Experimental techniques in nuclear and particle physics

(part 3)

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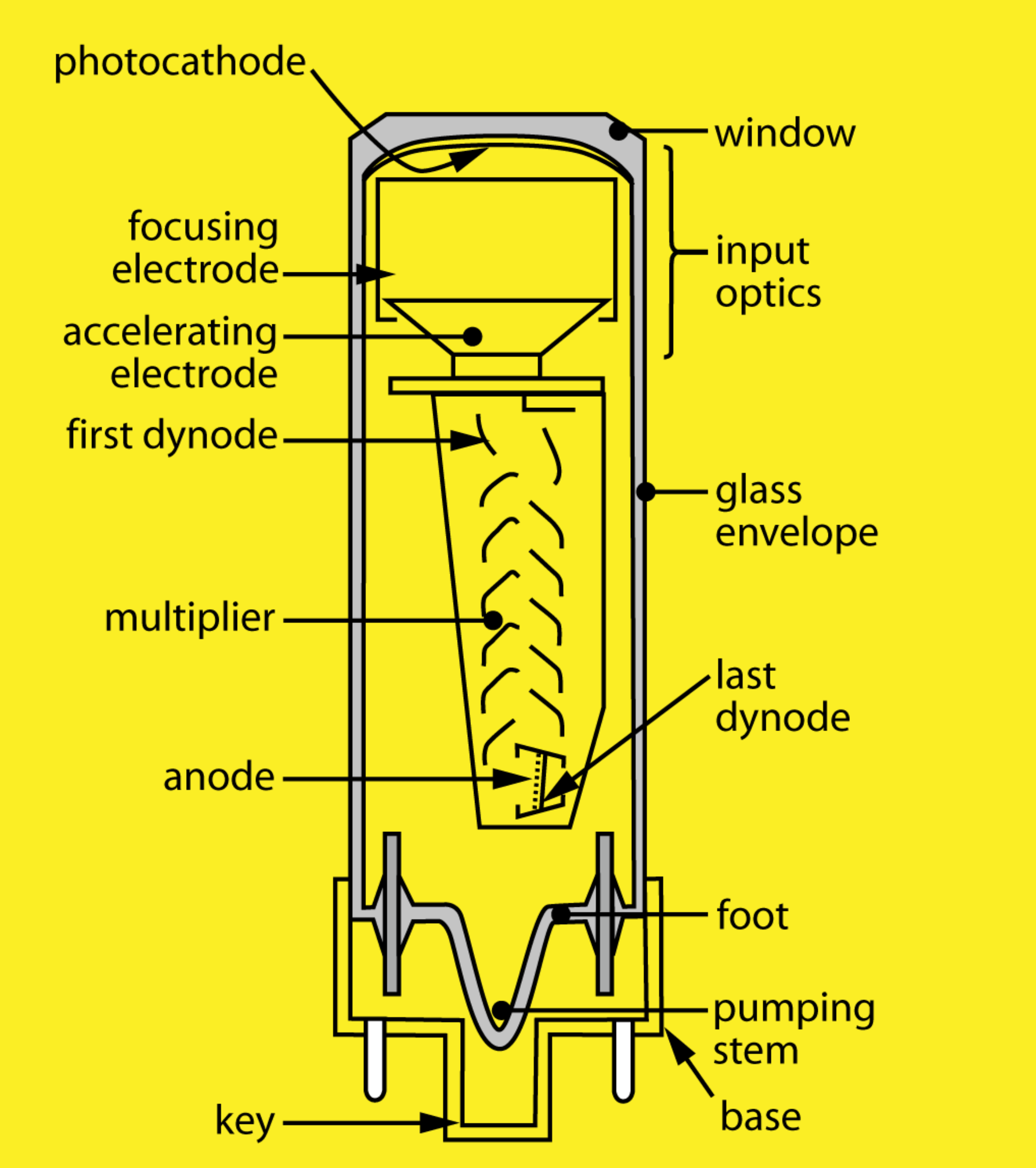
Table of content

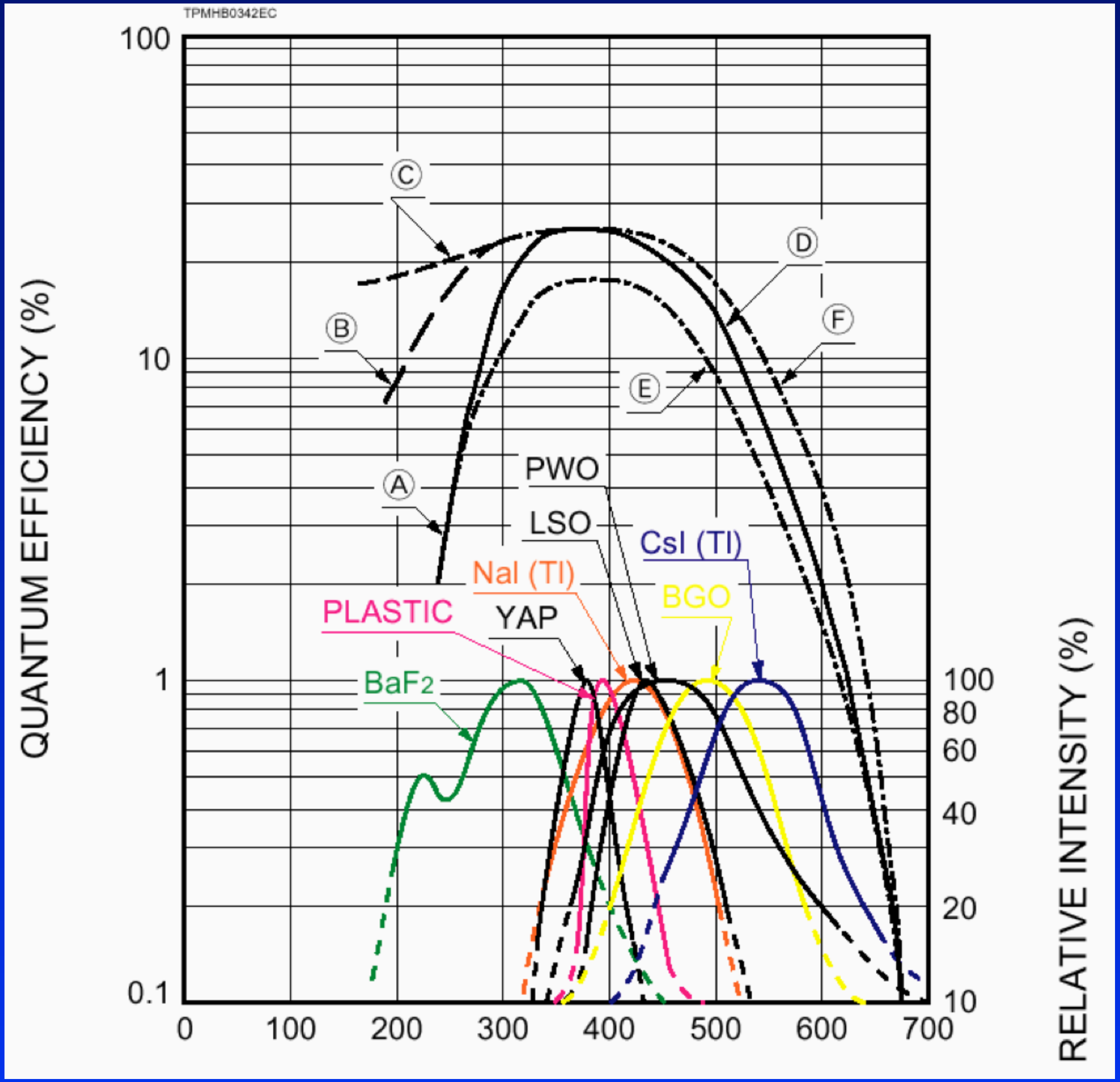
- Interactions of energetic subatomic particles in matter
- Introduction to detectors and detector techniques
- Detectors based on ionisation is gases
- Detectors based in ionisation in semiconductors
- Detectors based on scintillation
    - photodetectors
    - physics of scintillation
    - applications of scintillation detectors

Photodetectors

- Photomultiplier tube (PMT)
- Other vacuum photodetectors
- Solid state photodetectors


photocathode
window
focusing electrode
input optics
accelerating electrode
first dynode
glass envelope
multiplier
last dynode
anode
foot
pumping stem
key
base

Quantum efficiency: probability for a photon to give rise to a photoelectron. Electron extracted from the photo-cathode by photo electric effect.



K_2CsSb (Bialkali)
≈30%

Dark current

If the photocathode has a large QE

>> easily emission of thermal electrons

>> ≈100 /cm^2 !!

Source of noise!

Gain: electron multiplication on dynodes

Typical values:
Total voltage ≈1600V, 12 dynodes
Gain one dynode ≈ 3
Total gain ≈ 10^6

$$Gain = a^n \left(\frac{V}{n+1} \right)^{kn}$$

(a ; k) constants characteristic of dynode material (k≈0.7)
n: number of dynodes
V: voltage over PM

Noise considerations

Ideal photodetector & lightsource

$$\frac{\sigma\{S\}}{S}=\sqrt{\frac{1}{N_{photon}}}$$

Real photodetector

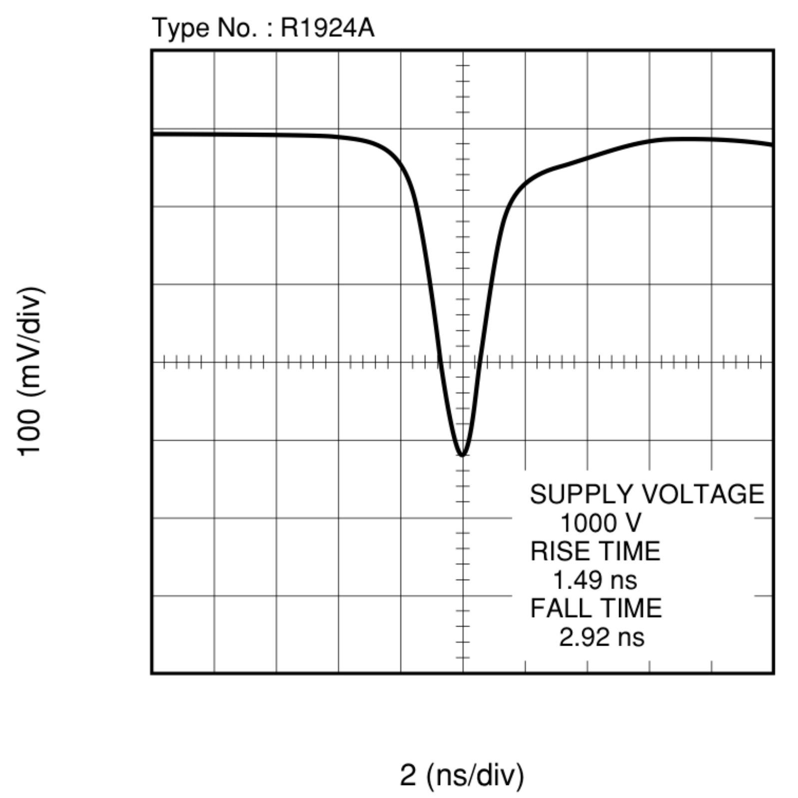
$$\frac{\sigma\{S\}}{S}=\sqrt{\left(\frac{\sigma_{lightsource}}{S}\right)^2+\frac{ENF}{QE\times N_{photon}}+\left(\frac{ENC/e}{Gain\times QE\times N_{photon}}\right)^2}$$

$$ENC^2=2e\times Gain\times\tau\times I_{dark\ \ current}+\frac{32}{3}kTC_d\frac{t_{transit}}{\tau}+\text{other}(\approx(10\text{e})^2)$$

$$ENF=\left(1+\frac{\sigma^2\{Gain\}}{\langle Gain\rangle^2}\right)$$

Timing

rise time



time jitter

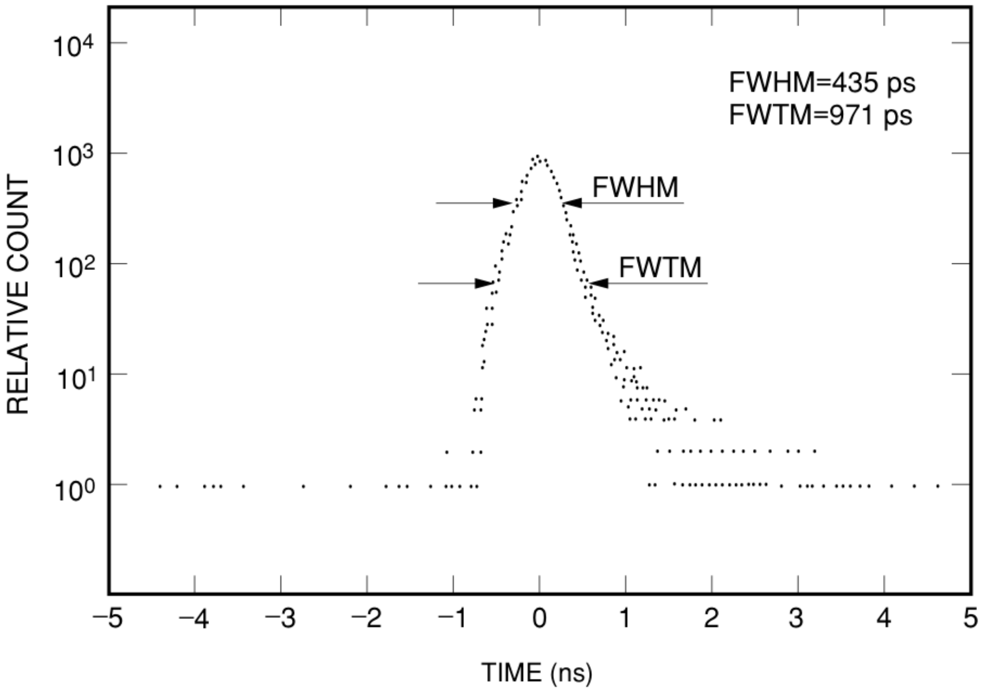


Figure 4-19: TTS (transit time spread)

Good timing need large signal /noise

Summary on PMTs

- large area: (relatively) inexpensive/unit area
- large gain: ≈ 10^6
- Quantum Efficiency ≈ 30%
- excess noise factor: ≈ 1.3
- timing: ≈ 1 ns
- dark current: ≈ $100e/s/cm^2 \times$ gain

However:

- bulky
- very sensitive to magnetic fields
- not easily subdivided in pixels

Other photodetectors

Other vacuum photodetectors

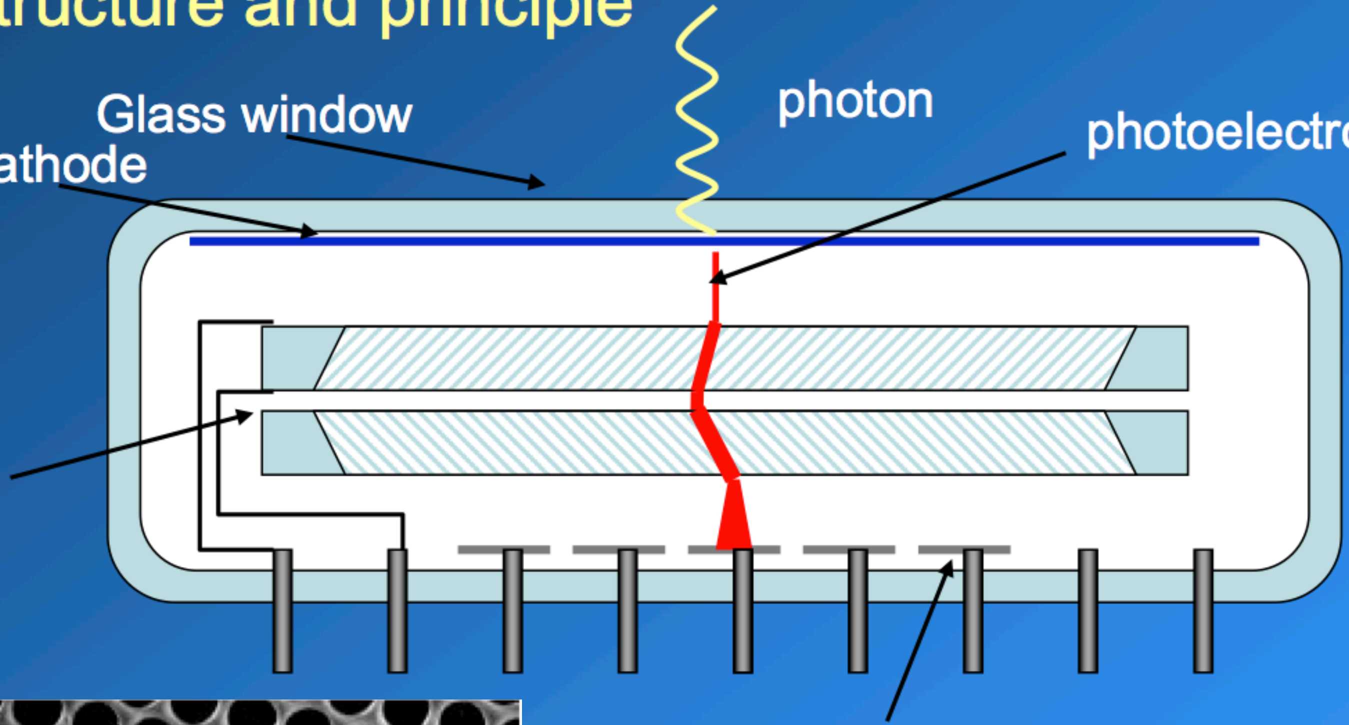
- Microchannel plate PMT
- Hybrid Photon Detector

Solid state photodetectors

- Photo diodes
- Avalanche photo diodes APD
- Silicon PMT

Microchannel plate PMT ; MCP-PMT

✓ Structure and principle



Glass window

photocathode

photon

photoelectron

ΔV ~ 300 V

ΔV ~ 3000 V

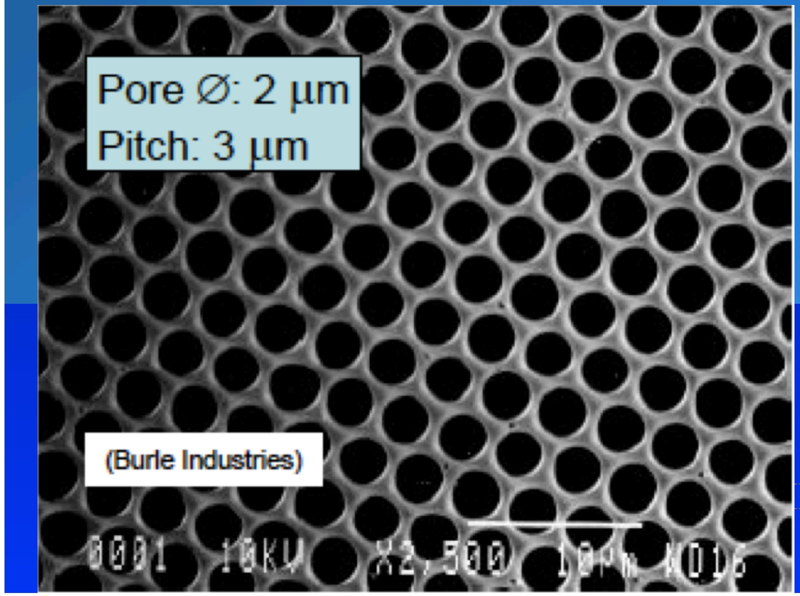
ΔV ~ 300 V

dual MCP

Gain ~ 10^6

Anode

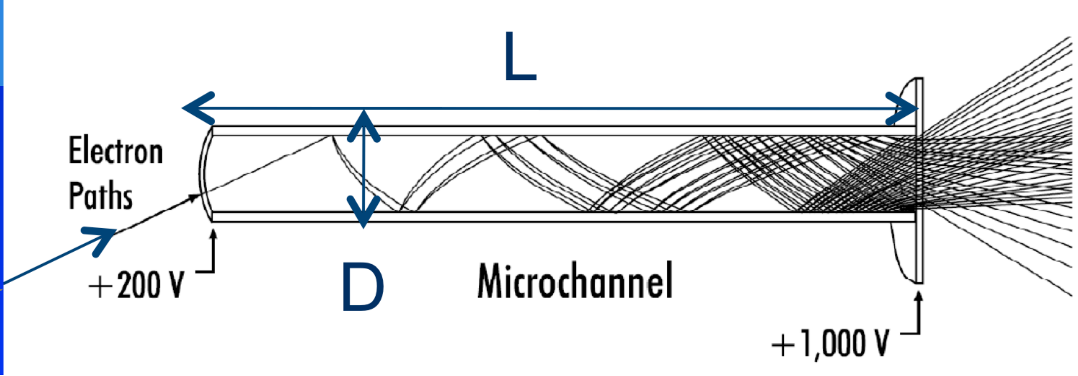
may be pixilated



Pore ∅: 2 μm

Pitch: 3 μm

(Burle Industries)



