

# Interactions of Particles with Matter – Part 1

Karol Krizka

[k.krizka@bham.ac.uk](mailto:k.krizka@bham.ac.uk)

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# Two Lectures

## Lecture 1: Physics of Particle Interactions with Matter

- Define “particle” interactions with “matter”
- Ionizing Radiation
- Non-Ionizing Radiation

## Lecture 2: Detecting Particle Interactions with Matter

- Efficiencies and energy resolutions for individual sensors
- Brief overview of silicon sensor technologies
- Gaseous detectors for tracking
- Signal formation in a single diode

# Further Reading

This is a survey lecture to summarize many mechanisms.

The following are references for a more in-depth understanding.

## Particle Data Group's Review

1 *34. Passage of Particles Through Matter*

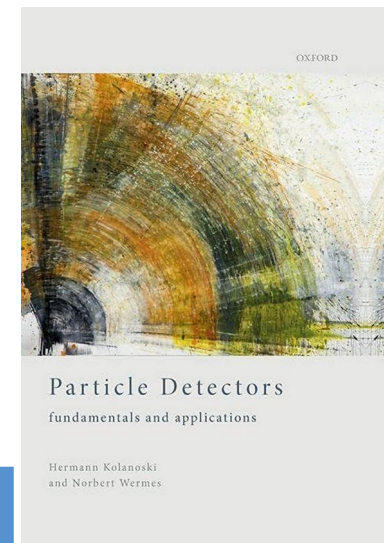
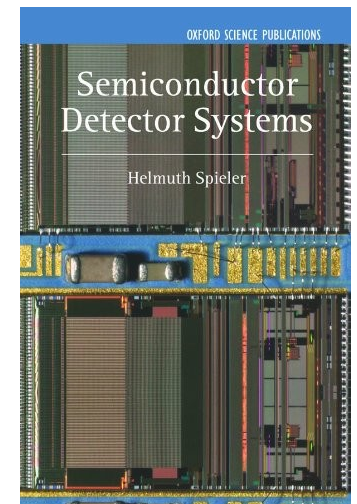
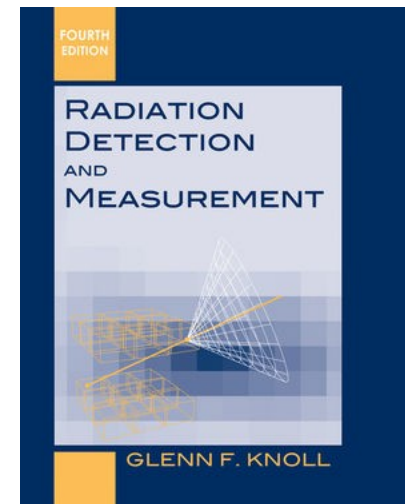
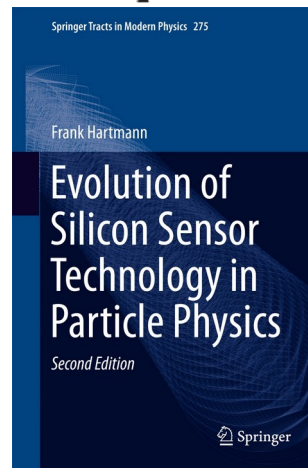
### 34. Passage of Particles Through Matter

Revised August 2021 by D.E. Groom (LBNL) and S.R. Klein (NSD LBNL; UC Berkeley).

## Applications of silicon strip and pixel-based particle tracking detectors

[Philip Allport](#) 

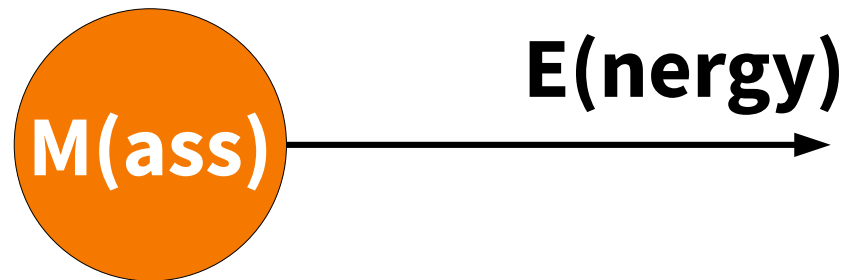
*Nature Reviews Physics* **1**, 567–576 (2019) | [Cite this article](#)



# Properties of a Particle

## How does it interact?

- Type (fermion, boson)
- Neutral, charged.
- Electroweak force, strong force.



# Example Types of Particles

How about other particles  
(muons, pions, taus)?

- **Ions**
  - protons, alpha particles, fission fragments
  - Straight tracks
- **Electrons**
  - Negative and positive
  - Scattered tracks
- **Neutrons**
  - Interact only with nucleons
- **Photons**
  - gamma-rays and X-rays
  - Interact with nucleons/electrons

## Charged Particles

- Ionize atoms along the way
- Can be followed via a “track”

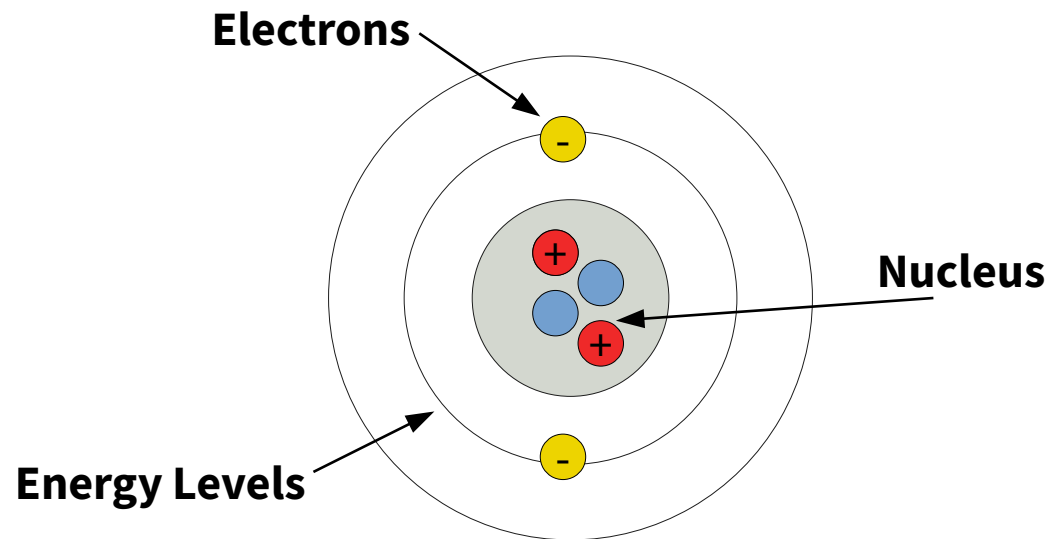
## Neutral Particles

- Identified via secondary tracks

# What is Matter?

## Bohr's Model of the Atom:

A very simplified view, but practical.

