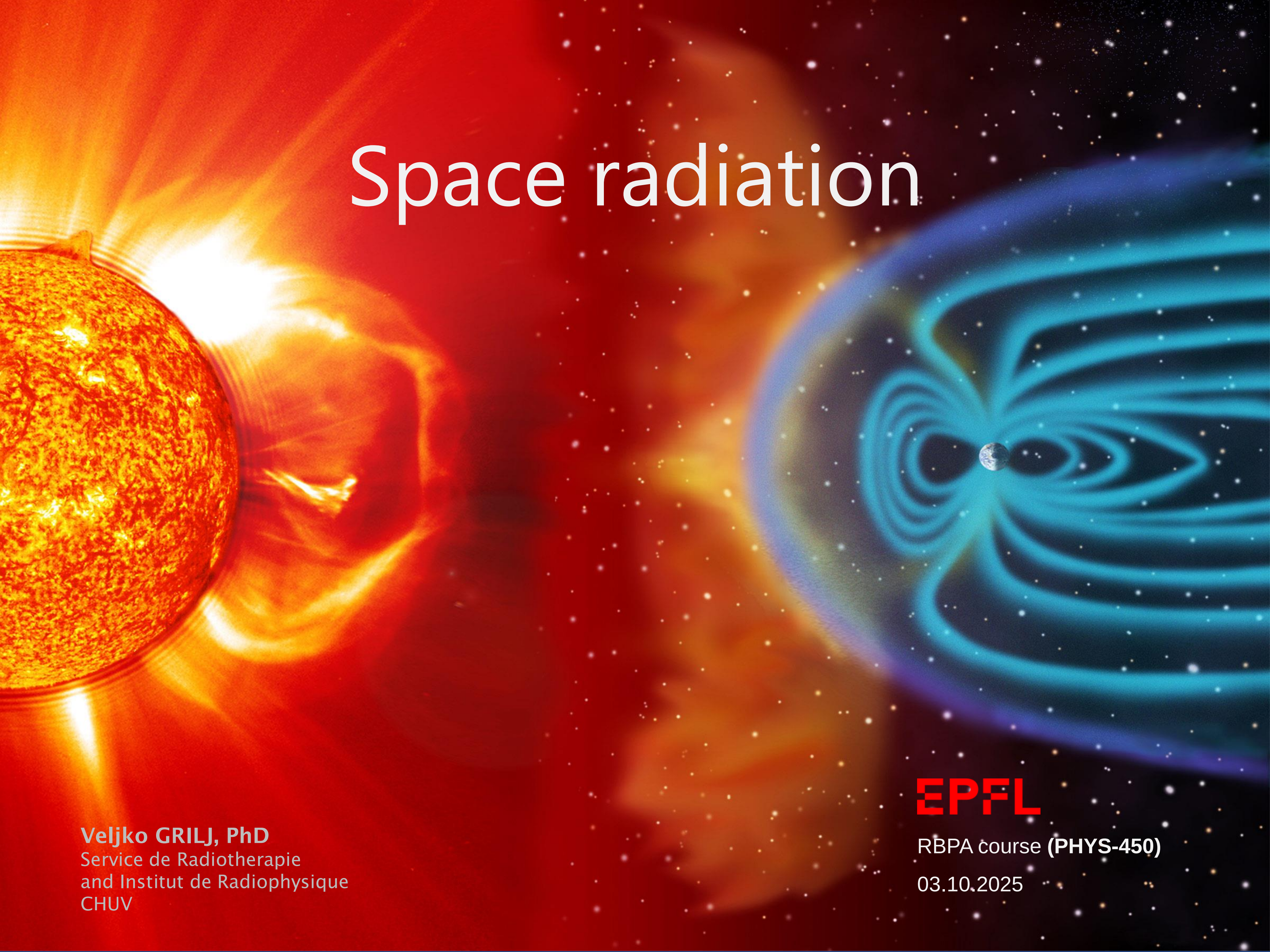


Space radiation

Veljko GRILJ, PhD
Service de Radiotherapie
and Institut de Radiophysique
CHUV

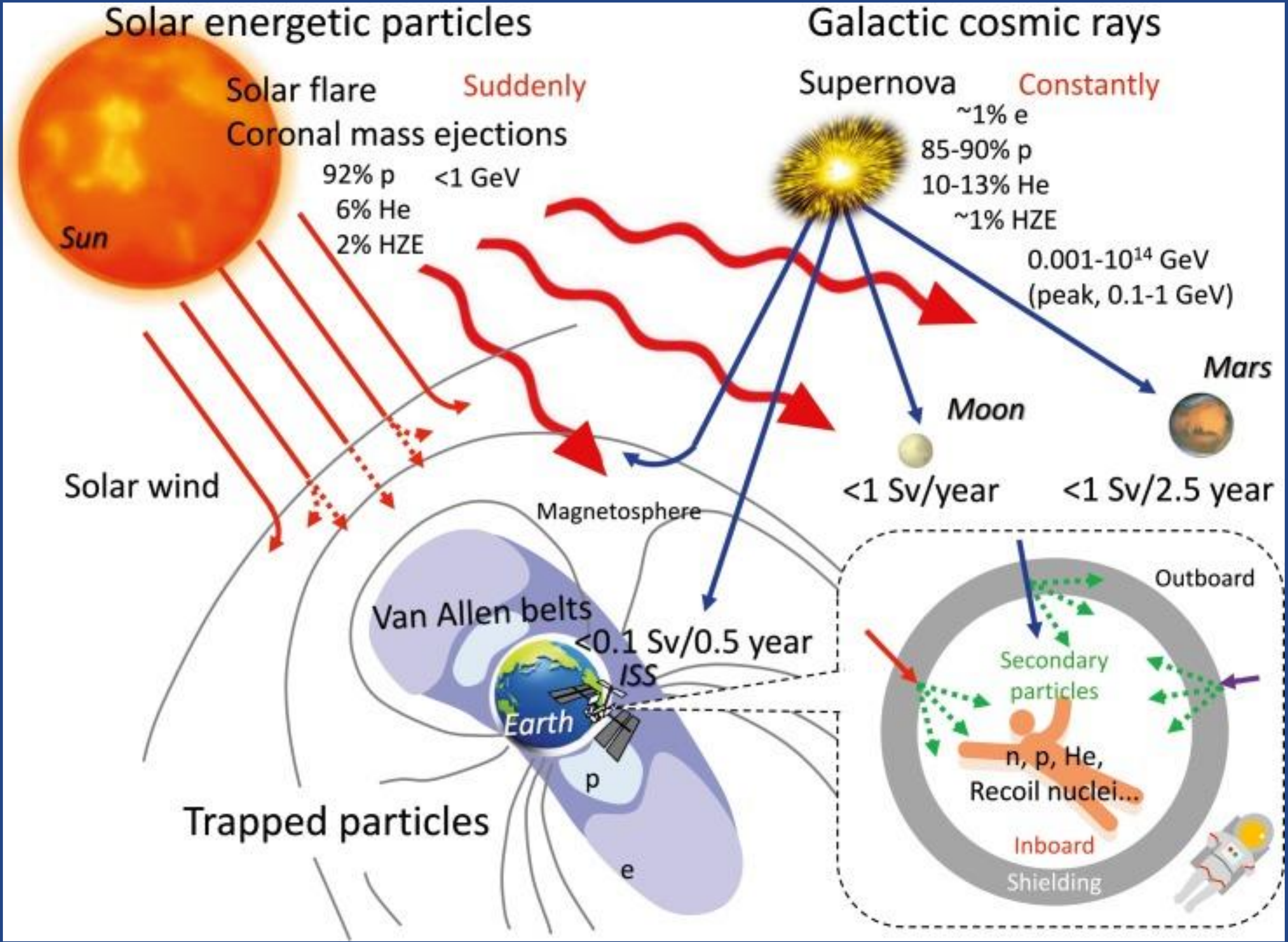
EPFL

RBPA course **(PHYS-450)**

03.10.2025

- What are sources of radiation in space?
- What is space radiation composed of?
- How are we protected from space radiation?

Overview of Lecture 4



Cosmic Rays

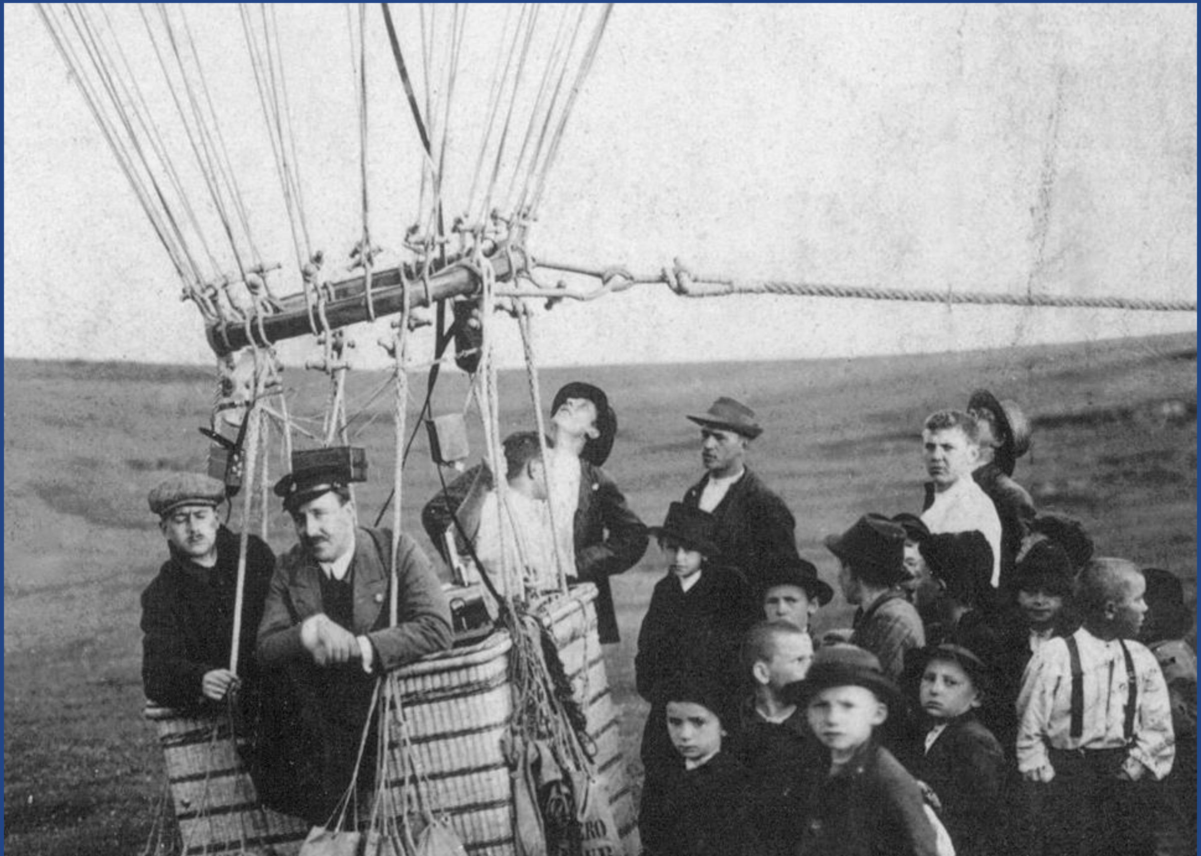
Discovery of Cosmic Rays

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

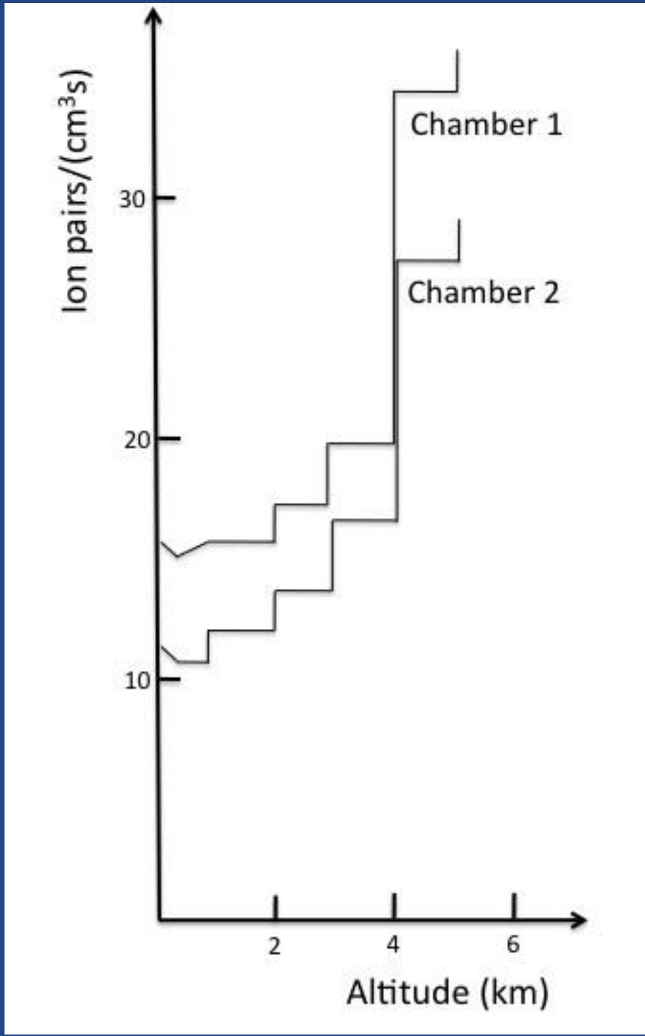
- In 1910, Thedore Wulf measured the intensity of radiation at the top of the Eiffel tower (300m), it was about a half of that on the Earth's surface
- According to calculations, at 300m above Erath the intensity of radiation should be only a few percent of that at the surface
- He concluded that there is radiation coming from above

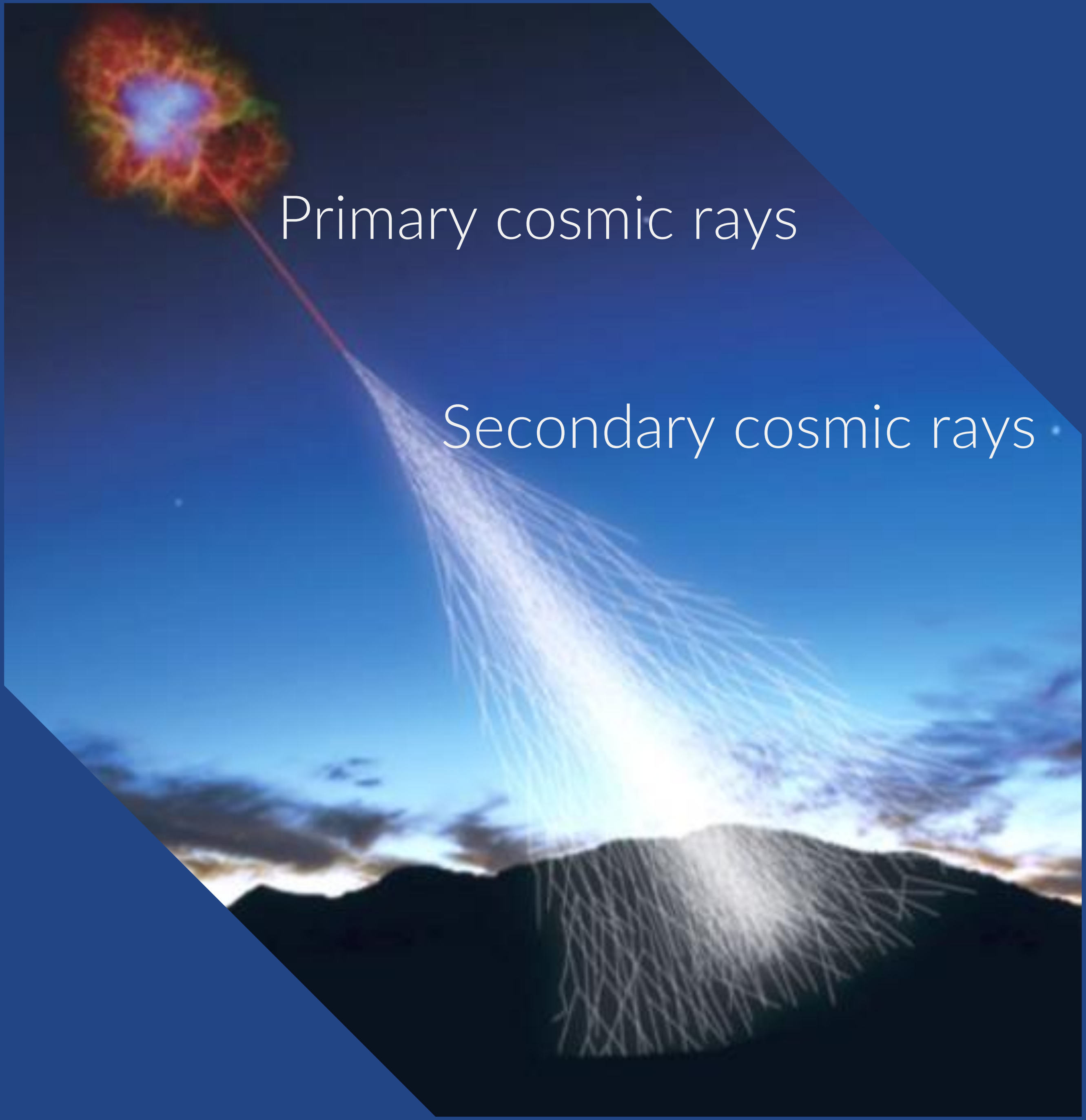
Discovery of Cosmic Rays

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



"The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above"




Primary cosmic rays
Secondary cosmic rays

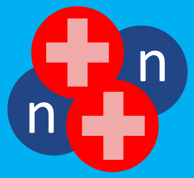
What are primary Cosmic Rays composed of?

