Basics of detectors

2026 Quark Net Workshop for High School Teachers

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Who am I ?

Staff page: https://www.bnl.gov/staff/mdiwan

- Worked at BNL since 1983 when I arrived as a graduate student.
- Worked on many large and small experiments.
- Initiated and promoted the neutrino program in the US that is now called DUNE.
- Recently I am working on various R&D projects including placing a detector in a lake to see neutrinos.
- In this lecture, we will go through some basics of detectors. In next one we will dig somewhat deeper and actually use some software that I will provide.

Plan of lecture

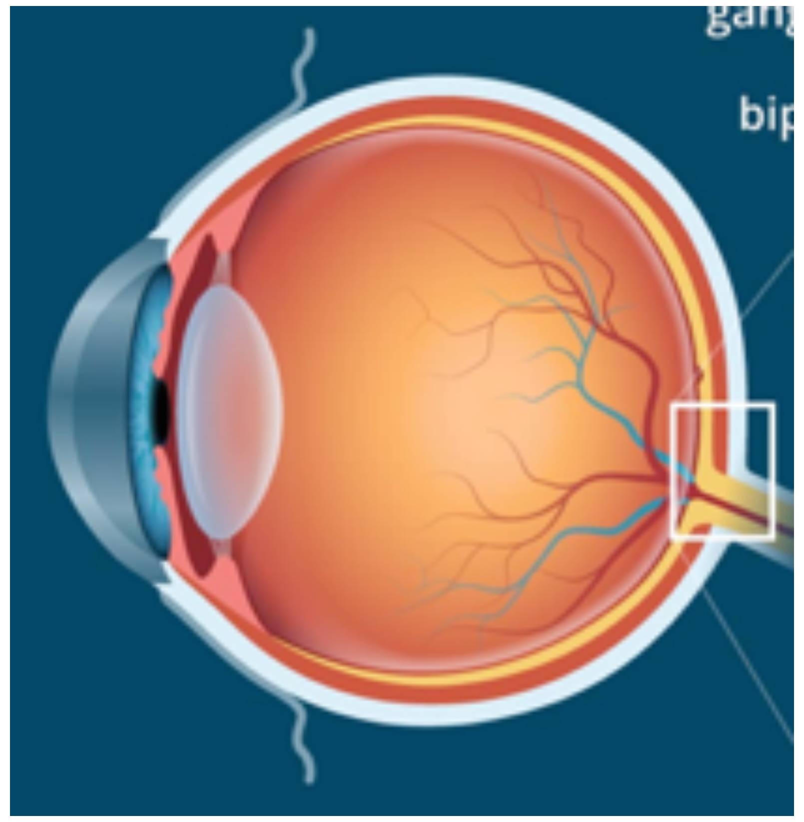
- Basics of Radiation Detectors
- Basics of particle interactions.
- Particle signatures in matter.
- Basic components of detectors.
- Detector types. Some examples as time permits.

I will use neutrino and cosmic ray detection in some of my examples, but most of the techniques are common in all radiation detection.

Some Basics

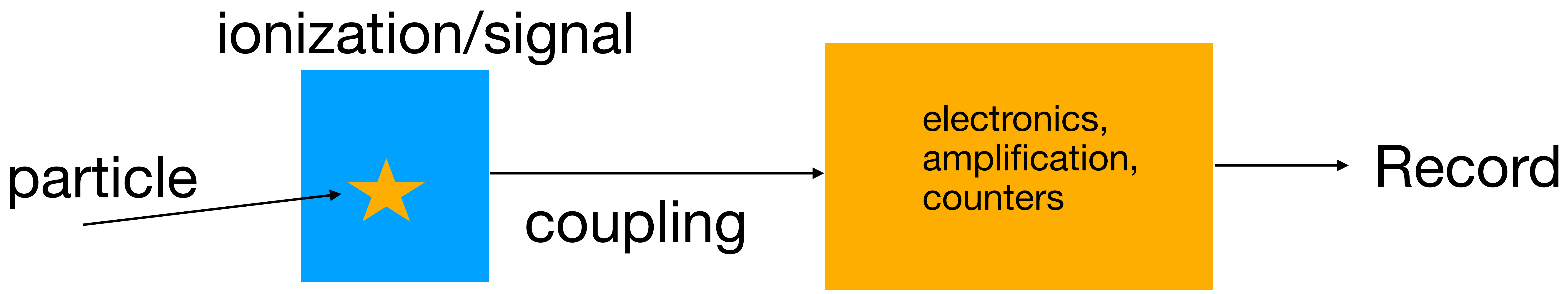
- We can only measure 4 quantities and their combinations:
  - Distance (units are meters)
  - Time (units are seconds)
  - Mass (units are kilogram)
  - Electric Charge (coulomb)

Example



- All detectors are built on the principle of charge detection.
- Any effect must be first be converted to free electric charge or motion of charge to be detected.
- This is regardless of whether detecting light, Higgs particles, neutrinos, or gravitational waves.

Radiation Detection



- ***Fast particles produce ionization in materials.***
- ***Depending on the material this ionization will produce current or light (or physical effects) which can be sensed.***
- ***There is a short list of particles that live long to produce such signals.***
- ***Electrons, Muons, Protons, Neutrons, Alpha, heavy nuclei, Gamma rays, Pions, Kaons.***

Let's now look at some data

It would be impossible to see a rare interaction in this !

This is the problem of doing sensitive experiment on the surface of the planet. There are too many cosmic rays as background.

Cosmic ray cloud chamber at the New York Hall of Science

The surface rate of cosmic ray muons is ~100 $m^{-2}sec^{-1}sr^{-1}$
Mean ~4 GeV
Flat below 1 GeV. $E^{-2.7}$ above 10 GeV.
Angular ~ Cos^2(Theta)

I will provide you code to do this calculation tomorrow.

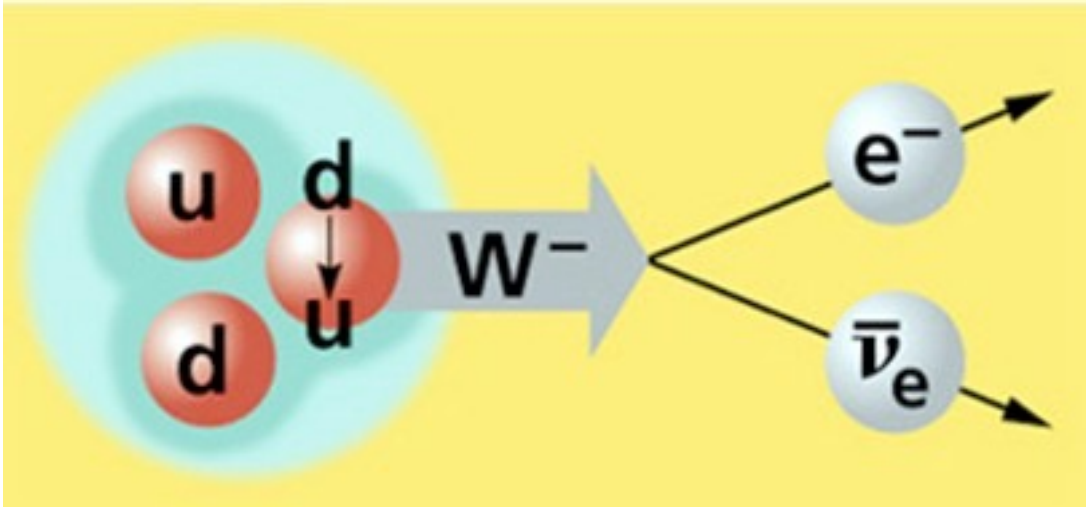
Example: Neutrino Detection

- ***Neutrinos are very light particles with no electrical charge.***
- ***They cannot stick together or to other ordinary things.***
- ***Just like photons, the signature of neutrinos must be first be converted into electrical particles before we can detect them.***
- ***There are hundreds of billions of neutrinos passing through us every second. The universe has almost as many neutrinos as particles of light.***
- ***But we cannot see them unless they produce another particle that can ionize material.***

