

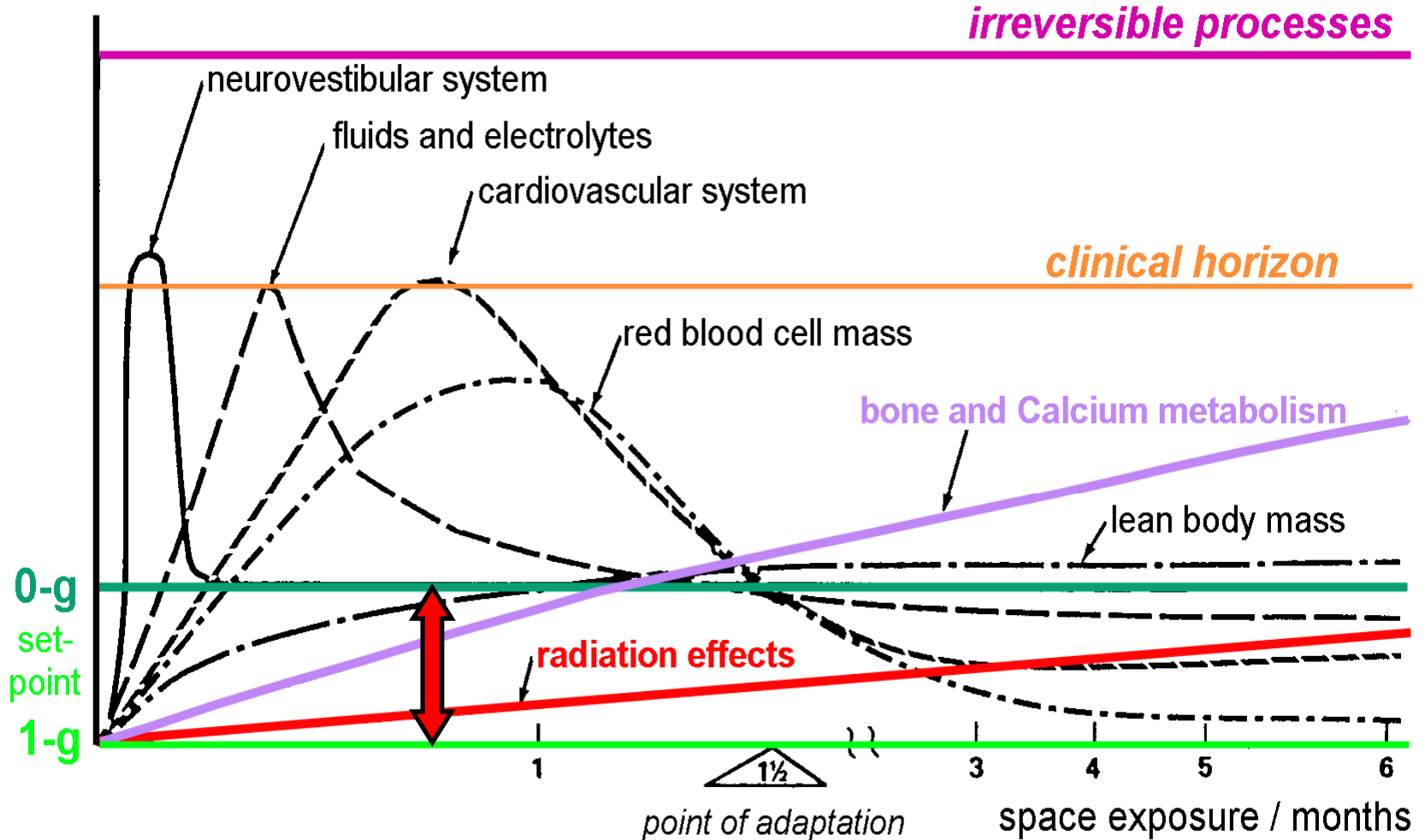


Impact of Space Radiation on Interplanetary Missions

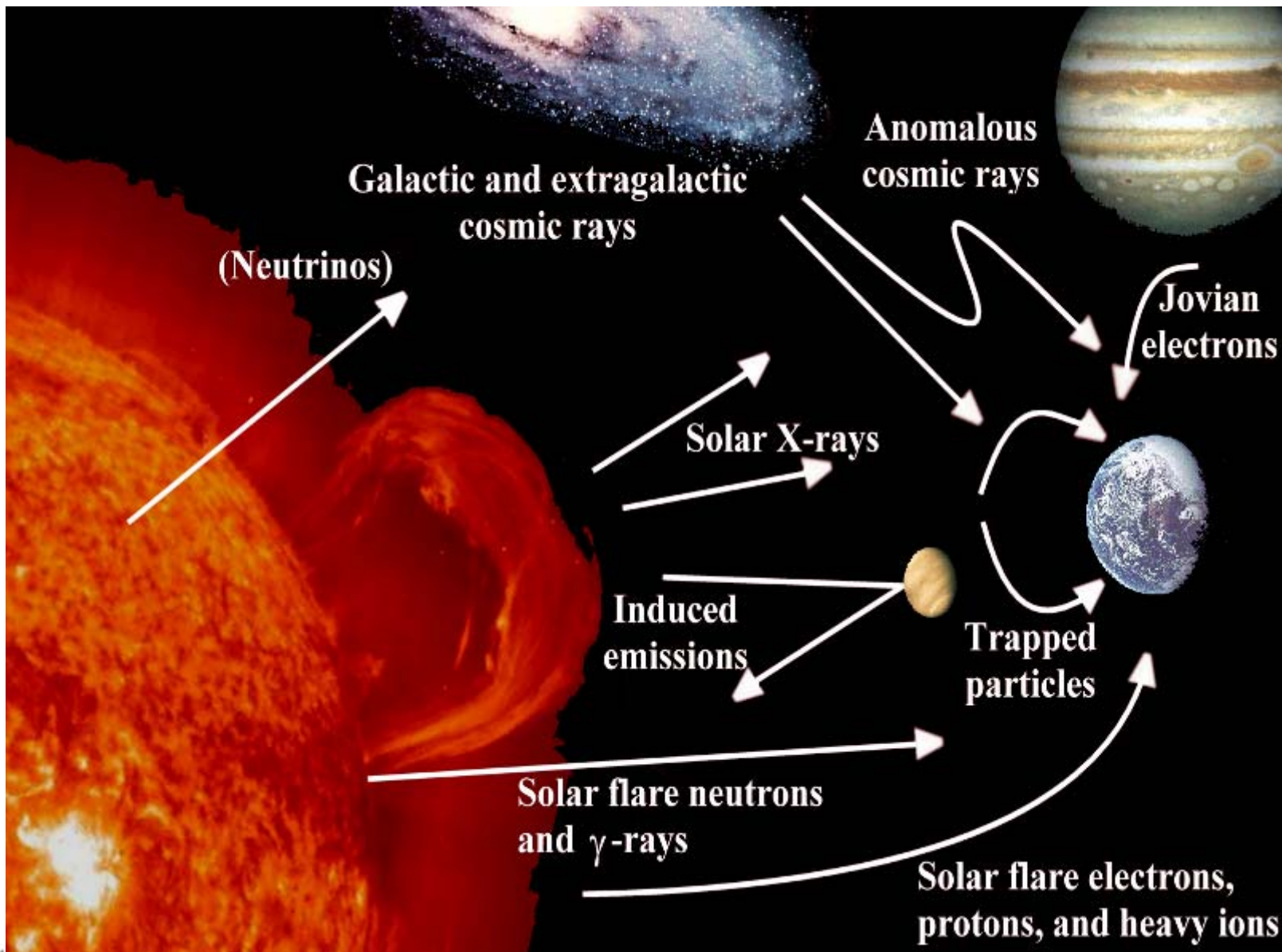
Günther Reitz

DLR – German Aerospace Center

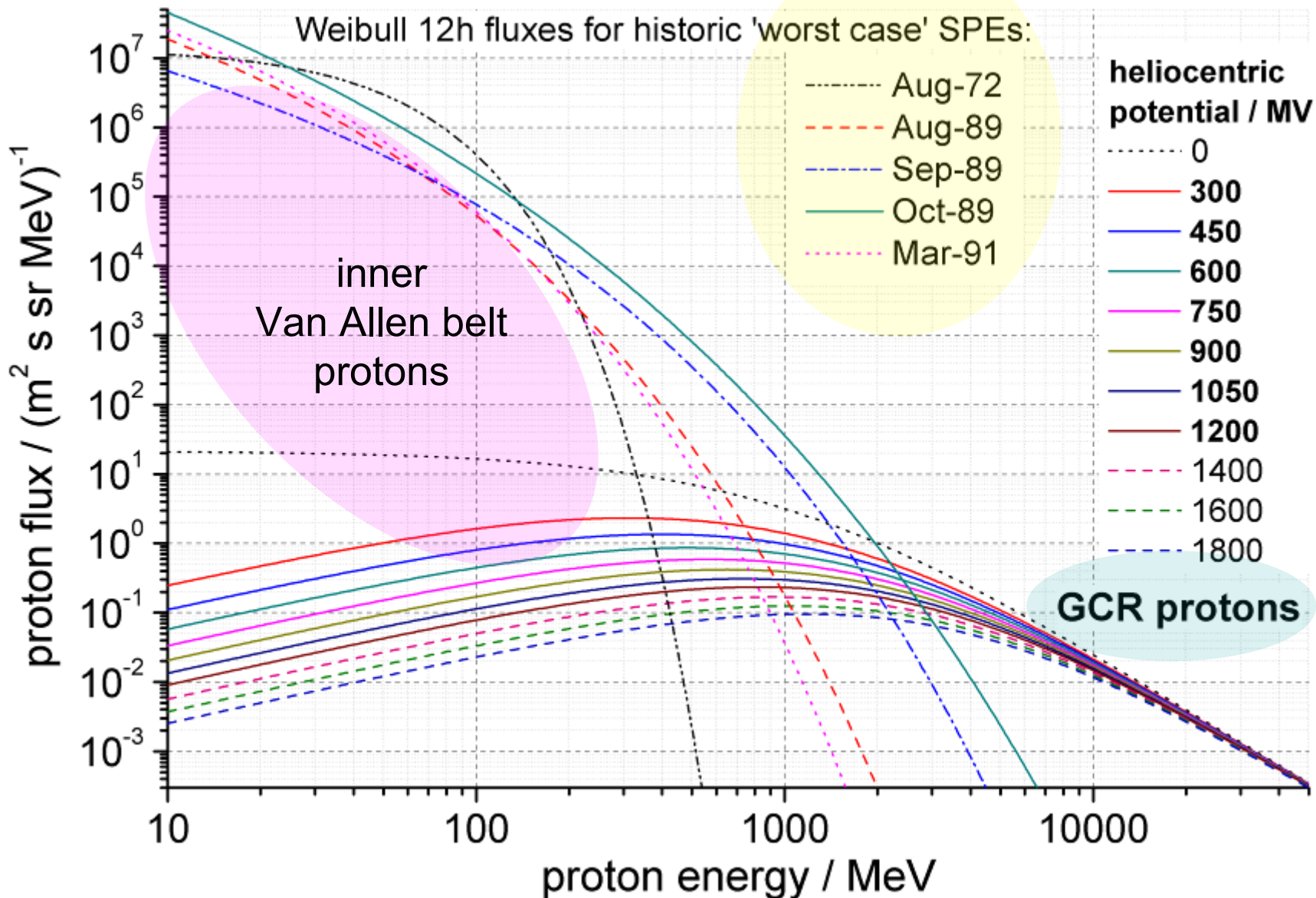
