

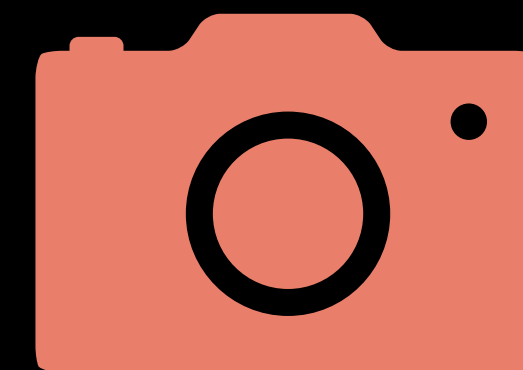
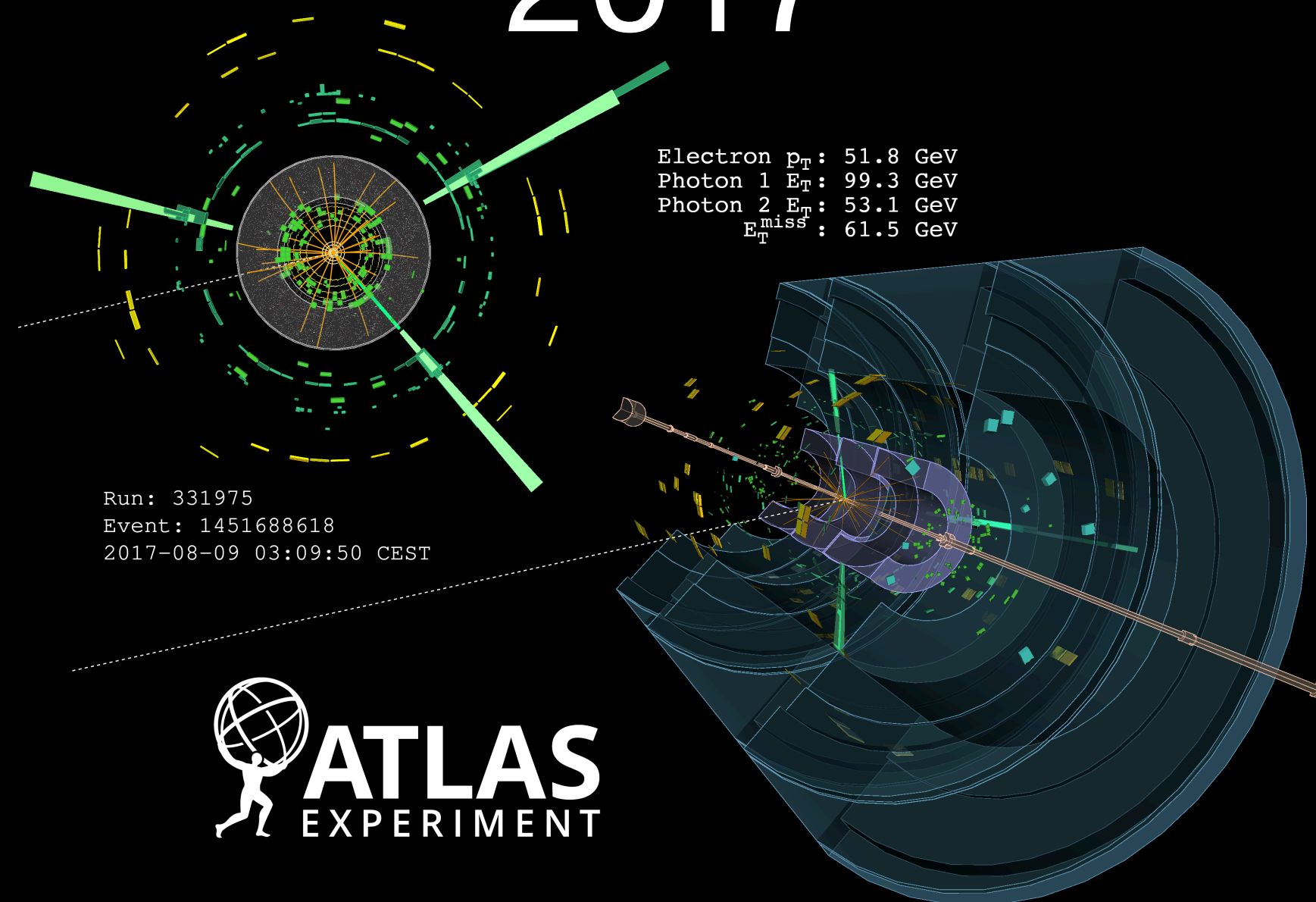
# PHYS 7363 - Experimental Particle Detection and Detectors I



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Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection and identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we “see” subatomic particles, this course is for you!

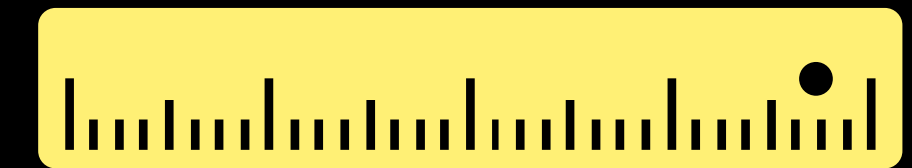
2017



Detect



Identify



Measure

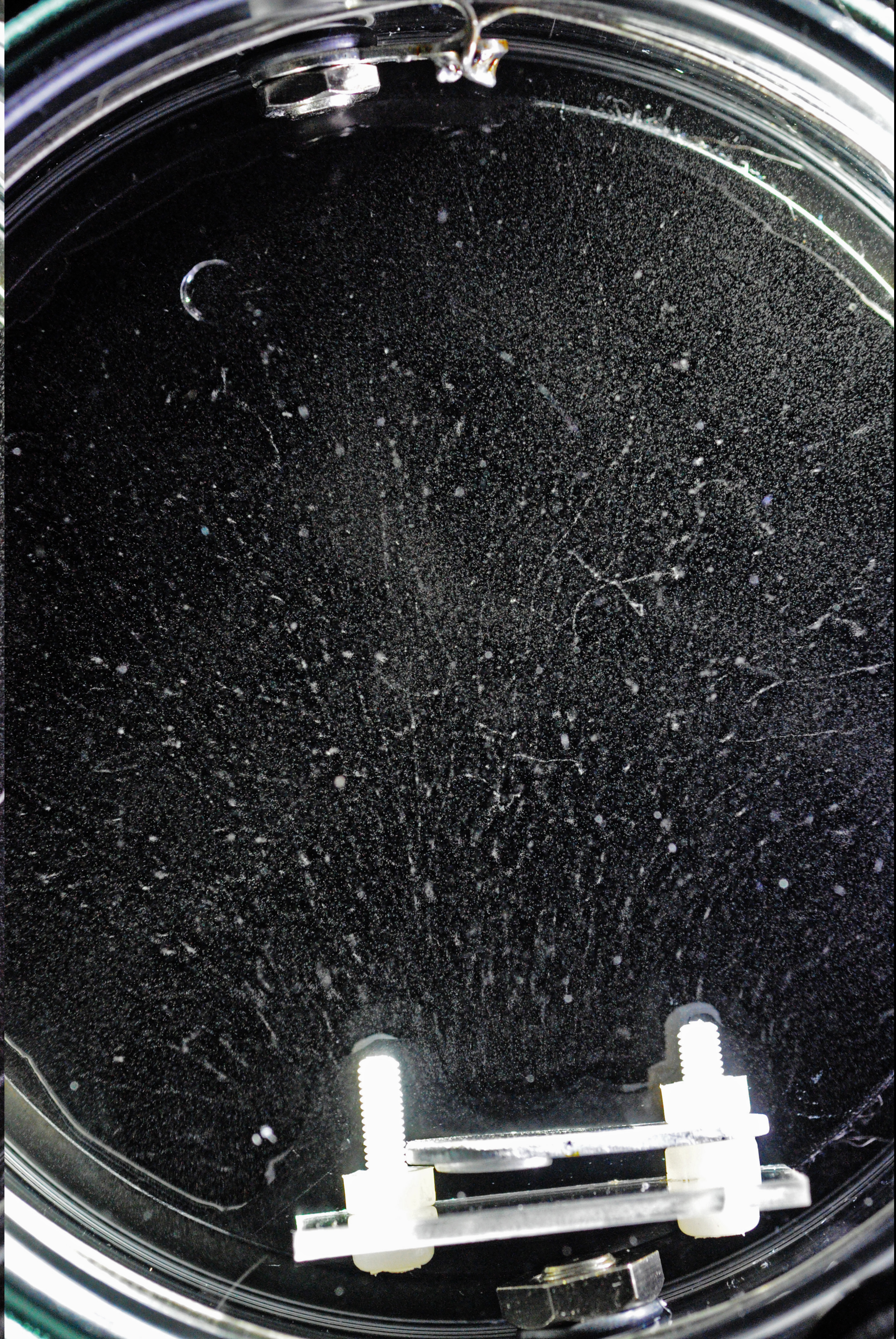
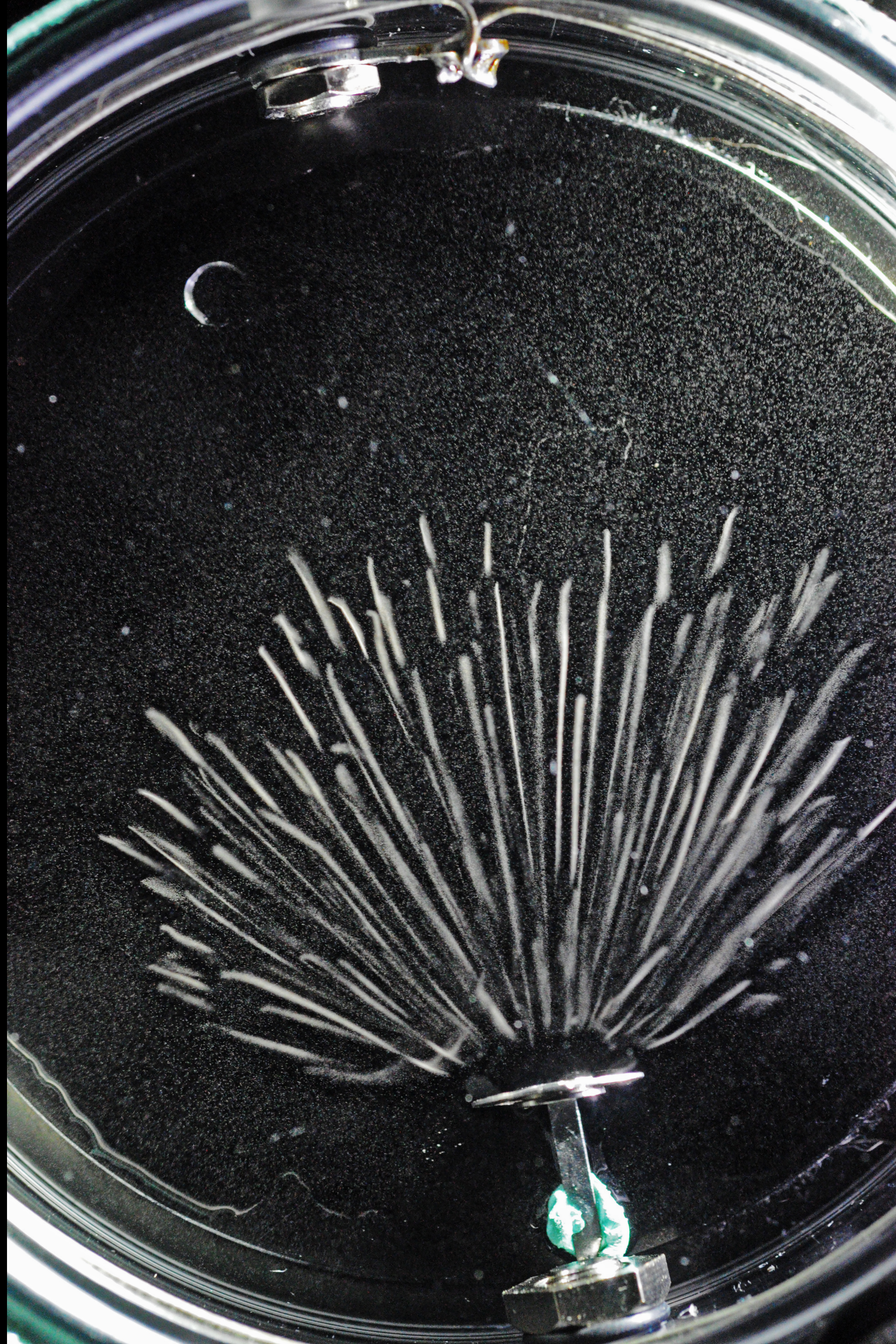
To discuss prerequisites (and any questions on the content of the course), please contact me: [saptaparnab@smu.edu](mailto:saptaparnab@smu.edu)



