



National Aeronautics and  
Space Administration



# Space Radiation: It's Everywhere We Want to Be

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*Space Radiation "Acting" Element Scientist*

NASA Human Research Program

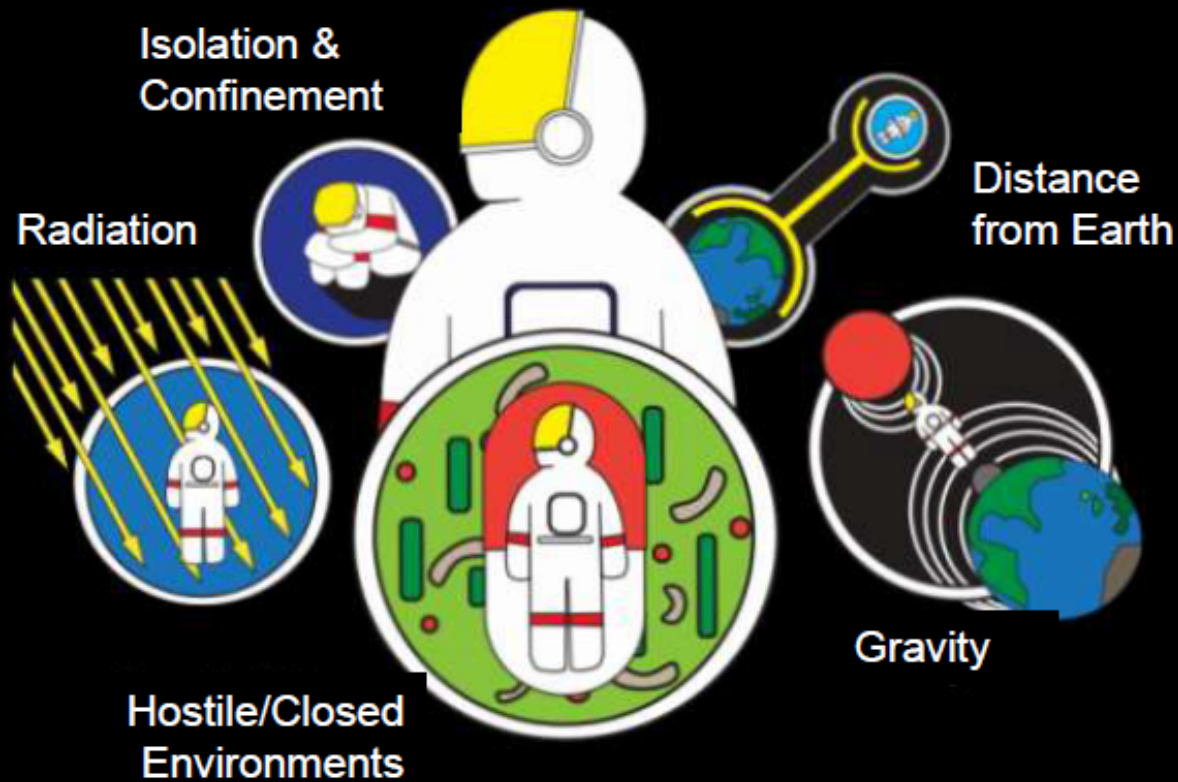
# Overview

- **Introductions**
- What is Radiation?
- Radiation Health Effects
- The Space Radiation Environment
- Health Risks for Spaceflight
- Risk Management and Uncertainties



# Human Research Program

Protect Astronauts' health and performance from five key hazards of spaceflight



...by researching how astronauts' bodies and minds adapt to the extreme environments of space

## On Earth

- Ground-based Analogs
- Laboratories
- Simulation & Training

## In Space

- ISS
- Gateway
- Moon
- Mars



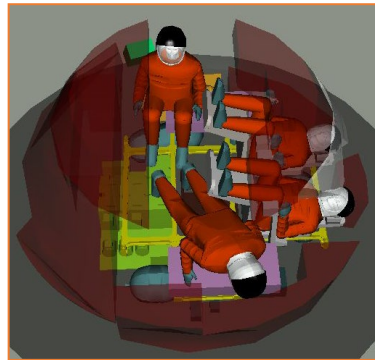
<https://www.nasa.gov/hrp>



NP-2019-03-005-JSC

# An Applied Research Program

- Scientific Goals
  - Understand and mitigate human health and performance risks due to the five known hazards of spaceflight
  - Enable development of human spaceflight medical and human performance standards
  - **Develop and validate technologies that serve to characterize and reduce health risks associated with human spaceflight**



# Space Radiation Research and Operations

## Space Radiation Element (SRE)

- Space radiation research
  - Cancer
  - Cardiovascular and Immune
  - Central nervous system
- Investigate strategies to characterize and mitigate **exposure effects**
- Evaluate new methods to assess crew risk from radiation exposure
- Recommend updates to Permissible Exposure Limits

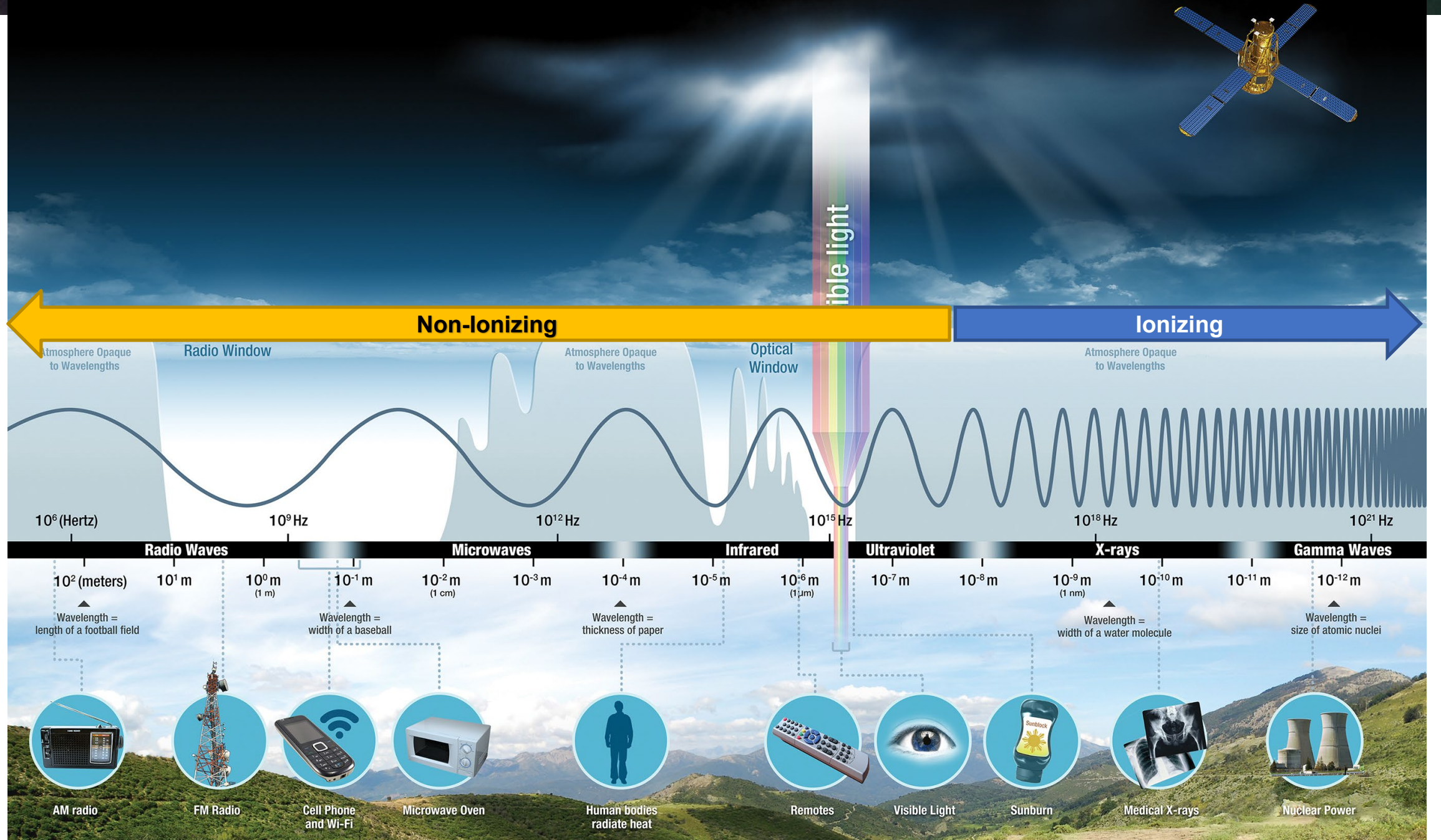
## Space Radiation Analysis Group (SRAG)

- Crew radiation risk projections and management
- Crew dosimetry and vehicle radiation monitoring
- Space weather monitoring and forecasting
- Radiation Console in MCC
- Recommend ALARA actions
- Develop **exposure** mitigation (shielding)
- Recommend updates to Permissible Exposure Limits

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• [https://en.wikipedia.org/wiki/Electromagnetic\\_spectrum#/media/File:Electromagnetic\\_spectrum,\\_NASA\\_illustration.jpg](https://en.wikipedia.org/wiki/Electromagnetic_spectrum#/media/File:Electromagnetic_spectrum,_NASA_illustration.jpg)

# Measuring Radiation

- **Dose**

- Absorbed dose

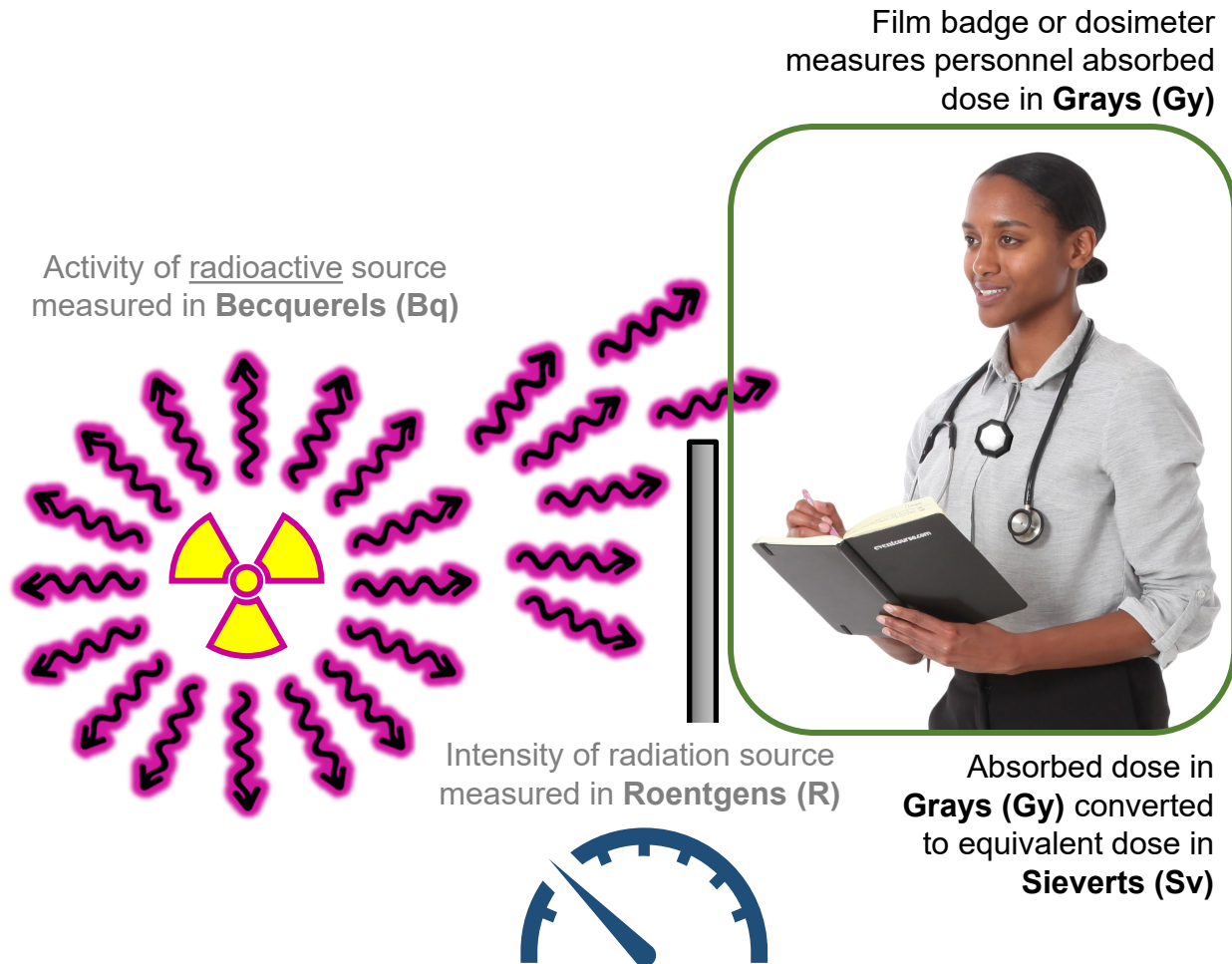
- Amount of energy absorbed in a unit of mass
      - SI unit: “Gray” (Gy) = J/Kg

- Equivalent dose

- Accounts for biological effectiveness of radiation
      - SI unit: “Sievert” (Sv) = J/Kg
      - Depends on radiation quality

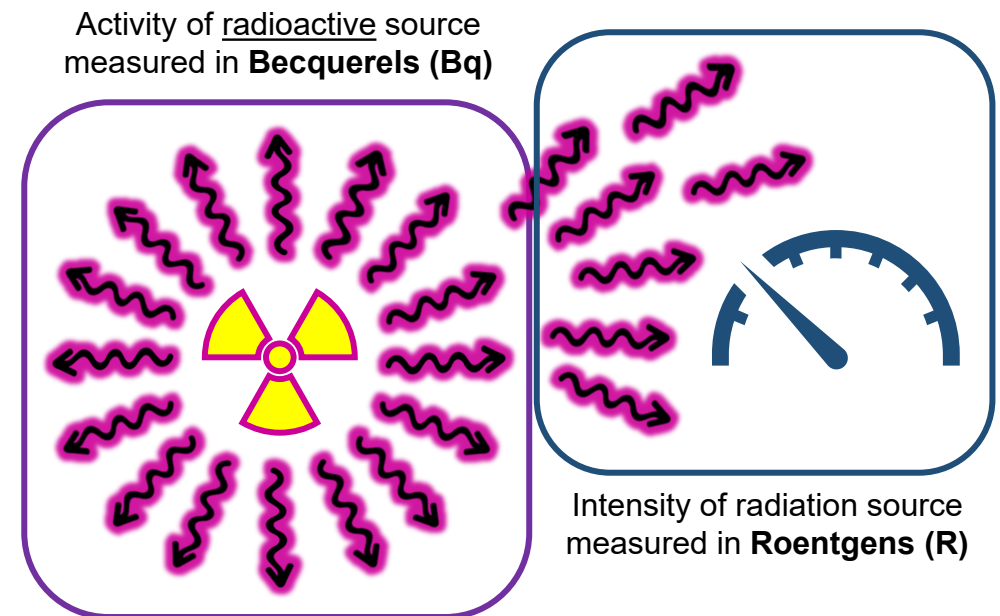
- Effective dose

- Adjusts for partial body exposures
      - SI unit: “Sievert” (Sv) = J/Kg
      - Depends on tissue sensitivity



# Measuring Radiation

- **Activity**
  - Rate of radioactive decay
  - Number of atoms that decay and emit radiation per second
    - SI unit: Becquerels (Bq)
- **Exposure**
  - Amount of energy emitted by a radiation source
  - Number of ionizations in air
    - SI unit: Roentgens (R)



# What is Radiation?

Propagation or transmission of energy in the form of **electromagnetic waves** or **particles**

## NON-IONIZING RADIATION

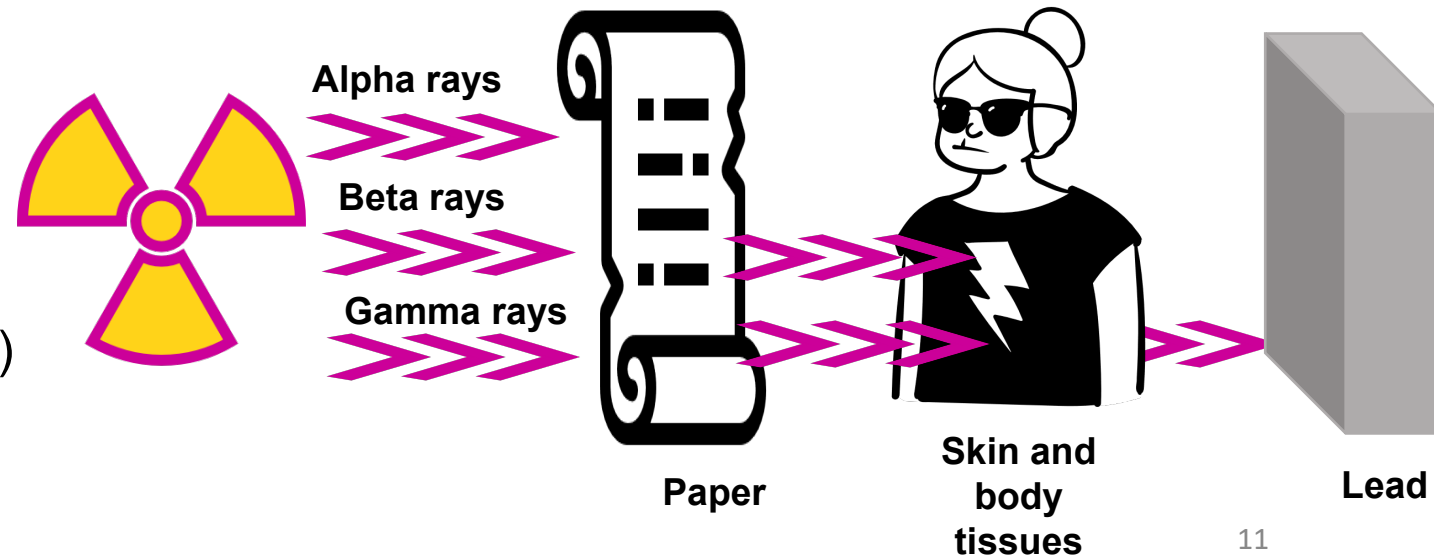
- Not carry enough energy to ionize matter
  - Cannot liberate electrons from atoms
  - Visible light
  - Microwaves
  - Ultraviolet light
- Enough energy to move/excite atoms

## IONIZING RADIATION

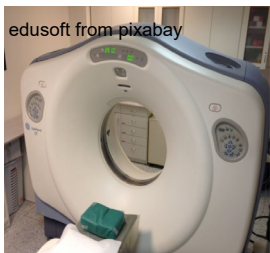
- Enough energy to ionize matter
  - Can liberate electrons from atoms
    - Ions can cause damage
    - Creation of charged particle
  - High energy ultraviolet
  - X-rays
  - Gamma-rays
  - High energy particles

# Terrestrial Radiation

- Types
  - Electromagnetic (wave) radiation
    - X- and gamma-rays
  - Limited particle radiation
    - Radioactive decay or remnants of cosmic radiation
      - Mainly neutrons, alphas, betas, pions, other light particles
- Sources
  - Naturally occurring
    - Can be artificially enhanced
  - Medical diagnostics and treatment
- Relatively easy to shield
- Background radiation exposure (U.S.)
  - Natural: 3 mSv/yr (mainly radon)
  - Manufactured: 3 mSv/yr (mainly medical)

