

Project Update

Development of Methodologies and Strategies for the Radiation Protection of Astronauts in Space

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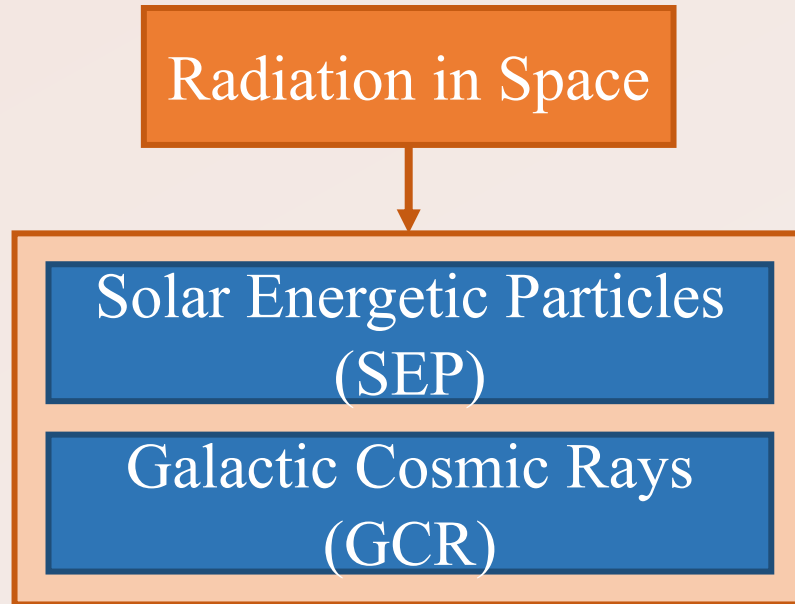
⁵CERN, Geneva, Switzerland

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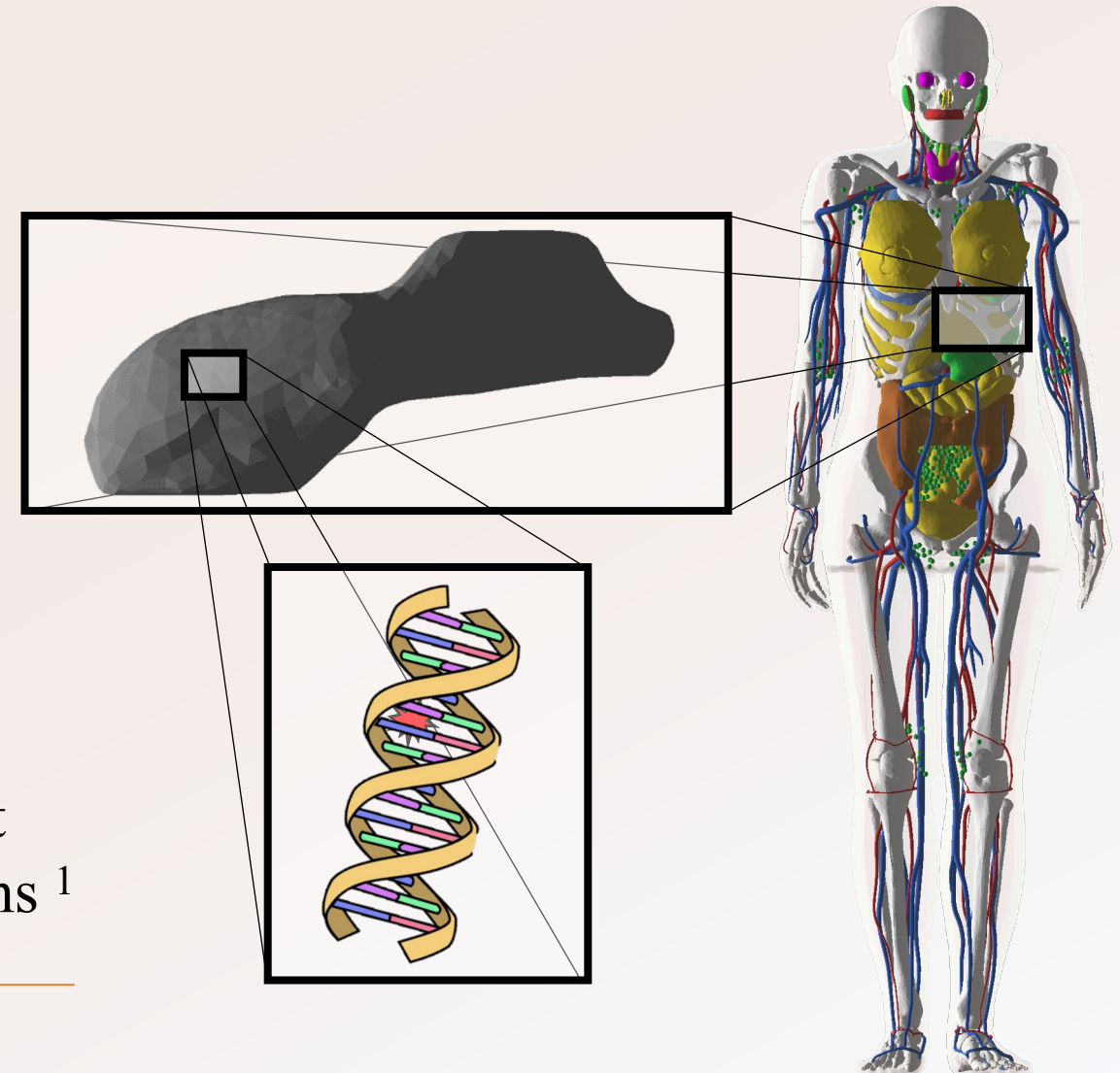
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Space Radiation



Considered one of the greatest and most uncertain risks for long-term space missions ¹

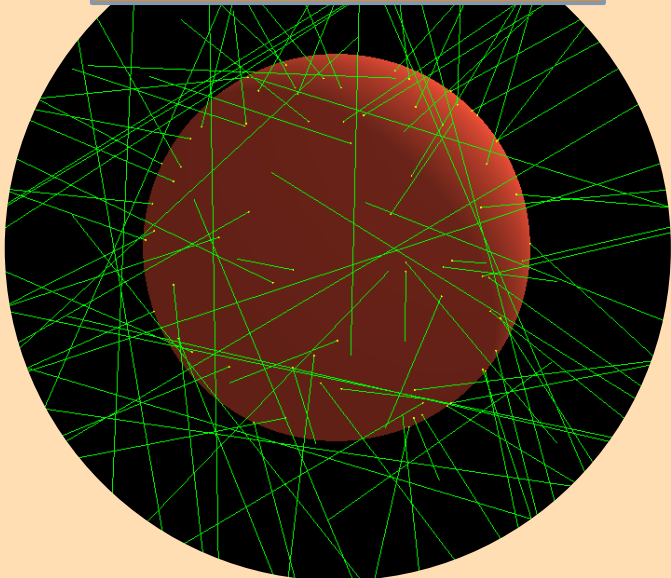
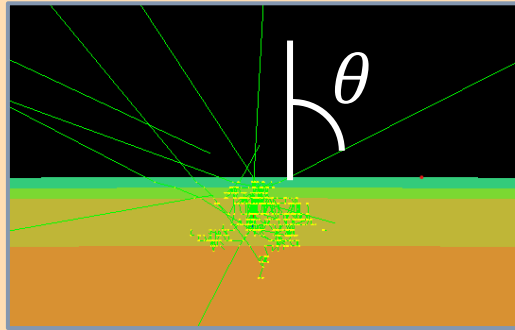
[1] – Cucinotta and Durante, 2006. *The lancet oncology* 7(5)



