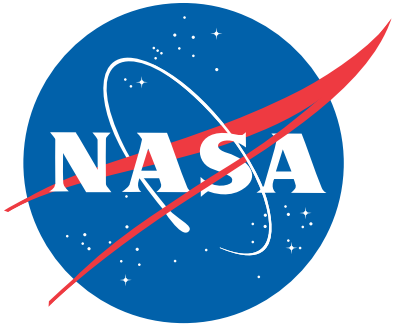




FRONTIERS OF SPACE RADIATION

John W. Norbury

NASA Langley Research Center, Hampton, Virginia, USA

February 6, 2018

Acknowledgements

Thanks to the following people for use of some of their slides:

Dr. Tony Slaba (NASA Langley Research Center)

Dr. Martha Clowdsley (NASA Langley Research Center)

Dr. Ryan Norman (NASA Langley Research Center)

Dr. Lisa Simonsen (NASA Langley Research Center)

Outline

1. Introduction to Space Radiation
2. Recent work at NASA Langley Research Center
   - Materials compared to Aluminum
   - Exposure versus depth
   - Pion contribution to dose
   - Light ion contribution to dose-equivalent
   - Galactic Cosmic Ray (GCR) simulation
   - Light ion cross sections
   - Alpha Magnetic Spectrometer (AMS)
3. Radiation & Space Exploration
   - Earth - Aircraft
   - Low Earth Orbit & International Space Station
   - Moon, Cislunar space & Deep Space Gateway
   - Mars & Deep Space Transport
   - Jupiter & Saturn
   - Interstellar & Intergalactic Space Travel
4. Outlook

Introduction to Radiation

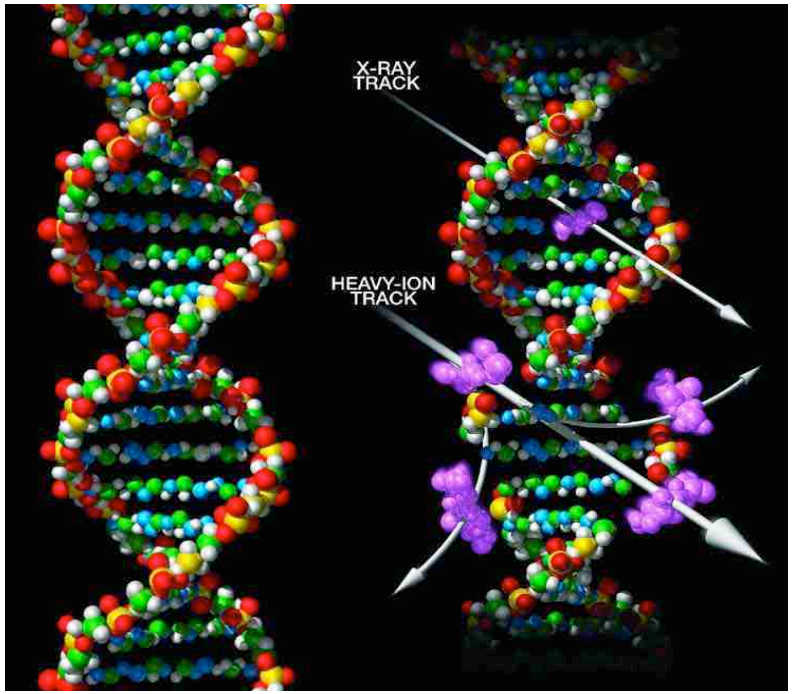
Unit of absorbed Dose

1 Gray (Gy) $\equiv$ 1 Joule/kg Energy/Mass

Unit of absorbed Dose Equivalent

Sievert (Sv) $\equiv$ Gray $\times Q$

Q = Quality factor



http://www.nasa.gov/centers/marshall/multimedia/photos/2003/photos03-183.html

Effective Dose

Average Dose Equivalent over all Tissues; also Sv

ICRP estimate: 5% per Gy = 5% per Sv for $Q = 1$

1 in 20,000 risk of fatal cancer per 1 mSv dose (lifetime)

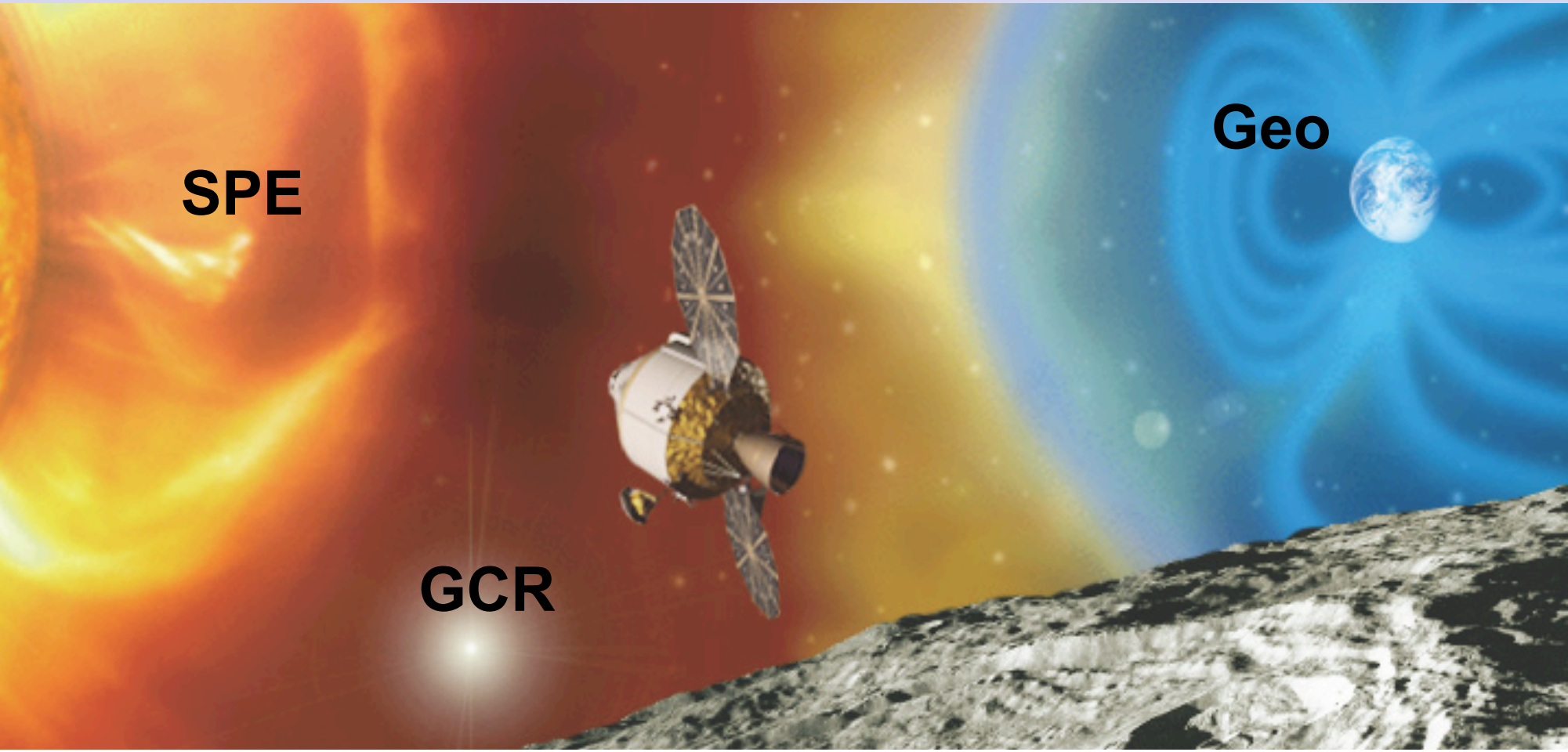
Introduction to Radiation

	Dose Equivalent (mSv)
Chest x ray	0.1
USA annual background	4
Public annual limit (above background)	1
International Airline crews	4
Radiation worker annual limit	20
No observed effects (A bomb)(instant)	200
Blood count changes	$>$200
Acute Radiation Syndrome (ASR)	1,000
Death (instantaneous dose)	3,000
ISS (with shield) annual*	150 - 300
Large solar flare (free space)	10,000

ICRP cancer risk estimate: 5% per Gy $\sim$ 5% per Sv (for Q=1)
1 in 20,000 risk of fatal cancer per 1mSv dose (lifetime)

*Depends of altitude & detector location

3 Sources of Space Radiation



https://oltaris.larc.nasa.gov

- Solar Particle Events (SPE)
- Galactic Cosmic Rays (GCR)
- Geomagnetically trapped particles (Geo)

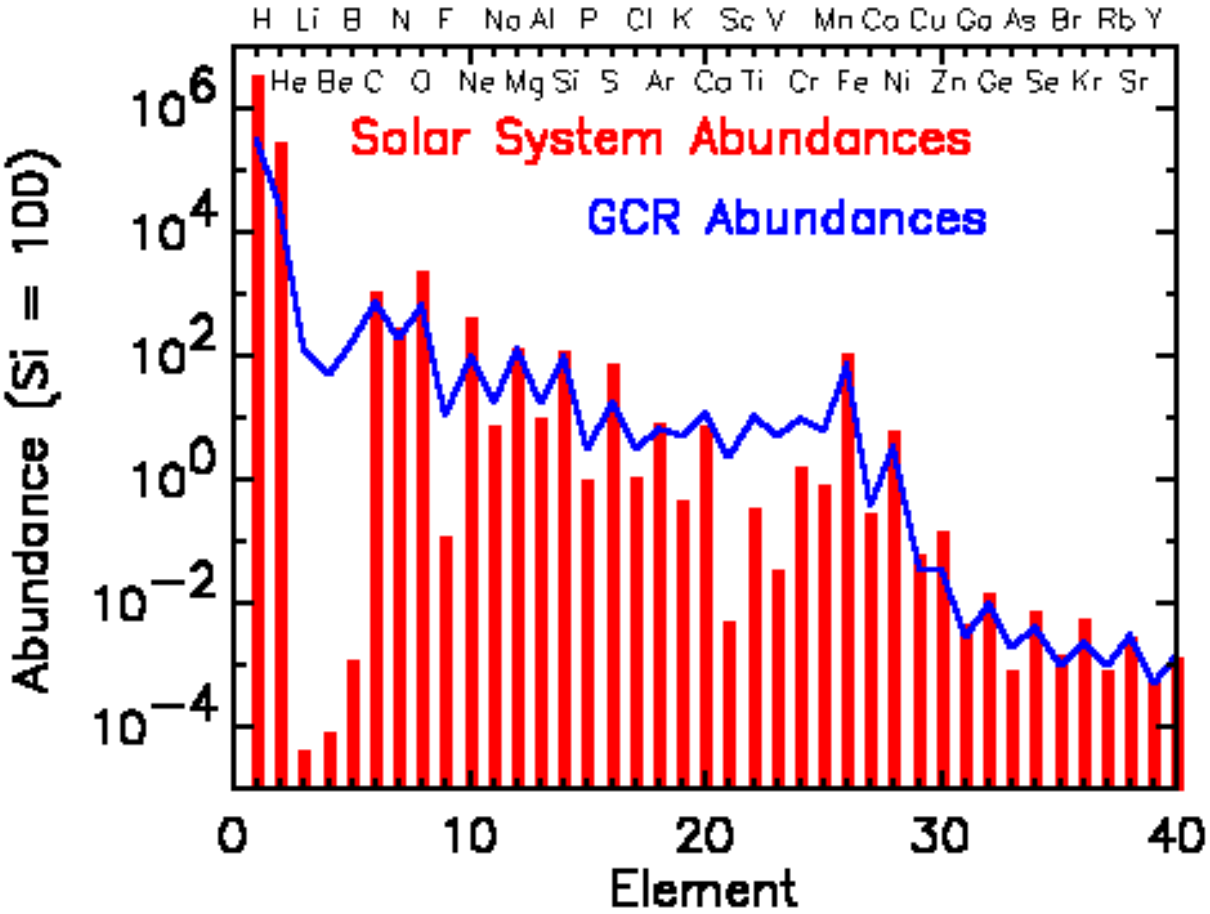
Space radiation problem

GCR (primary) composition

- 98% nuclei, 2% e^+e^-
- Nuclear component
  87% Hydrogen
  12% Helium
  1% heavy nuclei

GCR origin

- Emitted in stellar wind & flares & accelerated by supernova shock waves (within our Galaxy)

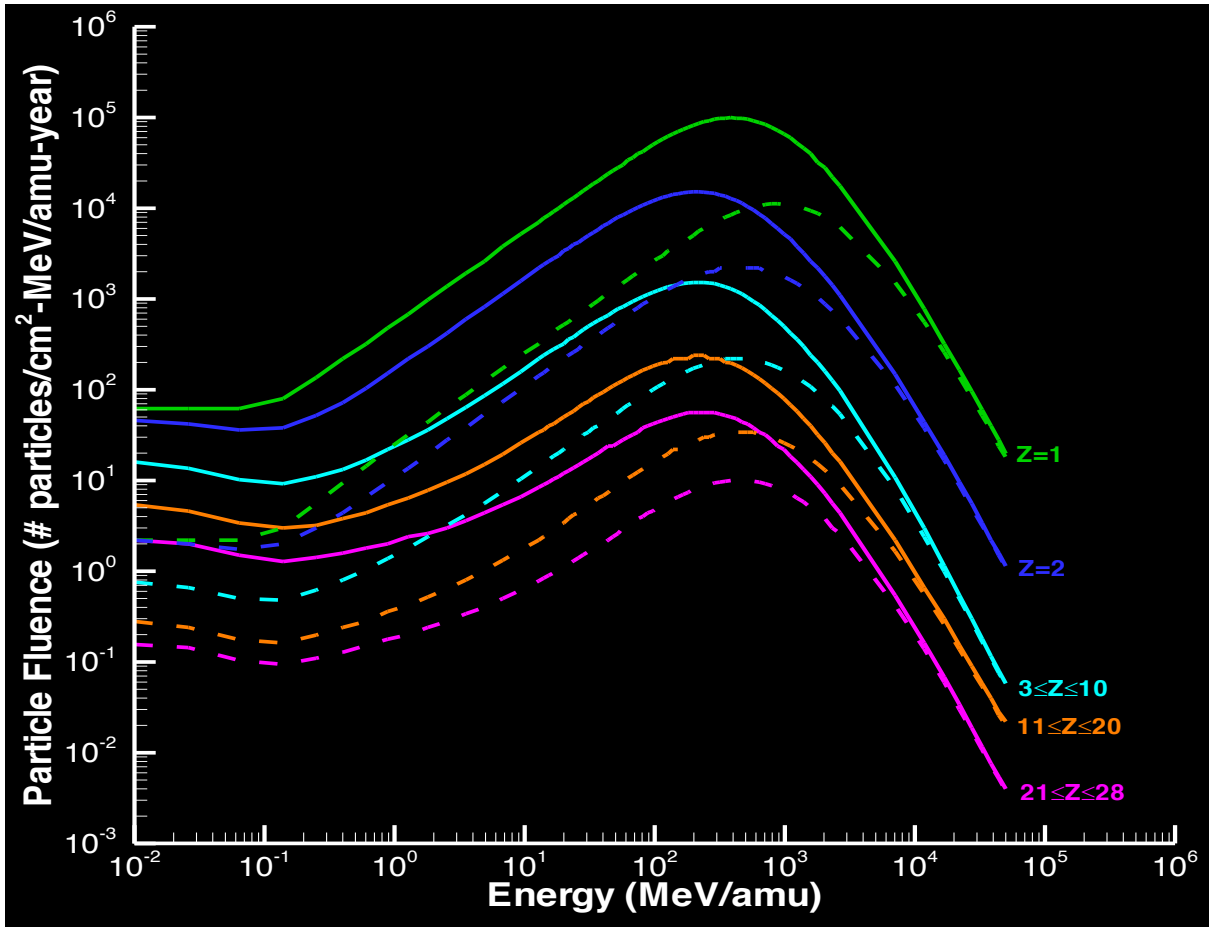


GCR elemental abundances

http://imagine.gsfc.nasa.gov/Images/science/abund2.gif

GCR (HIGH ENERGY < PEV)

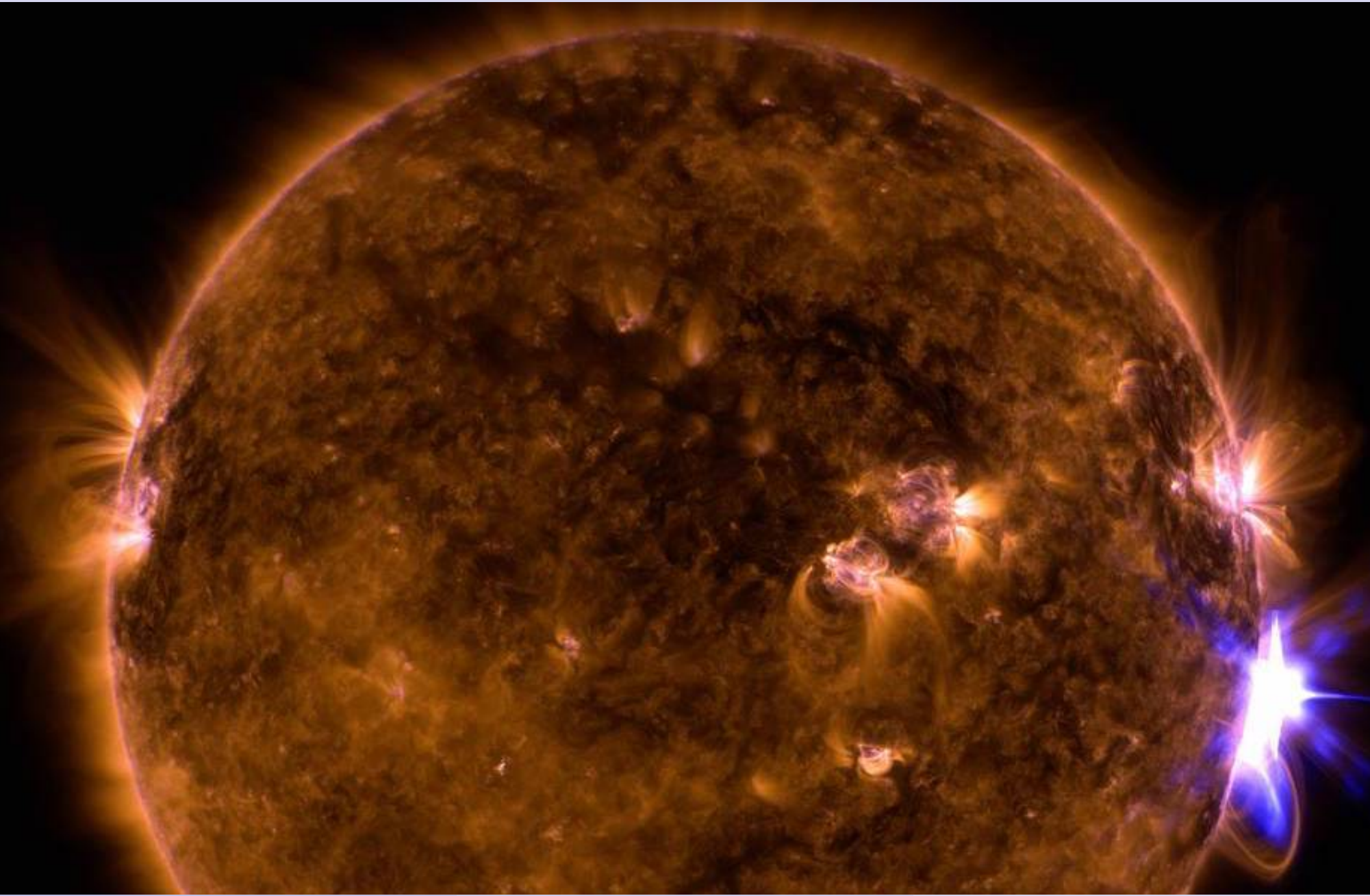
- Modulated by solar wind
  - Always present
  - Vary with solar cycle
- Not effectively shielded
  - Deeply penetrating
  - Secondary particles produced through fragmentation
- GCR exposure provides minimal risk for short duration missions, but long duration exposure increases the risk of cancer