Institute of Aerospace Medicine, Cologne



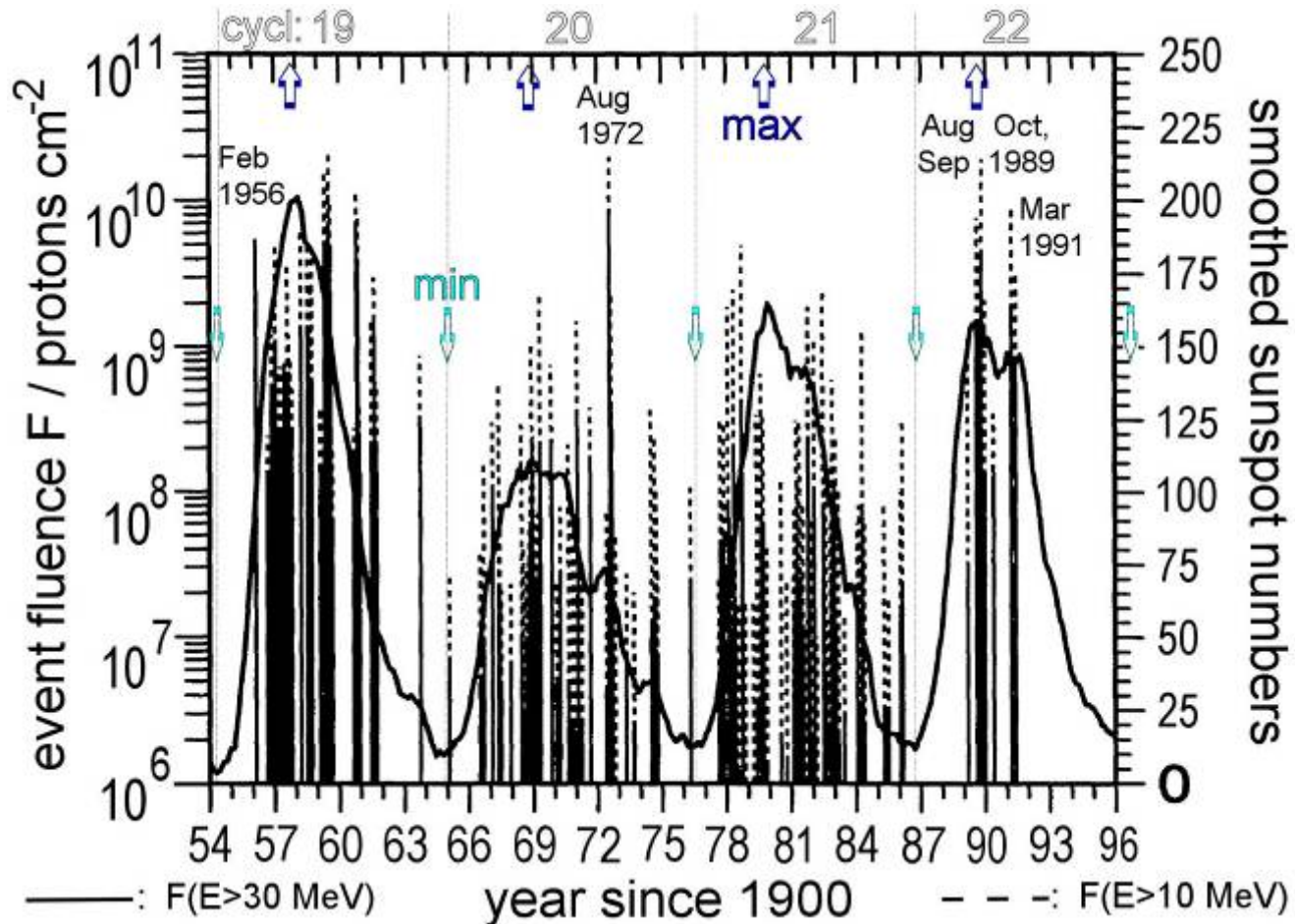
Time course of physiological shifts associated with acclimation to weightlessness



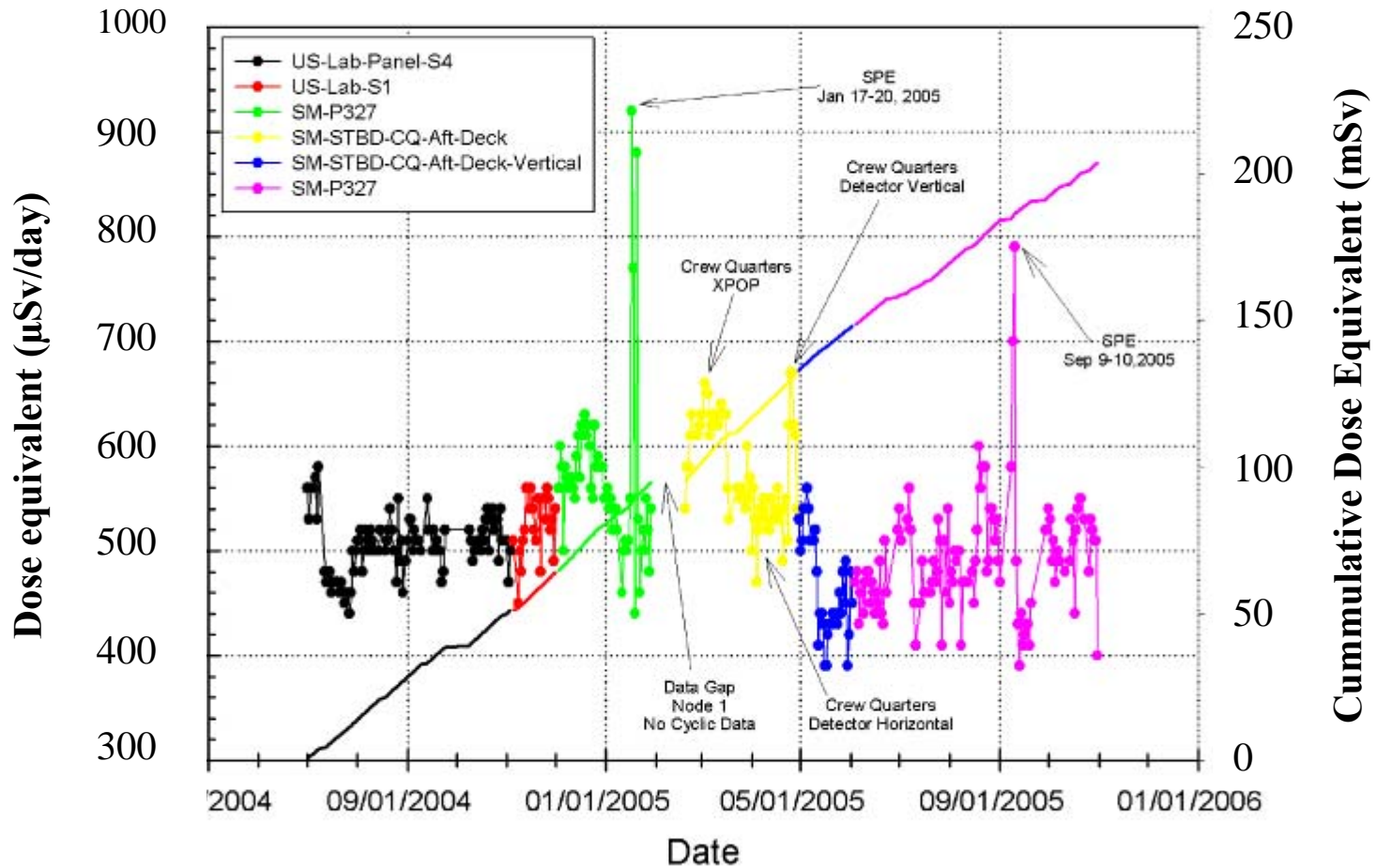
Fluxes of primary space radiation components



