Experimental techniques in nuclear and particle physics

(part 1)

S. Tavernier & D. Kotlinski

Table of content

Documentation and further reading

- Experimental techniques in Nuclear and particle physics, S. Tavernier, Springer, 2010

- Radiation detection and measurement, by Glen F. Knoll, 4rd edition, John Wiley & Sons, 2010

- Review of particle physics', Physics Letters (2010), This document is downloadable from the WEB at: http://pdg.lbl.gov/pdg.html.

- Nuclear Data Center tables, Brookhaven national laboratory, available from the WEB at http://www.nndc.bnl.gov/.

- Photomultiplier tubes, Hamamatsu, http://sales.hamamatsu.com/assets/pdf/catsandguides/PMT_handbook_v3aE.pdf

A few words about symbols and units

energy : eV, keV, MeV, GeV, TeV, PeV;   1eV=1.602 10^{-19} J
particle mass m: mc^2
for photon E=Pc= $\hbar\omega$
β, γ : relativistic parameters Lorentz transformation
α: fine structure constant ≈ 1/137
$\hbar, c$: not always written in equations
r_0 : classical electron radius ≈ 2.8 10^{-15} m
charge Z: as number of protons charges
radioactivity: bequerel Bq; 1 decay/s
absorbed dose: gray Gy; 1 J/kg
equivalent dose: siefert Sv

Interactions of energetic subatomic particles in matter

Subatomic particles?

The fundamental constituents of matter are quarks, leptons, and the quanta of force (gamma, W, Z, gluons). However, most of these you will never observe directly.

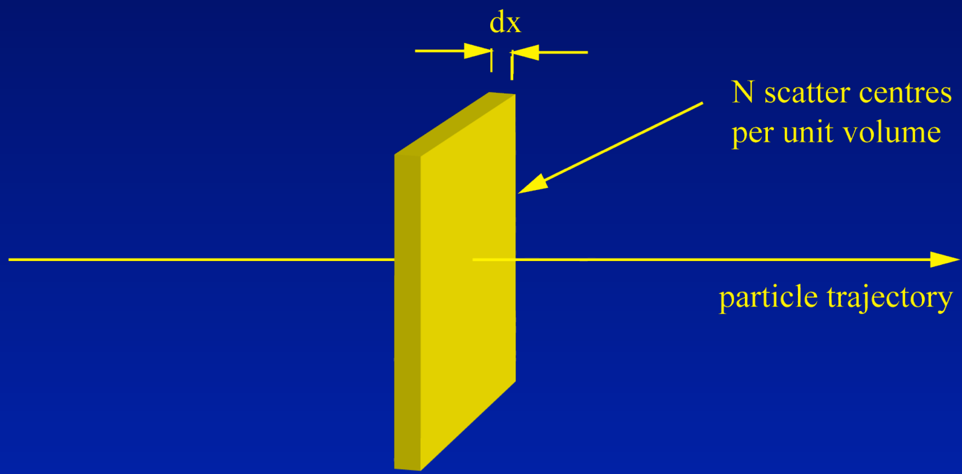
Table 1.4: List of the most common directly observable particles.

Particle	Mass	Lifetime	Charge	Main interactions
Electron	0.511 MeV	Stable	-1	Electromagnetic
Muon	105.7 MeV	$2.2\ 10^{-6}$ s	-1	Electromagnetic
Hadrons	see table 1.1	see table 1.1	0, +1, -1	Strong
Photon	0	Stable	0	Electromagnetic
Nuclei	1–240, times the proton mass	Many stable	1–92	Strong
Neutrinos	$< \approx 2$eV	Stable	0	Weak

Table 1.1: Some hadrons and their main properties. In this table the anti-particle of particle x is written as $\overline{\mathrm{x}}$.

Name	quark content	lifetime [s]	mass×c^2 [MeV]	main decay modes
π^+	$\{u, \bar{d}\}$	$2.6\ 10^{-8}$	139.6	$\mu^+\ \nu_\mu$
π^-	$\{d, \bar{u}\}$	$2.6\ 10^{-8}$	139.6	$\mu^-\ \bar{\nu}_\mu$
π^0	$\{u, \bar{u}\}, \{d, \bar{d}\}$	$1.2\ 10^{-17}$	135.0	$2\ \gamma$
K^+	$\{u, \bar{s}\}$	$1.2\ 10^{-8}$	473.7	$(\mu^+\ \nu_\mu), (2\pi), (3\pi)$
K^-	$\{s, \bar{u}\}$	$1.2\ 10^{-8}$	473.7	$(\mu^-, \bar{\nu}_\mu), (2\pi), (3\pi)$
K_l^o	$\{s\ \bar{d}\}, \{d\ \bar{s}\}$	$5.2\ 10^{-8}$	497.7	$3\ \pi$
K_s^0	$\{s, \bar{d}\}, \{d, \bar{s}\}$	$8.9\ 10^{-11}$	497.7	$2\ \pi$
proton	{u, u, d}	$> 10^{32}$ year	938.3	
neutron	{d, d, u}	898	939.6	$p\ e\ \bar{\nu}_e$
Λ^0	{d, s, u}	$2.63\ 10^{-10}$	1115.7	$(n\ \pi^0), (p\ \pi^-)$
$\bar{p}$	$\{\bar{u}, \bar{u}, \bar{d}\}$	$> 10^{32}$ year	938.3	
$\bar{n}$	$\{\bar{d}, \bar{d}, \bar{u}\}$	898	939.6	$\bar{p}\ e^+\ \nu_e$
$\bar{\Lambda}^0$	$\{\bar{d}, \bar{s}, \bar{u}\}$	$2.63\ 10^{-10}$	1115.7	$(\bar{n}\ \pi^0), (\bar{p}\ \pi^+)$

Cross section σ and mean free path λ



$$dW = dxN\sigma$$

1 barn= 10^{-24} cm^2

Nucleus N $\Rightarrow N = \dfrac{\rho N_{Avogadro}}{A_r}$

Mean free path = $\lambda = \dfrac{1}{N\sigma}$

Electromagnetic interactions of charged particles

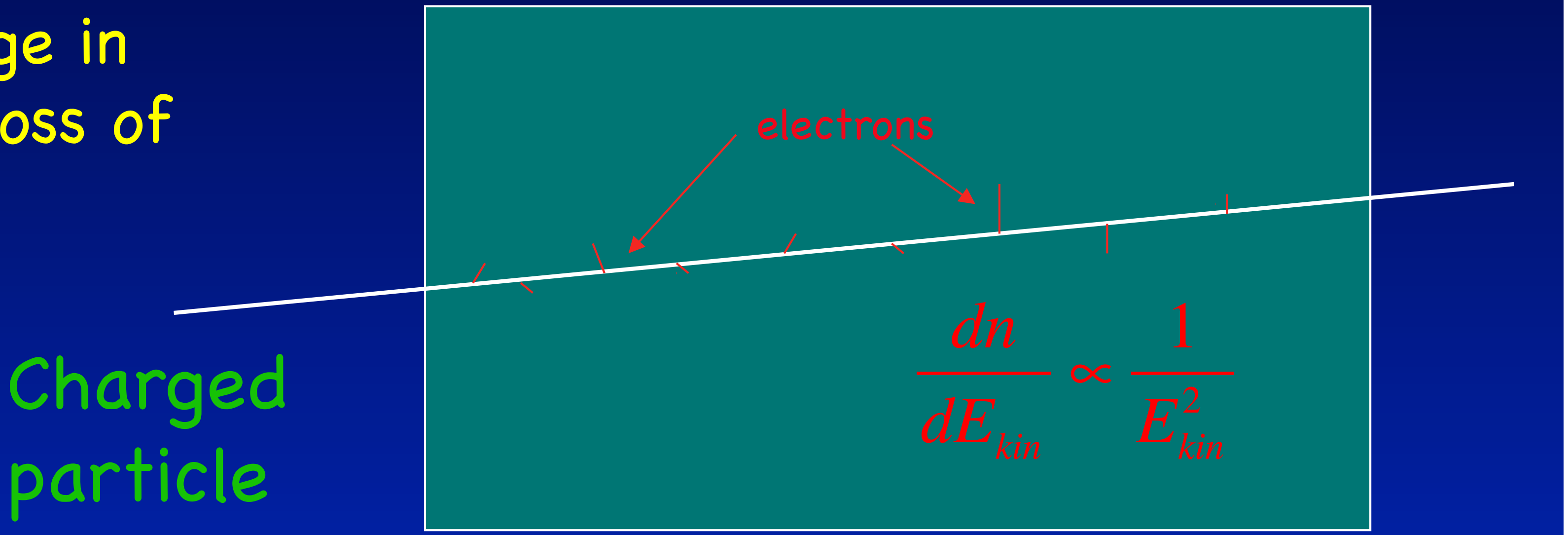
For a high energy particle, and to first approximation, matter can be seen as a collection of loosely bound electrons and nuclei

- collisions with nuclei

- collisions with electrons

Collisions with electrons:

little change in direction, loss of energy



$$\frac{dn}{dE_{kin}} \propto \frac{1}{E_{kin}^2}$$

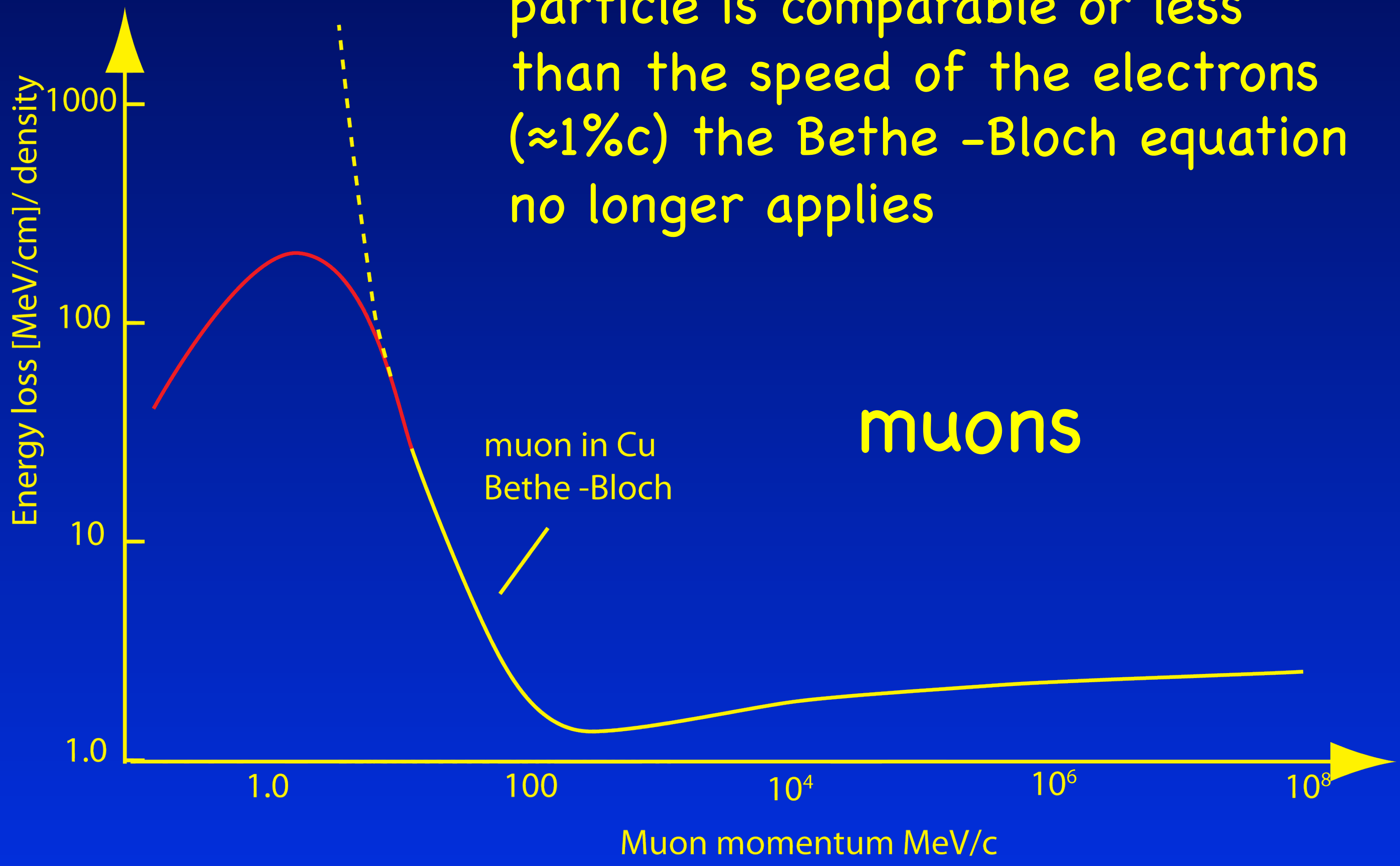
Bethe-Bloch equation for energy loss due to collisions with electrons

$$-\frac{dE}{dx} = \rho \frac{Z_{nucl}}{A_r} (4\pi N_A \; r_0^2 \; m_e \, c^2) \frac{Z^2}{\beta^2} \left[\frac{1}{2} \ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta)}{2} \right]$$

$$-\frac{dE}{dx} \approx \rho \; (2 \; MeV \; cm^2) \frac{Z^2}{\beta^2}$$

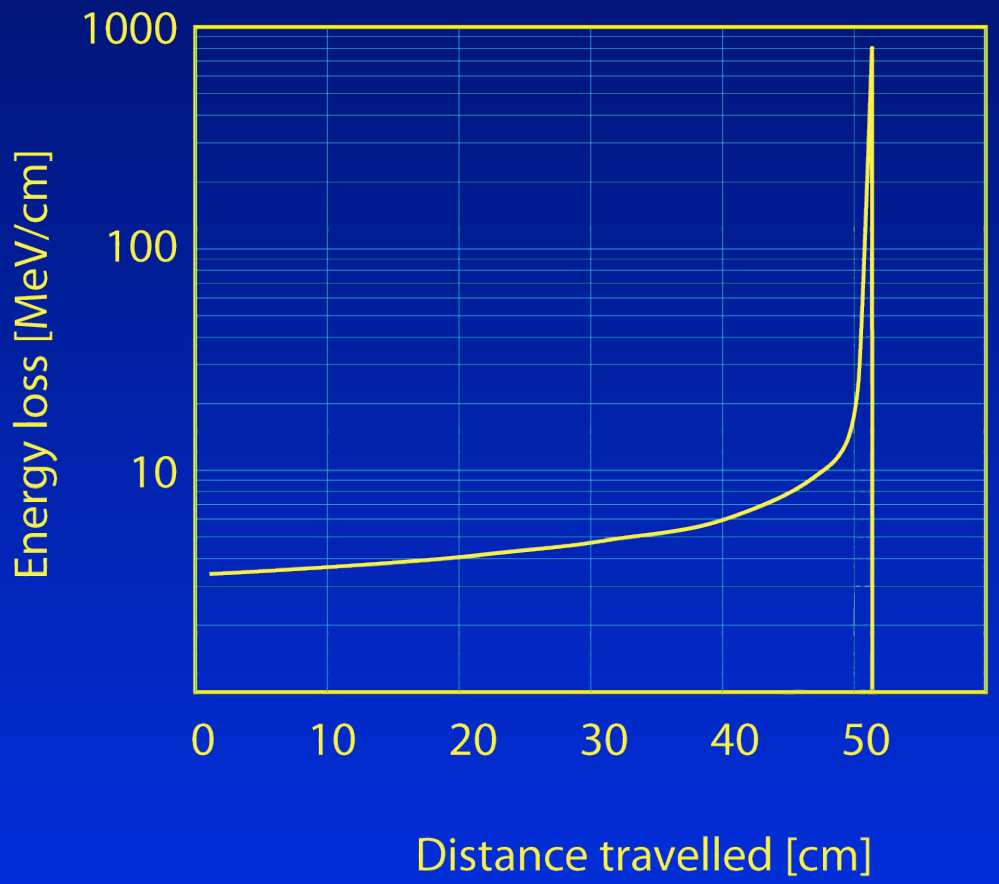
for electrons similar

If the velocity of the charged particle is comparable or less than the speed of the electrons (≈1%c) the Bethe -Bloch equation no longer applies

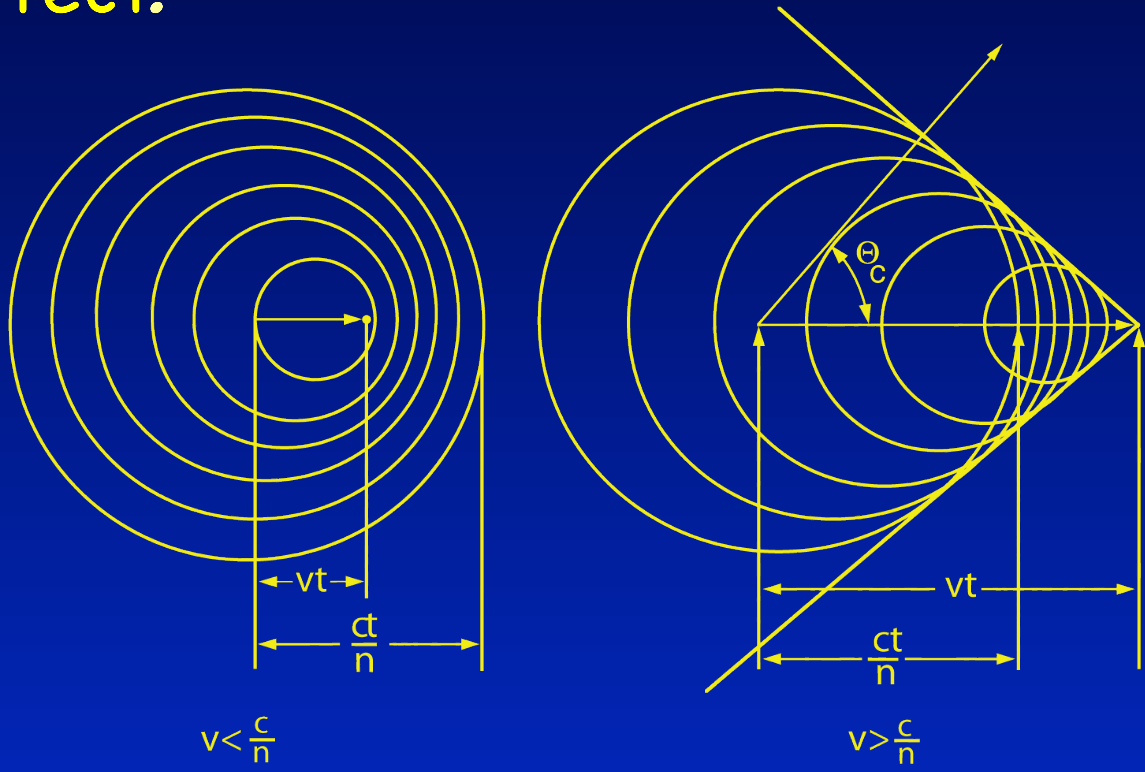


muons

Range of a 300 MeV proton in water



Cherenkov effect.



$$\frac{d^2E}{d\hbar\omega\,dx} = \hbar\omega\,\frac{Z^2\alpha}{\hbar c}\left[1 - \frac{c^2}{n^2v^2}\right]$$

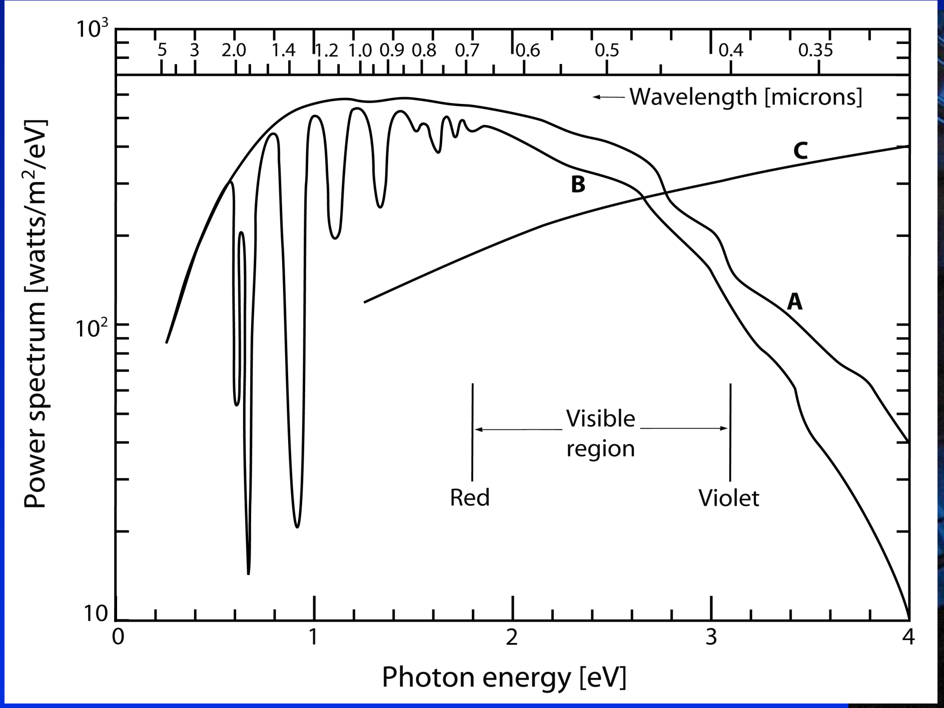
$$v > \frac{c}{n}$$

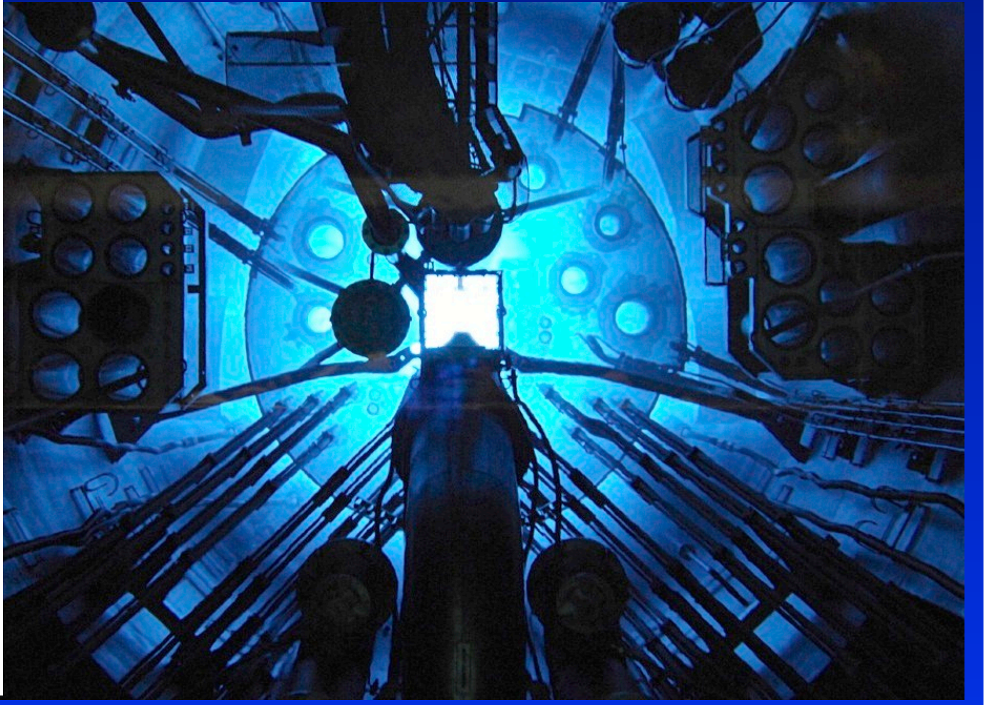
$$E_{threshold} = mc^2\left(\sqrt{\frac{n^2}{n^2-1}} - 1\right)$$

$$\cos(\theta_c) = \frac{c}{nv}$$

In water ≈ 220 photons/cm in visible (400-700 nm)
about 100-1000 times less than a good scintillator!

