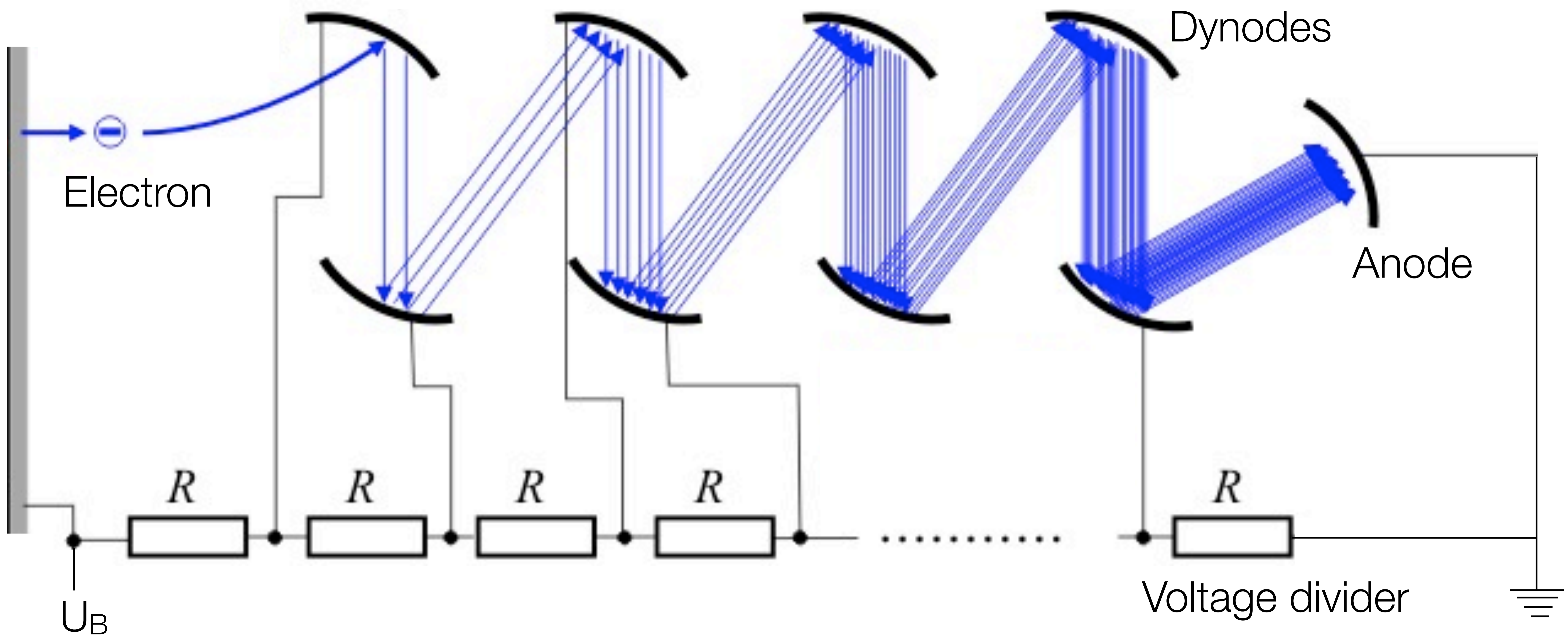
4-step process:

Electron generation via ionization
Propagation through cathode
Escape of electron into vacuum

Q.E. ≈ 10-30%
[need specifically developed alloys]



Photomultipliers – Dynode Chain



Multiplication process:

Electrons accelerated toward dynode
Further electrons produced ➛ avalanche

Secondary emission coefficient:
$\delta = \#(e^- \text{produced})/\#(e^- \text{incoming})$

Typical: $\left.\begin{matrix}\delta = 2 - 10 \\ n = 8 - 15\end{matrix}\right]$ ➛ $G = \delta^n = 10^6 - 10^8$

Gain fluctuation: $\delta = kU_D$; $G = a_0 (kU_D)^n$
$dG/G = n\,dU_D/U_D = n\,dU_B/U_B$

Photomultipliers – Dynode Chain

Optimization of

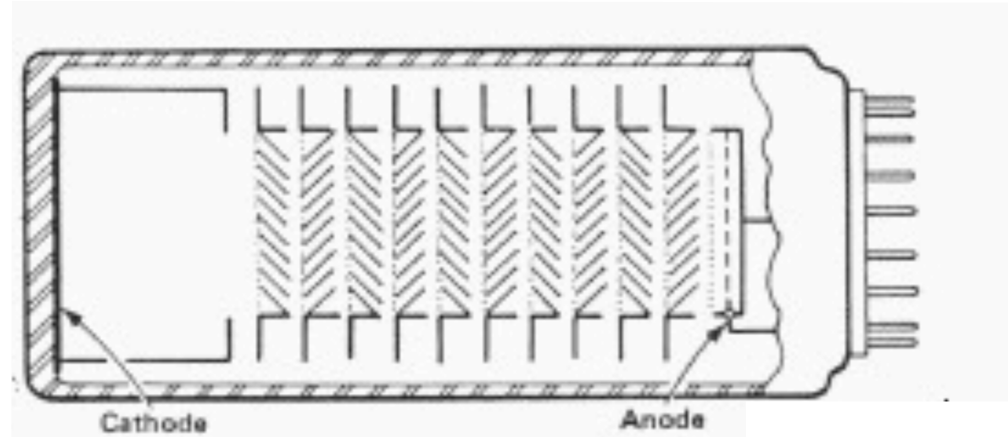
PMT gain
Anode isolation
Linearity
Transit time

B-field dependence

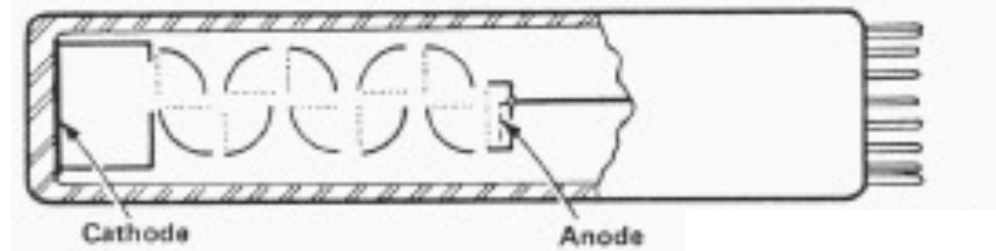
PM's are in general
very sensitive to B-fields !

Even to earth field (30-60 μT).
μ-metal shielding required.

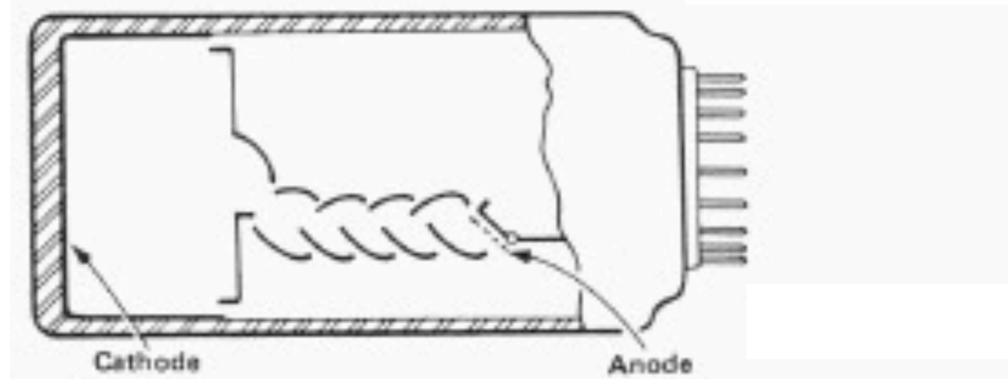
Venetian
blind



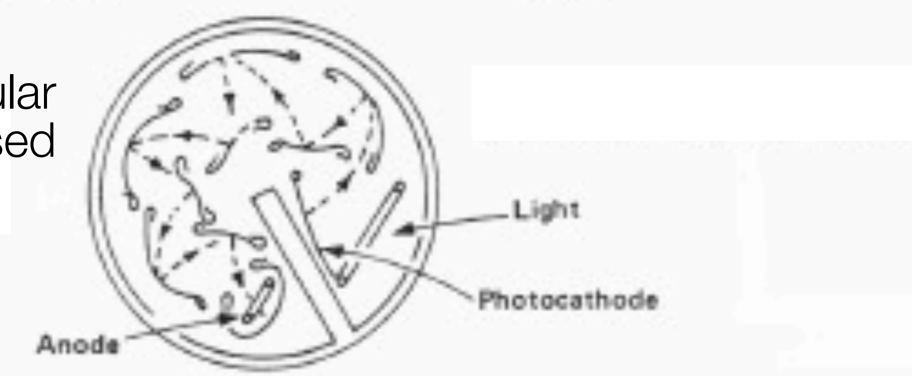
Box and
grid



Linear
focused



Circular
focused



Photomultipliers – Energy Resolution

Energy resolution influenced by:

Linearity of PMT: at high dynode current possibly saturation by space charge effects; $I_A \propto n_\gamma$ for 3 orders of magnitude possible ...

Photoelectron statistics: given by poisson statistics.

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

with n_e given by dE/dx ...

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

light collection efficiency

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

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 ...

