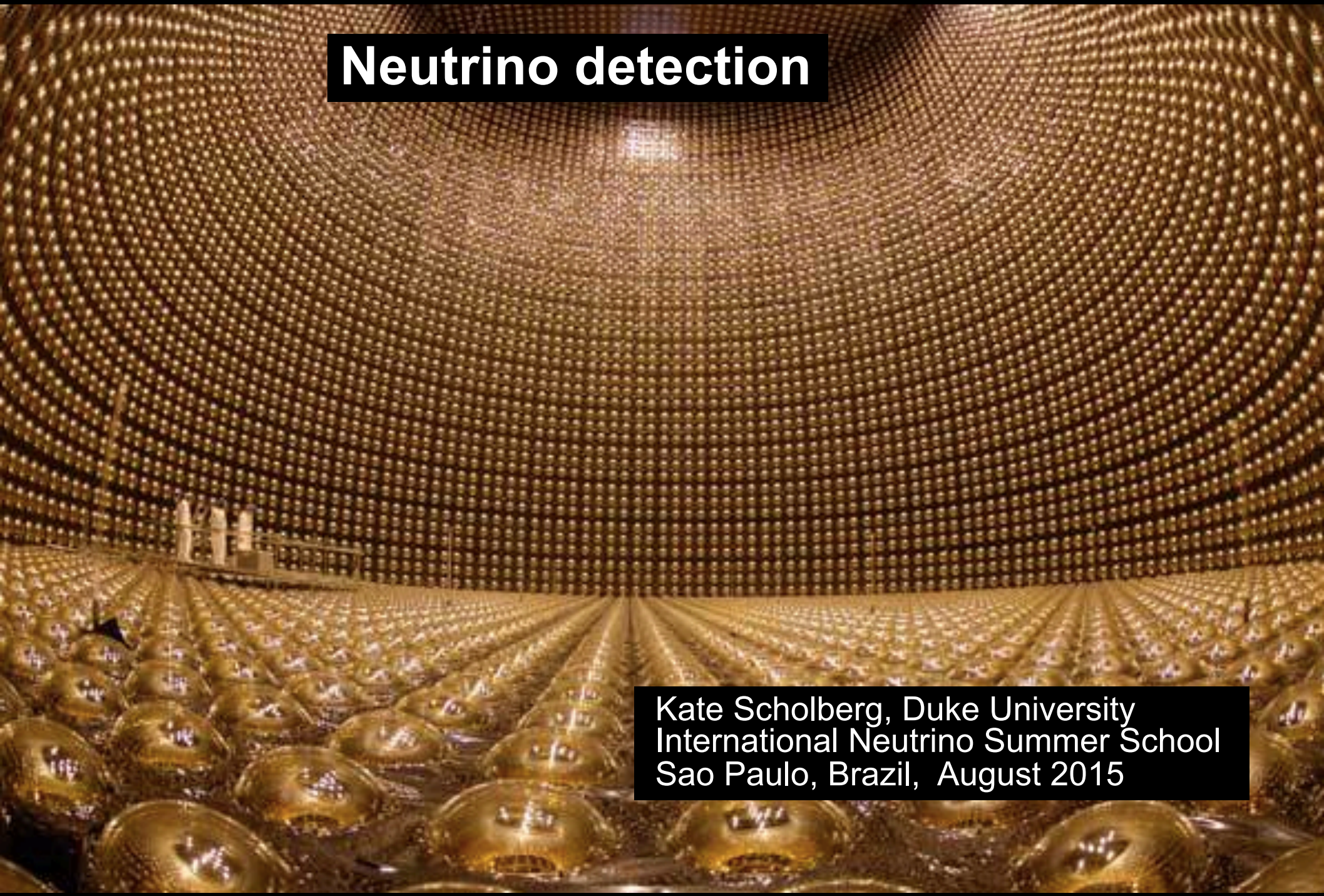
Neutrino detection

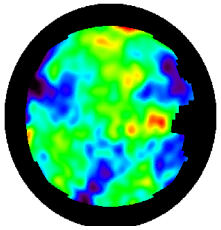


Kate Scholberg, Duke University
International Neutrino Summer School
Sao Paulo, Brazil, August 2015

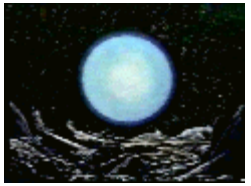
Sources of ‘wild’ neutrinos

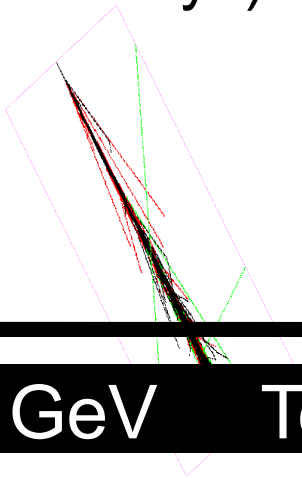
The Atmosphere
(cosmic rays)

The Big Bang



Super
novae

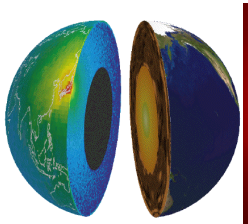


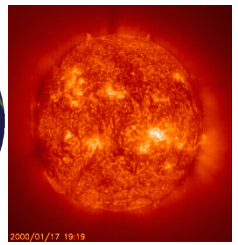


AGN's, GRB's

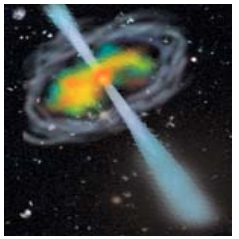
meV eV keV MeV GeV TeV PeV EeV

Radioactive
decay in the
Earth





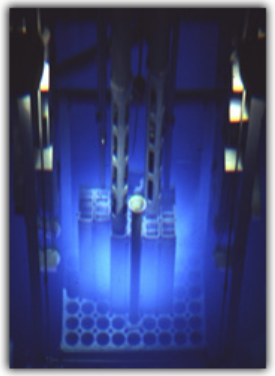
The Sun



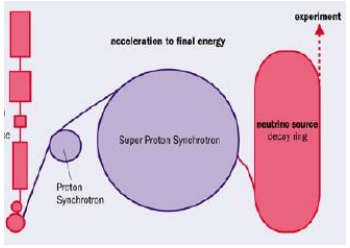
Sources of ‘tame’ neutrinos

Proton accelerators

Nuclear reactors

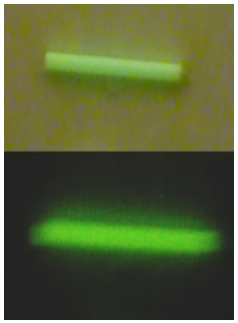


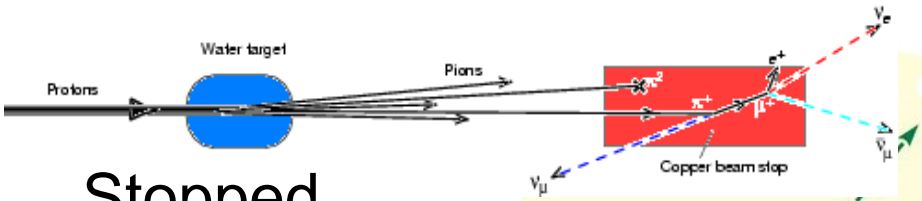
Beta beams



eV keV MeV GeV TeV

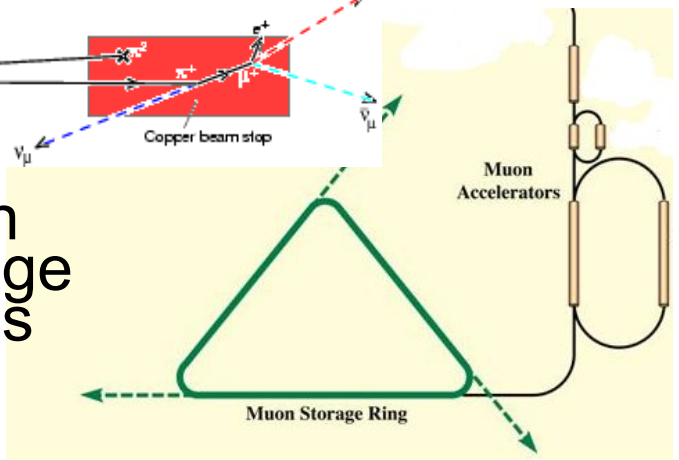
Artificial radioactive sources





Stopped pion sources

Muon storage rings



Lecture overview

Lecture 1: general principles of neutrino interactions and particle detection

Lectures 2, 3, 4: detection strategies, organized by energy range

Outline for Lecture 1

- **Neutrino interactions**

- **Particle detection**
  - energy loss
  - specific particles:
    - charged particles
    - photons
    - neutrons

What do we want from a neutrino detector?

depends on the source and the physics:

Geordi La Forge's special visor that can see neutrinos:

What do we want from a neutrino detector?

depends on the source and the physics:

Geordi La Forge's special visor that can see neutrinos:

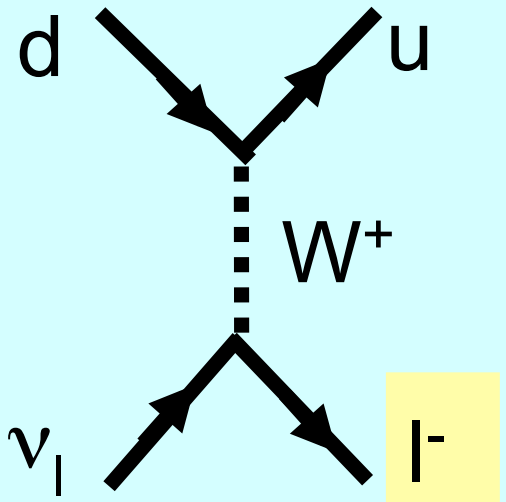
- flavor/CP state
- time of interaction
- energy
- direction
- position of interaction

plus pretty much always want:

- high statistics (mass,efficiency)
- low background

Neutrino interactions with matter

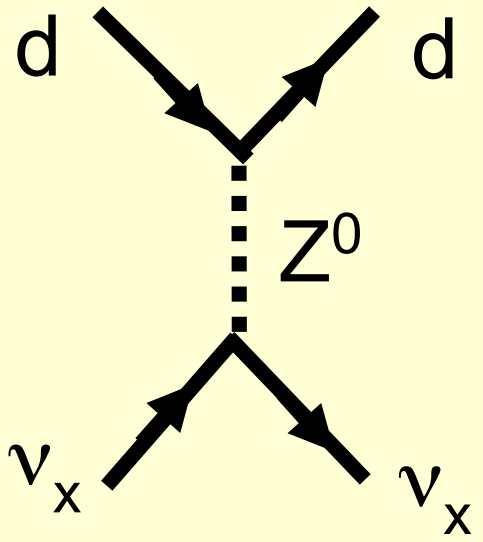
Charged Current (CC)



$\nu_l + N \rightarrow l^{\pm} + N'$

Produces lepton with flavor corresponding to neutrino flavor
(must have enough energy to make lepton)

