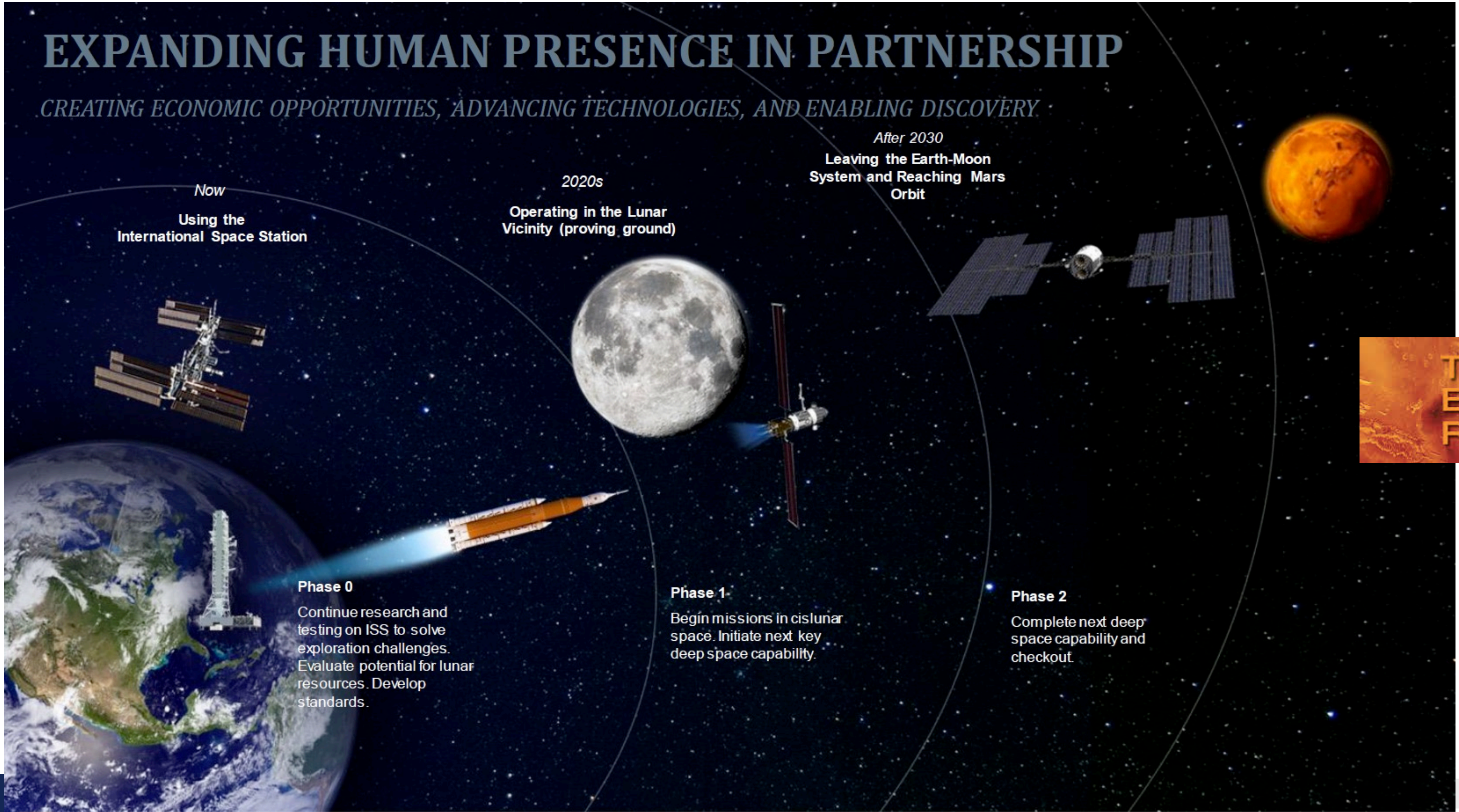
Ground-based research for radiation protection in space travel

Marco Durante

The global exploration roadmap – ISECG 2020



Life **2014**, *4*, 491-510; doi:10.3390/life4030491

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Review

Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit

Jeffery C. Chancellor [1,2], Graham B. I. Scott [1,3] and Jeffrey P. Sutton [1,4,*]

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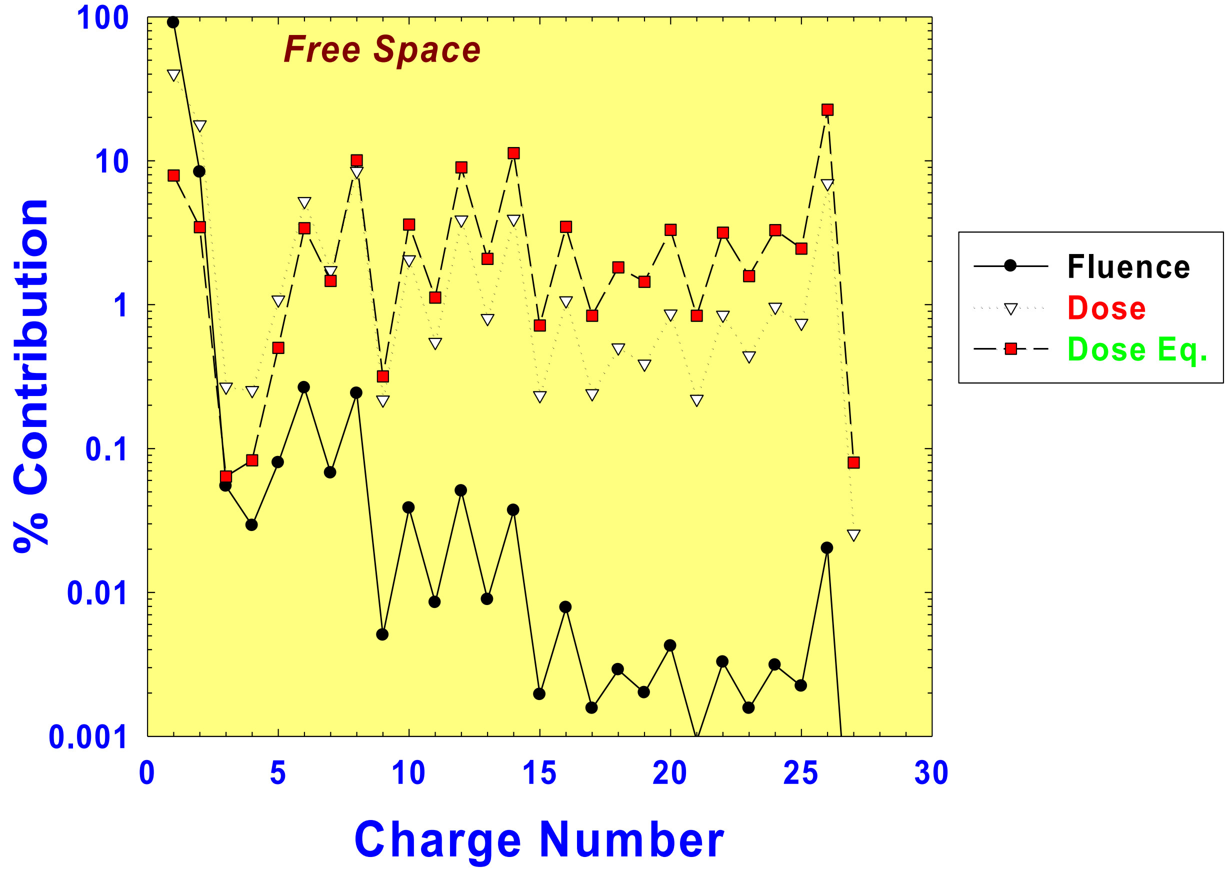
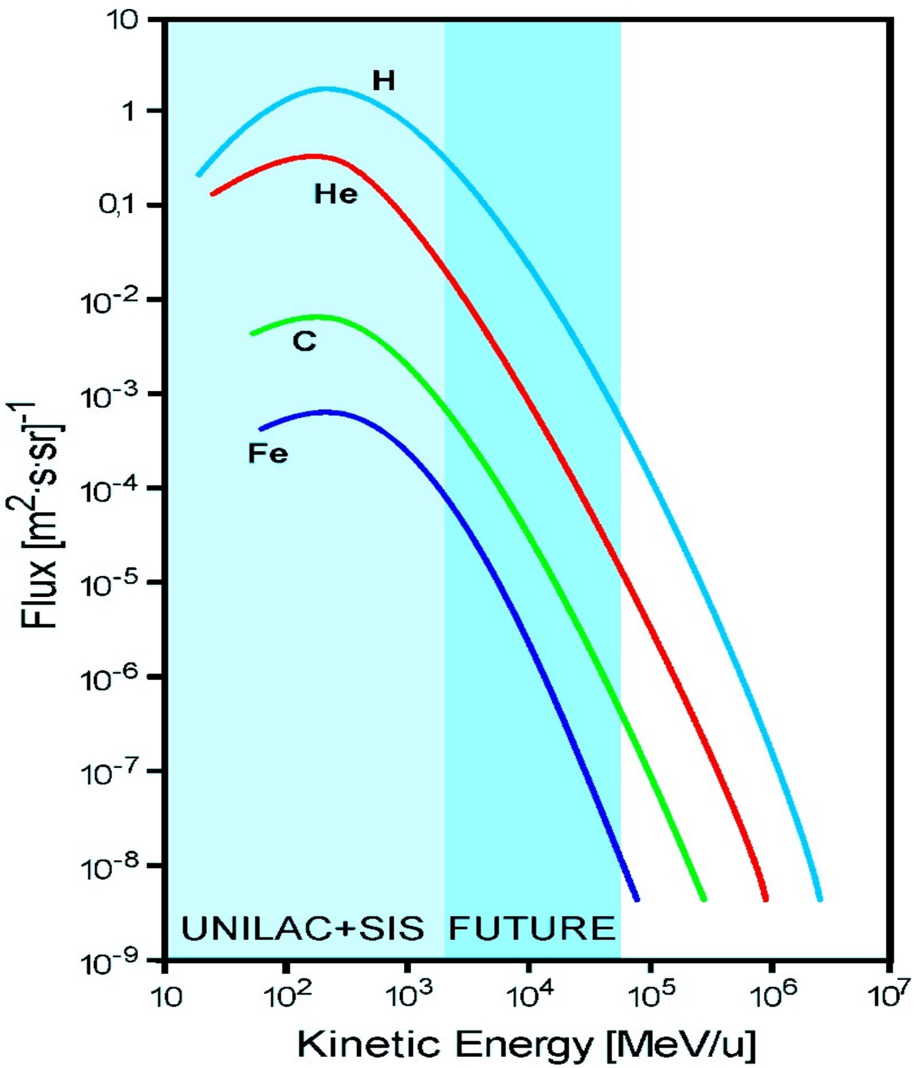
Galactic Cosmic Radiation

FAIR esa

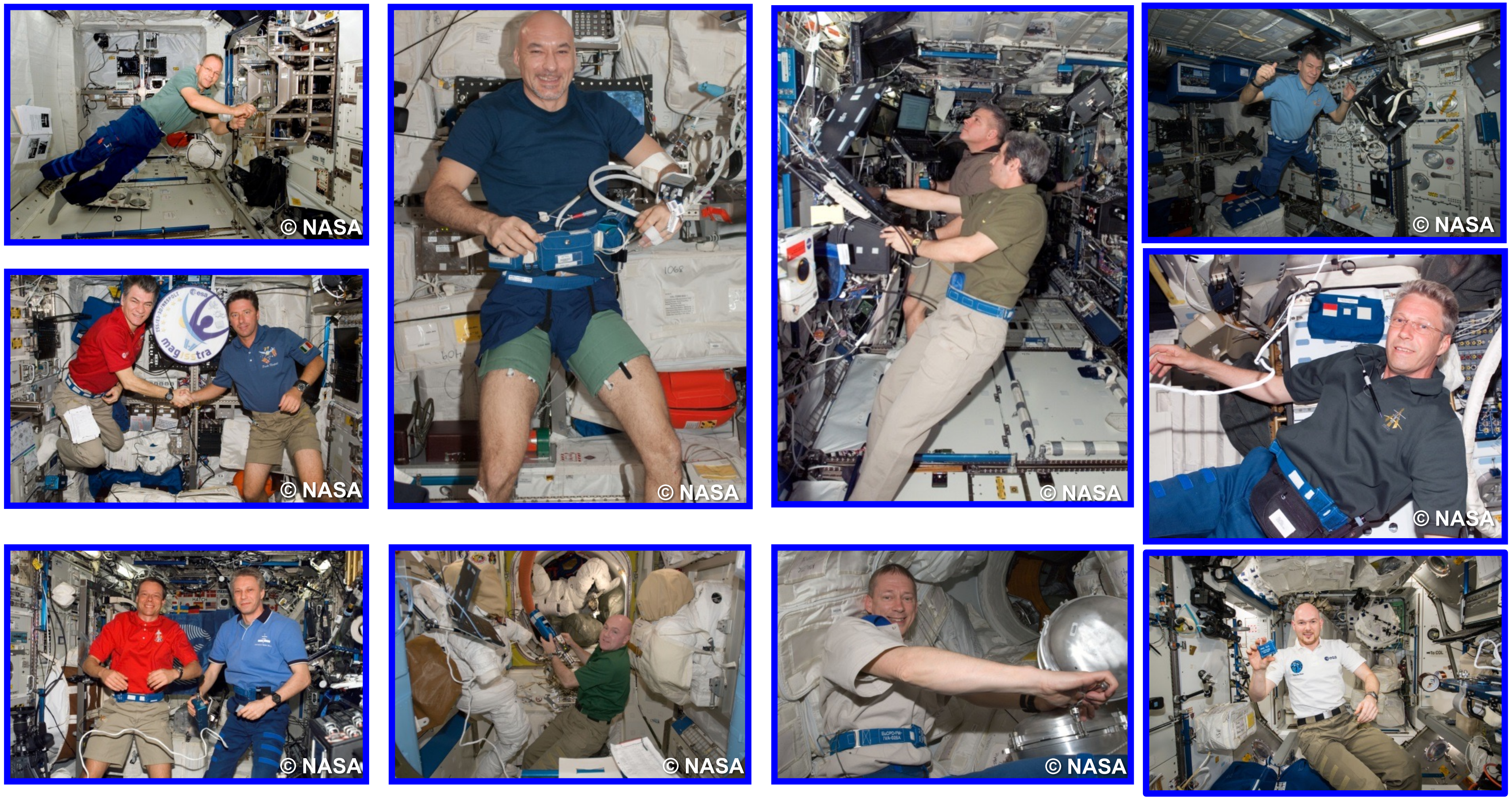
GCR Charge Contributions





Durante and Cucinotta, *Rev. Mod. Phys*. 2011

PERSONAL DOSIMETRY



Personal dosimetry: Surveillance of the radiation exposure of astro – and cosmonauts (passive)

Radiation dose during the travel to Mars and on the planet's surface measured by RAD on MSL

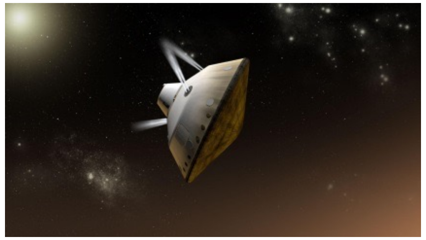
RAD Instrument Overview

RAD – The Radiation Assessment Detector for MSL

RAD was selected for MSL to characterize the radiation environment (charged and neutral) on the surface of Mars. RAD consists of:

- Solid state detector telescope & CsI calorimeter for charged particles.
- Plastic scintillator w/ anti-coincidence logic to detect neutrons.
  - CsI detects γ-rays also, but RTG background is high.

- Mass = 1.56 kg
- Power = 4.2 W
- Volume = 10 x 12 x 20 cm^3
- Field-of-View = 65 deg. (full angle)
- Geometry Factor = 1 cm^2 sr



Launch date: 26.11.2011

Landing date: 06.08.2012

Dose summary for Mars & ISS

GCR dose in different mission scenarios based on the recent MSL measurements (Zeitlin et al., 2013; Hassler et al., 2014). Inspiration Mars is a 501 flyby mission. Mars sortie assumes a 30-days stay on the planet, and Mars base 500 days. Both those design reference missions (Tito et al., 2013) assume a 180 cruise to/from Mars.

