Properties of Charged Particle Radiation

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SHINE Practicum

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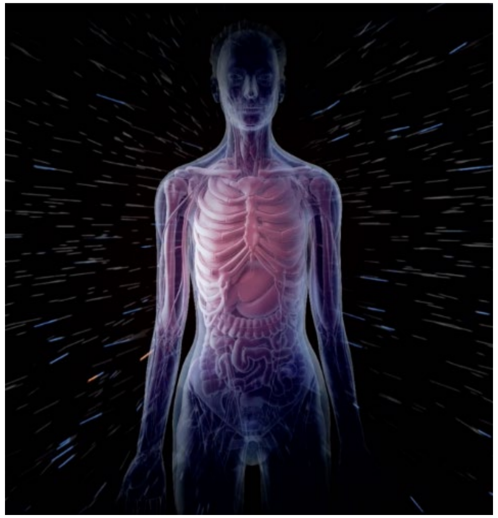
Space Radiation Overview

- Space radiation is identified by NASA as one of the five hazards of human spaceflight
- Space radiation-induced health risks include
  - Carcinogenesis
  - Cardiovascular disease and other degenerative tissue effects
  - Acute and late central nervous system effects

[NASA.gov]

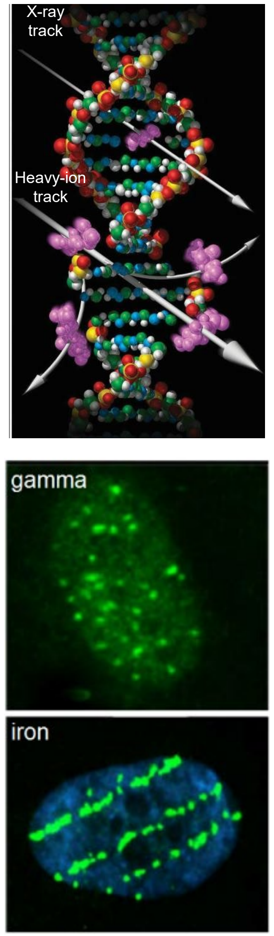


Space Radiation Overview

- Space radiation is qualitatively different than any form of radiation on Earth

Radiation sources on Earth

- Mainly gammas and x-rays
  - Waste, accidents, weapons
  - Occupational (medical and nuclear industries)
  - Natural terrestrial sources (e.g. radon)
- Epidemiological data exist to guide risk assessment and set conservative protection limits
- Protection strategies guided by
  - Limiting exposure time
  - Increasing distance from source
  - Shielding



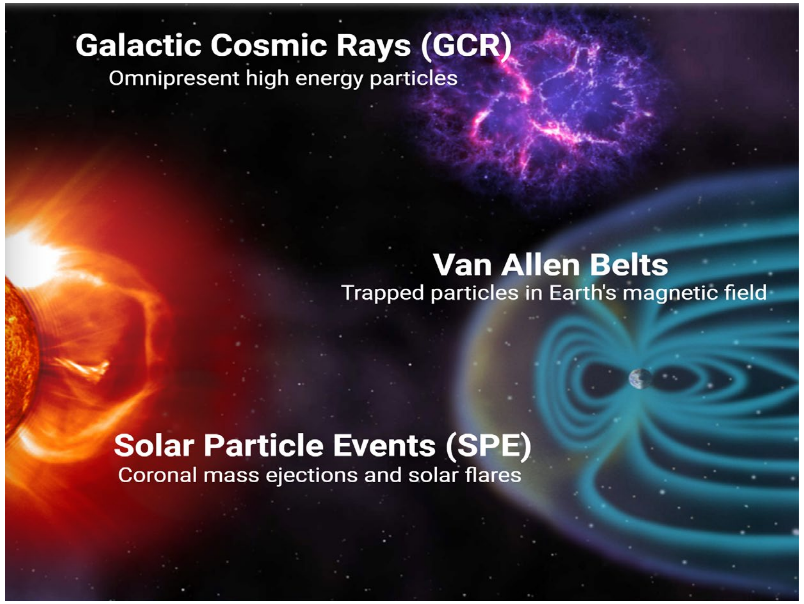
[NASA.gov]

Space Radiation

- Highly energetic particle radiation
  - Everything on the periodic table of elements
  - Able to penetrate shielding and tissue
- No direct means of assessing health risks
  - Limited human data
  - Lack of mechanistic knowledge
- Earth protection strategies do not work
  - Exposure time controlled by mission requirements
  - Space radiation is ubiquitous
  - Shielding strategies are limited

Space Radiation Environment

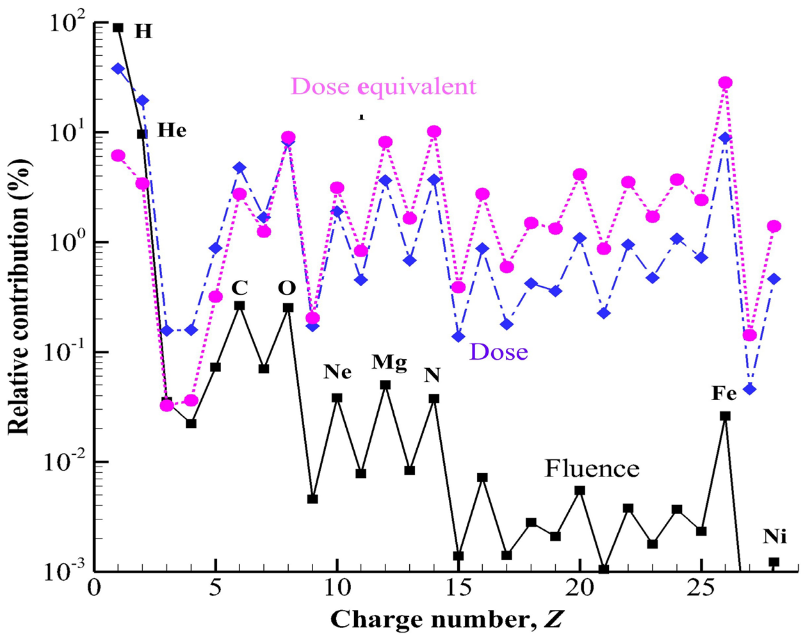
- **Trapped Particle Radiation**
  - low energy protons (< 250 MeV) and electrons (< 7 MeV)
  - Continuous exposure at altitude up to 40,000 km
  - can be shielded; mainly relevant to ISS
- **Solar Particle Events**
  - Medium to high-energy protons from coronal mass ejections
  - Intermittent exposure with peak activity during solar max
  - Can be effectively shielded to prevent severe acute radiation syndrome
- **Galactic Cosmic Rays**
  - Highly penetrating, complex mixed field including protons and heavier nuclei
    - protons (85%), helium ions (12%)
    - high charge and energy (HZE) ions (1%) (lower flux but biologically significant)
  - Chronic low-dose rate exposure that varies with solar cycle
  - Difficult to shield due to energy and complexity of field
  - Physical properties of HZE particles differ vastly from terrestrial radiation with adverse biological affects contributing to health risks



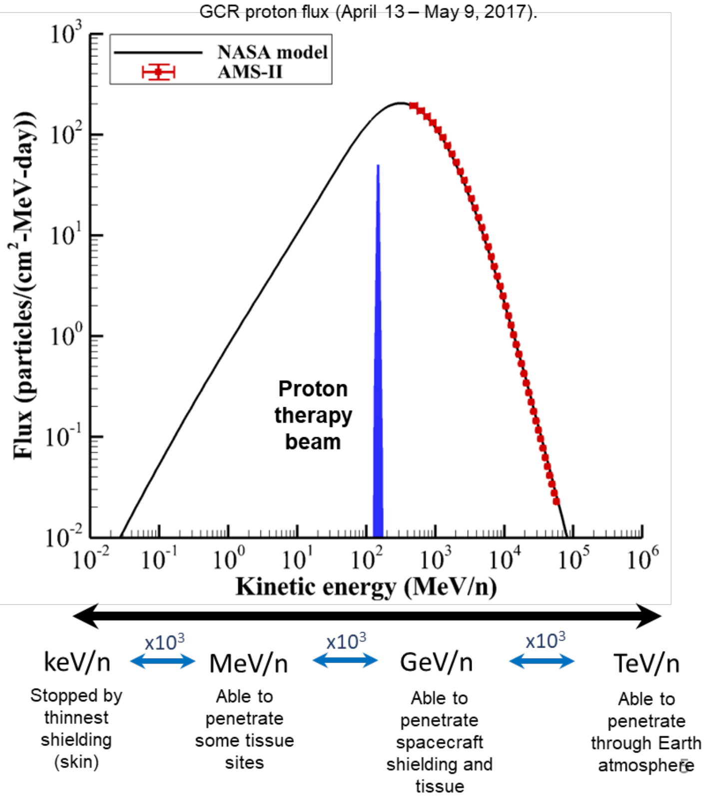
[Image adapted from NASA.gov]