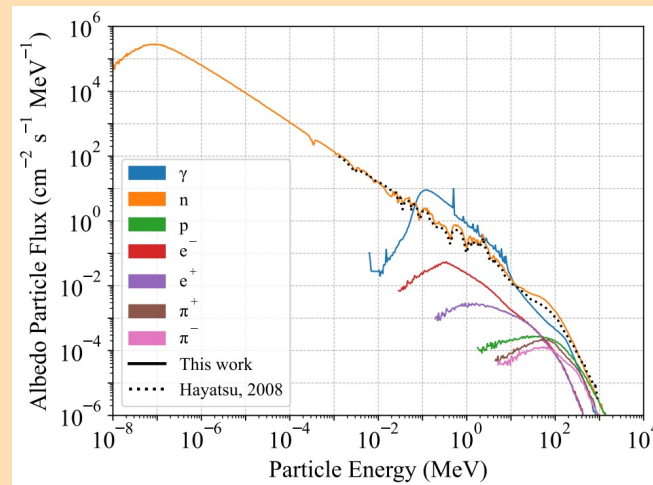
Lunar Nanodosimetry

A multiscale approach ① - ③ was implemented:

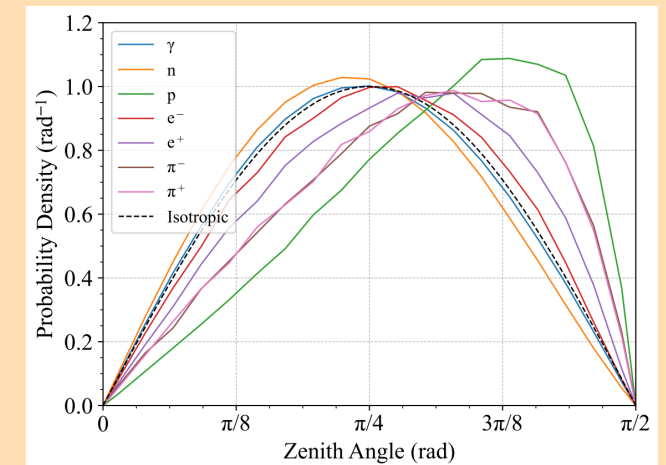
① Backscattered Lunar Radiation (BLR)



Composition of lunar shells from the literature ^{2, 3}



Backscattered radiation spectra



Zenith angle distribution

[2] – Mesick, et. al., 2018. *Earth and Space Science*, **5**(7)

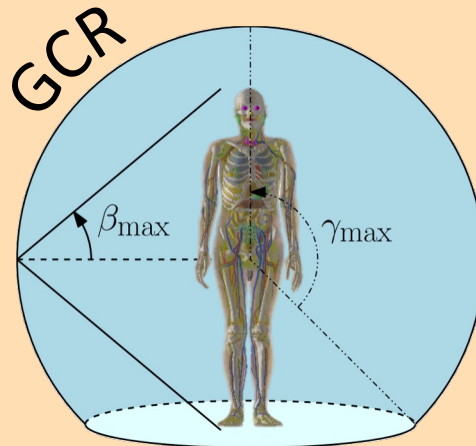
[3] – McKinney, et. al., 2006. *Journal of Geophysical Research: Planets*. **11**(6)

[4] – Hayatsu, et. al., 2008. *Biological Sciences in Space*, **22**(2)

Lunar Nanodosimetry

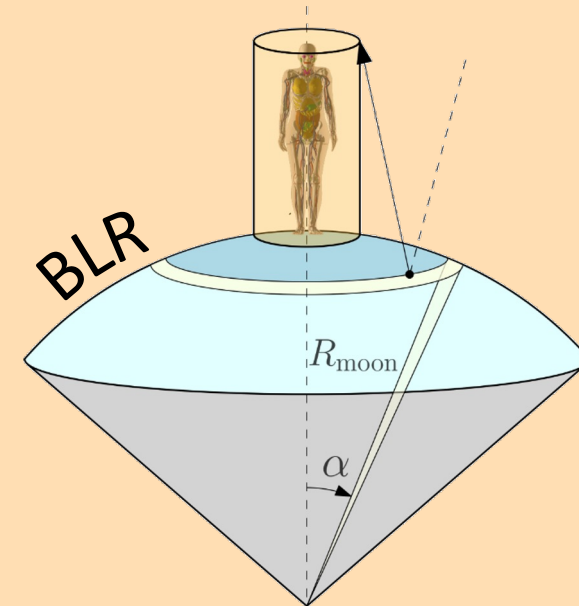
2

Radiation in Organs



- Isotropic above feet
- Angular biasing applied ⁵:

$$N = \Phi 2\pi^2 R^2 \sin^2 \beta_{\max} [1 - \cos \gamma_{\max}]$$



- Uniform over surface
- Custom energy and angular distribution
- Novel biasing applied

