Human missions to Mars: a space radiation odyssey

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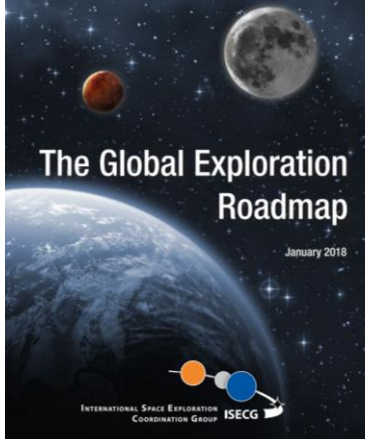
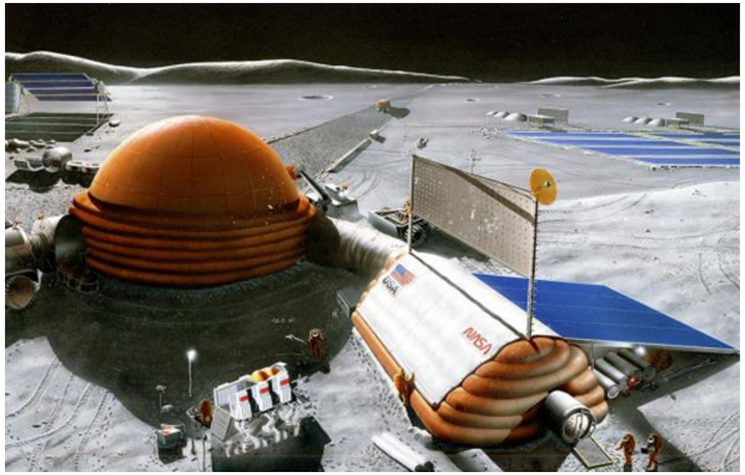
Image courtesy of https://www.businessinsider.com.au/nasa-mars-crewed-exploration-plans-sls-2017-4?r=US&IR=T

Roadmap to Mars

Main goal of human exploration as defined by the International Space Exploration Coordination Group, ISECG, 2013



Picture courtesy of ESA



Picture courtesy of NASA

Picture courtesy of NASA

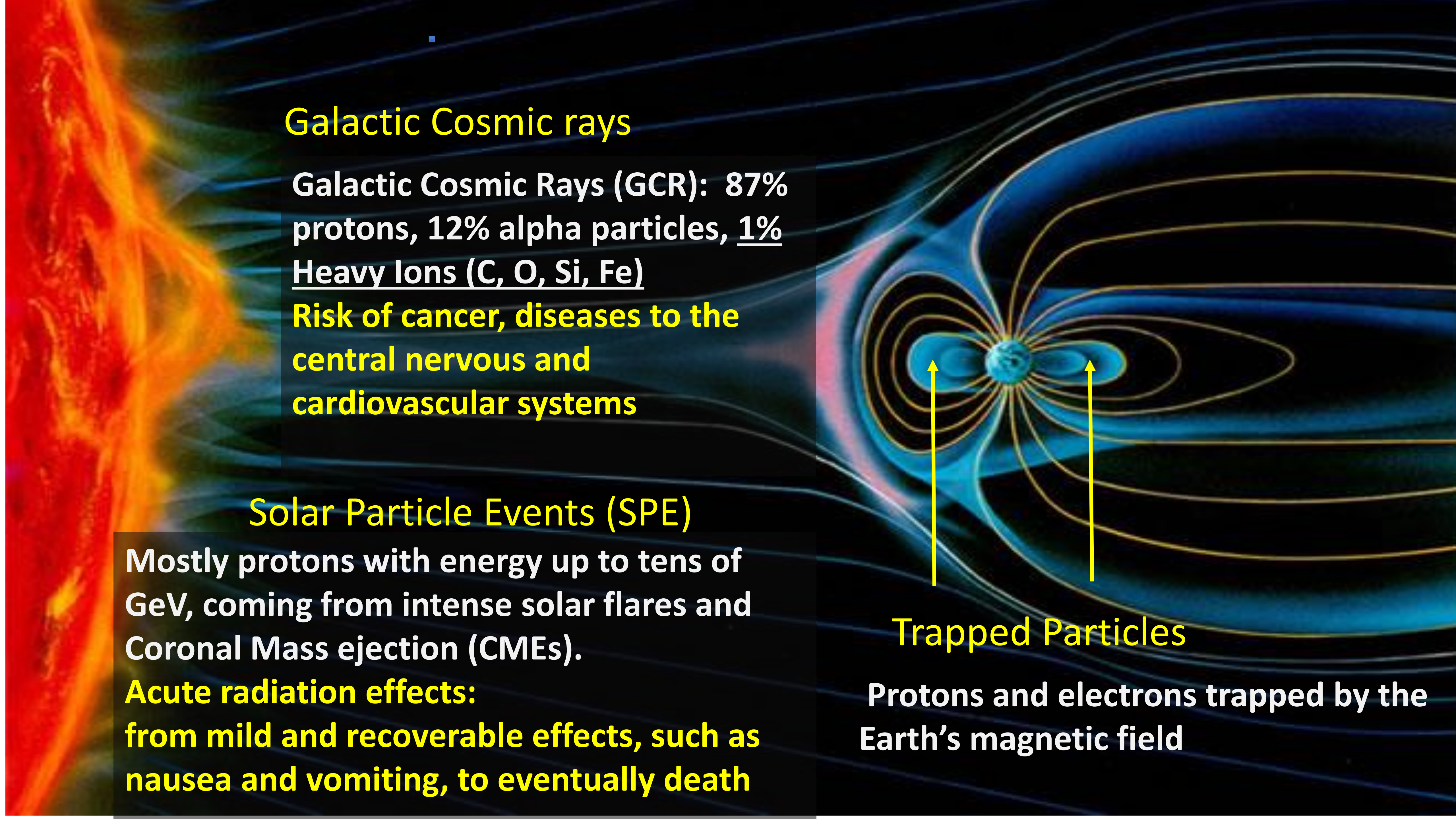
ISS since the 2000s → Artemis III mission (2025) Long term: lunar outpost → First human mission to Mars (next decade?)

Risks to astronauts' health

Credit: Getty

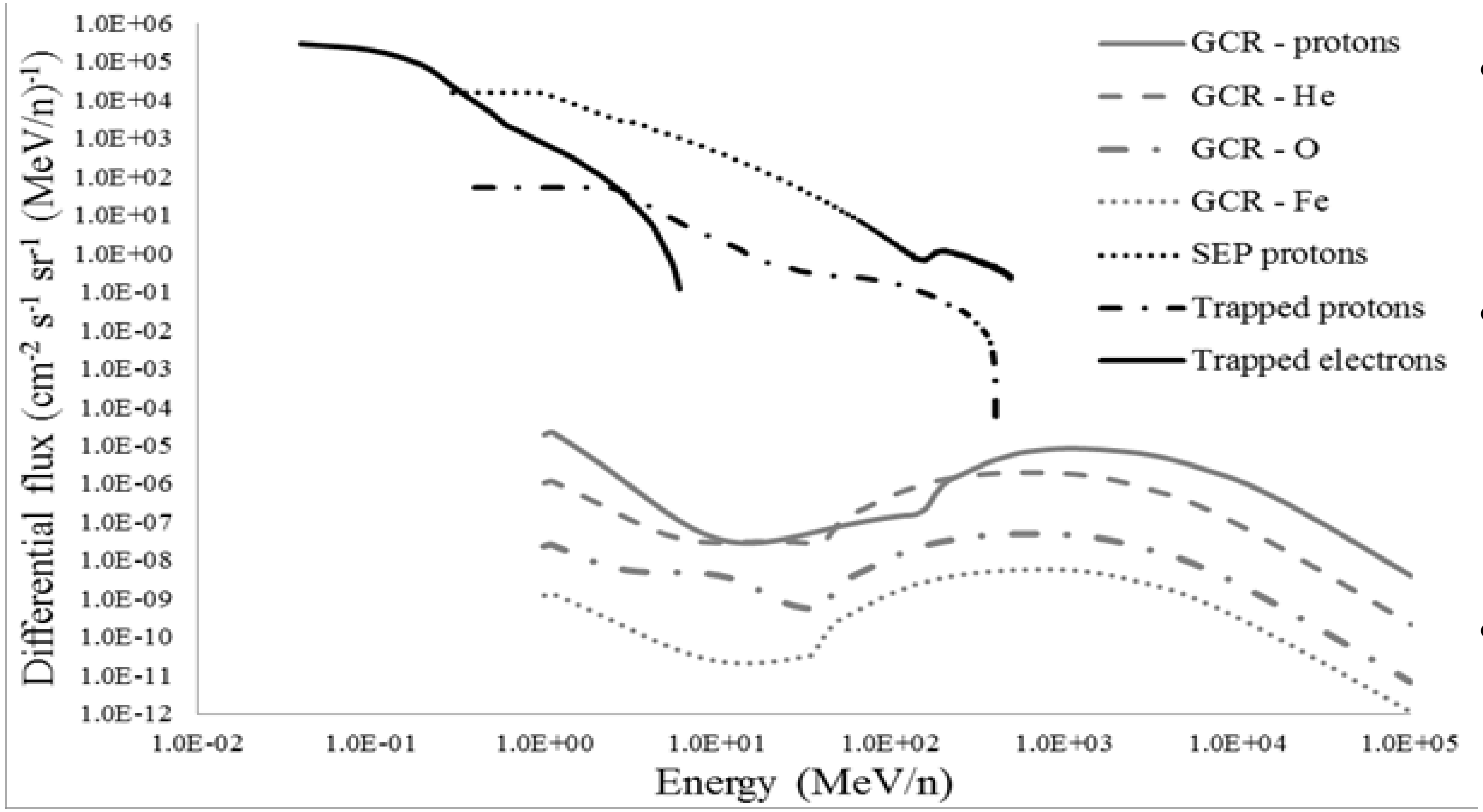
- Physiological problems caused by reduced gravity
- Psychological and medical problems caused by isolation
- Acute and late risks caused by exposure to cosmic radiation

M. Durante, Space radiation protection: Destination Mars, Life Sciences in Space Research, vol. 1, 2014, pp. 2-9



Galactic Cosmic rays
Galactic Cosmic Rays (GCR): 87% protons, 12% alpha particles, 1% Heavy Ions (C, O, Si, Fe)
Risk of cancer, diseases to the central nervous and cardiovascular systems
Solar Particle Events (SPE)
Mostly protons with energy up to tens of GeV, coming from intense solar flares and Coronal Mass ejection (CMEs).
Acute radiation effects:
from mild and recoverable effects, such as nausea and vomiting, to eventually death
Trapped Particles
Protons and electrons trapped by the Earth's magnetic field

Energy spectra of GCR and SPE



Plot courtesy of Dr Stefania Peracchi, ANSTO (former CMRP PhD student)

- Differential fluxes outside the ISS, calculated by means of **SPENVIS**
- SPENVIS: ESA's SPace ENVironment Information System (https://www.spenvis.oma.be/)
- GCR spectrum at solar minimum

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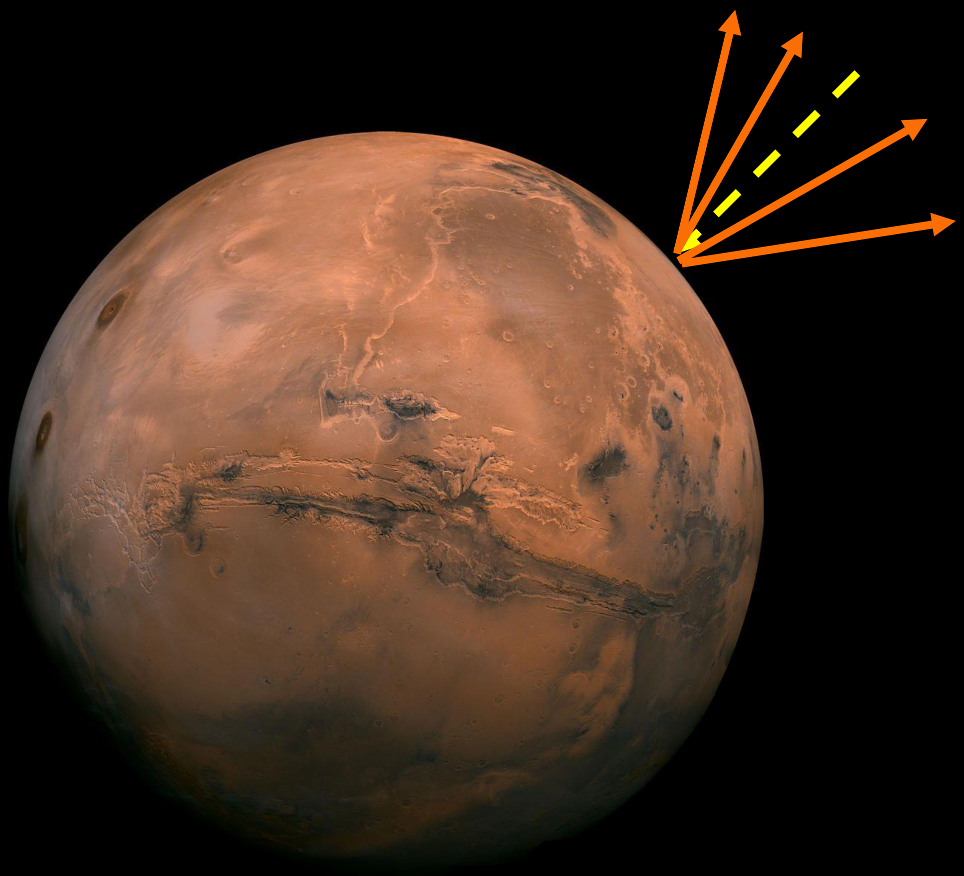
Courtesy: NASA

Magnetic field

Courtesy: Viking Orbiter - NASA/JPL-Caltech



Thinner atmosphere than Earth

No global magnetic field

Interactions of particles with the biological medium

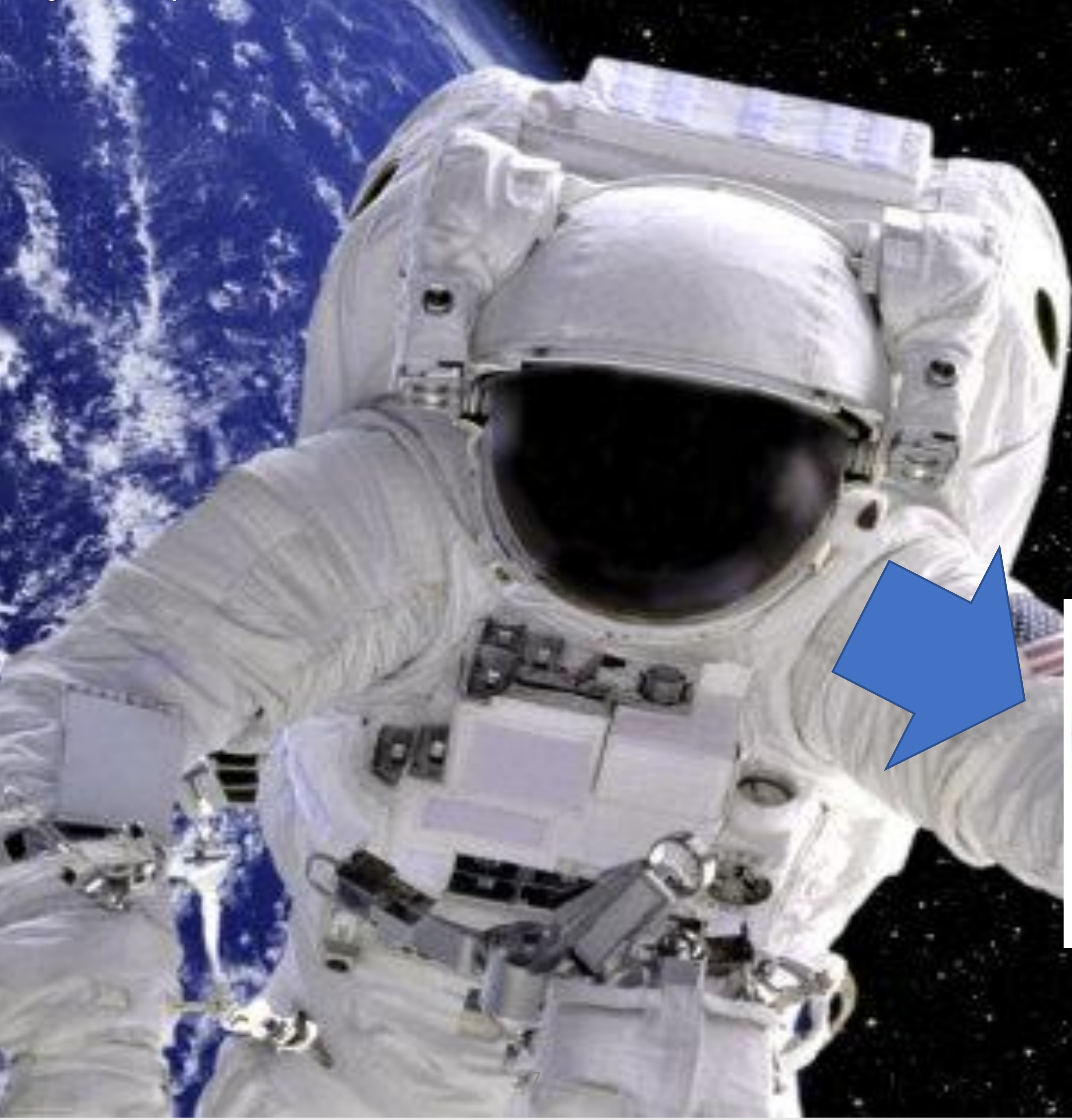
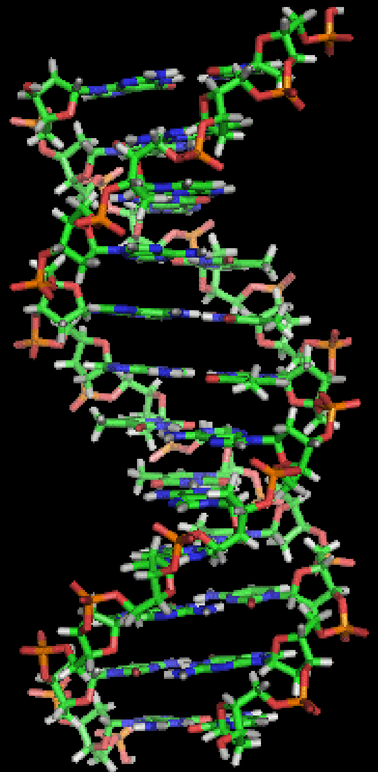


