Nanodosimetric Study of Radiation in the Organs of Astronauts on the Lunar Surface

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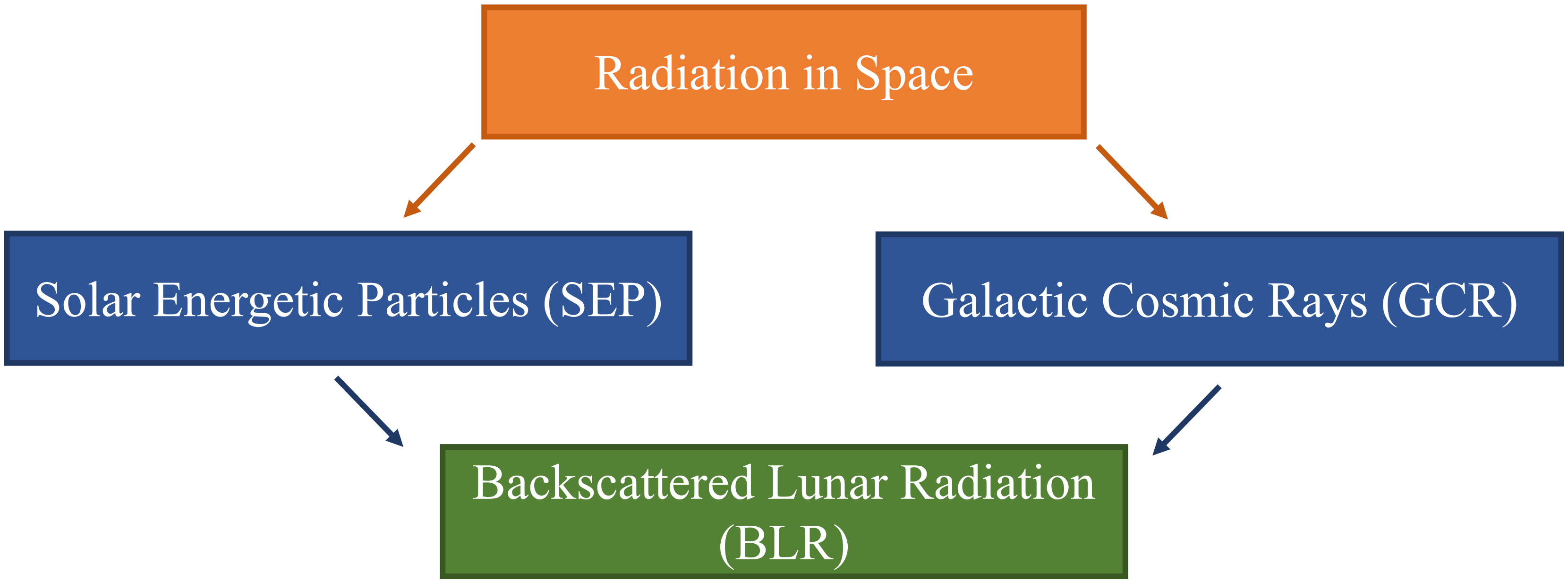
Space Radiation

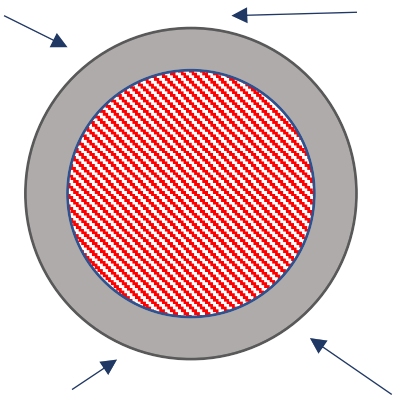
- Beyond the surface of Earth, the lack of an atmosphere and a geomagnetic field results in a *harsher* radiation environment



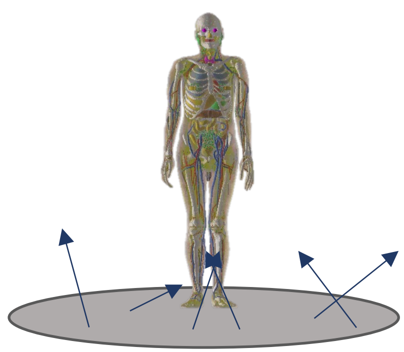
- Understanding the radiation environment in vital organs and potential DNA damage is paramount to astronaut safety
- Risks associated with radiation considered to have the greatest uncertainty for space missions
- Current focus on lunar missions

Lunar Nanodosimetry: Strategy

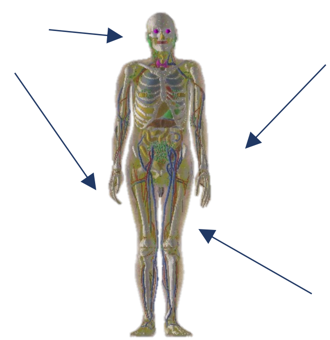
- A <u>multiscale approach</u> was implemented in order to assess radiation risk:
  1. Model the backscattered radiation on the moon
  2. Determine backscattered radiation incident on organs in the ICRP145 human phantom
  3. Determine primary GCR incident on organs
  4. Simulate the radiation incident on organs at the DNA scale, using a cell model



