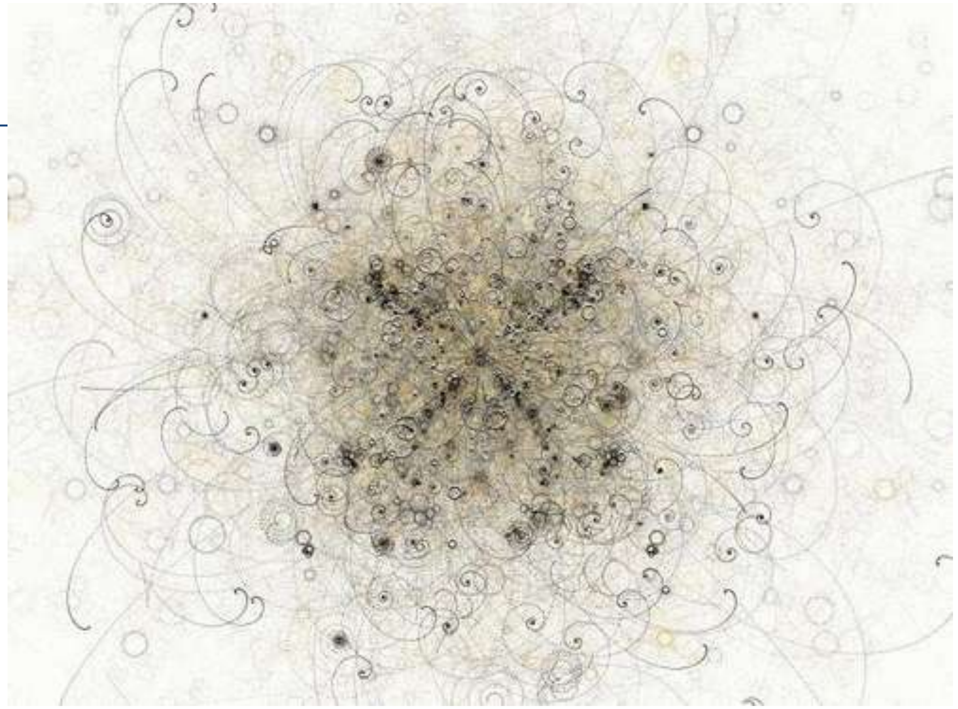
Announcements



Quiz:
- Assorted quizzes from earlier weeks. Pick up after class.
- Next quiz Friday

Homework:
Fourth HW posted. Due date **March 24 at 3pm** on gradescope

Paper:
-Outlines returned on gradescope – please take a look; reach out if you have questions
-Draft deadlines:
    - **Optional**, 3/28 in class: bring a paper copy to me by this date if you want feedback
    - For credit, 4/11 at 3pm, on gradescope

Midterm:
-Pick up graded midterms after class
-Will be curved to add 10 points to the score at the top of the page
- Note: your grade is the sum of your best four questions on the exam, the fifth question is not extra credit. in P803 it is the sum of question 5 and your best other three questions

Calorimetry

Calorimeter:

- Detector for energy measurement via total absorption of particles
- Also: most calorimeters are position sensitive to measure energy depositions depending on their location

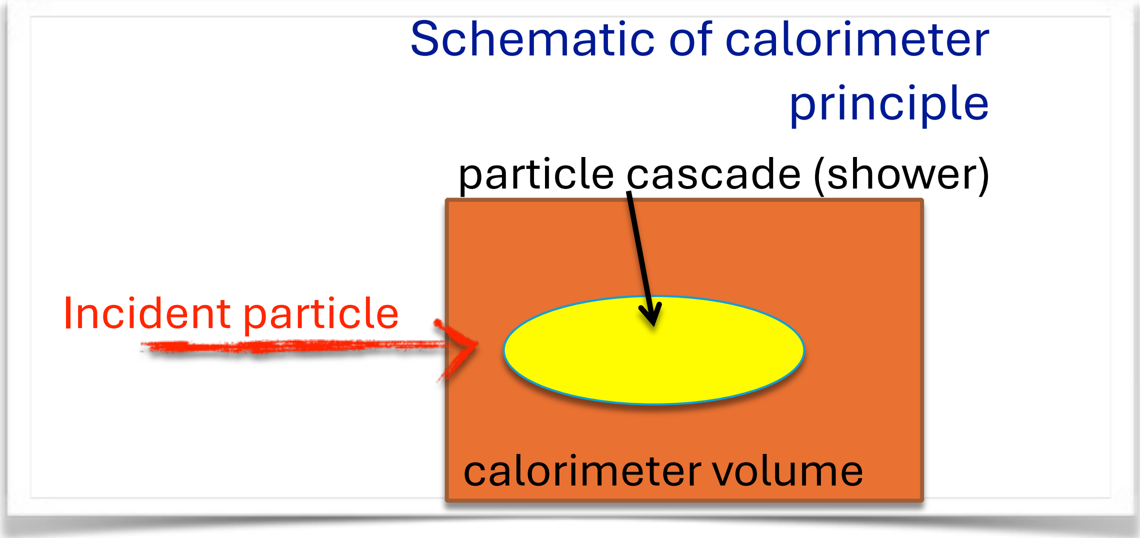
Principle of operation:

- Incoming particle initiates particle shower
- Shower composition and shower dimensions depend on particle type and detector material
- Energy deposited in form of: heat, ionization, excitation of atoms, Cherenkov light
- Different calorimeter types use different kinds of these signals to measure total energy

Important:

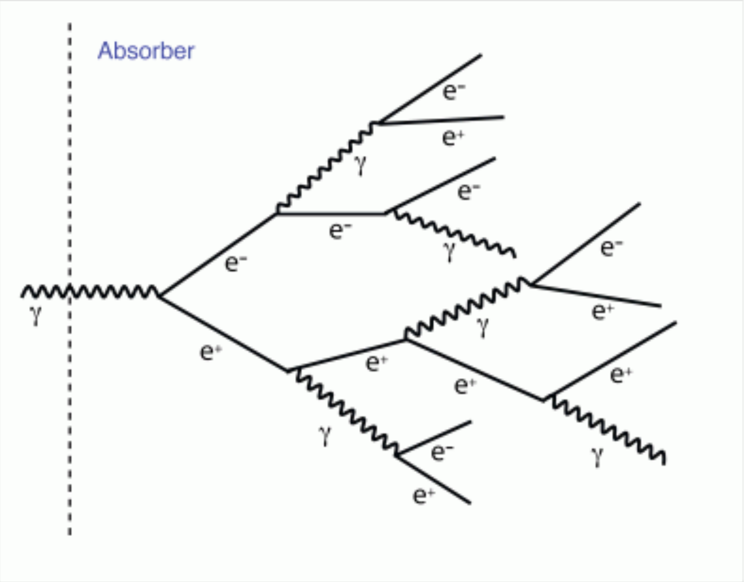
Signal ~ total deposited energy

[Proportionality factor determined by calibration]



Electromagnetic Showers

Reminder:
- Radiation length, X_0
- Dominant processes at high energies
  - Photons : Pair production
  - Electrons : Bremsstrahlung
- Both processes always follow a 1→2 particle production process



Pair production:

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

Bremsstrahlung:

$$\frac{dE}{dx} = 4\alpha N_A\frac{Z^2}{A}r_e^2\cdot E\,\ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$

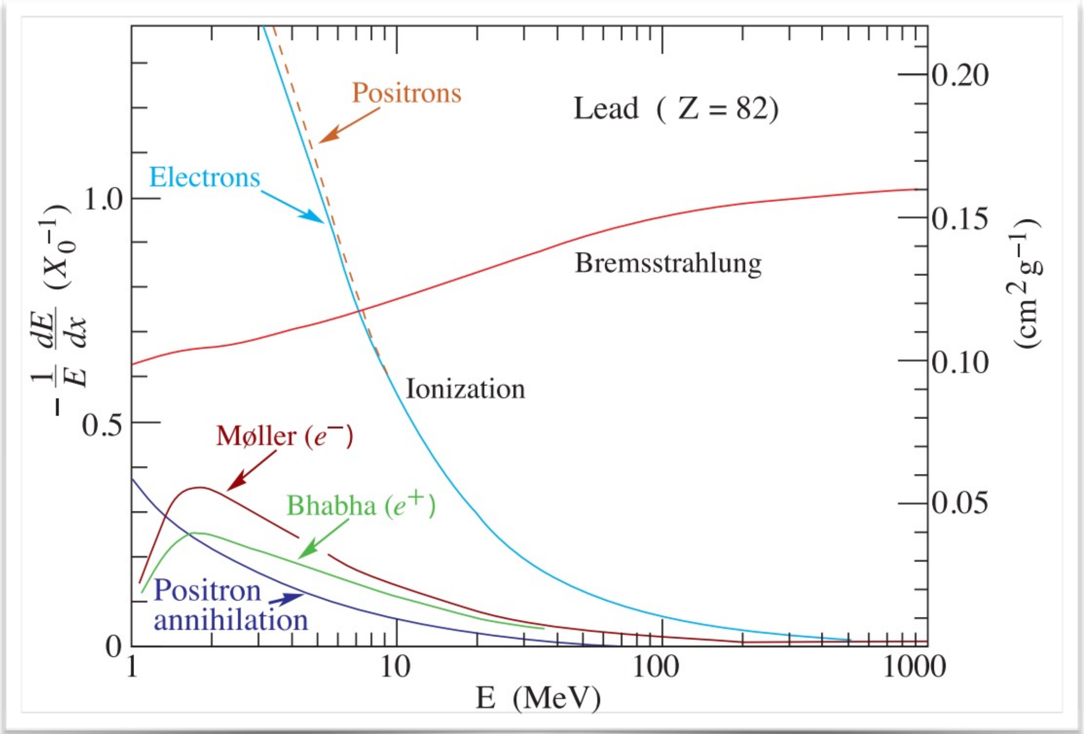
After passage of one X_0 electron has only (1/e)$^{\text{th}}$ of its primary energy ...
[i.e. 37%]

Analytic EM Shower Model

Critical Energy

$$\frac{dE}{dx}(E_c)\Big|_{\text{Brems}} = \frac{dE}{dx}(E_c)\Big|_{\text{Ion}}$$

Transition between importance of Bremsstrahlung vs. Ionization



<u>Assume:</u>

E > Ec : no energy loss by ionization/excitation, only by bremstrahlung & pair production.

