Instruments for x- and γ-ray astronomy

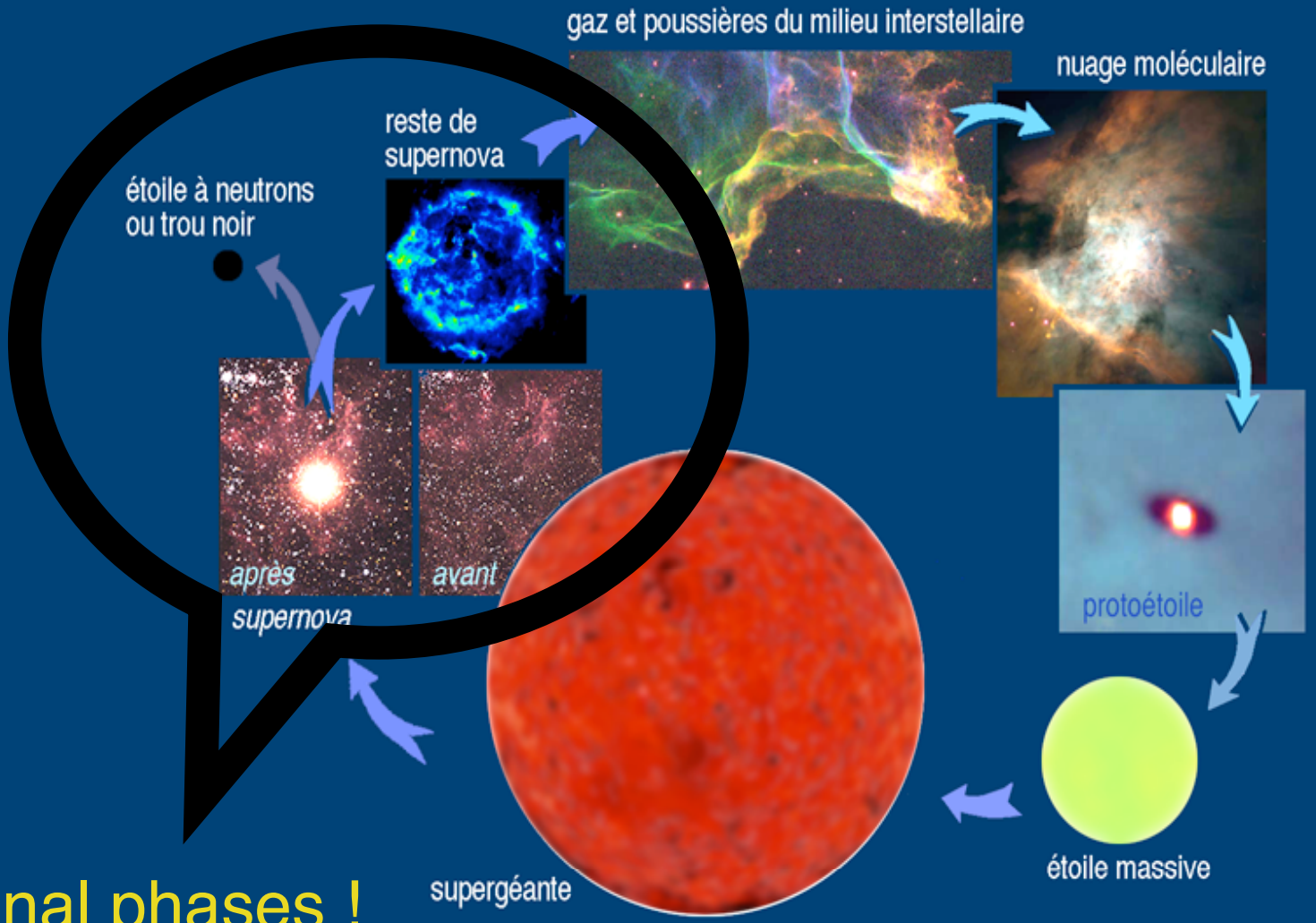
Detecting x- and γ-rays

- Detectors
  - *Gas-filled detectors*
  - *Scintillators*
  - *Semiconductors*

Telescope systems

- geometric optics
- quantum optics
- wave optics

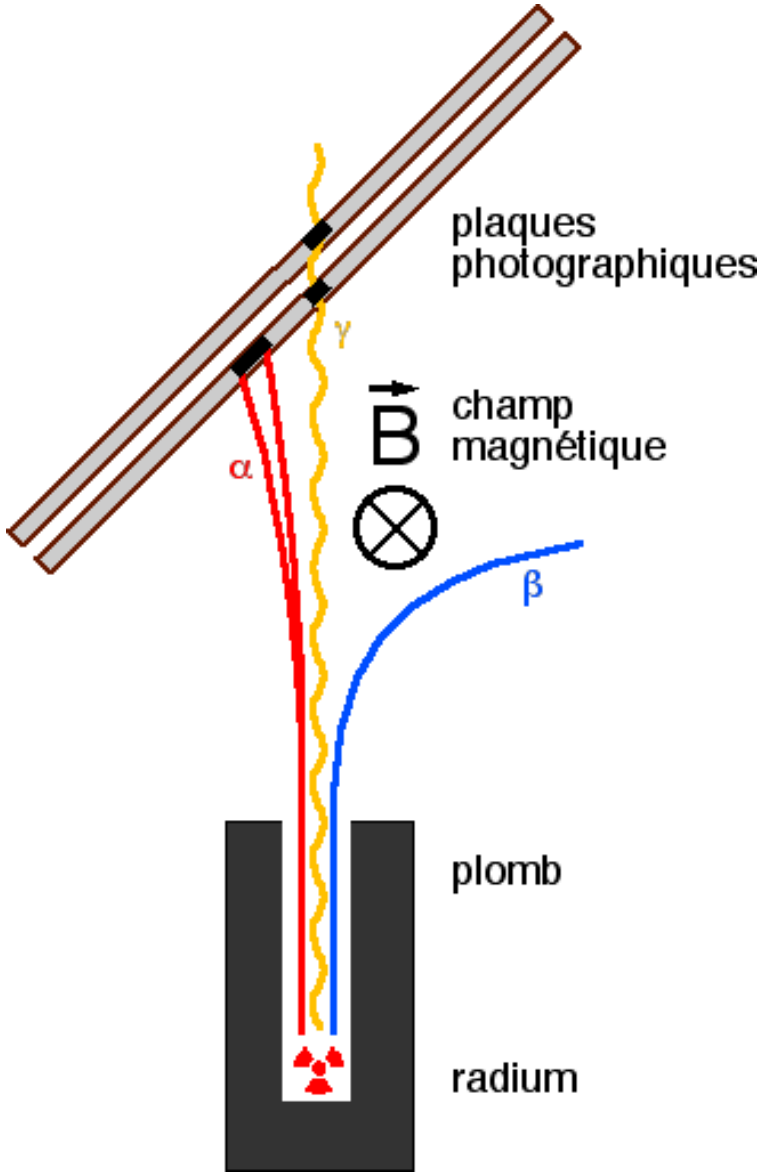
Life cycle of matter



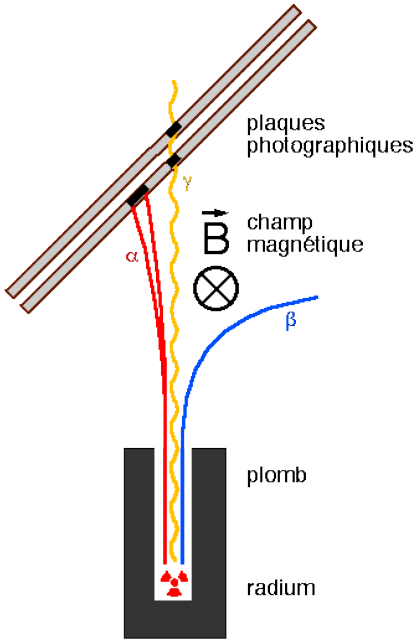
final phases !

Who's missing ?

IR	Herschel	1800
UV	Ritter	1801
radio	Hertz	1886
X	Röntgen	1895
γ	Villard	1900



Session de l'Académie des Sciences du 9 avril 1900



PHYSIQUE. — *Sur la réflexion et la réfraction des rayons cathodiques et des rayons déviables du radium* (¹). Note de M. P. VILLARD.

» Les rayons émis par un petit tube de verre rempli de matière active passaient par une ouverture rectangulaire de 6mm de largeur, pratiquée dans une barre de plomb, et traversaient un champ magnétique. Une plaque photographique 13 × 18, disposée sous une incidence presque rasante, enregistrait les trajectoires : dans ces conditions, on observe que les rayons admis dans le champ se divisent en deux groupes distincts, entièrement séparés après un trajet de quelques centimètres.

» L'un de ces groupes est dévié dans le sens prévu; l'autre, formé par les rayons non déviables, se propage rectilignement dans toute la longueur de la plaque. Ce faisceau non dévié est assez pénétrant pour impressionner, à 25cm de distance, une plaque sensible protégée par plusieurs feuilles de papier noir et une lame d'aluminium; on peut même lui faire traverser une lame de plomb de 0mm, 2 d'épaisseur.

» Les résultats complexes que j'avais observés s'expliquent donc sans difficulté : le faisceau qui, dans mes expériences, traversait sans se réfracter la lame d'aluminium inclinée, correspond aux rayons non déviables : l'expérience a en effet montré qu'il est insensible au champ magnétique. Les rayons déviables, au contraire, se comportent comme les rayons cathodiques et émergent normalement à la lame traversée (²).

» Je me propose de reprendre ces expériences avec des rayons déviables purs.

