Beam Loss Physics

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ACAS School for Accelerator Physics

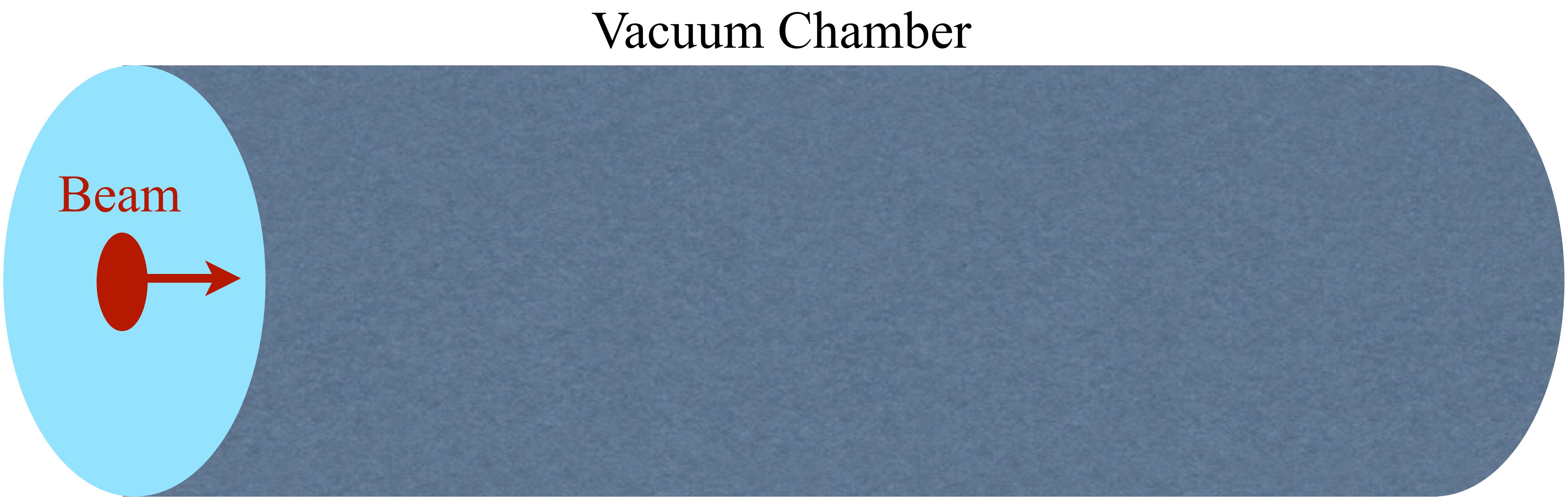
Outlook

- **Definitions and concepts**
  - Beam Losses
  - Beam Loss Monitoring
- **Beam Loss Categorization**
  - Examples
- **Interactions of particles with matter**
  - Sources of secondary particles
  - Sources of Beam Loss Monitoring signal

A graphical introduction

Introduction

- What are beam losses?
- What are Beam Loss Monitors?



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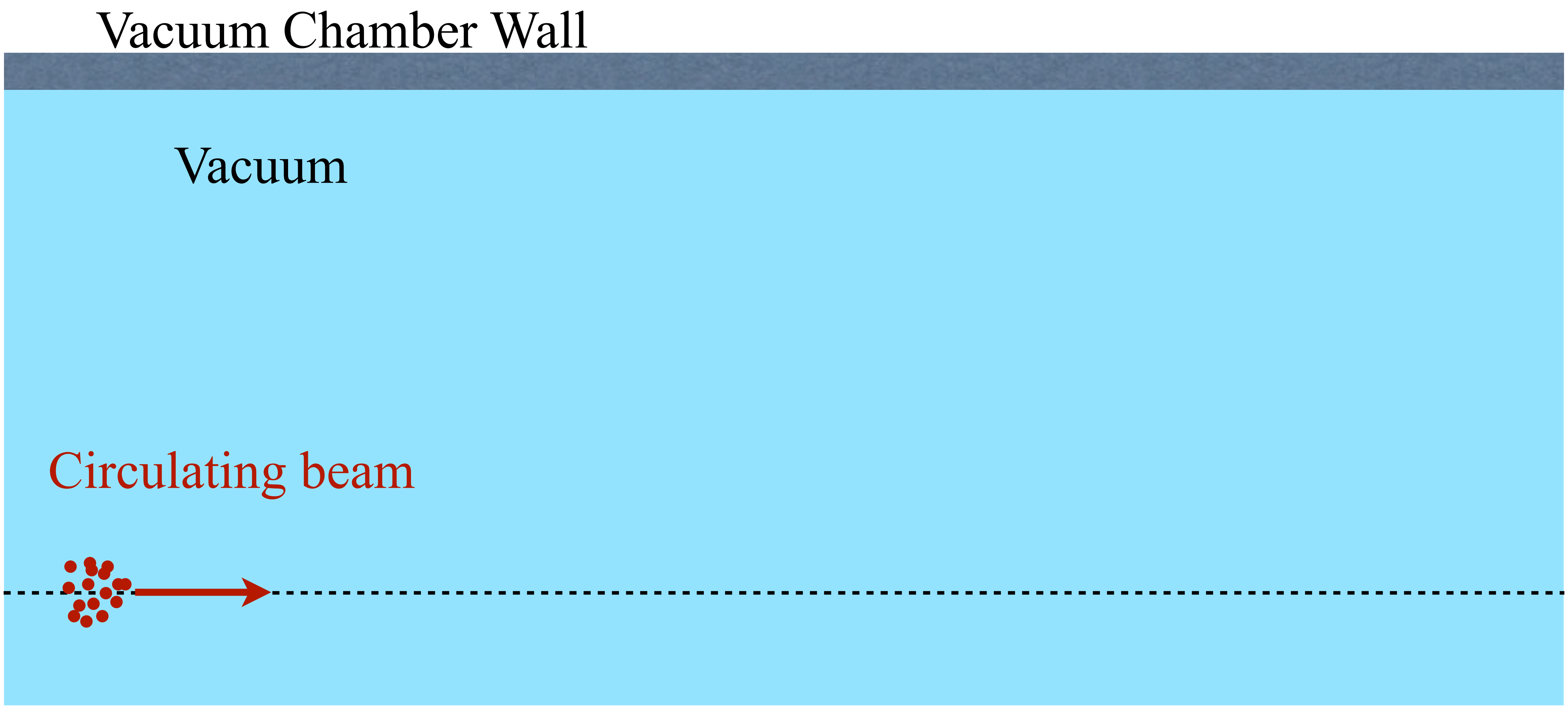

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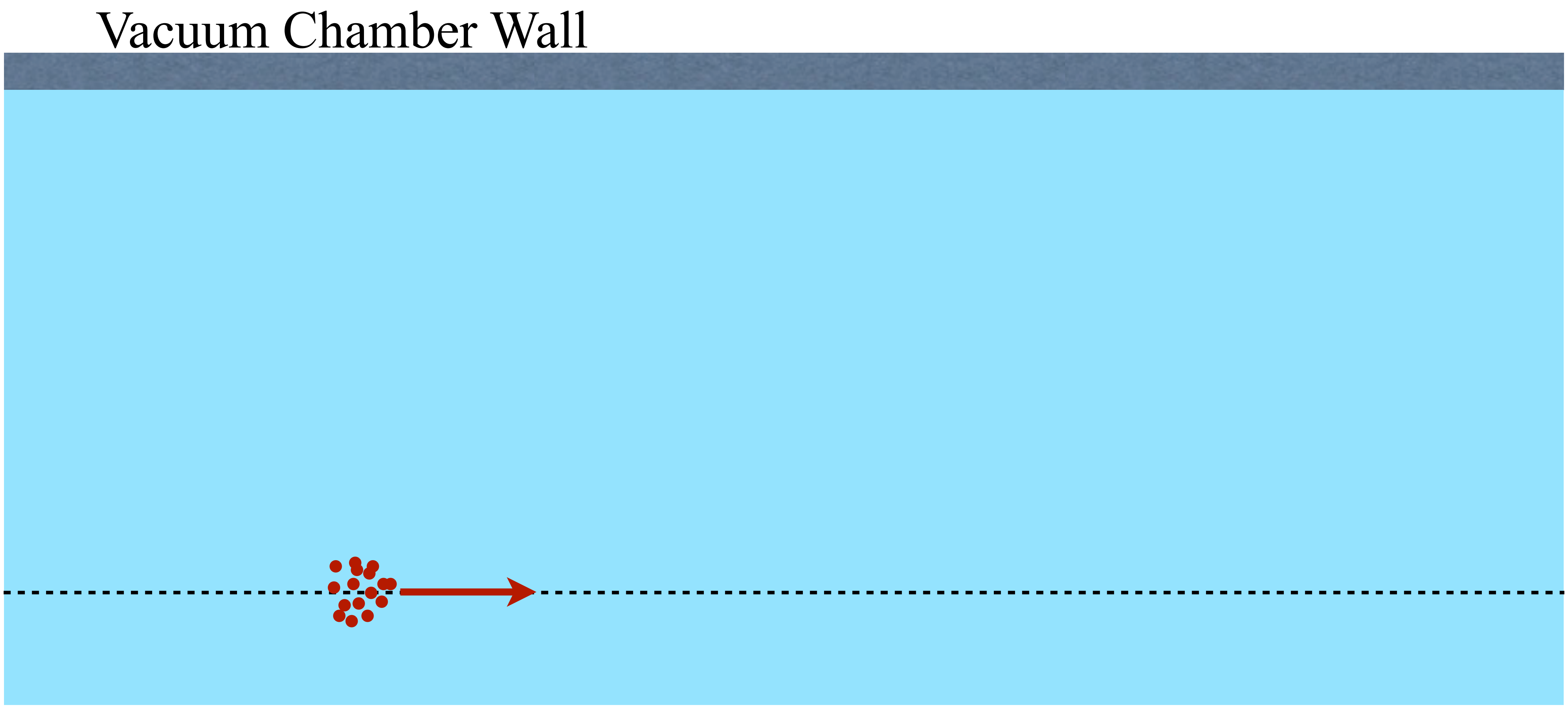

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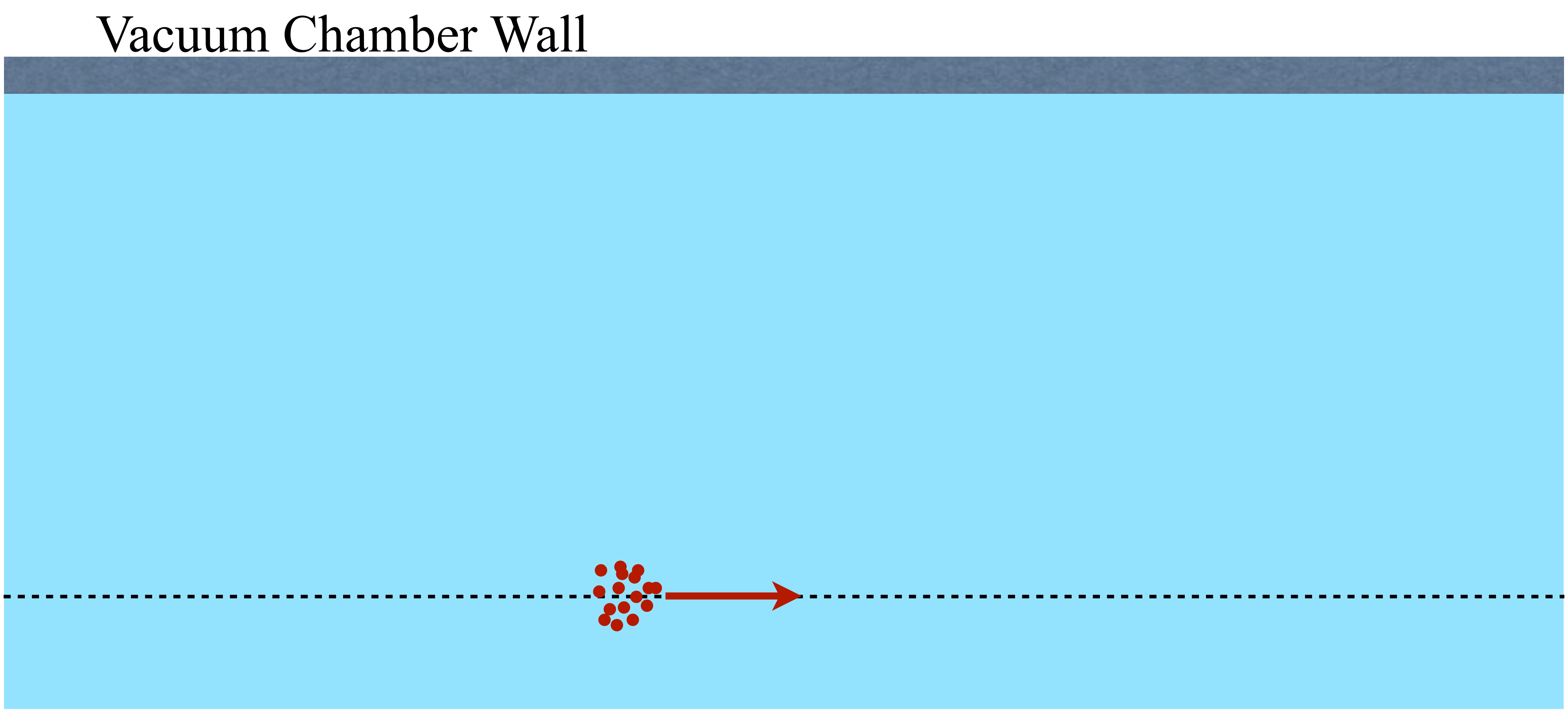

