Space radioprotection

Mauro Villa

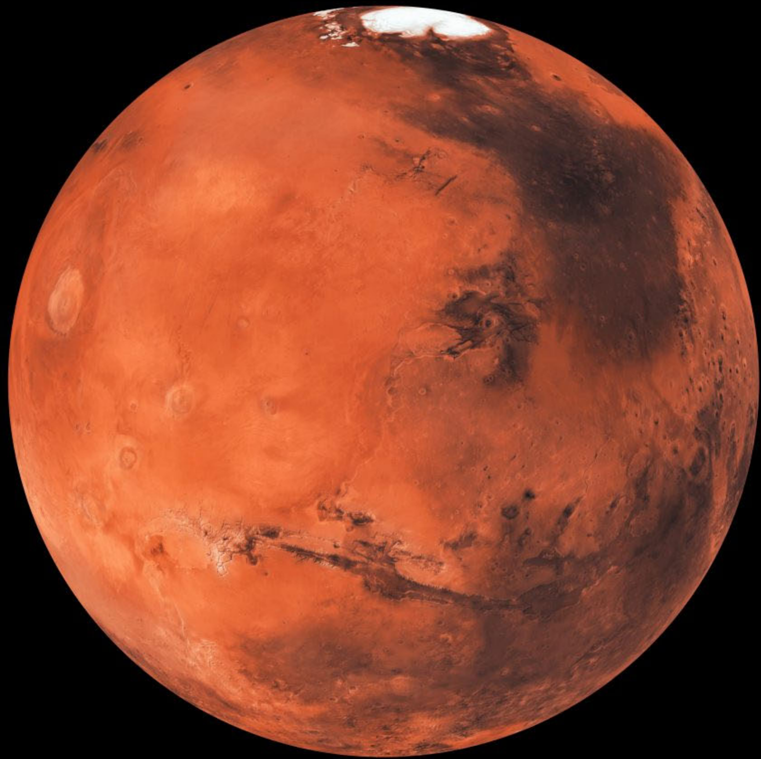
Bologna University and INFN Bologna

NTOF Nuclear Physics Winter School – 21-26 January 2024

Outline

- Setting the scene – a mission to mars
  - Fuel equation, Hohmann trajectory
- Outer space conditions
  - Solar wind
  - Solar particle events
  - Galactic cosmic rays
- Total Radiation doses
- Mitigation techniques
  - Passive techniques
  - Active techniques
  - Biological techniques
- Nuclear data
- Summary

A human mission to Mars



Rocket science (or better: rocket formulas)

- Without external forces:

$$\vec{F} = \vec{u}\frac{\mathrm{d}m}{\mathrm{d}t} = -\vec{u}\frac{\mathrm{dM}}{\mathrm{d}t} \quad \rightarrow \quad v_f = v_i + u\, ln\left(\frac{M_i}{M_f}\right)$$

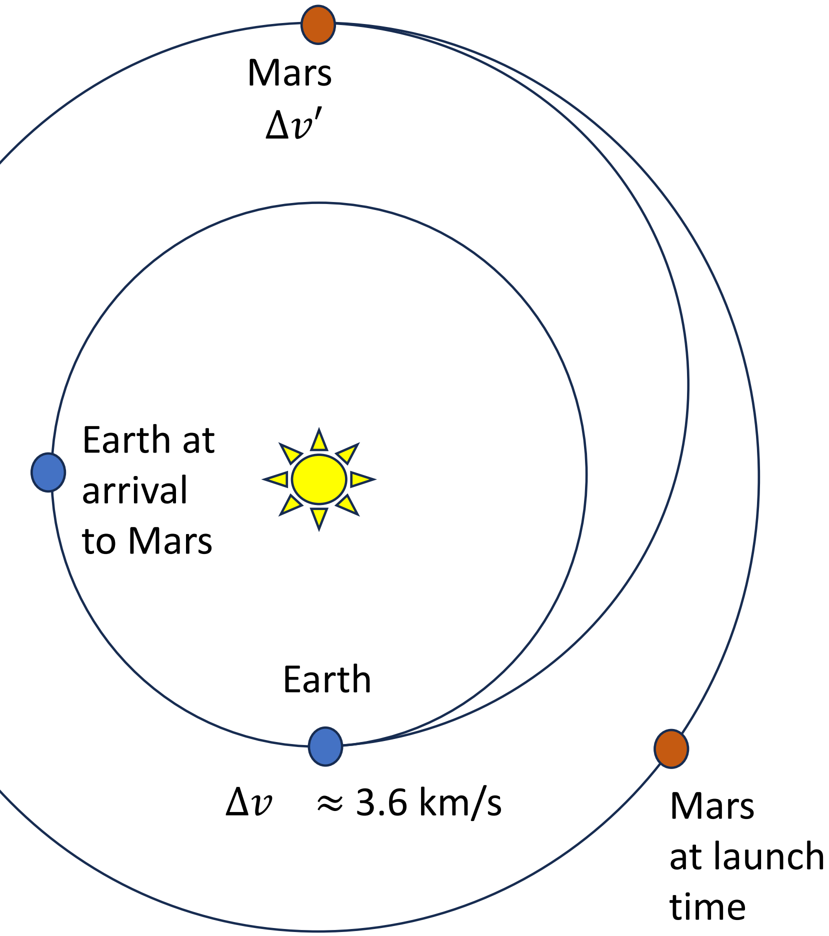
- Starting from ground:

$$\vec{F} = \vec{u}\frac{\mathrm{d}m}{\mathrm{d}t} - M\vec{g} - \vec{F}_{friction} \quad \rightarrow \quad v_f = 0 + u\, ln\left(\frac{M_i}{M_f}\right) - g(t_f - t_i) - |\text{corrections}|$$

- Numbers (typical values):
- u= 3 km/s ; low orbit (300 km) v_f= 7.8 km/s $\longrightarrow$ $\frac{M_i}{M_f} \approx 9$

Rockets are made in stages

Hohmann trajectories



Steps:

- Exiting Earth influence
- Inserting into a eliptical orbit around the sun (perielion=Earth, afelion=Mars)
- Descend into a low martian orbit (Mars influence sphere)
- Descend on Mars!

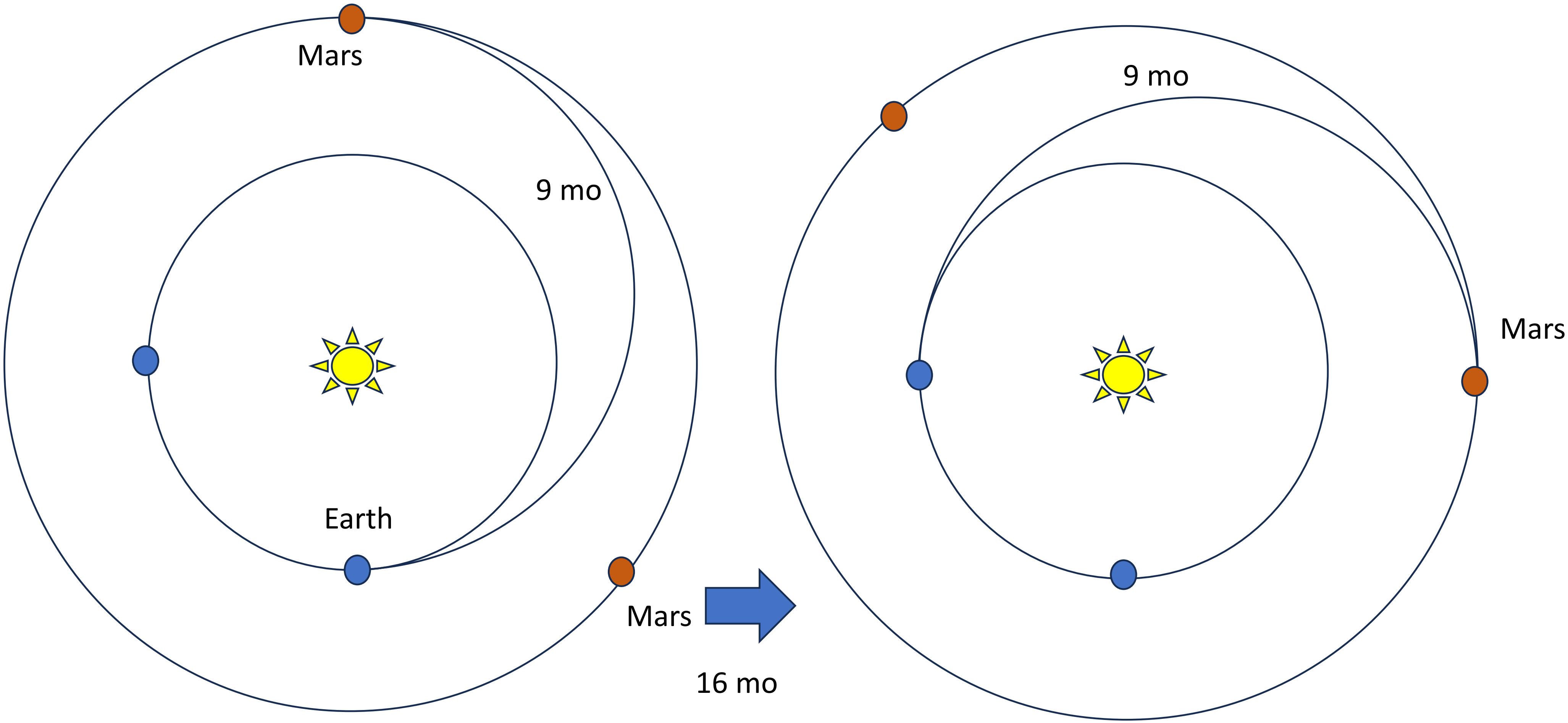
Minimal usage of fuel

Price to pay:

-Launch windows every 2 years

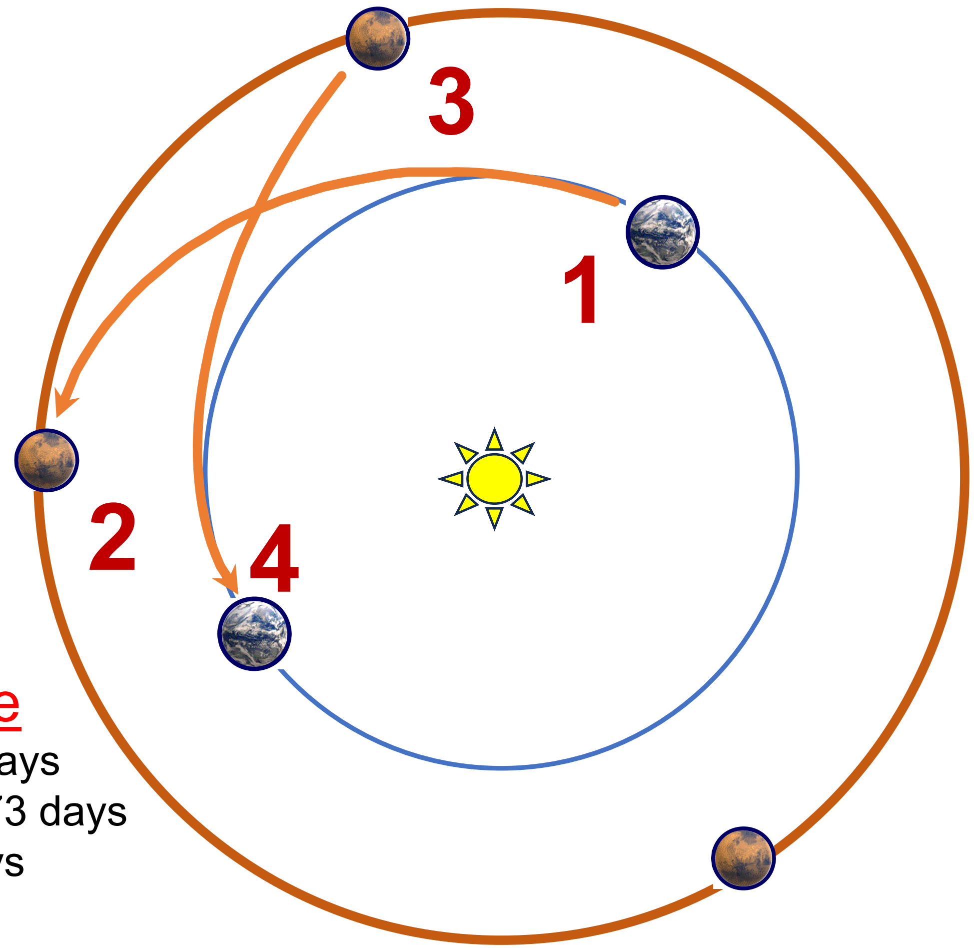
- Travel time about 270 days

Full mission: 34 months



Great variability on duration

- Hohmann trajectories are just the most economic ones
- Other solutions possible → transfer time from 5 to 9 mo, stay from 16 to 19 months



Flight Profile

Transit out: 161 days
Mars surface stay: 573 days
Return: 154 days

Space environment(s)

