Radiation Interactions with Matter

RT4220 – Lecture #8

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Review of Radiation

- Two types of Radiation:
  - **Charged Particles**
    - Alpha, Beta+, Beta-, Protons
  - **Electromagnetic Radiation**
    - X-ray, Gamma
- Particles interact with matter to shed energy, eventually thermalize and typically join atoms
- Most of the energy lost by particle is heat, ionizations are much less, but **very relevant biologically**

Charged Particles Interactions

Alphas, betas, protons, oh my~

Modes of Charged Particle Interaction

- Excitation of the Incident Atom (**Thermalization**)
  - Ever throw a ball underwater?

- Direct Collision with Electrons (**Ionization**)
  - Biological damage and potential Auger

- Direct Collision with Nucleus (Nuclear Reaction/**Bremsstrahlung**)
  - You love this one! High energy gamma production!

Charged Particle Thermalization

- Charged particle interacts with electron clouds at a distance, causing vibrations and giving off infrared
- Slow burn novella
- Any energy lost in this way is inconsequential to us
- Eventually, charged particle slows down to Brownian Motion status, harmless

Charged Particle Ionization

- Possible ionization modes:
  - Charged particle collides with **orbital electron** → secondary electron overcomes binding energy, excess is kinetic energy
  - Rarely, `` with **inner shell electron** → Auger + secondary electron
- If a secondary electron has enough energy to cause further ionizations, it's called a **delta-ray** ($\delta - \mathrm{ray}$)

Charged Particle Nuclear Interaction

- If a charged particle has high enough energy (say, alpha particle), it can penetrate the nucleus and start a **nuclear reaction**
- More likely, especially for electrons, particle **deflects** from the nucleus
- Particle rapidly accelerates (slows down, changes direction) → Bremsstrahlung!

Bremsstrahlung

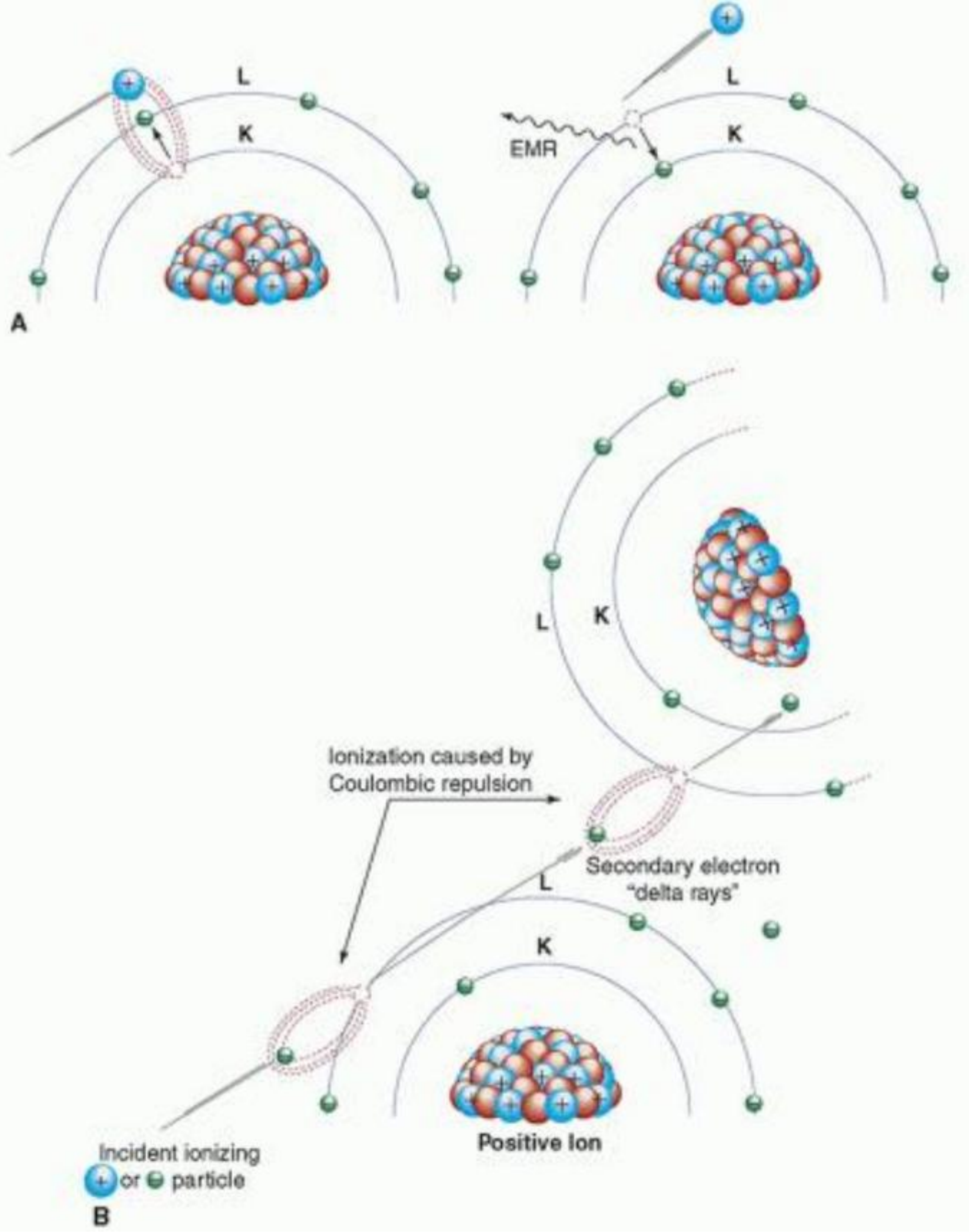
- German: “Braking Radiation” (like a car, vroom vroom, das auto)
- Hard and Fast acceleration of charged particle results in possibly high energy gamma
- Energy of gamma is a spectrum (has a maximum and average ITS NEVER ZERO)
- Angle of deflection determines energy of the photons
  - Slight deflection → low-energy photons
  - Great deflection → high-energy photons

Excitation VS Ionization and Delta-Ray

A. Excitation: Far encounter between charged particle and shell electron results in low energy deexcitation photon

B. Ionization: Close encounter between charged particle and shell electron pulls/pushes electron away from atom (now called secondary electron)

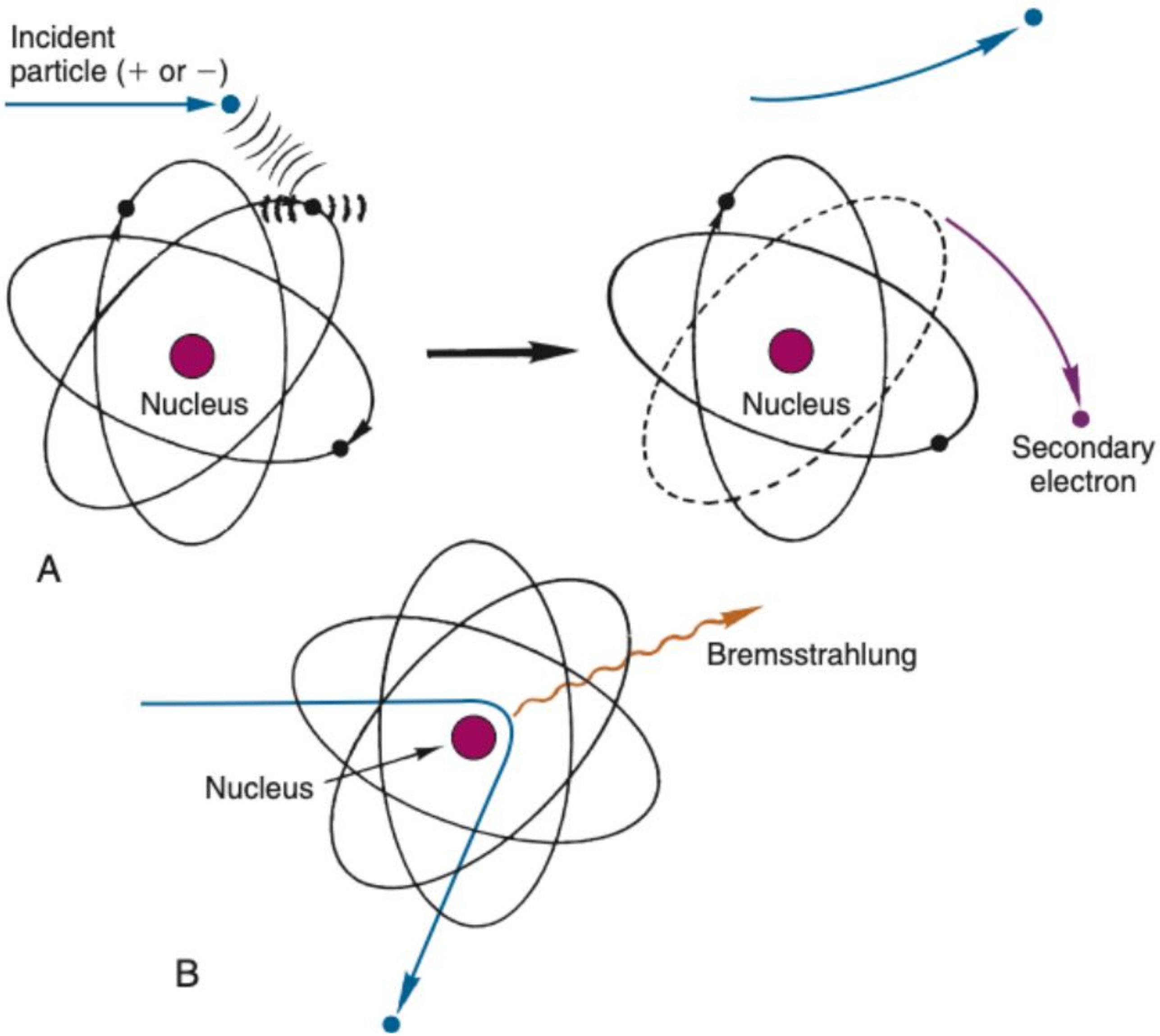
C. If secondary electron can ionize other atoms, it is called a delta-ray