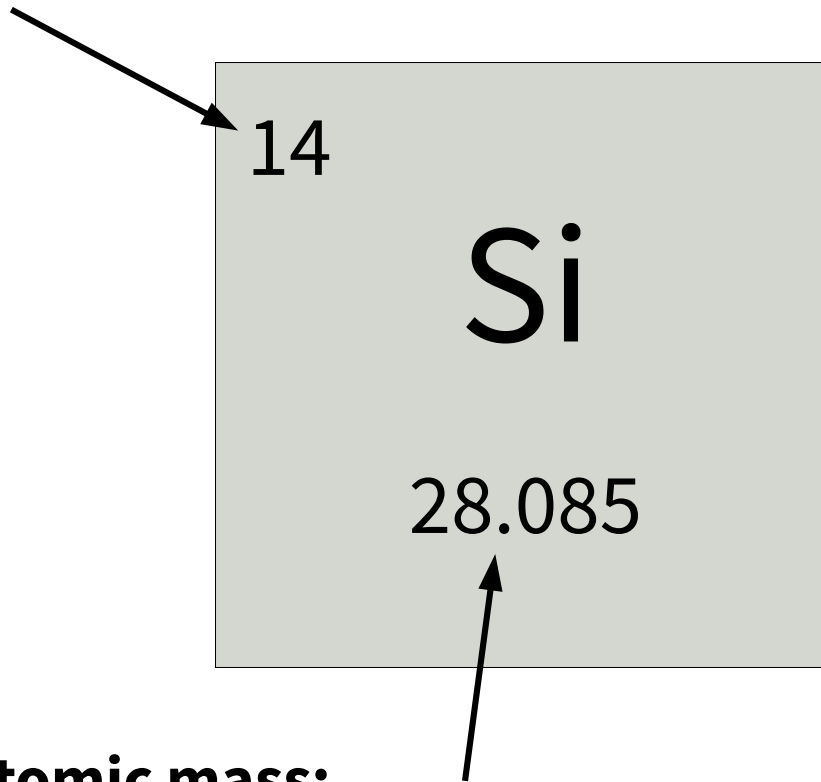


**Matter:** a collection of atoms bound together.

# Properties of Matter: Hadrons and Electrons

## Atomic number:

- How many protons.
- Roughly how many electrons. → **ionizing** interactions

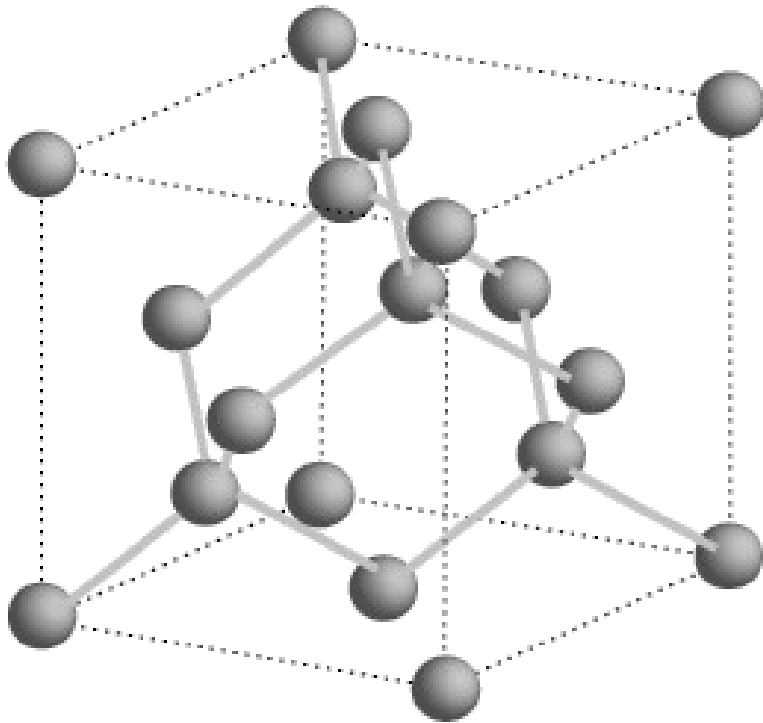


## Atomic mass:

- Roughly how many hadrons. → **non-ionizing** interactions

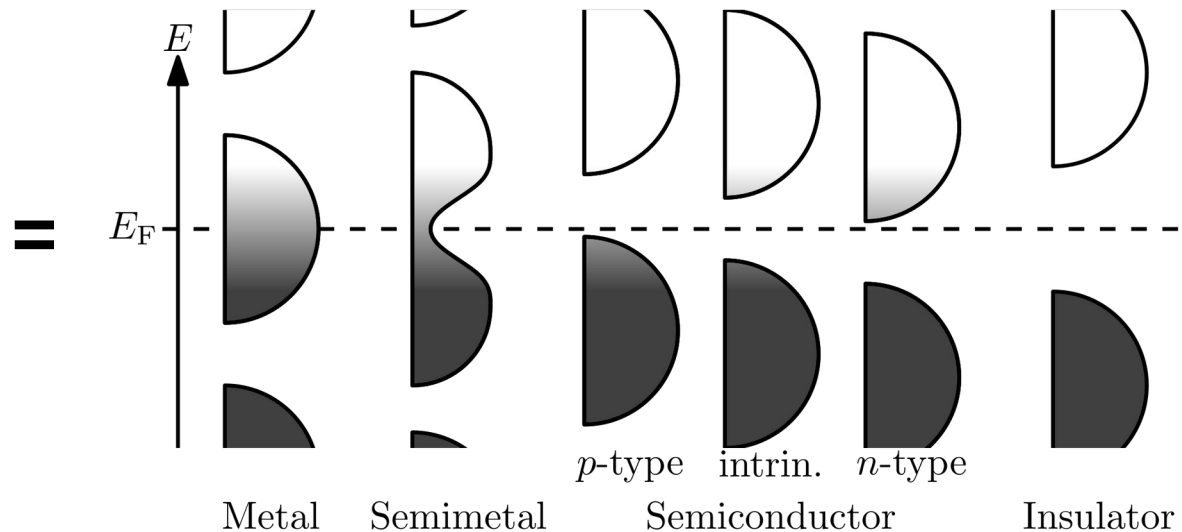
# Properties of Matter: Structure

Take a solid state physics if this interests you!

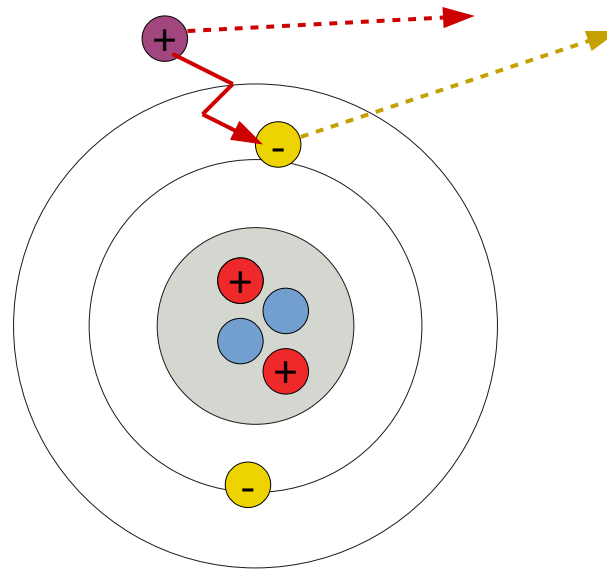


+

$$i\hbar \frac{d\Psi}{dt} = H\Psi$$



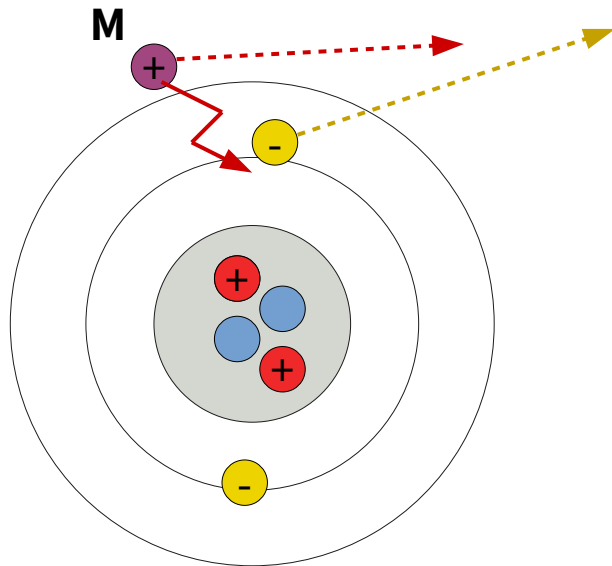
# Example Interaction With Matter (Ionizing)



## **Ionizing interaction:**

charged particle comes along and deposits energy to eject an electron from its orbital (or energy band)

# Two Body Elastic Collision



**Maximum energy transfer**

$$4 \frac{M m_e}{(M + m_e)} E$$

**For massive particles**

$$\approx 4 \frac{m_e}{M} E$$

ex:  $m_\alpha \approx 7000 m_e$

**Scattering is stochastic (random) process, but roughly**

- Massive particles go through material largely unaffected
- Light particles will scatter a lot

# The Bethe-Bloch Formula

## Stopping Power / Linear Energy Transfer

How much energy does an incoming particle lose per distance

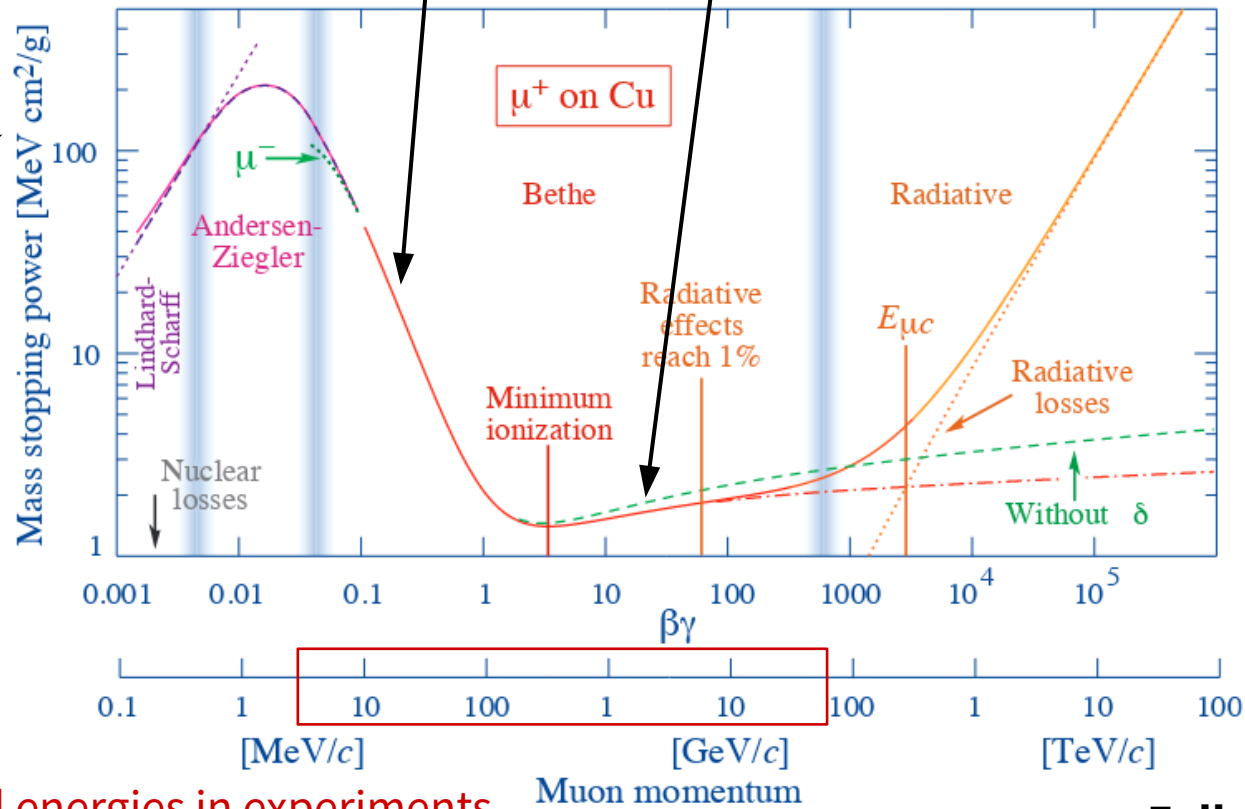
$$-\frac{dE}{dx} \cong \left( \frac{e^2}{4\pi\epsilon_0} \right)^2 \frac{4\pi z^2}{m_e v^2} N Z \left[ \ln \frac{2m_e v^2}{I} - \ln \left( 1 - \frac{v^2}{c^2} \right) - \frac{v^2}{c^2} \right]$$

- $e, m_e$ : charge and mass of electrons
- $z, v$ : atomic number and velocity of incoming particle
- $Z, N$ : atomic number and number density of material
- $I$ : effective ionizing potential of the material atoms
  - Usually measured from data. (examples: hydrogen = 20 eV, other elements =  $10 \times Z$  eV).