» Les faits précédents conduisent à admettre que la partie non déviable de l'émission du radium contient des radiations très pénétrantes, capables de traverser des lames métalliques, radiations que la méthode photographique permet de déceler. »

Telescope systems

aperture

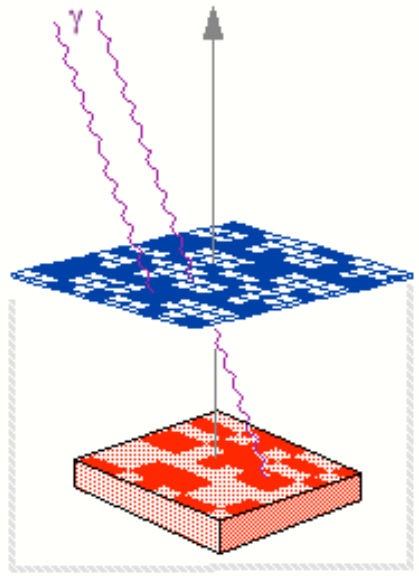
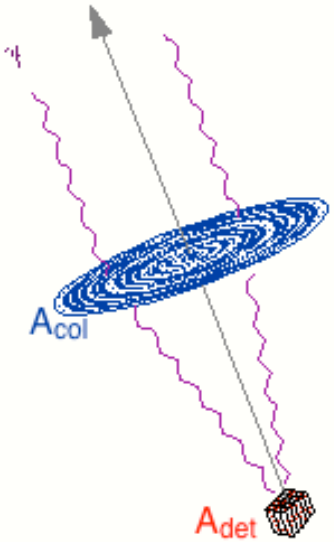
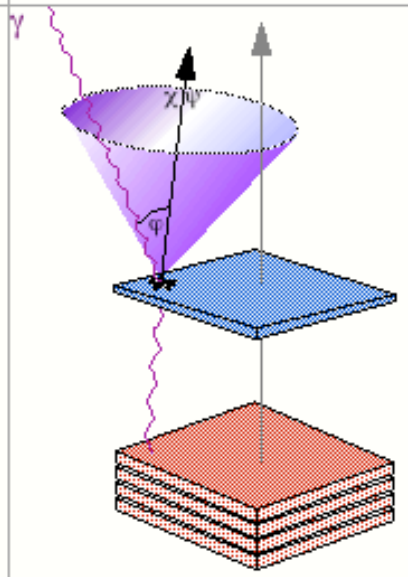
antenna
mirror
lens
Compton D1 detector
hodoscope
non / 4π

detector

coherent detection
bolometer
photovoltaic
film
photon counter

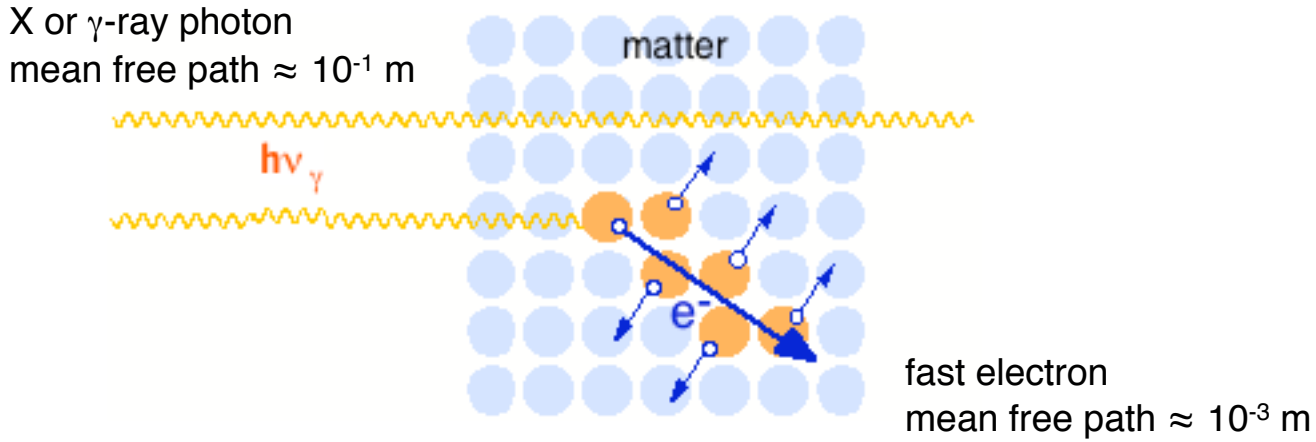
Instrument concepts in nuclear astrophysics

The instrumental categories in nuclear astrophysics reflects our current perception of *light* itself.

	geometric optics	**wave optics**	**quantum optics**
	absorbtion	**coherent scattering**	**incoherent scattering**
aperture / detector			
	e.g. Coded mask telescopes	**e.g. crystal lens telescopes**	**e.g. Compton telescopes**

Detecting x- and γ-rays

I conversion : Gamma-rays do not interact with matter unless they undergo a "catastrophic" interaction. In all cases of practical interest, Gamma-rays are detected by their production of secondary electrons.



II ionization of detector medium by fast electrons -> creation of large number of charge carriers

III collection (reconversion) of detector signal, current amplification and conversion by an ADC

Detecting x- and γ-rays

Gas-filled detectors

- Ionization chambers
- Proportional counters
- Geiger counters

Scintillators

- Scintillators
- Photomultipliers
- Spectral resolution : scintillators vs semiconductors

Semiconductors

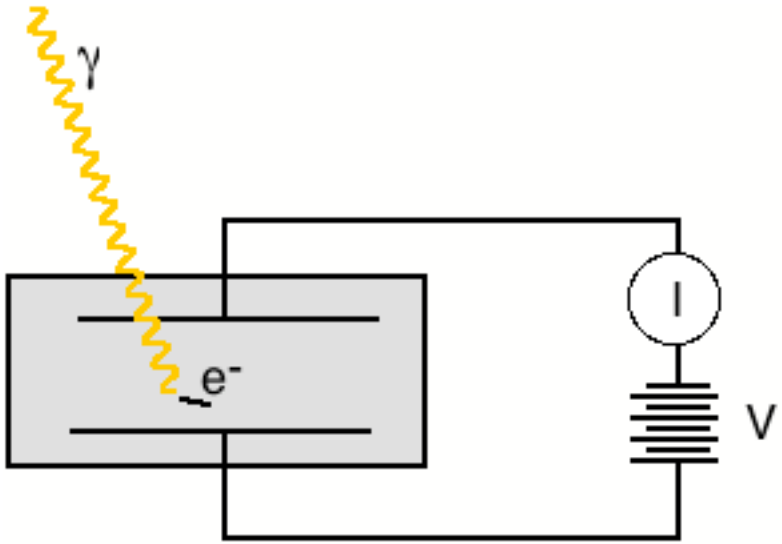
- Narrow gap / low temperature semiconductors
- Wide bandgap / high temperature semiconductors
- Examples

Detectors at ultra-low temperatures

- Bolometers
- Phonon-detectors

Gaz-filled detectors

Ionization chambers, Proportional counters, Geiger counters



creation of n_o ion pairs (free electron and positive ion)

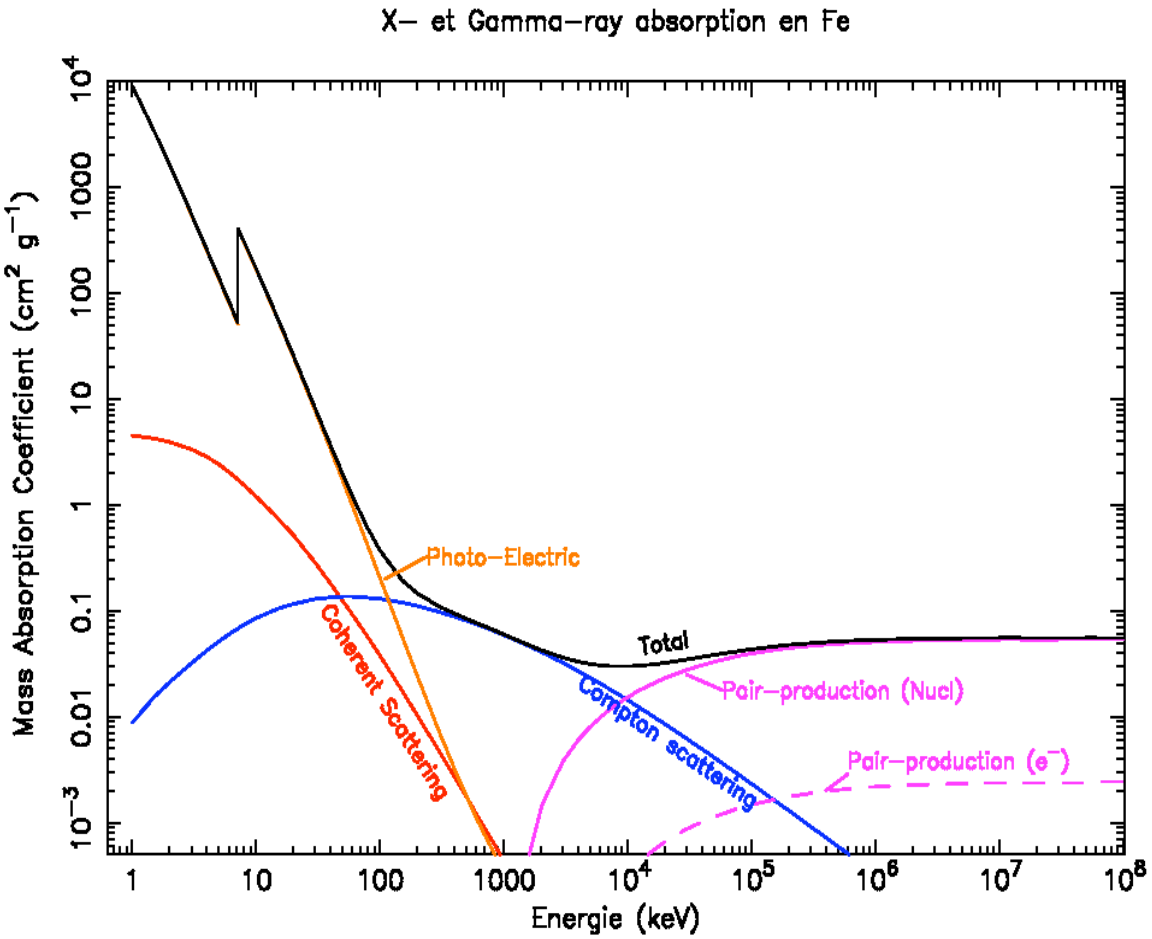
$n_o \approx E\gamma / W$ (e.g. N ≈ 30000 for a 1 MeV gamma-ray)

