III. Physikalisches Institut A

RWTH AACHEN UNIVERSITY

Experimental Techniques in Particle Physics (WS 2020/2021)

Gaseous detectors

01.12.2020

Prof. Alexander Schmidt

Date of the written exam

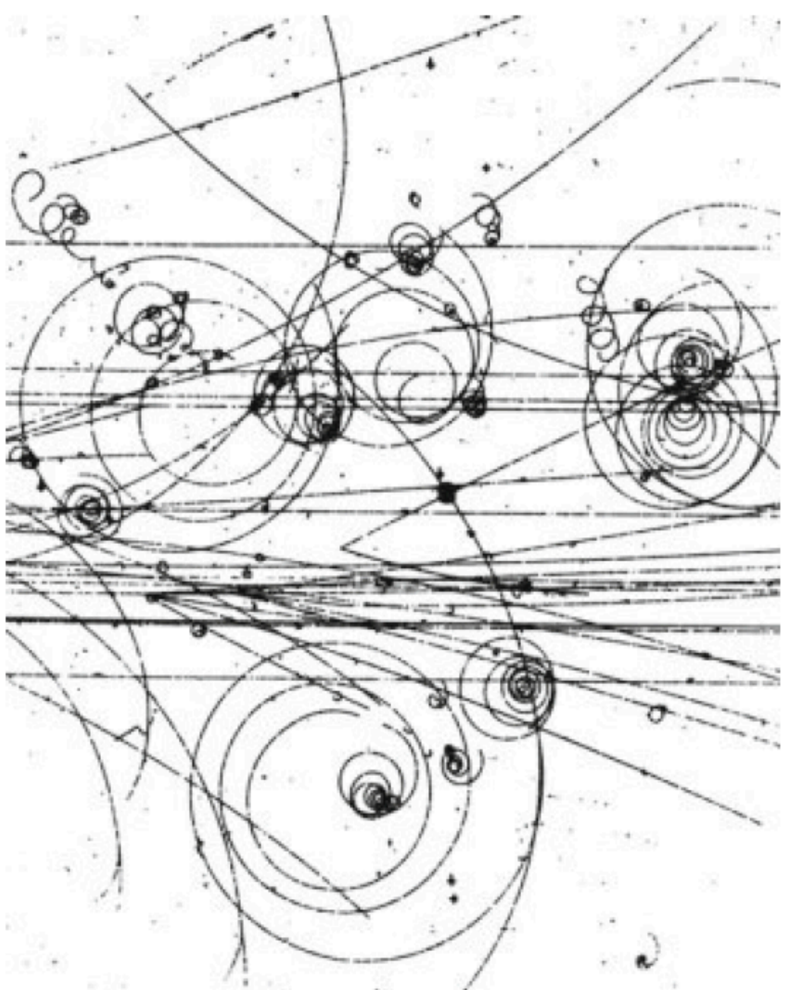
date: 16.03.2021

time: 14:30

location to be announced

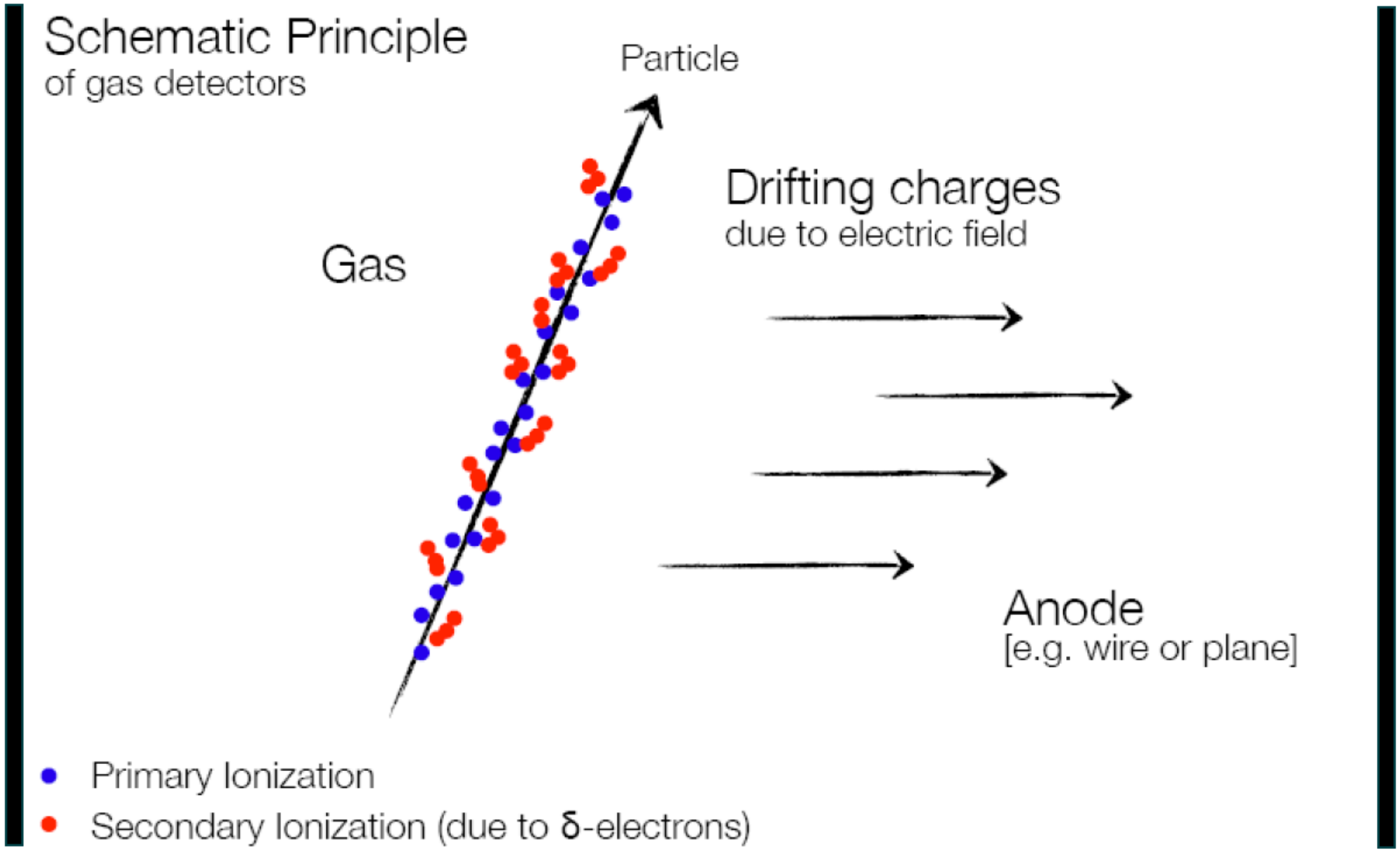
History

- the first real gas-based detectors were cloud chambers and bubble chambers
- fundamental discoveries until 1980s
- e.g. discovery of weak neutral currents at CERN in the 1970s



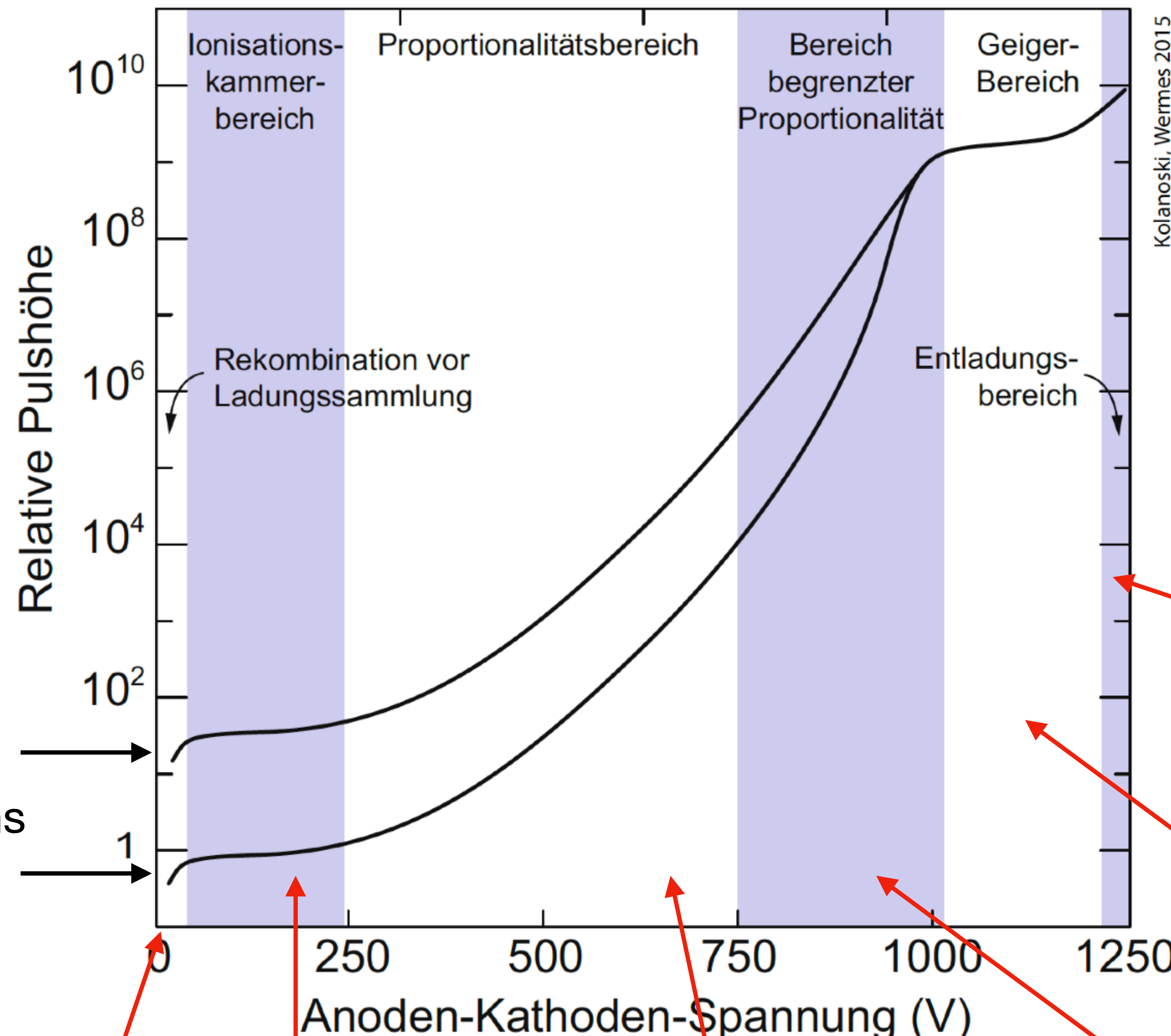
- they don't have electronic readout
- they take photographs of ionised gas from different perspectives to reconstruct a 3D picture
- the precision is extremely good
- target and detector are the same material (but not necessary to have a target at all in collider experiments)
- very high precision, but very low rates possible (too slow for modern experiments)

modern perating principle of a gas detector
(synonyms: gas-, gaseous-, gas-filled, gas-ionisation detector)



- gas-filled volume between anode and cathode
- voltage between anode and cathode
- collection of electrons and ions which are created by a passing charged particle
- gas has low density, passing particle is mostly undisturbed

The voltage determines the operation mode



two different primary ionisations

spontaneous self-discharge

no proportionality, always large secondary ionisation avalanches.

limited proportionality

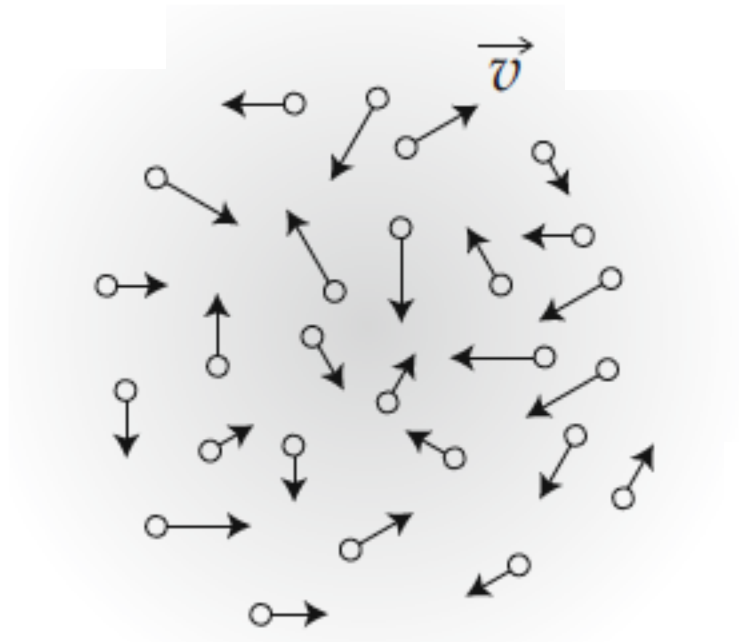
electrons and ions recombine to a fraction. Increasing voltage leads to less recombination, until saturation.