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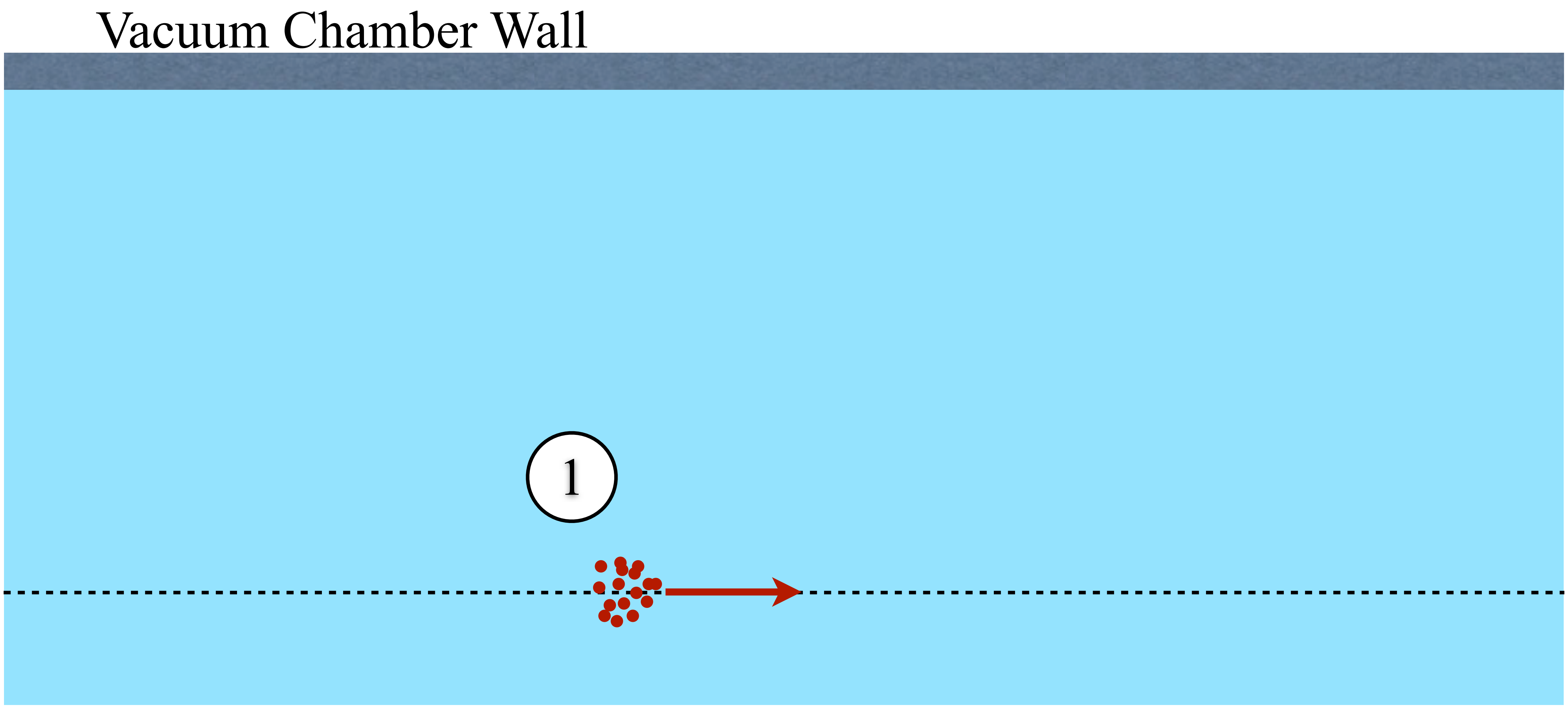

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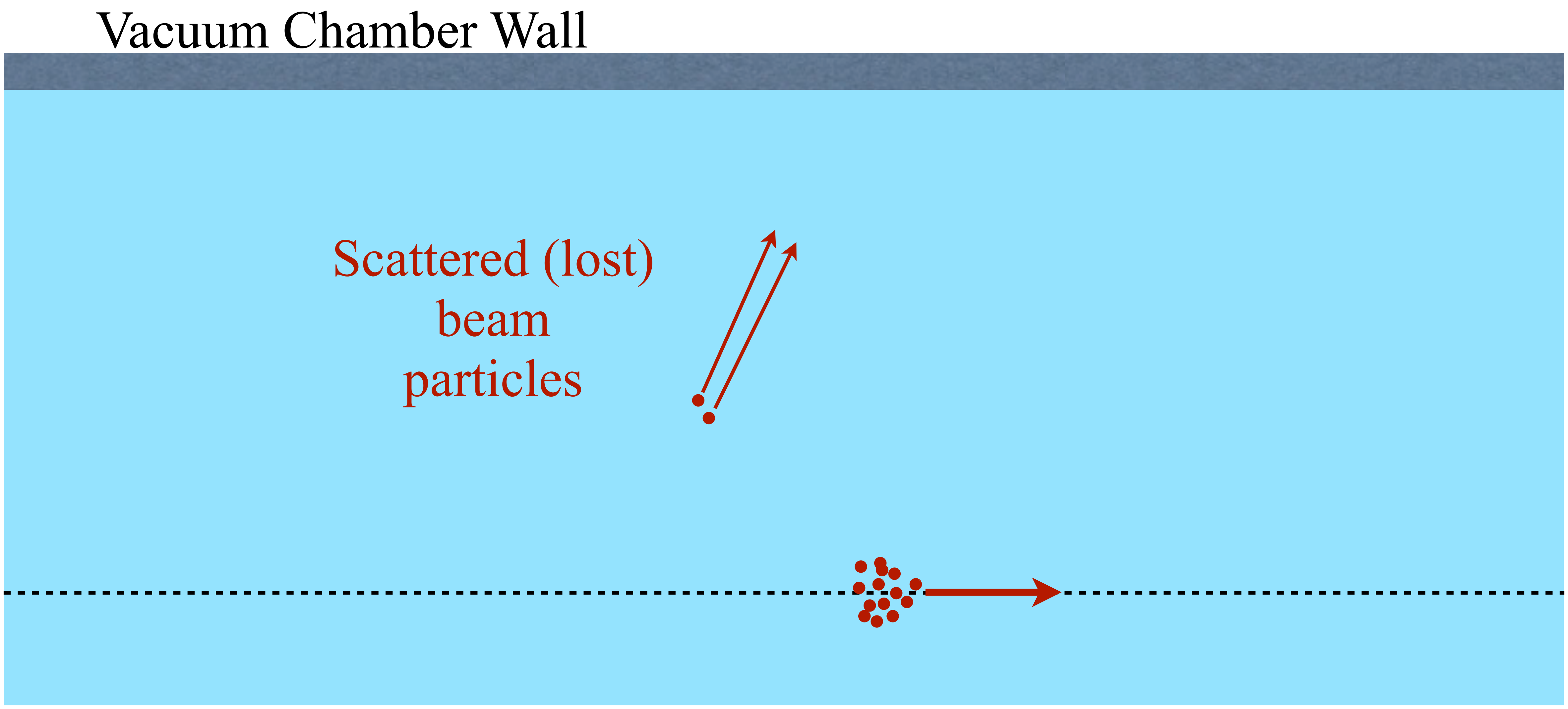

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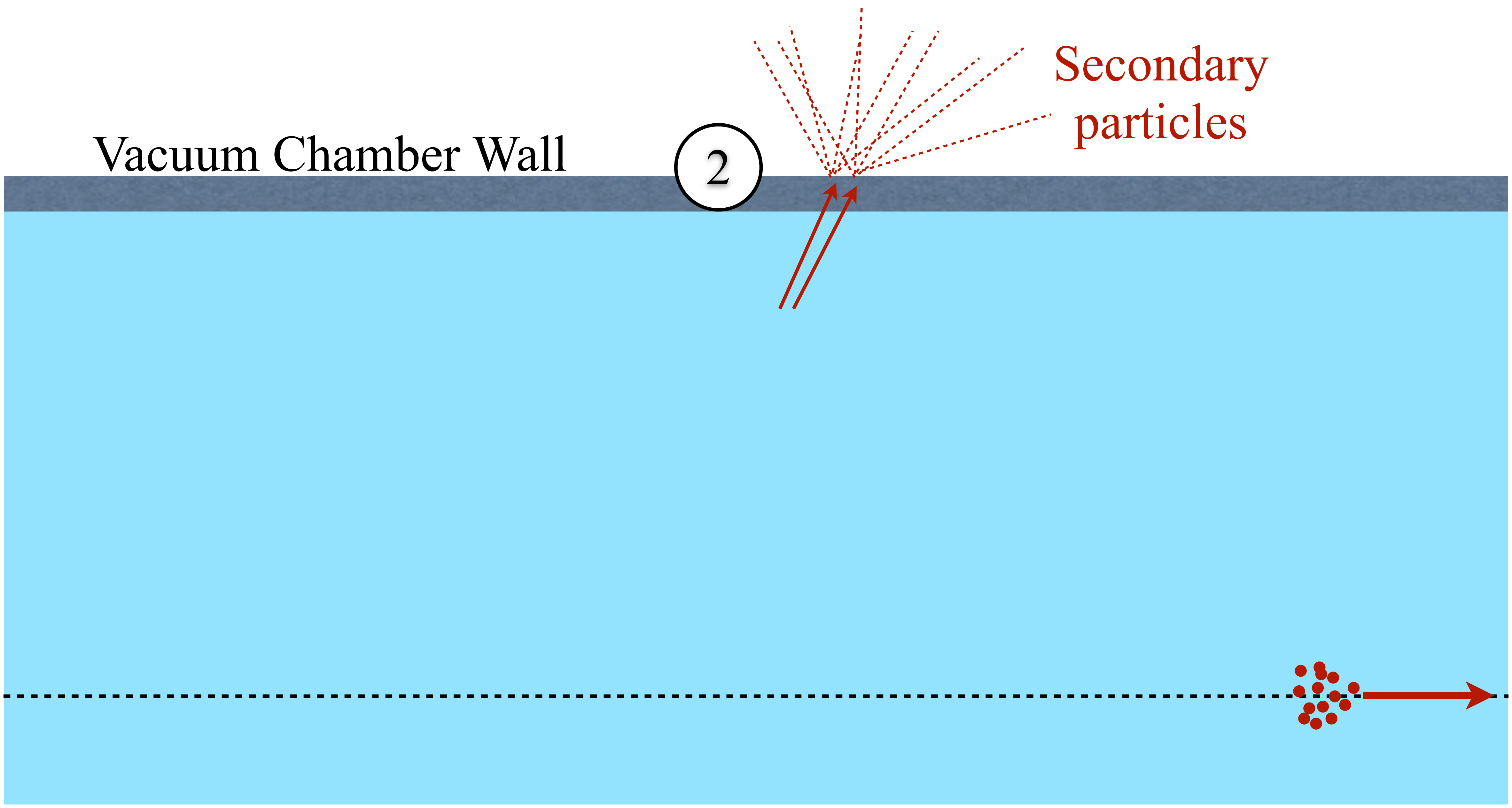

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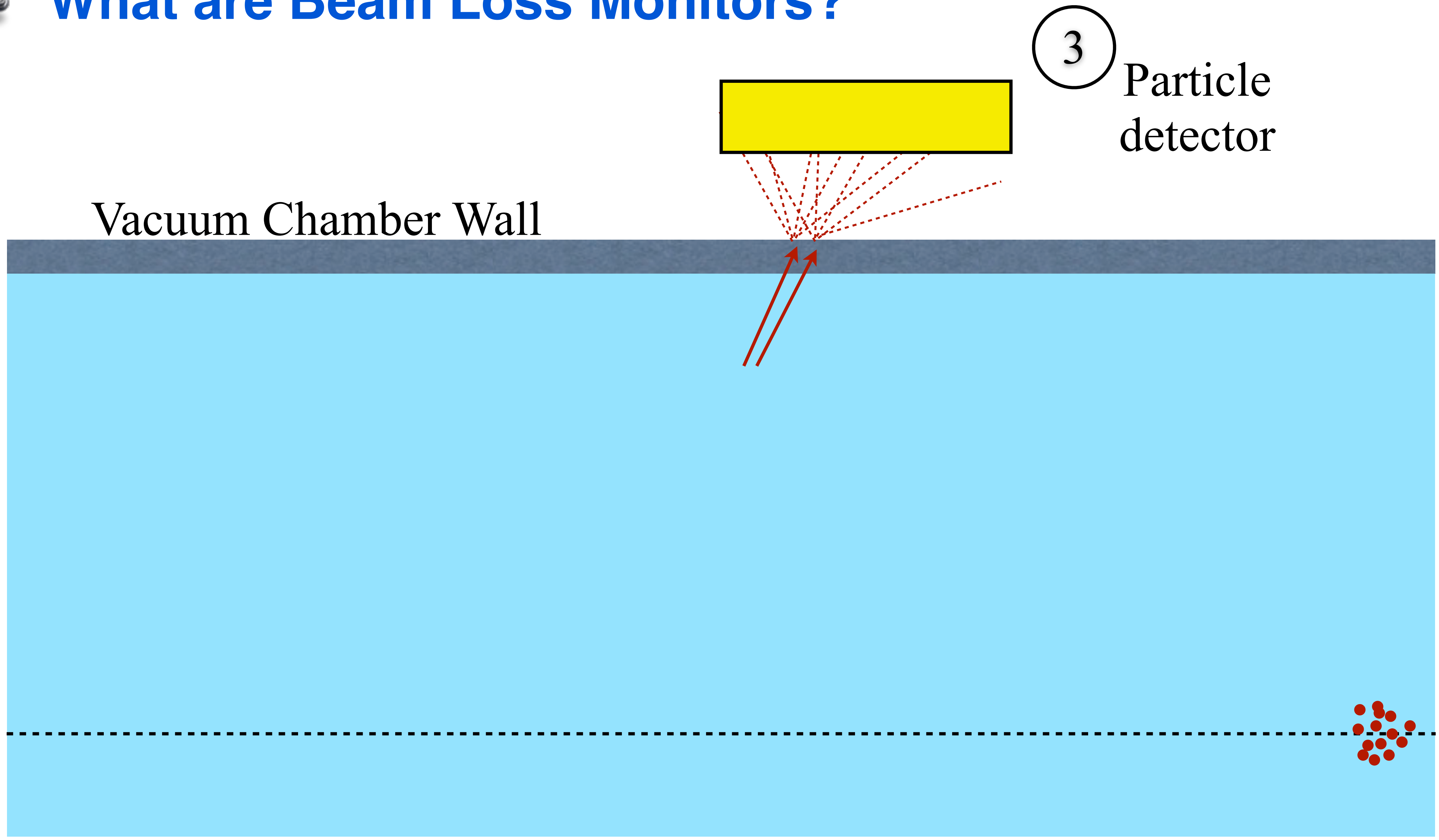
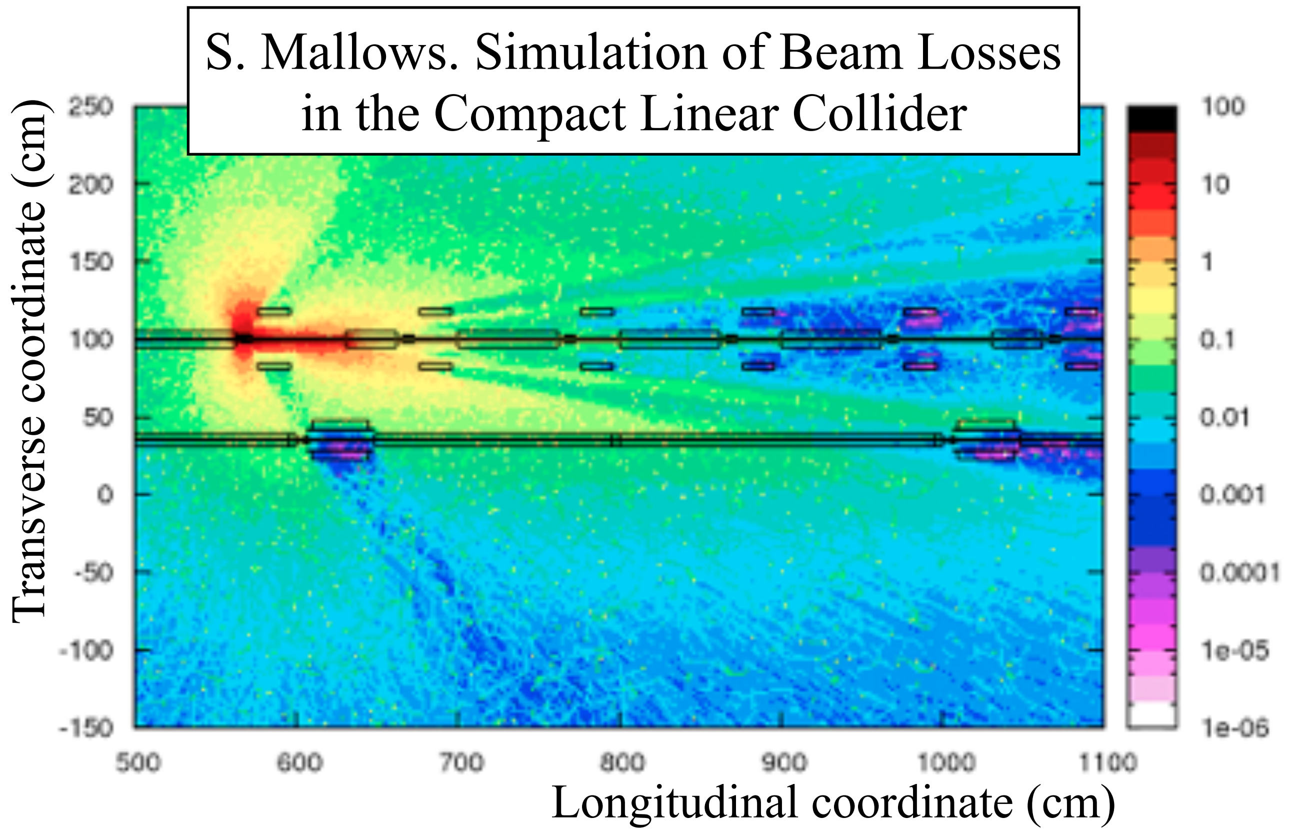