Main characteristics of MPC-PMT

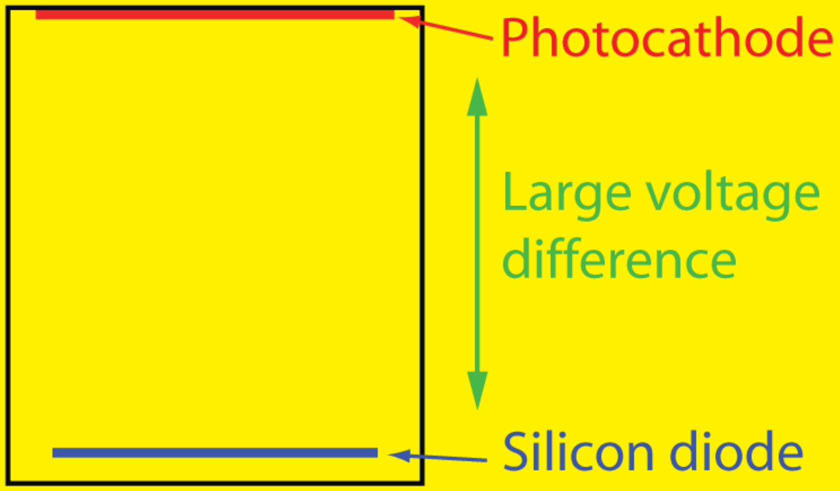
QE: ≈ 30%

Gain: single stage : 10^3-10^4 • Dual: 10^6-10^7

Good timing properties:

- Low transient time ≈1 ns
- Transient time spread ≈100 ps
- Sub-ns rise and fall time

Hybrid photon detector



Photocathode

Large voltage difference

Silicon diode

(a)

(b)

Main characteristics of hybrid photon detector

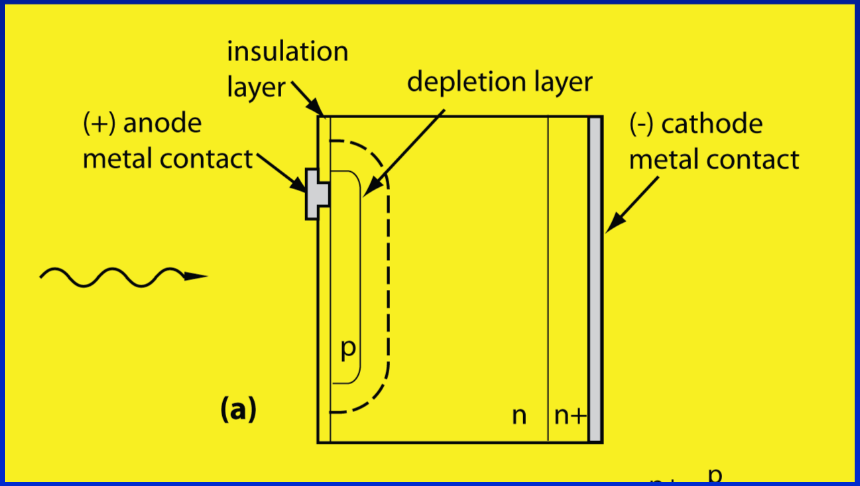
- QE: ≈ 30%
- Excess noise factor ≈ 1
- excellent single photon detection efficiency
- Gain= $\Delta V/3.62$ ≈ few 1000, but with APD ≈ 10^5-10^6
- easy subdivision in pixels
- bulky and expensive
- very high voltage

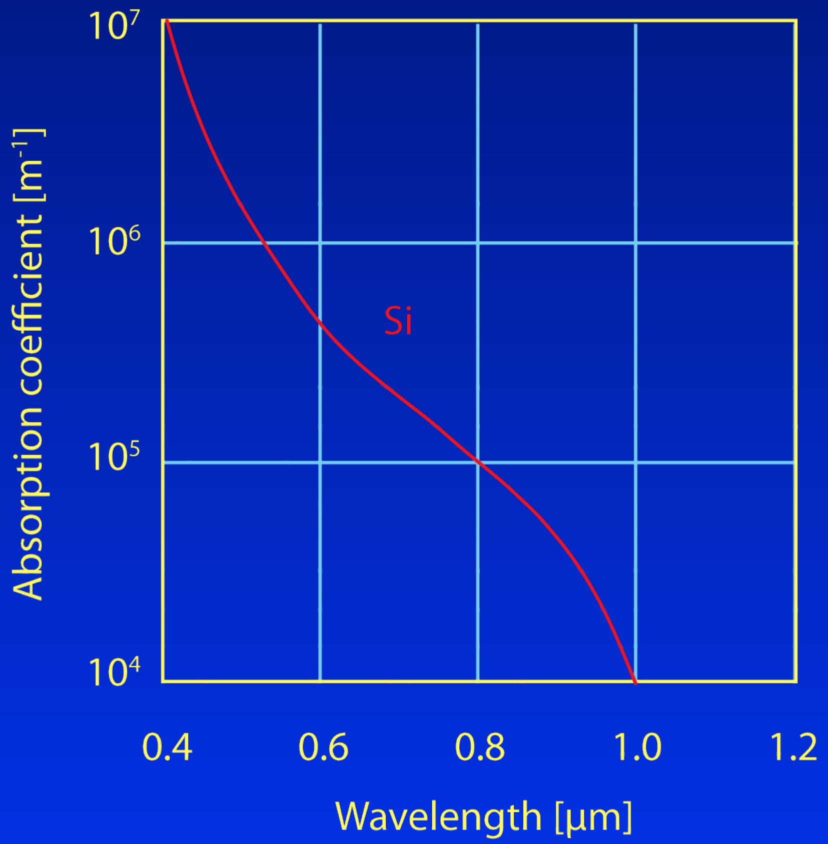
Solid state photodetectors

Photo diode
Avalanche Photo Diode
SiPMT

Silicon photodiodes

Electron from valence band to conduction band

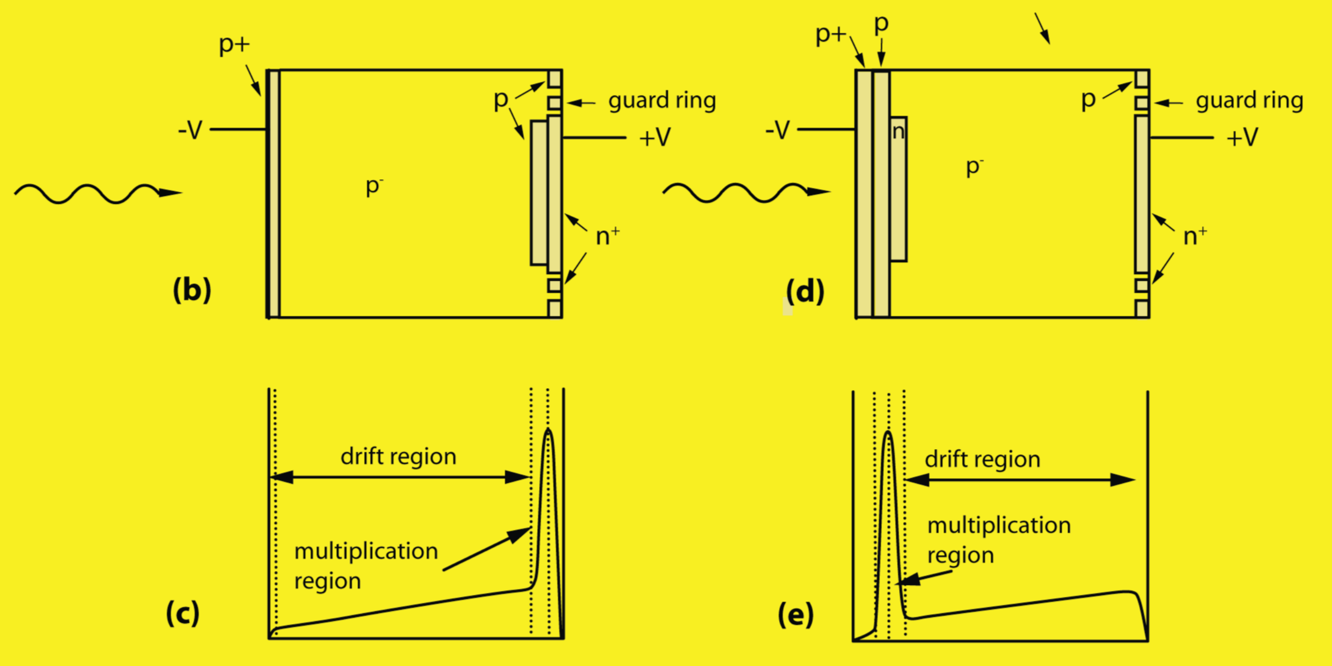




Main characteristics of silicon photodiodes

- No internal gain
- large QE ≈ 80%
- insensitive to magnetic fields
- low dark current

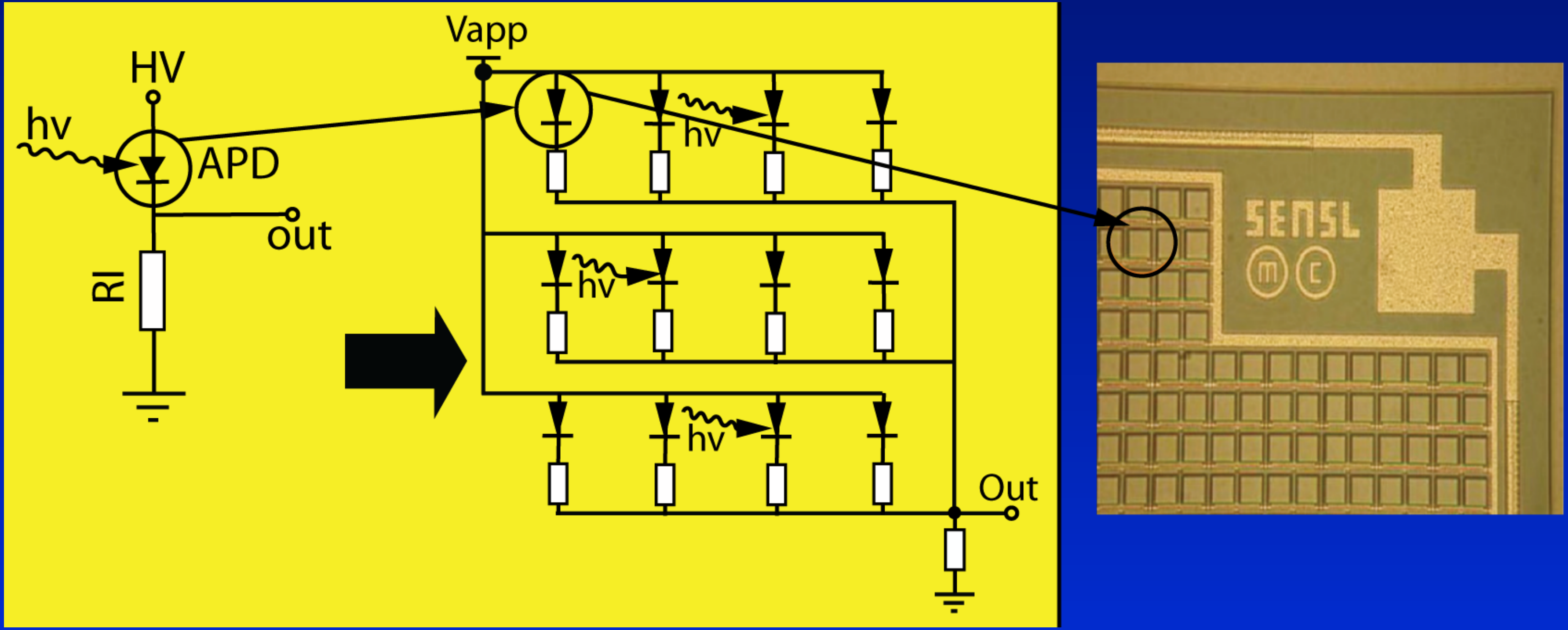
Avalanche photo diodes



Main properties Avalanche photo diodes

- moderate gain ≈50
- QE ≈ 70% @ 400 nm; 80% @ 500 nm
- insensitive to magnetic field
- dark current <≈ 1 nA/mm^2
- excess noise factor ≈2
- gain very dependent on temperature and applied voltage

SiPMT, Geiger mode APD, MPPC



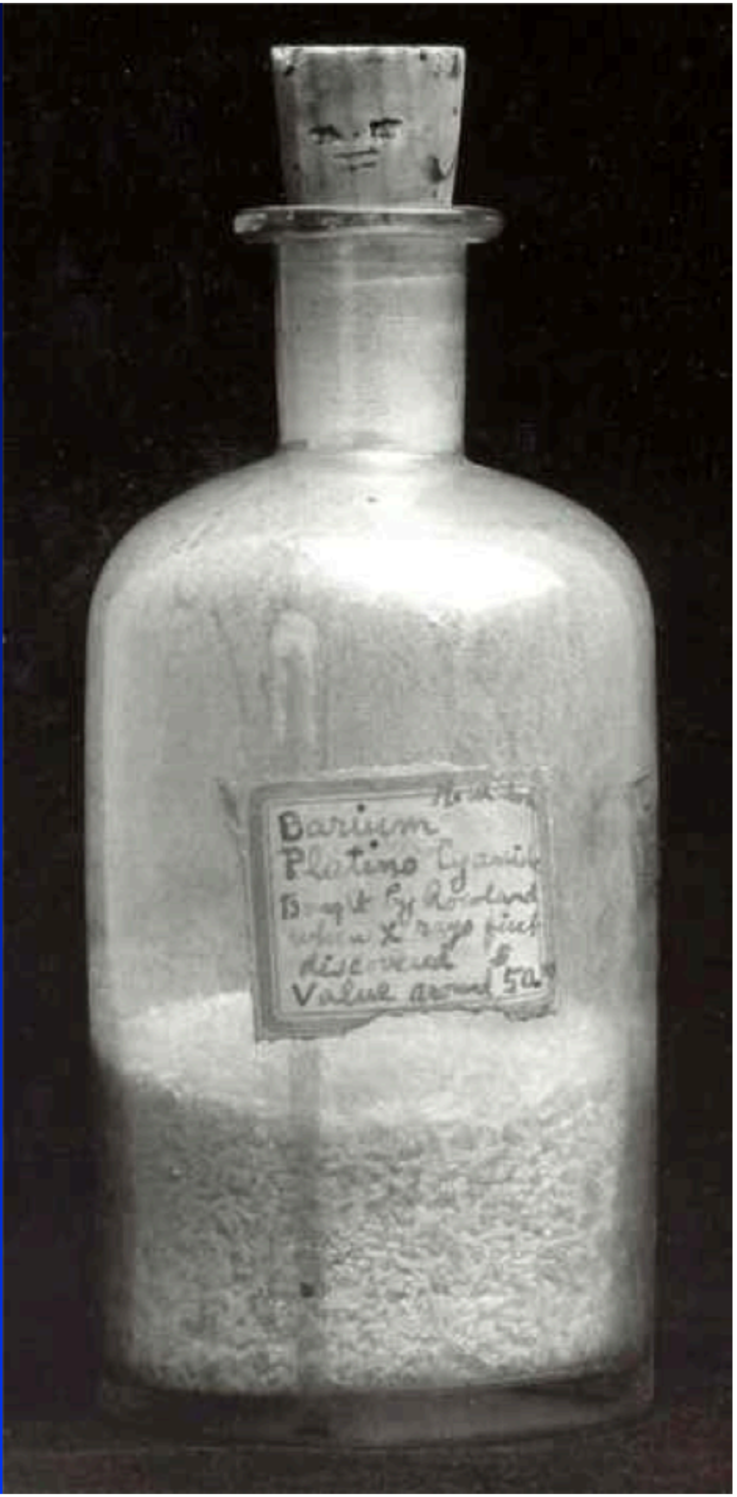
Main properties of SiPMT

- Large gain ≈ 10^6
- insensitive to magnetic fields
- photon detection efficiency= QE×Fill_factor
  10%-50%
- excess noise factor ≈ 1
- large dark current ≈ 10^6 pulses/mm^2≈ $\mu A/mm^2$

The physics of scintillation

Introduction to scintillators

Scintillators also are among the oldest particle detectors.
Röntgen discovered X-rays by observing a faint light emission from barium platino-cyanide. This was really the first observation of scintillation. Scintillation was also used by Rutherford in his famous scattering experiments. Rutherford used zinc sulfide to detect alpha particles.



Many transparent materials give off a faint light pulse when an energetic subatomic particle deposits energy.
This is called radio-luminescence.
If large pieces >> called scintillators
If powder >> called phosphors, but the word phosphors is also use for photo-luninescent materials (=wavelength shifters or fluors)

If a charged particle causes ionisation in a solid, the charges will (in general) not be extracted if a voltage is applied over the solid.

But to cause scintillation the charges only need to get to the nearest luminescence centre, and that is possible in many materials.

Scintillators broadly fall into two classes
with very different properties and applications

- Organic scintillators:
  mainly used for charged particle tracking

- Inorganic scintillators: mainly used for
  - gamma spectroscopy
  - as phosphors for X-ray imaging (radiology)

Organic scintillators

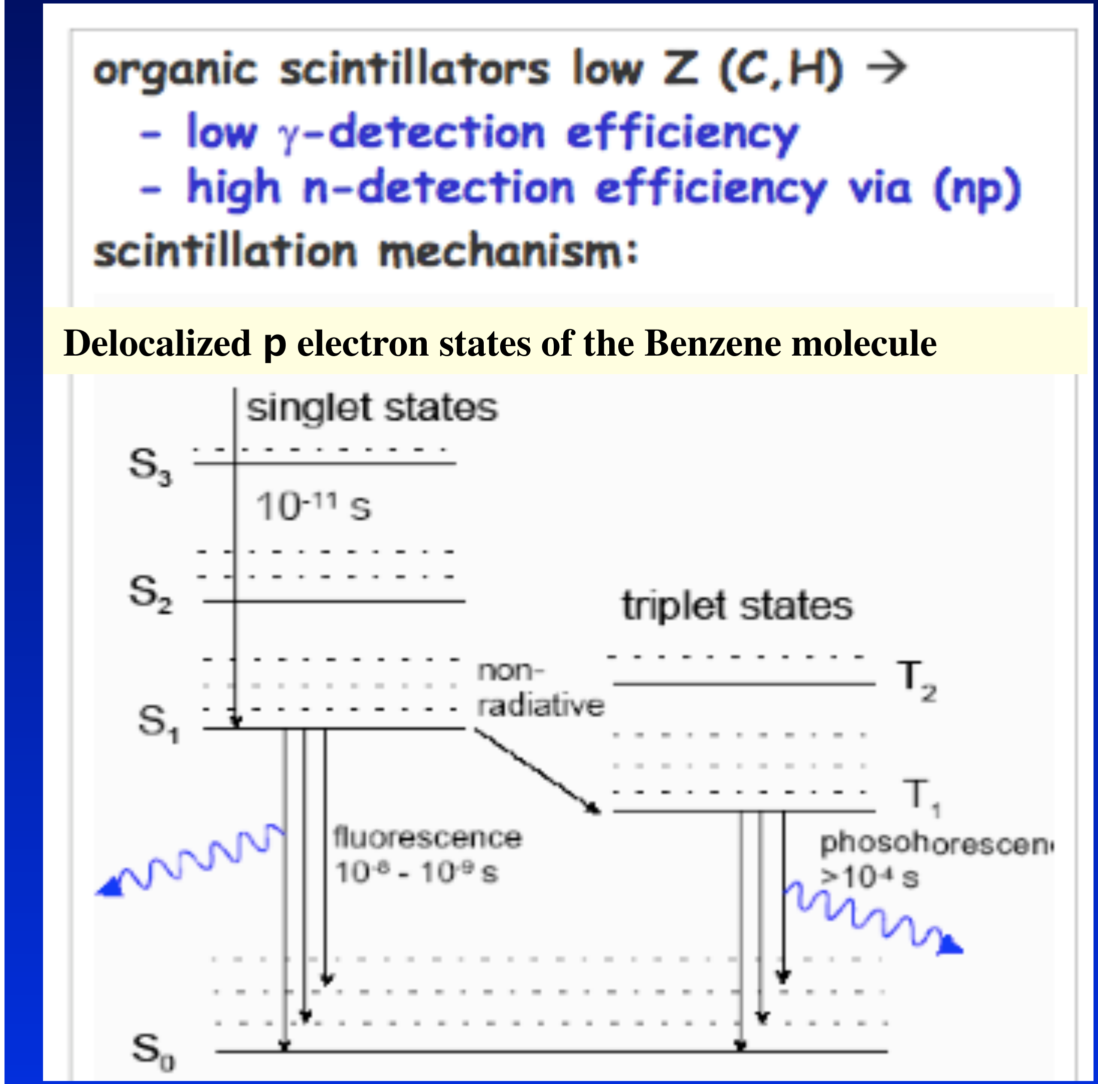
Crystalline solids: anthracene, stilbene: today hardly ever used

Organic liquids: Liquid containing aromatic rings: e.g. (1,2,4-trimethylbenzene) and linear alcaylbenzene (LAB); + wls fluors dissolved in it: e. g. p-Terphenil, PPO (2,5-Diphenyloxazole)

Plastics scintillators:

A plastic organic scintillator is a polymerizable organic compound (methylmethacrilate, vinyltoluene, styrene) containing aromatic rings, + wls fluors dissolved in it at 1% level

Liquid and plastic scintillators



organic scintillators low Z (C,H) →
- low γ-detection efficiency
- high n-detection efficiency via (np)

scintillation mechanism:

Delocalized p electron states of the Benzene molecule

The liquid or plastic base scintillates in the UV, but the m.f.p of this emission is very short (<< 1mm). One or more "fluors" (i. e. wale length shifters) are dissolved in the plastic. The primary fluor (1%) shifts this to longer wavelength, often a secondary fluor (0.05%) is added to shift the emission to even longer wavelengths.