E < Ec : energy loss only via ionization/excitation

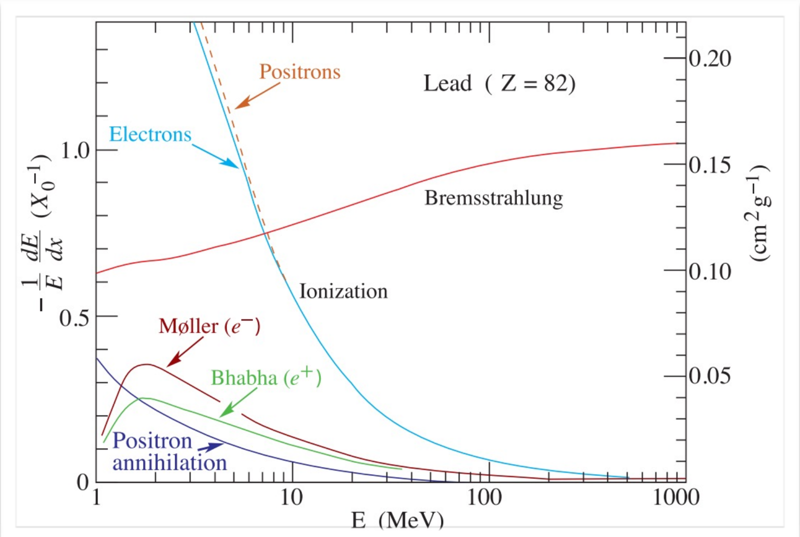
Analytic EM Shower Model

<u>Simple Shower Model:</u>
Only two dominant interactions: Pair production and Bremsstrahlung

- γ + Nucleus ➛ Nucleus + e^+ + e^-
[Photons absorbed via pair production]

- e + Nucleus ➛ Nucleus + e + γ
[Energy loss of electrons via Bremsstrahlung]

Shower development governed by X_0
- After a distance X_0 electrons remain with a fraction of their initial energy
- Photon produces e^+e^- pair after $9/7\ X_0 \sim X_0$



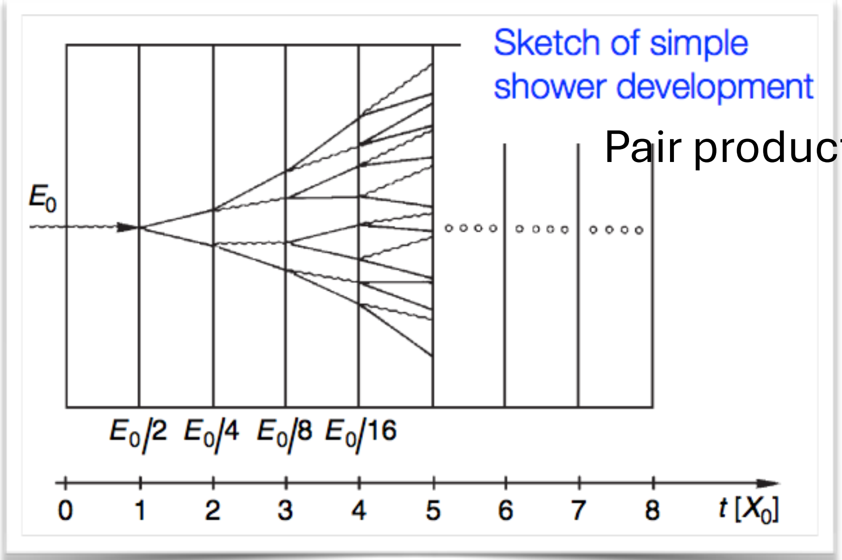
Simplification:
Bremsstrahlung:
$E_\gamma = E_e \approx E_0/2$
Pair Production:
$E_{e+} \approx E_{e-} \approx E_0/2$

<u>Assume:</u>
E > Ec : no energy loss by ionization/excitation
E < Ec : energy loss only via ionization/excitation

Analytic EM Shower Model

Shower characterized by
- Number of particles in shower
- Location of shower maximum
- Longitudinal shower distribution
- Transverse shower distribution

Longitudinal components measured in radiation length, use this instead: $$t = \frac{x}{X_0}$$



Pair production -> Brem

Analytic EM Shower Model

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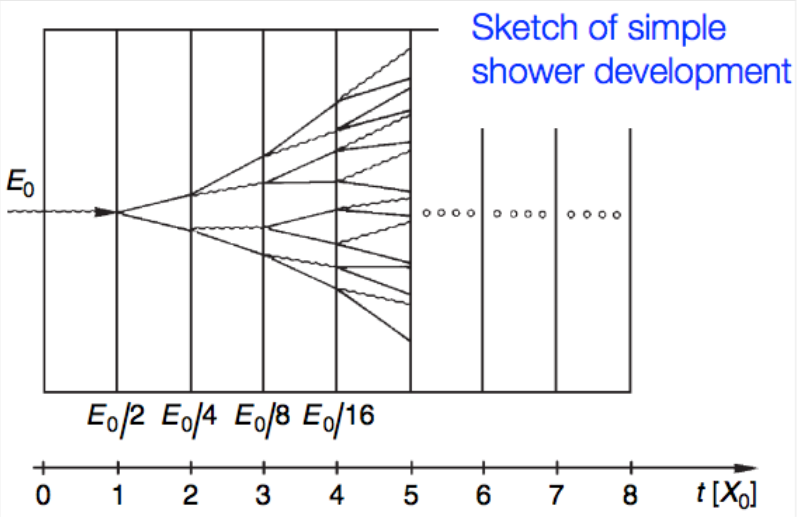

Number of shower particles after depth t:

$$N(t) = 2^t$$

Energy per particle after depth t:

$$E = \frac{E_0}{N(t)} = E_0 \cdot 2^{-t}$$

$$\rightarrow \quad t = \log_2(E_0/E)$$

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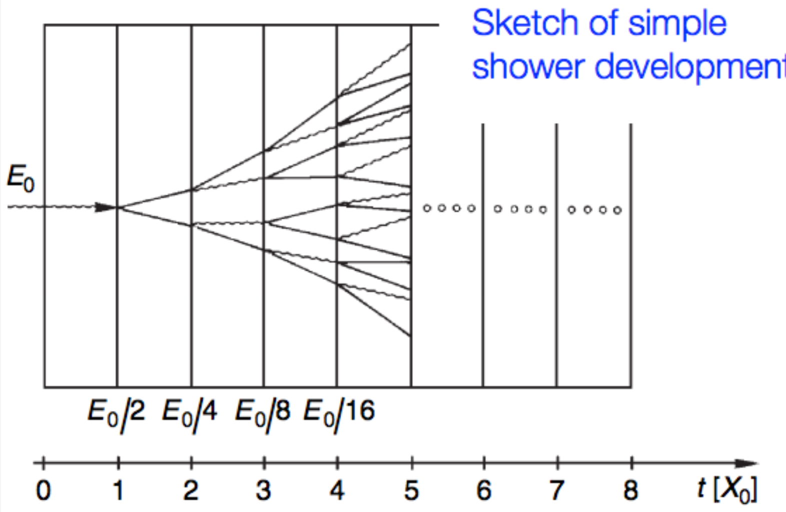

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Energy per particle after depth t:

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$$\rightarrow \quad t = \log_2(E_0/E)$$

Total number of shower particles with energy E_1:

$$N(E_0, E_1) = 2^{t_1} = 2^{\log_2(E_0/E_1)} = \frac{E_0}{E_1}$$

Number of shower particles at shower maximum:

$$N(E_0, E_c) = N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c} \propto E_0$$

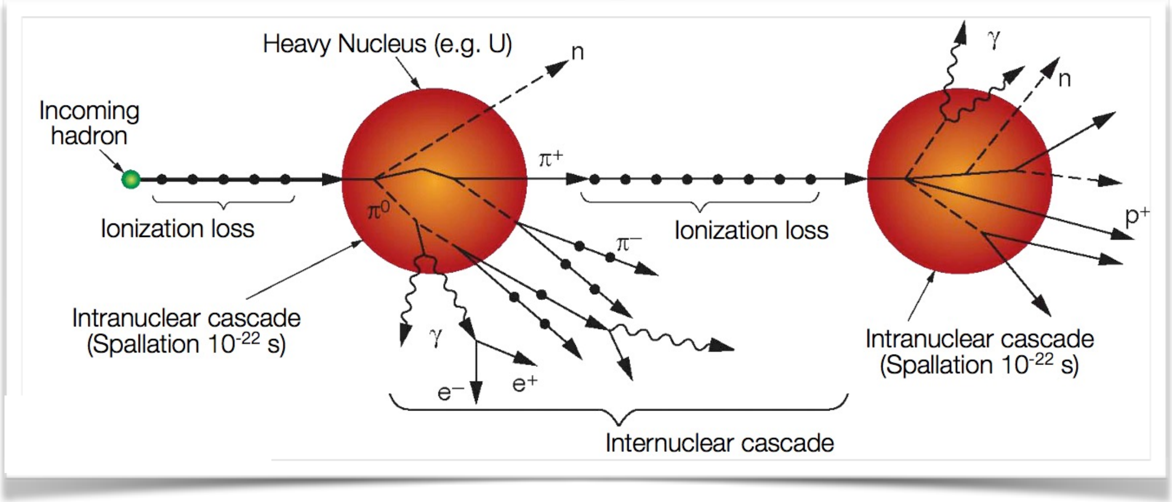
Shower maximum at:

$$t_{\max} \propto \ln(E_0/E_c)$$

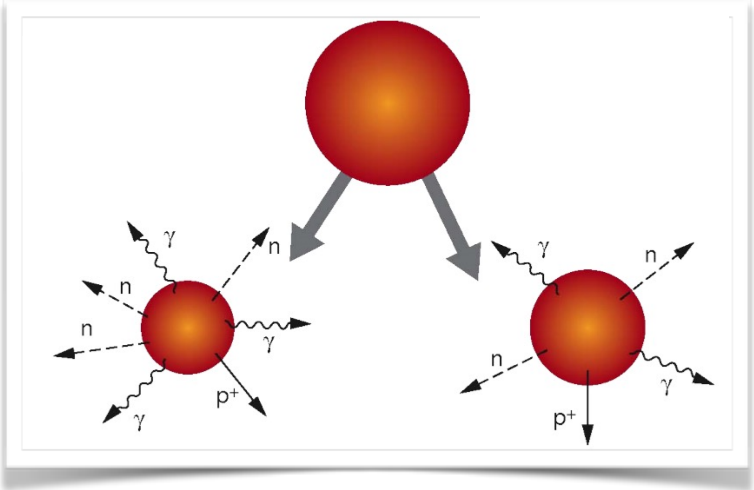
Hadronic Showers

Hadronic showers begin with hadronic interactions
- collectively with nuclei
- individually with nucleons