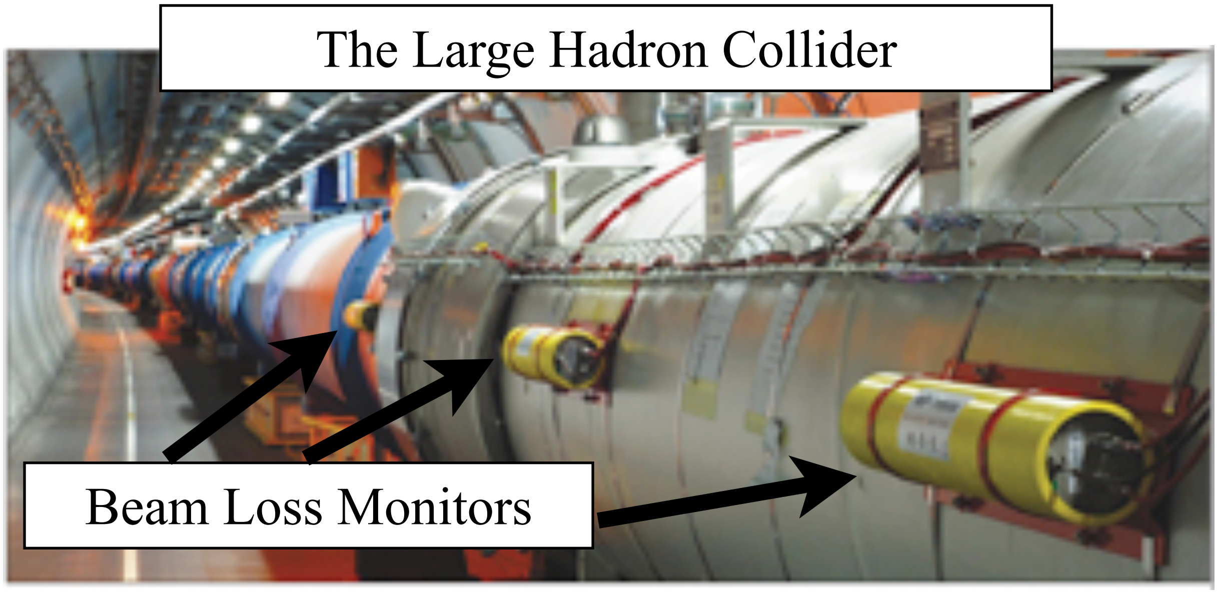
Definitions and main goals

Definitions

- **Beam Losses**
  - Particles deviating from the design orbit and hit the aperture limit
    - **Mechanisms for beam loss?**
  - Impact of particles produce secondaries
    - **Mechanisms for secondary particle generation and detection?**

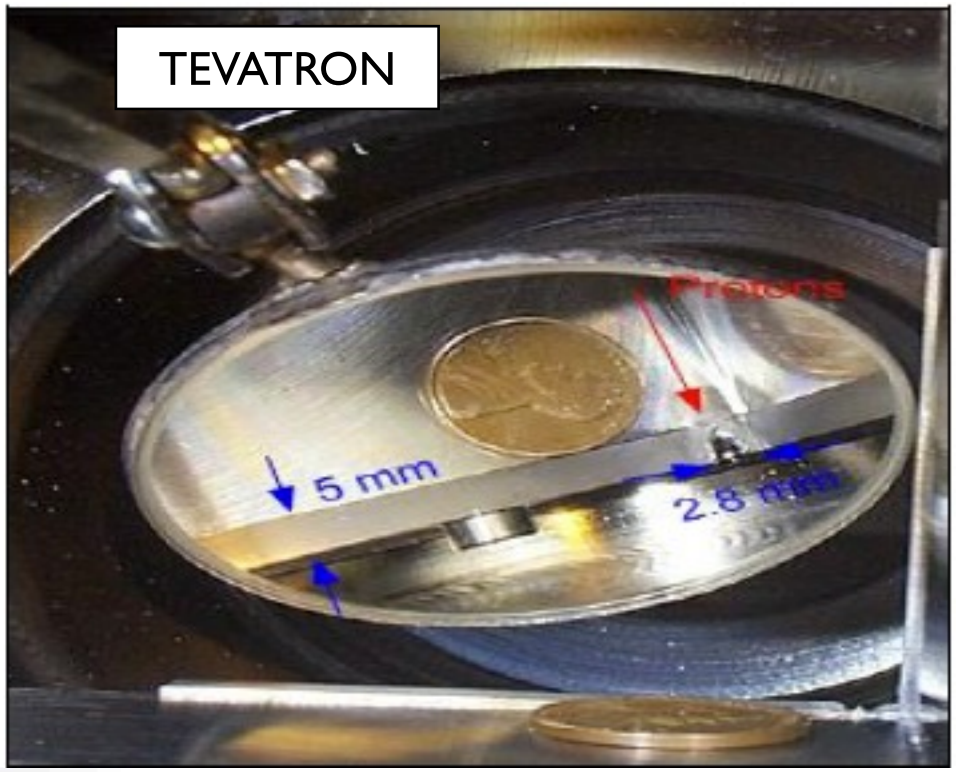


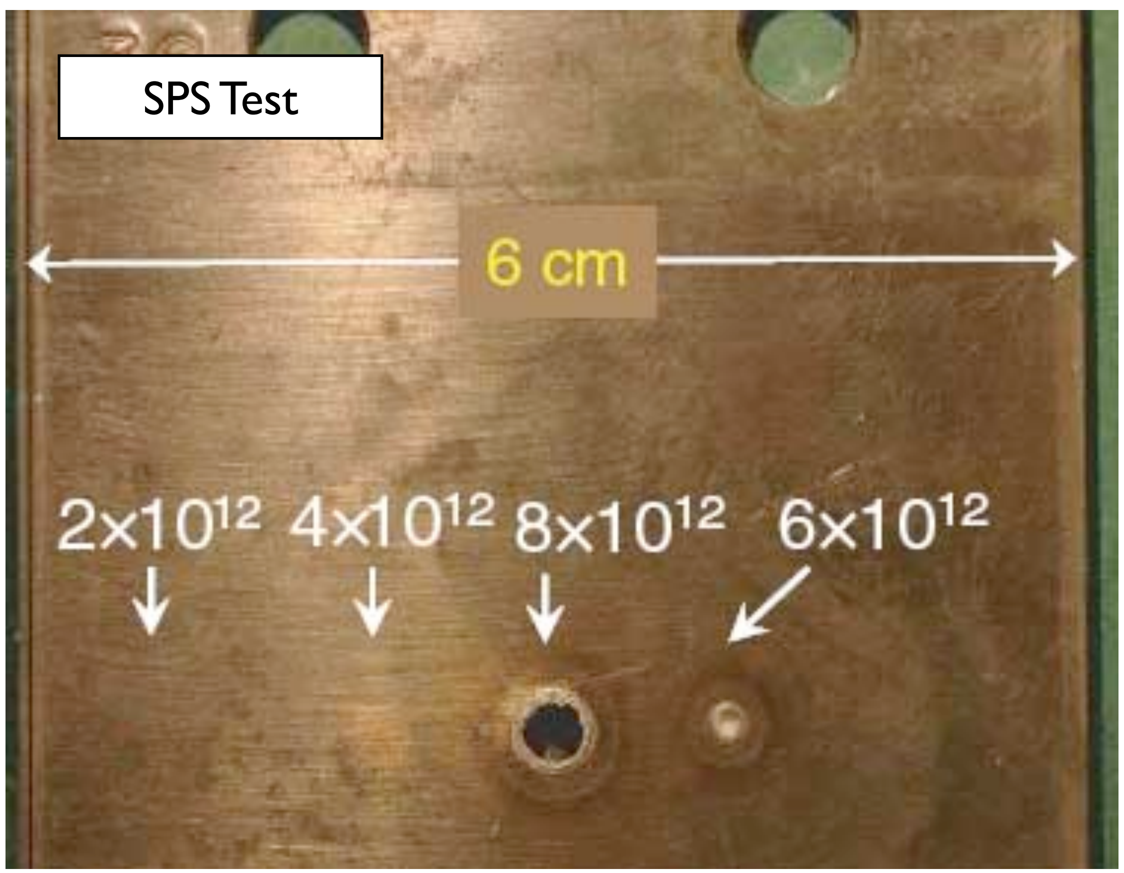
- **Beam Loss Monitors**
  - Ionizing radiation detectors located around an accelerator
    - **Detector technologies?**
    - **Read out electronics?**
    - **Detector location?**



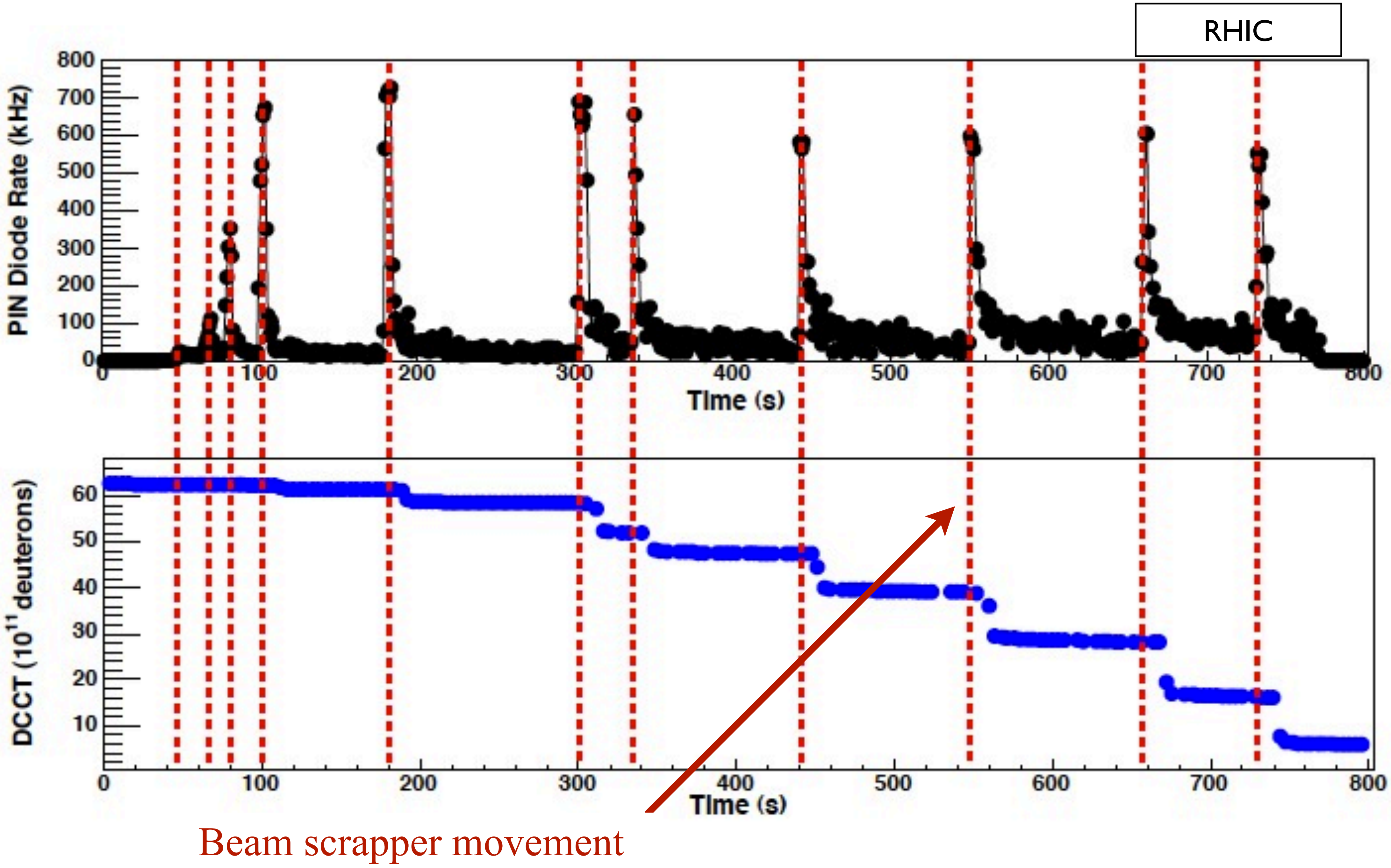
Avoid beam induce damage:

- High power beams may have catastrophic consequences
- Reduce down time of the machine due to replacement/repairs