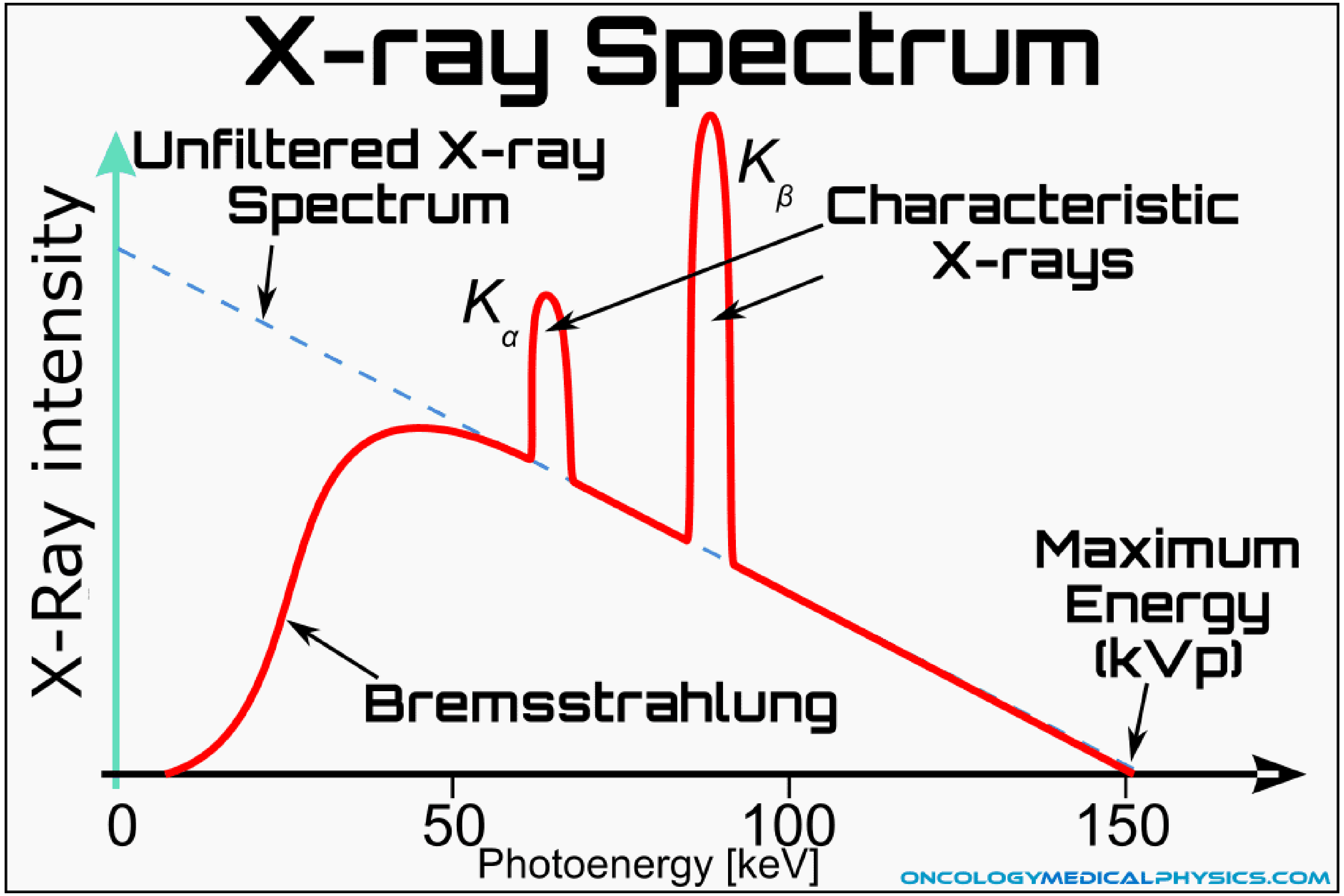
Ionization VS Bremsstrahlung

A. Ionization: charged particle bumps off an electron, origin of electron determines Auger/Char. Rad., secondary electron can be a delta-ray

B. Bremsstrahlung: near nuclear interaction causes rapid acceleration which gives off photons, these photons can wreak havoc



Bremsstrahlung Spectrum



Collisional and Radiation Losses

- Collisional Losses: Energy deposited typically stays very close to the source
  - Excitation and Ionization
  - Generally greater than radiation losses

- Radiation Losses: Energy can travel very far
  - Bremsstrahlung
  - Increases greatly for **high-energy charged particles** and **high atomic number targets (Z)**

Collisional VS Radiation Losses

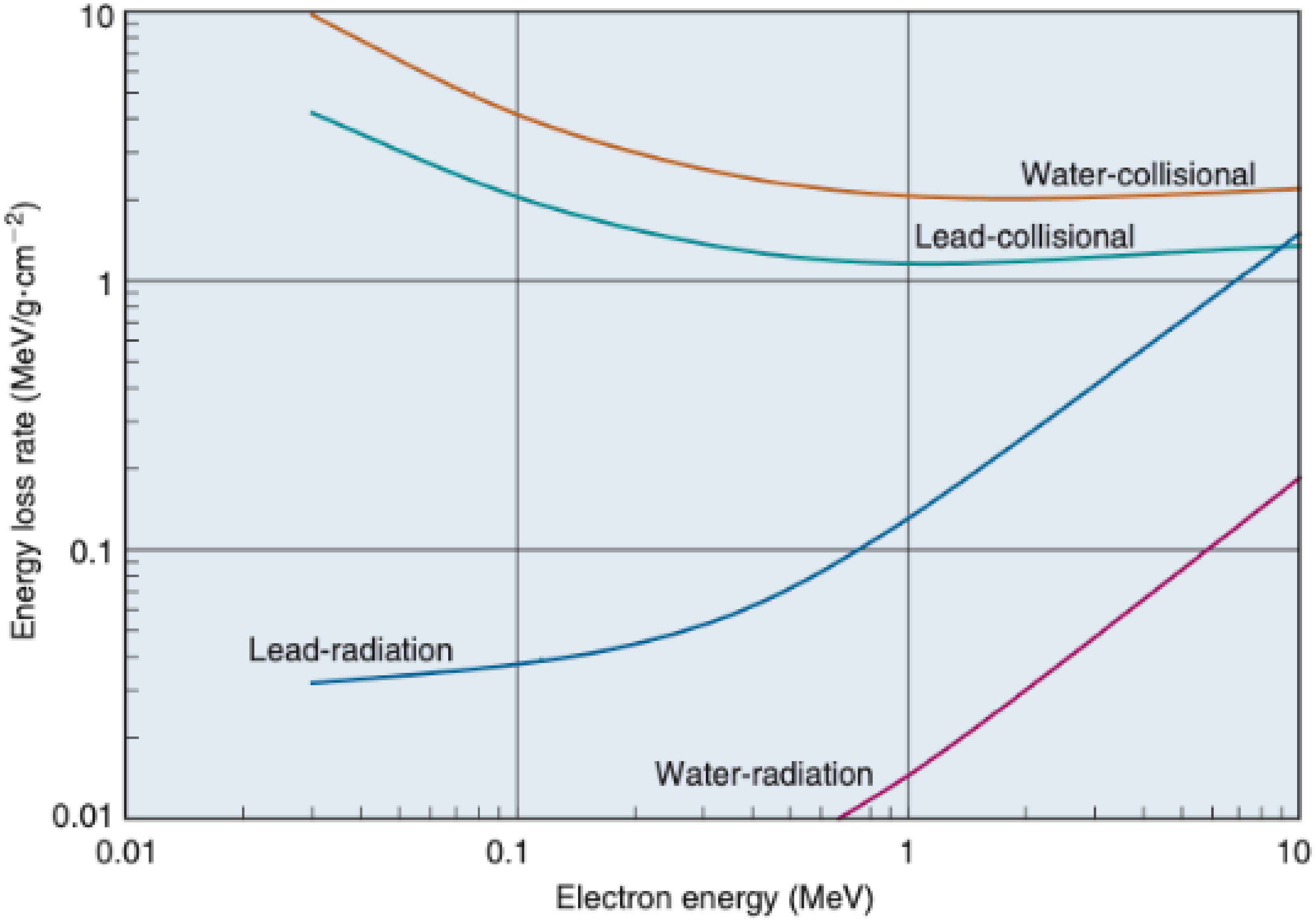
First Line (Yellow): Low-Z target, collisional losses

