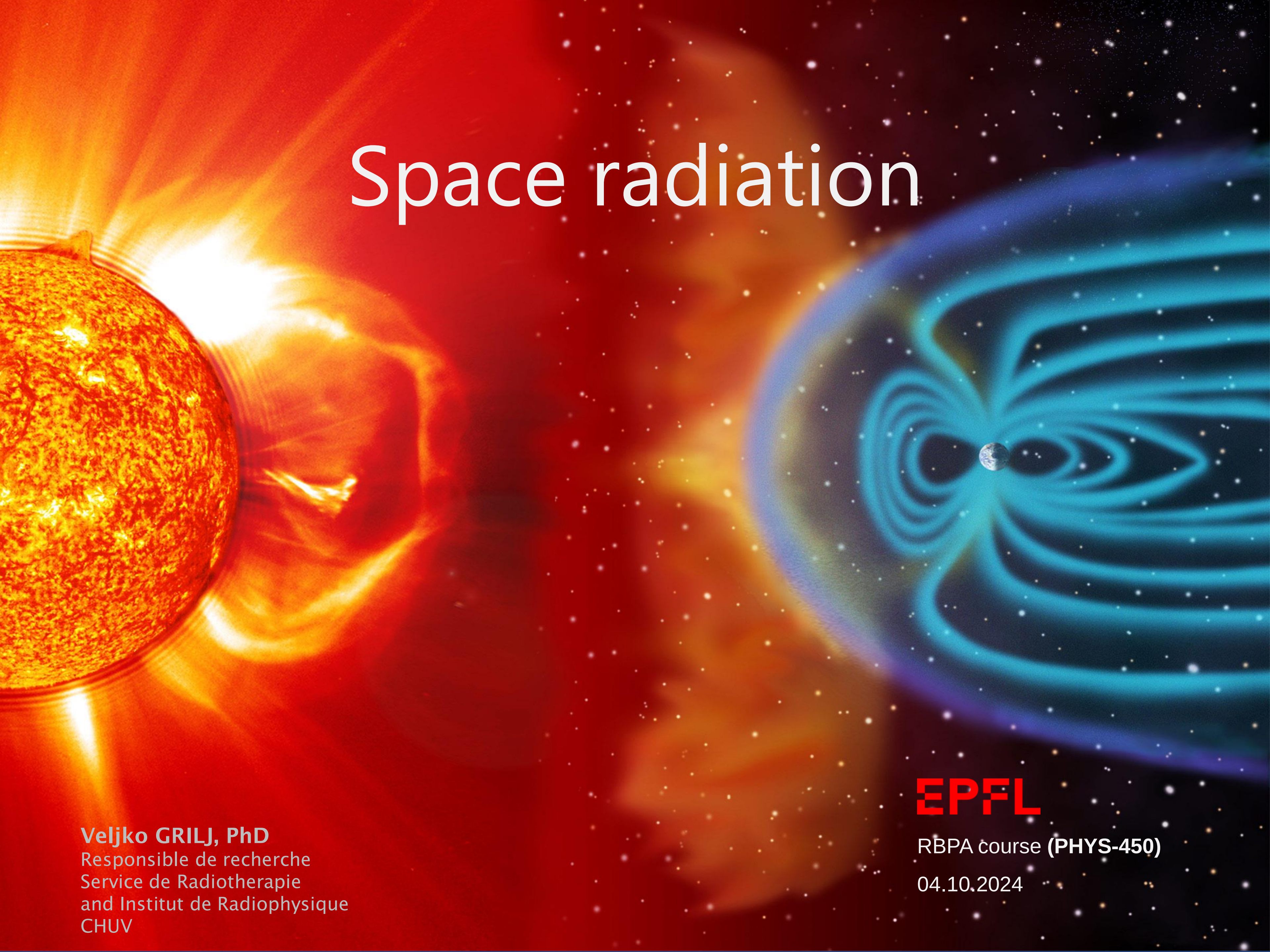

Space radiation

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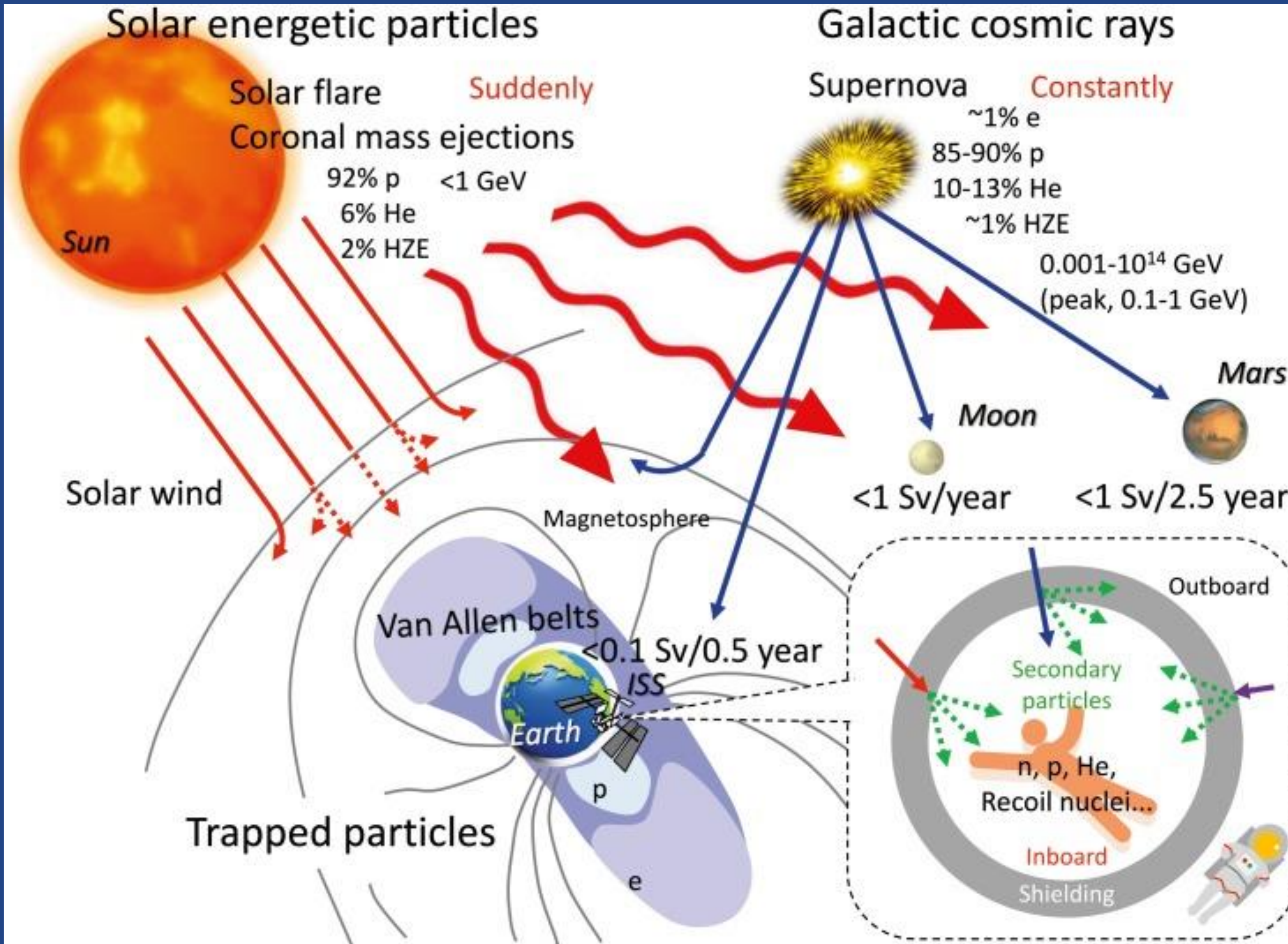
CHUV

EPFL

RBPA course **(PHYS-450)**

04.10.2024

Overview of Lecture 4



Cosmic Rays

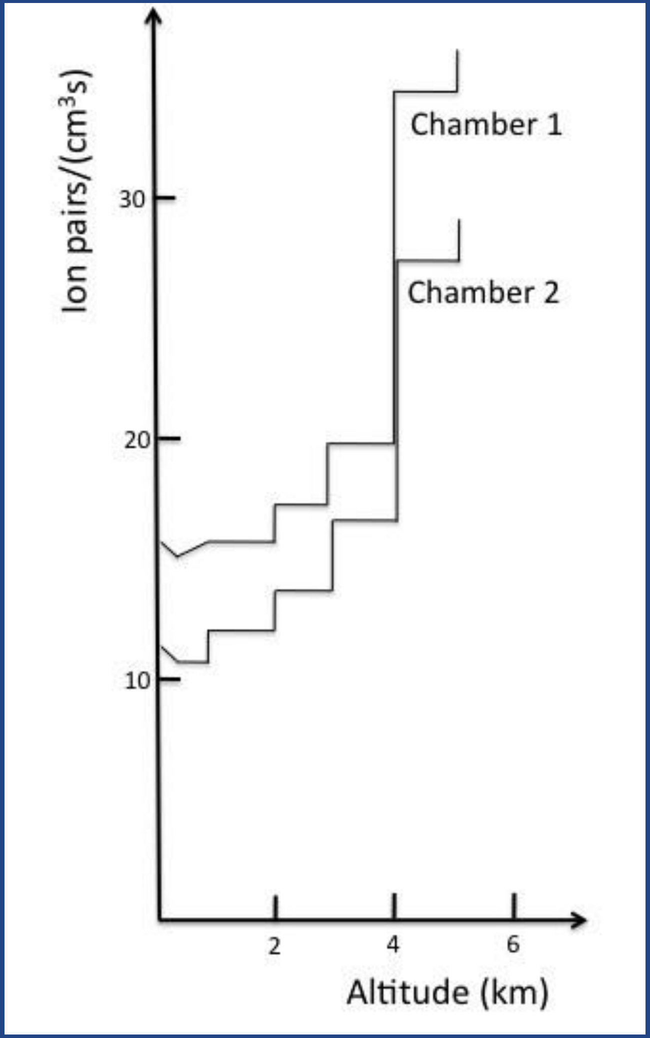
Discovery of Cosmic Rays

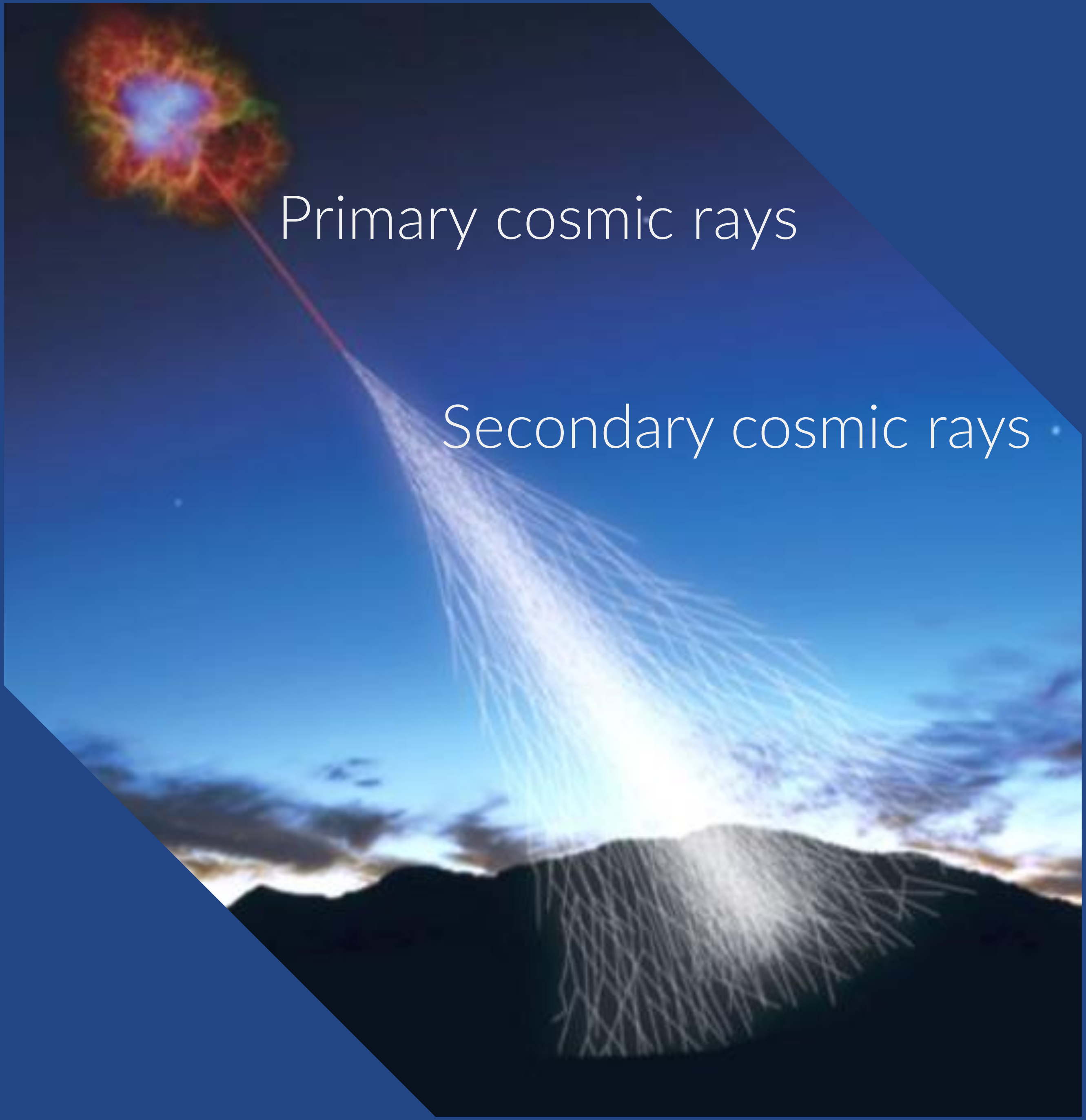
- One of the great puzzles at the turn of the 19^{th} century was spontaneous discharge of charged electroscope plates
- It was assumed that the origin of this were radioactive elements in Earth's crust

- Thedore Wulf measured the intensity of radiation at the top of the Eiffel tower (300m), it was about a half of that on the Earth surface
- According to calculations, at 300m above Erath the intensity of radiation should be only a few percent of that at the surface
- He concluded that there is radiation coming from above

Discovery of Cosmic Rays

- Discovered in 1912 by Victor Hess during a balloon flight
- 4 times higher ionization rate at an attitude of 5300 m



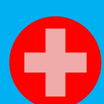

Primary cosmic rays
Secondary cosmic rays

What are primary Cosmic Rays composed of?

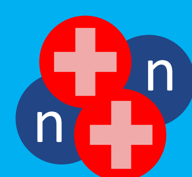
- Primary/galactic cosmic rays (GCR) are high energy charged particles that propagate through the Universe

Composition:

90% protons



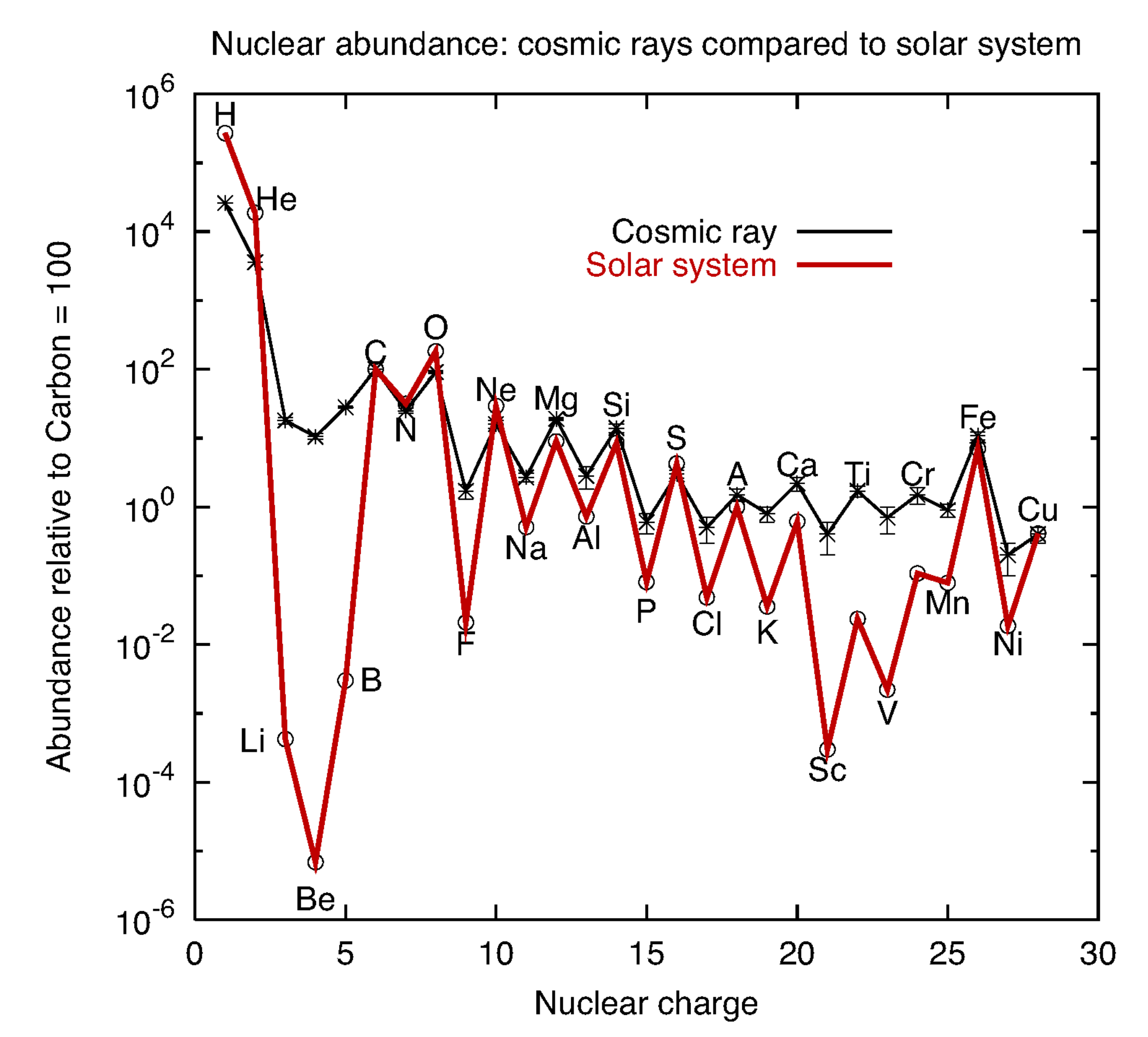
9% helium



1% other

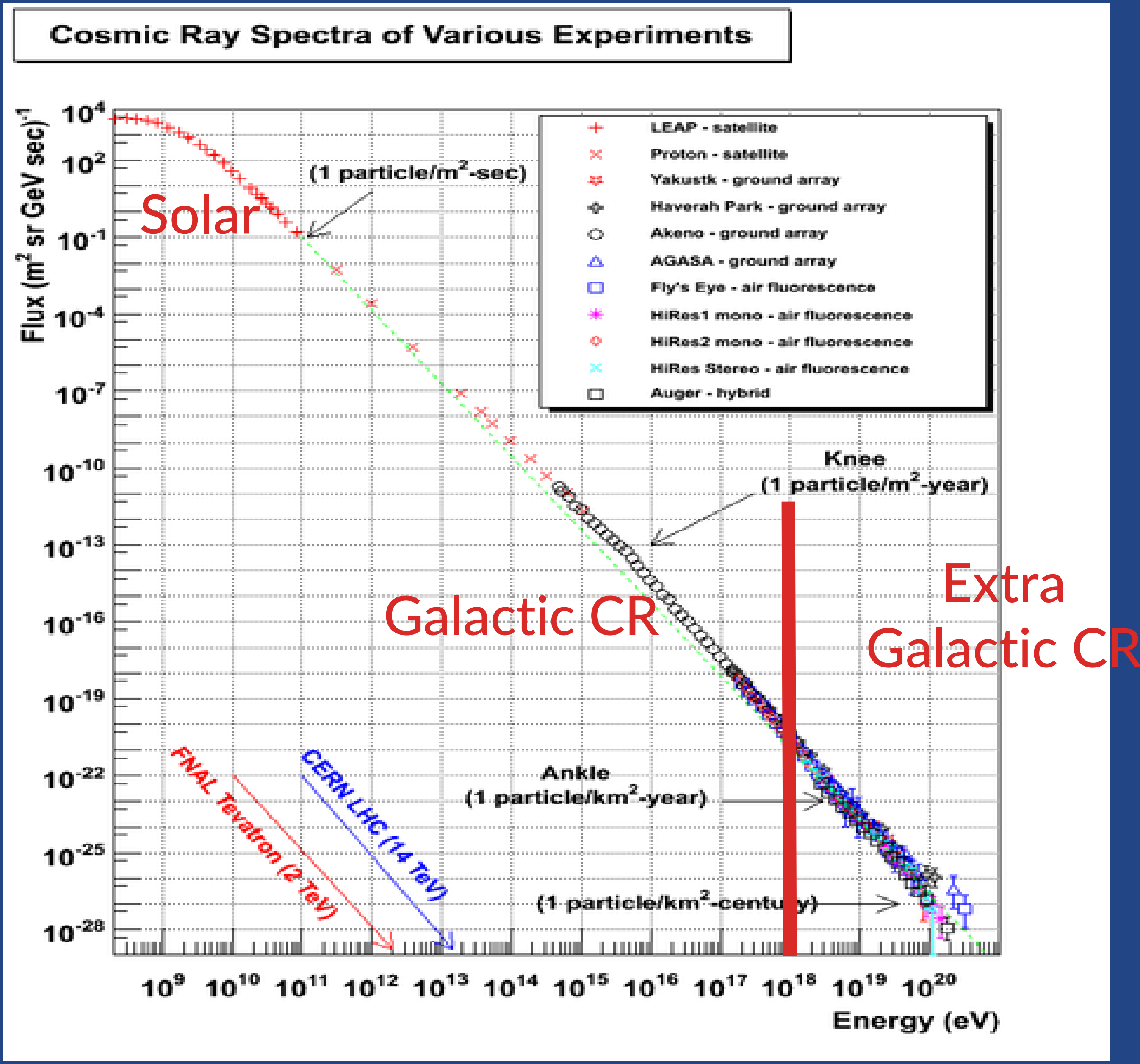
Electrons
Neutrons
Heavy atoms
Anti-matter

What are primary Cosmic Rays composed of?



- ➢ Chemical composition of cosmic rays indicates their stellar origin

Energies of primary cosmic rays



How are particels with E > 10^{20} eV measured?

- High energetic CR produce cascades of secondary radiation when they interact with gasses in the atmosphere

Example: Fly's Eye Mirrors, Utah, USA – highest-energy (3×10^{20} eV) cosmic ray ever detected by observing light produced by cosmic ray striking the atmosphere

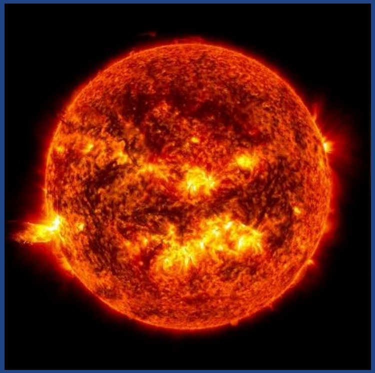
Where do primary cosmic rays come from?

Sources of primary cosmic rays:

Galactic sources

Supernova remnants

Sun



Extra galactic sources

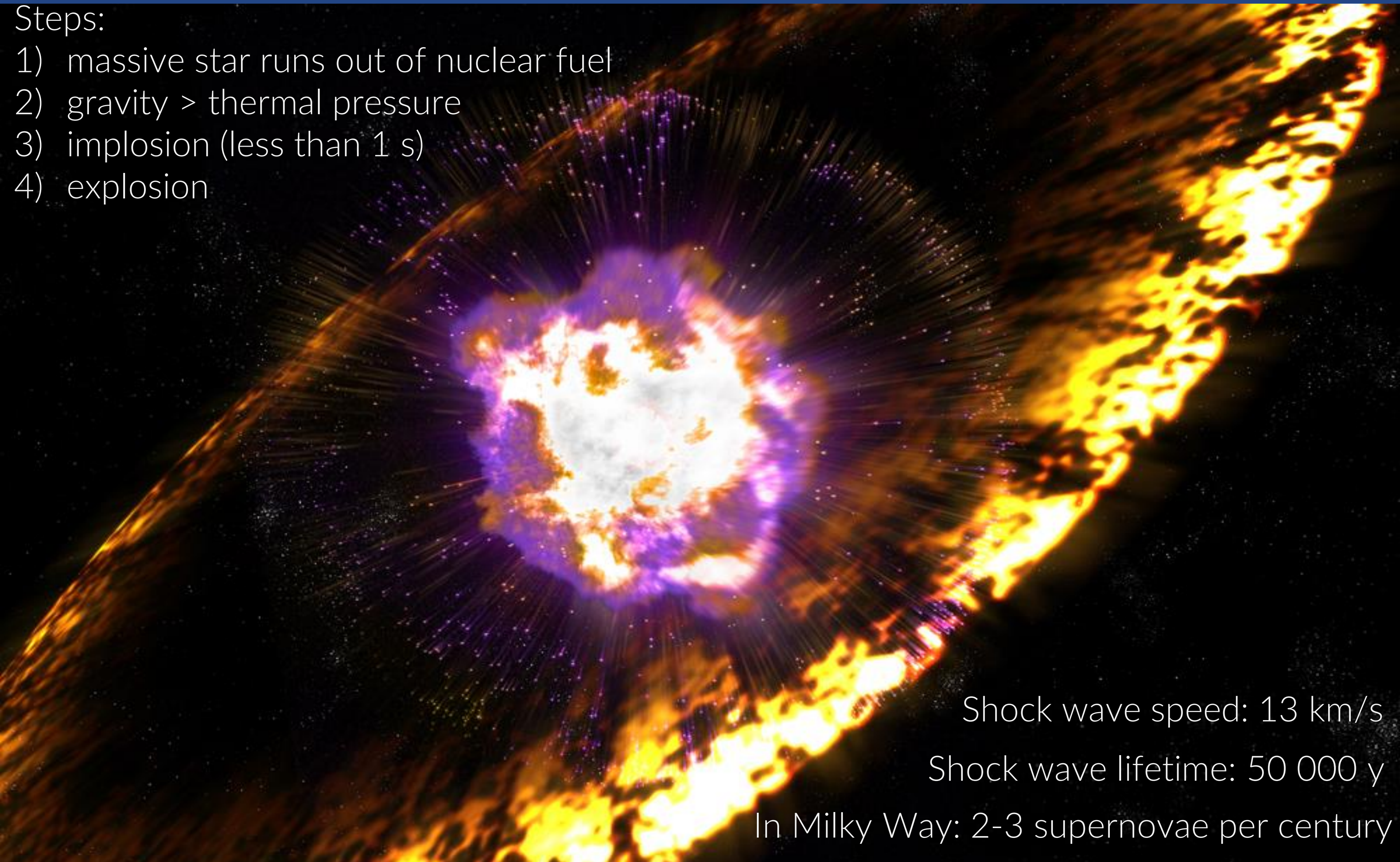
Unknown (Active Galactic Nucleus?)

Cosmic rays from supernova (SN) remnants

- majority of cosmic rays are accelerated by shock waves in SN remnants

Steps:

1) massive star runs out of nuclear fuel
2) gravity > thermal pressure
3) implosion (less than 1 s)
4) explosion



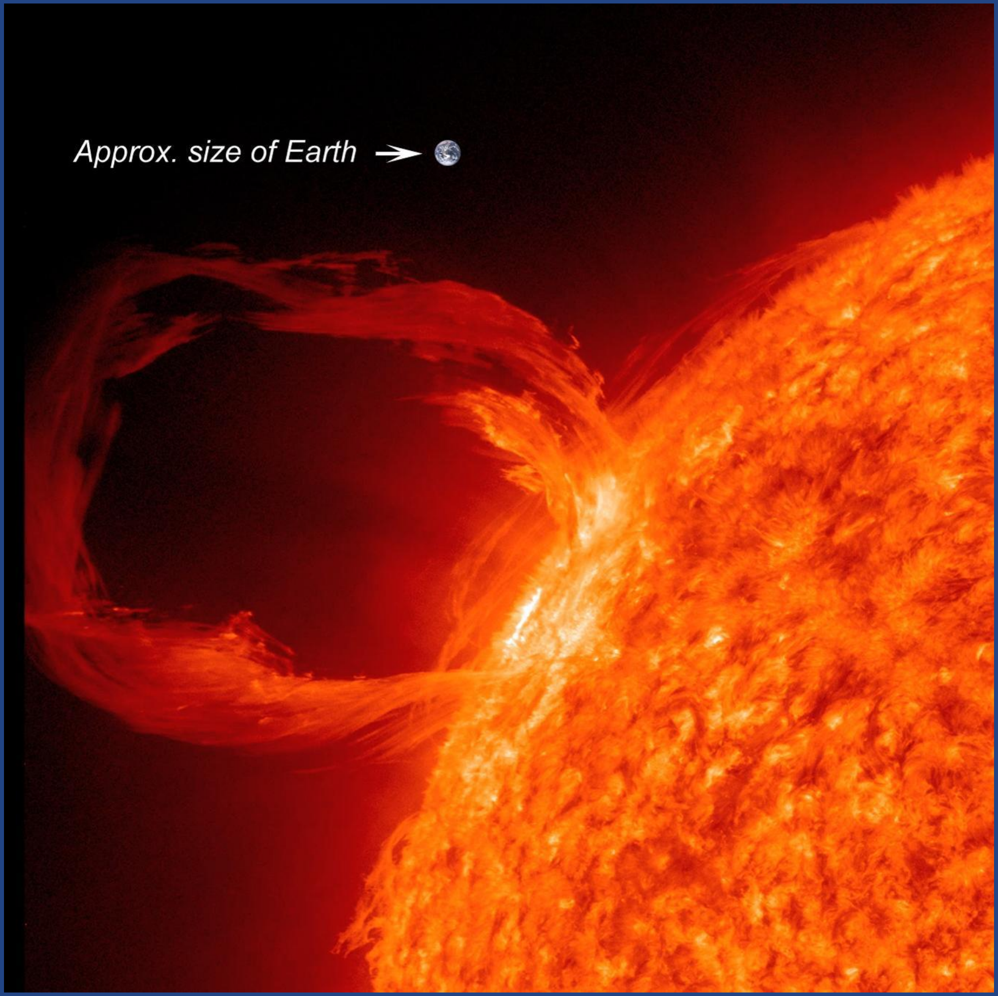
Shock wave speed: 13 km/s

Shock wave lifetime: 50 000 y

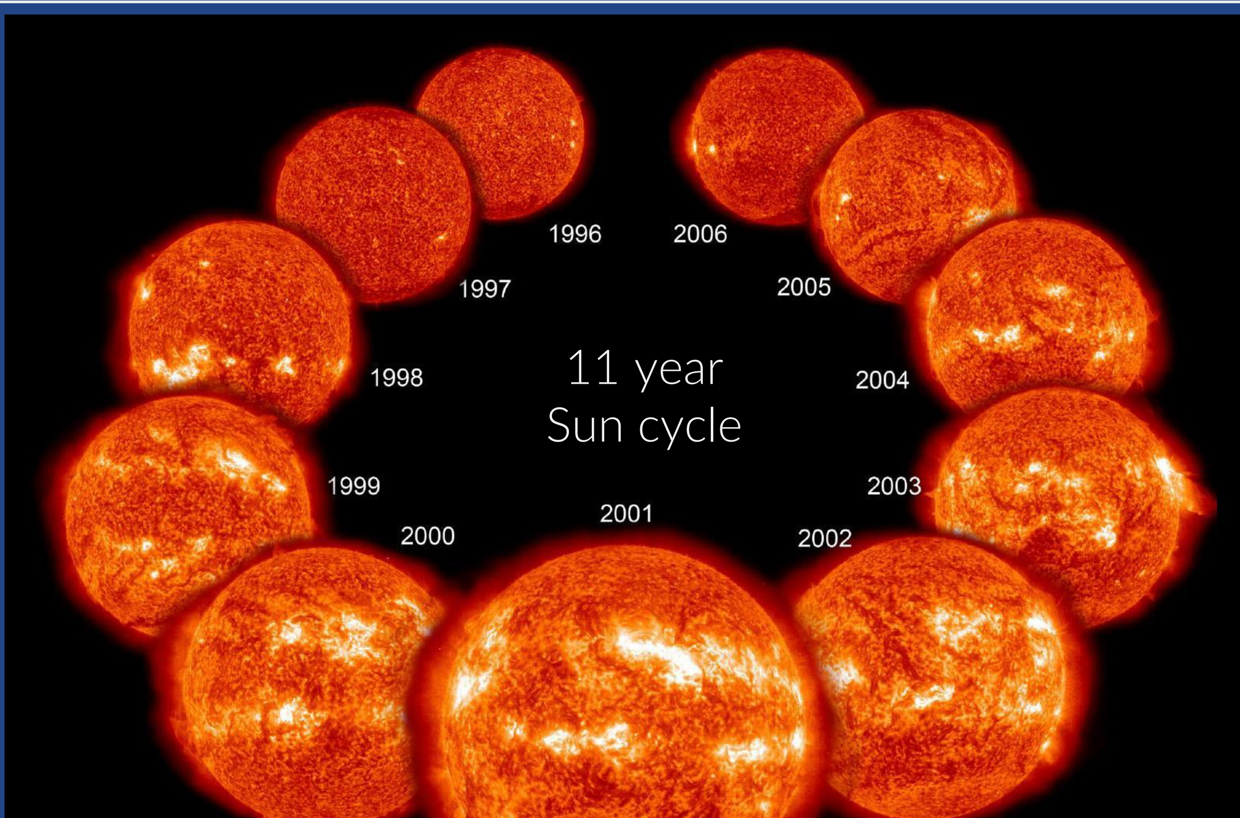
In Milky Way: 2-3 supernovae per century

Cosmic rays from the Sun

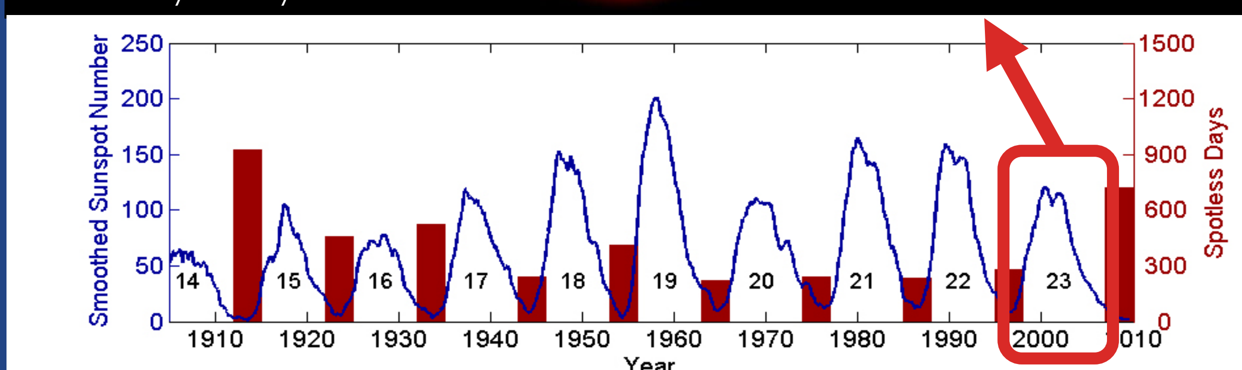
- Mainly protons and electrons but also heavier elements
- By energy: up to 10 GeV (low compared to GCR)
- By amount: depending on event in which they were produced (can go up to 1 000 000 times more than GCR)