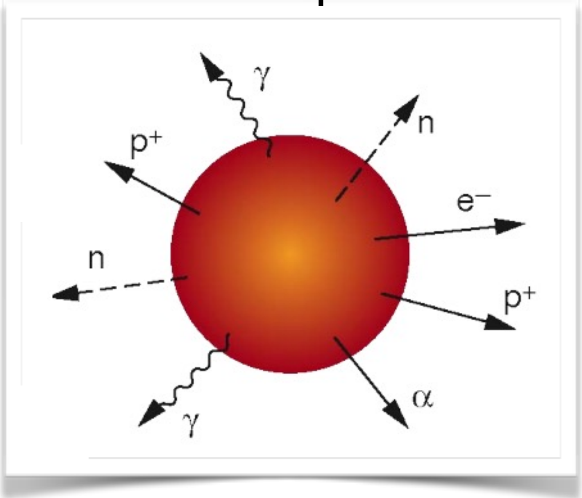
Nuclear Excitation



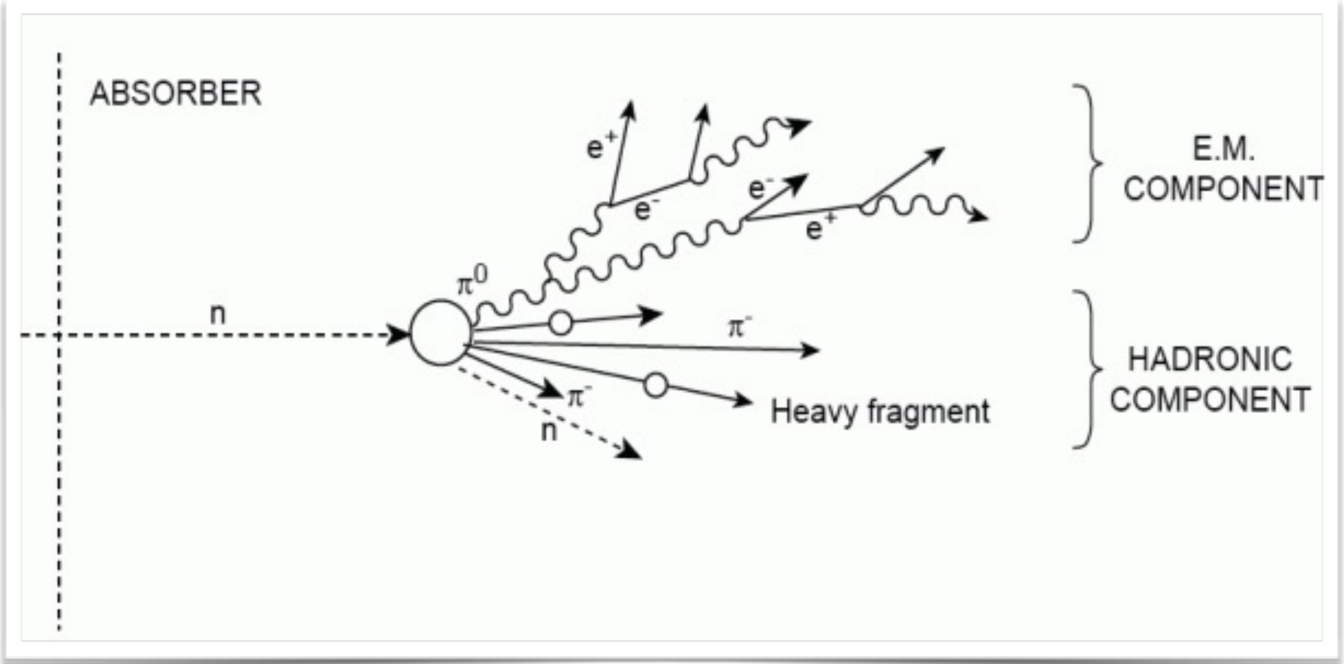
Fission



Nuclear Evaporation



Hadronic Showers



Hadronic interaction:

Elastic:

$$p + \mathrm{Nucleus} \rightarrow p + \mathrm{Nucleus}$$

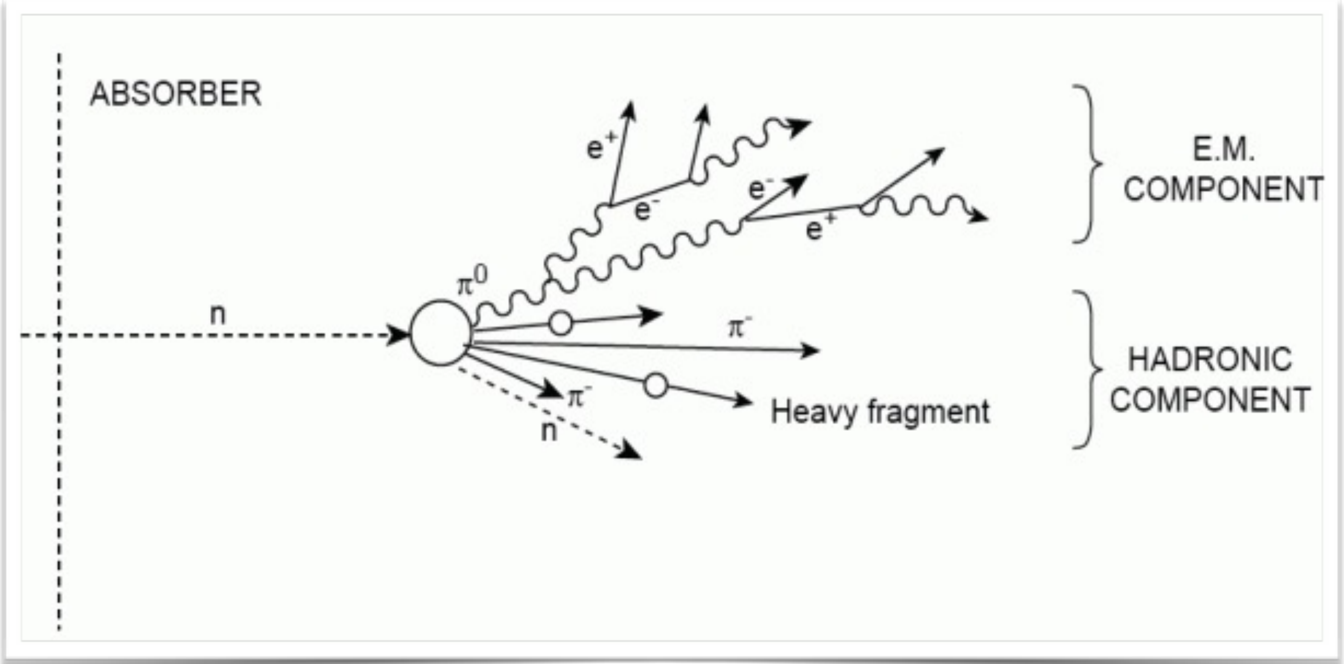
Inelastic:

$$p + \mathrm{Nucleus} \rightarrow \pi^+ + \pi^- + \pi^0 + \ldots + \mathrm{Nucleus}^*$$

$$\left[\begin{array}{ll} \mathrm{Nucleus}^* & \rightarrow \mathrm{Nucleus\ A} + n, p, \alpha, \ldots \\ & \rightarrow \mathrm{Nucleus\ B} + 5p, n, \pi, \ldots \\ & \rightarrow \mathrm{Nuclear\ fission} \end{array}\right]$$

Can have separate calorimeters to capture the EM and the hadronic components

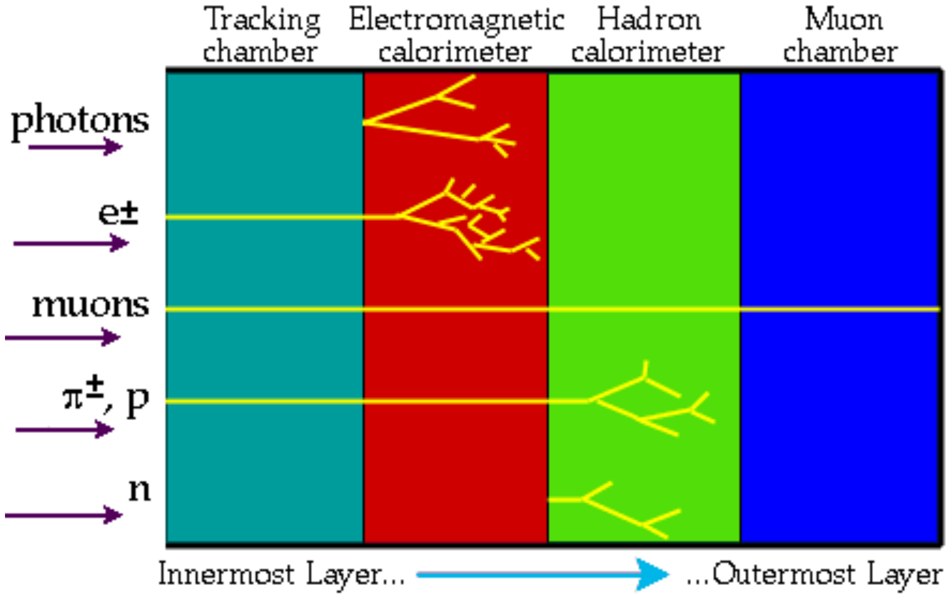
Total Calorimetry



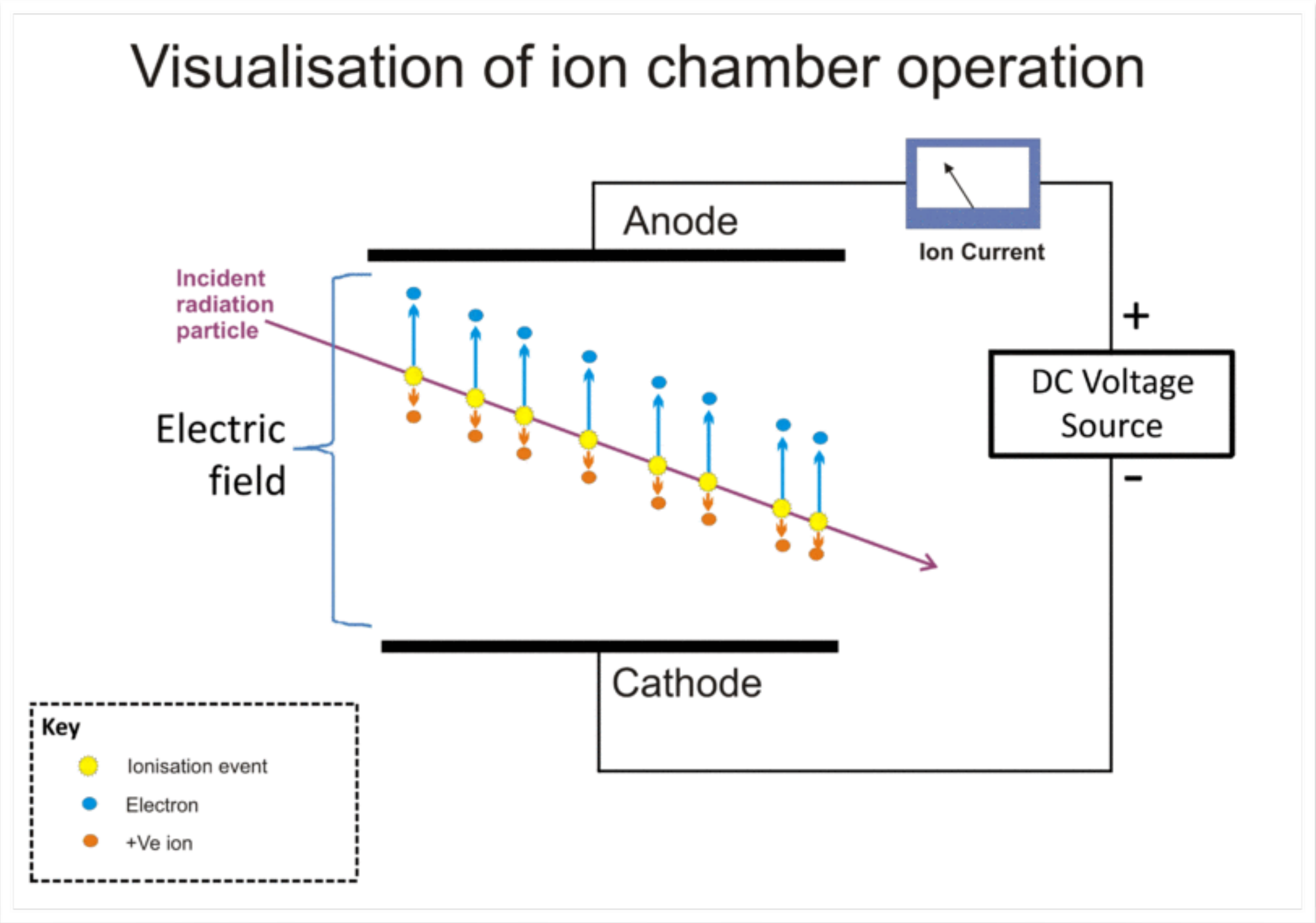
Cascade energy distribution:
[Example: 5 GeV proton in lead-scintillator calorimeter]

