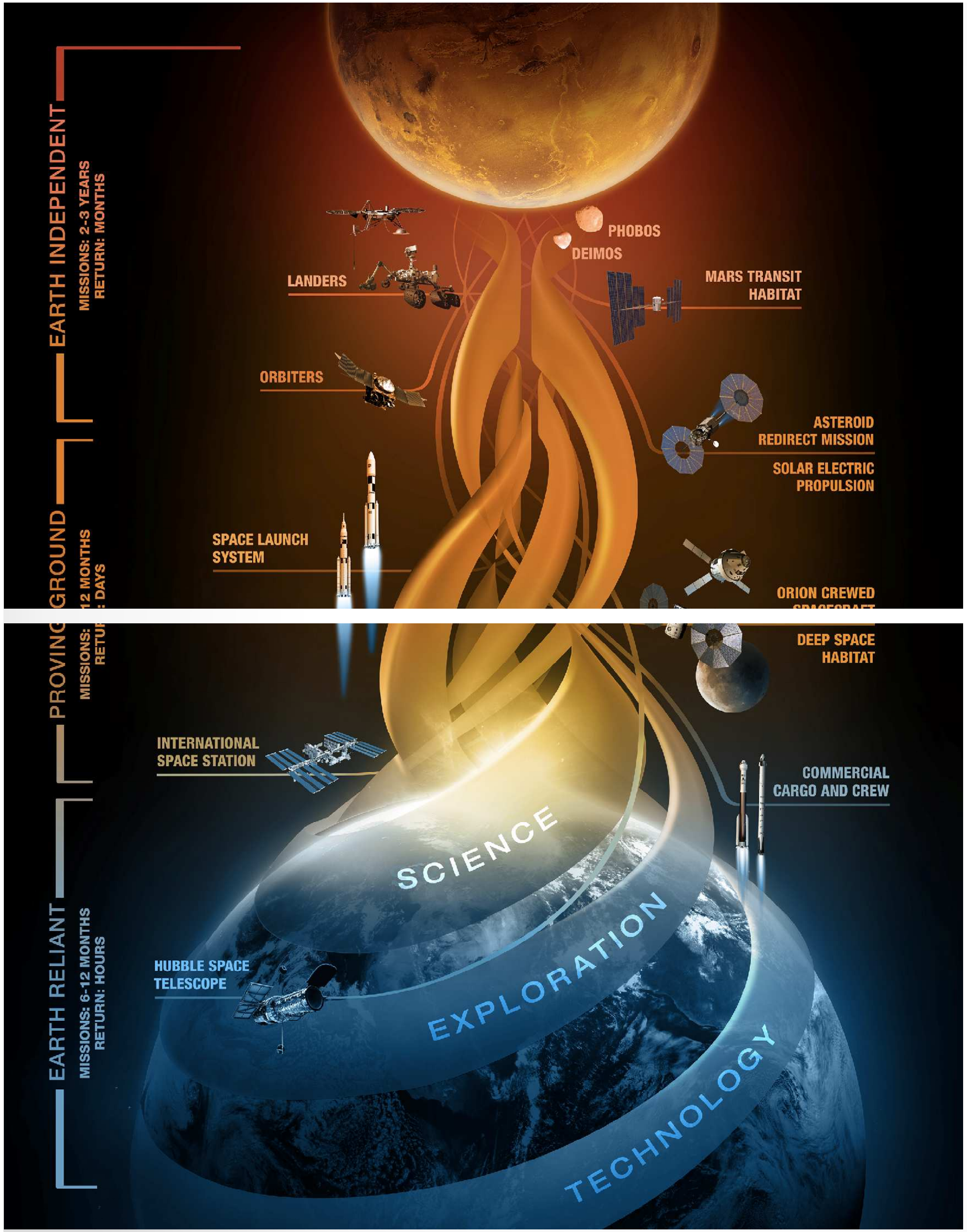
February 13, 2018 Cogne

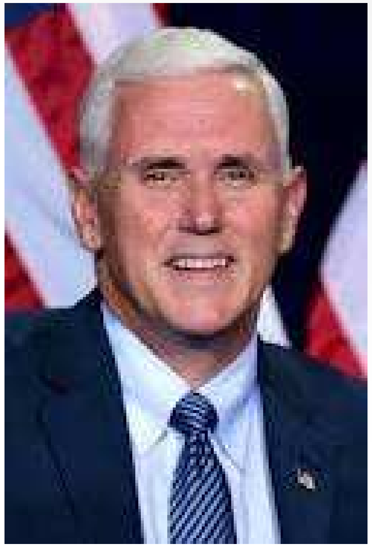
Heavy ions in therapy and space – part II

Space radiation protection

TIFPA

Marco Durante





NASA has been directed to develop a plan for an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system, returning humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations

Mike Pence, October 6, 2017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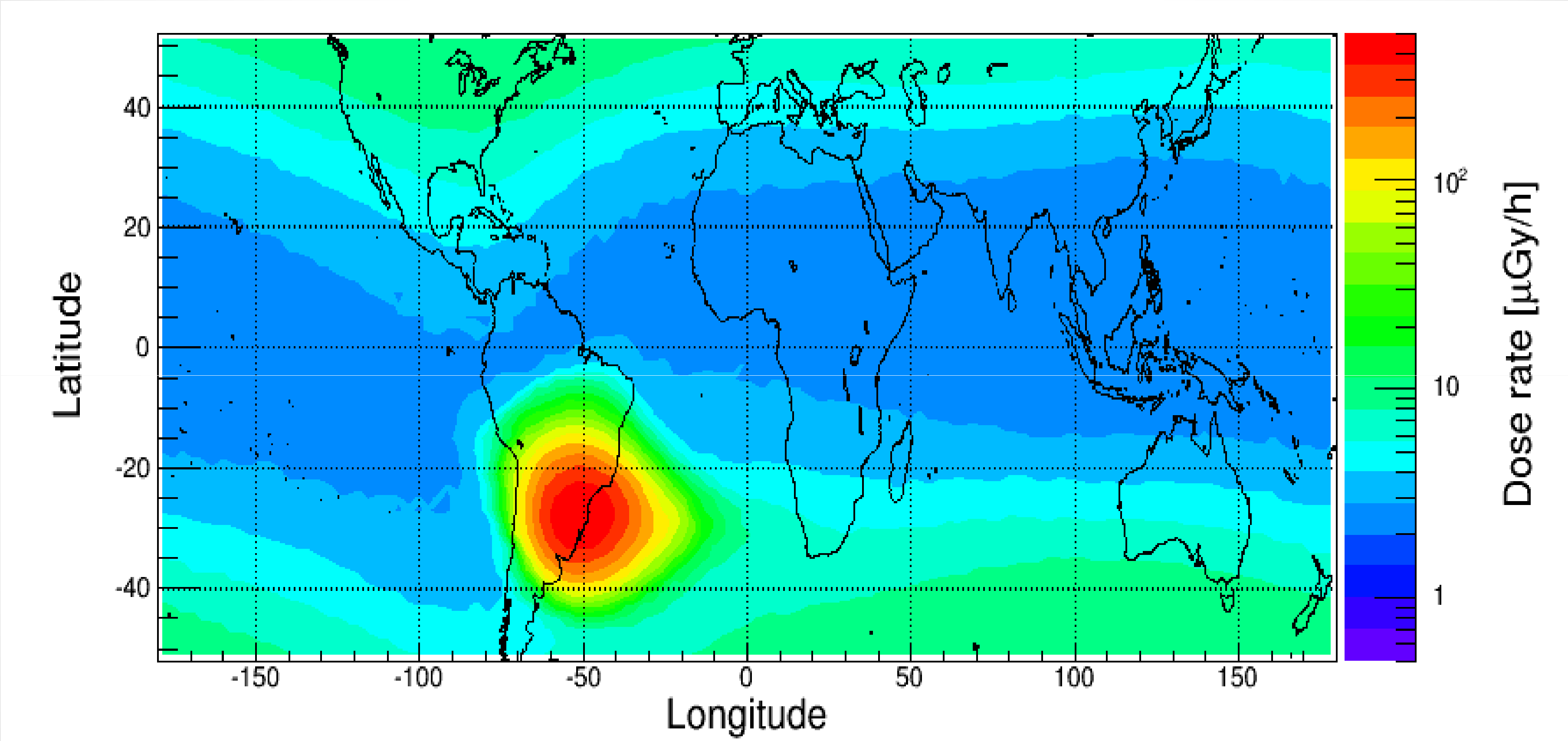
Health in Deep Space

1. Protection from space radiation (particularly very high energy heavy ions)
2. Psychosocial and behavioural problems
3. Physiological changes caused by microgravity

Modified by Mike Lockwood

RADIATION ENVIRONMENT - ISS



DOSIS 3D (2012 – ongoing): Variation of absorbed dose over ISS orbit (active radiation detectors)

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

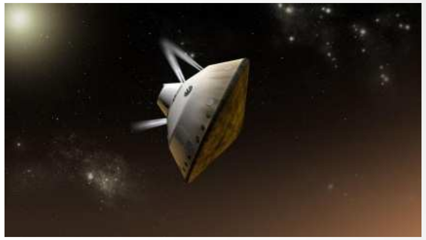
RAD Instrument Overview

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).

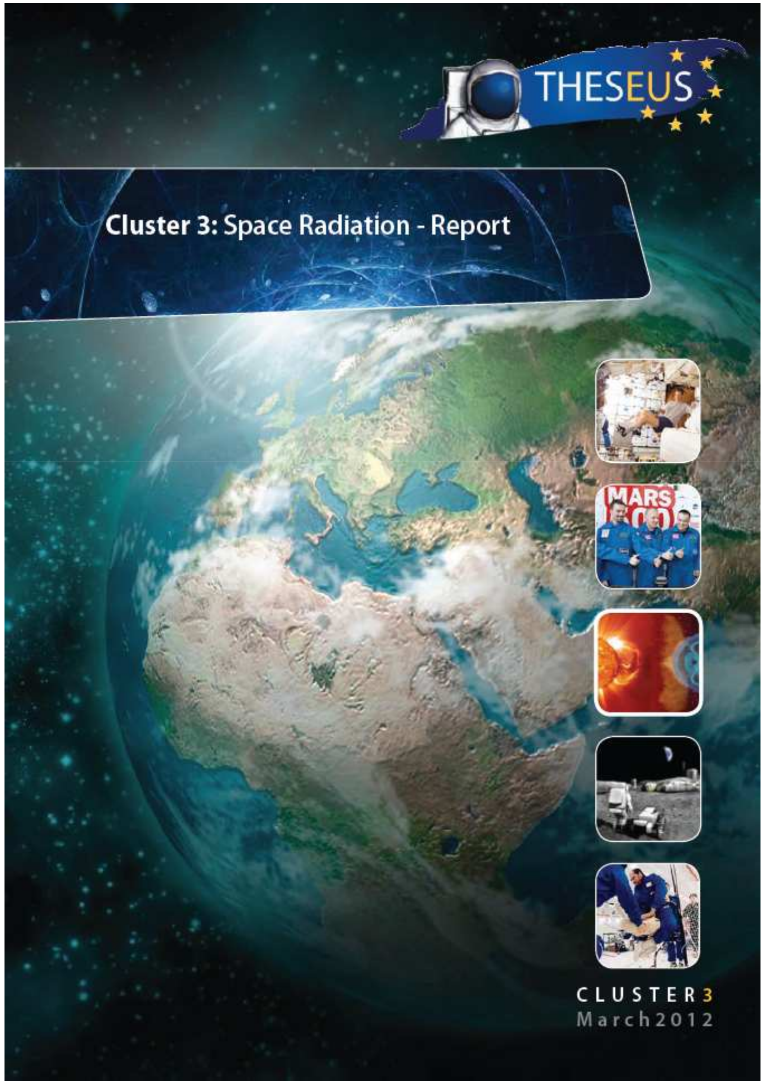
Missions	Solid Cancer, Sv	Leukemia, Sv	Circulatory Disease, Gy-Eq
1-Y Solar Min	0.187 (0.175)	0.109 (0.104)	0.132 (0.126)
1-Y Solar Med	0.146 (0.138)	0.084 (0.08)	0.10 (0.096)
1-Y Solar Max	0.10 (0.094)	0.054 (0.052)	0.072 (0.064)
1-Y Solar Min and 0.5-Y Solar Med	0.26 (0.244)	0.151 (0.144)	0.182 (0.174)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