Galactic Cosmic Rays

- Galactic cosmic rays (GCR) are the main radiation hazard for long duration exploration missions

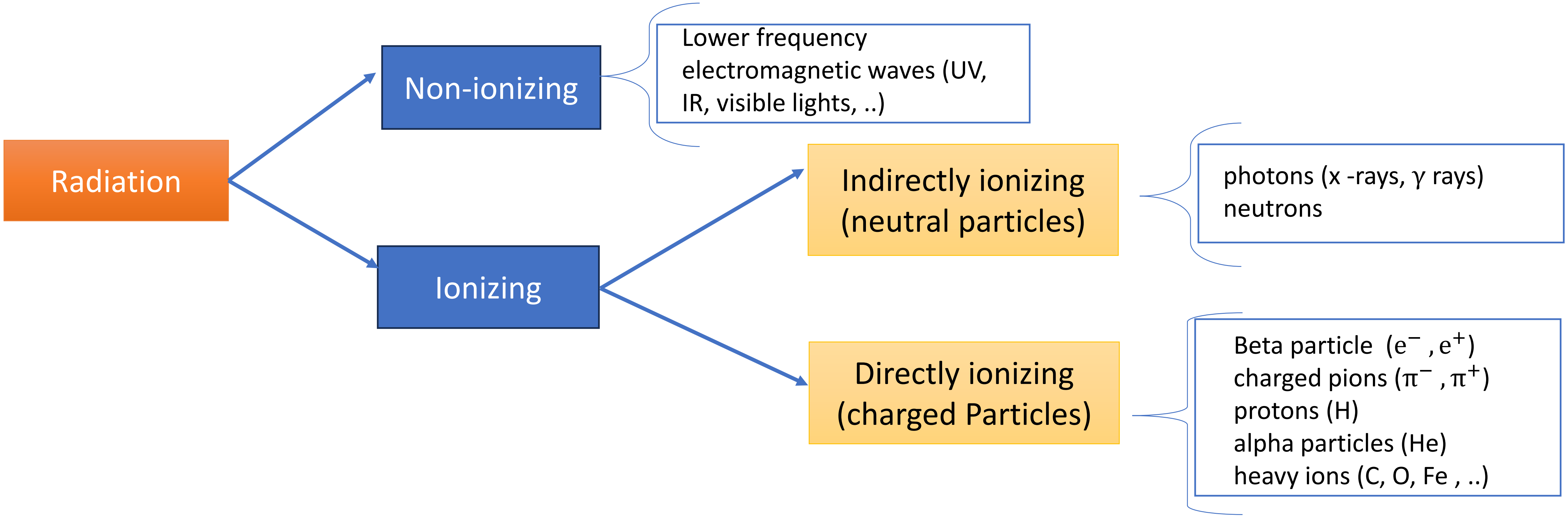


Relative contributions of different
elements in the 1976 solar minimum GCR environment
[Simonsen, Slaba, Guida, 2020]

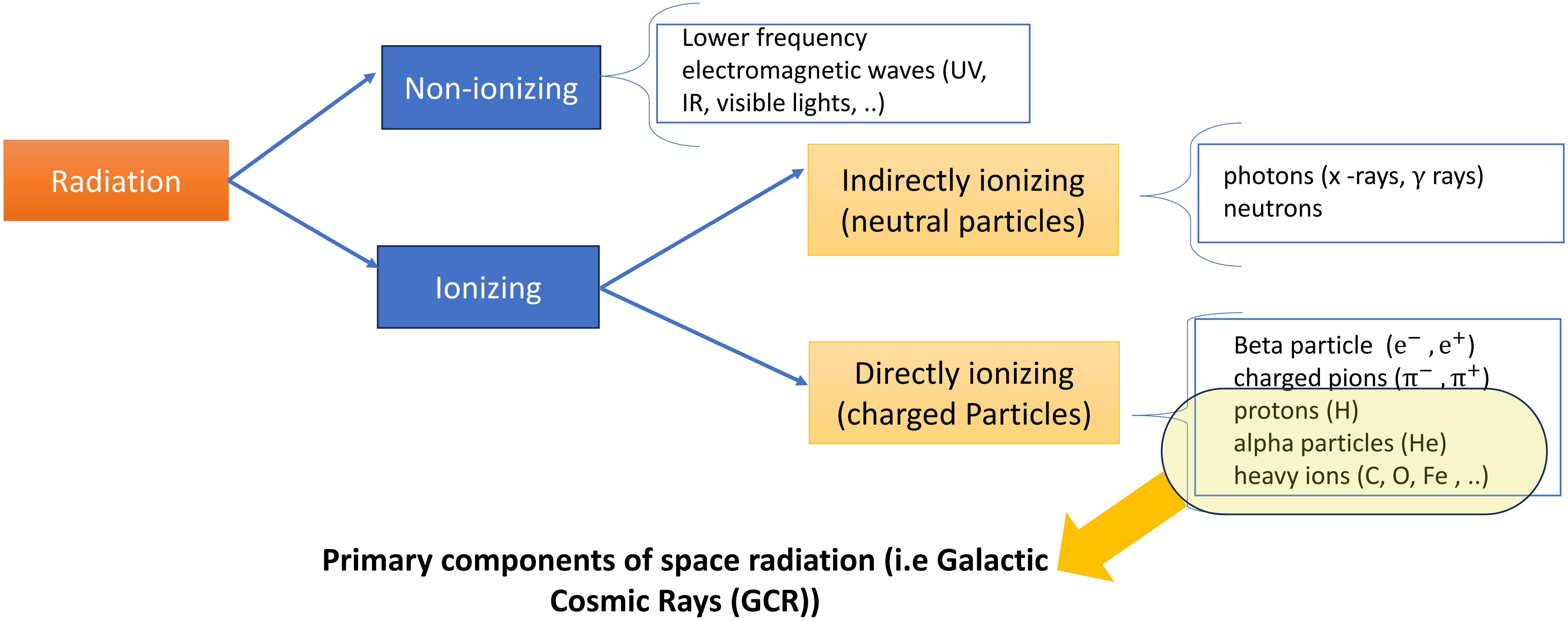


[Image courtesy of Tony Slaba]

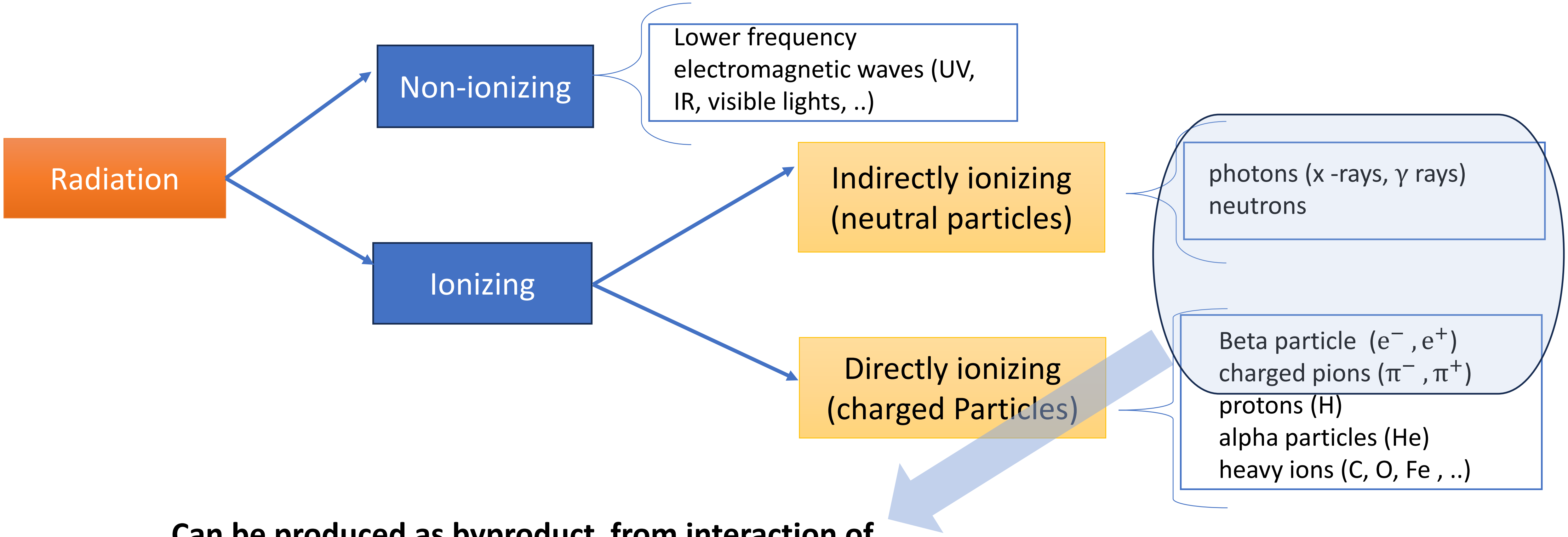
Interaction of Radiation With Matter



Interaction of Radiation With Matter



Interaction of Radiation With Matter



Can be produced as byproduct from interaction of primary charged particles (i.e from GCR) with target material (i.e tissue & shielding)