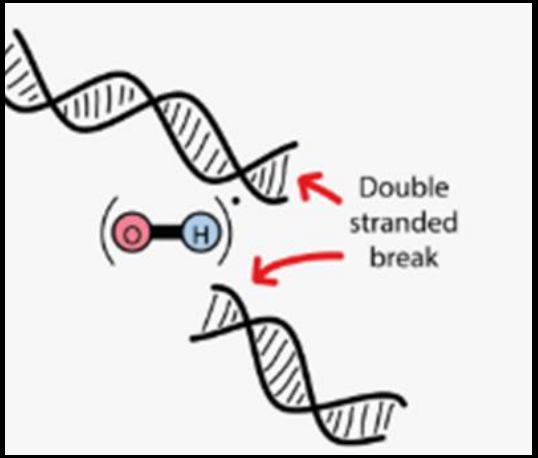
Image: Dieter Spears/Inhaus Creative

cellular scale



DNA scale

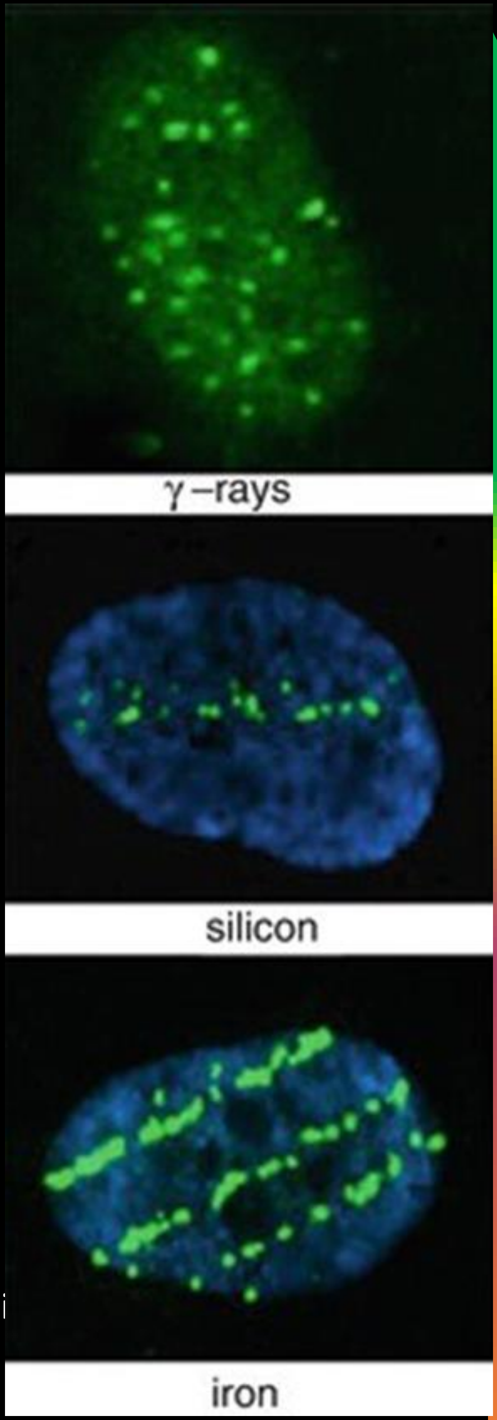
Radiation interaction with DNA



Reference:
Cucinotta FA, Durante M (2009) Risk of radiation carcinogenesis. Available on the NASA Human Research Program website at. http://humanresearchroadmap.nasa.gov/Evidence/reports/Carcinogenesis.pdf. Accessed 23 May 2014

Courtesy: NASA

https://srag.jsc.nasa.gov/SpaceRadi



Better

Biological knowledge

Poor

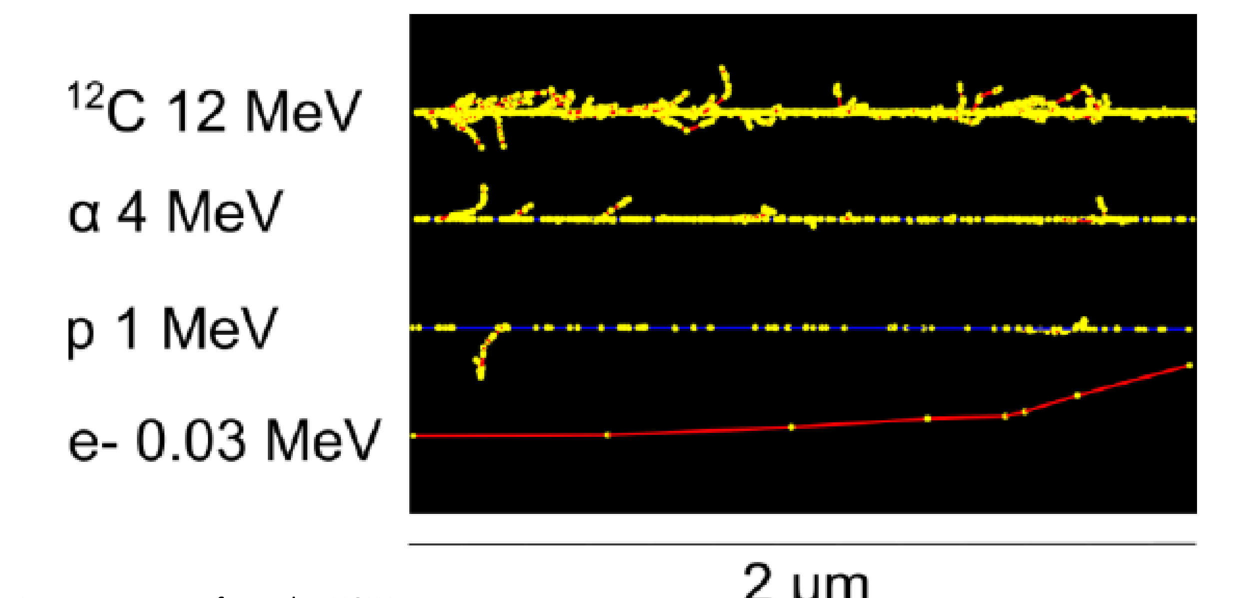


Image courtesy of D. Bolst, UOW

Calculation of dose equivalent

Dose multiplied by Q factor

- Q(LET): International Committee of Radiological Protection (ICRP) Publication 60
- Q(y): International Commission on Radiation Units and Measurements (ICRU) Report 40
- $Q_{NASA}(Z,E)$: National Aeronautics and Space Administration (NASA) TP-2011-216155

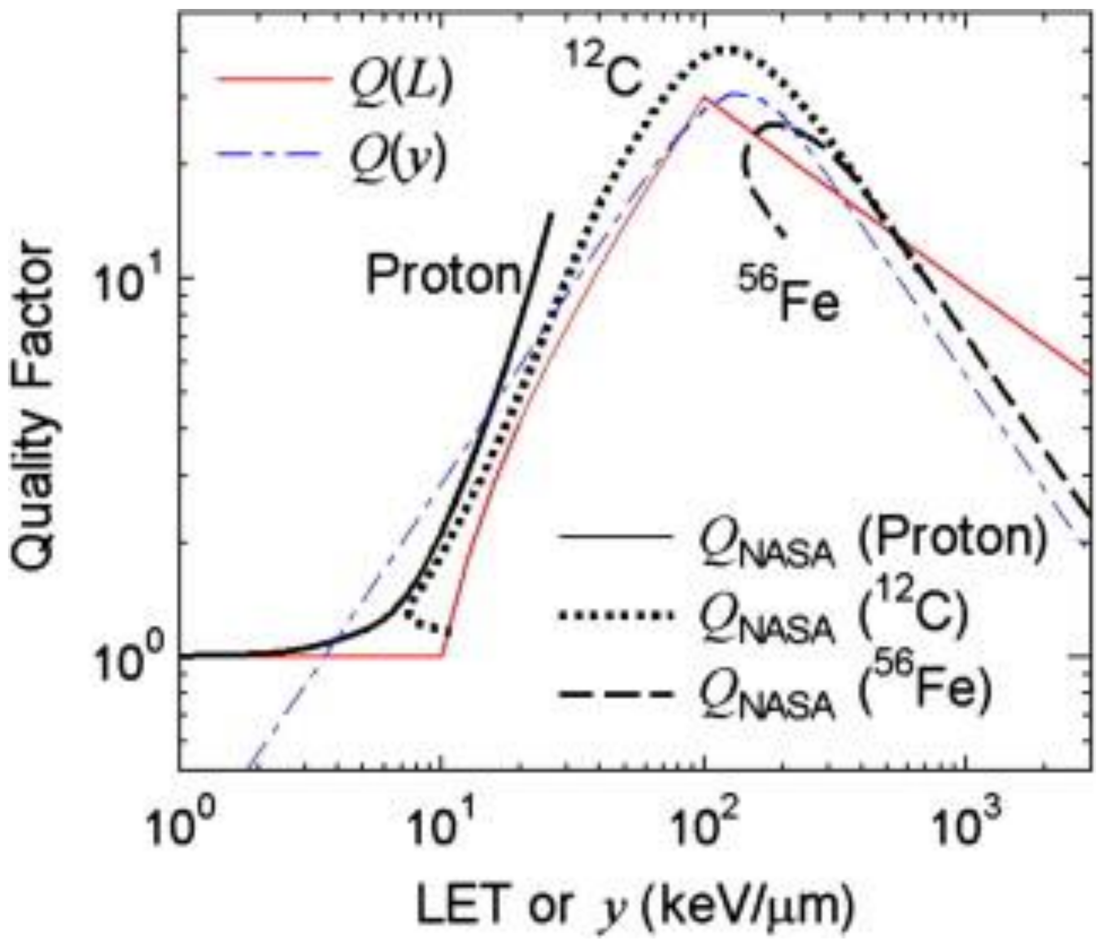


Figure courtesy of Sato, T., et al., 2013, *Advances in Space Research*, *52*(1), pp.79-85.

Radiation protection challenges

- **600 mSv for the total career of an astronaut, due to space flight radiation exposure.**
  - This limit is universal for all ages and sexes (NASA 2022)
  - ~1-2 mSv/day in interplanetary space and 0.5-1 mSv/day on Mars due to GCR
  - Dose due to SPE to be added on top: up to 100 mGy/hr inside a space vehicle
  - 6 months on the ISS: ~100 mSv (debate on the cancer risk, nevertheless, to date, no astronaut has been diagnosed with cancer attributable to space radiation)
  - Dose equivalent for a human mission to Mars: between 0.6 -1 Sv
  - Limitations of the modelling: there are no bio-physical models that can accurately estimate all acute, degenerative and carcinogenic risks specific to the space radiation environment

Bibliography:

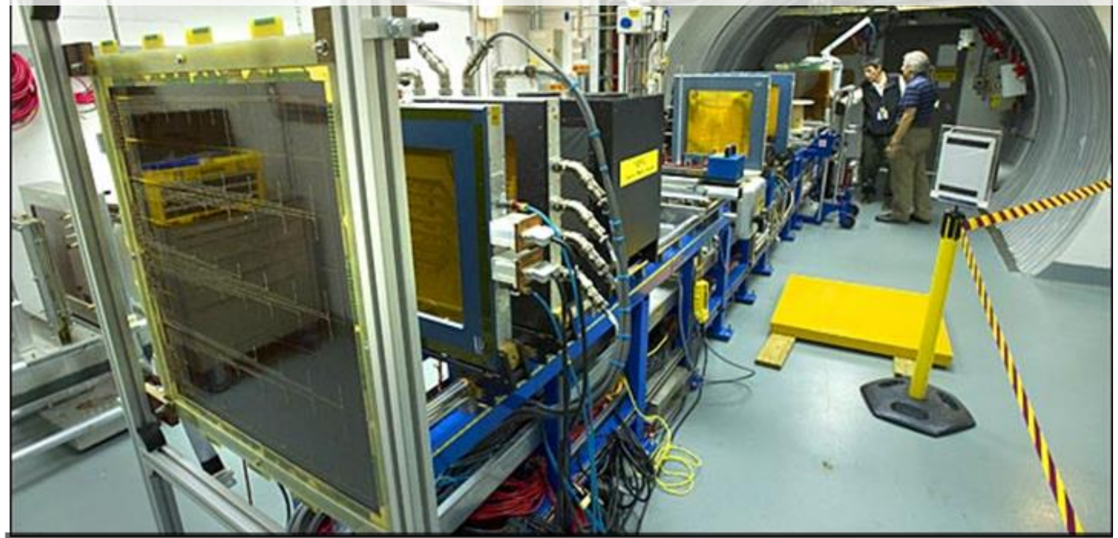
- National Aeronautics and Space Administration (NASA). NASA Space Flight Human-System Standard; Volume 1: Crew Health. NASA-STD-3001, V. 1 Rev. B. NASA (2022).
- Schimmerling, W., and Cucinotta. F. A. (2006). Radiation Protection Dosimetry 122 (1-4): 349–53.
- Chancellor, J. C, et al. (2018) Microgravity 4, article n. 8
- Strigari, L., et al. (2021), Frontiers in Public Health

Multidisciplinary research

Research in

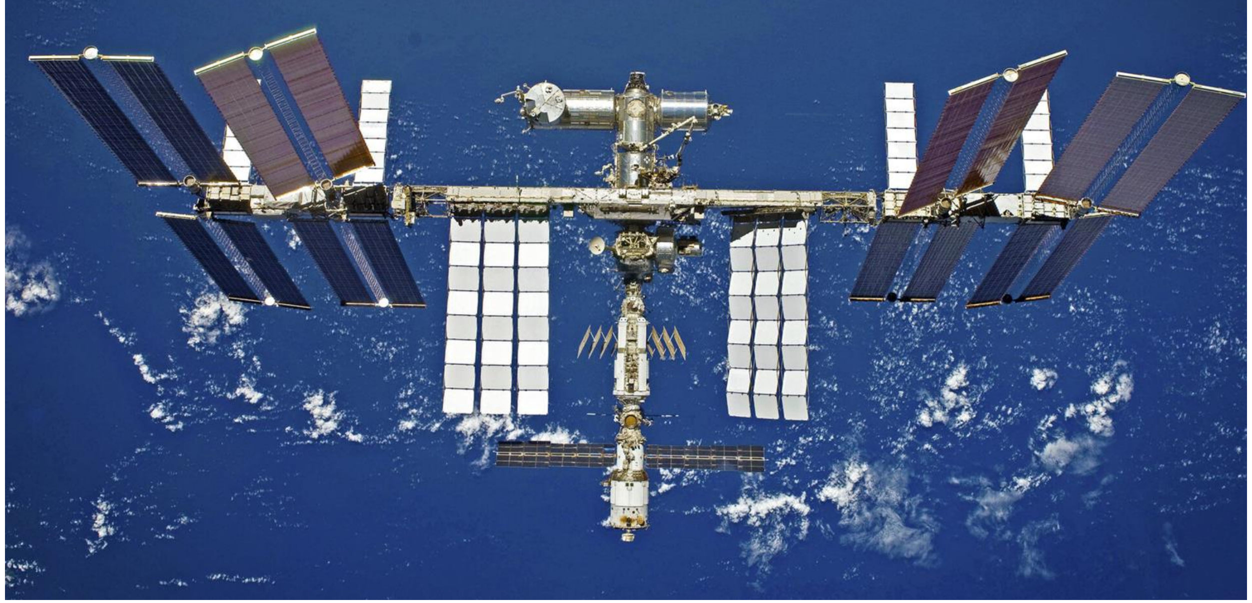
- Radiobiology
- Medicine
- Radiation detectors
- Development of concepts of transfer vehicles and planetary shelters
- Development of shielding solutions
- etc

Experiments in Earth accelerator facilities

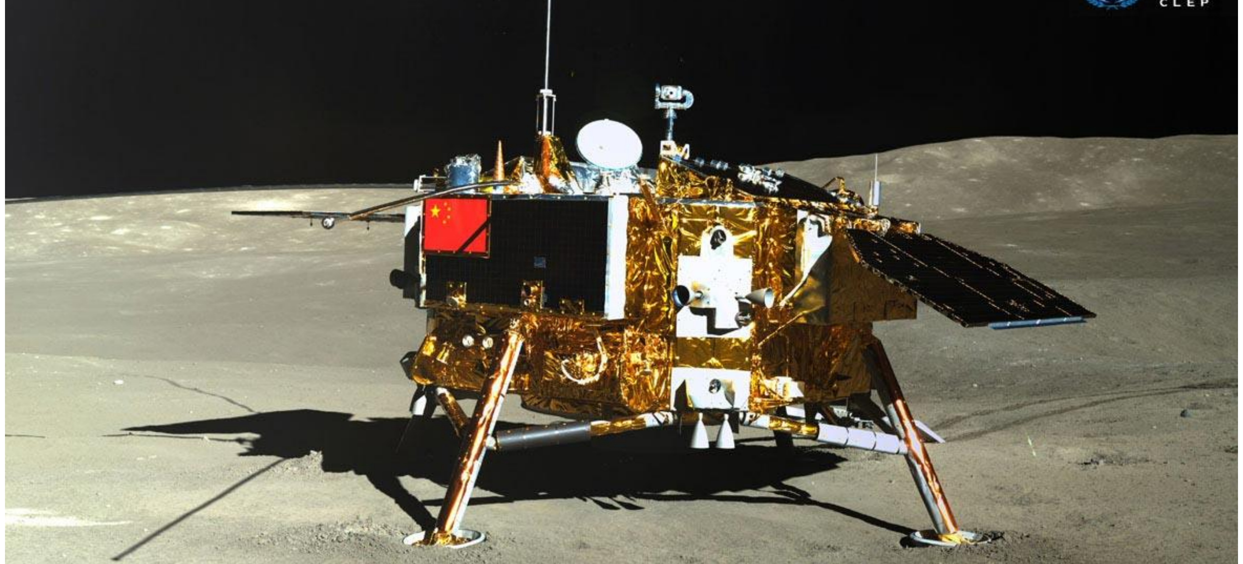


The NASA Space Radiation Laboratory (Brookhaven National Lab, US)

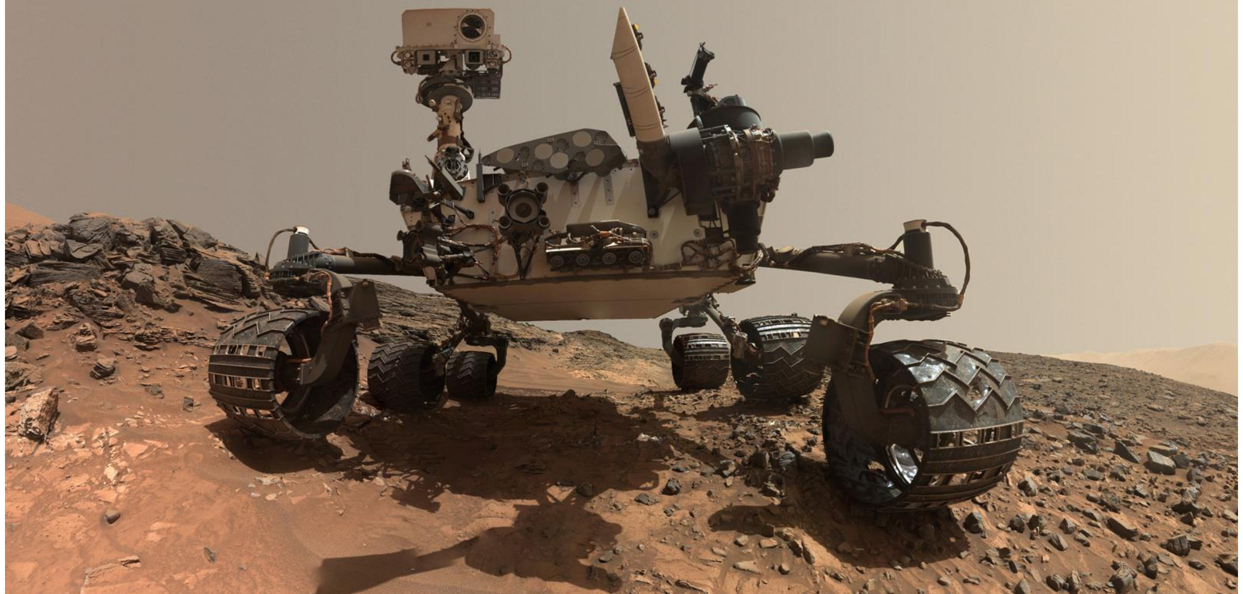
Experiments on the ISS



The Chang’e-4 lunar probe: Lunar Lander neutron



Curiosity



Monte Carlo Radiation physics simulations


GEANT4 A SIMULATION TOOLKIT

Developed by an international scientific collaboration

Overview

Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. The three main reference papers for Geant4 are published in Nuclear Instruments and Methods in Physics Research A 506 (2003) 250-303, IEEE Transactions on Nuclear Science 53 No. 1 (2006) 270-278 and Nuclear Instruments and Methods in Physics Research A 835 (2016) 186-225.