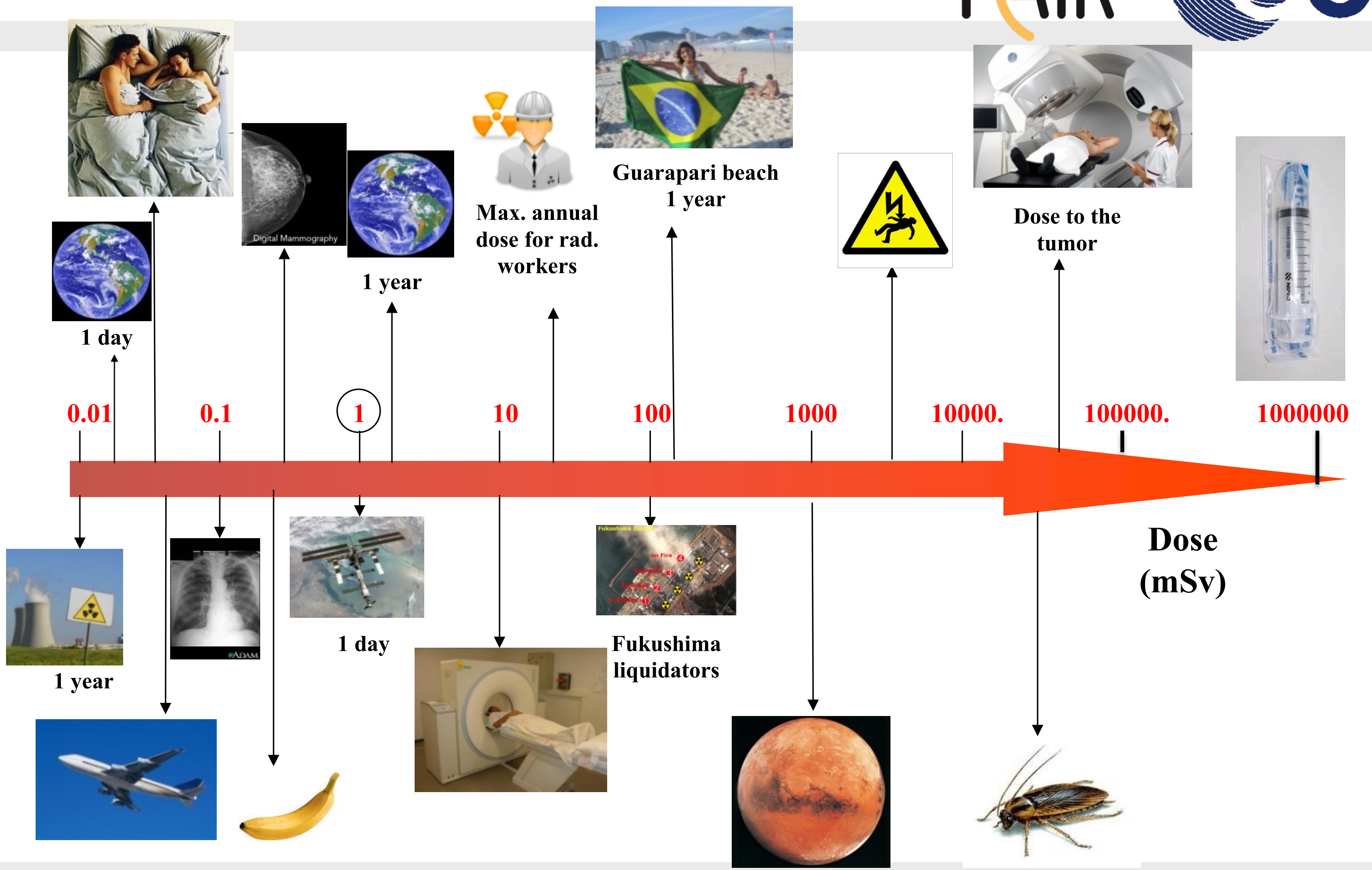
	GCR dose rate (mGy/day)	GCR dose-equivalent rate (mSv/day)	Inspiration Mars (Sv)	Mars sortie (Sv)	Mars base (Sv)
MSL cruise (Zeitlin et al., 2013)	0.46	1.84	0.92	0.7	0.98
MSL on Mars (Hassler et al., 2014)	0.21	0.64			

Table 2. Summary of International Space Station (ISS) organ dose equivalents for solid cancer, leukemia and circulatory disease risk estimates for different solar cycle conditions for females (males).

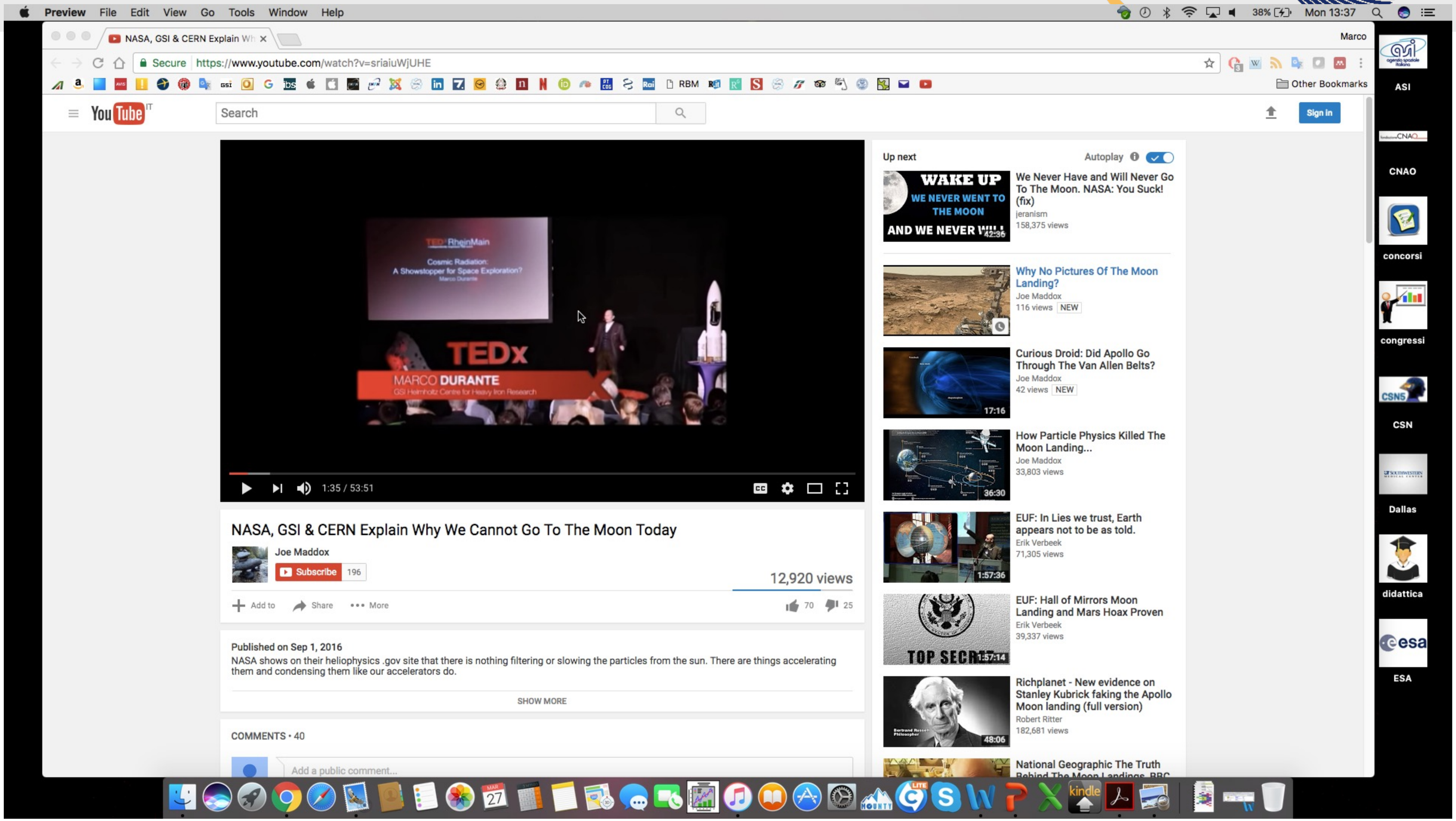
Missions	Solid Cancer, Sv	Leukemia, Sv	Circulatory Disease, Gy-Eq
1-Y Solar Min	0.187 (0.175)	0.109 (0.104)	0.132 (0.126)
1-Y Solar Med	0.146 (0.138)	0.084 (0.08)	0.10 (0.096)
1-Y Solar Max	0.10 (0.094)	0.054 (0.052)	0.072 (0.064)
1-Y Solar Min and 0.5-Y Solar Med	0.26 (0.244)	0.151 (0.144)	0.182 (0.174)
1-Y Solar Min, 0.5-Y Solar Med, and 0.5-Y Solar Max	0.31 (0.291)	0.178 (0.171)	0.215 (0.205)

Predictions are for single or multiple ISS missions. Solar cycle conditions considered are average solar minimum (Solar Min), average solar maximum (Solar Max), or median solar cycle (Solar Med), with solar modulation parameters for these conditions described in [2].

doi:10.1371/journal.pone.0096099.t002


1 day
1 year
Max. annual
dose for rad.
workers
Guarapari beach
1 year
Dose to the
tumor
0.01
0.1
1
10
100
1000
10000.
100000.
1000000
Dose
(mSv)
1 year
1 day
Fukushima
liquidators
Digital Mammography

Disclaimer



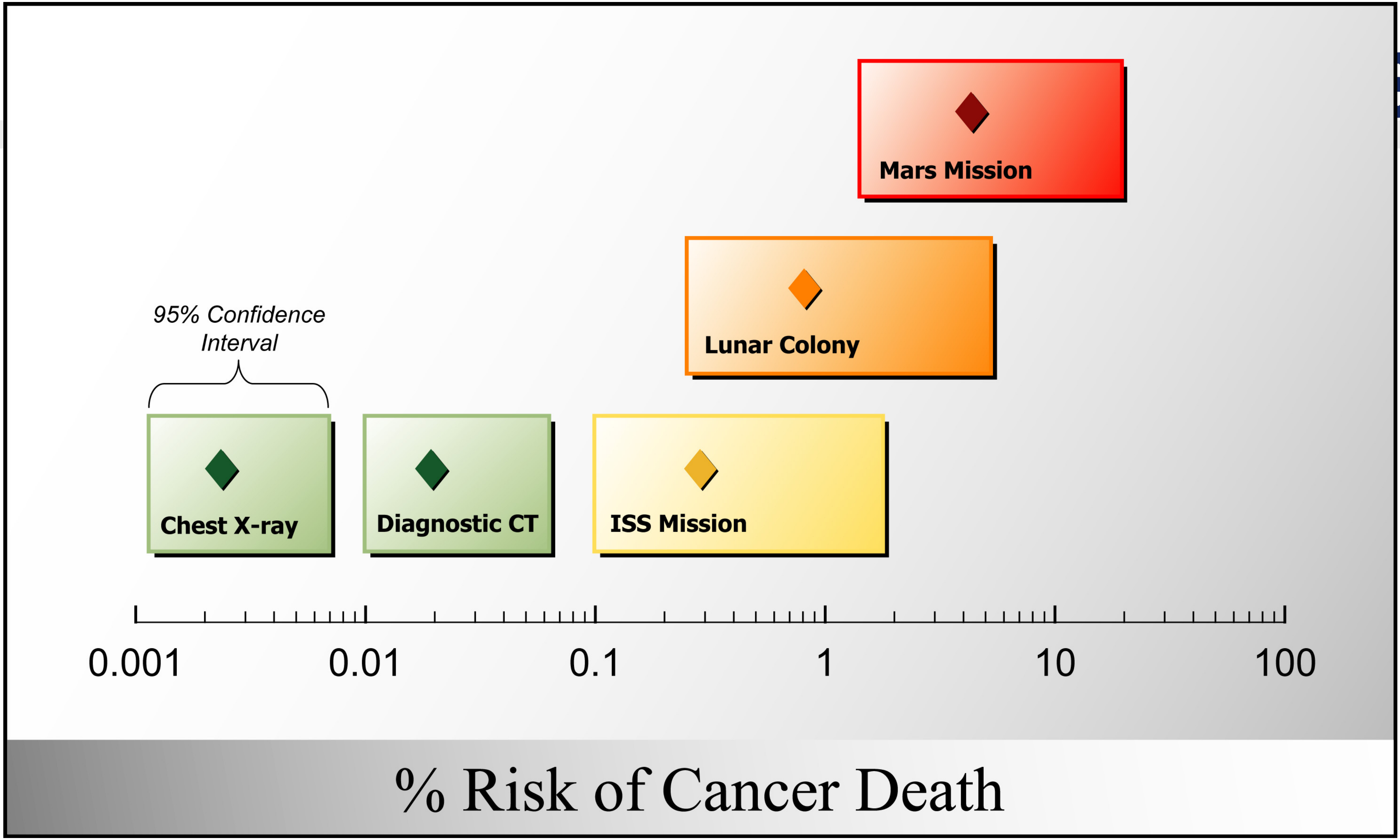
I do believe that humans landed on the Moon!

REFERENCE

- http://www.theseus-eu.org/

- Radiation risks:

- 1. Cancer
- 2. Tissue degenerative effects
  - 2.1 CNS
  - 2.2 Cardiovascular
  - 2.3 Cataracts
- 3. Acute syndromes (SPE)
- 4. Hereditary effects



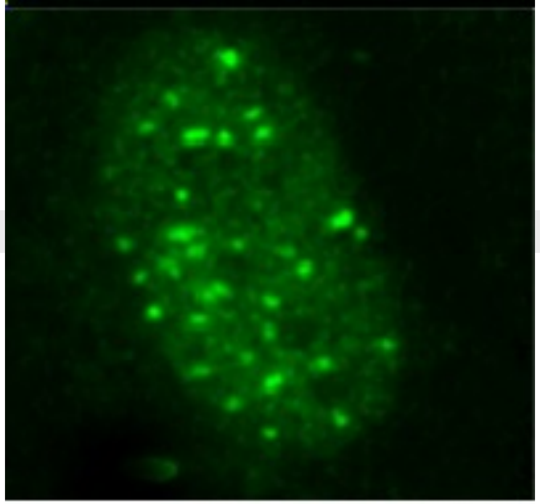
Durante & Cucinotta, *Nature Rev. Cancer* (2008)

Biological effects of heavy ions

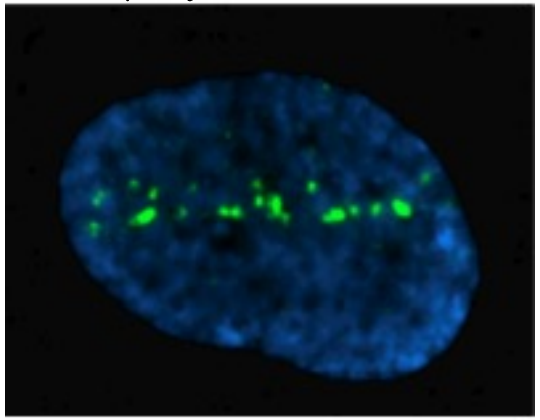
No human epidemiological data

Sources of uncertainty

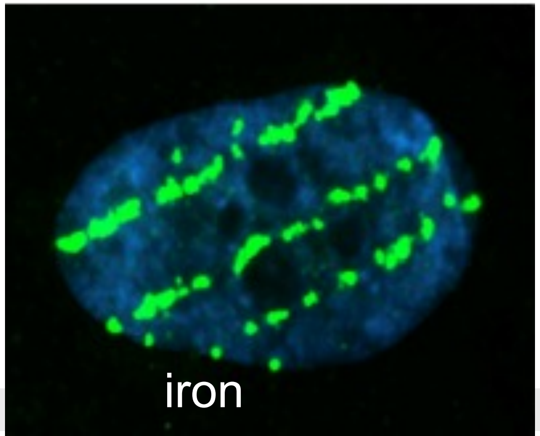
Durante & Cucinotta, *Nature Rev. Cancer* (2008)