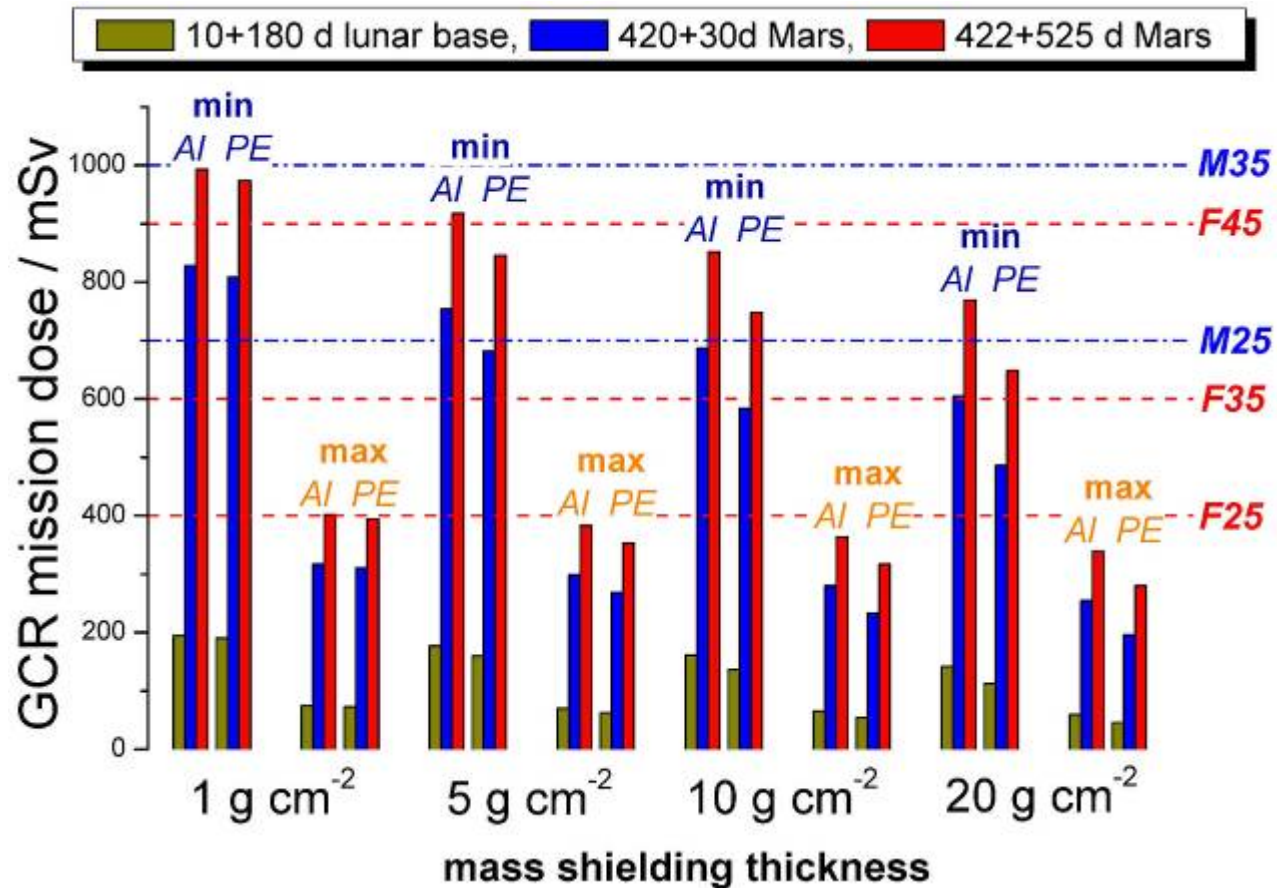
Occurrence of major and extreme solar particle events in solar cycles No. 19 to 22



ISS TEPC During 2005 (Dose Equivalent Rate)



Estimated BFO mission doses from galactic cosmic rays for interplanetary missions



Worst^{\$} case' SPE radiation exposures in Sv during different mission phases for critical tissues under different mass shielding

Mission Phase	Space suit (0.3)			Equipment room (5)			Radiation shelter (10)		
	Skin	Lens	BFO	Skin	Lens	BFO	Skin	Lens	BFO
Free Space	295	81.3	4.2	6.5	5.5	1.9	2.6	2.4	1.3
Lunar Surface	148	40.7	2.1	3.2	2.7	1.0	1.3	1.2	0.6
Martian Surface	0.5	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.25

given in parentheses in equivalent g/cm² Aluminium;

Lens = ocular lens, BFO = blood forming organs

^{\$} 1956 February 23rd event as approximated by 10X flux of 1989 September 29th event.

irradiation 

MOLECULES

physical stage
 10^{-18} - 10^{-12} s

excitation and ionisation of atoms and molecules

physico-chemical stage
 10^{-12} - 10^{-9} s

recombination



chemical stage
 10^{-9} - 10^{-3} s

water radiolysis,
peroxidation ...

modified amino-
acids, enzymes ...

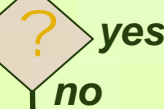
broken molecular bonds,
chromosomes, skeletons ...



biochemical stage
 10^{-3} - 10^3 s

CELLS

repair (enzymatic)