Second Line (Green): High-Z target, collisional losses

Third Line (Blue): High-Z target, radiation losses

Fourth Line (Magenta): Low-Z target, radiation losses

Notice log-scale, flipped behavior between Coll. And Rad. losses



Charged Particle Tracks in Matter

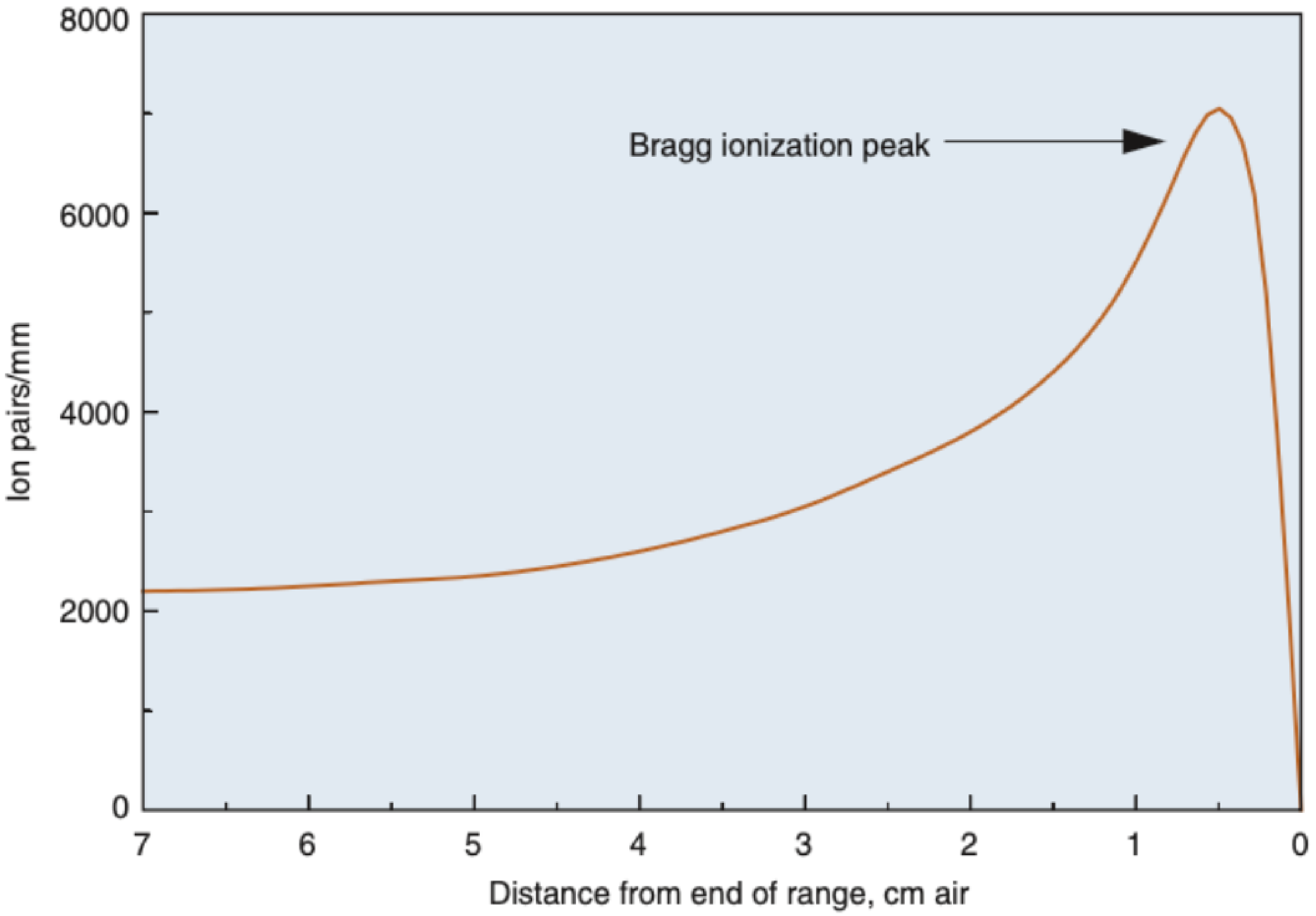
- Charged particles leave behind wake of ionized atoms and secondary electrons about 100 um wide due to delta-rays
- Path of particle varies greatly by particle weight and charge:
  - **Alpha particles travel straight** due to very few bremsstrahlung and relative size difference compared to electrons, slow, continuous loss of energy
  - **Beta particles travel tortuous path** due to them being the same size as the secondary electrons and bremsstrahlung, catastrophic events are typical
- Speed of particles with the same kinetic energy varies greatly:
  - 4 MeV KE alpha travels 10% of the speed of massless things
  - 1 MeV KE beta travels 90% of the speed of massless things
- Density of ionization wake differs greatly:
  - **Alpha particles lose energy much faster** → dense wake
  - **Beta particles lose energy much slower** → less dense wake

Energy Loss Dependence

- Energy loss per unit of distance **depends on**:
  - **Energy of the particle** (Relativity, Coll./Rad. Loss Changes)
  - **Composition of target** (Atomic Number)
  - **Density of target** (More Targets)
- This concept is described with physics words:
  - **Linear Stopping Power** $(\mathrm{S_l})$: Total energy loss per unit distance [MeV/cm]
  - **Linear Energy Transfer** (LET): Energy lost and deposited "locally" along the track [keV/um]
    - In the low energy domain, radiation losses are low, so $\mathrm{LET} \cong \mathrm{S_l}$
    - Alpha LET: ~100 keV/um in soft tissue
    - Beta LET: ~0.2 – 2.0 keV/um between 10 keV and 10 MeV in soft tissue
  - **Specific Ionization** (SI): Number of ion pairs produced per unit length (1/mm)

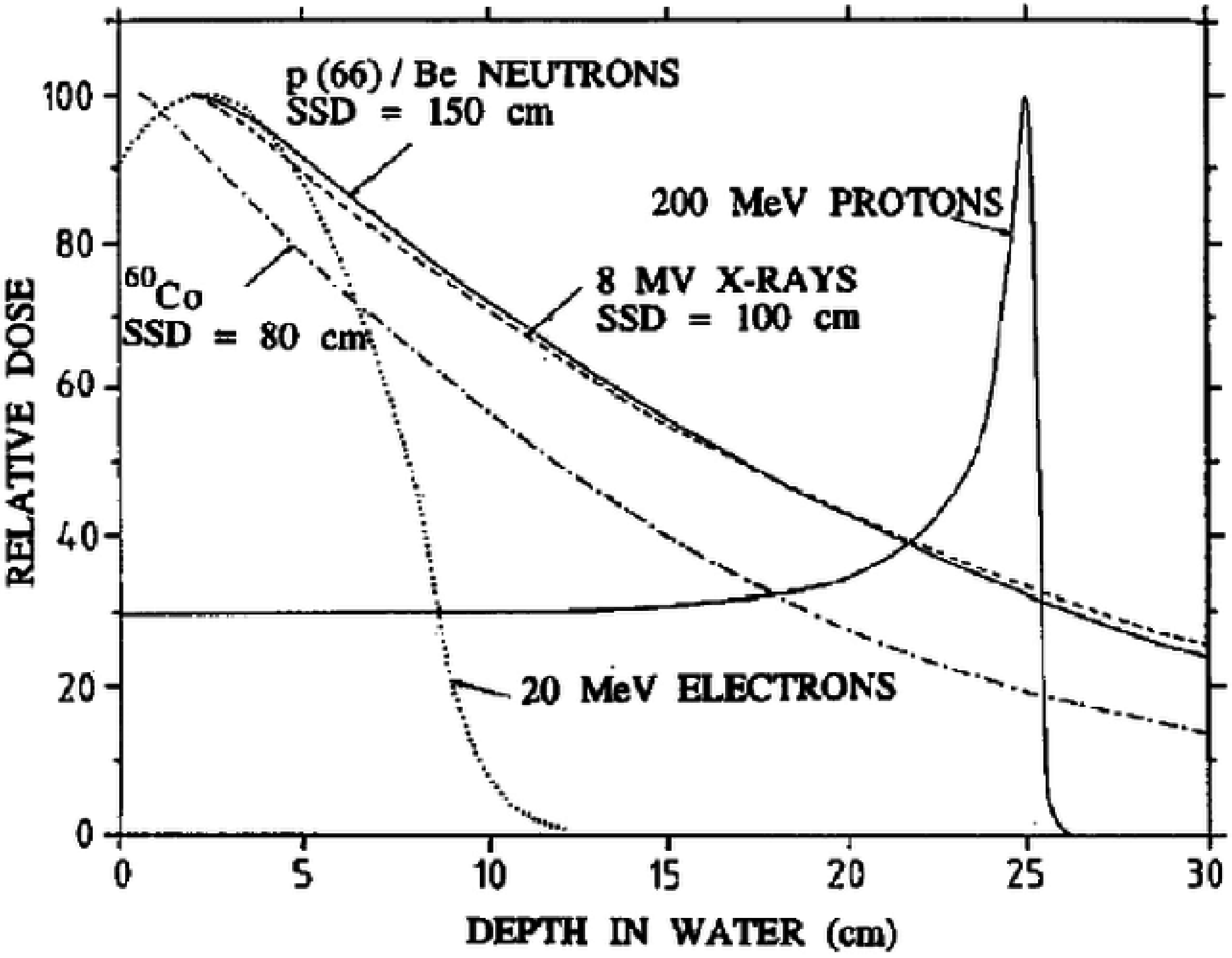
Bragg Peak

- As a **charged particle slows down**, its **ionization density increases**
- Heavy charged particles peak very sharply near the end of their track
- Differs greatly from beta particles and photons