Pressure 0, no gas;   high temperature variability <-100°C, >+100°C

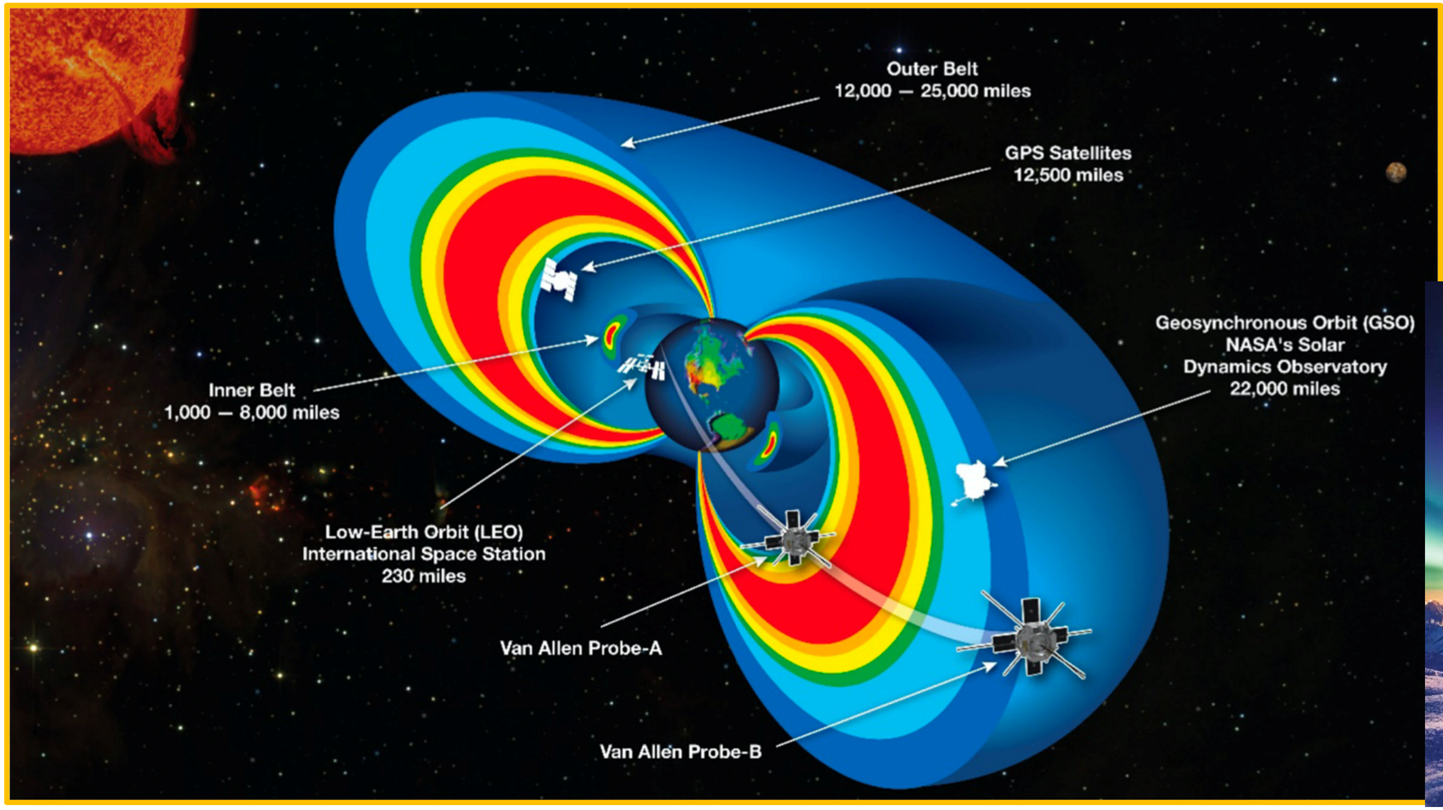
- Low Earth Orbit (<500 km)
- Up to the moon distances
  (380.000 km)
- Deep space
  (beyond moon distance)

Space radiation

- Galactic Cosmic Rays GCR (all ions)
- Solar wind (protons)
- Solar Particle Events SPE
  (mainly protons)
- Trapped particles
  (protons and electrons)
- Albedo radiation
  (electrons, protons, neutrons)

Low and near earth orbits

Earth magnetosphere protects us from low energy radiation



Radiation:

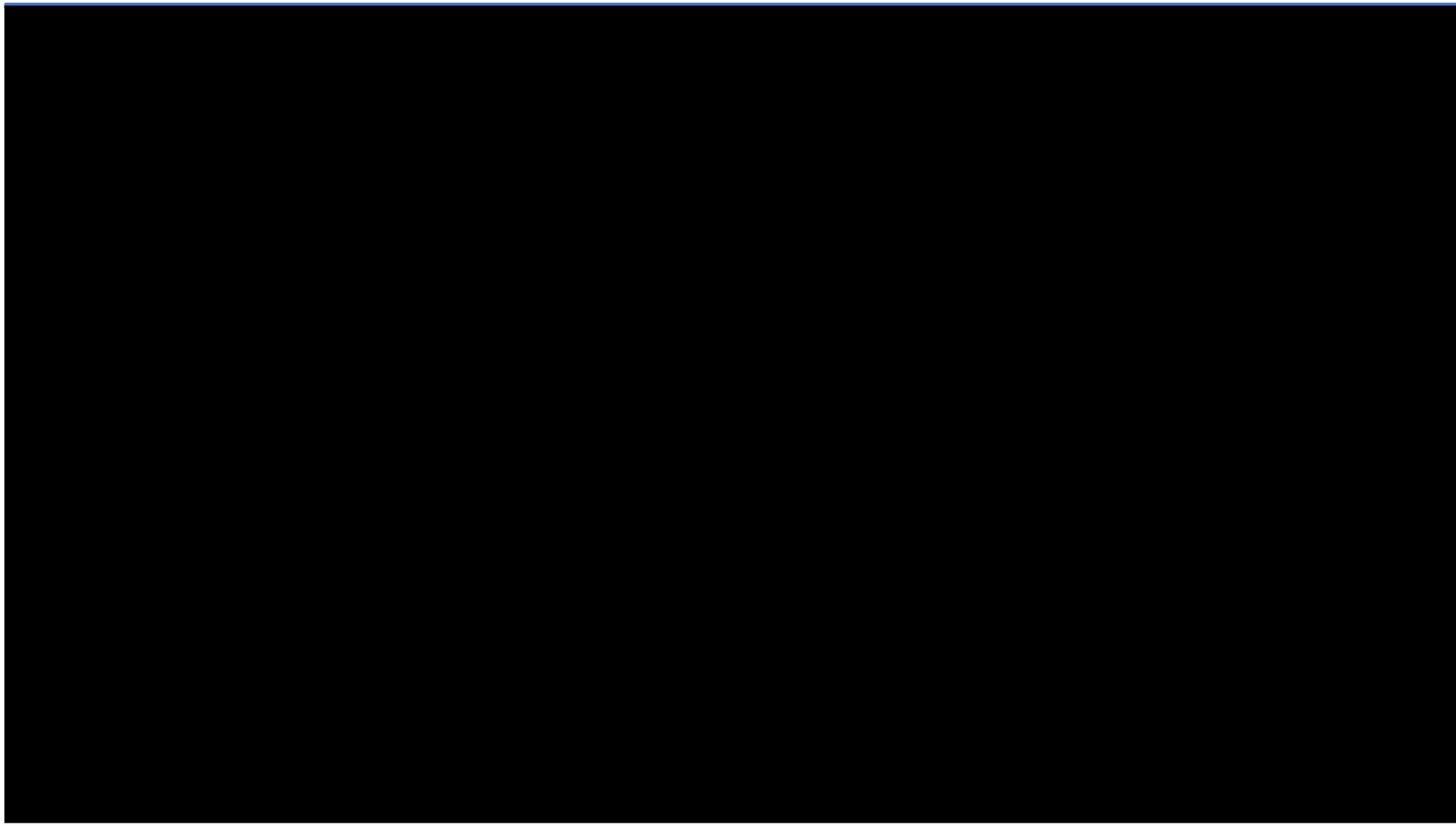
- Trapped particles
- high energy particles
- albedo radiation

Solar particle events

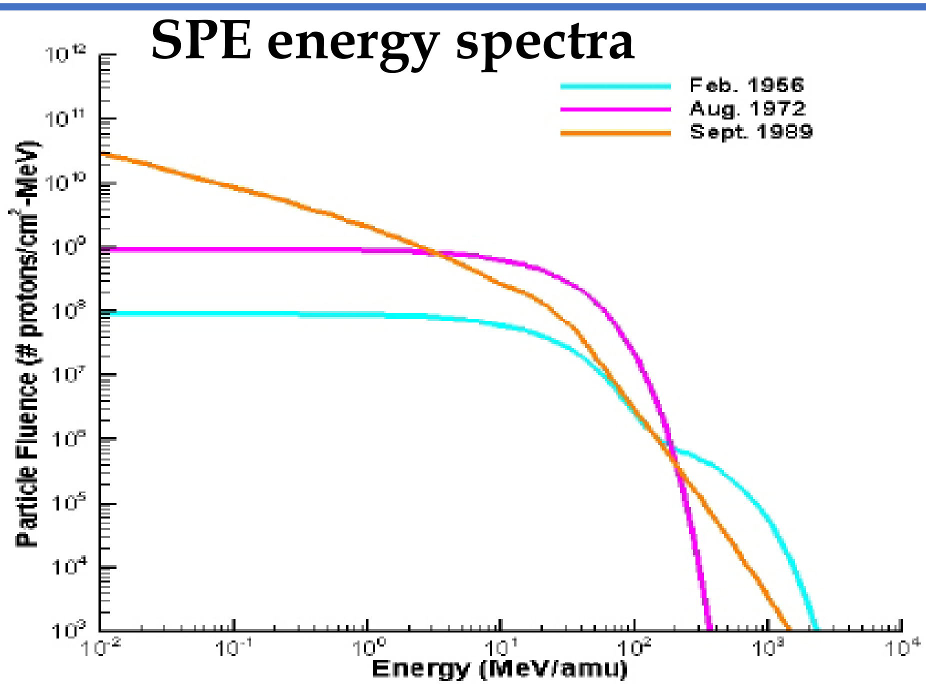
Very dangerous and not predictable

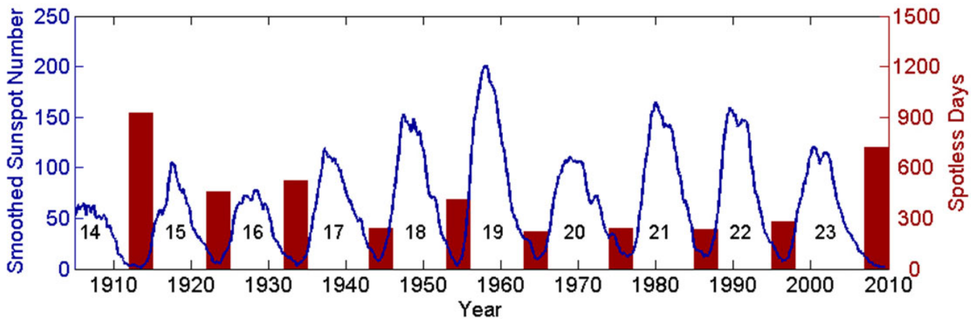
Solar particle events

Very dangerous and not predictable



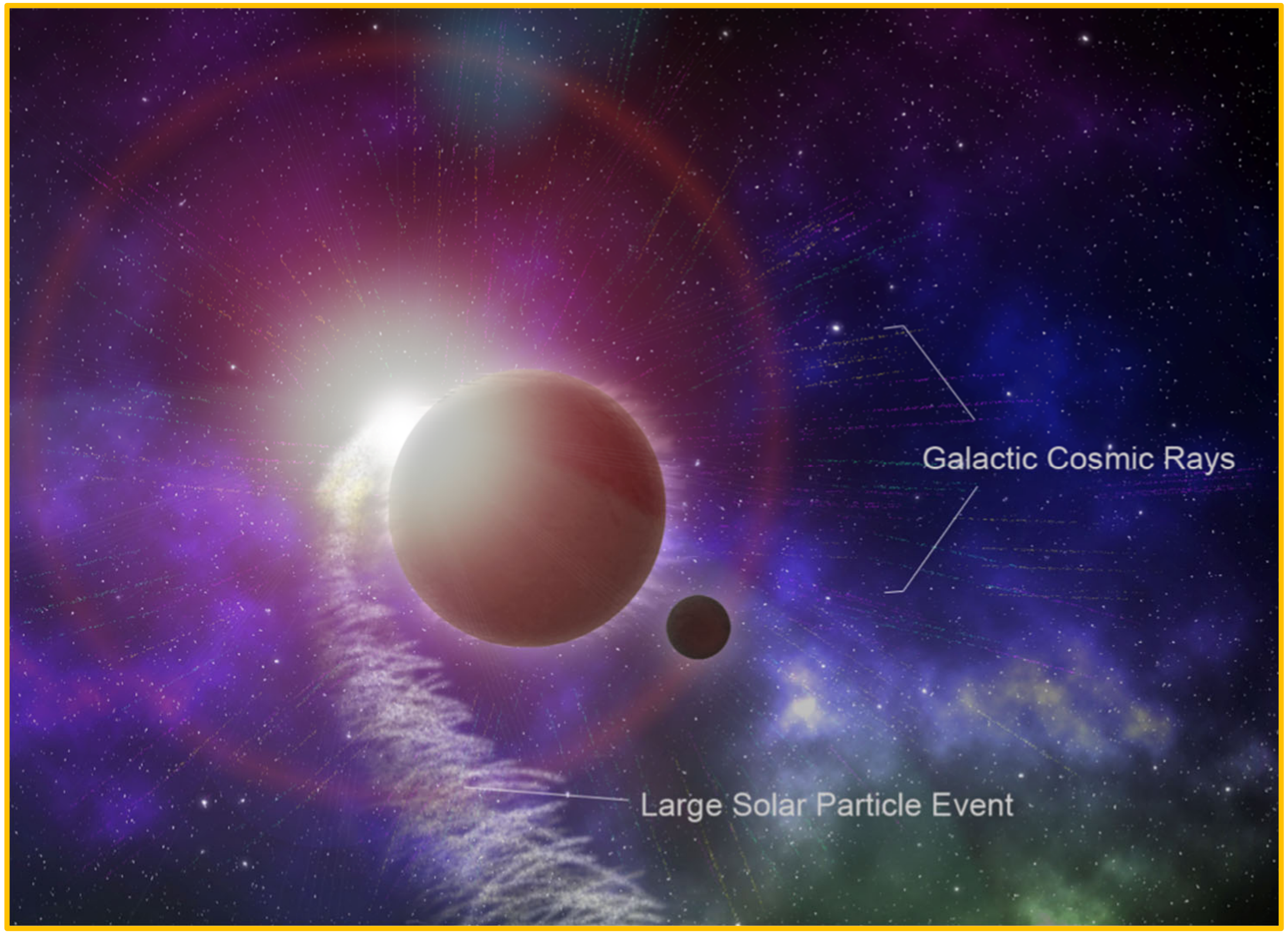
Solar particle events





- Injection of charged particles originating from:
  - solar flares
  - fast coronal mass ejections
- Particle energies from few MeV/u to tens of GeV/u
- They last from 1 hour to several days
- Flux can be high enough to kill a man if directly exposed (SPE 1972)
- Their occurrence is related to the sun spot (solar activity) but they are unpredictable