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

Composition:

90% protons

9% helium



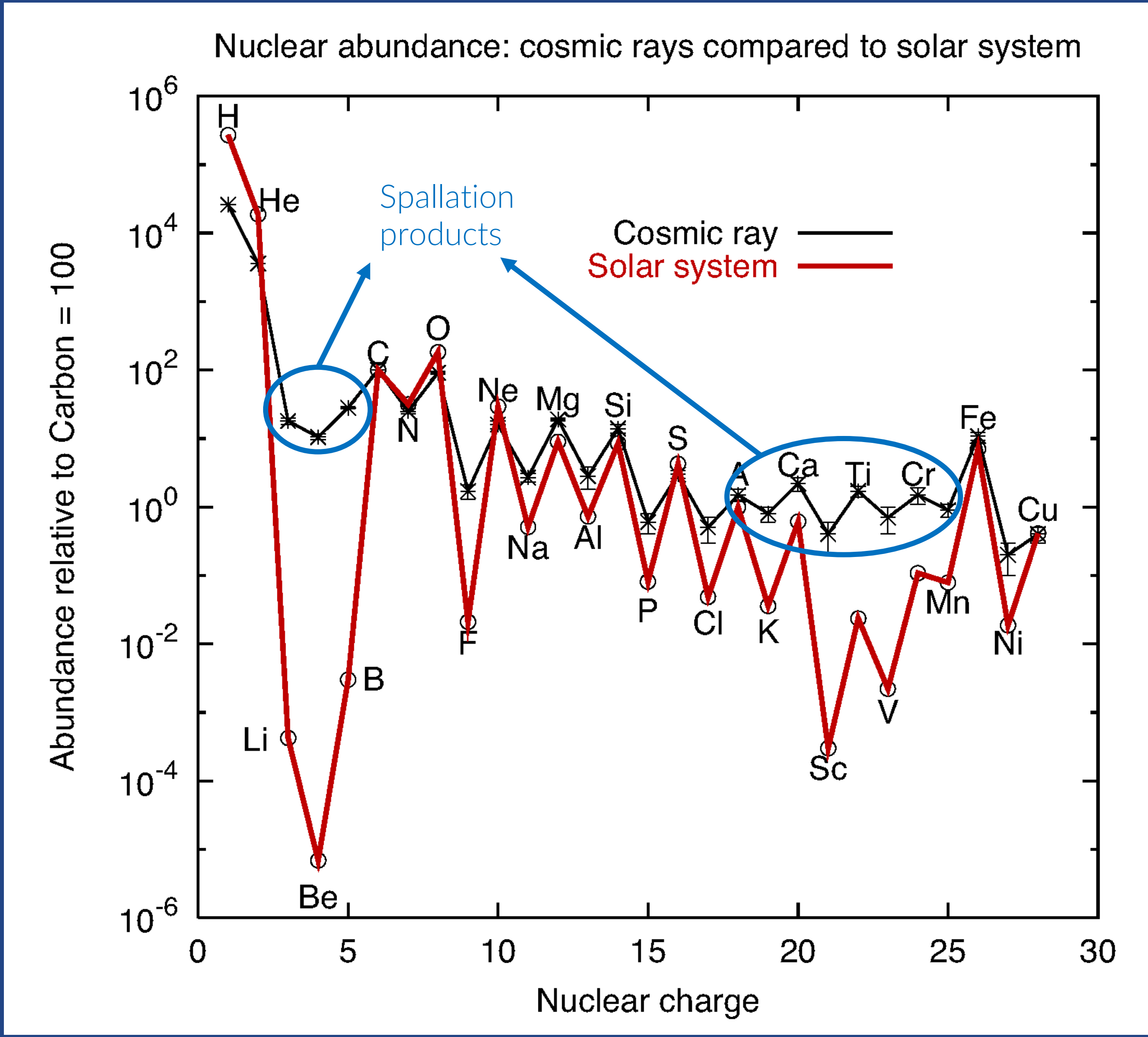
1% other

Heavy nuclei

Electrons

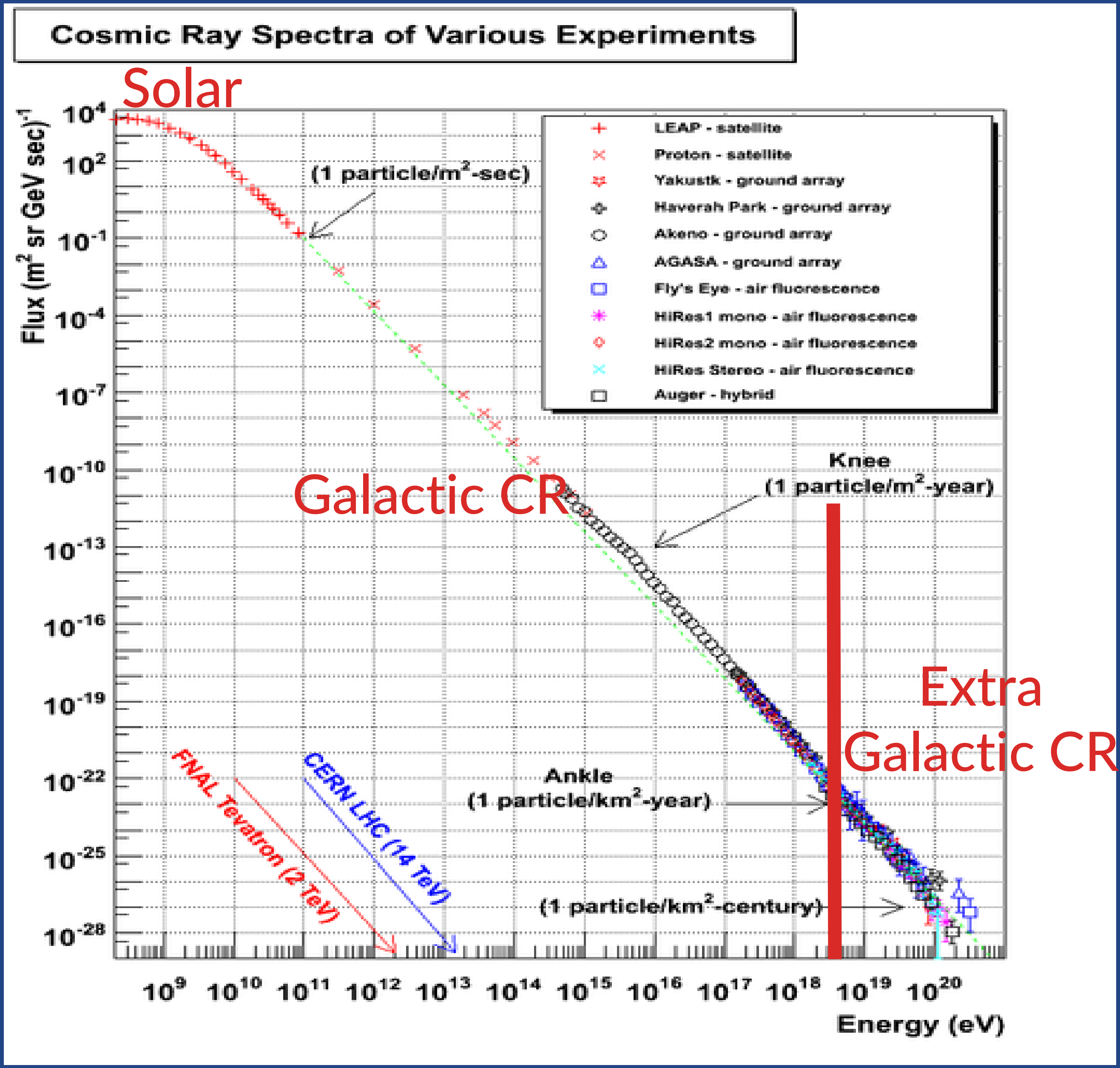
Positrons

What are primary Cosmic Rays composed of?



- ➢ Chemical composition of cosmic rays indicates their stellar origin

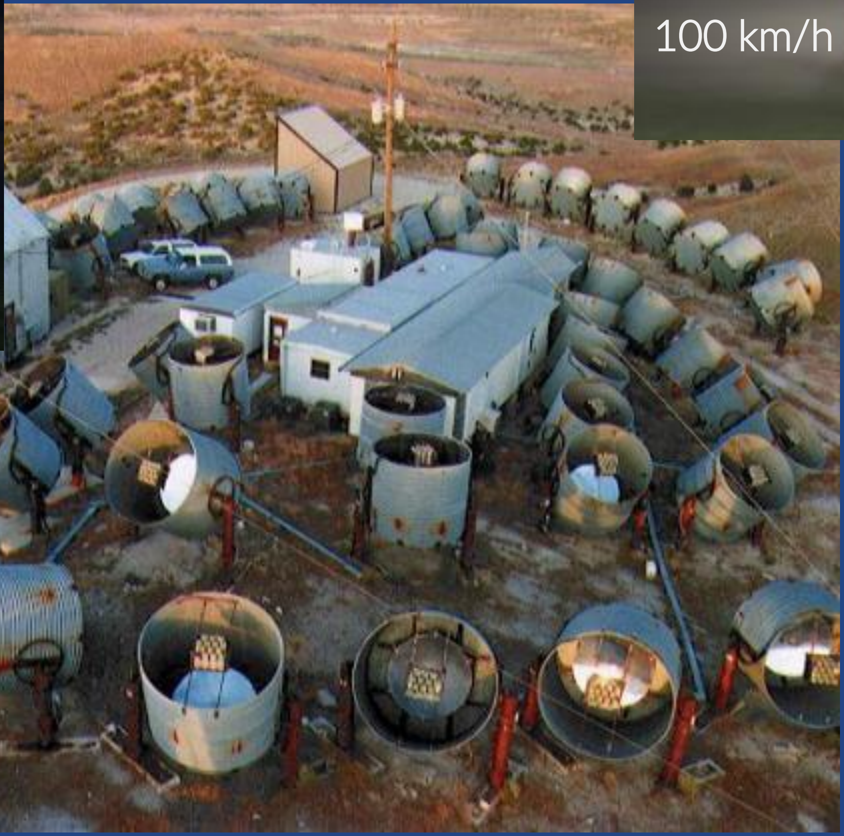
Energies of primary cosmic rays



Highest energy cosmic ray

- High energetic CR produce cascades of secondary radiation in atmosphere

"Oh-My-God" particle: Fly's Eye Mirrors, Utah, USA – highest-energy ($3x10^{20}$ eV) cosmic ray ever detected by observing UV light produced by excited nitrogen molecules (atmospheric fluorescence).

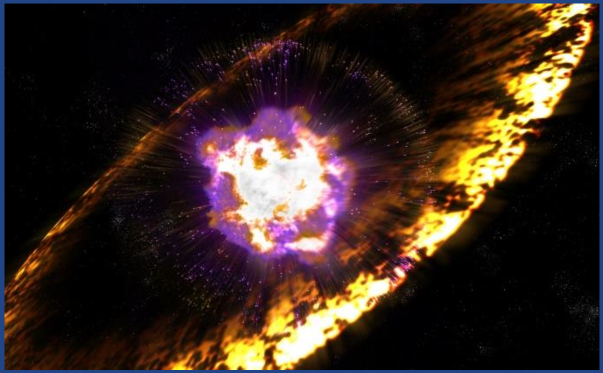


Where do primary cosmic rays come from?

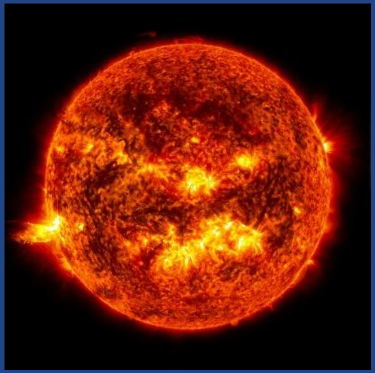
Sources of primary cosmic rays:

Galactic sources

Supernova remnants



Sun

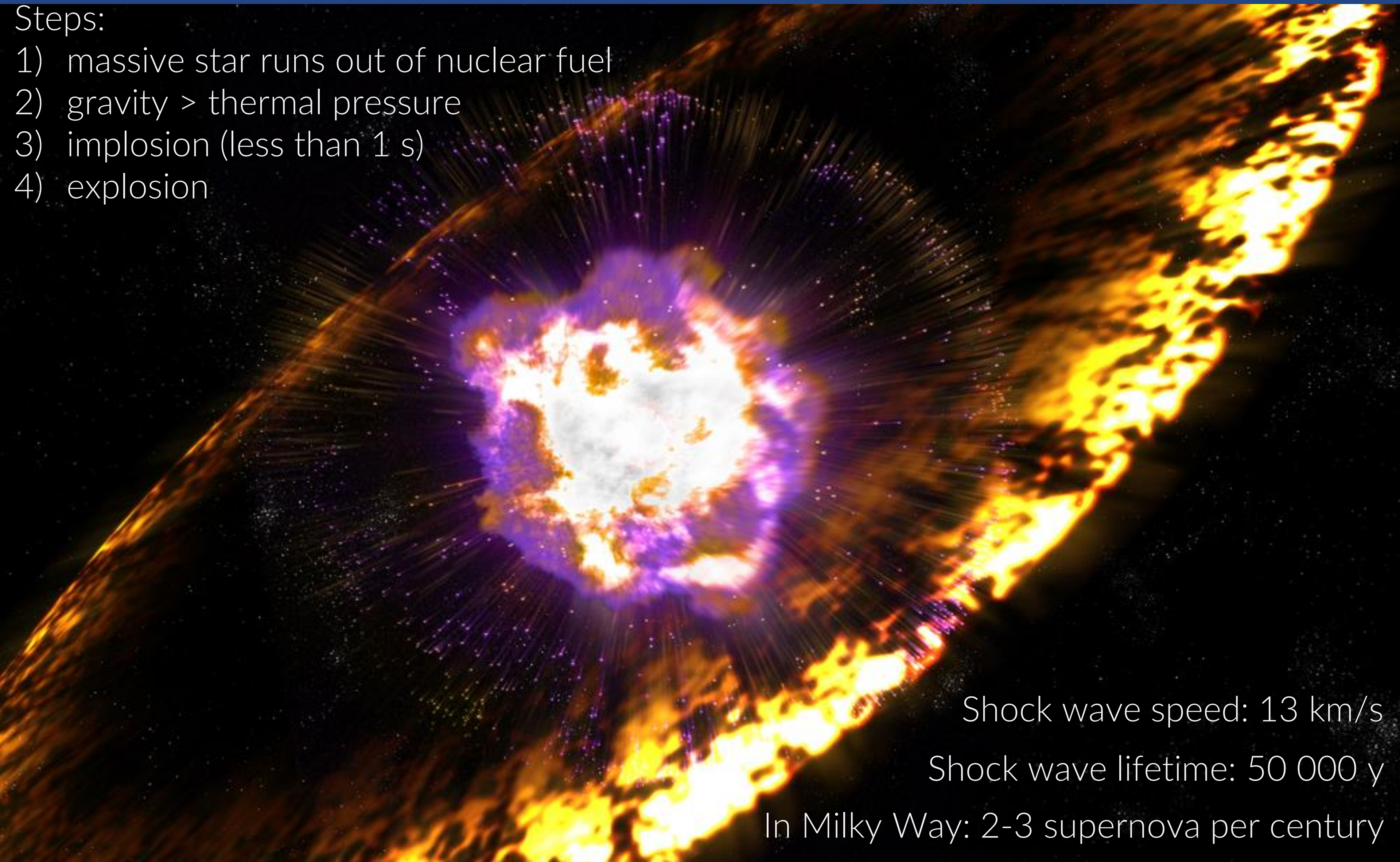


Extra galactic sources

Unknown (Active Galactic Nucleus?)

Cosmic rays from supernova (SN) remnants

- majority of cosmic rays are accelerated by SN shock waves



Steps:

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

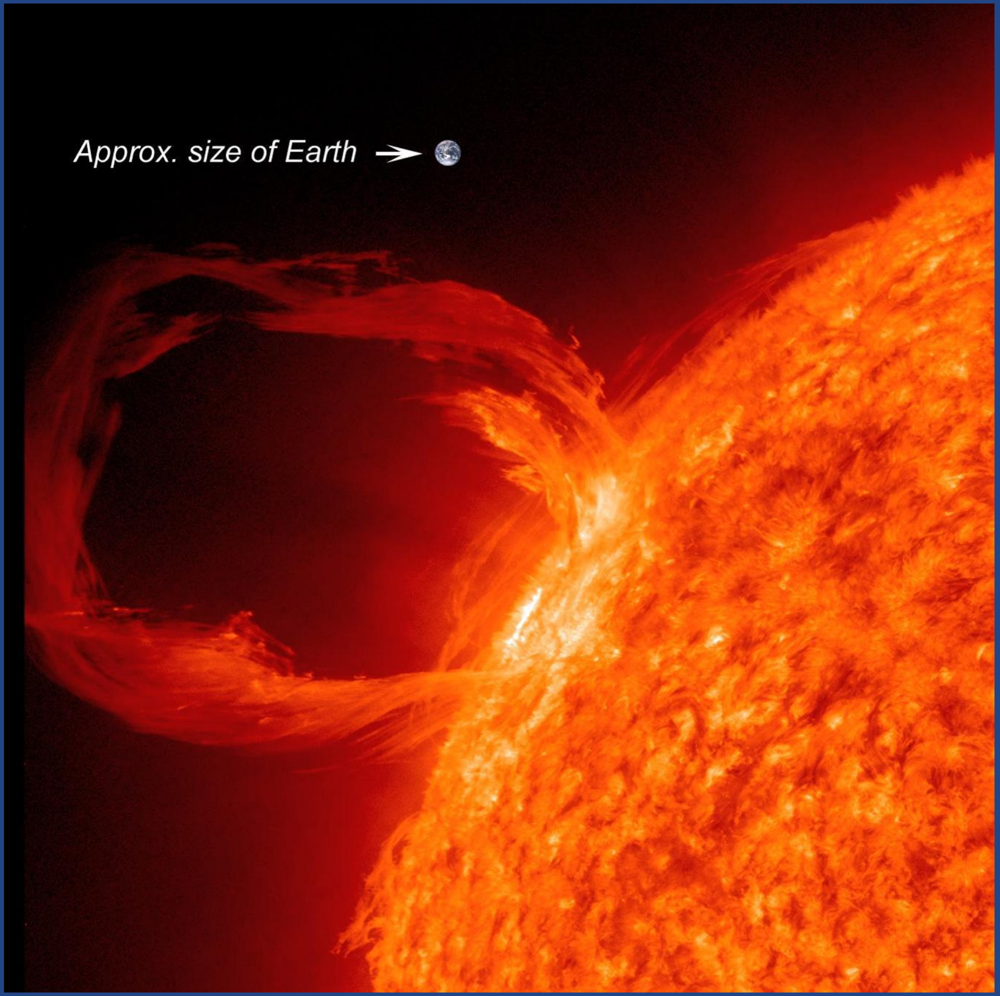
Shock wave speed: 13 km/s

Shock wave lifetime: 50 000 y

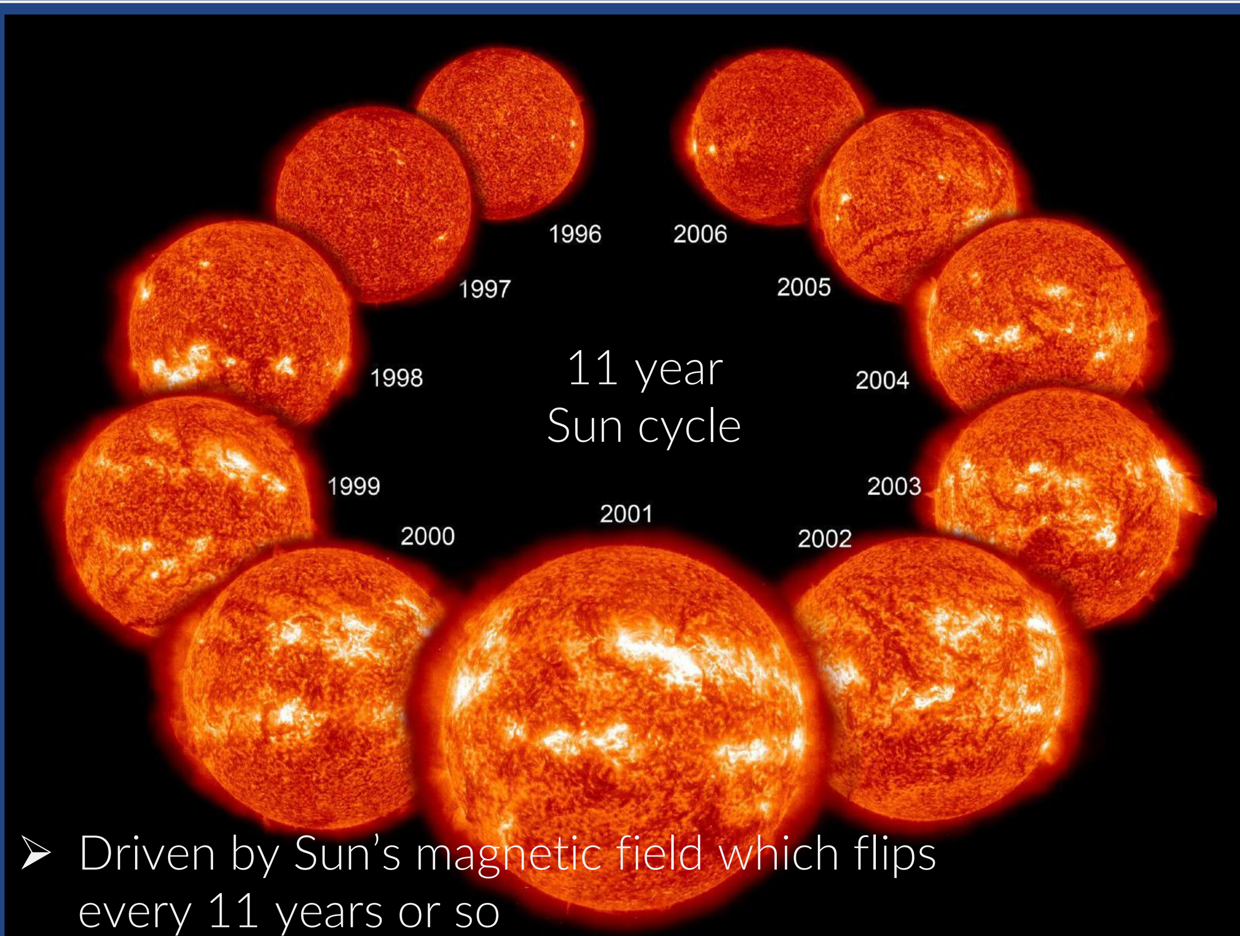
In Milky Way: 2-3 supernova per century

Cosmic rays from the Sun

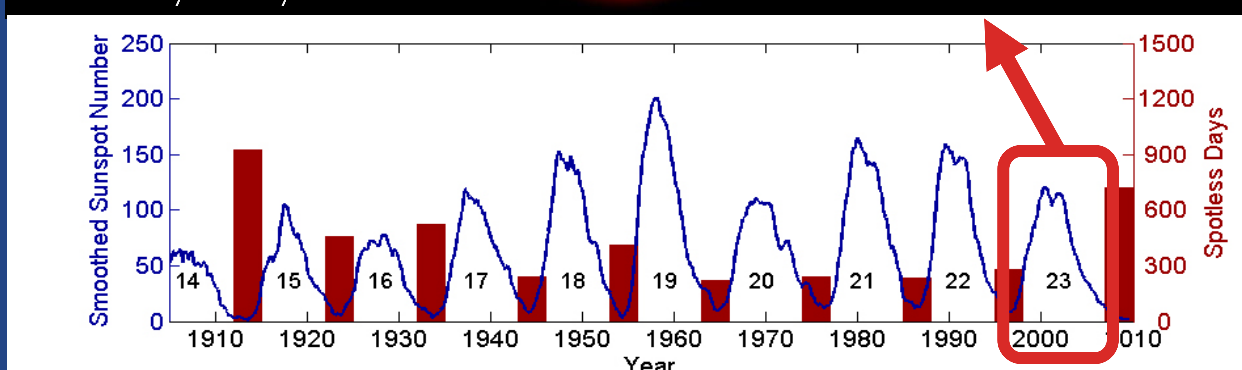
- Protons (95 %) and electrons but also heavier elements
- Up to 10 GeV (low energy compared to GCR)
- During a solar storm the flux of solar CR can increase by a factor of 100 000



Cosmic rays from the Sun



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



Space weather

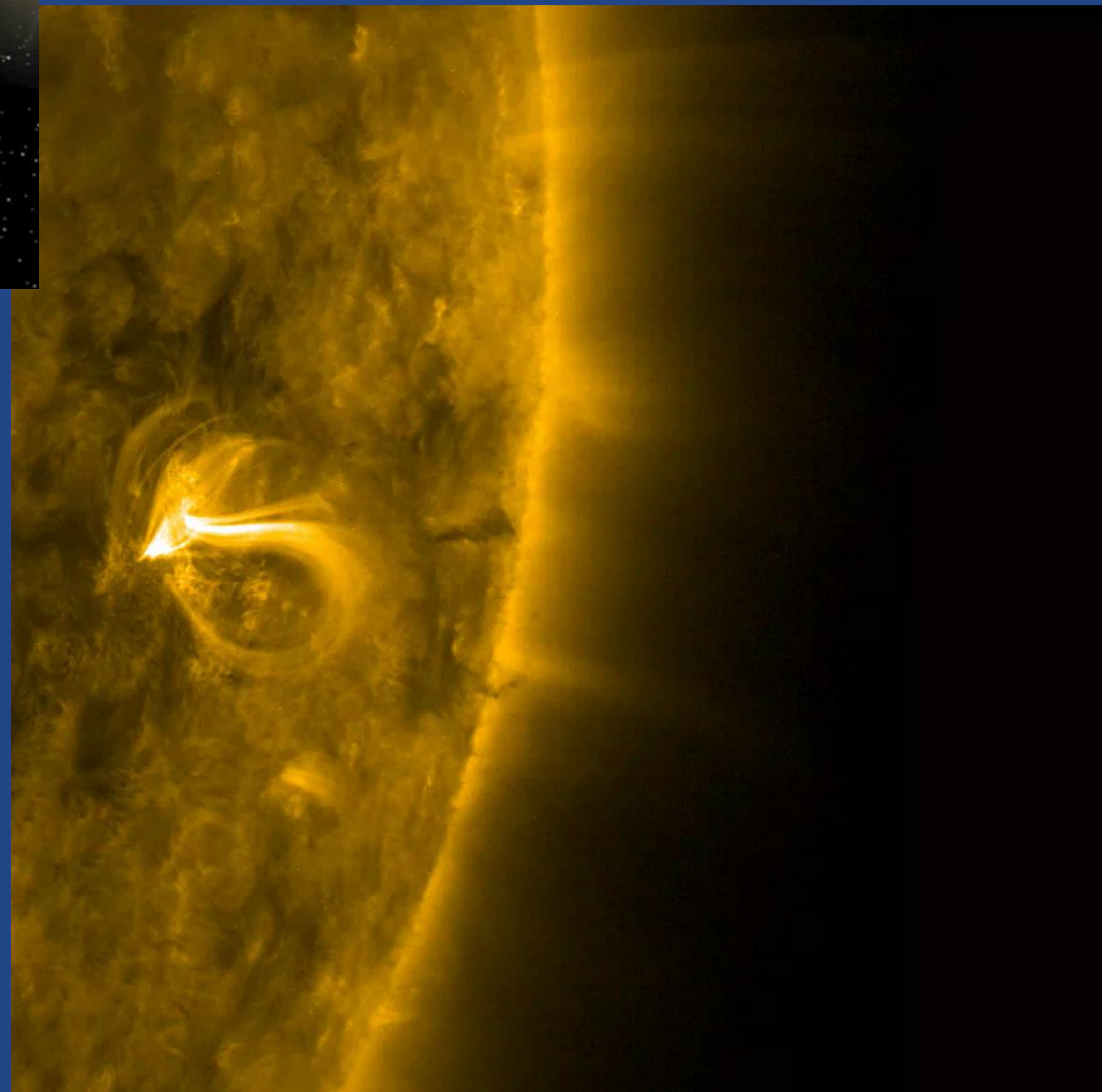
- ➢ Solar wind
- ➢ Solar flares
- ➢ Coronal mass ejection

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

- Particle flux from CME is enough to kill a man
- During solar maximum: ~ 3 CME per day
- During solar minimum: ~ 1 CME per 5 days

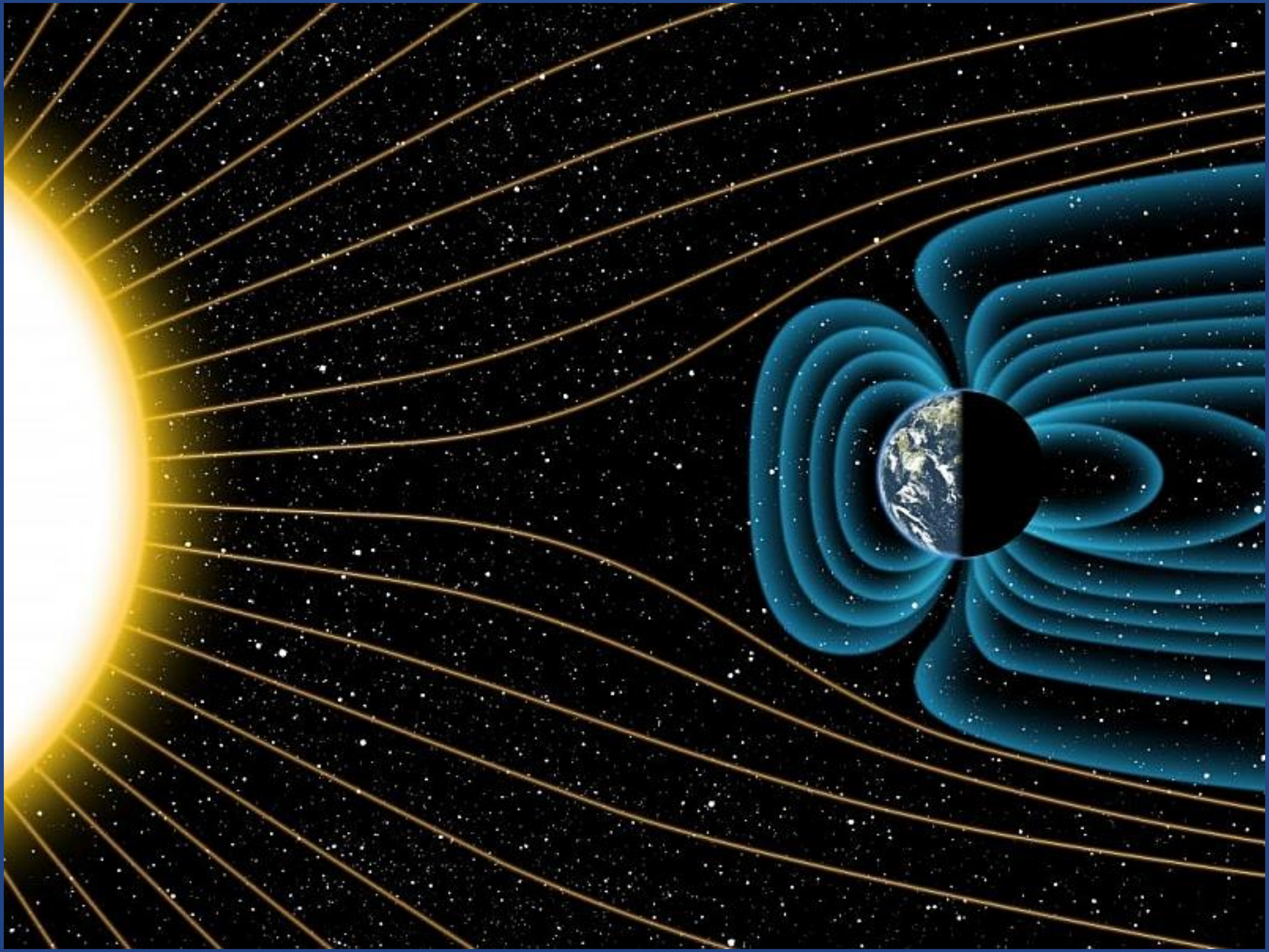
Coronal mass ejection

- CME recorded by Atmosphere Imaging Assembly aboard NASA's Solar Dynamics Observatory on 22.01.2018

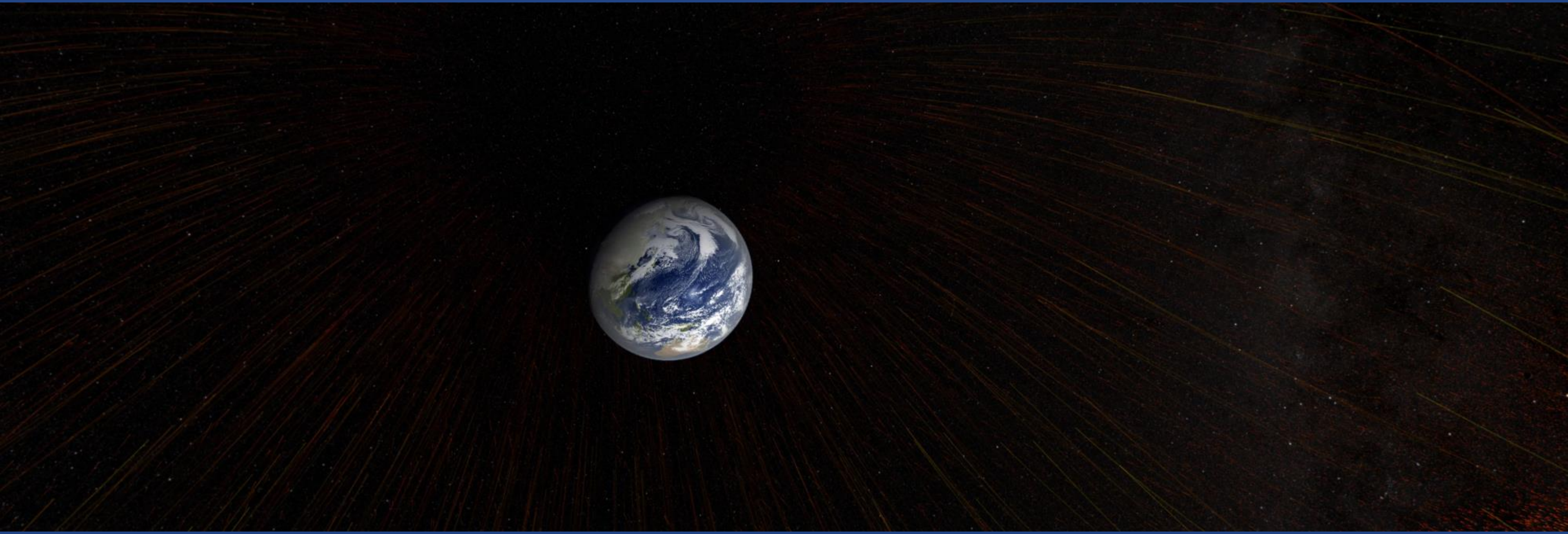


How is Earth protected?

