Agent-Based Modeling of Microbes in Deep-Space Radiation: Direct and Indirect Effects on Viability and Metabolism

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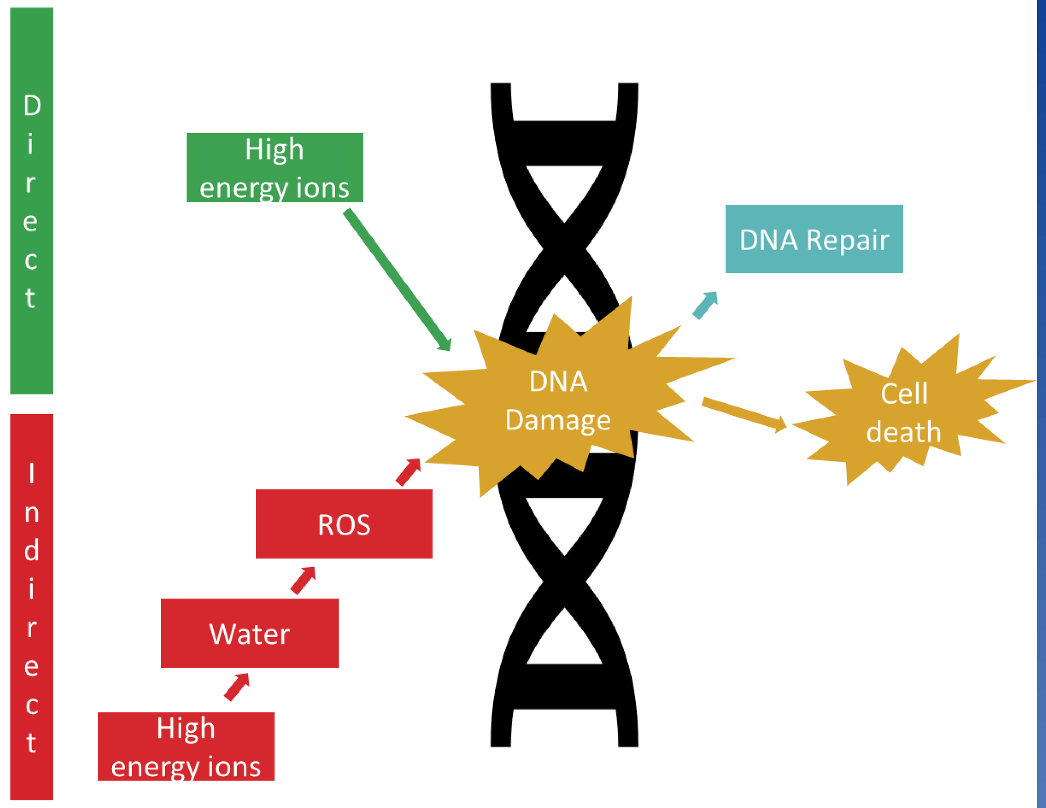
Motivation

The study and modeling of long-term deep space radiation effects in biological systems is necessary to reduce the risk in humans for Mars missions and space habitation.

- Current models does not simulate microbial cells under ionizing space radiation.
- Deep Space experiments expensive and inaccessible.
- Ground testing is costly and limited in long term exposure.