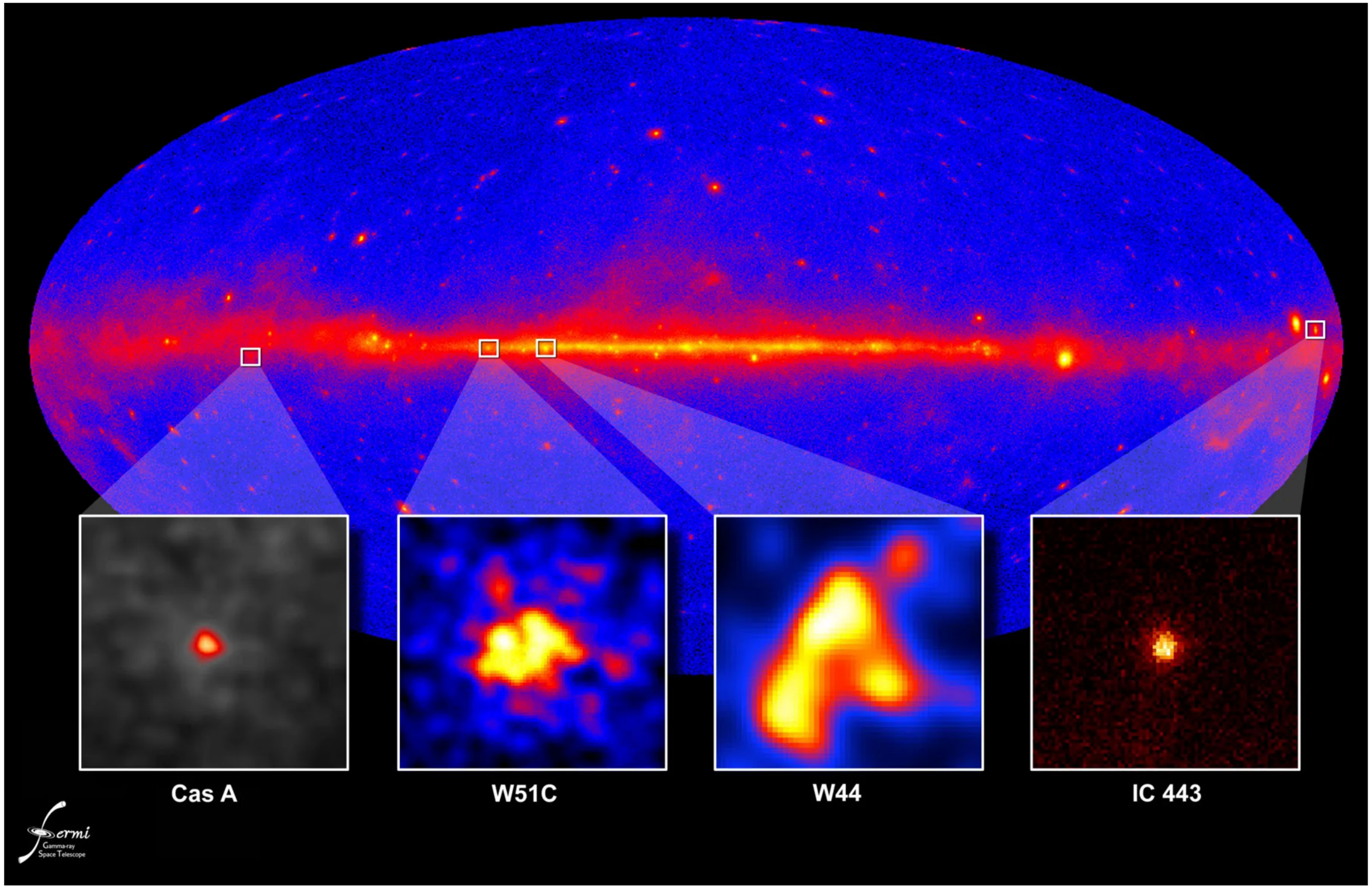
Galactic cosmic rays



SuperNova events
Stellar collapses
Gamma ray bursts
…

Constant production outside the solar system

Gamma rays with E>1 GeV

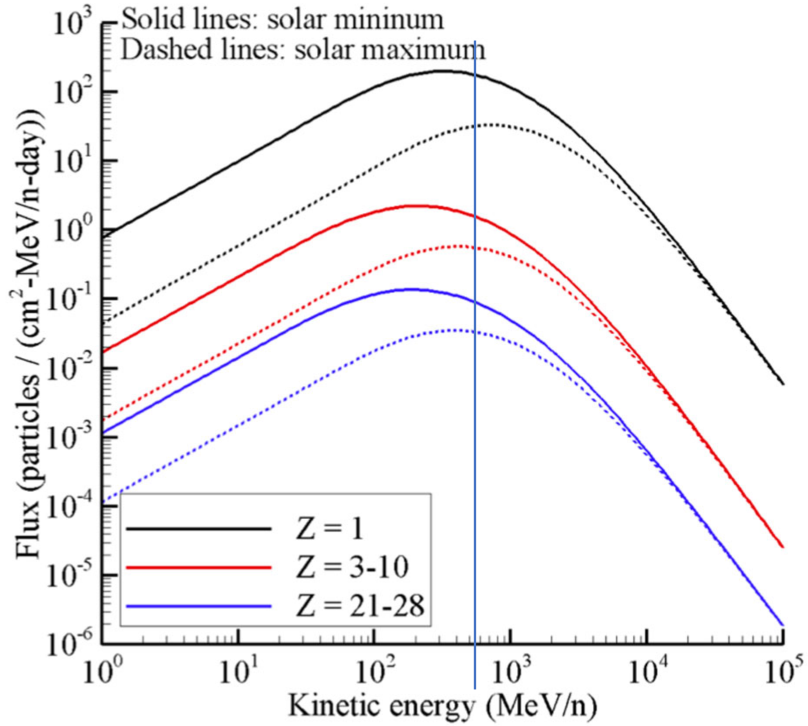


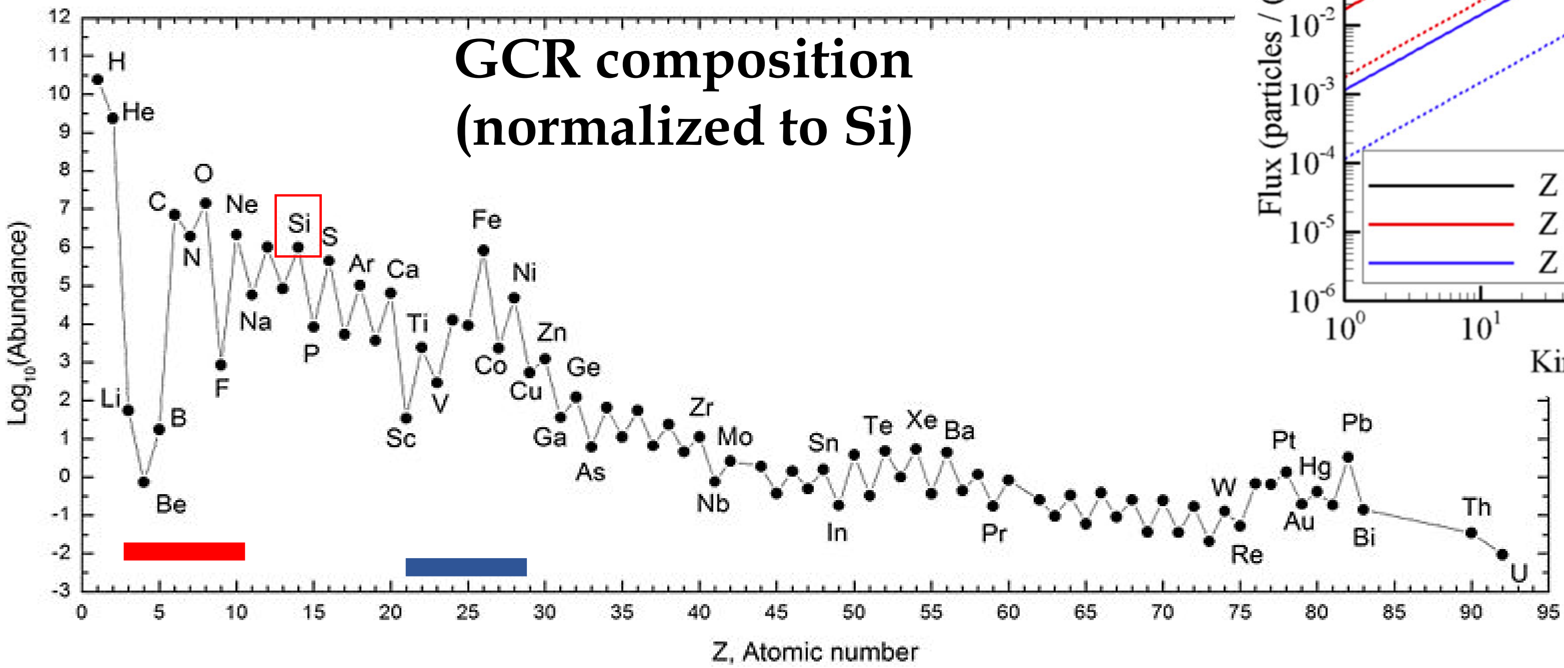
High resolution high energy gamma rays from FERMI

Supernova remnants

Galactic Cosmic Ray composition (GCR)

- Broad spectrum of particles (most of the periodic table) and energies (from keV to TeV)
- Exposures differ by approximately a factor of 2 between nominal solar extremes

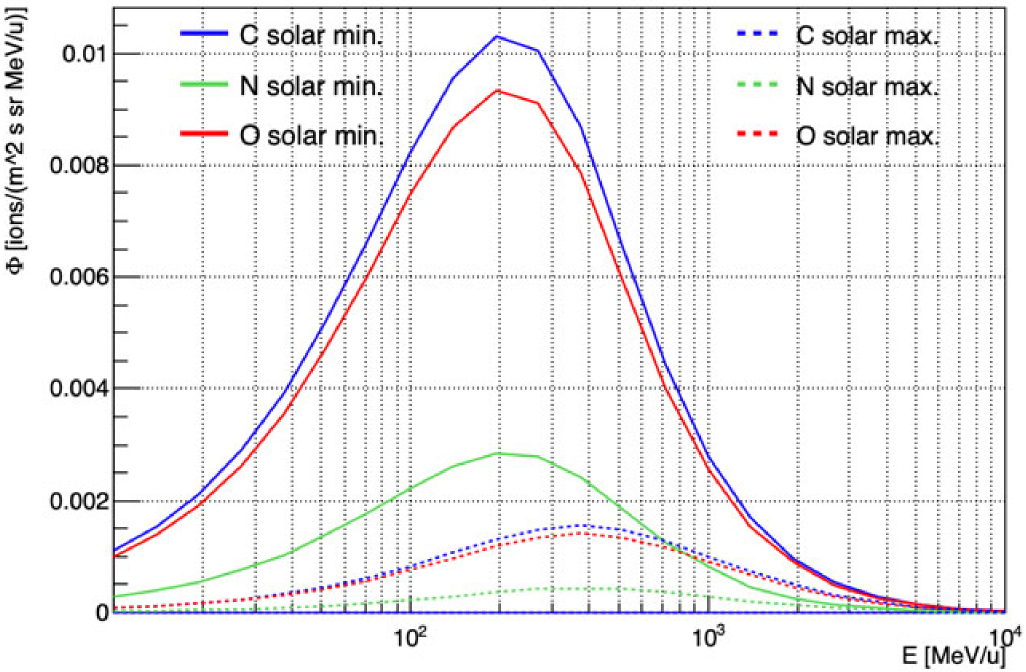




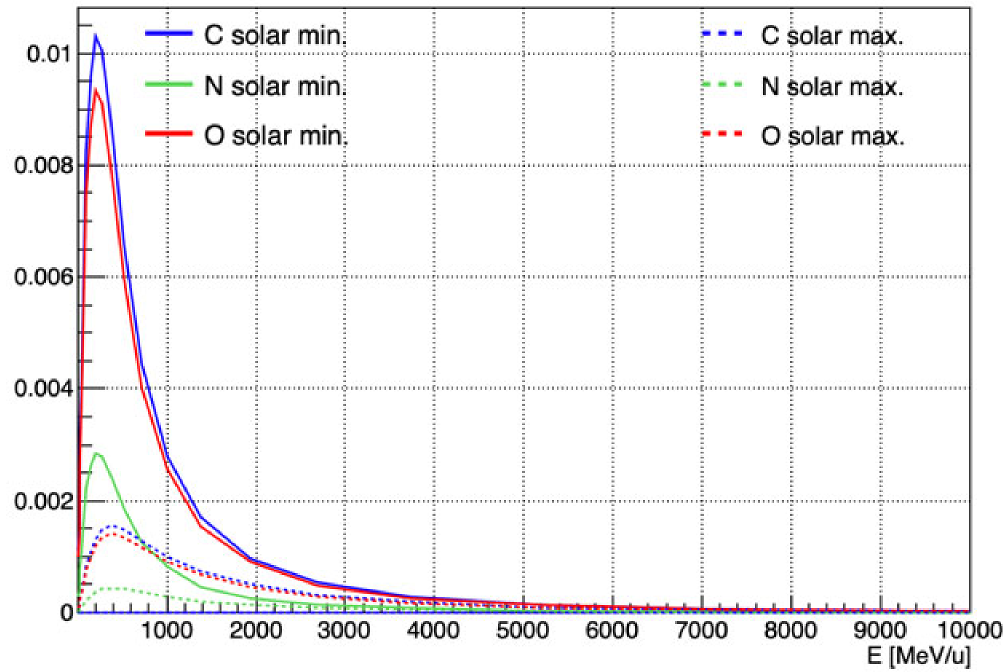
Example for C,N,O spectra

No geomagnetic cut-off
(i.e. far from earth)