Properties of plastic scintillators.

(Just one typical example)

Kowaglass SCSN-32, polystyrene based scintillator

Light yield: 8'000 photons /MeV, or ≈16'000 photons/cm

Decay time : 3.6 ns

Emission wavelength: 423 nm

Light attenuation length: 250 cm

Refractive index : 1.58

Density : 1.08

Radiation length : 30 cm

The biggest advantage of plastic scintillators is the ease of mechanical processing, availability in large sizes, often as sheets, and also as scintillating fibres

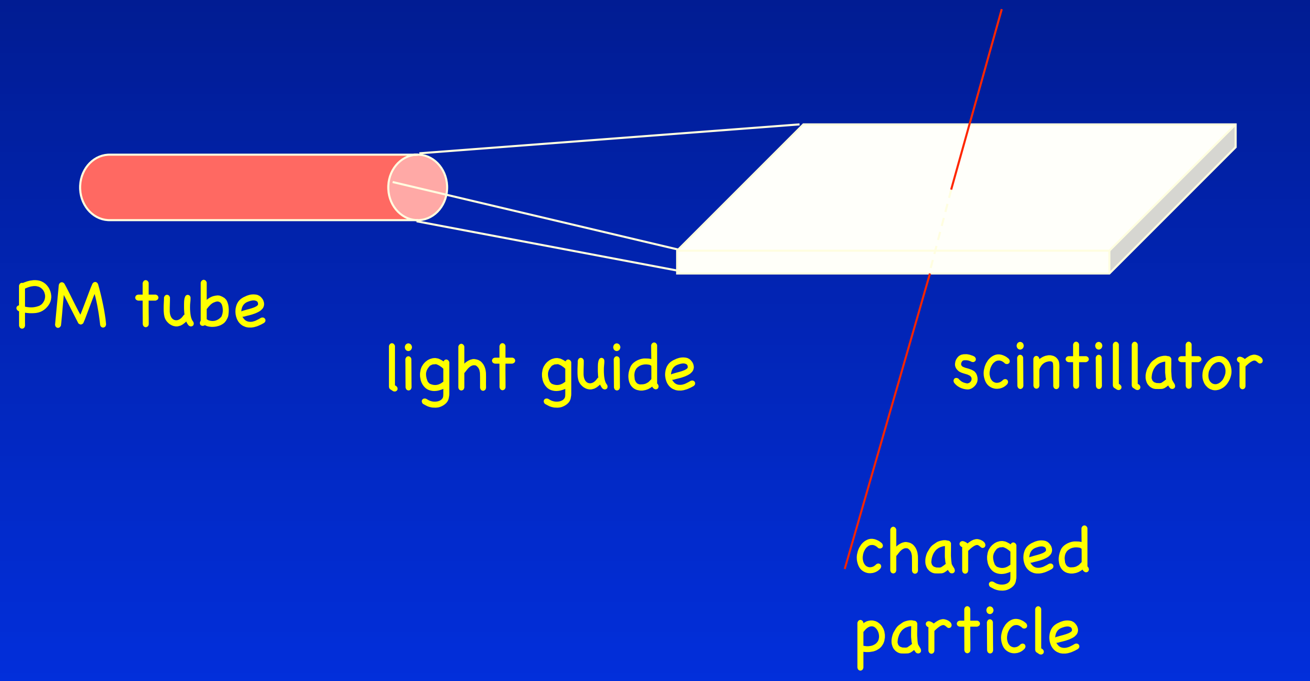
Liquid Scintillators have a very reduced light response to heavily ionising particles such as alpha particles or nucleons with an energy in the MeV range.

Light yield depends on ionisation density (Birks' law).

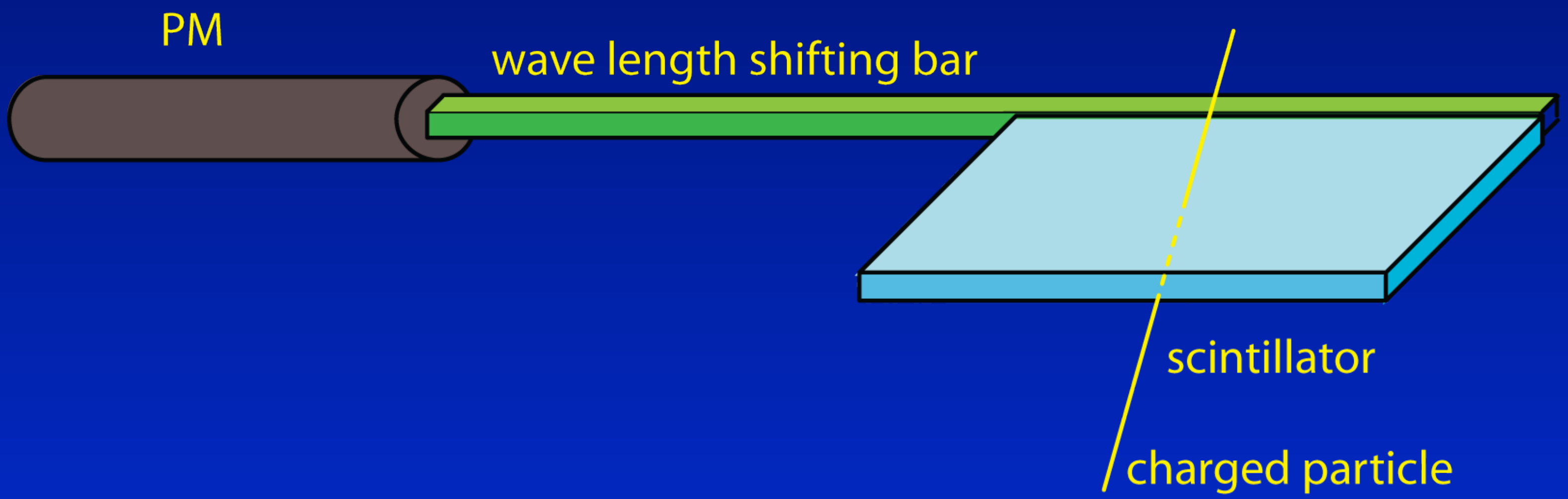
$$\frac{d(LY)}{dx} = (LY)_0 \frac{dE/dx}{1 + k_b (dE/dx)}$$

A plastic scintillator used as a detector of charged particles, light guided to the edge by internal reflection.

When using a light funnel, the surface of the photodetector should be equal the surface of the edge



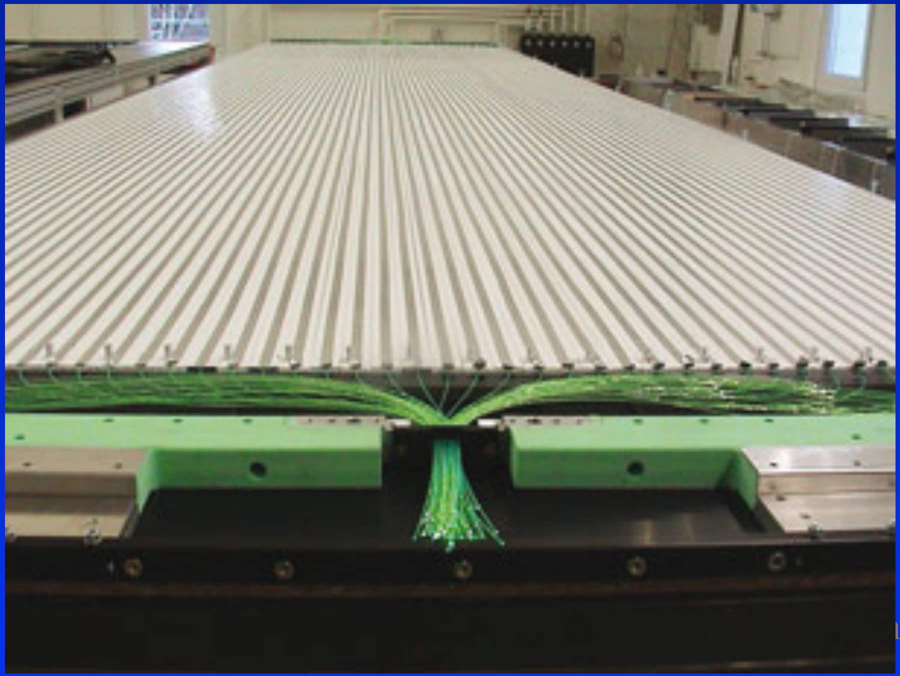
Wave length shifter readout is more efficient if a large surface needs to be read

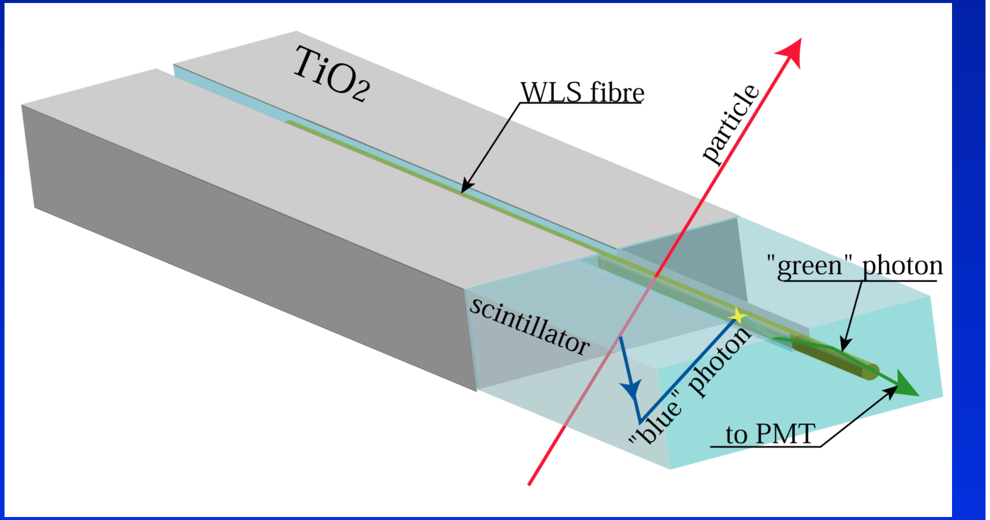


Applications of liquid & plastic scintillators

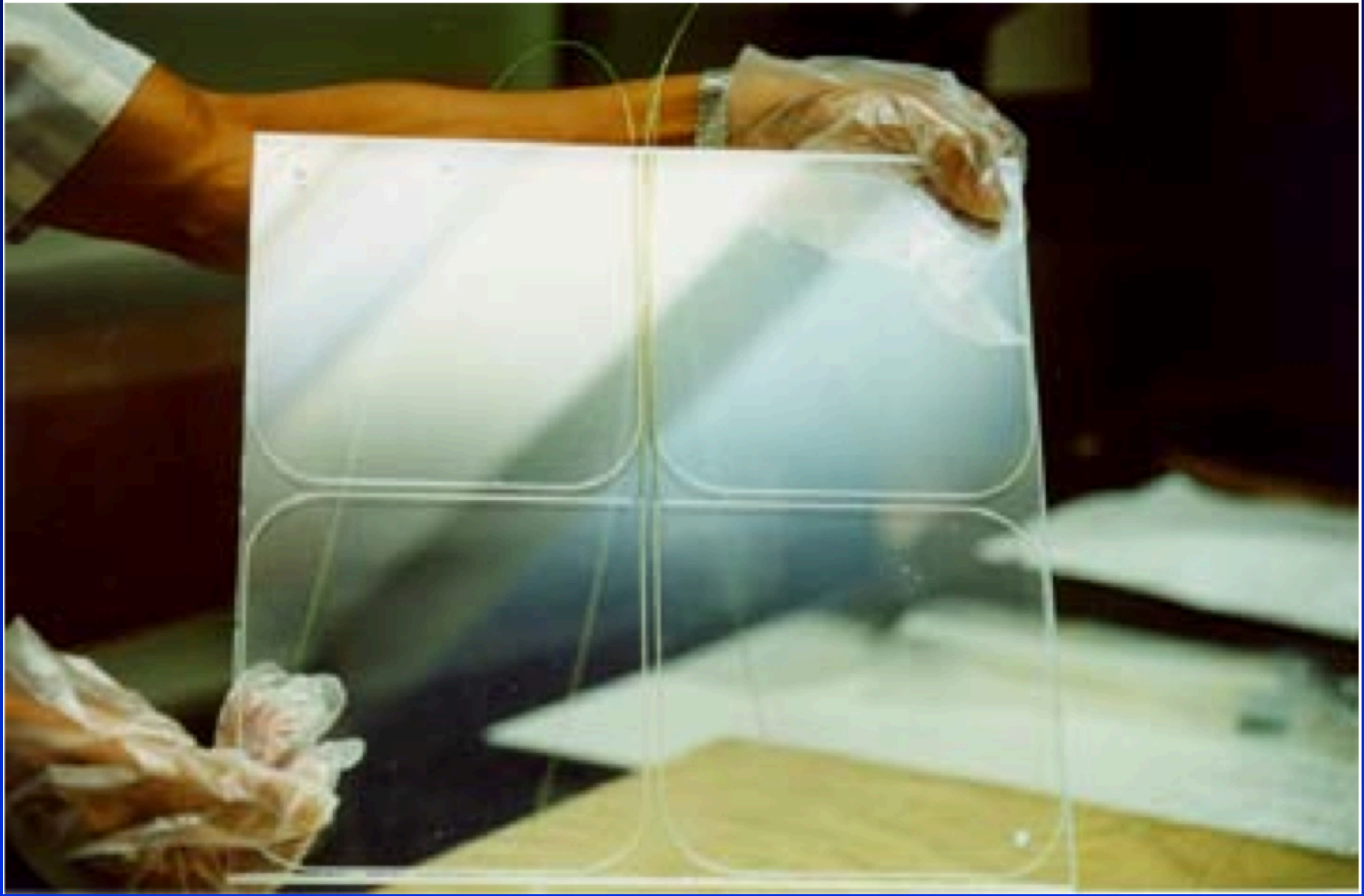
Plastic: particle tracking and timing

Example: OPERA neutrino velocity measurement based on signal in plastic scintillator strips with wavelength shifting fibres read on both ends with Hamamatsu 64 channel PMTs.

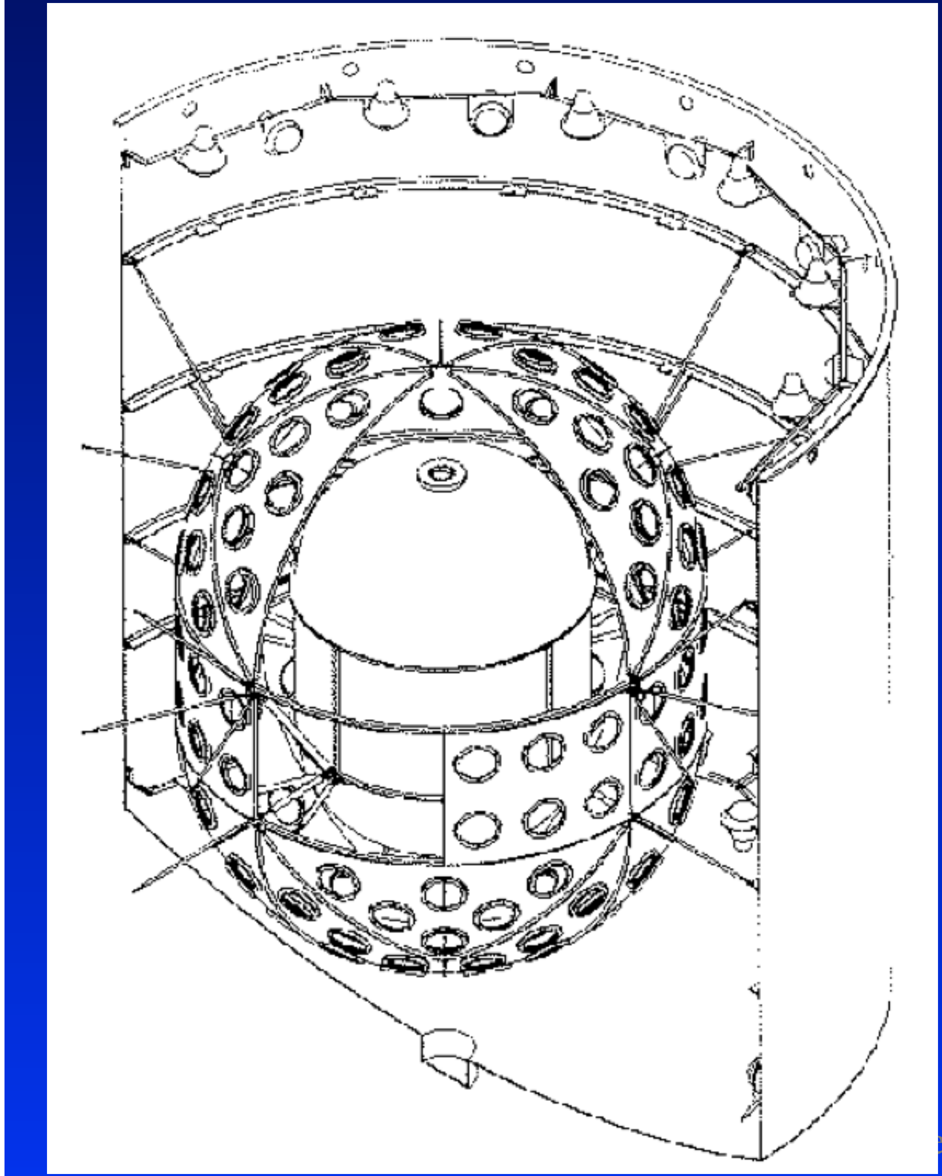




WLS fibre readout in CMS hadronic calorimeter



Chooz experiment: liquid scintillator ≈ 110 tons liquid scintillator
Nuclear reactor ≈ 10^{21} anti neutrino/s ≈ 1.5 MeV



p + $\bar{\nu}_e$ -> neutron + e^+

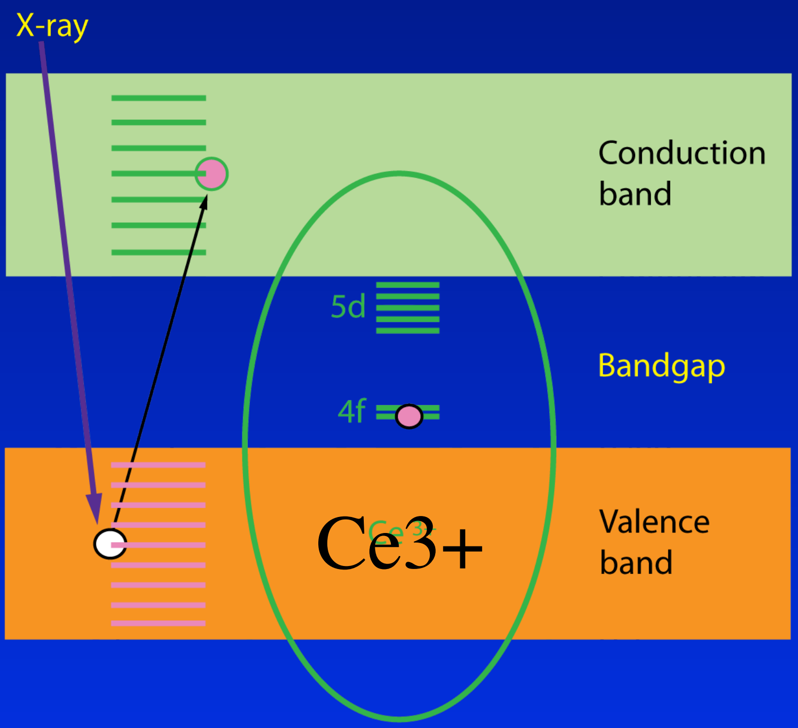
- (1) Gd loaded scintillator to detect neutron (≈8 MeV)

- (2) unloaded scintillator: positron energy and 2xgamma from e+ annihilation (≈3MeV)

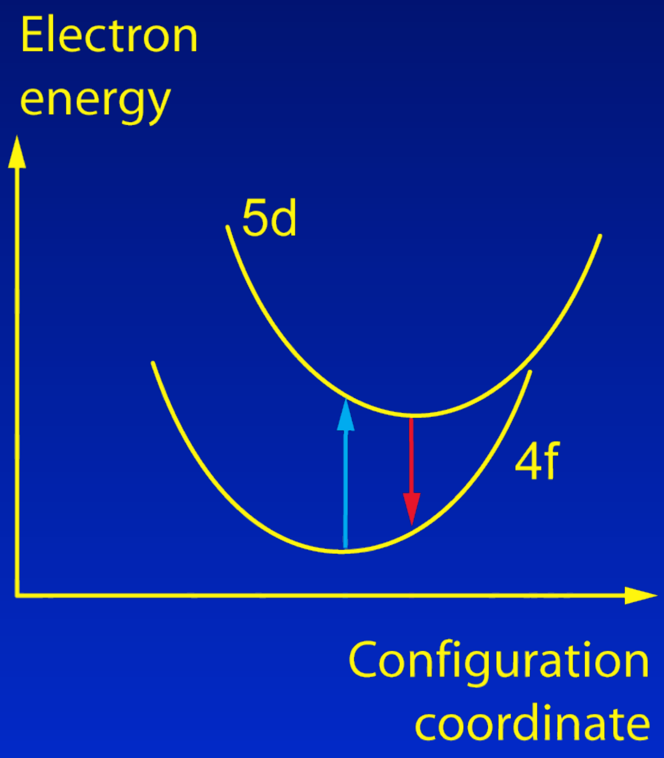
- (3) veto shield scintillator

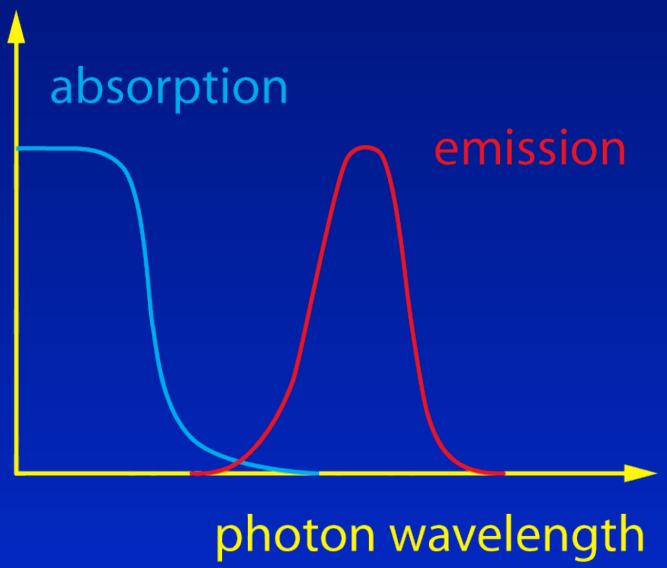
Inorganic scintillators

Usually ionic crystals with luminescence centres, e.g. Ce^{3+} at the % level.