# The Bethe-Bloch Formula Plotted

$$-\frac{dE}{dx} \approx \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2}{m_e v^2} NZ \left[ \ln \frac{2m_e v^2}{I} - \ln \left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2} \right]$$

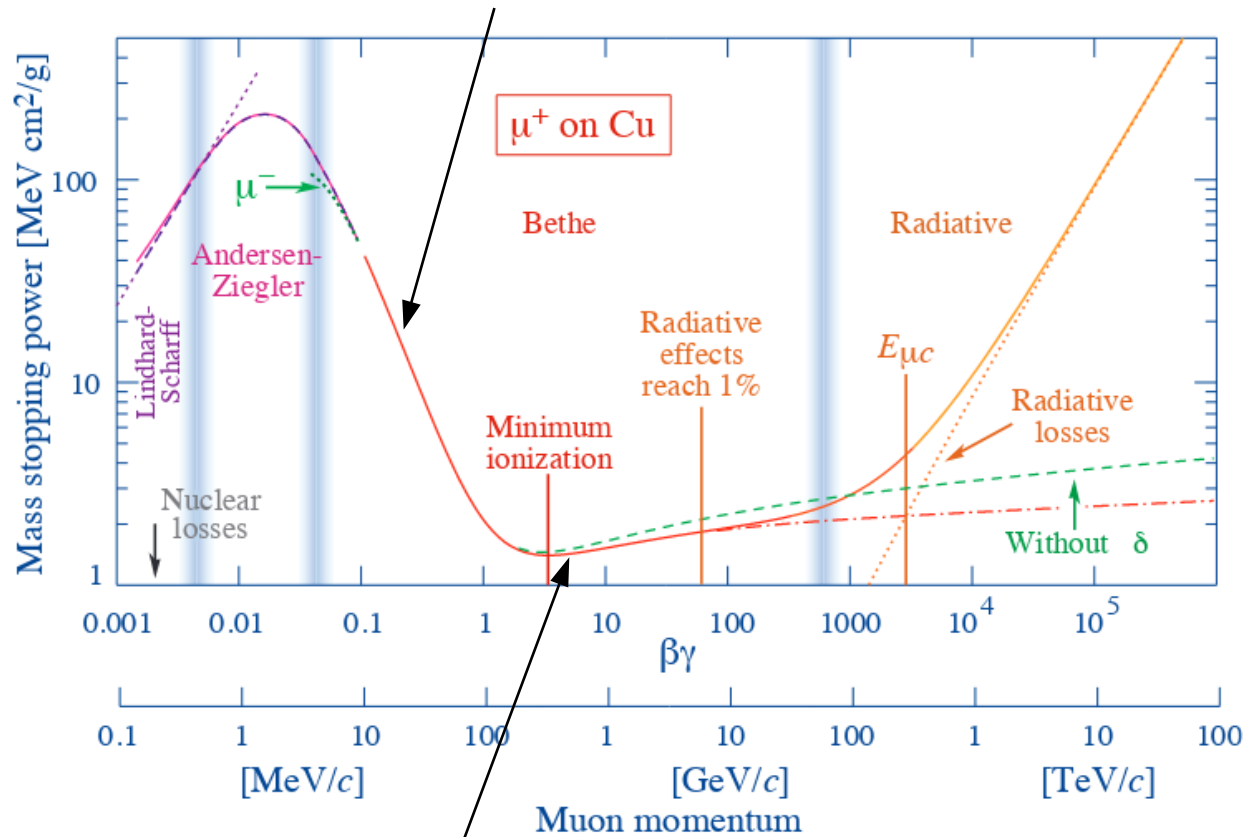
Independent of material density



Full relativistic formula  
at <https://pdg.lbl.gov/>

# The Bethe-Bloch Formula: Two Regimes

**Source of Bragg Peak:** “Slow” particles deposit energy fast and slow down even further.



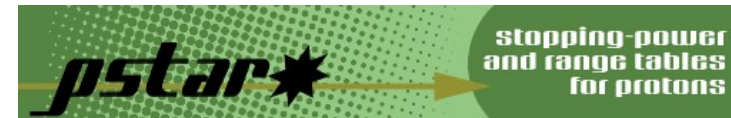
## Minimum Ionizing Particles (MIPs):

“Fast” particles lose constant and small amount of energy.

# Protons in Different Materials

## Tables for protons impacting on different materials.

- Proton accelerators are common irradiation facilities
- Lots of protons out of in the LHC collisions.



Material:

Graph stopping power  
 Total Stopping Power  
 Electronic Stopping Power  
 Nuclear Stopping Power

Graph range:  
 CSDA Range  
 Projected Range

Graph detour factor

No graph

Submit Reset

Material list:  
1: Hydrogen  
2: Helium  
4: Beryllium  
6: Carbon, Amorphous (density 2.0 g/cm<sup>3</sup>)  
6: Graphite (density 1.7 g/cm<sup>3</sup>)  
7: Nitrogen  
8: Oxygen  
10: Neon  
13: Aluminum  
14: Silicon  
18: Argon  
22: Titanium

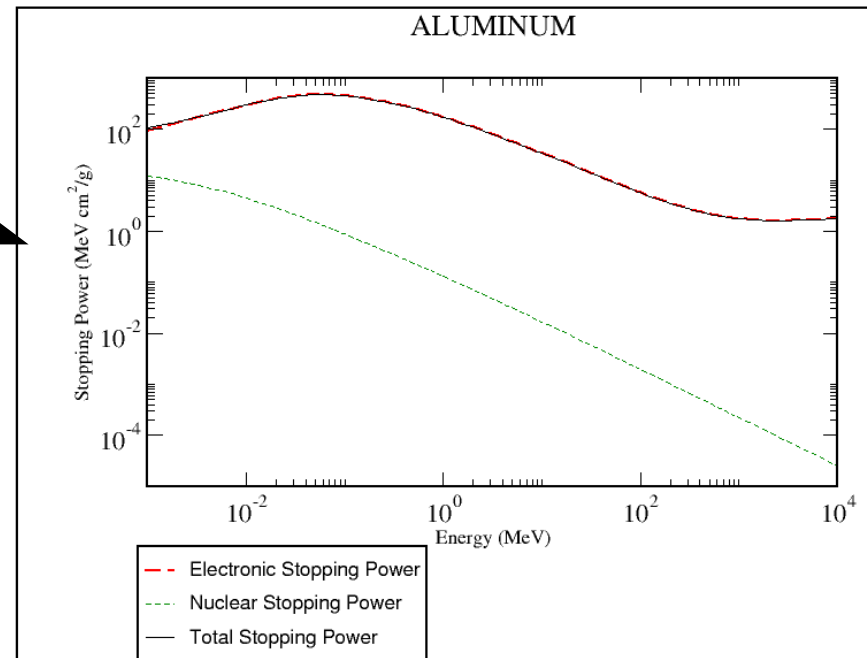


Table of values also available.

Protons: <https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html>

Electrons: <https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html>

# The Bethe-Bloch Formula: Non-Relativistic

For non-relativistic particles: terms in [...] can be neglected.

(higher order corrections)

$$\frac{dE}{dx} \cong \left( \frac{e^2}{4\pi\epsilon_0} \right)^2 \frac{4\pi z^2}{m_e v^2} N Z \left[ \ln \frac{2m_e v^2}{I} - \ln \left( 1 - \frac{v^2}{c^2} \right) - \frac{v^2}{c^2} \right]$$

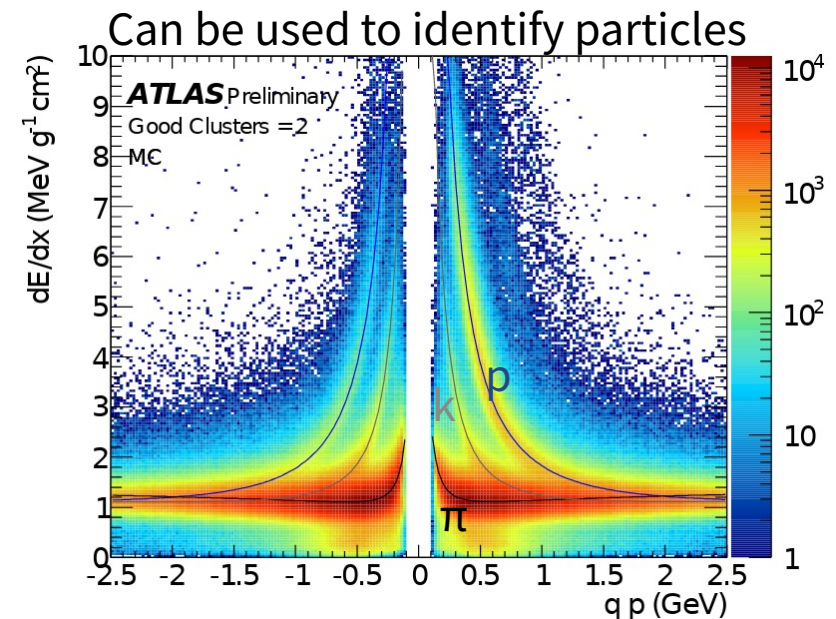
*Note: In the original image, the first term is marked with  $\approx 1$ , the second term with  $\approx 0$ , and the third term with  $\approx 0$ .*