# Schedule

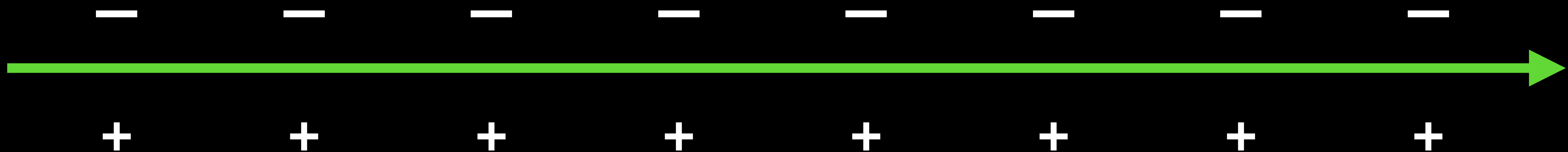
Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6 <input checked="" type="checkbox"/> 1.5 hours	7	8 <input checked="" type="checkbox"/> 1.5 hours	9	10	11	12
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	20	21	22	23 <input checked="" type="checkbox"/> 1.5 hours	24 <input checked="" type="checkbox"/> 1.5 hours	25	26
	27: Midterm	28	29 <input checked="" type="checkbox"/> 1.5 hours	30	31 <input checked="" type="checkbox"/> 1.5 hours	1	2
November	3 <input checked="" type="checkbox"/> 1.5 hours	4	5 <input checked="" type="checkbox"/> 1.5 hours	6	7 <input checked="" type="checkbox"/> 1.5 hours	8	9
	10 <input checked="" type="checkbox"/> 1.5 hours	11	12 <input checked="" type="checkbox"/> 1.5 hours	13	14 <input checked="" type="checkbox"/> 1.5 hours	15	16
	17 <input checked="" type="checkbox"/> 1.5 hours	18	19	20	21	22	23
	24	25	26	27	28	29	30
December	1	2	3	4	5	6	7
	8	9	10	11	12	13	14

Particle tracks from radioisotopes in an expansion cloud chamber: (Left) Alpha tracks from Am-241 source, with one beta track possibly from its daughter radionuclide, Pa-233. (Right) Beta tracks from Sr-90/Y-90 source.



# Basics of gas-filled detectors

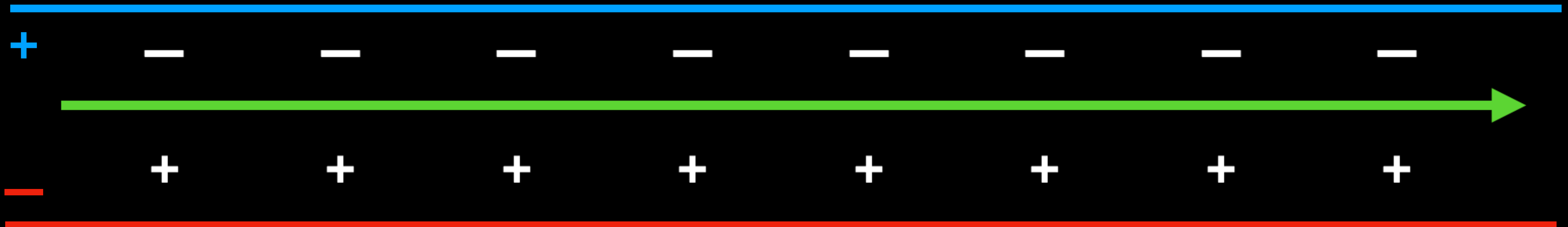
- Ionization of the detector gas
  - Signal is produced when charged particles ionize the gas in the detection chamber



- If the gas is neon, the positive member of each ion pair is a neon ion ( $\text{Ne}^+$ ), while the negative member of the pair is a freed electron ( $e^-$ )
- If the detector gas is air, the positive member of the ion pair is usually a positively charged nitrogen molecule ( $\text{N}_2^+$ ) and the negative member of the pair is a freed electron ( $e^-$ )

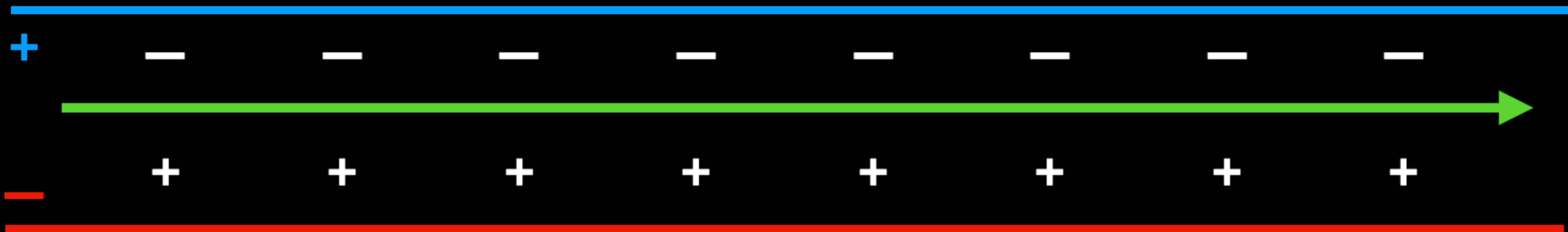
# Basics of gas-filled detectors

- Ion: charge is +, freed particle  $e^-$
- Absence of electric field: Ion pairs created in the gas of the detector simply recombine
- Presence of electric field:
  - If the ionization occurs between two oppositely charged electrodes, and if the electric field is sufficiently strong, the positive and negative parts of the ion pairs will separate and be collected at the electrodes



# Electrodes

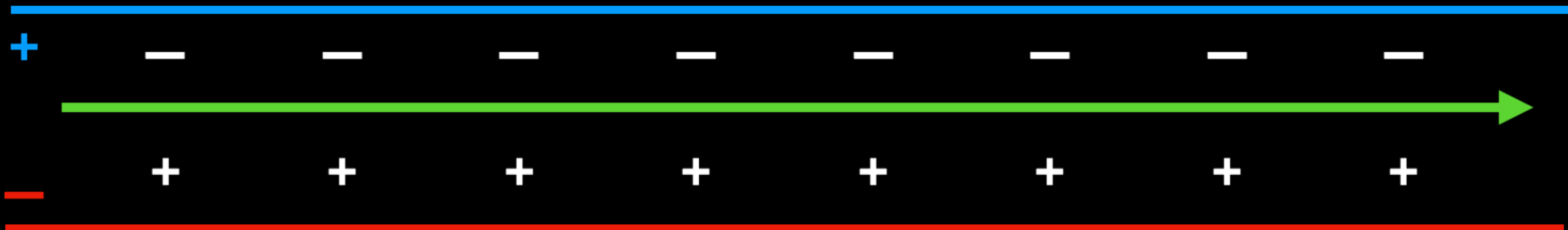
- An electric field is established by creating a potential difference between two electrodes
- The potential difference is the voltage applied across the electrodes
  - Anode: the positively charged electrode
  - Cathode: the negatively charged electrode