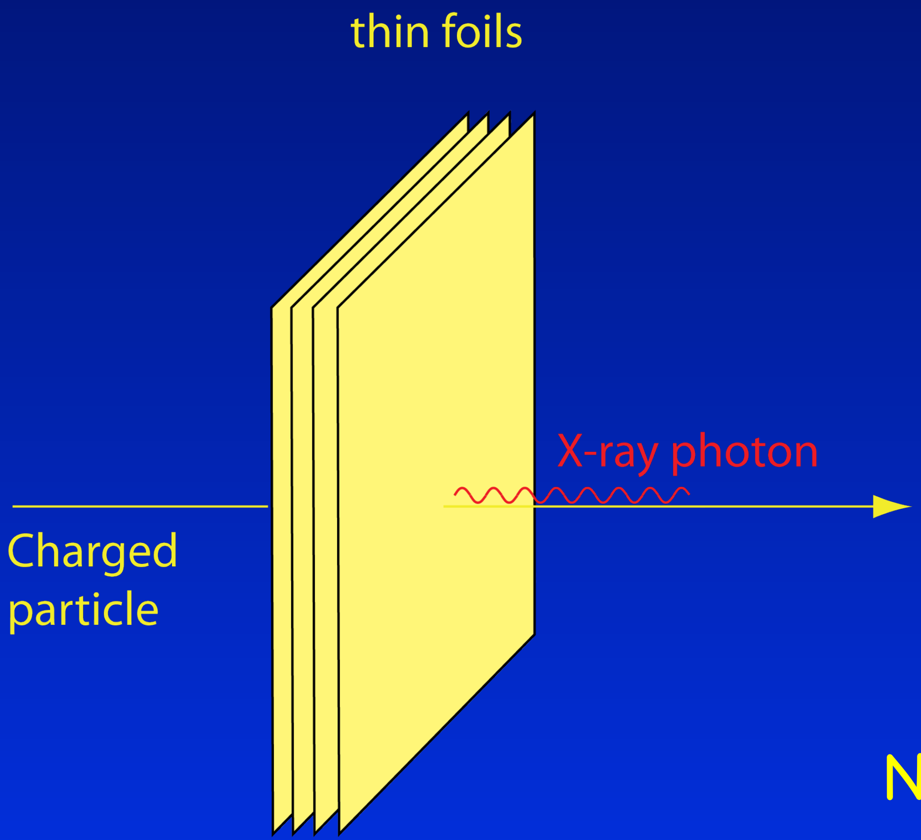
Interest stems from 'v' dependence intensity and angle





Transition radiation

Plasma frequency $\hbar\omega_p = \sqrt{4\pi N_e r_0^3}\ m_e c^2 / \alpha \approx \rho \times 20\ eV$



$$\langle E \rangle = \alpha Z^2 \gamma \hbar\omega_p / 3$$

Number of photons

with $E > \gamma\hbar\omega_p / 10$

$$N_\gamma \simeq 0.8\ \alpha\ Z^2 \simeq 0.59\%\ Z^2$$

foils need thickness> $\dfrac{\gamma c}{\omega_p}$

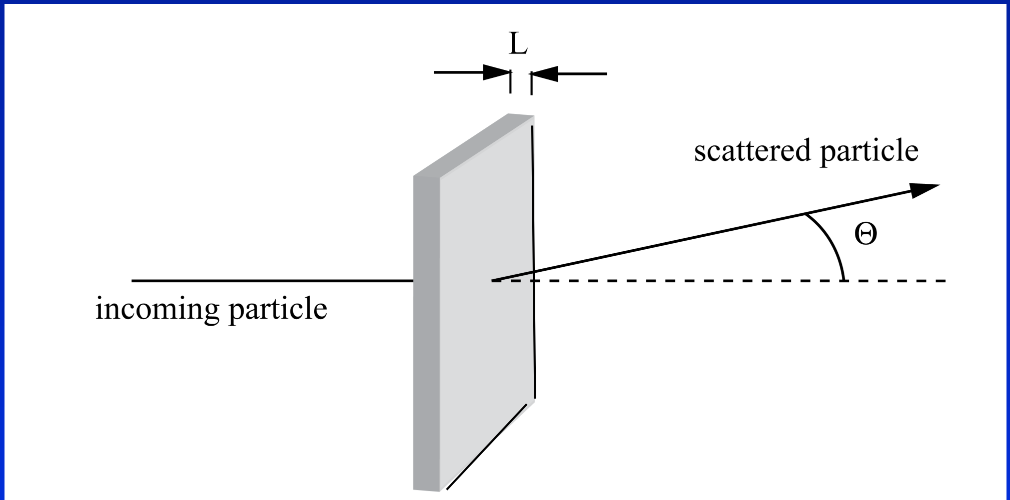
Notice the effects is $\propto \gamma$
and is significant only at large γ

Collisions with nuclei:

little energy loss, change of direction

$$\sqrt{\langle\Theta^2\rangle} = \frac{Z}{Pc\beta}(20\ MeV)\sqrt{\frac{L}{X_0}}$$

radiation length= $X_0 = \dfrac{A_r \times 716.4\ [cm^{-2}]}{\rho\ Z_{nucl}(Z_{nucl}+1)\ln\left(\dfrac{287}{\sqrt{Z_{nucl}}}\right)}$



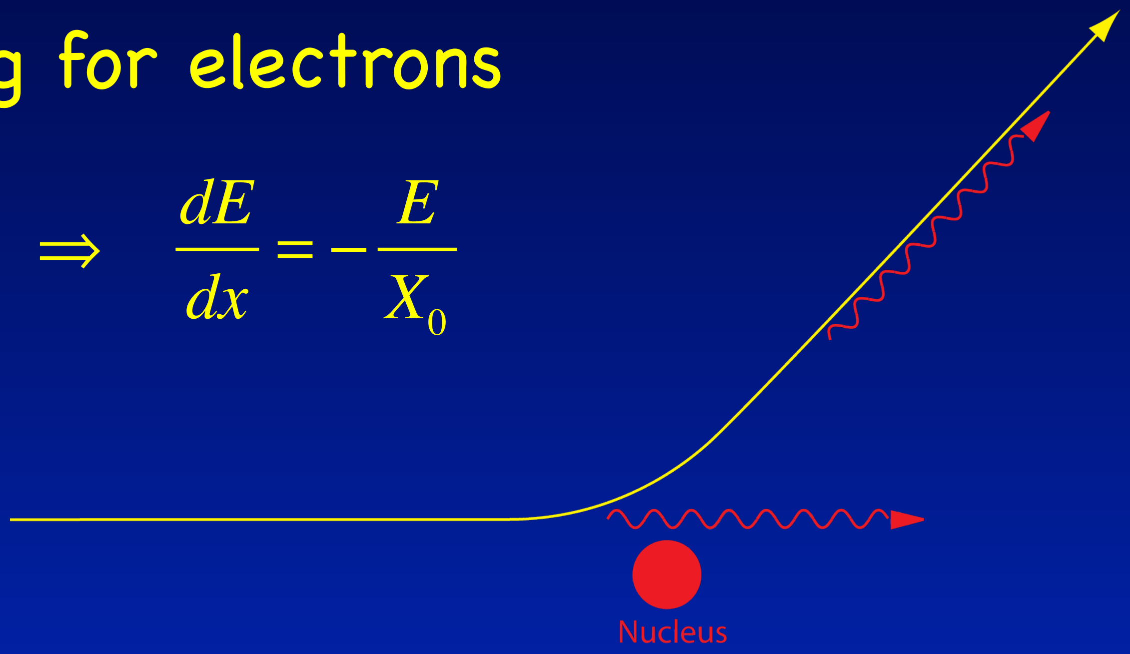
$$\sqrt{\langle\Theta_p\rangle^2} = \frac{1}{\sqrt{2}}\sqrt{\langle\Theta\rangle^2}$$

Table 2.1: Radiation length X_0 for some common materials

Material	Radiation length X_0
Air	304 m
Water	36 cm
Shielding concrete	10.7 cm
Nylon	36.7 cm
Aluminium (Al)	8.9 cm
Silicon (Si)	9.36 cm
Iron (Fe)	1.76 cm
Lead (Pb)	0.56 cm
Uranium (U)	0.32 cm

Bremsstrahlung for electrons

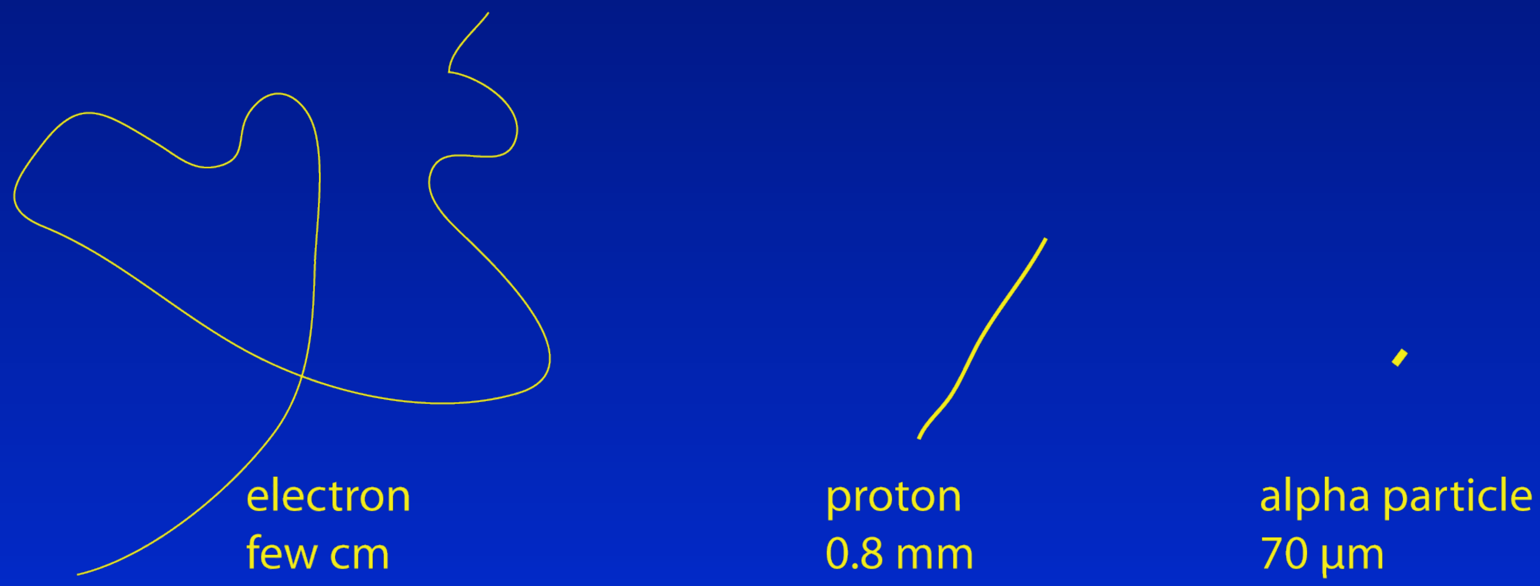
$$\frac{dN}{dx\ d\hbar\omega} = \frac{1}{\hbar\omega}\frac{1}{X_0} \quad \Rightarrow \quad \frac{dE}{dx} = -\frac{E}{X_0}$$



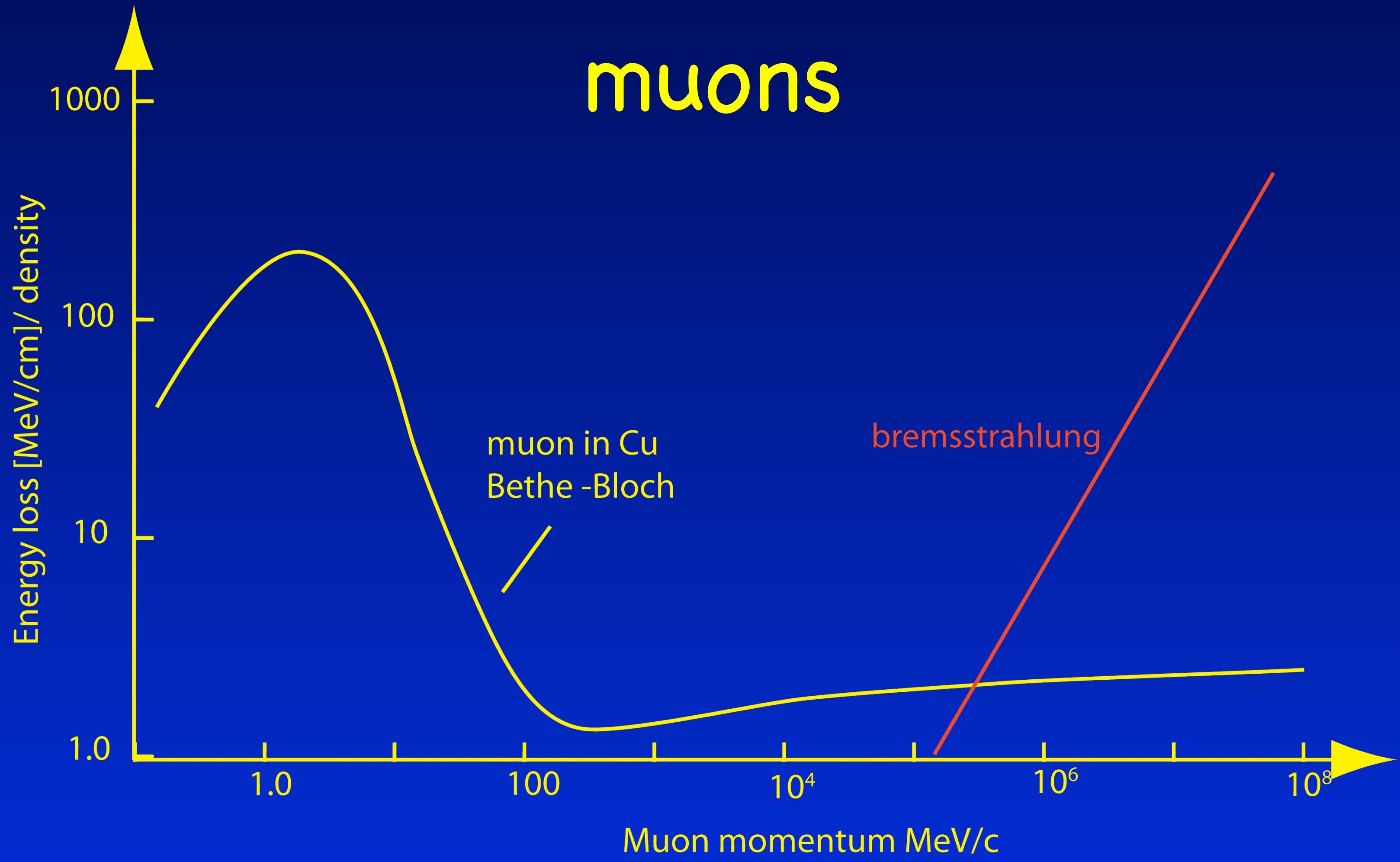
Will exceed energy loss by ionisation if E> $E_c = \frac{800\,MeV}{(Z+1.3)}$

For particles≠electron, emission is suppressed by a factor $(m_{electron}/M)^2$; significant only at very high energy

Summary interactions of low energy charged particles (10 MeV in silicon)



muons


1000
100
10
1.0
Energy loss [MeV/cm]/ density
1.0
100
10^4
10^6
10^8
Muon momentum MeV/c
muon in Cu
Bethe -Bloch
bremsstrahlung

Interactions of energetic photons in matter

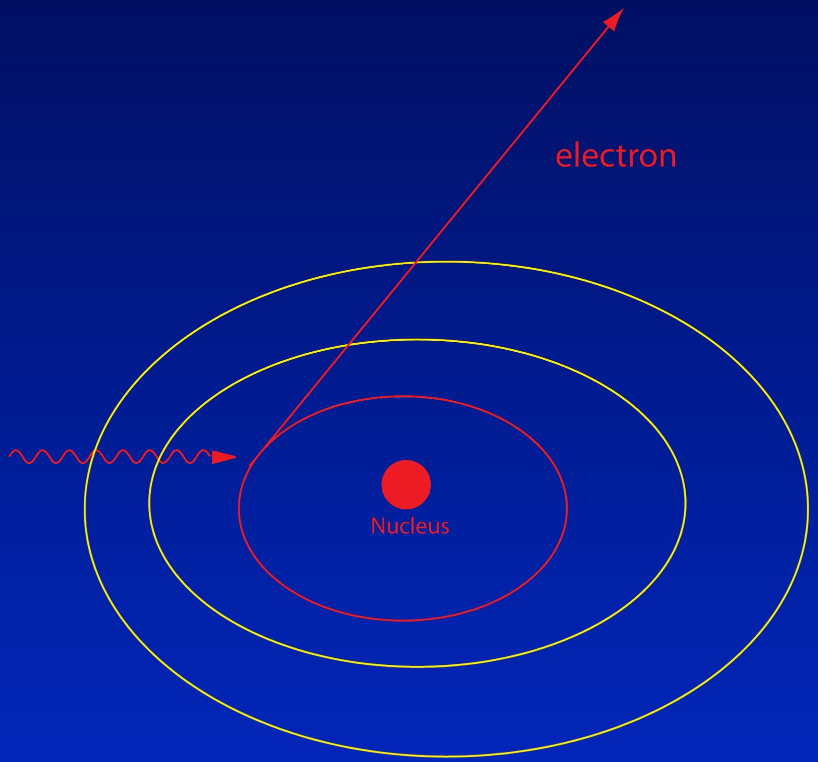
X-rays and gamma rays

- photoelectric effect
- compton scattering
- pair creation

Photoelectric effect

well above threshold >>

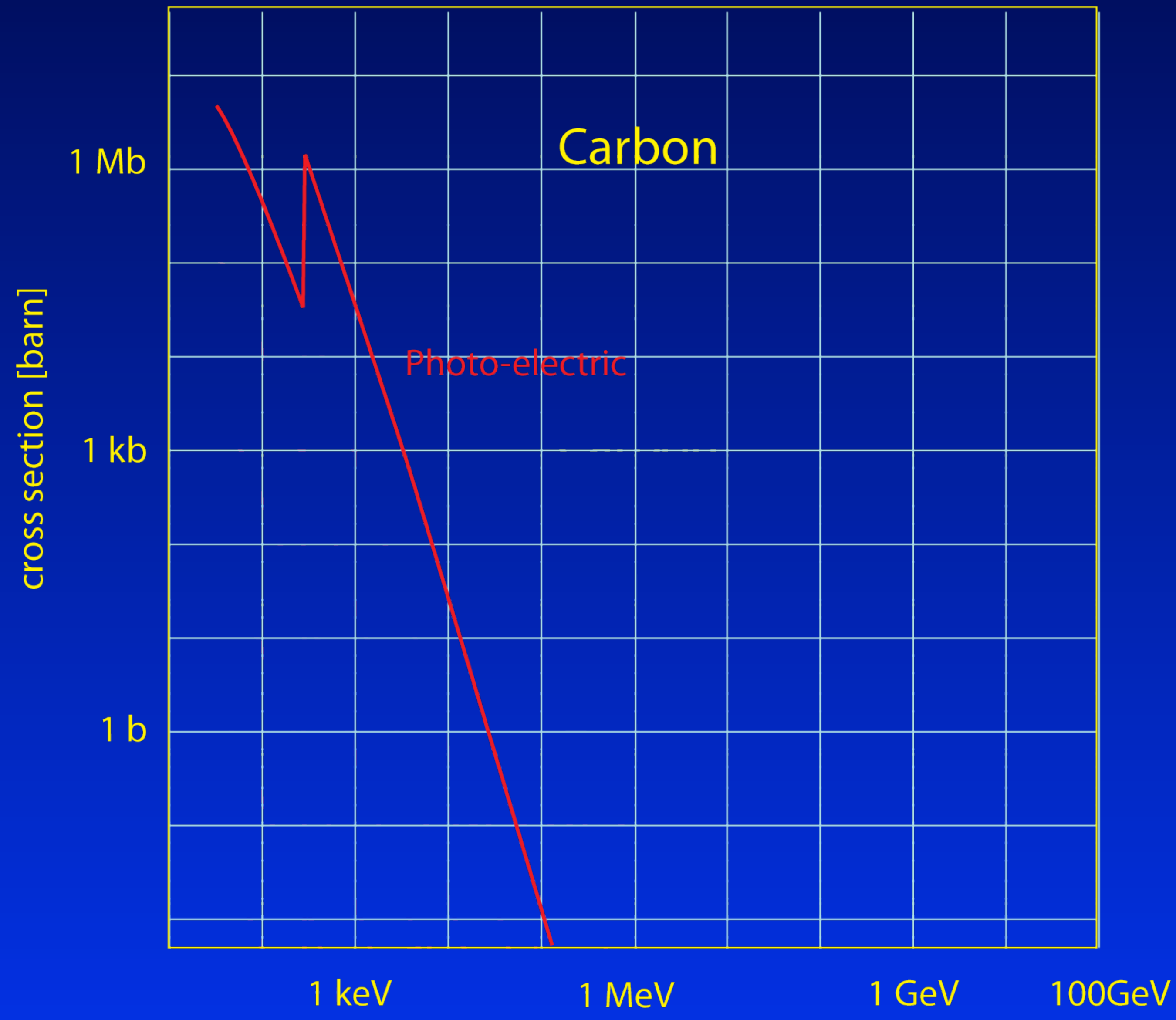
$$\sigma_{p.e.} = \frac{8\pi r_0^2}{3} \, 4\sqrt{2} \, \alpha^4 \, Z_{Nucl}^5 \left(\frac{m_e c^2}{E_\gamma} \right)^{7/2}$$



$$E_{kinetic} = \hbar\omega - E_{binding}$$

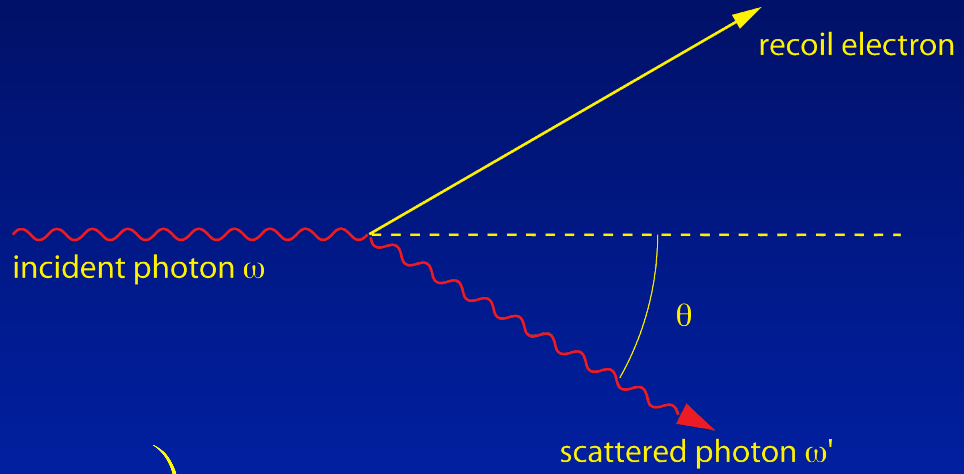
+ X-rays or Auger electron

80% of time on innermost electron


Carbon
1 Mb
1 kb
1 b
cross section [barn]
Photo-electric
1 keV
1 MeV
1 GeV
100GeV