## Incoming Particle

- $dE/dx \propto z^2/v^2 \propto M_z^2/E$

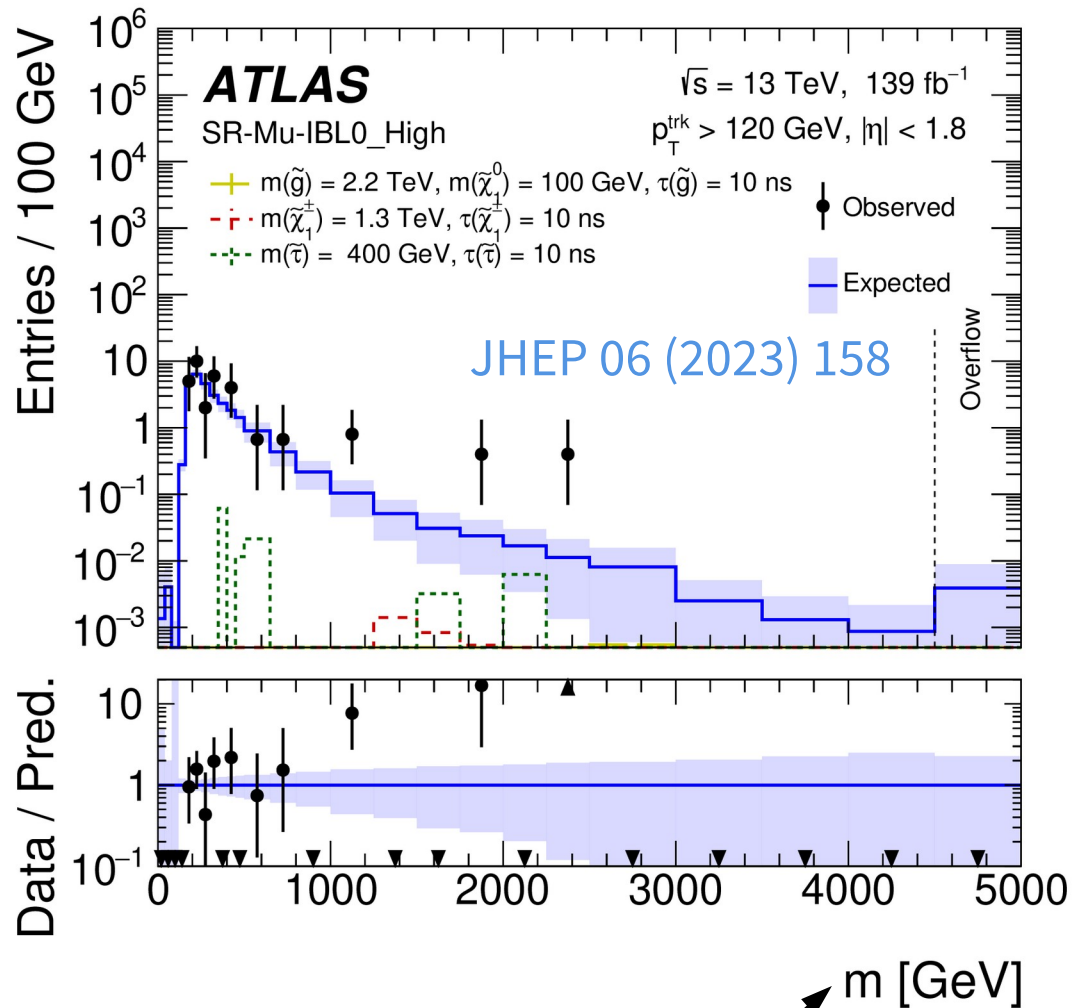
## Material:

- $dE/dx \propto NZ$  (electrons per unit volume)



# Particle ID w/ dE/dx and BSM Physics

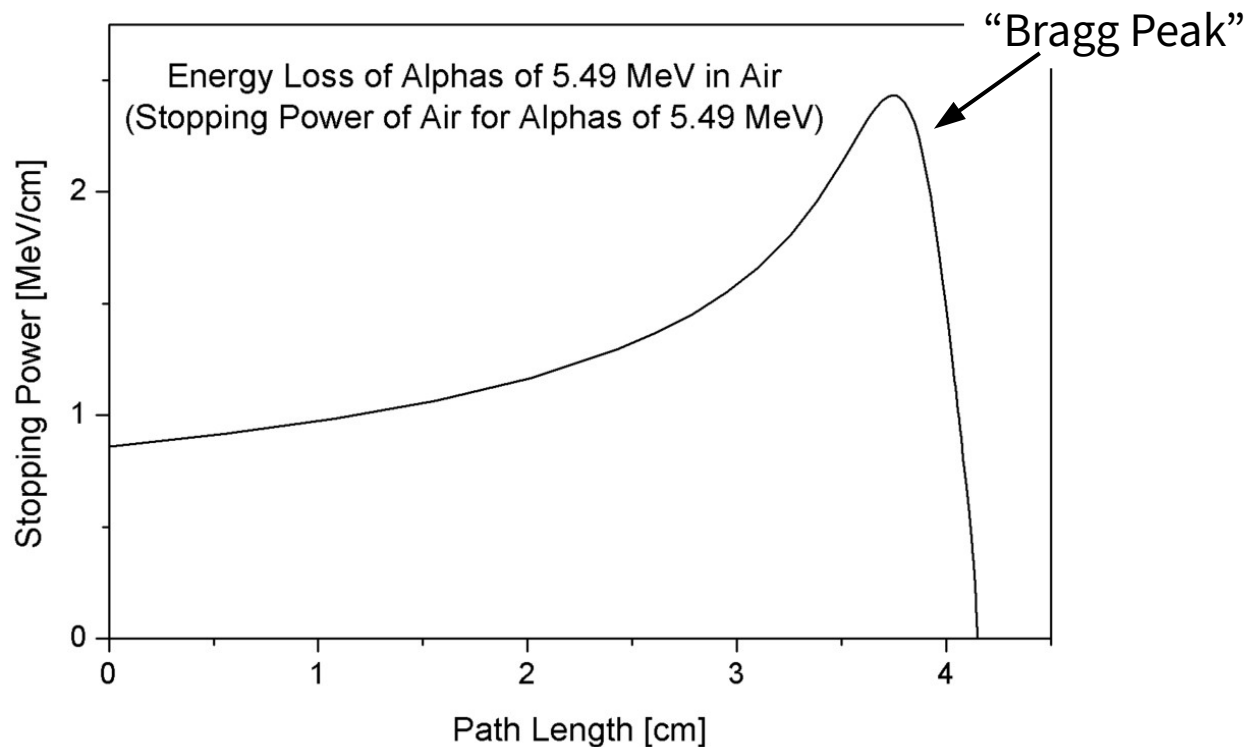
ATLAS search for *slow, massive, long-lived* new particles.



Reconstructed from track  $p_T$  and pixel detector  $dE/dx$

# Bragg Peak

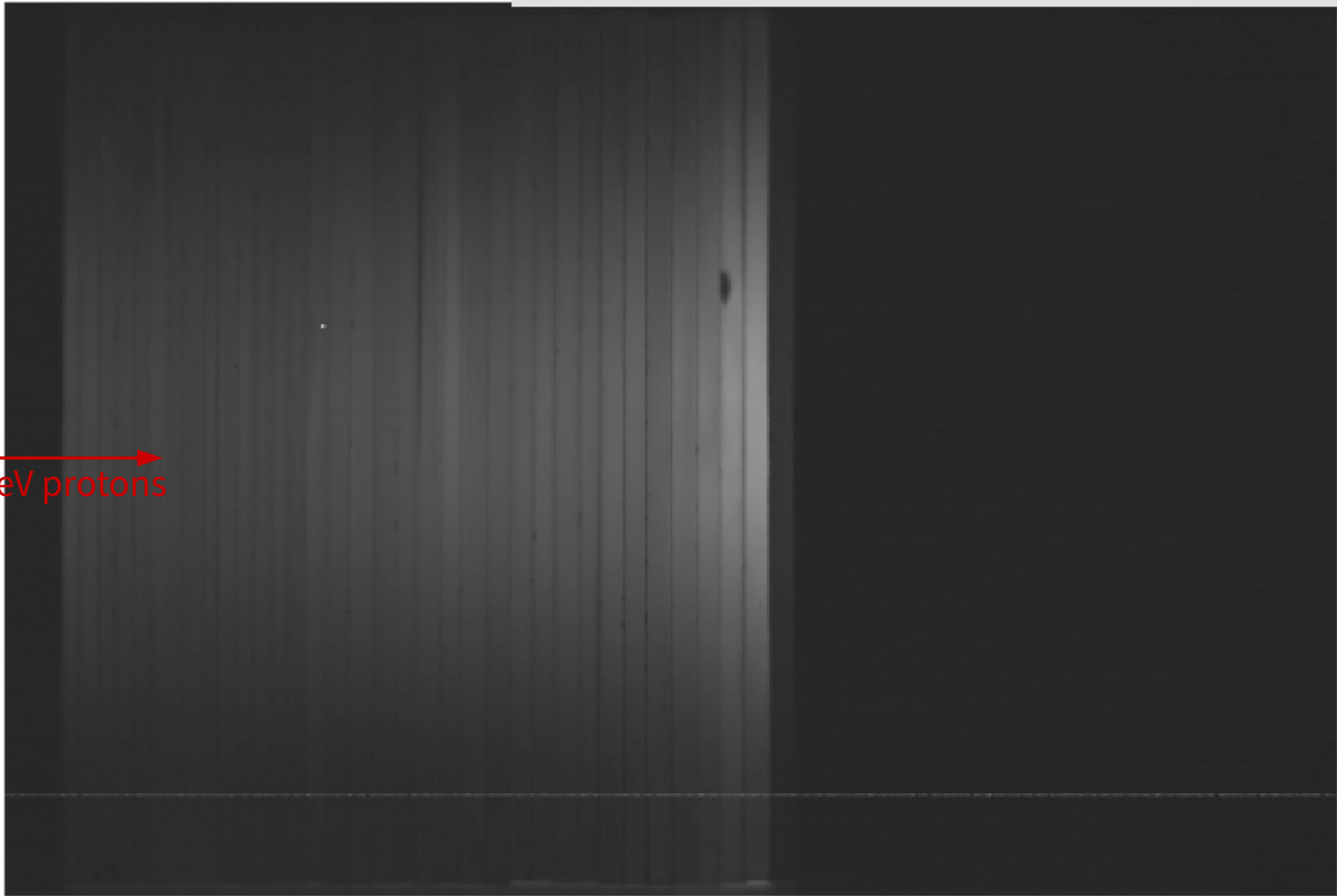
- **Most energy is deposited at end of trajectory**
  - Result of integrating Bethe-Block
- **Bethe-Block underestimates stopping power**
  - Ions pick up electrons from material  $\rightarrow$  become less charged