early biological stage
 10^3 - 10^6 s

genetic damage

somatic damage

apoptosis/necrosis

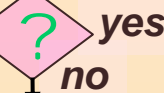


disease in progeny

cell transformation

tissue/organ
failure, disease

tissue regulation



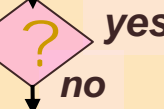
tumour promotion

progression

system failure,
early death

latent period
 10^6 - 10^9 s

immune surveillance

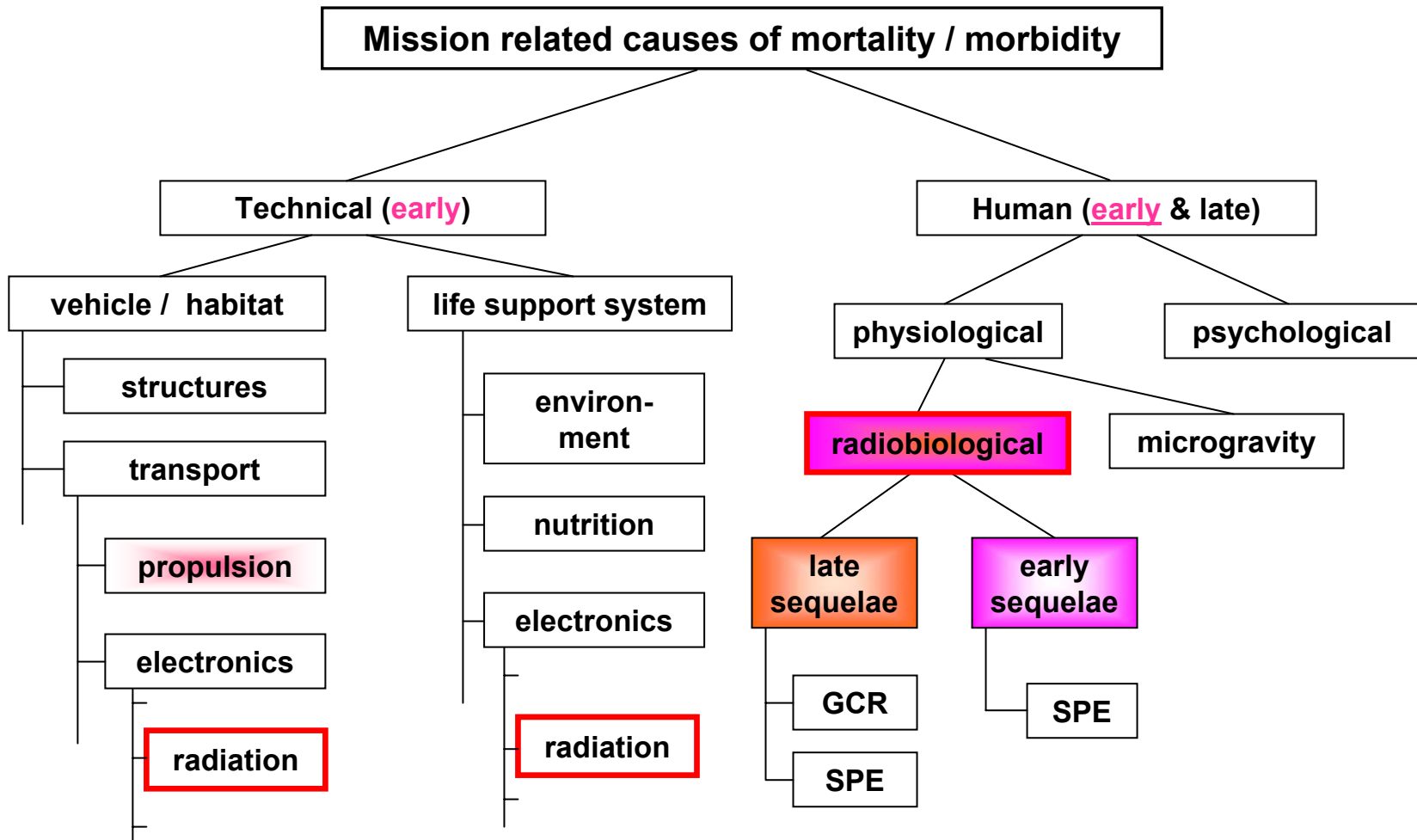


ORGANISM

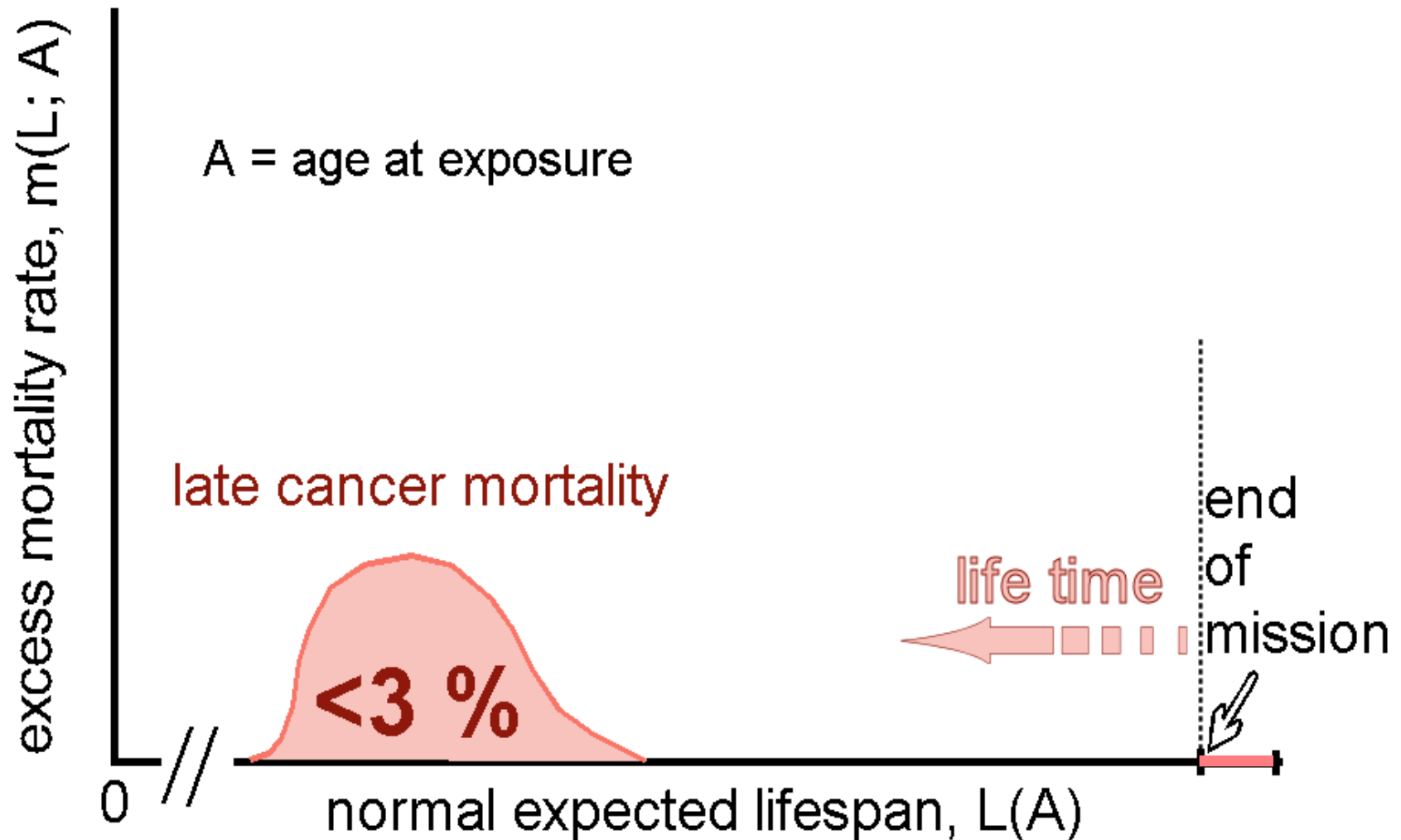
cancer, late death



'Fault tree' for fatal events



Late Cancer Mortality Risk



Major sources of uncertainty of risk estimation from space radiation field

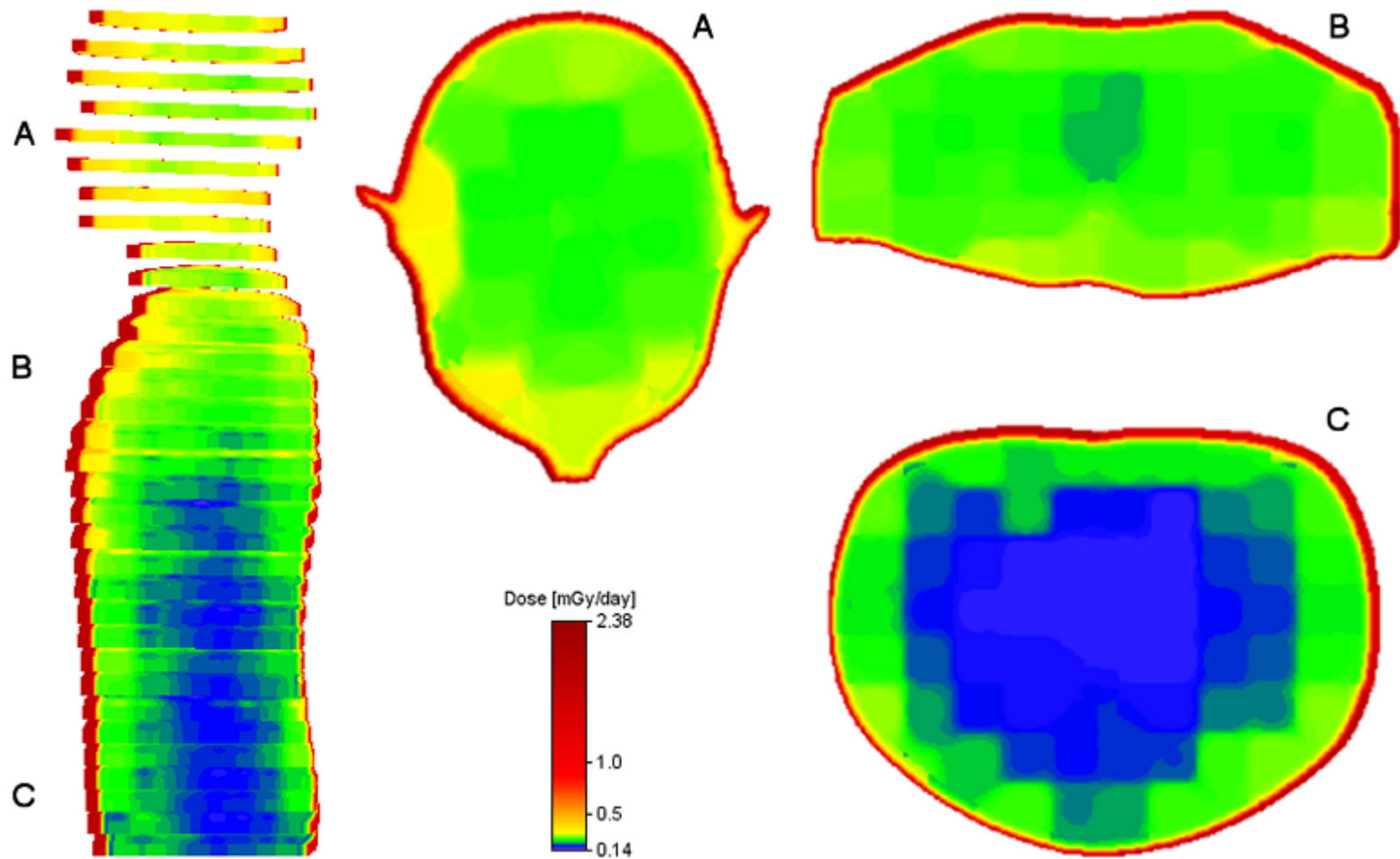
Source	R_y	Q(L)	Φ (L)
Physical Particle Environment Transport through shielding			\pm (10-15)% \pm 50%
Biological DDREF, extrapolations across nationalities, risk projections till end-of-life, dosimetry, etc Radiation quality dependence of human cancer risk	200 – 300% (mult.)	200 – 500% (mult.)	

The MATROSHKA Facility – Passive radiation detectors



Thermoluminescence detectors (TLDs) and Nuclear Track Etch detectors
Total Number : ~ 6000

Median-sagittal plane of the 3D model of MATROSHKA including “skin dose” distribution.