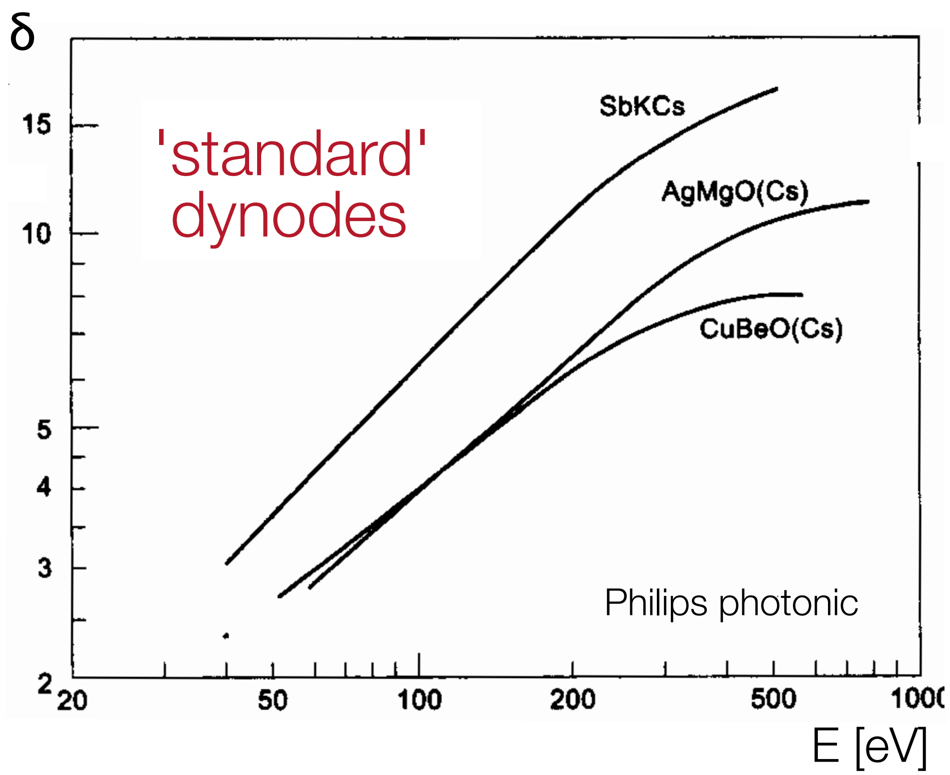
$$\left(\frac{\sigma_n}{\langle n\rangle}\right)^2 = \frac{1}{\delta} + ... + \frac{1}{\delta^N} \approx \frac{1}{\delta - 1}$$

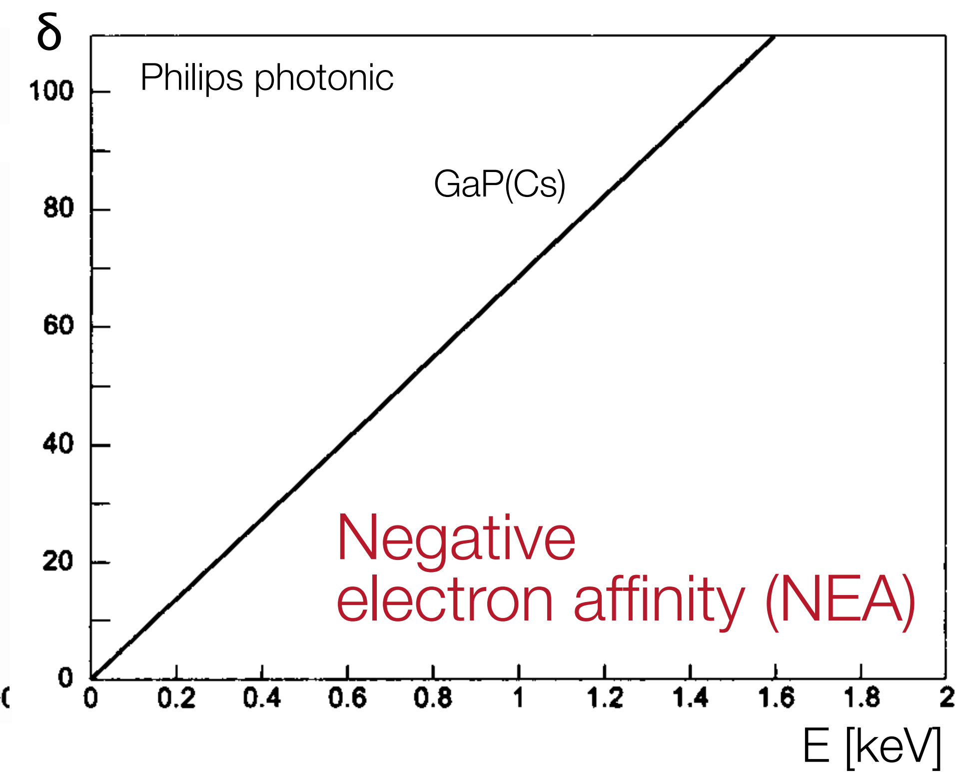
$\sigma_n/\langle n\rangle$ dominated by first dynode stage ...