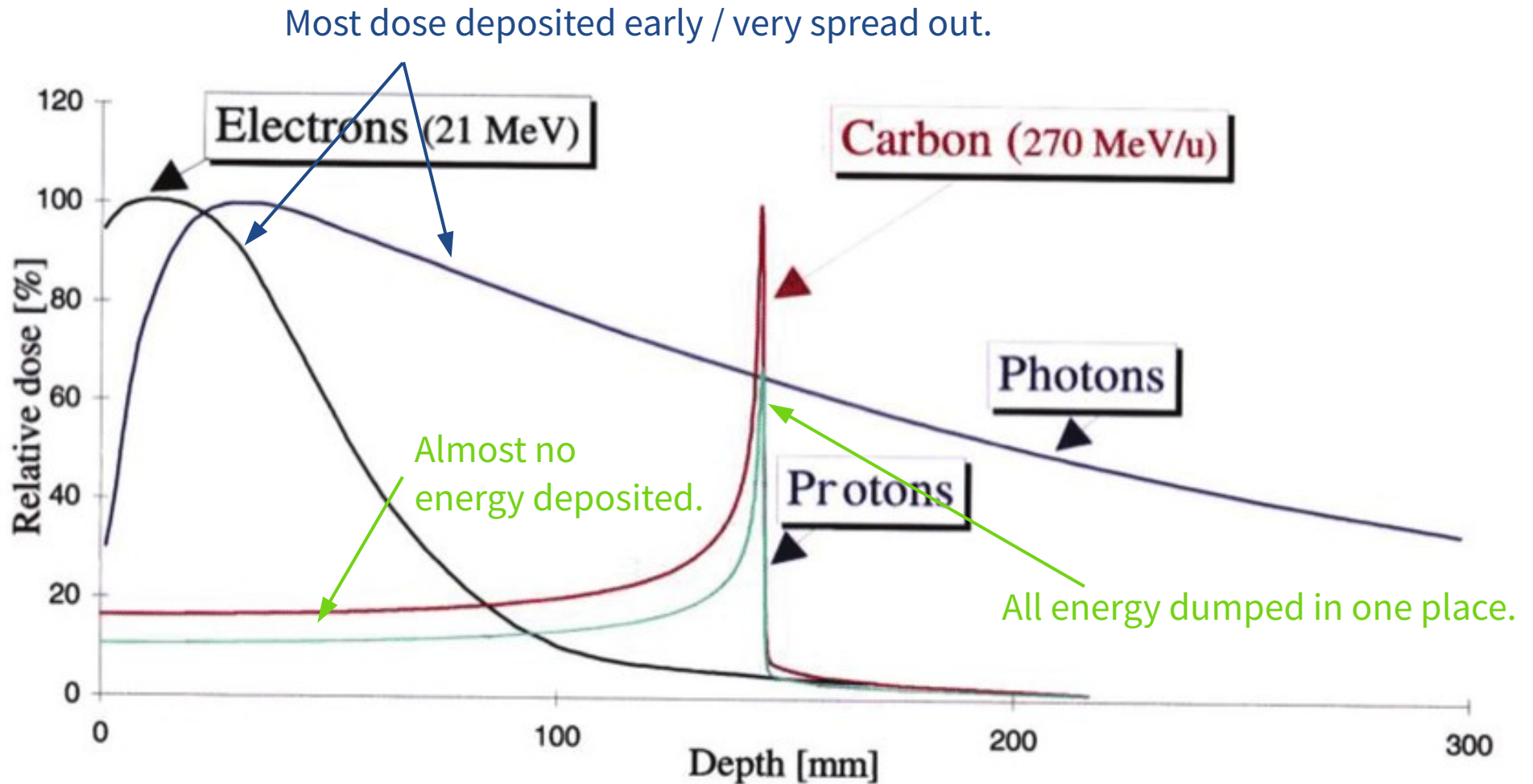
# Bragg Peak in Action

Credit: [A scintillator-based range telescope for particle therapy](#)

106.17 MeV protons →



# Total Dose vs Depth

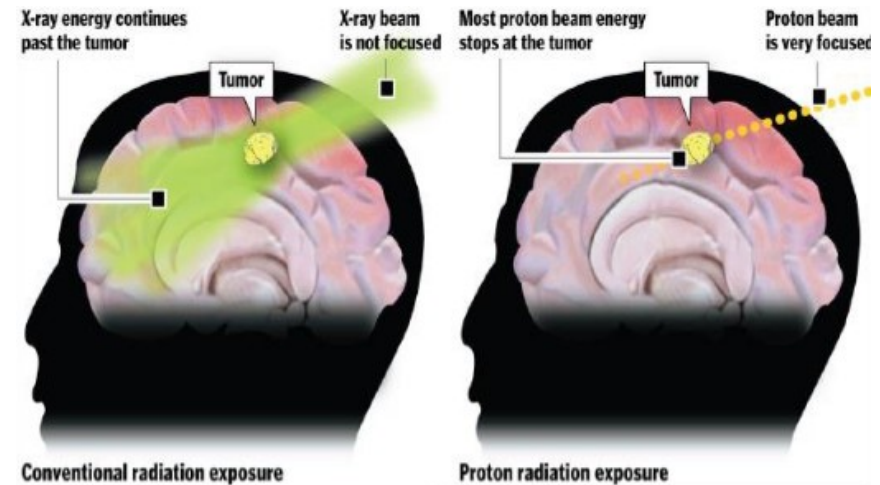
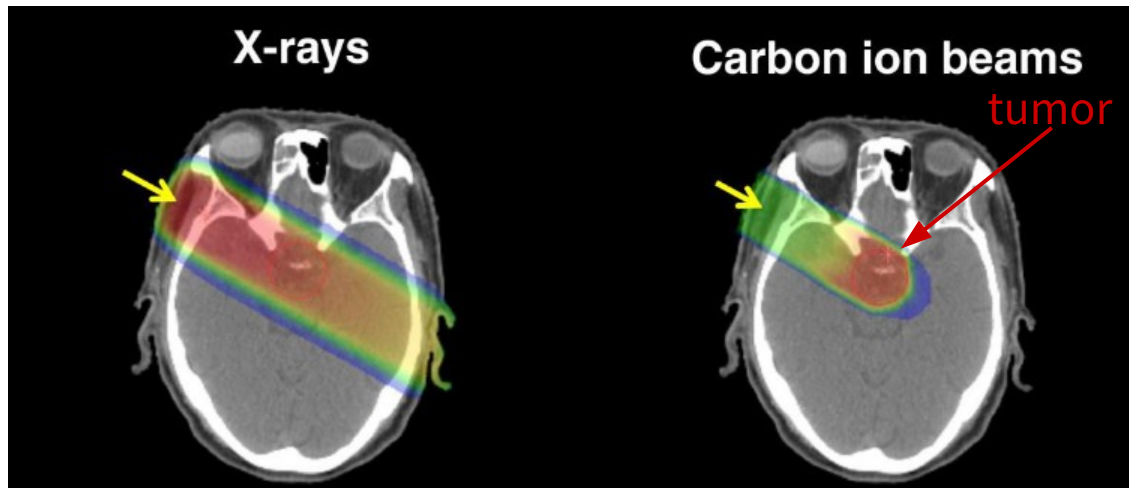


Credit: [Advanced Radiation Treatment Planning of Prostate Cancer](#)

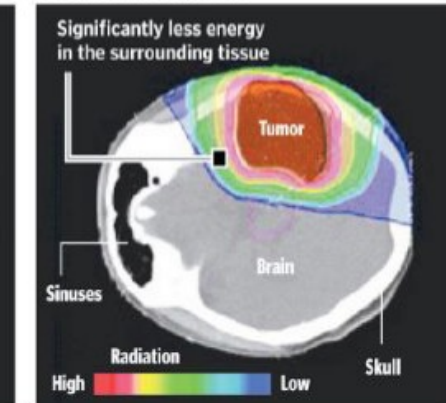
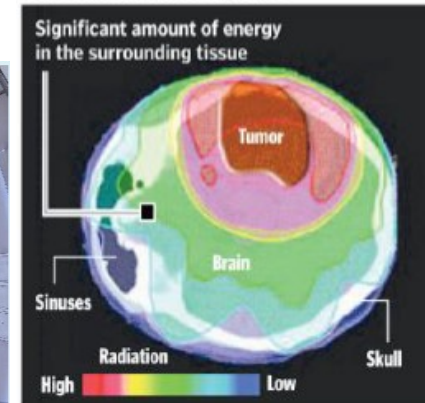
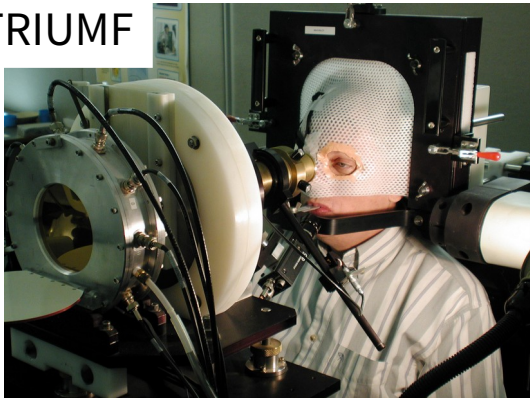
# Radiation Therapy for Cancer

Set the ion energy to place Bragg Peak at tumor.

Minimizes irradiating healthy tissue on the way.



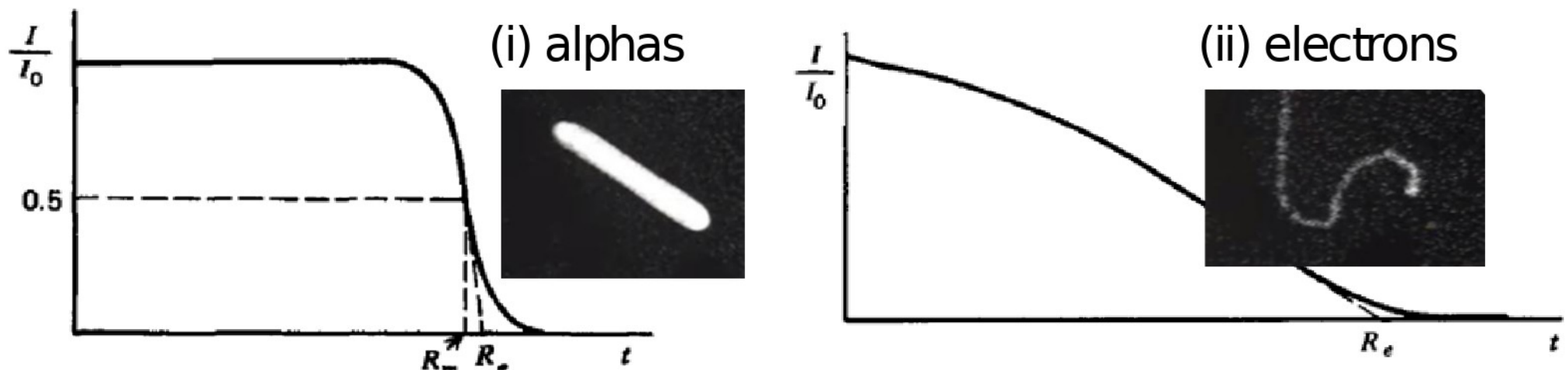
TRIUMF



# Electrons

**Electrons** do follow Bethe-Block, but are **very light!**

- Even electrons from radioactive decays can be relativistic, but...
- A large fraction of its energy can be deposited in a single interaction.
- Trajectory will include large scattering → even shorter depth.