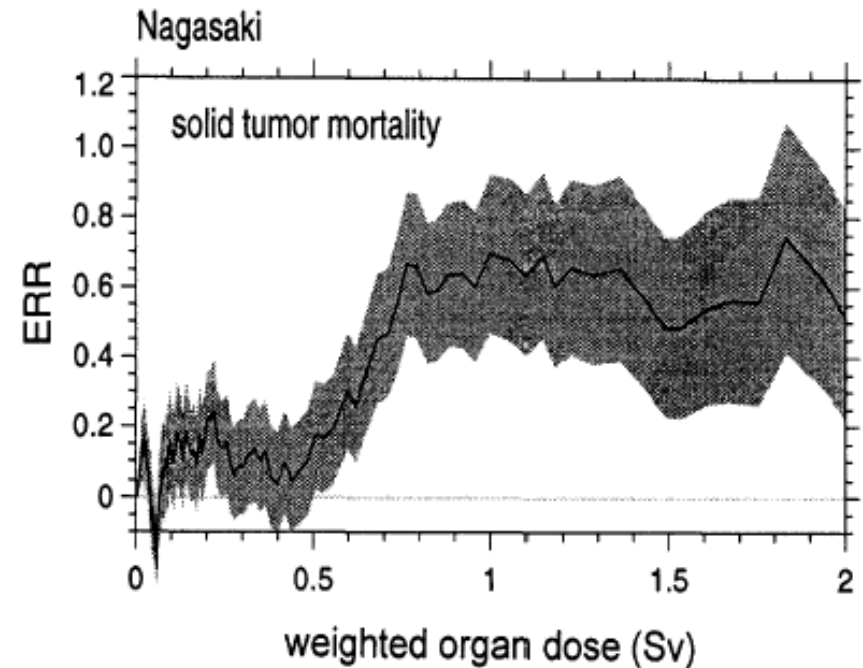
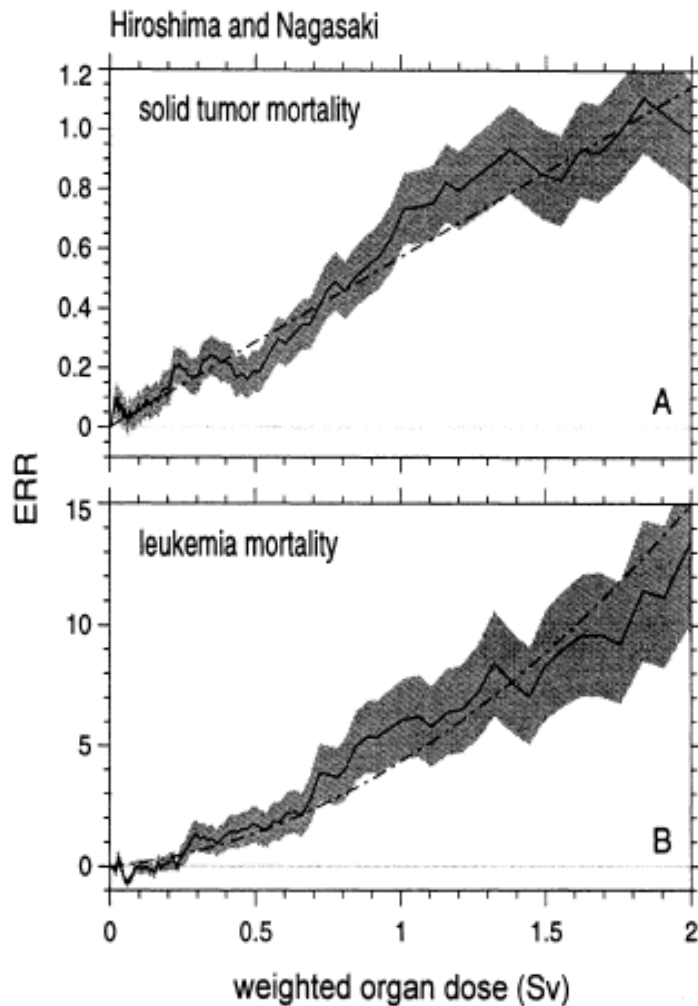
Cosmic Rays versus A-bomb Exposure

Exposure Conditions for Dose-Effect Curve on Late Cancer Mortality^{\$}

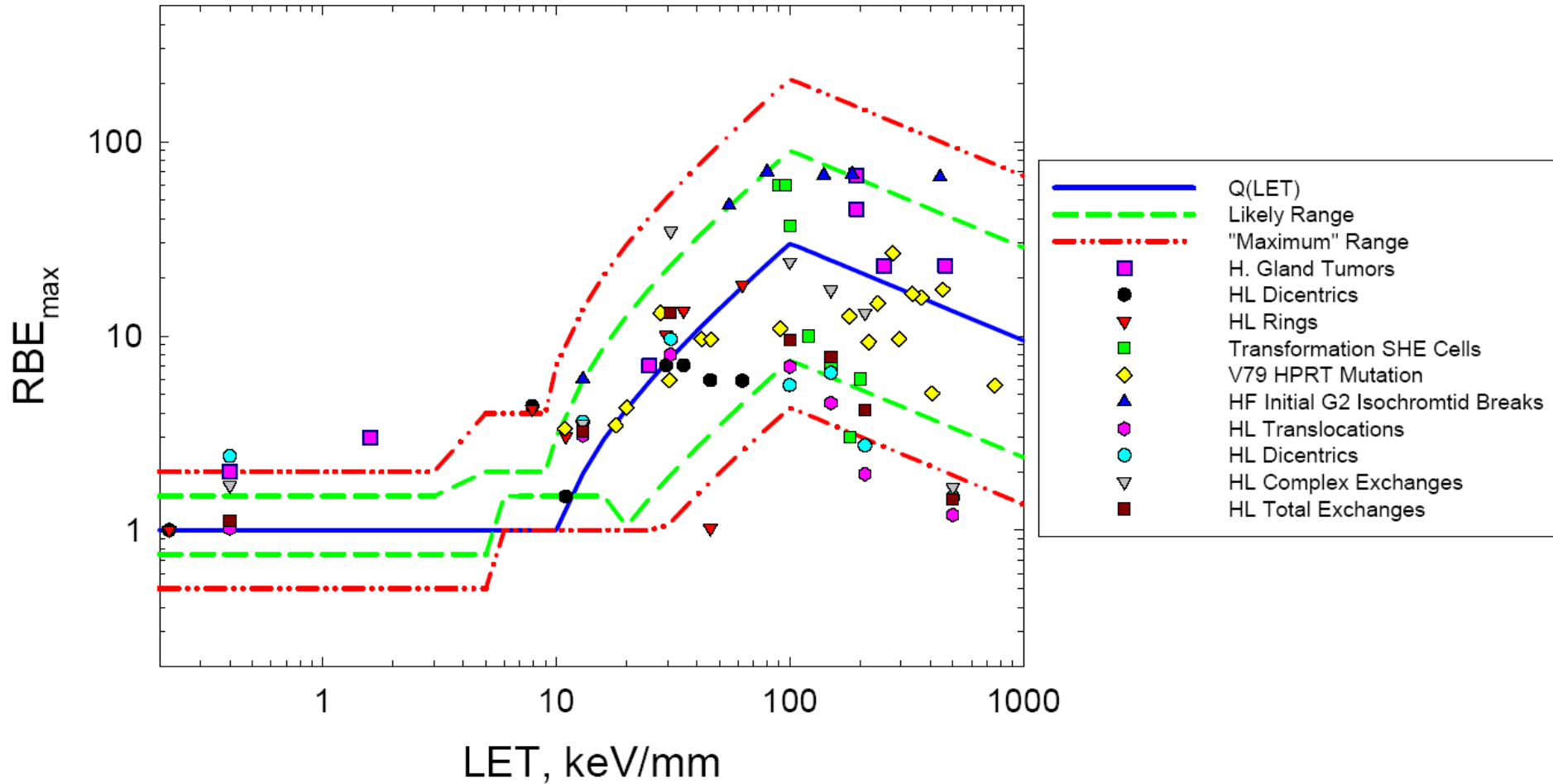
Exposure Parameters	A-Bomb Exposures	Space Exposure
Dose rate, Duration	Instantaneous/acute, seconds	GCR: chronic/protracted, months – years; SPE: acute, hours-days
Radiation Quality	Low-LET gamma-ray	Most complex mixture of disparate radiation qualities conceivable
Body Distribution	Essentially homogeneous	Depending on external shielding, inhomogeneous
Exposed Population	Common age-, gender-, health status distribution	Selected for physical/ psychic prowess, age and health
Environmental Conditions	Normal terrestrial	microgravity, confined ecological system, artificial/technical components dominating

^{\$} Data base: Atomic bomb survivor epidemiology

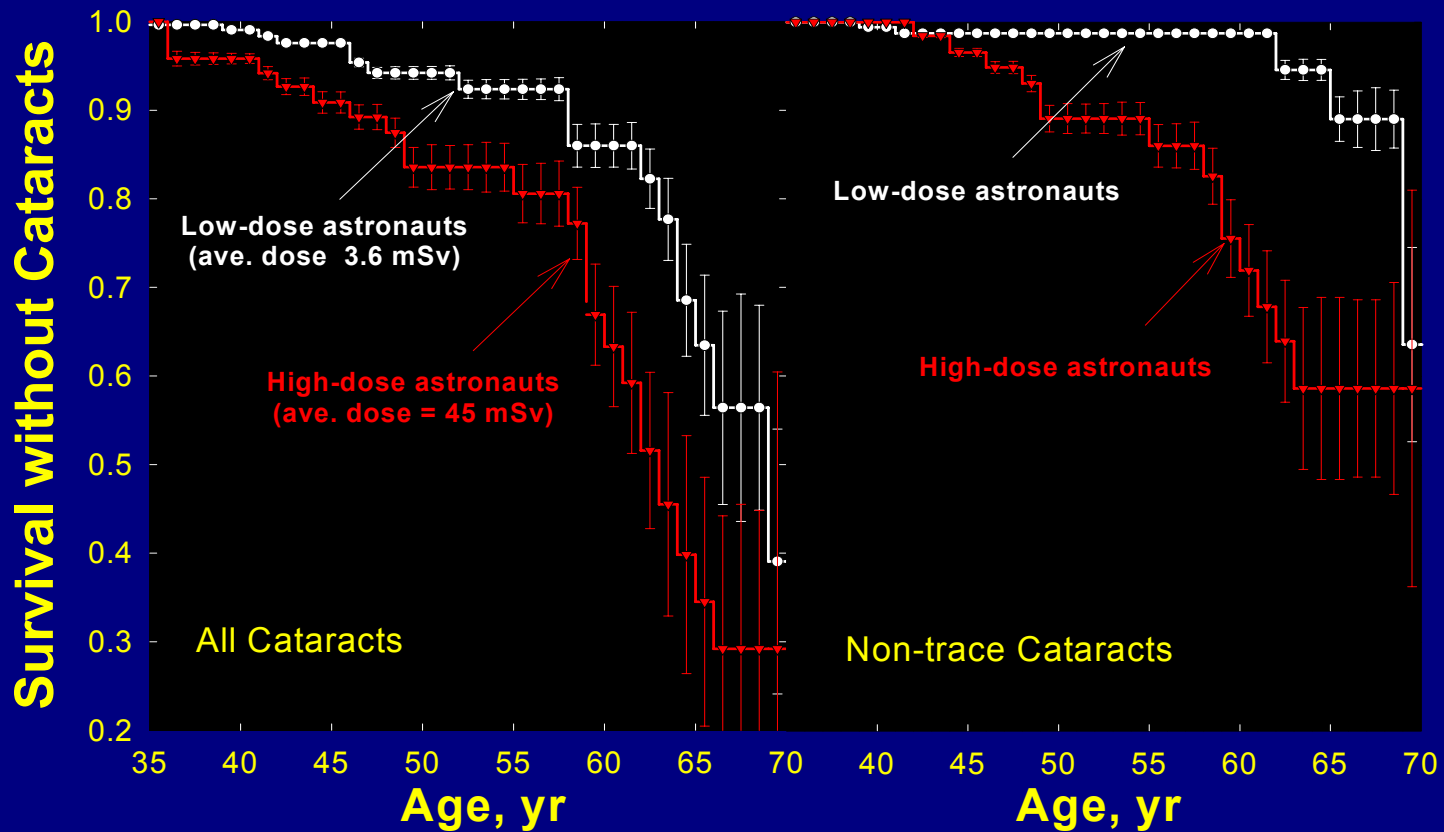
Cancer Mortality Dose Response Functions for Atomic Bomb Survivors in “selection free” Representation