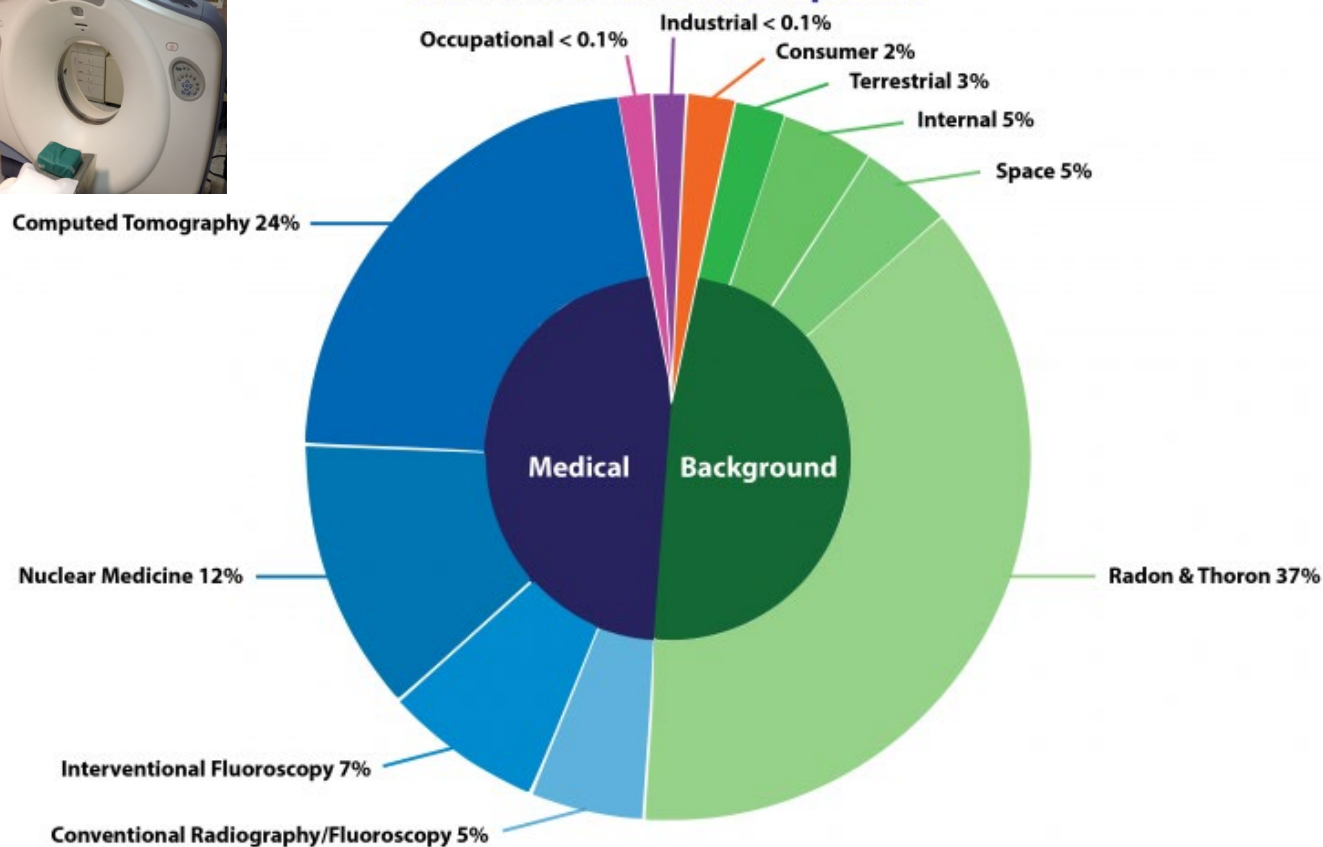


# Terrestrial Radiation



edusoft from pixabay

## Sources of Radiation Exposure



Location	~Average Total Dose Equivalent (mSv/yr)
Average U.S.	3
Houston	1
Denver	2
Kerala, India	13

### Average Annual Radiation Dose

Sources	Radon & Thoron	Computed Tomography	Nuclear Medicine	Interventional Fluoroscopy	Space	Conventional Radiography/Fluoroscopy	Internal	Terrestrial	Consumer	Occupational	Industrial
<b>Units</b>											
mrem (United States)	228 mrem	147 mrem	77 mrem	43 mrem	33 mrem	33 mrem	29 mrem	21 mrem	13 mrem	0.5 mrem	0.3 mrem
mSv (International)	2.28 mSv	1.47 mSv	0.77 mSv	0.43 mSv	0.33 mSv	0.33 mSv	0.29 mSv	0.21 mSv	0.13 mSv	0.005 mSv	0.003 mSv

(Source: National Council on Radiation Protection & Measurements, Report No. 160)

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- **Radiation Health Effects**
- The Space Radiation Environment
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- Risk Management and Uncertainties



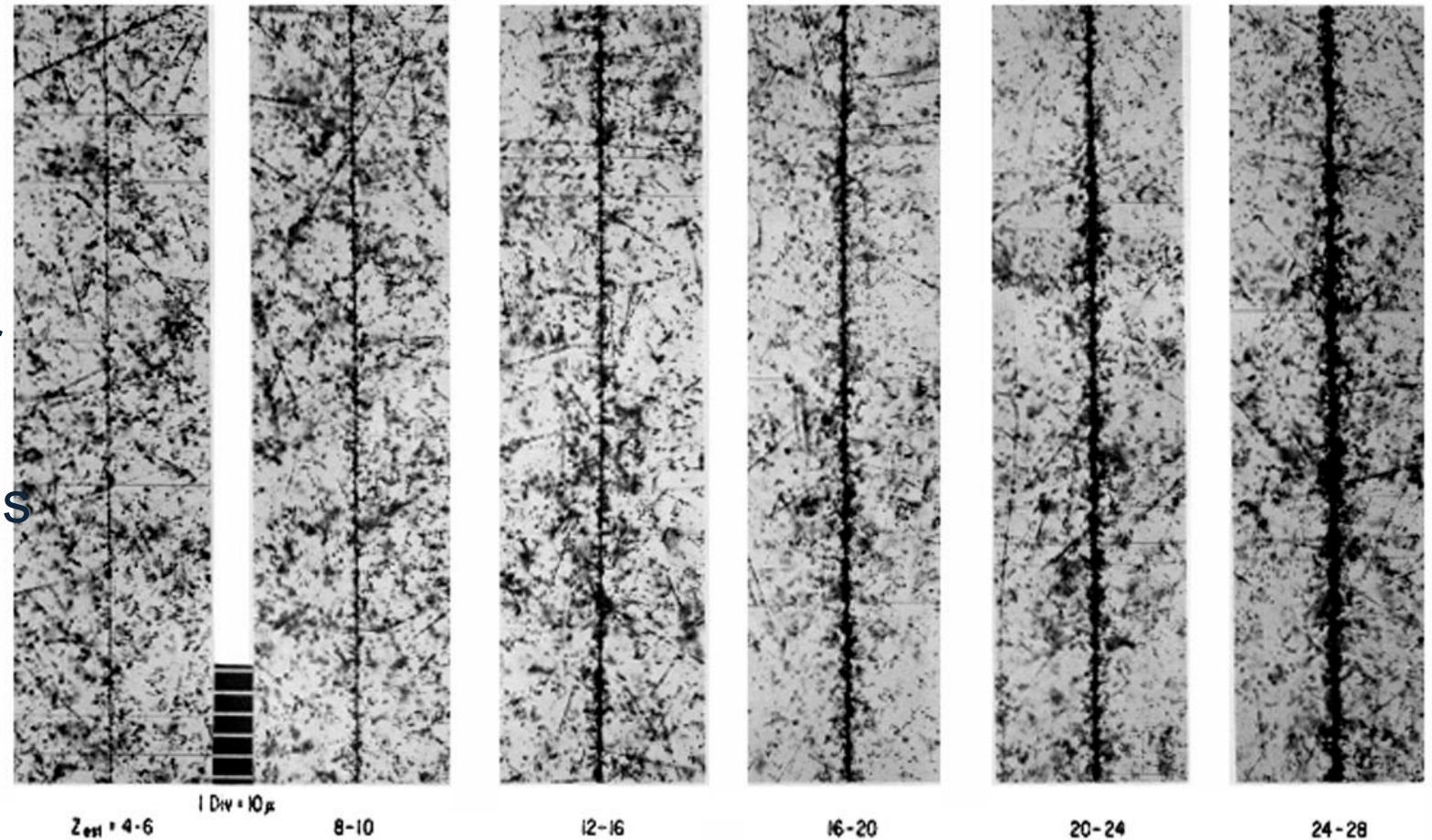
# BLEO Exposure

Space radiation is complex and unlike terrestrial radiation

- High energy, fully ionized particles
  - ✓ Deposit energy along tracks quantified by linear energy transfer (LET)
  - ✓ Ionization density depends on LET and charge ( $Z$ )

- GCR composition

- 87% protons
- 12% helium
- 1% High charge & energy (HZE) ions  $Z > 2$



High Energy Sections of HZE Particle Tracks in Ilford G.5 Emulsion Flown on Apollo 8

# Observed Effects of Radiation on Humans

## Deterministic

- Driven by **cell killing/inactivation**
- Tissue damage and functional loss past a threshold
- Severity increases with dose



- Examples:
- Acute radiation syndrome
  - Heart disease\*
  - Cataract
  - Sterility

## Stochastic/Probabilistic

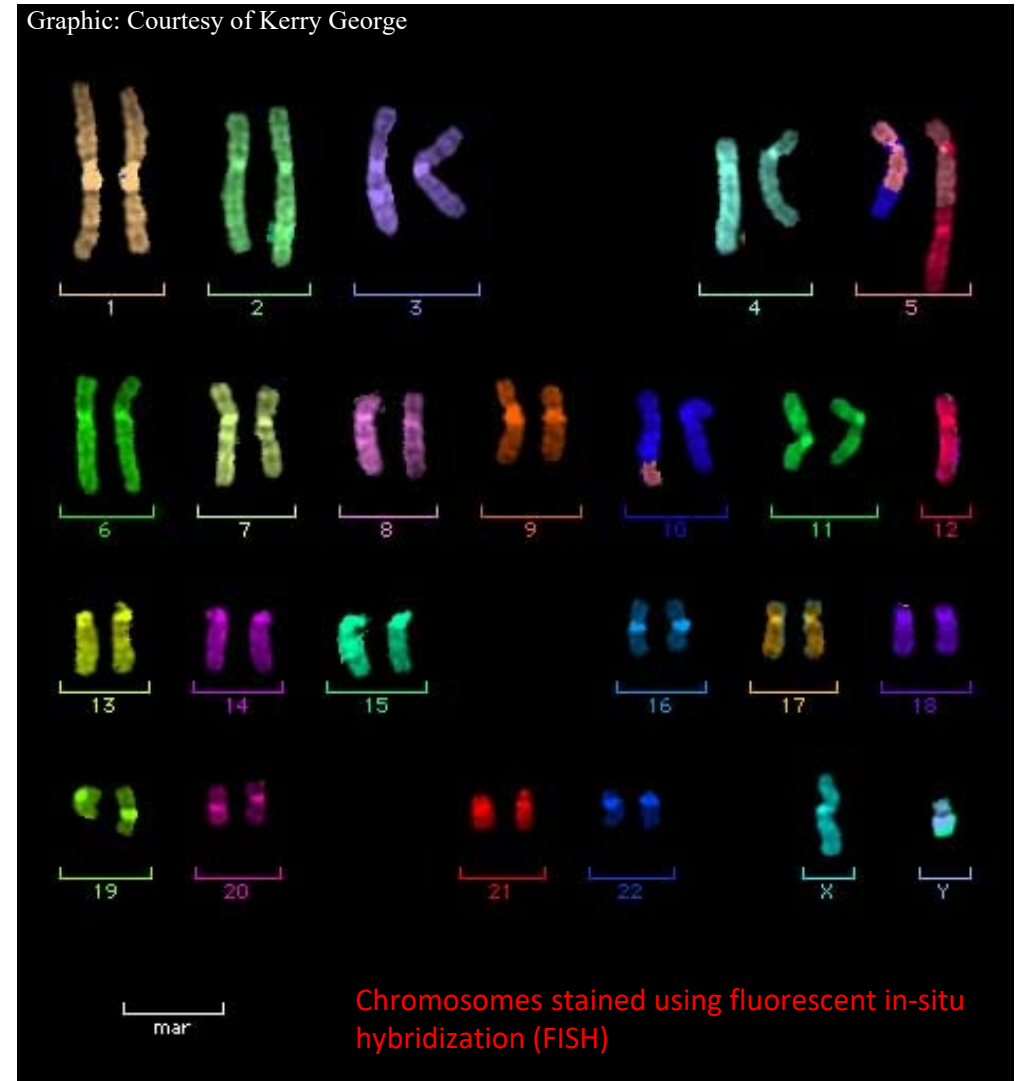
- Driven by **cellular mutations**
- Effect probability increases with dose
  - Assume no threshold
- Severity does NOT increase with dose



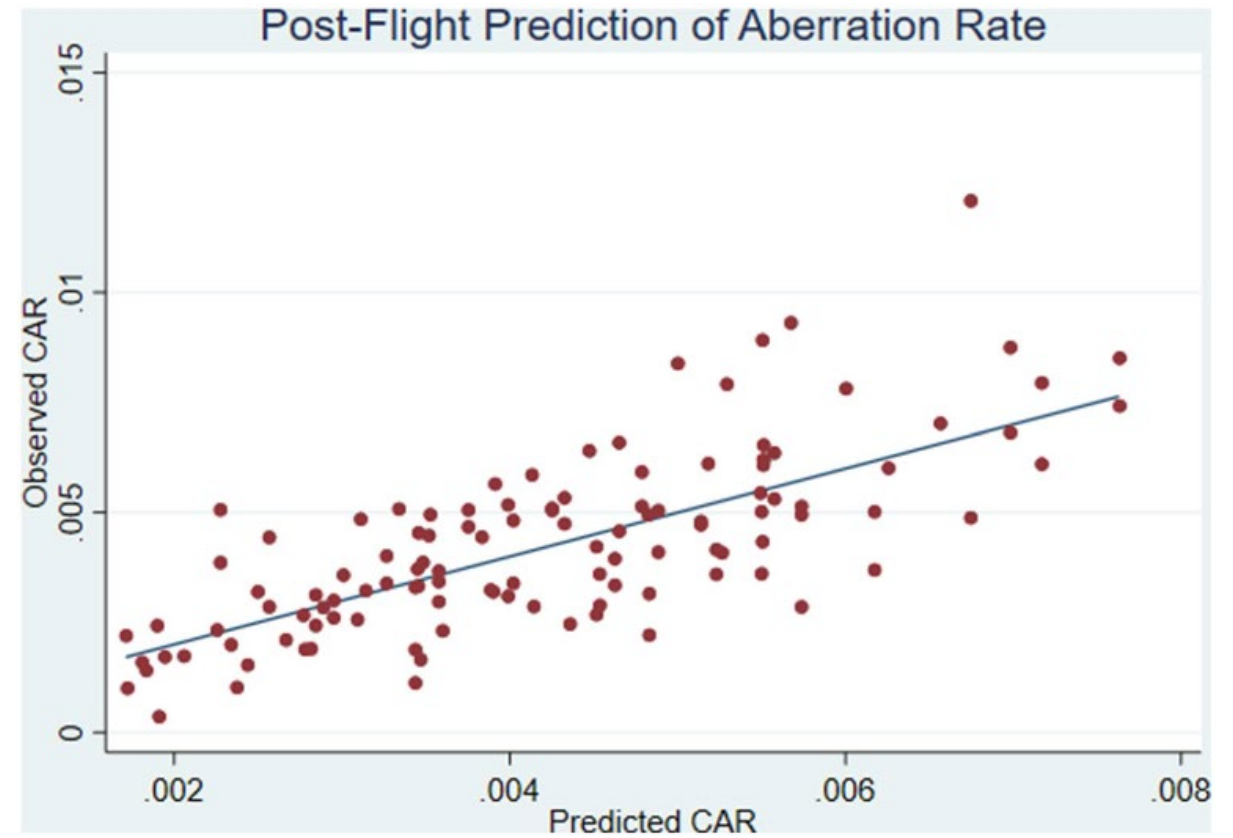
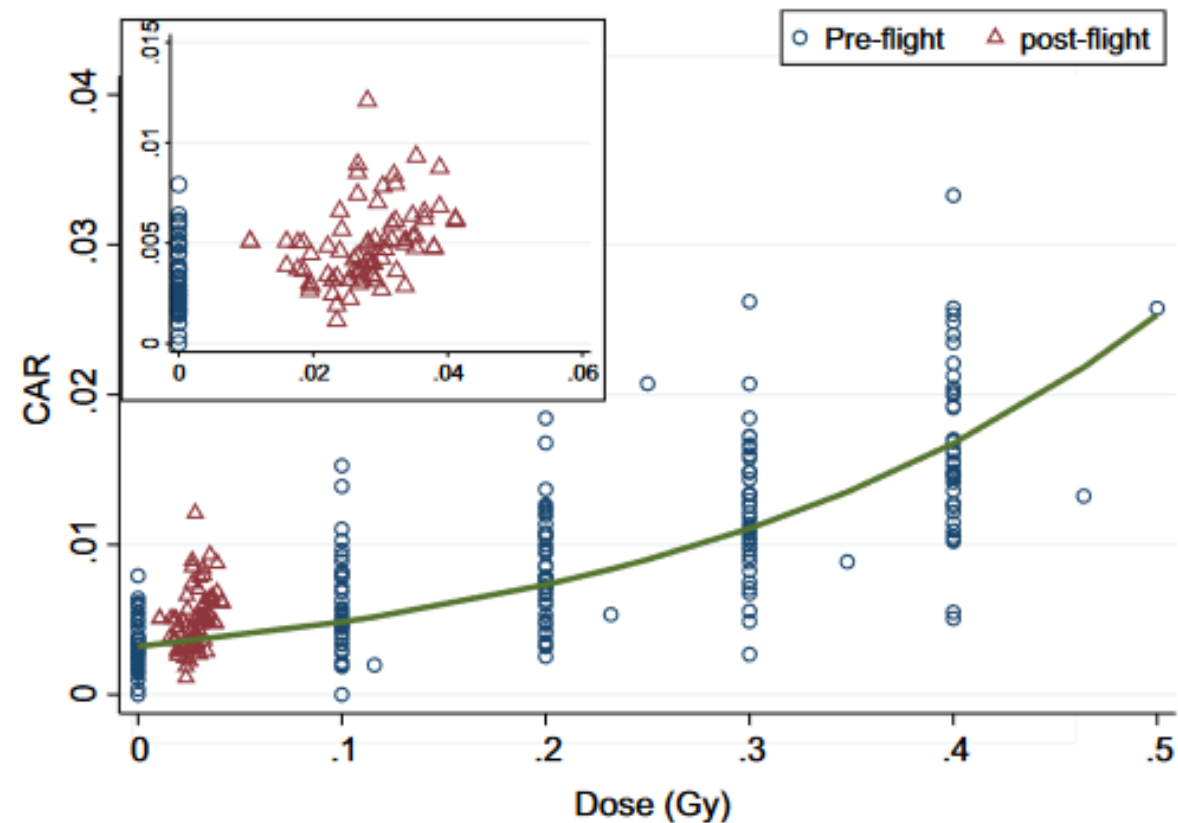
- Examples:
- Solid cancers
  - Leukemia

# DNA Damage and Repair

- Ionizing radiation induces DNA damage
  - Crosslinking
  - Nucleotide base damage and loss
  - Hydrogen bond breakage
  - ~1,000 single strand breaks/Gy
  - ~70 double strand breaks/Gy
    - Most hazardous form of DNA damage
- Damage alters physical configuration of DNA
  - Detected by cell
  - Initiates repair mechanisms
  - Repair depends on damage AND cell
- Accumulation of un- or mis-repaired damage lead to health effects