Credit: <http://microcosm.web.cern.ch/en/cloud-chamber-video#overlay-context=en/cloud-chamber>

# Neutrons

**Neutrons are uncharged** → **no interactions w/ electrons** of atoms.  
Interacts mainly with **nucleus** via strong force.

Also **protons** and WIMP Dark Matter.

Examples at moderate energies:

- **Scattering (elastic/inelastic): recoiling nucleus to ionize electrons**
  - Need large energy transfer (ie: light nucleus).
  - No measurement of neutron properties (random scattering).
  - Cross-section inversely proportional to velocity.
- **Radioactive Capture: (low energy) neutron captured by nucleus**
  - Gamma-ray is emitted, hard to detect.
- **Nuclear reactions (n,p), (n,  $\alpha$ ), (n, fission): detect charged results of decay**
  - Indirect relation to neutron energy.

# Photons

## Photoelectric Absorption

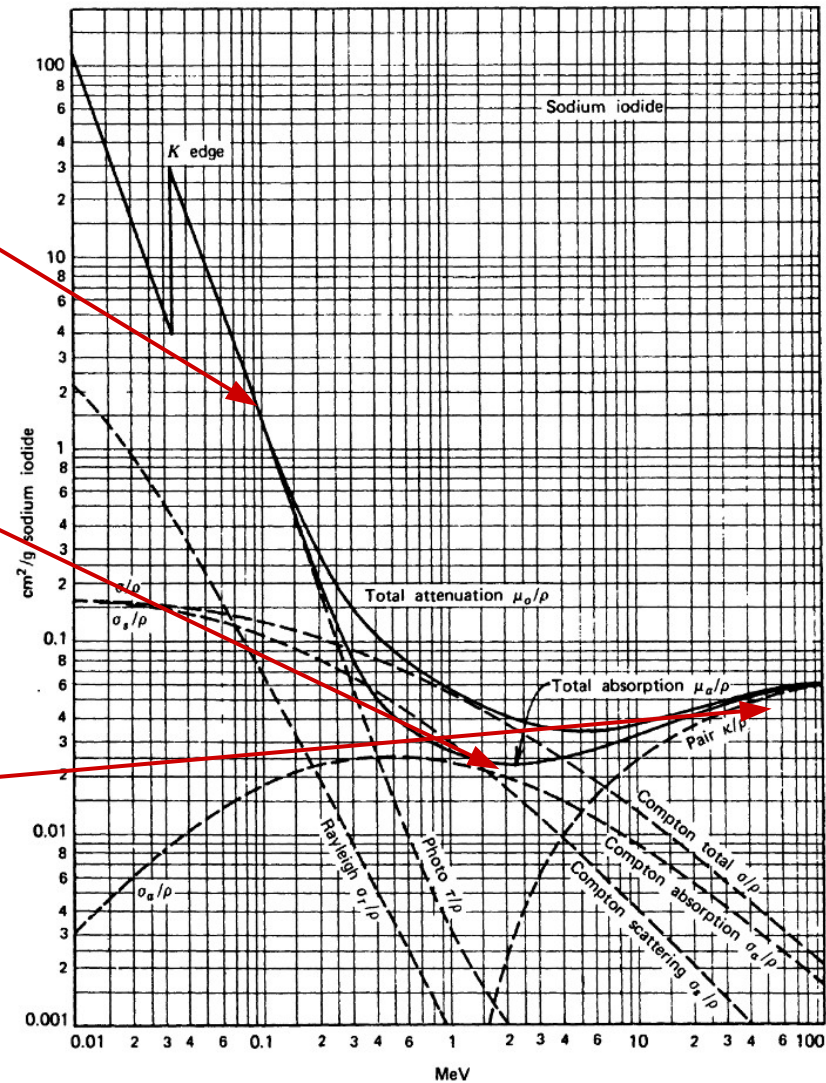
low energy, high Z

## Compton Scattering

always

## Pair Production

only at high energy



**Figure 2.18** Energy dependence of the various gamma-ray interaction processes in sodium iodide. (From *The Atomic Nucleus* by R. D. Evans. Copyright 1955 by the McGraw-Hill Book Company. Used with permission.)

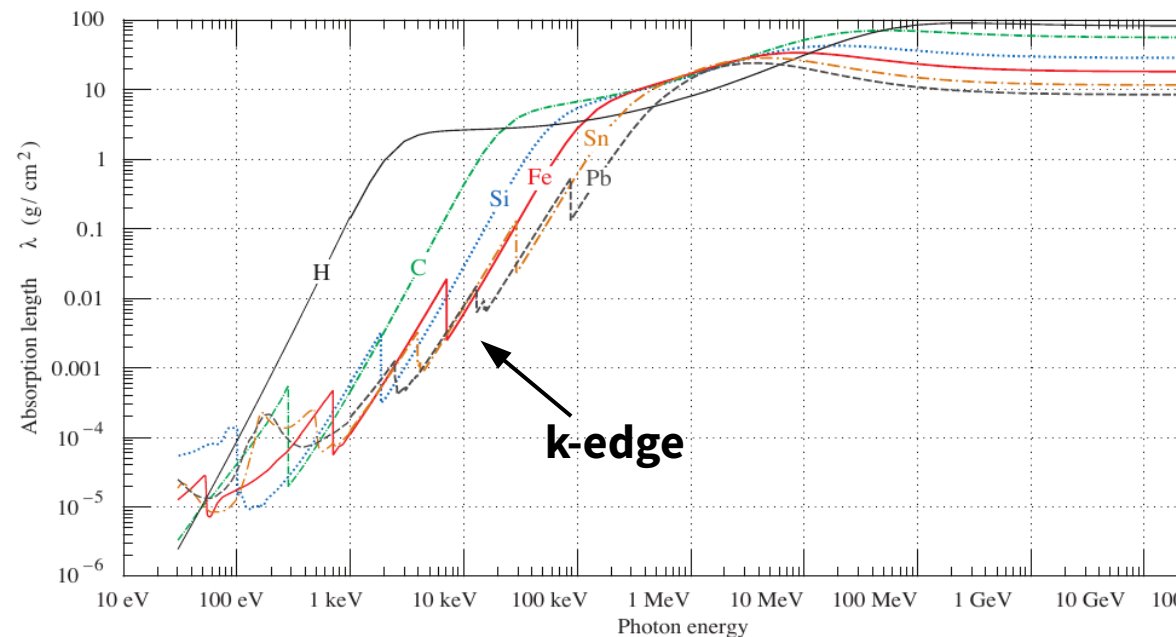
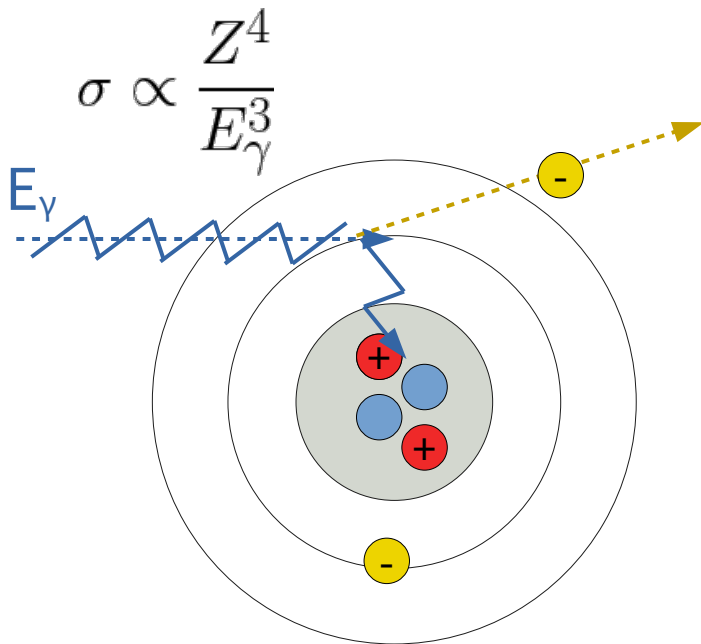
# Photoelectric Absorption

- Entire energy of photon is absorbed to emit an electron

$$E_e = E_\gamma - E_{BE}, E_{BE} \text{ is binding energy}$$

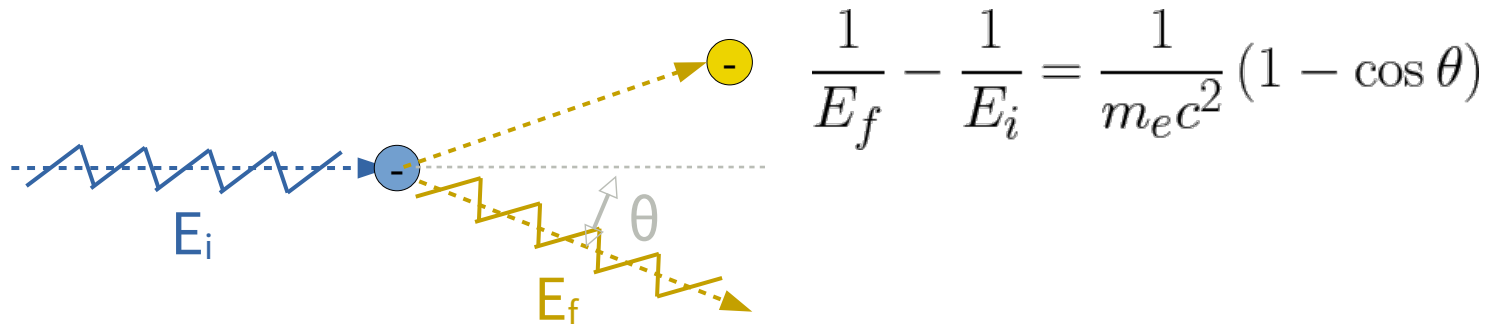
- Require nucleus to absorb for momentum conservation

- Mainly occurs with inner-shell electrons (K-electrons)
- Outer electrons involved when K-e  $E_{BE}$  too high



# Compton Scattering

## Photons scattering off electrons



## Cross-section depends on

- Inversely proportional to energy (Klein-Nishina formula)
- Proportional to number of electrons ( $Z$ )