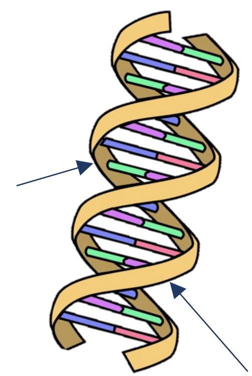
1 – Lunar Radiation



2 – Lunar radiation + phantom



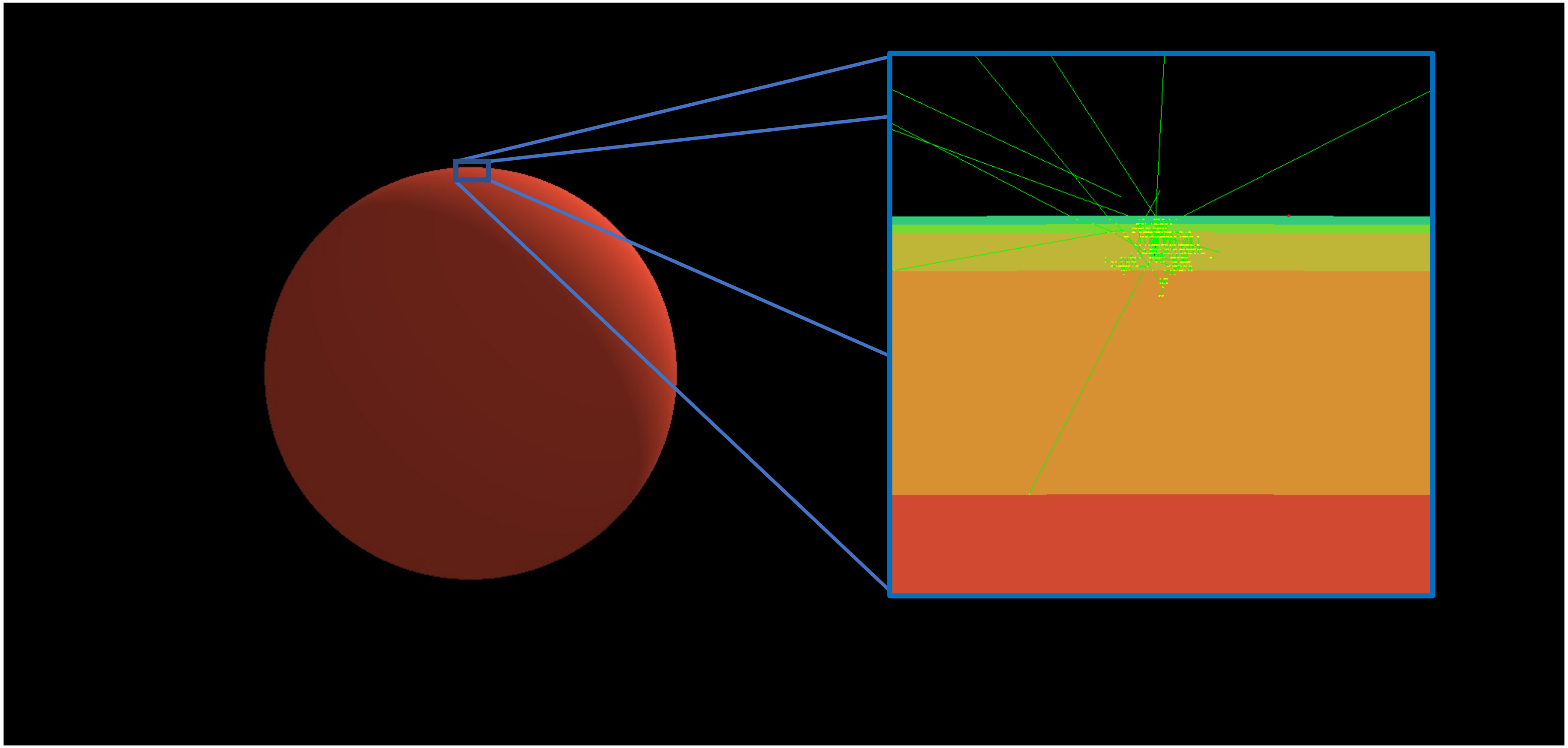
3 – GCR + phantom



4 – DNA-scale

Lunar Nanodosimetry: Strategy

- Backscattered radiation from the lunar surface was simulated using a multilayer lunar volume
- More details in following talk by M. J. Large



Backscattered Lunar Radiation (BLR)

- Human phantom simulations performed in Geant4 11.0.1
- The radius of the disk was chosen to be 10 m
- However, this could be limited to model the effects of defects on the lunar surface

