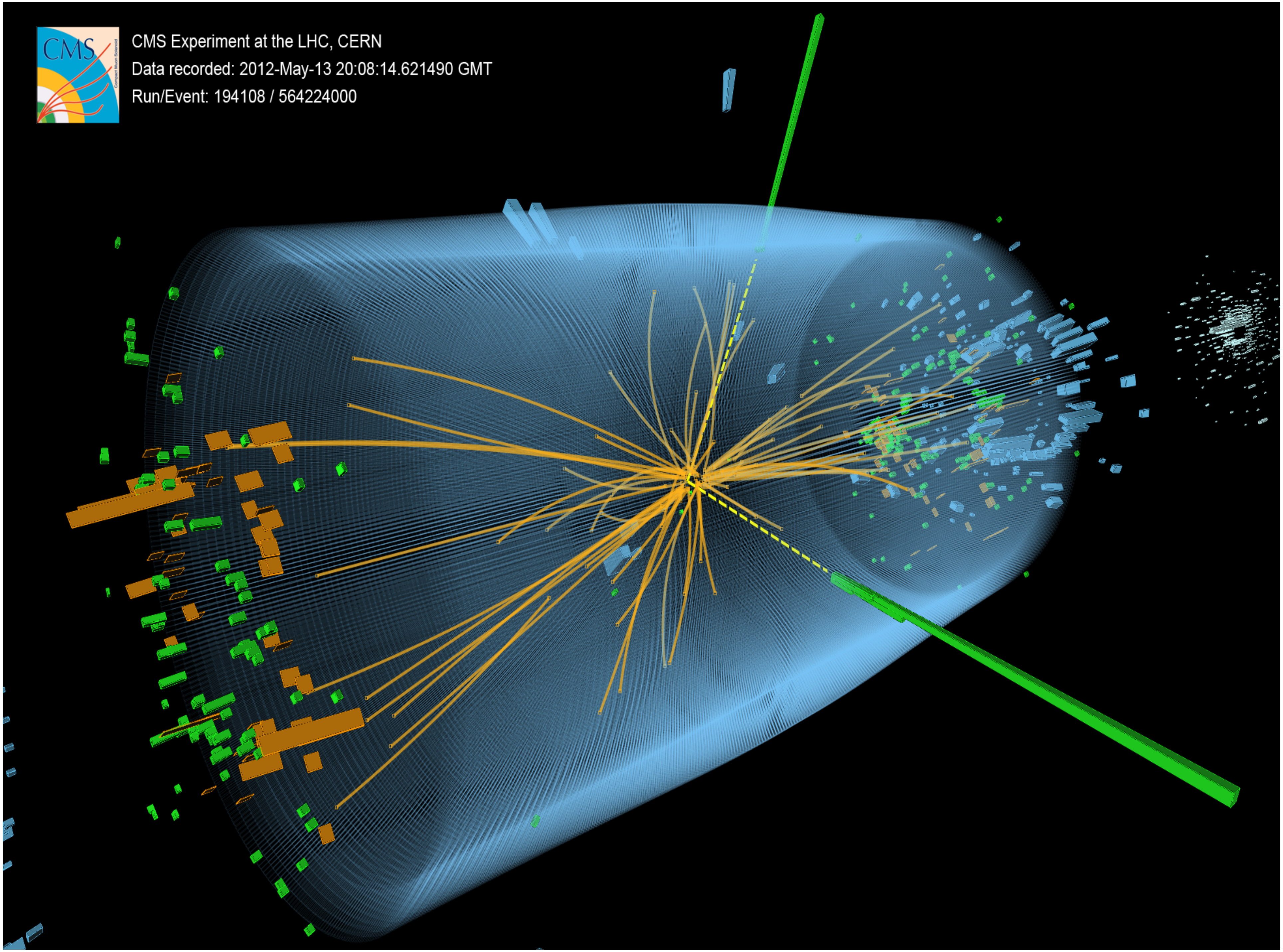
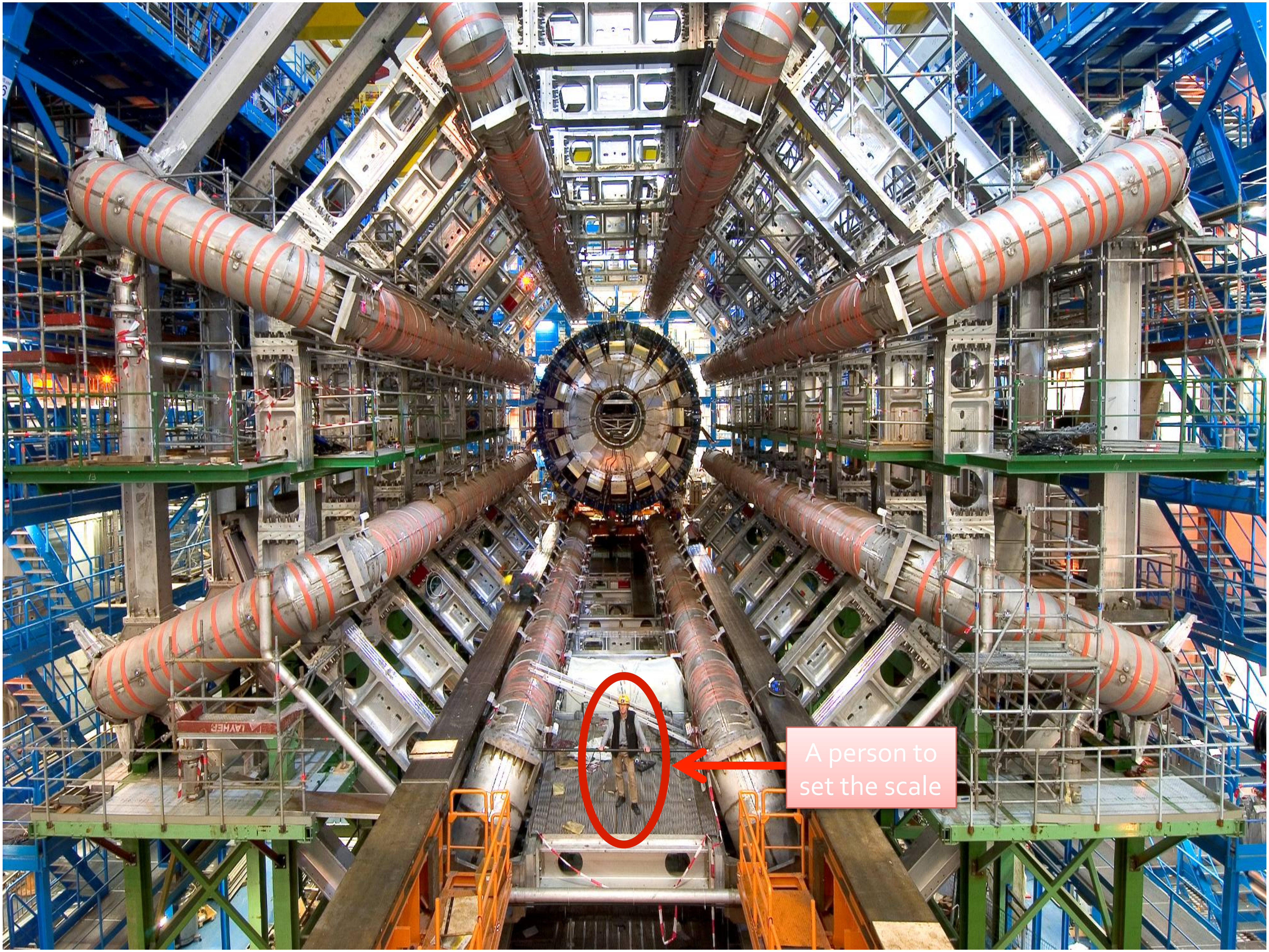
Roger Rusack, The University of Minnesota.