... important for single photon detection

Photomultipliers – Energy Resolution

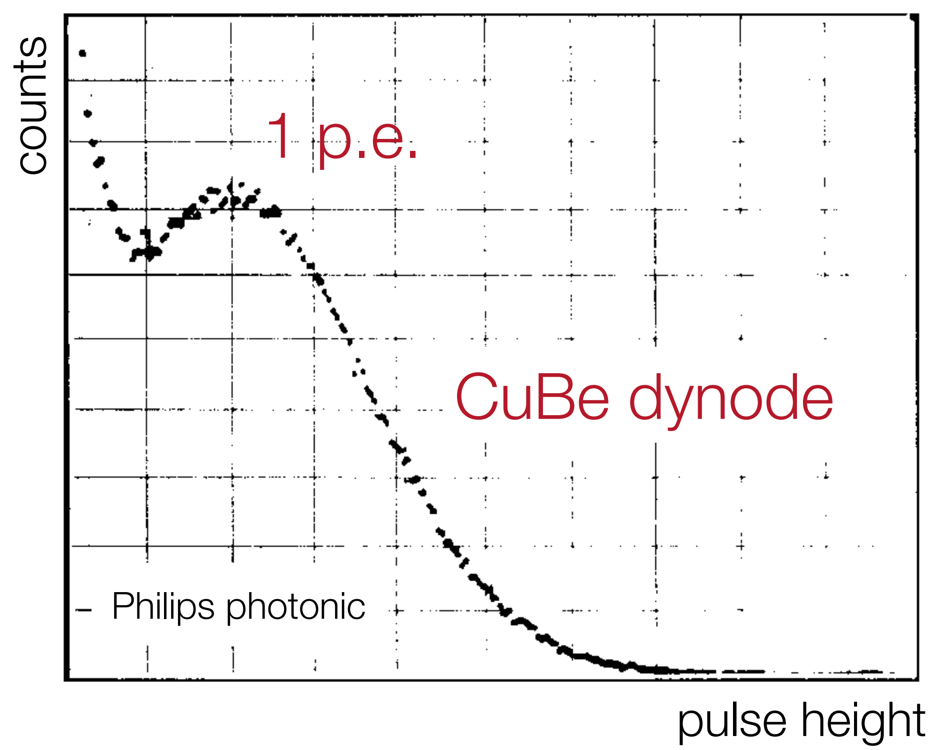
For detection of single photons

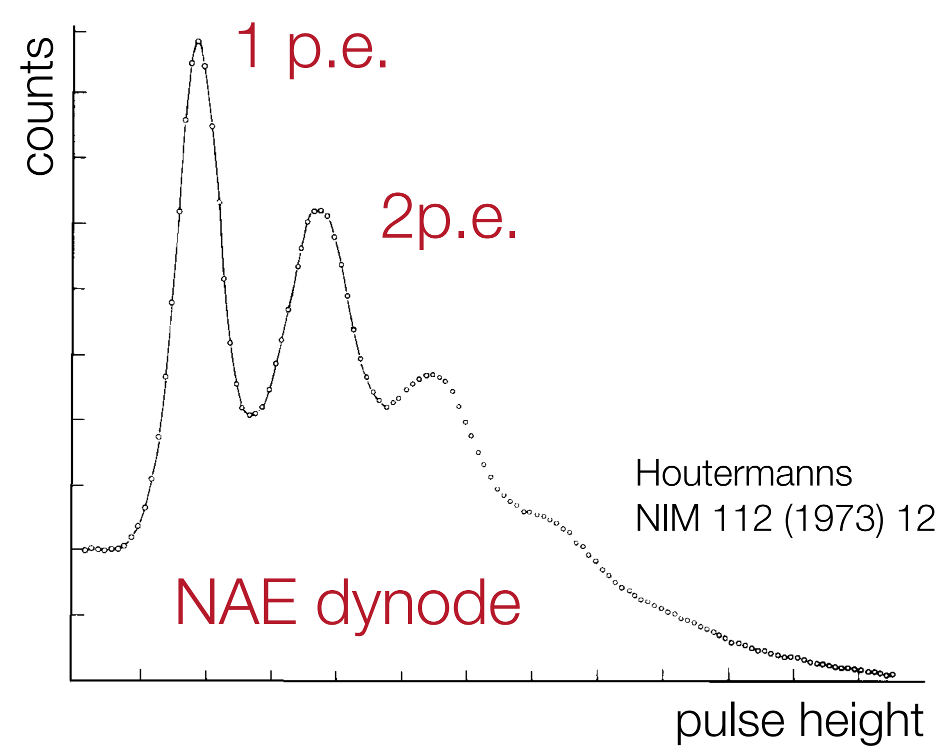




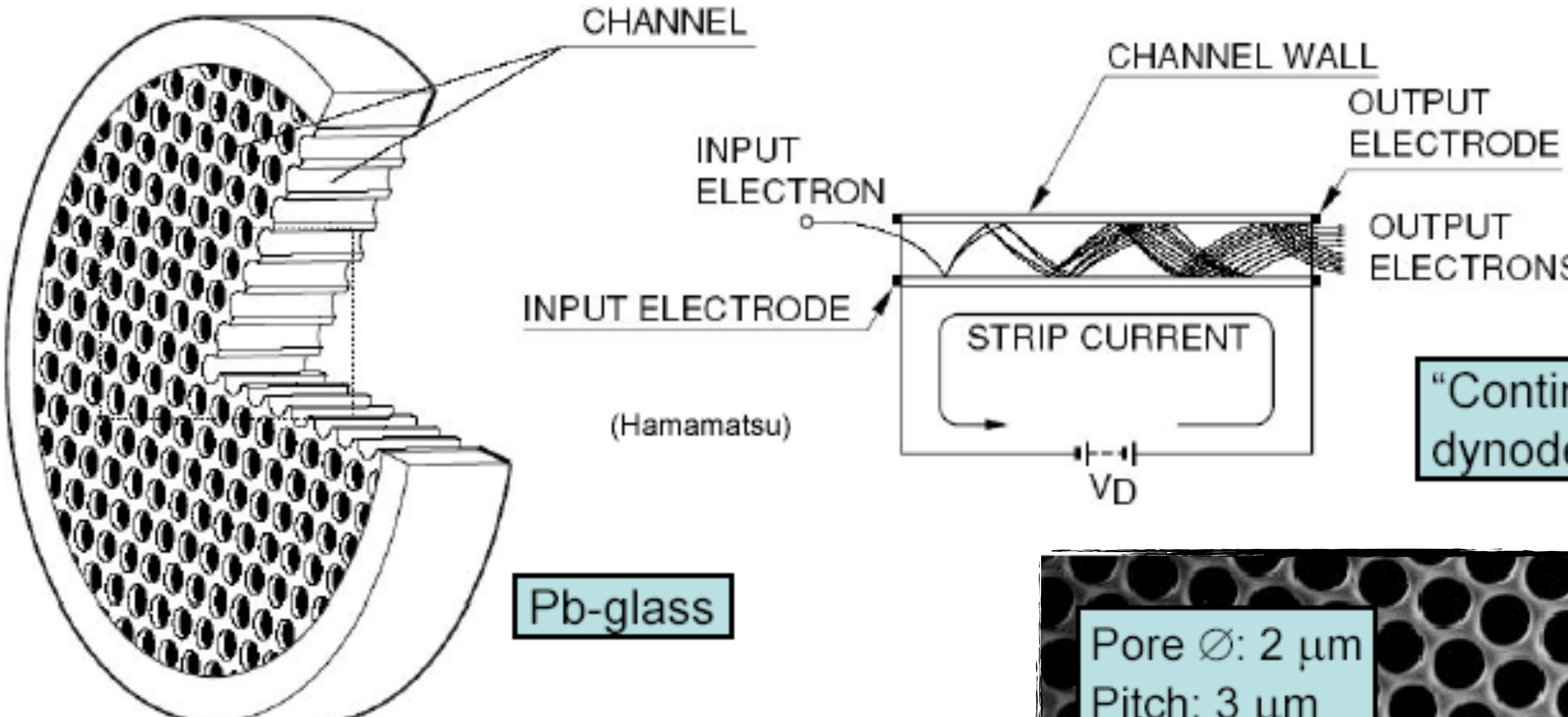
Large δ !

... yields better energy resolution

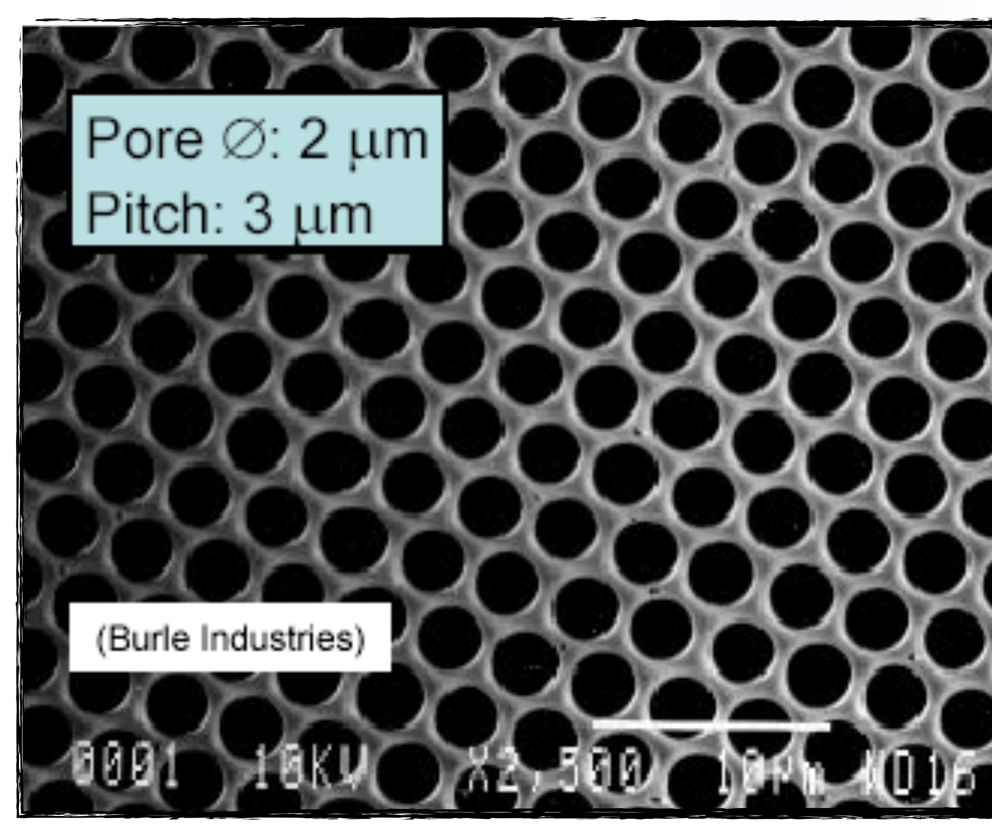




Micro Channel Plate



"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

Silicon Photomultipliers

Principle:

Pixelized photo diodes operated in Geiger Mode

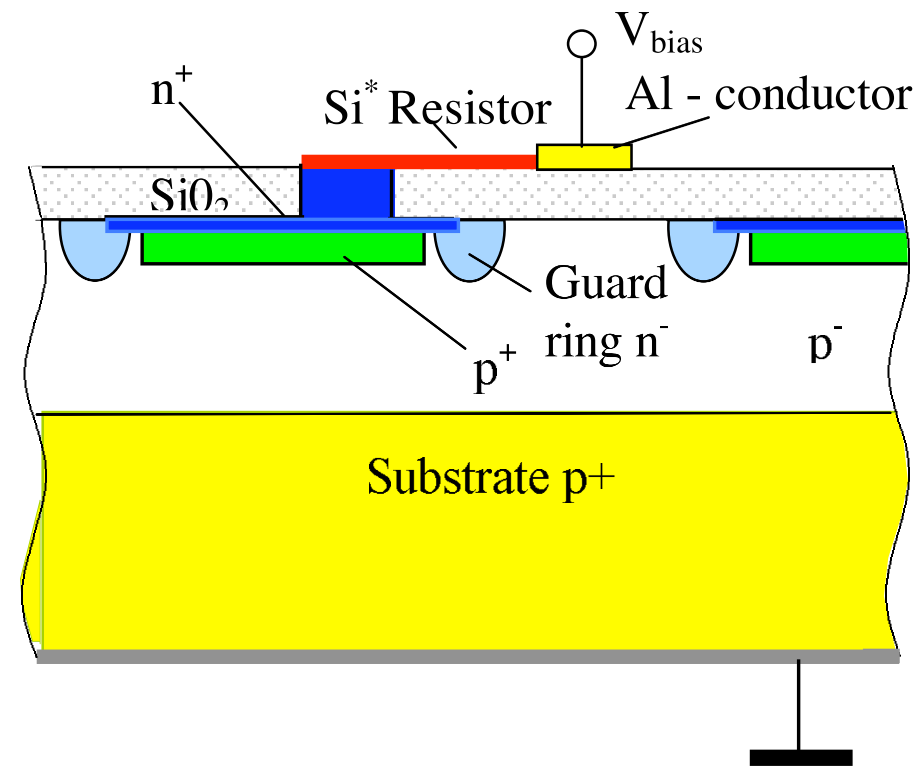
Single pixel works as a binary device

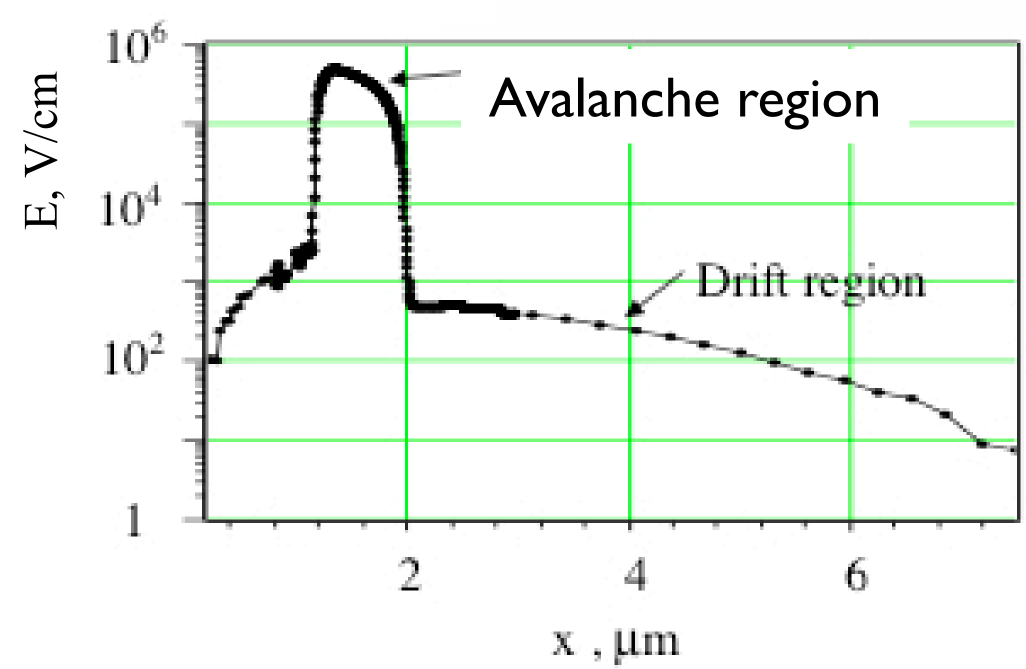
Energy = #photons seen by summing over all pixels