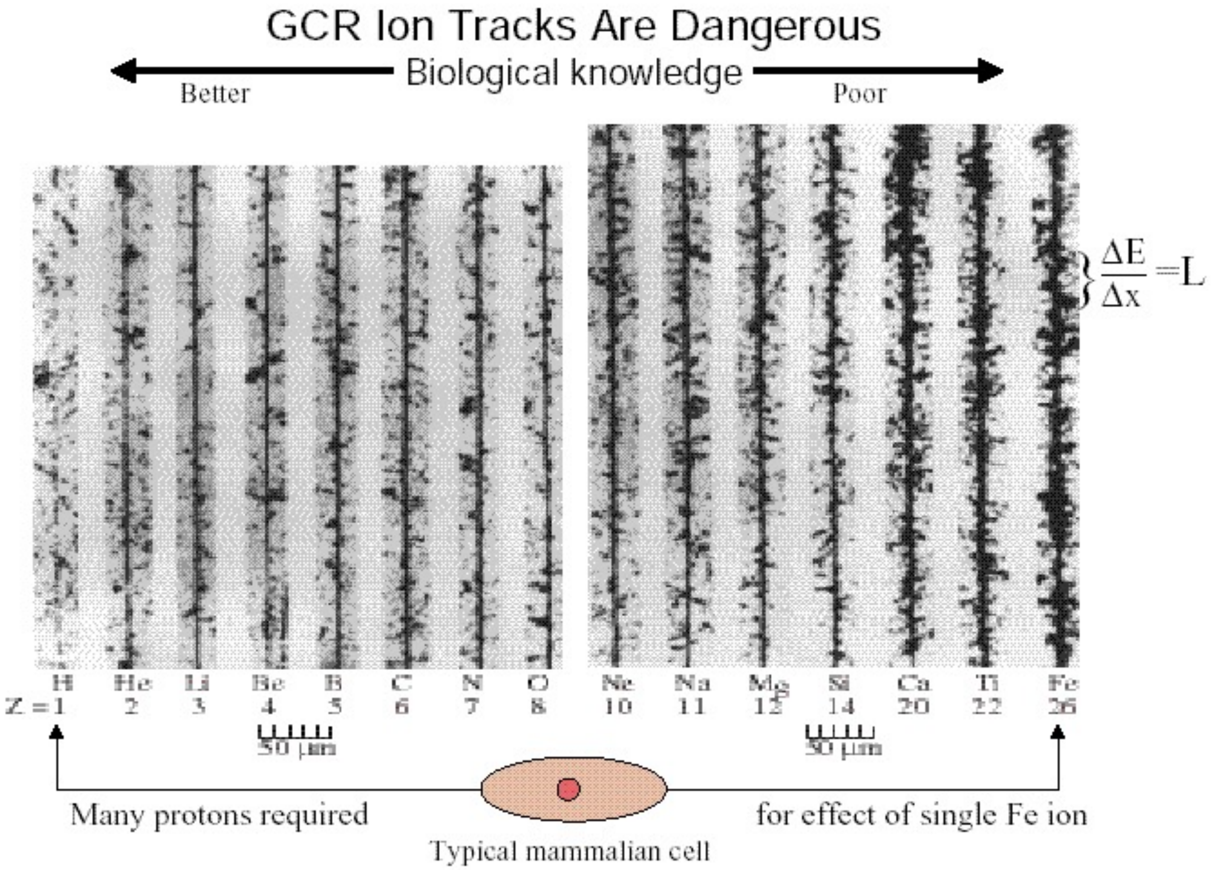
γ-rays



silicon

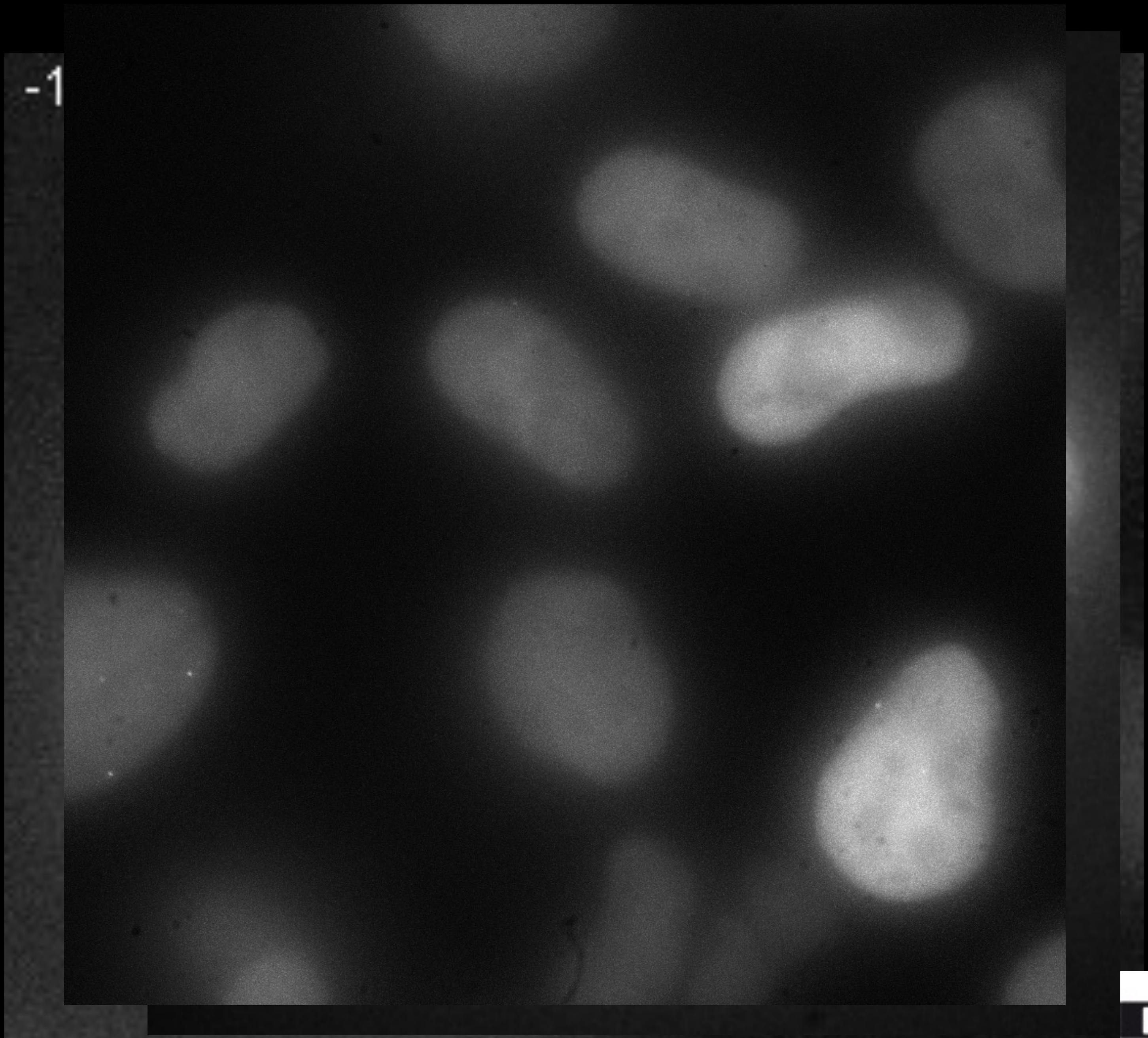


iron



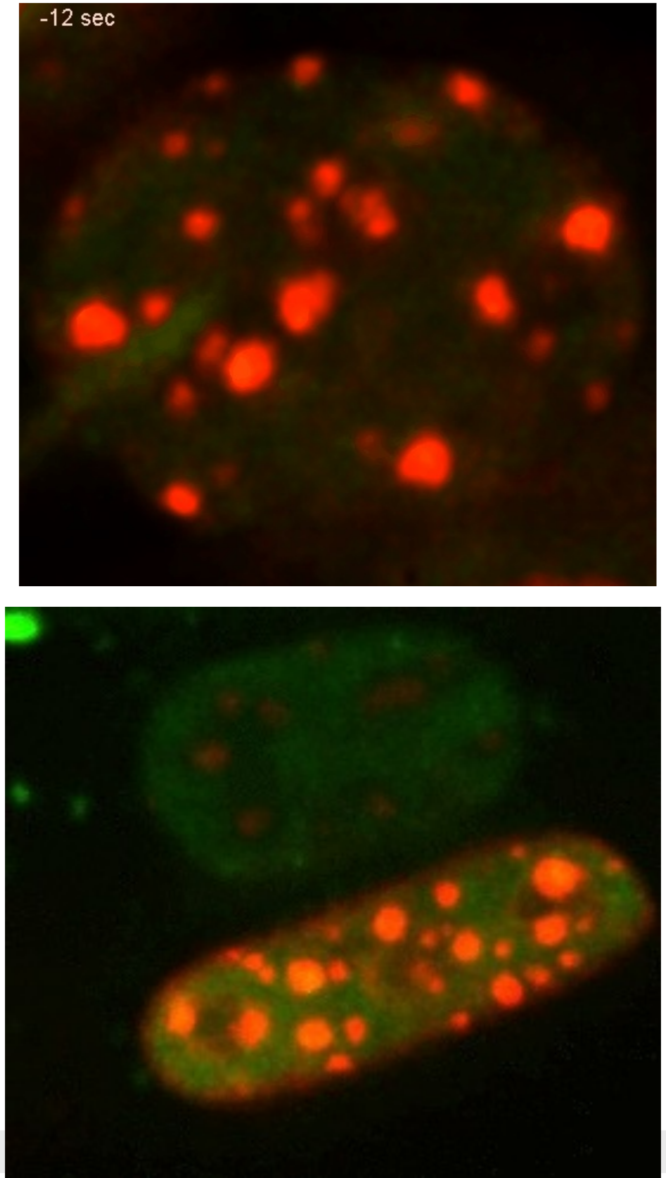
Cucinotta and Durante, *Lancet Oncol.* 2006

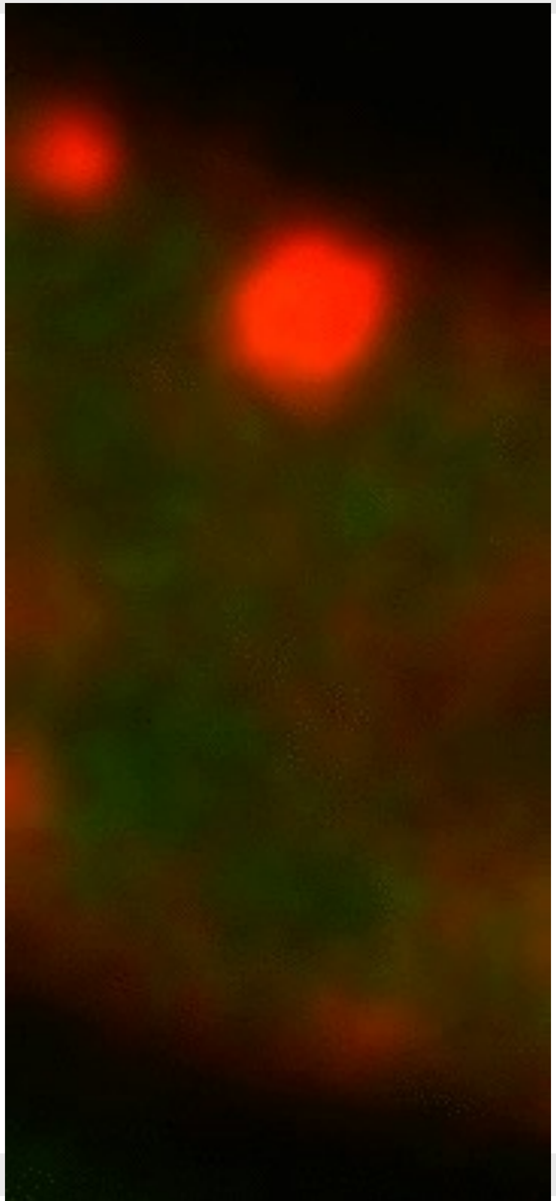
Live cell imaging DNA repair protein recruitment at DSB sites

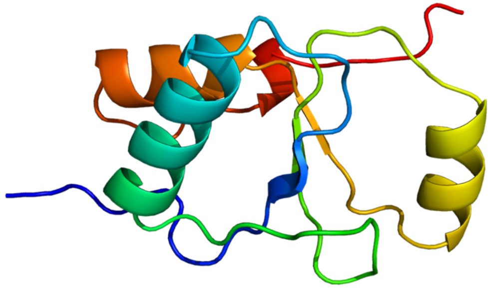


Jakob *et al., Proc. Natl. Acad. Sci. USA* 2009; *Nucl. Acids Res*. 2011

Recruitment of XRCC1 to heterochromatin and euchromatin after exposure of mouse embryo fibroblasts to heavy ions