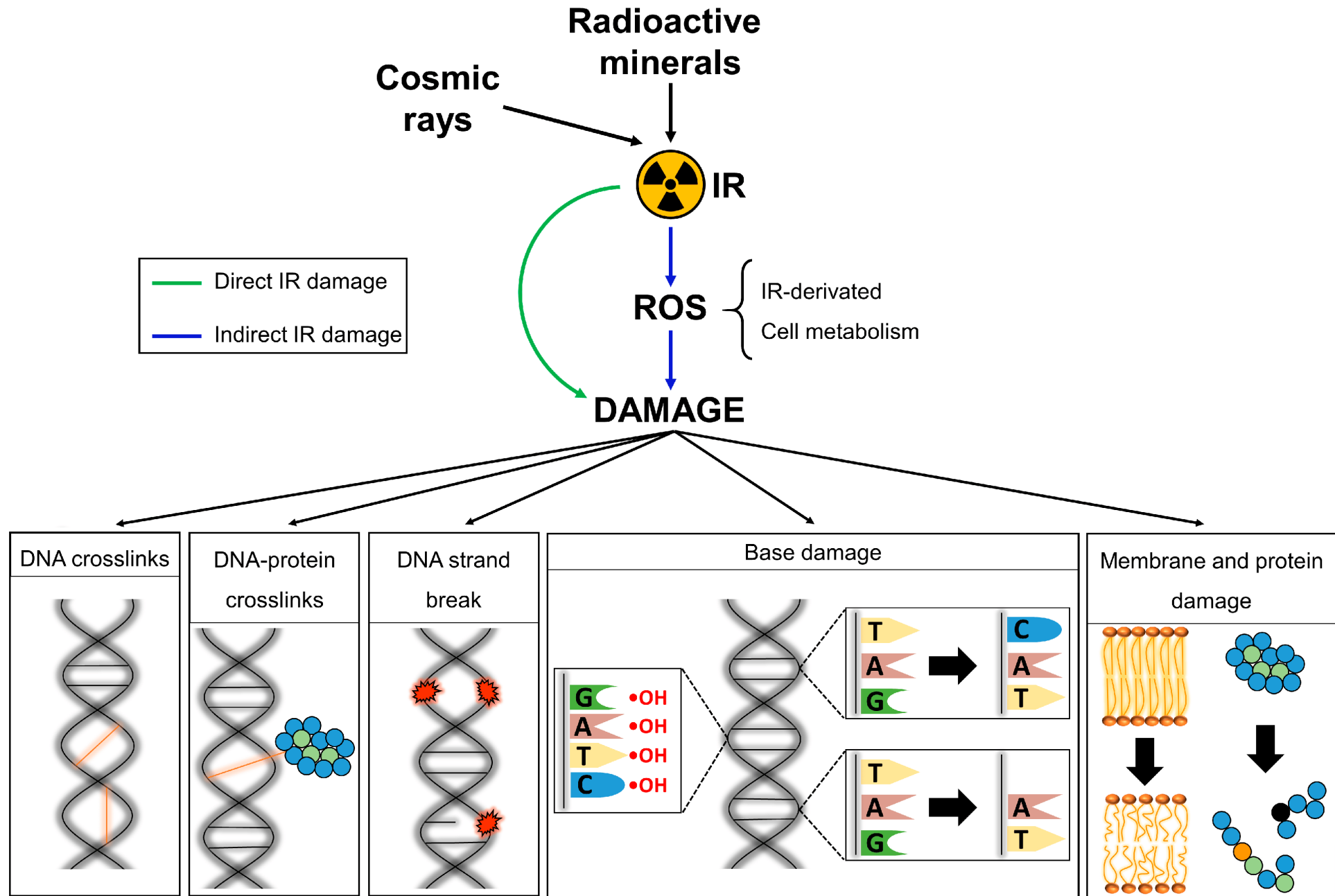
# Chromosomal aberrations



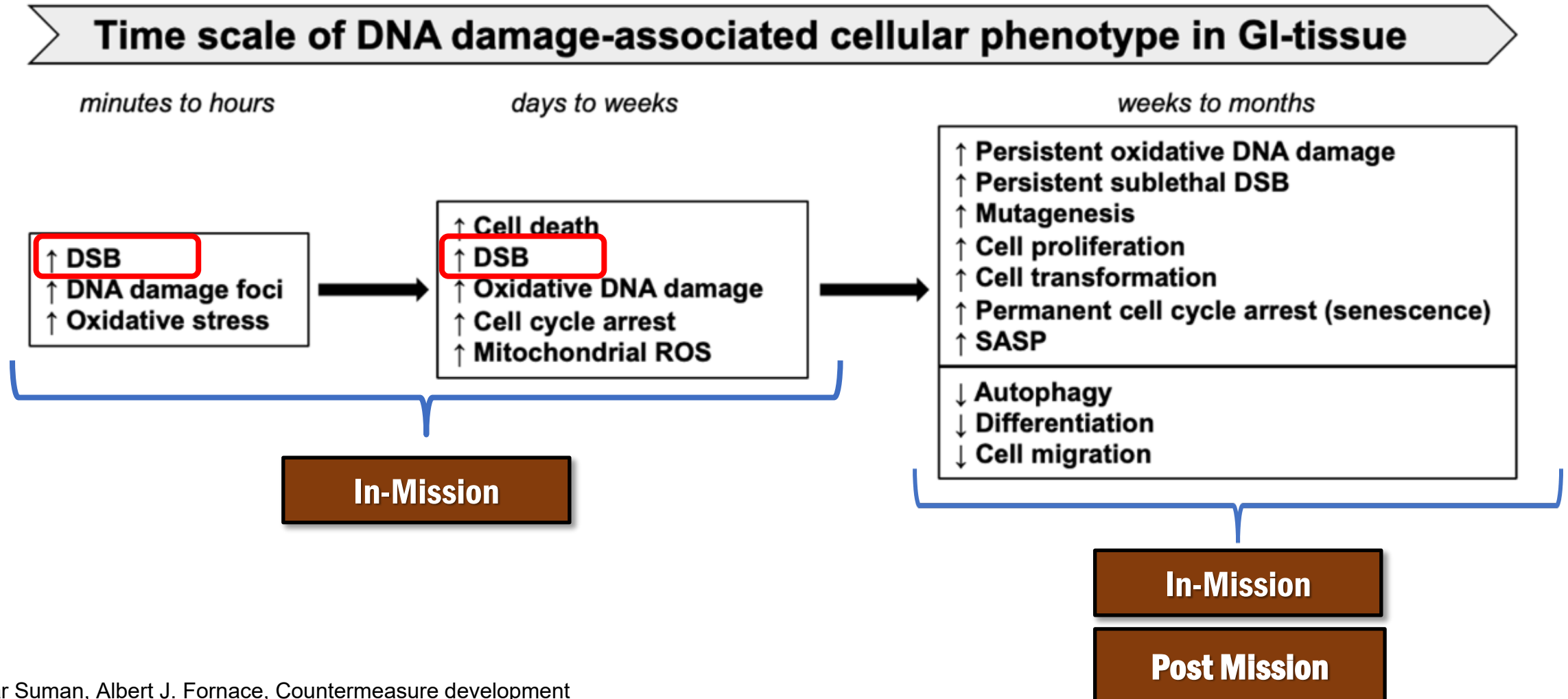
Observed chromosome aberration rate (CAR) in lymphocytes collected from the ISS crewmembers pre-flight (blue circles) and post-flight (red triangles), plotted against dose where "dose" is either the ex-vivo gamma-ray dose in Gy (pre-flight) or the estimated BFO dose in Gy, received during flight

**RISK  
FACTOR**

Feiveson, A., *et al.* Predicting chromosome damage in astronauts participating in international space station missions. *Sci Rep* **11**, 5293 (2021).



# Radiation Damage



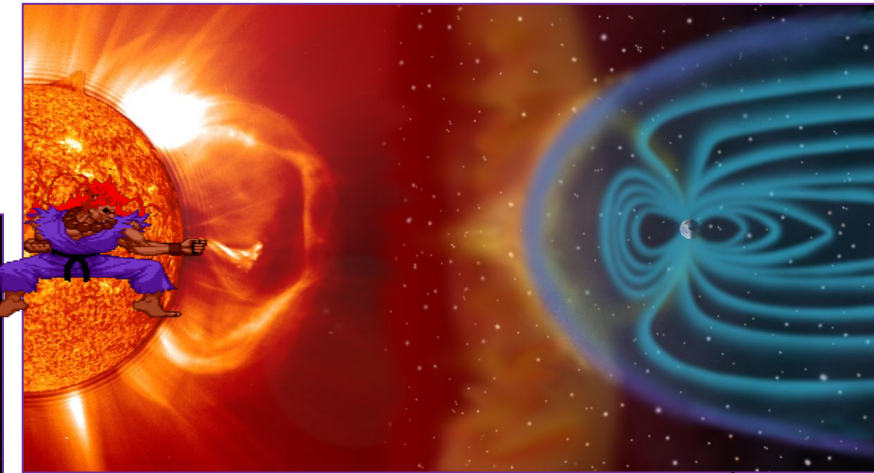
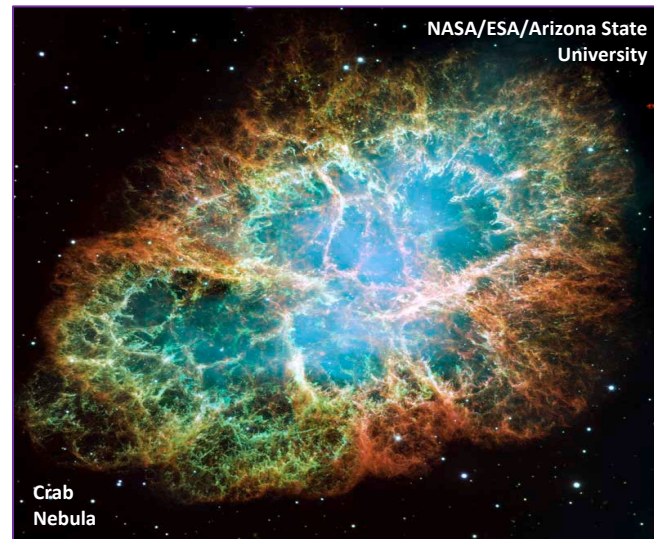
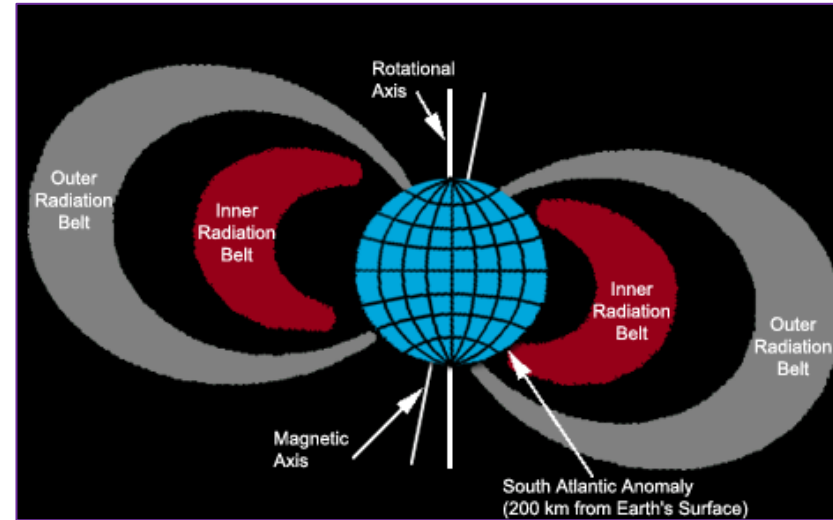
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# Space Radiation

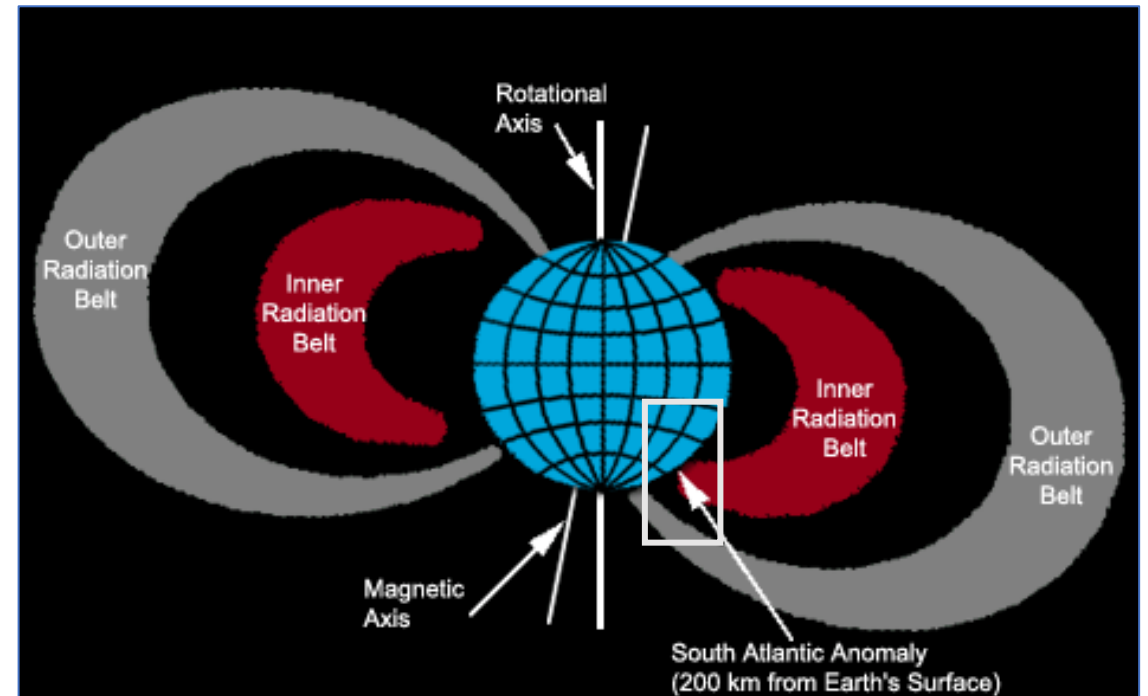
- Why does NASA care about radiation?
  - Space is a “radiation environment” Workplace hazard
    - Astronauts are radiation workers
- Space radiation is different than terrestrial radiation
  - Mainly high energy particles
    - Trapped Radiation
    - Solar Particle Events (SPE)
    - Galactic Cosmic Rays (GCR)



gif by Crazy Picture/CC BY-SA 3.0

# Trapped Radiation – “Van Allen Belts”

- Energetic particles trapped in Earth’s magnetic field (magnetosphere)
  - Protons – Inner Belt
    - South Atlantic Anomaly (SAA)
  - Electrons – Inner and Outer Belt
    - EVA hazard: can penetrate EVA suit but not spacecraft
    - Most prevalent in areas of high-risk orbital alignment or “horns”
- Exposure altitude/trajectory dependent

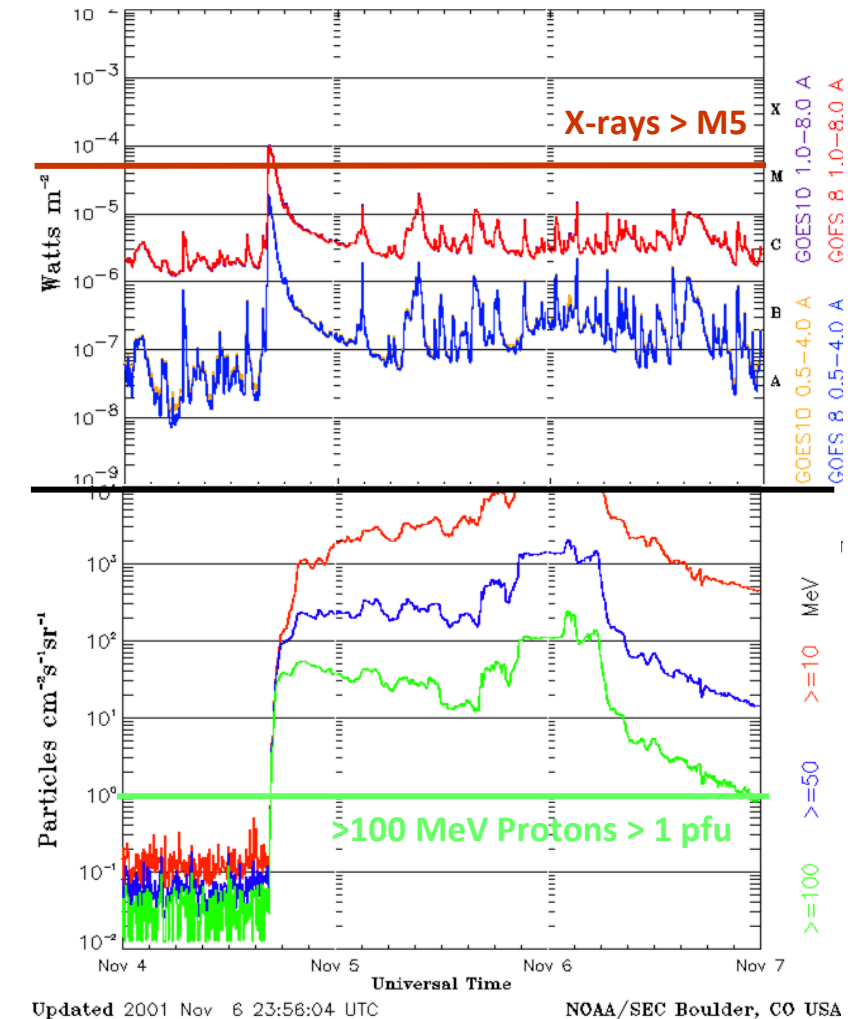


# Solar Events

- Originate from solar energy releases
- Cause largest changes in local radiation environment
- Predominantly protons
  - Energies up to 1000 MeV
  - **>10 MeV penetrate a spacesuit**
  - **>100 MeV penetrate typical spacecraft**

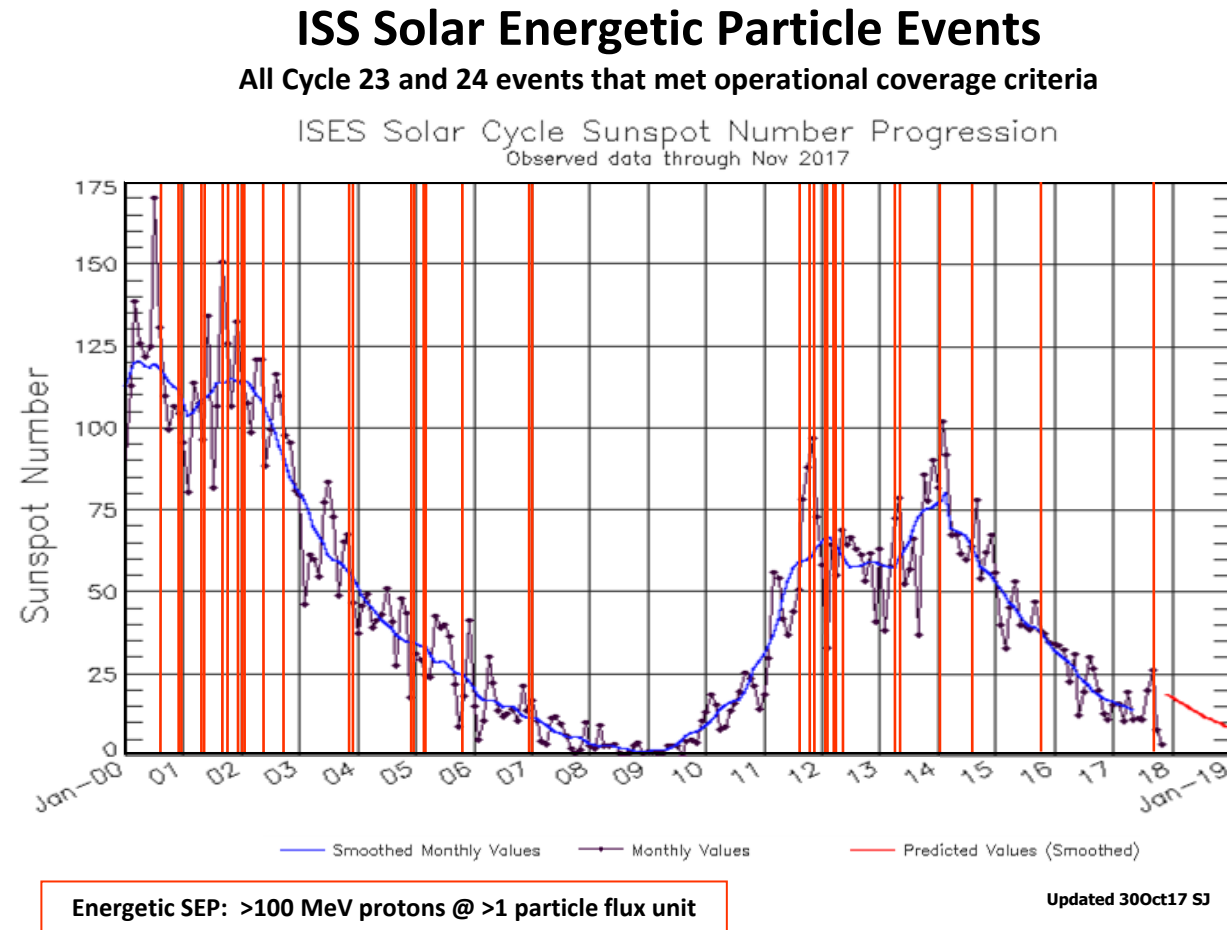
visit [www.swpc.noaa.gov](http://www.swpc.noaa.gov)

SPACE WEATHER PREDICTION CENTER -  
NATIONAL OCEANIC AND ATMOSPHERIC  
ADMINISTRATION



# Solar Events

- Cannot forecast solar events
  - Frequency increases in Solar Max
  - Intensity or duration not impacted by solar cycle
  - Multiple events possible as regions migrate and develop
  - Difficult to project event evolution
- Minimal crew exposures to date
  - Significant protection by Earth's geomagnetic field
  - Fortunate "phasing"