Features:

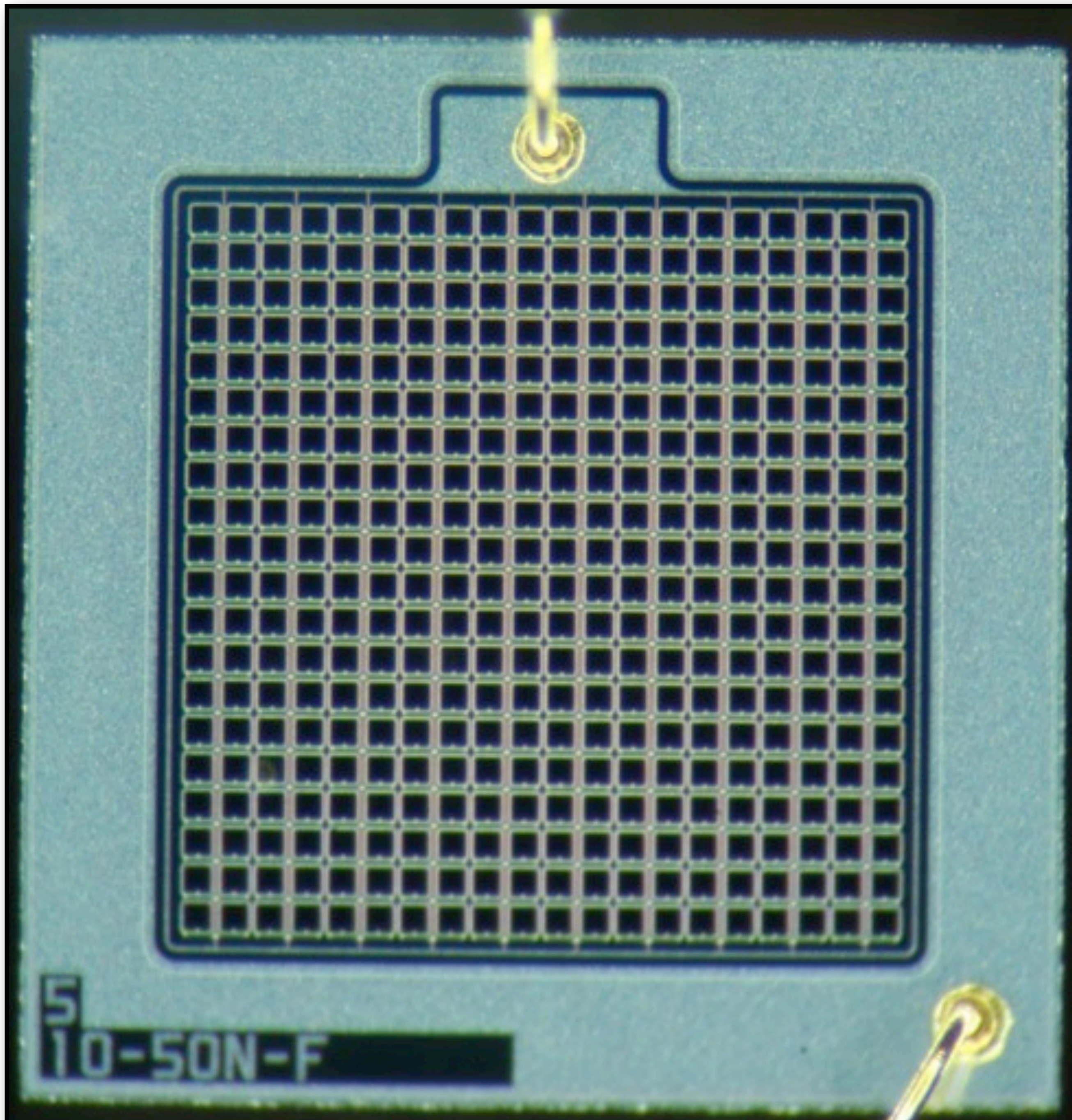
Granularity	:	10^3 pixels/mm^2
Gain	:	10^6
Bias Voltage	:	< 100 V
Efficiency	:	ca. 30 %