$$\text{pdf}(\alpha) = p_{\phi}(\alpha) \cdot p_{\cos \theta}(\alpha)$$

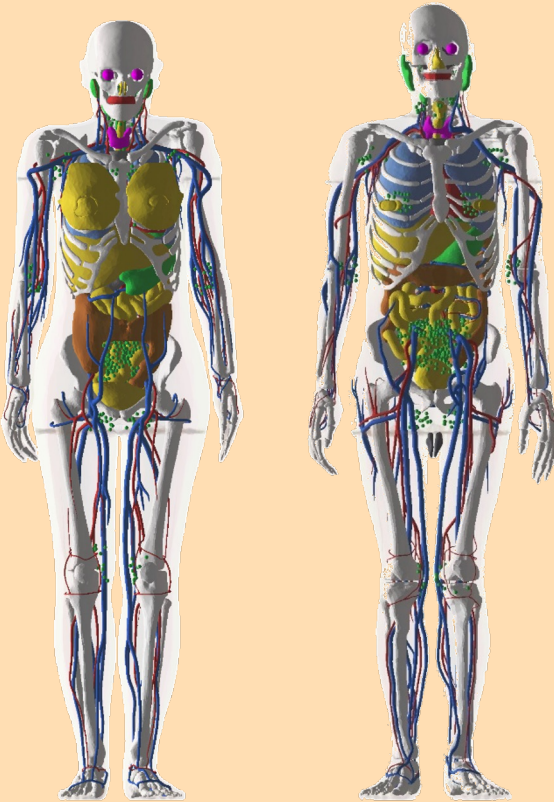
Analytical

Numerical

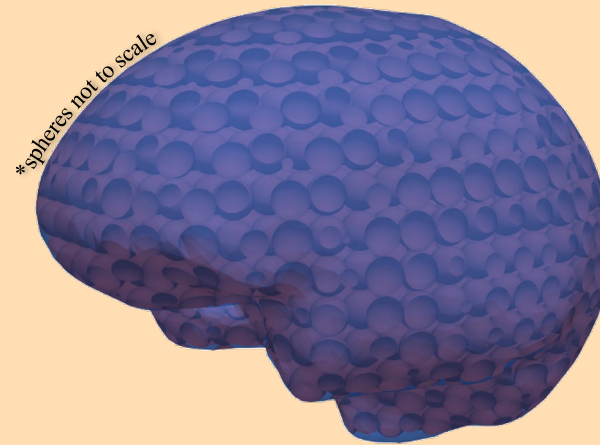
Lunar Nanodosimetry

2

Radiation in Organs

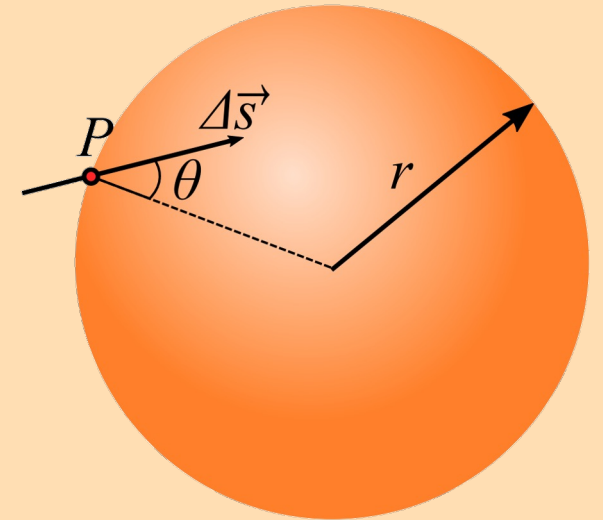


Human Phantoms



- 10 um lattice of virtual scoring spheres
- Step limit applied in organs of interest

Scoring Lattice



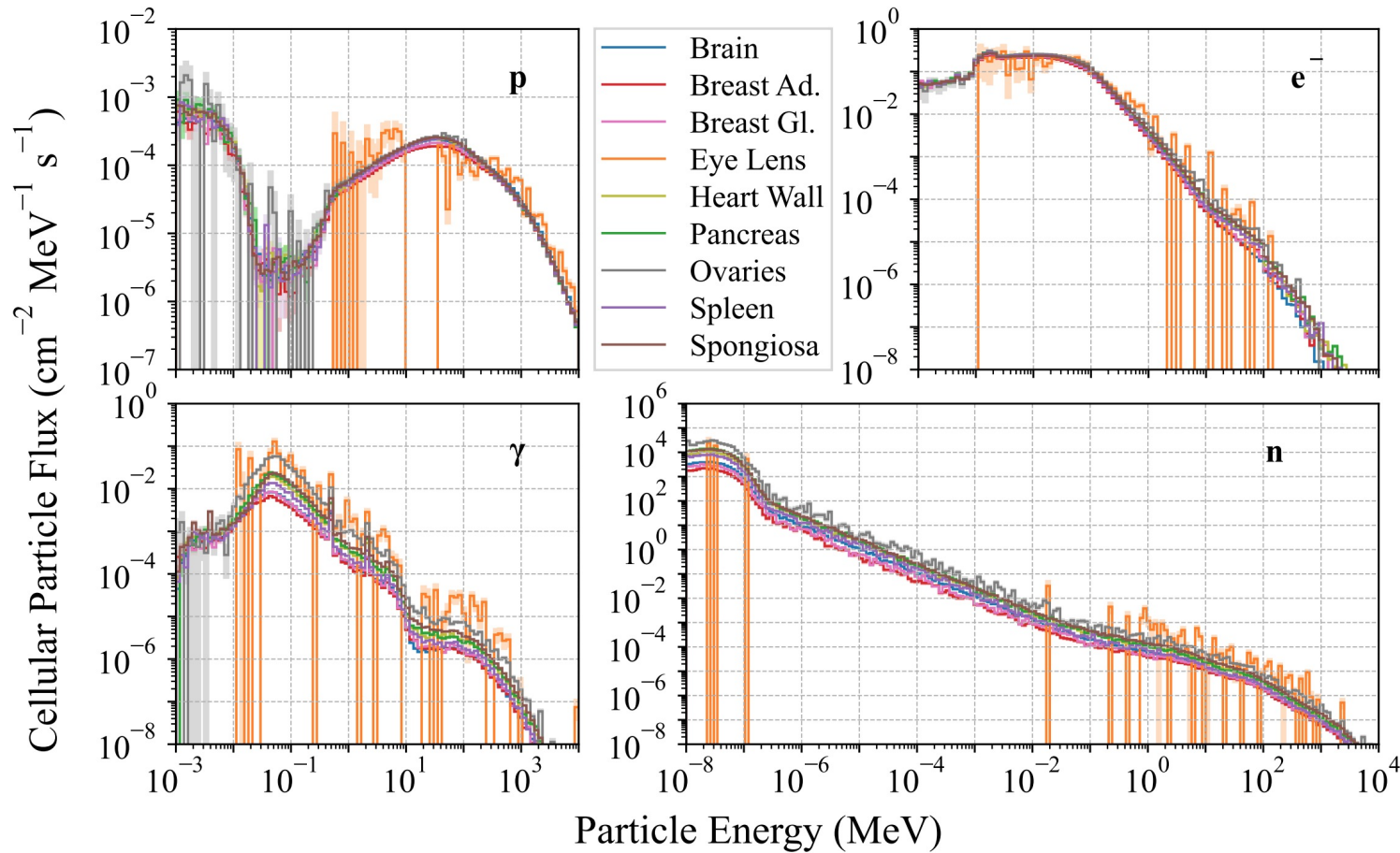
- Particle type, energy and $\cos\theta$ stored at entrance