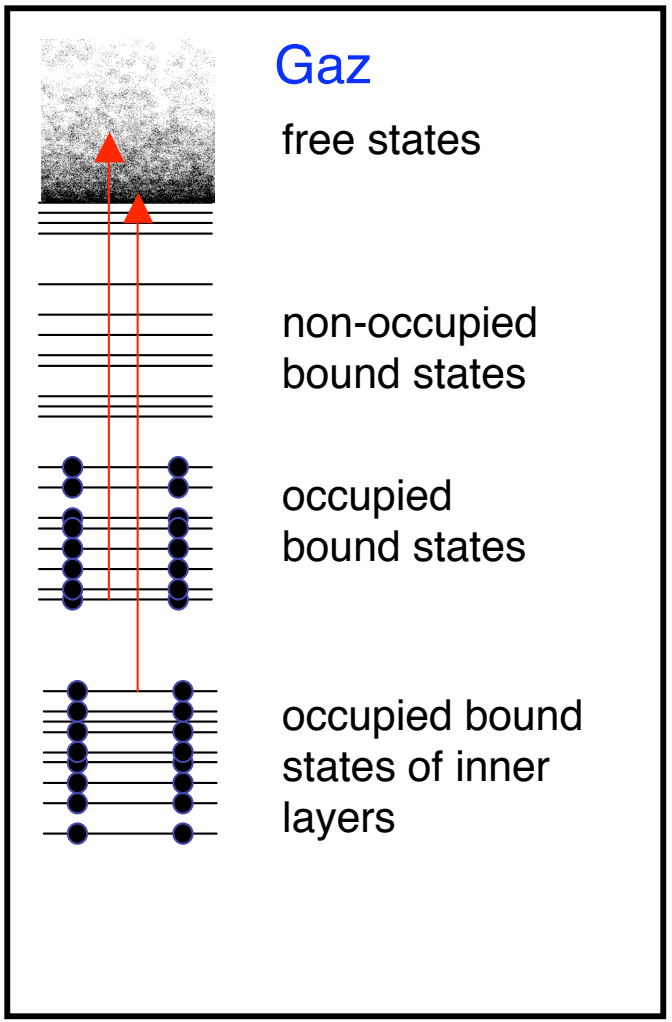
E_i ionization energy (least tightly bound e) ≈ 10 - 20 eV

W average energy required to produce ion pair ≈ 30-35 eV

$E\gamma \sim n_o$ (for W independent of $E\gamma$)

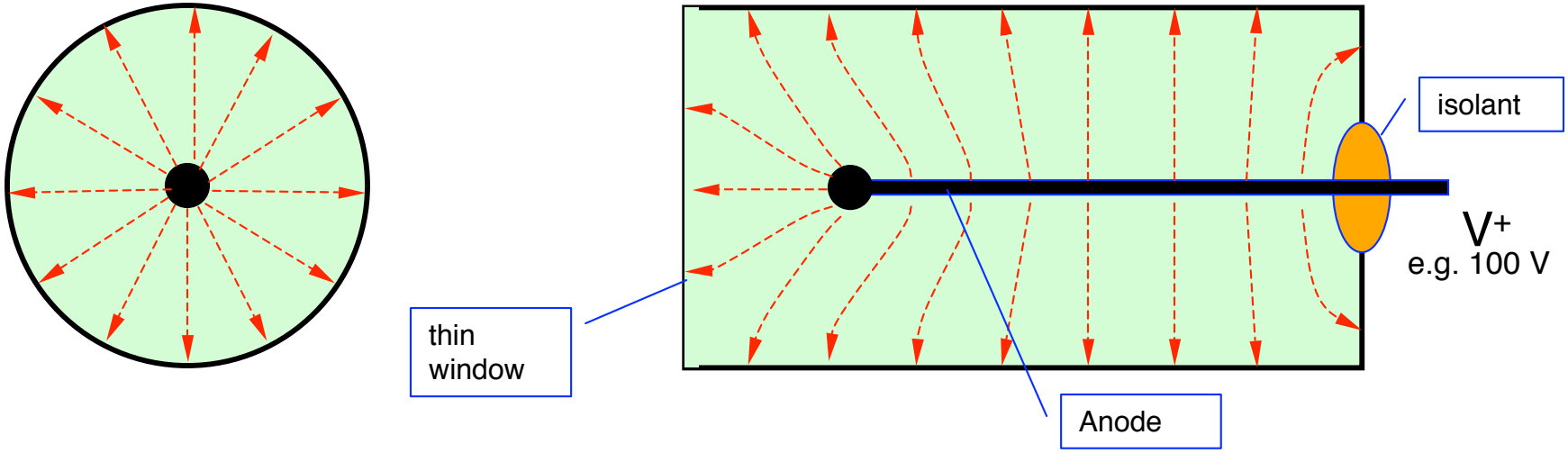
Gaz detectors





x rays :
photoelectric absorption is most likely

Gaz-filled detectors



with enhancing electric field ... recombination of electrons and ions is overcome :

ionisation chambers

- all charges created by direct ionization are collected
- usually operated in current mode (radiation dose meas.)

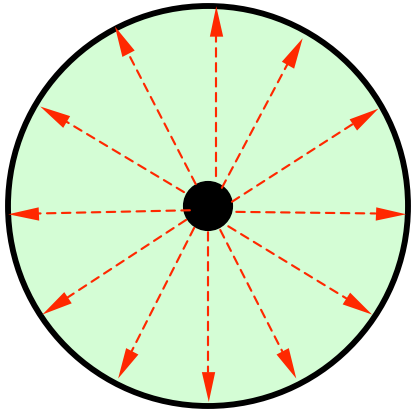
proportional counters

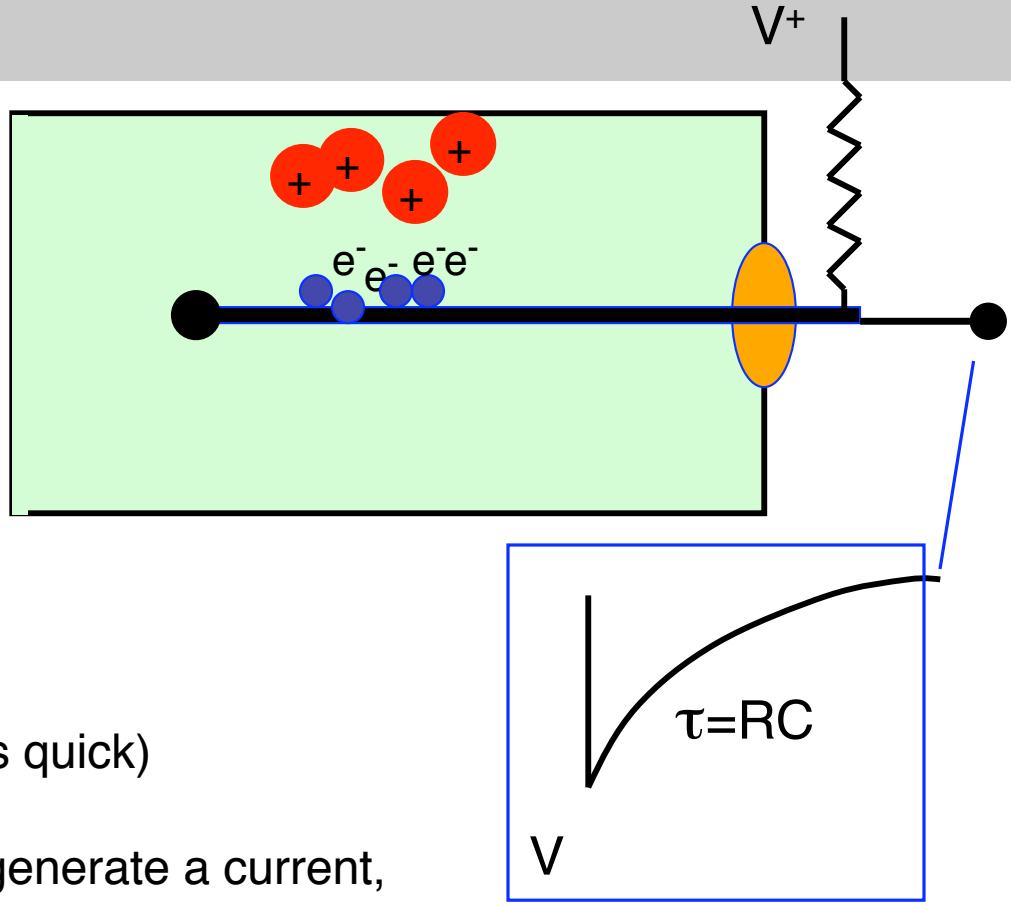
- gas multiplication of directly ionized charge
- amplified charge proportional to incident photon energy

Geiger counters

- gas multiplication by typically 10^6 to 10^8

ionisation chambers





e- drift towards anode (quick)
ons drift towards cathode (less quick)

while large photon fluxes will generate a current,
photons arriviving one by one => series of pulses (charge dq = hν/W)

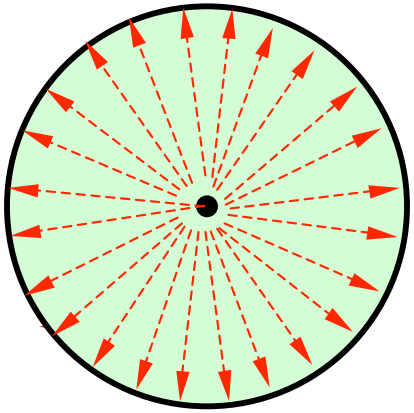
the capaciy of the detector being C, pulses of dV=dq/C will be produced

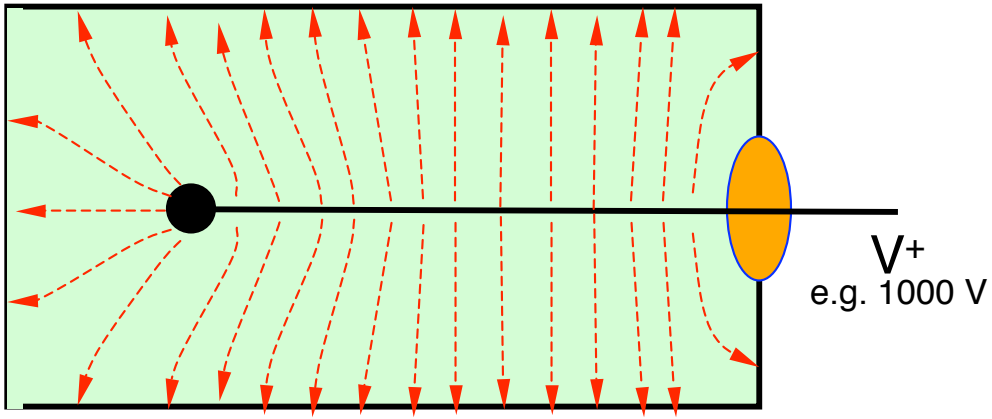
after every pulses there is an exponential recovery with a characteristic time of RC
where RC is the resistance in serie with the HV supply.