Quality Factors (Q) and Radiobiological Efficiency (RBE)

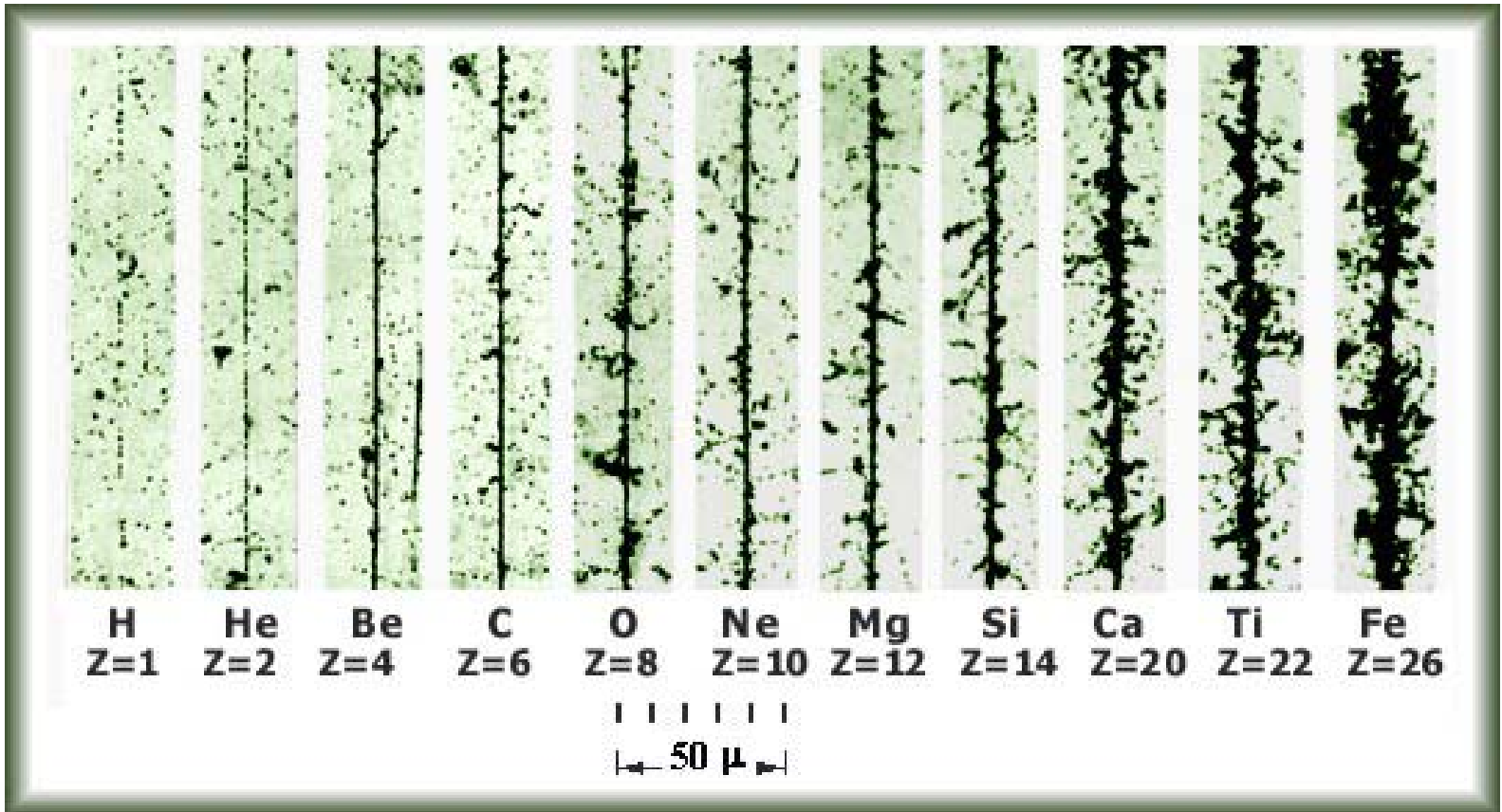
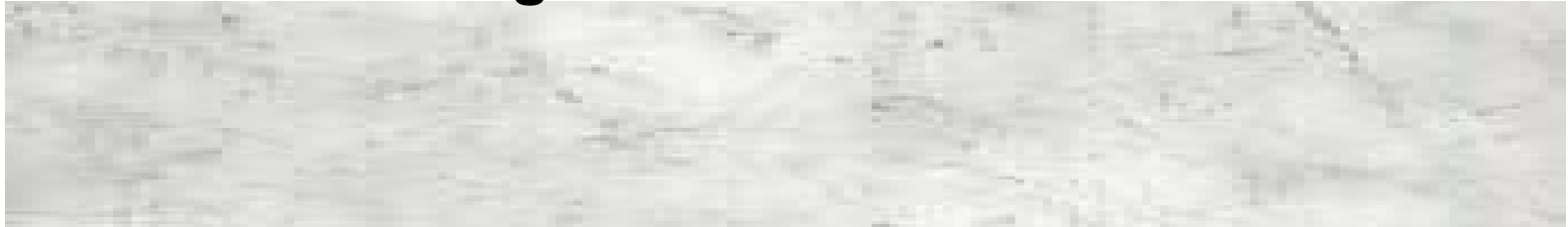


Astronaut Cataracts: Space Radiation

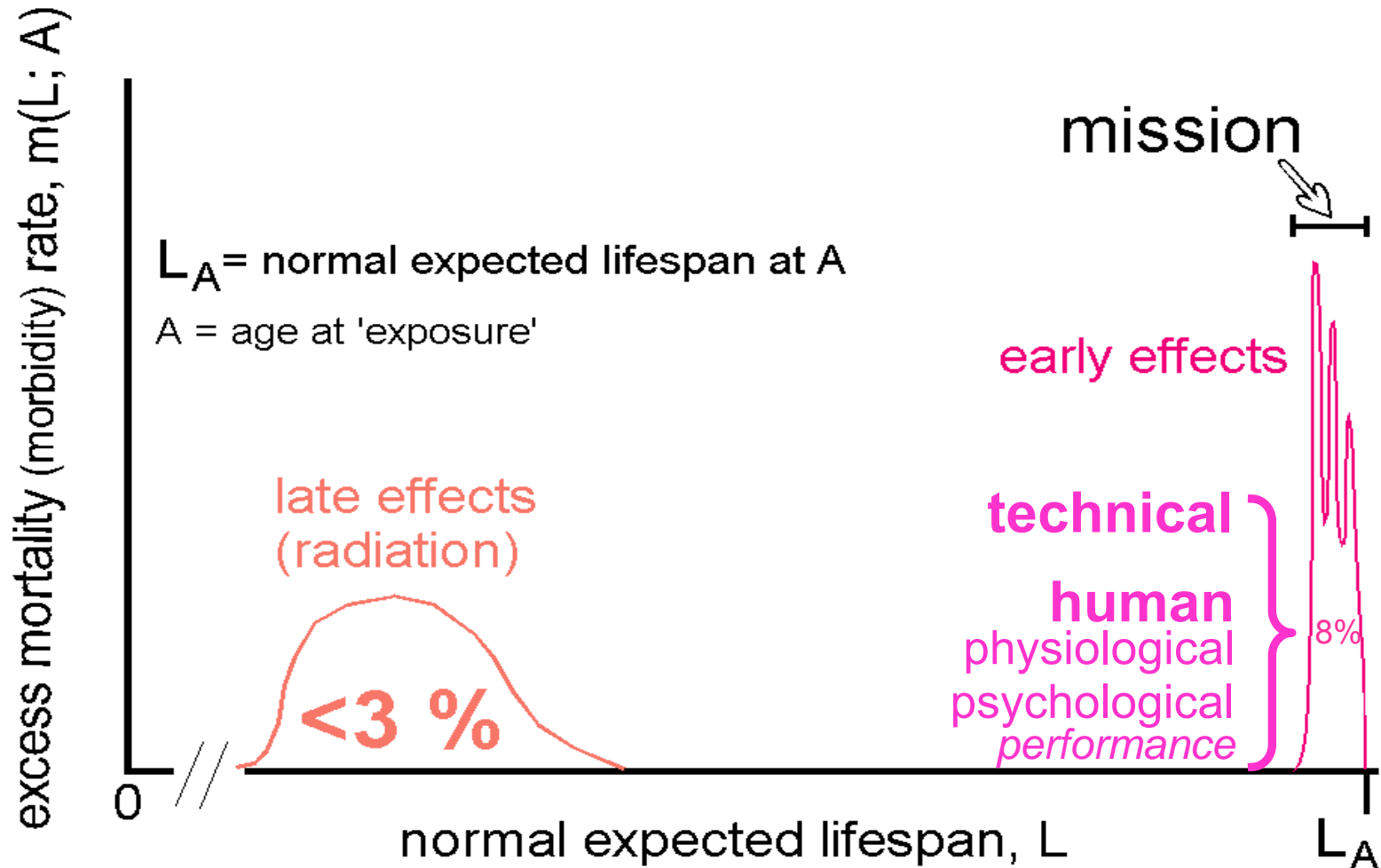


Visual tracks of heavy ions - demonstrating uneven distribution of 'dose'