Energy Deposition by Particle Type

- **Electrons:** Peak, then quickly deposit their energy, not nearly as quick as protons and very long compared to alphas (not shown)
- **Protons:** Constant energy transfer, slow burn, LET increases sharply, BRAGG PEAK, no more protons
- **X-rays (Photons):** Log-style very slow energy deposition, approaches infinity depth
- **Neutrons:** VERY SIMILAR to photons



Use Cases for Different Particle Types

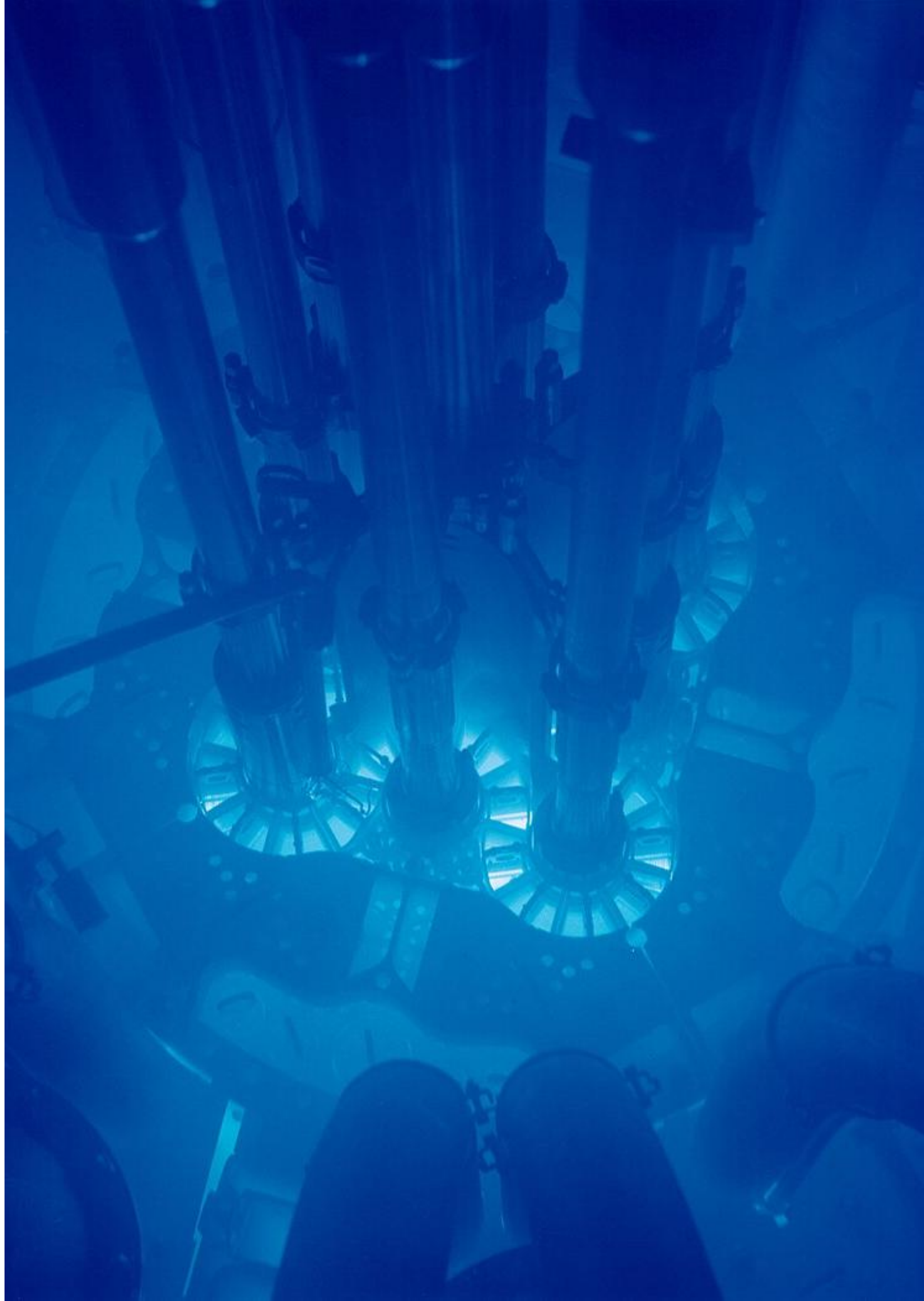
- Alphas: Not super useful, cannot penetrate beyond dead skin layer, if only we could get it inside the body and deposit it in the tumor! (THERANOSTICS)
- Betas: Somewhat localized energy deposition, but cannot penetrate deep into the body without serious harm to normal tissue
- Protons: Extremely localized energy deposition, but prohibitively expensive and requires utmost precision (forget treating lungs!)
- Photons: Energy deposition is very-well studied, can penetrate through the whole body to reach deep tumors
- Neutrons: Ask Dr. Jay Burmeister, Karmanos was KING of the Neutron World under his stewardship, now defunct globally, afaik

Fun Side Note: Cherenkov Radiation

"Chair-ing K'o'f"

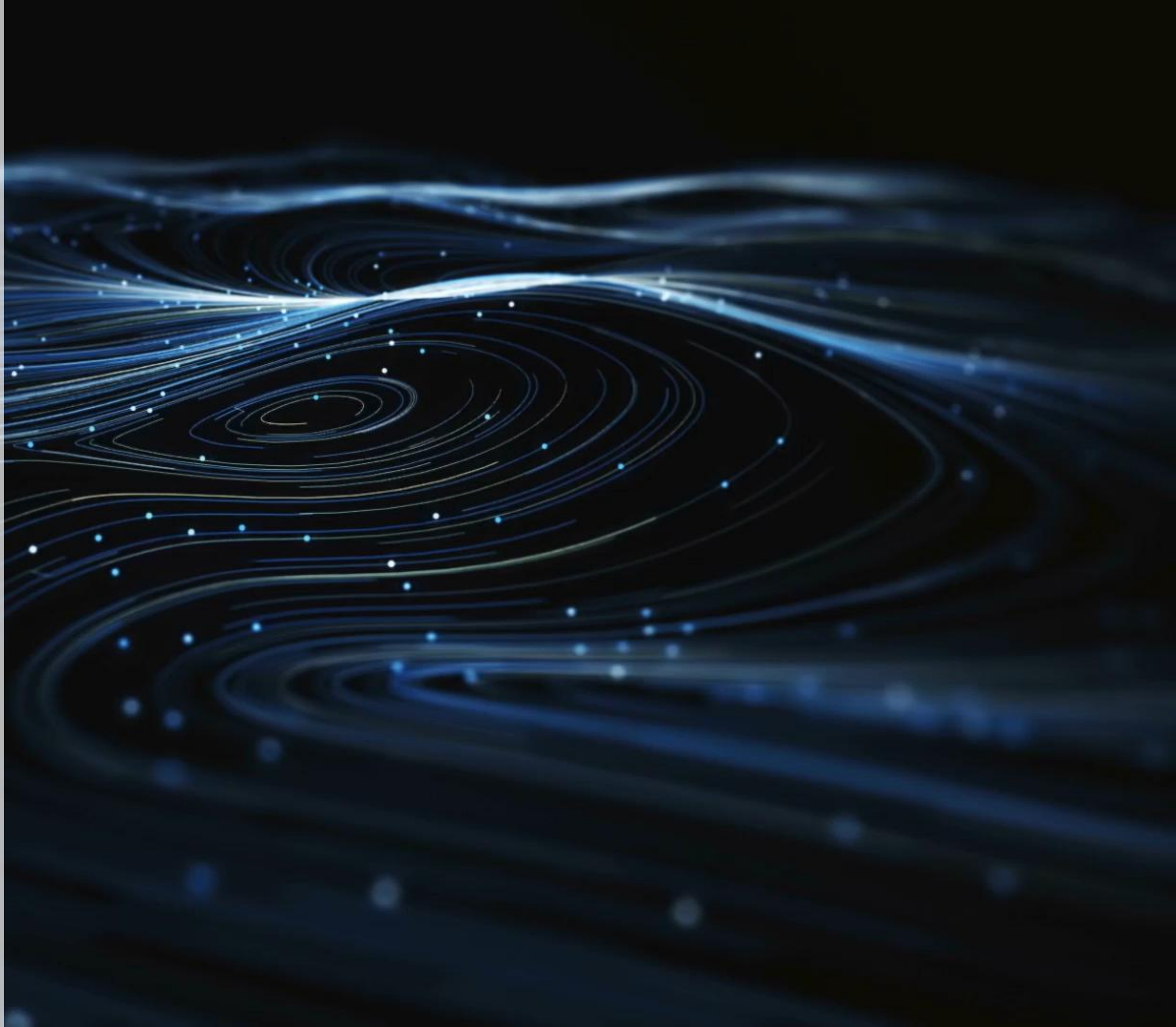
A VERY fast charged particle slows down in a medium (say, water), thus emitting photons; if the particle travels faster than the photons propagate through the medium, then constructive interference occurs which allows us to see the radiation with our own eyes. The charged particle is literally traveling faster than the light can propagate in the water creating a "sonic-boom" like effect, but for light.

