Monte-Carlo Simulation of Heavy Ion Track Structure
Calculation of local dose and 3D time evolution of radiolytic species

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Importance of heavy ions

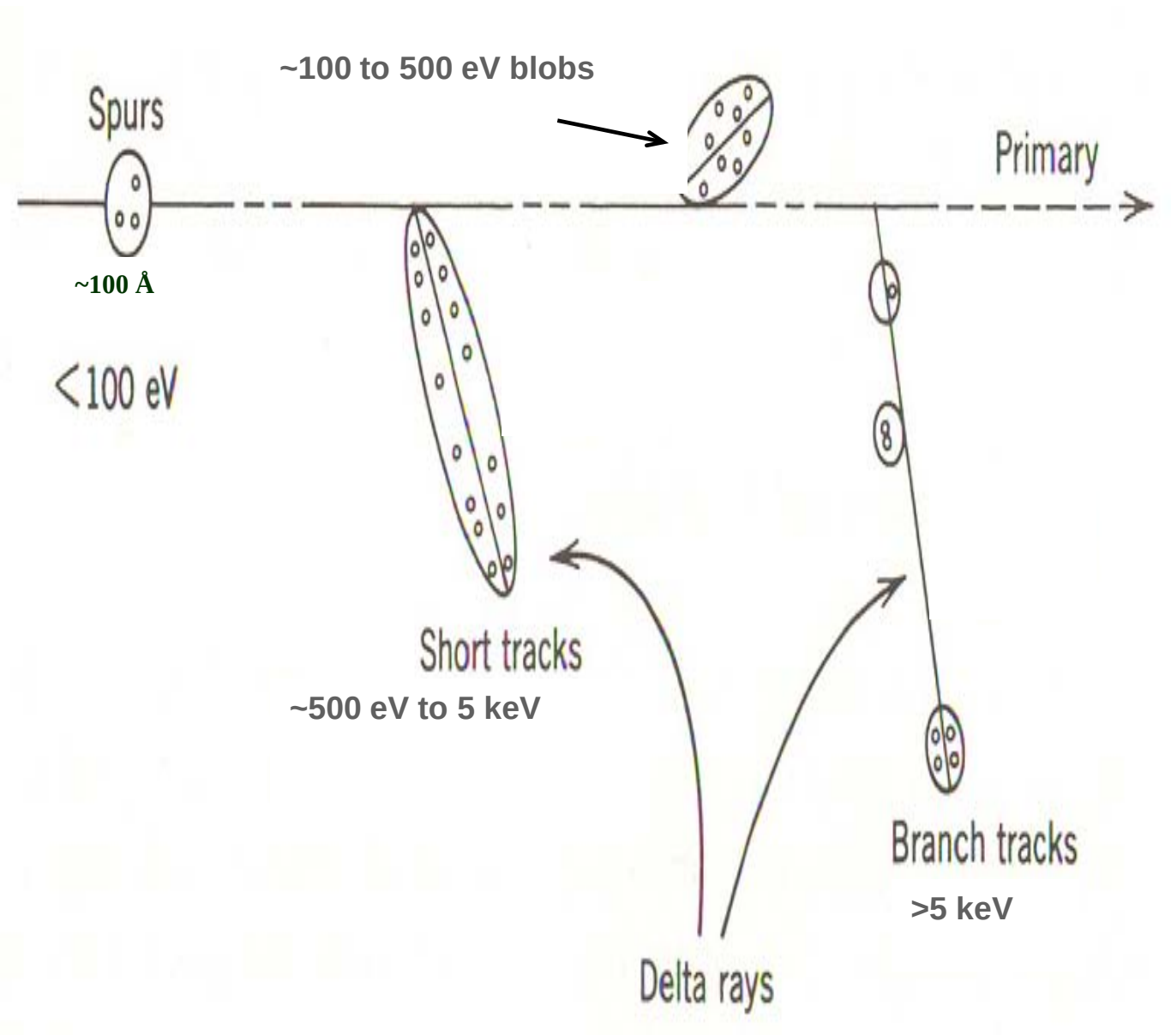
- Heavy ions have gained considerable importance in radiotherapy due to their advantageous dose distribution profile and high Relative Biological Effectiveness (RBE)
- Heavy ions are difficult to produce on Earth, but they are present in space and it is impossible at this moment to completely shield astronauts from them
- The risk of these radiations is poorly understood, which is a concern for a 3-years Mars mission [1]