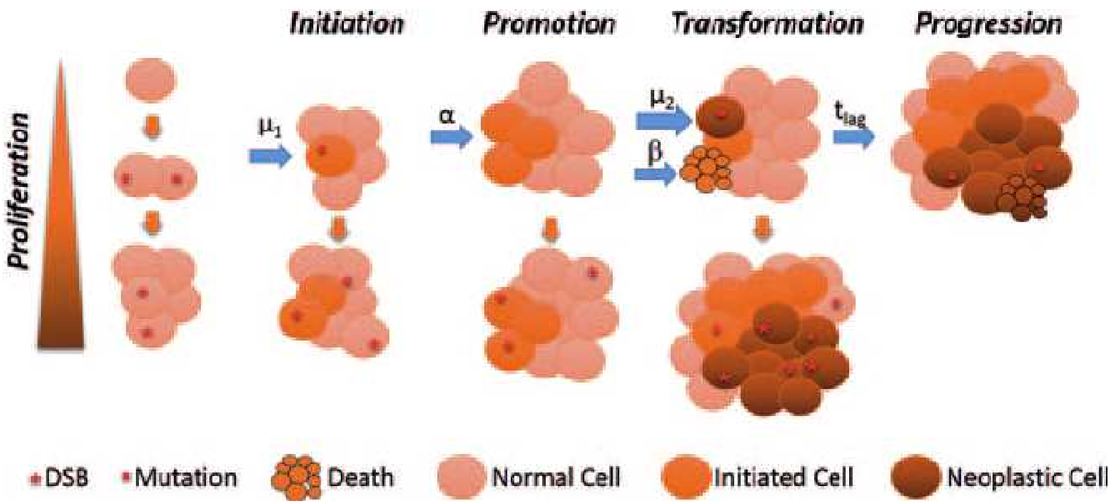
Durante, *Life Sci. Space Res.* 2014

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



1. Carcinogenesis

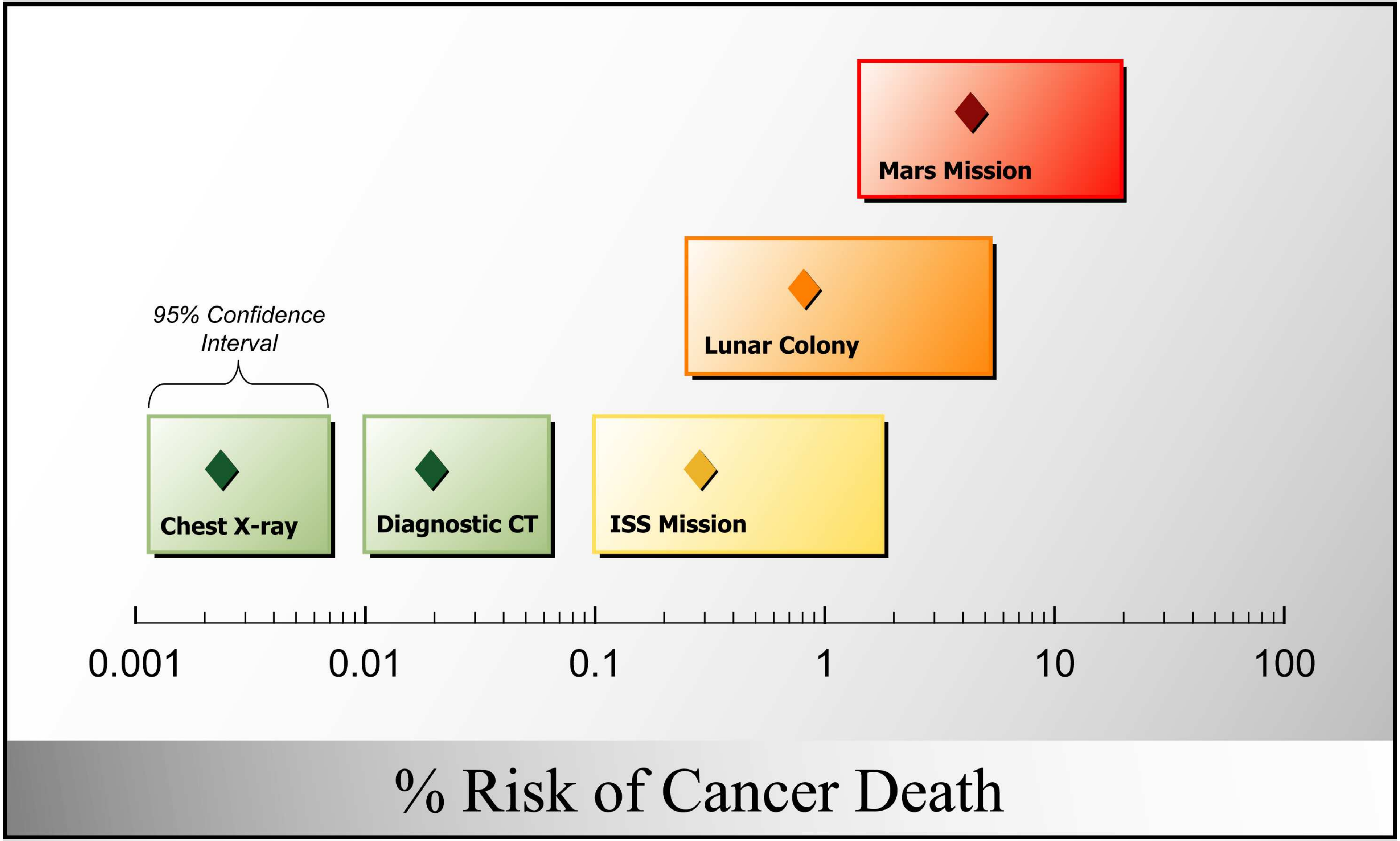


Dose limits

NASA uses the risk model and set the astronauts‘ carreer limits to **3% REID within 95% CI**

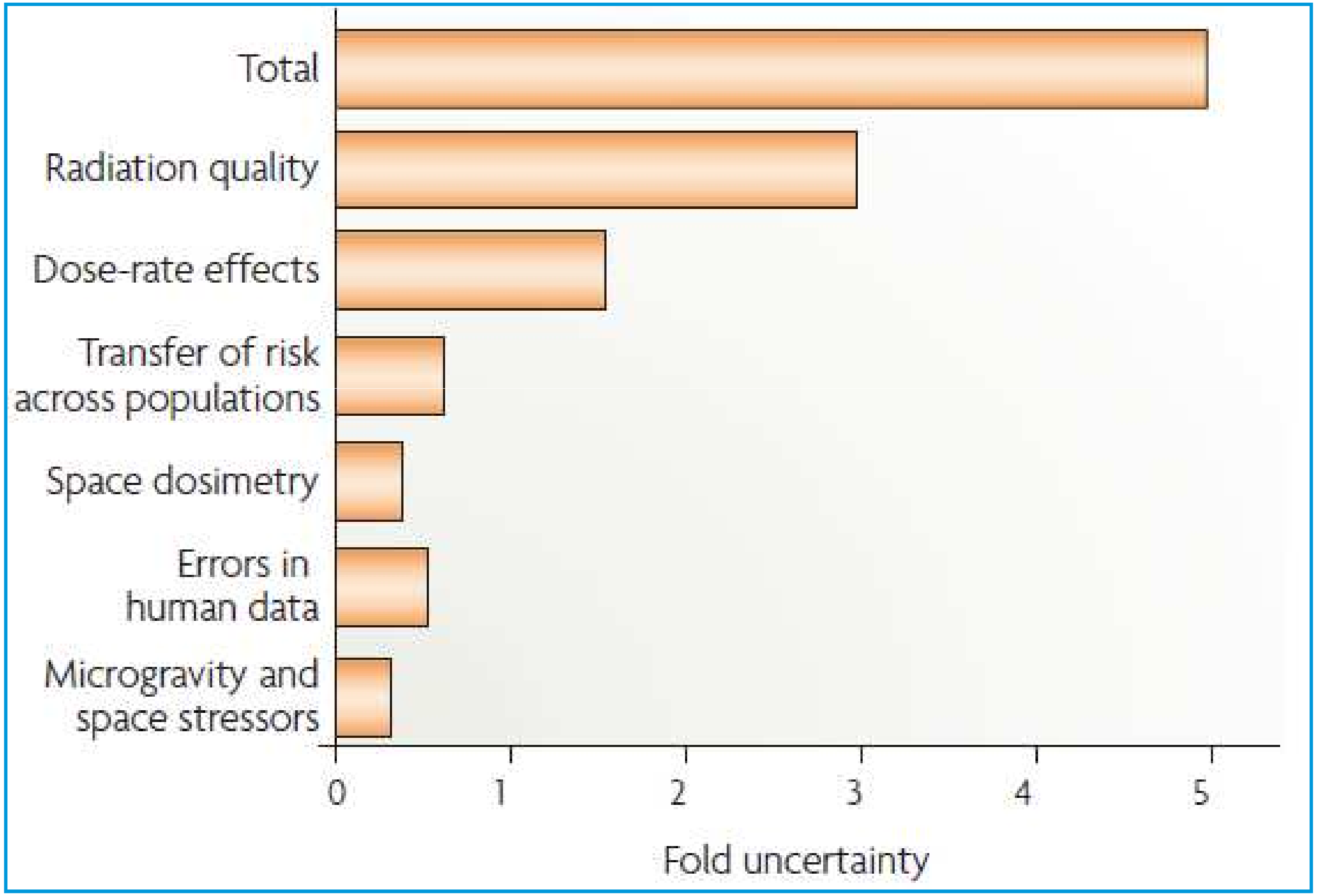
		Age at first exposure, (yr)			
Space agency	Gender	30	35	45	55
NASA (USA)	Female	0.47	0.55	0.75	1.1
	Male	0.62	0.72	0.95	1.5
JAXA (Japan)	Female	0.6	0.8	0.9	1.1
	Male	0.6	0.9	1.0	1.2
ESA		1.0	1.0	1.0	1.0
FSA (Russia)		1.0	1.0	1.0	1.0
CSA (Canada)		1.0	1.0	1.0	1.0

Dose limits in Sv – for NASA, the numbers are for ISS excluding cardiovascular risk



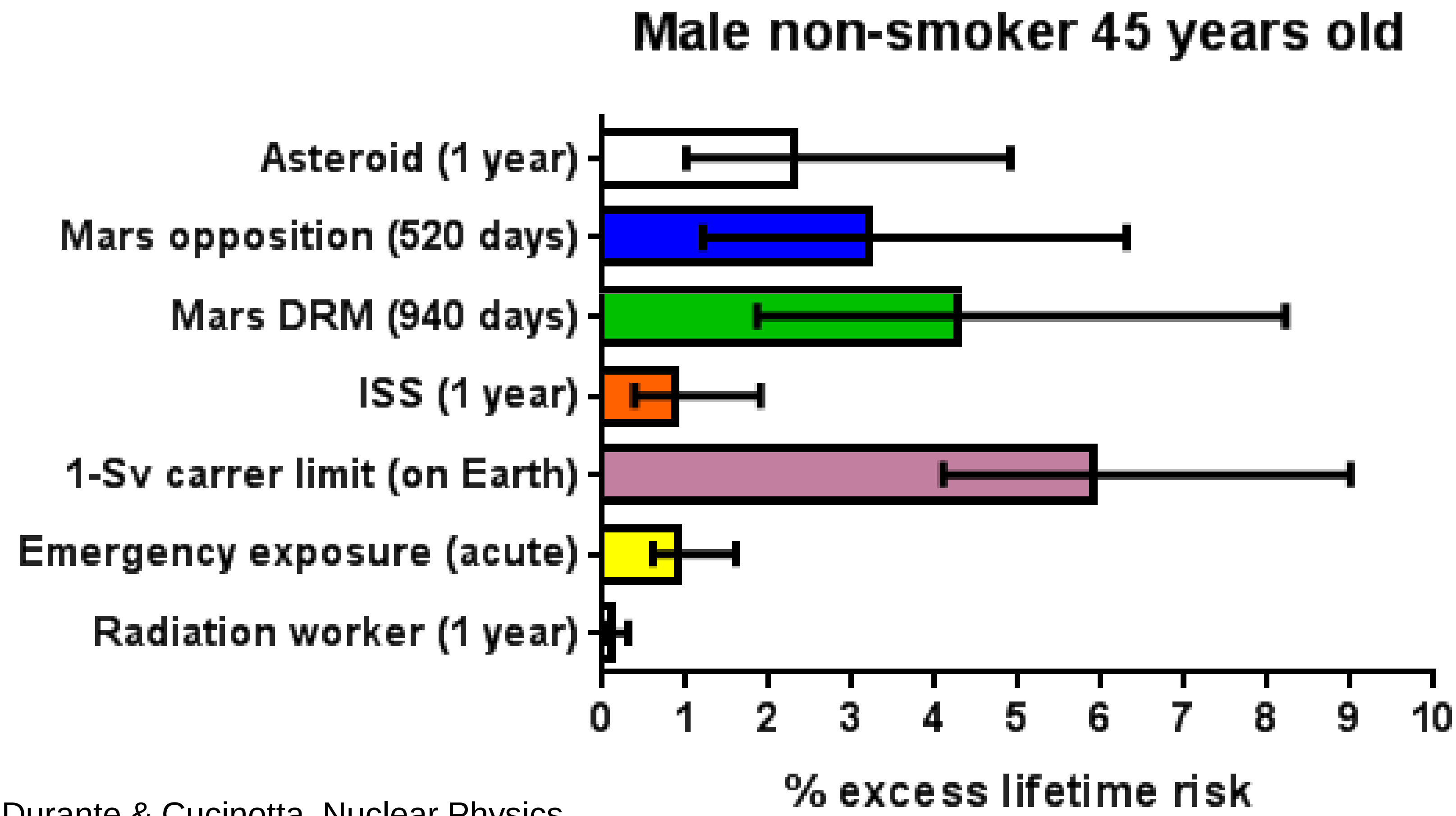
Durante & Cucinotta, *Nature Rev. Cancer* (2008)

RADIATION RISKS AND UNCERTAINTIES



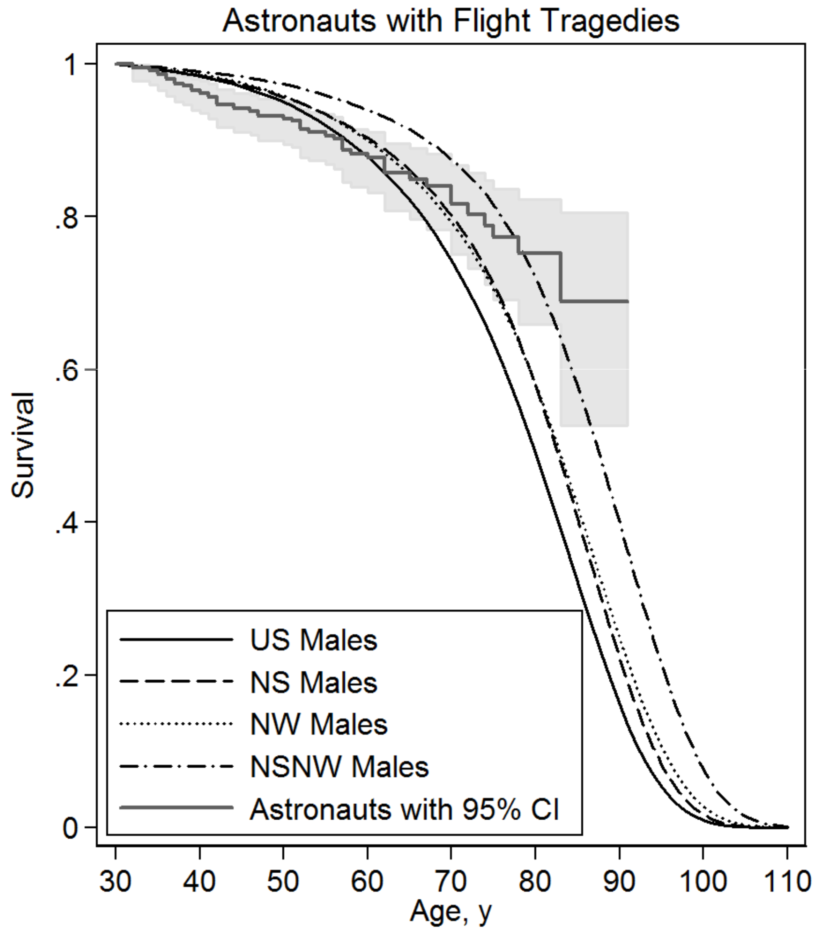
Durante & Cucinotta, *Nature Rev. Cancer* (2008)