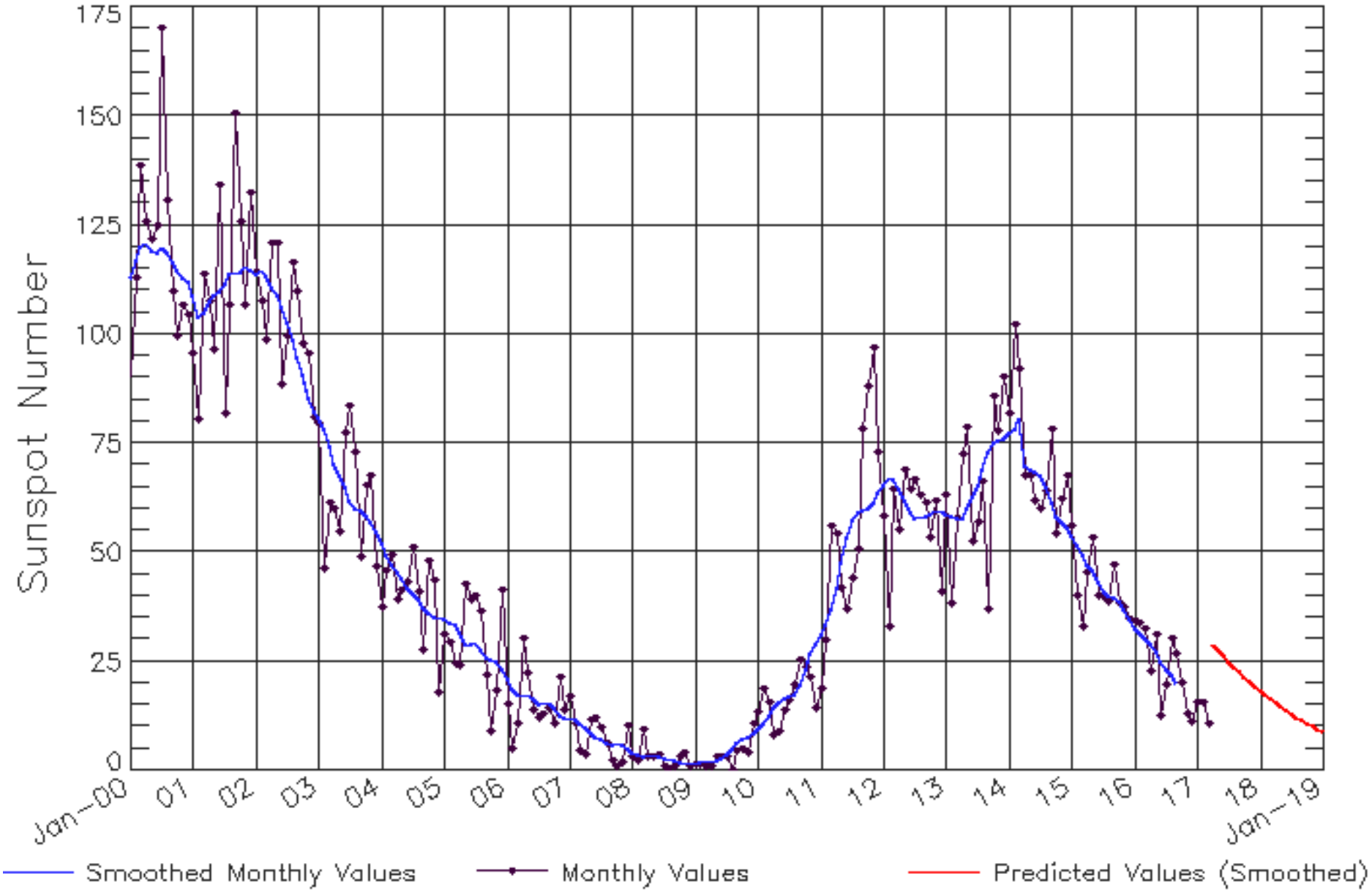
GCR spectra

M. Clowdsley & D. Moore, NASA

Solar Particle Events (SPE)



Solar Particle Events 11 year cycle

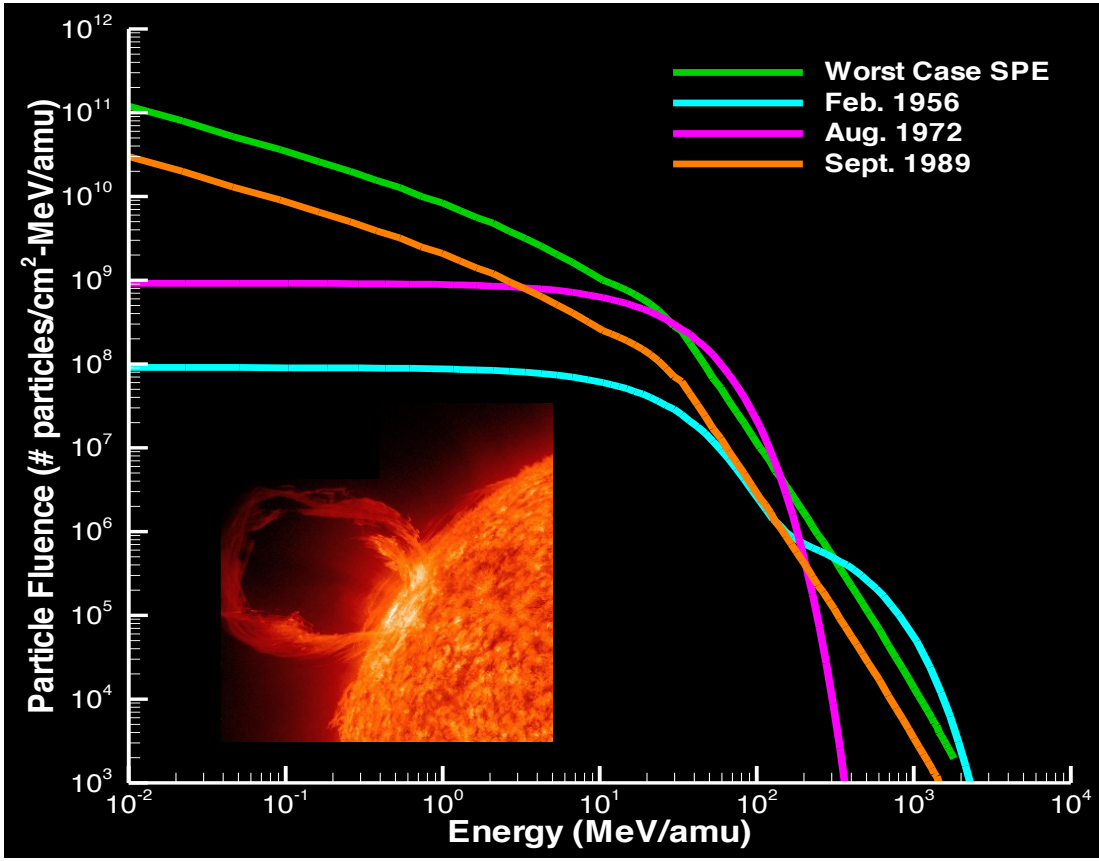


NOAA, 2017

Solar Particle Events (SPE)

e, p & some heavy nuclei < 1 GeV/N $(v \sim 0.9c)$

- Low to medium energy protons associated with coronal mass ejections
- Large SPE rare & short lived
- Spectrum and duration vary
- Effectively shielded but optimization required to reduce mass
- Accurate forecasting & dosimetry needed
- Unshielded exposure to large SPE could result in acute radiation syndrome

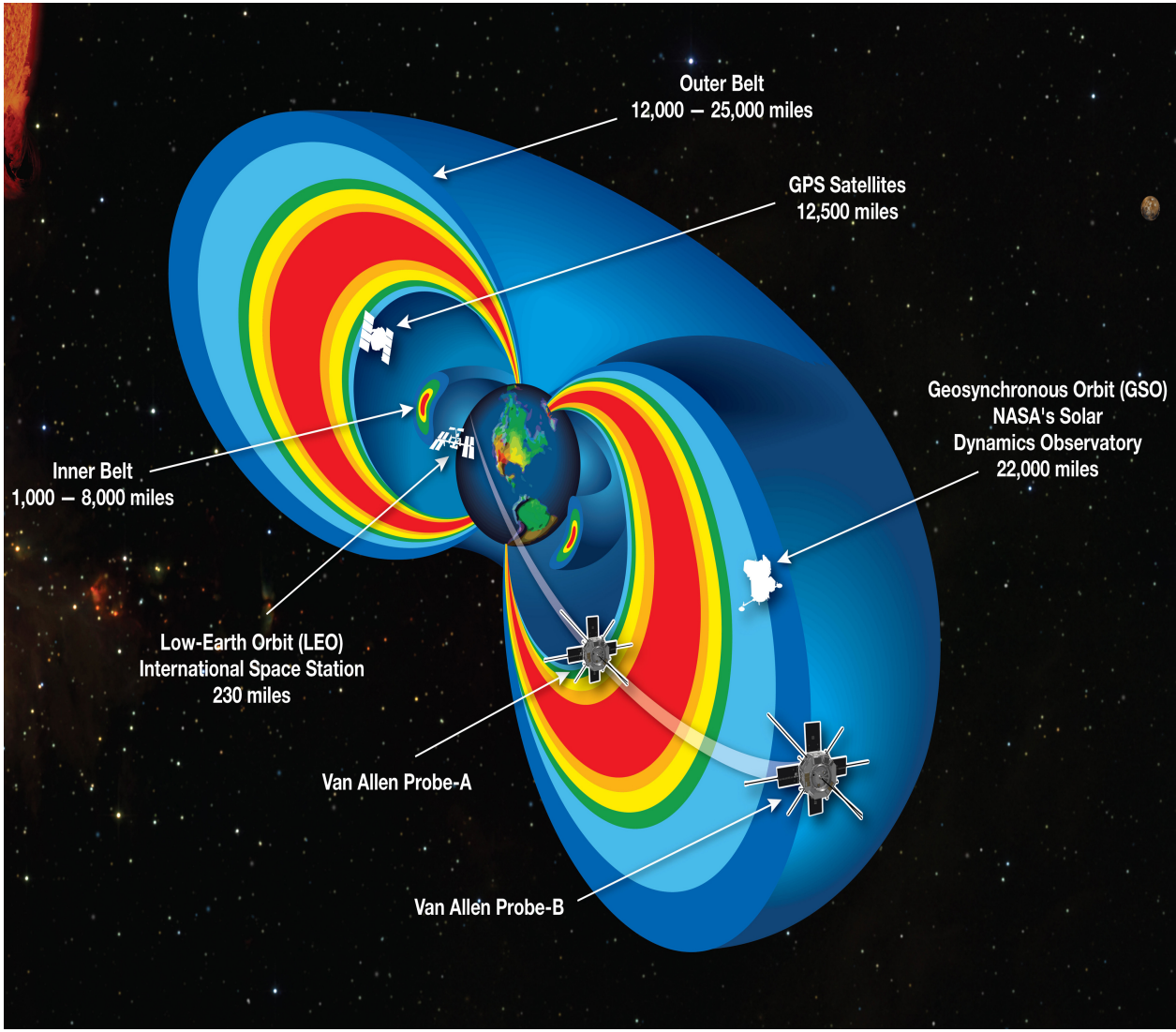


SPE proton spectra

M. Clowdsley & D. Moore, NASA

Geomagnetically Trapped Particles

- Low to medium energy protons and electrons
- Effectively mitigated by shielding
- Mainly relevant to ISS
- Minimal risk for missions beyond LEO
  - if transits through belts short



Van Allen radiation belts

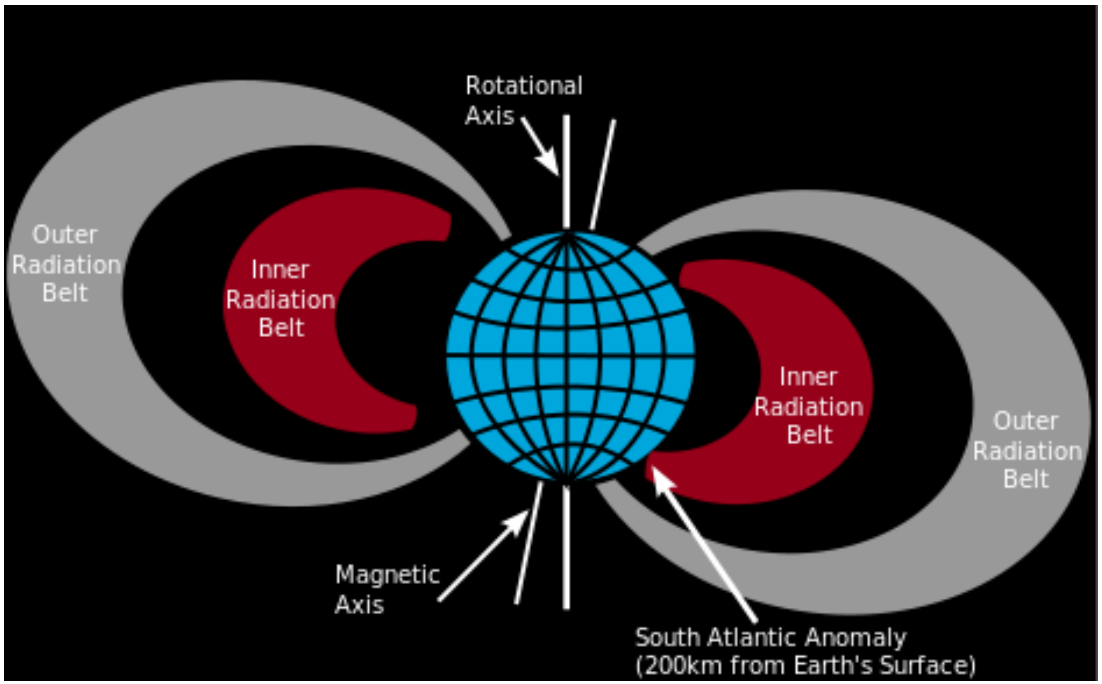
Geomagnetically Trapped Particles

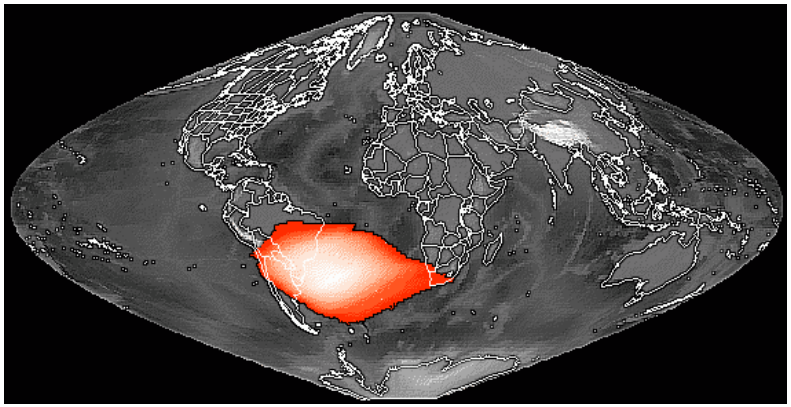
Inner belt: 0 - 3 R_E = 18,000 km - mainly p

- Starts about 3,000 km
- But SAA dips down to 400 km

Outer belt: 3 - 12 R_E = 36,000 km (e,p) - mainly e

(LEO: 200 - 500 km GEO: 22,000 miles = 35,000 km)



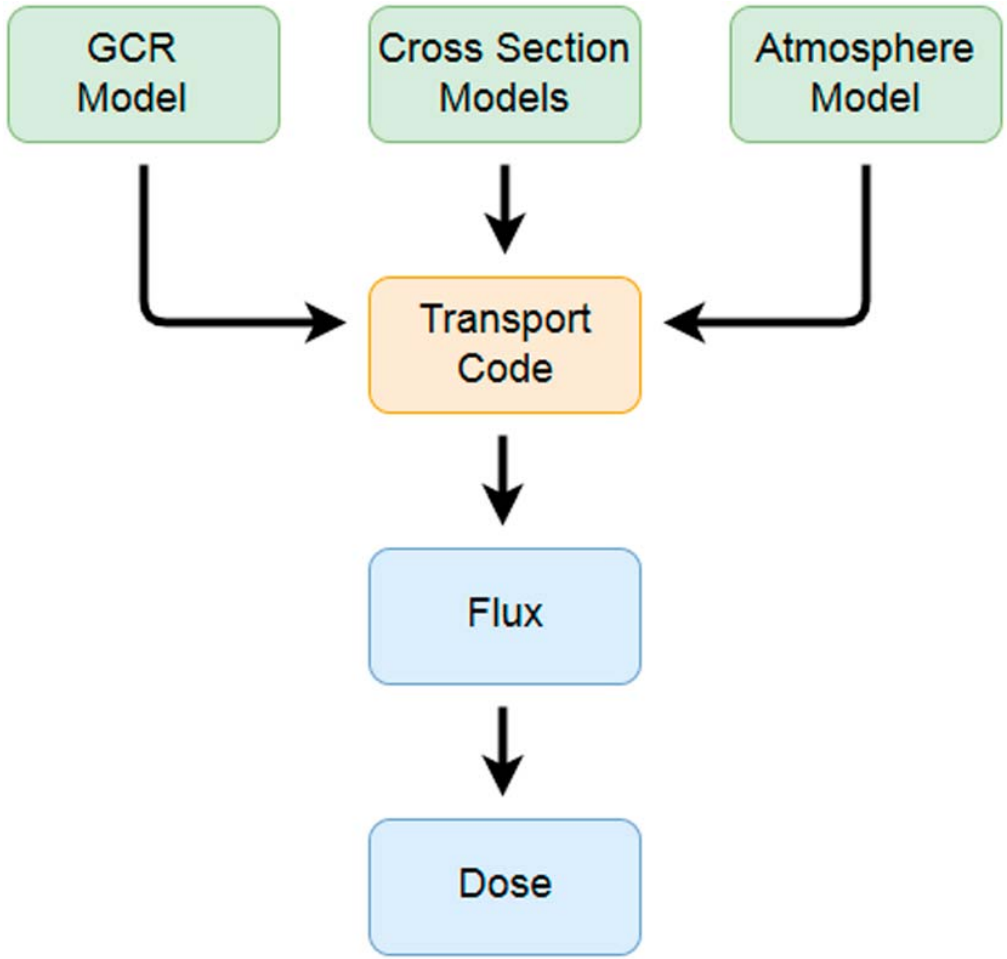


NASA

http://science1.nasa.gov/science-news/science-at-nasa/2001

Radiation & Dose

- Large variety of physics, engineering and biology goes into dose predictions



Norman et al., Space Weather 14, 764, 2016

Space Radiation Risks

- Risk of Radiation Carcinogenesis
  - Morbidity and mortality risks
- Risk of Acute & Late Central Nervous System (CNS) Effects
  - Changes in motor function and behavior or neurological disorders
- Risk of Degenerative Tissue or Other Health Effects
  - Degenerative changes in the heart, vasculature, and lenses
  - Diseases related to aging, including digestive, respiratory disease, endocrine, and immune system dysfunction
- Risk of Acute Radiation Syndromes due to Solar Particle Events
  - Prodromal effects (nausea, vomiting, fatigue), skin injury, and depletion of the blood-forming organs

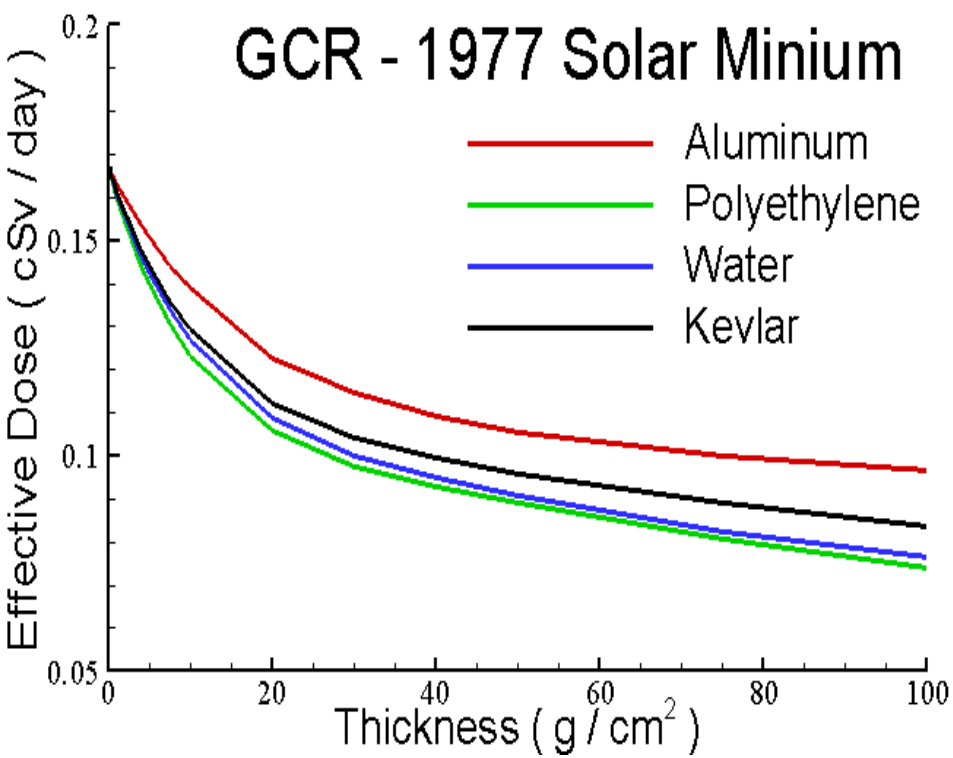
RADIATION LIMITS

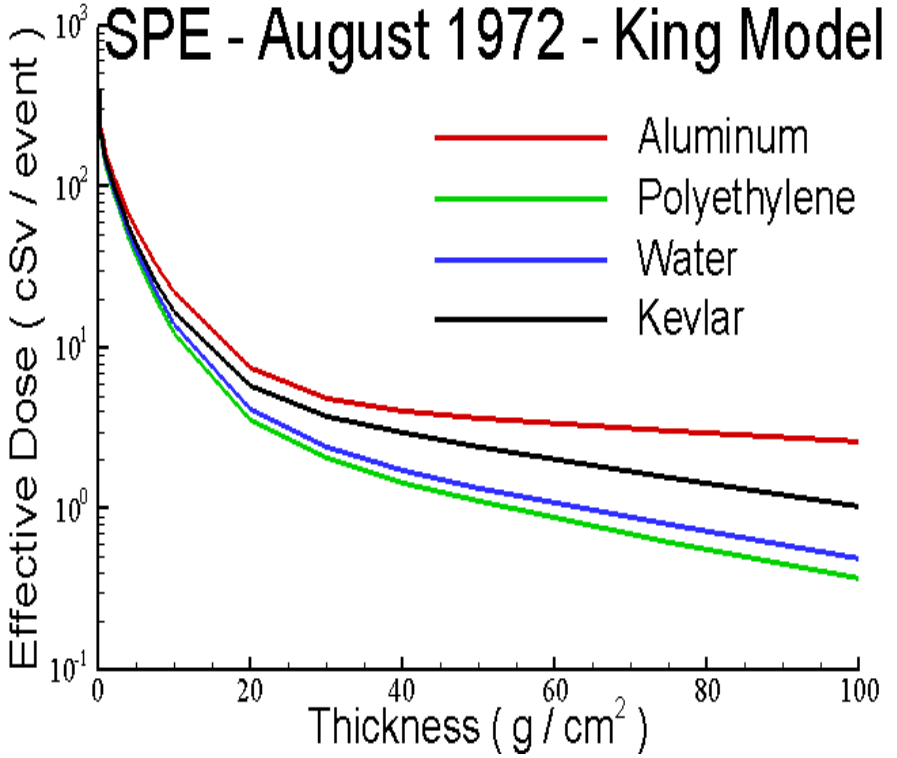
- NASA defines both short-term and long-term career dose limits
- Short-term limits set to prevent occurrence of clinically significant, (deterministic) non-cancer health effects
- Long-term career limits constrain an acceptable level of risk of contracting cancer
  - Risk of USA population contracting cancer (morbidity) $\approx$ 40%
  - Risk of USA population dying from cancer (mortality) $\approx$ 20%
    - Females 19%, Males 23%
  - NASA Risk Exposure Induced Death REID
    = 3% at 95% confidence limit (CL)