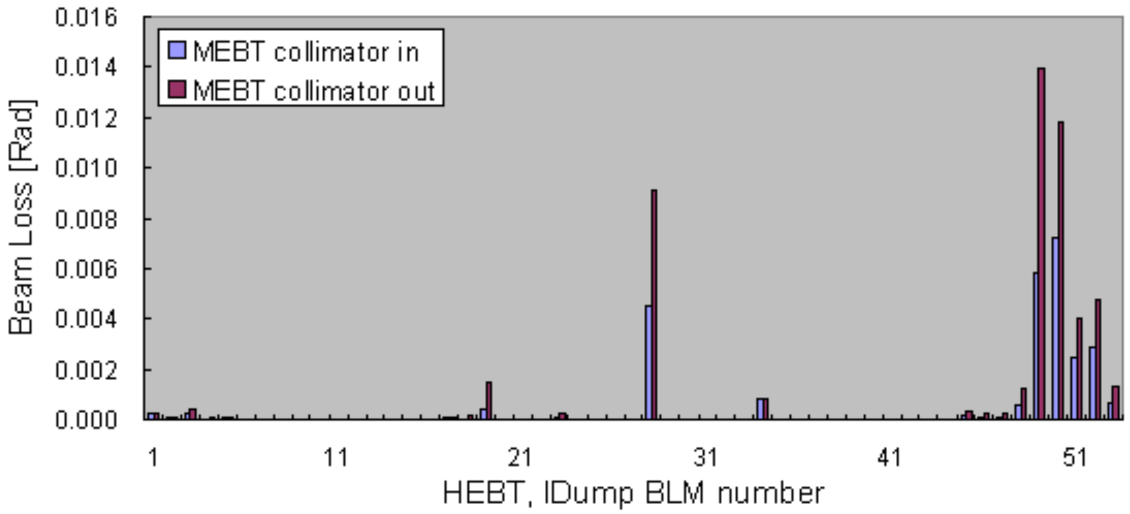


Optimization of operation

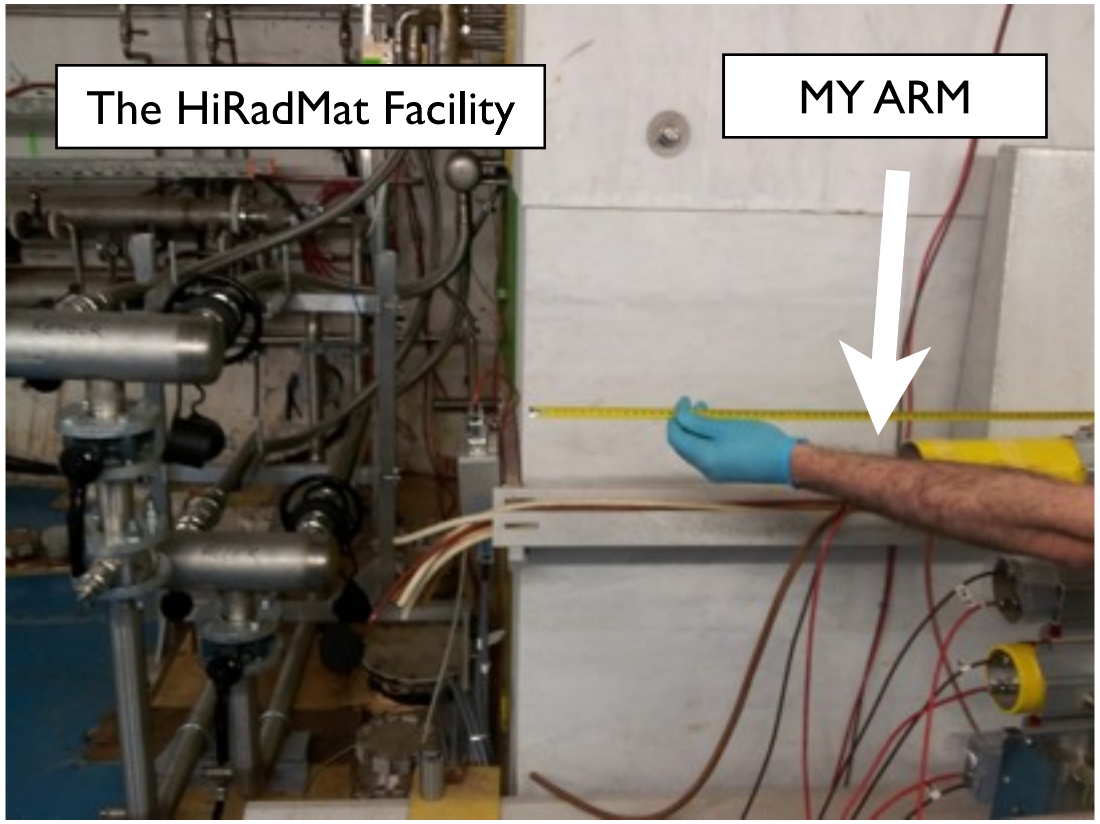


Keep activation levels low:

- Reduce production of radiation waste
- Protect personnel against radiation hazard



Plot of measured beam loss along the HEBT and IDump (Injection Dump) with the MEBT collimator in and out. Data shows significant reduction in beam loss in the HEBT and IDump with the MEBT collimation.



Beam Loss categorization: Examples

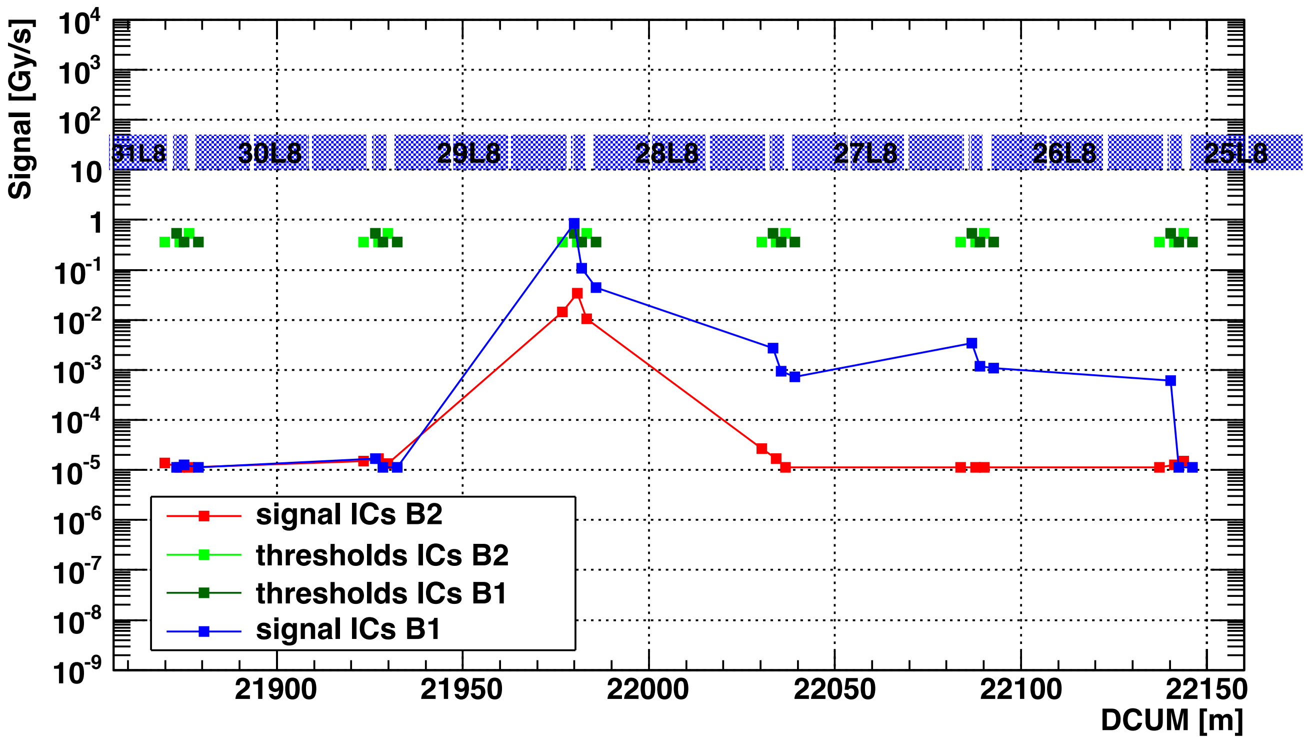
Type of Beam Losses I

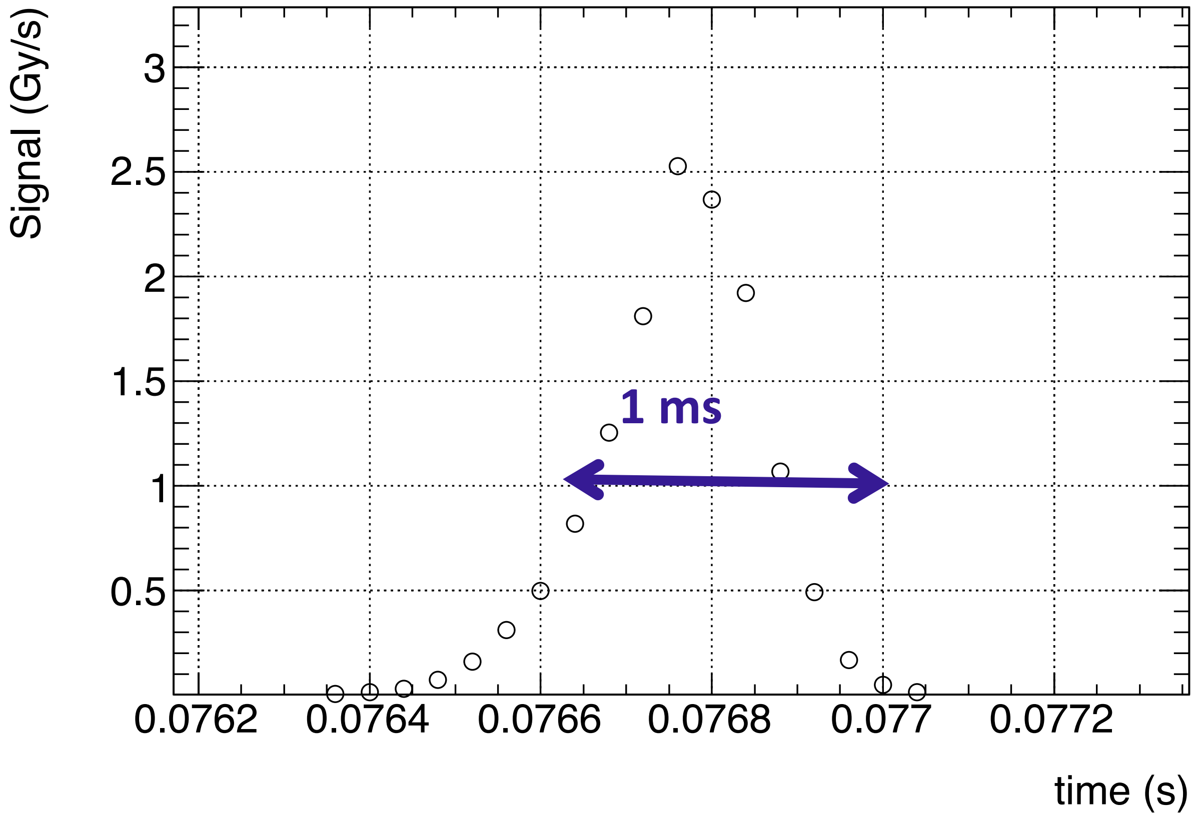
Irregular beam losses:

- They are avoidable but sometimes tolerated
- Uncontrolled: Occur due to malfunctioning of one (or several) accelerator components
  - **RF trips (in electron machines)**
  - **Obstacles in the beam**
  - **Dust**
  - **Vacuum leaks**

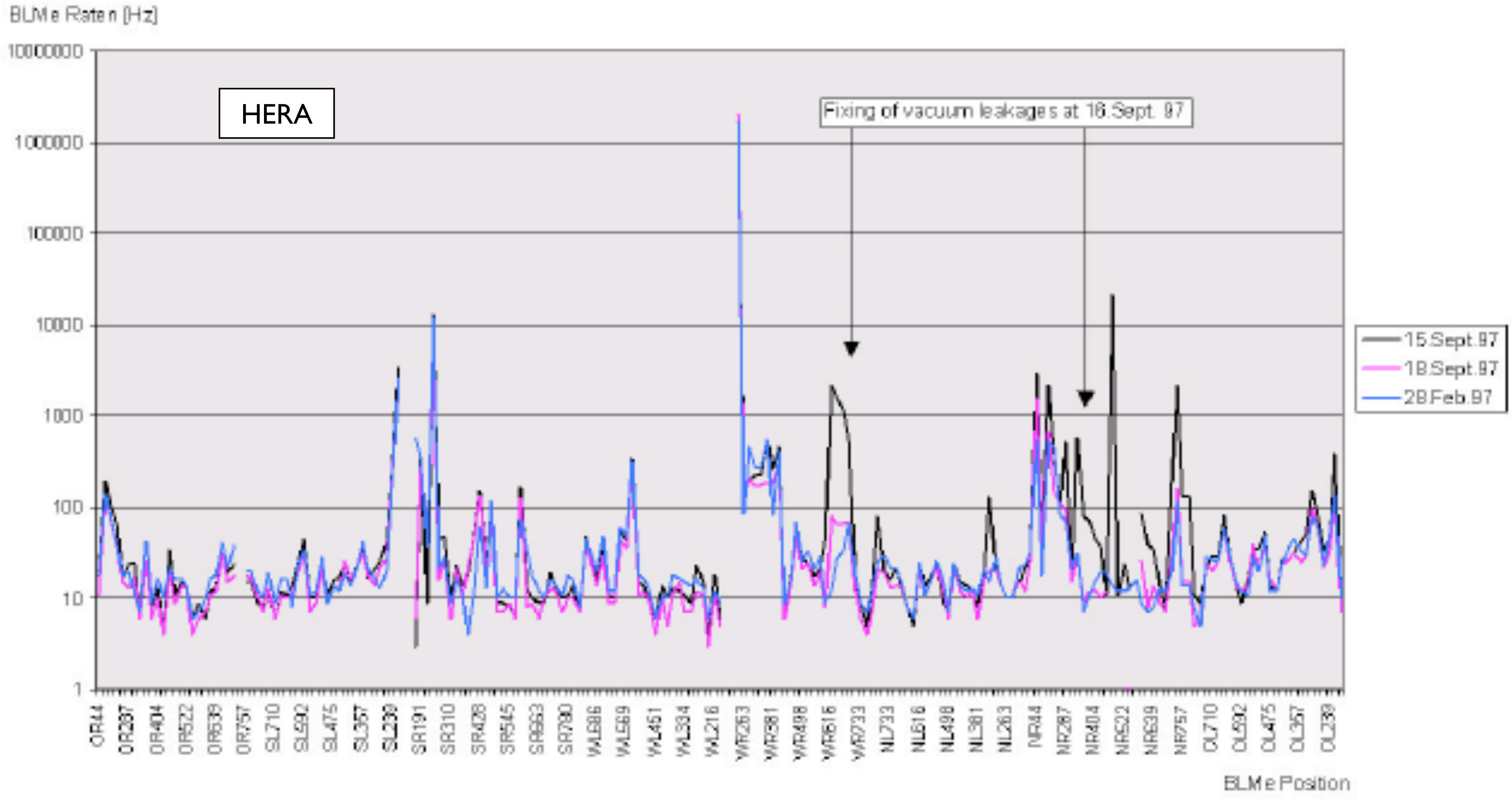
Unidentified Flying Objects

- **Fast and localized loses around the LHC ring of duration ~1 ms**
  - Believed to be caused by the interaction of protons with 1-100 µm metallic dust
  - Events only observed with the BLM system (magnet quench potential)





Vacuum



BLMe Raten [Hz]
HERA
Fixing of vacuum leakages at 16.Sept. 97
15.Sept.97
18.Sept.97
28.Feb.97
BLMe Position

Obstacles into the beam

- **The Large Electron-Positron Collider LEP**
  - 27 km housed in the current LHC tunnel between 1989 and 2000
  - On June 1996, during a commissioning phase, a strange object was found in the vacuum chamber

Obstacles into the beam

- **The Large Electron-Positron Collider LEP**
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  - On Jun … commis … strange object w … vacuum chambe