PARTICLES INTERACTIONS AND GAS DETECTORS

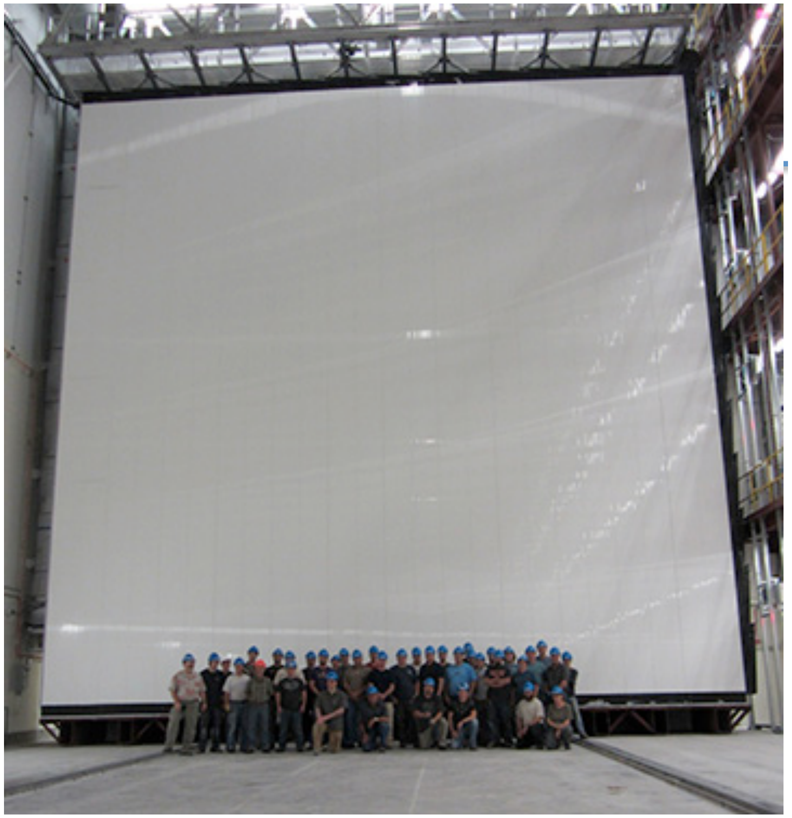
Introduction

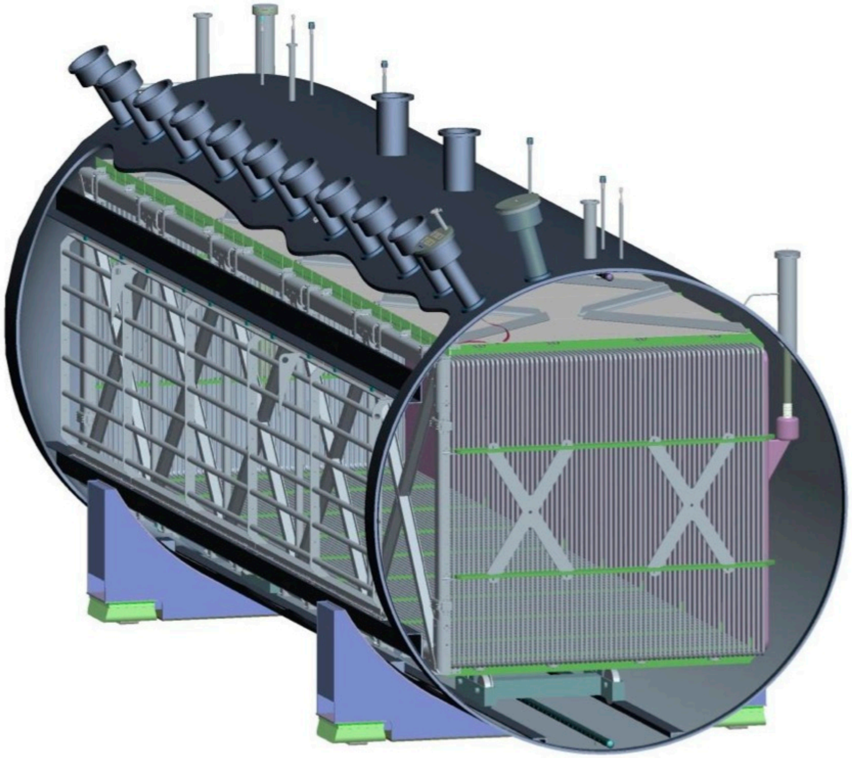
- I want to fill in the gap that is often there between the physical process that we are studying and data analysis with which many of you are familiar.
- I want at least to start to answer for you the questions
  - What are the physical processes of the particle's interaction with matter and the have lead to this thing we call data?
  - What are the different ways we exploit these interactions.
  - Why on earth did you choose the make the detector that way?
- These are introductory lectures intended to complete a picture for you.
- Please ask questions as we go along – lunch can wait….


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000



A person to set the scale





Sources

- Books:
  - “Radiation Interaction in Matter and Detection” C. Leroy and P-G Rancoita. 3rd edition.
  - “Techniques for Nuclear and Particle Physics Experiments” W. R. Leo.
  - “The Physics of Particle Detectors” D. Green
  - “Particle Detectors” C. Grupen and B. Schwartz.
- Publications:
  - Particle Date Book.
  - Various NIM articles.
- Talks
  - ‘Detectors for Particle Physics’ D. Bortoletto’s CERN summer school 2015.
  - ‘Experimental Techniques’ T. S. Virdee, European School of HEP 1998.

Many notes and comments and slides from friends and colleagues.

Outline

In this series of lectures I want to introduce to the novice the principles of the detection of particles.

Lecture 1 will focus on the fundamental interactions of particles and introduce gas detectors.

Lecture 2 I will talk about the physics of liquid argon detectors and solid state detectors.

Lecture 3 will be discuss scintillation light and it's detection.

Lecture 4 will be on detector systems.

This will be a personal view of the field of detectors
I make no pretense to be exhaustive.

Who am I?

I am a professor of physics at the University of Minnesota

I have been an experimental physicist since I started graduate school.

I have worked on many detectors systems, among others the Fermilab main ring the ISR, the SPS, the Tevatron, the anti-proton accumulator, NOvA, CMS at the LHC.

Most recently I have been one of the main designers of the High-Granularity Calorimeter for CMS.

To understand how detectors of ionizing radiation work first
one needs to understand how particles interact with matter.

Start Simple

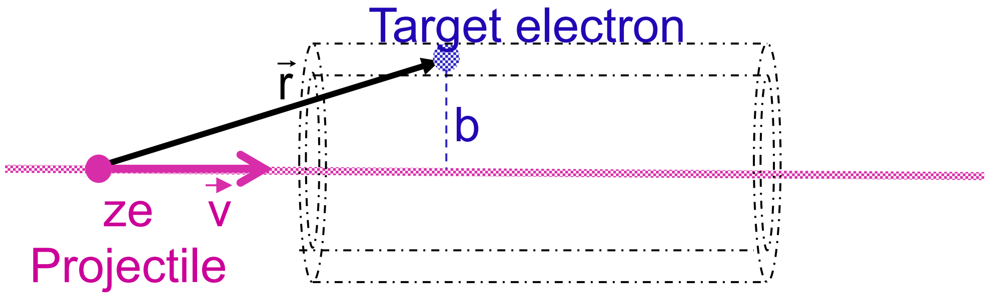
- Non-relativistic calculation by Bohr of the loss of energy due to ionizing particle.
- Consider the energy transfer from a moving particle to an electron in an atom
- Use this to find the energy lost by a particle as it traverses a medium.

Non-relativistic model (Après Niels Bohr)

Non-relativistic model!

$$\Delta p = \int F\,dt = e\int E_{\perp} dt = e\int E_{\perp}\frac{dx}{v}$$

$$\text{Gauss's Law} \rightarrow \Delta p = \frac{2ze^2}{4\pi\varepsilon_0 bv}$$



$$\Delta E = \frac{\Delta p^2}{2m_e} = \frac{2z^2e^4}{(4\pi\varepsilon_0)^2 b^2 v^2 m_e}$$

Integrate ΔE over values of b from head on to a reasonable maximum value to find dE.

$$dE \approx \int_{b_{\min}}^{b_{\max}} \Delta E \times \frac{\rho N_A Z}{A} \times 2\pi b\,db\,dx$$

$$-\frac{dE}{\rho dx} = \frac{2}{m_e}\left(\frac{ze^2}{4\pi\varepsilon_0 v}\right)^2 \frac{N_A Z}{A} 2\pi \ln\left(\frac{2m_e v^2}{I}\right)$$

$b_{\min}$

$b_{\max}$

I is the mean excitation potential of the medium ≈ 10 Z eV

Bethe-Bloch Equation

For moderately relativistic particles with mass $\gg m_e$ the Bethe-Bloch equation for the mean rate of energy loss by ionizing radiation can be used:

$$-\frac{dE}{dx} = N_A \frac{Z}{A} \frac{4\pi\alpha^2(\hbar c)^2}{m_e c^2} \frac{Z_i^2}{\beta^2} \left\{ \ln\left[\frac{2m_e c^2 \gamma^2 \beta^2 W_{\max}}{I^2} \right] - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right\}$$

$1/m_e \Rightarrow$ Energy is lost mainly to electrons.