Lin-Log scale



Lin-Lin scale



Notice for example that peak energy for C,O moves from ~300 MeV/u at solar min to ~500 MeV/u at solar max

It is also evident that, from the point of view of radiation protection, solar max is a safer condition with respect to solar min as far as GCR are concerned

Quantify space radiation

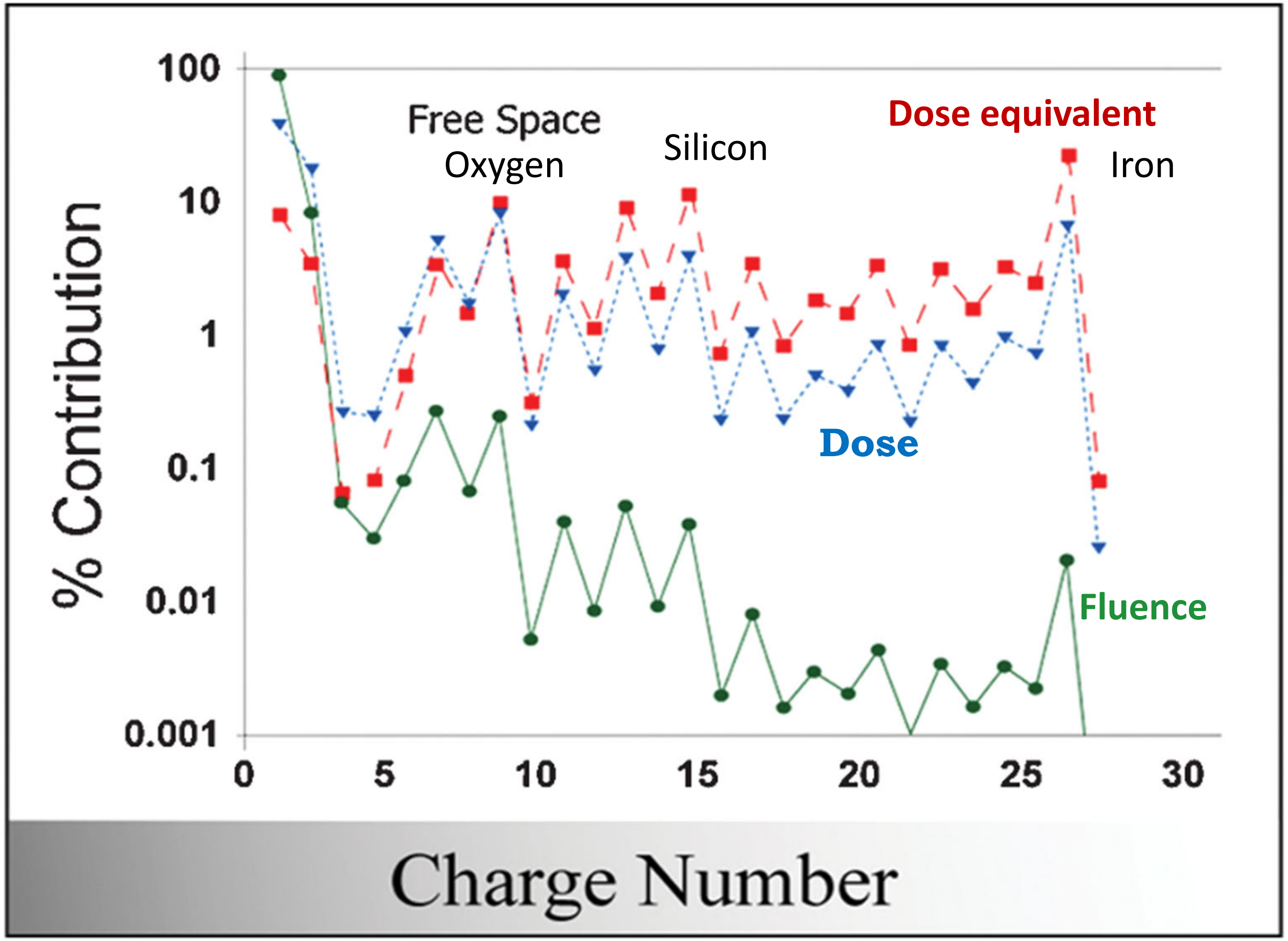
a) Fluence, abundance: Φ

b) Dose $D = \frac{dE_{abs}}{dm} \rightarrow$ in single layers $D = \frac{NdE}{dm} = \frac{dE}{dx}\frac{N\,dx}{\rho\,(Adx)} = S\frac{\Phi}{\rho}$

c) Dose equivalent $H = D \times W_R \times W_T$

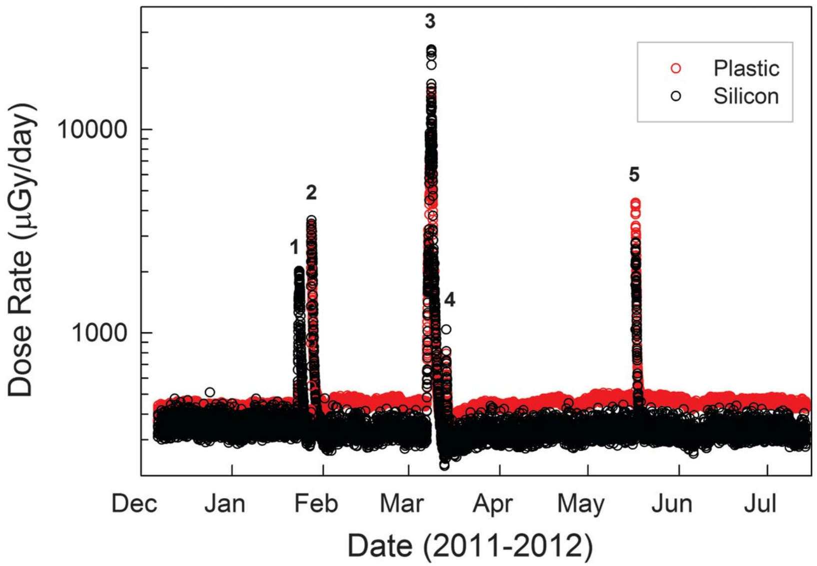
Radiation type	w_R
X and γ rays	1
Electrons and muons	1
Protons and charged pions	2
α particles and heavy ions	20
Neutrons	2–20 (see Fig. 2)
Organ	w_T
Breast, bone marrow, lung, colon, stomach	0.12
Gonads	0.08
Bladder, liver, esophagus, thyroid	0.04
Bone surface, brain, salivary glands, skin	0.01
Remainder	0.12

Quantify space radiation



To the dose equivalent,
high Z, low fluence ions
can be as important
as low Z ions with high fluence

Mars mission: doses



Dose equivalent recorded dayly by Curiosity during travel: 1.84 mSv/d, and on the surface: 0.64 mSv/d (Earth: 8 μSv/d)

Mars: NO magnetosphere and very thin atmosphere → no protection from GCR and SPE

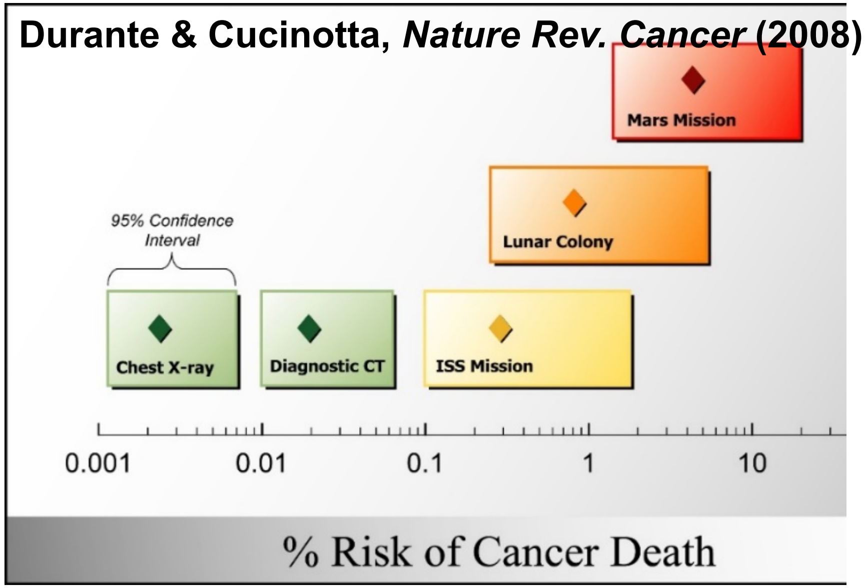
Radiation (measured by MSL):

- **Travel: 700 mSv/year**
- **On Mars: 240-300 mSv/year**

- **On earth: 1-6 mSv/year**

shielding is needed both during flight and on Mars!

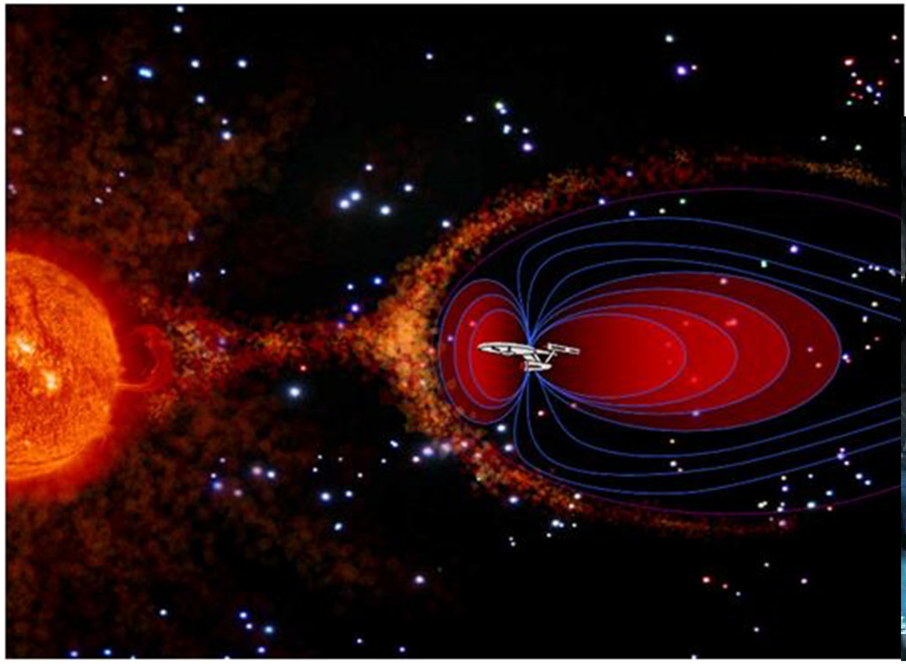
>1 Sv expected for the whole mars mission



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

Countermeasures

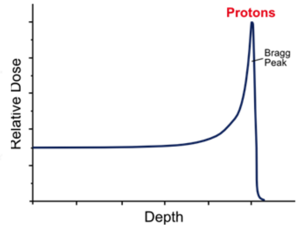
- Passive shielding
- Active shielding
- Biology-based approaches



Passive contermeasure: Shielding material selection

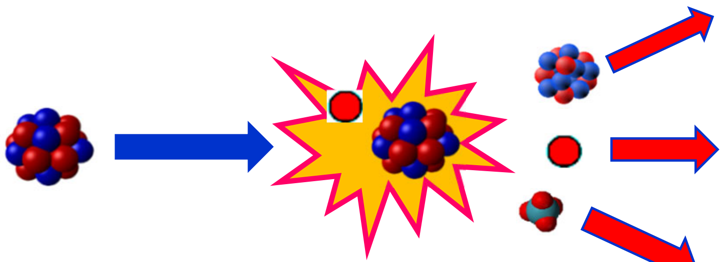
Electromagnetic interactions

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



Slow down and stopping

Nuclear fragmentation



Isotope- and charge-changing

Liquid H_2

Plastic (PE)

