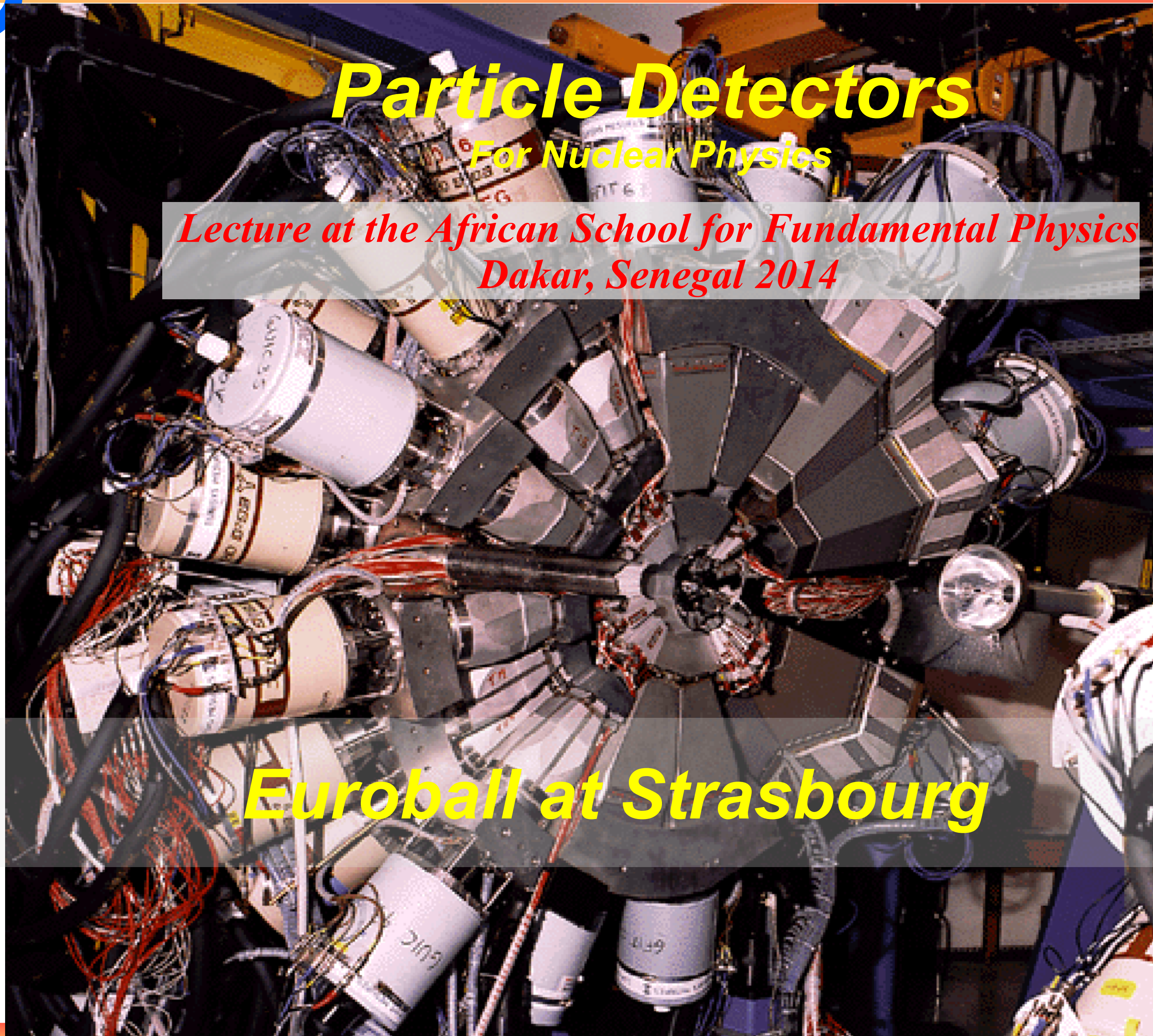
Particle Detectors

For Nuclear Physics

Lecture at the African School for Fundamental Physics
Dakar, Senegal 2014



Euroball at Strasbourg

Particle Detectors

Lecture at the African School for Fundamental Physics
Dakar, Senegal 2014

Goal of my lecture:

to understand how particle physics experiments are being built

Main focus on the example LHC

Lecture I

Lecture II

Lecture III

- **Nuclear physics detectors**
- **Scintillators**
- **Semiconductor detectors**

Exercises!!!!!

μ = 0.6 cm^{-1}

μ = 0.18 cm^{-1}

μ = 0.007 cm^{-1}

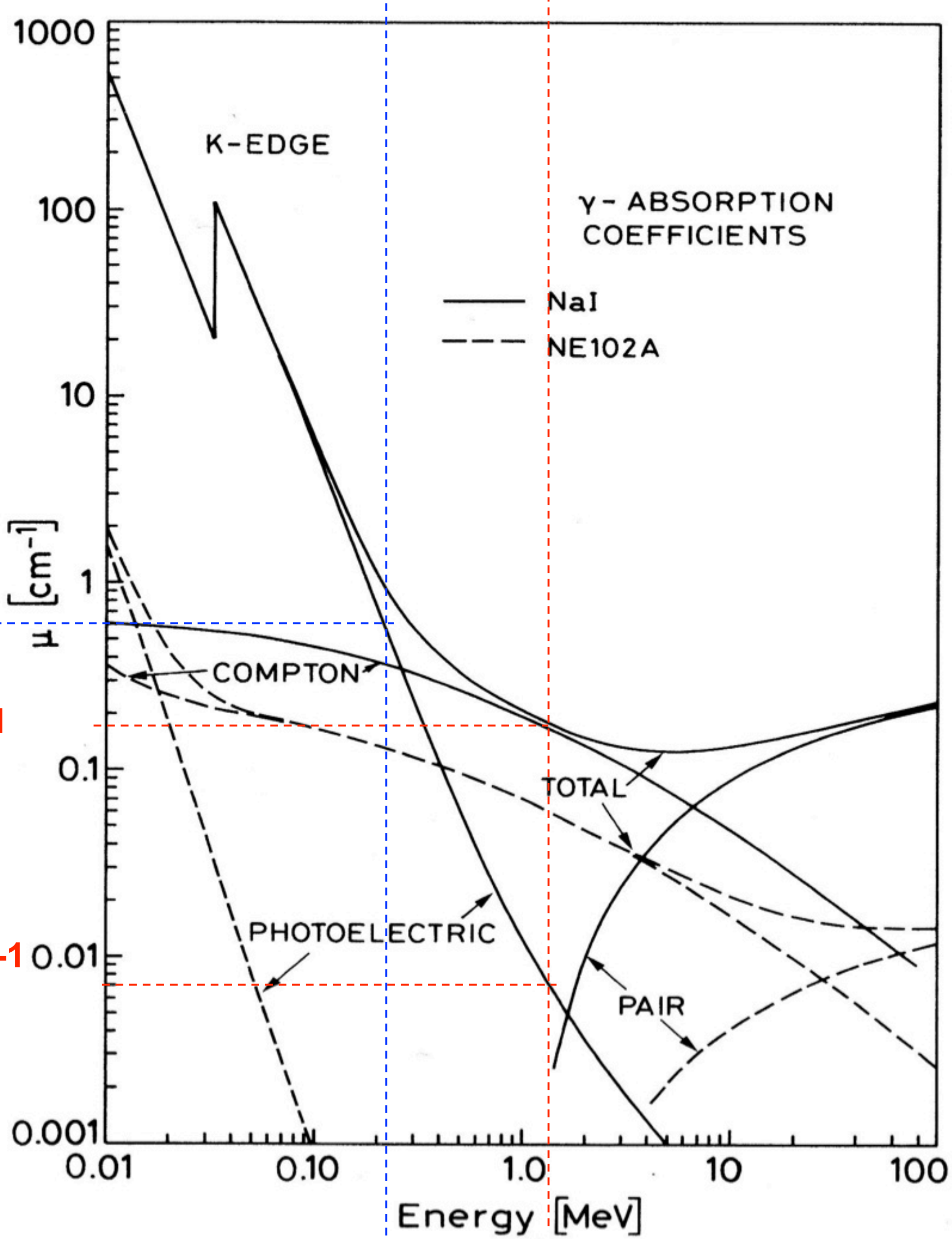


Photo-electric effect

Absorption of γ

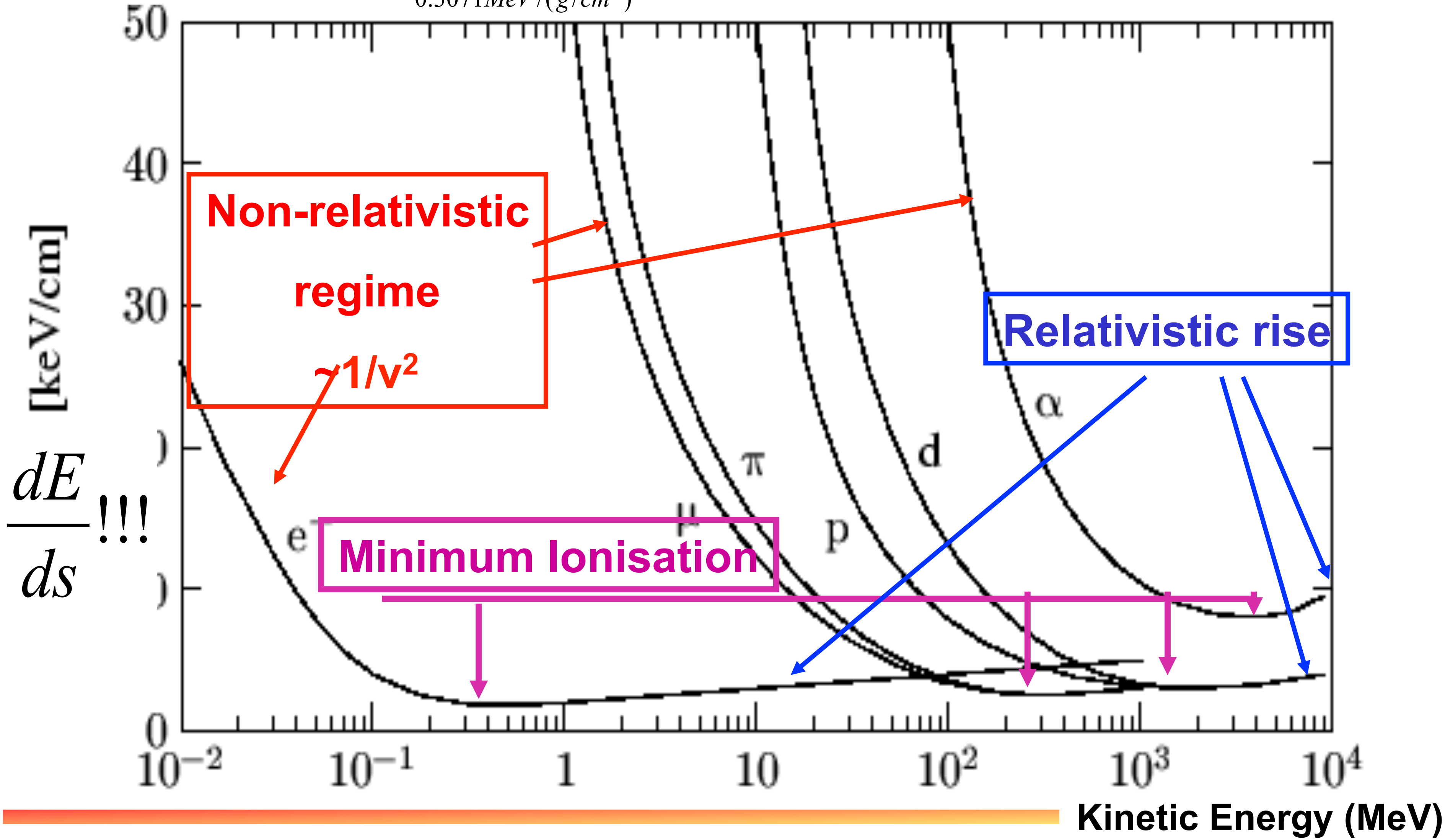
Compton scattering

scattering γ –> γ'

Creation of (e^+e^-) pairs

Absorption of γ

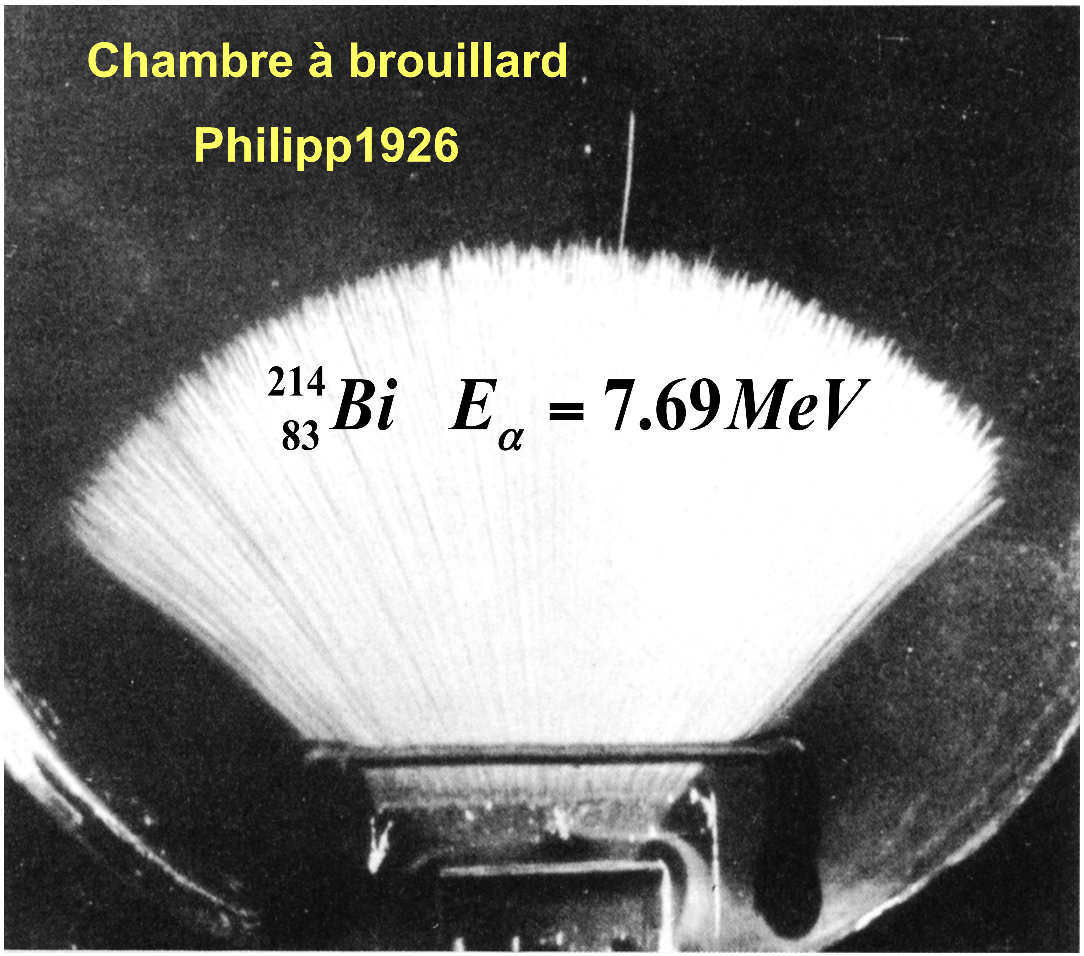
$$-\frac{1}{\rho}\frac{dE}{ds} = -\frac{dE}{dx} = \underbrace{4\pi N_{Av} r_e^2 m_e c^2}_{0.3071\,MeV/(g/cm^2)} \frac{Z}{A} z^2 \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2 \cdot T_e^{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$

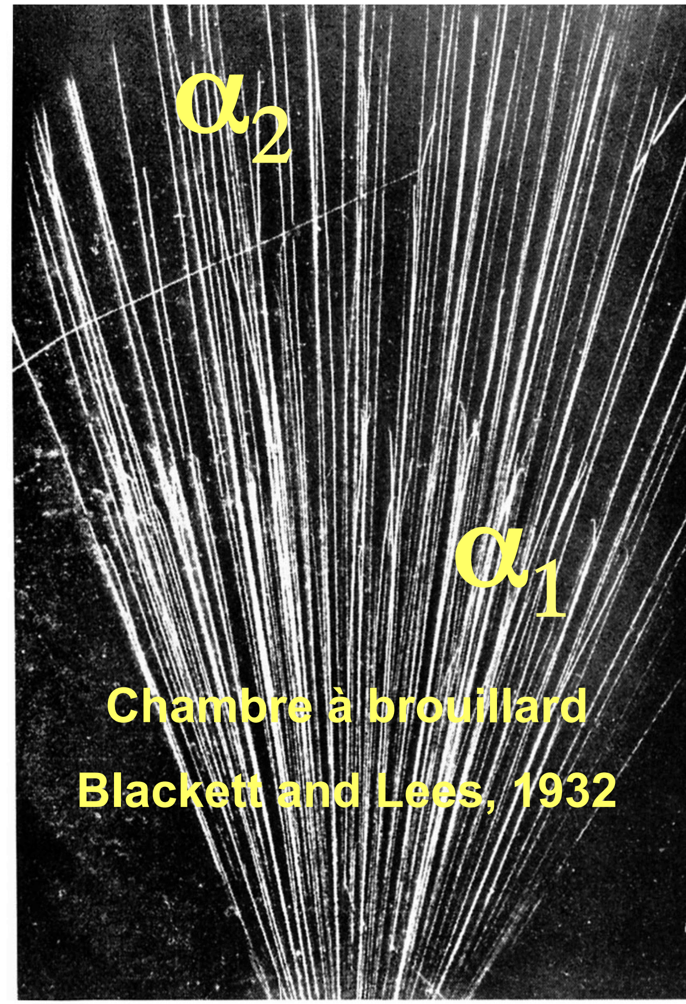


Cloud Chamber

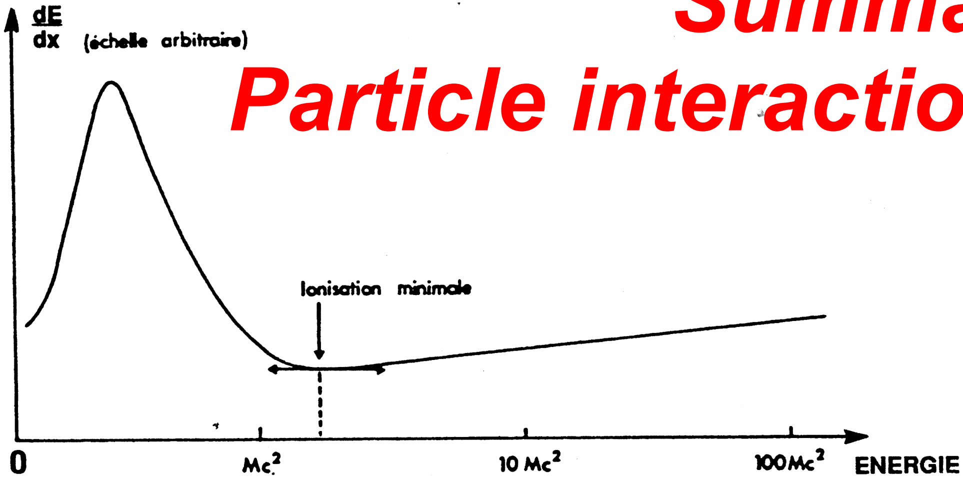
$$^{212}_{82}Pb \xrightarrow{\beta^-} {}^{212}_{83}Bi \quad E_\alpha = 6.09\,MeV$$

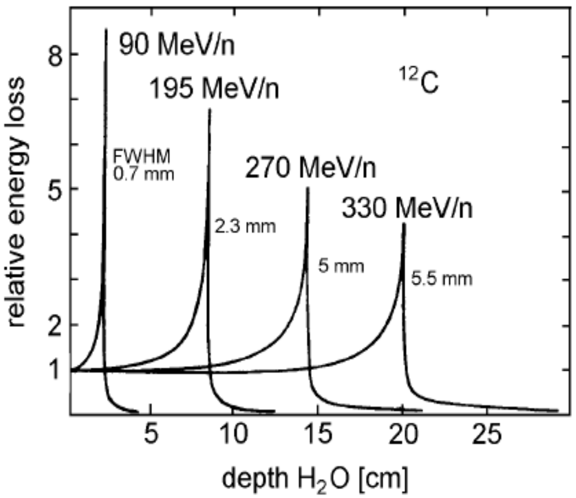
$$\xrightarrow{\beta^-} {}^{212}_{84}Po \quad E_\alpha = 8.78\,MeV$$





Summary
Particle interaction with matter





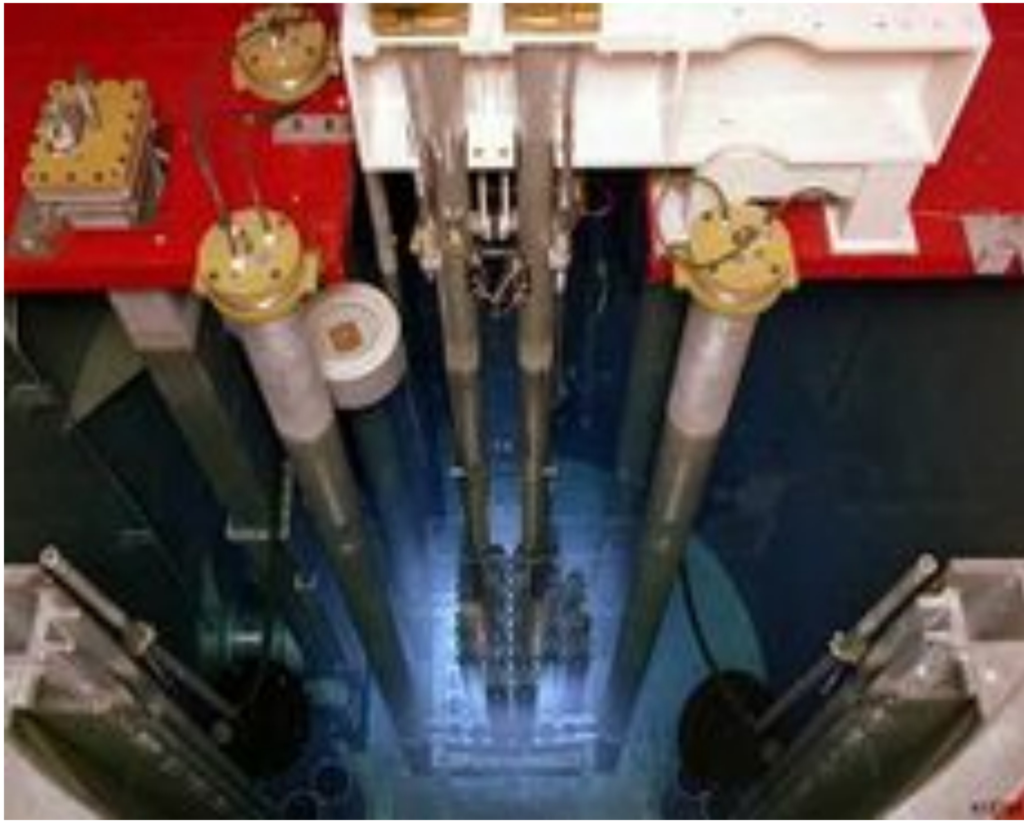
Heavy charged particles

- loose continuously kinetic energy along their path (ionization) with small fluctuations until they are stopped after a well defined distance; until that point their number remains constant and they travel on a straight line.

