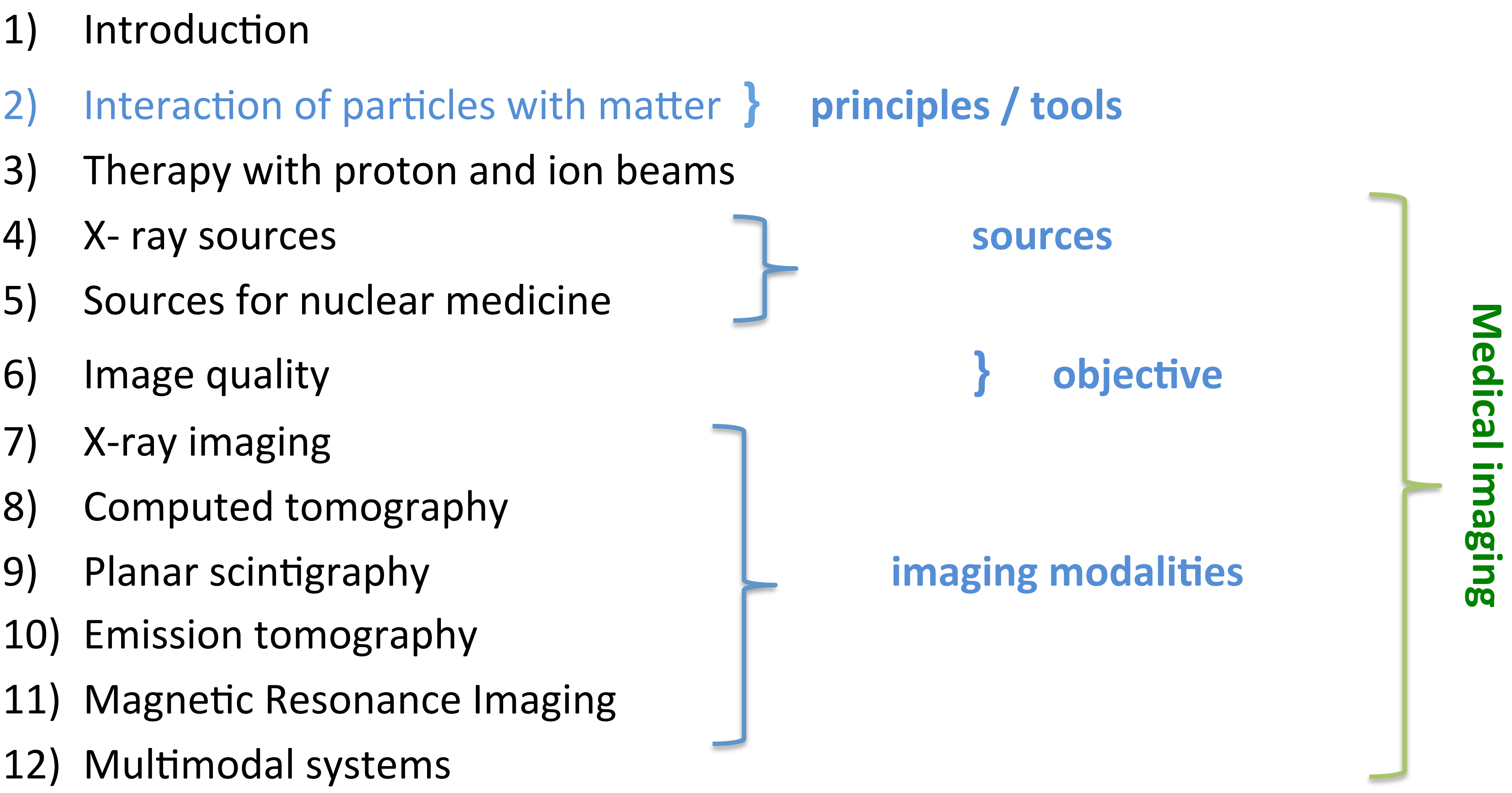
Structure of the course



1) Introduction
2) Interaction of particles with matter } **principles / tools**
3) Therapy with proton and ion beams
4) X- ray sources
5) Sources for nuclear medicine

sources

6) Image quality } **objective**
7) X-ray imaging
8) Computed tomography
9) Planar scintigraphy
10) Emission tomography
11) Magnetic Resonance Imaging
12) Multimodal systems

imaging modalities

Medical imaging

The course will not cover ultrasound and optical imaging

1. Therapy

Particle of interest:	photons, electrons, protons, ions
Energy range:	~1-500 MeV

2. Imaging

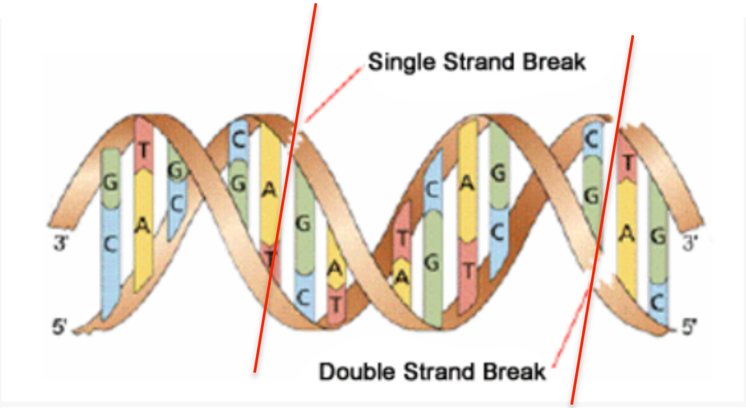
Particle of interest:	photons
Energy range:	~10-511 keV

Therapy

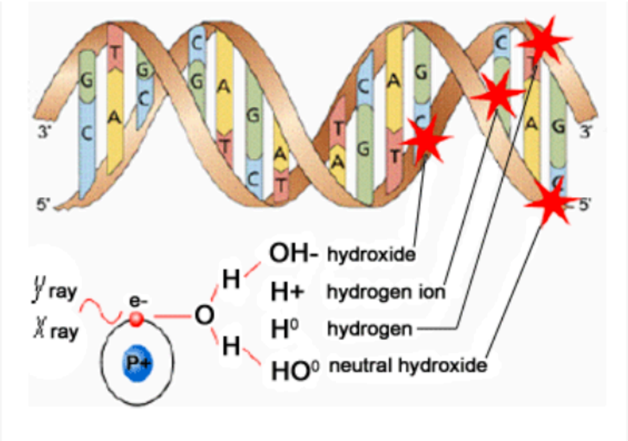
When ionizing radiation comes in contact with a cell any or all of the following may happen:

1. It may pass directly through the cell without causing any damage.
2. It may damage the cell but the cell will repair itself.
3. It may affect the cell's ability to reproduce itself correctly, possibly causing a mutation.
4. It may kill the cell. The death of one cell is of no concern but if too many cells in one organ such as the liver die at once, the organism will die.