Ionization energy of charged particles (p,π,μ)	1980 MeV [40%]
Electromagnetic shower (π^0,η^0,e)	760 MeV [15%]
Neutrons	520 MeV [10%]
Photons from nuclear de-excitation	310 MeV [6%]
Non-detectable energy (nuclear binding, neutrinos)	1430 MeV [29%]
	5000 MeV

Can have separate calorimeters to capture the EM and the hadronic components



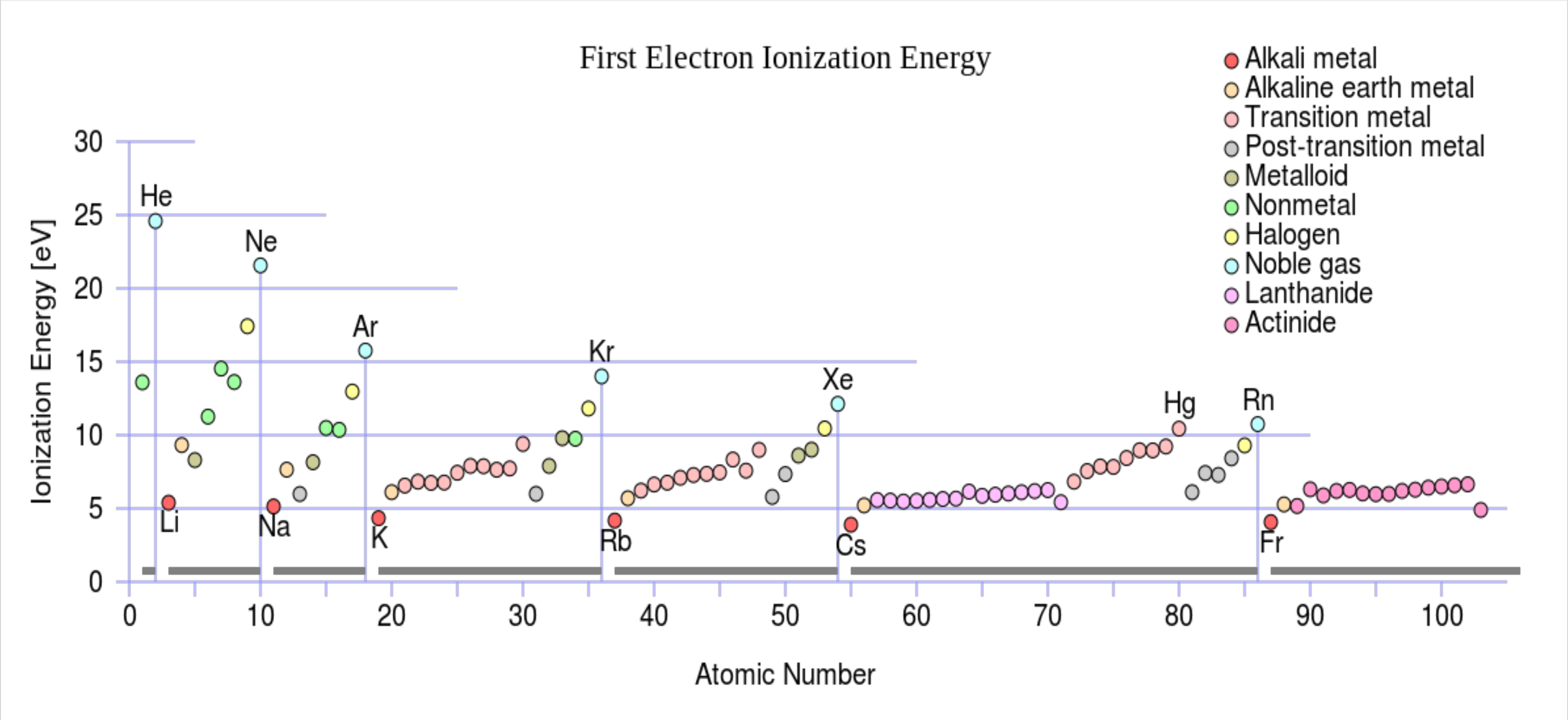
Gas Detectors



electron-ion pair production typically needs an energy of 30±10eV

Work at very low energies

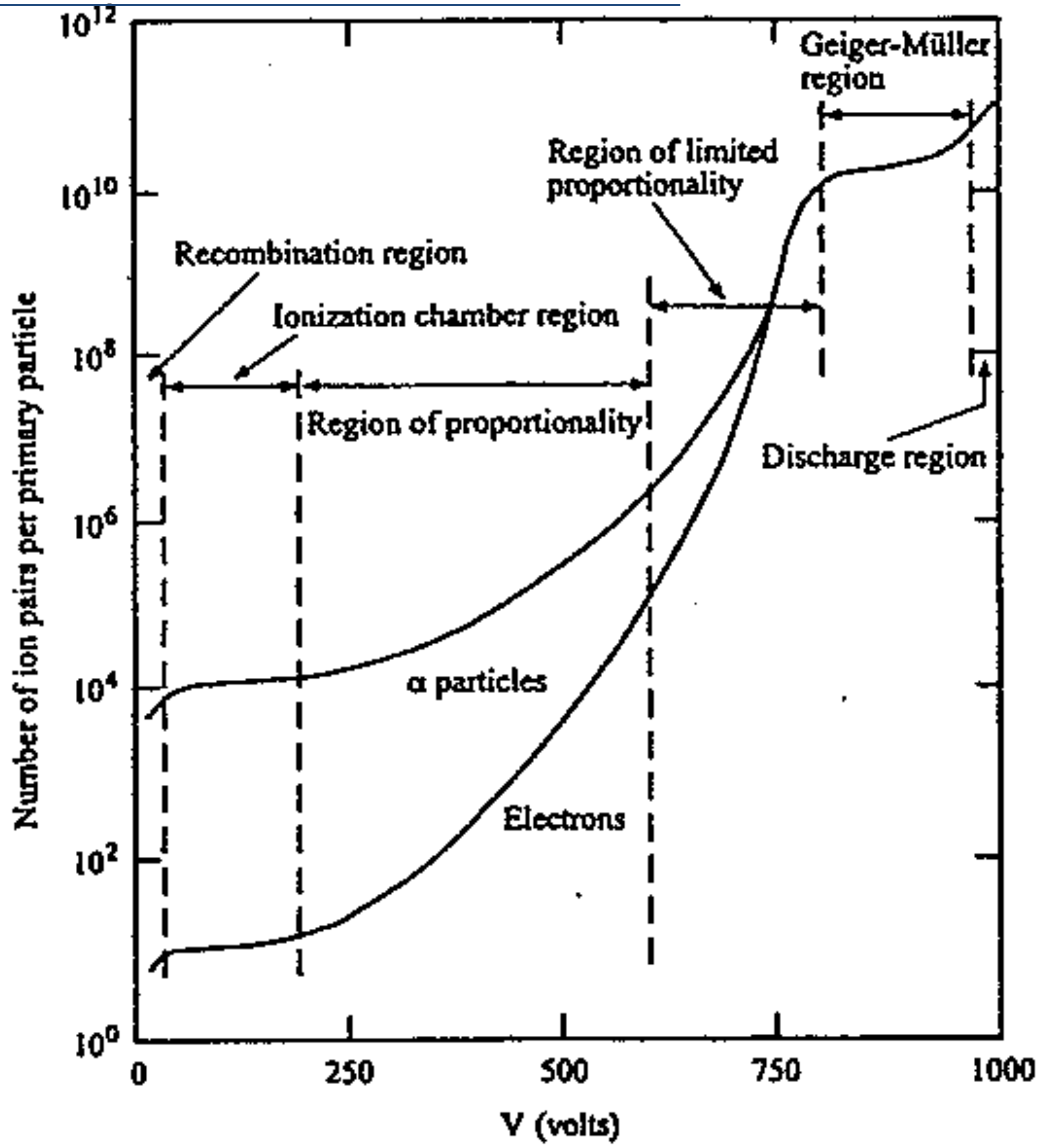
Gas Detector Materials



electron-ion pair production typically needs an energy of 30±10eV

Gas Detectors

- There are several regions for detector operation depending on the voltage applied
- recombination region: At low applied energies, the output signal is very small, because electron-ion pairs recombine before reaching the electrodes - not useful for a detector
- ionization chamber region: When the voltage increases, the numbers of pairs increases to a saturation level, which means a complete collection of all charge - small pulse
- region of proportionality: Electric field is sufficiently high to produce secondary ionization
- Geiger-Müller region: Ionized as many electrons as you can in the gas; saturation of secondary ionization, all nearby electrons collected. Cannot distinguish between alphas and electrons
- Breakdown or discharge region: Breakdown of gas, ionization even without particles passing through

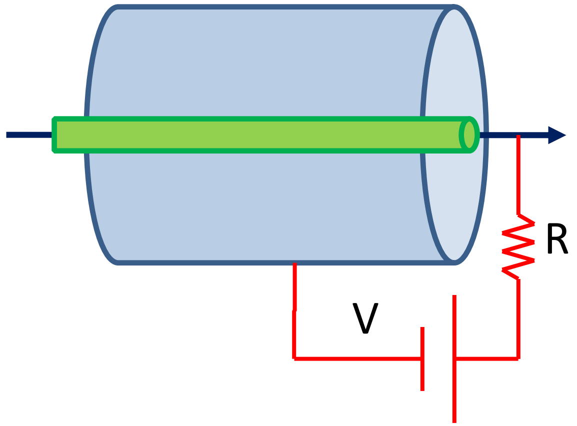


Ionization Chamber

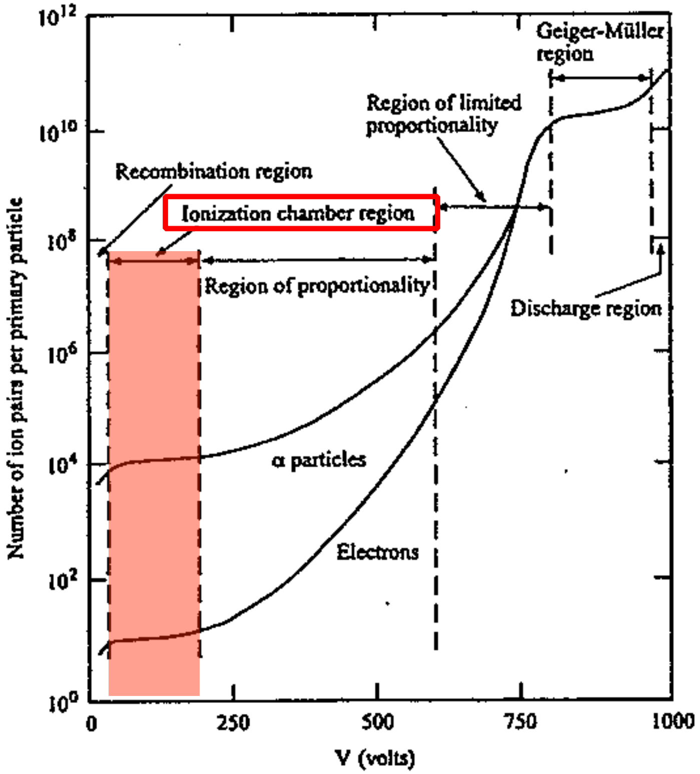
Ionization chamber:

- At low applied energies, the output signal is very small, because electron-ion pairs recombine before reaching the electrodes (recombination region).
- When the voltage increases, the numbers of pairs increases to a saturation level, which means a complete collection (region of ionization).