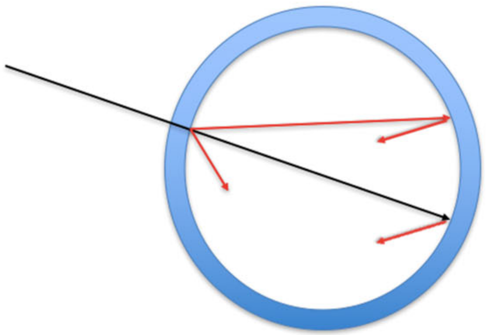
Water

Aluminum

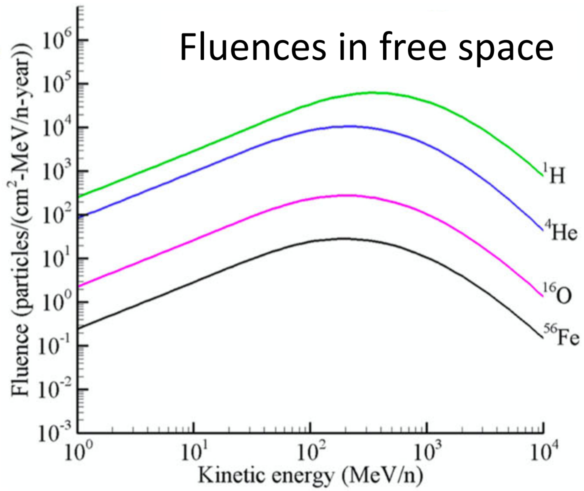
Concrete

Lead

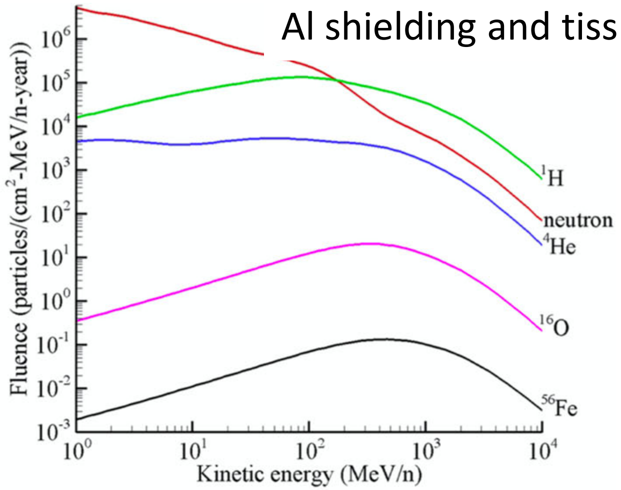
Shielding in deep space

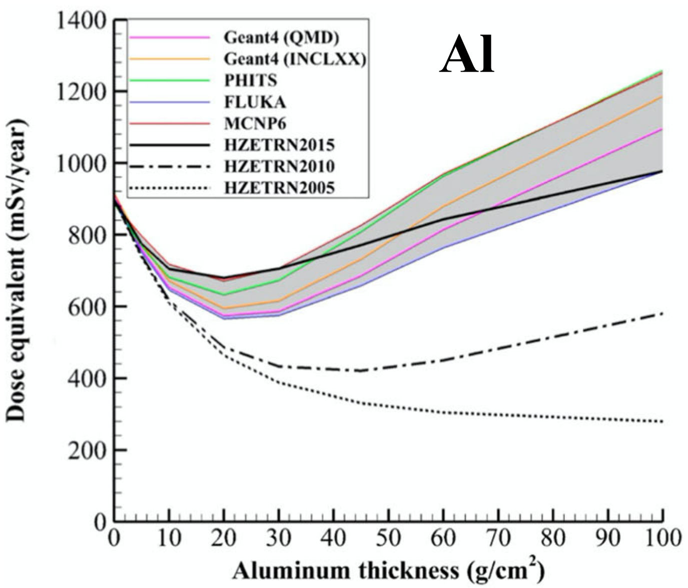


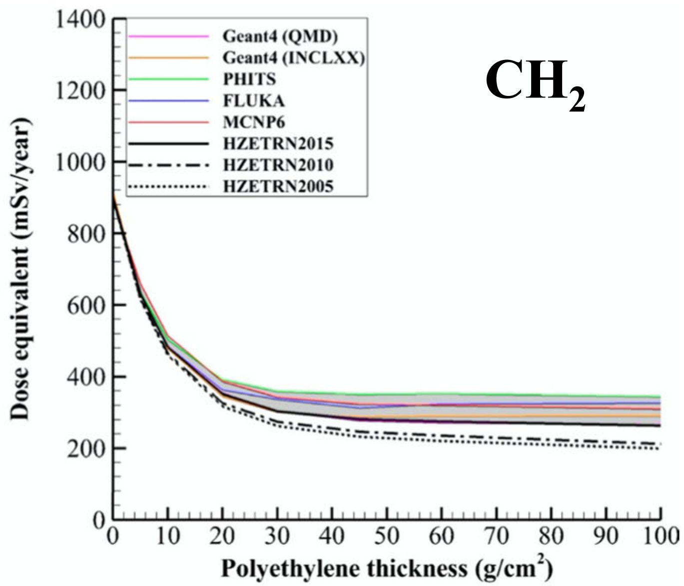
Fluences in free space



Fluences behind 20 g/cm^2 Al shielding and tissues



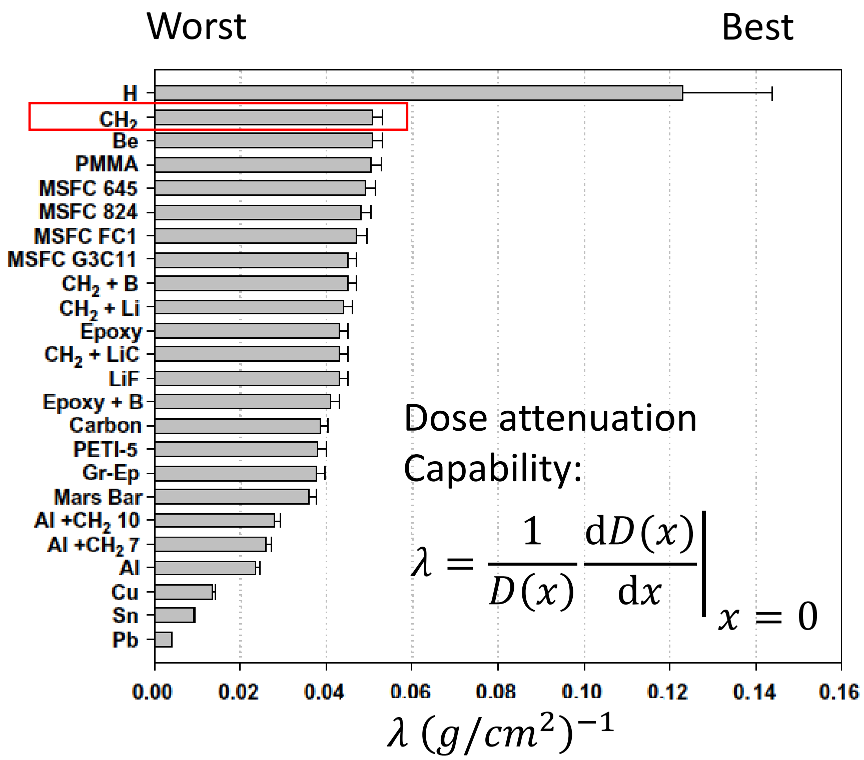




Transport codes indicate that the strategy of “the more the better” does not always work in space.

Material effectiveness as shielding

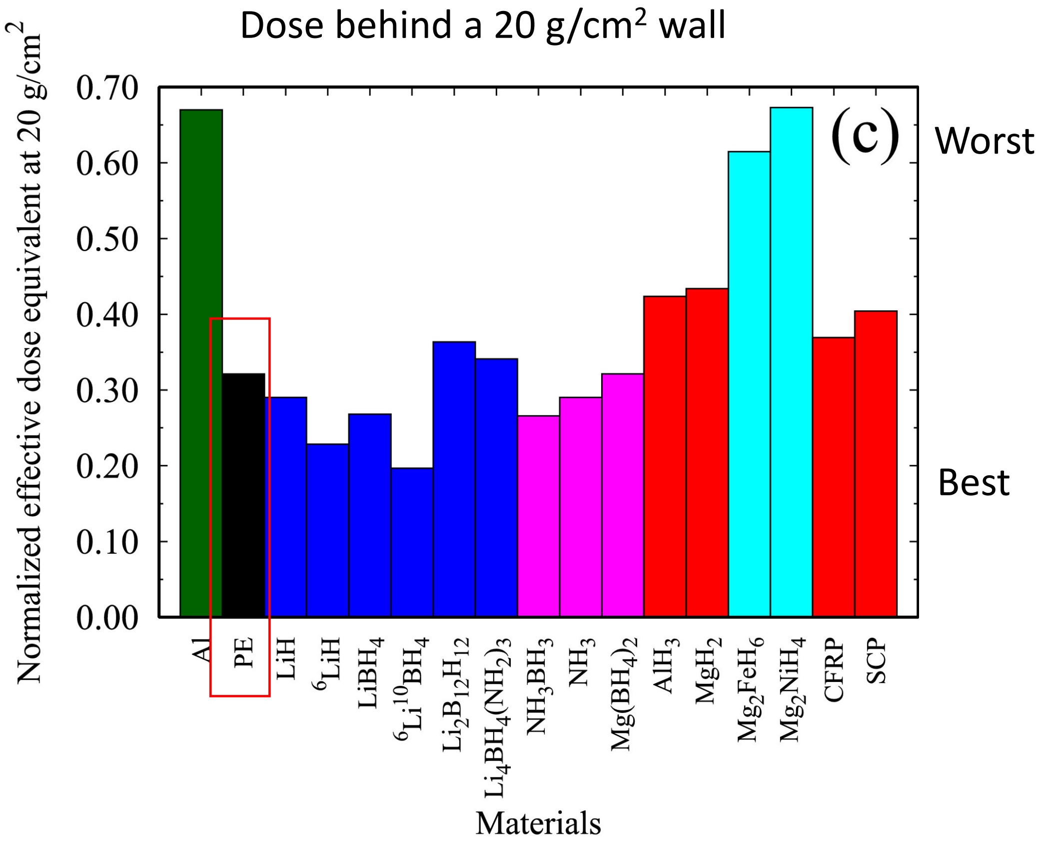
1 GeV/u ^{56}Fe as proxy of GCR



Dose attenuation Capability:

$$\lambda = \frac{1}{D(x)} \frac{\mathrm{d}D(x)}{\mathrm{d}x}\bigg|_{x=0}$$

$x = \rho\, \Delta L$ in g/cm^2



Composite GCR contribution and Exposure limits for astronauts

Expected effective dose (total body) for a mission to Mars of 650 days (Ramos et al 2023 Int J Mol Sci)

Solar Min

Al Thickness (g/cm^2)	Equivalent Dose (mSv)
0	986.7
0.3	904.5
1	812.1
2	770.4
5	729.0
10	681.6
20	708.5

Solar Max

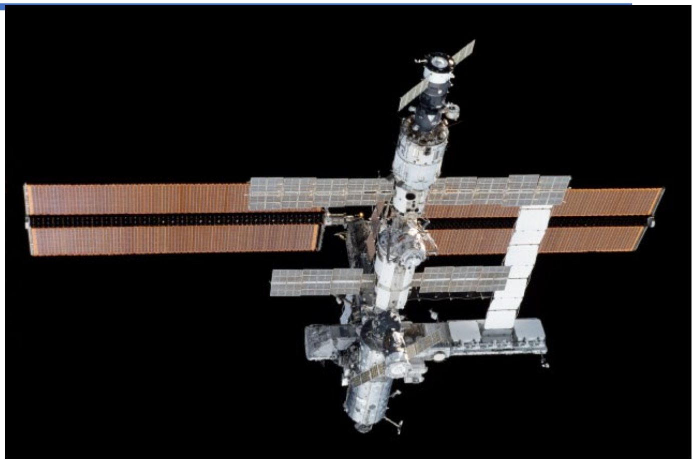
Al Thickness (g/cm^2)	Equivalent Dose (mSv)
0	240.9
0.3	249.2
1	279.5
2	319.6
5	254.1
10	227.6
20	266.4

Limits for the whole career

ESA/RSA: 1 Sv
NASA: 0.6 Sv (!)
JAXA: 0.5-1 Sv
age- and sex-dependent

This is one of the main reasons why there are efforts to try to go back on the Moon at the end of 2025 and to go to Mars in 2035: **Solar Max!!!**

Shielding on ISS



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

SPE countermeasures to be taken by astronauts

A ~fast warning of SPE is possible: ~ 1 hour in advance

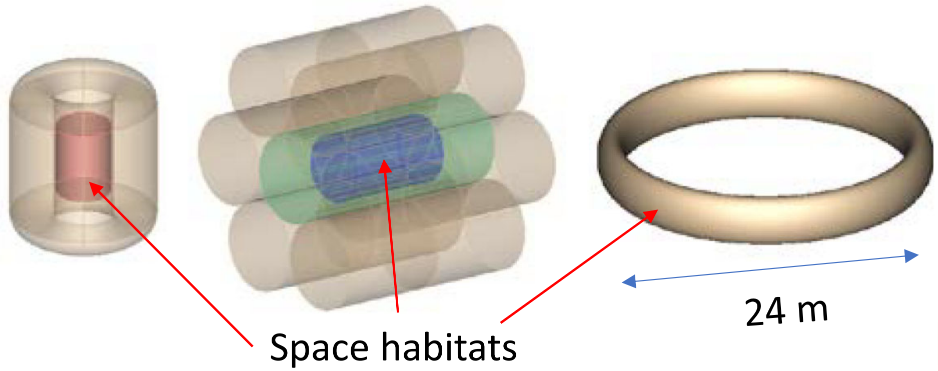
At present astronauts can take shelter under their baggages in the cargo bay

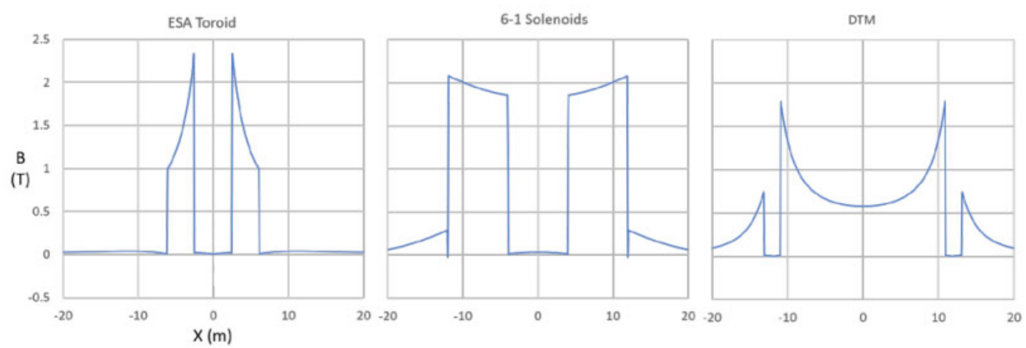
https://www.youtube.com/watch?v=70GrihLXmSs