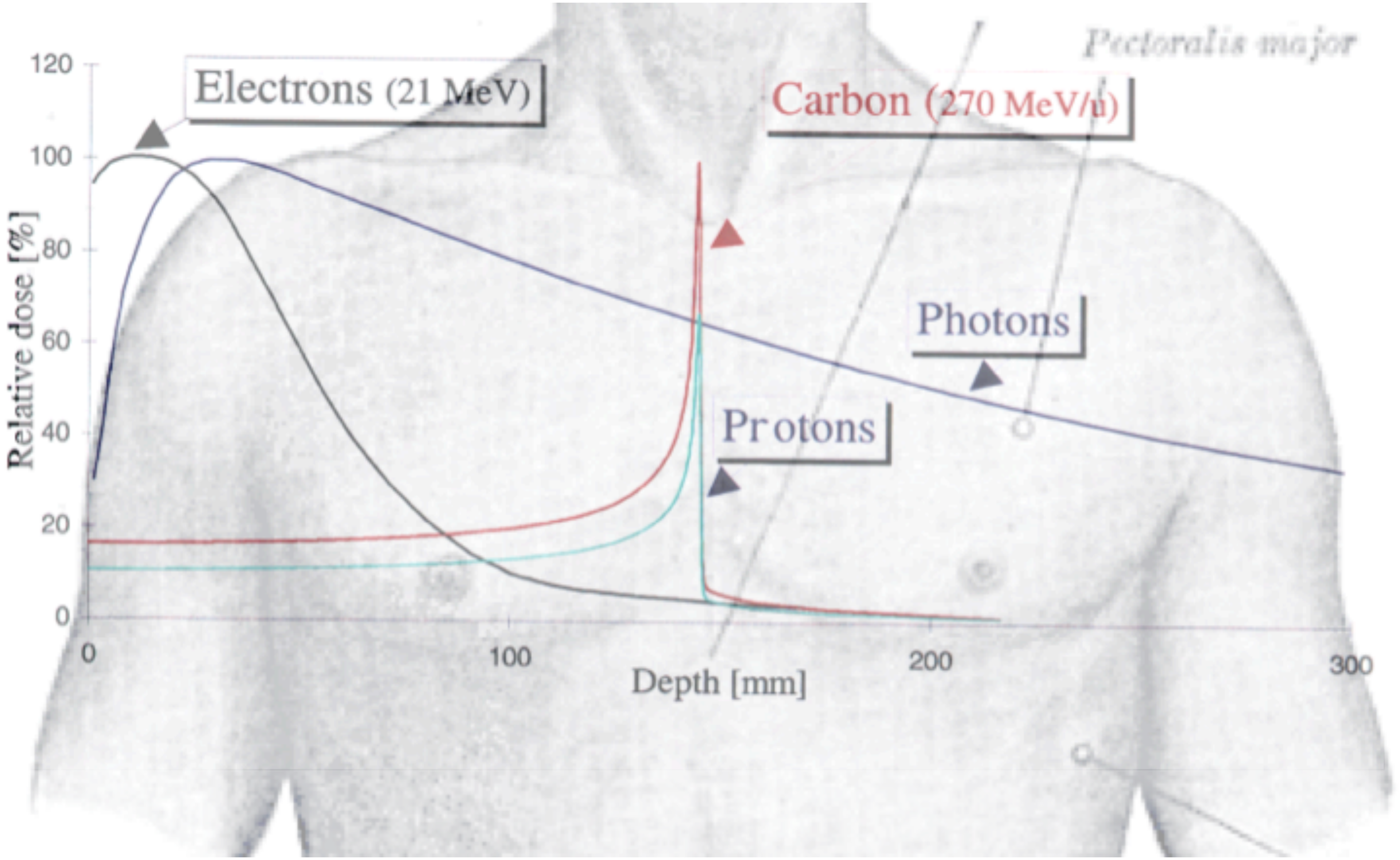
Direct damage of ionizing radiation



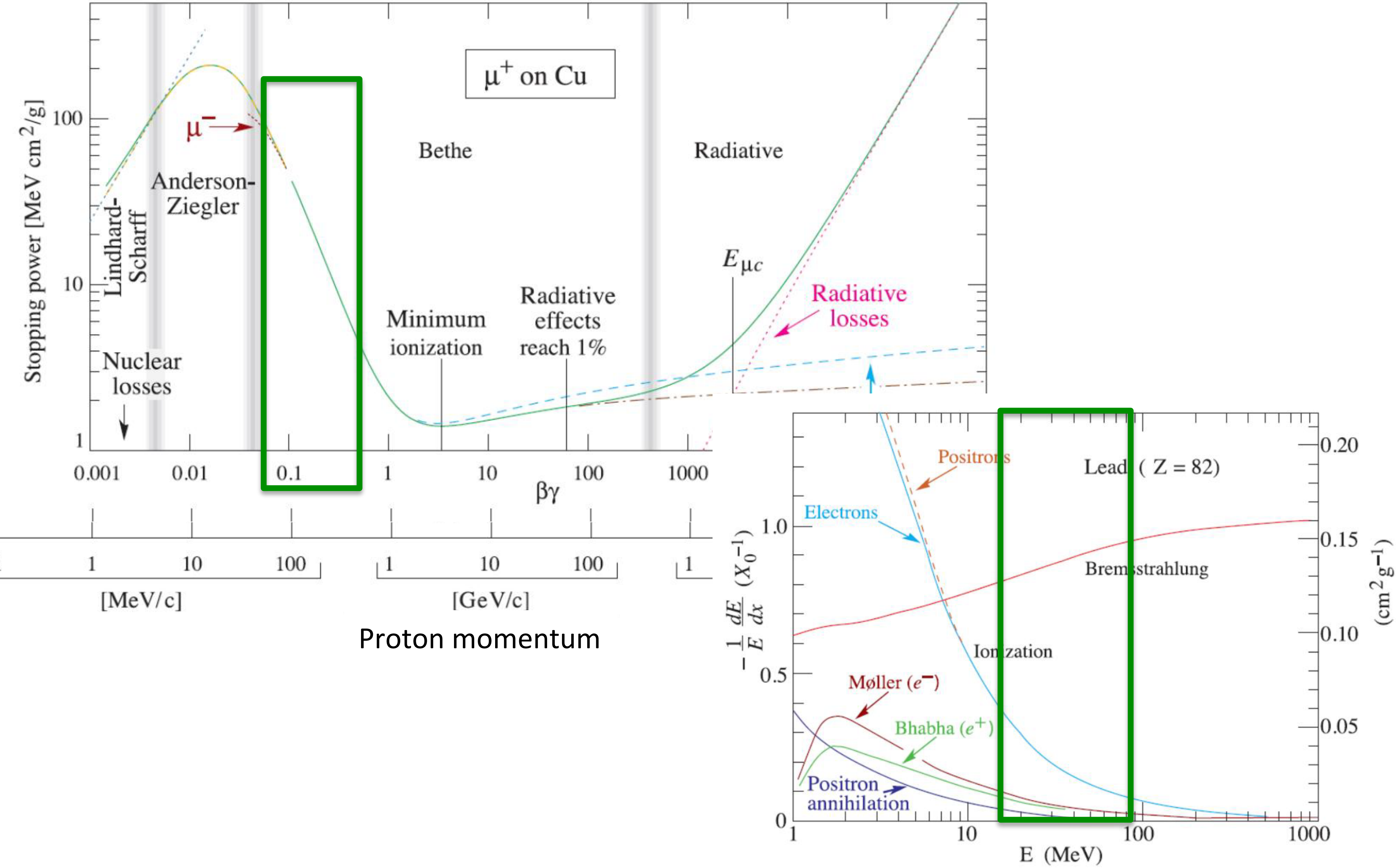
Indirect damage via radical formation



Interaction of particles and matter

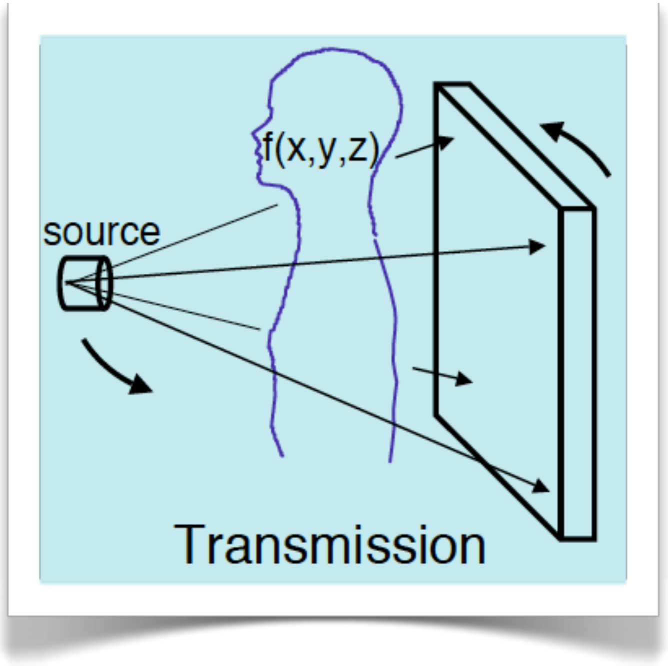


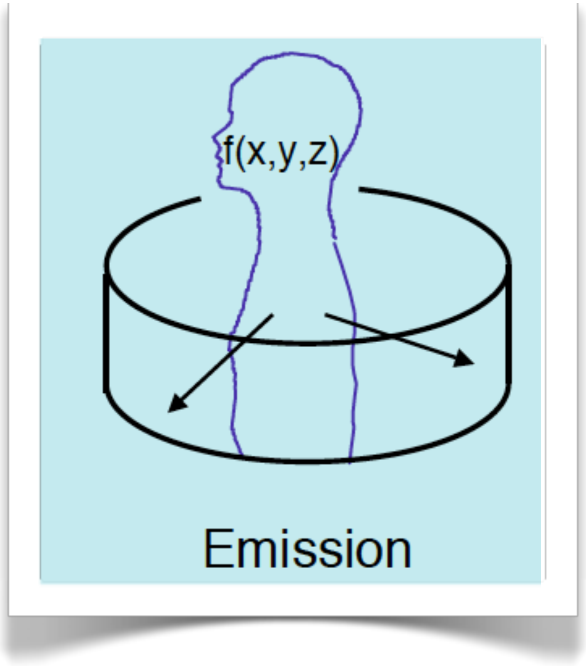
Interaction of particles and matter



Proton momentum

Medical imaging





- absorption of particles proportional to material density
- anatomical structure

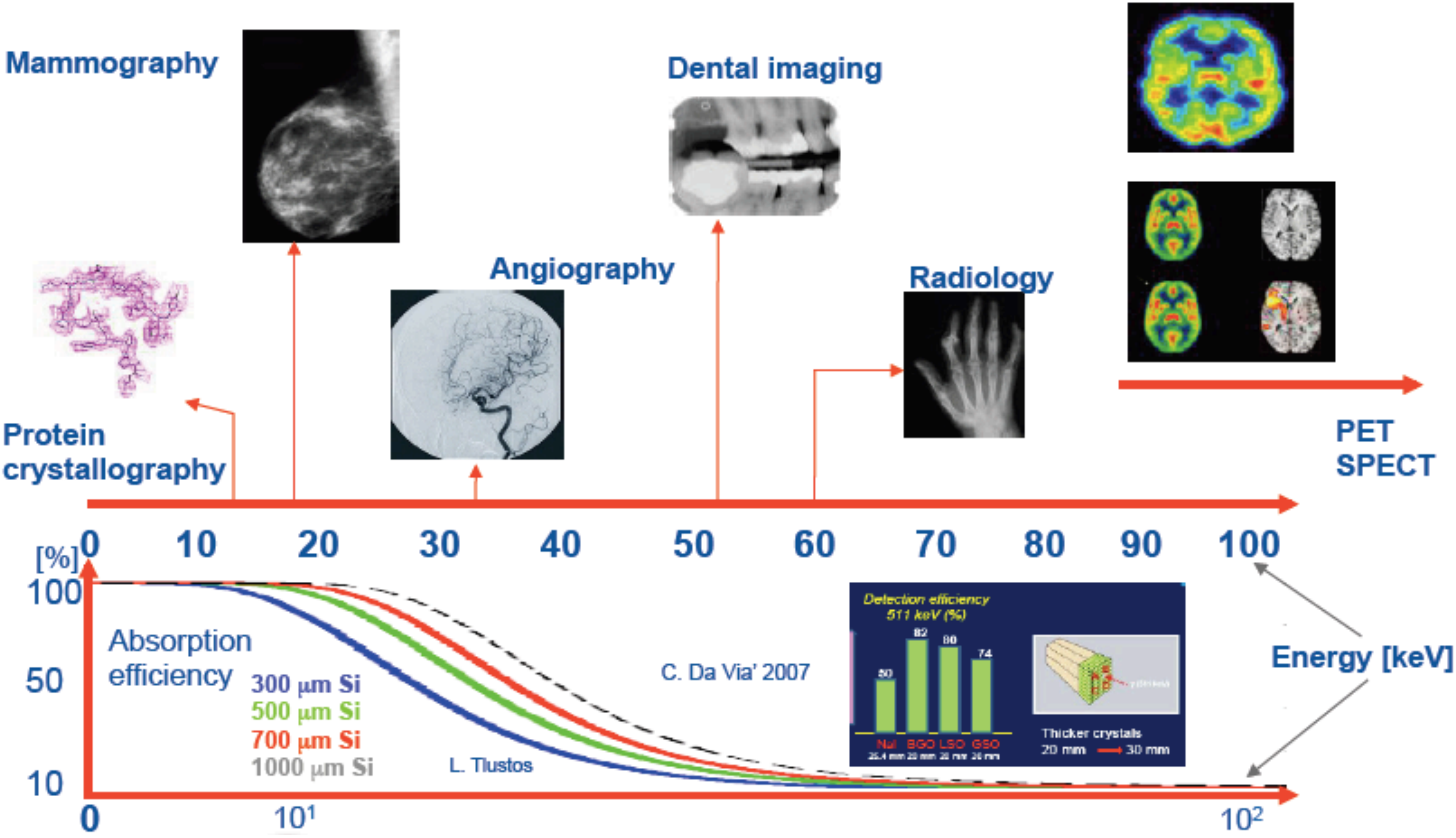
- rate of emissions depends on concentration of particles
- concentration related to the functional activity of cells

X-ray photons: 10-100 keV

Gamma photons: 100-511 keV

Two key questions:

1. What processes occur in the body ?
2. What processes to use for the detection / which materials ?



Detection of photons

- Interactions of photons and matter
  - Relevant energy range 10-511 keV

- Conversion of photon energy into a measurable signal
  - Detector principles (scintillator + photo-detector, silicon? gas?)

