Új Nemzeti Kiválóság Program

VIII. Detectors

Lorant Csige
Laboratory for Nuclear Physics
Hungarian Academy of Sciences

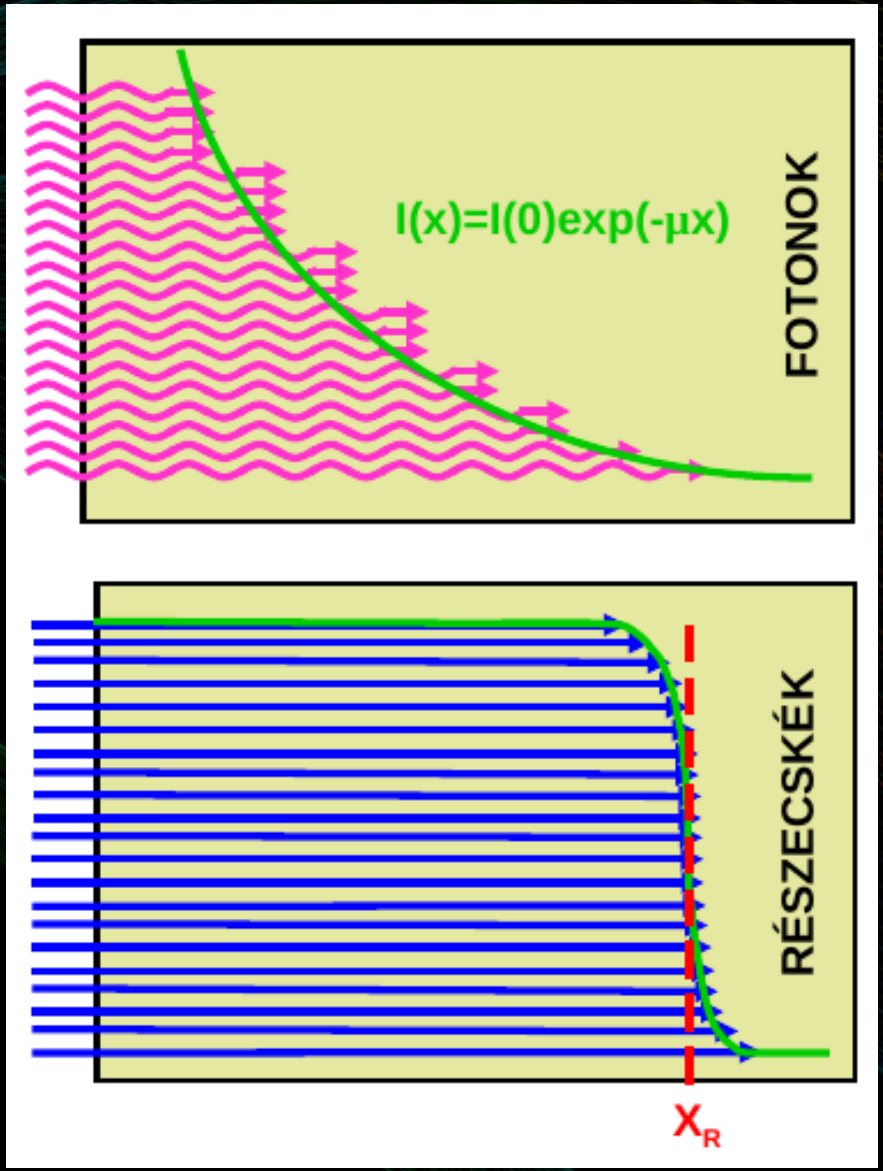
Radiation interaction with matter

- Radiations:
  - alpha, beta, gamma particles and neutron
  - charged particles or neutral particles
  - heavy or light particles
- Interactions:
  - excitation (photon)
  - ionization (charge carriers)
  - radiations: Bremsstrahlung, Cherenkov, transition radiaton

- Matters:
  - gas, liquid, solid state (crystal)
  - element, composites, mixtures
  - isolator, conductors, semi-conductors

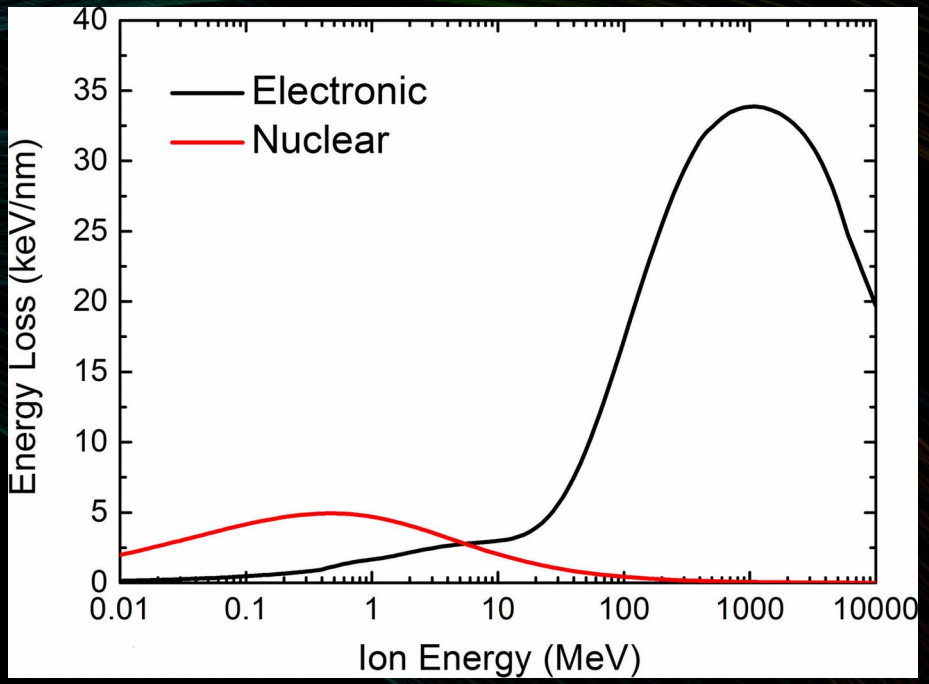
Photons vs. Particles

- Photons: intensity drops with distance, energy is constant
  - μ: linear attenuation coefficient
  - 1/μ: mean range
- Particles: energy drops with distance, intensity is constant
  - range: X_R
  - small (~1%) variation is the range: *straggling*



Charged particles

- Processes:
  - inelastic scattering: electronic stopping, at ~MeV
    - Coulomb interaction of particle charge with atomic electrons → energy loss by excitation or ionization
  - elastic scattering: „nuclear” stopping, at <100 keV (end of trajectory)
    - particle interacts with the atom without „modifying” the state of the electrons → energy loss of the particle is not significant
    - loss in radiation detectors
  - radiations (Cherenkov, Bremsstrahlug, transition radiaton): at very high energies (and for electrons)
    - critical energy: energy loss by bremsstrahlung is equal to ionization energy loss



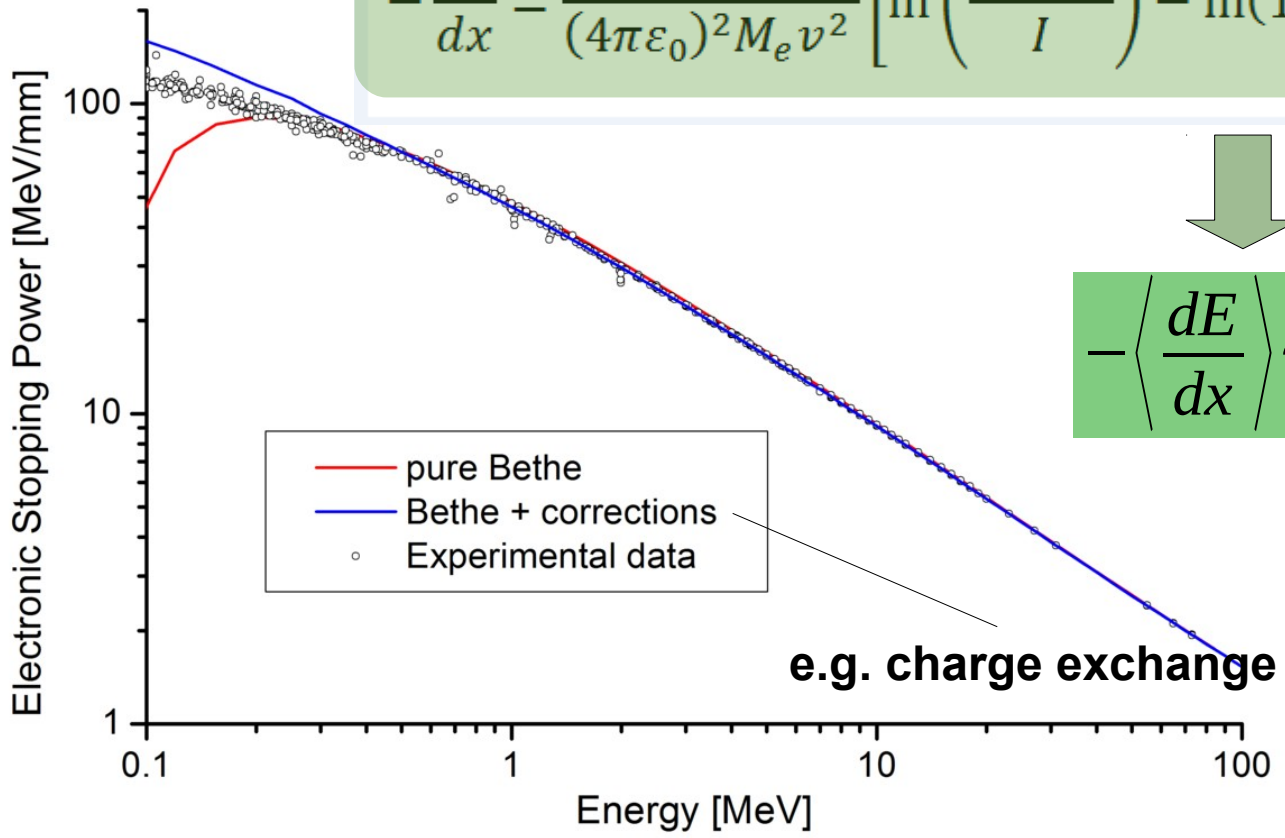
Stopping power: S=-dE/dx

Bethe-Bloch formula

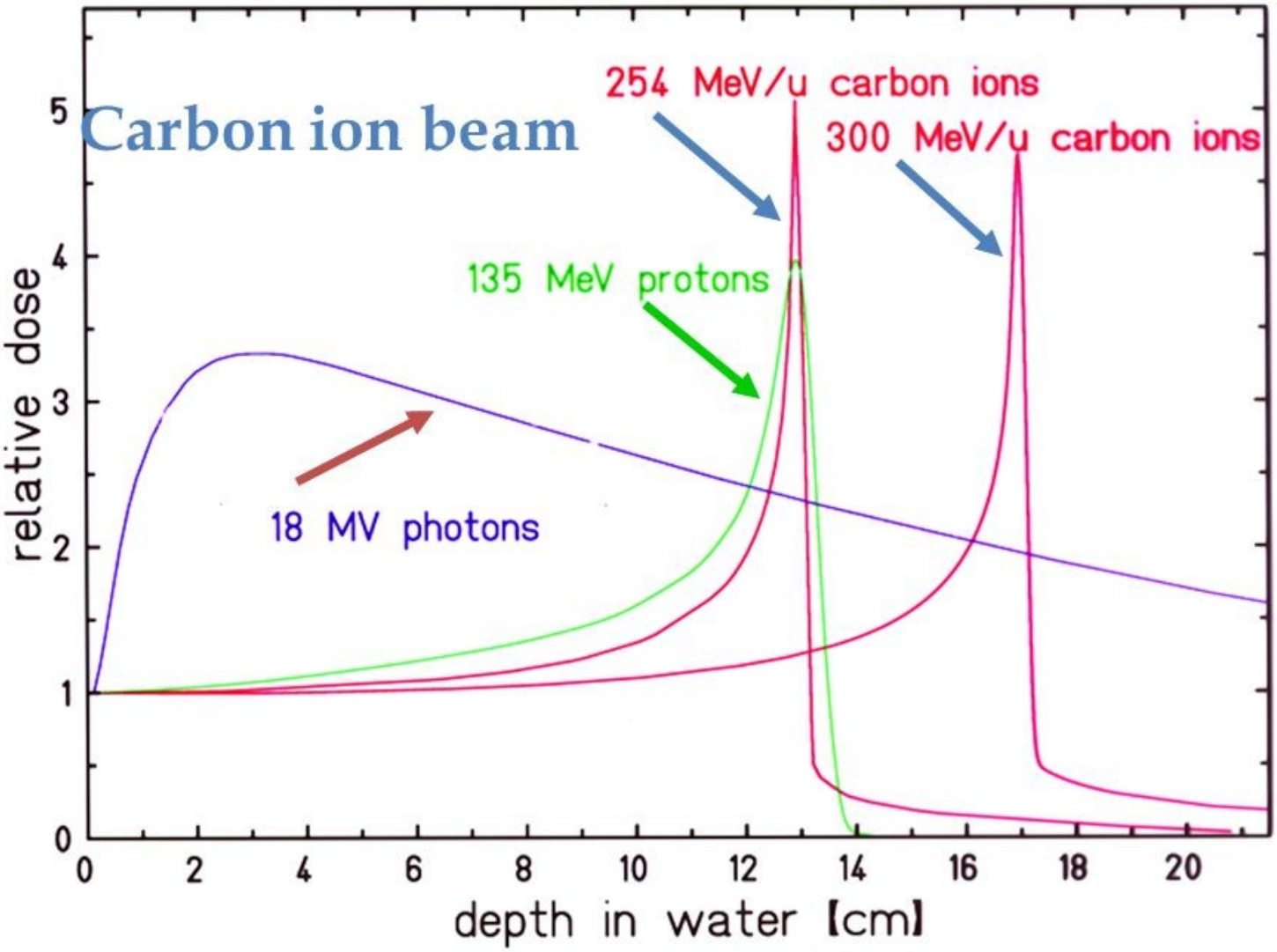
- Describes the energy loss per distance of charged particles (ions) in matter
- For electrons: due to their small mass, it is a little bit different
  - relativistic corrections, quantum mechanical indistinguishability, larger bremsstrahlung

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 NZ}{(4\pi\varepsilon_0)^2 M_e v^2}\left[\ln\left(\frac{2M_e v^2}{I}\right) - \ln(1-\beta^2) - \beta^2\right]$$

$$-\left\langle\frac{dE}{dx}\right\rangle \sim \frac{1}{v^2}$$

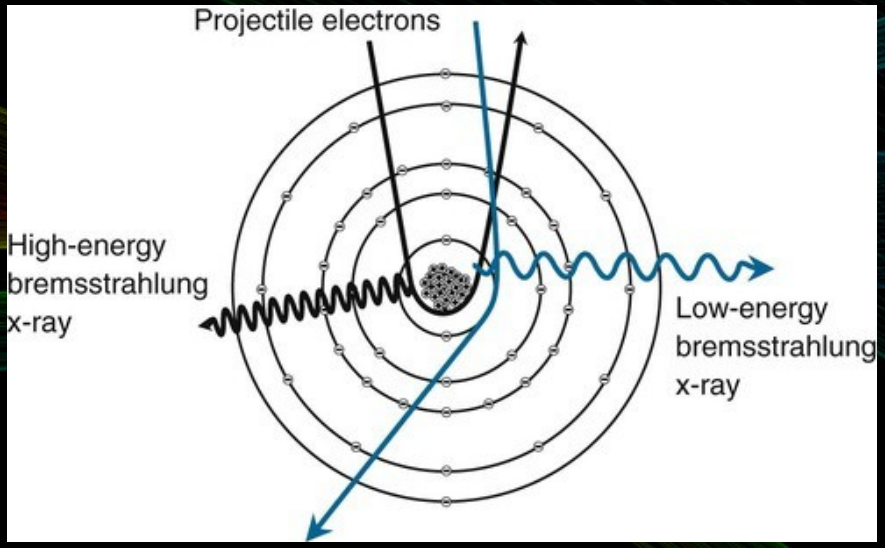


Bragg curve – cancer therapy



Radiative processes of charged particles

- At high energies: bremsstrahlung, Cherenkov radiation, transition radiation



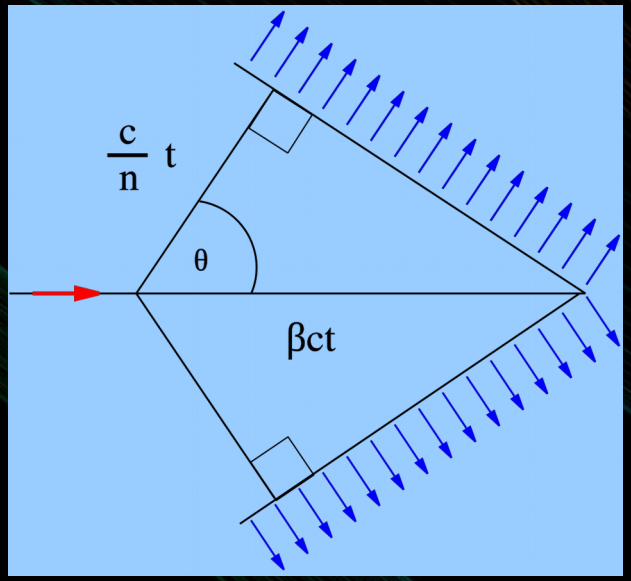
- Bremsstrahlung (braking radiation):
  - deceleration of a charge particle when deflected by another charged particle → EM radiation
  - continuous spectrum up to E_e
  - significant only for electrons since $m_e=m_p/1836$ (m_e is small)

$$-\left\langle \frac{dE}{dx} \right\rangle \sim \frac{Z^2 E}{m^2 c^4}$$

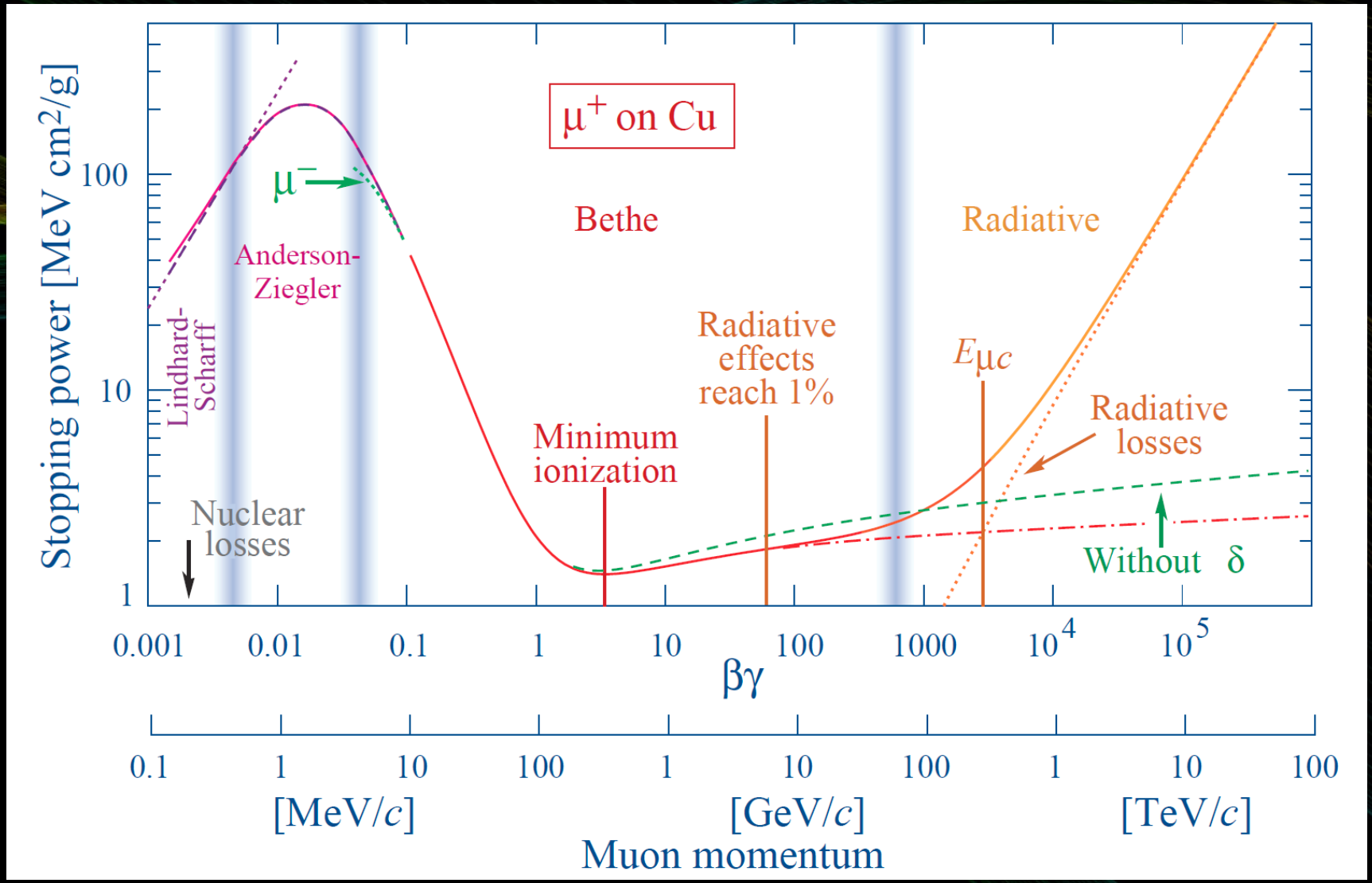
- Cherenkov radiation:
  - light is emitted when particle velocity is larger than the velocity of light in a dielectric material (n: index of refraction)
  - emission angle ($\beta=v_p/c$):
- Transition radiation
  - emitted at the boundary of different dielectric materials

$$\frac{c}{n} < v_p < c$$

$$\cos\theta = \frac{1}{n\beta}$$

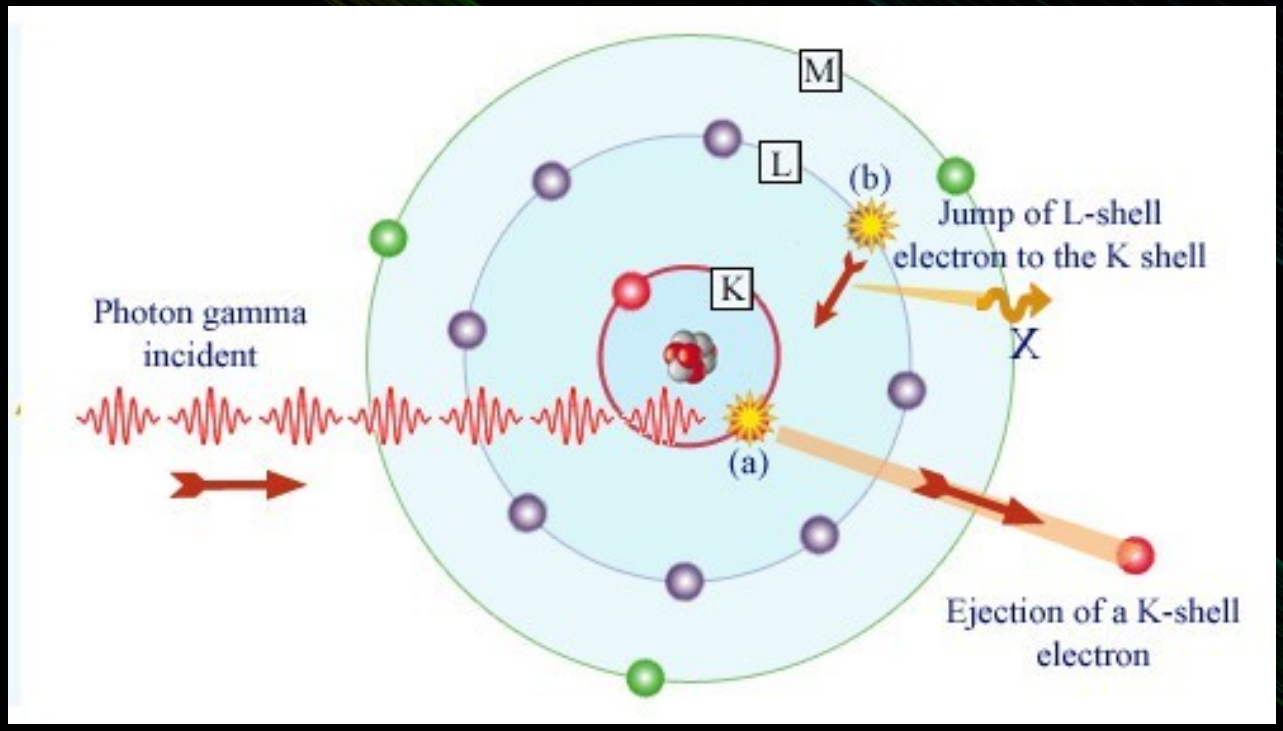


Energy loss of muons



Interactions of photons with matter

- Photoelecric effect: interaction of a photon and a K (or M, L) shell electron
  - electron is emitted with energy defined by the photon energy and the binding energy of the K (L, M) shell electron
  - cross section for K shell emission is higher the for L shell
  - charateristic X-rays and Auger electrons after photoelectron emission
  - governing process at low photon energies



Energy of photoelectron:

$$E_e = h\nu - E_b$$

Cross section of photoelectric effect

$$\sigma \sim \frac{Z^5}{E^3}$$

Interactions of photons with matter

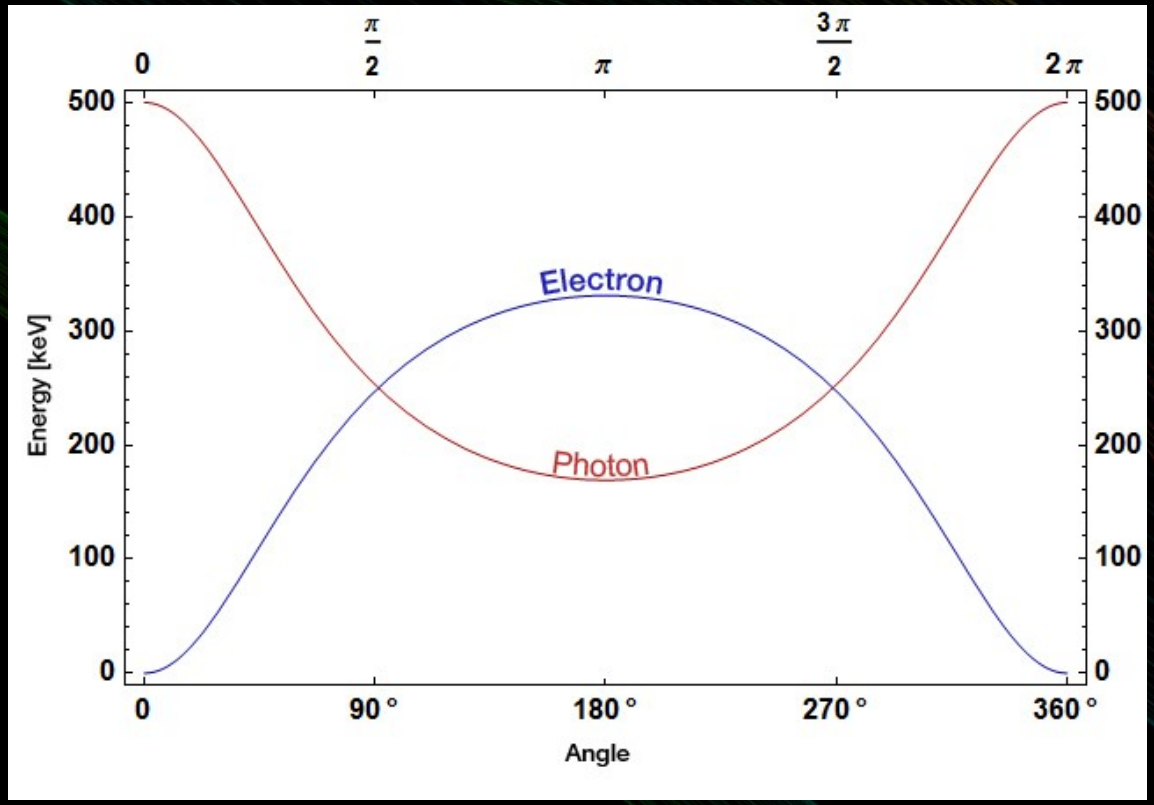
- Compton scattering: inelastic and incoherent scattering of photons by atomic electrons (typically by weakly bounded electrons)
  - electron is emitted, the wavelength of photon is shifted (Compton shift)
  - momentum is assigned to photons → momentum and energy conservation
  - high probability at intermediate gamma energies

Energy of scattered photon:

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\Theta)}$$

Cross section of Compton scattering:

$$\sigma \sim \frac{Z}{E}$$



Interactions of photons with matter

- Compton scattering:
  - direction of the scattered photons described by Klein-Nishina formula

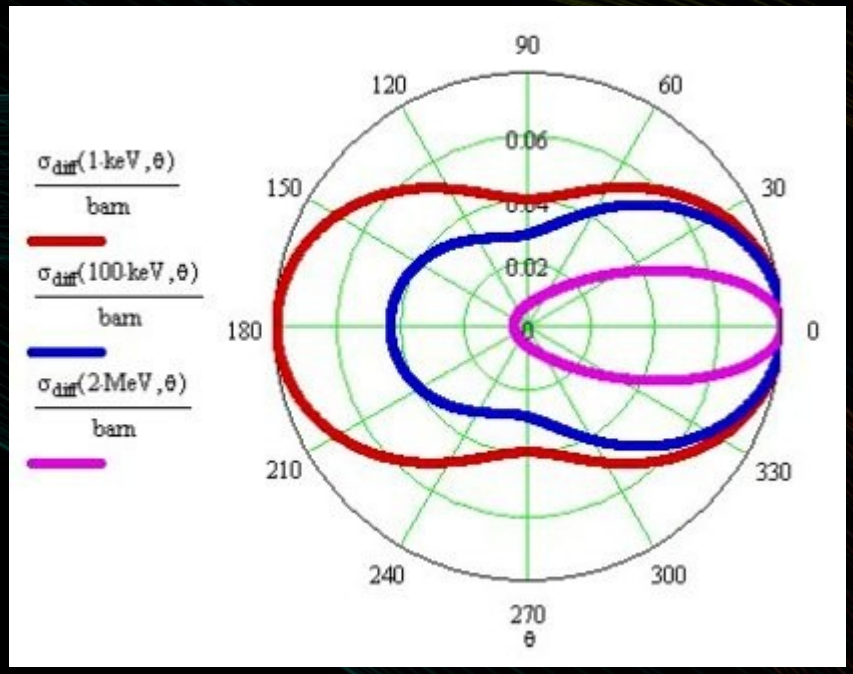
$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left[\frac{1}{1+\alpha(1-\cos\theta)}\right]^2\left[1+\cos^2\theta+\frac{\alpha^2(1-\cos\theta)^2}{1+\alpha(1-\cos\theta)}\right]$$

r_e : Classical electron radius (2.82×10^{-13}cm)

$\alpha = \frac{h\nu}{m_e c^2}$.