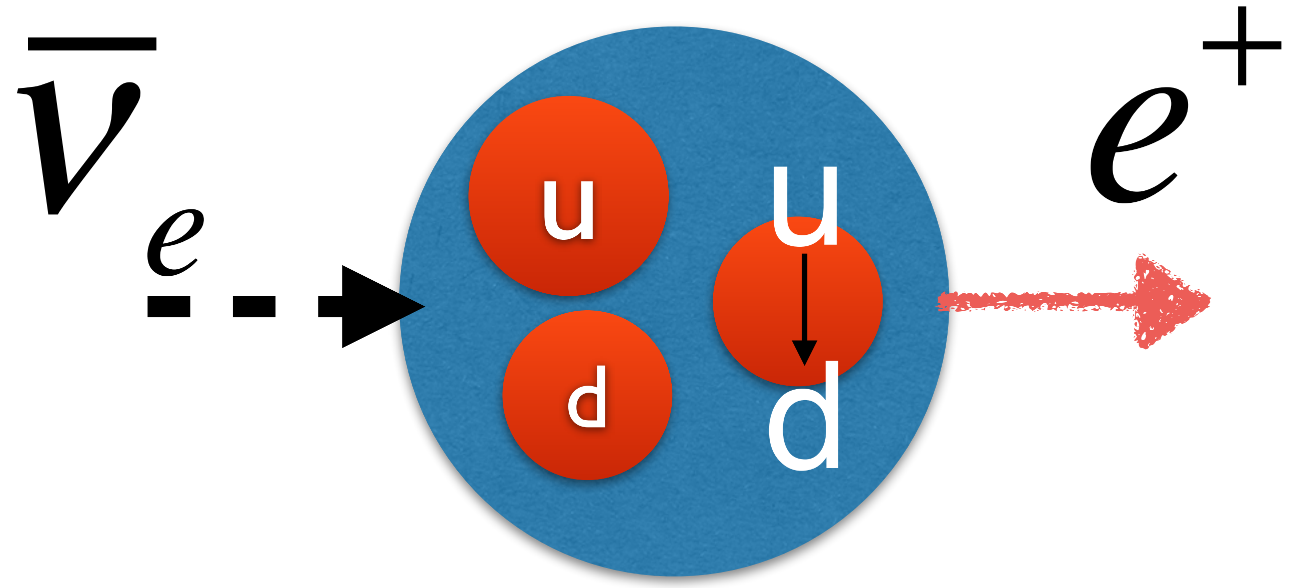
Neutrinos convert via the weak interaction.

- ***Radioactivity (beta decay) is a process that converts ordinary charged matter inside nuclei into neutrinos.***
- ***There is "inverse radioactivity" that converts neutrinos into charged particles.***
- ***Both of these are called weak interactions because they are rare.***
- ***Now, when you raise the central collision energy high enough weak interaction stops becoming rare. This is what we do at the colliders:LHC.***

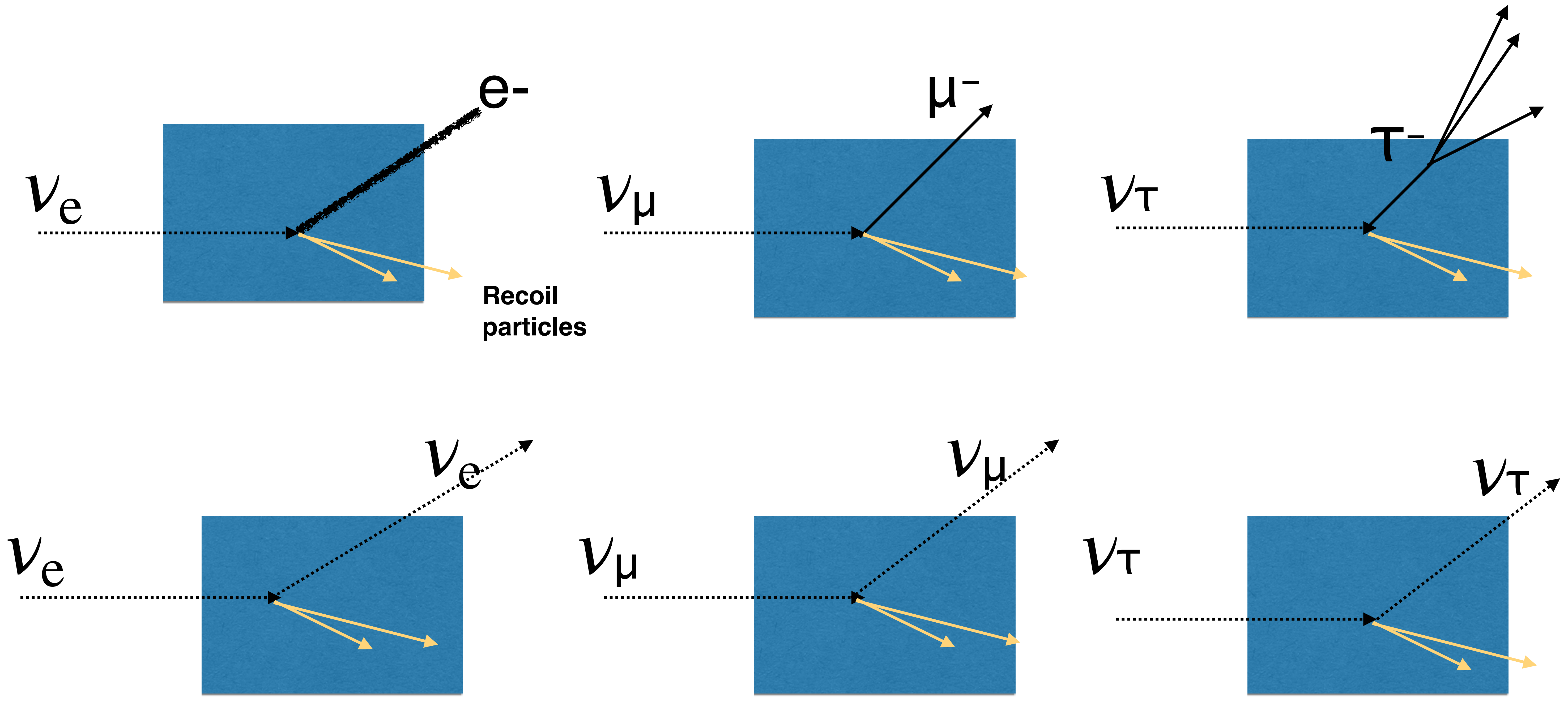
$$n \to p\, e^- \bar{\nu}_e$$



$$\bar{\nu}_e + p \to e^+ + n$$

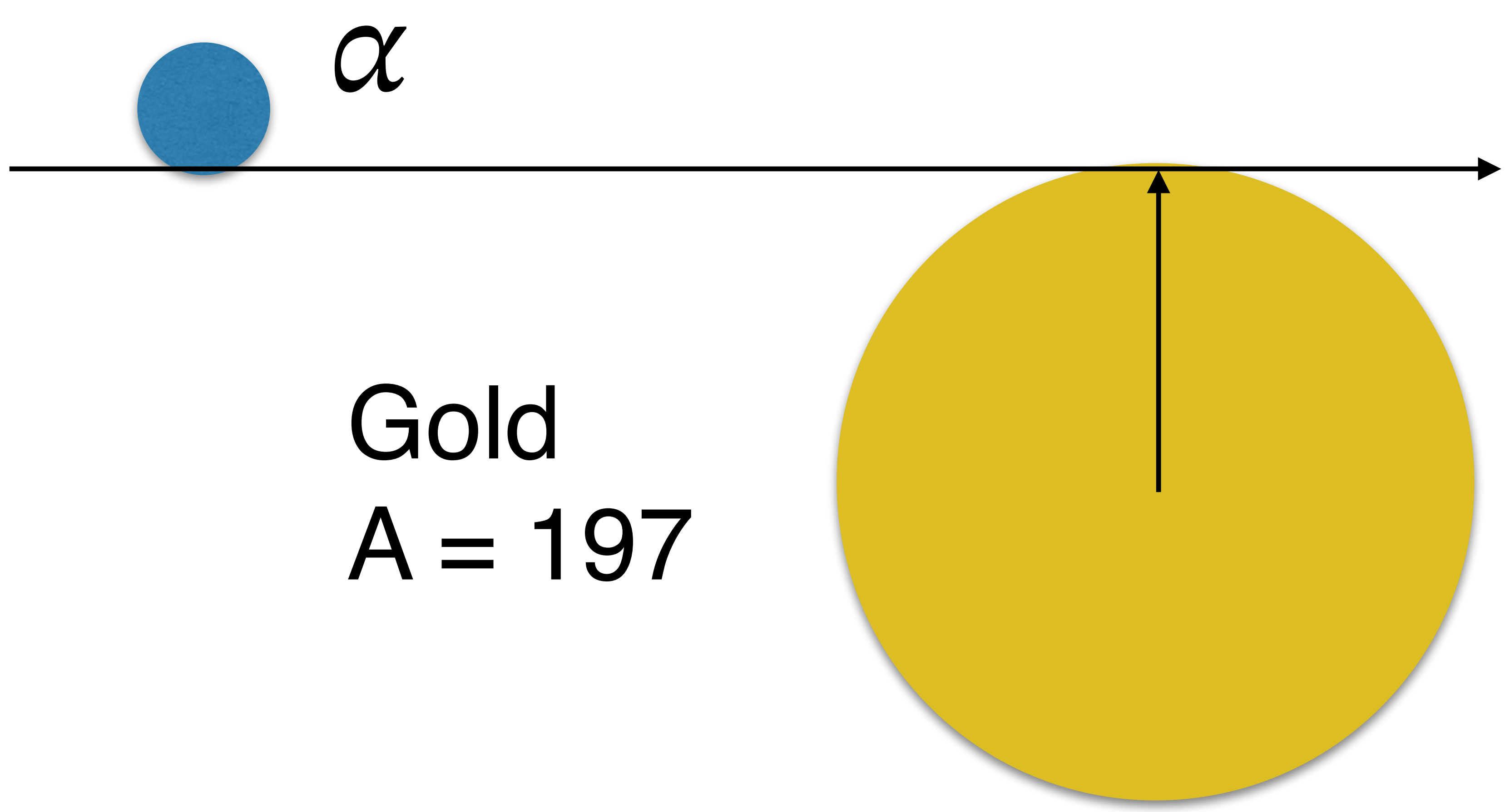


Neutrino Detection for 3 types of neutrinos



- ***The neutrino is invisible as it enters a detector. Rarely interacts and leaves charged particles that can be detected.***
- *Neutrino collision on atoms in detectors produces a charged lepton. The electron, muon, tau have very different signatures in a detector.*
- *Neutrino can also collide and scatter away leaving observable charged particles.(Neutral Current)*

Example of alpha particle collision: Cross section for particle collisions



Radius of a gold nucleus is

$R = 1.2 \times \sqrt[3]{197}\, fm = 7\, fm$

fm is $10^{-15} m$

Cross section for alpha particle is then

$\sigma \approx \pi R^2 \approx 1.5 \times 10^{-24}\, cm^2$

In particle physics, the cross section between any two particles is the area transverse to their relative motion within which they must meet to order to interact. It is the effective size.