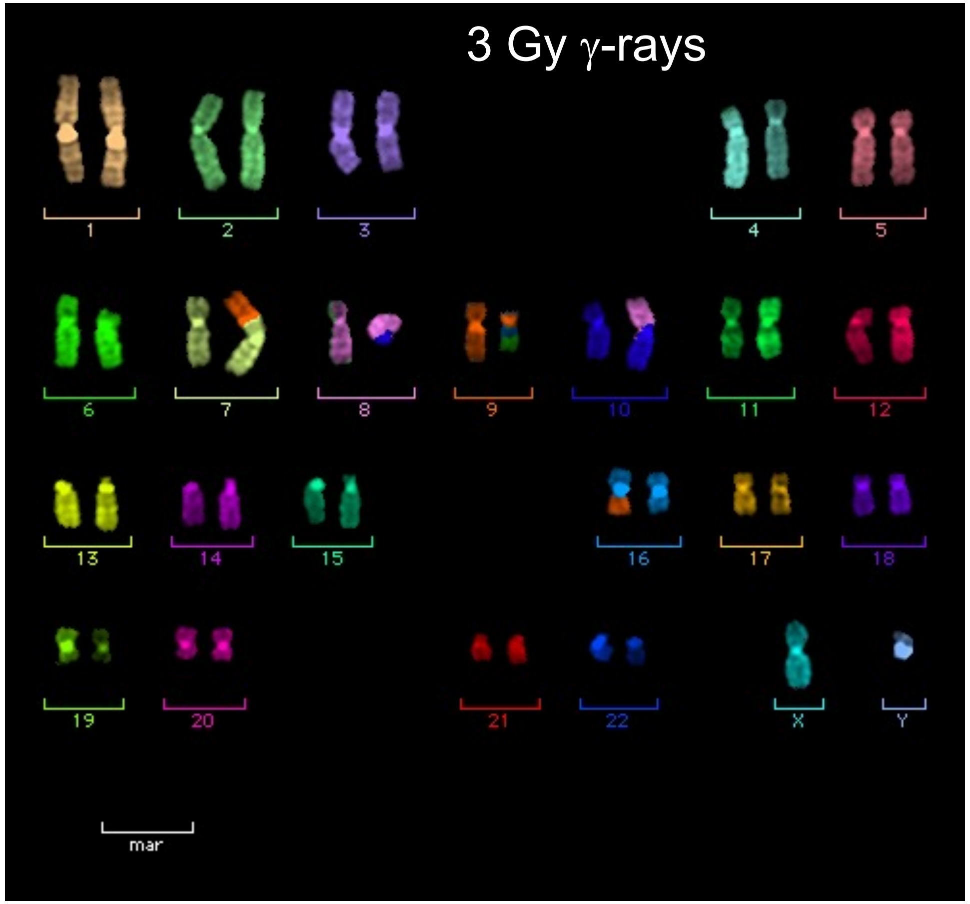


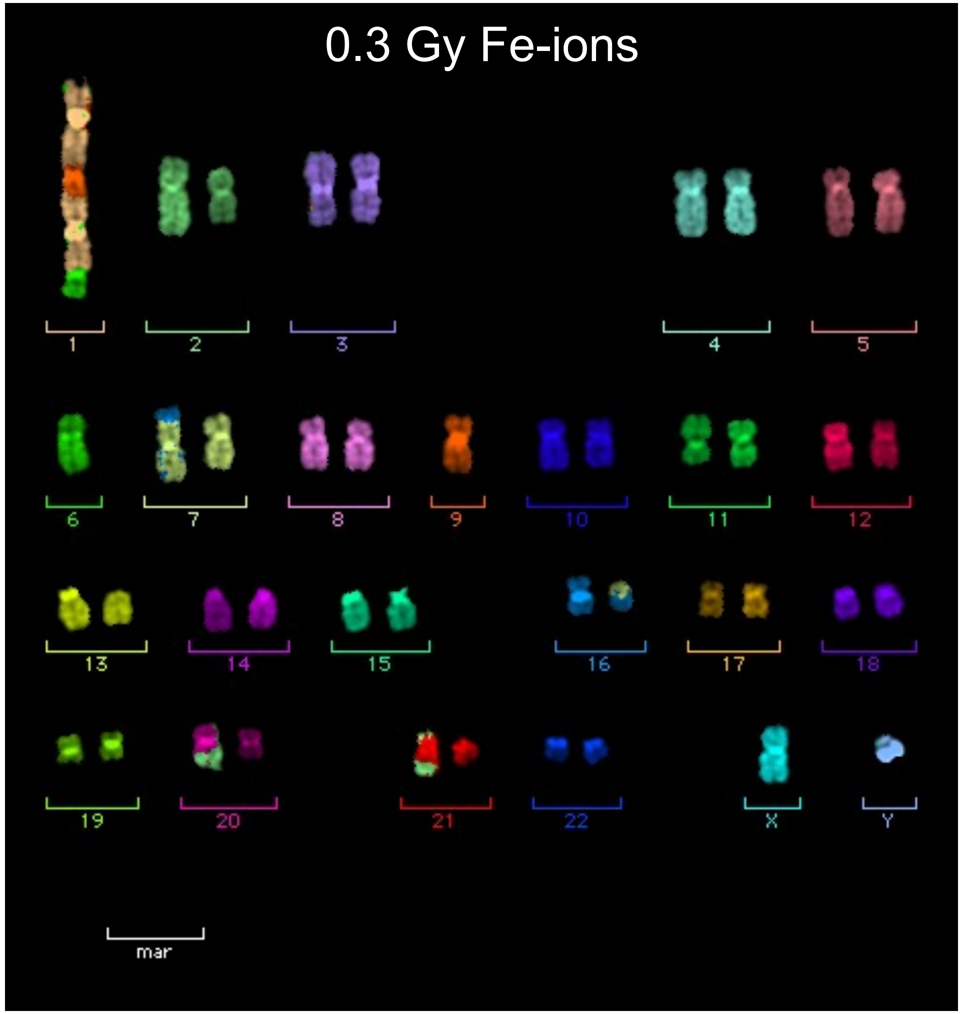


X-ray repair complementing defective in Chinese hamster cells (SSB and β-excision repair pathways)

Jakob *et al.*, *Nucl. Acids. Res.* 2011

Chromosomal aberrations induced by heavy ions





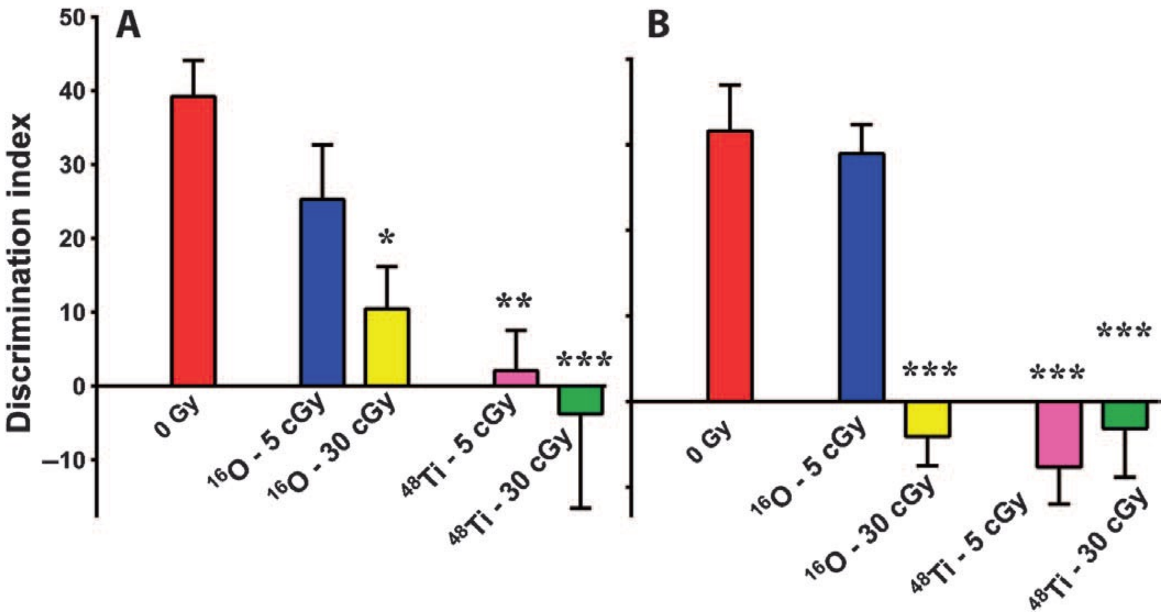
Durante *et al.*, *Radiat. Res.* 2002

RESEARCH ARTICLE Parihar *et al.* Sci. Adv. 2015;1:e1400256 1 May 2015

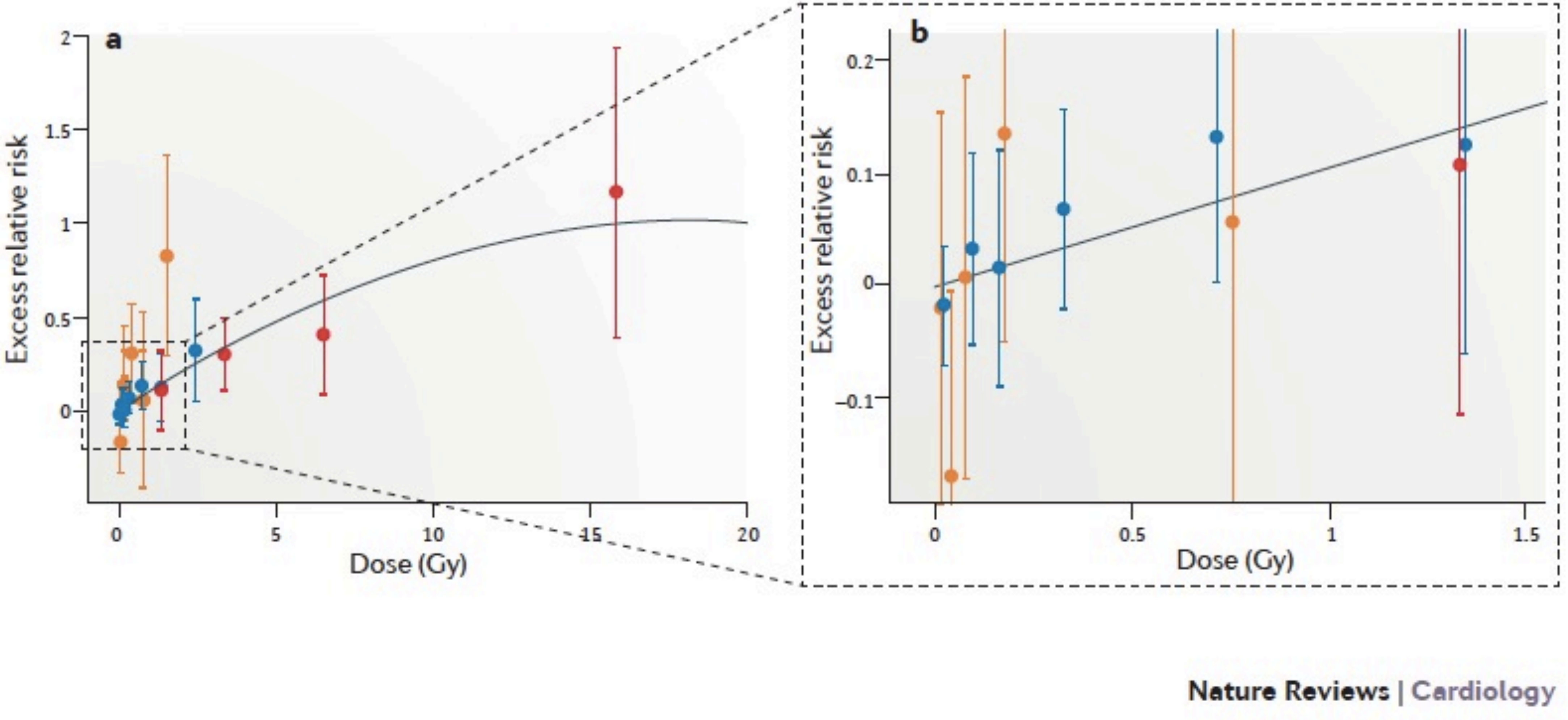
COGNITIVE NEUROSCIENCE

What happens to your brain on the way to Mars

Vipan K. Parihar,[1] Barrett Allen,[1] Katherine K. Tran,[1] Trisha G. Macaraeg,[1] Esther M. Chu,[1] Stephanie F. Kwok,[1] Nicole N. Chmielewski,[1] Brianna M. Craver,[1] Janet E. Baulch,[1] Munjal M. Acharya,[1] Francis A. Cucinotta,[2] Charles L. Limoli[1]*



Risk of radiation-induced late cardiovascular disease



Hughson, Helm & Durante, *Nat. Rev. Cardiol*. 2018

SCIENTIFIC REPORTS

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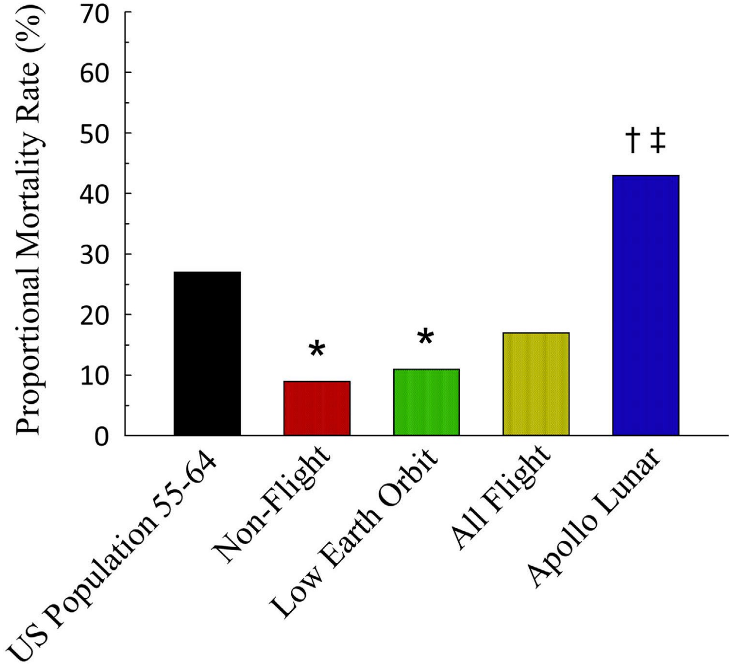
Apollo Lunar Astronauts Show Higher Cardiovascular Disease Mortality: Possible Deep Space Radiation Effects on the Vascular Endothelium

Received: 09 May 2016
Accepted: 22 June 2016
Published: 28 July 2016

Michael D. Delp[1], Jacqueline M. Charvat[2], Charles L. Limoli[3], Ruth K. Globus[4] & Payal Ghosh[1]

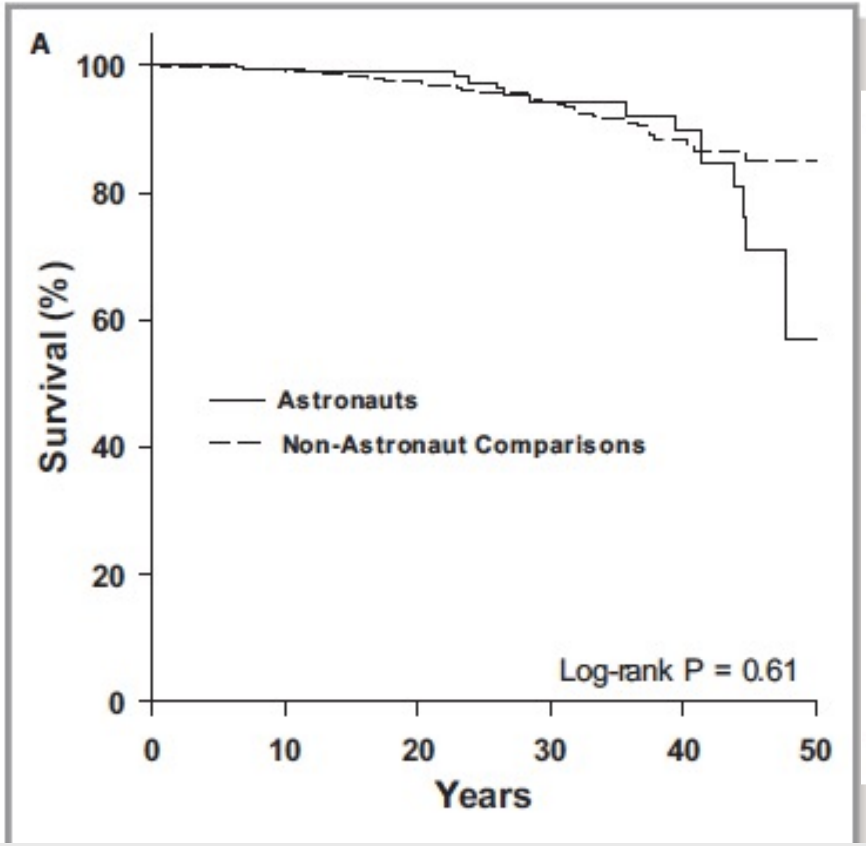


	Cardiovascular Disease	Cancer	Accident	Other
Reference Groups				
US Population Ages 55–64, (n = 338, 127)	27%	34%	5%	35%
Non-Flight Astronauts, (n = 35)	9%*	29%	53%*	9%*
Astronaut Groups				
All Flight Astronauts, (n = 42)	17%	31%	43%*	10%*
Low Earth Orbit Astronauts, (n = 35)	11%*	31%	49%*	9%*
Apollo Lunar Astronauts, (n = 7)	43%†‡	29%	14%^	14%

Incidence Rate of Cardiovascular Disease End Points in the National Aeronautics and Space Administration Astronaut Corps