Recent work at NASA Langley Research Center (LaRC)



RECENT LARC WORK: EXPOSURE VERSUS DEPTH



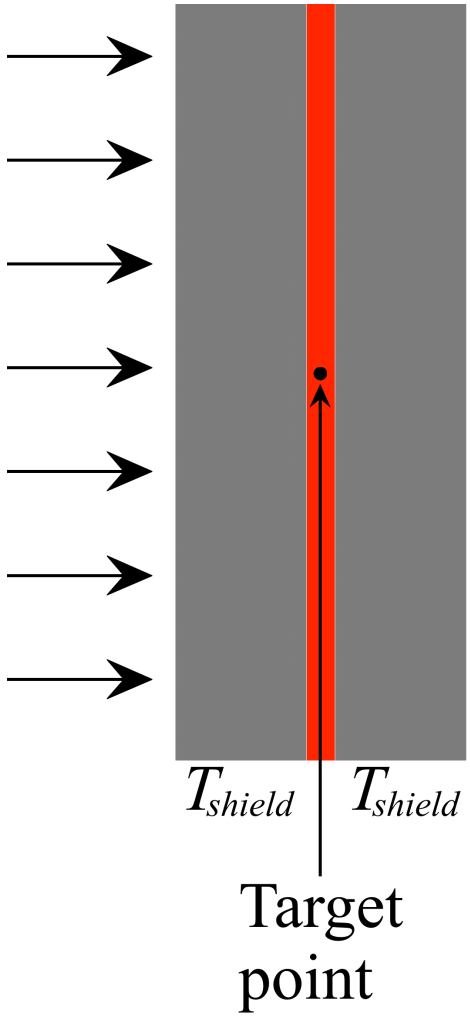


- Shielding materials are more effective for Solar Particle Events (SPE) than for GCR environment
- Hydrogen rich materials provide better protection
- Calculations - single slab material - dose falls smoothly with depth

RECENT LARC WORK: EXPOSURE VERSUS DEPTH

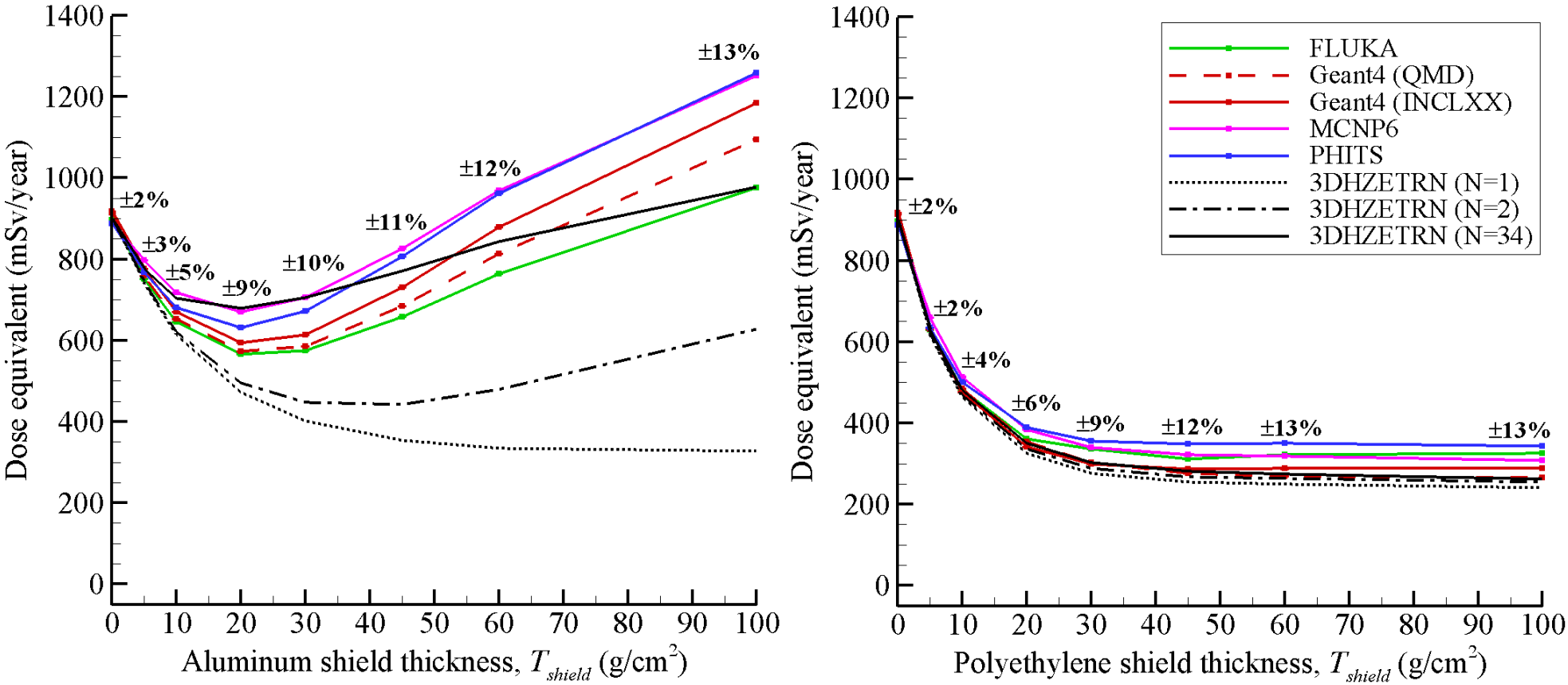
- Dramatic new result:
  - Appearance of minimum in dose-equivalent versus depth curve
  - Minimum is for GCR, not SPE
- Drastically changes spacecraft radiation shielding paradigm
- Previously, it was thought that increased shielding has diminishing effectiveness for GCR protection (passive shielding strategies are inefficient for GCR protection)
- The newly discovered minimum shows that increased shielding beyond the minimum actually results in worse radiation protection
  - for Al shielding
- There is an optimal thickness ($\sim$20 g/cm^2), which significantly alters the way spacecraft need to be designed in order to achieve the maximum radiation protection

Recent LaRC work: Exposure versus depth



Particles produced in both the front & back shield, and the front & back tissue material contribute to radiation exposure at a target point. The GCR external environment impinges from the left, as shown by the arrows. T_{shield} represents the shield thickness. Slaba et al., Life Sci. Space Res. 12, 1, 2017

RECENT LARC WORK: EXPOSURE VERSUS DEPTH



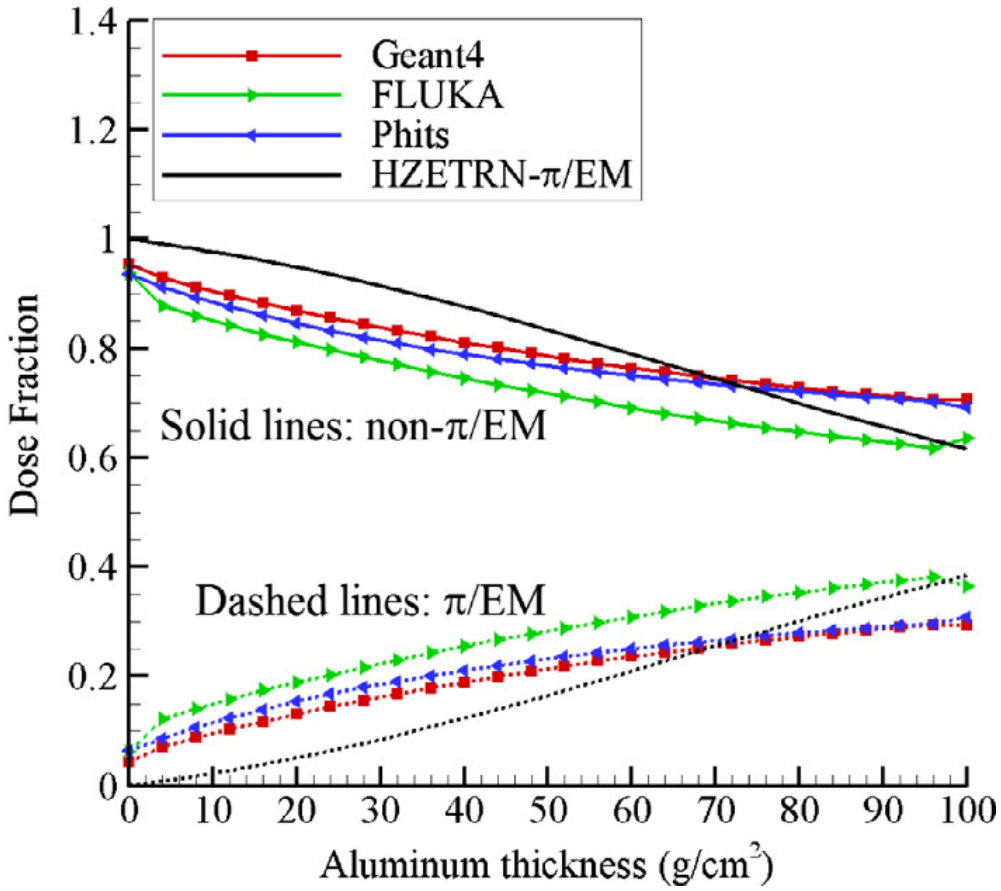
Annual dose-equivalent versus shielding thickness for the front-back shield geometry

Slaba et al., Life Sci. Space Res. 12, 1, 2017

RECENT LARC WORK: PION CONTRIBUTION TO DOSE

- New cross section models and transport methods have enabled quantitative estimates of pion contribution to dose in space radiation environments
- It has been found that the pion contribution can be as large as 20% in standard shielding scenarios, and as large as 40% for thick shielding
  - note this refers to dose, not dose-equivalent (small contribution)
- The large contribution of pions to dose for thick shielding regions represents a significant and important new discovery in space radiation physics
- Clearly the effects of pion production and the associated electromagnetic cascade must now be included in space radiation transport codes

RECENT LARC WORK: PION CONTRIBUTION TO DOSE

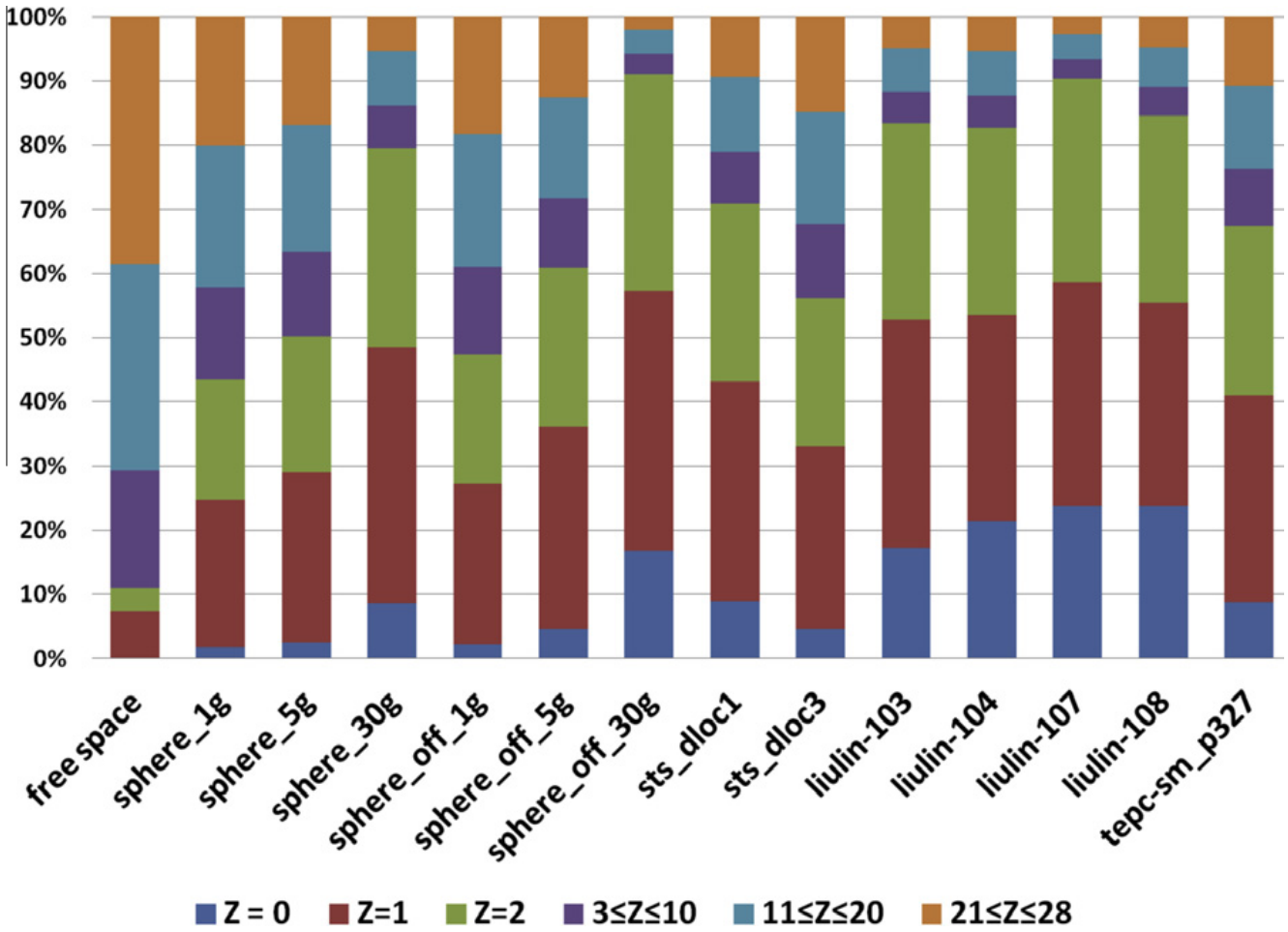


Dose fraction versus depth in Al slab exposed to a full GCR spectrum, as calculated by various different transport codes. EM refers to the electromagnetic cascade resulting from pion (π) production. Slaba et al., Adv. Space Res. 52, 62, 2013

Recent LaRC work: Light ion contribution to dose-equivalent

- Light ions are isotopes of Hydrogen & Helium
  - proton = ^{1}H, deuteron = ^{2}H, triton = ^{3}H, helion = ^{3}He, alpha = ^{4}He
- Experiments at NASA Space Radiation Laboratory (NSRL): common setup Fe & other heavy beams at 1 GeV/n.
- Now lighter beams with variety of energies available, it is important to ask which beams are most important for space radiation
- Recent studies - neutrons & light ions - large contributions to dose-equivalent for typical spacecraft shielding. Heavy ions at high energy important for thinly shielded regions.
- Solicitations for last several years have included wider range of ions & energies. GCR simulation developed to address this.

RECENT LARC WORK: LIGHT ION CONTRIBUTION



Calculated % contribution to blood forming organ dose-equivalent for free space (far left), simple spherical geometries in free space, and detector locations inside the space shuttle orbital vehicle (STS) and the ISS (liulin, tpec) in free space. Norbury & Slaba, Life Sci. Space Res. 3, 90, 2014

Light ions dominate dose-equivalent for realistic thick spacecraft shielding

Recent LaRC work: GCR simulation

NSRL at Brookhaven National Lab on Long Island, NY

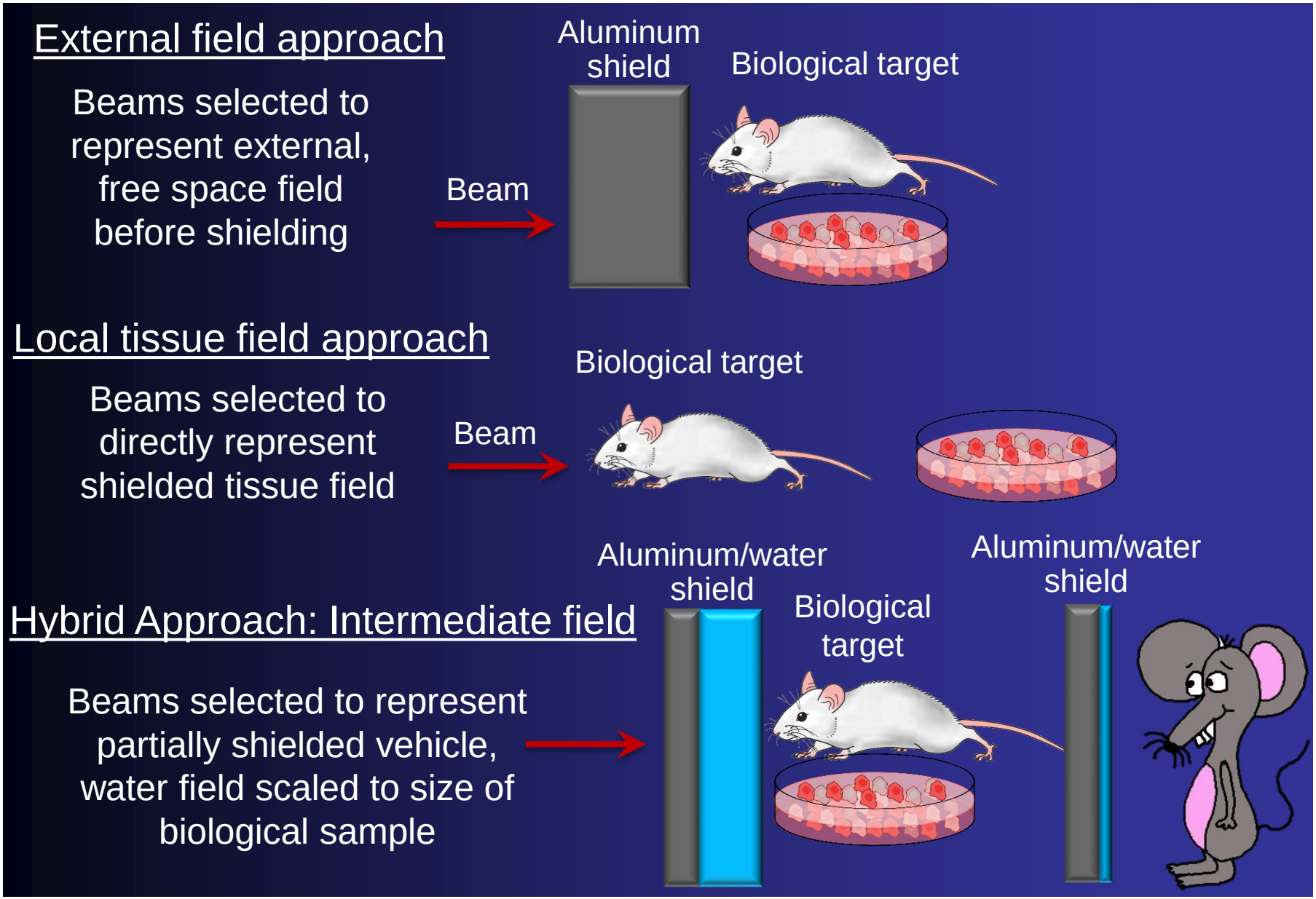
- Single high energy beam (e.g. Fe) not realistic GCR spectrum
- Light ions dominate dose-equivalent
- But single light beam (e.g. He) not realistic GCR spectrum either
- Simulate realistic GCR spectrum
- Protons: 4 GeV
- He - Fe: 1.5 GeV/n



Recent LaRC work: GCR simulation

- GCR consists of protons and heavier nuclei with energies relevant to space radiation from 10 MeV/n to about 50 GeV/n
- Due to facility constraints, most radiobiology experiments used single beams at fixed energy
- With recent advances in beam switching technology, it is now feasible to rapidly switch ion species and energy, making it possible to simulate the GCR environment with a variety of beams at a variety of energies
- Spectra calculated for new GCR simulation capability at NSRL
- Availability of GCR simulation at NSRL provides a major new experimental tool for the study of space radiobiological effects

Recent LaRC work: GCR simulation



provided by L. Simonsen (NASA Langley)