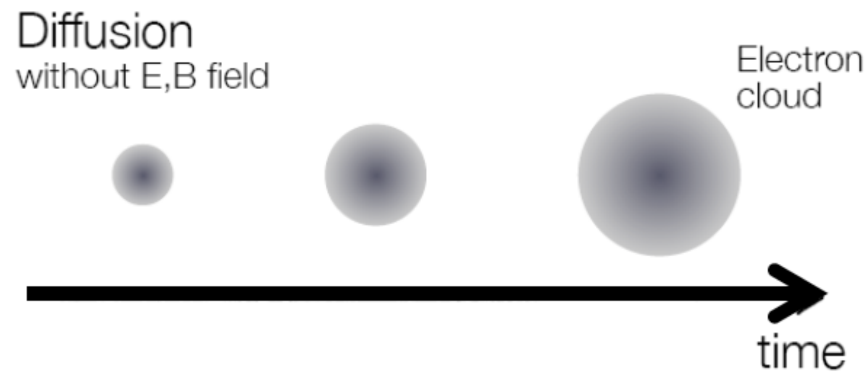
all primary electrons and ions drift to readout electrodes.

secondary ionisation leads to avalanche proportional to primary ionisation

Transport of charges through the gas: diffusion

chaotic movements of charges in gas





classic kinetic theory of gases:

size of cloud $\sigma = \sqrt{6Dt}$

diffusion coefficient *D* depends on particle type and gas type (derived from Maxwell distribution)

diffusion coefficient *D*:

$$D = C_i \frac{1}{p\sigma}\sqrt{\frac{T^3}{m}}$$

$$C_e = \frac{2\sqrt{2}}{3\sqrt{\pi}} = 0.53$$

$$C_I = \frac{2}{3\sqrt{\pi}} = 0.38$$

<u>typical numerical example:</u>

$D_e \approx 1000 \frac{cm^2}{s}$ $\qquad$ $D_I \approx 0.1 \frac{cm^2}{s}$

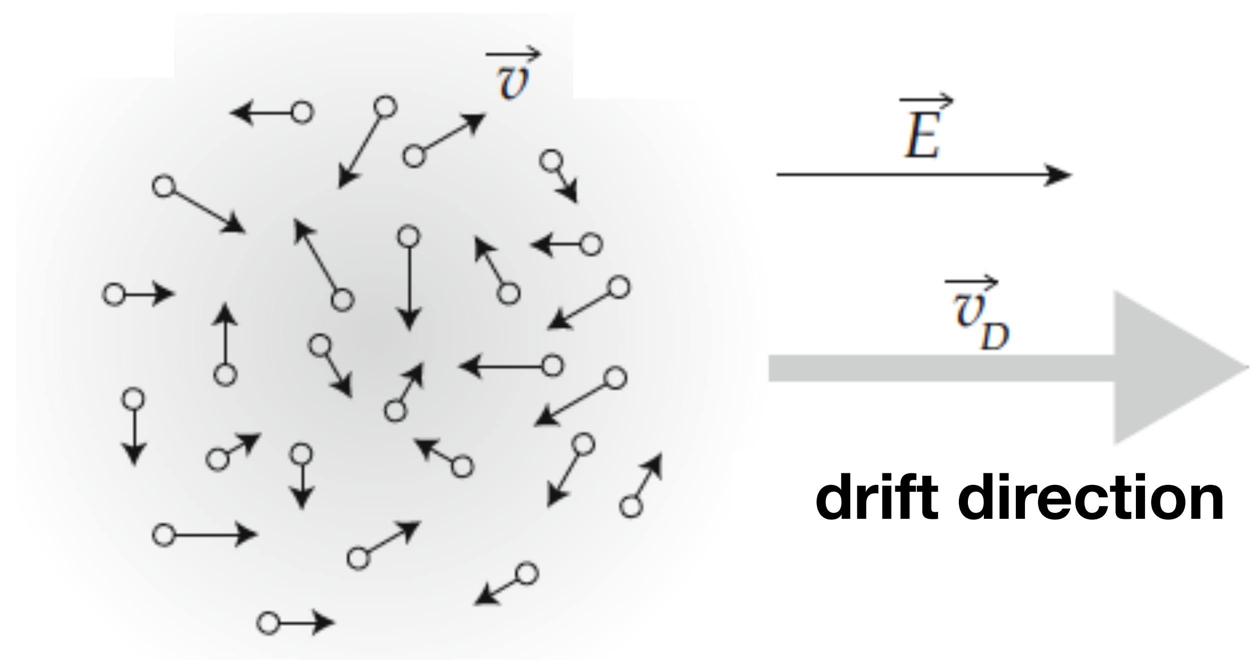
Gauß width after drift of 1 μs:

$\sigma_e \approx 1\ mm$ $\qquad$ $\sigma_I \approx 10\ \mu m$

→ electron cloud expands faster

Transport of charges through the gas: drift velocity

E field applied !



→ net effect: constant drift velocity

$v_d = \mu|\vec{E}|$; μ: mobility

→ microscopic model:

$$\mu = \frac{e}{m}\tau = \frac{e}{m}\frac{\lambda}{\langle v\rangle} = \frac{e}{T}D$$

→ typical values:

$$v_d(e) \approx 100\,\frac{\mu m}{ns}; \qquad v_d(I) \approx 0.01\,\frac{\mu m}{ns}$$

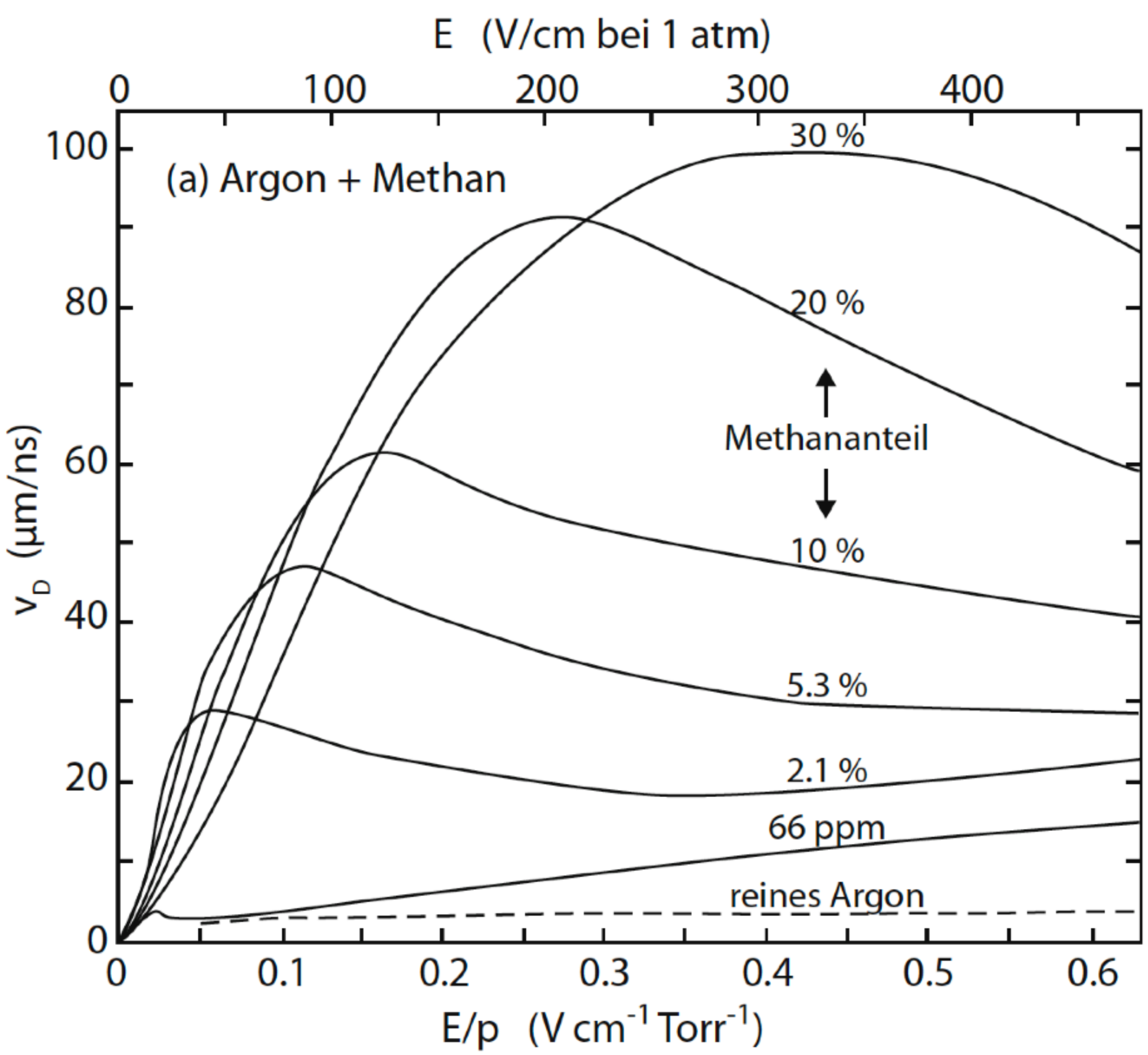
Transport of charges through the gas: ion/electron drift

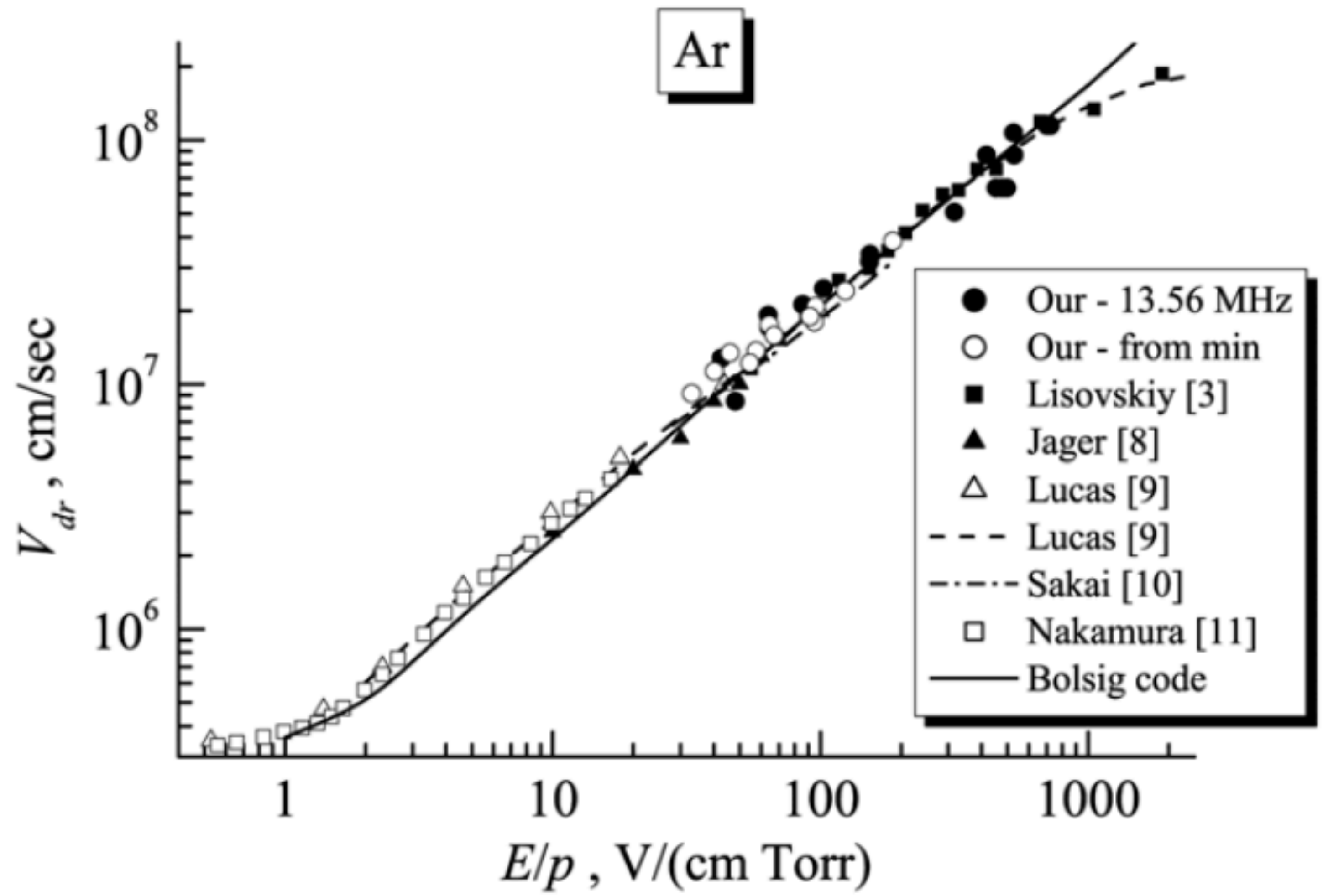
- ions drift slower than electrons
- mobility is independent of the field (no inelastic scattering etc…)
- examples:

Gas	Ionen	μ^+ (cm^2 V^{-1} s^{-1})
H_2	H_2^+	13.0
He	He^+	10.2
Ar	Ar^+	1.7

- electrons can drift very fast and can do inelastic scattering
- scattering cross-sections become energy dependent (excitation of atomic states etc…)
- depends on specific gas mixture
- examples next slide

Transport of charges through the gas: electron drift

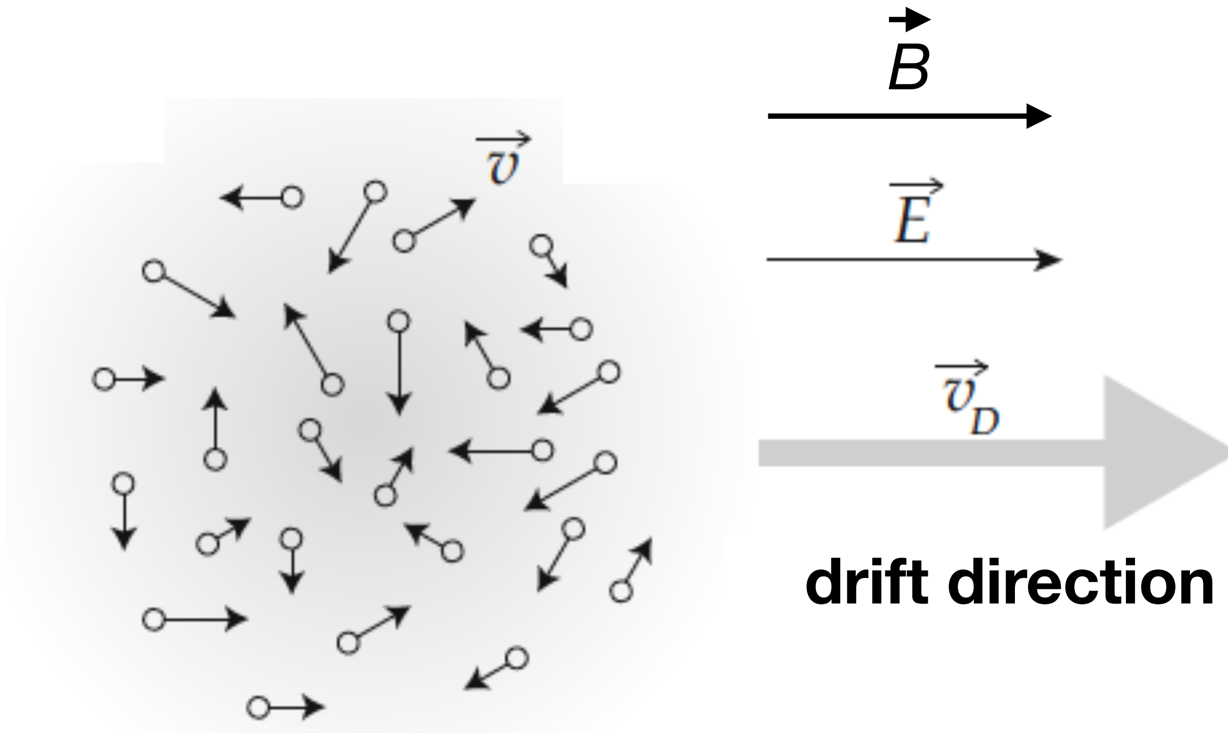


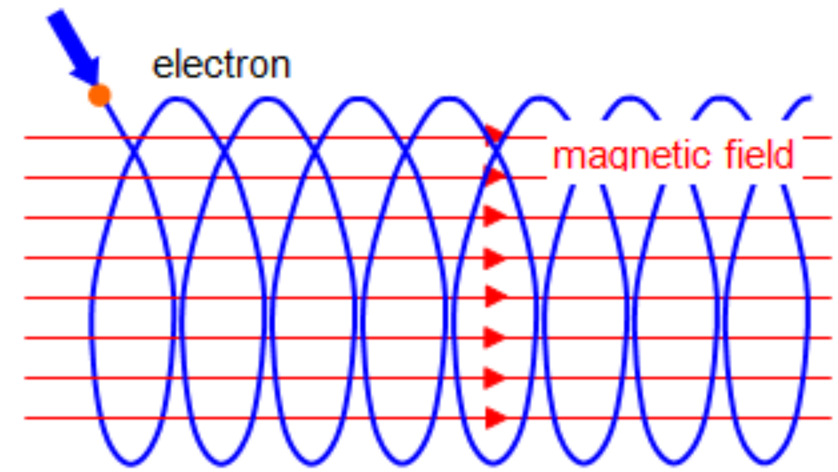


- energy dependence of (inelastic) scattering cross sections plays important role!
- gas mixture allows to adjust the desired drift behaviour
- quite stable linear behaviour for **pure argon**

Drift with B field

E field and B field applied !





- **longitudinal** drift velocity is the same if *B* and *E* field are parallel
- **transverse** (!) diffusion D_T is much reduced (factor 10 or more)

$$D_T = \frac{D}{1 + \omega^2 \tau^2}$$ (where ω is the angular velocity)

- long drift distances are facilitated this way (time projection chambers, see later)

- calculation of all effects needs to consider many things:
  - scattering of charge carriers in gas, dependence on pressure, temperature, cross sections, energy, …
  - statistical treatment of atomic movement, diffusion
  - external fields in arbitrary direction
  - use Boltzmann transport equation, Langeville equation, Diffusion equation, Maxwell equations

Signal formation: general principle

<u>remember last lecture:</u>

- Shockley-Ramo-Theorem etc…
- moving charged particle induces signal in readout electrodes (even before it reaches the electrode)

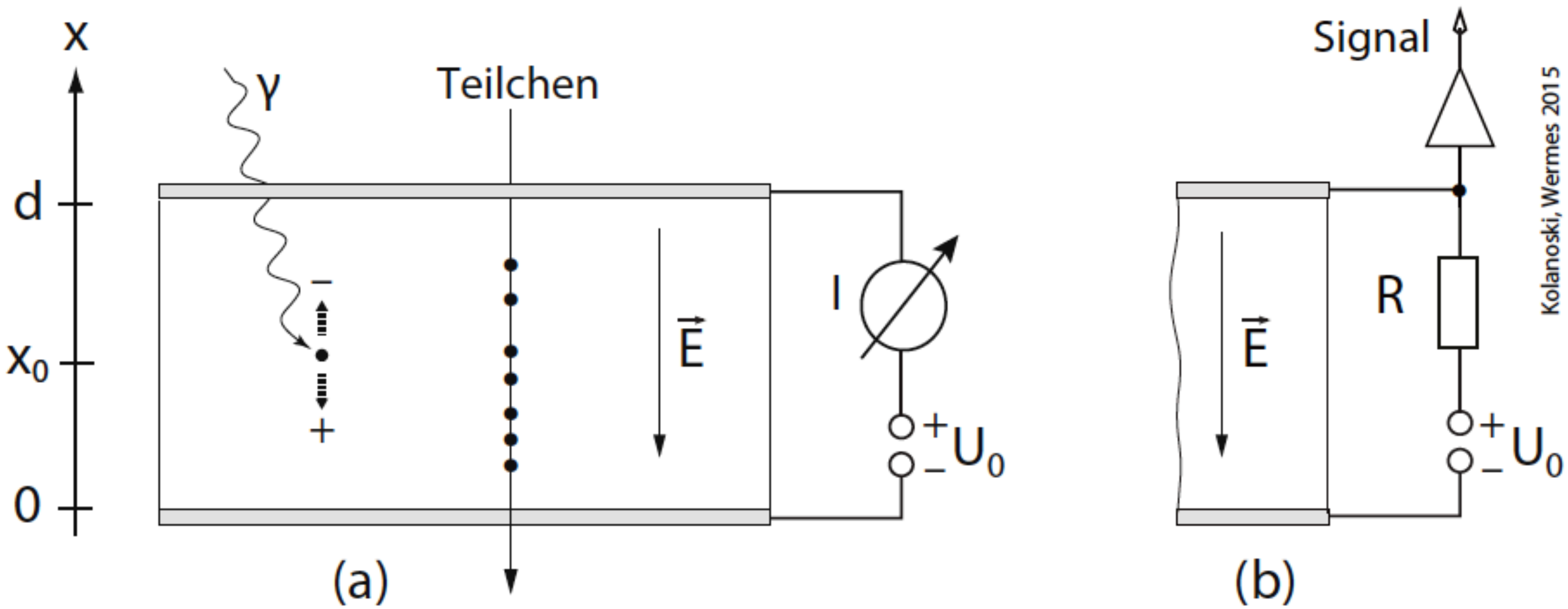
$$i(t) = q \cdot \overrightarrow{E_w} \cdot \vec{v}$$

$$Q(t) = \int_0^t i(\tau)\, d\tau = q \int_{x_1}^{x_2} \overrightarrow{E_w} d\,\vec{x}$$

With q: charge, E_w: weighting field, v: velocity

- How to get the weighting field?
  - Calculate the electrostatic field for each electrode by:
  - removing the signal charge
  - setting the electrode to U = 1V and all others to 0 V