Interaction of radiation with biological media

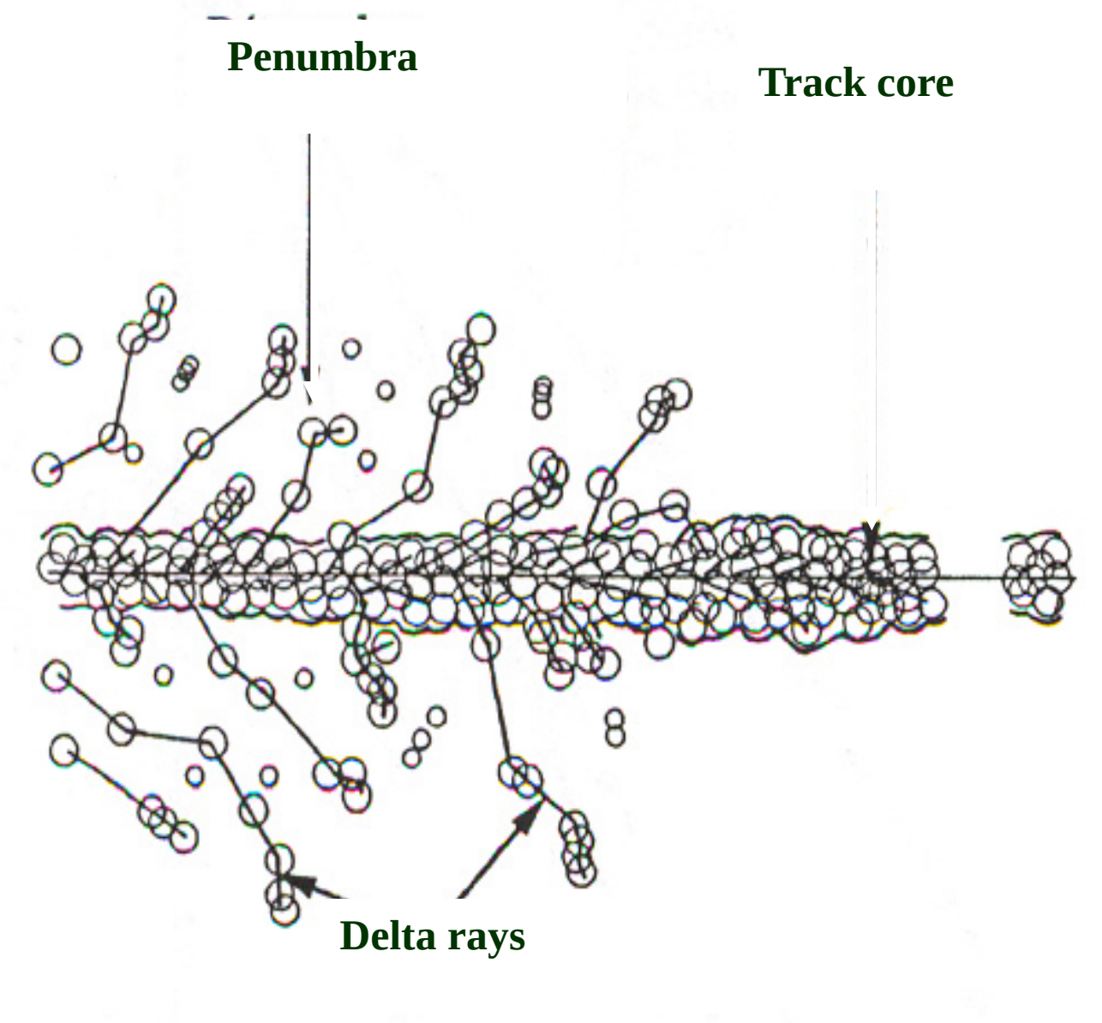
- The effects of radiation are mainly due DNA damage such as DNA double-strand breaks (DSBs), although non-targeted effects are also very important
- DNA can be damaged by the direct interaction of radiation and by reactions with chemical species produced by the radiolysis of water [2]
- The energy deposition is of crucial importance to understand biological effects of radiation
- Therefore, much effort have been done recently to improve models of radiation tracks

Energy deposition by ionizing radiation

Primary energy loss events in low-LET tracks [3]

