Charged particles

Methods and instrumentation for nuclear and particle physics

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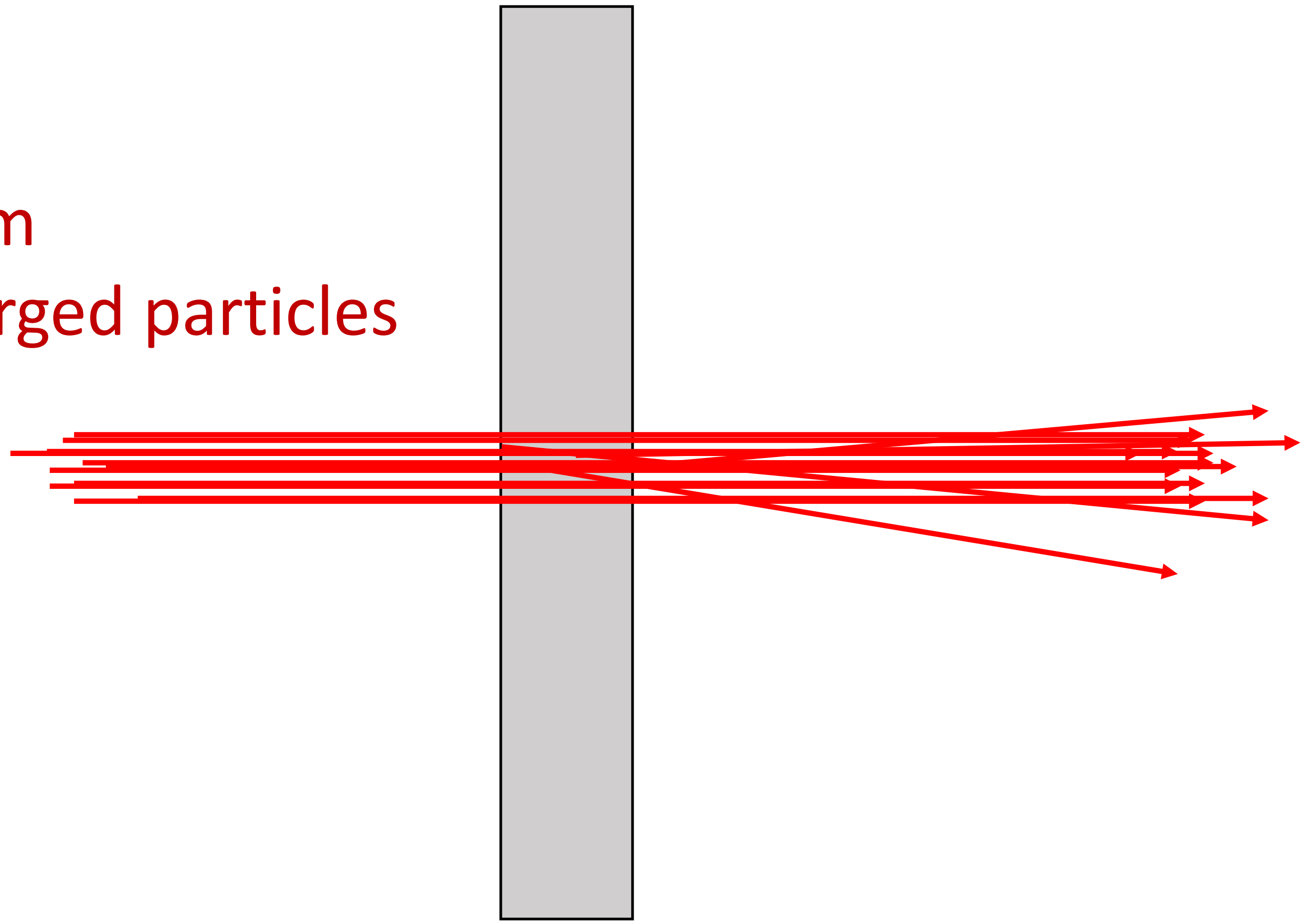
A thin detector that the beam passes through

A beam
of charged particles



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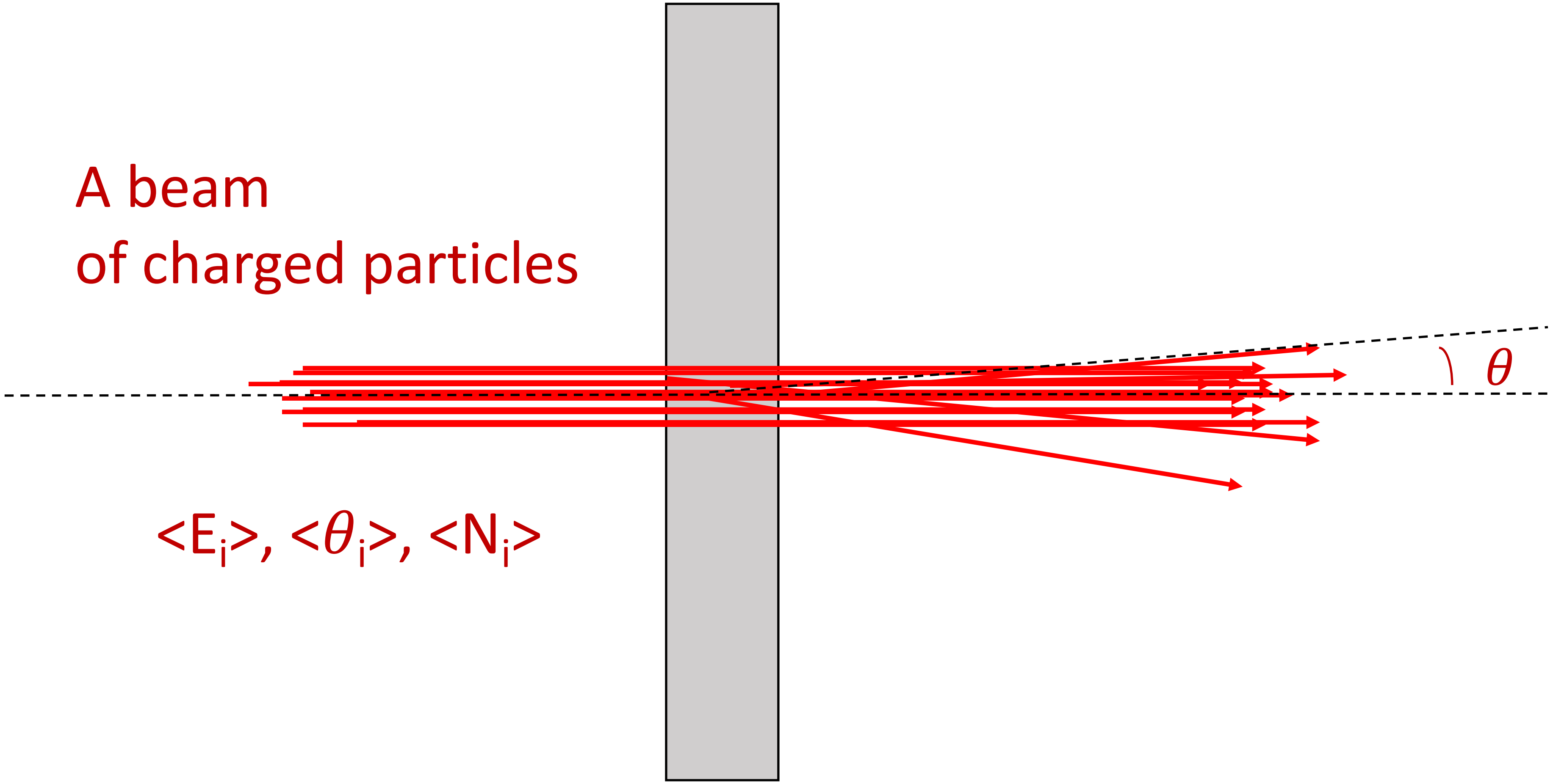

$\langle E_i \rangle$, $\langle \theta_i \rangle$, $\langle N_i \rangle$

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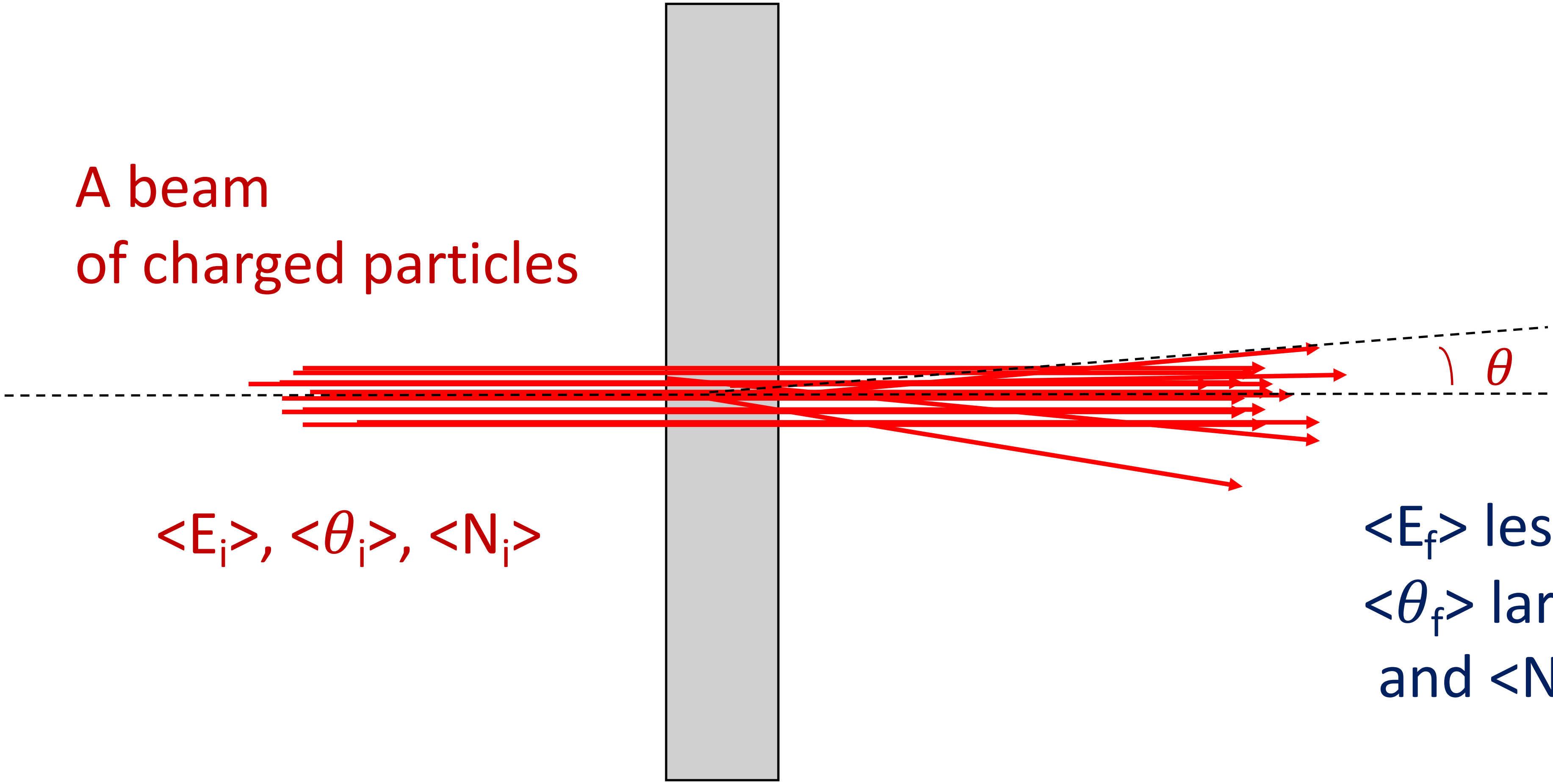