Compton scattering (on free electron)

$$\hbar\omega' = \frac{\hbar\omega}{\left(1 + \frac{\hbar\omega}{m_e c^2}(1+\cos\theta)\right)}$$

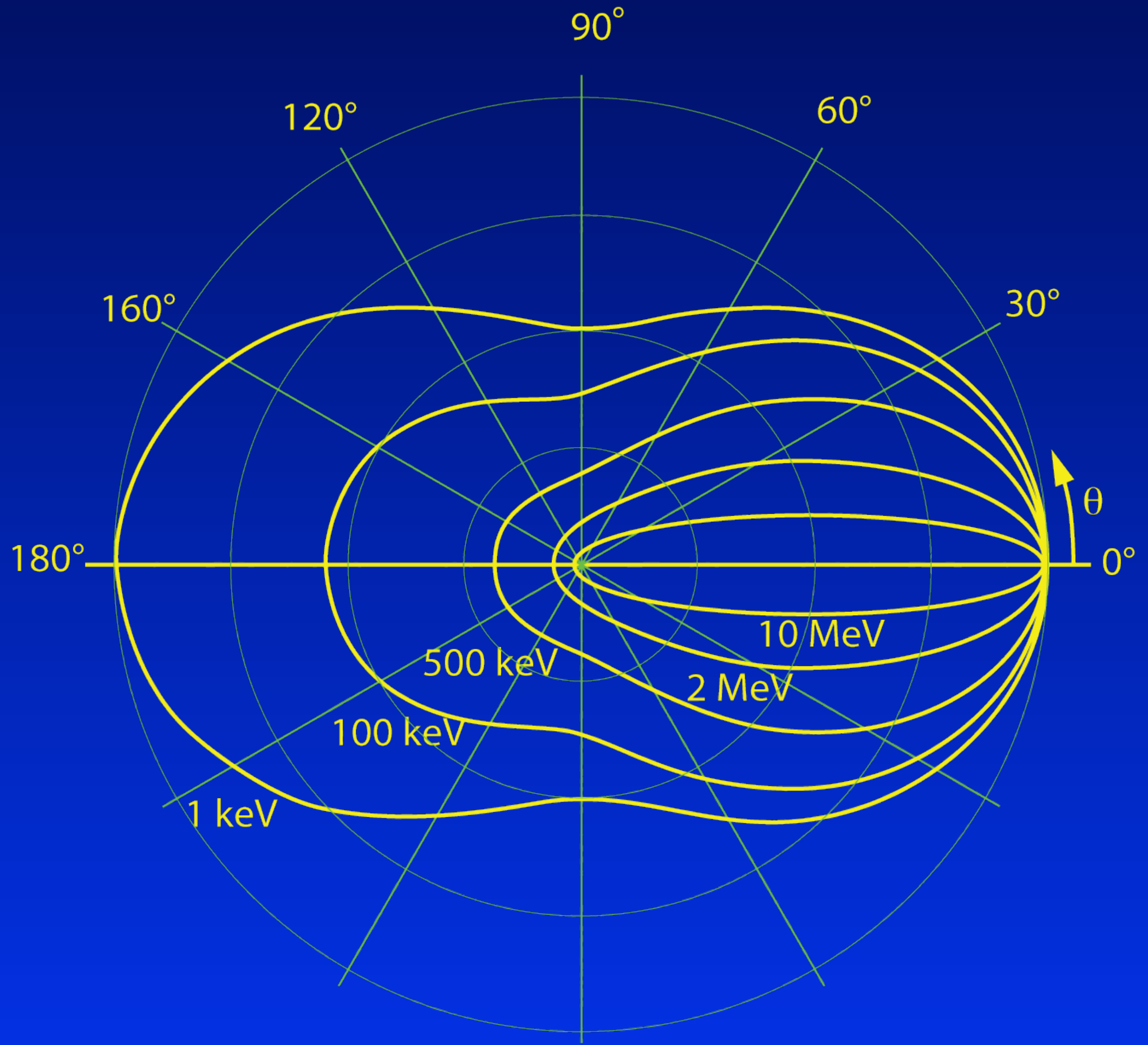


$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{\hbar\omega'}{\hbar\omega}\right)^2\left(\frac{\hbar\omega}{\hbar\omega'} + \frac{\hbar\omega'}{\hbar\omega} - \sin^2\theta\right)$$

$$\sigma = \frac{8\pi}{3} r_0^2 \qquad \hbar\omega \ll m_e c^2$$

$$\sigma = r_0^2 \pi \frac{m_e c^2}{\hbar\omega}\left[\ln\left(\frac{2\hbar\omega}{m_e c^2}\right) + \frac{1}{2}\right] \qquad \hbar\omega \gg m_e c^2$$

Angular distribution Compton scattering



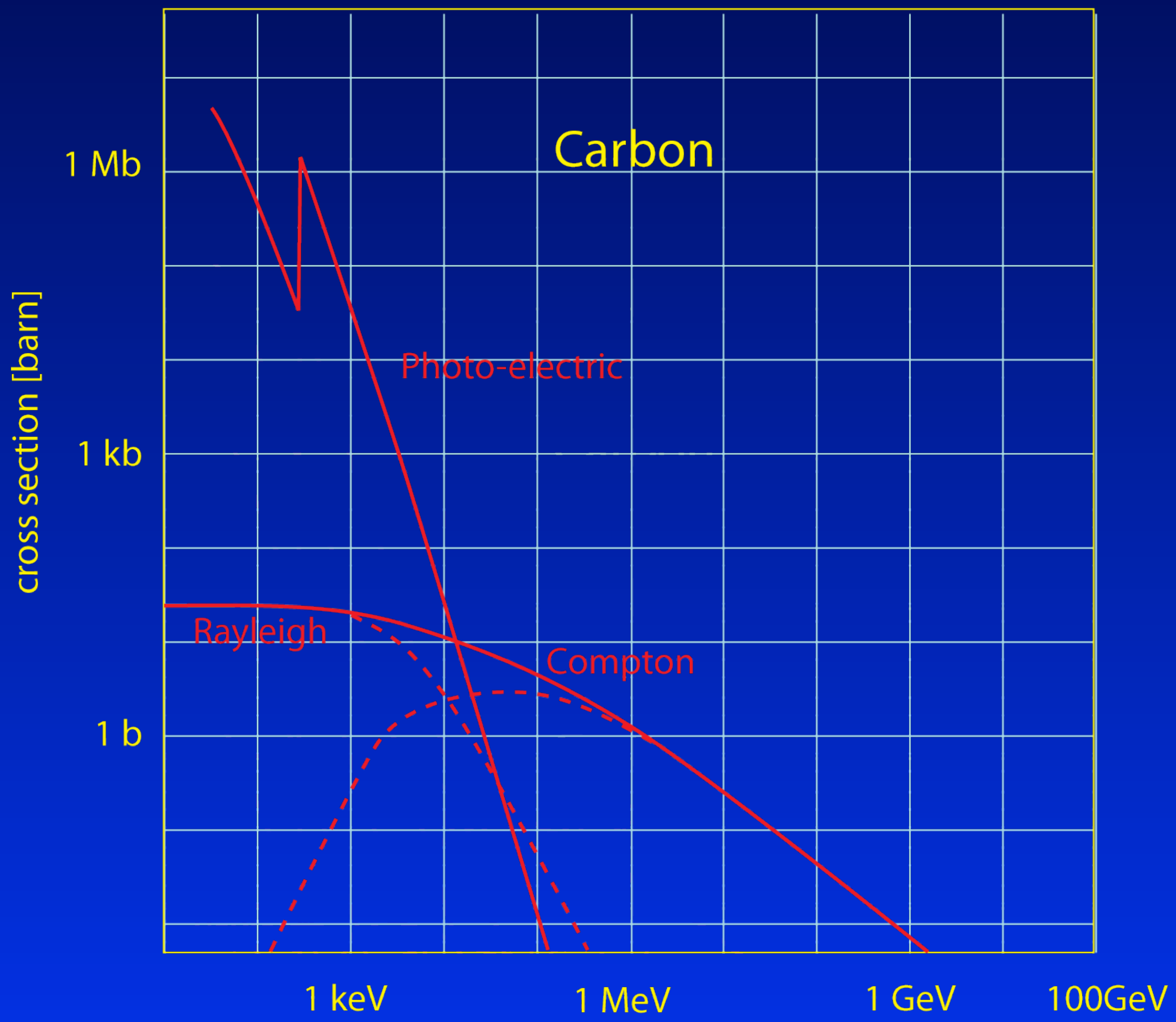
Compton scattering (on electron bound in atom)

Usually on a weakly bound outer electron

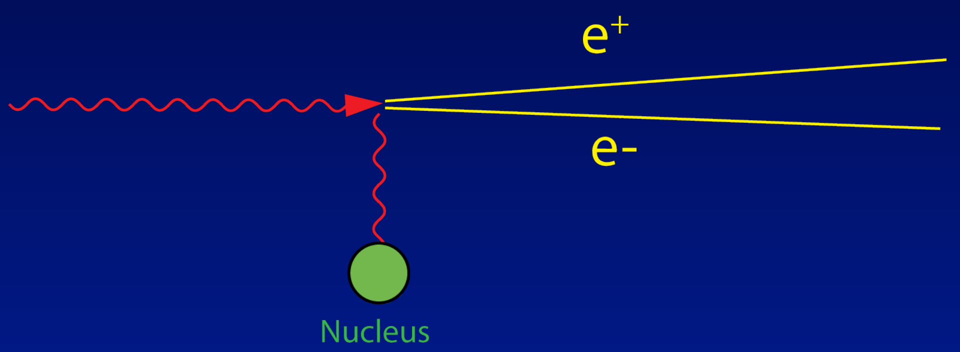
If electron remains bound in atom
=> coherent Compton, also called Rayleigh scattering

If atom ionised
=> incoherent Compton

Total cross section (coherent + incoherent), and angular distribution of scattered gamma still more ore less the same as on free electron


Carbon
1 Mb
1 kb
1 b
cross section [barn]
Photo-electric
Rayleigh
Compton
1 keV
1 MeV
1 GeV
100GeV

Pair creation



Threshold E> $2m_ec^2$

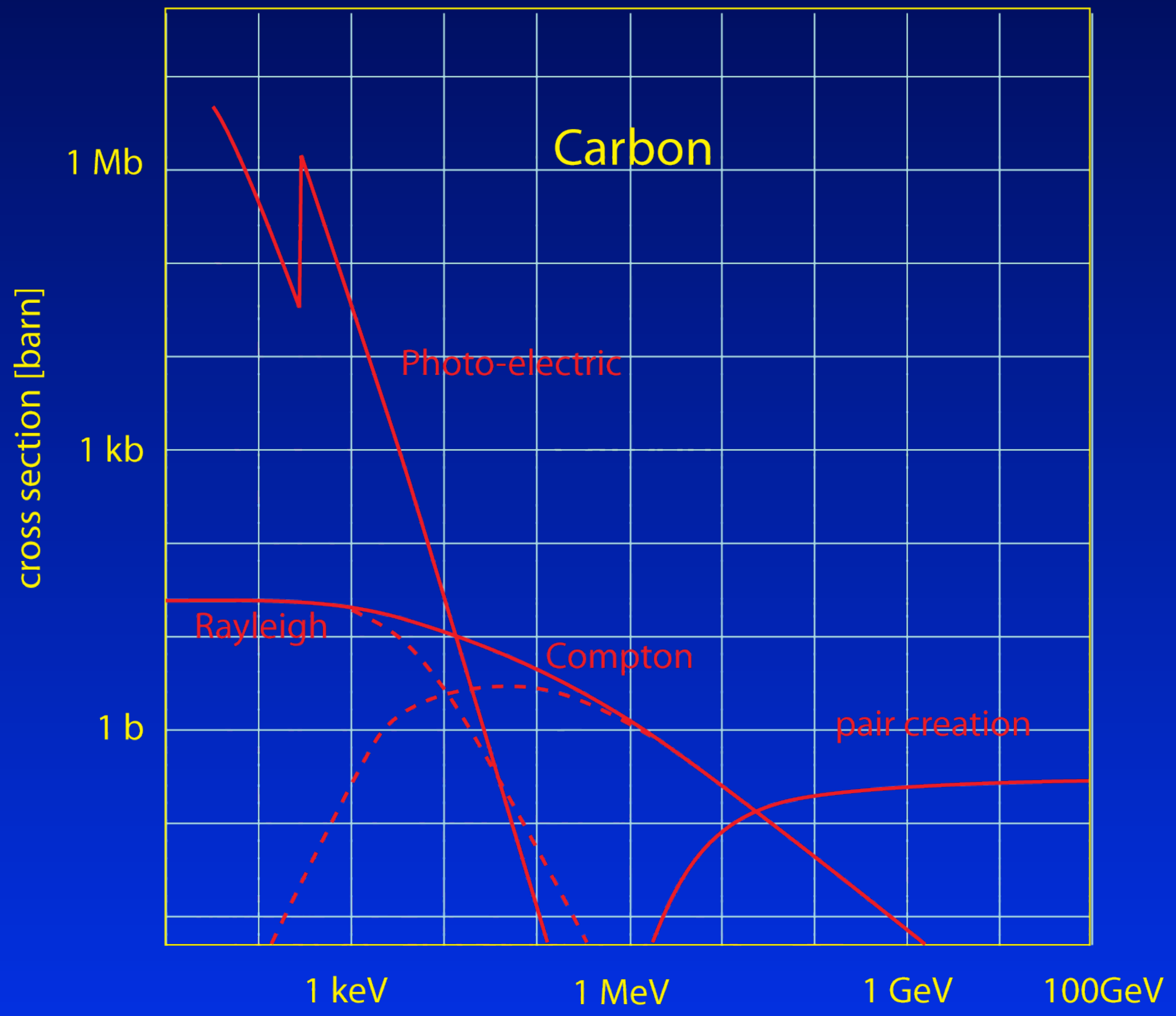
$$\frac{d\sigma}{dx} = \frac{1}{X_0}\frac{A_r}{\rho N_A}\left[1 - \frac{4}{3}k(1-k)\right] \quad ; \quad k = E_e / \hbar\omega$$

$$\sigma = \frac{7}{9}\frac{1}{X_0}\frac{A_r}{\rho N_A}$$

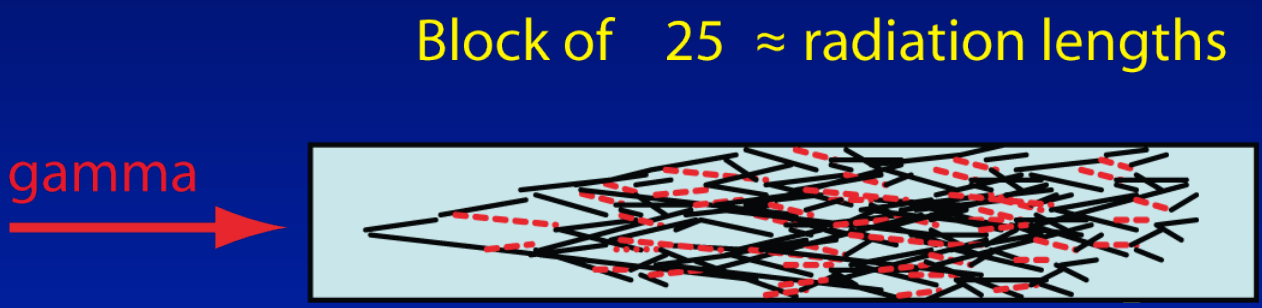
for E>> $2m_ec^2$

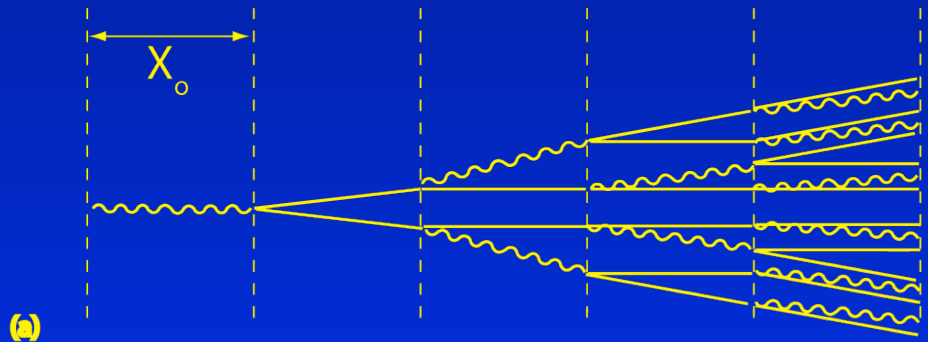
Probability pair creation $dW = \frac{7}{9}\frac{dx}{X_0}$

Summary


Carbon
1 Mb
1 kb
1 b
cross section [barn]
Photo-electric
Rayleigh
Compton
pair creation
1 keV
1 MeV
1 GeV
100GeV

Interaction of a high energy gamma ray or electron in matter





$$X_0 = \frac{A_r \times 716.4\ [cm^{-2}]}{\rho\ Z_{nucl}(Z_{nucl}+1)\ln\left(\frac{287}{\sqrt{Z_{nucl}}}\right)}$$

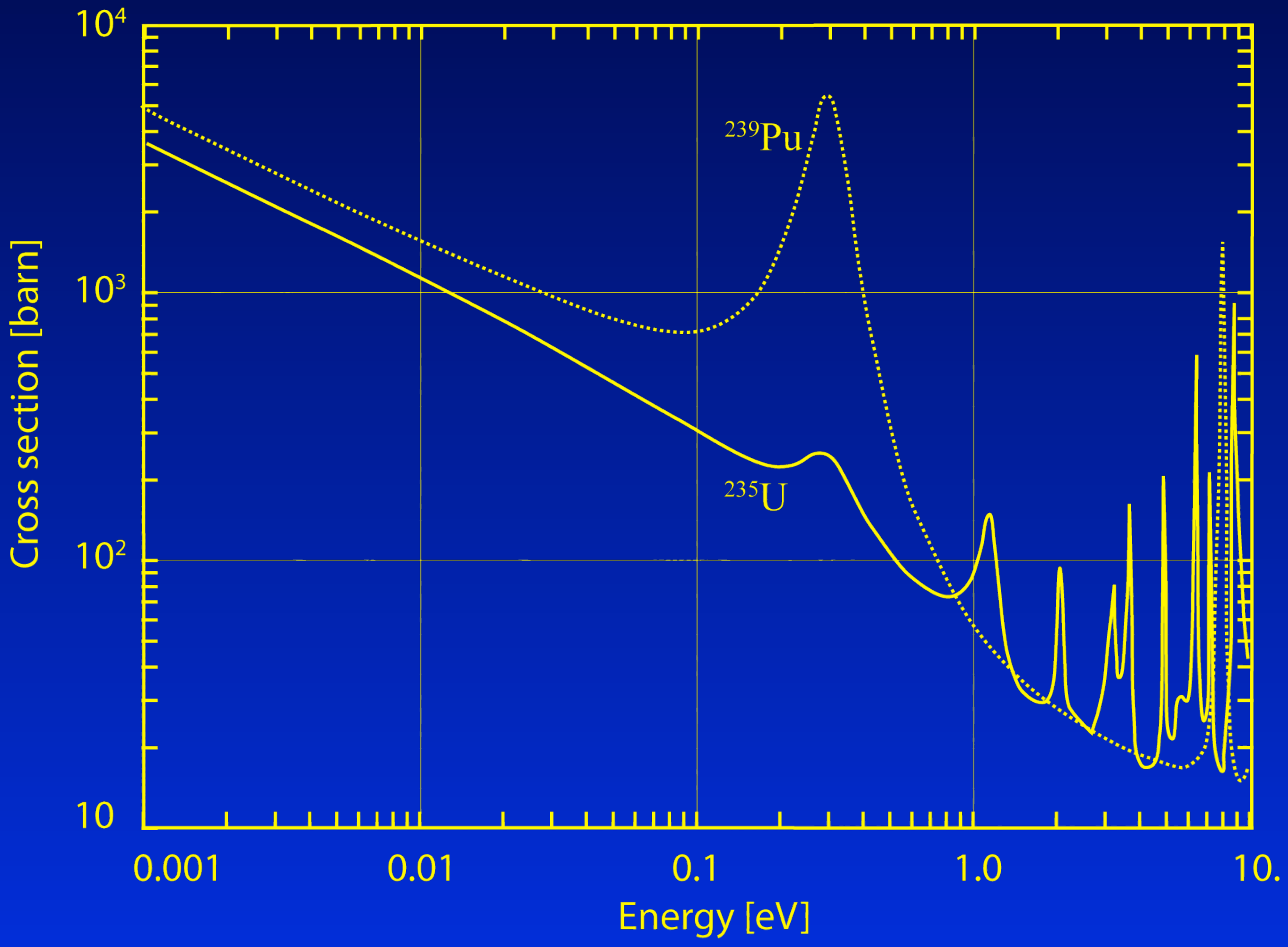
$$E_c \approx \frac{800\,MeV}{Z_{nucl}+1.2}$$