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



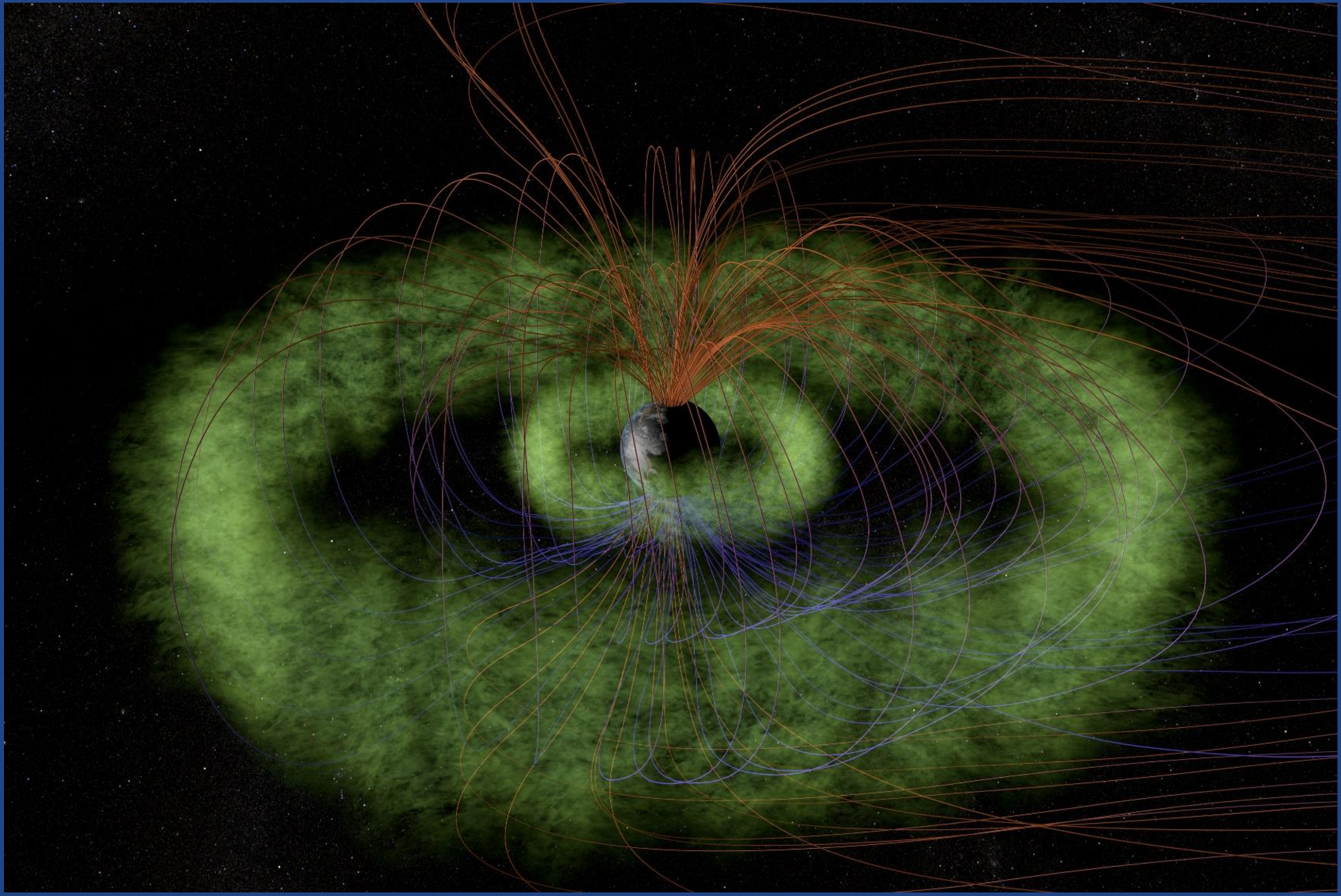
Magnetosphere shielding from Solar CR



Van Allen belts

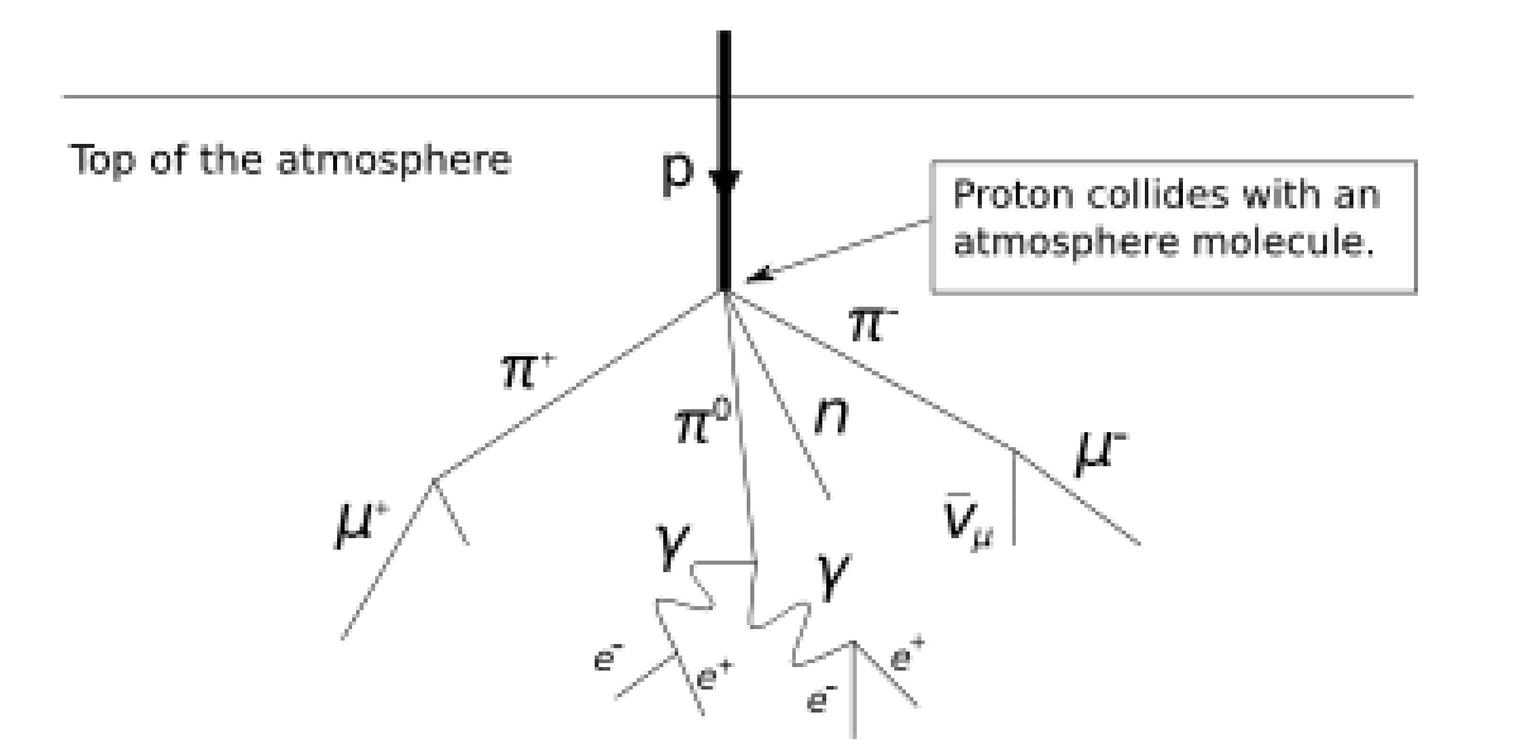
- ➢ Magnetic field traps charged particles

- Inner belt (1000 – 10 000 km above Earth); outer belt (15 000 – 60 000 km above Earth)
- Inner belt composed of protons from CR Albedo neutron decay, outer mainly electrons from the sun



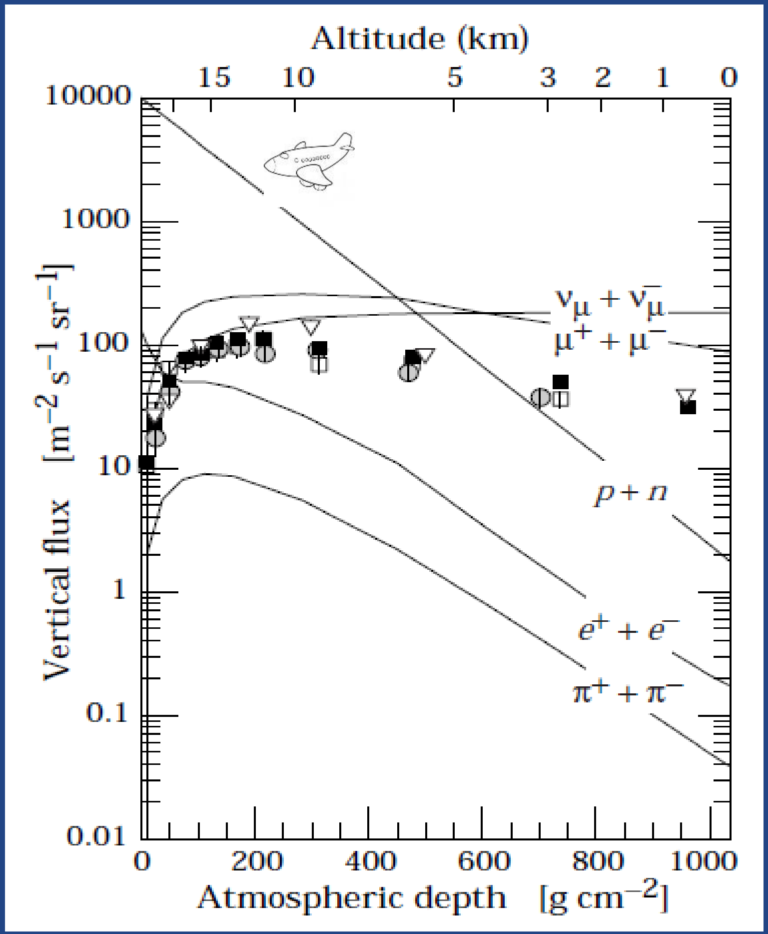
What gets through the magnetosphere and atmosphere?

- 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: muons, pions, neutrons, electrons, photons ✓



Cosmic rays around us

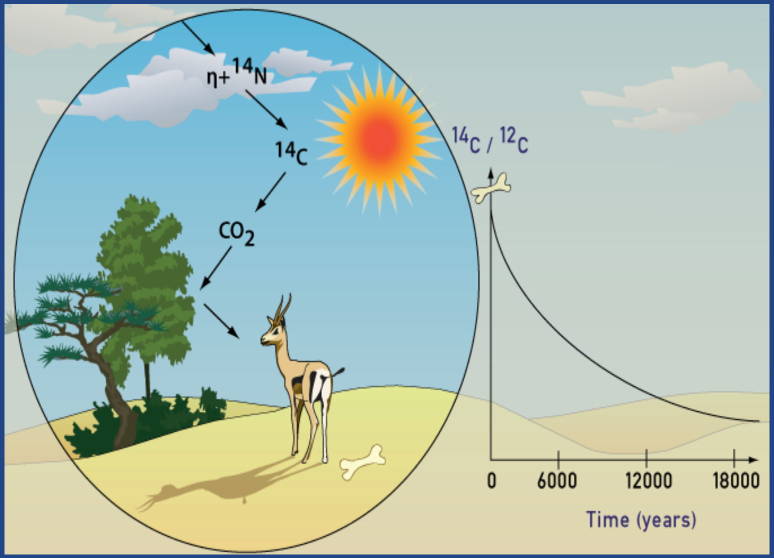
- Cosmic ray fluxes decrease through the atmosphere:



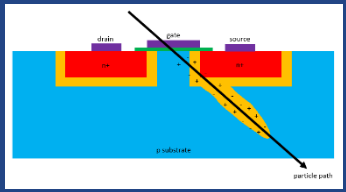
At sea level:
Mostly muons (1 per s through palm)

- Non-radiobiological effects of Cosmic rays:

1) Carbon-14 dating



2) Single event upsets
- bit flip in electronics

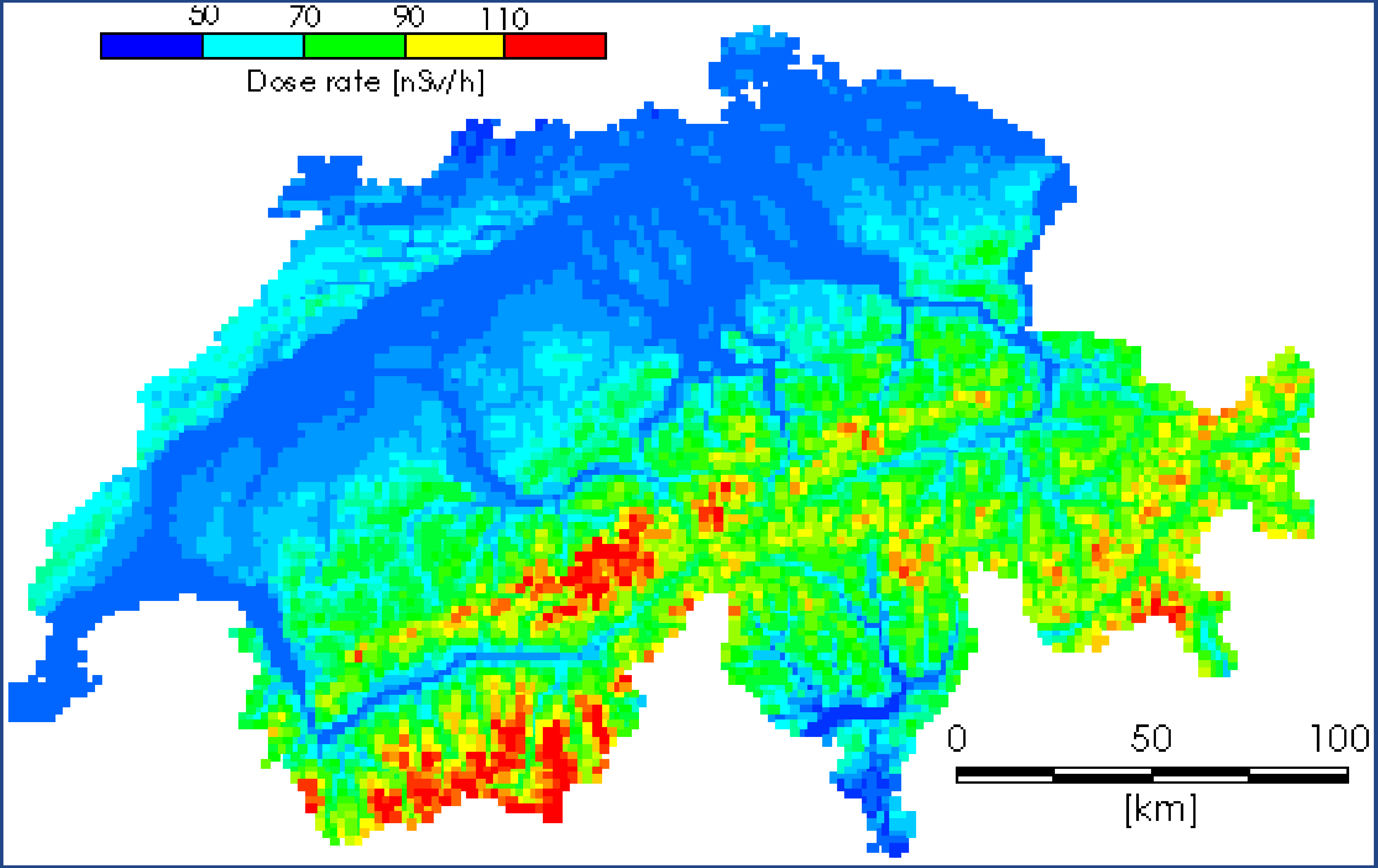


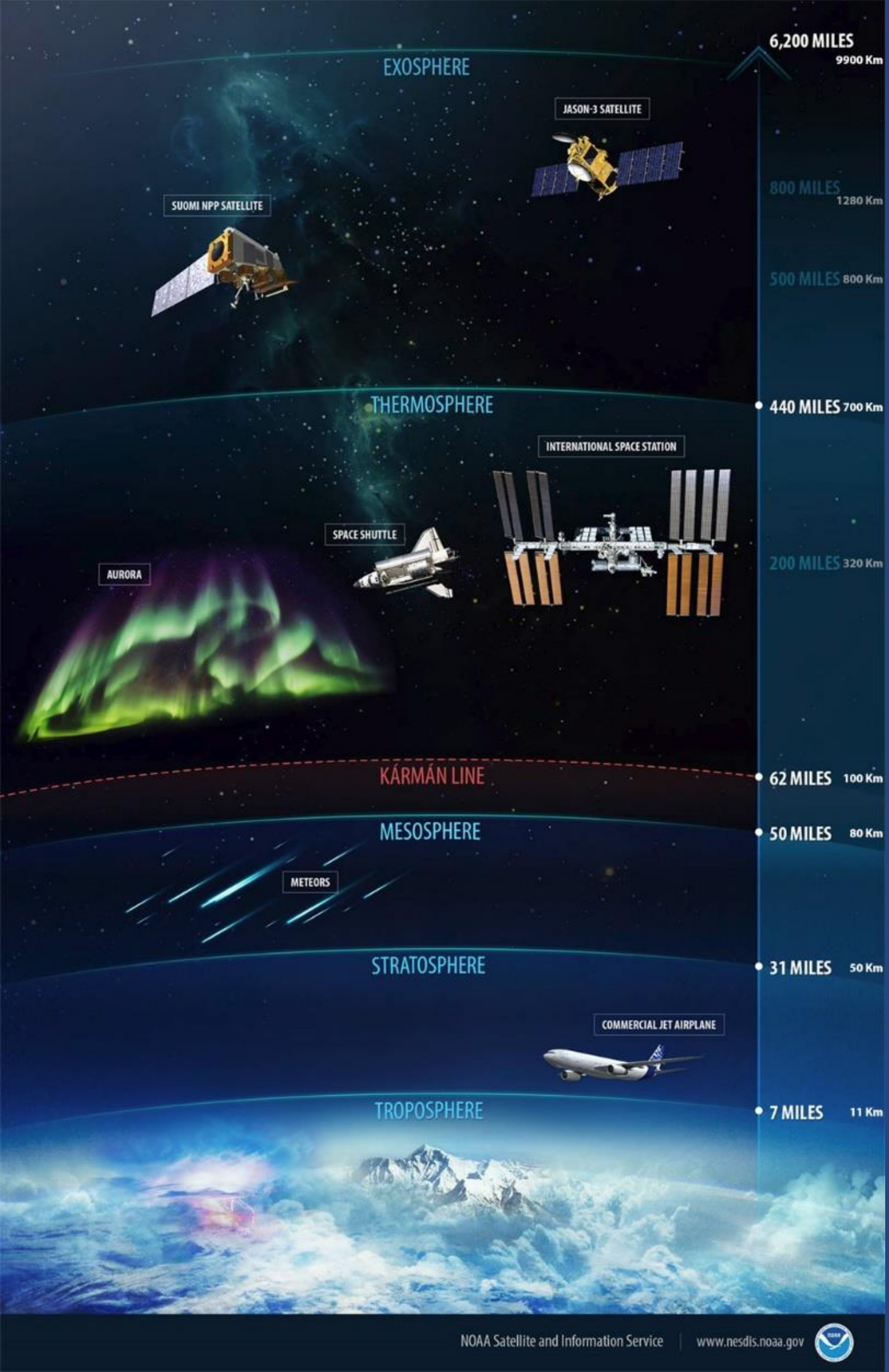
3) Communication system upsets
- geomagnetic storms (CME)
- GPS, satellites…