Volumetric Scoring Sphere

Lunar Nanodosimetry

2

Radiation in Organs



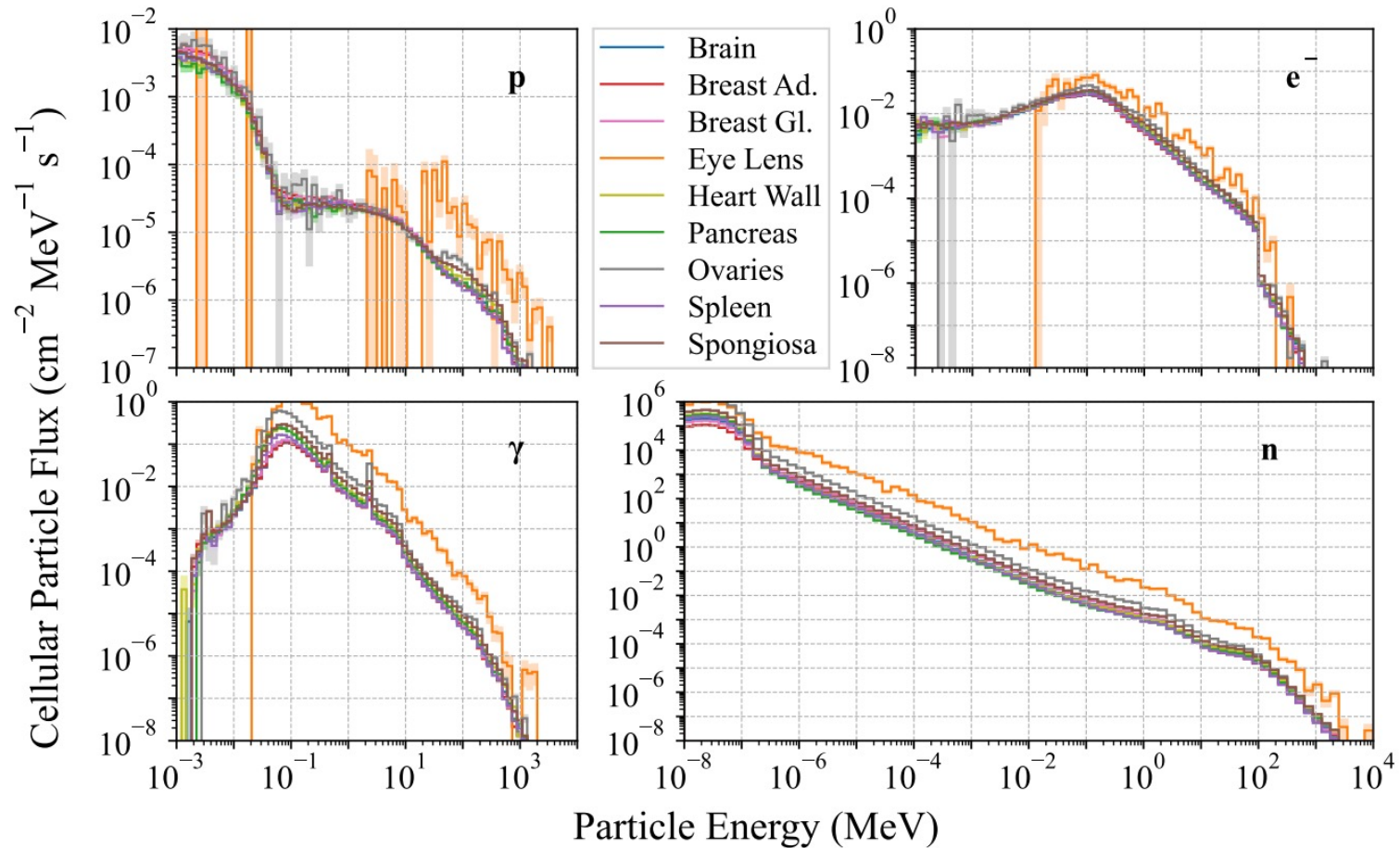
Cellular particle flux due to *GCR protons* incident on the female phantom

- Normalised to the surface area of all the scoring spheres inside of each organ

Lunar Nanodosimetry

2

Radiation in Organs



Cellular particle flux due to *BLR* incident on the female phantom

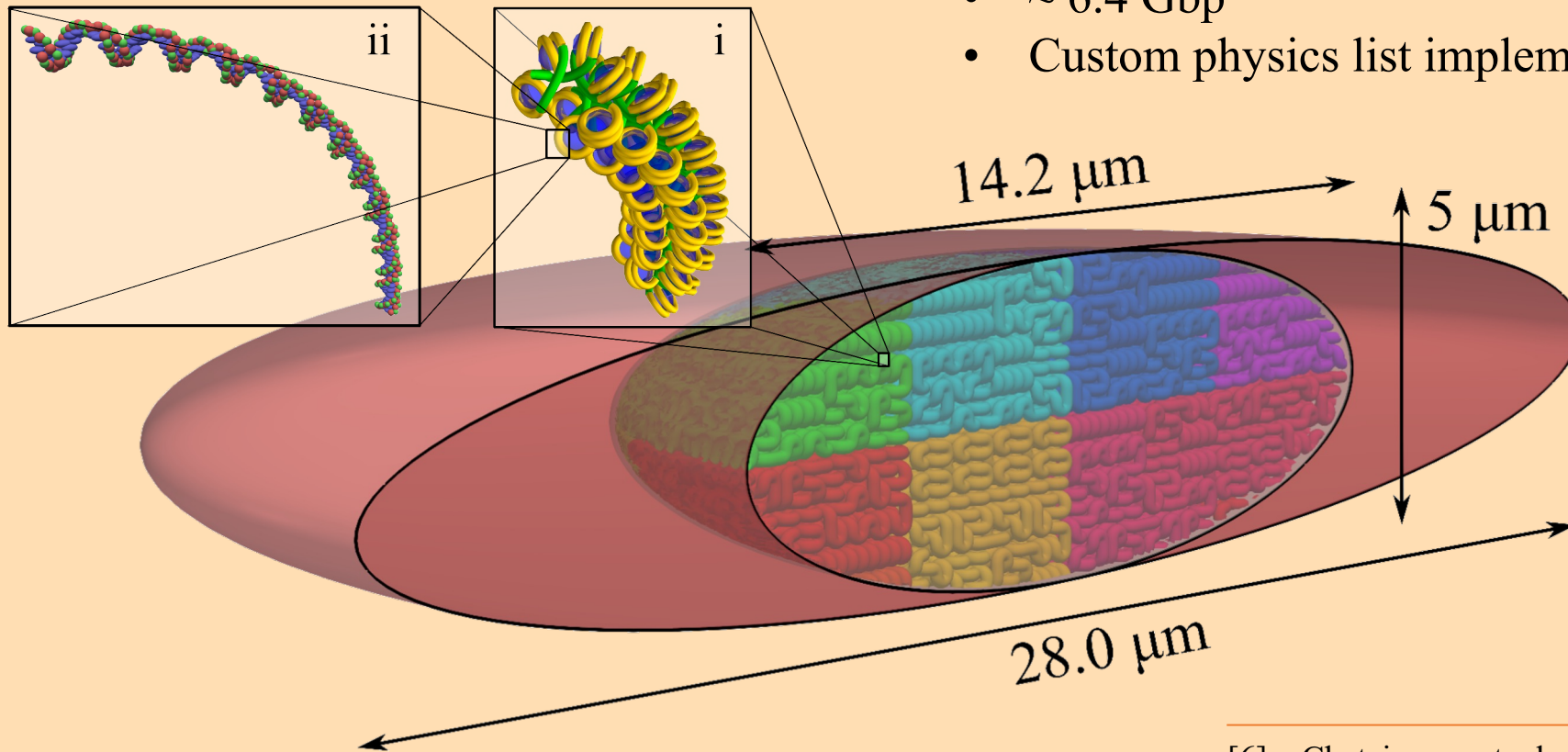
- Normalised to the surface area of all the scoring spheres inside of each organ
- Compared to GCR, higher yields of neutrons, gammas and high energy electrons