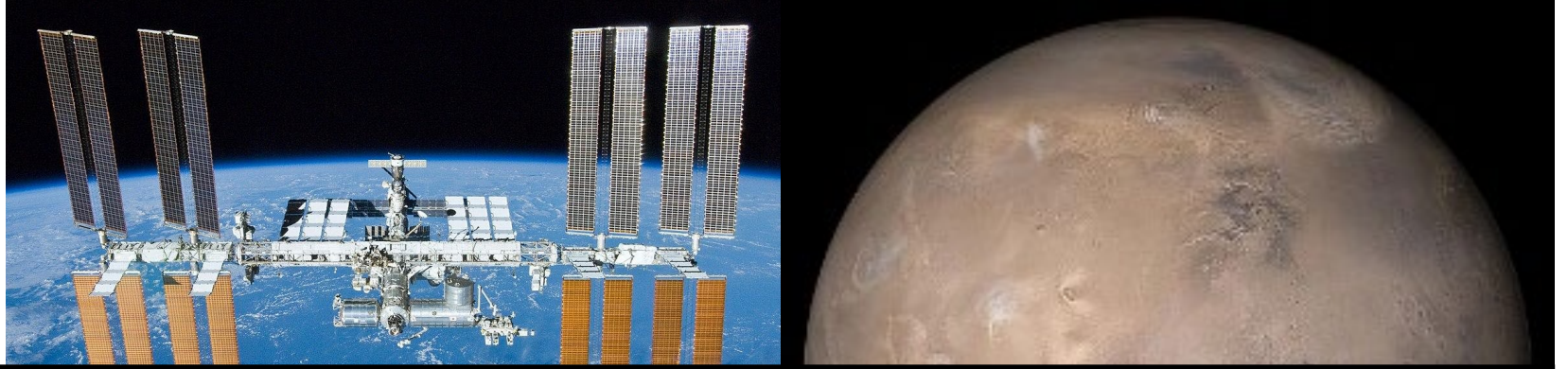


# Galactic Cosmic Rays

- Originate outside the solar system
- Modulated by the solar cycle
  - Highest at Solar Minimum
  - Lowest at Solar Maximum
- Composition
  - Protons (H): 87%
  - Helium (He): 12%
  - Heavier particles: 1%
    - High atomic number and energy (HZE) particles
    - Increased biological damage
- Penetrating radiation



# The Space Radiation Environment



Exposure Type	ISS (51.6° inclination)	Beyond Leo Earth Orbit
Galactic Cosmic Rays (GCR)	<ul style="list-style-type: none"> <li>• <b>Limited to polar regions</b></li> <li>• <u>Fractionated</u> low dose-rate</li> <li>• ~ 87% protons, 12% Helium, 1% HZE</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Continuous</b></li> <li>• <u>Chronic</u> low dose-rate</li> <li>• ~ 87% protons, 12% Helium, 1% HZE</li> </ul>
Trapped Radiation	<ul style="list-style-type: none"> <li>• <b>South Atlantic Anomaly (SAA)</b></li> <li>• Fractionated low dose-rate</li> <li>• Protons</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Transit through Van Allen Belts</b></li> <li>• Quasi-acute</li> <li>• Protons</li> </ul>
Solar Particle Events (SPEs)	<ul style="list-style-type: none"> <li>• <b>Limited to polar regions</b></li> <li>• Fractionated low dose-rate</li> <li>• Protons</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Full Event</b></li> <li>• Quasi-acute</li> <li>• Protons</li> </ul>
Neutrons, Secondary Radiation	<ul style="list-style-type: none"> <li>• Shielding</li> <li>• <u>Chronic</u> low dose-rate</li> </ul>	<ul style="list-style-type: none"> <li>• Shielding</li> <li>• <b>Planetary (albedo)</b></li> <li>• <u>Chronic</u> low dose-rate</li> </ul>

# The Space Radiation Environment

- Doses depend on mission and solar parameters
  - Duration
  - Trajectory and shielding
    - Determine source exposure
    - Effects radiation
    - EVAs
  - Solar cycle
    - 11-year cycle
    - Modulates GCR and trapped radiation fluence, as well as SPE *likelihood*
- Each crew member is badged
- Active radiation area monitoring

Exposure Type	Dose Rate or Dose
ISS – IV: 51.6° @ 400 km	300 – 450 μGy/day
GCR in “free space” in water CRaTER (2009 to present)	250 – 550 μGy/day
1972 event – IV “free space”	200 – 400 mSv
Sheltered 1972 event	~ 80 mSv

*IV: Intravehicular (Inside a vehicle or habitat)*



## Average tracks per cell nucleus per year, dose (mGy/year), and percent contribution of particles to dose normalized to 500 mGy.

Particle Type	Average tracks per cell nuclei <sup>a</sup>	Dose (mGy/Year)	Percent contribution (%)	Percent contribution of normalized dose to 500 mGy (%)
$\pi$ /EM	0.1	15.5	11.6	0
Neutron	N/A	1.1 <sup>b</sup>	0.8	0
hydrogen	126	86 <sup>c</sup>	64.2	73.3
helium	7	22.5 <sup>d</sup>	16.8	19.2
HZE	0.5	8.9	6.6	7.6
total	133.6	134	100	100

<sup>a</sup>Assumes a cell nucleus cross section of  $100 \mu\text{m}^2$

<sup>b</sup>Dose exclusively from heavy target fragments ( $Z \geq 3$ ) produced from inelastic neutron interactions.

<sup>c</sup>Includes contributions from elastic and inelastic reaction products of  $Z = 1$  from neutron interactions.

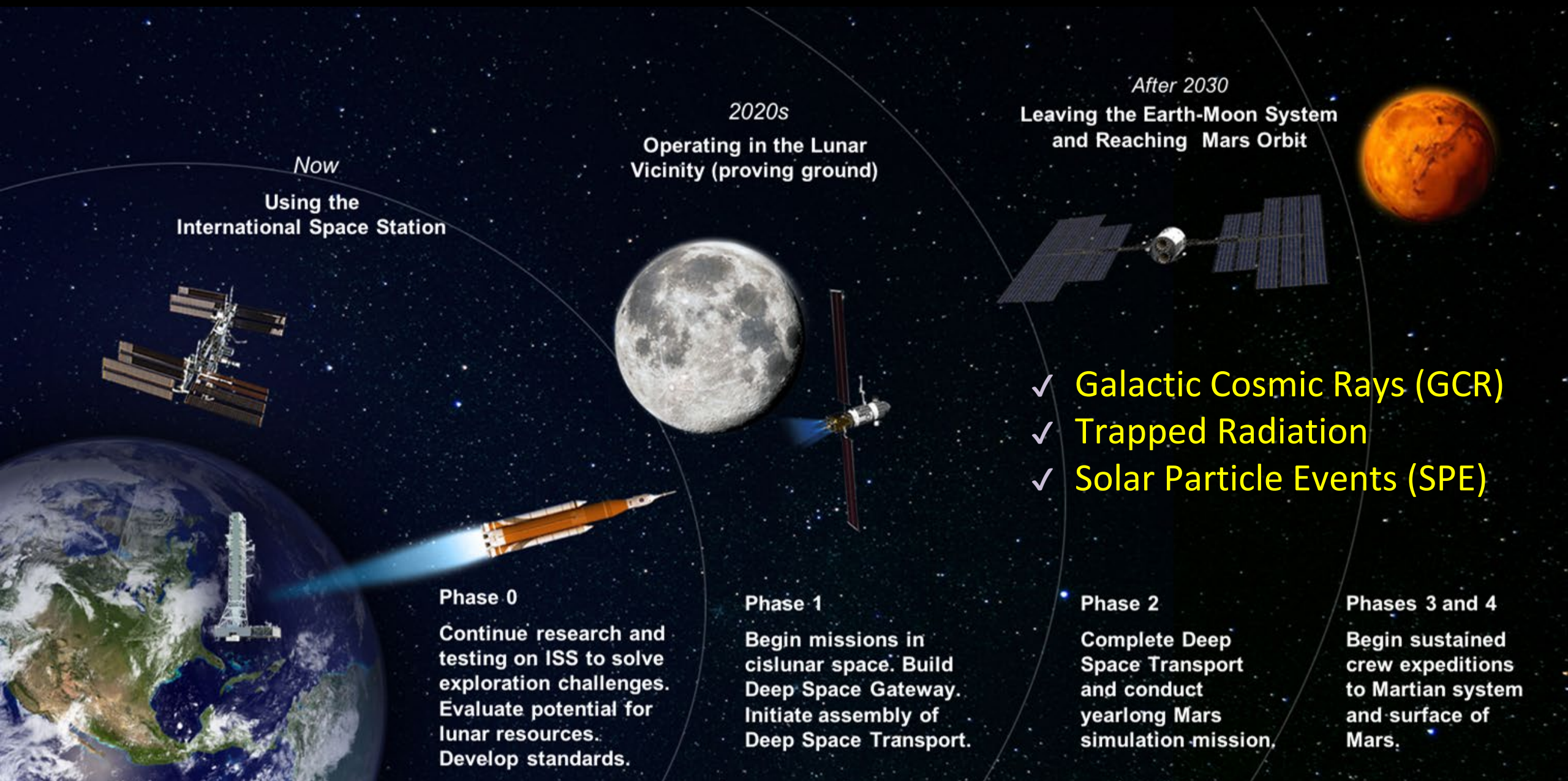
<sup>d</sup>Includes contributions from inelastic reaction products of  $Z = 2$  from neutron interactions.

**Abbreviations:** EM, electromagnetic radiation; HZE, high charge and high energy ions

Simonsen LC, et al. (2020) NASA's first ground-based Galactic Cosmic Ray Simulator: Enabling a new era in space radiobiology research. PLOS Biology 18(5): e3000669. <https://doi.org/10.1371/journal.pbio.3000669>



# Planned Exploration Activities



*Now*  
Using the International Space Station



**Phase 0**  
Continue research and testing on ISS to solve exploration challenges. Evaluate potential for lunar resources. Develop standards.

*2020s*  
Operating in the Lunar Vicinity (proving ground)



**Phase 1**  
Begin missions in cislunar space. Build Deep Space Gateway. Initiate assembly of Deep Space Transport.

*After 2030*  
Leaving the Earth-Moon System and Reaching Mars Orbit

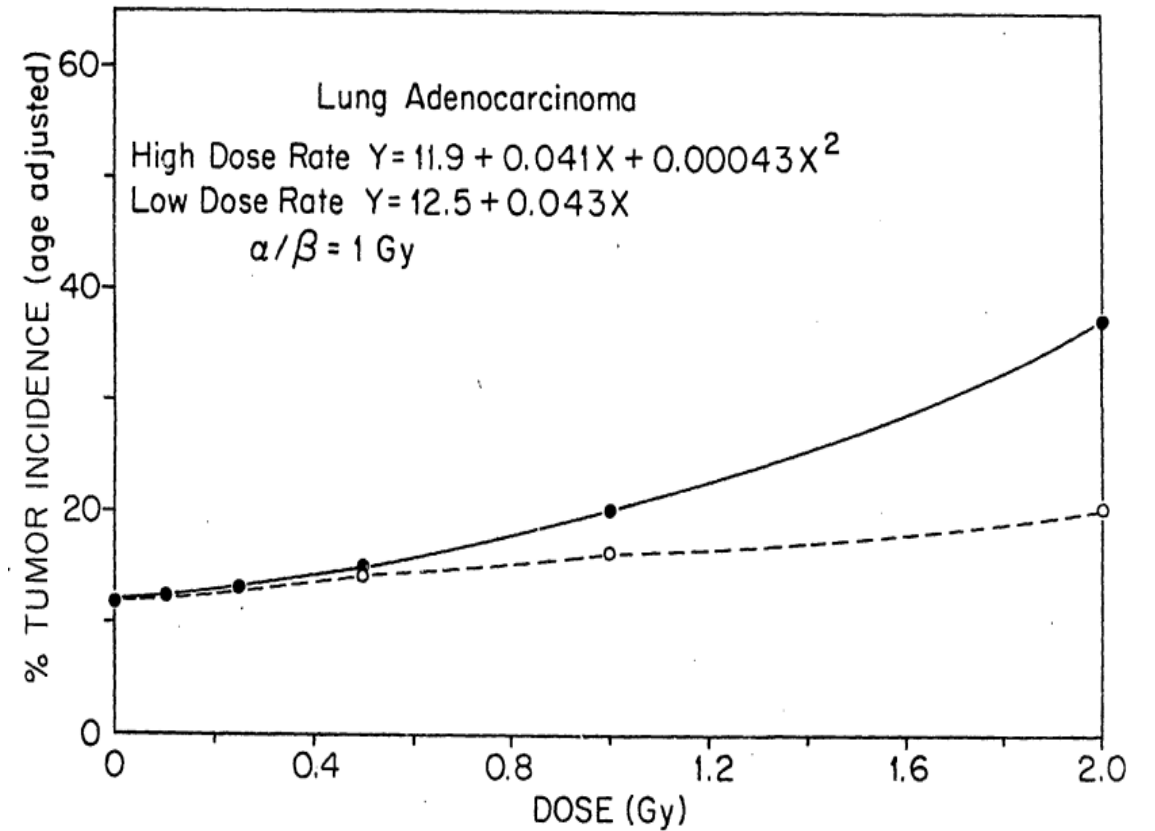
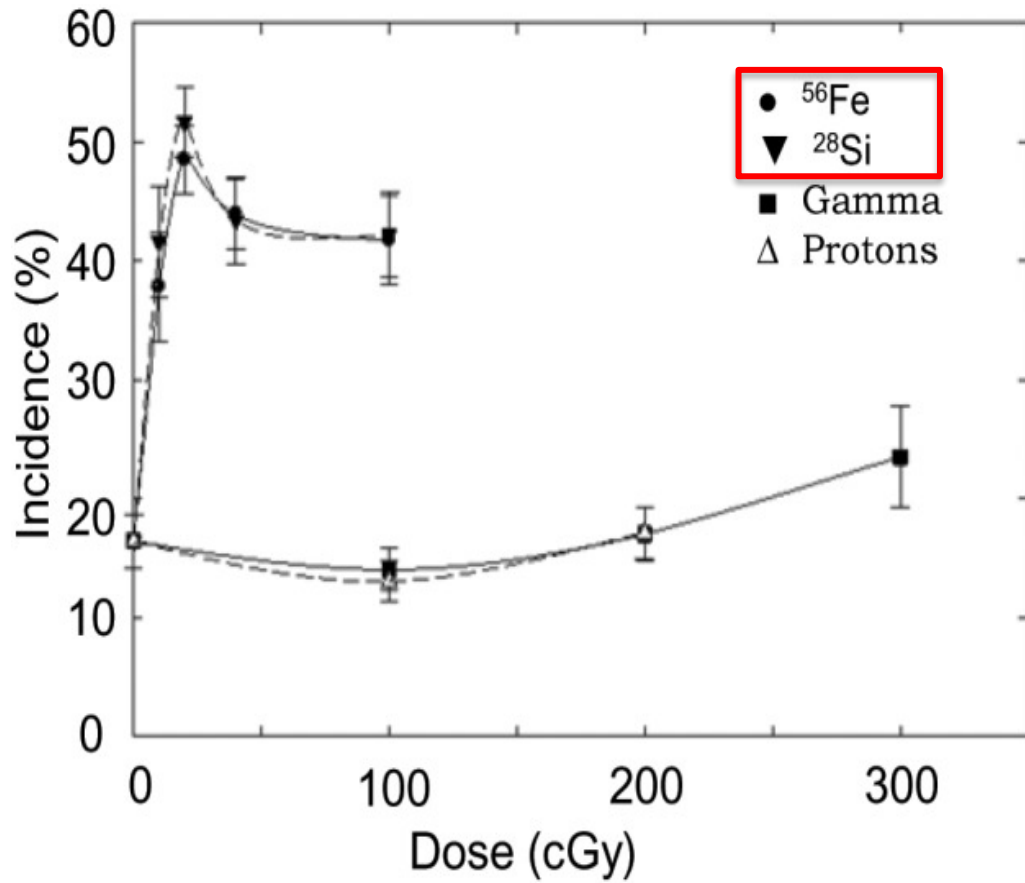


- ✓ Galactic Cosmic Rays (GCR)
- ✓ Trapped Radiation
- ✓ Solar Particle Events (SPE)

**Phase 2**  
Complete Deep Space Transport and conduct yearlong Mars simulation mission.

**Phases 3 and 4**  
Begin sustained crew expeditions to Martian system and surface of Mars.

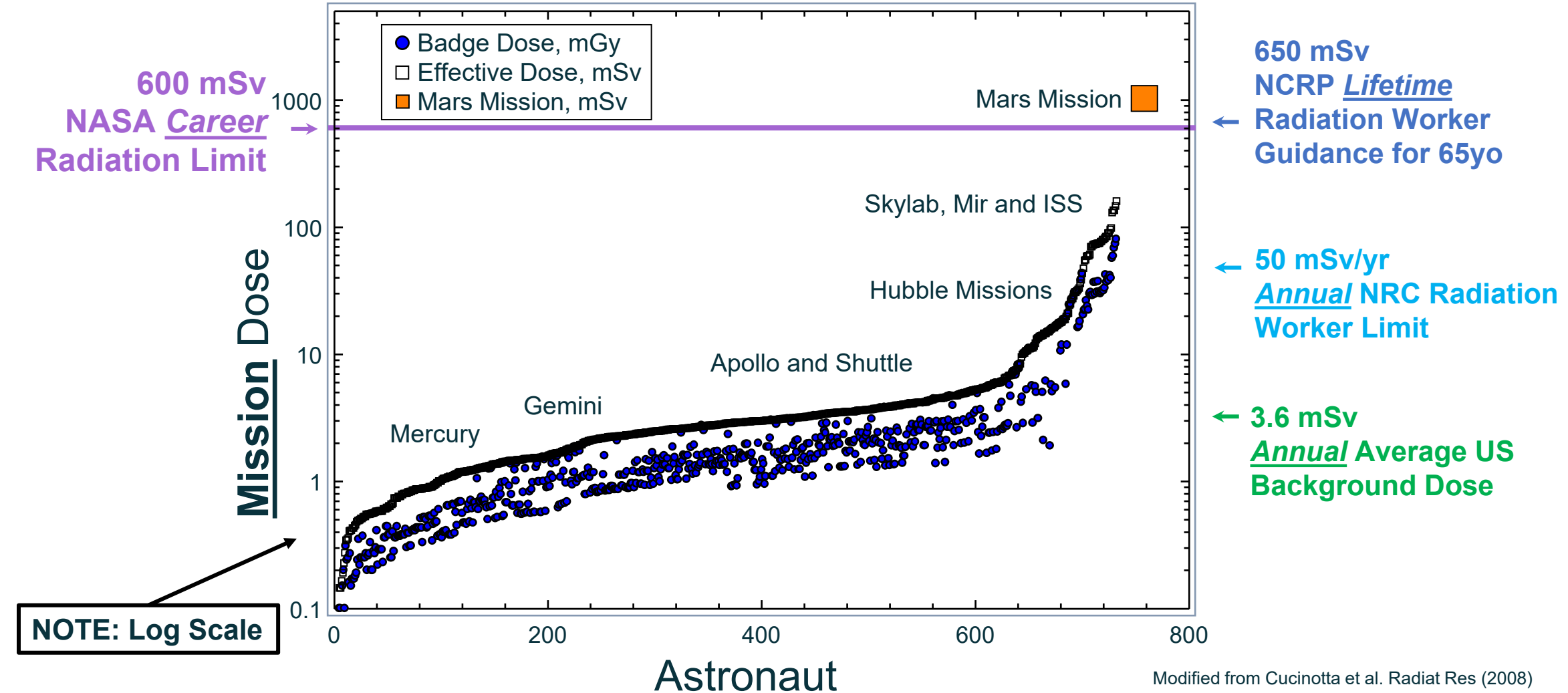




Weil et. al. (2014, PLOS One)

Ullrich (1986, Oakridge National Lab Annual Report)

# Historical NASA Crew Mission Doses





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# HRP Integrated Path to Risk Reduction

Unique ID	Exploration DRMs Exploration Mission Milestones (HRP Delivery Dates) RISKS	Artemis Launches LxC	FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30 FY31 FY32 FY33 FY34 FY35 FY36 FY37 FY38 FY39 FY40 FY41 FY42 FY43																			
1	Spaceflight Associated Neuro-ocular Syndrome (HHC-SANS)	4x4	[Risk reduction chart for HHC-SANS]																			
2	Celestial Dust Exposure (ExMC-Dust)	4x4 *	[Risk reduction chart for ExMC-Dust]																			
3	Cardiovascular Adaptations (HHC-Cardiovascular)	4x4 *	[Risk reduction chart for HHC-Cardiovascular]																			
4	Cognitive or Behavioral Conditions (HFBP-Behavioral Med.) *IN WORK*	5x3 *	[Risk reduction chart for HFBP-Behavioral Med.]																			
5	Injury from Dynamic Loads (HFBP-Dynamic Loads)	5x4*	[Risk reduction chart for HFBP-Dynamic Loads]																			
6	Spaceflight Induced Changes to Bone (HHC-Bone Fracture)	4x4 *	[Risk reduction chart for HHC-Bone Fracture]																			
7	Team Performance Decrements (HFBP-Team) *IN WORK*	5x5*	[Risk reduction chart for HFBP-Team]																			
8	Human Systems Integration Architecture (HFBP-HSIA)	5x3 *	[Risk reduction chart for HFBP-HSIA]																			
9	Injury Due to EVA Operations (HHC-EVA)	5x5*	[Risk reduction chart for HHC-EVA]																			
10	Inadequate Food and Nutrition (HHC-Food and Nutrition)	3x4	[Risk reduction chart for HHC-Food and Nutrition]																			
11	Medical Conditions In-Mission Long Term Health (ExMC-Medical Conditions)	5x4 *	[Risk reduction chart for ExMC-Medical Conditions]																			
12	Ineffective or Toxic Medications (ExMC-Pharm)	5x3*	[Risk reduction chart for ExMC-Pharm]																			
13	Renal Stone Formation (ExMC-Renal Stone)	4x4*	[Risk reduction chart for ExMC-Renal Stone]																			
14	Altered Immune Response (HHC-Immune)	4x3*	[Risk reduction chart for HHC-Immune]																			
15	Host-Microorganism Interactions (HHC-Microhost)	4x3*	[Risk reduction chart for HHC-Microhost]																			
16	Vestibular Sensorimotor Impacts (HHC-Sensorimotor)	4x2*	[Risk reduction chart for HHC-Sensorimotor]																			
17	Space Radiation Carcinogenesis (SR-Carcinogenesis)	1x1	[Risk reduction chart for SR-Carcinogenesis]																			
18	Sleep Loss and Circadian Misalignment (HFBP-Sleep)	5x2	[Risk reduction chart for HFBP-Sleep]																			