- Readout of the signal
  - Energy measurements
  - Time measurements

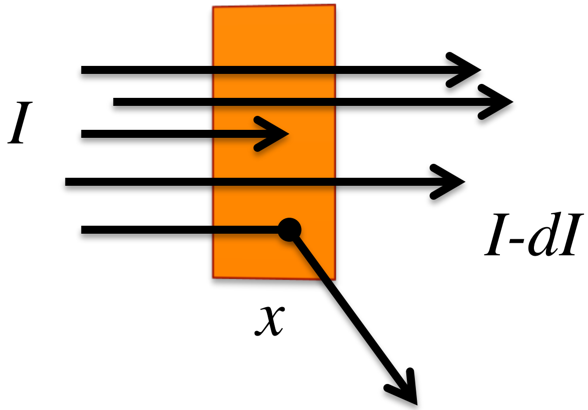
Interactions of photons with matter

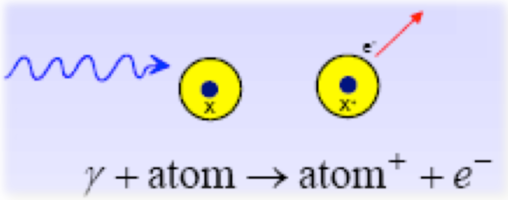
Characteristic for interactions of photons with matter:

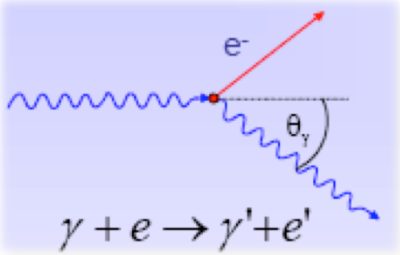
A photon is removed from the “beam” after one single interaction either because of total absorption or scattering

1) Photoelectric Effect

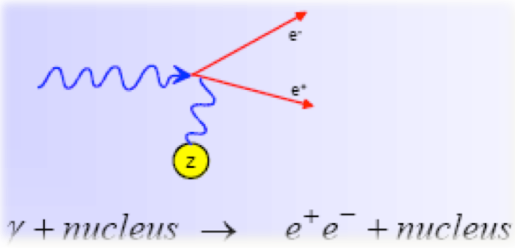
2) Compton Scattering







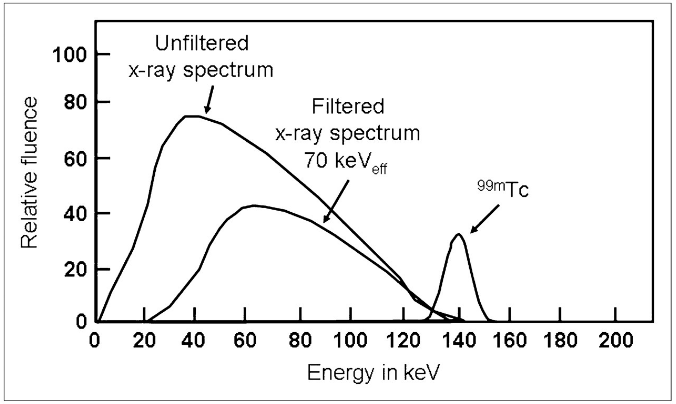
3) Pair Production

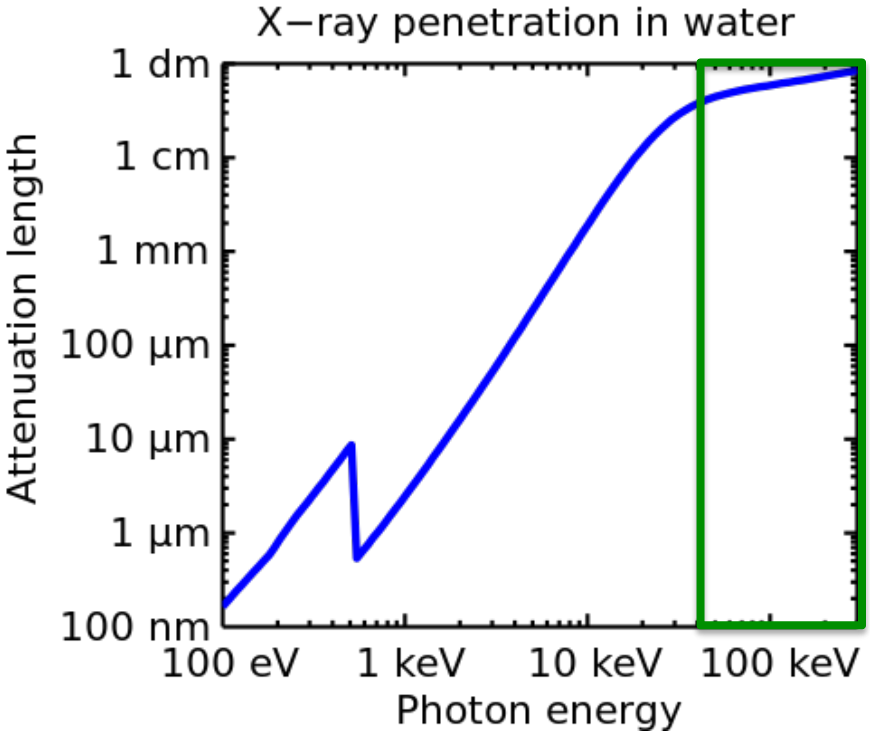


$$I(x) = I_0 e^{-\mu x},\ \ \mu = \frac{N}{A}\sum_{i=1}^{3}\sigma_i$$

$\lambda = 1/\mu$ Mean free path

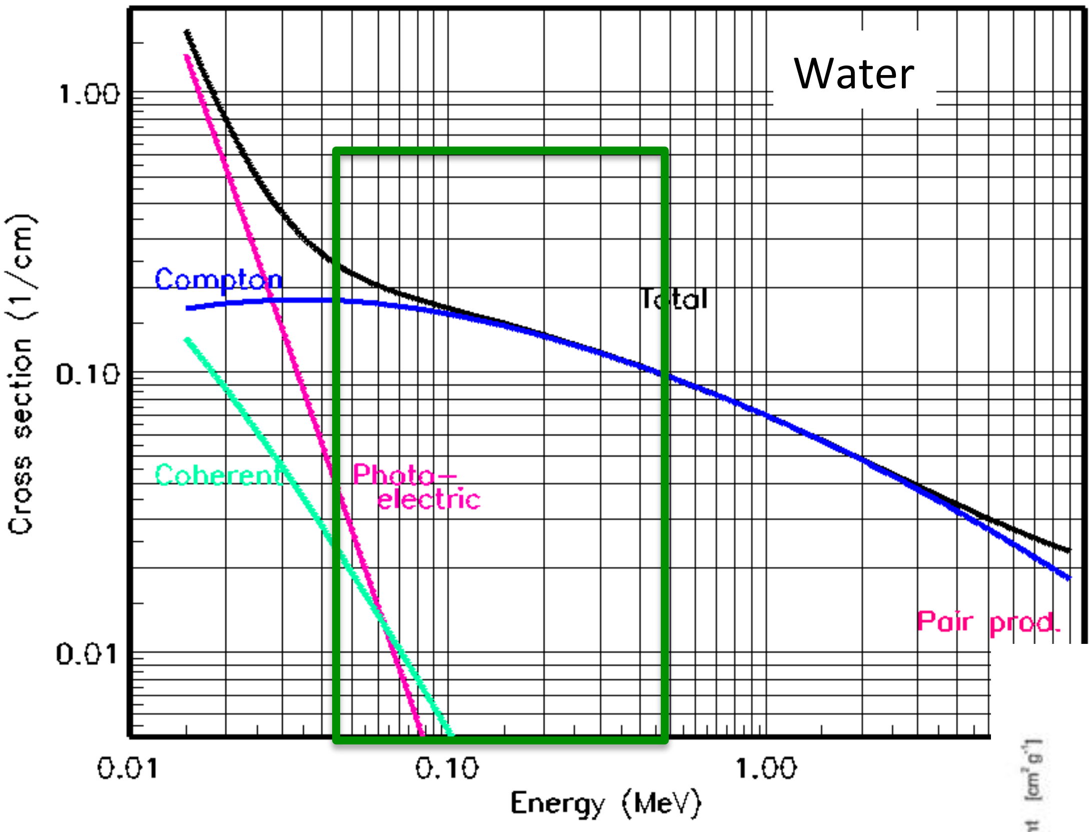
Interactions of photons with matter



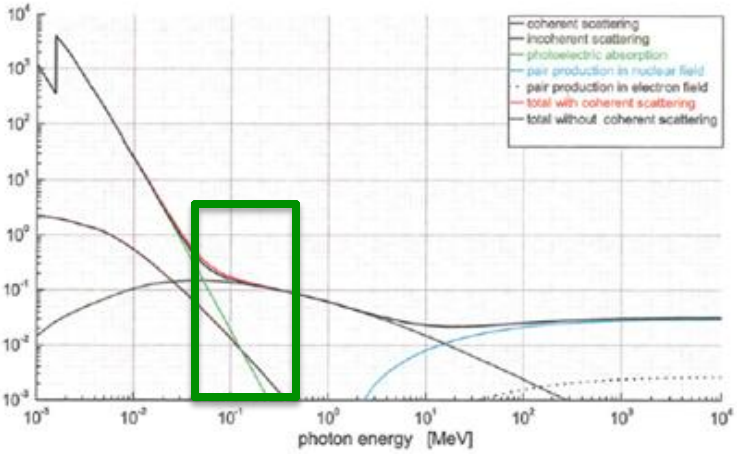


Relevant range of energy 40-150 keV
PET: 511 keV

Interaction of photons with matter



Silicon



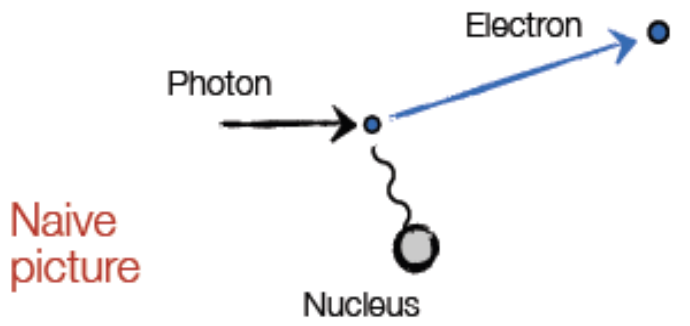
Relevant range of energy 40-150 keV
PET: 511 keV

Photoelectric effect

From energy conservation:

$$E_e = E_\gamma - E_N = h\upsilon - I_b$$

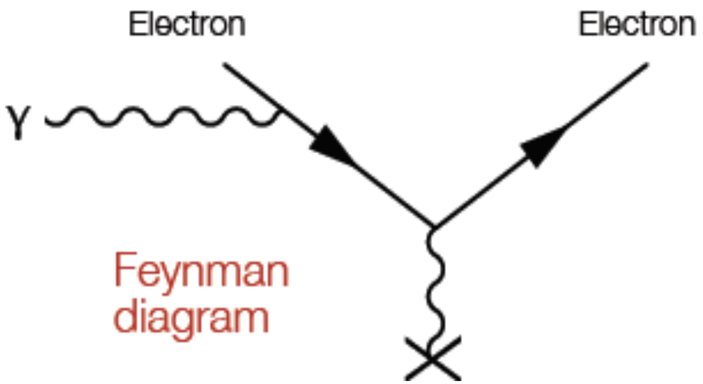
I_b = Nucleus binding energy
introduces strong Z dependence



➔ Photon “disappears” and transfers ALL its energy to an electron

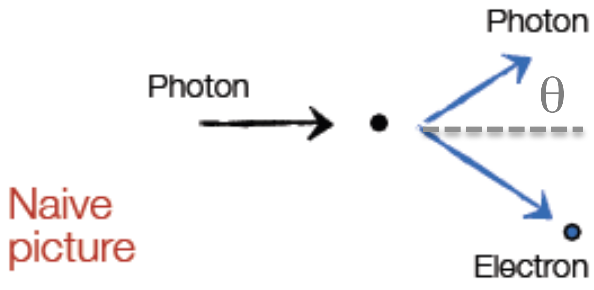
$\gamma + \text{atom} \rightarrow e^- + \text{atom}^+$

➔ Convert electron energy into charge to obtain a measurable signal



Compton scattering

Best known electromagnetic process (Klein–Nishina formula)



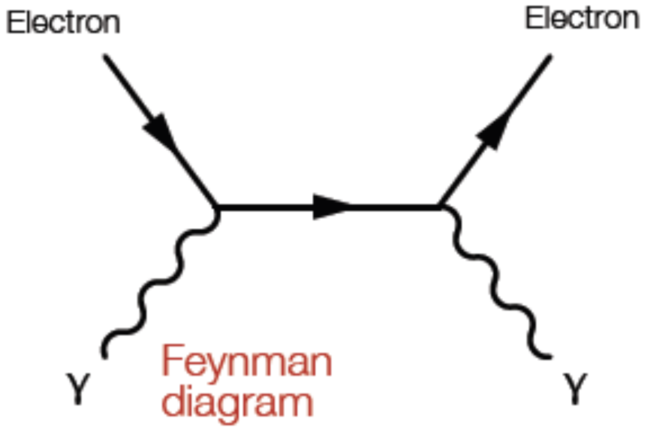
for $E_\gamma << m_e c^2$ $\boxed{\sigma_c \propto \sigma_{Th}(1-2\varepsilon+\frac{26}{5}\varepsilon^2)}$

