Space-Radiation Risk Modeling

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The Multi-model Ensemble Risk Assessment (MERA) project

Human Research Program: to develop methods to protect the health and performance of astronauts in space.

MERA Goals: to develop robust and accurate tools for evaluating space radiation health risks to support mitigation strategies, informed consent, and operations.

My work: to build predictive track structure models that can (1) link initial radiation-induced DNA damage to intermediate cellular cancer biomarkers (e.g., chromosome aberrations) and (2) extrapolate limited experimental data to complex space radiation environment.

MERA Project Scientist
Individual risk assessment

MERA Project Manger
Lung cancer

Cancer ensemble risk model
GCR simulator design

Medical countermeasure &
Mitigation assessment
Biologically-based risk models

CVD risk models
Late CNS risk assessment
Combined spaceflight risks

MERA Project Manger
Engineering design

Track structure & biophysics
CVD clinical prediction models
CNS risk modeling

Chromosome aberration modeling
Track structure & biophysics

Risk communication
Radiation transport

Dose response modeling

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Resume

Education (specialty medical physics):

- (2009-2014) **IMT Atlantique (Campus Mines de Nantes), Nantes, France -** Engineering degree (equivalent B.Sc. + M.Sc.)
- (2015-2019) **University of Lyon, Lyon, France** – Ph.D. degree (and teaching assistant). *Physical, chemical and biological modelling for gold nanoparticle-aided radiation therapy: towards a better understanding and optimization of the radiosensitizing effect*

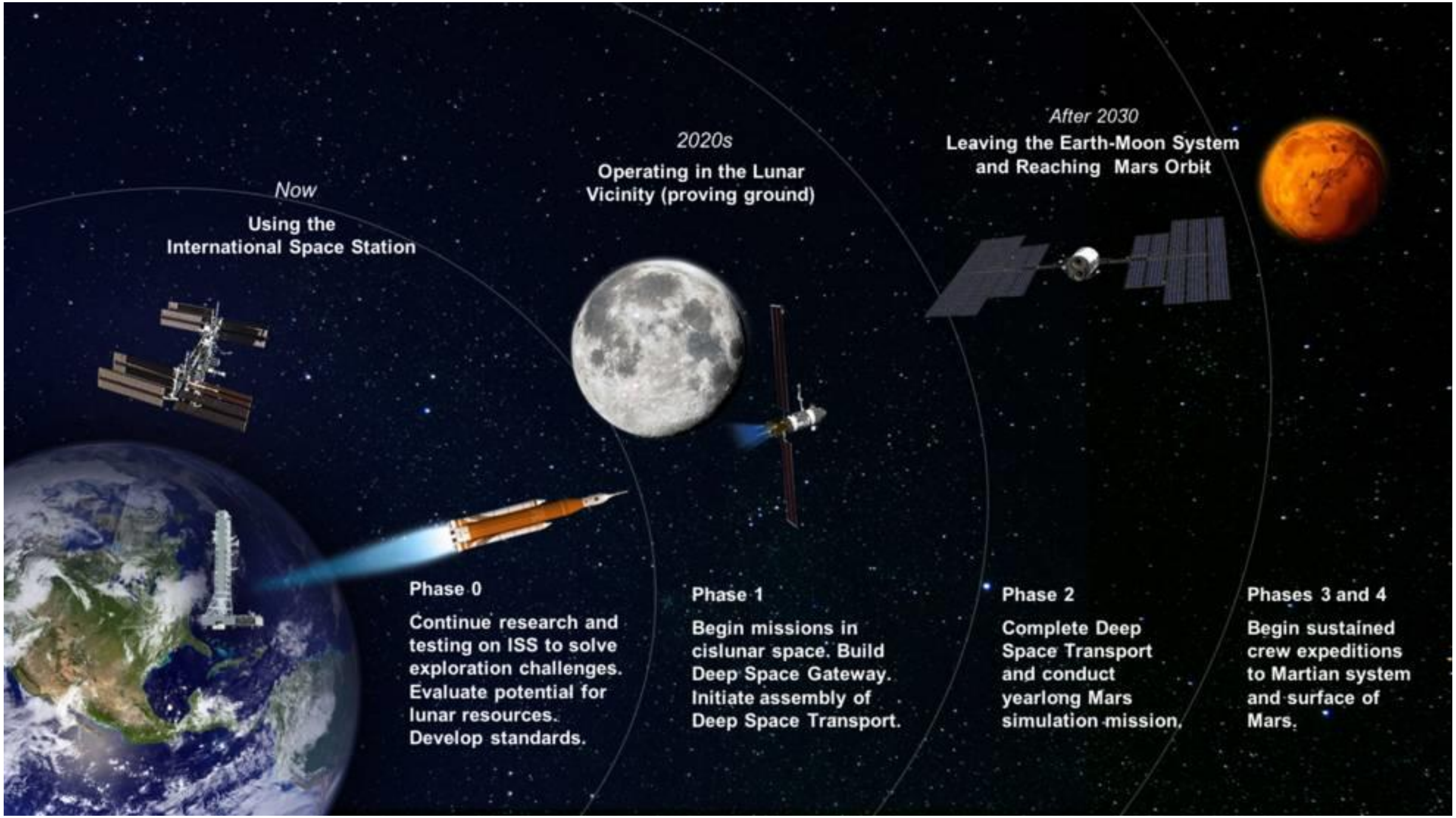
Research:

- (2014) **University of Adelaide, Adelaide, Australia -** *Design of a Geant4 simulation of the SAHMRI cyclotron solid target for the prediction radioisotope production* (application available in Geant4 release)
- (2020-now) **NIA/AMA, Hampton, USA -** *Relating space radiative environments to ground-based experiments for radiobiology studies* (switch from medical-radiation application to space-radiation application)

Areas of expertise:

- Monte Carlo (track-structure) radiation transport (RITRACKS, Geant4)
- Biophysical modeling (DNA damage, DNA damage repair, chromosome aberration formation, 3D nuclear DNA architecture, micro/nanodosimetry, radical species, cell survival, etc.)
- Coding (c/c++, python, scientific computational calculation)
- little bit: data fitting, visualization, cross section calculation

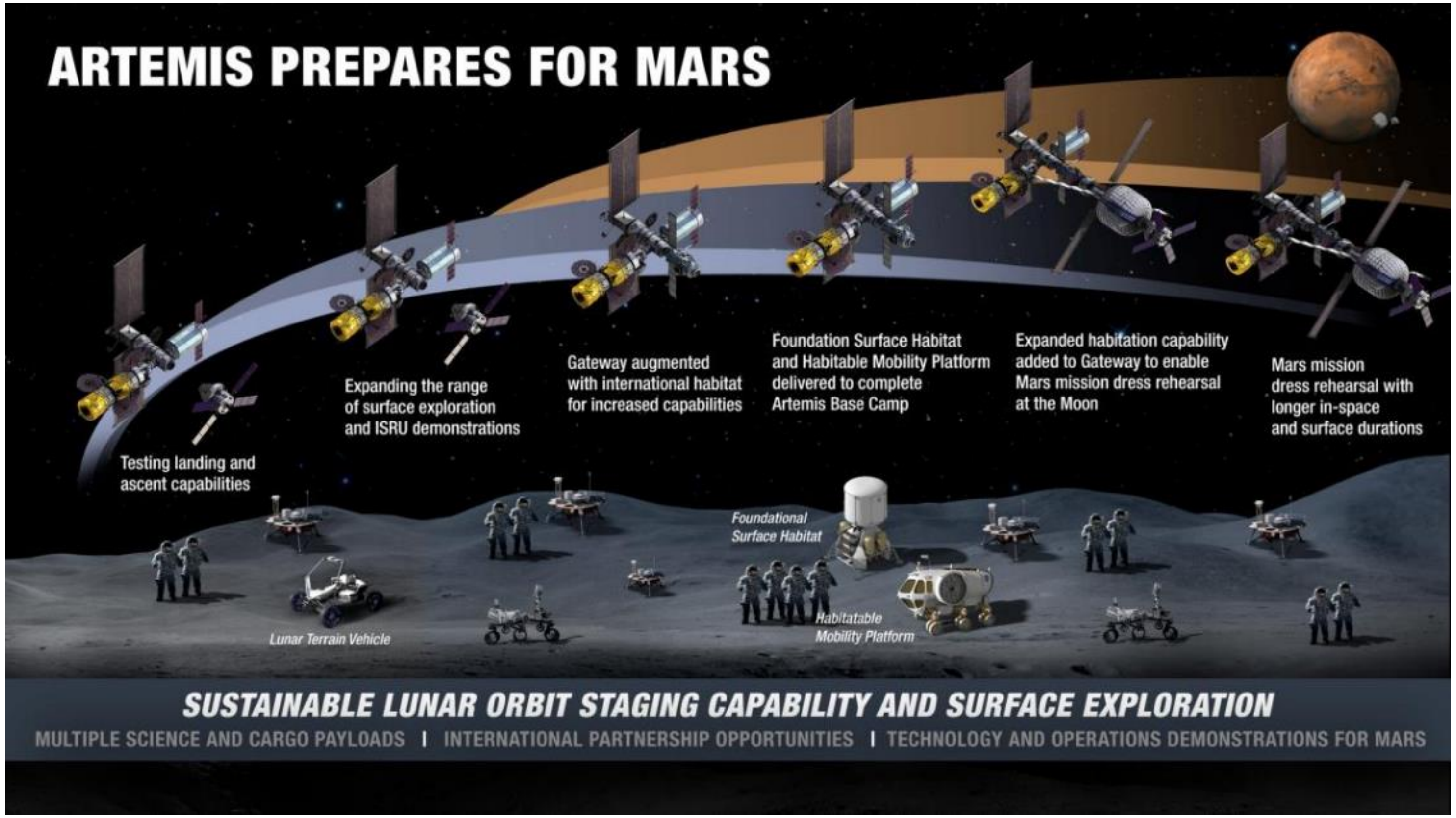
Planned exploration activities



Spaceflight hazards

- **Altered Gravity**
  - Challenges: reduced muscle mass, bone loss, fluid shifts, sensorimotor changes
- **Isolation / Confinement / Altered Light-Dark Cycles**
  - Challenges: behavioral changes, sleep issues, fatigue, mood changes, team dynamics
- **Hostile / Closed Environment**
  - Challenges: altered immune system, dust exposure, temperature changes, elevated carbon dioxide, exposure to contaminants
- **Distance from Earth**
  - Challenges: ineffective medications, food storage, lack of medical care and equipment, communication lag
- **Increased Radiation Exposure**
  - Challenges: acute radiation syndrome, cardiovascular diseases, central nervous system decrements, **carcinogenesis**