$h\nu$: Energy of incident gamma ray

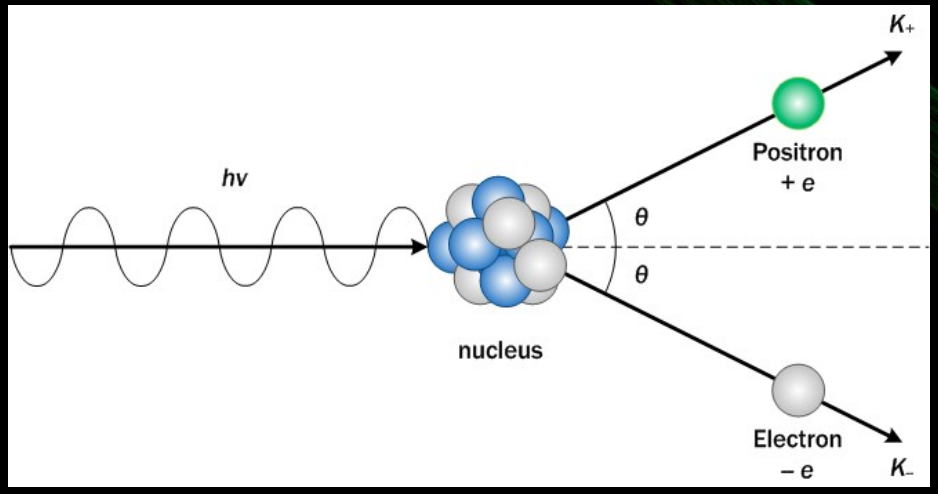
$m_e c^2$: Electron rest mass energy



- Rayleigh scattering:
  - elastic, coherent scattering
  - low energy limit of Compton scatttering, when $h\nu << mc^2$
  - typically Θ<20 degree
- inverse Compton scattering:
  - if electrons are not at rest (e.g having relativstic energies) → shifting up photon energies!!
  - new type of monoenergetic, high energy, intense gamma source (ELI-NP Bucharest, HIGS facility Durham, US)

Interaction of photons with matter

- Pair production: an energetic gamma photon produces an electron-positron pair near a nucleus (in the strong electric field of the nucleus)
  - energy treshold is 1022 keV according to the rest energy of electron and positron (m_0c^2=511 keV)
  - momentum AND energy conservation requires the nucleus to take away the momentum of the photon
  - positron and electron energies are not strictly equal thus directions are not symmetric to the incoming gamma
  - positron is not stable: after deceleration → annihilation with an electron → 2γ with Eγ = 511 keV and with Θ=180˚ (it is a prompt process!)
  - dominating process at large photon energies



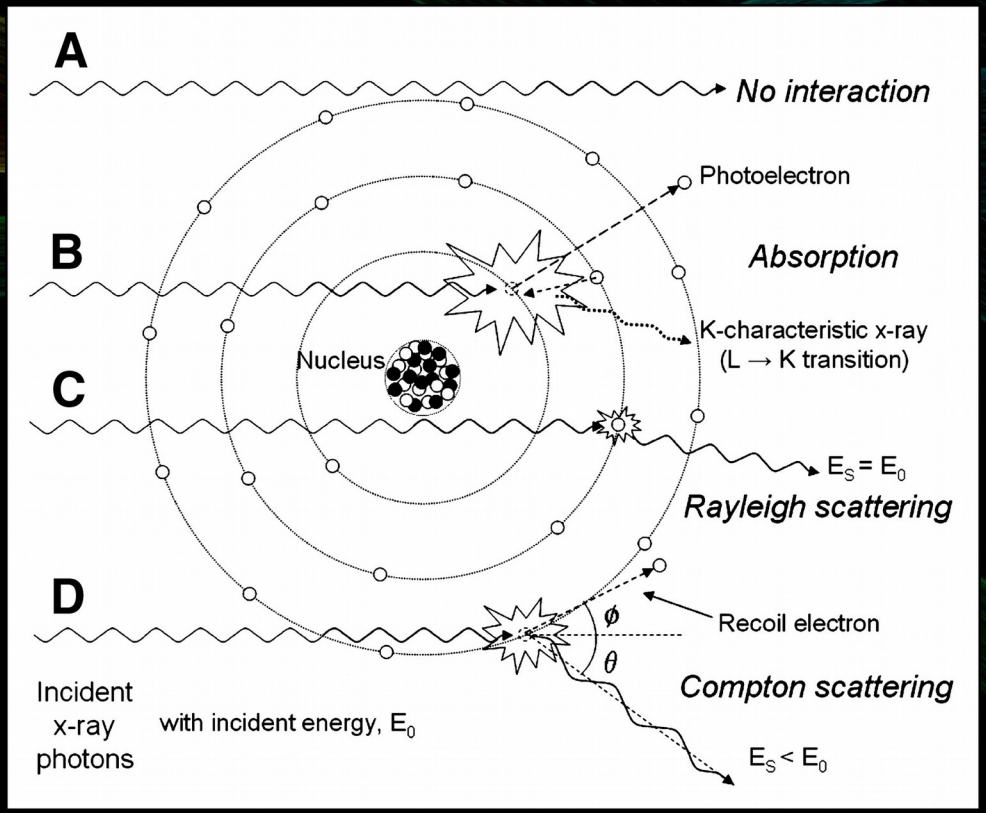
Energy balance:

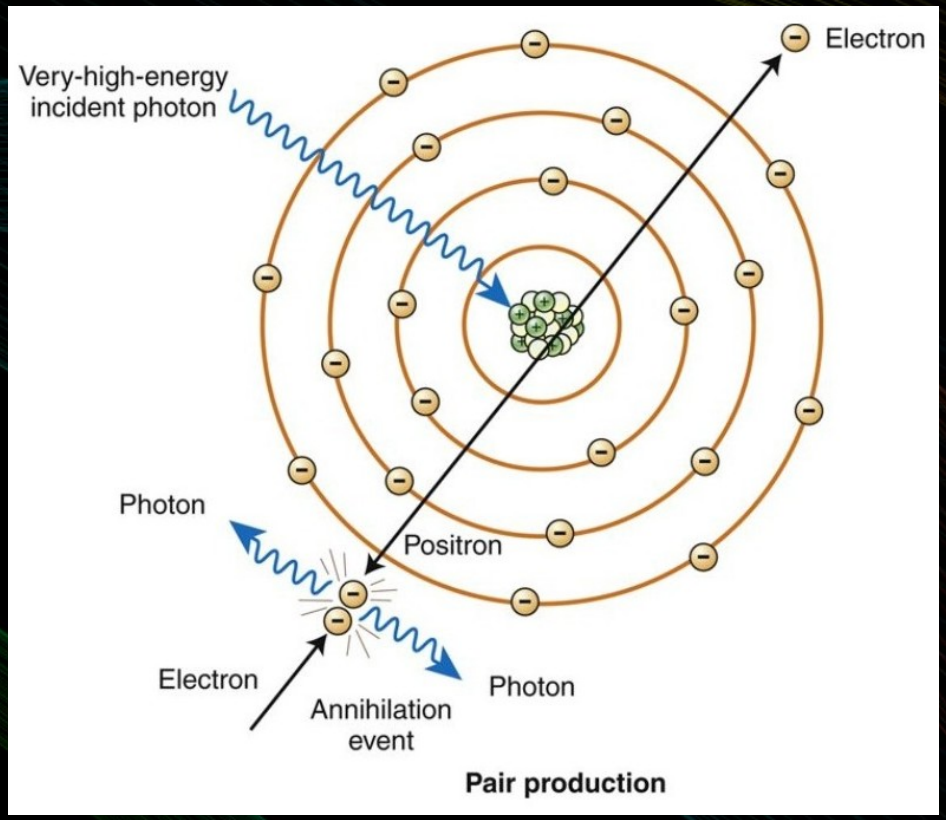
$$E_\gamma = 2m_{0\,c}^2 + E_{ke} + E_{kp}$$

Cross section:

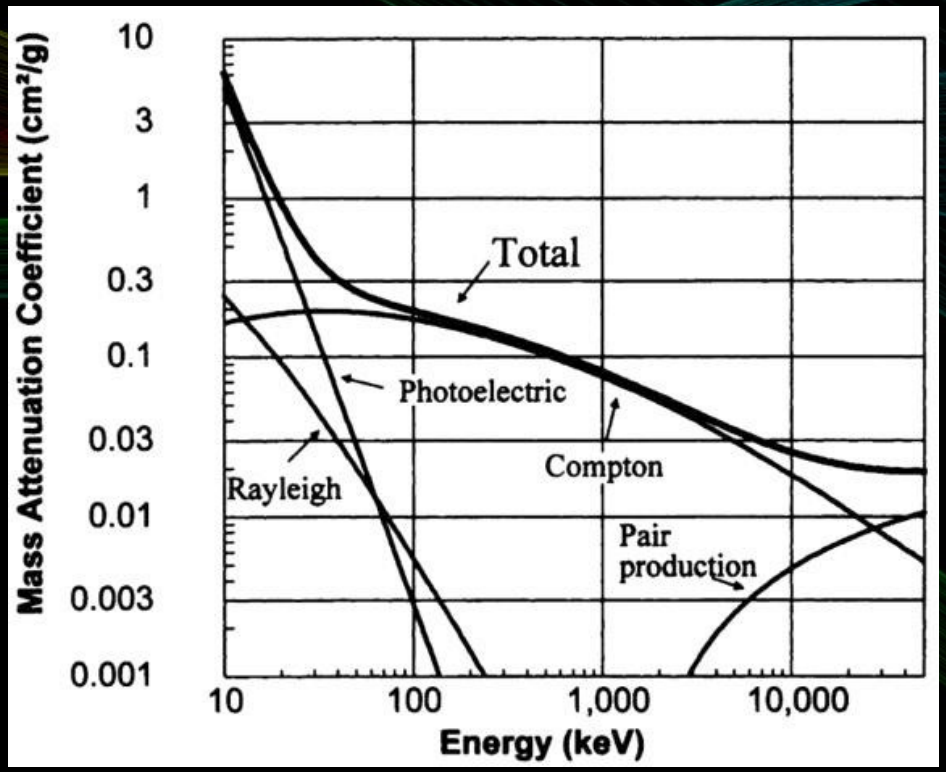
$$\sigma(E,Z) = f(E)\cdot Z^2$$

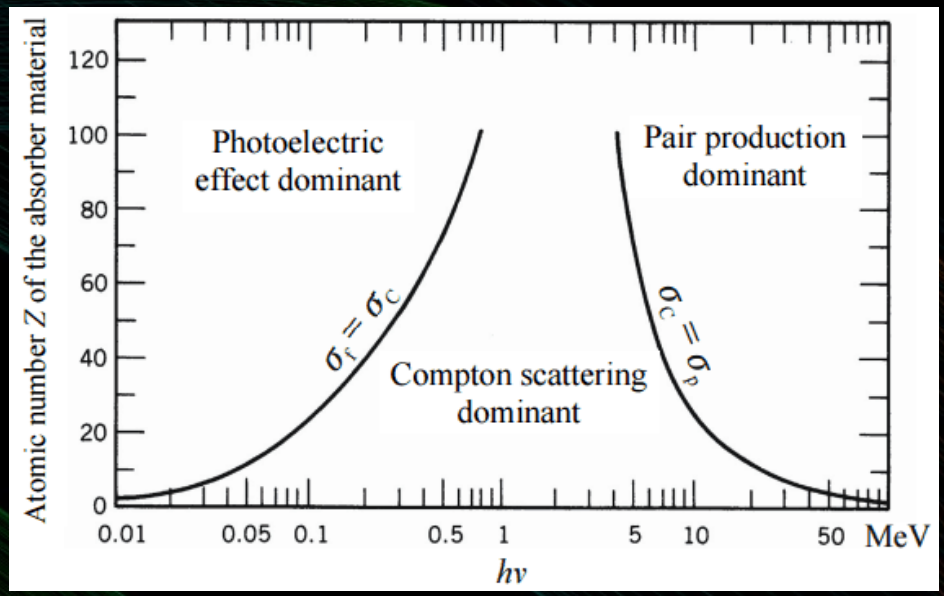
Interactions of photons with matter: summary





Interactions of photons with matter: summary



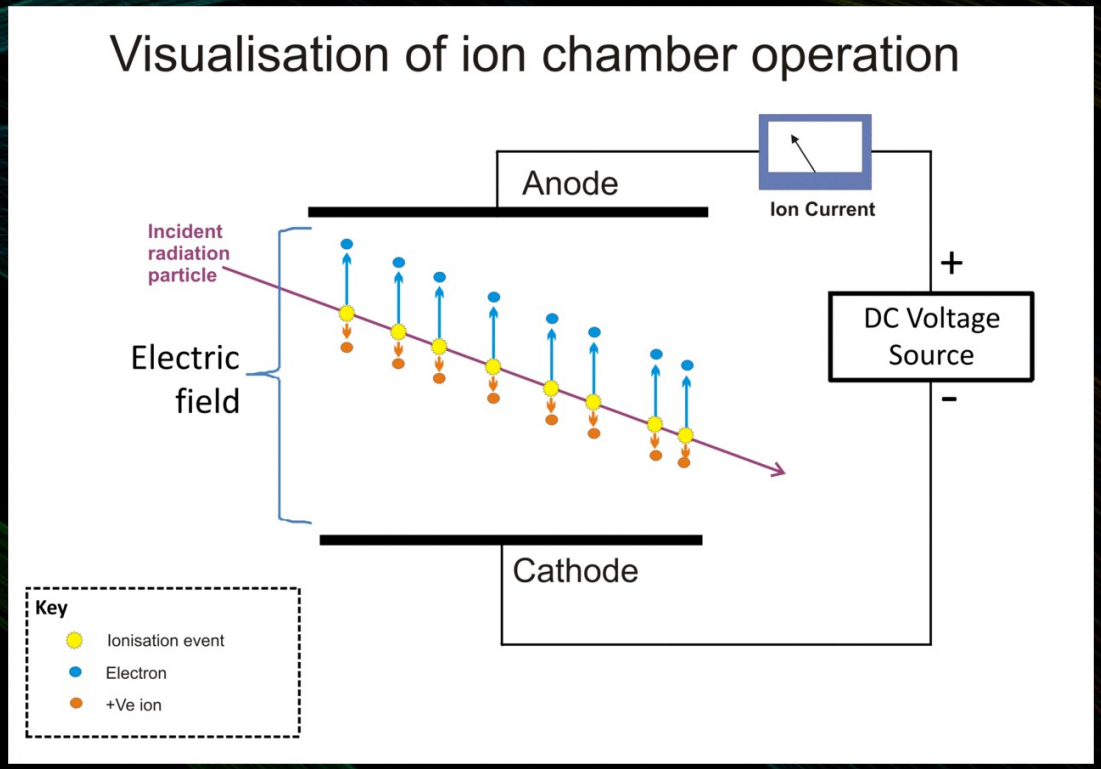


Types of particle detectors

- Particle counters: registration of individual evenets (time information + possible energy, position, etc.)
  - ionization counters:
    - gas detectors
    - semiconductor detectors
    - scintillation detectors
    - Cherenkov detectors
- Tracking detectors:
  - Cloud chambers, bubble chambers
  - Solid state track detector
  - Telescope detectors
- Dosimeters: not individual event, but detection of avarage on a time interval
  - photoplate
  - ionization detectors: current measurement
  - thermoluminescent dosimeters
  - induced radioactivity
  - radiation damage
  - calorimeters

Gas-filled detectors: introduction

- Operation principles:
  - gas ionization: particle-matter interaction
  - electric signal: stem from ion electron pairs collected on electrodes by electric field



- Some key-points:
  - electron-ion pair creation
  - diffusion, recombination
  - drift velocity of electrons and ions with/without electric field
  - charge (electron) multiplication

Gas detectors: ionization process

- interactions of charged particles in a gas:
  - primary processes: excitation, ionization, dissociation, elastic collision
  - secondary processes: radiative transitions, charge exchange, electron capture, recombination, secondary ionization
- Ionization in gas: statistical process → Poission statistics
  - avarage energy needed per electron/ion pair creation w ~ 30 eV
  - ionization potential of gases are typically lower (E_i = 15.8 eV)
  - weak dependence on gas tand particle type

TABLE 5-1 Values of the Energy Dissipation per Ion Pair (the *W*-Value) for Different Gases[a]

Gas	*W*-Value (eV/ion pair)	
	Fast Electrons	Alpha Particles
Ar	26.4	26.3
He	41.3	42.7
H_2	36.5	36.4
N_2	34.8	36.4
Air	33.8	35.1
O_2	30.8	32.2
CH_4	27.3	29.1

Table 6.2. Measured Fano factors for various gas mixtures

Gas	*F*	Ref.
Ar 100%	$0.2^{+0.01}_{-0.02}$	[6.4]
	$<0.40 \pm 0.03$	[6.5]
Ar + 80% Xe	$<0.21 \pm 0.03$	[6.5]
Ar + 24% Xe	$<0.23 \pm 0.02$	[6.5]
Ar + 20% Xe	$<0.16 \pm 0.02$	[6.5]
Ar + 5% Xe	$<0.14 \pm 0.03$	[6.5]
Ar + 5% Kr	$<0.37 \pm 0.06$	[6.5]
Ar + 20% Kr	$<0.12 \pm 0.02$	[6.5]
Ar + 79% Kr	$<0.13 \pm 0.02$	[6.5]
Xe 100%	$<0.15 \pm 0.01$	[6.6]

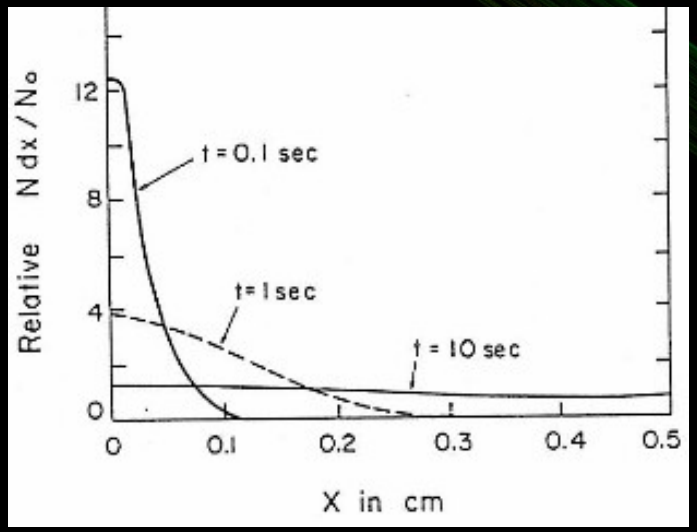
Number of pair created: $N_p = \frac{\Delta E}{W}$

E_p ~ 1 MeV
pairs ~ 30 000

Fano factor (< 1 !!): $\sigma_{N_p} = \sqrt{F \cdot N_p}$

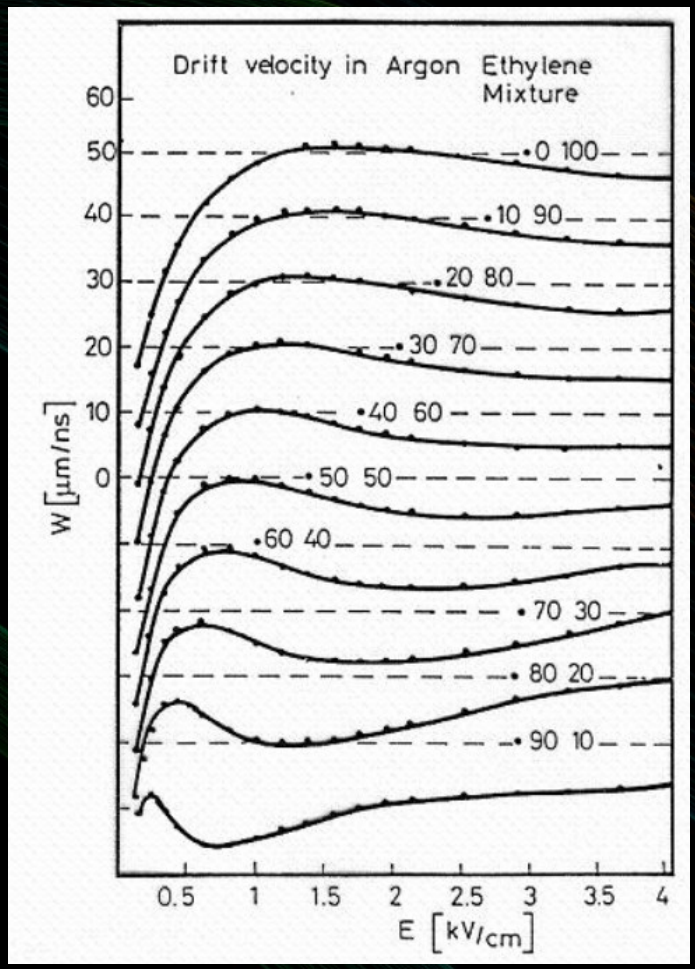
Charge transport in gases

- Free transport: thermal motion by interaction with gas molecules → thermal diffusion at *T* and *p*
  - ion mobility is much smaller than electron mobility
  - diffusion coefficient: $D \sim \frac{T^{3/2}}{\sqrt{m}\,p}$
  - diffusion equation: $\frac{1}{n_0}\frac{dn}{dx} = N\left(x_0, \sigma_D\right)$ $\quad \sigma_D = \sqrt{2\,Dt}$

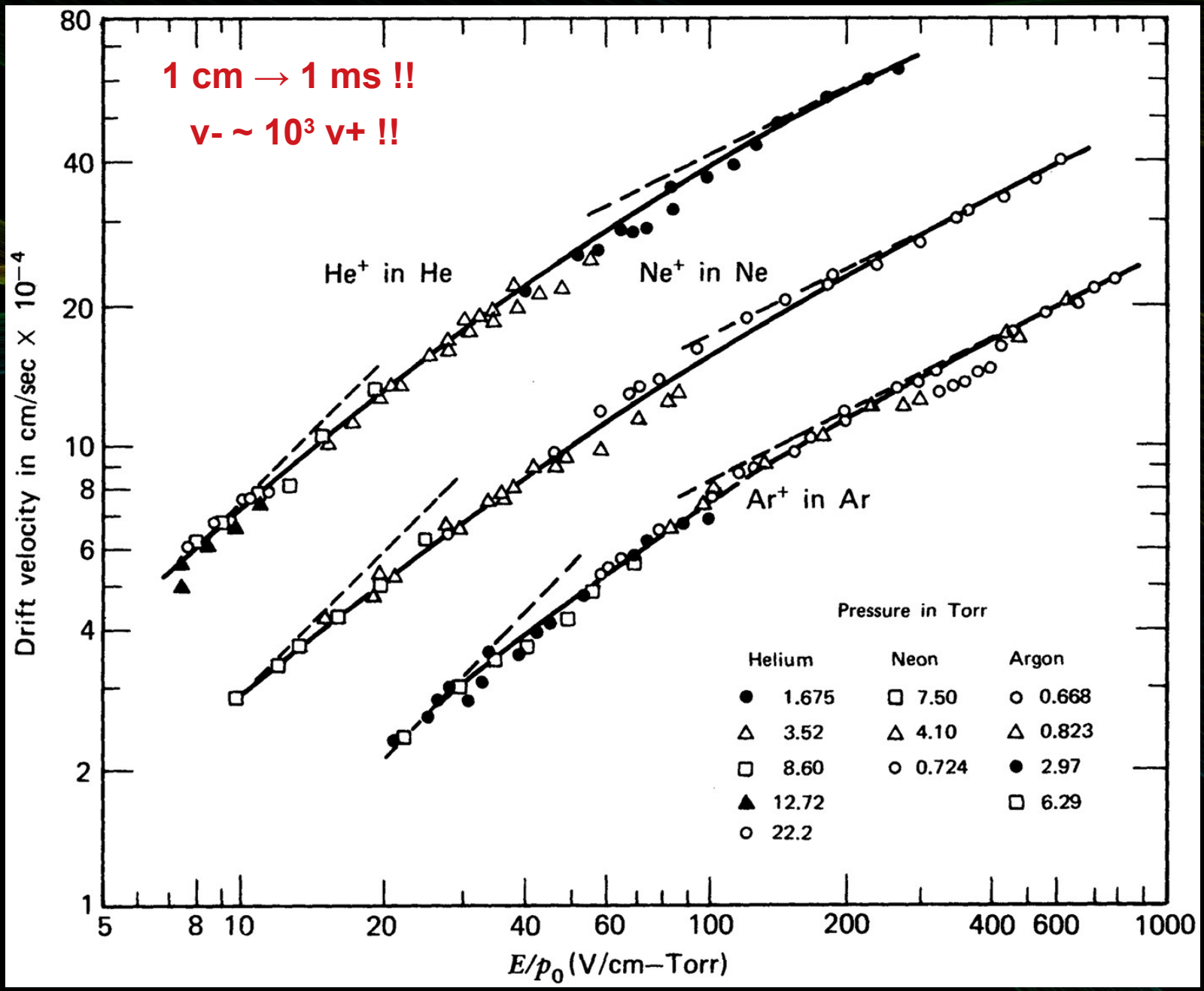


thermal equlibrium → recombination !!

- Driven transport: under electric field E → separates +/- charges
  - drift velocity: $v = \frac{eD}{kT}\frac{E}{p}$



Charge transport in gases



Secondary processes

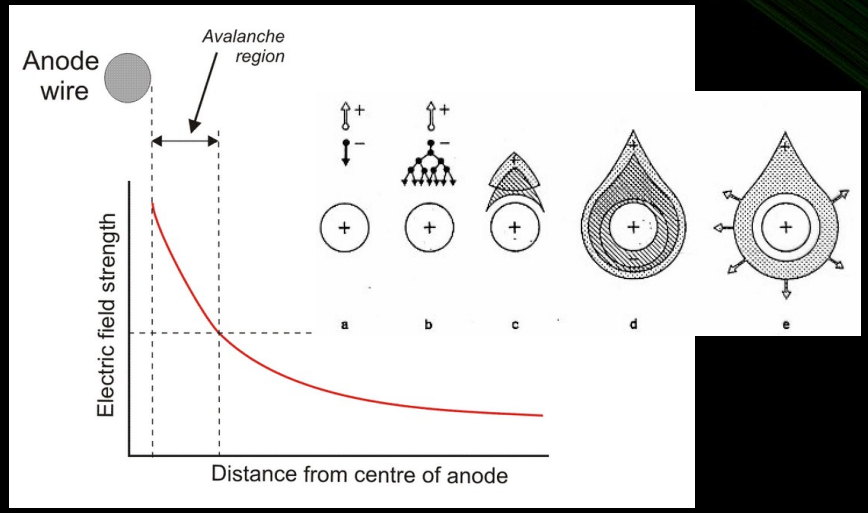
- if electric field is high enough → electrons can ionize molecules → secondary electrons are produced
- if electric field is even higher → secondary electrons many times
  - Townsend coefficient :

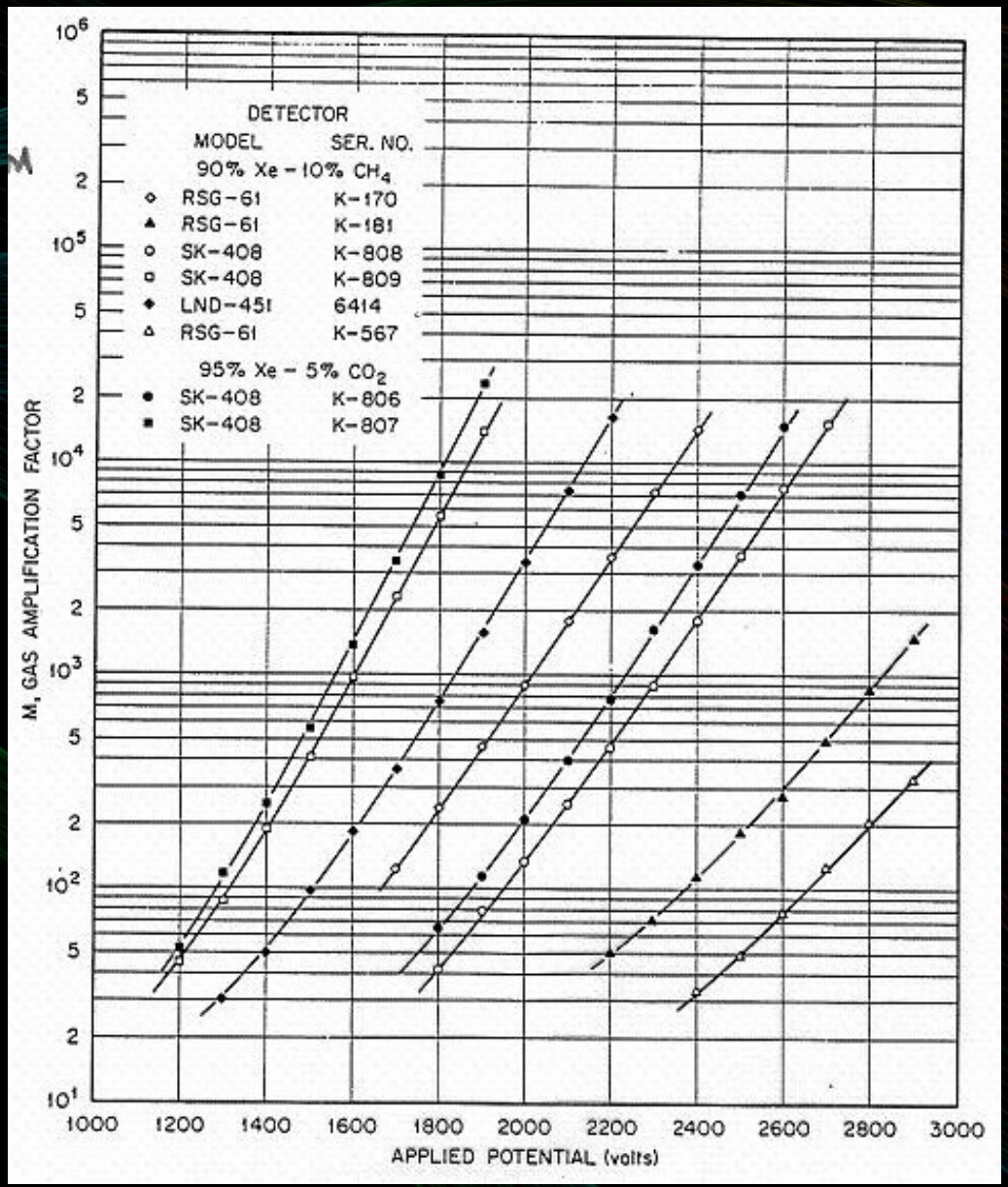
$$\frac{dn}{n} = \alpha\, dx \qquad n(x) = n(0)e^{\alpha x}$$

  - multiplication factor:

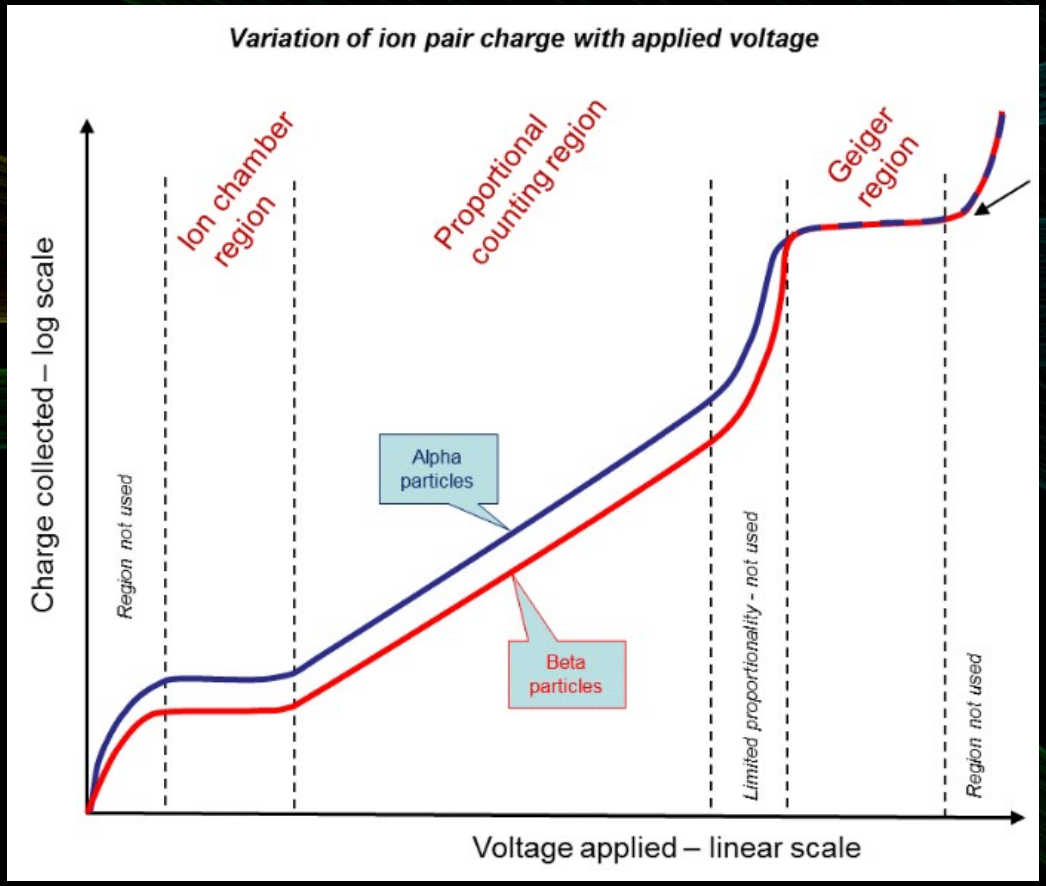
$$M = e^{\int \alpha(x)dx}$$

- avalanche formation:





Region of operation of gas detectors

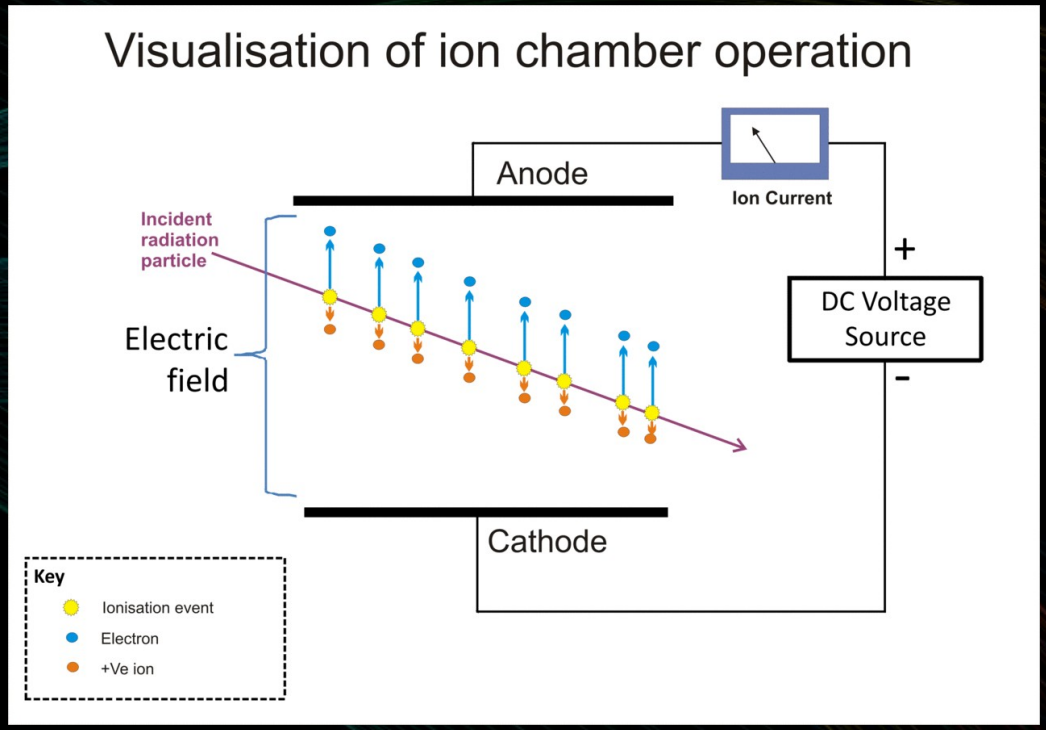


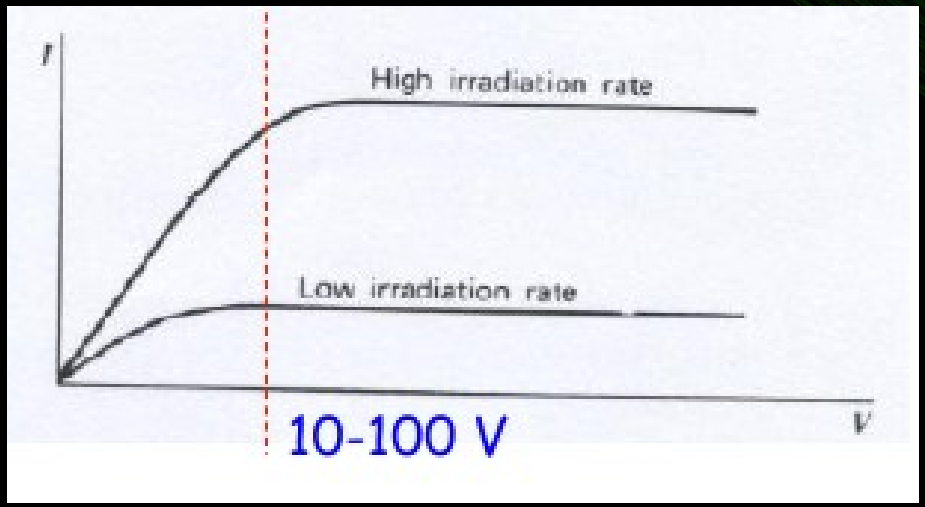
1. Recombination before reaching the electrodes → loss of signal
2. Created pairs reach the electrodes under voltage V → signal proportional to primary ionization
3. Secondary electrons are created and extracted, number of secondary electrons are proportinal to incoming energy → signal is proportional to secondary ionization
4. Region of limited proportionality → not used
5. Discharge in the full gas → signal is independent of energy

- Operation depends on the geometry of the chamber, size of the wires, type of gas, pressure, high voltage

Ionization chamber

- A container filled with gas:
  - e.g. Ar+CH_4 mixture at p=0.5-2 bar
- 2 isolated electrode at high voltage at U=1-5 kV
- Operation modes:
  - current mode: current indicates the rate of ion formation
  - pulse mode: detecting individual event

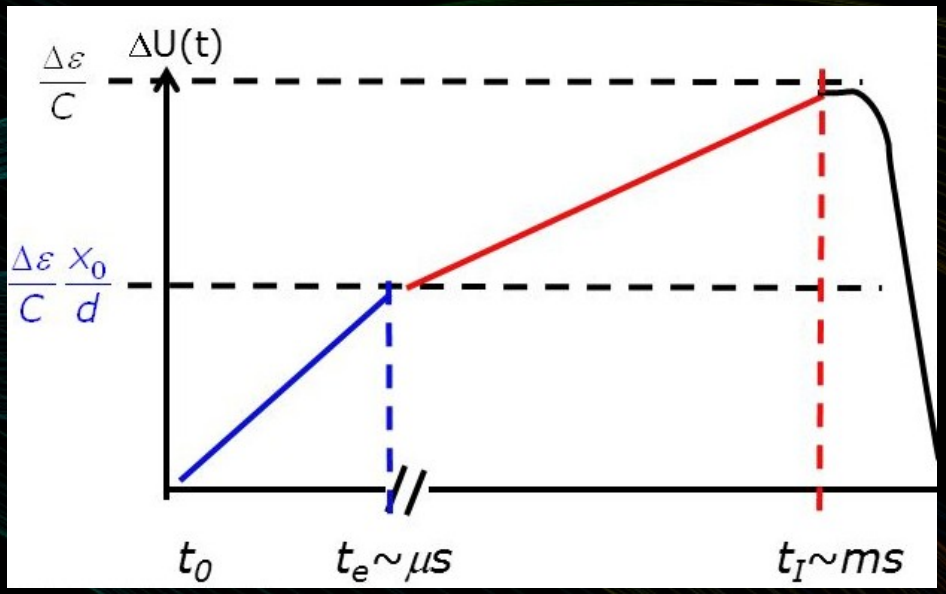


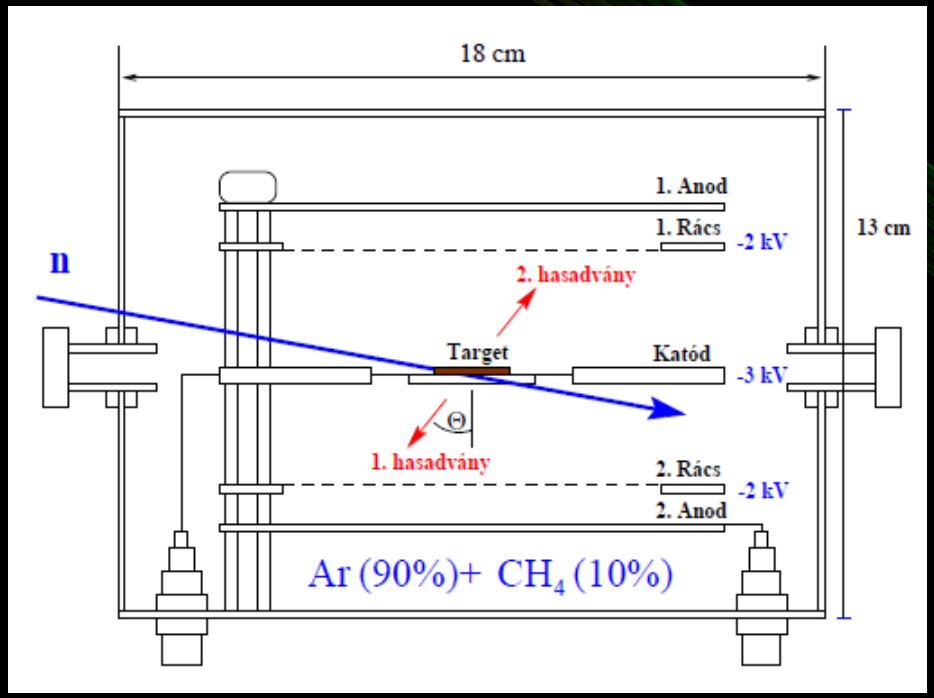


- Detection efficiency: 100% for charged particles, 1% for photons (low Z materials, low density)
- Singal: e.g E_α = 3 MeV
  - w=30 eV → n=E/w=10^5 e-ions
  - V=Q/C=0.5 mV → amplification!!

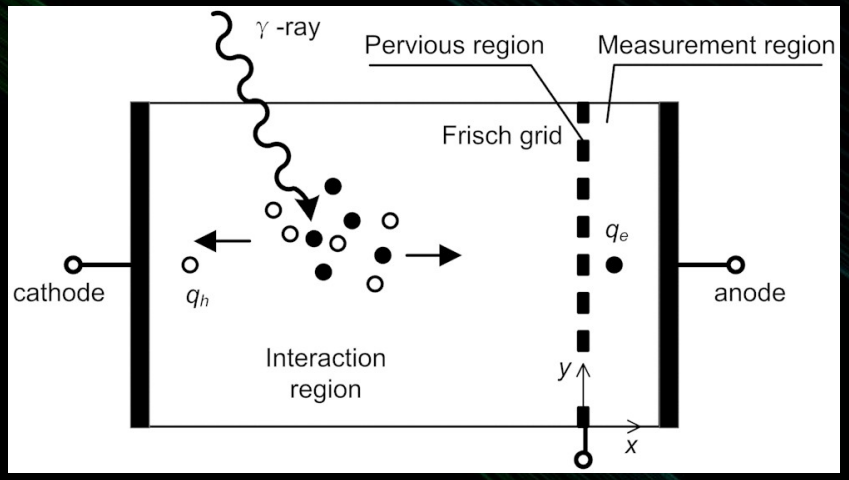
Ionization chamber

- Due to the different drif velocities of electrons and ions, the signal has a fast and a slow component → using only the fast electron component
- The signal amplitude is position dependent!

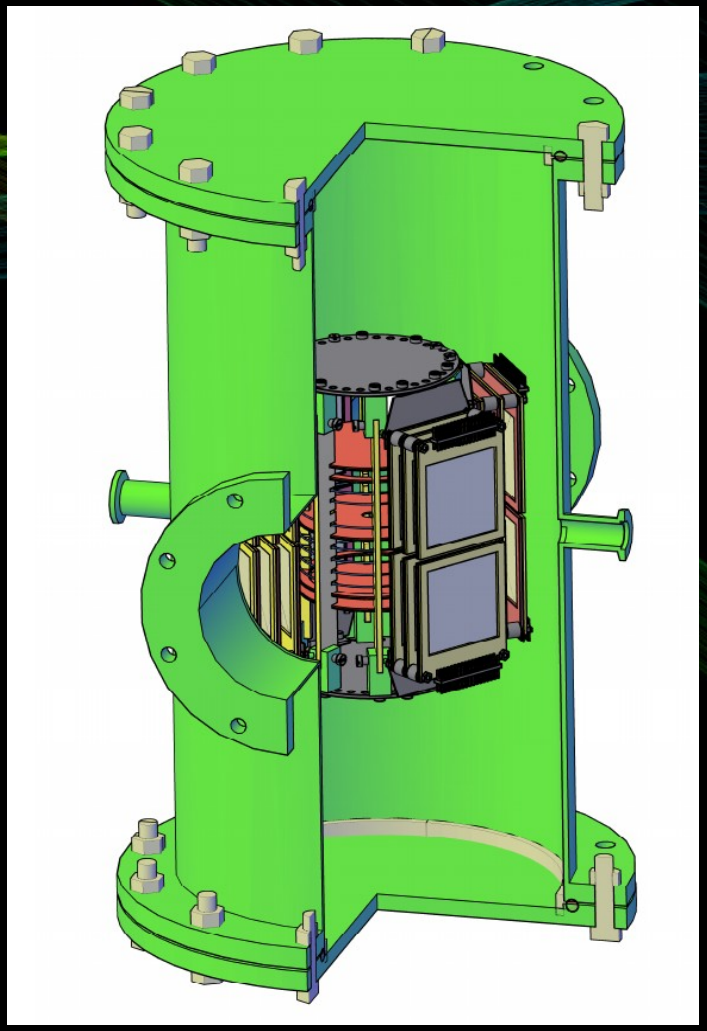


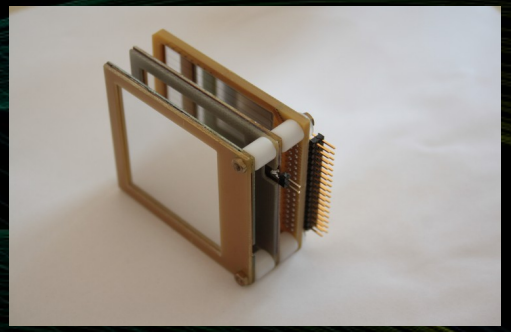


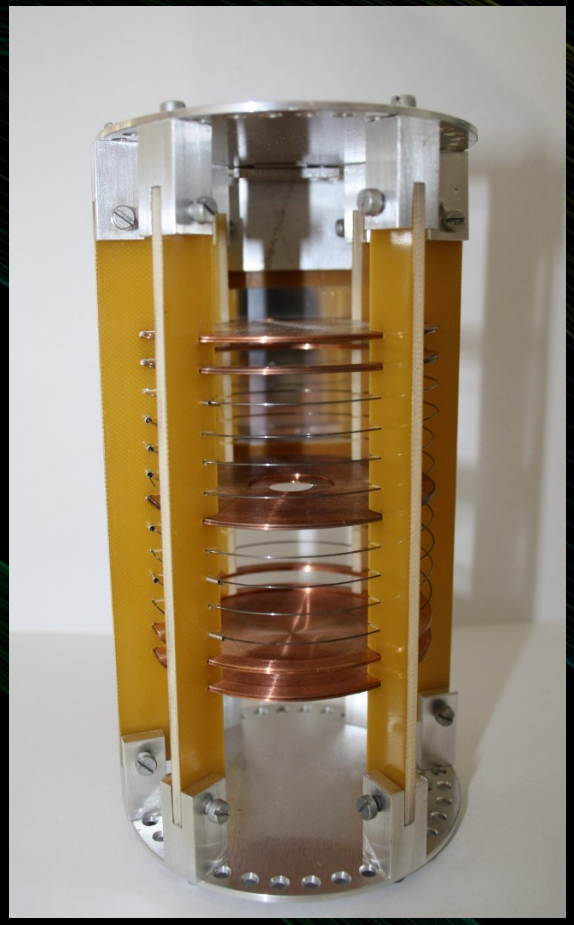
- Frisch-grid ionization chamber:
  - removes the effect if slow ions → no position dependency of signals



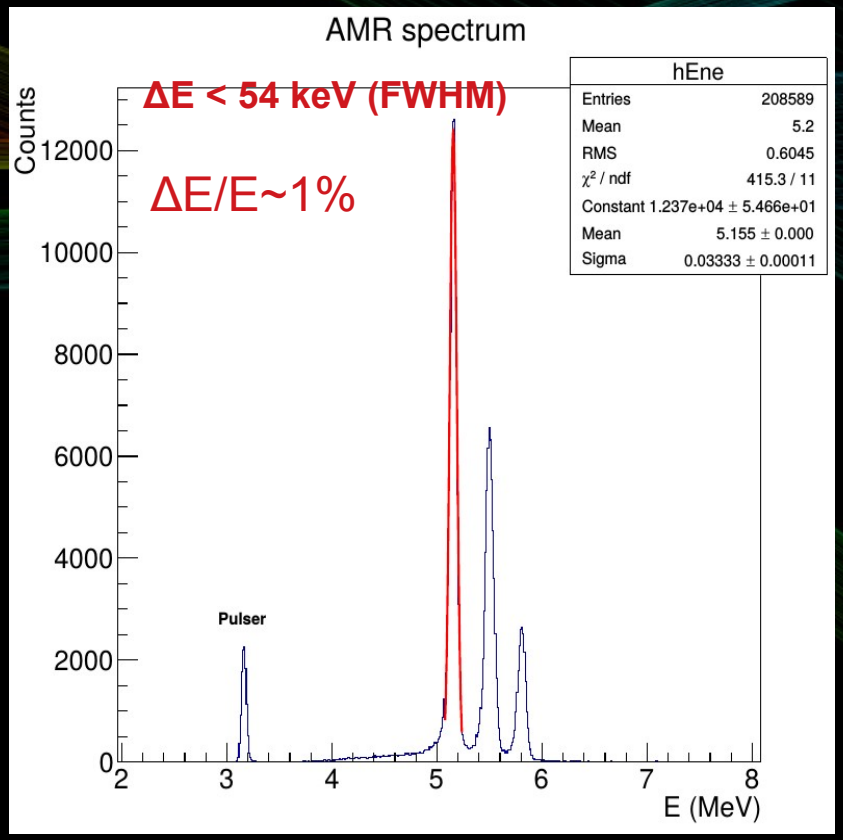
Development of an ionization chamber at Atomki

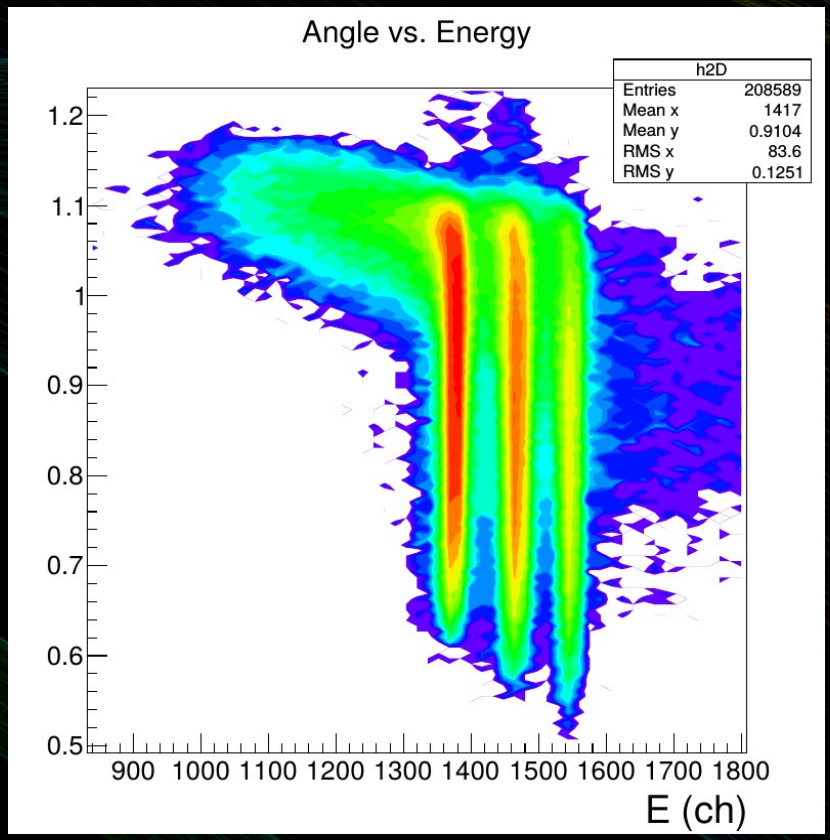




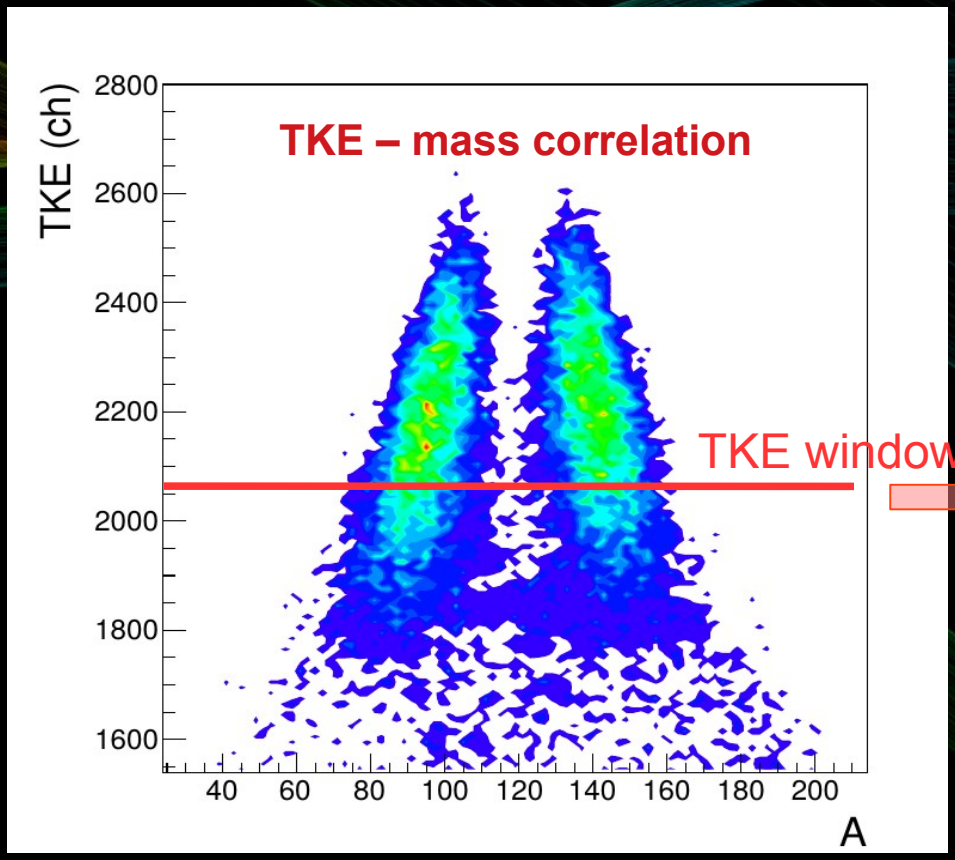


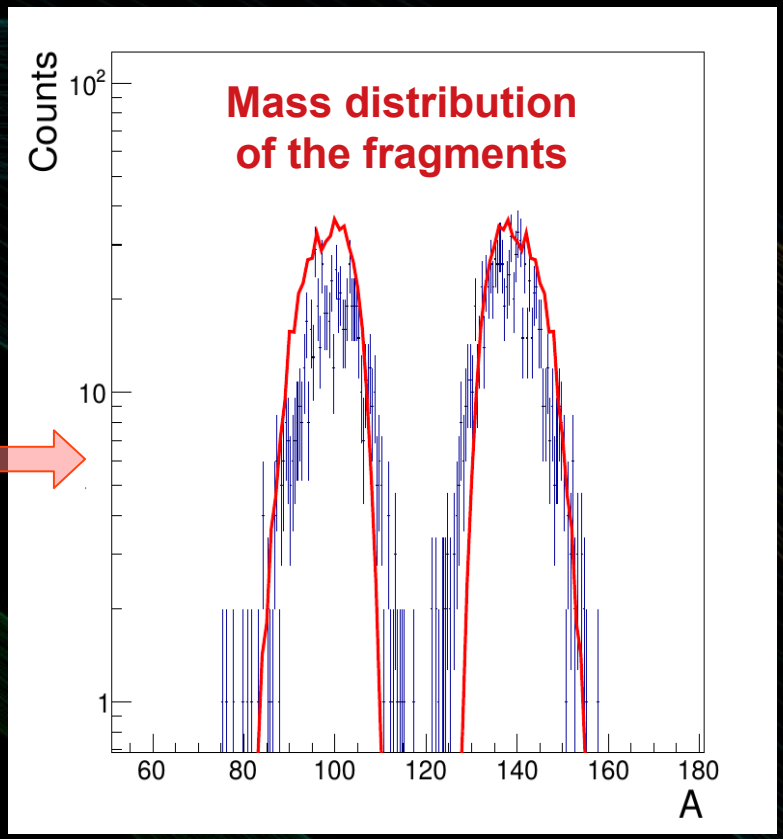
Development of an ionization chamber at Atomki





Development of an ionization chamber at Atomki



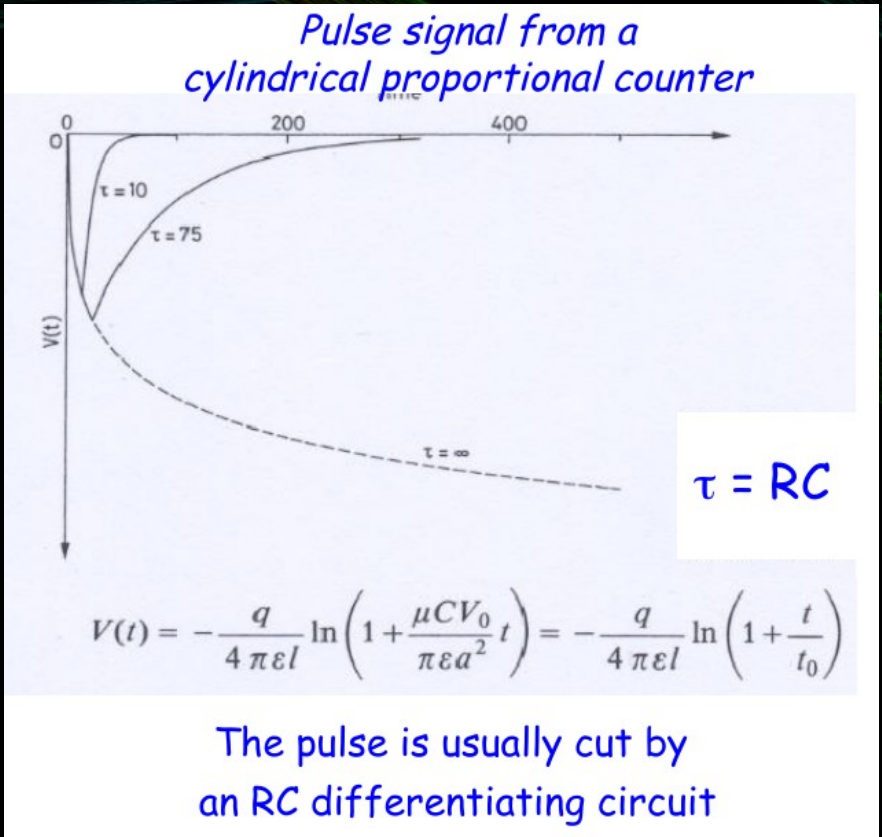


Proportional counters

- Goal: signal amplification by the multiplication of the primary e/ion pairs
  - at high voltage → electrons gain kinetic energy enough to ionize the gas
  - at p=1 bar → U=10^6 V/m
  - best geometry: cylindrical

$$E(r)=\frac{V_0}{\ln(b/a)}\frac{1}{r}$$

a: radius of anode
b: radius of cathode

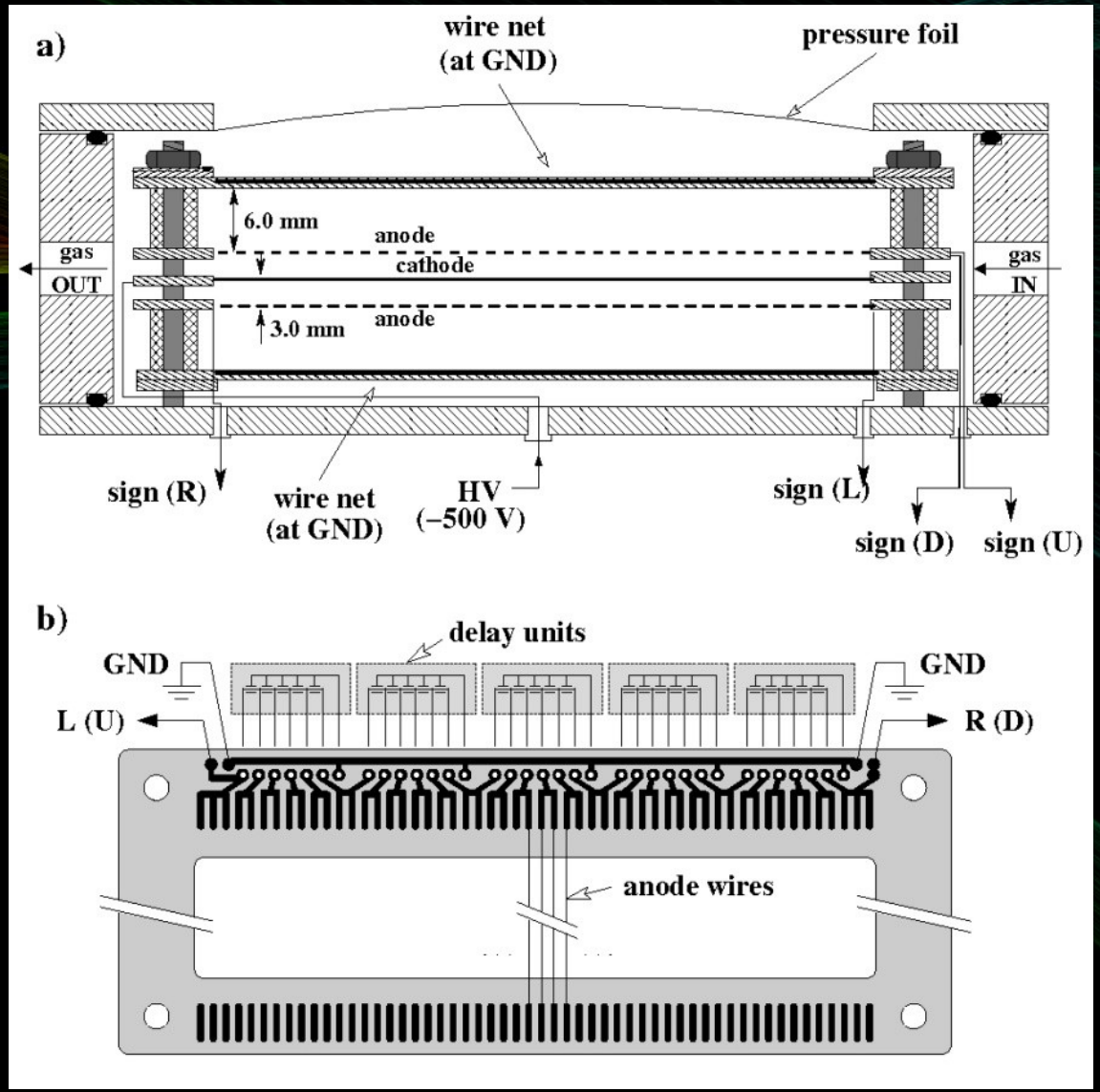


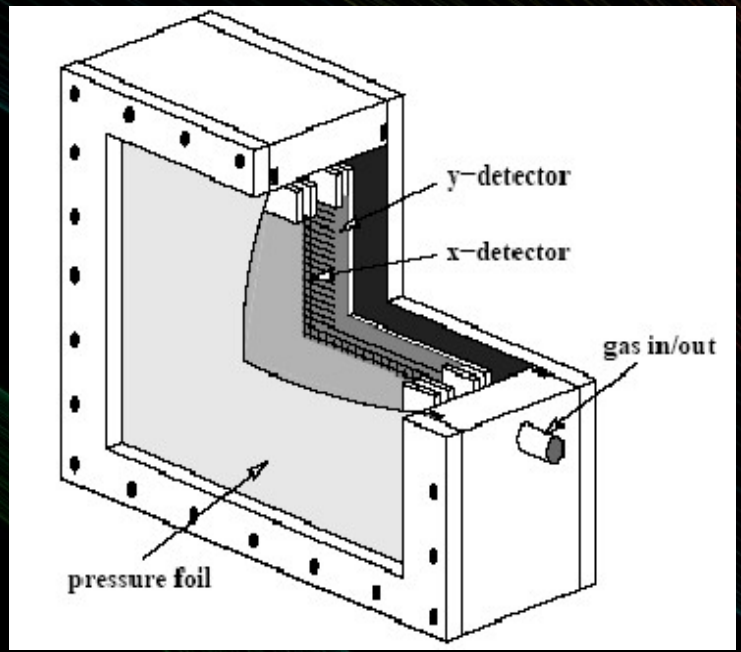
Example: V=2 kV with a=80 micron and b=1 cm → E(a)=10^6 V/m

In planar geometry one would need U=10^5 V!!