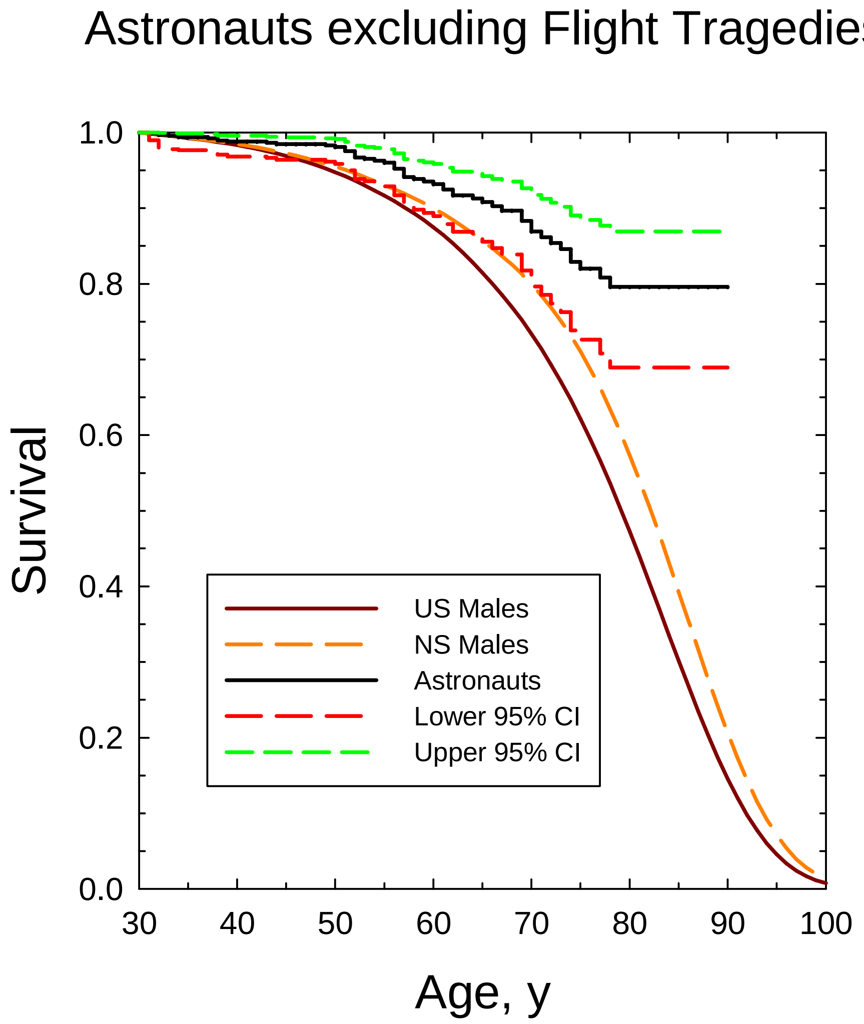
Estimates of cancer mortality risk and 95% CI for different space mission scenarios and terrestrial exposures.



Durante & Cucinotta, Nuclear Physics News 2014

NASA ASTRONAUTS' CAUSE-SPECIFIC MORTALITY





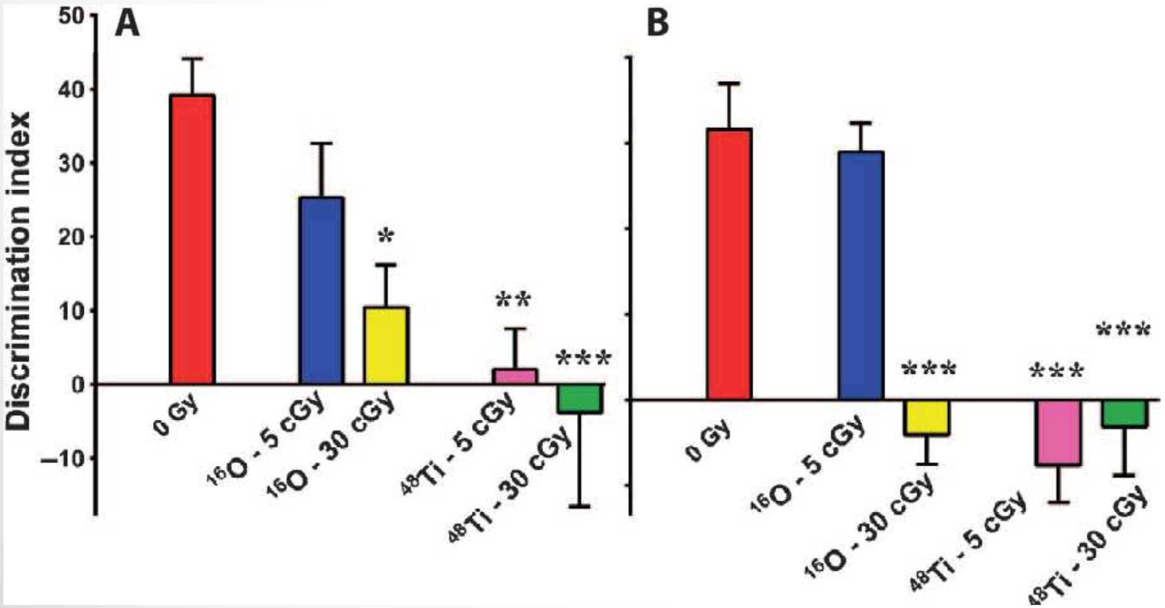
2. CNS

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

COGNITIVE NEUROSCIENCE

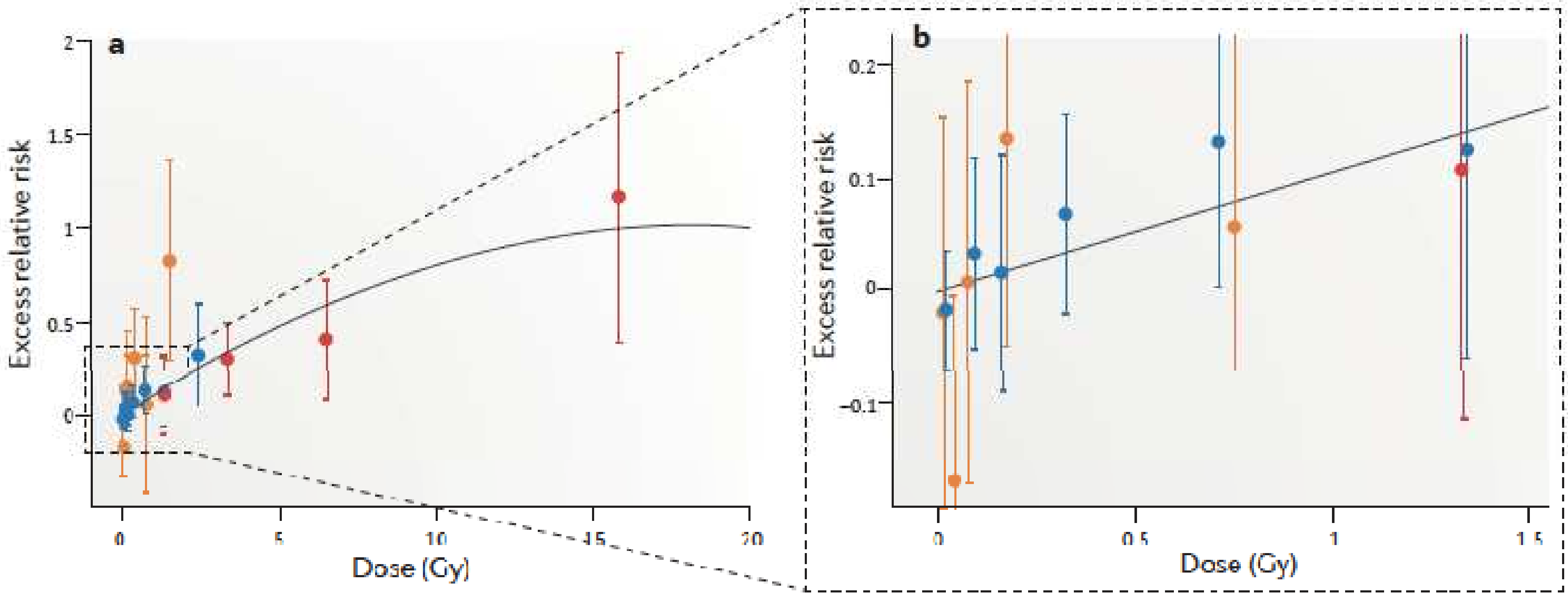
What happens to your brain on the way to Mars

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]*



3. Heart

Risk of radiation-induced late cardiovascular disease



Nature Reviews | Cardiology

Hughson et al., Nat. Rev. Cardiol. 2017

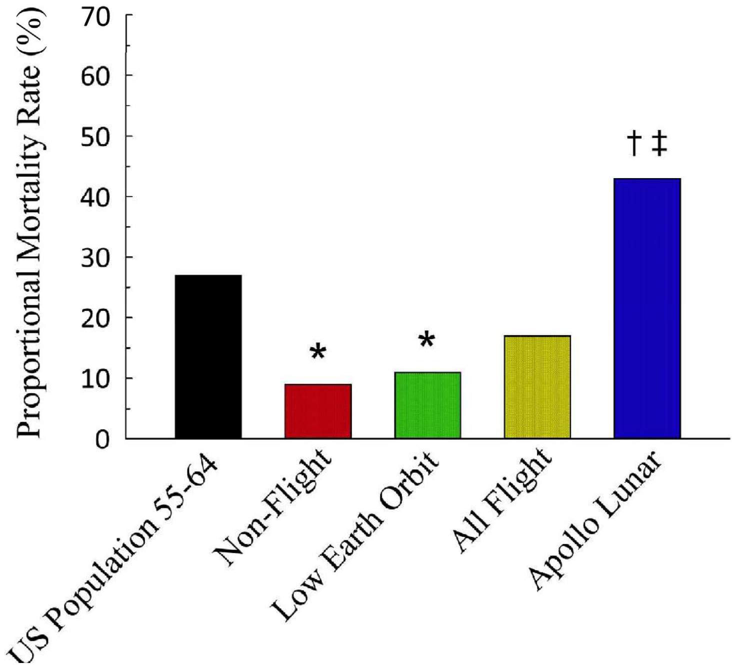
SCIENTIFIC REPORTS

OPEN

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

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

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

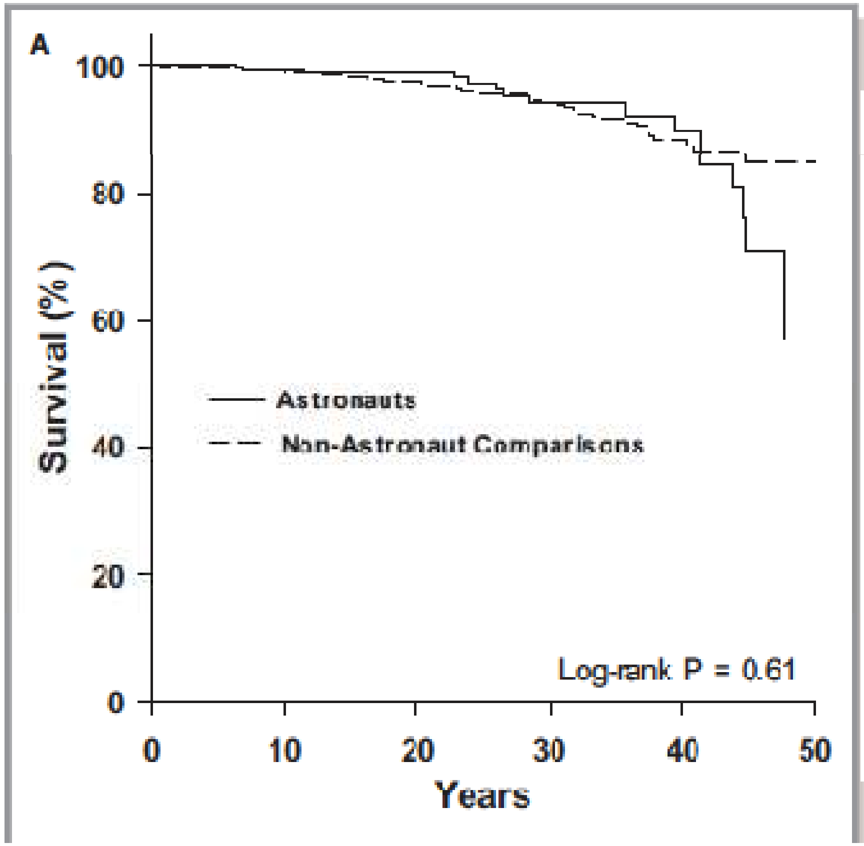


	Cardiovascular Disease	Cancer	Accident	Other
Reference Groups				
US Population Ages 55–64, (n = 338, 127)	27%	34%	5%	35%
Non-Flight Astronauts, (n = 35)	9%*	29%	53%*	9%*
Astronaut Groups				
All Flight Astronauts, (n = 42)	17%	31%	43%*	10%*
Low Earth Orbit Astronauts, (n = 35)	11%*	31%	49%*	9%*
Apollo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