$1/\beta^2 \Rightarrow$ Slower particles loose more energy.

Energy loss stops when $2\, m_e v^2 <$ the energy required to excite an electron in the material to a higher state.

Energy loss is $\propto Z_i^2$

There is a minimum value of dE/dx at $\beta\gamma \approx 4$.

For higher β the ionization will continue to rise – the relativistic rise.

Bethe-Bloch

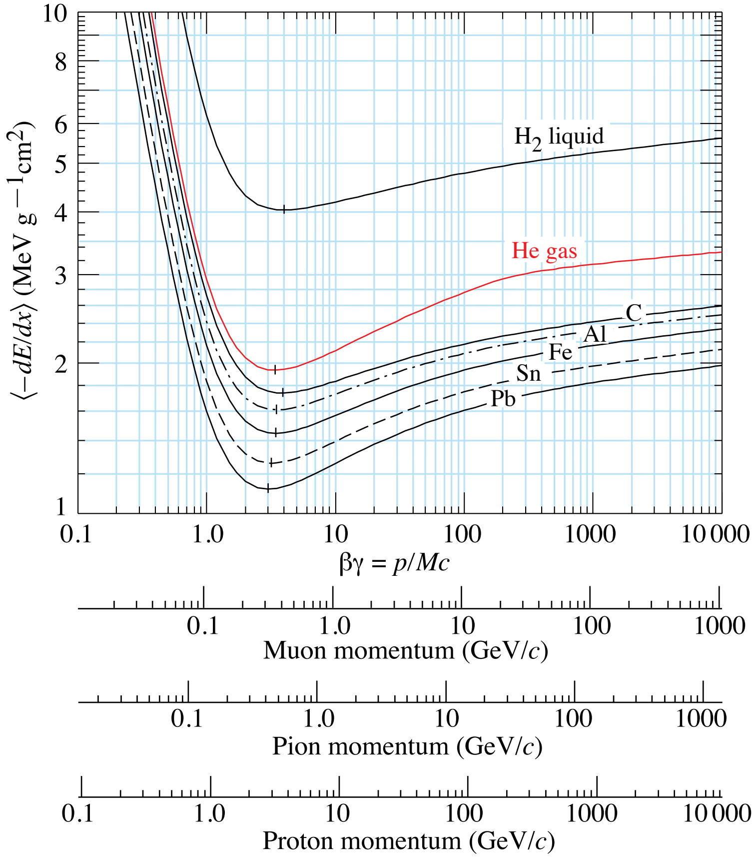
$$-\frac{dE}{dx} = N_A \frac{Z}{A} \frac{4\pi\alpha^2(\hbar c)^2}{m_e c^2} \frac{Z_i^2}{\beta^2} \left\{ \ln\left[\frac{2m_e c^2 \gamma^2 \beta^2 W_{\max}}{I^2} \right] - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right\}$$

The range of validity of the Bethe-Bloch equation is from βγ between 0.1 and 1000 with a precision of ~1%.

Note that a 'mip' is a minimum ionizing particle or a muon with about 300 MeV/c momentum.

$W_{\max}$ is the relativistic max energy transfer.

From PDG



Useful Quantity

A useful quantity to estimate the energy loss by a relativistic particle crossing a medium is the areal density g/cm^2.

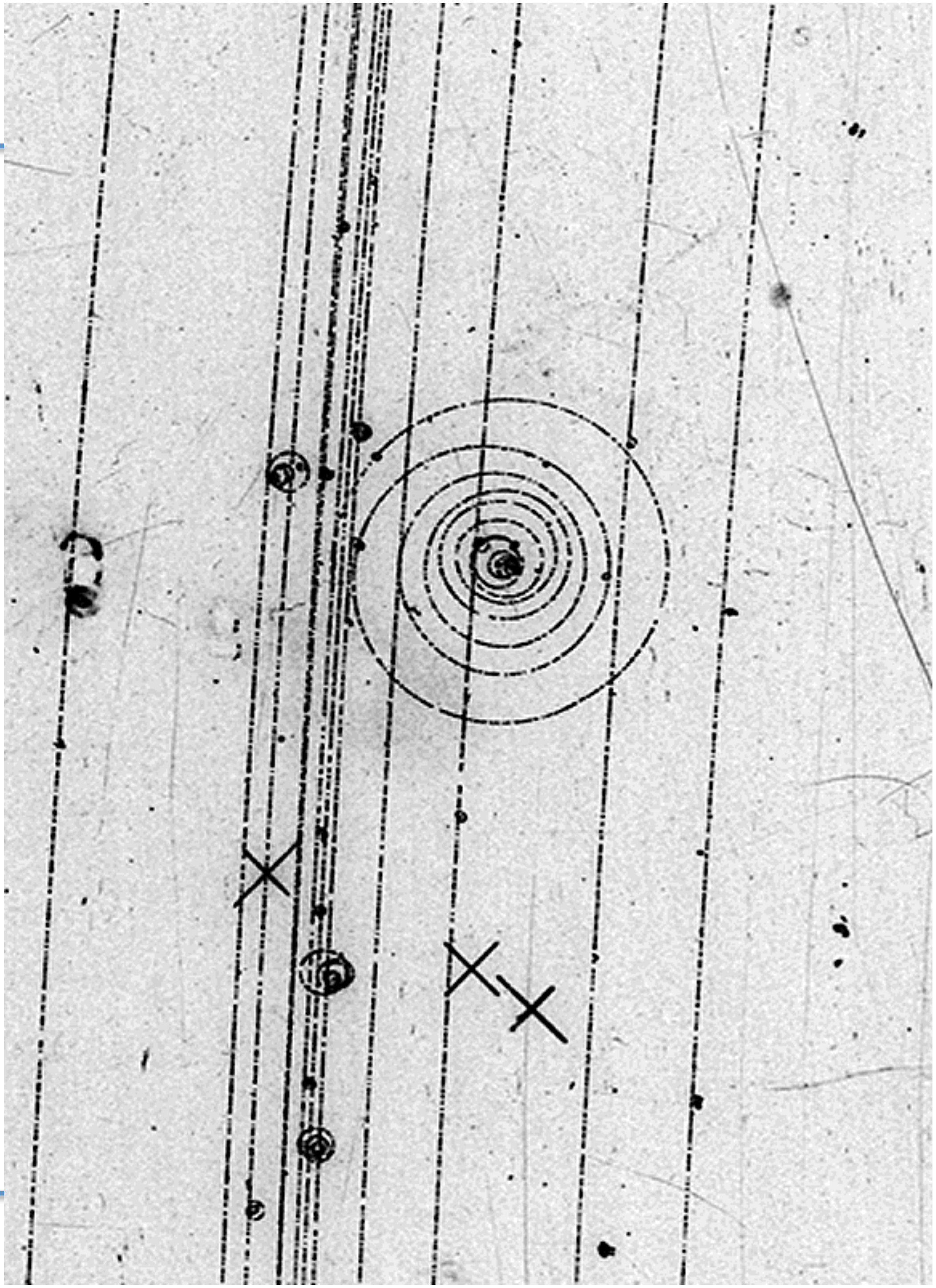
$$\frac{1}{\rho}\frac{dE}{dx} = 1.5 - 2 \ \frac{MeV}{g.cm^2}$$

For example if you want to find the energy loss in 300μ of silicon.