More about cross section

- ***Quantum physics is very strange. There are no hard spheres and the cross section depends on many things:***
  - ***The two types of particles. (alpha and Gold …)***
  - ***Their spin orientation if any.***
  - ***Their relative velocities.***
  - ***The type of interaction that they exhibit: electrical, weak, or strong !***

Neutrinos have extremely small cross section. Even for Neutrino on Gold. But ordinary particles have huge cross sections and therefore they can interact in matter and produce signals.

Units

Most of physics can be approached by understanding the value of numbers that are assigned to quantities. All values come with a units. Detector physics has its own language of units.

- Charge: Coulombs. electrons have $1.602 \times 10^{-19}C$
- Current: Ampere = Coulombs/sec.
- Power: $Watts = \text{Joules/sec} = (\text{kg m}^2/\text{sec}^2)/\text{sec} = \text{Newton m/sec} = \text{Volt} \times \text{Ampere}$
- $\text{Volts} = \text{Joules/Coulomb}$
- An electron that goes through 1 Volt then has $1.602 \times 10^{-19}\text{joule}$ = 1 eV
- This is used throughout physics as a defining units for energy, mass, and momentum.
- energy: eV Mass: eV/c^2 and momentum: eV/c
- MeV: 10^6eV GeV: 10^9eV etc.

A little bit about relativistic kinematics

Fast particles follow the rules of relativity. Energy, momentum, velocity need to account for the rules of relativity.

- Relativity has two rules: 1. All rules of physics are the same even if you are moving at a constant speed. 2. Speed of light in vacuum is constant. 299,792,458 m/sec.
- This means if you speed up a particle its energy will keep rising, but it will never exceed the speed of light. Some formulas without proof are here:
- For particle of mass M, $c = \text{speed of light}, \beta = \text{v/c}, \gamma = \dfrac{1}{\sqrt{1-\beta^2}}$
    - $E = mc^2\gamma$ (notice that for zero velocity, you get $E = mc^2$
    - $P = mc\beta\gamma$
    - You can calculate $E^2 = (Pc)^2 + (mc^2)^2$ This is total energy
    - Kinetic energy is $T = mc^2\gamma - mc^2$

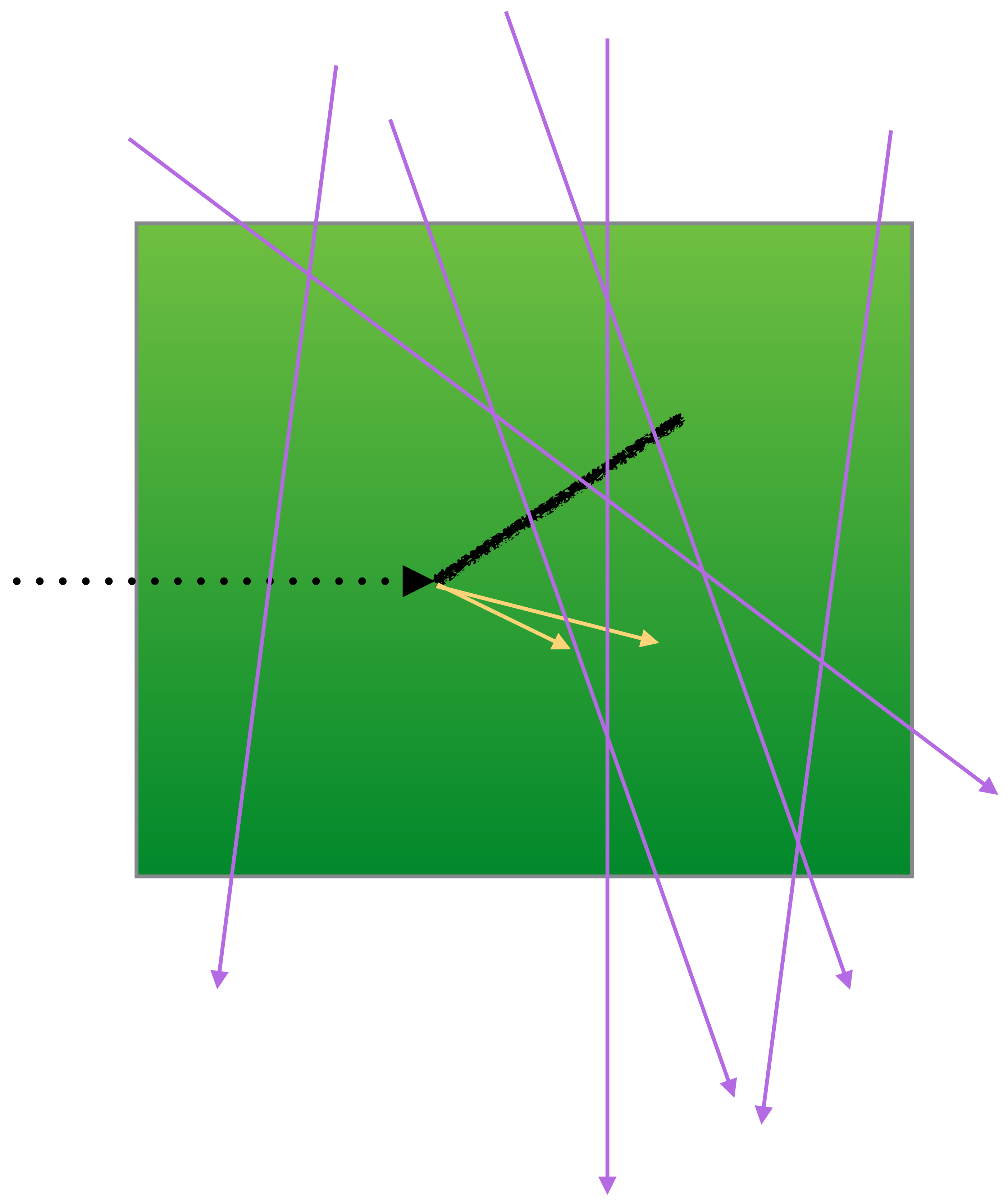
Common particle masses

These are the particles that yield most of the radioactivity and ionization signals

- All charged particles can have opposite charges.
- neutrons interact with atomic nuclei to cause ionization.
- Gamma rays interact to produce electrons and positrons to cause ionization.
- Fast particles have longer lifetimes due to relativity by factor of γ

Particle	Mass	Charge	Lifetime
Electron	0.511 MeV	1	stable
Proton	0.938 GeV	1	stable
Neutron	0.939 GeV	0	15 min
deuteron	1.875 GeV	1	stable
Muon	105 MeV	1	2.2 microsec
Pion	135 MeV	1	26 nanosec
gamma	0	0	stable
Various nuclei	~Z+A GeV	Z	various

Summarize so far



- ***Radiation particles interact in blocks of material and leave energetic charged particles.***
- ***This includes cosmic rays that are always present.***
- ***The energetic charged particles ionize the material as they slow down freeing electrons from atoms making negative charged electrons, and positive ions.***
- ***This ionization causes physical effects:***
  - ***bubbles in cloud chambers,***
  - ***dark spots in photographic plates***
  - ***current in properly made sensors***
  - ***florescence in special materials.***
- ***We register these effects by various means. pictures, electronics ?***

Collision of a heavy particle with an electron

$(E_i = M\gamma,\ p_i = M\beta\gamma)$ $(m_e, p_o = 0)$ $(E_f,\ p_f)$ (E_e, p_e)

This is called a 4 vector. It is used in relativistic calculation.