Signal formation: parallel plates

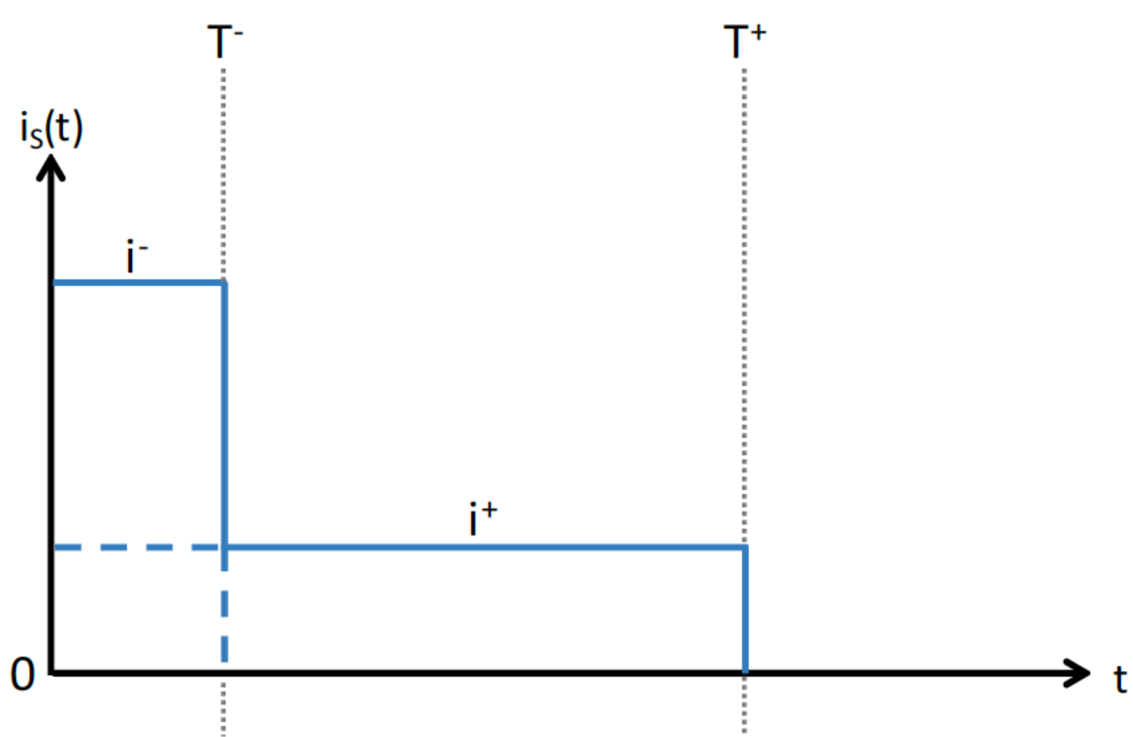


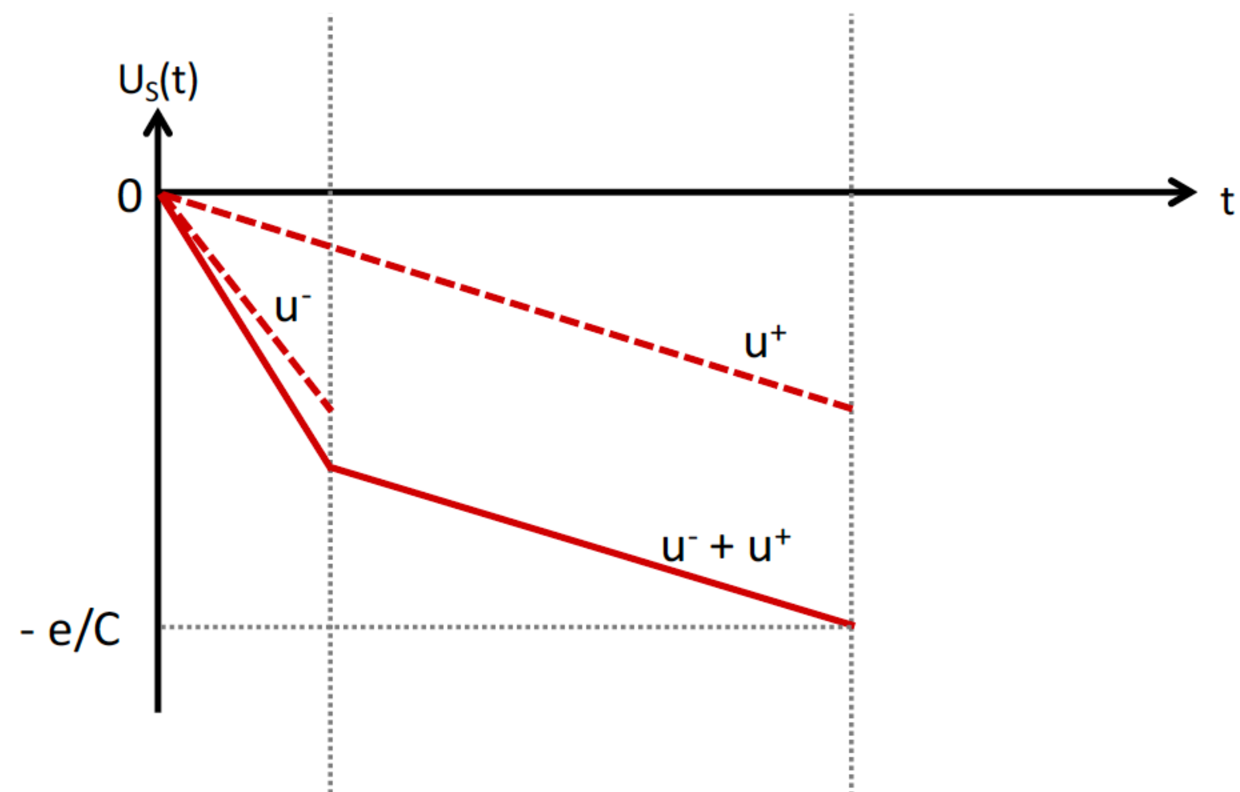
principle:

- point-like ionisation from photons **or** extended ionisation track from charged particles
- signal read out as current or as voltage as function of time

Signal formation: parallel plates

- arrival time: $T^- = \dfrac{d - x_0}{v^-}\,, \qquad T^+ = \dfrac{x_0}{v^+}\,,$
- current: $i_S^- = \dfrac{e}{d}\,v^- \qquad\qquad i_S^+ = \dfrac{e}{d}\,v^+$
- voltage: $u_S(t) = u_S^-(t) + u_S^+(t) = \begin{cases} -\dfrac{e}{Cd}(v^- + v^+)t & 0 < t < \min(T^-, T^+) \\ -\dfrac{e}{Cd}(d - x_0 + v^+ t) & \text{für } T^- < t < T^+\,, \\ -\dfrac{e}{Cd}(x_0 + v^- t) & T^+ < t < T^-\,. \end{cases}$



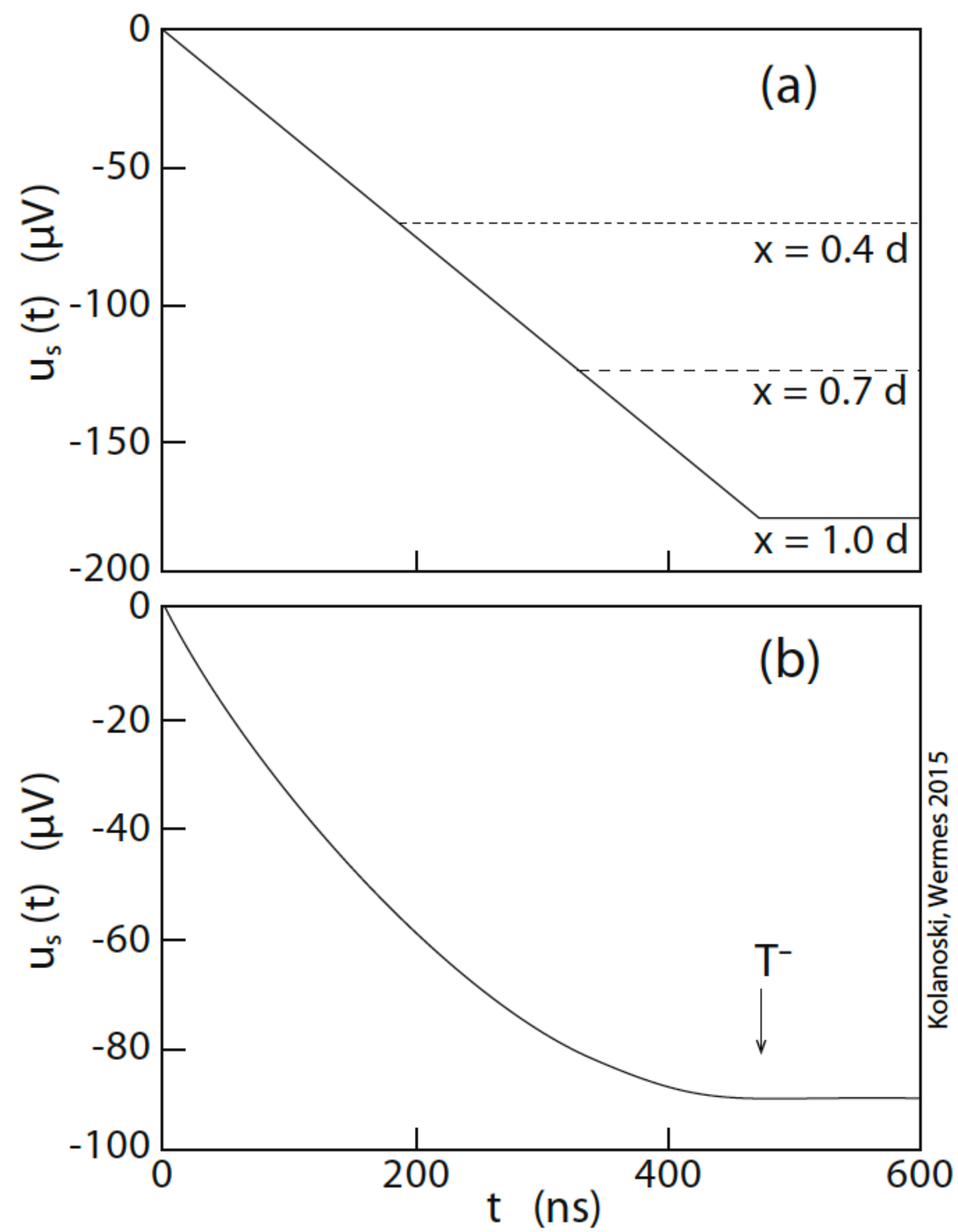


(signal formation in cylindrical geometry, see later…)

Signal formation: parallel plates

- note that the maximal signal is independent of the position of the initial ionisation
- the maximal signal is therefore the same for an “ionisation track” and a point-like ionisation (see previous slide)

- the time-dependence (shape) of the signal-development is however very different



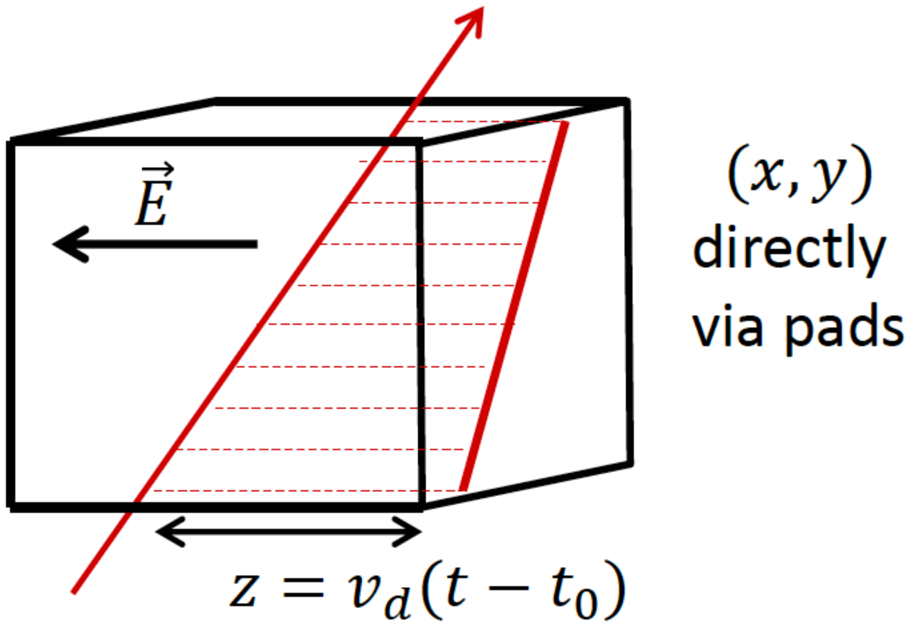
- the electron-signal is usually extremely fast (microseconds) while the ion-signal is slow (milliseconds)

- the diagram shows the electron-signal only
  - for point-like charges (top), deposited at a distance x from the electrodes
  - and a continuous track (bottom)

- the continous track can be derived by subdividing the track into many small single charge deposits