$\langle E_i \rangle$, $\langle \theta_i \rangle$, $\langle N_i \rangle$

$\langle E_f \rangle$ less than $\langle E_i \rangle$
$\langle \theta_f \rangle$ larger than $\langle \theta_i \rangle$,
and $\langle N_i \rangle \cong \langle N_f \rangle$

A thin detector that the beam passes through

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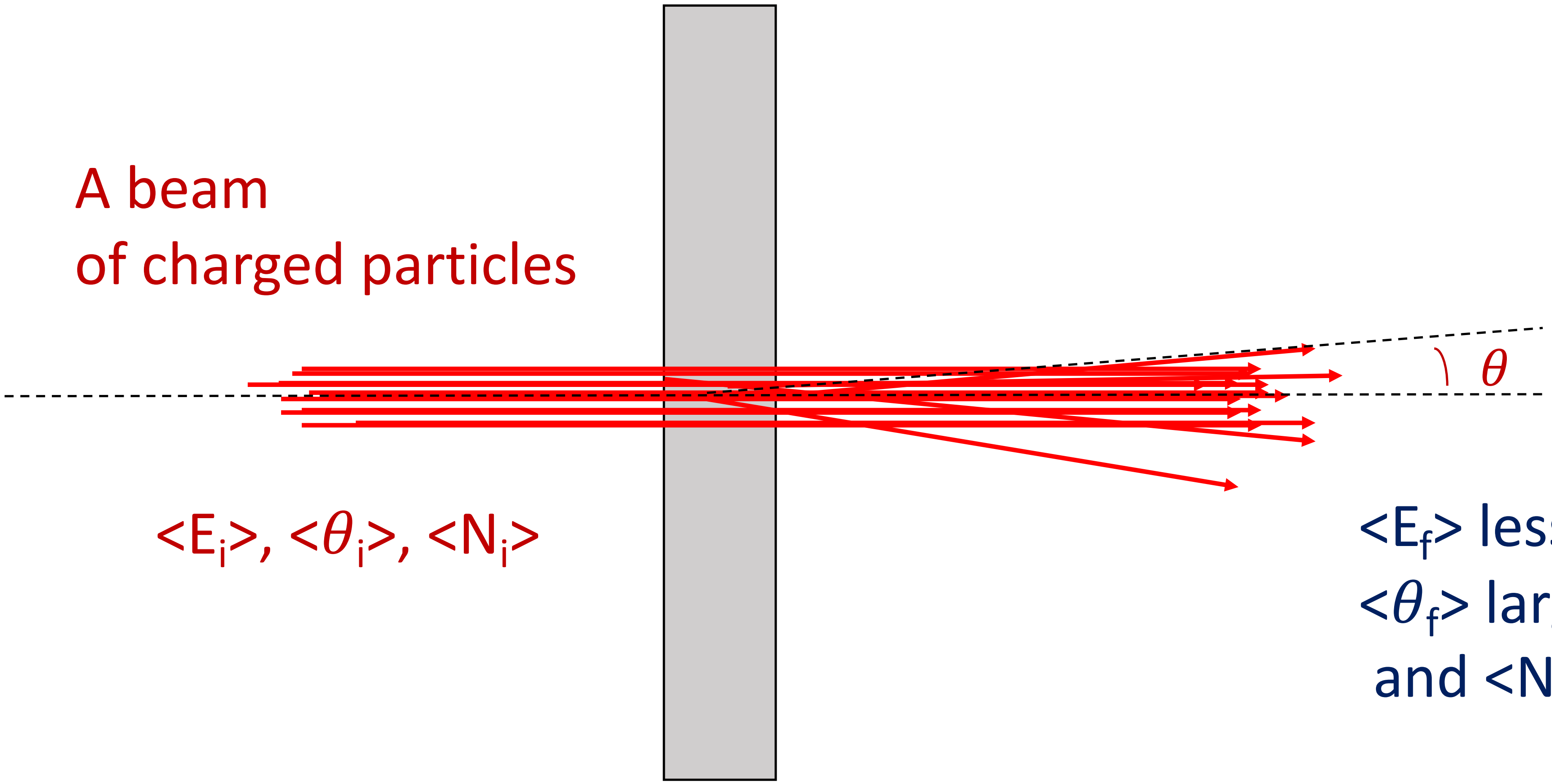

$<E_i>$, $<\theta_i>$, $<N_i>$

$<E_f>$ less than $<E_i>$,
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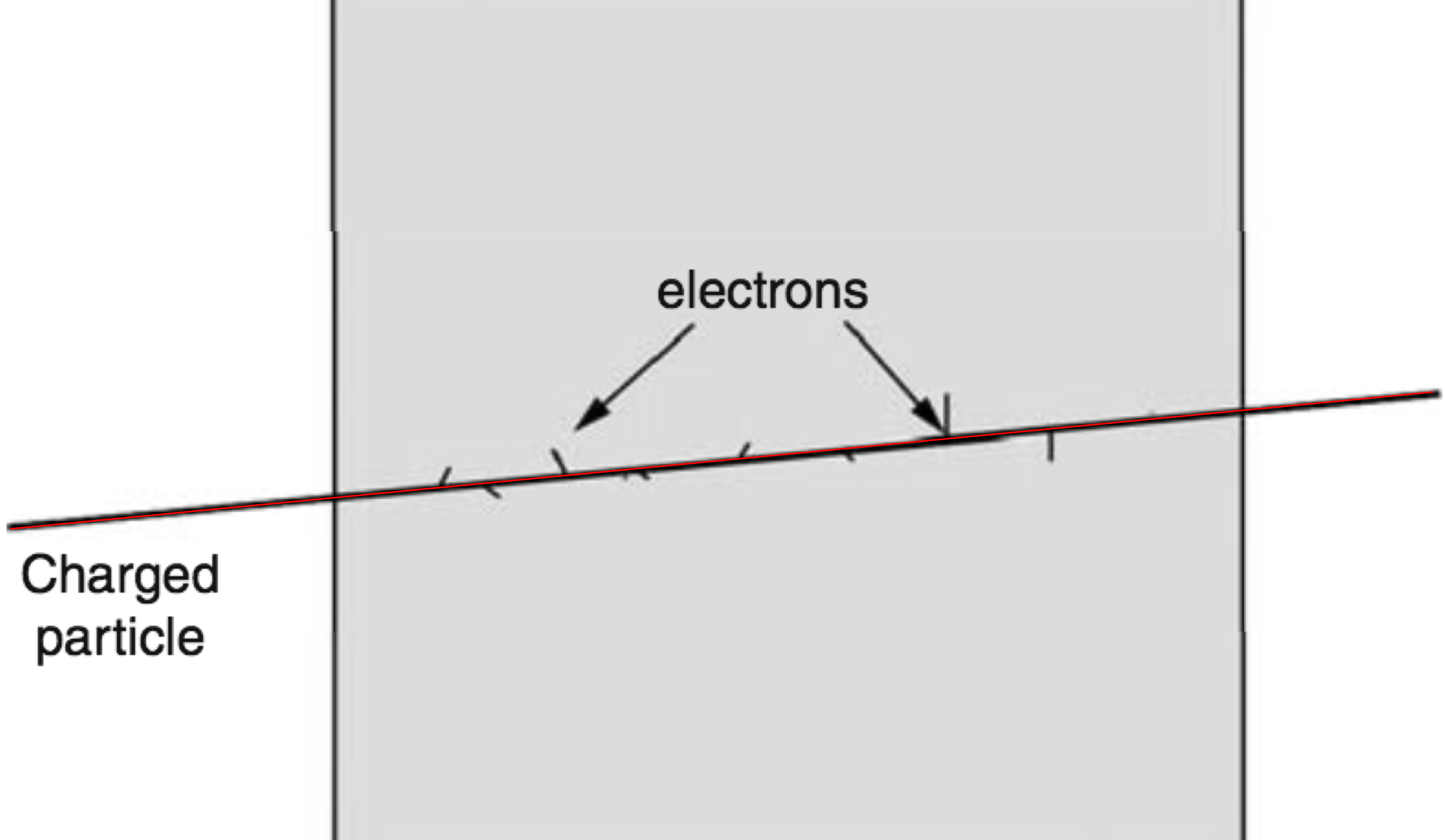

electrons
Charged
particle

Important things that happens to beam as it passes through matter

- Multiple scattering (the beam will occupy a larger volume)
- The energy will be spread out (energy straggling)
- The beam will lose energy (degradation)

We will begin with energy loss due to interactions with atomic electrons.