Proportional Counters

ionisation are rarely used as radiation detectors in high energy astronomy

proportional counters have spectroscopic capabilites





very similar, bu
- thinner node
- higher voltage

as a consequence
=> high electric field close to the anode
⇒e- that are close to the anode,
⇒ free e^- will be accelerated to energies larger than the ionization energies => additional ion pairs
avalanche ! (signal amplification by ~10^4)

Proportional Counters

At higher electric fields, free e^- will be accelerated to energies larger than the ionization energies => additional ion pairs

threshold for gas multiplication ~ 10^6 V/m (at 1 atm)

$dn_e/n_e = \alpha\, dx$ increase of number of e^- per unit pathlength

α Townsend coeff. ~ with field strength

$n(x) = n_e(0)e^{\alpha x}$ exponential growth : Townsend avalanche

in a proportional counter

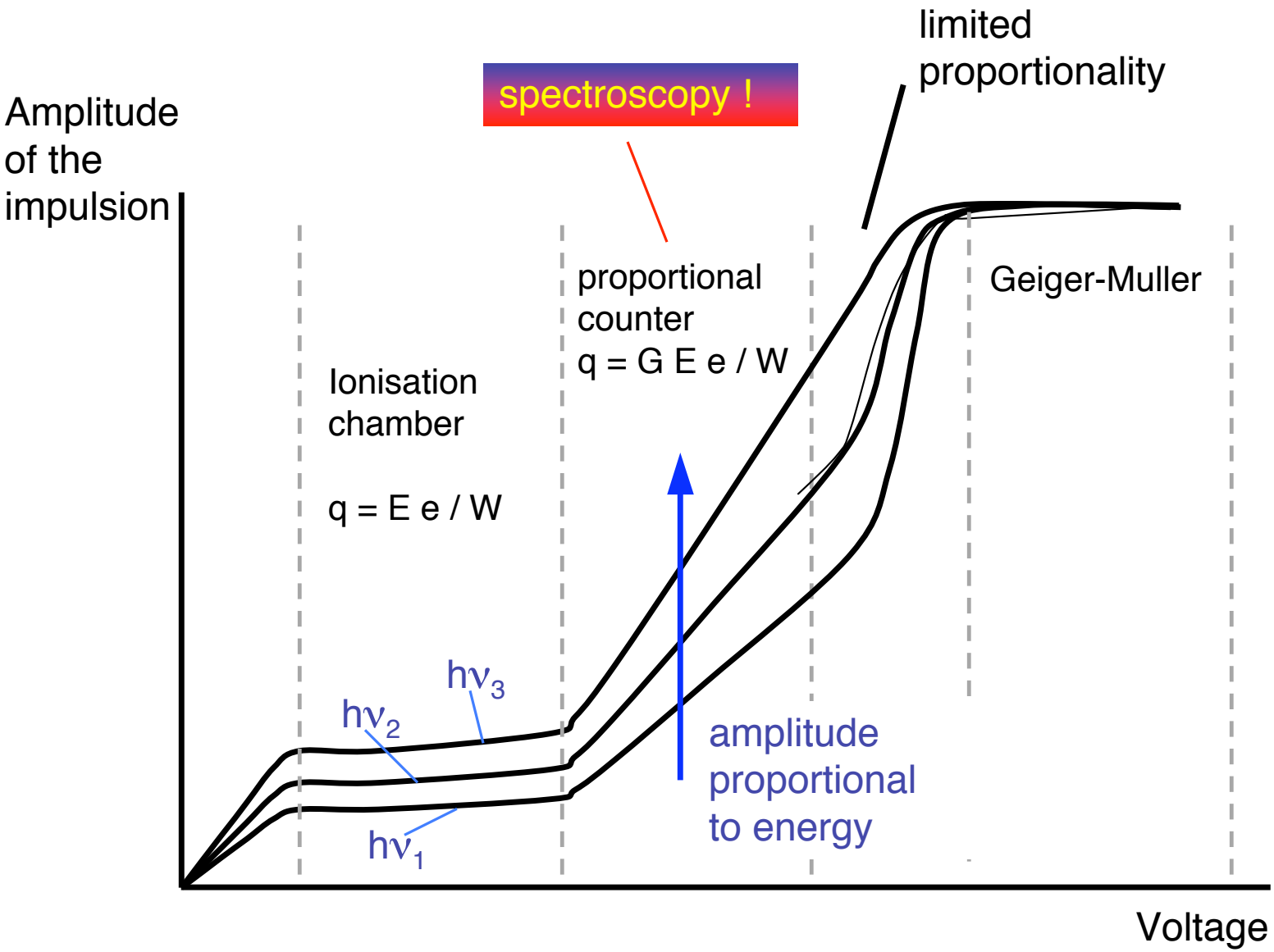
- the avalanche terminates when all e^- collected
- $n_{\text{secondary ion pairs}} \sim n_{\text{primary ion pairs}} \sim E\gamma$
- multiplication by > 10^3 (=> external amps.)
- improved S/N with resp. to ion chambers

fill gases : e.g. Ne, Ar, Xe

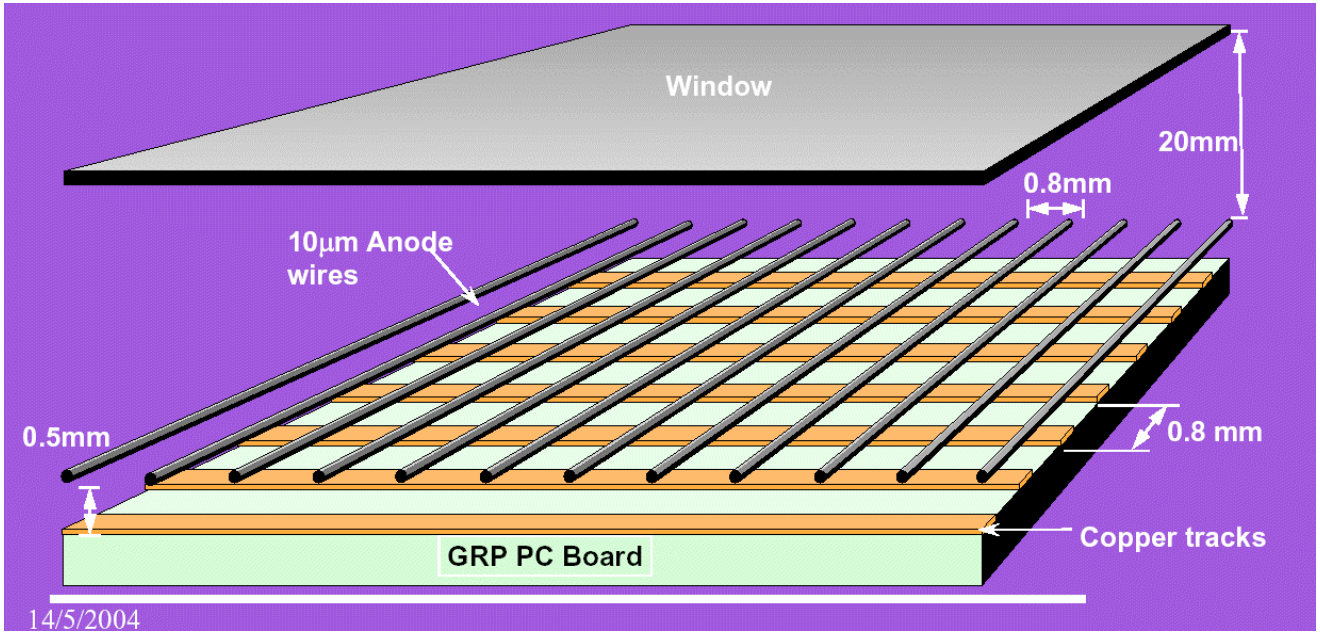
quench gas : absorbs undesired UV photons (e.g. CH_4)

energy resolution : 10% - 13% (12% for Ar + 0.5 % CH_4)

Proportional Counters



MWPCs



MWPC
(Multiwire Proportional Counter)

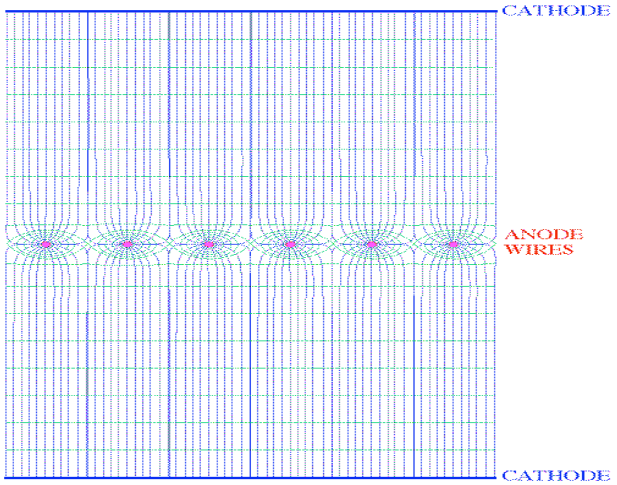


Fig. 1: The multiwire proportional chamber: thin, parallel anode wires are mounted symmetrically between two cathode meshes.

Scintillators

fluorescence

- instantaneous emission of visible light after excitation / ionization
- (>< phosphorescence - retarded fluorescence)

the ideal scintillator :

- converts fast electron energy into scintillation light with high efficiency
- linear conversion
- medium transparent to its own scintillation light
- fast decay time of induced luminescence (fast signals)
- large size at constant quality
- refraction index ≈ 1.5 (close to glass <-> PMT's)

two main scintillator types

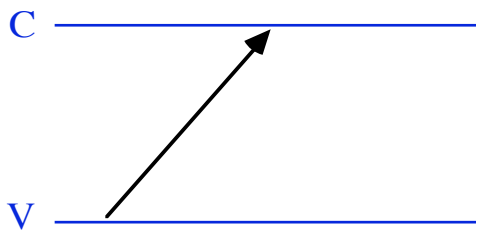
organic scintillators (liquid, plastic) <-> PSD/neutrons

inorganic scintillators : spectroscopy (<-density)

inorganic scintillators

electrons in isolators / semicond. can only occupy two discrete energy bands

- *conduction* band : e^- can freely migrate through crystal
- *forbidden* band (band gap) : no e^- in pure crystal
- *valence* band : e^- bound at lattice sites



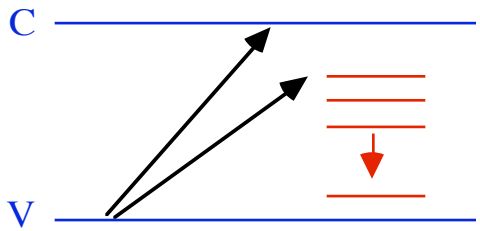
Problem : return of e^- to valence band inefficient, at best emission of an UV photon

Solution :

small amounts of activators (impurities) modify band structure

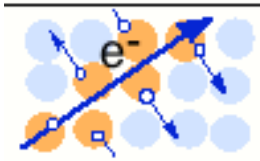
=> ∃ excited states within gap

=> deexcitation to valence band results in the emission of visible photons

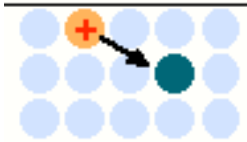


inorganic scintillators *Scenario of an interaction*

γ-ray interaction with matter produces a secondary e⁻
photoeffect, Compton, pair-production

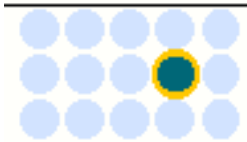


ionization : fast e⁻ traversing crystal gen. a large number of e⁻/hole pairs
e⁻ are raised from the valence-band to the conduction-band

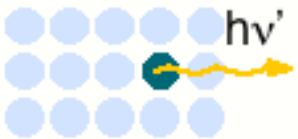


holes quickly drift to an activator site
$E_{ionization}$ of impurity < $E_{ionization}$ of typical lattice site

e⁻ are free (conduction)
until they encounter an ionize impurity ...