The question is what is the maximum kinetic energy $W = T_e = E_e - m_e$

$$T_e = \frac{2m_e\gamma^2\beta^2}{(1 + \frac{2m_e\gamma}{M} + \frac{m_e^2}{M^2})}$$

(derivation in backup slide)

This is exact

Calculate

how much max kinetic energy for an electron for some fast particles

particle	mass (MeV)	Kinetic energy	gamma	Tmax
electron	**0.511**	10 MeV	20.56	10 MeV
Muon	**105.65**	10	1.09	0.20 MeV
Muon	**105.65**	1000	10.47	100 MeV
Proton	**938**	100	1.10	0.23 MeV
Proton	**938**	1000	2.07	3.33 MeV

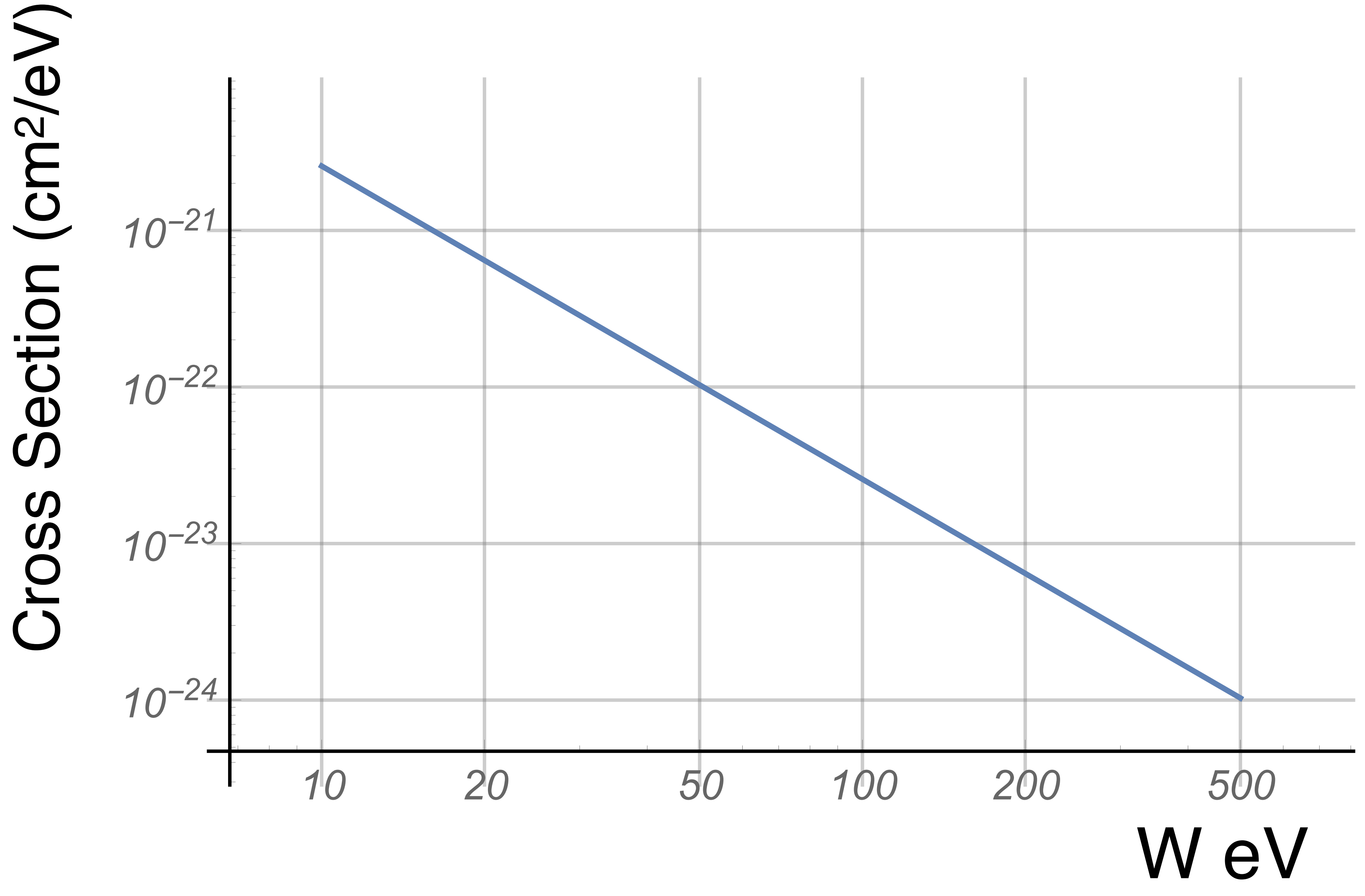
To first order collisions depend on the velocity of the fast particle. Except for electrons.

Ionization Energy Loss

Most of the energy loss of fast charged particles is due to single collisions with atomic electrons. In most collisions energy W is lost with W < 100 eV.

There is a Maximum energy loss in single collision on free electrons.

$$W_{\max} \approx 2m_e\beta^2\gamma^2 / (1 + 2\gamma m_e / M)$$



$$\frac{d\sigma(W,\beta)}{dW} = \frac{k_r}{\beta^2}\frac{(1-\beta^2 W / W_{\max})}{W^2}$$

$$k_r = 2\pi r_e^2 m_e z^2 = 2.54955 \times 10^{-19} z^2 \cdot eV \cdot cm^2$$

We know how to calculate and simulate this in great detail in our detectors.

This is called ionization energy loss

Understanding ionization in materials (story is somewhat more complicated)

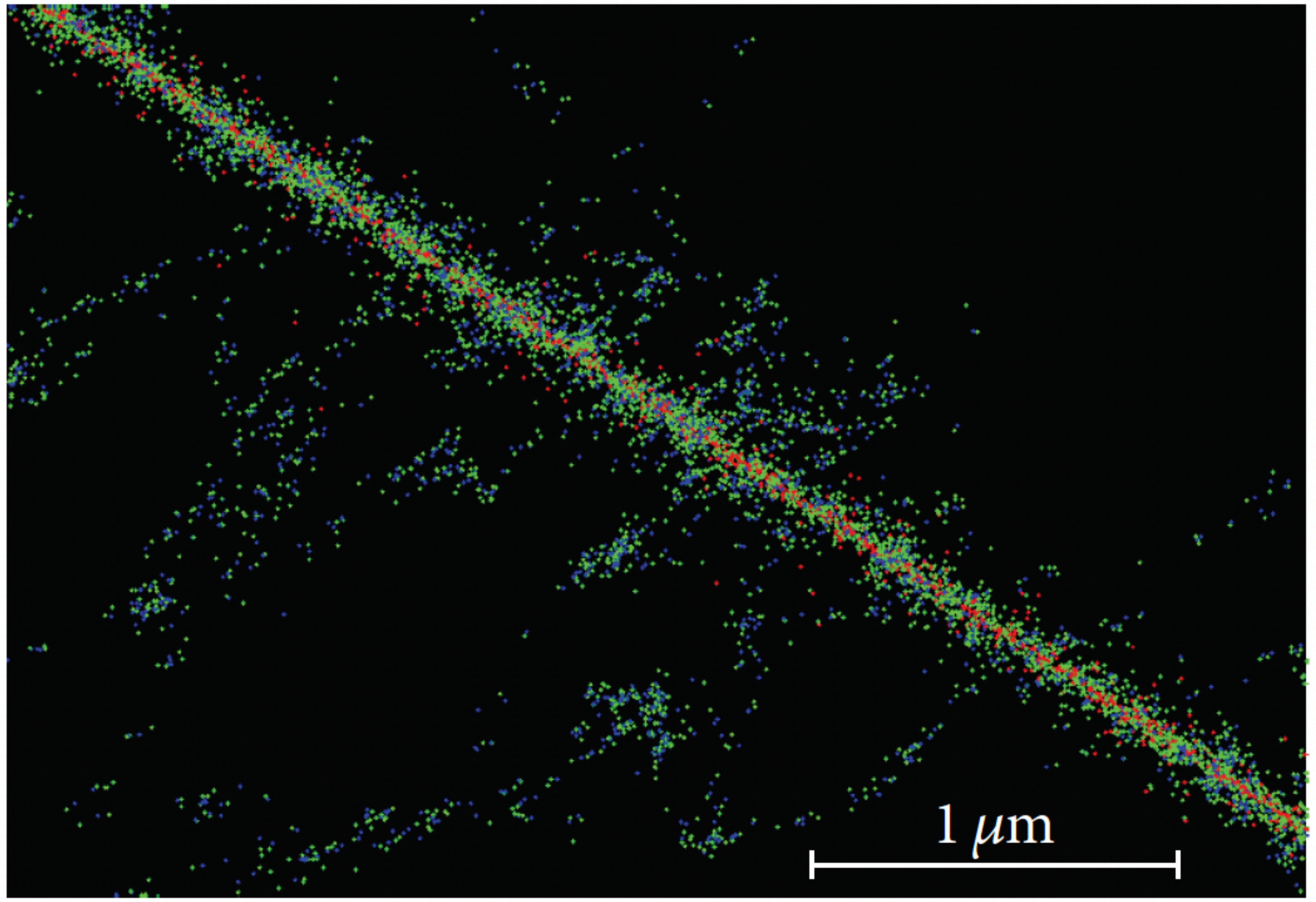


FIGURE 1: The track structure of a single proton in water. Simulated using RITRACKS. Red: proton ionisation, green: electron ionisation, and blue: hydroxyl radicals.

Simulation.