Neutral Current (NC



Flavor-blind

It’s called the weak interaction for a reason

Photon-matter cross-sections

Neutrino-matter cross-sections

1 barn = 10^{-24} cm^2

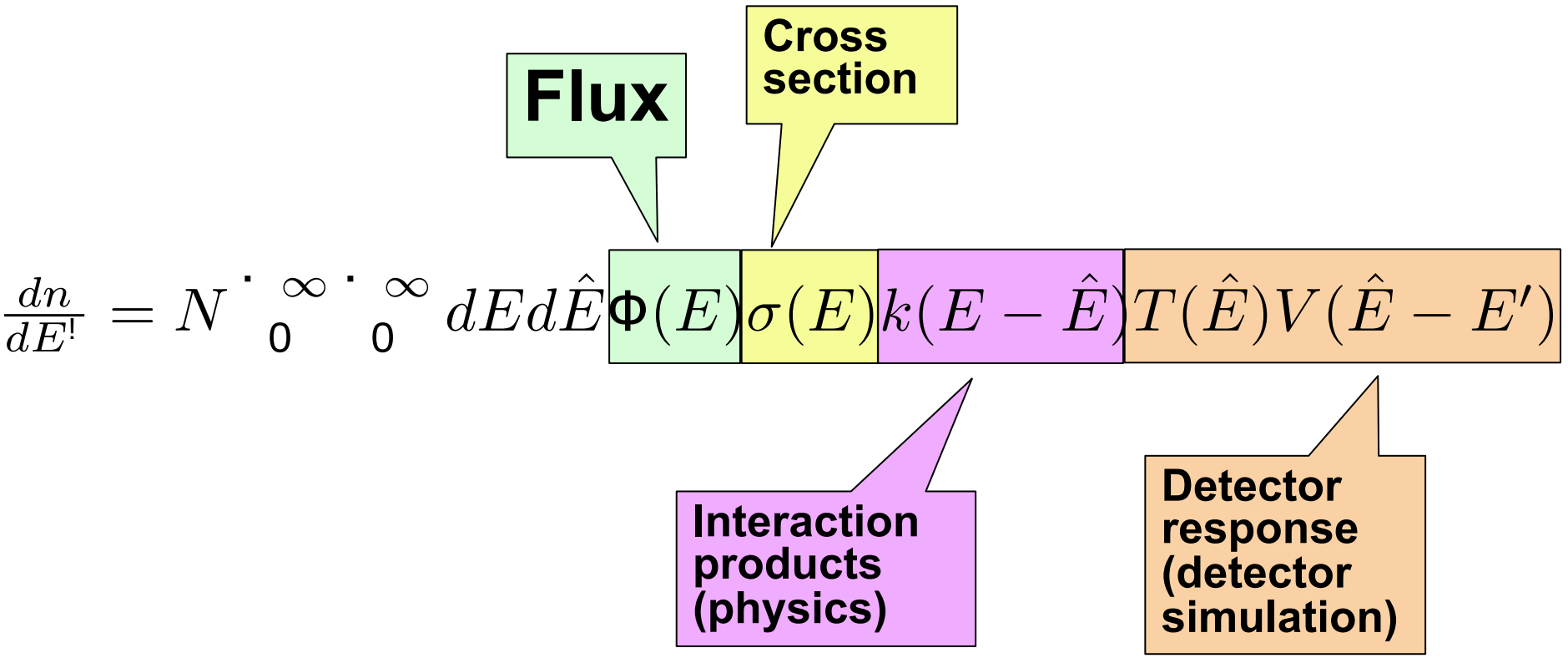
~10^{-24} cm^2

~10^{-40} cm^2

~16-17 orders of magnitude smaller

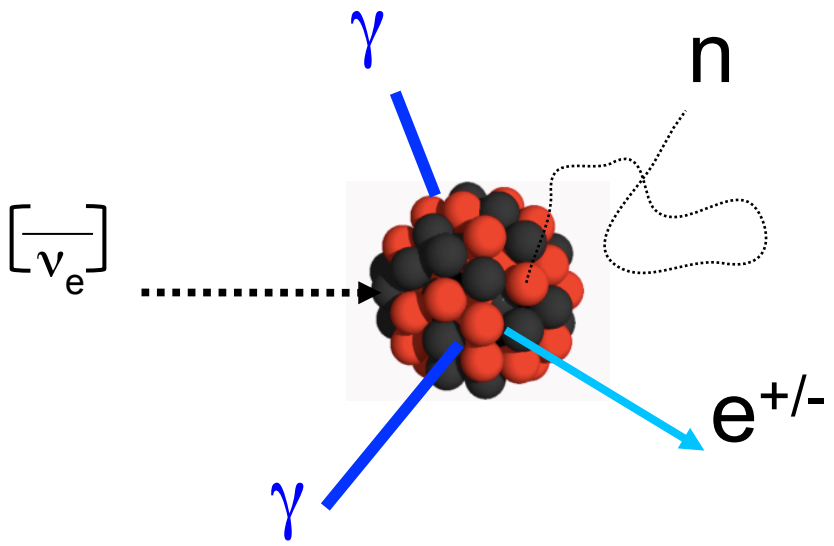
Event spectrum as a function of observed energy E', for a realistic detector

ßux ⊗ xscn ⊗ interaction products ⊗ detector respons



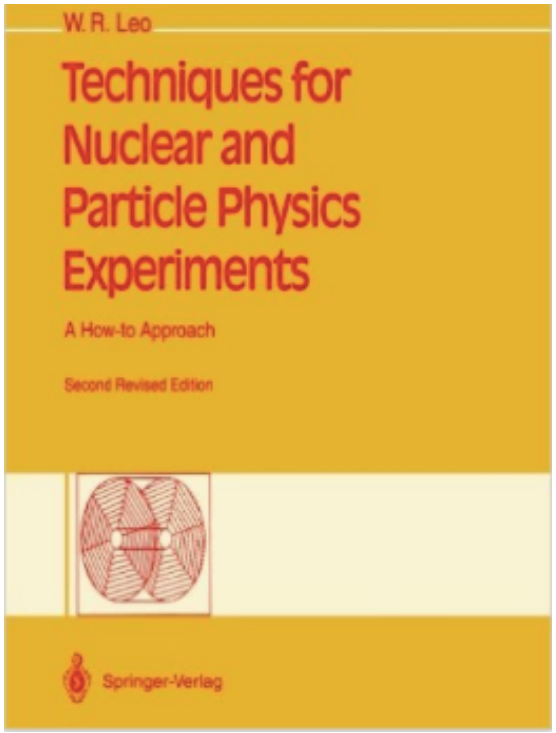
E': observed energy
k: observed energy for given neutrino energy
T: detector efficiency
V: detector resolution

Today: **physics of electromagnetic- or strongly-interacting particle detection.** with emphasis on cases common in ν experiments



- charged particles
  - "heavy" (μ, π, p, ...)
  - e^+, e^-
- photons
- neutrons

References:



Essential for experimentalists!

32. PASSAGE OF PARTICLES THROUGH MATTER

Revised September 2013 by H. Bichsel (University of Washington), D.E. Groom (LBNL), and S.R. Klein (LBNL).

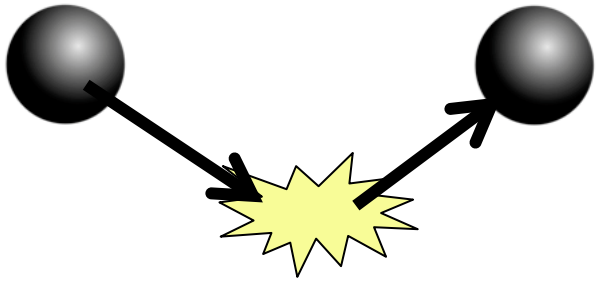
This review covers the interactions of photons and electrically charged particles in matter, concentrating on energies of interest for high-energy physics and astrophysics and processes of interest for particle detectors (ionization, Cherenkov radiation, transition radiation). Much of the focus is on particles heavier than electrons ($\pi^{\pm}$, p, etc.). Although the charge number z of the projectile is included in the equations, only $z = 1$ is discussed in detail. Muon radiative losses are discussed, as are photon/electron interactions at high to ultrahigh energies. Neutrons are not discussed. The notation and important numerical values are shown in Table 32.1.

PDG review (points to online databases)

Energy loss of particles in matter

Particles lose energy by interactions with atoms as they move through matter (and may also decay into other particles, or create new particles)

particles deposit energy and change direction

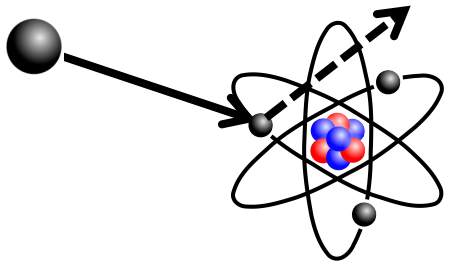


Common energy-loss processes	Inelastic collisions w/ atomic electrons	
	Soft (excitations)	Hard (ionization, secondaries)
	Elastic scattering from nuclei	
	Cherenkov radiation	
Rare energy loss processes (but still potentially important)	Nuclear reactions	
	Bremsstrahlung	

First: **"Heavy"** (heavier than $e^{\pm}$) **charged particles**

$\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, α, ...

In "normal" cases,
most energy loss is from **inelastic collisions,**
e.g., ionization of atoms



"stopping power" $\dfrac{dE}{dx}$

as a function of
projectile, material, energy,
... in basic approximation
can be calculated w/
classical E&M (Jackson)

behaves statistically, but there are many collisions,
so fluctuations are typically small

The QM calc for relativistic particles:
“Bethe” or “Bethe-Bloch” equation

Mean rate of energy loss

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \rho$$

Symbol	Definition	Value or (usual) units
α	fine structure constant	
	$e^2/4\pi\epsilon_0\hbar c$	$1/137.035\,999\,074(44)$
M	incident particle mass	MeV/c^2
E	incident part. energy γMc^2	MeV
T	kinetic energy, $(\gamma-1)Mc^2$	MeV
W	energy transfer to an electron in a single collision	MeV
k	bremsstrahlung photon energy	MeV
$m_e c^2$	electron mass $\times\ c^2$	$0.510\,998\,928(11)$ MeV
r_e	classical electron radius	
	$e^2/4\pi\epsilon_0 m_e c^2$	$2.817\,940\,3267(27)$ fm
N_A	Avogadro's number	$6.022\,141\,29(27) \times 10^{23}$ mol^{-1}
z	charge number of incident particle	
Z	atomic number of absorber	
A	atomic mass of absorber	g mol^{-1}
K	$4\pi N_A r_e^2 m_e c^2$	$0.307\,075$ MeV mol^{-1} cm^2
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	
$\hbar\omega_p$	plasma energy	$\sqrt{\rho \langle Z/A \rangle} \times 28.816$ eV
	$\sqrt{4\pi N_e r_e^3}\ m_e c^2/\alpha$	$\hookrightarrow\ \rho$ in g cm^{-3}
N_e	electron density	(units of r_e)$^{-3}$
w_j	weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
X_0	radiation length	g cm^{-2}
E_c	critical energy for electrons	MeV
$E_{\mu c}$	critical energy for muons	GeV
E_s	scale energy $\sqrt{4\pi/\alpha}\ m_e c^2$	21.2052 MeV
R_M	Molière radius	g cm^{-2}

good to ~% in MeV-GeV range and intermediate Z materials

$$0.1 \lesssim \beta\gamma \lesssim 1000$$

The QM calc: **"Bethe" or "Bethe-Bloch" equation**

Mean rate of energy loss

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \rho$$

$$\frac{dE}{dx} \propto \rho \text{ , the material density}$$

PDG expression for "stopping power" is really

$$\frac{1}{!} \frac{dE}{dx}$$

$\mathrm{MeV\ cm^2/g}$

I will drop the ρ, but in practice you need to remember to multiply by it

A few features of the Bethe-Bloch equation:

Mean rate of energy loss

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

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z	charge number of incident particle	
Z	atomic number of absorber	
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K	$4\pi N_A r_e^2 m_e c^2$	0.307 075 MeV mol^{-1} cm^2
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	
$\hbar\omega_p$	plasma energy	$\sqrt{\rho\,\langle Z/A\rangle} \times 28.816$ eV
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E_c	critical energy for electrons	MeV
$E_{\mu c}$	critical energy for muons	GeV
E_s	scale energy $\sqrt{4\pi/\alpha}\ m_e c^2$	21.2052 MeV
R_M	Molière radius	g cm^{-2}

$$W_{\max} = \frac{2m_e c^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

(basic kinematics)

Most quantities are basic physics constants, except:

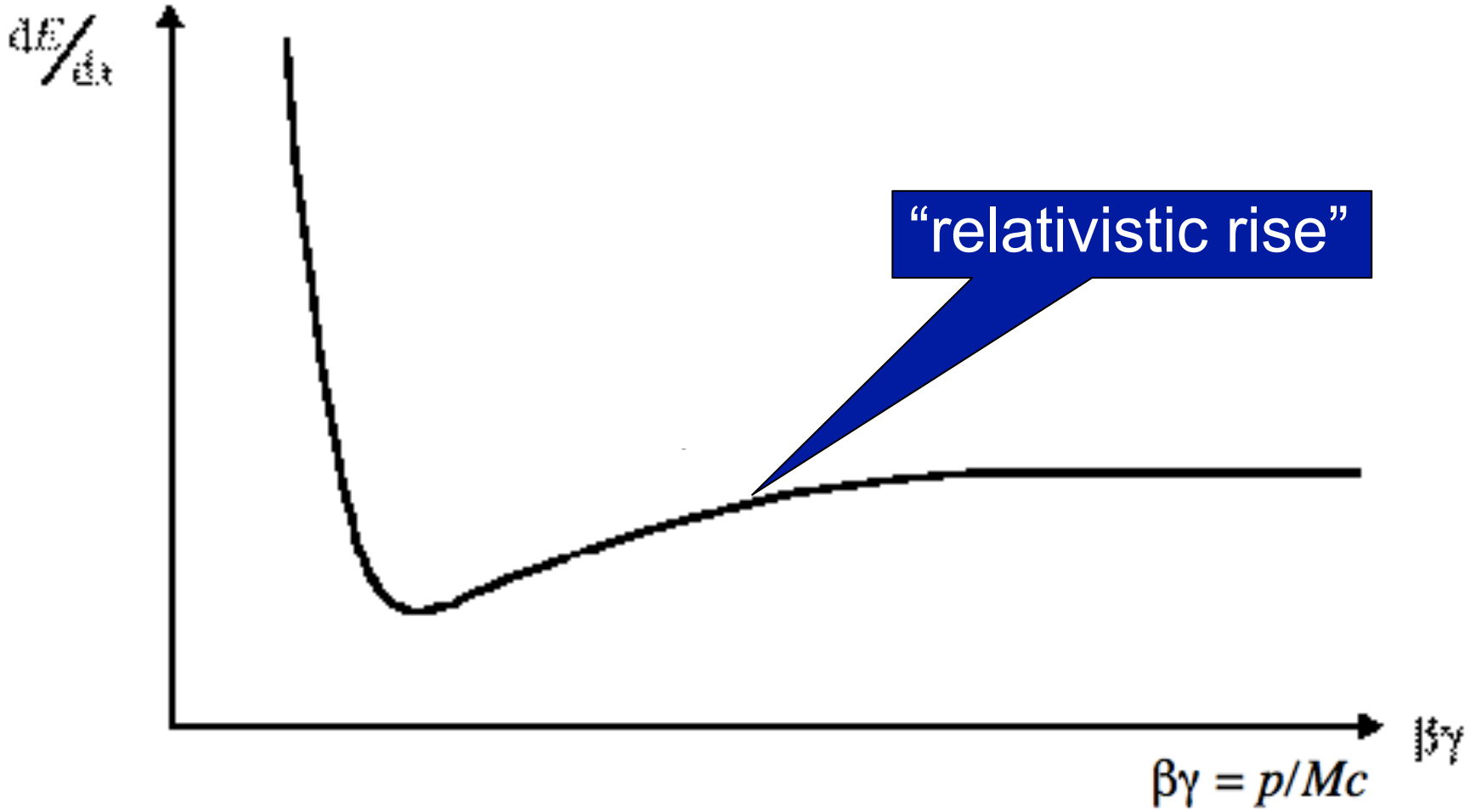
δ: "density correction" (~measured)

I: mean excitation energy (measured)