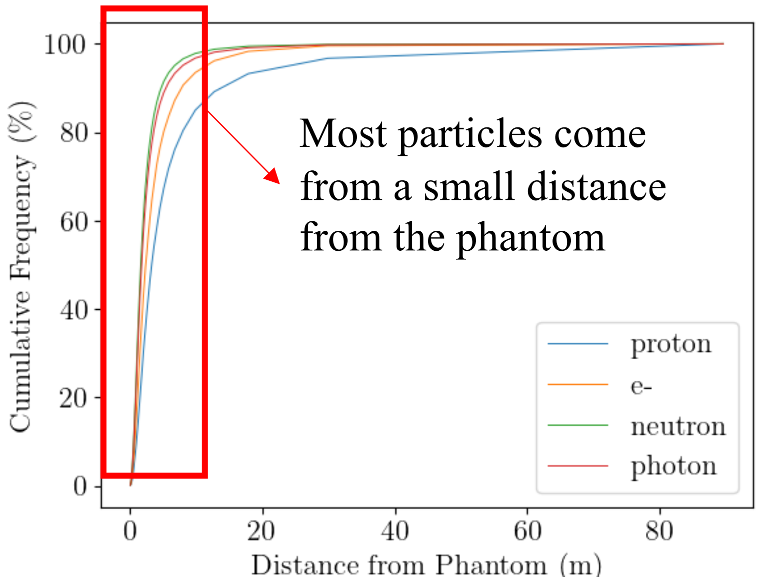
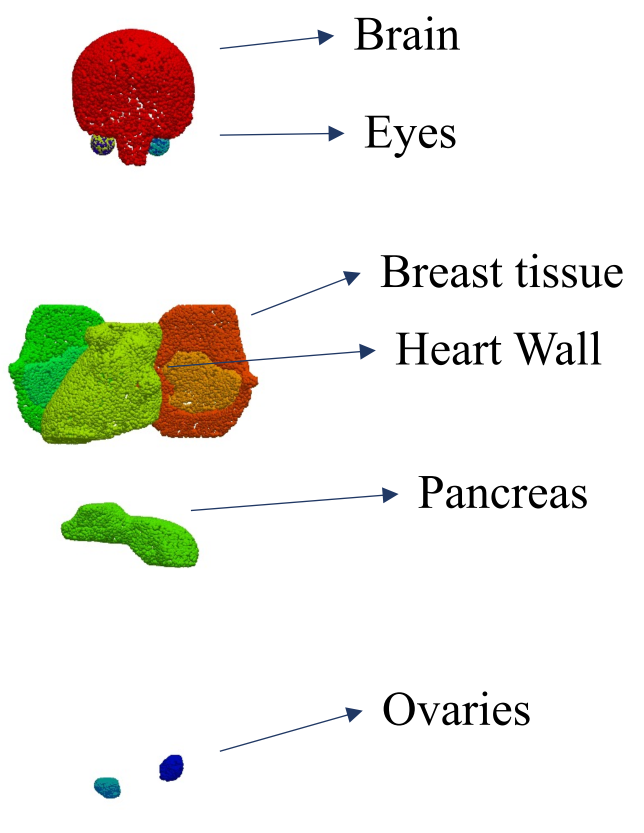


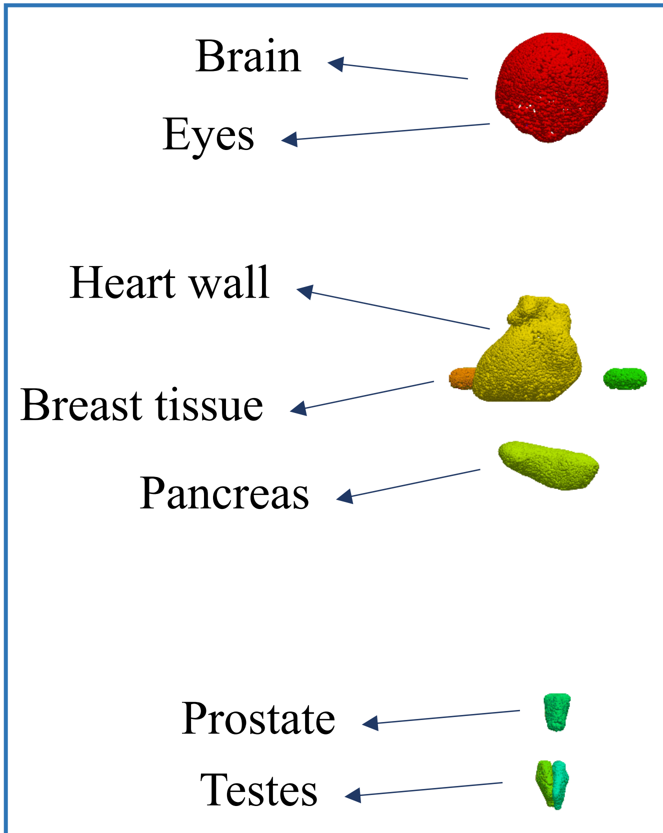
Figure: Cumulative frequency of particles which may hit the phantom based on the zenith angle distribution of BLR from GCR protons

Radiation Entering Organs

- Particles *entering* organs of interest are stored in a PSF
  - Only recorded if the particle or a parent of this particle has not already been recorded



Female Phantom



Male Phantom

Geant4 Space Radiobiology Physics List

- The GCR spectrum consists of many high energy protons and ions
- The secondary radiation spectrum consists of many low energy neutrons and high energy protons and electrons
- Currently Geant4-DNA can simulate:
  - Protons up to 100 MeV
  - Electrons up to 1 MeV
  - Ions up to 100 MeV / nucleon