The stokes shift allows the light to leave the crystal





How is scintillation generated in inorganic solids?

STEP 1: gamma-ray interaction gives rise to a large number of e-h pairs after $\approx 10^{-12}$ s. (free or excitons)

$$N_{e-h} = \frac{E_\gamma}{b.E_{BG}} \qquad \left[E_{BG} = energy\ bandgap\right]$$

$$E_\gamma = energy\ gamma\ ray$$

$$b = 1.5 - 2\ for\ ionic\ crystals$$

Maximum yield: $$N_{e-h} \approx \frac{1}{2} \cdot \frac{1'000'000}{E_{BG}[eV]}$$

CsI:Tl E_{BG} = 6.2 eV

=> N_{max} = 80'000 Photons/MeV

Experimentally 65'000 Photons/MeV

STEP 2:
Electrons and holes reach the luminescence centre, influenced by traps. Most unpredictable part of the process.

STEP 3:
Excitation and decay of luminescence centre

Most efficient scintillators have extrinsic luminescence centres, also called activators:

NaI:Tl^+, CsI:Tl^+, CaF2: Eu^{2+}, BaFBr:Eu^{2+} , Lu_2SiO_5:Ce^{3+}

But luminescence in absence of an activator also occurs. Pure $Bi_4Ge_3O_{12}$ [BGO] scintillates at 480nm.

BGO is an efficient scintillator at low temperature, thermally quenched at room temperature.

Non-linear response and energy resolution

Scintillators have a very reduced response to strongly ionising particles such as alpha particles or nucleons with an energy in the MeV range.

An alpha particle of 1 MeV will typically produce 0.25-0.8 times less light than a gamma (electron) of the same energy. (α/β ratio)

In alkali halides there is also a reduction in light if the ionisation density is very low

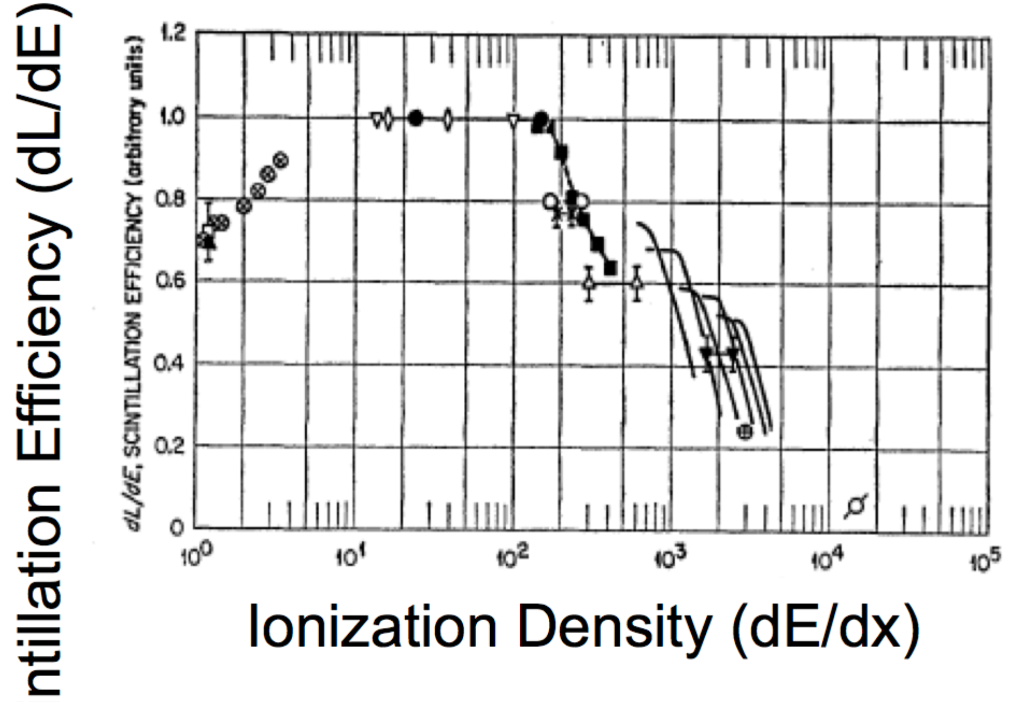
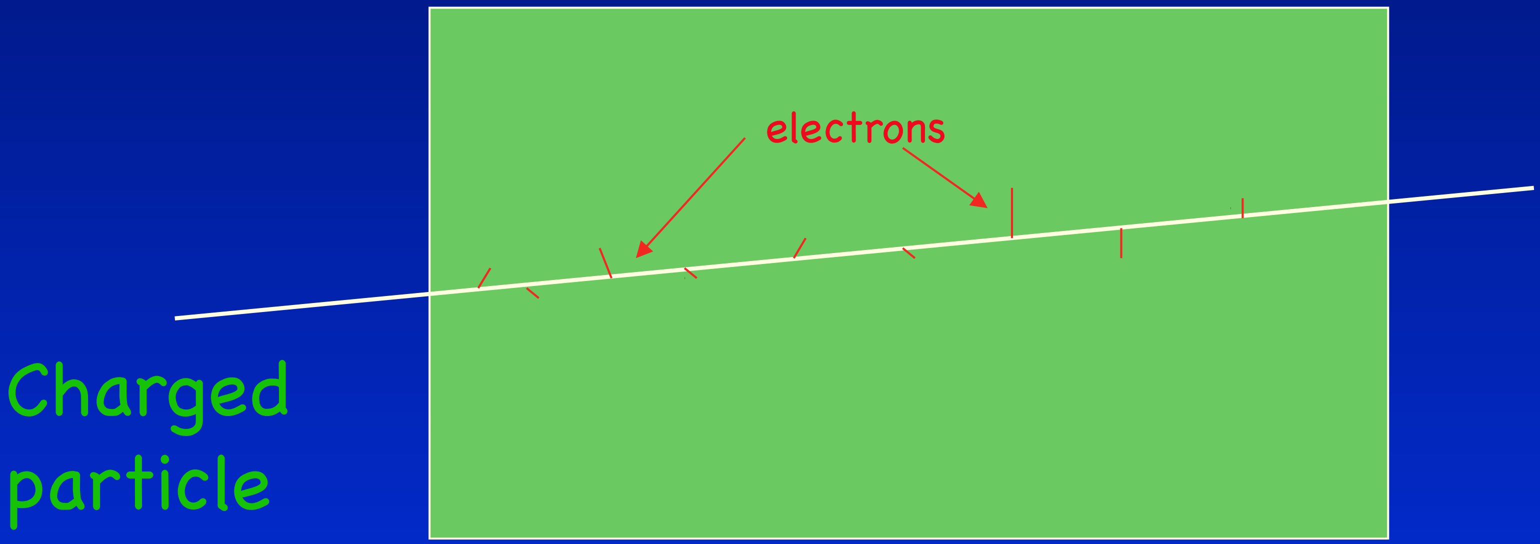
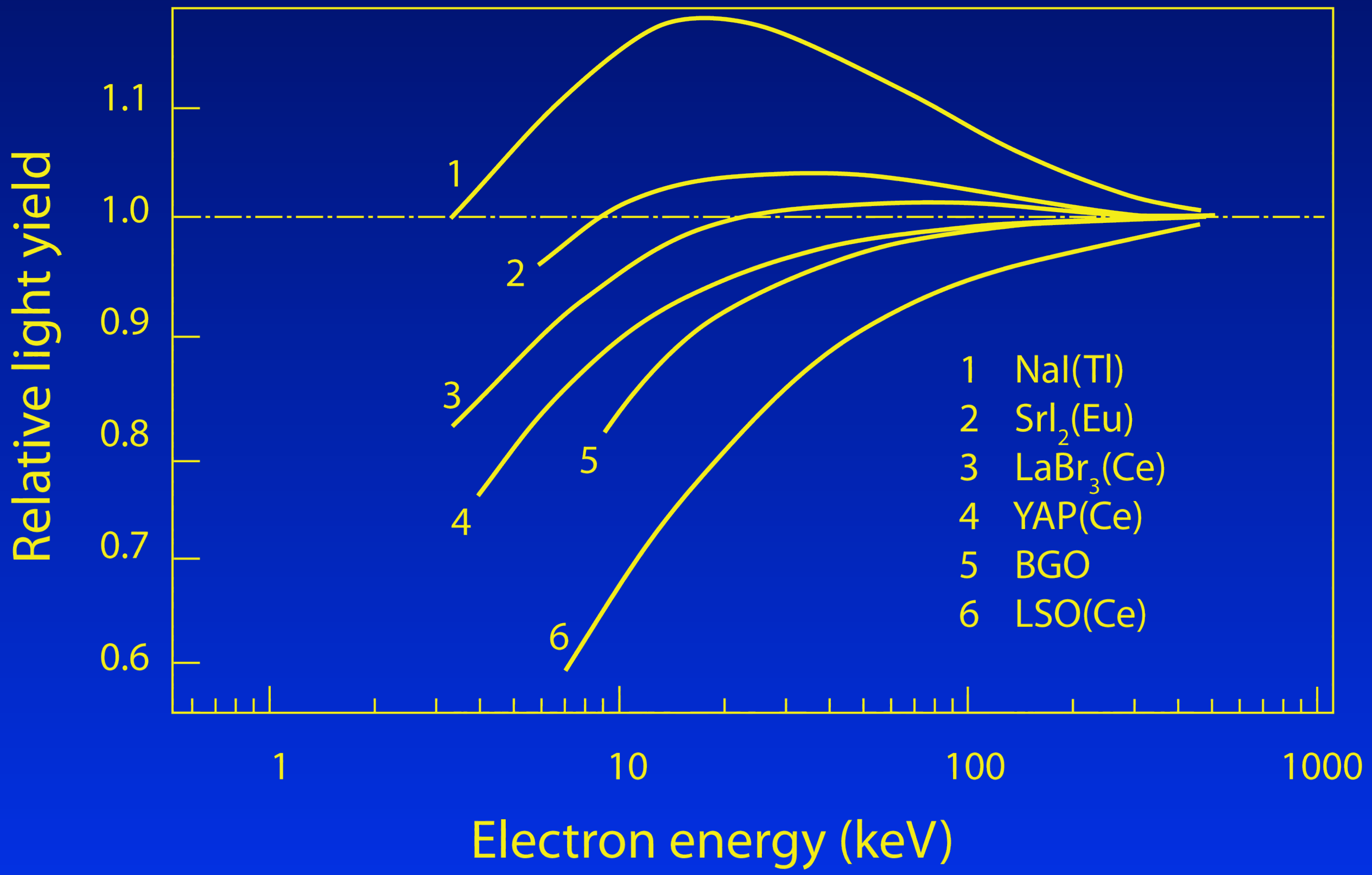


FIG. 2. Scintillation efficiency as a function of dE/dx for various particles in NaI(Tl).

A single electron track will give rise to a large number of lower energy electron tracks each different ionisation density.



The scintillation signal from an electron is not linearly related to the energy



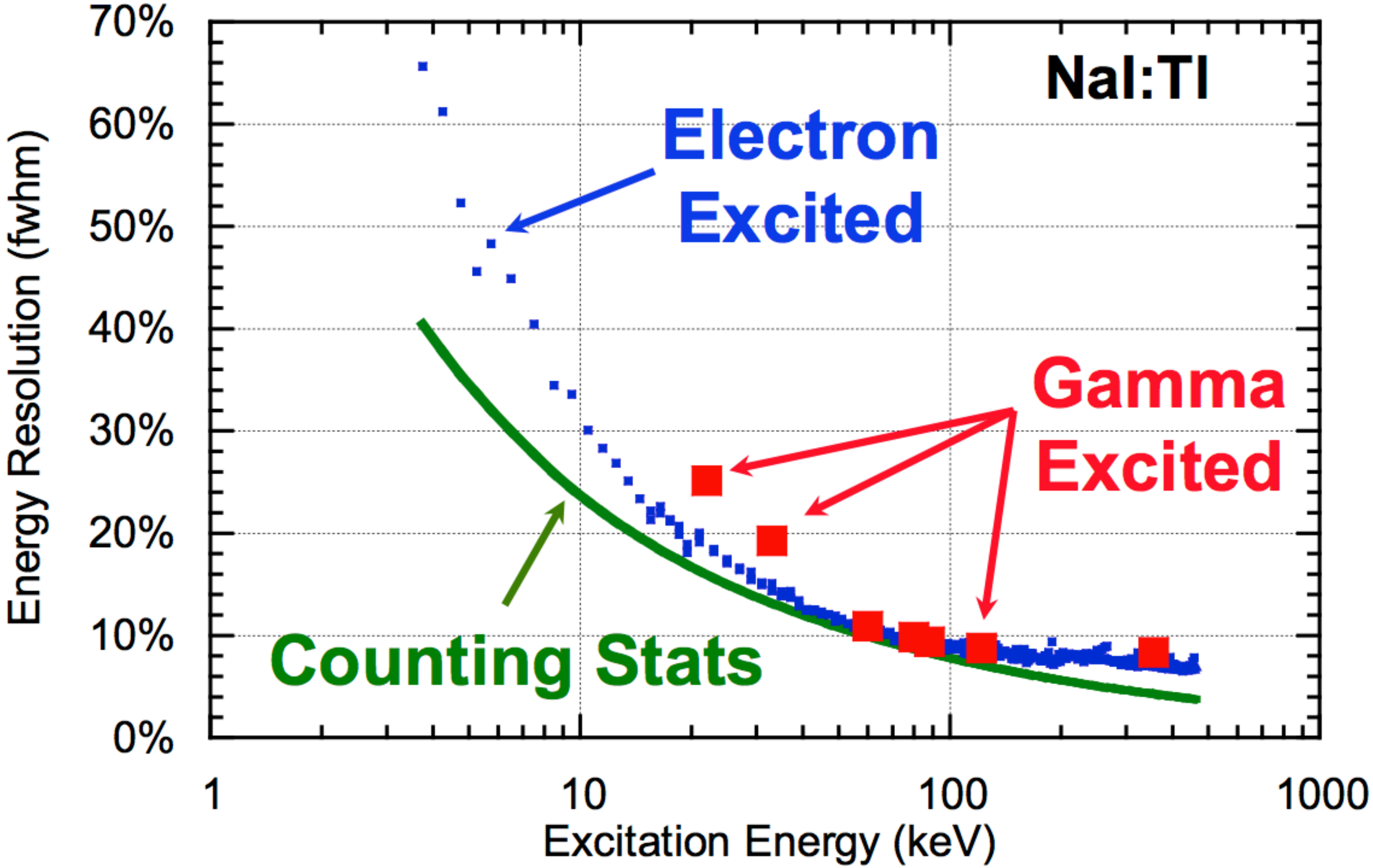
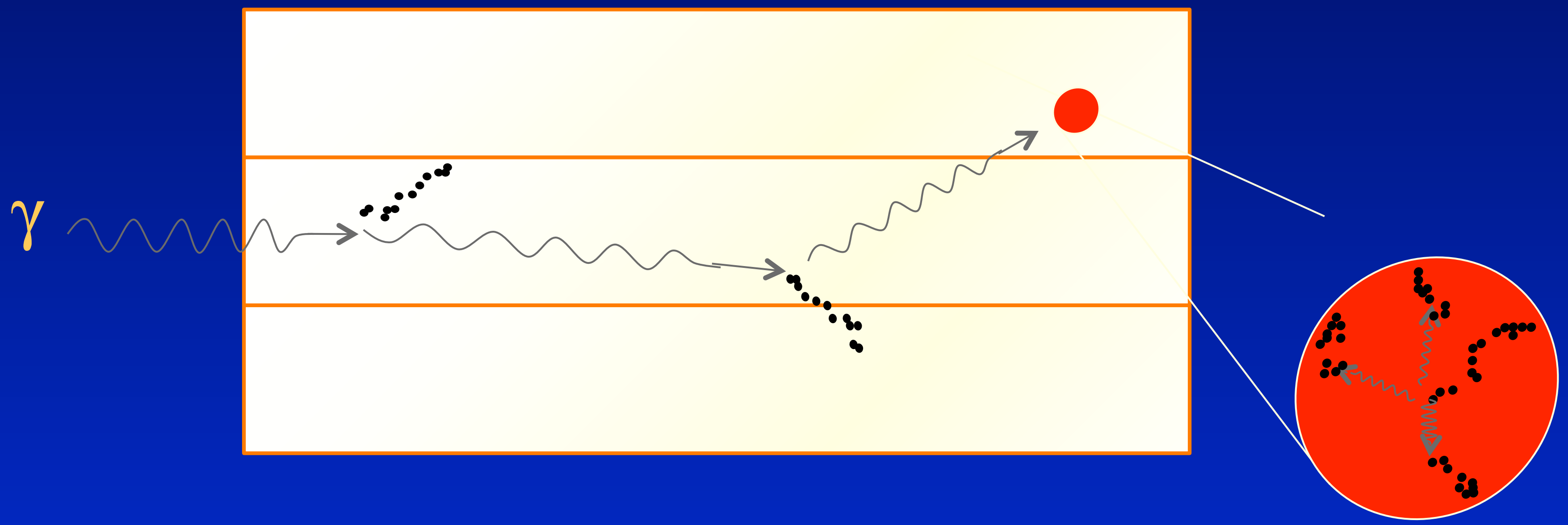


Figure from W.W. Moses, et al., IEEE Trans. Nucl. Sci. NS-55, pp. 1049, 2008

This non linear energy response to electrons results in a degraded energy resolution



In scintitillators the light yield depends on the ionisation density. Such an effect is not observed with semiconductors. However, carrier mobility and diffusion in commonly used semiconductors (covalent crystals) are up to 3 orders of magnitude larger than in scintillators (ionic crystals).

Energy resolution for gamma detection in inorganic scintillator

$$R^2 = R^2_{\text{intrinsic}} + R^2_{\text{lightyield}}$$

$$R^2_{\text{lightyield}} \propto \frac{1}{N_{\text{photoelectrons}}}$$

Intrinsic energy resolutions for a few crystals

NaI:Tl	5.7±0.2 %	
BGO	4.2±0.6 %	
CsI:Tl	5.9±0.3 %	
LSO:Ce	6.6±0.4 %	$D=0.02\ \text{cm}^2/\text{s}$
YAP:Ce	1.0±1.0 %	$D= 0.1\ \text{cm}^2/\text{s}$

In detector grade germanium; $D \approx 200\ \text{cm}^2/\text{s}$

Decay characteristics

Emission characteristics are determined by the luminescence centre and only moderately influenced by the host matrix

Example Ce3+ decay: 5d->4f allowed dipole transition

$$\Gamma = \frac{1}{\tau} = \frac{4}{3}(2\pi)^3 \ \alpha \ \frac{\nu^3}{c^2} \ n\left(\frac{n^2+2}{3}\right)^2 \ \left|\langle i|\vec{r}|f\rangle\right|^2$$

Decay : exponential

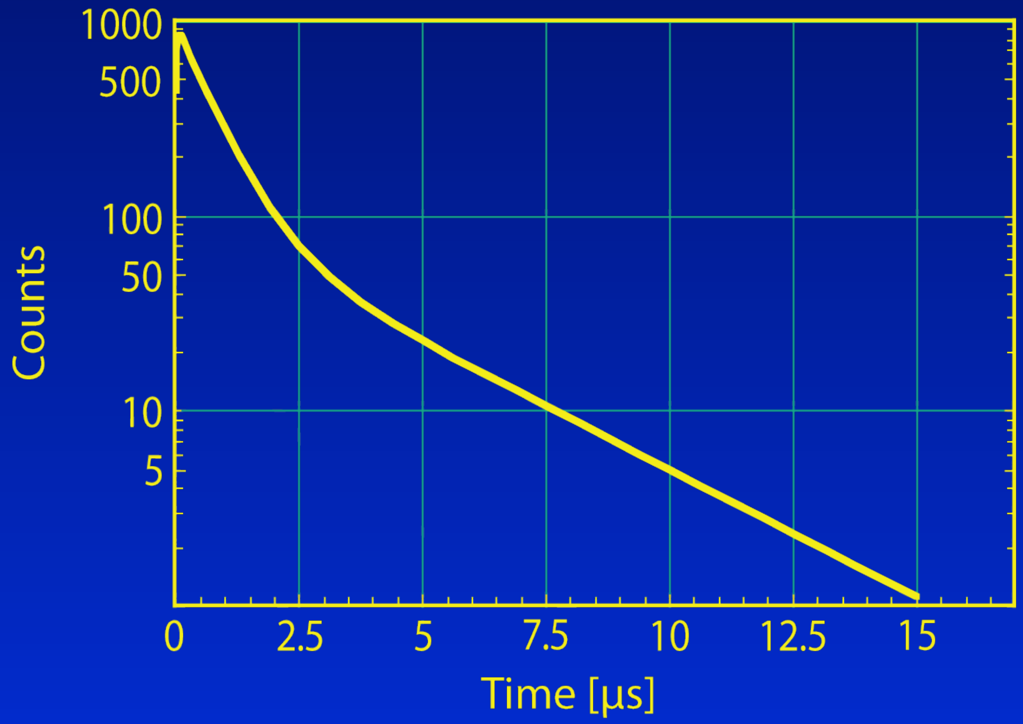
BUT ....