What this function looks like:

usually drawn log-log

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



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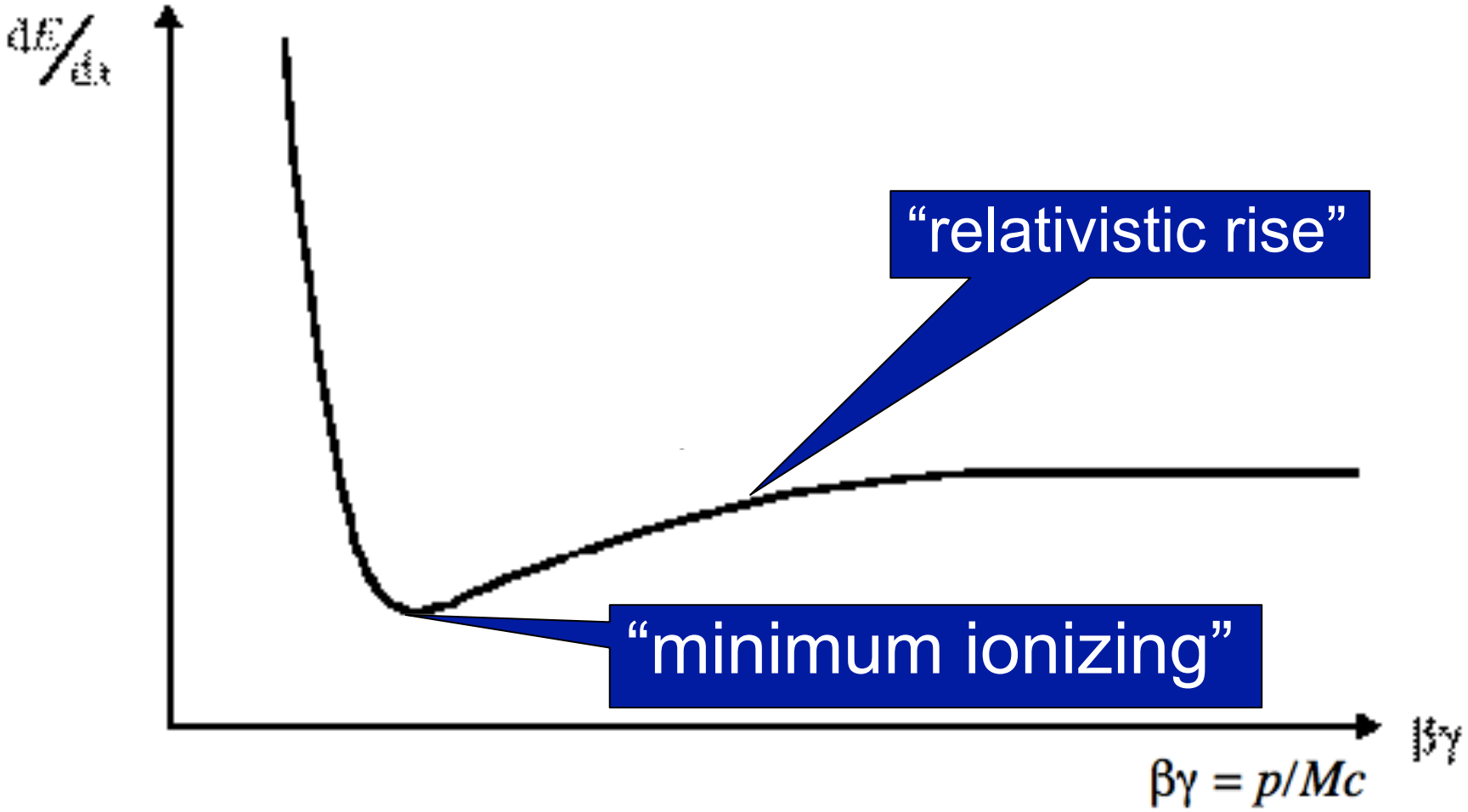

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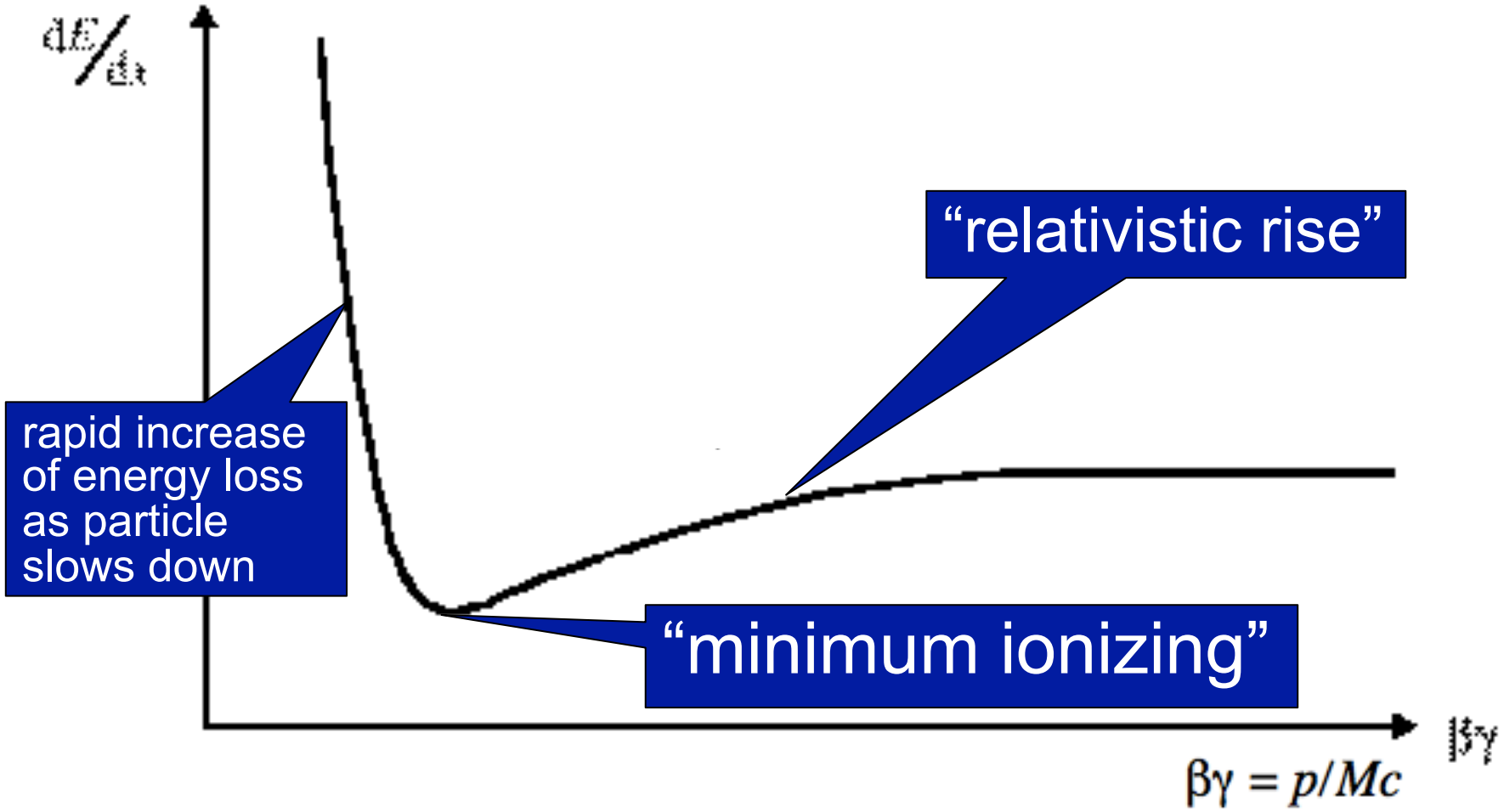


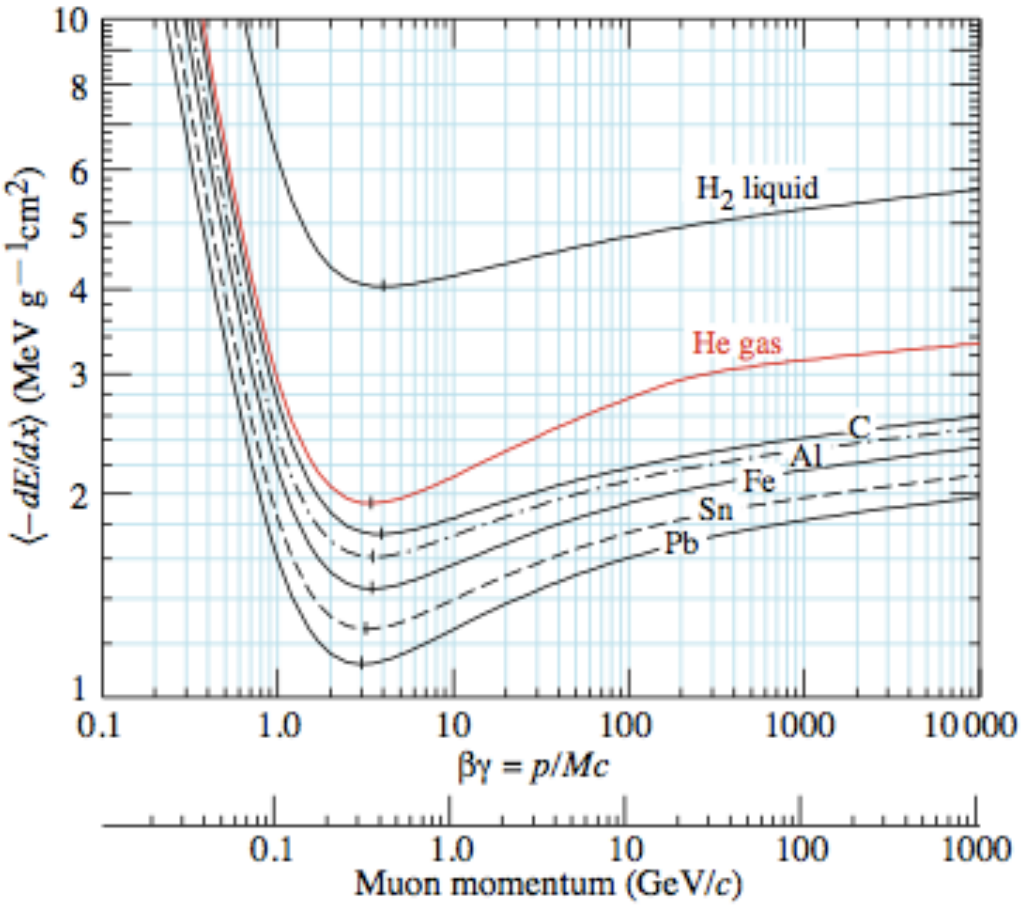
For different materials:

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

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{Z}{A}$$

of target material

(~0.5, so relatively weak dependence on target material)



For different incident particles:

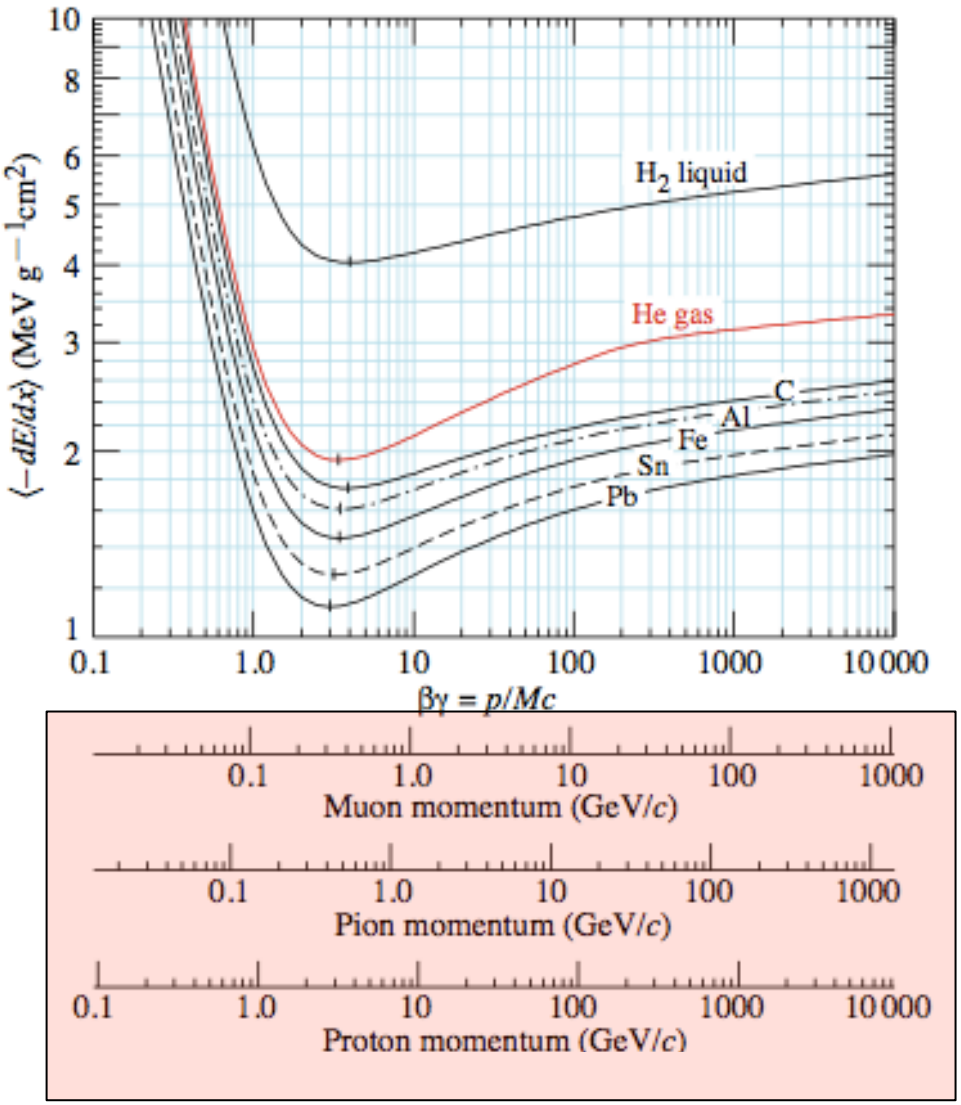
$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$$\left\langle \frac{dE}{dx} \right\rangle \; ! \quad z^2$$