Planned Exploration Activities

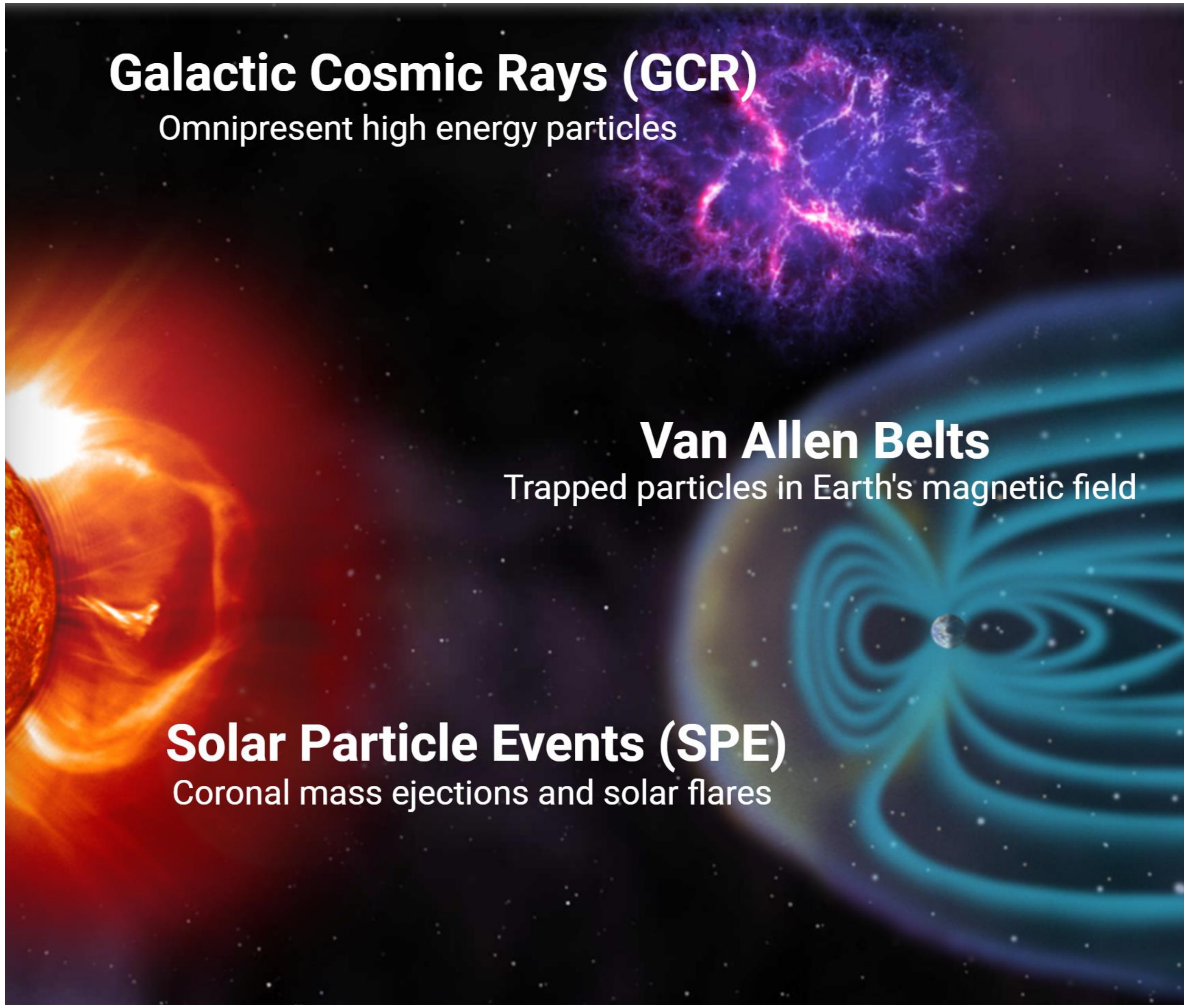


Permissible Exposure Limit (NASA's limit for radiation exposure during an astronaut's career): effective dose of **600 mSv**

*Mission exposures are estimated average rates calculated external to a human body located inside 20 gm/cm2 of aluminum shielding during solar minimum. **Dose-equivalent value (mSv) is the product of the absorbed dose (mGy) and radiation quality factor. The range of mission-related exposure estimates uses both NASA-defined and ICRP 60 quality factors. Estimates from C. Werneth, T. Slaba, J. Huff. Image credit: NASA

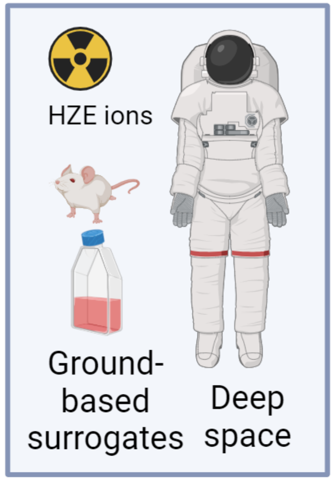
*Radiation Exposure Scenario	Duration	Dose (mGy)	**Dose Equiv. (mSV)
Space exposure			
International Space Station in low Earth orbit	180 – 365 days	30 – 120	50 – 200
Sortie to lunar vicinity (free space)	30 days	20	55
Lunar surface mission	45 days	25	70
Sustained lunar operations	1 year	100 – 120	300 – 400
Lunar orbit (Gateway)	1 year	175 – 220	**500 – 650**
Mars Mission	650 – 920 days	300 – 450	**870 – 1200**
Medical exposure (imaging)			
Chest x-ray		0.1-0.23	0.1-0.23
Full body computed tomography		50-100	50-100
Occupation dose limit (whole body)			
USA	/year		50
France	/year		20