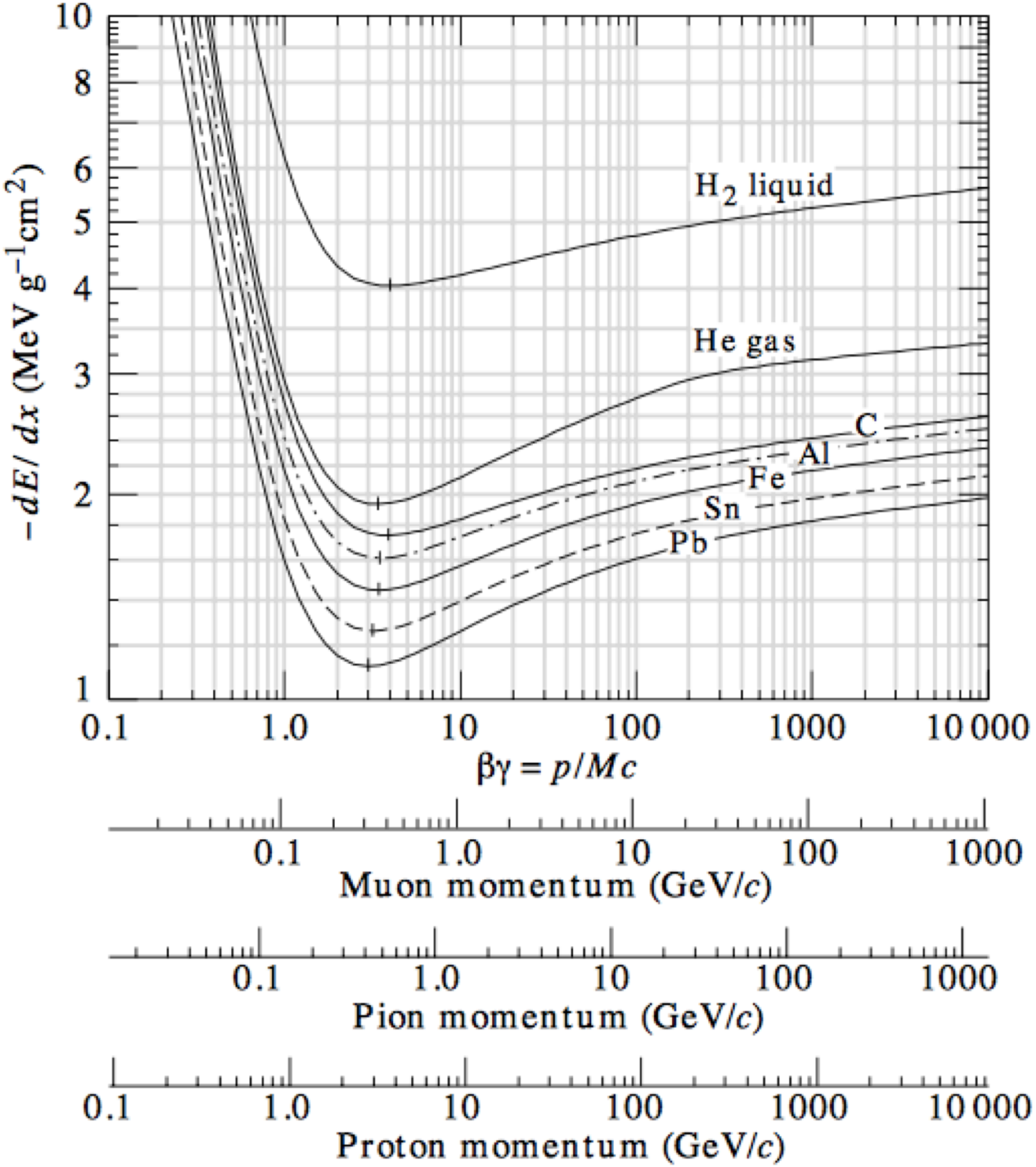
As a first approximation: matter is a mixture of nuclei at rest and (free) electrons.

Various beams are sent through a fixed target. What particle type loses most energy?

A) Muon with 0.2 GeV/c momentum
B) Pion with 10 GeV/c momentum
C) Proton with 0.1 GeV/c momentum
D) Carbon ion with 0.1 GeV/c momentum

Chose between option 1 and 2. Explain why:

1) A < B < C < D
2) D < C < B < A



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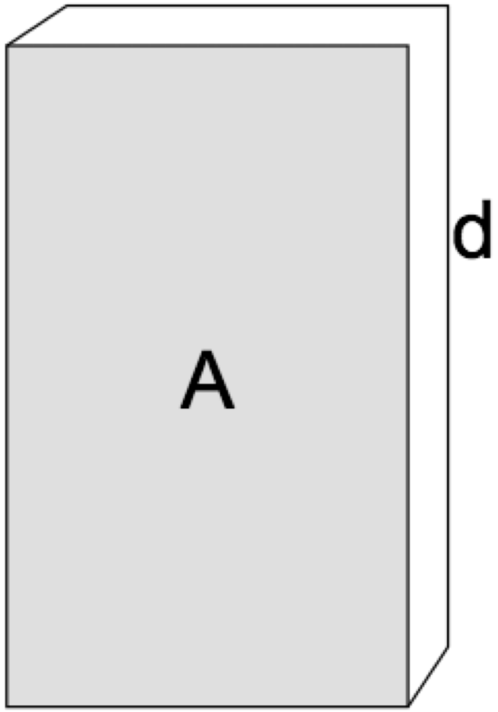
What do we mean by thickness?



Physical thickness:

$$m = \rho V = \rho d A \Rightarrow d = \frac{m}{A\rho} \qquad [\mathrm{um}]$$

Mass thickness:

$$t = \frac{m}{A} \qquad [\mathrm{mg/cm^2}]$$

Much used as «thickness» in subatomic physics

Assumptions - Bethe-Bloch

- Particle is heavy compared to the electron (basically anything but the electron and neutrino)
- The particle has a lot of energy compared to the atomic electron (> 1 MeV)
- The charged particle moves fast (compared to the electrons)

The Bethe-Bloch formula (formula also known by many other names)

- This formula enables you to calculate rather accurately the energy loss due to interactions with atomic electrons in matter
- The derivation of the formula uses the assumption that the electrons are «free», but the formula works rather well even thought atoms are also just excited, not always ionized

Some variations of how the formula is presented:

http://pdg.lbl.gov:

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

Leo:

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

Tavernier:

$$\frac{dE}{dx} = \rho\frac{Z_{\mathrm{nucl}}}{A_{\mathrm{r}}}(0.307\,\mathrm{MeV cm^2/g})\frac{Z^2}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2}\right) - \beta^2 - \frac{\delta(\beta)}{2}\right] \tag{2.3}$$

http://pdg.lbl.gov:

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

Leo:

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We'll stick with this version in the lectures, but the one on top for the exercise

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Average energy per particle, E,
loss per distance x

Density of the material

$$\frac{dE}{dx} = \rho \frac{Z_{\text{nucl}}}{A_{\text{r}}} (0.307 \, \text{MeV} \, \text{cm}^2/\text{g}) \frac{Z^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} \right) - \beta^2 - \frac{\delta(\beta)}{2} \right] \tag{2.3}$$

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Dimensionless charge of the nuclei in the material

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Particle charge squared

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Average energy per particle, E, loss per distance x

Particle speed divided by the speed of light

Dimensionless charge of the nuclei in the material

Density of the material

Particle charge squared

$$\frac{dE}{dx} = \rho \frac{Z_{\mathrm{nucl}}}{A_{\mathrm{r}}} (0.307\,\mathrm{MeV\,cm^2/g}) \frac{Z^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta)}{2} \right] \tag{2.3}$$

Average energy per particle, E, loss per distance x

Particle speed divided by the speed of light

Mean excitation potential, usually determined from experiments

Density of the material

Dimensionless charge of the nuclei in the material

Particle charge squared

Maximum energy transfer to electrons

$$\frac{dE}{dx} = \rho \frac{Z_{\mathrm{nucl}}}{A_{\mathrm{r}}} (0.307\,\mathrm{MeV cm^2/g}) \frac{Z^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta)}{2} \right] \tag{2.3}$$

Average energy per particle, E, loss per distance x

Particle speed divided by the speed of light

Mean excitation potential, usually determined from experiments

Not all terms are equally important

The «qualitative» Bethe-Bloch:

$$\frac{dE}{dx} \approx \rho\,(2\,\mathrm{MeV cm^2/g})\frac{Z^2}{\beta^2}$$

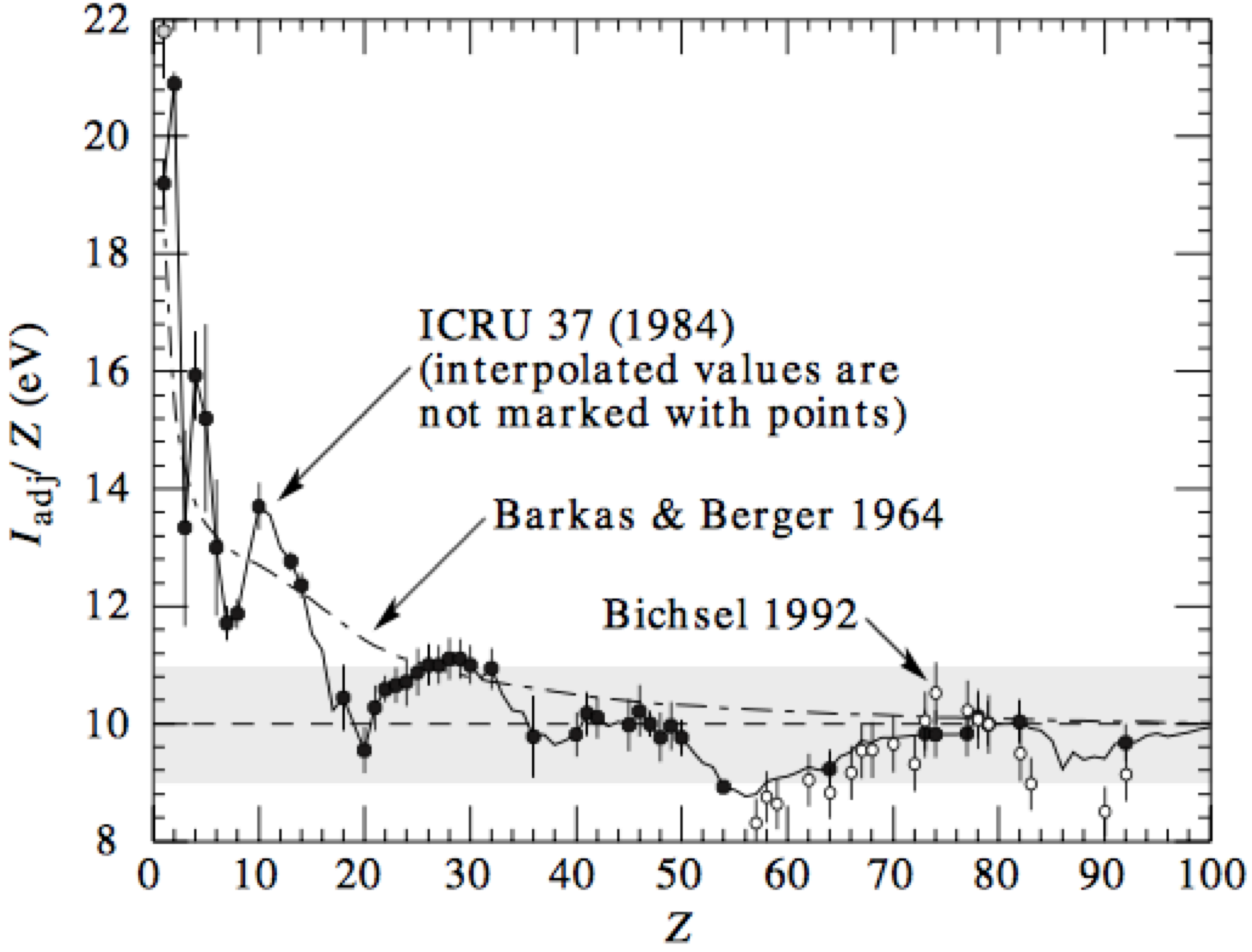
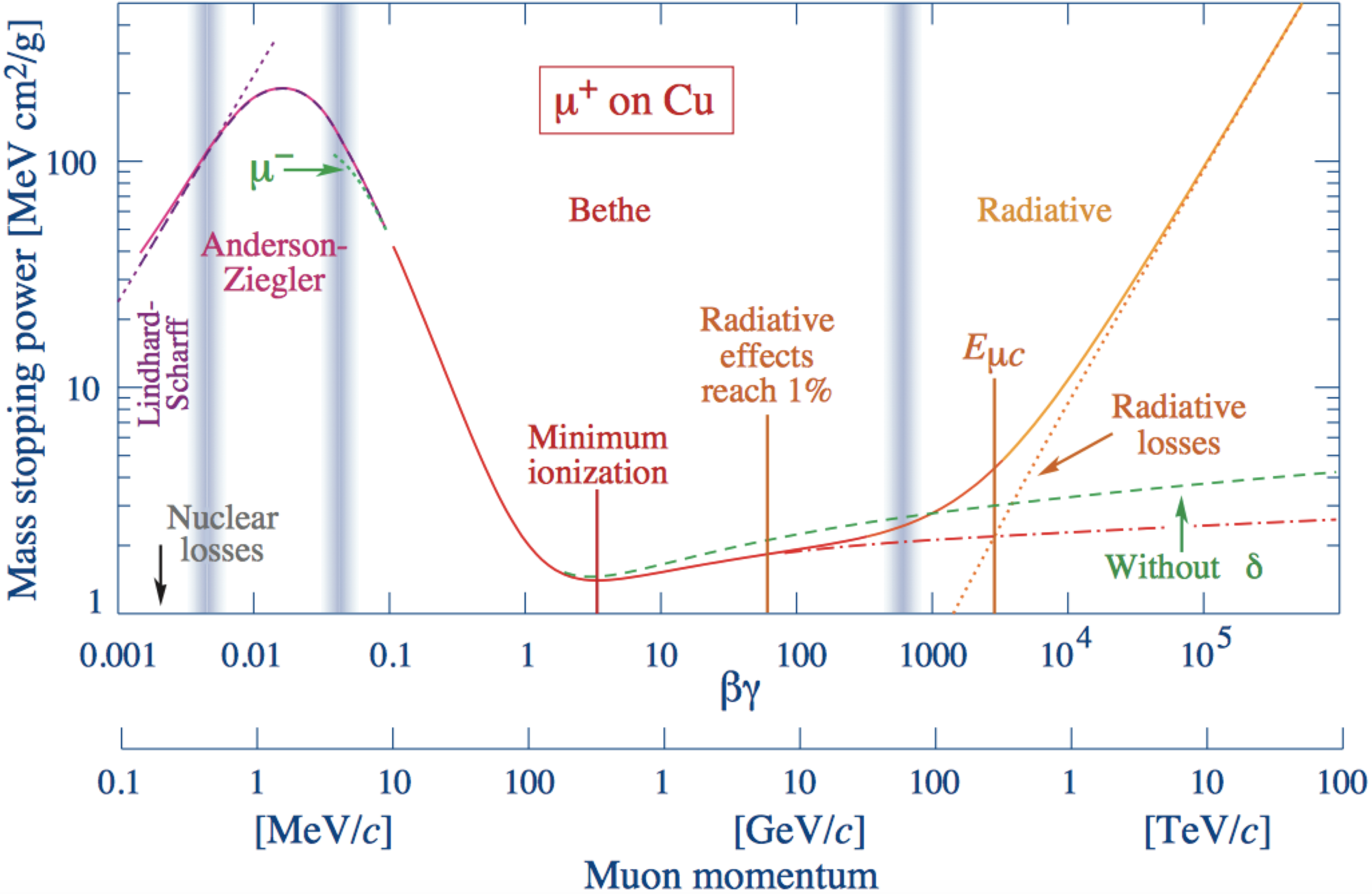


Figure 27.5: Mean excitation energies (divided by Z) as adopted by the ICRU [12]. Those based on experimental measurements are shown by symbols with error flags; the interpolated values are simply joined. The grey point is for liquid H_2; the black point at 19.2 eV is for H_2 gas. The open circles show more recent determinations by Bichsel [14]. The dotted curve is from the approximate formula of Barkas [15] used in early editions of this *Review*.

http://pdg.lbl.gov/2018/reviews/rpp2018-rev-passage-particles-matter.pdf



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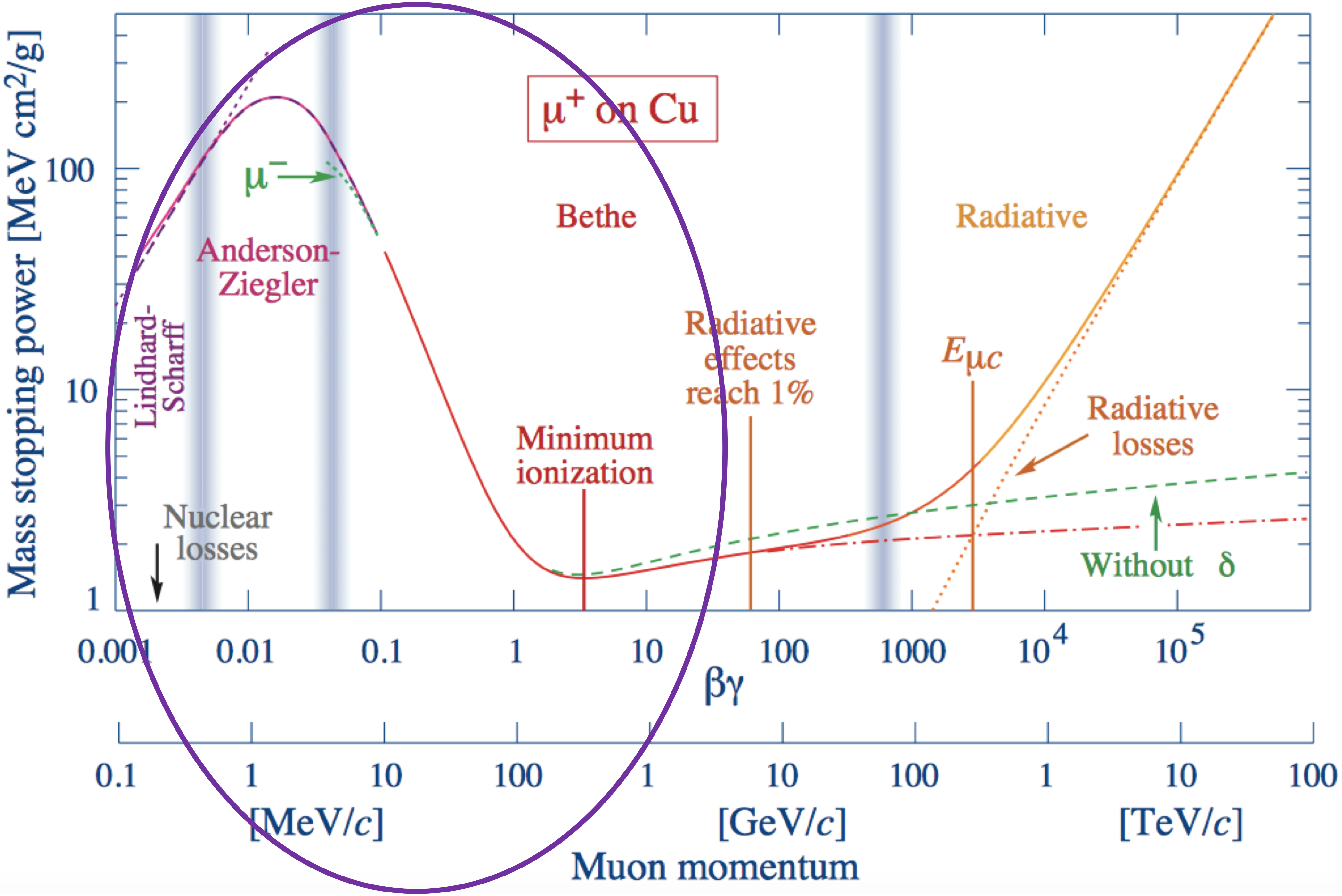