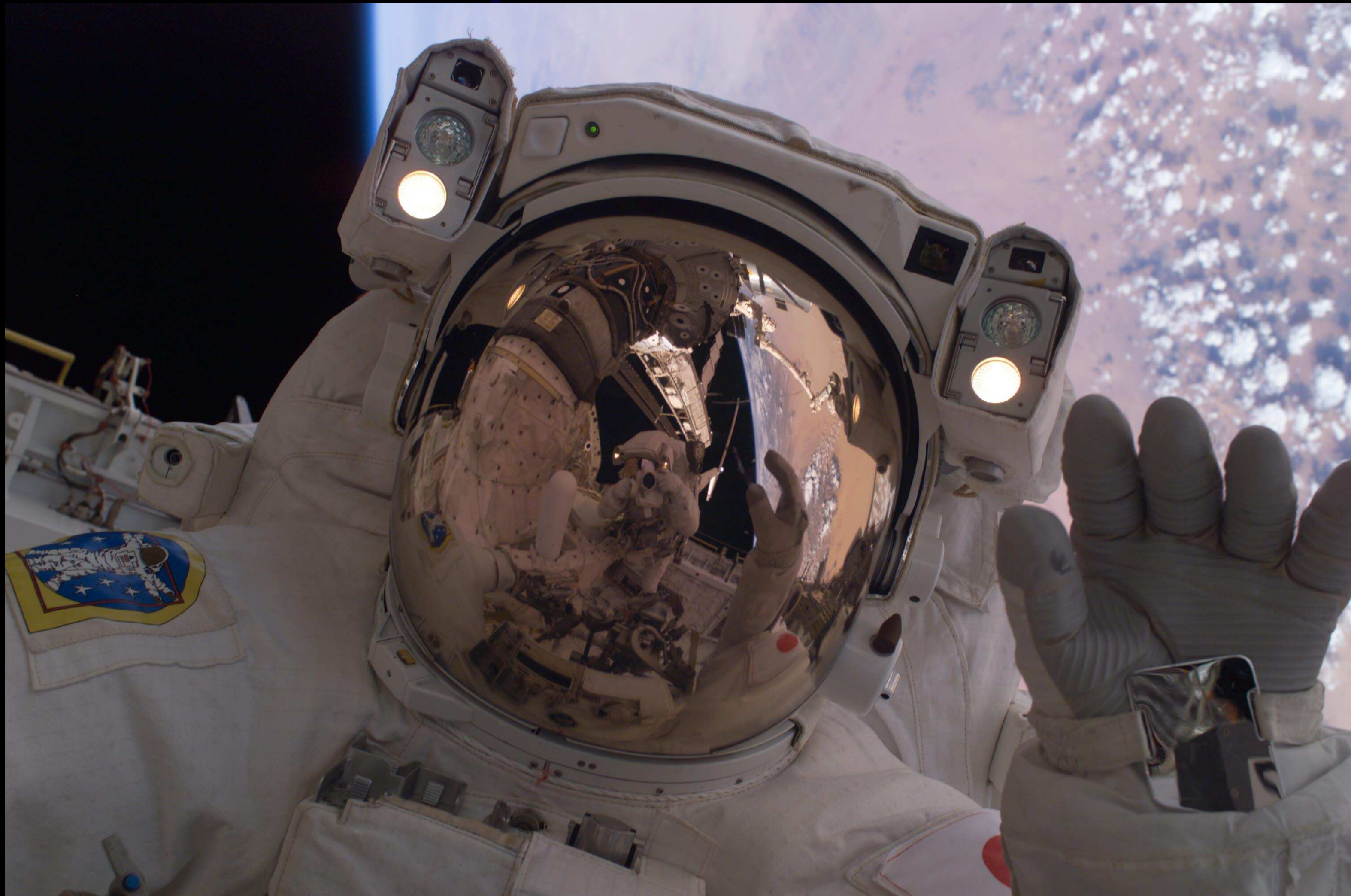
Incidence Rate of Cardiovascular Disease End Points in the National Aeronautics and Space Administration Astronaut Corps

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.)



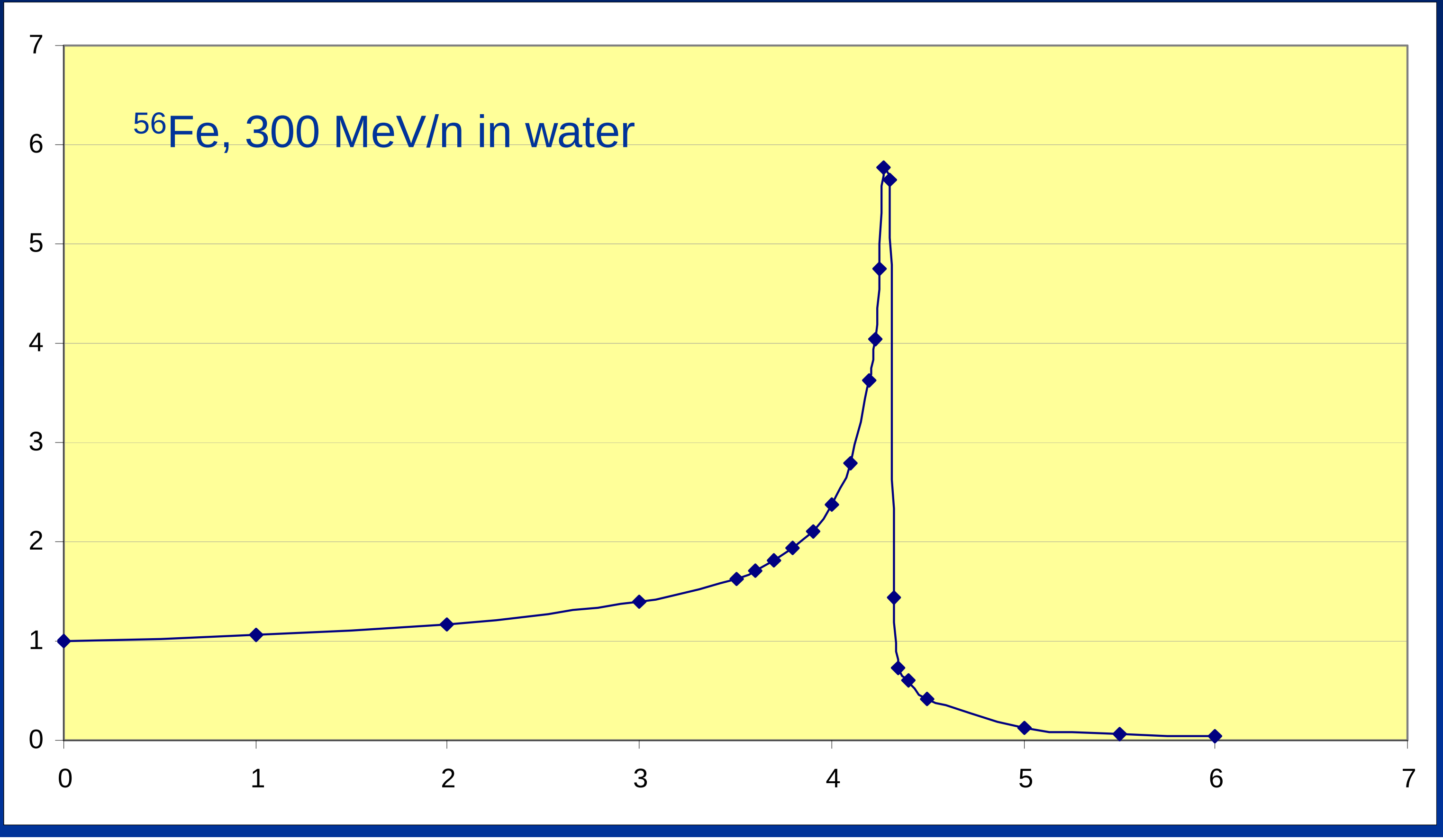
	Astronauts		Nonastronaut Comparisons	
	Frequency	Incidence Rate (Per 1000 PY)	Frequency	Incidence Rate (Per 1000 PY)
All CVD events	16	2.34	46	2.15
MI	7	1.02	21	0.98
CHF	5	0.73	4	0.19
Stroke	5	0.73	17	0.80
CABG	5	0.73	22	1.64
Multiple	5	0.73	17	0.79
CAD events	9	1.32	30	1.40



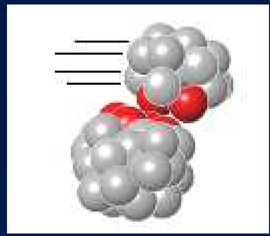
4. Countermeasures: shielding

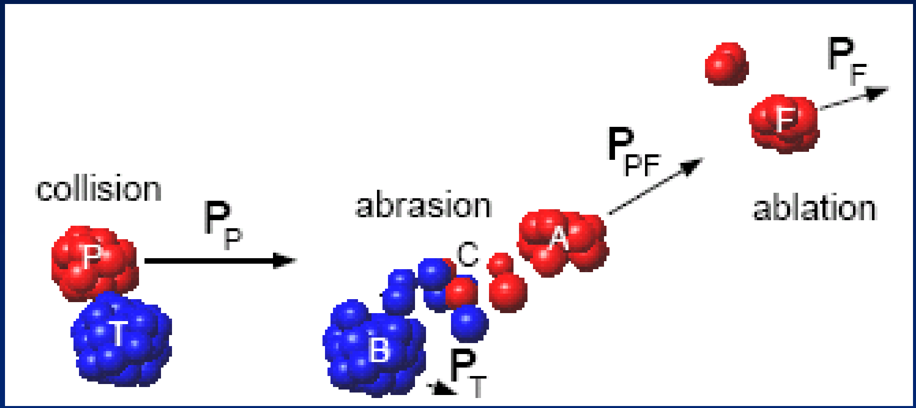
Ionization energy loss (Bethe-Bloch formula)

$$-\frac{dE}{\rho dx} = k\frac{Z}{A}\cdot\frac{z^{*2}}{\beta^2}\left(\log\frac{2\gamma^2\beta^2 m_e c^2}{I} - \eta\right)$$



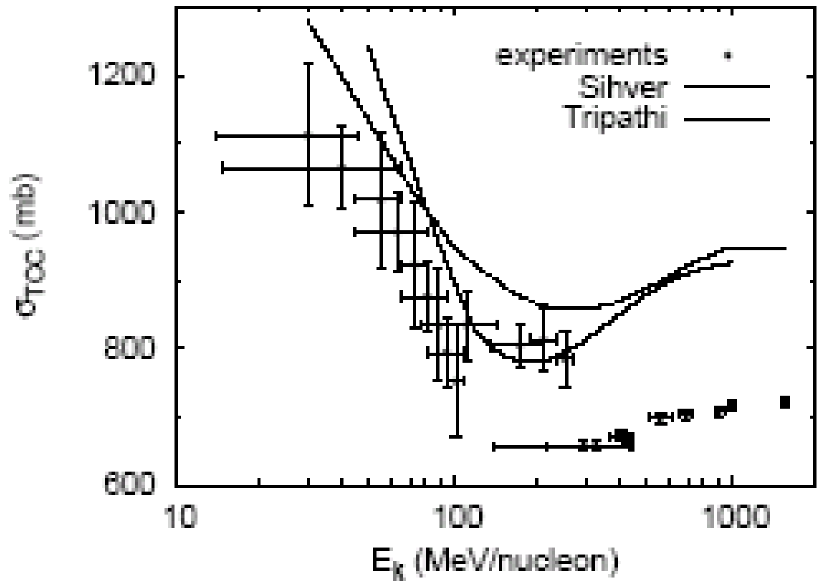
Nuclear fragmentation





Abrasion-ablation model

Energy dependence (^{12}C on graphite)



$$\sigma = \pi r_0^2 \left(A_p^{1/3} + A_T^{1/3} - b \right)^2$$

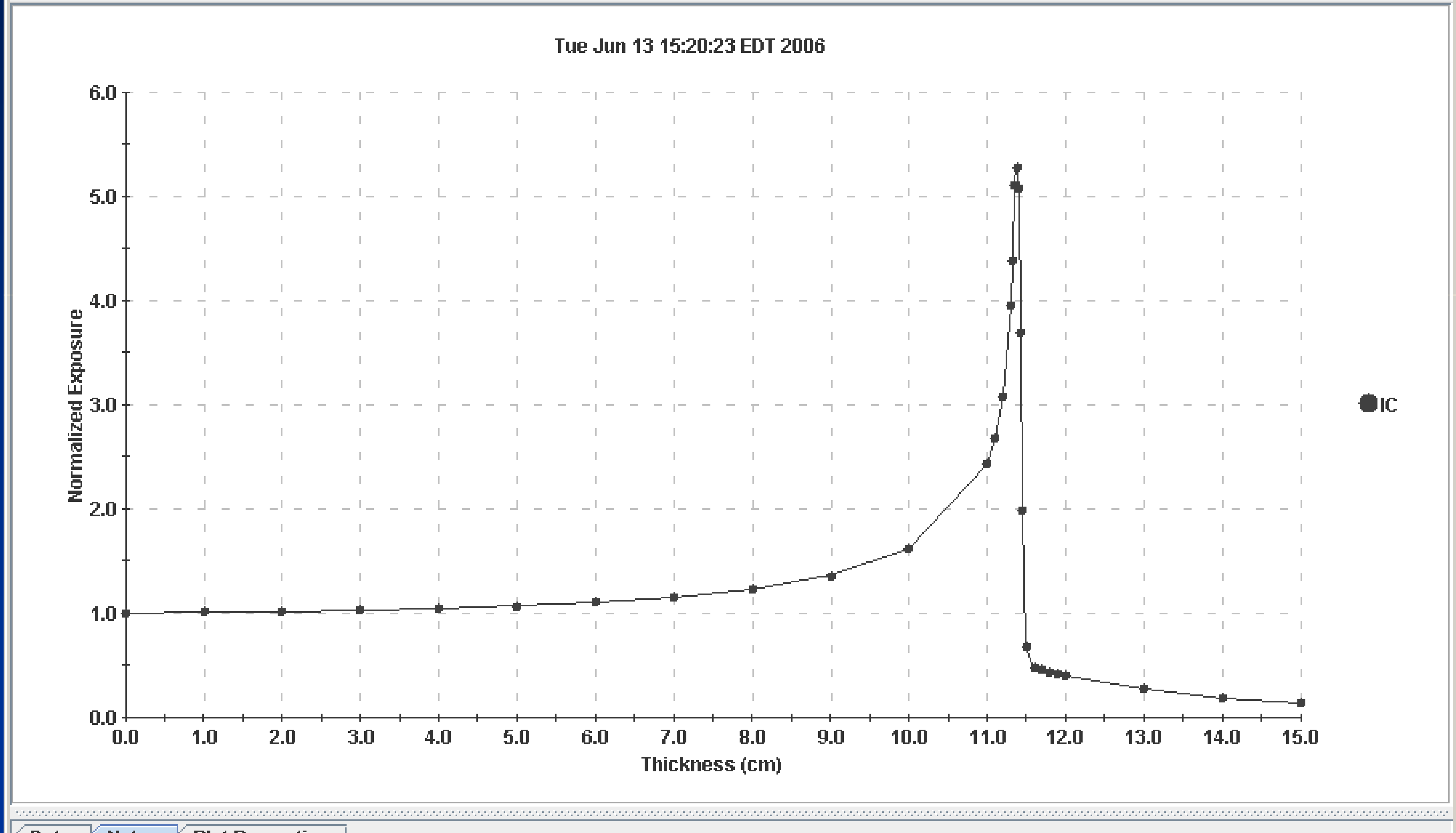
Geometrical approximation (Bradt-Peters formula)