## Linear attenuation coefficient: $\mu = n\sigma$

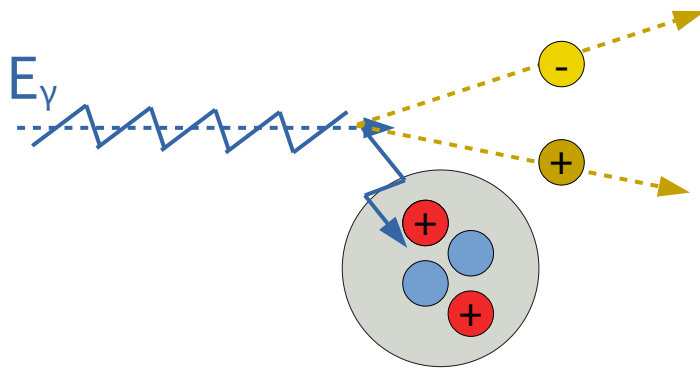
- Number density of atoms:  $n = \rho N_A / A$
- Cross-section:  $\sigma \propto Z$

$$\frac{\mu}{\rho} \propto \frac{Z}{A}$$

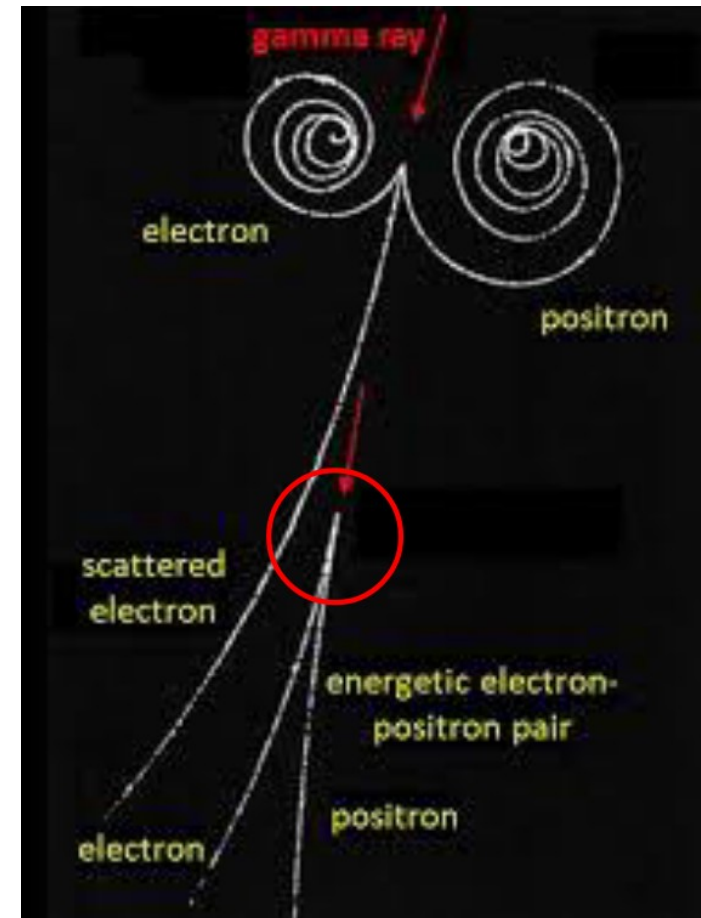
# Pair Production

Photon converts into  $e^+/e^-$  pair

Needs to “scatter” off of a nearby nucleus to conserve momentum



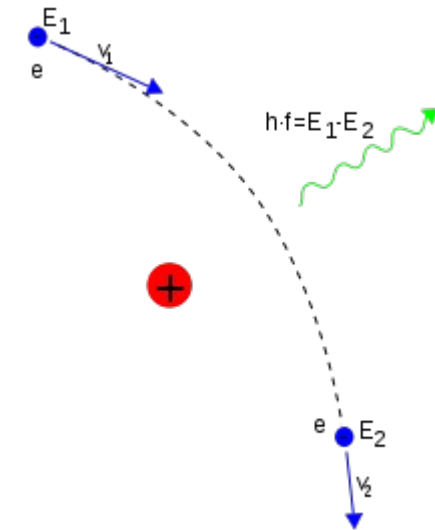
- **Requires  $E_\gamma > 1.022 \text{ MeV}$** 
  - Produce two electrons ( $2x m_e$ )
- **Cross-section depends on**
  - Proportional to  $E_\gamma$ , significant above 5 MeV
  - Proportional to  $Z^2$



# Relativistic Phenomena

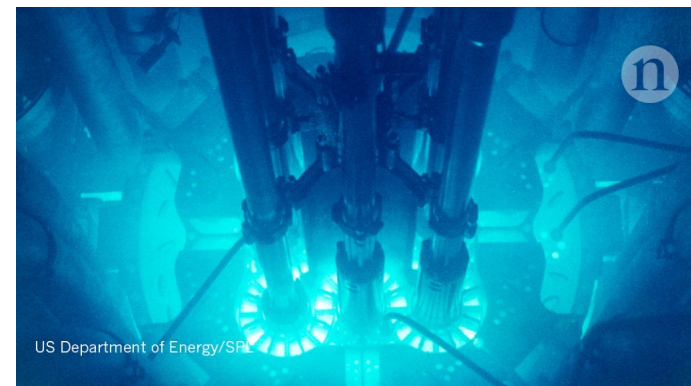
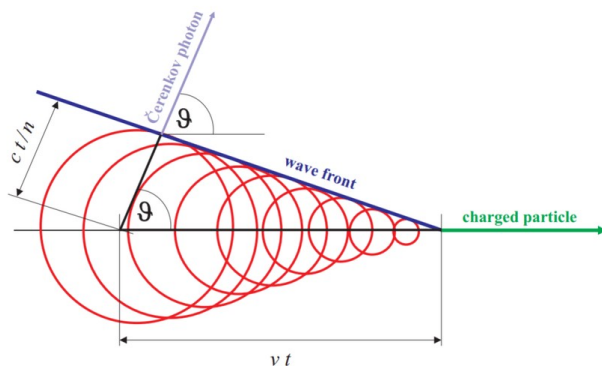
## Bremsstrahlung (“parking radiation”)

- Accelerating charged particle radiate photons
- Charged nucleus = source of acceleration
- Combined with pair production = EM cascades



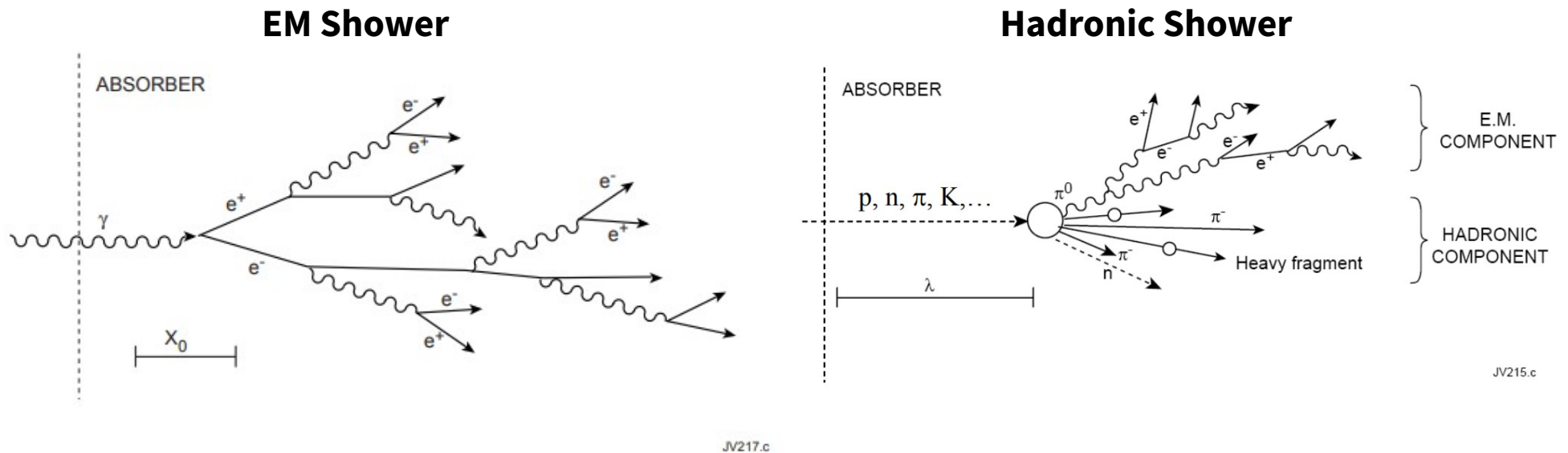
## Chernekov Radiation

- Speed of light in material is less than speed of light in vacuum
- Highly relativistic particle can travel faster than light in *that medium*
- Result is a “light shockwave” in the visible spectrum



# High Energy Interactions: Absorbing

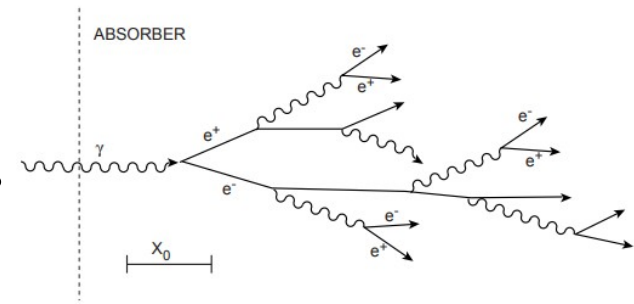
Multiple interactions until critical (low) energy is reached.



