A Nanodosimetric Study of Lunar Radiation in the Organs of Astronauts

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Outline

- Multiscale Lunar Simulation
- Radiobiological Validation
- Space Microdosimetry

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Multiscale Lunar Nanodosimetry Simulation

Space Radiation

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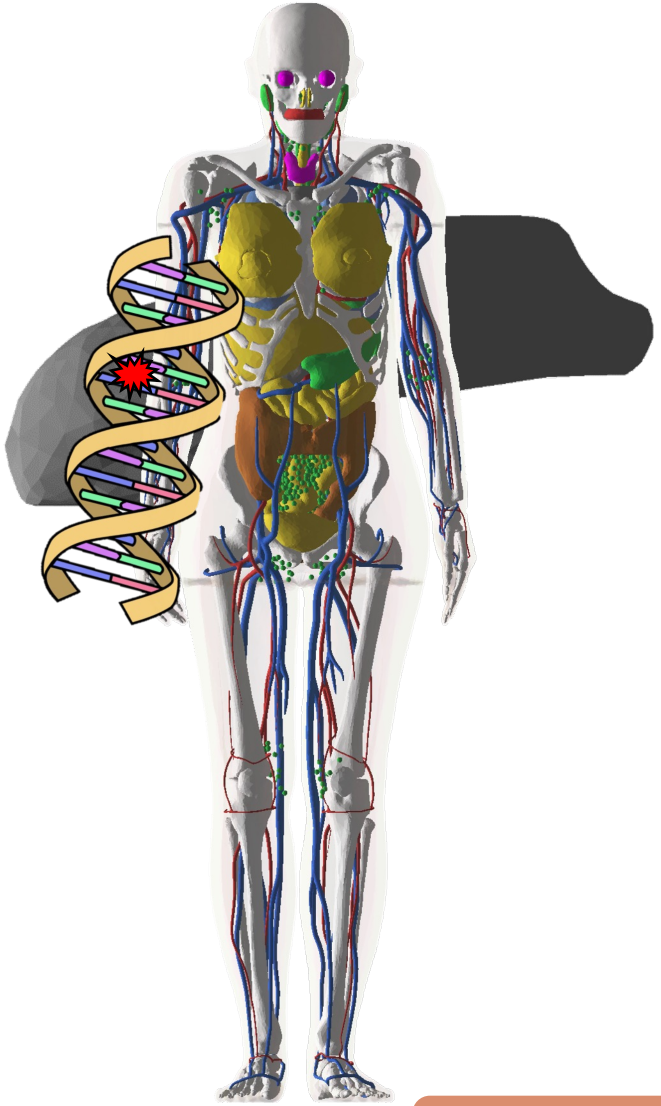
Radiation in Space

- Solar Energetic Particles (SEP)
- Galactic Cosmic Radiation (GCR)

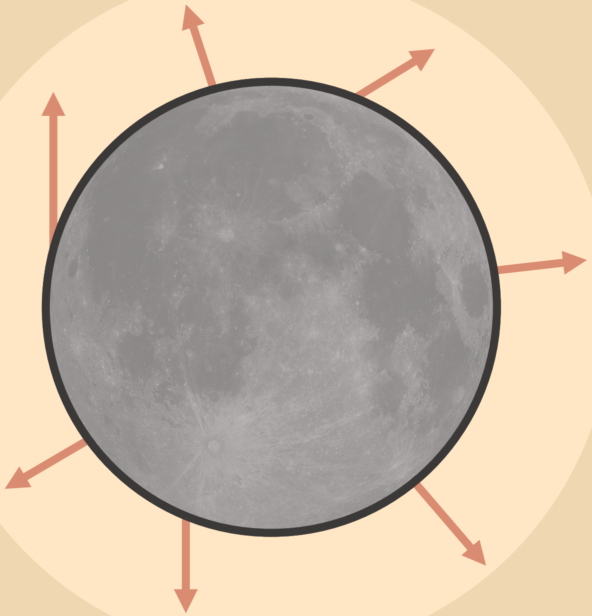
Considered one of the greatest and most uncertain risks for long-term space missions [1]



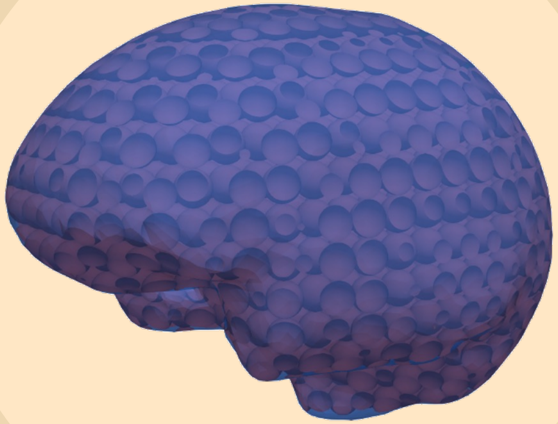
[1] – Cucinotta and Durante, 2006. *The lancet oncology* **7**(5)

Multiscale Lunar Nanodosimetry Simulation

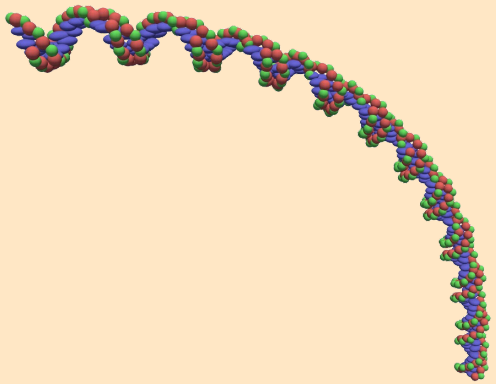
1 Backscattered Lunar Radiation



2 Cellular Radiation



3 DNA Damage



Backscattered Lunar Radiation

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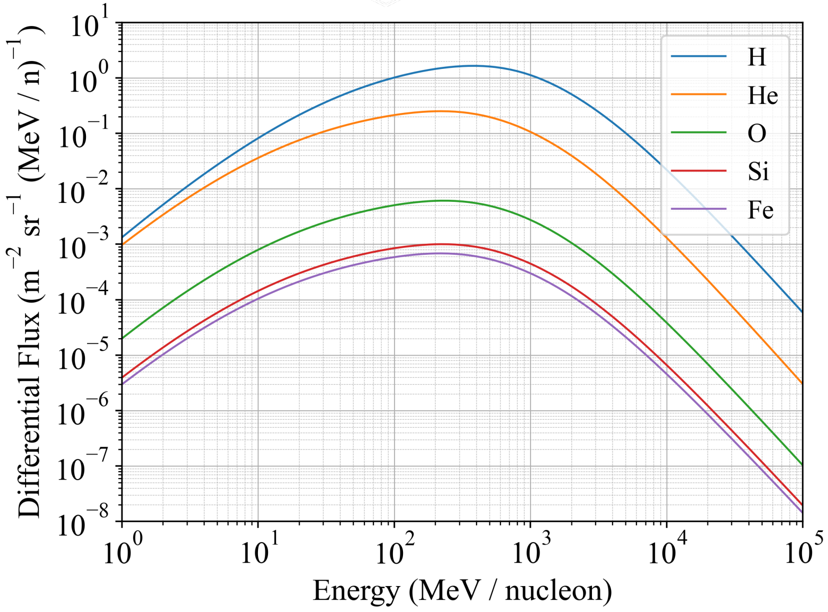
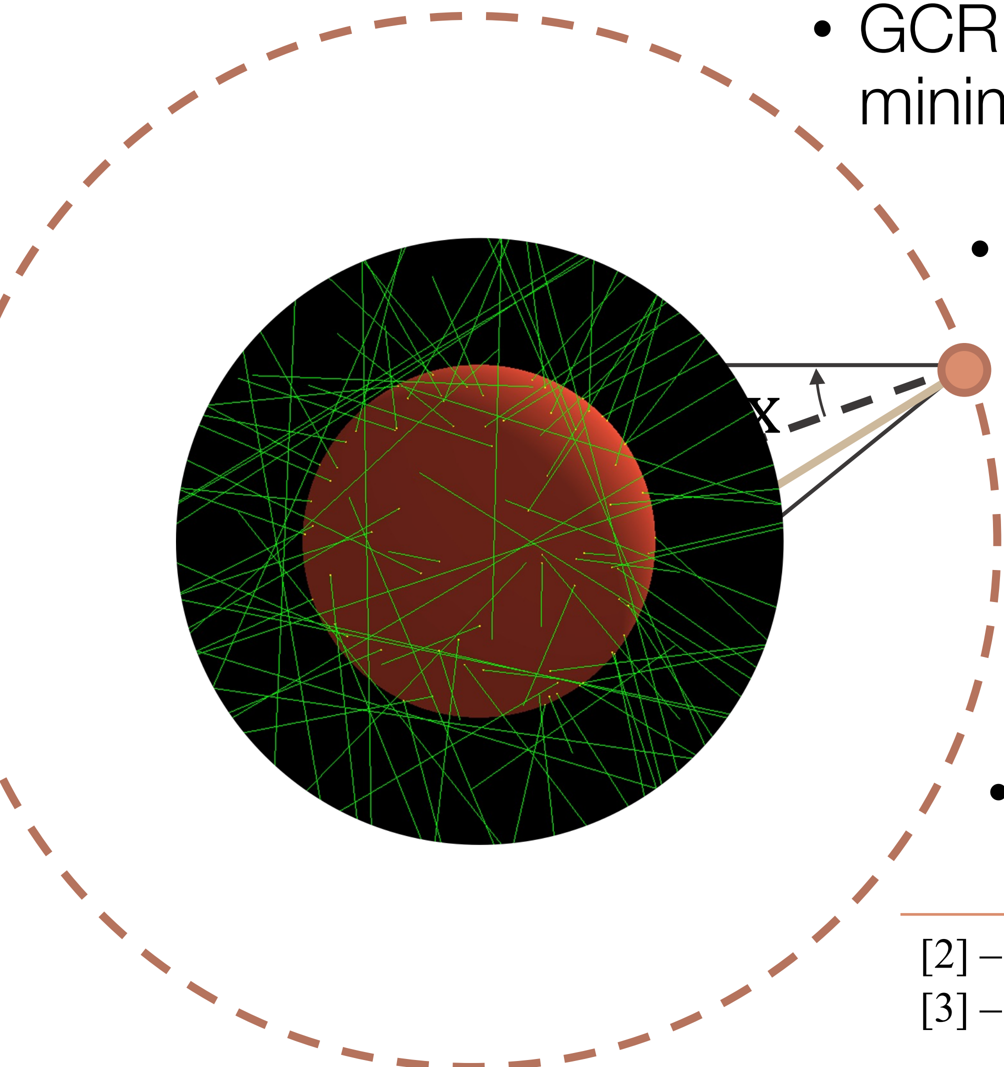


- The moon was modelled as a perfect sphere



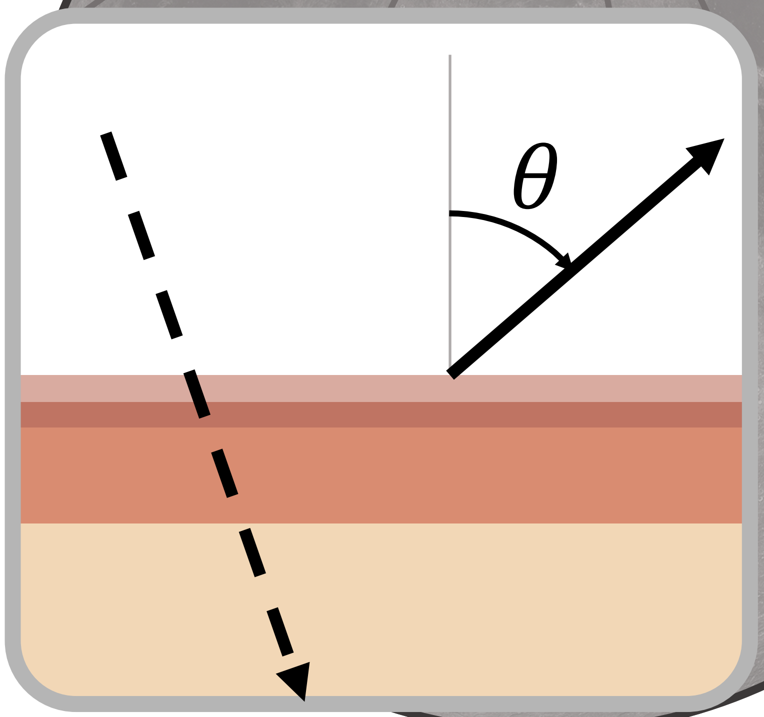
- GCR protons at solar minimum used
- Spectra from SPENVIS model ISO-15390[2]
- Emitted from a sphere with a cosine angular distribution
- Inward zenith angle considered up to θ_{max}
- Normalised according to Santin[3]

[2] – Kruglanski et al., 2009. RADECS.
[3] – Santin, 2007. *Geant4 Tutorial, Paris*.