Cosmic rays from the Sun



➢ Driven by Sun's magnetic field which flips every 11 years or so



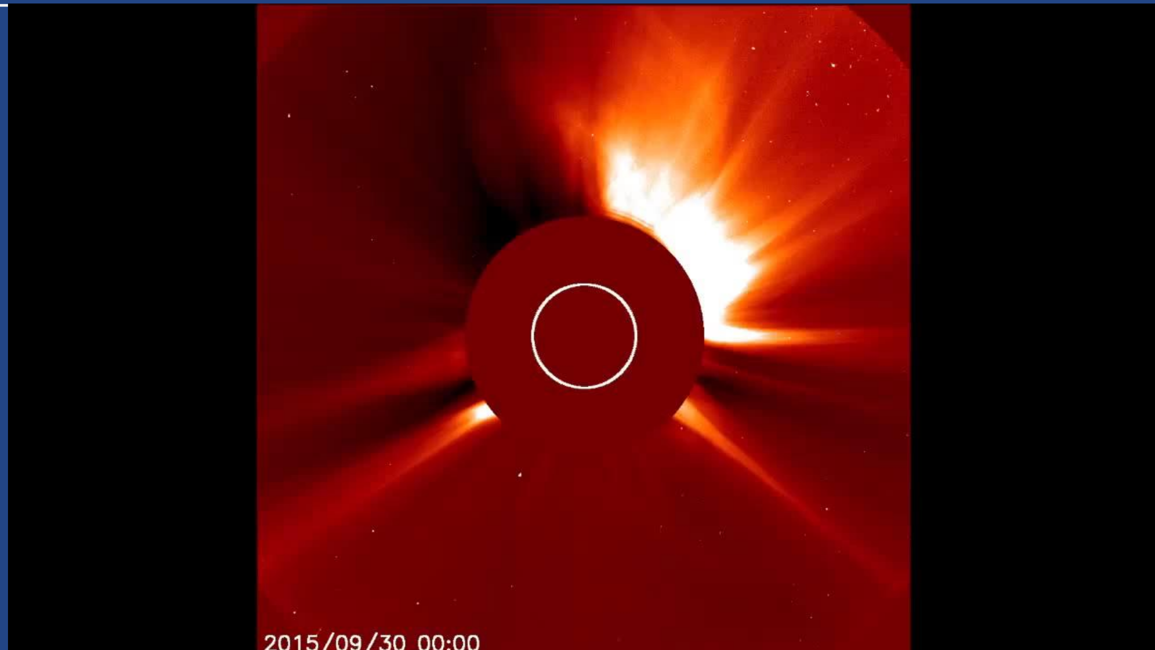
Space weather

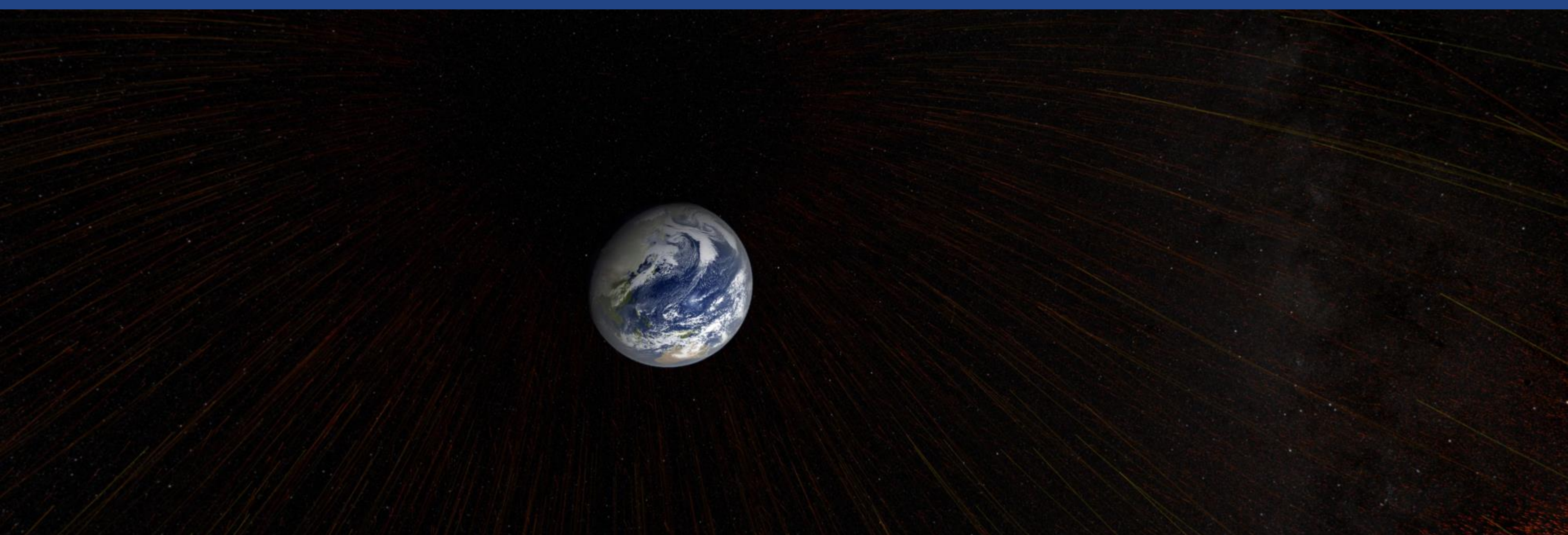
- ➢ Solar wind
- ➢ Solar flares
- ➢ Coronal mass ejection

10^2 - 10^6 increase in the flux of energetic particles (E=10 MeV-1 GeV)

- Particle flux from CME could be enough to kill a man
- During solar maximum: ~ 3 CME per day
- During solar minimum: ~ 1 CME per 5 days
- Solar wind increases shielding from CR

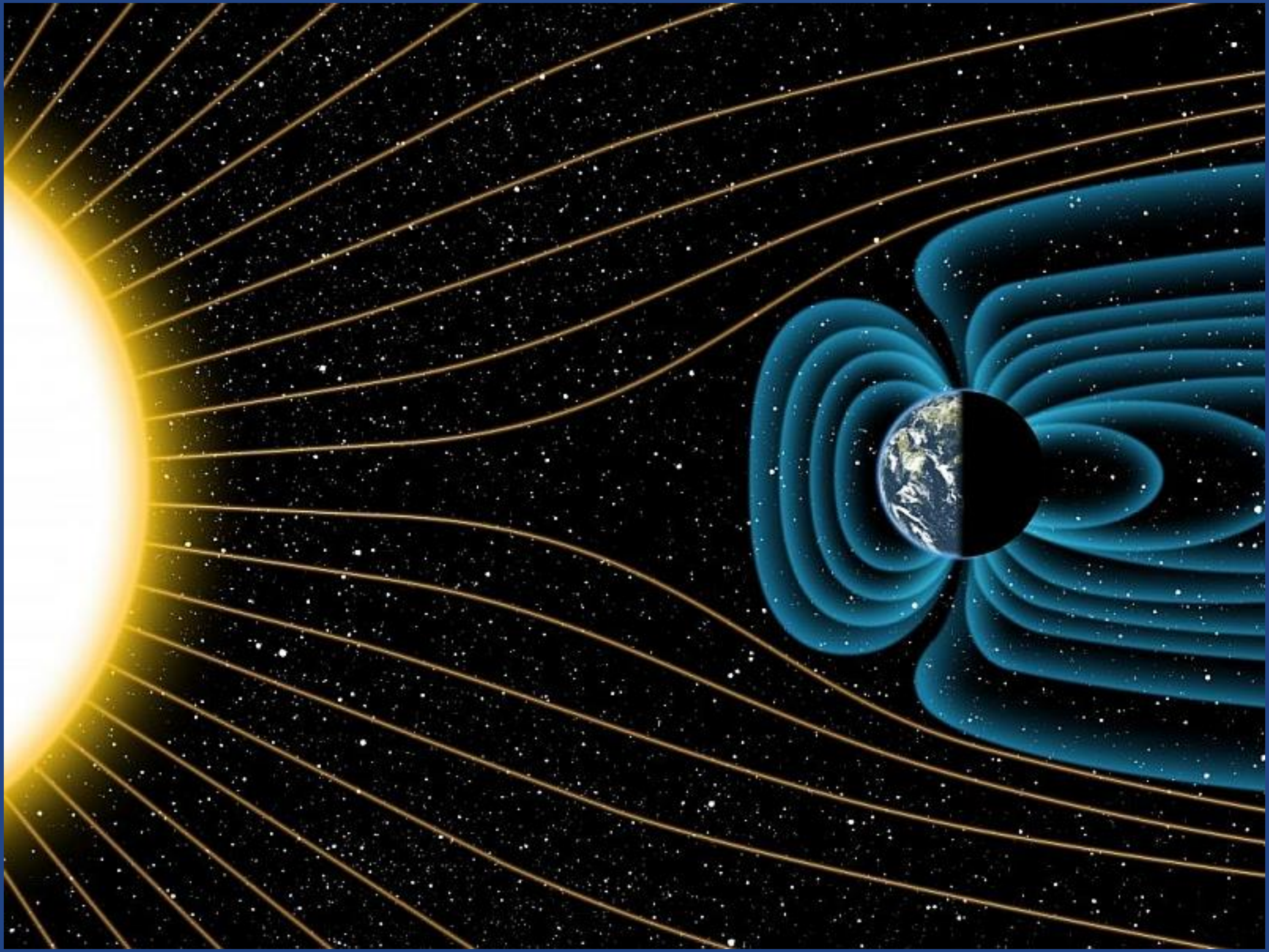
Radiation from the Sun – Coronal Mass Ejection





How is Earth protected?

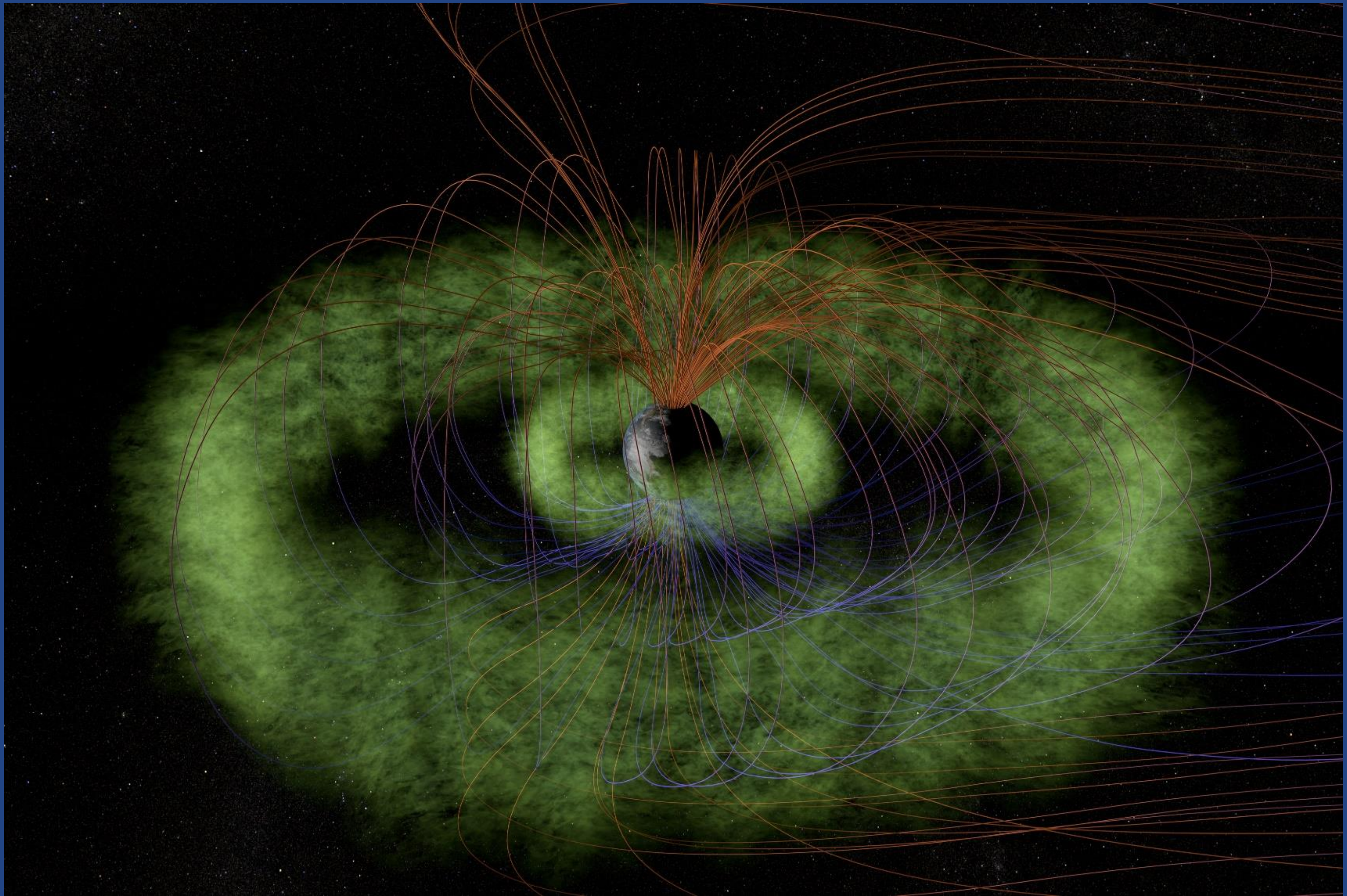
- Earth's magnetic field and atmosphere are good radiation shields



Van Allen belts

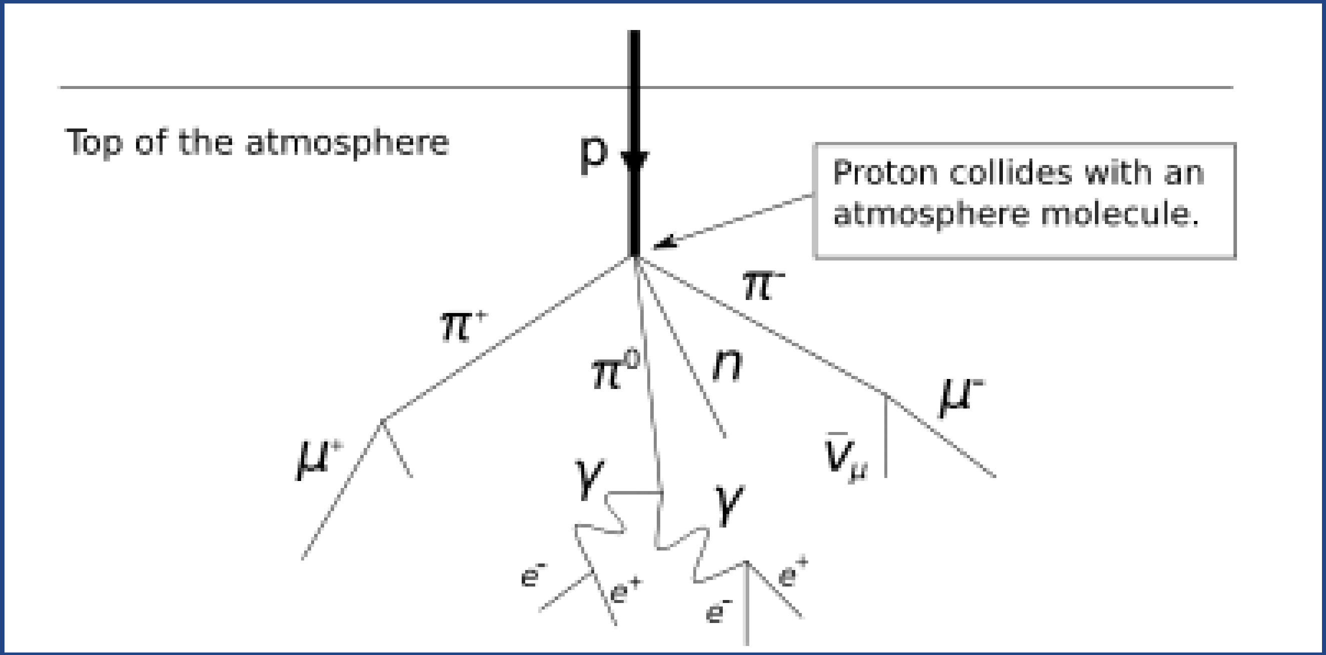
- ➢ Magnetic field traps electrons and protons from solar wind

- Inner belt (1000 – 10 000 km above Earth); outer belt (15 000 – 60 000 km above Earth)
- Inner belt composed of electrons and protons, outer mainly electrons
- Electron energies from hundreds of keV to several MeV, proton energies > 100 MeV



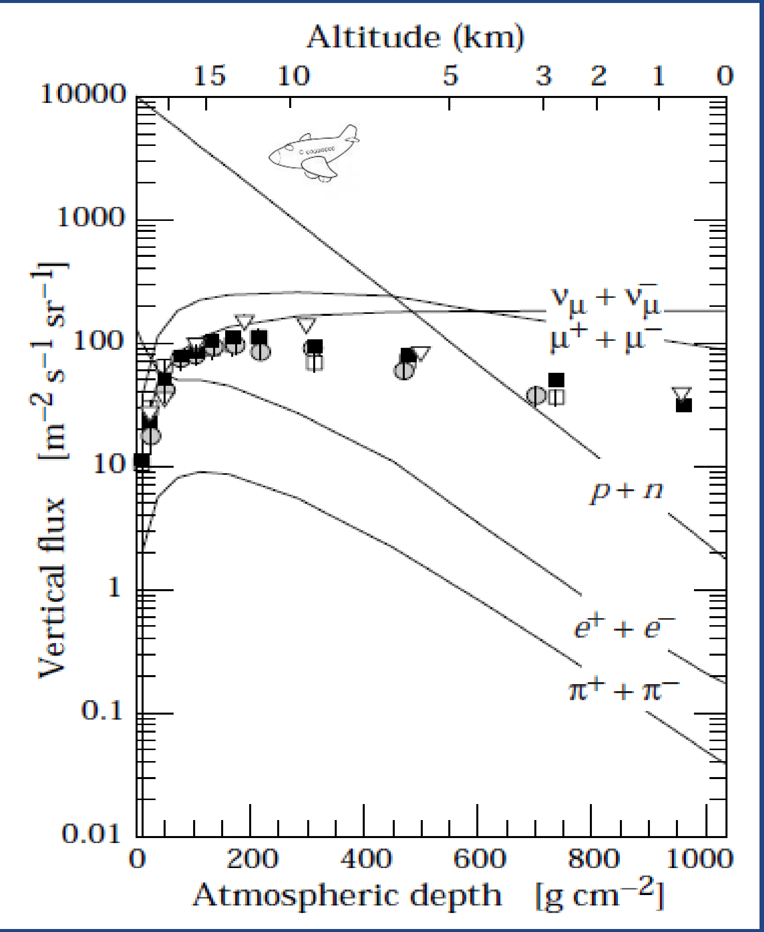
What gets through the magnetosphere and atmosphere?