Space Radiation Environment

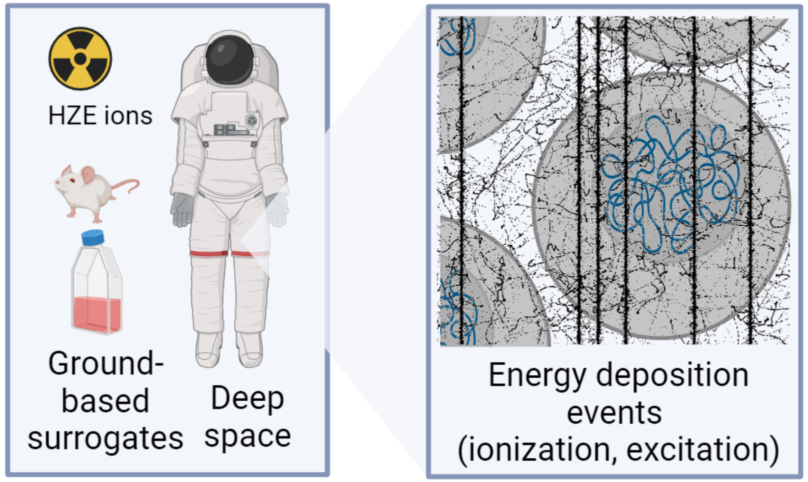


- **Trapped Particle Radiation**
  - What: low energy protons (< 250 MeV) and electrons (< 7 MeV)
  - When: continuous
  - Where: altitude up to 40,000 km
  - Mitigation: can be shielded; mainly relevant to ISS
- **Solar Particle Events**
  - What: medium to high energy protons
  - When: sporadic
  - Where: ubiquitous beyond magnetosphere
  - Mitigation: can generally be shielded
- **Galactic Cosmic Rays**
  - What: low (< MeV/n) to high (> TeV/n) energy leptons (2%), protons (85%), helium ions (12%) and **high charge and energy (HZE) ions (1%)**
  - When: continuous
  - Where: ubiquitous beyond magnetosphere
  - Mitigation: can not be shielded entirely;
  - **Biological effect of HZE ions poorly understood, and potentially prone to adverse side effects (carcinogenesis, central nervous system decrement, cardiovascular disease)**

Ionizing radiation effects on living matter



Ionizing radiation effects on living matter



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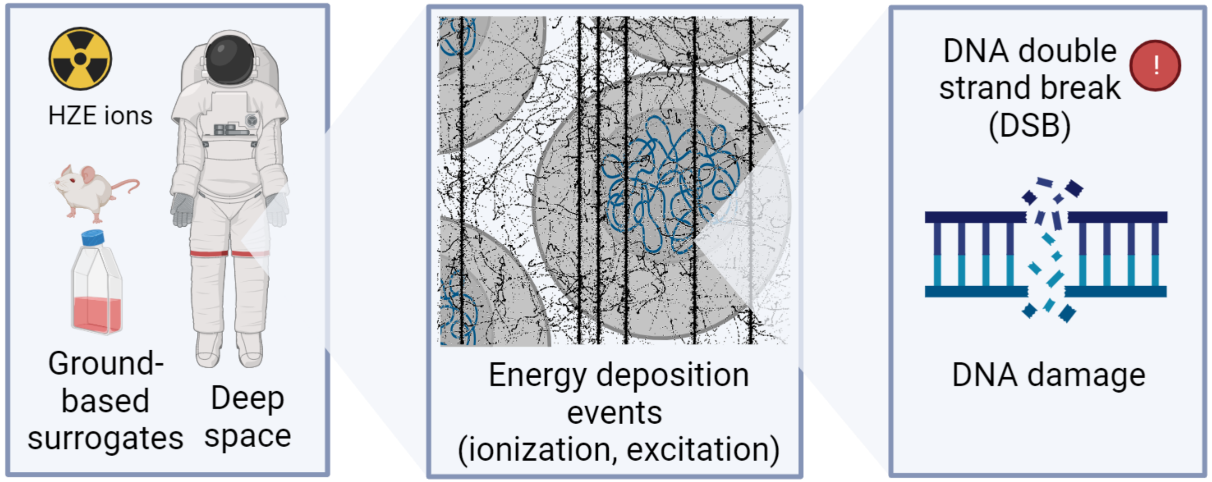