Works at room temperature!
Insensitive to magnetic fields



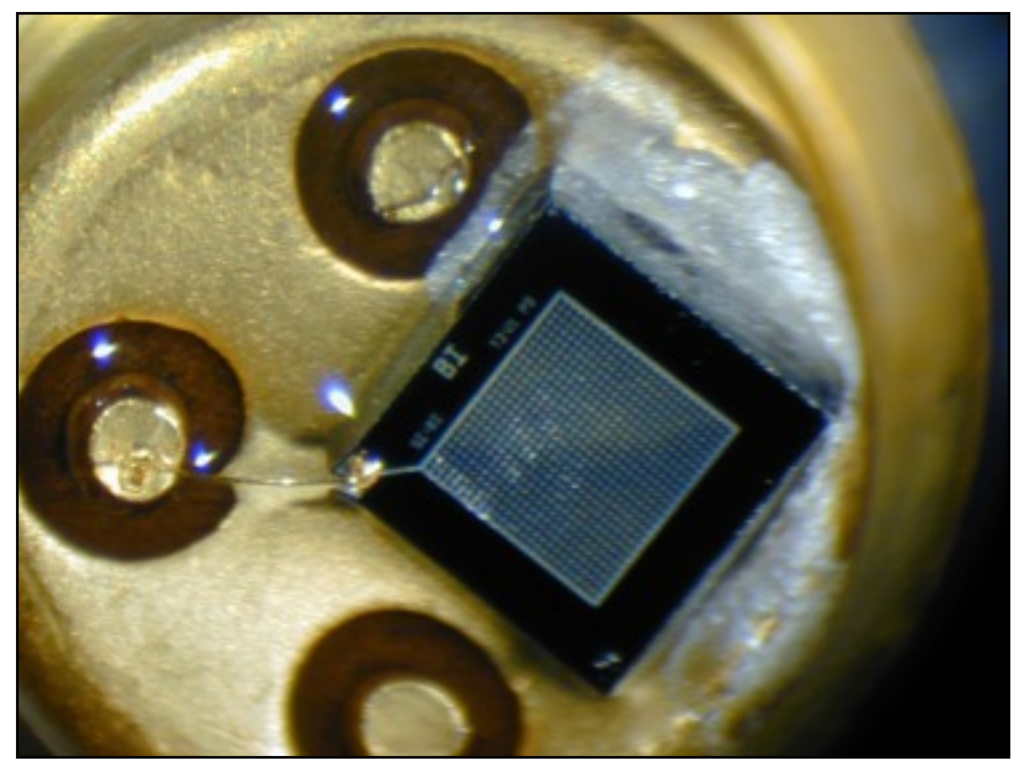


Silicon Photomultipliers

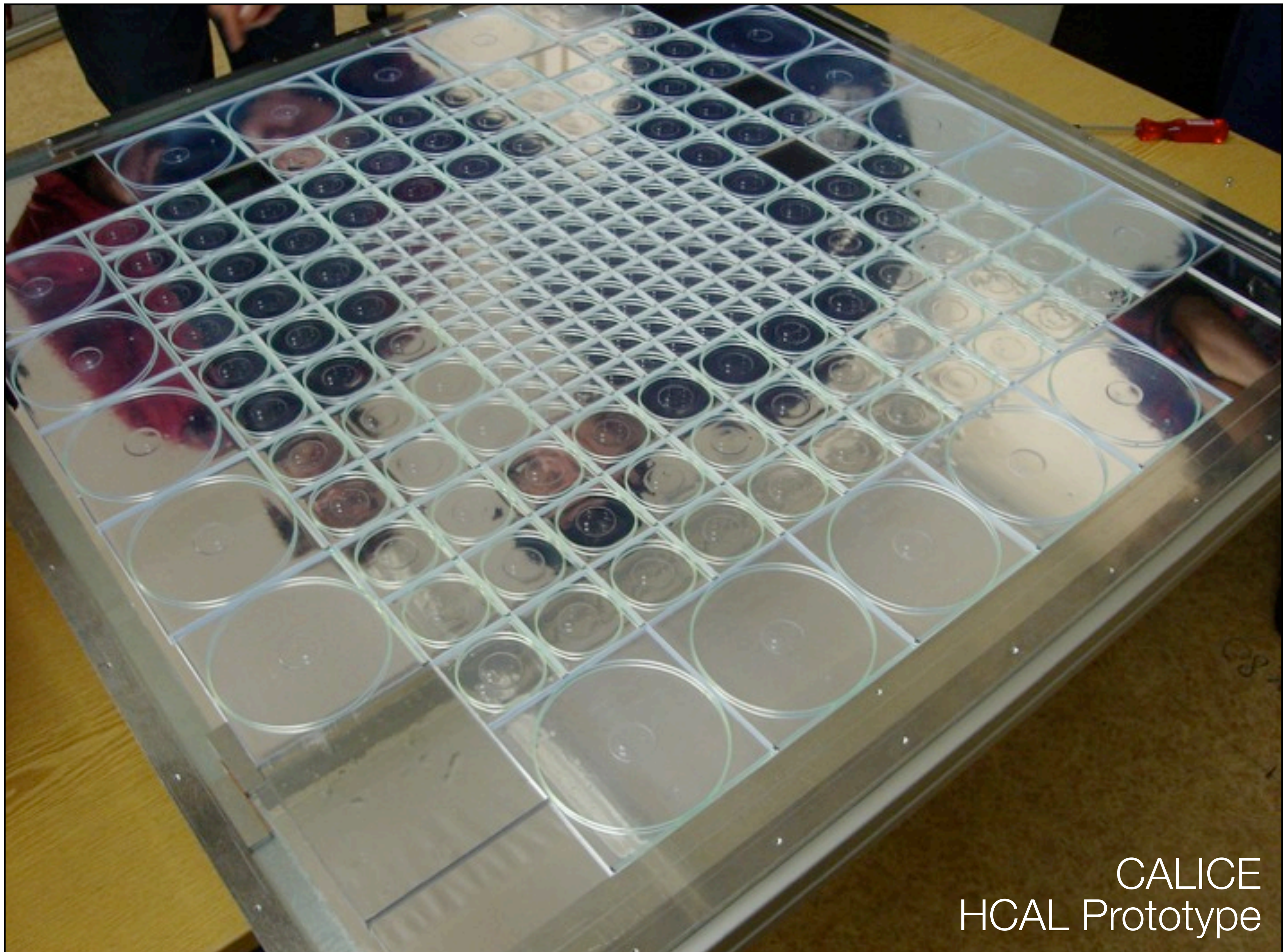


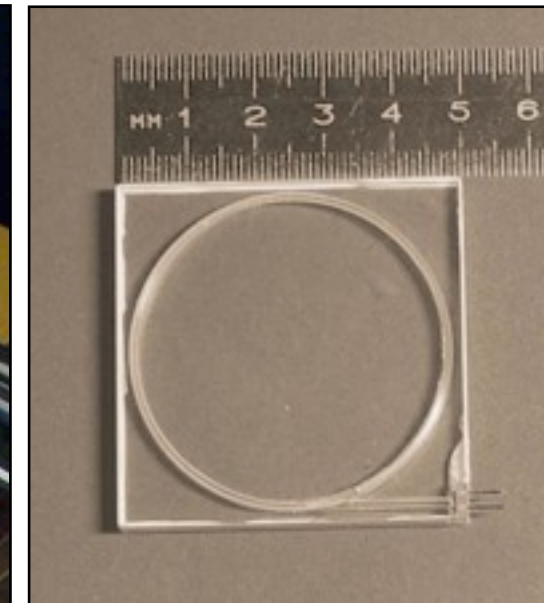
HAMAMATSU
MPPC 400Pixels

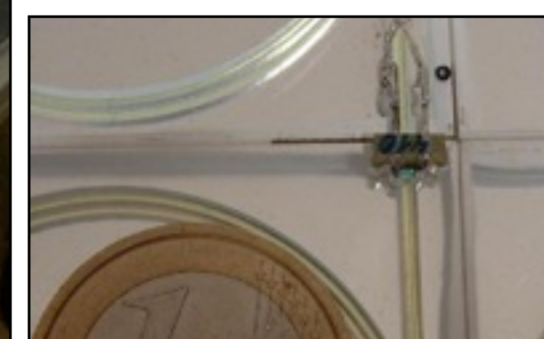
One of the first SiPM
Pulsar, Moscow

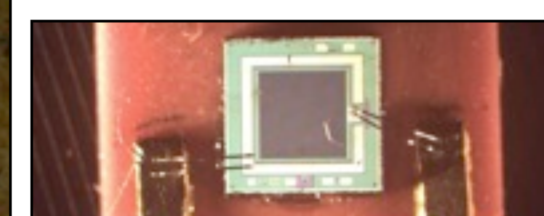


Silicon Photomultipliers





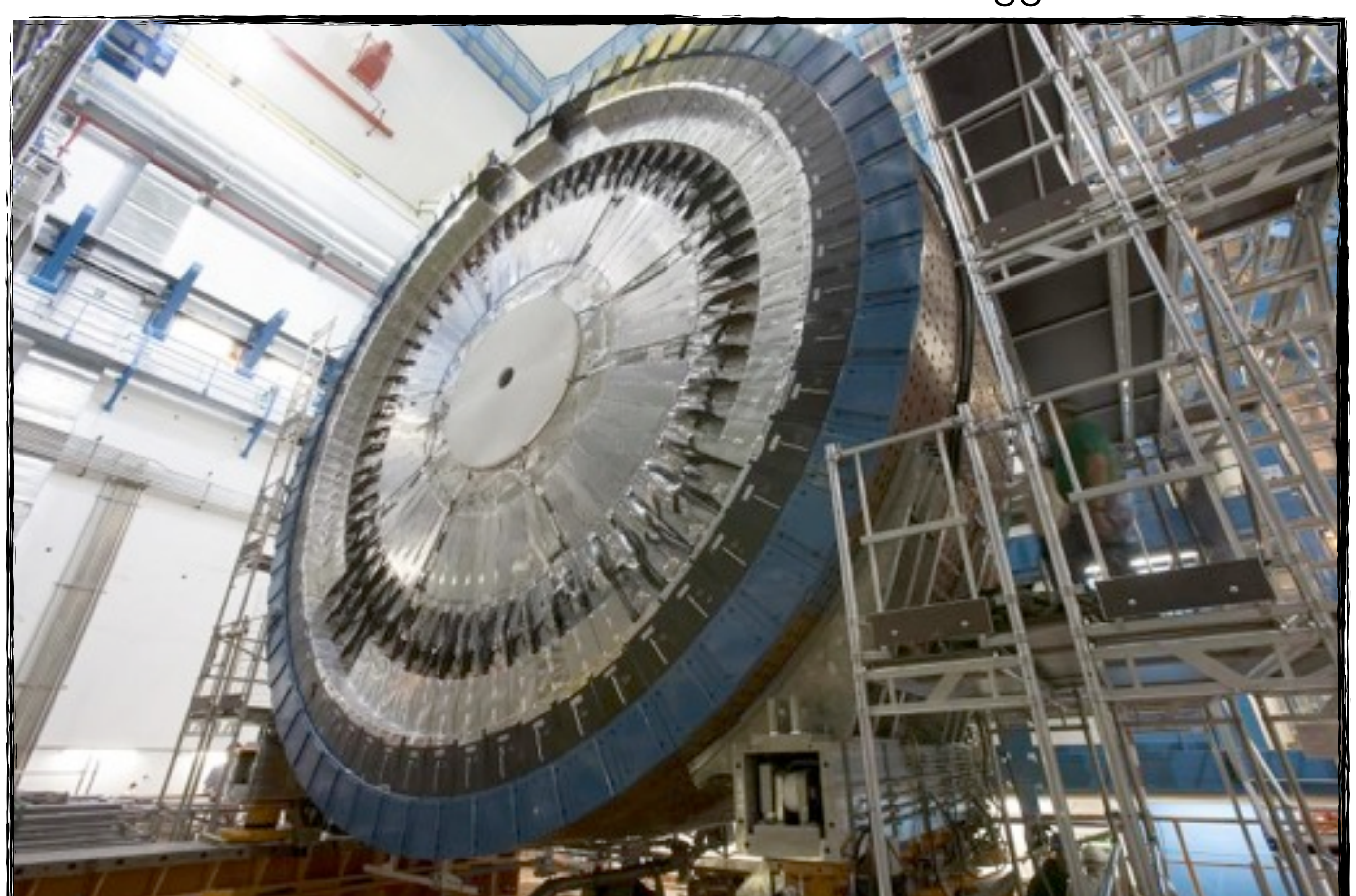




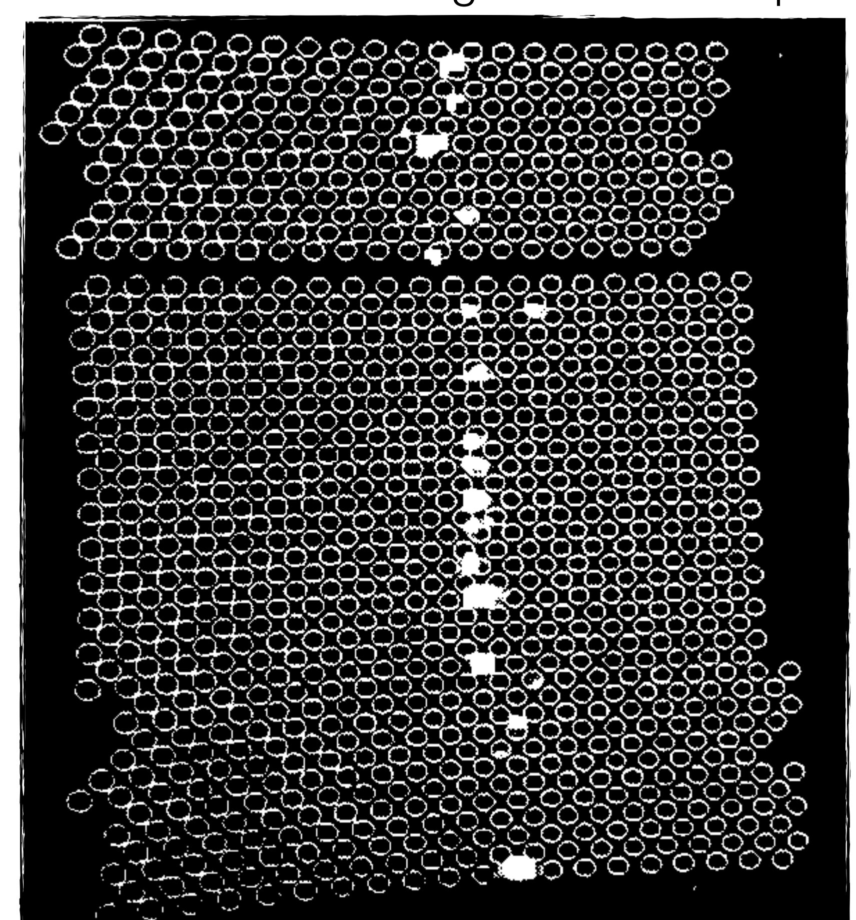
Scintillation Counters – Applications

Time of flight (ToF) counters
Energy measurement (calorimeters)
Hodoscopes; fibre trackers
Trigger systems

