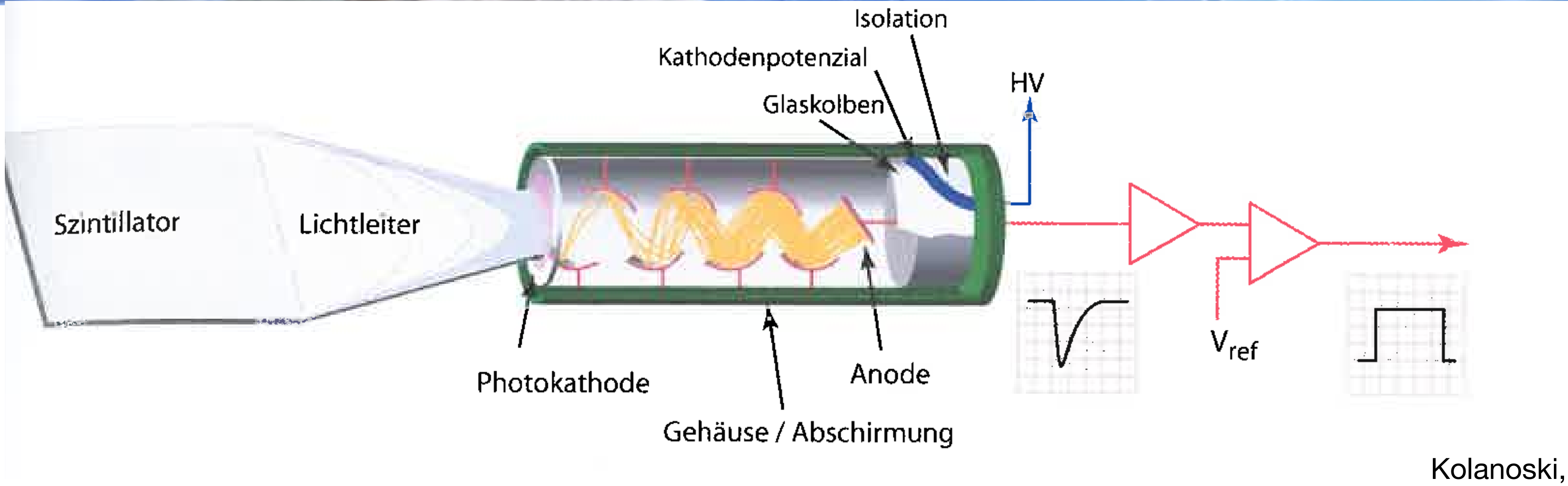
Scintillation Detectors

Particle Detection via Luminescence

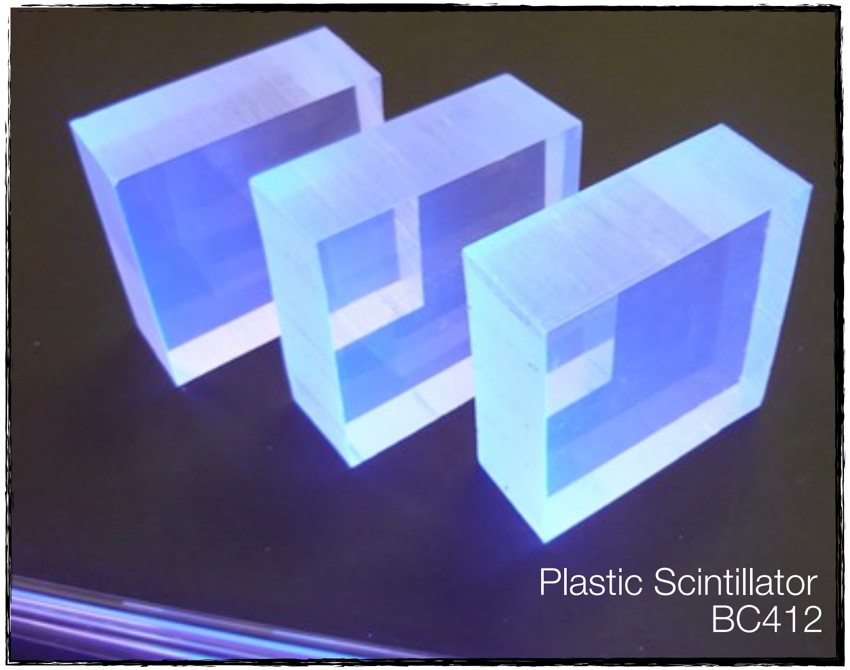


Kolanoski, Wermes

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

Inorganic Crystals

Materials:

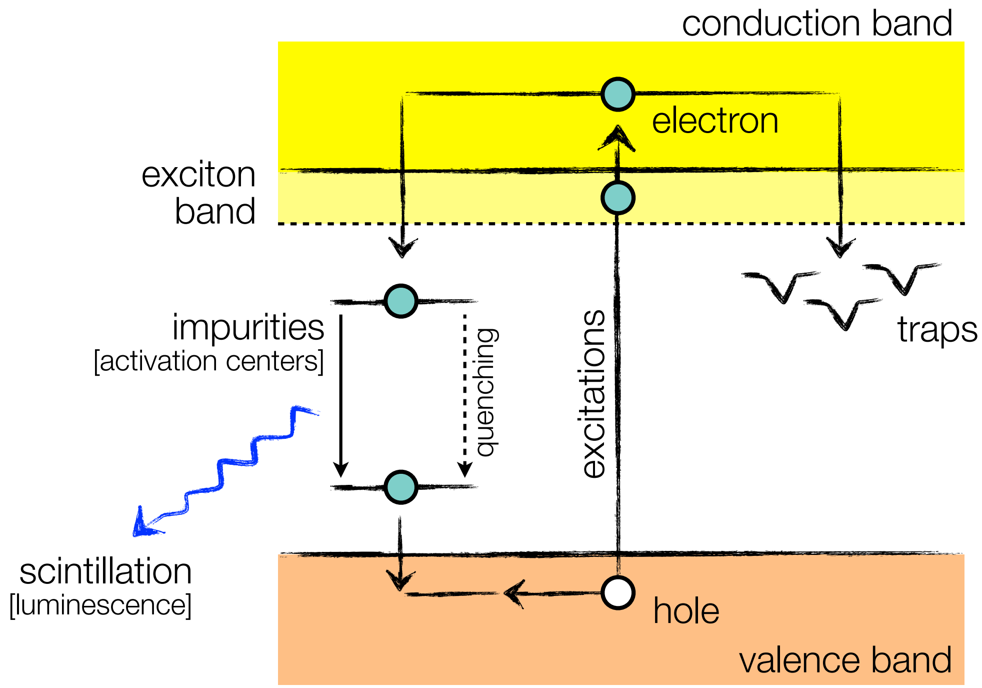
Sodium iodide (NaI)
Cesium iodide (CsI)
Barium fluoride (BaF_2)
...

Mechanism:

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

Time constants:

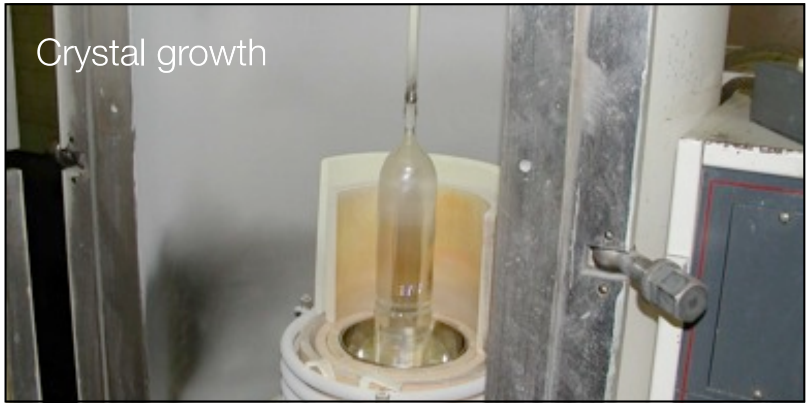
Fast: recombination from activation centers [ns ... µs]
Slow: recombination due to trapping [ms ... s]



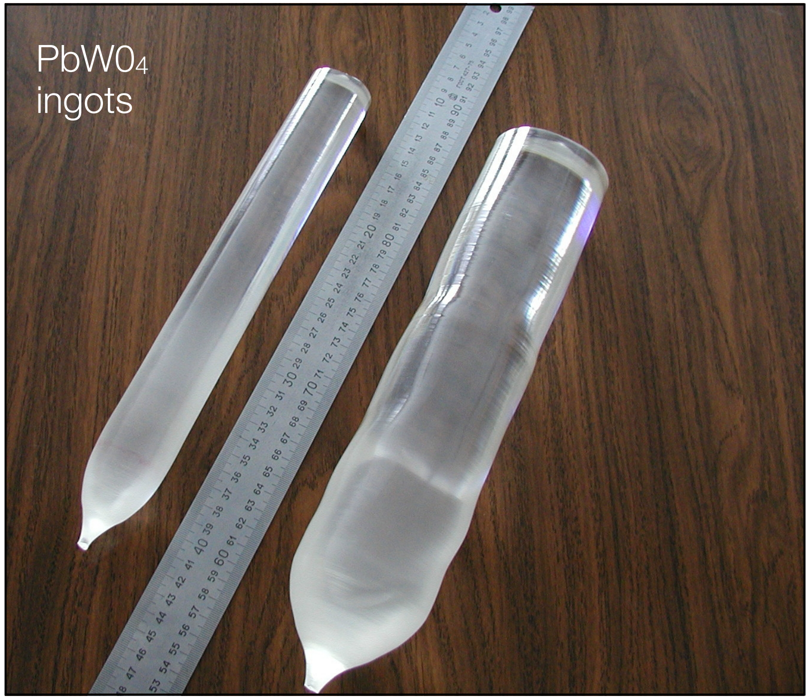
Energy bands in impurity activated crystal