Eg. Cylindrical shape with an inner anode of radius r_a and an outer cathode of radius r_c



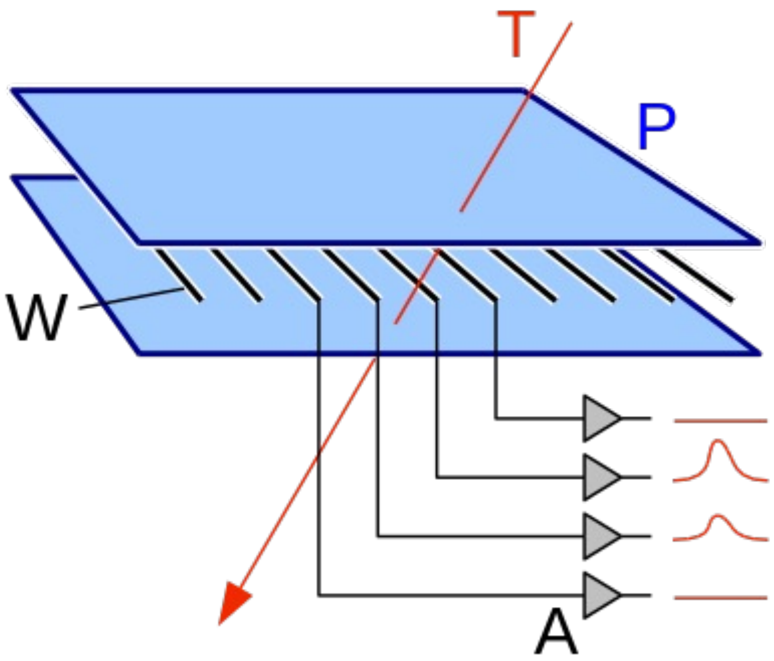
Electric field $E(r)$ is given by $\dfrac{V}{r \cdot \ln(r_c/r_a)}$

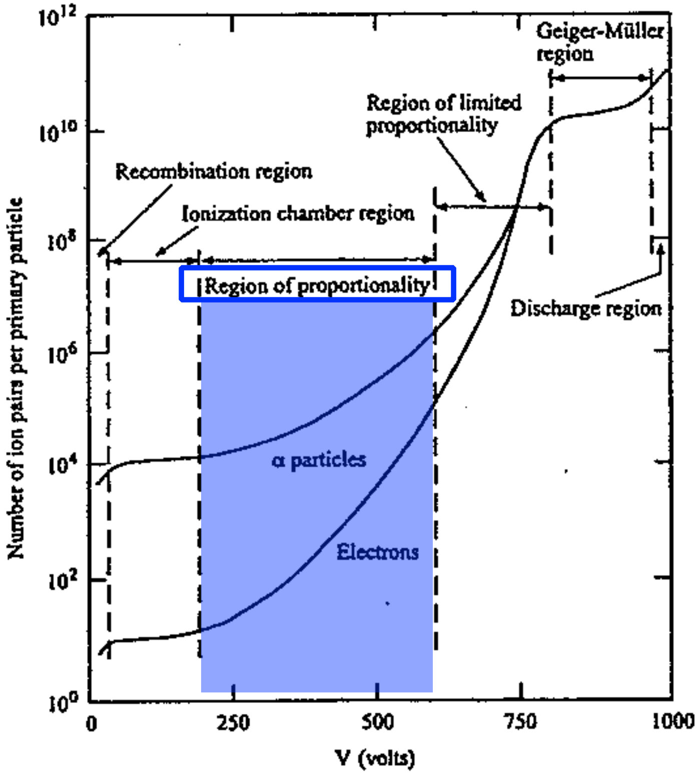


Wire Chambers

Wire chamber :

- Wire chambers are operated at the proportional region voltage, which is beyond the region of operation of the ionization chamber.
- In the proportional region, a cylindrical arrangement will produce electric field strengths of order 10^4-10^5 V/cm near the wire.





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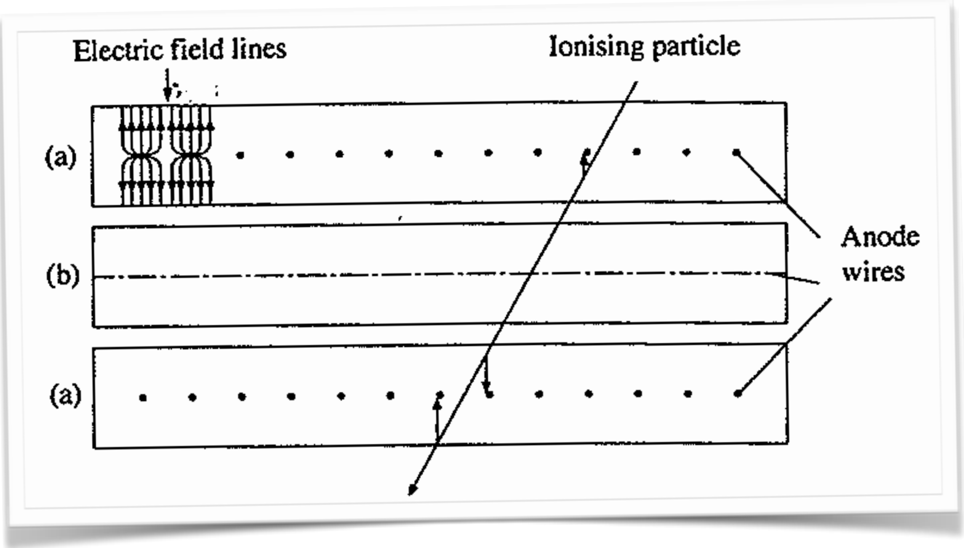
- With the high electric field, secondary ionization will be induced by the primary electron-ion pairs.

MWPC

Multi Wire Proportional Chamber

- The planes (a) have anode wires into the page and those in plane (b) are at right angles.
- The wire spacings are typically 2mm.
- A positive voltage applied to the anode wires generates a field.



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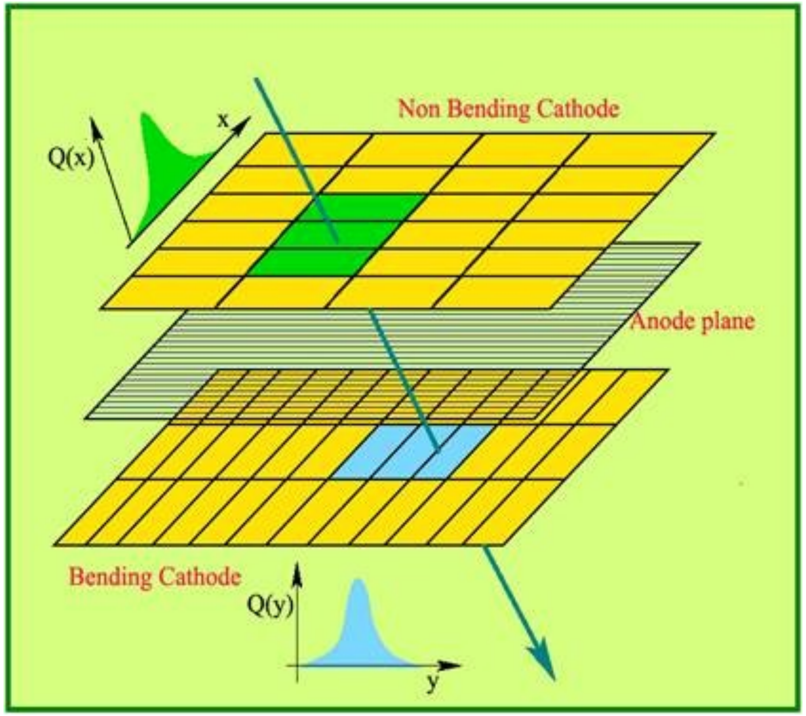
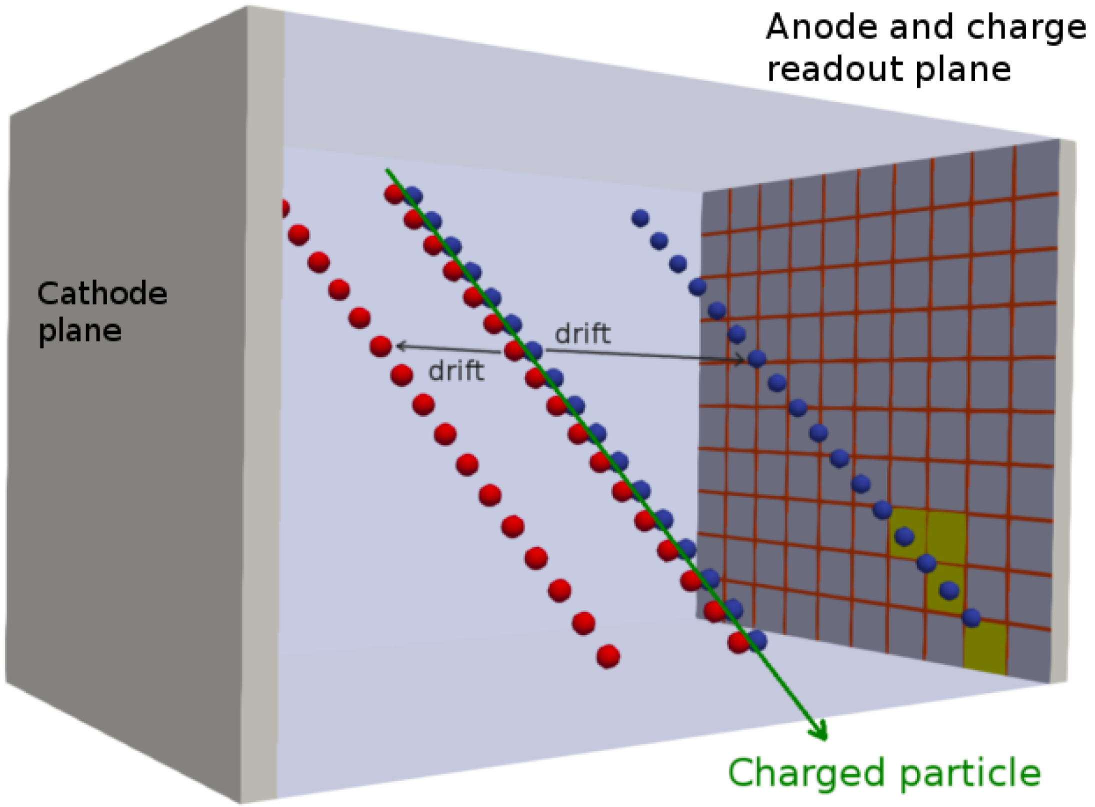