Ion: $^{8}O^{16}$

Peak Position: 11.375 cm

Kinetic nergy: 284.1 MeV/n

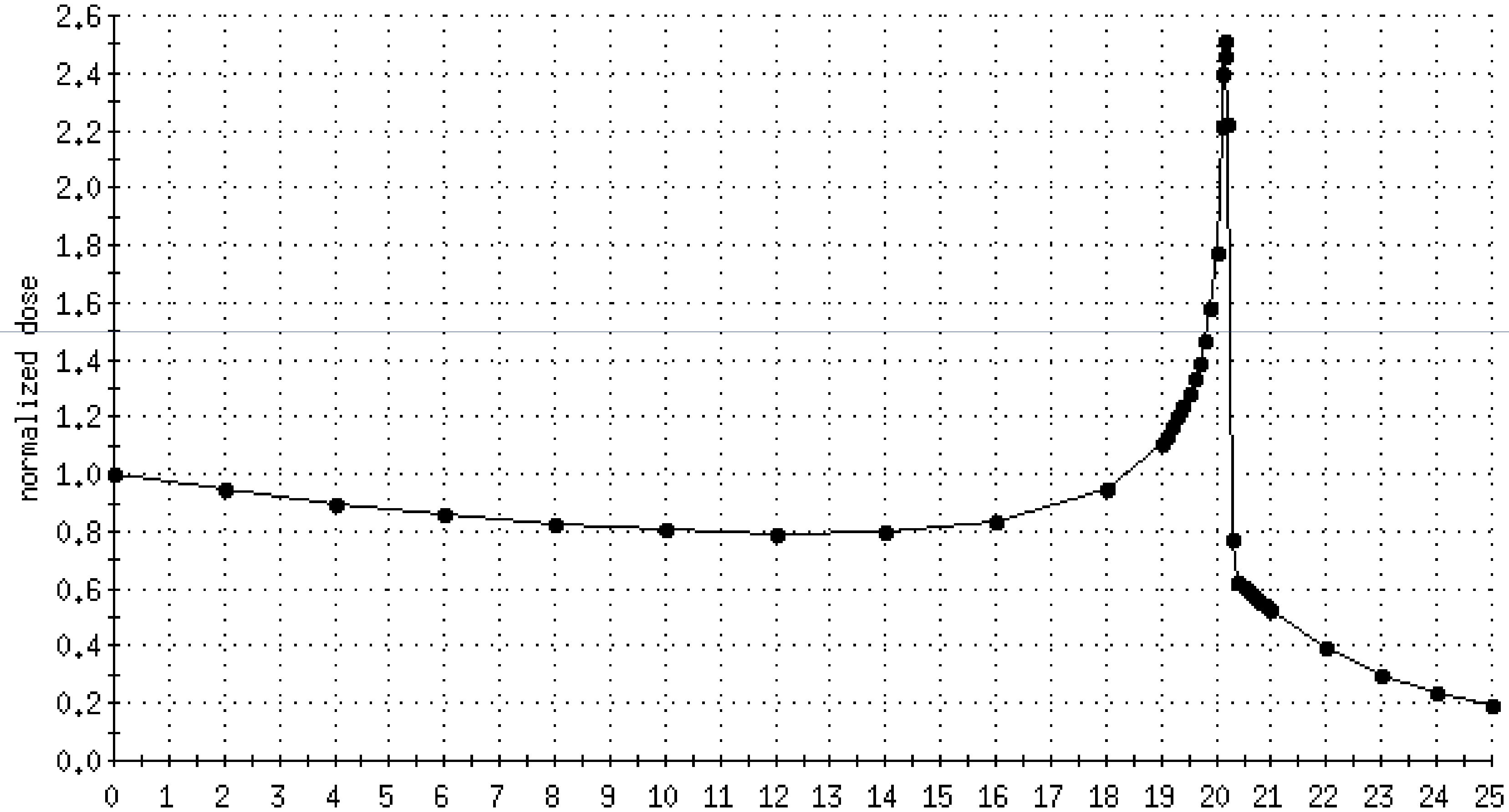
LET(water): 23.32 KeV/µm

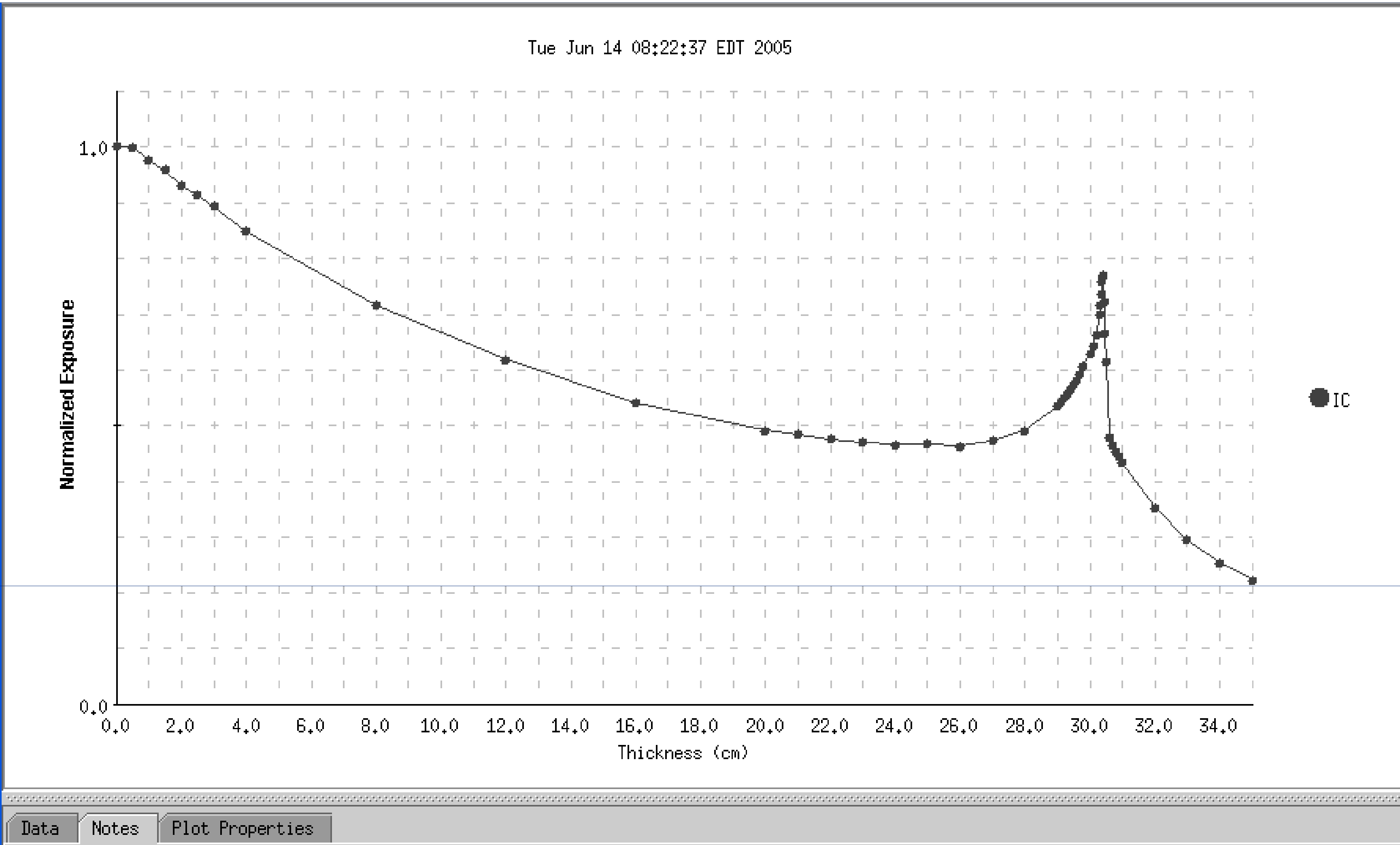


$^{14}Si^{28}$: Peak at 20.15 cm

KE = 575.4 MeV/n

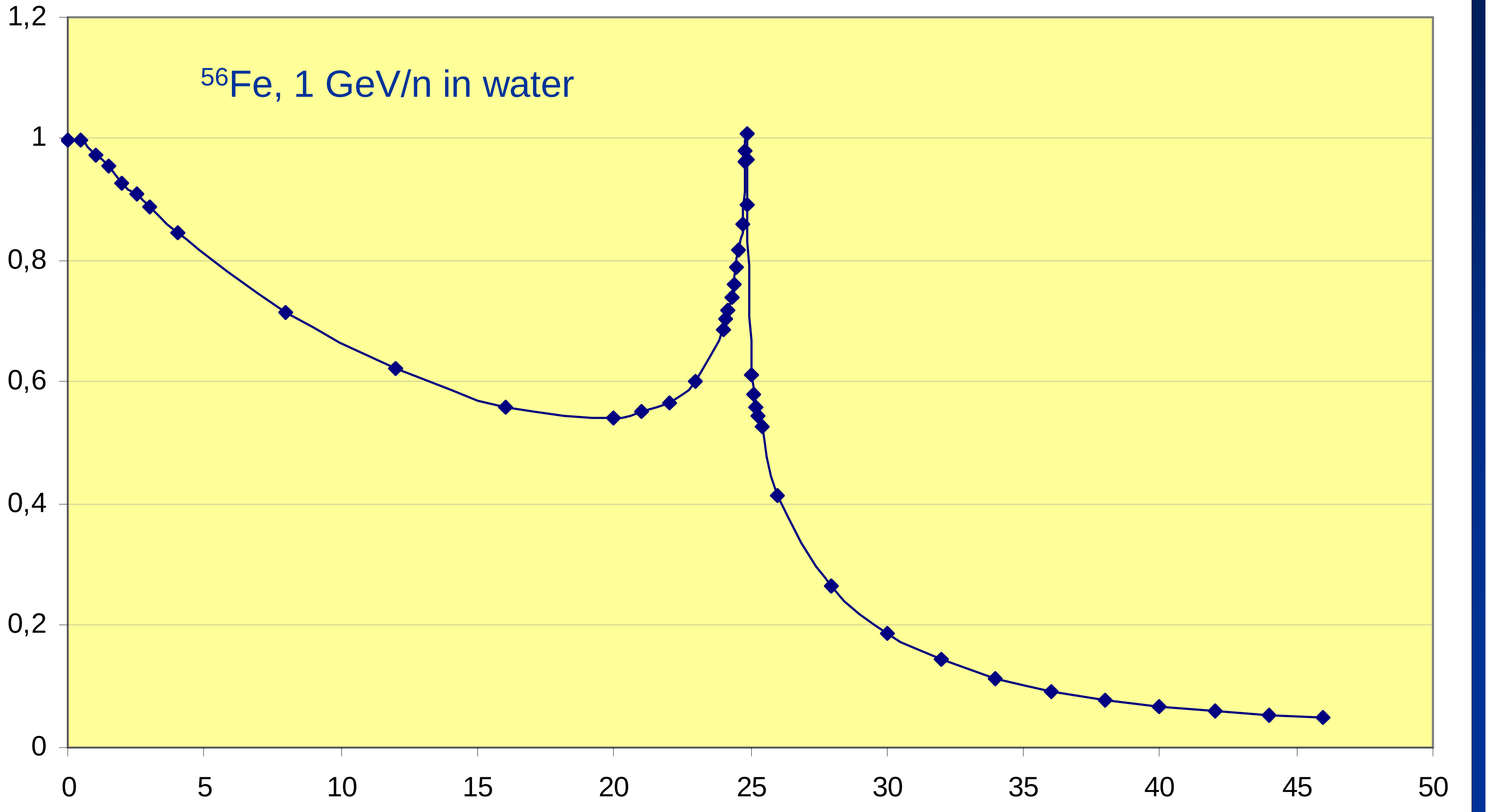
LET_{water} = 51.1 KeV/μm





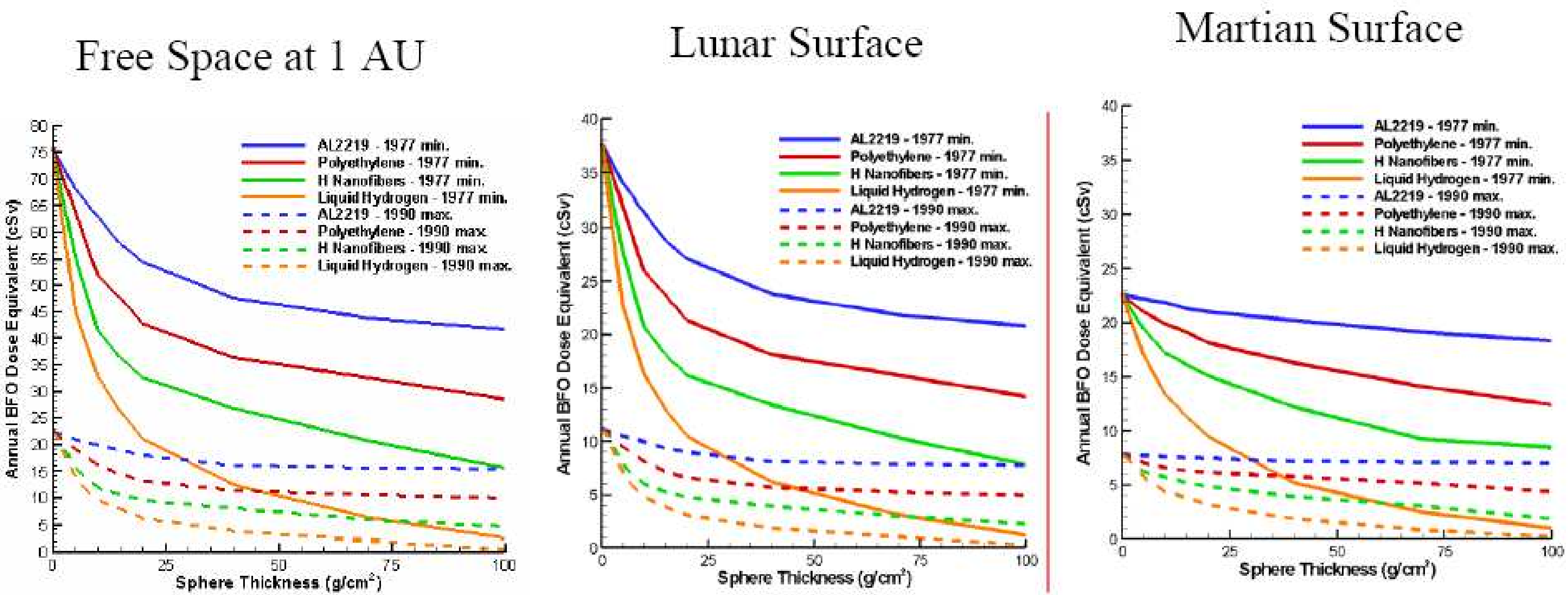
Ion: Ti
Peak: 30.4 cm
Kinetic Energy: 977.8 MeV/n
LET(water): 108.2 KeV/um

BROOKHAVEN NATIONAL LABORATORY



^{56}Fe, 1 GeV/n in water
1,2
1
0,8
0,6
0,4
0,2
0
0
5
10
15
20
25
30
35
40
45
50

Is shielding a solution?



Max GCR dose reduction

Aluminum ~ 30%

Polyethylene ~ 50%

Liquid hydrogen ~ 90%

"Best" shielding materials

- Liquid H_2
- Liquid CH_4
-
- Polyethylene (CH_2)
-
- H_2O
-
-
- Al—Inadequate shielding