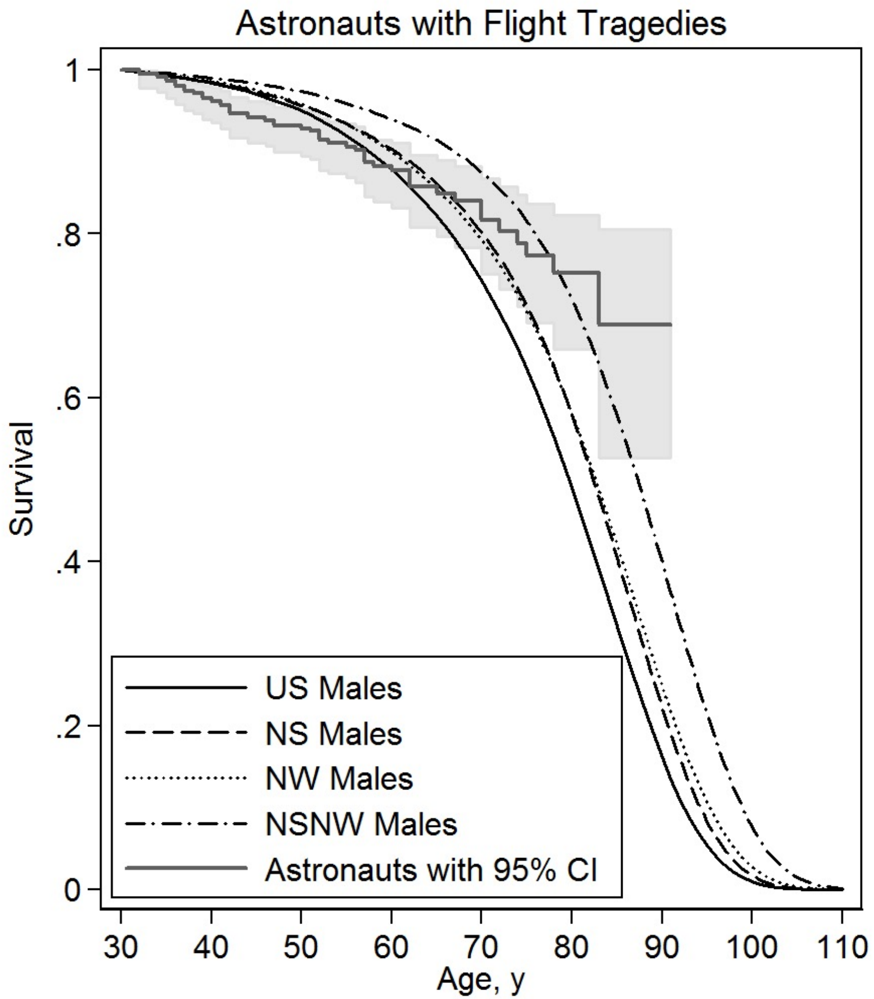
Carl J. Ade, PhD; Ryan M. Broxterman, PhD; Jacqueline M. Charvat, PhD; Thomas J. Barstow, PhD

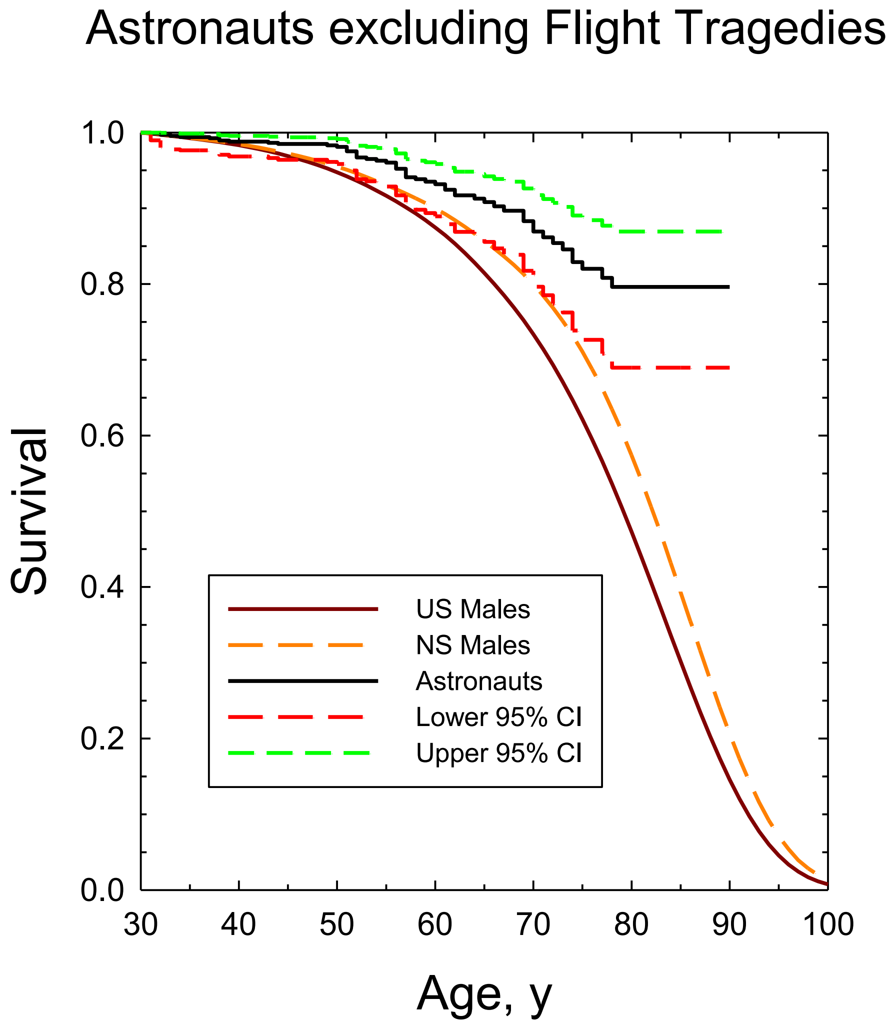
Conclusions—These findings suggest that being an astronaut is not associated with increased long-term risk of CVD development.
(*J Am Heart Assoc.* 2017;6:e005564. DOI: 10.1161/JAHA.117.005564.)



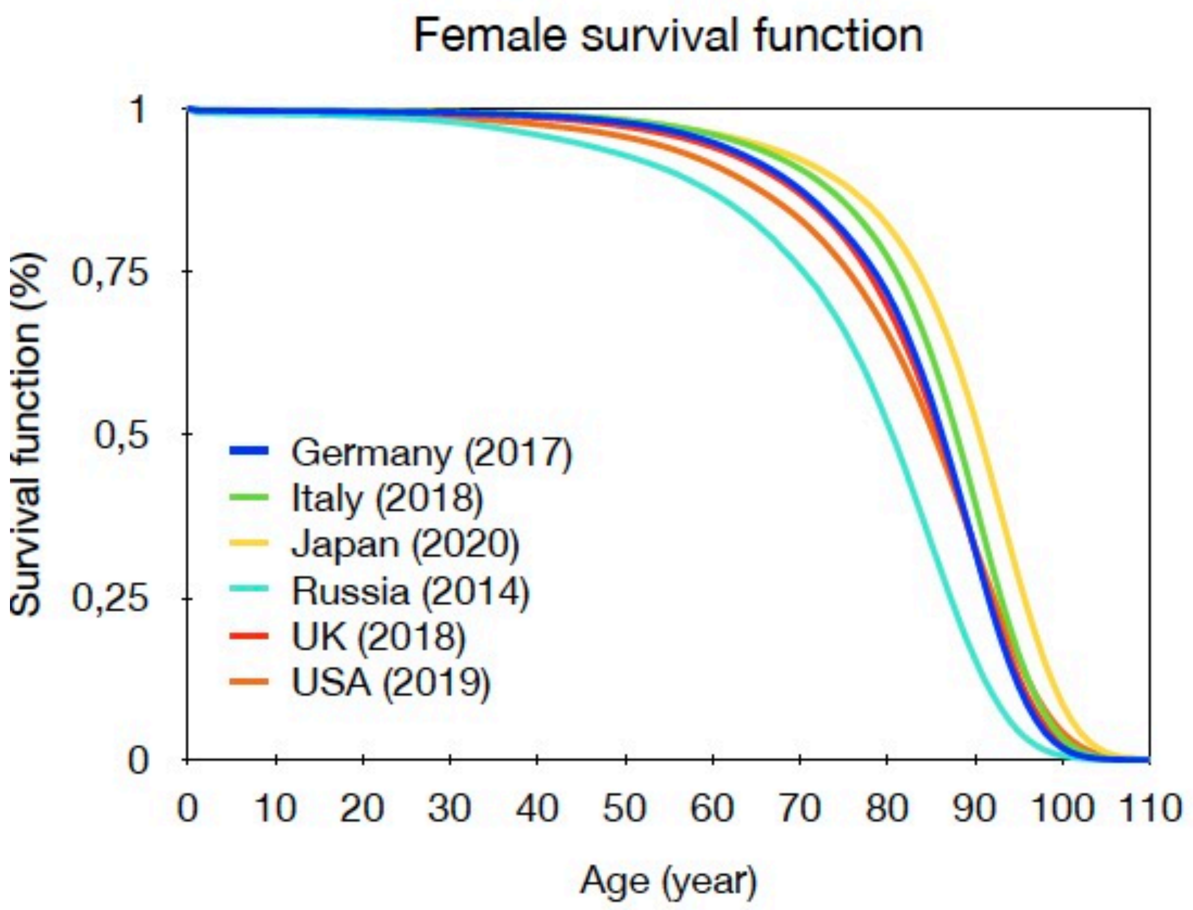
	Astronauts		Nonastronaut Comparisons	
	Frequency	Incidence Rate (Per 1000 PY)	Frequency	Incidence Rate (Per 1000 PY)
All CVD events	16	2.34	46	2.15
MI	7	1.02	21	0.98
CHF	5	0.73	4	0.19
Stroke	5	0.73	17	0.80
CABG	5	0.73	22	1.64
Multiple	5	0.73	17	0.79
CAD events	9	1.32	30	1.40

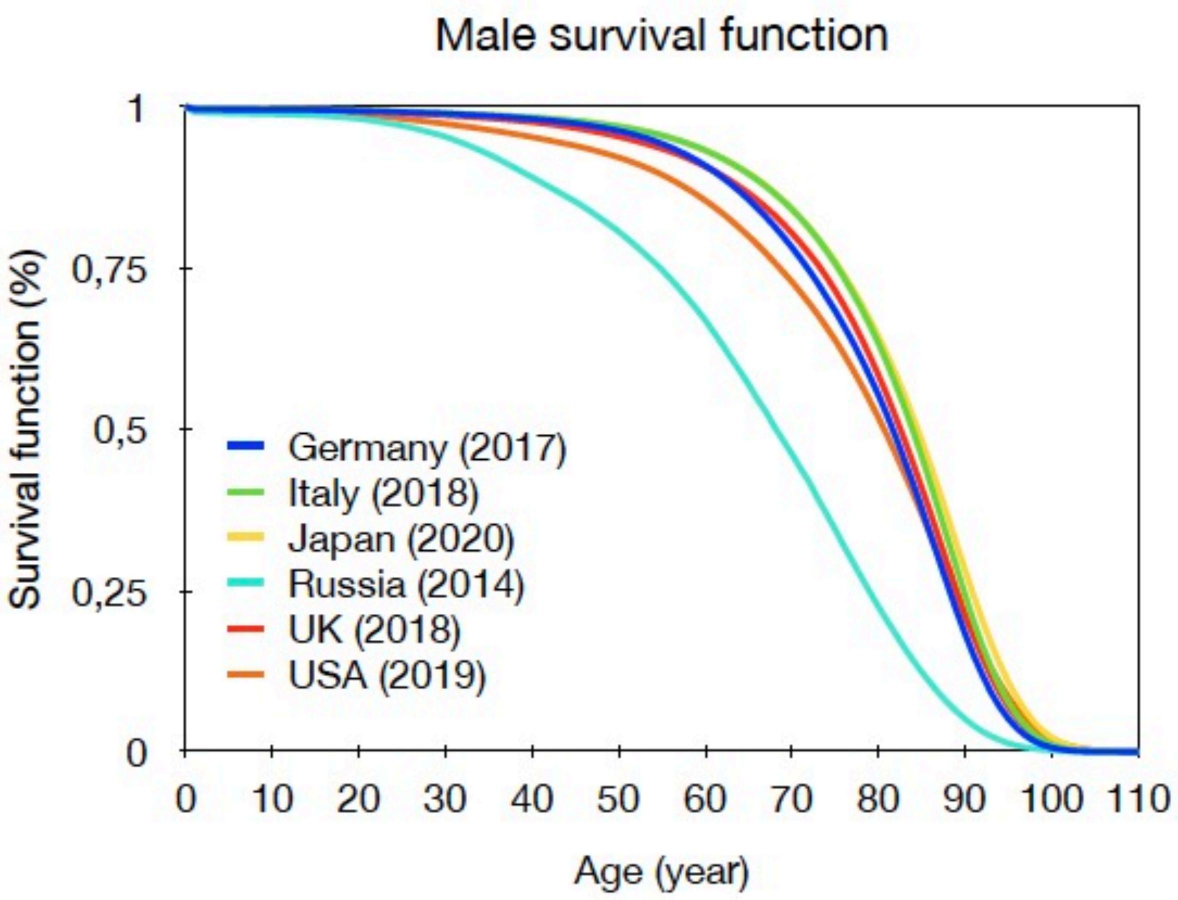
NASA astronauts' cause-specific mortality