- x rays, gamma rays – blocked in atmosphere ✘
- UV light – absorbed by ozone ✘
- low energy cosmic rays – blocked by magnetic field and atmosphere ✘
- ultra high energy cosmic rays – get through but rare ✓
- high energy cosmic rays – interact with atmosphere and produce particle showers: electrons, photons, muons, pions ✓



Cosmic rays around us

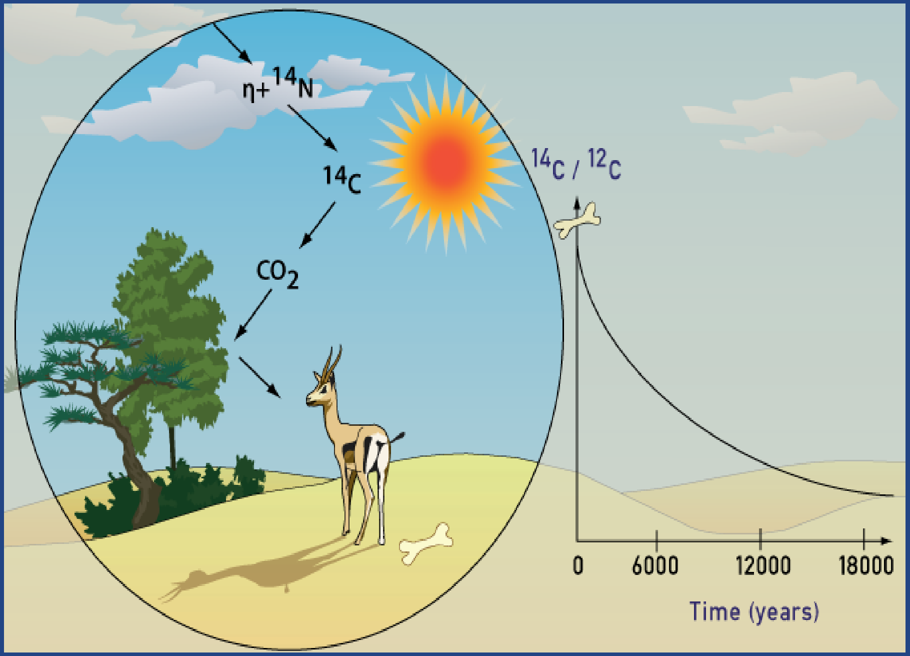
- Cosmic ray fluxes decrease through the atmosphere:



At sea level mostly:
1) Muons (1 per s through palm)
2) Neutrons

- Non-radiobiological effects of Cosmic rays:

1) Carbon-14 dating



2) Electronic equipment upsets
- single event upsets (bit flip)

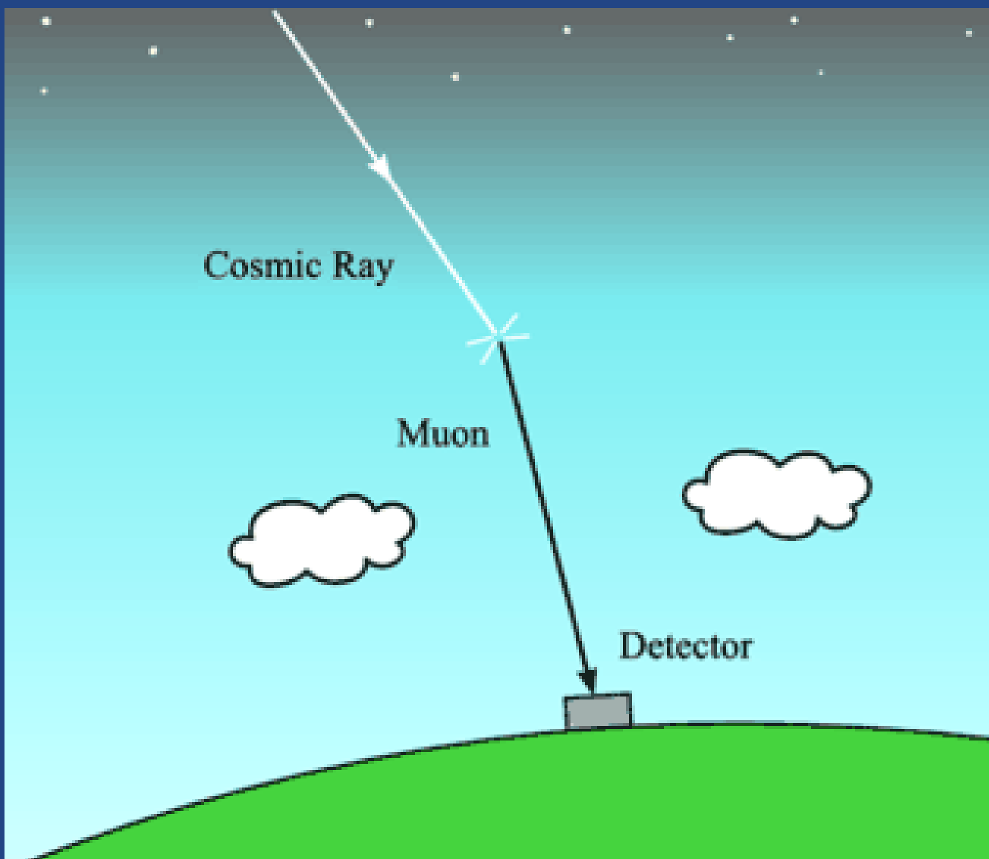
3) Communication system upsets
- geomagnetic storms (CME)
- GPS, satellites…

Why do we detect muons at sea level?

Muon created at 10 km with v = 0.98 c

Muon lifetime $T_{1/2}$ = 2.2 μs

How many should reach sea level?



v = 0.98 c = 0.98 x 3E8 m/s

d = 10 km

t = d/v = 34 μs = 15 $T_{1/2}$

$N/N_0 = 2^{-15}$ = 0.003%

Solution:

<u>Relativistic time dilation</u>

$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - \frac{u^2}{c^2}}}$$

$T_{1/2}$ = 2.2 μs * 5 = 11 μs

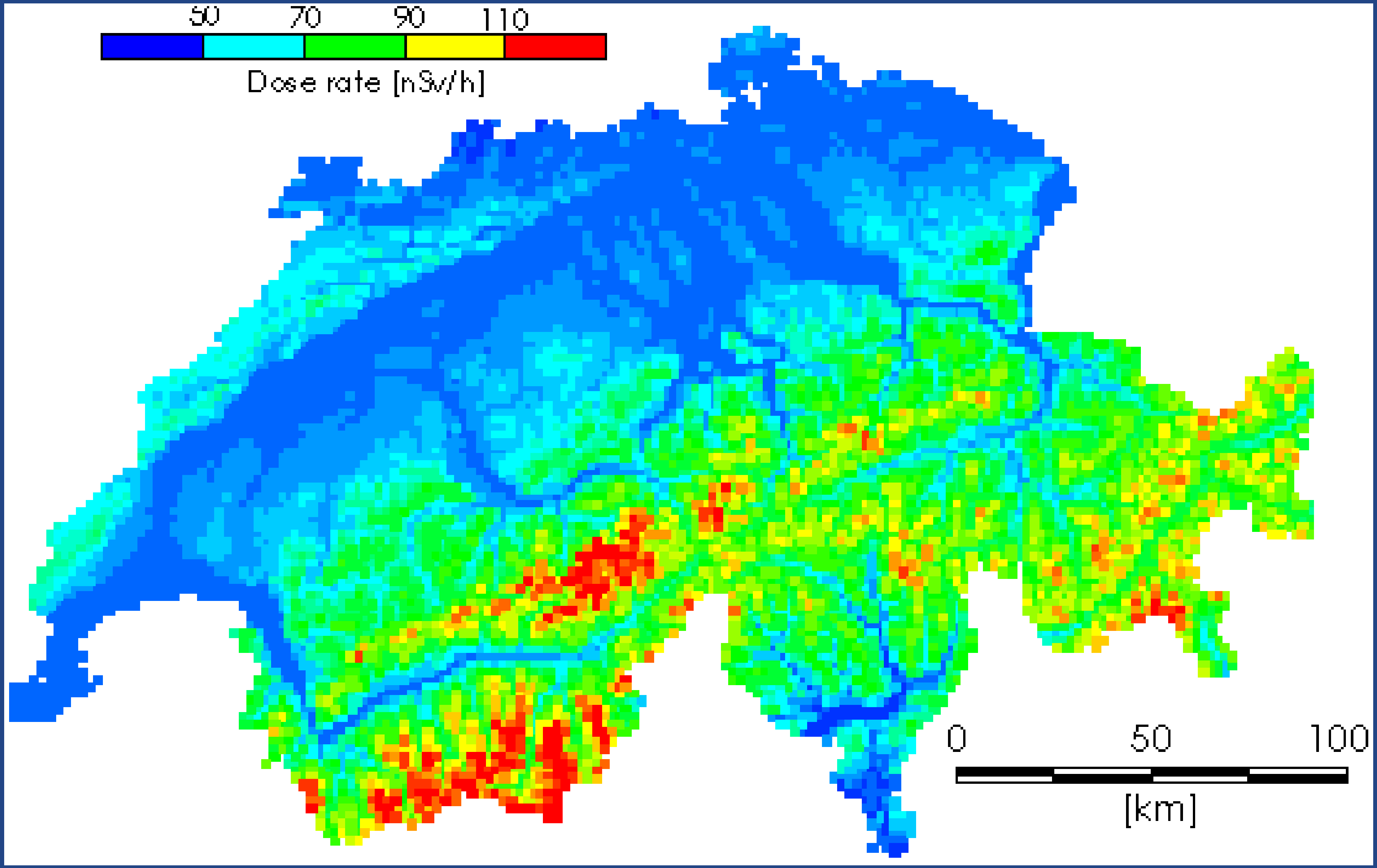
t = 34 μs = 3 $T_{1/2}$

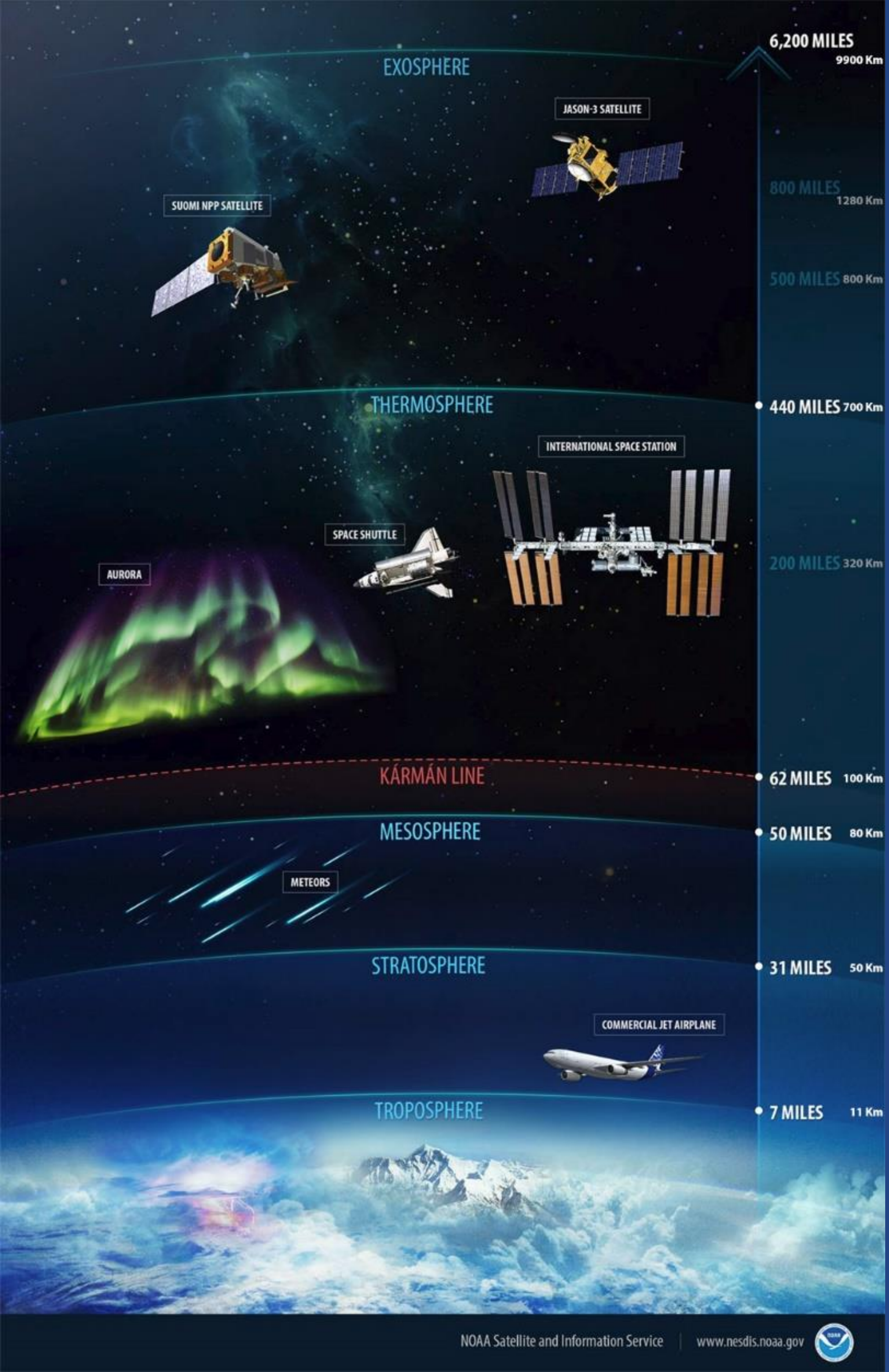
$N/N_0 = 2^{-3}$ = 12.5%

Space Radiation as Health Hazard

Space radiation dose on Earth

- Cosmic dose rate map of Switzerland



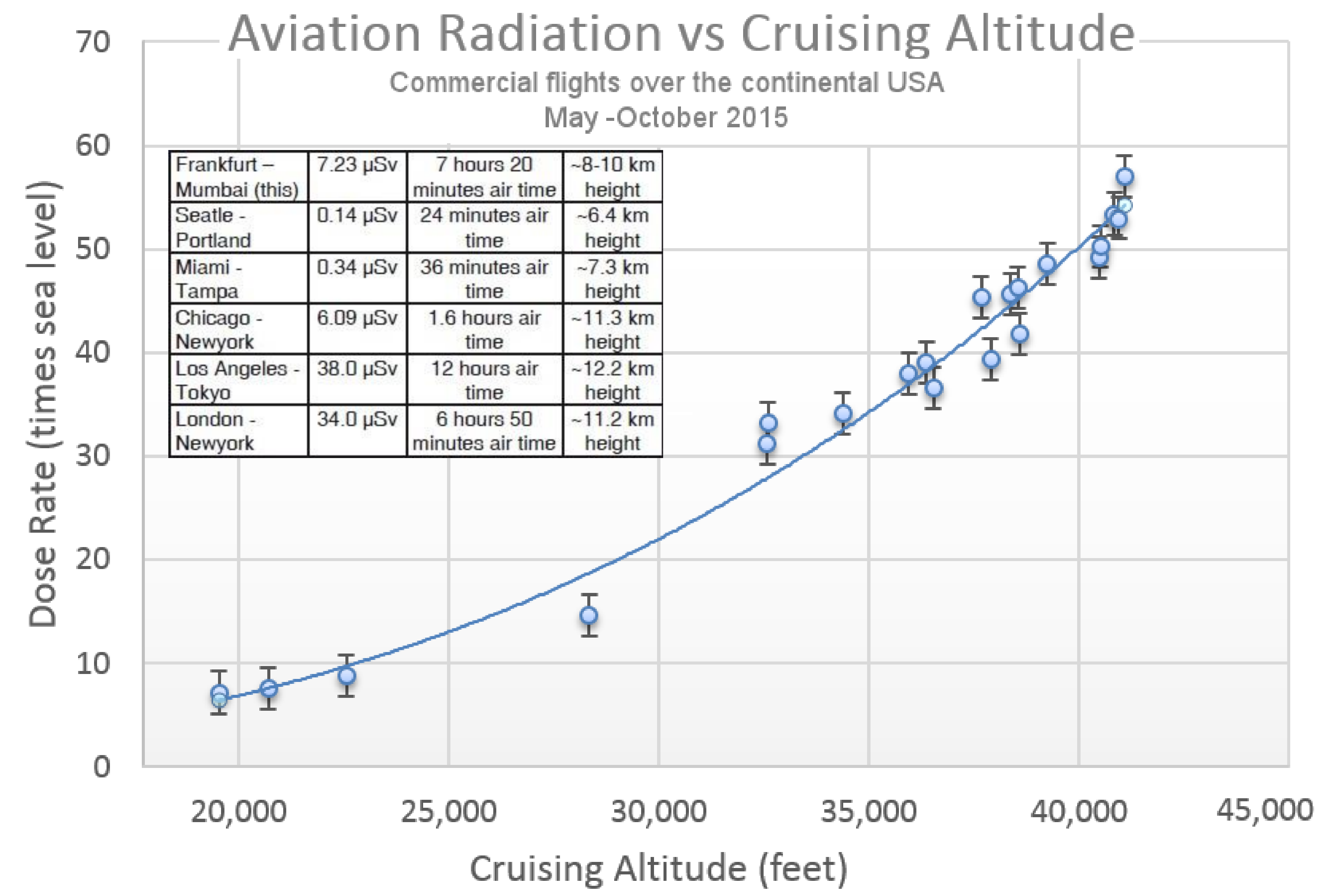


Interplanetary

Astronauts, ISS

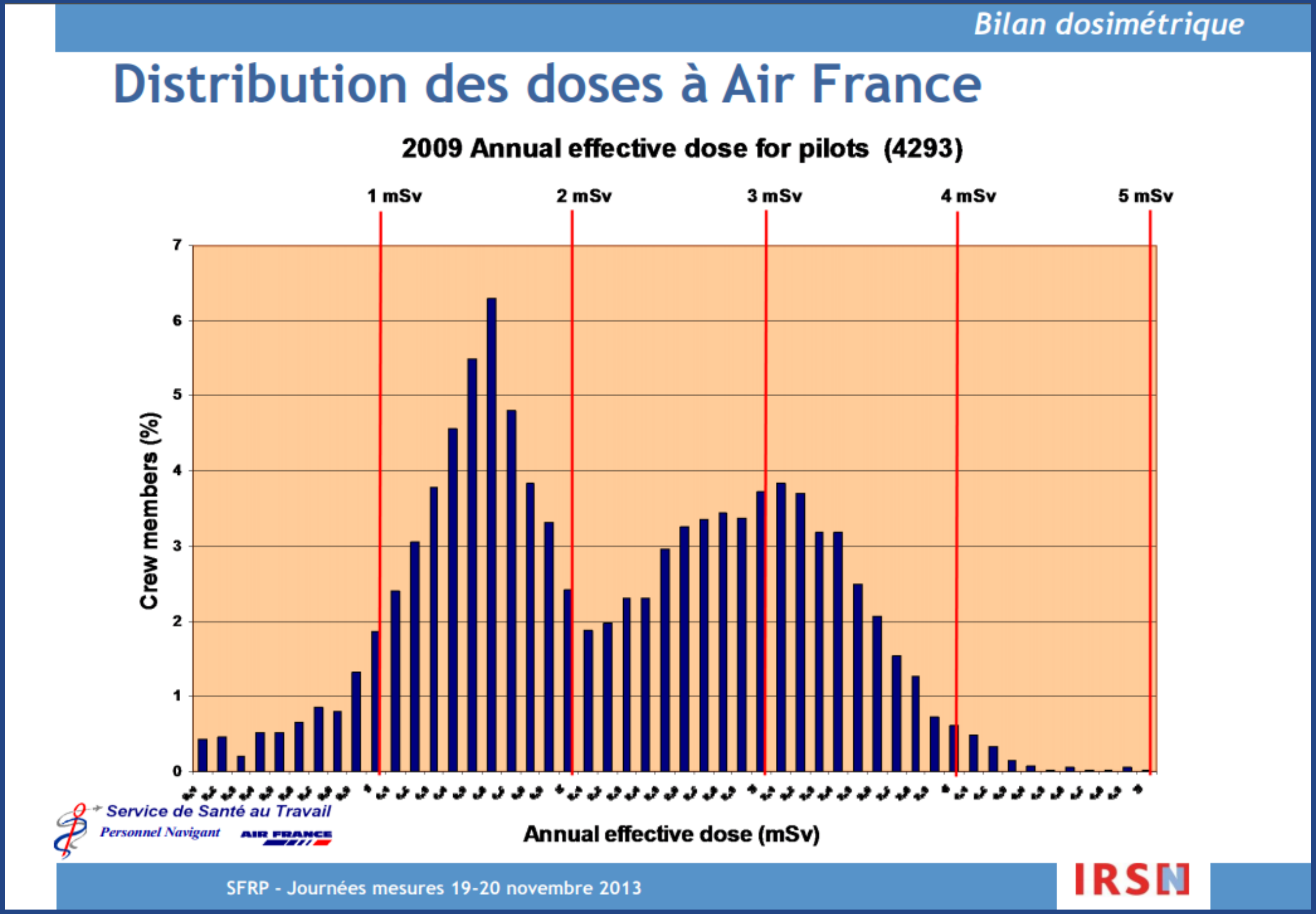
Air crew

Space radiation dose during commercial flights



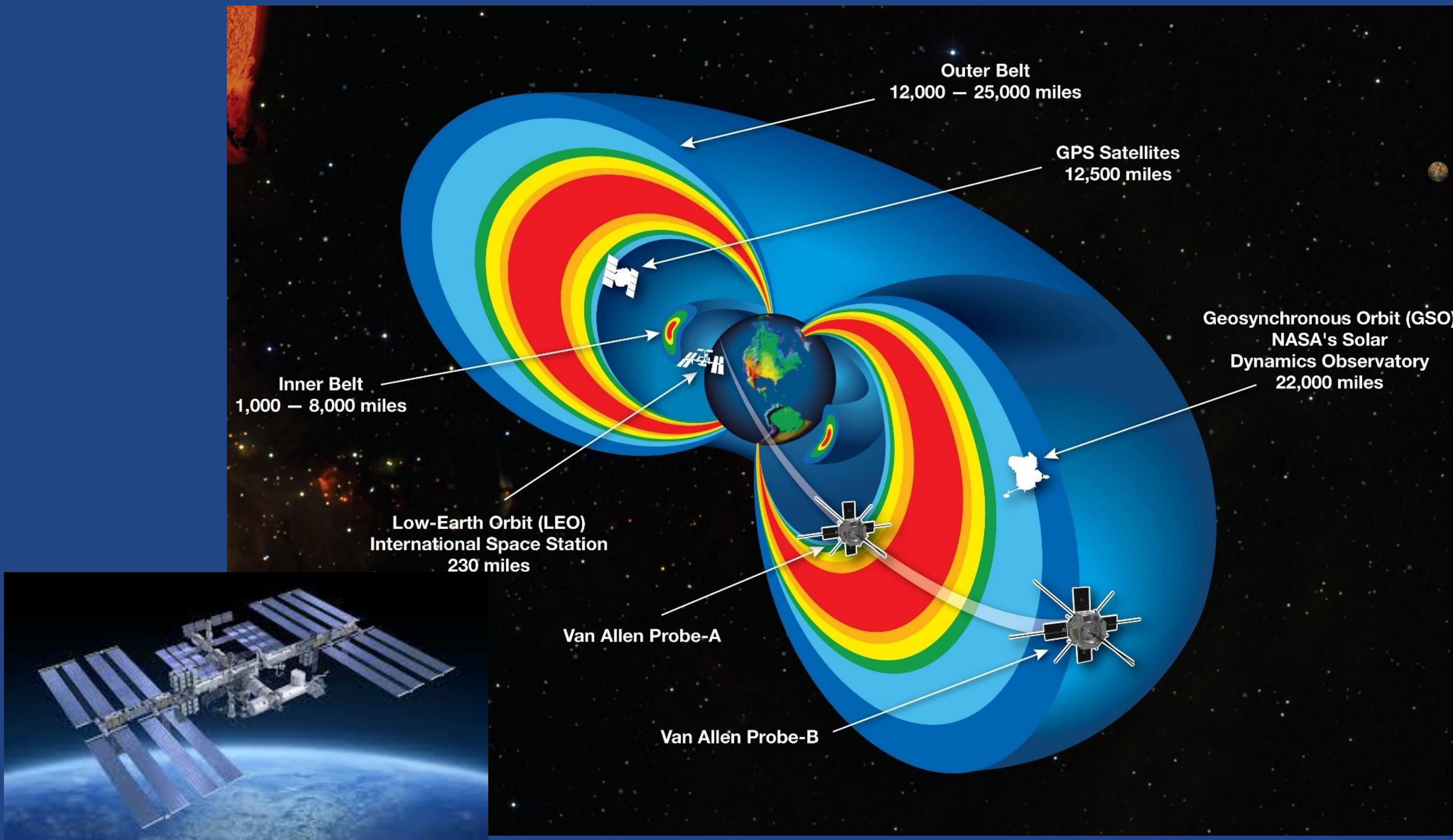
Frankfurt – Mumbai (this)	7.23 µSv	7 hours 20 minutes air time	~8-10 km height
Seatle - Portland	0.14 µSv	24 minutes air time	~6.4 km height
Miami - Tampa	0.34 µSv	36 minutes air time	~7.3 km height
Chicago - Newyork	6.09 µSv	1.6 hours air time	~11.3 km height
Los Angeles - Tokyo	38.0 µSv	12 hours air time	~12.2 km height
London - Newyork	34.0 µSv	6 hours 50 minutes air time	~11.2 km height

Space radiation dose for air crew



Radiation dose on ISS

- 6 month stay at ISS: 80 mSv - 160 mSv
  - ISS is outside of the atmosphere but still below the magnetosphere

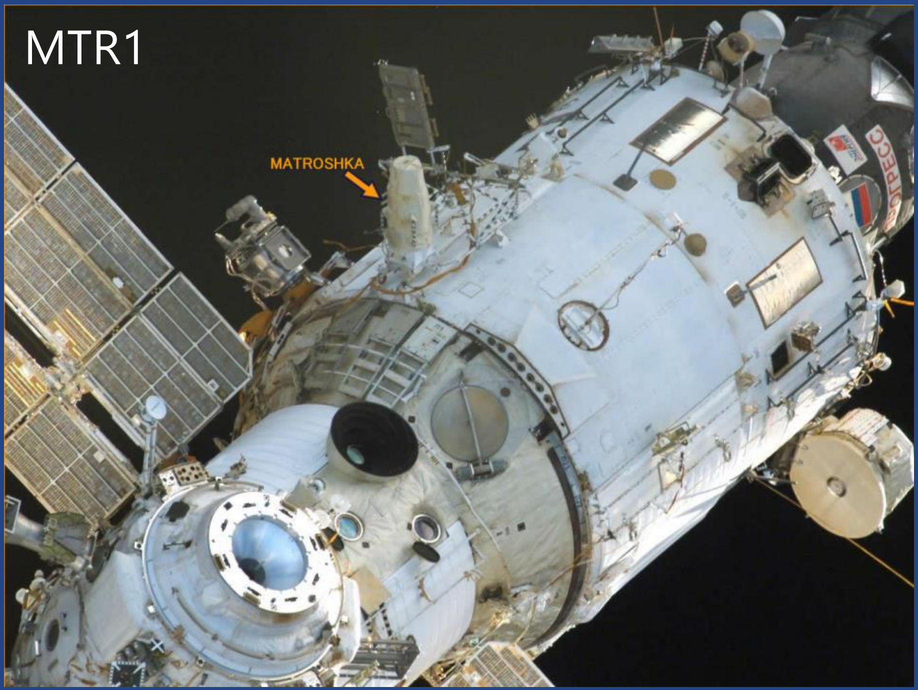


Dose monitoring on ISS

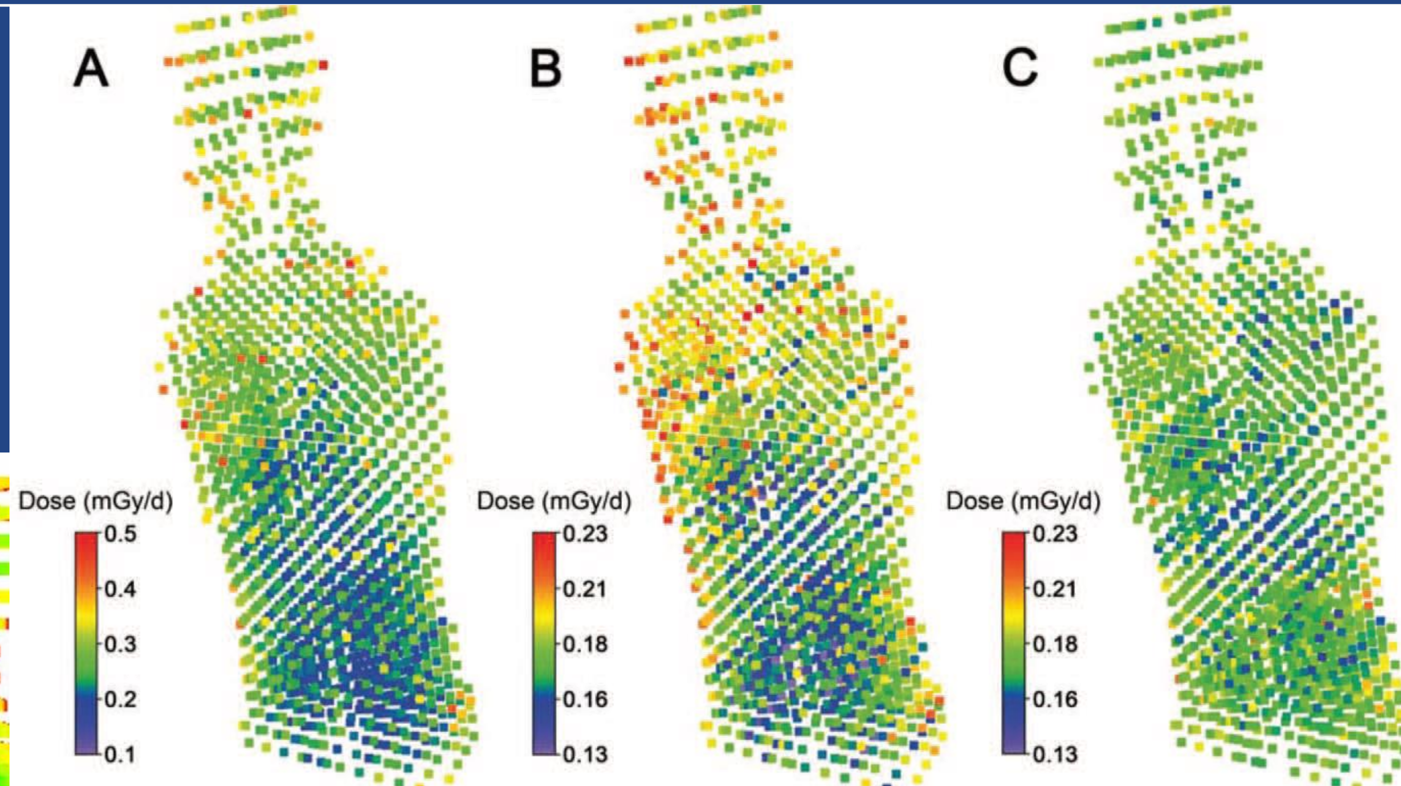
Matroskha experiments

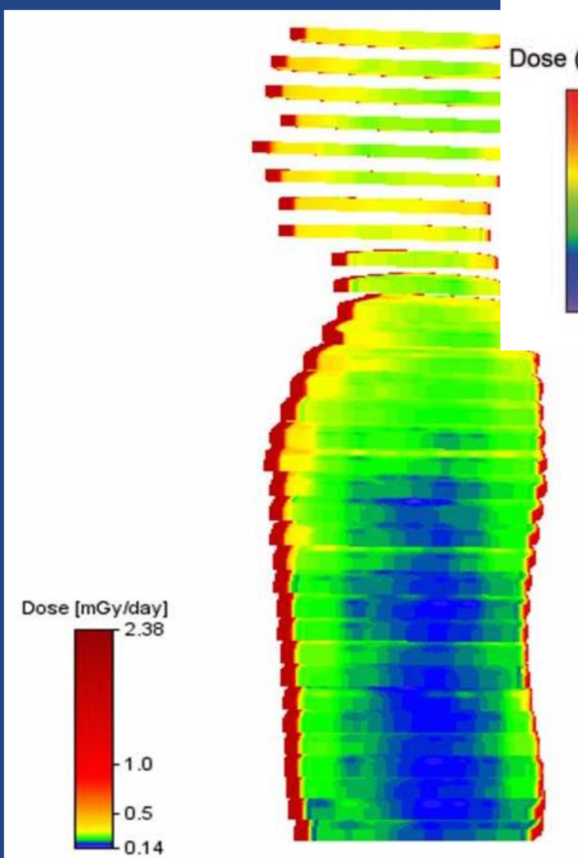
- anthropomorphic phantom
- made of soft tissue and bones
- composed of 34 slices for a total height of 850 mm
- equipped with detector holders

Additional devices on board:
- Thermoluminiscent dosimeters
- Tissue equivalent proportional counters