I Backscattered Lunar Radiation

- The moon was modelled as four concentric spherical shells

- Composition and thickness of each shell based on borehole data [4,5]
- Particles propagated to a depth of 10 m



	Layer 1	Layer 2	Layer 3	Layer 4
Depth:	0 – 22 cm	22 – 71 cm	71 – 224 cm	>224 cm
Density:	1.76 g/cm^3	2.11 g/cm^3	1.78 g/cm^3	1.79 g/cm^3
O	41.739%	41.557%	42.298%	42.636%
Si	19.026%	18.955%	19.668%	20.218%
Fe	13.496%	14.030%	12.277%	11.688%
Ca	7.541%	7.668%	8.020%	7.707%
Al	6.061%	5.977%	7.384%	7.598%
Mg	6.162%	6.026%	6.156%	6.091%
Ti	5.144%	4.905%	3.380%	3.198%
Na	0.292%	0.313%	6.026%	0.346%
Cr	0.287%	0.309%	0.264%	0.255%
Mn	0.176%	0.178%	0.152%	0.146%
K	0.067%	0.074%	0.086%	0.109%
Gd	0.004%	0.004%	0.004%	0.004%
Sm	0.003%	0.003%	0.003%	0.003%
Th	0.001%	0.000%	0.001%	0.001%
Eu	0.001%	0.001%	0.001%	0.000%

- Particles leaving the lunar surface stored in a phase space file (PSF)
- Referred to as *backscattered lunar radiation* (BLR)

[4] – Mesick, et. al., 2018. *Earth and Space Science*, **5**(7)
[5] – McKinney, et. al., 2006. *Journal of Geophysical Research: Planets*. **11**(6)

I Backscattered Lunar Radiation

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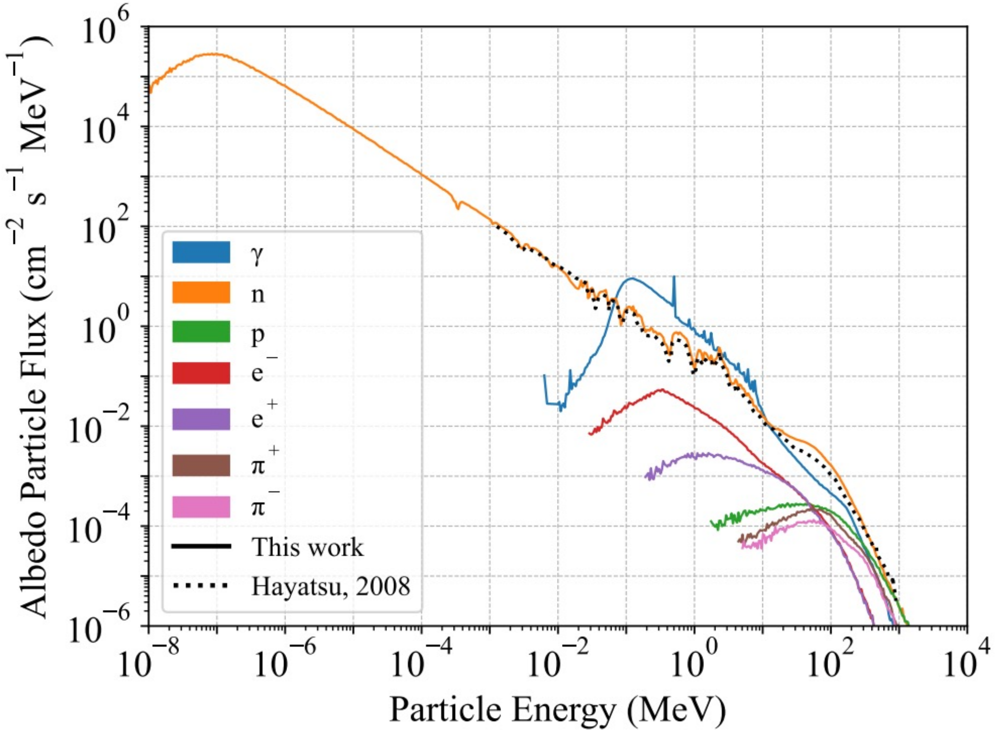
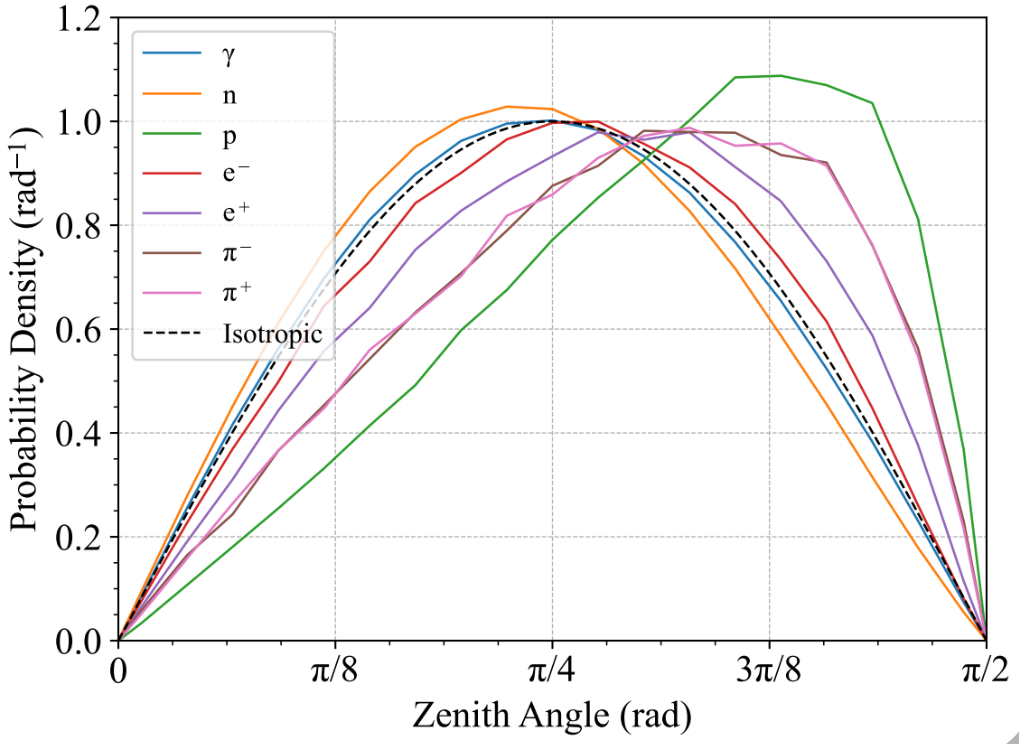
Backscattered Radiation Spectra



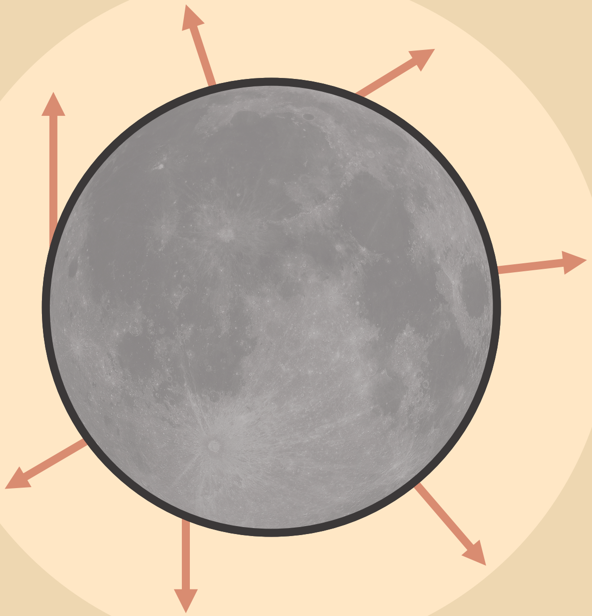
Zenith Angle Distribution



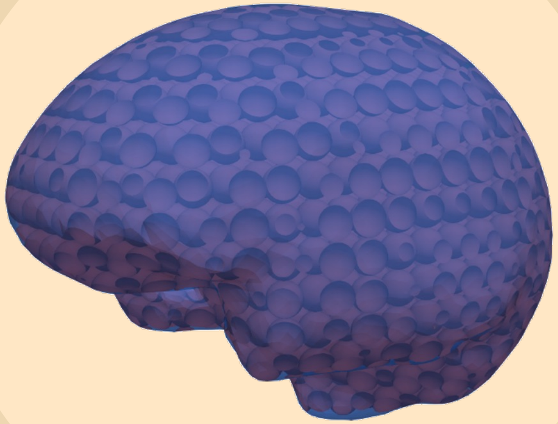
[6] – Hayatsu, et. al., 2008. *Biological Sciences in Space,* **22**(2)