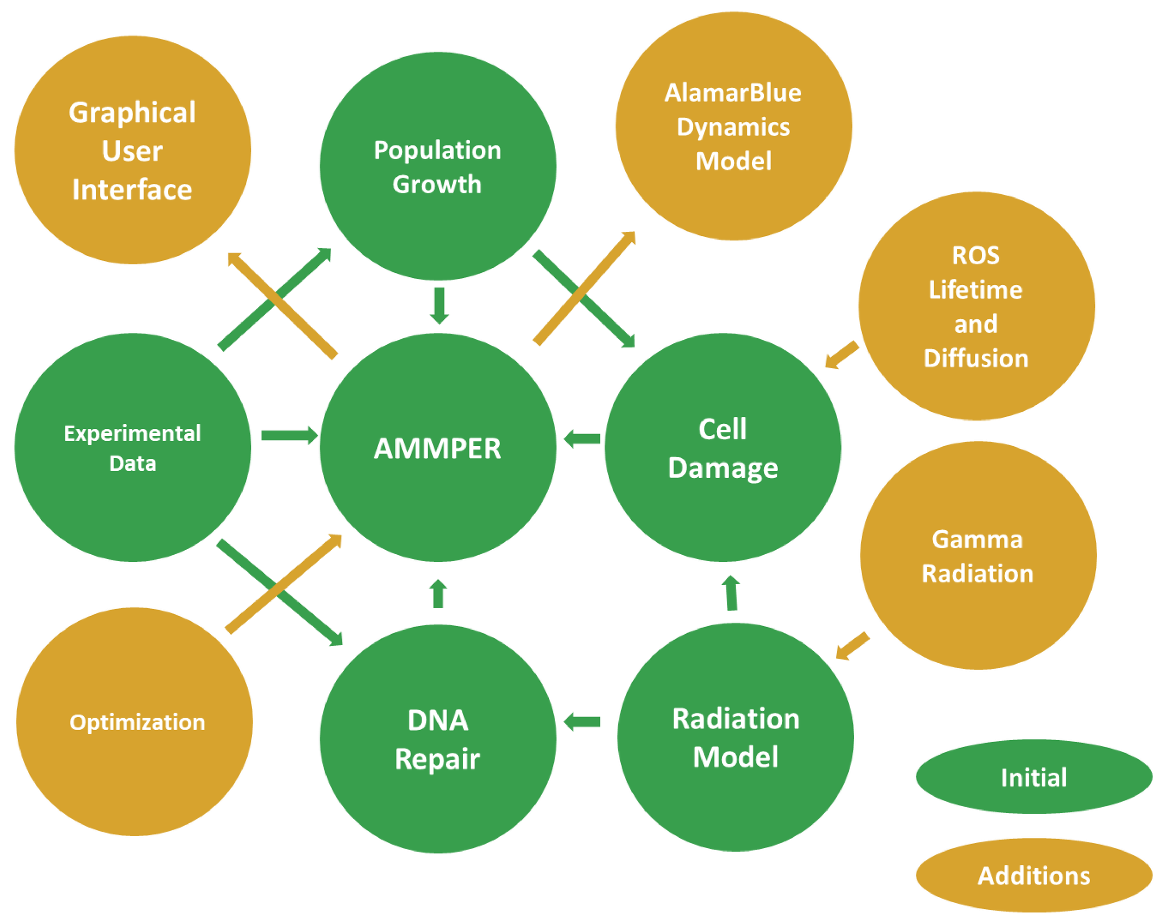
Deep Space Ionizing Radiation

- Galactic Cosmic Rays (GCRs) alter the chemical composition of matter by energy deposition which removes electrons from atoms.
- Radiation can cause indirectly DNA damage by generation of Reactive Oxygen Species (ROS) molecules.
- High ROS concentration can lead to cell apoptosis.