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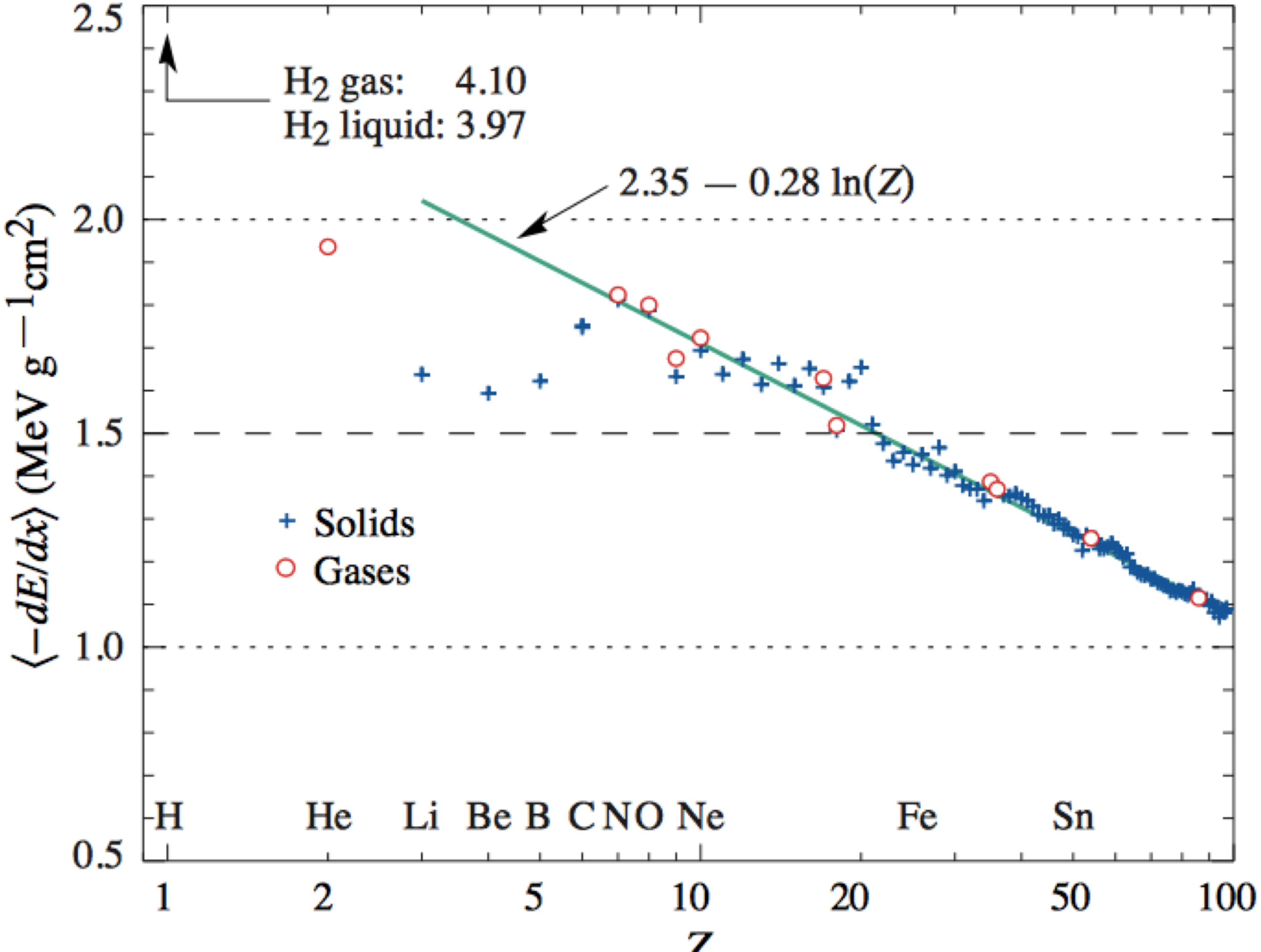


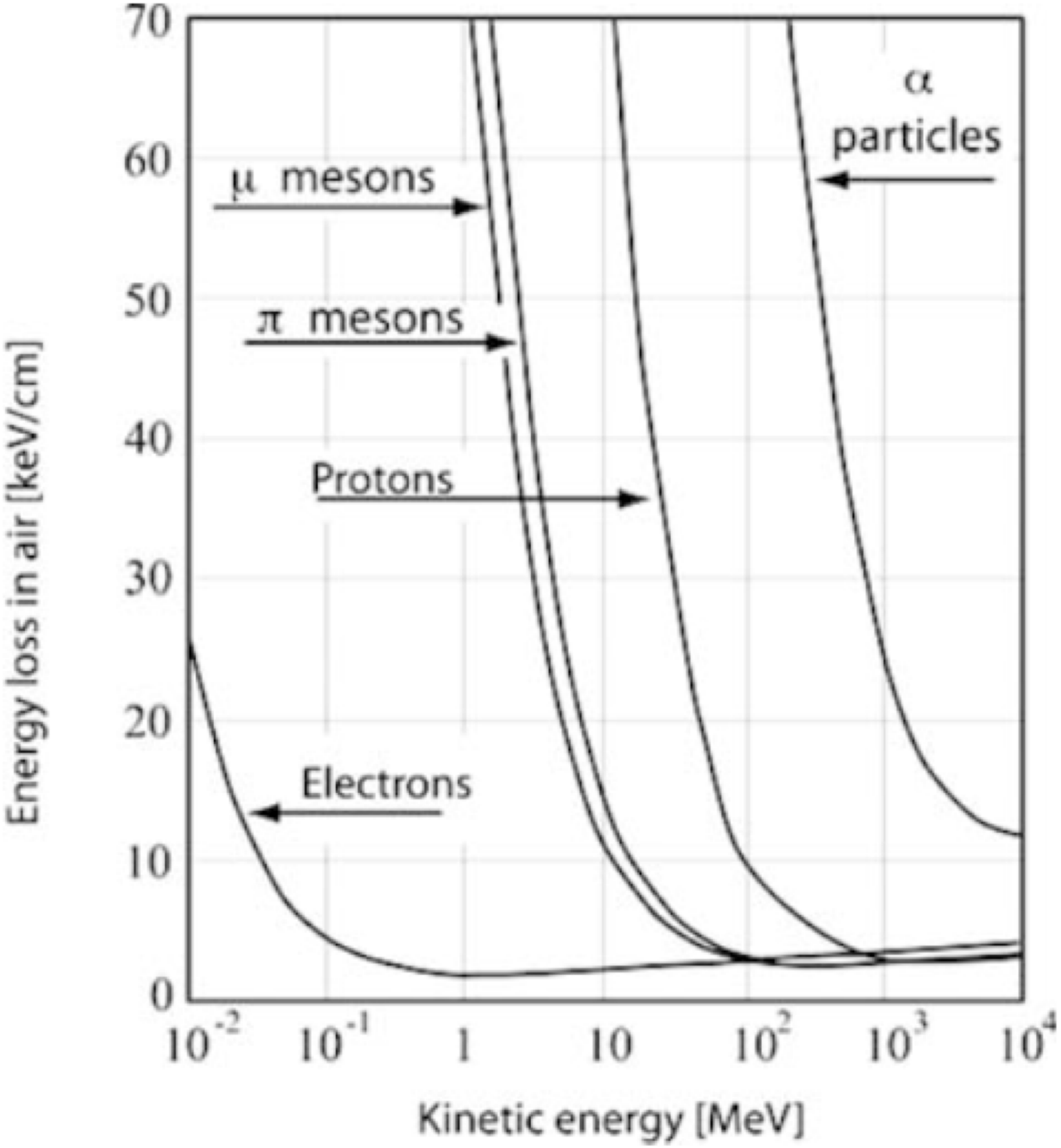
Figure 33.3: Mass stopping power at minimum ionization for the chemical elements. The straight line is fitted for $Z > 6$. A simple functional dependence on Z is not to be expected, since $\langle -dE/dx \rangle$ also depends on other variables.