Lunar Nanodosimetry

3

DNA Simulation

- Full human fibroblast geometry implemented based on *molecularDNA* example ⁶
- ~ 6.4 Gbp
- Custom physics list implemented

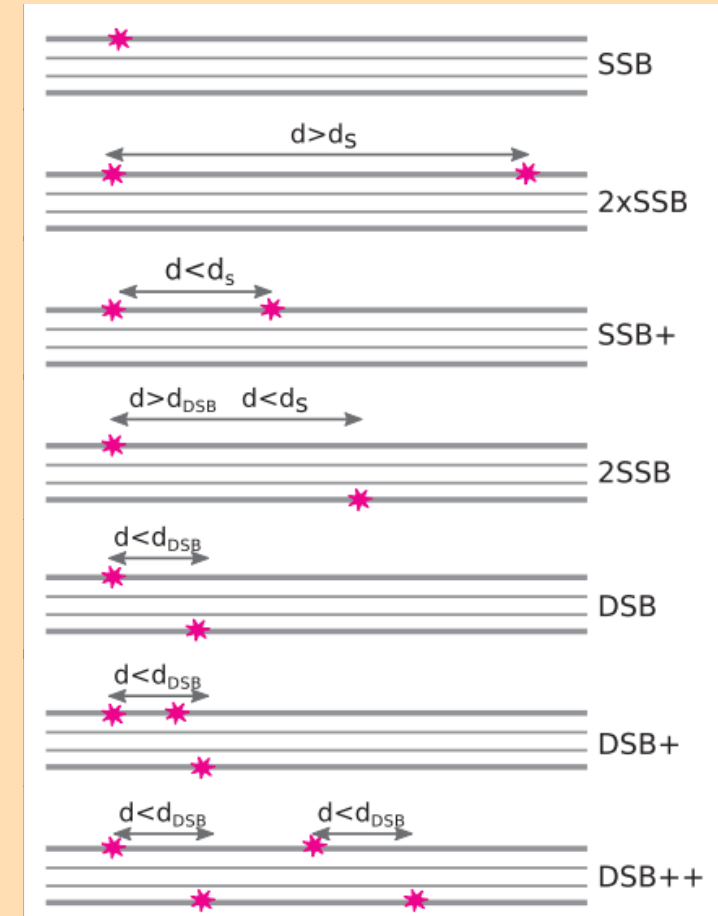
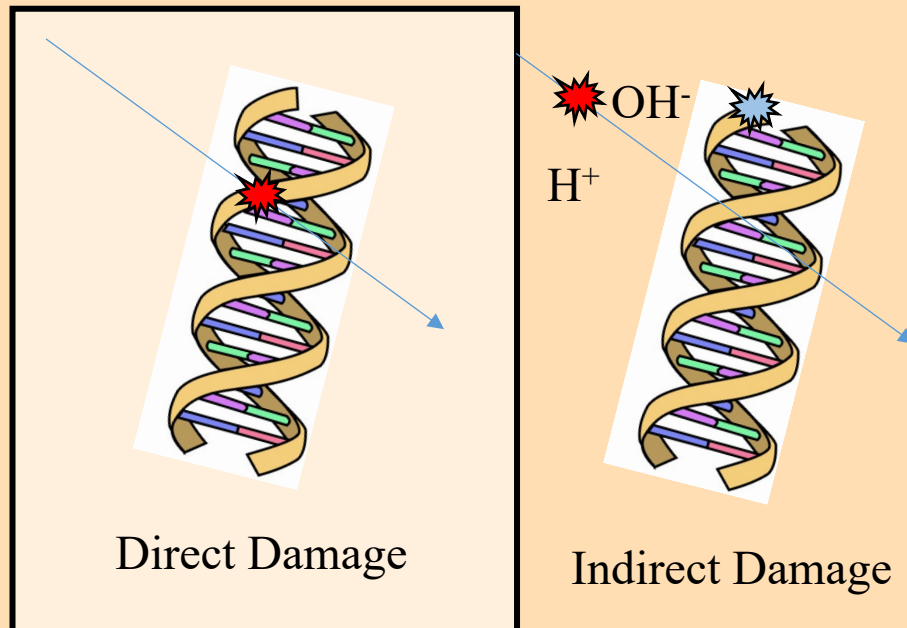


Lunar Nanodosimetry

3

DNA Simulation

- DNA damage is also scored using existing damage schemes ^{7,8}
- Both direct and indirect damage implemented