# Electrodes — common configurations

- General electrode configurations: parallel plate electrodes
  - Variations possible (coaxial electrodes)
- Parallel plate electrodes are used in ionization chambers
- Uniform electric field:

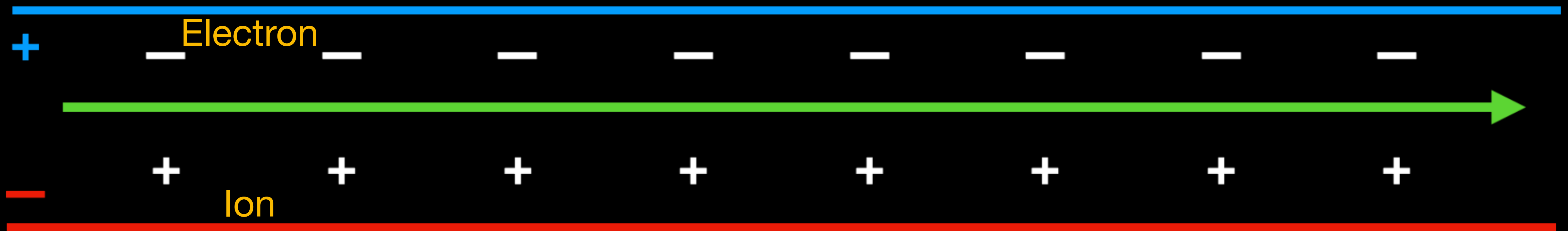
- Electric field strength (volts/m):  $\xi = \frac{V}{d}$ ,  $V =$  potential difference,  $d =$  distance between the two plates



# Drift velocity

- When the electric field is sufficiently large, ion pairs don't recombine
  - Electrons move to the anode
  - Positively charged gas ions move to the cathode

Anode



Cathode

# Drift velocity

- The drift velocity is the velocity at which the ions move towards the electrodes
- Given by the following formula:
  - Drift velocity ( $\nu$ ) =  $\mu \frac{\xi}{\rho}$
  - $\xi$ : electric field strength
  - $\nu$ : drift velocity
  - $\mu$ : mobility factor
  - $\rho$ : gas pressure
- As the positive ions and electrons move to the electrodes, they collide with various gas molecules and sometimes transfer their charge to those molecules (depending on the latter's electronegativity)
- If an electron collides with a highly electronegative molecule (e.g.  $O_2$ ), the electron will be captured and the now negatively charged gas molecule rather than the electron proceeds to the anode

# Particle Responses

- For typical gas detectors (as the detectors used for low energy experiments),  $\beta$ -particles usually transfer a small portion of their energy to the detector gas
  - a typical electron/beta particle produces 100 ion pairs per cm of travel, a 1 MeV electron might have a range of 300 cm (The average energy lost by a charged particle per ion pair produced is approximately 34 eV)
- It is possible for some alpha particles to expend all their energy in the detector gas
  - A typical  $\alpha$  particle (He-4 nucleus) produces 40,000 ion pairs per cm. A 6 MeV  $\alpha$  particle will have a range of about 4.5 cm
- Photons might interact directly with the detector gas, but they are more likely to interact with the detector wall (the cathode)
- In some of these interactions, an electron is “knocked off” the detector wall.
  - This electron then traverses the gas inside the detector chamber
  - This electron might, or might not, have sufficient energy to cause further ionizations

# Particle Responses

- With ion chambers and proportional counters, the magnitude of the detector signal depends on the number of ion pairs produced in the gas by the incident charged particle
- Generally:
  - $\alpha$  particles produce the largest signal
  - $\beta$  particles produce the small signal
  - $\gamma$  produce the smallest signal

# Modes of operation

- A gas detector can operate in one of the two modes:
  - Current mode
  - Pulse mode

# Current mode of operation

- In the current mode, the system measures the current from the detector chamber rather than count the pulses
- If current is measured in units of amperes, then,
  - 1 ampere = 1 coulomb per second
- Current is charge per unit time or Coulombs per second
  - $I = Q/t$
  - $I$  is the current
  - $Q$  is the charge collected (coulombs)
  - $t$  is the time (seconds)
    - $Q = ne$
    - $n$  = number of collected electrons
    - $e$  = charge of each electron ( $1.6 \times 10^{-19}$  C)

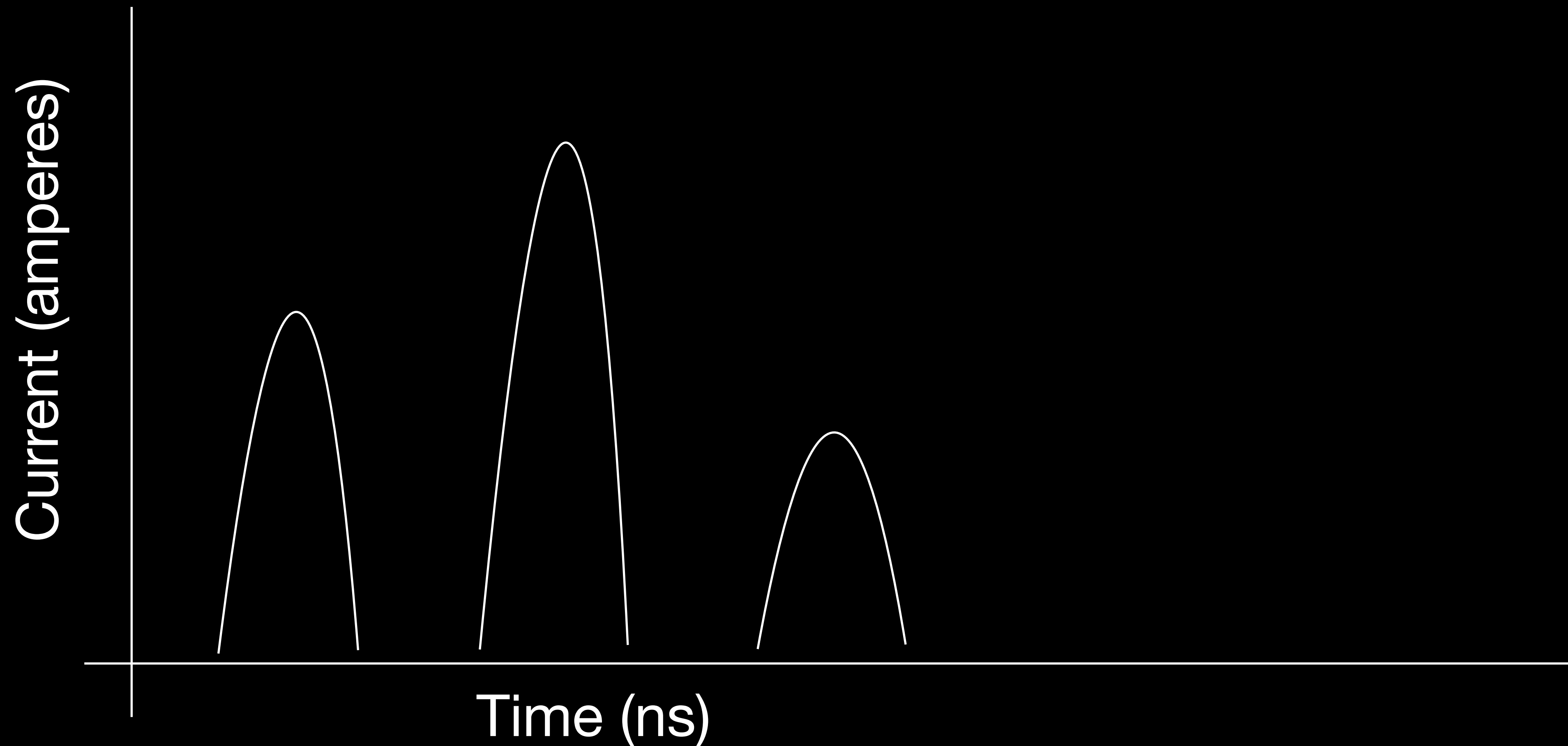
# Current mode of operation

- If one million electrons are collected by the anode over a time period of 10.7 ns, what is the current?
- If it took, 8 ns for the electrons to reach the anode, what is the current?
- If it took, 16 ns, the current is?

**In each of these three cases, exactly the same amount of ionization occurred in the detector gas and exactly the same charge was collected at the anode**

# Current mode of operation

- Defining the total charge as the area under the curve:
  - Charge (coulombs) = current (amperes) X time (sec)



# Pulse mode of operation

## Pulse characteristics: voltage (V)

- As long as the detector gas is not ionized, the potential difference between the anode and cathode is constant
- During the movement of the electrons and positive ions to the electrodes, the potential difference decreases
- After some period of time, the voltage stops decreasing and returns to the baseline voltage
- This decrease and recovery in the voltage is the pulse. The maximum change in the voltage is the pulse height (amplitude)

# Pulse mode of operation

## Pulse characteristics: current ( $I$ )

- The movement of electrons to the anode induces a current from the anode during each pulse
- The magnitude of the current depends on the pulse charge and the duration of the pulse
- $I = Q/t$  ( $I$  is the current (amperes),  $Q$  is the charge in coulombs,  $t$  is the time in seconds)

# Pulse mode of operation

## Pulse characteristics: charge ( $Q$ )

- The charge ( $Q$ ) of the pulse is the charge of the electrons reaching the anode
  - $Q = ne$  ( $Q$  is the charge in coulombs,  $n$  is the number of electrons reaching the anode,  $e$  is the charge of an electron)
- The charge is the only pulse characteristic that is always related to the energy deposited in the detector gas