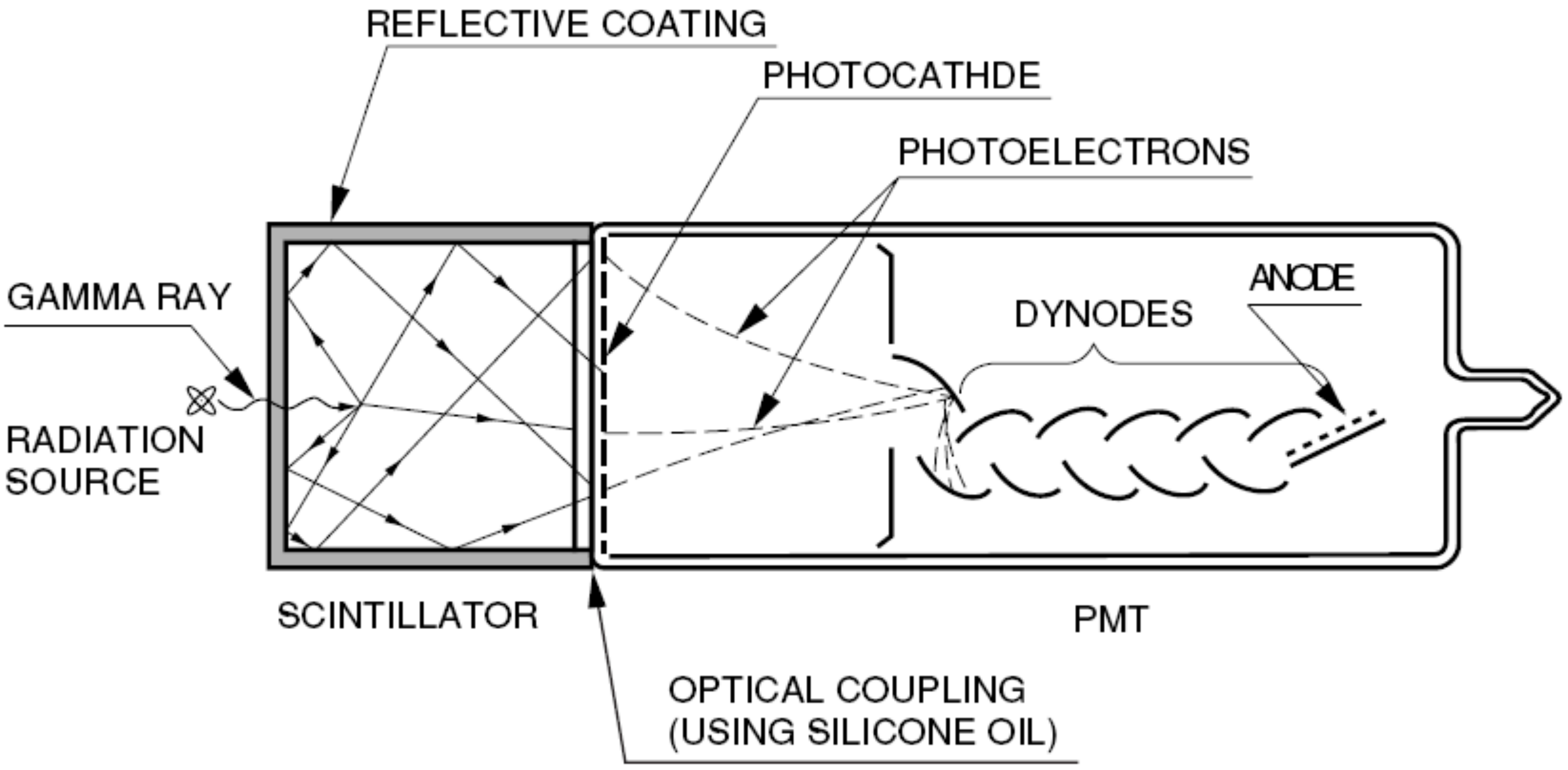
Exercise

Blue light in a reactor

1. **What produces the light?**
2. **Water n=1.333. calculate the minimal energy of an electron to produce Cerenkov light**



Photomultiplier



The gain

$$G = \eta \cdot \delta^N$$

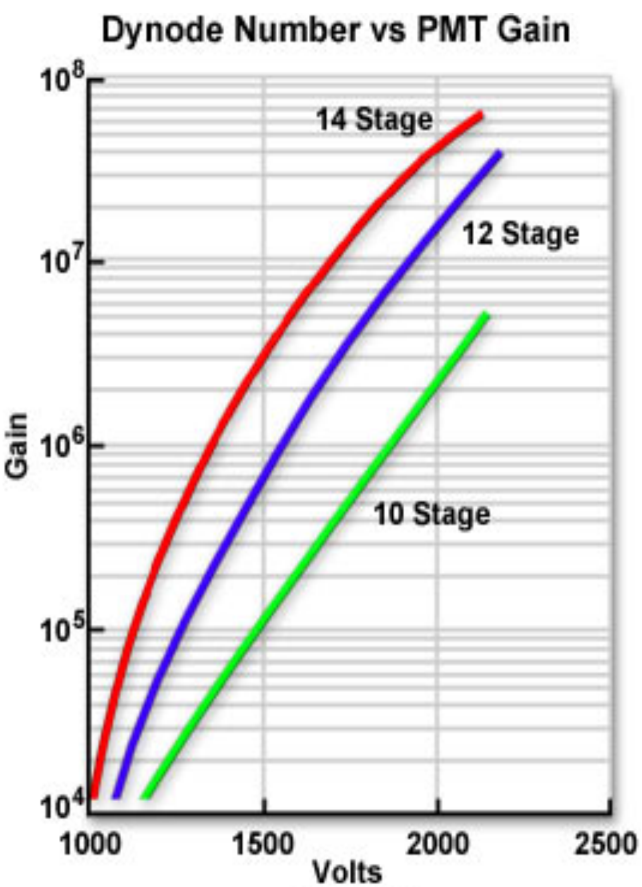
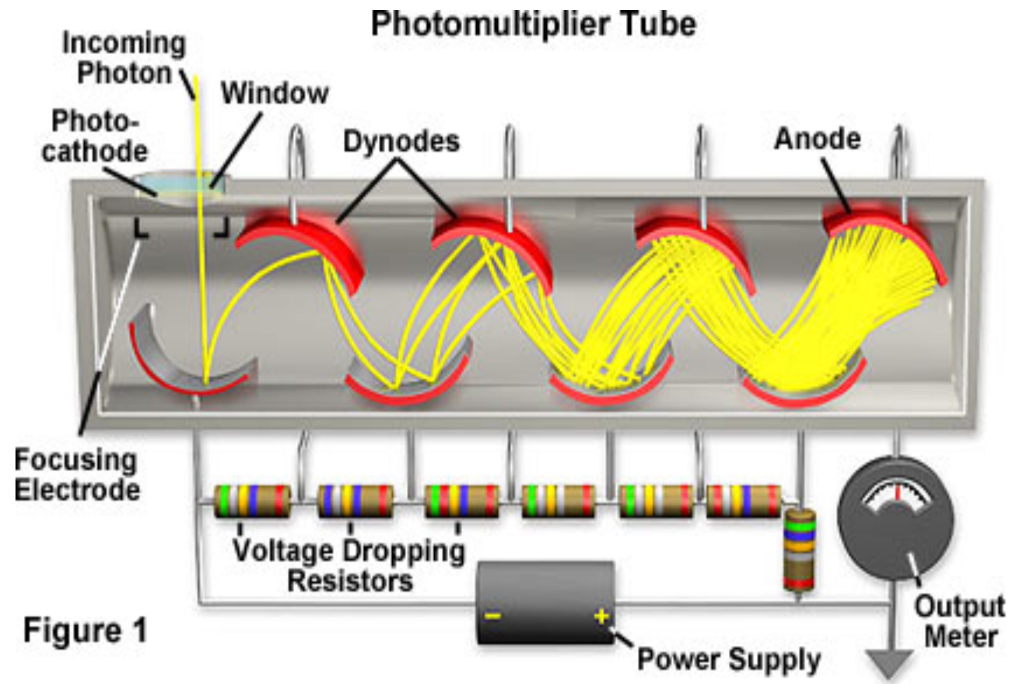
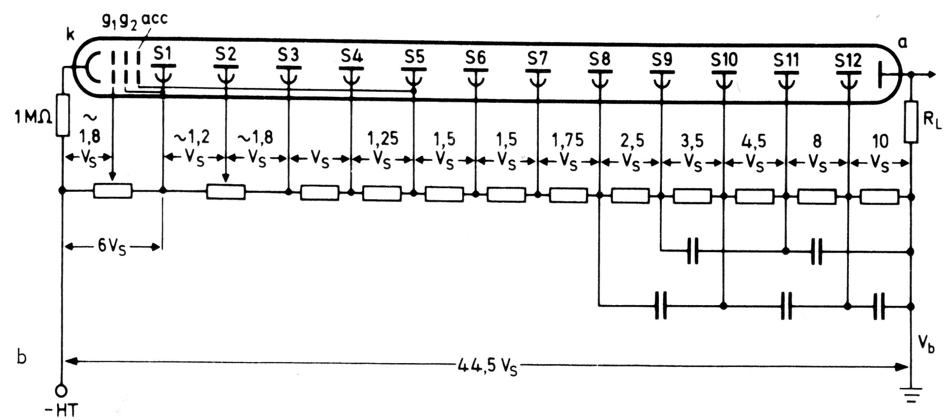


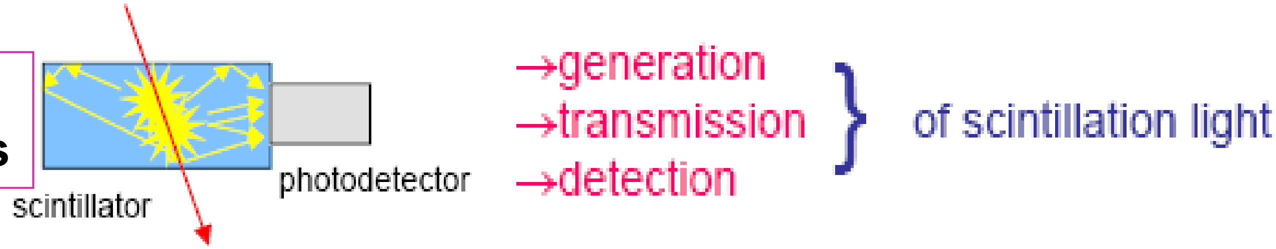
Figure 1





Scintillators

Fluorescence : < 10 ns
Phosphorescence >> 10 ns



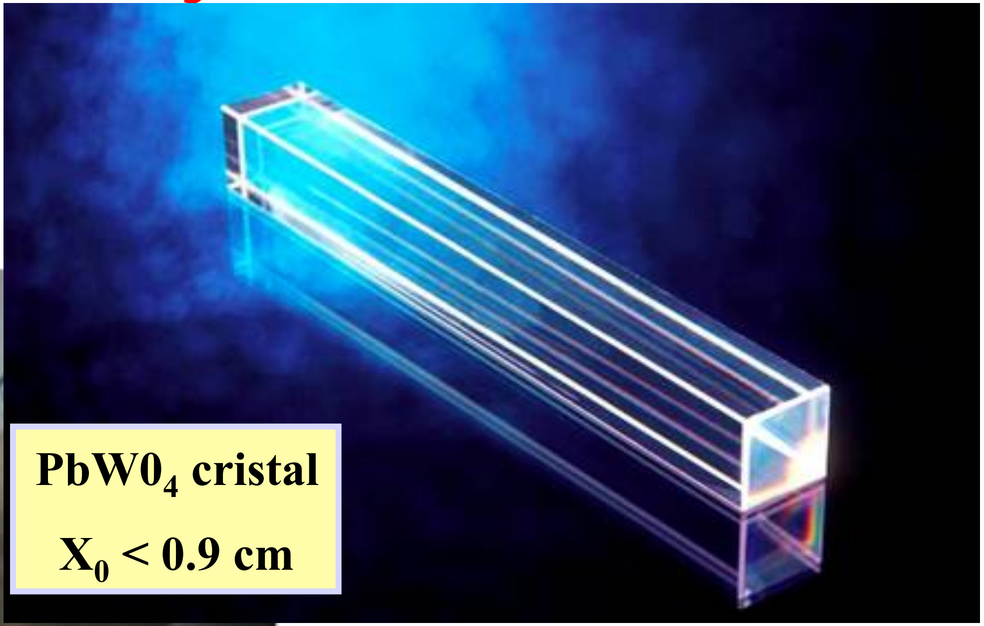
- **Inorganic Scintillators**
  Crystal structure
  - → 40 000 $h\nu$/MeV
  - High Z material,
  - High density
  - Time constants of ns - µs
  - High price!
  - ~ radiation hard

  Used for
  - Gamma detection
  - Medical imaging
  - Electromagnetic calorimeters

- **Organic scintillator**
  plastic or liquid
  - → 10 000 $h\nu$/MeV
  - low Z,
  - Low density ≈ 1g/cm^3
  - Large choice of emission spectra
  - Time constants of typically ns
  - “low” price
  - Sensitive to radiation

  Used for
  - Charged particle detection
  - TOF, Veto counters, calorimeters

Scintillator crystal



$PbW0_4$ cristal

$X_0 < 0.9$ cm

CMS

Scintillator - crystals

Three steps!
1. Absorption ⇒excitons/ionisation
2. Transfer to activator
3. Fluorescence of the activator

Excitons:

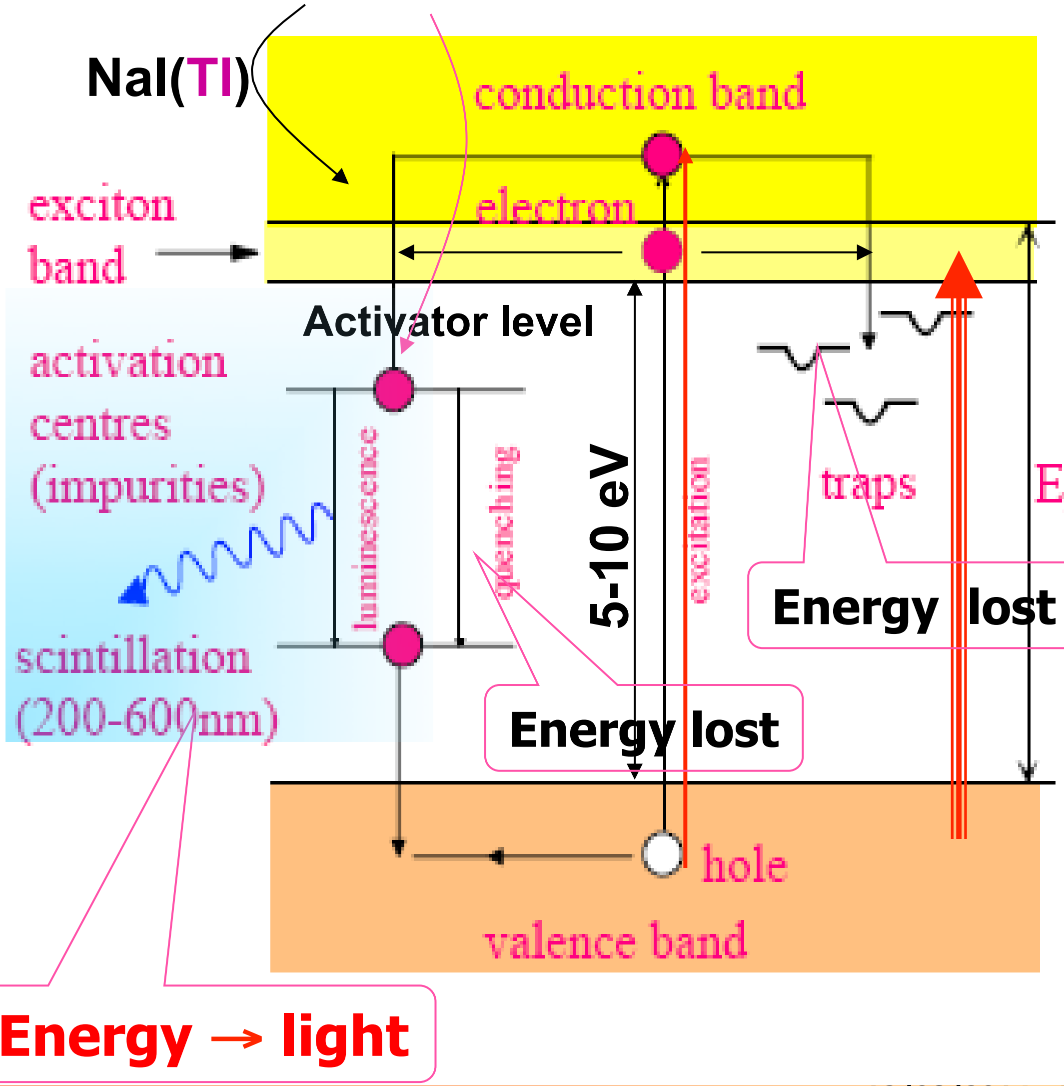
Pairs (e-,trou) (⇒ band below conduction band), but mobile within the crystal, will hit the activator atoms :

Transfer of energy

→ Excitation of activator atom

→ Radiative transition: light

→ Non-radiative transitions: vibrations (phonons) of the whole crystal, (energy loss)



Light emission of energy $E = h\nu$

$$E = h\nu < E_{gap};\ \tau_d = 0.02 - 1\ \mu s$$

$$\frac{dN(t)}{dt} = \frac{N_0}{\tau_d} \exp\left(-t/\tau_d\right)$$

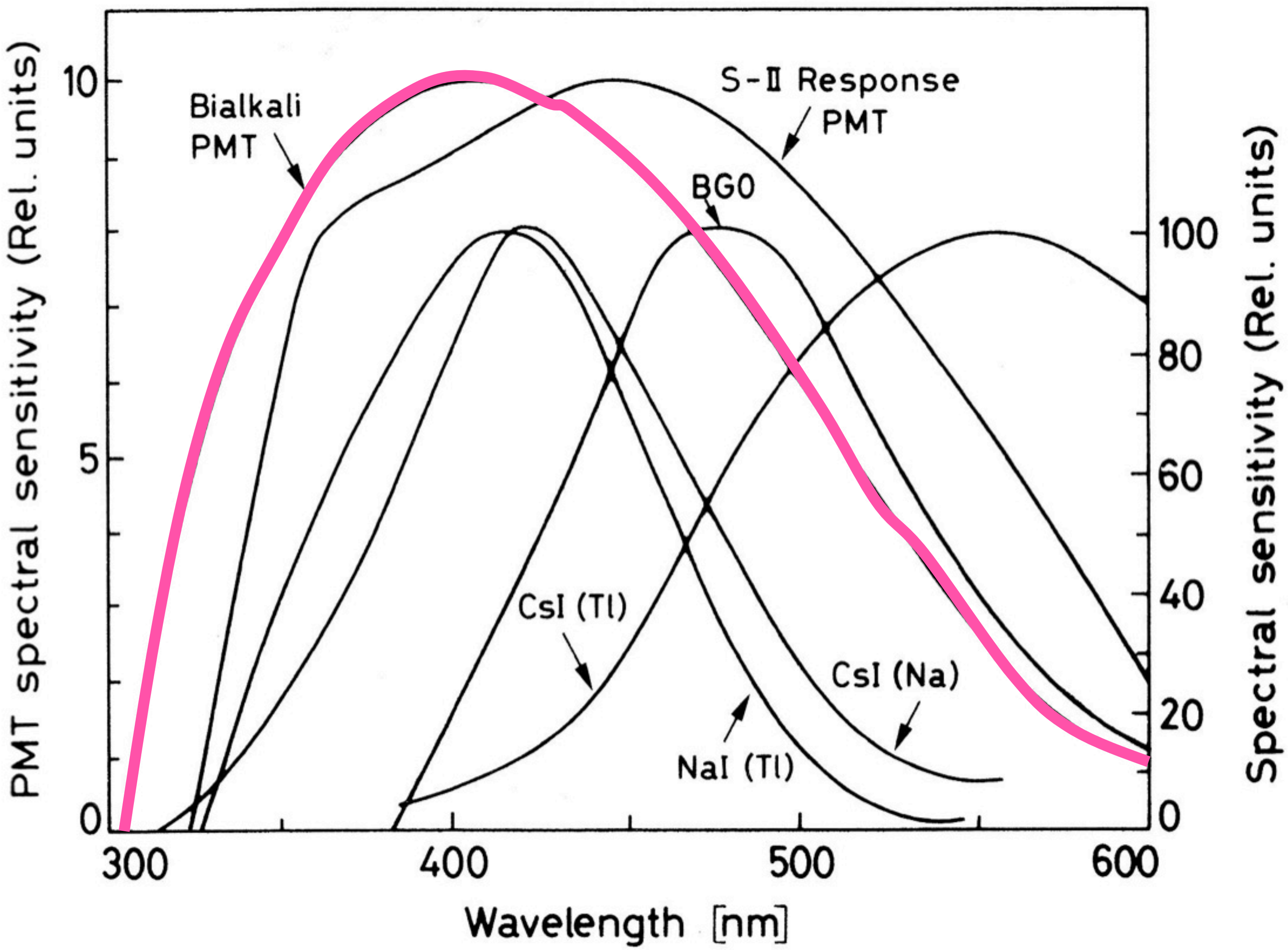
$$\lambda_{max} \approx 410 - 600\ \text{nm}$$

Summary of practical inorganic scintillator materials

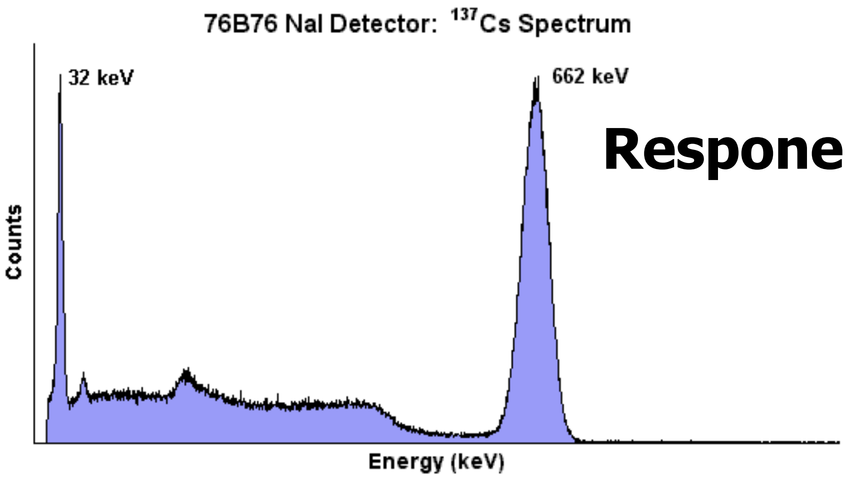
(from Derenzo)

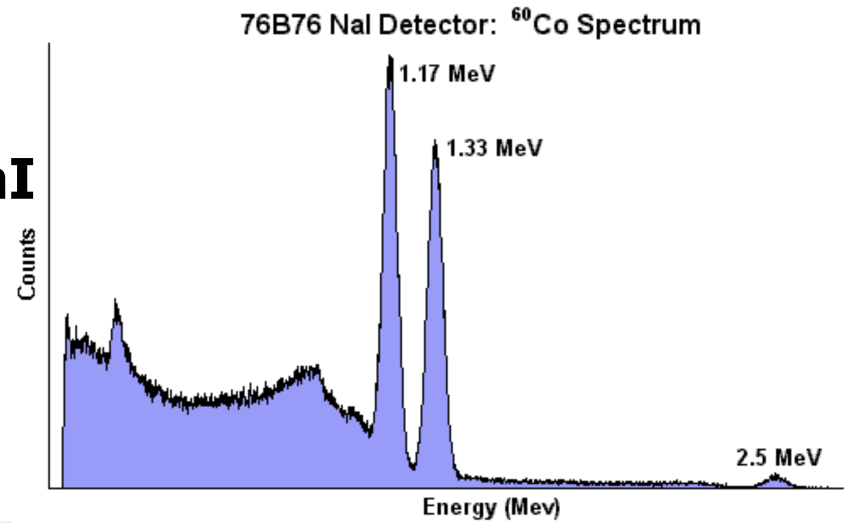
Material	Form	λ_{max} (nm)	τ_f (ns)	ρ (g/cm^3)	Photons per MeV
NaI(Tl) (20°C)	crystal	415	230	3.67	38,000
pure NaI (-196°C)	crystal	303	60	3.67	76,000
$Bi_4Ge_3O_{12}$ (20°C)	crystal	480	300	7.13	8,200
$Bi_4Ge_3O_{12}$ (-100°C)	crystal	480	2000	7.13	24,000
CsI(Na)	crystal	420	630	4.51	39,000
CsI(Tl)	crystal	540	800	4.51	60,000
CsI (pure)	crystal	315	16	4.51	2,300
CsF	crystal	390	2	4.64	2,500
BaF_2 (slow)	crystal	310	630	4.9	10,000
BaF_2 (fast)	crystal	220	0.8	4.9	1,800
Gd_2SiO_5(Ce)	crystal	440	60	6.71	10,000
$CdWO_4$	crystal	530	15000	7.9	7,000
$CaWO_4$	crystal	430	6000	6.1	6,000
CeF_3	crystal	340	27	6.16	4,400
$PbWO_4$	crystal	460	2, 10, 38	8.2	500
Lu_2SiO_5(Ce)	crystal	420	40	7.4	30,000
$YAlO_3$(Ce)	crystal	390	31	5.35	19,700
Y_2SiO_5(Ce)	crystal	420	70	2.70	45,000