Space Radiation as Health Hazard

Space radiation dose on Earth

- Cosmic dose rate map of Switzerland



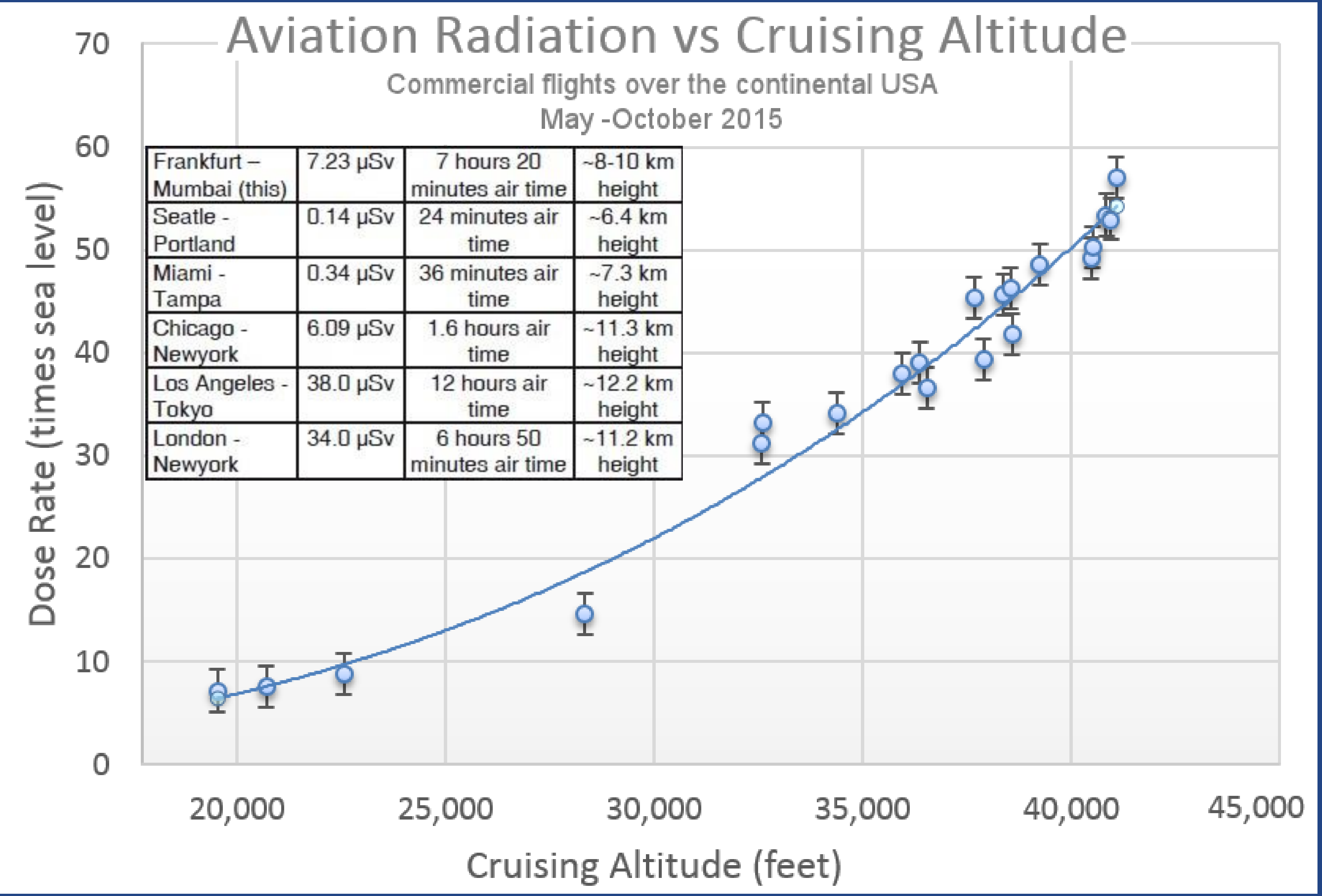


Interplanetary

Astronauts, ISS

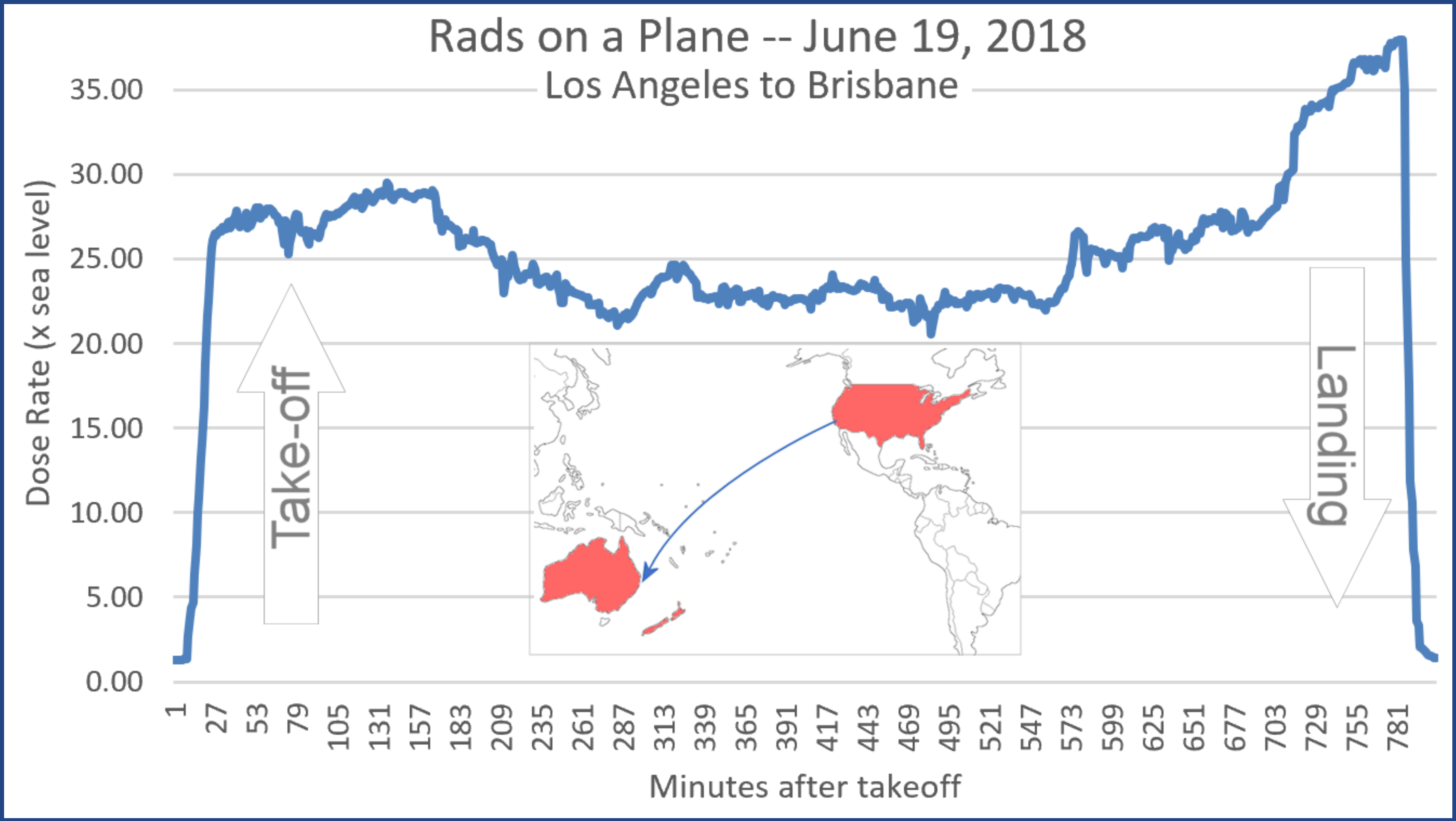
Air crew

Space radiation dose during commercial flights



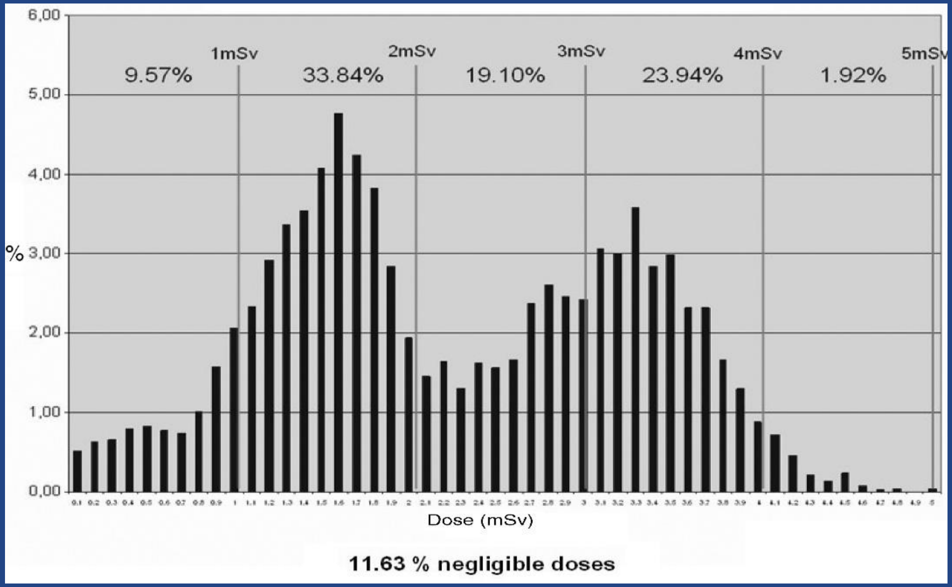
Frankfurt – Mumbai (this)	7.23 μSv	7 hours 20 minutes air time	~8-10 km height
Seatle - Portland	0.14 μSv	24 minutes air time	~6.4 km height
Miami - Tampa	0.34 μSv	36 minutes air time	~7.3 km height
Chicago - Newyork	6.09 μSv	1.6 hours air time	~11.3 km height
Los Angeles - Tokyo	38.0 μSv	12 hours air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

Dose accumulation on flight from US to Australia



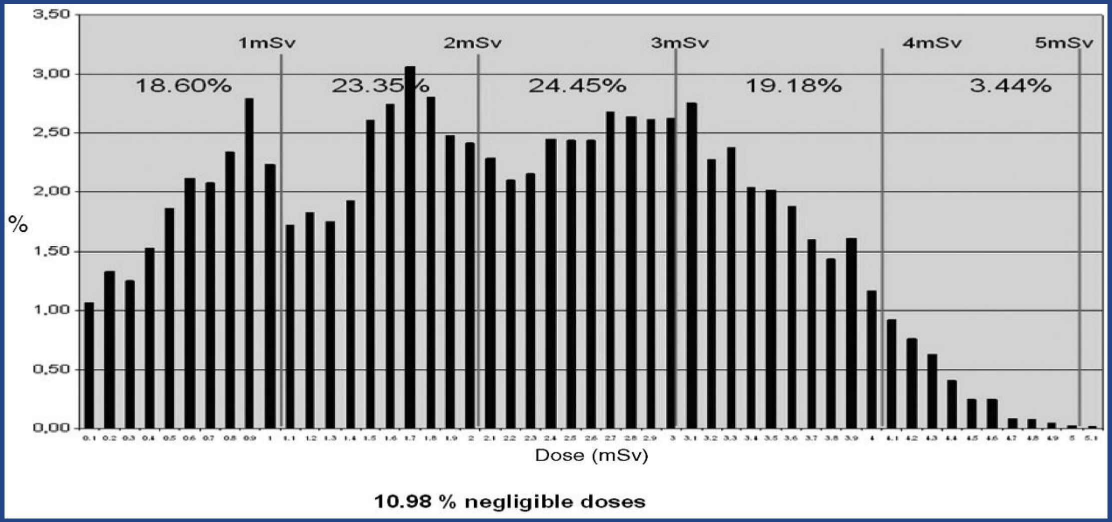
Space radiation dose for air crew

Dose distribution for flight deck crew



Air France data for 2007

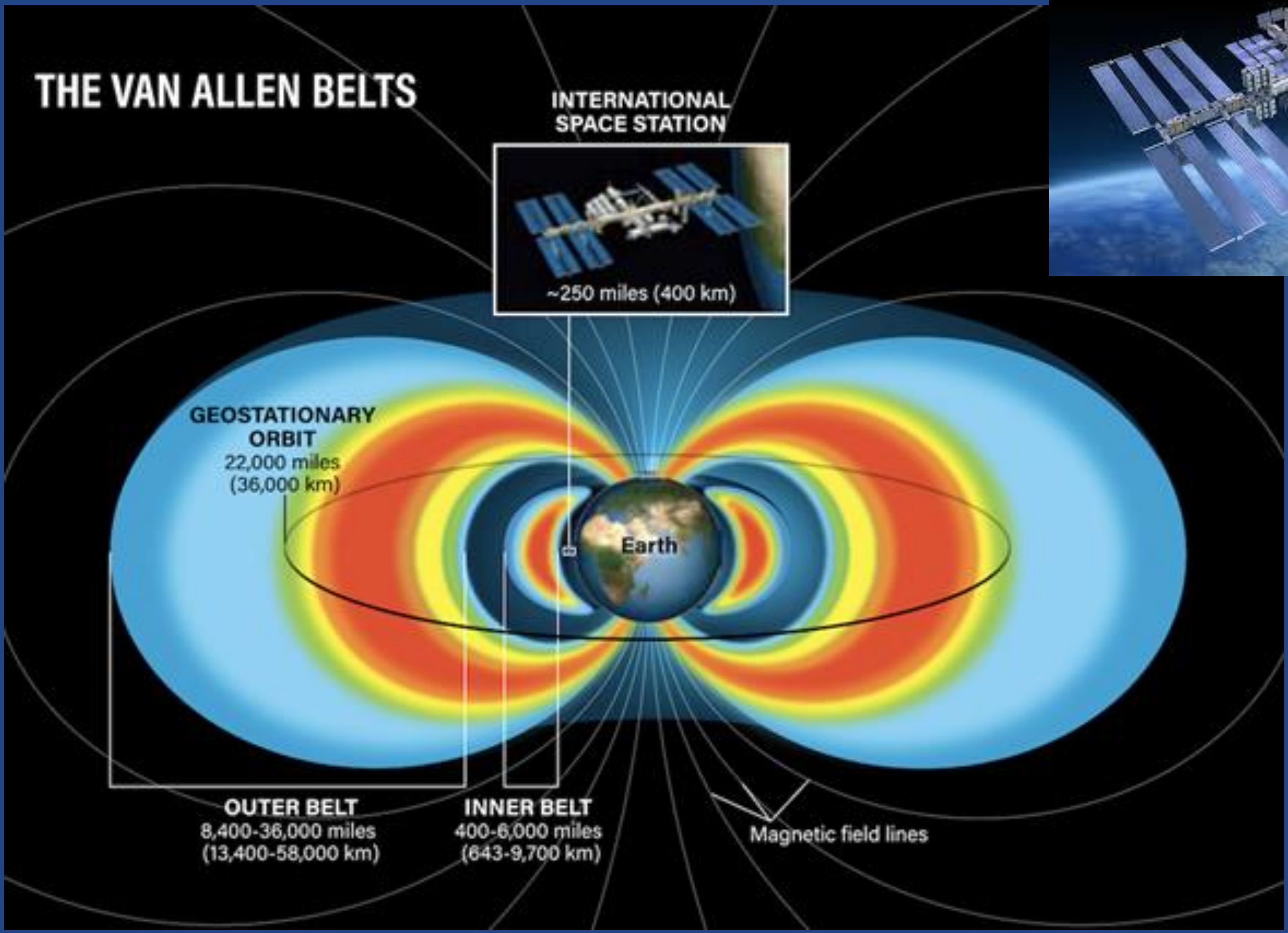
Dose distribution for cabin crew



- Annual average dose for flight crew is around 2 mSv
- Over a 40-y career that is 80 mSv

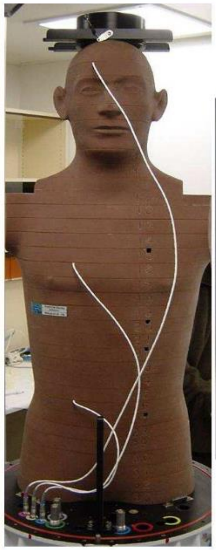
Radiation dose on ISS

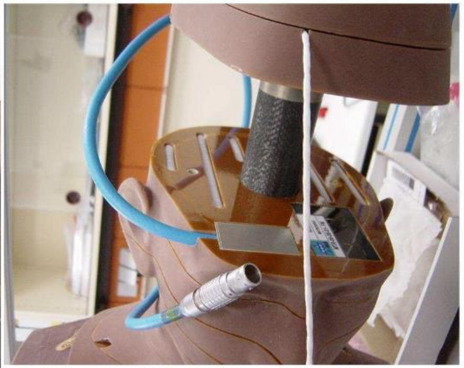
- 6 month stay at ISS: 80 mSv - 160 mSv
  - ISS is outside of the atmosphere but still below the magnetosphere