# Pulse mode of operation

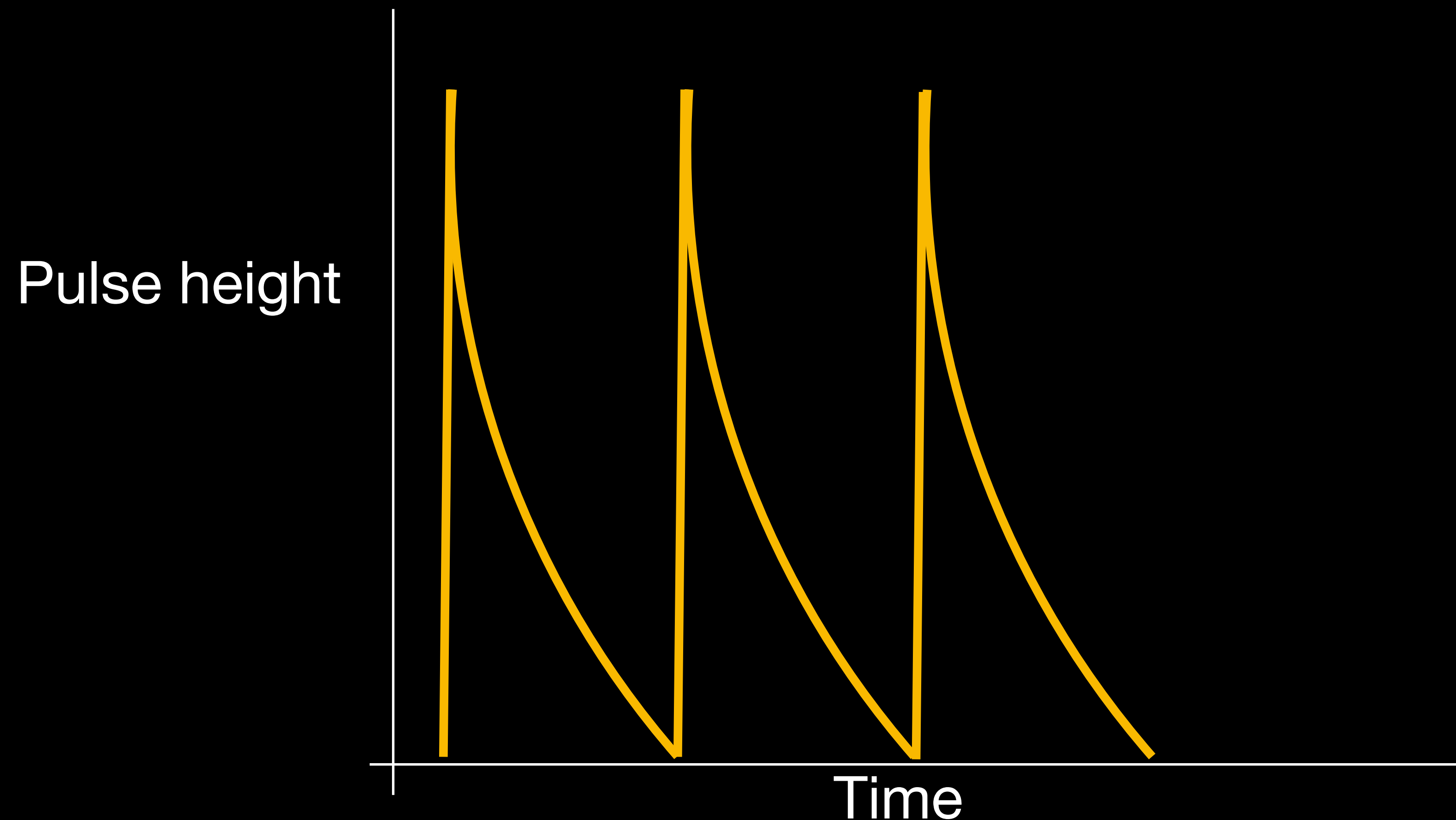
## Analyzing the pulses

- When a detector operates in the pulse mode, we might:
  - Count the pulses
  - Measure the pulse height (amplitude)
- For the pulse height to carry useful information about the energy deposited in the detector gas, it must be directly related to the collected charge
- Need to make a judicious choice of the time constant ( $\tau$ ) for the pulse height to be related to the collected charge
  - Time constant ( $\tau$ )  $\gg$  charge collection time

# Pulse mode of operation

## Relating pulse height to the total collected charge

- Time constant ( $\tau$ )  $\gg$  charge collection time



The output pulse from the detector is negative, i.e., the voltage decreases. Nevertheless, it is common to illustrate the pulse as if it were positive

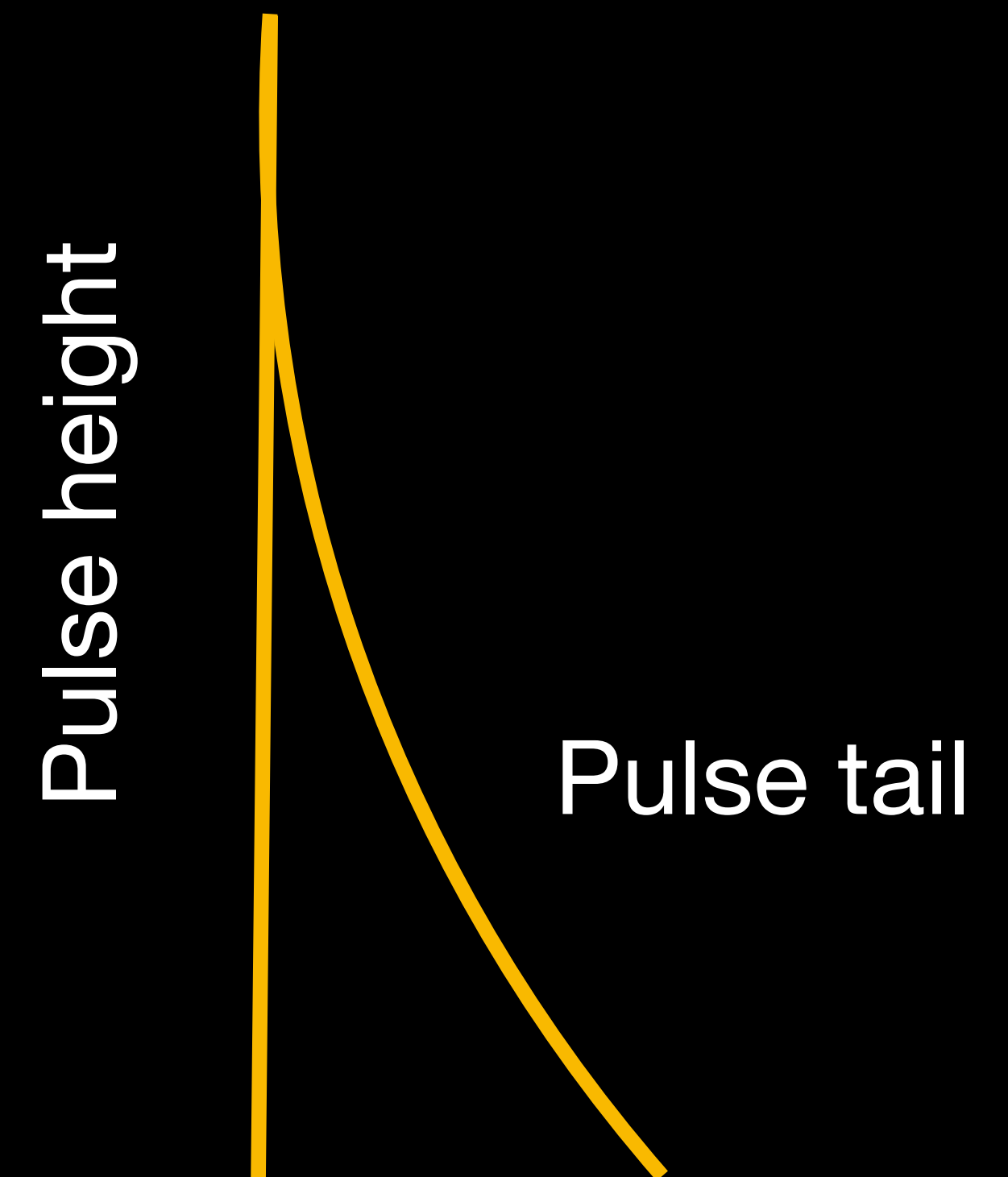
# Pulse mode of operation

## Pulse Rise and the Maximum Voltage

- Time constant ( $\tau$ )  $\gg$  charge collection time
- The time that the pulse takes to reach its maximum voltage (rise time) is determined by the charge collection time
- When the maximum voltage is directly related to the collected charge:

- $$V_{max} = \frac{Q}{C}$$

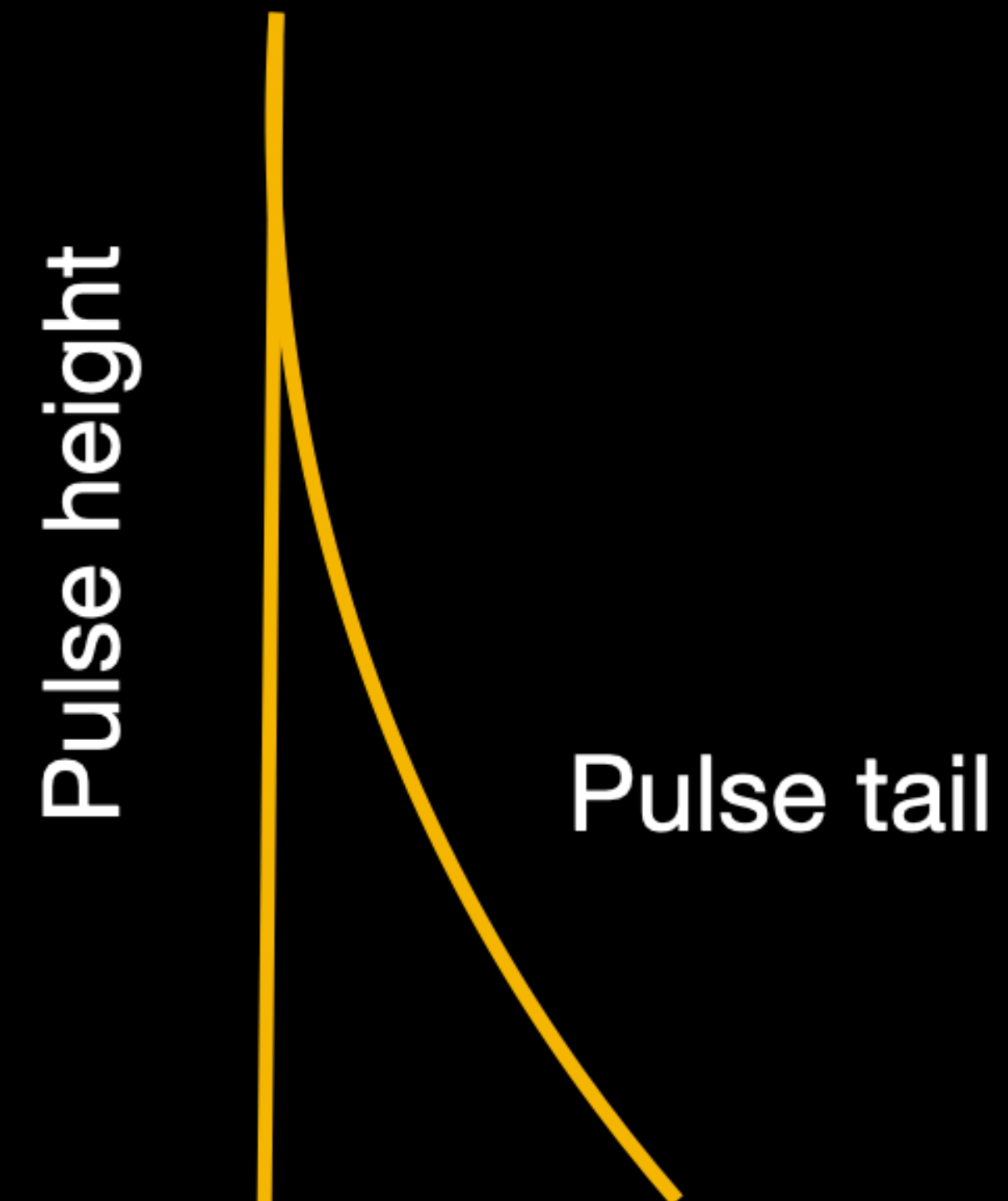
- $V_{max}$  = maximum voltage decrease (volts)
- $Q$  is the charge collected by the anode (coulombs)
- $C$  is the detector capacitance (farads)



# Pulse mode of operation

## Pulse tail and the time constant

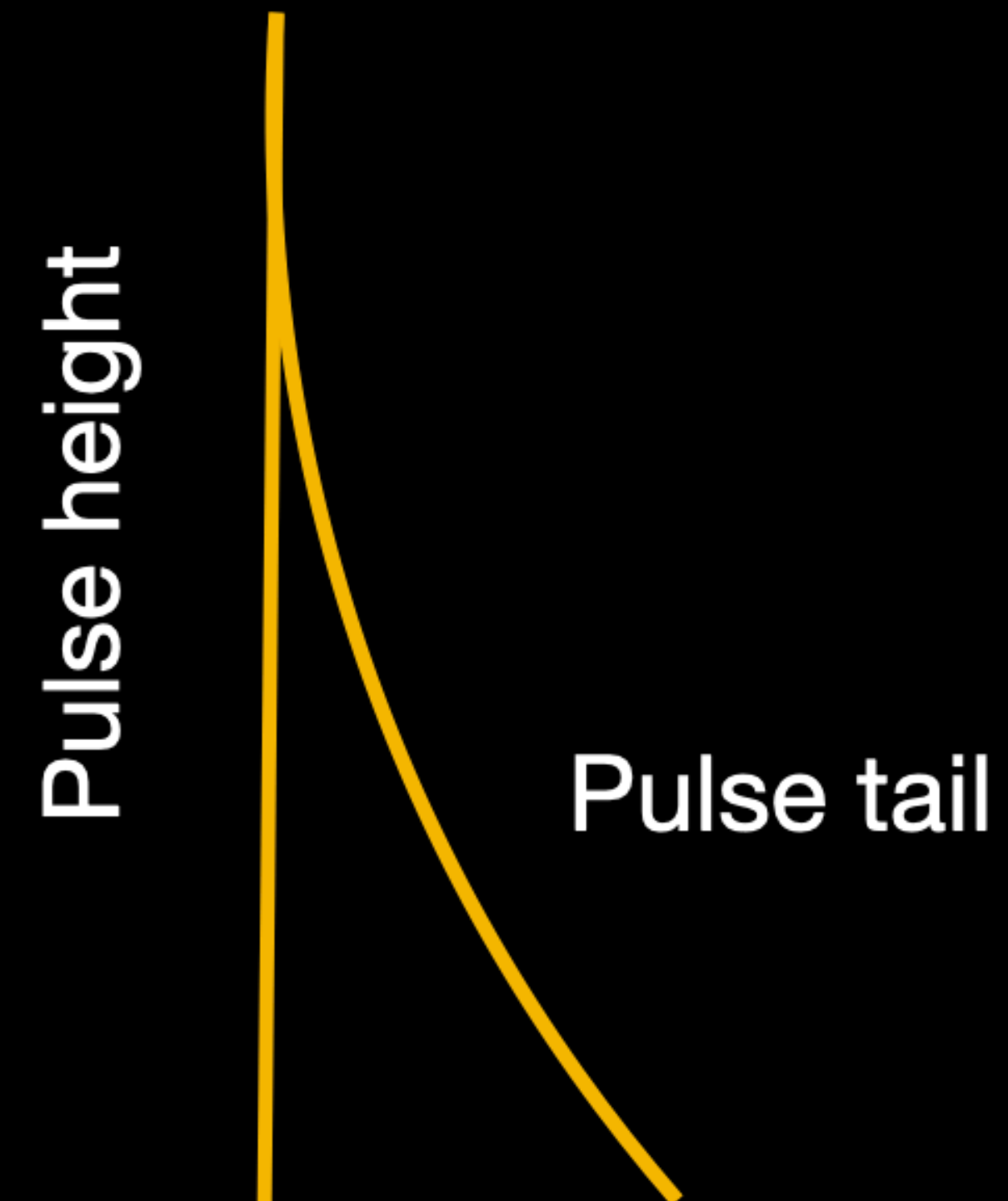
- The rate at which the pulse returns to the baseline voltage is controlled by the electronic characteristics of the system
- Specifically the length of the pulse tail is determined by the time constant:
  - $\tau = RC$
  - $\tau$  is the time constant (seconds)
  - $R$  is the circuitry input resistance (ohms)
  - $C$  is the circuitry and detector capacitance (farads)



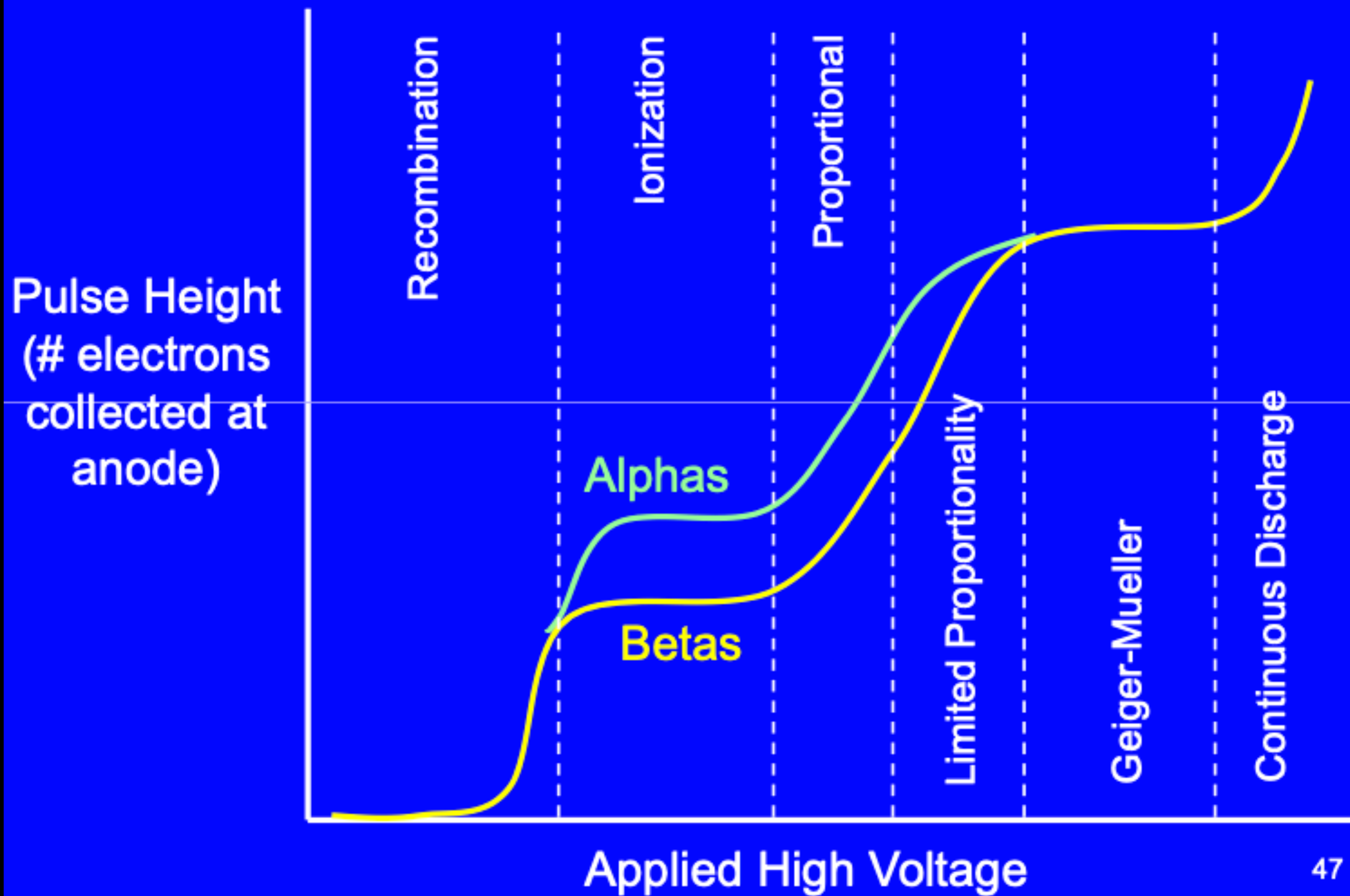
# Pulse mode of operation

## Pulse tail and the time constant

- $V_t = V_{max} e^{-\frac{t}{\tau}}$
- $V_{max}$  = maximum voltage at time  $t=0$
- $V_t$  is the tail's voltage at time  $t$
- $\tau$  is the circuitry time constant