Interaction of Ionizing Radiation With Matter

Charged Particles

- **$e^- e^+$**
  - Coulomb interaction with target e^- ionization/excitation
  - Elastic scattering from target nuclei
  - Bremsstrahlung
  - Cherenkov
- **Ions**
  - Coulomb interaction with target e^- ionization/excitation
  - Inelastic collision with target nuclei (more relevant for HZE ions)
  - Elastic collision with target nuclei

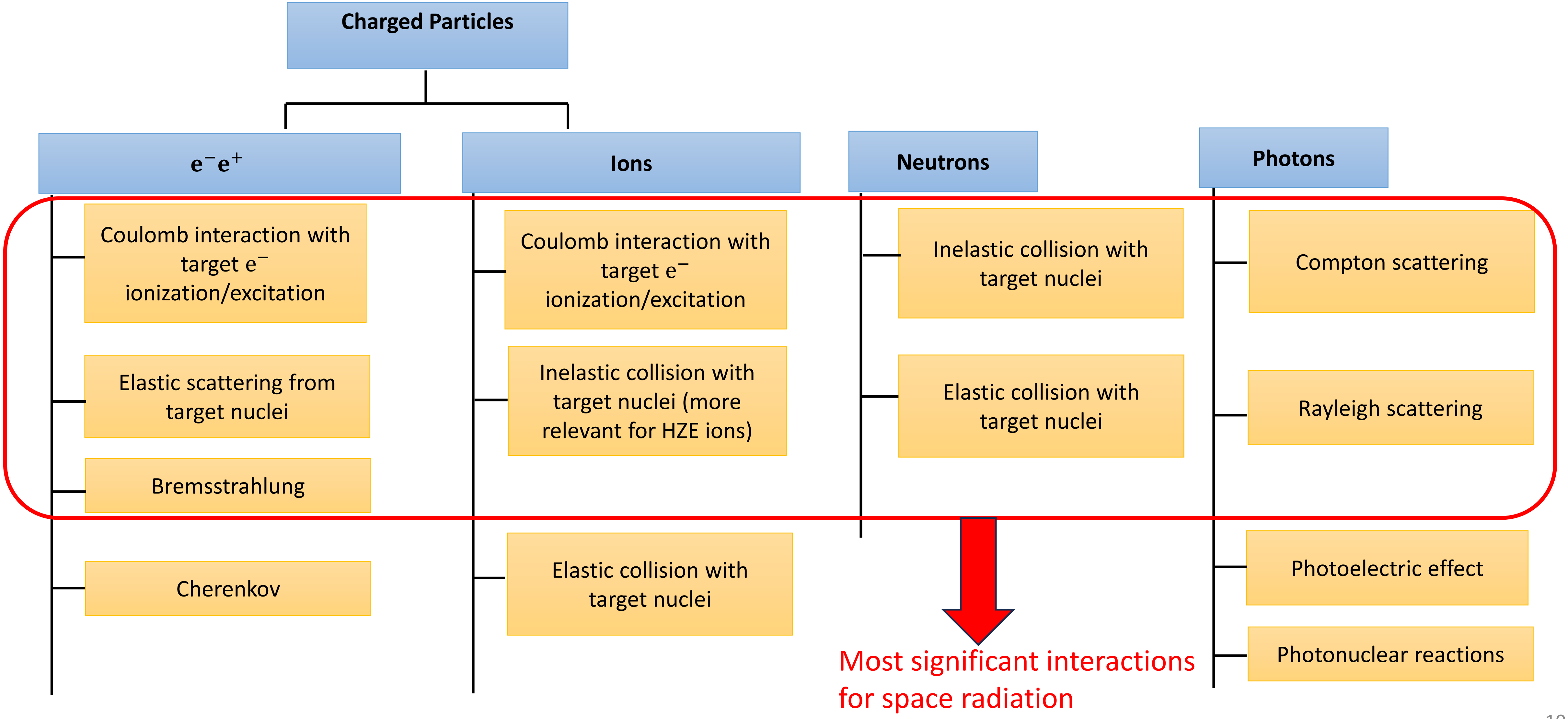
Neutrons

- Inelastic collision with target nuclei
- Elastic collision with target nuclei

Photons

- Compton scattering
- Rayleigh scattering
- Photoelectric effect
- Photonuclear reactions

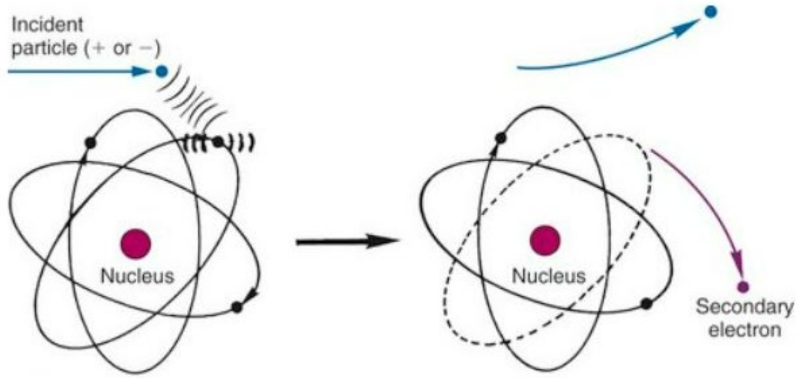
Interaction of Ionizing Radiation With Matter



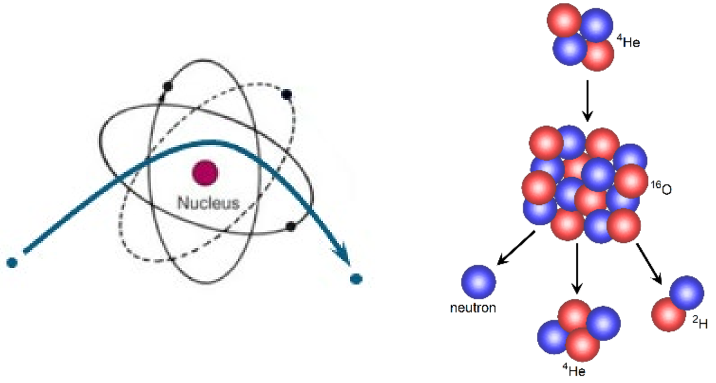
Interaction of Charged Particles With Matter

- As particles passes through matter (shielding and/or tissue), physical interactions modify the original particles and may result in the production of secondary particles
  - Combination of atomic and nuclear interactions
  - Energy of primary particles are modified
  - Secondary particles (e.g. neutrons, pions , …) are produced

Atomic interaction with target electrons

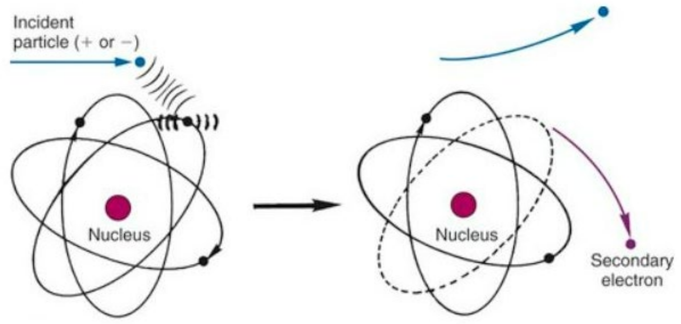


Nuclear interaction with target nuclei

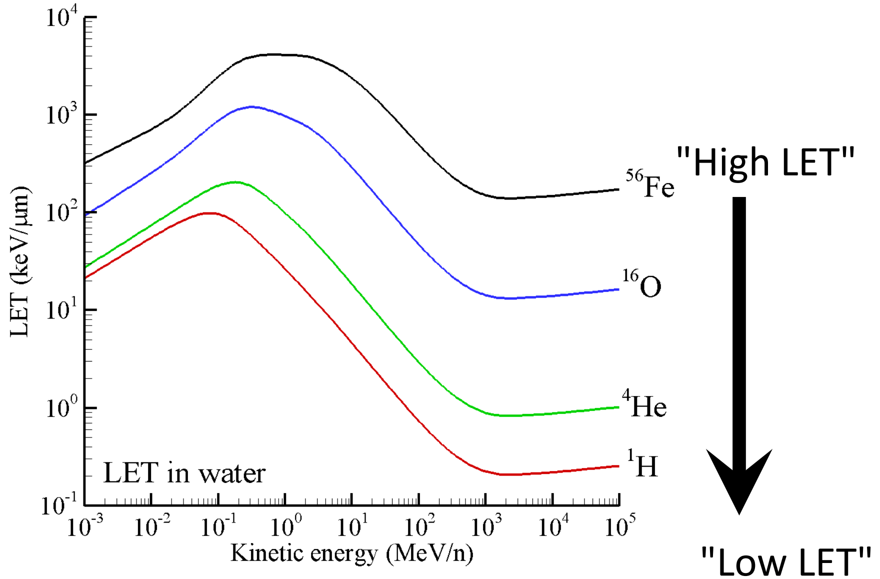


Atomic Interactions

- Coulomb interaction between ions and orbital electrons of target nuclei
  - Ionization and Excitation
- Main physical mechanism for energy deposition
- Production of delta rays along the ion track (track structure)
- Energy loss commonly expressed as linear energy transfer (LET)
- LET and track-structure are used to quantify biological effect