- █ High L x C: Requires Mitigation
- █ Med L x C: Requires Mitigation
- █ Low L x C

Risk Class: ISS Required     Risk Class: ISS Not Required     ▲ Milestone: Requires ISS     ▲ Ground Based: Milestone     Anticipated (PRR-Color Change) Shift  
▲ Completed (PRR-Color Change) Shift     █ High LxC     █ Mid LxC: Requires Mitigation     █ Mid LxC: Accepted     █ Low LxC  
▲ Optimized     Insufficient Data     ▲ Exploration Mission Milestone     ▲ Mission Date  
 \* (Asterisk) Updated to New HSRB LxC 5x5 Scale

PPBE20 Baseline  
 HRP-Approved  
 27 June 2018

# Space Radiation Health Risks

- In-Mission Effects
  - Acute effects
    - Very large high-energy solar events
      - MILD symptoms IF they occur at all given doses
  - *Potential* early changes to the central nervous system
    - Behavior or memory decrements
    - Observed only in animal models at relevant doses
- Long Term Health (post-mission)
  - Cancer
    - Space radiation may cause unique impacts
  - Degenerative
    - Cardiovascular disease
    - Cataracts
    - Immune changes
  - *Potential* late changes to the central nervous system
    - Behavior or memory decrements
    - Neurodegenerative disease
    - Observed only in animal models at space relevant doses

# A Note on Acute Radiation Syndrome

- **Large** amounts of radiation can lead to serious *acute* consequences or death
  - How large? It depends...
    - Dose-rate
    - Body location and coverage
    - Individual sensitivity
- Severity increases with total dose and dose rate

Dose Range (Gy)	Prodrome	Manifest Symptoms	Survival Expectancy
0.5 – 1.0	Mild	Slight decrease in blood cell counts	Almost certain survival
1.0 – 2.0	Mild-moderate	Mild bone marrow (BM) damage	High probability of survival (>90%)
2.0 – 3.5	Moderate	Moderate to severe BM damage	Probable survival (>50%)
3.5 – 5.5	Severe	Severe BM damage Slight gastrointestinal (GI) damage	Death within 3.5 – 6 weeks (50%)
5.5 – 7.5	Severe	Pancytopenia Moderate GI damage	Death probable within 2 – 3 weeks
7.5 – 10.0	Severe	Severe GI damage Hypotension	Death probable within 1 – 2.5 weeks
10.0 – 20.0	Severe	Severe GI damage Pneumonitis Neurologic signs (altered mental status, cognitive dysfunction)	Death certain within 5 – 12 days
>20.0	Severe	Cerebrovascular collapse, coma Fever Shock	Death certain within 2 – 5 days

# What About Spaceflight?

- Concern ONLY for a LARGE SPE
  - Total whole-body doses can approach concerning levels – if you could stay outside that long...
  - During a solar event, get inside!
    - A little shielding goes a long way and there's breathable air
  - Life-threatening doses **highly unlikely**

Dosimetry quantities	August 1972 SPE				October 1989 SPE				September 1989 SPE			
	EVA 0.3 g/cm <sup>2</sup>	Spacecraft 5 g/cm <sup>2</sup>	10 g/cm <sup>2</sup> shielding	25 g/cm <sup>2</sup> shielding	EVA 0.3 g/cm <sup>2</sup>	Spacecraft 5 g/cm <sup>2</sup>	10 g/cm <sup>2</sup> shielding	25 g/cm <sup>2</sup> shielding	EVA 0.3 g/cm <sup>2</sup>	Spacecraft 5 g/cm <sup>2</sup>	10 g/cm <sup>2</sup> shielding	25 g/cm <sup>2</sup> shielding
$D_{skin}$ , cGy	2859.27	241.11	20.75	1.74	2416.88	134.75	22.99	5.21	716.83	49.86	9.92	2.56
$G_{stomach}$ , cGy-Eq	41.72	17.00	3.54	0.70	43.43	24.98	9.89	3.42	18.61	11.25	4.82	1.81
$G_{BFO}$ , cGy-Eq	138.65	46.34	7.52	1.11	95.70	45.49	15.04	4.63	37.94	19.32	7.05	2.39
$E$ , cSv	343.47	67.19	9.64	1.89	222.47	52.54	15.53	5.05	75.81	21.48	7.18	2.56
Total time, hrs	63				81				40			

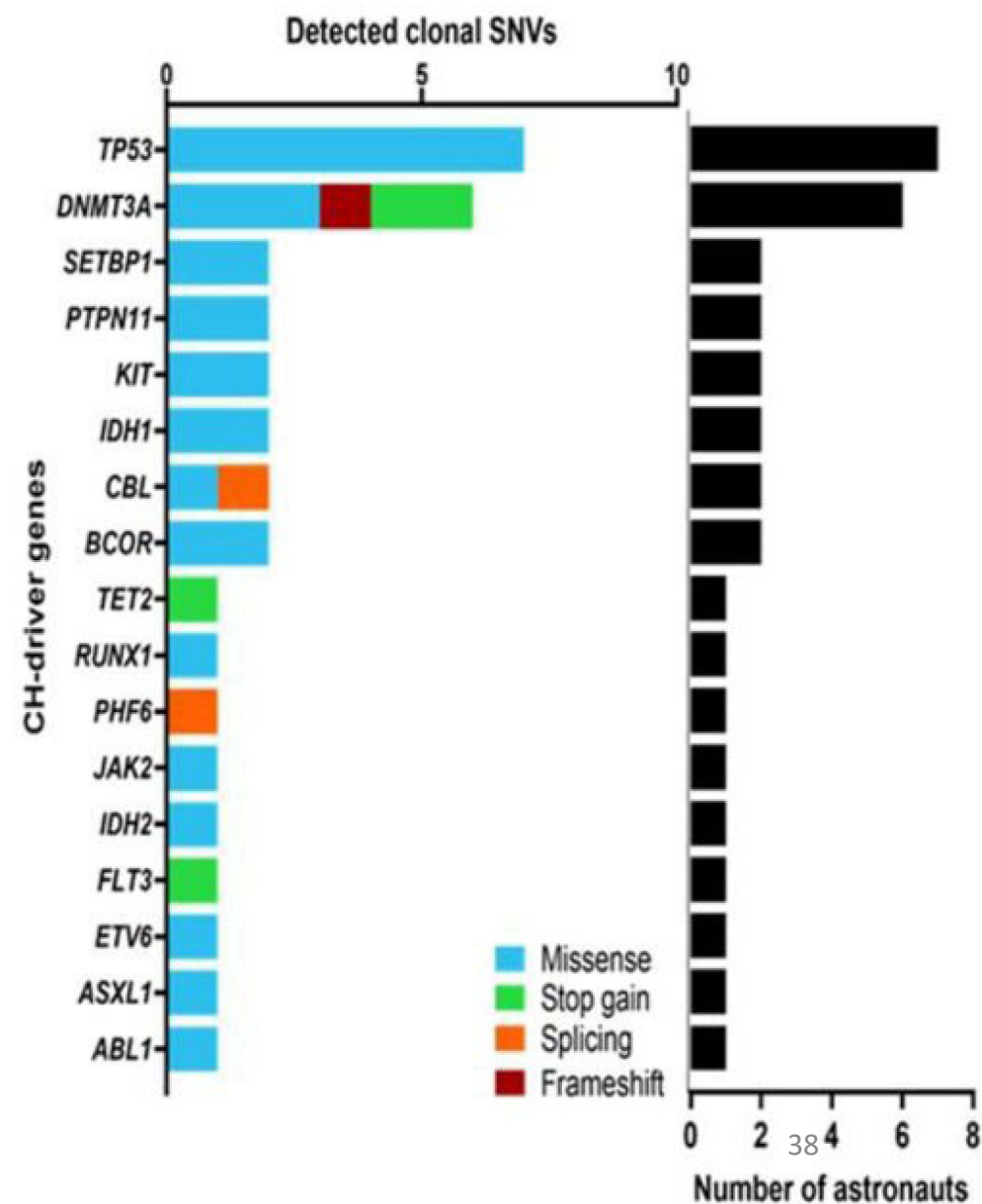
Dosimetry quantities in interplanetary space from total event spectra of three large SPEs. **NOTE:** EVA exposures (0.3 gm/cm<sup>2</sup>) listed are highly unlikely but illustrate the effectiveness of operational protocols where crew would shelter for the majority of event duration, which can last several days.



# Retrospective analysis of somatic mutations and clonal hematopoiesis in astronauts

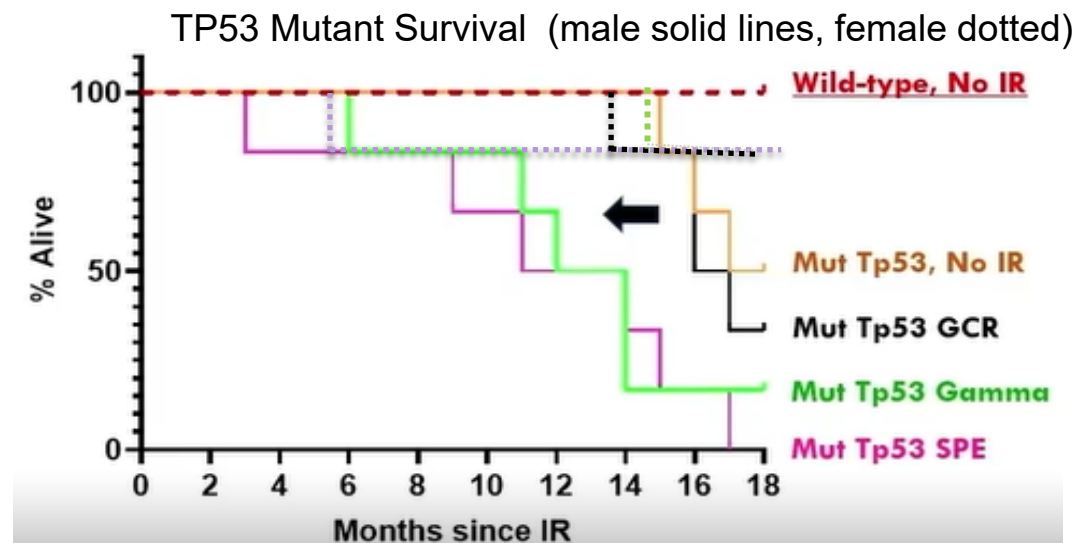
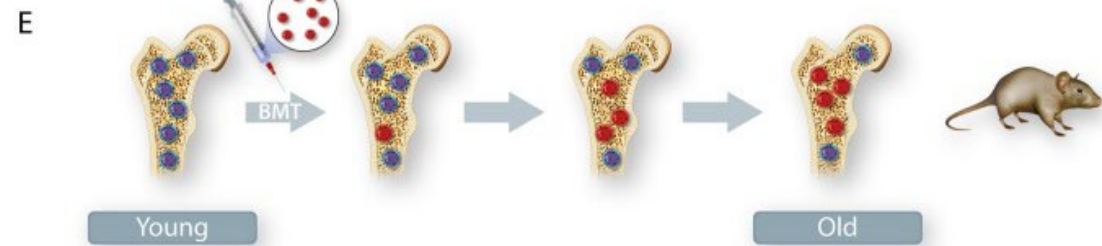
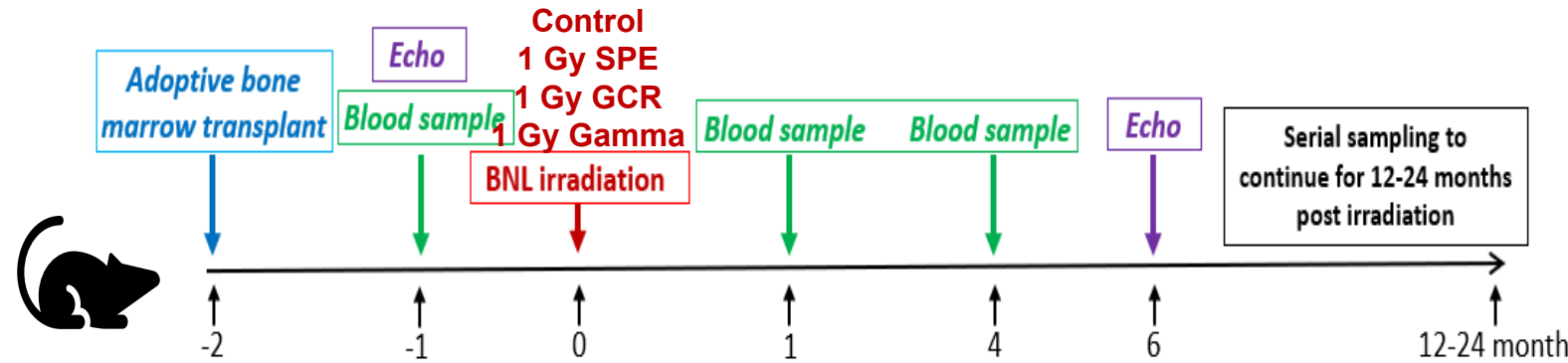
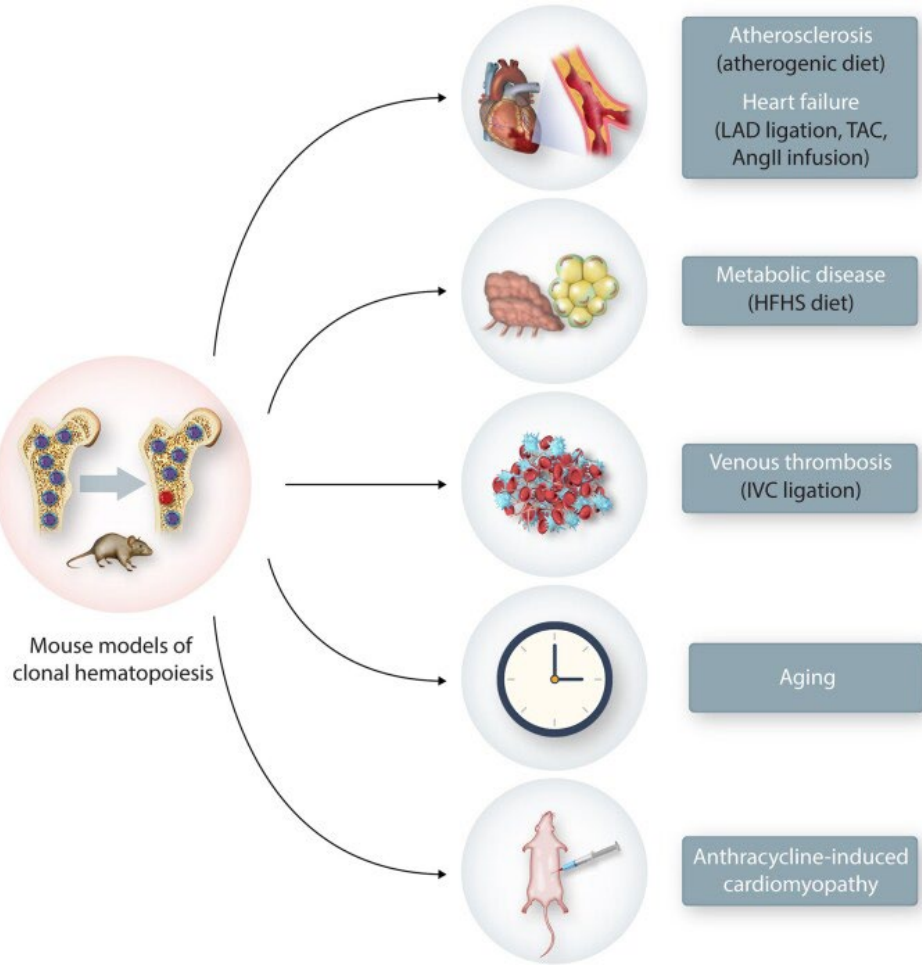
Agnieszka Brojakowska<sup>1,5</sup>, Anupreet Kour<sup>2,5</sup>, Mark Charles Thel<sup>1,2</sup>, Eunbee Park<sup>1,2</sup>, Malik Bissierier<sup>1</sup>, Venkata Naga Srikanth Garikipati<sup>3</sup>, Lahouaria Hadri<sup>1</sup>, Paul J. Mills<sup>4</sup>, Kenneth Walsh<sup>1,2</sup> & David A. Goukassian<sup>1</sup>✉

With planned deep space and commercial spaceflights, gaps remain to address health risks in astronauts. Multiple studies have shown associations between clonal expansion of hematopoietic cells with hematopoietic malignancies and cardiometabolic disease. This expansion of clones in the absence of overt hematopoietic disorders is termed clonal hematopoiesis (CH) of indeterminate potential (CHIP). Using deep, error-corrected, targeted DNA sequencing we assayed for somatic mutations in CH-driver genes in peripheral blood mononuclear cells isolated from de-identified blood samples collected from 14 astronauts who flew Shuttle missions between 1998–2001. We identified 34 nonsynonymous mutations of relatively low variant allele fraction in 17 CH-driver genes, with the most prevalent mutations in *TP53* and *DNMT3A*. The presence of these small clones in the blood of relatively young astronaut cohort warrants further retrospective and prospective investigation of their clinical relevance and potential application in monitoring astronaut's health.



# Space Radiation Exposure and Risk Mediated by Clonal Hematopoiesis

PI: Kenneth Walsh, University of Virginia



# Loss of Y (LOY)

The New York Times

## As Y Chromosomes Vanish With Age, Heart Risks May Grow

A study of mice might explain why.

Share full article



A scanning electron micrograph of human X and Y chromosomes suggests loss of the Y chromosome could explain...

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## Y chromosome linked to cancer and death risk in men

© 22 October 2014



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The Atlantic

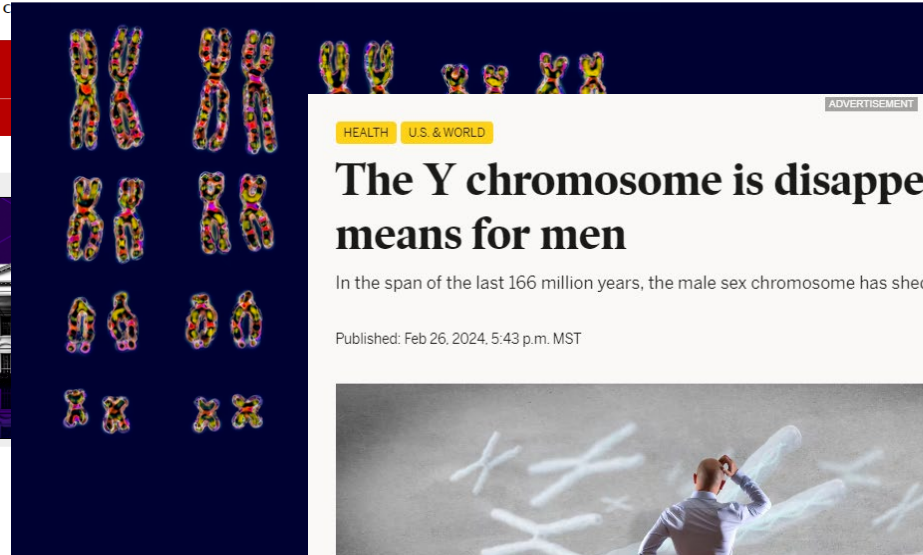
Sign In

SCIENCE

## The Disappearing Y Chromosome

It's surprisingly common for men to start losing entire chromosomes from blood cells as they age.

By Sarah Zhang



Human chromosomes, with a pair of XY and...