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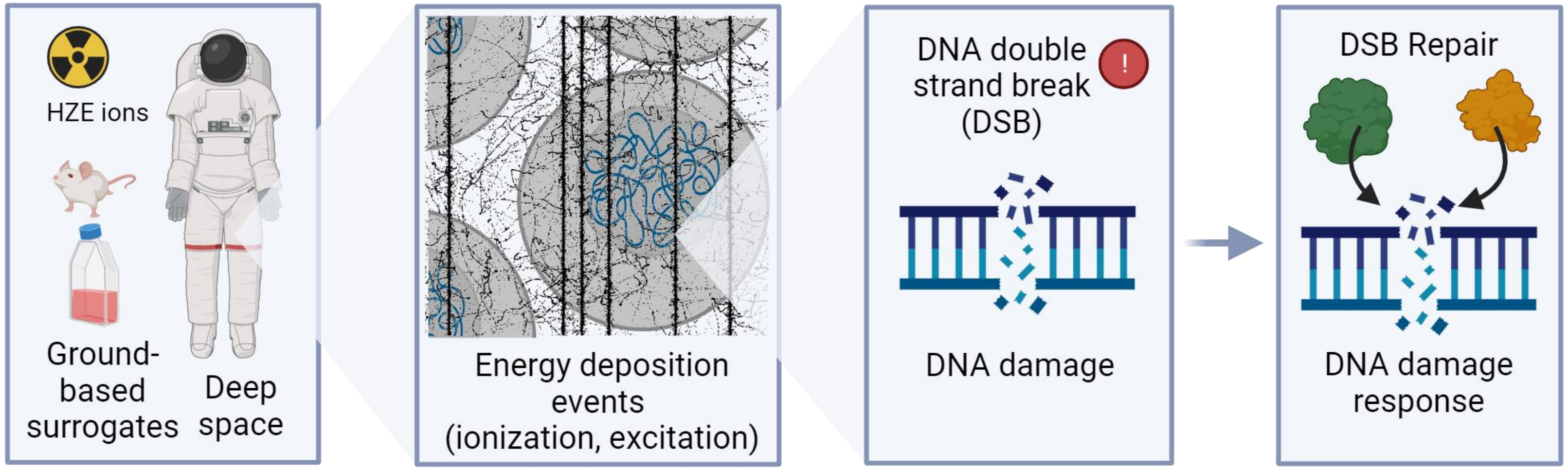

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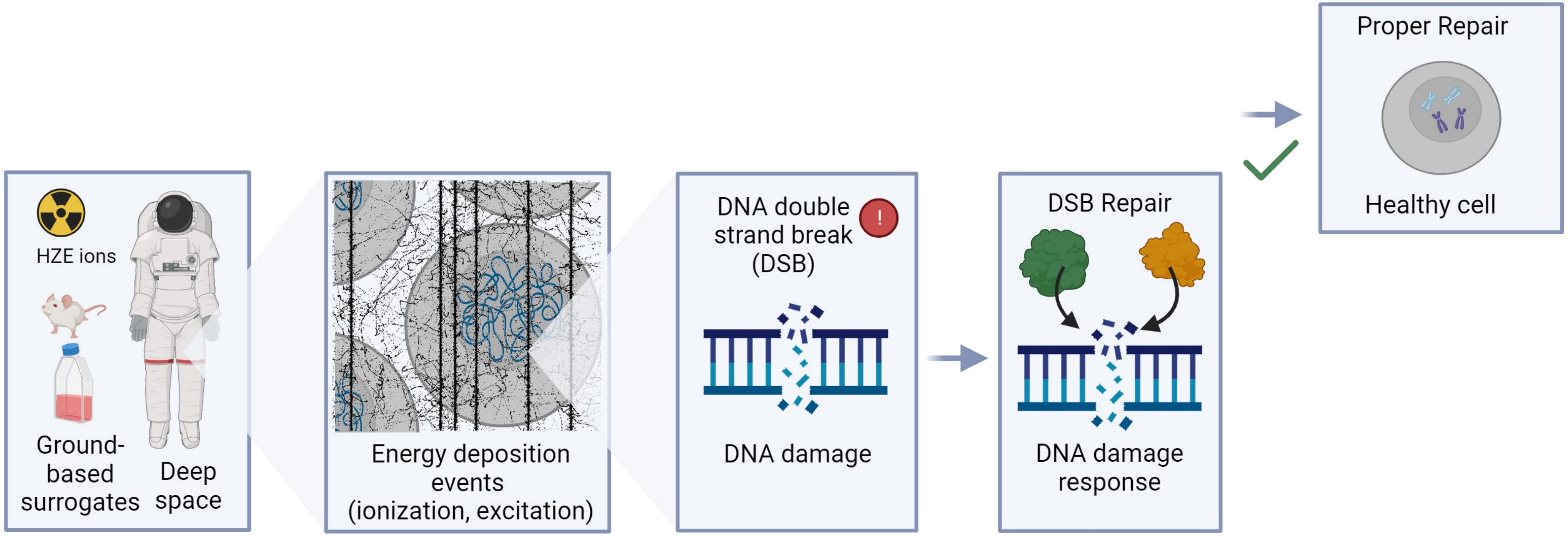