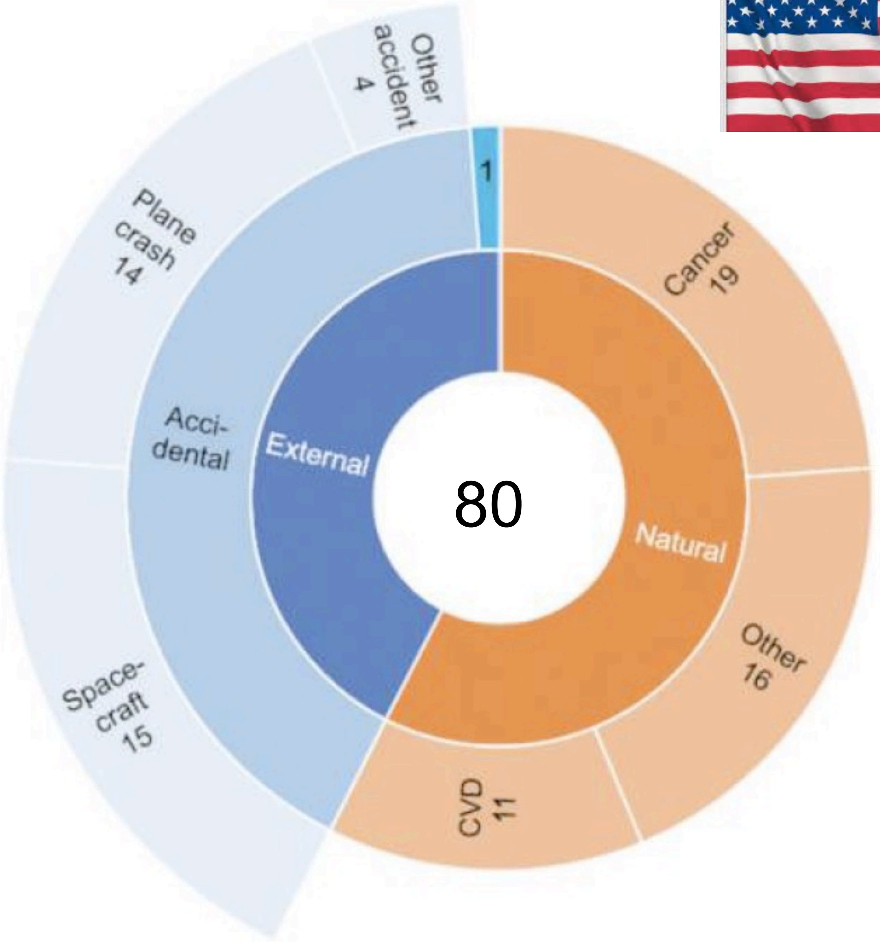
Survival of general population

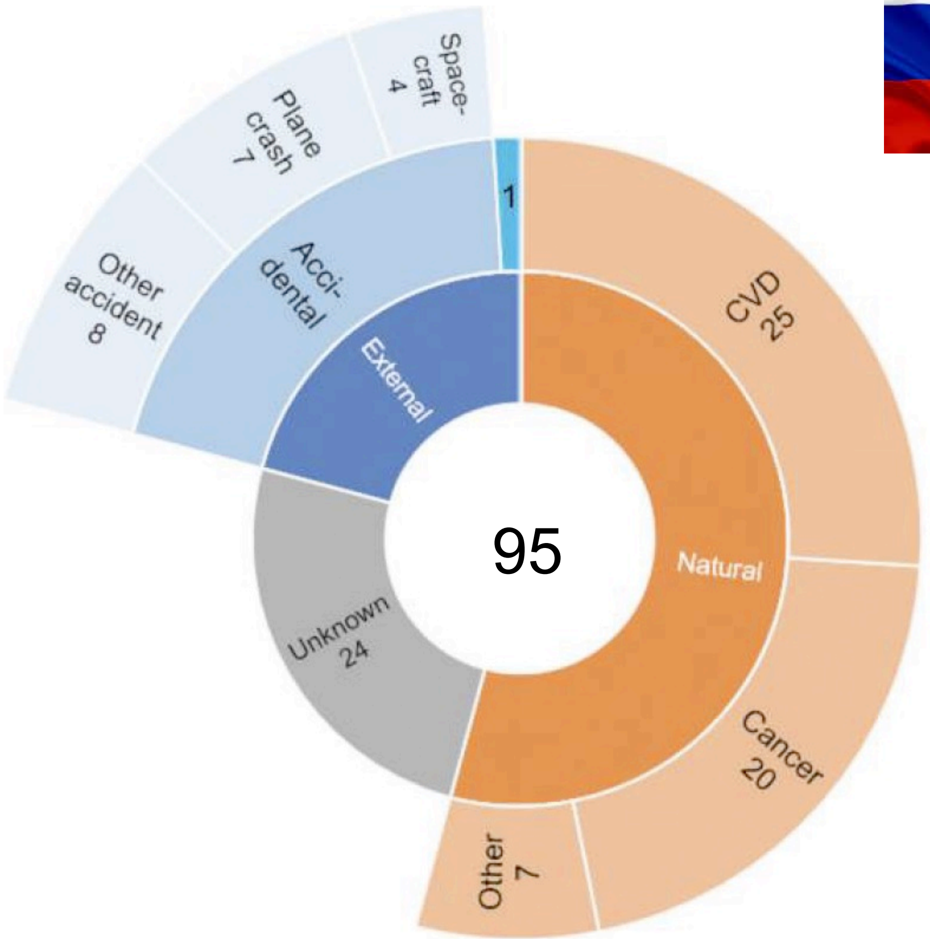




Boscolo and Durante, *Physics*, 2022

Astronaut mortality causes





Reynolds & Day, *Occup. Environ. Med.* 2021

SCIENTIFIC REPORTS

OPEN

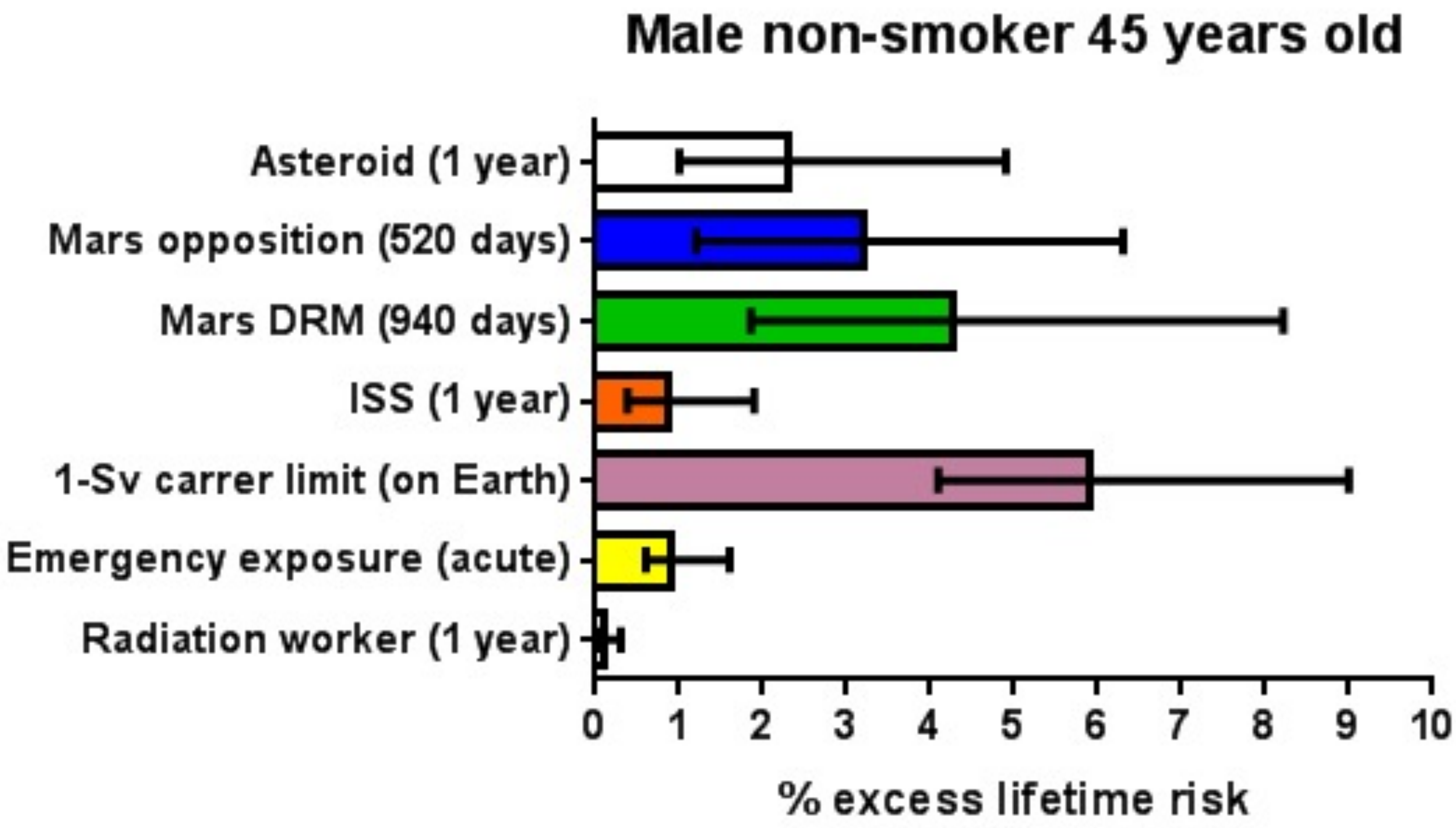
Received: 30 January 2019
Accepted: 24 May 2019
Published online: 04 July 2019

Contrapositive logic suggests space radiation not having a strong impact on mortality of US astronauts and Soviet and Russian cosmonauts

Robert J. Reynolds[1], Igor V. Bukhtiyarov[2], Galina I. Tikhonova[2], Steven M. Day[1], Igor B. Ushakov[3] & Tatyana Y. U. Gorchakova[2]

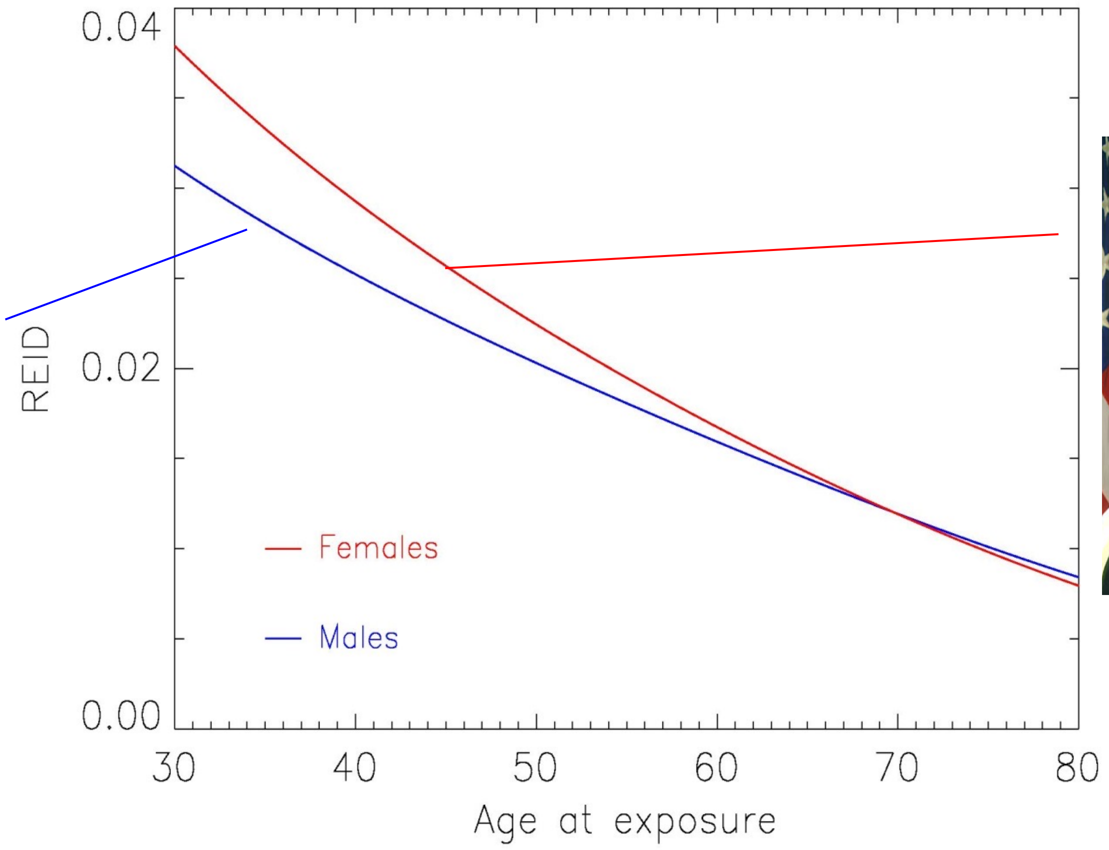
Space travelers are exposed to unique forms of ionizing radiation that pose potentially serious health hazards. Prior analyses have attempted to quantify excess mortality risk for astronauts exposed to space radiation, but low statistical power has frustrated inferences. If exposure to deep space radiation were causally linked to deaths due to two particular causes, e.g., cancer and cardiovascular disease, then those cause-specific deaths would not be statistically independent. In this case, a Kaplan-Meier survival curve for a specific cause that treats deaths due to competing causes as uninformative censored events would result in biased estimates of survival probabilities. Here we look for evidence of a deleterious effect of historical exposure to space radiation by assessing whether or not there is evidence for such bias in Kaplan-Meier estimates of survival probabilities for cardiovascular disease and cancer. Evidence of such bias may implicate space radiation as a common causal link to these two disease processes. An absence of such evidence would be evidence that no such common causal link to radiation exposure during space travel exists. We found that survival estimates from the Kaplan-Meier curves were largely congruent with those of competing risk methods, suggesting that if ionizing radiation is impacting the risk of death due to cancer and cardiovascular disease, the effect is not dramatic.

NASA limit (2012): 3% REID within 95% CI



Durante & Cucinotta, Nuclear Physics News 2014

REID: gender/age dependence



REID is larger for females than for males and decreasing with age. 30% difference@30 years

How to reduce risk uncertainty and develop new countermeasures?

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Astronaut Eileen Collins was the first woman to pilot the space shuttle in 1995. NASA

New NASA radiation standards for astronauts seen as leveling field for women

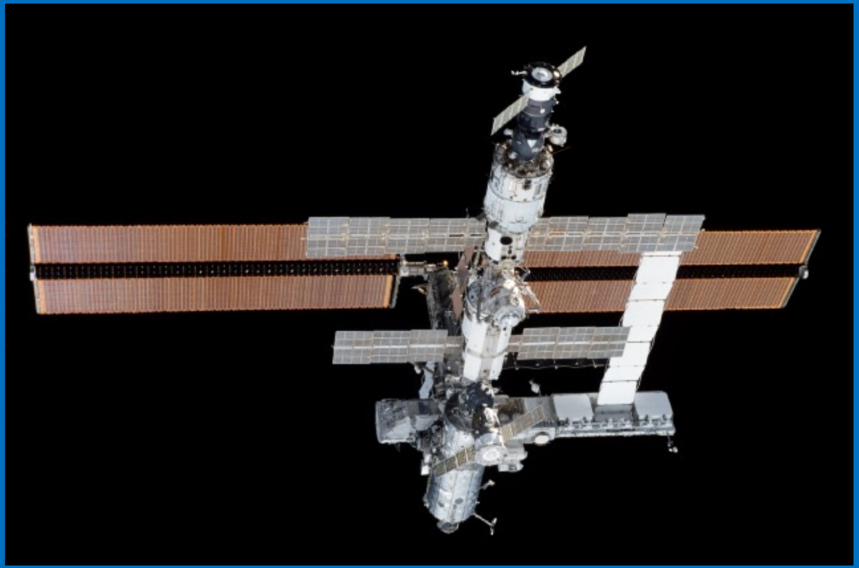
By Anil Oza | Jun. 29, 2021 , 10:35 AM

A blue-ribbon panel has endorsed NASA's plans to revise its standard for exposing astronauts to radiation in a way that would allow women to spend more time in space.

A report by the U.S. National Academies of Sciences, Engineering, and Medicine released on 24 June encourages NASA to proceed with its plans to adopt a new standard that limits all astronauts to 600 millisieverts of radiation

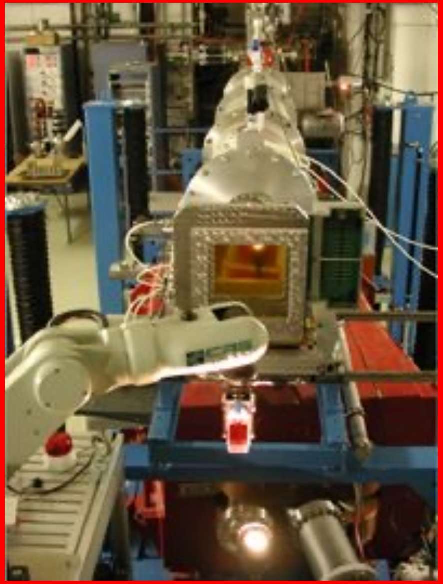
Blue team: research should be in space

- Mixed radiation field: protons+HZE+photons+neutrons
- Energies from few eV to TeV
- High fluence of protons (low dose rate) + low fluence HZE (high local dose)
- Exposure under strong stress conditions: microgravity, immune system depression, hypoxia
- Evidence that the space environment can affect organ functions, tissue growth, cellular metabolism and gene expression
- Space environment cannot be fully reproduced on Earth
- Space agencies think that space science = space flight



Red team: research should be on Earth

- Experiments in space are very expensive
- Many hindrances and boundary conditions, need custom hardware, very little crew time available, sometimes no sample return
- Experiments conditions are scarcely under control
- It is almost impossible to repeat the experiments
- Dose rate in space is very low (<1 mSv/day), but spaceflight related stress is very high: very low signal/noise ratio
- Accelerators can reproduce many aspects of the radiation environment



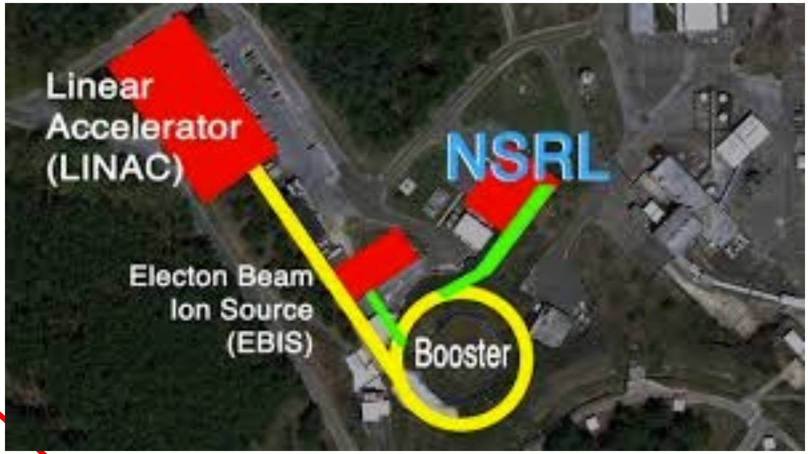
Ground-based research with heavy ions for space radiation protection

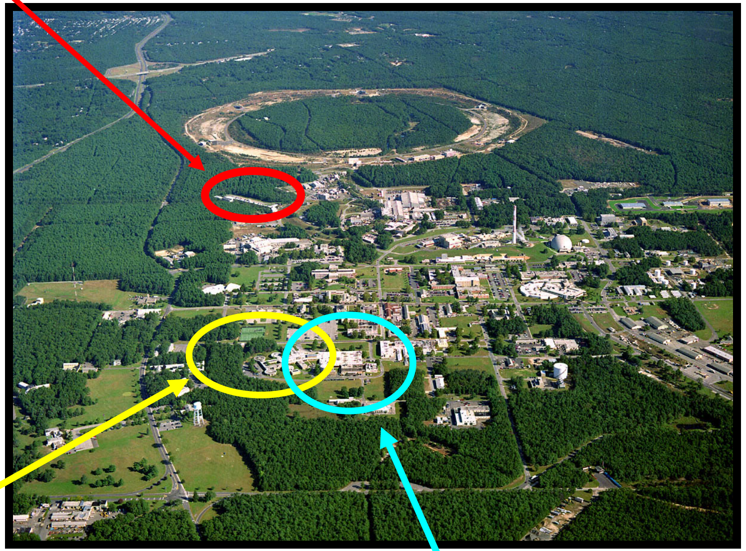
M. Durante [a,*], A. Kronenberg [b]

Advances in Space Research 35 (2005) 180–184

"our knowledge about space radiation risk comes from ground-based accelerator experiments"

NASA Space Radiation Health Program at the Brookhaven National Laboratory, Upton, NY





Medical Dept.