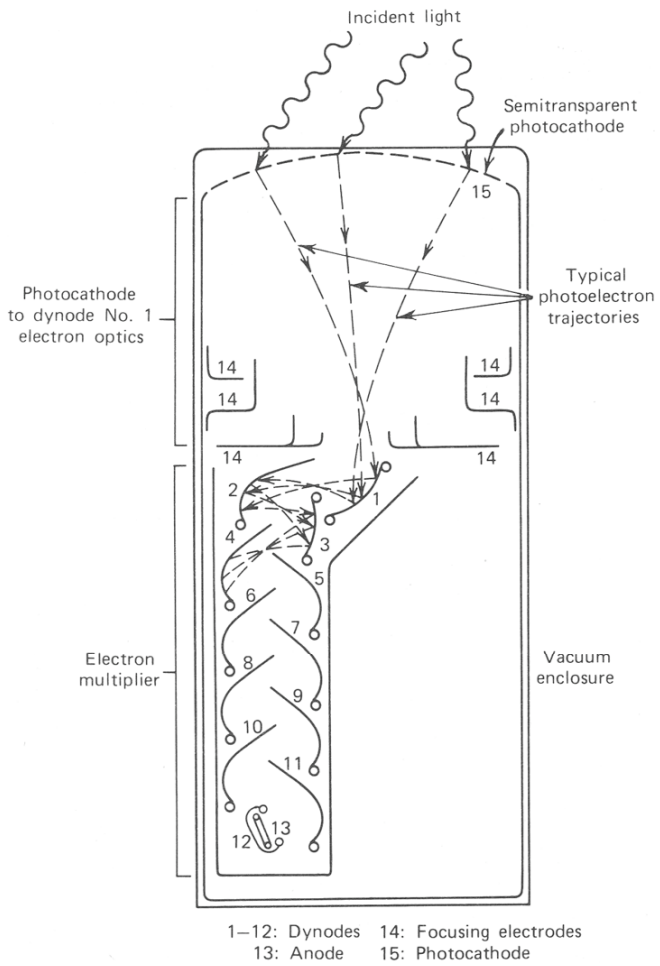
excitation : e⁻ fall into impurity => neutral, excited atom
(possibly with allowed transition to ground state)



deexcitation : transition in visible domain (for appropriate activators)
(excited states $t_{1/2}$ ~10^{-7}s)

visible photons interact with matter e.g on the photocathode of a PMT
(who transforms em-radiation back into electrons ...)

Photomultipliers (PMT)



Knoll 1989

photocathode

- conversion of incident photon -> photoelectron
- photoelectric effect : $h\nu = E_e + W$ (1.5-2eV) ≈ 3eV

  quantum efficiency QE ≈ 20-30%

electron multiplication

- $E_{photoelectron} < 1$ eV
- electrons are focused by electrodes
- secondary e^- emission on dynodes (bandgap≈2-3 eV)
- potential of 1st dynode $U_1 \approx X \cdot 100$ V => $X \cdot 30$ e^-

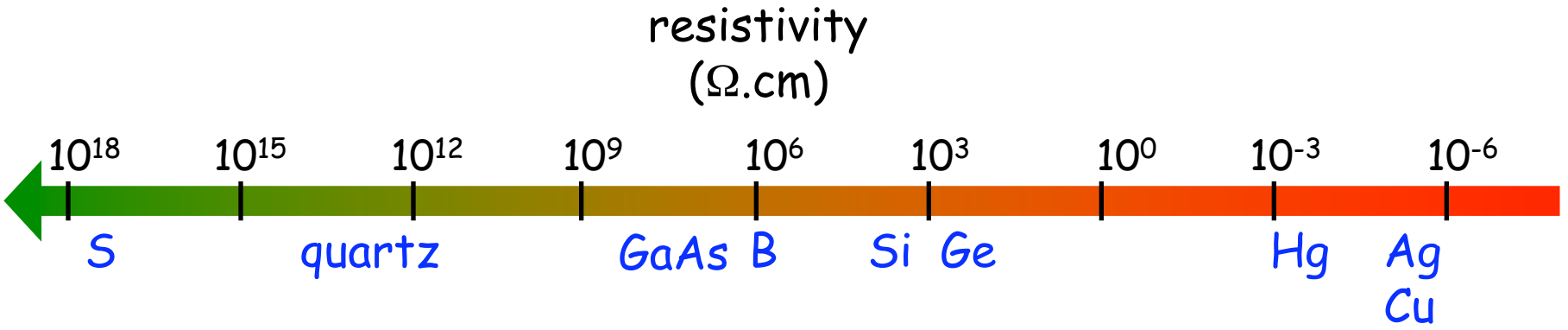
charge collection on anode

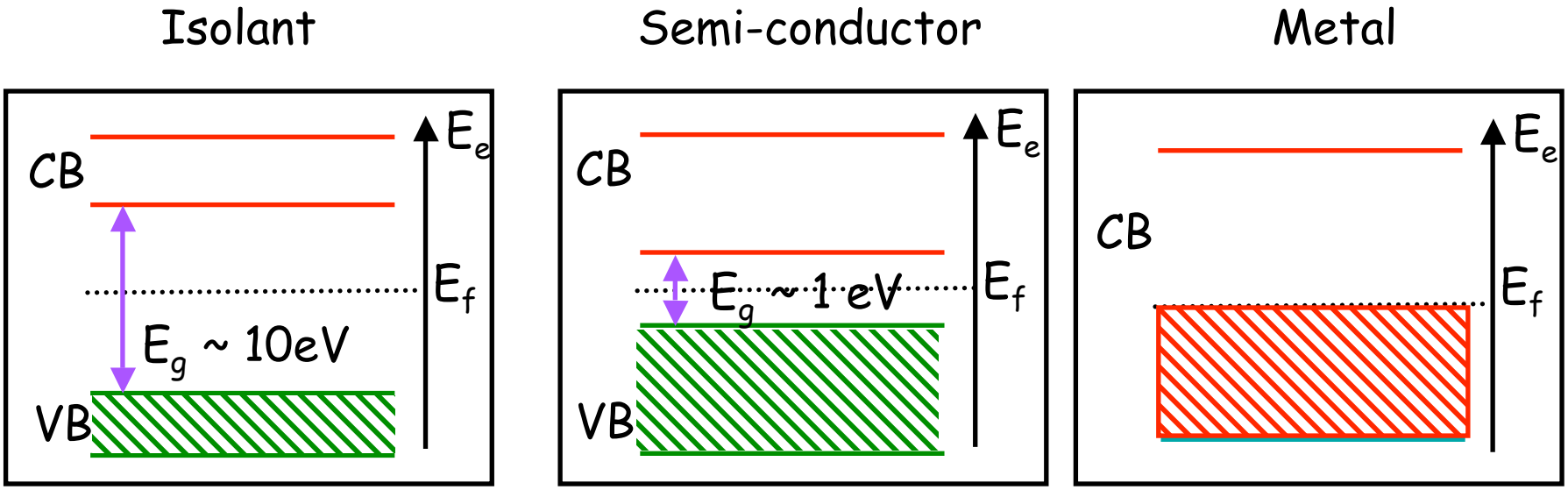
amplification factors of 10^7 - 10^9

effects on energy resolution :

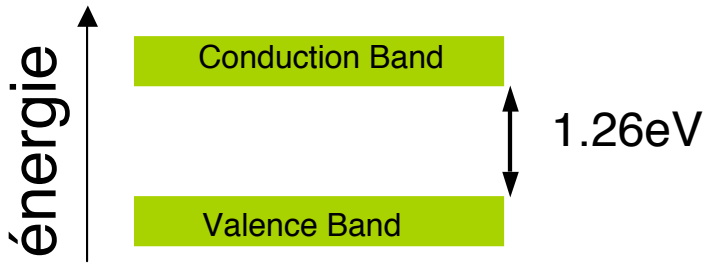
- electron statistics (PMT)
- gain variation
- information loss (vis. light refl. in crystal etc.)

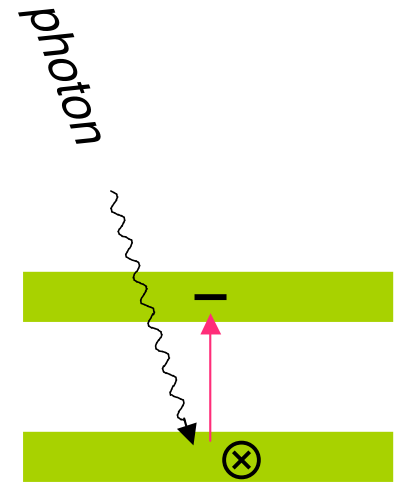
Semiconductor Detectors





Semiconductor Detectors





⊗: trou -: électron

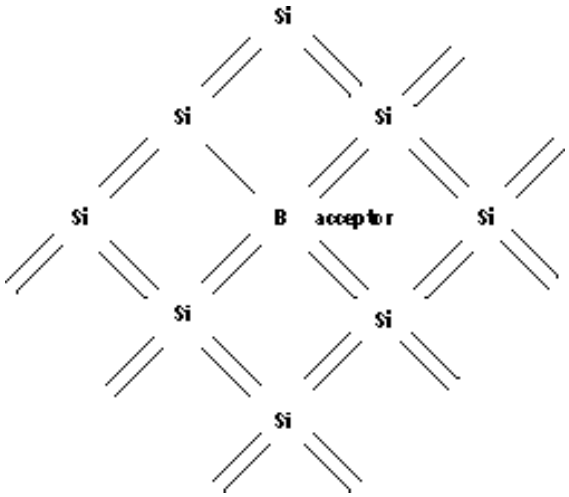
Semiconductor Detectors

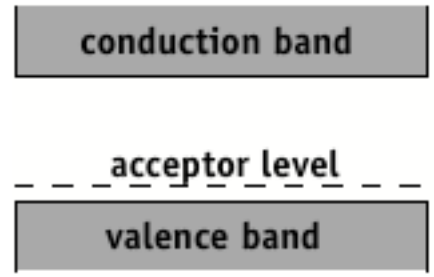
thermal agitation => n **e**$^-$ pass to the CB
leaving vacant p states in the VB : p **holes**