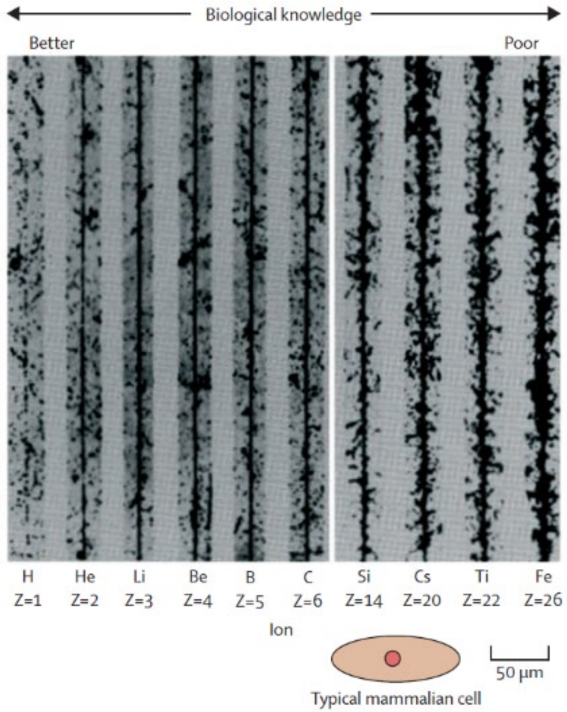


Coulomb interaction with electrons of target material leading to ionization event



[Image courtesy of Tony Slaba]

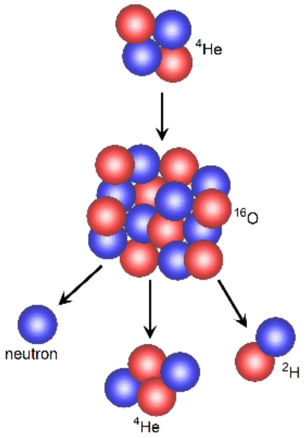
Charged particle tracks in nuclear emulsion



[Cucinotta & Durante (2009)]

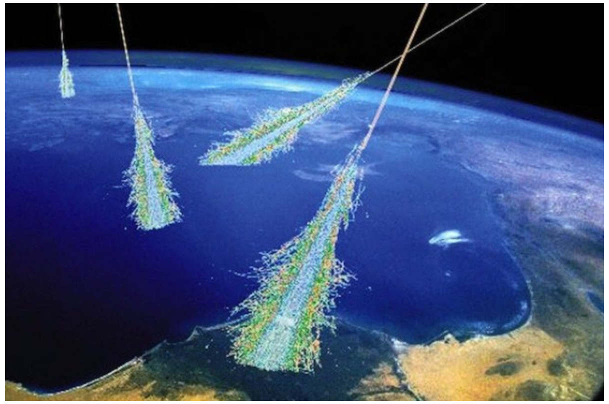
Nuclear Interactions

- Interaction between incoming radiation and target nuclei
- Nuclear interactions are very important in describing how space radiation is modified as it passes through shielding and tissue



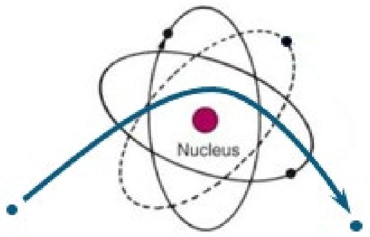
Depiction of nuclear interaction between ^{4}He and ^{16}O

- Nuclear inelastic collisions
  - Projectile and/or target nuclei "breaks-up"
  - Produced particles generated with a range of energies and directions
  - Secondary particles deposit energy and may suffer more collisions



Atmospheric cascade resulting from inelastic nuclear collisions [NASA.gov]

- Nuclear elastic collisions
  - "pool-ball" type collision
  - No particles are lost, and no new-particles are produced
  - Dominant physical interaction for neutrons



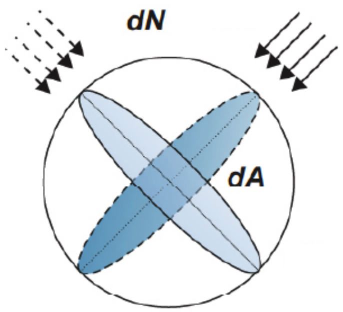
Elastic nuclear interaction

Important Quantities

Fluence:

- Describes number of particle that pass through a cross-sectional area
- In biology experiments fluence is expressed as the number of particles hitting the cross-sectional area of the cell nucleus (hits/cell)

$$\Phi = \frac{dN}{dA} \quad \left[\frac{\text{particles}}{\text{cm}^2}\right]$$



Absorbed Dose

- Describe mean energy imparted per unit mass

$$D = \frac{d\bar{\varepsilon}}{dm} \quad [\text{Gy}]$$

Dose Rate

- The dose of ionizing radiation delivered per unit time.

$$\dot{D} = \frac{dD}{dt} \left[\frac{\text{Gy}}{\text{sec}}\right]$$

Stopping Power / Linear Energy Transfer

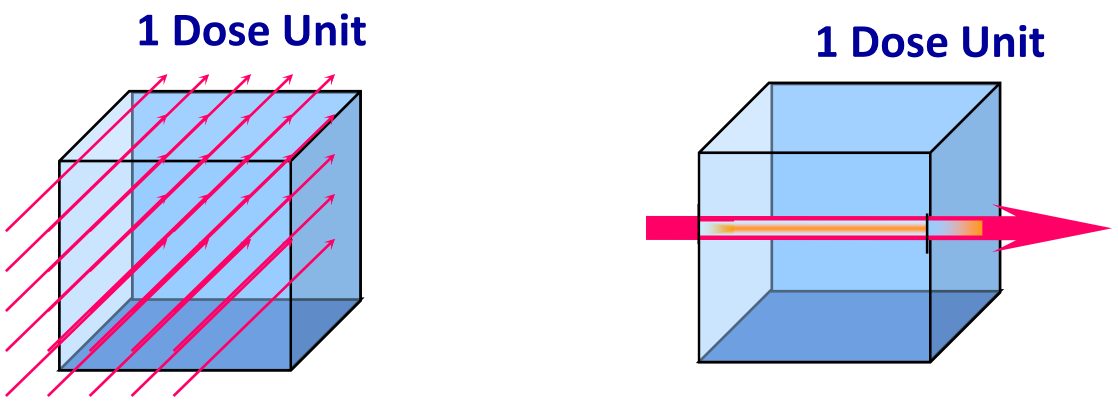
- Describe energy loss per unit path length

$$S = \frac{dE}{dx} \quad \left[\frac{\text{MeV}}{\text{cm}}\right]$$

High LET vs Low LET radiation

- Dose is defined as energy absorbed per unit mass *(irrespective of the spatial distribution of the absorbed energy)*

Dose is Useful but Insufficient



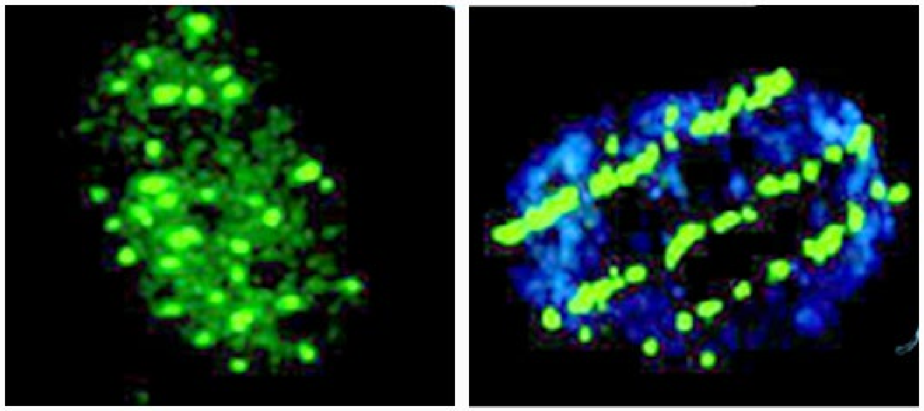
Low LET radiation deposits energy in a uniform pattern