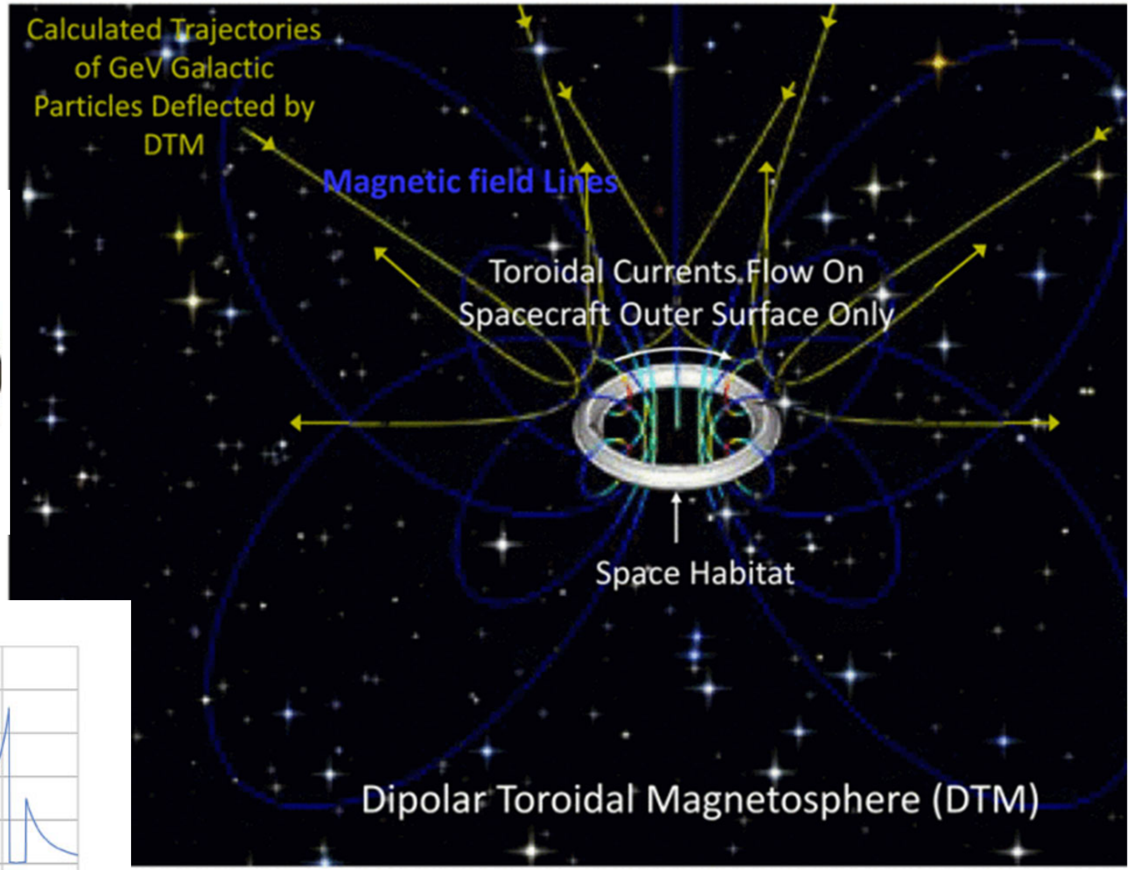
Active shielding: a ship magnetosphere

An intense magnetic field can deviate the charged particles also in space → solutions with high B fields

Toroidal field; conceptual solutions:

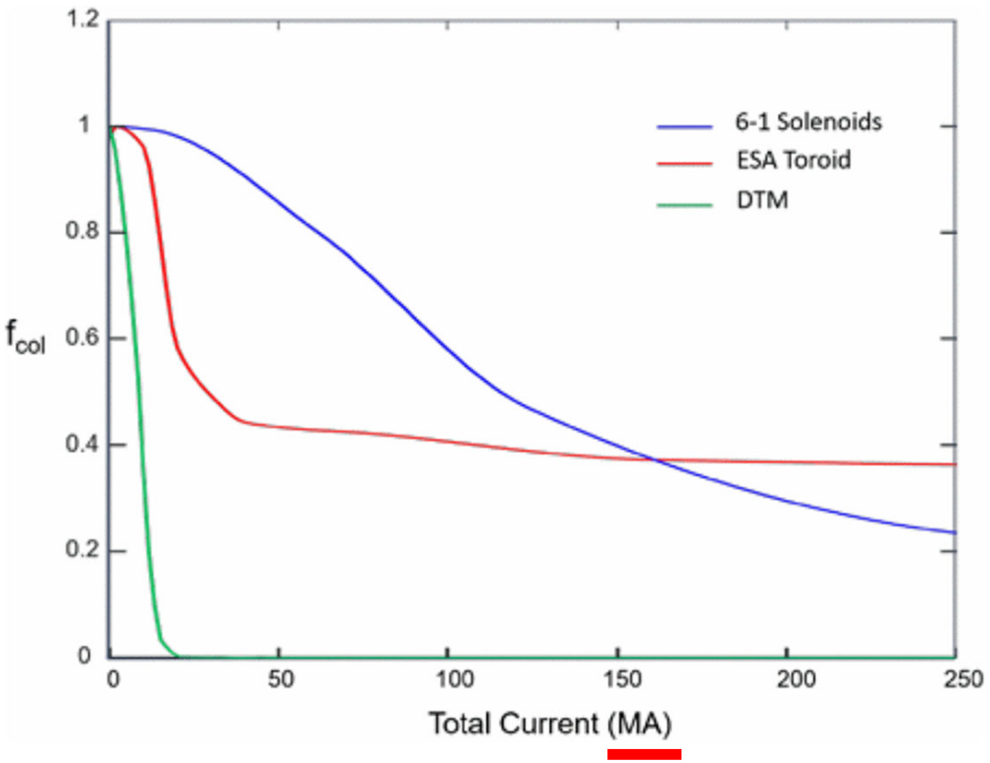






Magnetosphere effect

Fraction of E=500 MeV protons reaching habitat



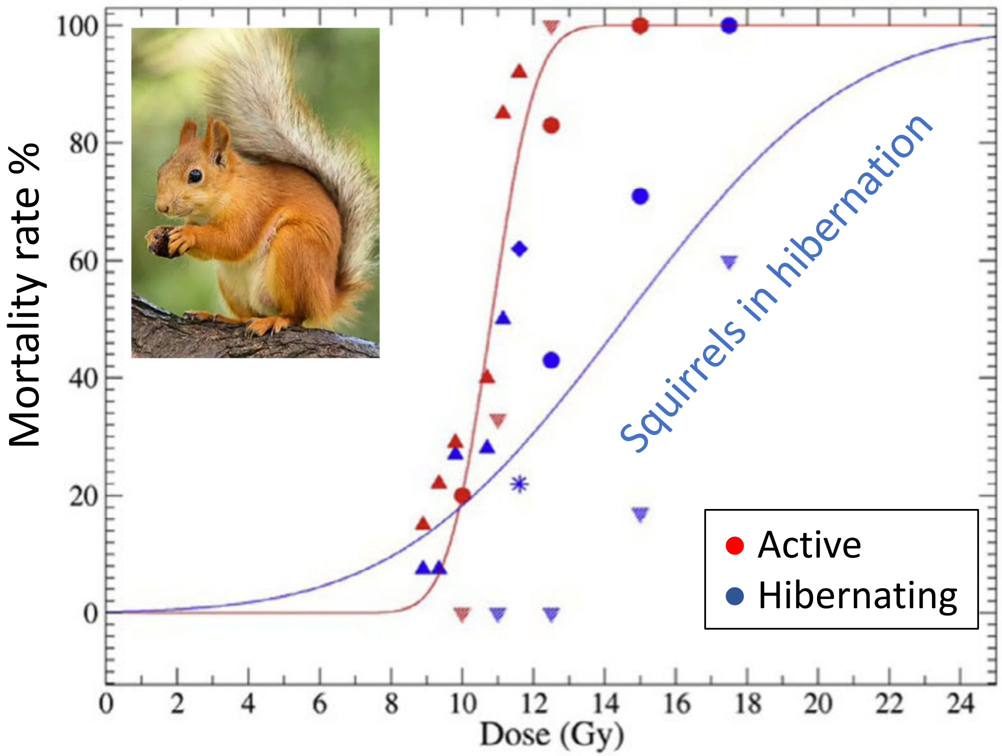
Effective for limited region of space (5m diam)
B up to 1.5 T

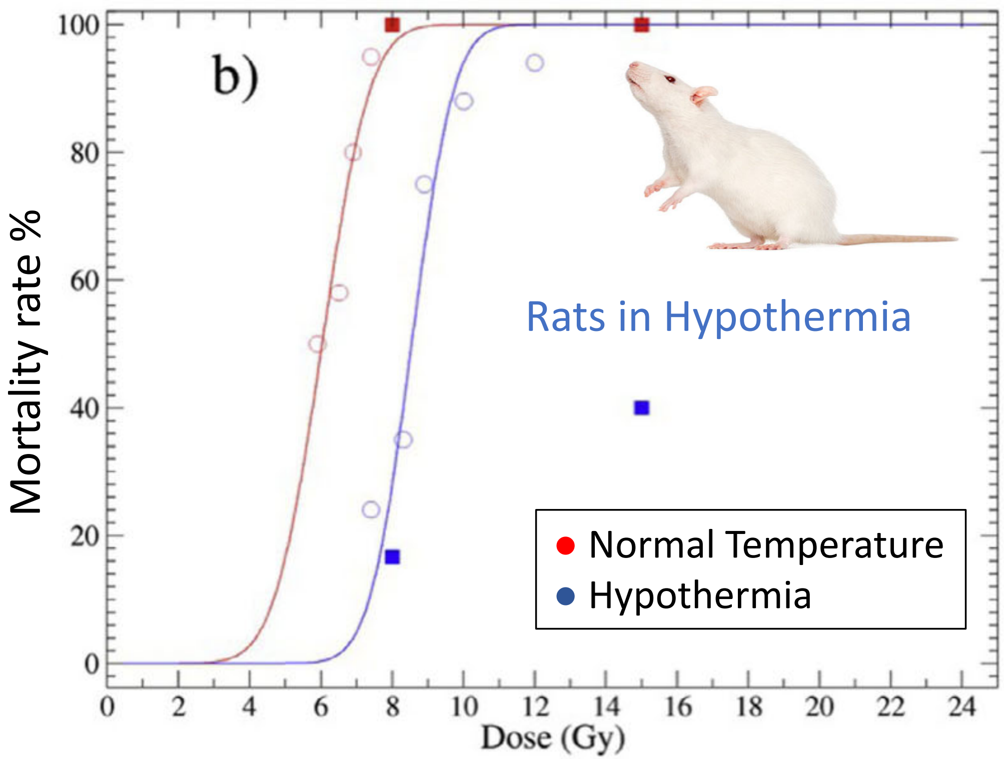
Concerns on the weight and power

Unlikely it will be
a proper solution
for the moment

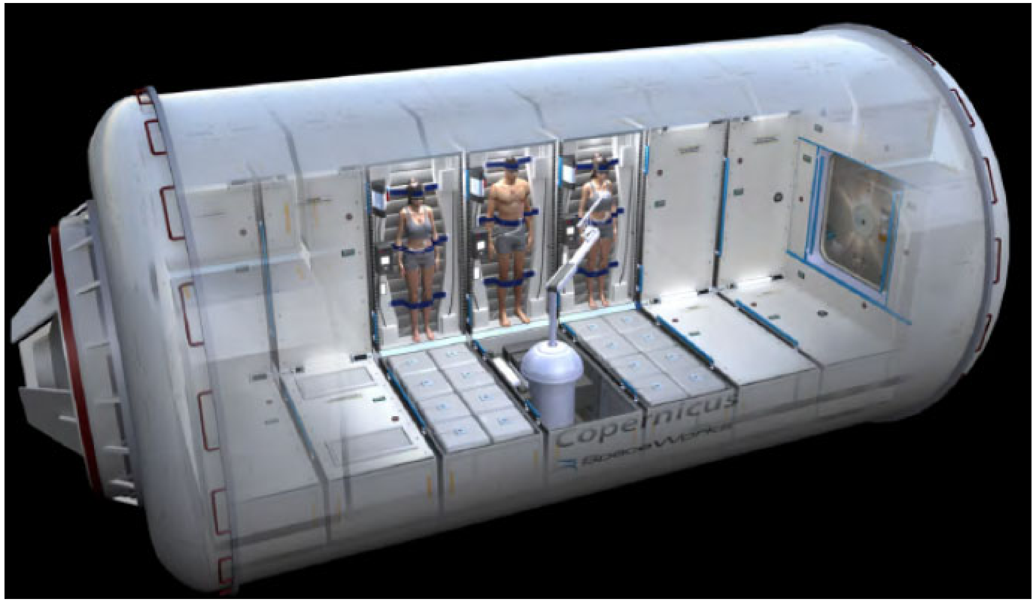
Biology-based approach: hibernation & hypothermia

Reducing the methabolic activity increases the radiation resistance





It’s not Science fiction!