Recent LaRC work: Light ion cross sections

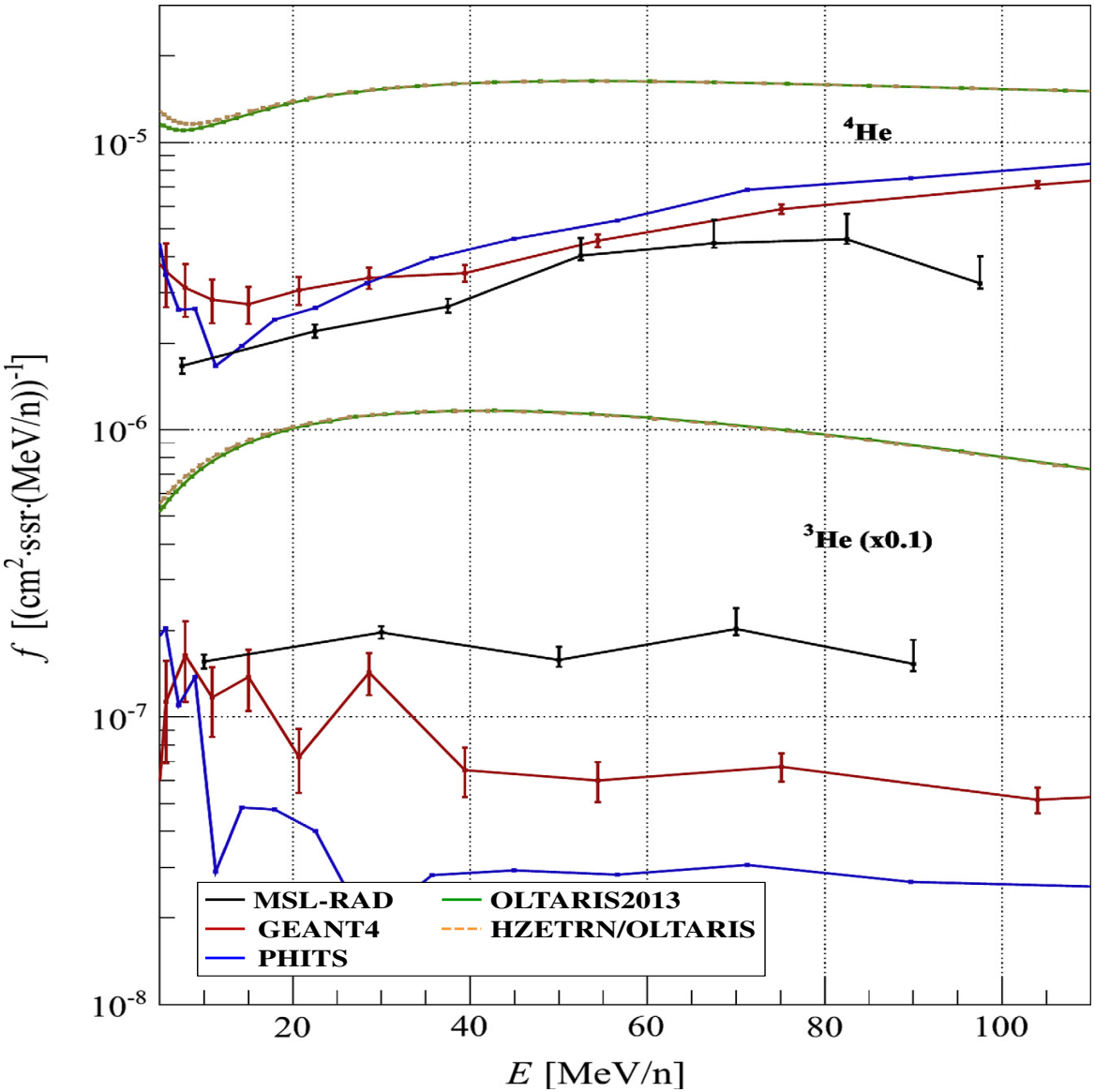
- Light ions are isotopes of Hydrogen & Helium
  - proton = ^{1}H, deuteron = ^{2}H, triton = ^{3}H, helion = ^{3}He, alpha = ^{4}He
- Light ions dominate dose-equivalent
  - For realistic shield thicknesses ($\geq$ 20 g/cm^2)
- Light ions are scattered at large angles
  - Require 3-dimensional transport & nuclear physics
  - 3DHZETRN & double differential cross sections
- Mars Science Laboratory Radiation Assessment Detector (MSL-RAD) light ion flux measurements highlight the need for improved nuclear interaction models
  - Light ion model results show moderate to large discrepancies over the MSL-RAD energy range
  - Model errors are mainly attributed to inaccurate light ion nuclear physics models
  - Discrepancies don't contribute significantly to dose-equivalent, but improvements would yield better agreement with MSL-RAD

Recent LaRC work: Light ion cross sections

- Transport codes show largest differences for light ions
  - GEANT, FLUKA, MCNP, PHITS, HZETRN, SHIELD(Russia)
  - Due to uncertain light ion nuclear physics models (coalescence & heavy ion breakup) and lack of experimental data
- Light ion cross section measurements needed
  - To improve inaccurate light ion nuclear physics models
- Light ion cross section measurements represent largest gap in cross section database Norbury et al., Rad. Meas. 47, 315, 2012
- Light ion cross sections represent the largest physics uncertainty in space radiation

RECENT LARC WORK: LIGHT ION CROSS SECTIONS

- MSL-RAD measurements show large discrepancies relative to models for light ions

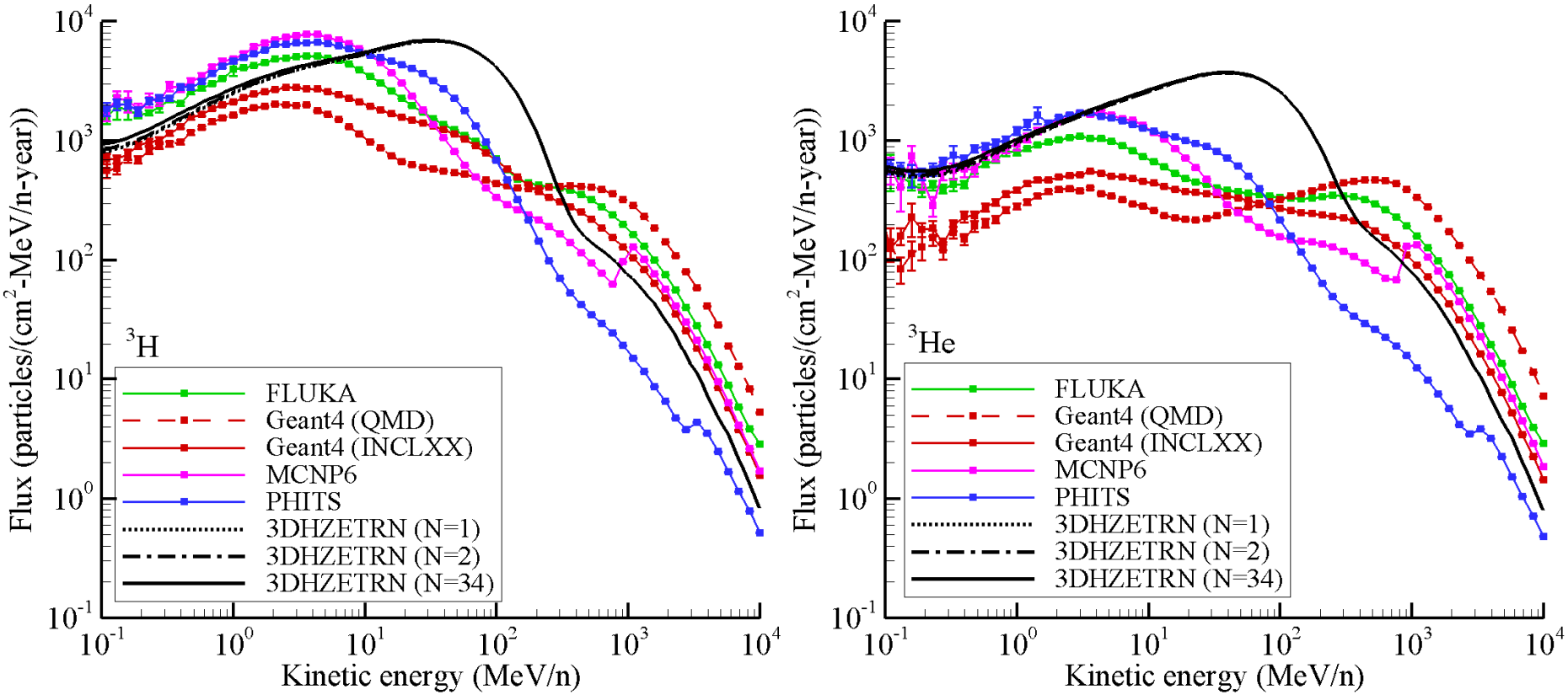


He isotope transport calculations compared to MSL-RAD data

Matthia et al., J. Space Weath. Space Clim. 6, A13, 2016

Transport codes show largest differences for light ions

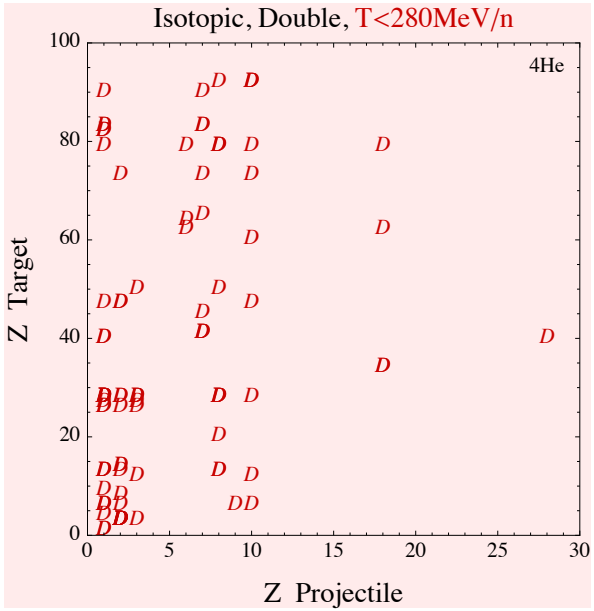
(Thick shield)

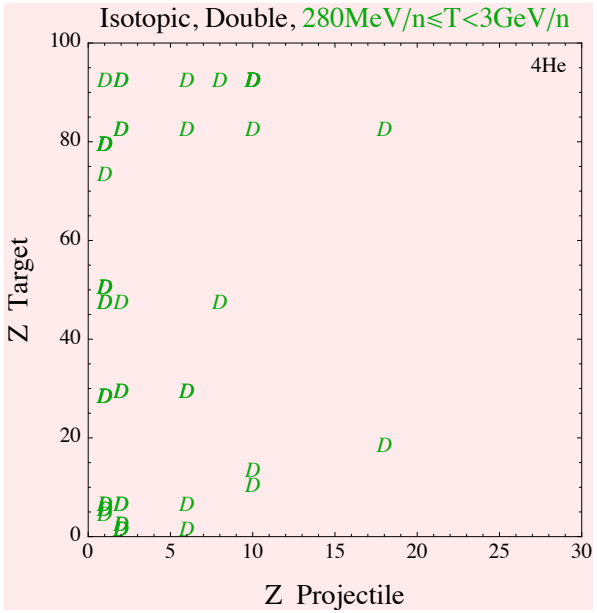


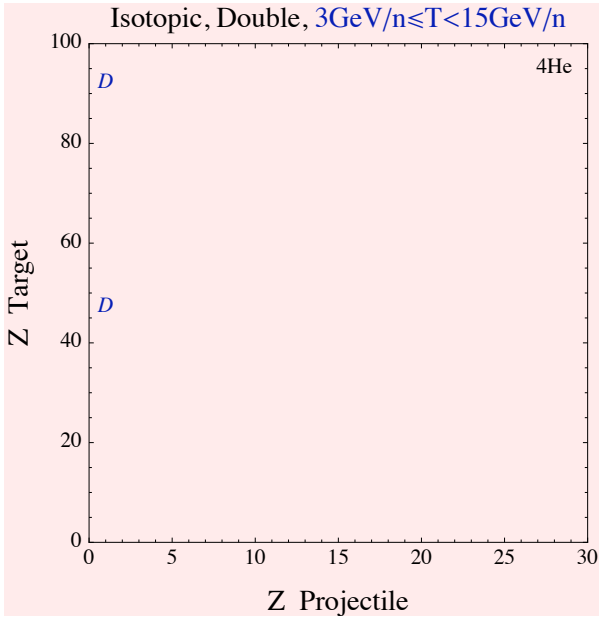
^{3}H and ^{3}He flux behind 60 g/cm^2 Al shield for GCR minimum spectrum

Slaba et al., Life Sci. Space Res. 12, 1, 2017

RECENT LARC WORK: LIGHT ION CROSS SECTIONS



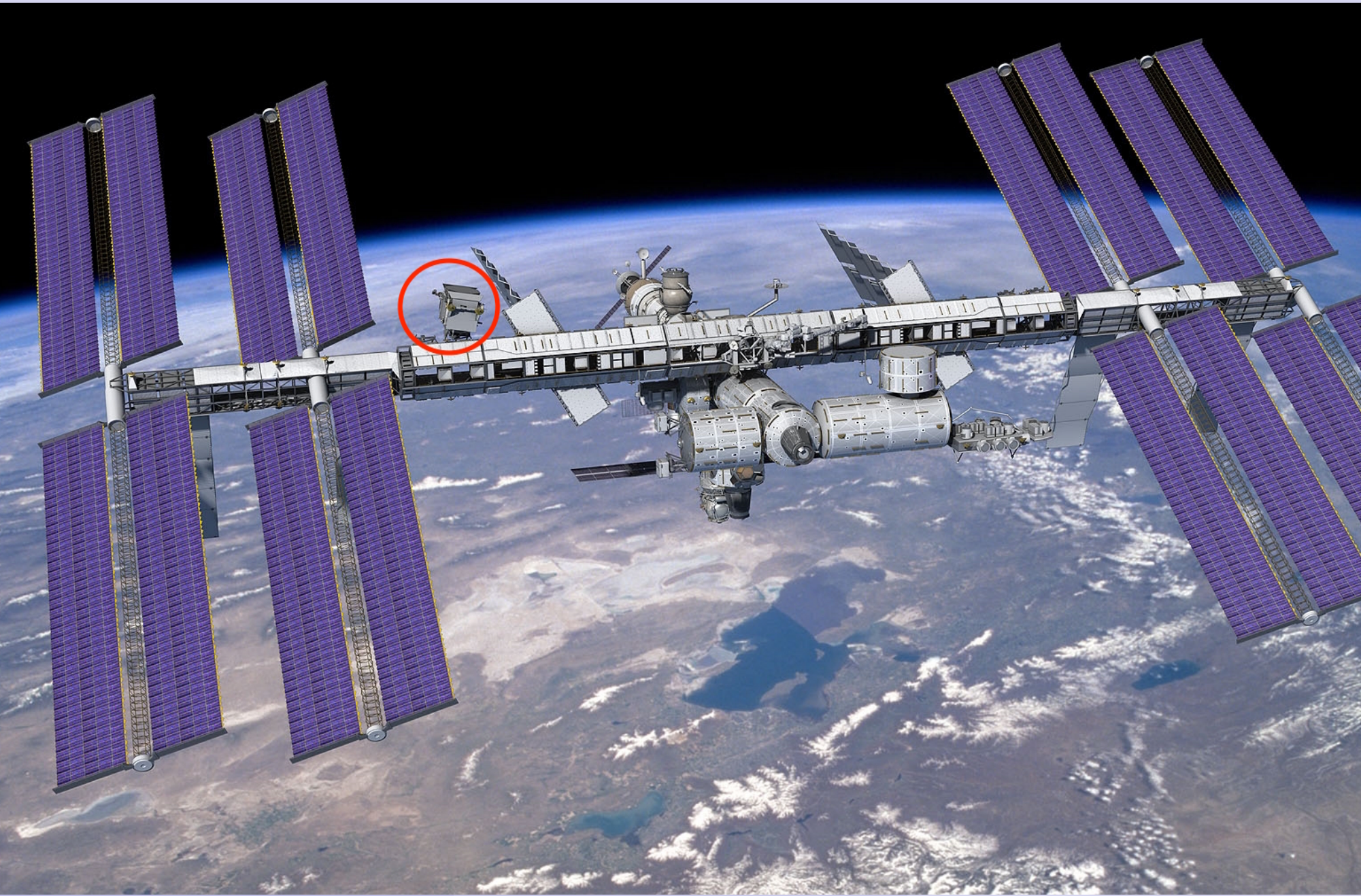




Double differential (D) cross section measurements for ^{4}He fragment production

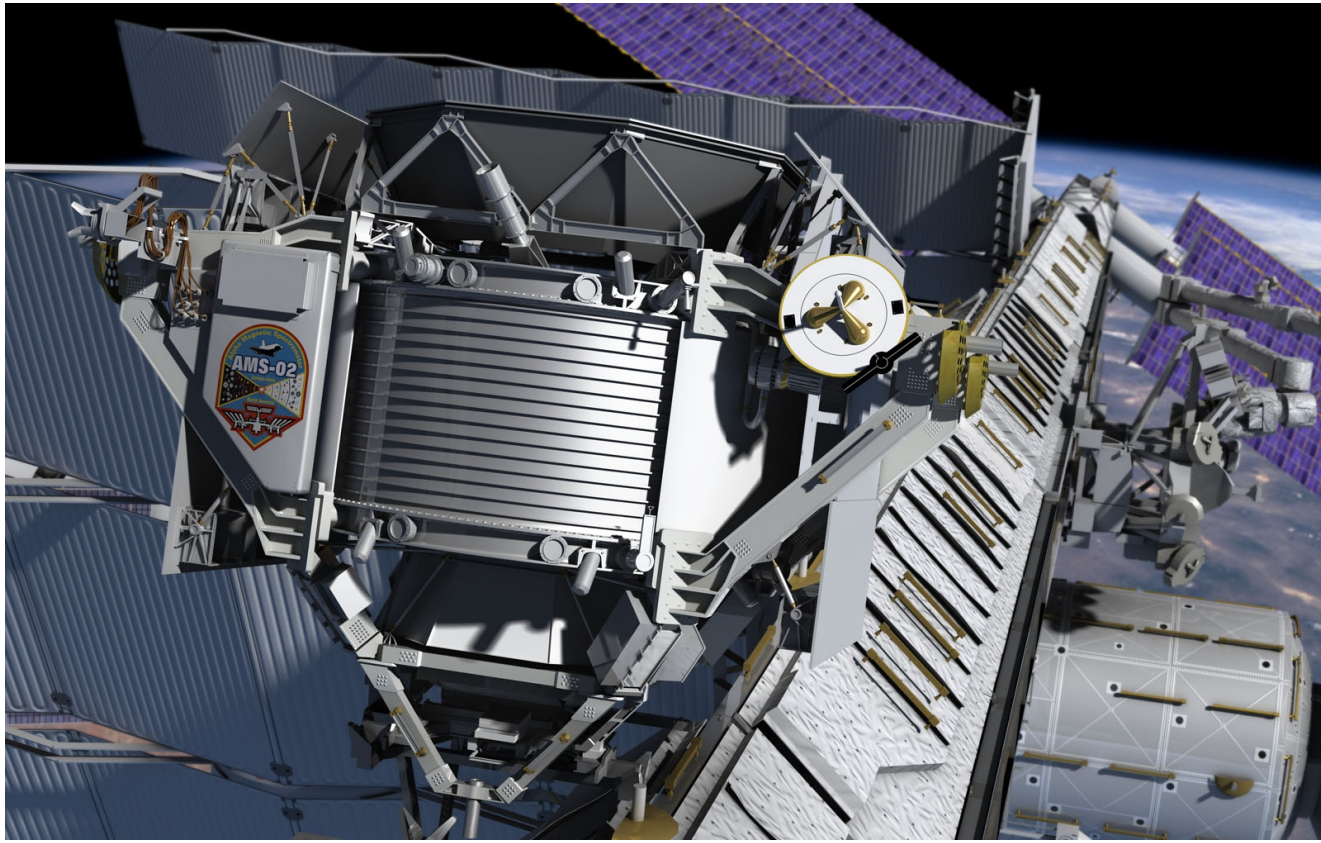
Norbury et al., Rad. Meas. 47, 315, 2012

Alpha Magnetic Spectrometer (AMS)



Alpha Magnetic Spectrometer (AMS)

- Main purpose to search for dark matter
- Also detects GCR - data can be used to refine GCR models



Recent LaRC work: AMS - Introduction

- Sensitivity studies for GCR environmental modeling:
- A variety of sensitivity studies have been performed to quantify relative importance of specific ions and energies in the GCR spectrum to exposure behind shielding and tissue.
  Slaba & Blattnig, Space Weather 12, 217, 2014
- Highly efficient methods have been developed to propagate GCR model uncertainty into exposure quantities behind shielding. Slaba & Blattnig, Space Weather 12, 217, 2014
- These efforts led to automated procedures that were subsequently used to refine GCR model parameters and significantly reduce uncertainties.
  - Resulted in 2014 Badhwar-ONeill GCR model. O'Neill, Golge, Slaba, NASA TP 2015-218569
- These quantitative assessments were used to inform and define requirements for obtaining new and highly significant measurements from the Alpha Magnetic Spectrometer (AMS-2) detector on the ISS. This updated GCR model has now been integrated with NASA cancer risk model.
- An important realization from these studies is that 90% of the effective dose is contributed from GCR energies above 500 MeV/n, which is the upper energy limit of the Advanced Composition Explorer / Cosmic Ray Isotope Spectrometer (ACE/CRIS) satellite, which has contributed to most of the GCR data .
- Higher energy data are needed, which is why the AMS-2 measurements are so important.