ρ = 2.329 g/cm^3 $\Rightarrow \Delta E$ = 1.5 × 2.3 × 0.03 MeV ≈ 100 KeV.

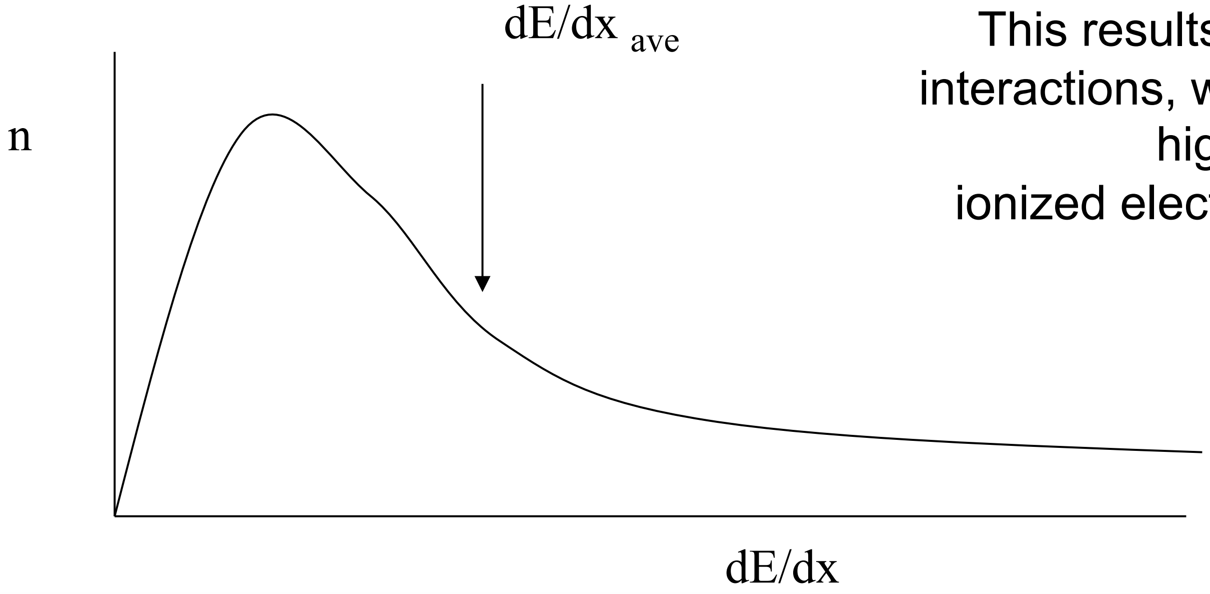
Not all collisions are equal!

Collisions where there is a large energy transfer to an electron --- enough to produce a δ – give a tail to the distribution.



Energy Loss Distribution

- Bethe-Bloch equation yields the AVERAGE energy loss per unit path length. If many identical particles pass though the same (thin) material (so that each particle does not lose a substantial fraction of its initial energy), the distribution of deposited energy follows the "Landau Distribution."



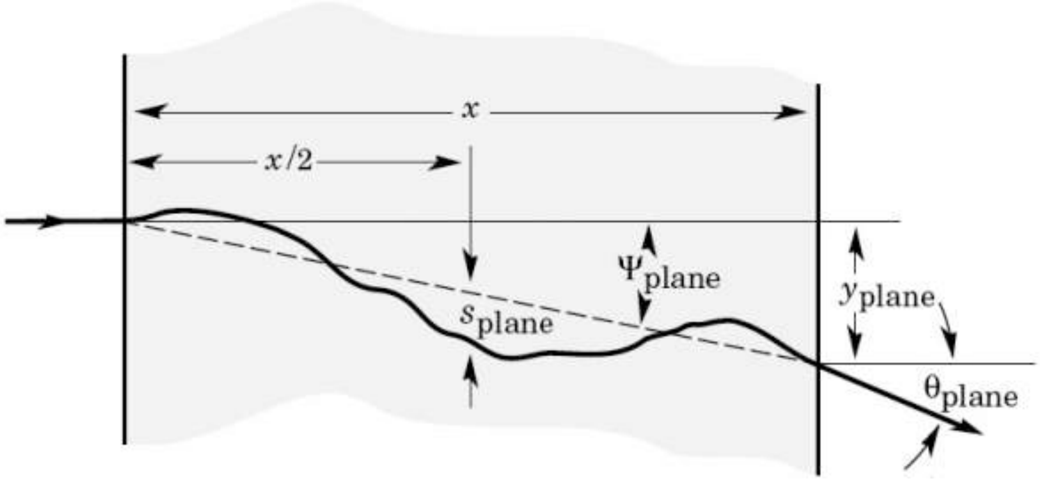
Note long high energy tail.
This results from (rare) close interactions, which make relatively high-energy
ionized electrons, "delta rays."

Multiple Scattering

When the particle scatters in the electric field of a nuclei, ⟹ large acceleration ⟹ a change in direction, with little loss of energy.

Rutherford scattering:

$$\frac{d\sigma}{d\Omega} \approx \frac{1}{\sin^4 \theta/2}$$



The scattering angle *θ* in a plane is well described a Gaussian with the width

$$\theta_0 = \frac{13.6MeV}{\beta cp} z \sqrt{\frac{x}{X_0}}$$

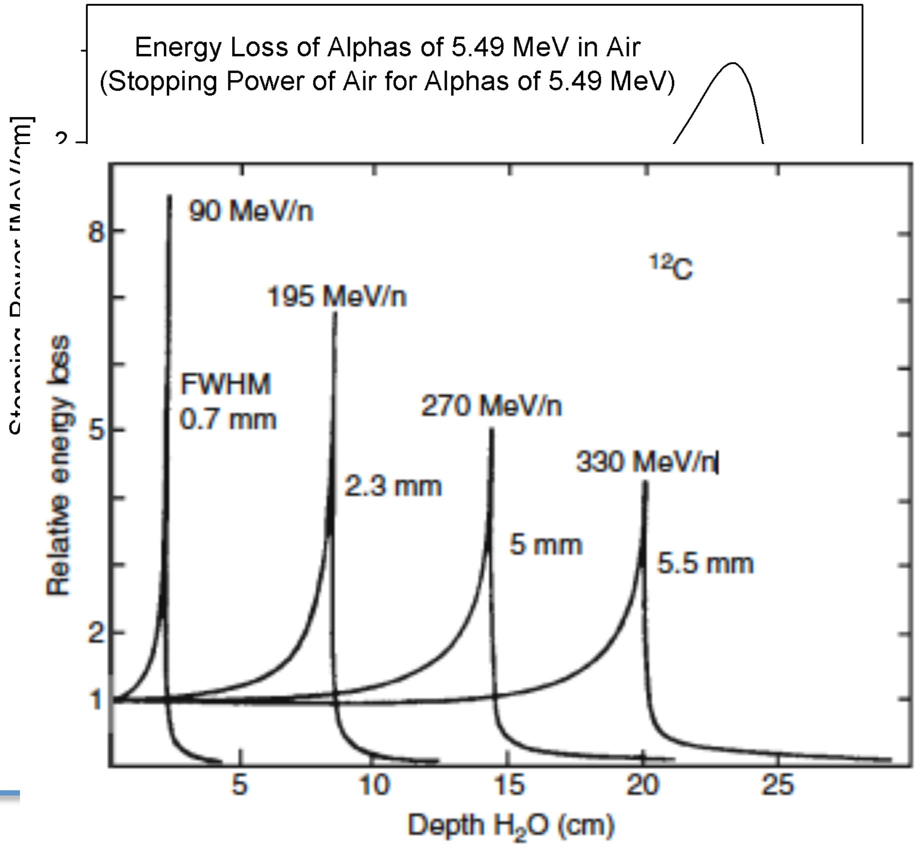
X_0 is the radiation length of the material

Multiple scattering is a limiting factor in momentum measurements.