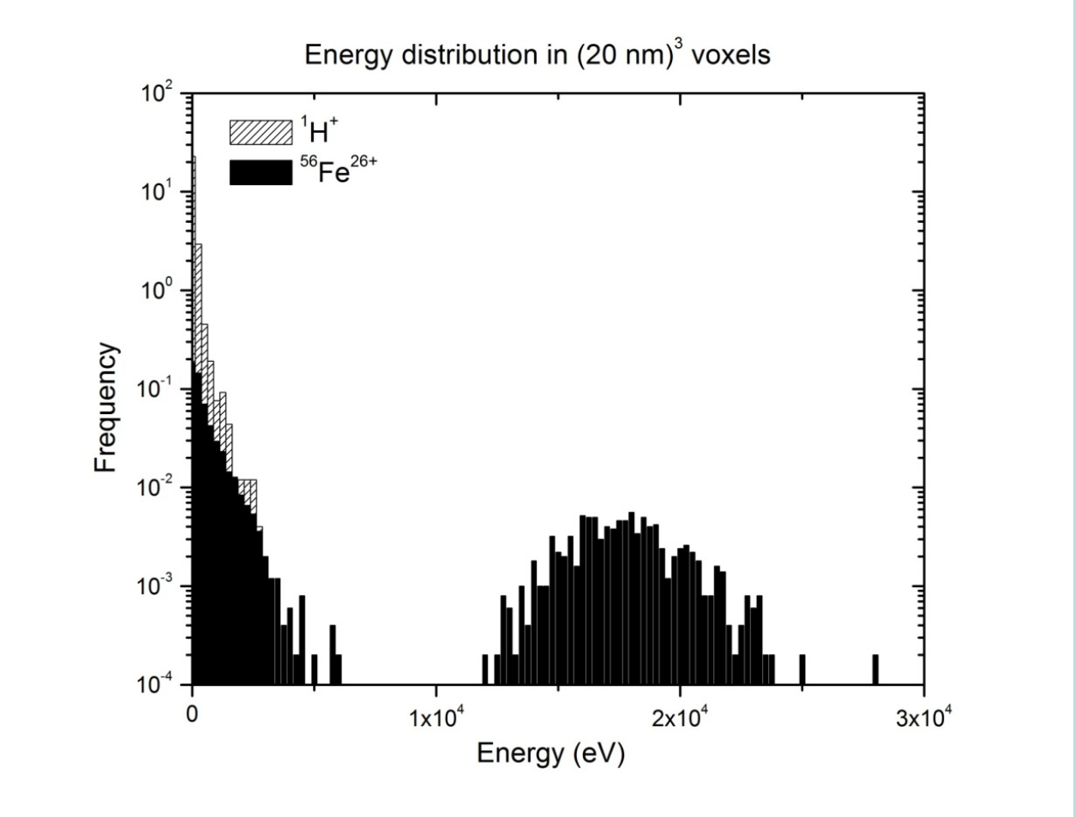


Primary energy loss events in high-LET tracks [4]