Recent LaRC work: AMS results

Three models will be compared to AMS data:

- Badhwar - O'Neill (BON14) model

  O'Neill, Golge, Slaba, NASA Tech. Paper 218569, 2015

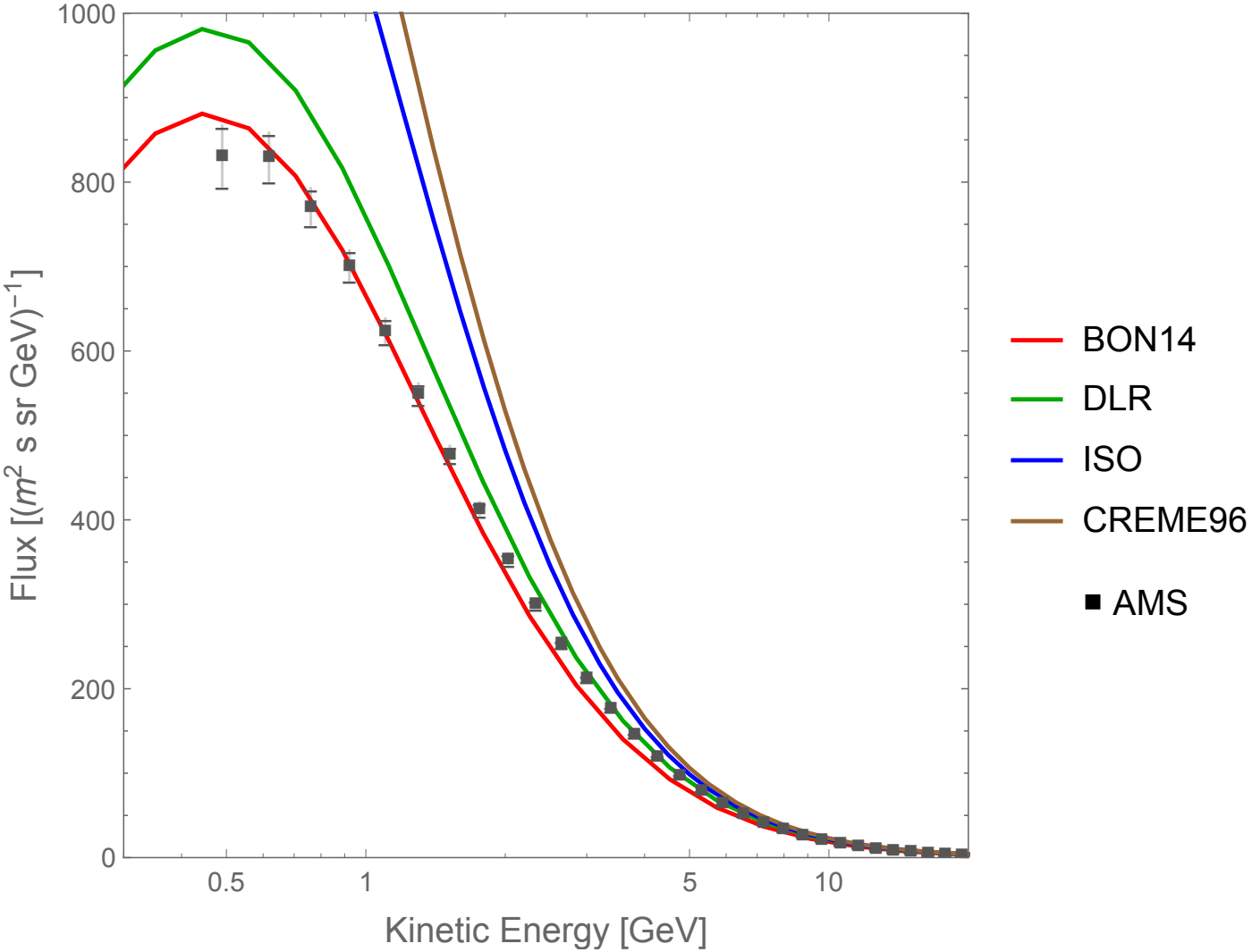
- DLR model

  Matthia et al., Adv. Space Res. 51, 329, 2013

- ISO15390 model - taken from SPENVIS

  Nymmik et al., Adv. Space Res. 17, 19, 1996

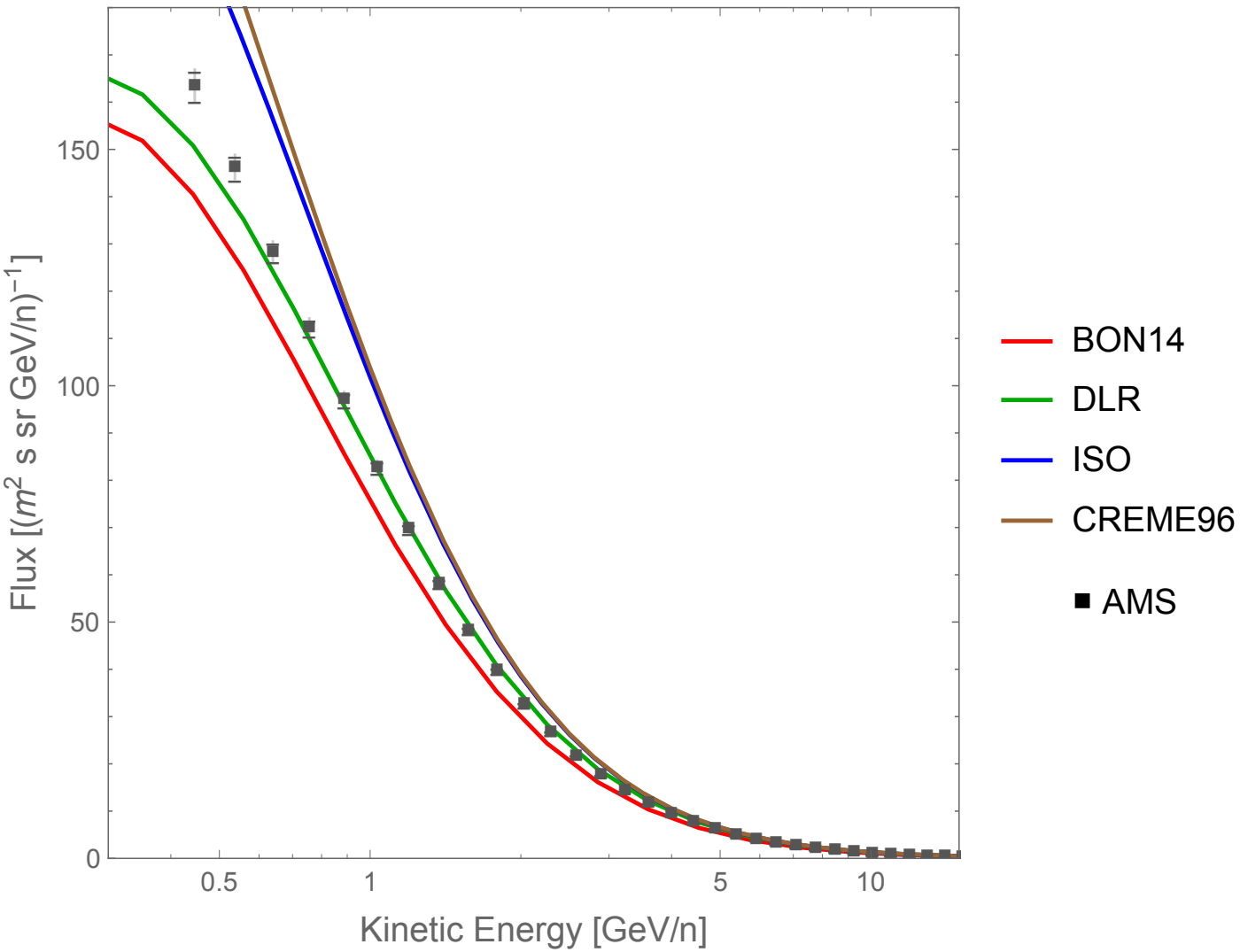
HYDROGEN FLUX VS. KINETIC ENERGY



Model comparisons to data

AMS data of sufficient quality to distinguish between models

HELIUM FLUX VS. KINETIC ENERGY



Model comparisons to data

Radiation & Space Exploration



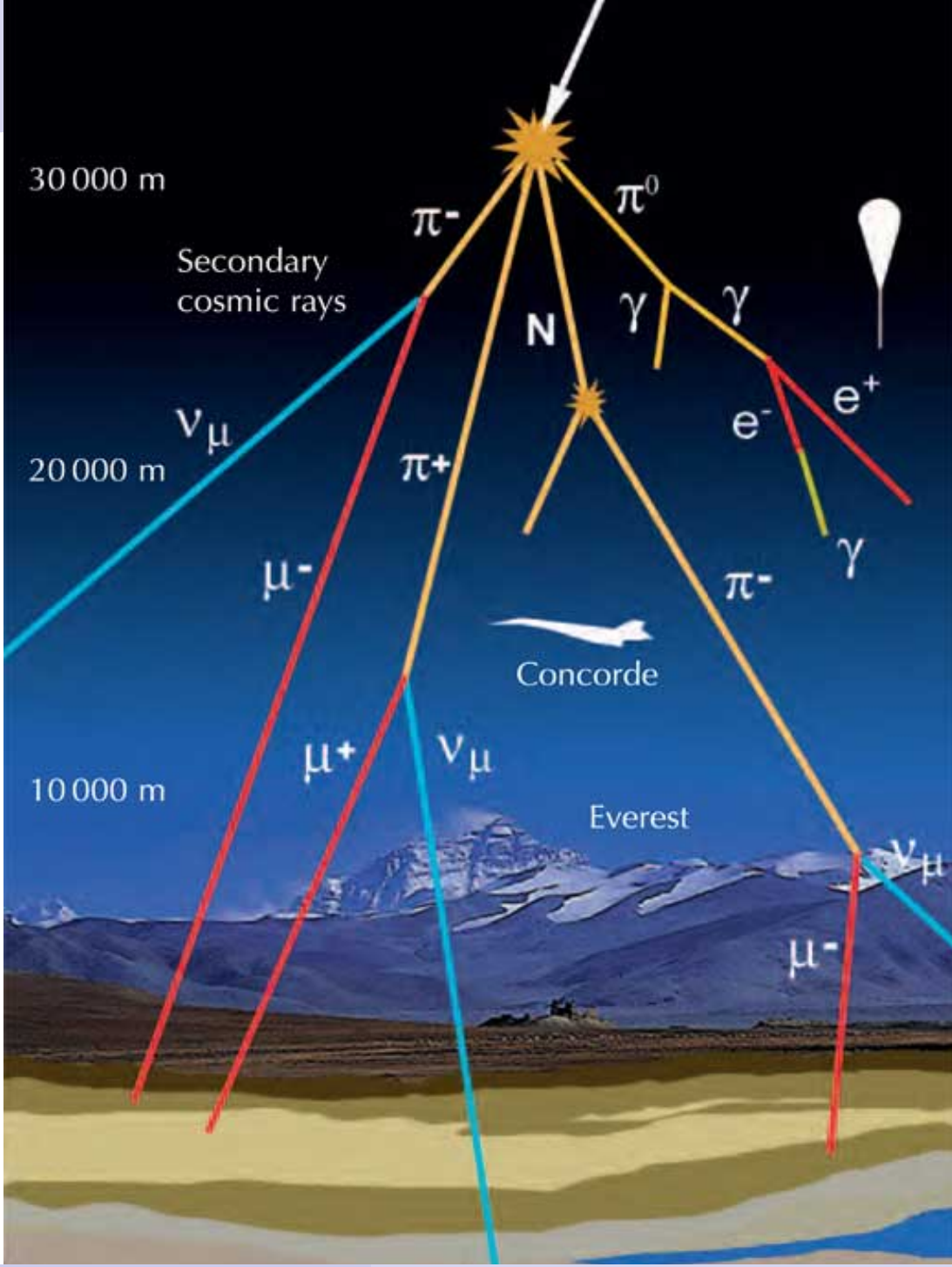
Aircraft



AIRCRAFT

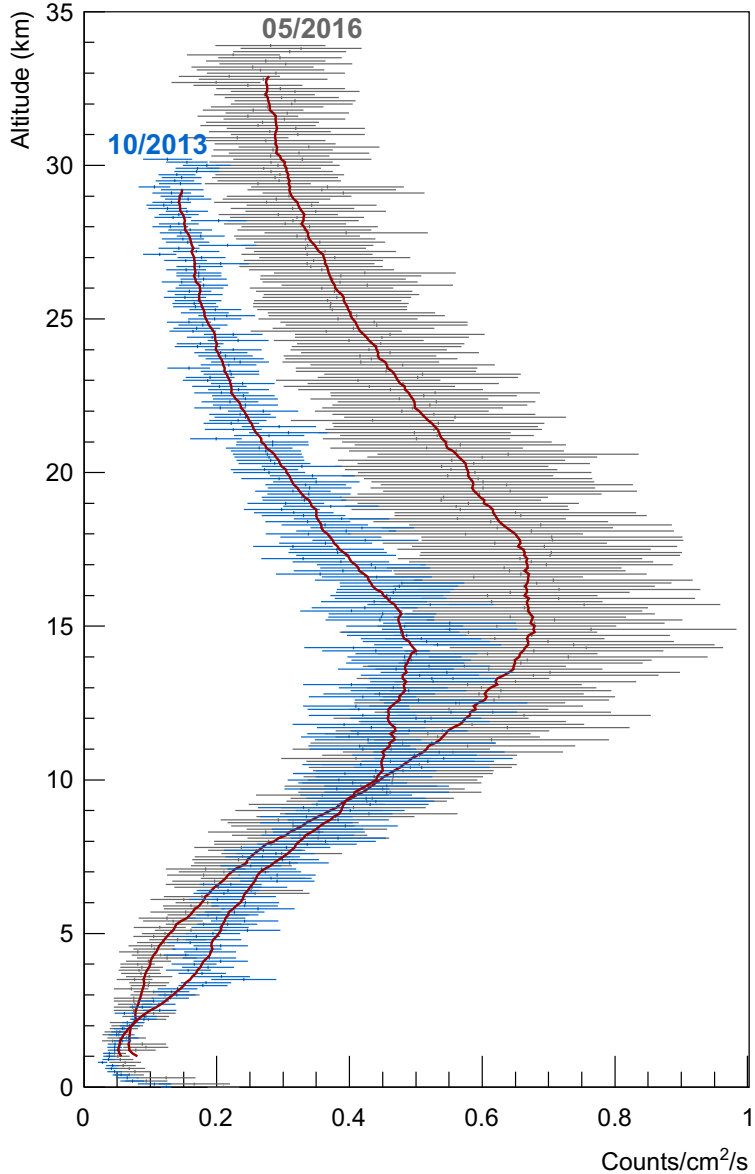
Cosmic ray cascade in Earth atmosphere

http://www.scienceinschool.org/2010/issue14/cloud/maltese



Aircraft - Pfotzer maximum

Vertical profile of the secondary cosmic ray counts. Two different data sets from two missions during different phases of solar activity are shown: (blue) October, 2013 when the Sun undergoes maximum activity and (gray) May, 2016 after the solar maximum period.



Sarker et al., Adv. Space Res. 60, 991, 2017

Aircraft

- Oct. 2008 Airbus plane (Perth - Singapore) struck by cosmic ray
- Inertial reference computer unit failed
- Sharply lost altitude
- Caused injury to occupants and damage to plane
- Landed safely





Kerby, Mashnik, Los Alamos National Lab Report LA-UR-14-27533

Aircraft

- *Possible* health effects on female airline crew
- Miscarriages
- Menstrual disorders
- Breast cancer (probably circadian)
- Hard to dis-entangle radiation vs. circadian rhythm disruption



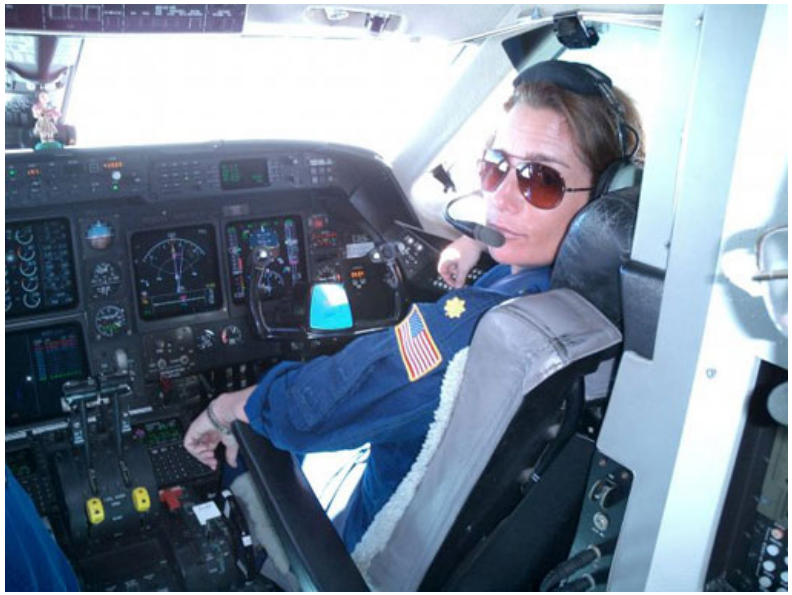


Figure Credits:

https://www.bls.gov/ooh/images/2731.jpg

https://oceanservice.noaa.gov/profiles/aug09/finn.html

AIRCRAFT

- Domestic crews 1 - 2 mSv /yr



- International crews $<$ 4 mSv / yr
- Pregnant woman $<$ 5 mSv
  (to fetus per pregnancy)



https://www.cdc.gov/vitalsigns/zika/images/homepage_734x546px.jpg

AIRCRAFT - WHY ALL THE CONCERN NOW?

- NCRP & ICRP have lowered radiation worker exposure
  - 50 mSv / yr to 20 mSv / yr
- Air crews most highly exposed of any occupation group
- FAA criticized for not paying enough attention
- Many more polar flights
- Future High Speed Civil Transport (HSCT) radiation levels
  - 3 times higher than for crews of subsonic transport
- Only solution available now:
  - reduce flight hours
- NAIRAS - Mertens (Langley)



Low Earth Orbit & International Space Station



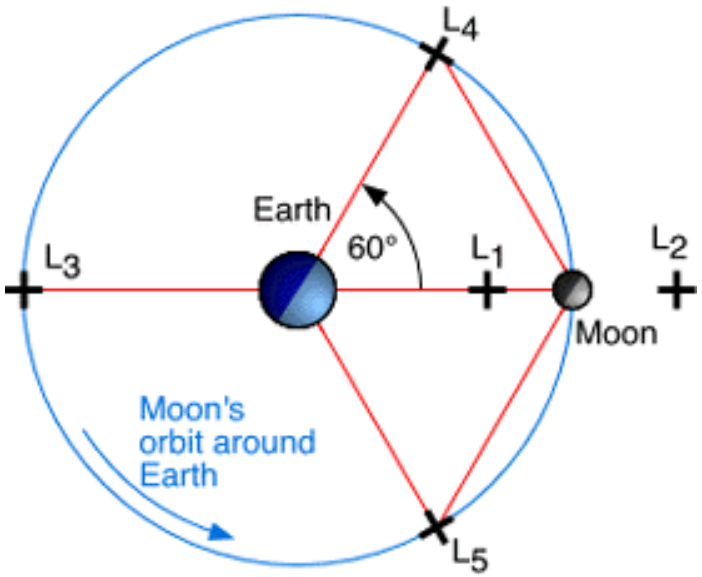
Low Earth Orbit & International Space Station

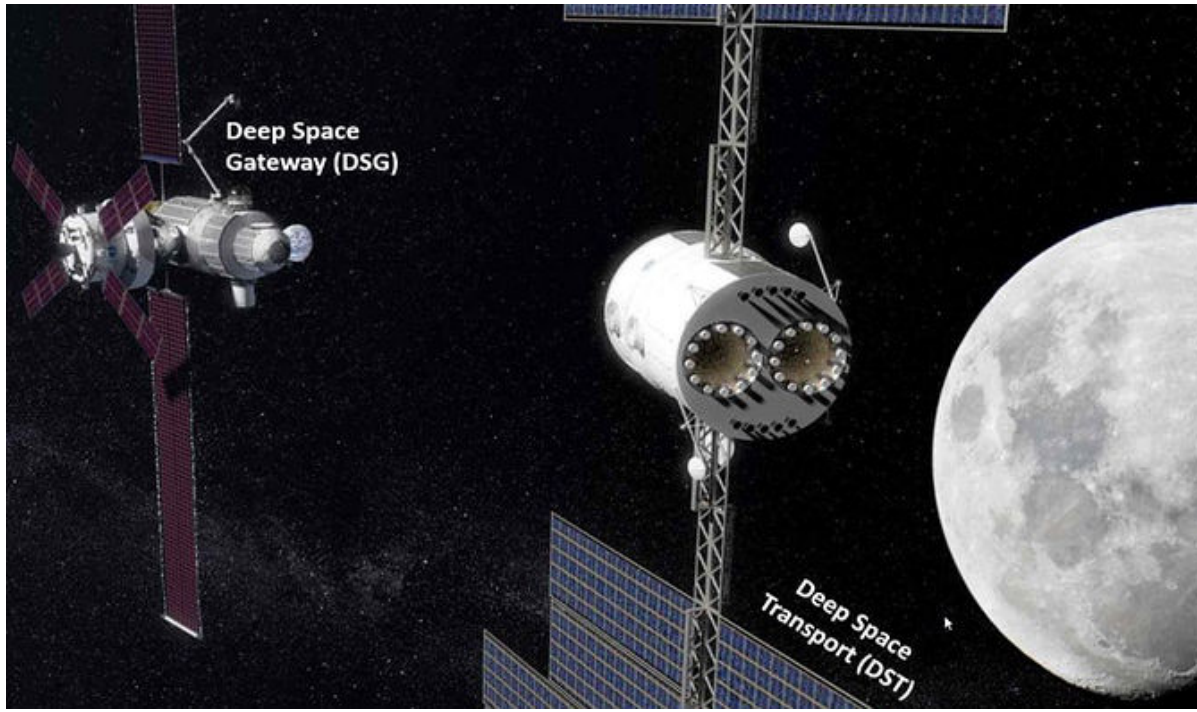
- ISS $\sim$ 150 – 300 mSv/year
- Depends on altitude and detector location
- No spacewalks through SAA



Cislunar space & Deep Space Gateway

Plans underway for human missions to Cislunar space
- Construction of Deep Space Gateway
- Radiation levels much higher than Low Earth Orbit (LEO)
- Storm shelter from SPE will be constructed