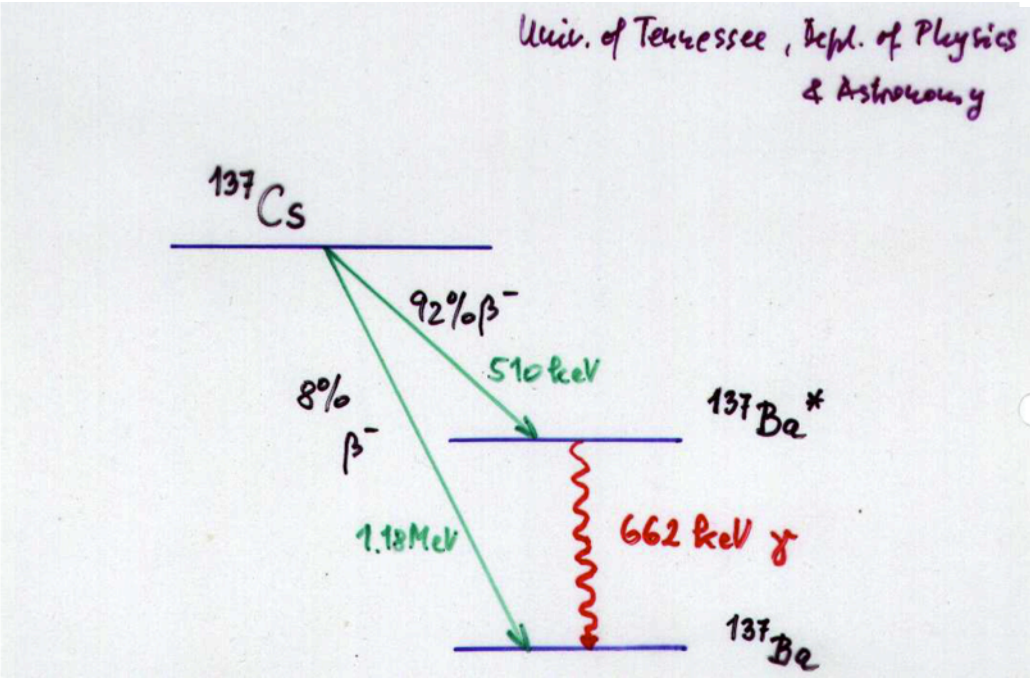
Emission spectra of inorganic scintillators

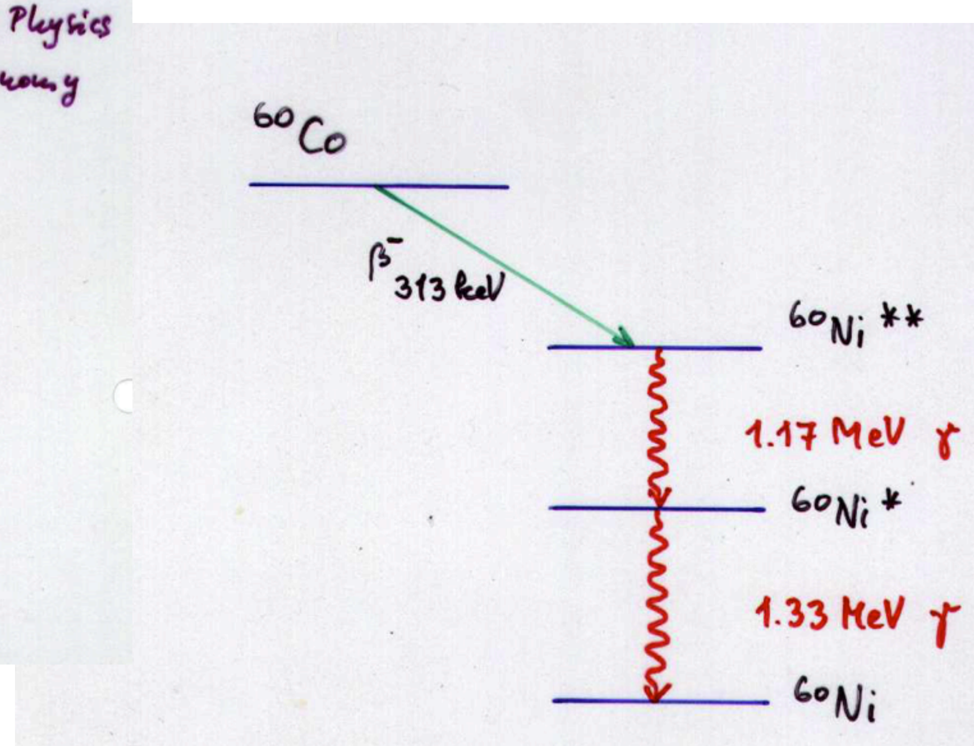


Respone of NaI





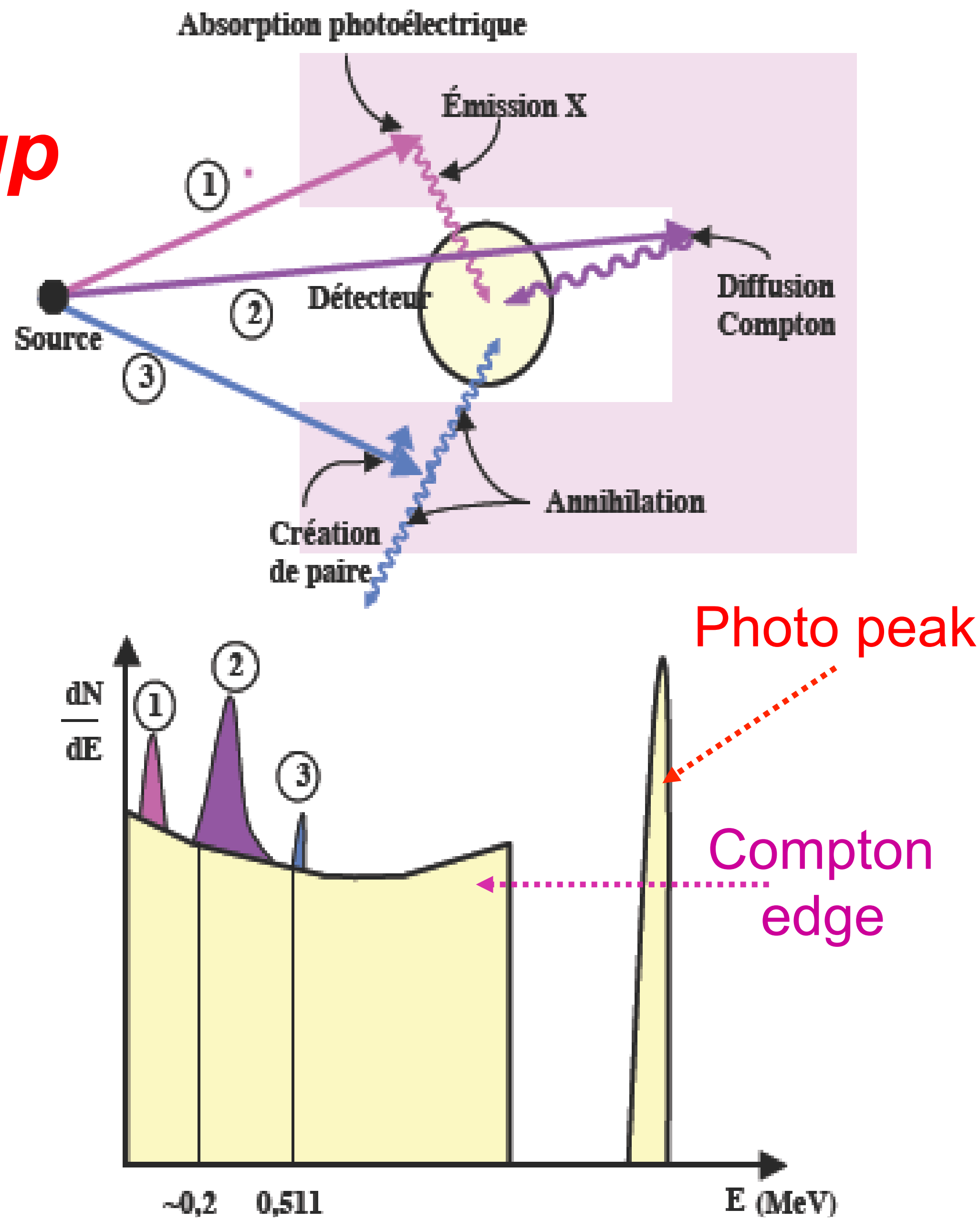




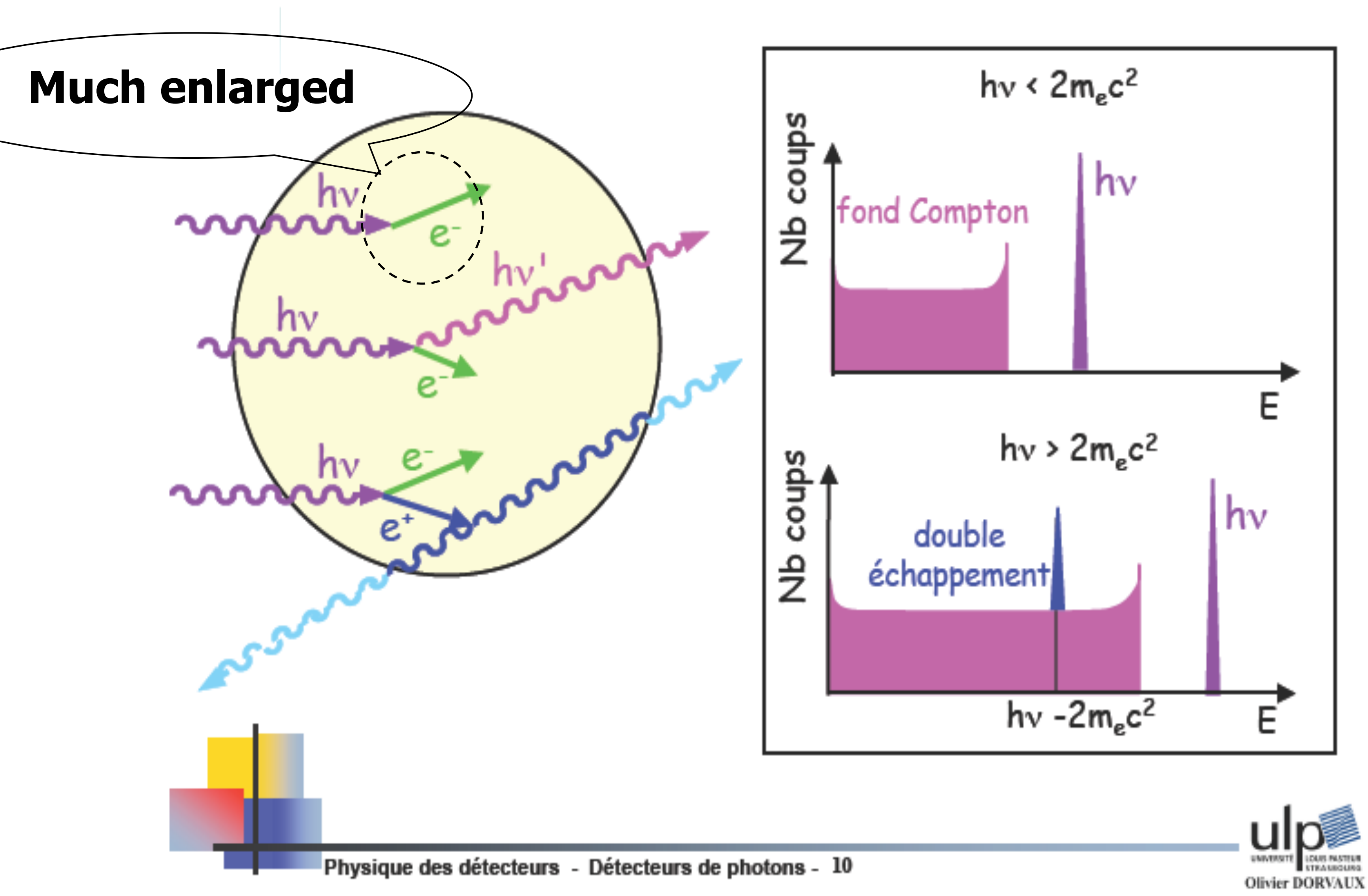
Real detector set up

Material around :

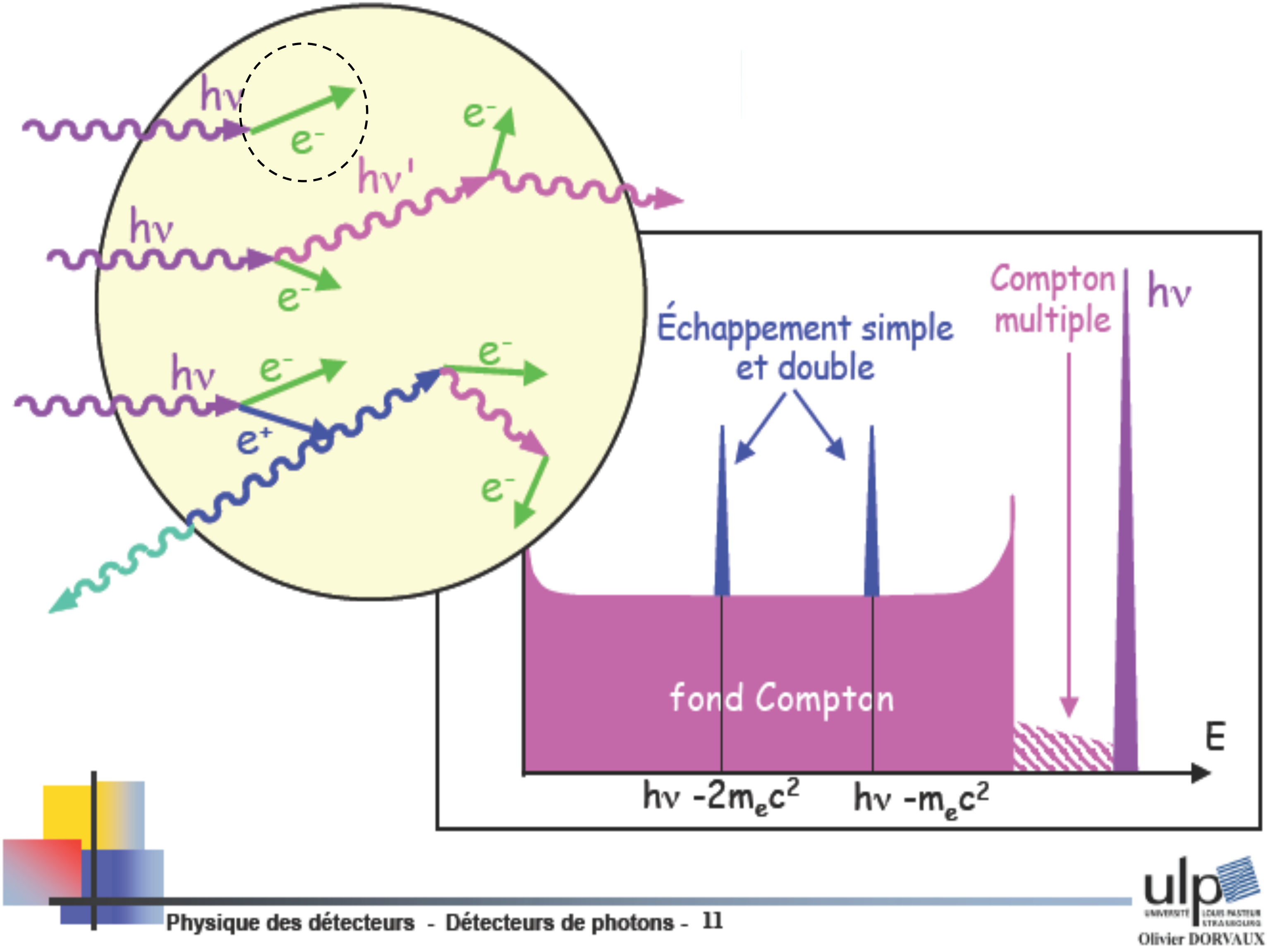
- Generation of X-rays
- Retrodiffusion Compton
- Radiation from annihilation



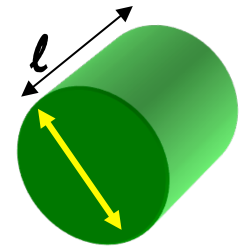
Energy distribution in a photon detector



Energy distribution in a photon detector



NaI (Tl)



- Reference/standard of efficiency: $\varepsilon = 1{,}22 \times 10^{-3}$
  - Cylindrical detector NaI(Tl), 7,62(∅) x 7,62(ℓ) cm^3
  - Source of ^{60}Co (1,33 MeV) at 25 cm

Properties of NaI:

- Z = 53 high ⇒ good efficiency
- Relatively short decay time (230 ns)
- intense signal
- Relative good energy resolution
- But NaI is very hygroscopic!!

Exercise : verify efficiency!

Efficiency of a detector

(valid in general!!)

- **Absolute or total efficiency**

$$\varepsilon_{tot} = \frac{\left(\text{particles or gammas}\right)\ \text{registered}}{\left(\text{particles or gammas}\right)\ \text{emmitted}}$$

  - This depends on the geometry between the source and the detector (its distance and opening, its solid angle)

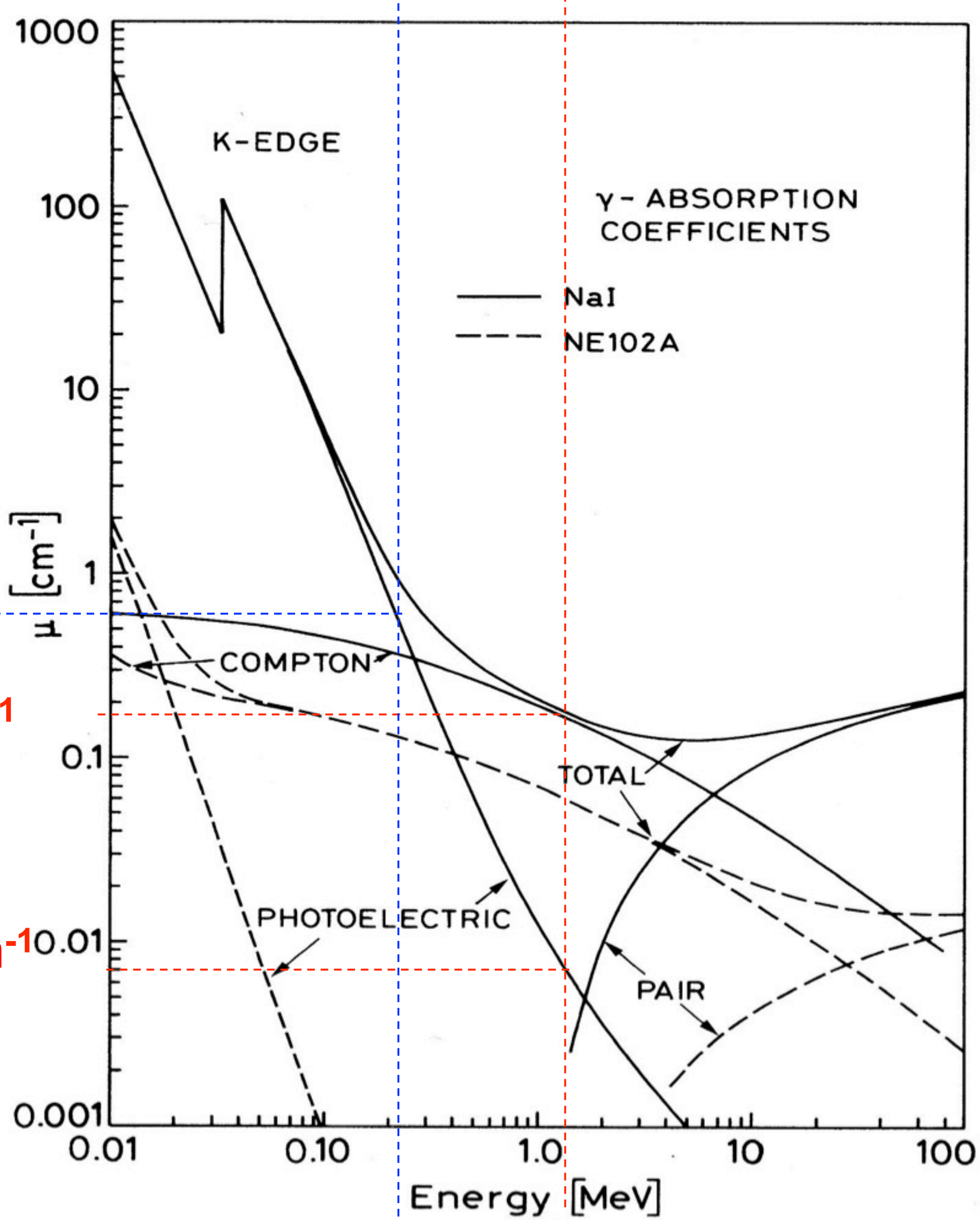
$$\varepsilon_{tot} = \underbrace{\left[1-\exp\left(\frac{-S_p}{\lambda}\right)\right]}_{\text{probability of an interaction}} \times \underbrace{\frac{\Delta\Omega}{4\pi}}_{\text{probability of an emmission in the solid angle of the detector}}$$

$$\varepsilon_{tot} \cong \varepsilon_{\text{int}} \times \varepsilon_{geom}$$

$$\lambda = \text{attenuation length; } \left\{\frac{1}{\lambda} = \sigma \cdot n_b\right\};\ S_p = \text{Depth of the detector}$$

- **Intrinsic efficiency**

$$\varepsilon_{\text{int}} = \frac{\left(\text{particles or gammas}\right)\ \text{"registered"}}{\left(\text{particles or gammas}\right)\ \text{in the acceptance of the detector}}$$



μ = 0.6 cm^{-1}

μ = 0.18 cm^{-1}

μ = 0.007 cm^{-1}

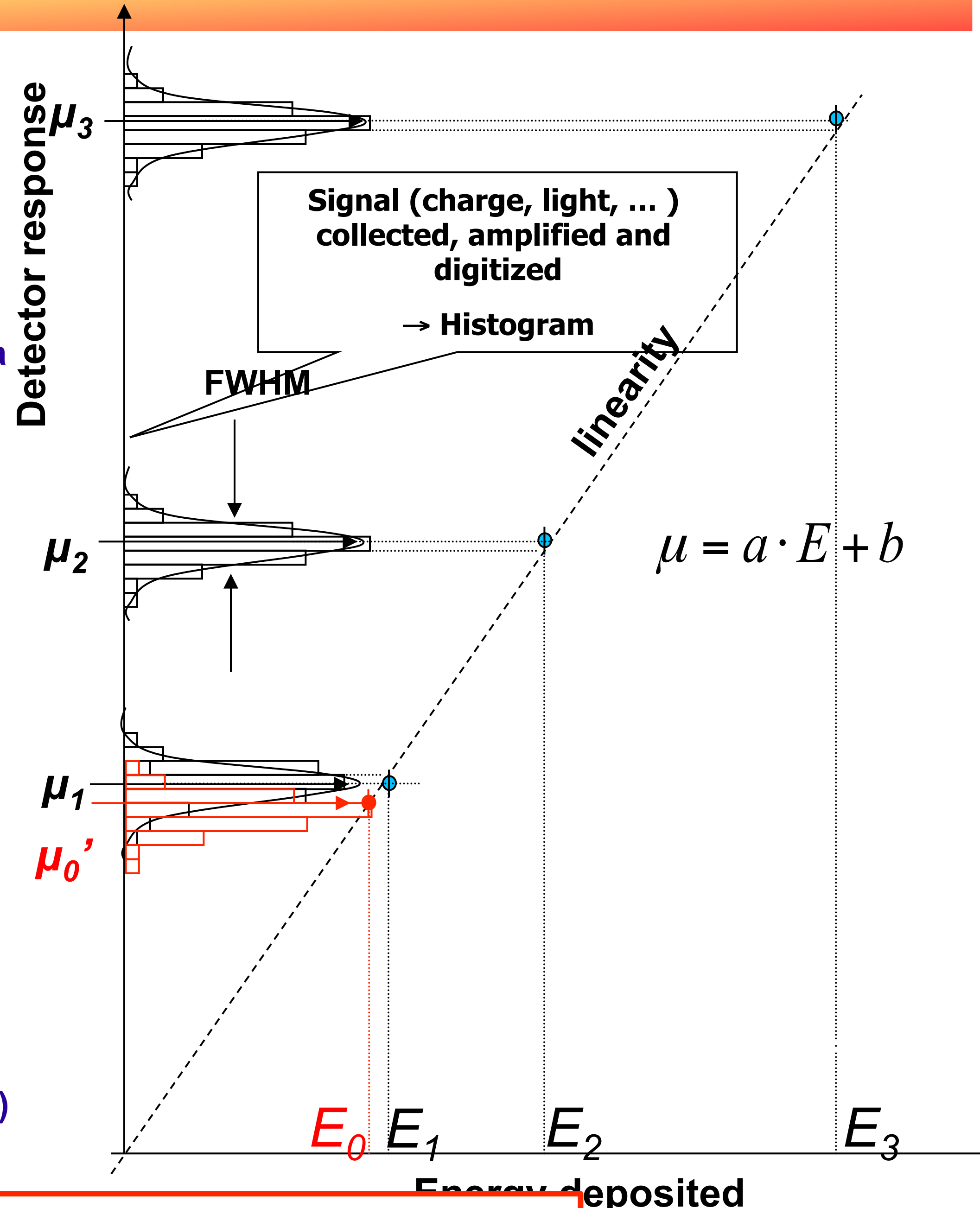
Energy Resolution

Detector response :