Nuclear interactions
At MeV energy

Hadrons (bound states of quarks) undergo nuclear interactions: protons, neutrons etc. At MeV energies: strong resonance effects, cross section is variable and can be very large

- protons, alpha particles: will usually loose all energy by ionisation and just stop, occasionally undergo a nuclear interaction

- neutrons, will always end up making a nuclear interaction


10^4
10^3
10^2
10
Cross section [barn]
^{239}Pu
^{235}U
0.001
0.01
0.1
1.0
10.
Energy [eV]

Nuclear interactions

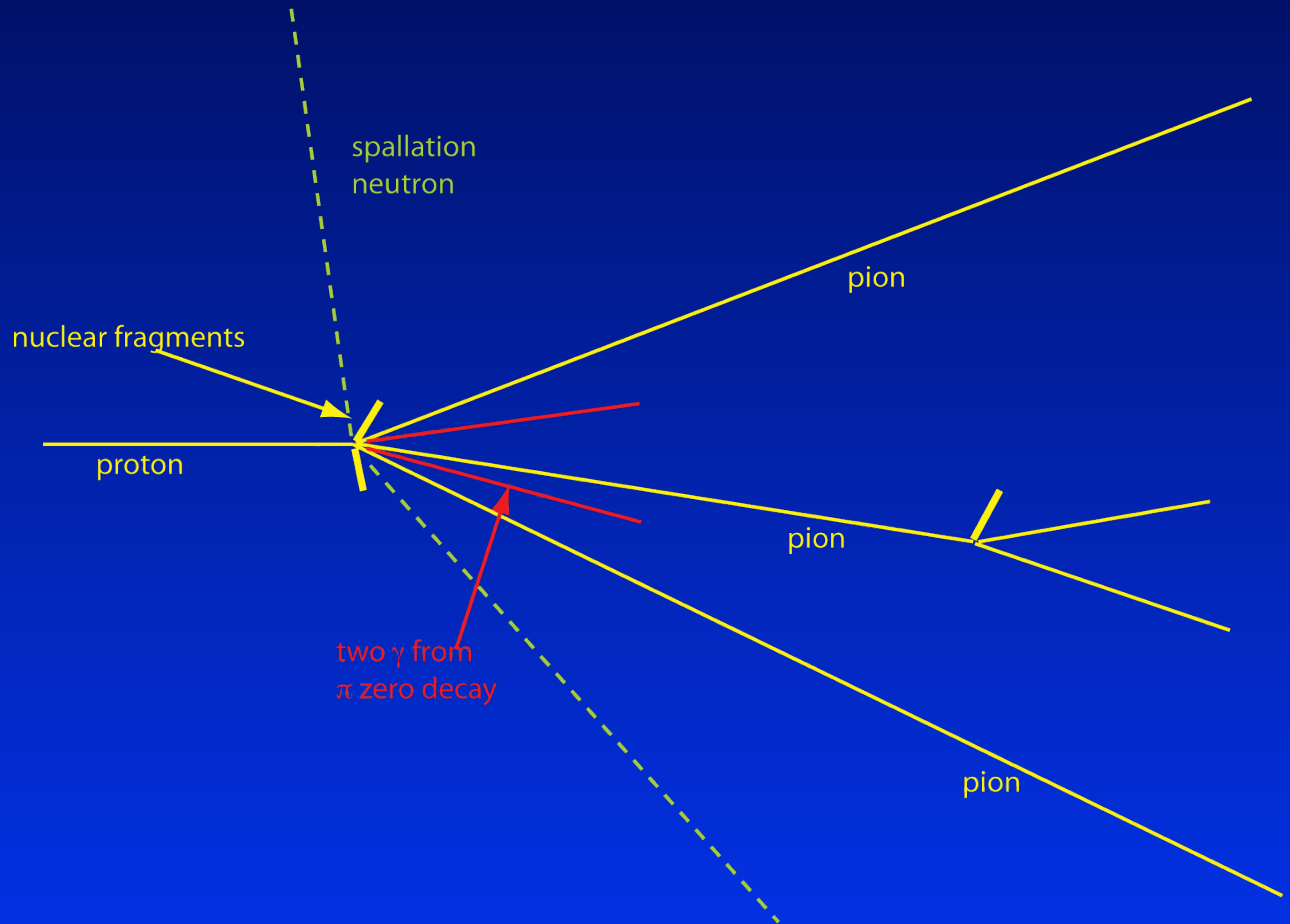
At high energy E>> MeV

Constant cross section approximately the same for all hadrons

$$m.f.p. \approx \frac{A^{1/3}}{\rho}\, 35 g\ cm^{-2}$$

m.f.p. hadrons in water ≈ 60 cm; in iron ≈ 10 cm

Interaction of a high energy hadron in matter



Electrons, muons, gamma rays only rarely undergo nuclear interactions.

However, at very high energy (> 10^{20} eV) gamma rays, photonuclear interactions become dominant.

Neutrino interactions

Neutrinos have no charge and are insensitive to nuclear interactions.

MeV neutrino m.f.p ≈ 1 light year on normal matter!

At high energy $\sigma \propto E_\nu$

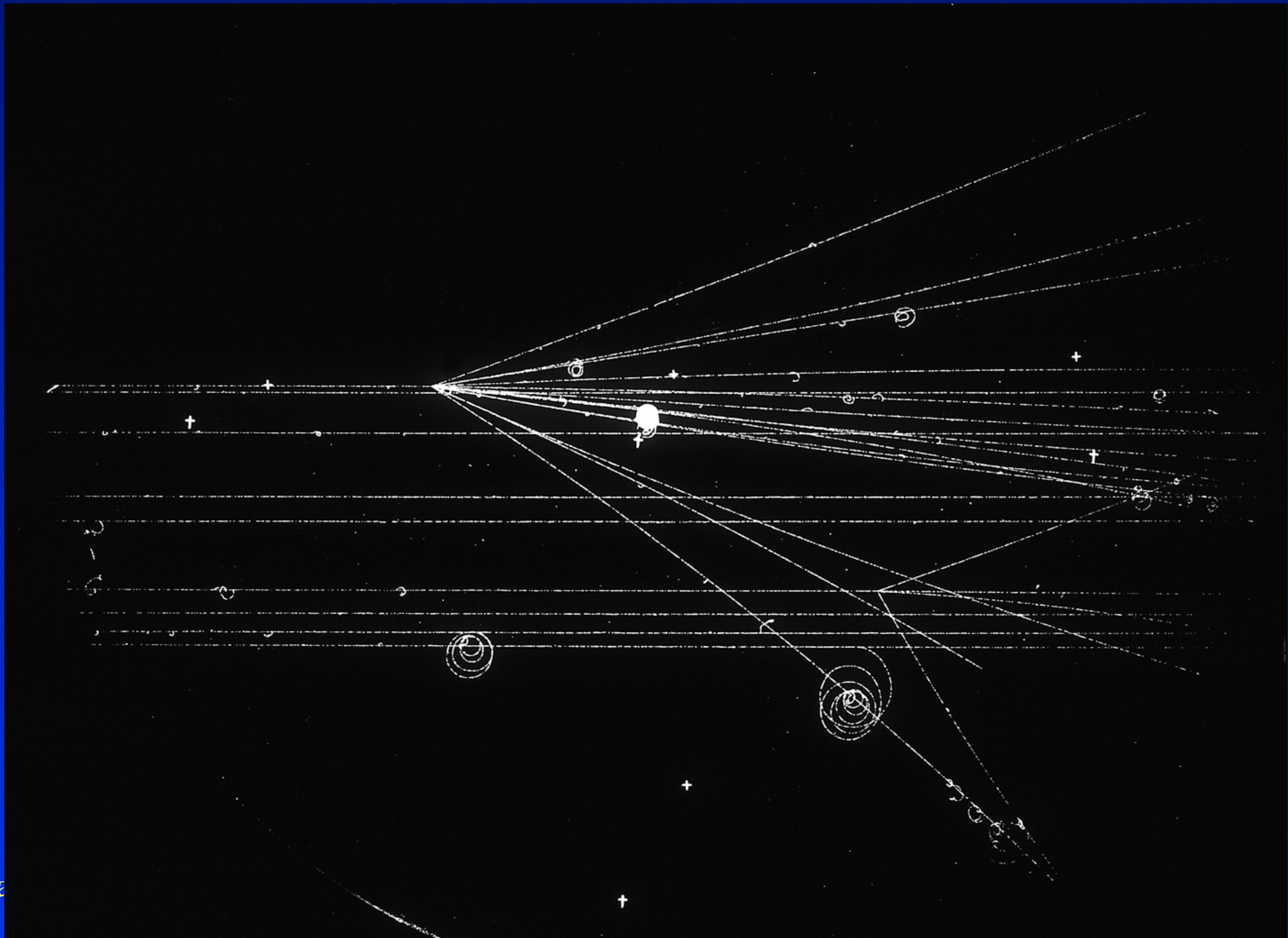
Introduction to detectors and detector techniques

All detection of energetic subatomic particles is based in their electromagnetic interactions. Neutral particles must first interact and then one can detect the charged particles produced in the interaction.

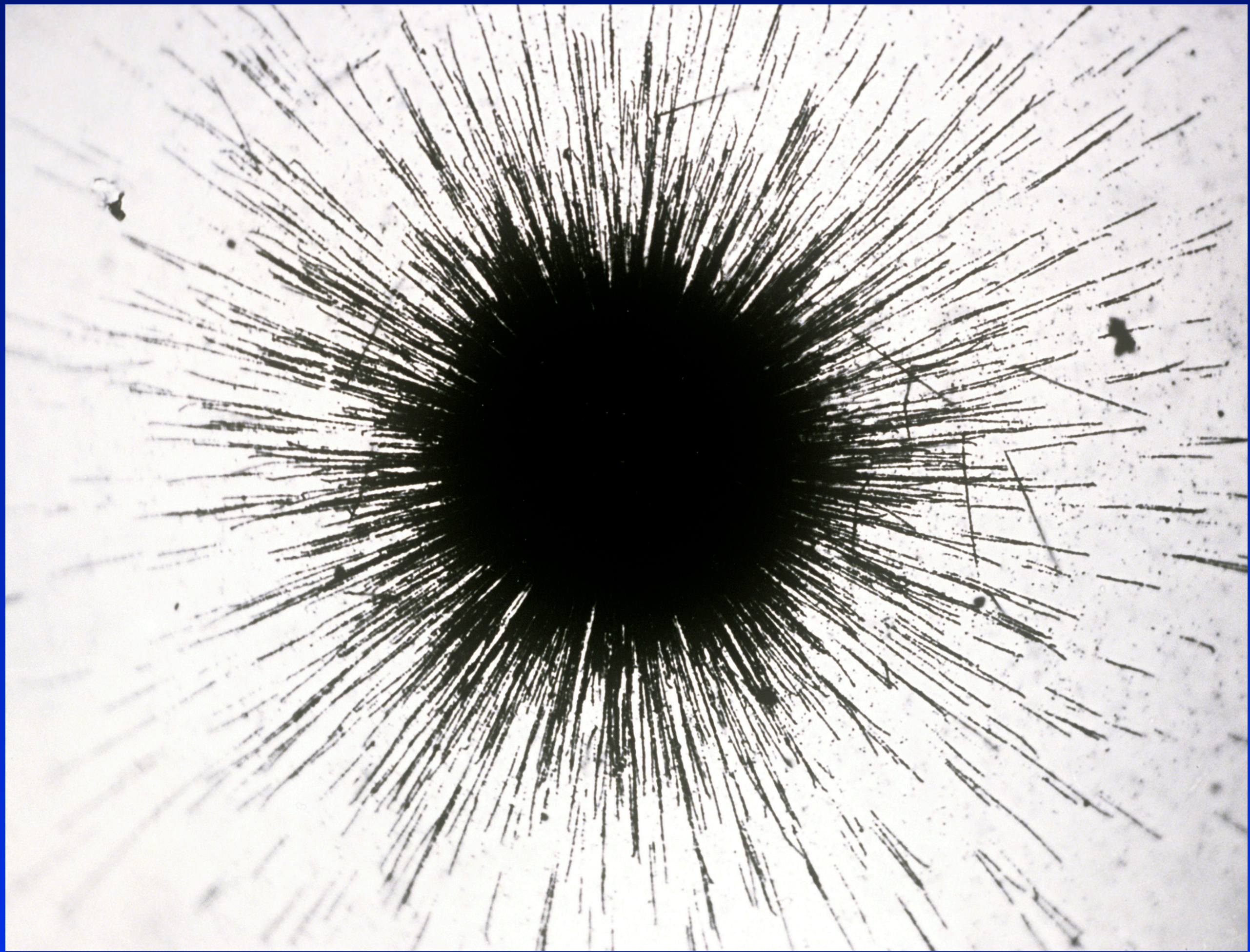
Most detectors are base on the ionisation produced by charges particles in matter. As a result, most detectors belong to one of the following categories

- detectors based on ionisation in gases
- detectors based on ionisation in semiconductors
- detectors based on scintillation

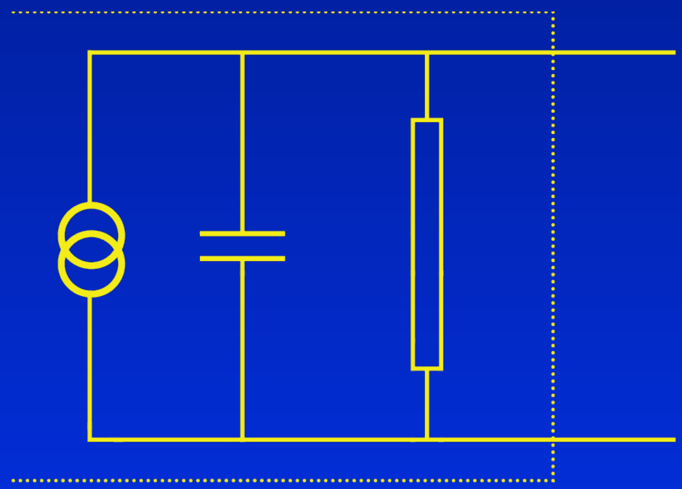
Years ago, many detection methods relied on making tracks visible, e.g. bubble chamber, spark chamber etc.



Most of these methods have fallen in disuse. One significant exception is the nuclear emulsion.



Today, nearly all detection is based on the fact that energetic subatomic particles induce some small electrical pulses . From the electronics point of view the detector is a current source, and it has a capacitance and a resistance.



Current mode and pulse mode measurements

Simple instruments will only measure the average current in the detector. However, it is much better to observe the individual pulses. The pulses provide amplitude and time information that can be very useful.

- example amplitude: 3He tube: amplitude allows distinguishing neutrons from gamma induced pulses

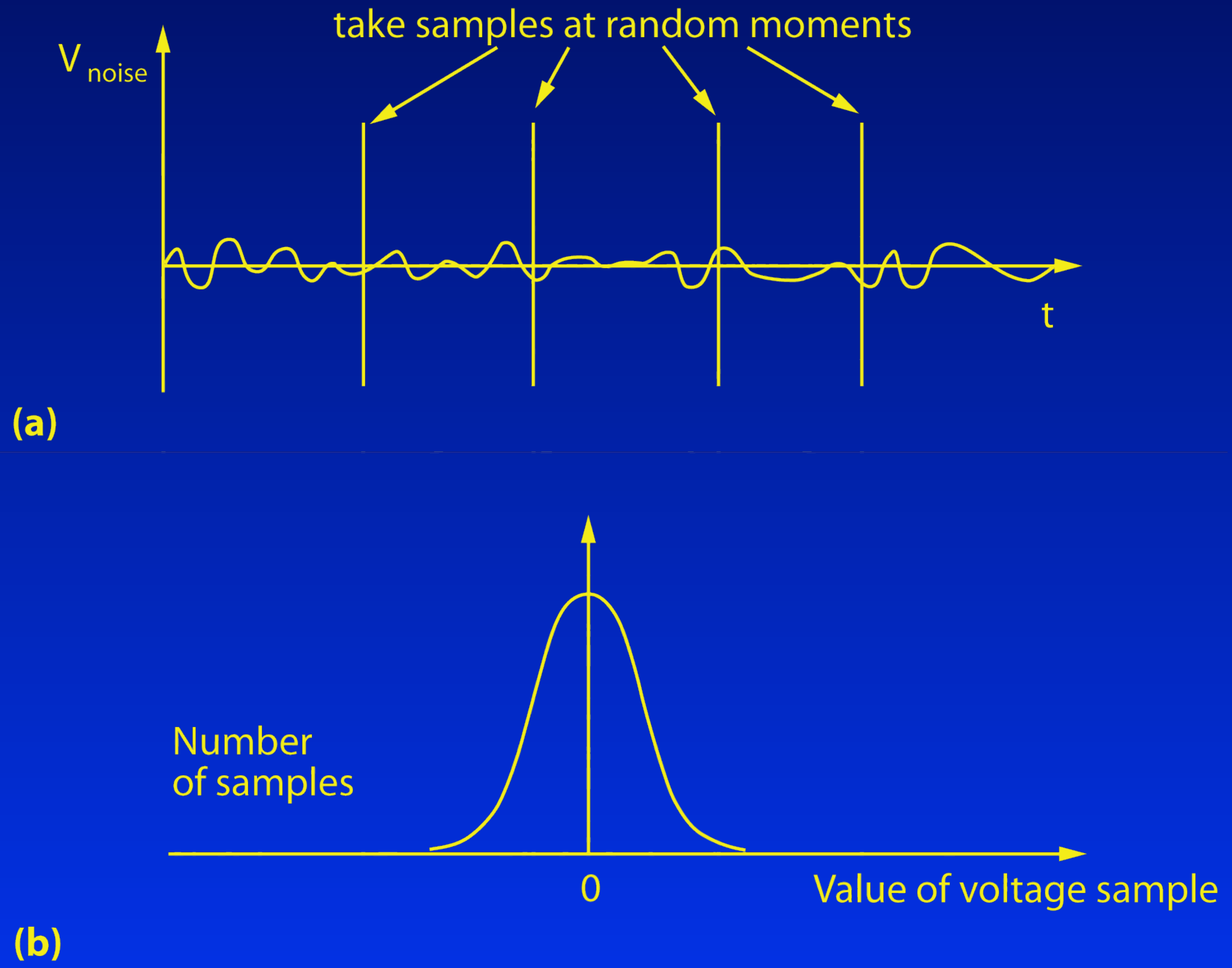
- example timing: coincidence of two gamma rays characterises a positron annihilation

Noise in detector systems

The signal from a detector is often very small. The signal can be difficult to see because of the electronic noise that is always present in any system. The two main types of electronic noise are
- pick-up noise, is avoidable in principle
- intrinsic noise, is unavoidable

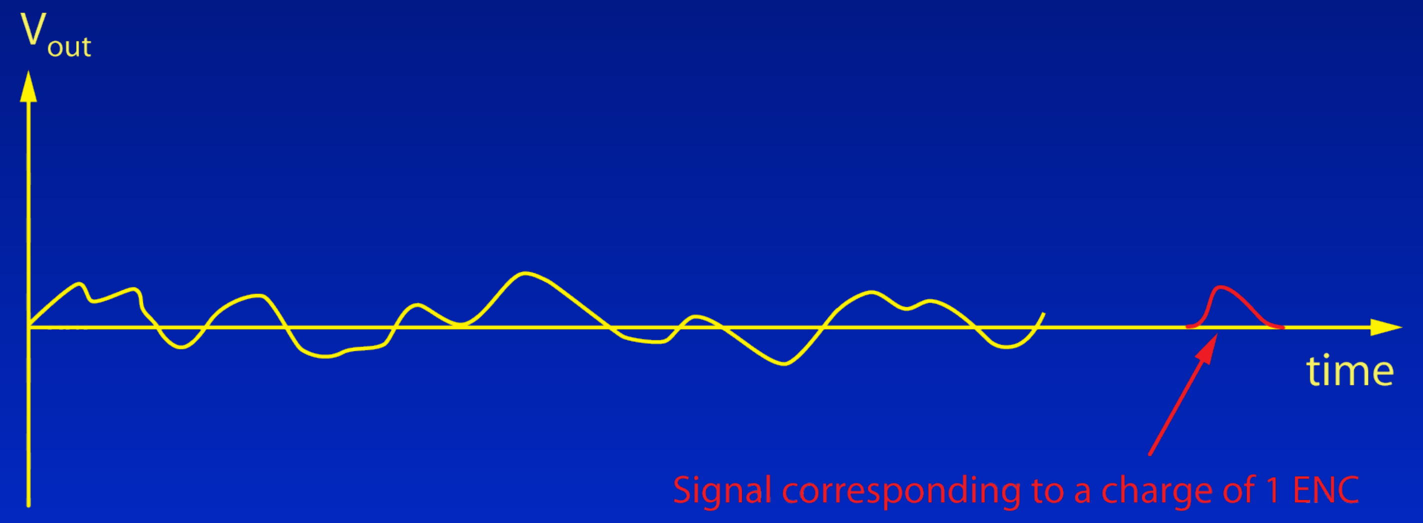
In addition, there can be physical noise, i. e, real interactions of subatomic particles, but not the ones we want to see. This last type of noise is more often referred to as "background".