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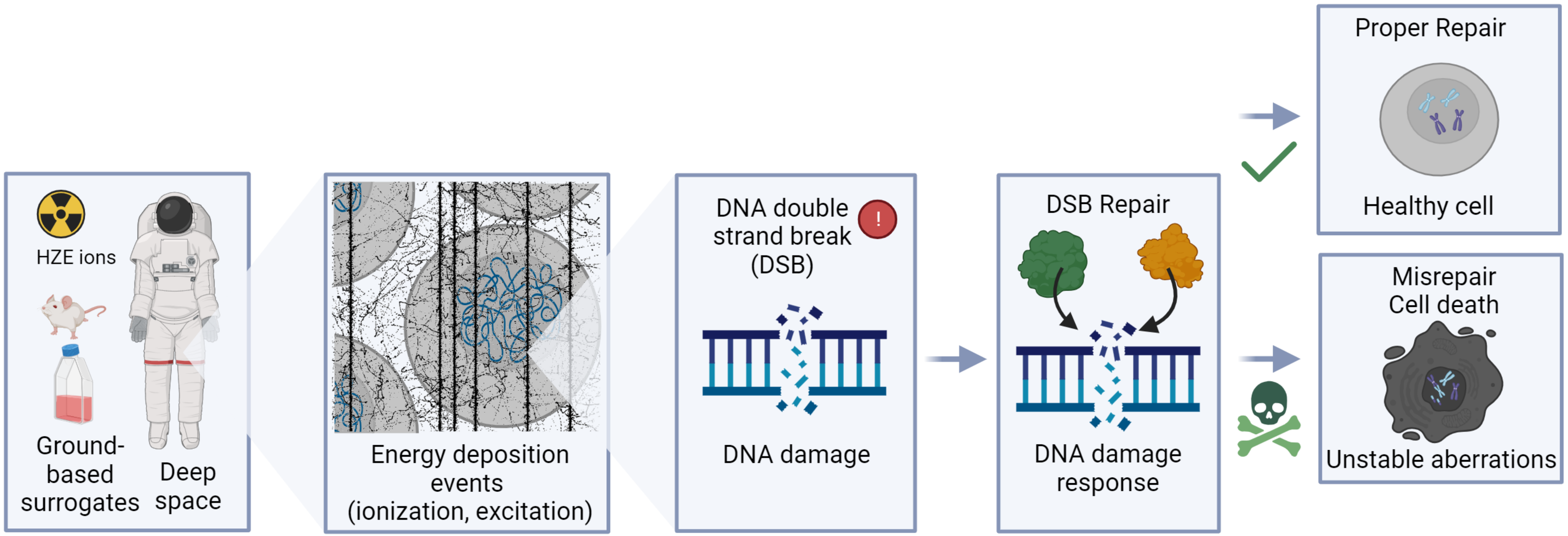

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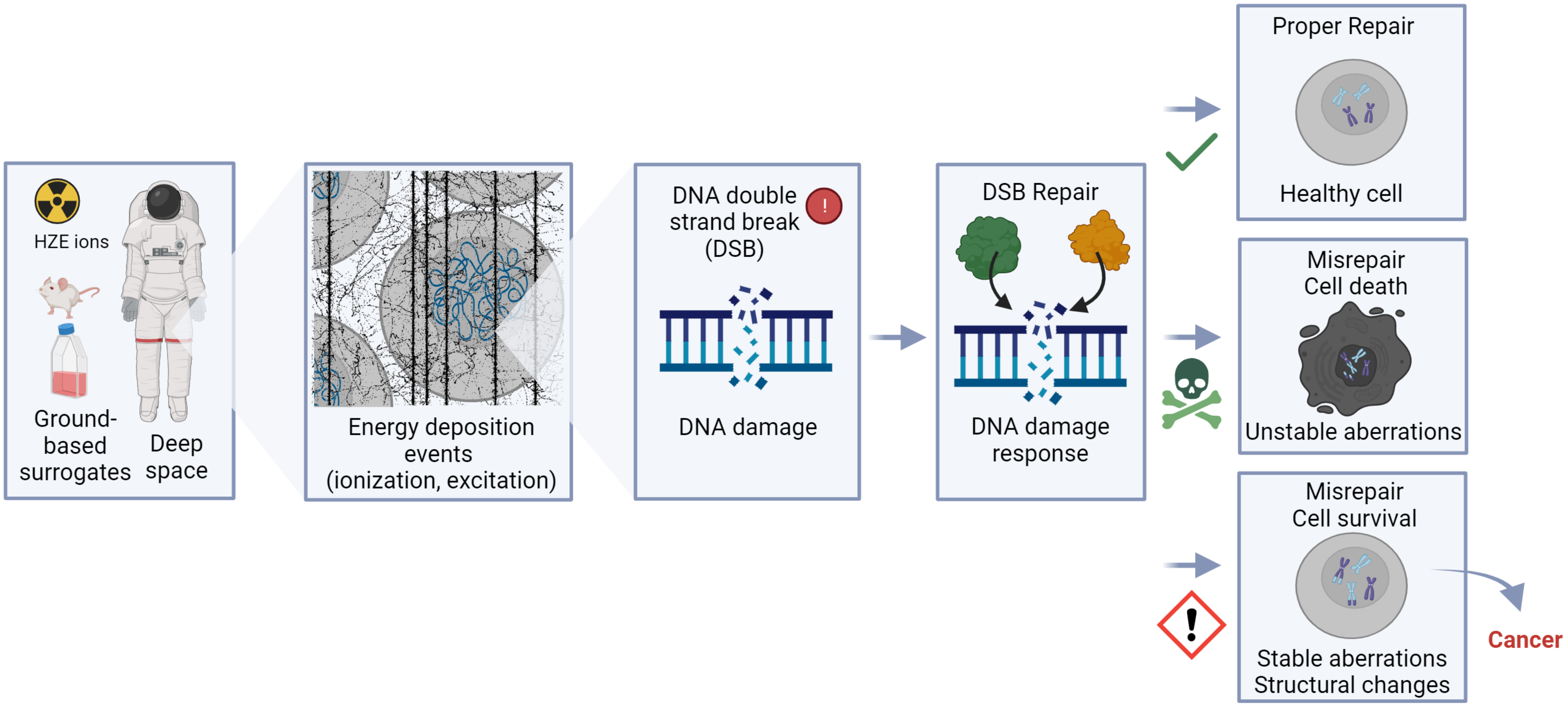
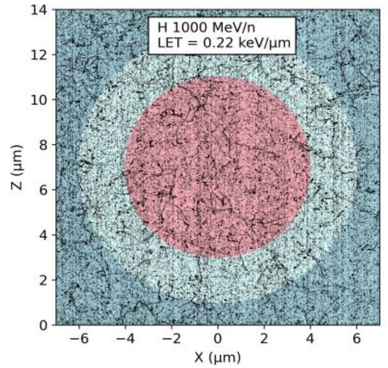