- For a fixed energy the detector will respond each time slightly different (also around the photo peak)
- All measurements will be distributed around a mean value with a certain width
- This distribution can be approximated by a Gaussian with
  - Mean μ and
  - A width FWHM
- The resolution *R* is defined by

$$R := \frac{\mathrm{FWHM}}{\mu} = 2.35\frac{\sigma}{\mu}$$

μ, σ^2 = mean and variance of the distribution



However, please note :

very often people talk about the resolution of their detector and what they (including myself) really mean or quote is σ / μ and NOT "*R*"

You cannot distinguish two energies closer than the FWHM

Gaussien or normal distribution

±1σ = 68.3% confidence level

±2σ = 95.5%

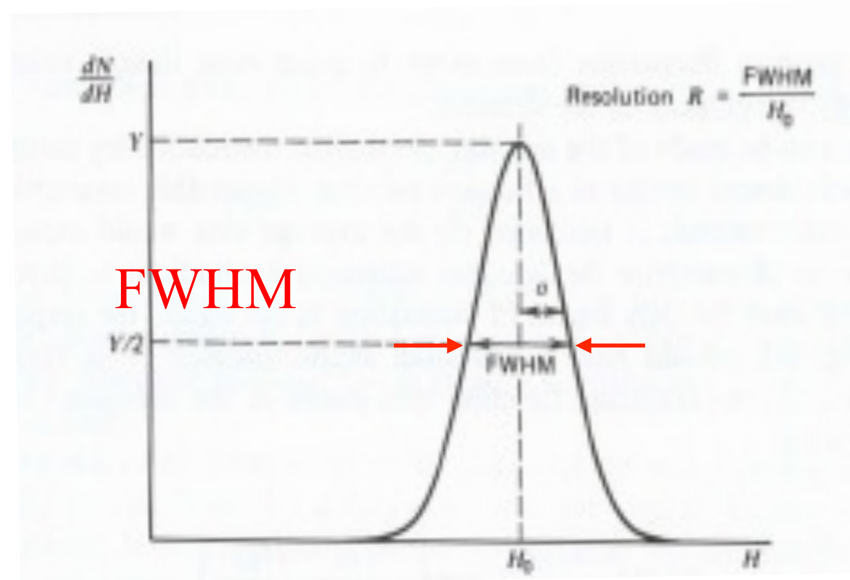
±3σ = 99.7%

$$P(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right);$$

μ = *mean*

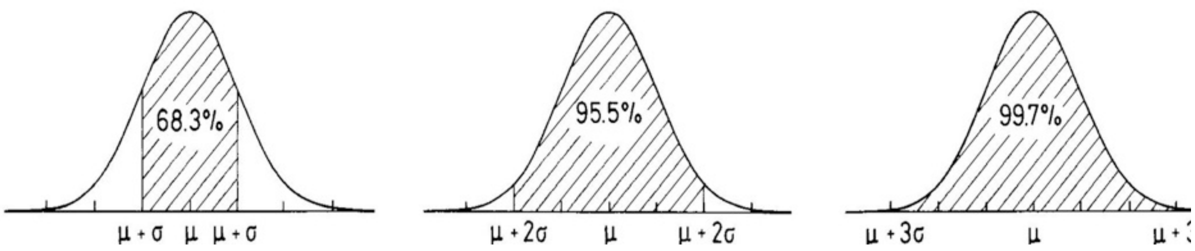
σ^2 = variance;

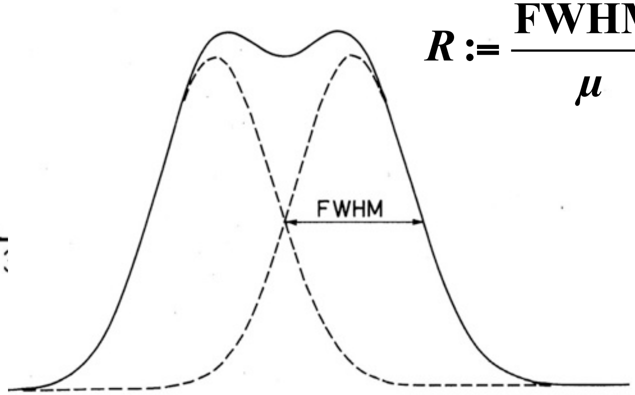
FWHM =2.35 σ



Resolution

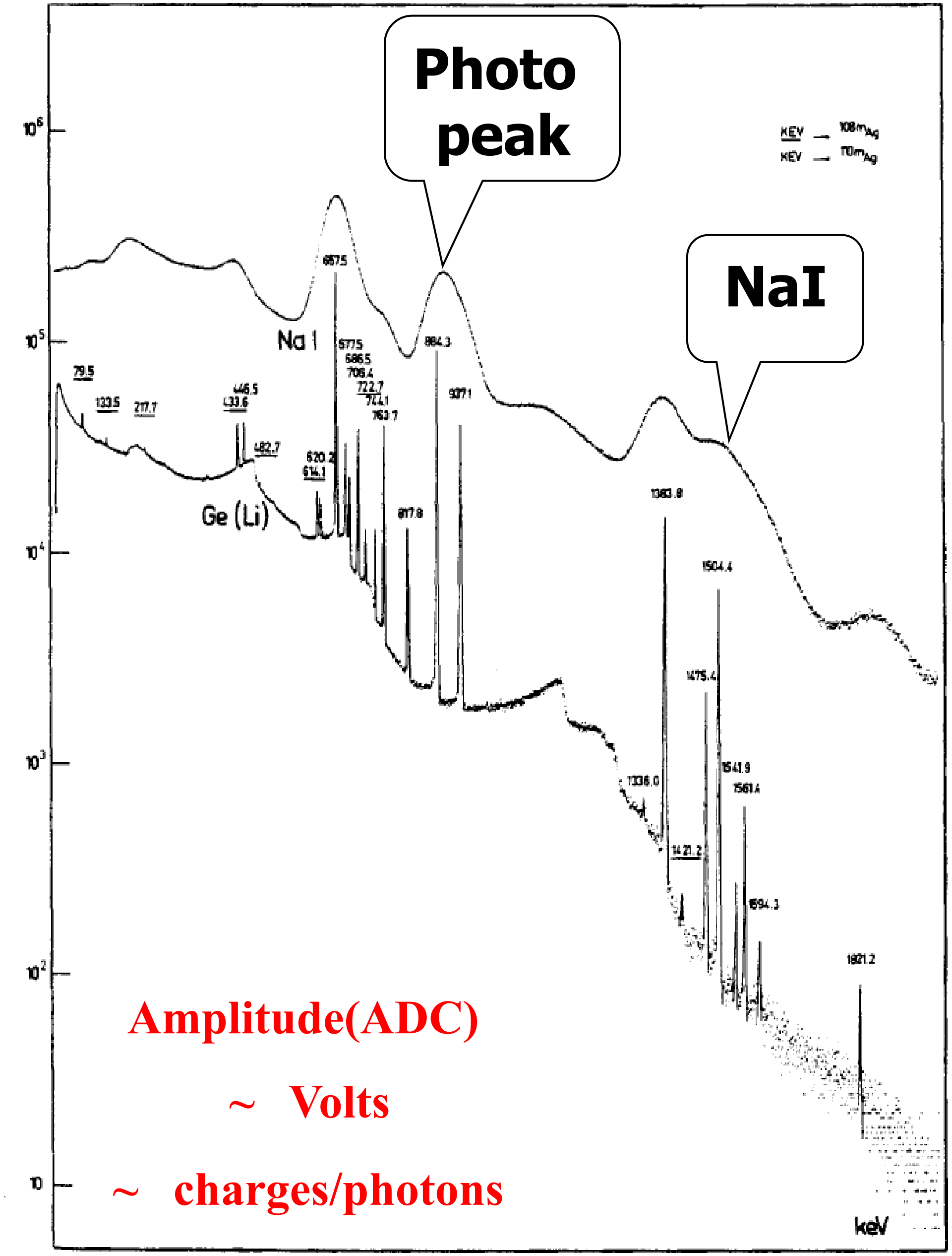
$$R := \frac{\text{FWHM}}{\mu}$$





Impossible to separate two signals closer than FWHM

Resolution



Amplitude(ADC)

~ Volts

~ charges/photons

~ energy of gamma

$$N_{h\nu} = \frac{E}{w};\ dN_{h\nu} = \sqrt{N_{h\nu}} = \sqrt{\frac{E}{w}}$$

Statistics strictly Poisson $\Rightarrow \sigma^2 = \mu$;

$$dE/E = dN_{h\nu}/N_{h\nu} \sim \frac{1}{\sqrt{N_{h\nu}}}$$

$NaI: w \approx 25\,eV/photon_{scint} \Rightarrow 40000\,h\nu/MeV$

Incomplete collection of scintillation photons and finite quantum efficiency will reduce the mean number of photo-electrons

$$N_{pe} = N_{h\nu} \times \varepsilon_{collection} \cdot \varepsilon_{quantic};$$

$$dN_{pe} = \sqrt{N_{pe}} = \sqrt{N_{h\nu} \times \varepsilon_{coll.} \cdot \varepsilon_{quant.}}$$

$$\varepsilon_{coll.} \approx 0.2 - 0.8;\ \varepsilon_{quant.} \approx 0.2\,(PM)$$

$$dE/E = dN_{pe}/N_{pe} \cong \frac{1}{\sqrt{N_{pe}}} = \frac{1}{\sqrt{N_{h\nu} \times \varepsilon_{coll.} \cdot \varepsilon_{quant.}}}$$

$$F \approx 1;\ \varepsilon_{coll.} \approx 0.4;\ \varepsilon_{quant.} \approx 0.2\,(PM)$$

$\Rightarrow dE/E = \sigma_E/E \approx 1.5\%$ à $1.333\ MeV$

$R = 2.35 \times 1.5\% = 3.6\% \xrightarrow{\text{experimental}} (5-8)\%$

Organic scintillators

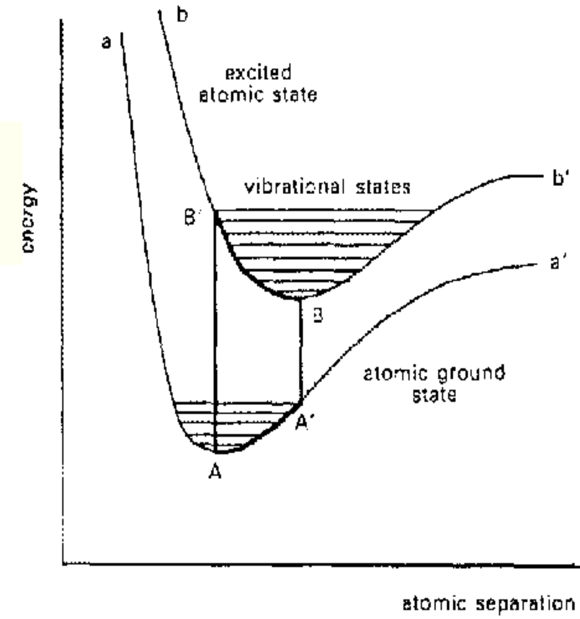
- Liquids and plastics
- Solvent which absorbs the energy
- The excitation energy of the solvent is transferred to the dopant
- Emission, reabsorption and re-emission of light
- Shift towards longer wave lengths
- Fast response, about 5ns
- Liquids :
  - Solvents liquids: xylene, tolene,benzene,phenylcyclohexane,triethylbenzene,decaline
  - Dopants for liquids: p-Terphenyl ($C_{18}H_{14}$), PBD($C_{20}H_{14}N_2O$), PPO($C_{15}H_{11}NO$), POPOP($C_{24}H_{16}N_2O_2$), ≈ 3g/l
- Solids:
  - Solvents plastics polyvinyltoluene, polyphenilbenzene, polystyrene.
  - Primary dopants for plastics : PBD, p-Terphenyl, PBO, 10g/l
  - Secondary dopant POPOP to shift the light to longer wavelengths.
- Quality depends largely on low level of impurities

Organic Scintillators

fluorescence

Prompt emission.

- fluorescence (durée ~ ns-μs)
- phosphorescence (durée ~ μs-min)

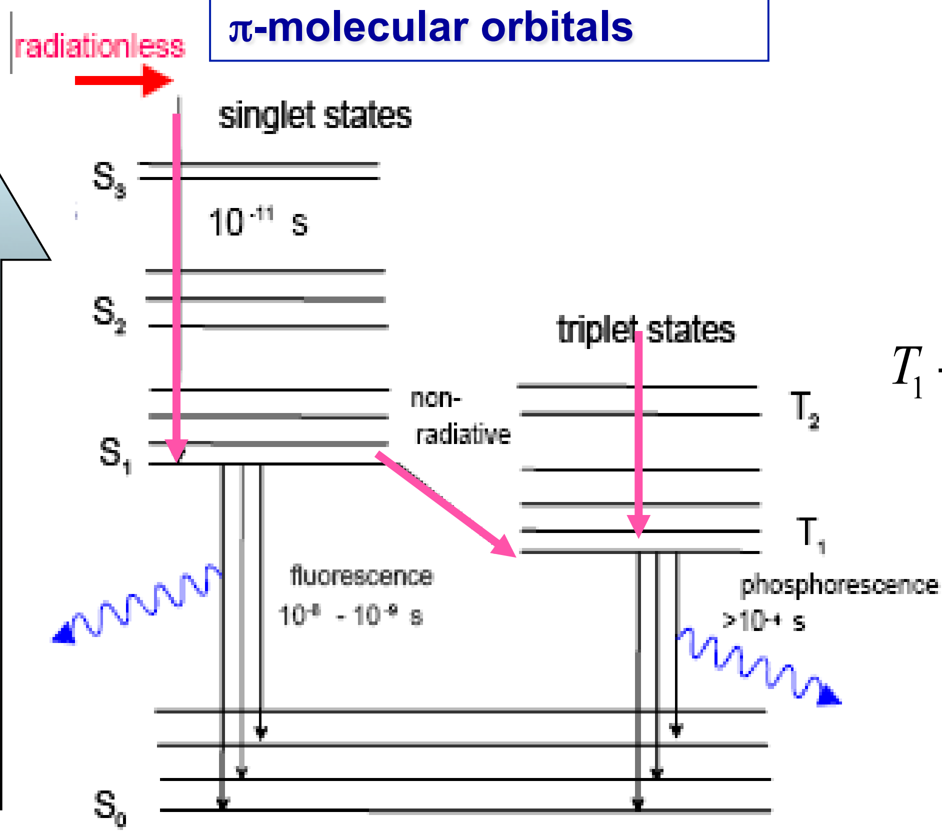


Valence electrons of the π-molecular orbitals

Radiation less transitions

(Förster)

The energy absorbed by the solvent is transferred to the dopant without radiation



$$T_1 + T_1 \rightarrow S_0 + S_1 + phonons$$

Phosphorescence : Slow emission

Organic Scintillators

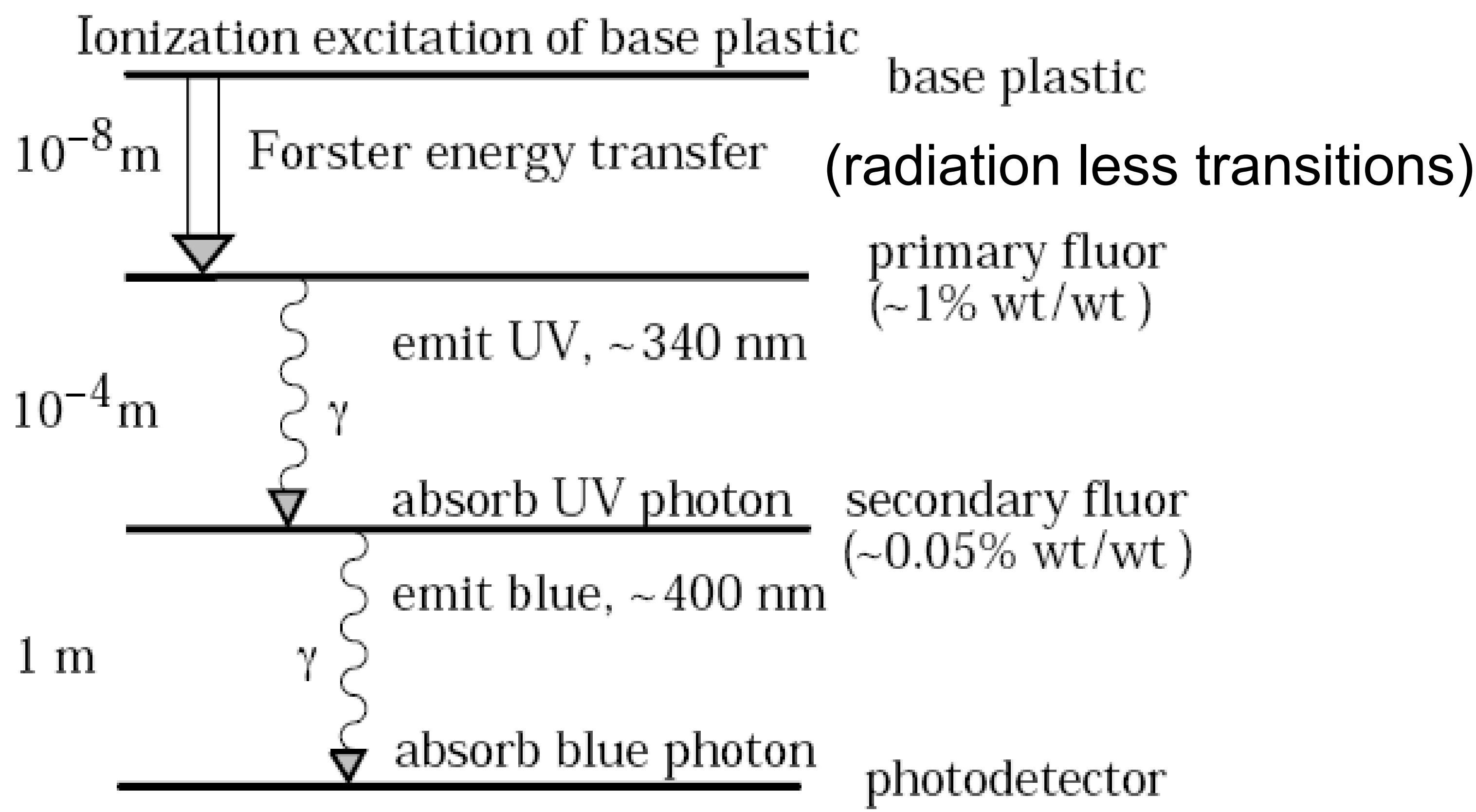
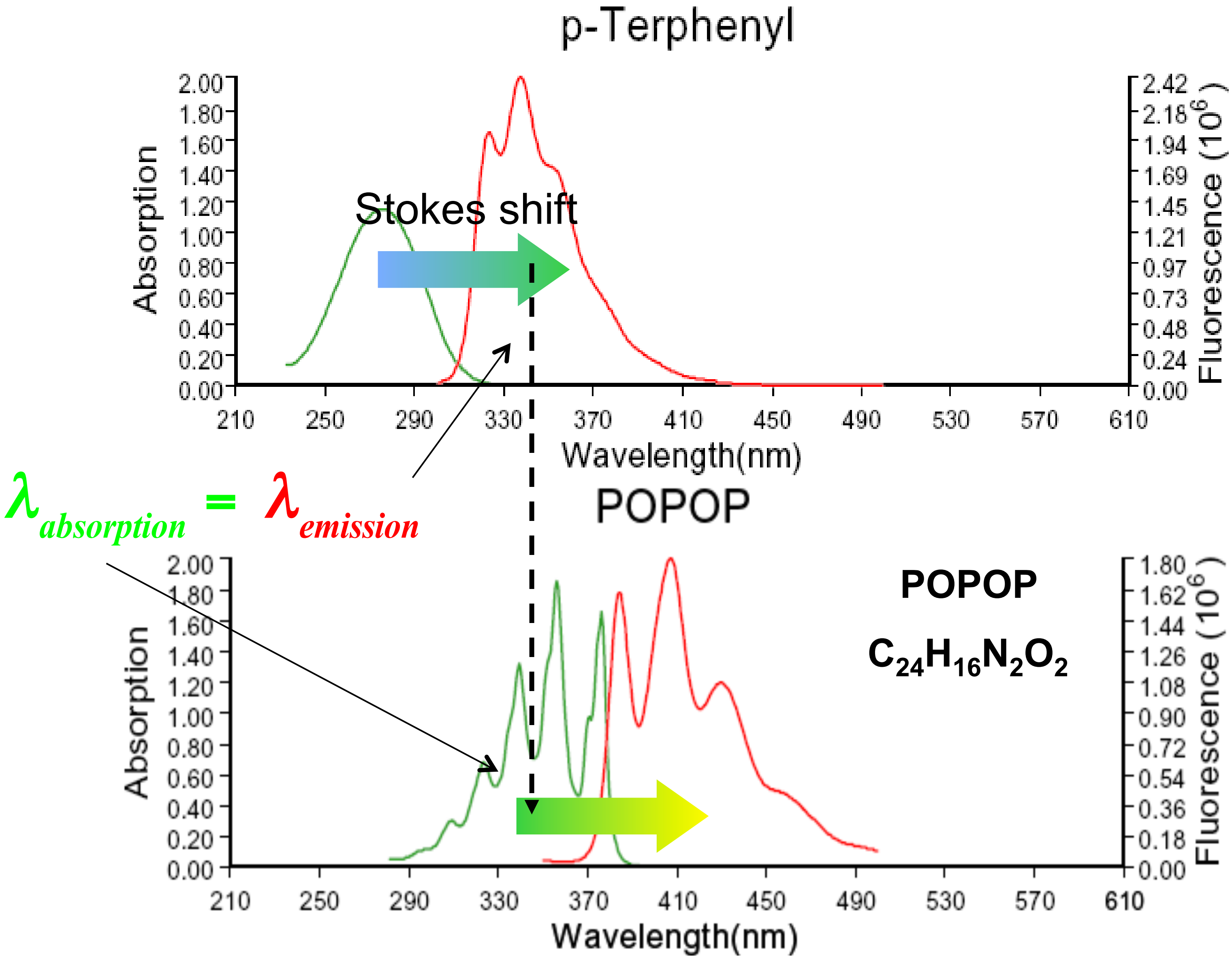
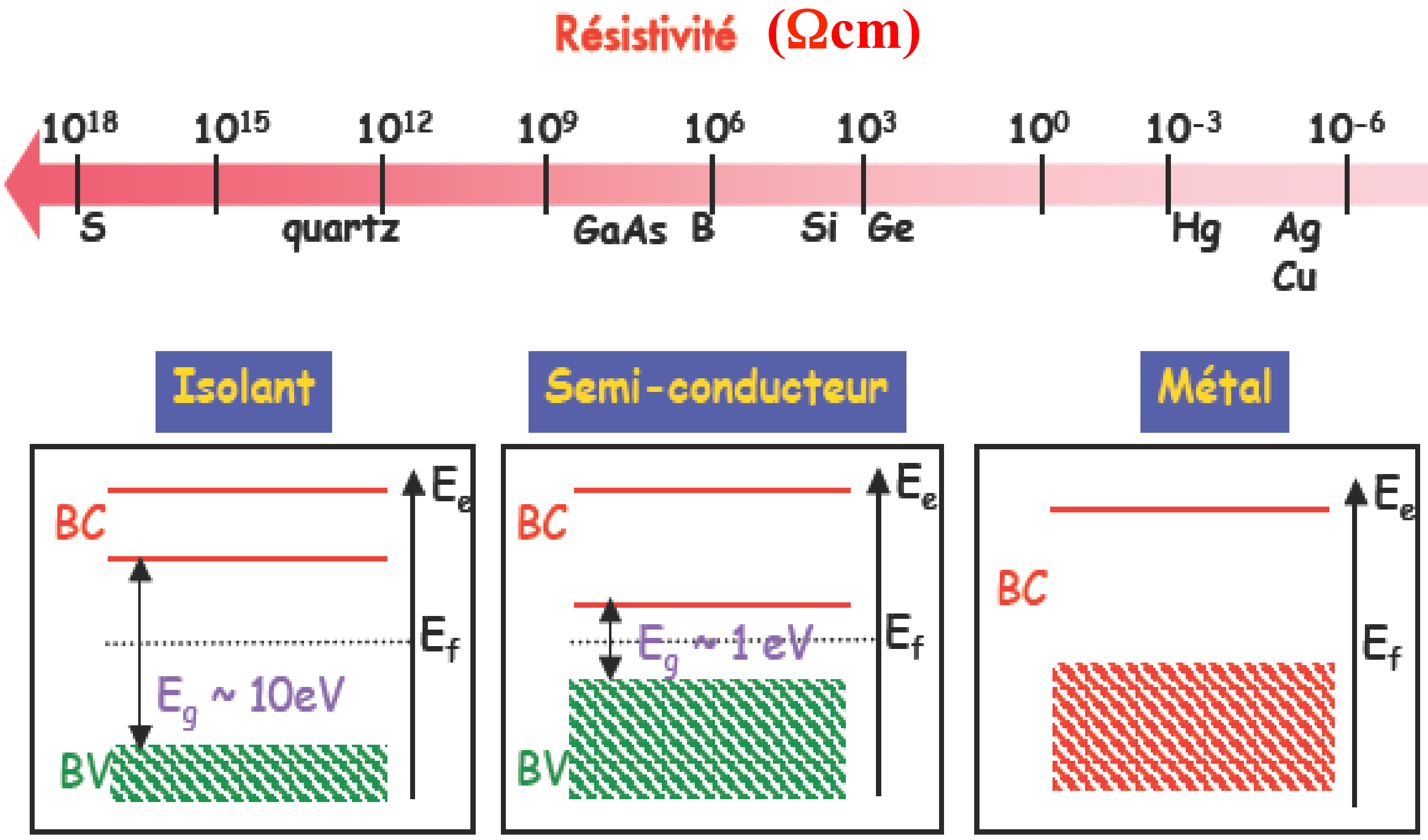


Figure 28.1: Cartoon of scintillation "ladder" depicting the operating mechanism of plastic scintillator. Approximate fluor concentrations and energy transfer distances for the separate sub-processes are shown.