Detailed understanding of cross sections and molecular states in liquid is needed for this level of simulation. Geant-DNA and RITRACKS are codes developed to specifically understand water ionization.

Reference: Douglas, Penfold, Bezak, Computational and Mathematical Methods in Medicine, June 2015

Also see H. Bichsel (2006) on corrections to dE/dx for atomic effects.

Example of nucleus slowing down in emulsion

Z = 24

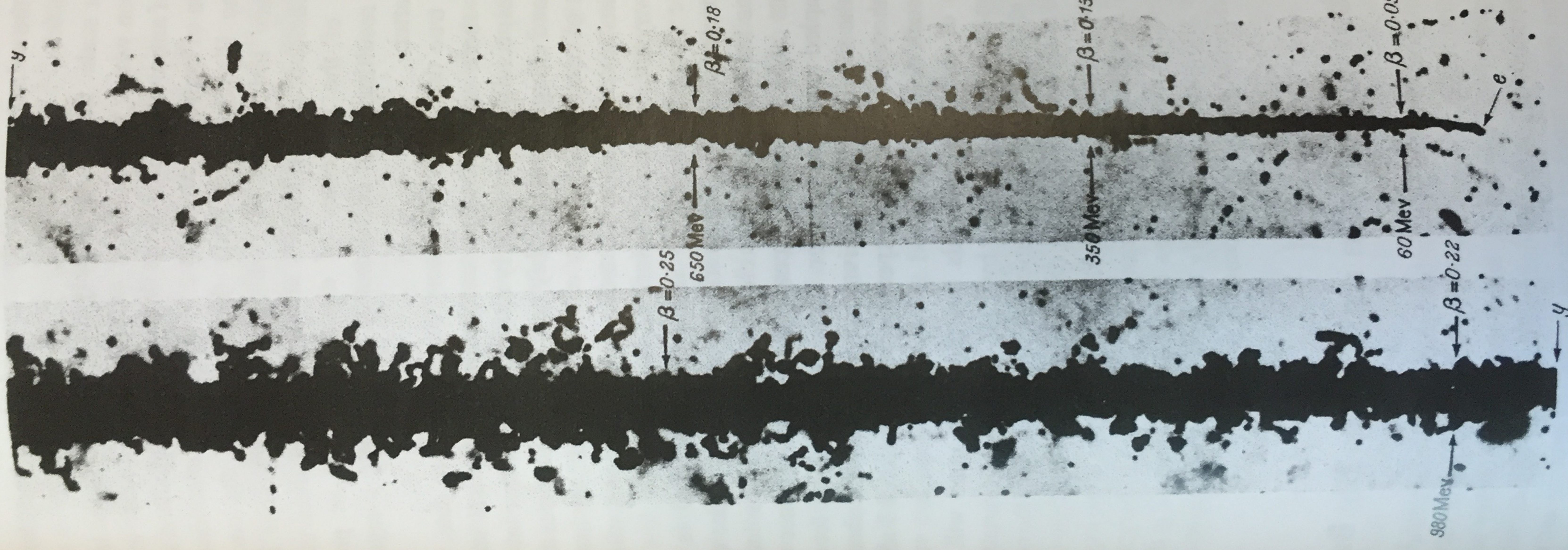
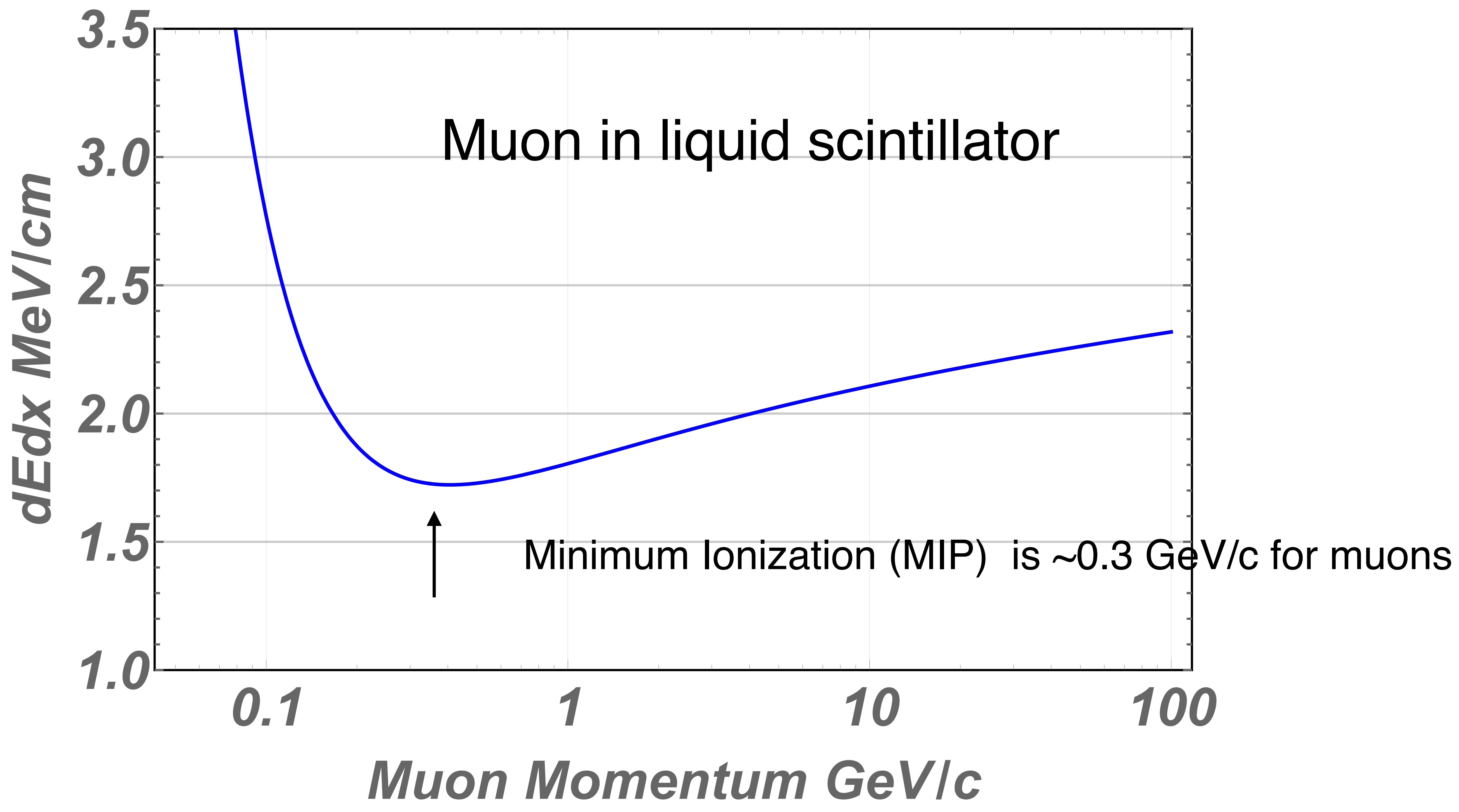


Fig. 6.3 Track of a primary cosmic ray chromium nucleus ($Z = 24$) observed in nuclear emulsion flown on a balloon. The track, of total length 400μm, is shown in two adjacent sections, starting from left top, and terminating at bottom right. As the ionization is proportional to Z^2, the track is initially very dense in comparison with that of the singly charged antiproton in Fig. 6.2. As the nucleus slows down, its velocity becomes comparable with that of electrons in the chromium atom, so it successively collects electrons into the various shells K, L, and so on, the track tapers down and finally it comes to rest as a chromium atom. Had this been an antinucleus of order 100 secondary pions would have been produced as the antinucleus slowed down and annihilated.