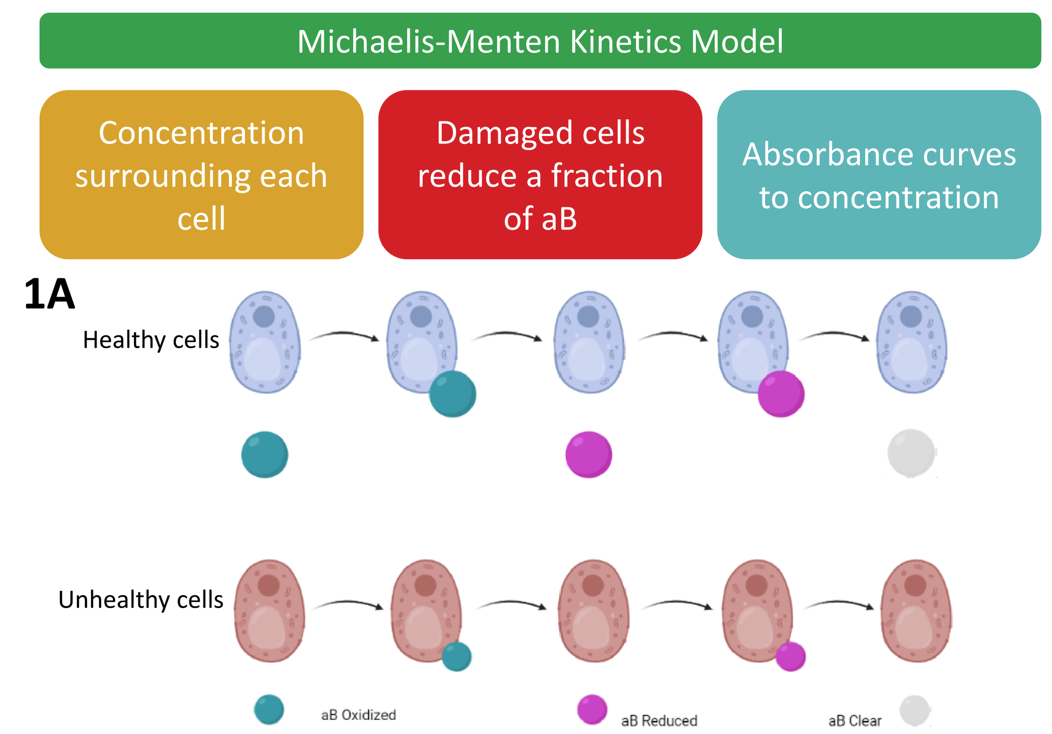
AMMPER: Agent-based Model for Microbial Populations Exposed to Radiation

- AMMPER simulates yeast cells in a cubic medium.
- Radiation events create ROS molecules that affect cells.
- Cells can be in a damaged, healthy or dead state.
- Model is parametrized with Biosentinel data.

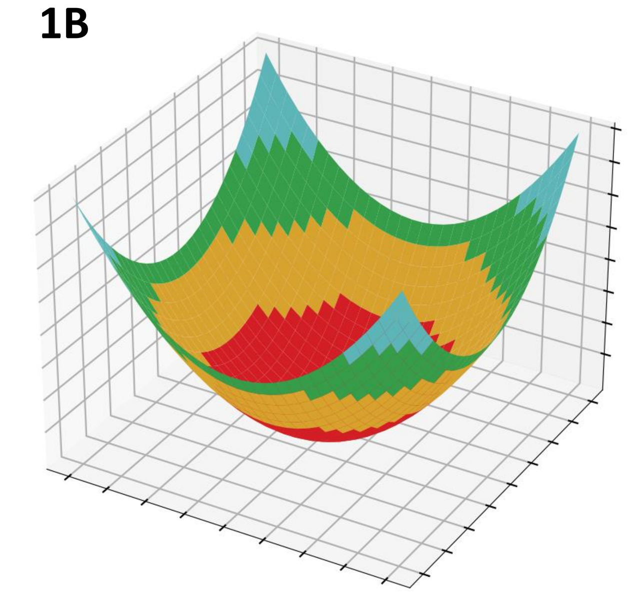


Cell Metabolism and alamarBlue (aB)