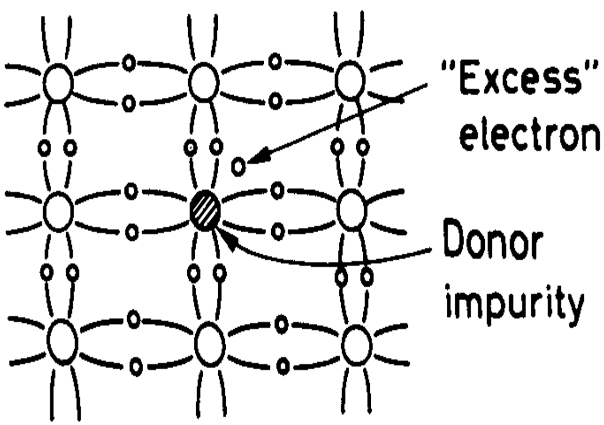
Absorption and emission

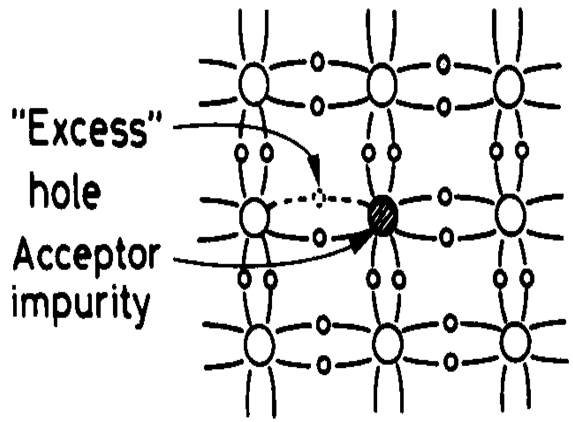


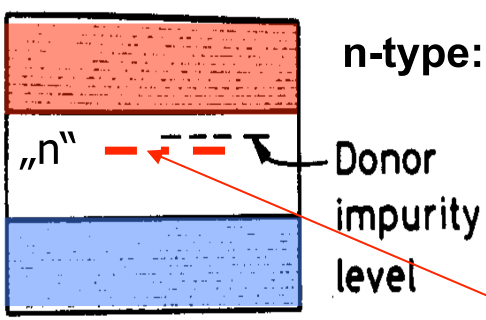
Semi-conductors



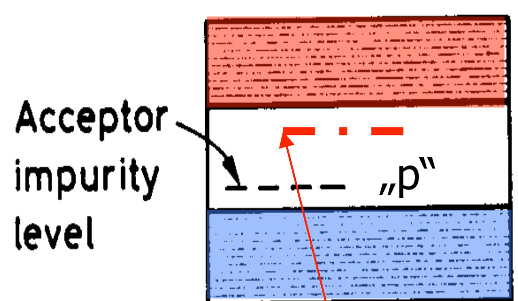
„Doped“ Semi-conductors



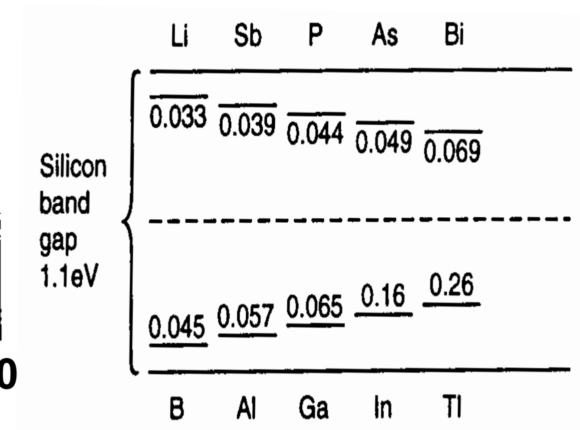




n-type: $N_D > N_A \approx 0$



p-type: $N_A > N_D \approx 0$



Energy levels within the band gap corresponding to various n- and p-type dopants [6]

Intrinsic / High Purity: 1.5 10^{10}/cm³
(N_A = 6.022 10^{23}/cm³ !!)
n, p : 10^{13}/cm³
n^+, p^+ : 10^{20}/cm³

W.Dulinski

Impurities
- **traps**
- **recombination**

Semi-conductor detectors

Material	E_g [eV]	w [eV]	Mobility (velocity/E)		τ_e [s]	τ_h [s]	density	Z [a.m.u]
			μ_e [cm^2/Vs]	μ_h [cm^2/Vs]			g/cm^3	
C (diamond)	5.5	13	1800	1200	$2\ 10^{-9}$	$2\ 10^{-9}$	3.515	6
Si	1.12	3.61	1350	480	$5\ 10^{-3}$	$5\ 10^{-3}$	2.33	14
Ge	0.67	2.98	3900	1900	$2\ 10^{-5}$	$2\ 10^{-5}$	5.32	32
GaAs	1.42	4.70	8500	450	$5\ 10^{-8}$	$5\ 10^{-8}$	5.32	31,33
CdTe	1.56	4.43	1050	100	$1\ 10^{-6}$	$1\ 10^{-6}$		48,52
HgI_2	2.13	4.20	100	_	$1\ 10^{-6}$	$2\ 10^{-6}$		53,80

$$\frac{dN}{N} = \frac{1}{\sqrt{N}} \;;\quad E \sim N; \qquad N = \text{numb. of (e,h))}$$

Parameters Values for Materials Used in Fabricating Semiconductor Radiation Sensors [3]

W.Dulinski

Inverse Polarisation

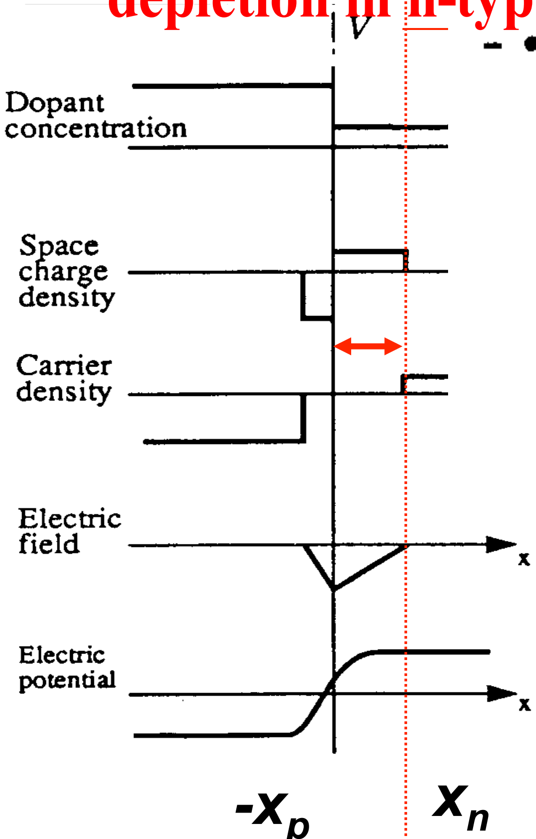
$$d\big|_{V_{bias}} = x_n + x_p = \sqrt{\frac{2\varepsilon\left(\phi_0 + V_{bias}\right)}{e}\frac{\left(N_A + N_D\right)}{N_A N_D}}$$

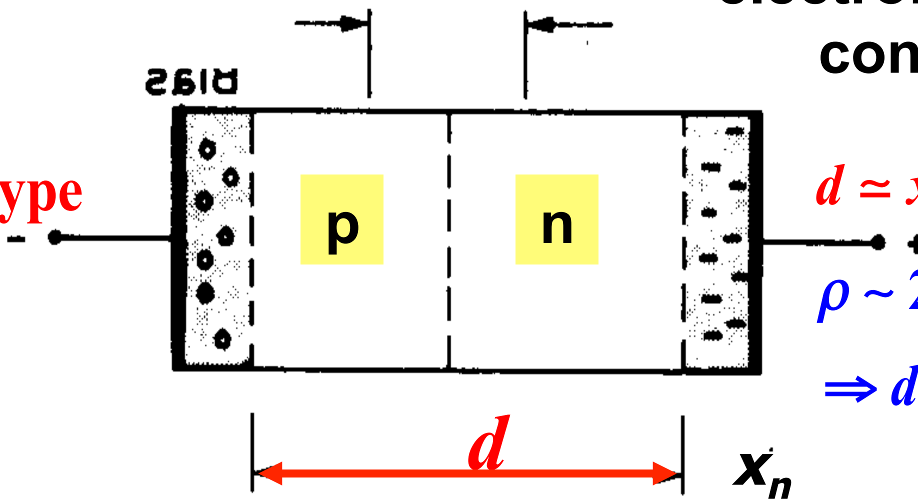
Holes move to « - »

electrons move to contact "+"

$N_A \gg N_D$

depletion in n-type



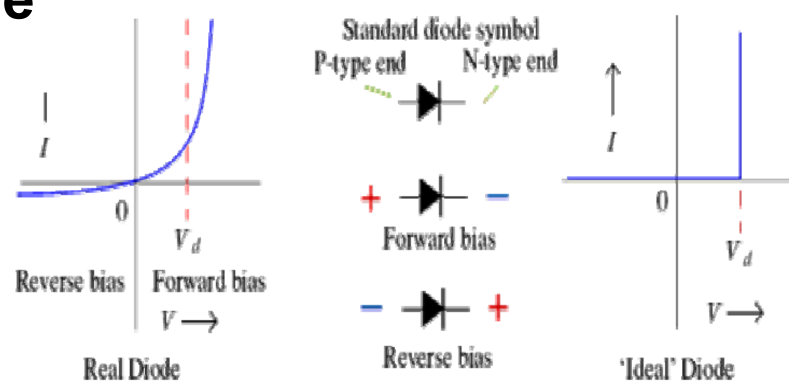


Depletion zone

$d \simeq x_n \approx 0.53\sqrt{\rho_n \phi_0}\ \mu m$

$\rho \sim 2\cdot 10^4\ \Omega cm,\ \phi_0 \sim 1V$

$\Rightarrow d \sim 75\ \mu m$



Junction p-n

0.1-2μm ⇒ perte d'énergie

Diffused or Ion implanted

Diffused & Ion implanted

oxide window

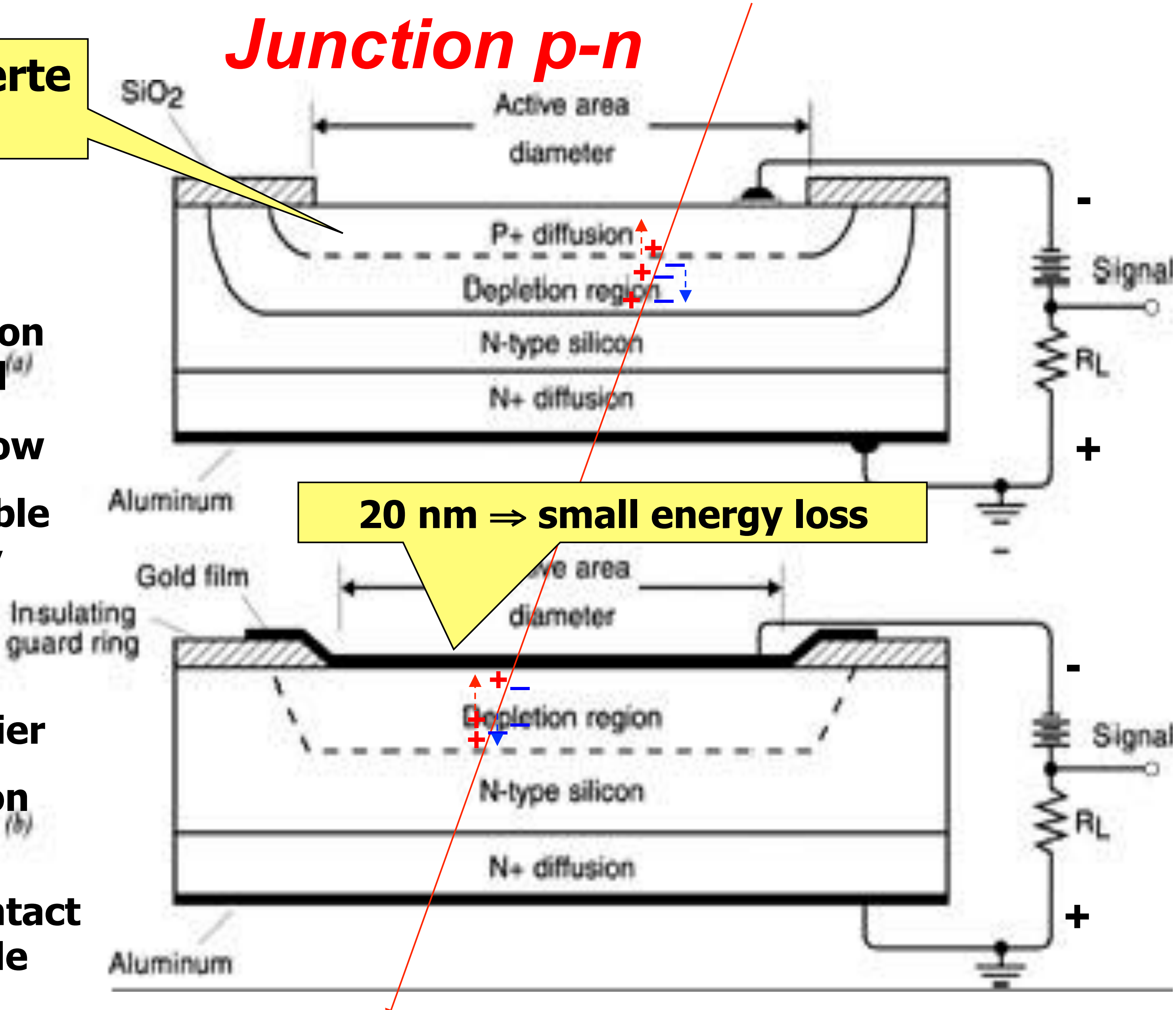
robust, flexible geometry

Shottky barrier

Shottky barrier

metal-silicon junction

thin metal contact more fragile



G.Hall

Surface barrier detectors

Interaction of charged particles in silicon

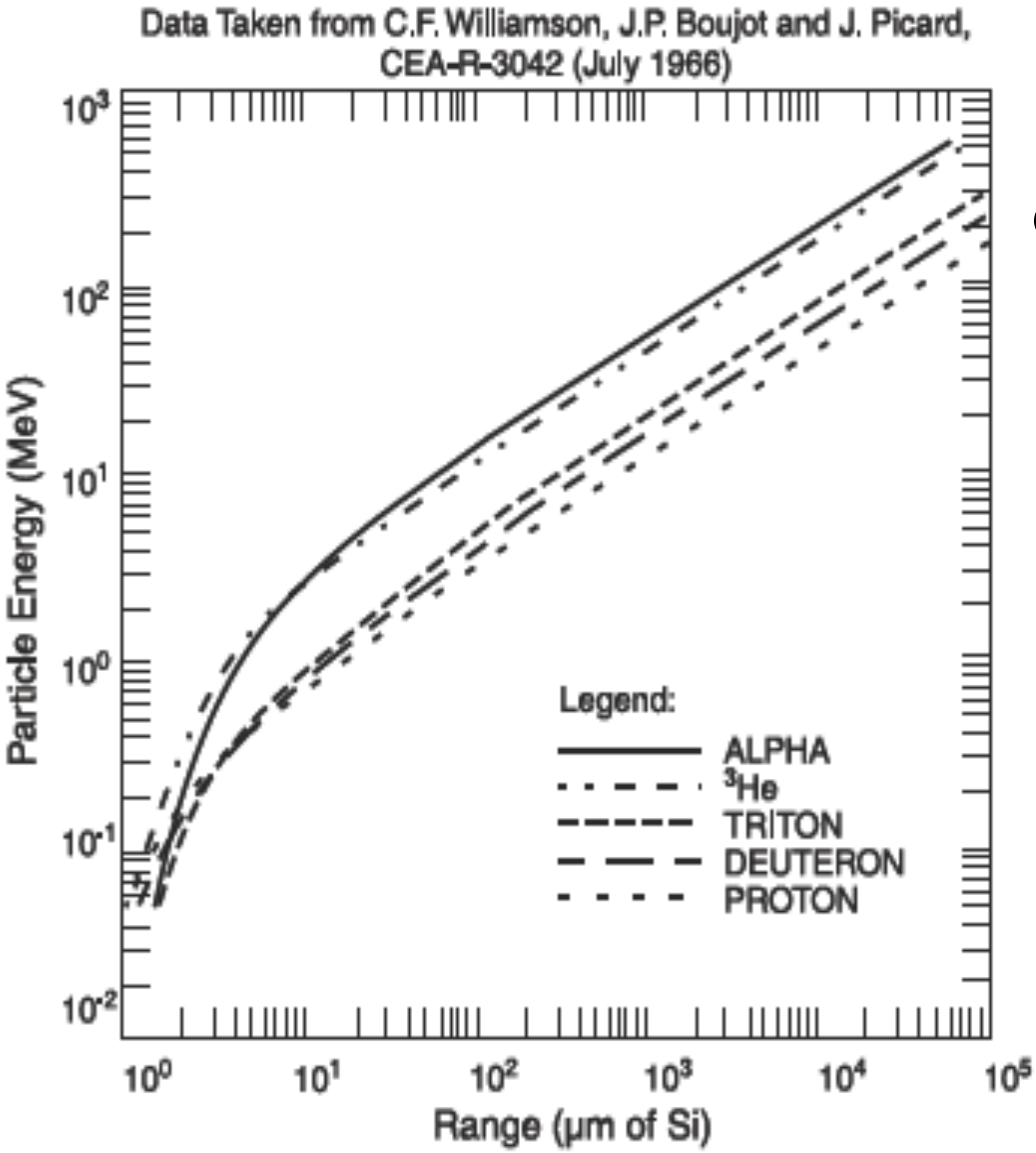


Figure 1.10 Range-Energy Curves in Silicon

Fission fragment spectrum

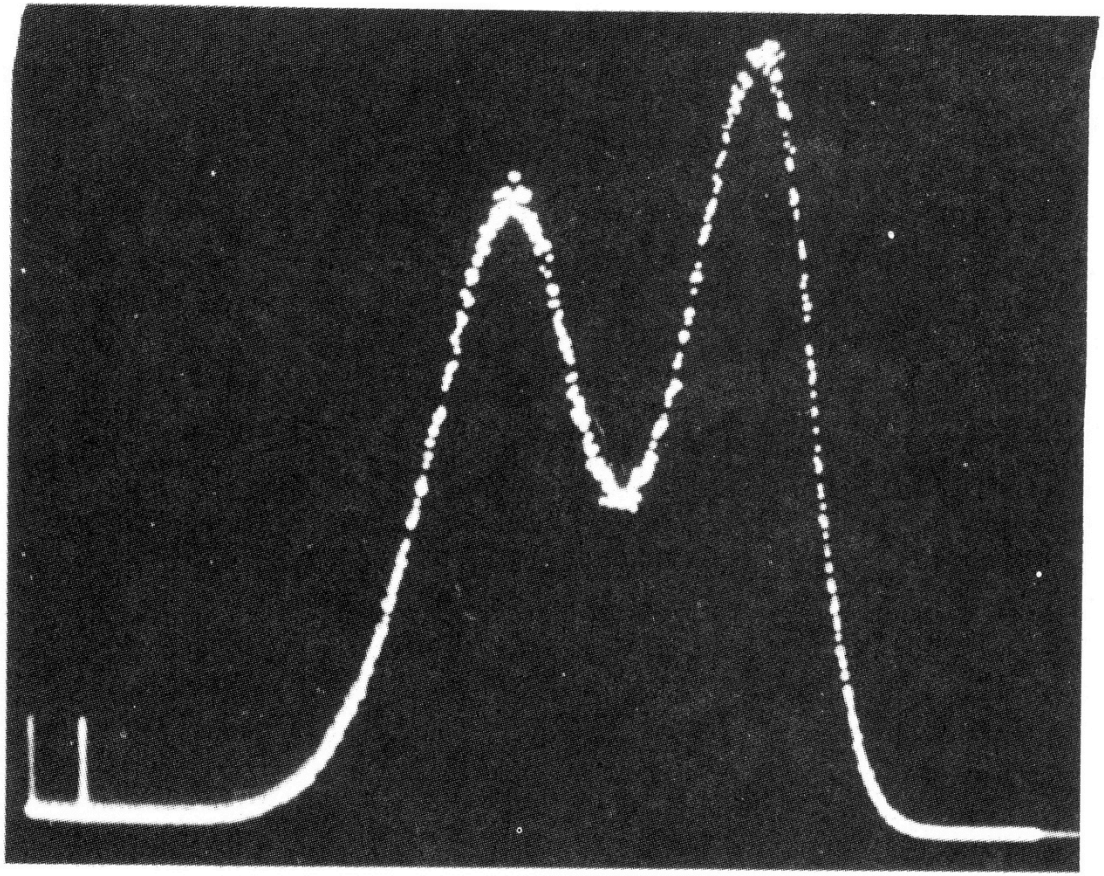
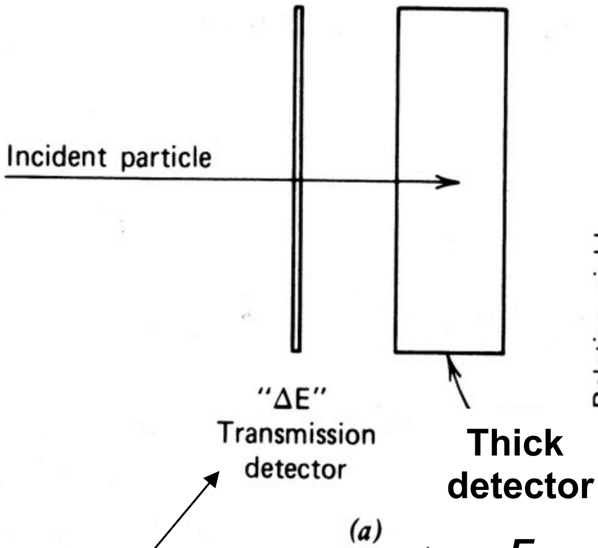
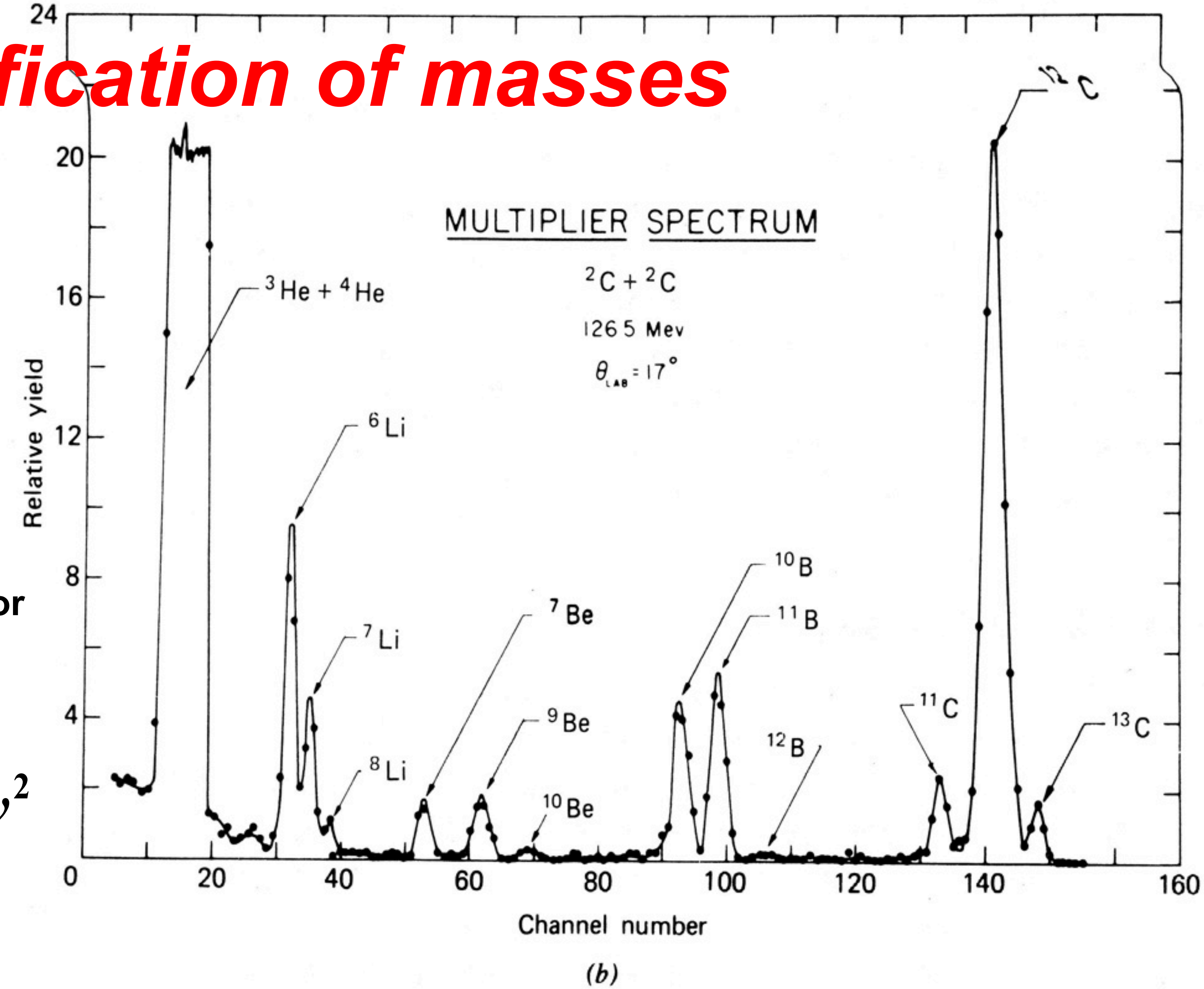