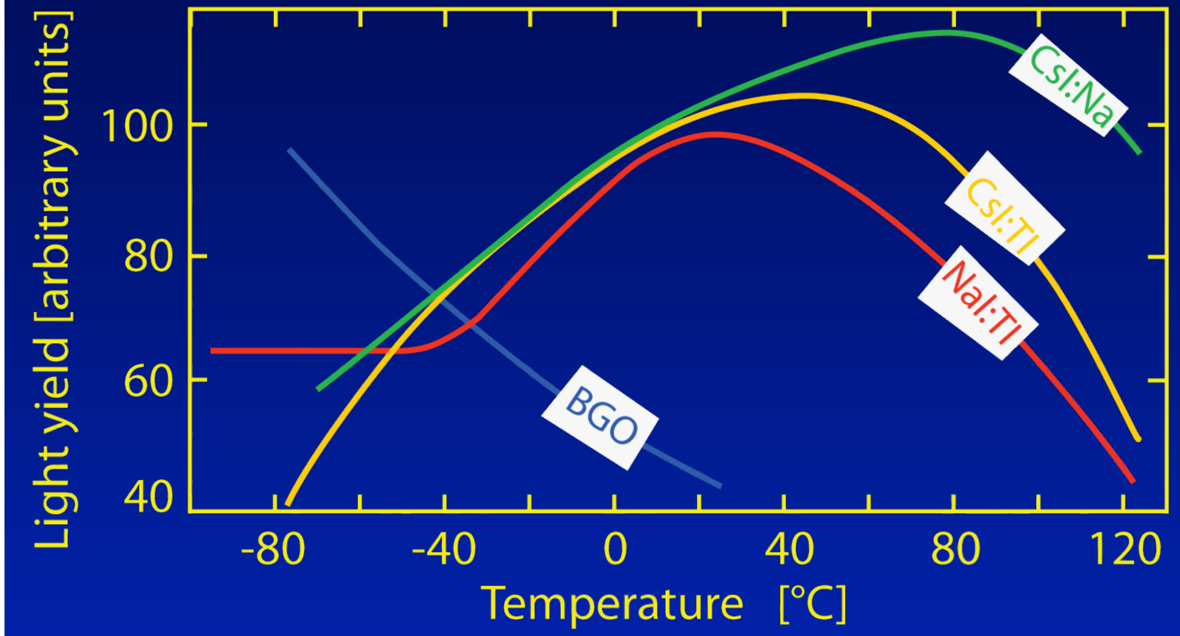
- more than one type of luminescence centre
- traps capture electrons and holes

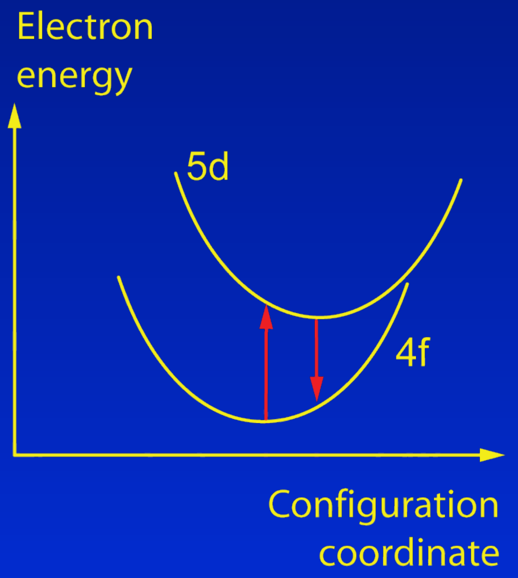
-> slower rise time

-> afterglow

CsI:Tl decay spectrum





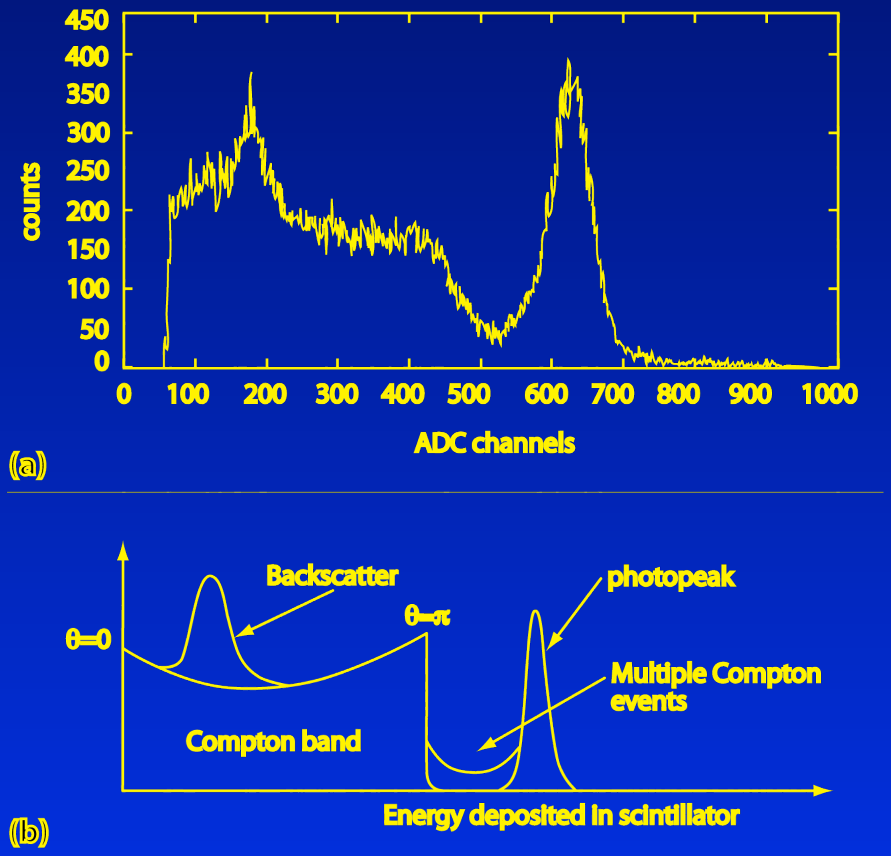


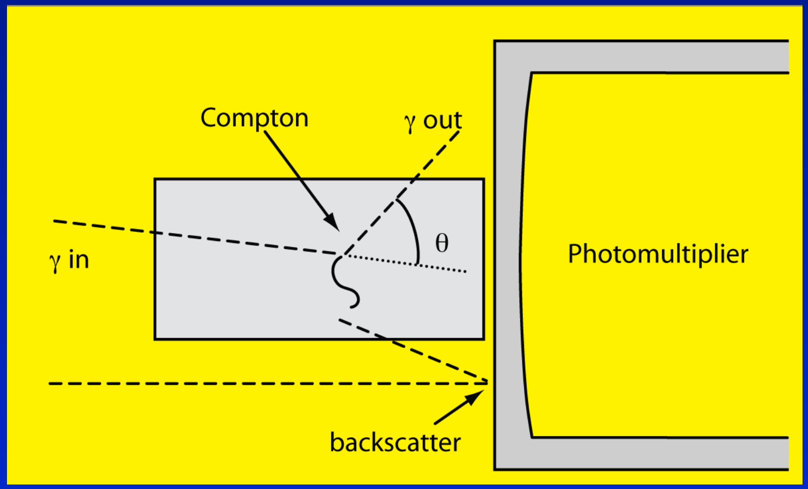
Thermal quenching

few scintillators are efficient at elevated temperature

Applications of inorganic scintillators

A keV to MeV gamma ray in a crystal





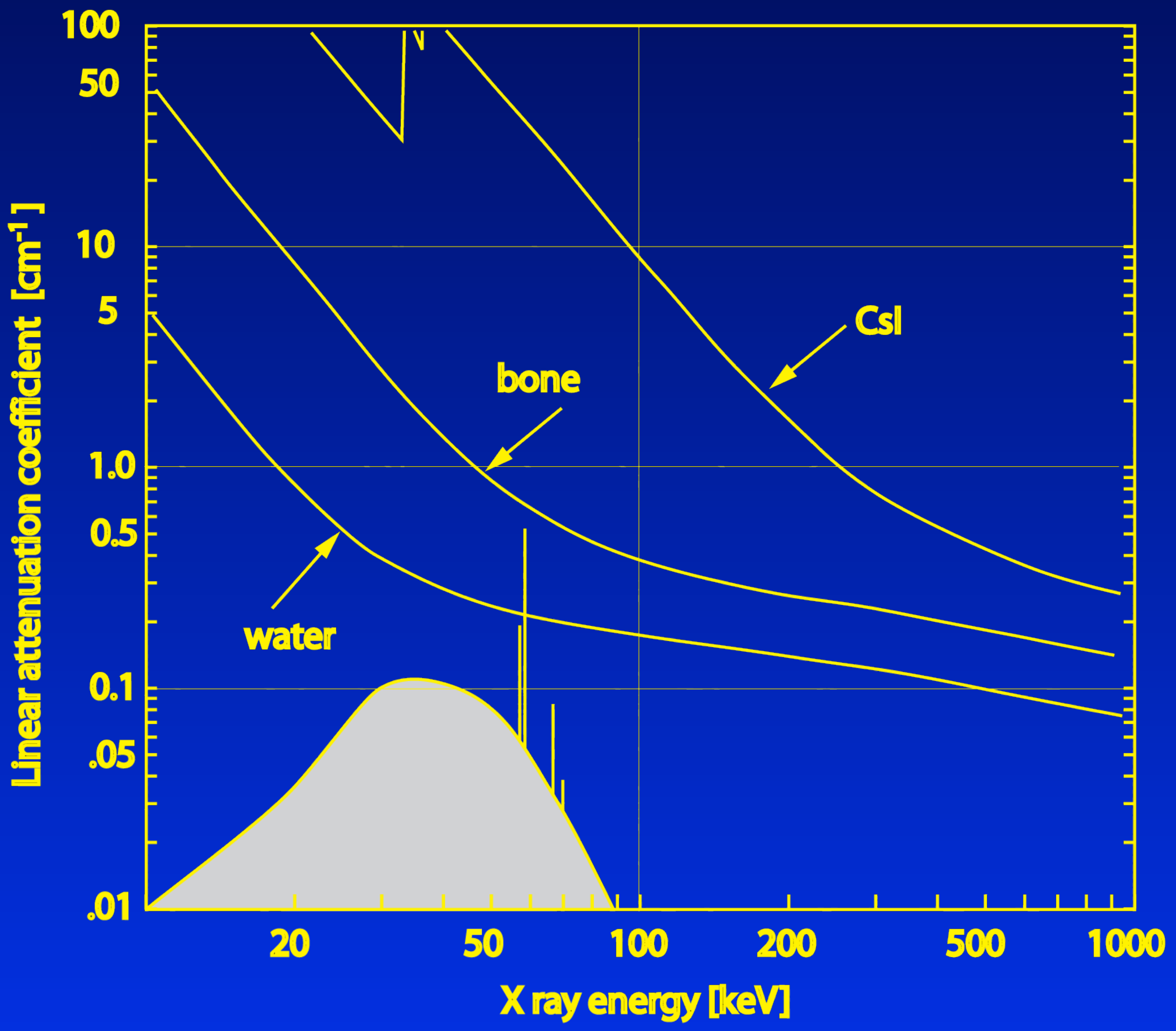
Scintillators in medicine

X-ray detection, radiology, CT-scanner

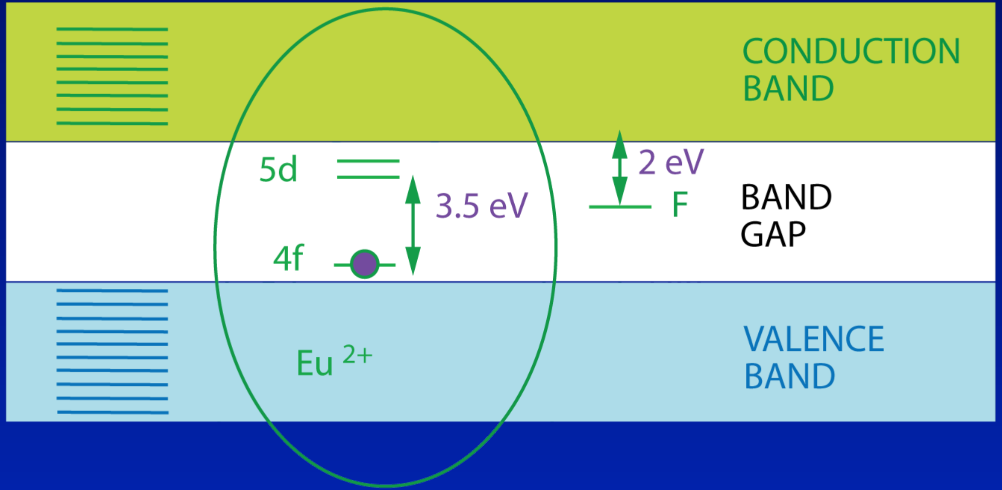
Single gamma detection: scintigraphy, SPECT

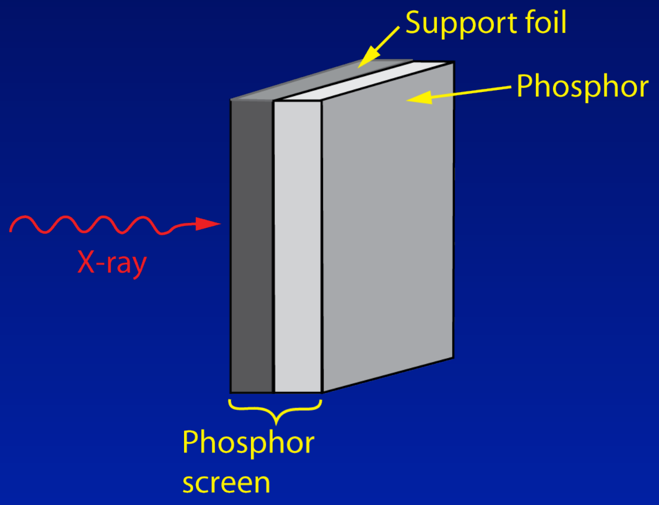
Positron emission tomography (PET)

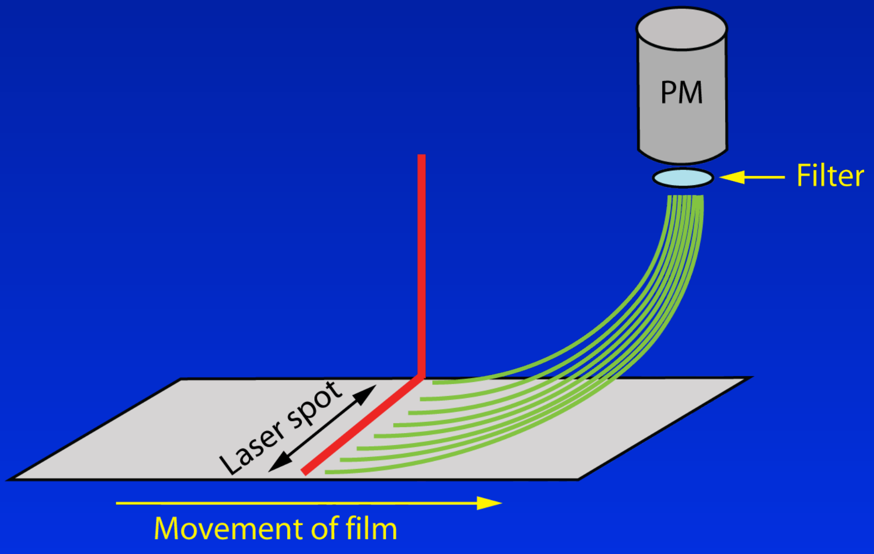
X-ray detection



Computed radiography (X-ray imaging)