Many particles exceeding these energies in the cosmic spectrum

- Hybrid Geant4 and Geant4-DNA physics list implemented

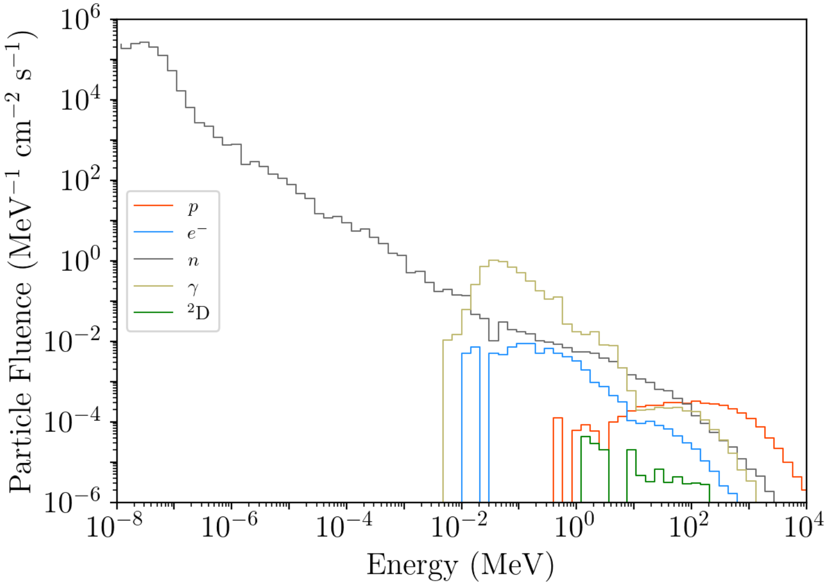
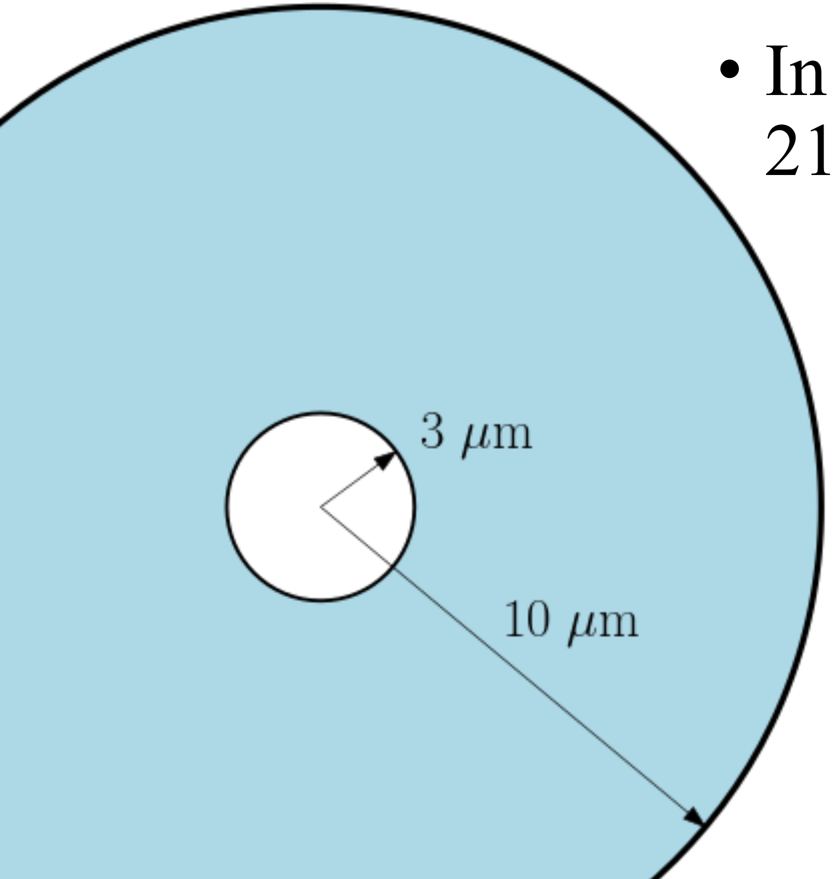