Detector type: long drift distance in TPC

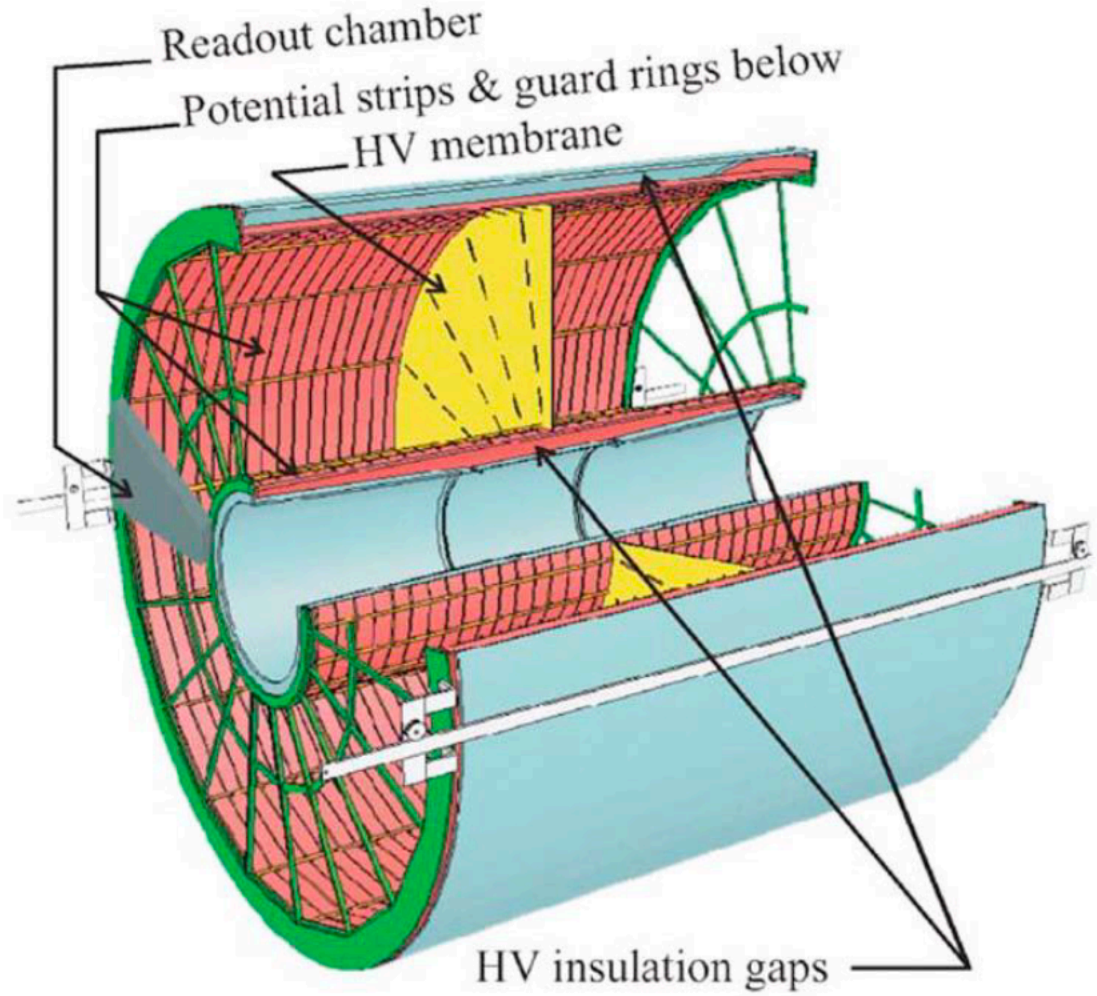
TPC: time projection chamber



- Very little material that particles pass
  - Small multiple scattering
  - Little photon conversion
  - Little bremsstrahlung for electrons/positrons

- Challenges of very long drift distances (several meters)
  - Diffusion must be limited
  - Sufficient fast drift gas at moderate electric field strength
  - High requirements on field homogeneities ($\vec{E}$ and $\vec{B}$)
  - Pure gas to avoid signal loss due to electron attachment
  - Limitation of ion backdrift

ALICE-TPC:

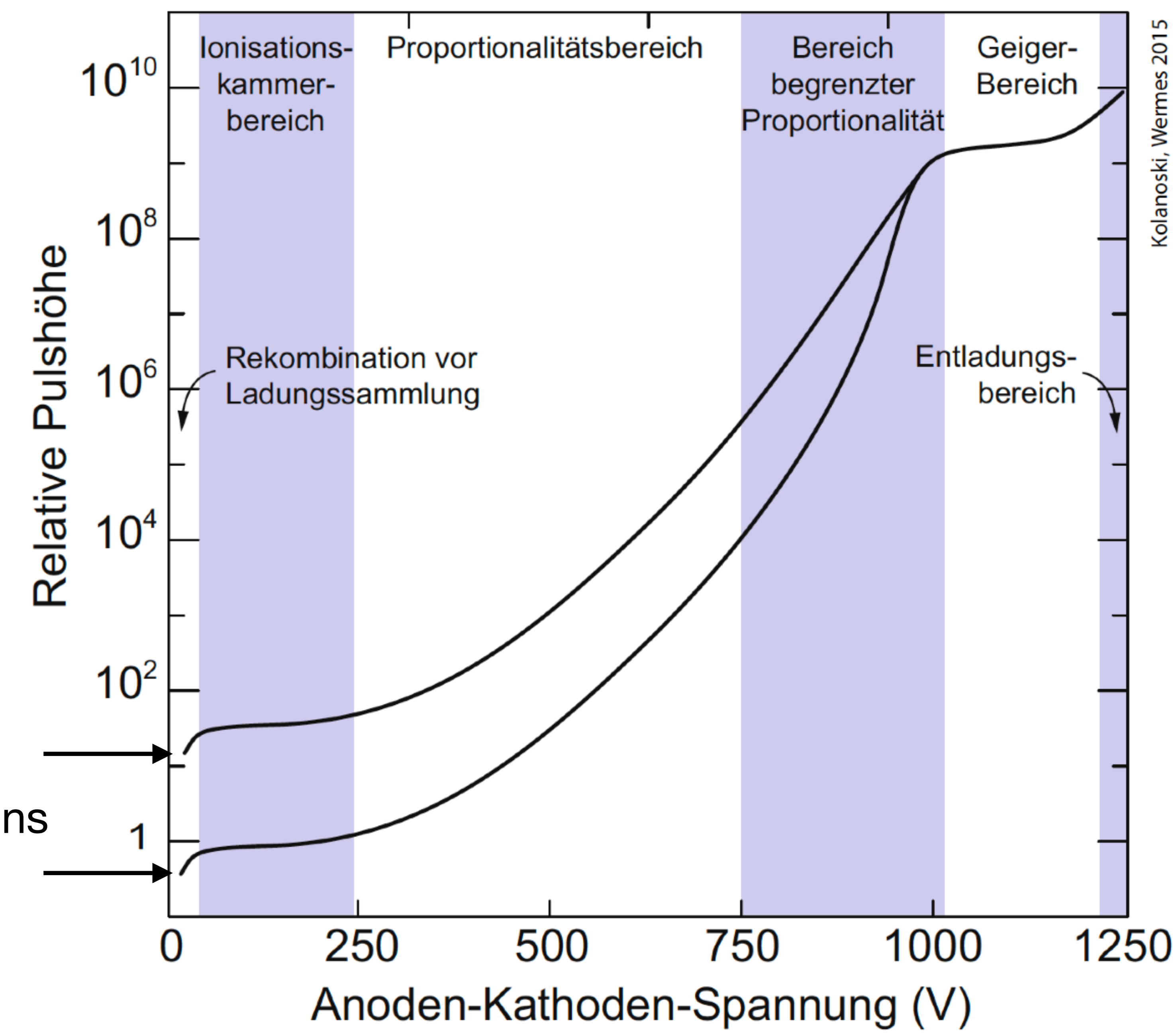


Readout chamber
Potential strips & guard rings below
HV membrane
HV insulation gaps

Gas amplification

so far we discussed this region

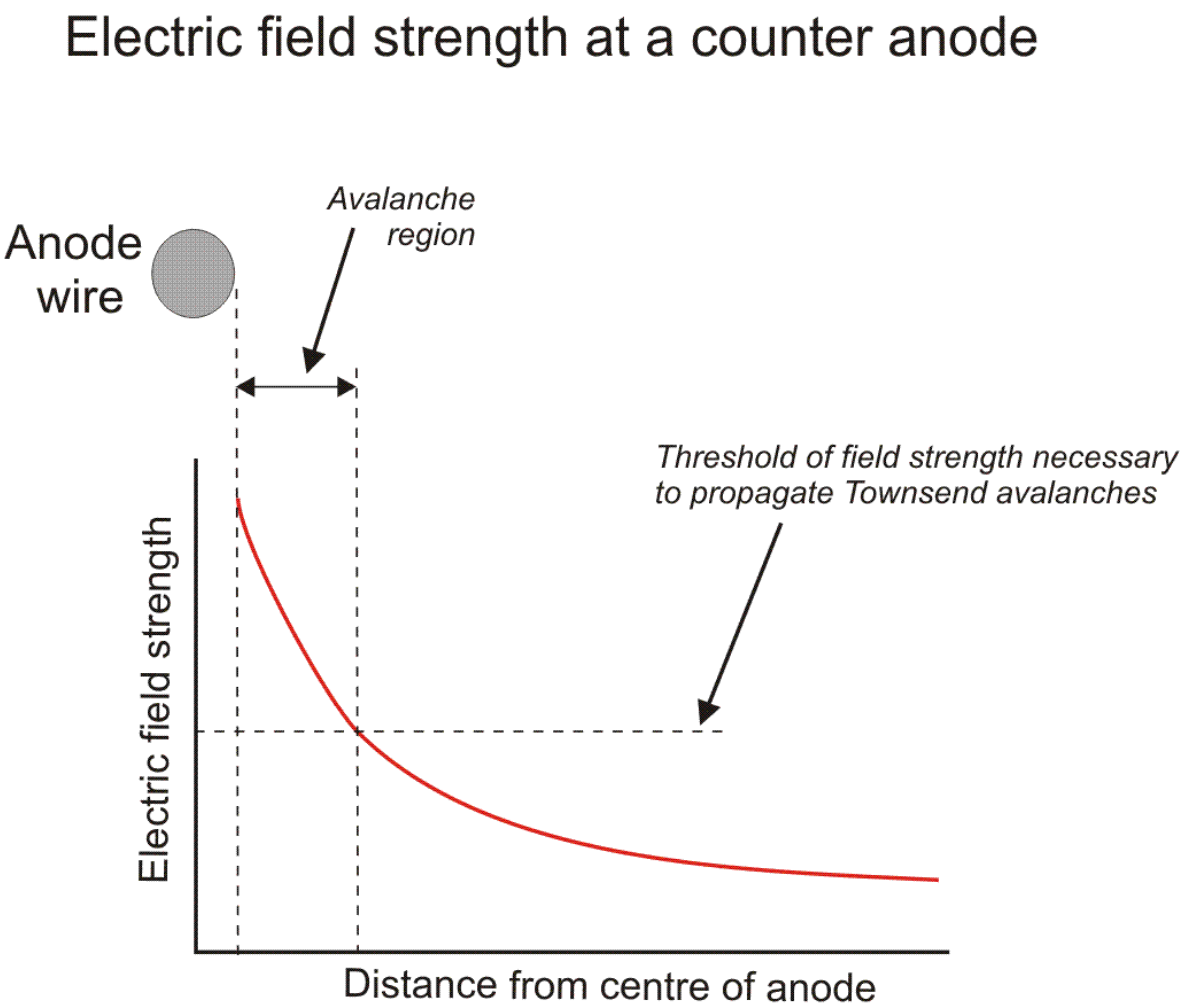
avalanches are created through secondary ionisation in stronger fields: amplification of the signal



two different primary ionisations

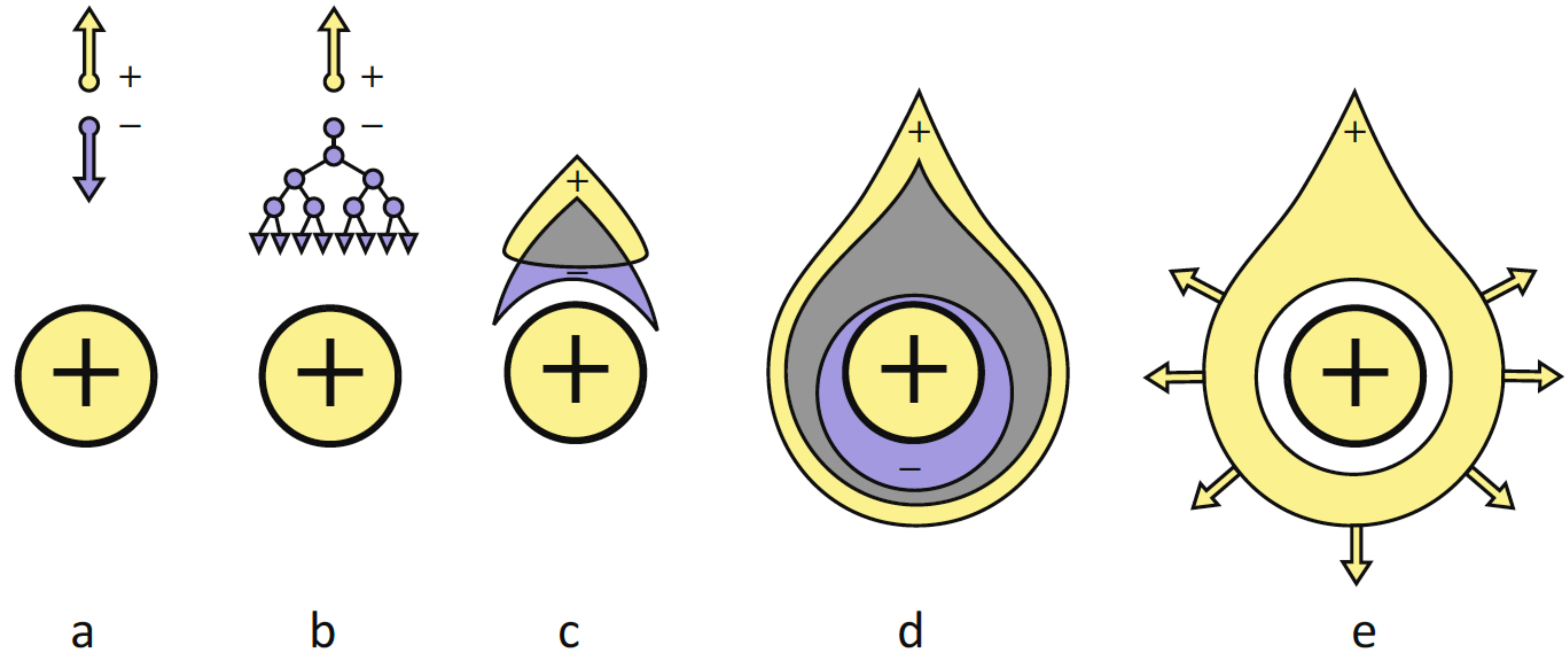
Gas amplification: field around wires

wire in proportional counter:



Gas amplification: field around wires

development of avalanche in proportional counter



primary electrons drift to anode	secondary ionisation close to anode, avalanche is created	charges in the avalanche are separated by E field	electrons diffuse faster than ions, avalanche goes around the whole wire	positive charges drift slowly to cathode

Gas amplification

- the ratio between number of final electrons *N* and number of primary electrons N_0 is the gas gain *G*:
- it can be calculated from the **1st Townsend coefficient** α which is the number of ionisations created by a free electron per distance unit

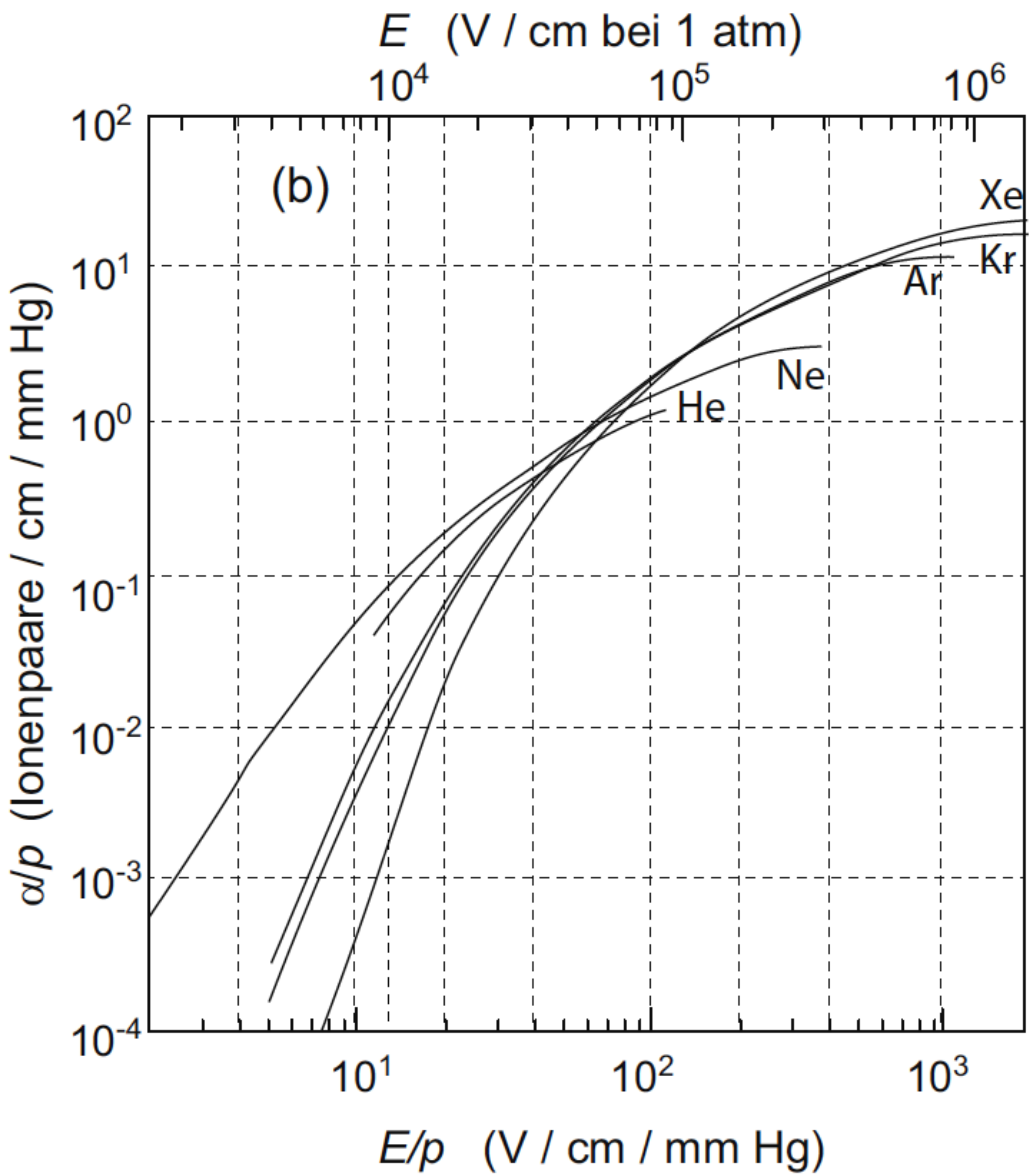
$$\alpha = \sigma_{ion} \cdot n = \underbrace{\sigma_{ion}}_{\text{Ionisation cross section}} \cdot \frac{N_A}{V_{mol}}$$

$$\sigma_{ion} = \sigma_{ion}(E) \Rightarrow \alpha = \alpha\left(\left|\vec{E}\right|\right) = \alpha(\vec{x})$$

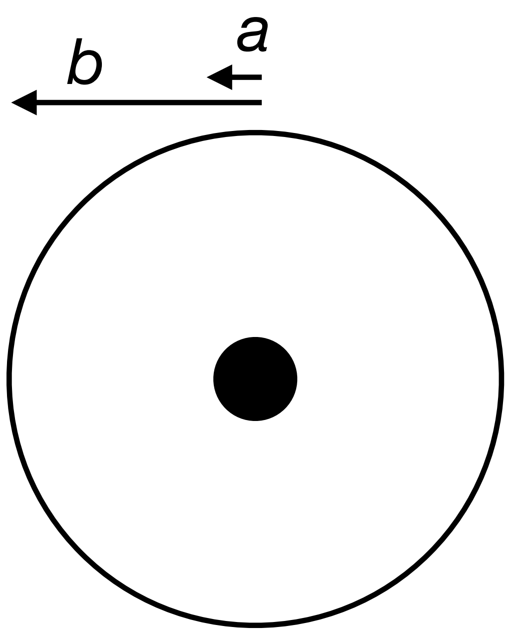
$$dN = \alpha N \, dx$$

$$N(x) = N_0 \exp\left(\int \alpha(x) dx\right) \equiv N_0 \cdot \overbrace{G}^{\text{Gas gain}}$$

Gas amplification: 1st Townsend coefficient



Example: cylindrical "proportional chamber"



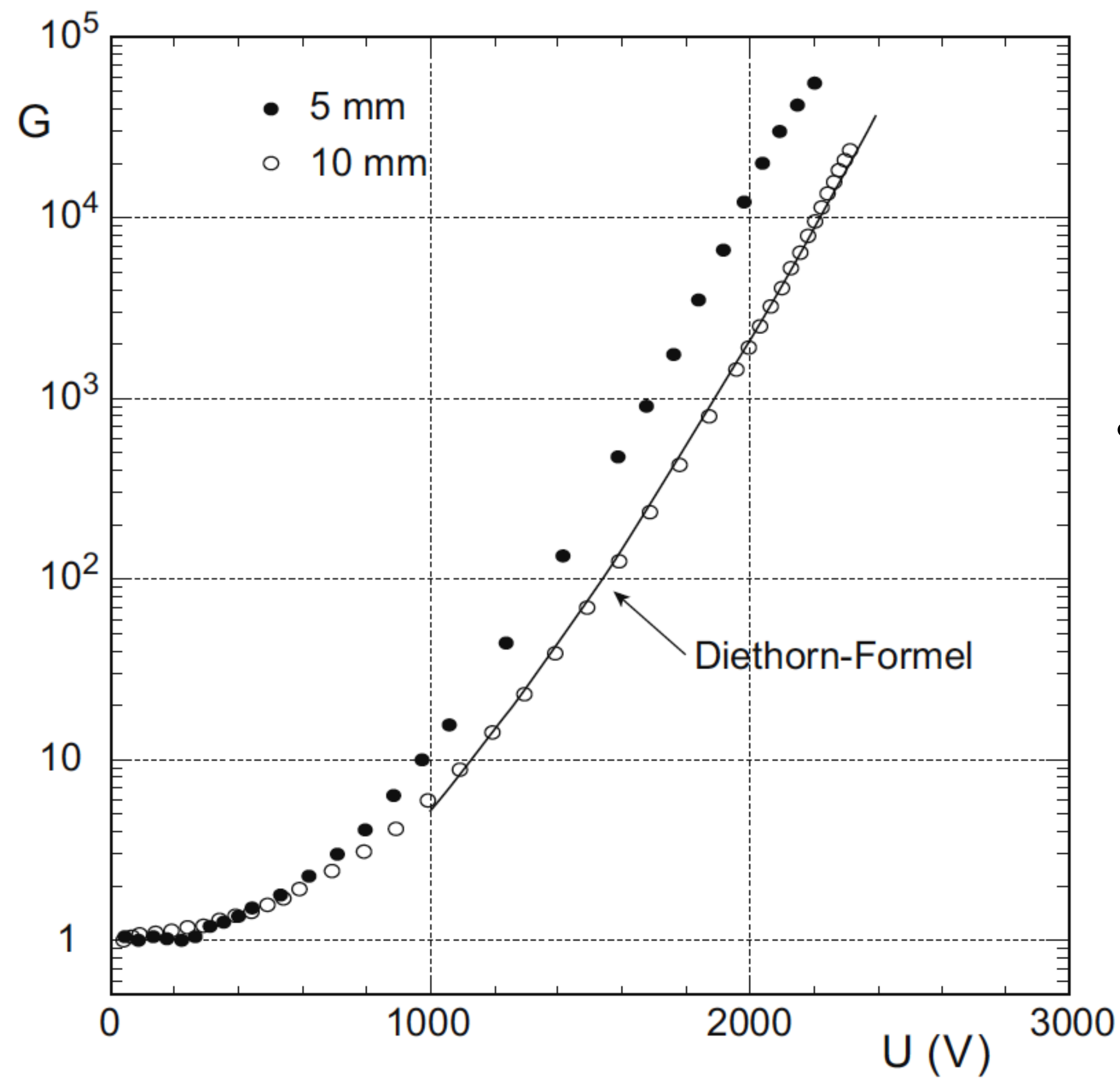
- anode wire diameter: 2*a*
- tube diameter: 2*b*
- electric field $E(r) = \frac{U}{r \ln \frac{b}{a}}$
- insert into expression for *G* (previous slides)
- some math and approximations lead to Diethorn formula:

$$\ln G = \frac{U \ \ln 2}{\ln \frac{b}{a} \Delta U} \ln \left(\frac{U}{a \ \ln \frac{b}{a} E_{min}(p_0) \frac{p}{p_0}} \right)$$

- where the Diethorn parameters ΔU and E_{min} depend on gas type and mixture and are usually measured
- example for CF4/CH4 mixture in 80:20 ratio: $\Delta U = 53.8 \text{ V}, \ E_{min} = 39.2 \, \text{kV/cm}$ (see plot next slide)