Bragg Peak

$$-\frac{dE}{\rho dx} = \left(\frac{1}{4\pi\varepsilon_0}\right)^2 \frac{4\pi n e^4}{m_e}\frac{z^2}{v^2}\left\{\ln\left[\frac{2m\gamma^2 v^2}{I(1-\beta^2)}\right]-\beta^2\right\}$$

- For low energy massive particles when v is small the term $1/v^2$ dominates the Bethe-Bloch formula.
- At low energy the ionization is at a maximum
- This effect is used in proton therapy to treat tumors where the energy can be tuned to deposit energy exactly where it is needed.



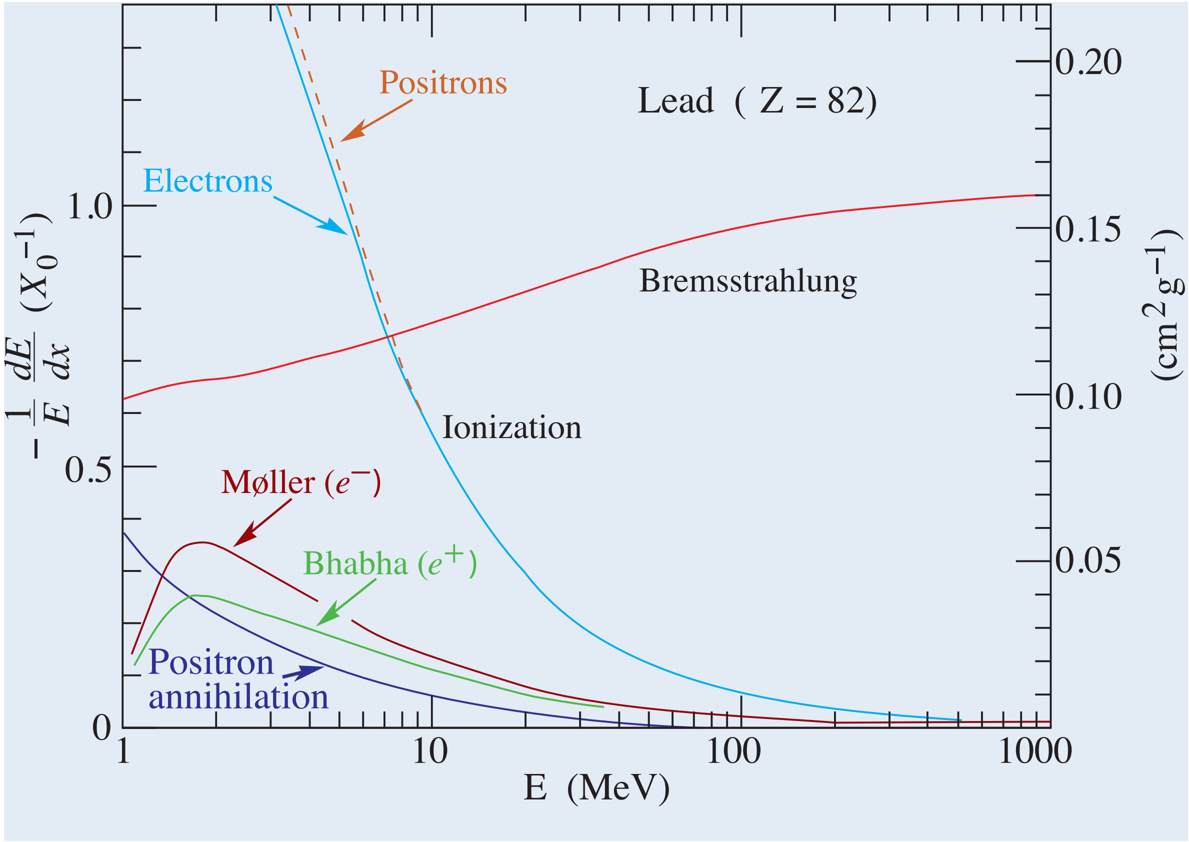
Energy Loss by Electrons

Bethe-Bloch does not apply to electrons – assumed incoming mass ≫ m_e.

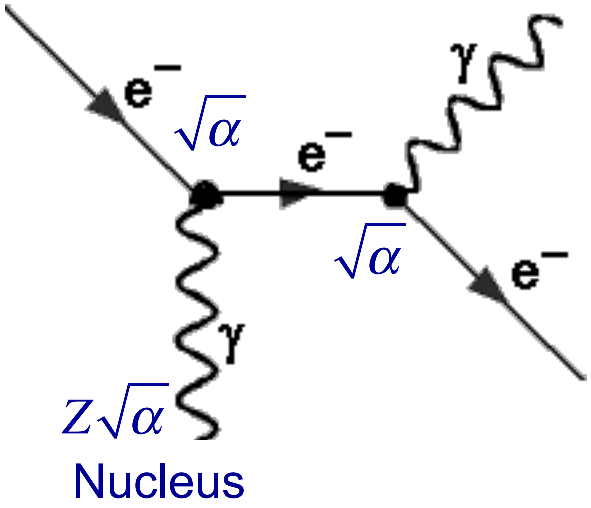
At low energies electrons loose energy by ionization.

At higher energies the electron interacts with the intense electric field of the nucleus and and radiates a photon.

This process is known as *Bremsstrahlung*.



Bremsstrahlung



Cross section $\sigma \propto \frac{Z^2\alpha^3}{m_e^2c^4}$

And the energy loss:

$$-\frac{dE}{dx}\bigg|_{brem} \approx \left[4n\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2c^4}\ln\frac{183}{Z^{1/3}}\right]E$$

Nuclei per unit volume

Screening term

Since energy loss is proportional to the electron's energy we get:

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

With X_o – the *radiation length* – is given by $X_0 \approx \left[4n\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2c^4}\ln\frac{183}{Z^{1/3}}\right]^{-1}$

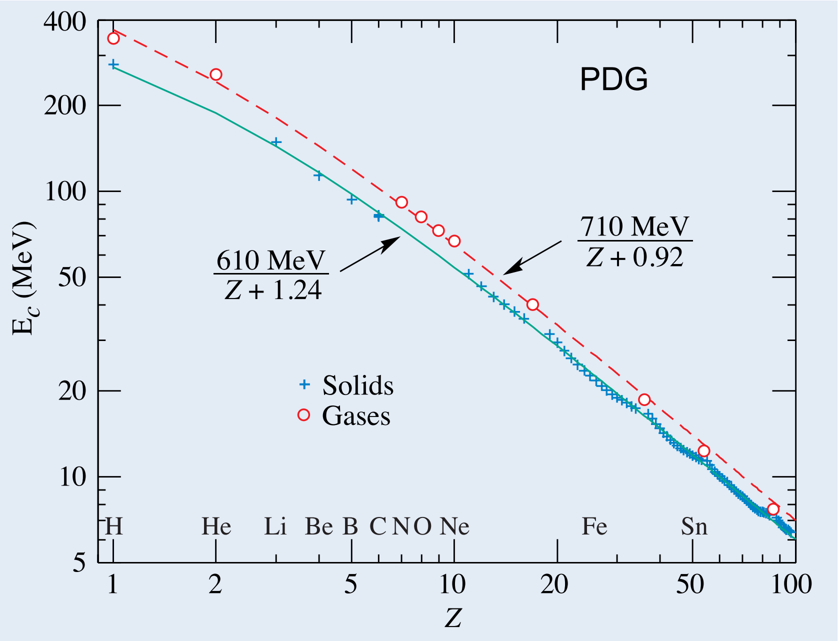
Critical Energy

We have:

$$\left.\frac{dE}{dx}\right|_{Brem} \propto E \text{ and } \left.\frac{dE}{dx}\right|_{Ioniz.} \propto \ln(E)$$

The critical energy is defined as the energy where:

$$\left.\frac{dE}{dx}\right|_{Brem} = \left.\frac{dE}{dx}\right|_{Ioniz.}$$



The value of the critical energy depends on the medium:

For Solids

$$E_C \approx \frac{610\text{ MeV}}{Z+1.24}$$

For lead $E_C \approx 7.3$ MeV

$E_c \propto m^2$; a muon with *E > 300 GeV,* will loose energy predominantly by bremsstrahlung.

Photon Interactions

There are three main ways that a photon can interact and free an electron in the medium.