High LET radiation deposits energy in a non-uniform pattern

[Image courtesy of Greg Nelson]

Gamma Rays (low LET)

Iron Particles (High LET)



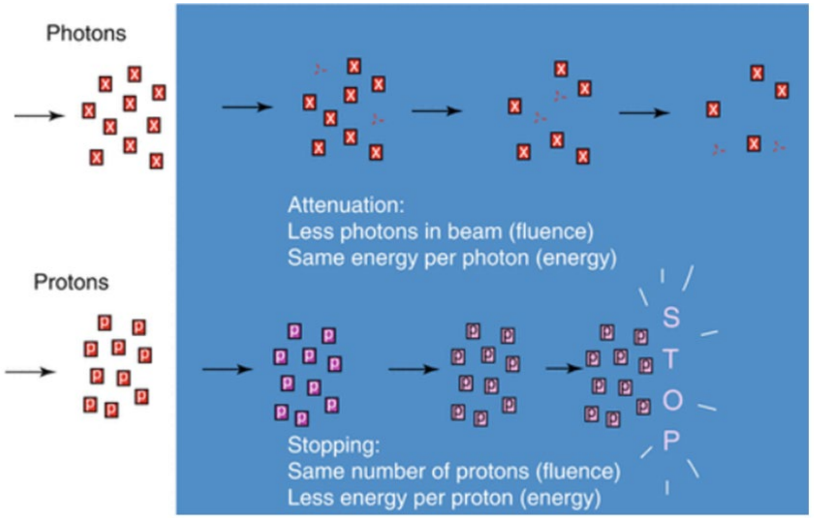
[Cucinotta & Durante (2009)]

Energy loss of Charged Particles

- Photons (X-rays/Gamma Rays)
  - $N(x)/N_o = e^{-\mu x}$
    - $N(x)/N_o$ is fraction of photons left at depth x
    - μ is linear attenuation coefficient
- Charged Particles
  - Linear Energy Transfer (LET) or Stopping Power given by Bethe-Bloch formula:

$$\frac{dE/dx}{\rho} = 4\pi r_o^2 \frac{N_e m_e c^2 z^2}{\beta^2}\left[\ln\left(\frac{2mec^2\beta^2}{I(1-\beta^2)}\right) - \beta^2 - \Sigma_i\left(\frac{c_i}{Z}\right)\right]$$

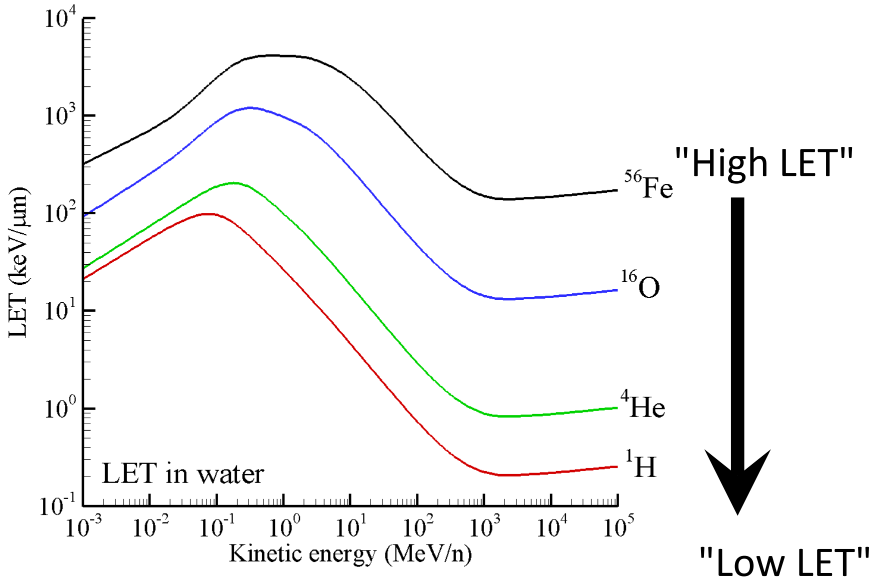
  - N_e is electrons per gram of medium (target material)
    - $N_e \propto \frac{Z}{A}$, Z= atomic number (medium) , A=atomic mass (medium)
  - ρ is density of medium and I is ionization constant of medium
  - β is v/c (v= velocity of particle) and z is charge of particle
  - The important component is: $dE/dx \propto z^2/\beta^2$



[Chang, Lasley, ,Das, Mendonc & Dynlacht (2014)]

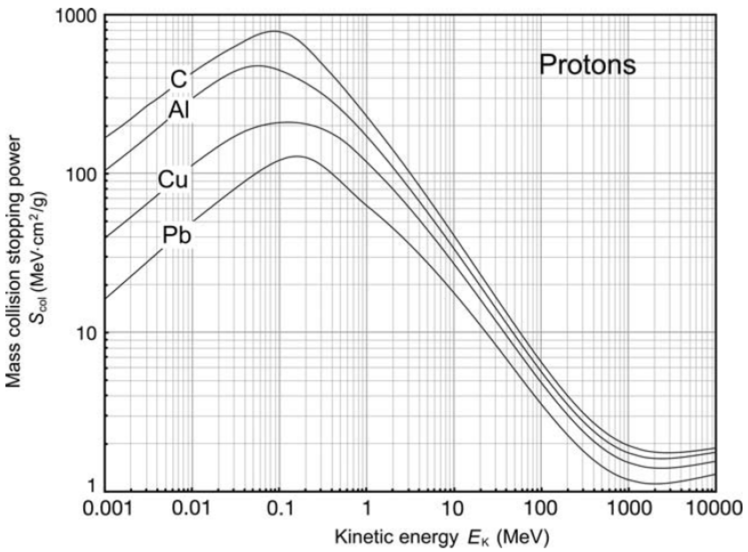
Energy loss of Charged Particles

- Important component of stopping power/LET for energetic particles (i.e HZE ions) is the dE/dx $\propto$ **z^2/β^2** relationship at higher energies@ (KE $\gtrsim$ 0.1 MeV/n)
  - LET increases as the particle slows down (as its kinetic energy decreases)
  - LET increases with charge of the particle (i.e heavier ion have higher LET)
- BUT LET Also dependens on absorber material: $\frac{dE}{dx} \propto \frac{Z}{A} \rho$



[Image courtesy of Tony Slaba]

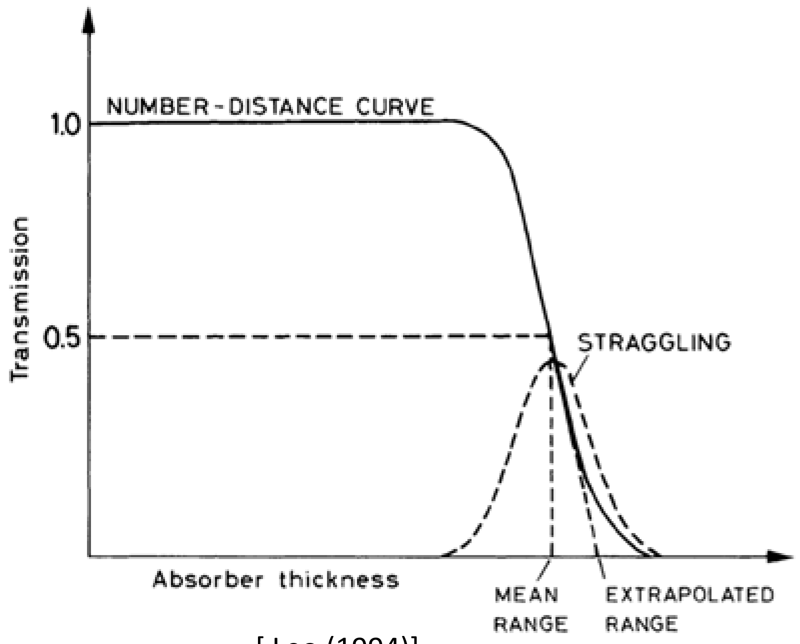
$$-\frac{dE}{\rho dx} \propto k \frac{Z}{A} \cdot \frac{z^2}{\beta^2}$$