- https://www.nasa.gov/general/torpor-inducing-transfer-habitat-for-human-stasis-to-mars-2/
- https://www.nasa.gov/general/advancing-torpor-inducing-transfer-habitats-for-human-stasis-to-mars/

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Life Sciences in Space Research

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Review Article

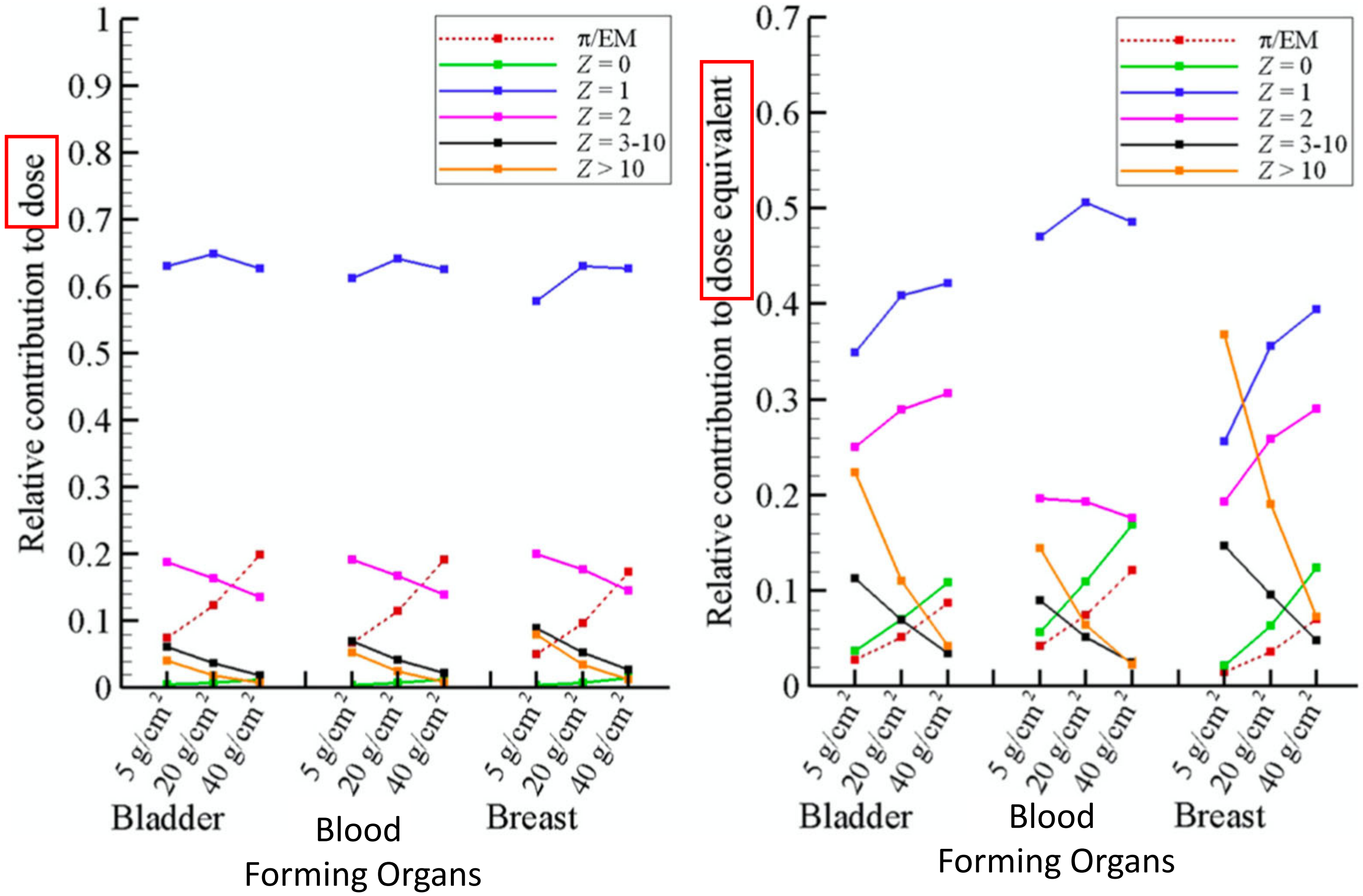
Hibernation for space travel: Impact on radioprotection

CrossMark

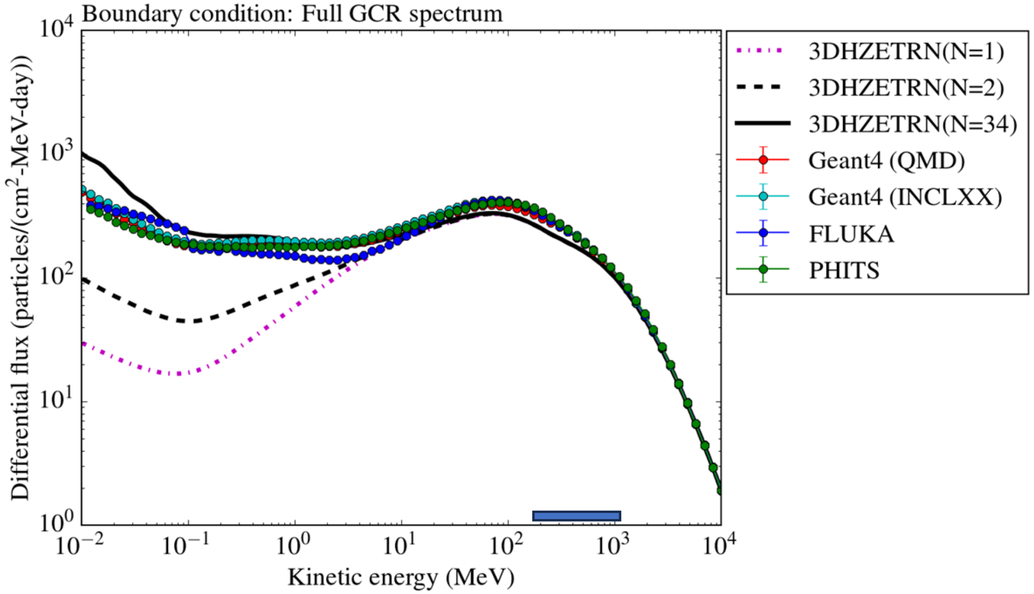
Matteo Cerri [a,b], Walter Tinganelli [c], Matteo Negrini [b], Alexander Helm [c], Emanuele Scifoni [c], Francesco Tommasino [c,d], Maximiliano Sioli [b,e], Antonio Zoccoli [b,e], Marco Durante [c,*]

Nuclear uncertainties in light ions production

Because of nuclear fragmentation, light ions (H and He isotopes) dominate the contribution to both the dose and dose equivalent. To validate MC predictions, measurements of production cross sections for these isotopes are necessary.



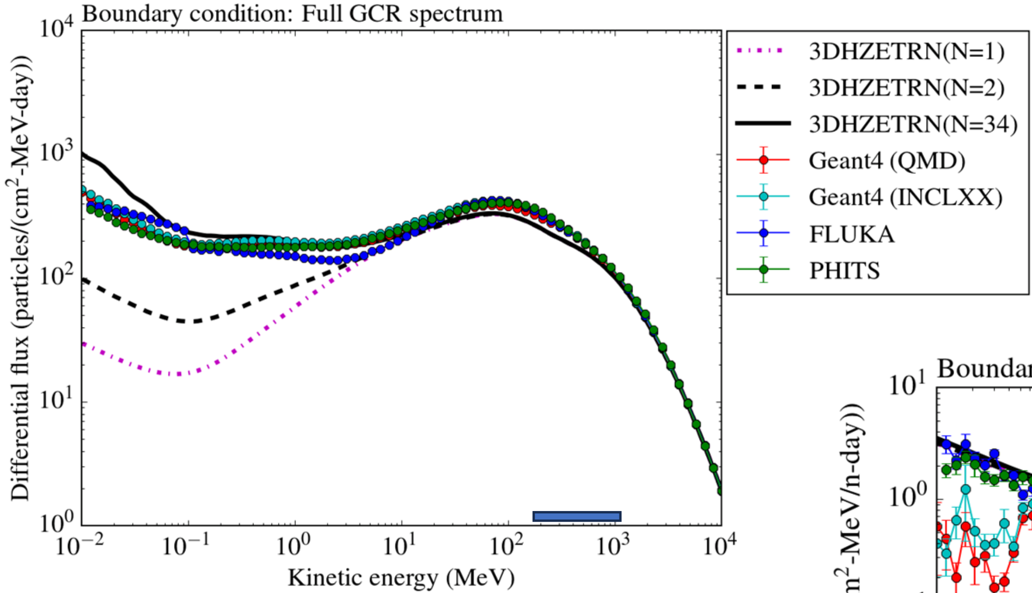
What codes predict light ions production



Protons

GCR spectrum interacting with 20 g cm^{-2} Al shielding

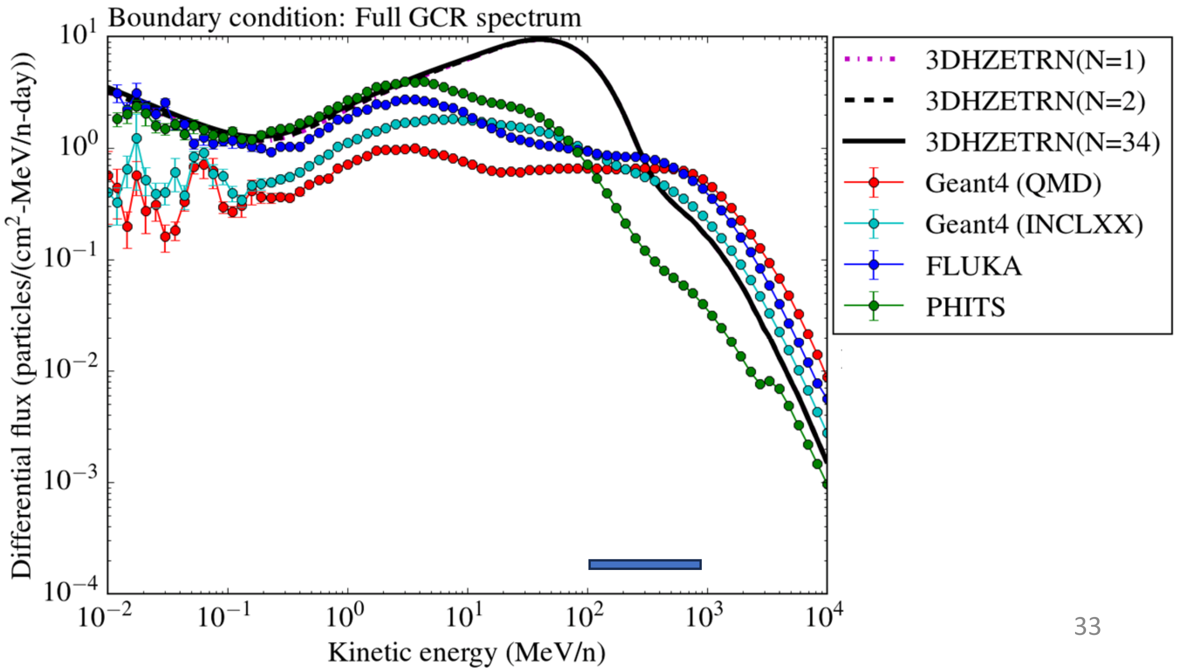
What codes predict light ions production



Protons

GCR spectrum interacting with 20 g cm^{-2} Al shielding

^{4}He (d, t, ^{3}He)

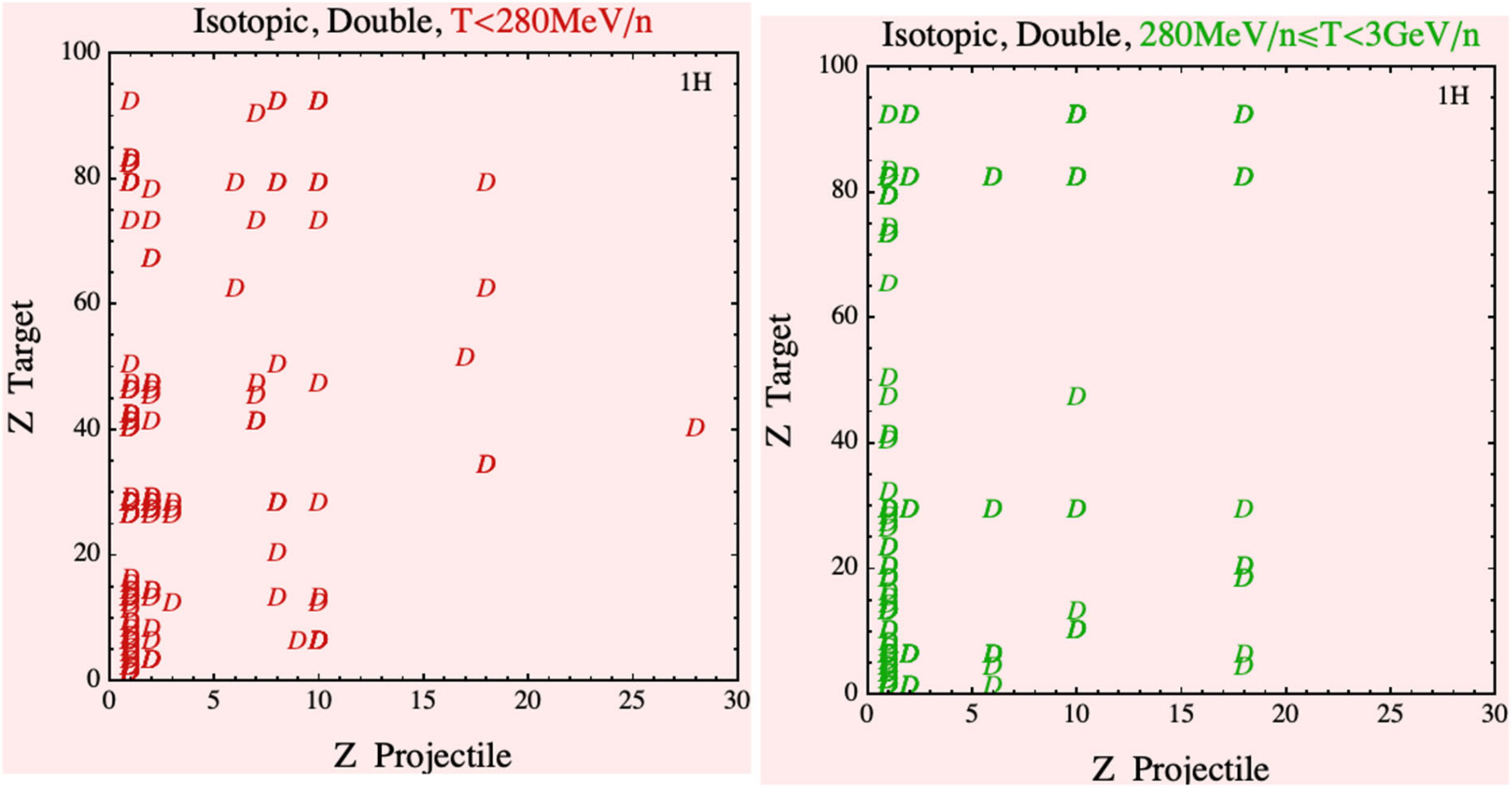


Why this great variability ??