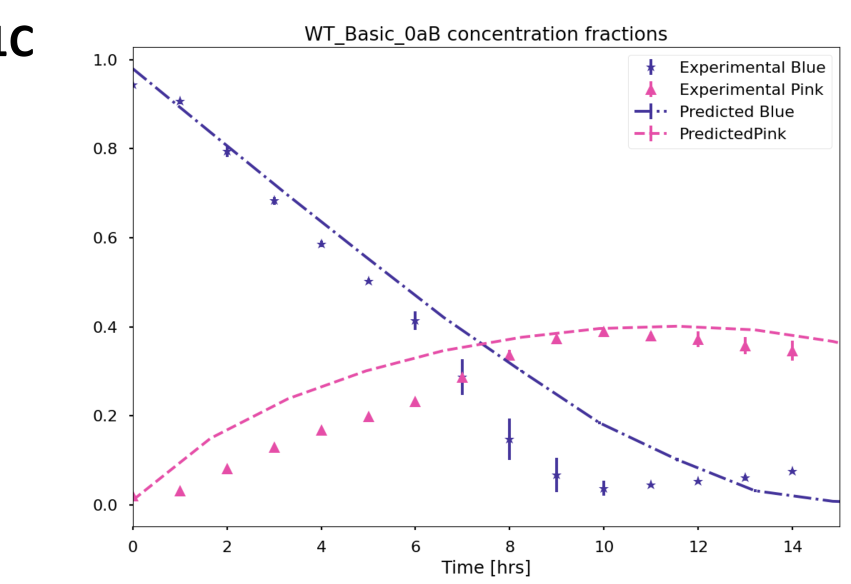
- The effects of ionizing radiation in cell health and metabolism are not well understood.
- The BioSentinel mission measures those effects using the metabolic dye aB.
- **Although Michealis-Menten Kinetics Model is simplified, it recapitulates experimental results exceptionally.**



1B



1C



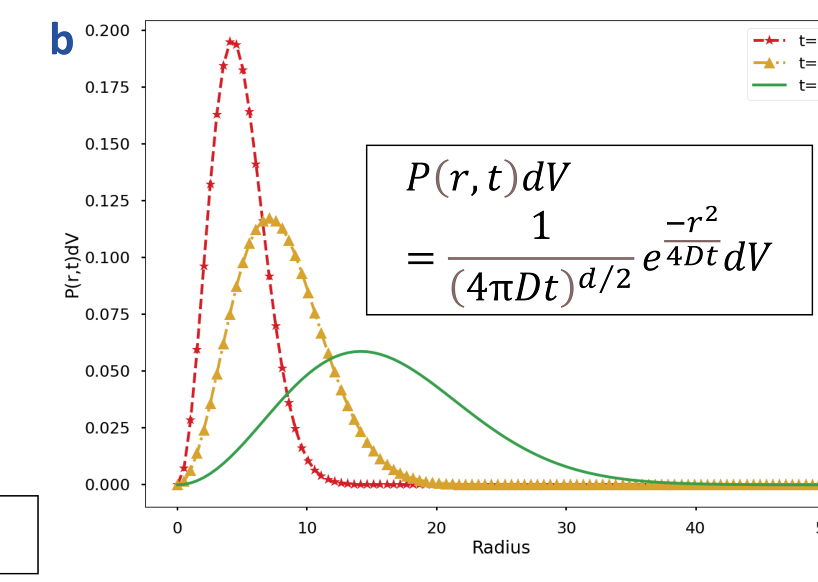
1A. aB metabolism simple Michealis-Menten enzyme kinetics model diagram. The blue oxidized aB transitions to a pink reduced form after reaction with yeast metabolic byproducts. **1B**. Grid-parameter search in two dimensions sketch. A 4-tensor grid-search was performed to find optimal parameters that minimized vertical deviations. **1C**. aB fractional concentration curves. Model fits experimental Biosentinel data with a 0.63 vertical absolute mean error.