# The Six Region Curve



# Region 1: Recombination Region

- **Recombination region:**
  - At the lowest voltages, the strength of the electric field is sufficiently low that many of the primary ion pairs created in the gas by the incident charged particle simply recombine
  - If no electrons reach the anode, there is no pulse

# Region 2: Ionization Region

- **Ionization region:**
  - In the ionization region, the electric field is just strong enough to prevent recombination of the ion pairs produced in the gas
  - At least one electron reaches the anode for each primary ion pair created by the incident radiation

# Region 3: Proportional Region

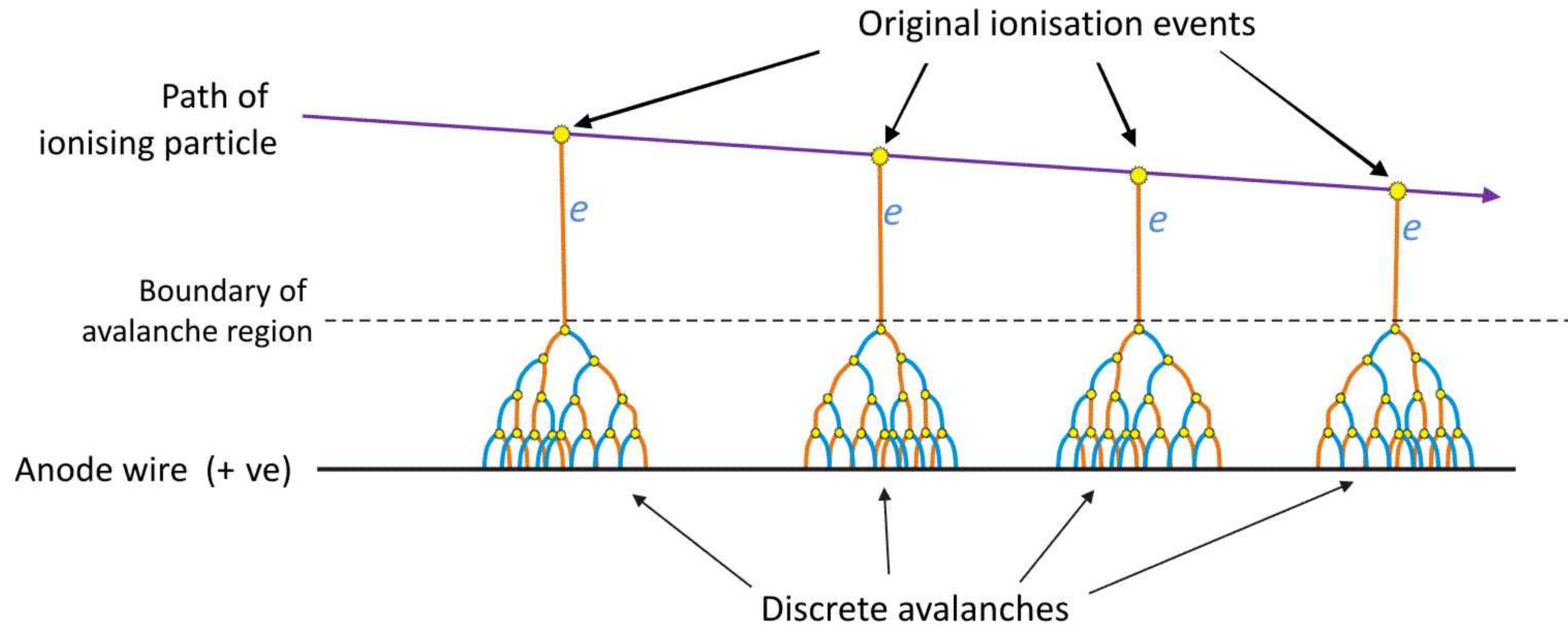
- **Proportional region:**
  - The applied high voltage is greater and the electric field is substantially stronger than in the ionization region
  - When the electric field is strong, electrons gain enough kinetic energy to create secondary ion pairs
  - The electrons produced in these secondary ion pairs, along with the primary electrons, continue to gain energy as they move towards the anode, and as they do, they produce more and more ionizations

# Region 3: Proportional Region

- **Proportional region:**
  - The result is that each electron from the primary ion pairs produces a cascade, or avalanche of ion pairs (Townsend avalanche)
  - For every primary ion pair created in the chamber by the ionizing radiation,  $10^2$  to  $10^4$  electrons reach the anode
  - The increase in the number of electrons is referred to as the multiplication factor
  - As the high voltage increases, the distance from the anode at which the field strength exceeds  $10^6$  V/m increases
  - As the avalanches are initiated further away from the anode, the multiplication factor (and pulse size) increases

# Basic principle

Creation of discrete avalanches in a proportional counter



# Region 4: Region of Limited Proportionality

- **Region of Limited Proportionality**
  - The high voltage and the multiplication factor are larger than in the proportional region
  - What is now different is that pulse size is no longer linearly related to the number of primary ion pairs produced by the incident radiation. In other words, doubling the number of primary ion pairs, doesn't double the pulse size
  - This increases the uncertainty of using pulse size to distinguish different types of radiation

# Region 5: Geiger-Mueller Region

- Geiger-Mueller Region

- At the high voltages associated with the Geiger-Mueller Region, the avalanche spreads along the complete length of the anode
  - avalanches not only involve ionization, they also involve the excitation of gas molecules. When excited molecules in an avalanche de-excite, they can emit UV photons
- In this region, the size of the pulse is totally independent of the number of primary ion pairs produced by the incident radiation
- In other words, alpha particles, beta particles and photons produce pulses of exactly the same size
- There is a complete loss of proportionality between the radiation energy deposited in the detector gas and the pulse size

# Region 6: Continuous discharge

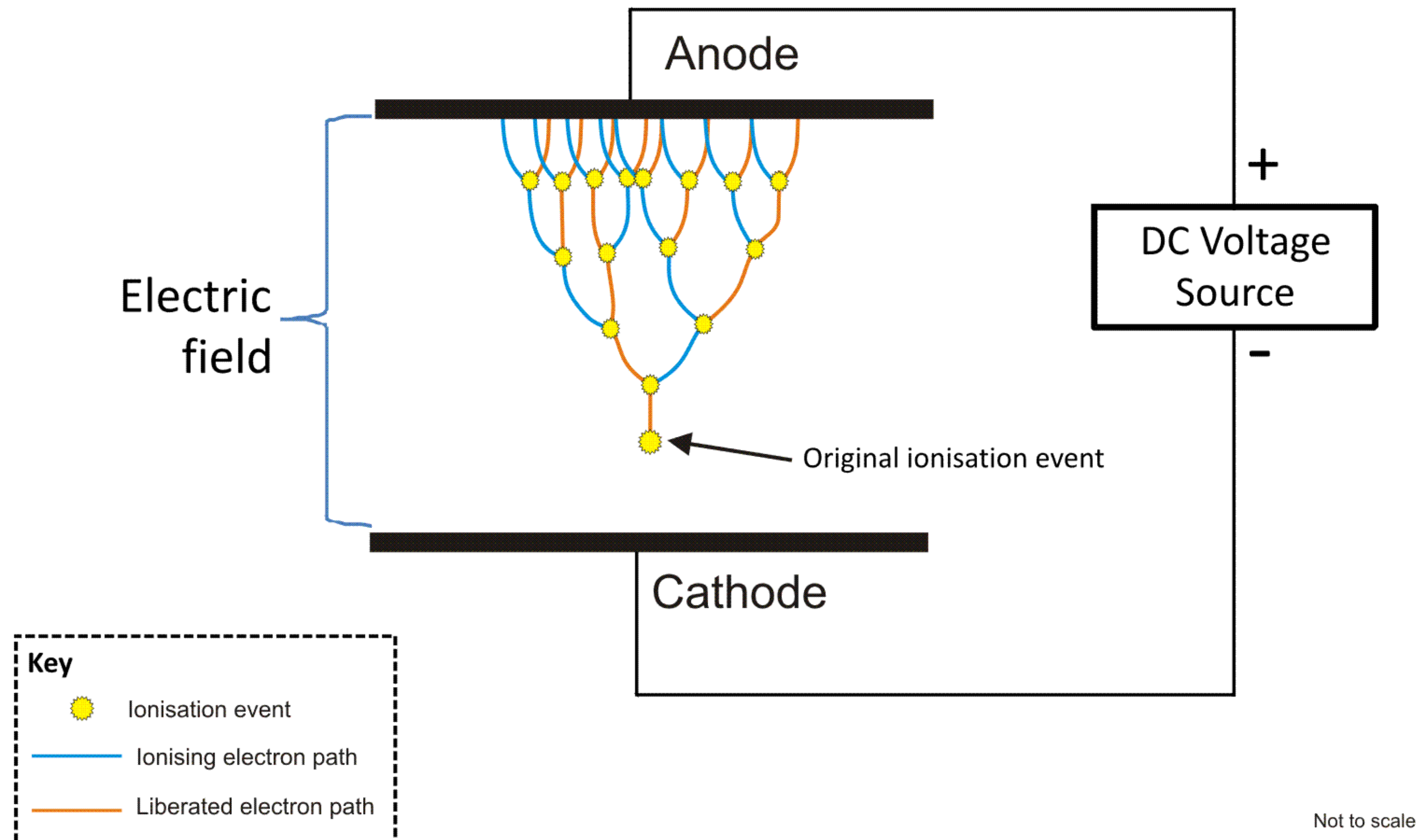
- Continuous discharge
  - In this region, arcing will occur that can result in a complete breakdown of the gas
  - Any extended operation in this region will destroy the tube