Multiscale Lunar Nanodosimetry Simulation

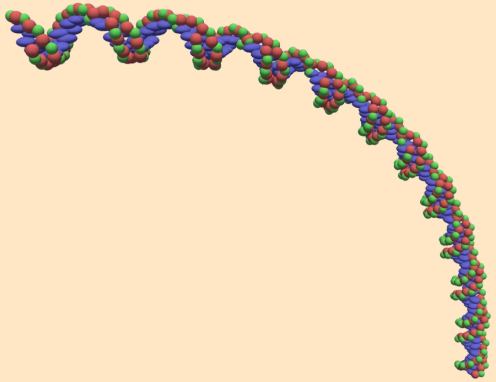
1 Backscattered Lunar Radiation



2 Cellular Radiation



3 DNA Damage



2 Cellular Radiation

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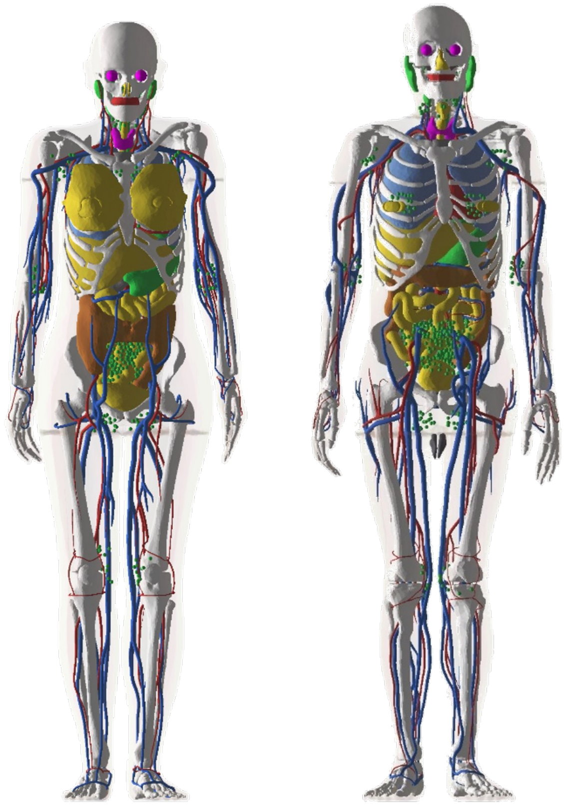
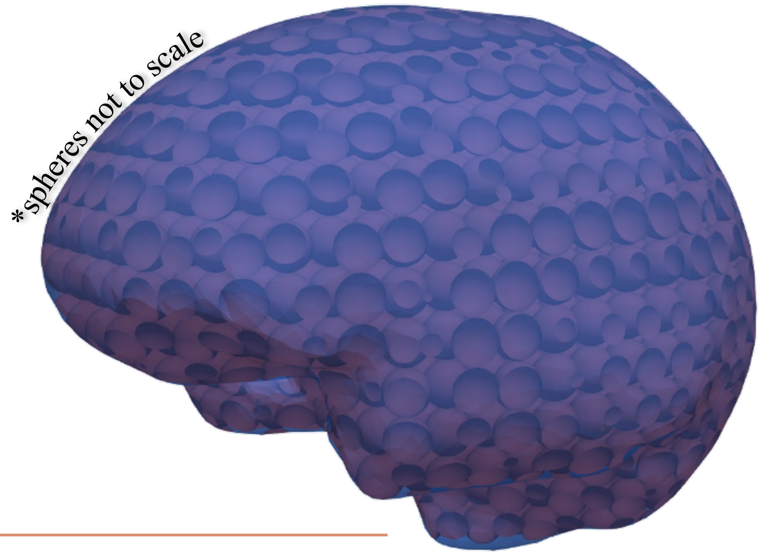
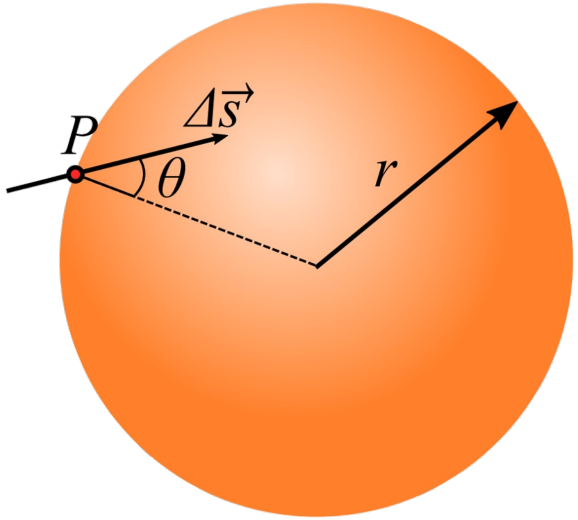
- Male and female ICRP145 tetrahedral mesh phantoms used [7]



Consist of ~8.4 million tetrahedra

- Particles were scored inside different organs by considering a spherical lattice of 10um spheres
- A virtual scoring approach used to limit steps only inside organs of interest





[7] – ICRP Report 45

2 Cellular Radiation

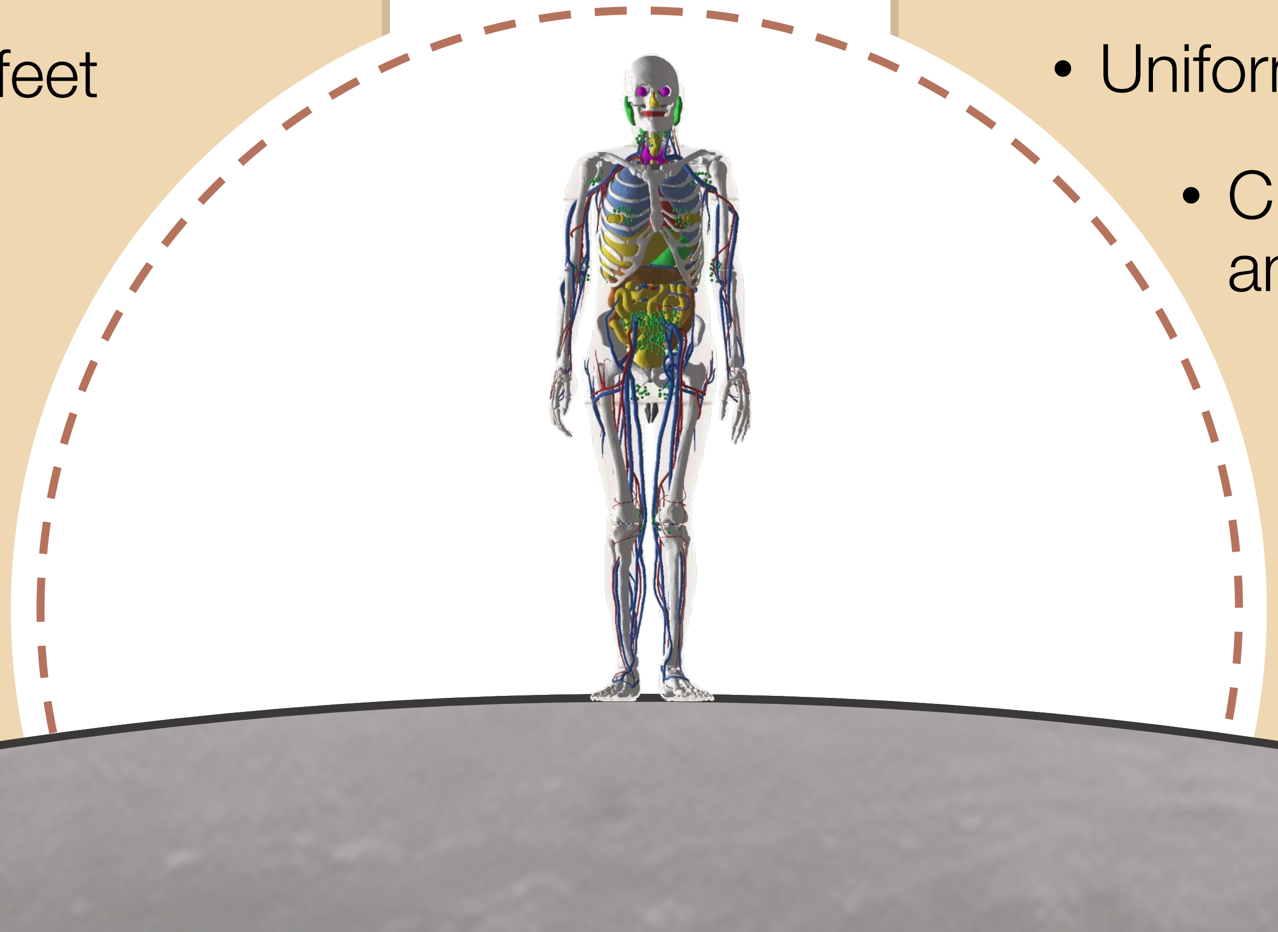
- Radiation field considered separately for GCR and BLR

GCR

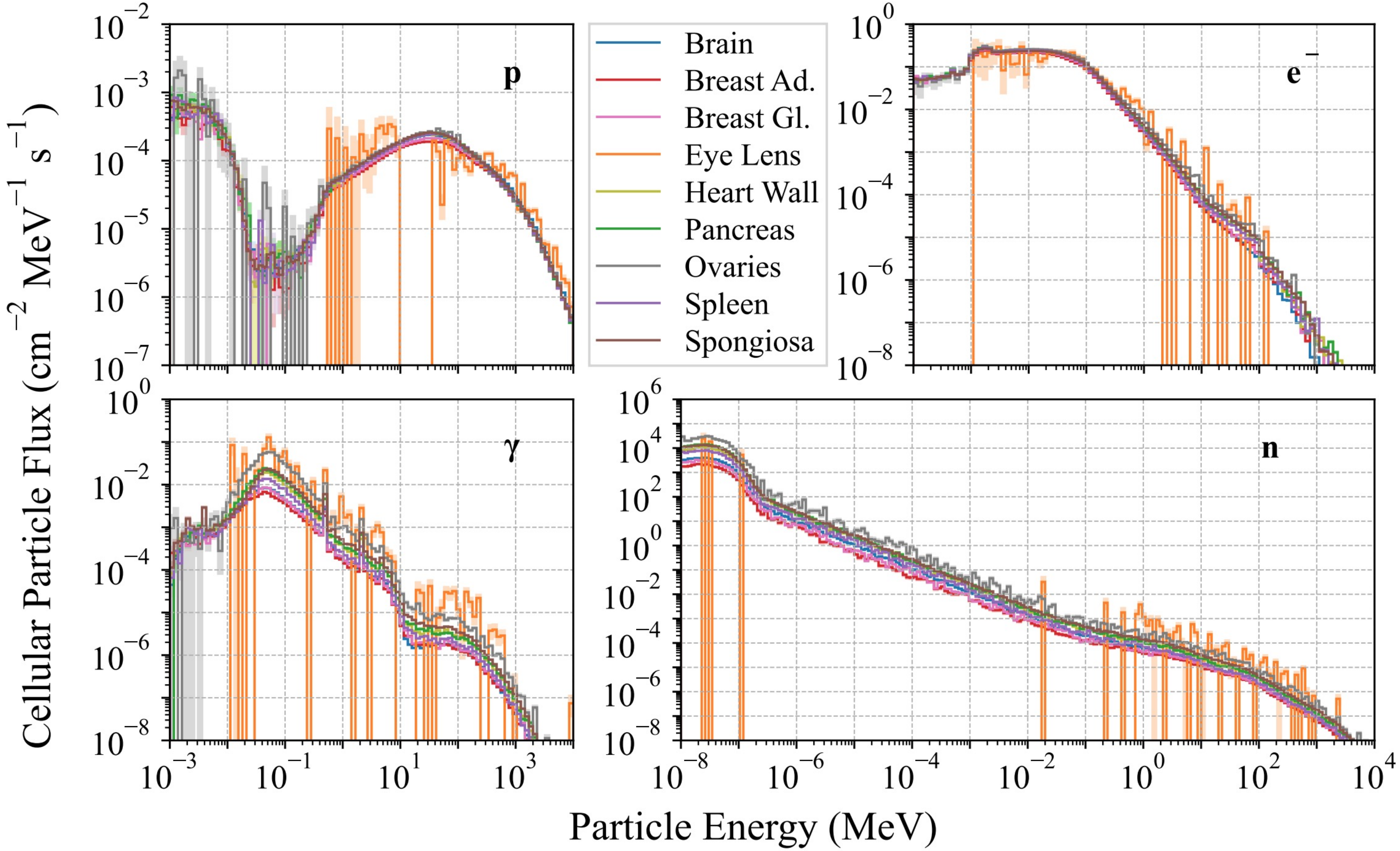
- Isotropic above feet
- Angular biasing applied
- Same SPENVIS spectra

BLR

- Uniform over surface
- Custom energy and angular dist.
- Novel biasing applied
- To the horizon (2.5 km)