Dose monitoring on ISS



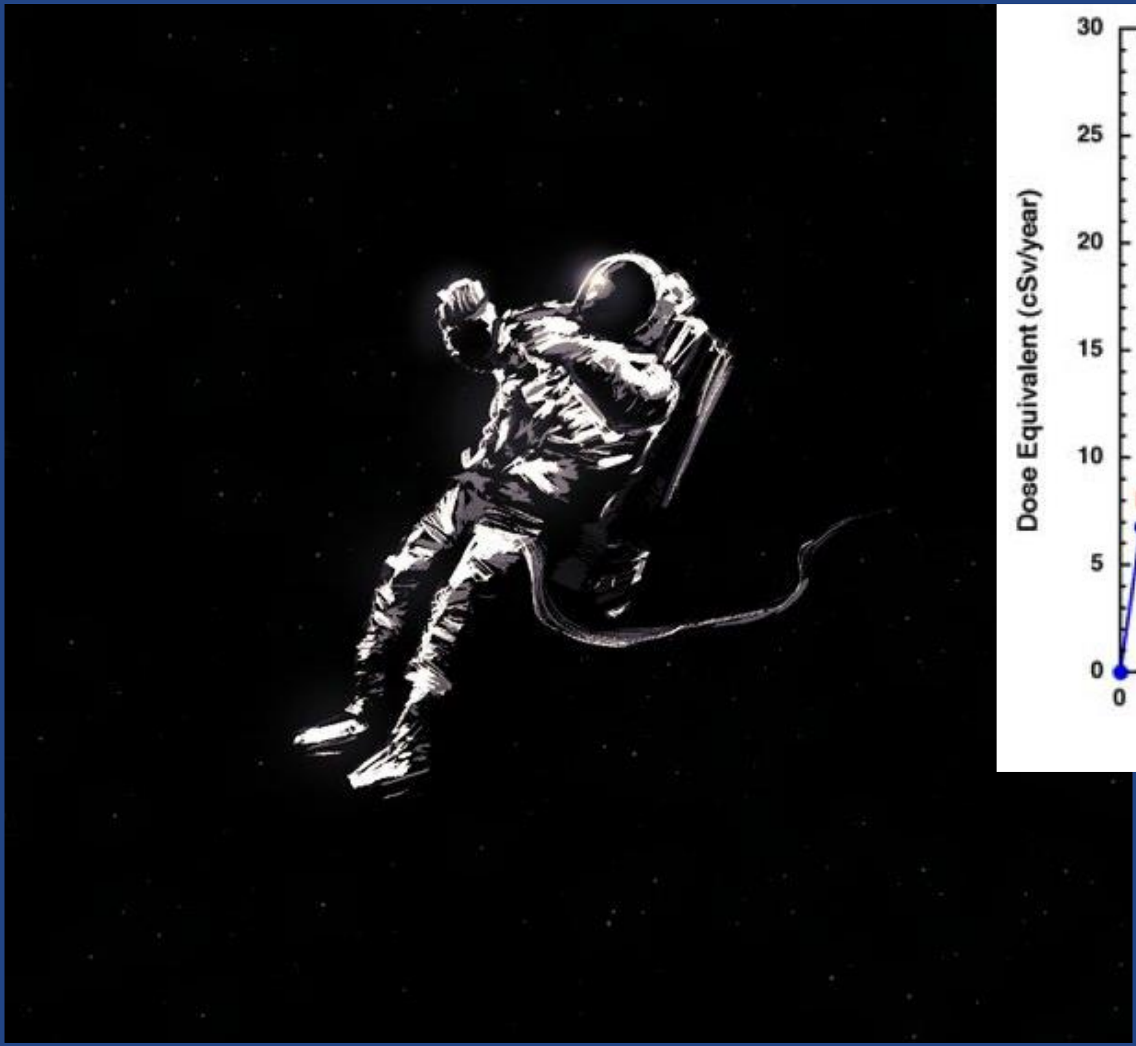


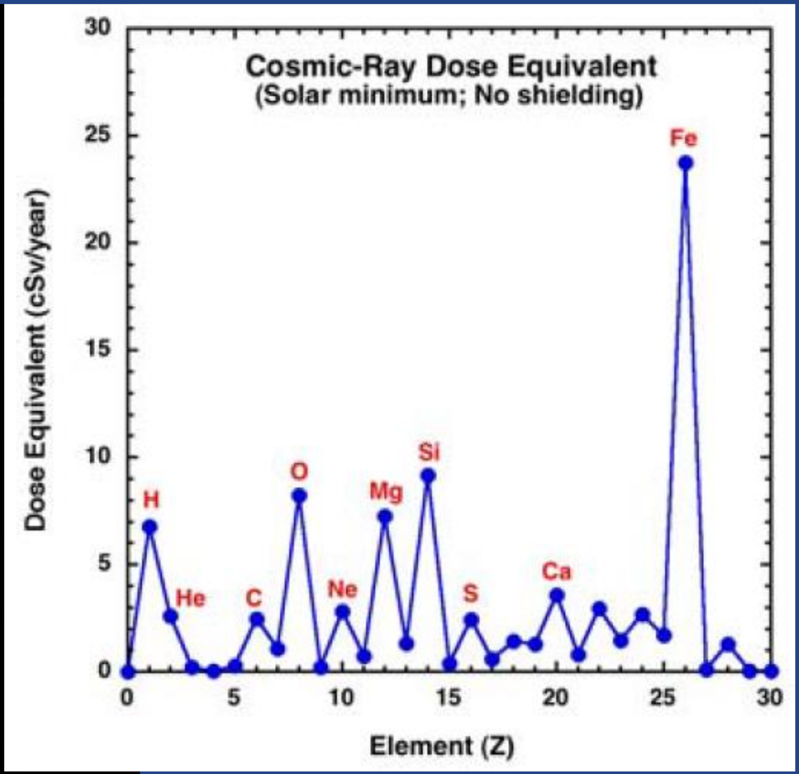
Skin dose:

- Extravehicular Activity: 2.5 mGy/day
- ISS: 1 mGy/day

Self-shielding: organs receive 0.2 mGy/day

Radiation dose in interplanetary space

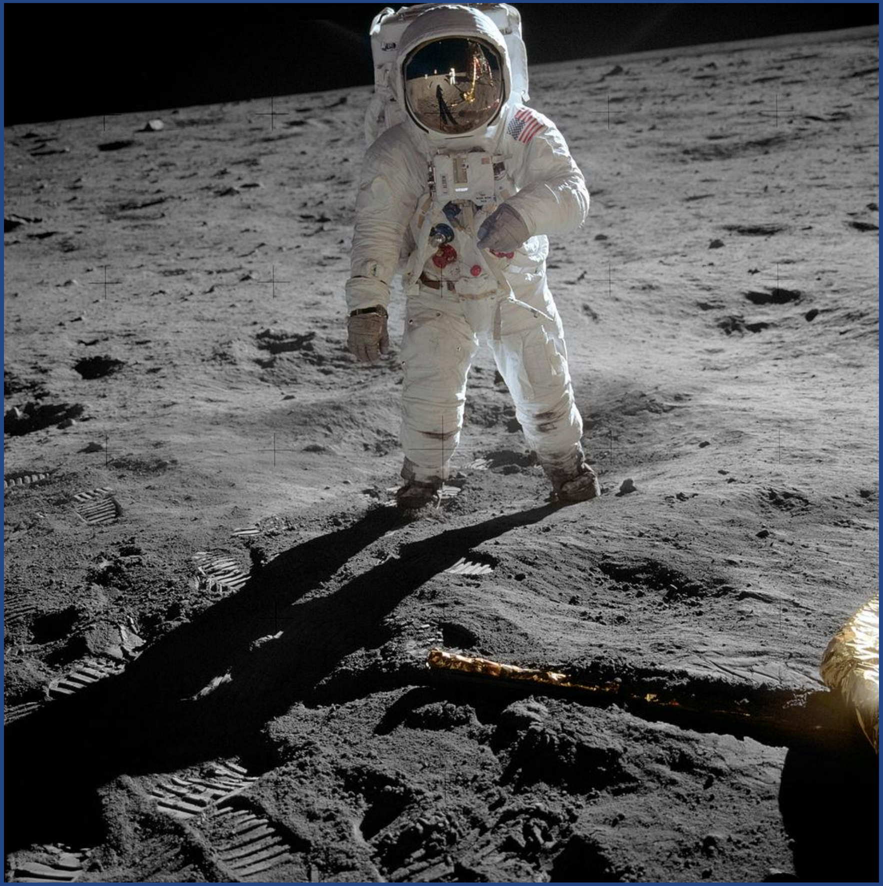




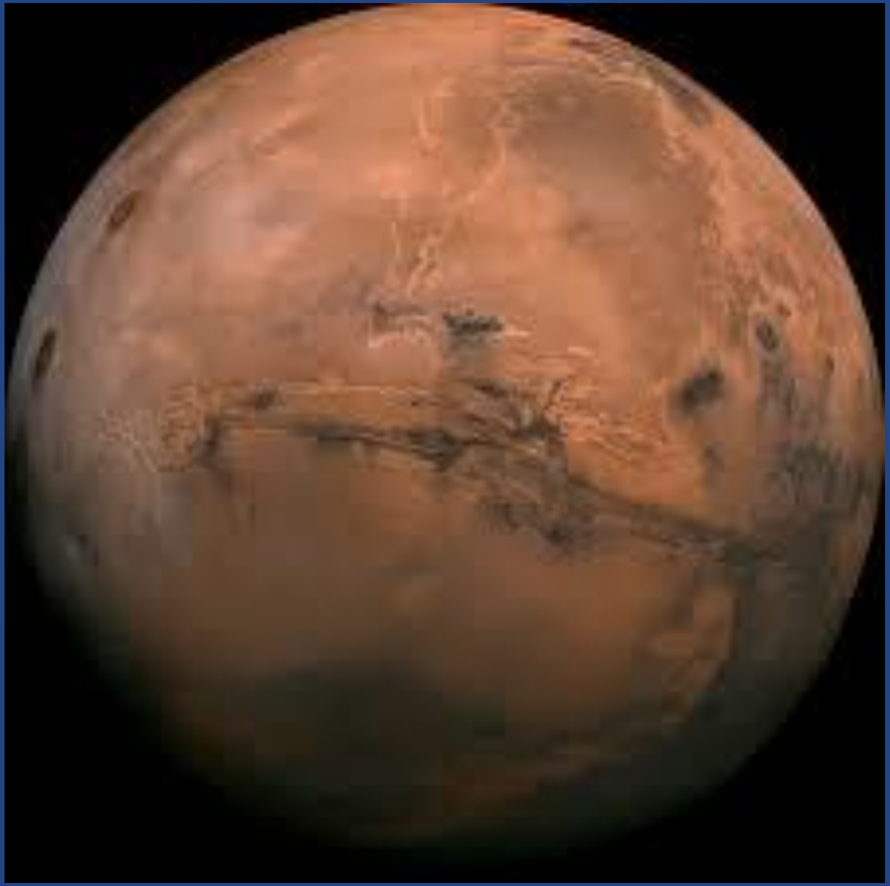
Annual dose to unshielded man in deep space: 400 - 800 mSv