Biological effect of HZE ions – importance of high linear energy transfer (LET)

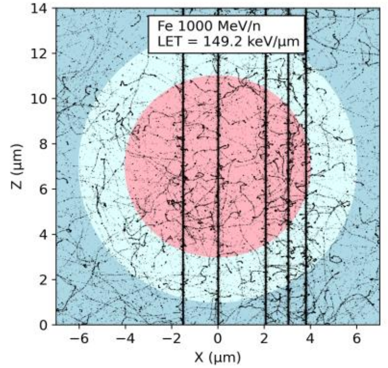
Energy deposition events in biological medium → Cellular damage, including DNA breaks → Cellular response: chromosome aberrations, cell death, mutation … → Tissue response: tumor incidence, cardiovascular disease, central nervous system decrement

Low LET



0.5 Gy sparsely ionizing

High LET



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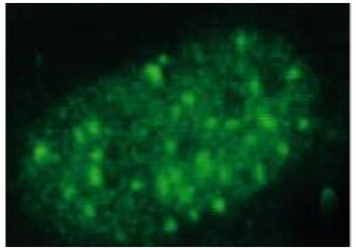
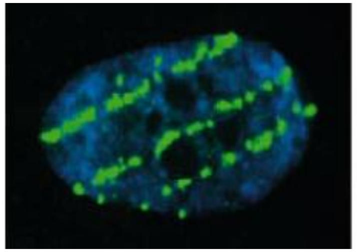
Low LET

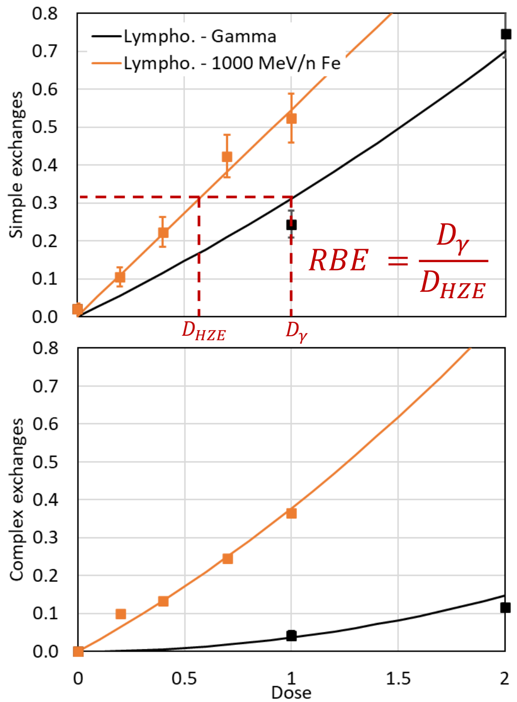


DNA damage homogeneously distributed

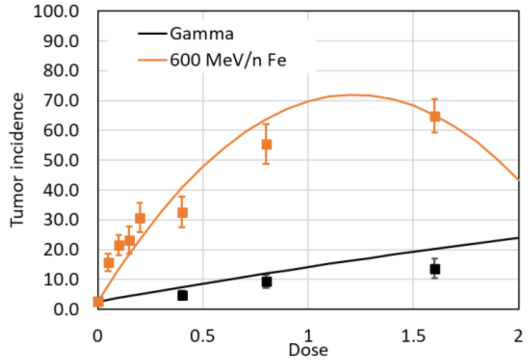
High LET

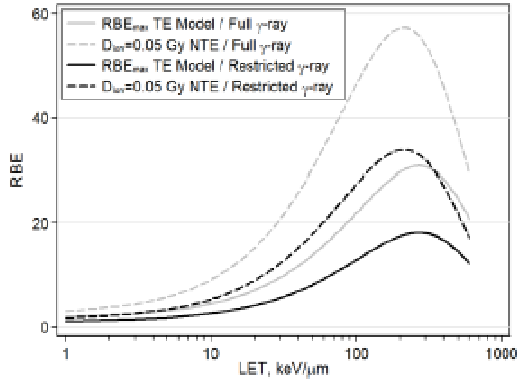


Clustered DNA damage along ion tracks



Increased incidence of biological cellular endpoint for a given dose





Increased incidence of biological tissue endpoint for a given dose

Ref. Desai et al (2005). Radiation Research, 164(4), 518-522. Loucas, B. D et al (2013). Radiation Research, 179(1), 9-20. Cucinotta, F. A et al. (2011). NASA/TP-2013-217375