Very Cool!



Electromagnetic Radiation Interactions

Oh, that’s gammas and x-rays!



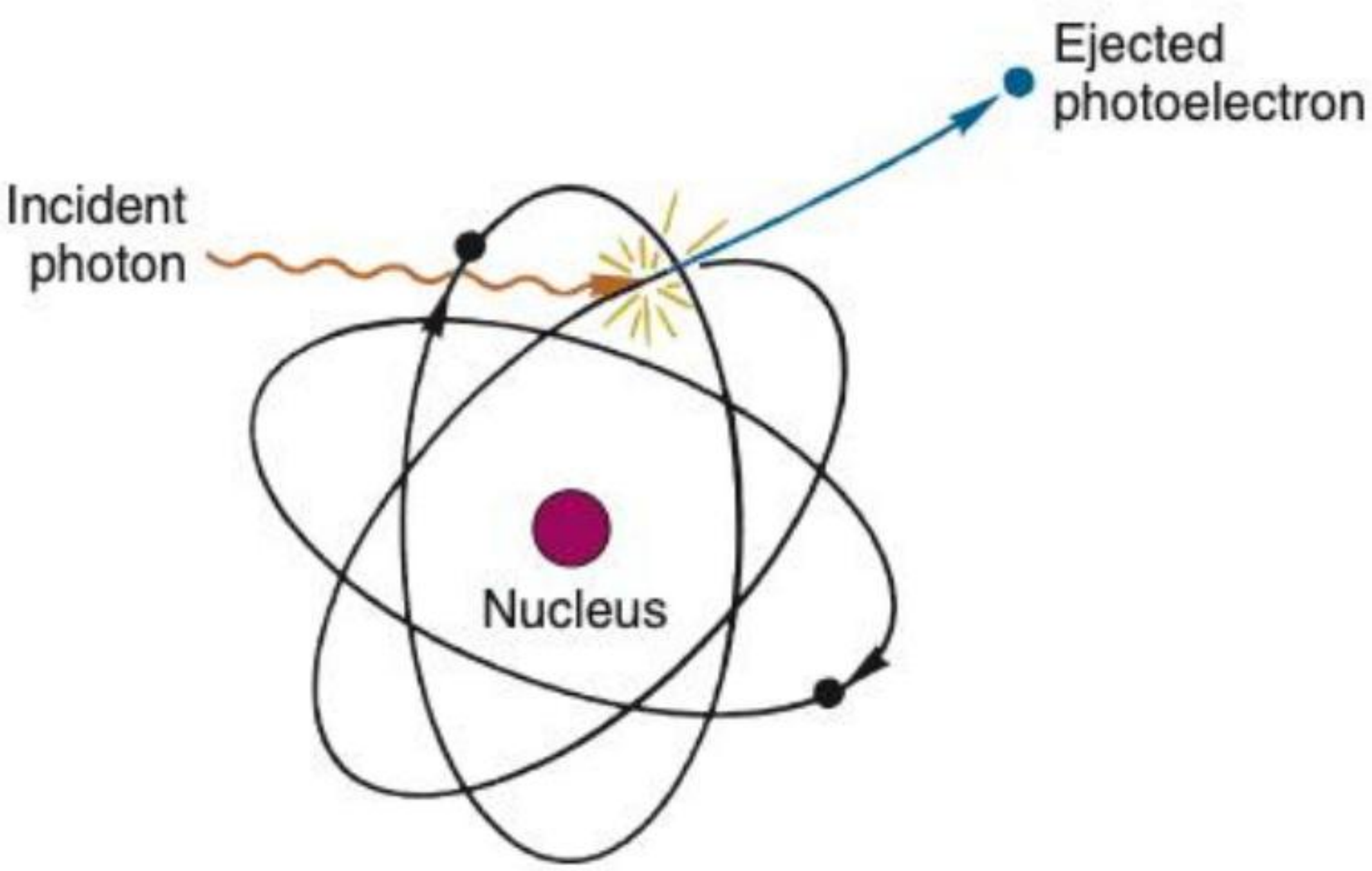
Photon Interactions with Matter

ONLY 5, NO MORE NO LESS:

- **Photoelectric Effect**
- **Compton Scattering**
- **Pair Production**
- **Coherent Scattering**
- **Photonuclear Effect**