http://pdg.lbl.gov/2018/reviews/rpp2018-rev-passage-particles-matter.pdf

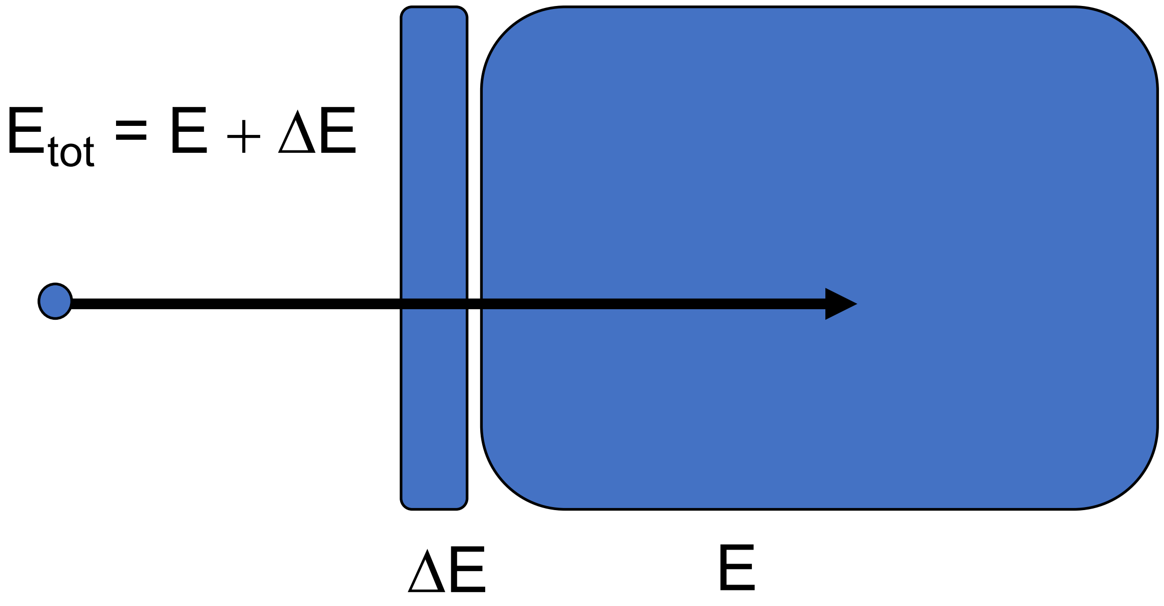
Some examples of energy loss

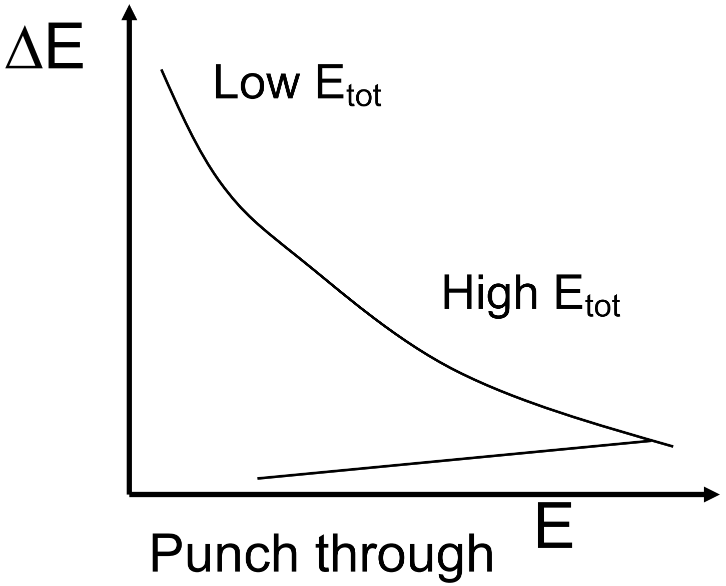
Energy loss in air

The image is from «Experimental Techniques in Nuclear and Particle Physics» by Tavernier



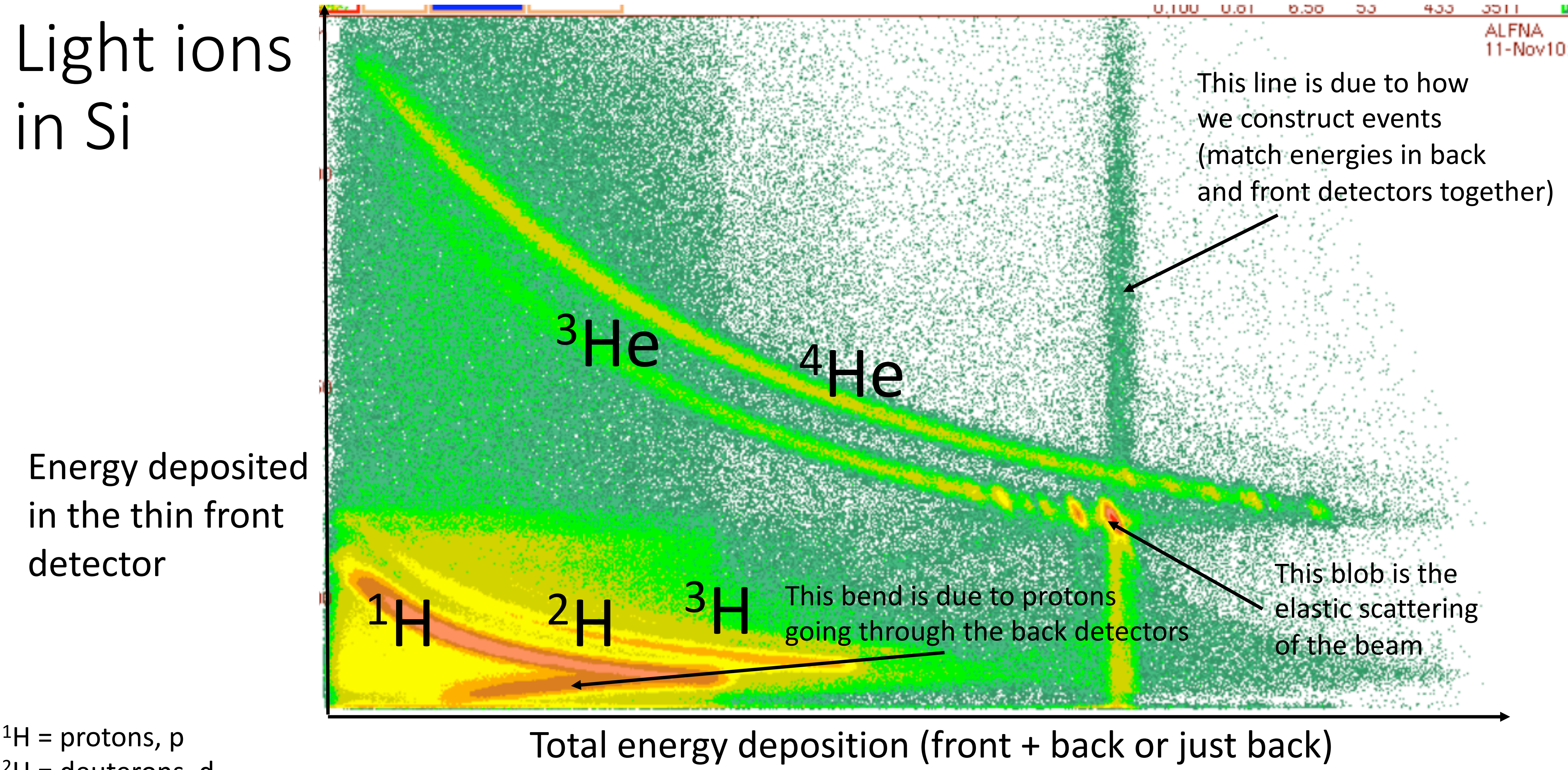
«Particle telescope»





Light ions in Si

The color intensity represents the number of counts in that pixel. Red = many.

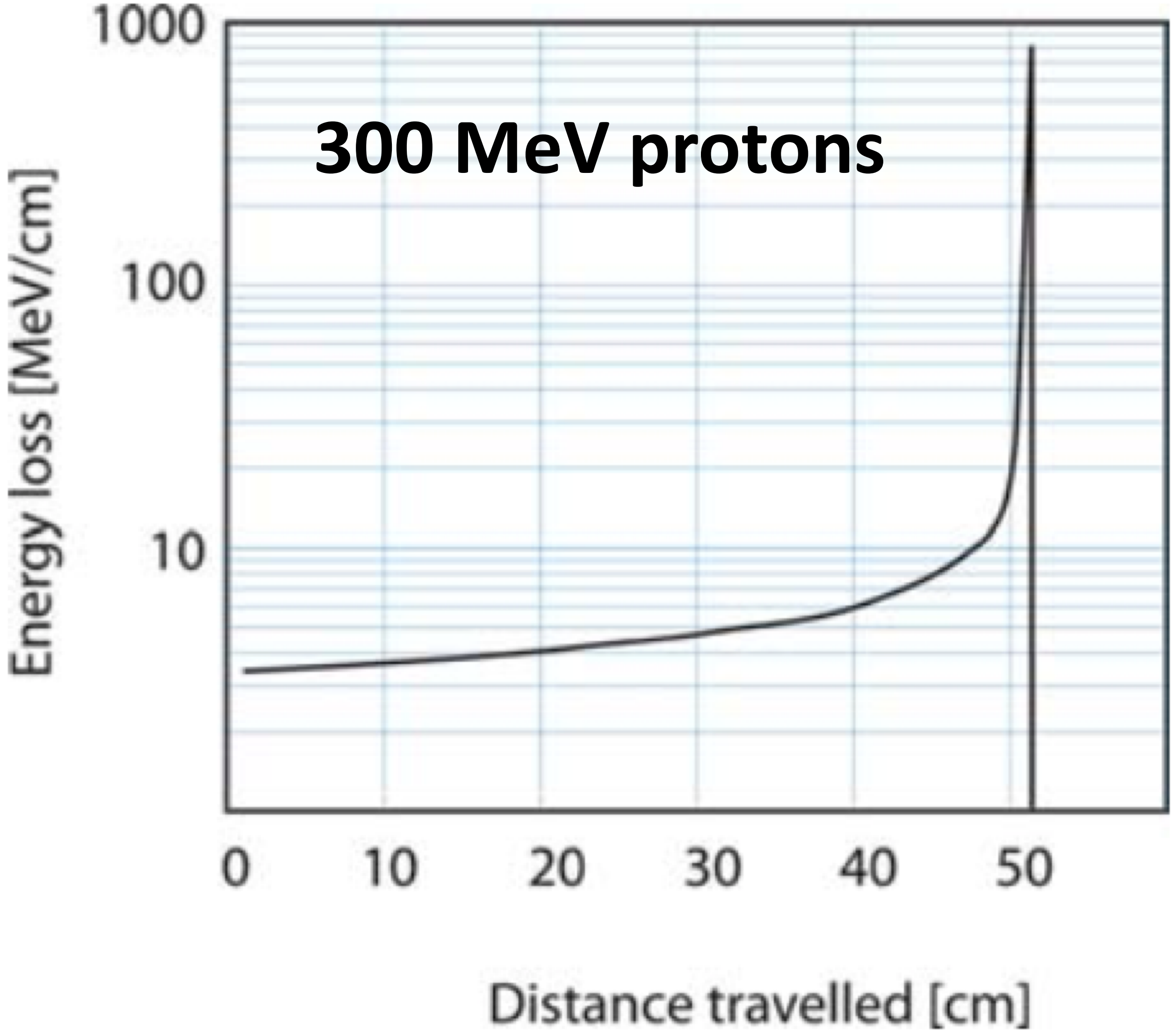


^{1}H = protons, p
^{2}H = deuterons, d
^{3}H = tritions, t

Energy loss in water as a function of depth

The image is from «Experimental Techniques in Nuclear and Particle Physics» by Tavernier.