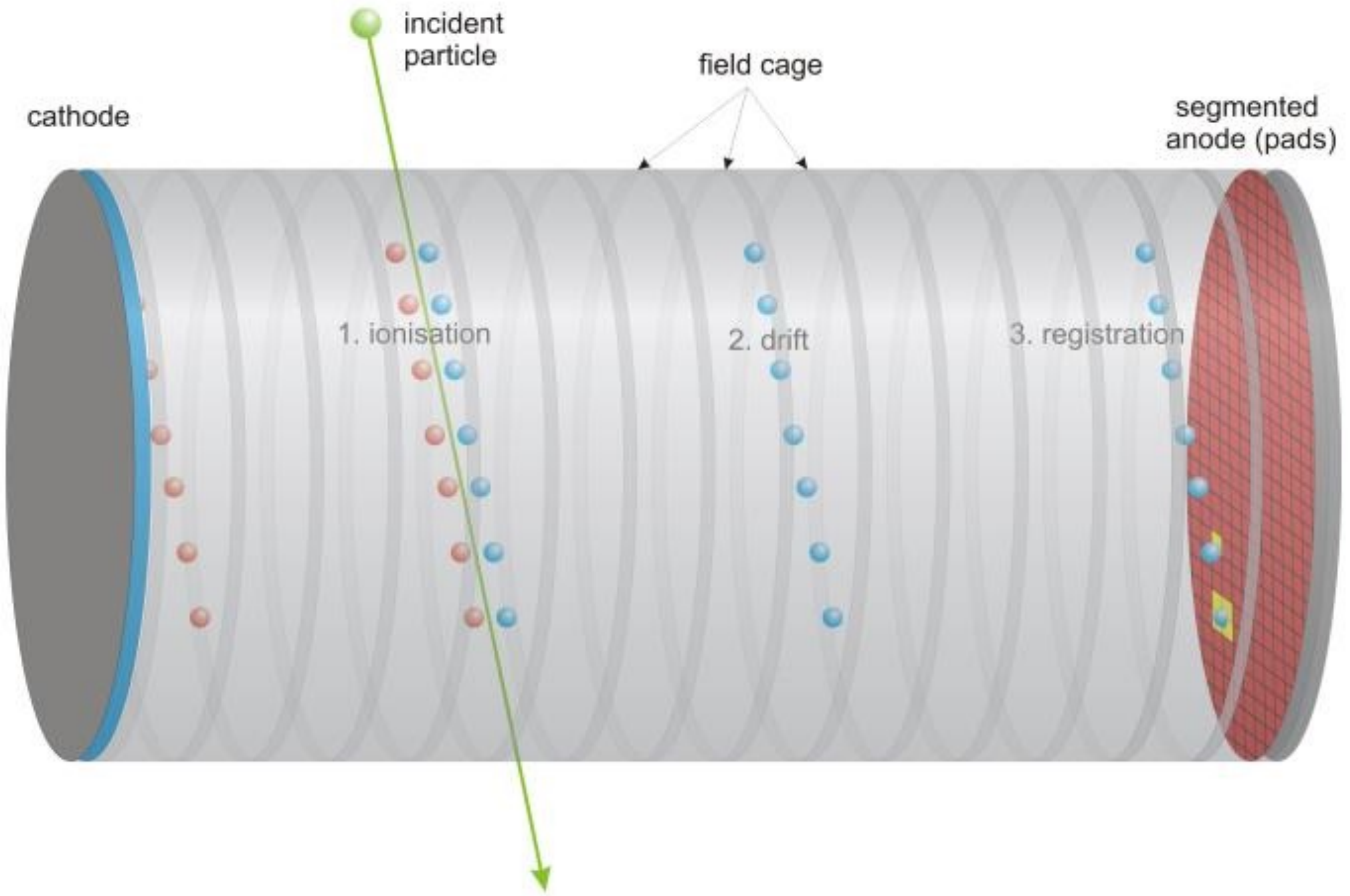
Time Projection Chambers

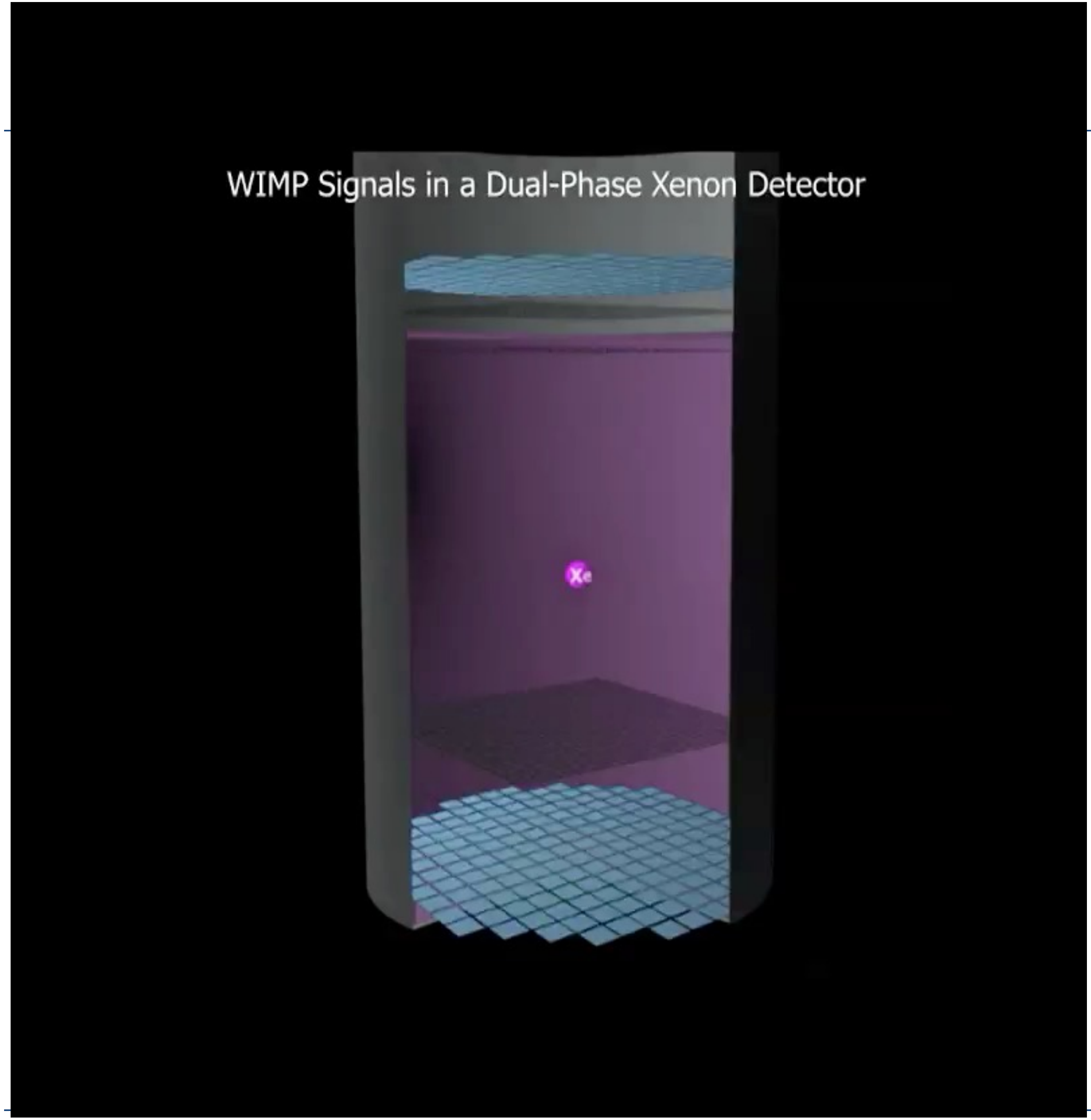
Time Projection Chamber (TPC) :
One of the most advanced applications of proportional and drift chamber. Electrons formed along the track of an ionizing particle drift under the electric field E towards one of the endcaps along helical trajectories.