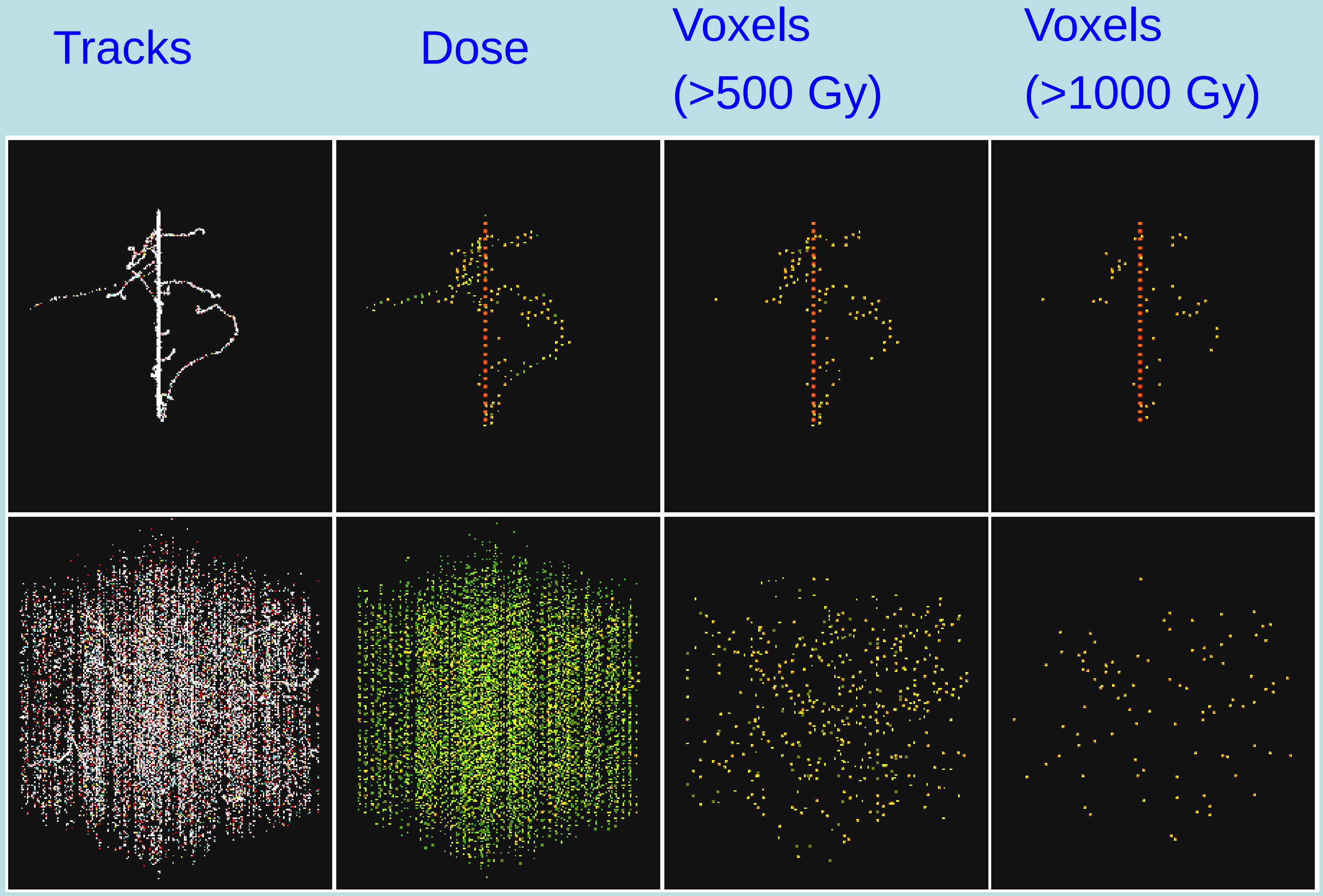


Simulation of heavy ion tracks

- The radiolysis of water is simulated by Monte-Carlo methods, a mathematical technique used to simulate stochastic systems
- A cube of 5µm x 5µm x 5µm is irradiated by a $^{56}Fe^{26+}$, 1 GeV/amu ion (LET~150 keV/µm) and by 450 $^{1}H^{+}$, 300 MeV/amu ions (LET~0.3 keV/µm) for a total dose of ~100 cGy
- The dose is calculated in voxels of 20 nm x 20 nm x 20 nm
- The spatial distribution of dose is different for high and low-LET radiations
- In both high and low LET radiations, many voxels receive a low dose. Voxels which receive very high dose appears only in high-LET tracks.