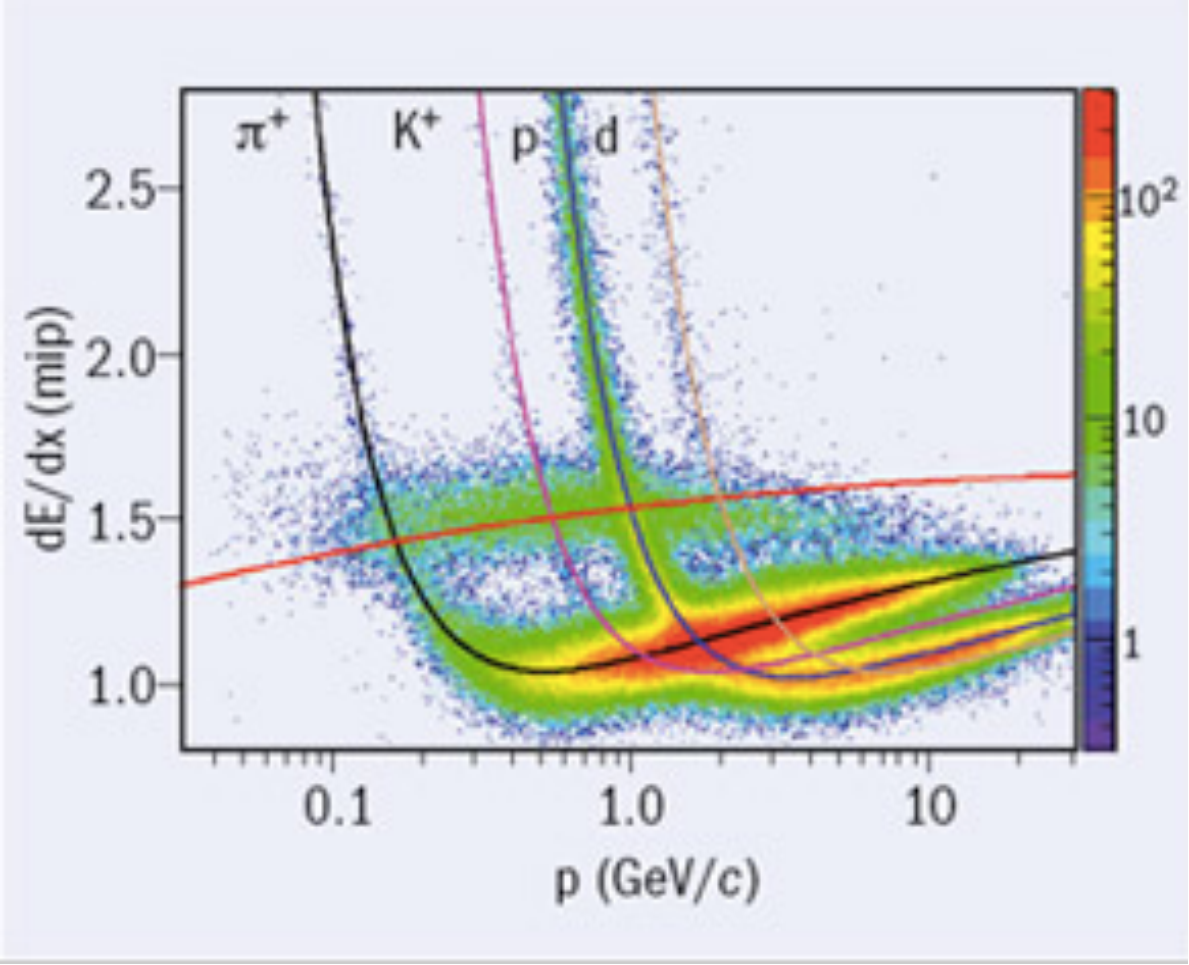
and depends on $\beta\gamma$

$$\beta\gamma = p/Mc$$

of incident particle



Particle ID using dE/dx



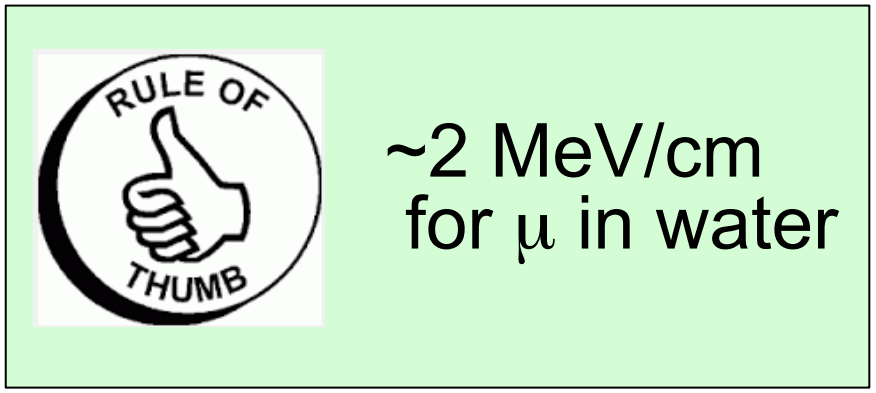
A common technique: if you know p and dE/dx, you can determine the particle type

Terminology note:

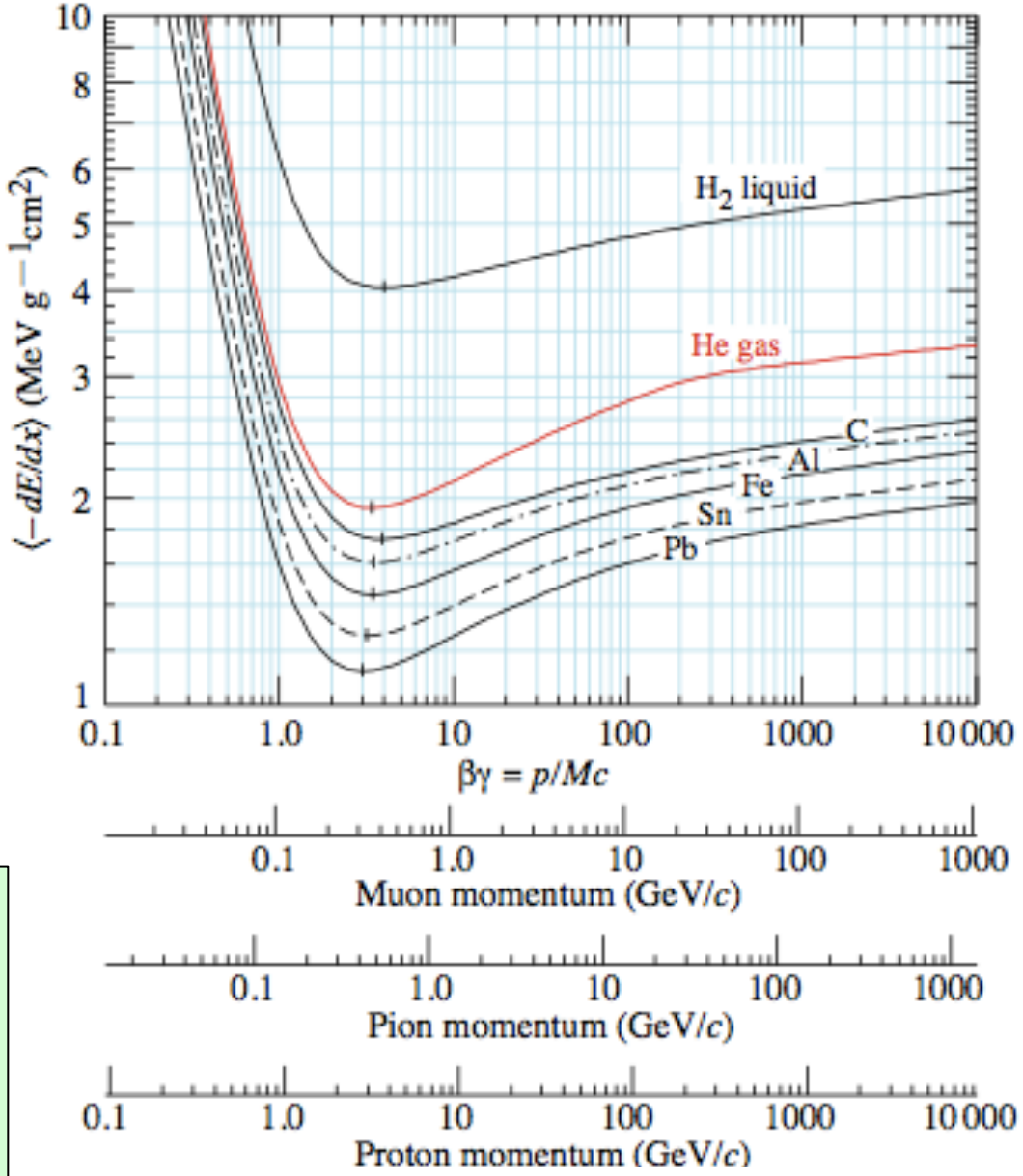
minimum in similar place for given incident particle $\beta\gamma$

"mip": minimum ionizing particle

since relativistic rise is slow, can often estimate energy loss using mip assumption

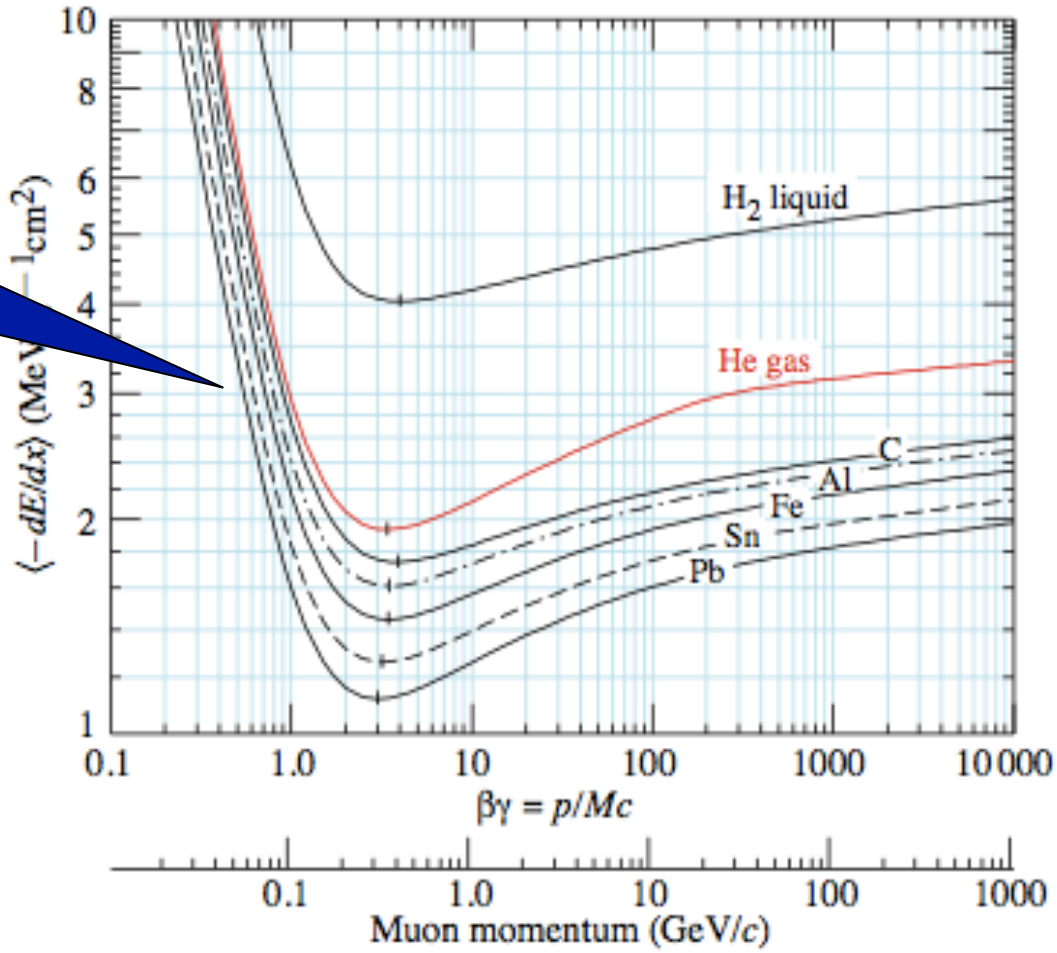


~2 MeV/cm for μ in water

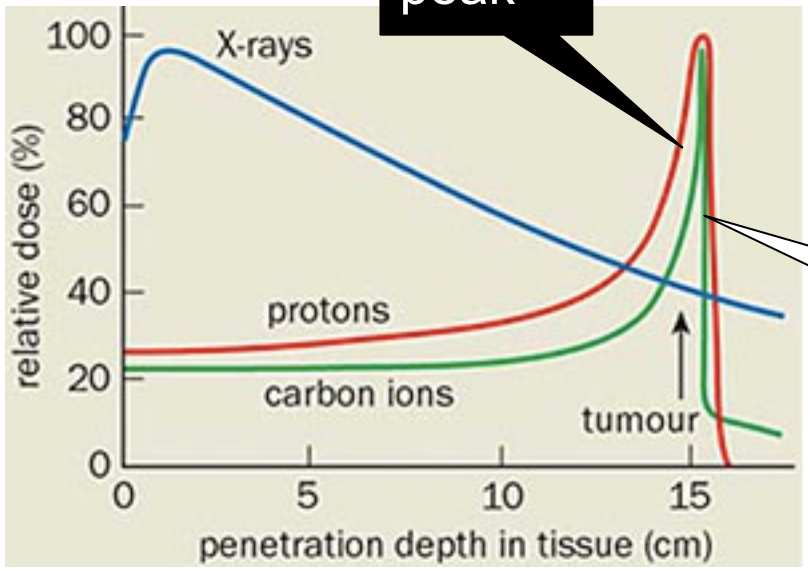


\begin{aside}

rapid increase of energy loss as particle slows down (BB breaks down)



Cute, and useful consequence:



Energy mostly dumped at the end of the particle's range... useful for killing tumors w/o damaging healthy tissue