-
-
- Pb
-

Best

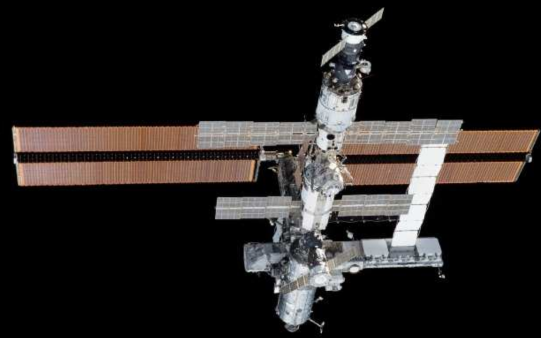
Worst

Potential range for new and multi-functional shielding materials: CH_4 adsorption on carbon forms; polymer composites; hydrides and hydride/carbon or hydride/polymer composites

Projectile interactions per unit target mass:
Ionization ~ Z/A (Bethe-Bloch formula)
Fragmentation ~ $A^{-1/3}$ (Bradt-Peters formula)

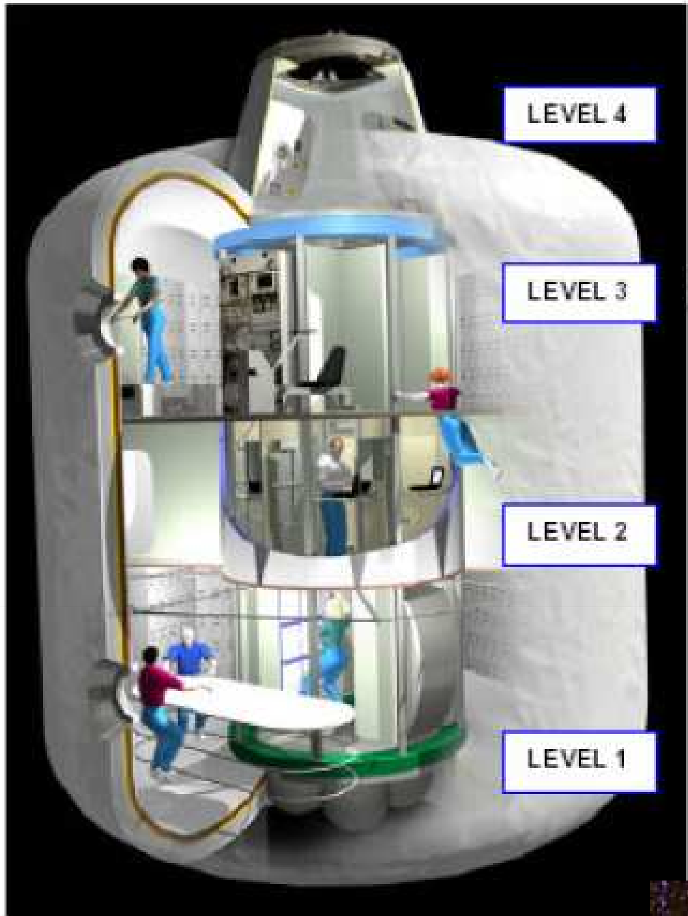
Durante & Cucinotta, *Rev. Mod. Phys*. 2011

Shielding on ISS

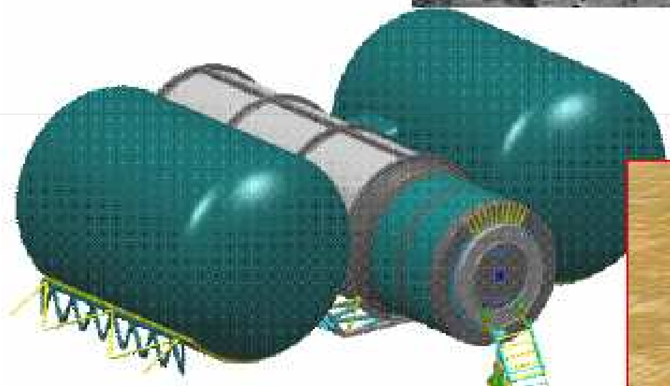


- Sleep station outfitted with PE and water
- Thin, flat panels are PE shields
- Stowage water packaging above the sleep station

Transhab



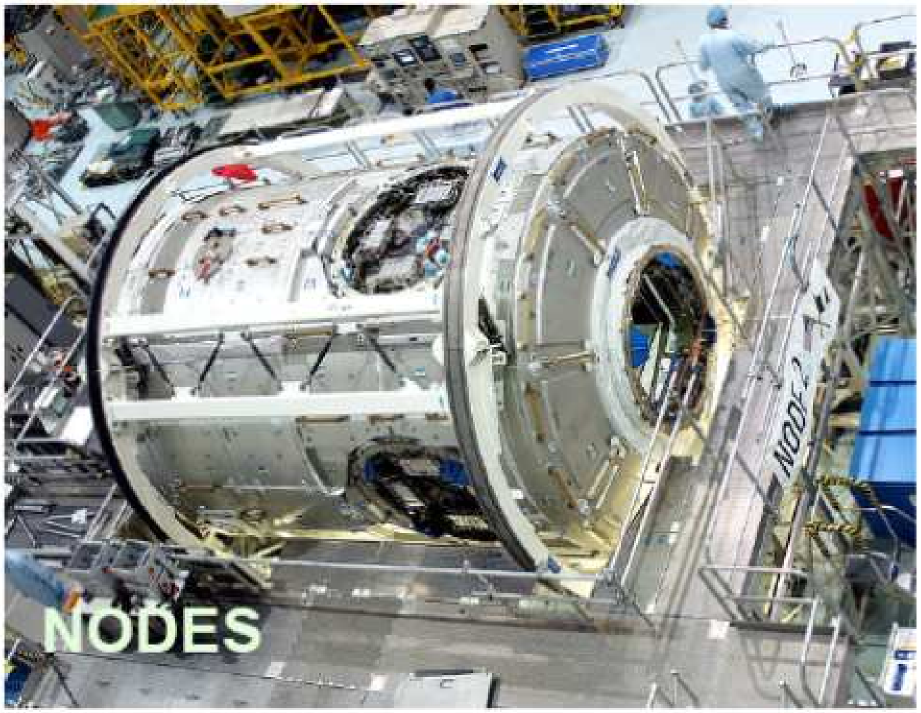
Rigid core (3.3 m) and inflatable exterior shell (8.3m)