The intrinsic noise has a smooth frequency spectrum

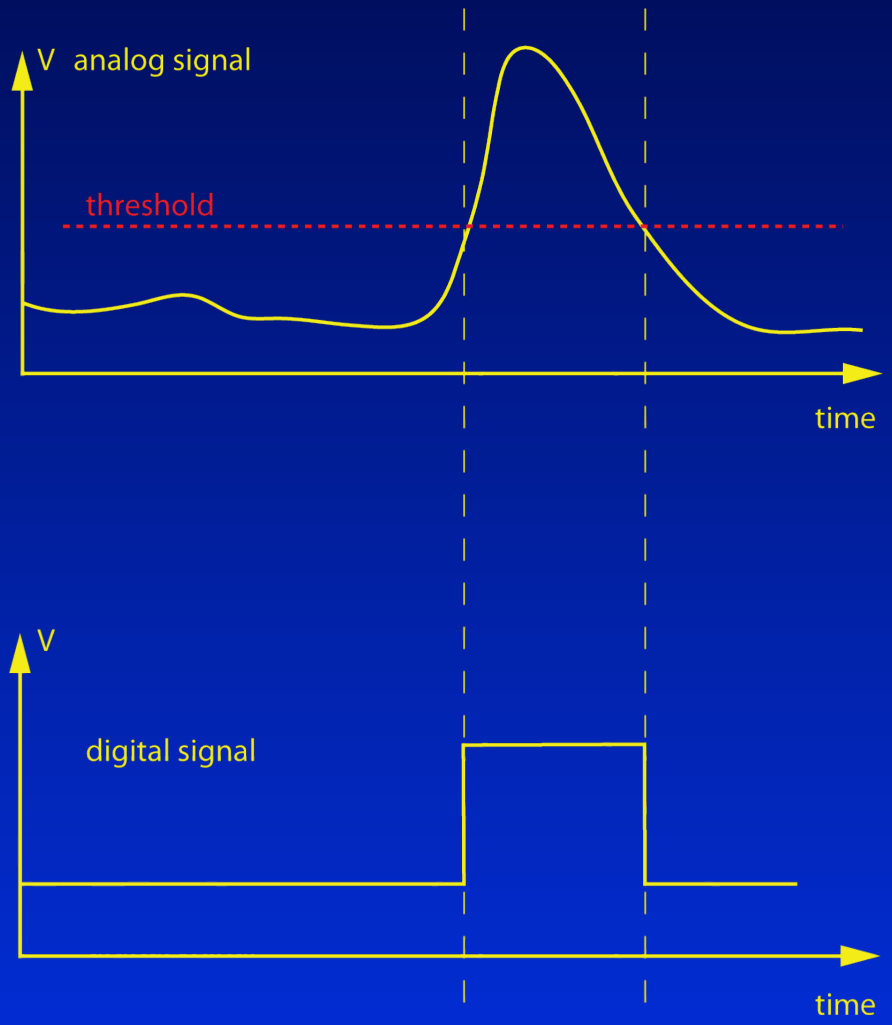


Definition of "equivalent noise charge" (ENC)

A short charge signal that gives a pulse such that the peak of the signal = one noise r.m.s.



The equivalent noise charge is usually expressed as a number of electrons



There is a signal if some threshold amplitude is crossed.

A signal of one equivalent noise charge is completely lost in the noise. A signal should be about 10 times the equivalent noise charge to be comfortable visible above the noise.

In a well designed system the pickup noise is small. The main sources of intrinsic noise are

- the shot noise caused by the dark current in the detector, the corresponding ENC is

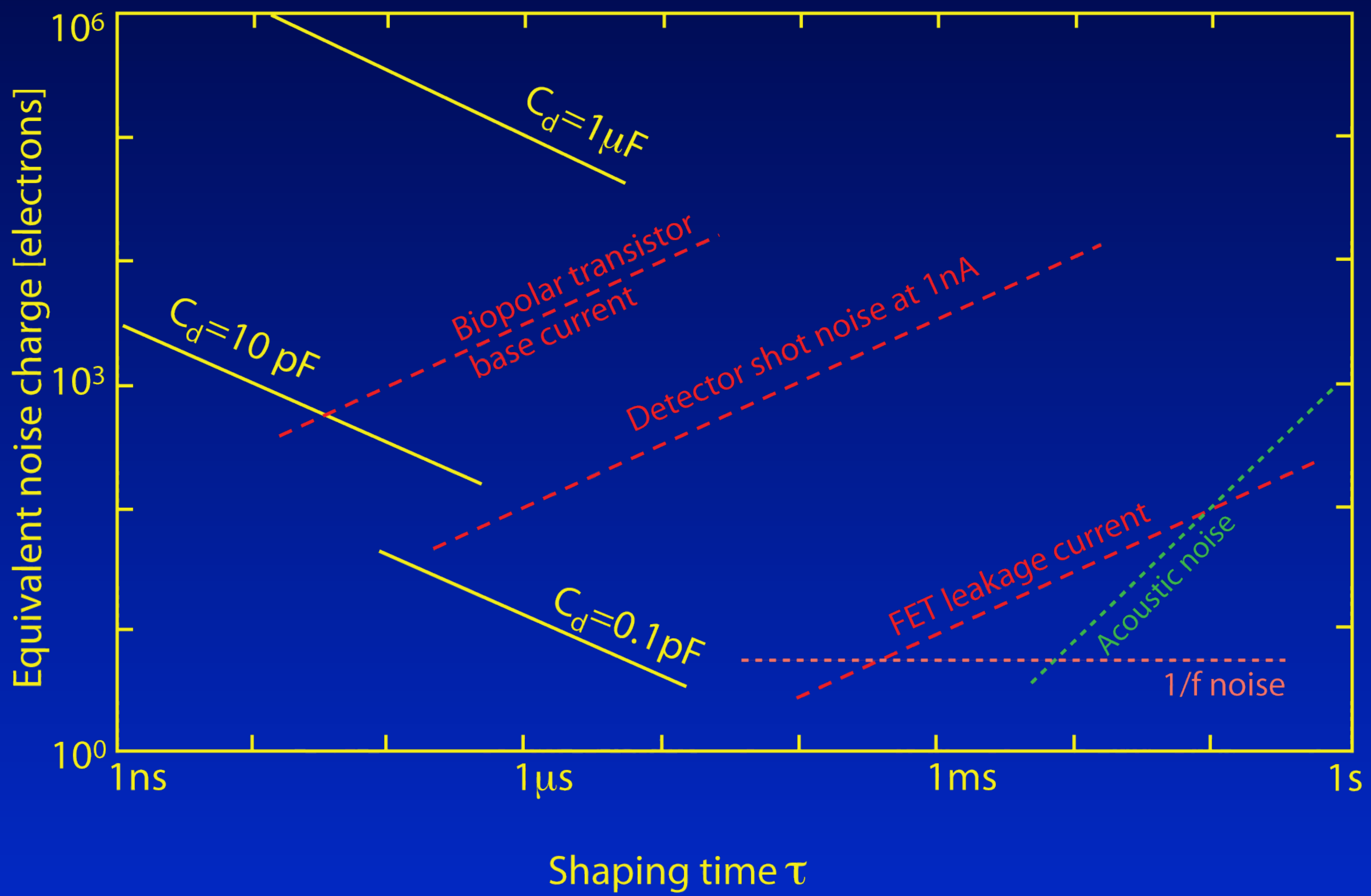
$$\sqrt{2Q\ \tau\ I_{dark\ \ current}}$$

- the thermal noise of the first transistor, the corresponding ENC is given by

$$\sqrt{\frac{32}{3}kTC_d\frac{t_{transit}}{\tau}}$$

The shaping time τ is related to the bandwith (BW) of the amplifier. It determines the maximum count rate the system can handle

To have low noise the detector should have
- large internal resistance and therefore low leakage current
- low capacitance

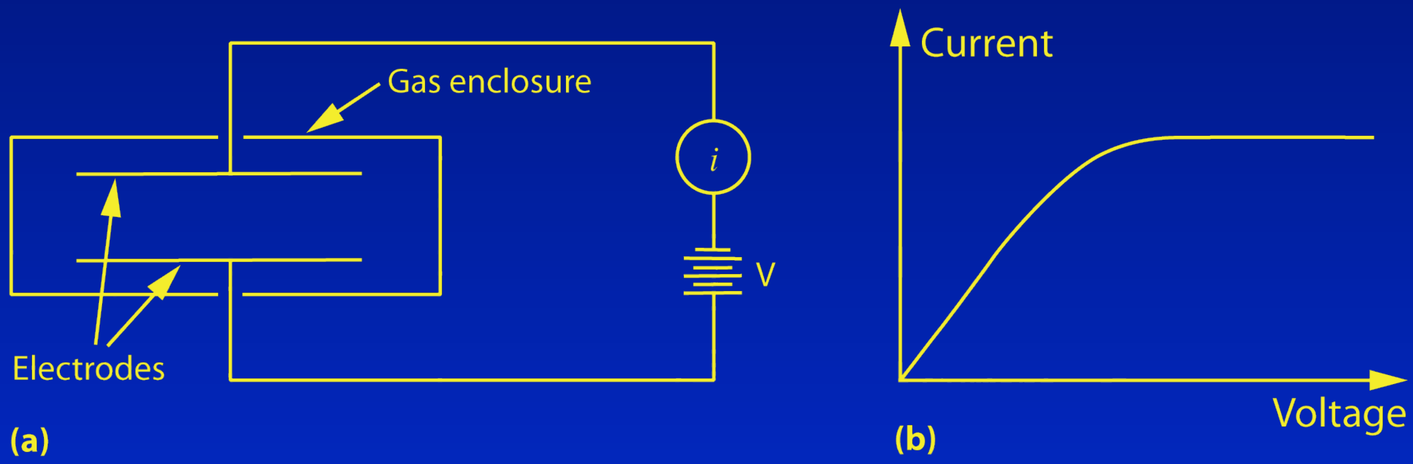


Overview of different contributions to the noise as a function of the pulse shaping time. Some other noise contributions are also shown.

Detectors based on ionisation in gases

Basics of detectors based on ionisation in gasses

An electric field of a few 100 V is sufficient to collect ionisation in a gas



Let us first discuss the creation and movement of electrons and ions in a gas

Table 4. 1: Energy loss characteristics in some commonly used gasses. Energy loss, the number of electron-ion pairs and the number of primary electrons is for charged particles at minimum ionisation.

Gas	Ionisation potential [eV]	Mean energy /electron–ion pair 'W' [eV]	Energy loss [keV/cm]	Number of electron–ion pairs [cm^{-1}]	Number of primary electr.[cm^{-1}]
Ar	15.7	25.0	2.53	106	25
Xe	12.1	22	6.87	312	41
He	24.5	41.6	0.345	8.3	5
H_2	15.6	36.4	0.32	8.8	5.2
N_2	15.5	34.8	1.96	56.3	10
Air		33.8	2.02	59.8	
O_2	12.5	30.2	2.26	74.8	22
CH_4	12.6	30	1.61	54	37
C_2H_6	11.5	26	2.91	112	48
Isobutane/i-C_4H_{10}	10.6	26	5.67	220	90
CO_2	13.8	34	3.35	100	35

Under the influence of an electric field the electrons and ions move

$v = \mu E$, μ= mobility

For ions Ion-Ion collision cross section is independent of the kinetic energy of the ion

$$\rightarrow \quad v_d = \frac{a}{2}\Delta t = \frac{eE}{2M}\frac{\lambda}{v_t} = \frac{e\lambda}{\sqrt{12kT\ M}}E$$

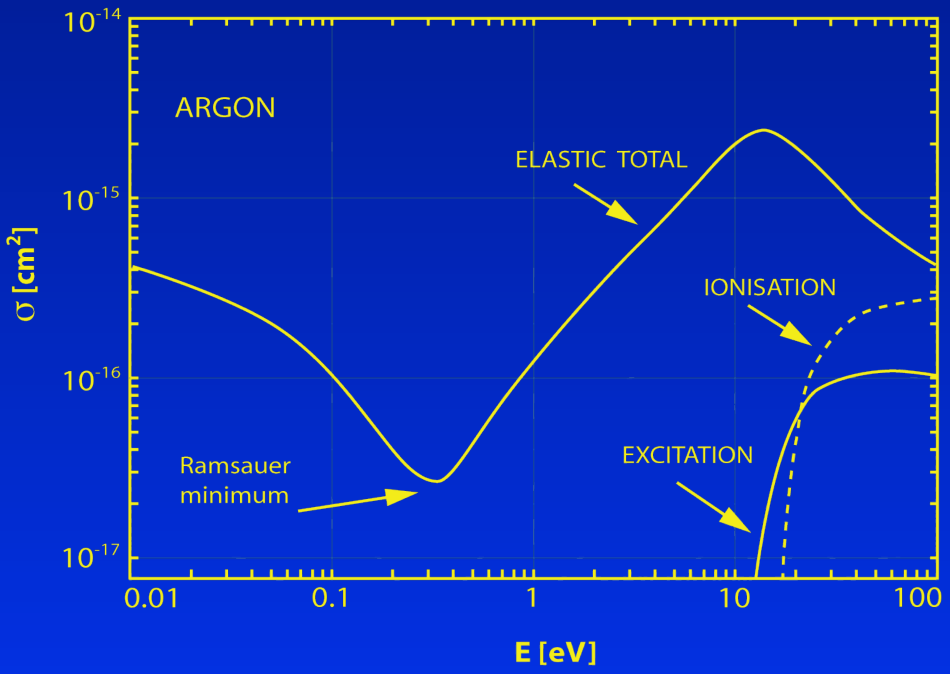
Mobility few [cm²/Vs]

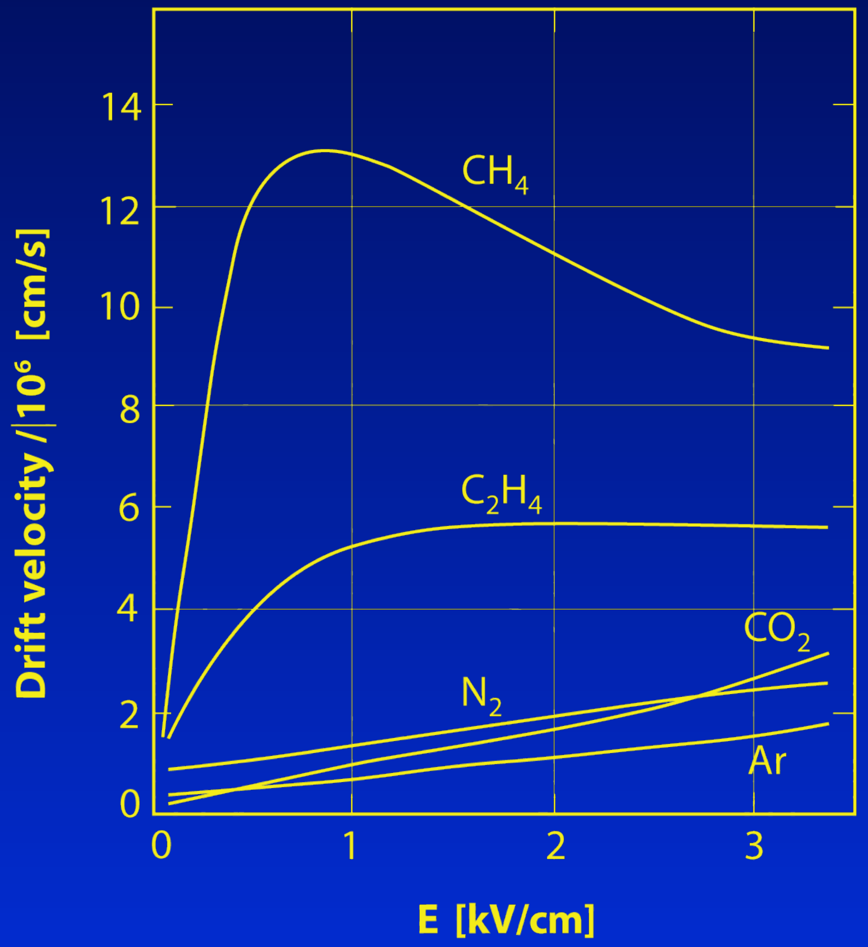
at E=1000 V/cm >>> ➔ few 10^3 cm/s

For electrons drift velocity

$v=\mu(E)\,E$

Electron atom collision cross section is very dependent of the kinetic energy of the electron





A number of phenomena occur when electrons and ions drift in a gas in presence of an electric field

- if E sufficiently large, electron multiplication
- charge transfer: $A^+ + B^0 \to A^0 + B^+$
- electron capture $e^- + A^0 \to A^-$
- diffusion, longitudinal or transverse

$$\sigma = \sqrt{(2D / v_d)l} \qquad \mu = \frac{q}{kT} D$$

D=diffusion coefficient; l=drift distance

What you should remember

1) For ions : ion-molecule collisions σ is independent of E_k
   ion velocity is proportional to electric field E

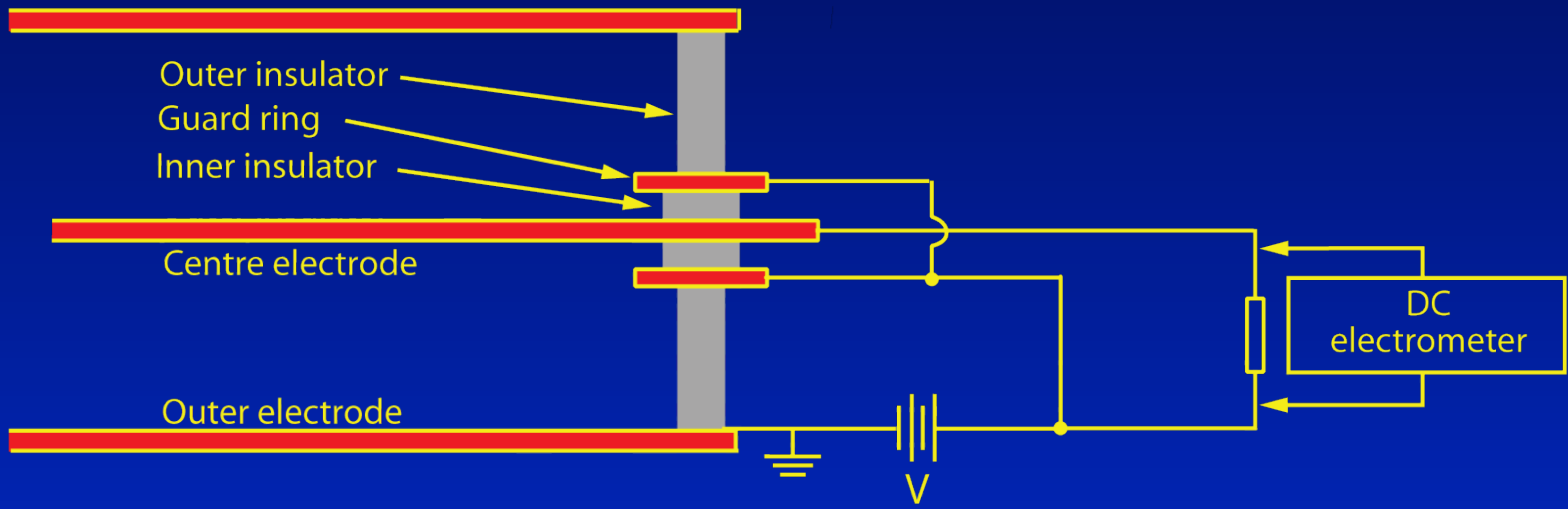
2) For electrons
   electron-molecule collisions σ is strongly dependent on E_k
   electron velocity is NOT proportional to electric field E
   the mean free path (m.f.p.) of electrons >> m.f.p. of ions

3) At fields of interest (≈1kV/cm)
   ion velocity is typically few 10^3 cm/s
   electron velocity few 10^6 cm/s

4) Charge multiplication sets in at much lower fields for electrons than for ions

5) Minimum ionising particles produce ≈ 100 electron-ion pairs /cm

Ionisation chambers



Very small current, e.g. 1000 minimum ionising tracks/s current 2 10^{-14} A! Beware of leakage currents

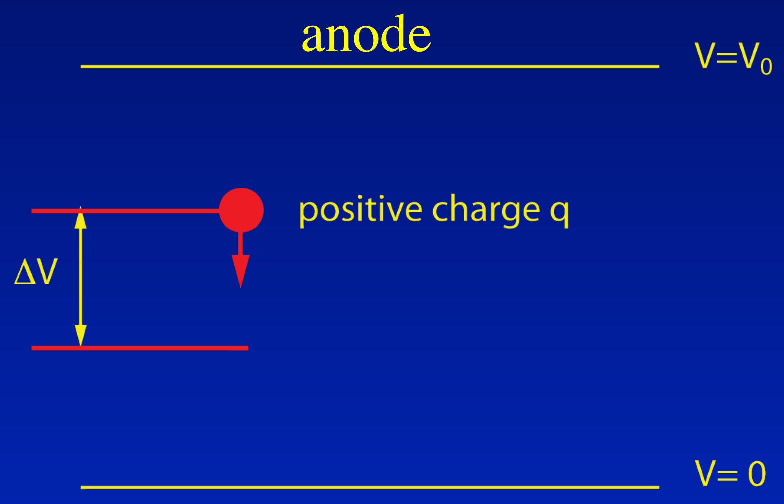
Consider only one ion. When does the signal appear on the anode? Use energy conservation!

$$d(\frac{1}{2}CV_0^2) = V_0 C dV_0 = -q|\Delta V|$$

$$dV_0 = -\frac{q|\Delta V|}{CV_0}$$

$$\Delta Q = -\frac{q|\Delta V|}{V_0} = \frac{q\ \Delta V}{V_0}$$

$$i = \frac{dQ}{dt} = \frac{q}{V_0}\frac{dV}{dt} = \frac{q}{V_0}\frac{dV}{ds}\frac{ds}{dt}$$



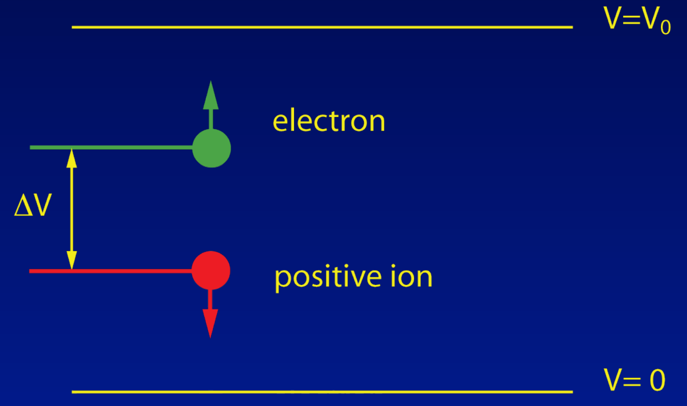
Signal on cathode = minus signal on anode

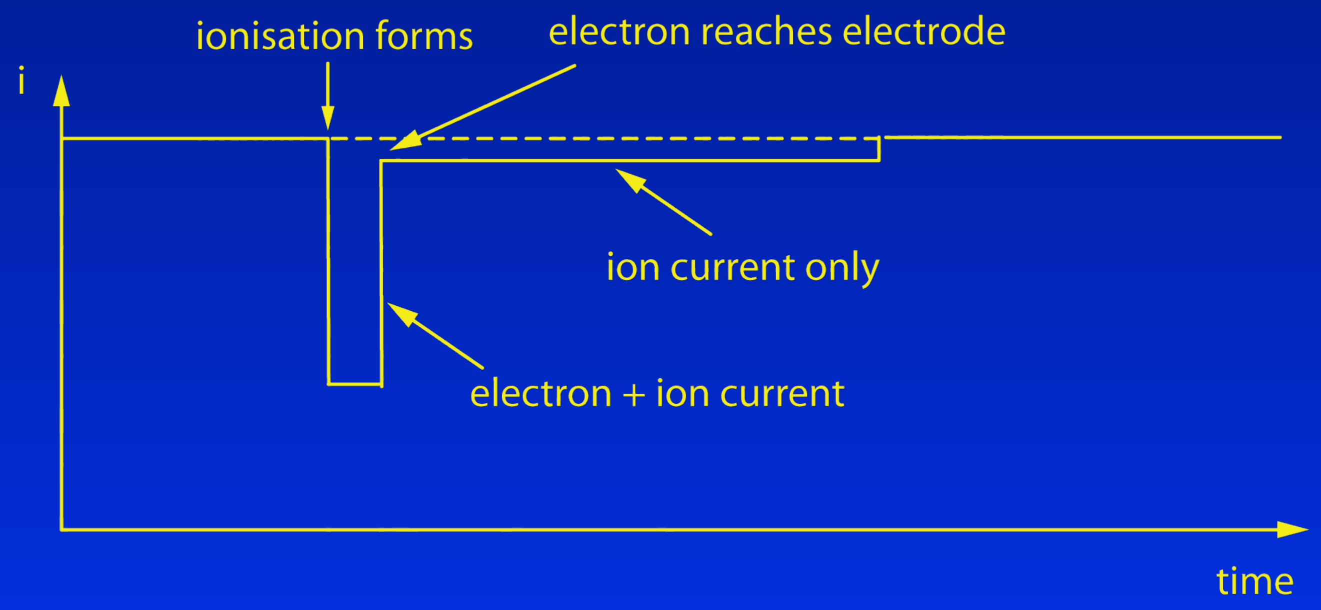
This is completely general, the motion of the charges induces an apparent current in the electrodes given by

$$i = \frac{q}{V_0}\frac{dV}{ds}\frac{ds}{dt}$$

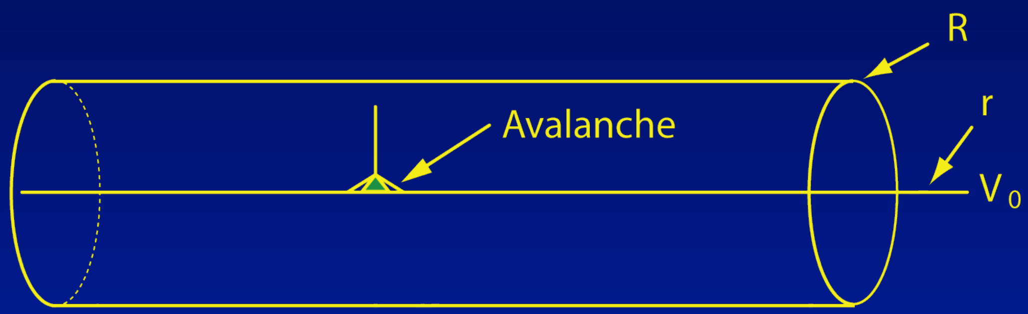
If more than 2 electrodes, same equation but he potential used in calculating dV/ds is the weighting potential (Cramer Rao theorem).
Weighting potential: all electrodes at V=0, except the electrode under consideration at $V=V_0$

The signal of one electron ion pair. The signal is very small!