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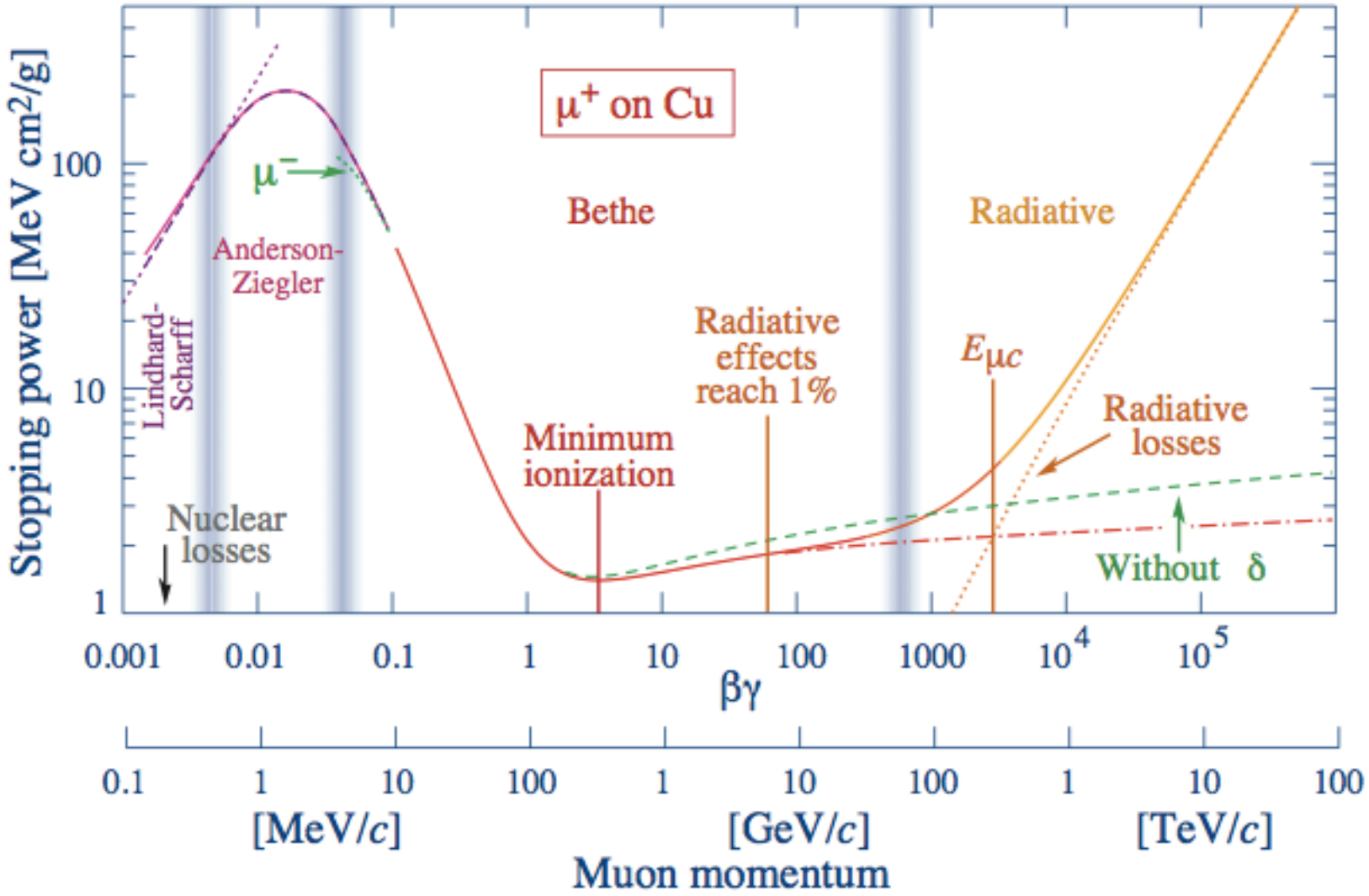
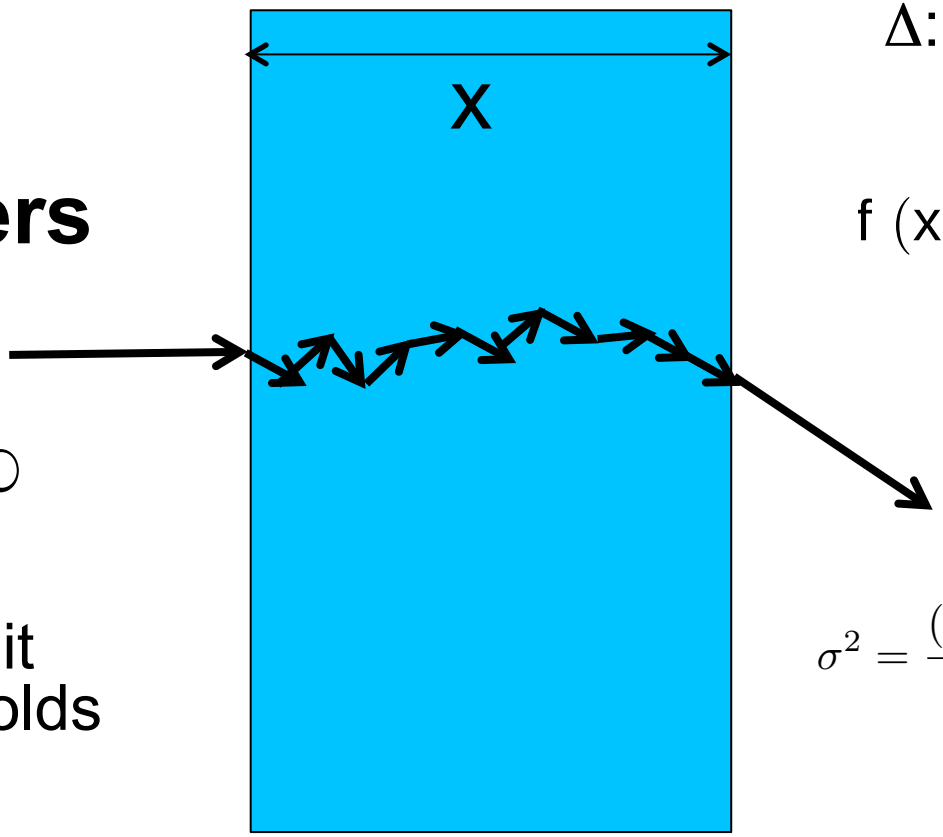
Be aware: Bethe-Bloch primarily valid for “intermediate” energies



This was mean energy loss... what about **distribution** of energy loss?

Depends on thickness of absorber...
no. of collision events N determines fluctuation behavior

Thick absorbers



Δ: energy loss

$$f(x, \Delta) \propto \exp\left(\frac{-(\Delta - \bar{\Delta})^2}{2!\ ^2}\right)$$

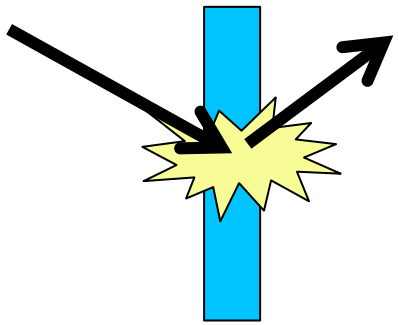
$$N \to \infty$$

Central limit theorem holds

$$\sigma^2 = \frac{(1 - \frac{1}{2}\beta^2)}{1 - \beta^2} 4\pi N_a r_e^2 (m_e c^2)^2 \rho \frac{Z}{A} x [\mathrm{MeV}^2]$$