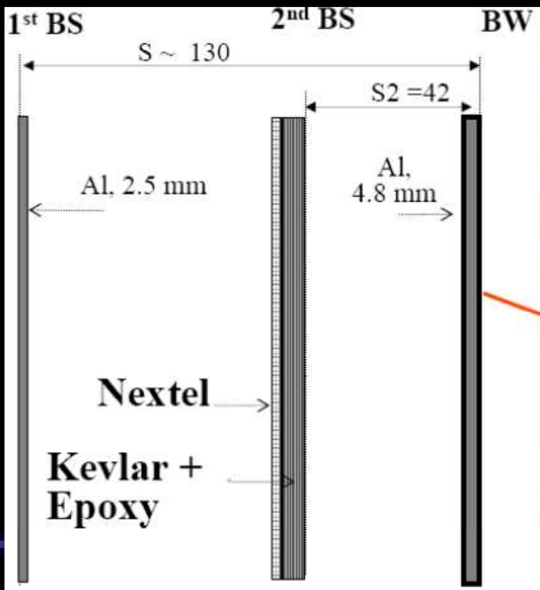


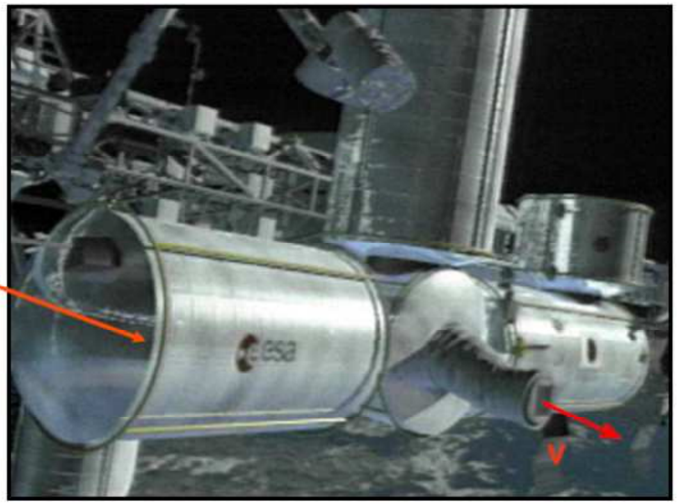
Surface habs

Inflatable modules

Kevlar epoxy (rigidized) → Micro-meteoroid Orbital Debris (MMOD) Shield







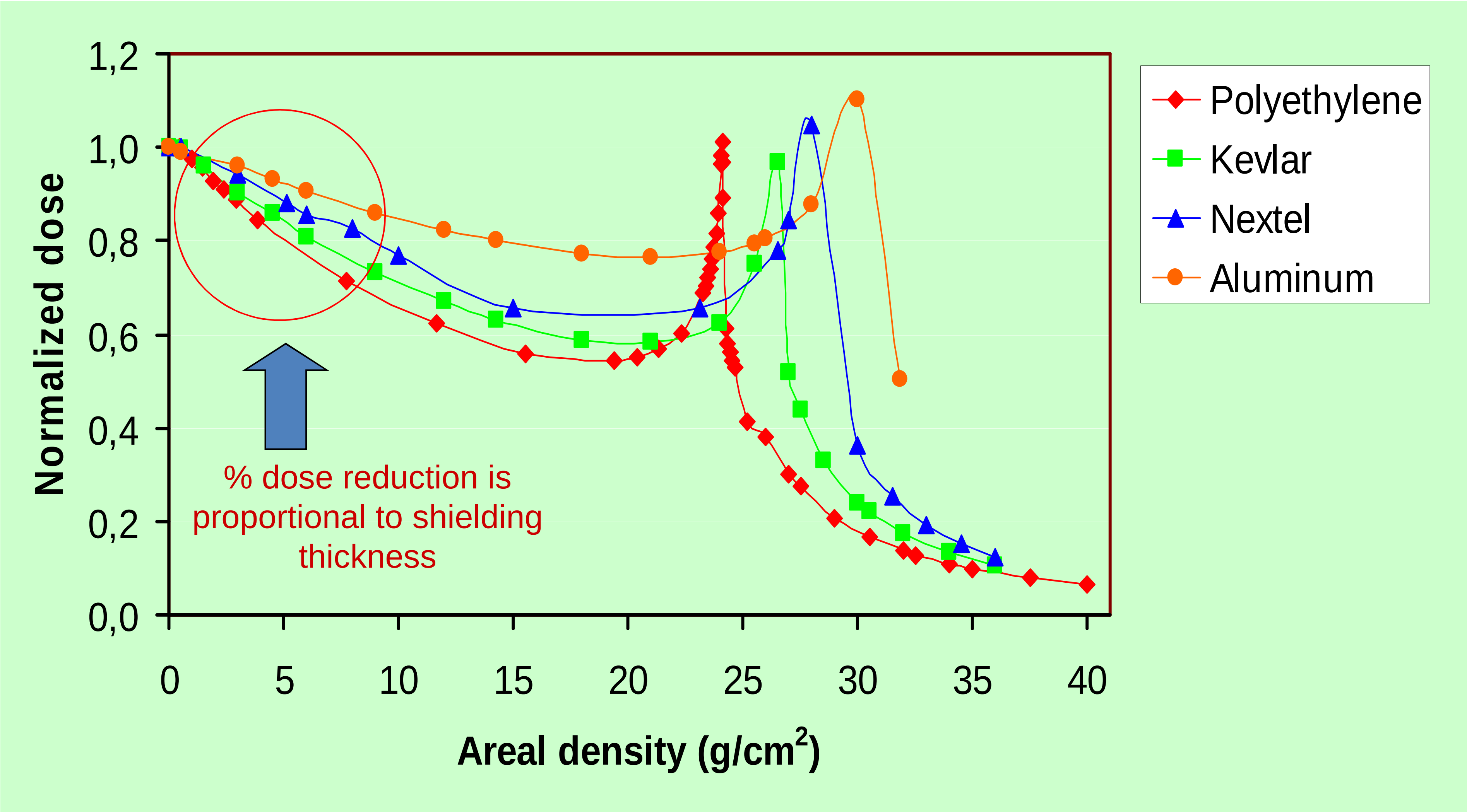
Columbus

ALCATEL ALENIA SPACE
An Alcatel/Finmeccanica company

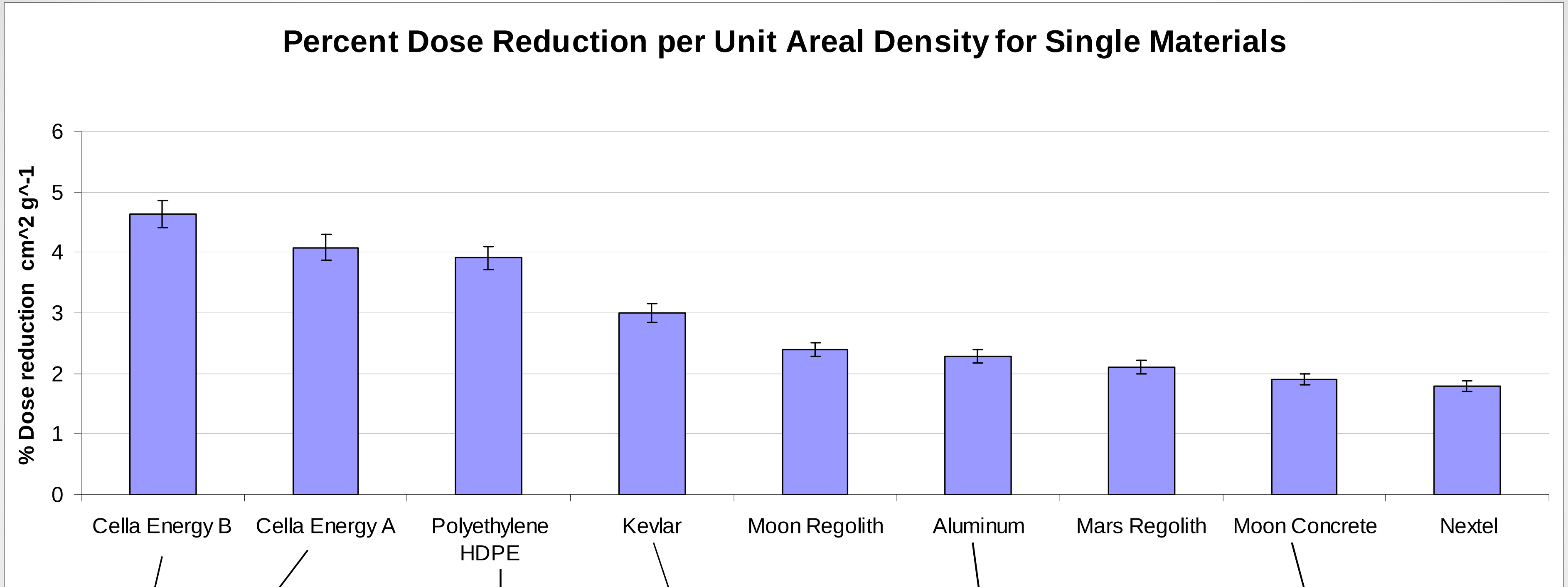
Protection by ISRU materials

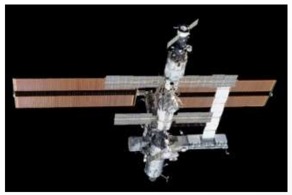
© G. Otto, GSI

Measurements of the relative shielding effectiveness sing the initial slope of the Bragg curve for heavy ions



Shielding test results, ROSSINI, 2012-16



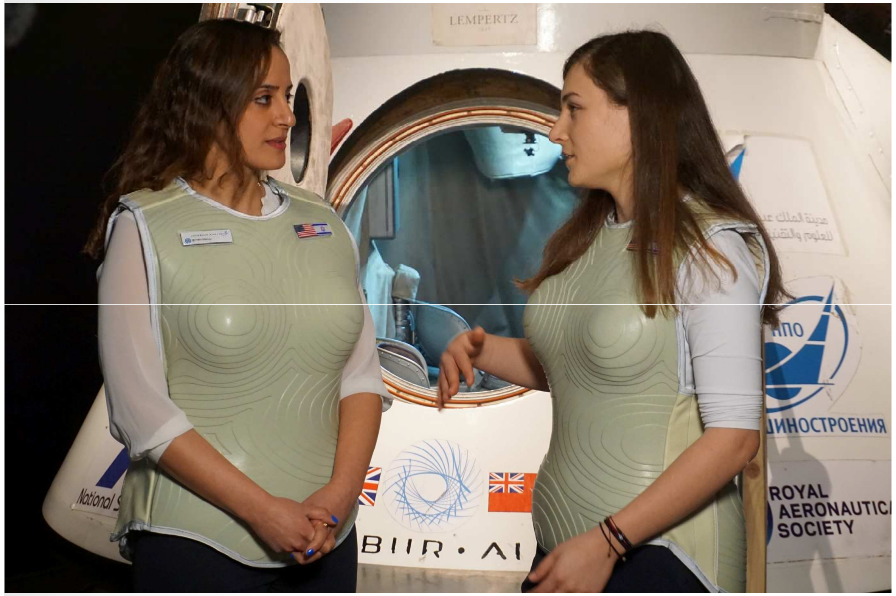



ESCHILO TILES
+ dosimeters
ALTEINO
Apr. 2005 (ENEIDE mission)