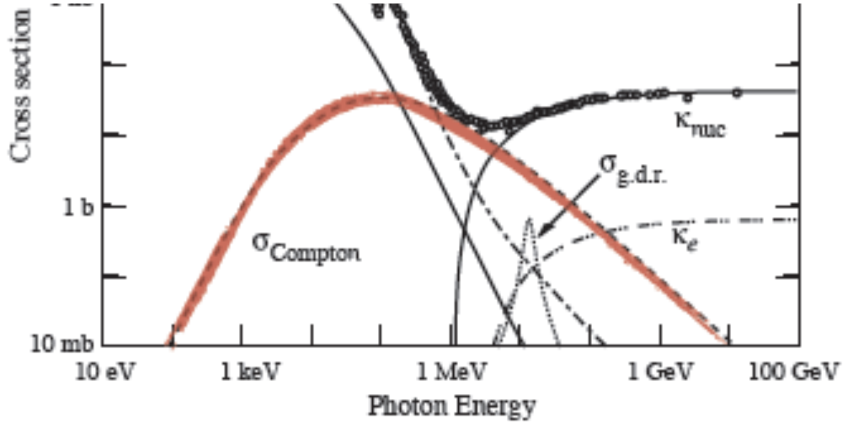
Thompson cross-section:
$\sigma_{Th} = 8\pi/3\ r_e^2 = 0.66$ barn

$$\varepsilon = \frac{E_\gamma}{m_e c^2}$$

$\gamma + e^- \rightarrow (\gamma)' + (e^-)'$

➔ Photon is deviated and transfers PART of its energy to an electron





Compton scattering

From E and p conservation get the energy of the scattered photon

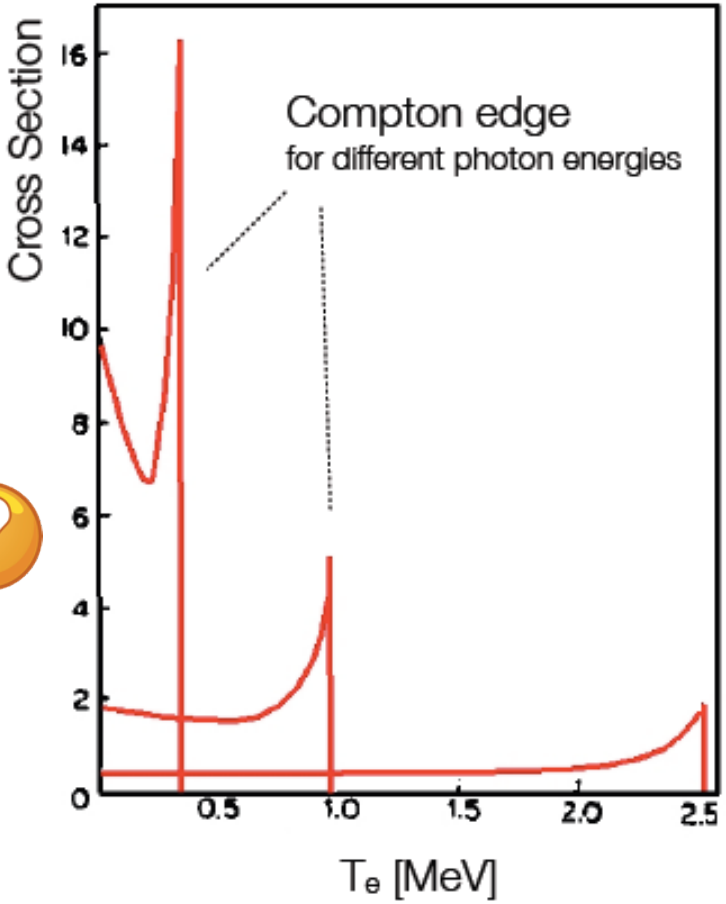
$$E_\gamma' = \frac{E_\gamma}{1+\varepsilon(1-\cos\theta)} \qquad \varepsilon = \frac{E_\gamma}{m_e c^2}$$

Kinetic energy of the outgoing electron:

$$T_e = E_\gamma - E_\gamma' = E_\gamma \frac{\varepsilon(1-\cos\theta)}{1+\varepsilon(1-\cos\theta)}$$

Max. electron recoil energy for $\theta = \pi$:

$$\boxed{T_{\max} = E_\gamma \frac{2\varepsilon}{1+2\varepsilon}}$$



Compton edge
for different photon energies

Transfer of complete γ-energy via Compton scattering not possible:

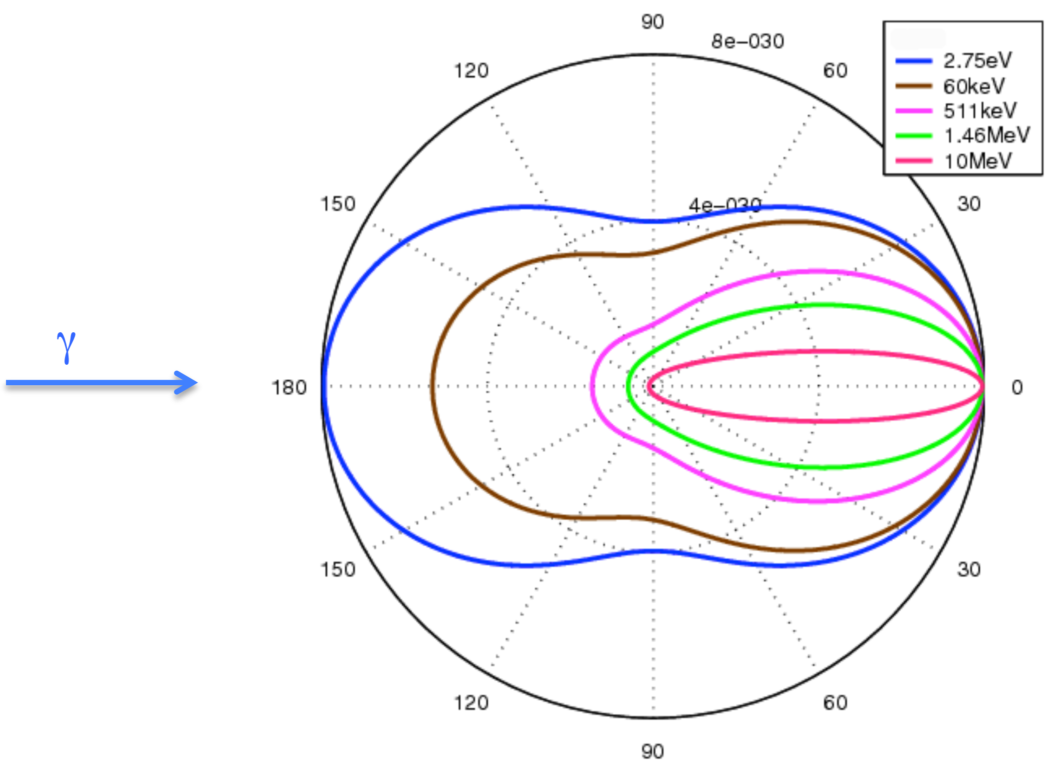
$$\Delta E = E_\gamma - T_{\max} = E_\gamma \frac{1}{1+2\varepsilon}$$

Important for single photon detection; if photon is not completely absorbed a minimal amount of energy is missing (Compton rejection in PET)

Spatial distribution of Compton photons

$$E_\gamma{}' = \frac{E_\gamma}{1+\varepsilon(1-\cos\theta)}$$

$$\varepsilon = \frac{E_\gamma}{m_e c^2}$$



- X rays (60keV) emitted during L to K shell transitions in X ray machines' favorably scatter forward through the patient although back scattering also occurs
- Photons generated through positron anihilation (511keV) during PET rarely scatter back
- Gamma-ray bursts (10MeV) almost exclusively forward scatter

Conversion of photon energy into a signal

1. the incident photon (40-511 keV) liberates an electron from the material lattice ➔ photo-electron or Compton effect

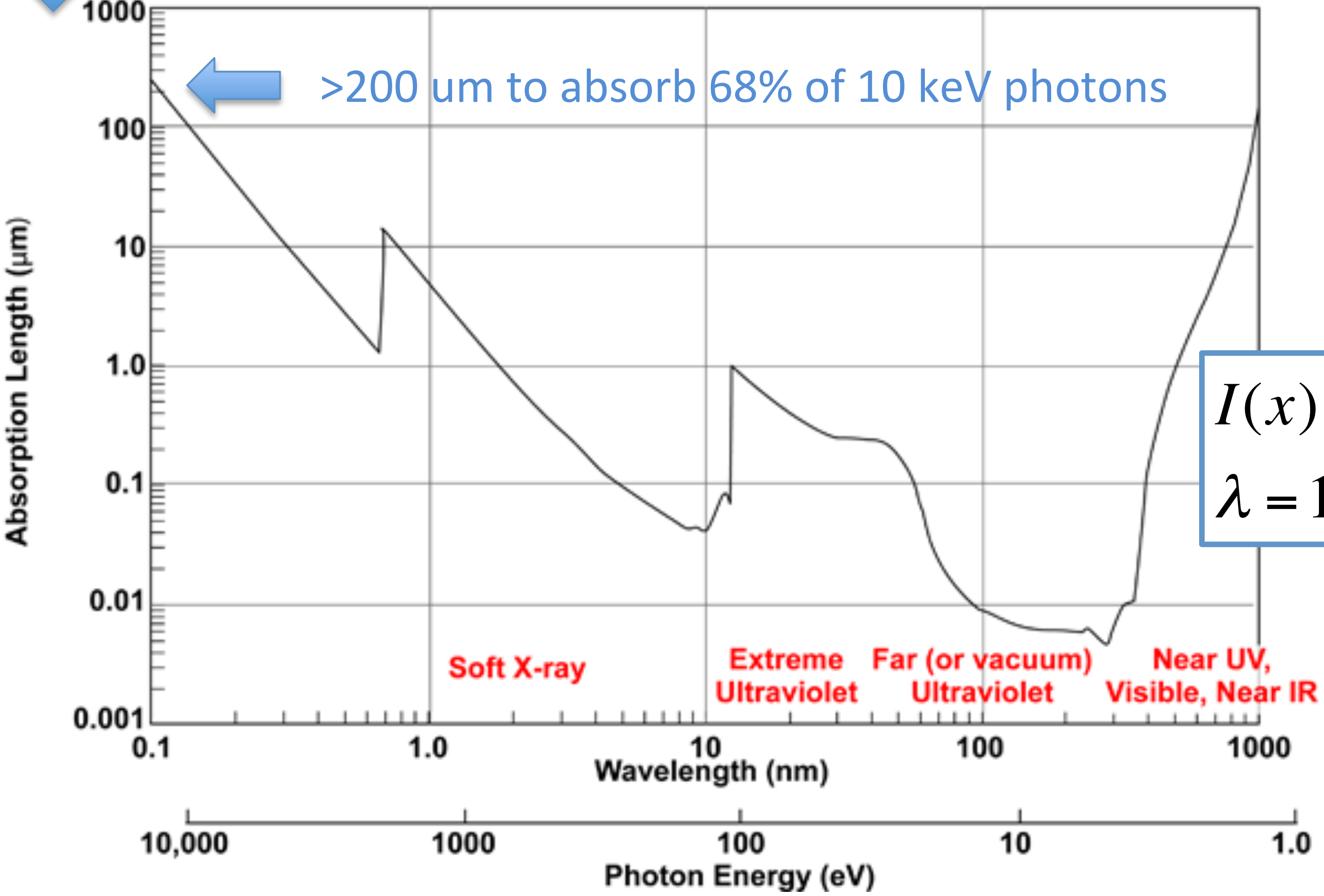
2. The electron ionizes further atoms in the lattice (what is the typical electron energy?)