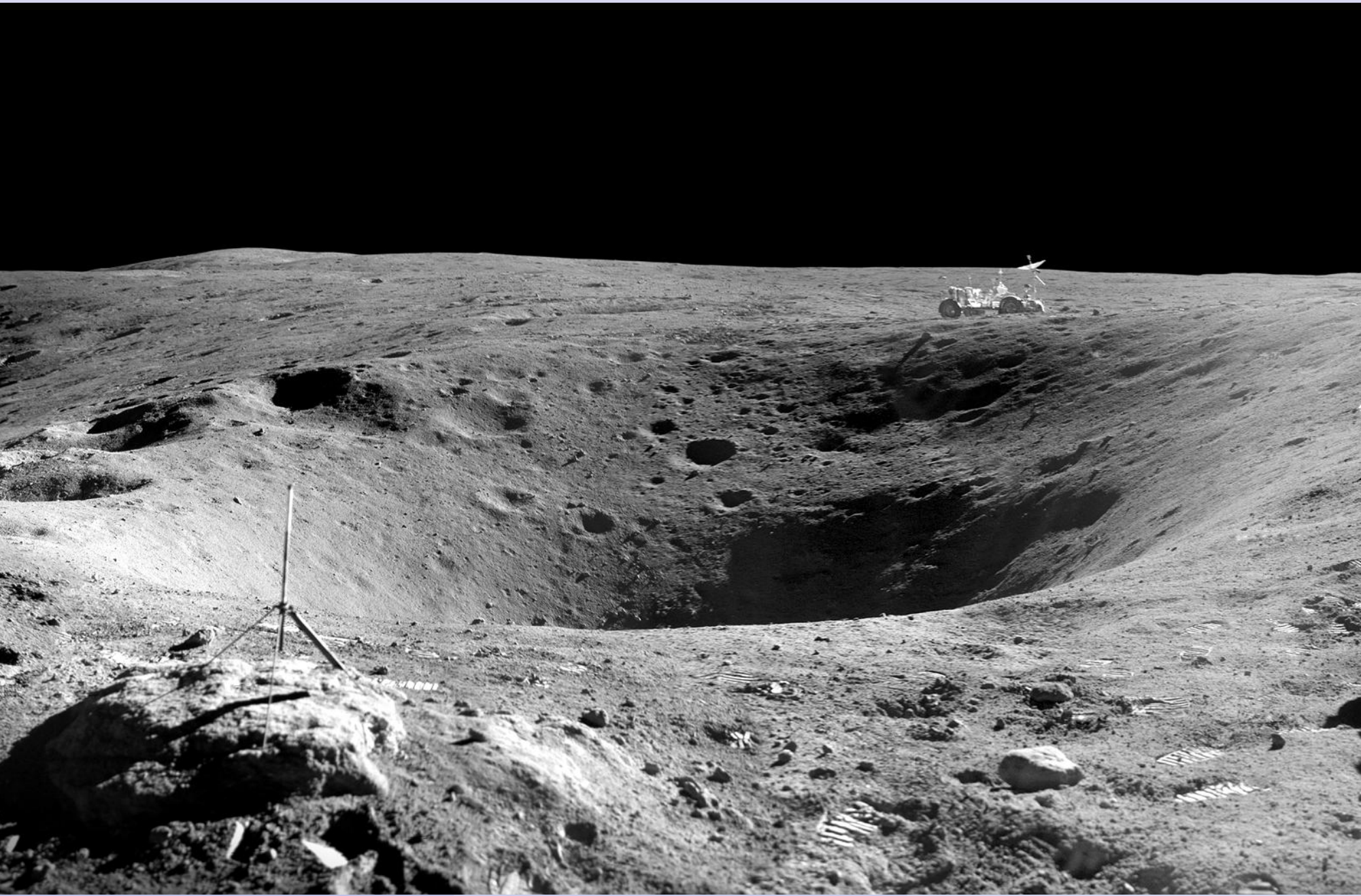




Lagrange Points

http://www.asi.org/images/1999/asi199900075.gif

Moon



Moon

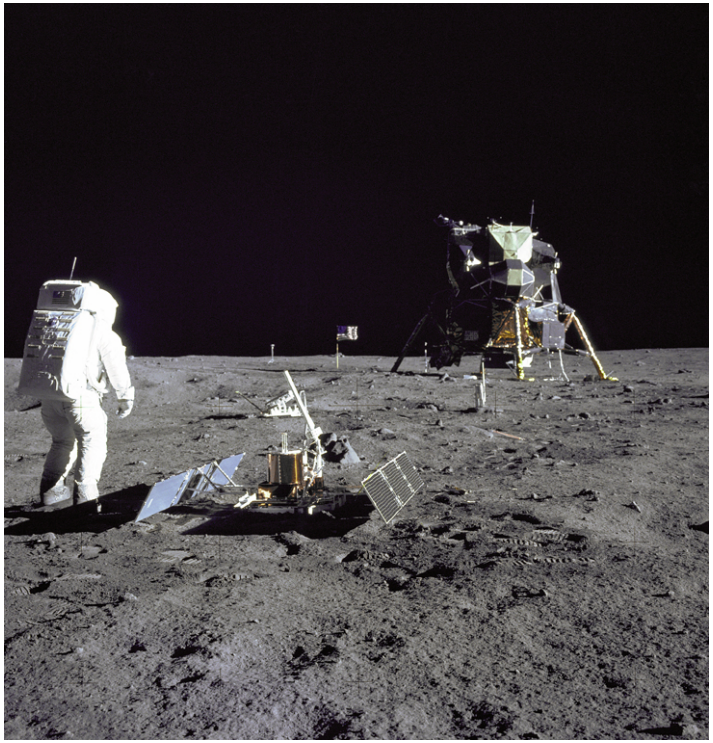
Short duration

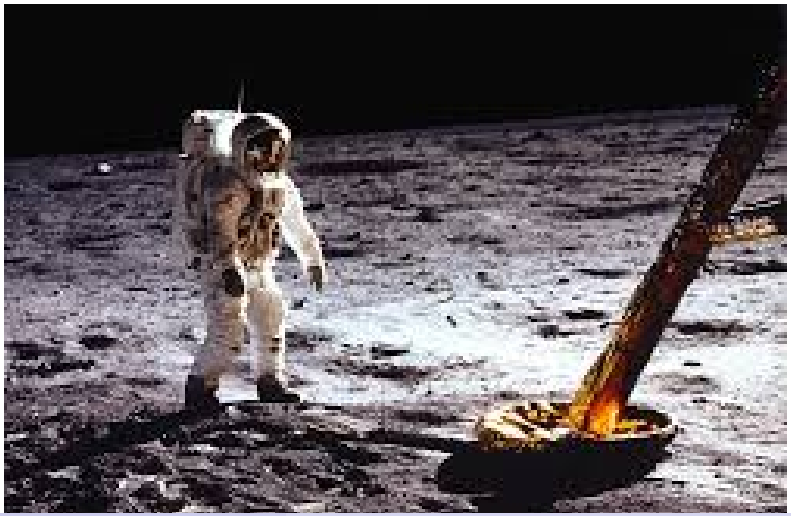
- Solar particle events

Long duration

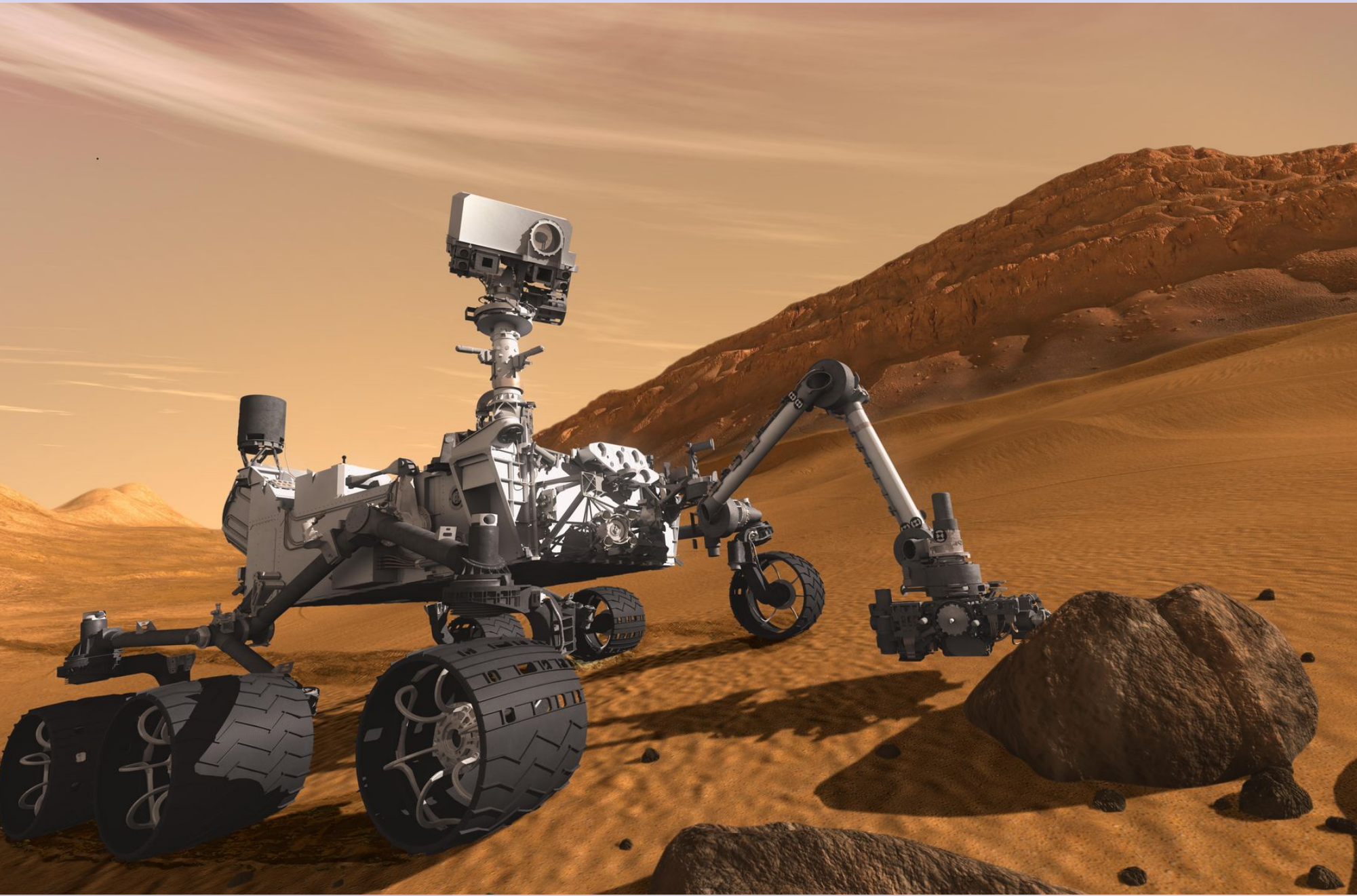
- Solar particle events
- Galactic cosmic rays







Mars



Mars

- Curiosity Mars Science Lab (MSL)
  Radiation Assessment Detector (RAD) Zeitlin et al. Science vol. 340, p.1080, 2013
- Mars transit inside vehicle: 1.84 $\pm$ 0.33 mSv / day

  MSL (one way) 253 days $\Rightarrow$ 466 mSv

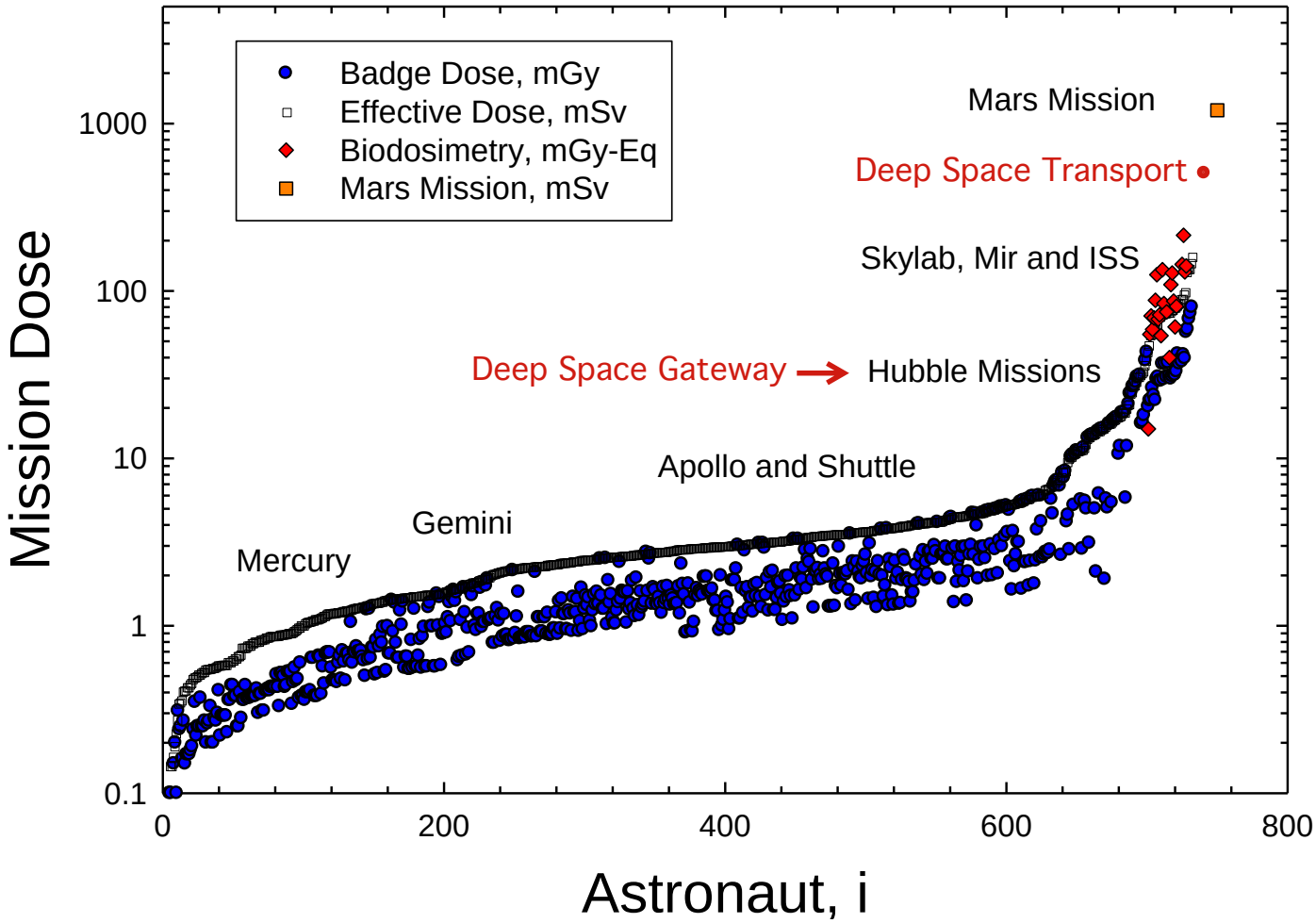
  - On surface: 0.7 mSv / day
- Opposition-class (short-stay) mission (200+30+400 days) $\approx$ 1 Sv
- Conjunction-class (long-stay) mission (200+500+200 days) $\approx$ 1 Sv
- Approaching and exceeding limits - 3 to 4 times over current PEL
- Estimate (95% CL) for 35 year old female who never smoked:
  (assuming 20 g/cm^2 aluminum shielding during solar minimum)

  7% for 1 year cislunar

  12% Mars mission (4 $\times$ PEL)

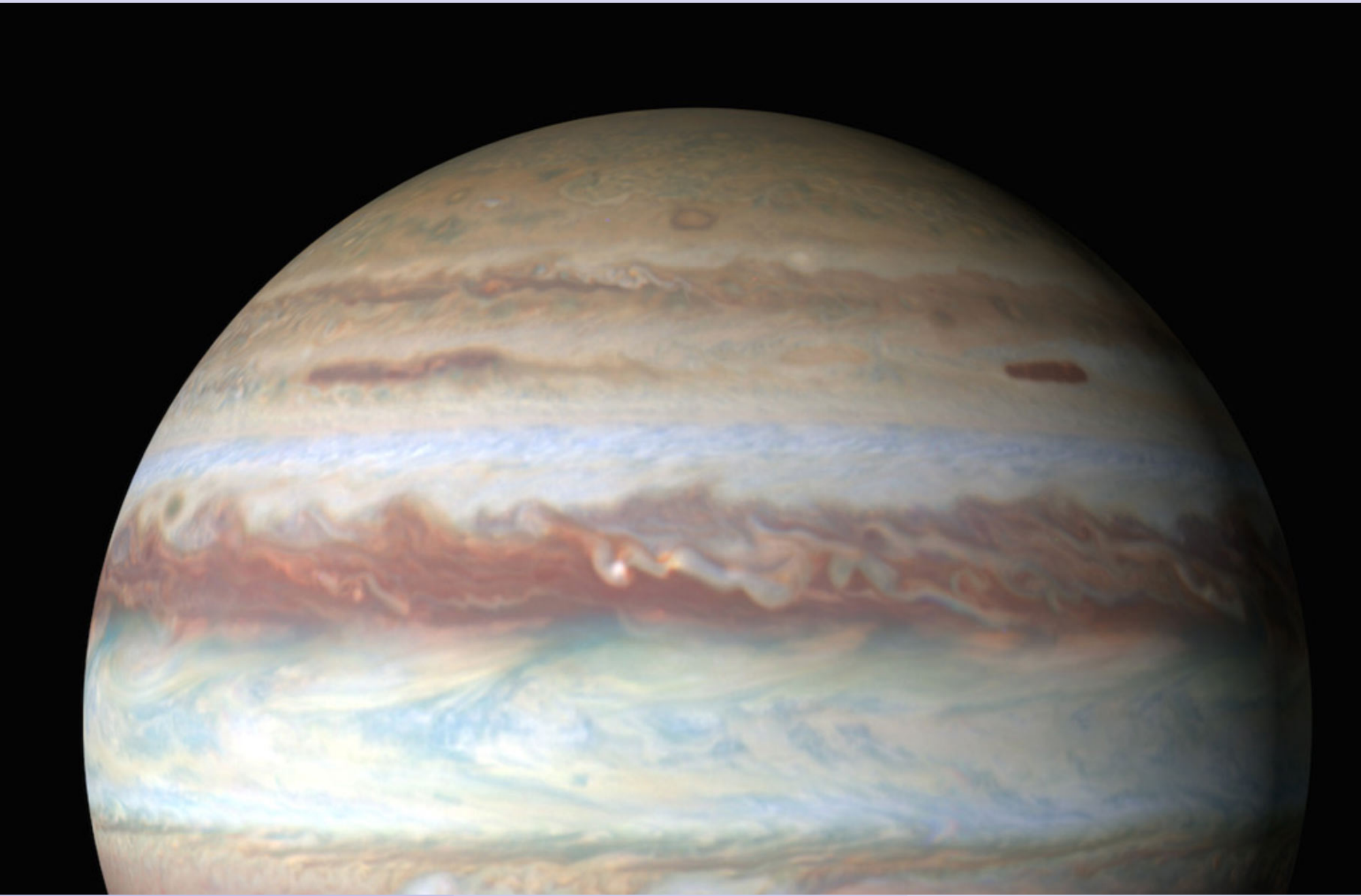
Radiation dose for Mars missions much larger than previous missions

Dose-rates 0.5 to 2 mSv/d



adapted from Cucinotta et al. Rad. Res., vol.170, p.127, 2008; using Lisa Simonsen update

JUPITER

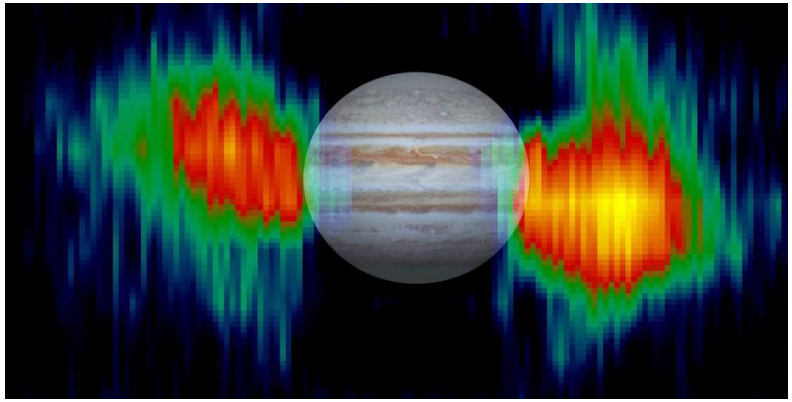


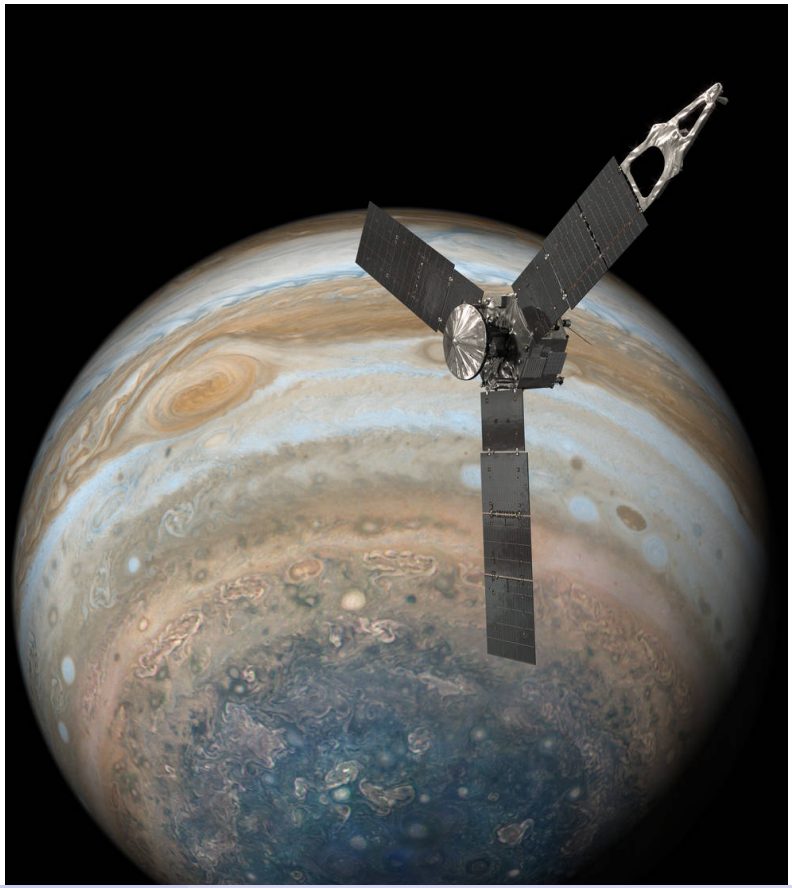
JUPITER

- Radiation belts are most intense in solar system

- Mostly energetic electrons, also proton & ions

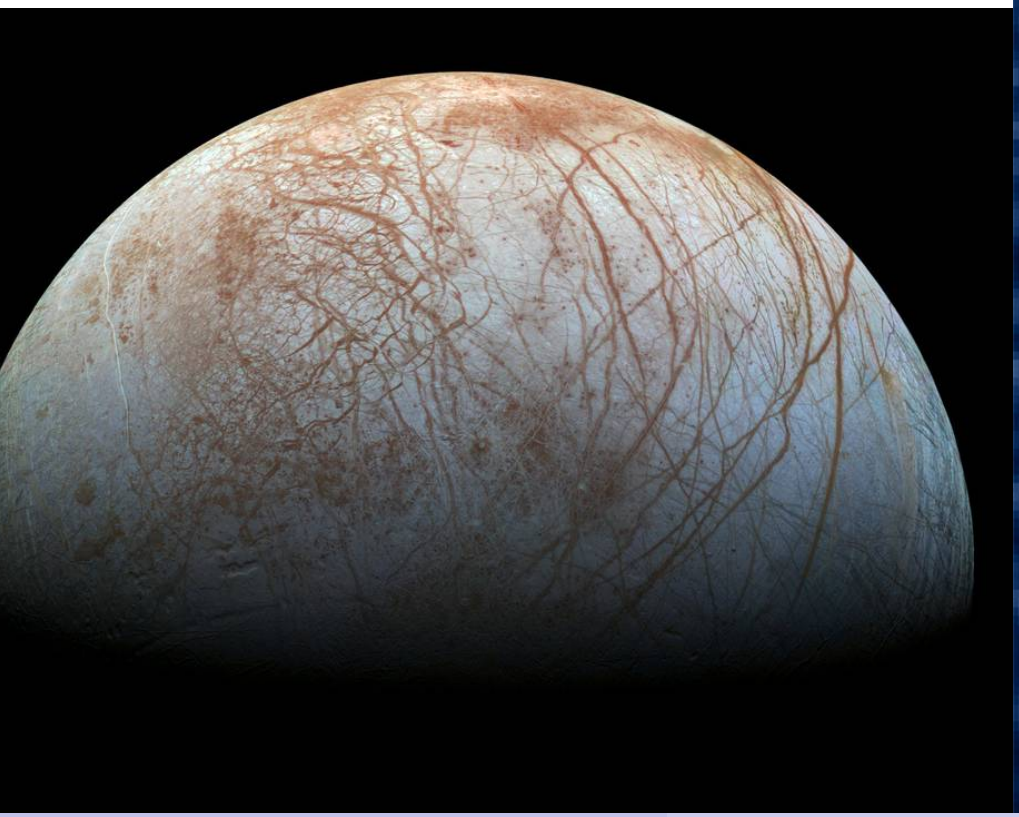
- Juno spacecraft recently found new belt near equator consisting of heavy ions