HEALTH U.S. & WORLD

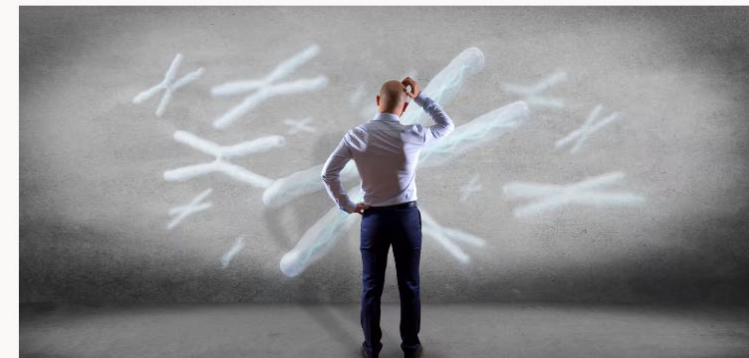
ADVERTISEMENT

## The Y chromosome is disappearing. Here's what it means for men

In the span of the last 166 million years, the male sex chromosome has shed the majority of its 1,600 genes

Published: Feb 26, 2024, 5:43 p.m. MST

VIEW COMMENTS SHARE



Scientists are monitoring the degradation of the Y chromosome in humans, and explaining what it means for the human race. | Adobe.com

By Alyssa Bradford  
Alyssa is a trending desk writer for the Deseret News. She covers health and travel.

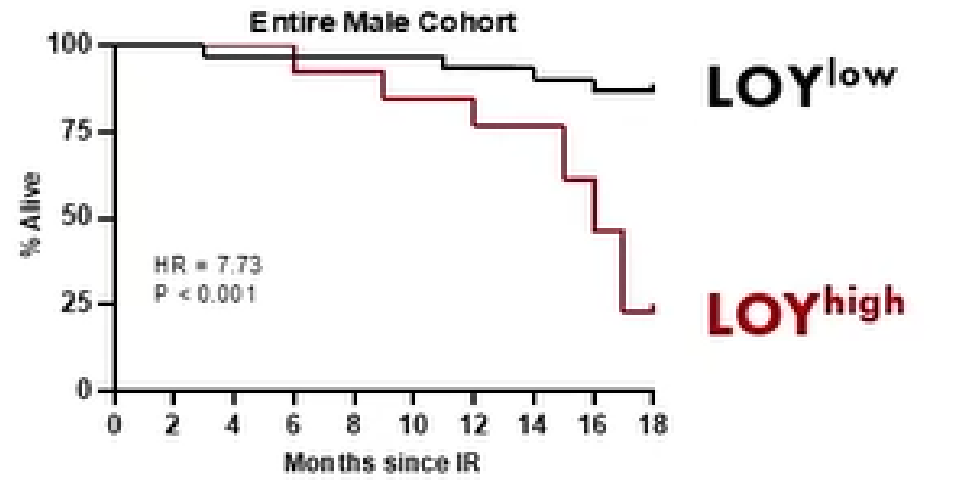
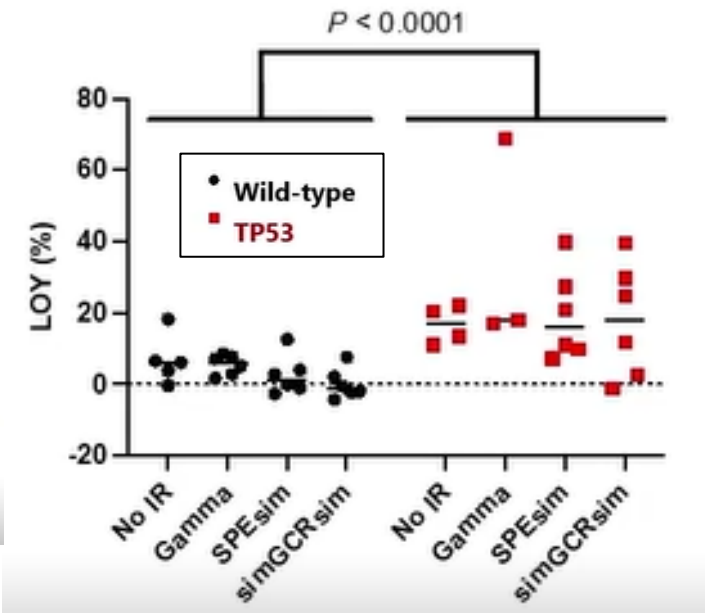
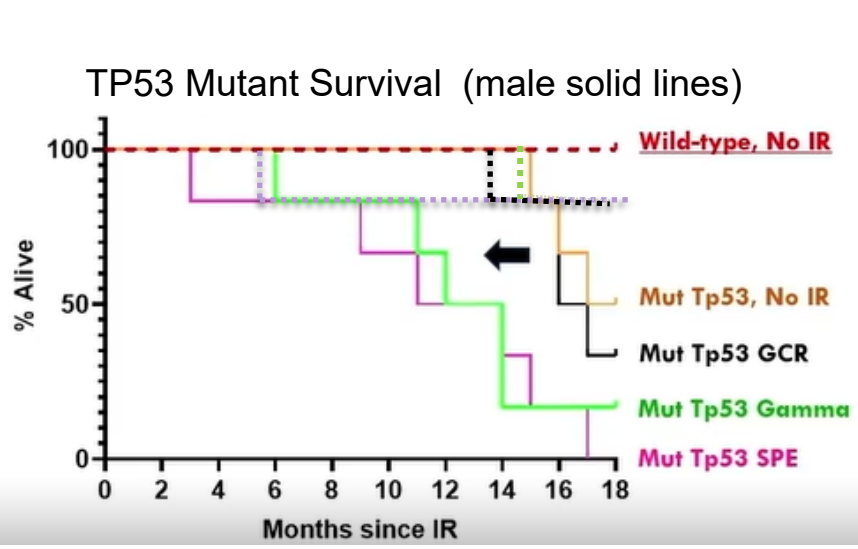
- Practice French
- Practice German
- Practice Italian
- Practice Spanish
- Practice Portuguese

**RELEVANCE:**

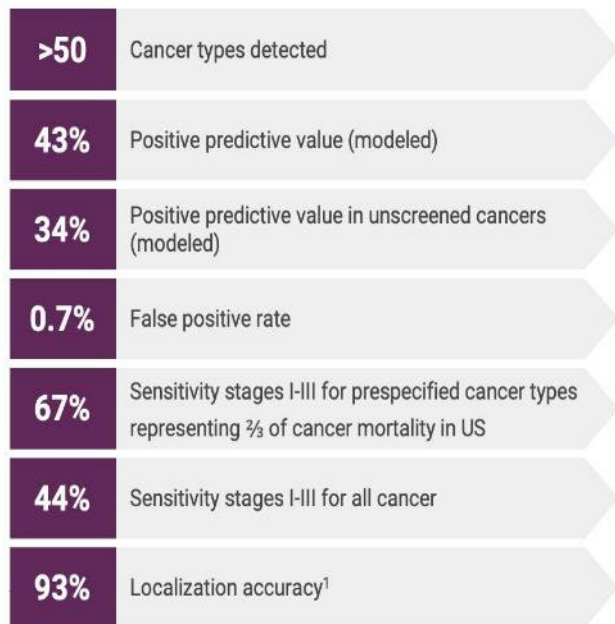
- Studying the effect of radiation on driving clonal hematopoiesis (CHIP), specifically TP53, PPM1D, TET2, and DNMT3A driver genes due to their association with CVD and cancer.
- Studying how the loss of the Y chromosome (LOY), only in male animals, may affect mortality in combination with CHIP and radiation
- Easily measurable could inform risk estimates but also post-mission surveillance for both cancer and cardiac**

**OBSERVATIONS:**

- Some forms of clonal hematopoiesis are promoted by space radiation, with striking effects on morbidity and mortality (e.g. TP53)
- Strong male-dependence of space radiation on survival in the TP53 condition may be partly explained by the tumorigenic effects of LOY.**

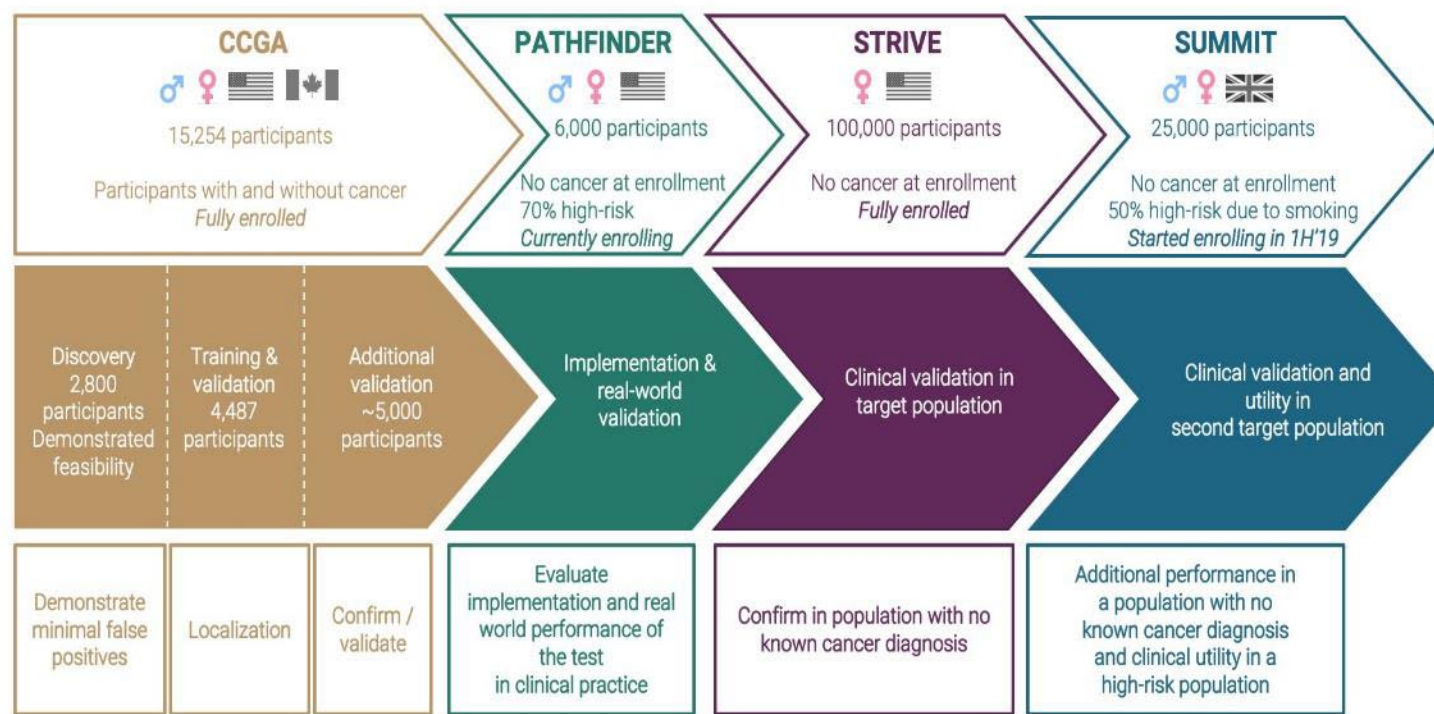


Key Performance Findings in CCGA-2 Sub-study



- > 45 types unscreened today, including**
- |                   |                      |
|-------------------|----------------------|
| Anorectal         | Pancreas             |
| Bladder           | Gallbladder          |
| Urothelial        | Plasma cell neoplasm |
| Esophagus         | Renal                |
| Gastric           | Sarcoma              |
| Head and neck     | Seminoma             |
| Liver             | Skin                 |
| Bile-duct         | Testis               |
| Lymphoid neoplasm | Thyroid              |
| Melanoma          | Uterine              |
| Myeloid neoplasm  | Vagina               |
| Ovary             | Vulva                |
| Lung <sup>2</sup> |                      |

- Types screened**
- |            |                   |
|------------|-------------------|
| Breast     | Lung <sup>2</sup> |
| Cervical   | Prostate          |
| Colorectal |                   |



May impact Clinical Car Guidelines. Potential impact for early diagnosis and better prognosis.

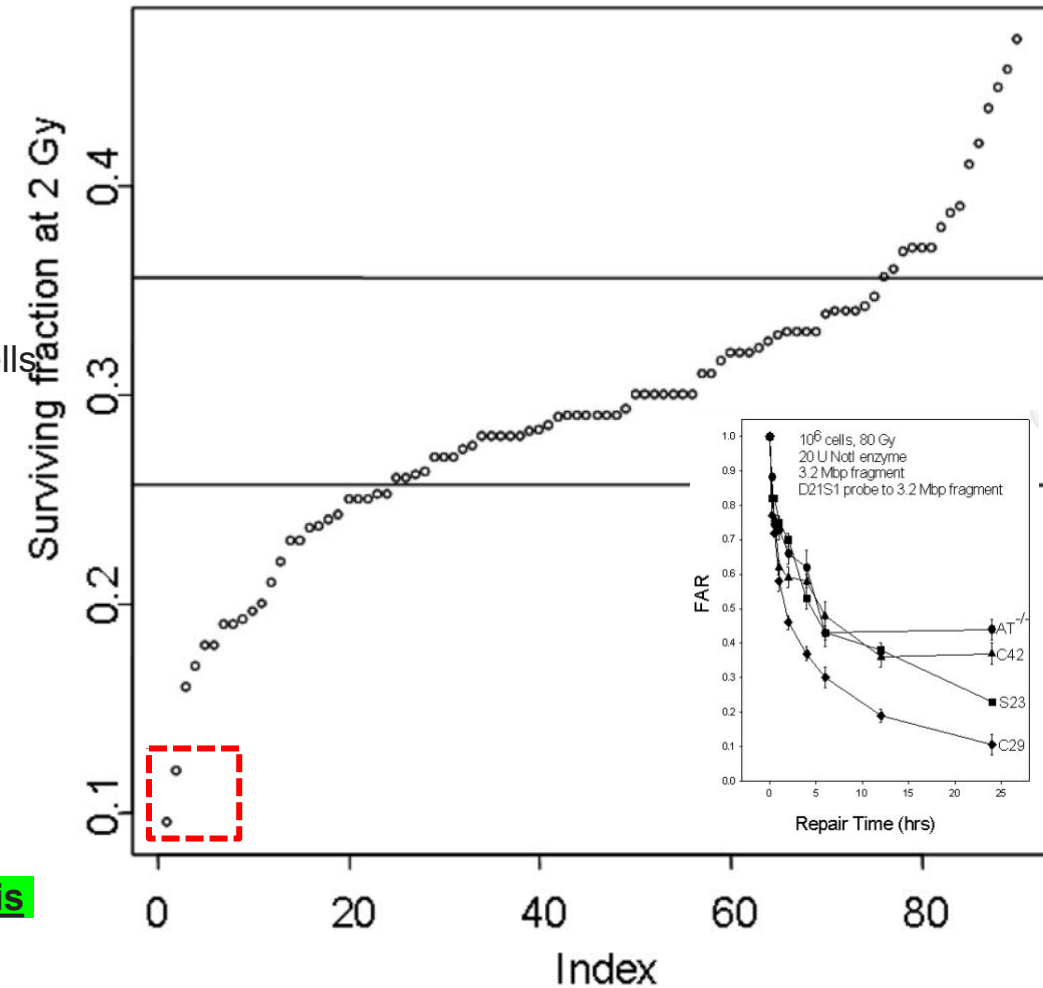
PI: Anthony "Tony" Davis / UTSW

PHSFs will be utilized to generate immortalized PHSFs and induced pluripotent stem cells (iPSCs) and iPSC-derived hepatocytes and lung epithelial cells whose intrinsic radiosensitivity is the same as that of the original PHSF from which it was derived.

Irradiation: Gamma, simplified GCRsim,

- clonogenic survival
- DNA repair
- DDR signaling
- genome stability
- mutation frequency and cellular and oncogenic transformation assays
- Transcriptome
- whole genome sequencing, DNA methylation, and RNAseq analysis

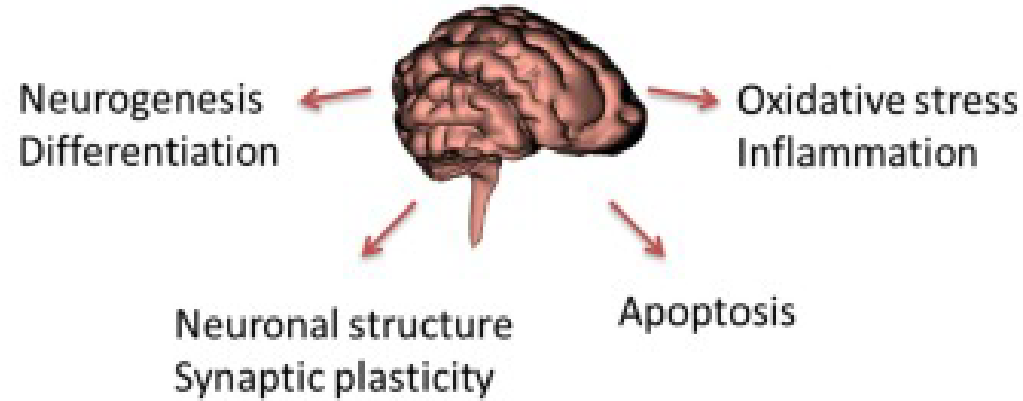
**The ability to identify individuals at greatest risk (or lowest risk) for carcinogenesis induced by low and high LET irradiations would be invaluable. Also may inform tissue sensitivity**



Radiosensitivity of 90 skin fibroblast cell lines as measured by SF2. Horizontal lines demarcate groups based radiosensitivity: radiosensitive, normal, and radioresistant.

**Dashed box:** Ataxia telangiectasis Cell Line

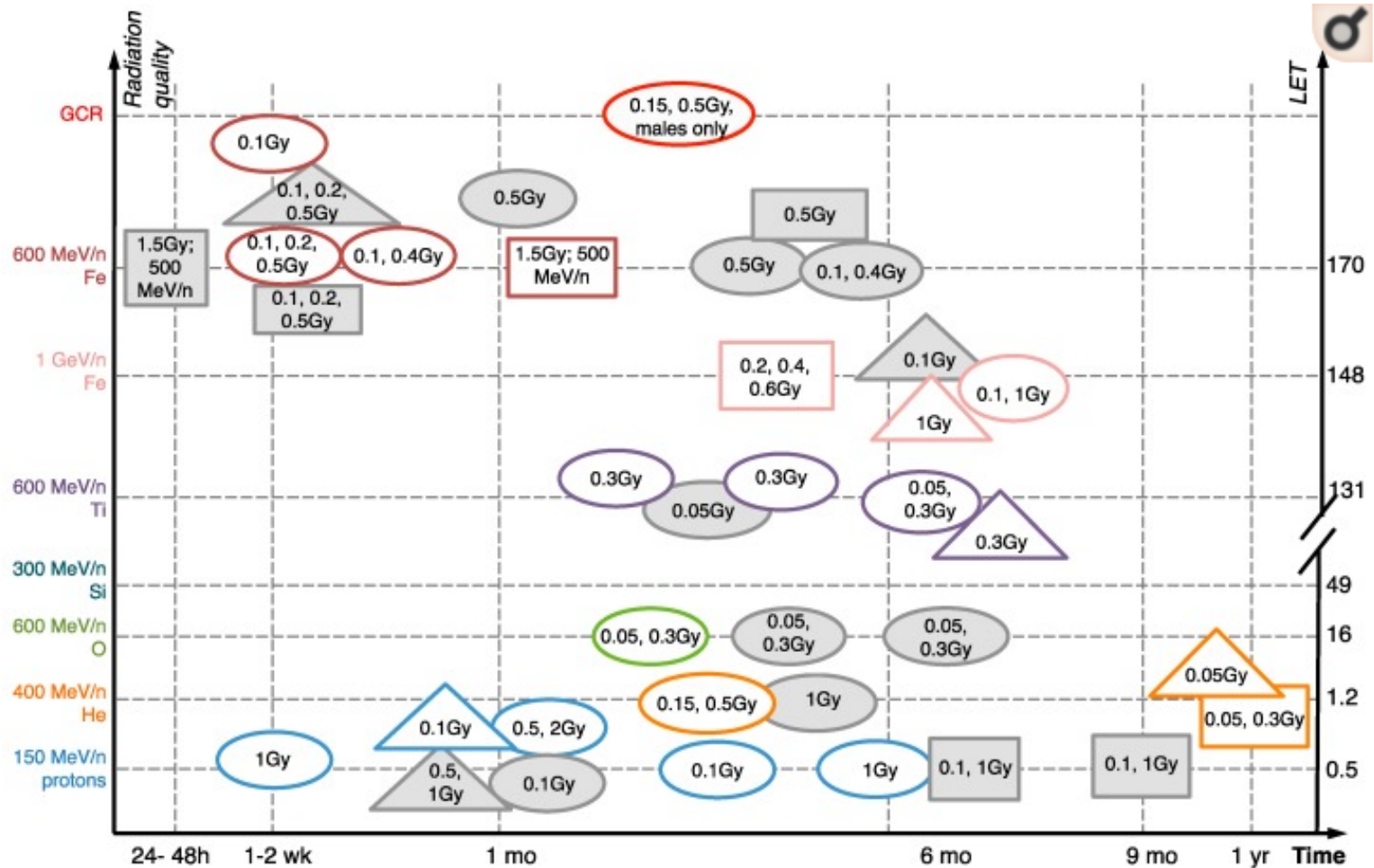
# Changes to the Central Nervous System after Space-Like Radiation Exposure



- Reduction in neuron **arborization** and **synapse number** (dendritic spines)
  - Persistent reductions for > 1 year after doses of high Linear Energy Transfer (LET) below 5 cGy
- Significantly reduced production of **new neurons** in brain
- Increased **activation of microglia** (signaling neuroinflammation)

# Memory Impairment in Animal Models

Development of memory impairments after HZE ion and simulated GCR irradiation. Doses (Gy) listed inside the shapes.