“Thin” absorbers

Central limit theorem does not apply...
single collisions can matter

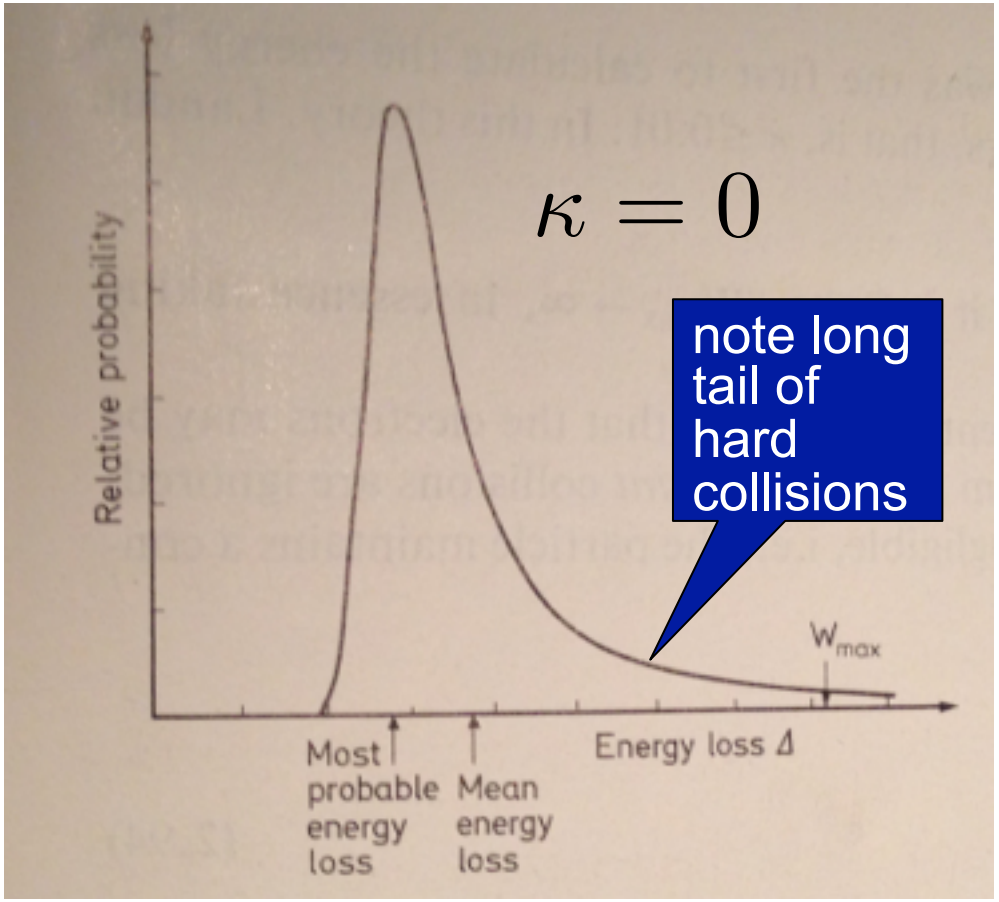


$$\kappa = \bar{\Delta}/W_{\max}$$

determines the behavior;
thin absorber corresponds to

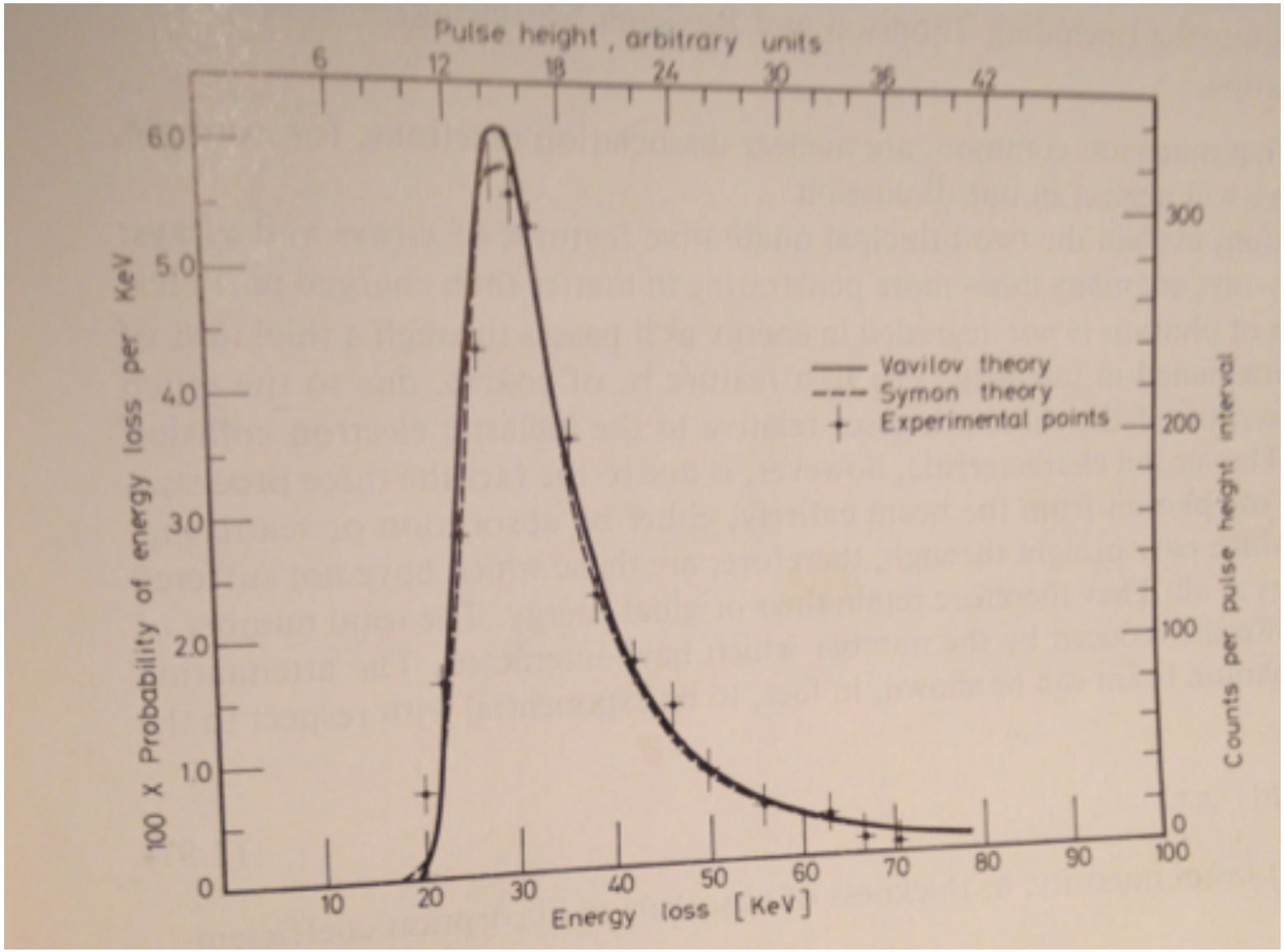
$$! < \ 10$$

Landau distribution

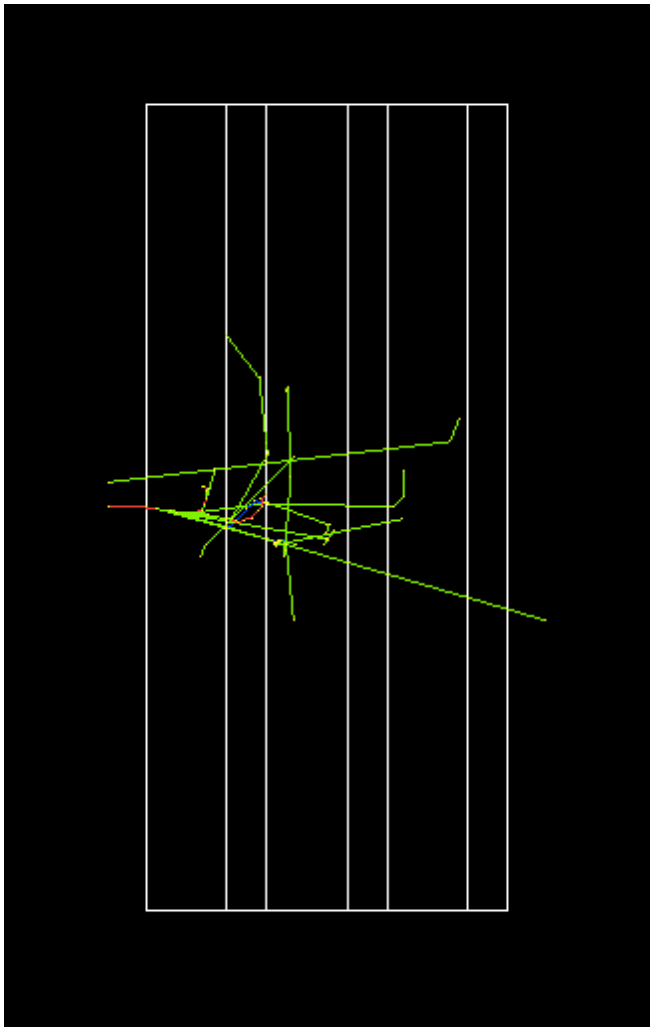


$$\Delta_{\text{most probable}} < \bar{\Delta}$$

Vavilov/Symon distributions
are refinements to the Landau
(function of κ)



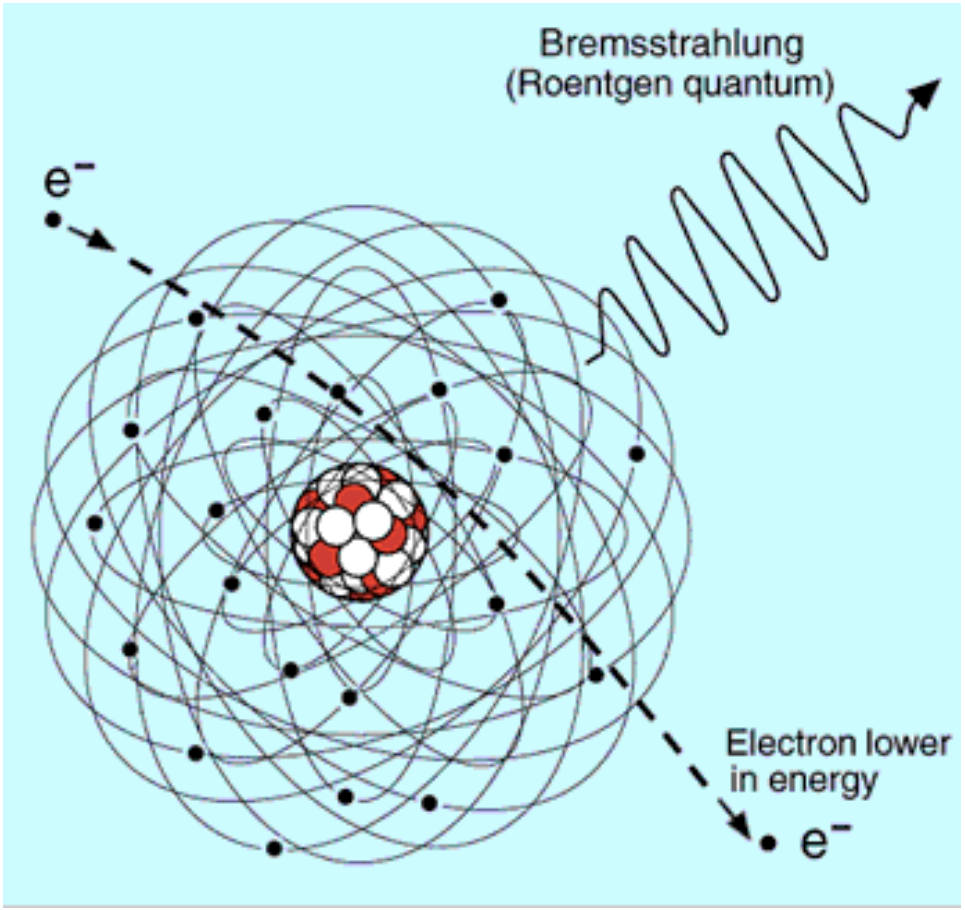
What about very thick absorbers?
... complicated, particle slows down...
➔ **in practice, use a Monte Carlo code**



- **Geant4** is the standard open-source detector simulation code
- Can specify desired materials, geometry, incident particles, physics processes
- May need tweaks for specialized applications

This was for “heavy” particles
(i.e., heavier than atomic electrons)

Electrons (and positrons) act differently...



In addition to collisional energy loss, they are easily deflected (accelerated) and they **radiate photons (bremsstrahlung)**

$$\text{prob} \propto \frac{1}{\text{m}^2}$$

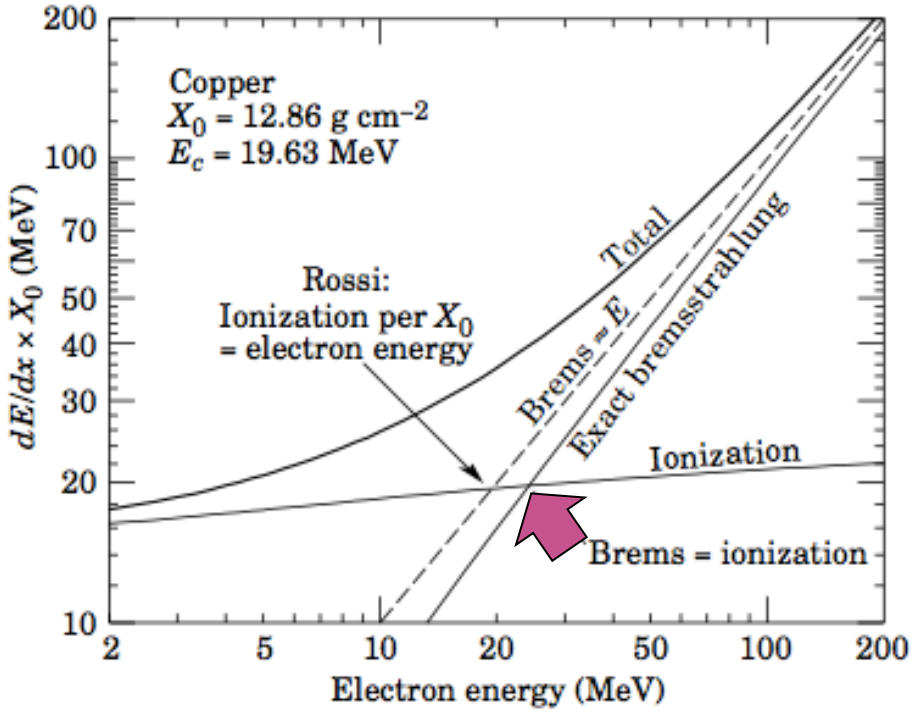
so brems from μ’s down by

$$m_e^2/m_\mu^2 = 0.511^2/106^2$$

$$\sim 4.5 \times 10^{-5}$$

$$\left(\frac{dE}{dx}\right)_{\text{tot}} = \left(\frac{dE}{dx}\right)_{\text{rad}} + \left(\frac{dE}{dx}\right)_{\text{coll}}$$

At a few tens of MeV (depends on medium) brem energy loss > ionization energy loss: crossover is called the **CRITICAL ENERGY E_c**



Bethe-Heitler approximation

$$E_c \approx \frac{1600 m_e c^2}{Z}$$

Table 2.2. Critical energies of some materials

Material	Critical energy [MeV]
Pb	9.51
Al	51.0
Fe	27.4
Cu	24.8
Air (STP)	102
Lucite	100
Polystyrene	109
NaI	17.4
Anthracene	105
H_2O	92

Another commonly used quantity to characterize radiation of electrons/positrons: **RADIATION LENGTH, L_{rad}**

In the high-energy limit where radiation loss dominates

$$E = E_0 \exp\left(\frac{-x}{L_{\mathrm{rad}}}\right)$$

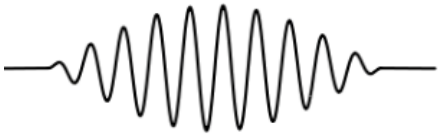
Table 2.3. Radiation lengths for various absorbers

Material	[gm/cm^2]	[cm]
Air	36.20	30050
H_2O	36.08	36.1
NaI	9.49	2.59
Polystyrene	43.80	42.9
Pb	6.37	0.56
Cu	12.86	1.43
Al	24.01	8.9
Fe	13.84	1.76
BGO	7.98	1.12
BaF_2	9.91	2.05
Scint.	43.8	42.4

Shorthand thinking:
L_{rad} is thickness for which you can expect to get an **electromagnetic shower** (more on this coming shortly)

Energy loss of photons in matter

In our context, this mostly means
x-rays and gamma rays

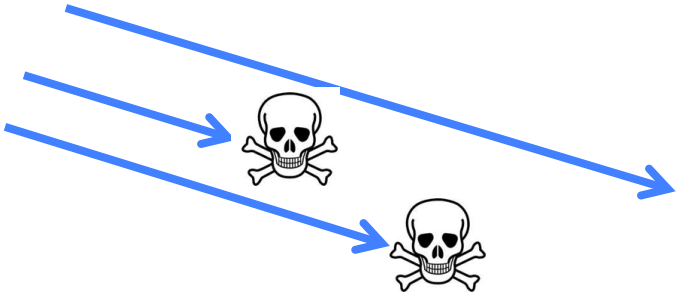


photons have no electric charge...
➔no Coulomb-induced collisions

4 electromagnetic energy loss mechanisms:

- photoelectric effect
- Compton scattering
- pair production
- (photonuclear effect)

most of these
destroy the photons rather than
change the energy (attenuation)