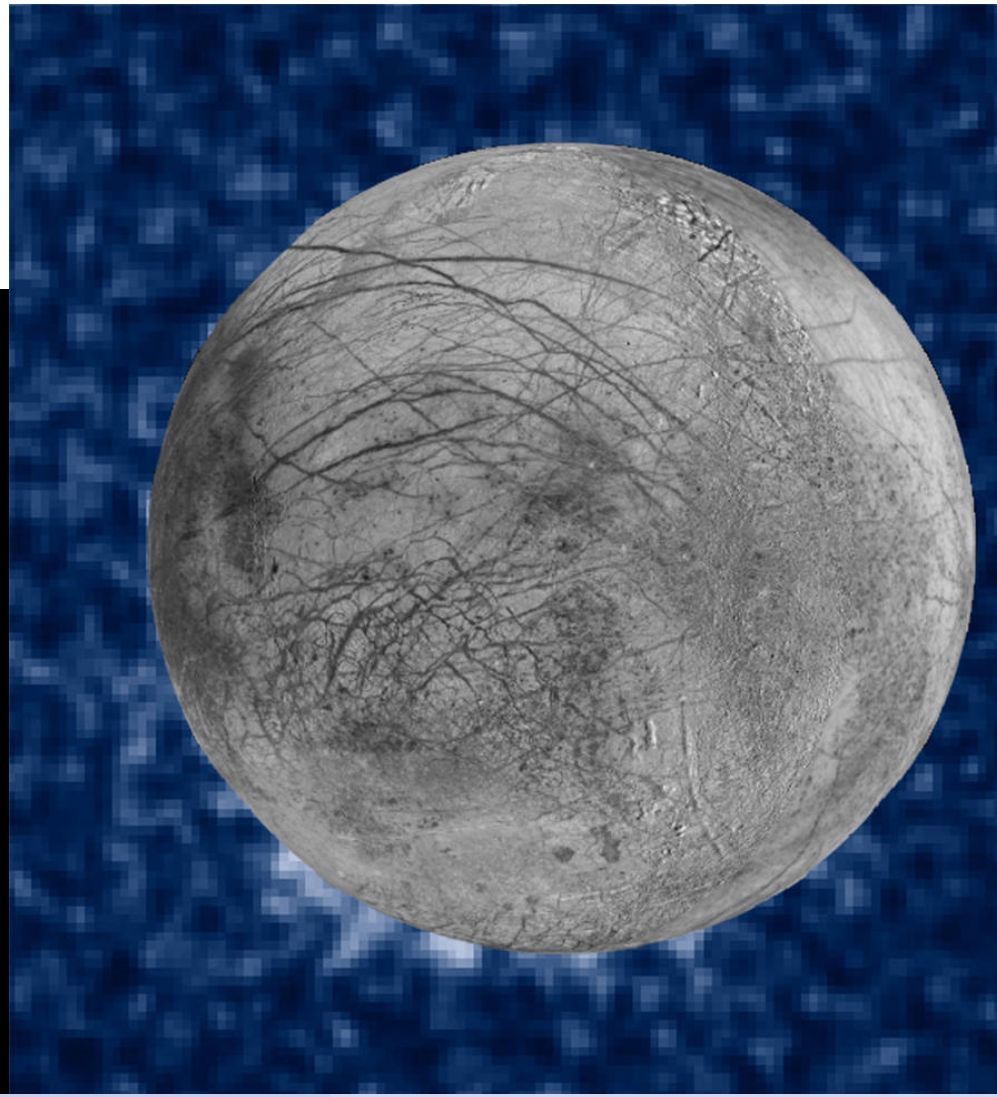




EUROPA

- Venting ocean world - possible life
- But resides in very high radiation zone



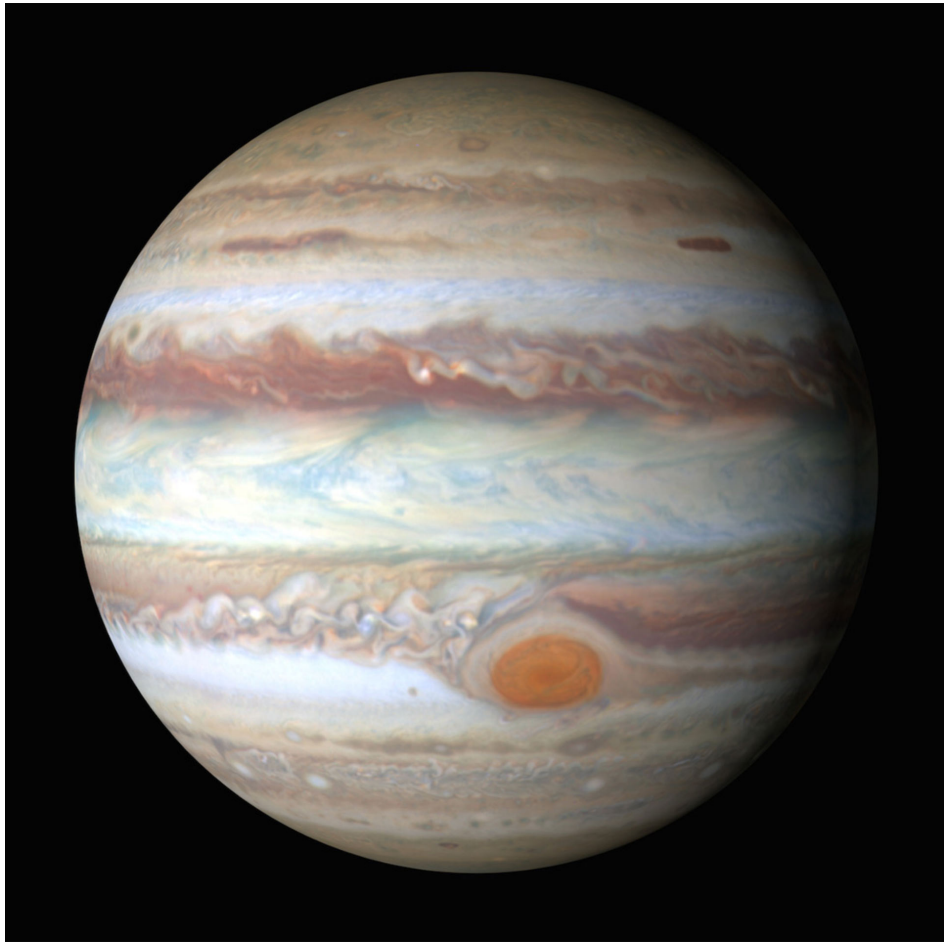


JUPITER

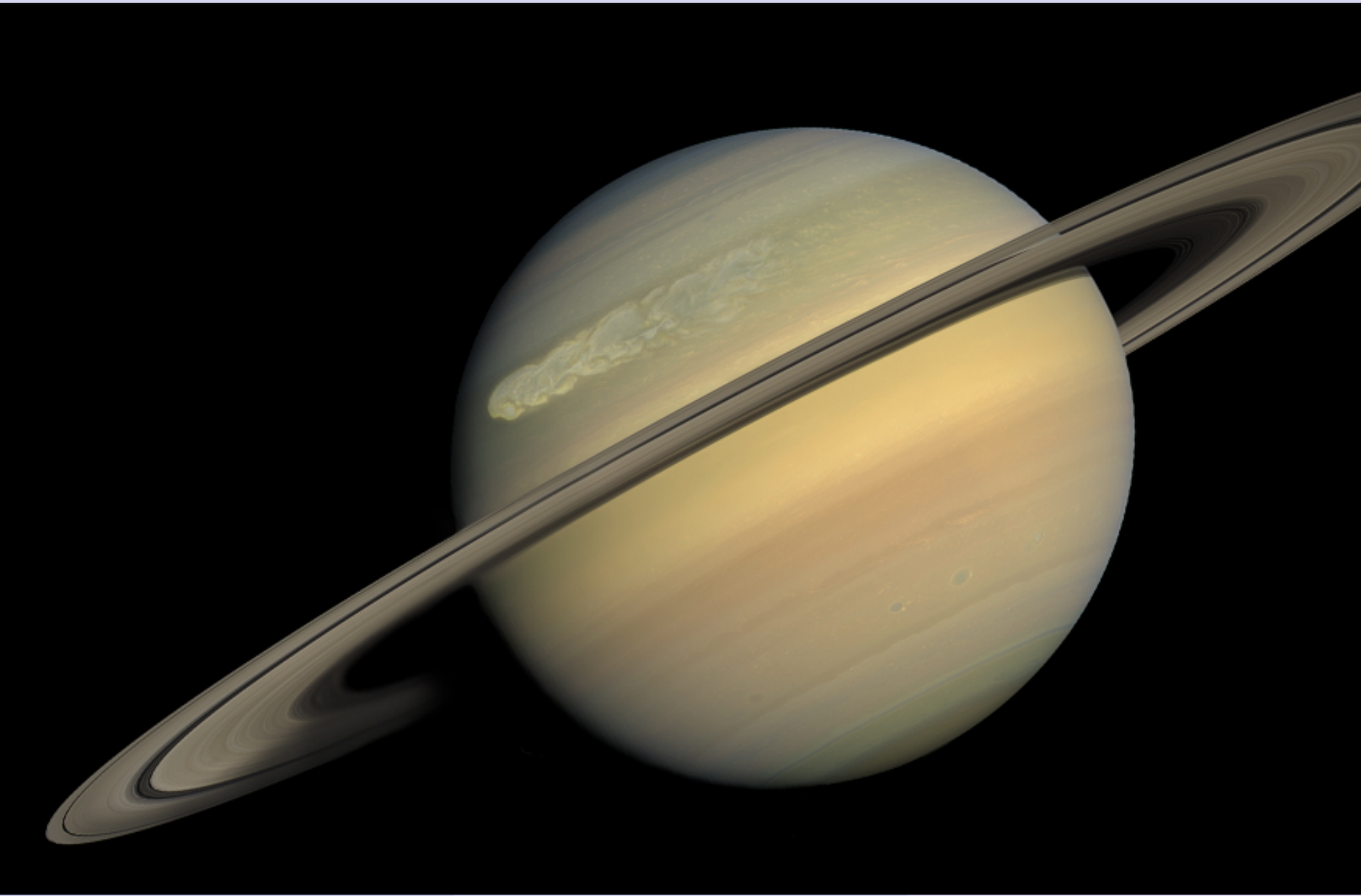
Intense radiation

- On Io, Europa, Ganymede humans could not survive for more than a few hours
- Callisto

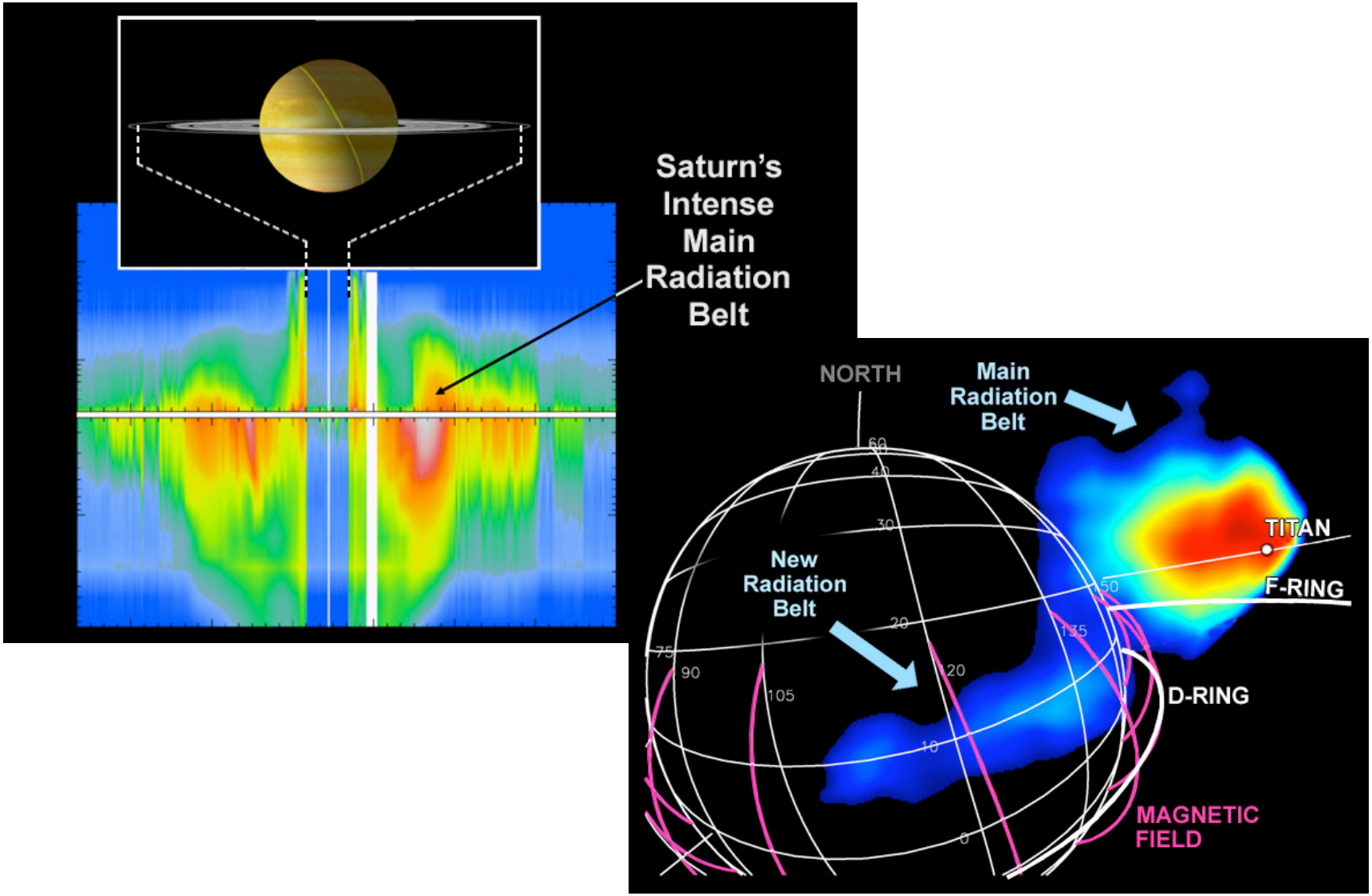




SATURN



SATURN



[http://www.universetoday.com/15381/radiation-on-saturn/]

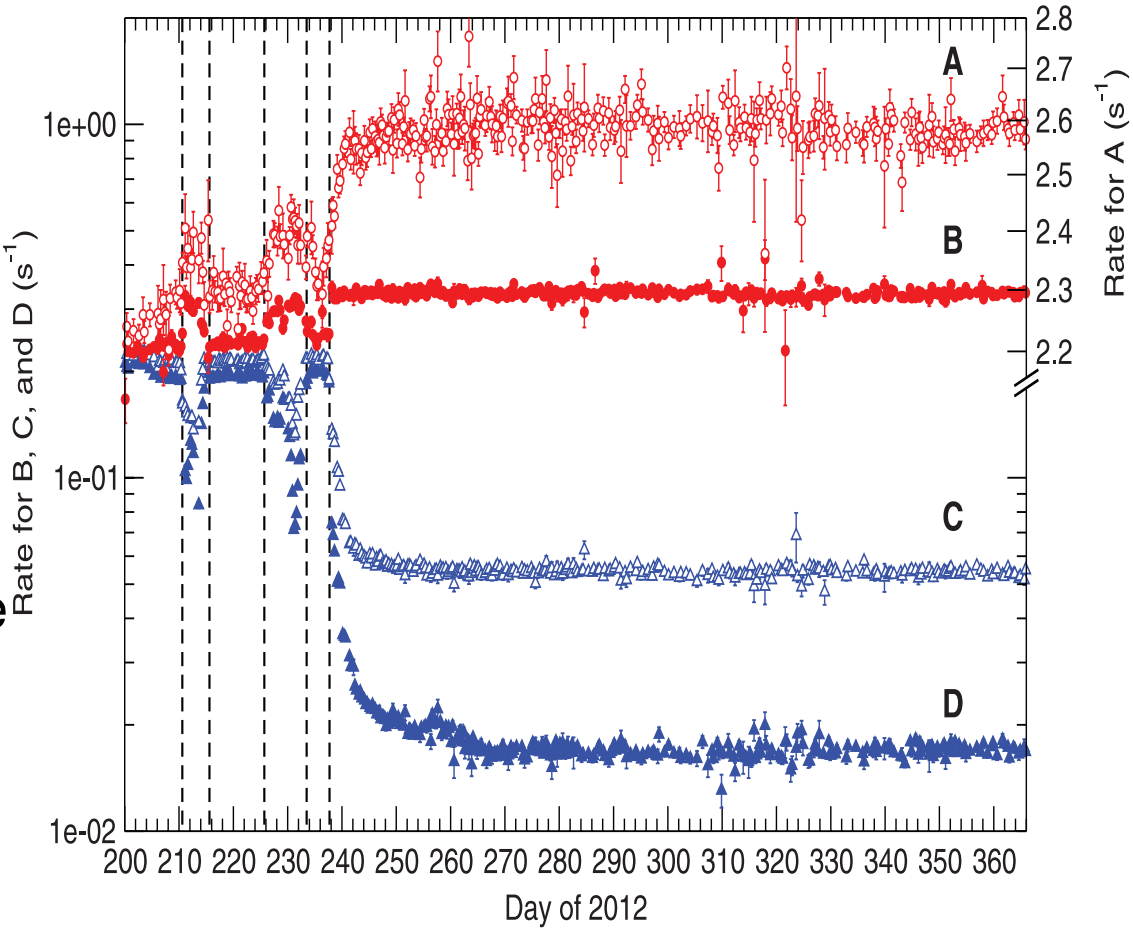
[http://www.nasa.gov/mission_pages/cassini/multimedia/pia06421.html]

INTERSTELLAR TRAVEL - VOYAGER

- Voyager 1 launch Sept. 5, 1977
- Jupiter, Saturn, Titan
- Now 13 billion miles from Earth
- Interstellar space Aug. 25, 2012
- GCR particle levels abruptly increased (see A in figure)
- Note Log scale

- Voyager 2 launch Aug. 20, 1977
- Jupiter, Saturn, Uranus, Neptune
- Now 11 billion miles from Earth