Dose measurements on ISS

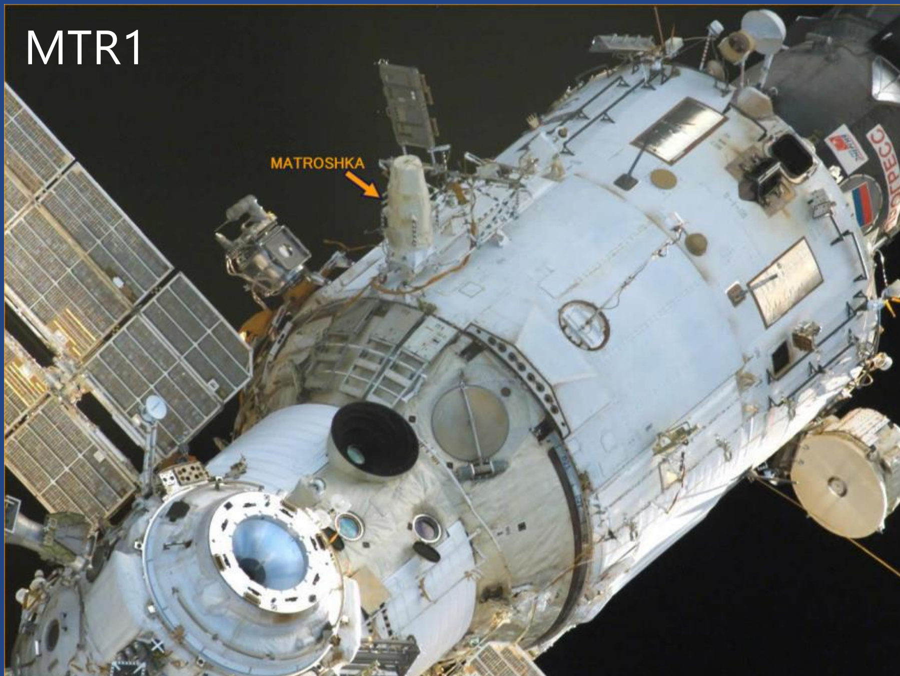
Matroskha experiments



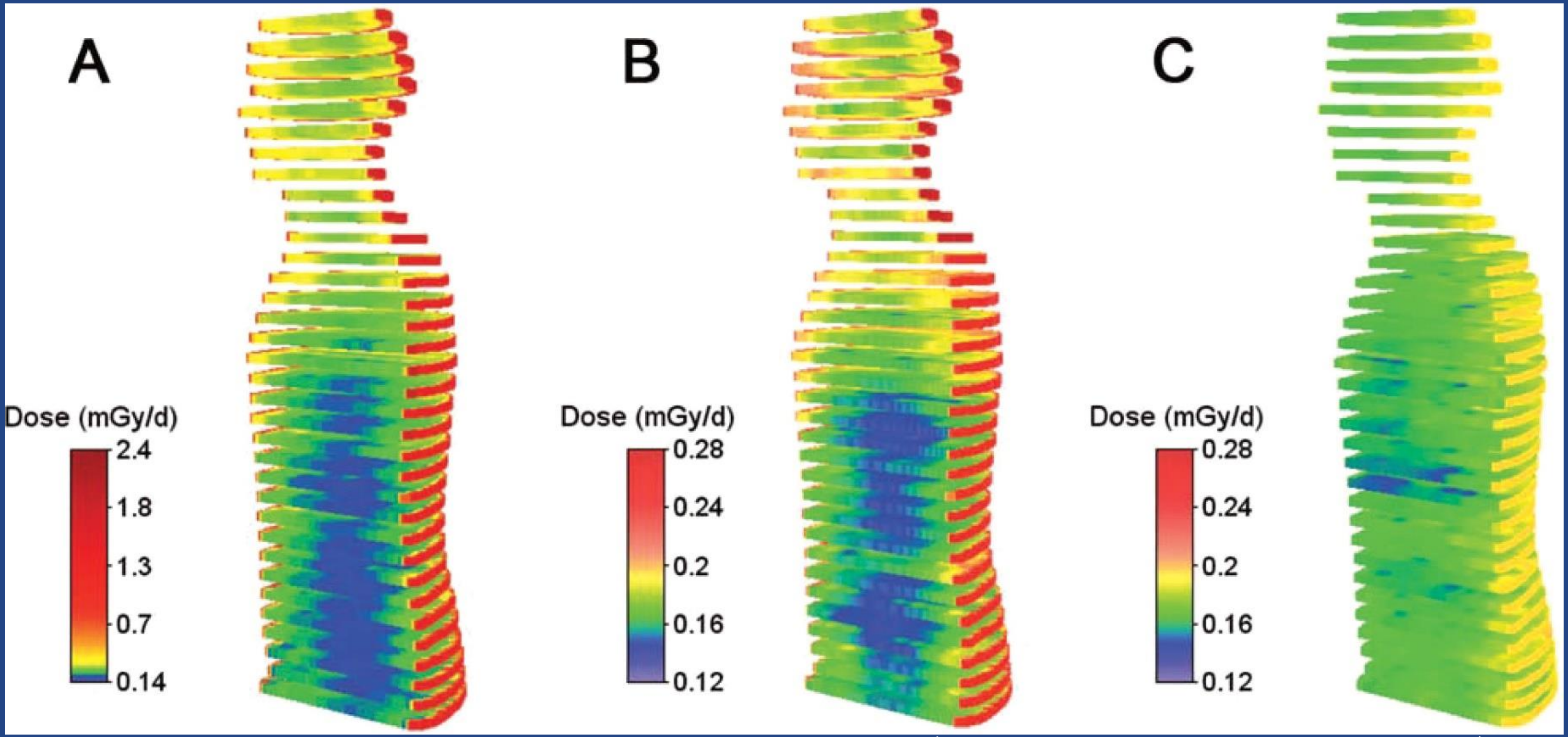


- anthropomorphic phantom
- made of soft tissue and bones
- composed of 34 slices for a total height of 850 mm
- equipped with detector holders

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



Matroshka experiment – key results



Extravehicular

Inside (less shielded area)

Inside (more shielded area)

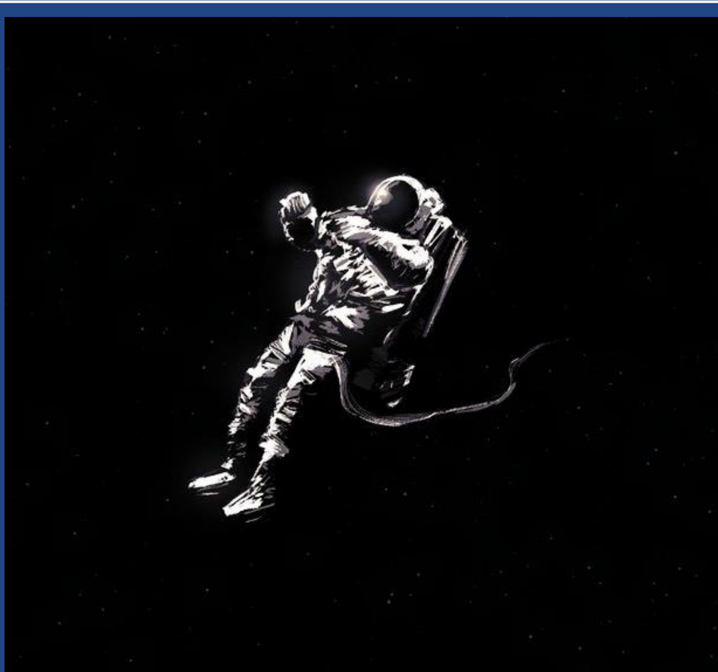
Skin dose:

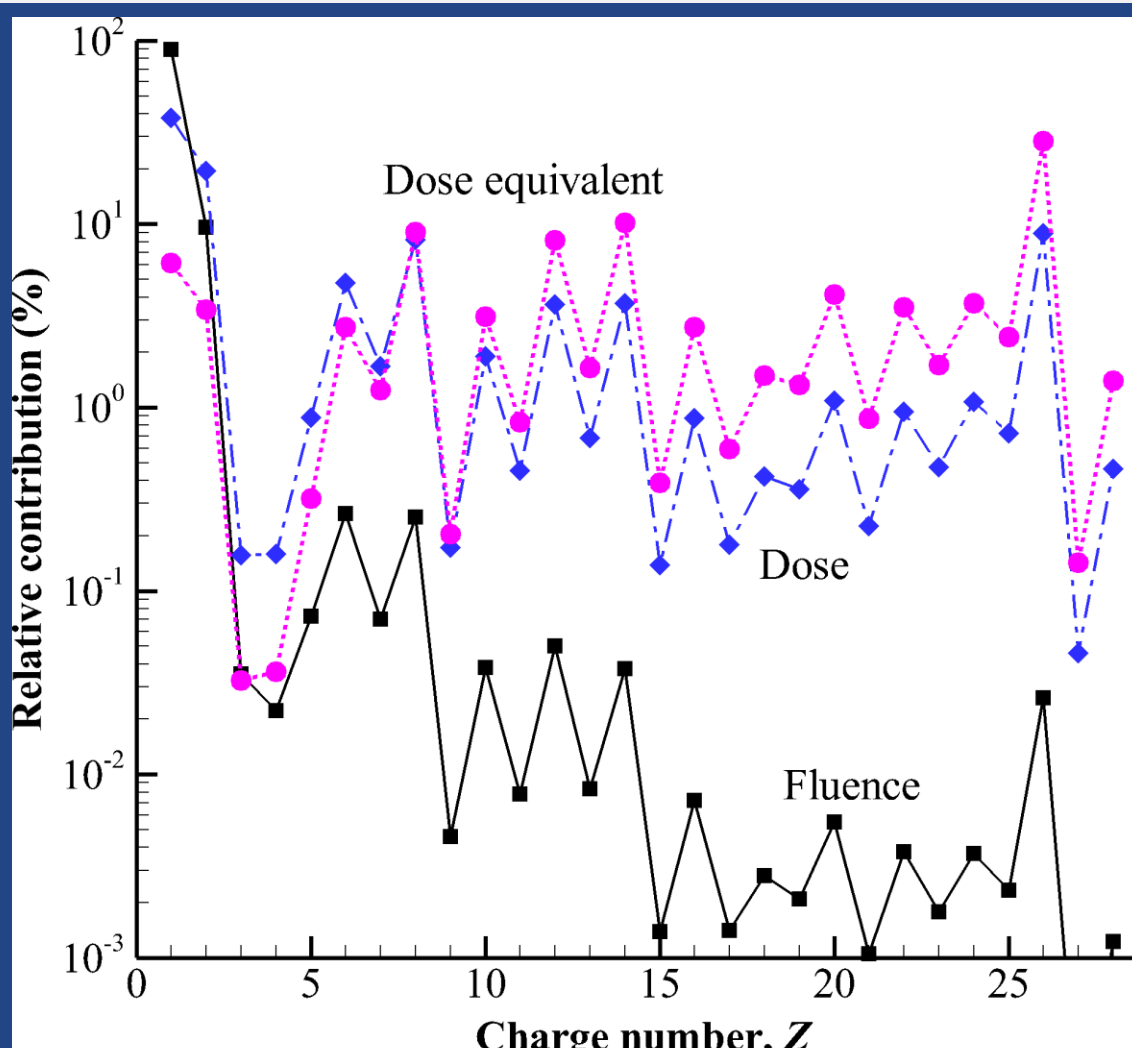
- Extravehicular Activity: 2.5 mGy/day
- Inside ISS: 1 mGy/day