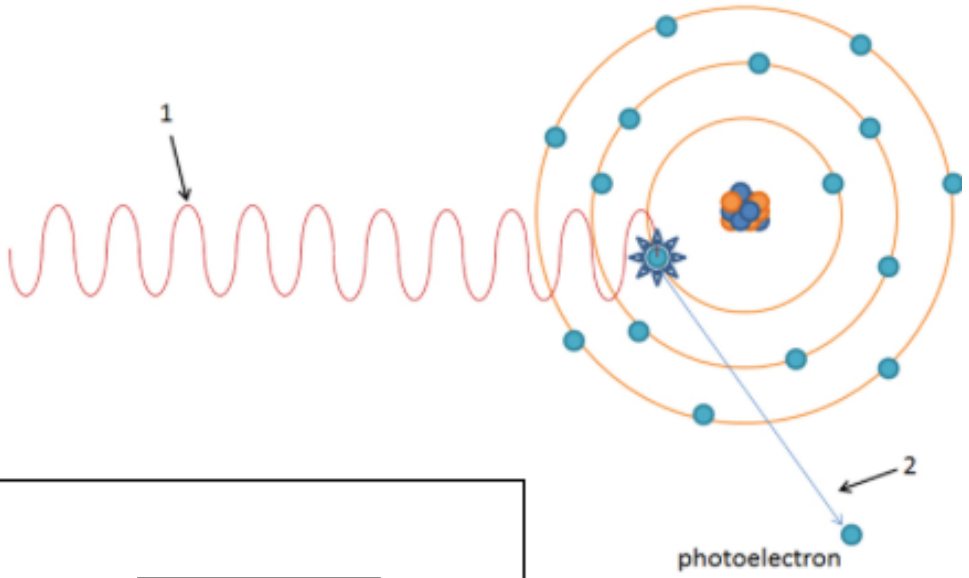


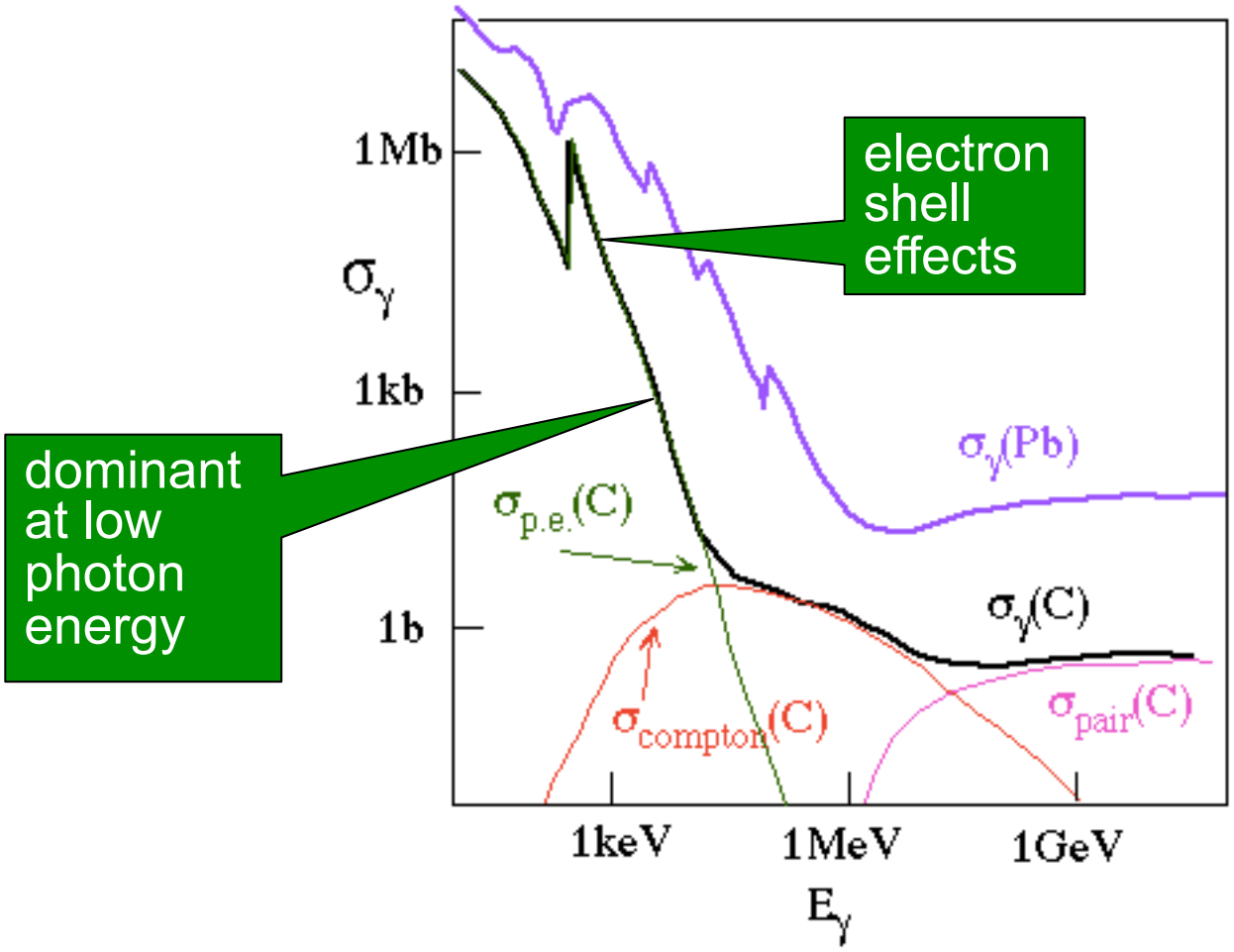
(Rayleigh scattering: scattering
off whole atoms; small at energies of
interest here)

Photoelectric Effect

Pop an electron out of an atom (photon is gone)

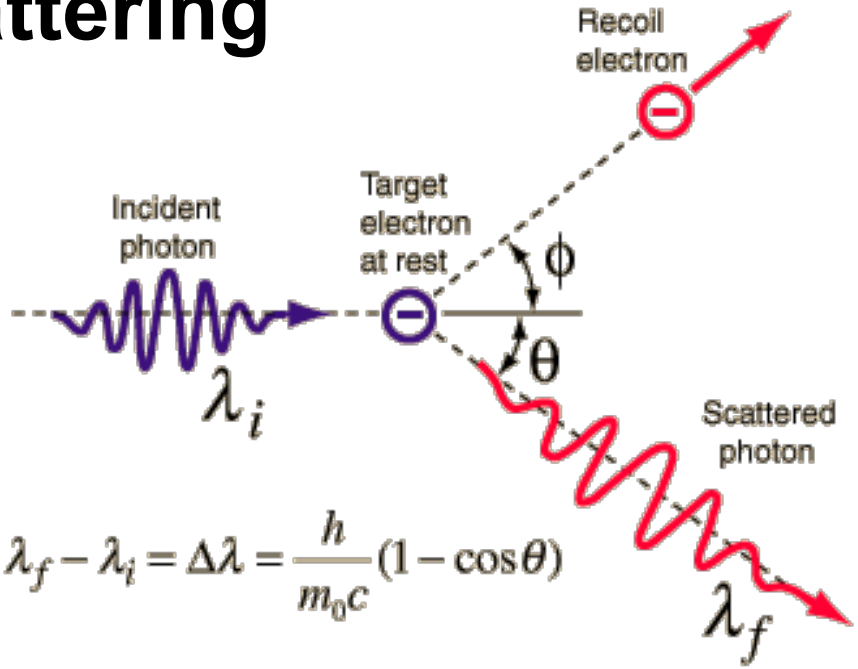
$$E_e = h\nu - \text{B.E.}$$

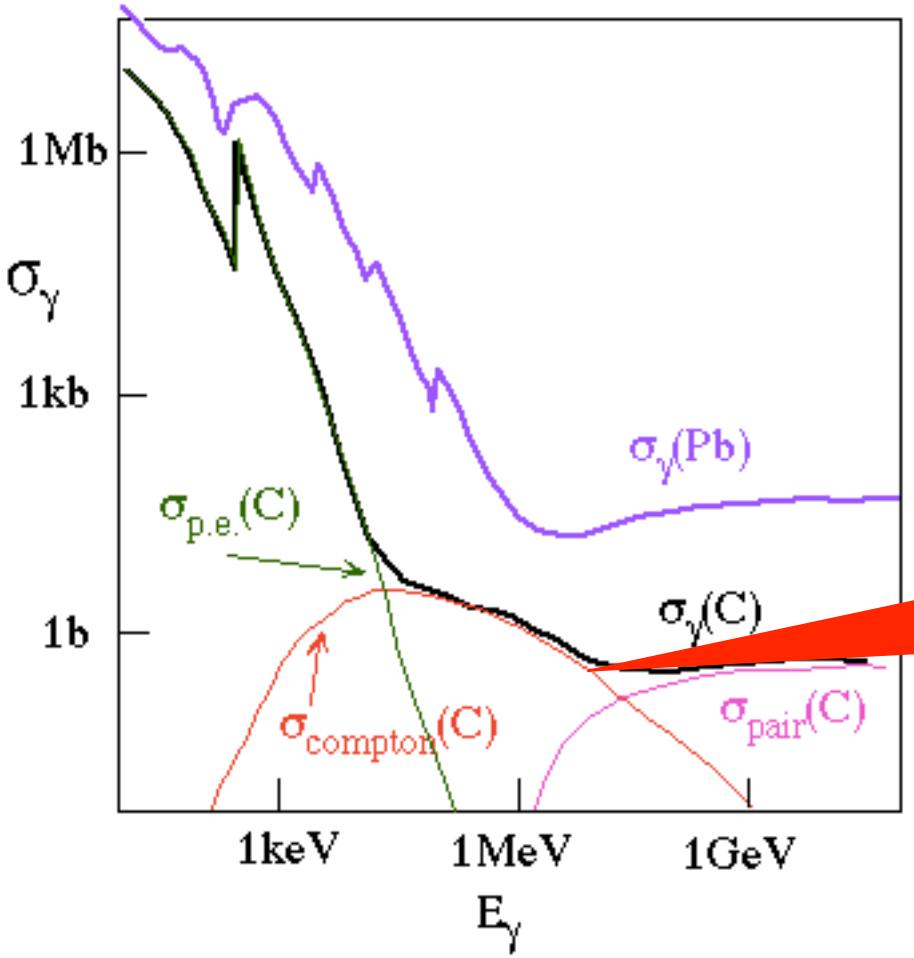




Compton Scattering

Kick an electron;
(the electron subsequently
loses energy... γ keeps going)

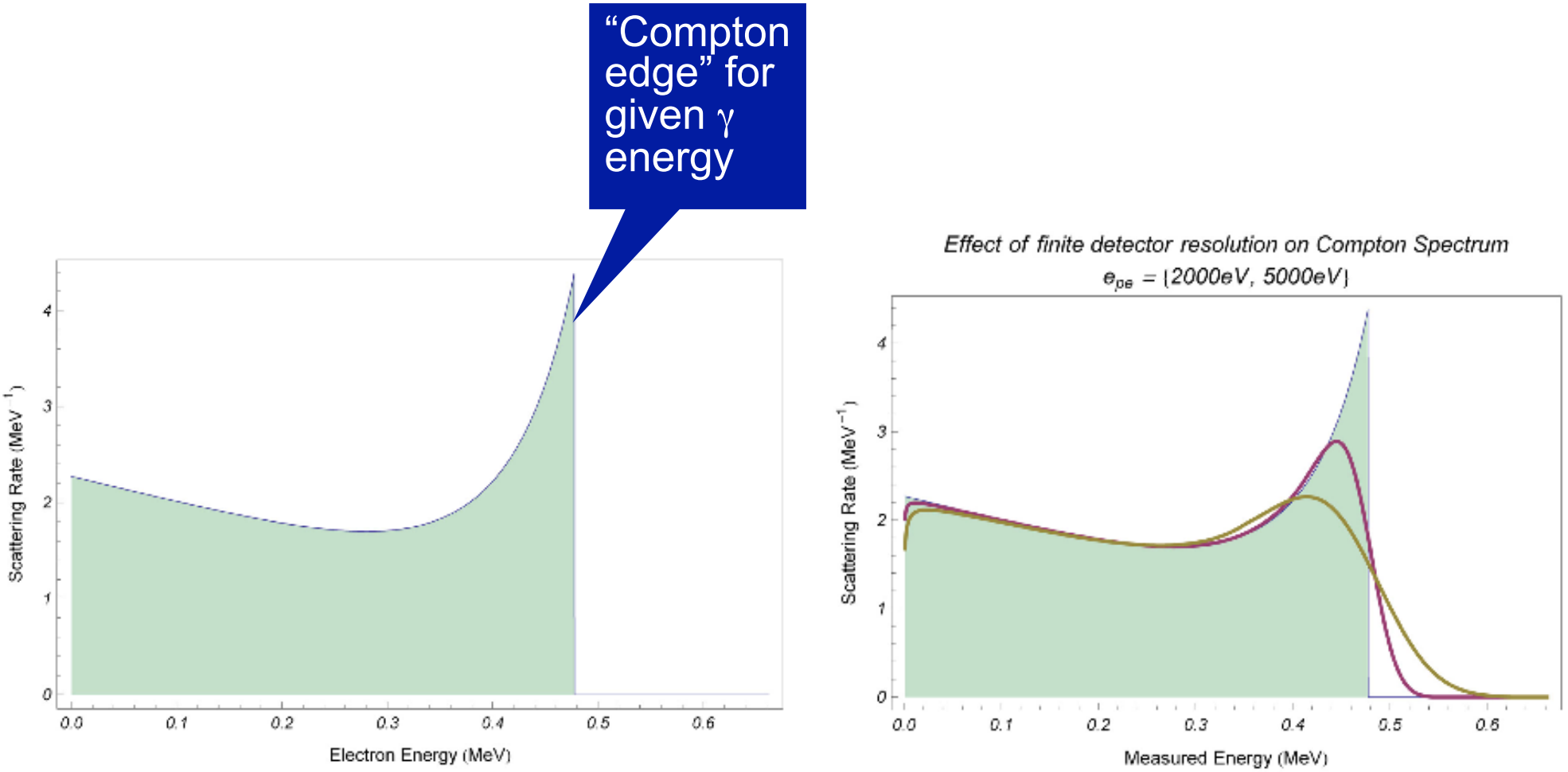




dominant at intermediate photon energy

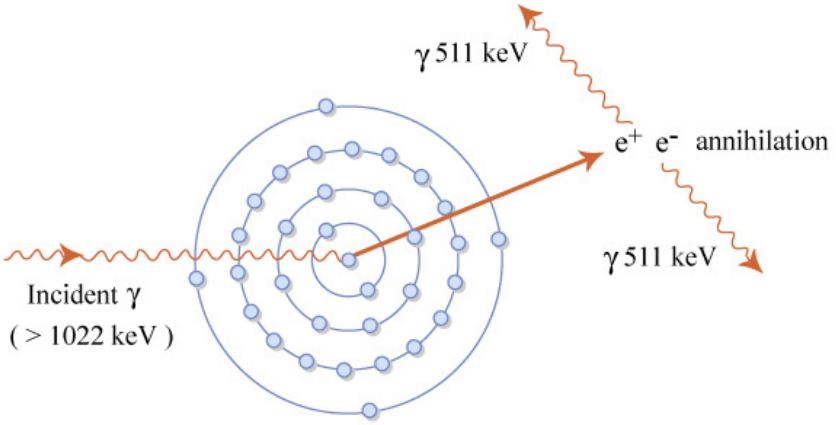
Cross section calculated with Klein-Nishina formula (QED)

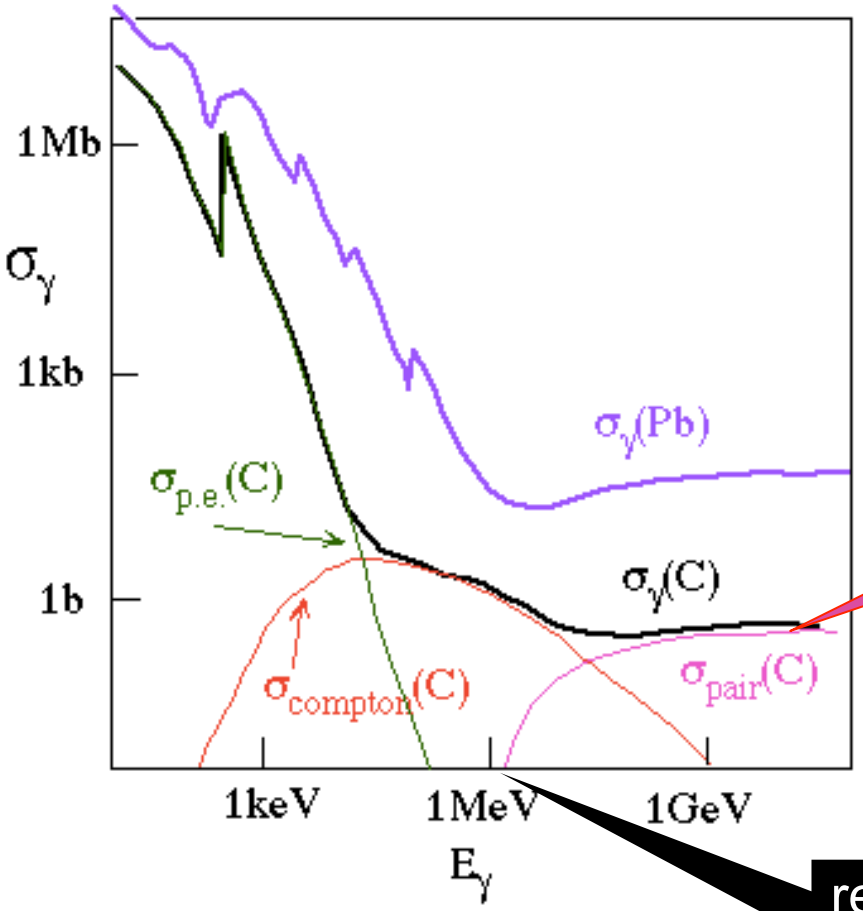
Compton recoil energy distribution



$$W_{\max} = h\nu\left(\frac{2\gamma}{1+2\gamma}\right) \qquad \gamma = \frac{h\nu}{m_e c^2}$$