Applications	User Support	Publications	Collaboration
A sampling of applications, technology transfer and other uses of Geant4	Getting started, guides and information for users and developers	Validation of Geant4, results from experiments and publications	Who we are: collaborating institutions, members, organization and legal information

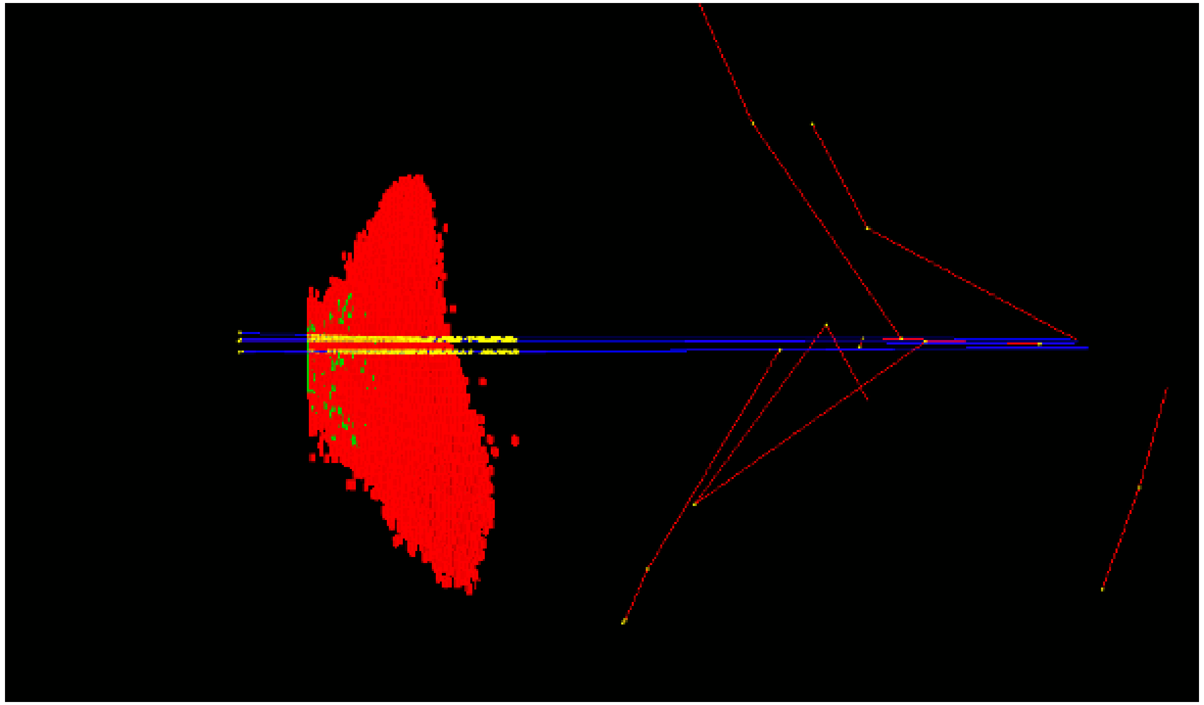
printer-friendly version

Events

- [Virtual] 25th Geant4 Collaboration Meeting, 21-25 September 2020.
- [Virtual] Geant4 Advanced Course @ CERN, 28 September - 2 October 2020.
- 9th International Geant4 School, Catania (Italy), 4-9 October 2020.
- 4th Geant4 International User Conference at the Physics-Medicine-Biology Frontier, Napoli (Italy), ~~19-21 October 2020~~. *** CANCELLED ***
- 4th LPCC Detector Simulation Workshop, CERN (Geneva), 2-3 November 2020.

Past Events

www.geant4.org



Courtesy: Geant4 « microbeam » advanced example

- Modelling both electromagnetic and hadronic interactions of particles with matter

In synergy with experimental measurements in Earth labs, ISS and space

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Radiation protection of astronauts by means of Geant4

Theme of research of the Centre For Medical Radiation Physics, University of Wollongong

Canberra Deep Space Communication Complex

Dist. Prof Anatoly Rozenfeld

Dr Linh Tran

Dr David Bolst

PhD student
Stefania Peracchi

PhD student
Matthew Large

PhD student
Jay Archer

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Outline of the Monte Carlo simulation study

- What is next …
- Multi-scale approach: study the early DNA damage in mission scenarios of interest (Moon)
- Explore shielding solutions (transport vehicles and planetary shelters)
- Validation of the simulation against experimental measurements performed on the ISS
- Development of a Monte Carlo simulation for radiation protection on the ISS

Acknowledgments

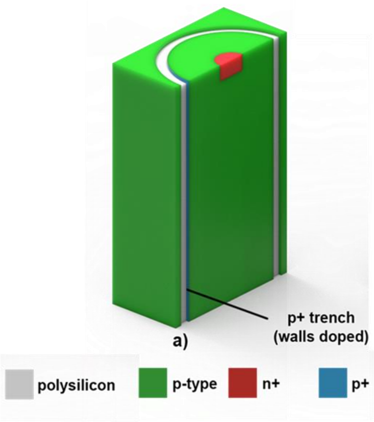
- ESA AO/1-10318/20/NL/CRS, EXPRO+
- ARC Discovery Project 230103091
- National Computational Merit Allocation Scheme 2021, 2022 and 2023

Heavy Ion Medical Accelerator at QST, Chiba
HIMAC, Japan

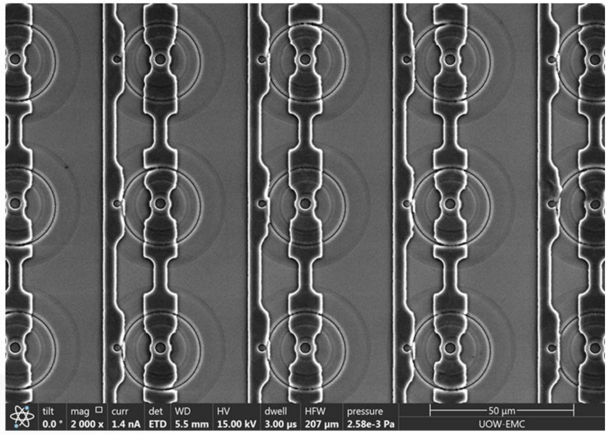
Dist. Prof. Anatoly Rozenfeld

HIMAC Bio-cave beam port with passive scattering delivery

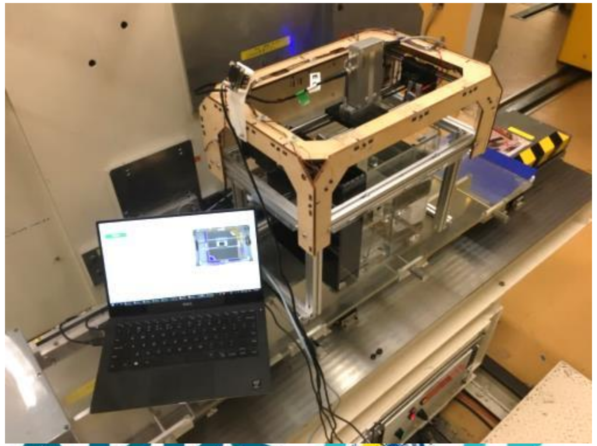
Silicon microdosimeters, CMRP, UOW

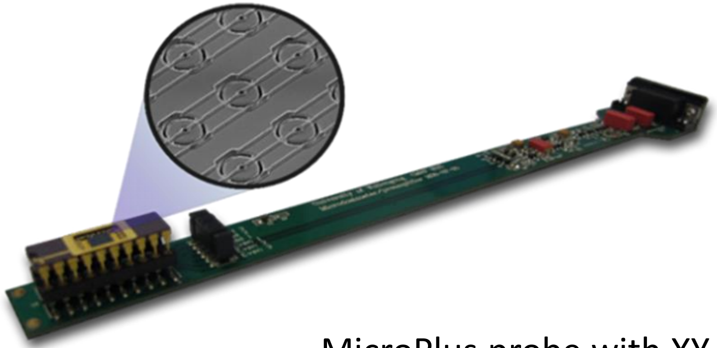


a)



b)





MicroPlus probe with XY-movement stage for high spatial resolution microdosimetry in a water or any solid phantom

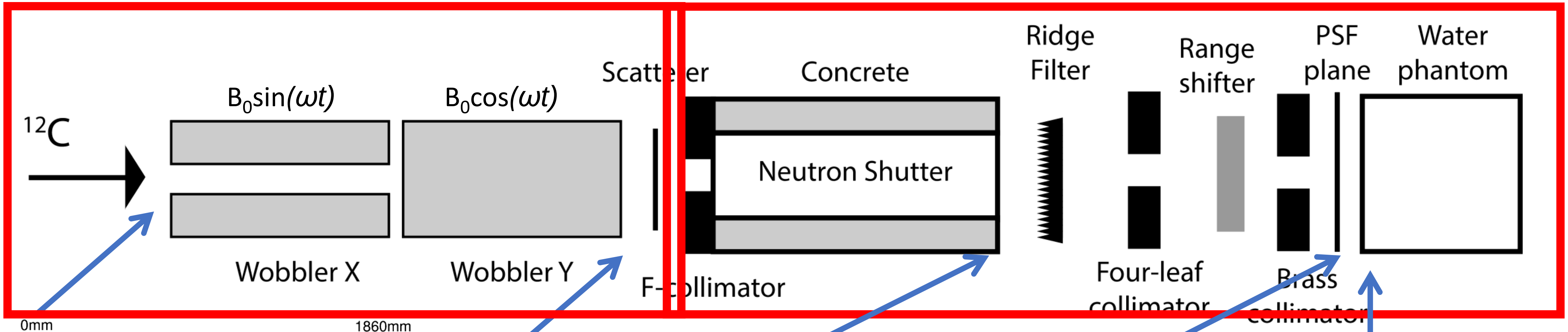
Validation of Geant4 physics models

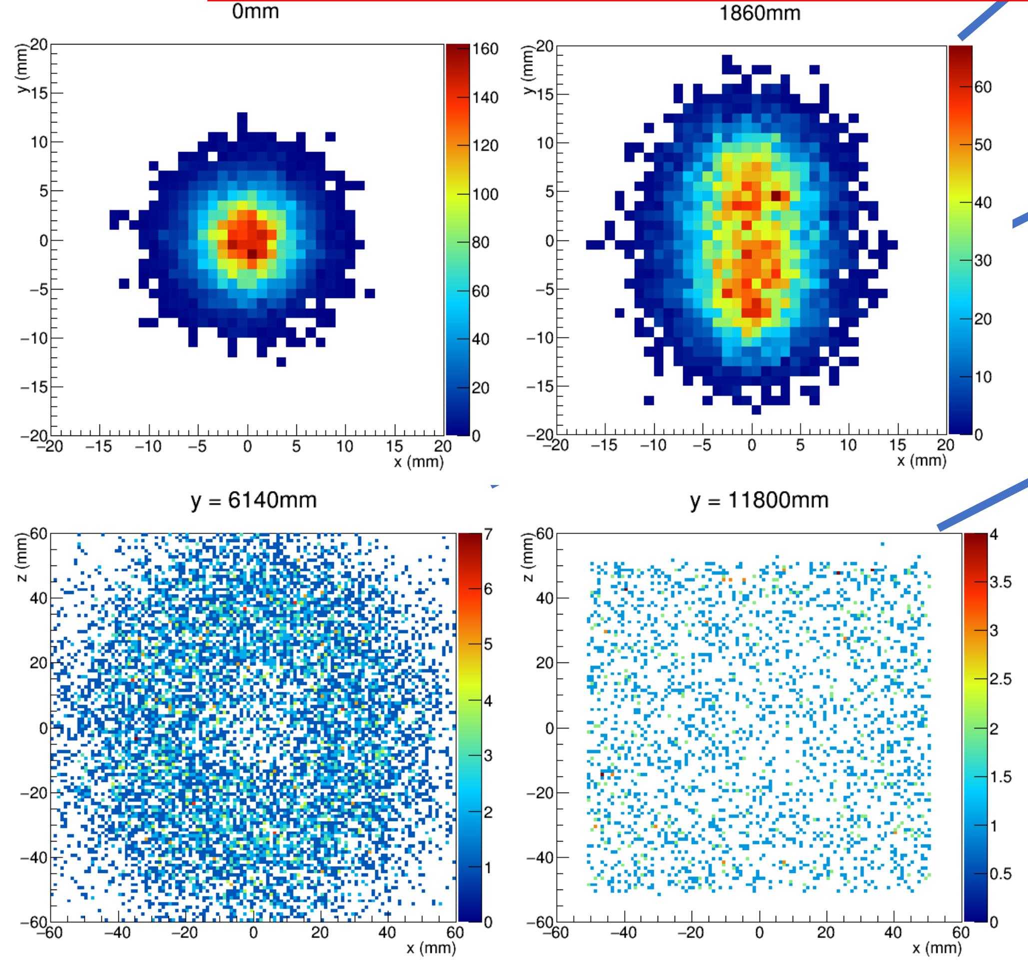
D. Bolst et al, PMB, vol. 65:045014

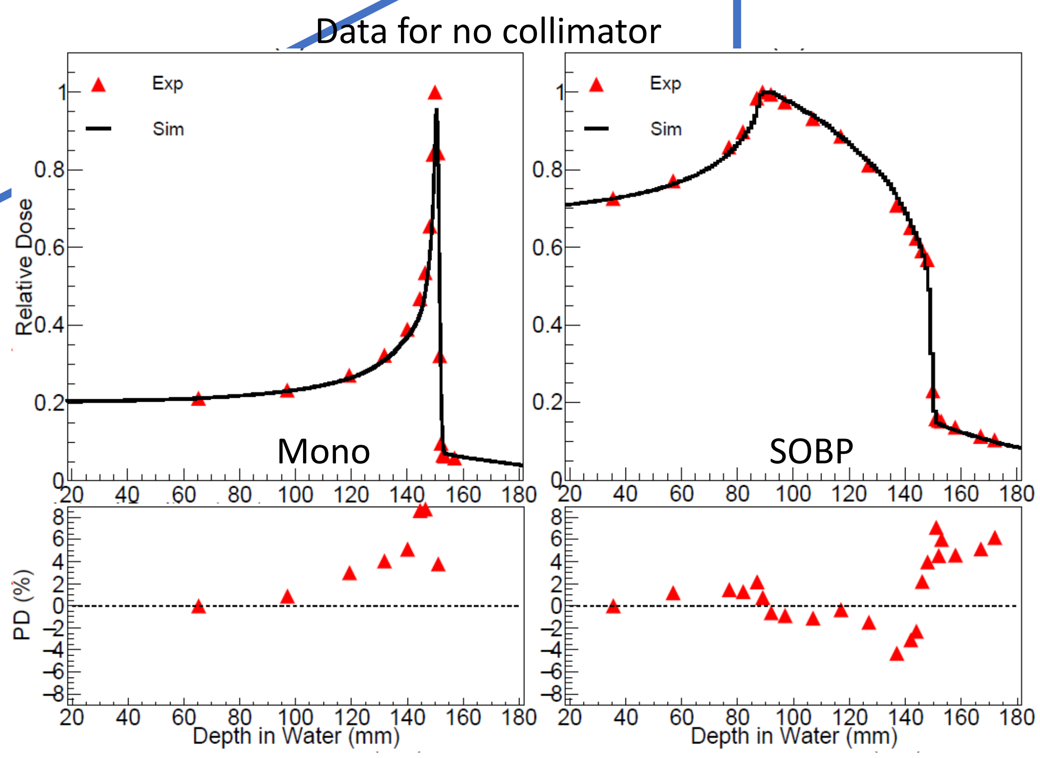
Experimental validation of Geant4 (version 10.2p3) against exp measurements done at HIMAC, QST, Chiba, using mono-energetic carbon, nitrogen and oxygen beams

Main author: Dr David Bolst

Ion	Primary energy ($MeV\ u^{-1}$)	Energy sigma (%)	Ta thickness (mm)	Range shifter (mm)	BP in phantom (mm)
^{12}C	288.6	0.2	0.434	0	149
^{14}N	180	0.36	0.434	0	49
^{16}O	400	0.15	0.649	86	91.5 (191.5)