ROS Diffusion and Lifetime

- Green's function for diffusion PDE (a) or Propagator is the fundamental solution (b) and models the diffusion of molecules in a medium.
- **No statistical significance differences between basic and complex ROS models or different half-lives.**

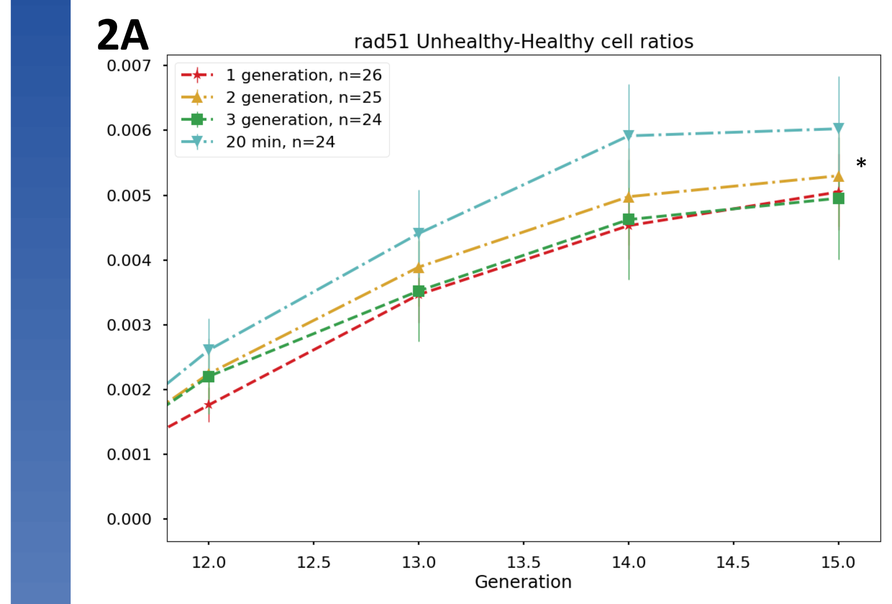
a $\partial_t u(\mathbf{r},t) = \nabla \cdot \left(D(u,r)\nabla u(\mathbf{r},t)\right)$