Anode consists of multiple planes of individual wires

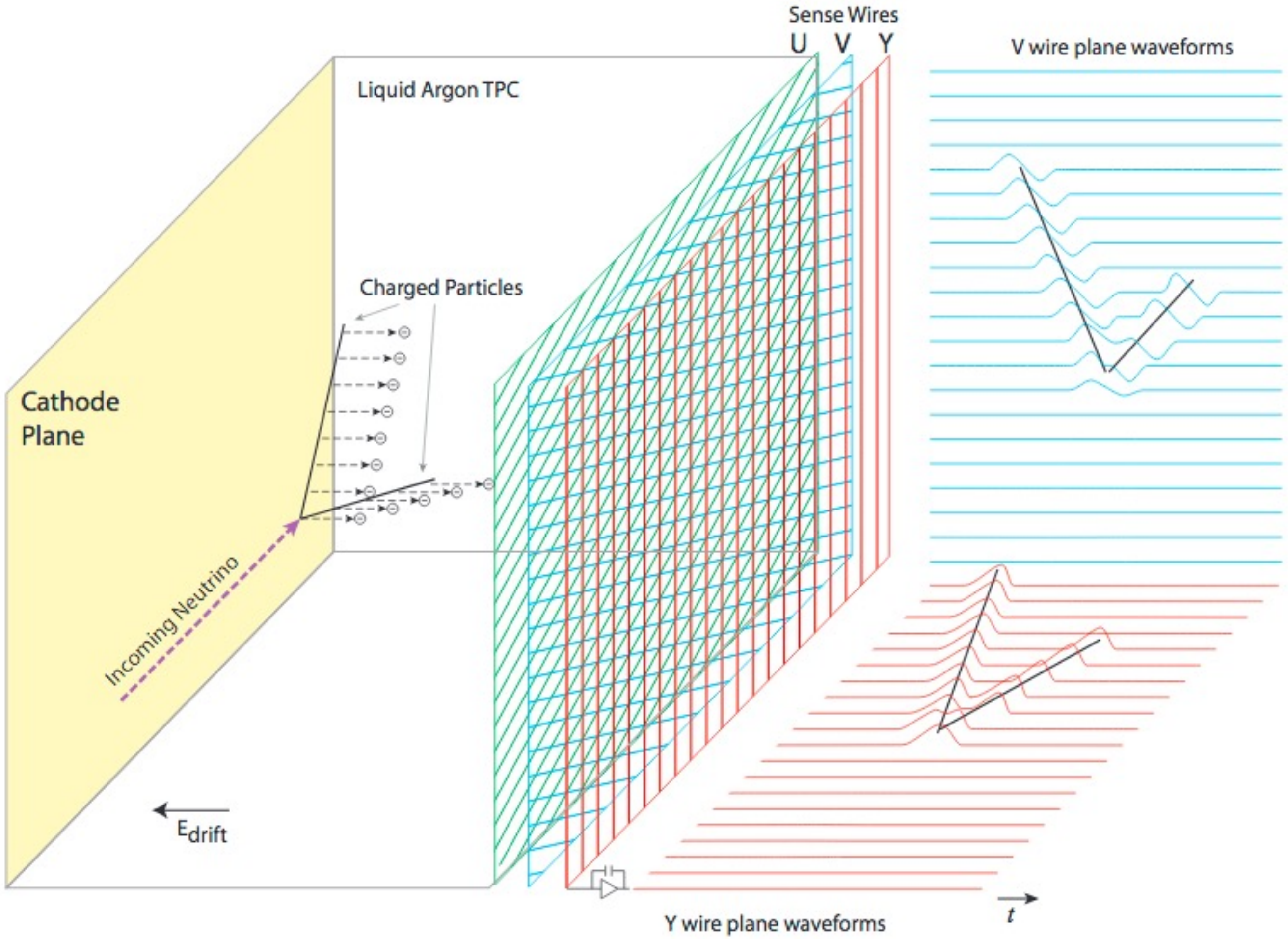
Time Projection Chambers




WIMP Signals in a Dual-Phase Xenon Detector
Xe

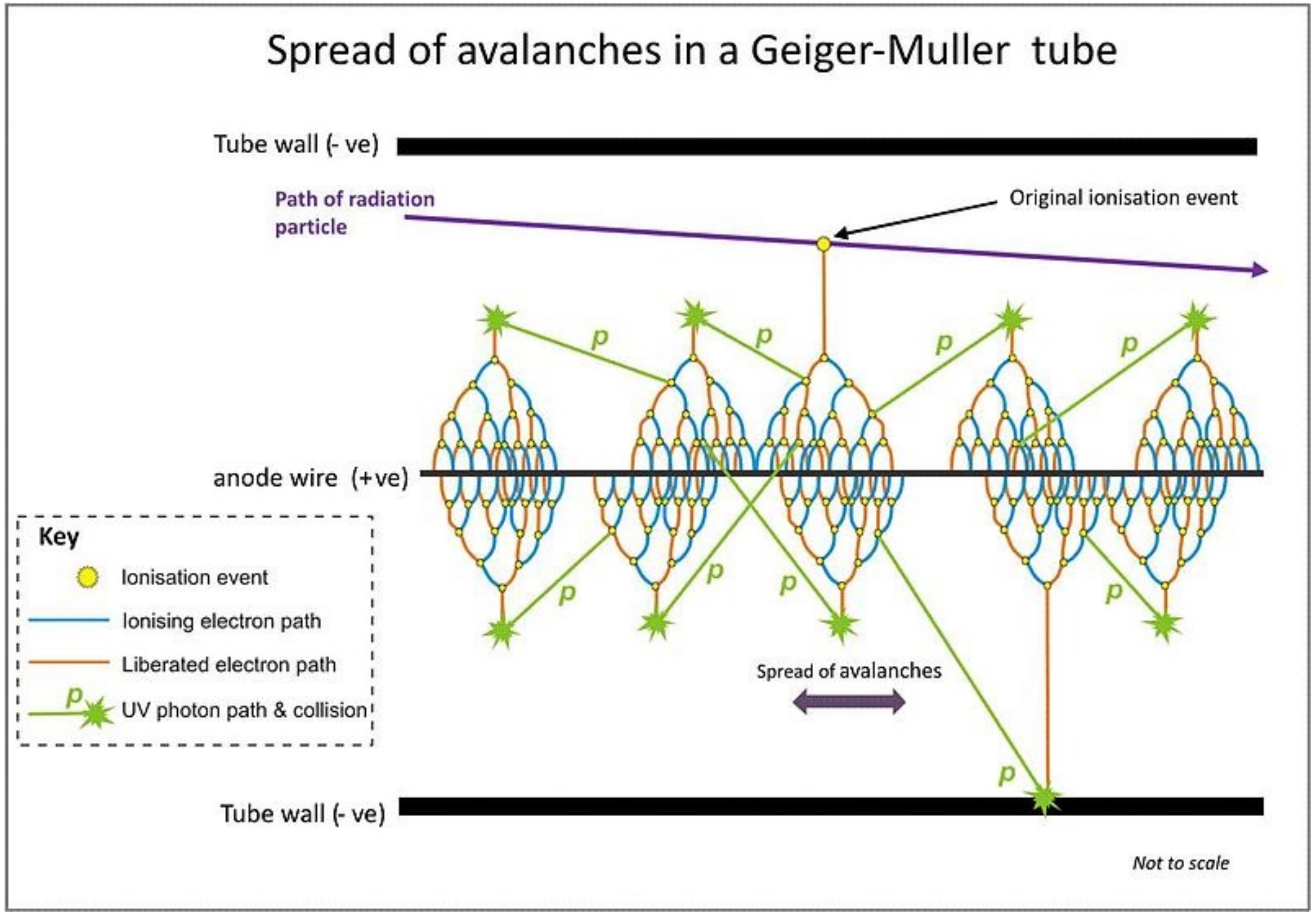
Dune far detector

- Liquid-Argon TPC - readout planes at the top
- 70,000 tons of Argon - active detector and drift medium

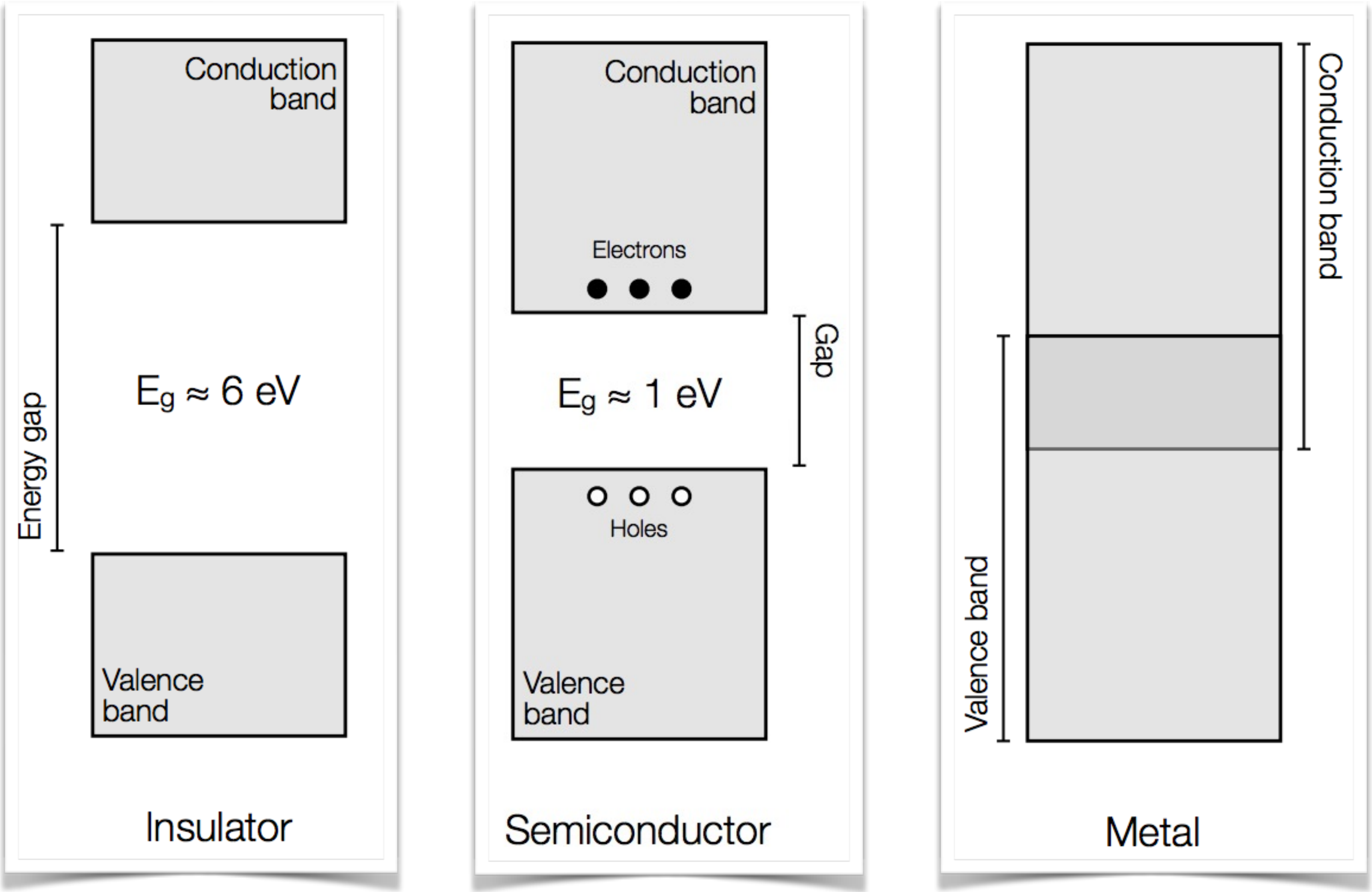


Beyond the Region of Proportionality

The Geiger-Muller region :
The output signal is independent of the energy loss of the incident particle.
Detectors working in this region are called as the Geiger-Muller counters.



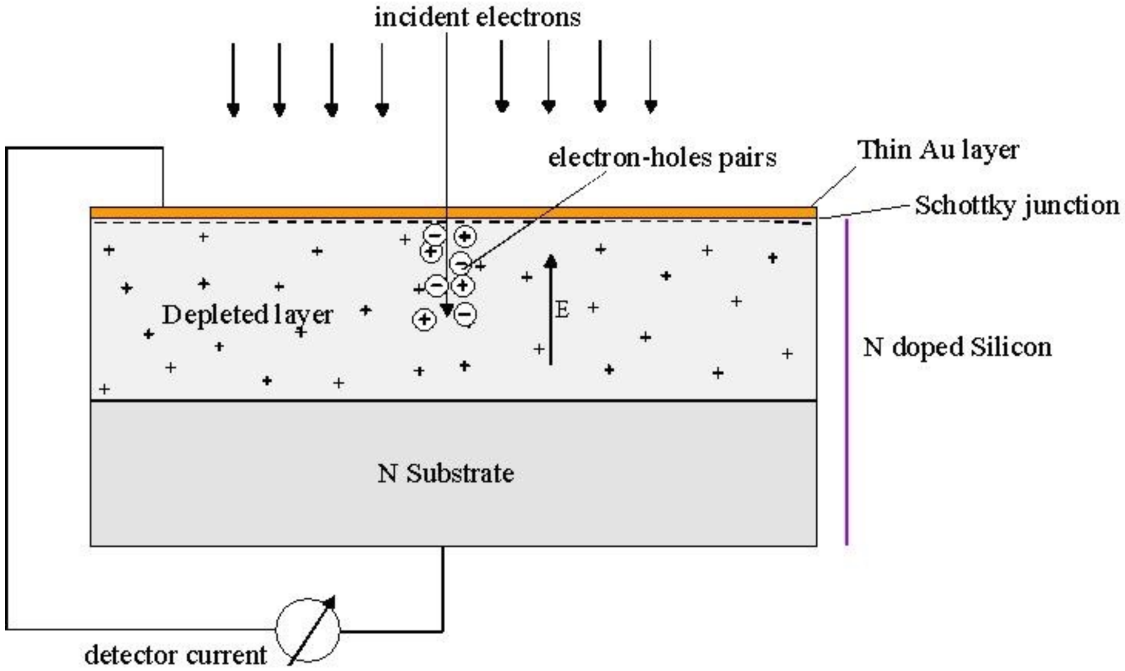
Semiconductor Detectors



Semiconductor Detectors

Solid-state detectors (Si, Ge) operate through the promotion of electrons from the valence band of a solid to the conduction band as a result of the passage of the incident particle.

The advantage of the solid-state detectors is the good energy resolution, because the energy loss required to produce electron-hole pair is only 3-4eV, compared to 30eV required in a gas detector.