This peak structure is called the «Bragg peak»



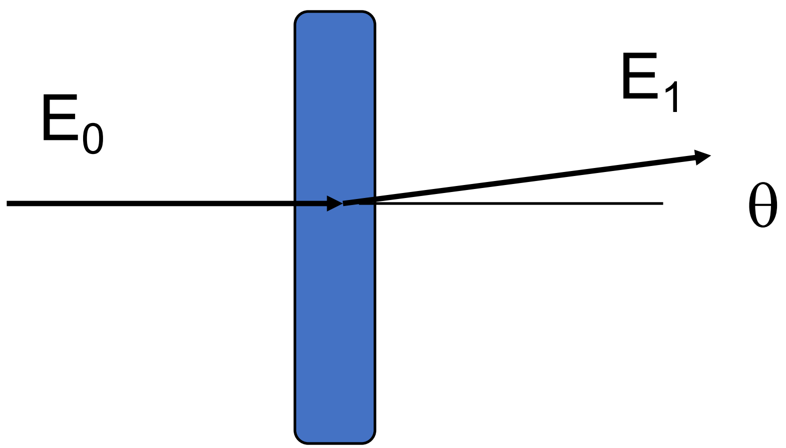
When do we need something more than Bethe-Bloch?

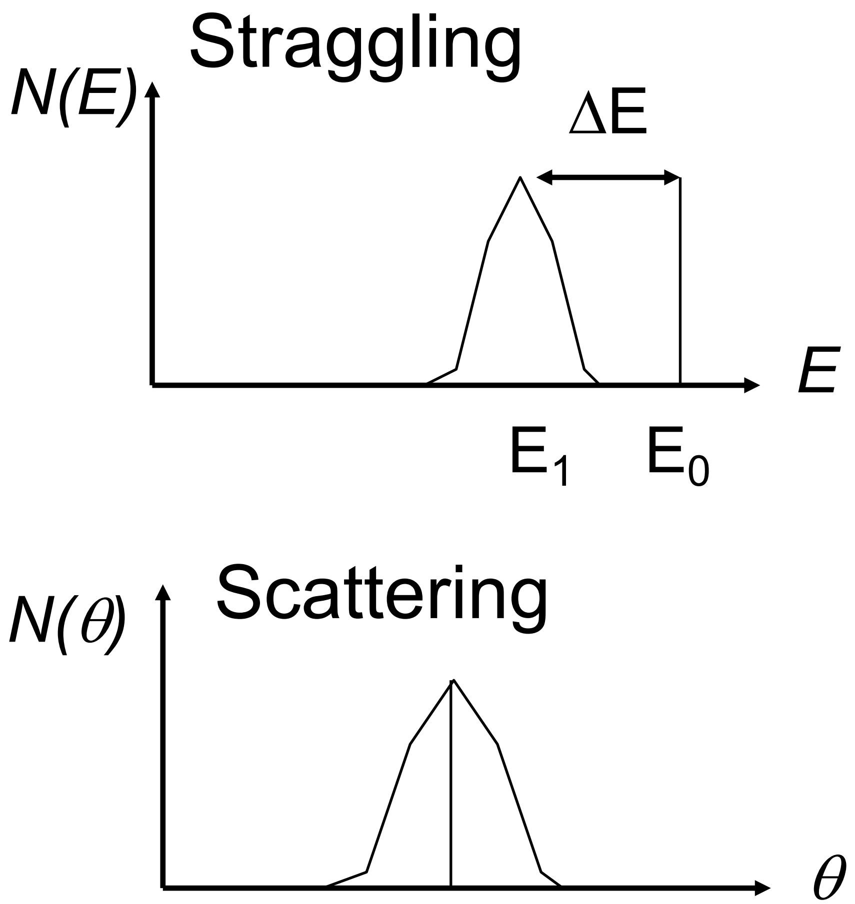
Bethe-Bloch is not sufficient

- For electrons and positrons (will come back to this next week)
- For very fast and rather light particles
- For very slow particles
- For ions with a large charge (> 2?)