b

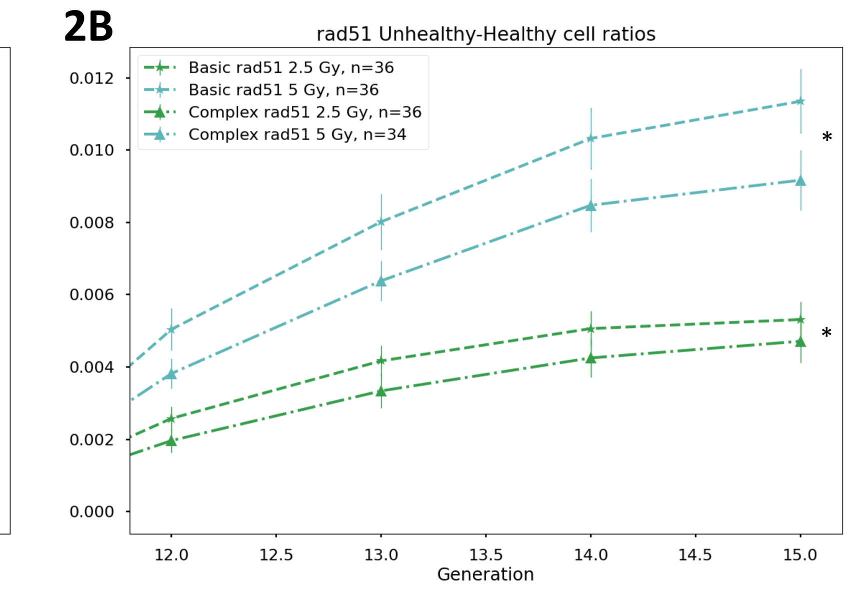


$$P(r,t)dV = \frac{1}{(4\pi D t)^{d/2}} e^{\frac{-r^2}{4Dt}} dV$$

2A



2B

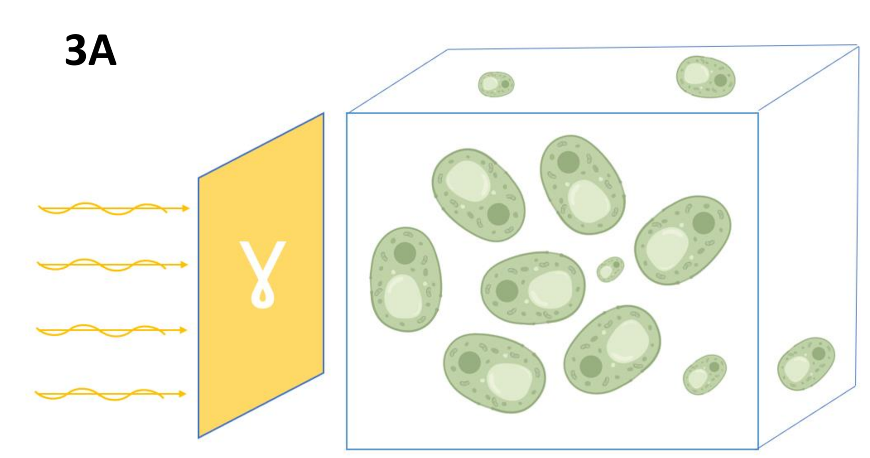


2A. ROS half-lives comparison. The model variance due to ion localization has a higher contribution than the duration of ROS molecules in the medium **2B**. Basic vs Complex ROS model comparison. Basic model considers ROS as eternal and static concentrations, while complex model takes ROS diffusion and lifetime as consideration. Complex and basic ROS models have similar behavior because diffusion causes more cells to be exposed however lowers the chance to damage cells since they are expose to less concentration. *Cumulative Link Mixed Model median comparison and individual pairwise Wilcoxon tests resulted in no statistical significance between the curves.

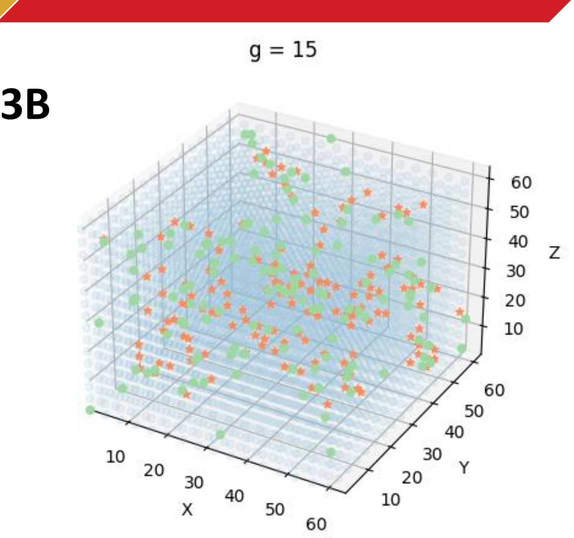
Gamma Radiation

Uniform probability density of generating a radiation event. → Parametrized to replicate experimental survival rate data → Ignored shielding due to small dimensions