# Gas amplification

- If the electric field is strong enough (near the anode of a wire chamber), the drifting electrons can be accelerated such that they can initiate secondary ionizations
  - An avalanche developed and the ionization charge is amplified with typical amplification factors of  $10^4 - 10^6$
  - The number  $\alpha$  of ions generated per path length, the so-called first Townsend coefficient is given by:
    - $\alpha = \alpha_{ion} n = \frac{1}{\lambda_{ion}}$  where  $\sigma_{ion}$  and  $\lambda_{ion}$  are the cross section for ionization and mean free path between ionizations, respectively

# Basic principle

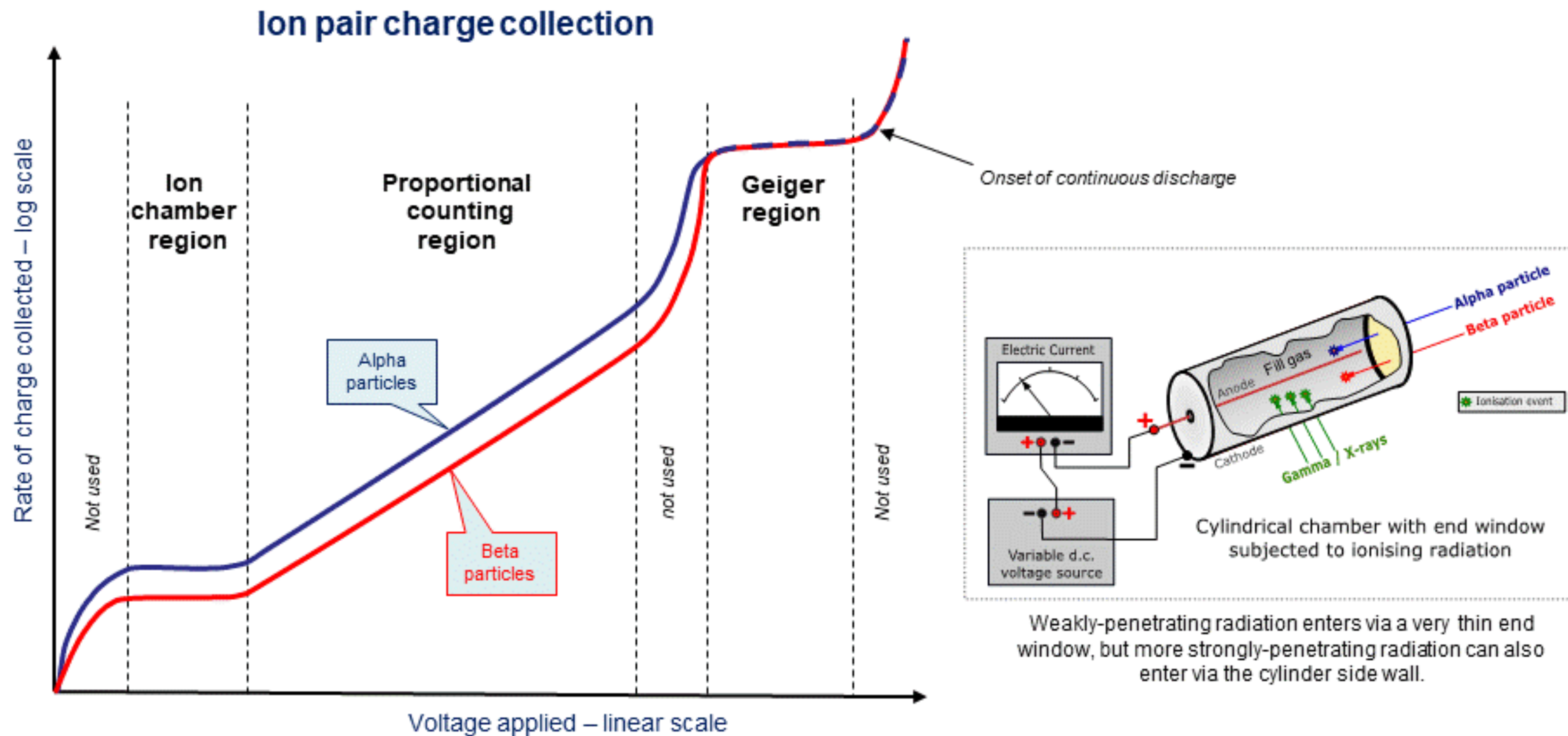
## Visualisation of a Townsend Avalanche



# Basic principle

## Practical Gaseous Ionisation Detector Regions

This shows an idealised plot of the three gaseous detection regions, using the concept of applying a variable voltage to a cylindrical chamber which is subjected to constant ionising radiation. Alpha and beta particles are separately plotted to demonstrate the effect of different radiation energies, but the same principles apply to all forms of ionising radiation.

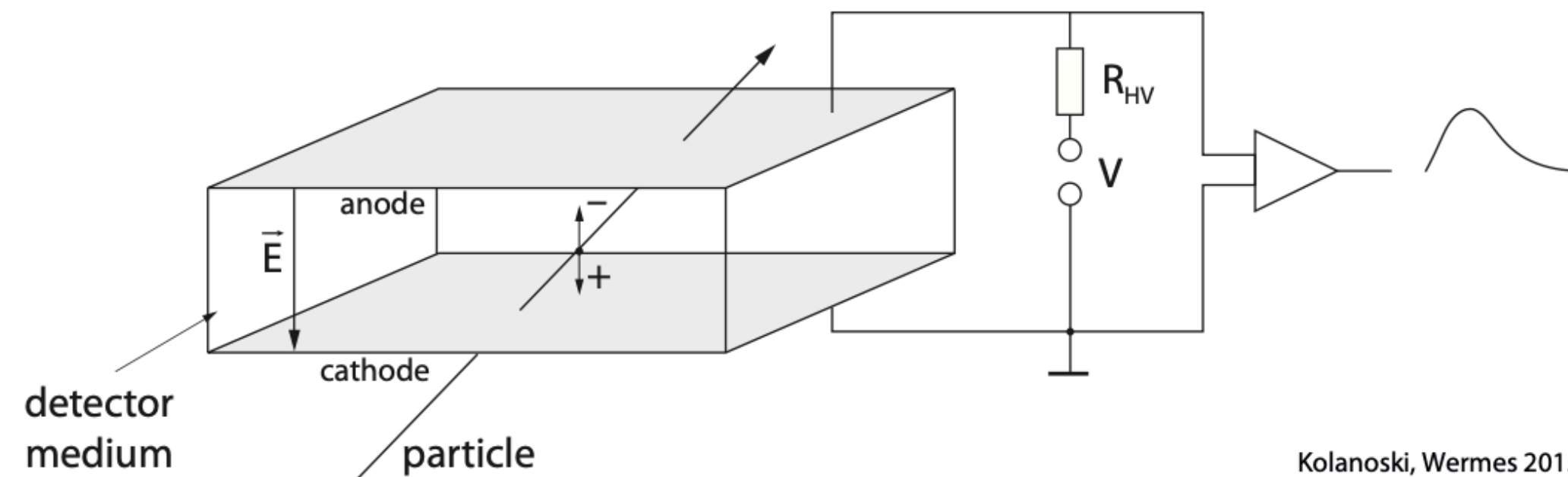


In the ion chamber region gas ionisation is direct and results in a current flow proportional to overall ionisation. At higher field strengths gas multiplication effects can be used, allowing output of individual ionisation events as measurable pulses.

In the proportional region, pulse sizes are proportional to the energy of each ionisation event. In the Geiger region a fill gas at reduced pressure ( $1/10^{\text{th}}$  atmosphere) allows greater multiplication but produces a uniform pulse for each ionising event regardless of its energy.