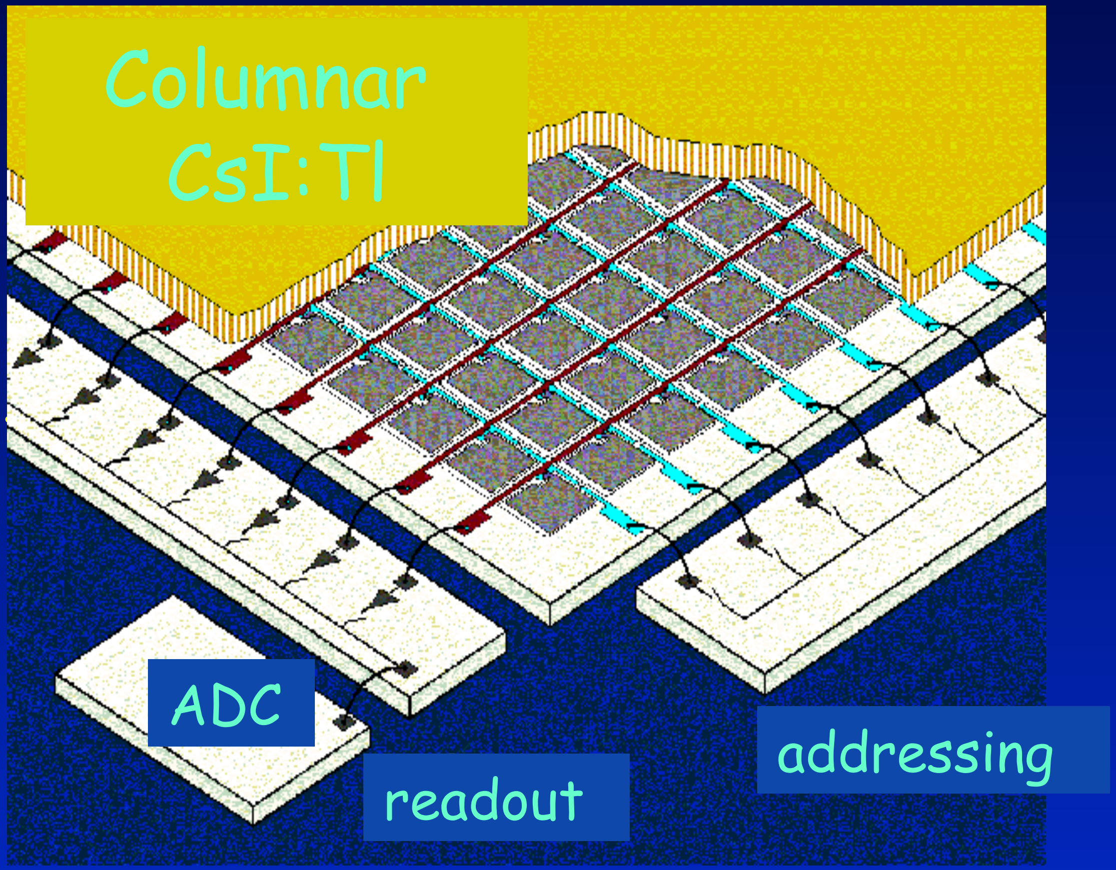


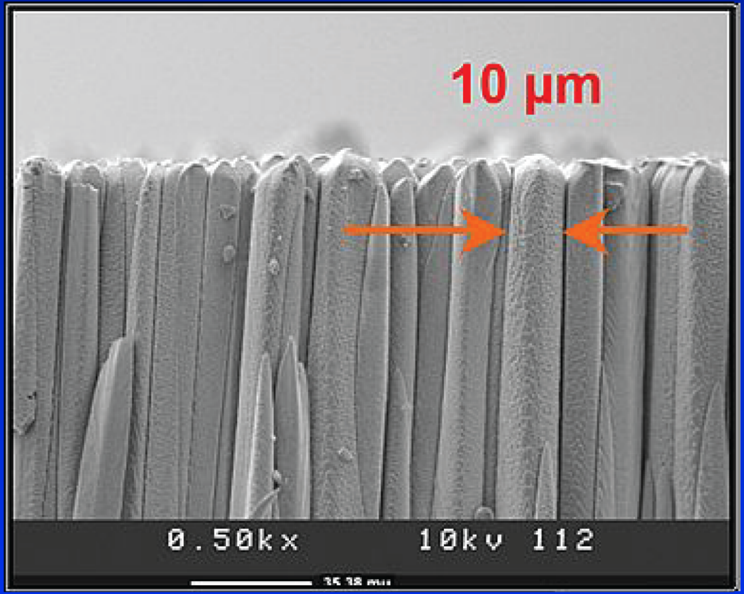


Phosphors
$BaFBr:Eu^{2+}$
$BaFI:Eu^{2+}$,
$CsBr:Eu^{2+}$

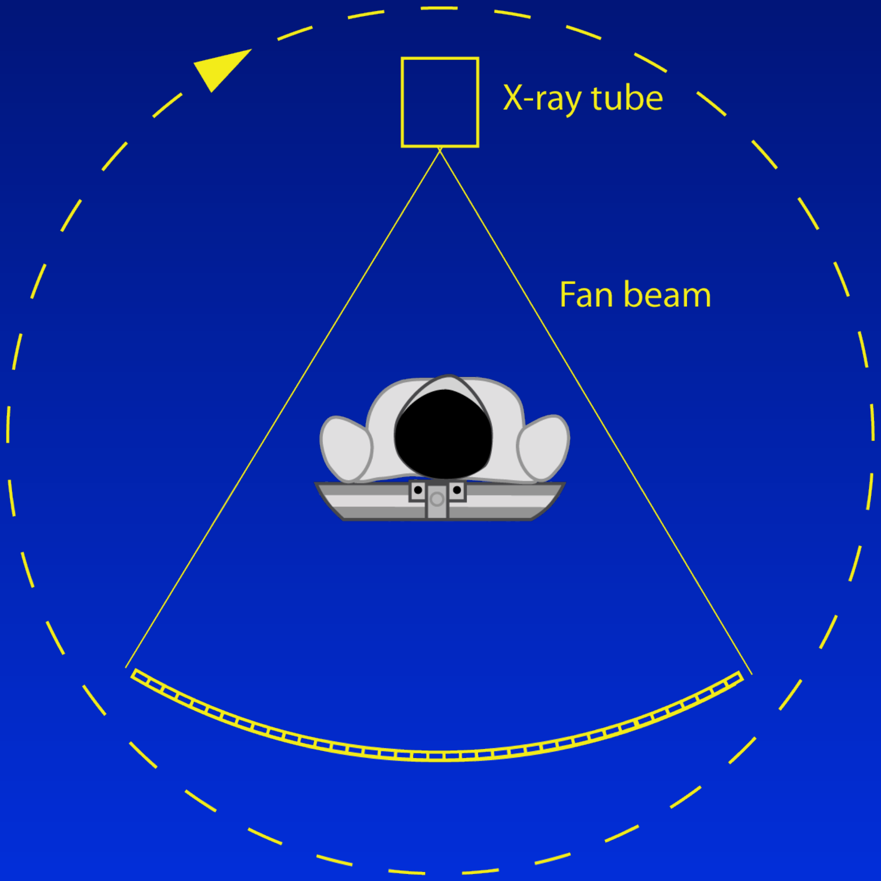
Digital radiography

Amorphous silicon photodiode array +CsI:Tl, Eu scintillato





The CT scanner



A transmission X-ray image is made along to all directions around the patient. Allows reconstruction of the 3D absorption density in the body.

- scintillator + photodiode
- measuring in DC mode

Commonly use scintillators for CT

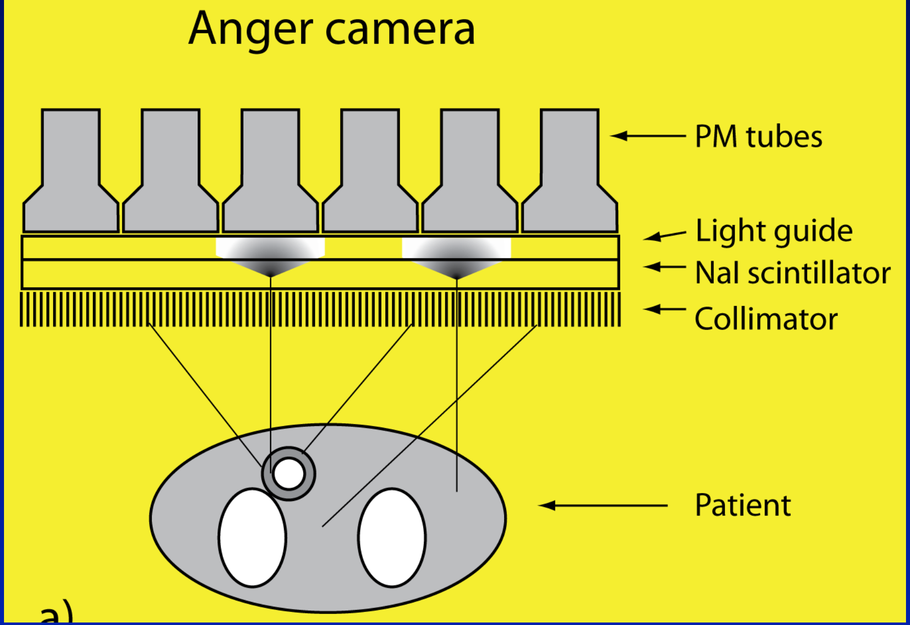
	CsI:Tl	$CdWO_4$	$(Y, Gd)_2O_3:Eu^{3+}$	$Gd_2O_2S:Pr^{3+}$
Type	crystal	crystal	ceramic	ceramic
Density	4.52	7.13	5.91	7.34
Emission [nm]	550	580	610	520
Light yield [rel]	100	30	67	75
Decay time [µs]	0.6	8.9	1000	3
Afterglow	yes	no	limited	no

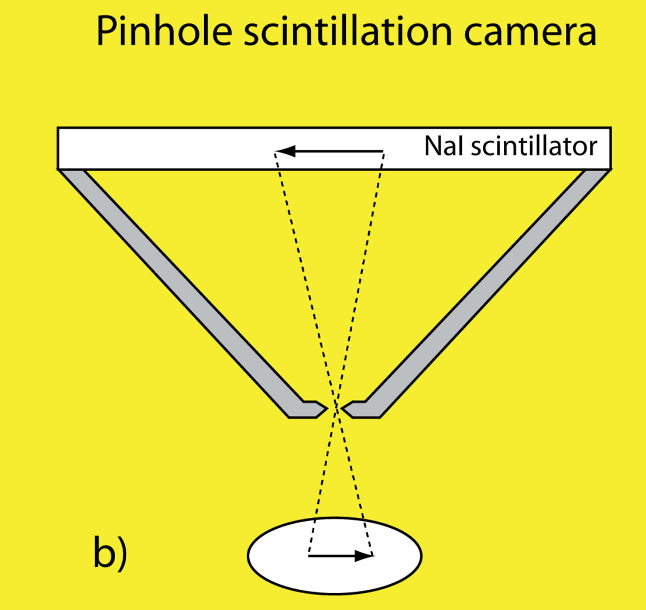
Scintillator requirements: large stopping power, large LY, no afterglow

Nuclear medicine
Scintigraphy, SPECT & PET

These are non invasive methods for imaging the distribution of a radioactively labelled compounds in the human body. This is often to as "molecular imaging", or functional imaging.

Scintigraphy: gamma camera (Anger camera)





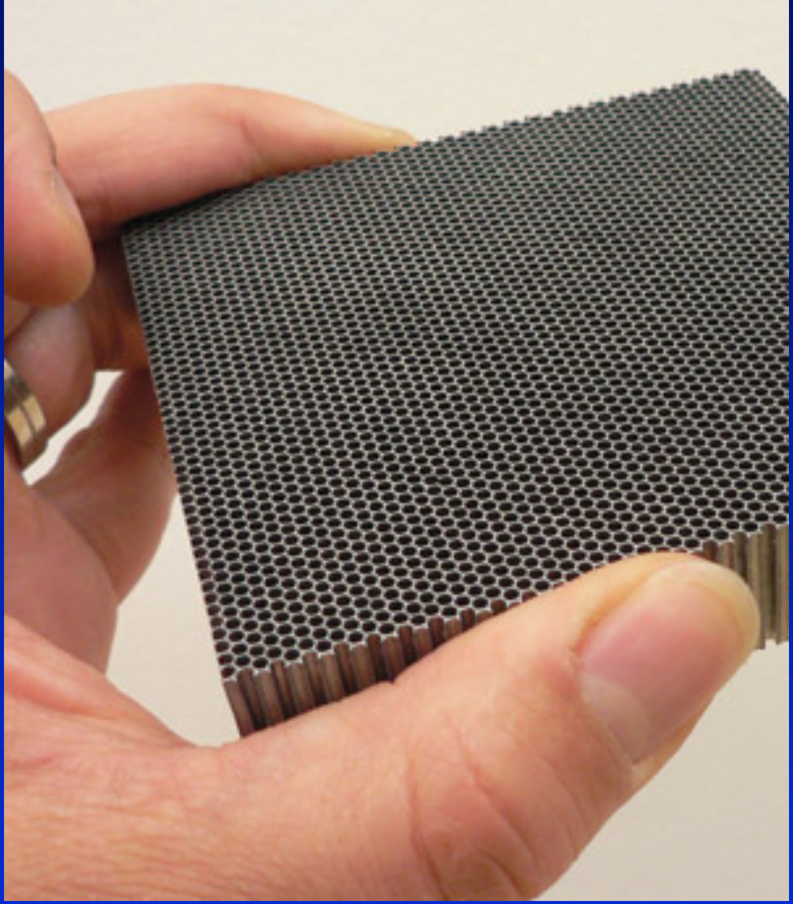
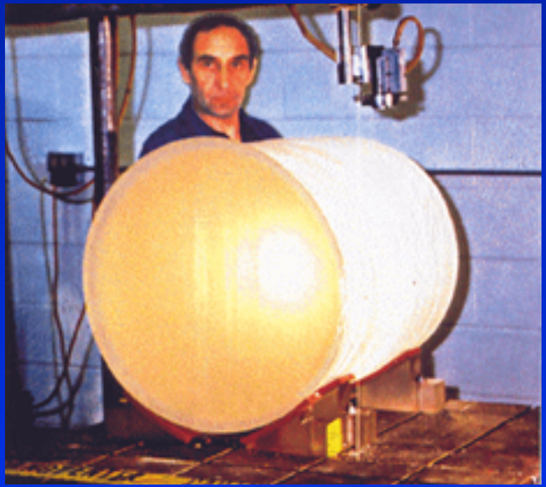


Table 18.2: Commonly used isotopes in gamma imaging.

Isotope	Symbol	Half life	Decay	Gamma energies [keV]
technetium-99	^{99m}Tc	6.01 h	IT(1)	140(89%)
iodine-123	^{123}I	13.3 h	ec(2)	159(83%)
iodine-131	^{131}I	8.02 d	β^-	364(81%)
thallium-201	^{201}Th	3.04 d	ec	69-83(94%), 167(10%)
gallium-67	^{67}Ga	3.26 d	ec	93(39%), 185(21%), 300(17%)

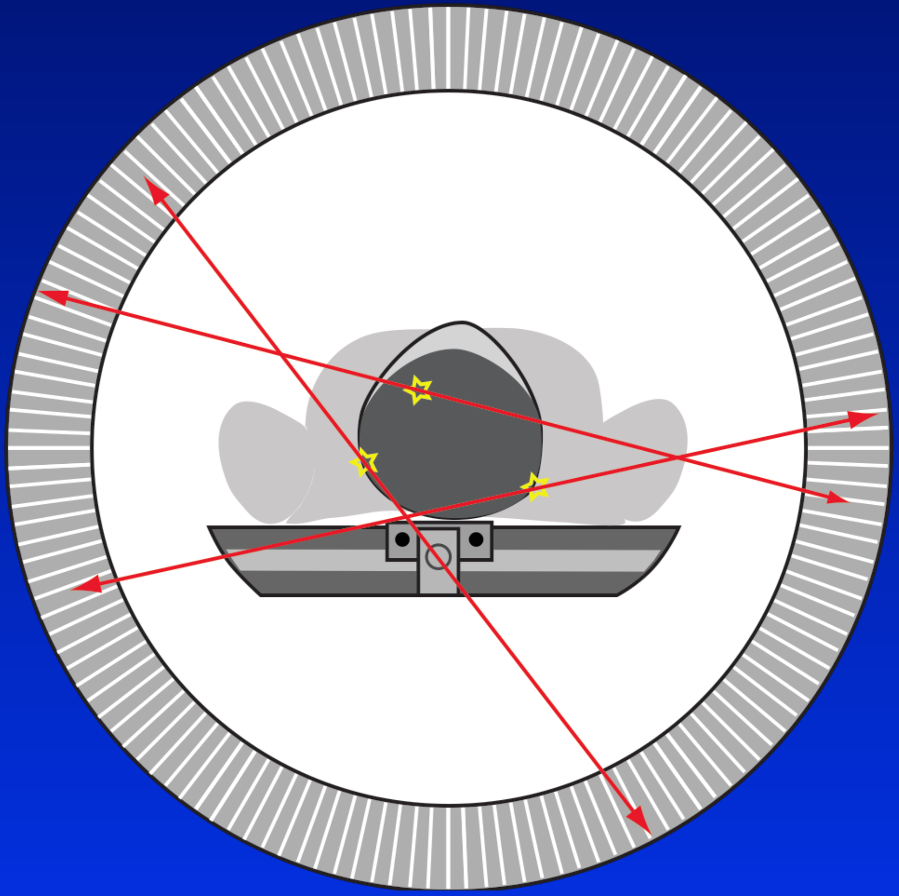
(1) IT= isomeric transition, (2) ec=electron capture

Scintillator: NaI;Tl; at 140 keV
m. f. p. ≈ 4 mm.
Scintillator requirements: large LY, moderately good stopping power, moderately good timing



SPECT:Single Photon Emission Computed Tomography tomographic images with a gamma camera

In Positron Emission Tomography a chemical compound is labelled with a positron emitting isotope. The labelled compound is injected in a patient.



After some time the isotopes decay. The emitted positron annihilates with an electron into two back-to-back gamma rays of 511 keV. Detecting the gamma rays reveals the position of the isotope.

The PET scanner is not observing space points, but a lines of response. The positron annihilation occurred somewhere along this line of response.

From a large set of lines of response, covering a sufficient number of directions around the patient, it is possible to reconstruct the 3-dimensional density distribution of the tracer.

This is usually done with an iterative reconstruction algorithm, and is very computer intensive.

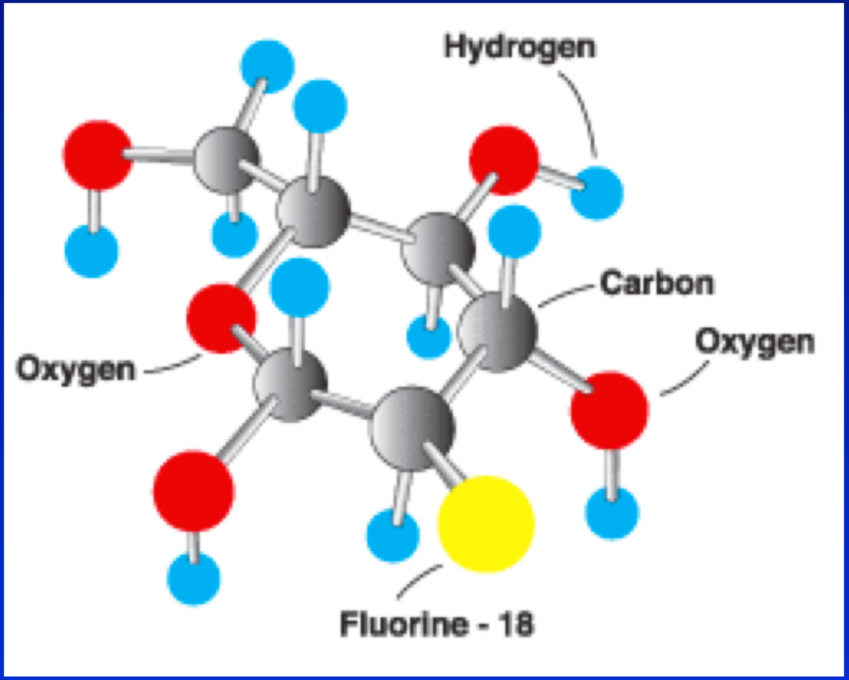

402.0
0.0

The most commonly used isotopes in PET are

Isotope	Decay time (1/2 life)
^{11}C	20 min
^{18}F	110 min
^{13}N	10 min
^{15}O	2 min

Producing these isotopes requires a cyclotron

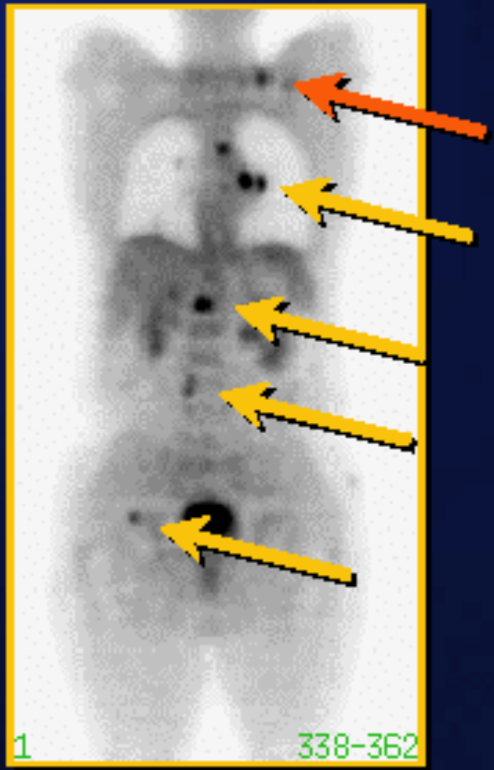
By far the most commonly used radiopharmaceutical is FDG (Fluoro2-deoxy-D-glucose), a 18F labelled glucose analog.



FDG is transported in the body in a very similar way as normal glucose. The metabolic product of FDG is trapped in the cell. Therefore the activity distribution directly reflects the metabolic activity of the cells

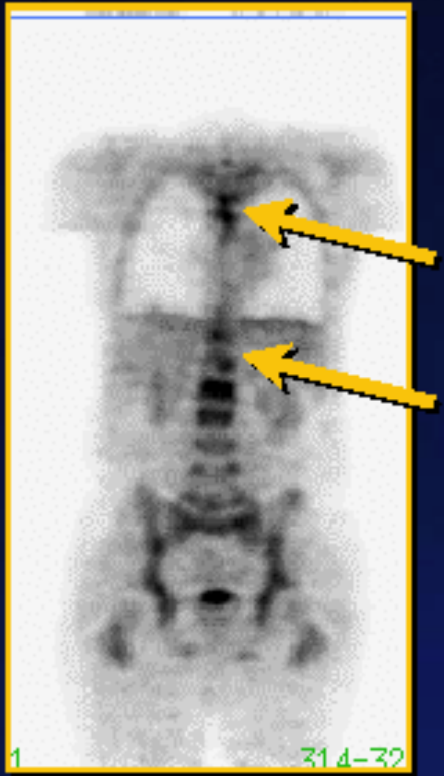
PET Case Study: Melanoma Staging & Follow-up

Before Therapy PET on 11/20/00



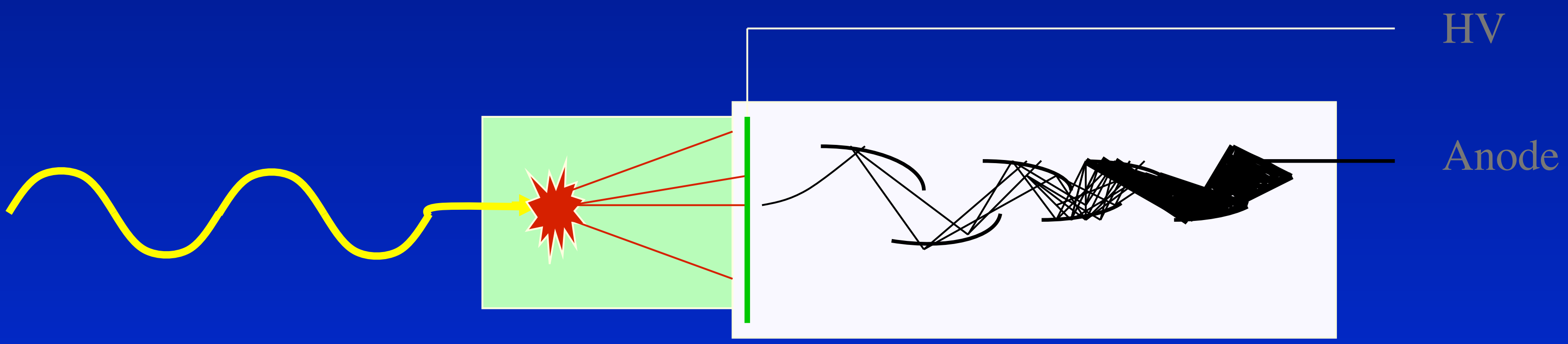
CT showed mass in left shoulder
But missed abdominal lesions