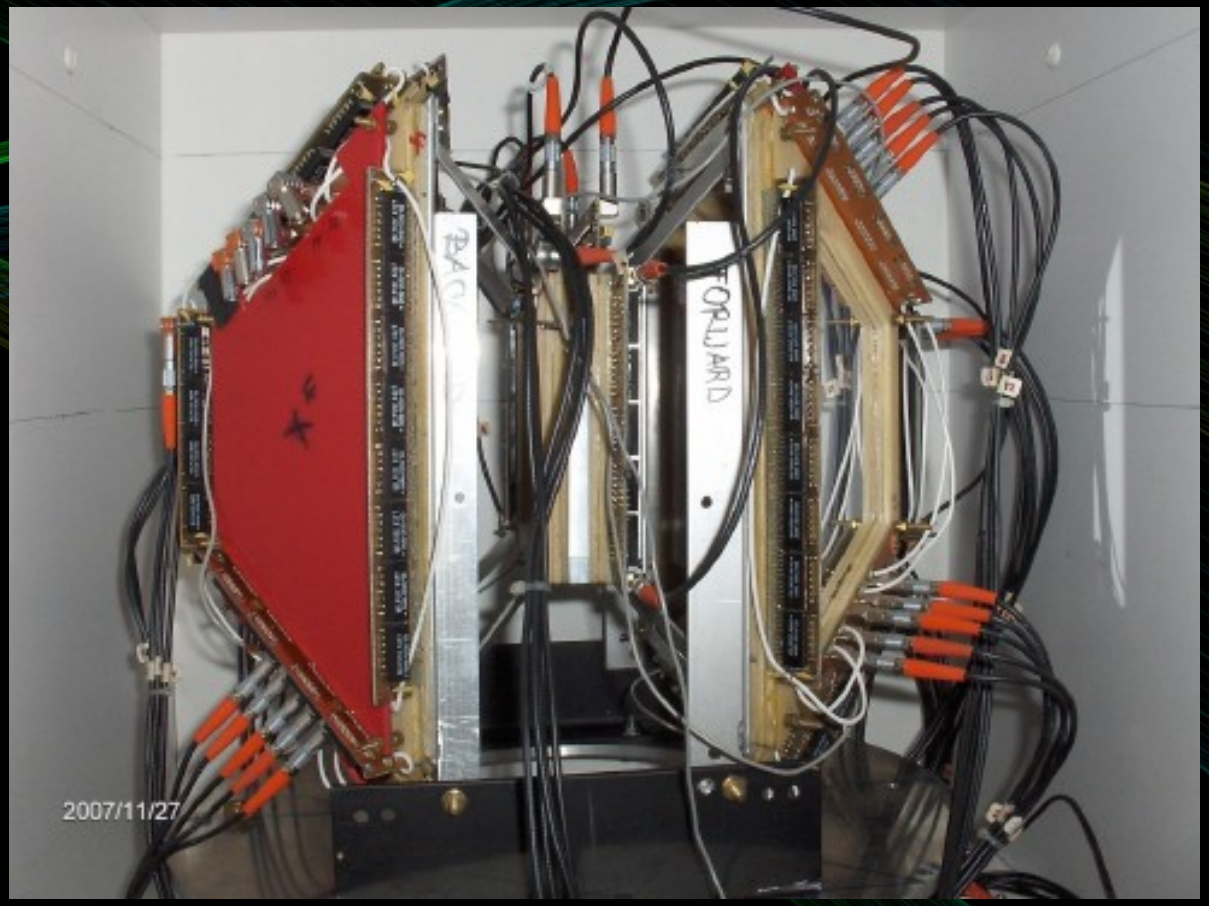
- Fast signals: rise time of the signal down to 0.5 ns
- Possible of making position sensitive counters:
  - readout techniques: center of gravity, charge division, delay time readout

Multiwire proportional chamber (MWPC)

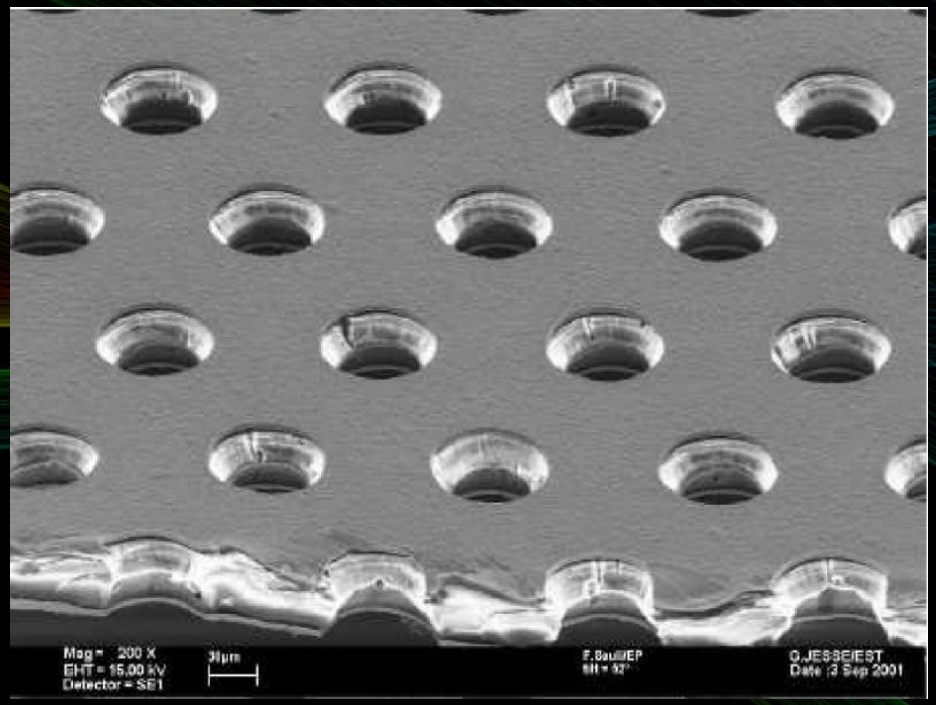




Multiwire proportional chamber (MWPC)

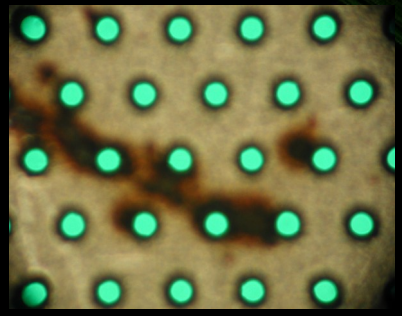


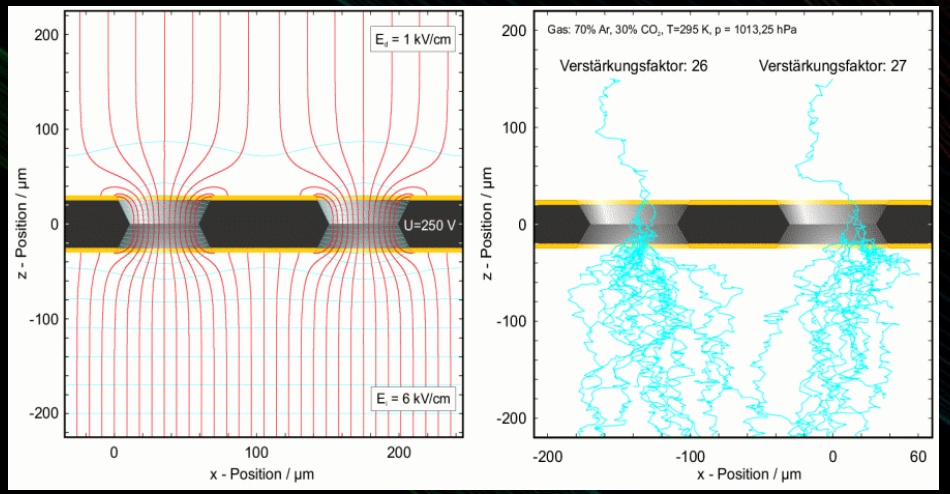
Gas Electron Multipliers



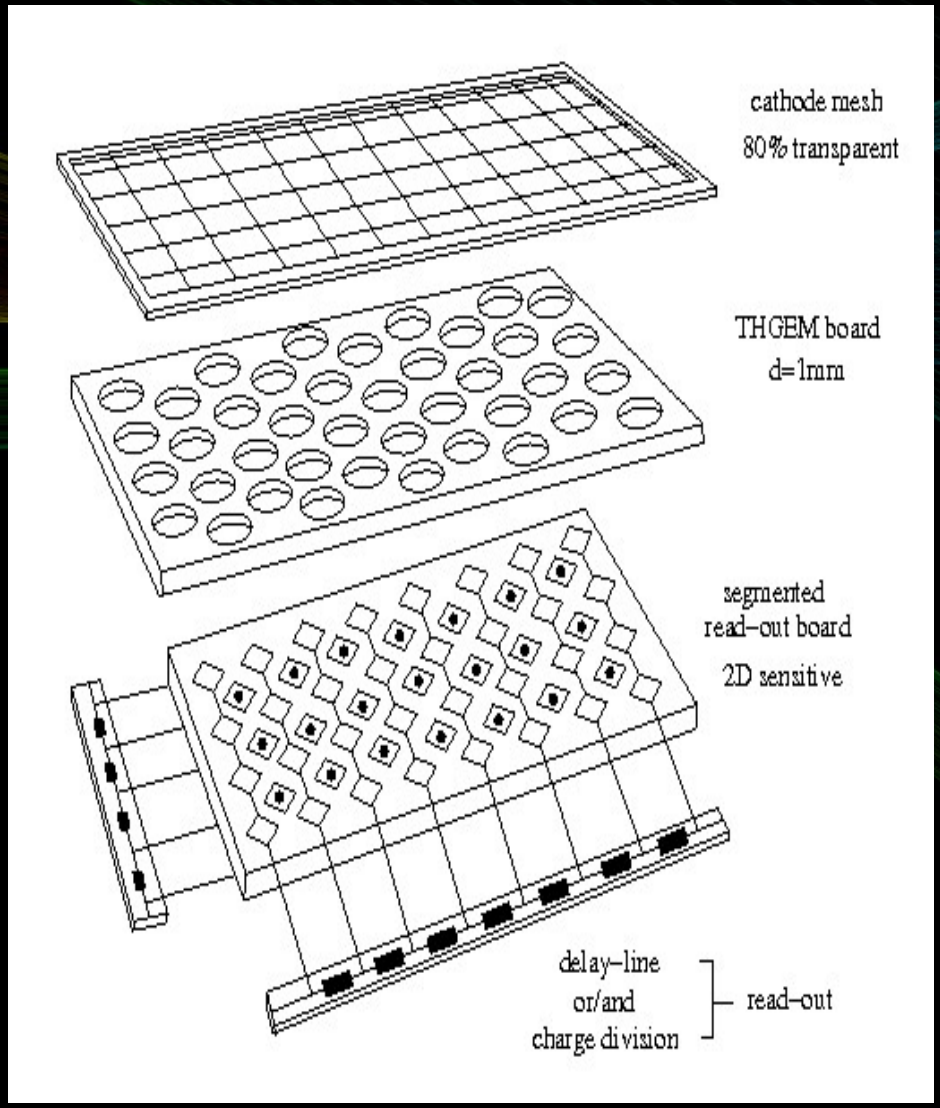
- Gas Electron Multiplier was invented at CERN in 1999
- Filling gas: isobutane, Ar+CH_4 Ar+CO_2
- Low pressure → fast signal
- Large amplification (10^5)
- hole ↔ pixel (charge localization)

- Drawbacks:
  - mechanical sensitivity
  - high voltage instability
  - clean laboratory is needed

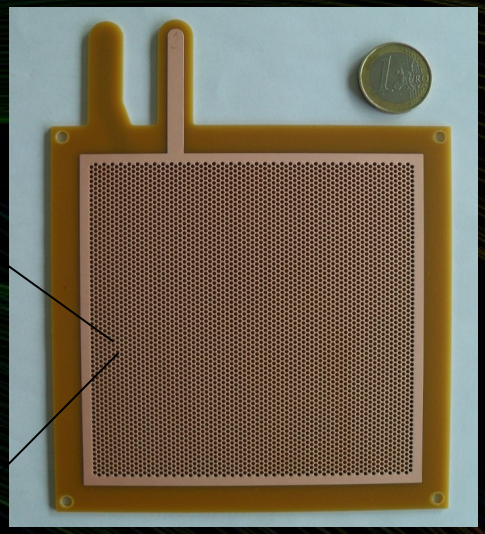


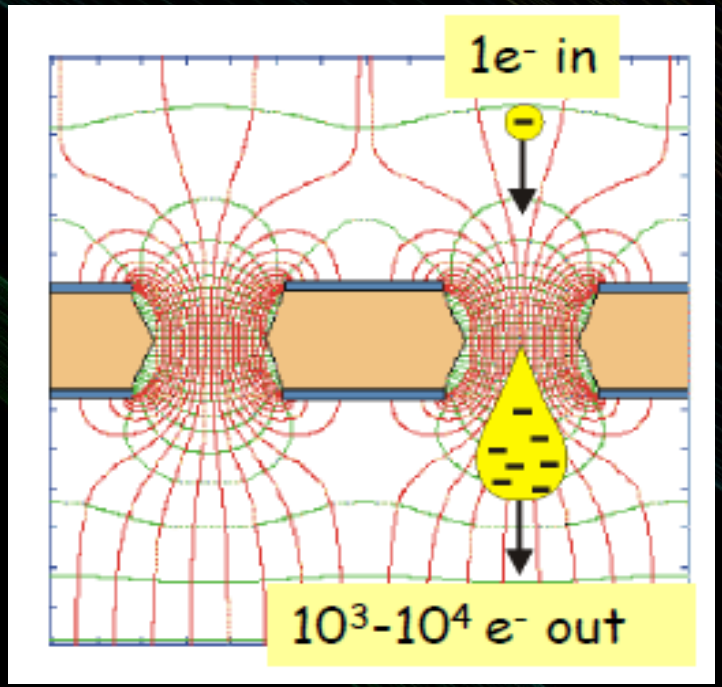


Thick Gas Electron Multipliers



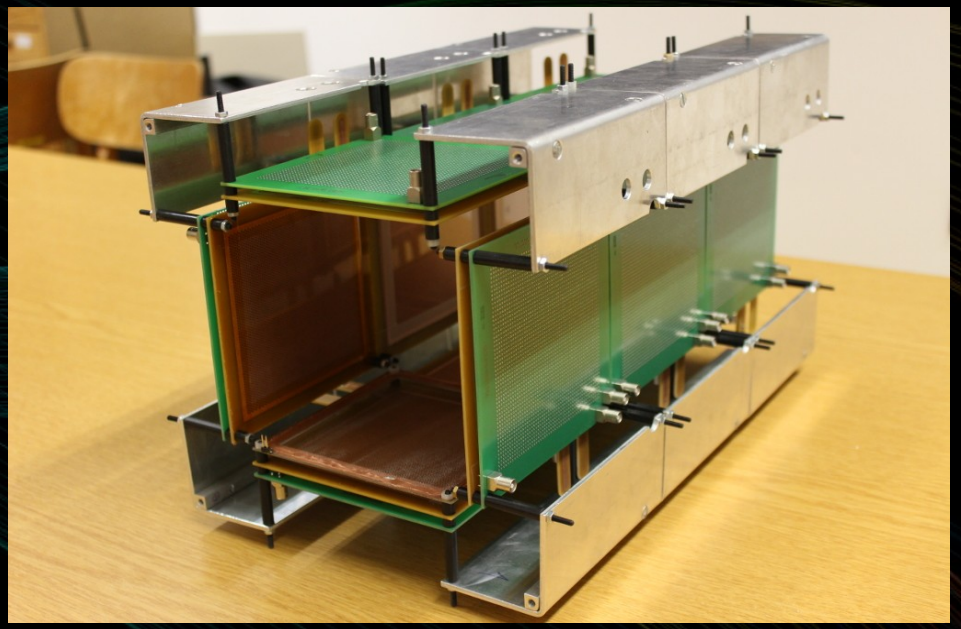
CERN (400 EUR)

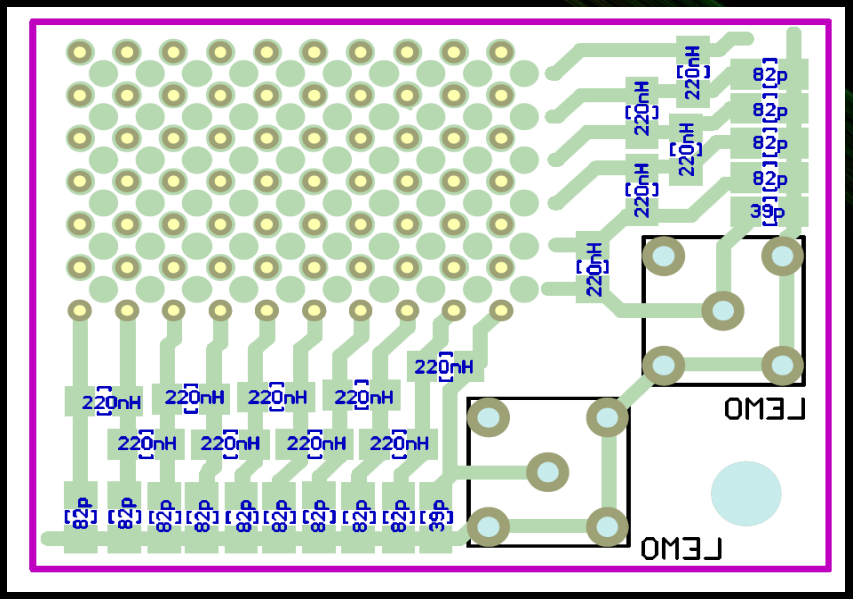


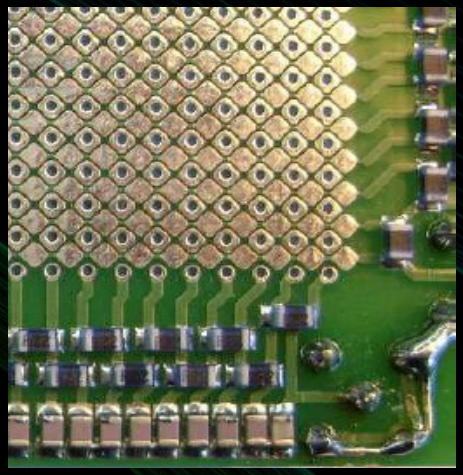


Gas Electron Multipliers

- Delay line read-out anode board:
- capacitors (82pF) and inductors (220 nH)
- 4 ns / line
- (t1-t2) gives the coordinates in one direction

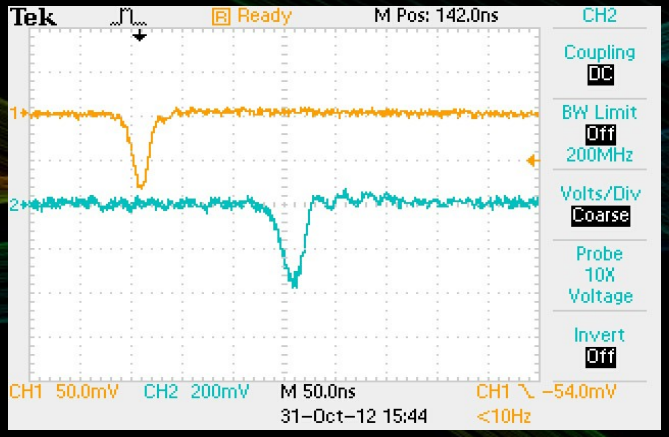


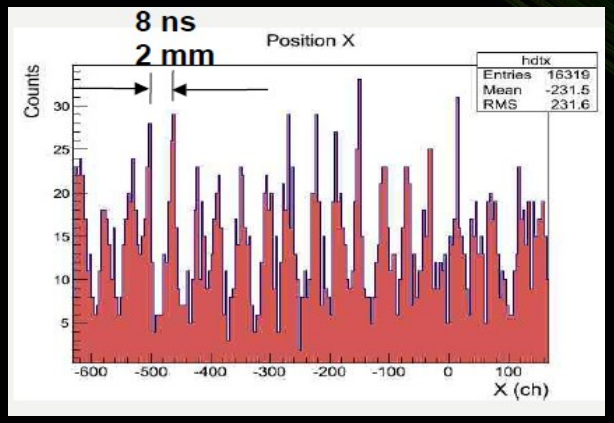


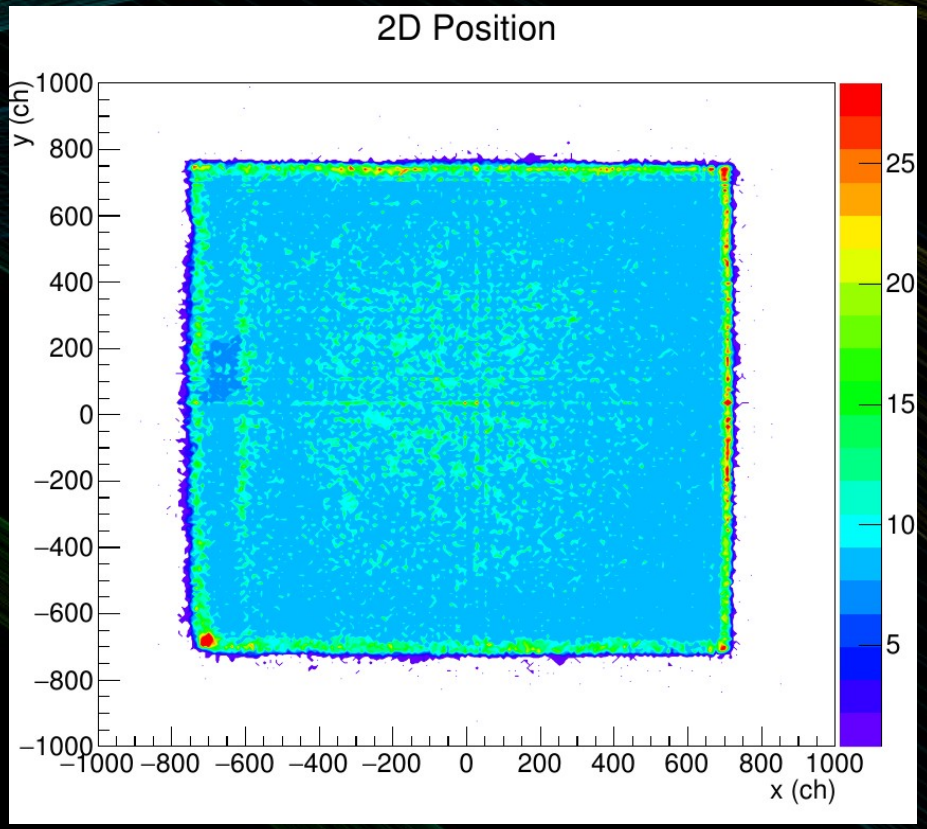


Th-GEM readout anode: 2 layers PCB

Gas Electron Multipliers





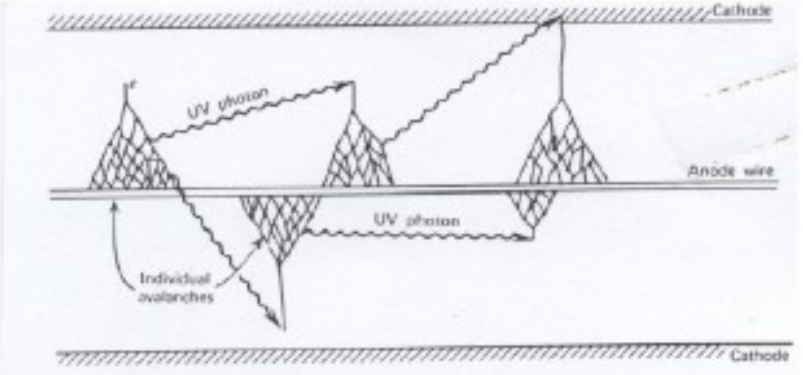


Geiger-Müller counters

for High Electric Fields:

Secondary avalanches are produced by photons emitted by excited atoms

$M \sim 10^{10}$



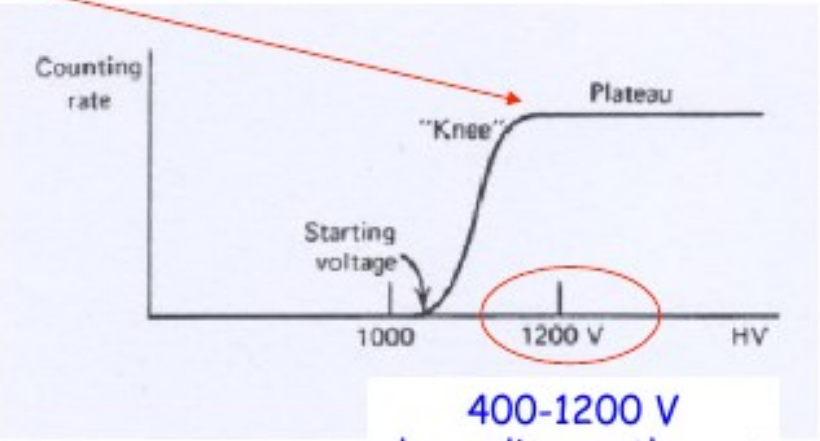
Entire volume gas is involved in the process

⇒ Loss of information on space
⇒ Loss of information on energy (NO spectroscopy)
⇒ identical output

Fill Gas: He, Ne or Ar

Noble gases

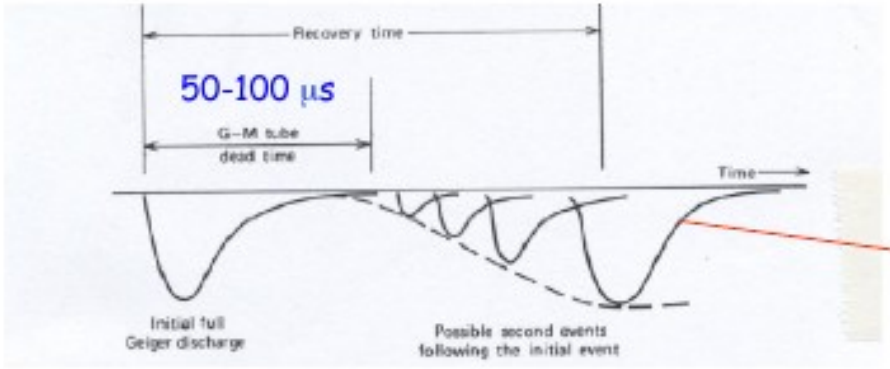
To avoid formation of **negative ions** being based on multiplication process



400-1200 V
depending on the gas

Geiger-Müller counters

The Geiger discharge stops when an **high ions (+) concentration** reduces the field E below the moltiplication threshold



Second full pulse appears when **ALL** ions (+) are collected to the cathode

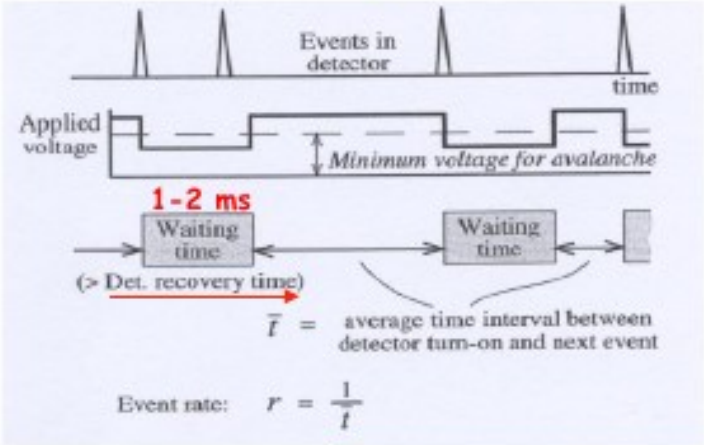
⇒ G-M tubes are limited to application with **low counting rates**

Method to improve effective counting range

1. **Time-to-first-count-method:**

   The high voltage is switched between two values:

   - **Normal** operating voltage
   - **lower** value below avalanche threshold

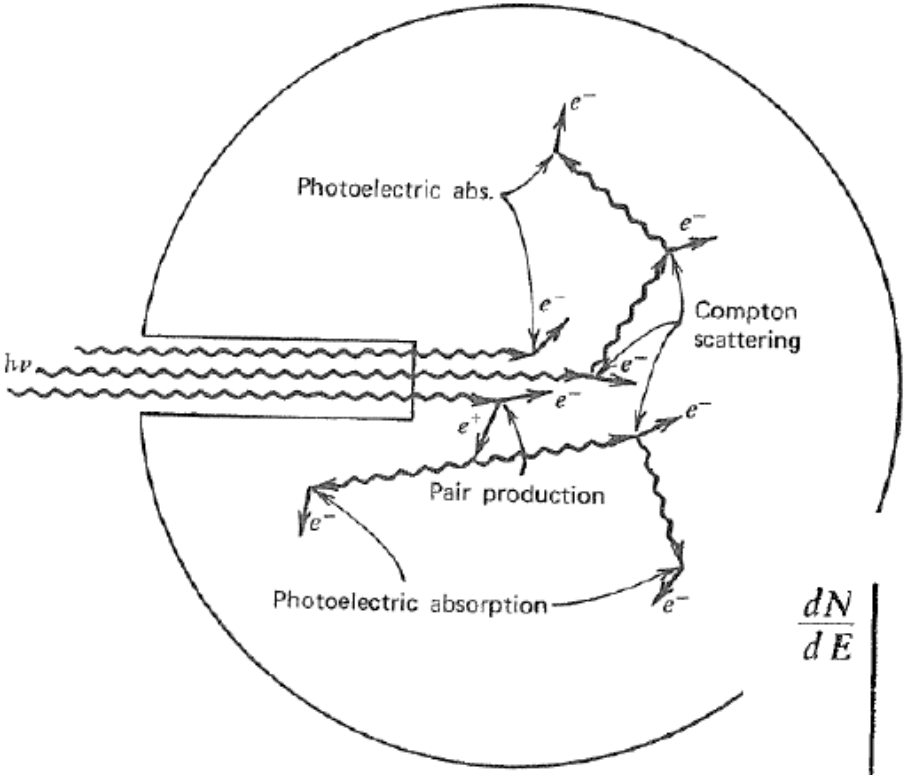


2. **Self-Quencing:**

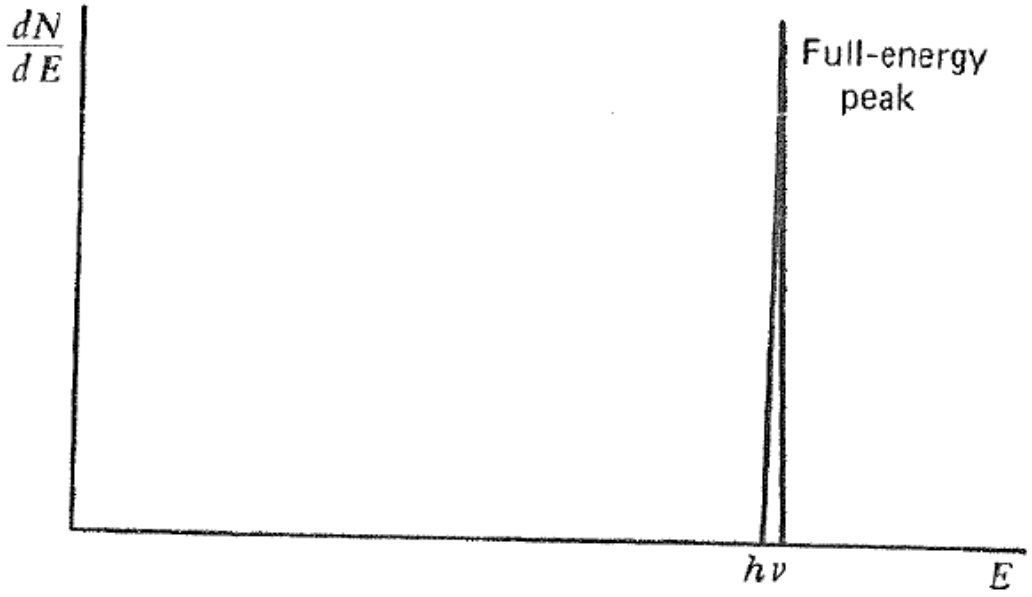
   addition of quench gas (5-10%) with complex molecule absorbing UV photons (ethyl alcohol ...)