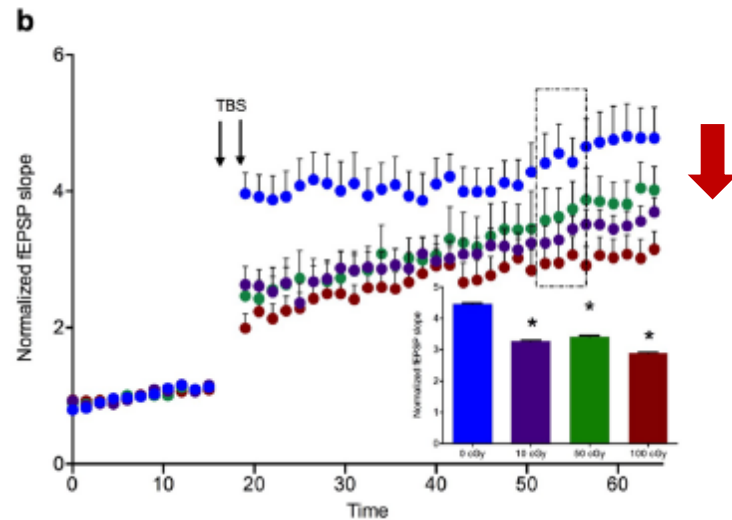
Grey color = no impairment. White = impairment.

(Ovals = novel object recognition, Squares = spatial memory, Triangles = fear conditioning )

# Physiological and Functional Changes

Electrophysiological and ion channel changes indicate persistent synaptic plasticity changes. These are accompanied by neuroinflammation and activation of microglia which can also regulate plasticity.

Hippocampal Slice Recordings at 2 Months after <sup>56</sup>Fe Exposure at 0, 10, 50 & 100 cGy Results in Reduction of Long Term Potentiation in Female Mice



Miry et al. Scientific Reports (2021) 11:4292

U-shaped dose responses for three glutamate receptor ion channels and a presynaptic marker. mRNA levels relative to controls for 10, 25 & 100 cGy <sup>16</sup>O ions.

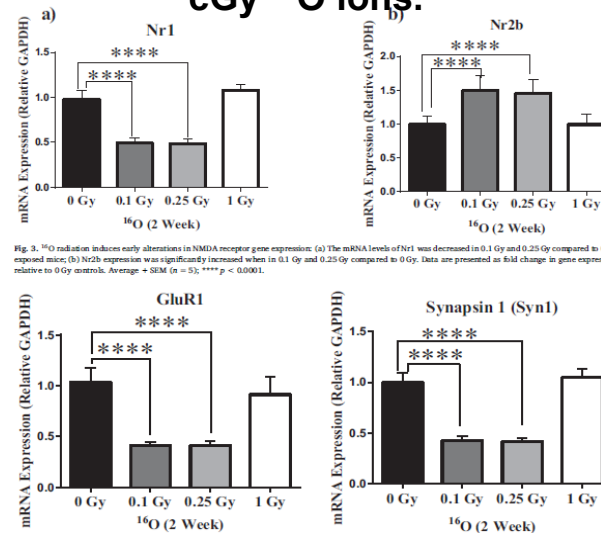
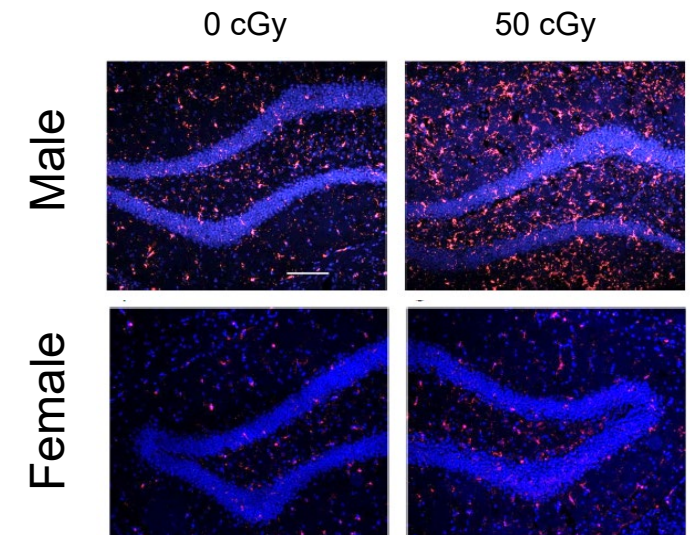


Fig. 3. <sup>16</sup>O radiation induces early alterations in NMDA receptor gene expression: (a) The mRNA levels of Nr1 was decreased in 0.1 Gy and 0.25 Gy compared to 0 Gy exposed mice; (b) Nr2b expression was significantly increased when in 0.1 Gy and 0.25 Gy compared to 0 Gy. Data are presented as fold change in gene expression relative to 0 Gy control. Average ± SEM (n = 5); \*\*\*\* p < 0.0001.

Kiffer et al. 2018. Radiat Res 189: 53–63

Sex differences: Microglia Activation (Red) in the Hippocampus (Nuclei Blue)

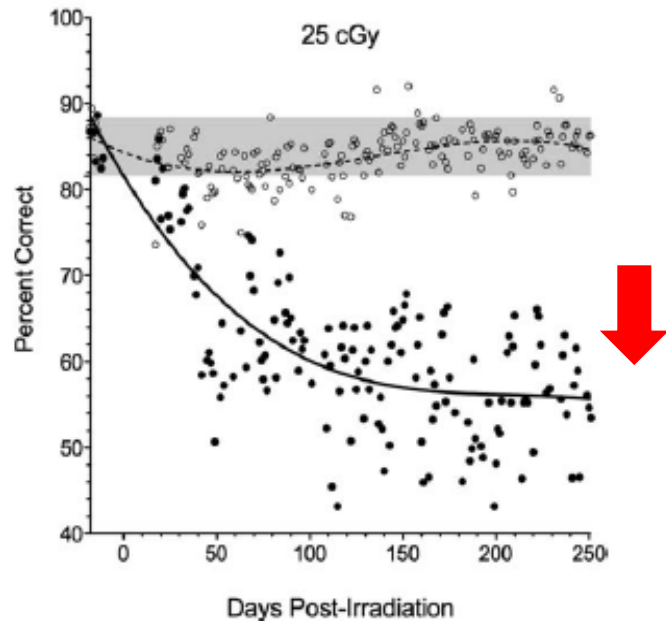


Krukowski et al. (2018) Brain, Behavior, & Immunity  
S0889-1591(18)30417-3

# Behavioral Responses

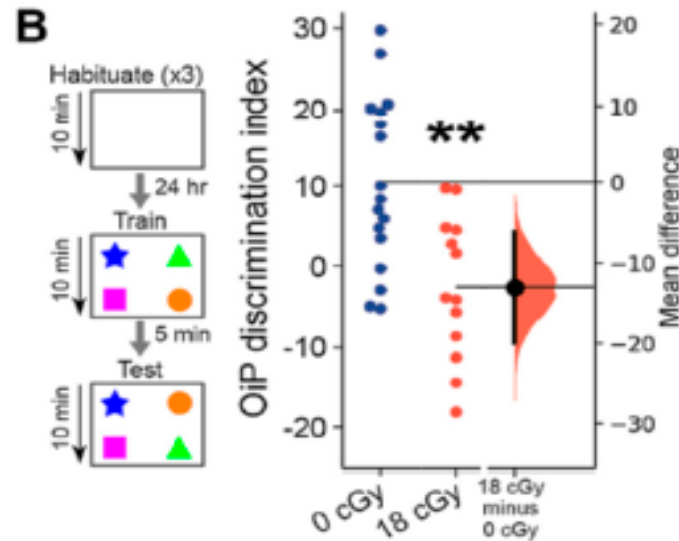
Persistent behavioral changes in cognitive, emotional and sensorimotor domains are observed in rats and mice after single or multi-ion exposures and neutrons.

In a high-fidelity human analog paradigm, psychomotor vigilance is impaired in rats after proton irradiation



Davis et al. (2014) Radiat. Res. 181, 258-271

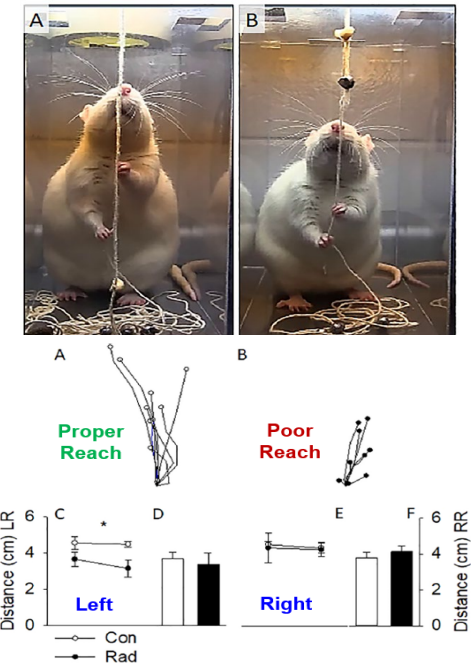
Object in Place Test Reveals Impairments in Spatial Memory after 18 cGy Neutron Exposure



Spatial memory behavior is perturbed by acute neutron irradiation in Object in Place (OiP) test to differentiate objects relocated to alternative locations.

Klein et al. (2021) Int. J. Mol. Sci. 22:9020

Movement topography is altered in the fine motor skill “string-pulling” test in rats after Si exposure.



Blackwell et al. (2020) Behav. Brain Res. 400, 113010

## RELEVANCE:

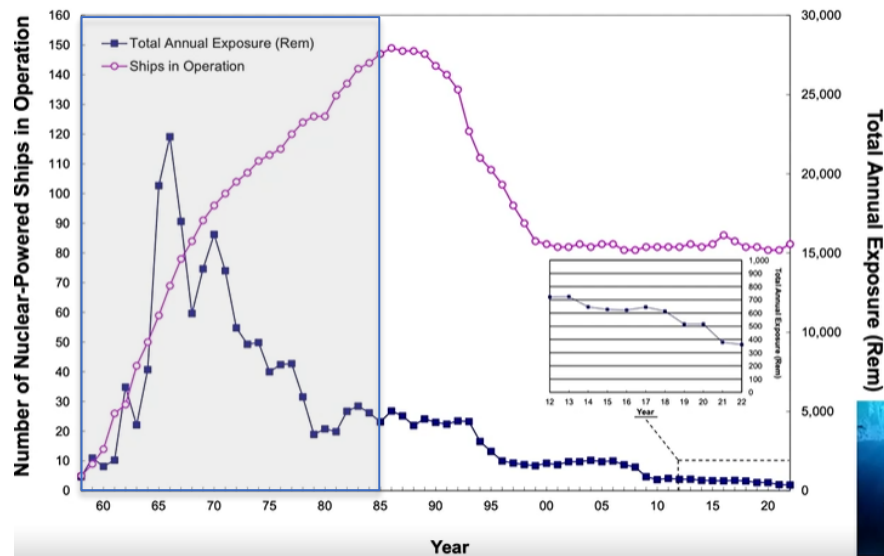
- Million Person Study (MPS) Navy Submariner Cohort – Terrestrial Space Analogue
  - Radiation exposure
  - Isolation and confinement
- could inform risk estimates but also post-mission surveillance
- Can be extended to other radiation associated risks

## OBSERVATIONS:

- August 2025 – scientific report will be prepared that evaluates any association between multiple stressors, and Alzheimer's, Parkinson's, depression and anxiety disorders at the level of mortality and incidence (as available at 2-years) for nuclear submariner cohort who first served from 1954-1985 and followed through 2021

## Radiation Exposure – Naval NPP 1958-2018

NNPP Report NT-23-2, May 2023



- Seeking CMS linkages for approximately 0.7M+ MPS radiation workers underway (submitting ~1 M)
- Priorities:
  - Cognitive function scores –workers admitted to a nursing home with scores
  - Alzheimer's, dementia, ALS and other motor neuron disease incidence
  - Parkinson's disease incidence (>>3,100)
  - Anxiety disorder incidence
  - Depression disorder incidence
- Tobacco Use algorithms / other relevant information on confounders
  - Chronic conditions
  - Obesity, Diabetes, etc.



# SachiBio – SBIR PHASE III

## Previous Funding:

- TRISH
- SBIR Phase I
- SBIR Phase II

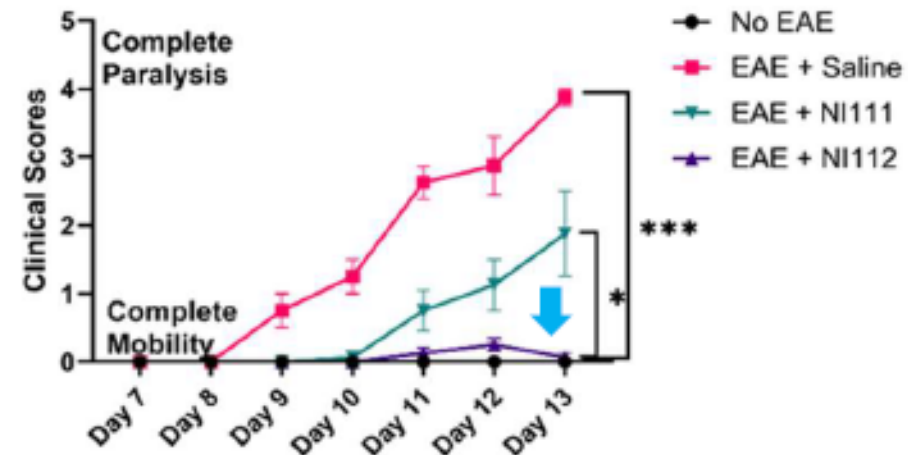
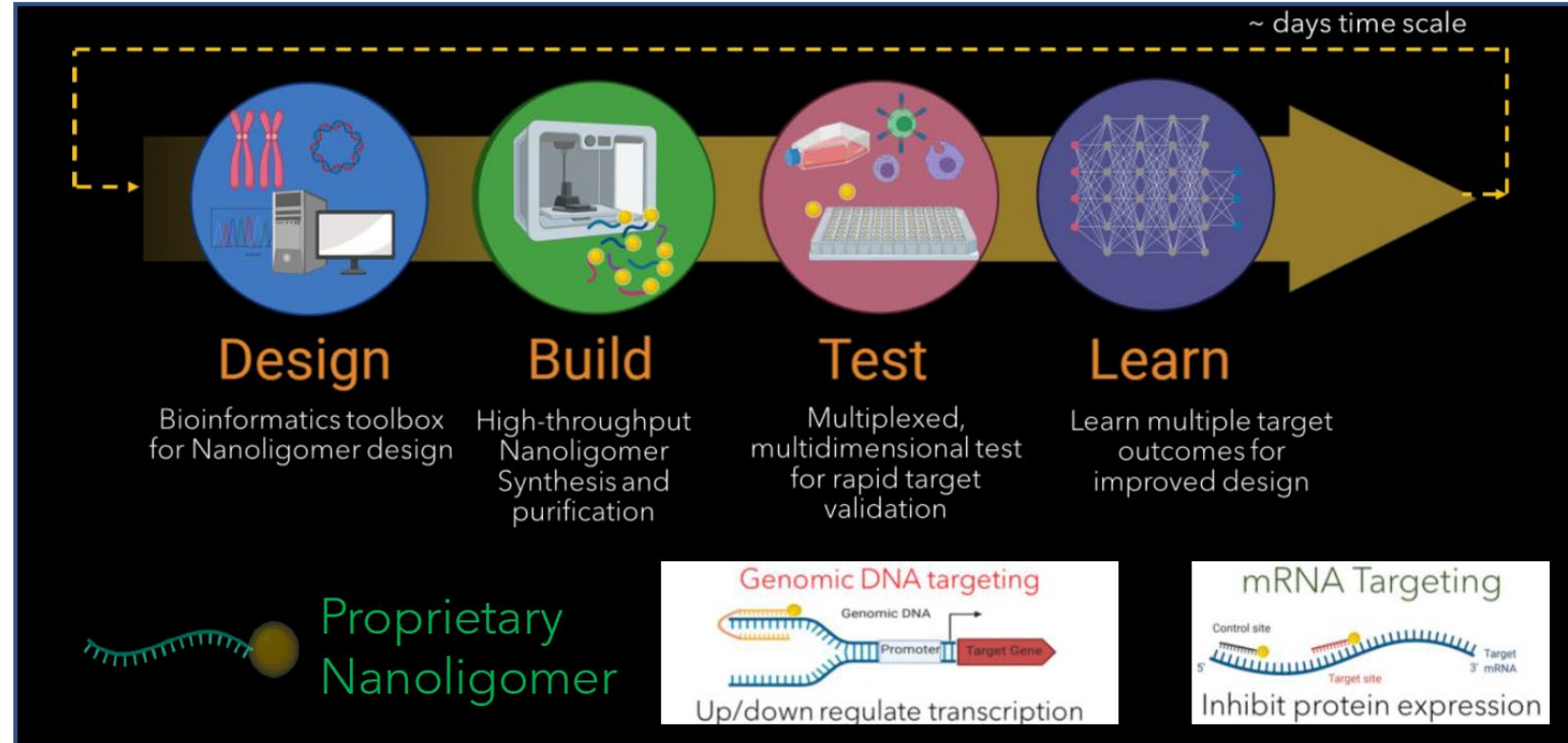
## Current Funding:

- InSpa
- SBIR Phase III

- 1.) Nanoligomer Technology
- 2.) AI capability to accelerate countermeasure target identification

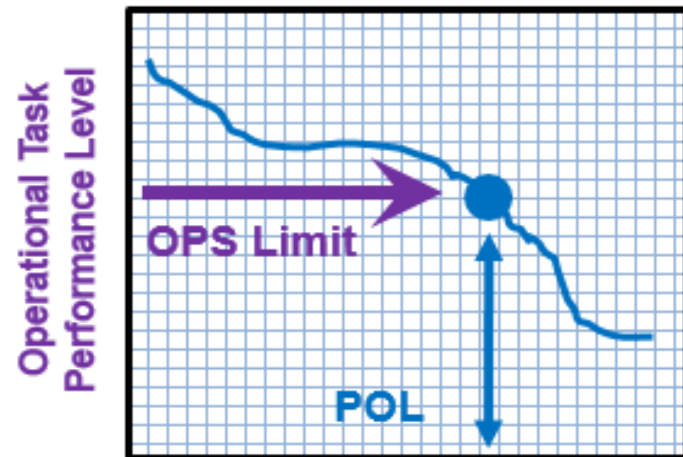
## Neuroprotection has been shown:

1. low-dose (0.1 Gy) GCR exposure
2. prion disease model
3. ALS model



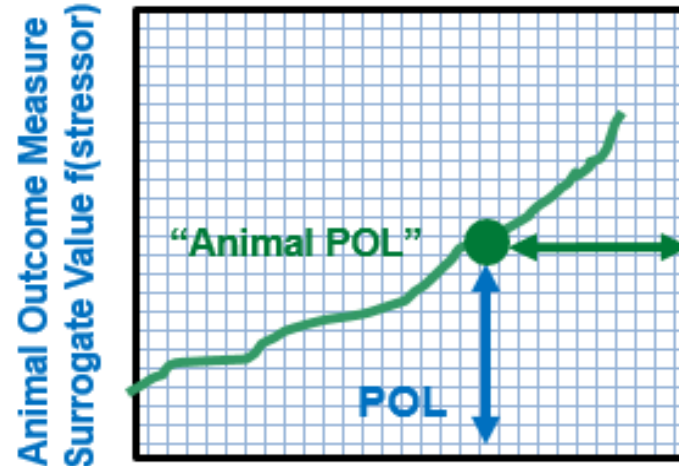
# How to Translate? NSCOR

Determine Operational Acceptable Impairment Limit & Surrogate Marker as Function of Model Stressor



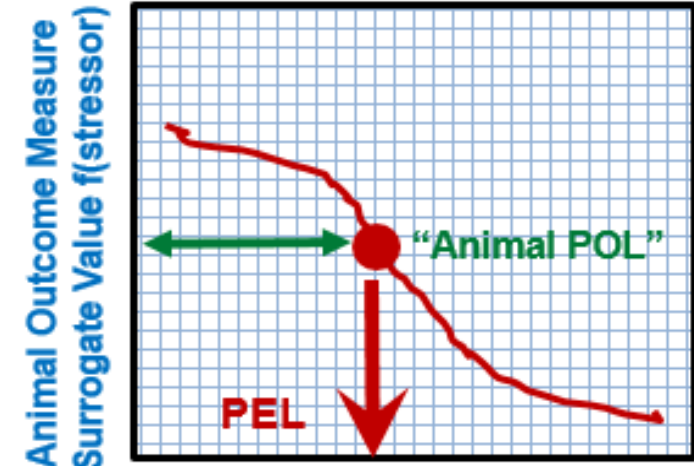
Human Outcome Measure Surrogate Value as Function of Stressor. POL is value at OPS limit.