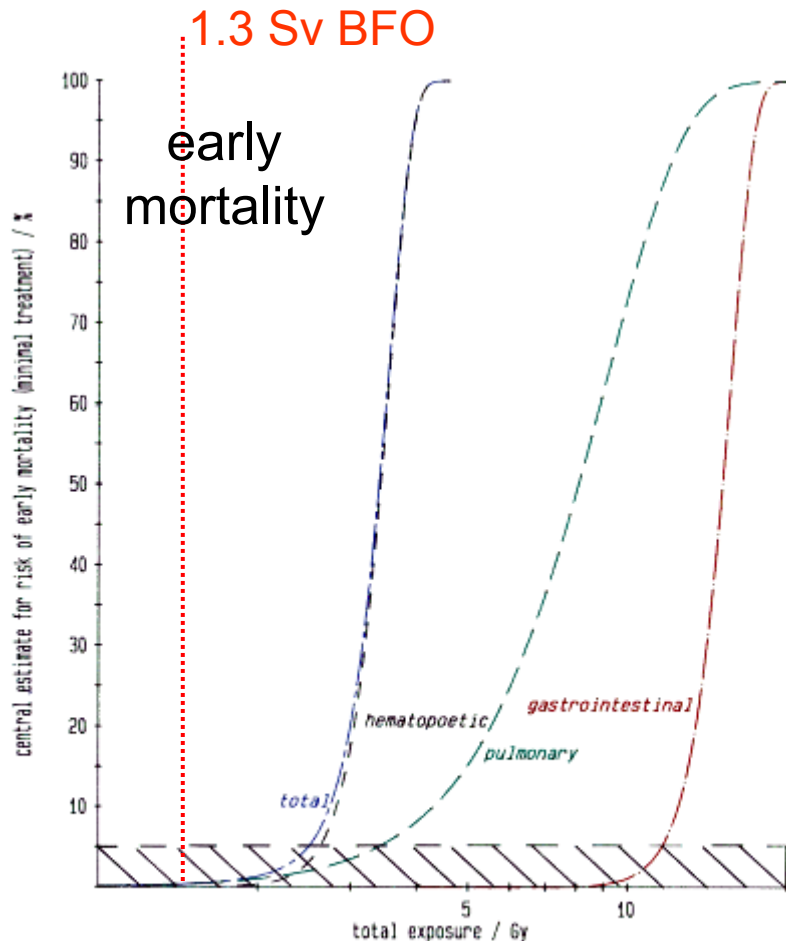
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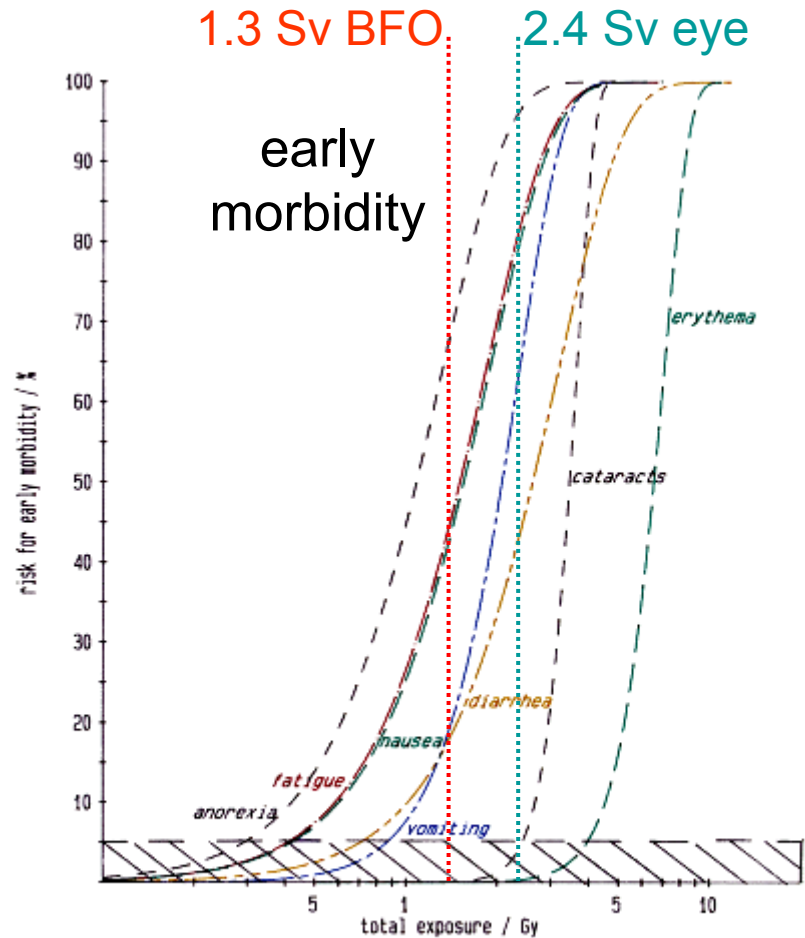
Total Risk in Explorative Missions



Early morbidity/mortality for worst case SPE behind 10 gm/cm² in interplanetary space

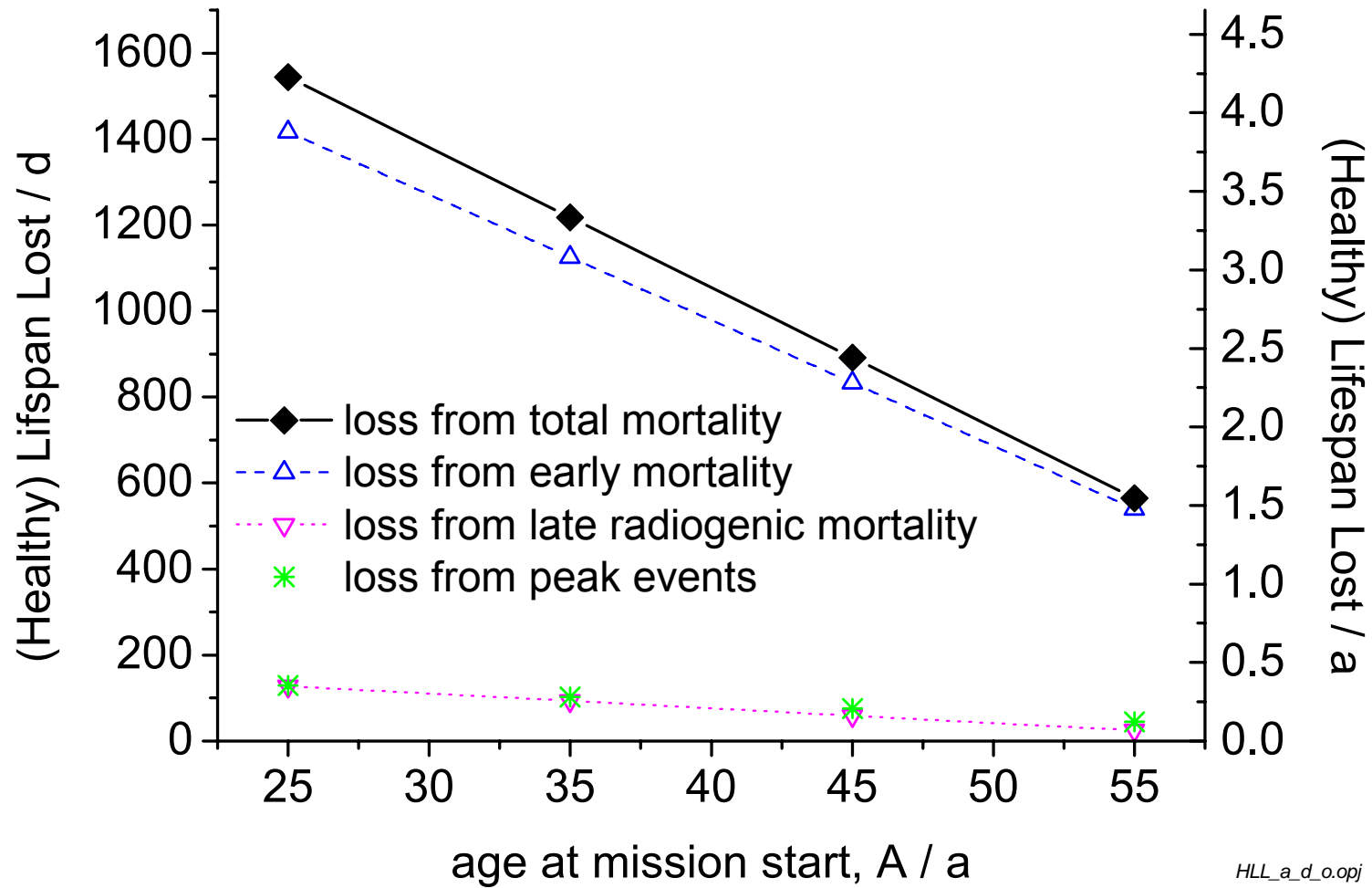


DOSE DEPENDENCE FOR CAUSES OF EARLY MORTALITY FOR A FRACTIONATION SCHEME OF 99 % INSTANTANEOUS AND 1% PROTRACTED EXPOSURE