Quenching gas is consumed (molecule disassociate) → Limit 10^9 counts

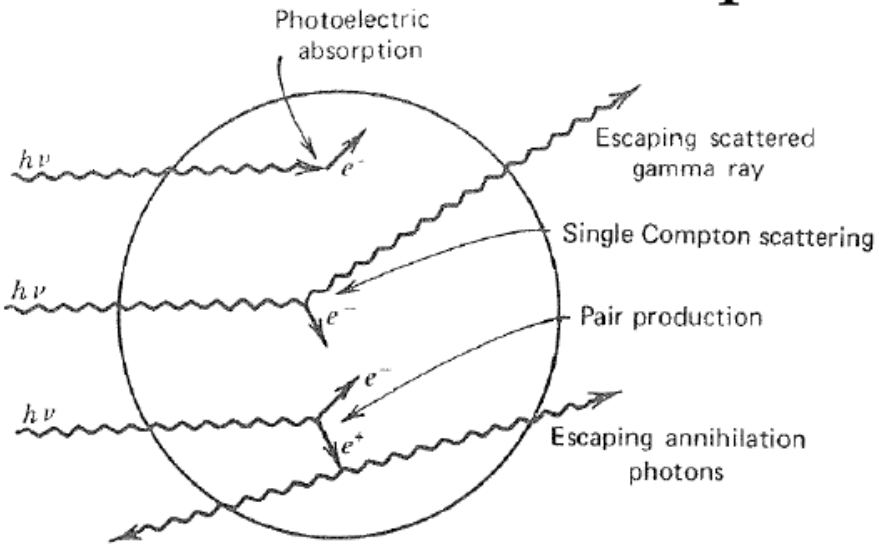
Basics of γ spectroscopy – I.



a very large detector

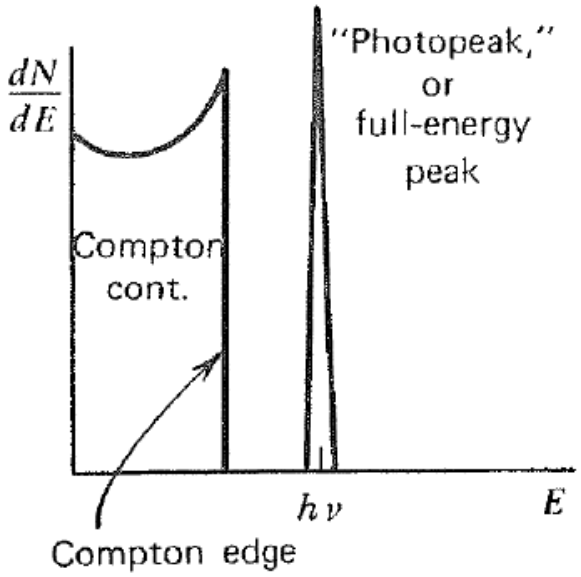


Basics of γ spectroscopy II.

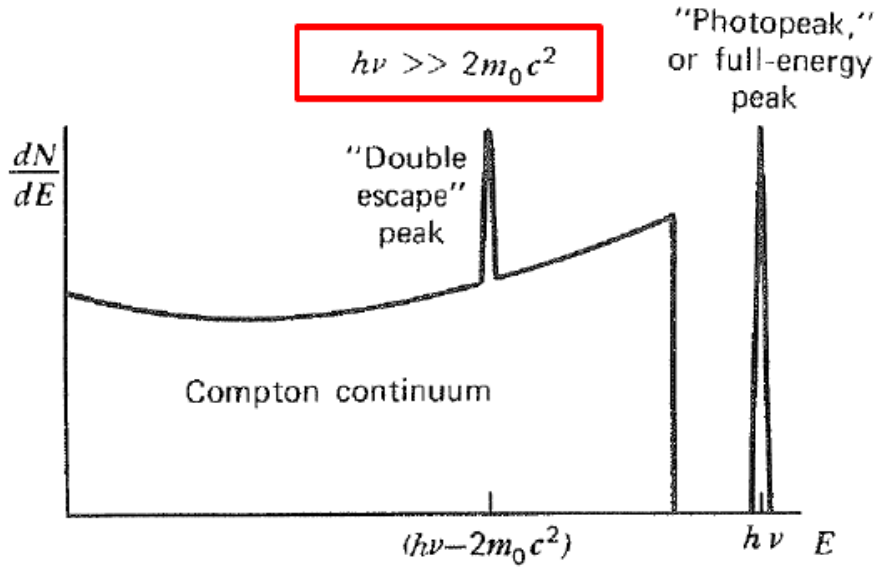


a very small detector

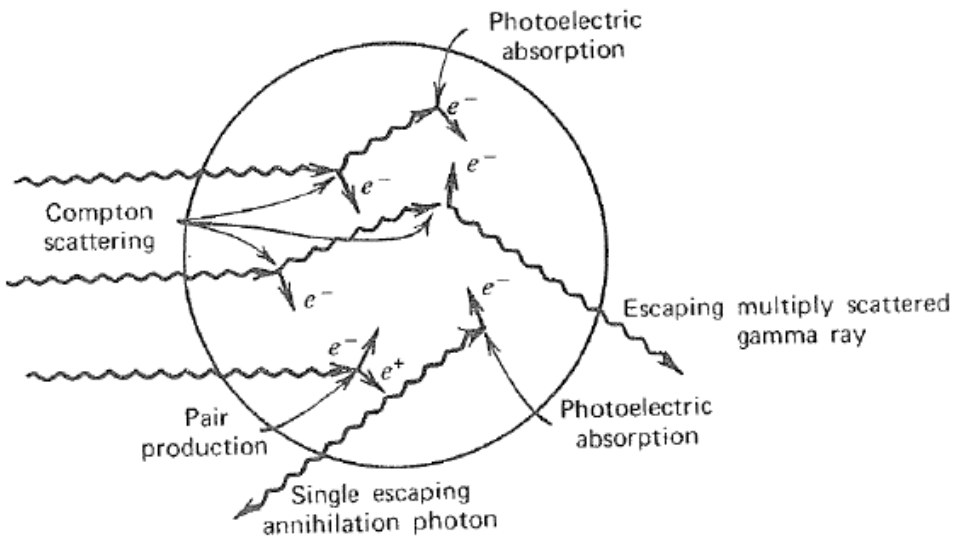
$h\nu < 2m_0c^2$



$h\nu >> 2m_0c^2$

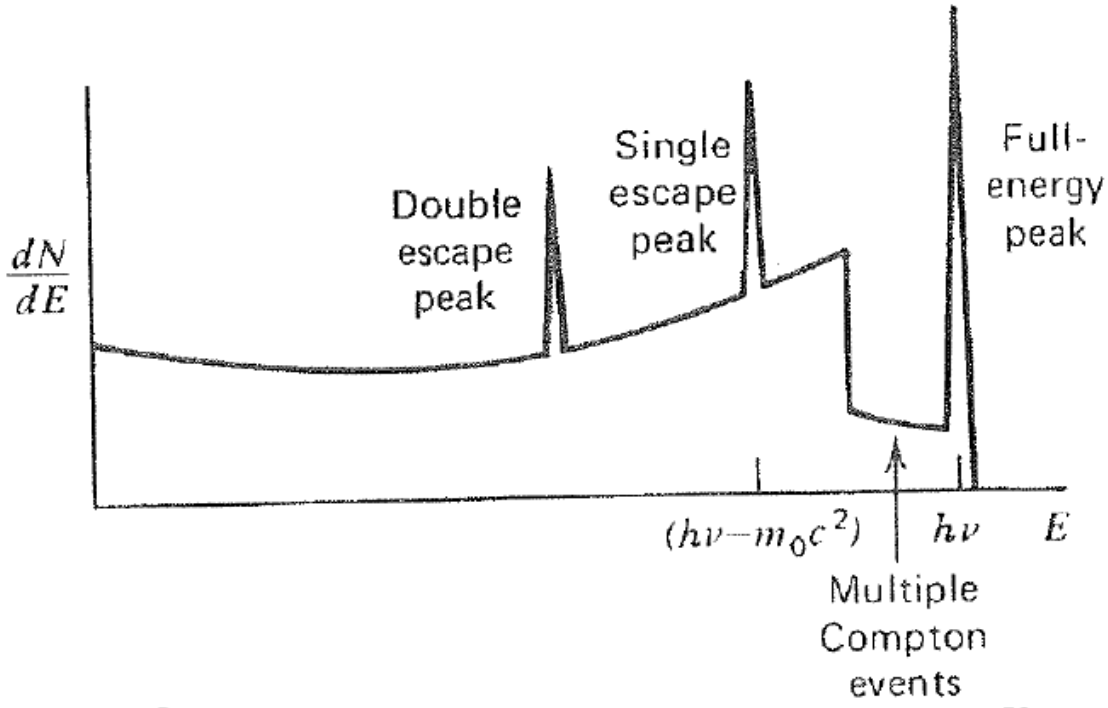


Basics of γ spectroscopy - III.

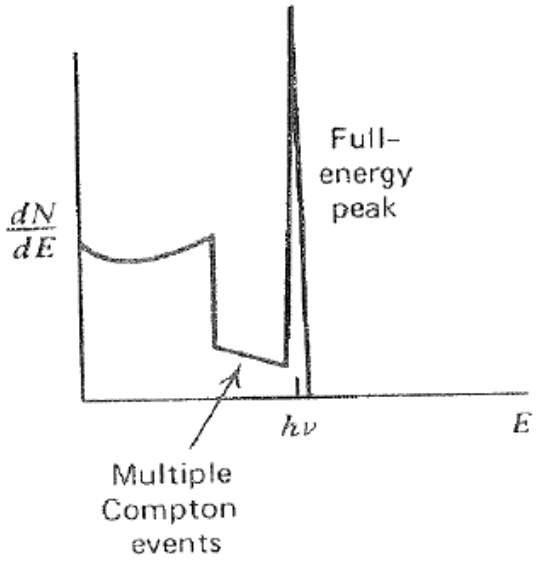


intermediate size detector

$h\nu >> 2m_0c^2$

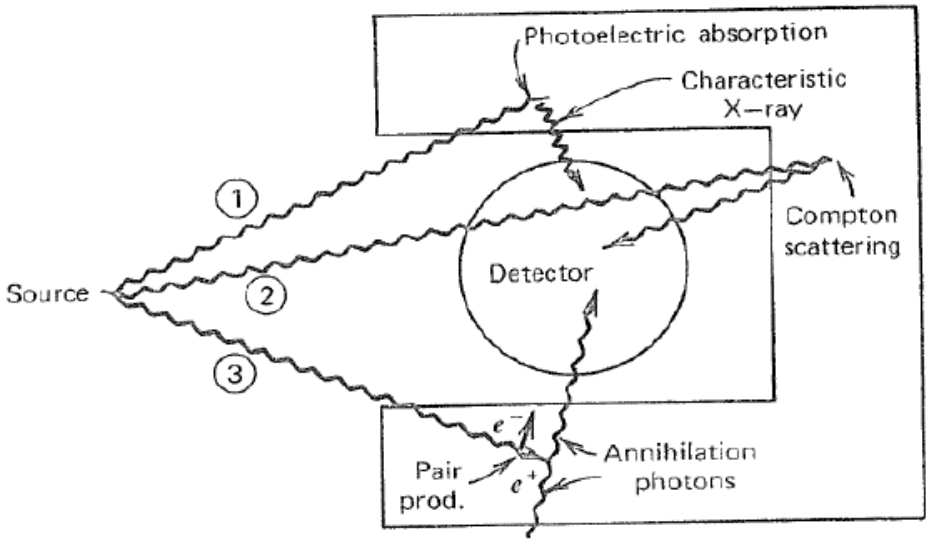


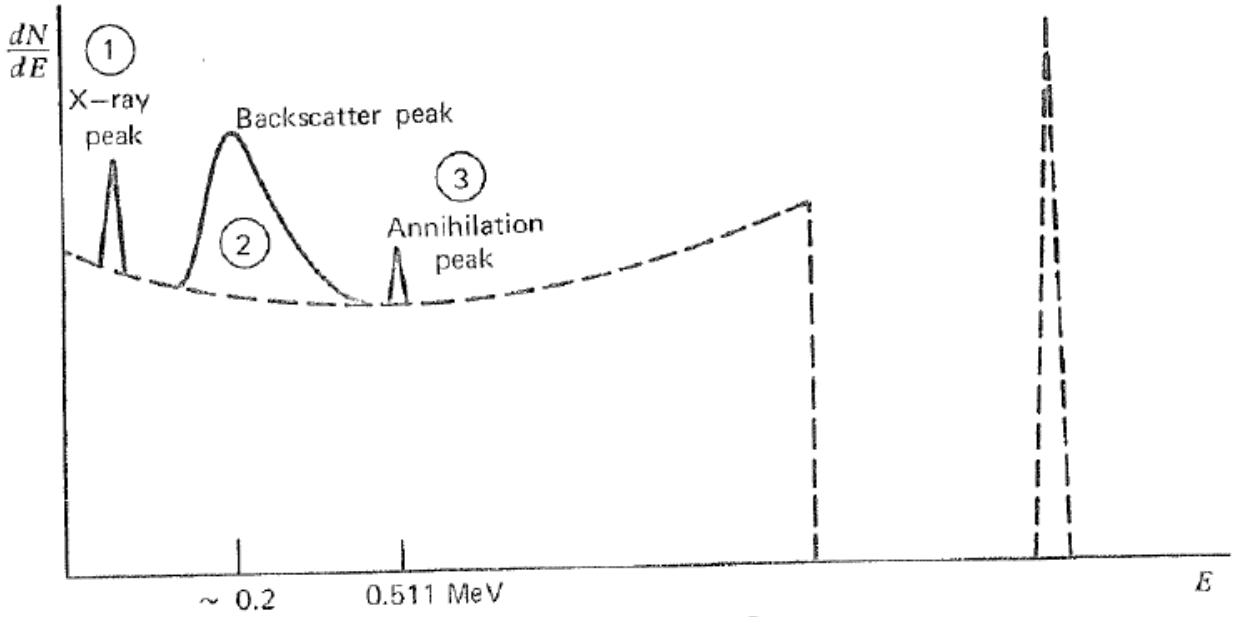
$h\nu < 2m_0c^2$



Basics of γ spectroscopy – IV.

a detector with shielding

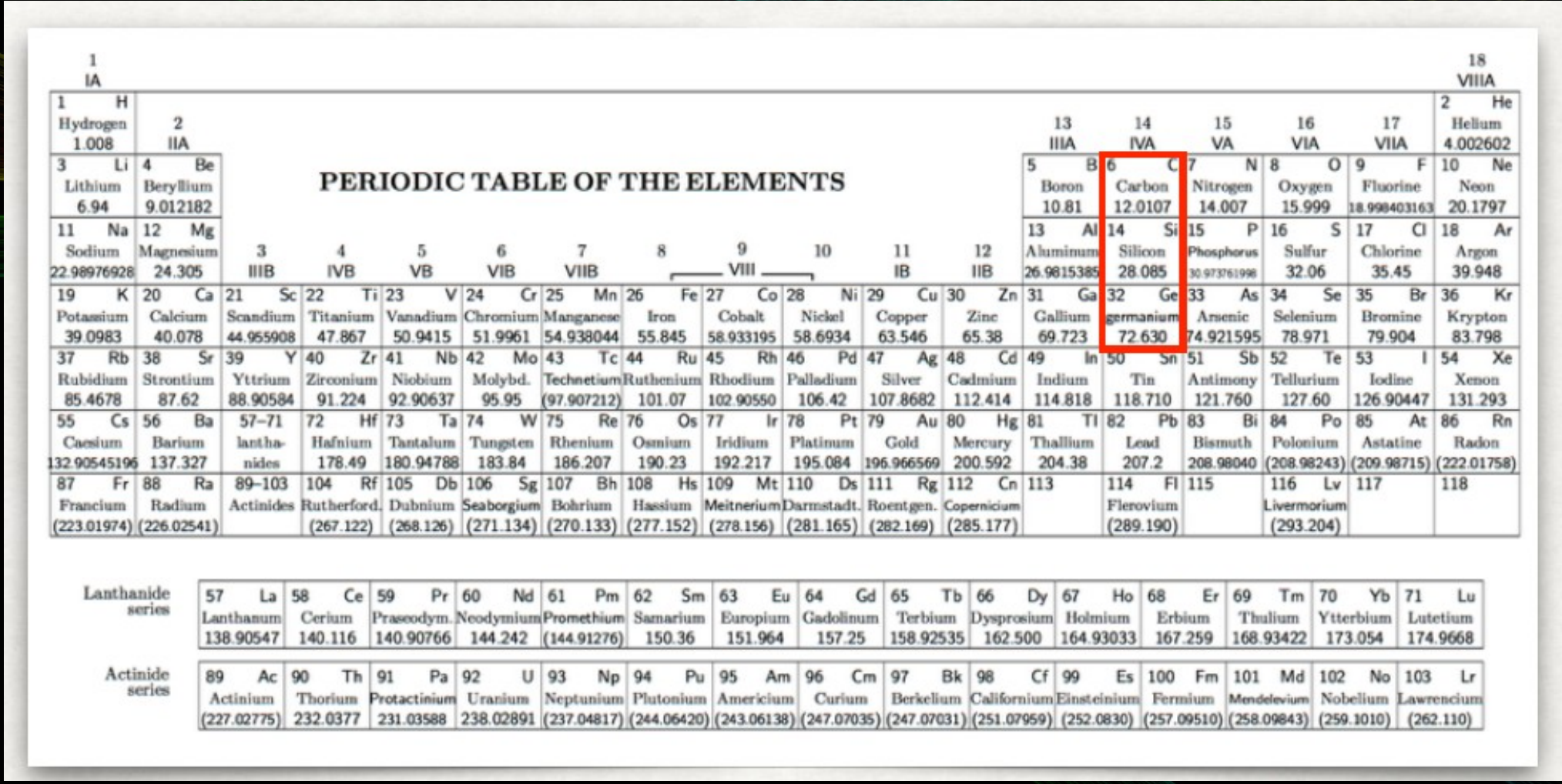




Semiconductor detectors: introduction

- IONIZATION as in gas detectors → solid state ionization chamber
  - but in semiconductors → solid materials with crystalline structure (Si, Ge)
  - electron-hole pairs (instead of electron-ion is gases)
- Semiconductors have resistances between that of conductors (low resistance) and insulators (high resistance).
  - This behaviour is governed by the energy band gap between valence and conduction bands in the device; E_g~ few eV.
- **Advantages**
  - use microchip technology: structures with few micrometer precision can be produced at low cost. Read-out electronics can be directly bonded to the detectors
  - only a few eV per electron-hole pair → 10 times more charge produced (wrt gas) → better energy resolution
  - high density compared to gases → need only thin layers (greater stopping power)
- **Disadvantages**
  - apart from Si, the detectors need to be cooled (cryogenics)
  - no multiplication
  - crystal lattices → radiation damage

Semiconductor detectors: introduction



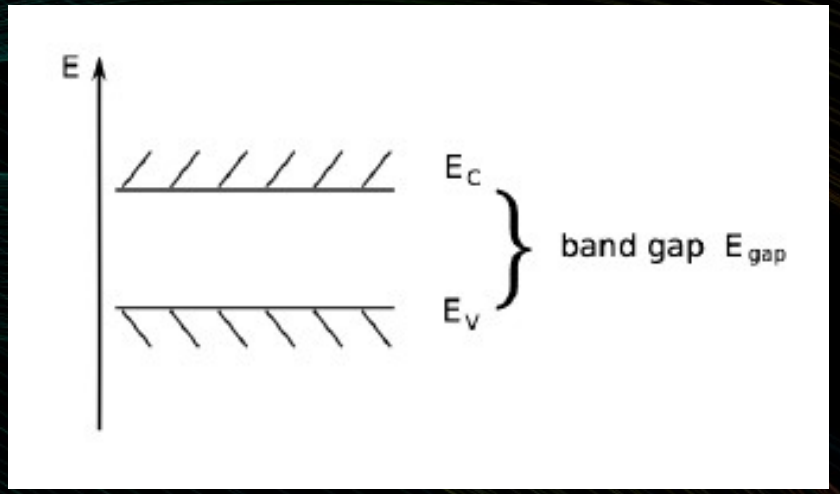
PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.008																	2 He Helium 4.002602
3 Li Lithium 6.94	4 Be Beryllium 9.012182											5 B Boron 10.81	6 C Carbon 12.0107	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998403163	10 Ne Neon 20.1797
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305											13 Al Aluminum 26.9815385	14 Si Silicon 28.085	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955908	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge germanium 72.630	33 As Arsenic 74.921595	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90637	42 Mo Molybd. 95.95	43 Tc Technetium (97.907212)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
55 Cs Caesium 132.90545196	56 Ba Barium 137.327	57–71 lantha-nides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.592	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.98243)	85 At Astatine (209.98715)	86 Rn Radon (222.01758)
87 Fr Francium (223.01974)	88 Ra Radium (226.02541)	89–103 Actinides	104 Rf Rutherford. (267.122)	105 Db Dubnium (268.126)	106 Sg Seaborgium (271.134)	107 Bh Bohrium (270.133)	108 Hs Hassium (277.152)	109 Mt Meitnerium (278.156)	110 Ds Darmstadt. (281.165)	111 Rg Roentgen. (282.169)	112 Cn Copernicium (285.177)	113	114 Fl Flerovium (289.190)	115	116 Lv Livermorium (293.204)	117	118

Lanthanide series	57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodym. 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (144.91276)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
Actinide series	89 Ac Actinium (227.02775)	90 Th Thorium 232.0377	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237.04817)	94 Pu Plutonium (244.06420)	95 Am Americium (243.06138)	96 Cm Curium (247.07035)	97 Bk Berkelium (247.07031)	98 Cf Californium (251.07959)	99 Es Einsteinium (252.0830)	100 Fm Fermium (257.09510)	101 Md Mendelevium (258.09843)	102 No Nobelium (259.1010)	103 Lr Lawrencium (262.110)

Principle of operation

- Detector operates as a solid state ionization chamber:
  - charged particles create electron-hole pairs
  - placing the crystal between two electrodes that set up an electric field → charge carriers drift and induce a signal



- Less than 1/3 of energy deposited goes into ionization. The rest goes into exciting lattice vibrations
- Effect: along track of primary ionizing particle plasma tube of electrons and holes with very high concentration (10^{15} – 10^{17} cm^{-3})
- Challenge: need to collect charge carriers before they recombine → very high purity semiconductor materials needed!!

Band structure

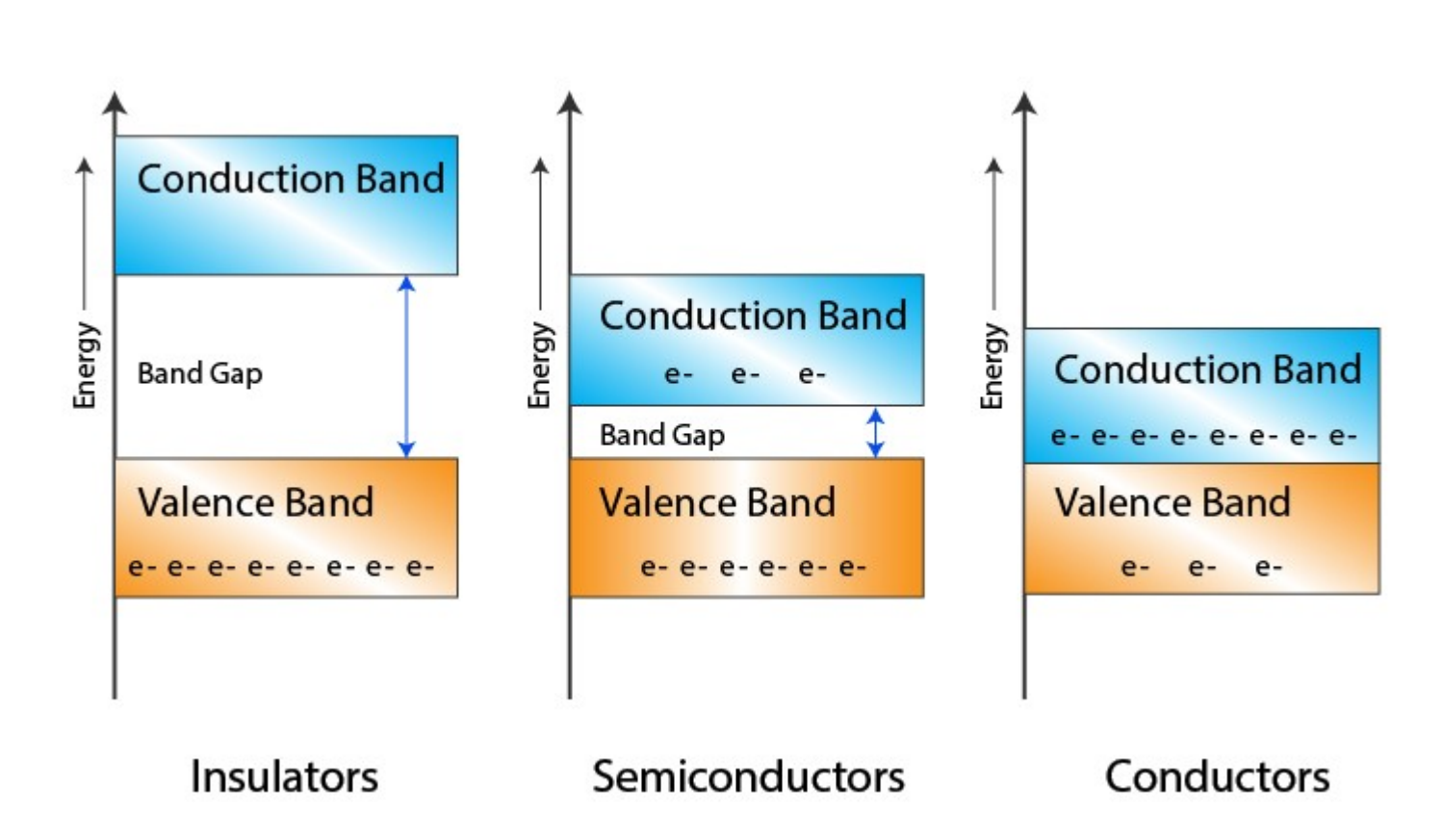
- Solid → crystalline structure of atoms in a lattice, with covalent bonds.
- The periodic arrangement of atoms in the crystal causes an overlap of electron wave-functions, which creates a “band” of energy states allowed for the outermost shell energy levels.
- Electrons are fermions: the Pauli principle forbids to have more than one electron in the same identical state and this produces a degeneracy in the outer atomic shell energy levels. This produces many discrete levels which are very close to each other, which appear as “bands”.
- The innermost energy levels are not modified, and the electrons remain associated to the respective lattice atoms.

- **CONDUCTION BAND**: electrons are detached from parent atoms and are free to roam about the whole crystal

- **VALENCE BAND**: electrons are more tightly bound and remain associated to the respective lattice atom

- **FORBIDDEN BAND**: in pure crystals, between the two bands above there are NO available energy levels

Band structure of solids



- **Insulators**: large energy gap → at normal temperatures no e- can reach conduction band
- **Semiconductors**: tha band gap is small → thermal energy can bridge the gap for a small fraction of electrons
- **Conductors**: valence band overlaps the conduction band → no band gap

Band structure - temperature

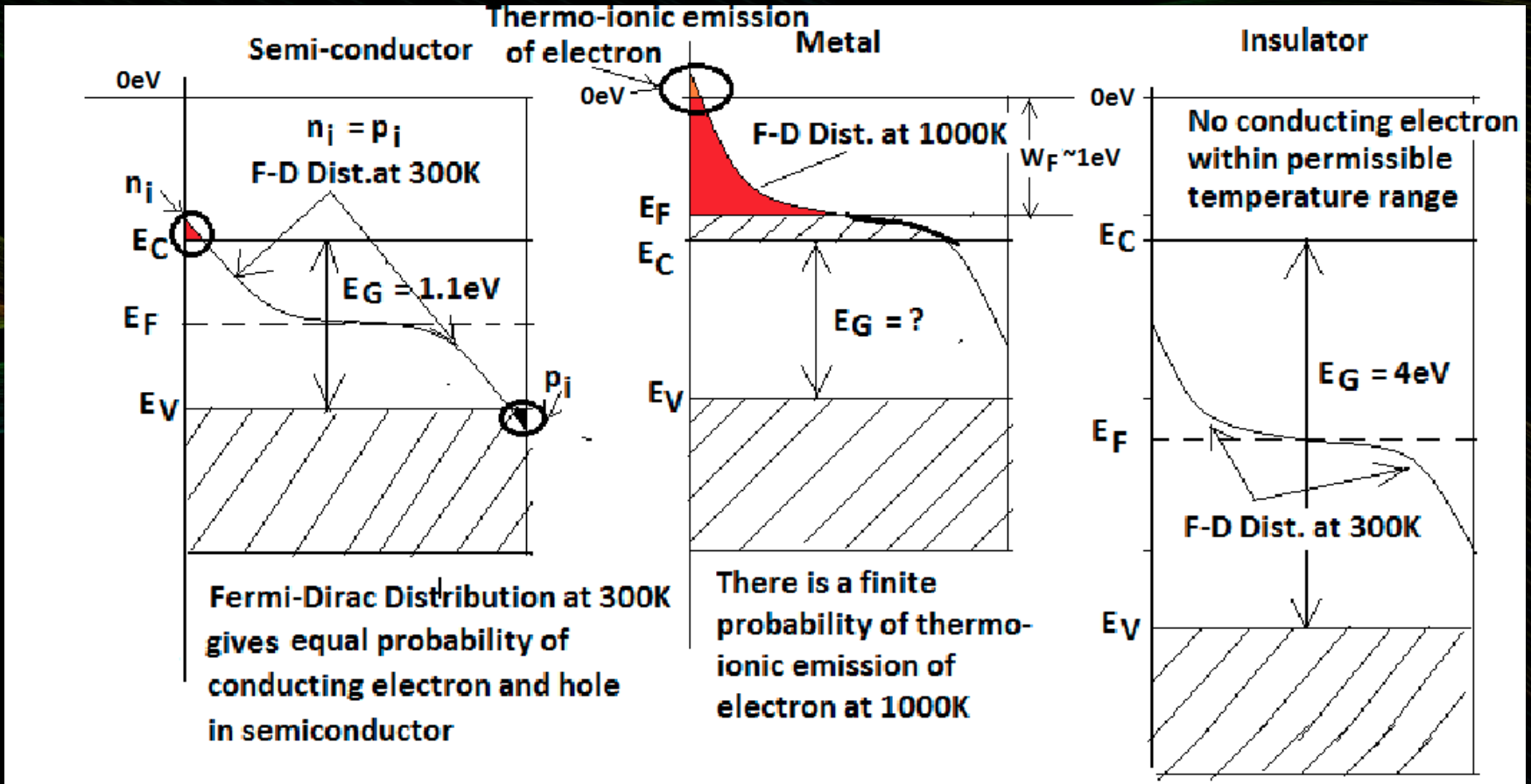


Figure 2.2.1.Comparative study of Semi-conductor,Metal and Insulator based on Energy-Band Diagram

- At sufficently high temeprature (room temp), some electrons can reach the conduction band and contribute to the electric current.
- Probability for e- having E:

$$P_e(E) = \frac{1}{e^{(E-E_f)/kT}+1}$$

$$E_f = \frac{\hbar^2 \pi^2}{2mL^2}\left(\frac{3N}{\pi}\right)^{2/3}$$

Fermi level

Semiconductors

- **Intrinsic semiconductors**: VERY PURE material

  Charge carriers are created by thermal or optical excitation of electrons to the conduction band: $N_- = N_+$

  - Difficult to produce large volumes of so pure materials. Impurities will govern the elevtrical properties of the semiconductor
  - Extremely low concentrations of charge carriers

- **Extrinsic or doped semiconductors**:

  Majority of charge carriers provided by impurity atoms at lattice sites of the crystal

  - Impurity atoms (pentavalent elements, donors) provide extra electrons → n-type (majority charge carriers: electrons)

  OR

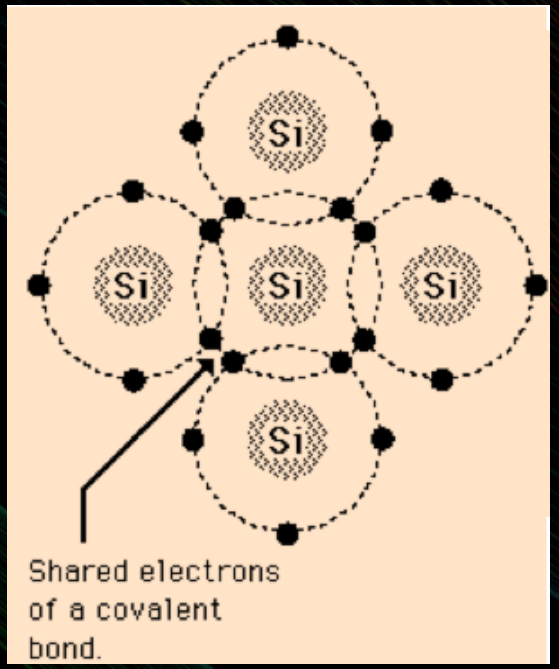
  - Impurity atoms (trivalent elements, acceptors) have insufficient number of electrons for the covalent bonds, free hole at impurity site, provide extra holes → p-type (majority charge carriers: holes)

Intrinsic semiconductors

- Crystalline lattice of Si, Ge: 4 valance electrons
- At zero temperature, all electrons participate in covalent bonds.
- At non-zero temperature: thermal energy can excite a valence electron into the conduction band. A hole = positive charge remains in the valence band
- Under the action of an E-field: the electron can move in the conduction band. In the valence band, other electrons can fill the hole → effective movement of holes (electric current)
- Intrinsic charge carrier concentration (~ the probability of generating thermally an electron-hole pair):

$$n_i = \sqrt{N_C N_V} \exp\left(-\frac{E_g}{2kT}\right) = AT^{3/2} \exp\left(-\frac{E_g}{2kT}\right)$$

	E_{gap}
Si	1.12 eV
Ge	0.66 eV
GaAs	1.43 eV



Intrinsic semiconductors

- The electrical behavior is determined by the mobility of charge carriers:
- Drift velocity: $v_D = \mu E$ (μ: mobility)
- Specific resistance: ρ (Ωm)
- Resistance $R=\rho\, l/A$, with length l and area A transverse to E

  As in gases: random thermal motion + drift in electric field
- In intrinsic semiconductors:
  - $\mu \simeq$ const. for E < 103 V/cm
  - $\mu \propto 1/\sqrt{E}$ for 103 V/cm < E < 10 4 V/cm
  - $\mu \propto 1/E$ for E > 104 V/cm → vD = μE is CONSTANT !!
- Saturates at about 10^7 cm/μs (similar to gases / trade off between energy acquired and collisions with the lattice here)

  → fast collection of charges: 10 ns for 100 μm drift

  → vh ≃ 0.3 – 0.5 ve (very different from gases!)