$$n = p$$

electric field : **e**$^-$ -> CB, **H**$^+$ -> VB

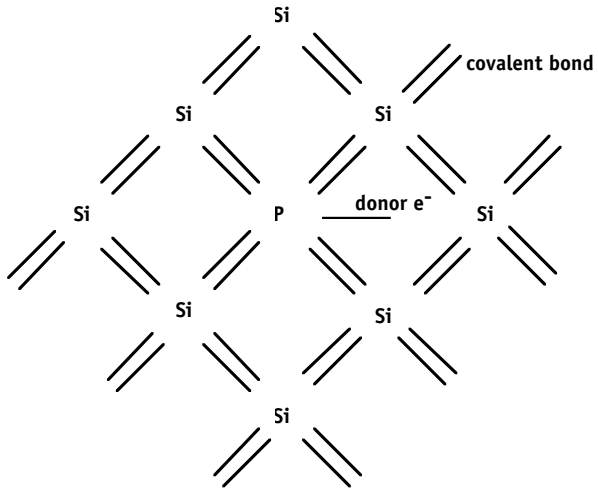
Semiconductor Detectors

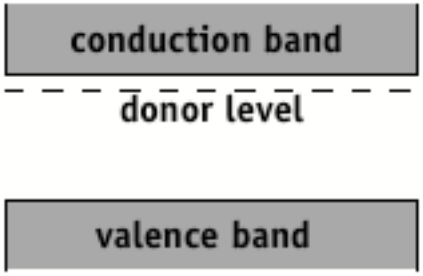




$p \approx N_A$ (p dominanted by acceptors)

holes are majority carriers
electrons are minority carriers

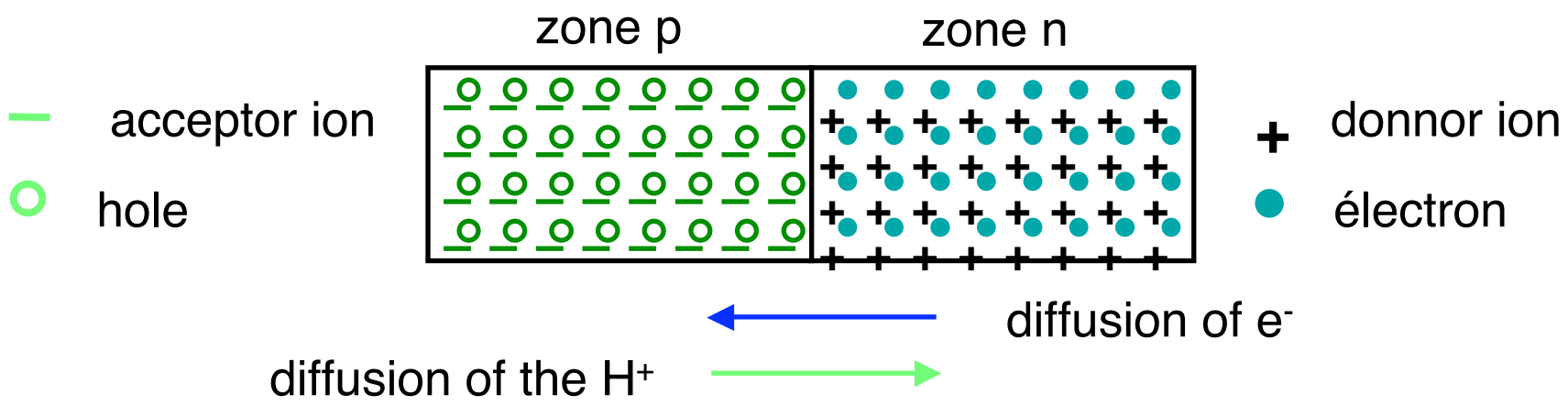


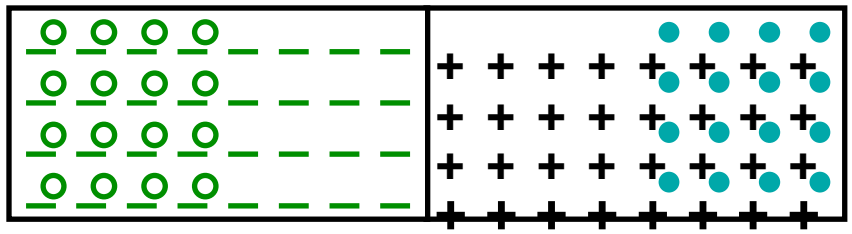


$n \approx N_D$ (n dominanted by donor e^-)

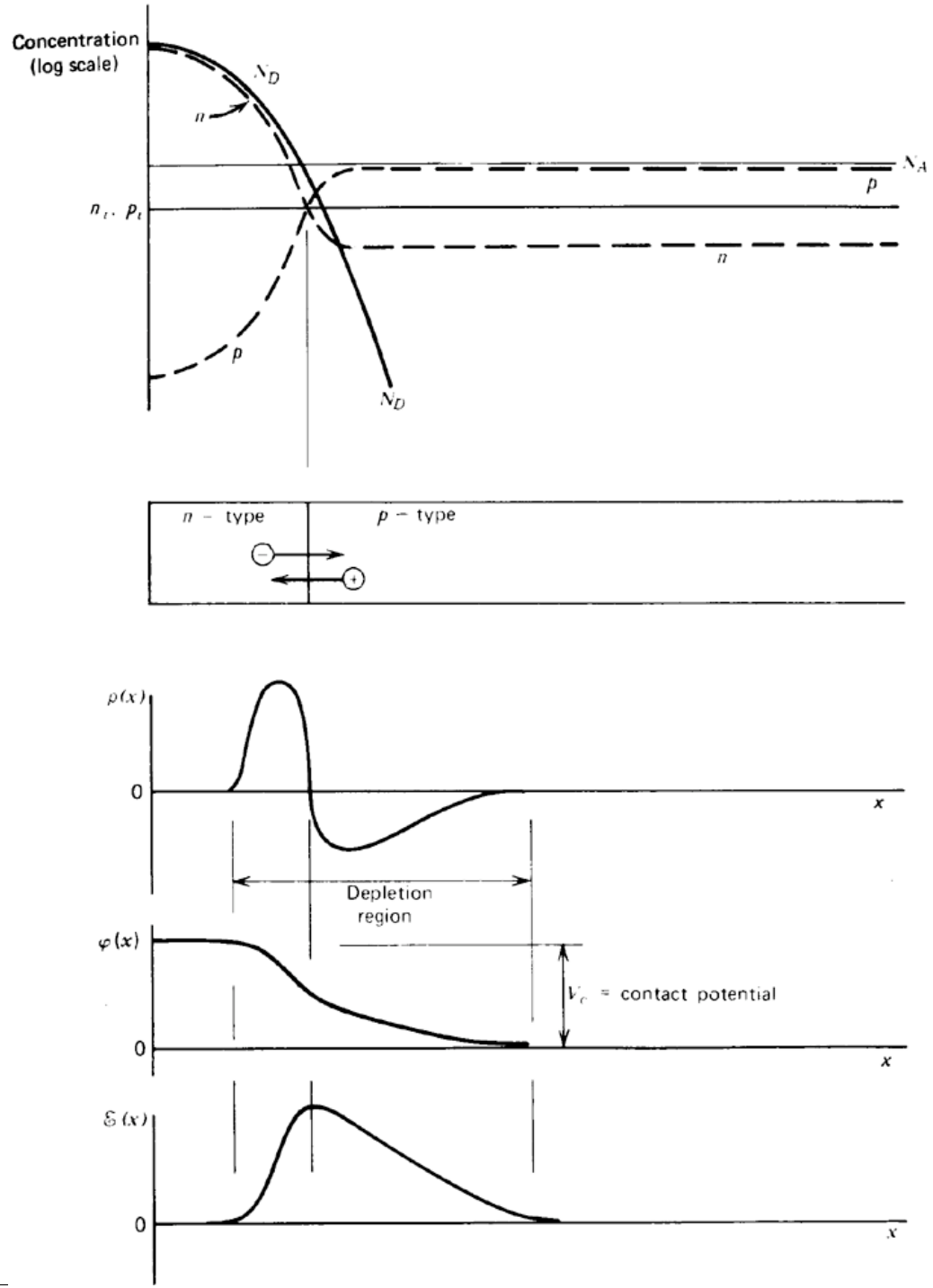
electrons are majority carriers
holes are minority carriers