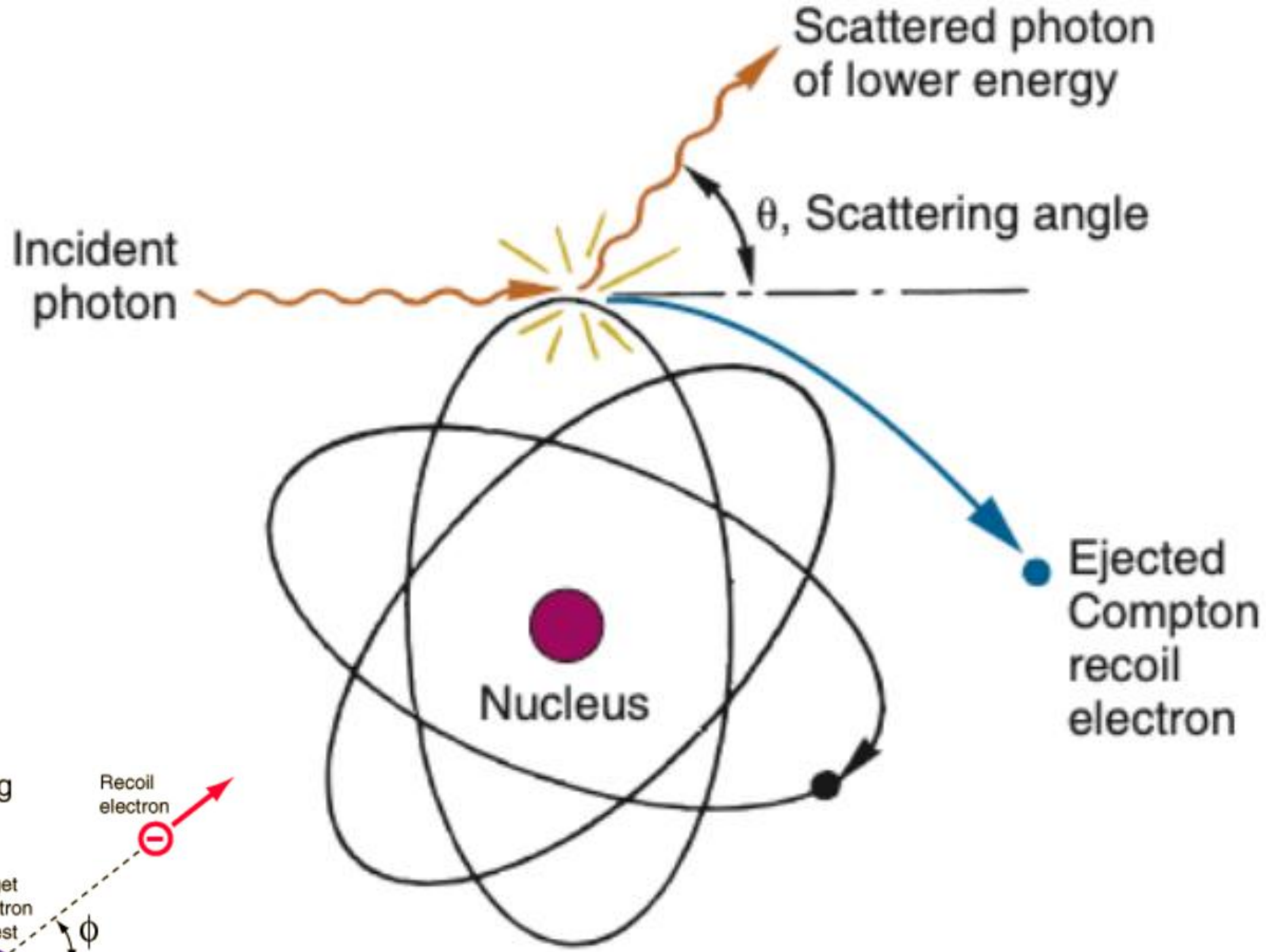
Photoelectric Effect

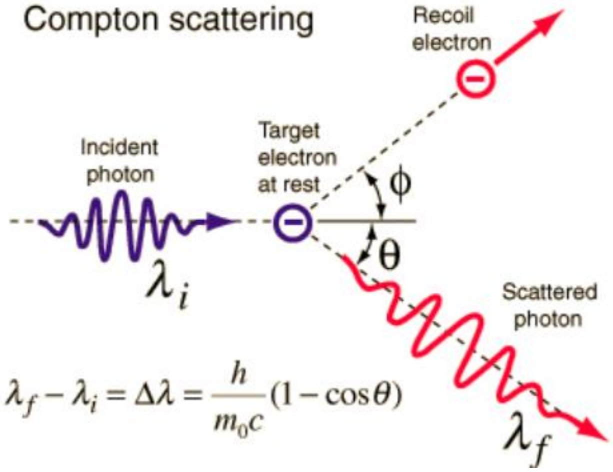
- Photon is **absorbed** by a shell electron
- Photoelectron is emitted with kinetic energy
- Thus, a photon has set in motion a **charged particle**, which will do stuff from the previous section
- KE = Photon energy – Binding Energy



Compton Scattering

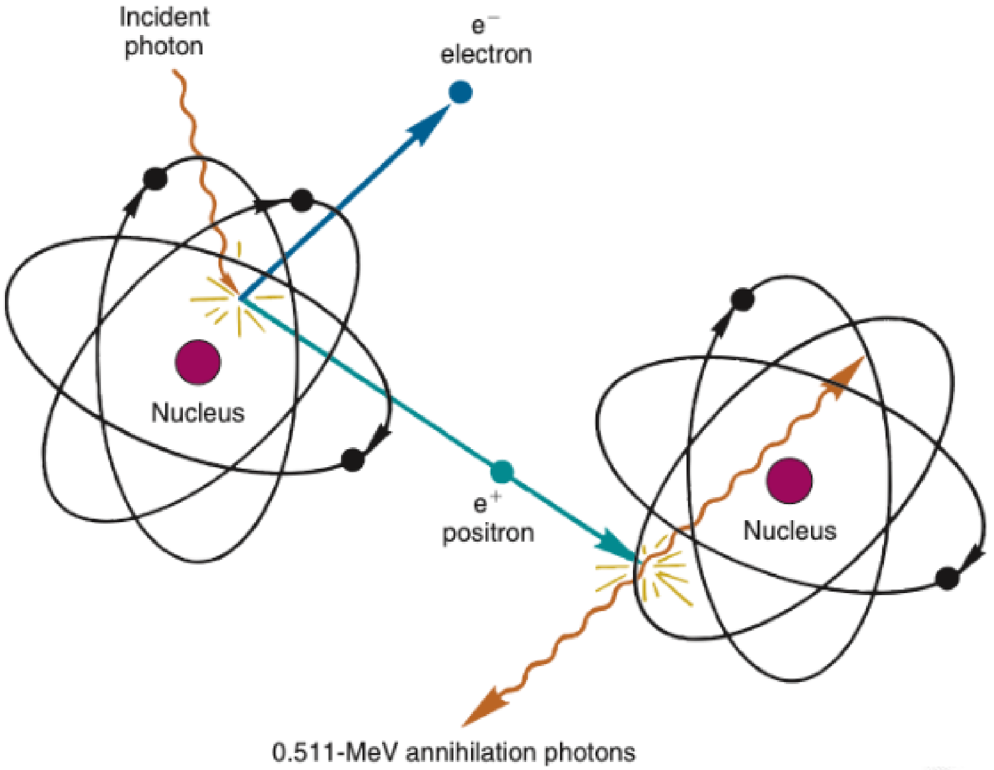
- Photon is **scattered** by a shell electron
- Energy is **split** between the Compton electron and photon
- Photon **continues**, interacts more
- Charged particle is **set in motion**

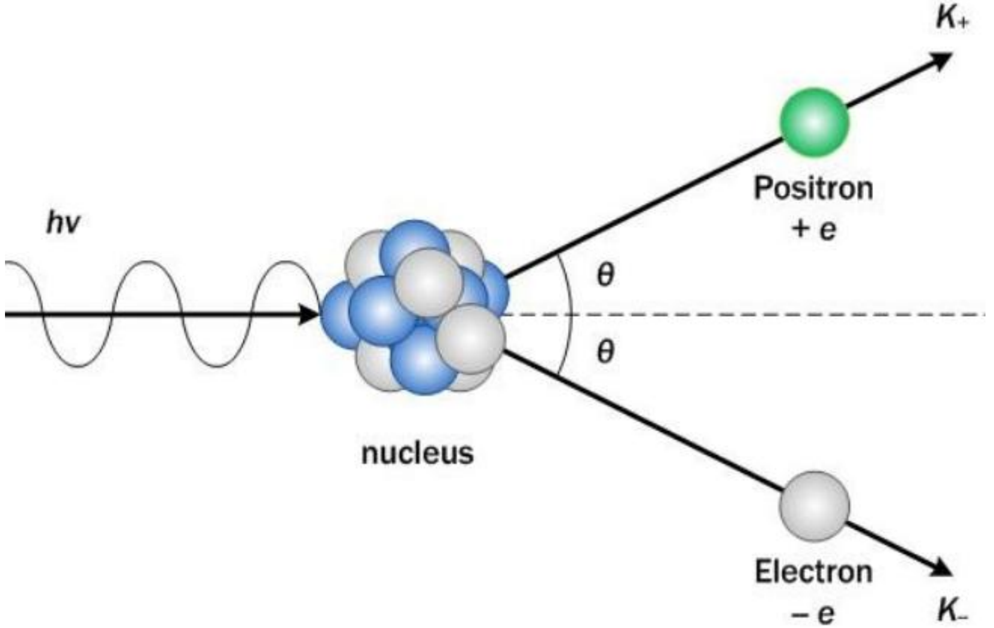




Pair Production

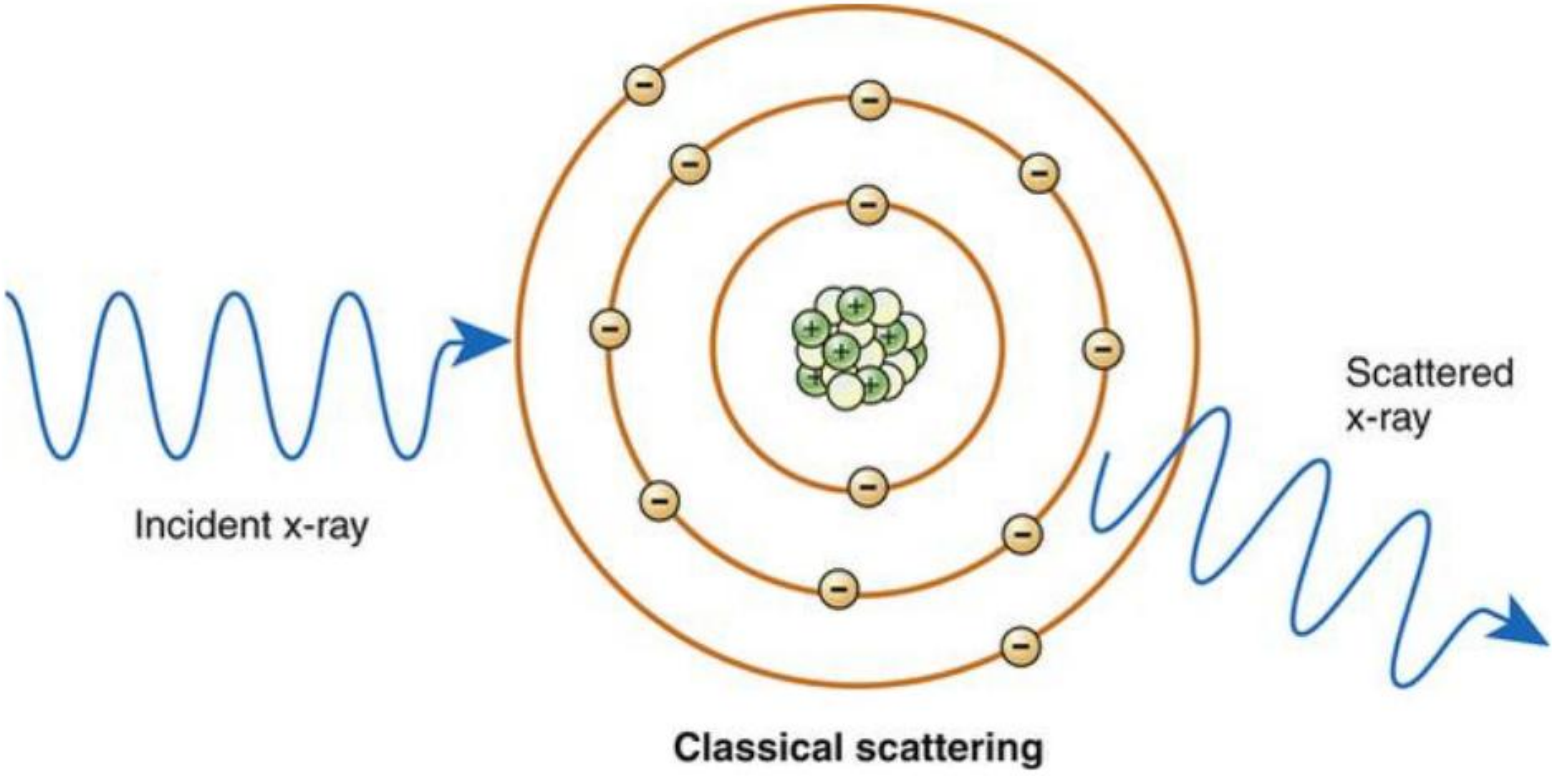
- Photon **consumed** by nucleus, creating positron/electron pair
- Pair typically travel in opposite directions, **do not interact with each other**
- **Positron** later **annihilates** into two opposed photons
- **MINIMUM ENERGY REQUIREMENT OF 1.022 MeV**