- Photoelectric effect:

$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma} \right)^n$$

$$n = \tfrac{7}{2} \text{ if } E_\gamma \ll m_e c^2$$

$$n \to 1 \text{ for } E_\gamma \gg m_e c^2$$

- Compton scattering – photon-electron scattering.
  - For each electron

$$\sigma_C \approx \frac{\ln E_\gamma}{E_\gamma}$$

for each atom

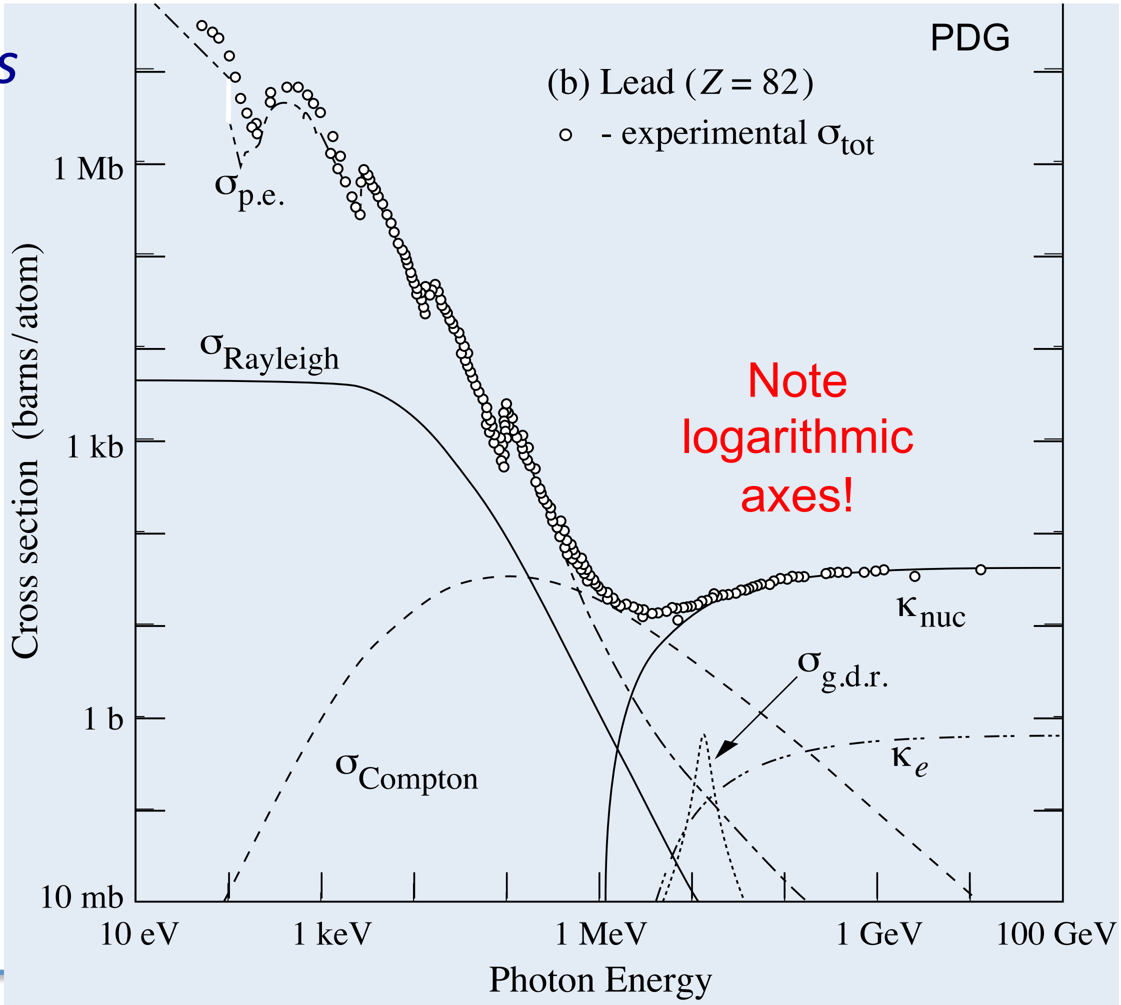
$$\sigma_C^{atom} \approx Z\sigma_C$$

- Pair production:

$$\sigma_{Pair} \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

Pair Production

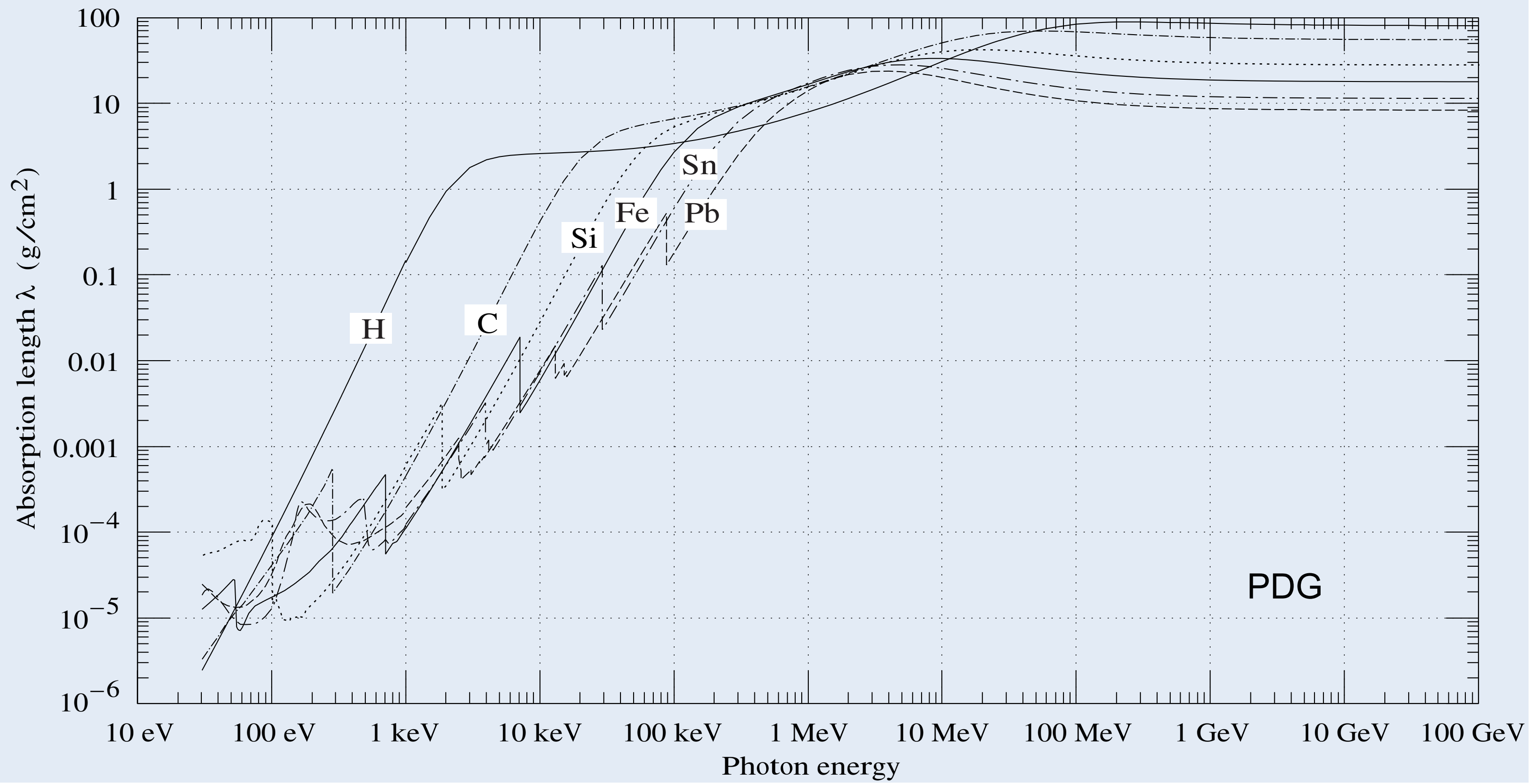
- *For $E_\gamma > 2\ m_e c^2$* photons can convert to an electron-positron pair in the electric field of the nucleus.
  - ($\gamma + N \rightarrow N + e^+ + e^-$).
- *Heavy nucleus takes less energy for a given momentum transfer.*
  - → Threshold energy higher for carbon than lead
- Cross-section ~ Z^2.