Radiation dose for traveling to Moon and Mars

- Environment: no atmosphere, no magnetic field

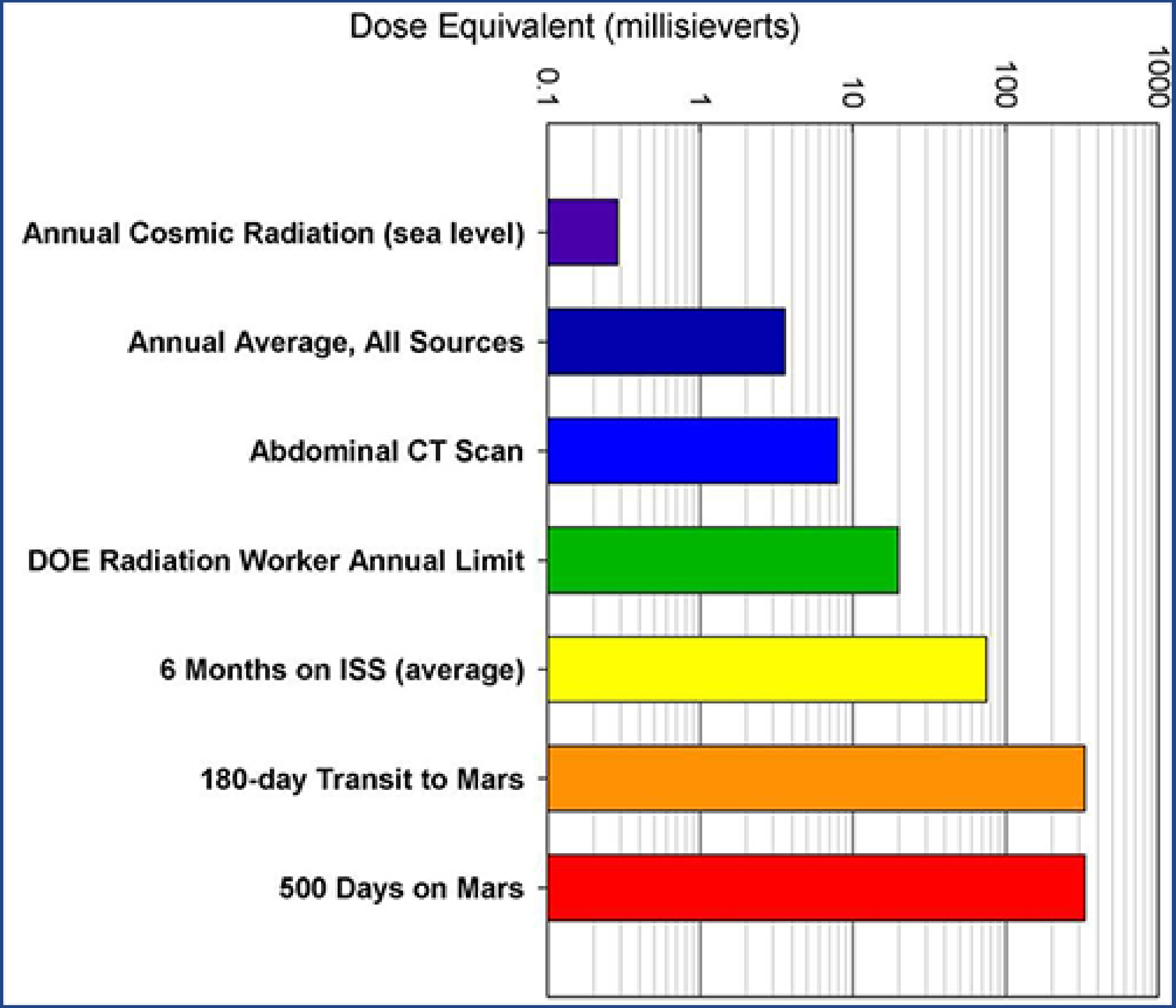


Apollo missions: up to 10 mSv total dose
One year on the Moon: 300 mSv



Shortest Earth-Mars round trip: 660 mSv
One year on Mars surface: 250 mSv

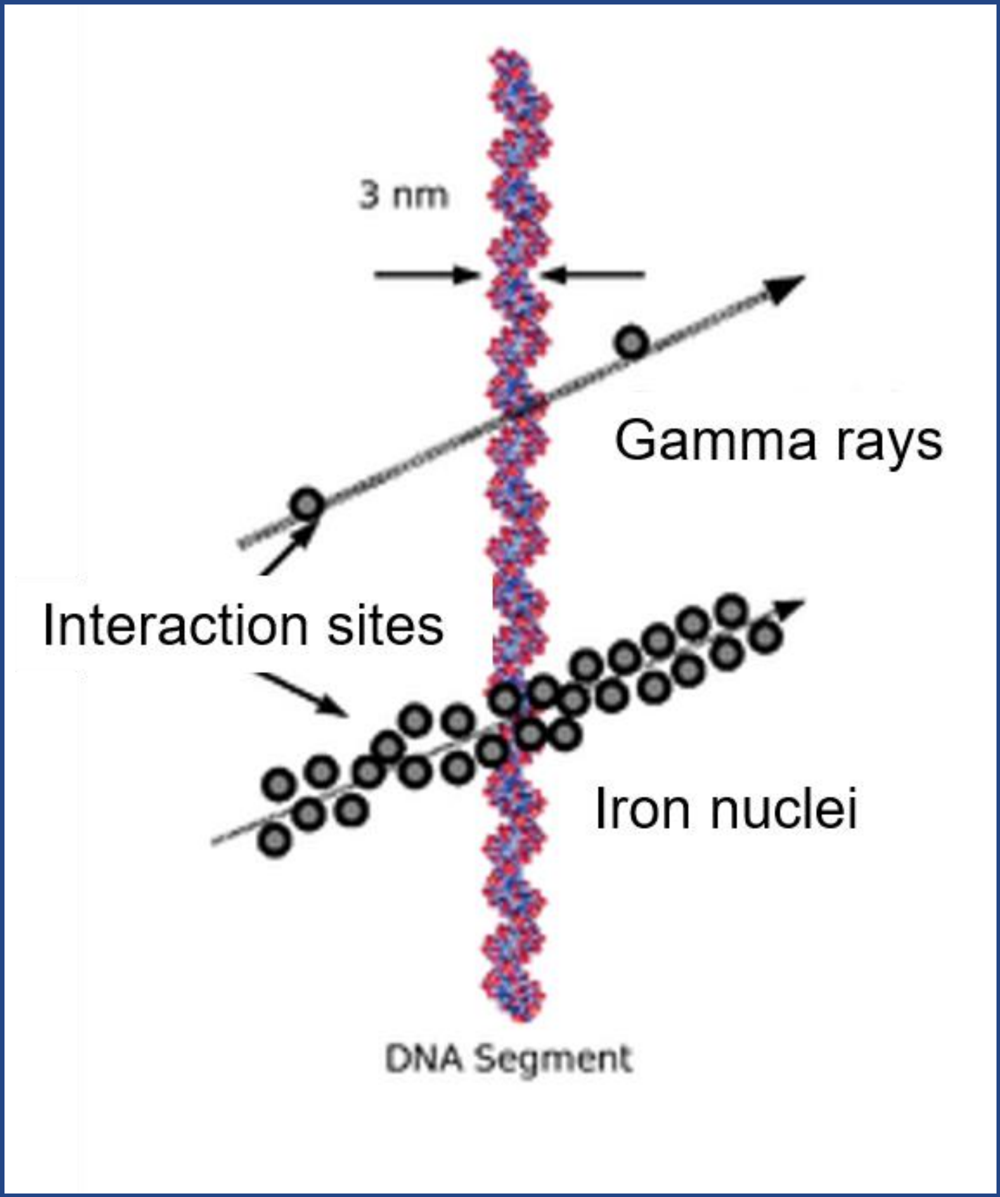
Equivalent absorbed dose - comparison



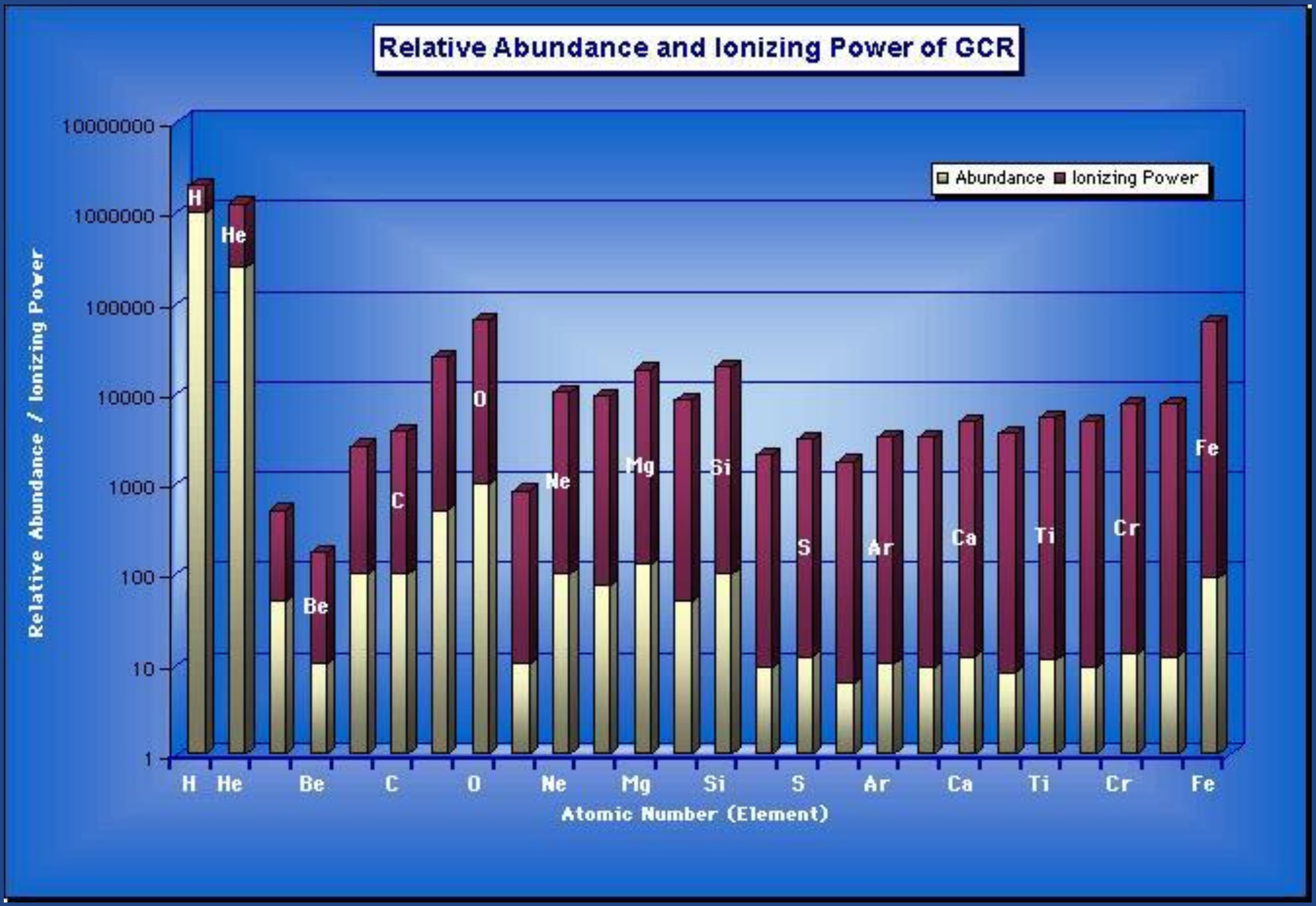
Biological effects of heavy charged particles

LET **(keV/µm)** = dE/dl

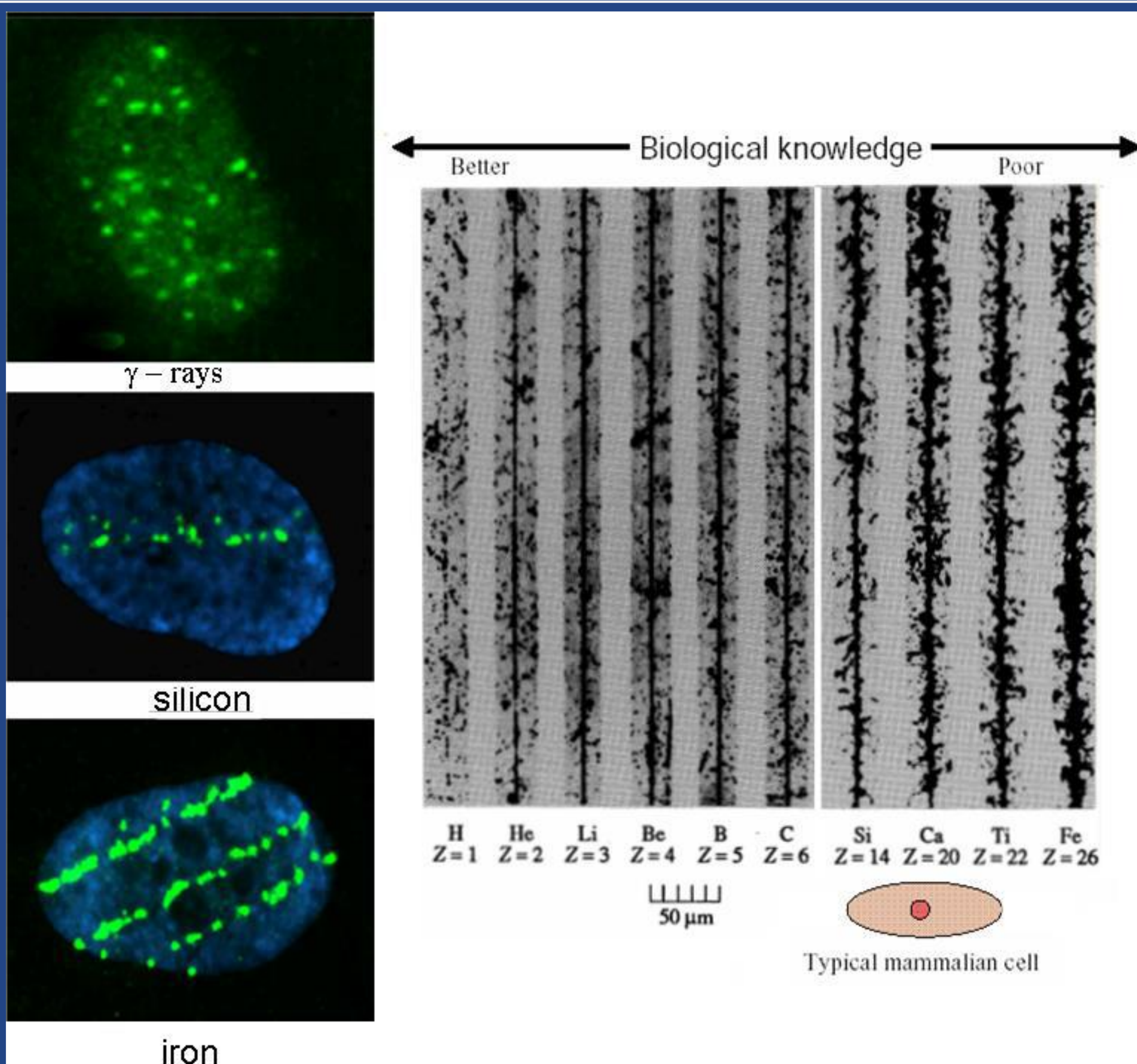
dE: average energy
dl: distance



CR abundance and ionizing power



Why is space radiation different from terrestrial sources?



Single HZE ions in cells leaving DNA breaks

Single HZE ions in photoemulsions leaving visible images

Risks from exposure to space radiation

Radiogenic cancers

- Blood borne cancers
- Solid cancers

Not mission critical on a trip to Mars

Normal tissue injury

- Acute radiation syndrome
- Cataracts
- Cardiovascular

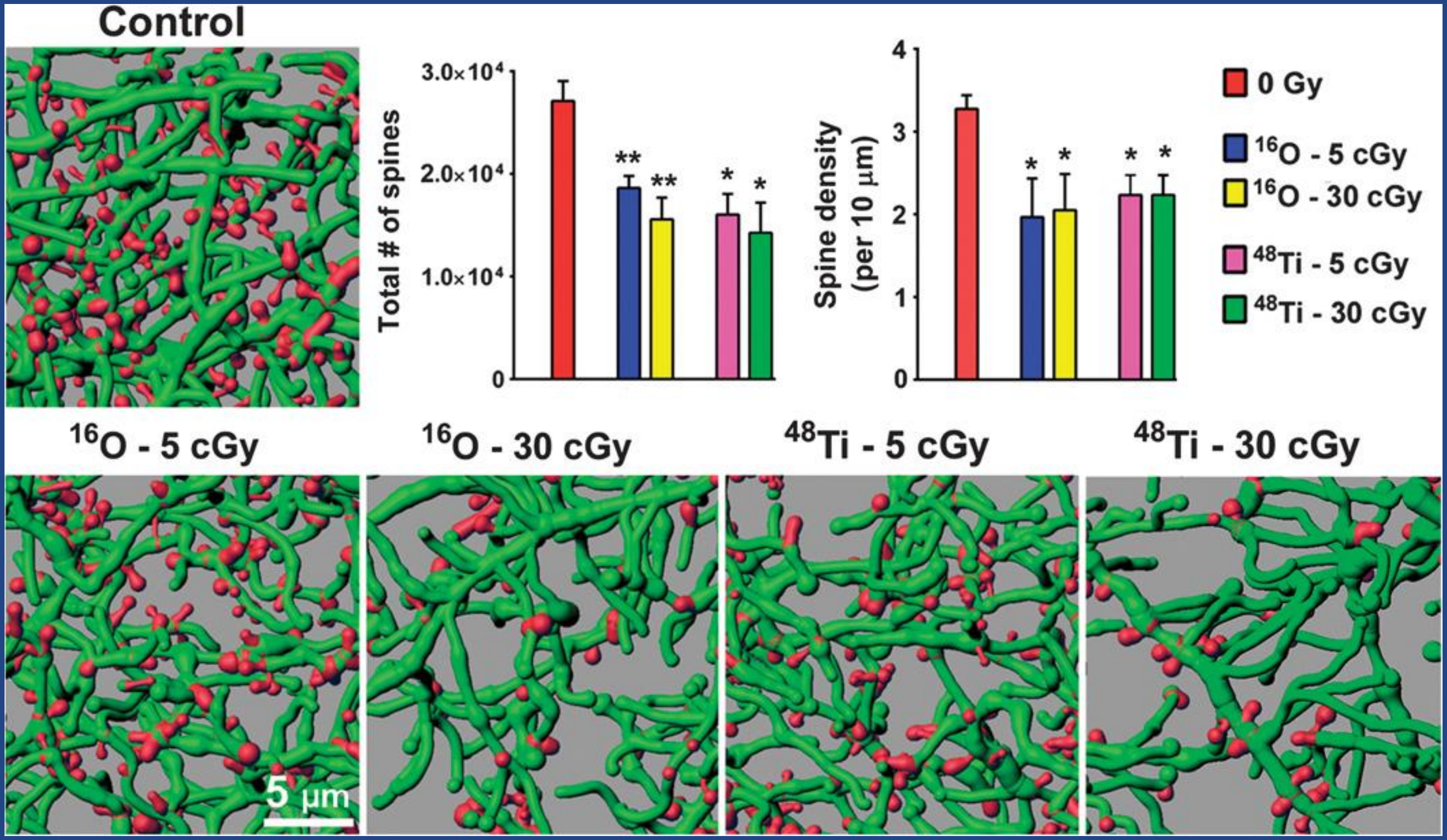
Not likely, too low doses

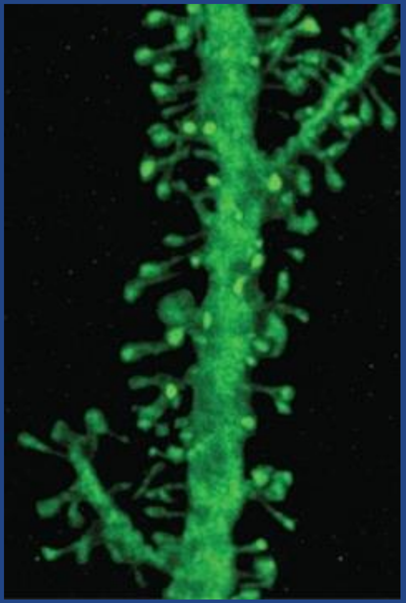
- Neurocognitive – CNS dysfunction?

Neurocognitive risks from space radiation

- Brain shows increased risk from high Z energetic particles even at low doses

Dendritic spine density at 8 weeks post exposure

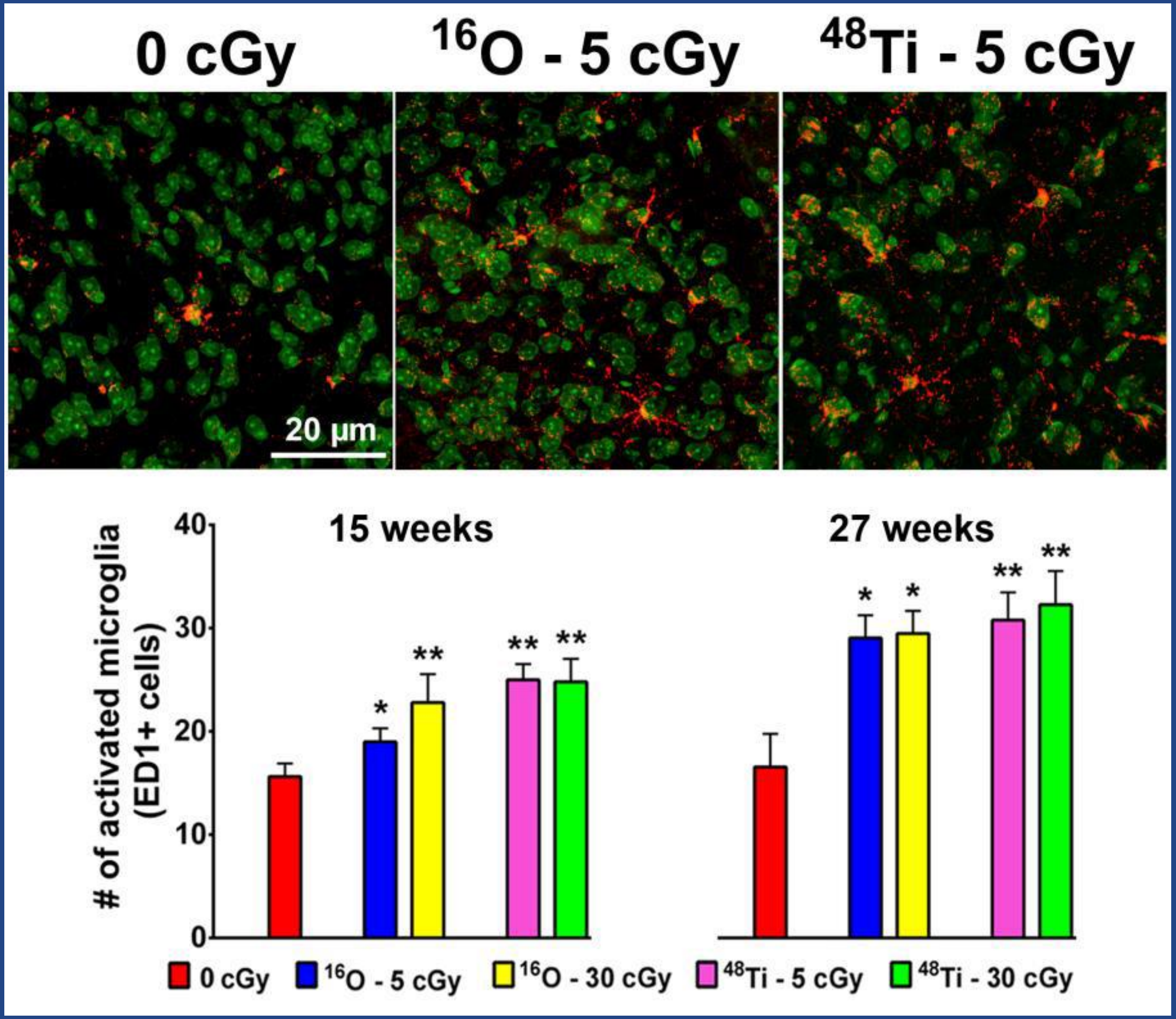




Parihar et al. Sci Adv 2015

Neurocognitive risks from space radiation

- Persistent neuroinflammation after charged particle irradiation



Neurocognitive risks from space radiation

- Cosimic radiation exposure can elicit significant disruptions in:
  - Learning and memory
  - Cognitive flexibility
  - Fear extinction
  - Executive function
  - Depression like beahviour

- Behavioral decrements are likely caused by alterations in neuronal structure and elevated inflammation that adversely impact neurotransmission at the network level

Space Radiation Countermeasures

How to protect astronauts from space radiation?

Prior to the mission

- Careful planning of the mission (orbit, space weather)
- Selection of crew members
- Accurate dose prediction

During the mission

- Monitoring environmental conditions
- Shielding
- Diet
- Dose monitoring

Example of careful orbit planning

- Slice view of Trans Lunar Injection orbit used for Apollo missions

Which materials to use for shielding?