Jan. 2006
MATROSHKA
RSC "ENERGIA"
esa
DTM TECHNOLOGIES
KAYSER
DLR


Jan. 2006
MATROSHKA
ИМБП
RSC "ENERGIA"
esa
PK
РОСАВИАКОСМОС
DTM TECHNOLOGIES
KAYSER
ITALIA
DLR

New shielding concepts



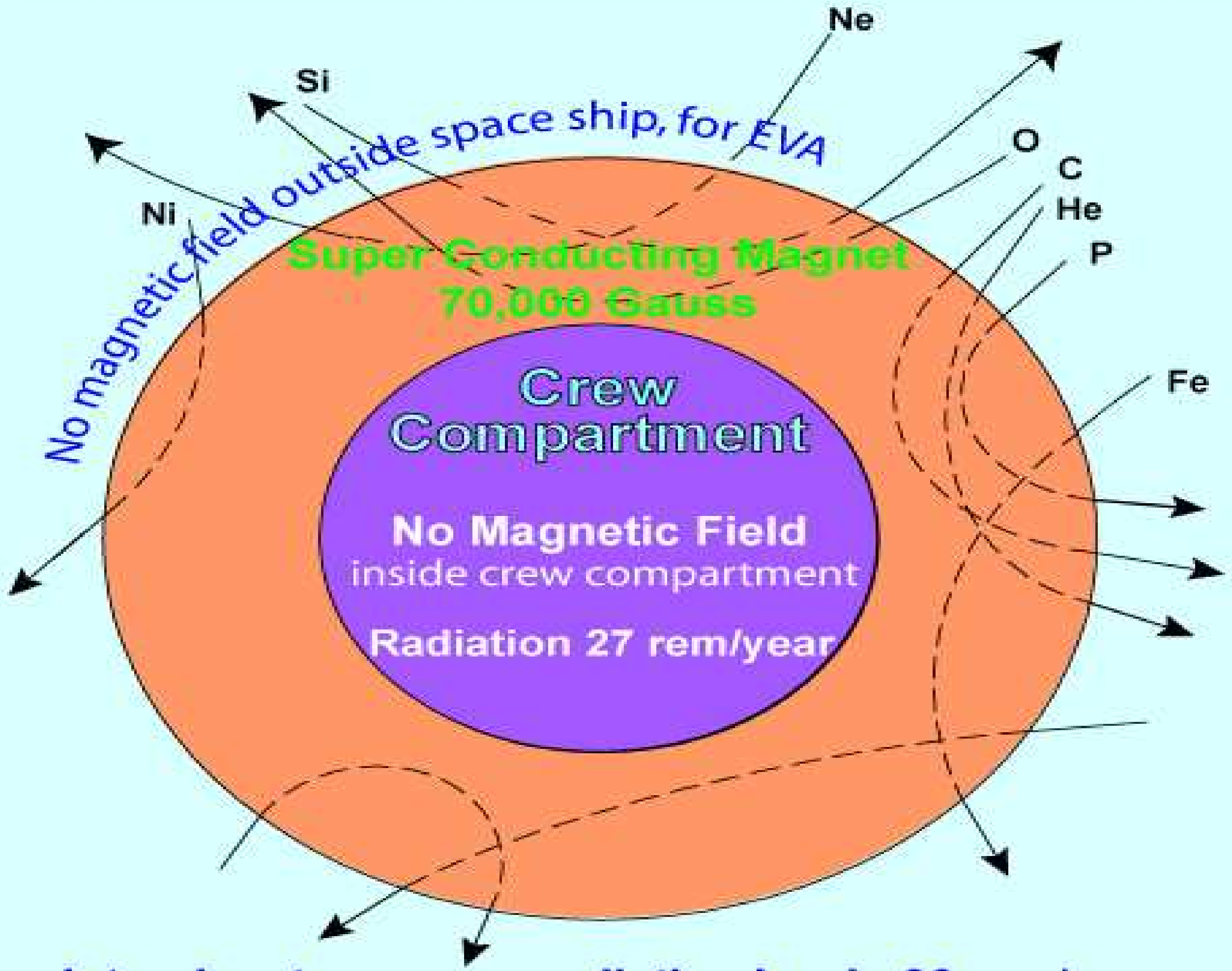
STEMRAD

NASA might build an ice house on Mars

December 30, 2016 by Nancy Atkinson, Universe Today

The Nation's Vision

4. Focus ISS research to support exploration goals; understanding space environment and **countermeasures.**



Interplanetary space radiation level - 90 rem/year

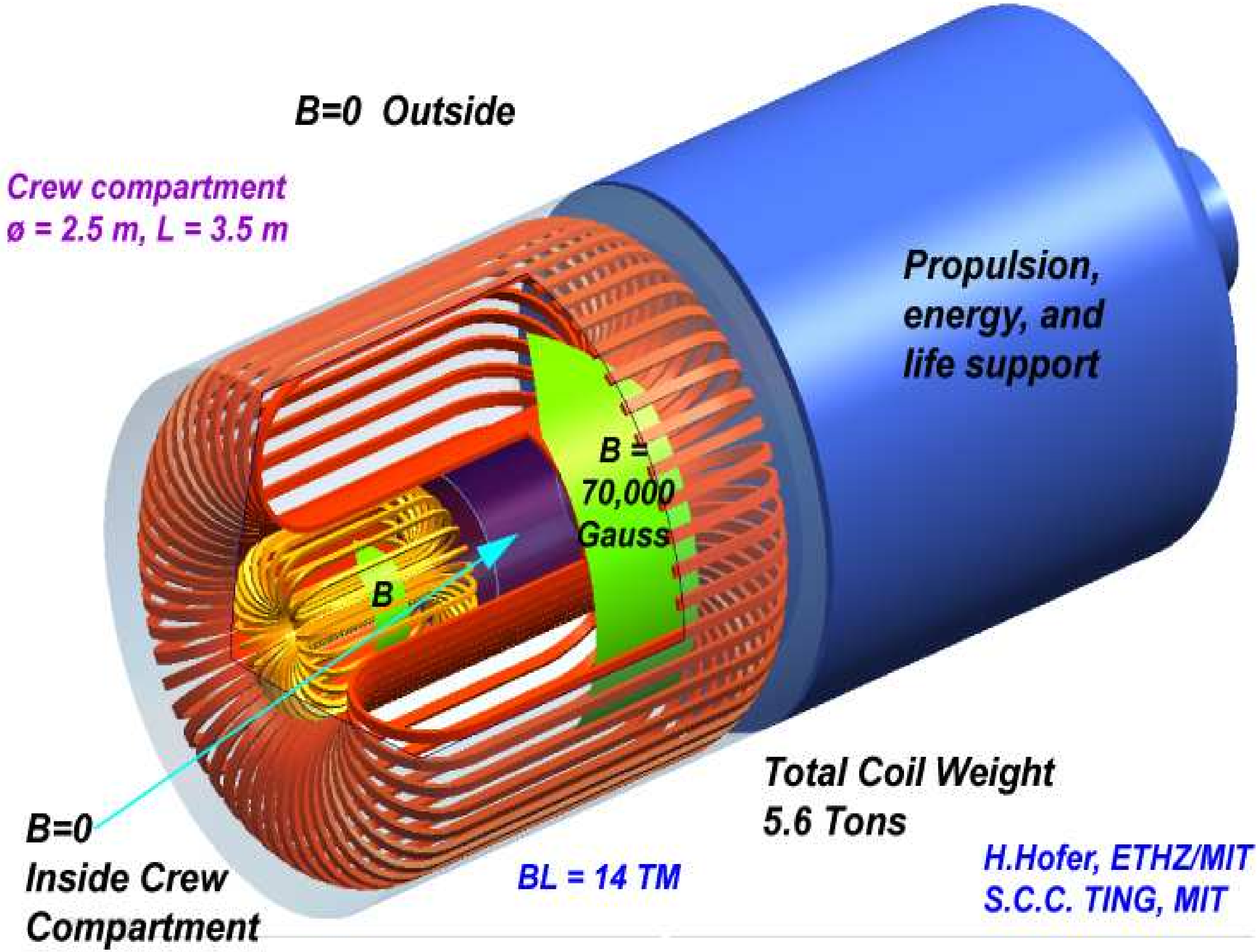
Lethal dose = 300 rem

With magnet, Crew compartment: 27 rem/year

ISS: 50 rem/year

y04K319_1a BeckerR

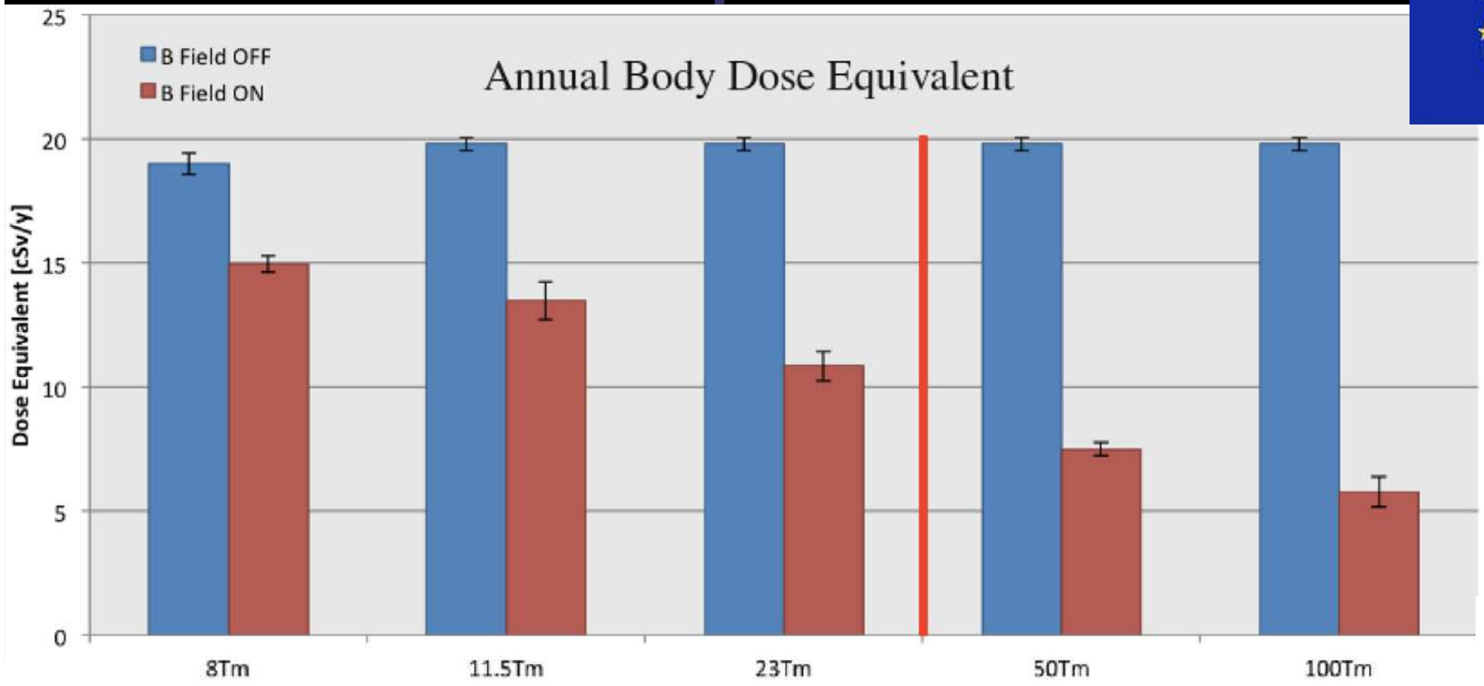
"Magnetic Faraday Cage" for Manned Flight to Mars

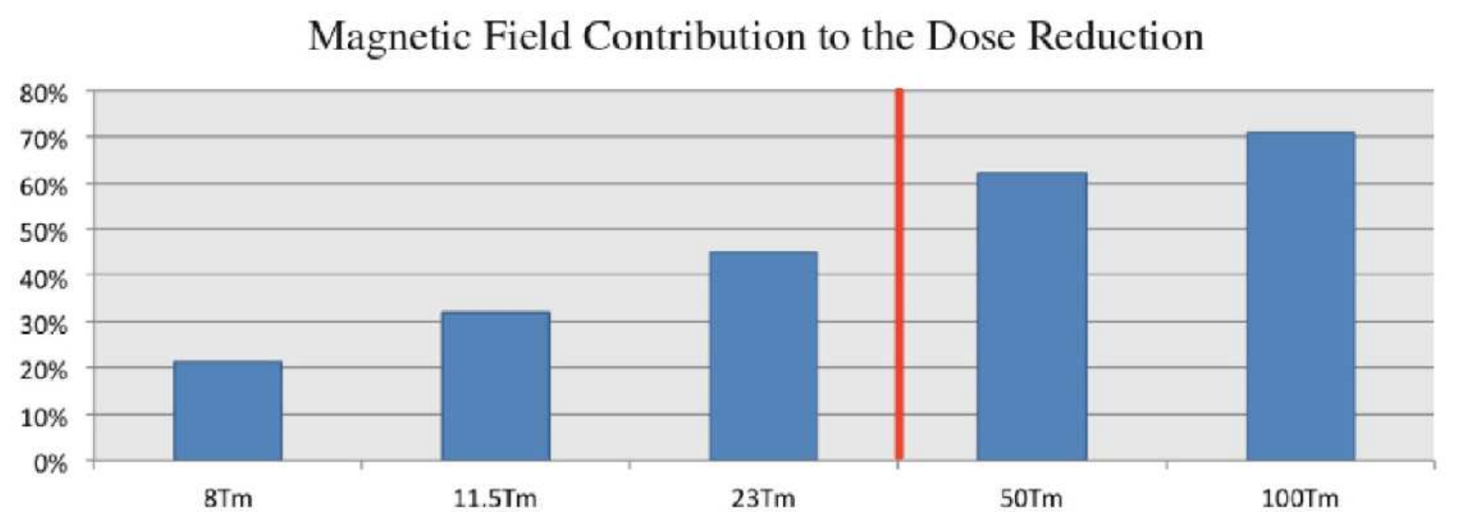


H.Hofer, ETHZ/MIT
S.C.C. TING, MIT

y04K322 d BeckerR

06.04.04 R.Becker (MIT)

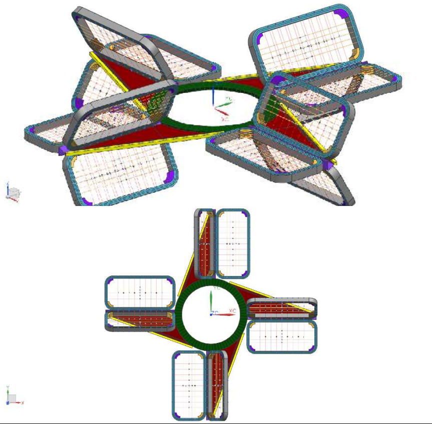




The Consortium

SR2S Space Radiation Superconducting Shield

SPA 2012 2.2.02 Key technologies for in-space activities

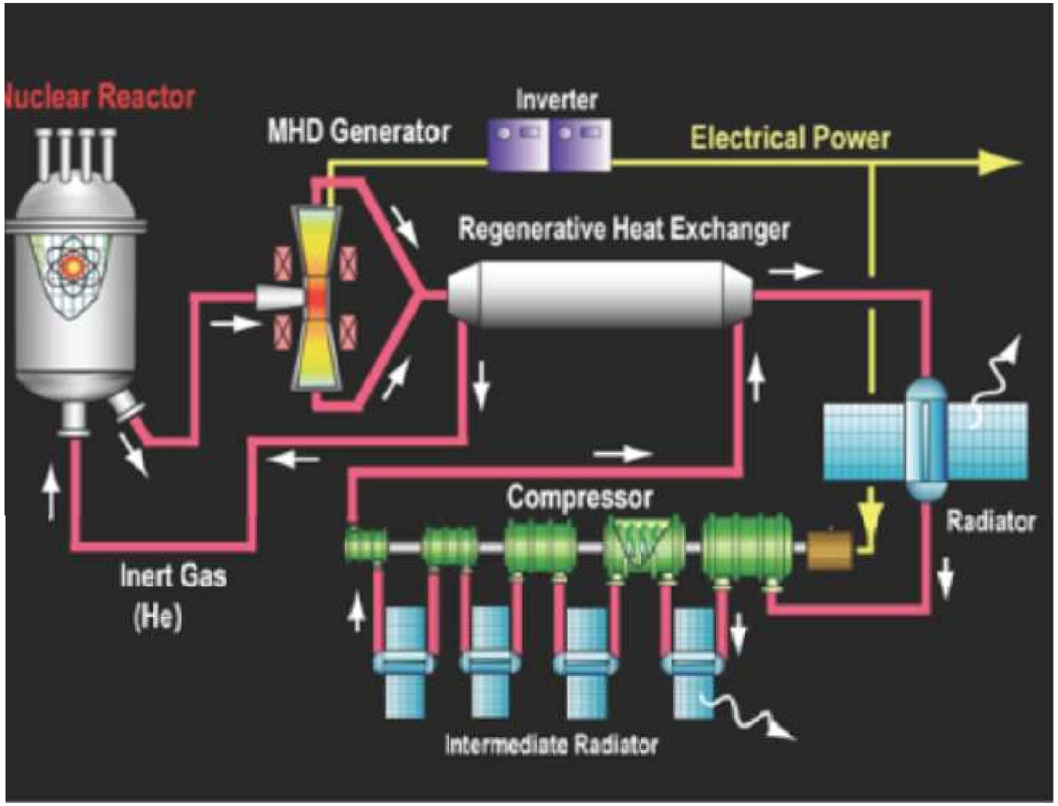


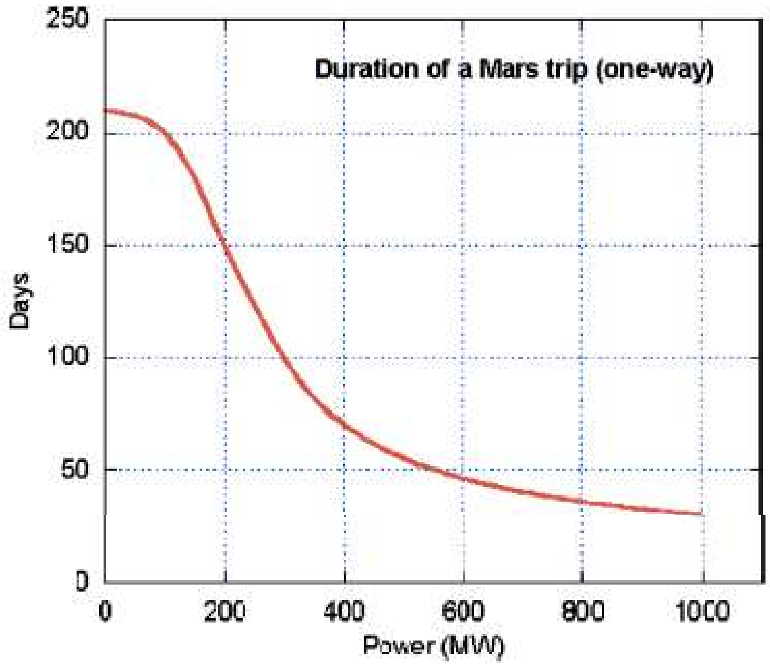
“Pumpkin” structure

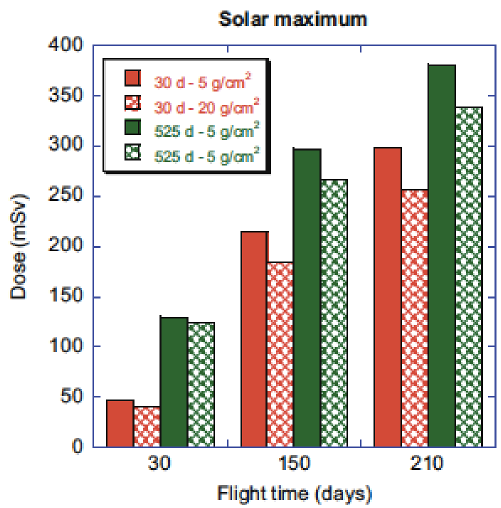
Burger et al. Front. Oncol. 2016

- ROSSINI2

The ultimate countermeasure







Durante & Bruno, *Eur. Phys. J*. 2010

5.Conclusions

- Space radiation is a potential showstopper for human space exploration
- Radiation protection in space and particle therapy share many common topics (carcinogenesis, CNS, CVD, modeling, radioprotectors etc.)
- Shielding is the only practical countermeasure but conventional materials are unable to ensure sufficient protection for long-term interplanetary missions
- Ground-based accelerators can be used for simulation of the space radiation environment and material testing, and many experiments can be of mutual interest for space and therapy

Thank you for attention!