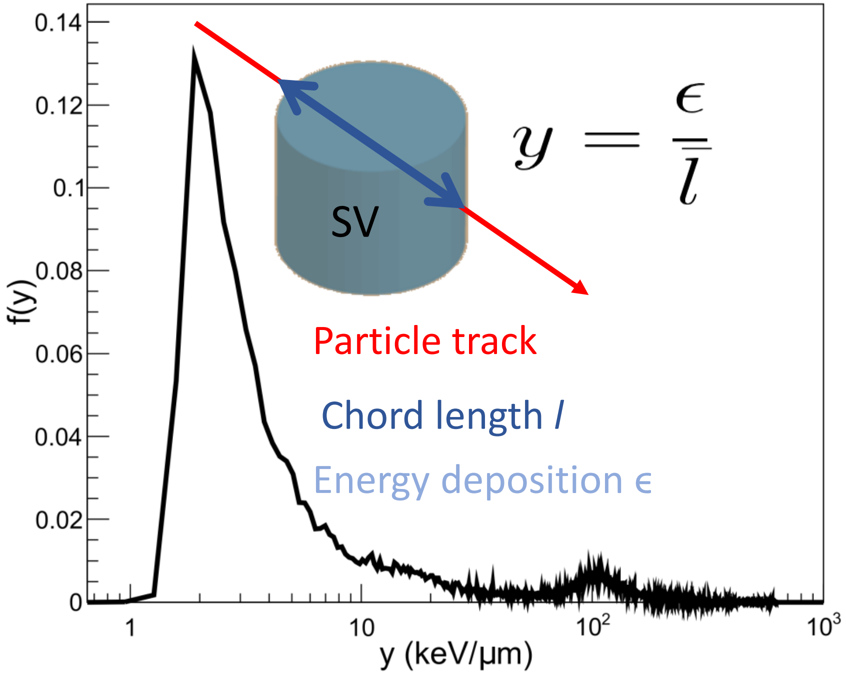


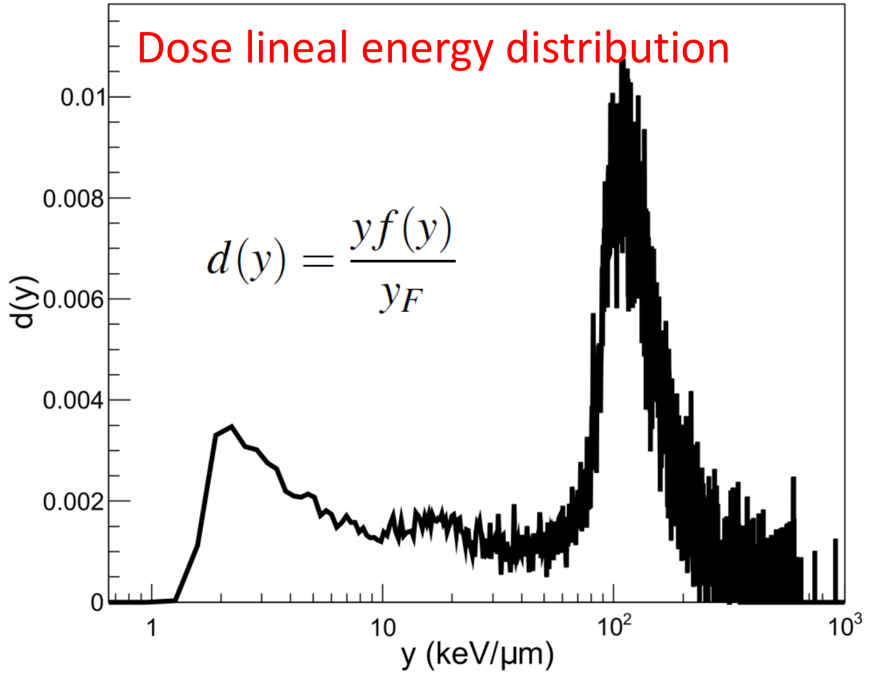


Mono Exp from Ploc et al. (http://wrmiss.org/workshops/sixteenth/Ploc.pdf.)
SOBP Exp from Yonai et al.
(Monte carlo study on secondary neutrons in passive carbon-ion radiotherapy: Identication of the main source and reduction in the secondary neutron dose)

Microdosimetric quantities

Irradiation of a 10 µm SV at the Bragg Peak of a 290 MeV/u ^{12}C in a water phantom



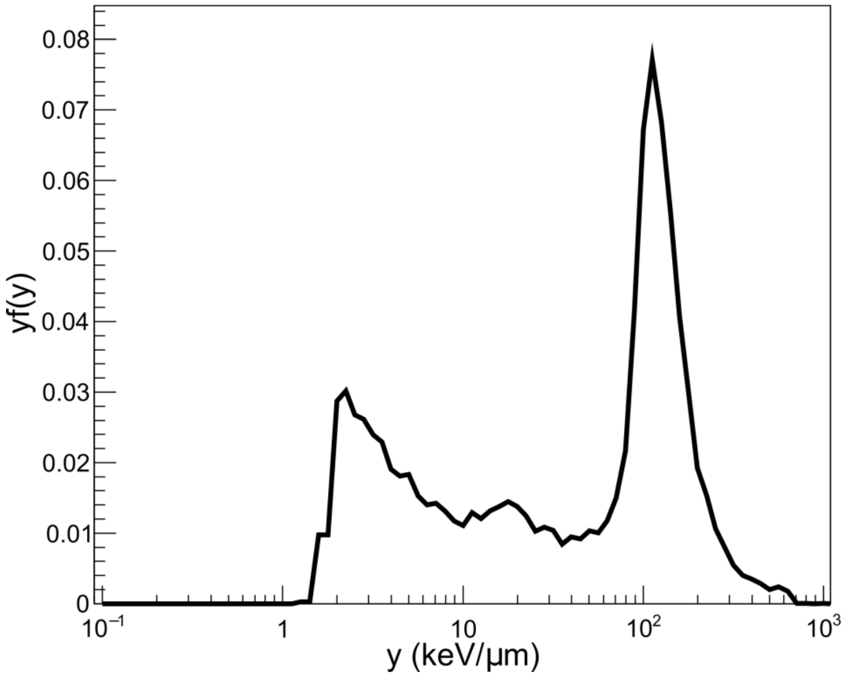


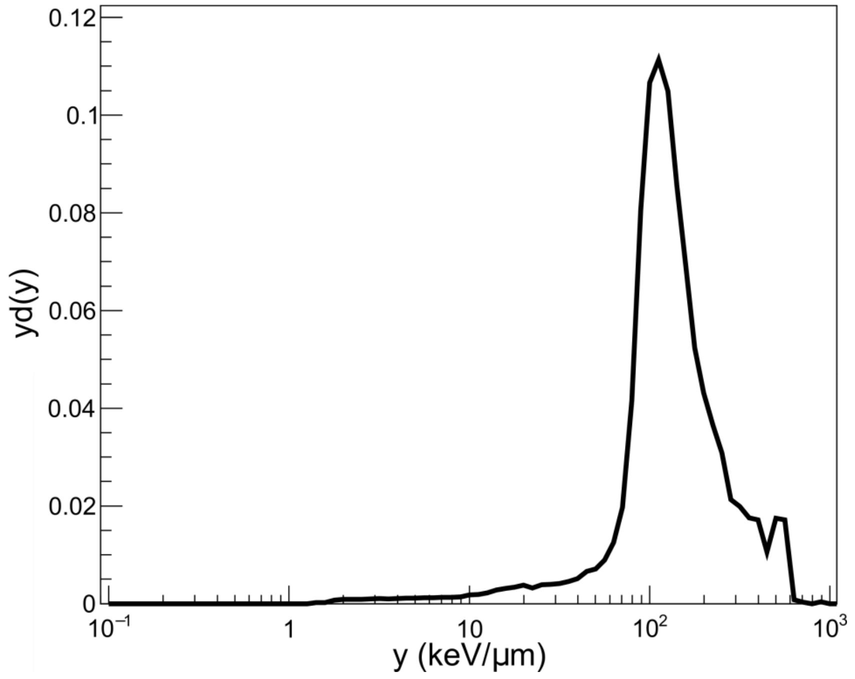
Frequency-mean lineal energy

$$y_F = \int y f(y) dy$$

Dose-mean lineal energy

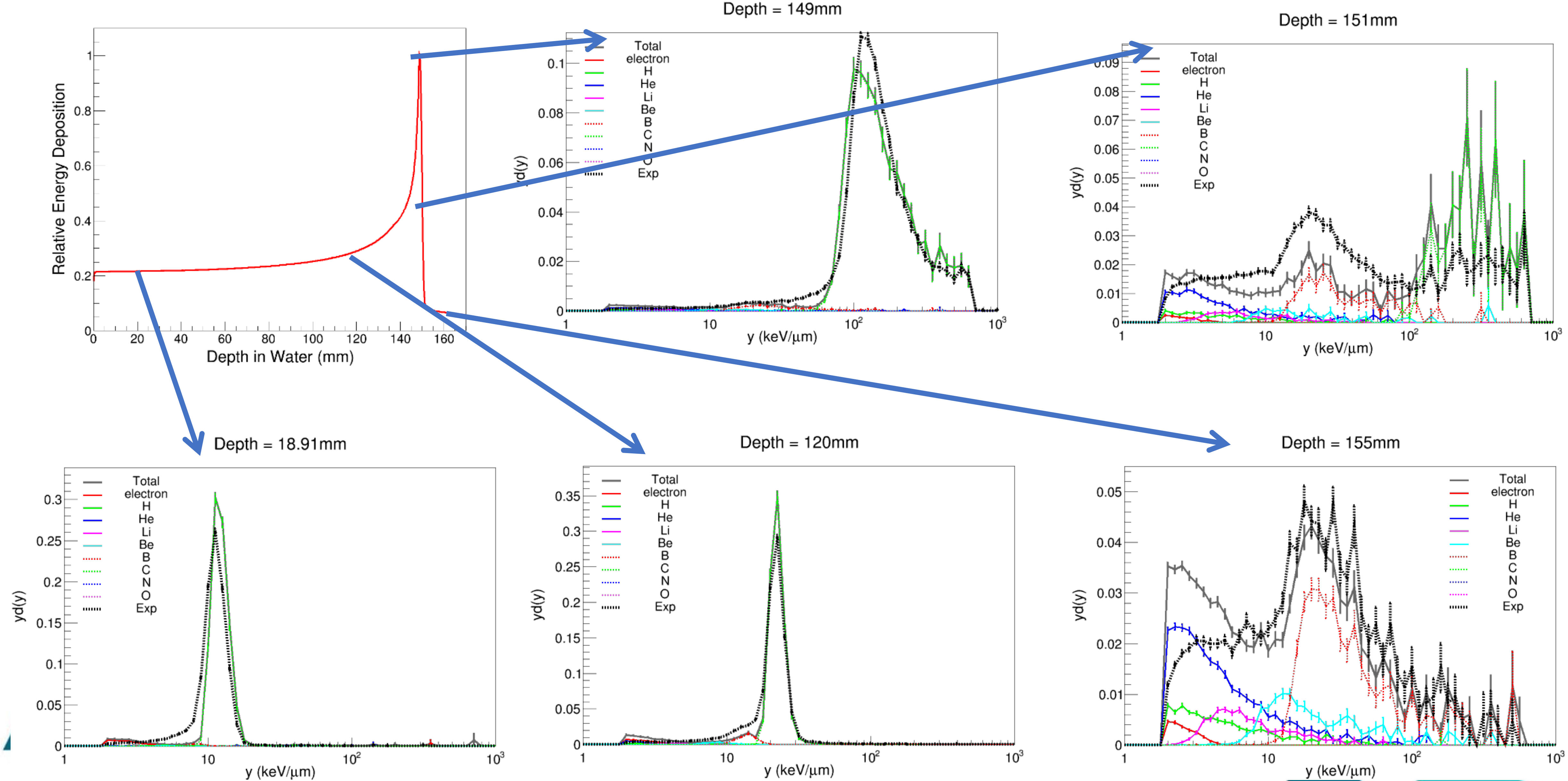
$$y_D = \frac{\int y^2 f(y) dy}{\int y f(y) dy} = \frac{\int y^2 f(y) dy}{y_F}$$