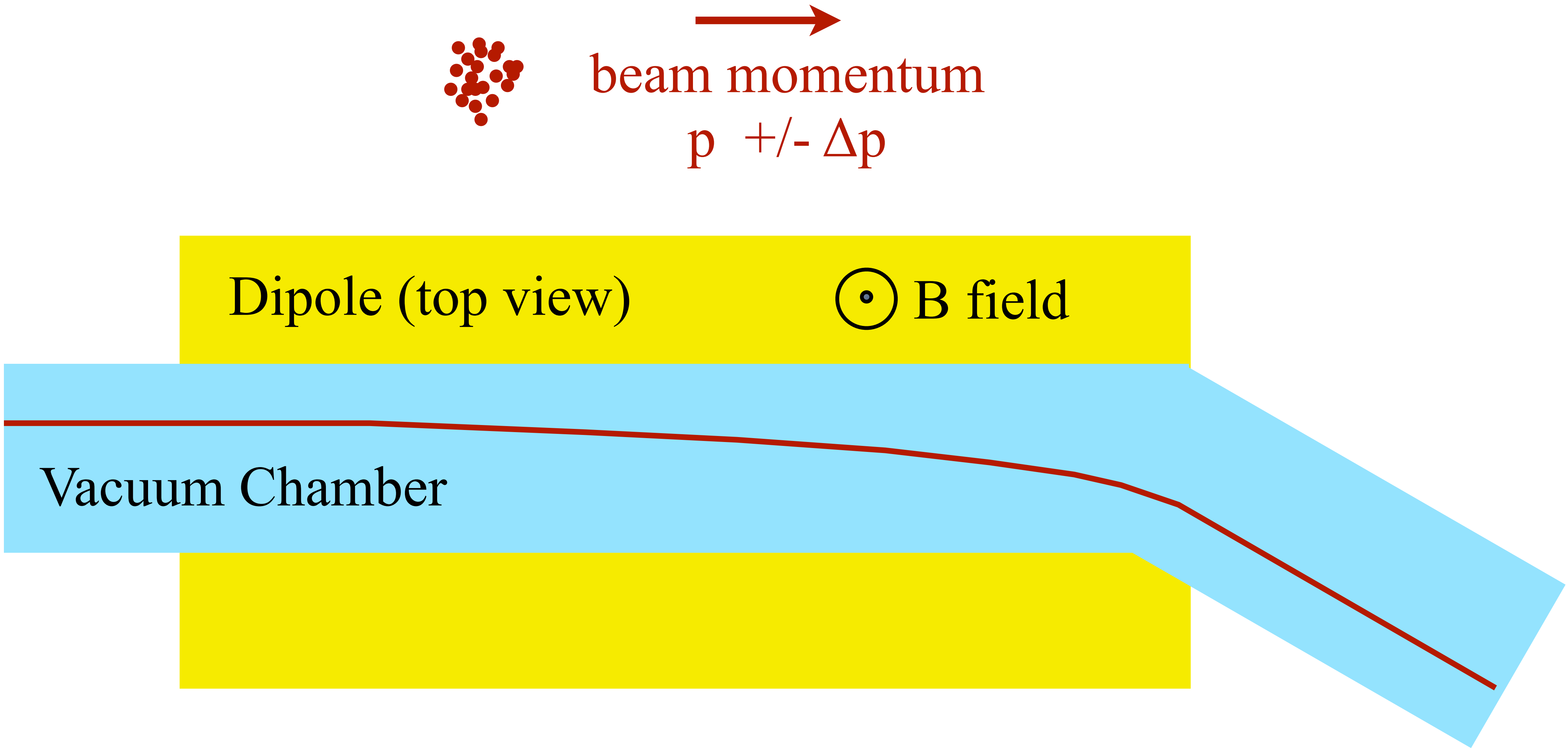
Type of Beam Losses II

Regular beam losses:

- They are unavoidable but controlled
- Typically localized at collimation systems or aperture limits
- Lowest possible loss rate defined by beam lifetime limitations
    - **Touscheck effect**
    - **Residual gas scattering**
    - **Collisions**
    - **Beam-beam interactions**

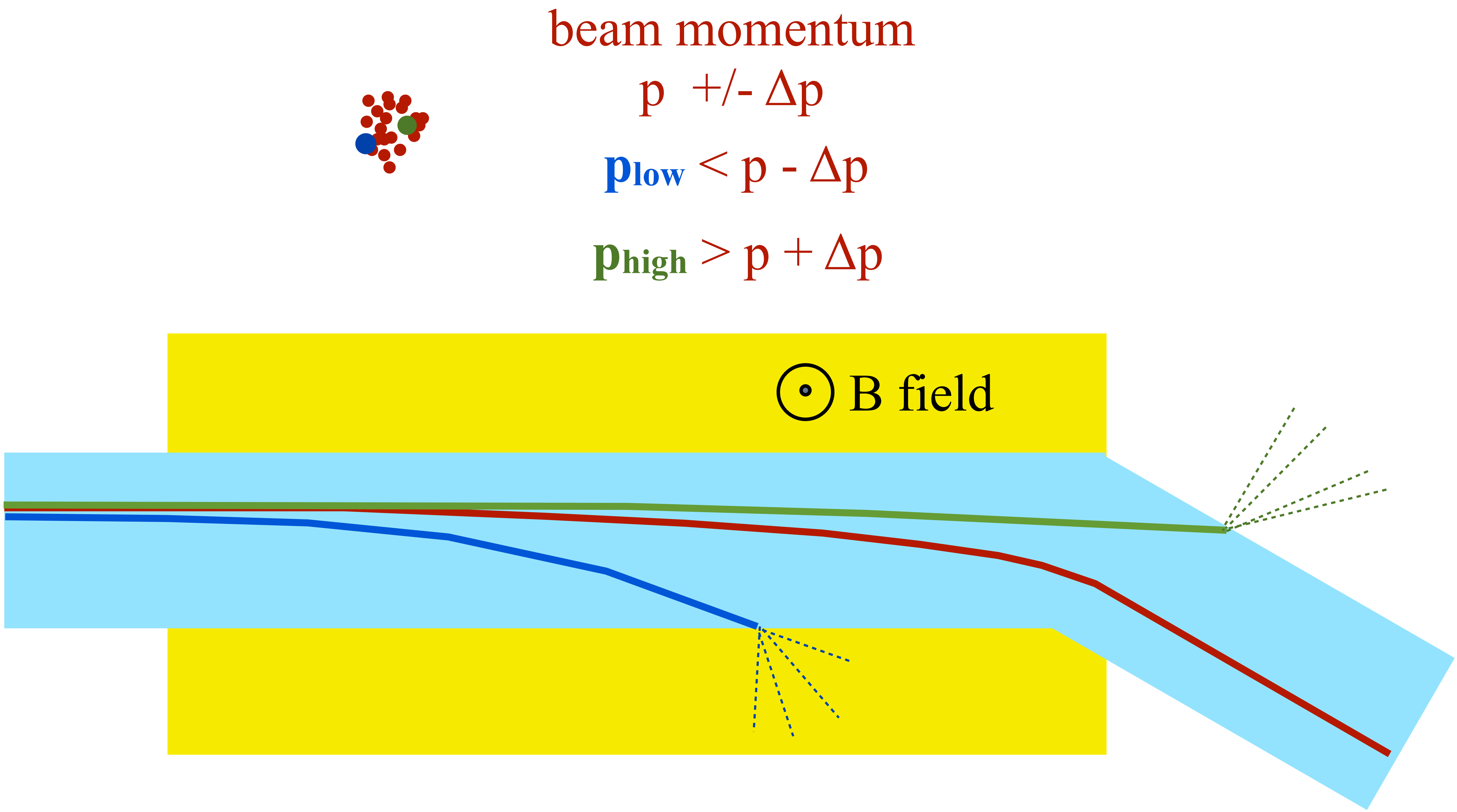
Beam through dipoles

- **Dipoles bend the trajectory of the beam particles**
  - Only particles with the “design” momentum will propagate with
  - Certain margin is given by me momentum acceptance Δp



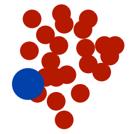
Touscheck Effect

- **Large angle intra beam coulomb scattering**
  - Momentum transfer from transverse to longitudinal direction phase space



Coulomb scattering

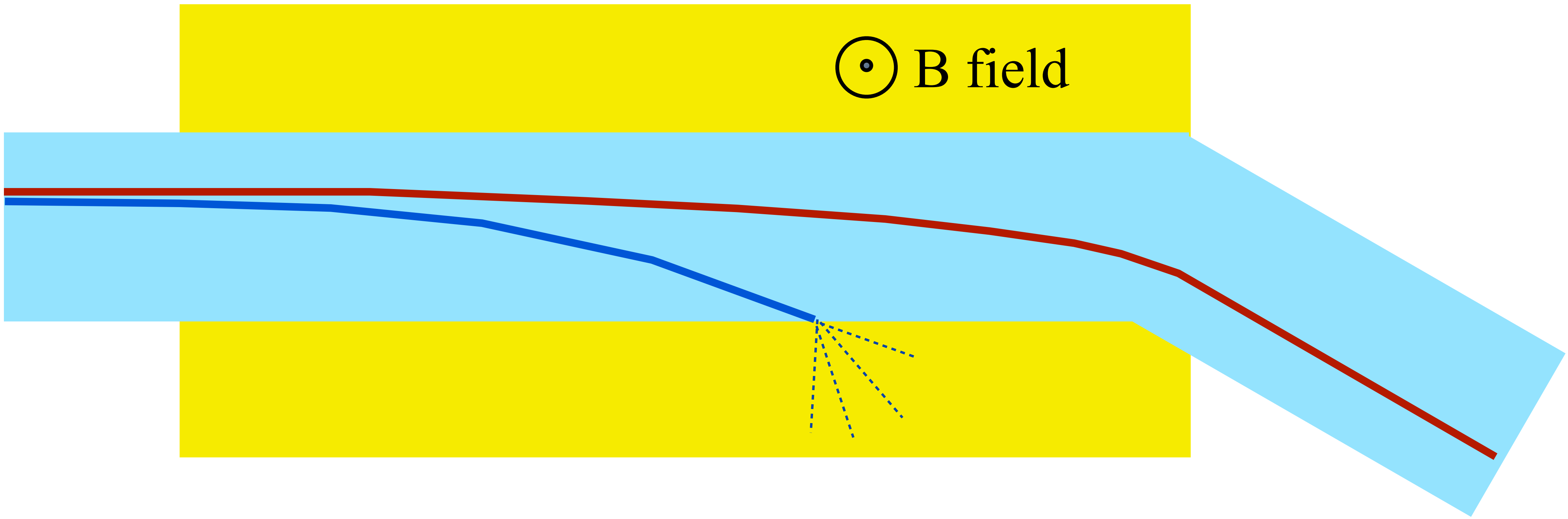
- Elastic: No momentum change but direction
- Inelastic: Momentum loss



beam momentum

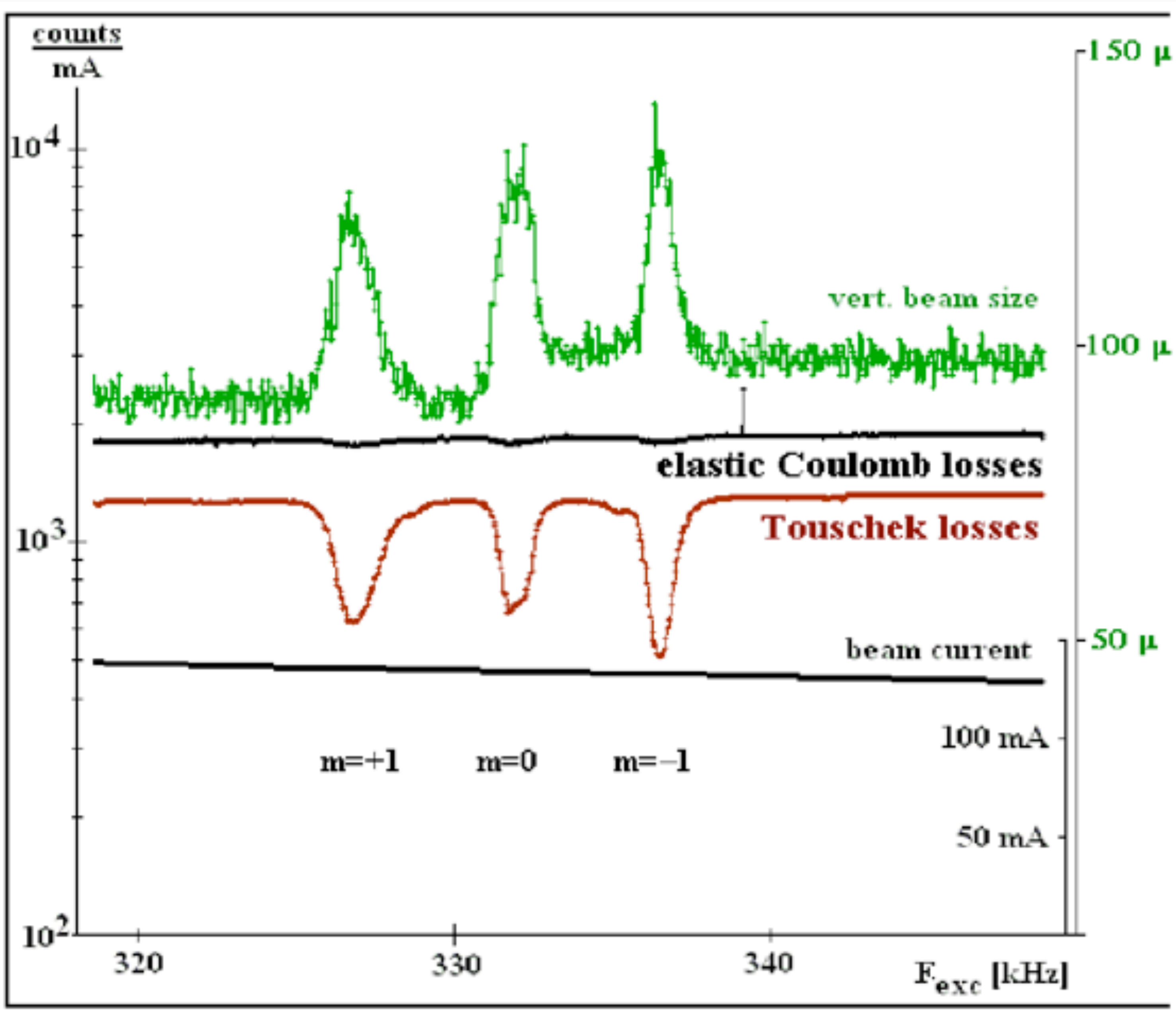
p +/- Δp

p_{low} < p - Δp



Touscheck and coulomb scattering

- **Adequate location of BLMs may be very useful to identify loss mechanisms**



Interactions of particles with matter
Examples

Interaction of particles with matter

- **Beam Loss Monitoring requires a good overview of particle physics**
  - What do we expect at the detector locations?
  - What are the physical process that produce a measurable signals
- **Interactions**
  - Charged particles
    - Ionization
    - Bremsstrahlung
    - Cherenkov
  - Photons
    - Photoelectric effect
    - Comptom effect
    - pair production
- **Mechanism for generation of secondary particles**
  - Electromagnetic and hadronic showers