ATLAS
Minimum Bias Trigger Scintillators

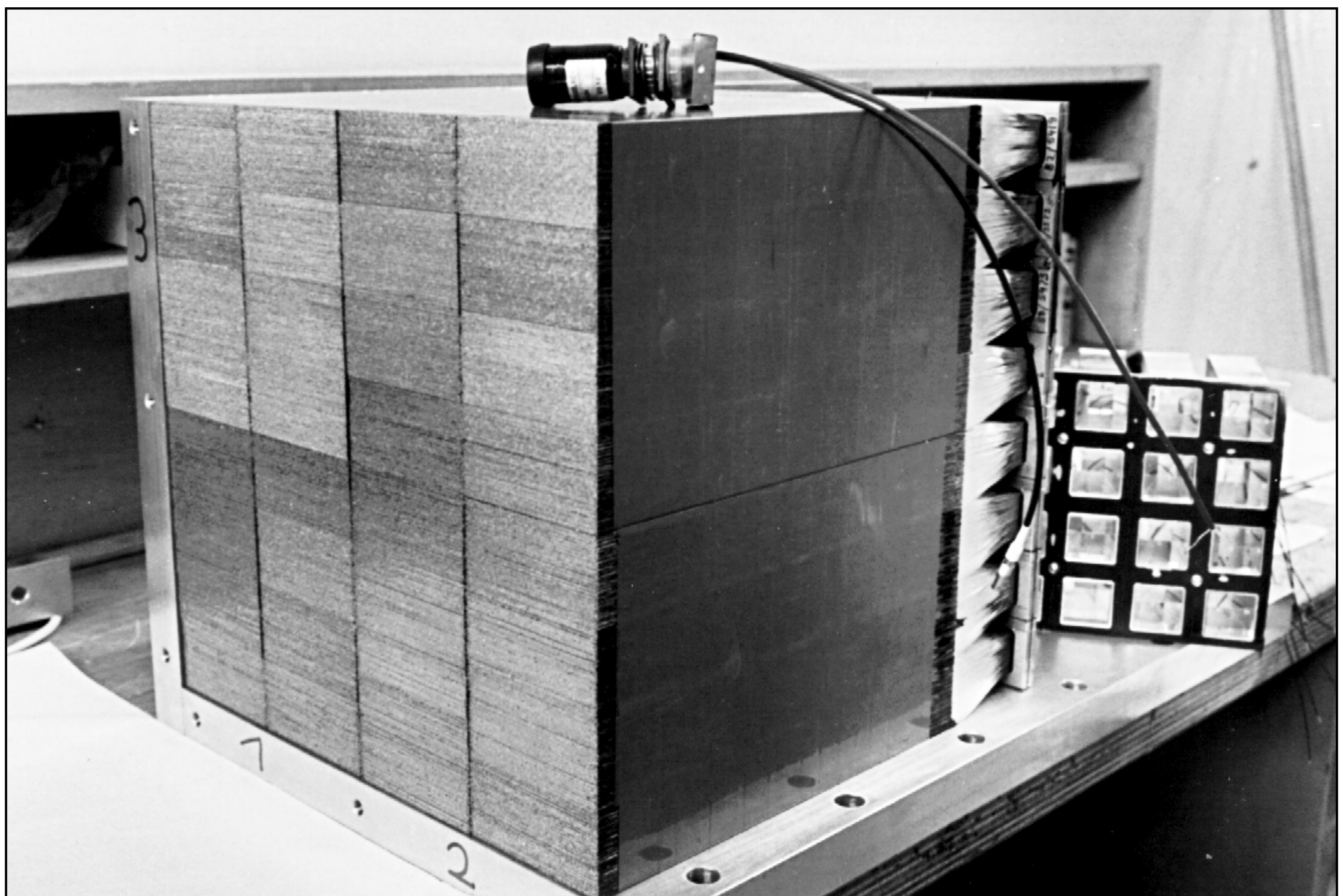


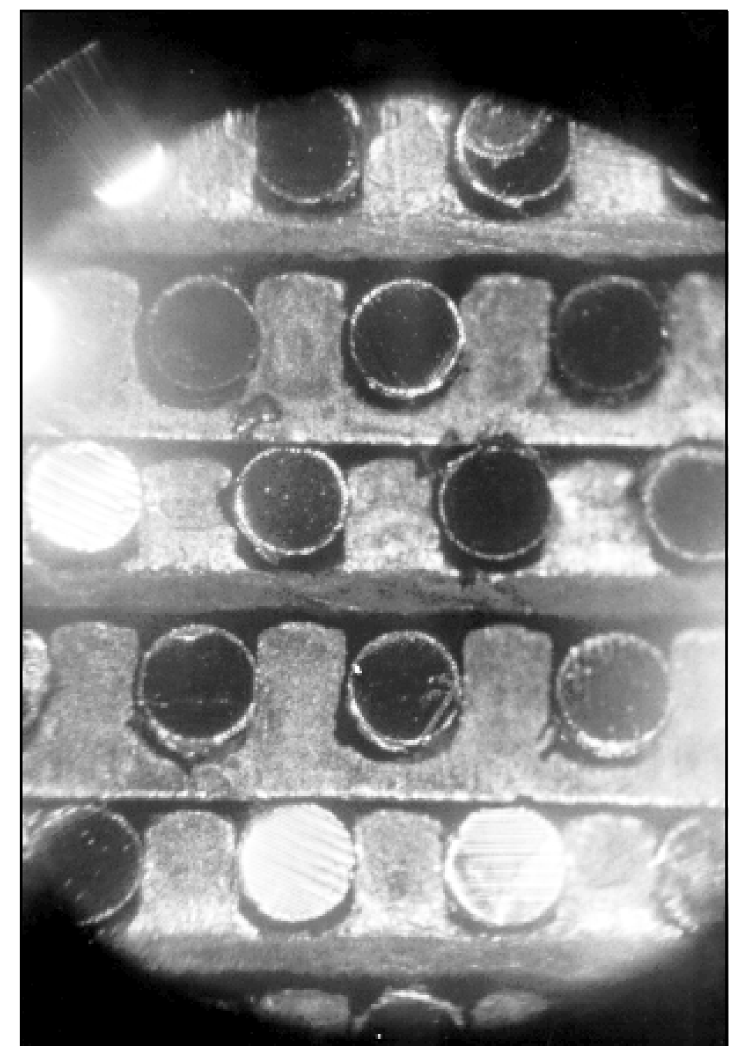
Particle track in
scintillating fibre hodoscope



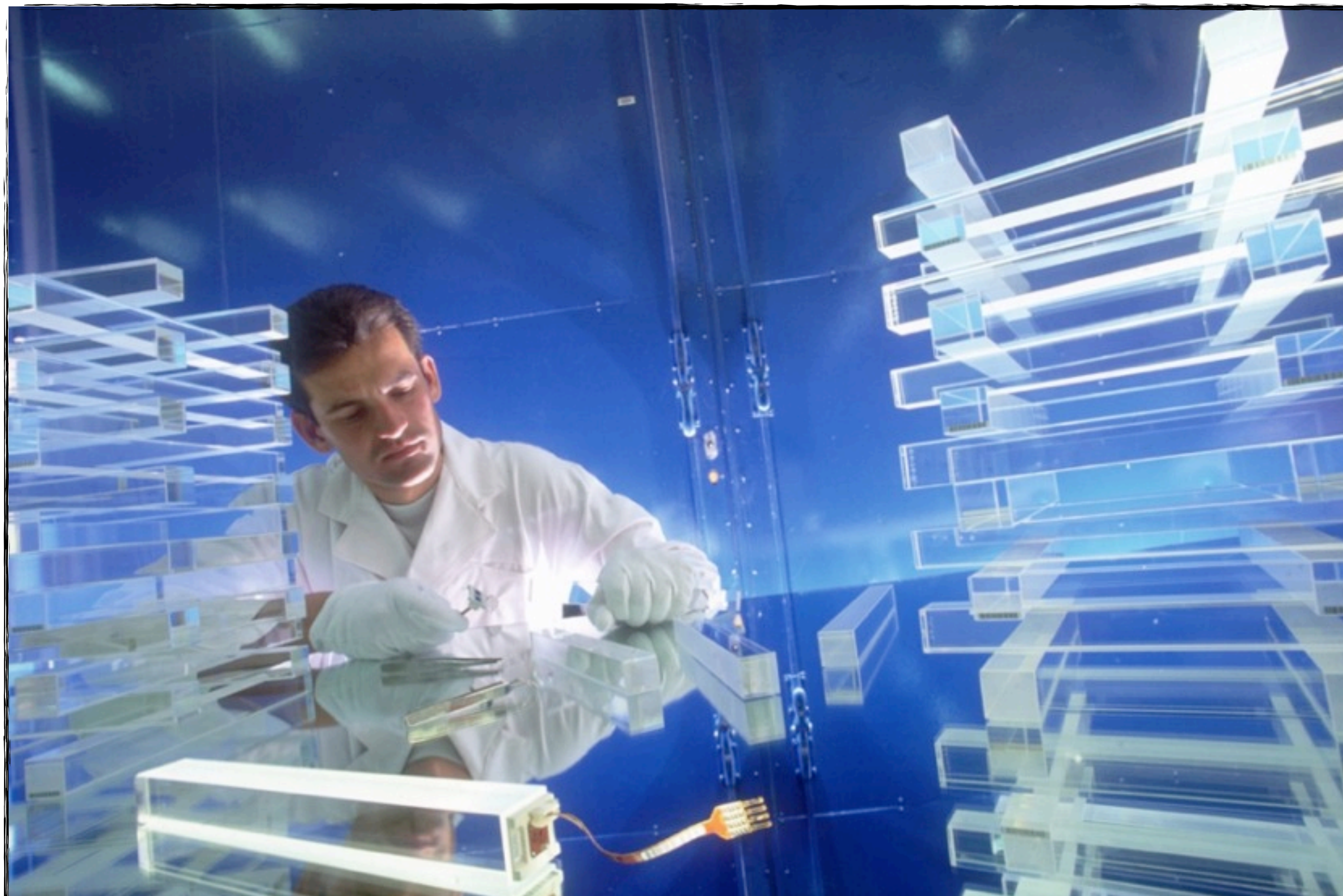
H1 – Spaghetti Calorimeter

Scintillator : BICRON BCF-12
Photosensor : Photomultipliers





CMS – Crystal Calorimeter (ECAL)