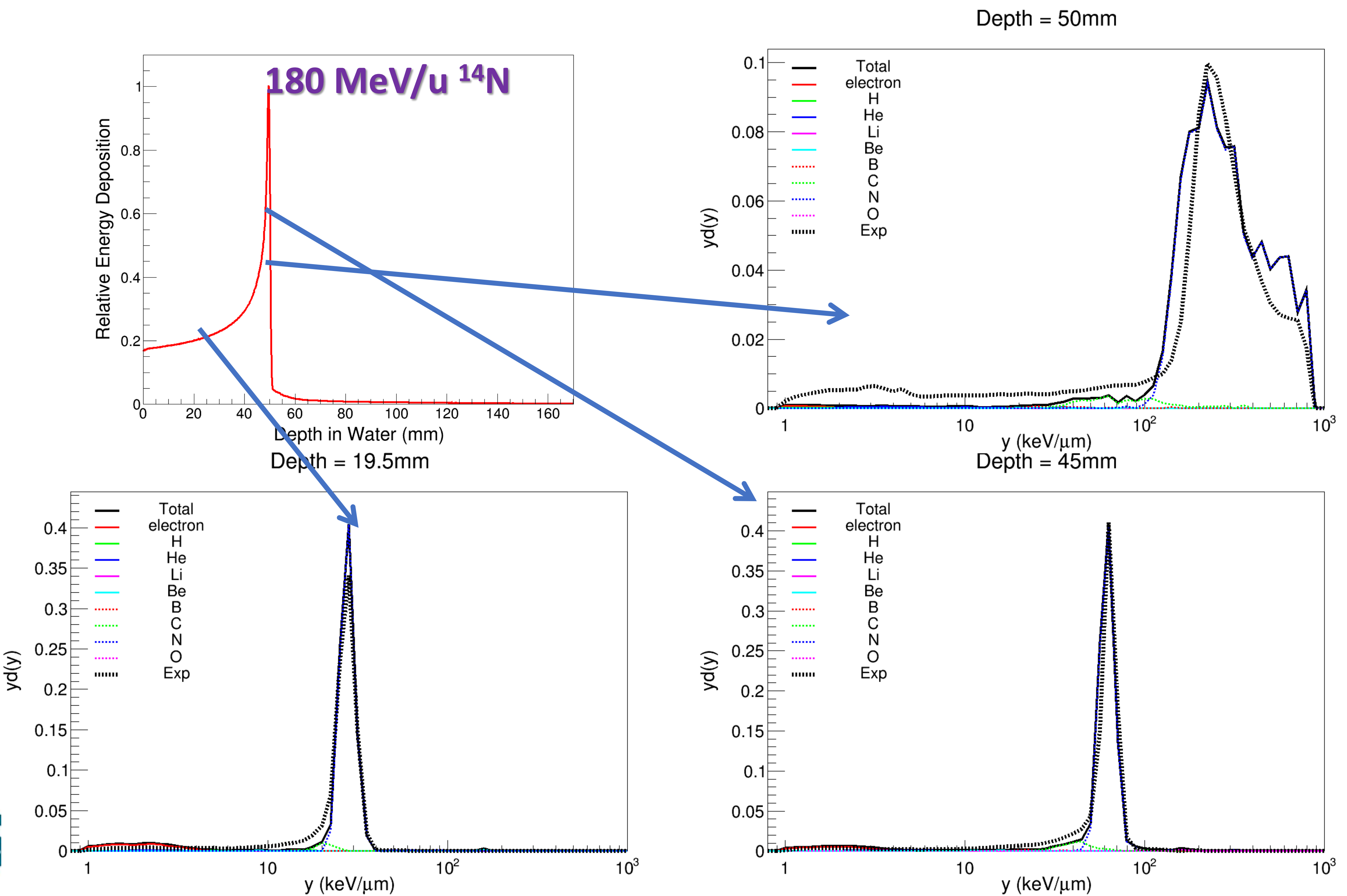




Comparison of Spectra 290 MeV/u ^{12}C

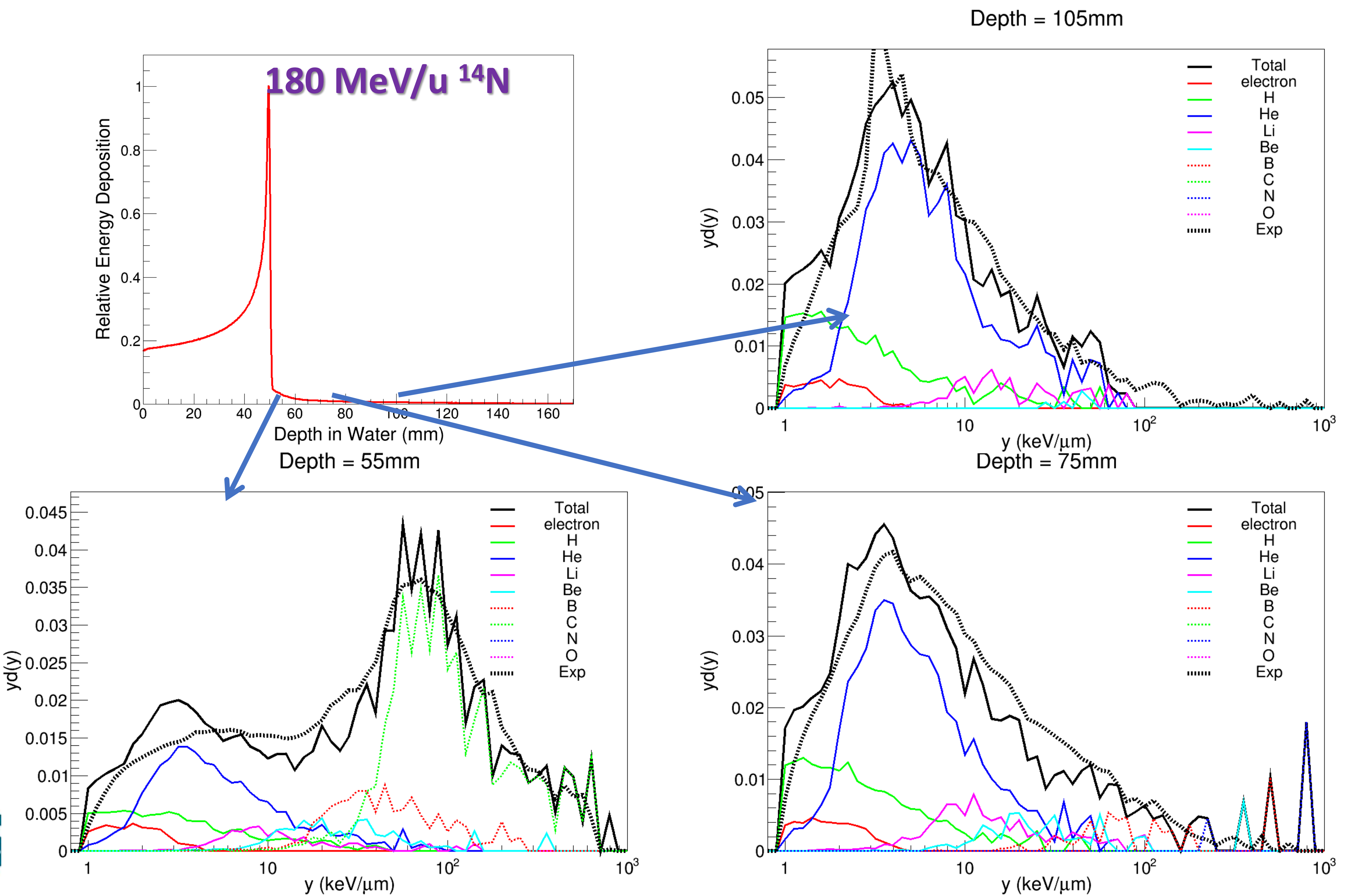
Results by D. Bolst, CMRP, UOW



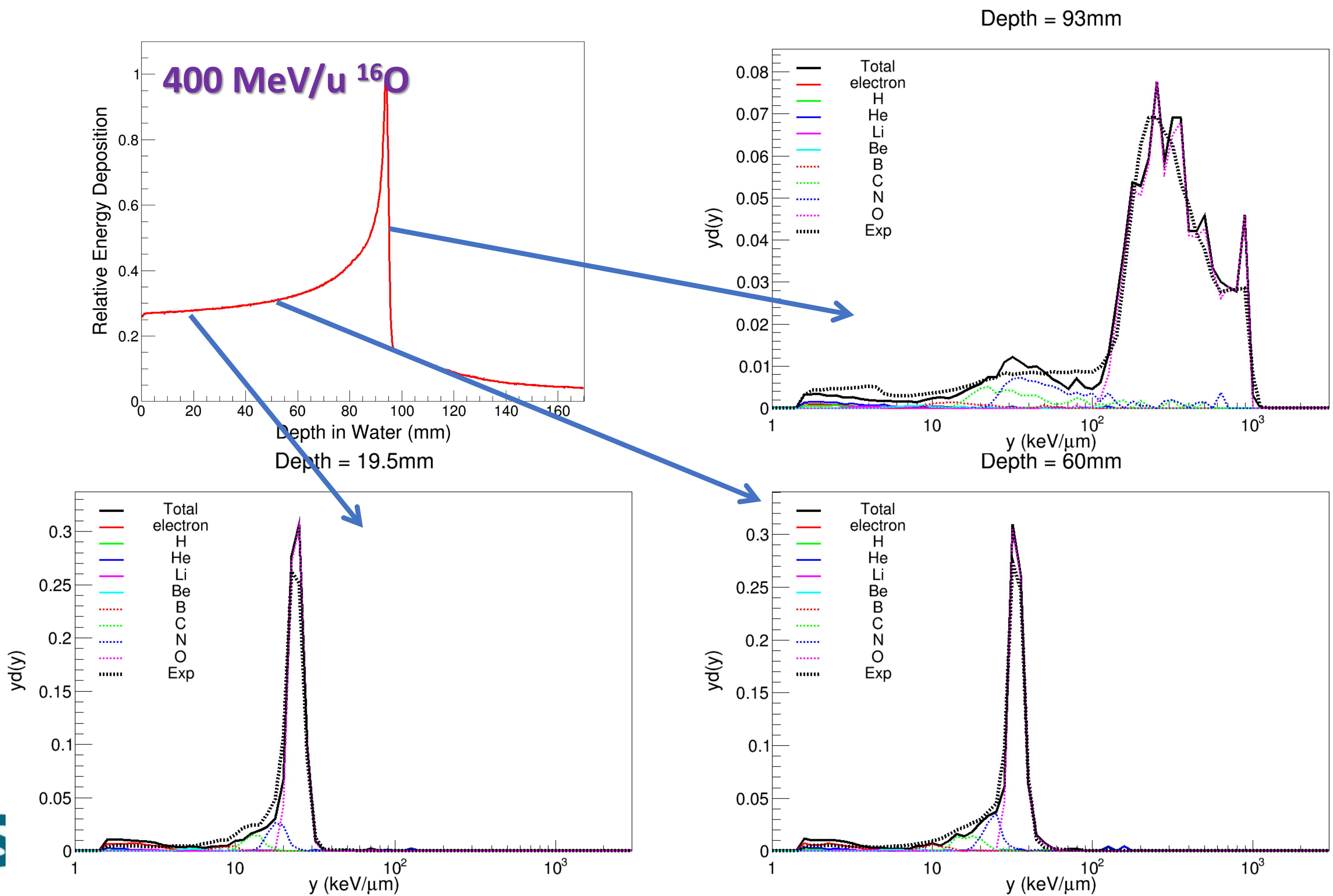


180 MeV/u ¹⁴N
Relative Energy Deposition
Depth in Water (mm)
0
20
40
60
80
100
120
140
160
0.2
0.4
0.6
0.8
1
Depth = 50mm
Depth = 19.5mm
Depth = 45mm
Total
electron
H
He
Li
Be
B
C
N
O
Exp
yd(y)
y (keV/µm)
1
10
10²
10³
0.02
0.04
0.06
0.08
0.1
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

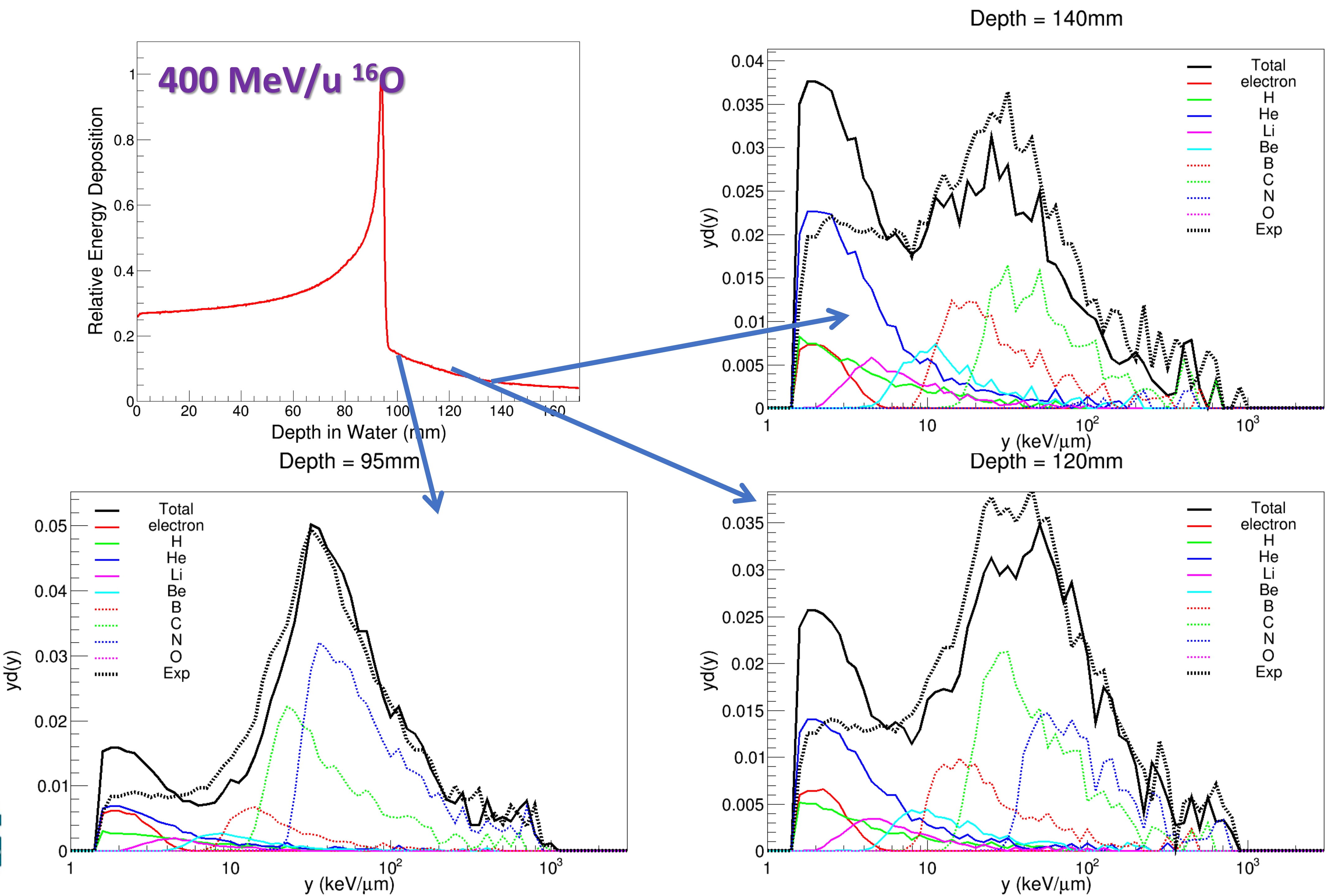
ARPS


180 MeV/u ^{14}N
Relative Energy Deposition
Depth in Water (mm)
Depth = 55mm
Depth = 75mm
Depth = 105mm
yd(y)
y (keV/µm)
Total
electron
H
He
Li
Be
B
C
N
O
Exp

ARPS



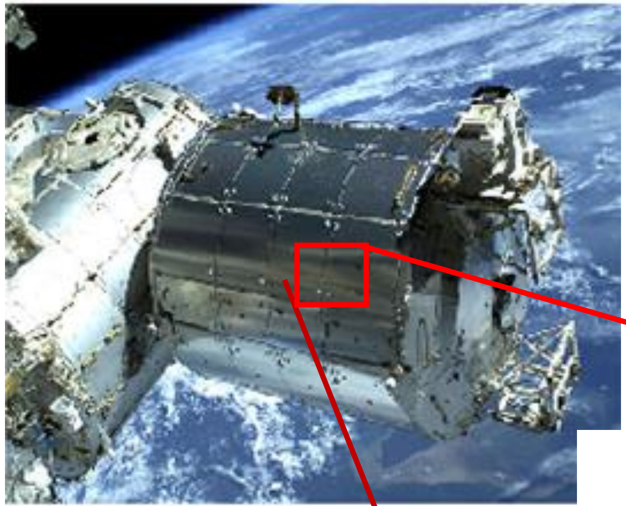
400 MeV/u 16O
Relative Energy Deposition
Depth in Water (mm)
Depth = 93mm
Depth = 19.5mm
Depth = 60mm
Total
electron
H
He
Li
Be
B
C
N
O
Exp
yd(y)
y (keV/µm)

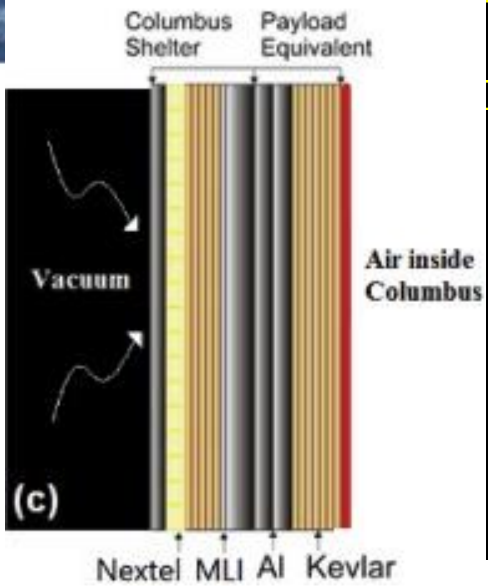

400 MeV/u 16O
Relative Energy Deposition
Depth in Water (mm)
Depth = 140mm
Depth = 95mm
Depth = 120mm
yd(y)
y (keV/μm)
Total
electron
H
He
Li
Be
B
C
N
O
Exp

ARPS

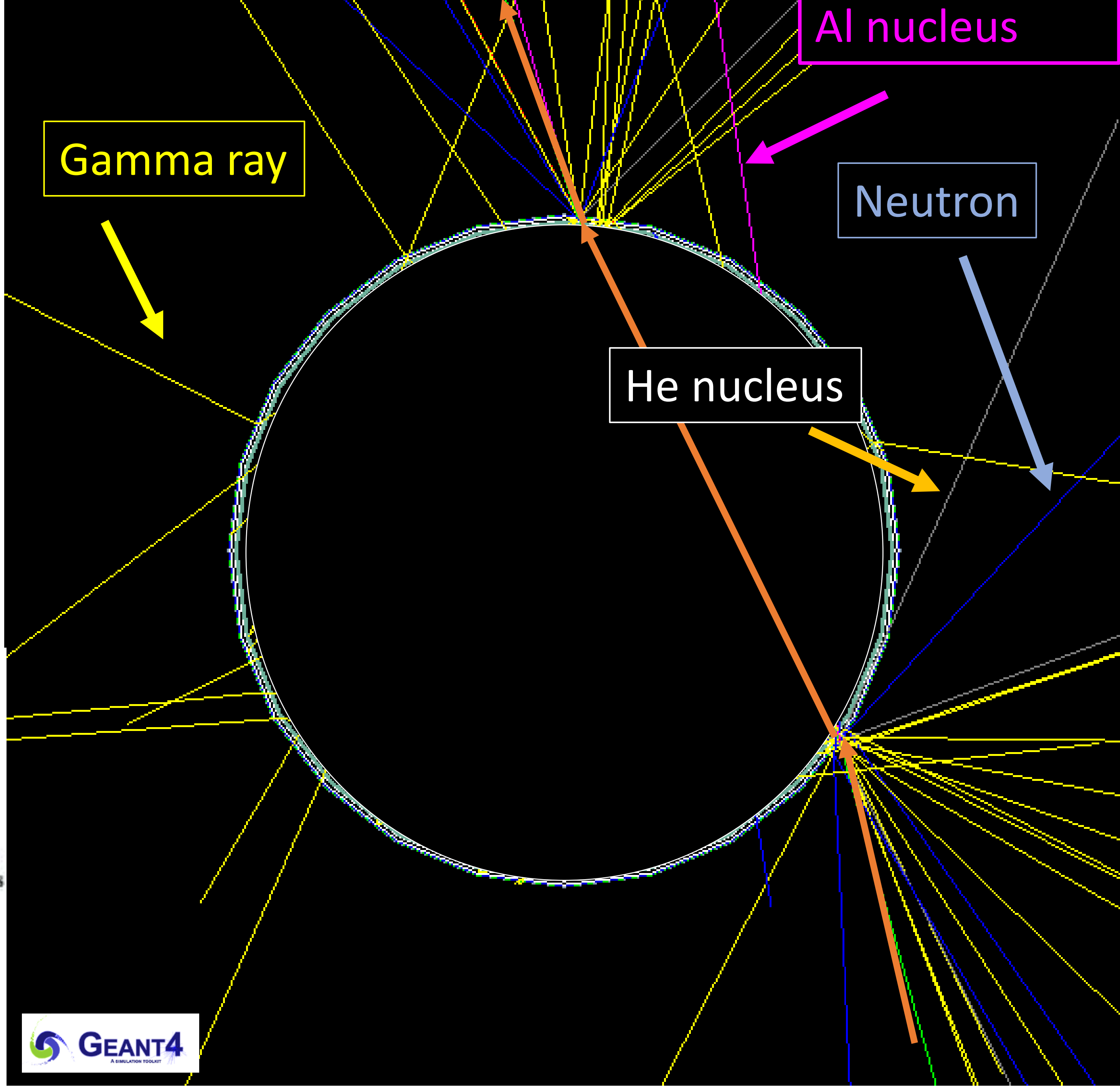
Model the space radiation environment

S. Peracchi et al., *Rad. Meas.* (129), 2019, 106182

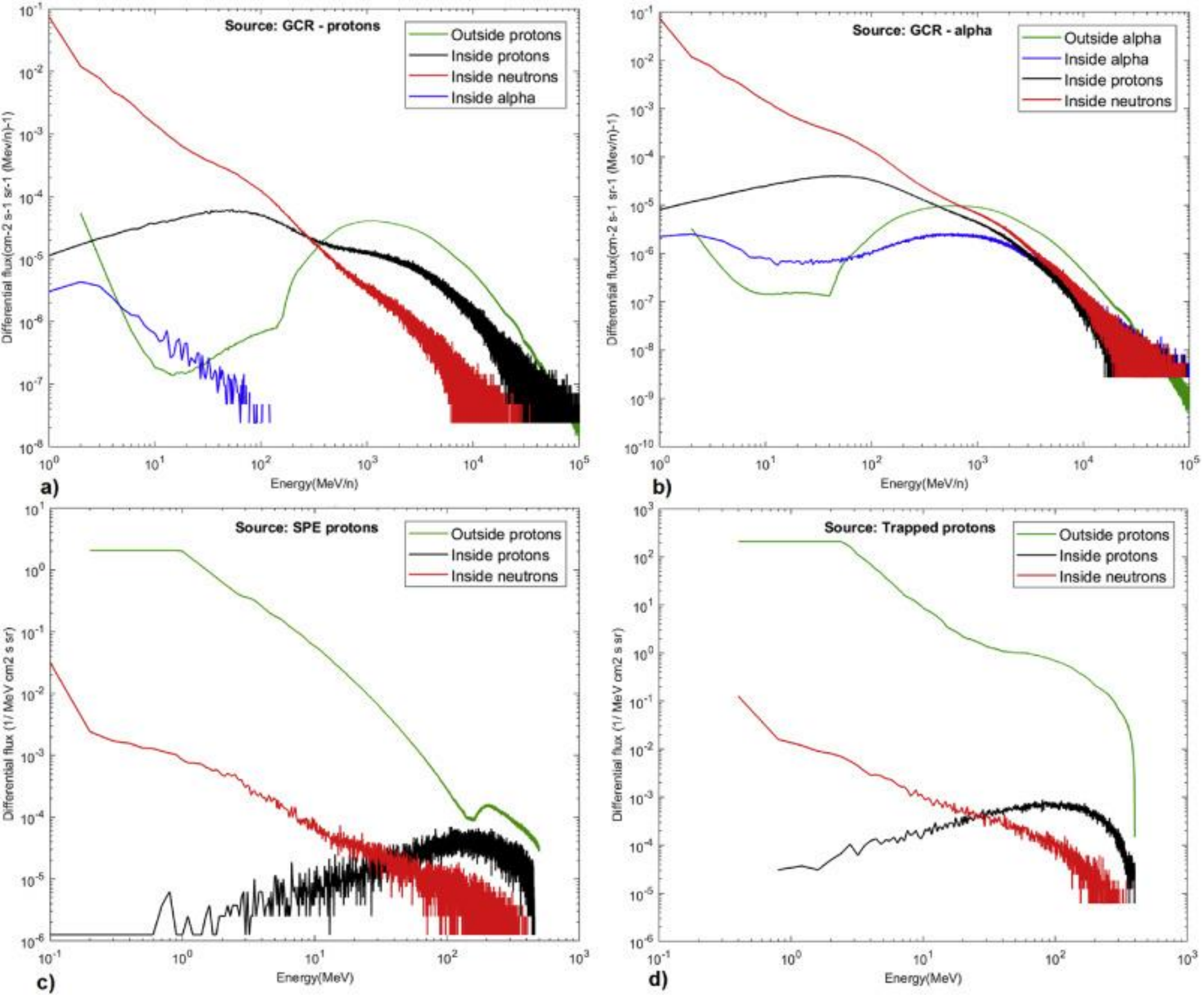




PhD student
Stefania Peracchi



Fluences of particles of interest in the Columbus module



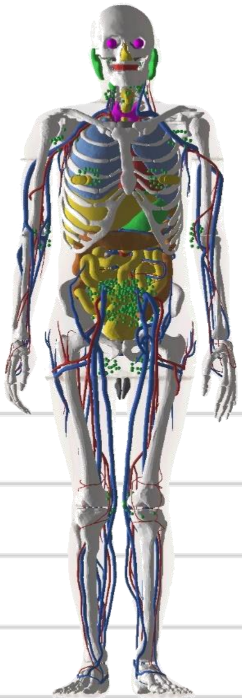
	Dose (μGy/day)	Dose equivalent (μSv/day)
GCR p	190	267
GCR α	39	60
SPE p	42	31
Trapped p	550	378