3. The ionization charge is either collected directly (semiconductor) or used to produce visible light* (scintillator)

* Note: visible light has energy in the range of 1-3 eV, for 100% conversion+collection efficiency (unrealistic) a 511 keV photon should generate O(511000) visible photons. In reality, the efficiency is only 5-10%.

Absorption of photons in silicon

10-1000 keV photons require more than standard wafer thickness



>200 um to absorb 68% of 10 keV photons

$$I(x) = I_0 e^{-x/\lambda}$$

$$\lambda = 1/\mu$$

Si: A = 14, density = 2.65 g/cm^3 ➔ need a denser material

Scintillator properties

	1962	1977	1995	1999	2001	2003	2007
	NaI	**BGO**	**GSO:Ce**	**LSO:Ce**	**LuAP:Ce**	**$LaBr_3$:Ce**	**LuAG:Ce**
Density [g/cm^3]	3.67	7.13	6.71	7.40	8.34	5.29	6.73
Atomic number	51	75	59	66	65	47	63
Decay time [ns]	230	300	30-60	35-45	17	18	60
* LY [10^3 hν / MeV]	43	8.2	12.5	27	11.4	70	>25
Peak emission [nm]	415	480	430	420	365	356	535
Refraction index	1.85	2.15	1.85	1.82	1.97	1.88	1.84

* Remember green-blue photon energy is in the range 1-2 eV
➔ 1 MeV = 1-0.5 10^6 green-blue photons
typical light yield is 5-10% of the total energy ➔ conversion efficiency

Absorption of photons in crystal

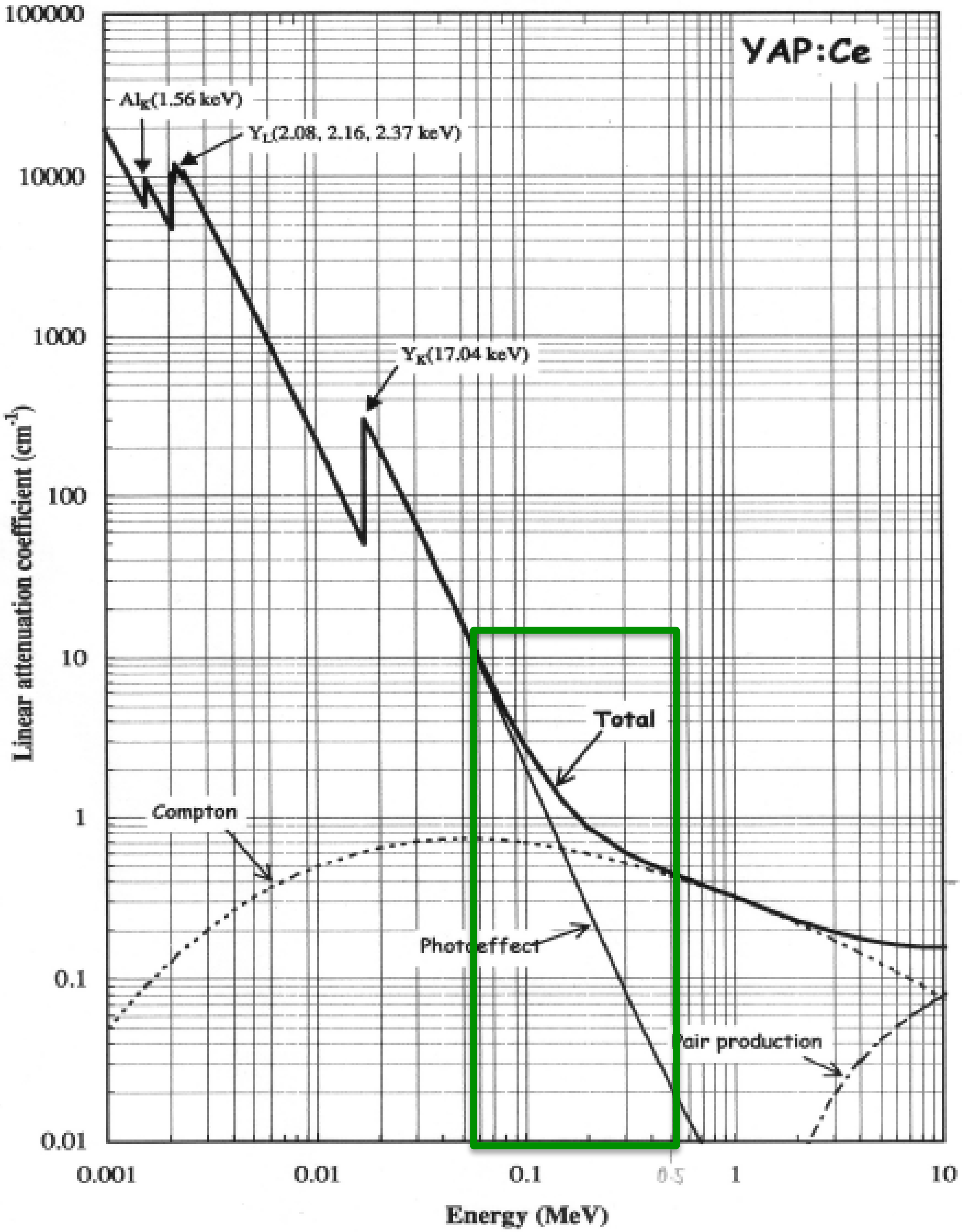
$$I(x) = I_0 e^{-\mu x},$$
$$\mu = 1/\lambda$$

linear attenuation coefficient

100 keV: λ ~ 1 cm

Typical length of crystals in PET/SPECT systems:
~ 1 – 5 cm

- Nothing like a 100% photon containment!
- Cost/efficiency optimization



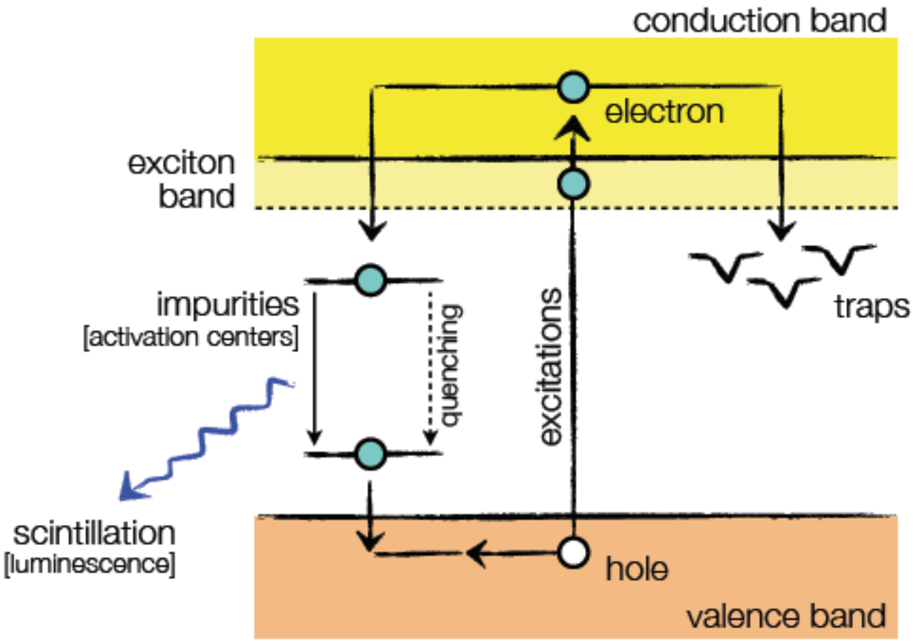
Inorganic scintillator

Mechanism:

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

Unwanted effects:

- Trapping in impurities
- quenching



Energy bands in impurity activated crystal

Time constants:

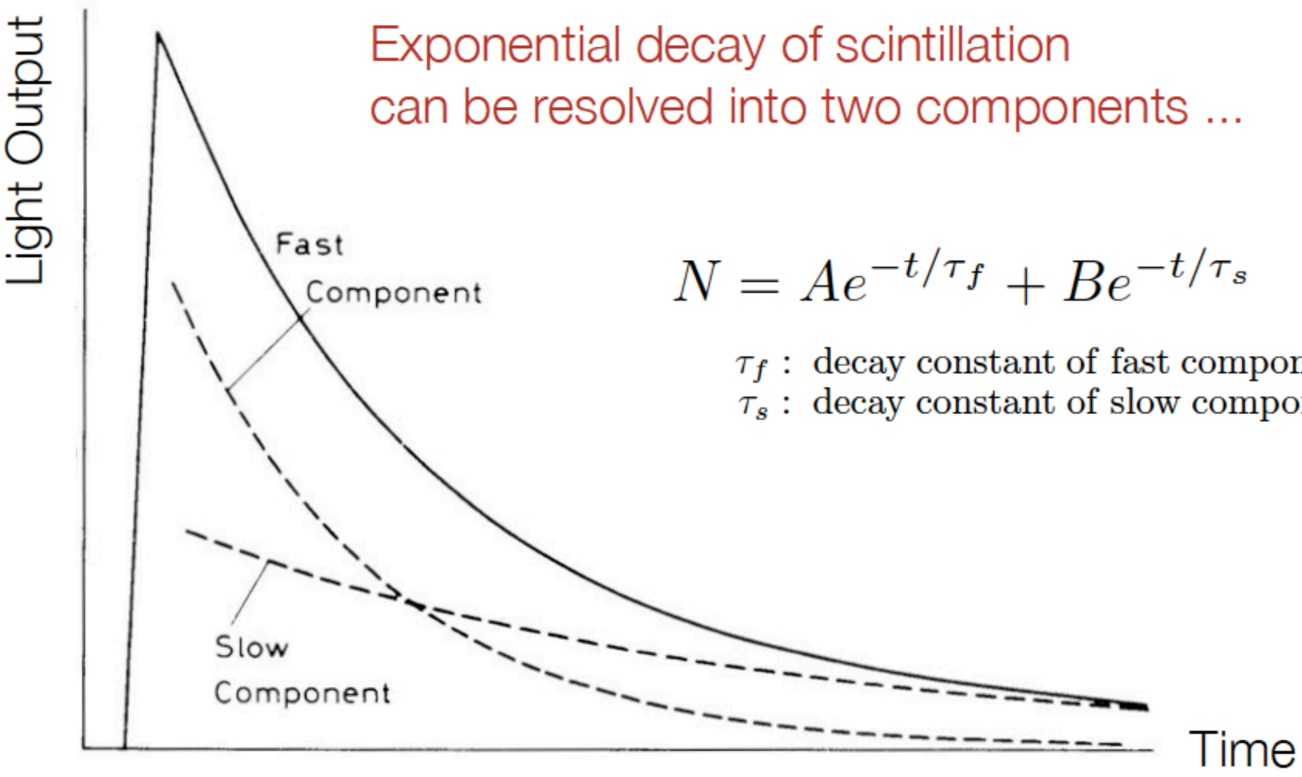
Fast: recombination from activation centers [ns ... **μ**s]

Slow: recombination due to trapping [ms ... s]

Materials:

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

Time constants



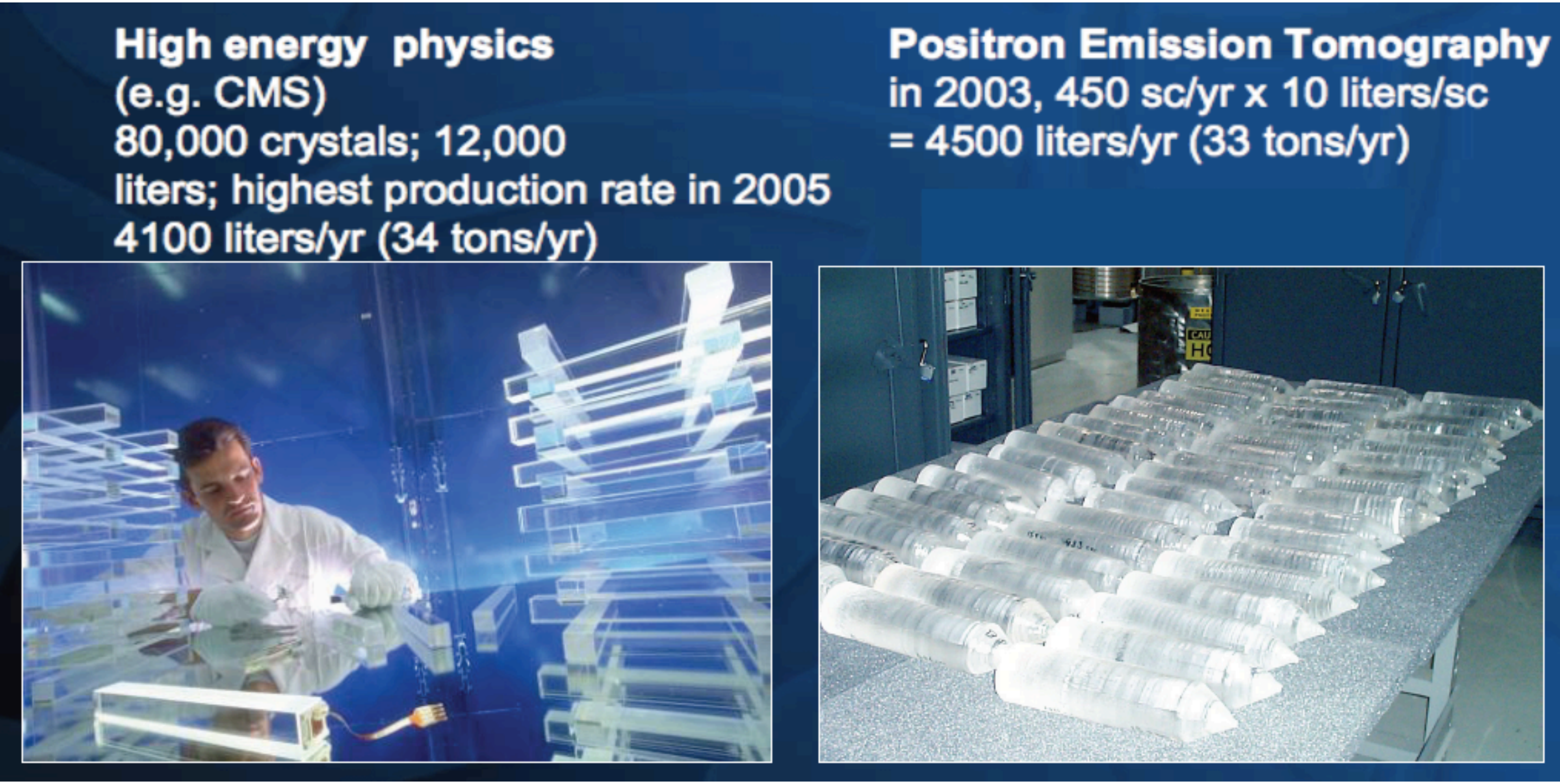
Exponential decay of scintillation
can be resolved into two components ...

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

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

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

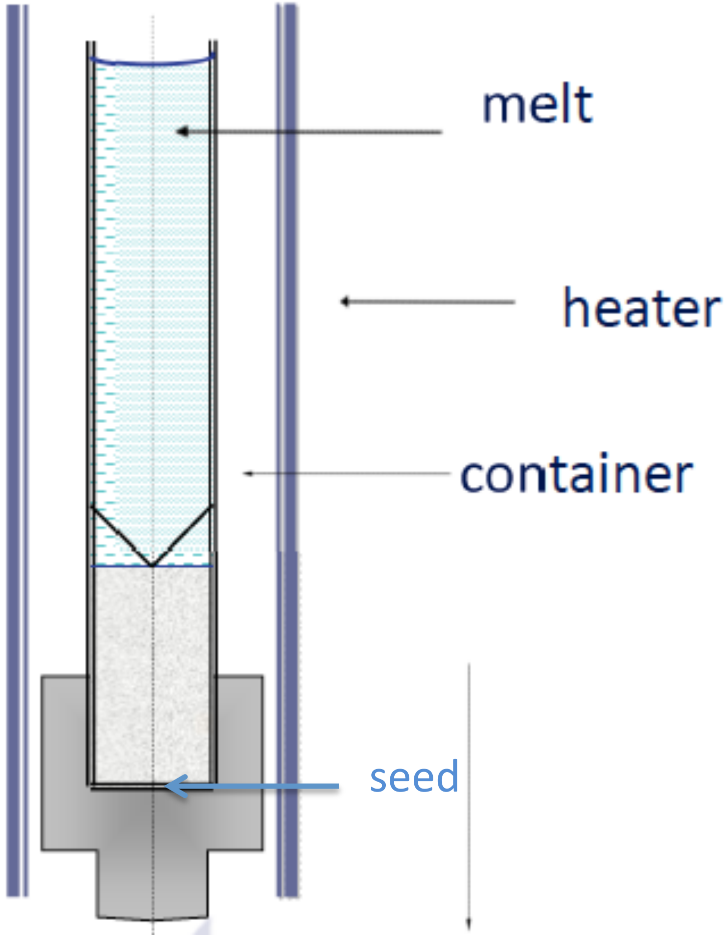
HEP and PET scintillator volume



High energy physics
(e.g. CMS)
80,000 crystals; 12,000
liters; highest production rate in 2005
4100 liters/yr (34 tons/yr)

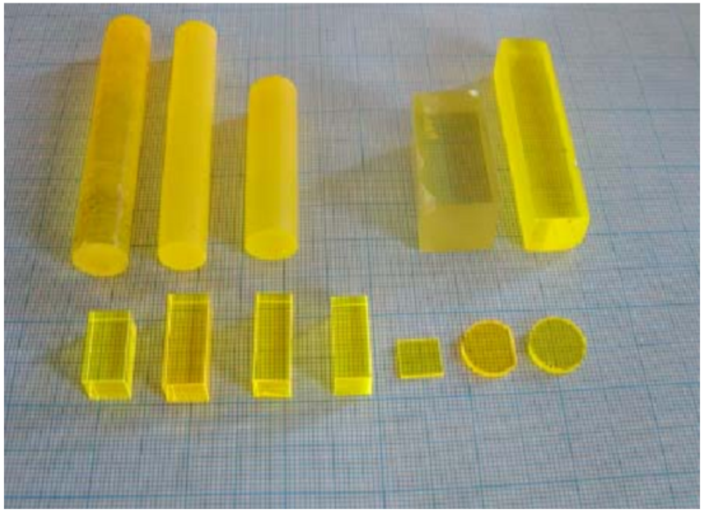
Positron Emission Tomography
in 2003, 450 sc/yr x 10 liters/sc
= 4500 liters/yr (33 tons/yr)

Crystal growth



Bridgman–Stockbarger technique

- the melt contained in a Mo crucible is progressively frozen from one end by slow pulling down to the cold zone.
- the seed material determines the crystallographic orientation of the grown single crystal.
- The container determines its shape
- Typical growth rate: mm/h



Y3Al5O12:Ce

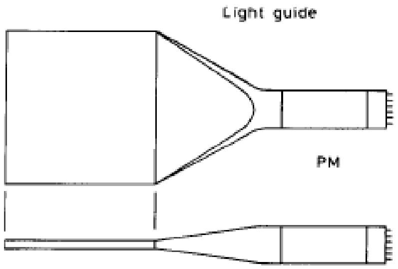
Detection of visible photons

Scintillation light is emitted in the visible (blue) range!

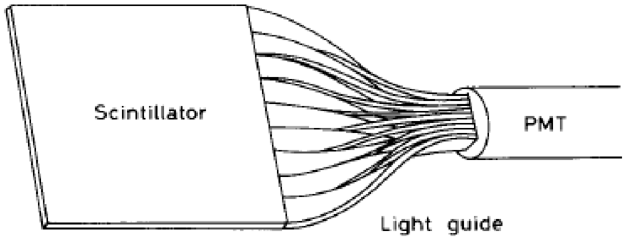
Next step:

Detect visible photons (1-3 eV)

Reading out light from a scintillator



"fish tail"



adiabatic

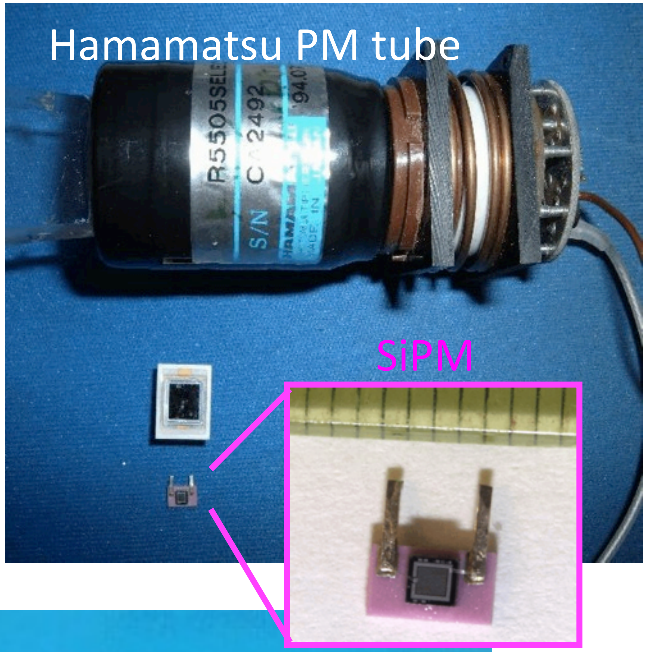
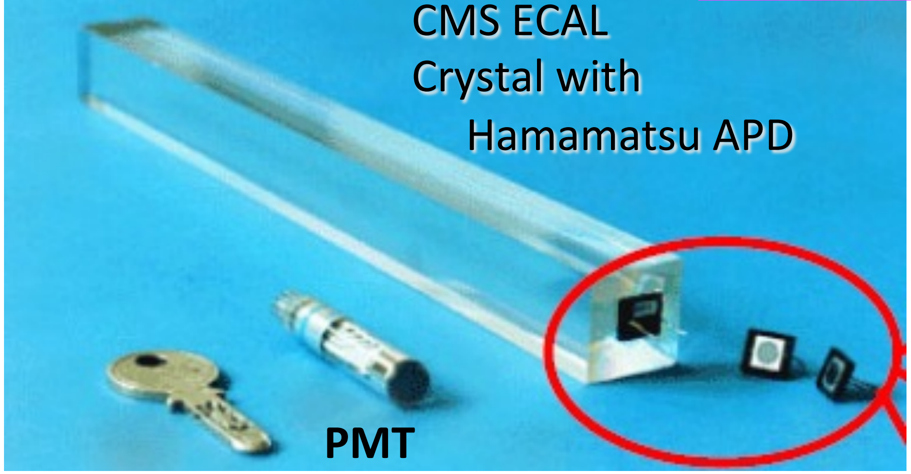


Photo-multiplier tubes are the past!

Be modern: go silicon!