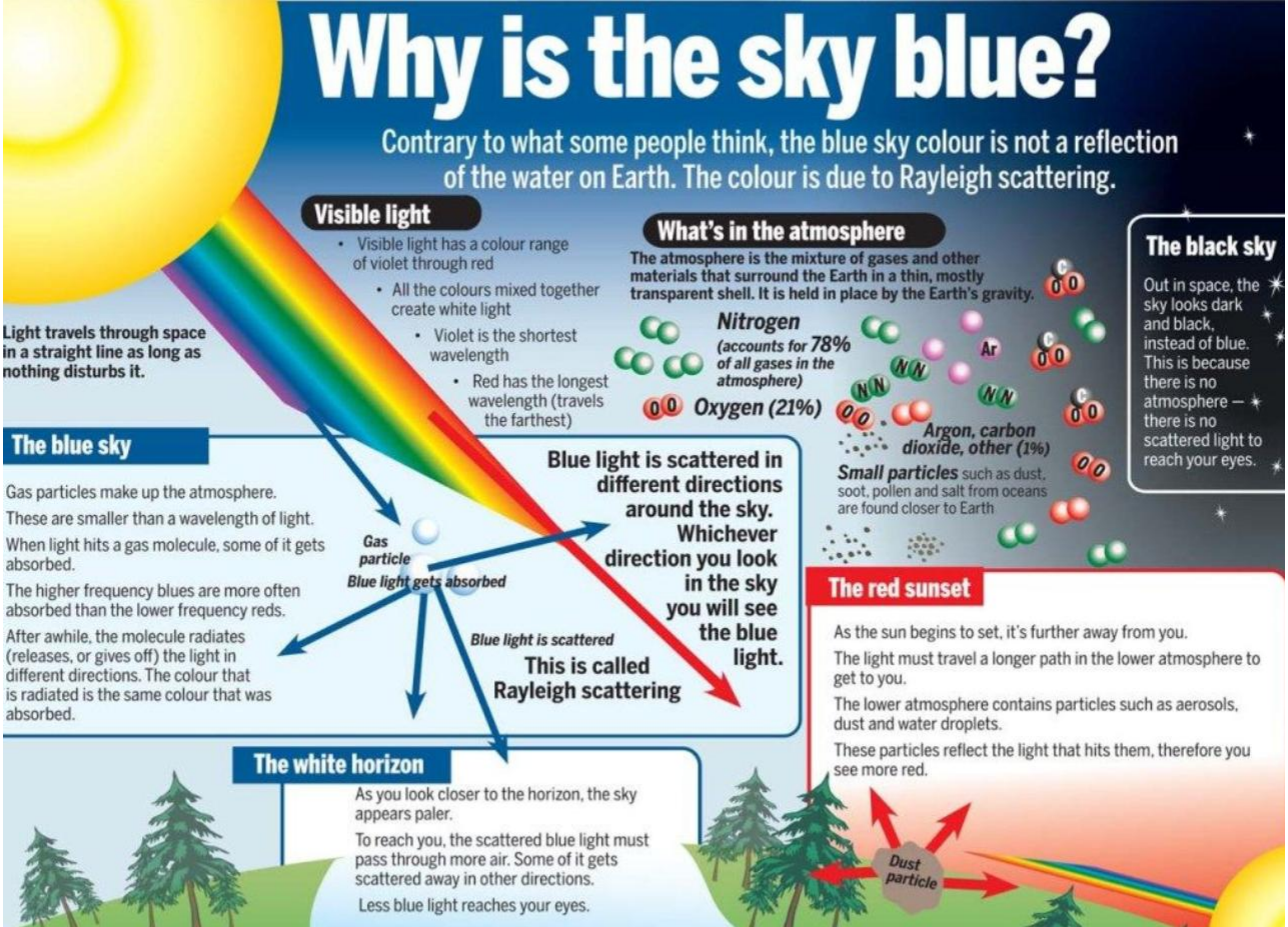




Coherent Scattering

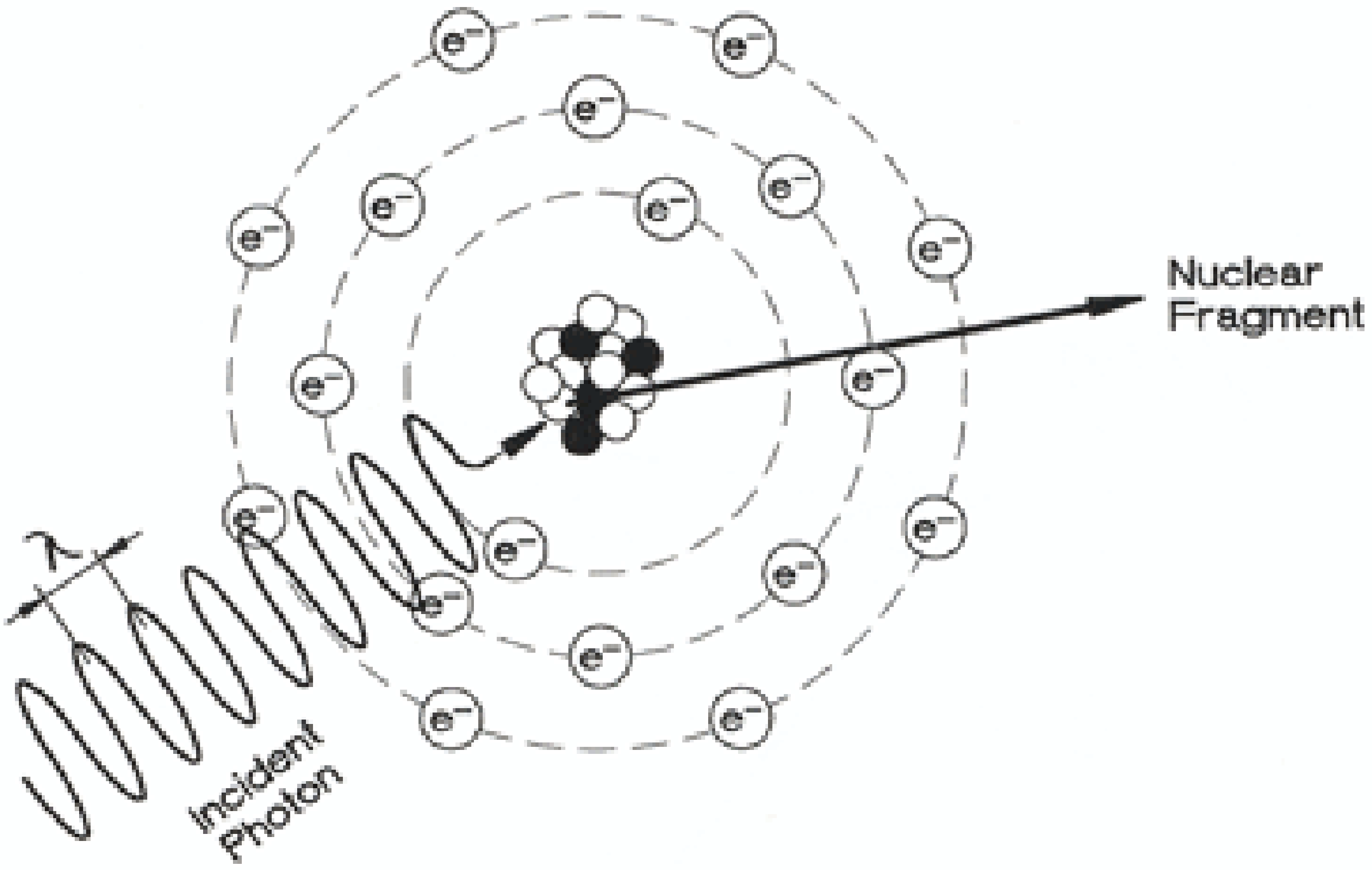
- Common misconception: Rayleigh scattering and coherent scattering are the same thing
- Reality: Coherent scattering has two modes, Rayleigh and Thompson Scattering
- More Reality: Nobody cares in medical physics because there is no energy exchange
- Rayleigh Scattering: Whole atom vibrates, scattering very low energy photon
- Thompson Scattering: Free electron scatters photon