Figure 11-15 ^{252}Cf fission fragment pulse height spectrum. The spectrum parameters defined on the diagram can be used for energy calibration and detector evaluation (see text). (From Bozorgmanesh[75] and Schmitt and Pleasonton.[83])

Identification of masses



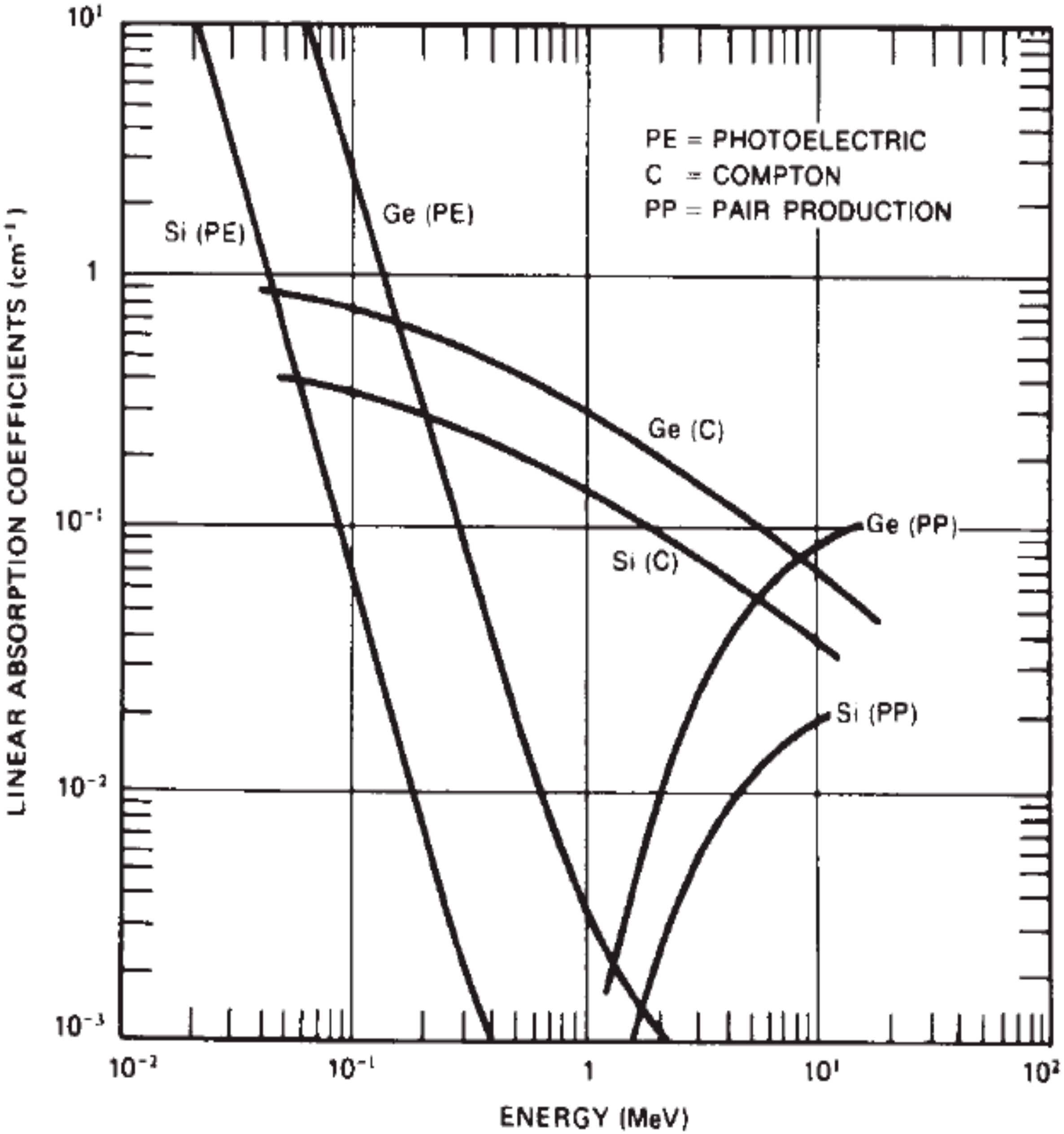


$$\frac{dE}{dx} \propto \frac{1}{v^2}; \quad E_{cin} = \tfrac{1}{2} m v^2$$

$$\Rightarrow$$

$$\frac{dE}{dx} \times E_{cin} \propto m$$

Figure 11-16 (a) A particle identifier arrangement consisting of tandem ΔE and E detectors operated in coincidence. (b) Experimental spectrum obtained for the $\Delta E \cdot E$ signal product for a mixture of different ions. (From Bromley.[90])



High Purity Germanium

Energy measurement of gammas

($|N_A - N_D| \cong 10^{10}$ cm^{-3}):

- **E_{gap} = 0.74 eV $\Rightarrow$ operation temperature : T= 77K**
- **w_{eh}=2.98 eV $\Rightarrow$excellent resolution**
  - **E_γ = 1 MeV, dE $\cong$ 1 keV**
  - **"High" photo peak efficiency**

Large volume detectors

- **Depletion zone :**

$$d\Big|_{V_{bias}} = x_n + x_p = \sqrt{\frac{2\varepsilon\left(\phi_0 + V_{bias}\right)}{e}\frac{\left(N_A + N_D\right)}{N_A N_D}}$$

$$N = N_A \ll N_D;\ \ \phi_0 \ll V_{bias}$$

$$d\Big|_{V_{bias}} = \sqrt{\frac{2\varepsilon V_{bias}}{eN}}\ ;\ N = N_A \text{ ou } N_D = \text{net impurity of material}$$

$$N = 10^{+13}\,atoms/cm^3;\ V_{bias} = 3000\,Volt;$$

$$d\Big|_{V_{bias}=3000Volt} = 2.2\,mm$$

- **High purity :**

$$N_A\ ou\ \ N_D = 10^{+10}\,atoms/cm^3;\ V_{bias} = 1000\,Volt;\ \varepsilon = 16\cdot\varepsilon_0;$$

$$\varepsilon_0 = 8.85\cdot 10^{-12}\ F/m;\ F = Coulomb/Volt\ ;\ e = 1.6\cdot 10^{-19}\,Coulomb$$

$$d\Big|_{V_{bias}=1000Volt} = 1.8\,cm$$

$$d\Big|_{V_{bias}=2000Volt} = 2.5\,cm$$

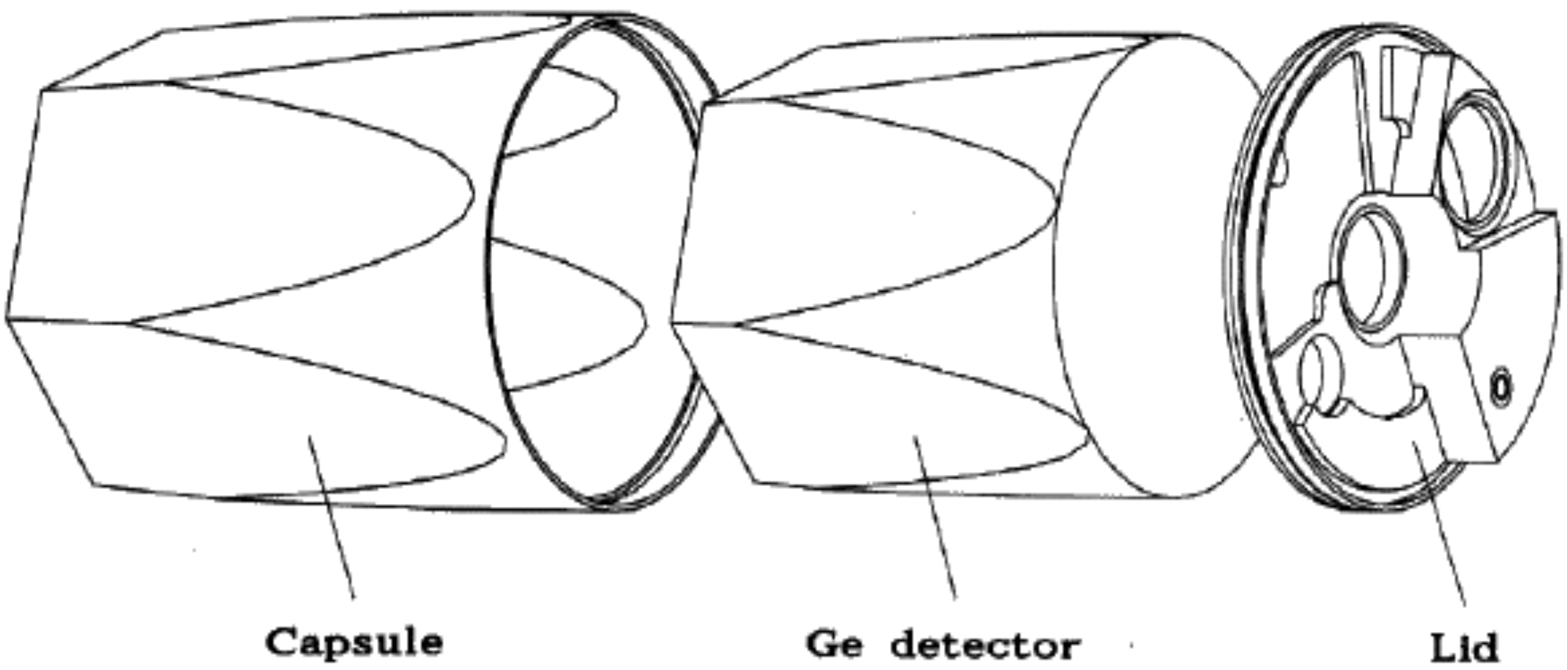
$$d\Big|_{V_{bias}=3000Volt} = 3.1\,cm$$

Germanium detectors

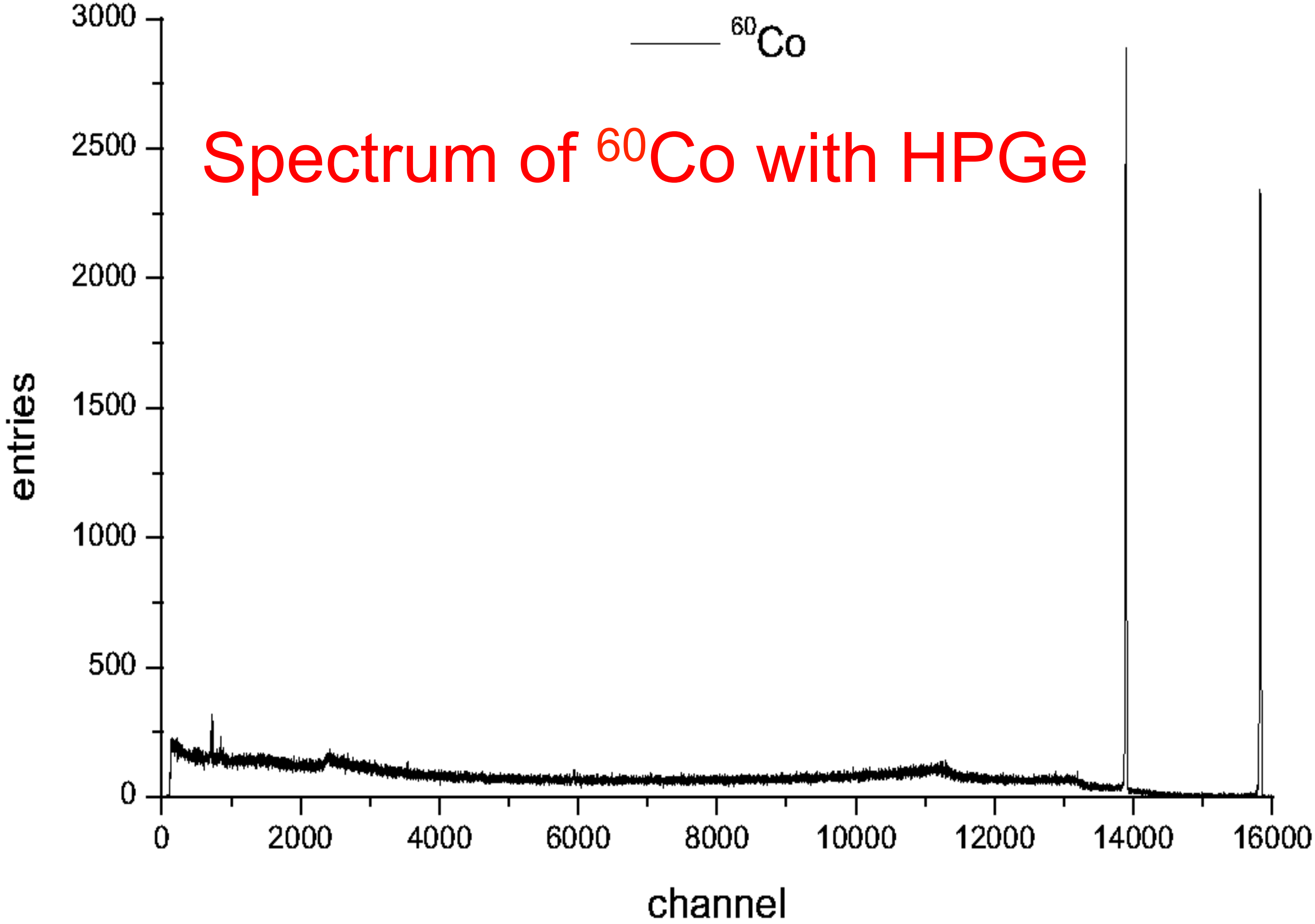
Operation temperature: T= 77K (Liquid Nitrogen)

Configuration : co-axial

Electronics is mounted very close to the Crystal

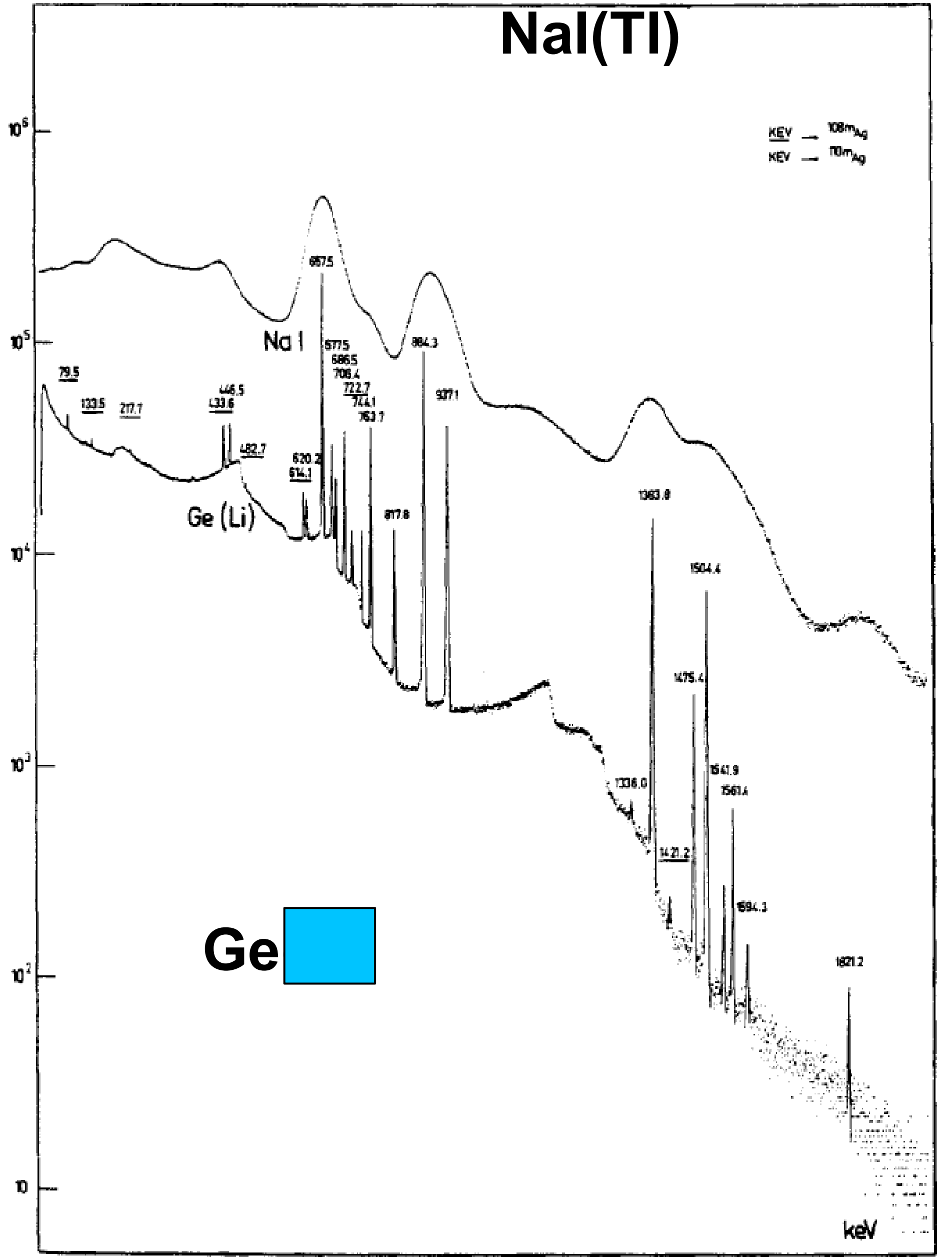


Spectrum of ^{60}Co with HPGe



HP-Ge detector

NaI(Tl)



$$N_{eh} = \frac{E}{w}\varepsilon_{collection}$$

$$dN_{eh} = \sqrt{N_{eh}} = \sqrt{\frac{E}{w}\varepsilon_{collection}}$$

Statistics : Poisson

$\Rightarrow \sigma^2 = \mu;\quad \mu = \text{mean};\ \sigma^2 = \text{variance}$

$$dE/E = dN_{eh}/N_{eh} \sim \frac{1}{\sqrt{N_{eh}}} = \frac{1}{\sqrt{\frac{E}{w}\varepsilon_{collection}}}$$

$\varepsilon_{collection} \approx 100\%;\ w = 2.98\,eV\quad E = 1\,MeV$

$\Rightarrow dE/E \approx 0.0017;$ Resolution $R = 2.35 \times dE/E = 0.4\%$

Fano factor:

$\sigma^2 = F_{ano}\mu;$

$F_{ano} \simeq 0.12\ (Ge, Si);\quad \sqrt{0.12} = 1/2.9$

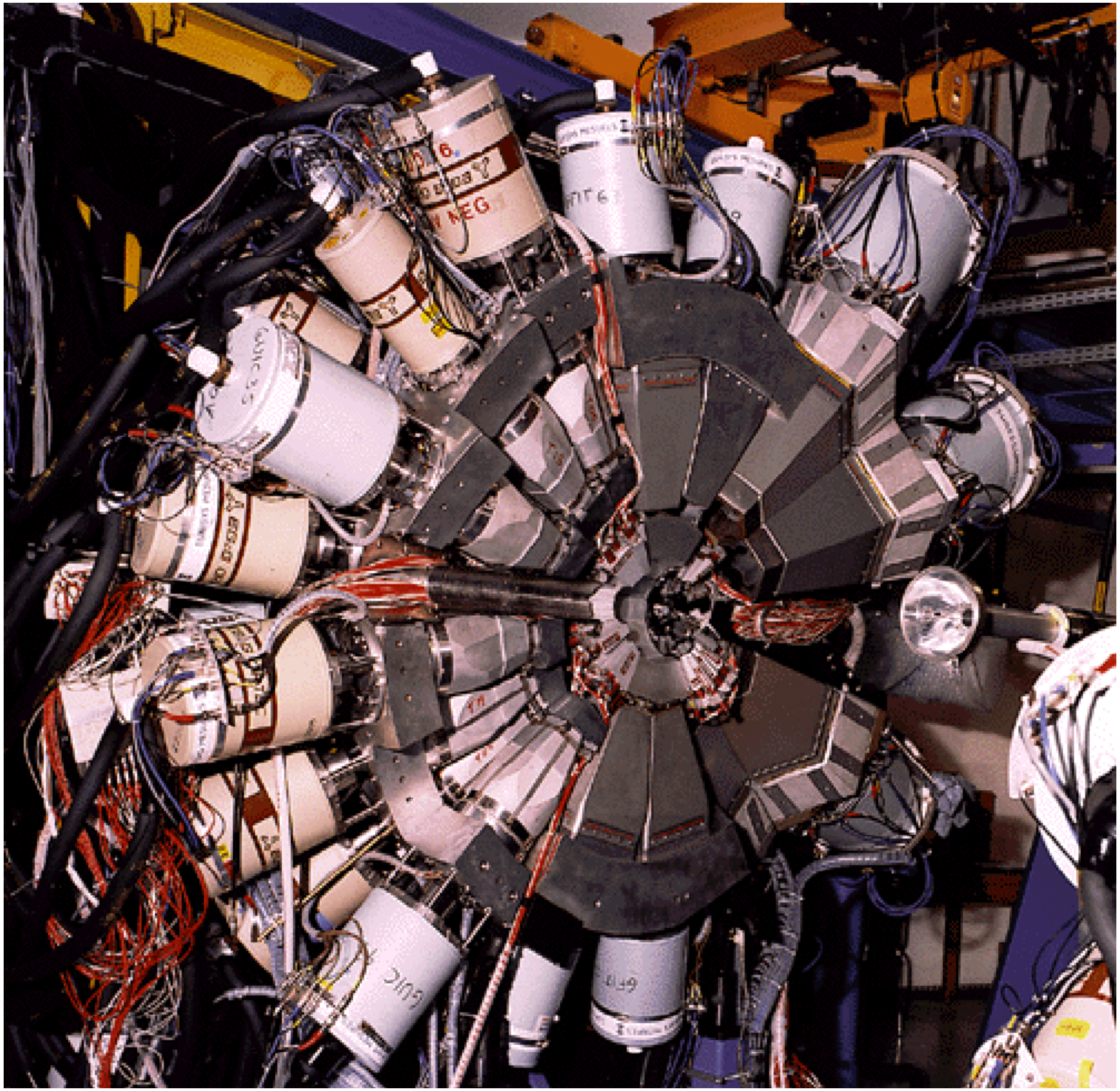
$$dE/E = dN_{eh}/N_{eh} \sim \frac{\sqrt{F}}{\sqrt{N_{eh}}} = \frac{1}{\sqrt{\frac{E}{wF}\varepsilon_{collection}}}$$

$dE/E = 0.0006;$ Resolution $R = 2.35 \times dE/E = 0.14\%$

Comparison with NaI:

$w = 25\,eV/photon_{scint}$ Light collection: 0.5 PM: $Q.E. \approx 0.20$

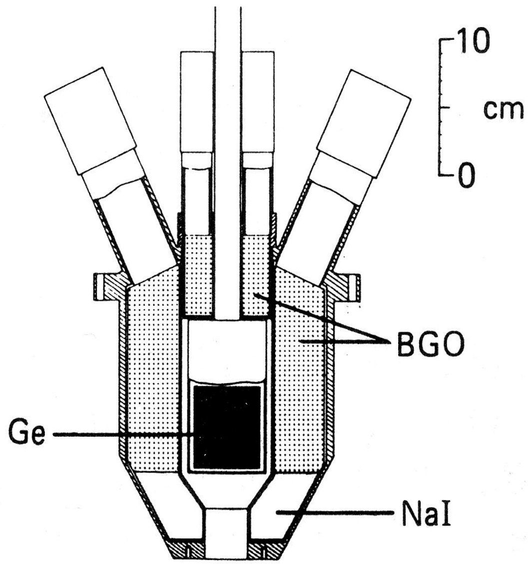
$dE/E \approx 1.6\%$ Resolution $R = 2.35 \times dE/E = 3{,}7\%$ à $1\,MeV$