After Therapy PET on 2/18/01



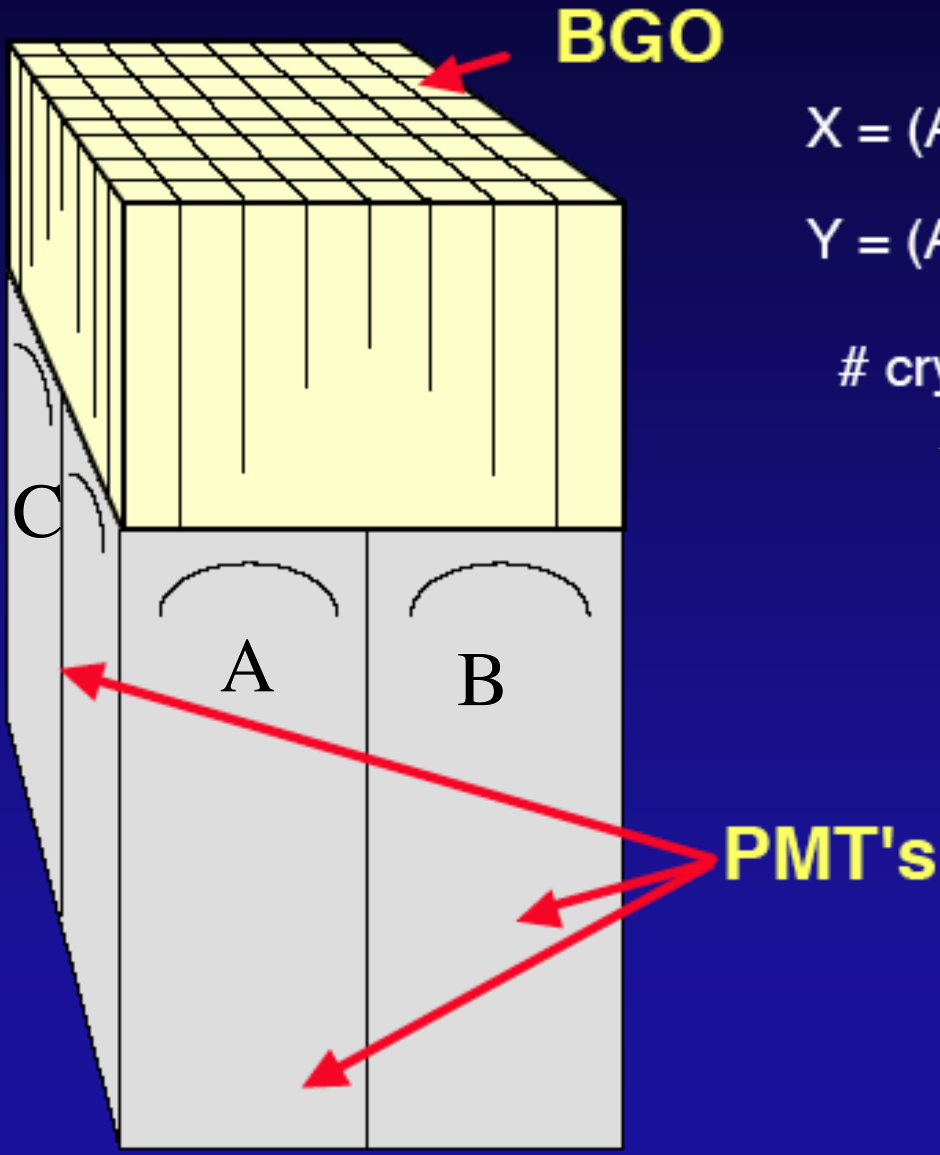
Normal post-therapy
bone marrow uptake

From the engineering point of view a PET scanner is a detector for 511 keV gamma rays that surrounds the patient.



Gamma ray Scintillator Photomultiplier tube

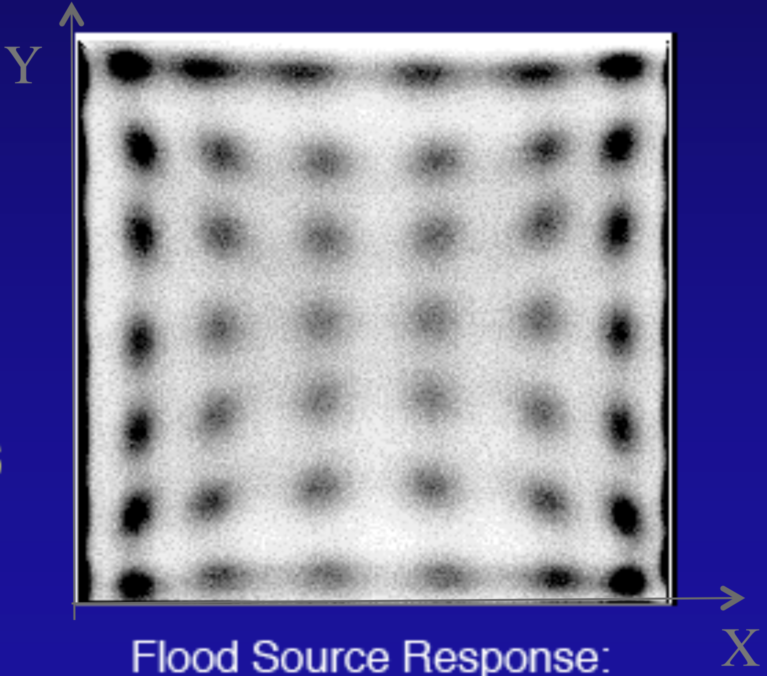
PET Block Detector



$$X = (A + B - C - D) / (A + B + C + D)$$

$$Y = (A - B + C - D) / (A + B + C + D)$$

crystals / # PM tubes = 9 to 16



Flood Source Response:
CTI/Siemens EXACT HR Block

A PET scanner should have

- spatial resolution in the image
- sensitivity: number of counts/s for a given activity in the patient.
- time resolution
- energy resolution

This needs scintillators with
- fast rise time and decay time
- large light yield
- large stopping power=short absorption length, large photofraction

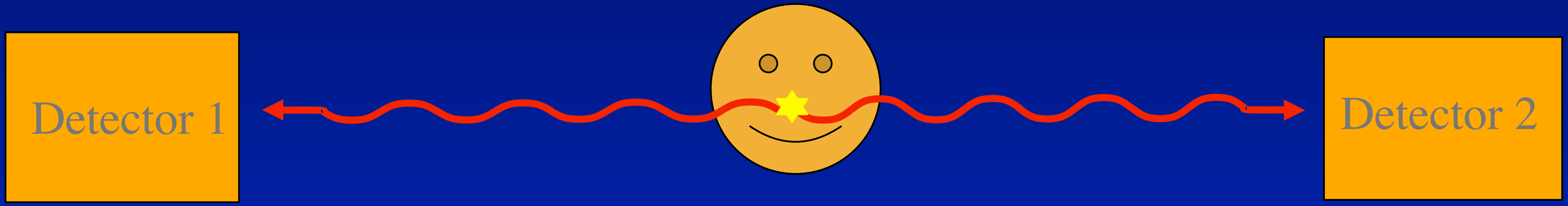
Scintillators for PET

Crystal	Att. length [mm]@522keV	Light Yield ph./MeV	λ [nm]	Decay time [ns]
BGO	10.4	9’000	480	300
NaI	28.6	40’000	410	230
GSO	14.1	8’000	440	60
LSO	11.4	30’000	420	40
LaBr	22.3	70’000	360	35

Time resolution is very important in PET to remove random coincidences

Needs $\Delta t \approx$ few ns

Time Of Flight (TOF)? Δx=15 cm => Δt =1 ns !



If Δt ≈20 ps events would be space points !
Leads to considerable reduction of noise in the image

For best timing, the rise time of the scintillator is very important, LSO has a rise time of 90 ps.
For materials with negligible rise time

time resolution $\propto \sqrt{\frac{\tau_{decay}}{N_{pe}}}$

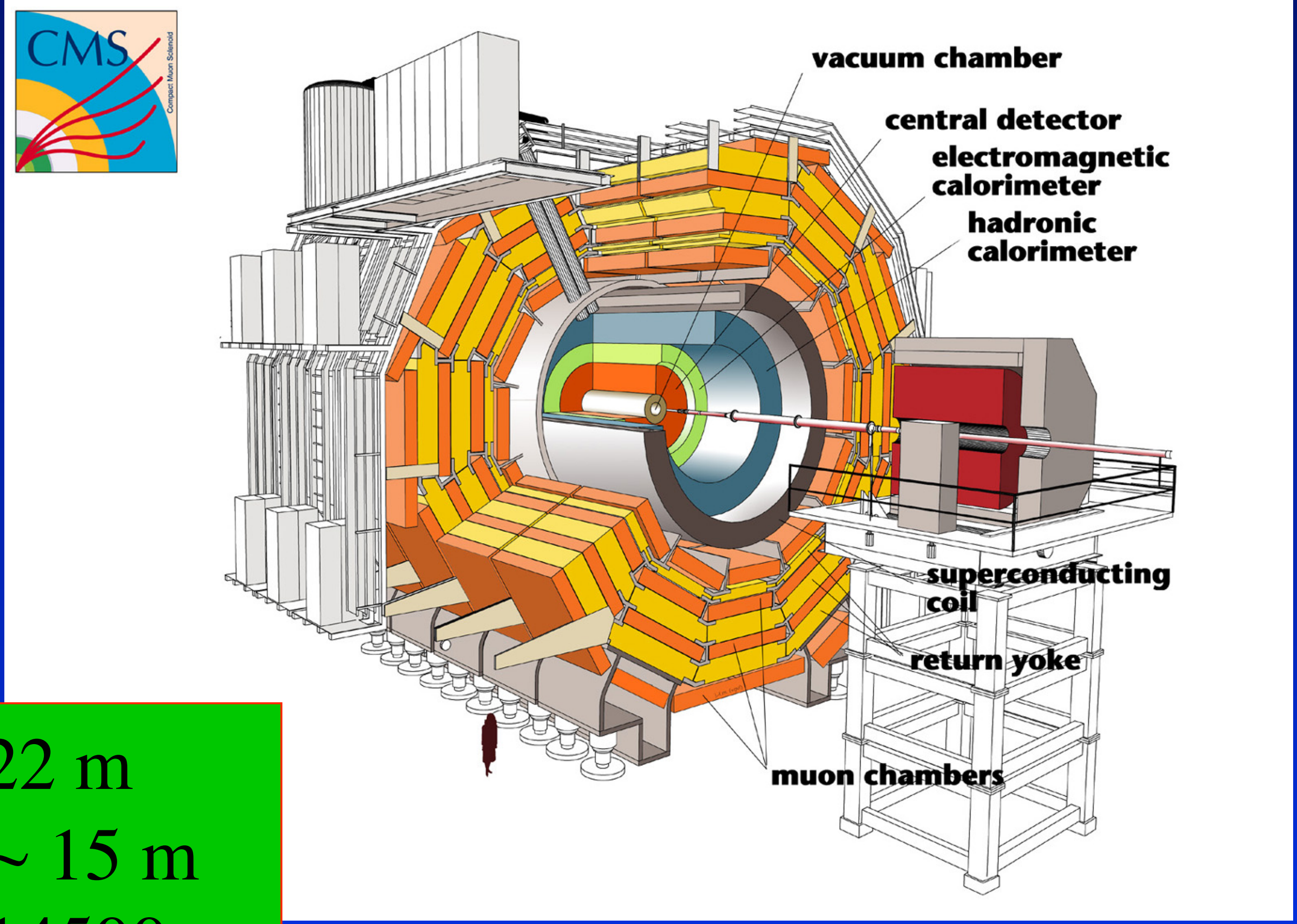
LSO + 0.3% Ca >> decay time ≈ 30 ns
LaBr:Ce ? rise time 370/800 ps.

Scintillators for high energy physics

High energy $\gg \approx 10$ MeV

Inorganic scintillators provide the best method for the detection of high energy gamma rays, or high energy electrons and positrons

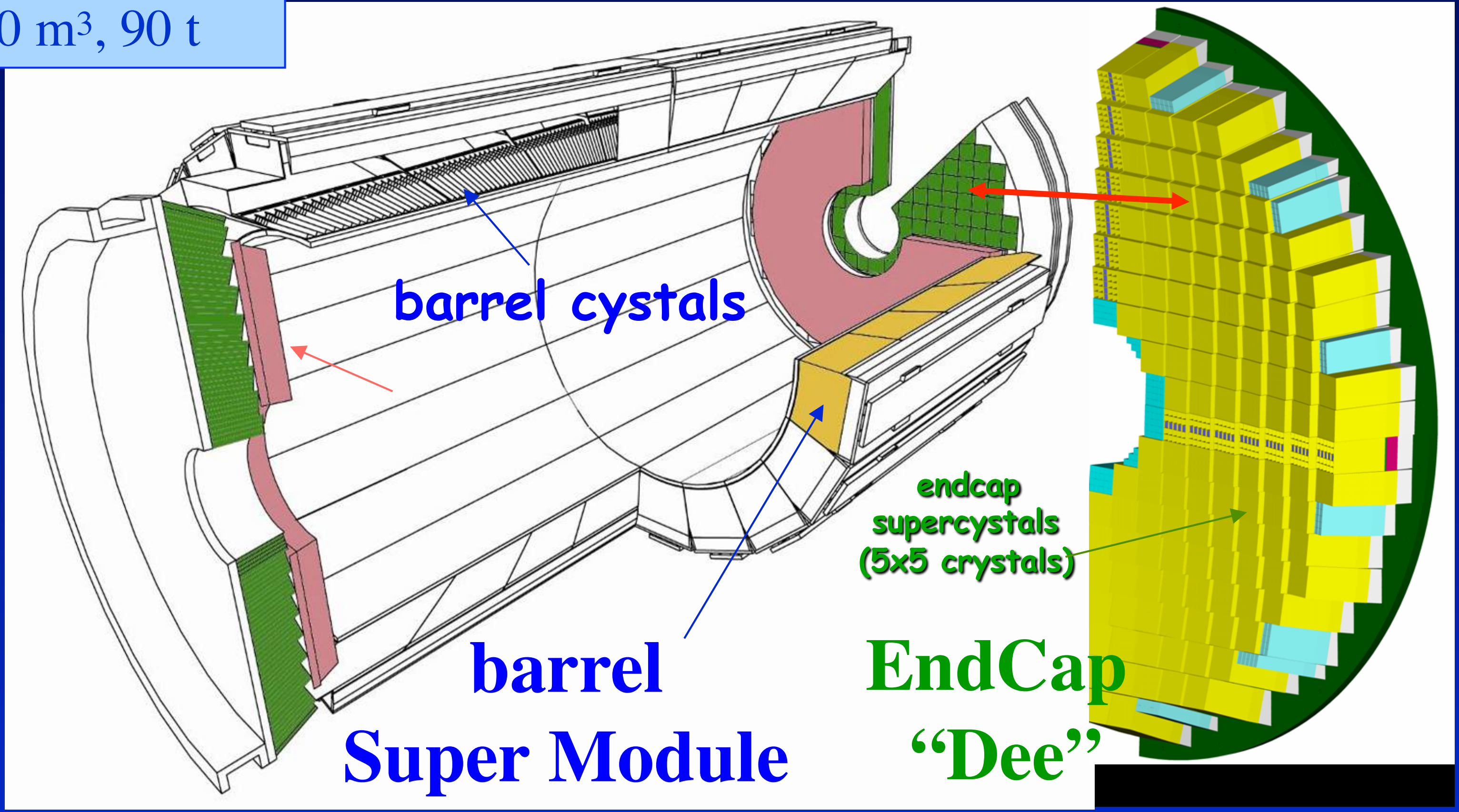
Compact Muon Solenoid



- Length ~ 22 m
- Diameter ~ 15 m
- Weight ~ 14500 t

Needs to detect gamma rays and electrons up to few 100 GeV

PWO: $PbWO_4$
about 10 m^3, 90 t

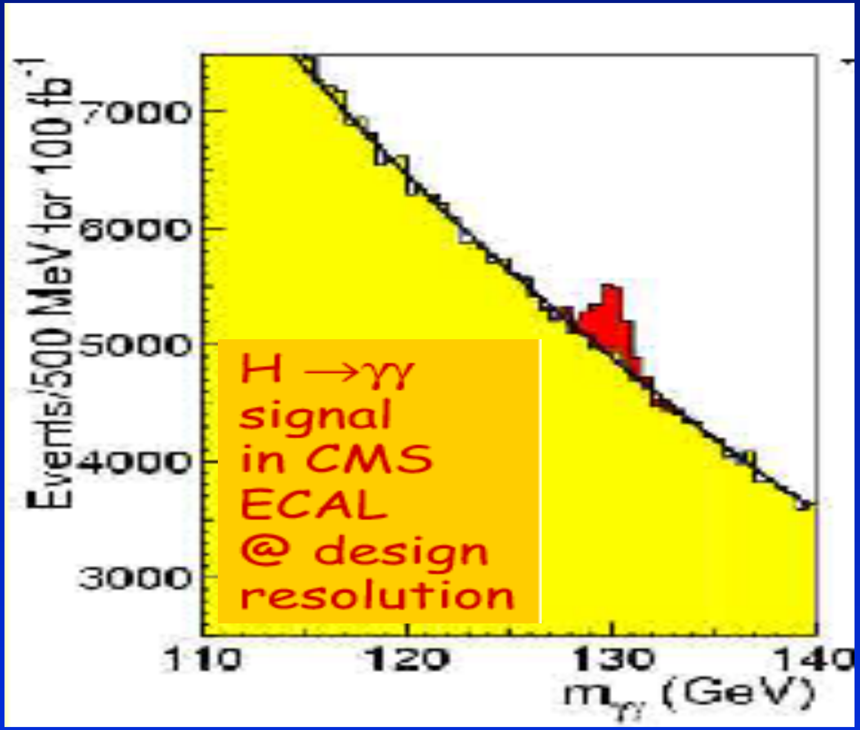


Barrel:
36 Super Modules
61200 crystals (2x2x23cm^3)

EndCaps:
4 Dees
14648 crystals (3x3x22cm^3)

For a light B_E_Higgs (only possibility left) H→$\gamma\gamma$ best channel. Narrow width, irreducible background:

ECAL resolution is crucial !