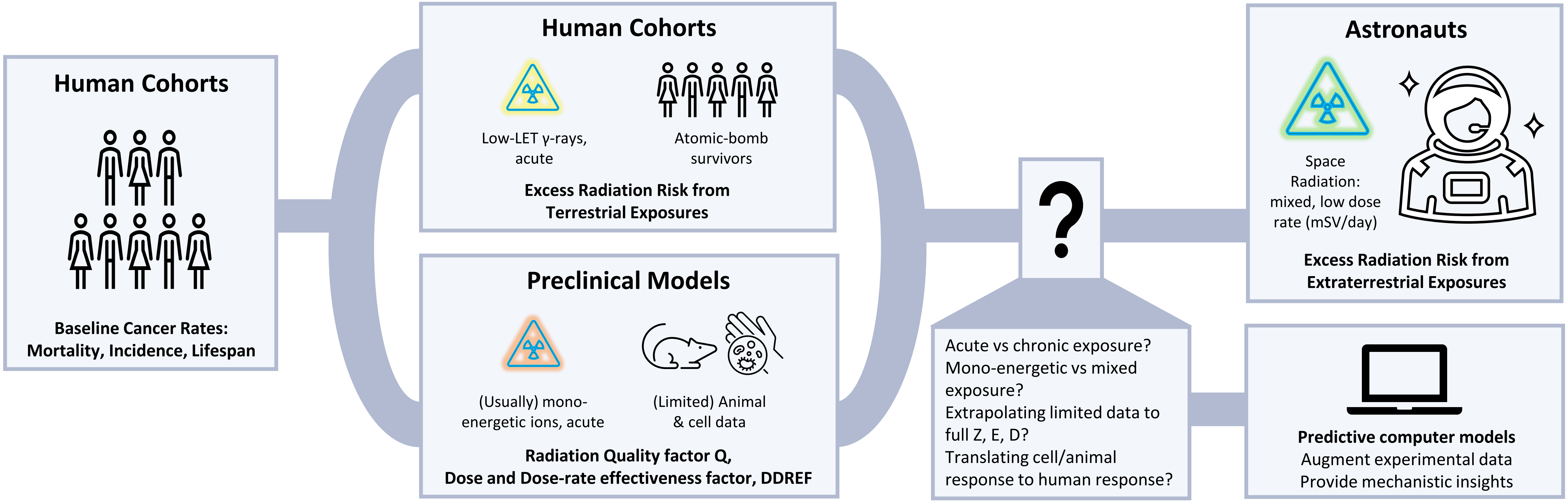
Earth to Space Cancer Risk Translation

$$REID = \sum_{T} \int_{a_E}^{\infty} \lambda_m^{(T)}(a, a_E, H_T) S(a, a_E, H_T)\, da$$

Summation over all radiosensitive tissues (T) and attained age (a) after exposure at age a_E

$\lambda_m^{(T)}(a, a_E, H_T) = F[Excess\ Risk(\gamma), Q, DDREF, Transfer]$, radiation induced mortality (m) rate for tissue T and exposure H_T (Sv)

Survival probability including additional radiation hazard (i.e., competing causes)



Slide credit ©Kathleen

Chromosome aberrations as a biomarker of radiation exposure

Formation

✓ Formed by misrepair of DNA break following exposure to ionizing radiation

Radiation exposure relevance

✓ Relate to dose

✓ Relate to radiation quality

Good ground-based surrogate

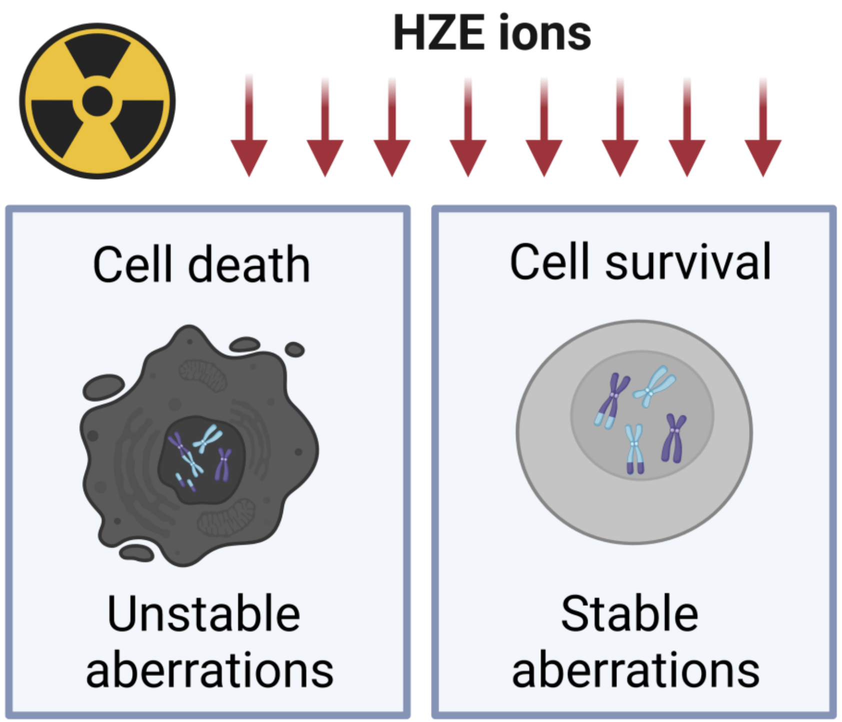
✓ Cost effective (compared to animal models)

✓ Measurable in both human and rodent cells

Mechanistic relevance

✓ Relate to cell fate

✓ Hallmark of carcinogenesis



Perspectives

✓ Pre-flight measures in blood's astronaut cells for individual radiosensitivity assessment

✓ In-flight measures in blood's astronaut cells for individual biodosimetry

Thanks!