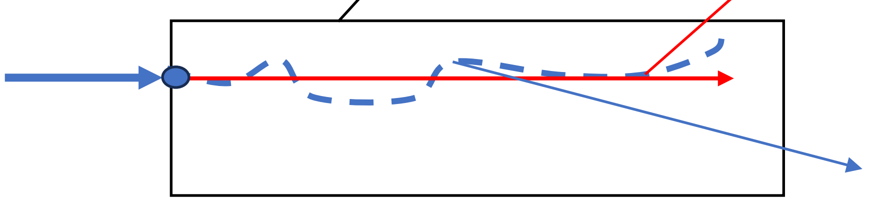
[Podgoršak (2016)]

Range of Charged Particles

- The range of a charged particle is the expectation value of the pathlength that it follows until it comes to rest (stopping) and is related to stopping power
- Range vs Pathlength:
  - Pathlength: total distance the particle traverses in its trajectory
  - Range: path length projected onto the particle's original direction
- Depends on target material, particle type and its energy
- Stochastic quantity: range straggling



[Leo (1994)]



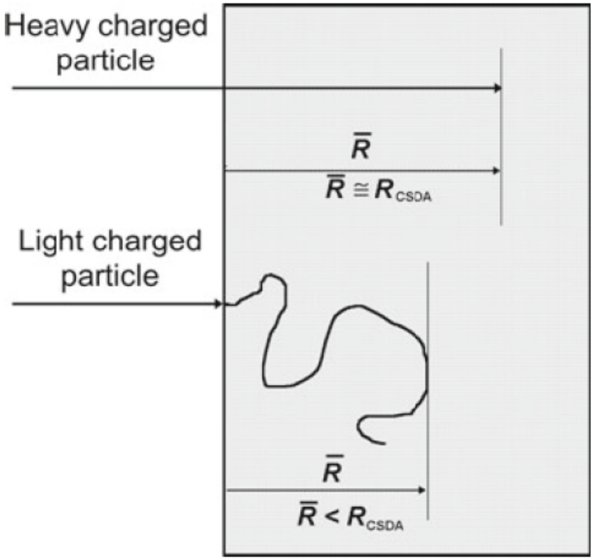
Range of Charged Particles

- ICRU introduced the term continuous slowing down approximation (CSDA) range to to approximate the average path length traversed by the charged particle as it slows down to rest.

$$R_{csda} = \int_0^{E_0} \frac{dE}{S_{tot}(E)}$$

- CSDA assumptions:
  - continuous energy loss by the particle
  - energy loss rate at each point along the particle's track equals to total stopping power
- Lighter particles deflect more and go through more scattering by nuclei of target material

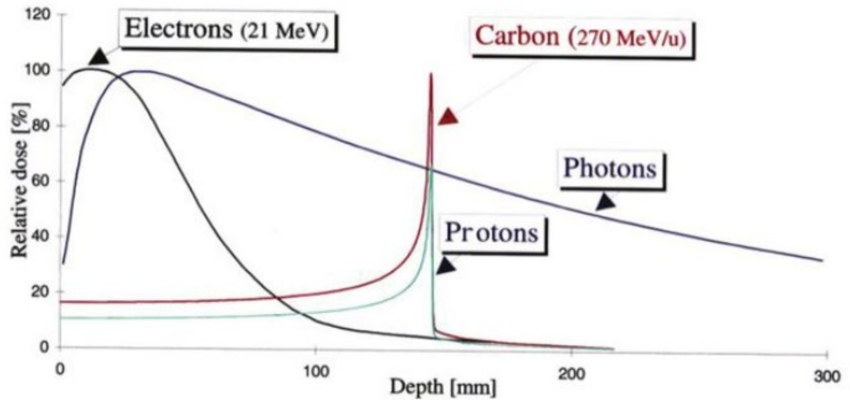
  → more deflection and range straggling
  - inversely proportional to square root of mass
  - the heavier the ion the projected range is closer to the CSDA range
    - Less deflection and less straggling

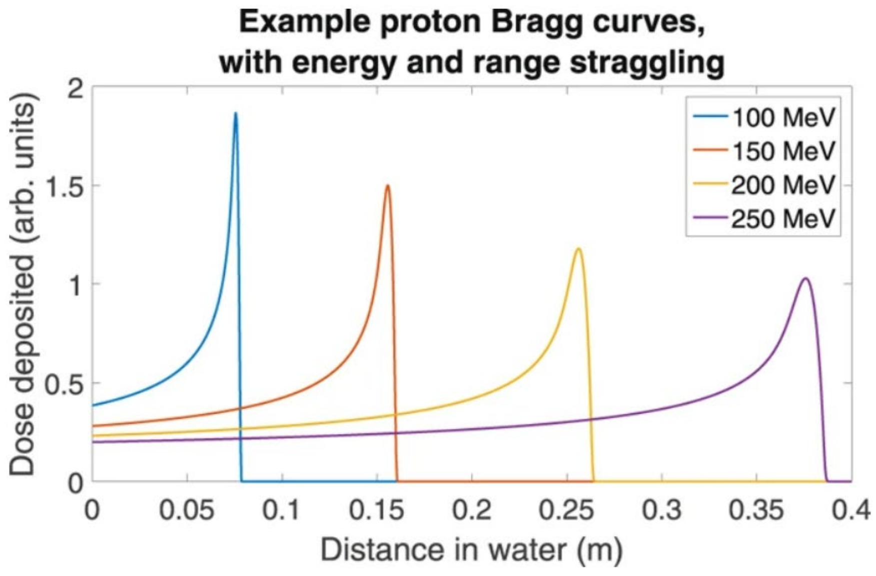


[Podgoršak (2016)]

Depth Dose Distribution of different types of radiation

- When energetic ions enter medium, they are slowed down by losing their kinetic energy mainly by ionizing the medium (atomic interactions).
- This energy loss (stopping power or LET) increases with decreasing particle velocity, giving rise to a sharp maximum in energy loss near the end of the range, known as the Bragg peak.
- Location of Bragg peak is close to CSDA range for heavier particles
- The lower the KE, shorter range and more pristine peak (less straggling)

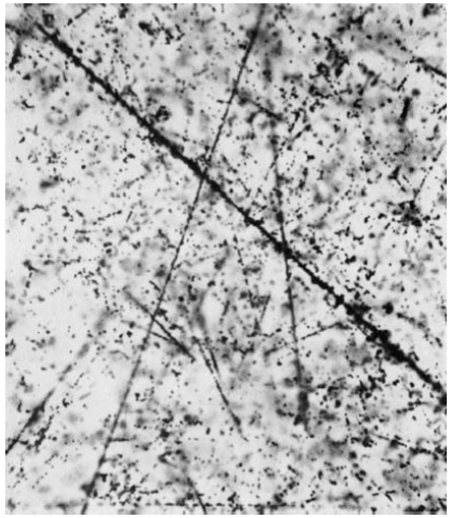




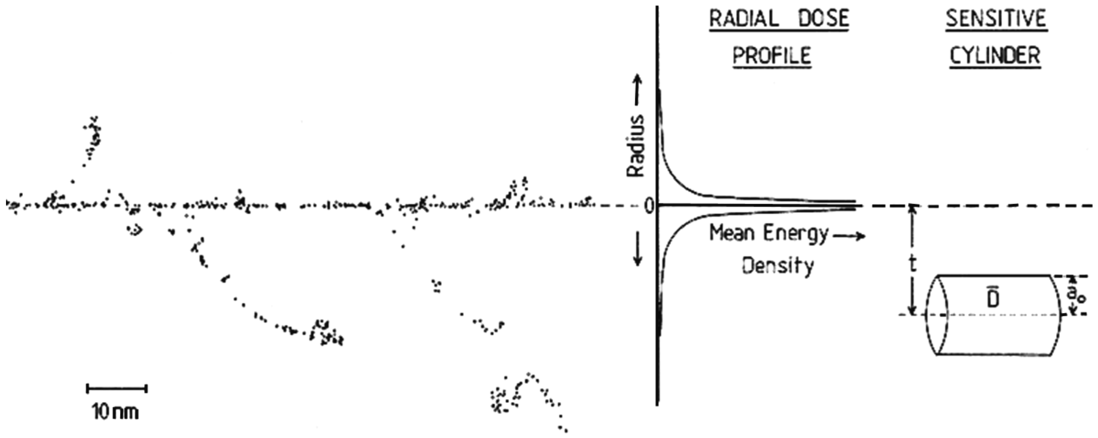
[Grimes, Warren& Partridge (2017)]

Track Structure

- Heavy charged particles mainly deposit their energy in the form of discrete tracks
  - Stochastic process depending on ionization events along path of ion
  - highest density of ionization occurs along the particle’s path (the **core**).
  - Around the core, there's a penumbra where secondary electrons (delta rays) cause additional ionizations radially away from the core.
  - Biological effect at DNA scale