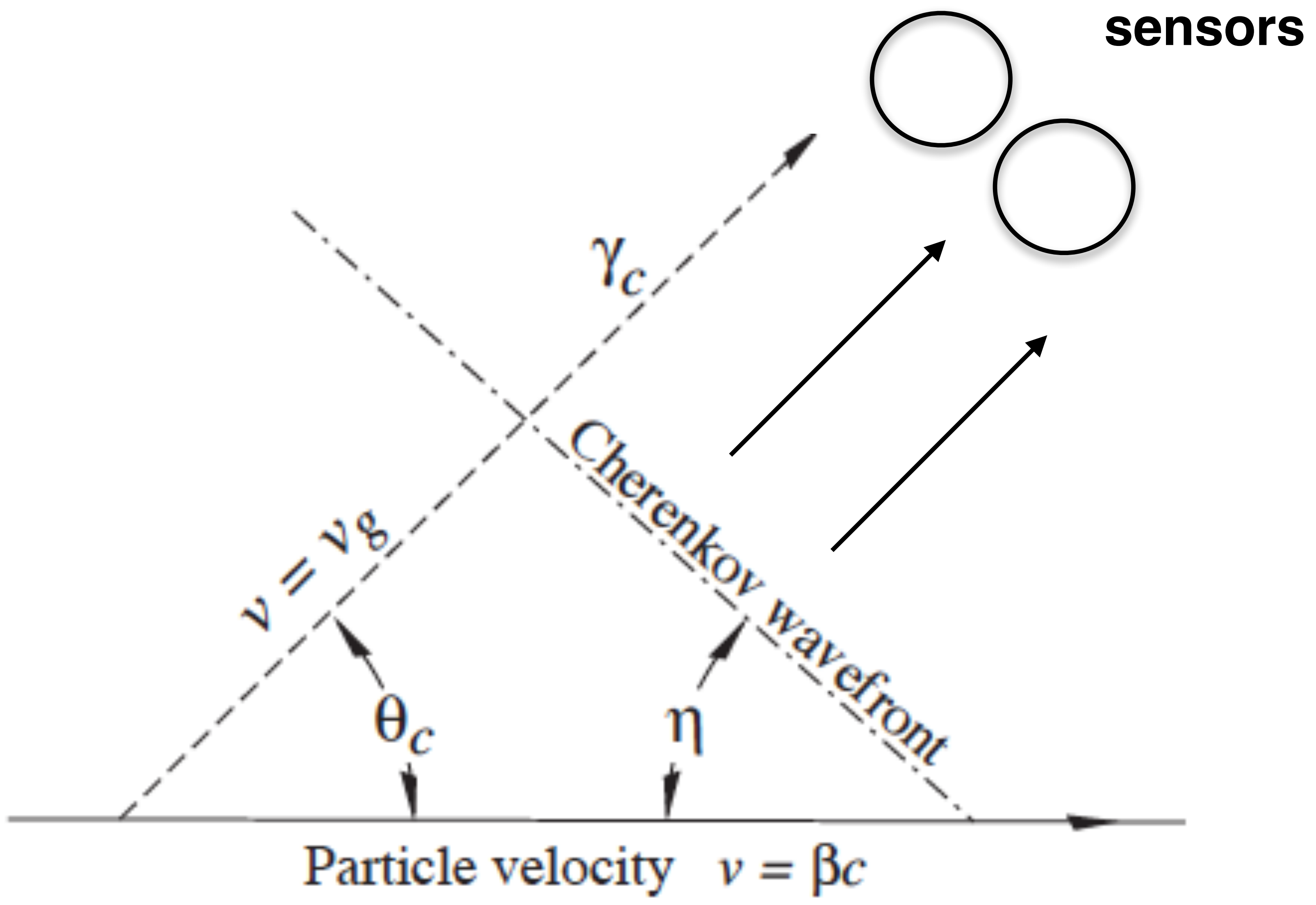
Ionization Energy loss of charged heavy particles



Tomorrow, I will provide code to do these kinds of calculations.

- ***The energy loss has a minimum and rises very quickly as particle slows.***
- ***This lost energy causes to 1) free electric charge, 2) scintillation light, 3) physical (bubbles) and chemical changes (photographic plates).***
- ***Energy loss depends on velocity. At very high energies most of the loss is due to radiation (or emission of gamma rays rather than ionization).***

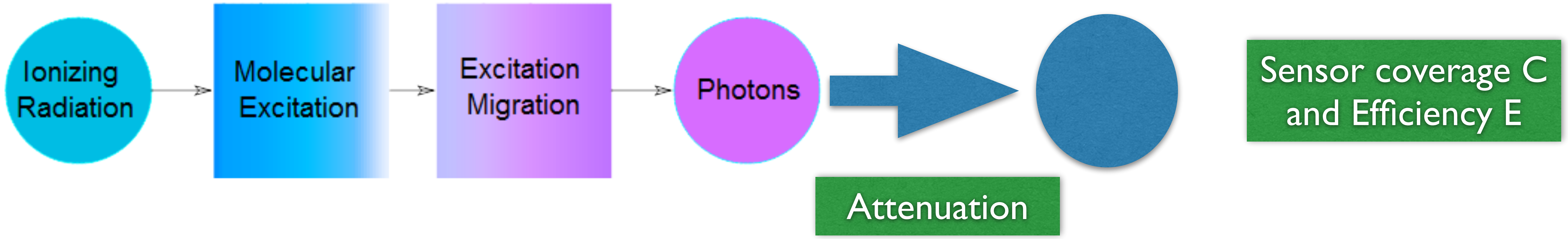
Cherenkov Radiation



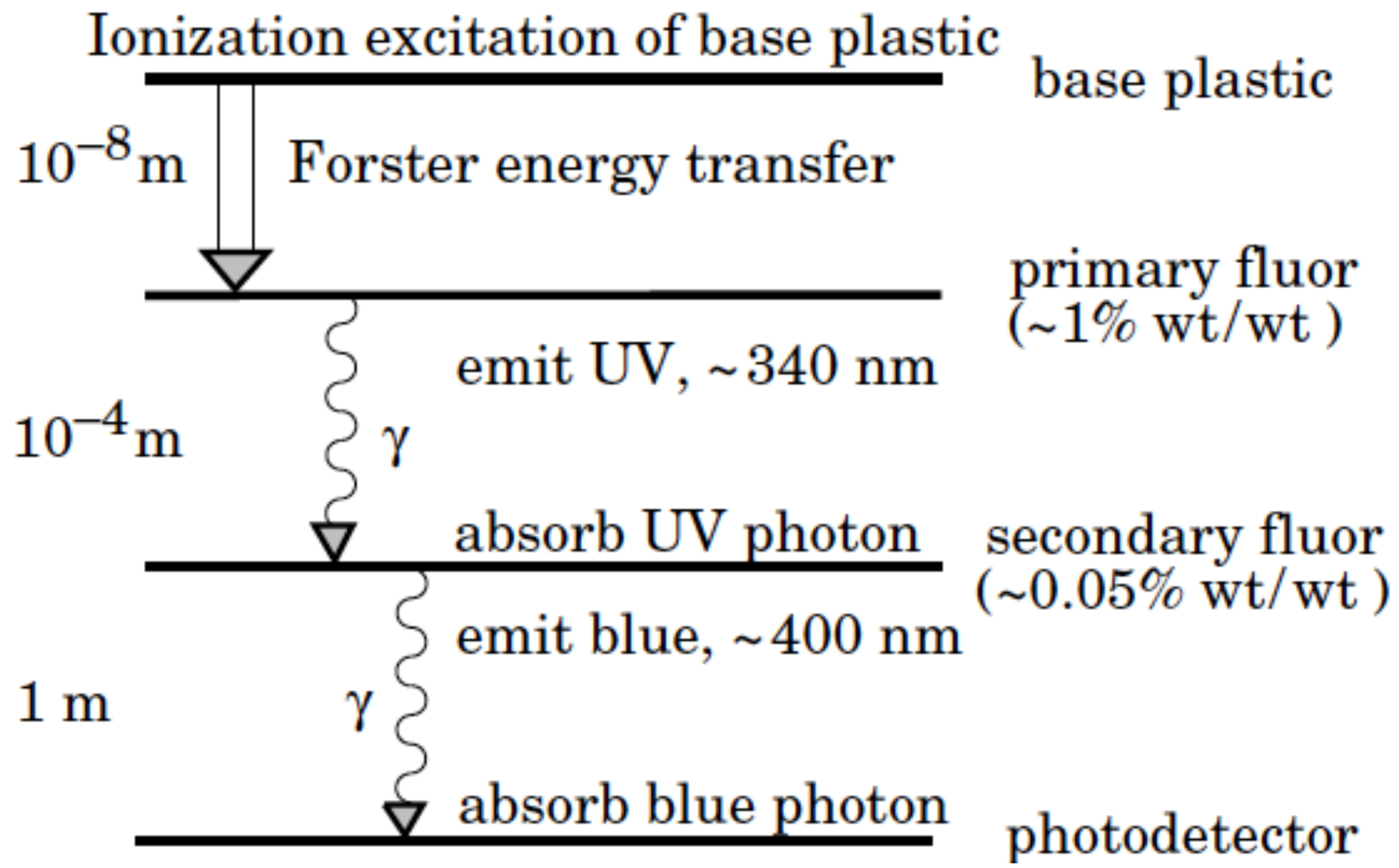
$$\cos\theta_c = (1/n\beta)$$
$$\theta_c + \eta \approx \pi/2 \quad \textit{because of dispersion}$$

- Cherenkov radiation: happens when particle moves faster than speed of light in a medium. This is used with gas, acrylic, and water.
- This radiation can be detected in sensors to reconstruct the particle. But it must have sufficient momentum to be above threshold. $\beta > 1/n$

Scintillation from ionization in plastics



Time scale ~ few ns due to first fluor (rise time)