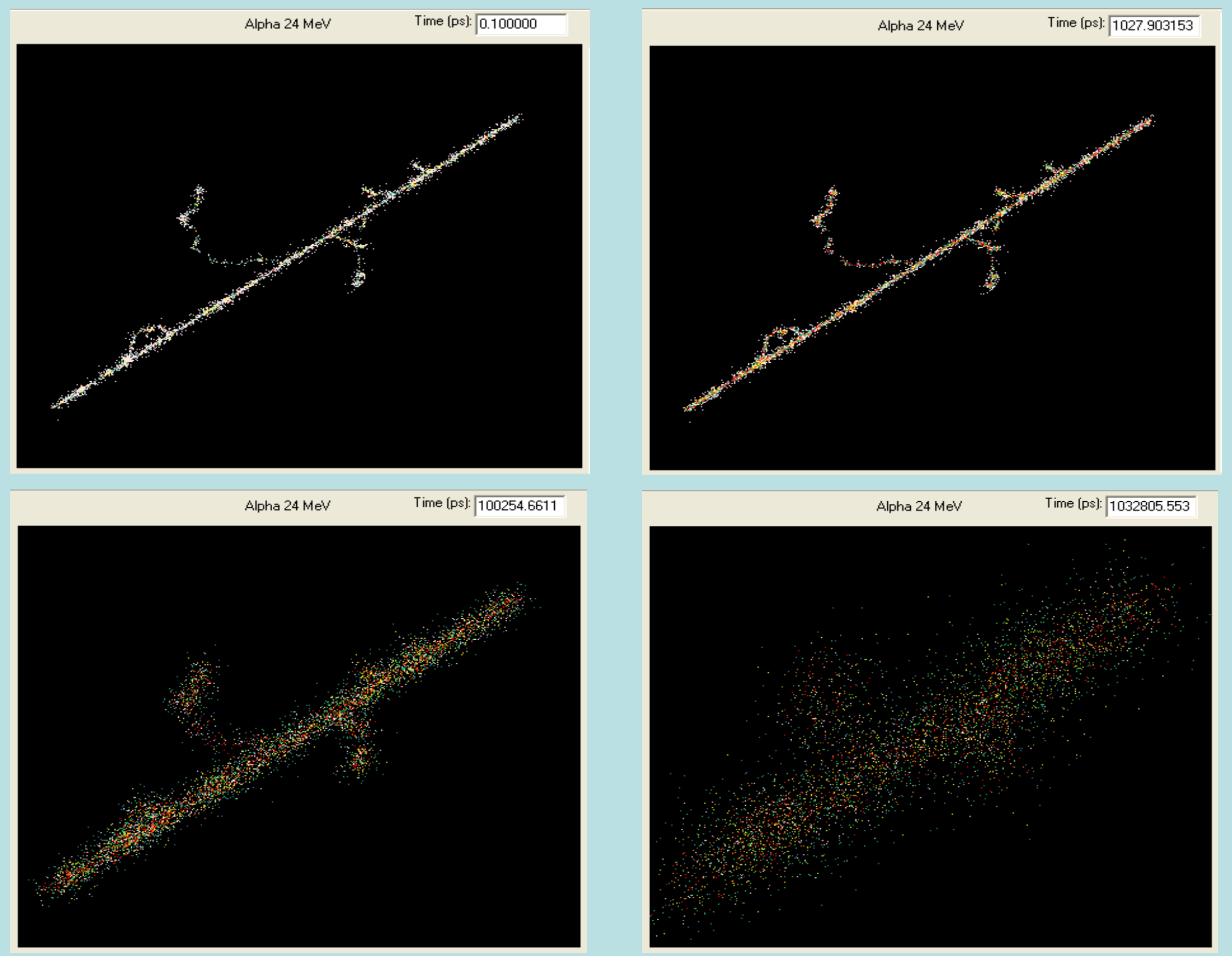


Distribution of dose in 3D voxels for $^{1}H^{+}$, 300 MeV/amu and $^{56}Fe^{26+}$, 1 GeV/amu ion calculated by the Monte-Carlo code RITRACKS [5]