3A



3B

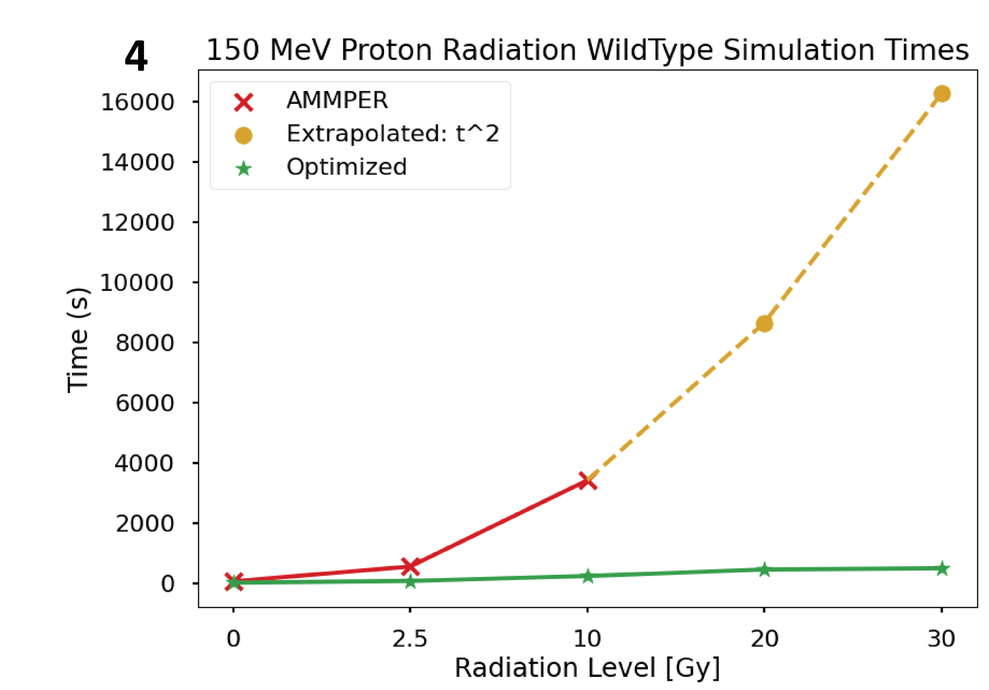


3A. Gamma radiation model sketch. A perpendicular plane is defined as a uniform probability density of generating an event which scans through all lattice squares, green cells represent yeast cells. **3B**. AMMPER gamma radiation simulation. Radiation events are highlighted in green, dead cells are orange in color, healthy cells are blue, the radiation is unlocalized contrary to ion particle radiation.

AMMPER Optimization

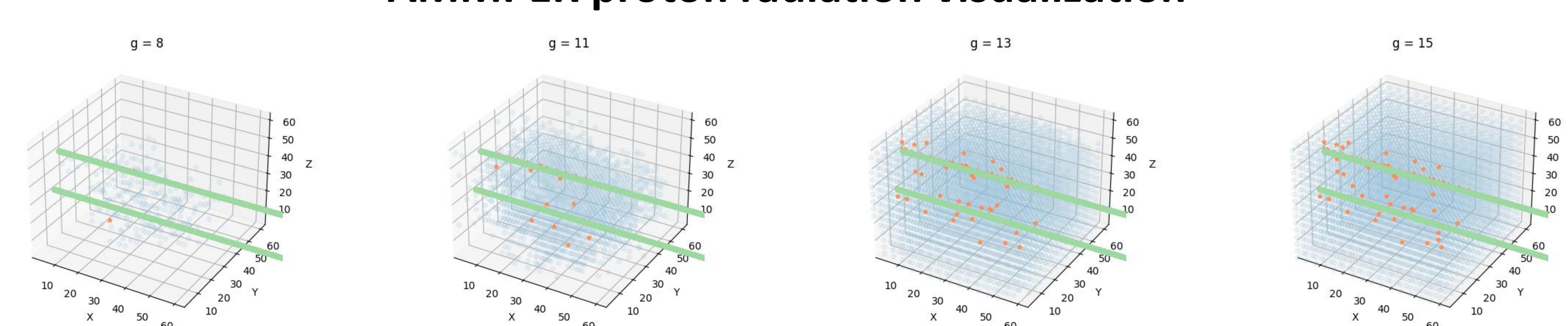
- Changed visualization function to plot all cells simultaneously, solved memory issue.
- Changed ROS damaging mechanism.
- **Reduced computational time from hours to minutes** (orders of magnitude faster).

4



4. AMMPER optimization plot. The effective use of memory allowed for the reduction of computational time by several orders of magnitude reducing minutes to seconds, and hours to minutes.

AMMPER proton radiation visualization



Watch videos of proton and gamma radiation here:

References | Acknowledgements

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