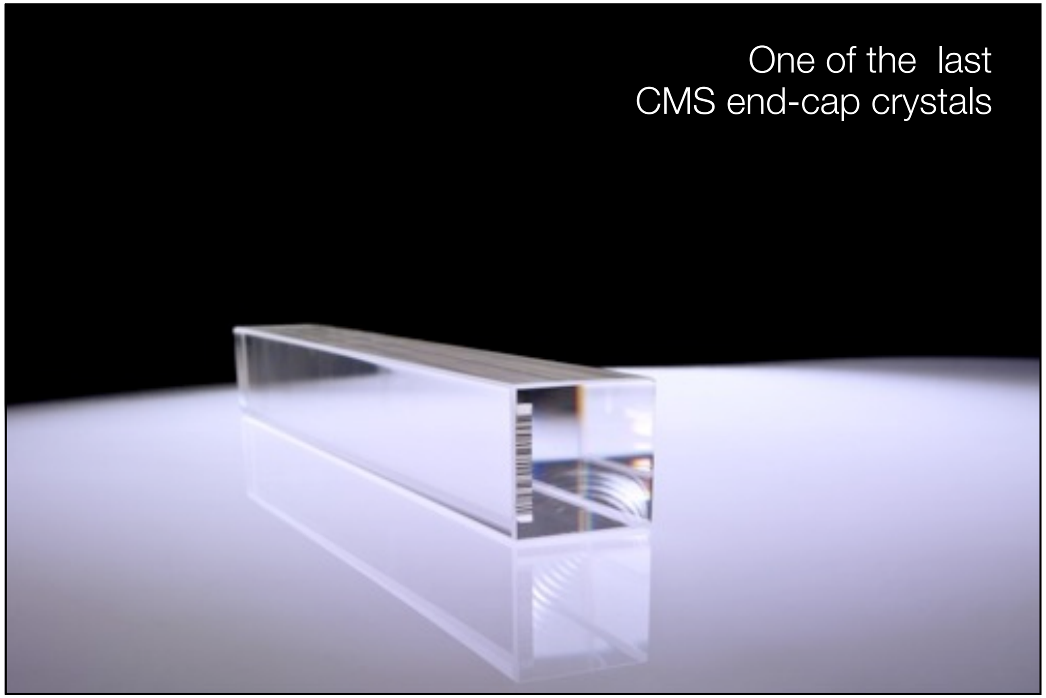
showing excitation, luminescence, quenching and trapping

Inorganic Crystals

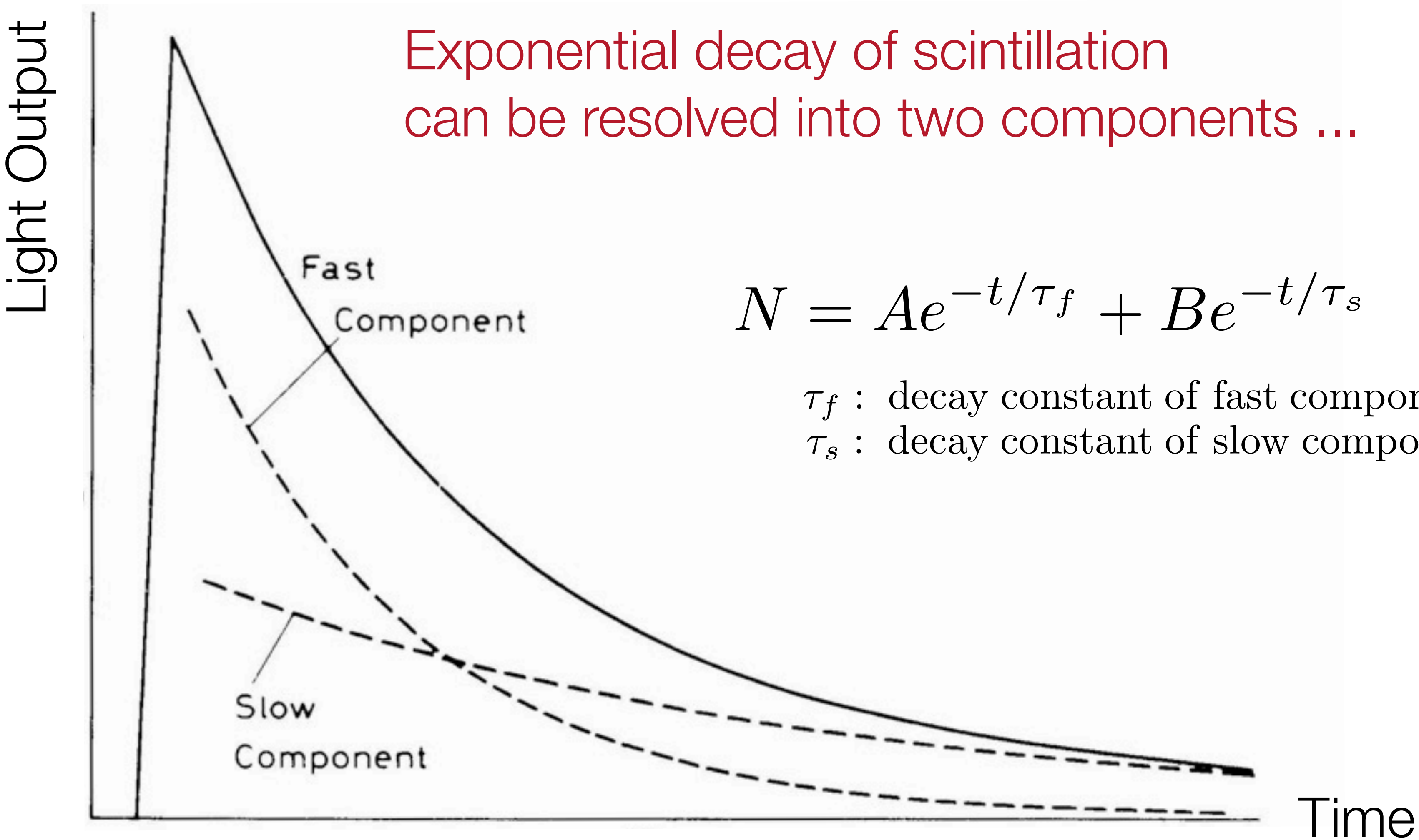


Example CMS
Electromagnetic Calorimeter





Inorganic Crystals – Time Constants



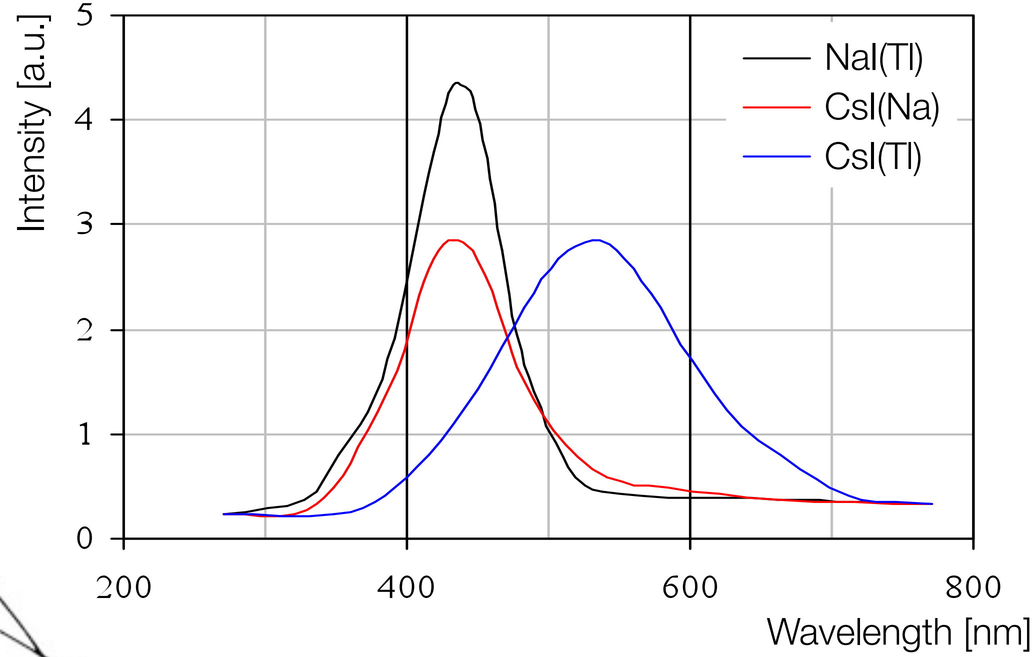
Exponential decay of scintillation
can be resolved into two components ...

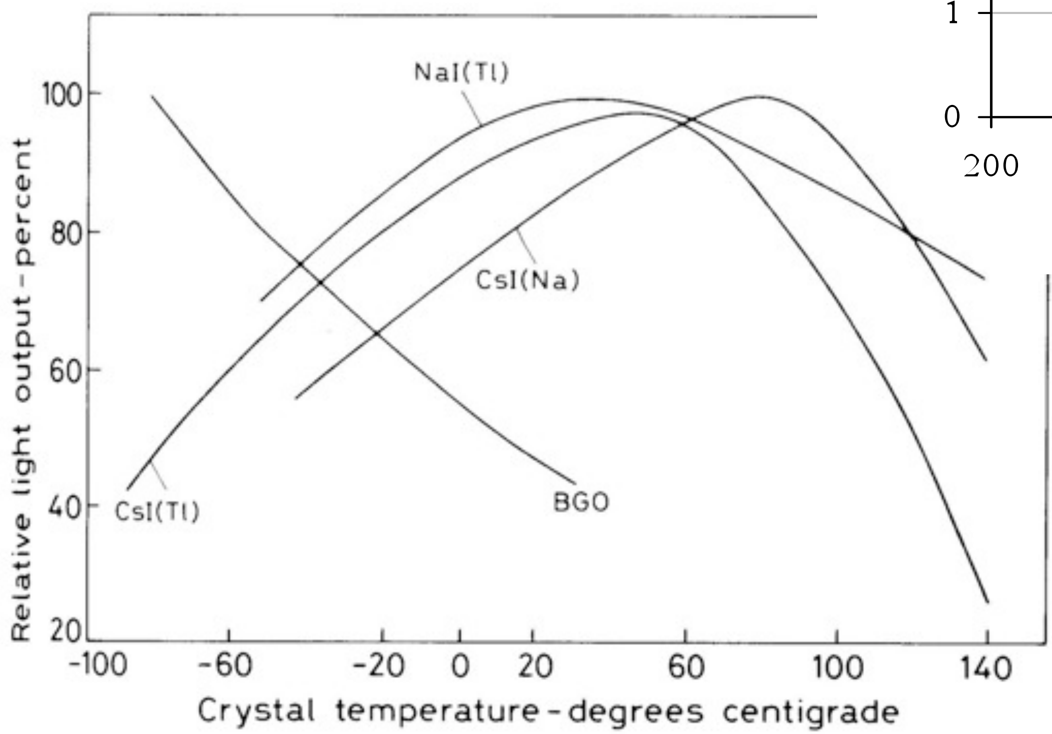
$$N = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$$