Figure: Radiation field in the pancreas due to incident primary GCR protons

Cosmic Radiation Nanodosimetry

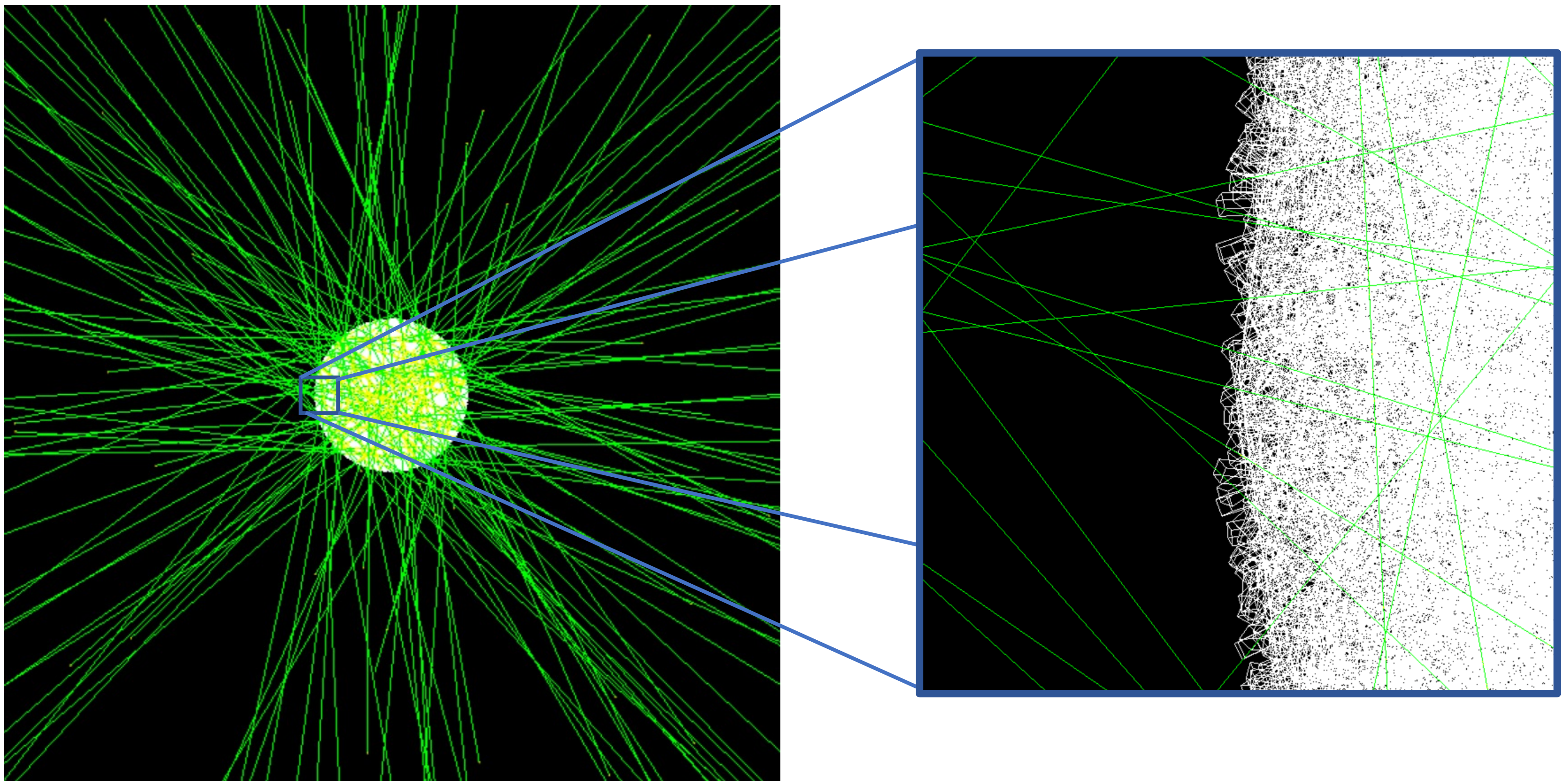
- Nanodosimetry performed using the *moleculardna* example[1] included in Geant4 11.0.1
- Consists of a 3um nucleus radius, 10um cell radius



- In the nucleus 200,000 straight 216bp DNA segments are used
  - G4EmDNAPhysics option 4 was implemented
    - Currently consider an isotropic source biased towards the cell nucleus

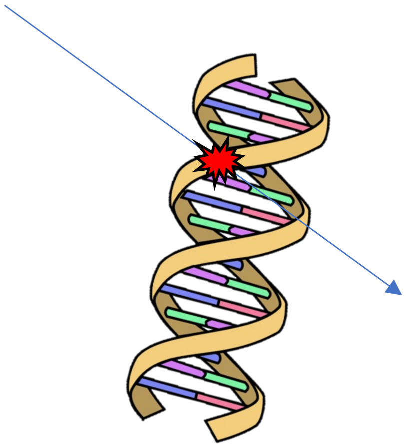
[1] – Chatzipapas et. al., 2022. *arXiv preprint*

Cosmic Radiation Nanodosimetry

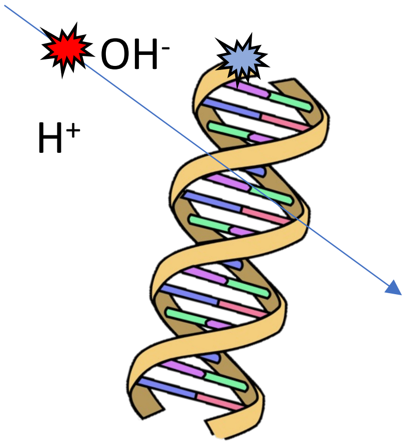


Damage Scoring

- The damage to the DNA can be due to:
  - Direct damage: due to direct *ionization* of the DNA itself
  - Indirect damage: due to the *chemical* interactions of induced hydroxyl radicals in the surrounding water with a DNA molecule