DOSE DEPENDENCE FOR CAUSES OF EARLY MORBIDITY FOR A FRACTIONATION SCHEME OF 80 % INSTANTANEOUS AND 20% PROTRACTED EXPOSURE

Days of Life Lost



HLL_a_d_o.opj

Information needed to calculate Risk for early effects

Early (*deterministic*) Effects

early morbidity

..prodromal syndrome
...fatigue, anorexia,
...nausea, diarrhea, vomiting

..erythema

..cataracts

..performance decrement

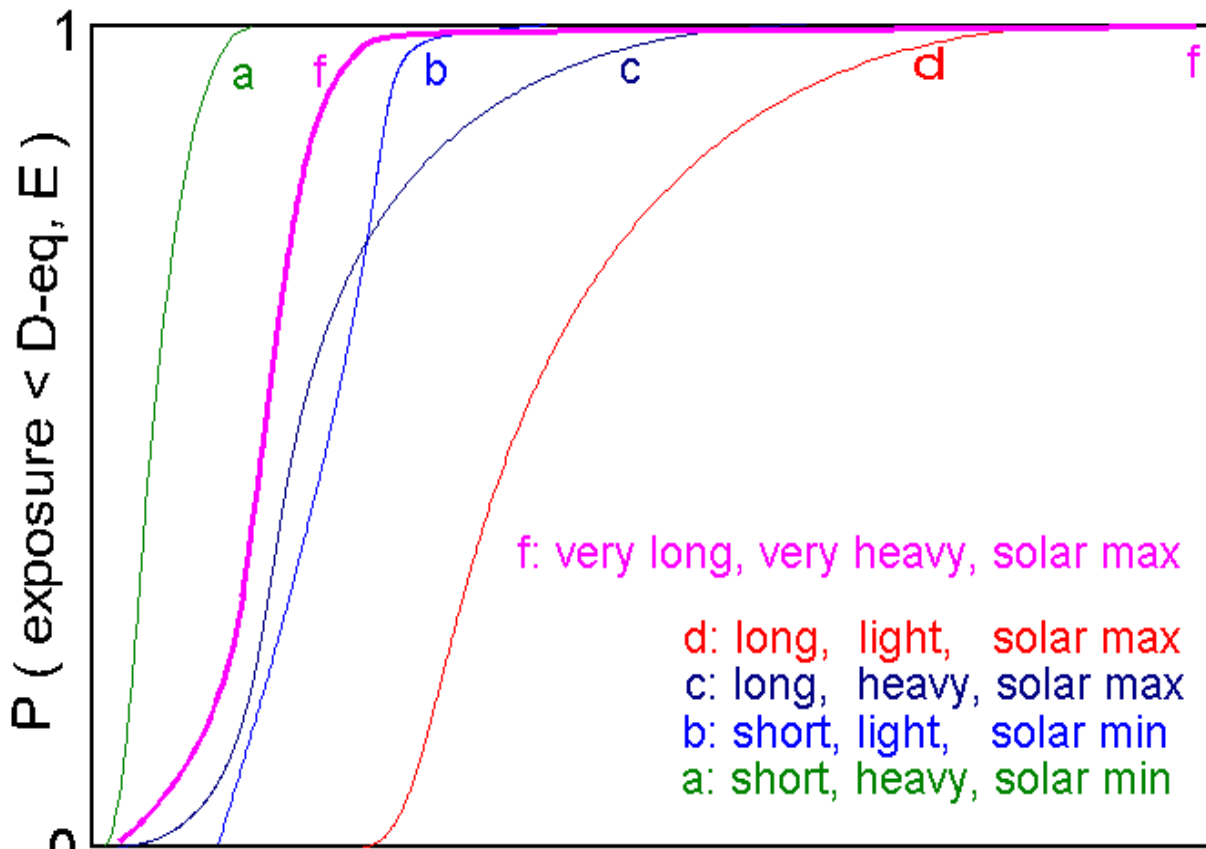
early mortality

..hematopoietic death

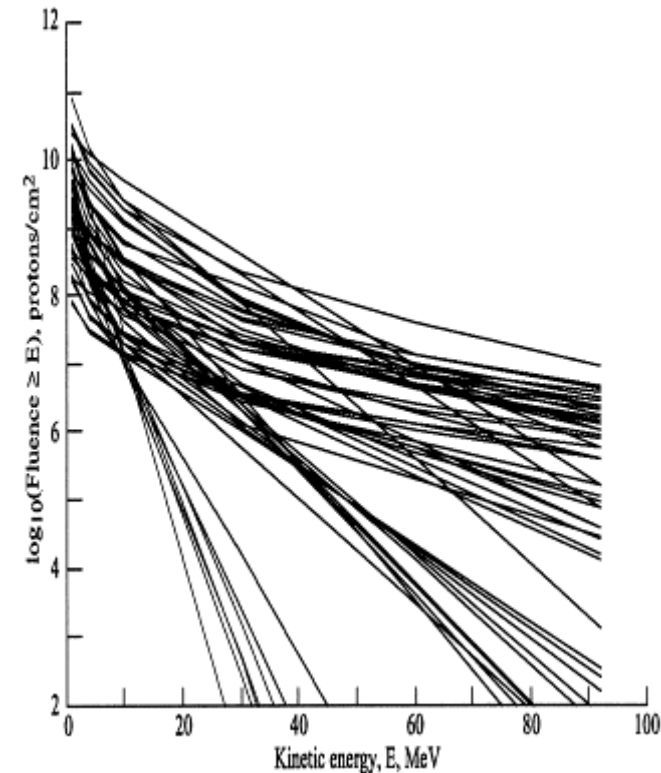
Performance Decrement

- Data for dose and time dependent performance decrements:
 - dose response functions for early radiation sequelae after instantaneous, whole body exposure (nuclear battlefield)
 - dose dependent temporal profiles of symptom severity
 - questionnaires filled in by military personnel of various assignments
- Performance decreases indirectly due to symptoms of acute radiation sequelae (fatigue, nausea, vomiting, diarrhea, cataracts, erythema)
Performance decrement profiles are task dependent
- **Integrated Performance Modelling** may provide advanced tools for solving this task

Required distribution functions for SPE produced radiation doses



SPE equivalent dose, D-eq, received during single event
 SPE total effective dose, E, received during mission



Estimated reliability objectives for the 1000 days Mars mission

Mission phase / Element reliability requirements	Earth Launch	Earth-Mars transfer 218 days	Mars aerocapture phase	Mars landing	Mars stay 525 days	Mars Launch	Mars-Earth transfer 204 days	Earth aerocapture phase	Earth - landing	Reliability goals
Launcher	0.99									0.99
Spacecraft	0.99712*	0.99712*	0.99	0.99712*	0.99712*	0.99	0.99712*	0.99	0.99712*	0.963
lethal illness or injury (≈70 diseases)	≅1	<u>0.9914</u>	≅1	≅1	<u>0.98</u>	≅1	<u>0.992</u>	≅1	≅1	<u>0.964</u>
Ground segment with communication system	0.999988*	0.999988*	0.999988*	0.999988*	0.999988*	0.999988*	0.999988*	0.999988*	0.999988*	0.9999
Overall Mission reliability requirement	risks materializes during the mission!									<u>0.919</u>

radiation risks excluded!

Countermeasures against radiation effects

Improve advance risk assessment

- develop proper risk criterion for exploratory LONG term missions
- integrate radiation risk assessment into total risk analysis
- reduce uncertainties for exposure estimates
- reduce uncertainties for dose effect relations (late & early)

Minimise radiation exposure

- optimise shielding design, include storm shelter (material & thickness)
- optimise mission design
 - duration
 - timeline relative to solar activity cycle
 - guaranteed shelter accessibility
- advance forecasting capabilities for solar particle events
- monitor and document exposure history and health status

Maximise radiation resistance

- select genetically resistant individuals
- modify dose response curve of 'normal' crew members
 - attenuate early effects by prior and post medication
 - mitigate late effects by prophylactic nutrition



Conclusions

Work still to be done

Reduction of uncertainties in risk assessment in radiobiology

- Extension of the ground based programm for investigation of biological effects of space radiation
- **Radiation biological experiments for selected endpoints onboard ISS**

Environmental and shielding studies

- Characterisation of the radiation environments
- Characterisation and selection of new vehicle construction materials
- Investigations of active shields
- Modell benchmarking and improvement

Major critical items for a mission to Mars

- Solar particle event danger
- Very long 0-gravity levels during interplanetary transfers
- Very high gravity levels at Mars arrival (aerocapture and landing)
- Almost no mission abort and fast return capability
- Delays of up to 45 minutes in bi-directional communication
- Optimal crew size, composition and corresponding education