Self-shielding: organs receive 0.2 mGy/day

Berger et al. Rad Res 2013

Radiation dose in interplanetary space



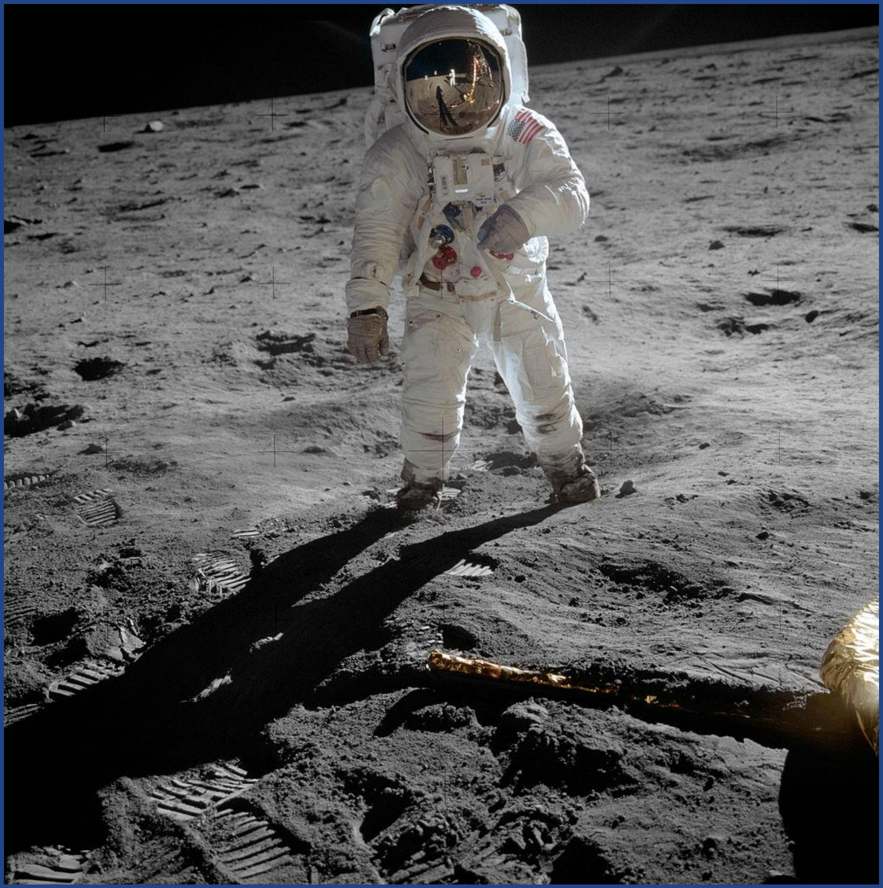


Annual dose to unshielded man in deep space: 400 - 800 mSv

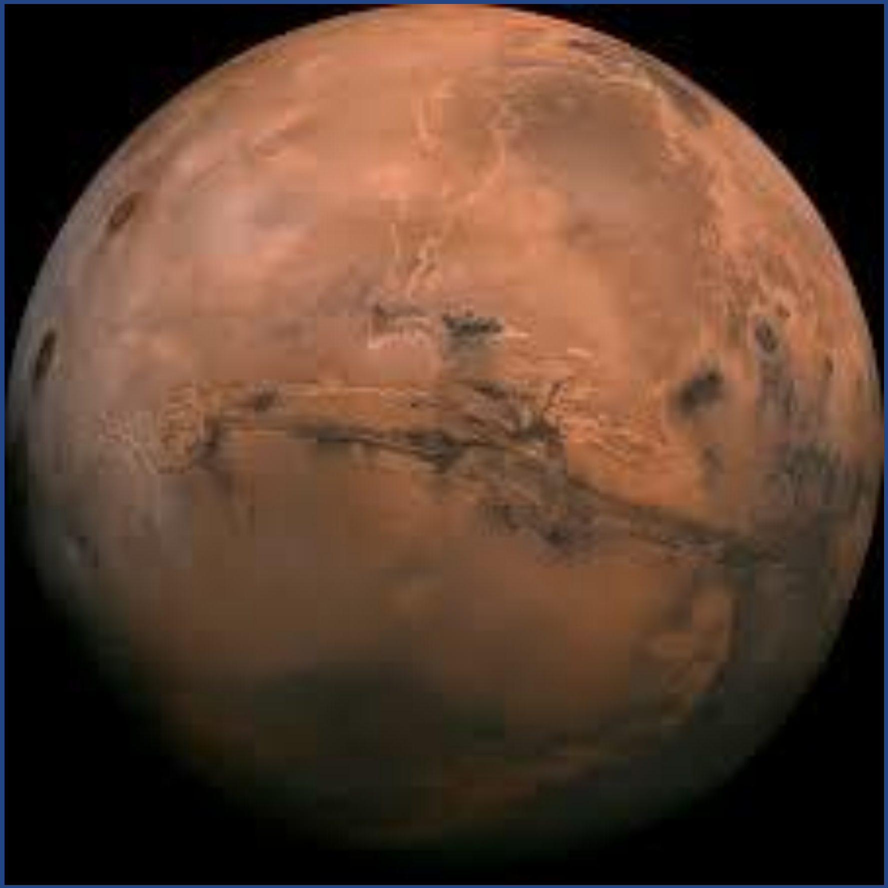
Simonsen et al. PLOS Bio 2020

Radiation dose for traveling to Moon and Mars

- Environment: no atmosphere, no magnetic field

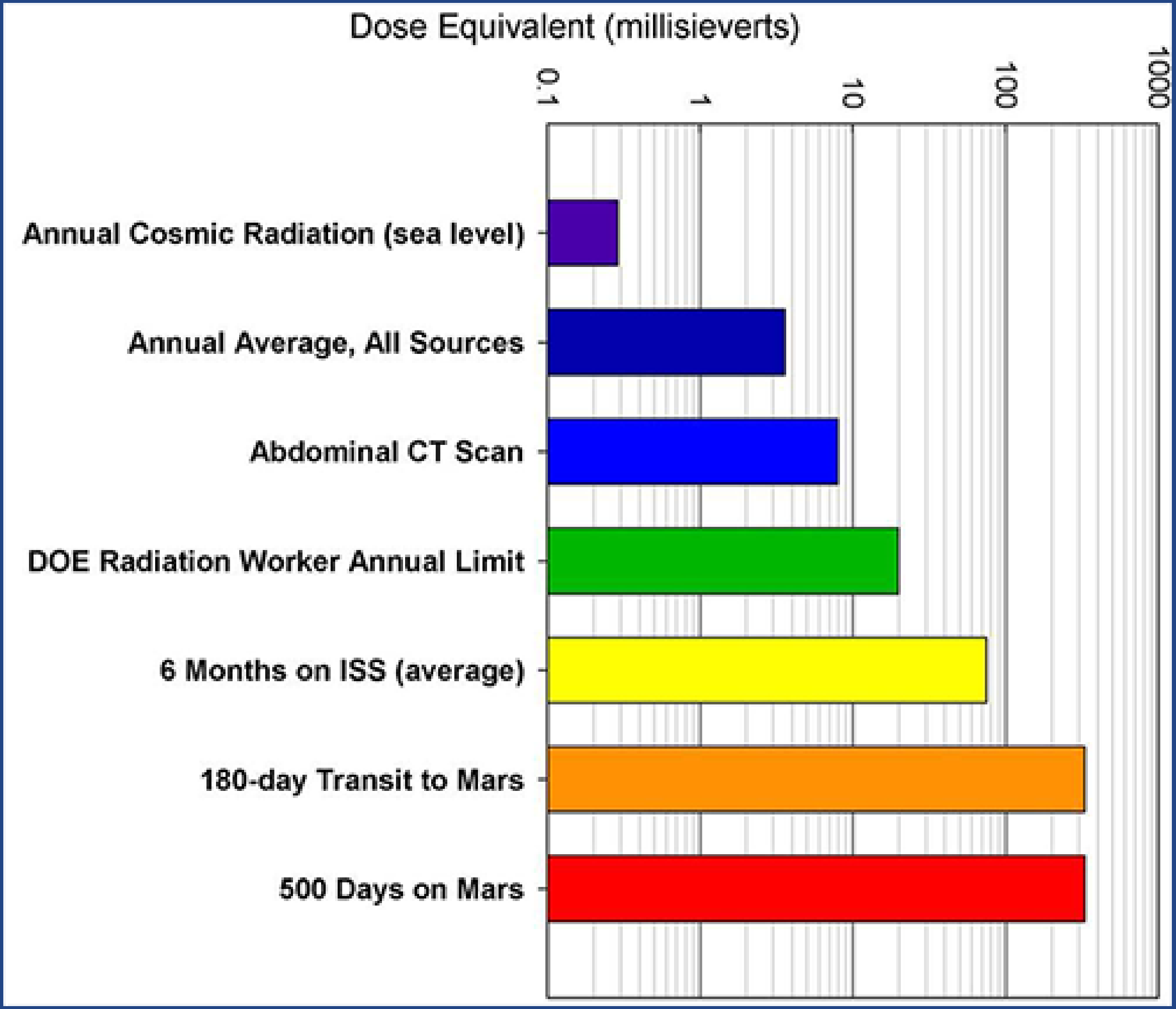


Apollo missions: up to 10 mSv total dose
One year on the Moon: 300 mSv



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

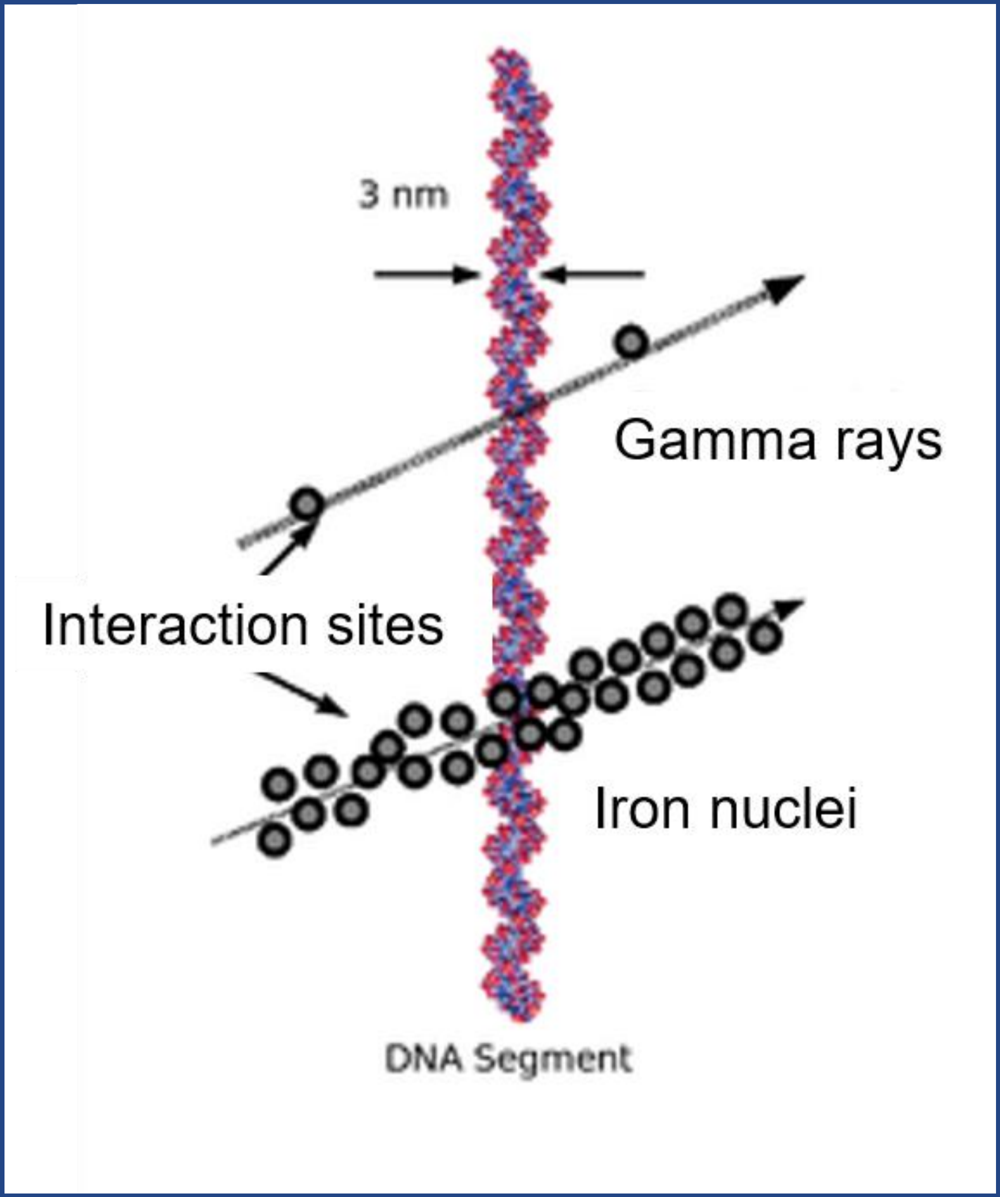
Equivalent absorbed dose - comparison



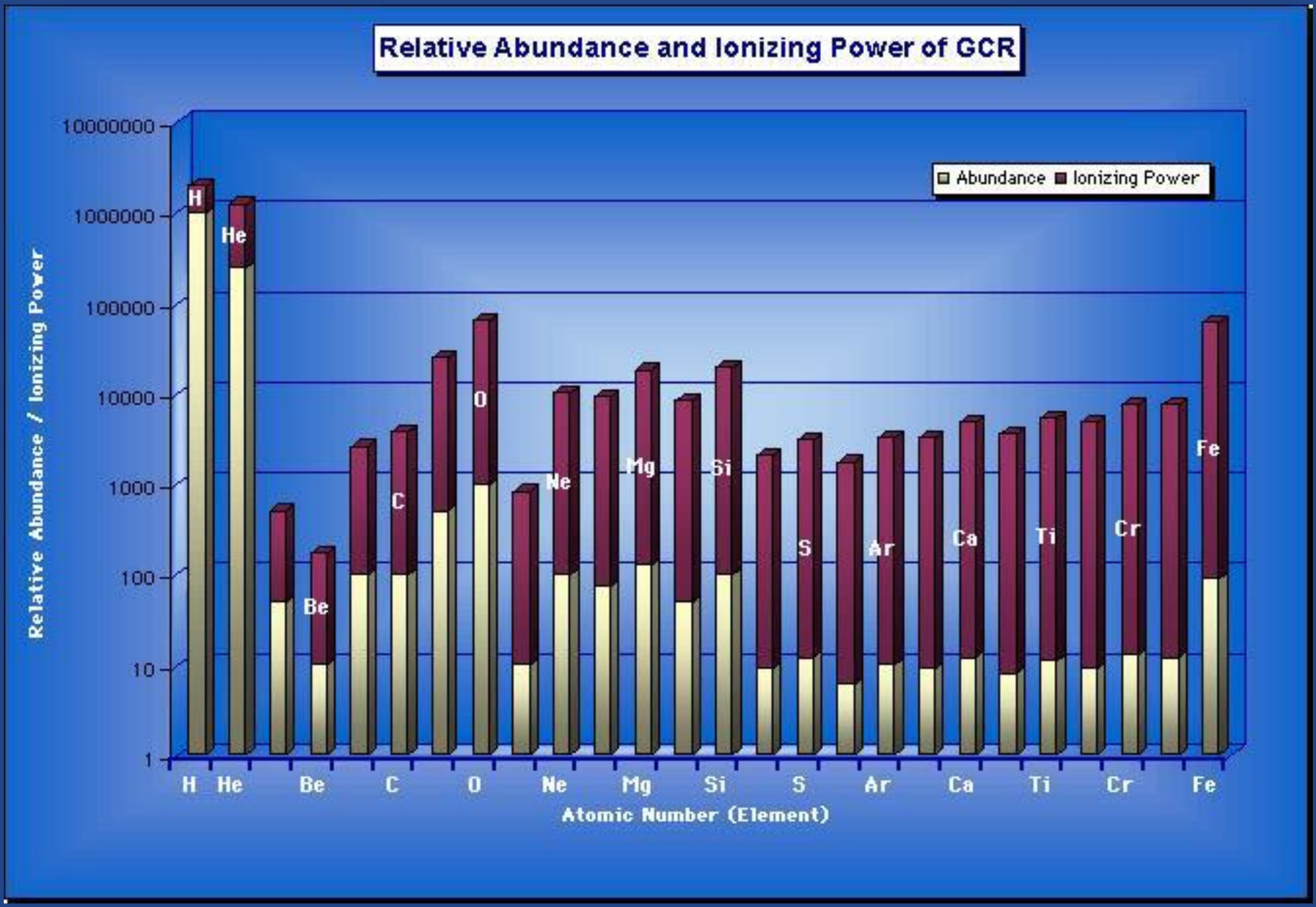
Biological effects of heavy charged particles

LET **(keV/µm)** = dE/dl

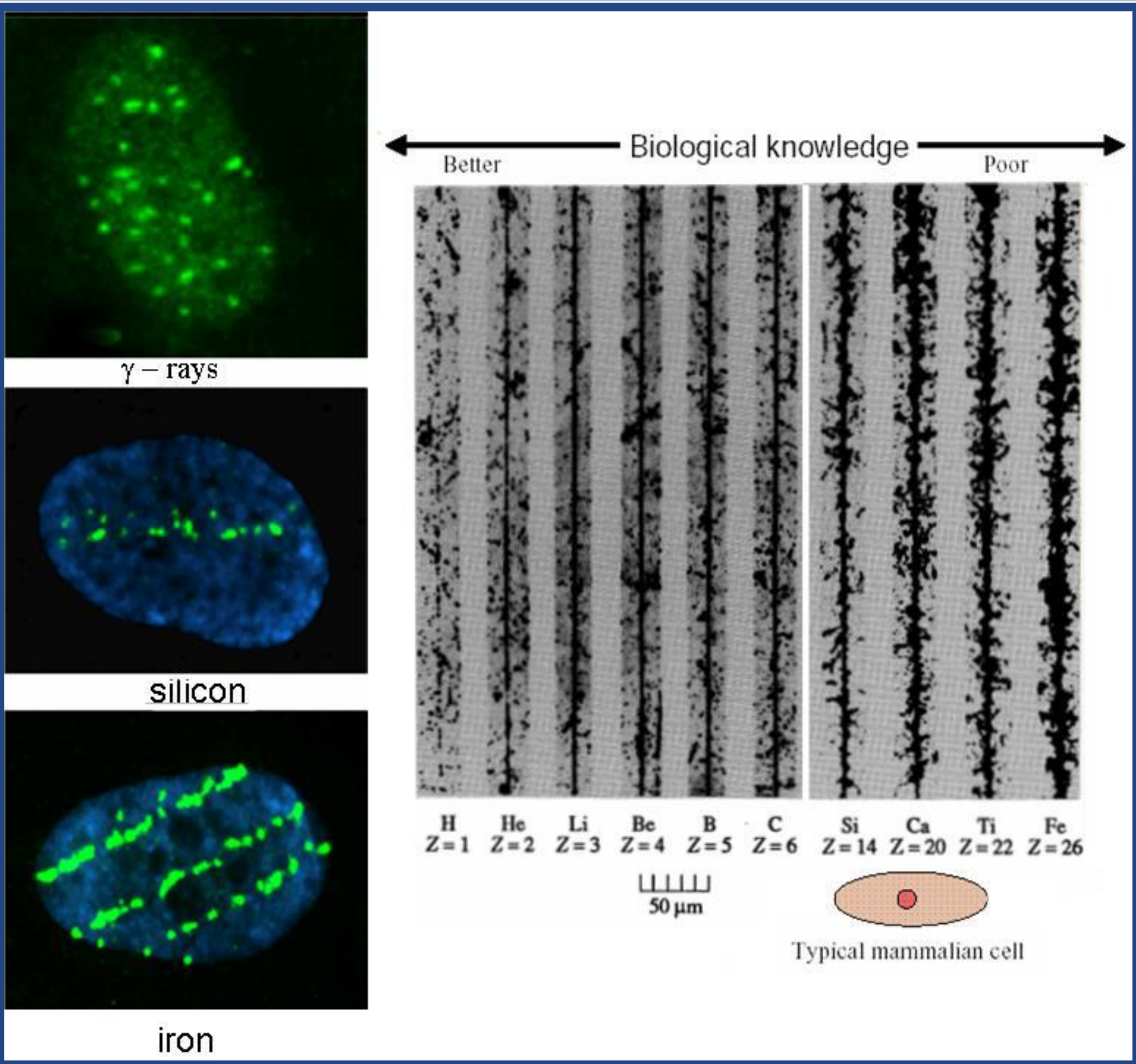
dE: average energy
dl: distance



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

Mission 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

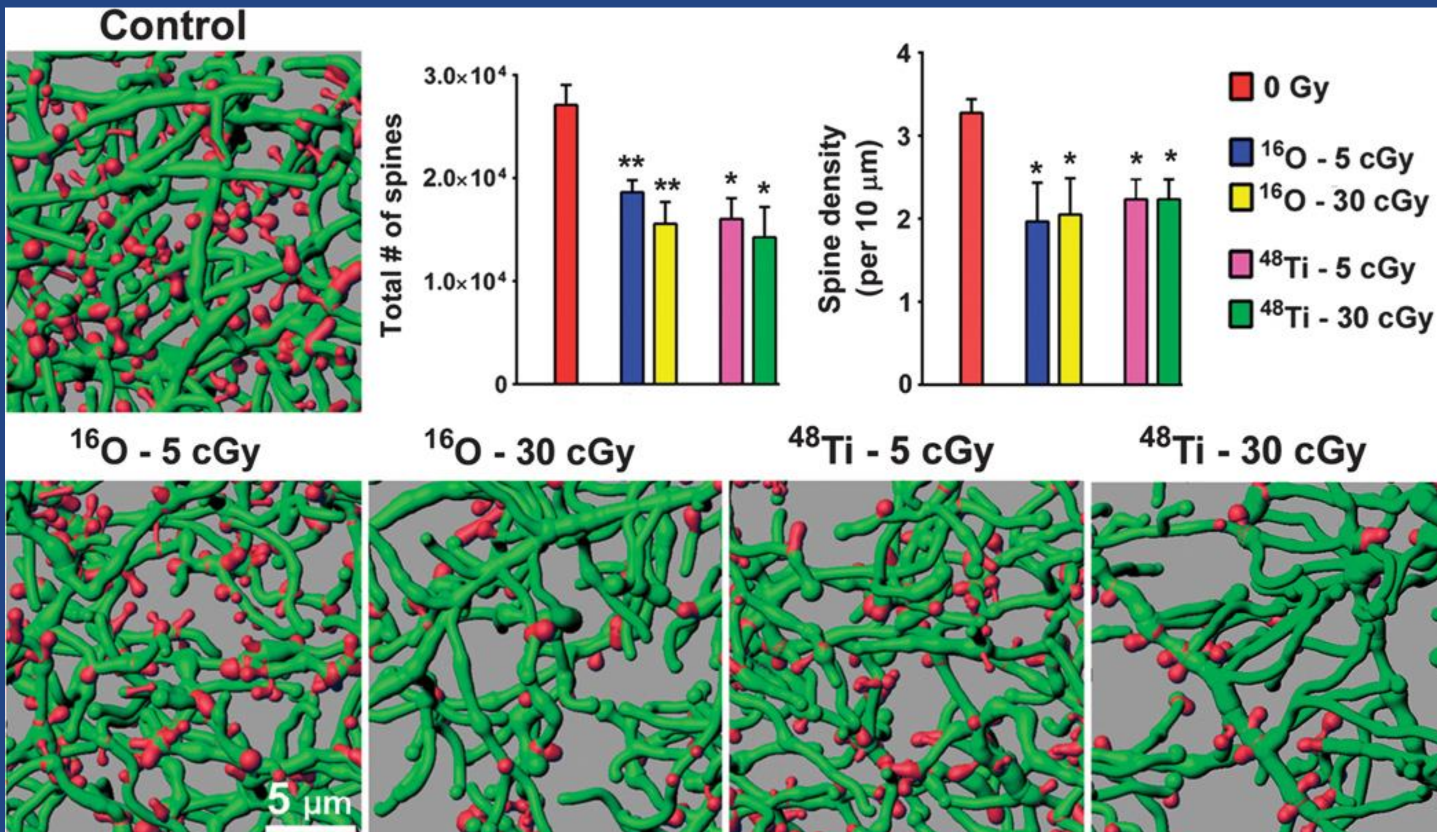
⇨ Not likely, too low doses

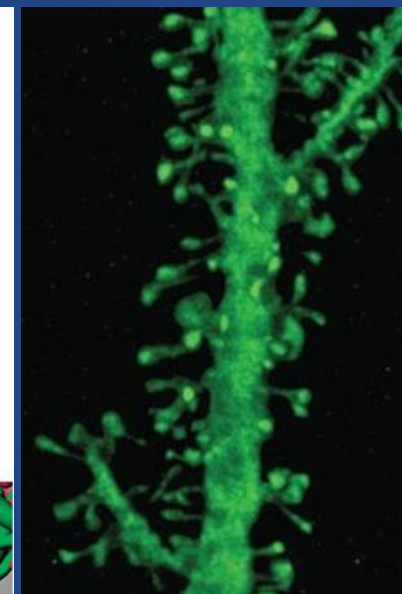
- Neurocognitive – CNS dysfunction?