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]

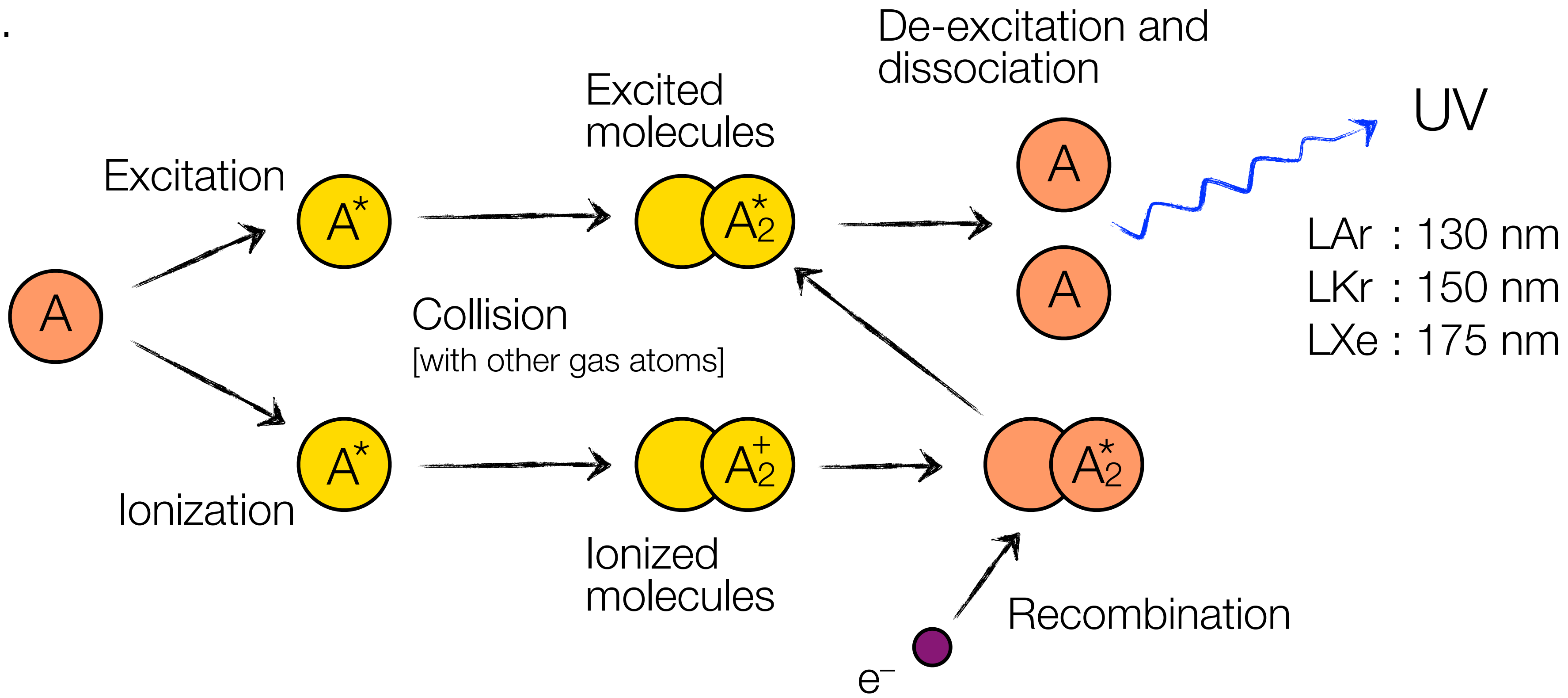
Scintillation in Liquid Nobel Gases

Materials:

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

Decay time constants:

Helium : τ_1 = .02 μs, τ_2 = 3 μs
Argon : τ_1 ≤ .02 μs



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 ➛ $\varepsilon_{sc} = 4 \cdot 10^4 \cdot 3\ \text{eV}/10^6\ \text{eV} = 11.3\%$
PBWO$_4$: 200 photons; 3 eV/photon ➛ $\varepsilon_{sc} = 2 \cdot 10^2 \cdot 3\ \text{eV}/10^6\ \text{eV} = 0.06\%$

[for 1 MeV particle]

Organic Scintillators

Aromatic hydrocarbon compounds:

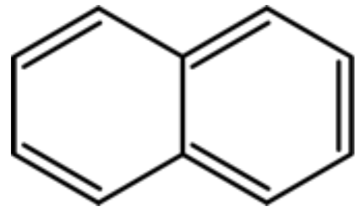
e.g. Naphtalene [$C_{10}H_8$]
Antracene [$C_{14}H_{10}$]
Stilbene [$C_{14}H_{12}$]
...

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

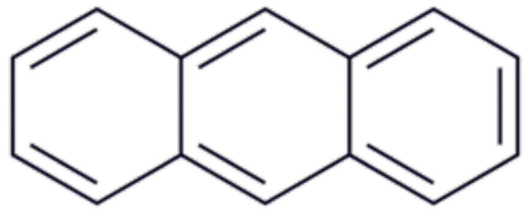
Scintillation light arises from
delocalized electrons in π-orbitals ...

Transitions of 'free' electrons ...

Naphtalene

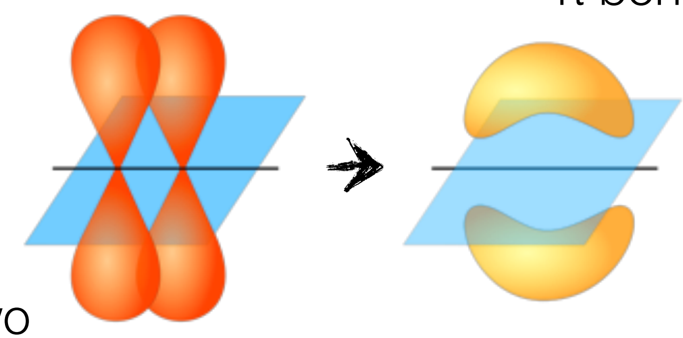


Antracene



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

π bond



Two p_z orbitals

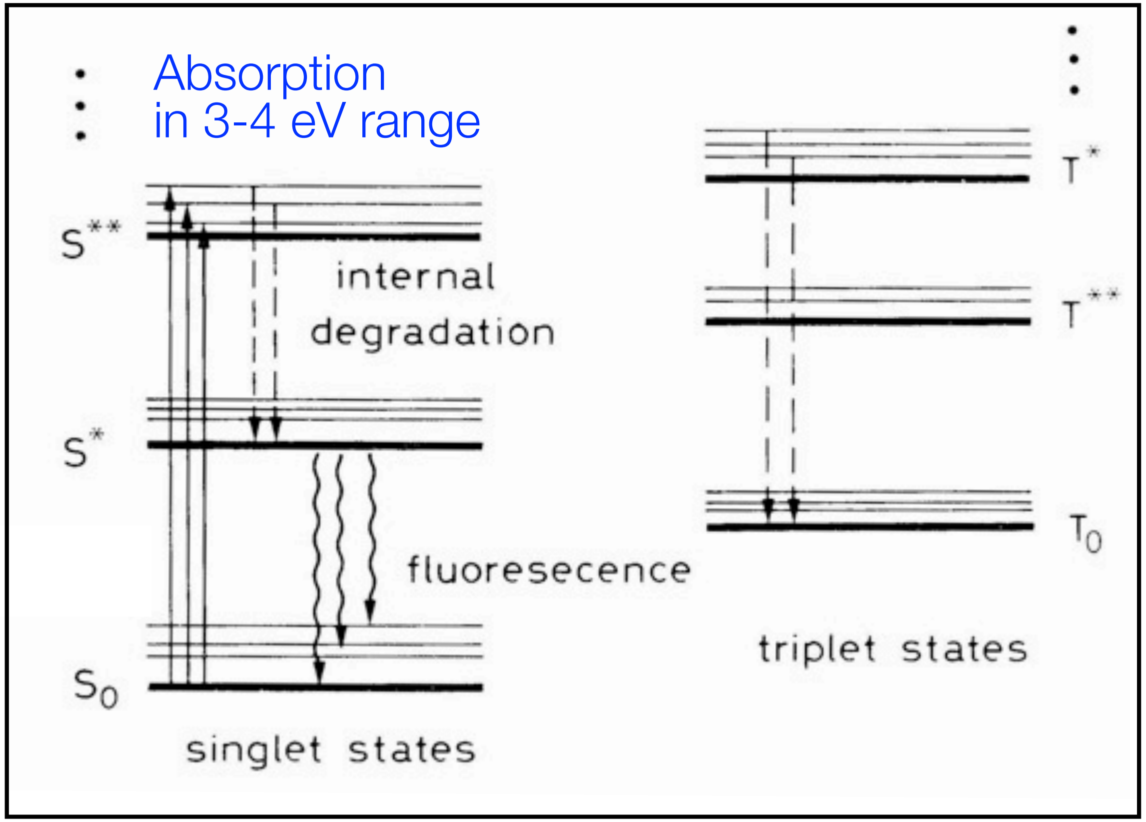
Organic Scintillators

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:

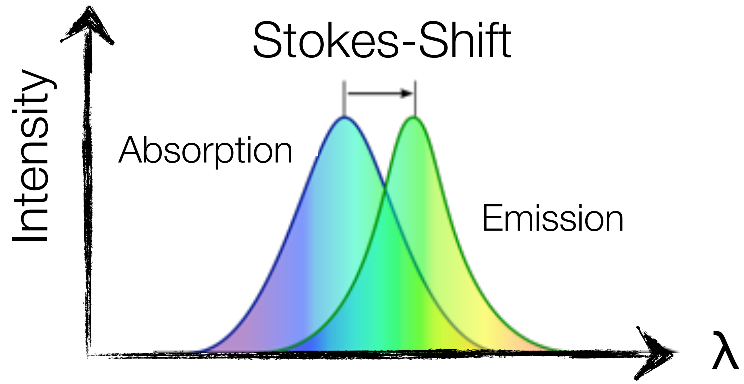
Shift of absorption
and emission spectra ...