② Cellular Radiation



Cellular particle flux in female phantom due to *GCR*

2 Cellular Radiation

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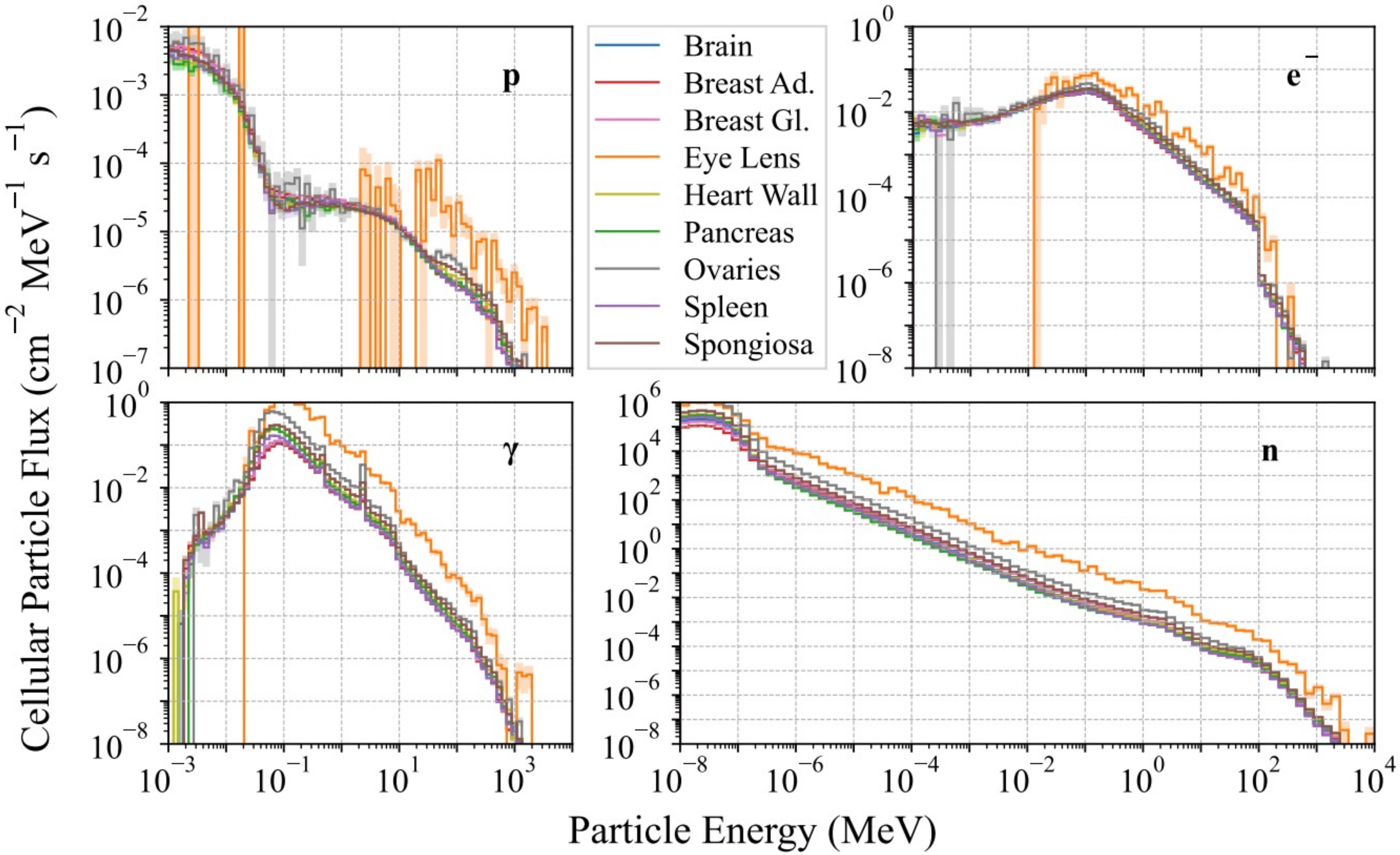

Cellular particle flux in female phantom due to *BLR*

2 Cellular Radiation

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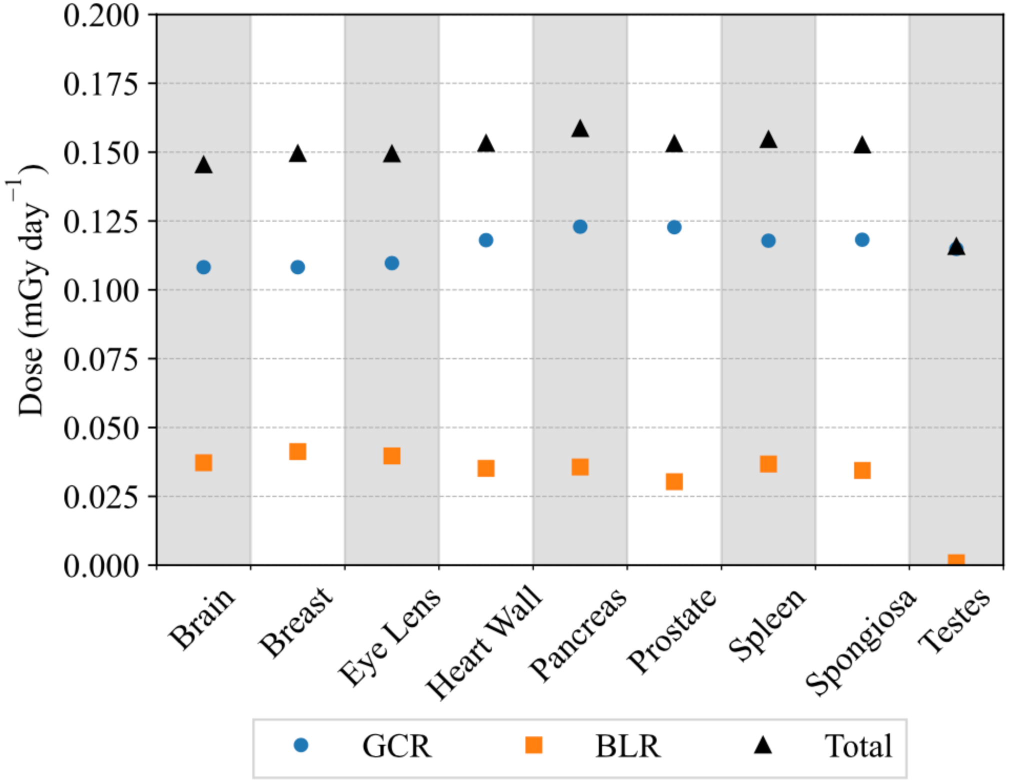
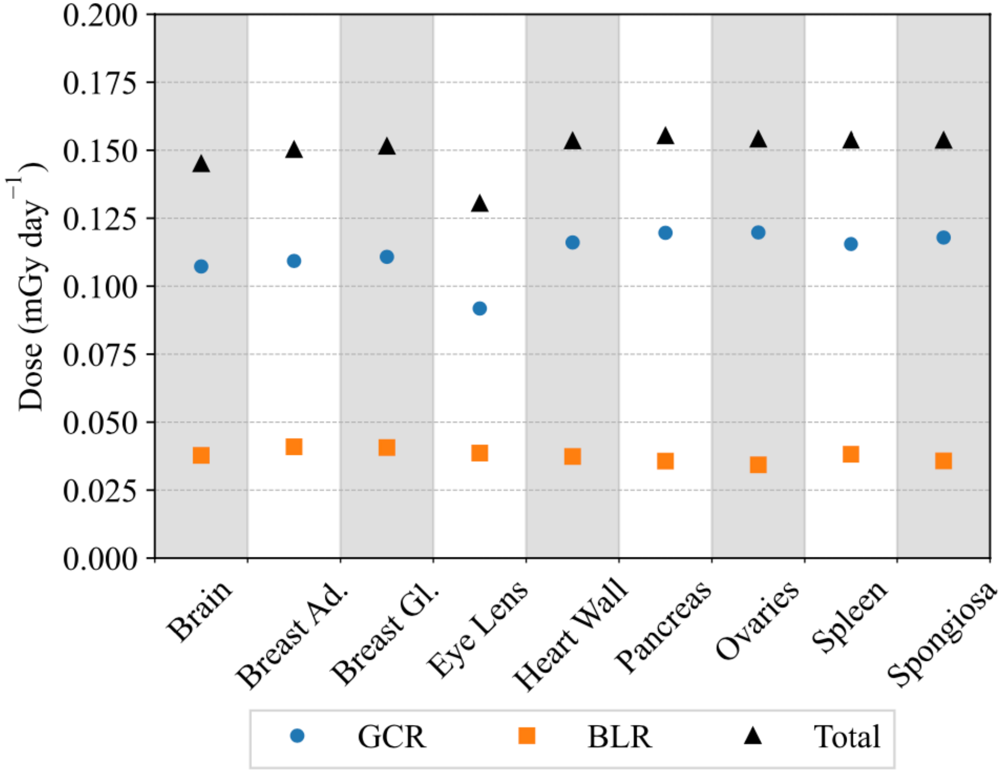
- Since particles are propagated through each phantom for GCR and BLR separately, we can obtain the absorbed dose in each organ:

Male

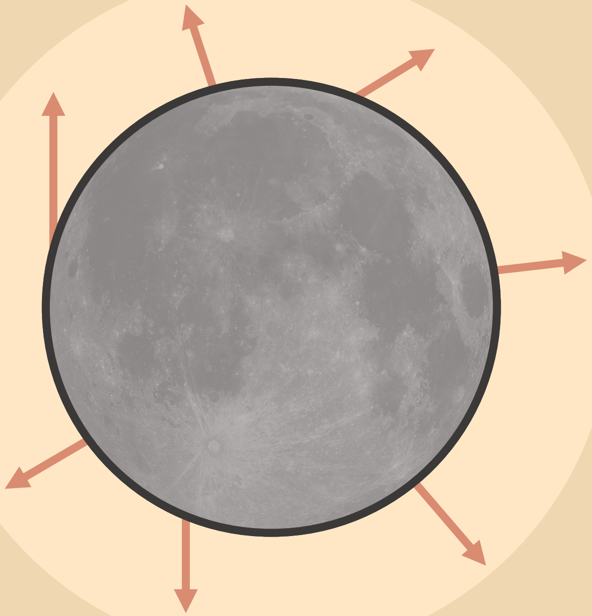


Female

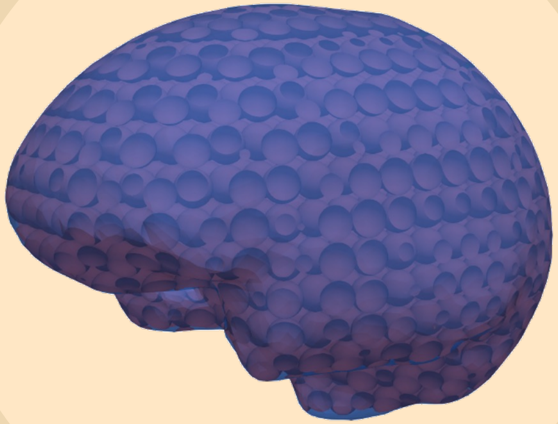


Multiscale Lunar Nanodosimetry Simulation

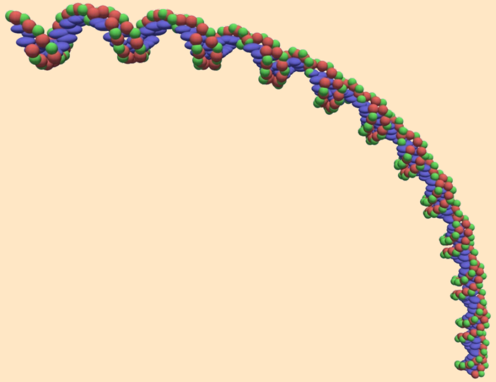
1 Backscattered Lunar Radiation



2 Cellular Radiation



3 DNA Damage



③ DNA Damage

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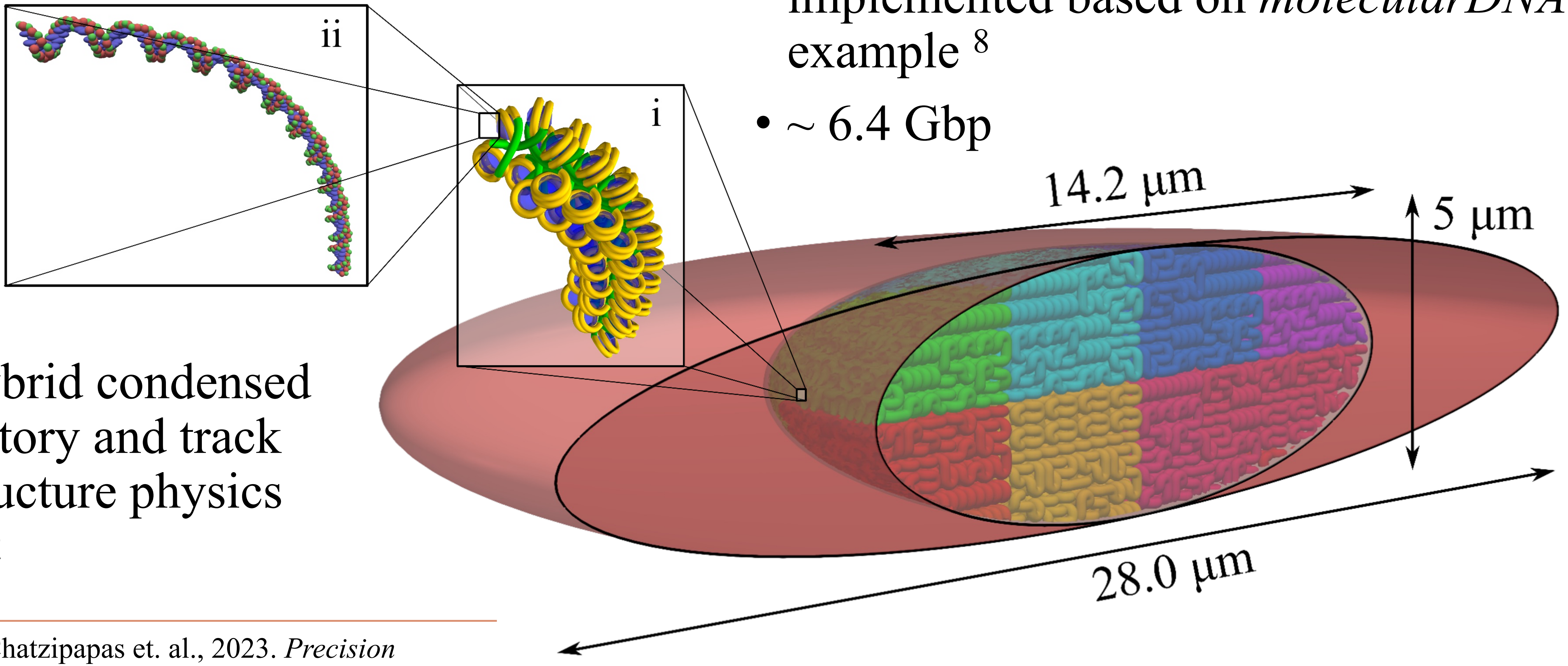
- Full human fibroblast geometry implemented based on *molecularDNA* example [8]
- ~ 6.4 Gbp

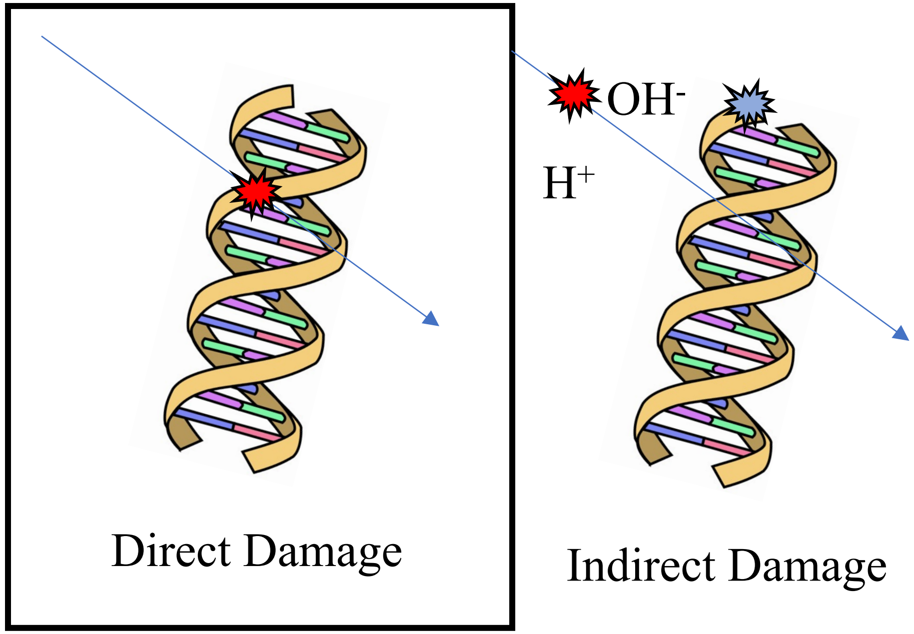


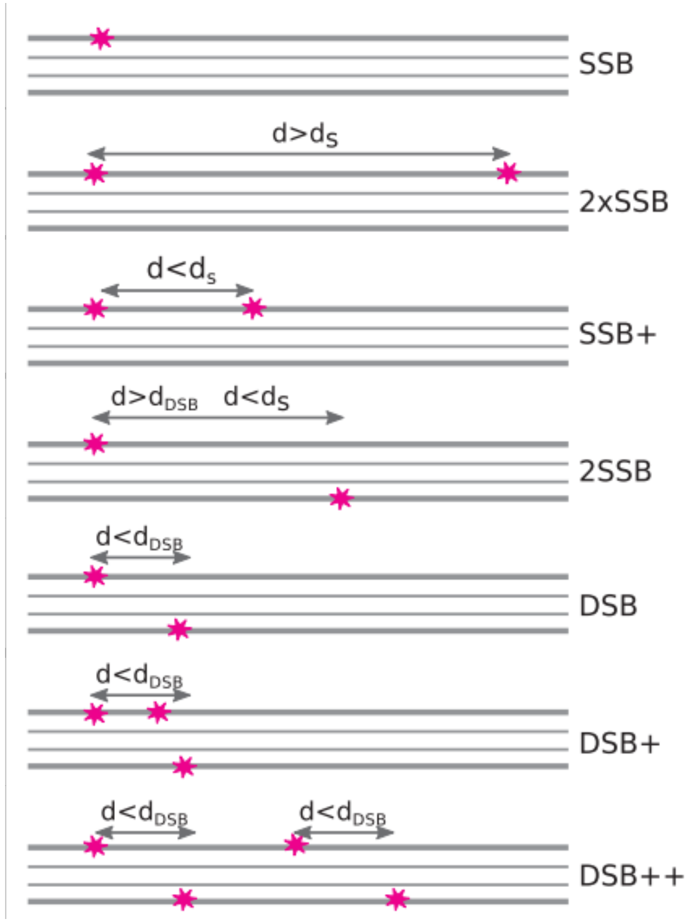
- Hybrid condensed history and track structure physics list

[8] – Chatzipapas et. al., 2023. *Precision Radiation Oncology*, **7**(1)

3 DNA Damage

- DNA damage is also scored using existing damage schemes [9,10]
- Both direct and indirect damage implemented





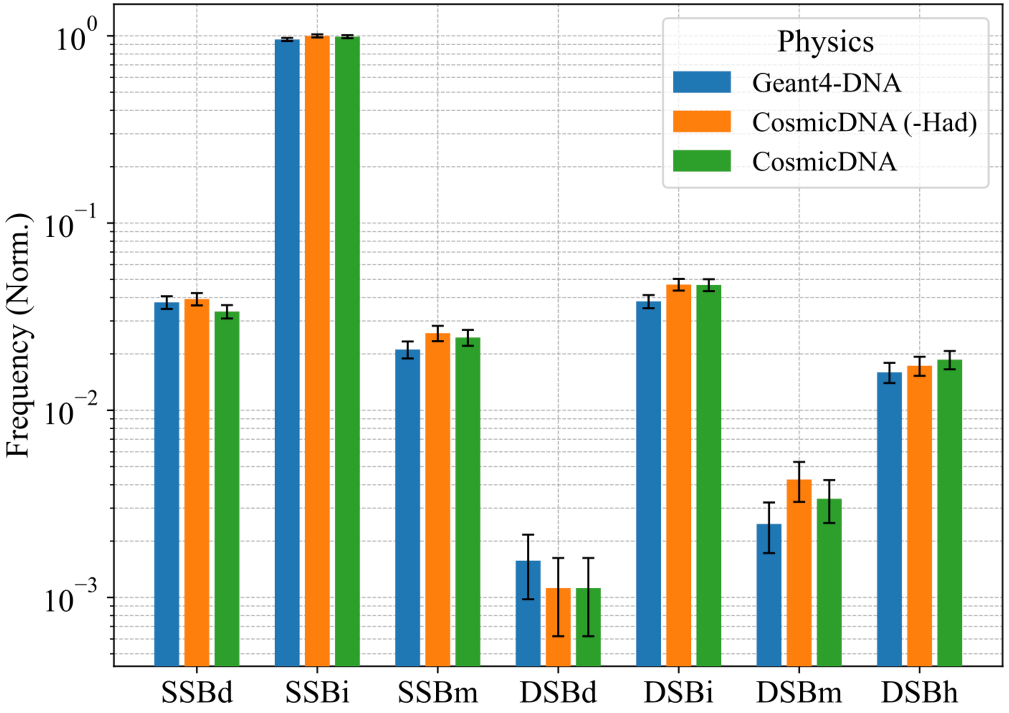
from Ref. 9

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

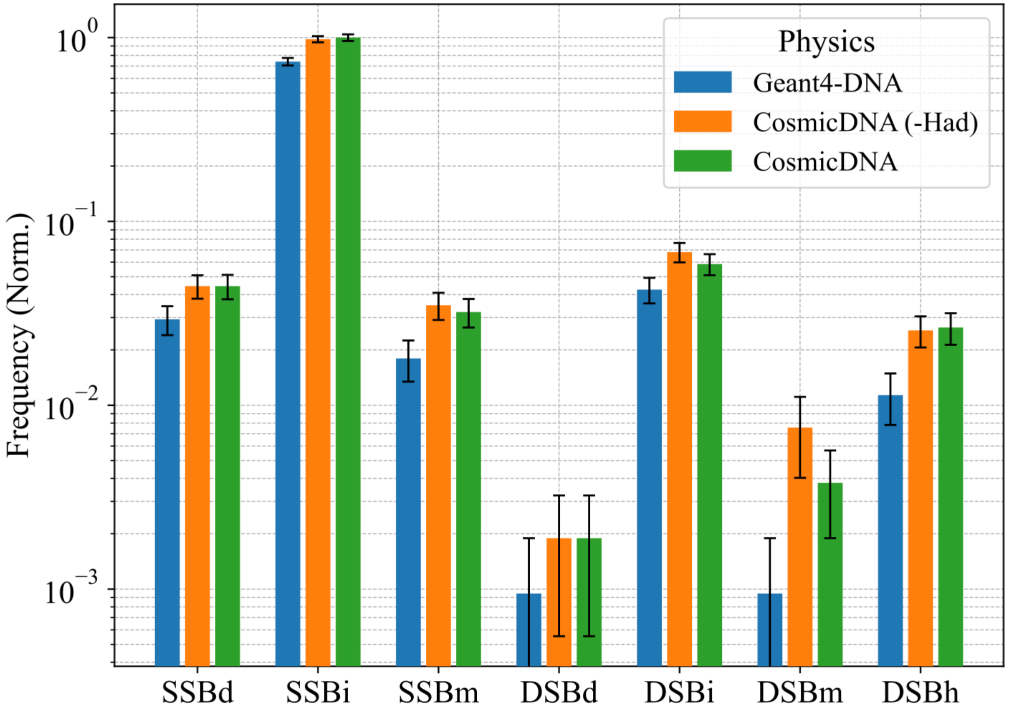
3 DNA Damage

- Condensed history models are required to model a great majority of induced damage:

GCR



BLR

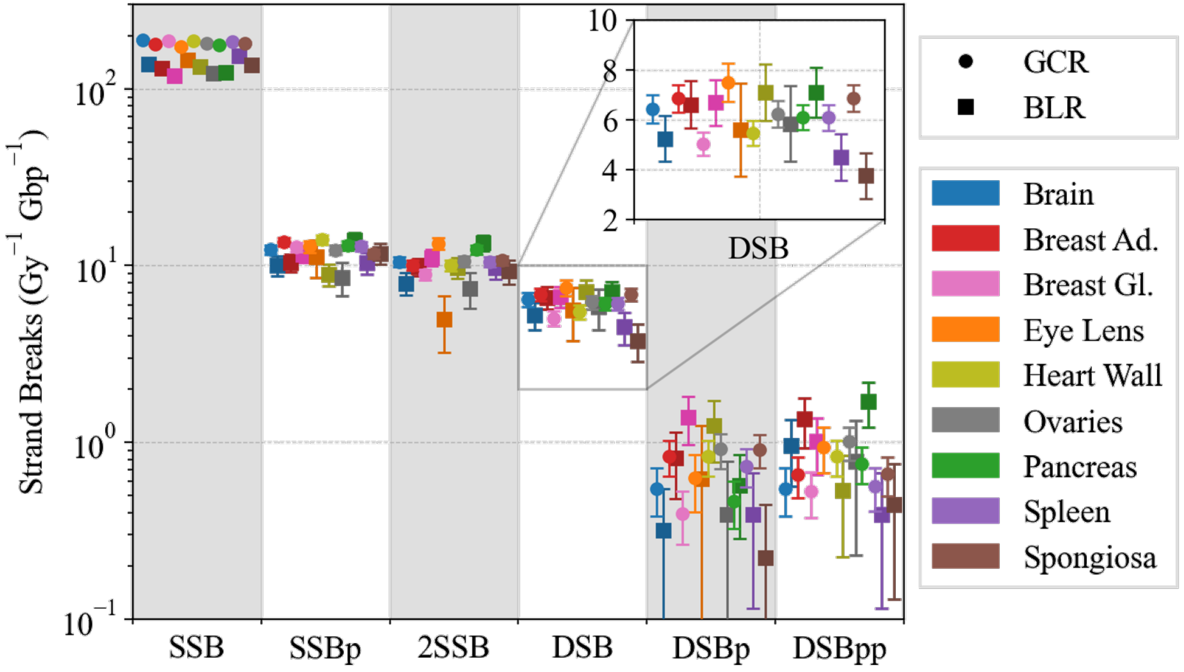


- Indirect damage most significant contribution

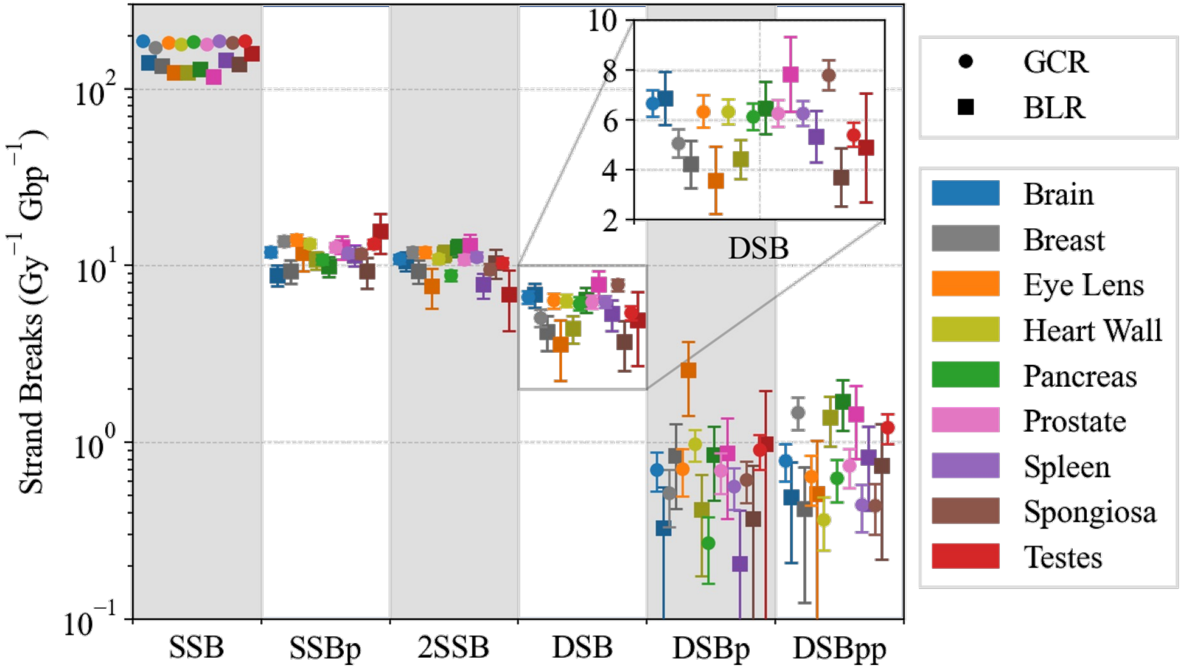
DNA Damage

- DSB yields similar to that of high energy protons [11,12]

Female



Male



[11] – Zhao et. al. 2020, *Biomedical Phys. Eng. Express*, **6**
[12] – Meylan et. al., 2017. *Scientific Reports*, **7**(1)

Next Steps...

- Extend to higher *Z* GCR particles
- Assess SPEs
- Further radiobiological validation of DNA damage and induction models
  - Radiobiological experiments are underway at ANSTO…

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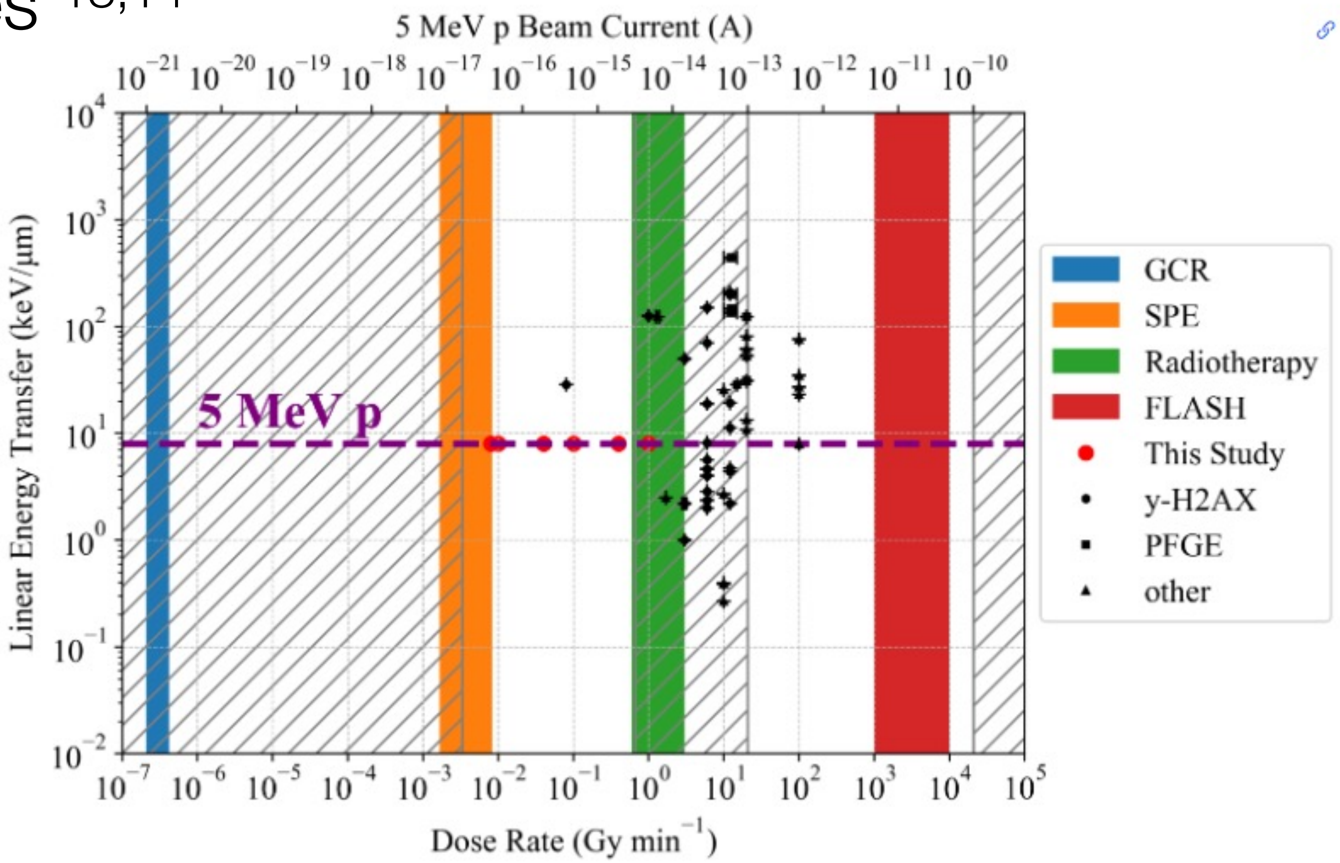
(preliminary)

Radiobiological Validation of Geant4-DNA

Radiobiological Validation of Geant4-DNA

- DNA damage induction and repair models have been validated using the cell survival of various cell lines [13,14]
- These assume:
  - short irradiation periods
  - higher dose rates than space

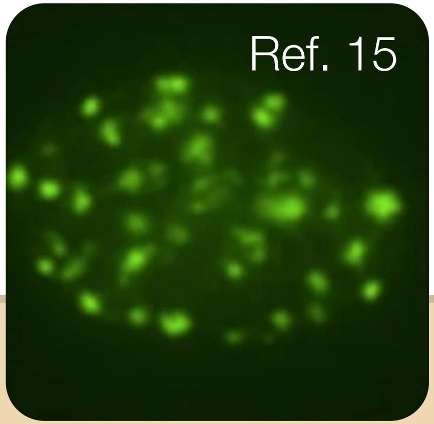


- Radiobiological data using lower dose rates are sparse in the literature
- SPE dose rates can be targeted at the Australian Nuclear Science and Technology Organisation (ANSTO)