Semiconductor Detectors : junction pn





equilibrium : zone w/o free carriers (depleted) : high resistivity

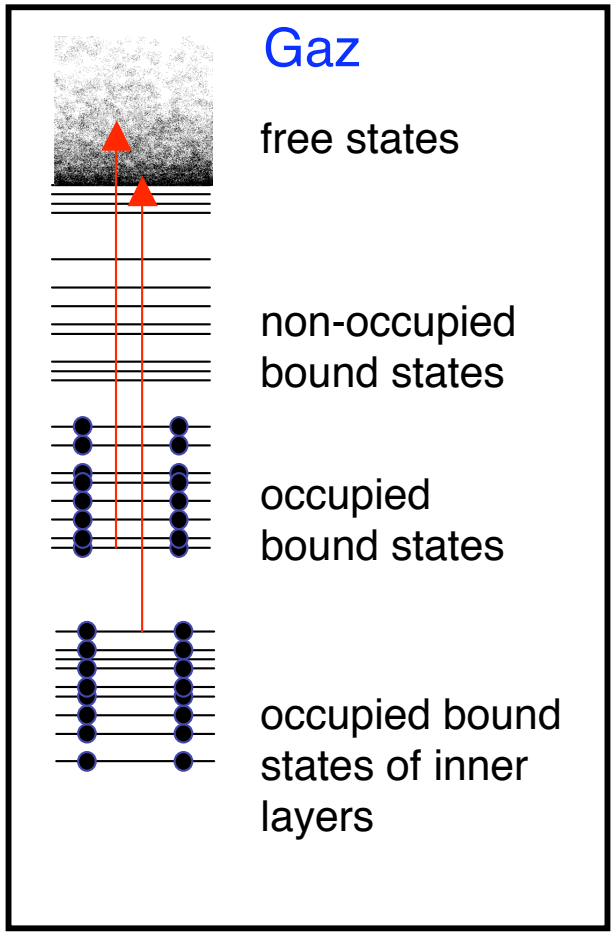


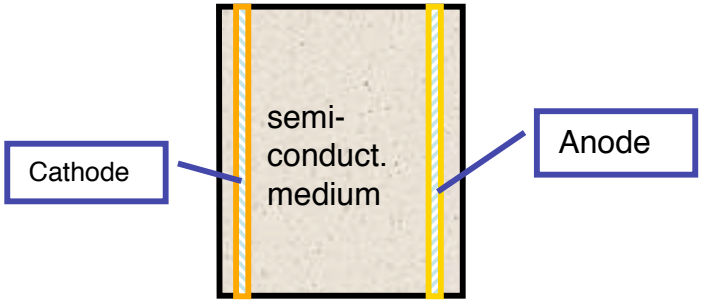
charge density

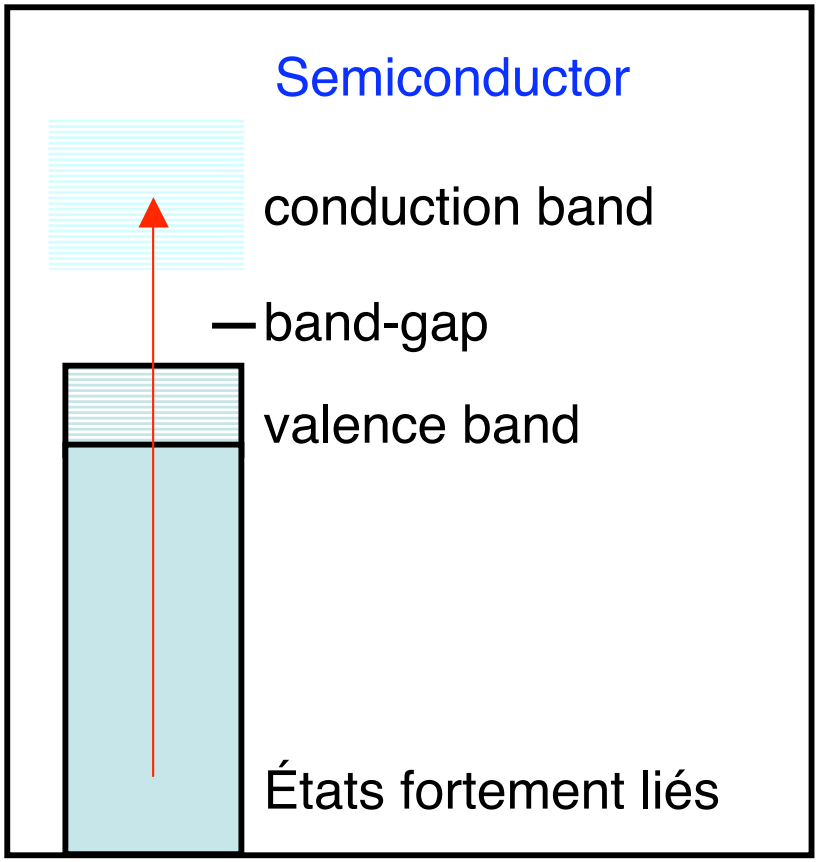
potential

electric field

Détecteurs à Gaz - Détecteurs à semi-conducteur







Gaz filled detectors vs. semiconductor detectors

Gaz filled detectors

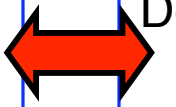
- Ions,
- free electrons

- Density ~ 0.01 g cm^{-3}

- window to contain gaz

- W (energy to form electron-ion pair)
  tens of eV

- maximum energy ~ 50 keV
  (high pressure Xe detector)



semiconductor detectors

- Holes in valence band,
- free electrons in conduction band

Density ~ 1.5 - 5 g cm^{-3}

window not (always) required

- W (energy to form electron-hole pair)
  some eV

- maximum energy ~ 10 MeV
  (large size Ge detectors)

Semiconductor Detectors

probability P that electron-hole pair is thermally generated

$P(T) \sim T^{3/2} e^{(-Eg/2kT)}$

T	temperature
E_g	bandgap energy
k	Boltzmann const

Intrinsic semiconductors (pure material) : $n_i = p_i \approx 2.4 \cdot 10^{13}$ cm^{-3} in Ge

n : concentration of e$^-$ in conduction band $\approx 1.5 \cdot 10^{10}$ cm^{-3} in Si

p : concentration of holes in valence band

Impurities / doping

eg. in Si $n_i \approx 10^{10}$ cm-3, with 2 ppm of impurities, this is 10^{17} atoms cm^{-3}

$np = n_i p_i$

$\Rightarrow \quad n \approx 10^{17}$ cm^{-3} , $p \approx 10^3$ cm^{-3}

Ionization energy : energy to form a e$^-$/hole pair *e* ~ 3 eV (Ge) , 30 eV (NaI)

Narrow bandgap semiconductor detector materials

Composition	Density [g/cm^3]	Mean Z	Bandgap [eV]	E e$^-$hole pair[eV]
Si (300 K)	2.33	14	1.12	3.61
Ge (77 K)	5.32	32	0.74	2.98

Wide bandgap semiconductor detector materials

room temperature : wider bandgap (> 1.5 eV) reduces thermal leakage current

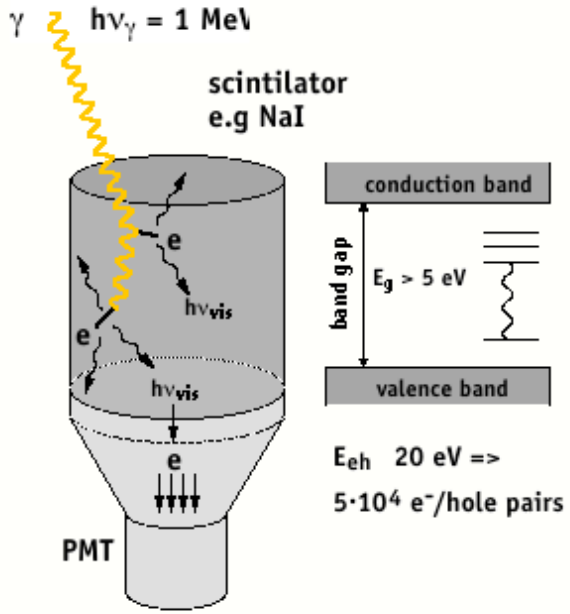
$p(T) \sim T^{3/2}\, e^{[-Eg/2kT]}$ probability that e^-/hole pair is thermally generated per unit time

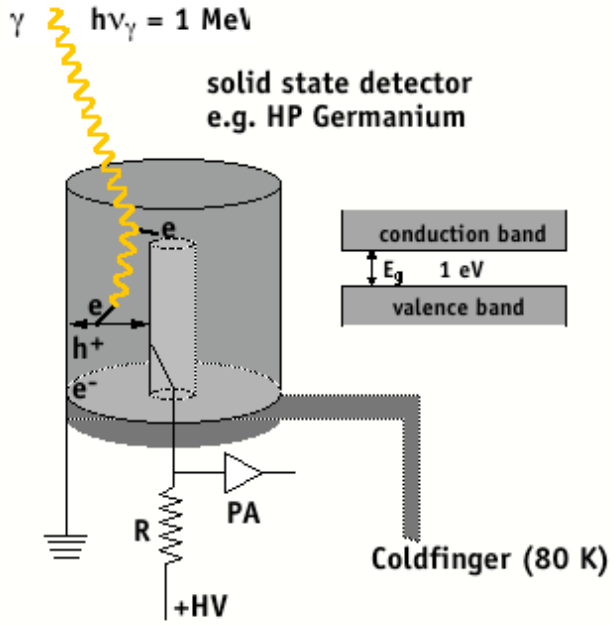
compound semiconductor materials with one or more high Z elements
=> excellent efficiencies

practical limitations : small size of sufficiently pure detectors
low drift velocities (holes)
=> recombination, trapping enhanced

Composition	Density [g/cm^3]	Mean Z	Bandgap [eV]	energy per e^--hole pair [eV]
CdTe	6.2	50	1.6	4.43
HgI_2	6.36	62	2.15	4.22

scintillator vs. semiconductor





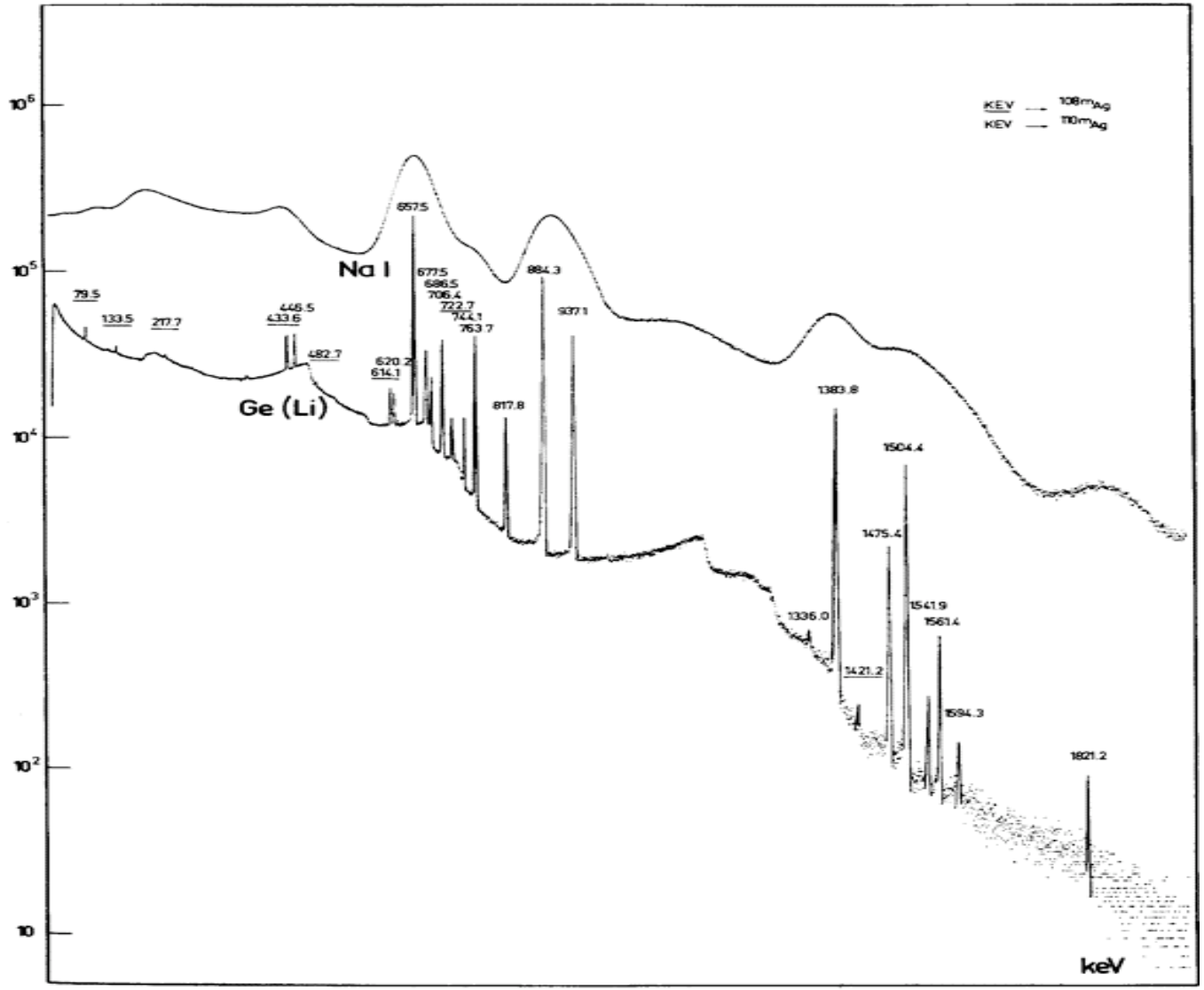
Scintillation eff. ~ 12% => 120 keV (V/UV)
Vis. photon energy ~ 3eV => 40'000 V/UV ph
on photocathode => 20'000 photons
quantum eff. QE ≈ 20% => 4'000 photo-e$^-$ (N_{sci})