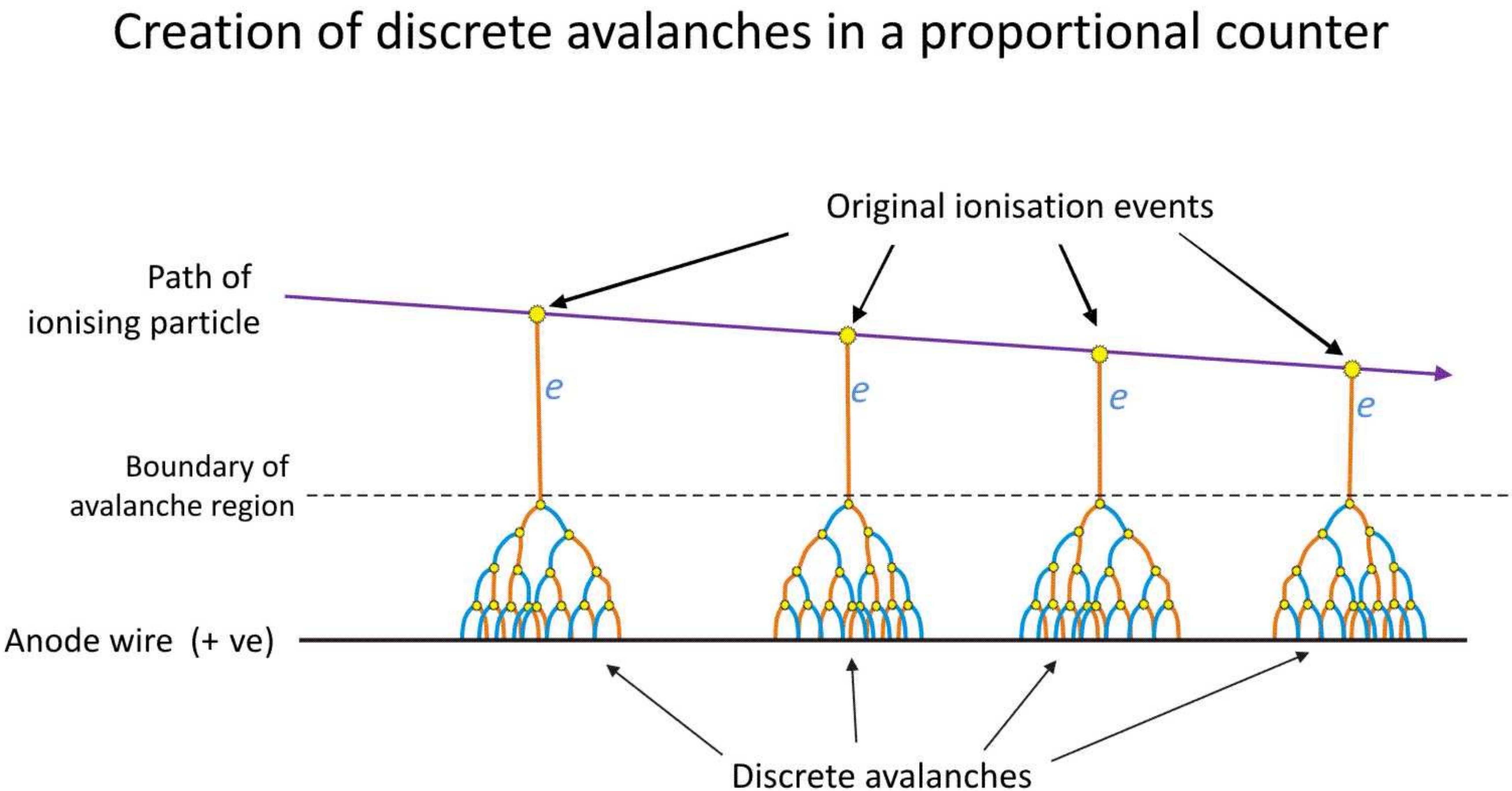
Example: cylindrical “proportional chamber”

- typical values for G are 10 (at U=1kV) and 10000 (at U>2kV)



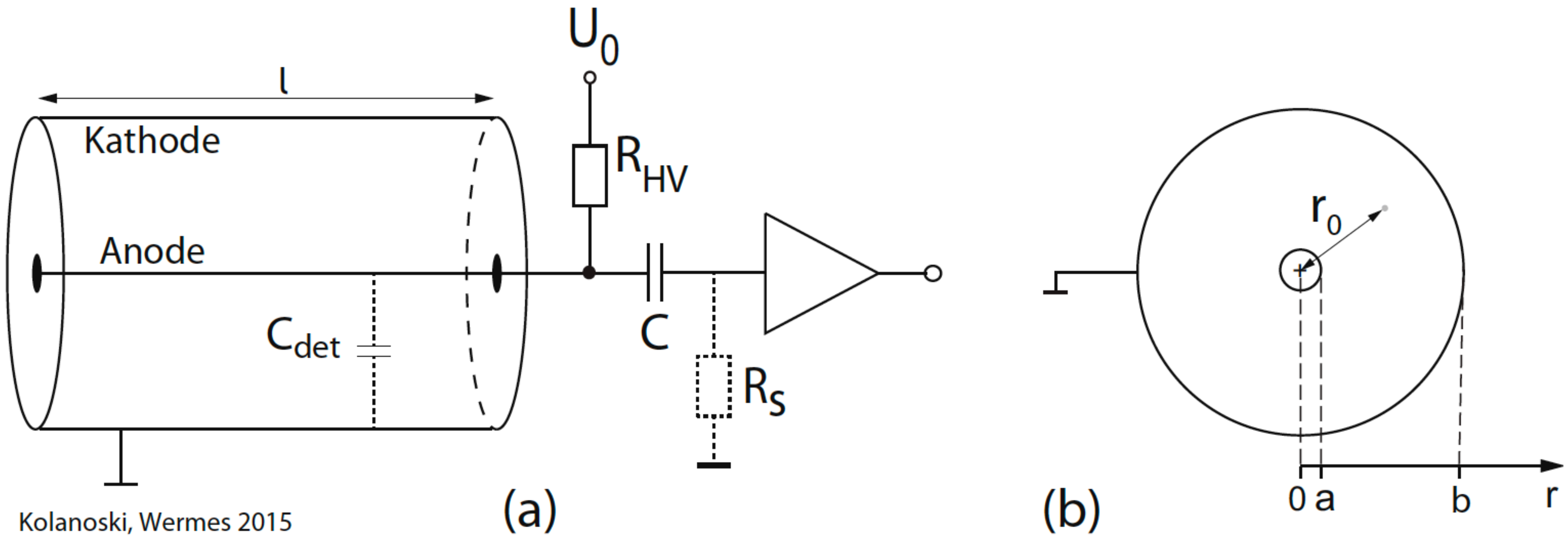
- CF4/CH4 mixture in 80:20 ratio:

Gas amplification: operating principle



➡N primary ionisations create N avalanches of GN charges

Signal formation: cylindrical proportional chamber



- fundamentally different from parallel drift chamber signal (see previous slides) because of avalanche close to the wire

- drift or primary ionisation negligible compared to secondary ionisation
- secondary ionisation happens only very close to wire → electrons are immediately absorbed by anode wire (small and short signal, almost negligible)
- the main signal is then created by ions that drift from the anode to the cathode
  - in the beginning the ions drift fast in a strong field
  - at larger distance, the drift gets slower

$$i_S^+(t) = \frac{Ne}{2\ln b/a}\frac{1}{t+t_0^+} \qquad \text{with} \qquad t_0^+ = \frac{r_0^2 \ln b/a}{2\mu^+ U_0}$$

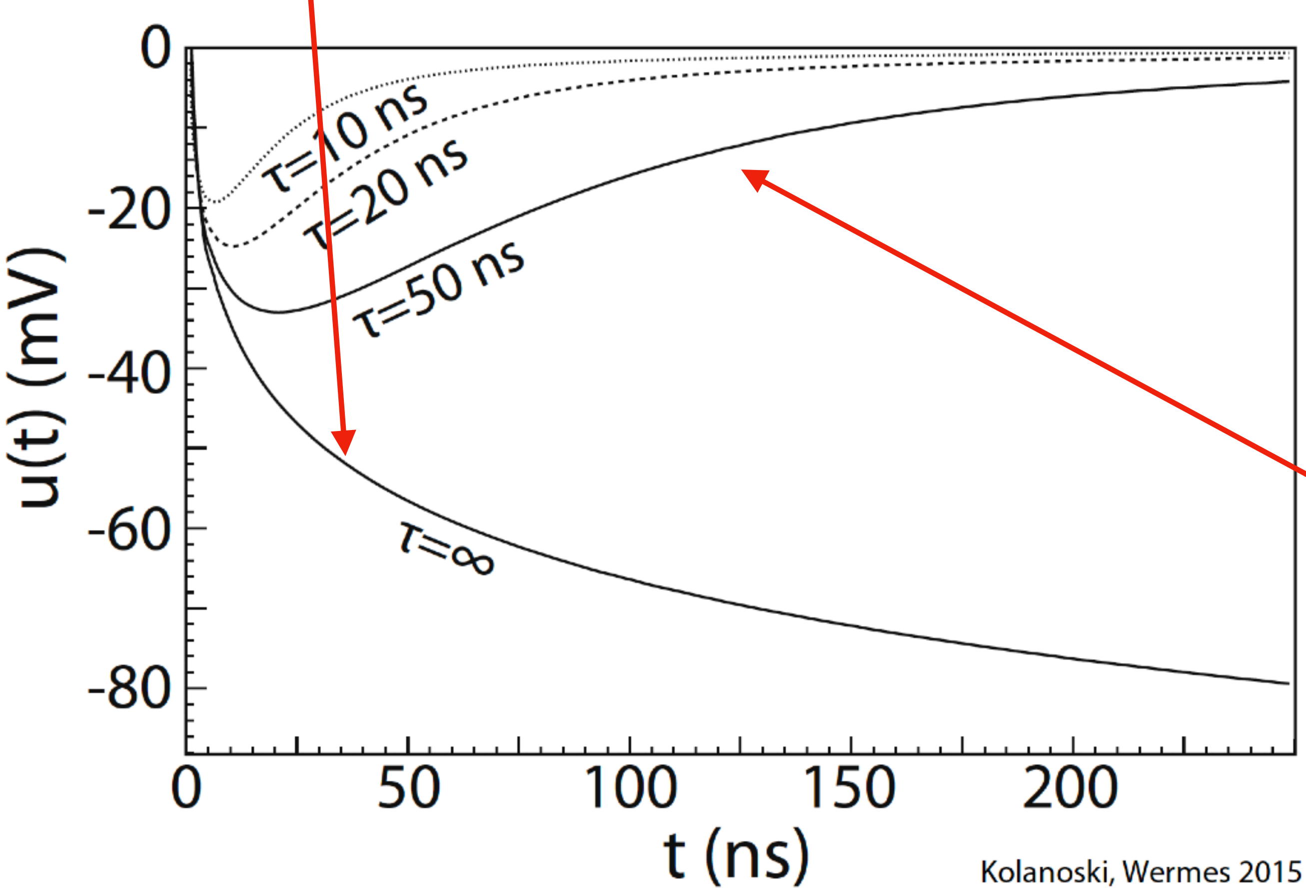
Signal formation: cylindrical proportional chamber

- the charge signal is obtained from integrating *i*

$$Q_S(t) \approx Q_S^+(t) = -\frac{N\,e}{2\ln b/a}\int_0^t \frac{dt'}{t'+t_0^+} = -\frac{Ne}{2\ln b/a}\ln\left(1+\frac{t}{t_0^+}\right)$$

- the voltage is obtained from the capacitance

$$u_s(t) = \frac{Q_S(t)}{C_l\,l} = -\frac{N\,e}{2\pi\epsilon_0\,l}\ln\left(1+\frac{t}{t_0^+}\right) \qquad \text{with} \quad C_l = \frac{2\pi\epsilon_0}{\ln b/a}$$



Kolanoski, Wermes 2015

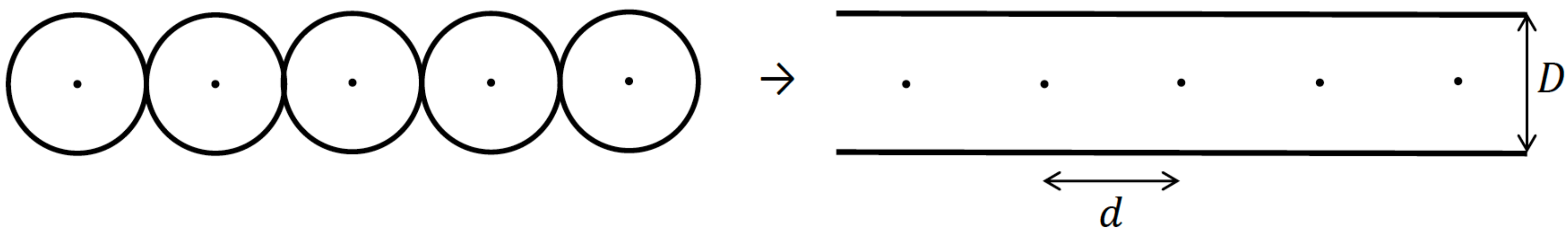
- this is very slow!
- experiments need to separate pulses which are close in time
- use resistance R_S (see picture last slide) to remove the voltage with time constant $\tau = R_S\,C_{det}$