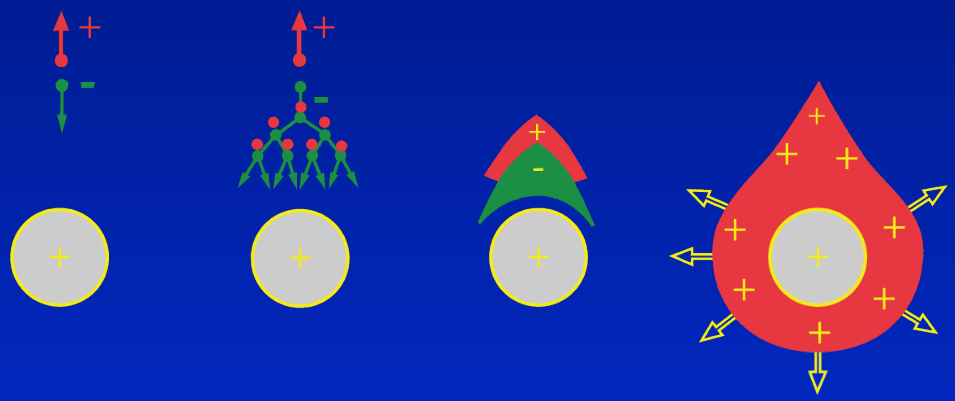




Electron multiplication allows getting a larger signal

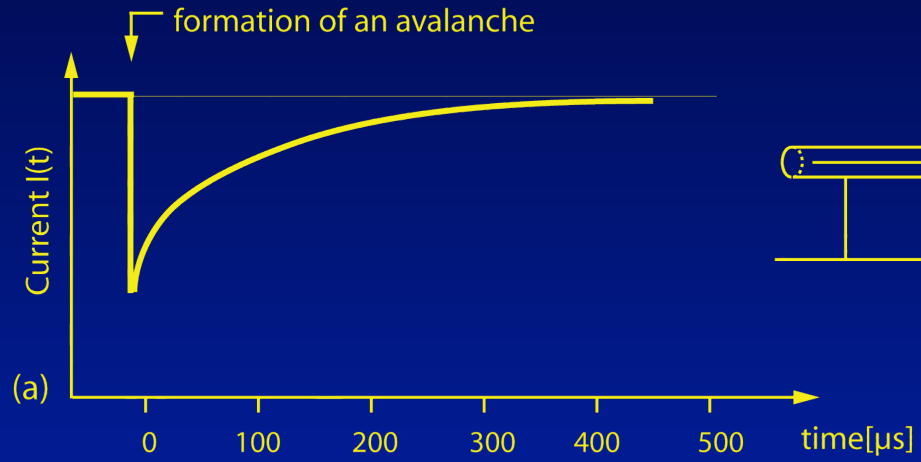


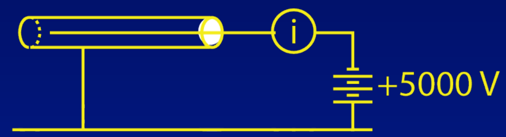
$$E(\rho) = \frac{V_0}{\rho \ln(R/r)}$$



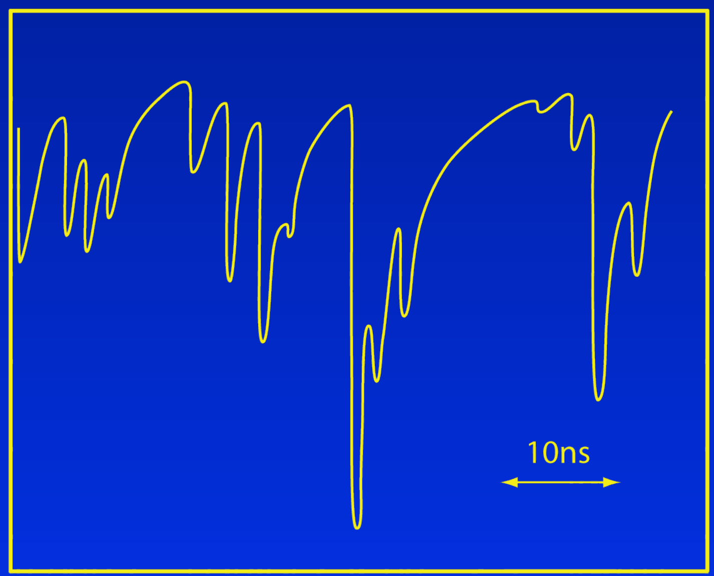
The signal comes almost entirely from the motion of the positive ions

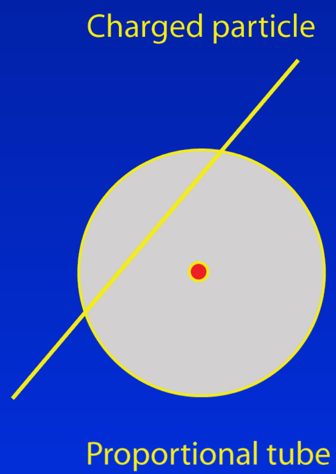
Signal from one electron

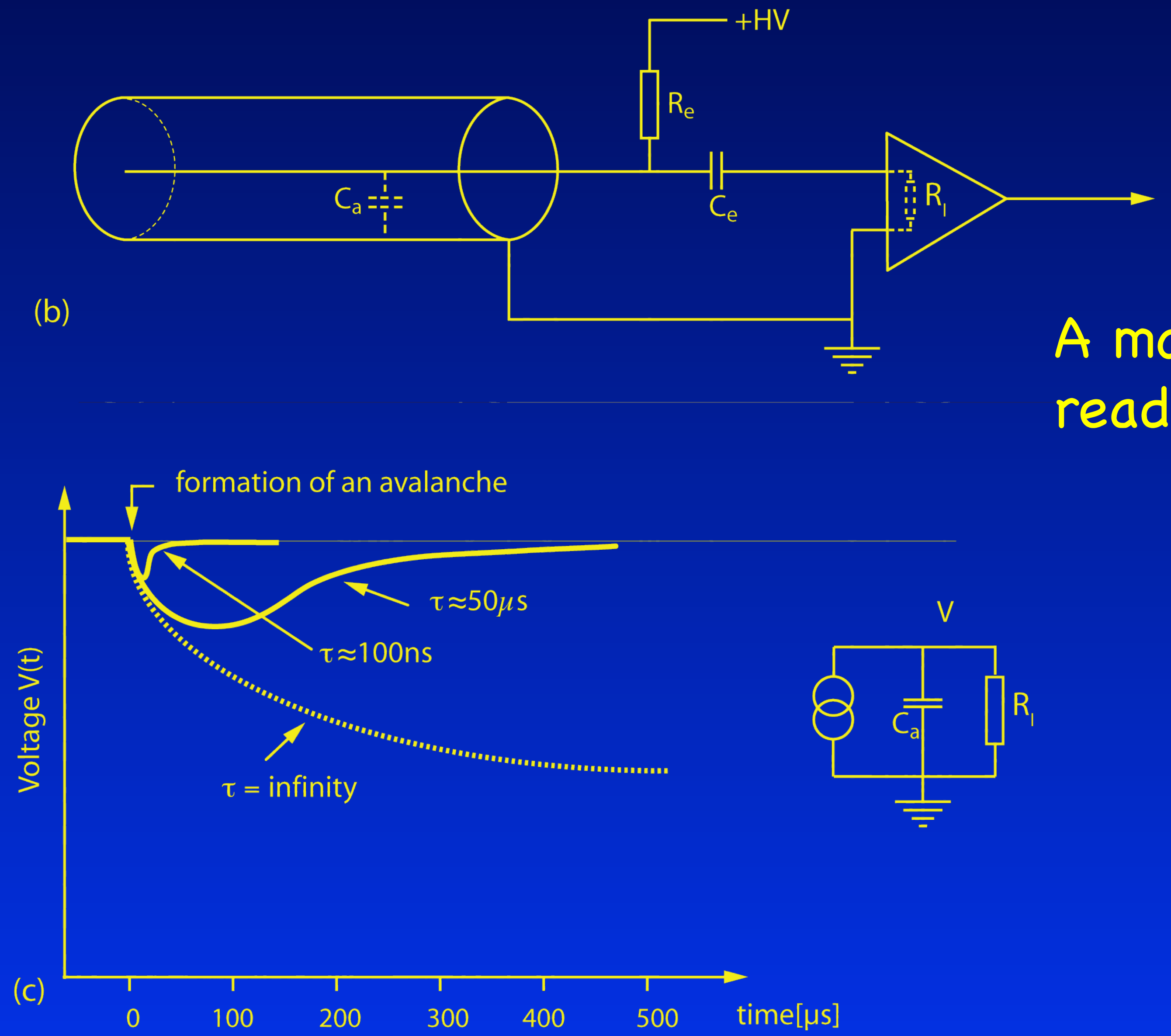




Signal from a track



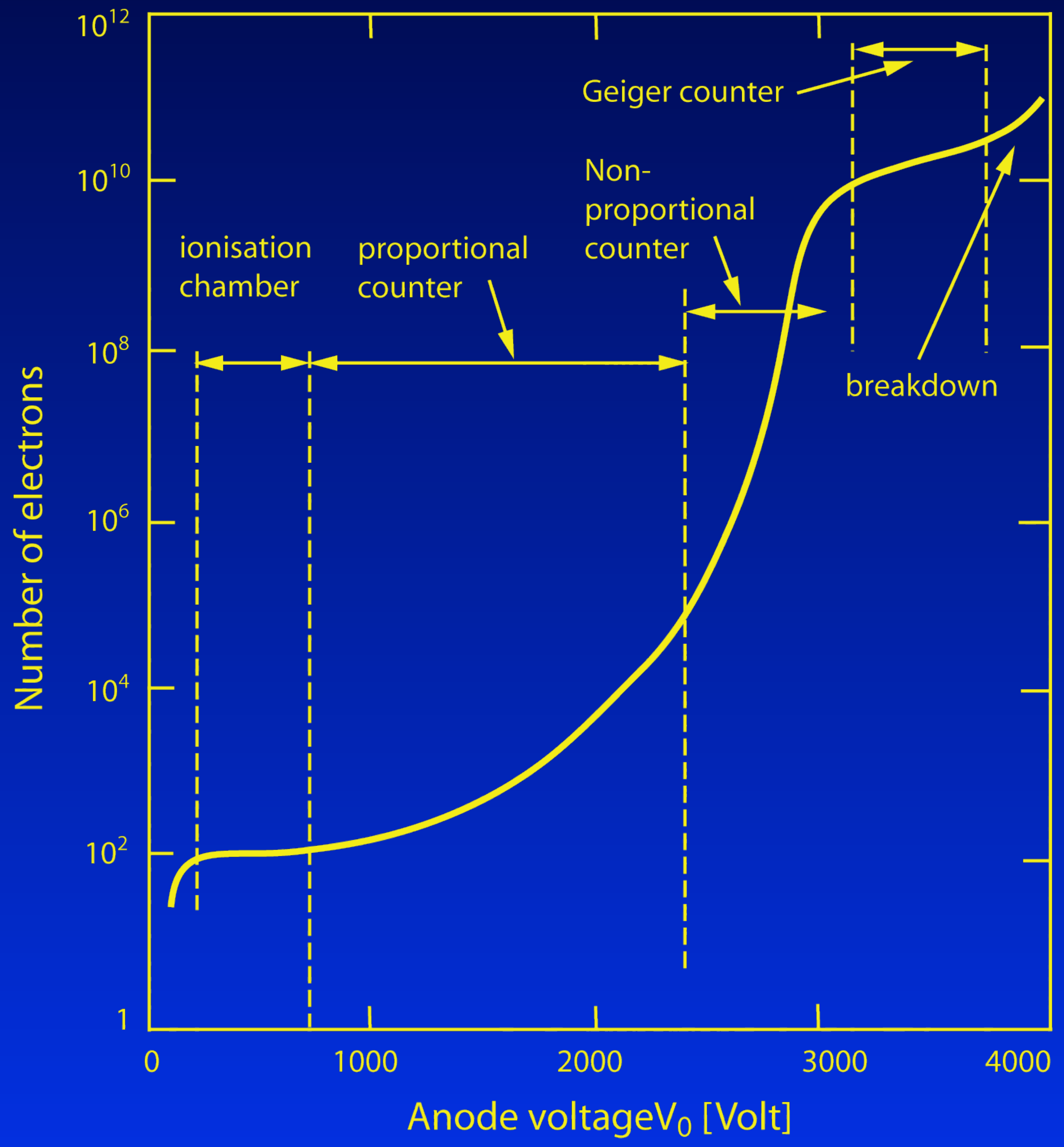




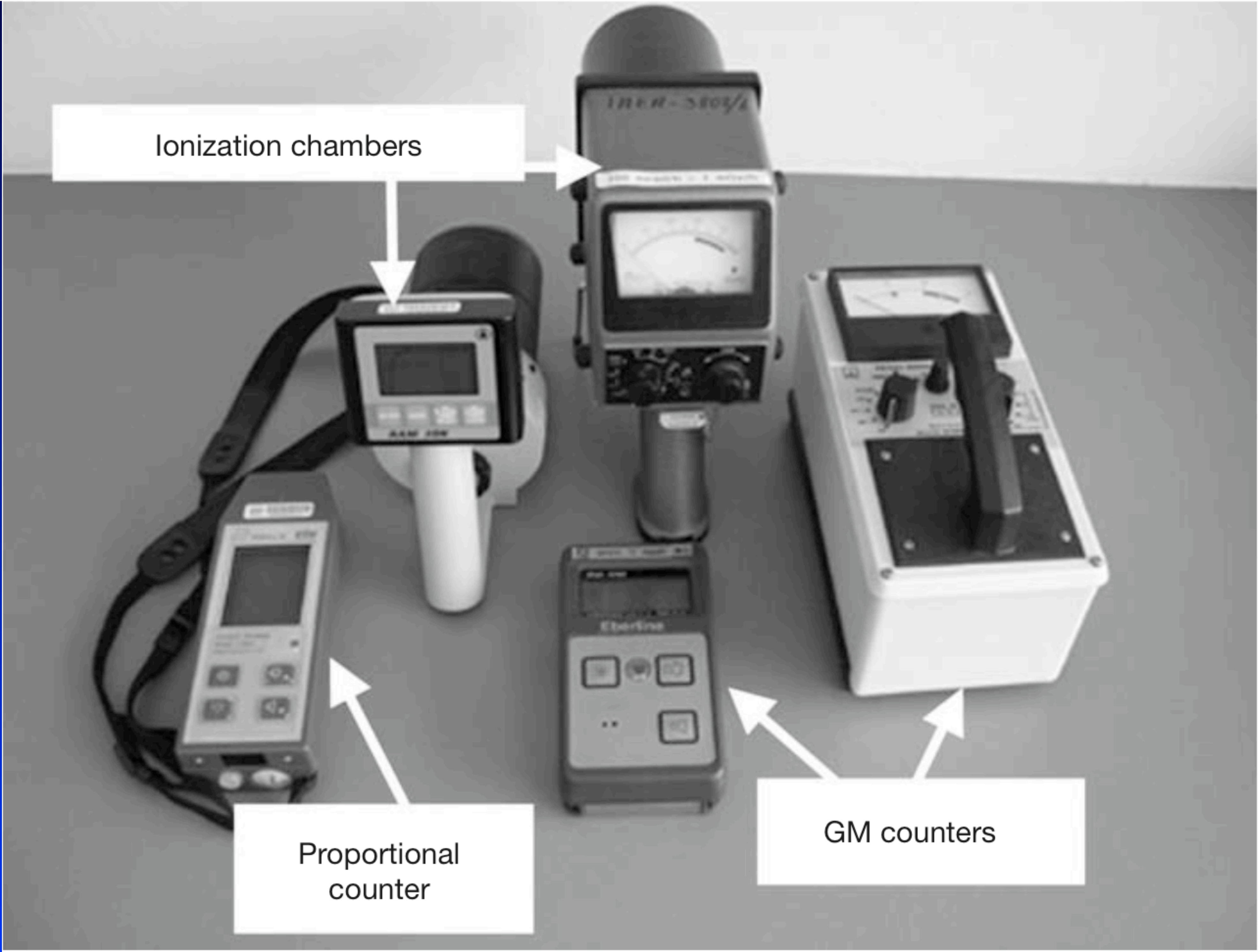
A more realistic readout electronics

Gas mixtures

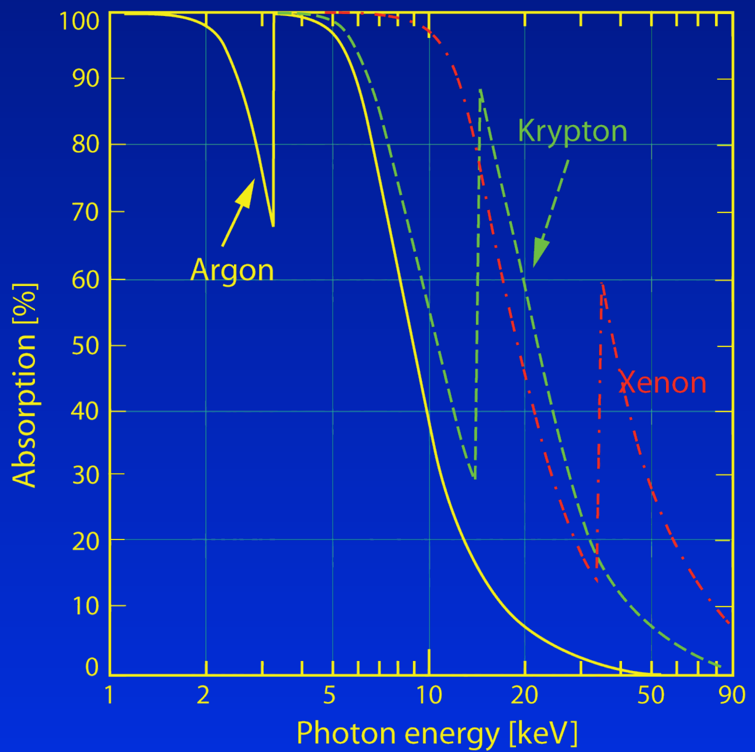
- the gas should not contain any electronegative component, no O_2, no air!
- noble gases (e.g. Argon) are fine
- nowever, pure noble gas > problem
- need quenching gas, typically 10% of some polyatomic gas, e.g. CH_4, i-C_4H_{10}


Number of electrons
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
0
1000
2000
3000
4000
Anode voltage V_0 [Volt]
ionisation chamber
proportional counter
Non-proportional counter
Geiger counter
breakdown

Instruments based on ionisation in gases


Ionization chambers
Proportional counter
GM counters
Eberline

Proportional tube as X-ray detector



absorption in 5 cm (no window!)