The main property of a calorimeter is its energy resolution

$$\frac{\sigma\{E\}}{E} = \sqrt{\frac{a^2}{E[GeV]} + b^2}$$

a=0.02-0.03; b=0.005-0.01

- statistical term: depends on light yield but also many other things, e.g, shower is not fully contained

- Constant term: mainly an issue of calibration

Scintillator requirements for high energy physics

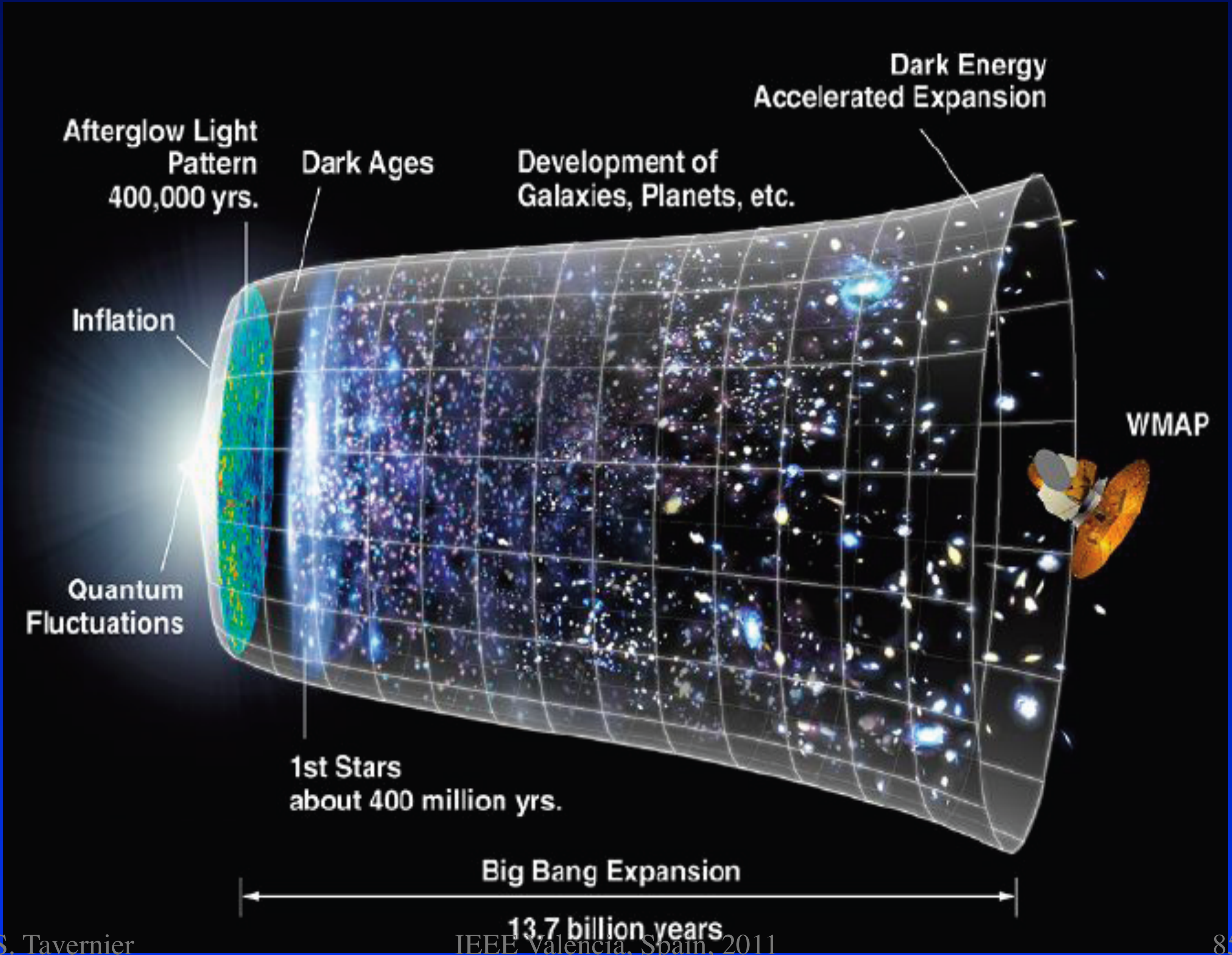
- stopping power, short radiation length X_0

- Molière radius $R_m = 0.035 \times X_0 \times (Z + 1.4)$
- decay time
- radiation hardness
- light yield far less important if mainly very high energy gamma rays need to be detected

Some popular crystals in HEP

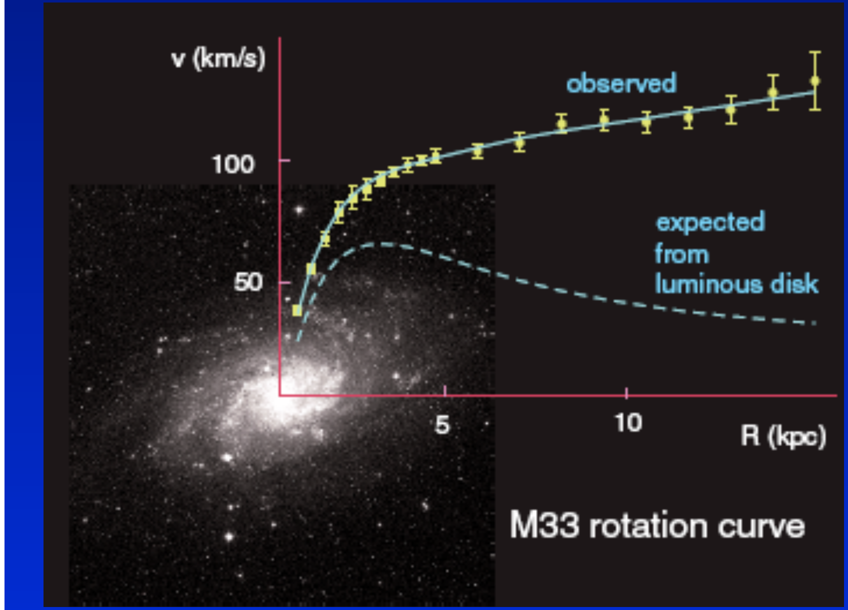
	NaI(Tl)	BaF_2	CsI(Tl)	CeF_3	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$
Xo [cm]	2.59	2.03	1.86	1.66	1.12	0.92 ☺
ρ [g/cm^3]	3.67	4.89	4.53	6.16	7.13	8.2
τ [ns]	230	0.6 620	1050	30	340	15 ☺
λ [nm]	415	230 310	550	310 340	480	420
$n@\lambda_{max}$	1.85	1.56	1.80	1.68	2.15	2.3
LY [%NaI]	100 ☺	5 16	85 ☺	5	10	0.5 ☹

Scintillators in astronomy and dark matter searches


Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years

WIMP-Dark matter searches

Evidence of Dark Matter
Rotation curve of spiral galaxies



L.Bergstrom Rep.Progr.Phys.63 (2000) 793

$V=(GM/r)^{1/2}$

Direct detection - elastic scattering off nuclei

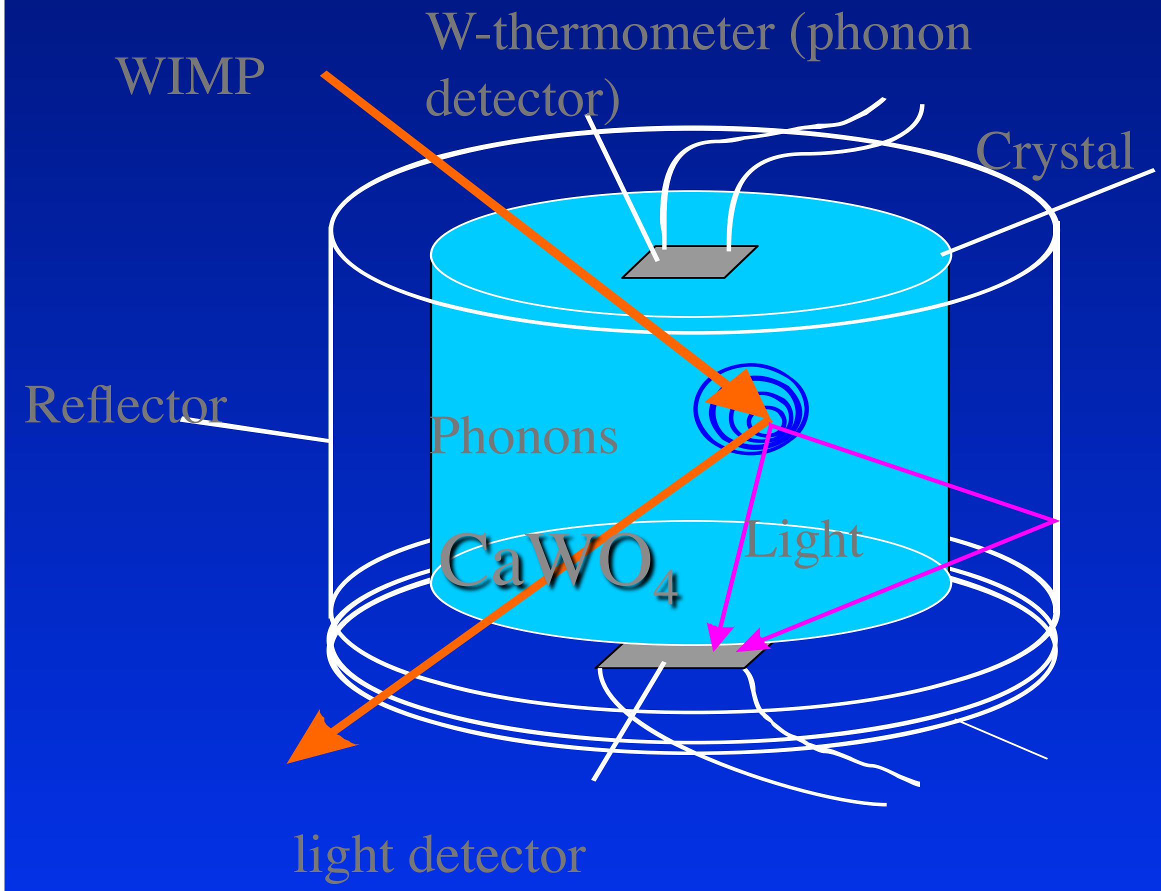
Features:

1. Low energy recoil → (≈20 keV)
   $E=1/2Mc^2 . (v/c)^2 \sim A$
2. Expected event rate ≈ 1/kg year
   $\sigma \sim A^2$

- Background rejection
- Detector mass ≈ 1000 kg

CRESST detector

- Gamma rejection using simultaneous observation of the light signal and heat signal.


W-thermometer (phonon detector)

WIMP

Crystal

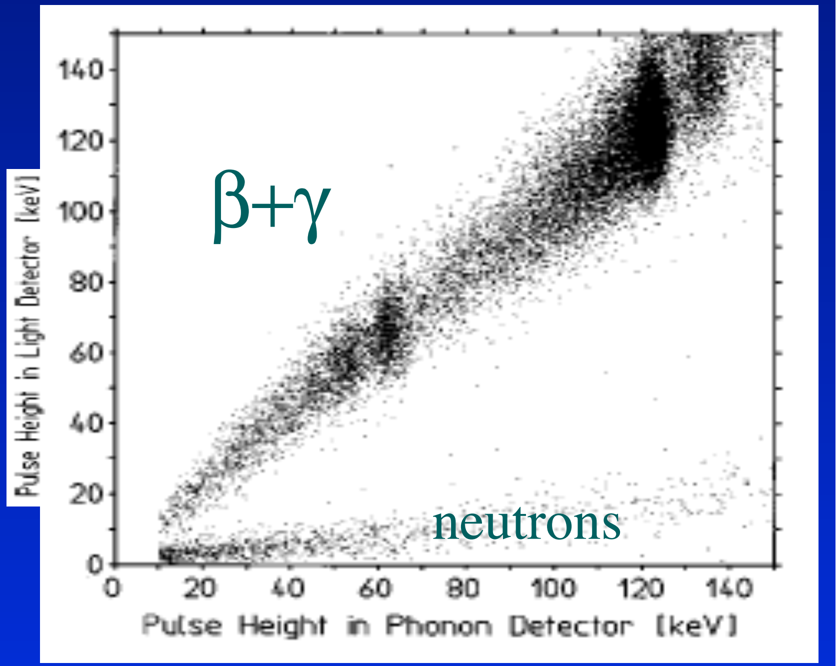
Reflector

Phonons

$CaWO_4$

Light

light detector



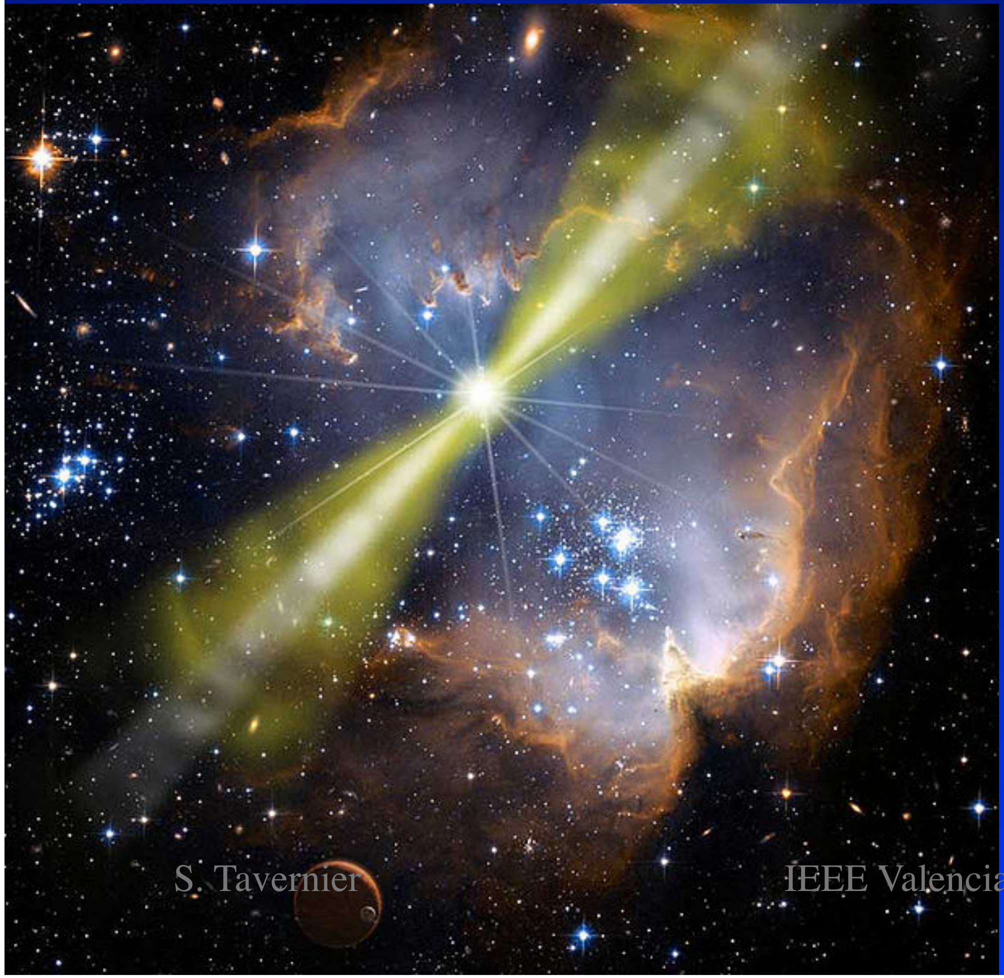
P.Meunier et al, Appl.Phys.Let 75 (1999) 1335

Scintillator requirements

- high light yield at low temperatures
  - ✓ large atomic number A
  - ✓ large light yield
- Radiopurity (ex Lu, Rb, K, U, Th)
- Suitable thermodynamics characteristics
- Possible candidates
  - ✓CaWO4 – satisfactory choice, currently in use, large ongoing effort to improve the material
  - ✓$ZnWO_4$ – scintillator under development for cryogenic application
  - ✓$CaMoO_4$ and $CdMoO_4$– material under investigation

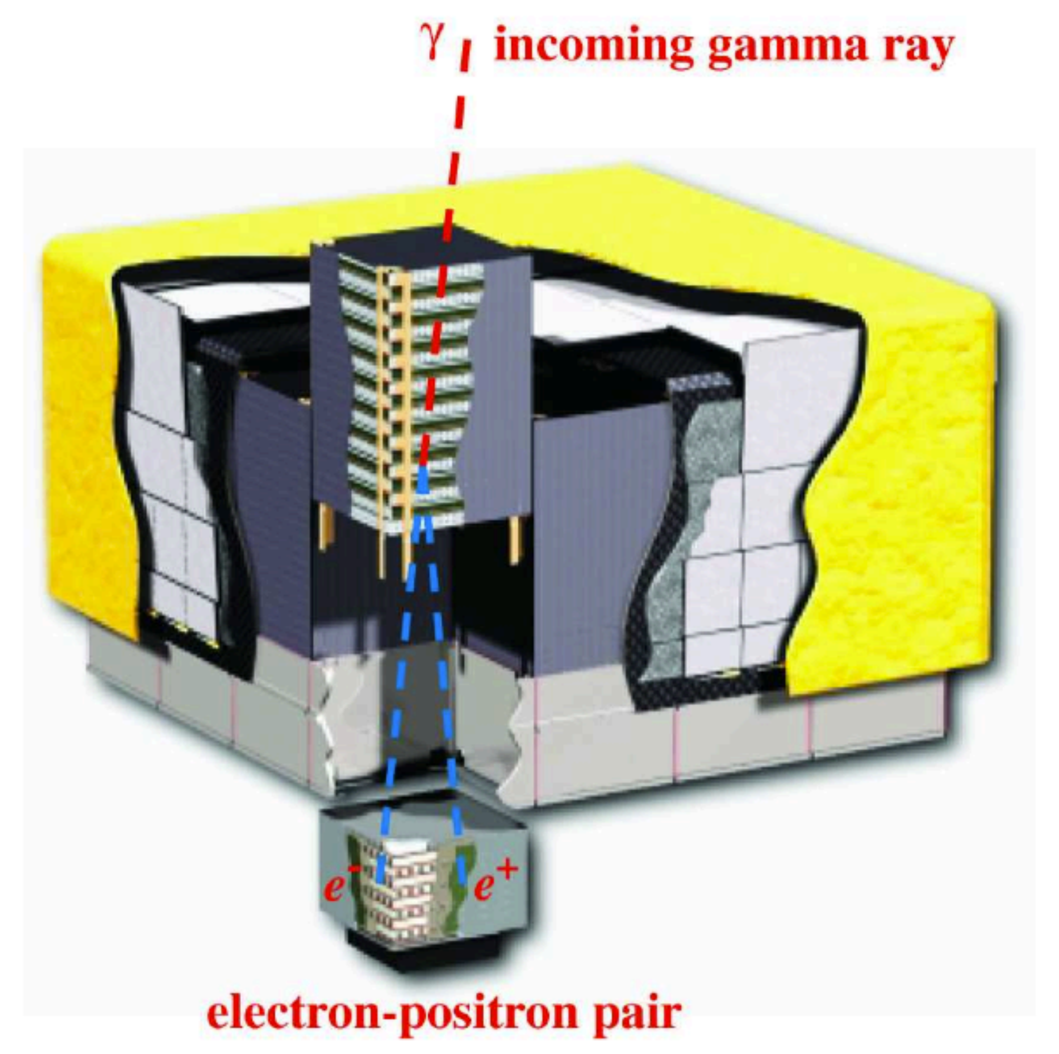
Gamma ray astronomy

Gamma rays are absorbed by the atmosphere and must be studied a satellite or balloon born observatory



Gamma ray bursts (GRB)
- are short energetic gamma bursts from distant galaxies
- allow us to see a glimpse of the most violent events universe

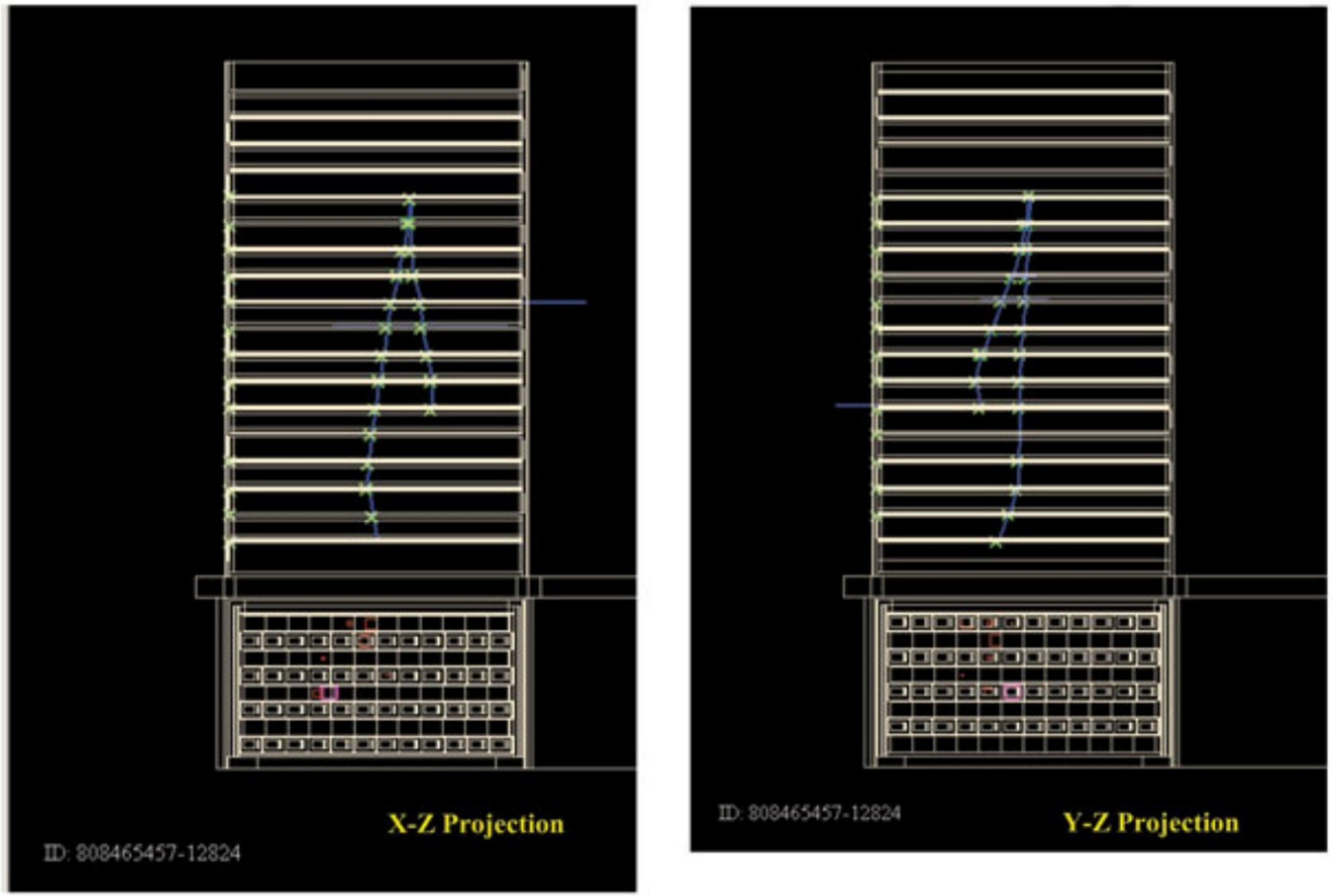
Fermi Gamma Ray Space TelescopeFGST- launched 2008



Large Area Telescope

- tunsten sheets silicon microstrip chambers
- CsI Scintillator with photodiode readout

Fermi GST- LAT, candidate gamma event



Candidate Gamma-ray Event in 1st LAT Flight Tower

Scintillators have many other applications

- Oil drilling
- Security
- Planetary exploration

Conclusion & Outlook

- This overview of instrumentation for the detection of subatomic particle is obviously incomplete. Not discussed: superconducting detectors, liquid ionisation detectors, large water or ice Cherenkov detectors etc.

- The field of particle detection is rapidly evolving, but detectors based on ionisation in gases, on ionisation in semiconductors and on scintillation are probably here to stay.

- The importance and role of electronics and software will continue to increase. Progress in micromachining and nanotechnologies will allow making types of detectors we have no idea of today.