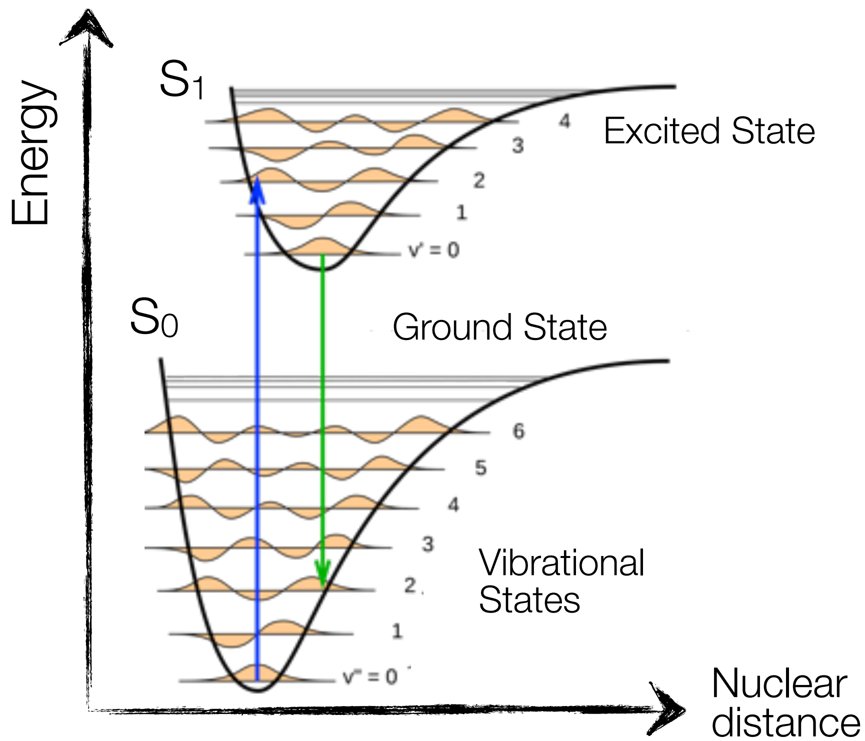
Shift due to

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



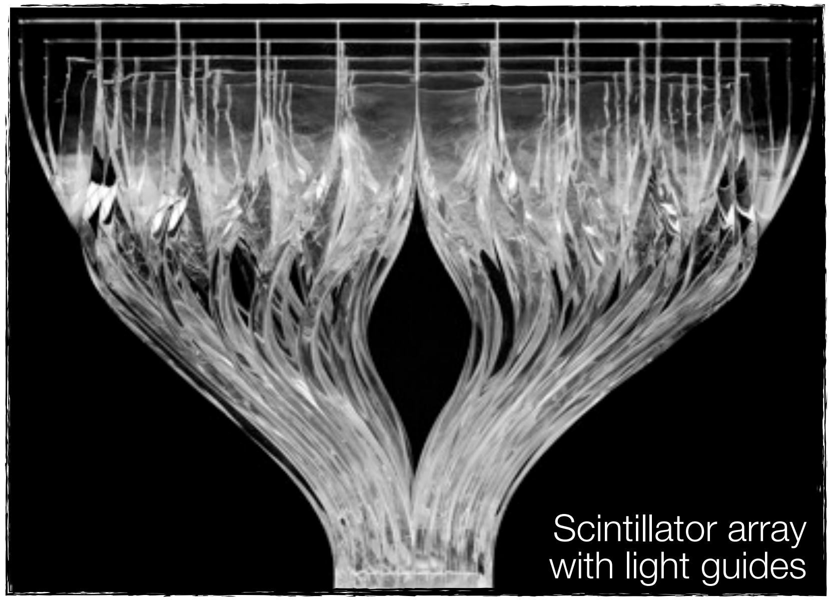


Plastic and Liquid Scintillators

In practice use ...

solution of organic scintillators
[solved in plastic or liquid]

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



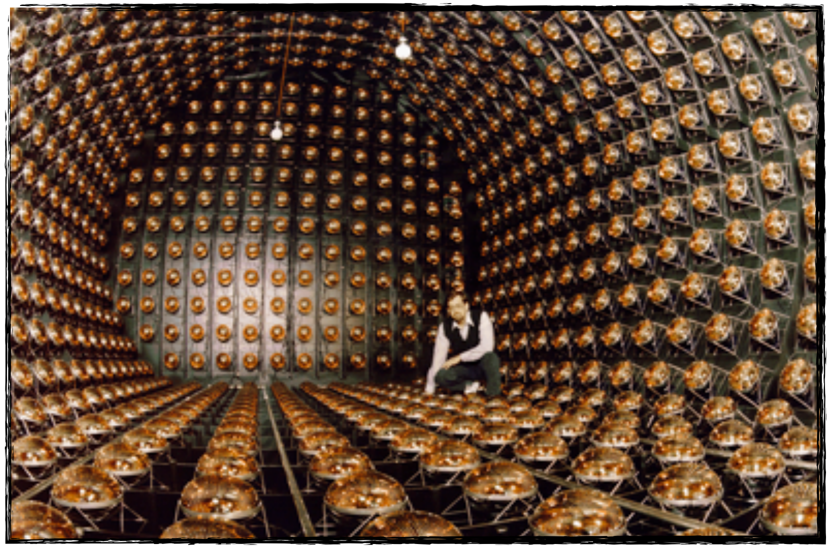
Scintillator array
with light guides

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

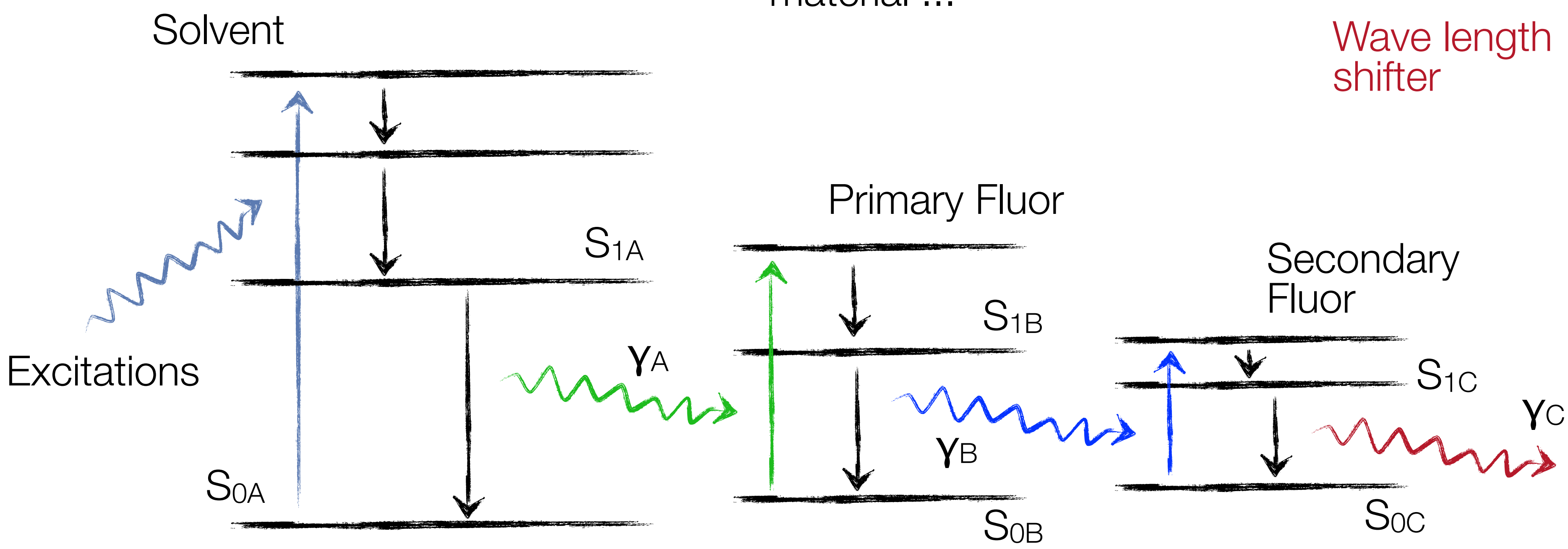
Energy deposit in base material ➝ excitation

Primary fluorescent B

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

Secondary fluorescent C

Wave length shifter



Wavelength Shifting

Principle:

Absorption of
primary scintillation light

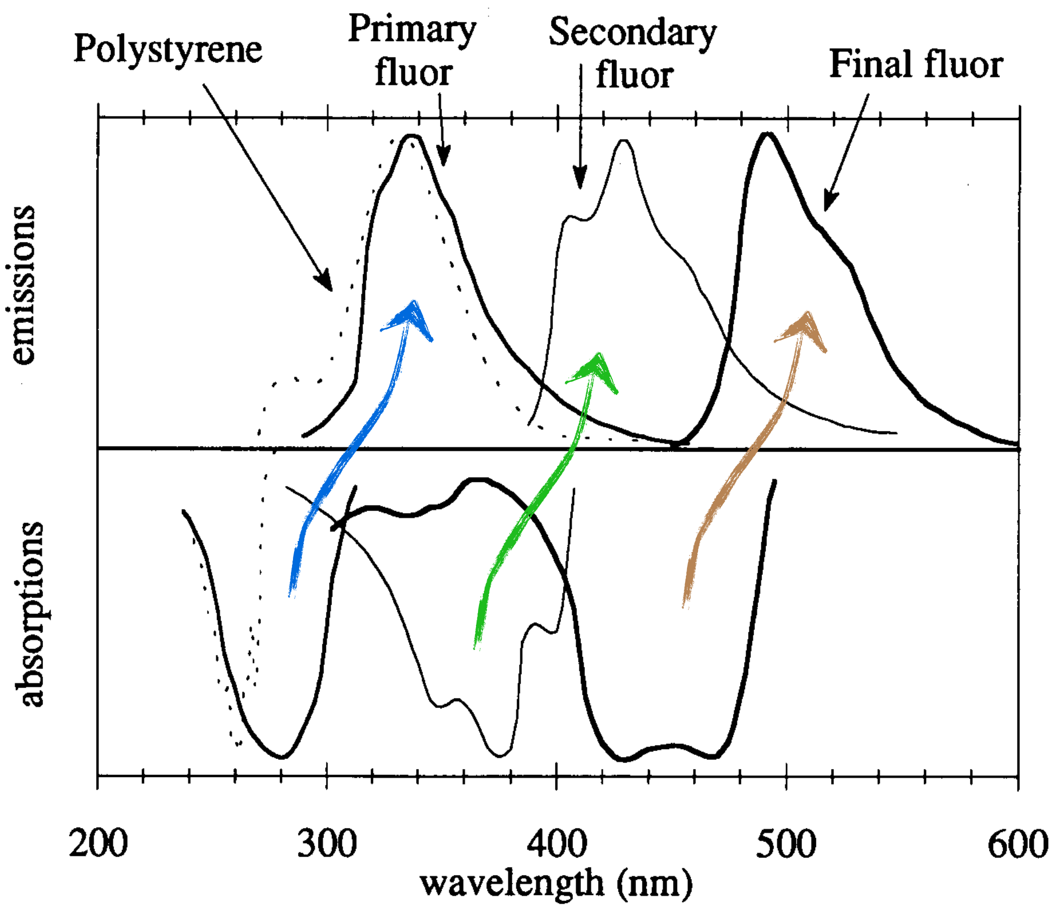
Re-emission at
longer wavelength

Adapts light to spectral
sensitivity of photosensor

Requirement:

Good transparency
for emitted light

Schematics of
wavelength shifting principle



Organic Scintillators – Properties

Light yield:
[without quenching]

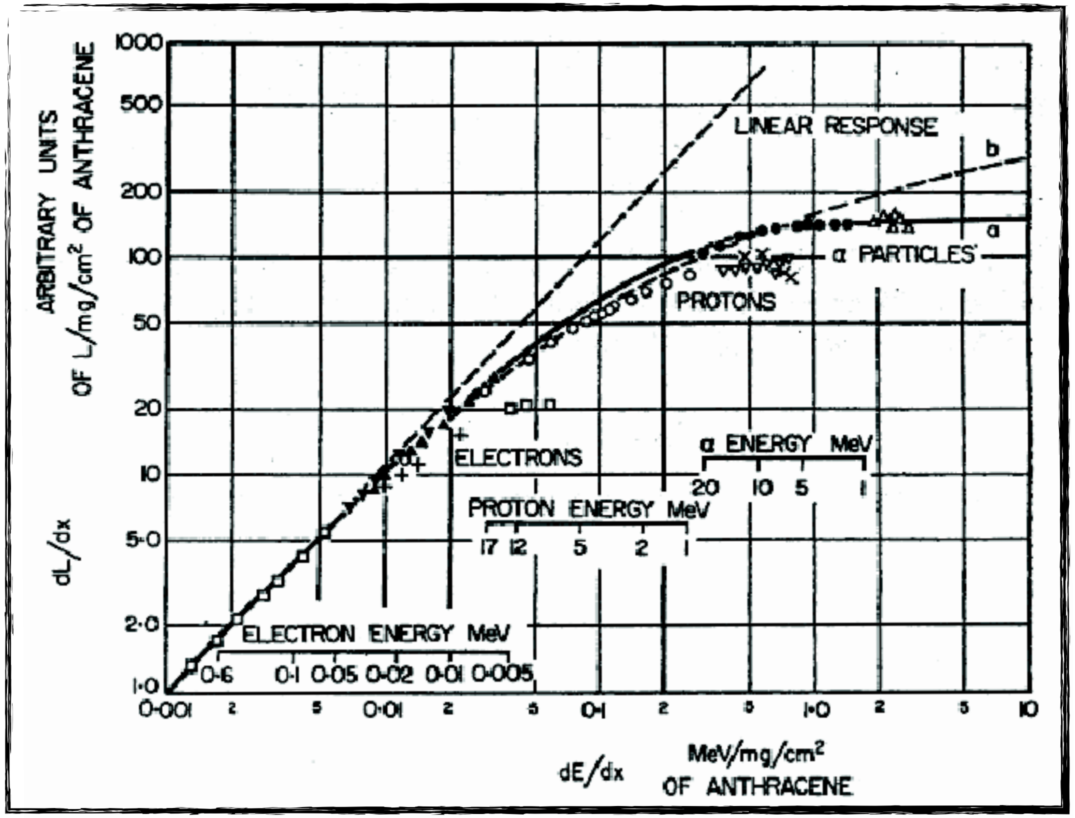
$$\frac{dL}{dx} = L_0 \frac{dE}{dx}$$

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 ...

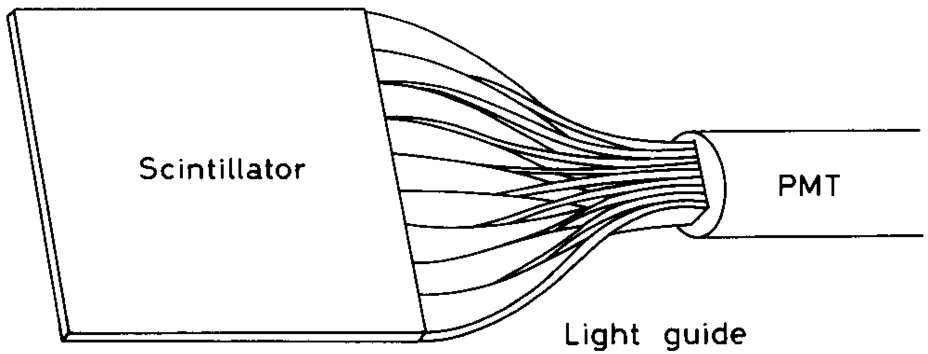
Response different
for different particle types ...

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]

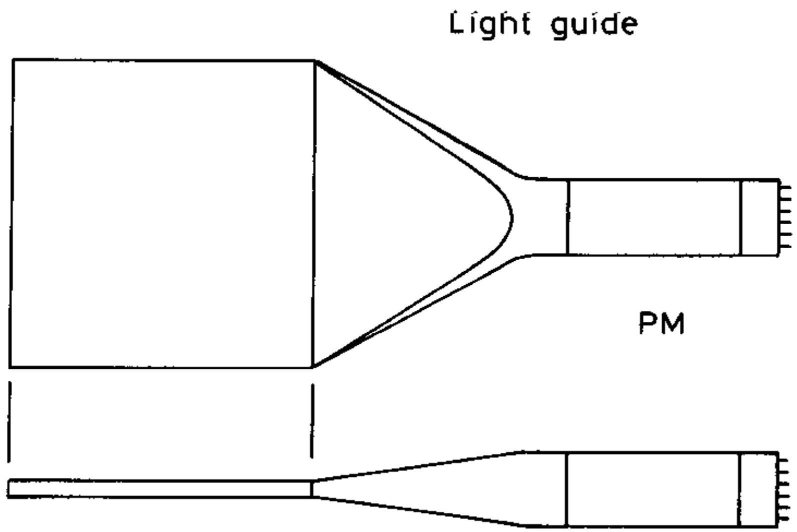


Liouville's Theorem:

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'

Photon Detection

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

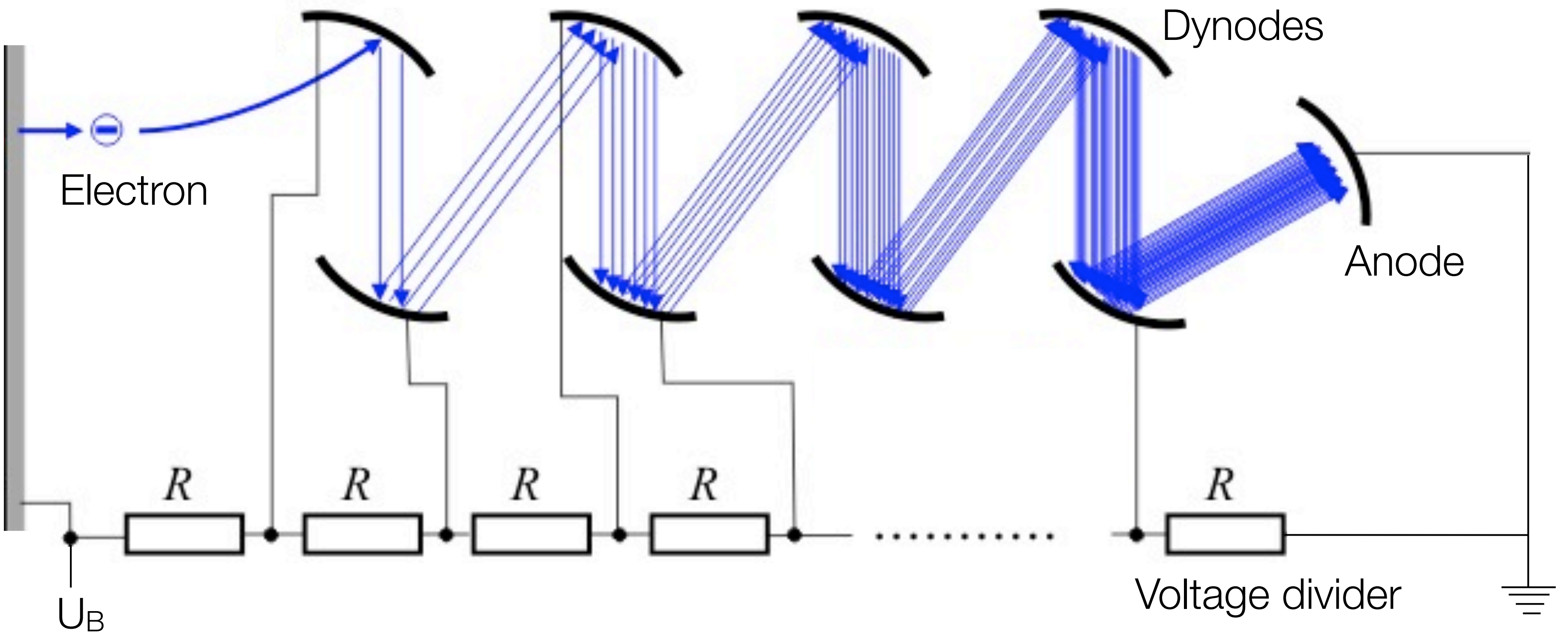
Requirement :