Pair production

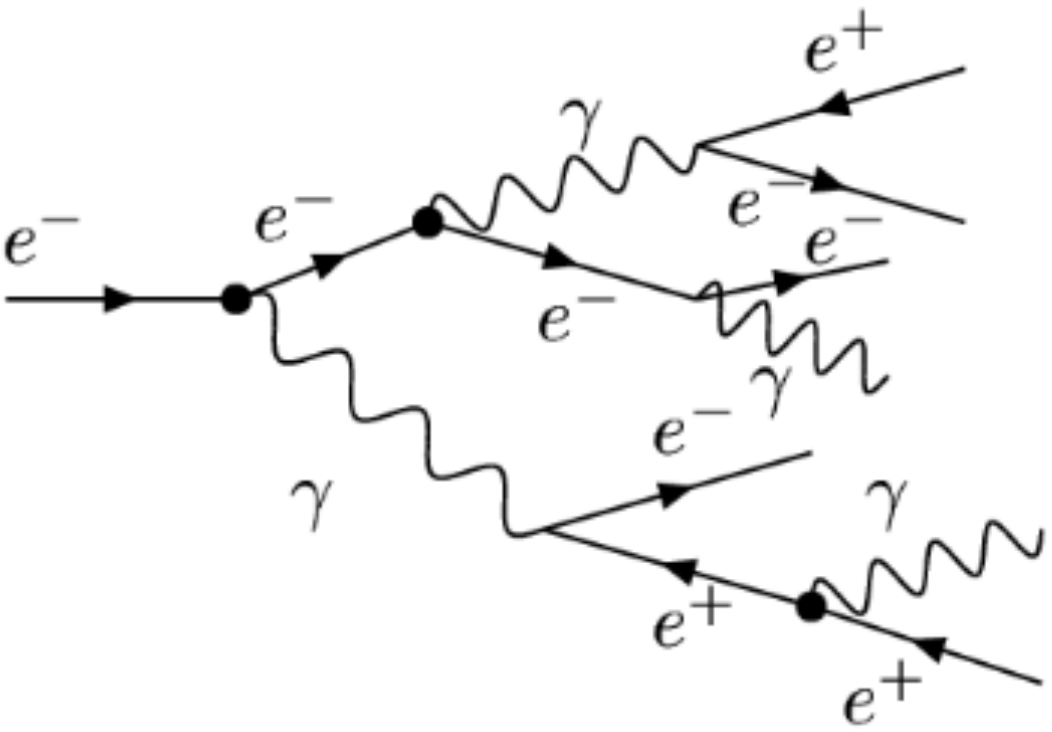




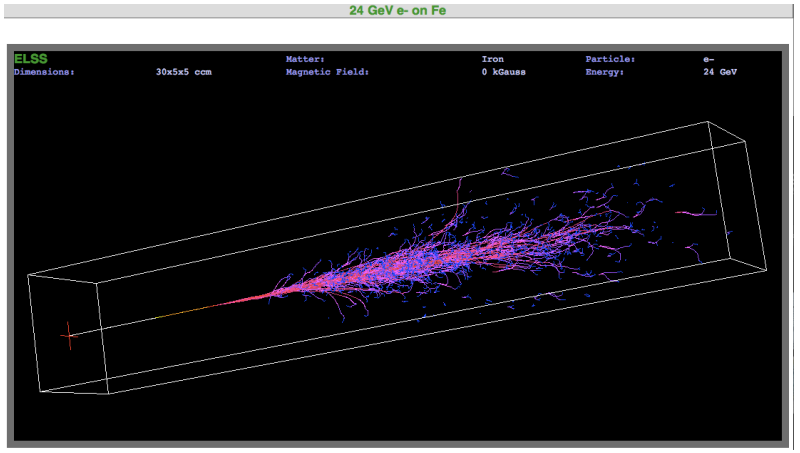
increases with energy and dominant at high energy

requires at least $2m_e$ of energy

Electromagnetic showers



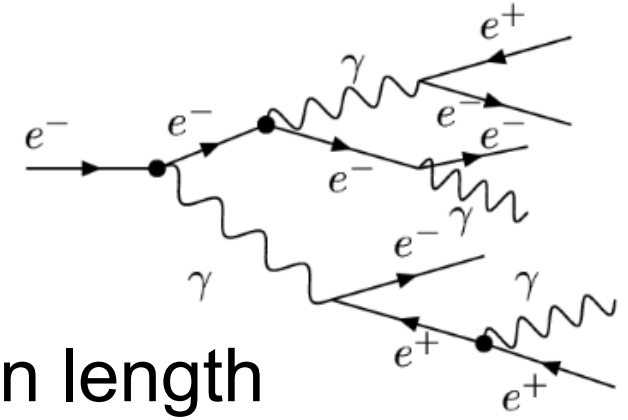
An avalanche!
Can start with either a photon or $e^{\pm}$



electron brems
➔ γ pair-produces
➔ $e^{\pm}$ brem
... until energies drop below pair-production threshold and/or E_c for electrons

Electromagnetic shower size estimate

(in radiation lengths)



- Start with energy E_0
- Photon will convert after ~1 radiation length
  ➔ $E_0/2$ for each of e^+, e^-
- Divide energy per particle again by 2 after another radiation length
- After t radiation lengths,

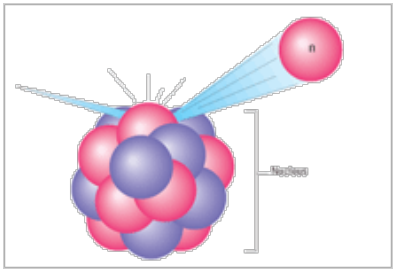
$$N \; ! \;\; 2^t \quad \text{so} \quad E \sim E_0/2^t \quad \text{for each particle}$$

$$E(t_{\text{max}}) = E_0/2^{t_{\text{max}}} = E_c$$

➔ $$\boxed{t_{\text{max}} = \frac{\ln(E_0/E_c)}{\ln 2}}$$

Neutron energy loss

Neutrons interact via the strong force
short range force, so rare interactions
... neutrons are penetrating, and
will tend to ping around

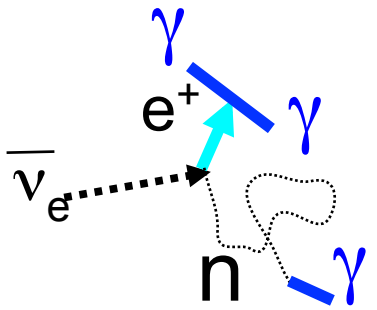


Mechanism	Reaction	Notes
Elastic scattering from nuclei	**A(n,n)A**	**Main mechanism of energy loss**
Inelastic scattering	A(n,n')A*, A(n,2n')B,..	Deexcitation products or other secondaries
Radiative neutron capture	n+(Z,A) ➔ γ + (Z,A+1)	~ 1/v, so requires low energy
Other nuclear reactions	(n,p), (n, d), (n, α), etc.	Low energies required
Fission		Low energies required
Hadronic showers		High energy (>100 MeV)

There are specialized codes for simulating neutrons
(e.g., MCNPX, FLUKA... G4 has a bad rep, but is fine for many applications)

Neutron moderation and capture

Common for low-energy neutrino experiments, e.g. neutron from inverse beta decay



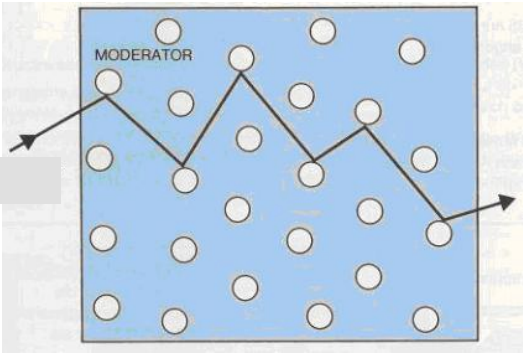
$$\bar{\nu}_e + p \;!\quad e^+ + n$$

$$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$$

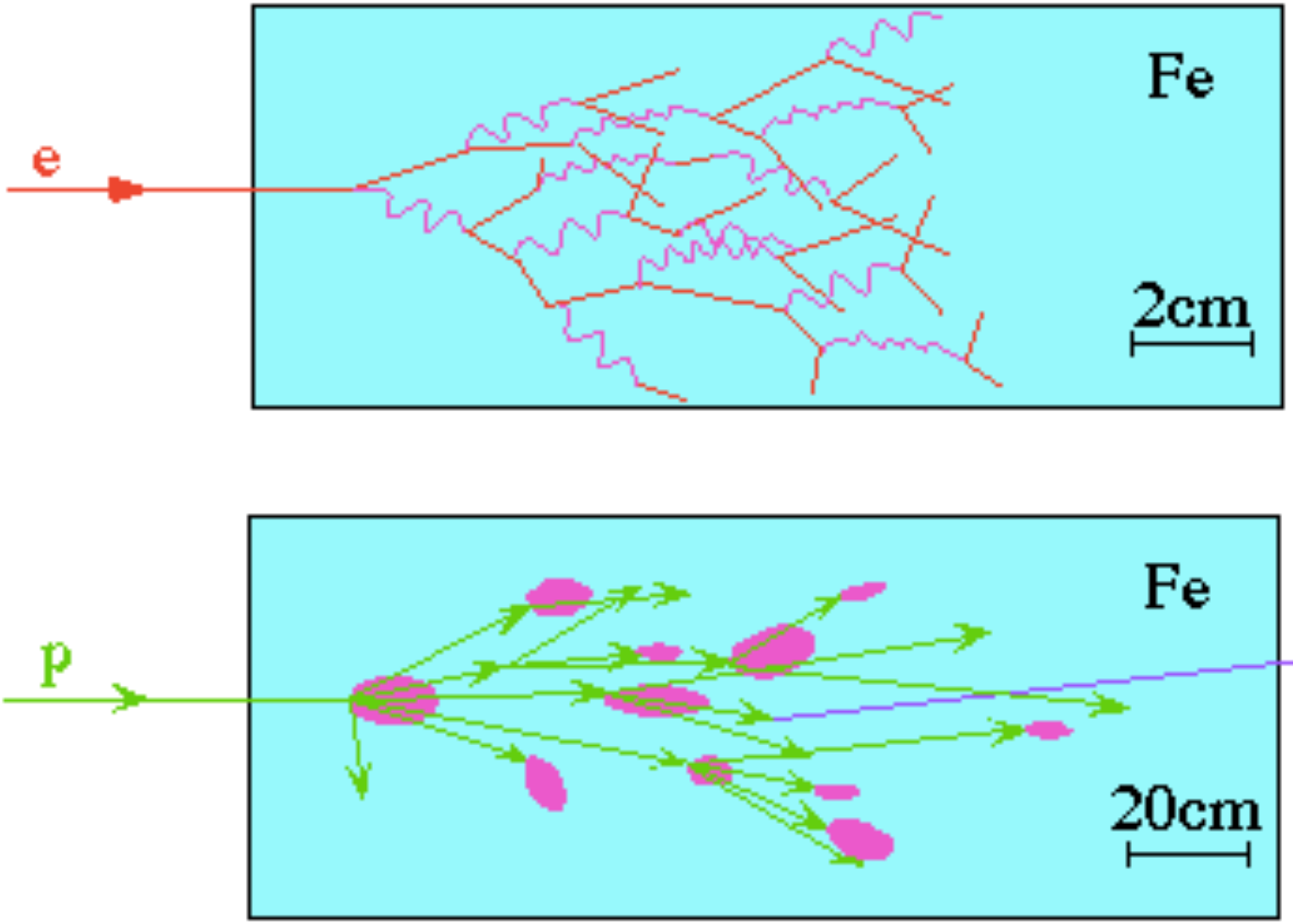
The neutron must thermalize (E~kT~1/40 eV) before capture ... “moderation” by multiple elastic scattering

Elastic kinematics: $\left(\frac{A-1}{A+1}\right)^2 E_0 < E < E_0$

For small A , nucleus takes more energy away per scatter ➔ moderators made out of light materials (hydrogen, carbon...)



Hadronic showers also relevant for
high energies (initiated by protons, neutrons,..)



What to take away from this lecture

- How to calculate neutrino event rates

$$R = \Phi \ \sigma \ N_t$$

- How to estimate energy loss

<u>Most important effects</u>**:** (for ν experiments)

- charged particles
  - "heavy" (μ, π, p, ...): **Bethe-Bloch (ionization)**
  - e^+, e^-: **collisions + radiation**
    (know critical energy/radiation length)
- photons: **PE + Compton + pair production**
- neutrons: **elastic scattering** (+ radiative capture)

Lecture overview

Lecture 1: general principles of neutrino interactions and particle detection

Lecture 2: neutrinos at GeV energies