Other electromagnetic interactions of charged particles

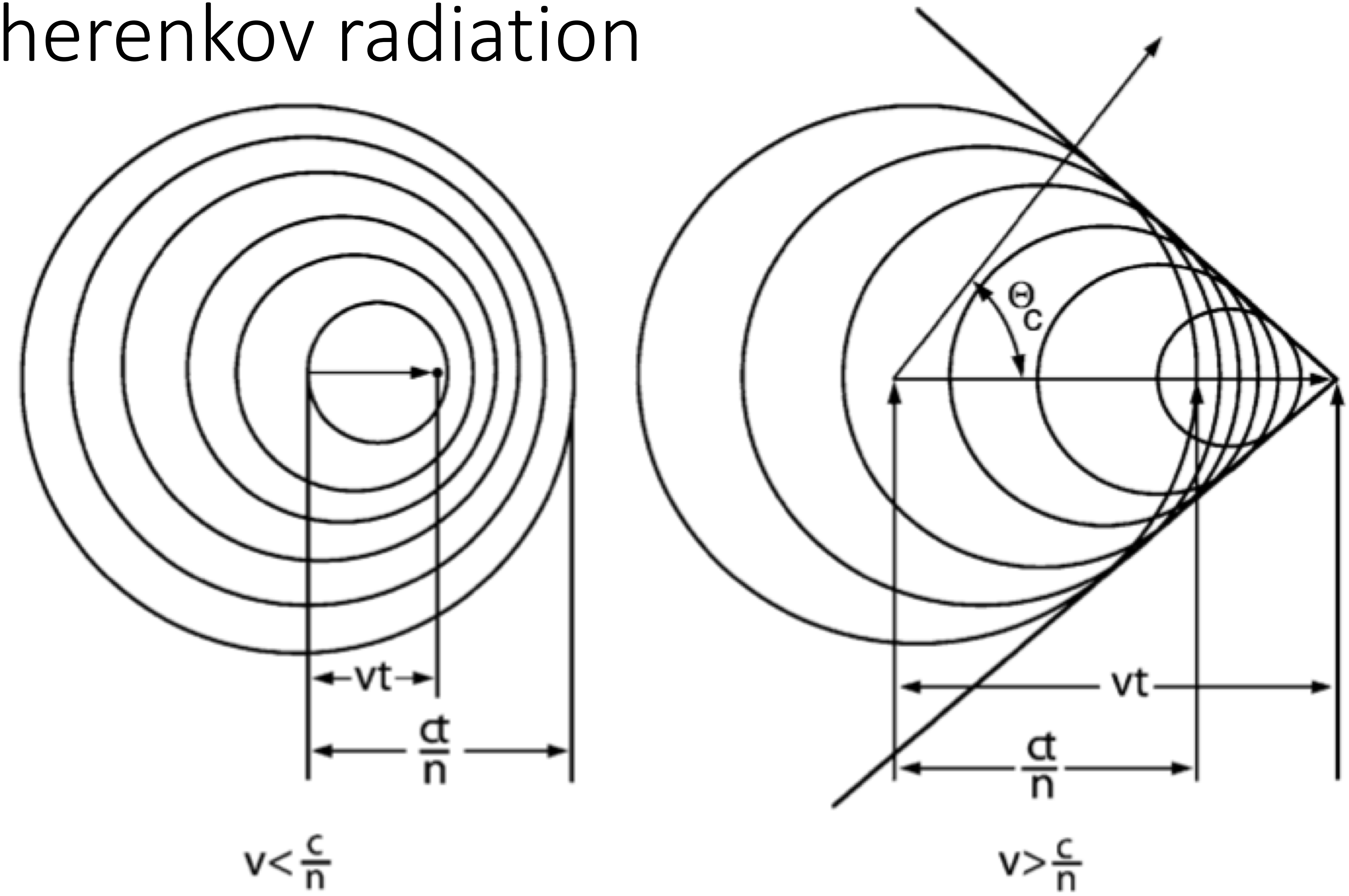
Scattering on atomic nuclei



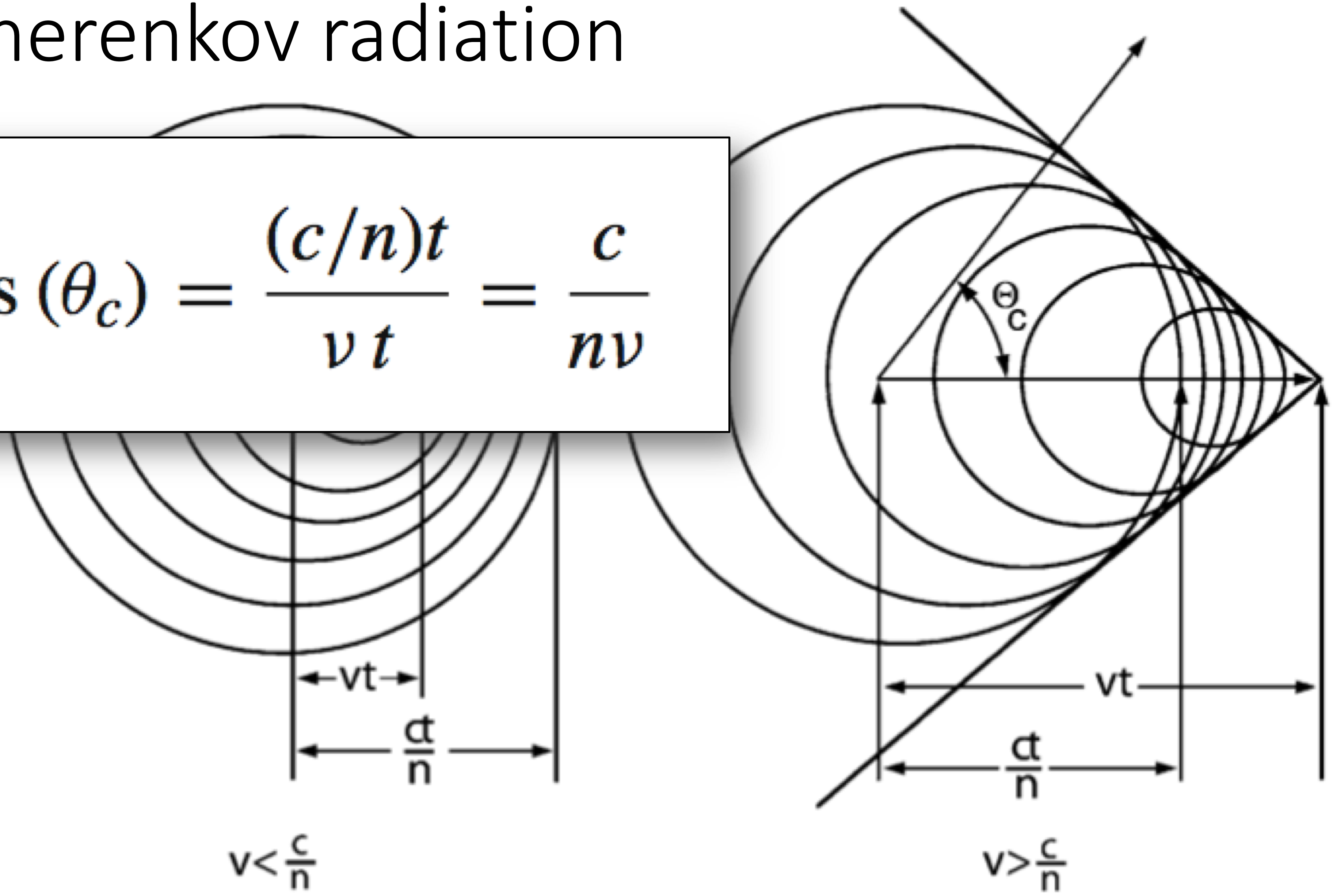


For a rather thin target or absorber

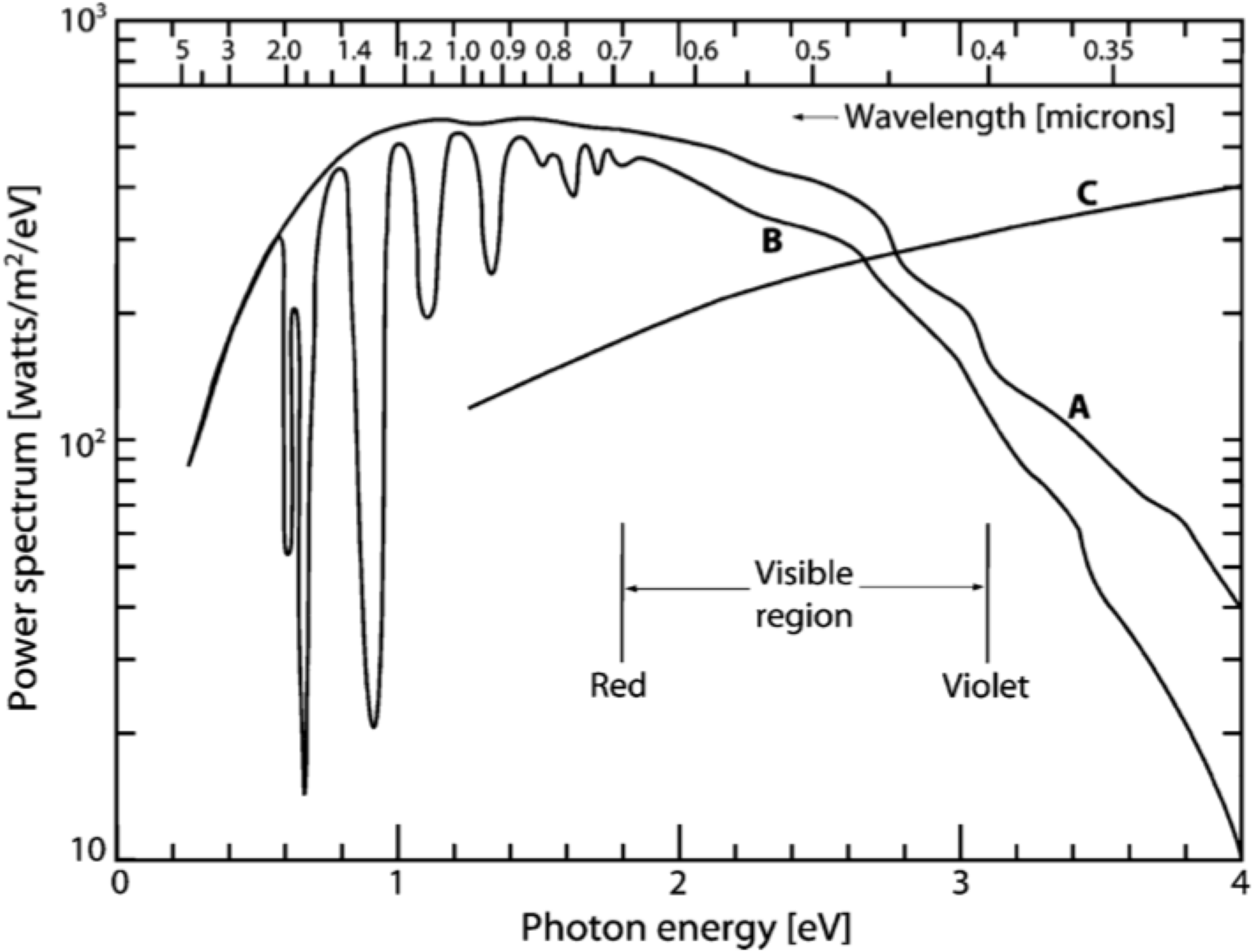
Cherenkov radiation



Cherenkov radiation



$$\cos(\theta_c) = \frac{(c/n)t}{v\,t} = \frac{c}{nv}$$

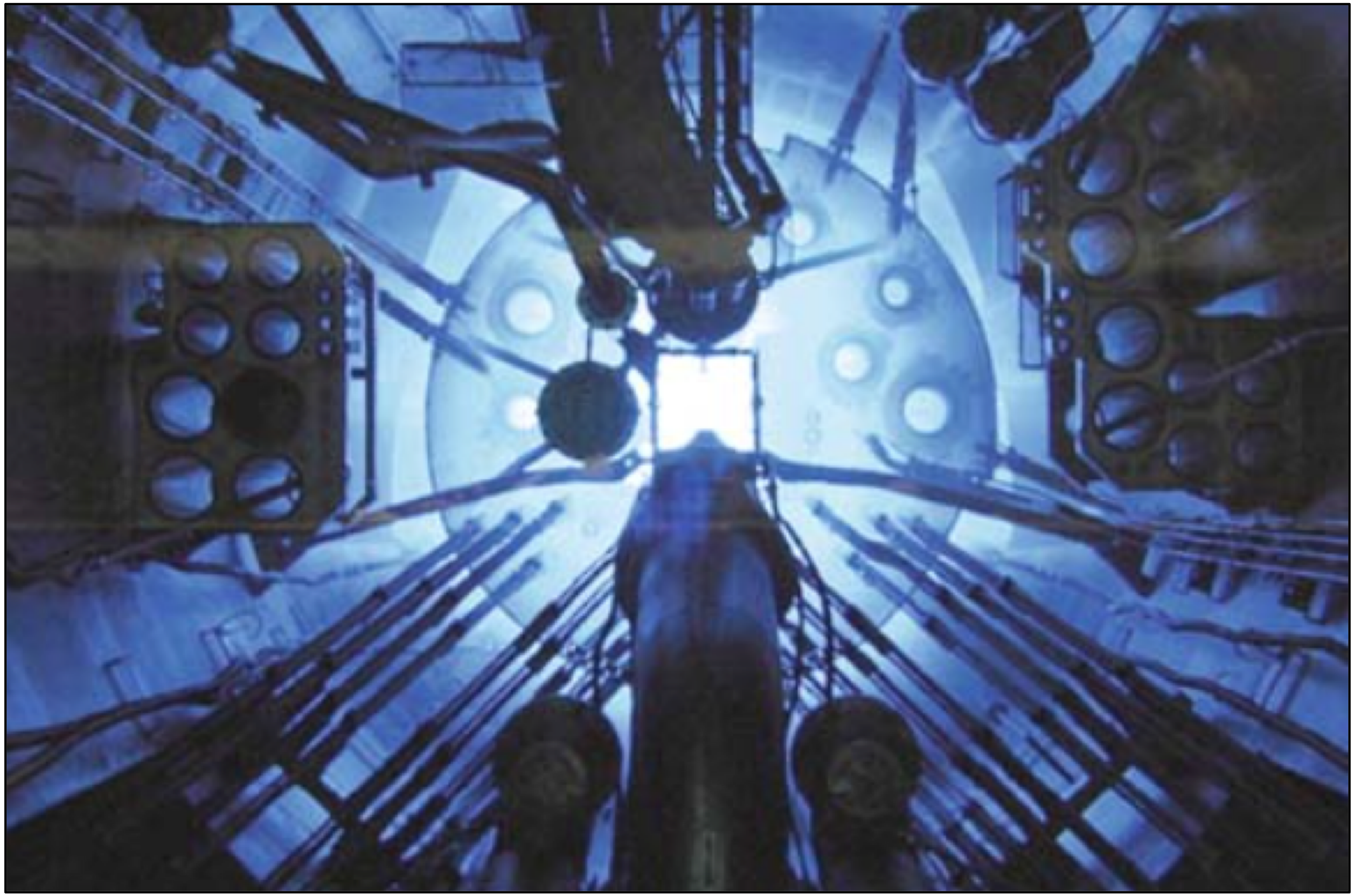


A: Sunlight above atmosphere

B: Sun at zenith

C: Cherenkov energy spectrum

Image from
the book:



The threshold for the Cherenkov effect for electrons in water is 264 keV and 486 MeV for protons => the light we see here is due to electrons.

Bremsstrahlung

Any charged particle undergoing acceleration will emit elec- tromagnetic radiation.

If a high-energy charged particle deviates from its trajectory due to a collision with a nucleus, this collision is necessarily accompanied by elec- tromagnetic radiation.

The emission is strongly peaked in the direction of flight of the charged particles.