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 – Dynode Chain



Multiplication process:

Electrons accelerated toward dynode
Further electrons produced ➛ avalanche

Secondary emission coefficient:

δ = #(e^- produced)/#(e^- incoming)

Typical: $\delta = 2 - 10$, $n = 8 - 15$ ➛ $G = \delta^n = 10^6 - 10^8$

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

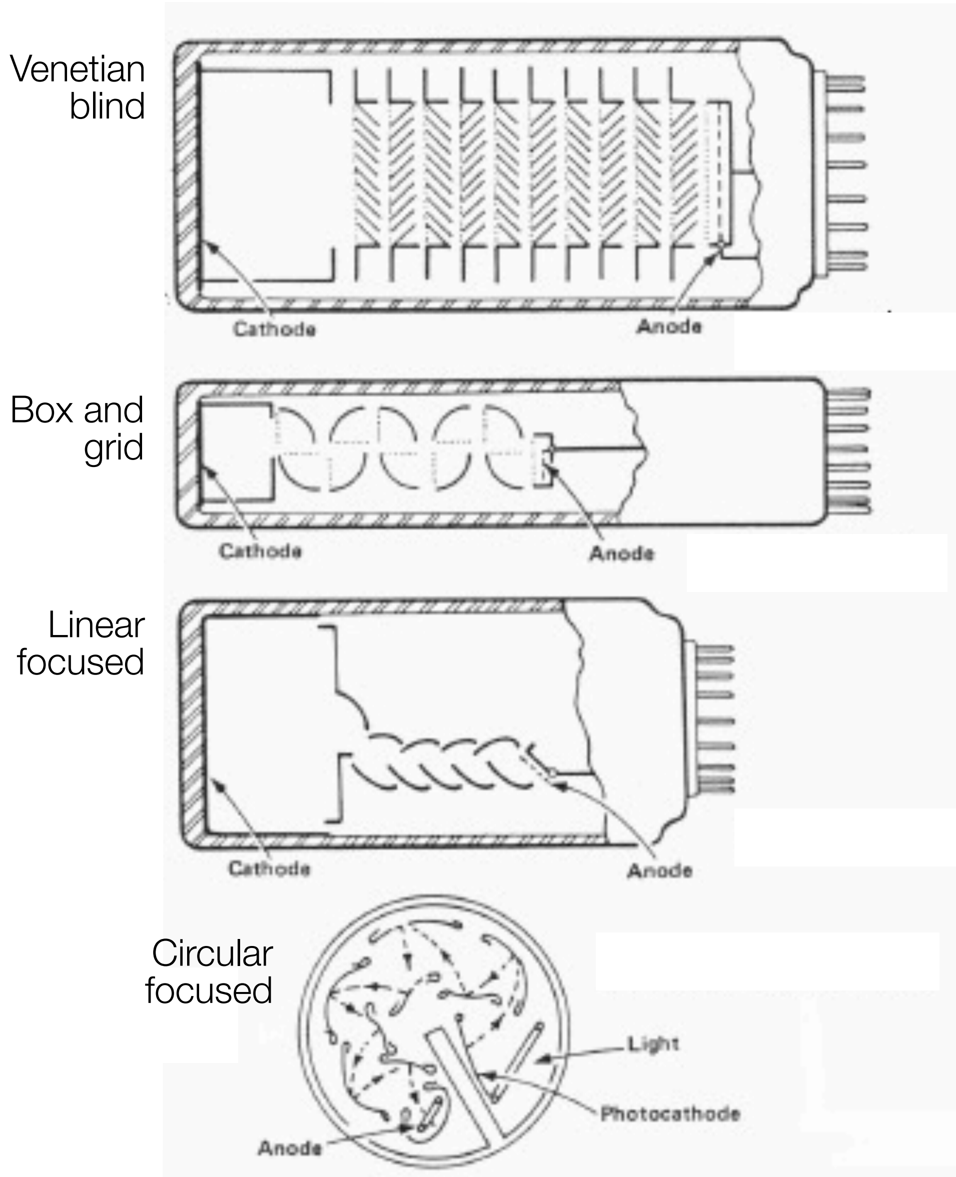
Optimization of

PMT gain
Anode isolation
Linearity
Transit time

B-field dependence

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

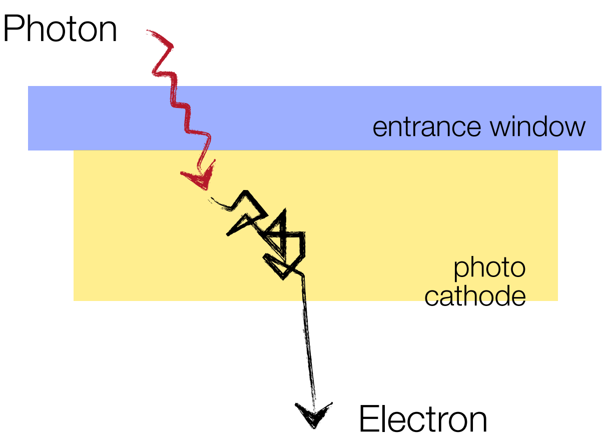
Even to earth field (30-60 μT).
μ-metal shielding required.

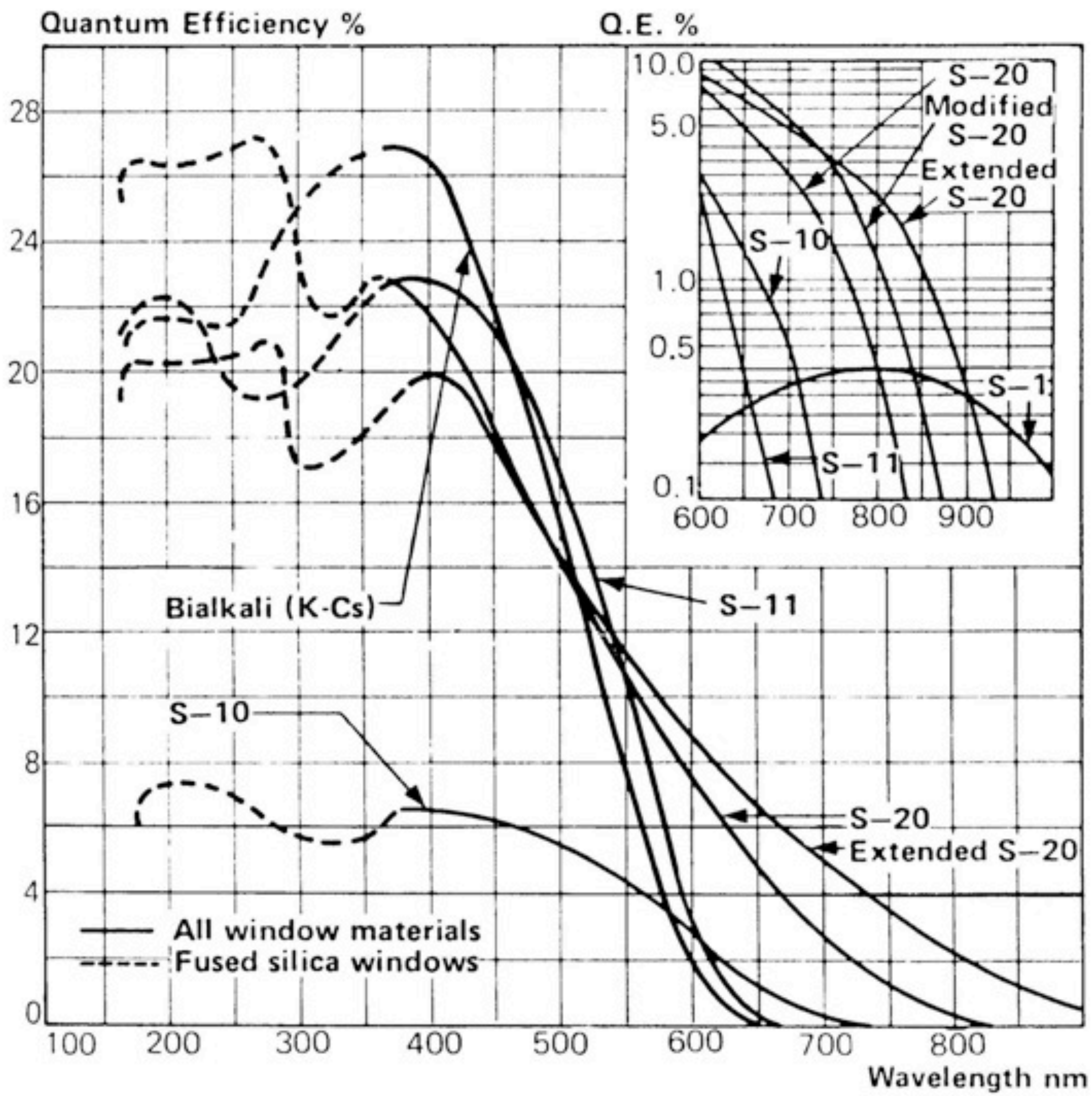


Photomultipliers – Photocathode

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 – 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 ...