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

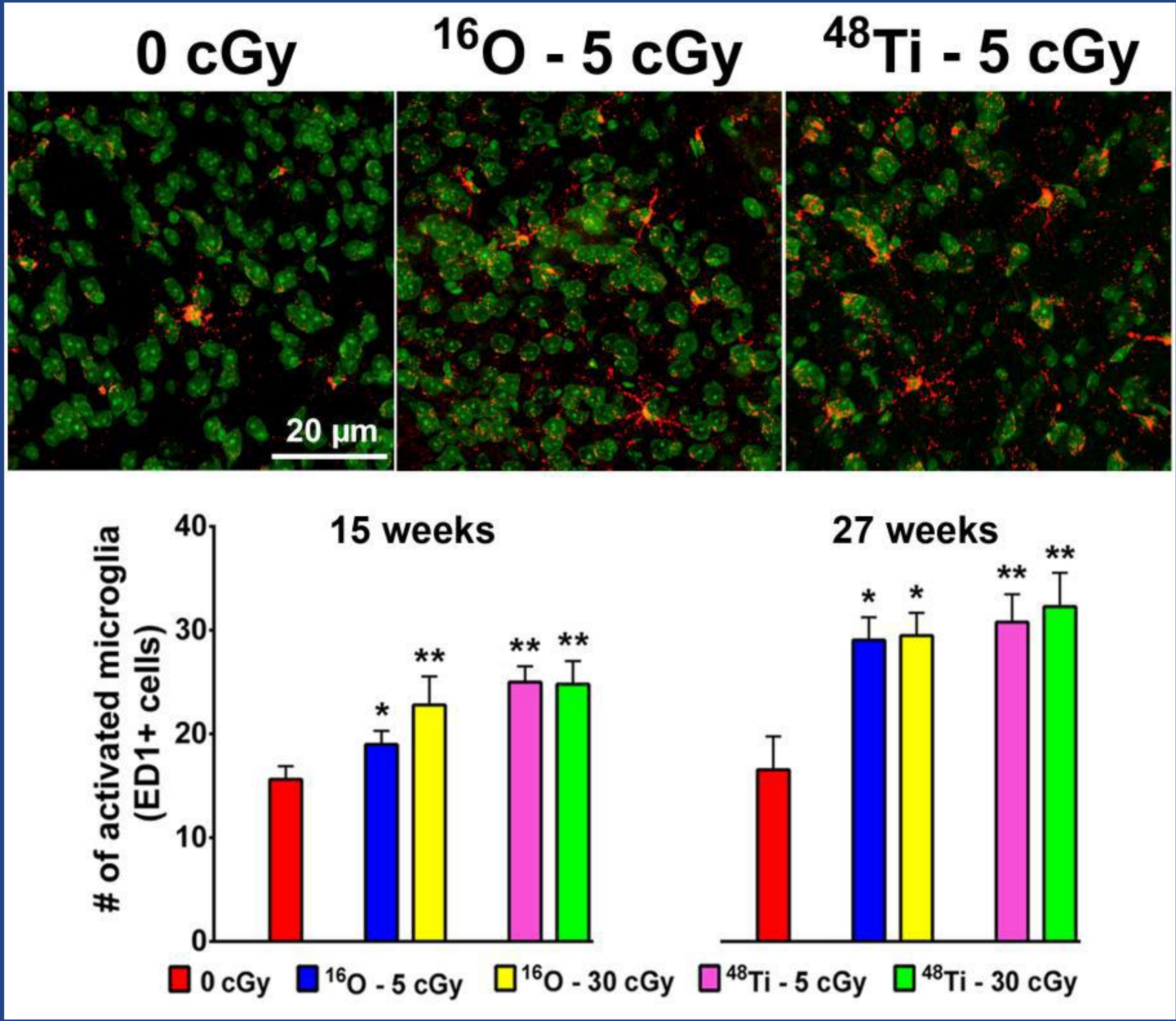




Parihar et al. Sci Adv 2015

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?

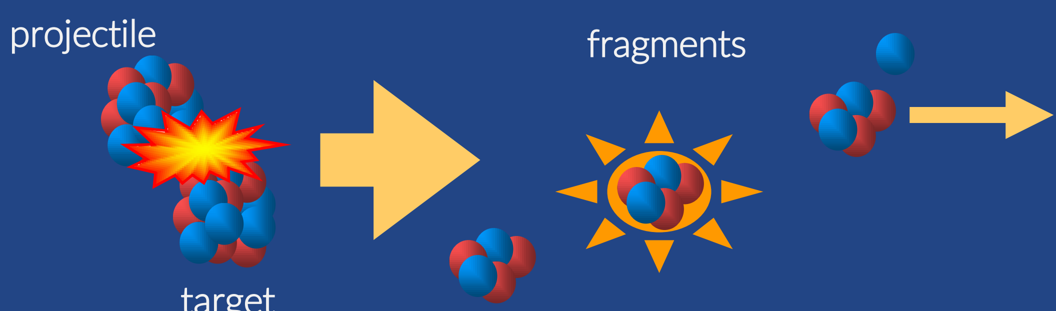
- Selection of the materials, two things to consider:

1) Stopping of charged particles:

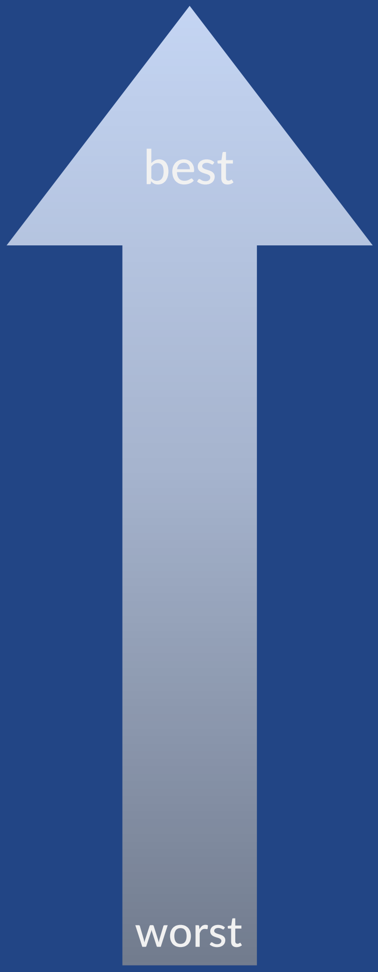
$$-\frac{dE}{\rho dx} = k\frac{Z}{A}\cdot\frac{z^{*2}}{\beta^2}\left(\log\frac{2\gamma^2\beta^2 m_e c^2}{I} - \eta\right)$$

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)

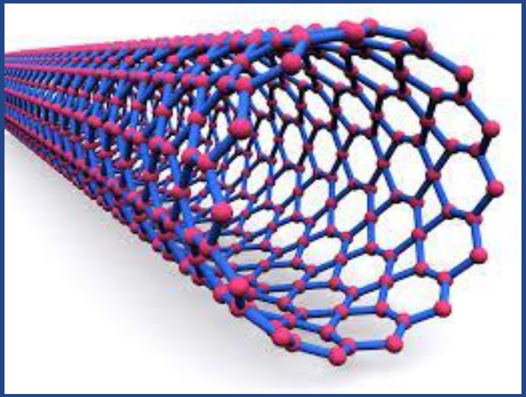
Shielding on ISS

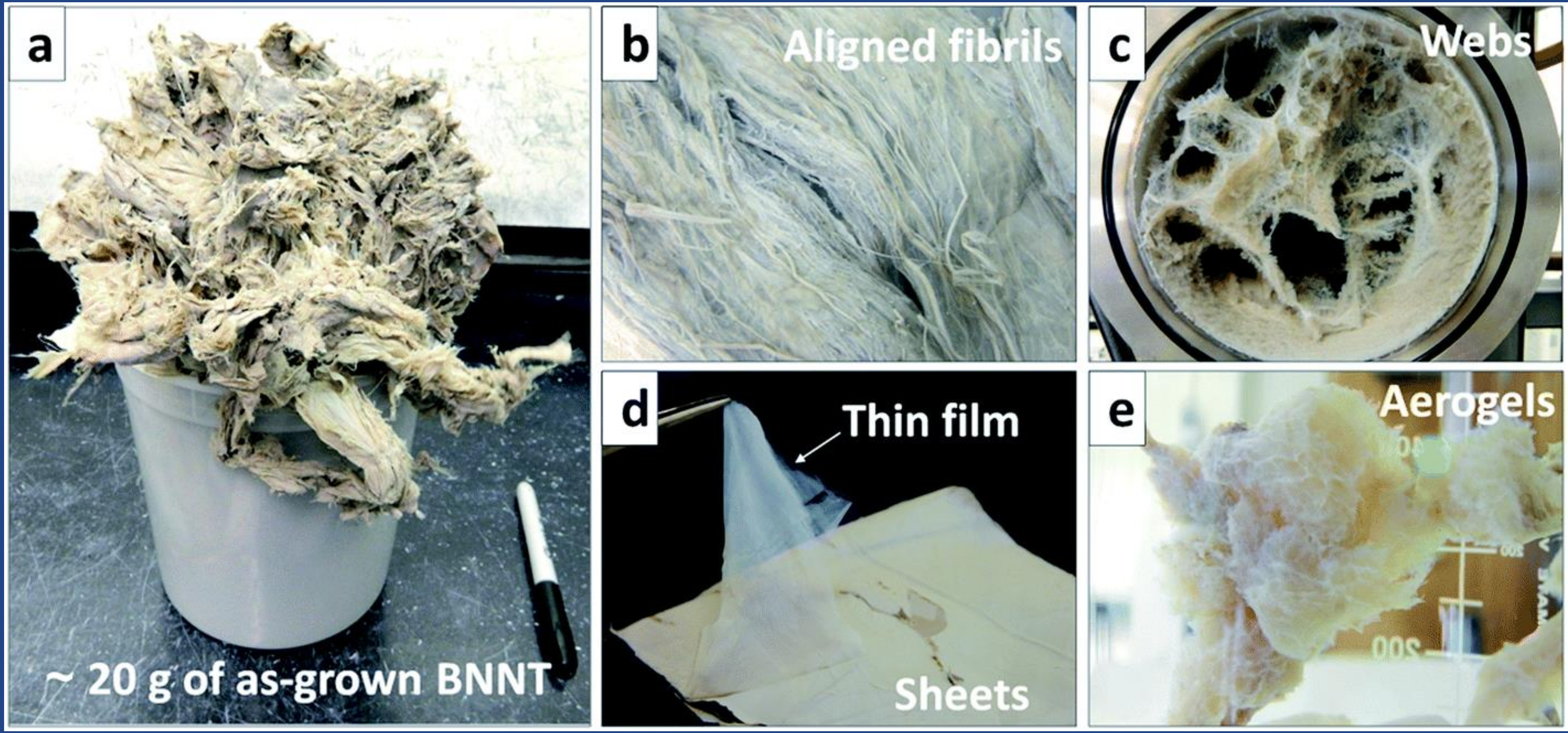
- Outside wall: aluminum
- Inside improvements: polyethylene and water

Temporary sleep station on the ISS with polyethylene panels and water storage above for enhanced radiation shielding

New materials

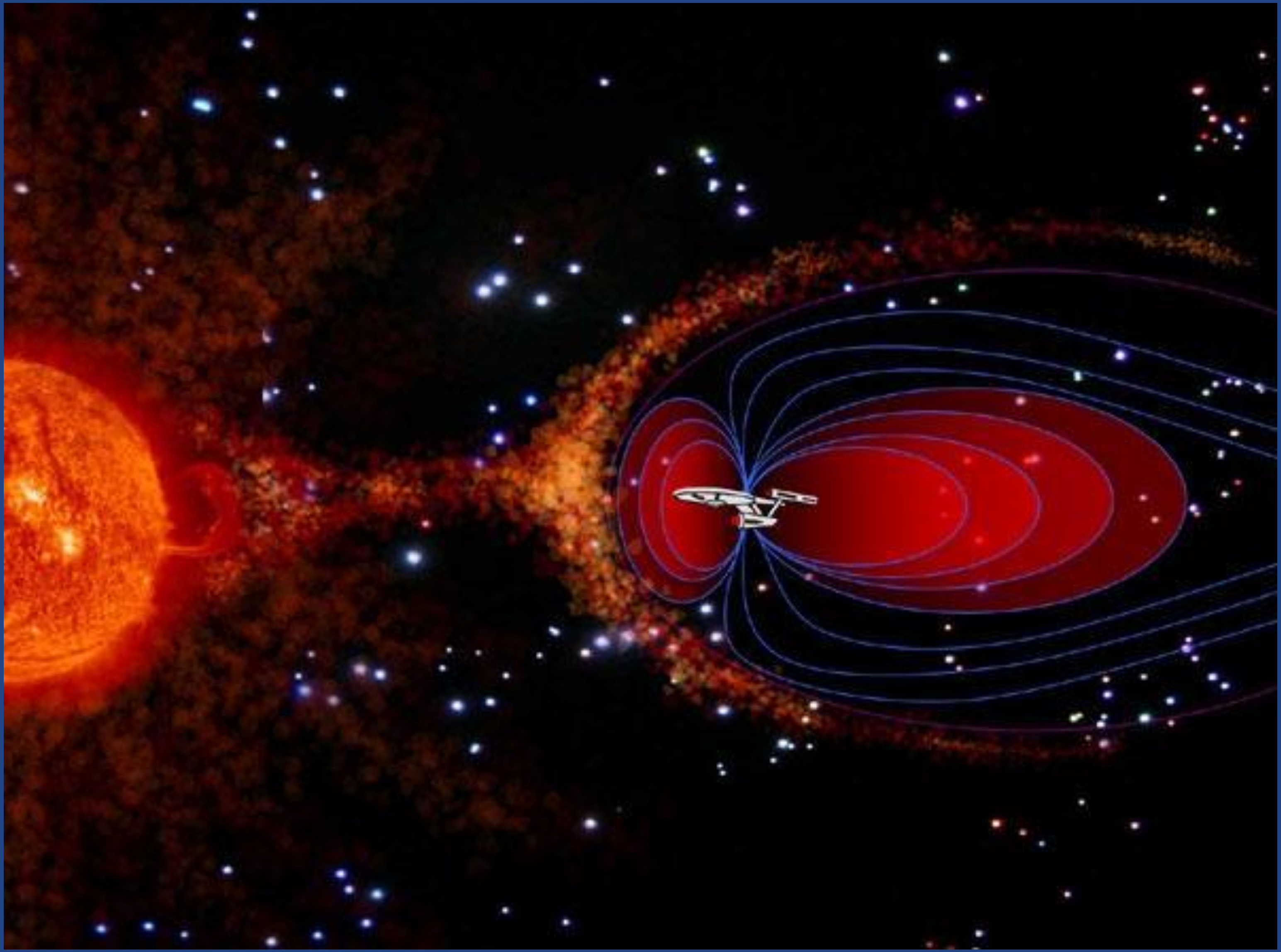
- Boron nitride nanotubes
  - Hydrogen storage or hydrogenation
  - Young modulus around 8 (10 for aluminum)
  - Stable until 1600 F (900 C)





Futuristic solution

- Spacecraft magnetic shielding

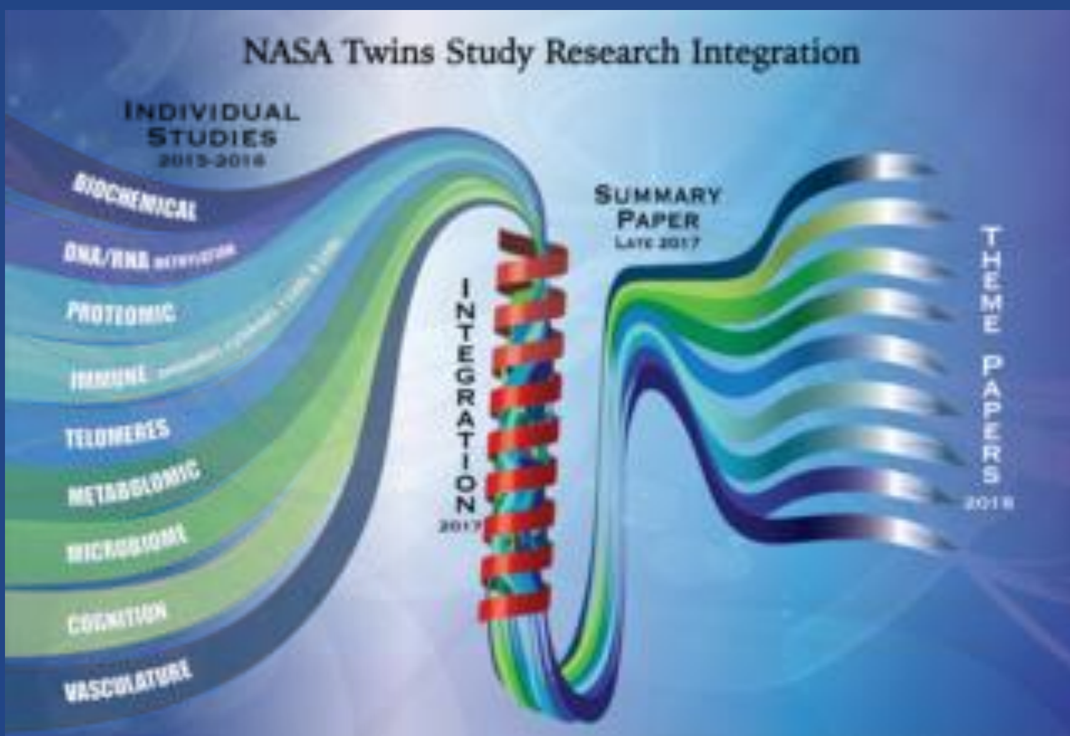


Estimating space travel risks

- 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: results

- 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. Some observed DNA damage is believed to be a result of radiation exposure.
- Atherosclerosis: biomarkers of inflammation elevated and the carotid artery wall thickened during and immediately after