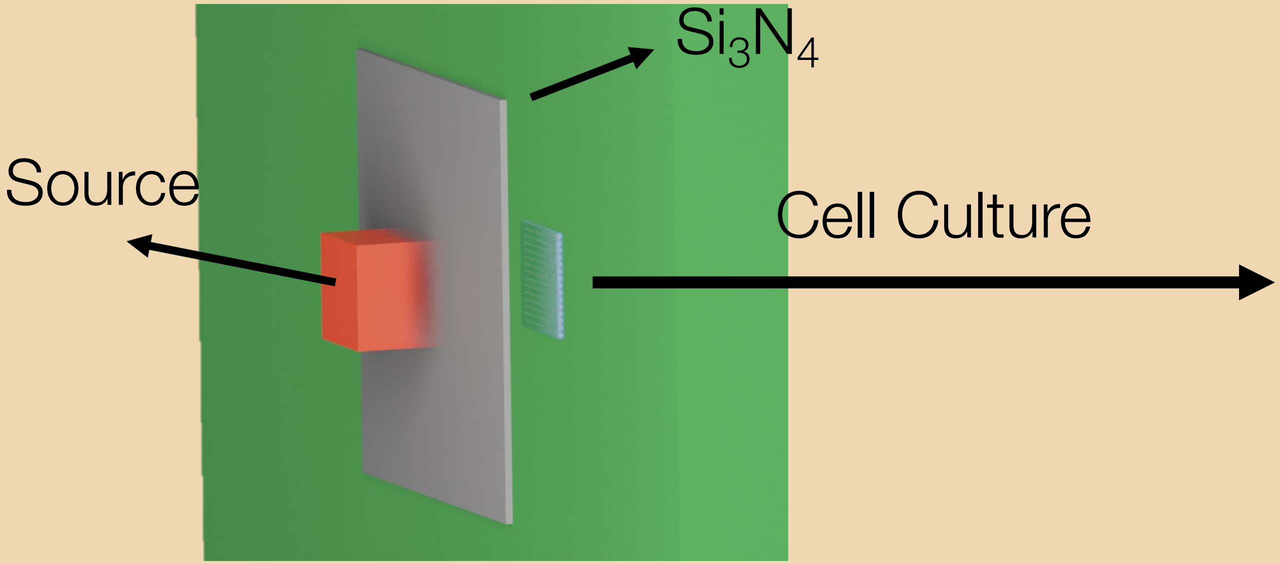
[13] – Chatzipapas et. al., 2023. *Precision Radiation Oncology*, **7**(1)
[14] – Sakata et al., 2020. *Scientific Reports*, **10**(1)

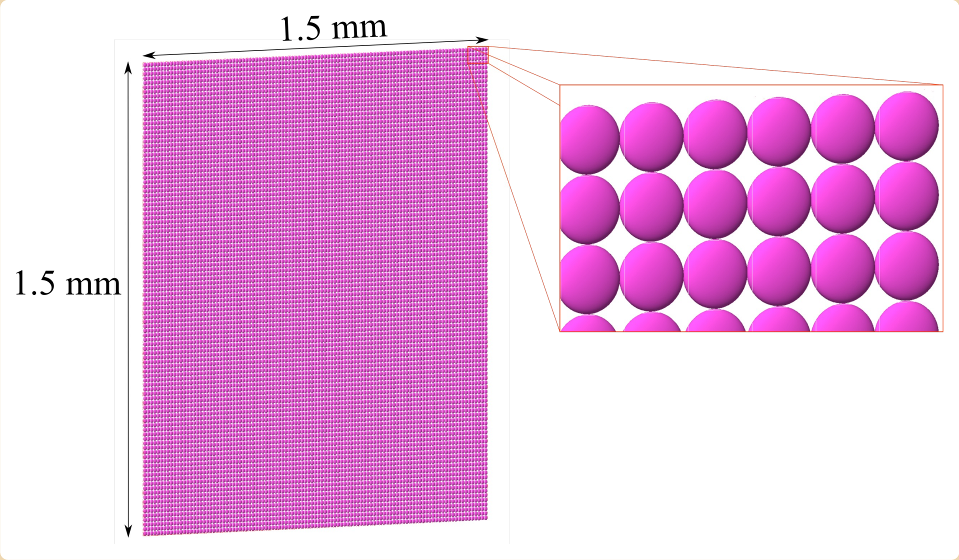
Radiobiological Validation of Geant4-DNA

- Locations of DSBs can be fluoresced using γ-H2AX foci [15]
- This can be simulated also using a multiscale approach:



I Radiation Entering Cells



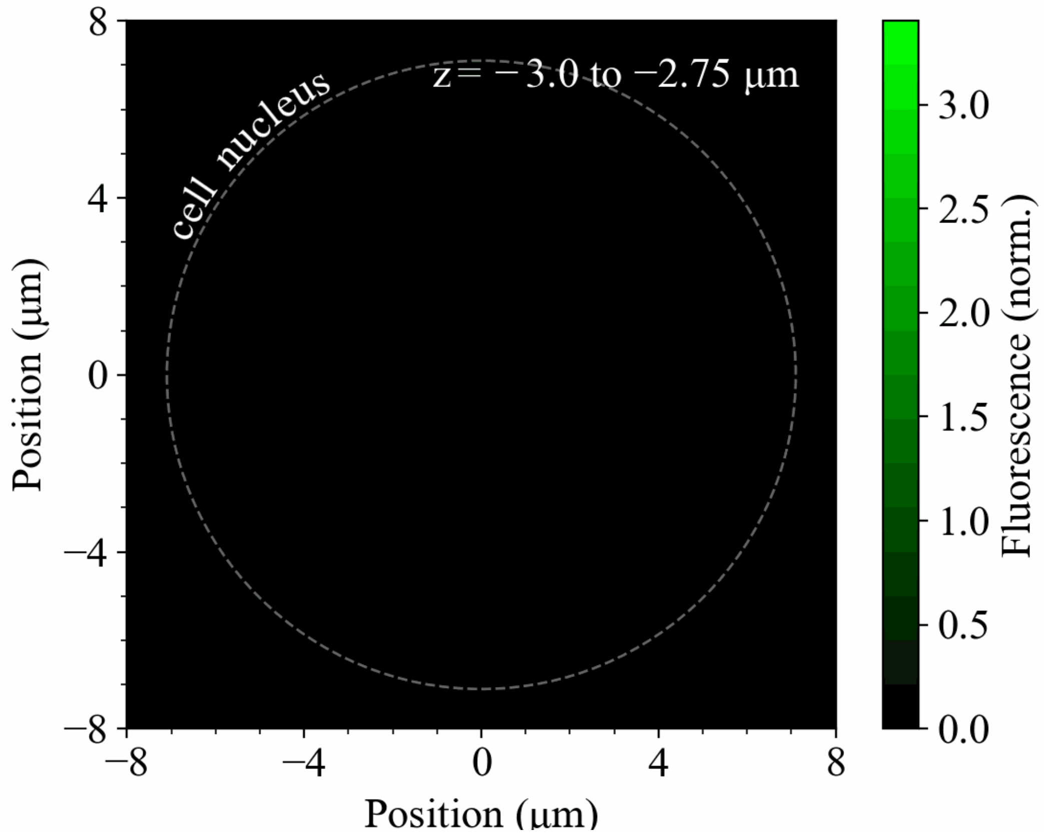


[15] – Kavanagh et. al., 2013. *Scientific Reports*, **3**(1)

Radiobiological Validation of Geant4-DNA

2 DNA Damage

- Spatial structure of DSBs can be resolved using Geant4-DNA
- Shown for 5 MeV protons



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Space Microdosimetry – LGADs

J. W. Archer[1], E. G. Villani[2,3], V. Pan[1], Z. Pastuovic[4], D. Hynds[2], A. M. BaniHani[1], J. Vohradsky[1], D. Bennett[1], M. Gazi[2], S. Peracchi[4], S. Guatelli[1], M. Petasecca[1], M. Lerch[1], D. Bortoletto[2], L. T. Tran[1] and A. B. Rosenfeld[1]

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Microdosimetry at CMRP

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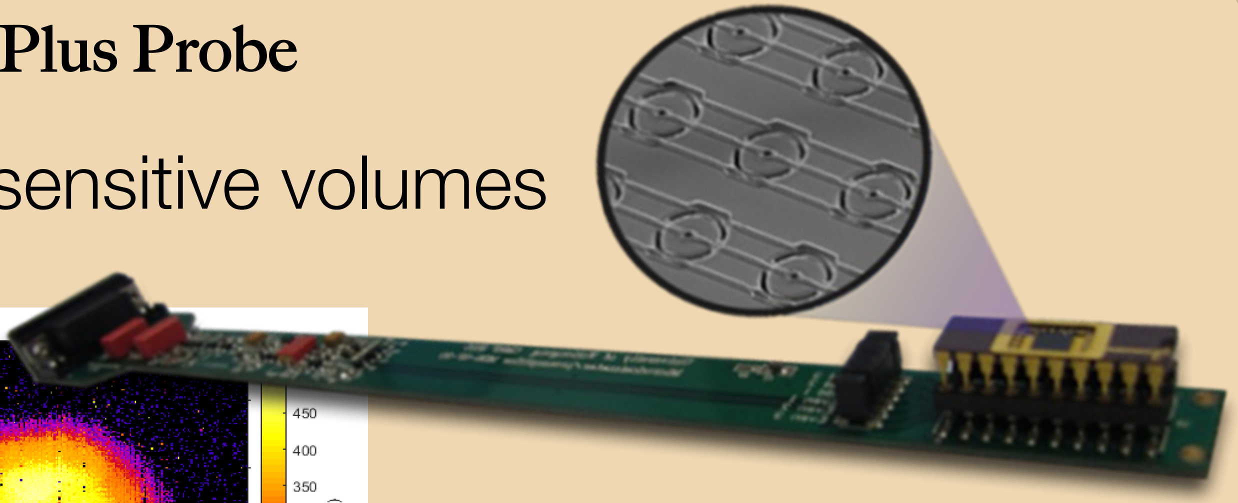
- Development of cylindrical microdosimeters