Direct Damage

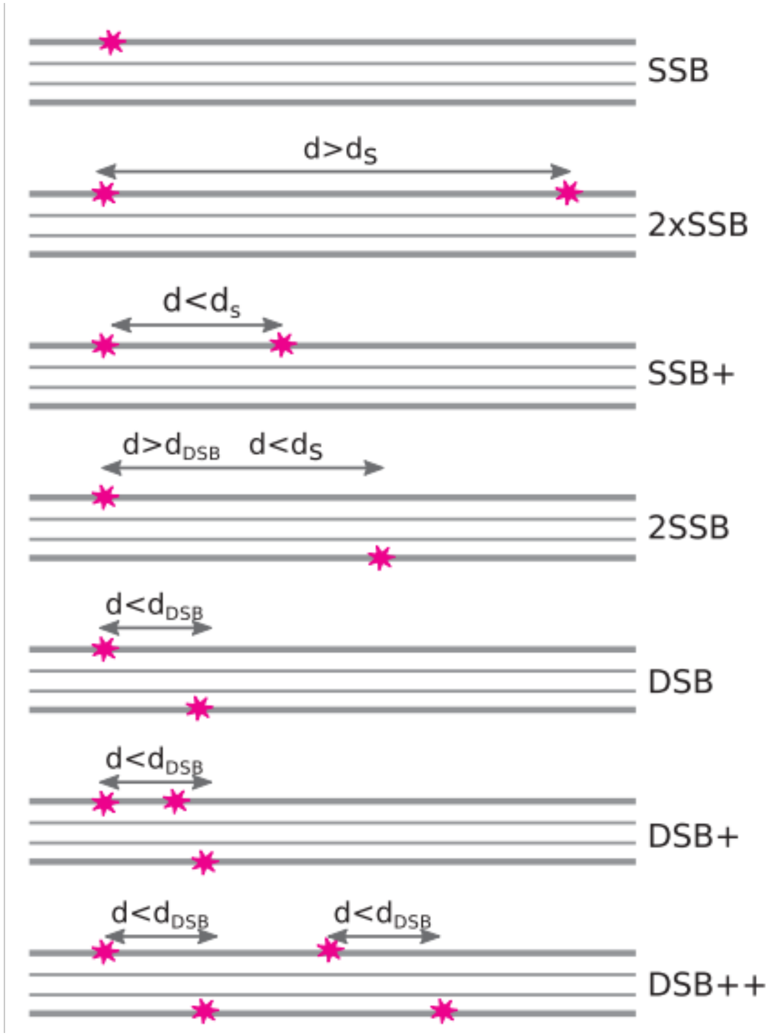


Indirect Damage

[2] – Sakata et. al, 2020. *Scientific Reports*, **10**(1)

Damage Complexity – Physics

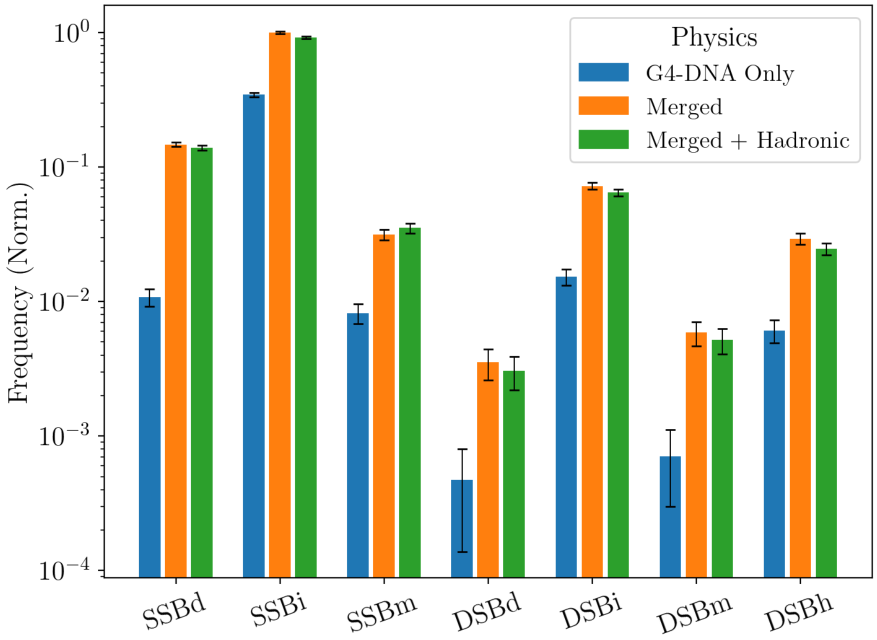
- DNA damage is also scored using the scheme implemented by Nikjoo et. al. and outlined by Lampe et. al.



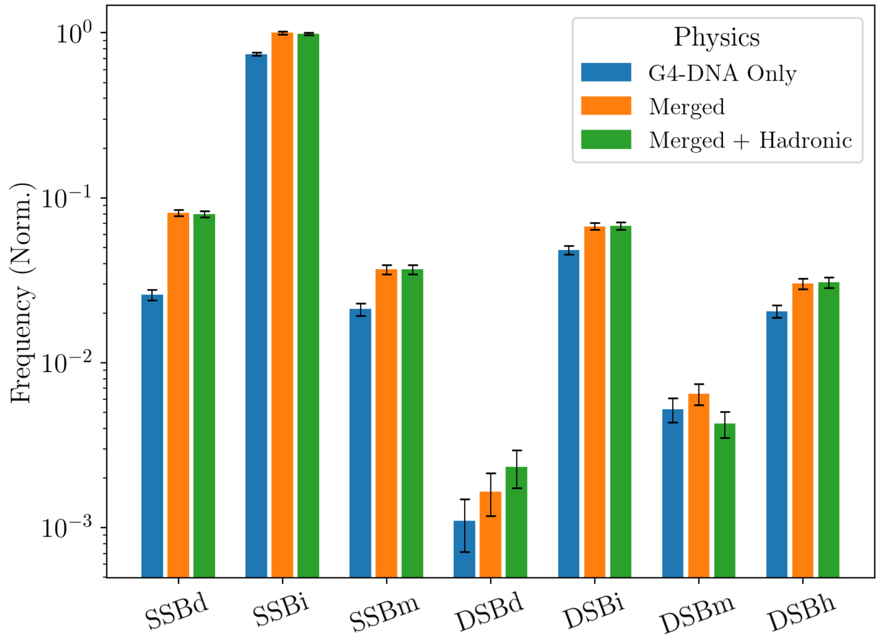
[2] – Lampe et. al., 2018. *Physica Medica*, **48**
[3] – Nikjoo et. al., 1997. *Int J Radiat Biol,* **71**(5)