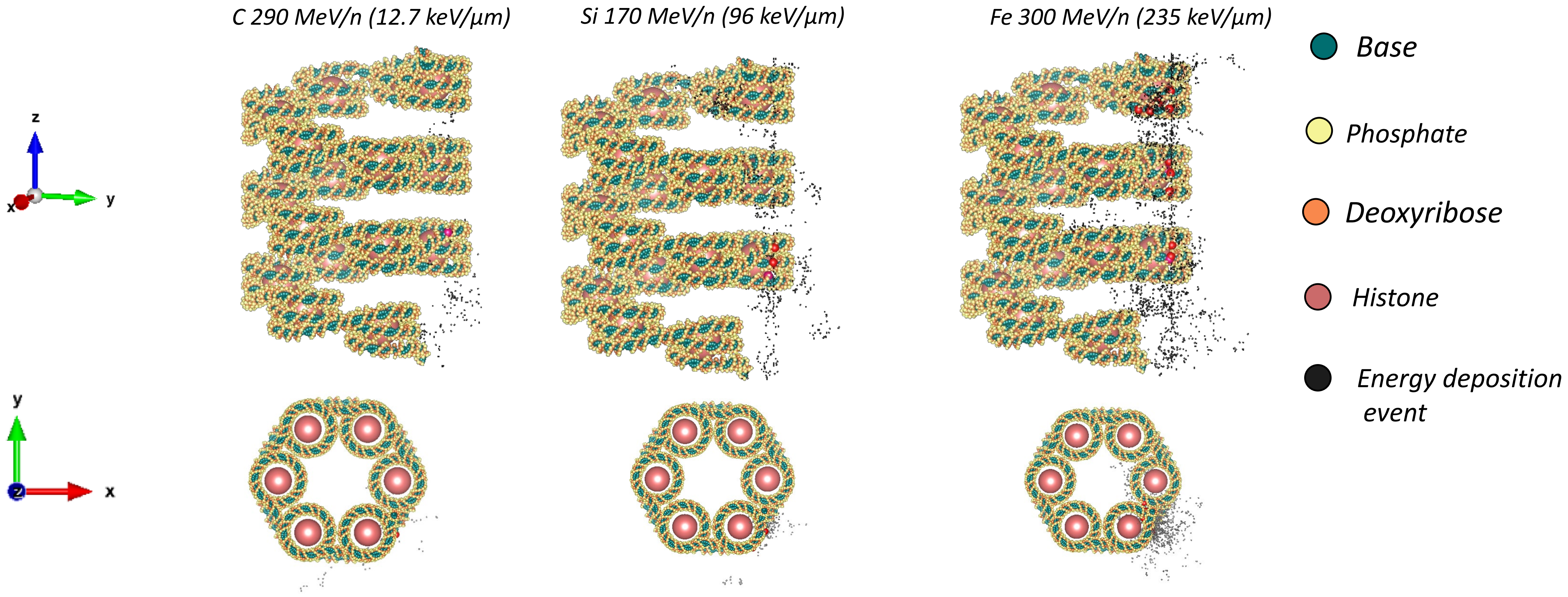


[Schaefer & Sullivan (1976)]



[Goodhead (1989)]

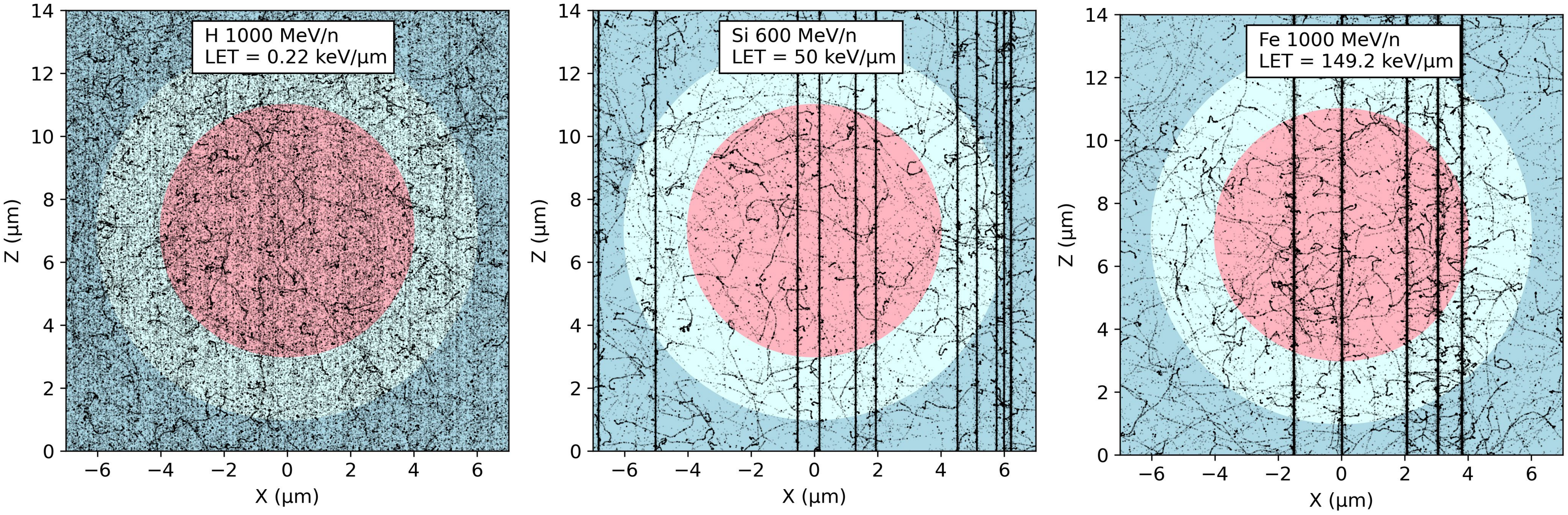
Track Structure at DNA Scale



[Image courtesy of Floriane Poignant]

Tracks and LET: Biological Impact

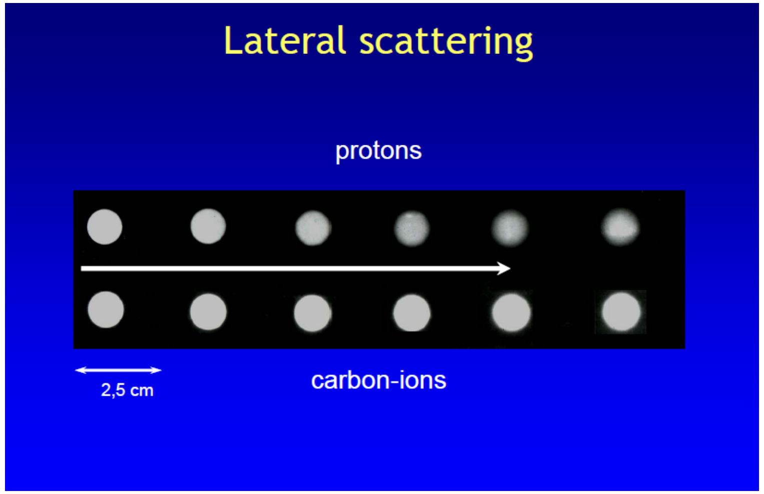
- Both LET and track structure are used to quantify biological effect
  - The energy deposition pattern of charged particles becomes significant at cellular (micro and nano) scale



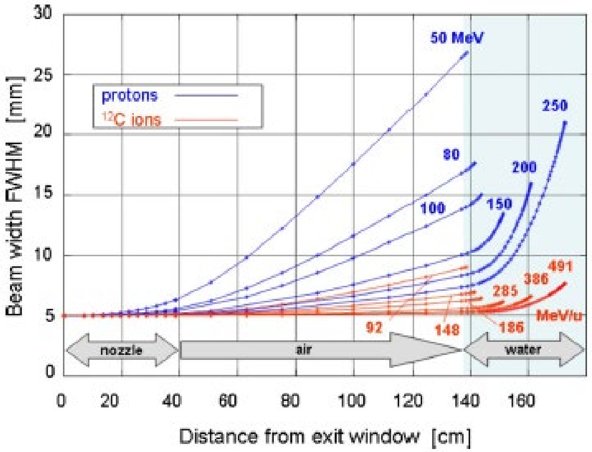
[Image courtesy of Floriane Poignant]

Lateral Scattering

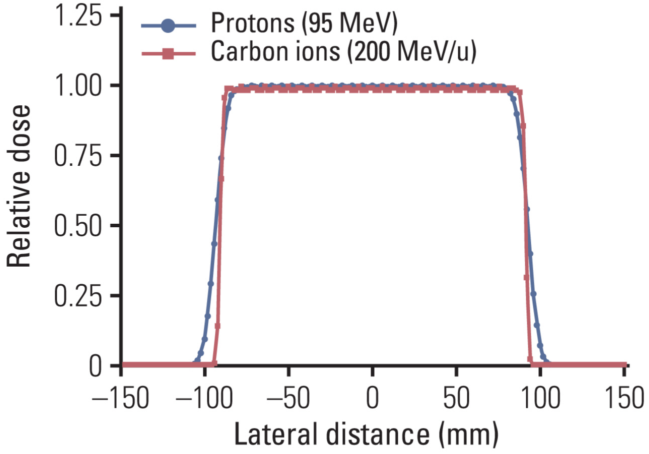
- As ions through a material, they collide with nuclei and electrons of the atoms in the medium and scatter
- Changes the beam shape and spatial spreading