Why is the sky blue?
Contrary to what some people think, the blue sky colour is not a reflection of the water on Earth. The colour is due to Rayleigh scattering.
Visible light
• Visible light has a colour range of violet through red
• All the colours mixed together create white light
• Violet is the shortest wavelength
• Red has the longest wavelength (travels the farthest)
Light travels through space in a straight line as long as nothing disturbs it.
What's in the atmosphere
The atmosphere is the mixture of gases and other materials that surround the Earth in a thin, mostly transparent shell. It is held in place by the Earth's gravity.
Nitrogen (accounts for 78% of all gases in the atmosphere)
Oxygen (21%)
Argon, carbon dioxide, other (1%)
Small particles such as dust, soot, pollen and salt from oceans are found closer to Earth
The black sky
Out in space, the sky looks dark and black, instead of blue. This is because there is no atmosphere — there is no scattered light to reach your eyes.
The blue sky
Gas particles make up the atmosphere.
These are smaller than a wavelength of light.
When light hits a gas molecule, some of it gets absorbed.
The higher frequency blues are more often absorbed than the lower frequency reds.
After awhile, the molecule radiates (releases, or gives off) the light in different directions. The colour that is radiated is the same colour that was absorbed.
Gas particle
Blue light gets absorbed
Blue light is scattered
This is called Rayleigh scattering
Blue light is scattered in different directions around the sky. Whichever direction you look in the sky you will see the blue light.
The red sunset
As the sun begins to set, it's further away from you.
The light must travel a longer path in the lower atmosphere to get to you.
The lower atmosphere contains particles such as aerosols, dust and water droplets.
These particles reflect the light that hits them, therefore you see more red.
Dust particle
The white horizon
As you look closer to the horizon, the sky appears paler.
To reach you, the scattered blue light must pass through more air. Some of it gets scattered away in other directions.
Less blue light reaches your eyes.

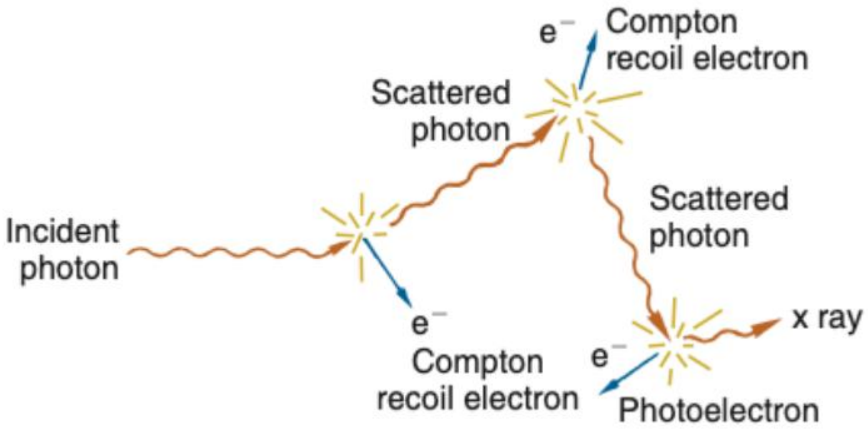
Photonuclear Effect

- Photon consumed by a nucleus, causing excited nuclear state
- Nucleus emits neutron or proton (nuclear fragment)
  - Proton does little
  - Slow Neutron can ACTIVATE other materials, making them radioactive
- Only relevant at VERY high energies (10 MeV)
- Very important for shielding concerns



Electromagnetic Radiation Track

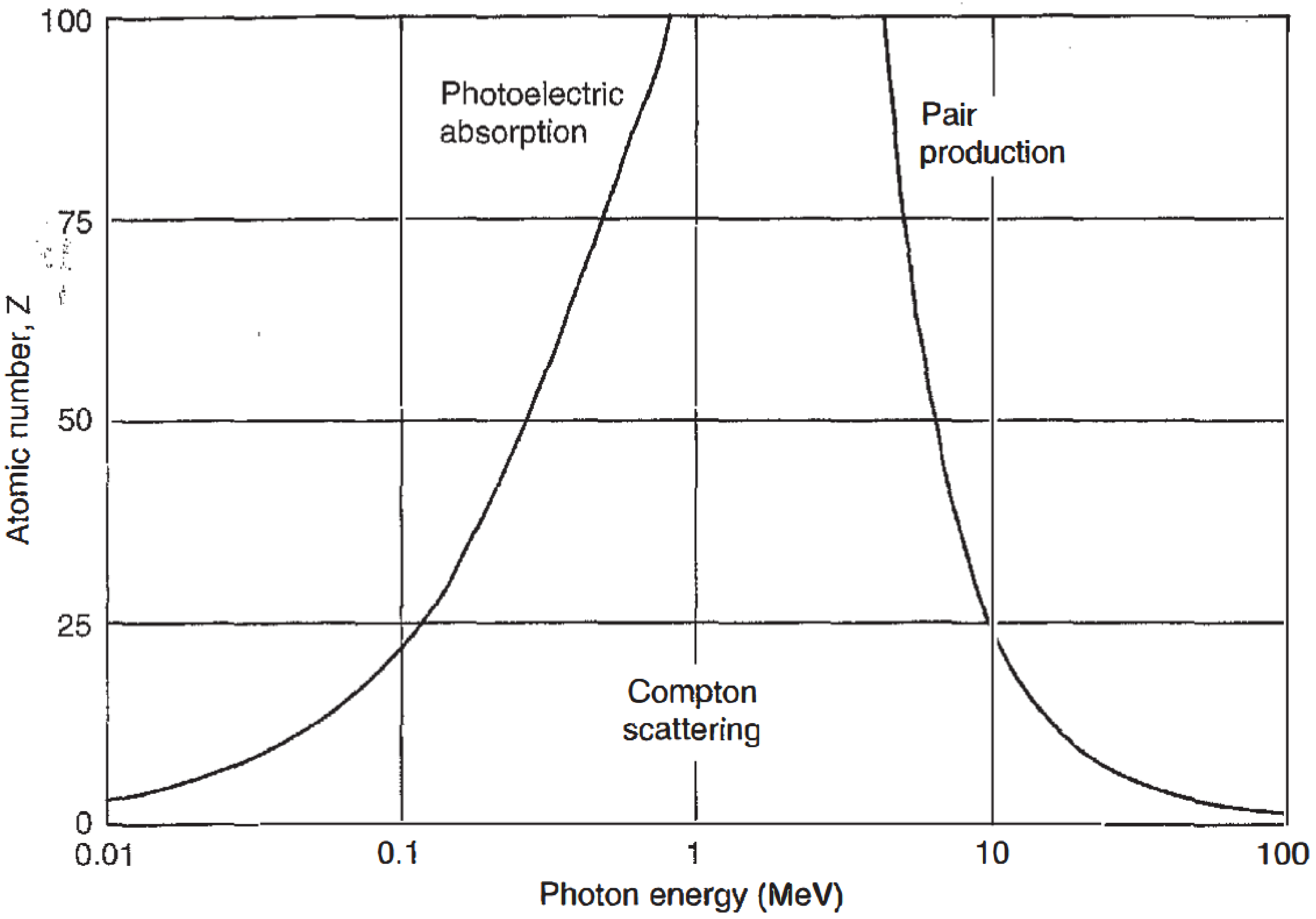
- Photons can undergo many interactions, thousands and thousands, or just one!
- All 5 modes are possible if the energy is high enough, but definitely not probable!
- Probability of each mode is highly dependent on target composition, particle energy, density, etc.
- Particle is erratic, typically forward focused, but spreads out and can even go significantly backward!
- Compton scattering is by far the most prevalent for 99% of what we do.



Dominant Interaction Domains

Ask a medical physicist student their favorite graph, 9/10 will say this one!

Shows the dominant domains of each of the three relevant photon interactions as a function of photon energy and atomic number.



Some Numbers (Humble Bragging)

- I programmed a Monte Carlo Simulation of photon interactions
- It followed EVERY photon, from start to finish, simulating physics
- 100,000 6X photons set in motion nearly 1,000,000 electrons in 2,281,157 interaction events
- In reality, these electrons would set in motion even more electrons (delta-rays)!
- I just simplified it by doing a CSDA approximation (thermalizing in a straight line constantly)
- Hundreds of lines of code, and too many hours.

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