  I = e • ni (μe + μh) E = σ E → conductivity: σ = 1/ρ ρ: resistivity

Recombination and trapping

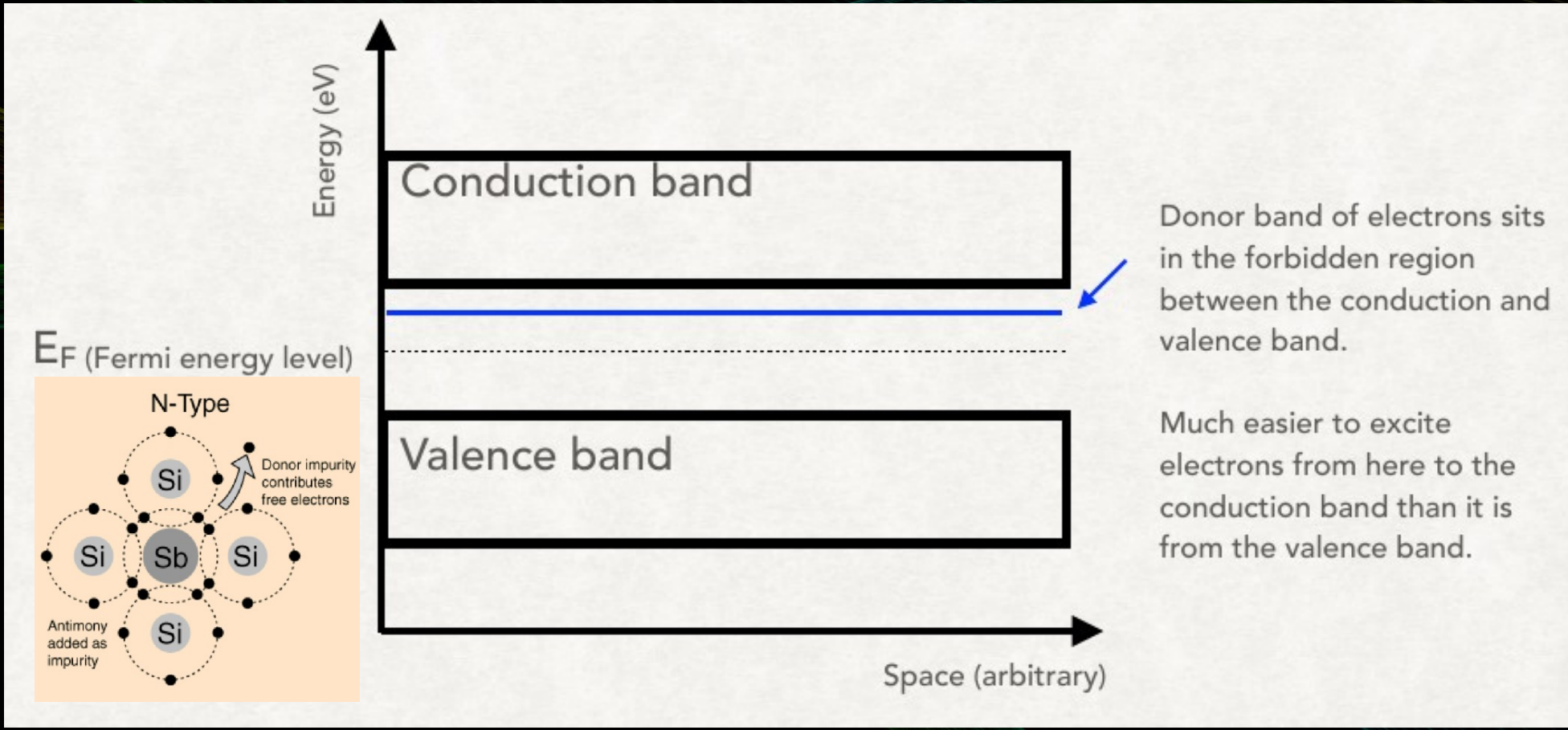
- **DIRECT RECOMBINATION**: an electron falls from the conduction to the valence band to fill a hole → produces a photon. It is a rare process, with long lifetime (the exact energy is needed)

- **IMPURITIES** in the crystal lattice can produce: (ALWAYS present!!)

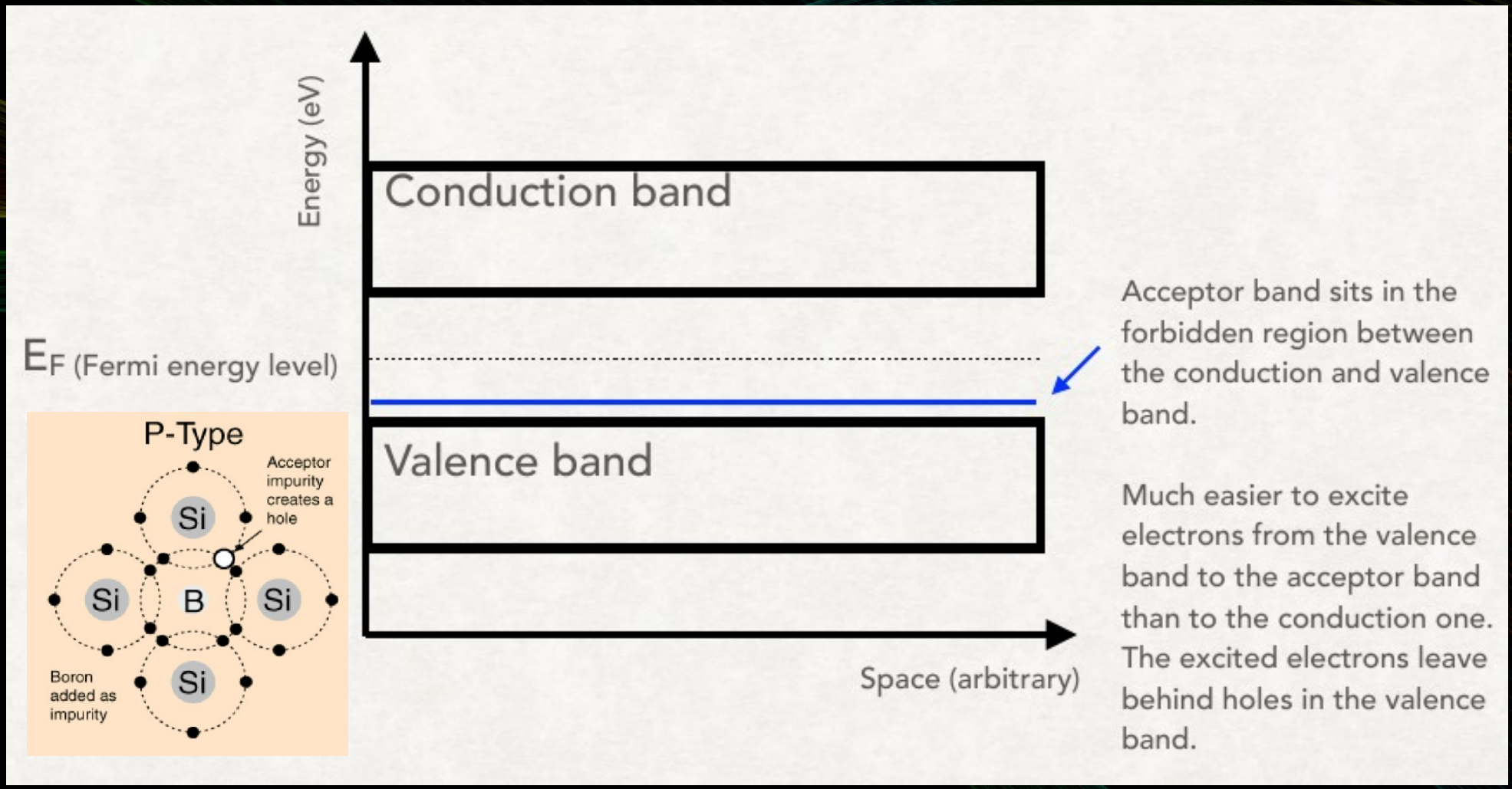
- **RECOMBINATION CENTERS**: additional levels in the forbidden gap can capture electrons from the conduction band, or holes from the valence band → reduction of the mean time a charge carrier remains free
  TRAPPING: of only electrons or holes, for some time → If the release time of the charge carriers is longer than the collection time in the detector, these processes produce a LOSS OF CHARGE

- **STRUCTURAL DEFECTS** include point defects (vacancies, positions in between lattice) and dislocations (displacement of a full line of atoms). Produced during growth of crystal or by thermal shock, plastic deformation, stress and radiation damage.

Doping – n type



Doping p-type



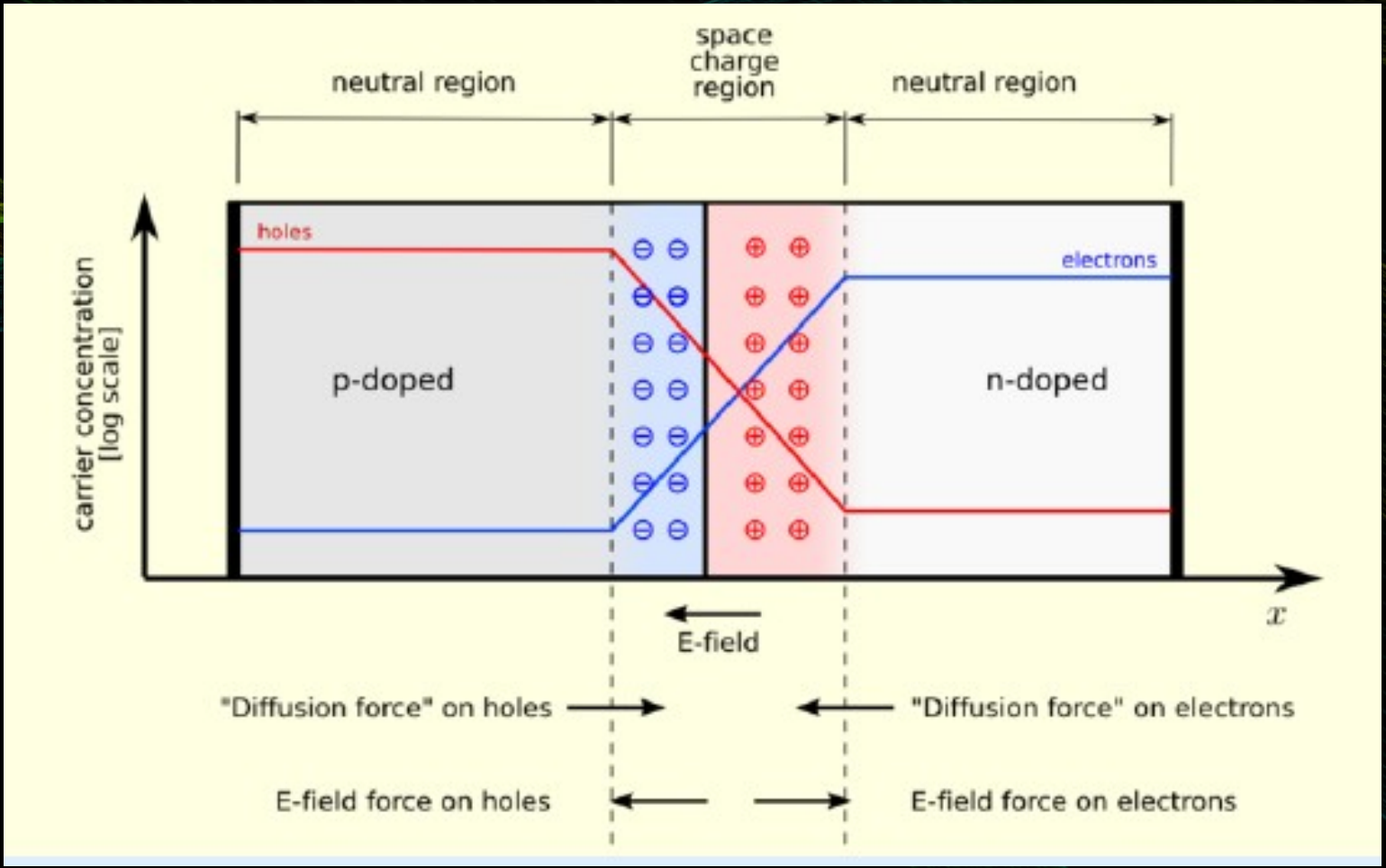
p-n junction

- To collect charge carriers produced through radiation interaction → by electric field (typically hunderds of volts).
- High voltage induces leakage current due to thefinite conductivity → 1 mm thick Si with a 1 cm2 area and a U=500 V → ~ 0.1 A
- However, an impulse current level produced by radiation interaction is only ~ μA!! → a p-n junction is required to reduce the leakage current to pickup the signal corresponding to the radiation interaction.
- Bring p and n materials “into contact” (in reality, done otherwise) → thermodynamic equilibrium
- Electrons diffuse from n to p semiconductor, and holes from p to n
- At the boundary there will be a zone with few free charge carriers (electrons and holes) → depletion layer
- Fixed charges are left behind (ionized donors and acceptors) → space charge
- E-field builds up and counteracts the diffusion, which stops eventually

  with $n \approx N_D$ and $p \approx N_A$
- Difference between Fermi energies on both sides gives:

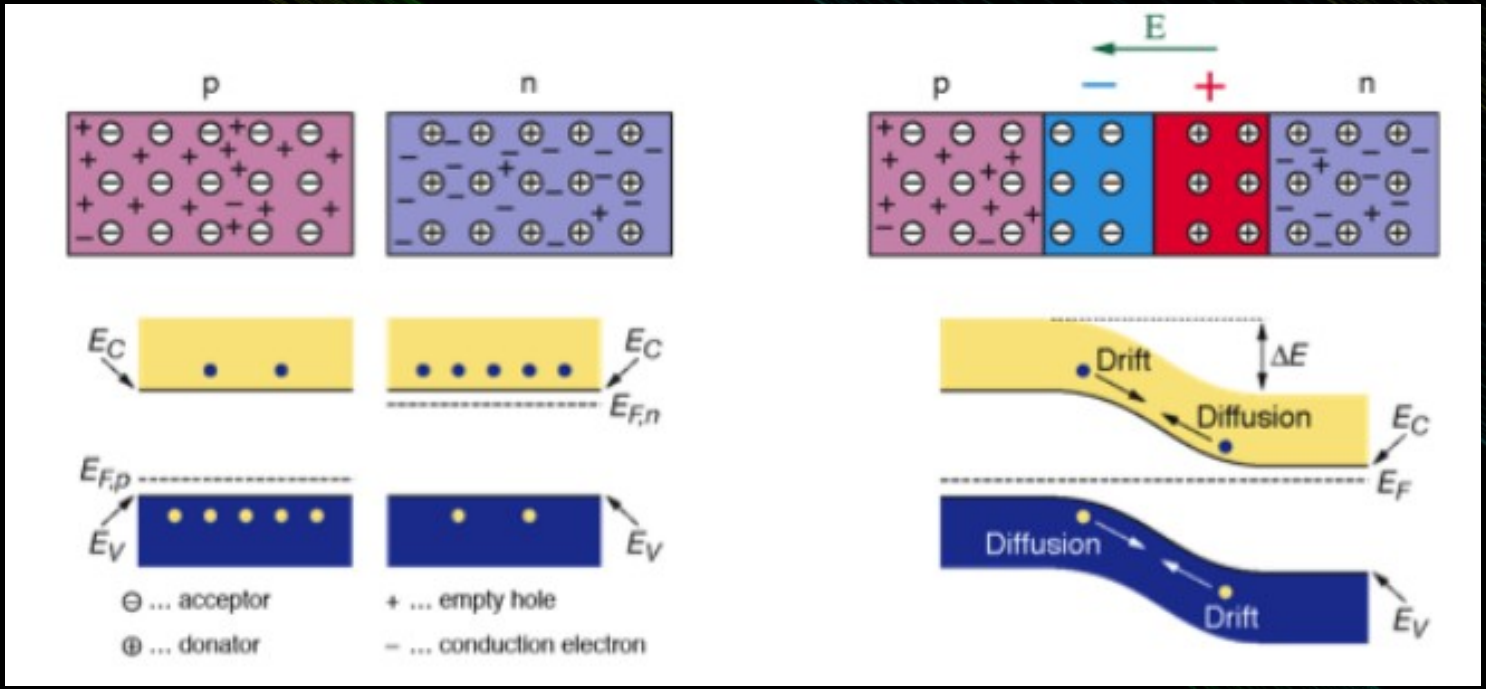
$$eV_D = E_C - kT \ln \frac{N_C}{N_D} - E_V - kT \ln \frac{N_V}{N_A} = E_{gap} - kT \ln \frac{N_C N_V}{N_D N_A}$$

p-n junction


space
charge
region
neutral region
neutral region
holes
electrons
p-doped
n-doped
carrier concentration
[log scale]
x
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

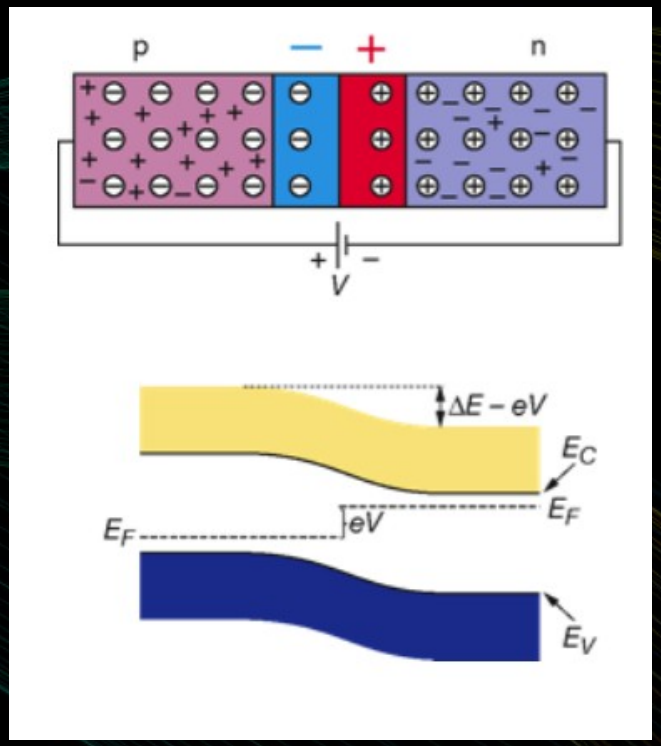
p-n junction

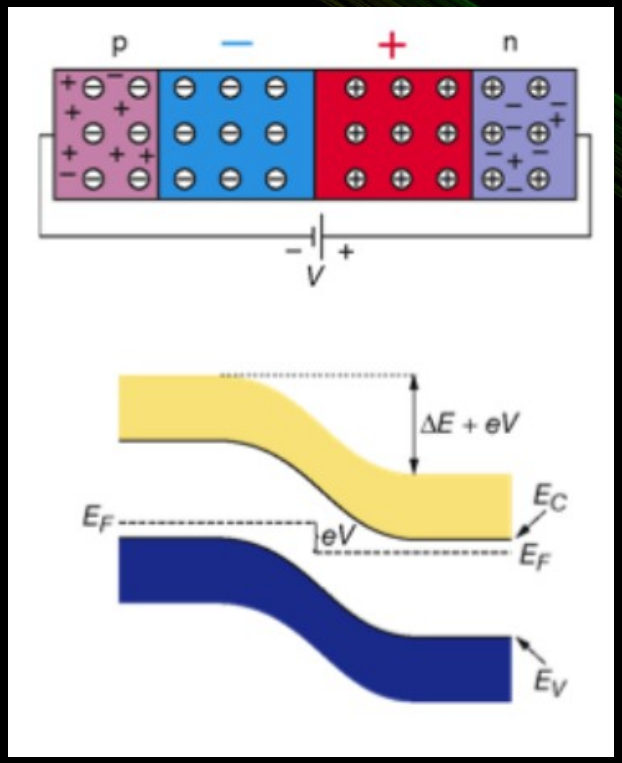
- At the interface of an n-type and p-type semiconductor the difference in the fermi levels cause diffusion of surplus carries to the other material until thermal equilibrium is reached. At this point the fermi level is equal. The remaining ions create a space charge and an electric field stopping further diffusion (contact potential).
- The stable space charge region is free of charge carries and is called the depletion zone → it is already a radiation detector!
- Poor quality: the depletion (sensitive) volume is thin and the electric field is not sufficient to collect the charge carriers quickly → recombination



p-n junction: forward and reverse bias

- Applying an external voltage V with the anode to p and the cathode to n e- and holes are refilled to the depletion zone. The depletion zone becomes narrower.
- The potential barrier becomes smaller by eV and diffusion across the junction becomes easier. The current across the junction increases significantly.



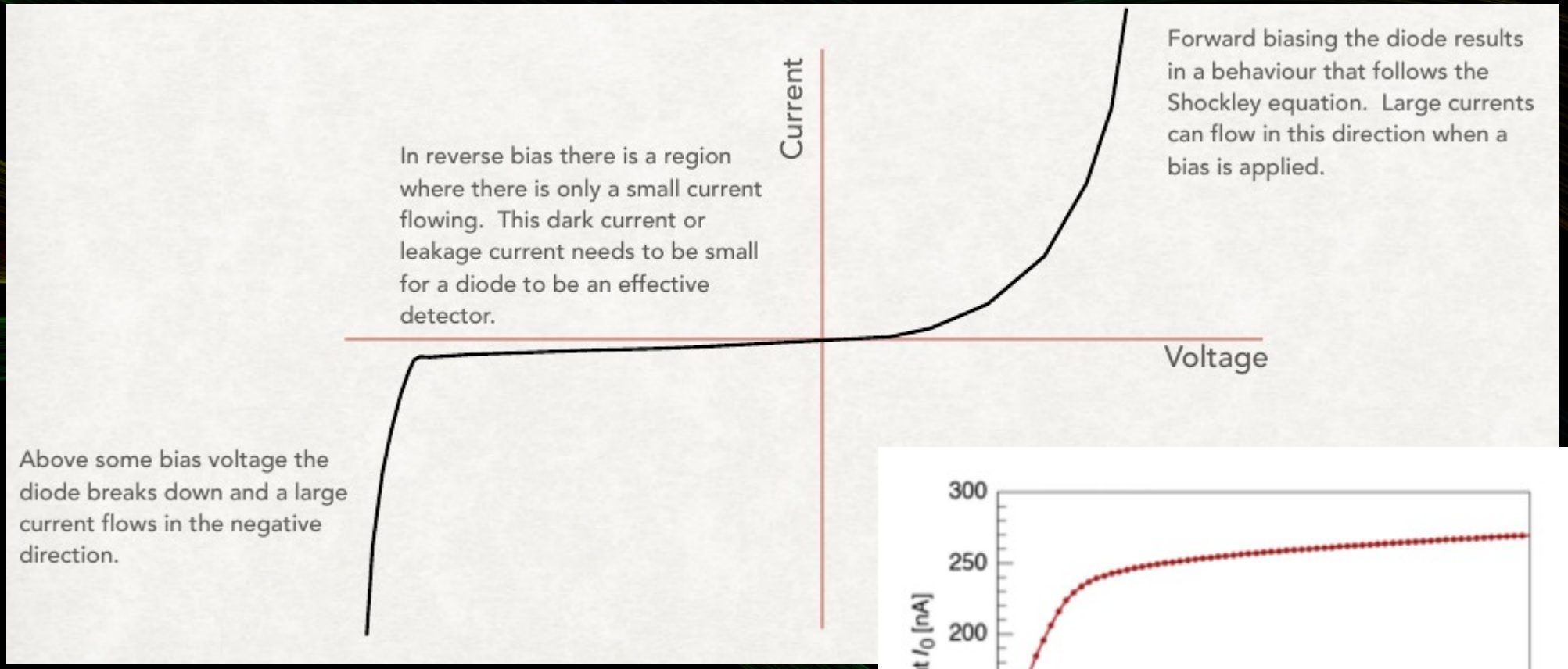


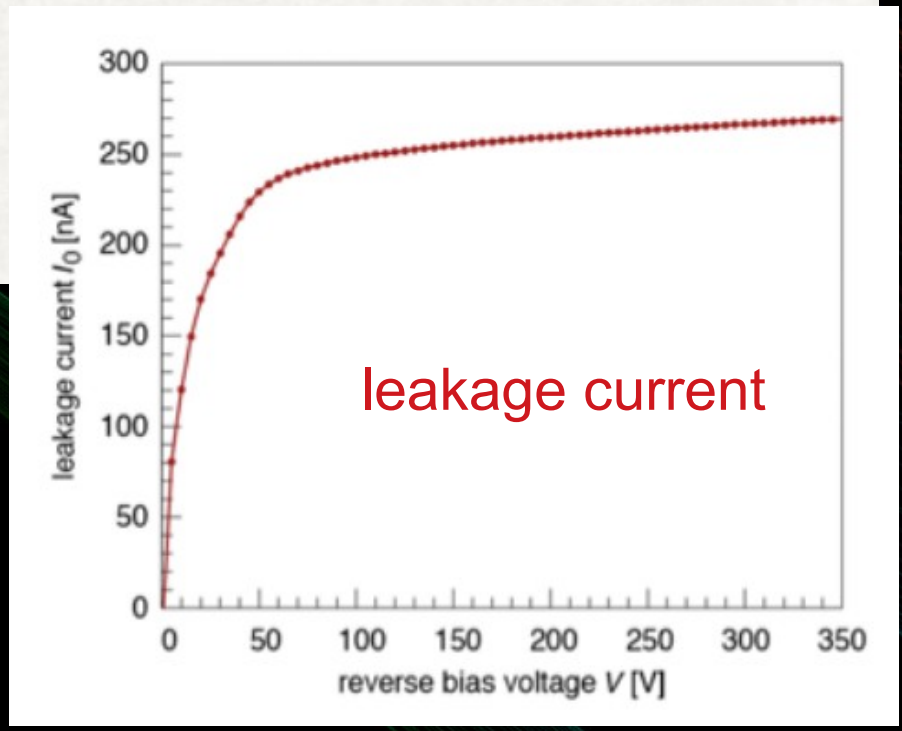
- Applying an external voltage V with the cathode to p and the anode to n e- and holes are pulled out of the depletion zone. The depletion zone becomes larger (W):

$$W \sim \sqrt{|U|}$$

- The potential barrier becomes higher by eV and diffusion across the junction is suppressed. The current across the junction is very small “leakage current”.

Voltage – current characteristics





Mobility of charge carriers

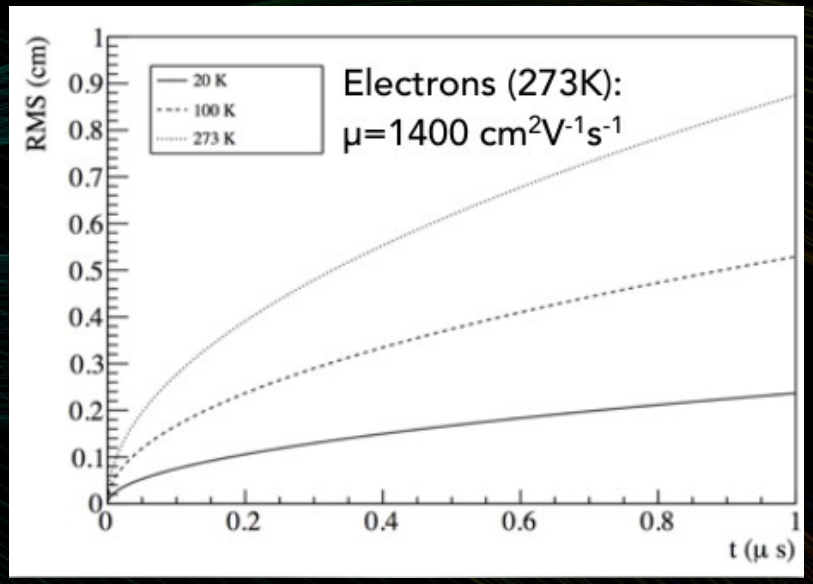
- Carrier mobility μ depends on the diffusion constant D and the temperature T of the semiconductor.

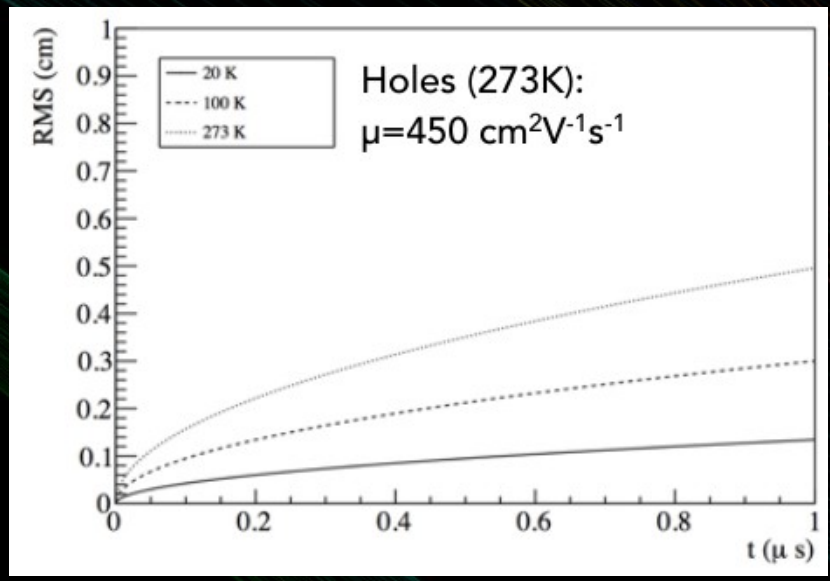
$$\mu = \frac{eD}{kT}$$

- D is related to the charge collection time and has variance 2Dt. The RMS of thermal diffusion is

$$\sigma = \sqrt{\frac{2\mu kTt}{e}}$$

- fast collection of charges: 10 ns for 100 μm drift
- $v_h \simeq 0.3 - 0.5\ v_e$ (very different from gases!)