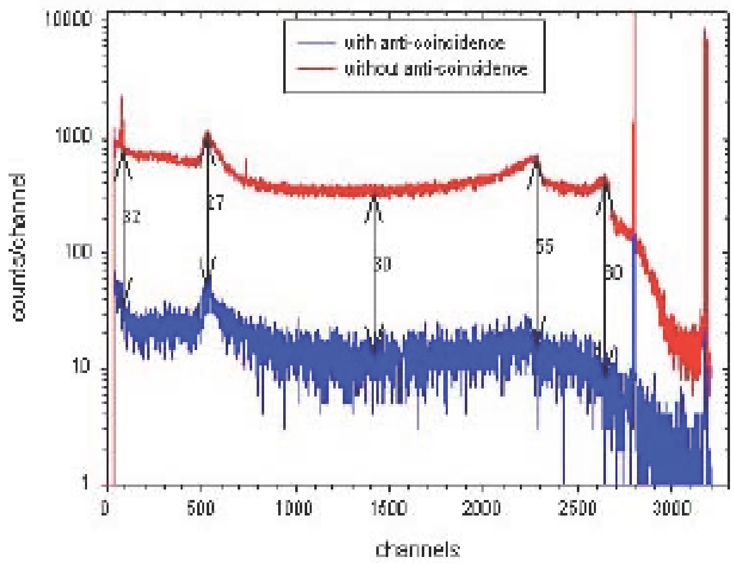


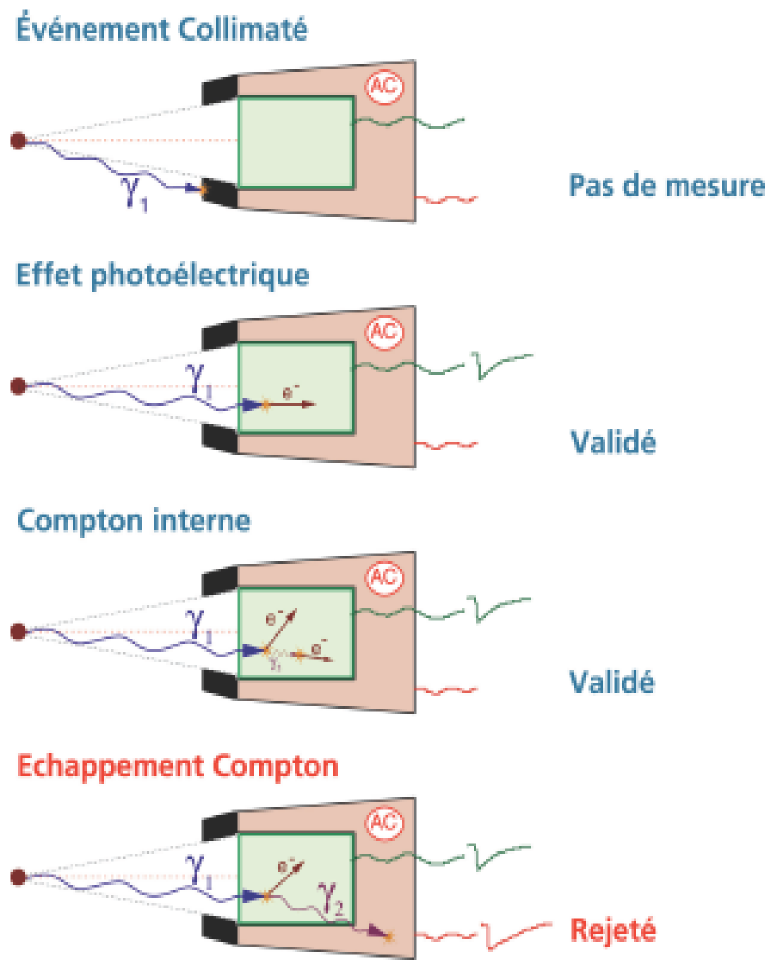
Euroball à Strasbourg

Il y a quelques années

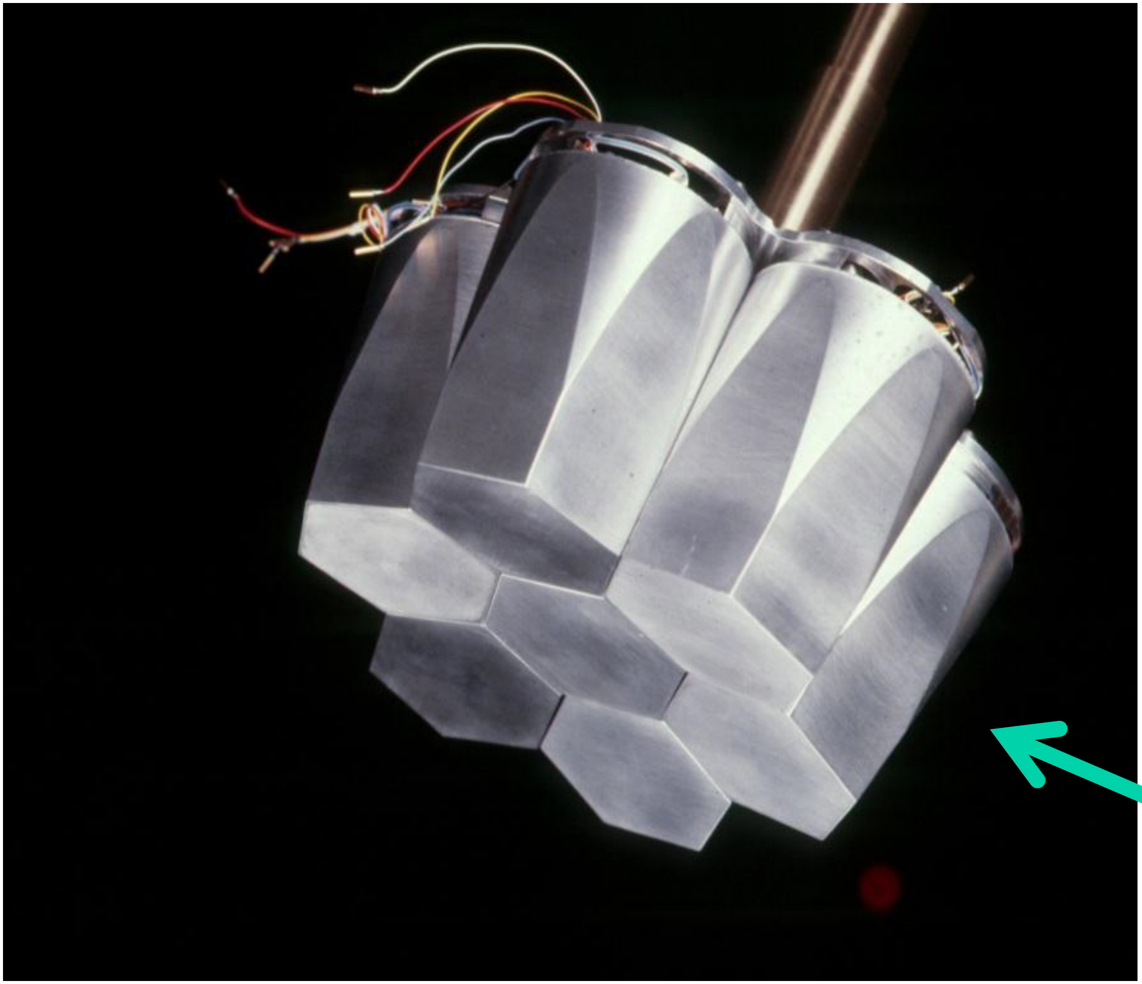
ti-Compton

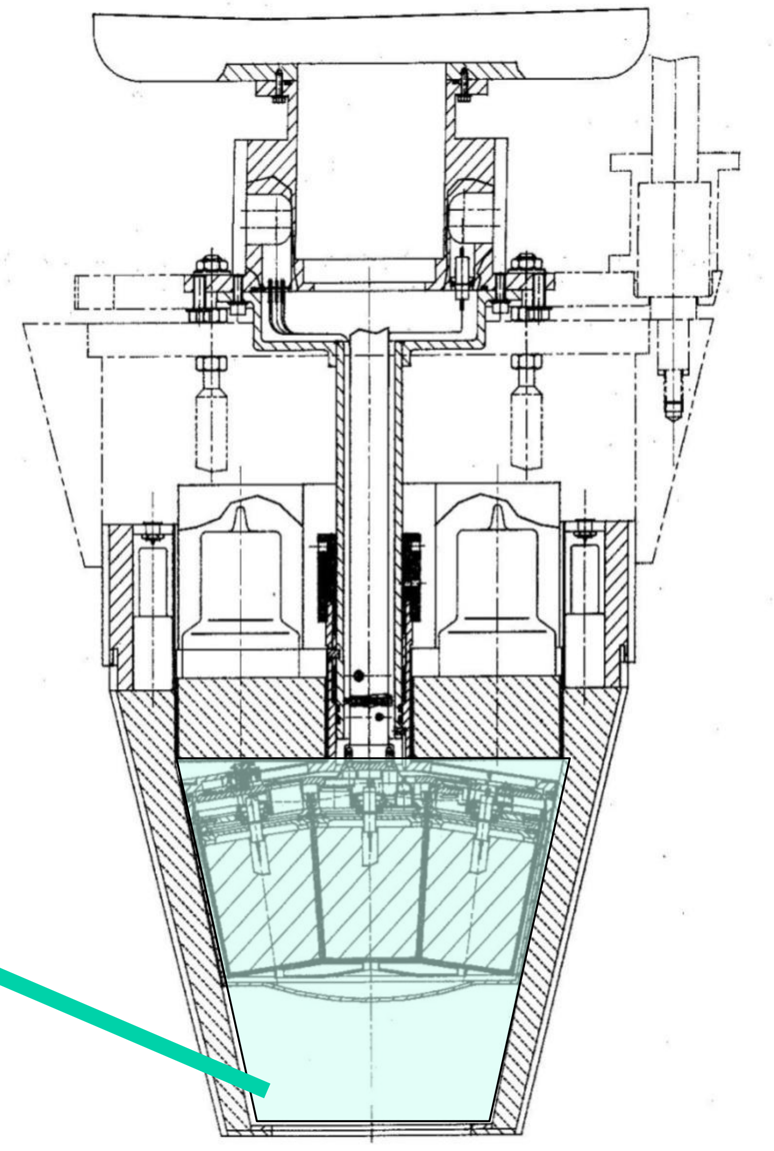

10
cm
0
BGO
Ge
NaI


with anti-coincidence
without anti-coincidence
counts/channel
channels
10000
1000
100
10
1
0
500
1000
1500
2000
2500
3000


Événement Collimaté
Pas de mesure
Effet photoélectrique
Validé
Compton interne
Validé
Echappement Compton
Rejeté
AC

The EUROBALL Cluster Detector 10kg HPGe



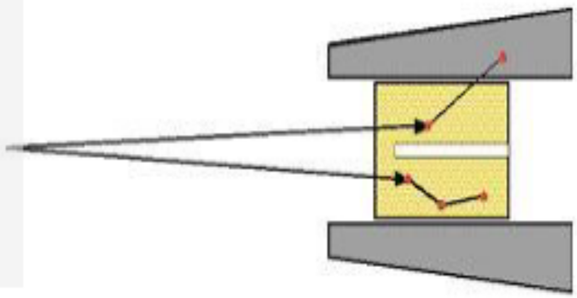


The idea of γ-ray tracking

Compton Shielded Ge

ε_{ph} ~ 10%
N_{det} ~ 100

Ω ~ 40%
θ ~ 8°



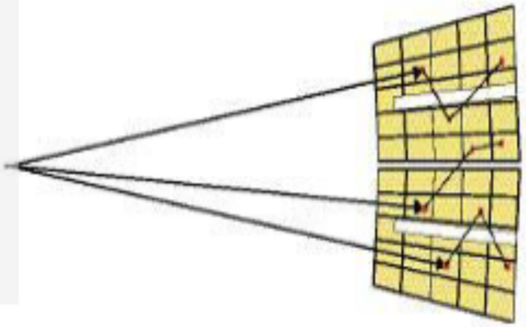
large opening angle means poor energy resolution at high recoil velocity.

Previously scattered gammas were wasted.
Technology is available now to track them.

Ge Tracking Array

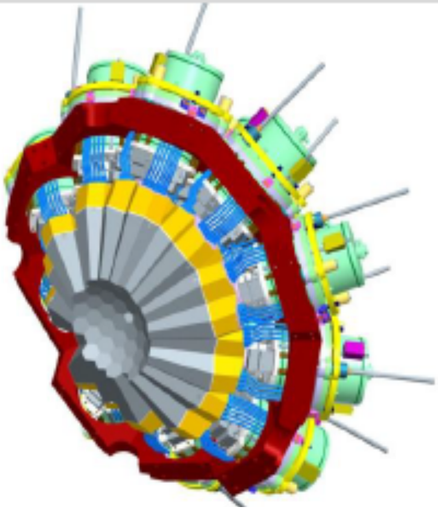
ε_{ph} ~ 50%
N_{det} ~ 100

Ω ~ 80%
θ ~ 1°



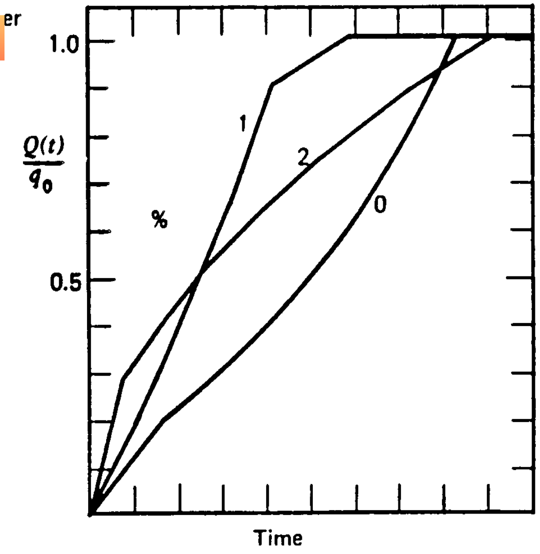
Combination of:

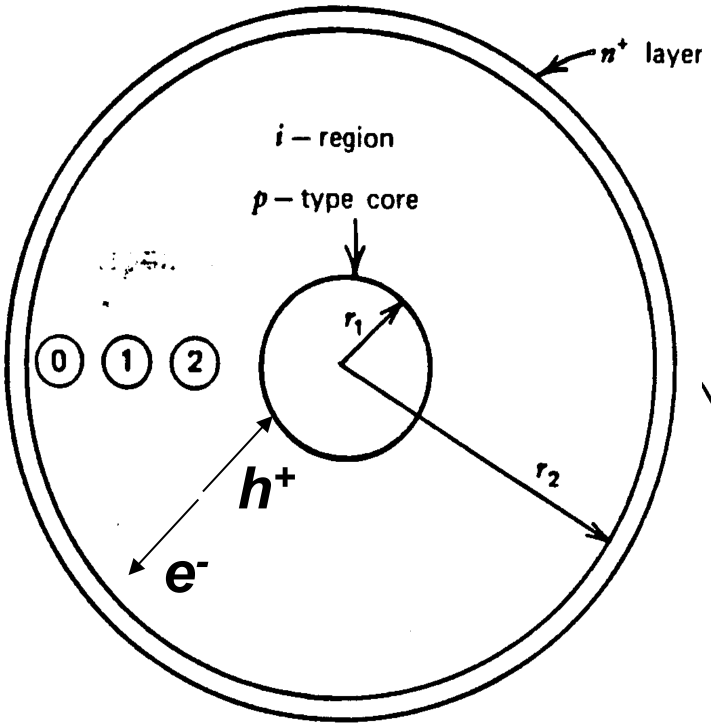
- segmented detectors
- digital electronics
- pulse processing
- tracking the γ-rays