# Gas-filled detectors

- In many particle physics experiments detectors are employed which measure charged particles through their ionization of gases
- Gas-filled detectors allow for the determination of particle trajectories in large volumes, often in a magnetic field
- Compared to semiconductor detectors gaseous detectors are in most cases cheaper, in particular for large volumes, and tend to present less material for the passing particles
- Ionization detectors: best for radiation fluxes containing large number of particles

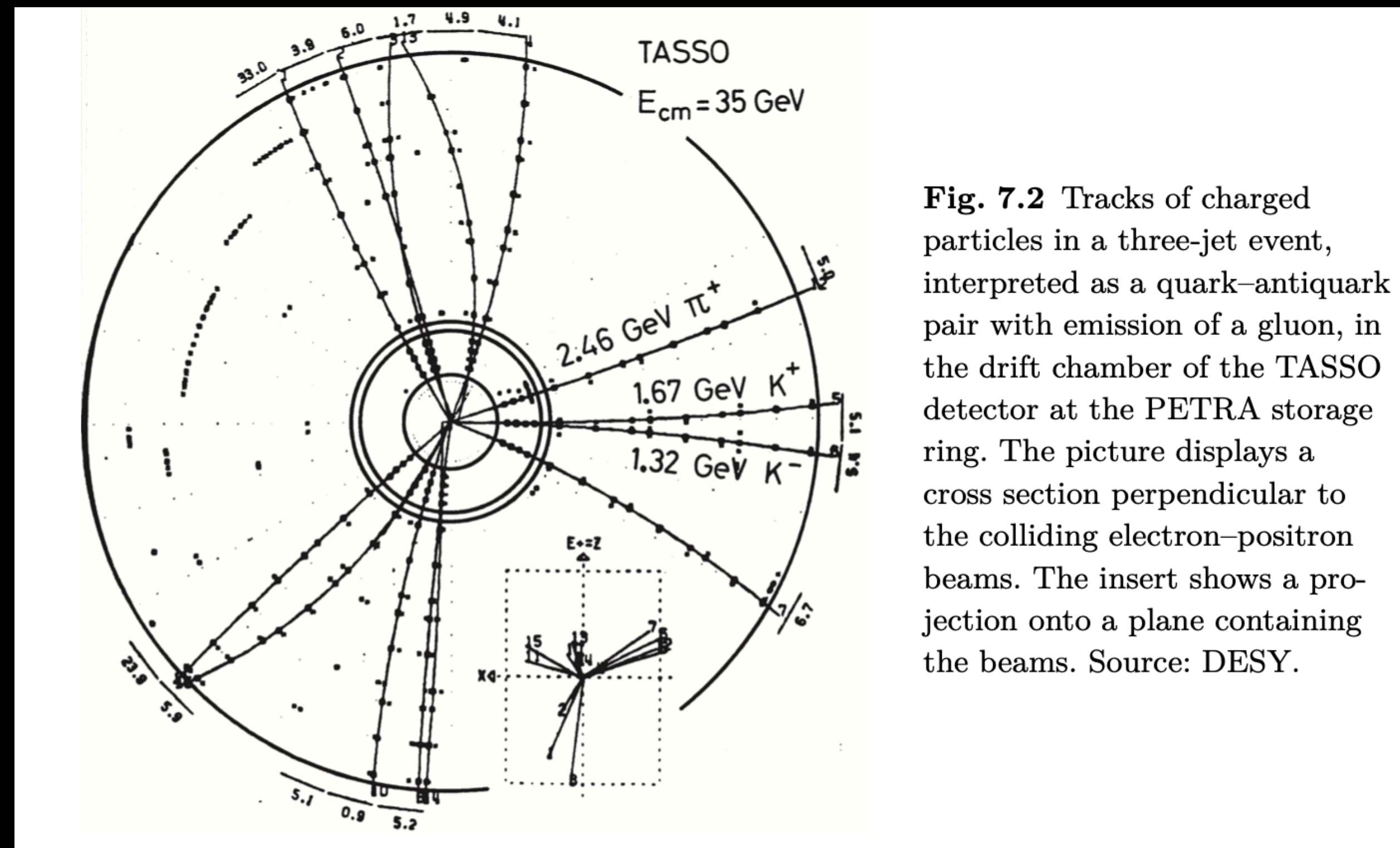


Kolanoski, Wermes 2015

**Fig. 7.1** Principle of an ionisation detector. The sensitive detector medium, in this case gas, resides between two electrodes with a voltage applied across. During the passage of a charged particle through the gas charges are liberated which move in the electric field towards the electrodes. The moving charges induce a current signal at the electrodes (see chapter 5). In principle, the detector is a capacitor which discharges upon ionisation of the medium. Electrically it acts as a current source.

# Gas-filled detectors

- Figure below shows as an example the tracks of a three-jet event in the central drift chamber of the TASSO experiment at the PETRA storage ring
- This chamber was put into operation in 1978 and was one of the first large drift chambers comprising a sensitive volume of about  $16 \text{ m}^3$  and 2340 readout channels
- Today such detectors for charged particles may have  $10^5$  or more readout channels

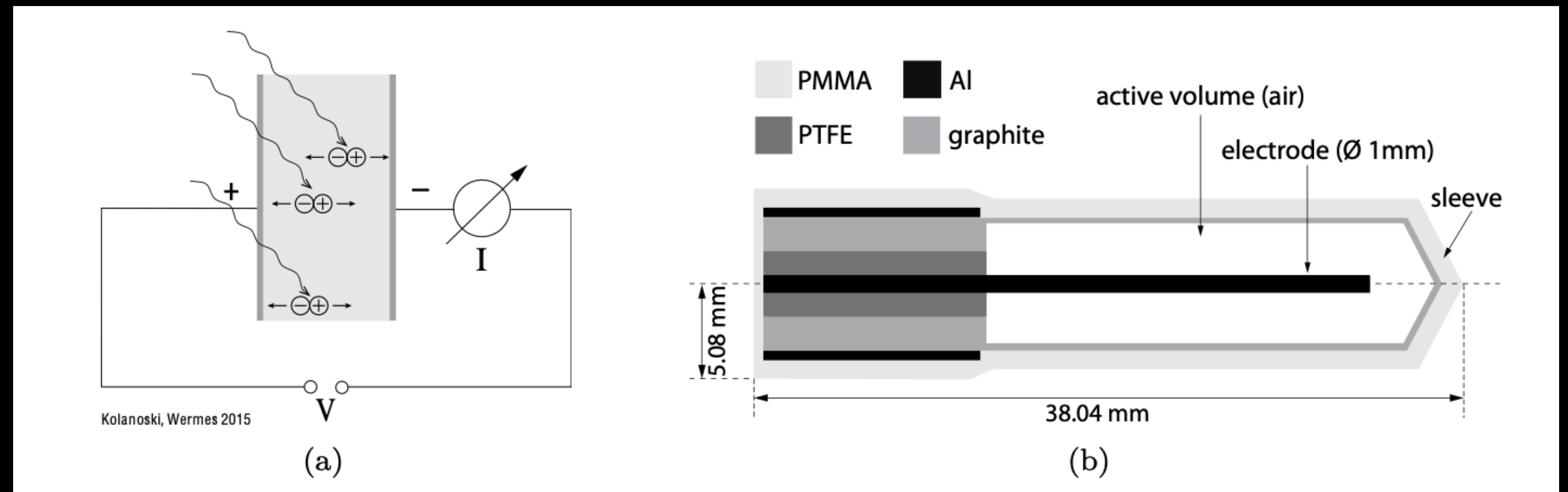


**Fig. 7.2** Tracks of charged particles in a three-jet event, interpreted as a quark–antiquark pair with emission of a gluon, in the drift chamber of the TASSO detector at the PETRA storage ring. The picture displays a cross section perpendicular to the colliding electron–positron beams. The insert shows a projection onto a plane containing the beams. Source: DESY.

# Detector types

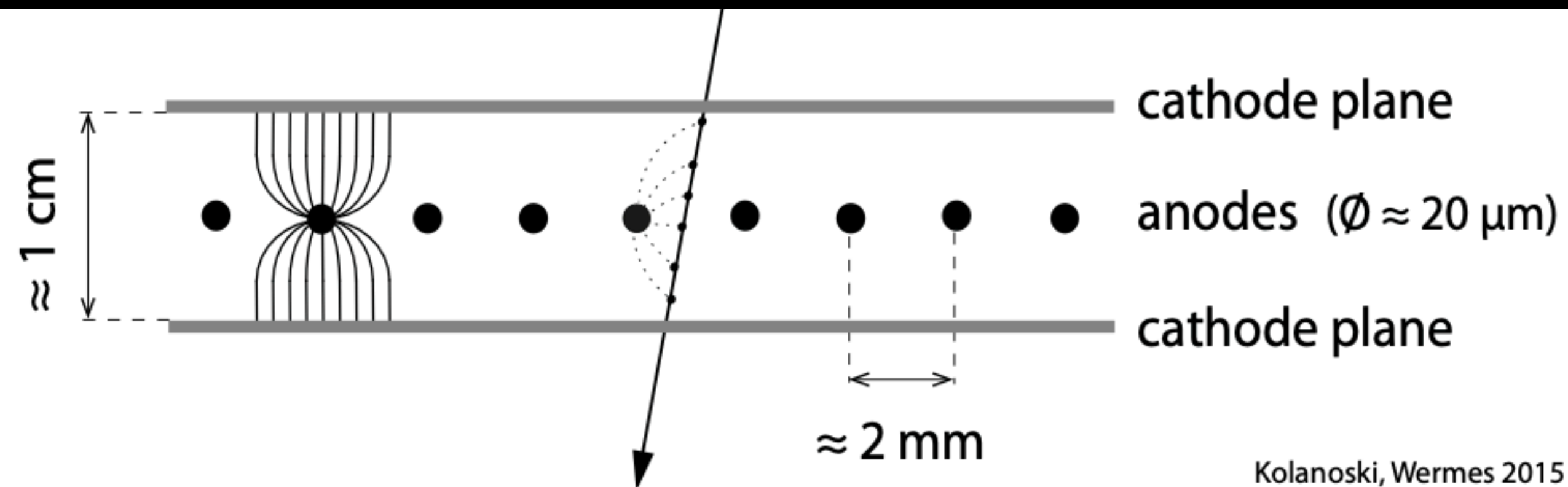
- For different application areas a variety of different detector types exist using gas as the sensitive medium
- Detectors which measure radiation fluxes (radiation monitors such as ionization chambers and proportional counters)
- Those which provide information about the locations where the particle passed the detector (position-sensitive detectors such as multi-wire proportional chambers, drift chambers and gaseous micro-structure detectors)

Ionization chamber is essentially a capacitor, charged up by a voltage  $V$ , which discharges due to the ionization in the capacitor volume. The current is a measure of the radiation flux.



# Position sensitive detectors

- Basic idea: gas-filled chamber with which the coordinate of a traversing particle can be detected



**Fig. 7.5** Principle of a position-sensitive multiwire proportional chamber (MWPC). The continuous lines represent the field lines around an anode and the dashed lines the drift paths of electrons generated by ionisation.