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

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

... important for single photon detection

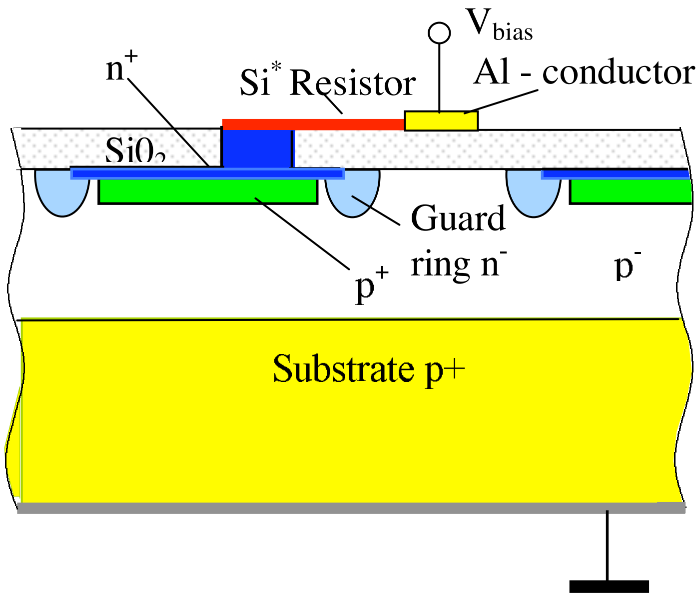
Silicon Photomultipliers

Principle:

Pixelized photo diodes
operated in Geiger Mode

Single pixel works as a binary device

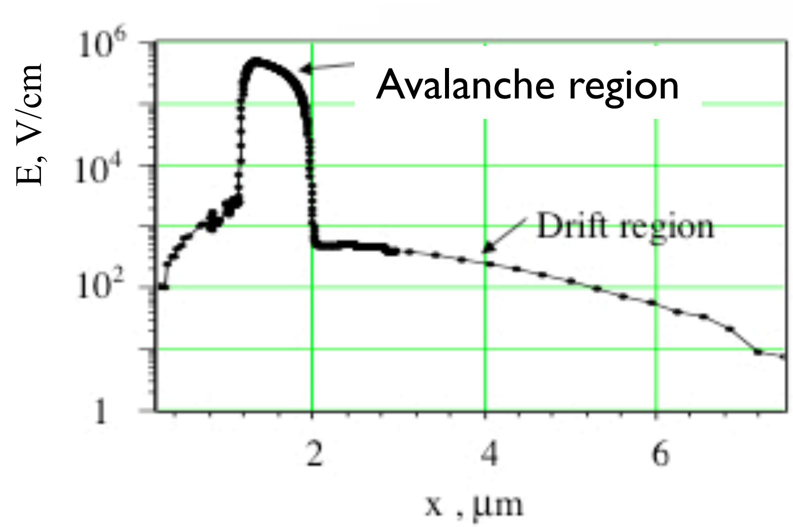
Energy = #photons seen by
summing over all pixels



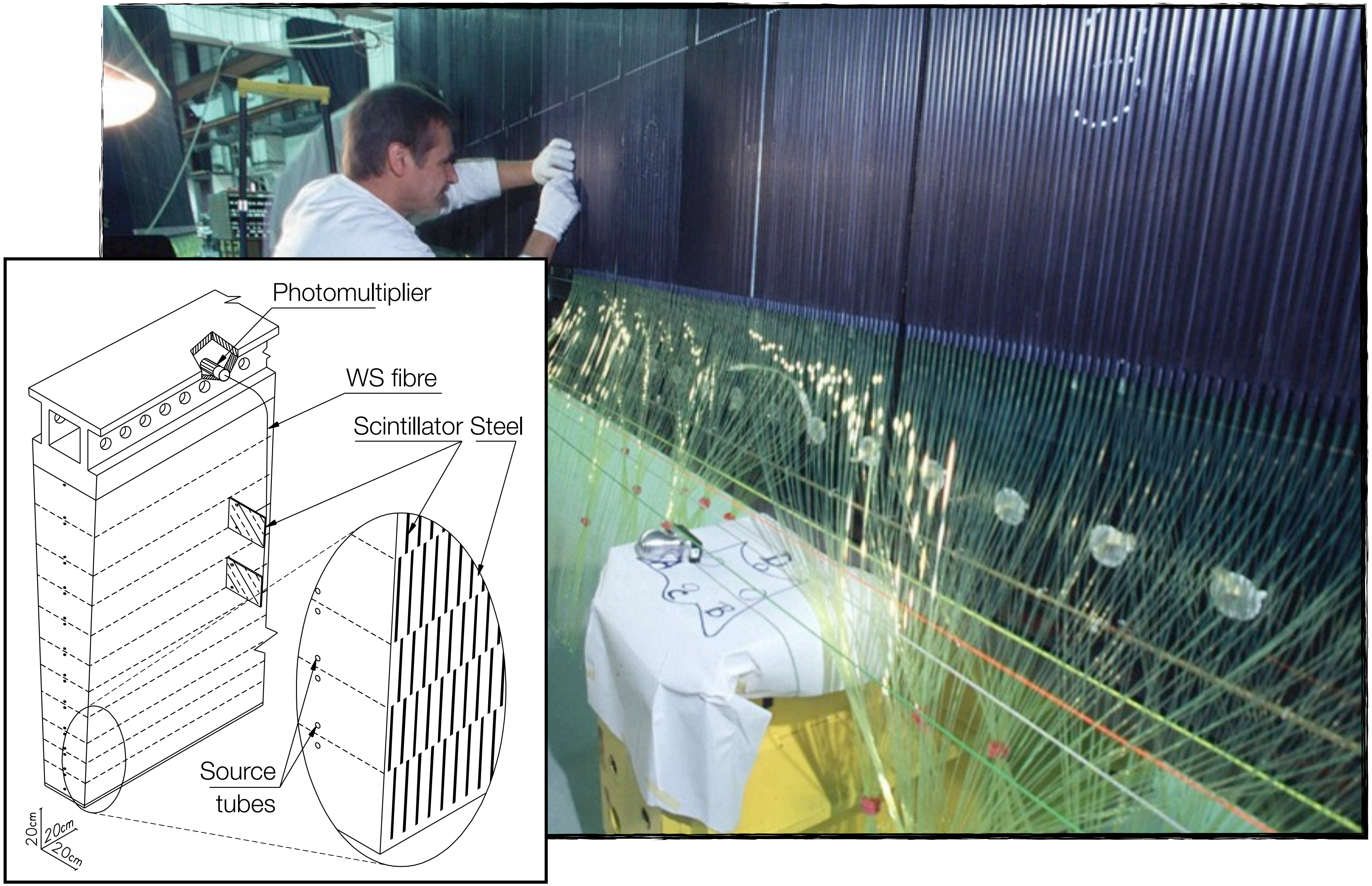
Features:

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

Works at room temperature!
Insensitive to magnetic fields



Scintillation Counters – Setup

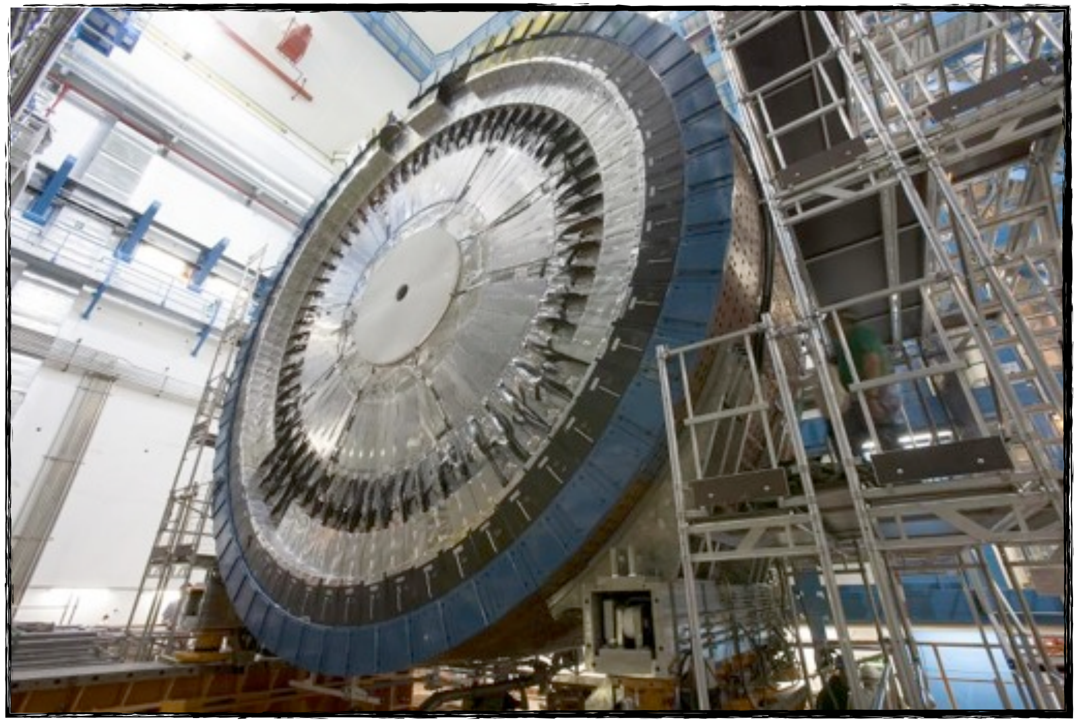


ATLAS Tile Calorimeter

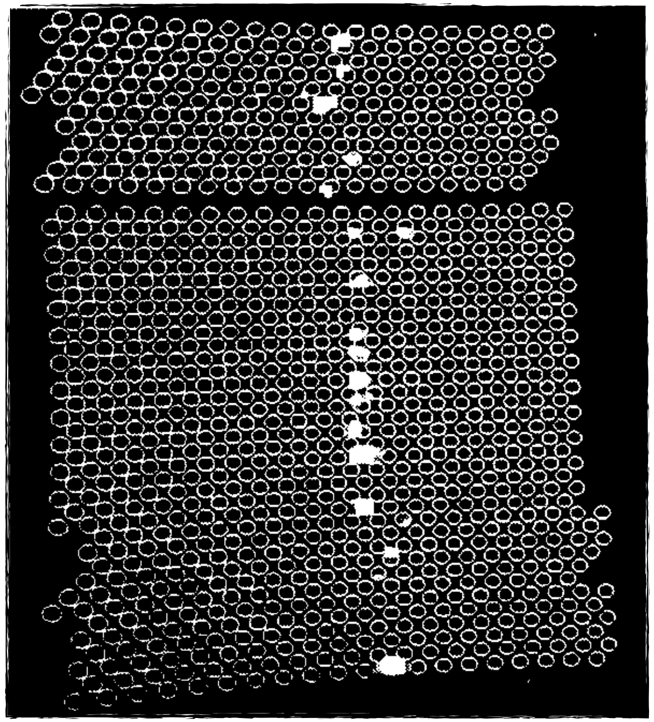
Scintillation Counters – Applications

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

ATLAS
Minimum Bias Trigger Scintillators



Particle track in
scintillating fibre hodoscope



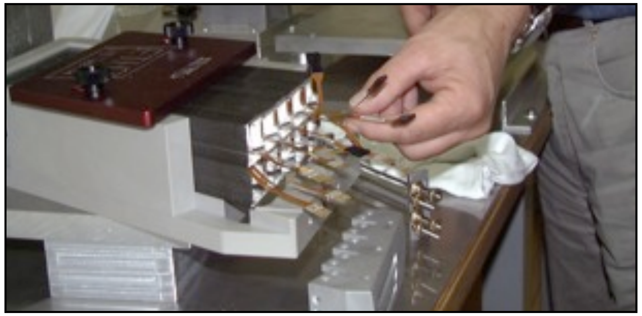
CMS – Crystal Calorimeter (ECAL)

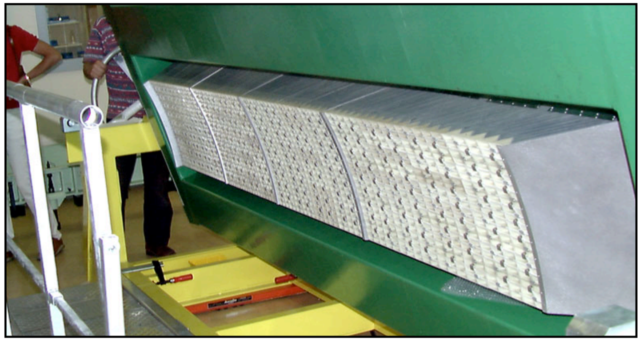
Scintillator : $PBW0_4$ [Lead Tungsten]

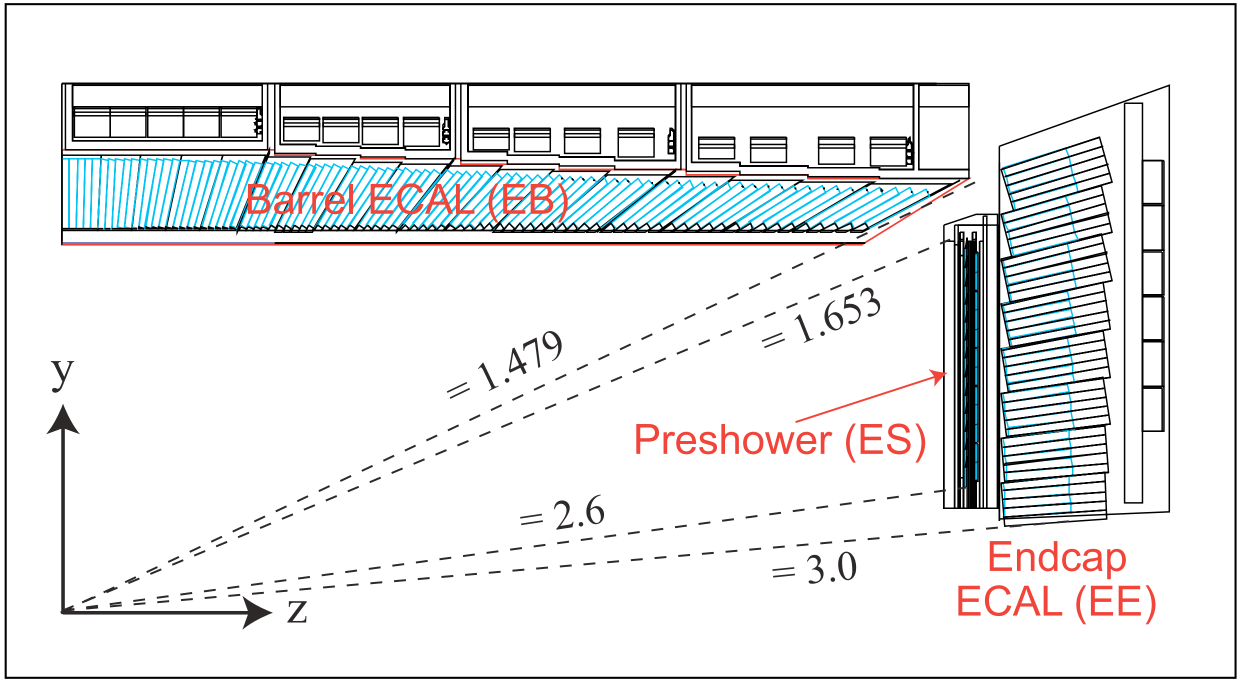
Photosensor : APDs [Avalanche Photodiodes]

Number of crystals: ~ 70000

Light output: 4.5 photons/MeV

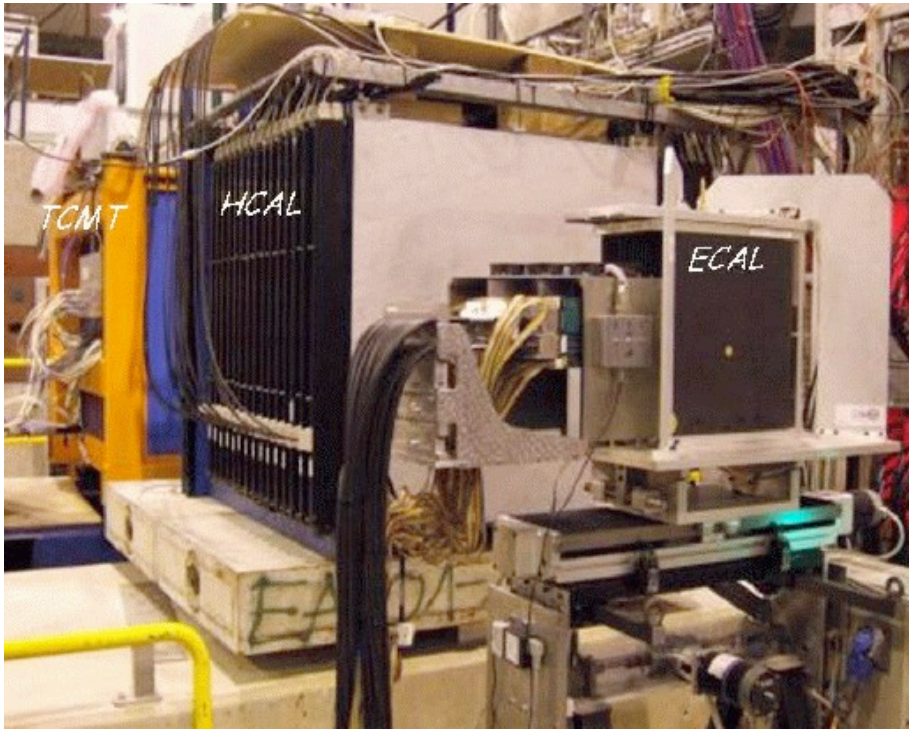






CALICE – Analogue HCAL

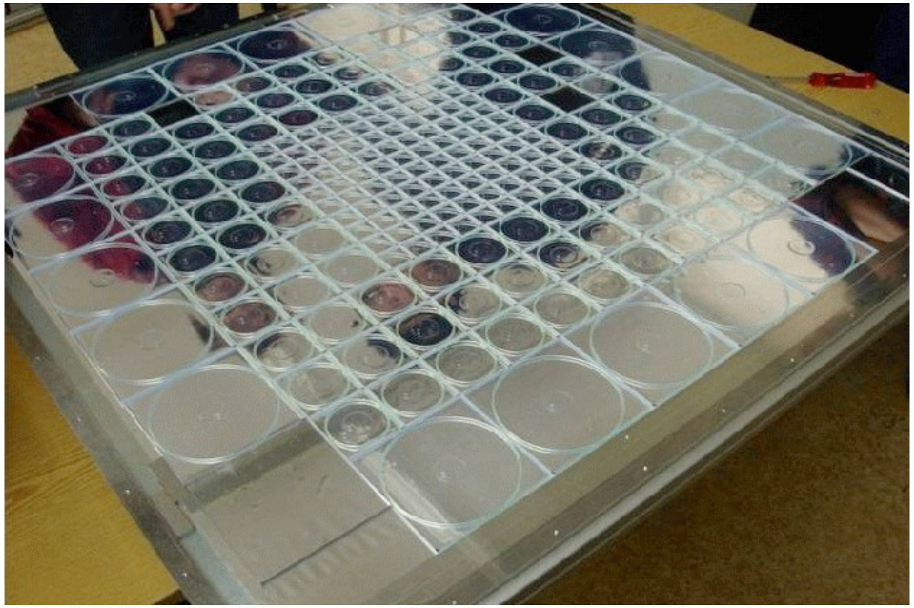
$1m^3$-Prototype
38 layers



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

Sandwich structure:

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



Scintillator : Plastic
Photosensor : SiPMs