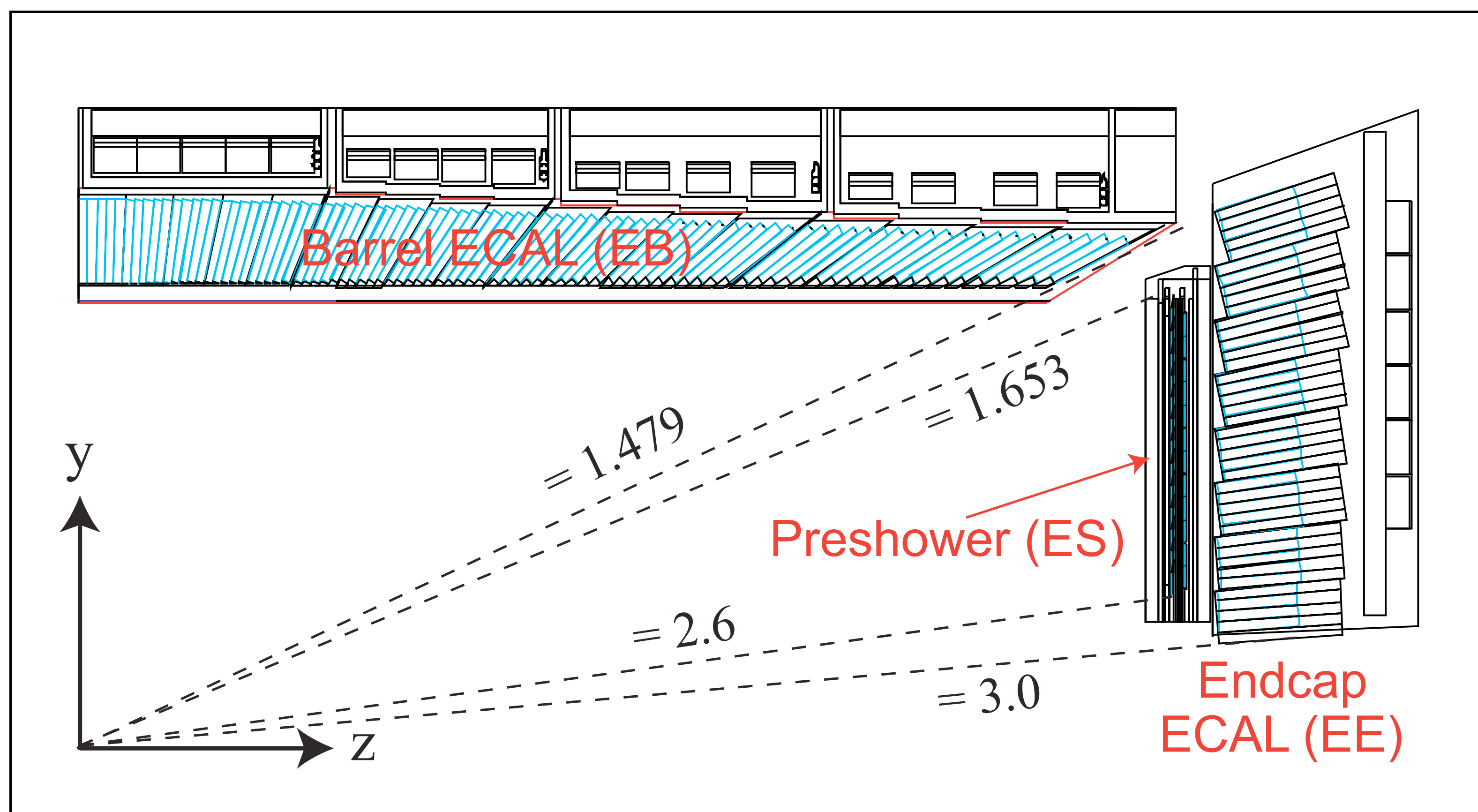
CMS – Crystal Calorimeter (ECAL)

Scintillator : $PBWO_4$ [Lead Tungsten]

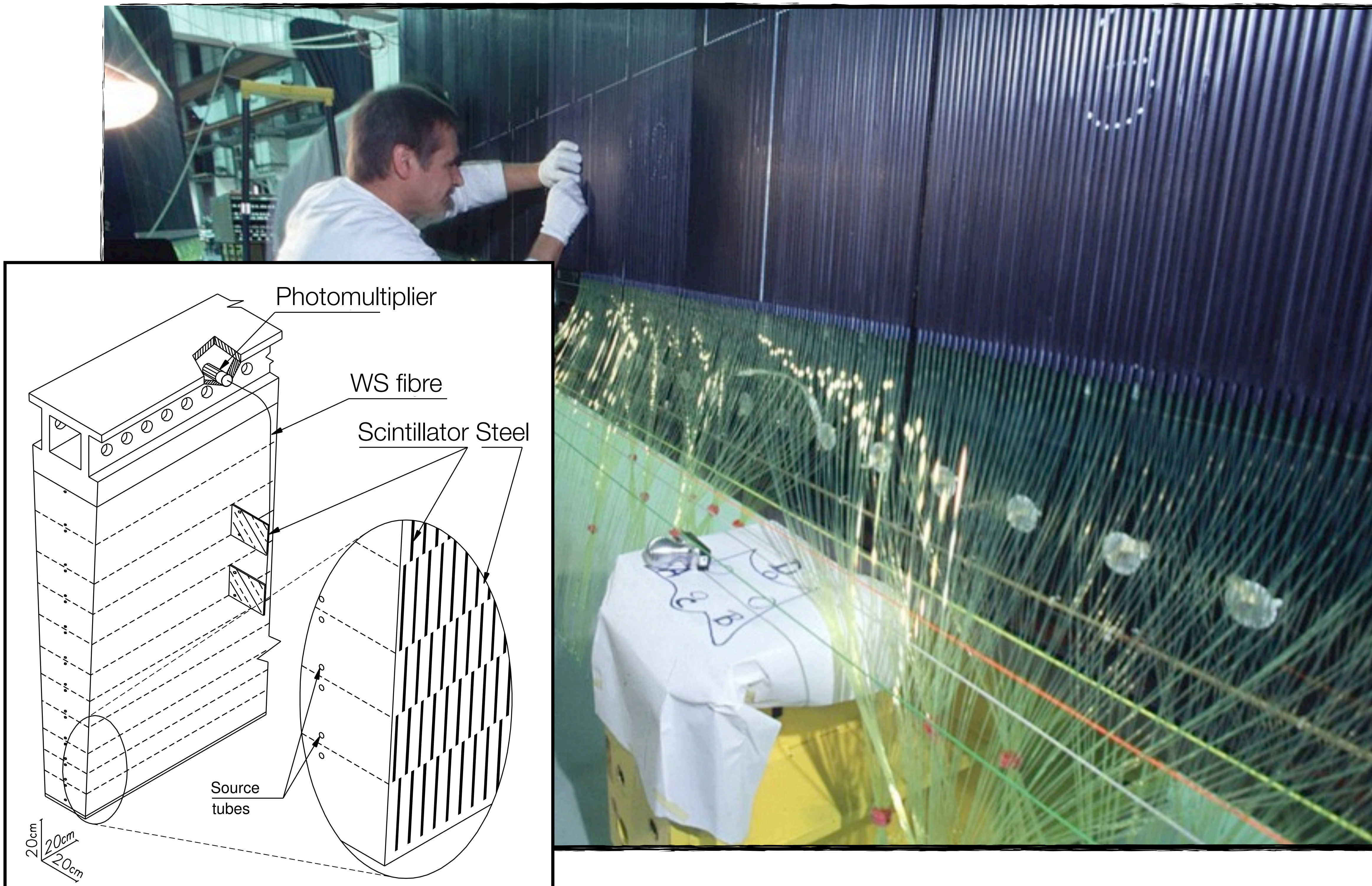
Photosensor : APDs [Avalanche Photodiodes]