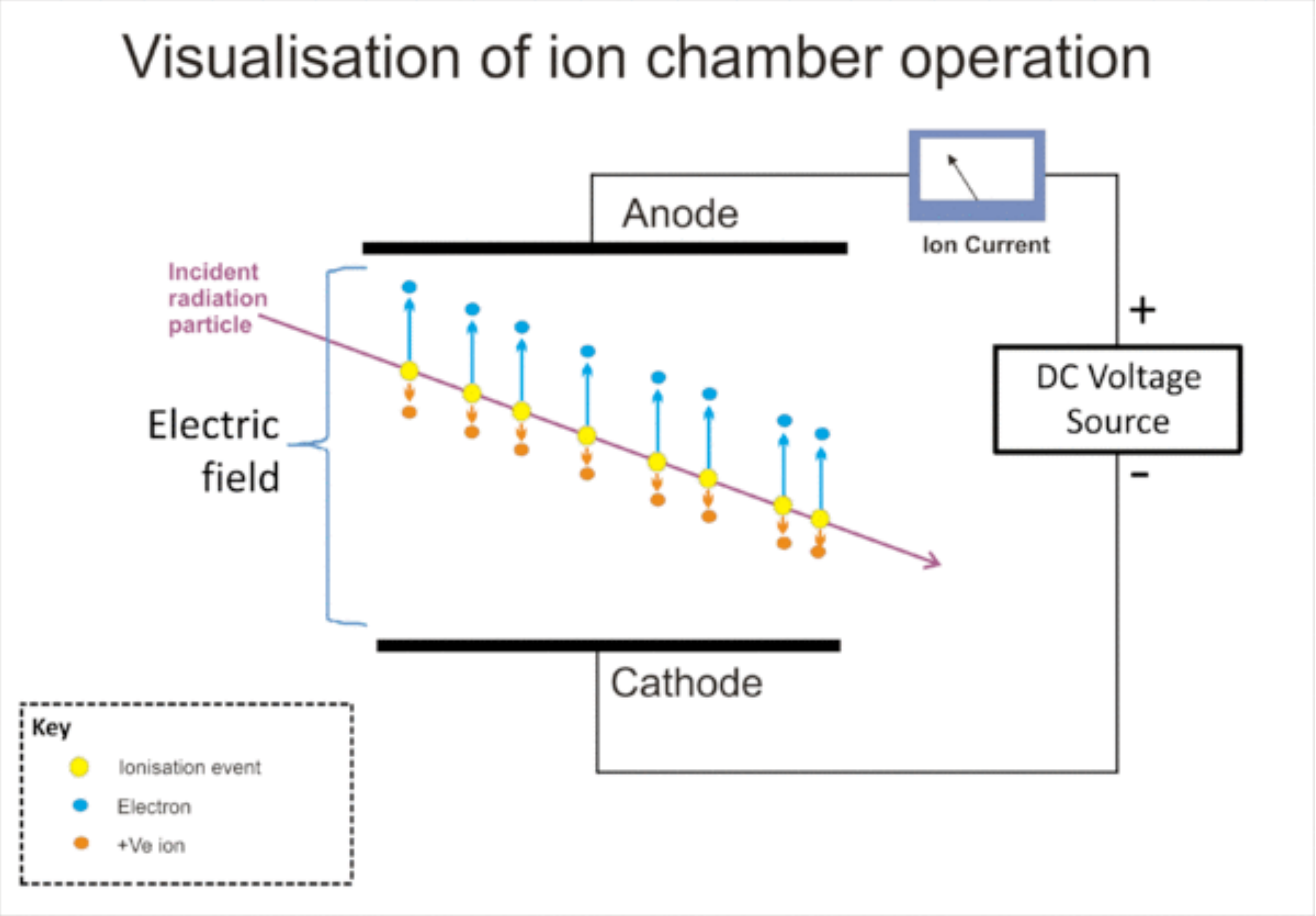


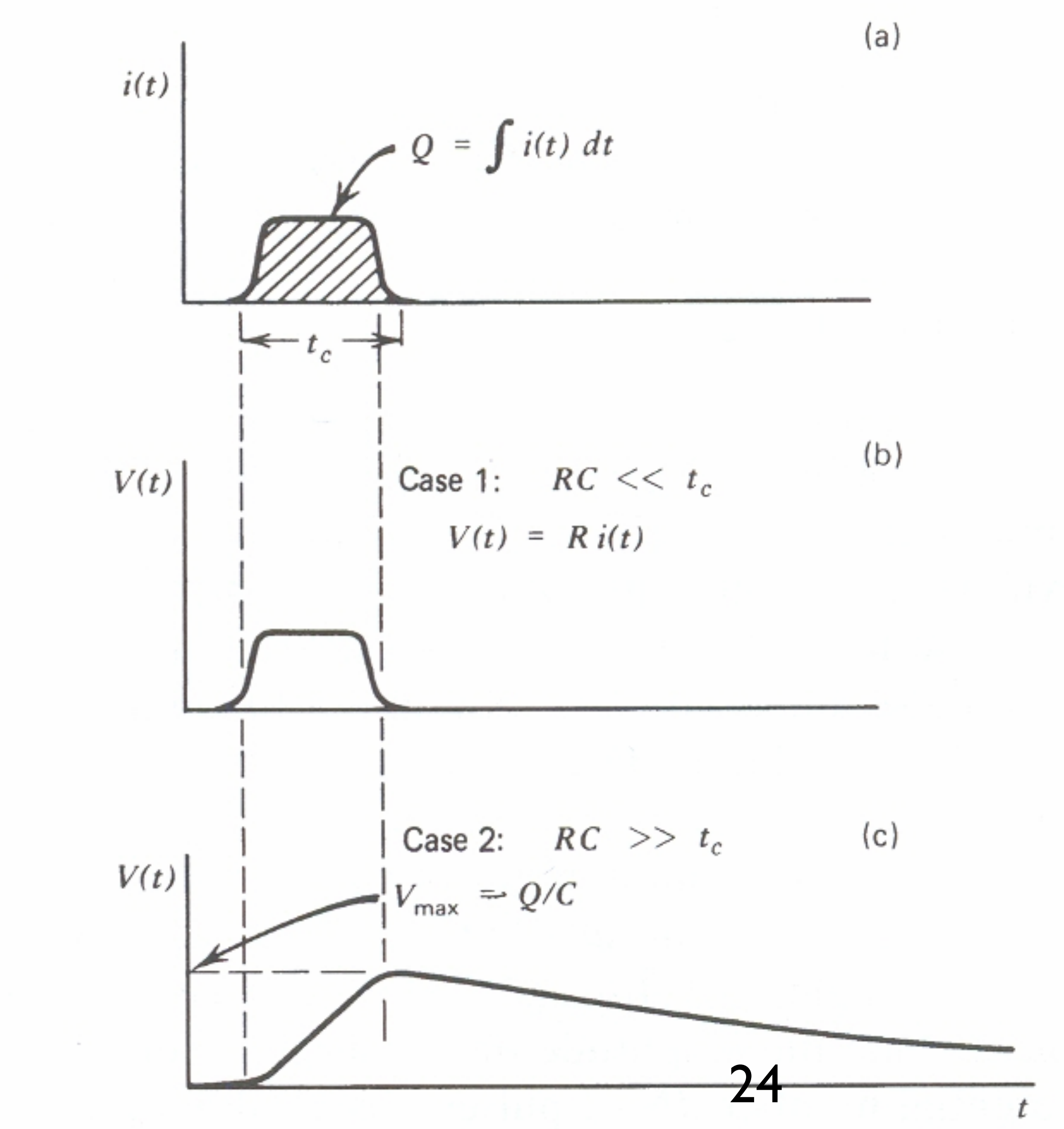
$$Typical \quad L \sim 10^4 \; photons / MeV$$

$$Yield = L \bullet C \bullet QE \bullet e^{-PathLength/\lambda}$$

- There are many scintillation mechanisms. Organic scintillators and noble liquids are important for neutrino physics.

Ionization detectors





material	W (ev/pair)
LAr	23.6
LXe	15.6
Silicon	3.6
Germanium	2.9
Diamond	~13
CdTe	5.2
LNe	36
LKr	19

- In gases, semiconductors, and pure insulators, ionization creates electron-ion pairs. W is the ionization energy needed to make a pair.
- Electrons generally move about 1000 times faster than ions.
- This current can be measured as voltage across a resistor (case 1) or pulse across a capacitor (case 2)

Energy loss of electrons and photons at high energies

$$1/X_0 \approx (1/716) \bullet \frac{Z^2}{A} \bullet Log(\frac{184}{\sqrt[3]{Z}})\,(gm/cm^2)^{-1}$$