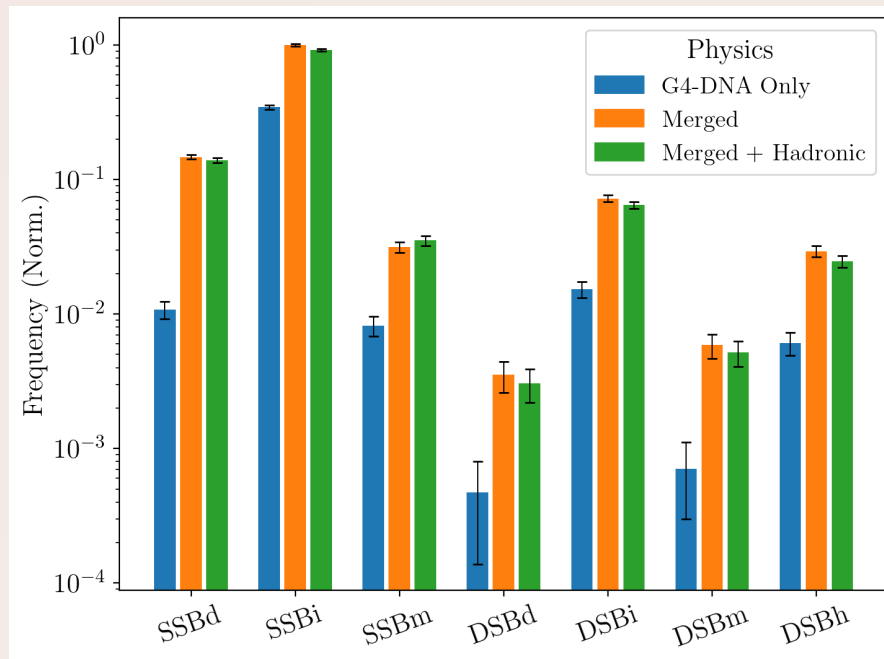


[7] – Lampe et. al., 2018. *Physica Medica*, **48**

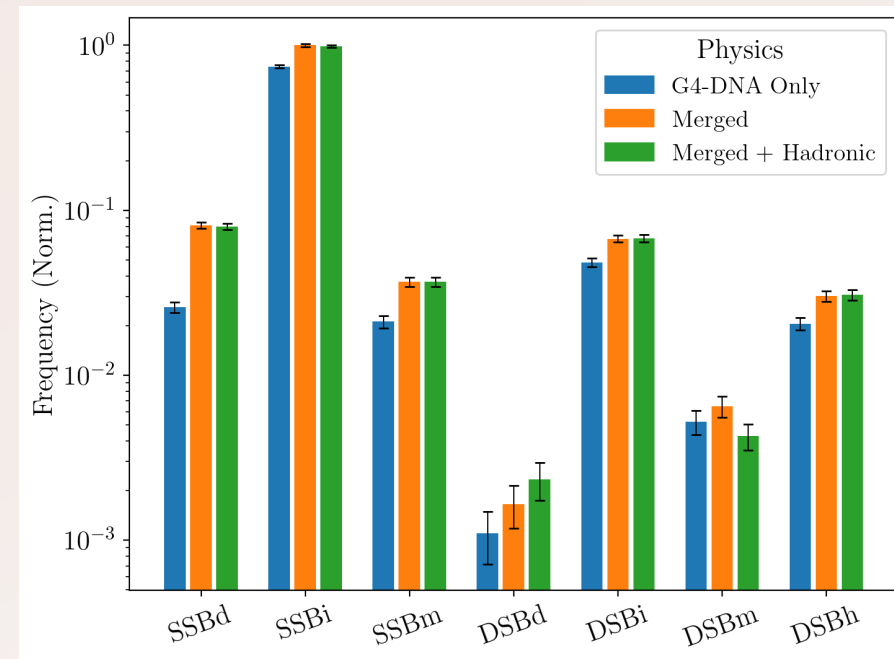
[8] – Nikjoo et. al., 1997. *Int J Radiat Biol*, **71**(5)