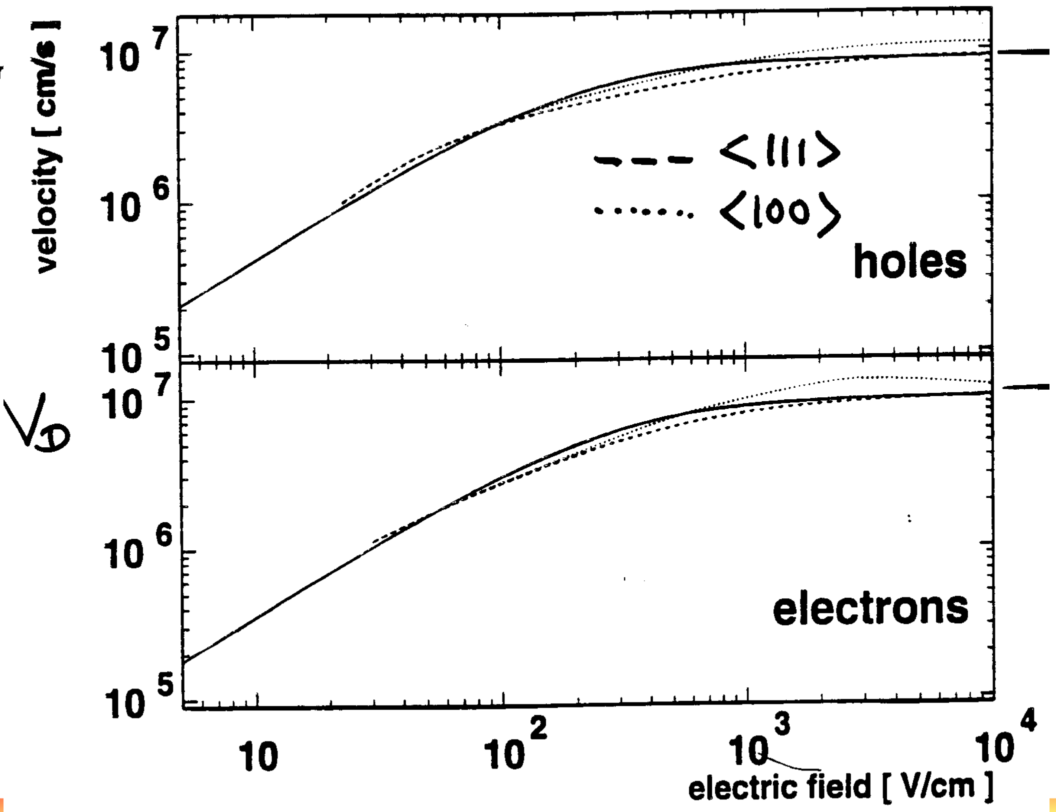


Formation du signal Ge-HP

Géométrie cylindrique

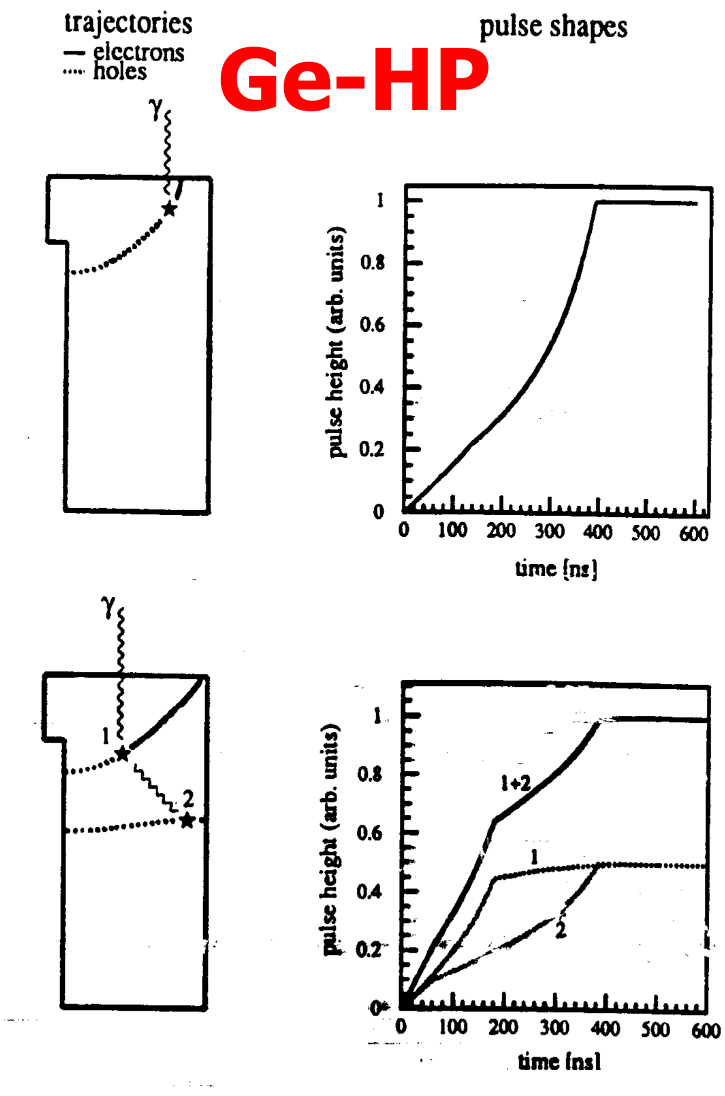


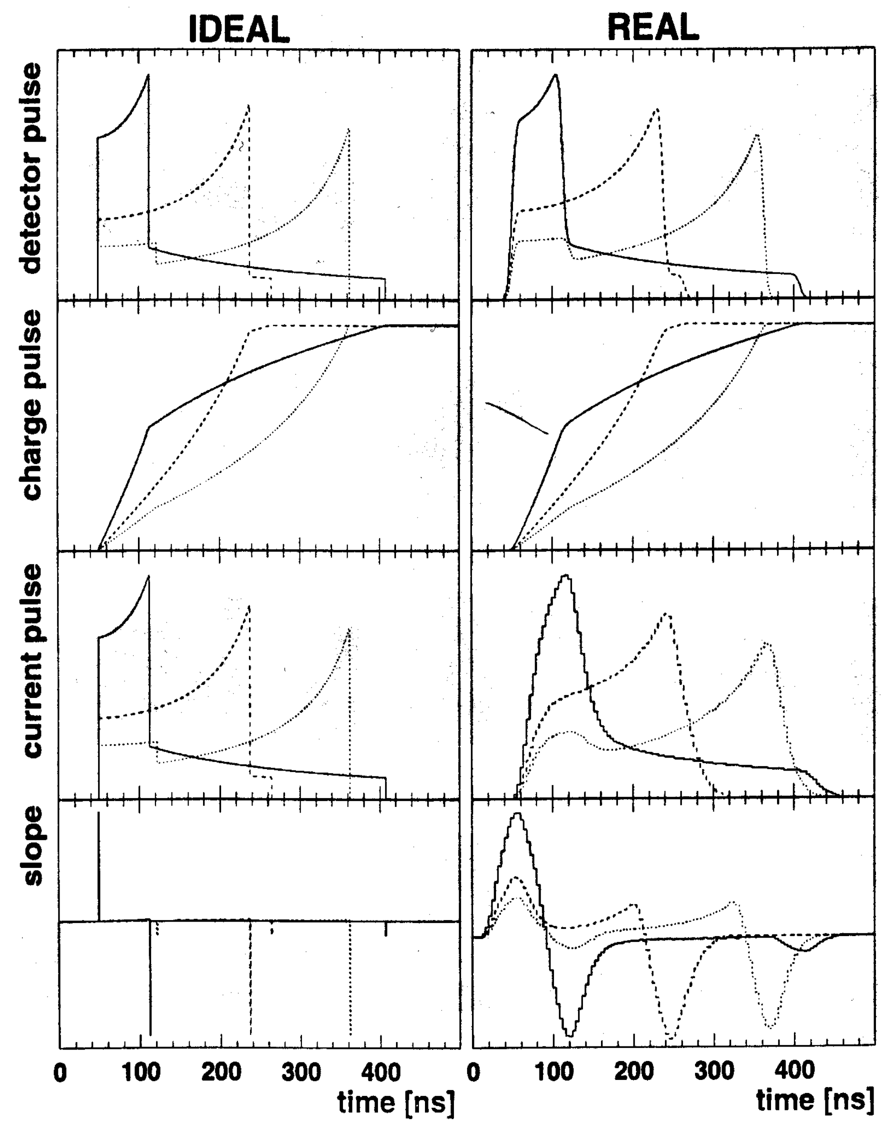




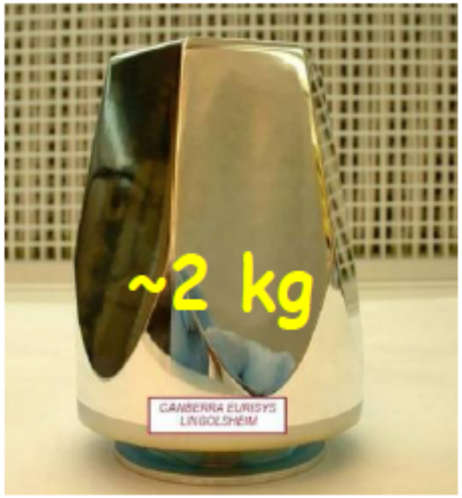
Interactions multiples

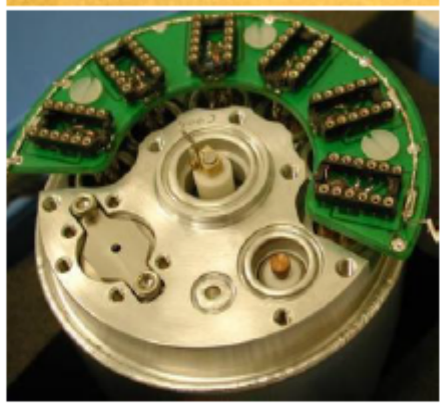
Ge-HP

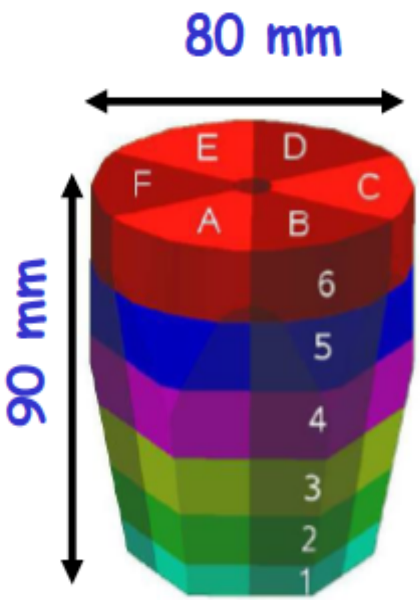




AGATA detectors and the AGATA triple-cluster







6x6 segmented cathode

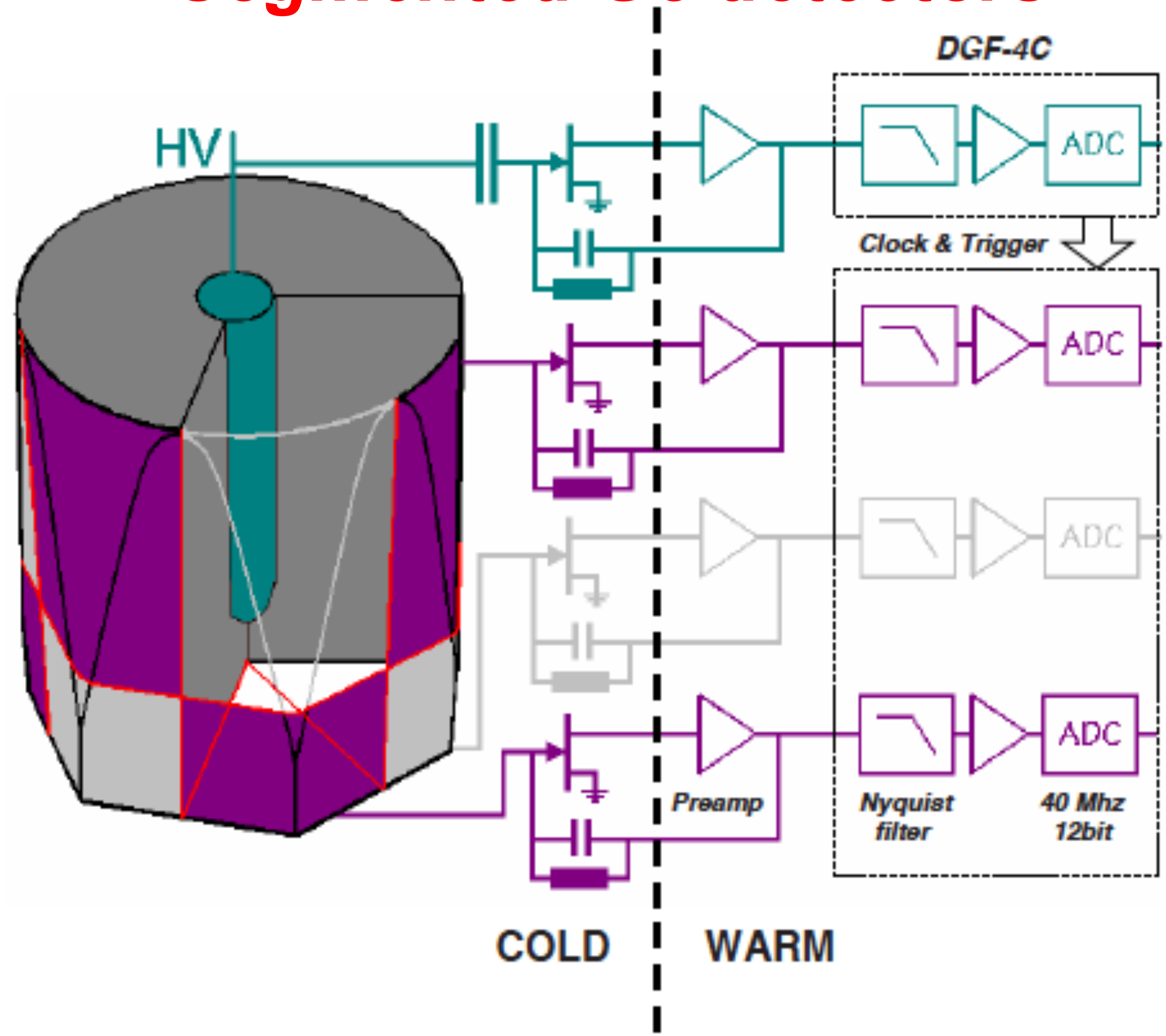
Symmetric detectors

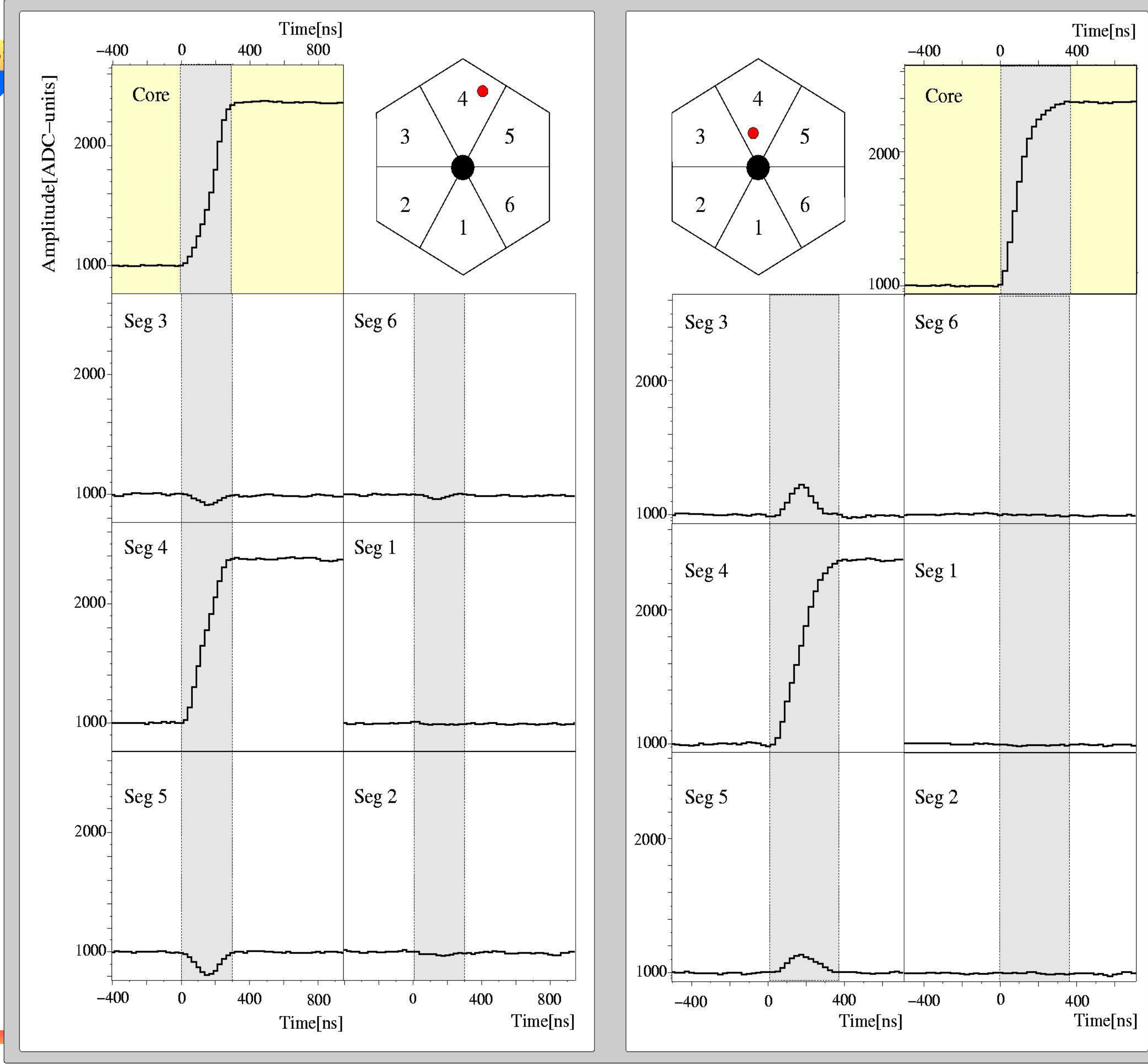
- 3 in use since 6 years
- Used in single cryostats or as a triple cluster

Asymmetric detectors

- 31 ordered
- 15 accepted
- 4 clusters operational

Segmented Ge detectors

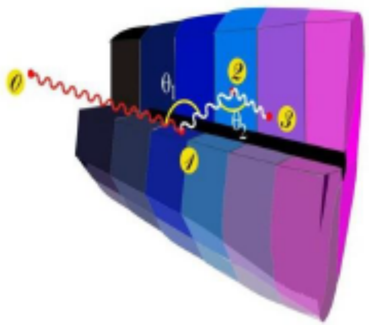



Time[ns]
Amplitude[ADC–units]
Core
Seg 3
Seg 6
Seg 4
Seg 1
Seg 5
Seg 2
4
3
5
2
6
1
–400
0
400
800
1000
2000
Time[ns]

Ingredients of Gamma-Ray Tracking

1

Highly segmented HPGe detectors



2

Digital electronics to record and process segment signals

3

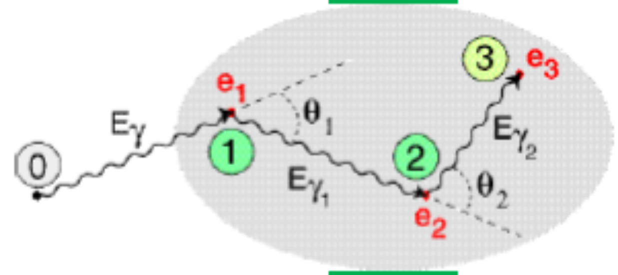
Pulse Shape Analysis to decompose recorded waves

Identified interaction points

$(x,y,z,E,t)_i$

4

Reconstruction of tracks evaluating permutations of interaction points



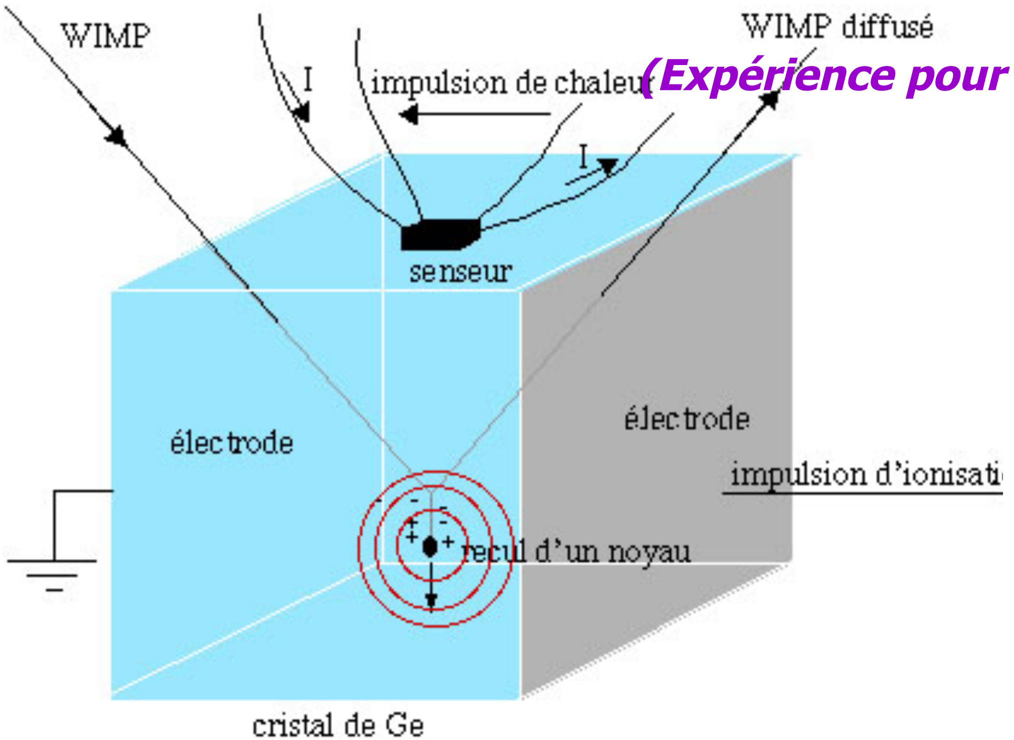
Reconstructed gamma-rays

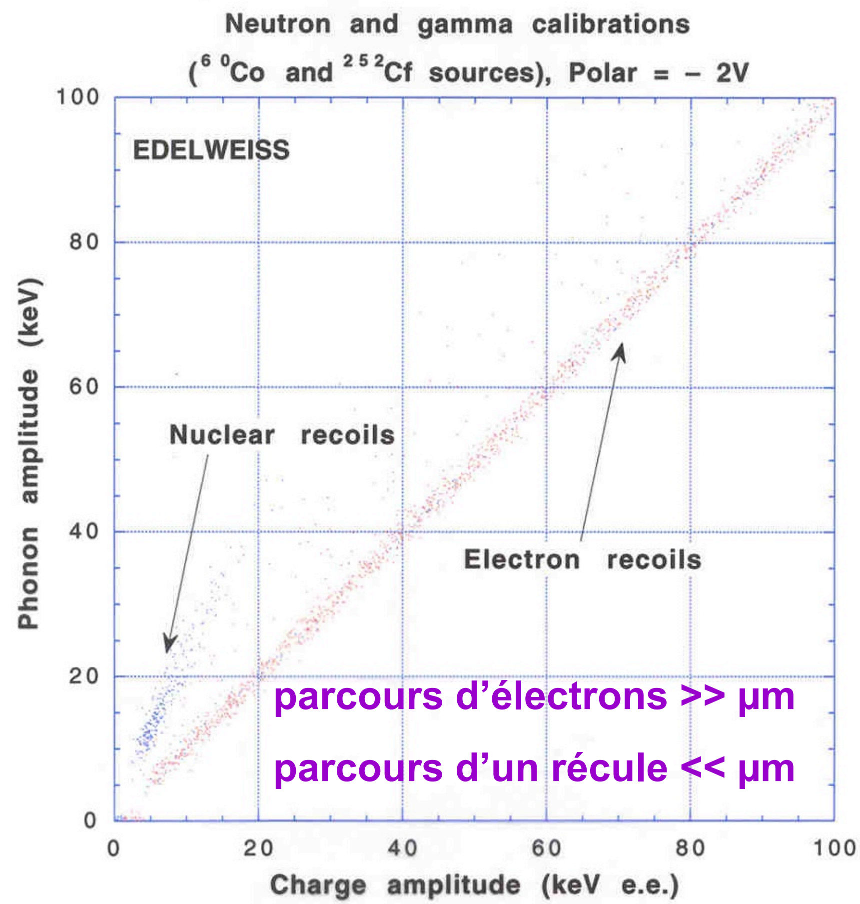
Conclusions
(nuclear detectors)

- High Z Scintillators are used for gamma spectroscopy, particular for anti Compton spectrometers
- Low Z (organic)-Scintillators used for particle detection/stopping
- Semiconductors: Si used for charged particle spectroscopy (alpha, protons, ... Fission fragments)
- Semiconductors: HP-Ge for high resolution and high efficient Gamma spectroscopy

EDELWEISS

(Expérience pour Détecter Les Wimps en Site Souterrain)



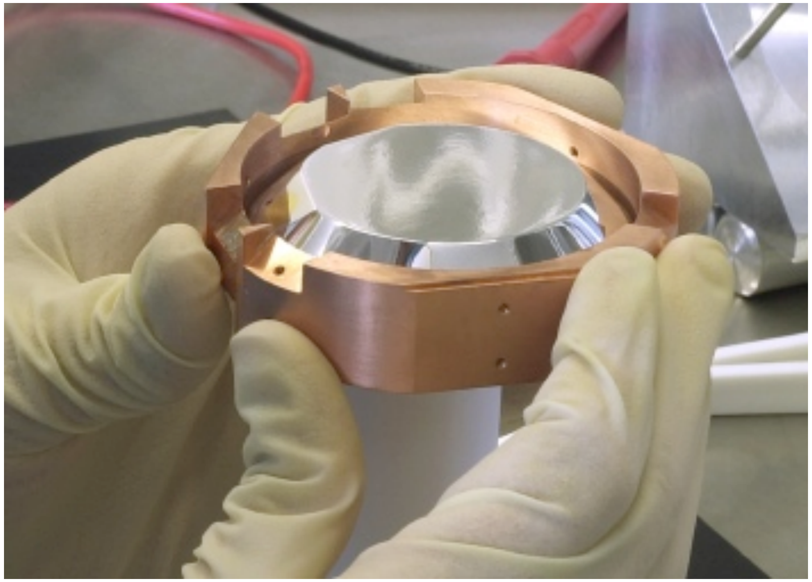


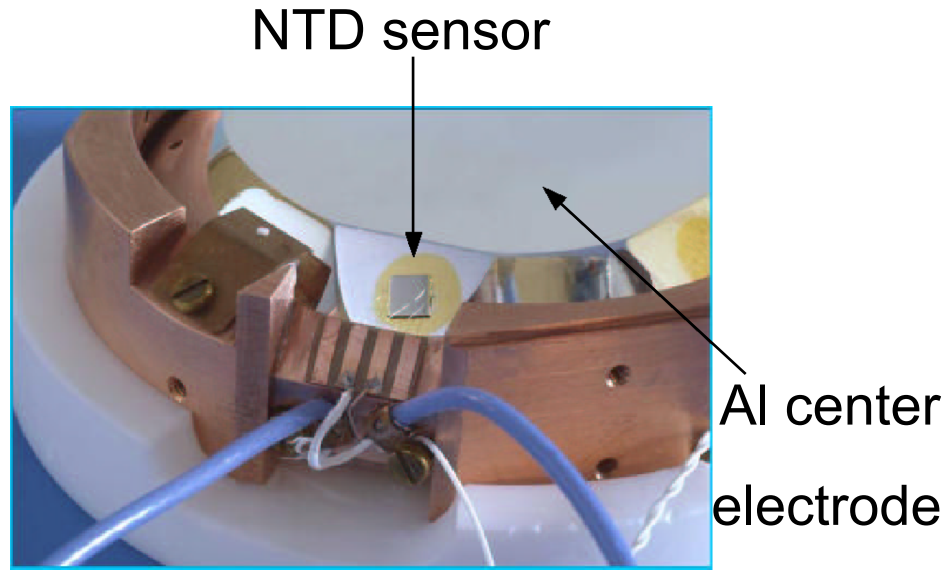
parcours d'électrons >> µm

parcours d'un récule << µm

- **Cristal of very pure "Ge" 1Kg,**
- **Very rare events 1 event/Kg/year !!**
- **Ionisation**
  - **some keV**
- **Heat/ mechanical vibration of cristal**
  - **$\Delta T \approx$ 10-6 mK => cryostat(^3He-^4He) à 10 milli-Kelvin**

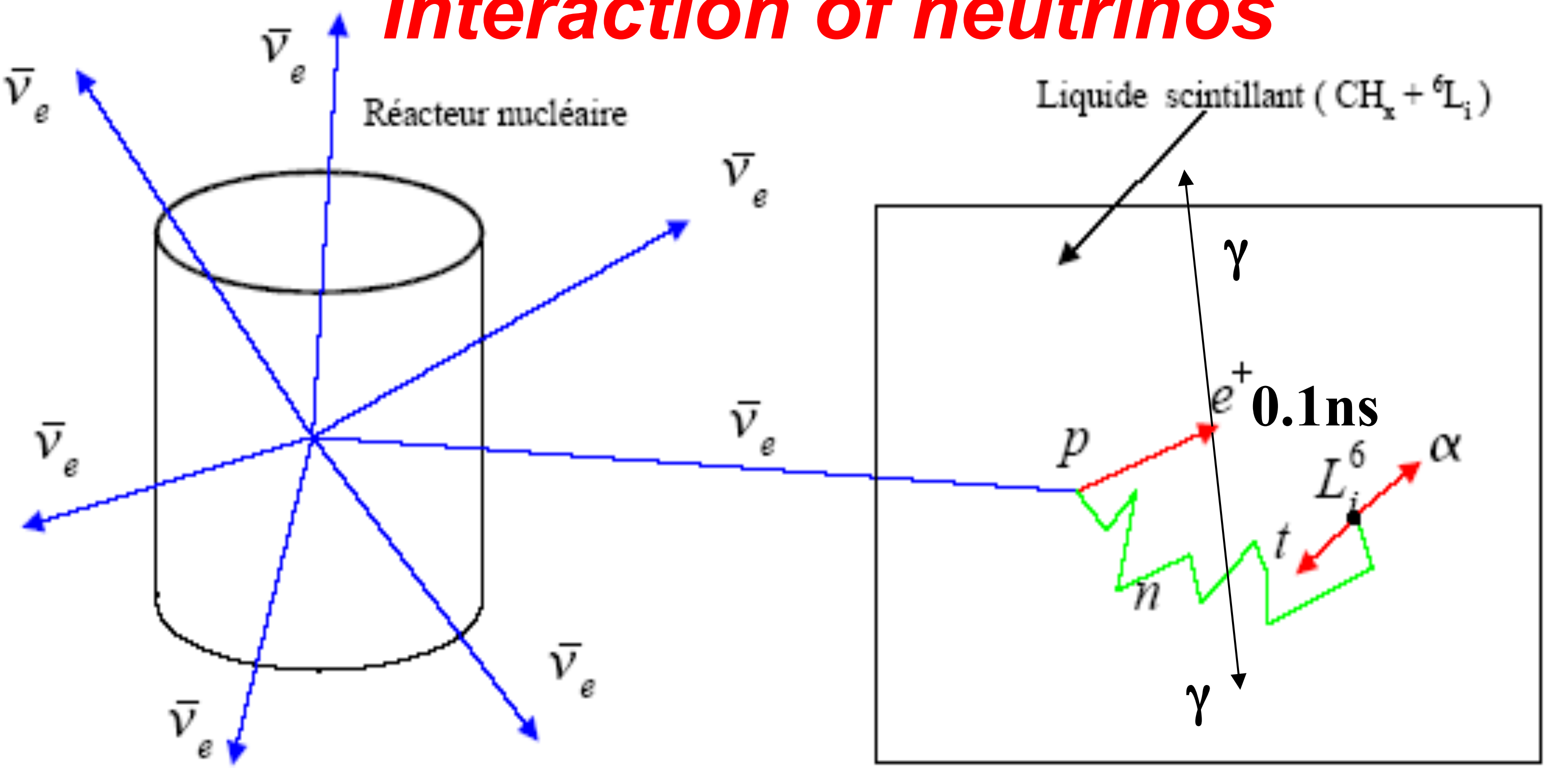
Ge ionization – phonon detectors I





- bolometer mass: 320 g
- 100nm sputtered Al layer as electrode (center + guard ring)
- 60nm Ge(Si) amorphous layer below electrode
- NTD sensor glued on sputtered gold pad on guard ring electrode
- electrical contacts/heat links via gold wire bonding (Ø=25μm)
- **operating temperature T=17.00±0.01mK**

Interaction of neutrinos



Reines & Cowan 1959

$\epsilon_{\nu} \sim 0$

La réaction de détection est : $\bar{\nu}_e + p \rightarrow n + e^+$, qui est rapidement (100 µs) suivie de la capture du neutron sur un noyau de L_i^6 selon la réaction : $n_{th} + L_i^6 \rightarrow \alpha + t + 4{,}8\,MeV$. Les particules chargées produisent des impulsions de scintillation en coïncidence . La signature de détection d'un neutrino correspond à l'enregistrement de deux impulsions lumineuses induites par le positon et la paire $\alpha - t$.

Liquid scintillator for the Double Chooz experiment