Detector type: proportional chambers

Multi Wire Proportional Chambers (MWPC)

- 1968 developed by Charpak et al. (CERN) → nobel prize 1992

- It is a layer of proportional counters without seperating walls

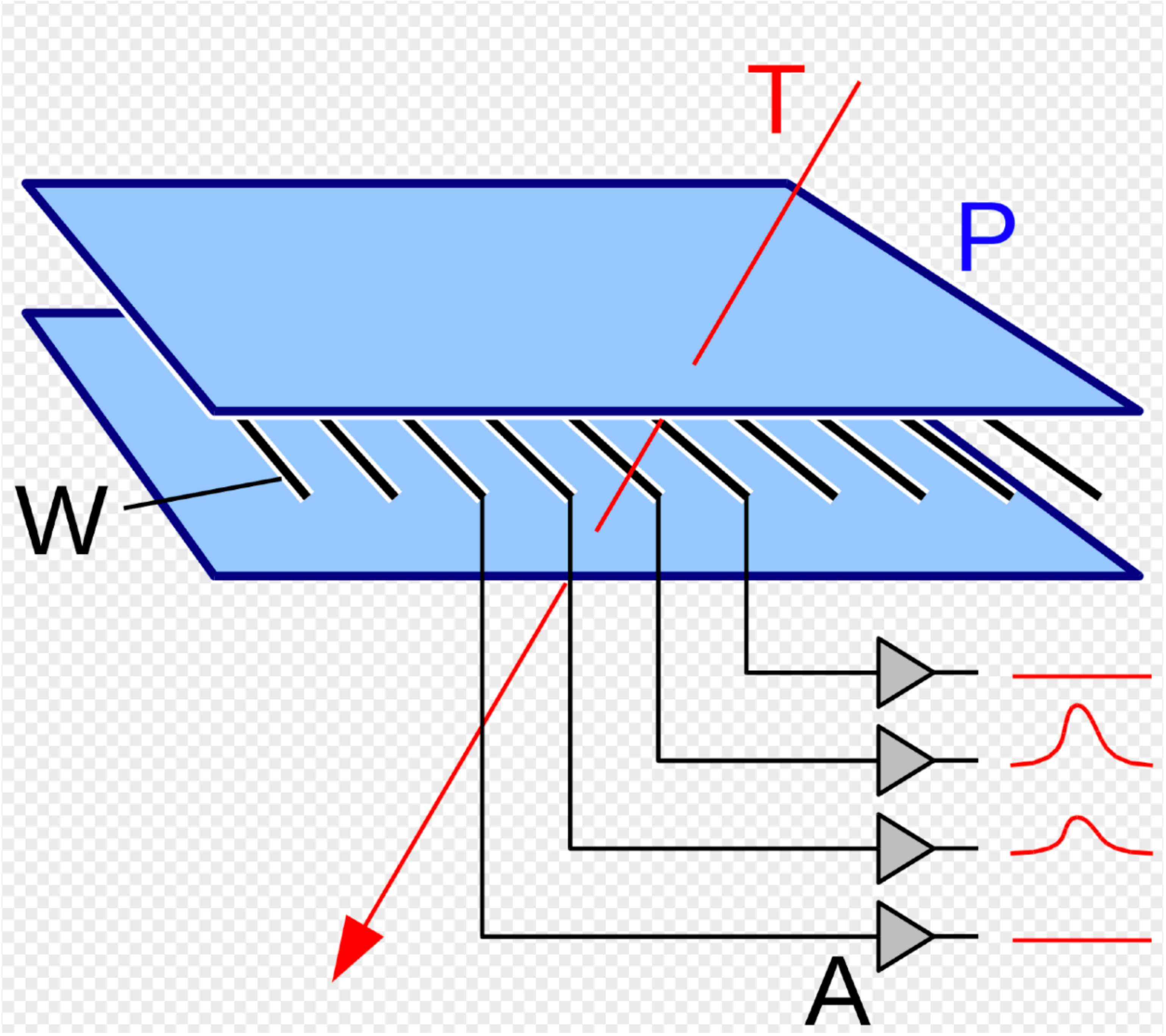


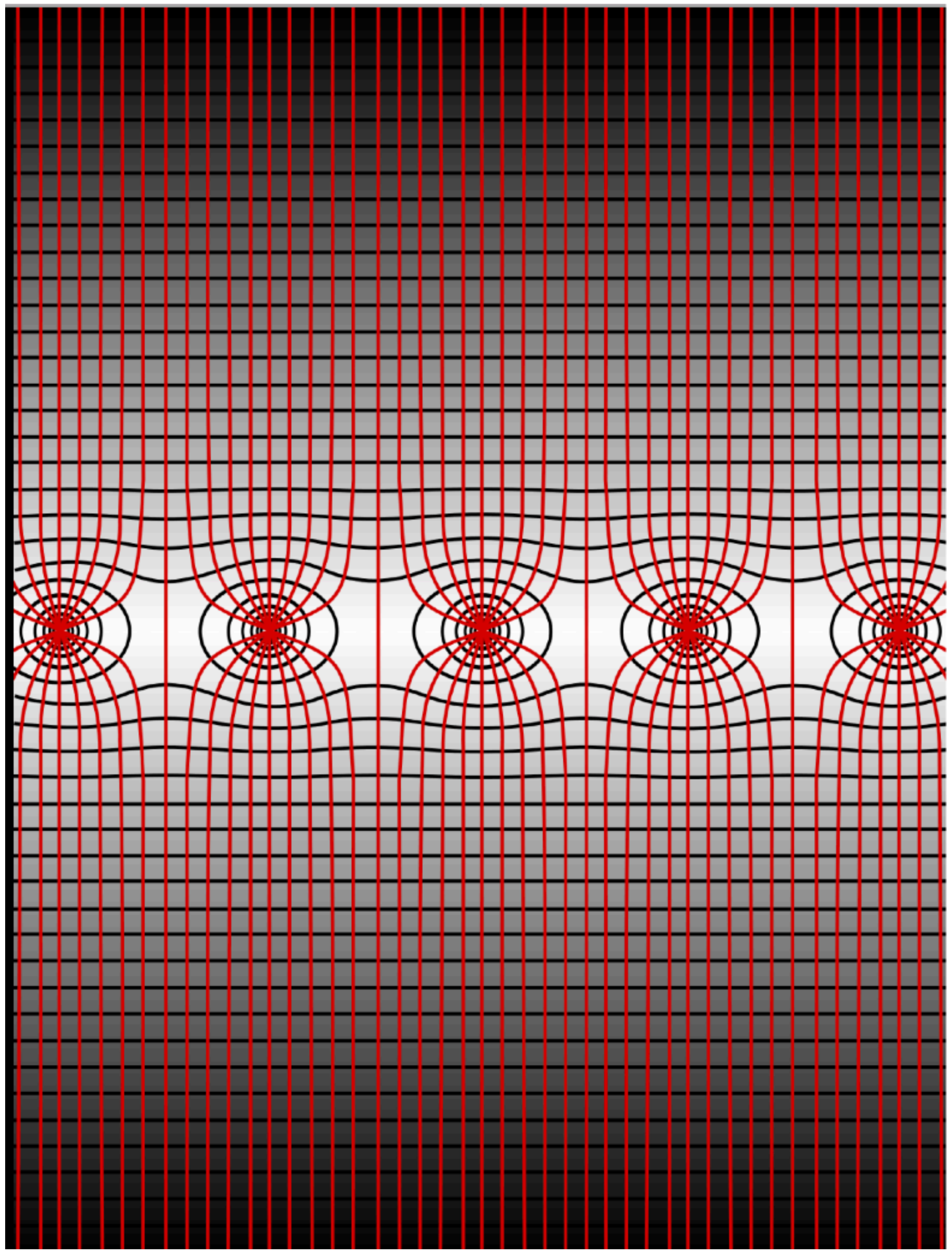
- Typical dimensions: $D \approx 10\,mm \quad d \approx 1-5\,mm$

- Position resolution: $\frac{1}{\sqrt{12}} d \approx 1\,mm$

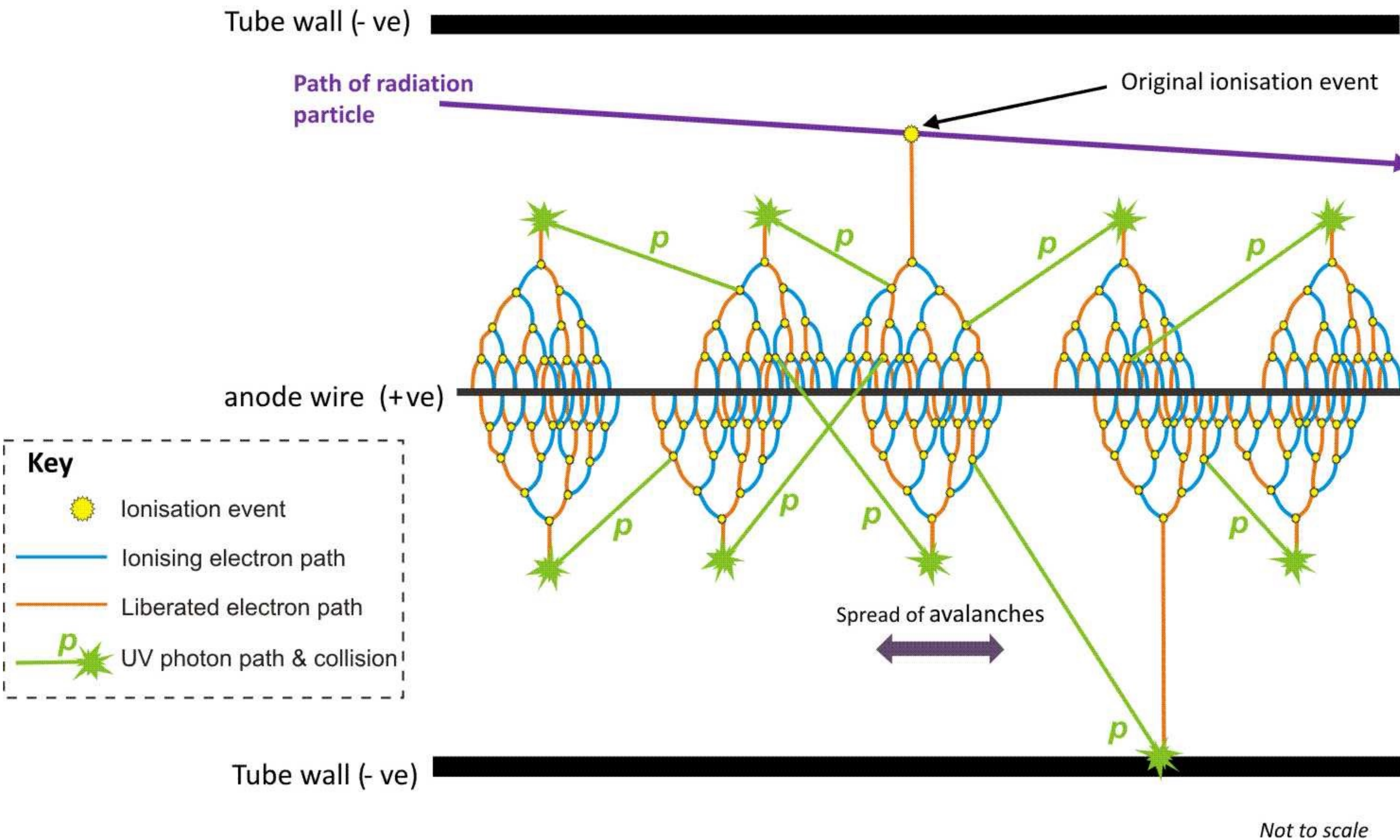
- At each wire electronic circuit → enables electronic data aquisition
  → first purely electronic detectors (advent of semiconductor electronics in 1960's)

Detector type: proportional chambers





Spread of avalanches in a Geiger-Muller tube



→useful only for "counting" of events

GEM: gas electron multiplier

- Voltage of $300 - 500\ V$ between both sides of perforated copper cladded capton foil
- High electric field inside holes yields gas amplification
- Triple GEM: $G \approx 10^5$
- Anode pads below GEM measure pure electron signal, can be kept at ground potential