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



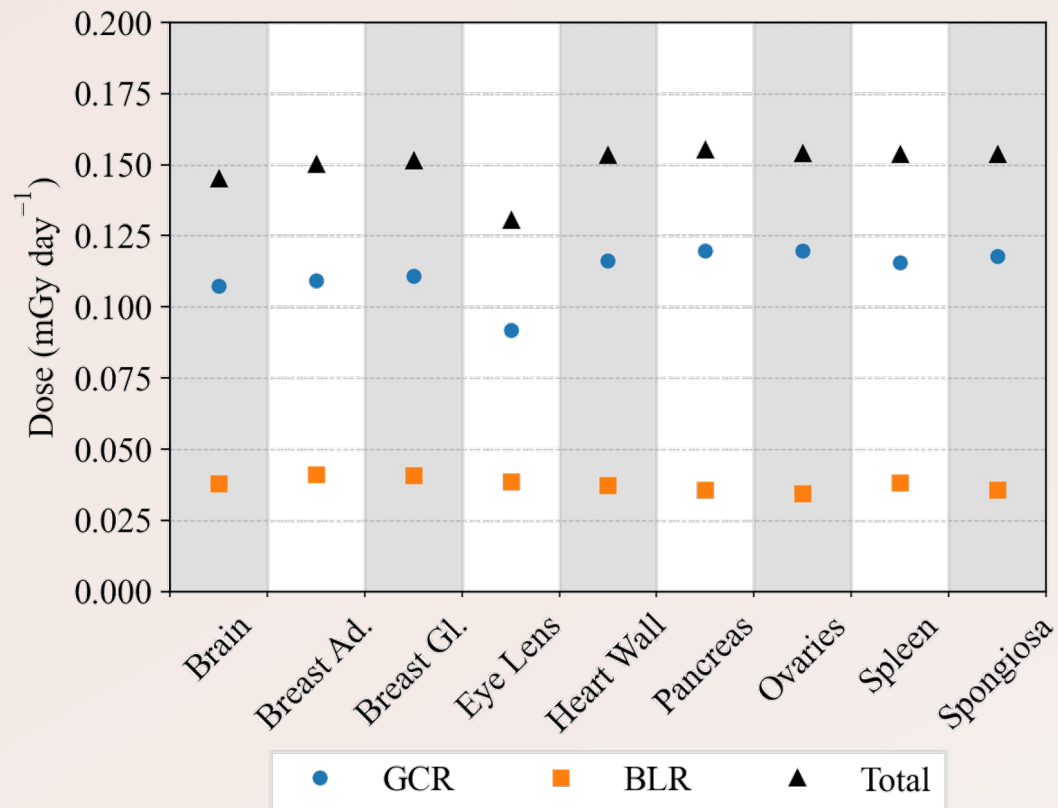
a) Primary GCR



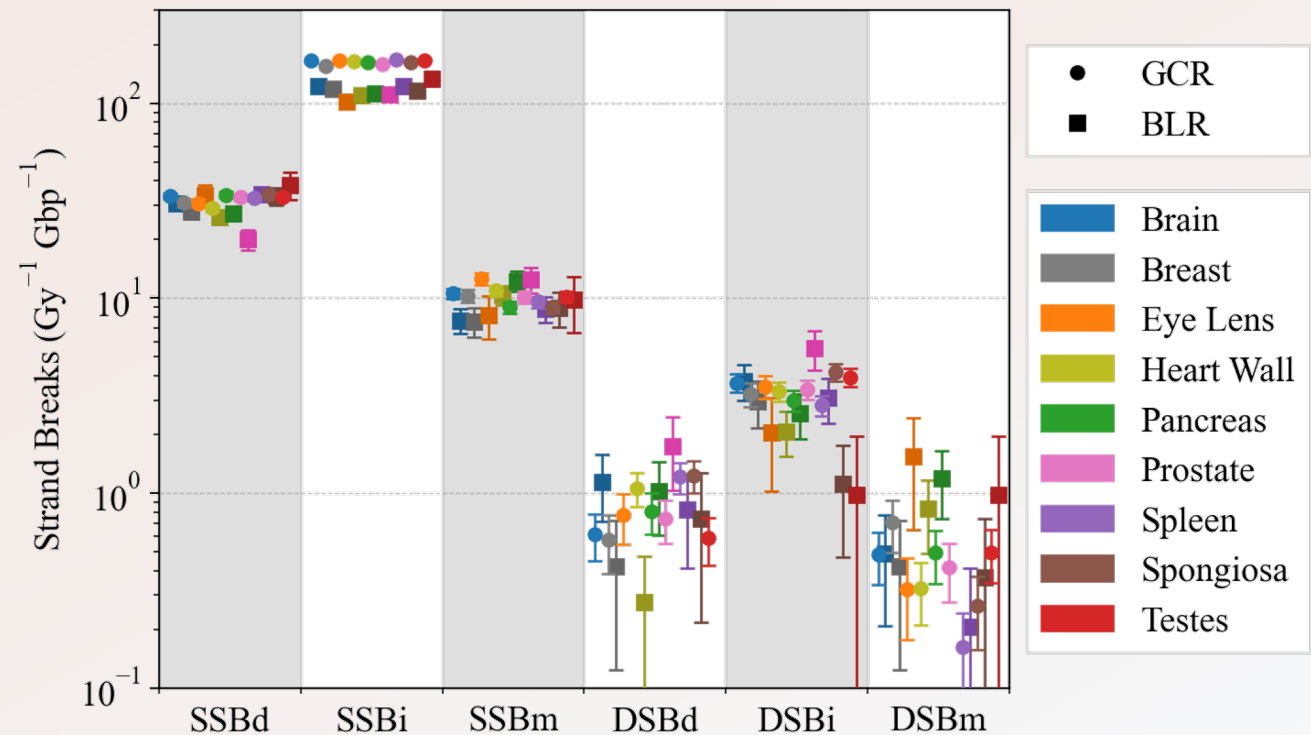
b) Backscattered Lunar Radiation

Organ Strand Break Yields

BLR makes a significant contribution to the dose on the lunar surface

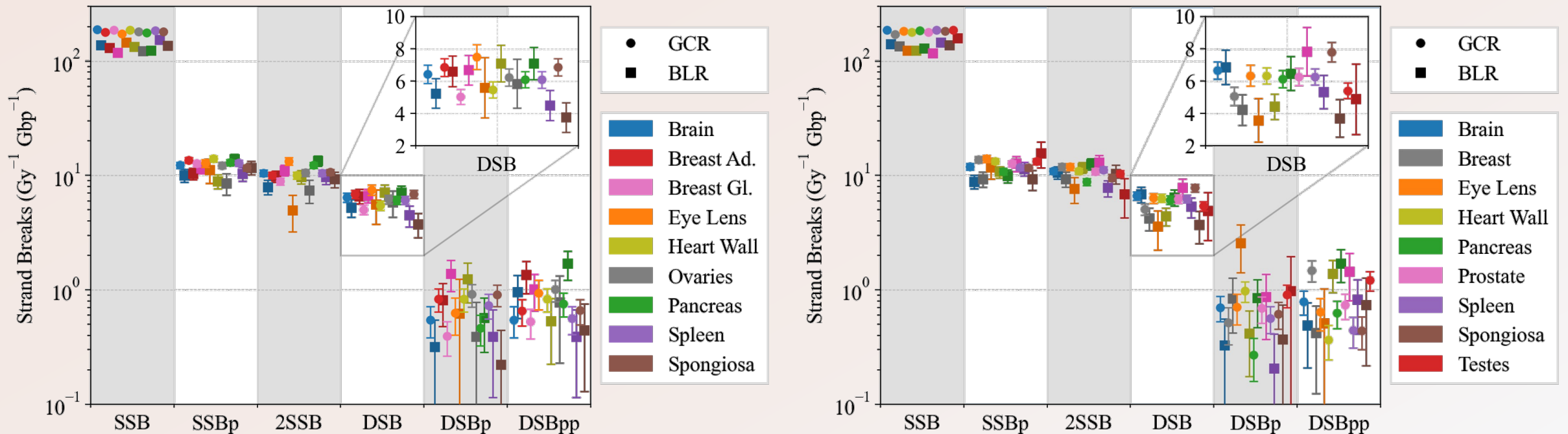


Indirect damage most significant mechanism of DNA damage induction



Organ Strand Break Yields

- DSB yield similar to that of high energy protons ^{9, 10}

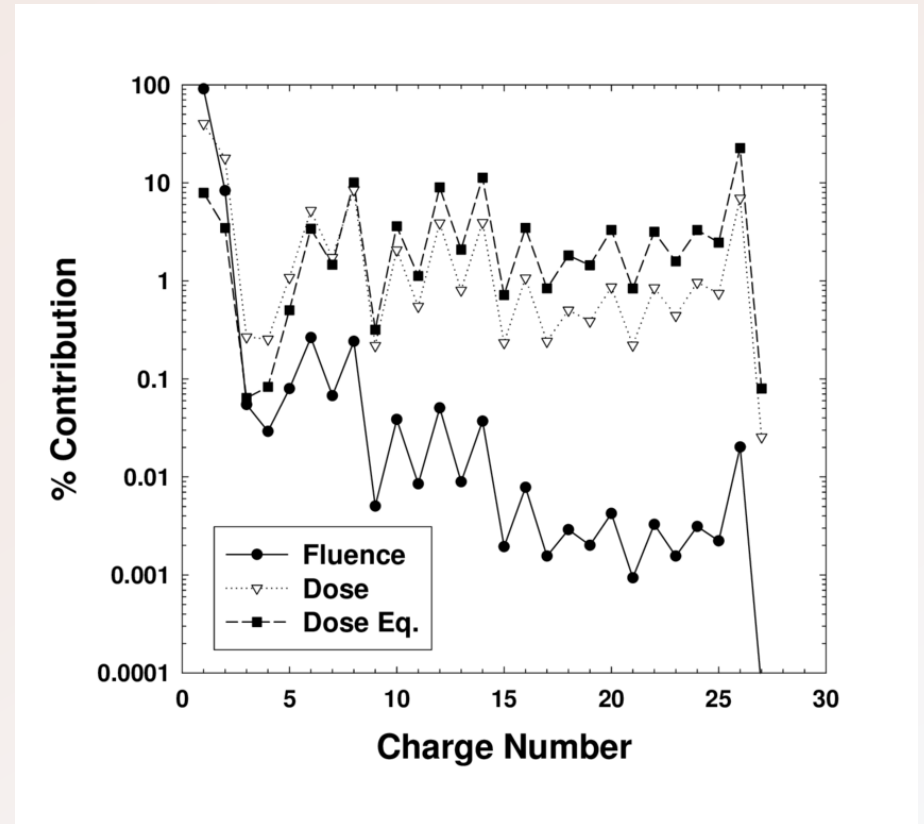


[9] – Zhao et. al. 2020, *Biomedical Phys. Eng. Express*, **6**

[10] – Meylan et. al., 2017. *Scientific Reports*, **7**(1)