Charged particles - Ionization

- **The energy loss per unit length is given by the Bethe-Bloch formula**

STOPPING POWER

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2\right]$$

$2\pi N_a r_e^2 m_e c^2 = 0.1535\ \mathrm{MeV cm^2 g^{-1}}$

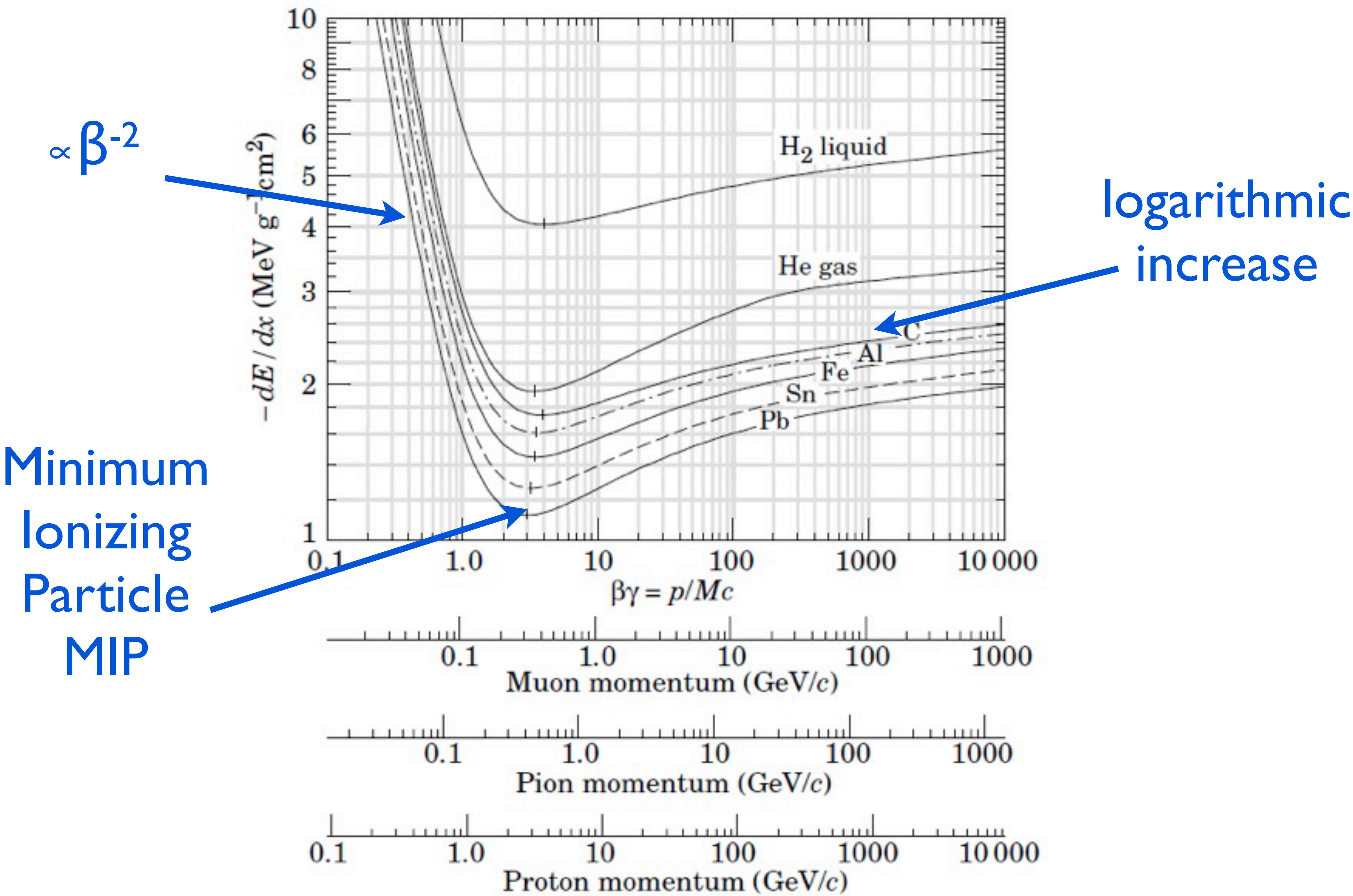
Fundamental constants

r_e=classical radius of electron
m_e=mass of electron
N_a=Avogadro's number
c=speed of light

Absorber medium
I=mean ionization potential
Z= atomic number of absorber
A=atomic weight of absorber
ρ=density of absorber

Incident particle
z=charge of incident particle
β=v/c of incident particle
$\gamma=(1-\beta^2)^{-1/2}$
W_{max}=max. energy transfer

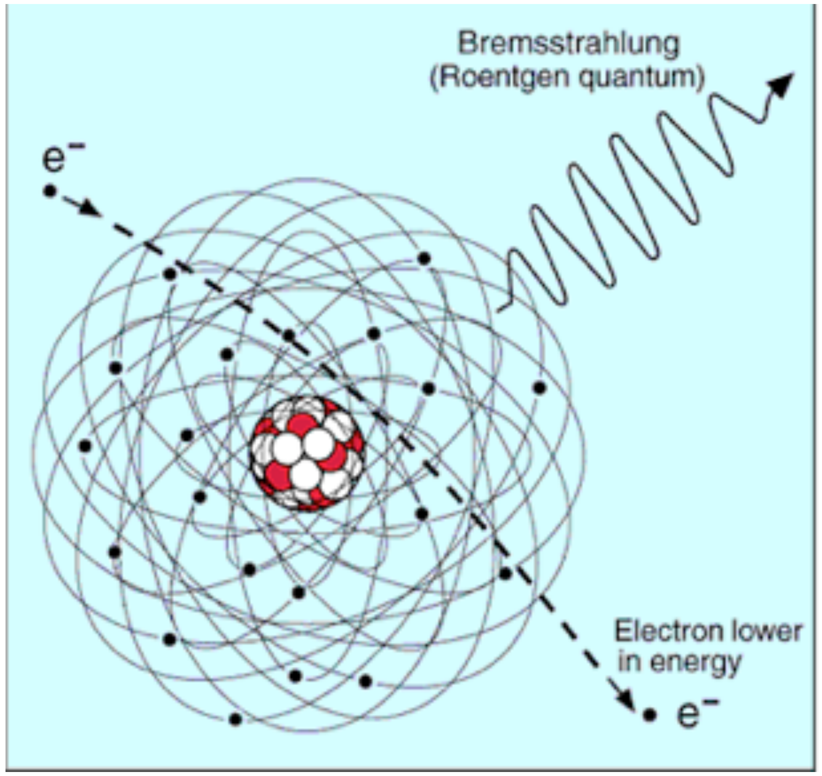
Charged particles - Ionization

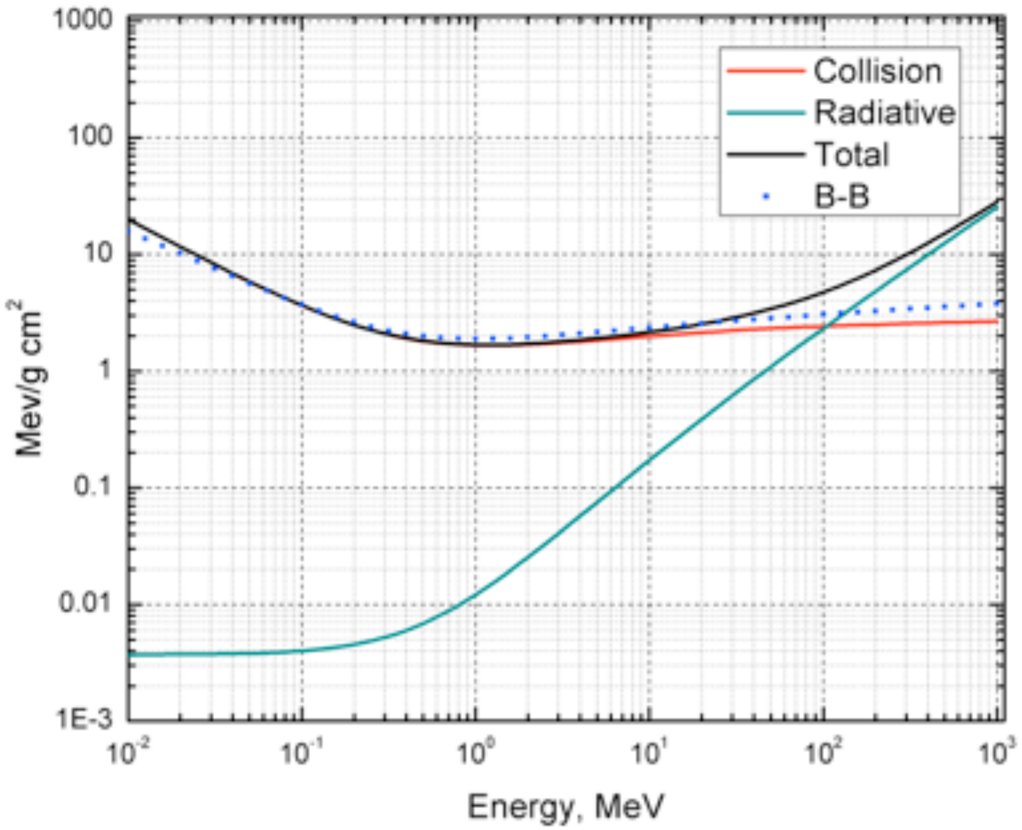


Charged particles - Bremsstrahlung

- **Emission of radiation when charged particles are decelerated in a coulomb field**
  - Depends on properties of the target material and incident particle

$$d\sigma/dE \propto (Z/M)^2 \ln E/E$$



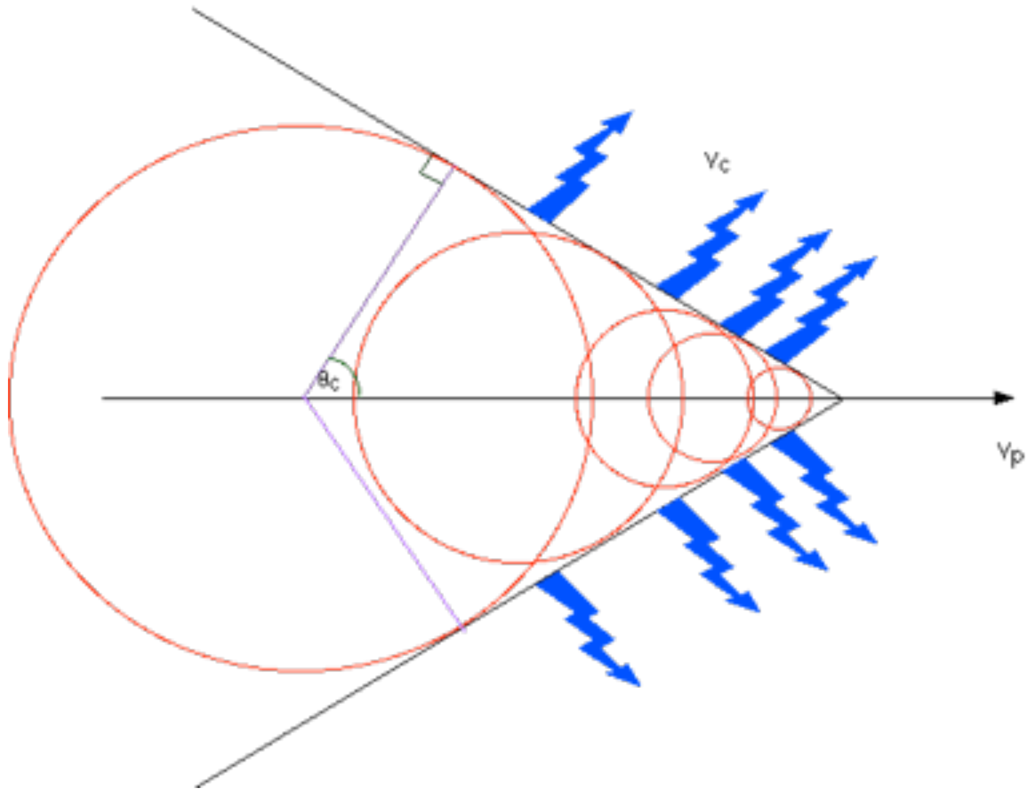


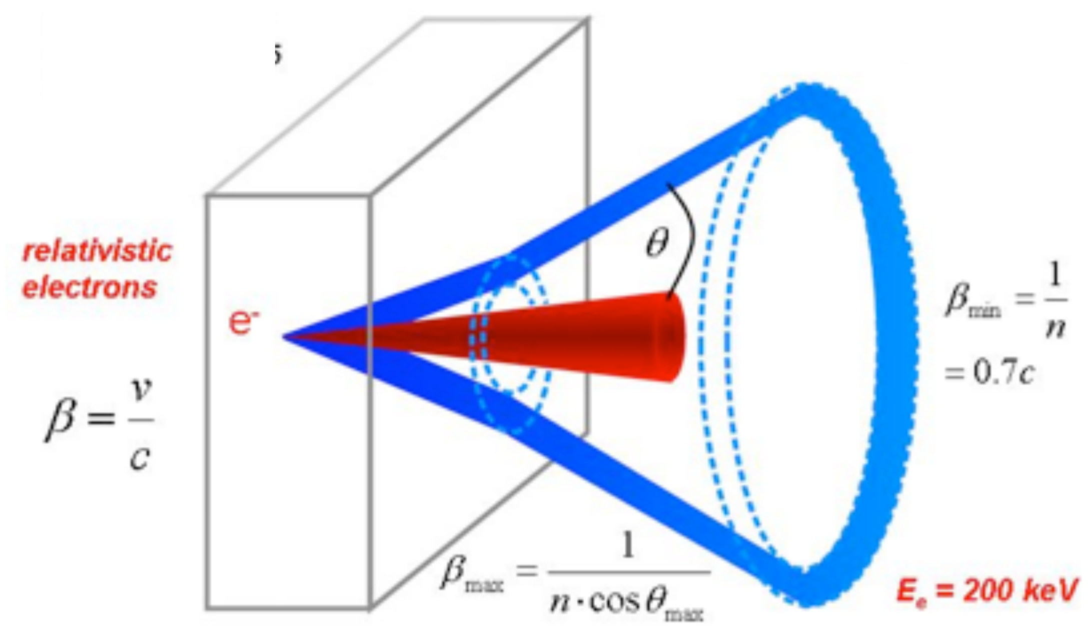
- **Dominant process at high energies**
  - $E > E_C$