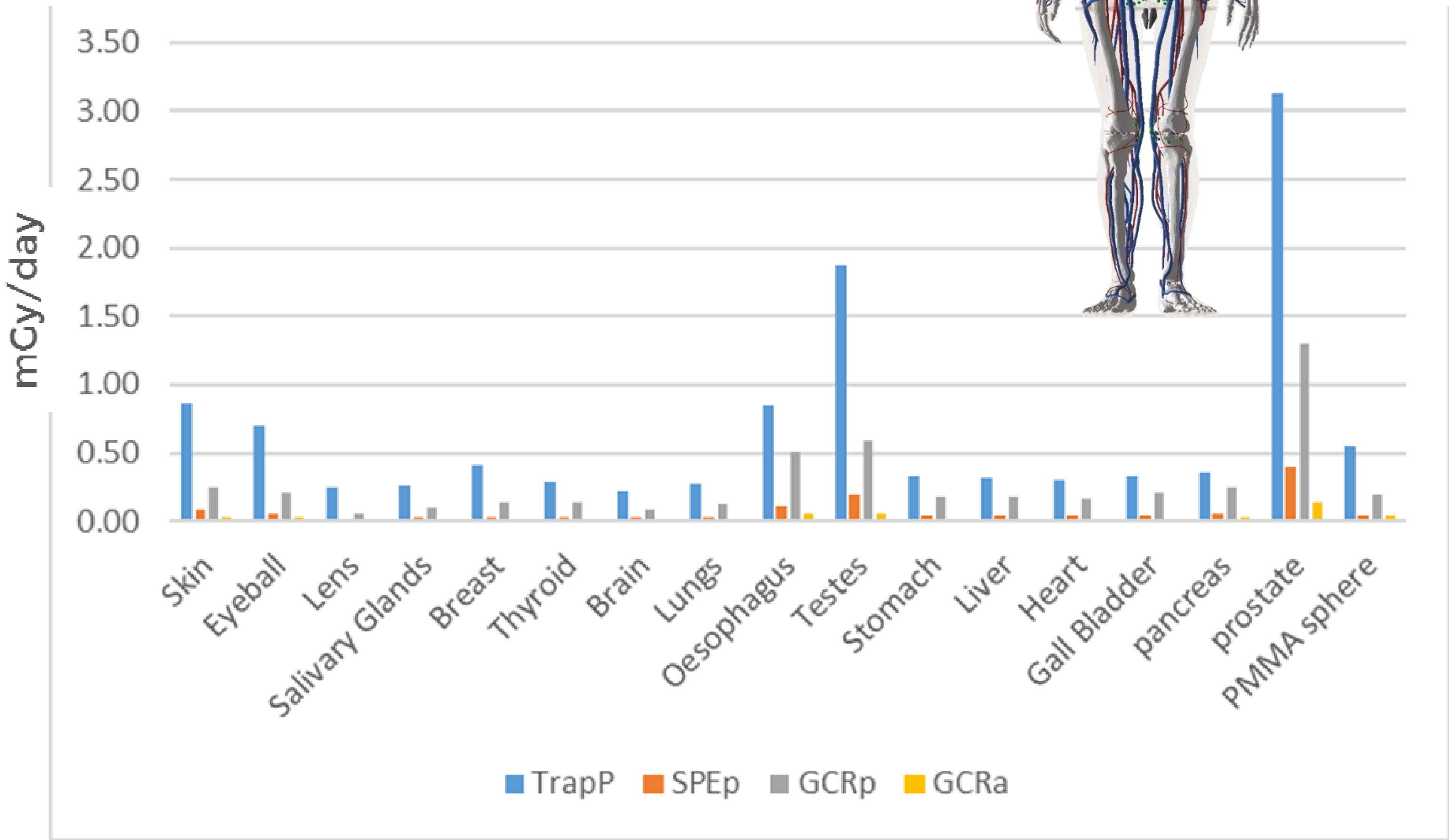
Results agree with experimental measurements performed by (L. Sihver and T. Berger et al., 2017) and (Dachev et al., 2017)

https://doi.org/10.1016/j.radmeas.2019.106182

Validation of the simulation

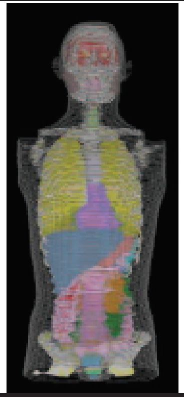
- Calculate doses in ICRP145 Human Phantoms (Ann ICRP . 2020 Oct;49(3):13-201)
- Measurements in Reitz, et al. (2008) *Radiation research* 171.2: 225-235





PhD student
Matthew Large

TABLE 2
Organ Dose Rates Calculated from TLD Depth-Dose Distribution



Organ	Dose rate (mGy/day)
Skin	0.94 (8)
Eyeball, lens	0.54 (8), 0.58 (12)
Salivary glands, breast	0.33 (7), 0.39 (10)
Thymus, thyroid, trachea, brain	0.28–0.30 (6)
Lungs, bones	0.26 (6), 0.28 (6)
Esophagus, testes	0.24 (6), 0.26 (7)
Colon, stomach, liver, red bone marrow, heart	0.22–0.24 (6)
Kidneys, gall bladder, small intestine, spleen, pancreas, prostate	0.20–0.22 (6)

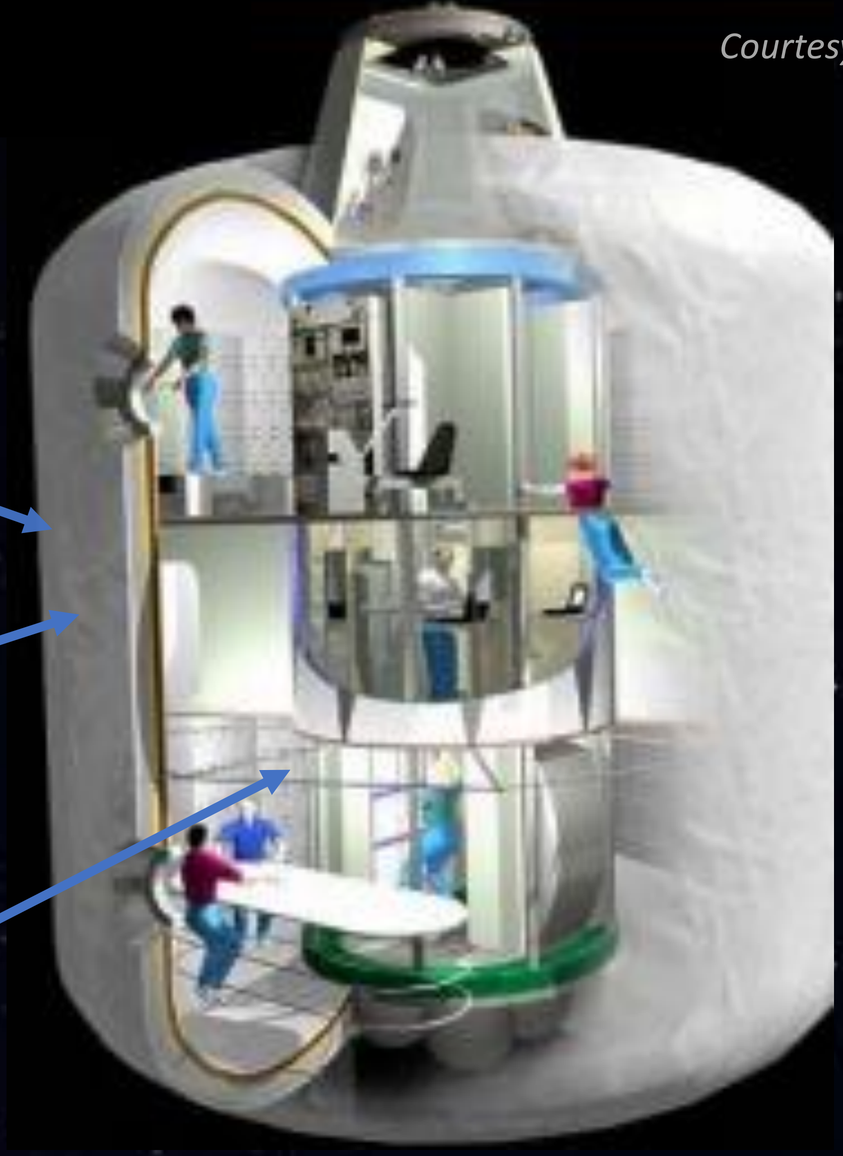
Note. Inset shows the organs of the Zubal phantom mapped and scaled into the voxel representation of MATROSHKA obtained from the CT slices. Values in parentheses specify measurement precision in percent.

Study shielding solutions

- Transfer vehicles to Mars
- Planetary shelters

Passive shielding for GCR and SPE

Courtesy of CBS/Paramount



Inflatable balloon

Doubling the polyethylene shielding thickness:
few % difference in the stopped GCR p

SPE shelter
A 75 cm water equivalent wall stops about ~98% of SPE protons

Transfer vehicle, design provided by Alenia Spazio

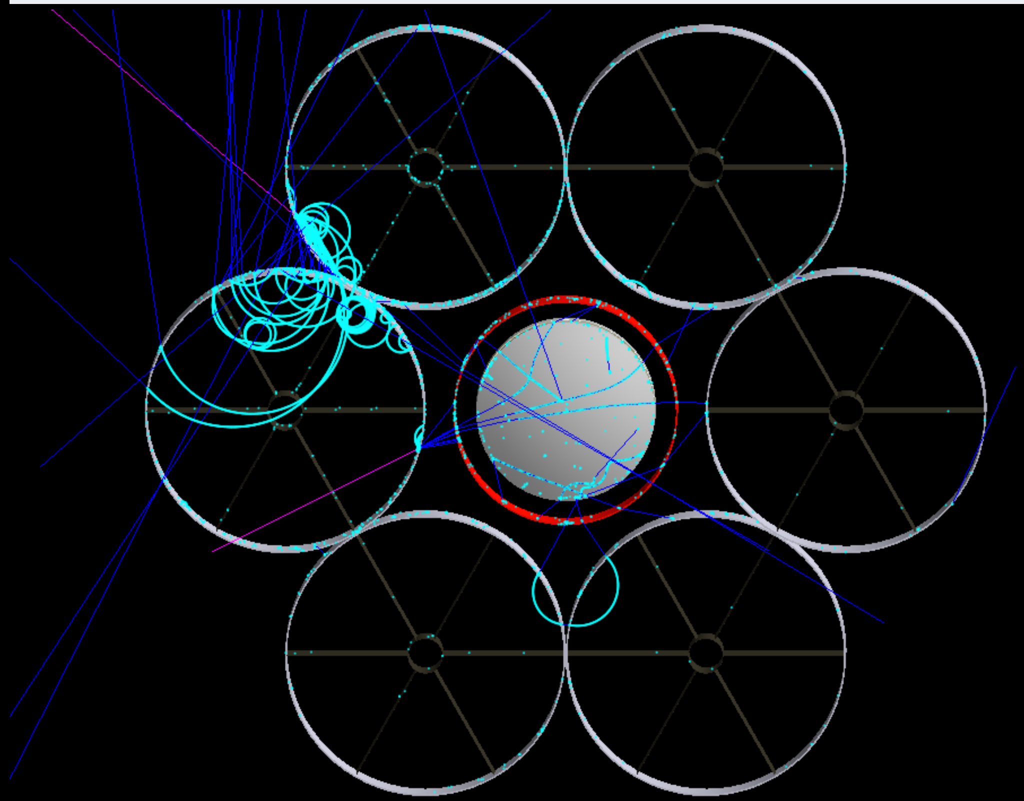
RESULTS BY S. GUATELLI, M. G PIA (INFN, GENOVA) AND P. NIEMINEN (ESA), WITHIN THE REMSIM PROJECT

Simulations to study active shielding solutions

https://www.nasa.gov/directorates/spacetech/niac/2012_Phase_II_Radiation_Protection_and_Architecture/

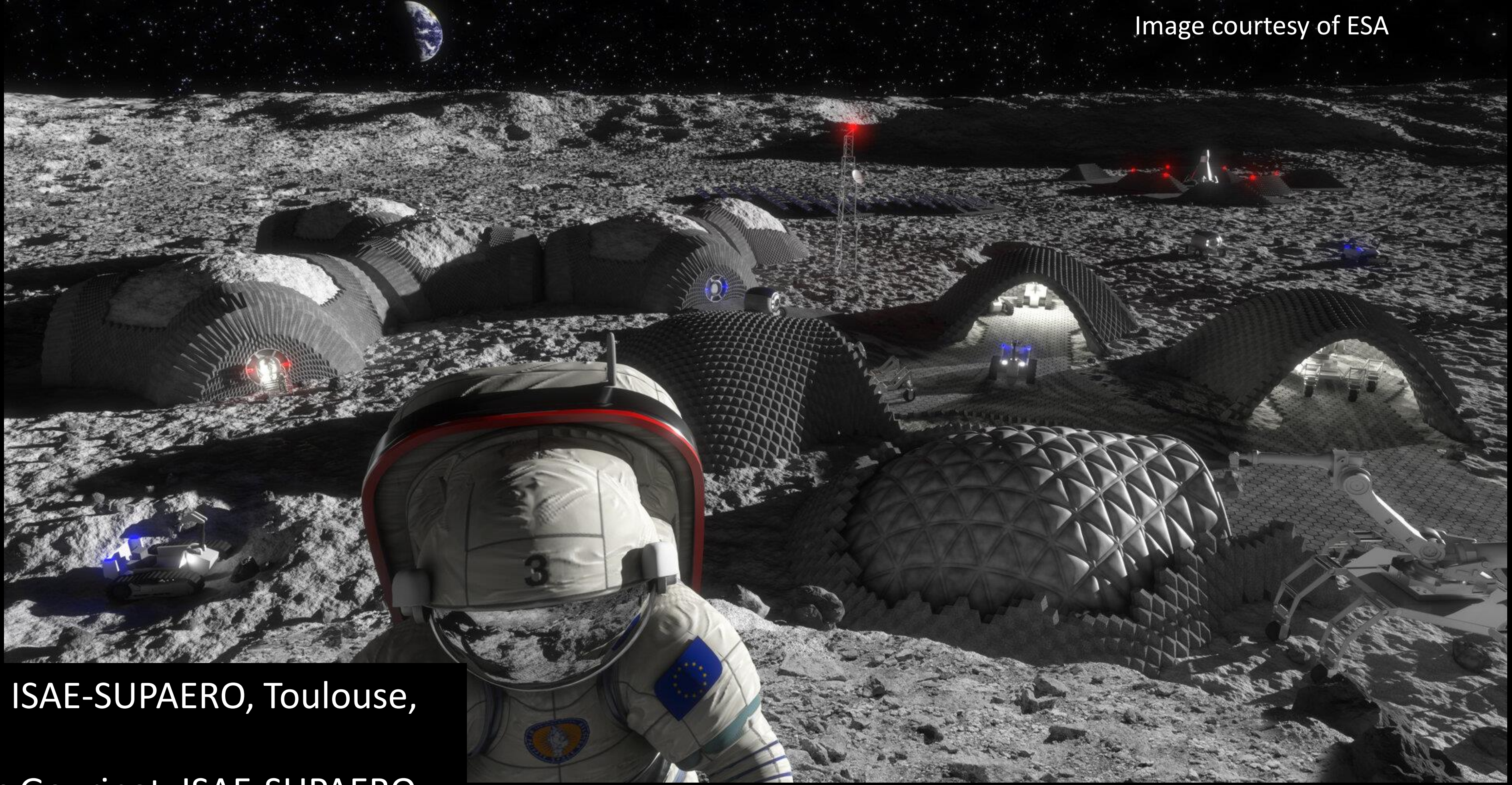
Image courtesy of NASA

Geant4 simulation study by K. Ferrone and S. Kry, The University of Texas MD Anderson Cancer Center



- Magnetic shielding can achieve:
  - 40%-60% reduction in cosmic ray dose with magnetic fields 1.5T-7T
  - to within NASA's current limits, given a magnetic field of 7 T

Image courtesy of ESA



PhD student Yulia Akisheva, ISAE-SUPAERO, Toulouse, France
Research Director: Prof Yves Gourinat, ISAE-SUPAERO
Mentor: A/Prof Susanna Guatelli

Radiation protection similar to the ISS with a thickness of 40 cm of compressed regolith (density= 4 g/cm^3)