Number of crystals: ~ 70000

Light output: 4.5 photons/MeV



ATLAS – Tile Calorimeter



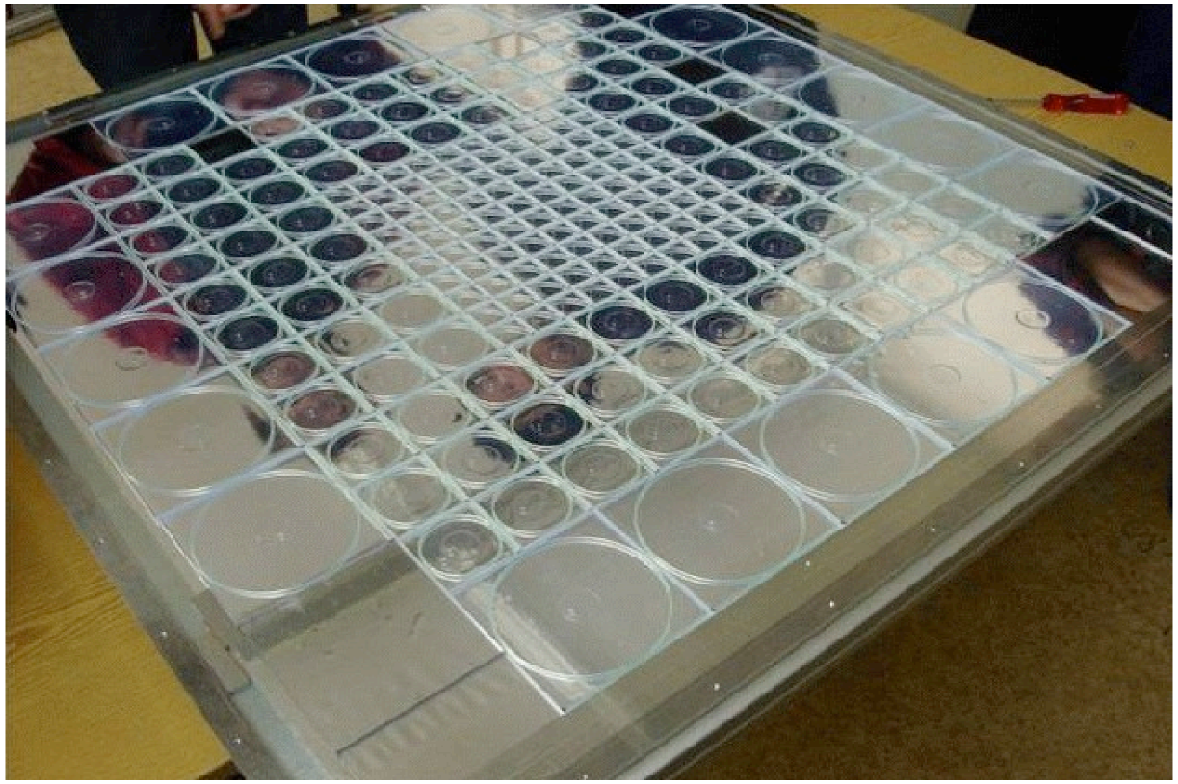
ATLAS Tile Calorimeter

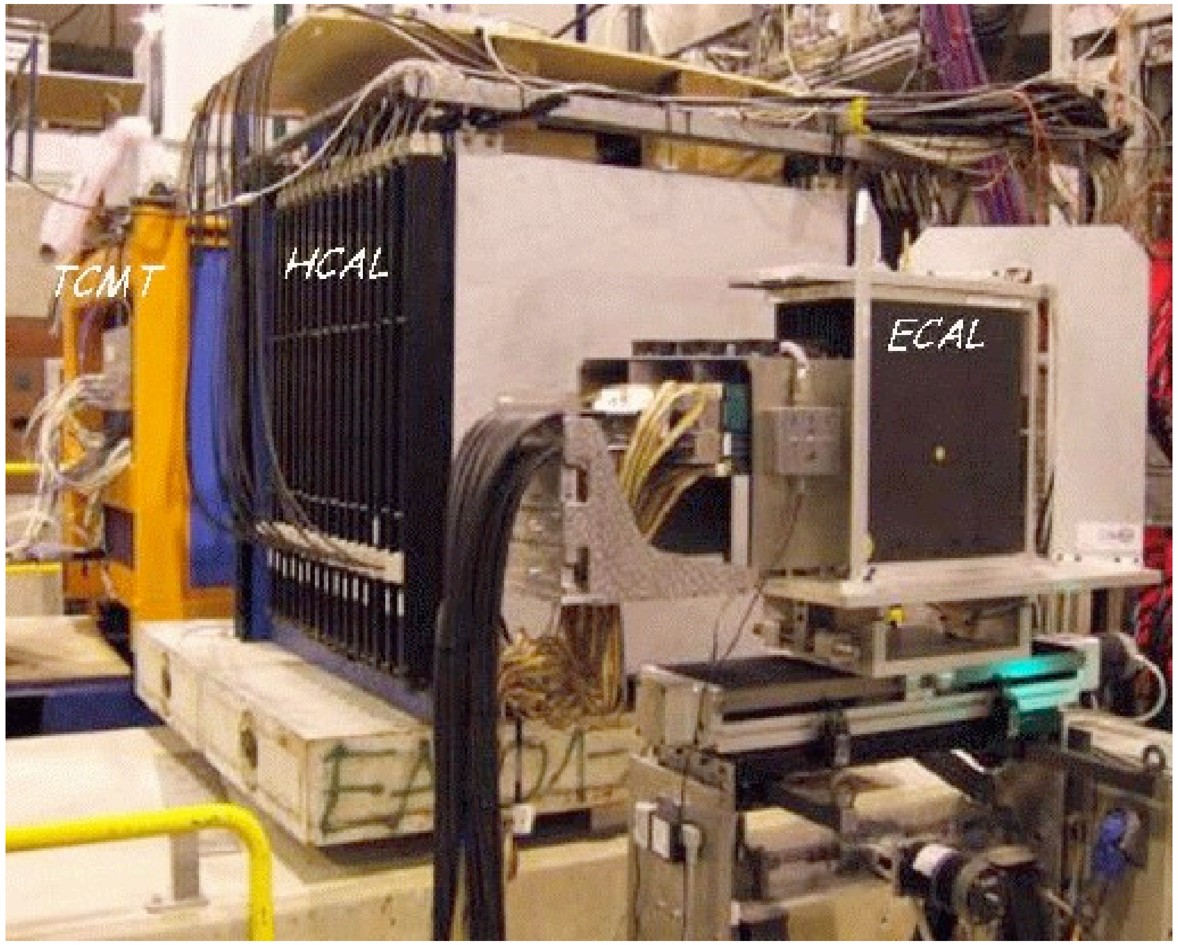
CALICE – Analogue HCAL

1m^3-Prototype
38 layers

Sandwich structure:

- Scintillator Tiles+WLS+SiPMs (.5 cm)
- Stainless steel absorber (1.6 cm)

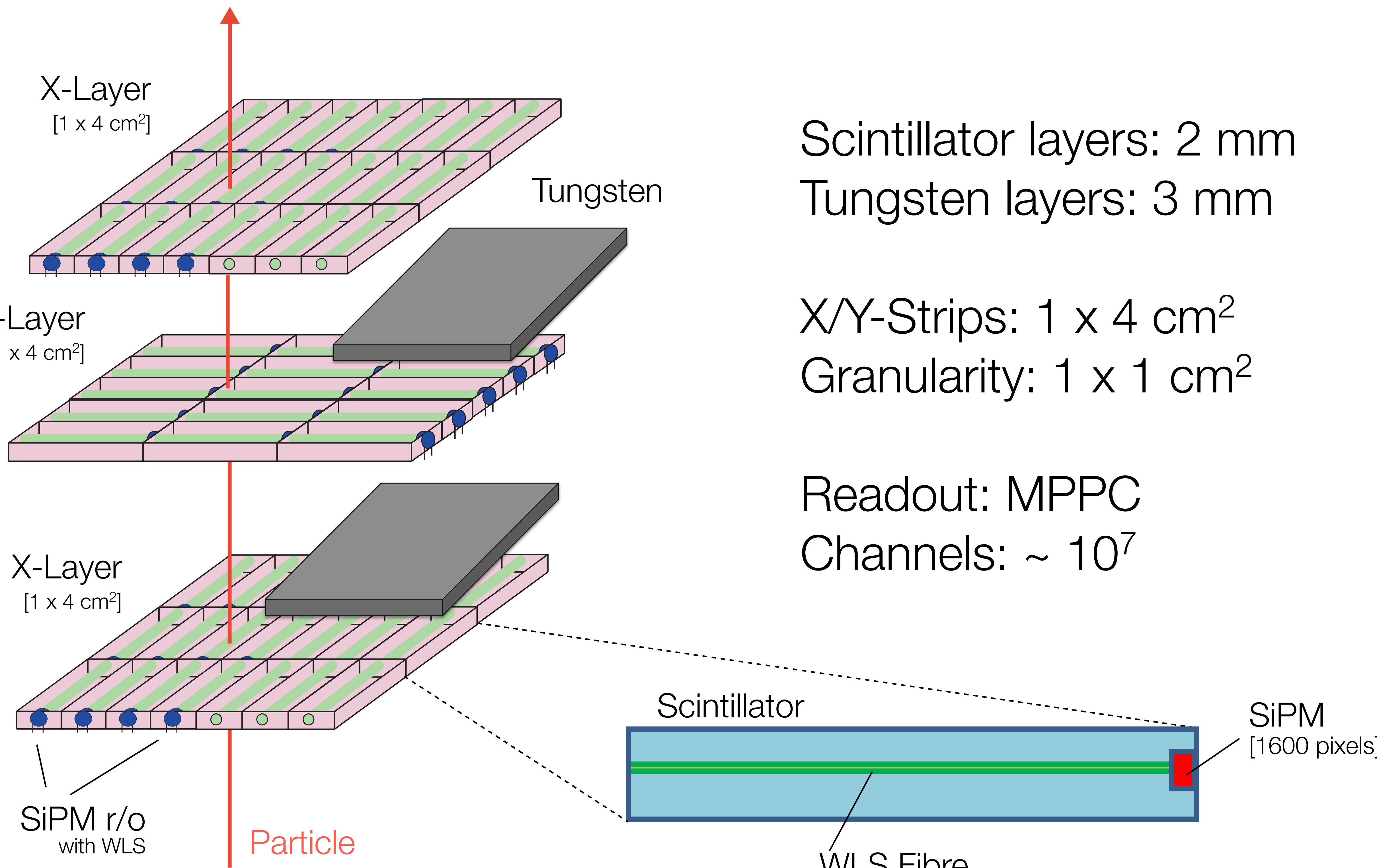




2006/2007 CERN Testbeam
[2008/09, Fermilab]

Scintillator : Plastic
Photosensor : SiPMs

CALICE – Scintillator ECAL



Scintillator layers: 2 mm
Tungsten layers: 3 mm

X/Y-Strips: 1 x 4 cm^2
Granularity: 1 x 1 cm^2

Readout: MPPC
Channels: ~ 10^7