Biology Dept.

ESA space radiation lab @GSI

The European lab for space radiation research

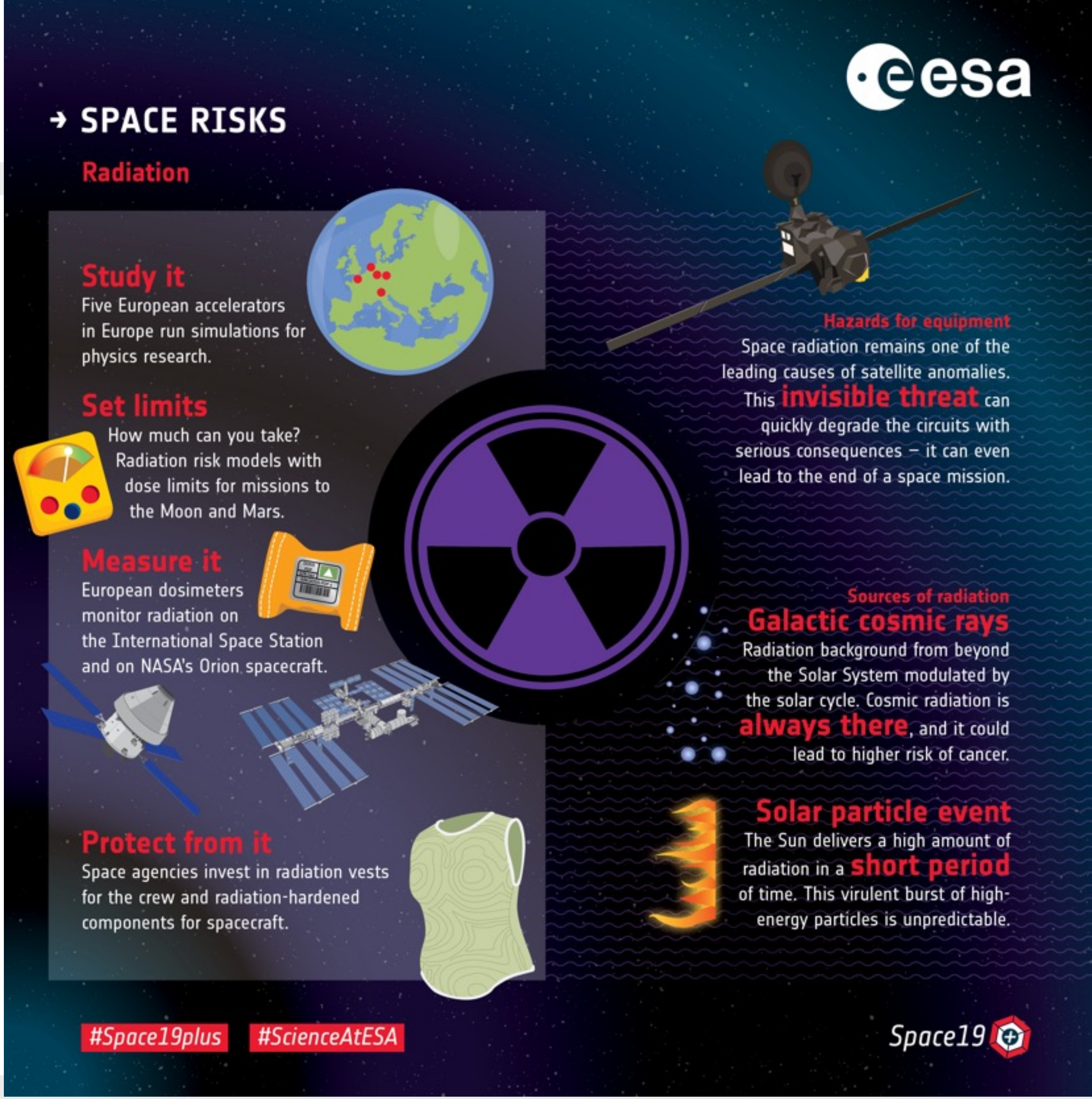
- All ions from H to U
- Max energy 10 GeV/n
- Intensity 10-1,000x the one at GSI SIS18
- Opening slated for 2025

MoU FAIR-GSI, 2018

ESA's Ground-Based Space Radiation Research

- Investigations into the **B**iological **E**ffects of Space **R**adiation (IBER), identifying and testing shielding material

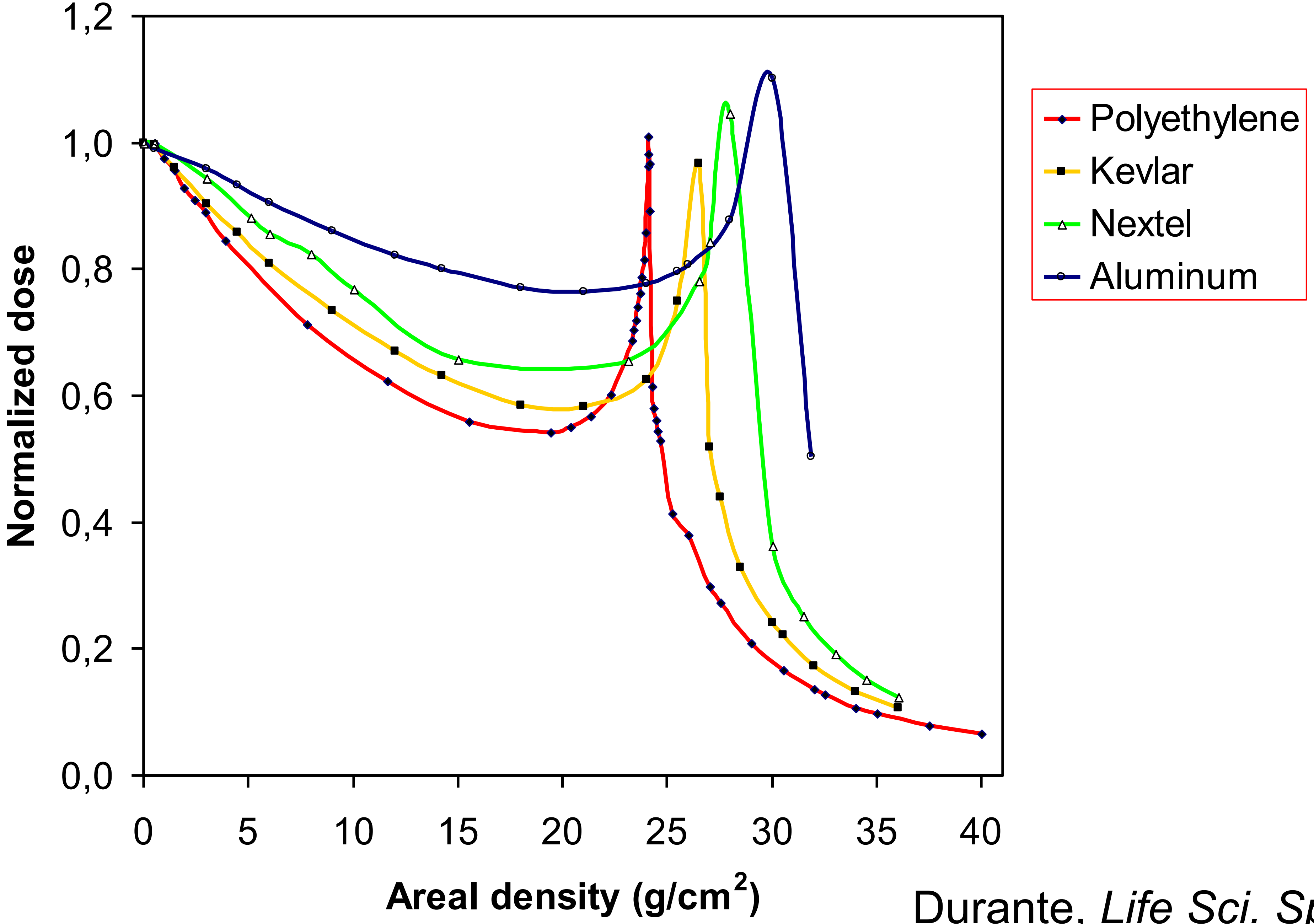
- Solicitation and implementation of experiments through **C**ontinuously **O**pen **R**esearch **A**nnouncement as well as a dedicated Announcement of Opportunity released (next in Spring 2022)