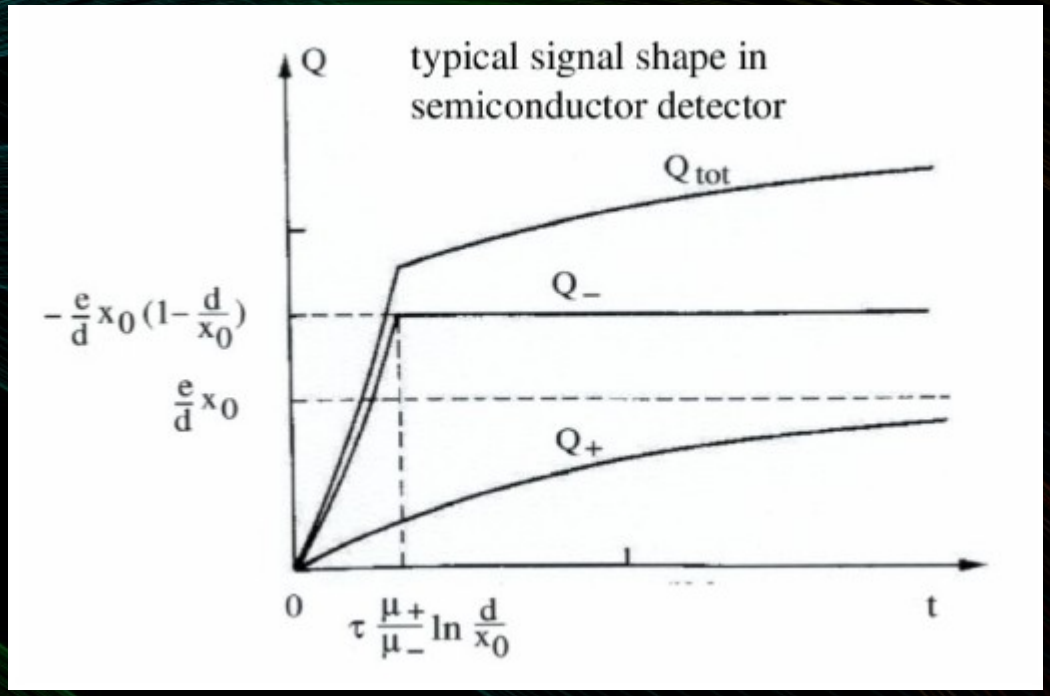




Signal of semiconductors

- Total charge signal:

  $Q - (t\ d\ ) + Q + (+\infty) = -e$
- Signal rise time essentially determined by: $\tau = \rho \cdot \epsilon \cdot \epsilon 0$
- In reality a bit more complicated:
  - Track not exactly a line charge (distributed over typically 50 µm width)
  - $\mu \neq$ constant
  - Some loss of charges due to recombination at impurities

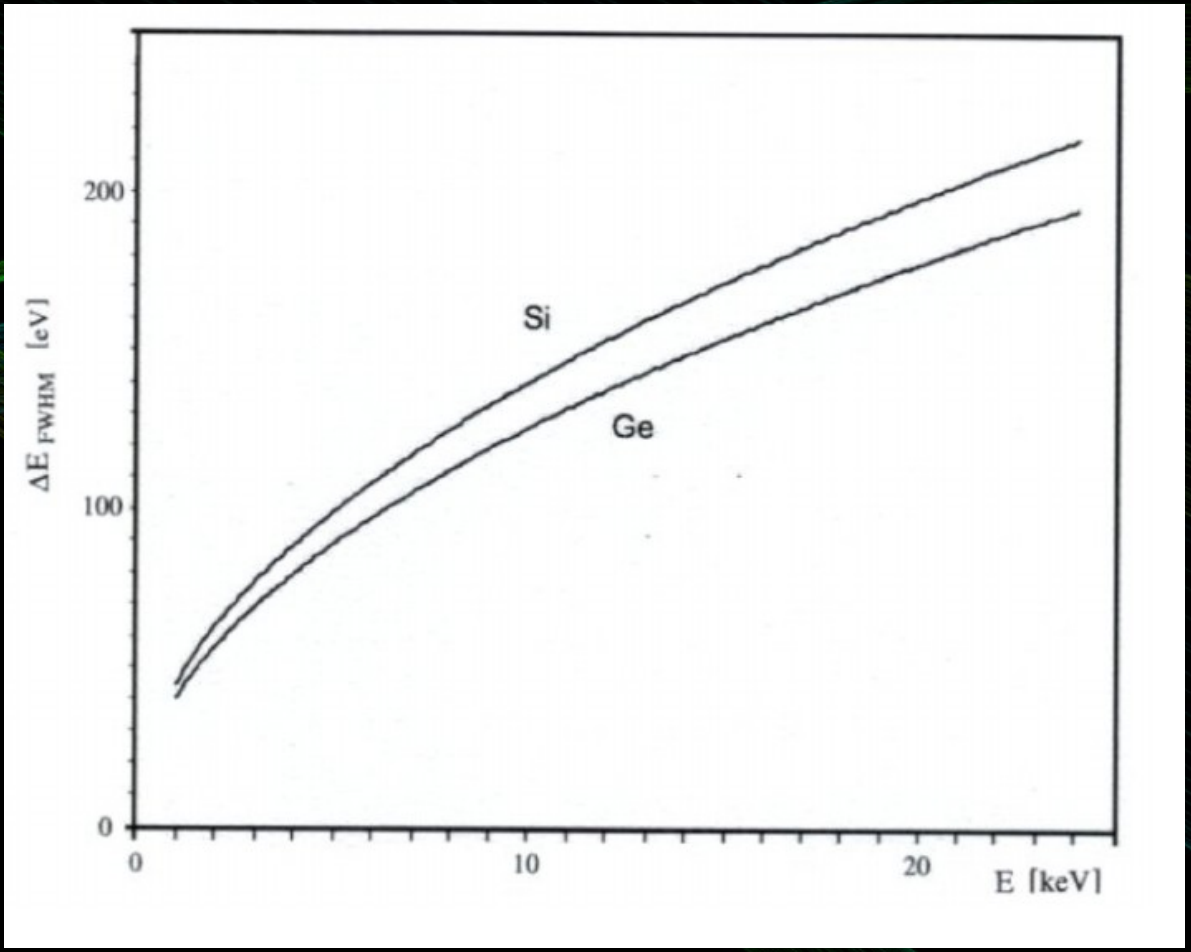


	$E_0^{300\ K}$	$E_0^{77\ K}$	E_{gap}
Si	3.6 eV	3.8 eV	1.1 eV
Ge	-	2.9 eV	0.7 eV

- Fano factor of Si is F≈0.1 !

$$\sigma = \sqrt{F\,N}$$

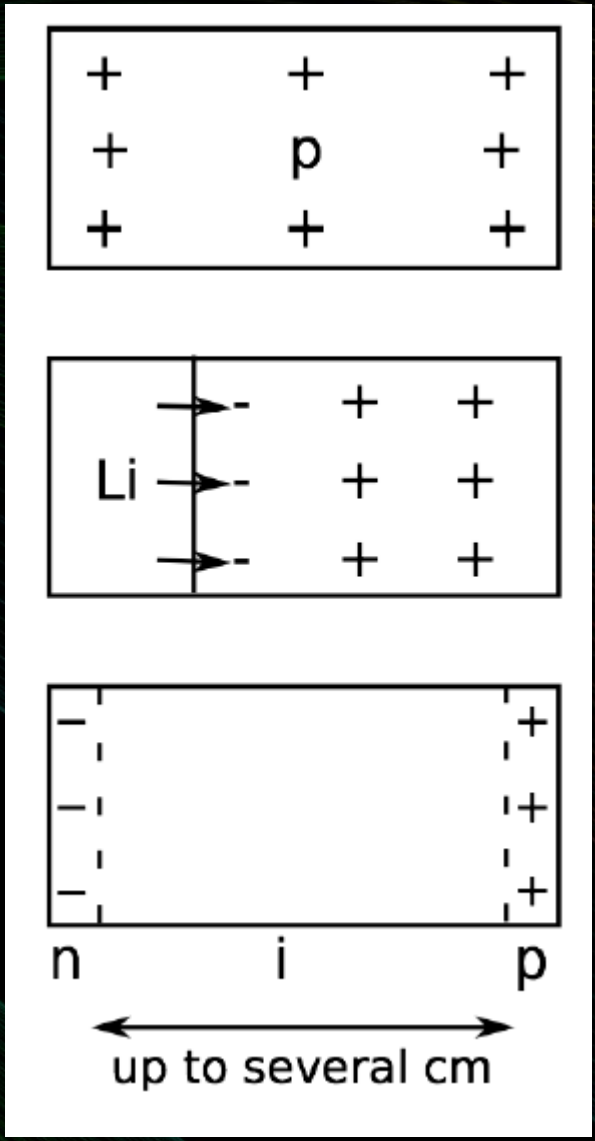
Energy resolution



- Statistics of charge carriers generated + noise + non-uniformities in charge-collection efficiency

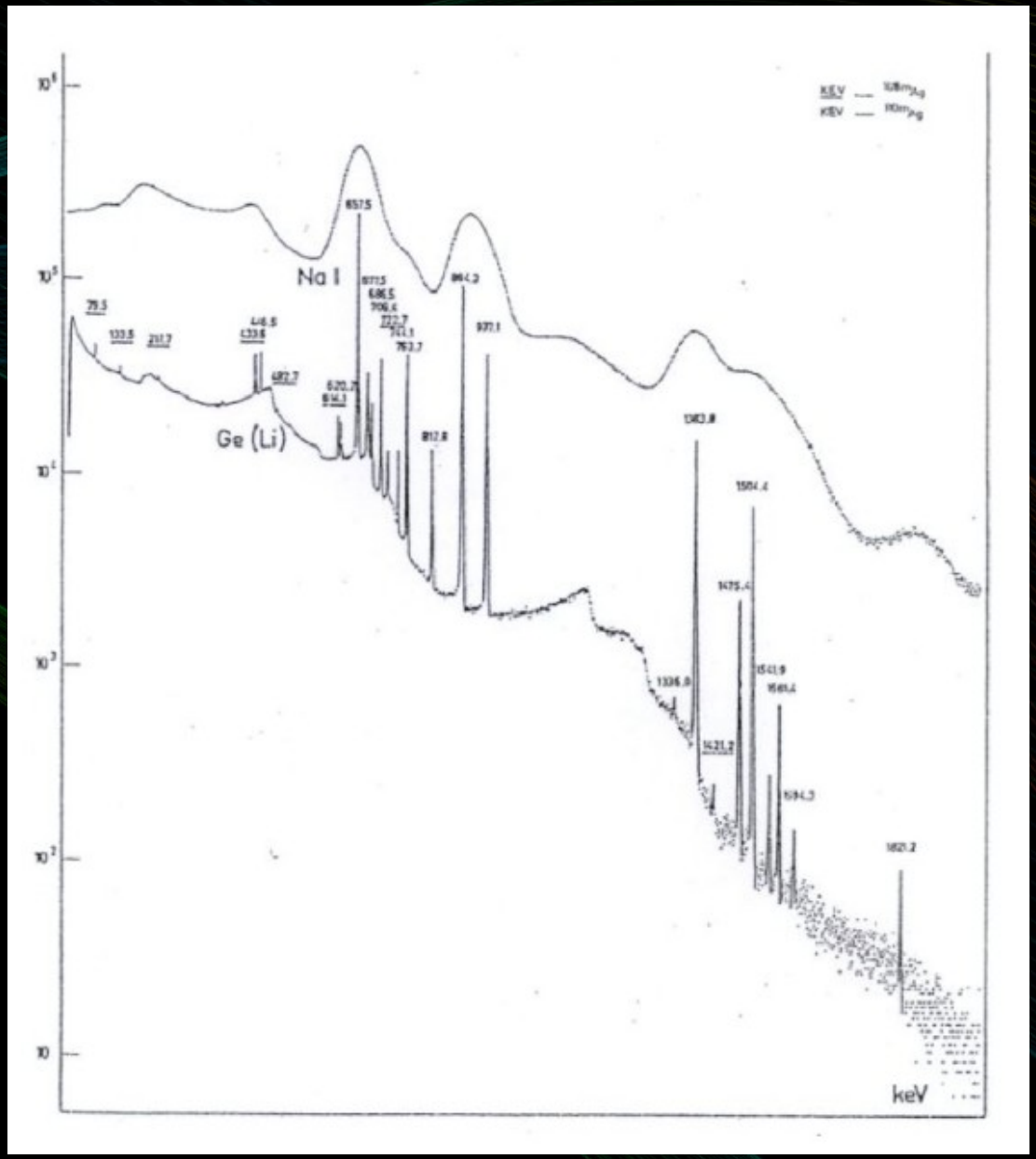
p-i-n detectors

- Way to get beyond a few mm thickness:
  - From the 1960ies: create a thick (1-2 cm) depletion layer with COMPENSATED material (very high resistivity)
- Start with high-purity p-type Ge or Si (acceptor is typically Boron)
- Bring in contact with liquid Li bath (350-400 ∘C) the lithium diffuses into Ge/Si
- Apply external field → positive Li-ions drift far into the crystal and compensate Boron ions locally
  - Typically 10^9 /cm3 Li atoms
- Needs to be cooled PERMANENTLY! (liquid N2) to avoid separation of Li impurities by diffusion!
- Application: γ spectroscopy
  - Larger cross section for photoelectric effect in Ge wrt Si → Ge(Li) preferred!
- Resolution much better than NaI scintillator, but efficiency significantly lower



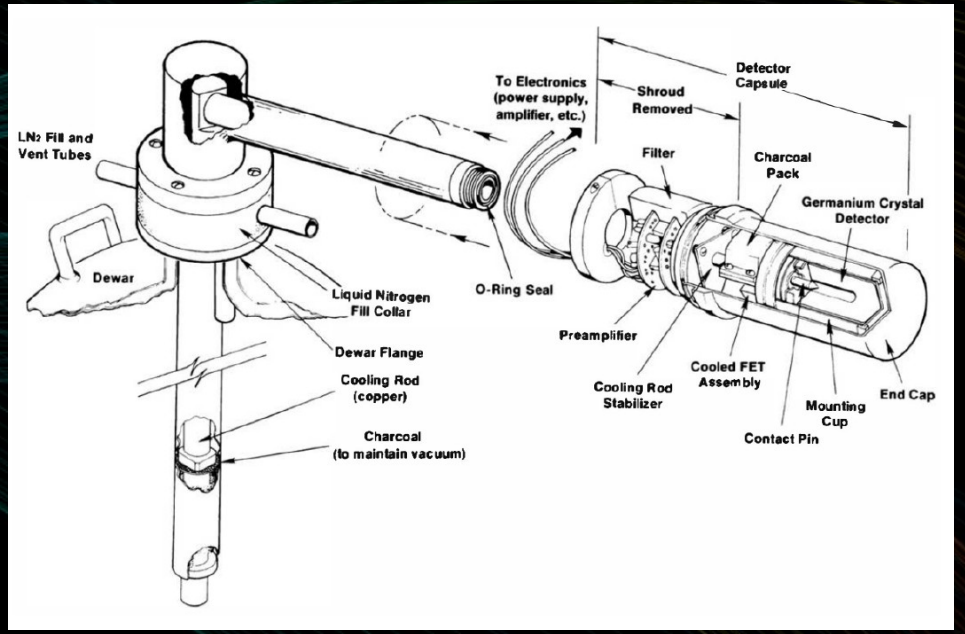
Energy resolution of Ge(Li)

- Comparison of gamma spectra obtained with NaI(Tl) scintillator and Ge(Li) semiconductor detectors
  - Decays of ^{108}Ag and ^{110}Ag
- Labelings are in keV
- Not in practice any longer

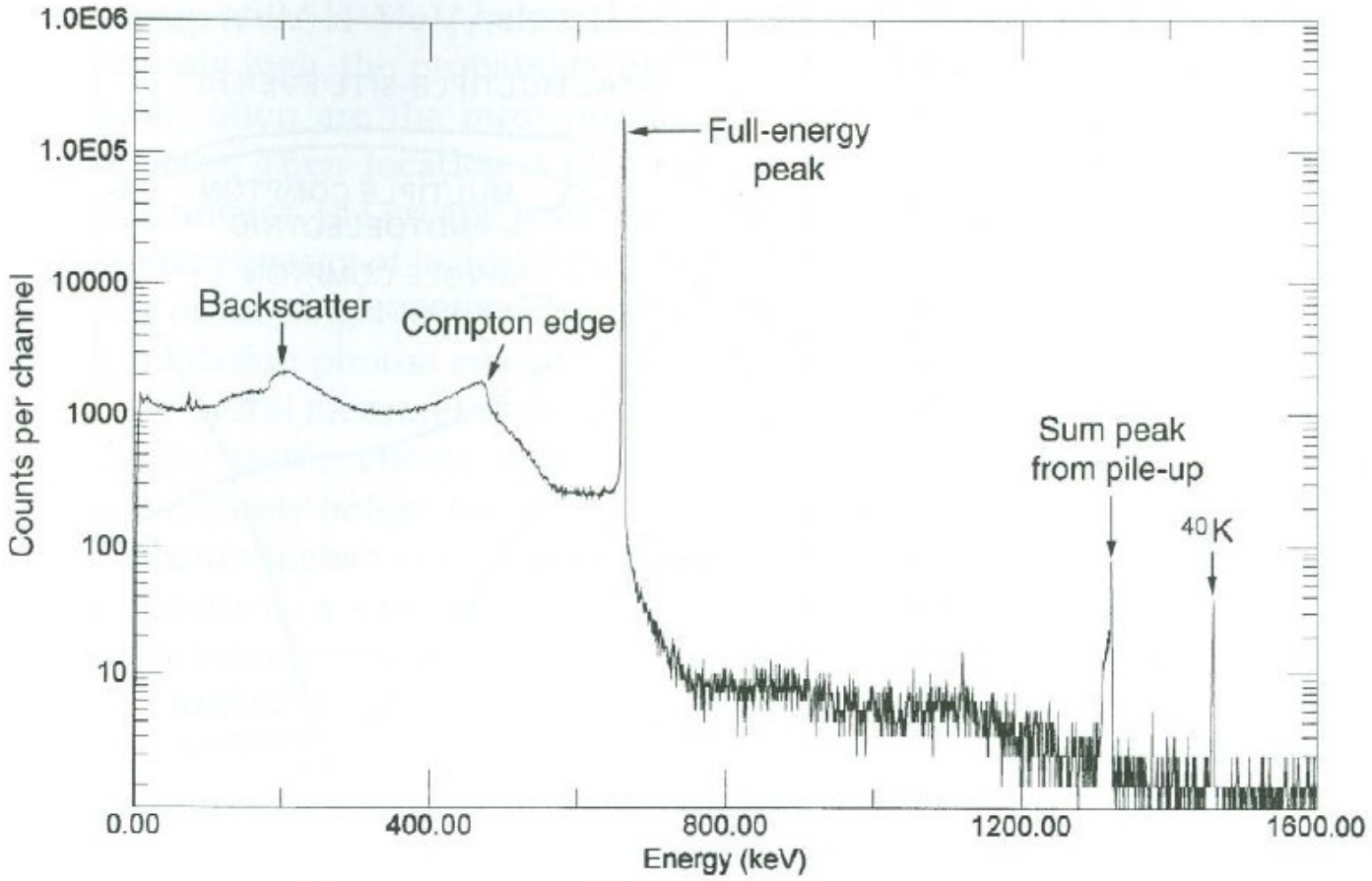


HPGe detectors

- Keep dark current low not by compensating impurities but by making the material VERY CLEAN itself
- Extremely pure Ge obtained by repeating the purification process (zone melting) → ≤ 10^9 impurities per cm^3
- Intrinsic later like compensated zone in Ge(Li), similar sizes possible
- Advantage: cooling only needed during use, to reduce the thermal noise
- The crystals can be p or n type according to the nature of residual impurity traces
- The junctions are carried out by doping with ion-implantation one of the faces of the quasi-intrinsic crystal which can be a very large volume

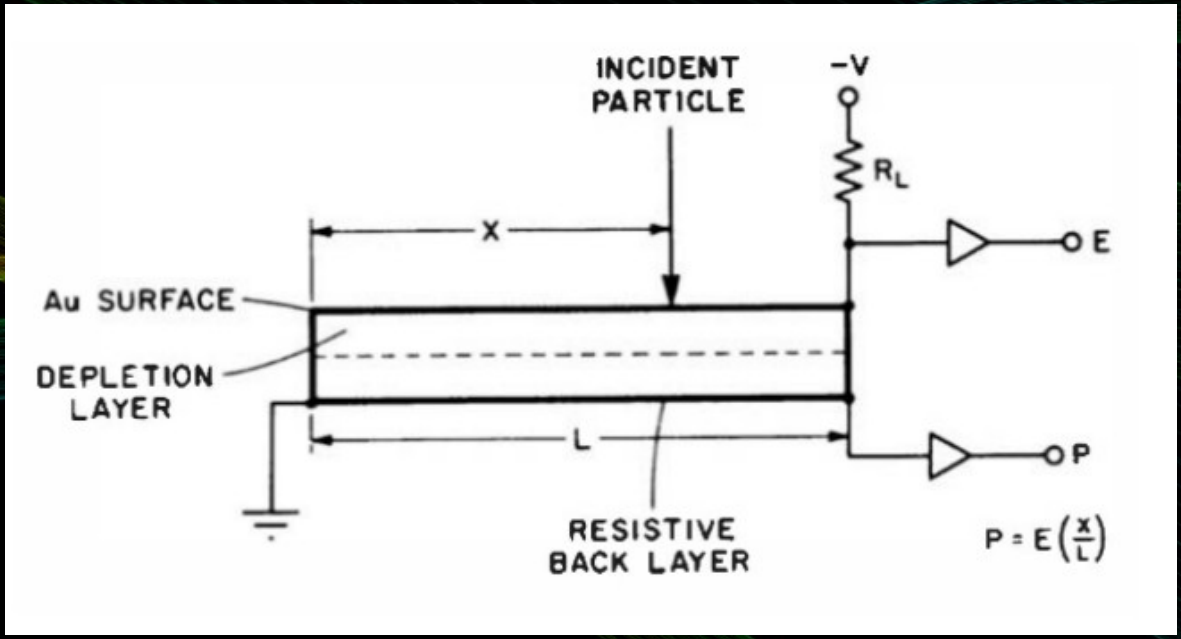


HPGe detector: γ spectroscopy



Spectrum of γ rays emitted by ^{137}Cs source

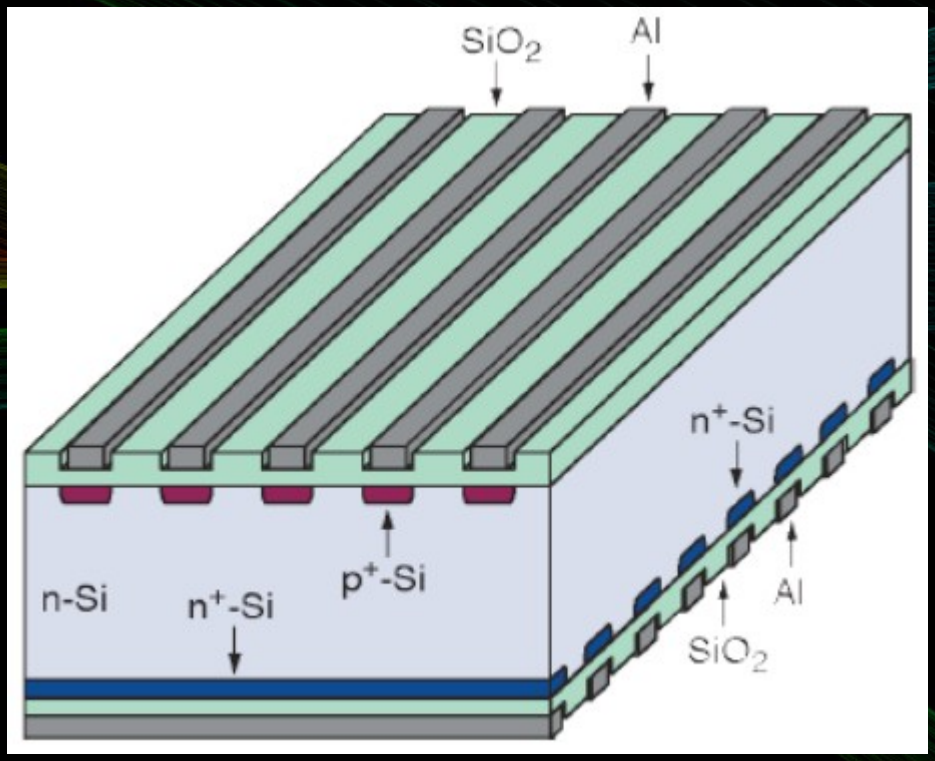
Position sensitive detectors

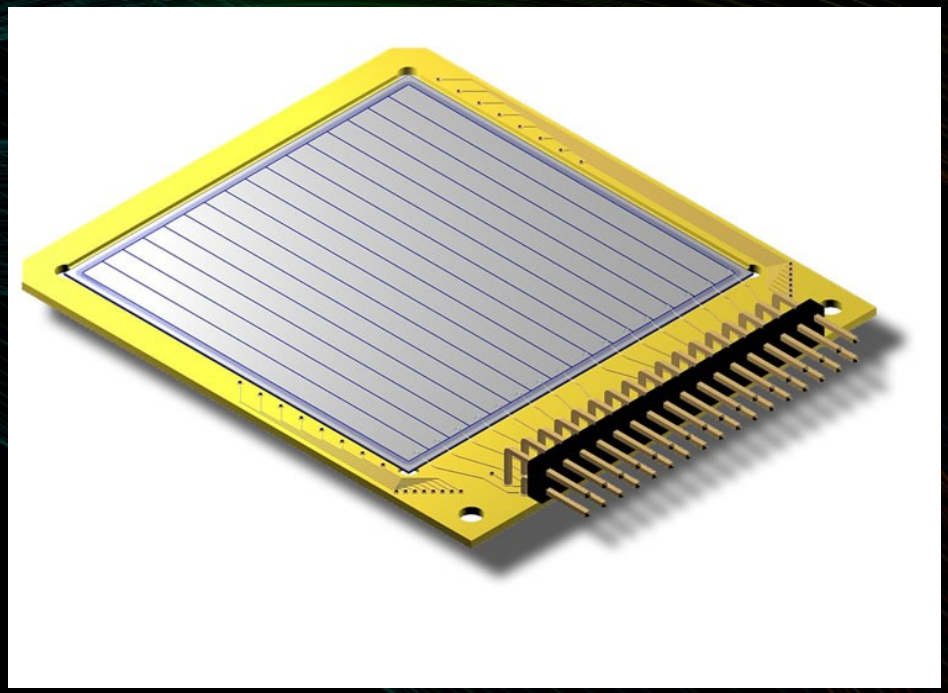


Resistive charge division readout

- Position along one direction by signals of two amplifiers
- Signal in E is proportional to the total energy deposition
- Resistive contact works as a charge divider
- Signal in P measures x/L
- Ratio P/E gives position independent of deposited charge

Position sensitive detectors





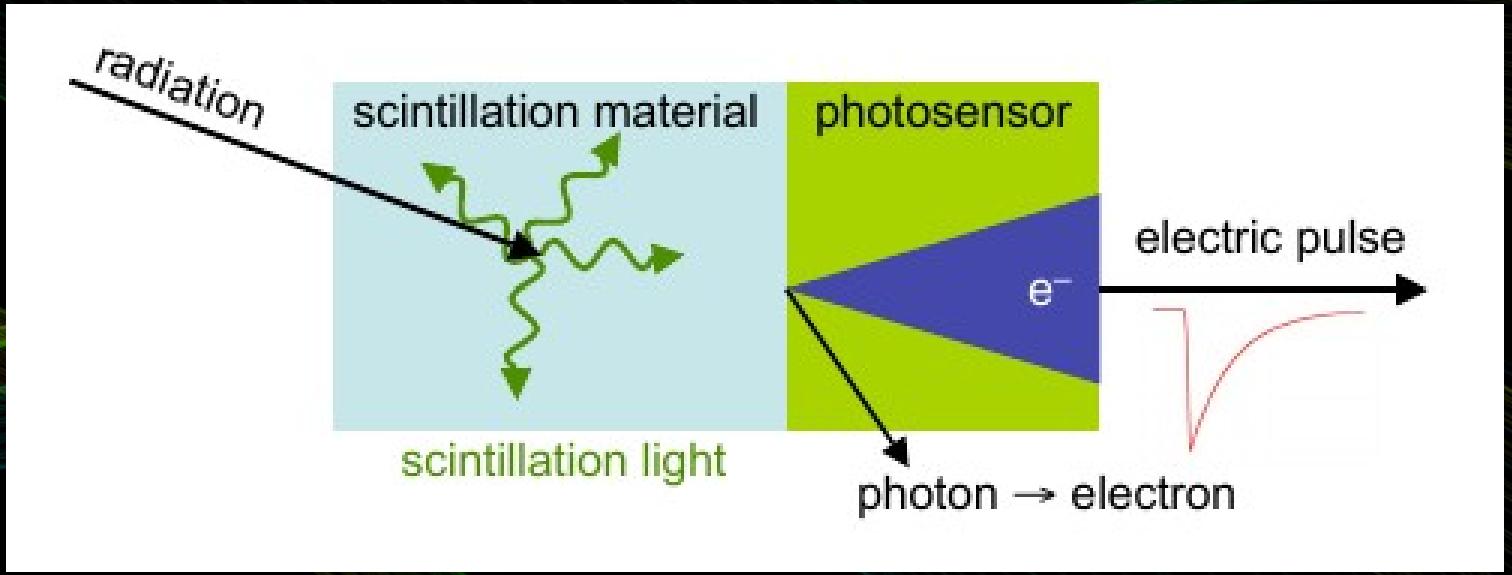
- Independent segments (strips), photolitography and ion implantation
- Independent readout of strips, reconstruction by center of gravity

Summary

- Silicon detectors (generally SSB or implantation) → principal use in spectroscopy (or detection) of charged particles (proton,alpha, ...) and for the determination of the trajectories of charged particles
  Particles stopped in 5mm Si(Li) detectors:
  - α up to 120 MeV kinetic energy
  - p up to 30 MeV
  - e up to 3 MeV

- Germanium detectors (generally HPGe) → principal use for detection and spectroscopy of γ rays

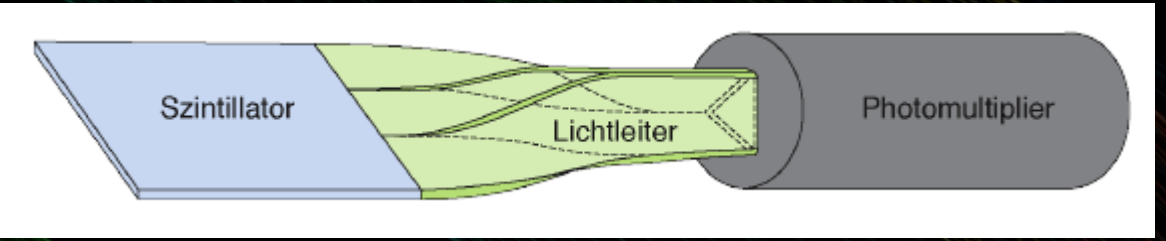
Scintillation detectors: introduction



- Luminescence: Emission of photons (visible light, UV, X ray) after absorption of energy. Energy deposition in the material by
  - Light ➔ Photoluminescence
  - Heat ➔ Thermoluminescence
  - Electric energy ➔ Elektroluminescence
  - Chemical reactions ➔ Chemoluminescence
- **Scintillation**: emission of photons following the excitation of atoms and molecules by radiation (γ, or particle radiation).

Scintillation detectors: an introduction

- **Fluorescence**: emission of light by a substance that has absorbed light or another electromagnetic radiation of a different wave length. In most cases the emitted light has a longer wavelength. The emission follows shortly after (appr. 10 ns). Fast component of signals.
- **Phosphorescence**: Similar to fluorescence, however the re-emission is not immediate. The transition between energy levels and the photon emission is delayed (ms up to hours). Slow component of signals



- A scintillation detector consists of a scintillating material, coupled to a light guide and a photo detector.
- The scintillating material converts γ- and particle-radiation into light (visible, UV).
- The light guide leads the light to the photo detector. A wavelength shifter is often used to match the wavelength to the response characteristics of the photo cathode.
- The photo detector converts the light into an electric signal. Various photo detectors are applied, e.g. photo multipliers, SiPMs, gaseous detectors.