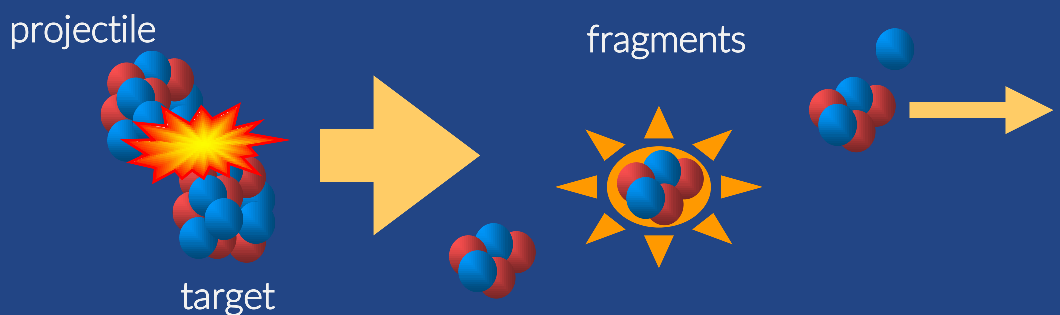
➢ Selection of the materials, two things to consider:

1) Stopping of charged particles:

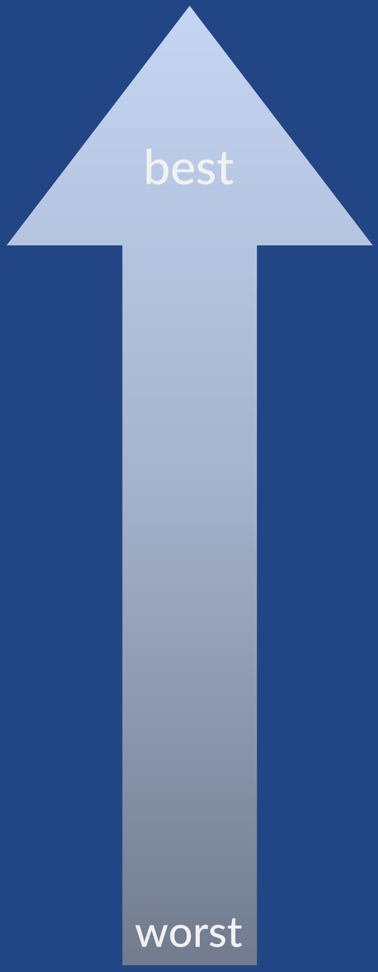
$$-\frac{dE}{\rho dx} = k\frac{Z}{A}\cdot\frac{z^{*2}}{\beta^2}\left(\log\frac{2\gamma^2\beta^2 m_e c^2}{I}-\eta\right)$$

Bethe-Bloch ~ $Z\,A^{-1}$

2) Particle break up:



COST!!!



Liquid H_2

Plastic (PE)

Water

Aluminum

Concrete

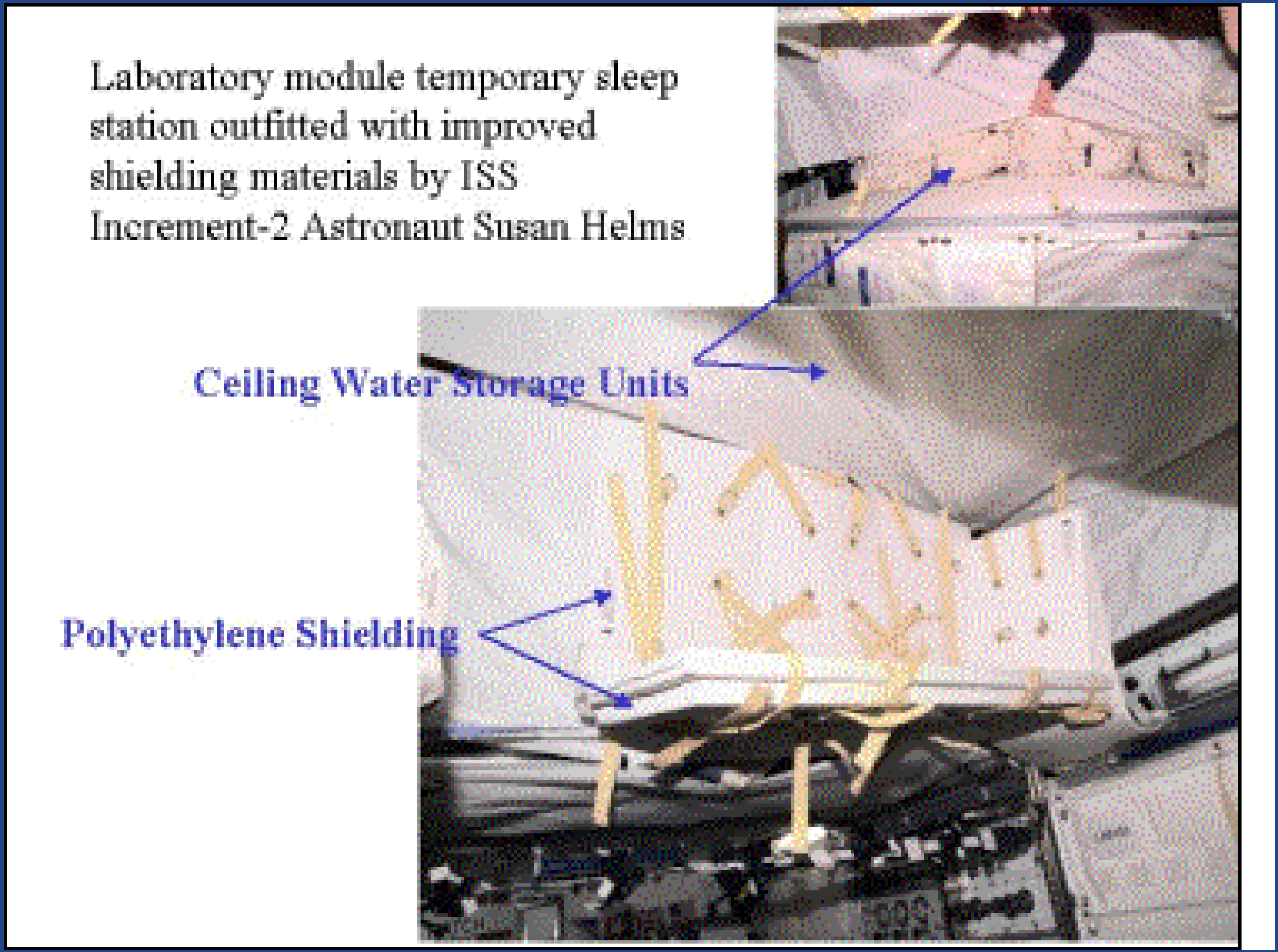
Lead

Shielding on Apollo missions

- Walls: aluminum, stainless steel
- No additional shielding besides heat shield (ablative plastic)

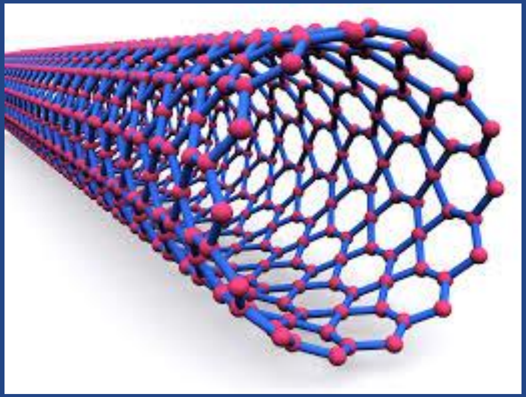
Shielding on ISS

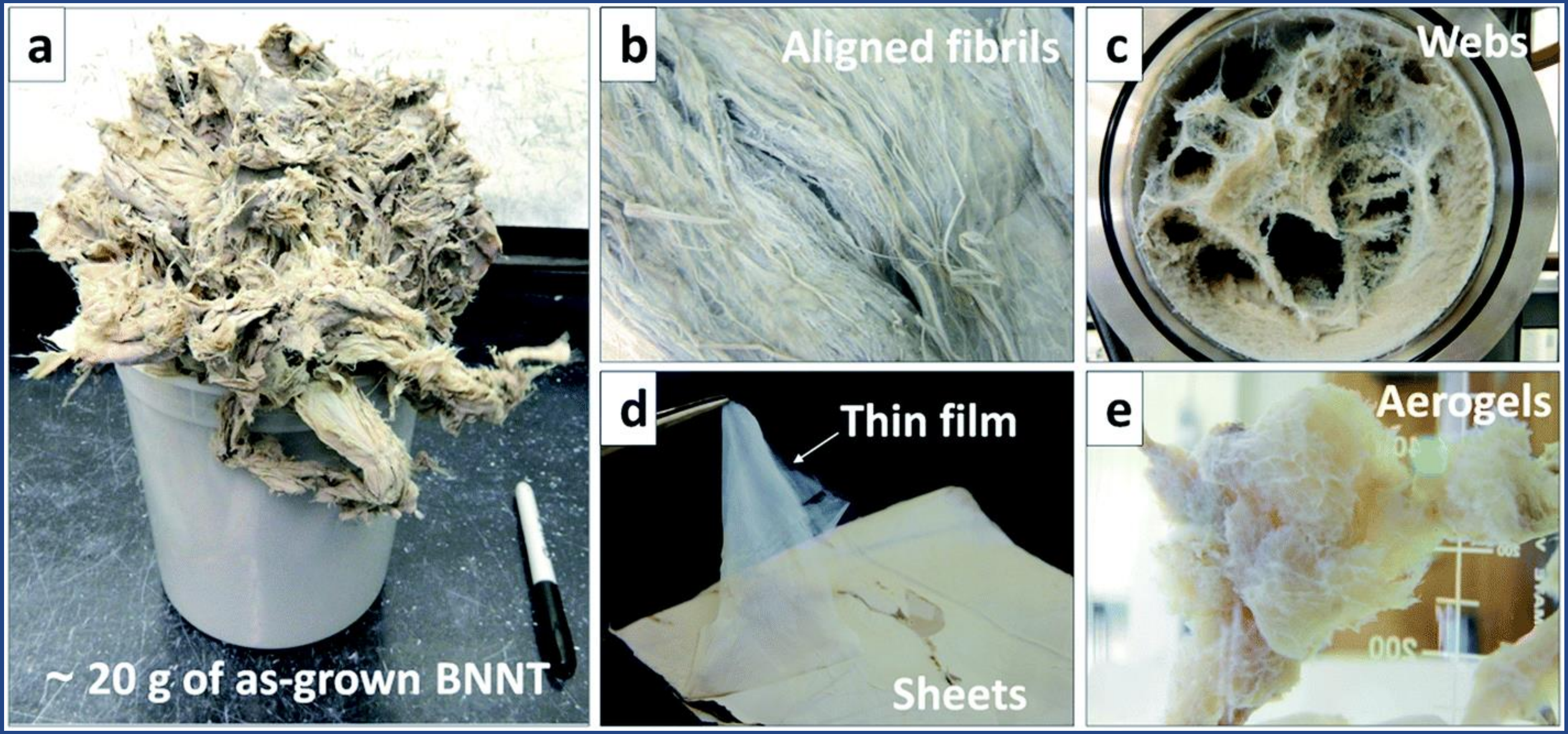
- Outside wall: aluminum
- Inside improvements: polyethylene and water



New materials

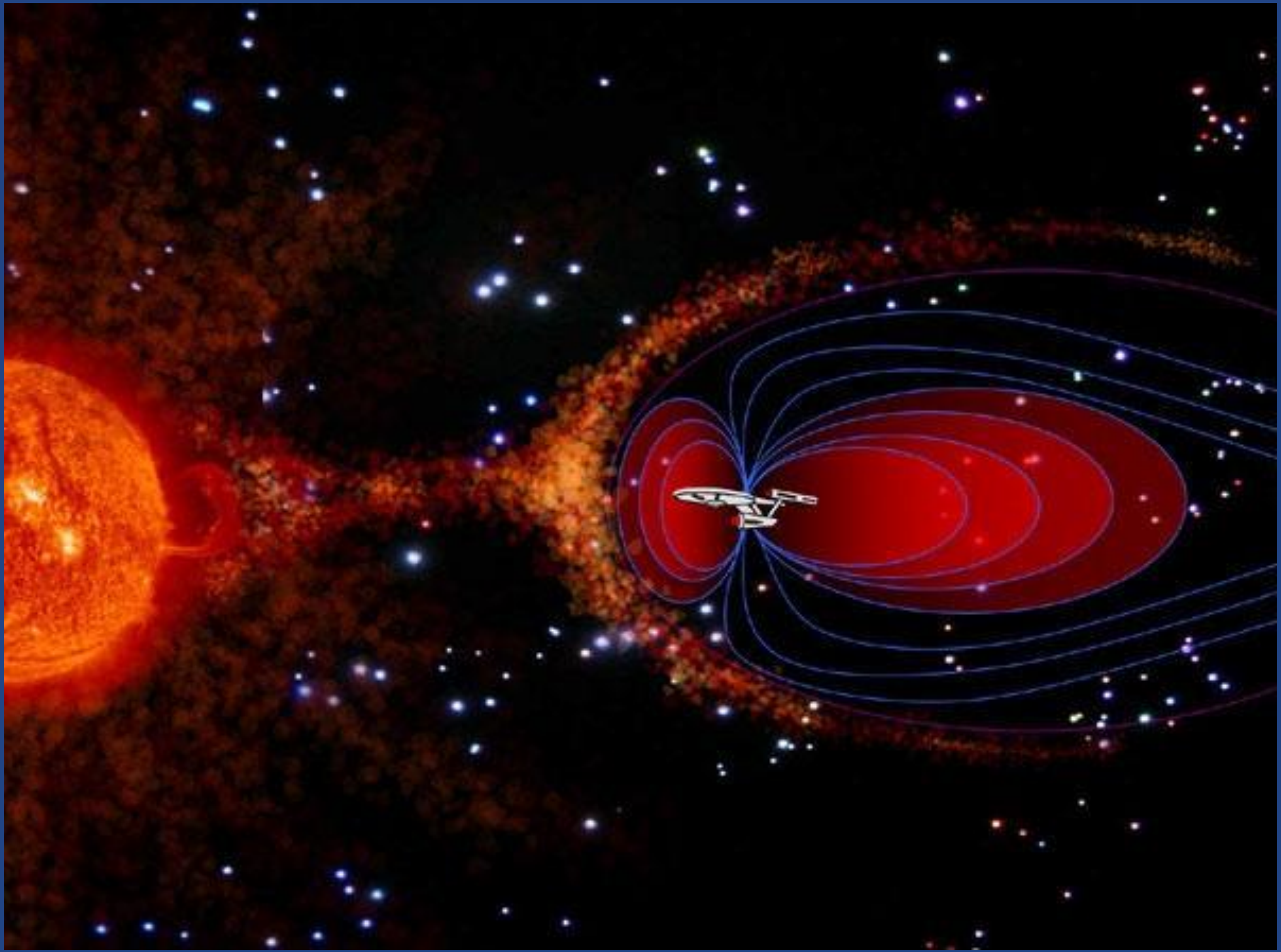
- Boron nitride nanotubes
  - Hydrogen storage or hydrogenation
  - Young modulus around 8 (10 for aluminum)
  - Stable until 1600 F (900 C)





Futuristic solution

- Spacecraft magnetic shielding

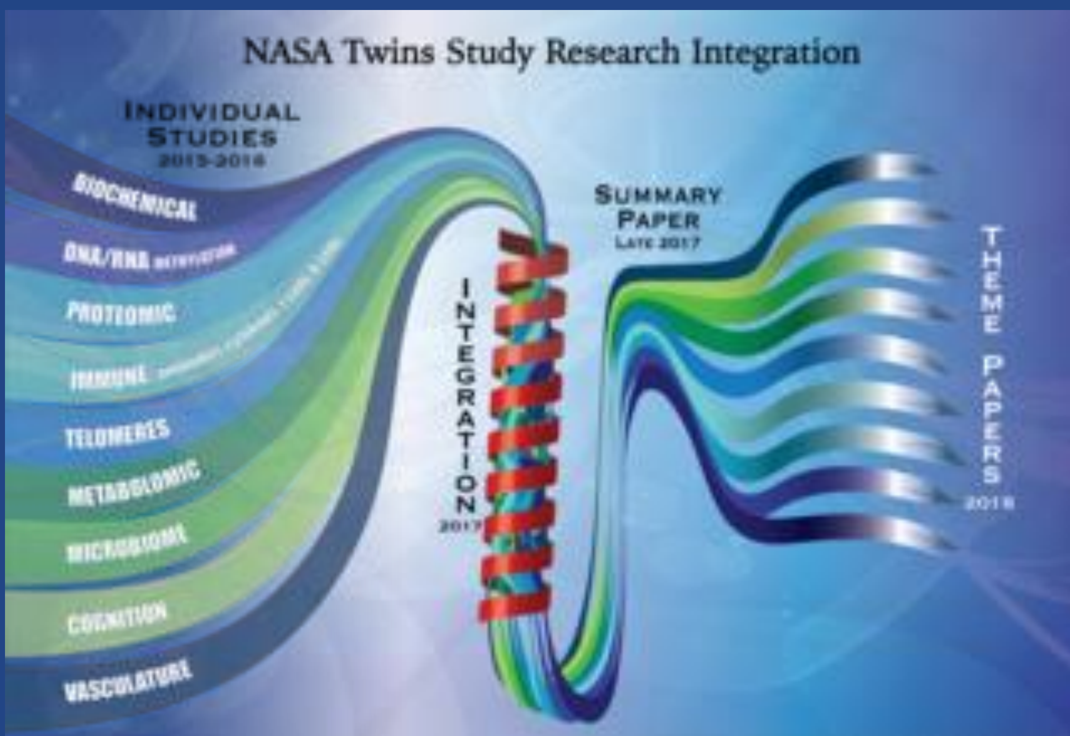


Estimating space travel risks

- Twins study: studying two individuals who have the same genetics, but are in different environments for one year

Scott Kelly → nearly one year living on ISS (returned march 2017
Mark Kelly → remained on Earth

12 investigations: human physiology, behavioral health, microbiology, microbiome, immunome, epigenomics, molecular or -omics studies…



Twins study: preliminary results from January 2018

- Telomeres: increased in length while in space but came back to preflight values in 48 hours
- Cognition: some decreases in cognitive performance after return
- Immunological responses: flu vaccine given aboard the space station produces same immune stimulation
- Microbiome: changes observed inflight can be explained by change in diet
- Genetics: 93% of genes' expression returned to normal postflight, 7% remained changed
- Atherosclerosis: biomarkers of inflammation elevated and the carotid artery wall thickened during and immediately after