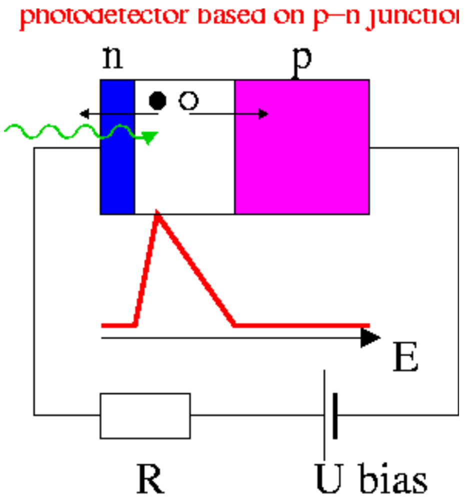


New photo-detecotrs

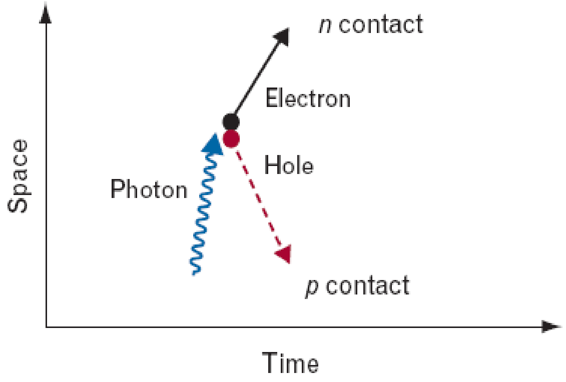
- Main drawbacks of PMTs: bulky shape, the high price and the sensitivity
- to magnetic fields.

- Photodiodes are semiconductors light sensors that generate a current or
- voltage when light illuminates the p-n junction.

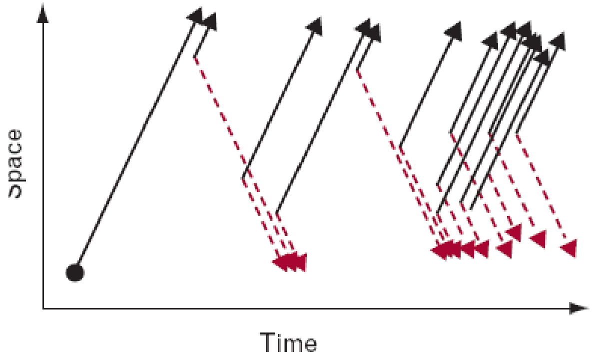
- ➔ Allow detection of light in 200-1150 nm



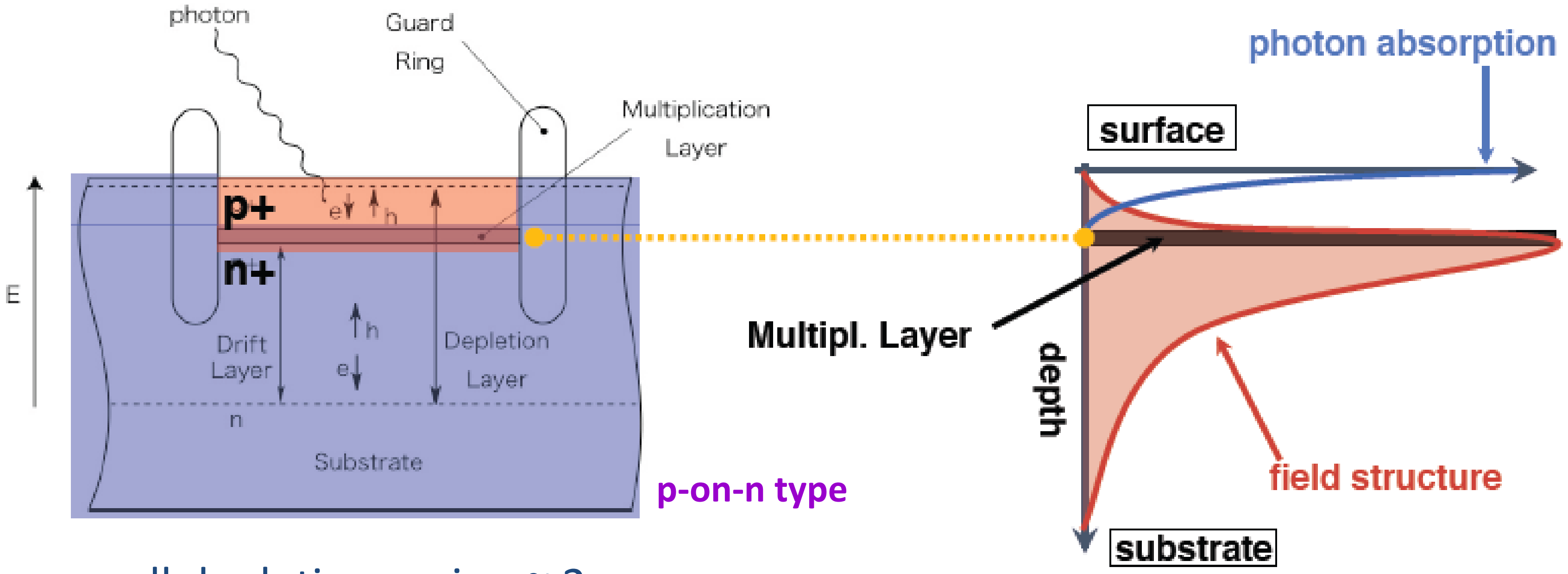
p-n junction



p-n junction + ($U_{bias} > U_{breakdown}$)



Working principle



-small depletion region ~ 2μm

-strong electric field (2-3)x10^5 V/cm

-carrier drift velocity ~ 10^7 cm/s

-very short Geiger discharge development < 500 ps

Photoelectric conversions occur above the multiplication layer

➔ electrons drift to the multiplication layer

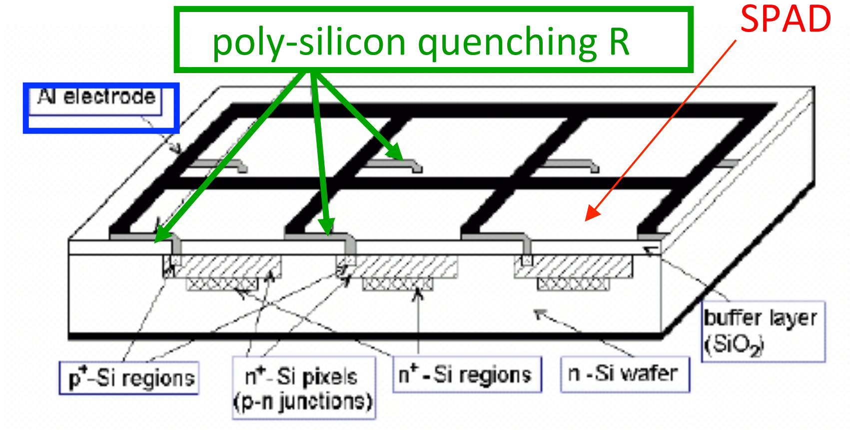
Random excitations occur mainly below the multiplication layer

➔ holes drift to the multiplication layer

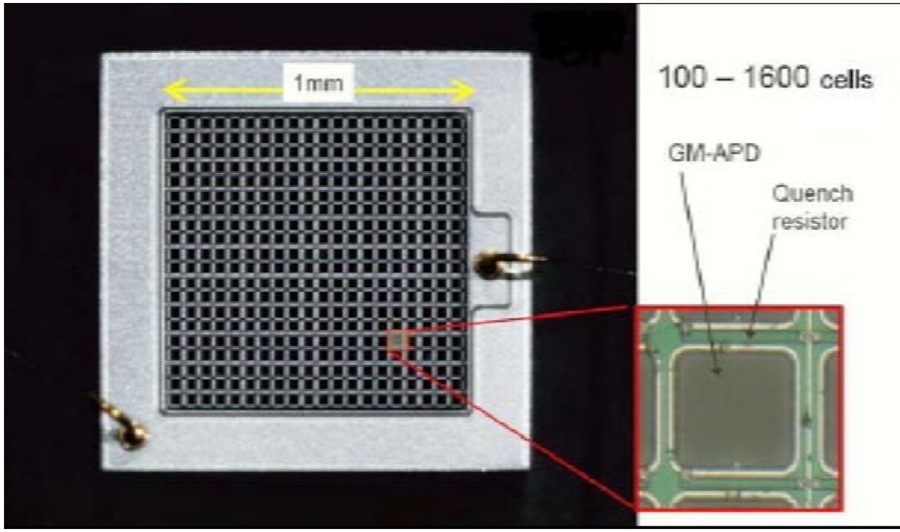
Silicon Photo-multiplier

A matrix of N x N pixels operated in Geiger mode (each pixel digital Geiger signal)
Read out as a sum of all pixels

➔ Gain ~ 10^6 electrons / 1 detector photon



➔ typically 100-1000 pixels / mm²



Some typical pixel parameter:
-pixel size ~20-30µm
-pixel capacitance C_{pixel} ~ 50fmF
-quenching resistor R_{pixel} ~ 1-10 MΩ

Detector Signal

- Detector signal generally a short current pulse:

  i =V/R (R = 50Ω, oscilloscope termination)

– thin silicon detector (10 –300 µm):	100 ps–30 ns
– thick (~cm) Si or Ge detector:	1 –10 µs
– proportional chamber:	10 ns –10 µs
– Microstrip Gas Chamber:	10 –50 ns
– Scintillator+ PMT/SiPM:	100 ps–1 µs

$$E \propto Q_s = \int i_s(t)\,dt$$

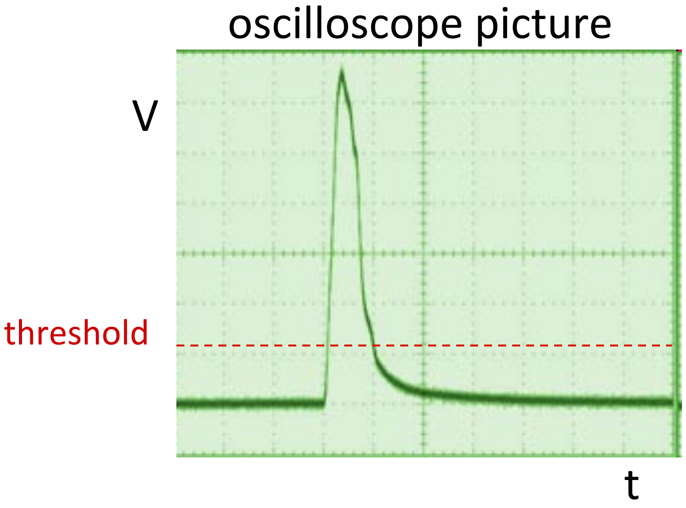

oscilloscope picture

Signal measurements

Various measurements of this signal are possible
Depending on information required:

- Signal above threshold
  digital response / event count
- Integral of current = charge
  ➔ energy deposited
- Time of leading edge
  ➔ time of arrival (ToA) or time of flight (ToF)
- Time of signal above threshold
  ➔ energy deposited by TOT

and many more …



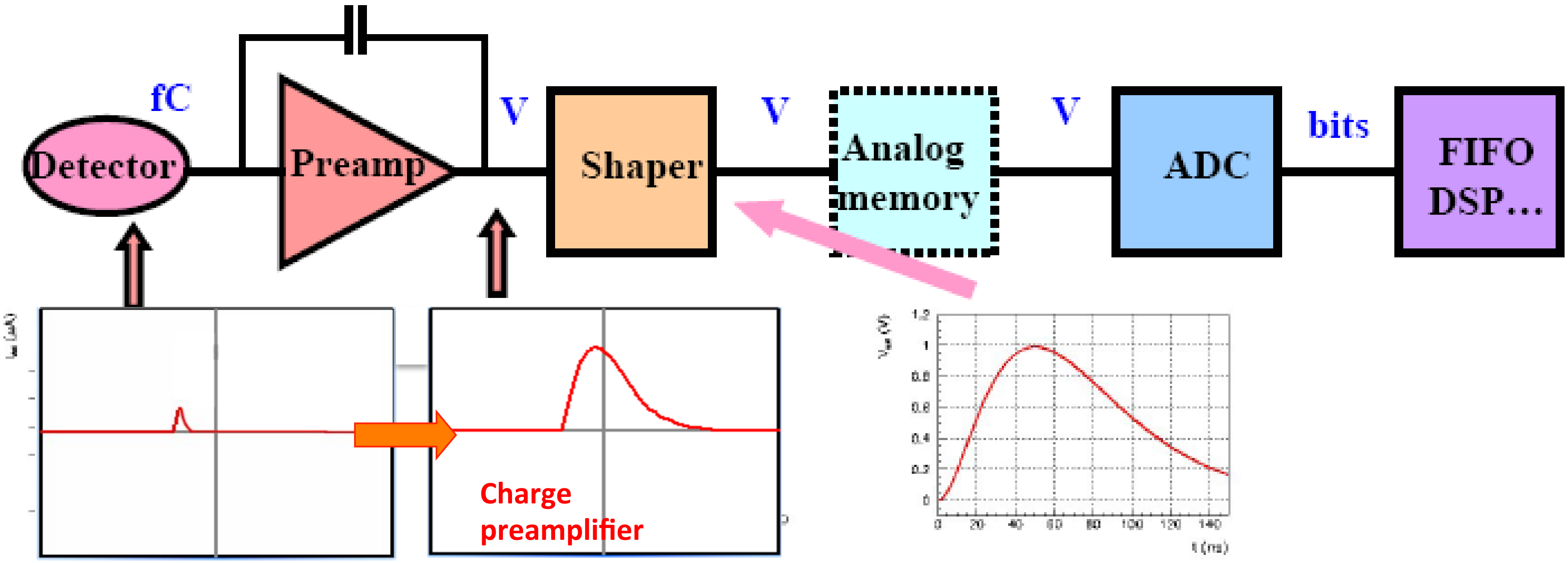
Key points of this lecture

1. **Relevant particles and energies for radio therapy ➔** physics of interaction
2. **Relevant particles and energies for medical imaging**
3. **Detection of photons (physics and detectors) :**

- Photons 40-511 keV interact in matter mainly via photo-electric or Compton effects
- All / or a part of the photon energy is transferred to an electron
- The electron ionizes the medium till it is fully absorbed
- A detector transforms this energy into measurable charge via ionization or visible light generation
- Visible light is measured with a photo-detector
- The charge signal from the detector is interpreted by the readout electronics to obtain energy and/or time measurements

Readout architecture for E meas.

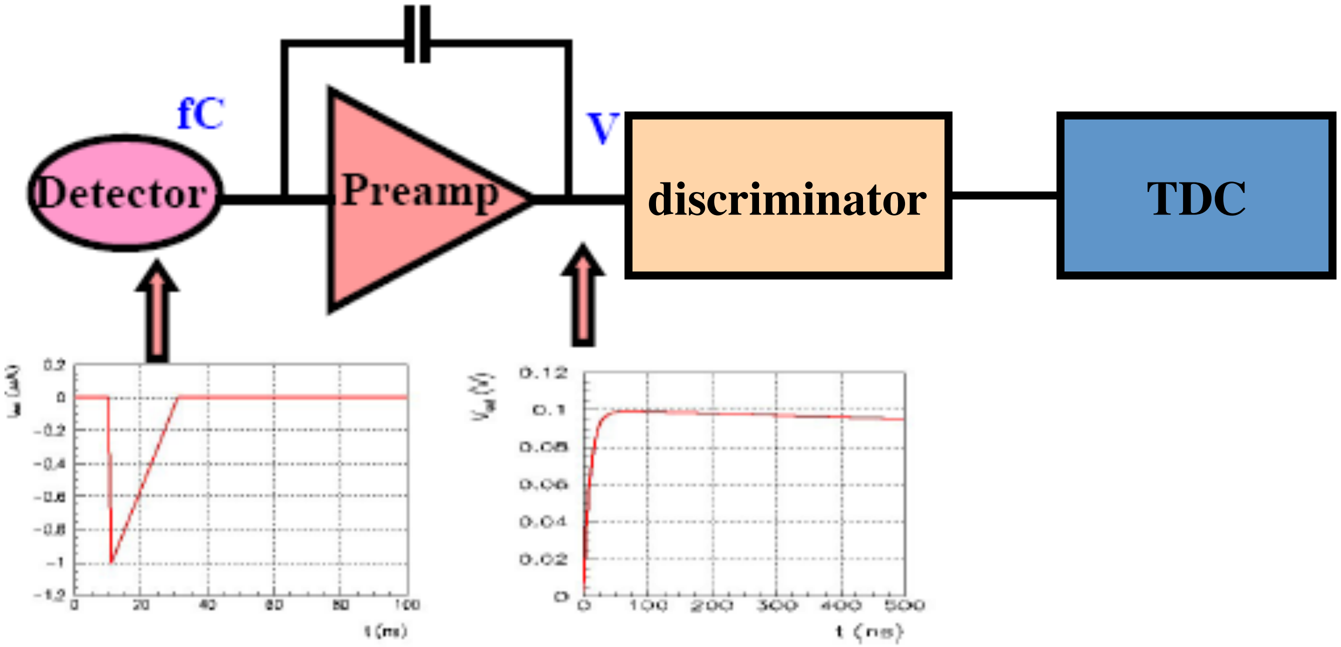
Most front-ends follow a similar architecture



- Very small signals (fC) -> need amplification (charge pre-amplifier)
- a shaper converts the charge into voltage
- measurement of voltage amplitude (Analog to Digital Converter, ADC)

Readout architecture for t meas.

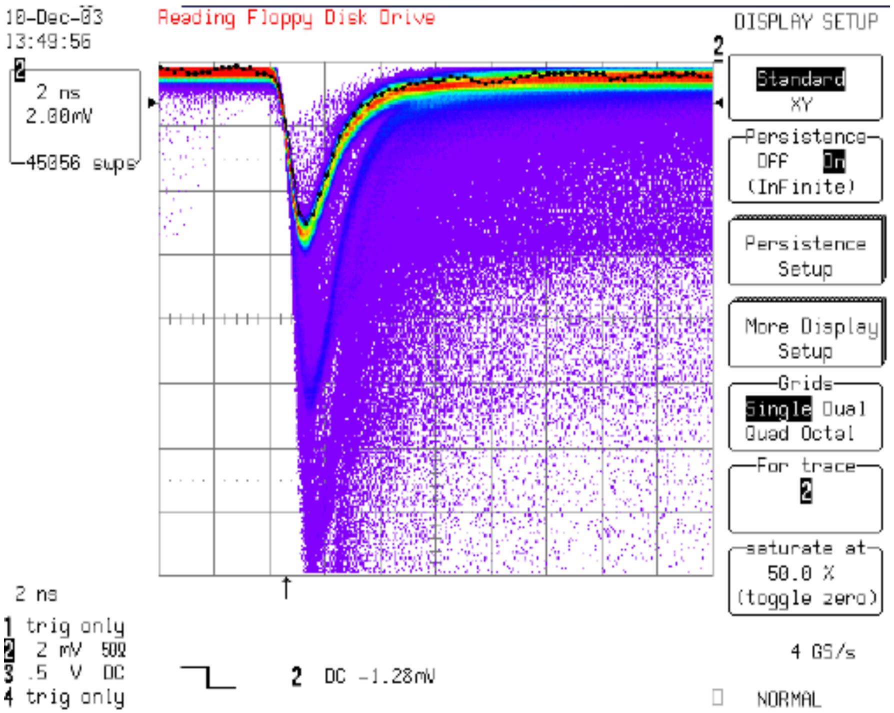
Most front-ends follow a similar architecture



- Very small signals (fC) -> need amplification (voltage pre-amplifier)
- … if voltage output larger than threshold voltage … (discriminator)
- measurement time of threshold crossing (Time to Digital Converter, TDC)

SiPM properties: single pixel resolution

SiPM output is the analog sum of all pixel signals

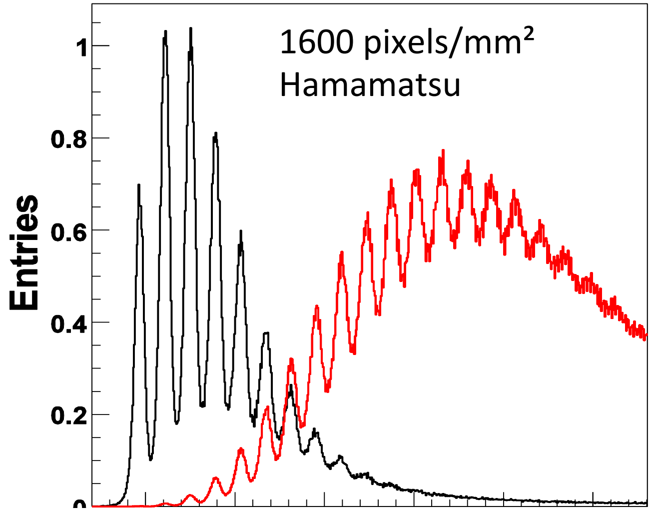

10-Dec-03
13:49:56
Reading Floppy Disk Drive
DISPLAY SETUP
2
2 ns
2.00mV
45056 swps
Standard
XY
Persistence
Off On
(Infinite)
Persistence Setup
More Display Setup
Grids
Single Dual
Quad Octal
For trace
2
saturate at
50.0 %
(toggle zero)
2 ns
1 trig only
2 2 mV 50Ω
3 .5 V DC
4 trig only
2 DC -1.28mV
4 GS/s
NORMAL

high gain ➔ pixel signal visible on scope

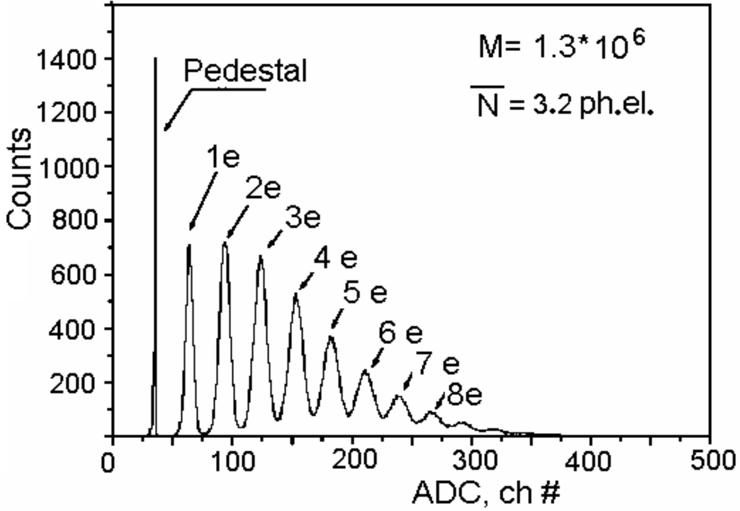
- signal rise time < 1 ns
- fast fall ~ 5-10 ns

recovery time tunable by choice of quenching R

$\tau \sim R_{pixel}C_{pixel} \sim 20 – 500$ ns



T=22 C, λ = 550 nm, AMPD type: PC1-mikr.



AMPD tested in LNP JINR and PSI