Physics List Strand Breakage

- Inclusion of non-DNA Geant4 physics results in a significant increase in *direct* and *indirect* damage
- Only small changes including hadronic physics



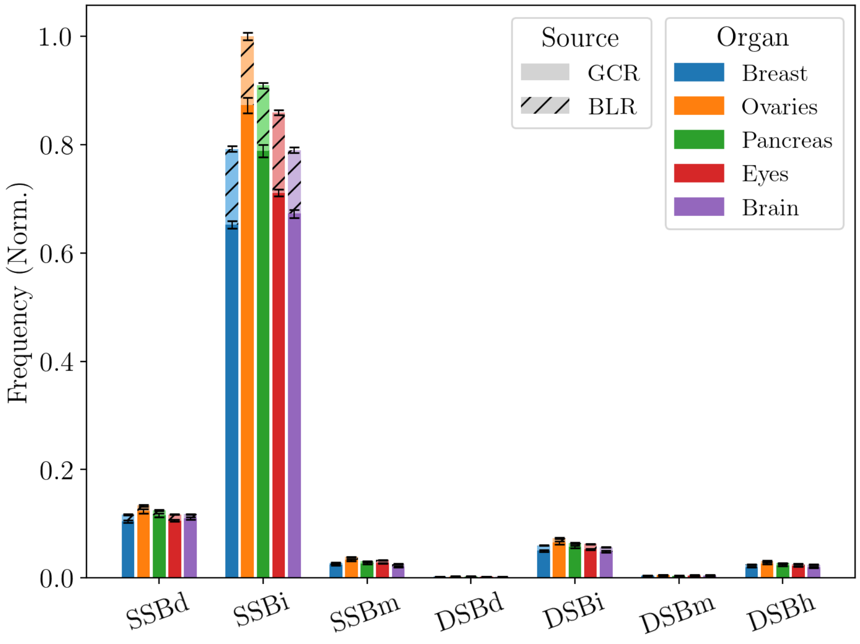
a) Primary GCR



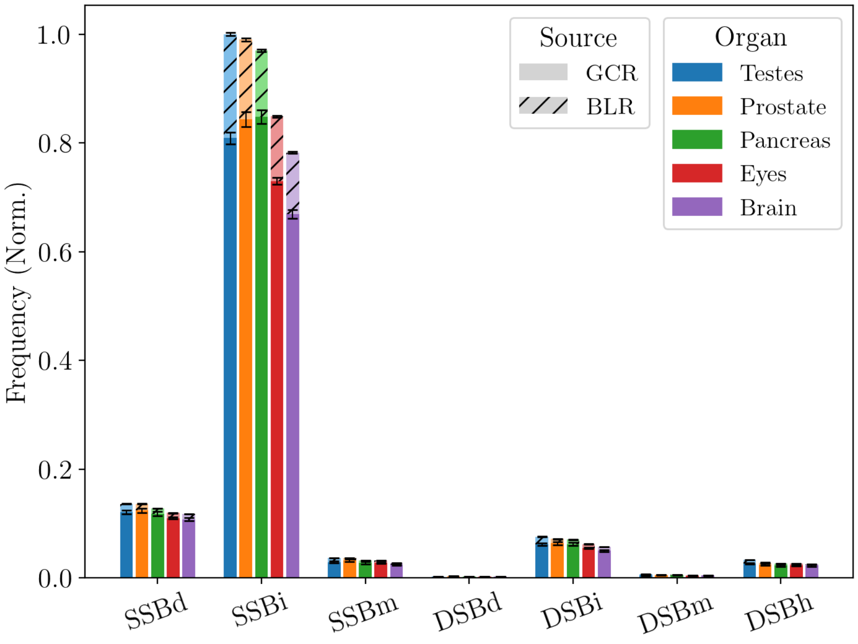
b) Backscattered Lunar Radiation

Organ Strand Breakage Rate

- *Origin* of strand breaks due to primary GCR and backscattered radiation
- *Indirect* damage is main source of damage
- Backscattered radiation also significant