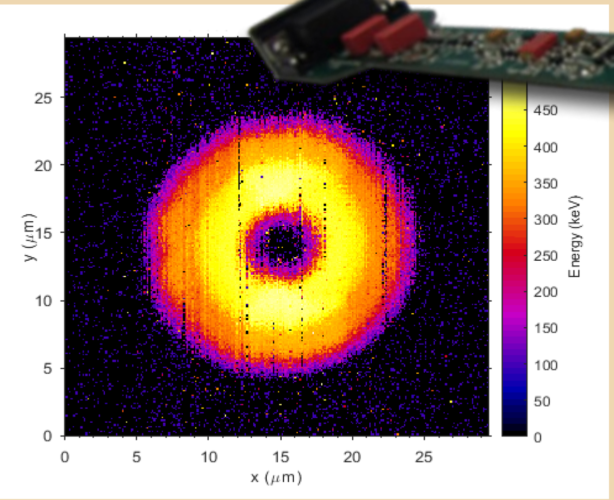
Design

- p-type
- n+
- p+

The MicroPlus Probe

- Array of sensitive volumes



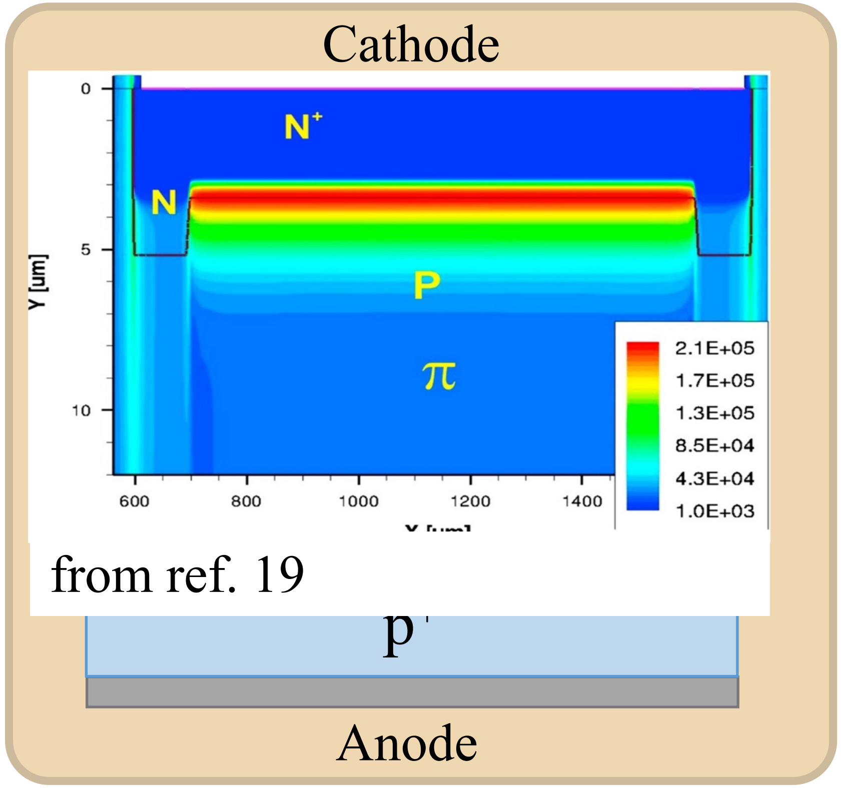


- Allows for high spatial resolution microdosimetry

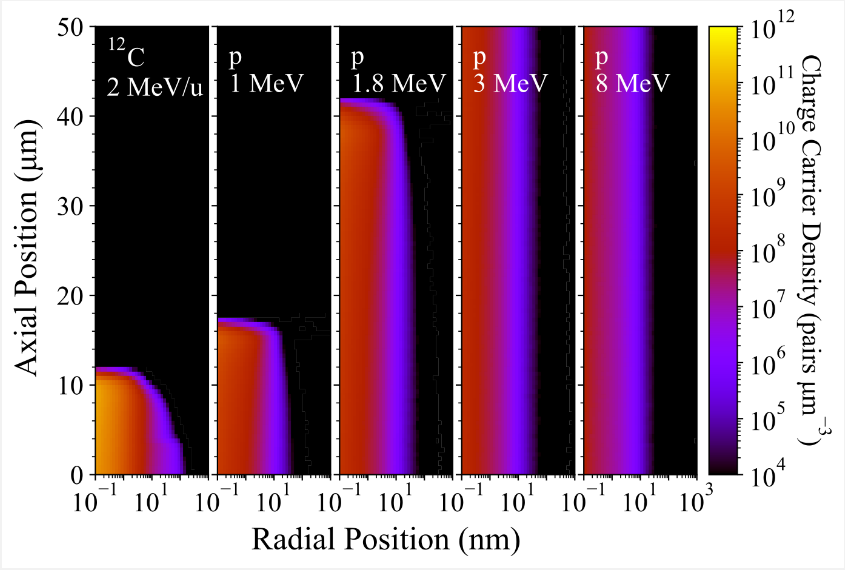
[16] – Tran et al., 2017. *IEEE Transactions on Nuclear Science*, **65**(1)
[17] – Tran et al., 2021. *Applied Sciences*, **12**(1)
[18] – Vohradsky et al., 2022. *Journal of Instrumentation*, **17**(3)

Space Considerations

- Issue with electronic noise for low LETs (< 0.8 keV/um)
- Assessing use of low gain avalanche diodes (LGADs)



- Gain depends on *induced charge density*
- Induced charge can be simulated using MicroElec models[20,21]



[19] – Pellegrini et. al., 2014. *NIMA* **765**
[20] – Audrey, et. al., 2012. *NIMB*, **288**
[21] – Gibaru, et. al., 2021. *NIMB*, **487**

LGAD Characterisation

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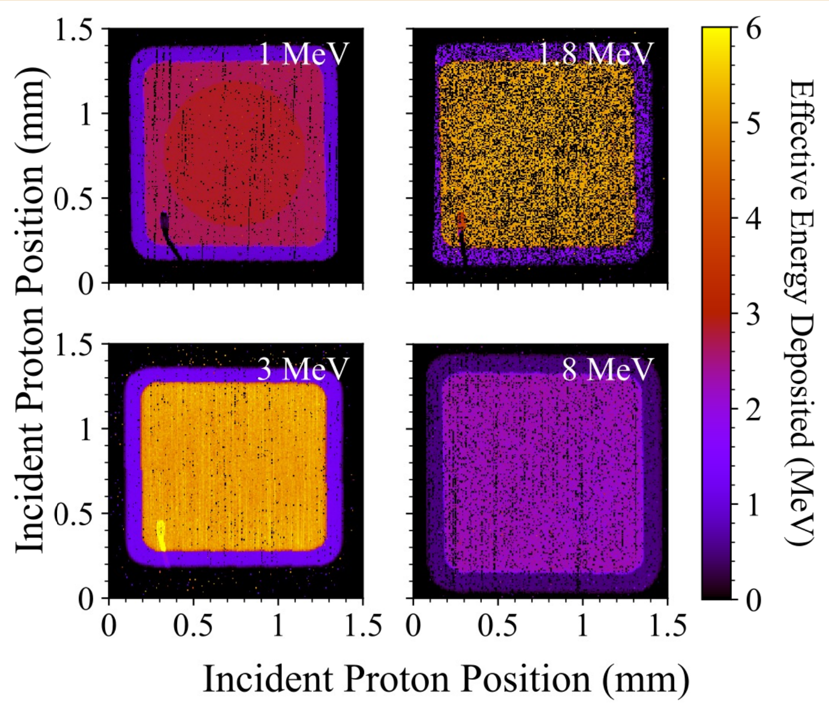
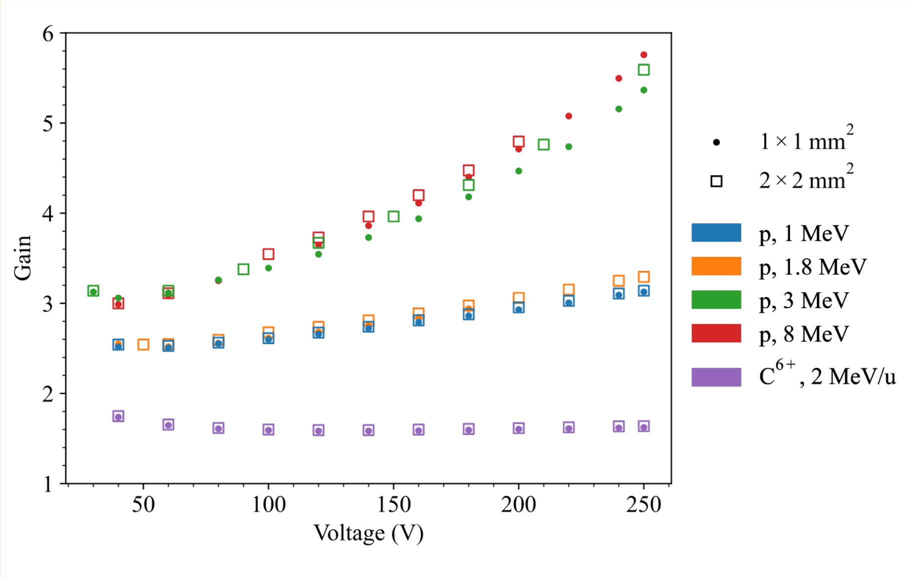
- Characterised using LGADs in collaboration with the University of Oxford[22,23]

IBIC



Gain



[22] – Mulvey et. al., 2022. *Journal of Instrumentation*, **17**(10)
[23] – Allport et. al., 2022. *NIMA*, **1037**

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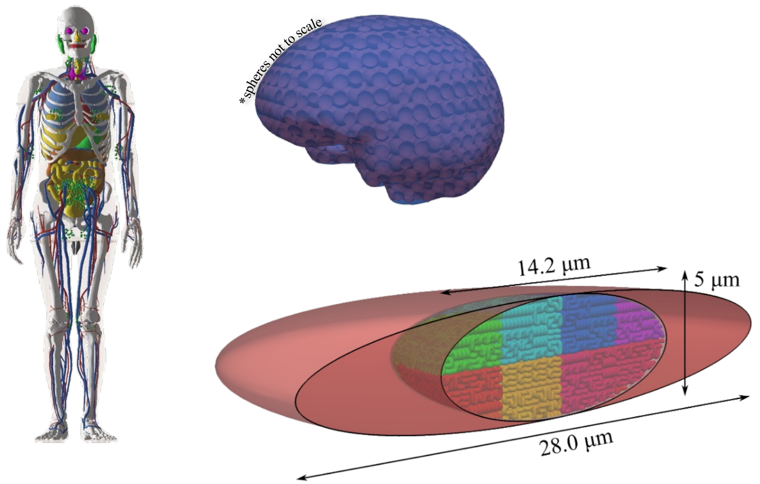
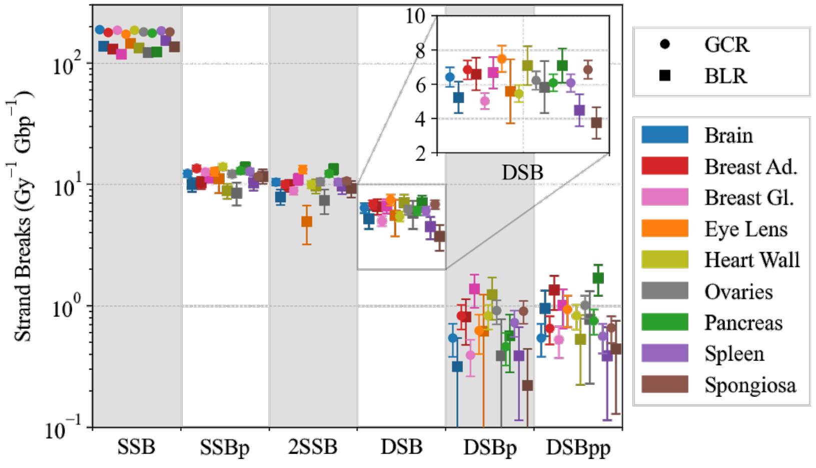
Thank you!

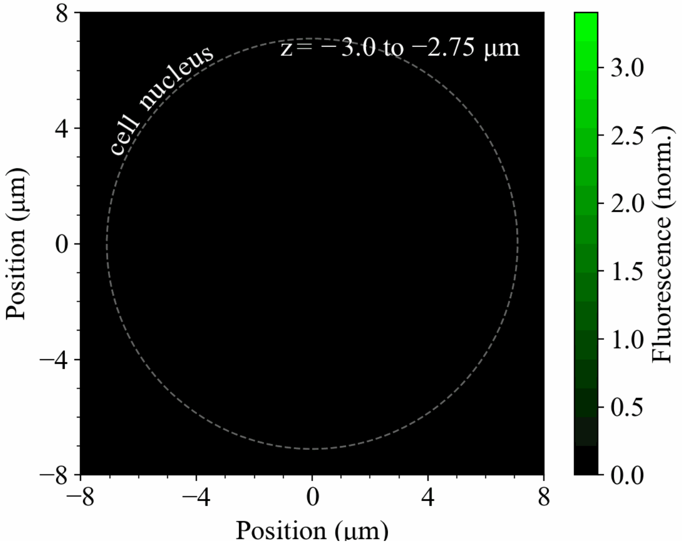
Summary

Multiscale simulation developed for lunar nanodosimetry





Further radiobiological validation undertaken



Space microdosimeter development and characterisation