[Jäkel et al. (2014)]



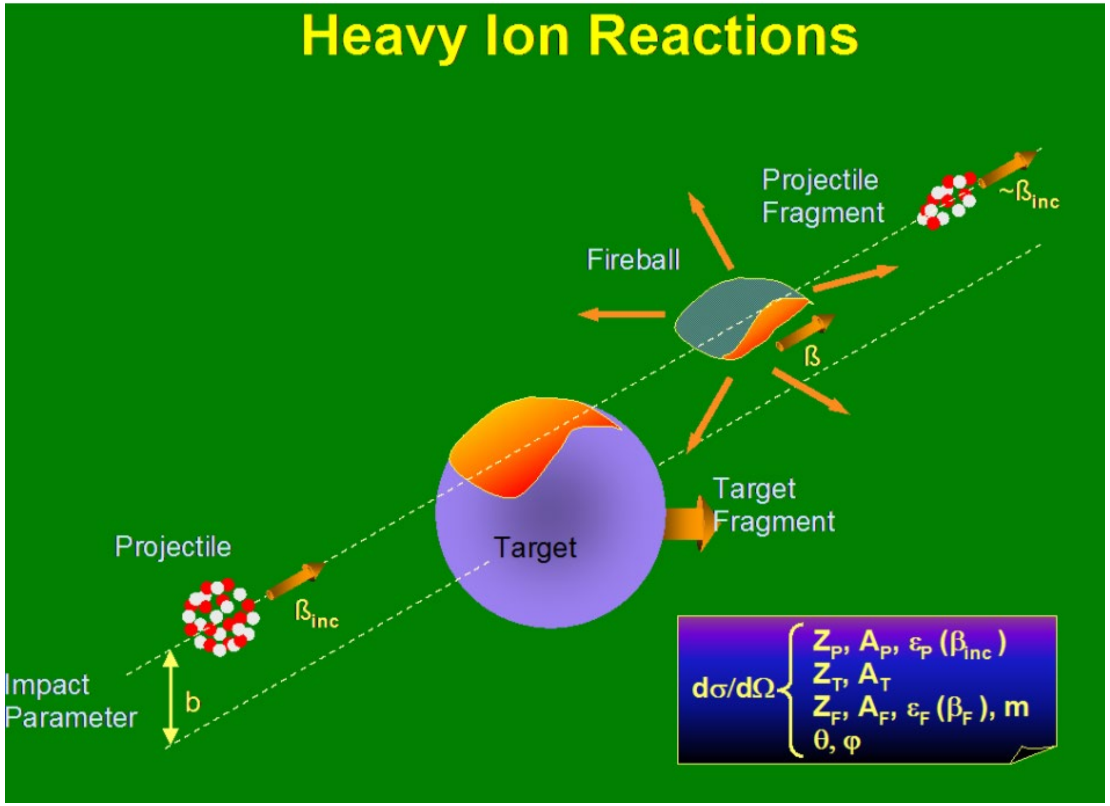
[Jelen et al .(2013)]



[Byun et al. (2021)]

Fragmentation (Nuclear Interactions)

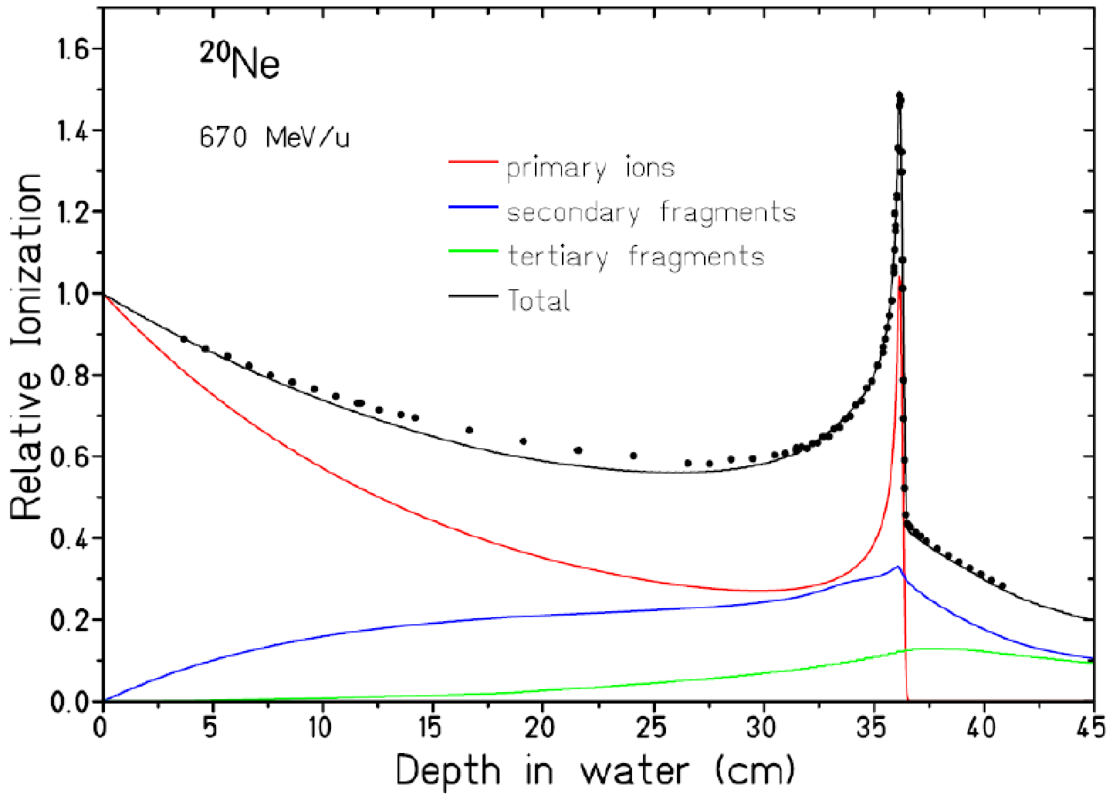
- Heavy particles (e.g. Carbon, Oxygen, Neon ions, HZE ions) undergo fragmentation



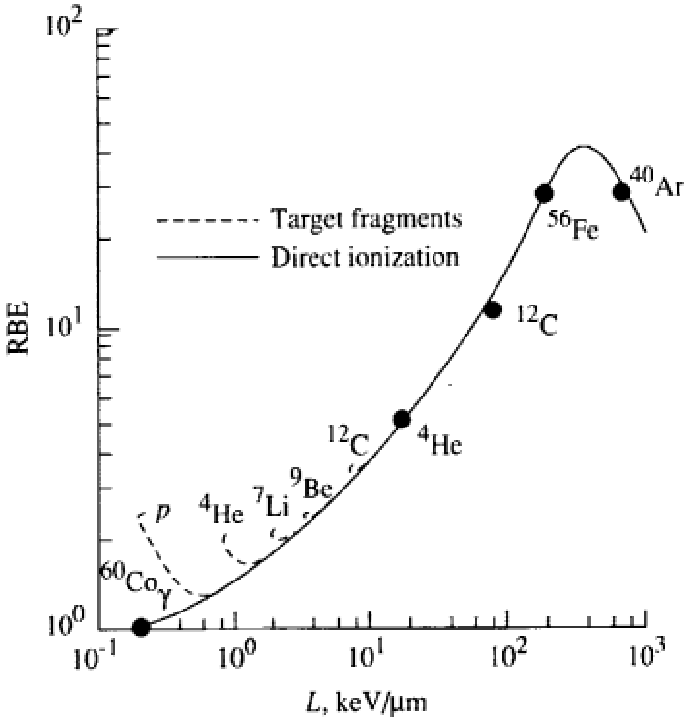
[Cucinotta (2012)]

Fragmentation

- Secondary fragments contribute significantly to the total dose for heavier ions (i.e. HZE particles in GCR)



[Huisman (2017)]



Relative biological effectiveness (RBE) for Harderian gland tumors including target fragment effect [Wilson (1993)]

Summary

- Space radiation is dominated by charged particles interactions
- The interactions can be atomic or nuclear
- Atomic interaction can be characterized by LET and track structure
  - Biological effect
- Nuclear interactions mainly cause fragmentation, which produces secondary radiation that contributes significantly to dose behind shielding