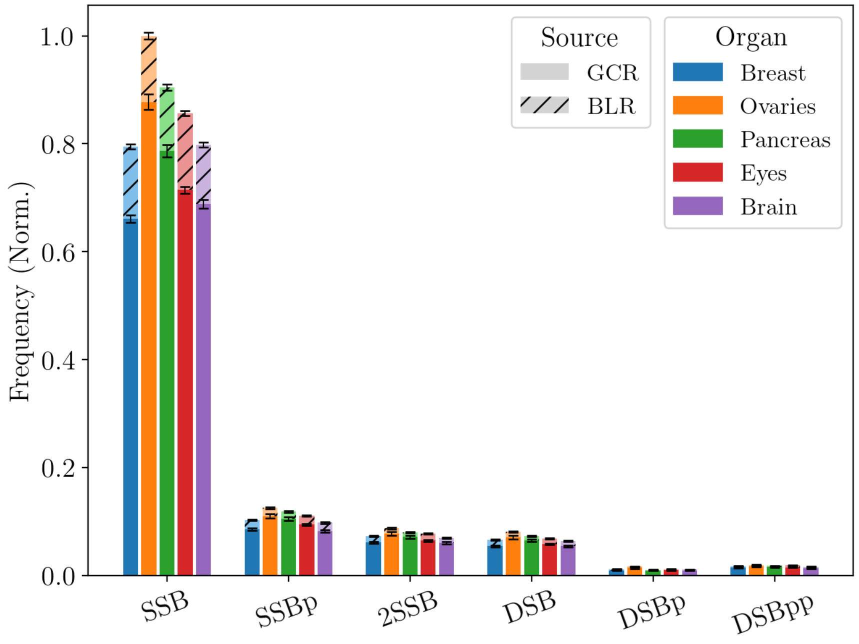
a) Female Phantom



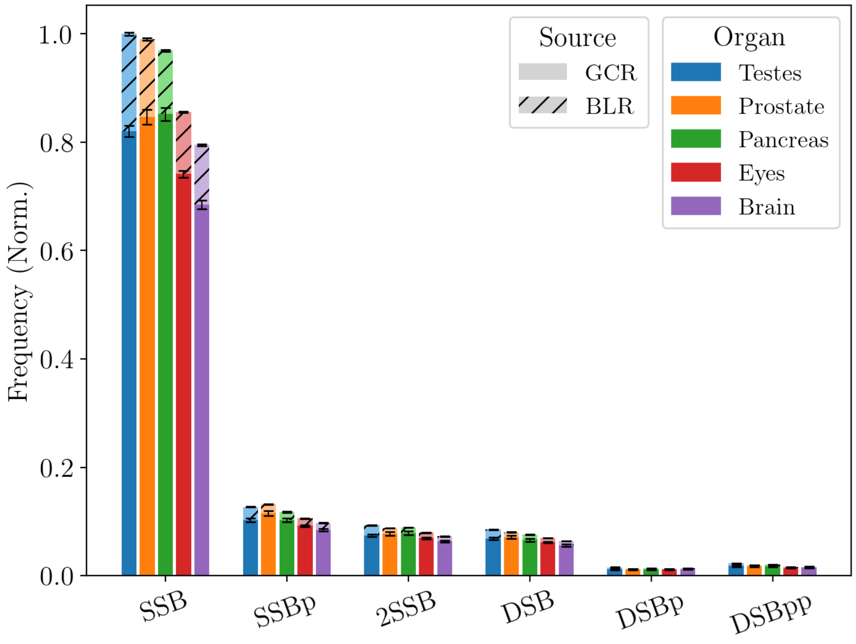
b) Male Phantom

Organ Strand Breakage Rate

- *Complexity* of strand breaks due to primary GCR and backscattered radiation
- More damage found in ovaries, testes, prostate and pancreas compared to the brain



a) Female Phantom



b) Male Phantom

Discussion and Next Steps

- Currently, only radiation *entering* organs are considered
  - Investigation into fragments in organs required
- Only damage generated by GCR protons considered here
  - Heavier ions also contribute to radiation damage in space [4]

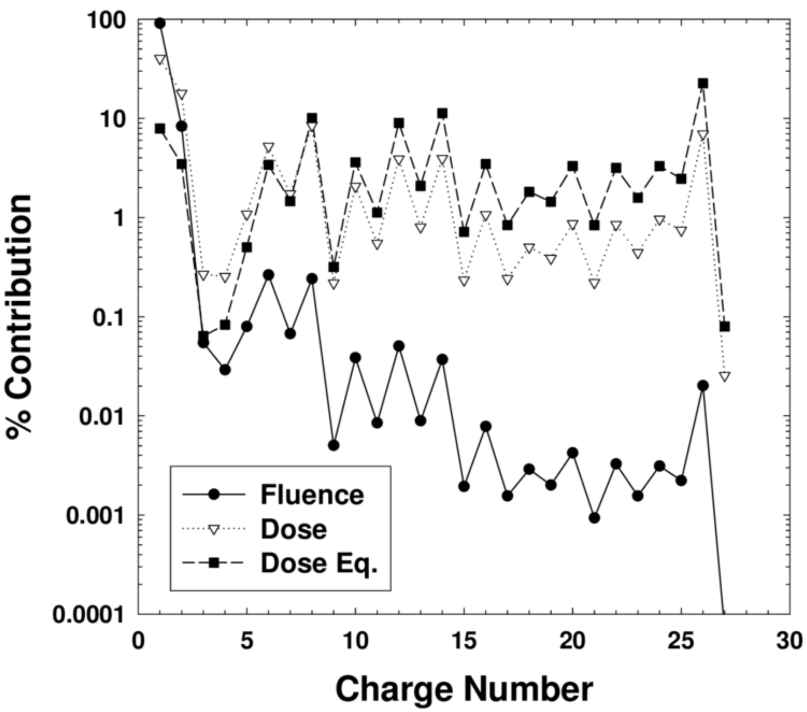


Figure: Contribution of different ions in the GCR spectrum to space radiation [4]

[4] – Cucinotta et. al., 2003. *Gravitational and Space Biology*, **16**(2)

Summary

- A nanodosimetric assessment of the space radiation environment is vital for understanding the long-term safety of astronauts
- Human phantom (*ICRP145*) and DNA models (*moleculardna*) have been applied to assess radiation damage in organs of interest
- High energy particles require hybrid Geant4-DNA and Geant4 physics lists
- Backscattered lunar radiation contributes significantly to DNA damage induction