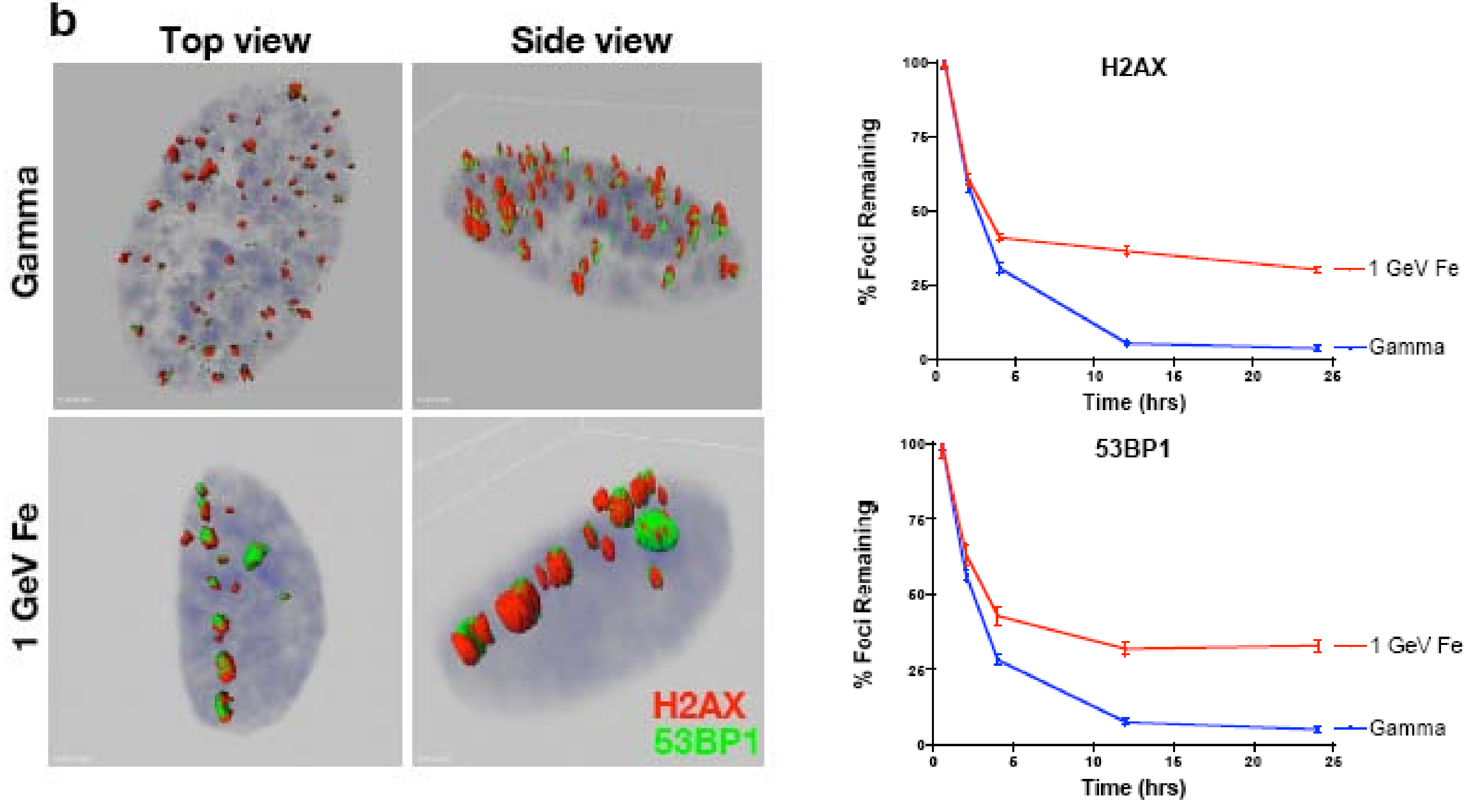
3D irradiation of a 5 µm cube by a $^{56}Fe^{26+}$, 1 GeV/amu ion (top) and by 450 $^{1}H^{+}$, 300 MeV/amu (bottom). The tracks are simulated (left) and the corresponding voxel dose is calculated. By applying a threshold on the dose voxels, the distribution of track end appears.

Track structure and evolution in time



Track structure and 3D time evolution [6] of the radiolytic species produced by a 6 MeV/amu $^{4}He^{2+}$ ion (LET ~25 keV/µm) in liquid water

Distribution of DNA damage within cell nuclei



Experimental distribution of DSBs in fibroblast nuclei observed in γ-H2AX experiments for γ-rays and $^{56}Fe^{26+}$, 1 GeV/amu ions (left). DSBs remaining as a function of time for these ions (right) [7]

Discussion

- The 3D distribution of dose voxels calculated by RITRACKS have an appearance very similar to DSB observed with γ-H2AX experiments
- In addition, since high-dose voxels appears only in high-LET radiation and DSBs which are difficult to repair are found only in high-LET tracks, we may hypothesis that DSBs created within these high-dose voxels may be of different nature than those created by low-LET radiation.

Conclusion

- Heavy ions are used in radiotherapy because of their dose distribution profiles and high RBE; however, they may also pose a substantial but poorly understood risk for astronauts on a 3 years Mars mission
- Monte-Carlo track structure simulations can be used to calculate dose deposited in an irradiated volume by high and low-LET radiation
- These simulations can contribute significantly to the understanding of DNA damage and non-target effects of ionizing radiation by providing important information such as the dose distribution as well as the 3D time evolution of the radiolytic species

References

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