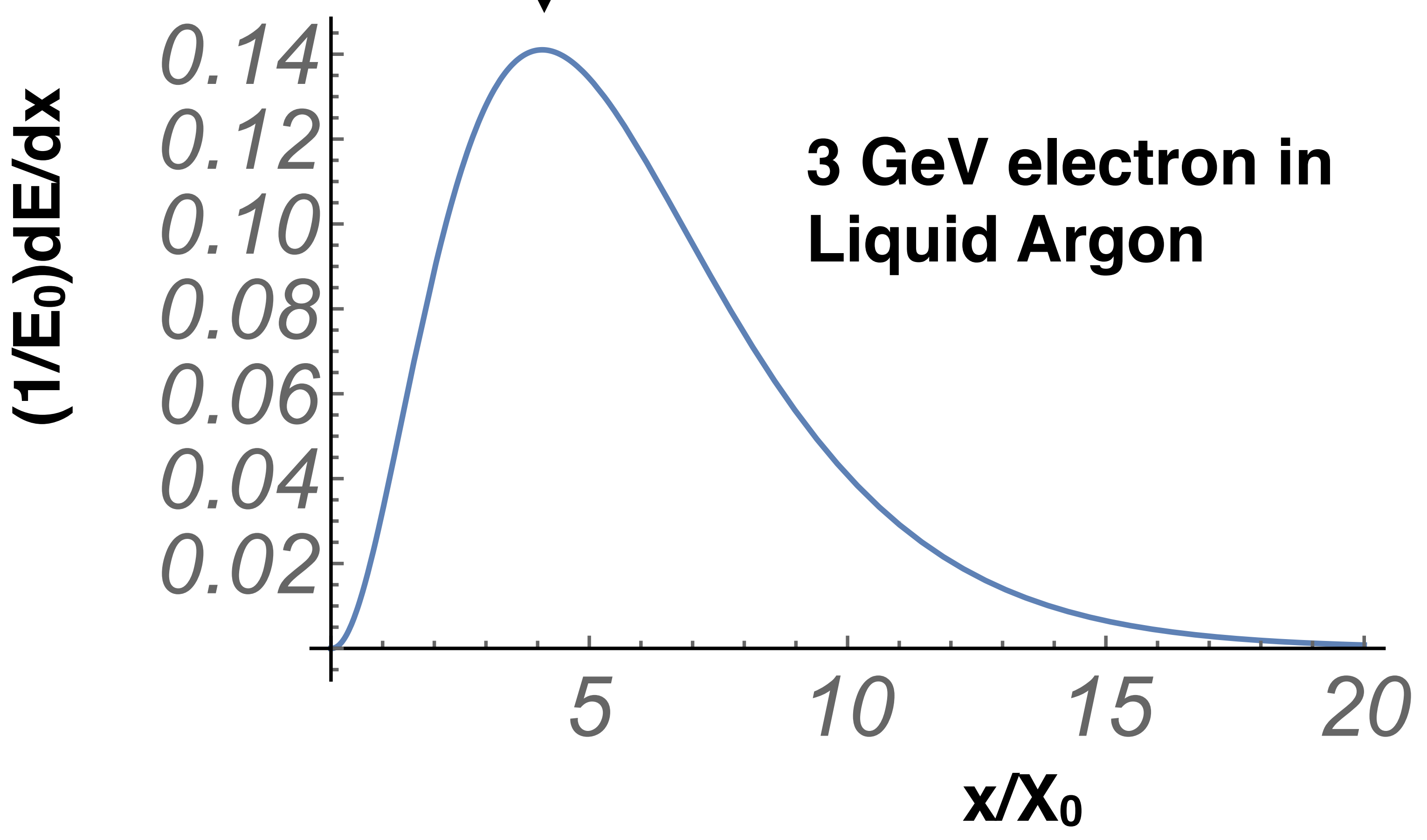
$$For\ Z > 4$$

$$dE/dt = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

$$t_{\max} = (a-1)/b = Log[E_0/E_c \pm 0.5]\{\pm for\ \gamma/e$$

$$b \sim 0.5\{Material\ dependent$$

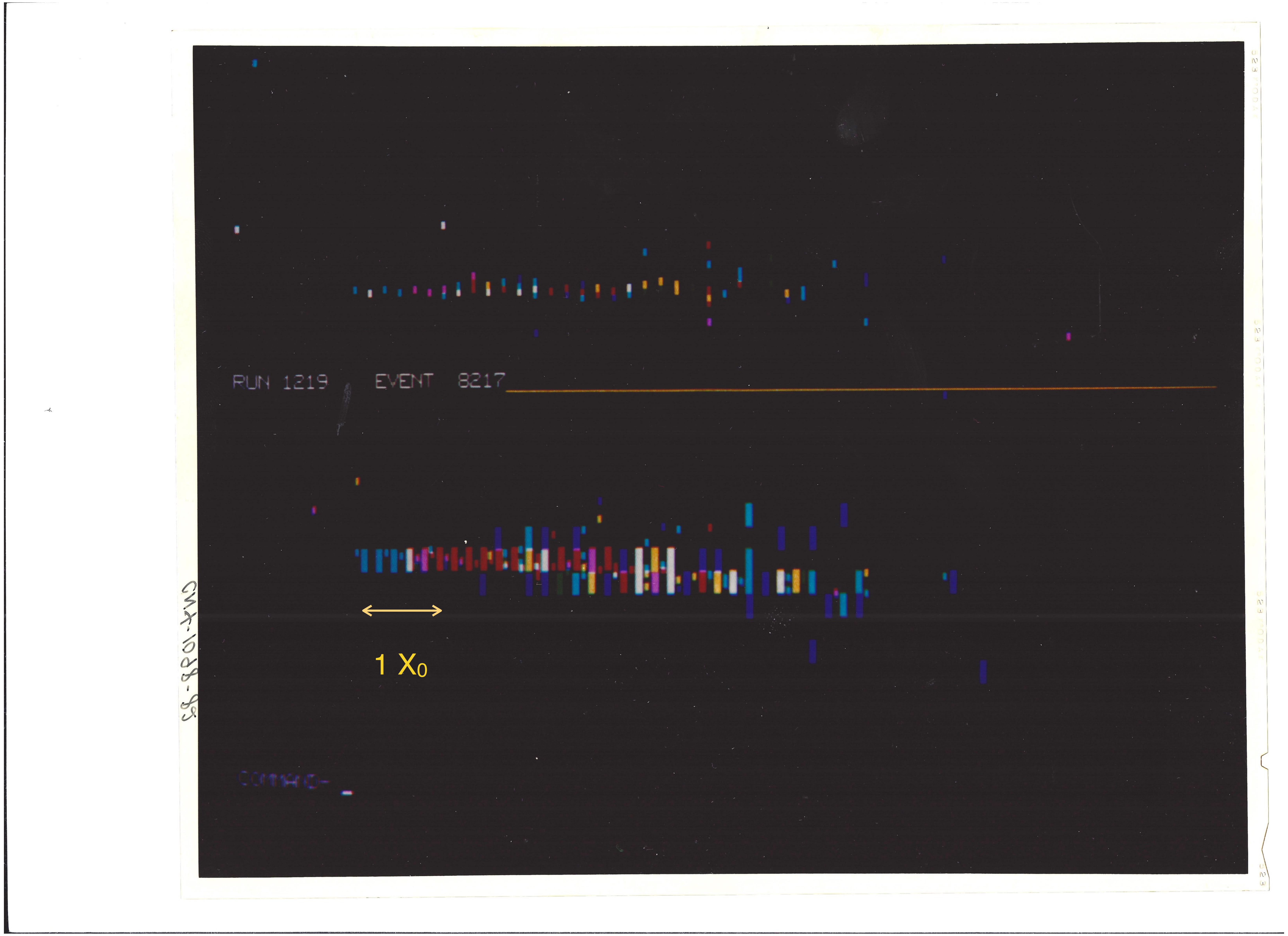
~57 cm



- Low E ($E_{critical}$ ~20 MeV/c) electron/ positrons lose energy similarly as heavy particles with corrections.
- High energy electrons lose energy by radiating photons. Fraction (1-1/e) energy is lost after mean distance X_0
- $E_{critical}$ when ionization=Bremsstrahlung
- Photons convert to pairs after (7/9)X_0

Material	Ecritical(MeV)
LAr	30.5
Water	78.3
Liquid Scint.	~102
Fe	21.7

Get to know http://pdg.lbl.gov/2015/AtomicNuclearProperties/



Electromagnetic shower from Experiment E734 in 1986. Example of neutrino electron elastic scattering. This is in liquid scintillator. Energy ~ 2 GeV.

Conclusion

- Radiation particles (including gamma rays) lose energy in materials as they slow down.
- We went through the various radiation particles that in normal situations are subject of detection in many applications: research and commercial.
- We went through the mechanisms of this energy loss.
- The ionization, light generation can be used to detect the particles.
- Tomorrow we will go through more detail.

Kinematics calculation of maximum energy transfer.

set c = 1

M m_e M m_e

$(E_i = M\gamma,\ P_i = M\beta\gamma)$ $(m_e, p_o = 0)$ $(E_f,\ P_f)$ (E_e, P_e)

4 vec: $p_i + p_0 = p_f + p_e$ => $p_i^2 + p_f^2 - 2p_ip_f = p_e^2 + p_0^2 - 2p_ep_0$

square of a 4 vec $(E, P_x, P_y, P_z)^2 = E^2 - P_x^2 - P_y^2 - P_z^2 = M^2$

$$2M^2 - (E_i(E_i + m_e - E_e) - P_i(P_i - P_e)) = 2m_e^2 - 2E_em_e$$

use $T = (E_e - m_e)$, momentum $\mathrm{P_i, P_f, P_0}$; $E_i^2 - P_i^2 = M^2$

do some algebra to get $2m_eP_i^2 = T((E_i + m_e)^2 - P_i^2)$

replace $E_i = M\gamma\ \ P_i = M\beta\gamma$ to get the final answer for T.