$R = 0.42\,(N_{sc}/F_{sci})^{1/2} \approx 25$

Energy to form e-/hole pair : $E_{eh} \approx 3$ eV
$N_{sem} \approx 10^6/3\text{eV} \approx$ 300'000 charge carriers
$F_{sem} \approx$ 0.06-0.14 (Fano factor)

$R = 0.42\,(N_{sem}/F_{sem})^{1/2} \approx 500$

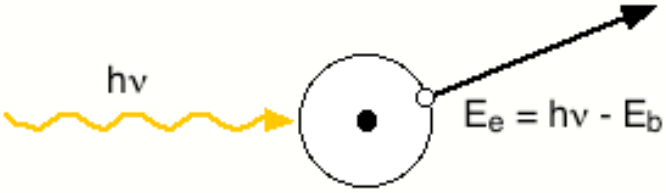
Comparison : scintillator / semiconductor spectra

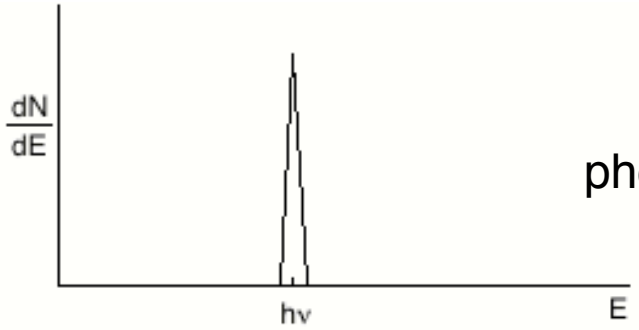


Knoll, 1989

γ-ray interaction and spectra

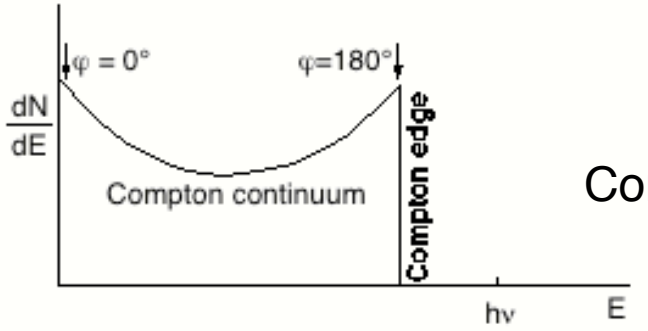
photoelectric effeect





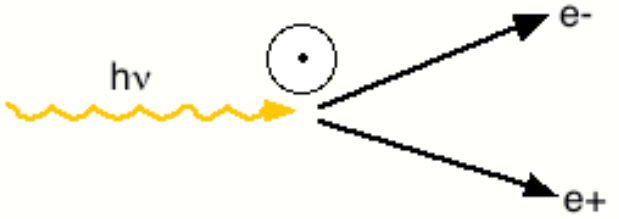
photopeak

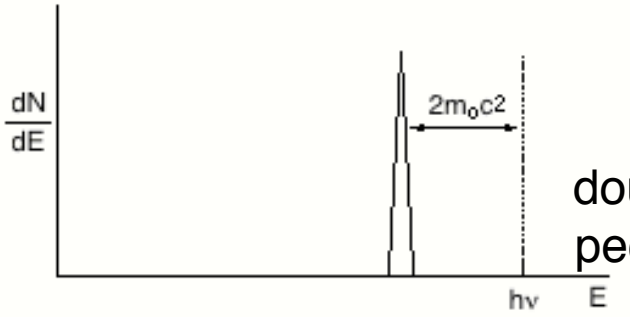
Compton effect



Compton edge

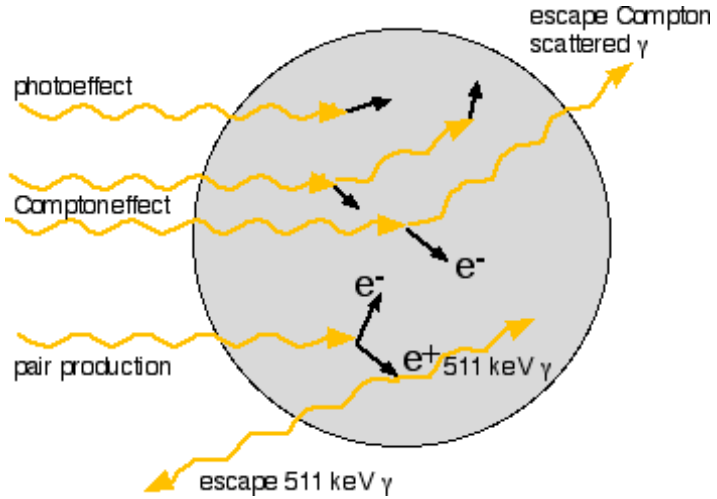
pair-production

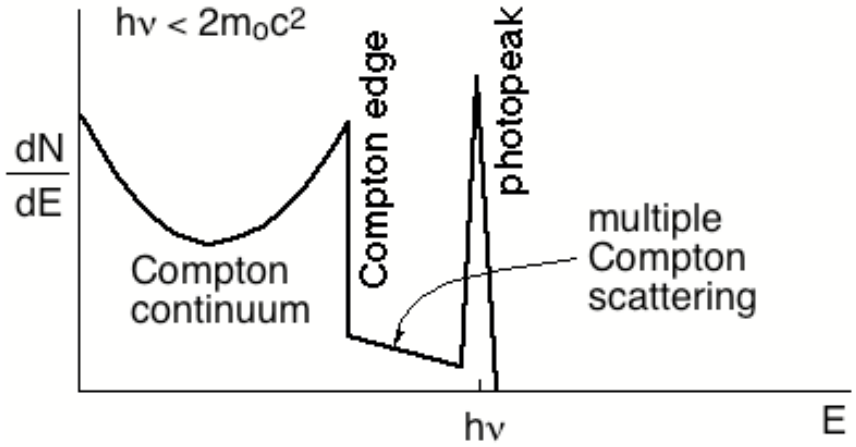


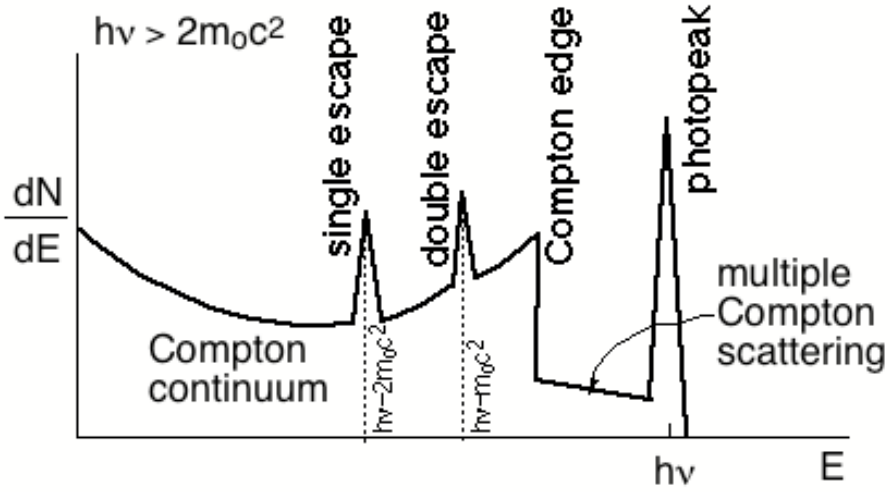


double escape peqak

Gamma-Ray Spectra







Compton edge

$$h\nu_c = h\nu - h\nu_b$$

$$h\nu_b = \frac{h\nu}{1 + (2\,h\nu/m_o c^2)}$$

coherent vs incoherent spectroscopy systems

coherent spectroscopy

spatial decomposition ("dispersive systems") or temporal modulation of incoming wave

uses periodic quality of light

spectrometer	domain	R
gratings	visible, UV	10^3-10^6
	soft X rays	10^2-10^3
Bragg-crystal	soft X rays	10^3
Fabry-Perot	visible, IR	10^4-10^6
heterodyne	radio	> 10^6
	mm, sub-mm	> 10^5
atomic resonance	visible, UV	10^7

resolution

eg. grating $R \leq 2N_a/\lambda$

N_a : grating width

incoherent spectroscopy

non-dispersive systems : measurement of photon energy deposit in detector

uses quantum quality of light

spectrometer	domain	R
semiconductors	soft X	< 50
tunneling junction	soft X	10^2-$(6 \cdot 10^2)$
NaI	hard X	< 10
CdTe	hard X	10-10^2
Ge	hard X, γ	10^2 - 10^3

resolution

eg. semiconductor $R \sim N^{1/2} \sim \varepsilon^{-1/2}$

N number of charge carriers produced

ε energy required to create e^-/hole pair

($\varepsilon > E_g$ bandgap energy)