Next Steps

- Currently, only GCR protons are considered
 - Higher Z ions contribute significantly to dose equivalent⁹
 - Current limitation in Geant4-DNA models
- Solar particle events should also be considered¹⁰
 - GCR: 416.0 mSv/yr
 - SEP: up to 2190 mSv/event

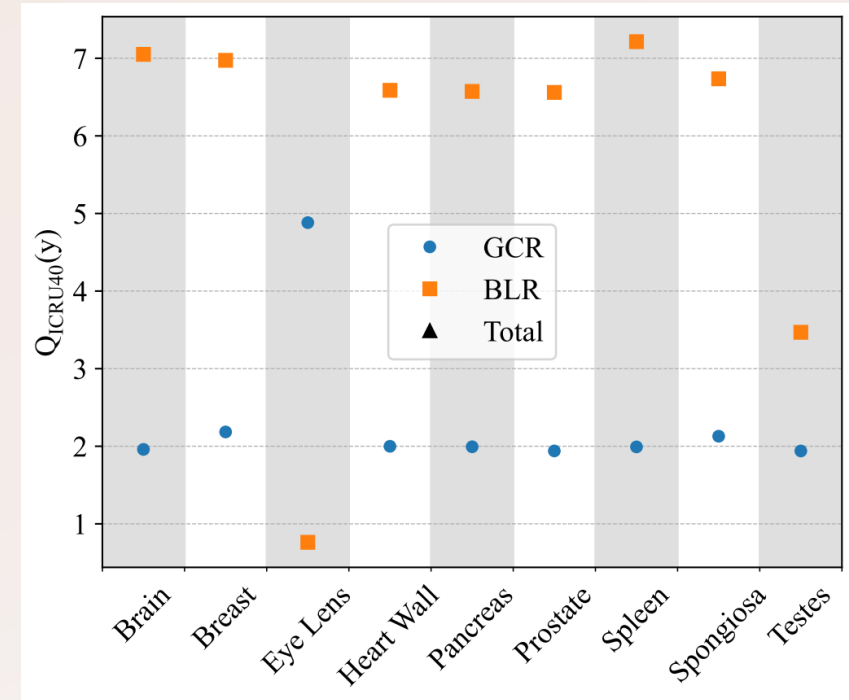
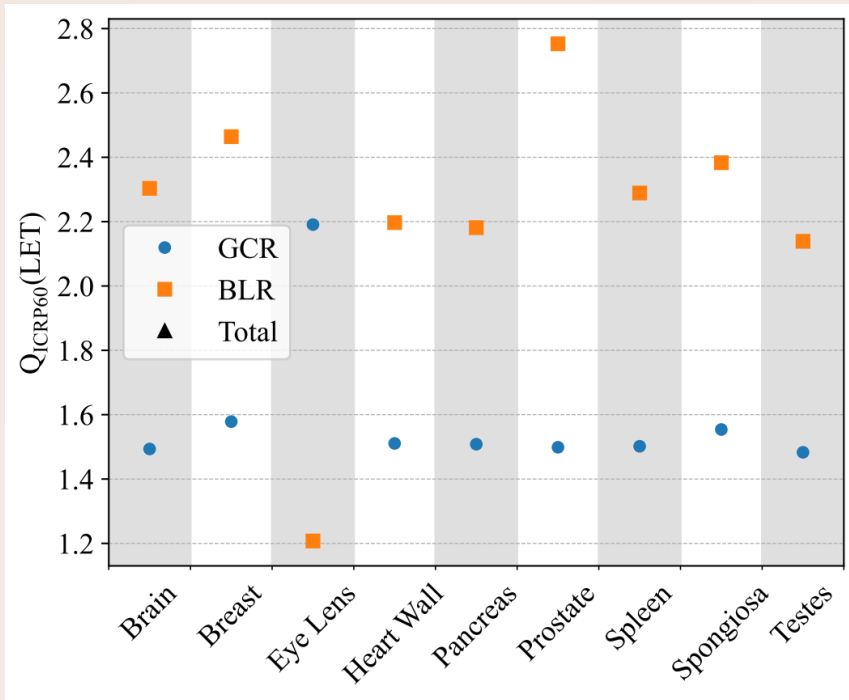


[9] – Cucinotta et. al., 2003. *Graviational and Space Biology*, **16**(2)

[10] – Naito et. al., 2020. *Journal of Radiological Protection*, **40**(4)

Next Steps

- Comparison to other methods common in radiation protection
- Preliminary quality factors using an LET-based¹¹ $Q(LET)$ and lineal energy-based quality factor¹² $Q(y)$:

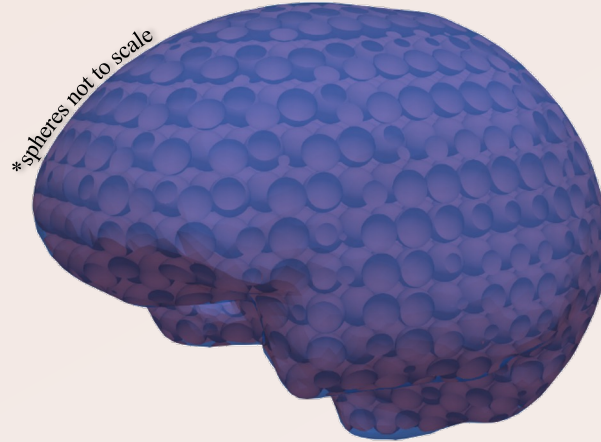


[11] – ICRP, 1991. *Ann. ICRP*, **21**(1-3)

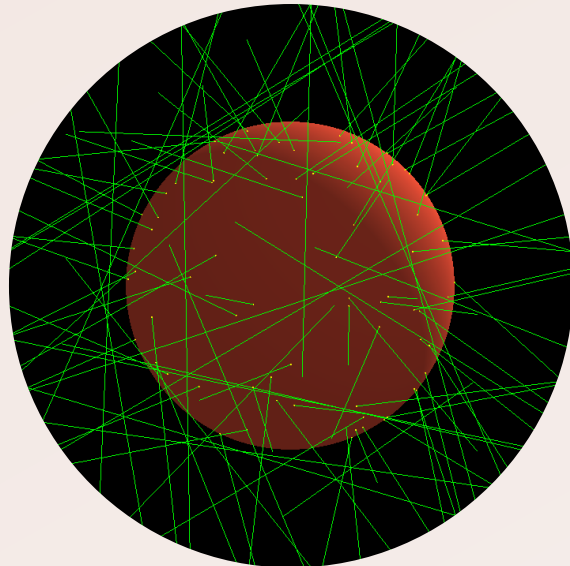
[12] – ICRU, 1986. Report 40.

Summary

- Monte Carlo simulations of DNA damage in space
- Applied to the lunar radiation environment



- Strand break complexities scored in different organs
- Preliminary results obtained for GCR protons



- Volumetric particle scoring method developed
- Determination of radiation field in different organs on cellular scale