Note logarithmic axes!

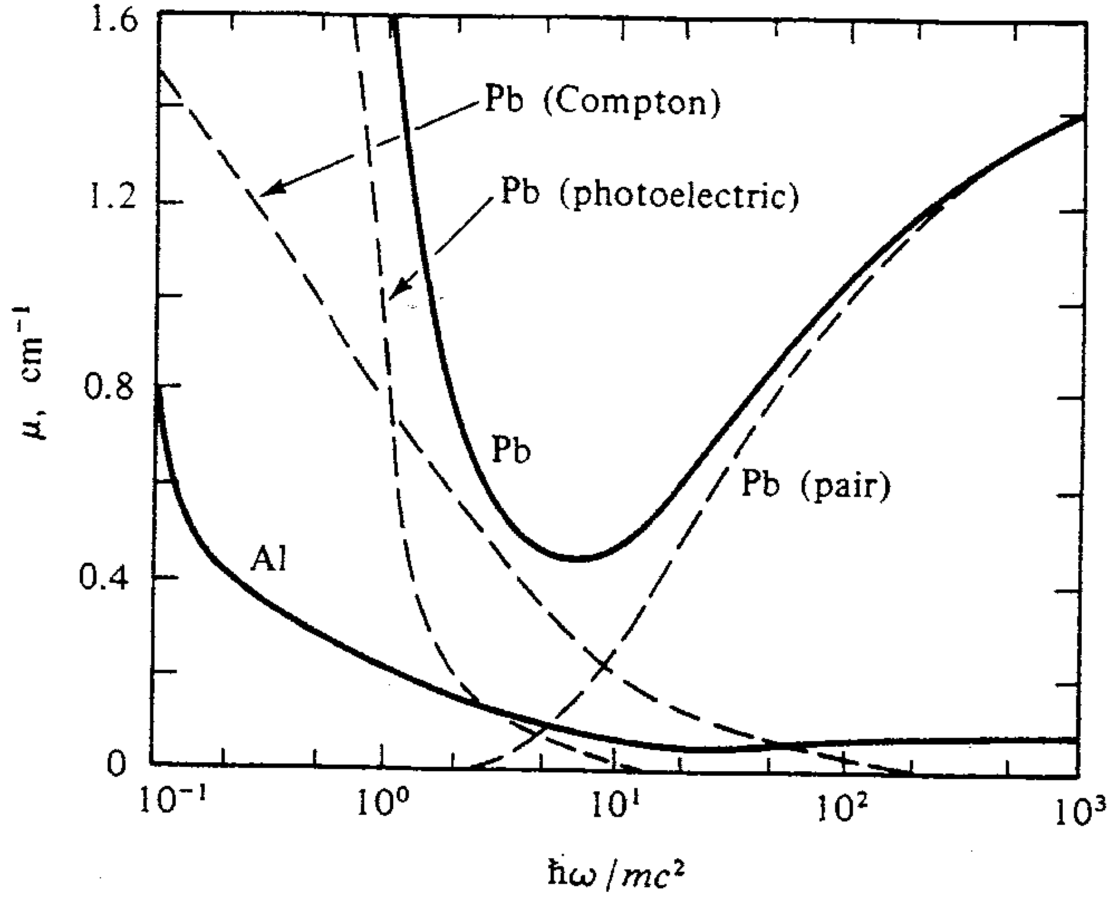
Photon Attenuation

With the rapidly decreasing cross-section the attenuation length of low energy photons increases rapidly with energy until Brem is the main process.



Photon Attenuation

Energy v Attenuation length for photons.



Note that the range of a 5 MeV photon is ~ 2 cm in lead.

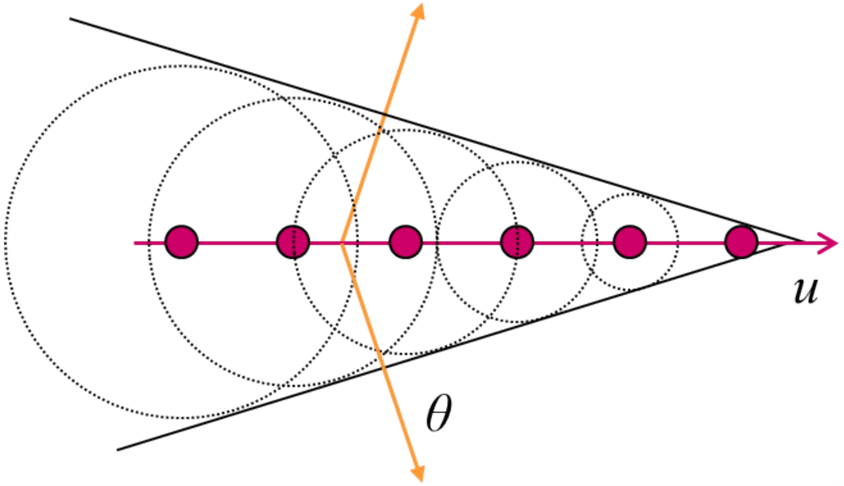
Čerenkov Radiation

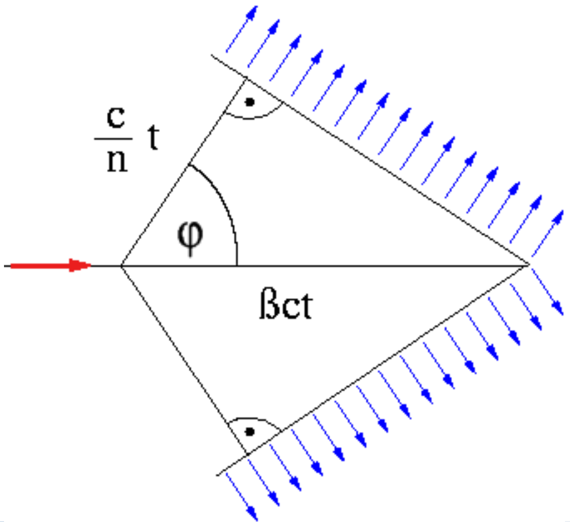
Not an ionization process, but an important technique in particle detection

Čerenkov radiation is emitted by a particle exceeding the velocity of light in the medium. $\beta > \beta_{thr} = 1/n$.

Čerenkov radiation is emitted in a cone along the trajectory with

$$\cos(\varphi_c) = \frac{1}{\beta n}$$





Čerenkov Radiation

The number of photons emitted per unit wavelength and length is:

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n(\lambda)^2}\right)$$

Strongly peaked at short wavelengths.

PMT’s are sensitive wavelengths 350 – 500 nm.

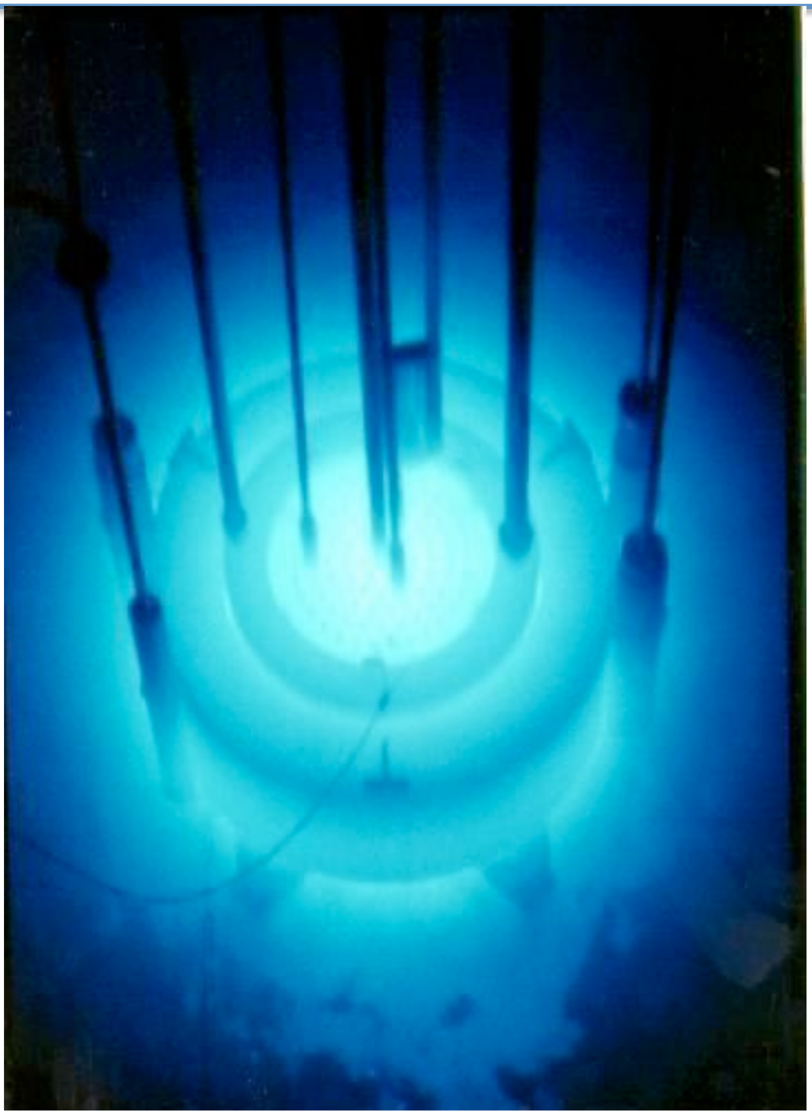
Integrating between these wavelengths:

$$\frac{dN}{dx} = \int \frac{2\pi z^2\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n(\lambda)^2}\right) d\lambda$$

$$= 2\pi \mathrm{z}^2\alpha \sin^2\varphi_c \int \frac{d\lambda}{\lambda^2} = 475 z^2 \sin^2\varphi_c \text{ photons/cm}$$

Energy loss is ~ 1 KeV cm^2/grm -- much less than through ionization.

Čerenkov radiation from electrons is the cause of the blue light seen around a reactor in water.



Transition Radiation

Transition radiation is emitted when a particle traverses a boundary where there is a change in refractive index.

Total energy emitted when a particle goes from a vacuum to a medium is

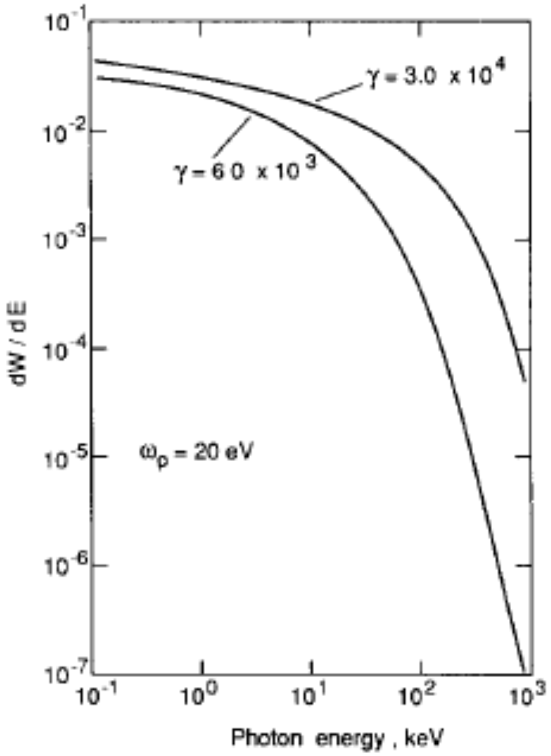
$$I = \alpha z^2 \gamma \hbar \omega_p / 3$$

ω_p is the plasma frequency of the material (ω_p = 13.8 eV for lithium and 20.9 eV for polyethylene)

The radiation is soft X-rays – 2 – 40 KeV for γ=10

The probability of emitting a photon is 1/137,
So detectors have many layers of radiators.

Since the energy loss increases with γ it is used in particle id for energies > 10 GeV.

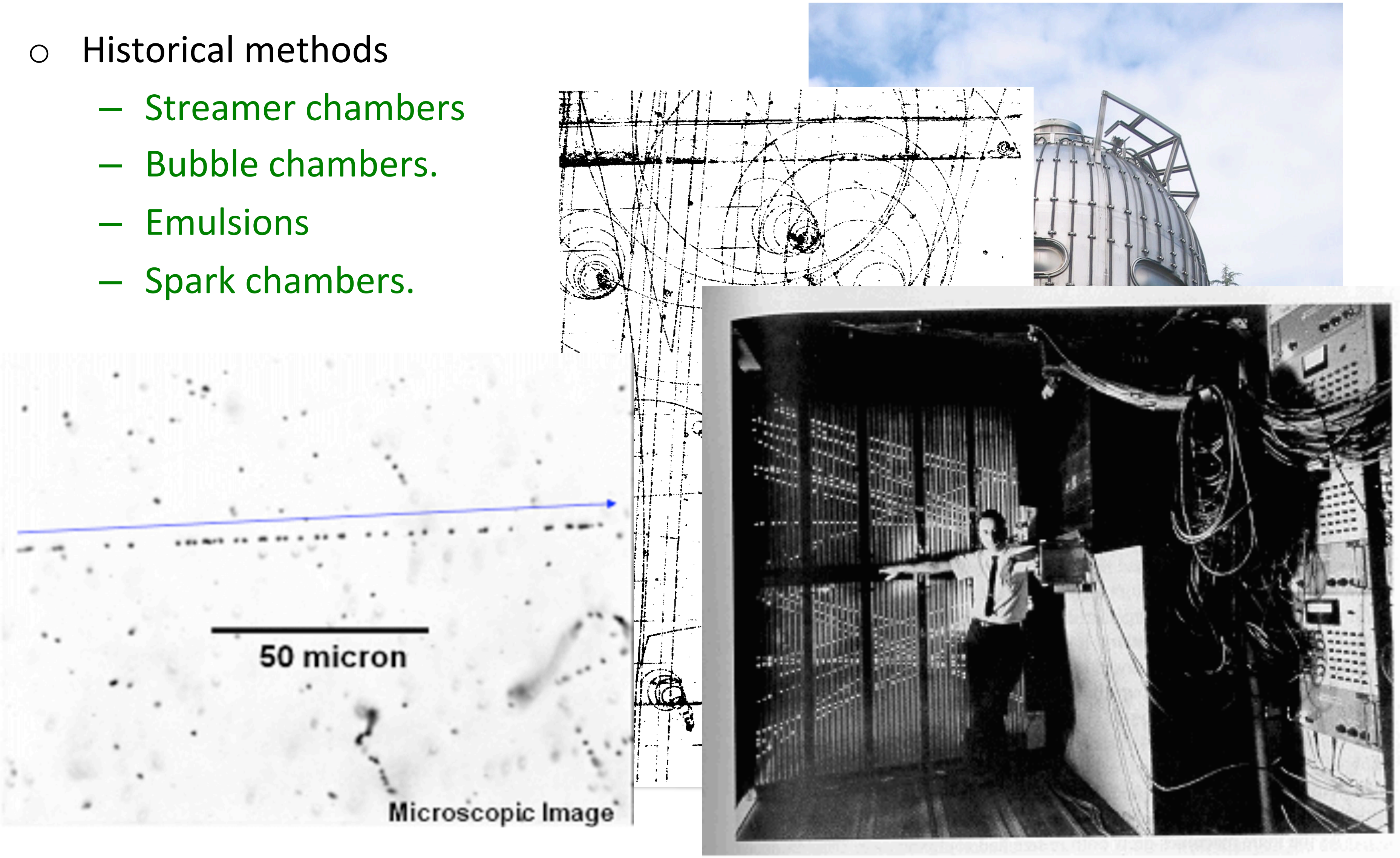


Dolgoshein NIM A326 p434.

Particle Detection in the Past

There have been many different methods of detecting the ionizing radiation

- Historical methods
  - Streamer chambers
  - Bubble chambers.
  - Emulsions
  - Spark chambers.



These methods were very effective in their time and yielded many fundamental results, from the muon neutrino to neutral currents.

They have been superseded by electronic (counter) detectors.
These began with the invention of the Multiwire Proportional Chamber by Georges Charpak in 1964.