- Exploited by calorimeters to measure particle's energy
  - Made from high  $Z$  materials that encourage the above processes

# Electromagnetic Shower

- Material is characterized by “radiation length”,  $X_0$ :  $E = E_0 e^{-x/X_0}$
- **Each step** causes energy to **split by two**.
- After **N splits**, energy is split into  **$2^N$  particles**.
- Continues **until** reaching critical energy ( $E_C$ ).
- Ionization losses exceed Bremsstrahlung



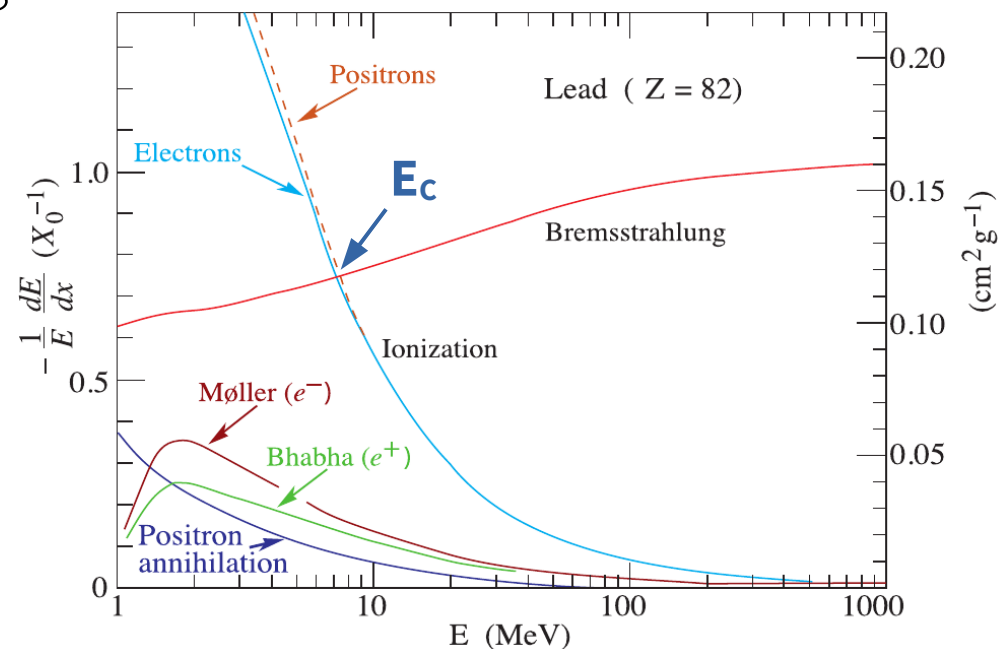
Shower depth

$$t_{MAX} \approx X_0 \ln \frac{E_I}{E_C} / \ln 2$$

Shower width

$$R_M = \frac{21 \text{ MeV}}{E_C} X_0 [\text{g/cm}^2]$$

“Moliere Radius”



# Hadronic Showers

- Material is characterized by “nuclear interaction length”

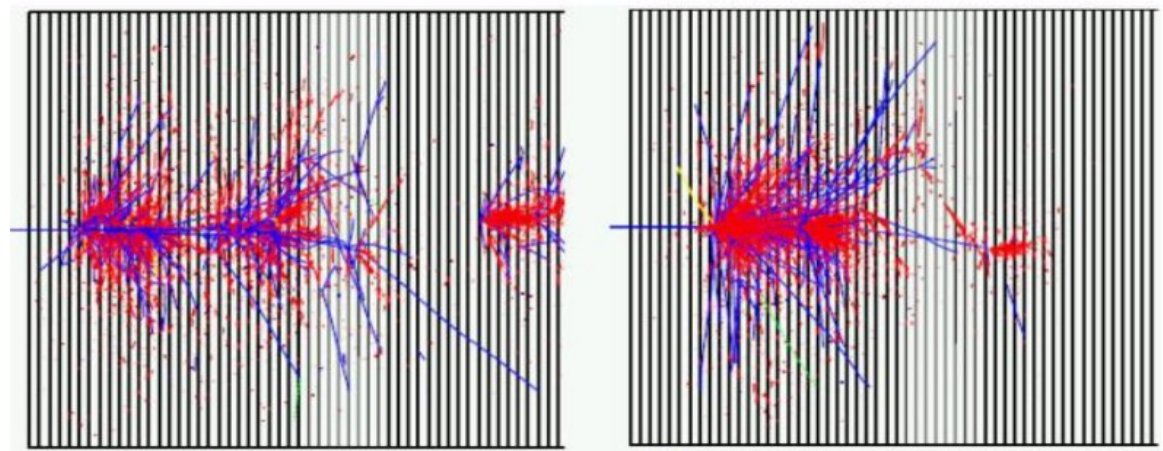
$$\lambda_l = A / (N_A \sigma_{inel}) \approx 35 \times A^{1/3} \text{ [g/cm}^2\text{]}$$

- Cross-section scales as  $\sigma_{inel} = A^{2/3}$
- Multiplicity of secondaries  $\ln(E)$**
- 1/3 of secondaries as pions

| material       | $X_0$ (g/cm <sup>2</sup> ) | $\lambda_n$ (g/cm <sup>2</sup> ) |
|----------------|----------------------------|----------------------------------|
| H <sub>2</sub> | 63                         | 52.4                             |
| Al             | 24                         | 106                              |
| Fe             | 13.8                       | 132                              |
| Pb             | 6.3                        | 193                              |

$t_{max} = \lambda_l (0.2 \times \ln(E[\text{GeV}]) + 0.7)$   
 $t_{95\%} \text{ (cm)} = 9.4 \times \ln(E[\text{GeV}]) + 39 \text{ [Fe]}$

Simulations of hadron showers



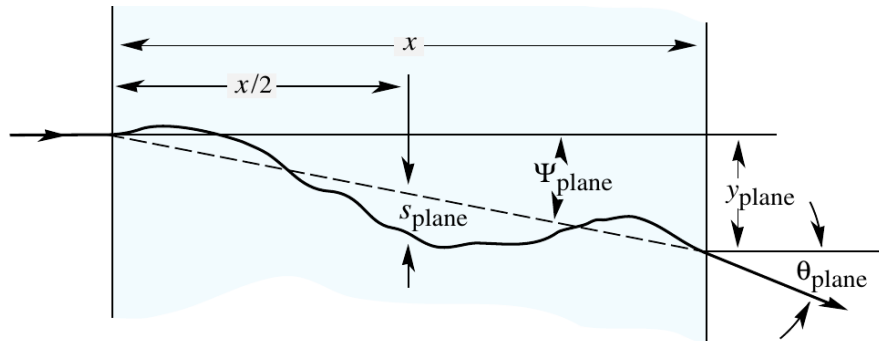
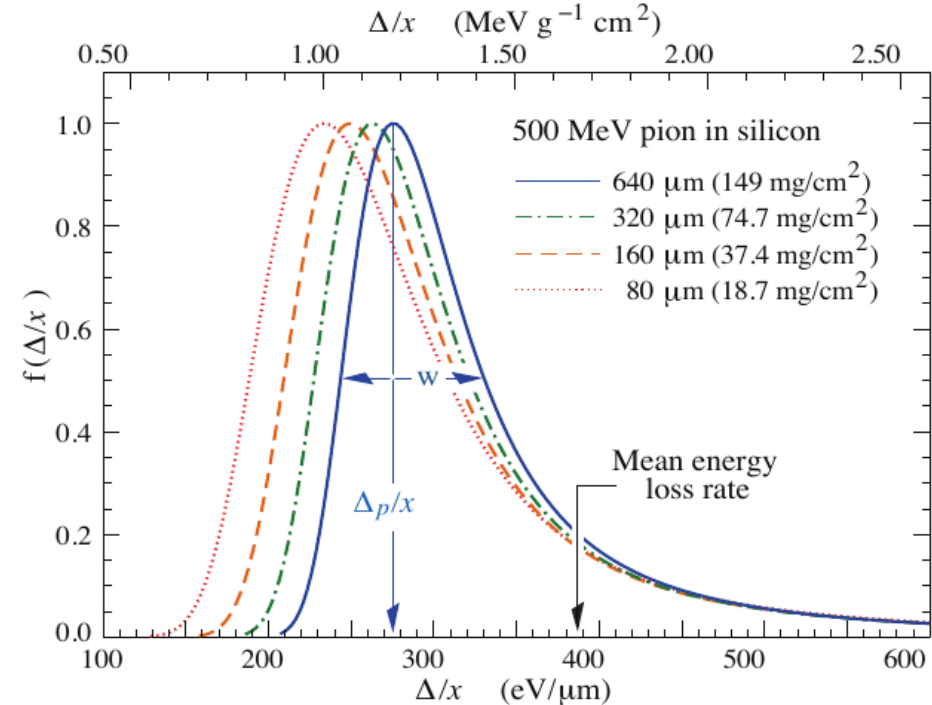
Red - e.m. component

Blue - charged hadrons

# High Energy Interactions: Passing Through

Multiple interactions without losing large fraction of energy.

- Example in **300  $\mu\text{m}$  silicon**
  - Typical peak energy loss is  $\sim 80$  keV
  - 3.6 eV to make an  $eh$ -pair
  - $\sim 22500e$  for each traversing particle
- $\Delta E$  fluctuations are Landau distr.
- Particle will also scatter at each interaction



$$\theta_{rms} \approx \frac{13.6 \text{ MeV}}{\beta c p} Z \sqrt{\frac{x}{X_0}}$$

## What happens to the material due to these interactions?

- **Total Ionizing Damage (TID)**

- Escaped electrons trapped inside structure
- Affects both sensors and electronics!

- **Single Event Errors (SEE)**

- High ionizing events inside electronics can cause bit flips

- **Displacement damage**

- Damage to the material lattice can change performance

- **Nuclear interactions**

- Changes to nucleus can cause materials to become radioactive

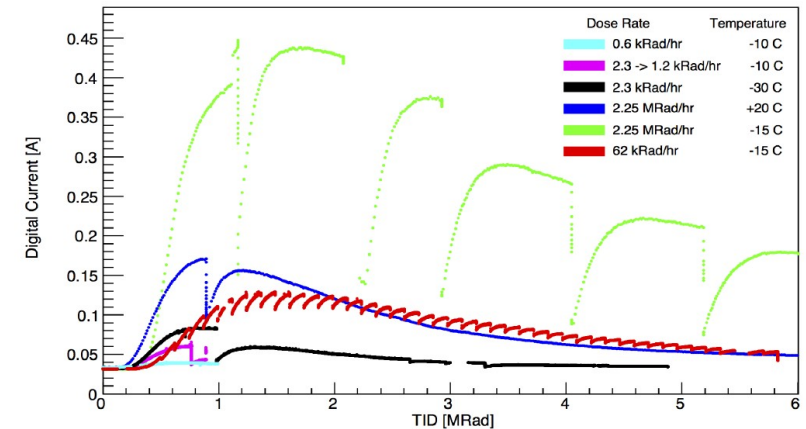


Figure 6.13: Digital current vs. TID for ABC130 chips during X-rays irradiations at different dose rates and temperatures.