Scaling Relation for Human to Homologous Animal Outcome Measures as Function of Model Stressor



Human Outcome Measure Surrogate Value as Function of Stressor

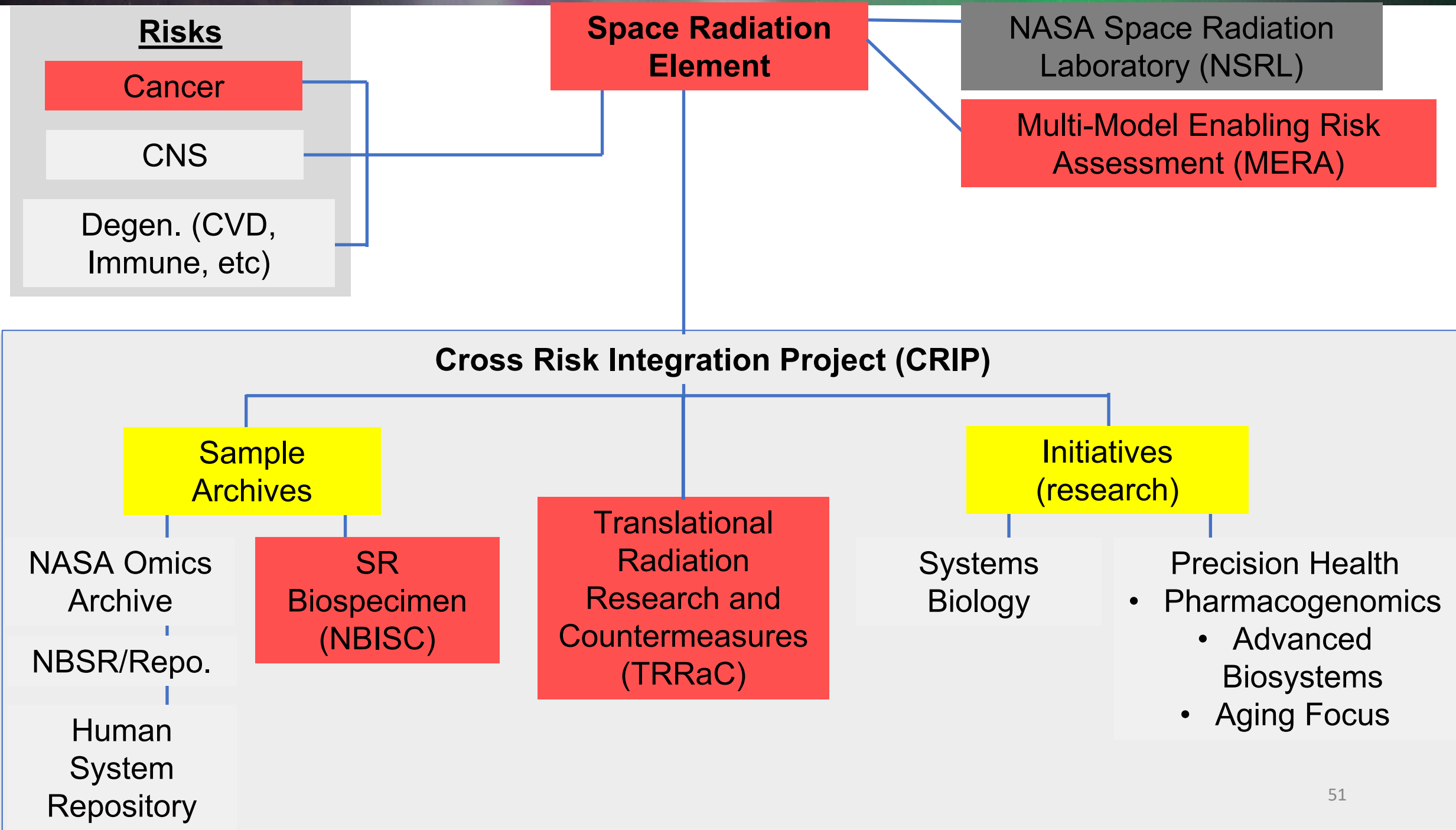
Determine "Equitoxic" Dose for Radiation & Stressor at POL Level. This is the radiation permissible exposure level.



Animal Outcome Measure as Function of Radiation Dose. PEL is radiation exposure associated with operational limit.

Figure 2. Effect Size versus exposure levels for setting POLs and PELs using animal intermediates and surrogate measures or biomarkers.





# Overview

- Introductions
- What is Radiation?
- Radiation Health Effects
- The Space Radiation Environment
- Health Risks for Spaceflight
- **Risk Management and Uncertainties**



# The Space Radiation Protection Challenge

- Traditional terrestrial protection strategies fall short in space:

- **Time**

- At some point you will always reach a limit



**Dose Limits**

- Distance

- There is no point source to move away from

- Shielding

- Energetic particles are penetrating
- Secondary particles

- NASA is exploring other protection strategies

- Individualized risk characterization
- Health surveillance including early disease detection
- Compound-based countermeasures

**As Low As Reasonably Achievable**

# ALARA



**Table 8.4-1.\* NASA Effective Dose (mSv/day) for Female Astronaut as Function of Shield Thickness during Solar Minimum and Maximum Conditions in Free Space**

	No Shielding	Aluminum Shield Thickness (g/cm <sup>2</sup> )				Polyethylene Shield Thickness (g/cm <sup>2</sup> )			
		10	20	40	60	10	20	40	60
Solar minimum**	1.52	1.28	1.21	1.23	1.34	1.14	1.04	1.03	1.07
Solar maximum***	0.63	0.57	0.55	0.60	0.68	0.50	0.48	0.51	0.56

\* The NASA effective dose is calculated using the NASA radiation quality factor and GCR tissue weights for a female astronaut (never smoker) [Cucinotta et al. 2013].

\*\* The 2009 solar minimum was calculated with the BON2020 model.

\*\*\* The 2001 solar maximum was calculated with the BON2020 model.

**Table 8.4-2. NASA Effective Dose (mSv/day) for Female Astronaut as Function of Shield Thickness during Solar Minimum and Maximum Conditions on Lunar Surface**

	No Shielding	Aluminum Shield Thickness (g/cm <sup>2</sup> )				Polyethylene Shield Thickness (g/cm <sup>2</sup> )			
		10	20	40	60	10	20	40	60
Solar minimum**	0.90	0.78	0.73	0.73	0.78	0.66	0.58	0.56	0.57
Solar maximum***	0.40	0.36	0.35	0.37	0.41	0.30	0.28	0.28	0.31

\* The NASA effective dose is calculated using the NASA radiation quality factor and GCR tissue weights for a female astronaut (never smoker) [Cucinotta et al. 2013].

\*\* The 2009 solar minimum was calculated with the BON2020 model.

\*\*\* The 2001 solar maximum was calculated with the BON2020 model.

# Space Radiation Protection

- Goal: **minimize** mission impacts AND long-term health risks
  - Exposure is unavoidable
- Three fundamental principles of radiation protection
  - Justification
    - Societal benefit outweighs risk
  - Limitation
    - NASA implements **dose** limits
  - Optimization
    - Monitor crew doses and implement dose reduction
    - As Low As Reasonably Achievable (ALARA)

# Storm Shelter

## Operational Protection Strategy for SPEs

<https://www.youtube.com/watch?v=70GrihLXmSs>



# Dose Limits – Non-Cancer

- Limits for specific organs/systems
  - Short- and long-term limits
    - Weighted by radiation scaling factor
  - **Prevent** tissue reactions
    - Clinically significant
    - Non-cancer effects

Current Dose Limits – Non-cancer

Organ	30-Day Limit (mGy-eq)	1-Year Limit (mGy-eq)	Career Non-Cancer Limit (mGy-eq)
Lens of the eye	1000	2000	4000
Skin	1500	3000	6000
Blood-forming organs	250	500	n/a
Circulatory system	250	500	1000
Central Nervous System*	500 mGy	1000 mGy	1500 mGy
Central nervous system (heavy particles, $Z \geq 10$ )*	n/a	100 mGy	250 mGy

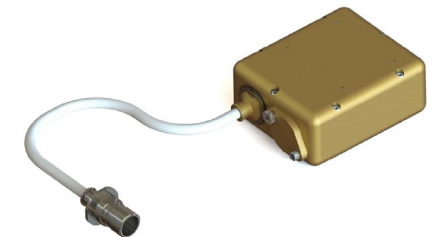
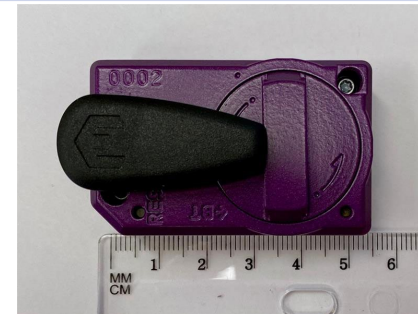
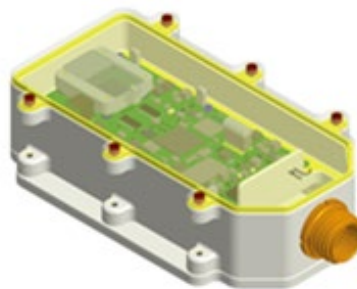
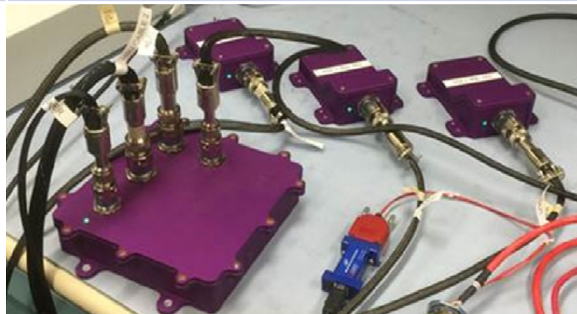
\*mGy used instead of mGy-eq

# Dose Limits – Cancer

- Updated limit as of January 2022
  - <https://standards.nasa.gov/human-factors-and-health>
  - 4.8.2 Career Space Permissible Exposure Limit for Space Flight Radiation: [V1 4030] An individual astronaut's total career effective radiation dose due to space flight radiation exposure shall be **less than 600 mSv**. This limit is universal for all ages and sexes.
- Based on a mean 3% Risk of Exposure-Induced Death (REID) from cancer
  - 35-year-old female
  - Lifetime probability of **excess** fatal cancer due to radiation exposure
- **Minimize** stochastic effects
  - Total solid cancers and leukemias

# Instrument Suite for Crewed Artemis Missions

Function	HERA	ARES	CAD	ARD
<b>Measurement</b>	<ul style="list-style-type: none"> <li>• Charged Particle Detector</li> <li>• Area monitoring of flux/species and dose</li> </ul>		<ul style="list-style-type: none"> <li>• Crew member dose rate/total dose</li> </ul>	
<b>Proposed mission(s)</b>	<ul style="list-style-type: none"> <li>• Orion/Artemis</li> </ul>	<ul style="list-style-type: none"> <li>• Gateway, Lander</li> <li>• (HERA heritage hardware)</li> </ul>	<ul style="list-style-type: none"> <li>• Personal dosimetry</li> </ul>	
<b>Use</b>	<ul style="list-style-type: none"> <li>• Real time radiation environmental monitoring</li> <li>• On-board alerting</li> </ul>		<ul style="list-style-type: none"> <li>• Real-time dose at crew</li> <li>• Worn by crew at all times <b>inside</b> crewed vehicles</li> <li>• Post mission crew risk assessment</li> <li>• Re-flight determination</li> </ul>	<ul style="list-style-type: none"> <li>• Real time dose at crew</li> <li>• EVA, integrated with xEMU</li> <li>• On-board alerting</li> <li>• Post mission crew risk assessment</li> </ul>
<b>Mass</b>	<ul style="list-style-type: none"> <li>• ~3kg</li> </ul>	<ul style="list-style-type: none"> <li>• &lt;2kg</li> </ul>	<ul style="list-style-type: none"> <li>• 35g</li> </ul>	<ul style="list-style-type: none"> <li>• 430g</li> </ul>
<b>Dimensions</b>	<ul style="list-style-type: none"> <li>• HPU: 19.3 cm x 17.5 cm x 4.6 cm</li> <li>• HSU (2 each): 13.5 cm x 10.7 x 5.3 cm</li> </ul>	<ul style="list-style-type: none"> <li>• 9.9 cm x 17.8 cm x 4.6 cm</li> </ul>	<ul style="list-style-type: none"> <li>• 5.7 x 3.4 x 2.6 cm</li> </ul>	<ul style="list-style-type: none"> <li>• 7 cm x 6 cm x 3 cm</li> </ul>





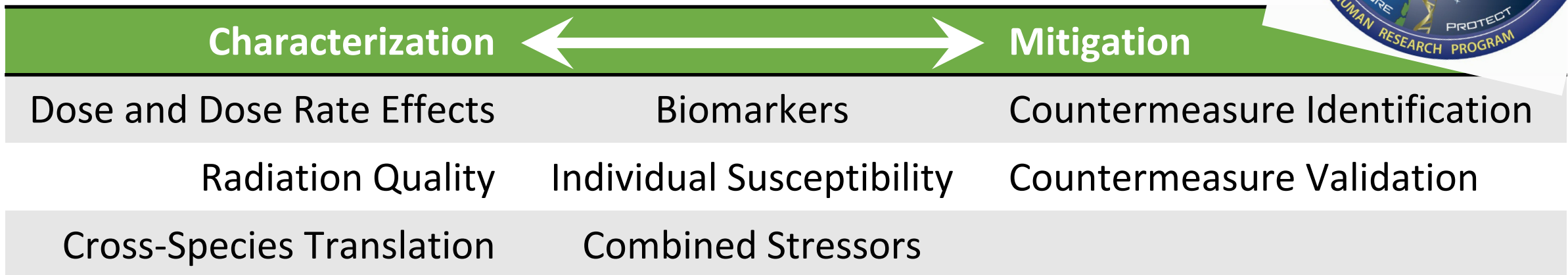
# Space Radiation Element Research

- Mission: Characterize and facilitate the management of the human health outcomes associated with space radiation exposure to protect astronaut health and wellbeing to enable human spaceflight

- Carcinogenesis
- Cardiovascular and Immune
- Central Nervous System



<https://humanresearchroadmap.nasa.gov/>



# The Big Picture

- Space radiation environment
  - Unavoidable
  - Differs from terrestrial environment



- Space radiation risks
  - Threat to mission success and long-term health
  - Understanding is incomplete and still evolving
  - Protection strategies differ from terrestrial environment
  - Radiation is one of numerous hazards in the hostile space environment



National Aeronautics and  
Space Administration



# Thank you for your attention! Questions?

[jsc-hrp-space-radiation-element@mail.nasa.gov](mailto:jsc-hrp-space-radiation-element@mail.nasa.gov)

# More Resources

- Space Radiation Element
  - <https://www.nasa.gov/hrp/elements/radiation>
- NASA Human Research Roadmap – link to risks, gaps, and funding priority (green = low, red = high)
  - <https://humanresearchroadmap.nasa.gov/>
- NASA Taskbook – Summaries of current and previously funded projects
  - <https://taskbook.nasaprs.com/tbp/welcome.cfm>
- Life Science Data Archive – Can request past data and search tissue repository
  - <https://lsda.jsc.nasa.gov/>
  - <https://lsda.jsc.nasa.gov/Biospecimen>
  - Instructions - <https://www.nasa.gov/hrp/elements/radiation/tissue-sharing>
- NASA GeneLab – Space-related omics database. Users can upload, download, share, store, and analyze spaceflight and spaceflight-relevant data from experiments.
  - <https://genelab.nasa.gov/>
- The Health Risks of Extraterrestrial Environments (THREE) – Open access space radiation literature
  - <https://three.jsc.nasa.gov/#section=main>

# NASA 3001 Vol1 Standard Update

- Radiation limit for FATAL CANCER shifted from a RISK limit to a **DOSE limit**
    - Anchored using 35-year-old female case (most protective)
- 

## ***4.8.2 Career Space Permissible Exposure Limit for Space Flight Radiation***

*[V1 4030] An individual astronaut's total career effective radiation dose due to space flight radiation exposure shall be **less than 600 mSv**. This limit is universal for all ages and sexes.*

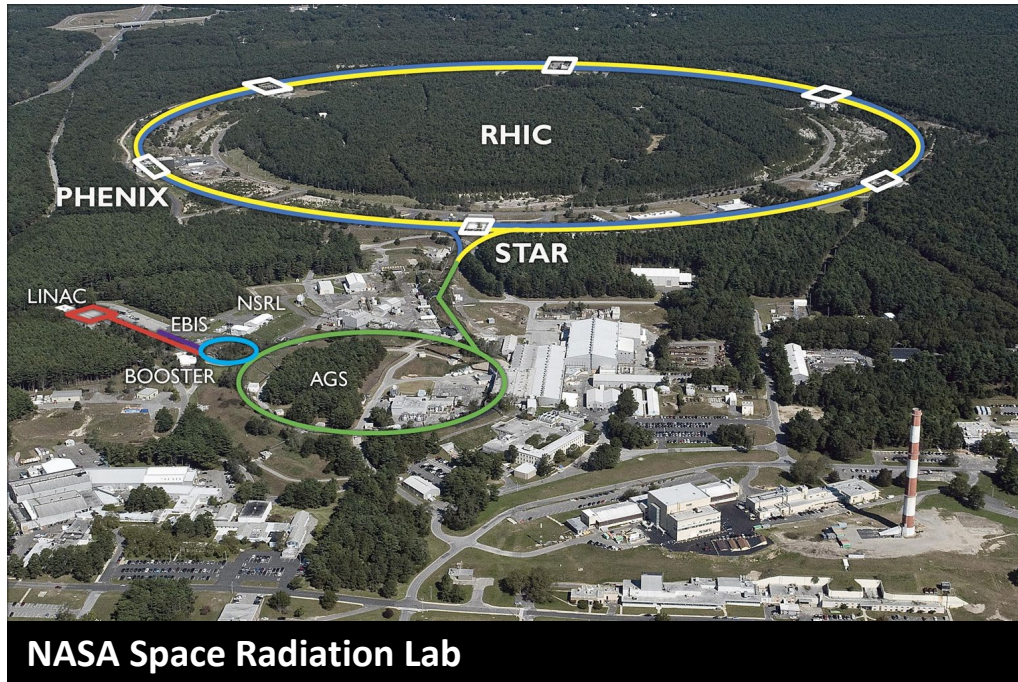
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# Common Questions

- Should I freeze my gametes?
  - No radiation related hereditary effects/germ-line mutations have been observed in human populations.
  - Exposures **during** pregnancy can impact fetal development. However, upon return it is safe from a radiation standpoint to get pregnant.
- Should I take iodine pills?
  - Iodine pills will **ONLY** prevent uptake of ingested radioactive iodine, which you will not be exposed to from space radiation.
- Why don't we shield with lead?
  - When fast moving particles hit lead, they create a shower secondary particles as they interact with the material.
- Why doesn't my medical exposure impact my flight eligibility?
  - Medical exposure provides a health benefit.

# Back-up

# Ground Analog – NASA Space Radiation Laboratory



- Personnel:
  - NSRL Liaison Physicist, Adam Rusek PhD
    - [rusek@bnl.gov](mailto:rusek@bnl.gov)
  - Biology Support Scientist, Peter Guida PhD
    - [guida@bnl.gov](mailto:guida@bnl.gov)
  - NSRL Management, Lisa Simonsen PhD
    - [lisa.c.simonsen@nasa.gov](mailto:lisa.c.simonsen@nasa.gov)
- Capabilities:
  - Acute or fractionated exposures “chronic”
  - Single ions
  - Multiple ions
    - Simplified GCR sim
      - 6 beams 5 ions: H (2 energies), Si, He, O, Fe
    - GCR sim
      - 33 beams, 7 ions: H (14 energies), He (14 energies), C, O, Si, Ti, Fe

<https://www.nasa.gov/analogs/nsrl/about>

<https://www.bnl.gov/nsrl/>