CMRP PhD student
Jay Archer

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

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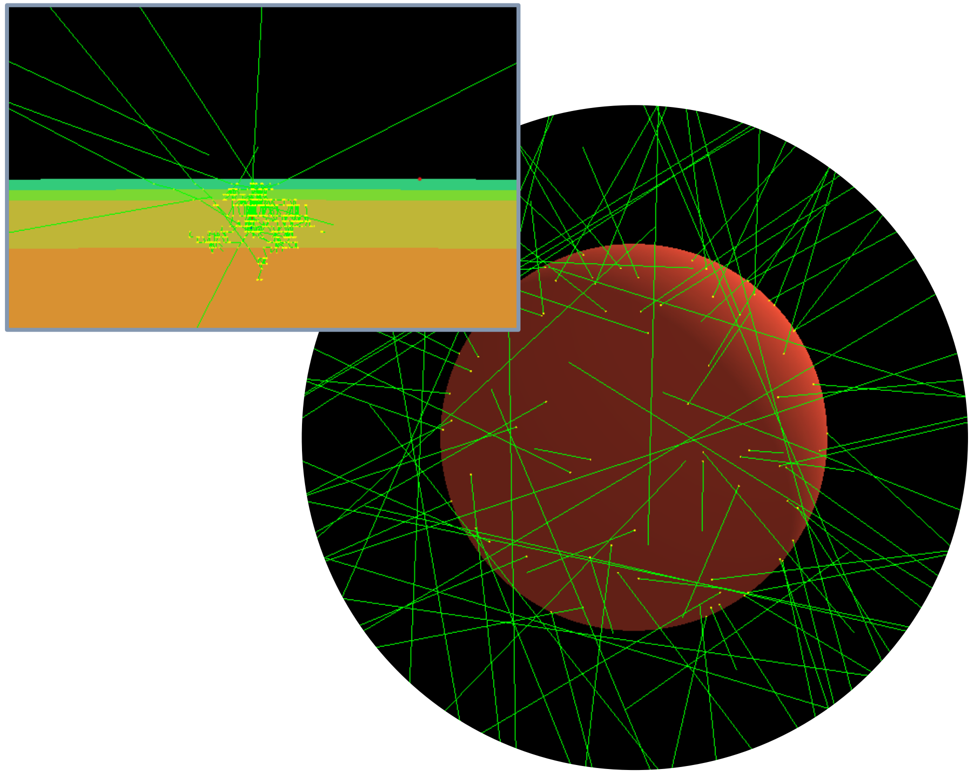
Lunar backscattered radiation: simulation set-up

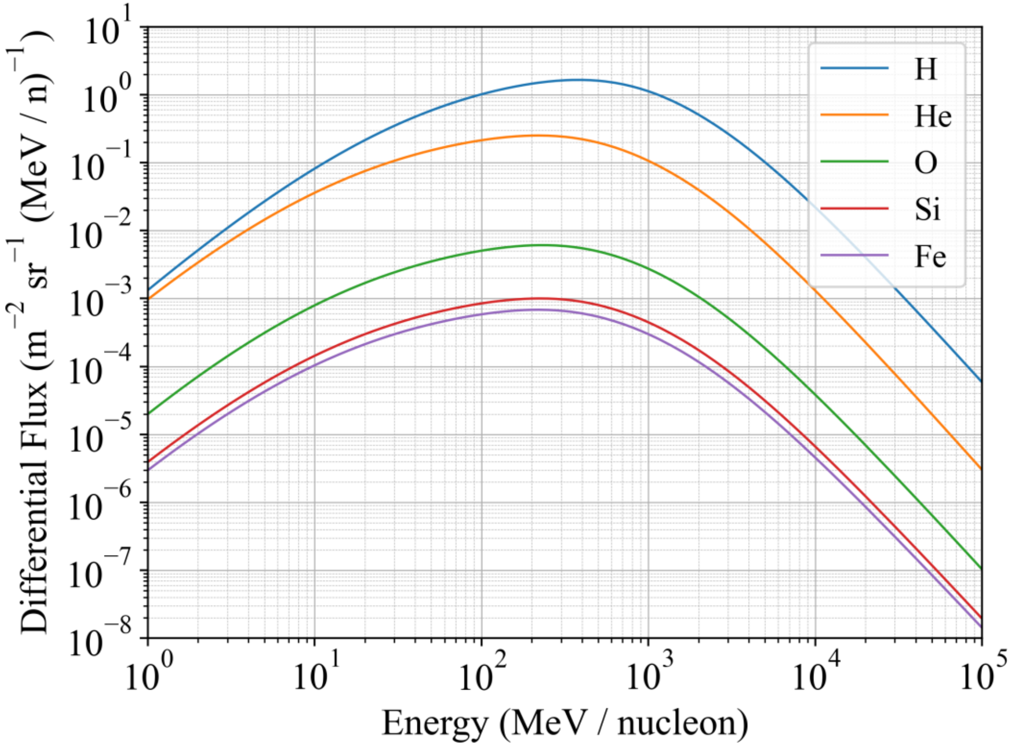
- Isotropic field of GCR protons

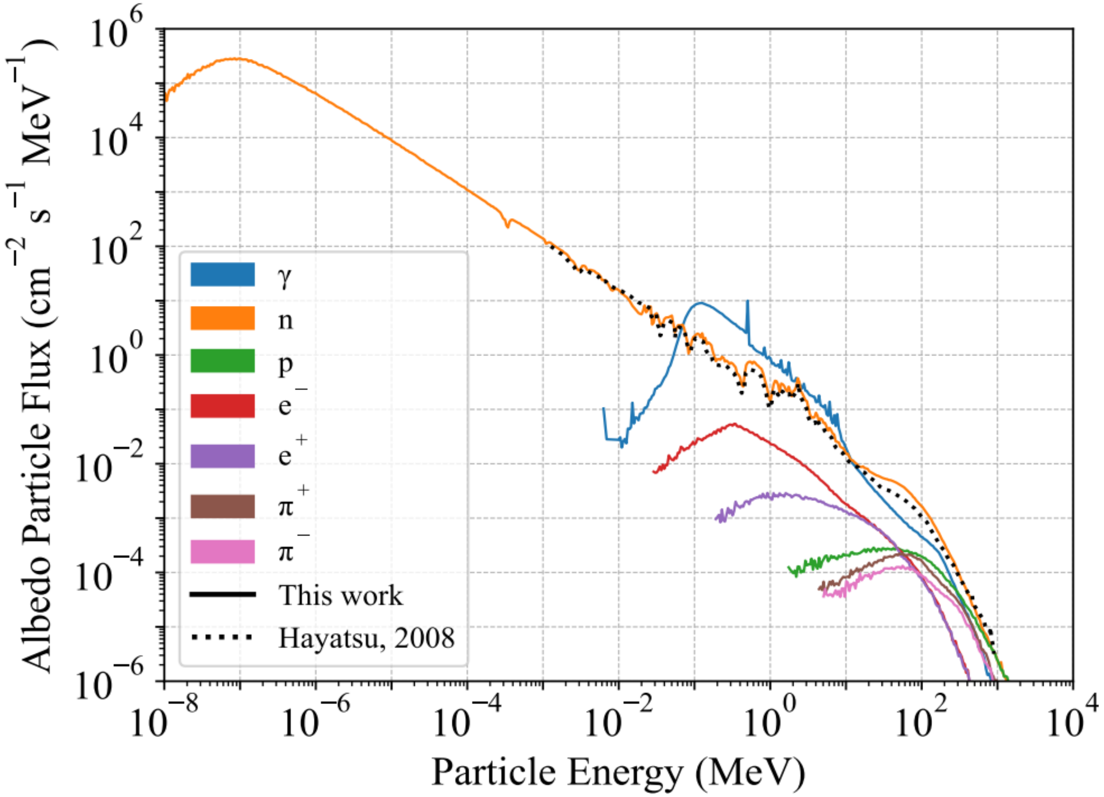


	Layer 1	Layer 2	Layer 3	Layer 4
Depth:	0 – 22 cm	22 – 71 cm	71 – 224 cm	>224 cm
Density:	1.76 g/cm^3	2.11 g/cm^3	1.78 g/cm^3	1.79 g/cm^3
O	41.739%	41.557%	42.298%	42.636%
Si	19.026%	18.955%	19.668%	20.218%
Fe	13.496%	14.030%	12.277%	11.688%
Ca	7.541%	7.668%	8.020%	7.707%
Al	6.061%	5.977%	7.384%	7.598%
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%

TABLE: Elemental composition of the Lunar Surface as implemented in Geant4. Layer compositions are presented as mass percentages, based on LNPE Borehole data following the works of McKinney *et al.* (2006) and Mesick *et al.* (2018).

Lunar backscattered radiation: results





Calculated via SPENVIS

- Near-Earth Interplanetary Space (1 AU from Sun)
- GCR model: ISO-15390 (standard)
- Solar activity data: Solar Minimum (late 2009)

Backscattered radiation spectra

Hayatsu, et. al., 2008. *Biological Sciences in Space*, **22**(2)

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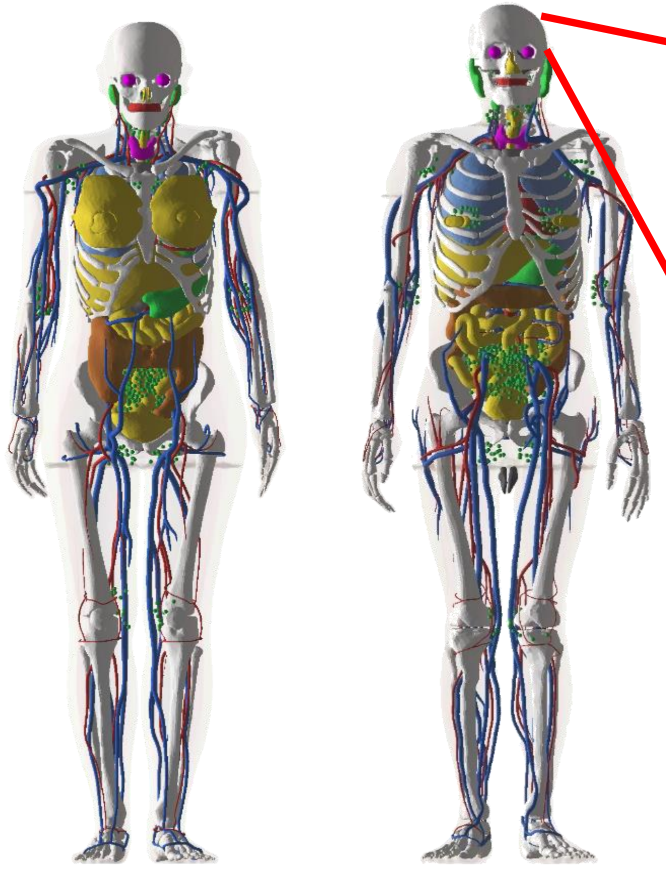
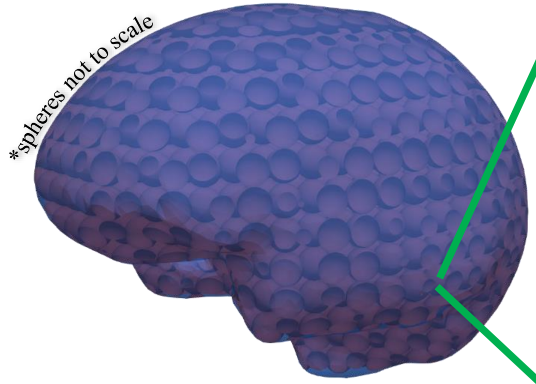
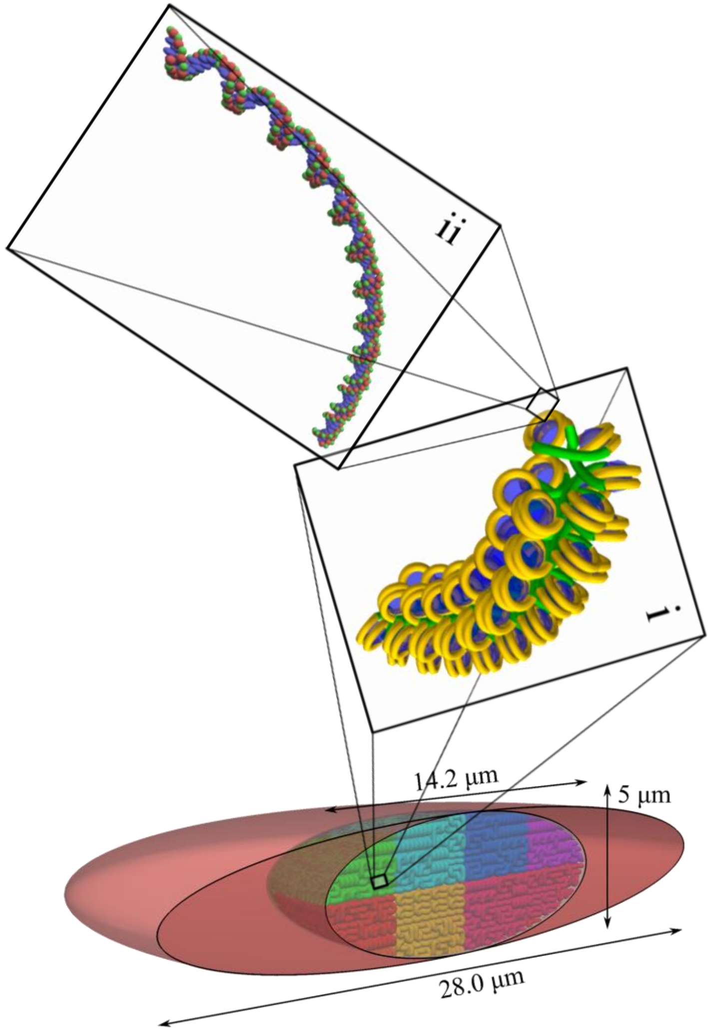
Multi-scale approach



Calculate doses in ICRP145 Human Phantoms (Ann ICRP . 2020 Oct;49(3):13-201)



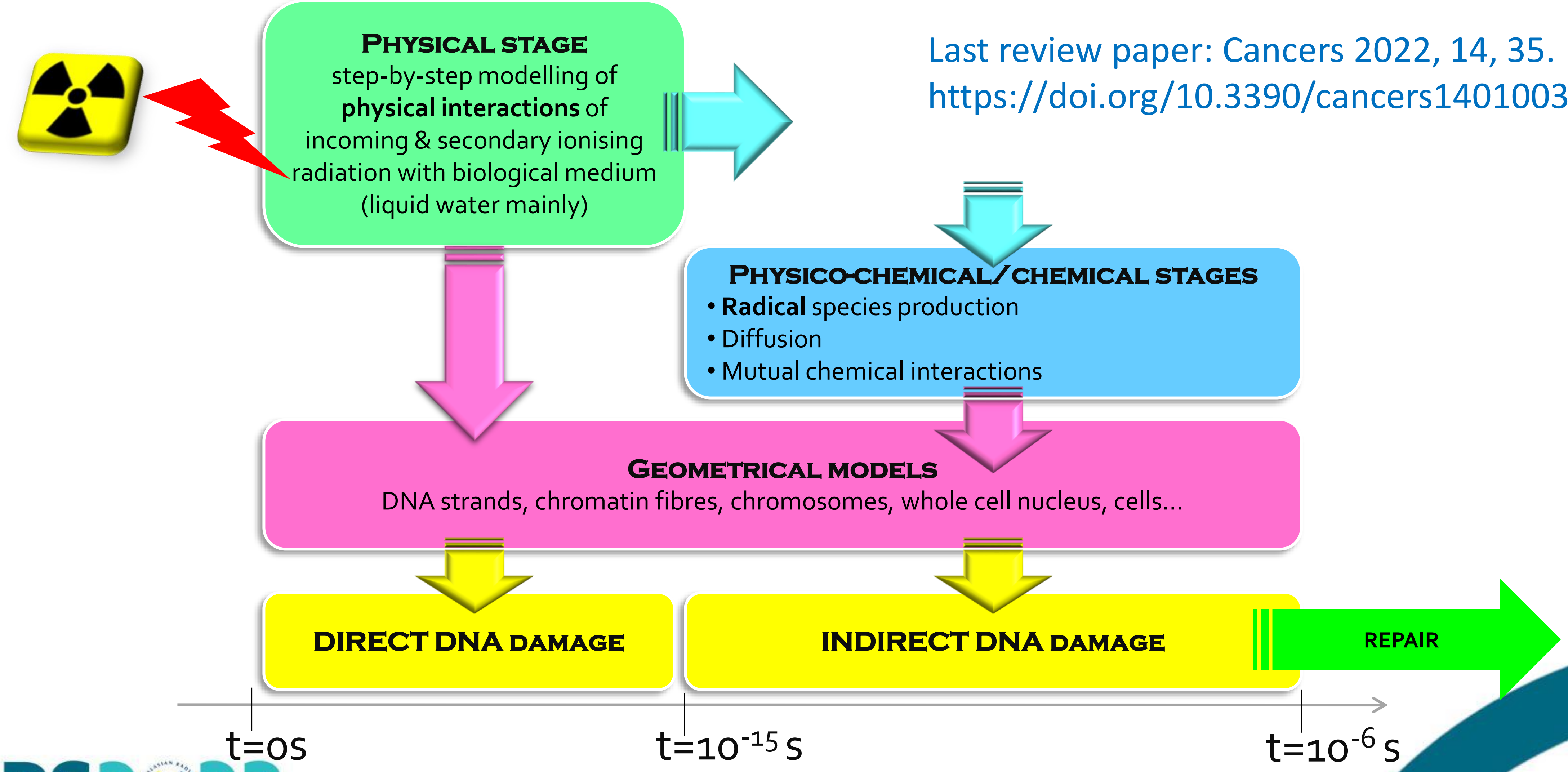
Record the radiation field when entering a 10 µm diameter scoring spheres in organs of interest



Calculation of the early DNA damage in a human fibroblast with ~6.4 Gbp (Geant4 molecularDNA, Chatzipapas et al. 2023, Precision Radiation Oncology, 7(1))

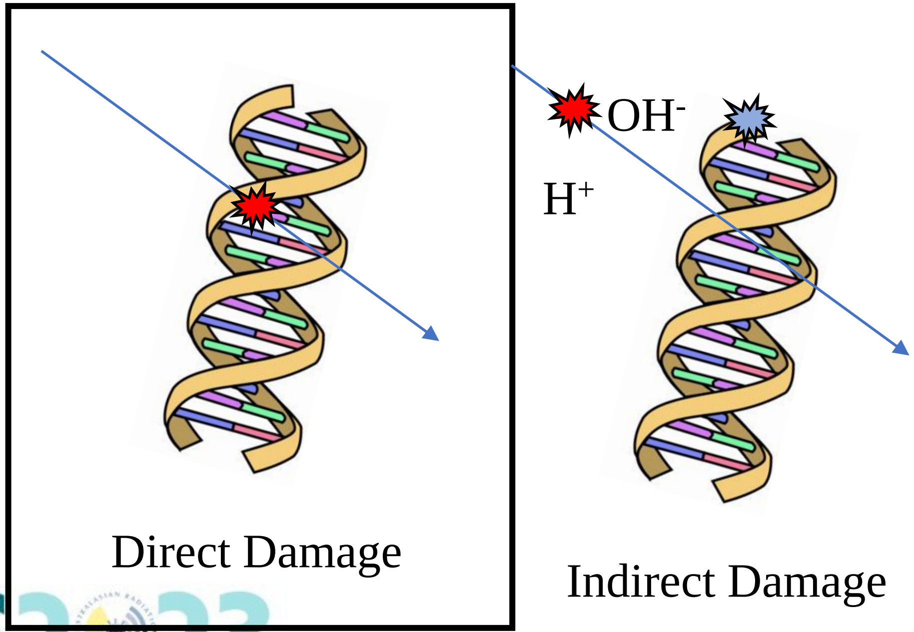
Estimation of the early DNA damage: Geant4-DNA