Existing experimental data for double-differential fragmentation cross sections $\frac{d^2\sigma}{dEd\Omega}$

^{1}H

$\frac{d^2\sigma}{dEd\Omega}$

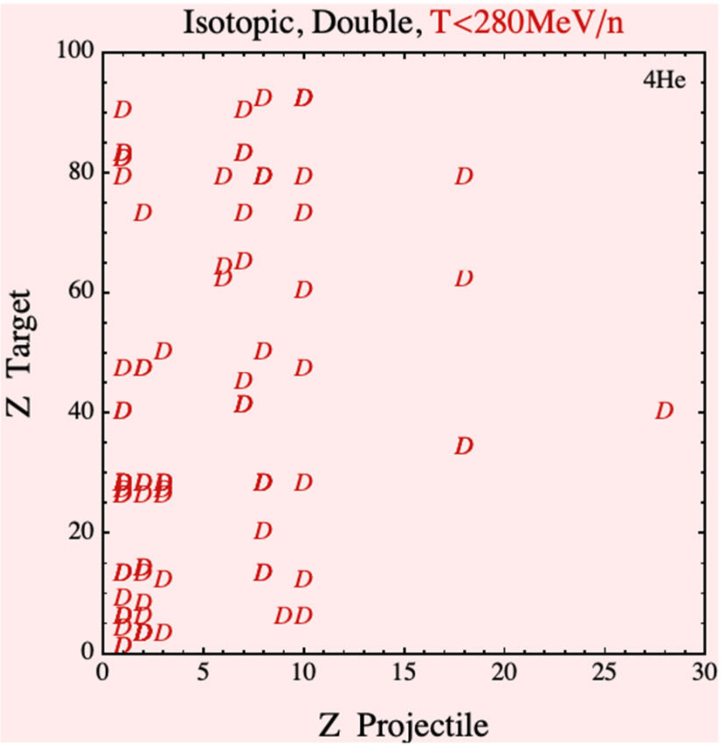


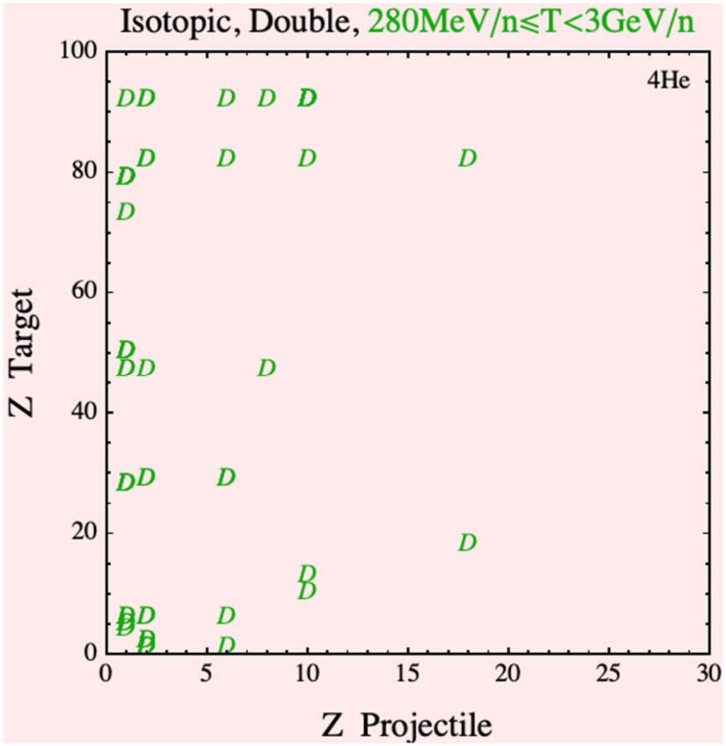
Full list available at Norbury et al. Rad. Meas. 47 (2012)

Existing experimental data for double-differential fragmentation cross sections $\frac{d^2\sigma}{dEd\Omega}$

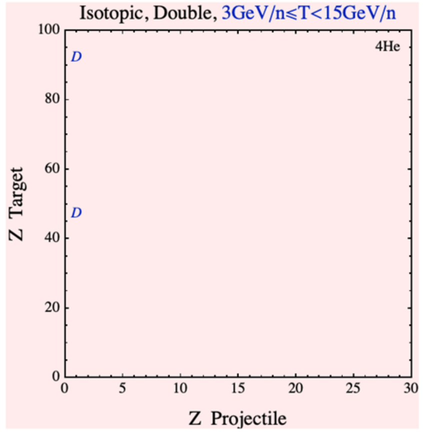
^{4}He

$\frac{d^2\sigma}{dEd\Omega}$





3 < T < 15 GeV/n



Full list available at Norbury et al. Rad. Meas. 47 (2012)

A quest for more

frontiers in Physics

REVIEW
published: 30 November 2020
doi: 10.3389/fphy.2020.565954

Are Further Cross Section Measurements Necessary for Space Radiation Protection or Ion Therapy Applications? Helium Projectiles

John W. Norbury[1]*, *Giuseppe Battistoni*[2], *Judith Besuglow*[3,4], *Luca Bocchini*[5], *Daria Boscolo*[6], *Alexander Botvina*[7], *Martha Clowdsley*[1], *Wouter de Wet*[8], *Marco Durante*[6,9], *Martina Giraudo*[5], *Thomas Haberer*[10], *Lawrence Heilbronn*[11], *Felix Horst*[6], *Michael Krämer*[6], *Chiara La Tessa*[12,13], *Francesca Luoni*[6,9], *Andrea Mairani*[10], *Silvia Muraro*[2], *Ryan B. Norman*[1], *Vincenzo Patera*[14], *Giovanni Santin*[15,16], *Christoph Schuy*[6], *Lembit Sihver*[17,18], *Tony C. Slaba*[1], *Nikolai Sobolevsky*[7], *Albana Topi*[6], *Uli Weber*[6], *Charles M. Werneth*[1] and *Cary Zeitlin*[19]

[1]NASA Langley Research Center, Hampton, VA, United States, [2]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Milano, Milan, Italy, [3]German Cancer Research Center (DKFZ), Heidelberg, Germany, [4]University of Heidelberg, Heidelberg, Germany, [5]Thales Alenia Space, Torino, Italy, [6]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany, [7]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia, [8]University of New Hampshire, Durham, NH, United States, [9]Technische Universität Darmstadt, Darmstadt, Germany, [10]Heidelberg Ion Beam Therapy Center, Heidelberg, Germany, [11]University of Tennessee, Knoxville, TN, United States, [12]University of Trento, Trento, Italy, [13]Trento Institute for Fundamental Physics and Applications (INFN-TIFPA), Trento, Italy, [14]Universita' di Roma "Sapienza", Roma, Italy, [15]European Space Agency, Noordwijk, Netherlands, [16]RHEA System, Noordwijk, Netherlands, [17]Technische Universität Wien, Atominstitut, Vienna, Austria, [18]Chalmers University of Technology, Gothenburg, Sweden, [19]Leidos Innovations Corporation, Houston, TX, United States

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***Correspondence:**
John W. Norbury
john.w.norbury@nasa.gov

Specialty section:

There is space for contribution in this interesting field!

Summary

Facts:

- Radiation represent a main limitation to space exploration
- Nuclear processes (and in particular nuclear fragmentation) strongly influence the effect of radiation on biological tissues
- Deterministic and Monte Carlo codes can provide radiation risk assessment for all mission scenarios in space, but there is a huge gap in the isotopic fragmentation cross sections (especially for light ions)

Take home messages:

- **Manned space explorations are cool but very risky**
- **Double differential fragmentation cross sections (especially for light ions) play a key role in improving the existing theoretical models and in providing measurements for validating and benchmarking them**
- **Your researches can make the difference!**

Thanks for the attention

Credits for slides, images and data

R. Spighi, M. Franchini, V. Patera, A. Sarti, G. Bisogni, G. Battistoni, M. Pullia, M. Necchi, S. Rossi, A. Pella, M. Colonna, S. Lorentini, and many others!

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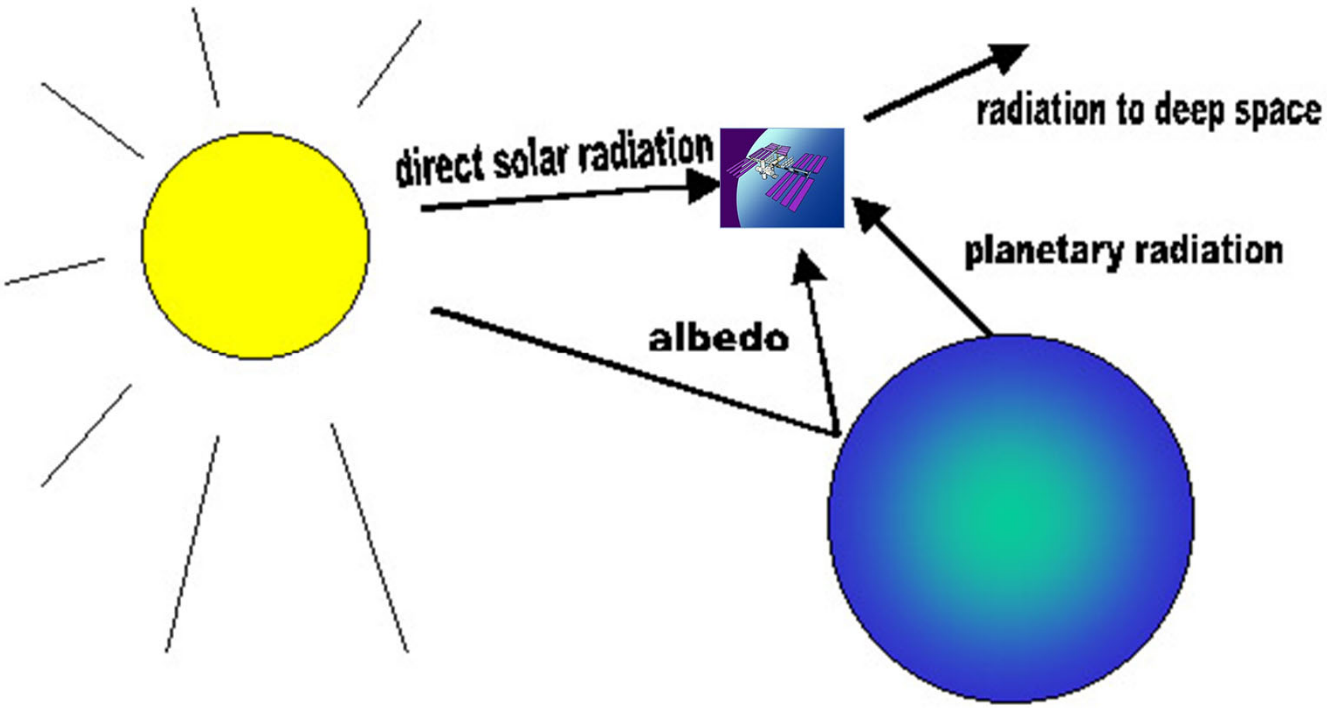
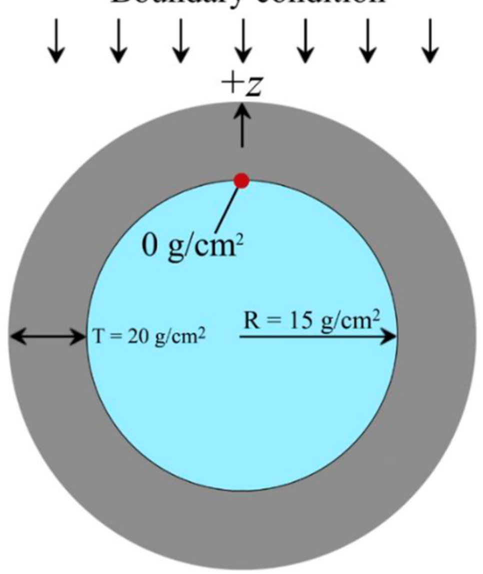
Albedo radiation

Particles (especially protons and neutrons) produced from the interaction of GCR with atmosphere



Comparison between state-of-the-art codes

Differences in nuclear interaction models still present and highlights need for further model development and experimental measurements



Tissue sphere with radius 15 g/cm^2 surrounded by 20 g/cm^2 of aluminum