Scintillation detectors: an introduction

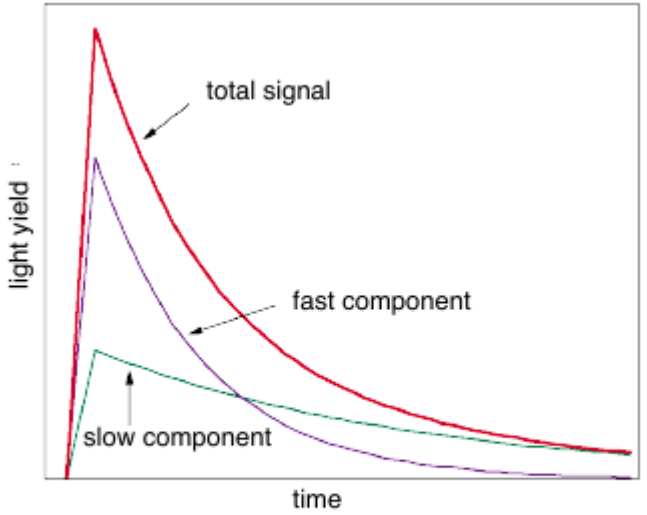
- Scintillating materials:
  - inorganic crystals, organic crystals,
  - organic liquids
  - plastic scintillators
  - nobel gases (gaseous and liquid)
  - scintillating glasses
- Applications in nuclear- and particle physics:
  - trigger detectors for slow detectors
  - time of flight counters (TOF-Counter)
  - calorimeters
  - position detectors (scintillating fibres)
  - detection and spectroscopy of thermal and fast neutrons
  - neutrino detectors (liquid scintillators)

- **Advantages:**
  - fast response time (especially organic scintillators, ~ ns)
  - sensitive to deposited energy
  - construction and operation simple ➔ cheap and reliable!
- **Disadvantages:**
  - aging (especially plastic scintillators)
  - radiation damage (especially plastic scintillators)!
  - hygroscopic (especially inorganic crystals)!
  - low light output (especially gaseous scintillators)!
  - in combination with the optical readout sensitive to magnetic fields (e.g. when using photo multipliers)!

Scintillation detectors: an introduction

- Many materials show luminescence. However, a useful scintillation detector has to fulfil the following requirements:
  - High light yield, i.e. high efficiency to convert the excitation energy into fluorescence.
  - Transparency with respect to the own fluorescence light. Otherwise the light is absorbed within the material itself.
  - An emission spectra matched to the spectral sensitivity of the photo detector. Matching can also be achieved by introducing a wave length shifter.
  - Short decay constant.
- Signal shape:
  - very fast rise time of the signal
  - a fast and a slow decay component (in organic scintillators) → slow component intensity depends on particle type → **pulse shape discrimination**
  - number of emitted photon:

$$N(t) = A\exp\left(-\frac{t}{\tau_f}\right) + B\exp\left(-\frac{t}{\tau_s}\right)$$



Signal vs. time of a scintillator with fast and slow component.

Light output

- Only a few per cent of the deposited energy is transferred into light. The remaining energy is used up by ionisation and other processes:
  - non-radiative de-excitation modes e.g. lattice vibrations, heat, impurity-related effects (called „quenching”)
  - phosphoresence
- Mean energy required to create a photon:
  - Anthracen ($C_{14}H_{10}$): ~ 60 eV
  - NaI(Tl): ~ 25 eV
  - BGO ($Bi_4Ge_3O_{12}$): ~ 300 eV
- Anthracen or NaI are often used as reference material, i.e. the light yield is given in percentage of the yield of Anthracen or NaI.
- In addition photons are lost in the scintillator itself (re-absorption) and in the light guide.
- Quantum efficiency of the photo detectors also only about 30%!

Materials

Material	Typ	Density [g/cm^3]]	max. emission λ [nm]	Light output [% Anthracen]	Decay time* [ns]
NaI:Tl	Inorgan. Cristal	3.67	413	230	230
CsI	Inorgan. Cristal	4.51	400‡	500‡	600‡
BGO (= $Bi_4Ge_3O_{12}$)	Inorgan. Cristal	7.13	480	35–45	350
$PbWO_4$	Inorgan. Cristal	8.28	440–500	≈2.5	5–15
Anthracen	Organ. Cristal	1.25	440	100	30
trans-Stilben	Organ. Cristal	1.16	410	50	4.5
p-Terphenyl	In liquid solution, plastic	–	440	≈58	5
t-PBD	In liquid solution, plastic	–	360	–	1.2
PPO	In liquid solution, plastic	–	355	–	?

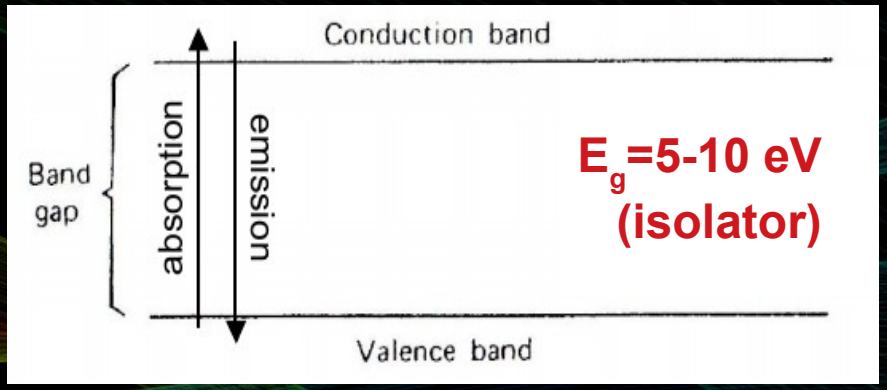
*main component

‡ at $T = 77$ K

Inorganic scintillators: overview

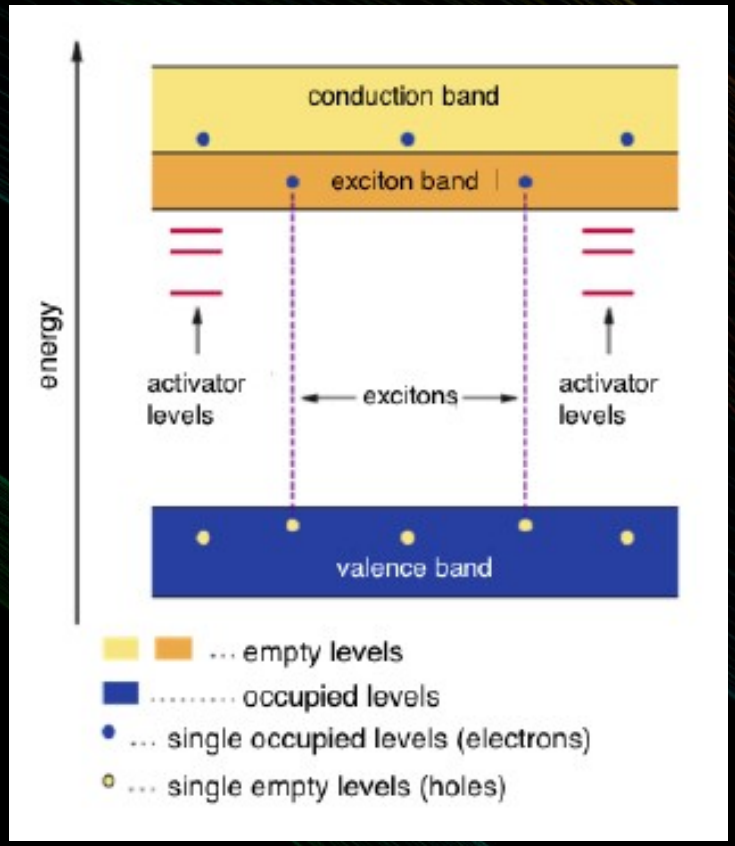
- Different types of inorganic scintillators:
  - inorganic crystals, glasses, noble gases (gaseous or liquid)
- Scintillation mechanism is different for inorganic crystals, glasses and noble gases. The consequence are very different response times.
  - inorganic crystals, glasses: rather slow (compared to organic crystals)
  - noble gases: fast
- Important inorganic crystals are:
  - NaI,CsI: as pure crystal or doped with Thallium ((NaI:Tl),(CsI:Tl)); BGO ($Bi_4Ge_3O_{12}$); BaF_2, CeF_3, $PbWO_4$, $LaBr_3$
- Wavelength of emitted light is 400–500 nm. (NaI: 303 nm, CsI: 580 nm)
- **Advantages:**
  - High density, short radiation length
  - High light output : ≈100%–400% of Anthracen
  - relative radiation resistant: especially: CeF_3, GSO, $PbWO_4$, (bad: BGO)!
- **Disadvantages:**
  - typically slower than organic scintillators: decay times are few hundred ns, due to phosporescence. (Exception: CsF_2 ~ 5 ns and $PbWO_4$ ~ 5–15 ns.)
  - some are hygroscopic (especially NaI but BGO, $PbWO_4$,CeF_3 are not hygroscopic.)

Inorganic crystals: mechanism

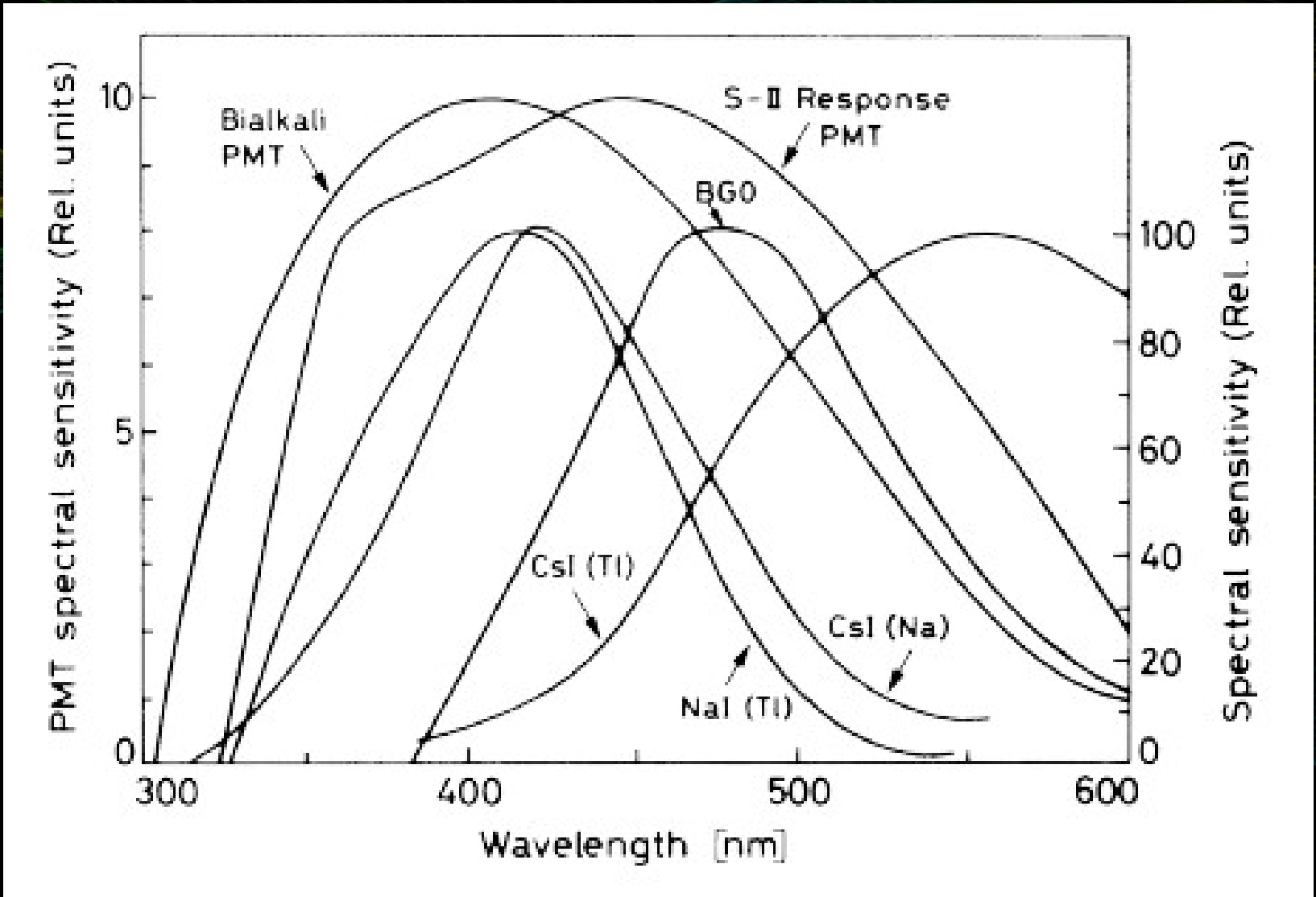


- radiation creates electron-hole pairs → recombination via photon emission
  - inefficient
  - photon energy > visible light
  - emission wavelength = absorption wavelength → self-absorption

- Activated inorganic scintillator:
  - absorbed energy excites electrons to the conduction band.
  - holes ionise activation sites
  - electrons migrate until they “drop” into an ionised activated site, leaving the activator in an excited state
  - excited activator state decay time (~50-500 ns) >> electron, hole migration time
  - activators (fluorescent ions as Tl or Ce) act as luminescence centers, recombination centers
  - scintillation photons of longer wavelength than pure scintillators → no self-absorption



Inorganic scintillators: emission spectra



Organic scintillator: an introduction

- Different types of organic scintillators:
  - organic crystals organic liquids, plastic scintillators
- Organic scintillators are aromatic hydrocarbon compounds
- The scintillation mechanism is due to the transition of electrons between molecular orbitals → organic scintillators are fast ~ few ns.
- Organic crystals consist of only one component
- Liquid- und Plastic scintillators are usually composed of 2–3 components:
  - Primary scintillator material
  - Secondary scintillator as wavelength shifting component
  - Supporting material
- The dependence of light output from energy deposition is usually not linear in organic scintillators: a high density of excited molecules along the particle track causes de- excitation without photon emission (quenching effect). → Light output becomes saturated
- Light output described by Birks law:

$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + K_B \frac{dE}{dx}}$$

K_B : 10^{-4} – 10^{-2} g/(cm^{2}MeV)

Organic - Plastic scintillators

- Plastic scintillators used in numerous applications in particle and nuclear physics.

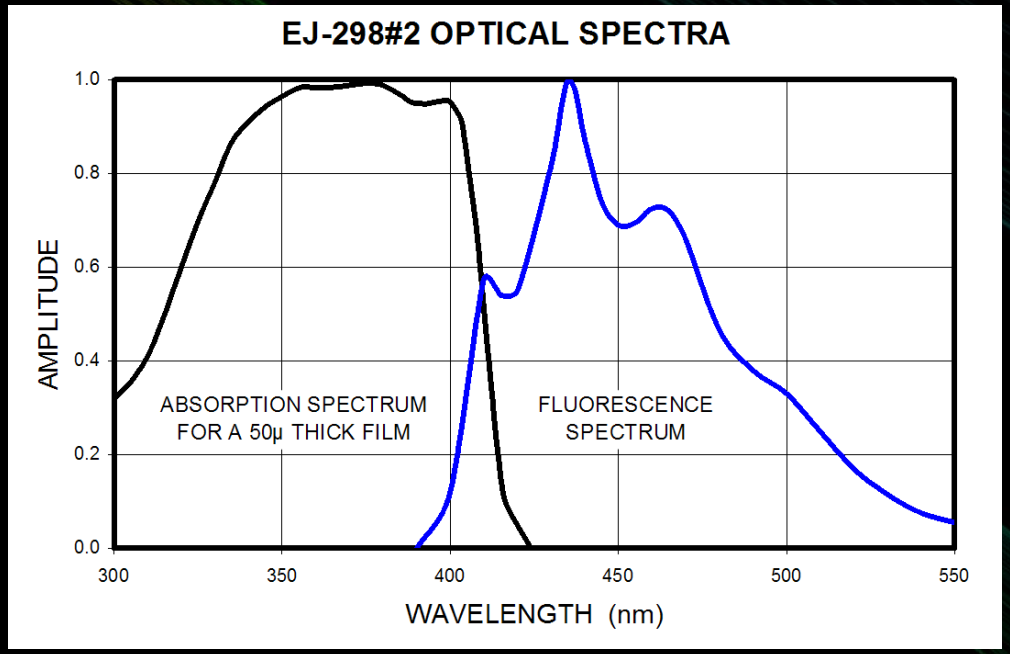
- Advantages:
  - Fast fluorescence: ≤ 3 ns
  - Any kind of shape possible
  - Easy to machine, cheap

- Disadvantage:
  - Not very radiation resistant

- The support structure is a polymere matrix containing a primary scintillator
  - matrix materials: Polyvinyltoluol, Polyphenylbenzol, Polystyrol, PMMA!
  - Primary scintillators: p-Terphenyl, PPO, t-PBD,...
  - wavelength shifter: POPOP, BBQ,...

Wavelength Shifter

- Wavelength shifter absorb photons of a certain wavelength and re-emit photons at a different wavelength (usually larger) to better match the scintillator light to the read out device.
- Important wavelength shifter materials:
  - POPOP (1,4-bis-[2-(5-Phenyloxazolyl)]-Benzen; C24H16N2O2)!
  - bis-MSB (1,4-bis(2-Methylstyryl)-Benzen; C24H22)!
  - BBQ (Benzimidazo-Benzisochinolin-7-on)!
- Wave length shifter can be mixed into the scintillator or integrated into the light guide.



Light guides

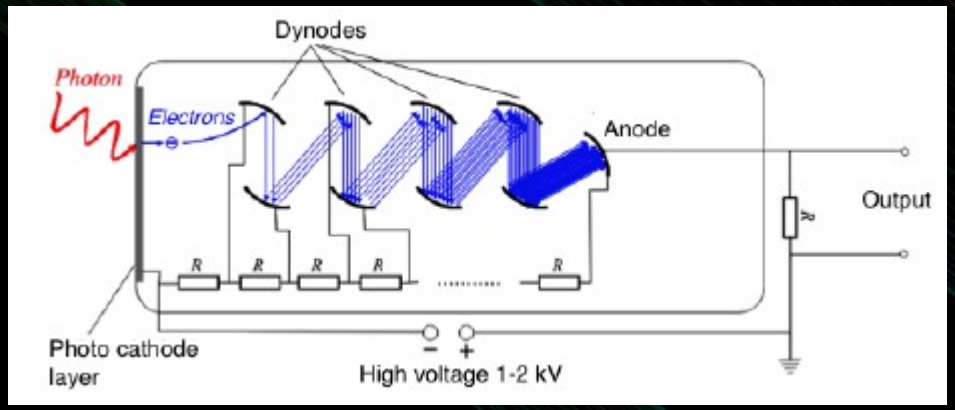
- Often scintillators cannot be directly coupled to the read out device for space constraints or magnetic fields. The shape of the scintillator also rarely matches the shape of the photo detector → use light guides for coupling!
  - Light is guided by total reflexion (surfaces polished and with reflective coating)
  - The shape of the light guide is irrelevant. Sharp kinks have to be avoided.
  - Commonly used material PMMA (Polymethylmethacrylat), often with wavelength shifter material added.

Photo detectors

- Different photo detectors used to read light from scintillators and transform it into electric signals:
  - “Classical” photomultipliers
  - “New” silicon devices: APD, SiPM
  - Hybrid Photon Detectors HPD
  - Gaseous Detectors
- **Photomultipliers**:
  - Photons hitting the photo cathode release electrons (photoelectric effect). The electrons are accelerated towards the 1st dynode and produce secondary emission. This process is repeated at each dynode and finally the largely amplified electrons reach the anode.
  - Quantum efficiency (QE) 10 – 30% depending on wave length, entry window material, photo cathode.

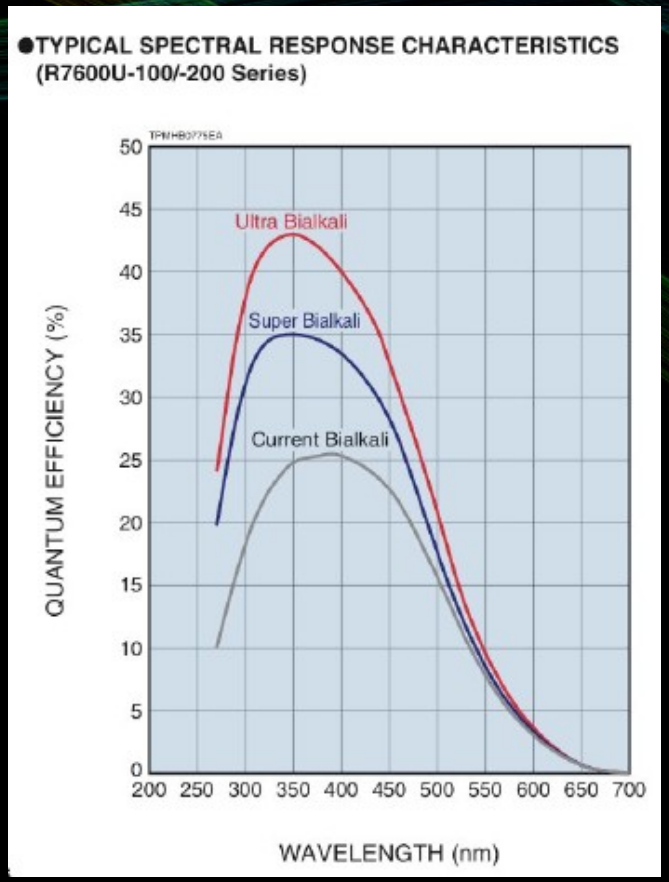
$$QE = \frac{\text{number of photoelectrons emitted}}{\text{number of incident photons}}$$

- Advantages:
  - high amplification gains 104 – 107
- Disadvantage:
  - sensitive to magnetic fields



Photomultipliers – photocathode & dynodes

- mutiple electrons emitted per incident electron
  - secondary emission ratio δ
- multiple (N) dynodes: gain = δ^N
- in practice overall gain up to ~10^7



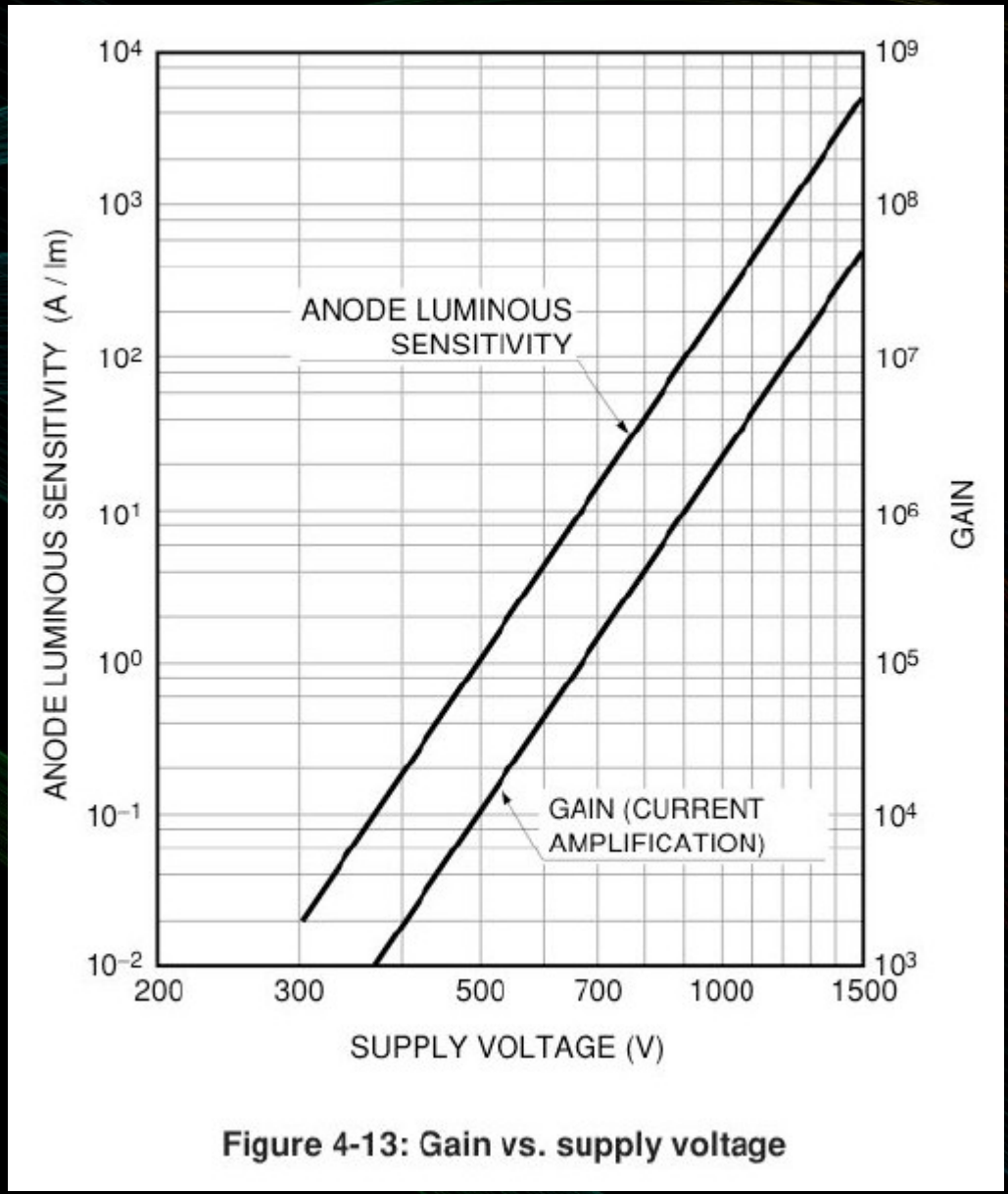
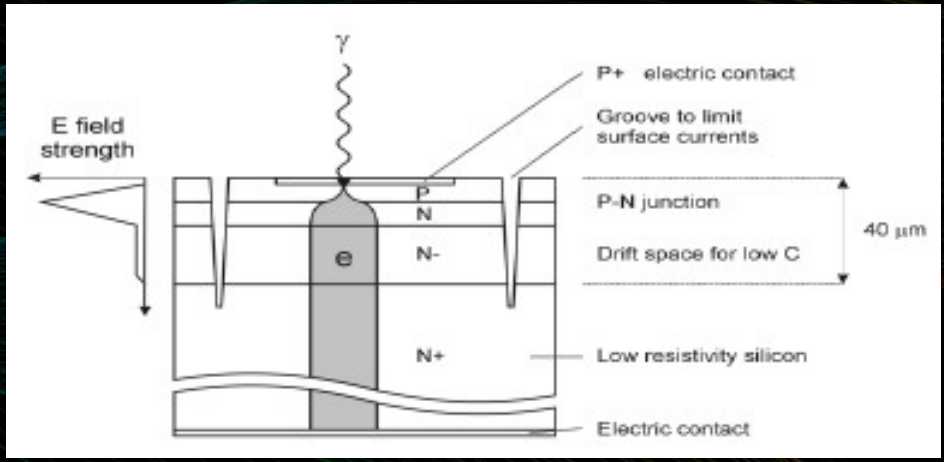


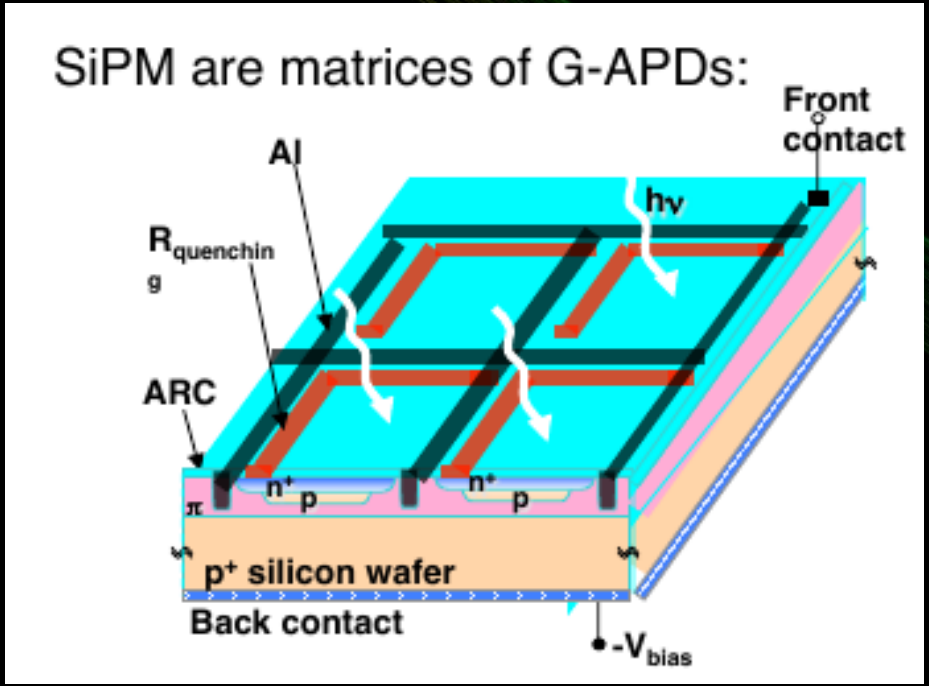
Figure 4-13: Gain vs. supply voltage

Variety of PMTs

APD, SiPM

- Avalanche Photo Diodes (APDs) are silicon devices operated in reverse bias mode in the breakdown regime. Geiger mode APDs (G-APD) operate in full breakdown, current limited by quenching resistor





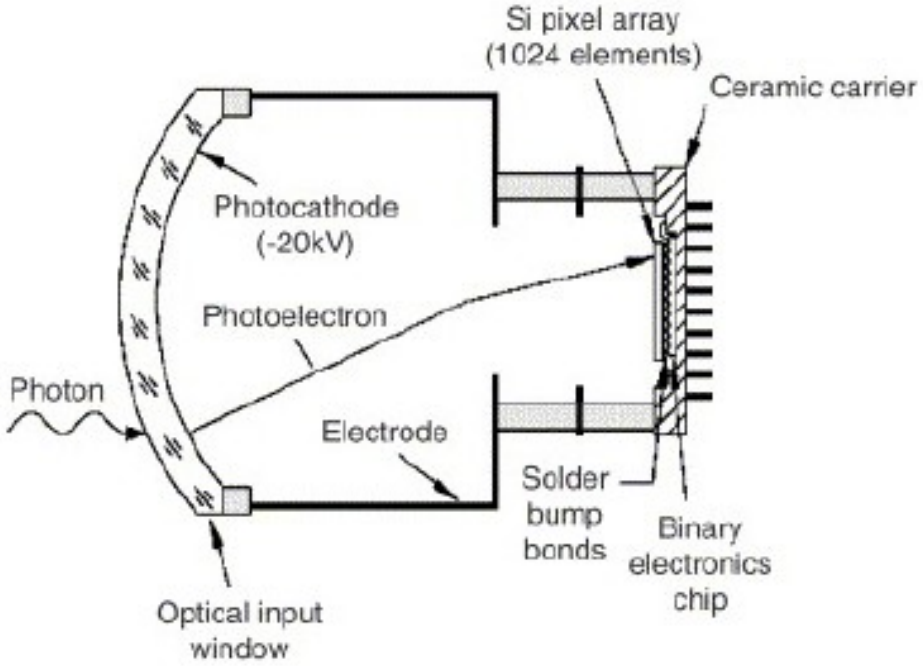
- APDs (operated in Geiger mode) can detect single photons!
- High gain in the range of 10^5 to 10^7
- Work at low bias voltage ~50 V
- Low power consumption
- Insensitive to magnetic fields
- Radiation hard
- Tolerant against accidental illumination
- Cheap

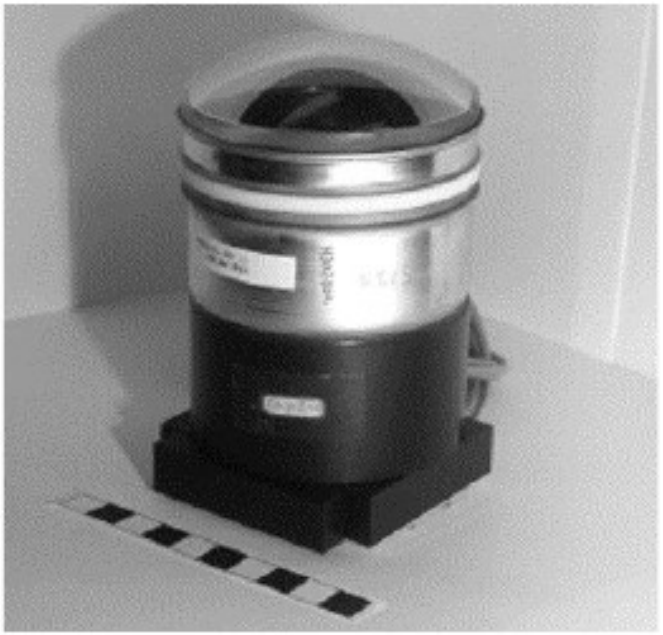
Summary on photosensors

	PMT	APD	SiPM
photo-detection efficiency [%]	20-40	60-80	20-40
gain	10^6-10^7	50-200	10^5-10^6
dynamic range	10^6	large	10^3 /mm^2
bias voltage [V]	1000-2000	50-500	20-70
1 phe resolution [%]	50	poor	4
time jitter (1σ) [ps]	200	>1000	50
magnetic field compatibility	no	yes	yes (up to 15 T)

Hybrid Photon Detectors (HPD)

- Photoelectrons are accelerated in vacuum (20 kV) and detected with a silicon hybrid pixel detector.





S. Eisenhardt, Nucl. Instr. Methods A 565 (2006) 234