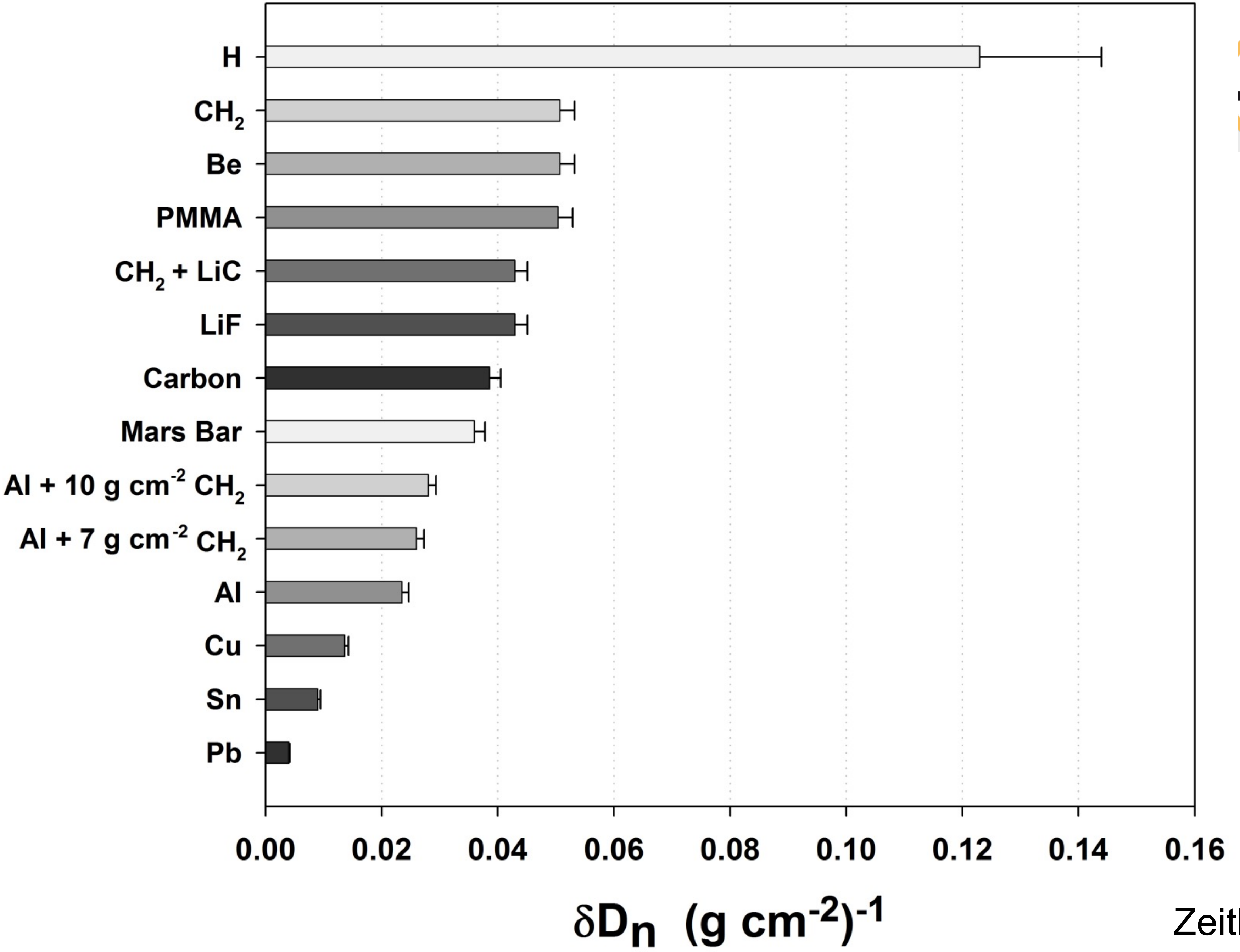
ROSSINI experiment

Schuy *et al.*, *Radiat. Res.* 2019

Giraudo *et al.*, *Radiat. Res.* 2018



Durante, *Life Sci. Space Res.* 2014



Zeitlin *et al., New J. Phys.* 2008

Effective dose from GCR behind different shielding materials

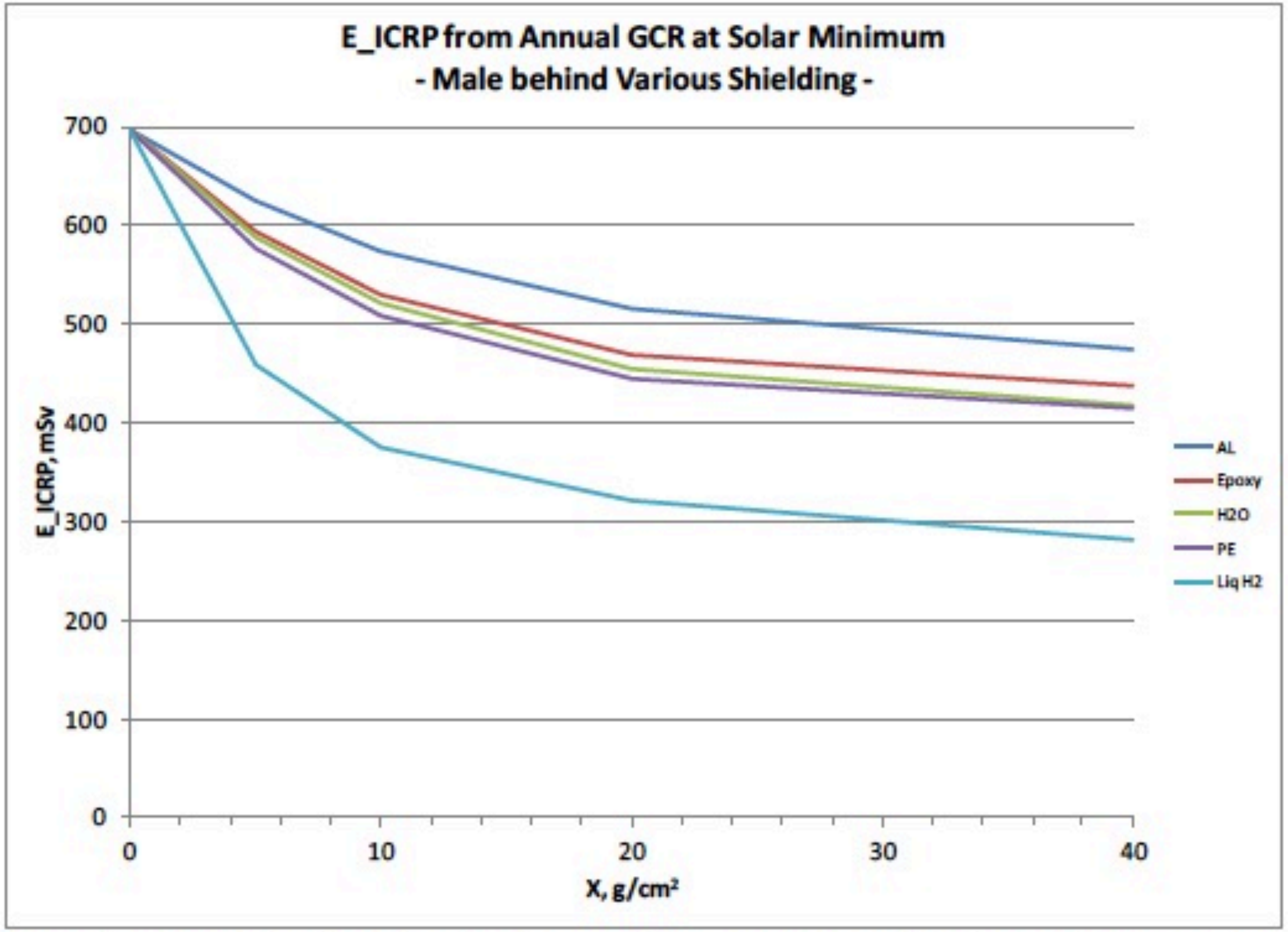
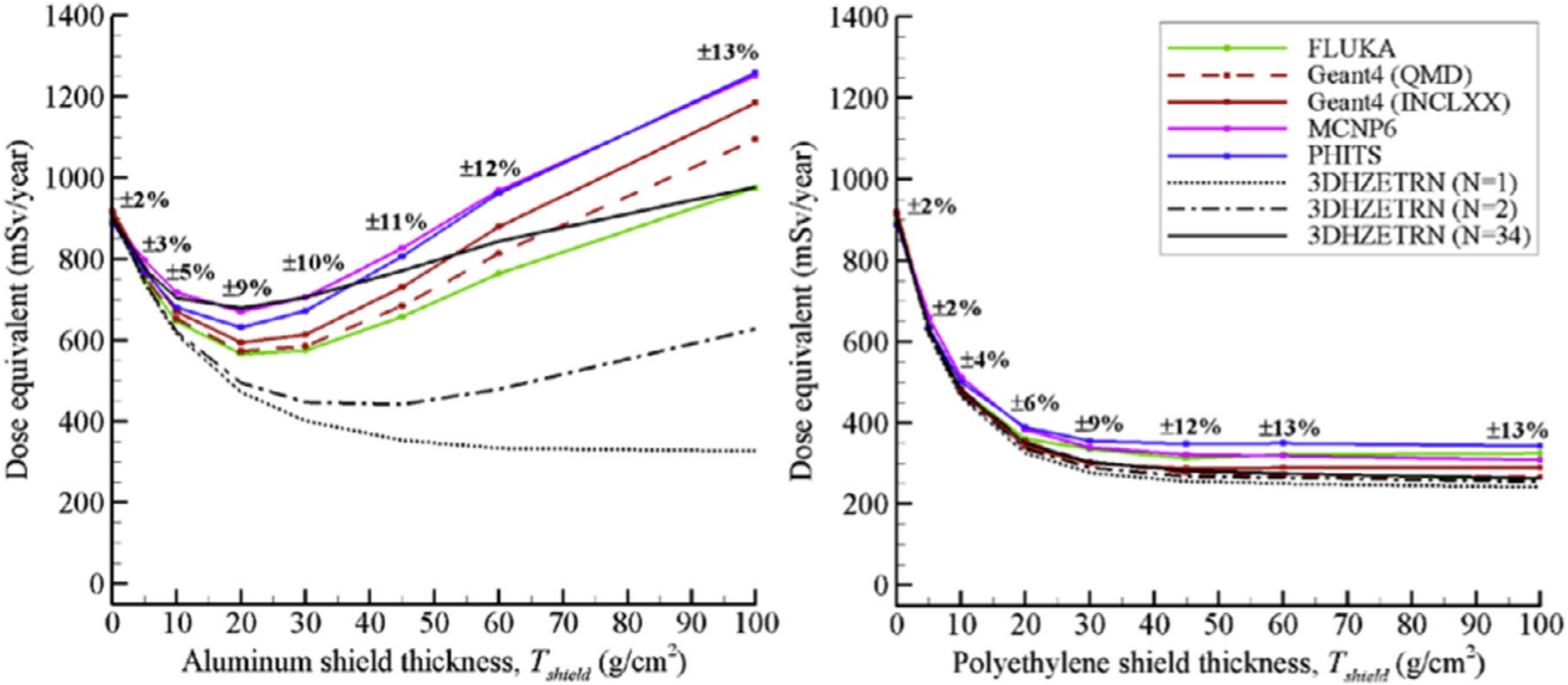


Figure 7a. Comparisons on depth-Effective dose estimates versus shielding thickness using the ICRP definition of quality factors for several materials. Calculations are for 1-year GCR exposures at solar minimum.

Evaluating shielding approaches to reduce space radiation cancer risks (NASA TM-2012-217361). Cucinotta FA, Kim MYH, Chappell LJ.

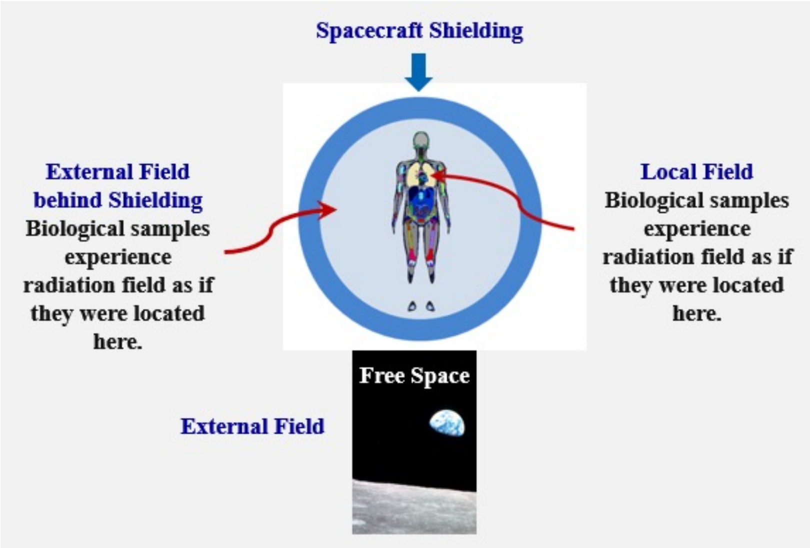


Slaba *et al.*, *Life Sci. Space Res*. 2017

NASA Space Radiation Laboratory GCR Simulation

Research emphases: research areas and techniques

Defined and delivered GCR reference environment radiation field compatible with NSRL operational and delivery parameters including animal care, cell requirements and logistics.



The radiation field found within the female deep tissue site (BFO) behind 20g/cm^2 of aluminum during solar minimum conditions is the reference field for the GCR simulator.

Slaba et al. (2016)

GCR Simulation Beam consists of 33 beams

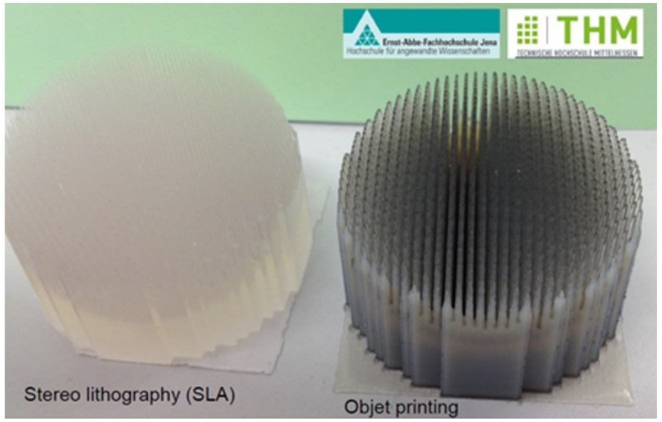
- *4 proton energies plus degrader*
- *4 helium energies plus degrader*
- *5 Heavy ions: C, O, Si, Ti, Fe*

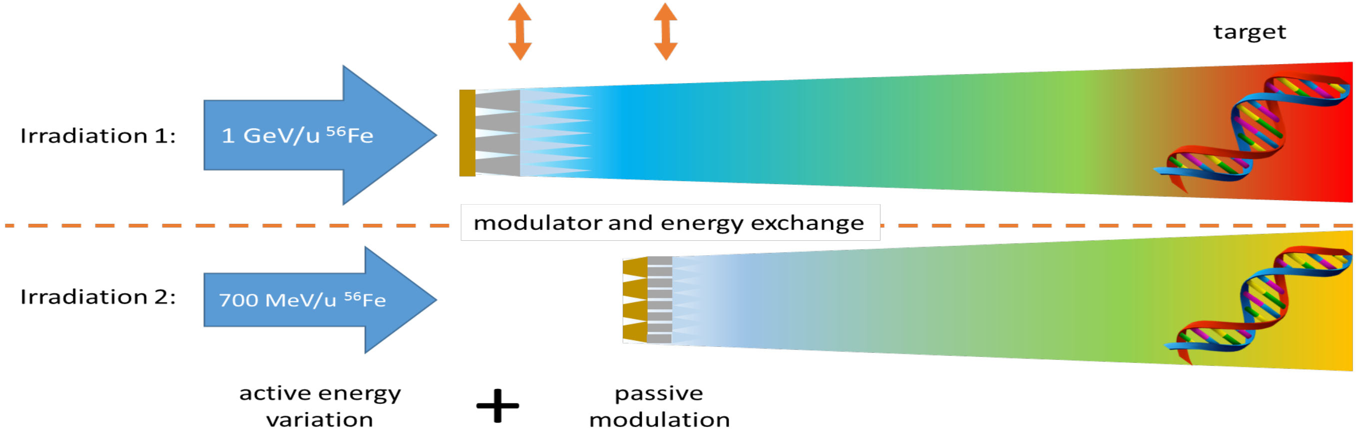
GCRsim beam selection normalized to 500 mGy

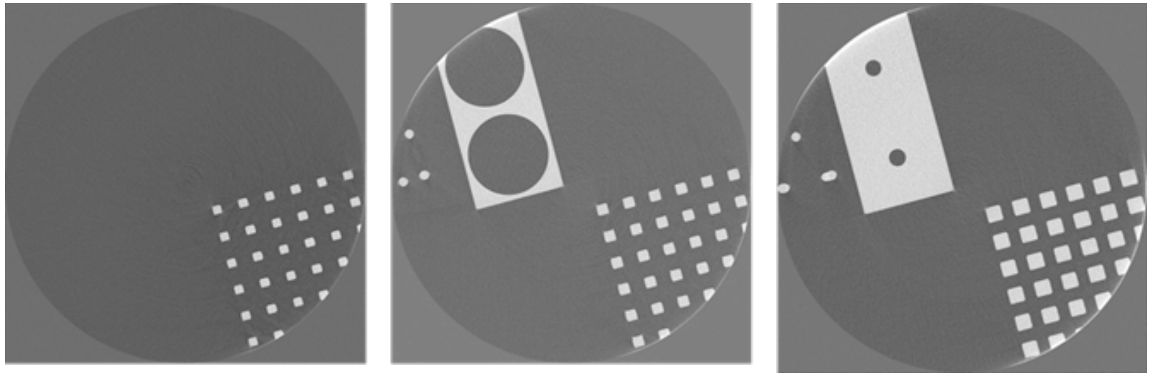
Ion	Energy (MeV/n)	Range (cm)	LET (keV/μm)	Dose (mGy)
^{1}H	20 - 100, 11 steps	*Polyethylene degrader for energies 20 to 100*		
^{1}H	150	15.9	0.54	35.0
^{1}H	250	38.1	0.39	68.9
^{1}H	1000	326.6	0.22	123.6
^{4}He	20 -100, 11 steps	*Polyethylene degrader for energies 20 to 100*		
^{4}He	150	16.0	2.17	7.5
^{4}He	250	38.3	1.56	16.4
^{4}He	1000	327.8	0.88	24.9
^{12}C	1000	110.1	7.95	11.7
^{16}O	350	17.0	20.8	15.4
^{28}Si	600	22.7	50.2	8.1
^{48}Ti	1000	32.5	109.5	4.5
^{56}Fe	600	13.1	175.1	4.1
Total				*500.0*

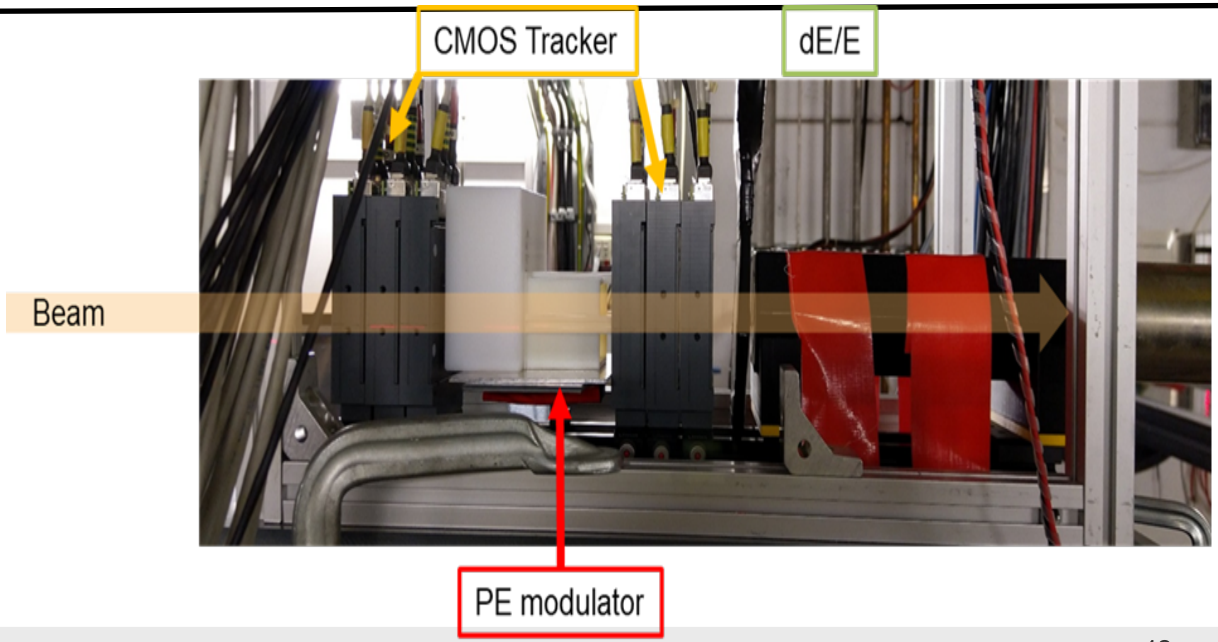
New infrastructures for FAIR tested in FAIR-phase-0 (March-June 2021)

GCR simulator









Schuy *et al.*, *Front. Phys*. 2020

ESA-FAIR Summer School in Darmstadt

www.gsi.de/esa-fair-summer-school.htm

Conclusion & Take-Home Messages

- Space radiation is the main health risk for humans in space and a potential showstopper for exploration
  - High uncertainty on radiation risk caused by the radiation quality difference compared to Earth
  - Lack of reliable countermeasures, due to the high energy of the cosmic radiation
  - Need for more research at high-energy particle accelerators
  - Need for common risk models and dose limits for international exploratory-class missions

Thanks you very much!

www.gsi.de/biophysik

Thank you!

FAIR esa

RADNEXT R2E CERN FAIR Phase 0 Research Program

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