$$E_C = 800\ \text{MeV}/(Z + 1.2)$$

Charged particles - Cherenkov effect

- **Light generated by particles traveling at v > v_{light}**

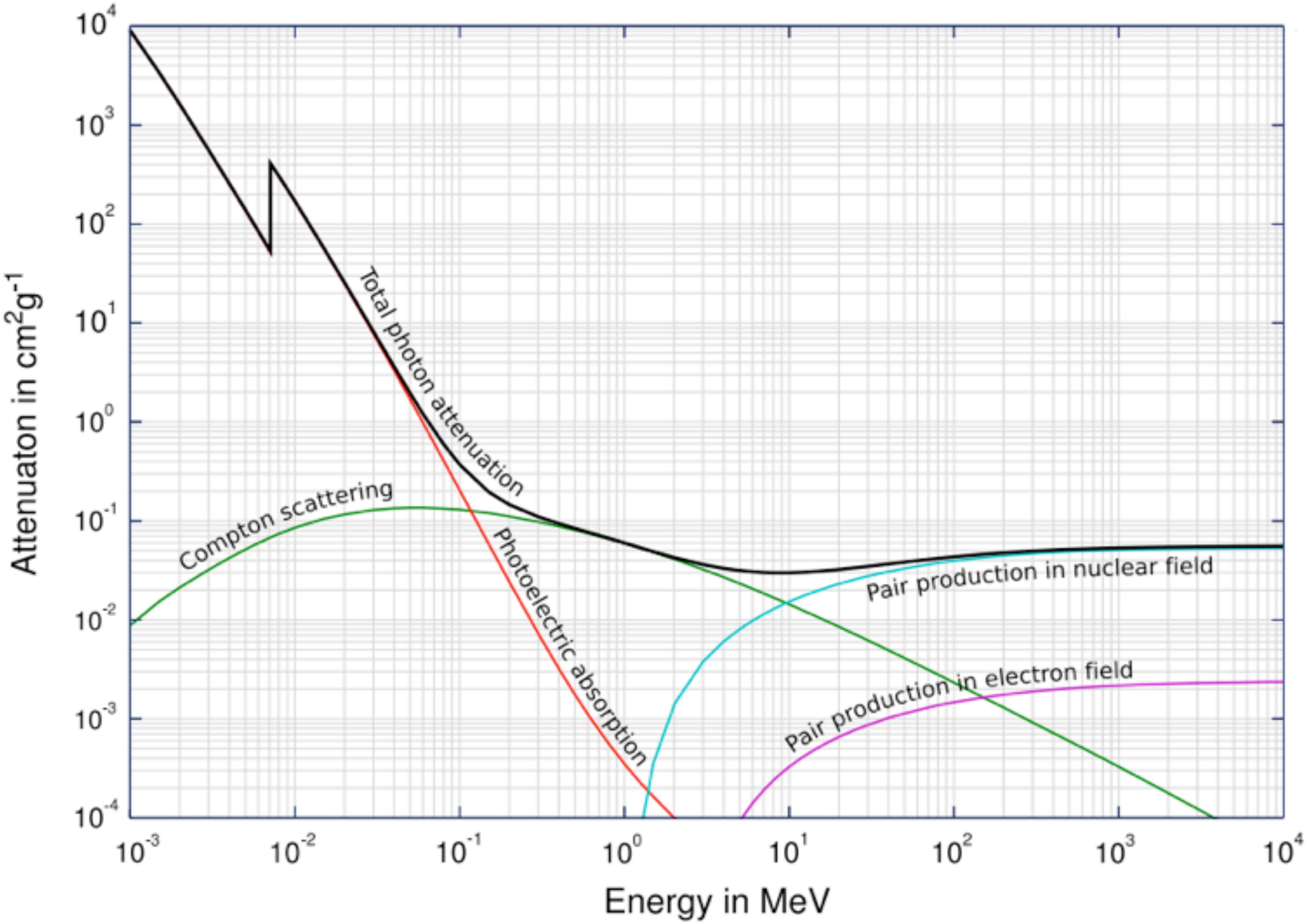




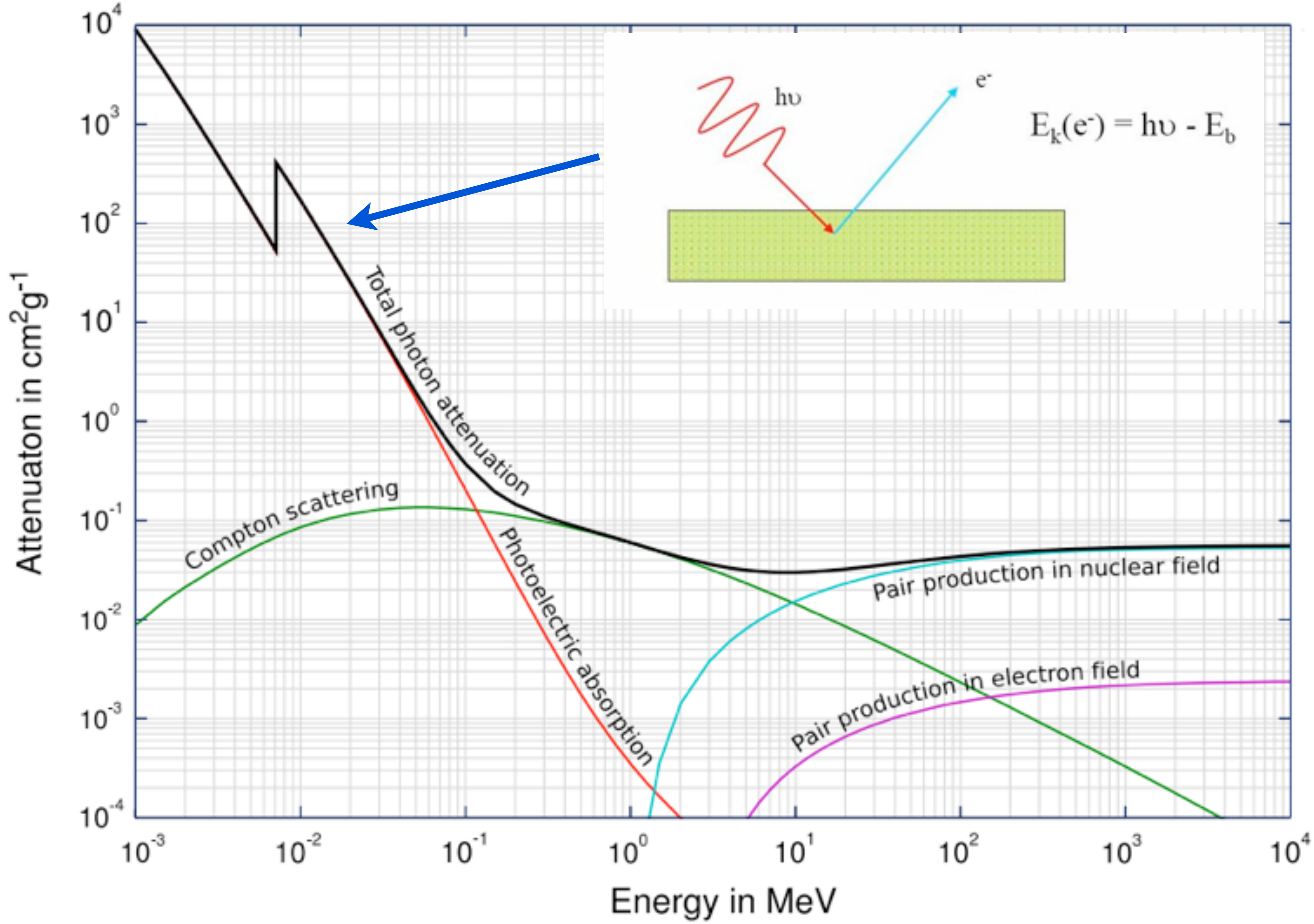
$$\frac{dN_{PH}}{dL} \propto 2\pi\alpha z^2 \sin^2\theta_C \int_{\beta n>1} \frac{d\lambda}{\lambda^2} \rightarrow \frac{d^2N_{PH}}{dLd\lambda} \propto \frac{1}{\lambda^2}$$

In Quartz
~1000 photons/cm
(200 - 900 nm)

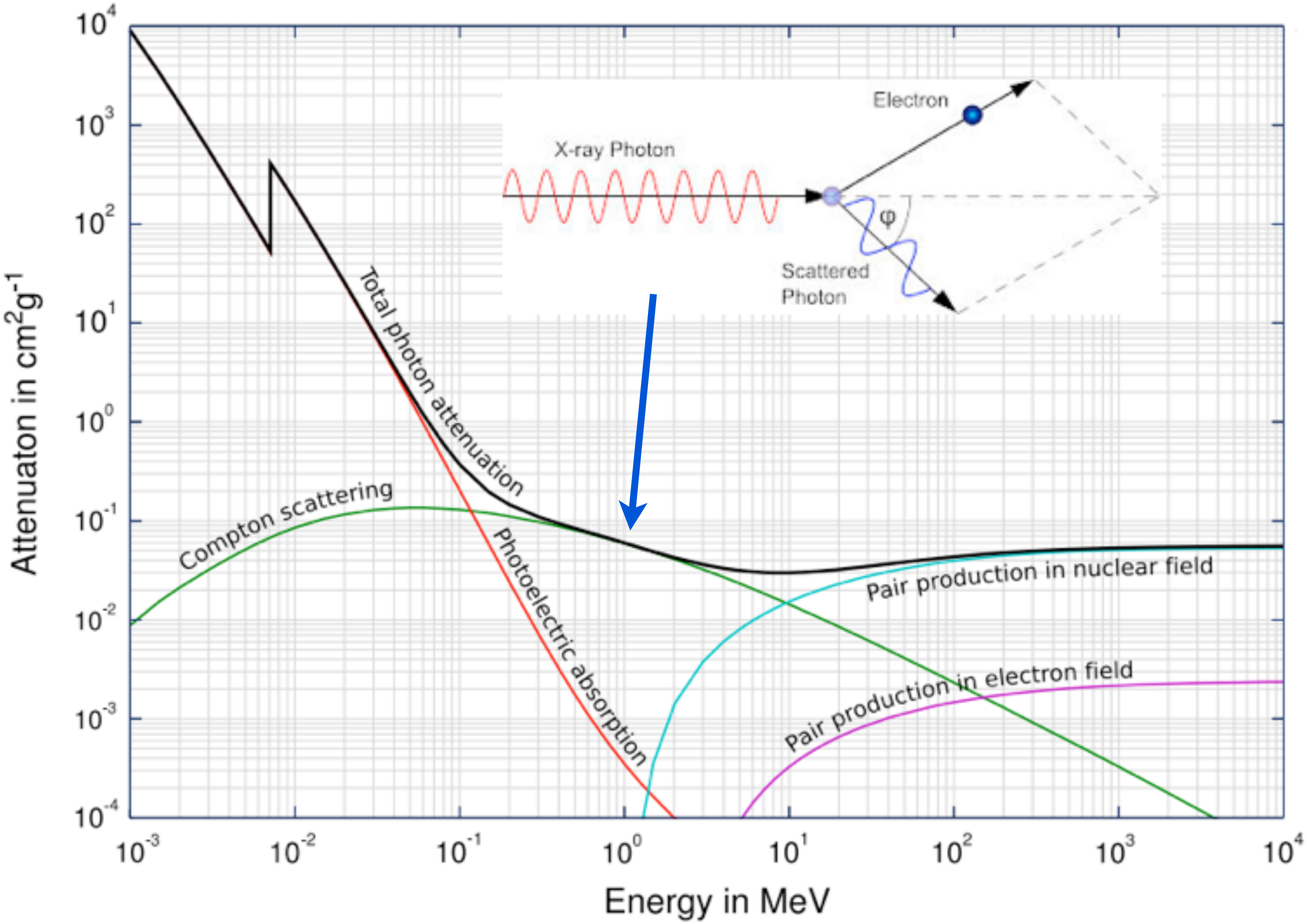
- **Photons interact with matter via three processes**



Photoelectric effect (Eɣ ≲ 100keV)

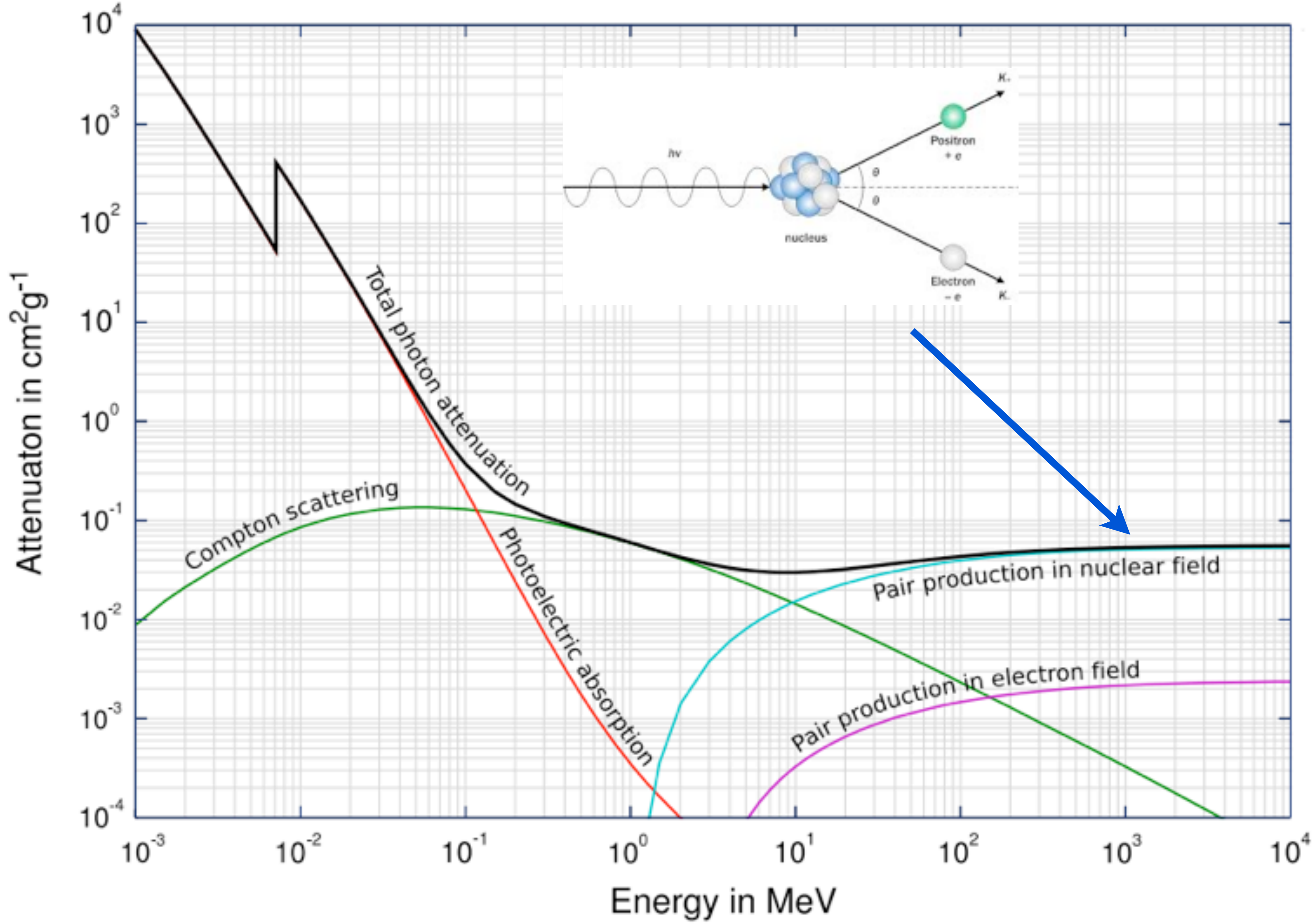


Comptom effect (100 keV ≲ E_γ ≲ 10 MeV)