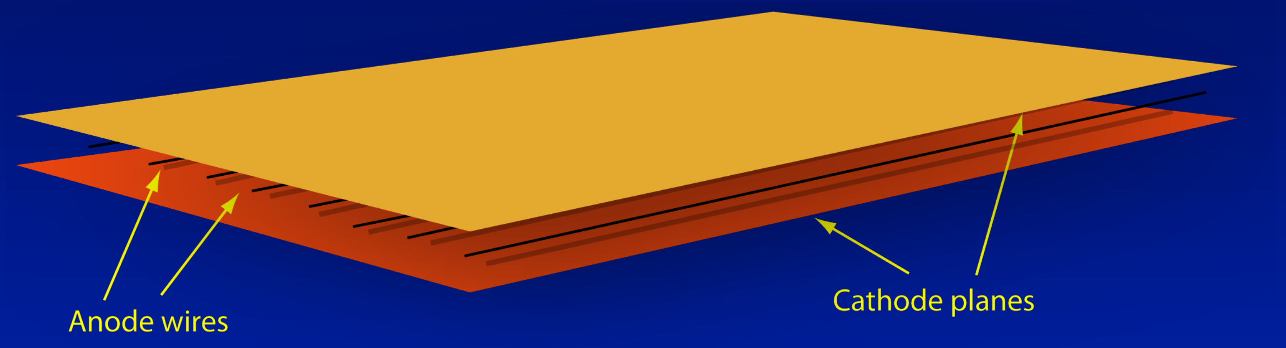
- detection efficiency
- energy resolution

$$\frac{FWHM[E]}{E} = 2.35\sqrt{\frac{(F_{fano}+b)\,W}{E}}$$

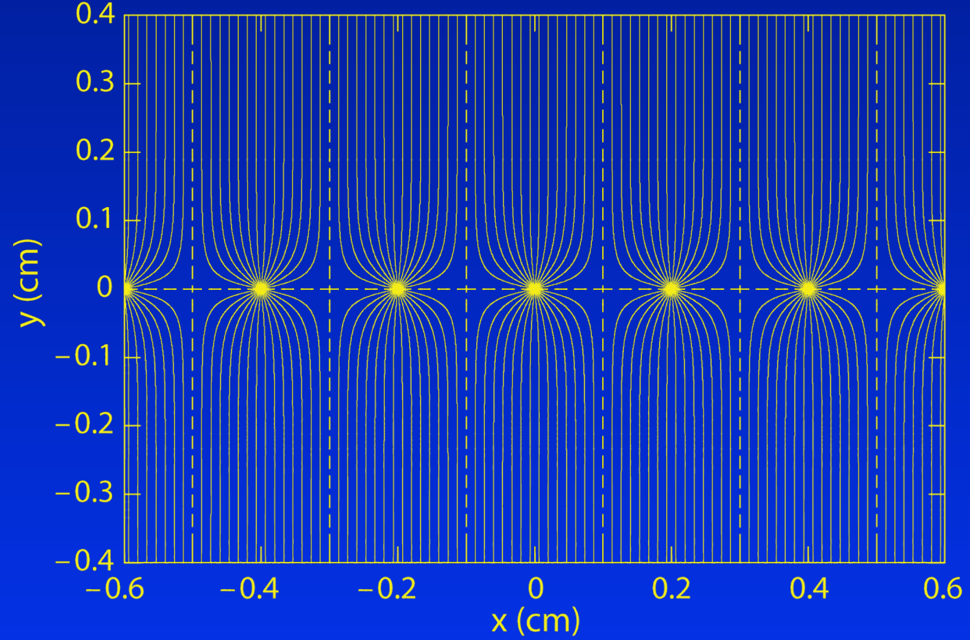
Fano factor F_{fano}=0.05-0.20

Gain fluct. $b = \frac{\sigma^2\{g\}}{\langle g\rangle^2} \approx 0.4 - 0.7$

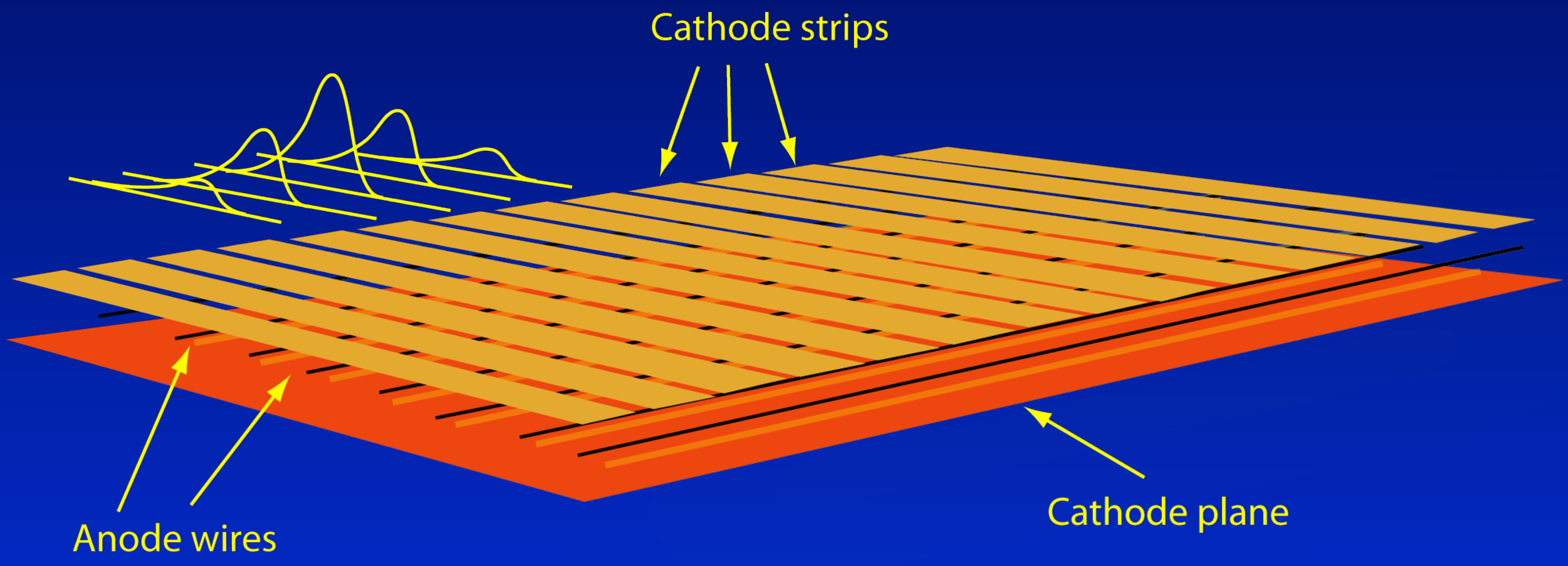
The main application of a gas chamber is for particle tracking multi-wire proportional chamber



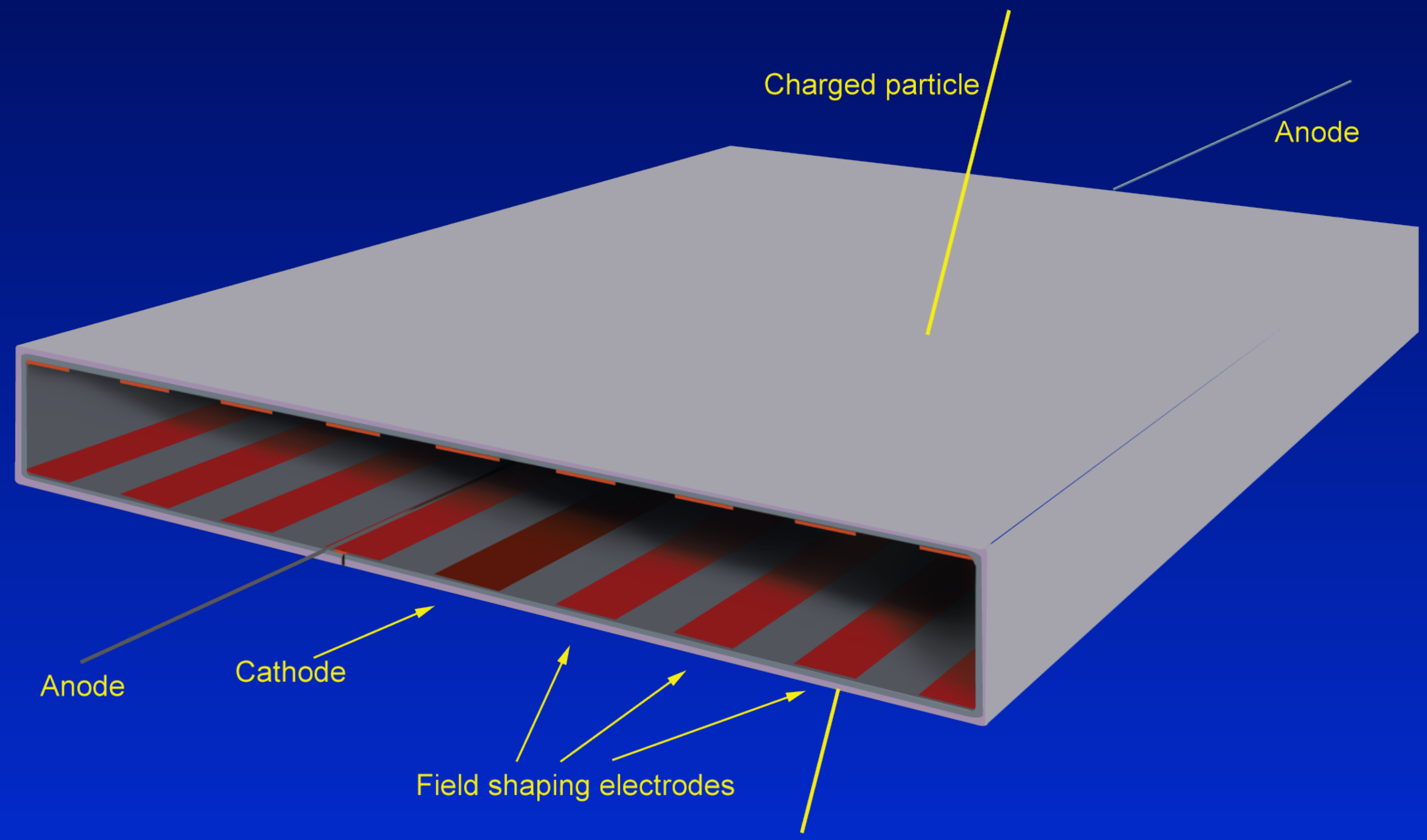
Wire spacing ≈ 2mm limited by electrostatic repulsion
Spatial resolution spacing/√12 mm



Cathode strip readout allows a better spatial resolution limited by range of delta electrons in gas r.m.s.≈ 50 μm



Drift chambers



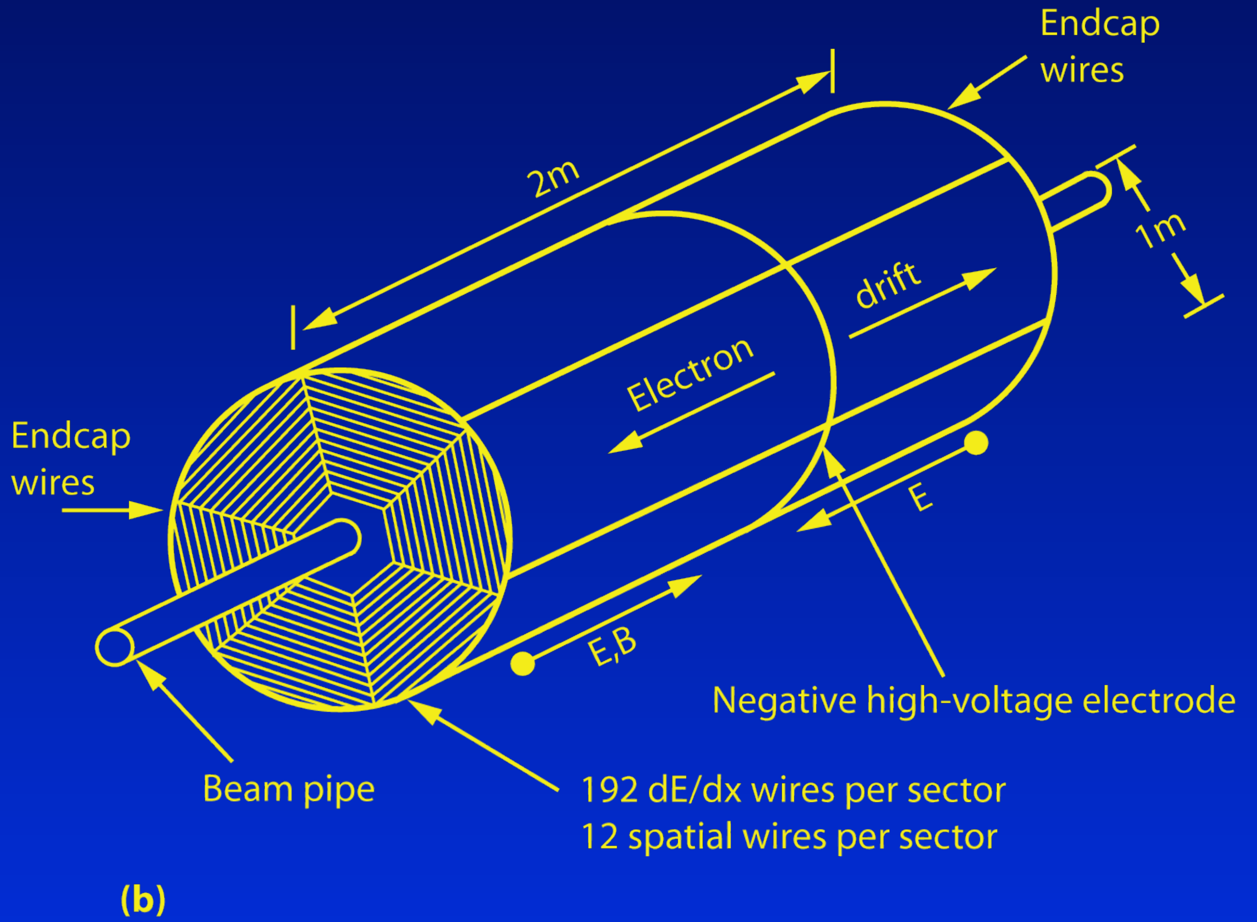
Beware: drift of electrons in the gas is influenced by magnetic field

$$v = \frac{e}{m_e}\frac{\tau}{1+\omega^2\tau^2}\left(\vec{E} + \frac{\omega\tau}{B}(\vec{E}\times\vec{B}) + \frac{\omega^2\tau^2}{B^2}(\vec{E}\cdot\vec{B})\vec{B}\right)$$

$$\omega = eB / m_e$$

If E//B, no influence on drift direction

Time projection chamber



In modern version GEM or MICROMEGAS

Wire chambers in brief

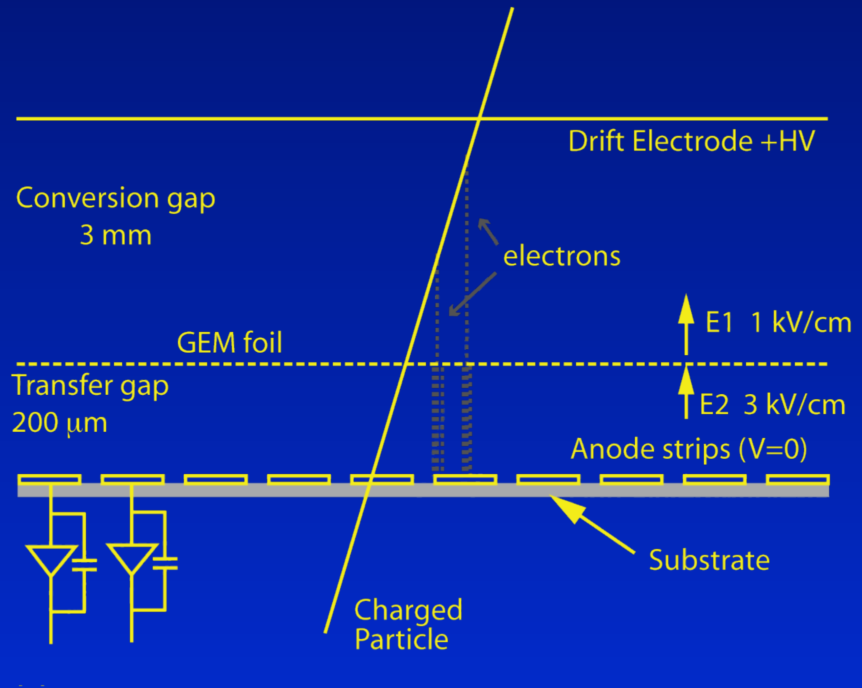
Simple and inexpensive devices > for large area
- need for constant gas flow
- aging: with proper care > few coulomb/cm wire
- the pulse shape is governed by the slow motion of the ions
- build-up of space charge from positive ions

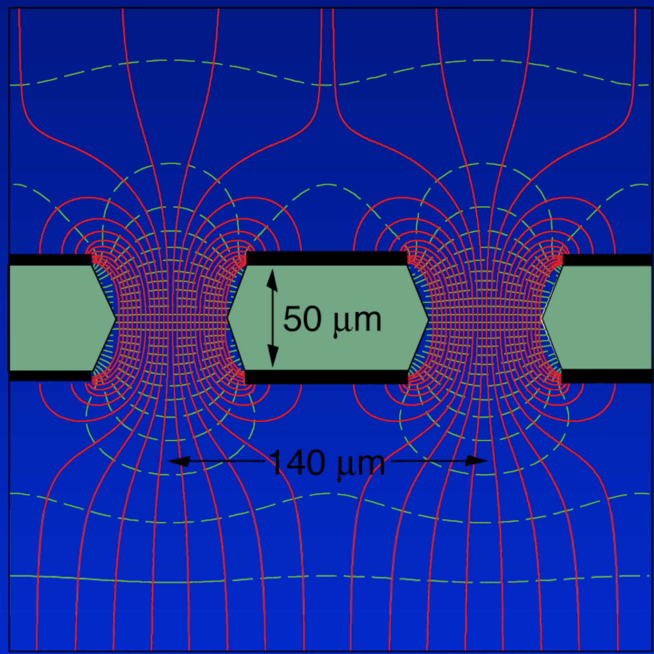
Maximum Rate : (charge/track) x count-rate ≈ 10^{10} /mm/s

To overcome limitations related to slow ion drift:

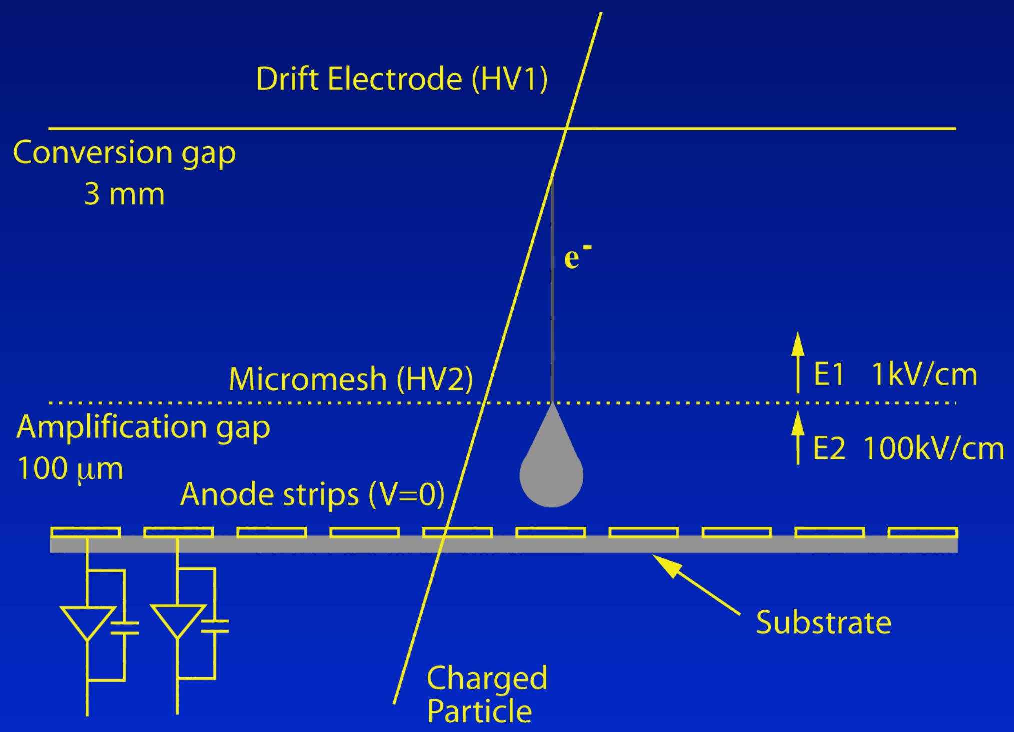
Micropattern gas detectors

Micropatter gas detectors: GEM counter

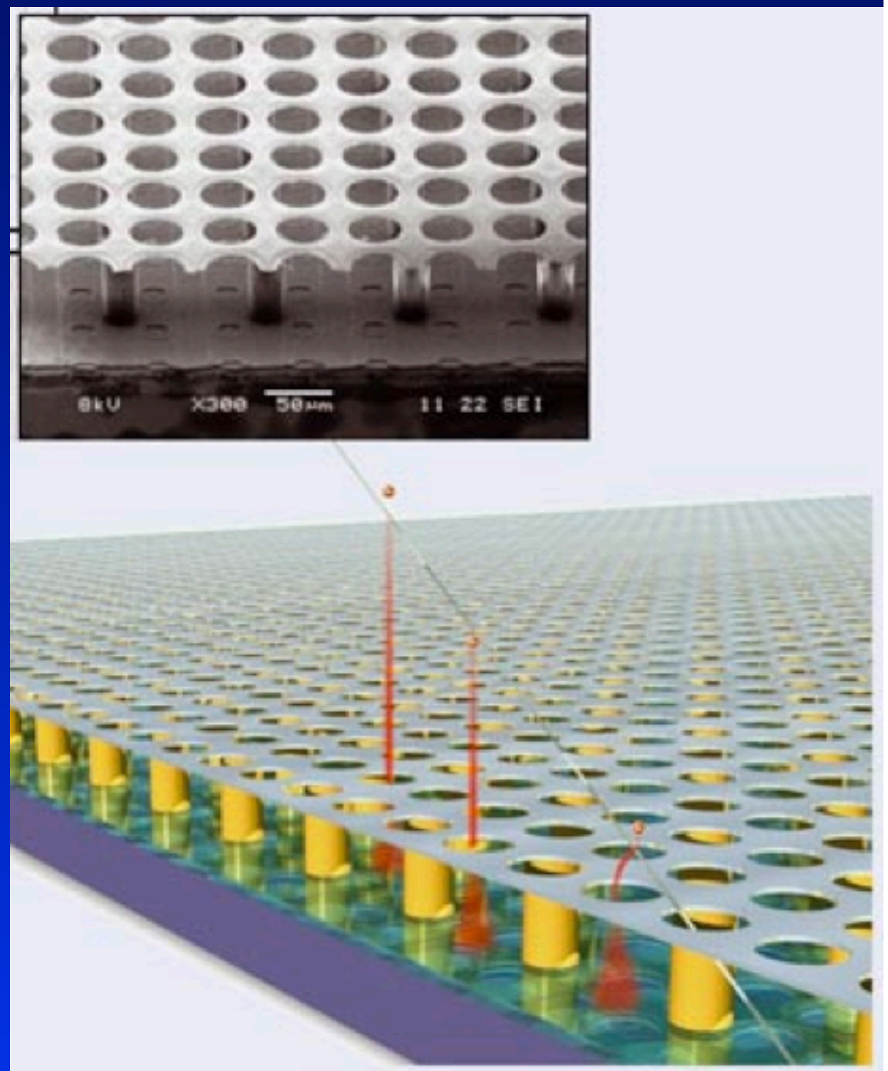




Micropatter gas detectors: MICROMEGAS

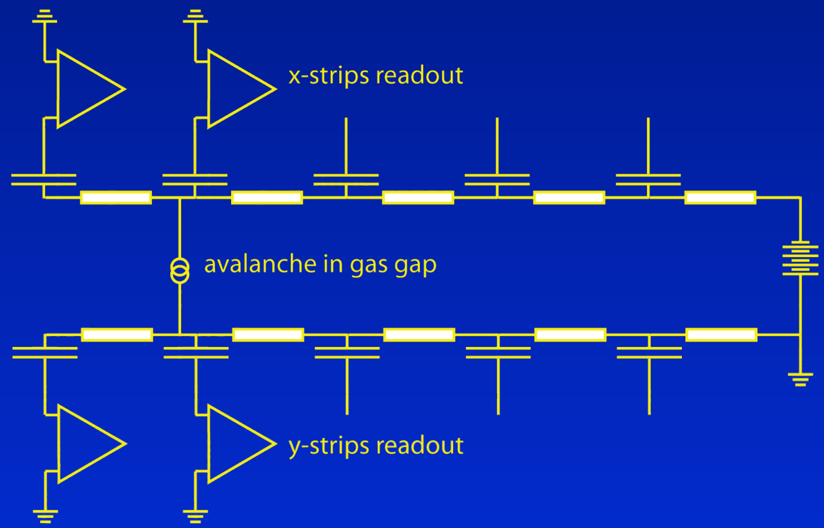


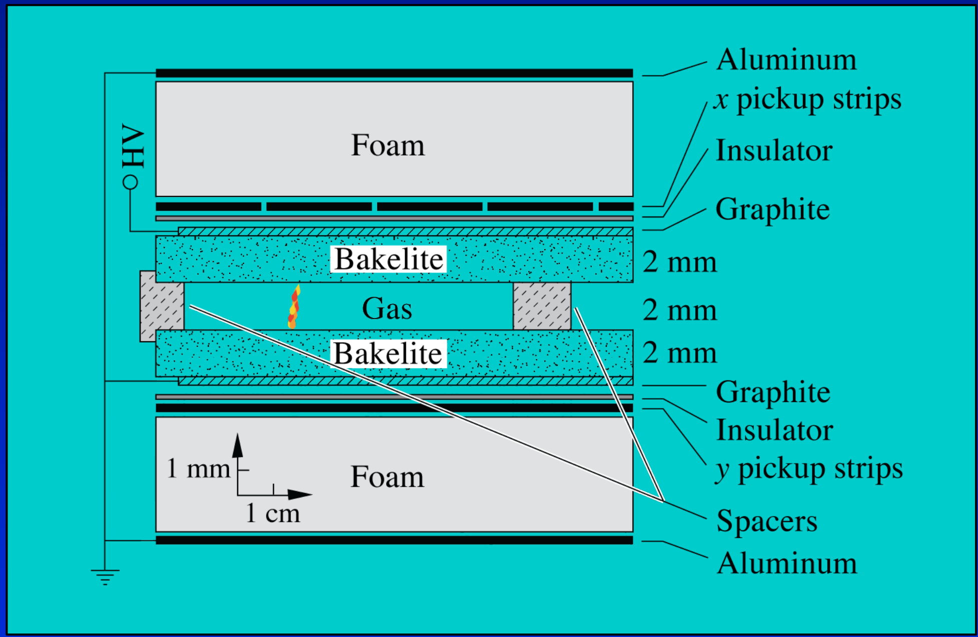
(b)



GEM detectors and MICROMEGAS, have achieve good timing ≈ 10 ns, large rates ≈ 25 kHz/mm^2, spatial resolution ≈ 50 μm, and resistance to radiation comparable to silicon detectors.

Resistive plate chambers

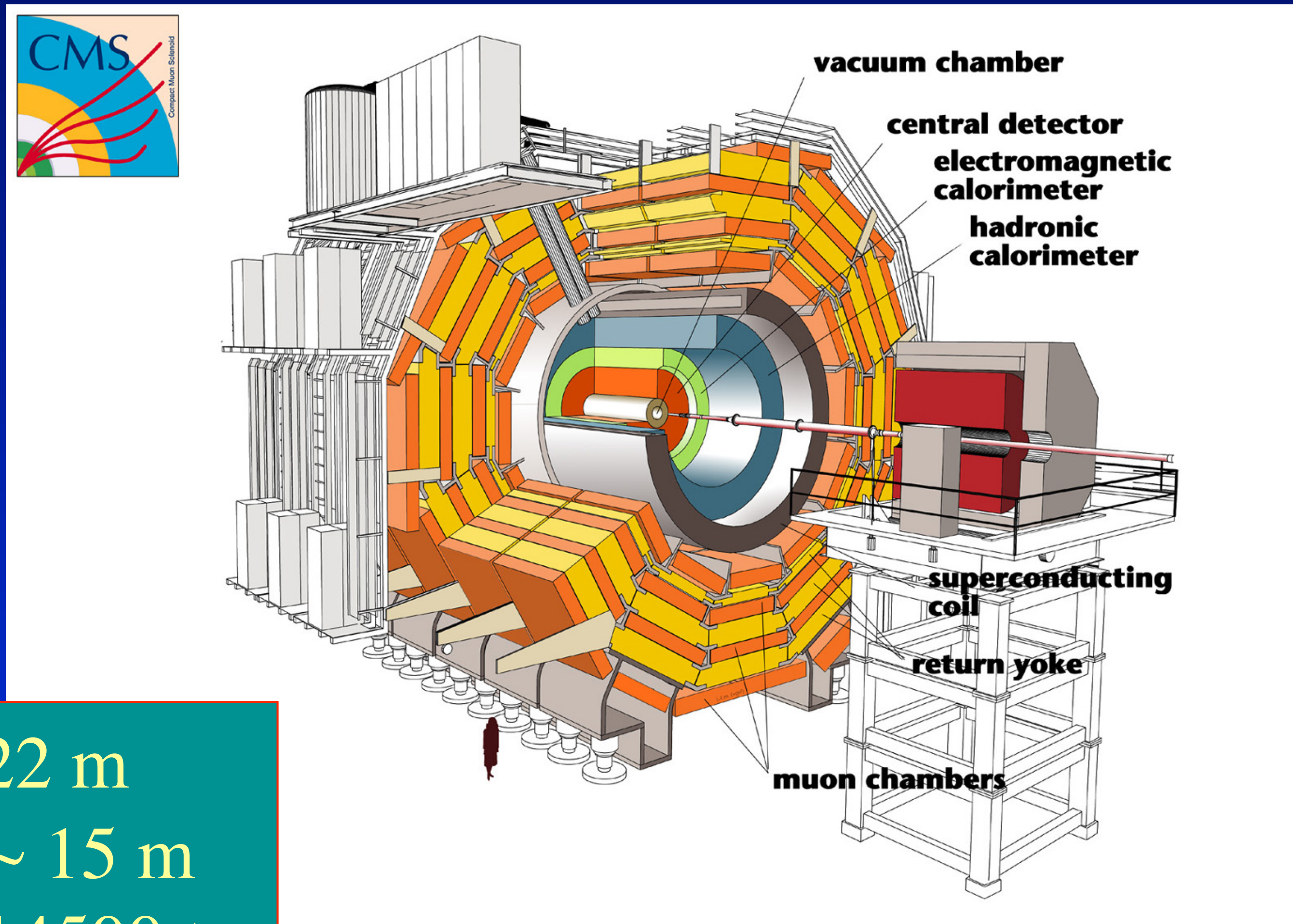




Applications of detectors based on ionisation in gases

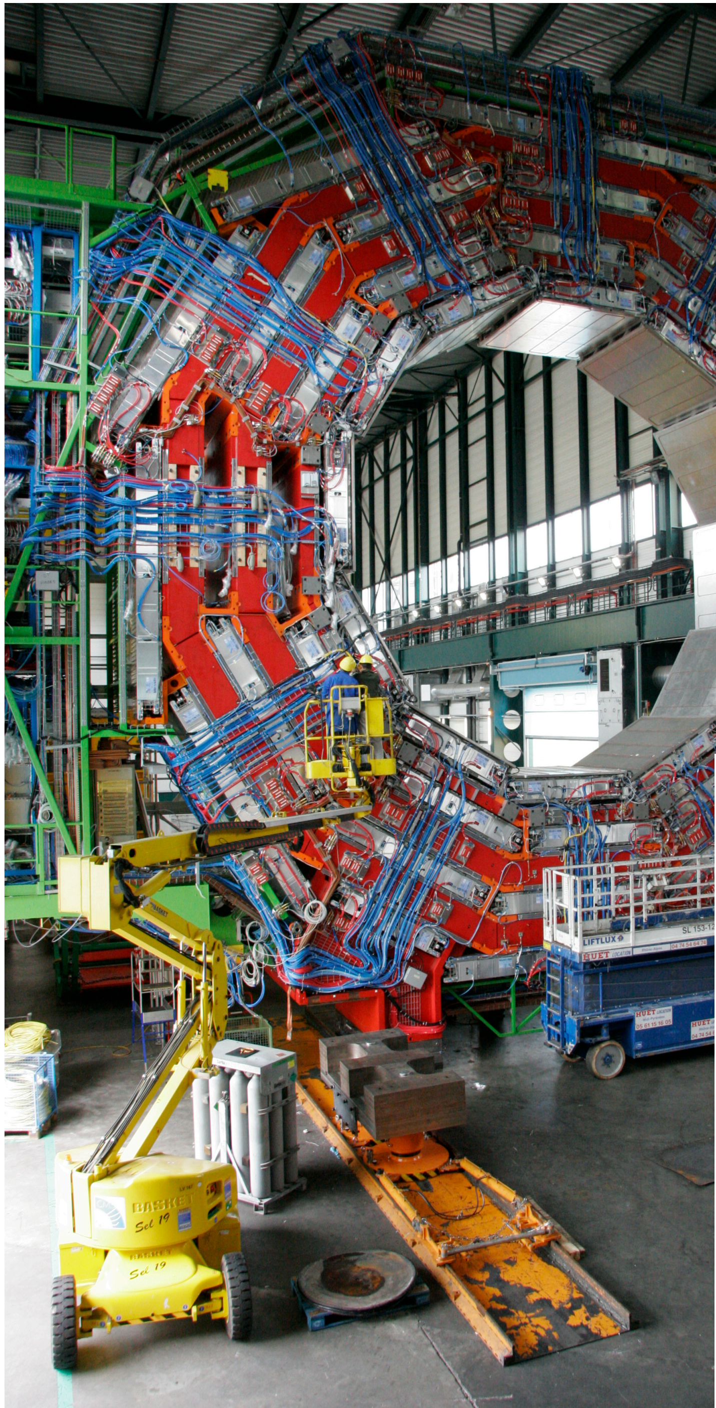
Mainly used for tracking of charged particles and when one does not need, or cannot afford, silicon tacking detectors, e.g. muon detection systems at high energy colliders.

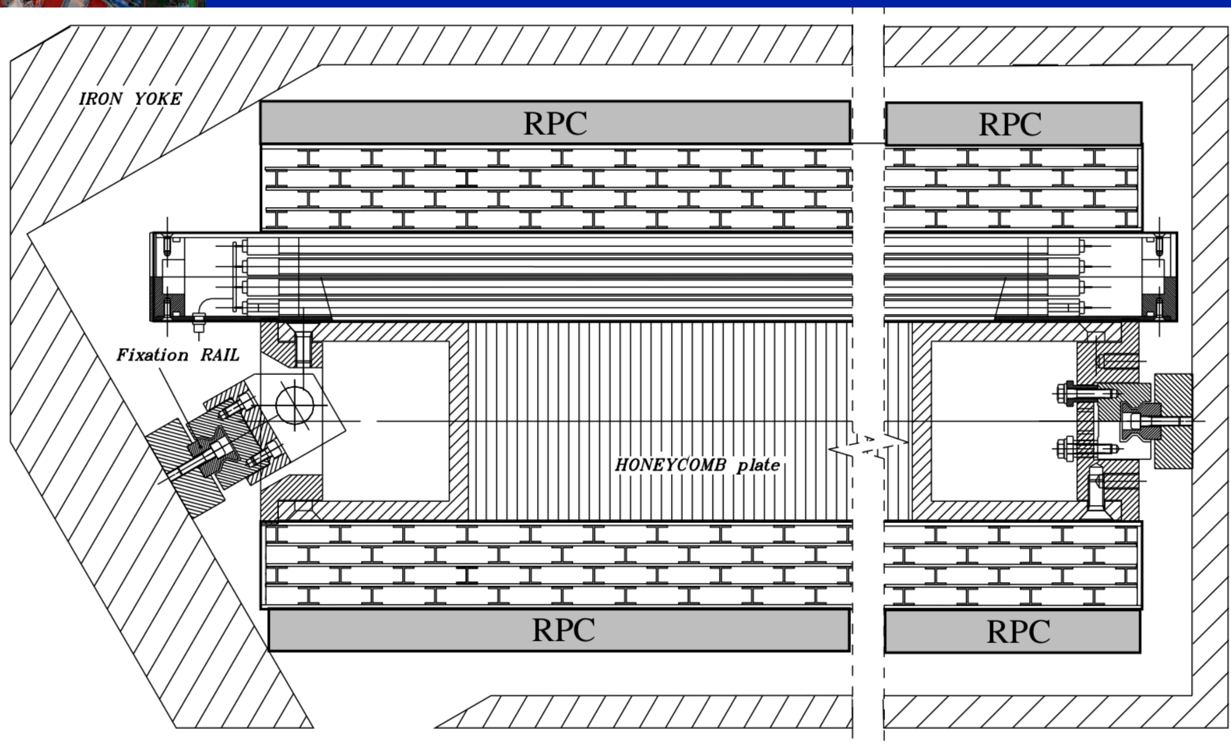
Compact Muon Solenoid



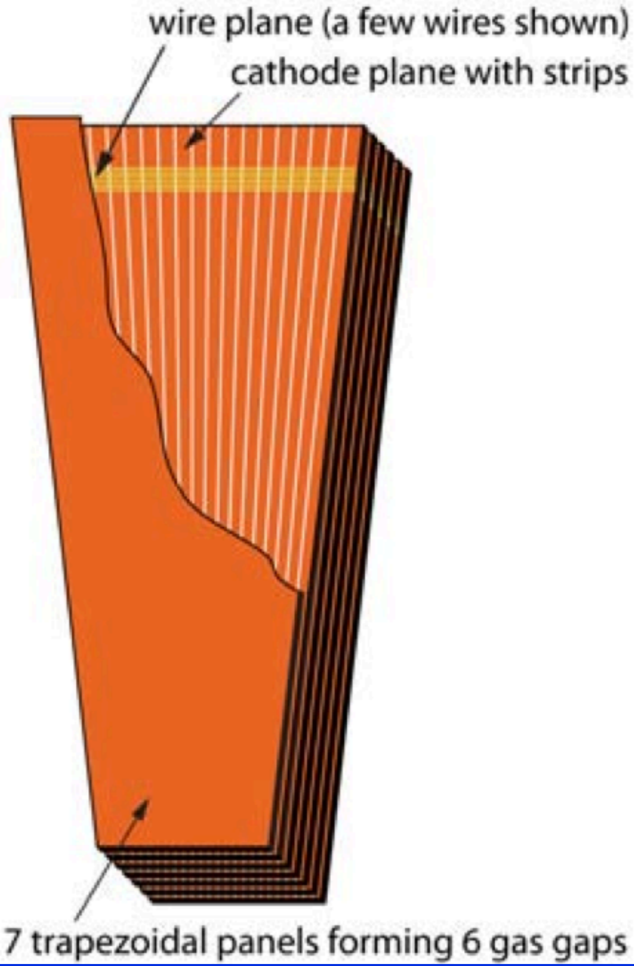
- Length ~ 22 m
- Diameter ~ 15 m
- Weight ~ 14500 t

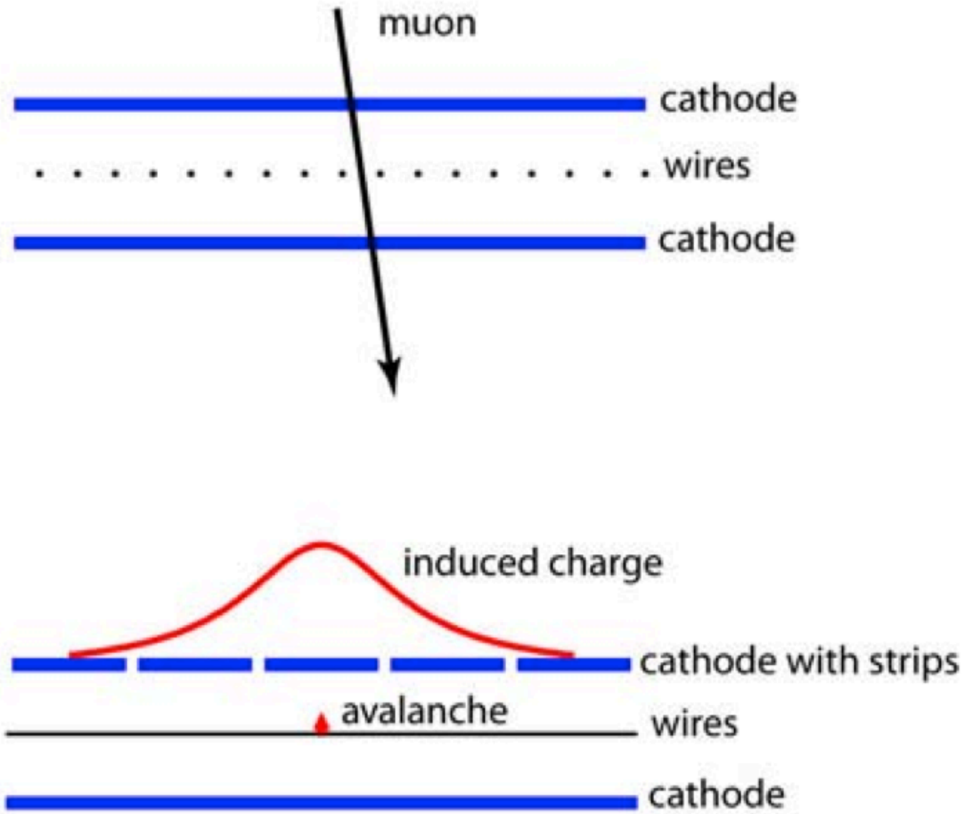
CMS: Muon system. Drift chambers in barrel.



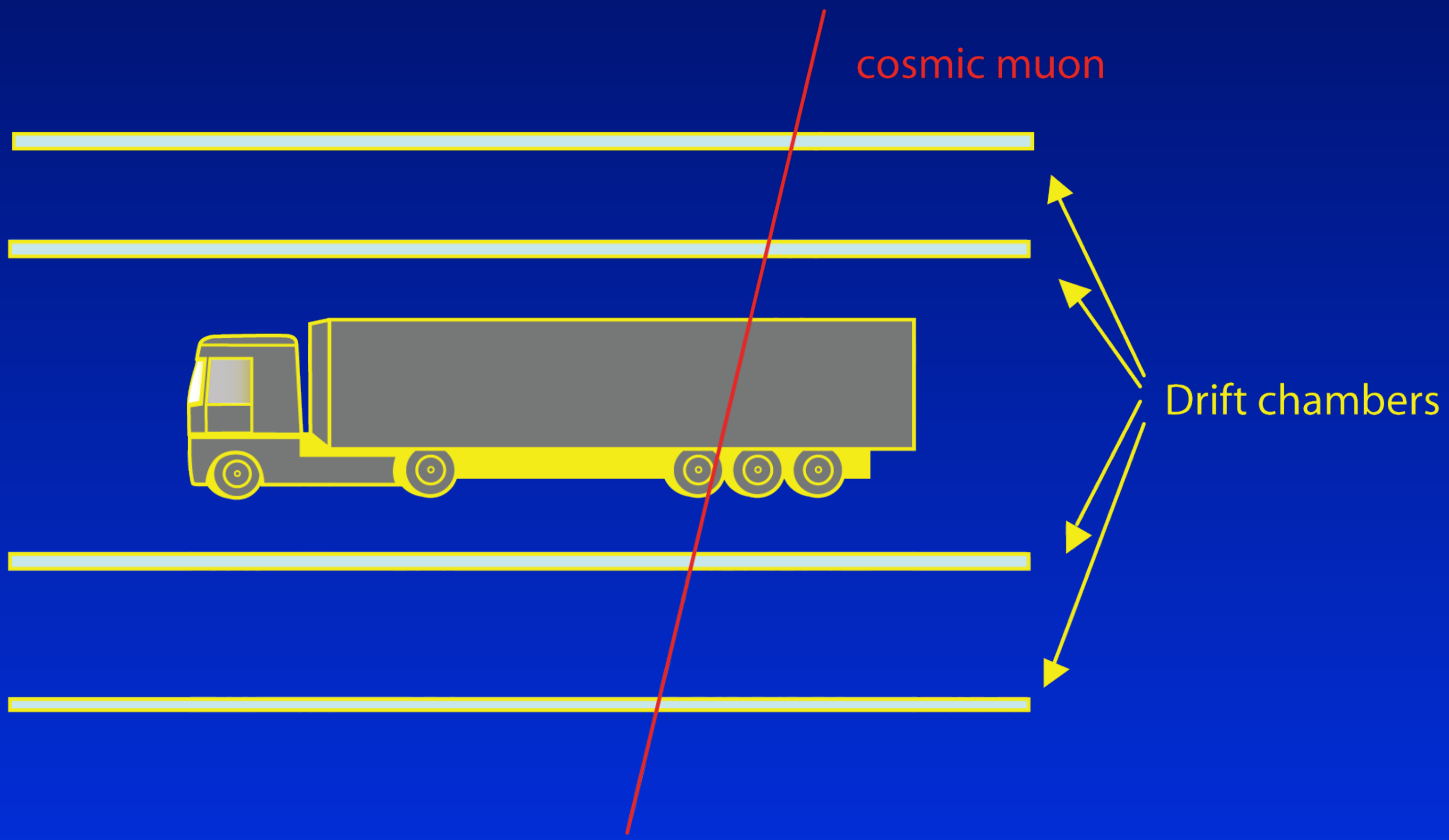


CMS: Muon system. Cathode strip chambers in barrel.





Wire chambers in homeland security



End of section on detectors based on ionisation in gases.