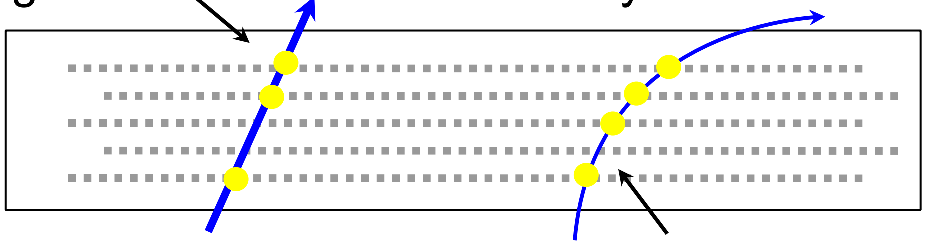
Energy required to produce electron-hole pair

	eV
Scintillator	100-300
Gas detector	10-30
Germanium	2.9
Silicon	3.7

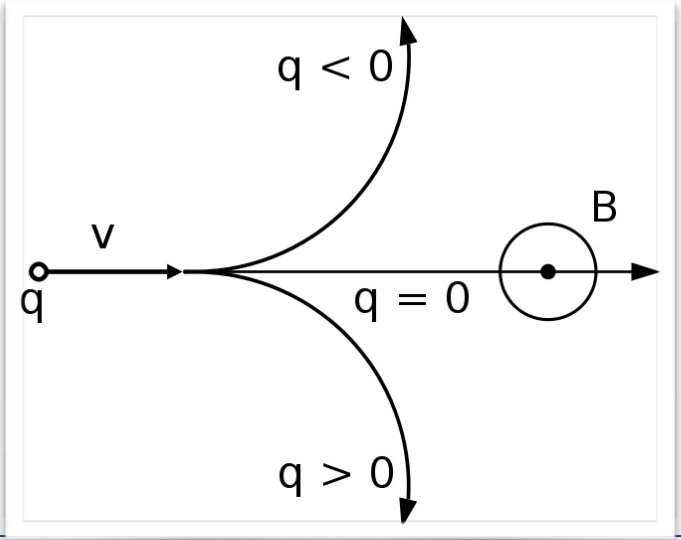
Silicon Ionization Detectors

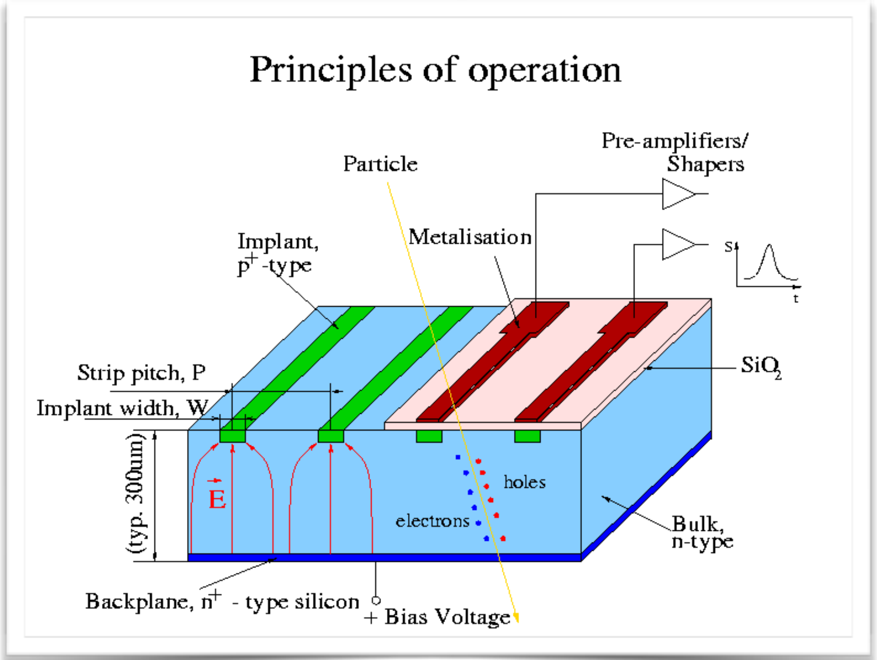
Semiconductor ionization created by passing particle charge

Particles ionize thin silicon layers and this charge can be collected to identify a “track”



By placing in a solenoidal magnetic field, Lorentz force on particle measures momentum

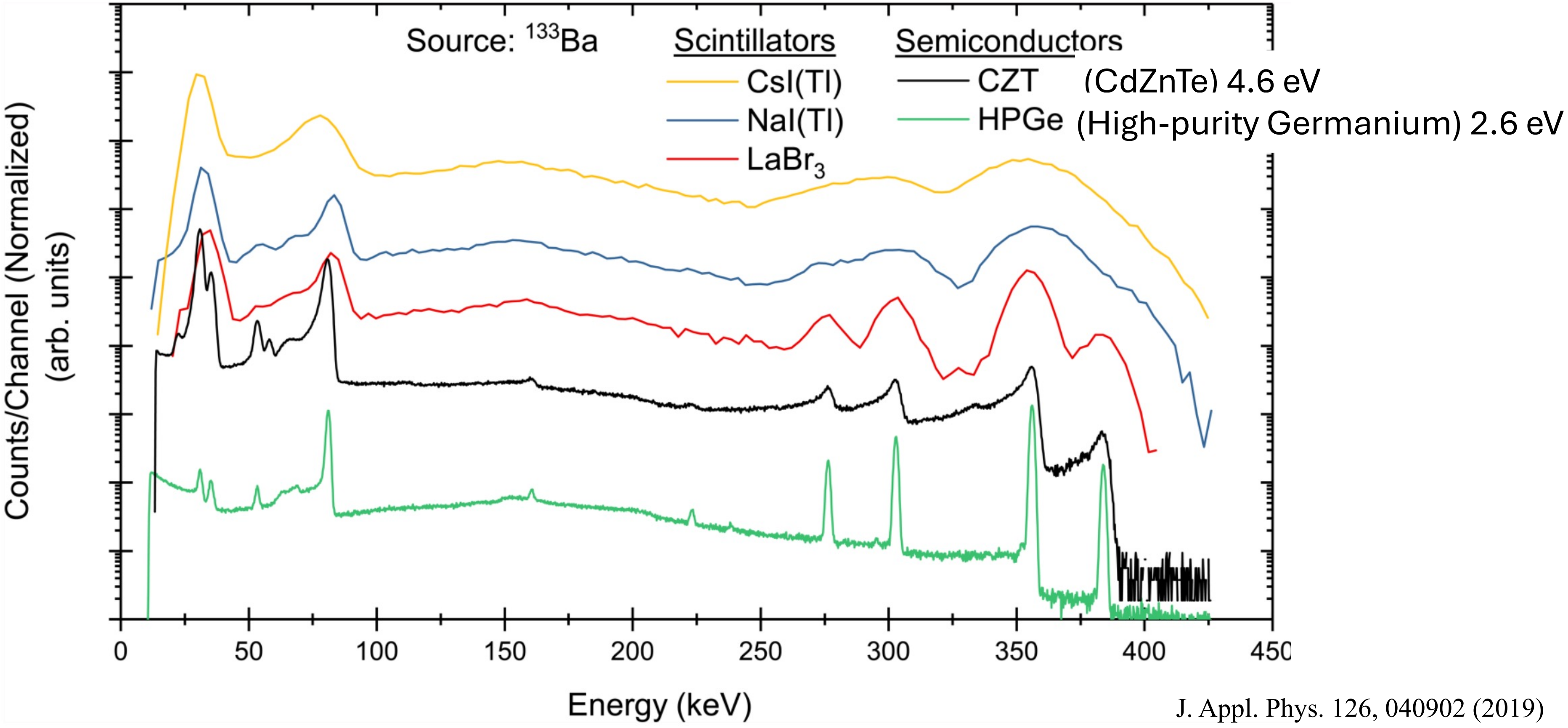




Real silicon detector
Thousands of these at ATLAS detector
Thousands of wires reading out each layer

Semiconductors vs scintillators

- Advantage: energy resolution
- Example: detecting decays of ^{133}Ba



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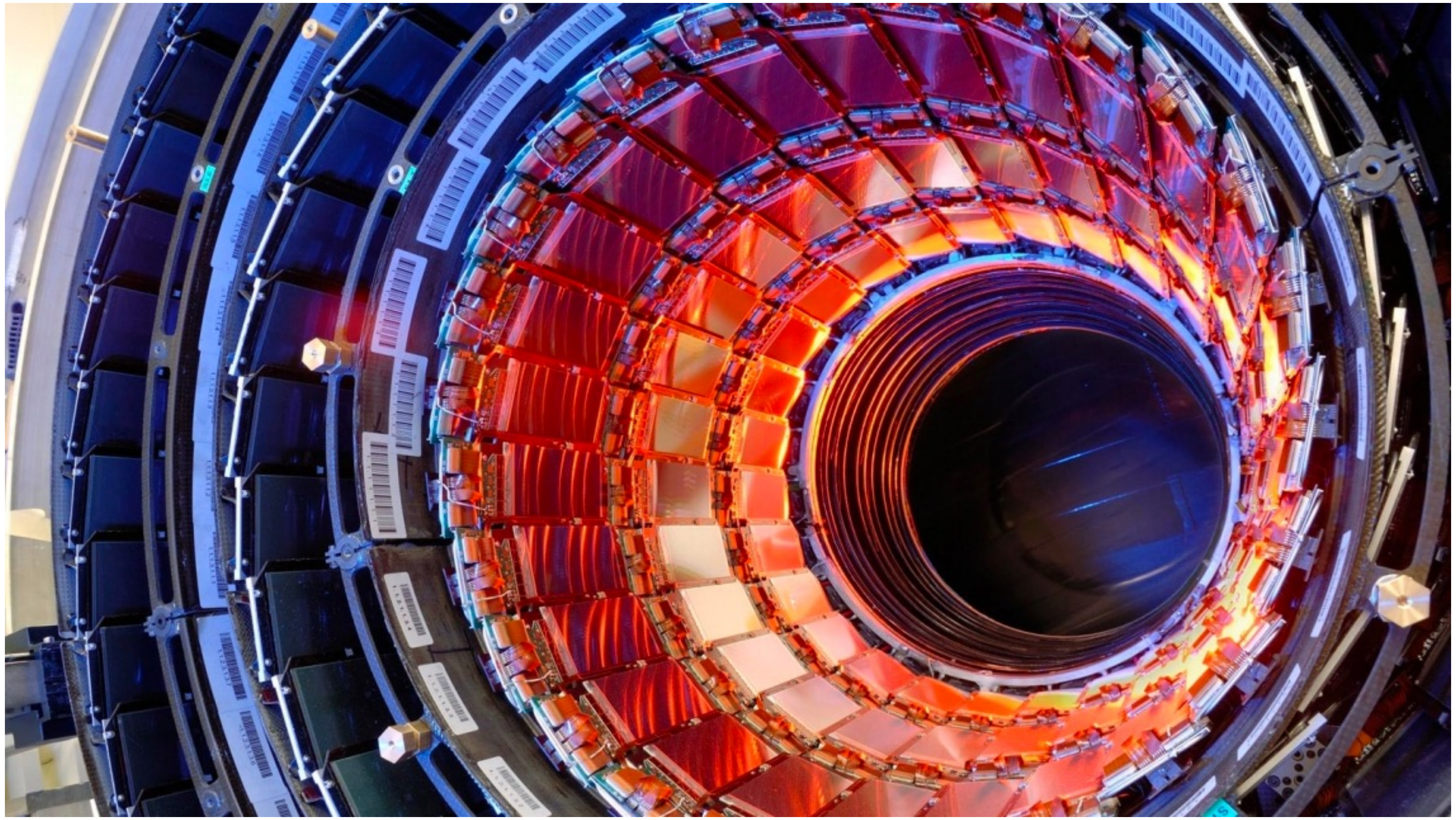
CMS silicon tracker

- Arranged in pixels and strips
- 75,000,000 readout channels
- 10 μm resolution



Recap / Up Next

This time:

Particle Detectors

- Detector strategies
- Particle Identification
- Detector Systems

Next time:

Multicomponent Detectors

- Comprehensive strategies
- Particle Identification
- Triggering