Photons IV

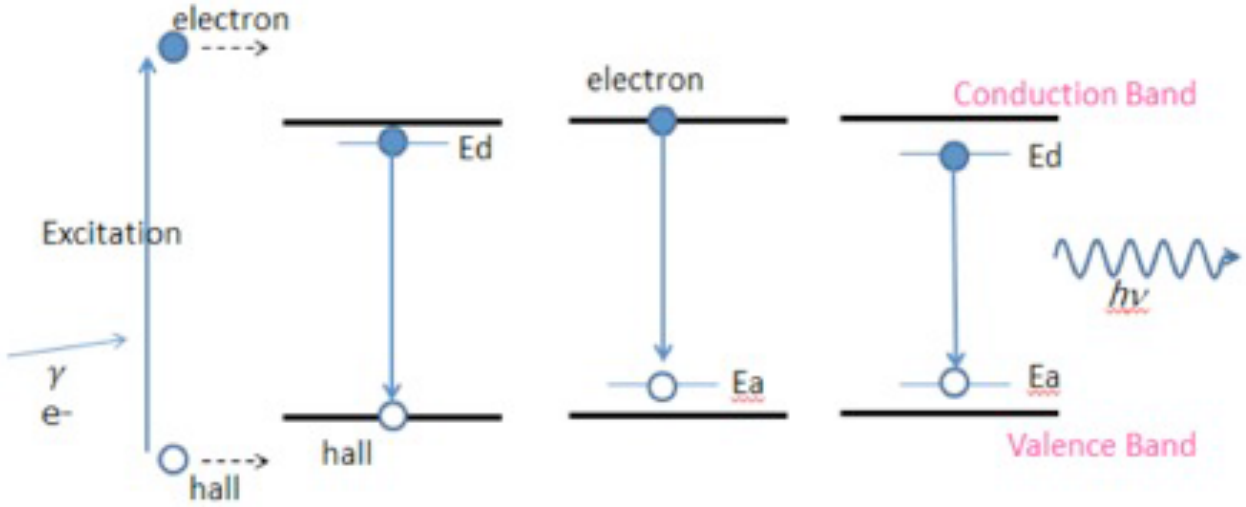
- **Pair production (Eɣ ≳ 10 MeV)**



- **Incoming radiation excites molecular levels that proceed to decay by emitting photons**
  - The photonic Yield is proportional to the ionization stopping power

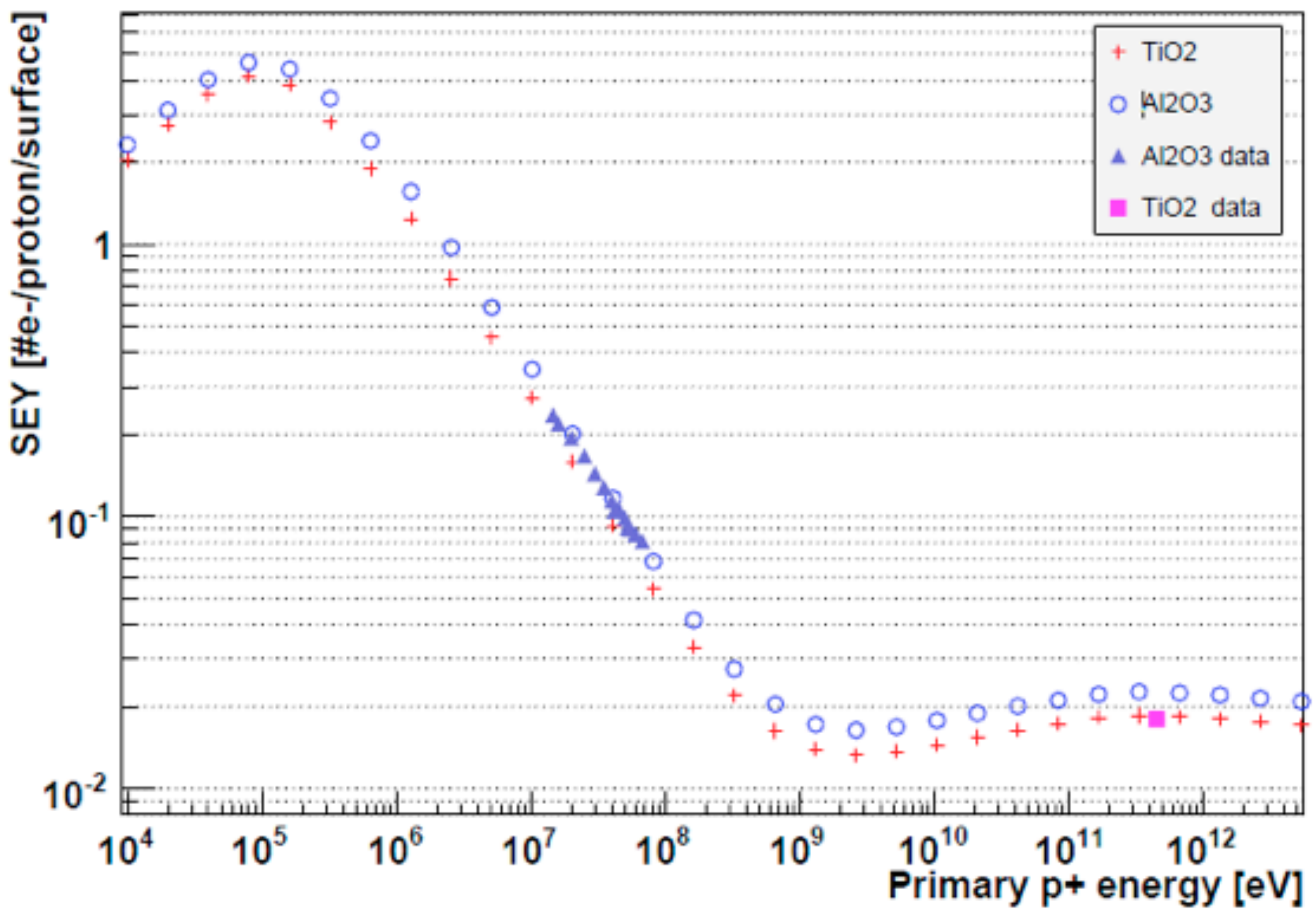
$$Y = dL/dx = R_S \, dE/dx$$

Rs: ratio of number of emitted photons to energy deposited by ionization



Secondary emission

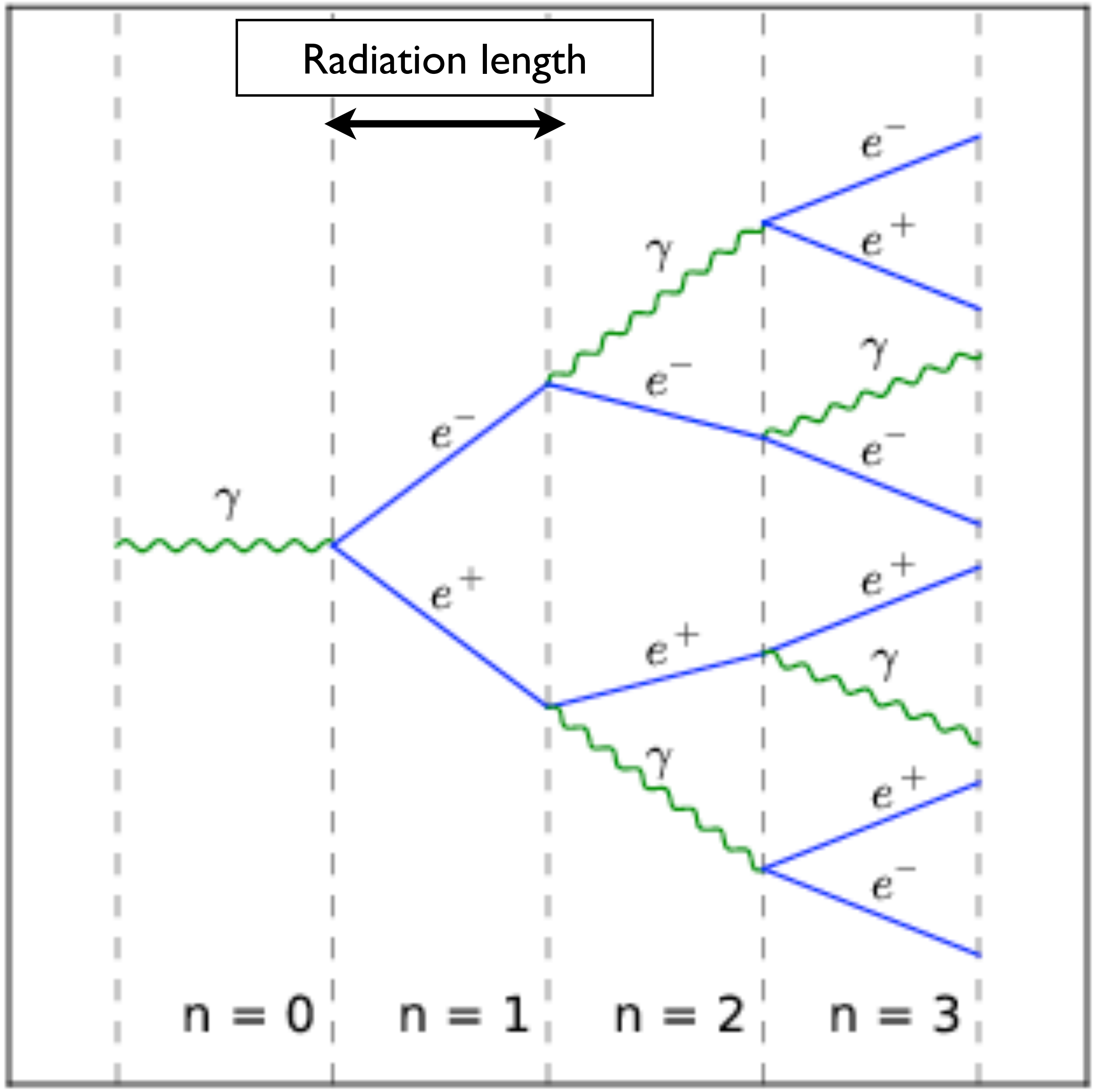
- **Emission of electrons from a metallic surface when crossed by high energy particles**



Electromagnetic showers

- **Mechanism for secondary generation at high energy:**
  - Electrons: Bremsstrahlung
  - Photons: Pair creation

- **Shower keeps developing until:**
  - $E_e < E_C$
  - $E_\gamma < 2\, m_e$



Hadronic showers

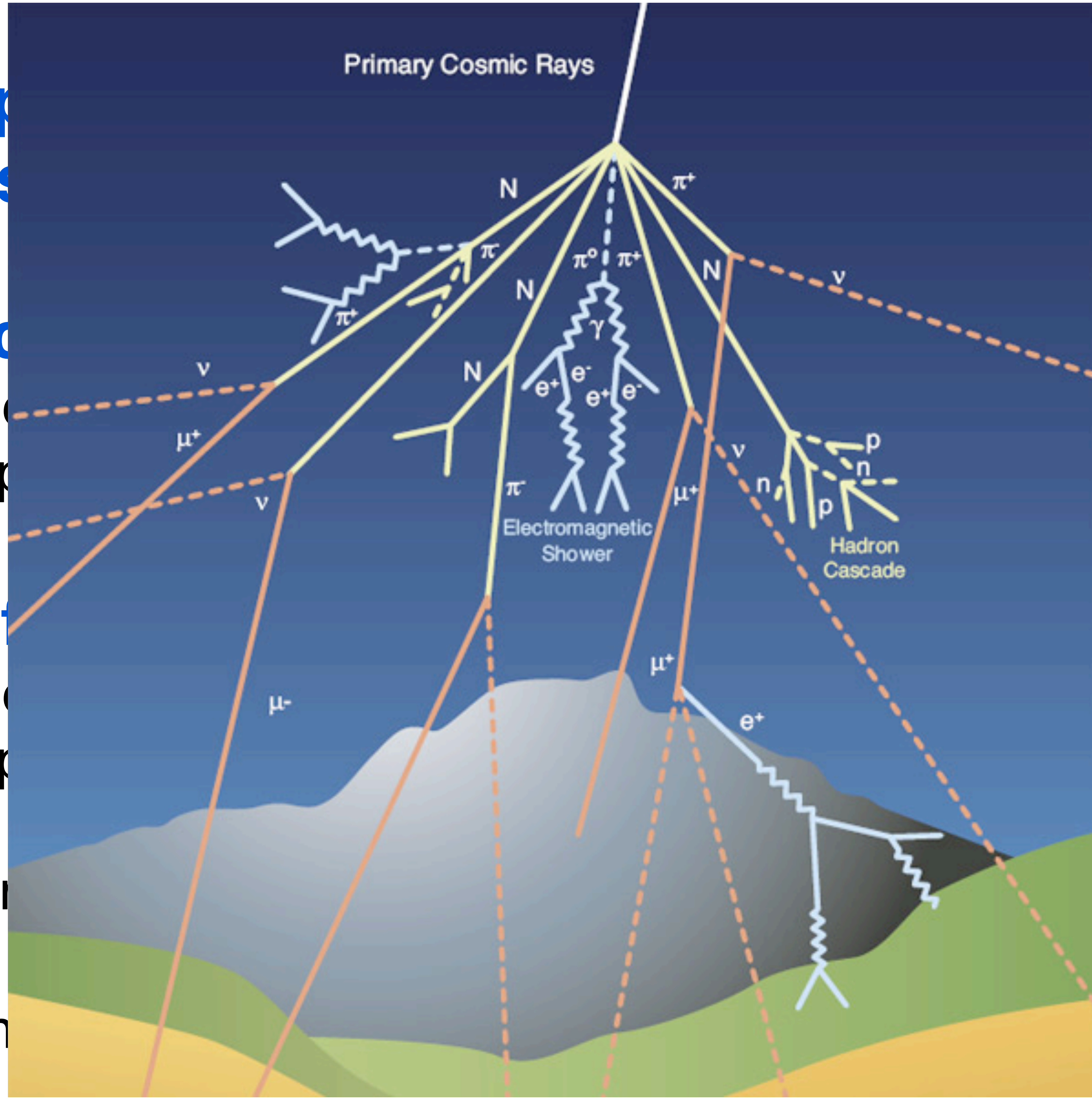
- **Affects particles that undergo strong interactions (hadrons)**

- **Similar concept to the electromagnetic case:**
  - After a certain mean free path, the primary interacts generating N new particles

- **Main differences the electromagnetic case:**
  - After a certain mean free path, the primary interacts generating N new particles
  - $N > 2$
  - Larger mean free path
  - Energy stops developing at $E \simeq 140$ MeV
  - Contains an EM component ($\pi^0 \rightarrow \gamma\gamma$)

Hadronic showers

- **Affects p… ctions (hadrons…**
- **Similar c… e:**
  - After a c… generating N new p…
- **Main diff…**
  - After a c… generating N new p…
  - N > 2
  - Larger r…
  - Energy…
  - Contain…



Radiation units

Radiation units

1 Ci = 3.7×10^{10} decays per second
Marie and Pierre Curie

1Bq= 1 decay per second
Henri Becquerel

Activity – how frequently radioactive materials disintegrates.

1 R = 2.58×10^{-4} C/kg (radiation ionizing 1 kg of dry air to this charge)
Wilhelm Röntgen
Exposure (how much of material was ionized)

Louis Harold Gray $1\ \mathrm{Gy} = 1\ \dfrac{\mathrm{J}}{\mathrm{kg}} = 1\ \mathrm{m}^2 \cdot \mathrm{s}^{-2}$

1 Rad = 0.01 Gy
Dose (how much energy was deposited)

1 Sv = 1 J/kg,
takes into consideration biological impact (quality factor)

Rolf Maximilian Sievert
Dose equivalent (how much harm the deposited energy caused to human)
1 Rem= 0.01 Sv

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