Last review paper: Cancers 2022, 14, 35.
https://doi.org/10.3390/cancers14010035

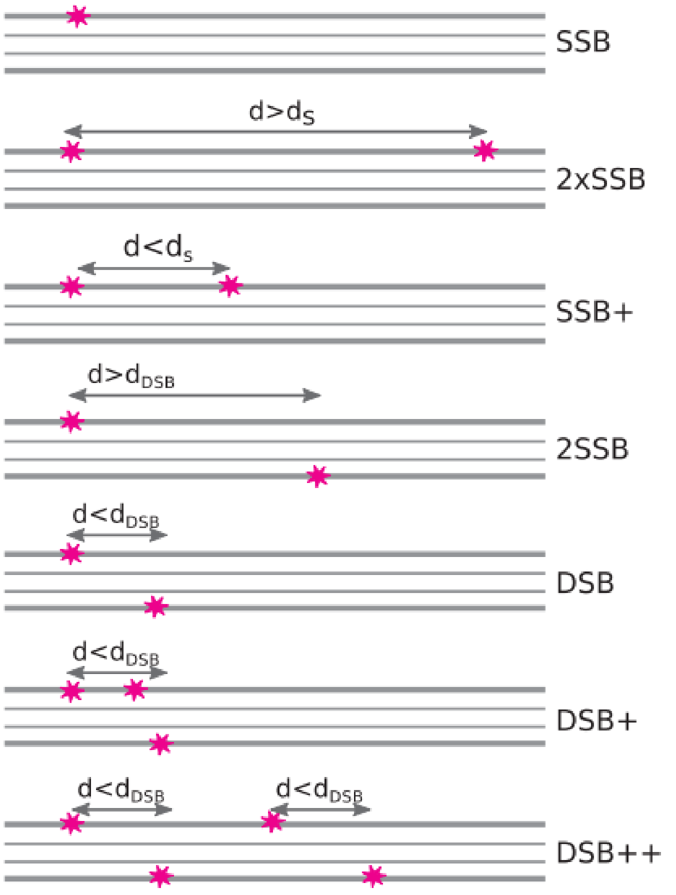


Early DNA damage: scheme

- DNA damage is scored using existing damage schemes [7,8]
- Both direct and indirect damage implemented



d_s and d_{DSB} are 100 base pairs



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

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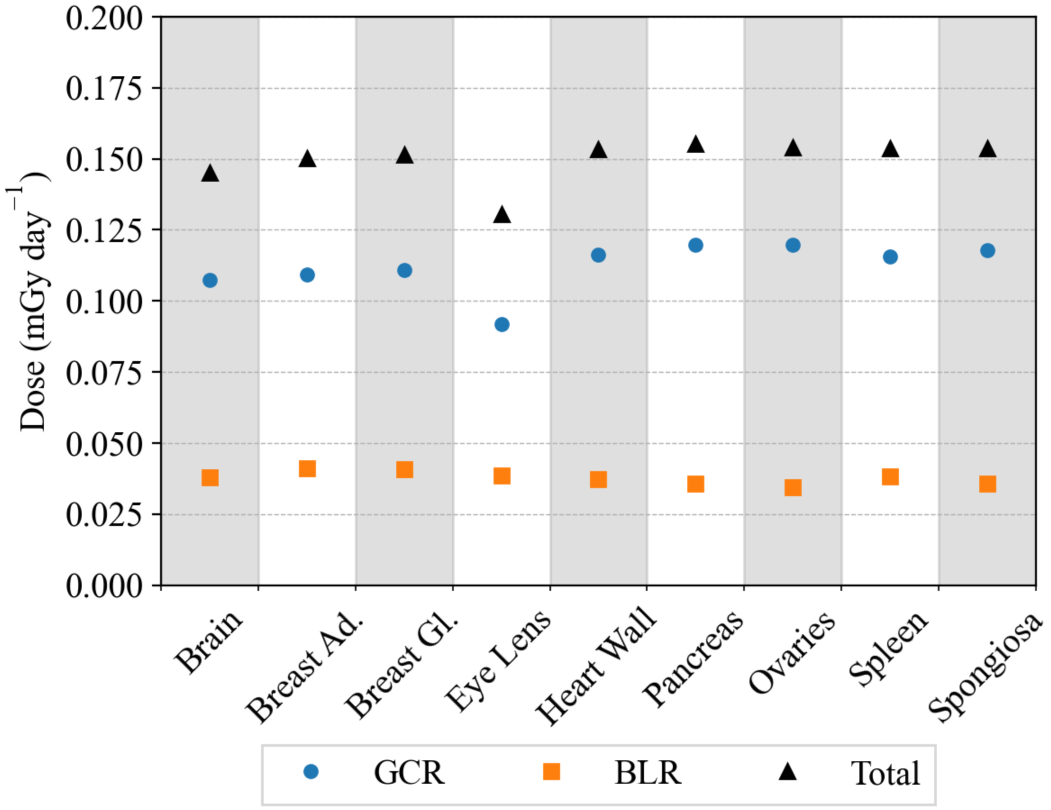
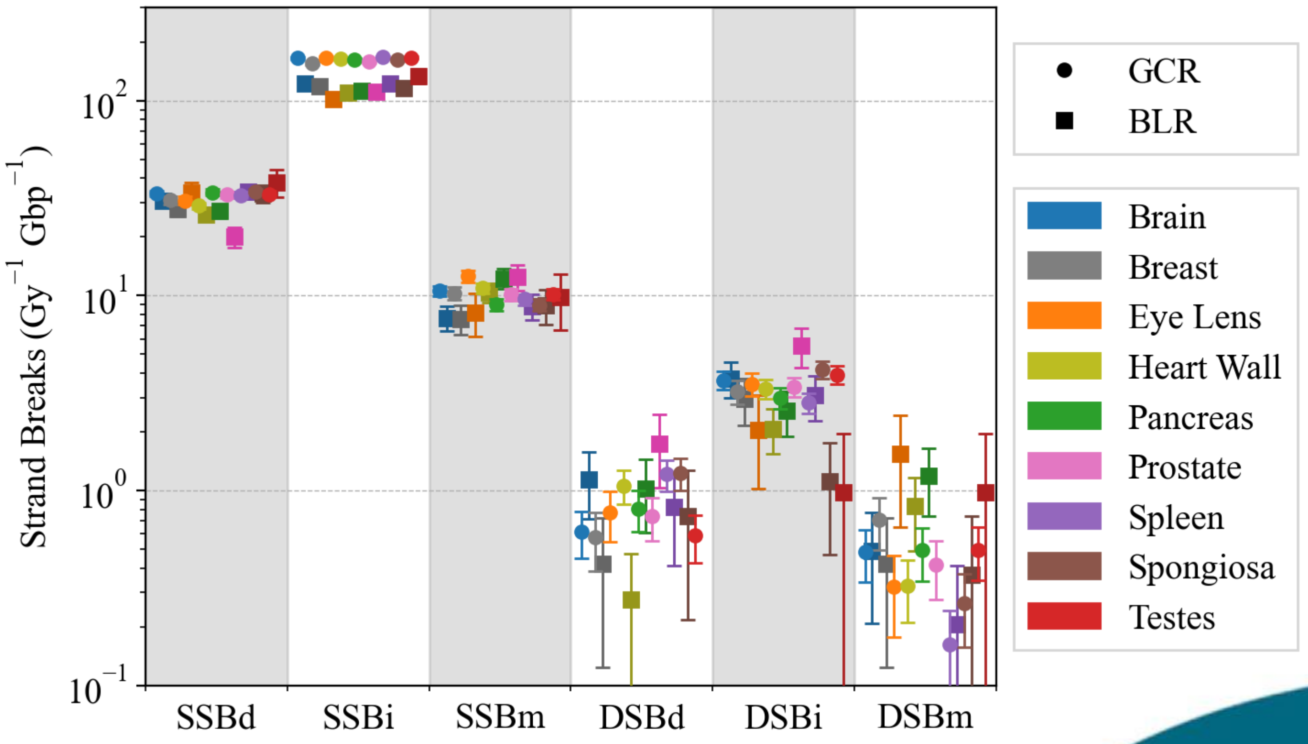
Early DNA damage: results

Backscattered lunar radiation makes a significant contribution to the dose



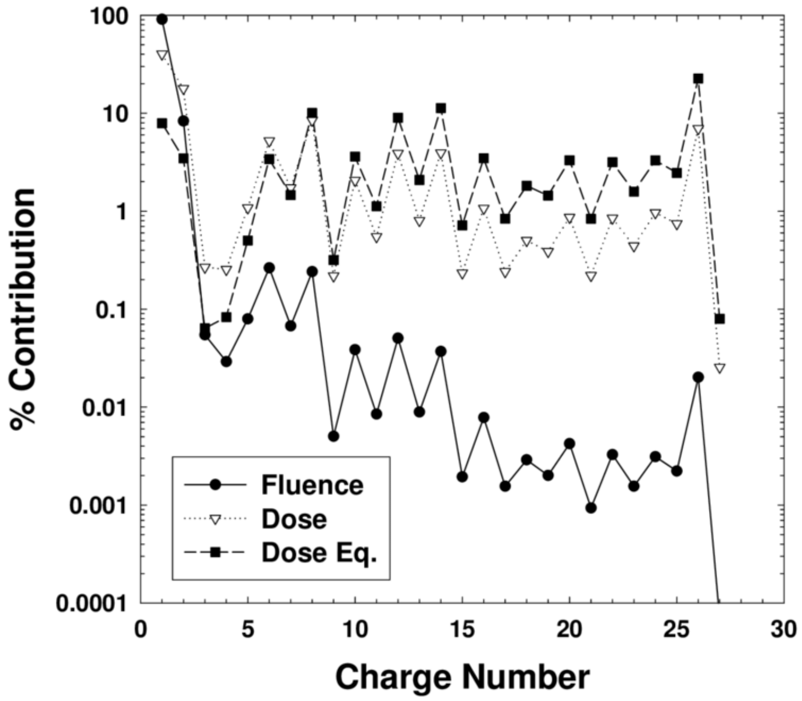
Indirect damage: the most significant mechanism of DNA damage induction



Next steps

- Currently, only GCR protons are considered
  - Higher *Z* ions contribute significantly to dose equivalent [9]

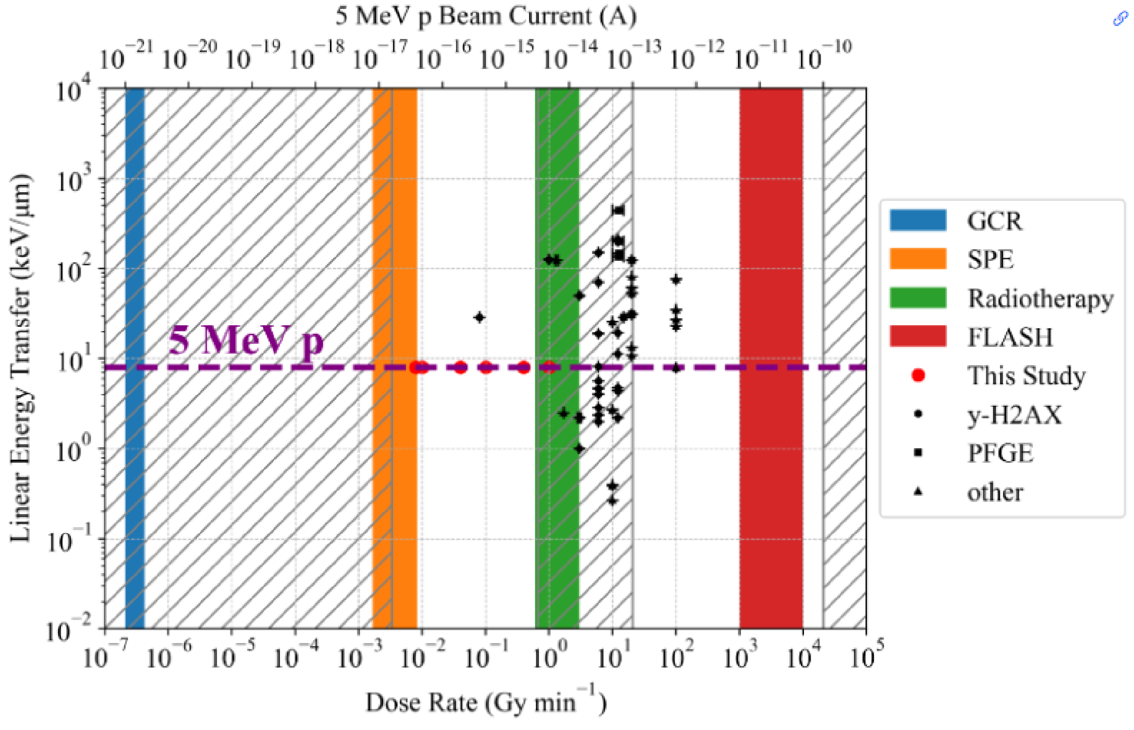
- Solar particle events should also be considered [10]
  - GCR: 416.0 mSv/yr
  - SEP: up to 2190 mSv/event



[9] – Cucinotta et. al., 2003. *Graviational and Space Biology*, **16**(2)
[10] – Naito et. al., 2020. *Journal of Radiological Protection*, **40**(4)

New activity: just kicked off

- Validate Geant4-DNA against experimental measurements performed at ANSTO, Lucas Heights, NSW, with protons, C and O ions (γ-H2AX)
- Study applicable cell repair models



(b) Parameter space of LETs and dose rates

Figure 2: Review of parameters in radiobiological experiments using protons in the literature with regions for different reference scenarios using beam currents available at ANSTO

- ANSTO Research Portal Proposal **AP16350**

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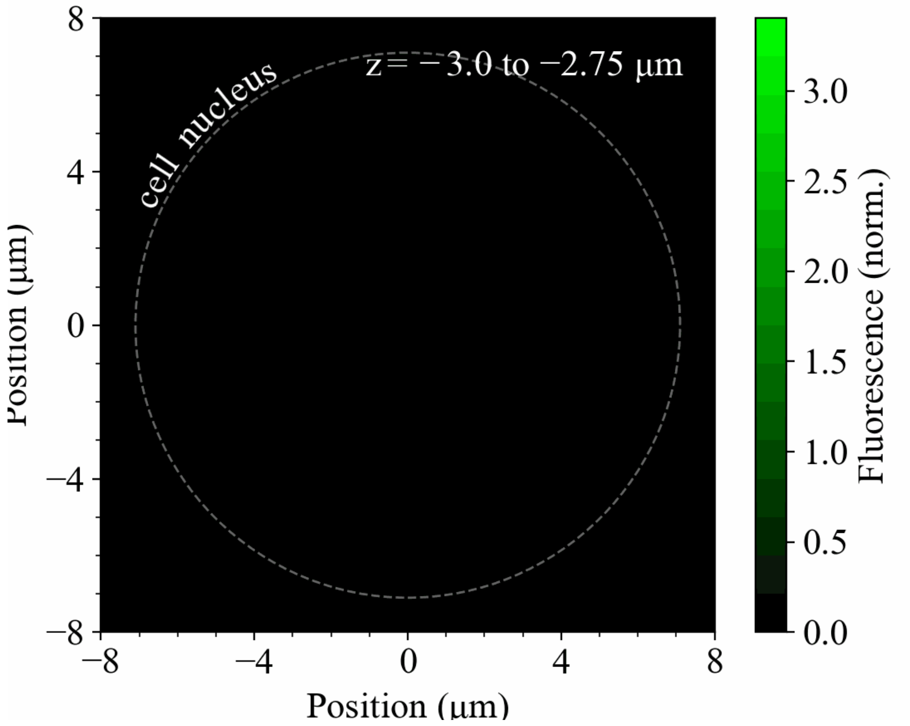
Geant4-DNA simulation



CMRP PhD student Jay Archer

Synergy with bio-medical applications on Earth (1)

- Geant4 QMD model has been improved for hadrontherapy
- Test this new QMD model for nuclear fragmentation for space radiation protection

Physics in Medicine & Biology

PAPER

Development of a more accurate Geant4 quantum molecular dynamics model for hadron therapy

Yoshi-hide Sato[1], Dousatsu Sakata[6,2,3], David Bolst[4], Edward C Simpson[5], Susanna Guatelli[4] and Akihiro Haga[6,1]

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DOI 10.1088/1361-6560/ac9a9a

Synergy with bio-medical applications on Earth (2)

- Huge international effort to improve Geant4 for High Energy Physics, Space Science and bio-medical applications
- G4-Med effort
- Geant4 for radiation protection studies in space … but also on Earth
  - Talk Dr S. Bakr, Cyclowest, "Findings of the Cyclowest Radiation Survey for the GE PETtrace Cyclotron at the Bayswater Site"
  - Talks by Dr D. Bolst, CMRP UOW,
    - "Shielding of defence personnel in gamma radiation environments using anthropomorphic phantoms in Geant4"
    - Talk by Dr Bolst, CMRP UOW, "Using an iterative shielding approach for the first carbon ion therapy facility in the US by means of Geant4"

MEDICAL PHYSICS

The International Journal of Medical Physics Research and Practice

Research Article

Report on G4-Med, a Geant4 benchmarking system for medical physics applications developed by the Geant4 Medical Simulation Benchmarking Group

P. Arce, D. Bolst, M.-C. Bordage, J. M. C. Brown, P. Cirrone, M. A. Cortés-Giraldo, D. Cutajar, G. Cuttone, L. Desorgher, P. Dondero, A. Dotti, B. Faddegon, C. Fedon ... See all authors

First published: 11 May 2020 | https://doi.org/10.1002/mp.14226 | Citations: 71

Summary and conclusions

- Three years Mars mission :
  ~ **Astronauts' career limit**
  ~ 10 times than 6 months on the ISS
- Monte Carlo simulations
  - Can model radiation interactions in radiation scenarios which can't be reproduced with current accelerator technology
  - Help to quantify the dose in different mission scenarios, to design shielding solutions, investigate the radiobiological effect of radiation at DNA level
- Synergy with bio-medical applications on Earth

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