- Pioneer 10, 11 also now in interstellar space, but no communication



Stone et al., Science 341, 150, 2013

Local Interstellar Spectra

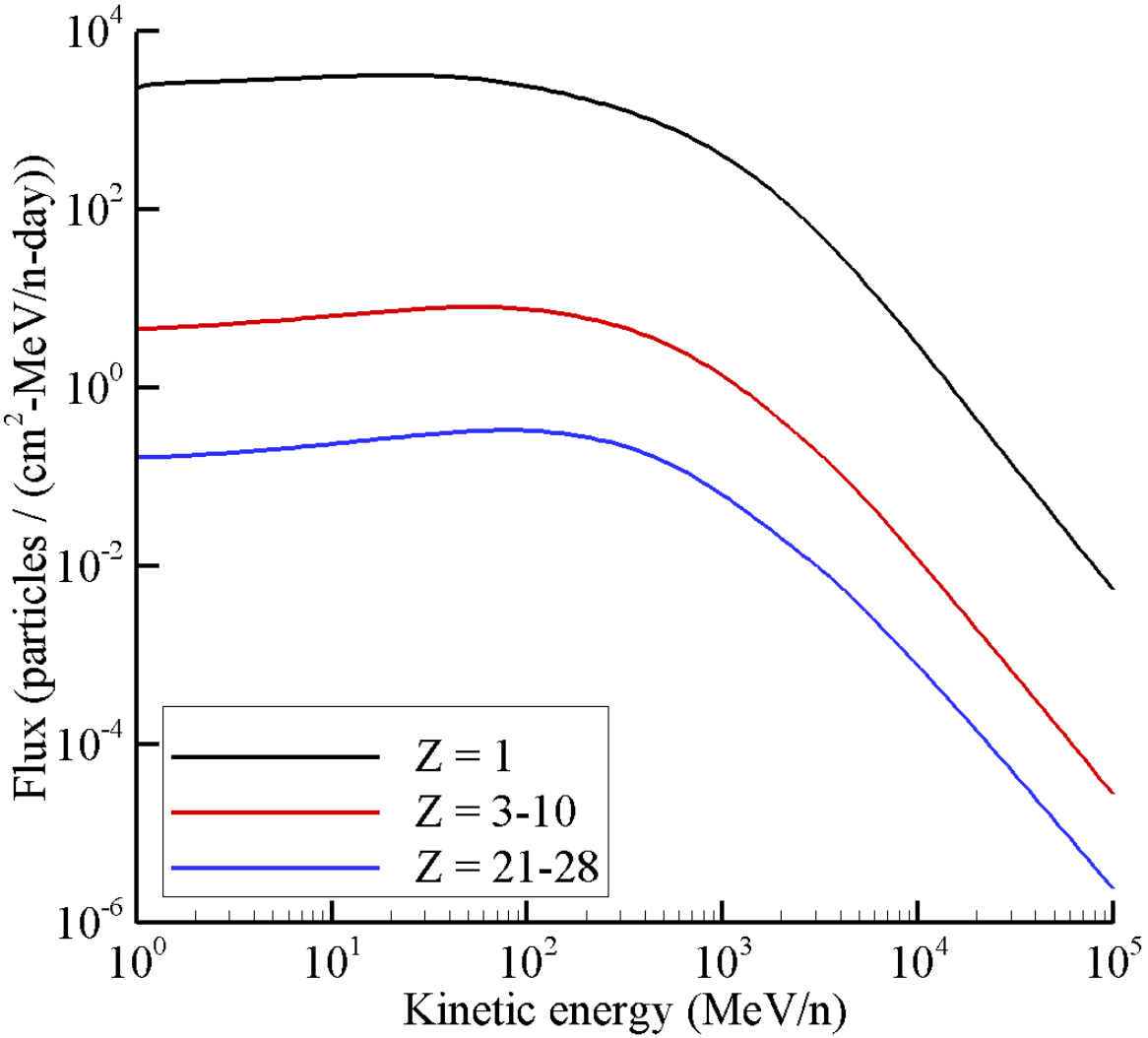


Figure provided by Tony Slaba (NASA Langley)

Local Interstellar & Earth Spectra (solar minimum)

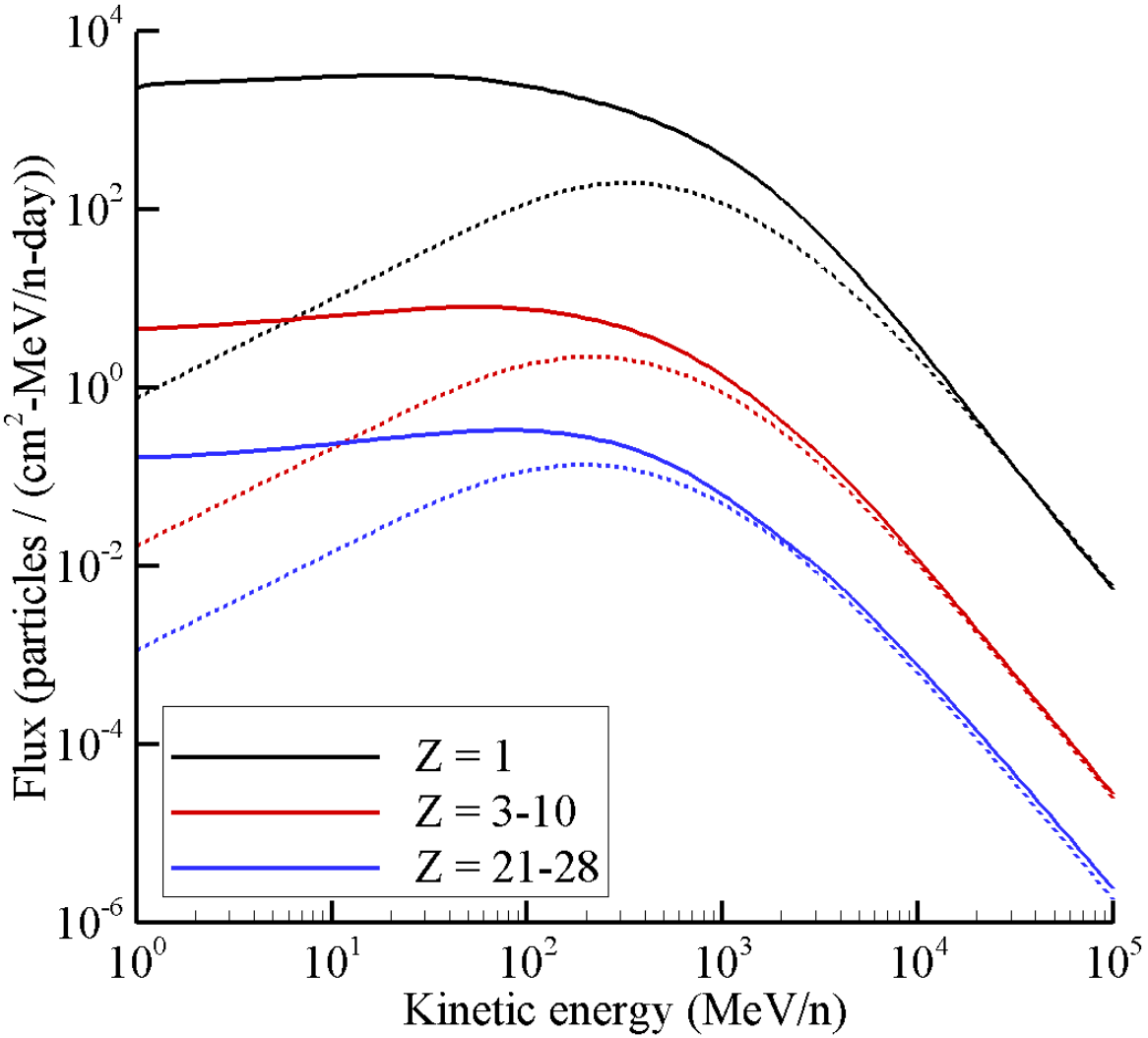


Figure provided by Tony Slaba (NASA Langley)

Local Interstellar & Earth Spectra (solar maximum)

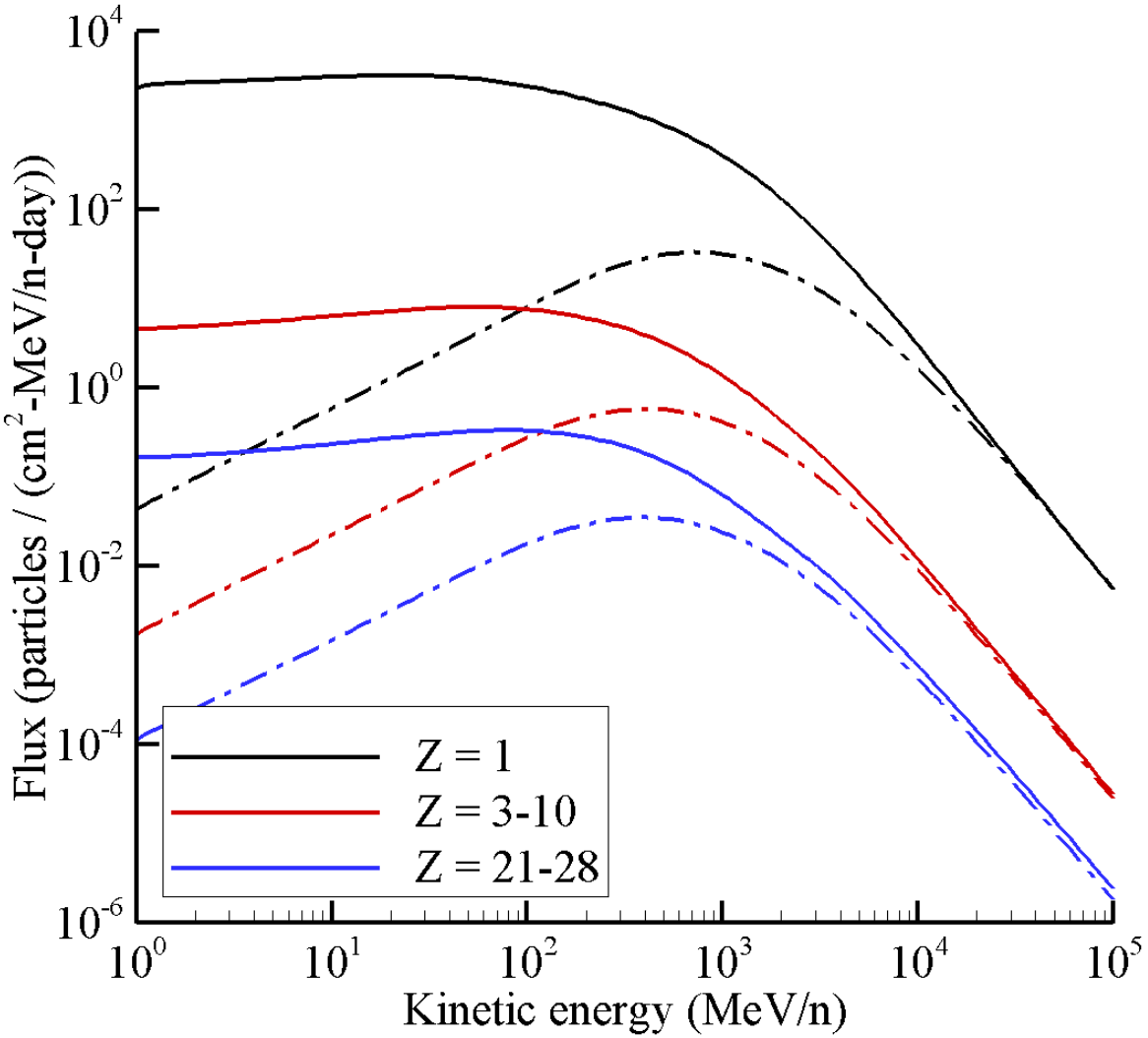
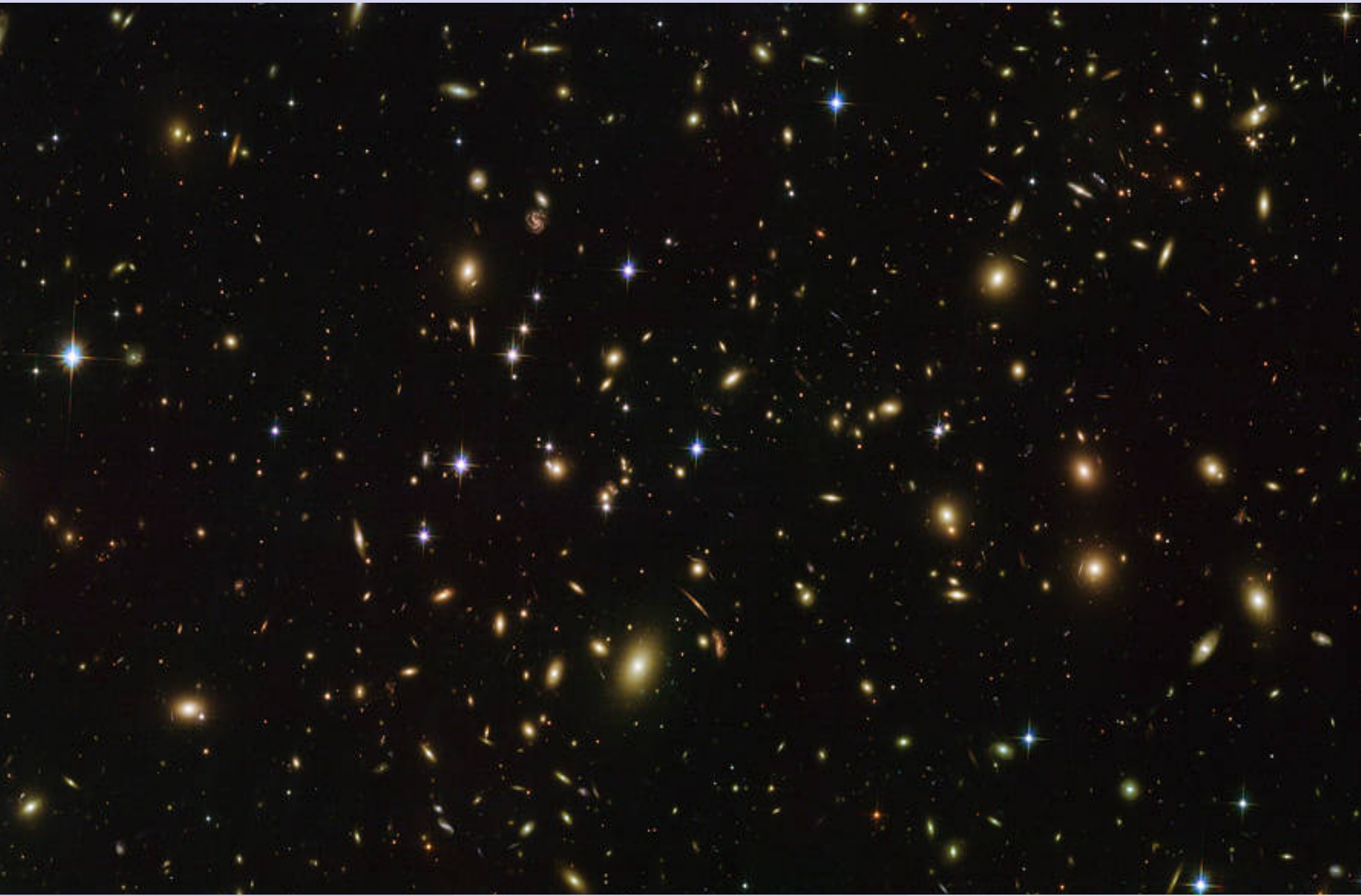


Figure provided by Tony Slaba (NASA Langley)

INTERSTELLAR TRAVEL

- Nearest star *Proxima Centauri* $\sim$ 4 light years (closer than α Centauri)
- Recently discovered planet – *Proxima b*
  Anglada-Escude et al., Nature 536, 437, 2016
- Several missions proposed
- Starshot - chip on laser sail - $v = .2c$ taking 20 years
- Dragonfly Perakis et al. Acat Astron. 129, 316, 2016
- "Deceleration of high velocity interstellar photon sails into bound orbits at α Centauri" R. Heller, M. Hippke, ApJL 835, L32, 2017

Intergalactic Space Travel



Intergalactic Space Travel

- Definition of speed, $v \equiv \frac{d}{t}$ (d = distance travelled, t = time)
- Light year $\equiv$ distance light travels in one year
  $= d = c \times t = c \times 1\text{year}$ (c = speed of light)
- E.g. time it takes light to travel 10 light years

$$t = \frac{d}{v} = 10 \times \frac{c \times 1\text{year}}{c} = 10\text{years}$$

Some ideas expressed here also appear at https://setiathome.berkeley.edu/forum_thread.php?id=34381

Intergalactic Space Travel

- Distance from Earth to edge of observable universe
  $\sim$ 50 billion light years (Diameter of observable universe $\sim$ 100 billion light years)
- Therefore, the time it takes a light beam to go from Earth to edge of observable universe is $t \sim 50$ billion years
- Travel to edge of universe impossible for humans?

  (Need to live for 50 billion years?)
- Need to travel faster than light?
- No!
  – time dilation & length contraction



INTERGALACTIC SPACE TRAVEL

- $\beta \equiv \frac{v}{c}$, $\quad \beta = 0$ for $v = 0$, $\quad \beta = 1$ for $v = c$
  $\gamma \equiv \frac{1}{1-\beta^2}$, $\quad \gamma = 1$ for $v = 0$, $\quad \gamma = \infty$ for $v = c$
  $\gamma = \text{huge}$ for $v \sim c$

- If travel at high speeds then distance is Lorentz contracted
  d = distance measured from Earth
  $\frac{d}{\gamma}$ = distance measured in spaceship
  - much smaller than d for $v \sim c$

- Travel to edge of universe $\frac{d}{\gamma} = \frac{\text{50 billion light years}}{\gamma}$ = small

- Can easily travel small distance in a human lifetime
  – as measured in spaceship frame
  – still 50 billion years measured in Earth frame
  – therefore can't tell people left on Earth what the journey was like

Intergalactic Space Travel

- Does this mean travel "faster than light"?
  – Yes! from spaceship frame
  – No, from Earth frame
- Standard definition $v \equiv \frac{d}{t} = \frac{\text{distance}_{\text{Earth}}}{\text{time}_{\text{Earth}}} = \frac{\text{distance}_{\text{spaceship}}}{\text{time}_{\text{spaceship}}}$
- Re-define speed $v_{\text{mixed}} \equiv \frac{\text{distance}_{\text{Earth}}}{\text{time}_{\text{spaceship}}} = \frac{\text{distance}_{\text{Earth}}}{\text{time}_{\text{spaceship}}/\gamma} = \gamma \frac{\text{distance}_{\text{Earth}}}{\text{time}_{\text{Earth}}} = \gamma \text{v}$

- If $v = c$ then $v_{\text{mixed}} = \gamma c \ > \ c$
- "Faster" than light!
- "Explains" why a human CAN travel to edge of universe within their lifetime
- But in a race between a light beam and a spaceship, the light beam will always win
- NOT faster than light measured in Earth frame
- Only "faster than light" using re-definition of speed v_{mixed}

Intergalactic Space Travel

- BUT, Can we move a spaceship to close to speed of light?
- YES!
- Accelerate at 1g for about 1 year (reach $\sim 0.9c$)
  – weightlessness problems go away!
- Use nuclear fusion reactor scooping up interstellar Hydrogen along the way



Intergalactic Space Travel

- Intergalactic Space Travel
- Accelerate at 1g $\rightarrow$ weightlessness not a problem
- Do it for 1 year $\rightarrow$ $v \sim c$ not a problem
- "Faster than light" travel not a problem

Intergalactic Space Travel

- Intergalactic Space Travel
- Accelerate at 1g $\rightarrow$ weightlessness not a problem
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- Problem is Space Radiation

Intergalactic Space Travel

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- Cosmic Microwave Background Radiation extremely blue shifted
- Spaceship will see a bath of extremely high energy gamma rays
- Will cause nuclei, neutrons, protons to dissociate
- Spacecraft will disintegrate

Intergalactic Space Travel

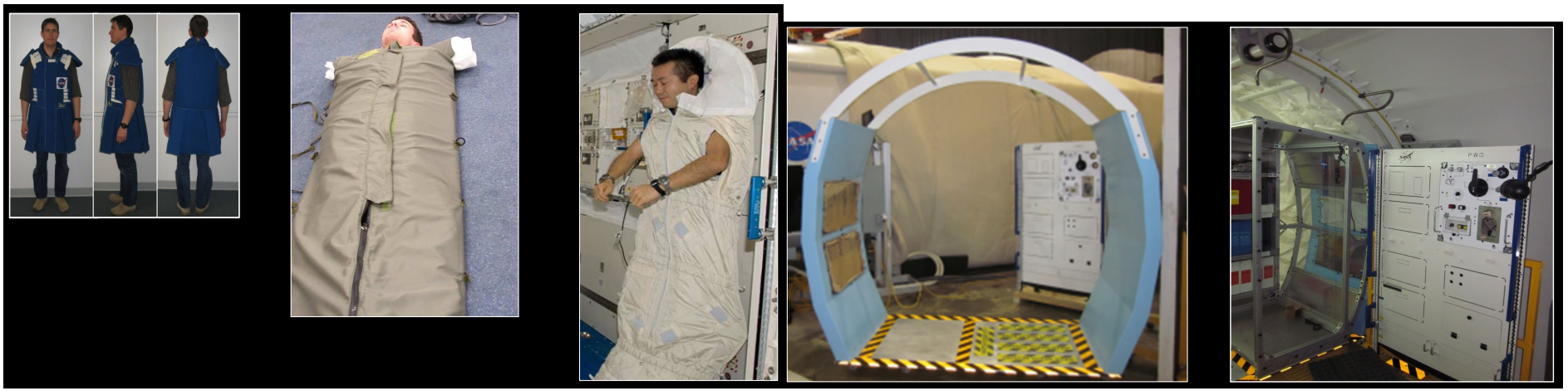
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- Cosmic Microwave Background Radiation extremely blue shifted
- Spaceship will see a bath of extremely high energy gamma rays
- Will cause nuclei, neutrons, protons to dissociate
- Spacecraft will disintegrate
- Shields up!

Outlook

- Space radiation risk areas
  - Cancer
  - CNS
  - Degenerative tissues
  - Acute radiation syndrome
- NASA radiation limit REID = 3% at 95% confidence
- Current Mars mission scenarios 4 $\times$ PEL
- Medical countermeasures & uncertainty reduction are important components of NASA strategy
- GCR simulation program currently underway

POSSIBLE NEAR-TERM RADIATION SOLUTIONS

- Pharmaceutical countermeasures
- Passive shielding (e.g. water walls, advanced shielding materials)
- Operations (e.g. travel during solar max)
- Advanced dosimetry
- Dose limits of international partners
- Faster rockets
- Improved space weather forecasting



POSSIBLE LONG-TERM RADIATION SOLUTIONS

- On Earth, we are protected by geomagnetic field and atmosphere
  - i.e. combination of “active” and “passive” shielding
  - our genome has also evolved to repair DNA damage
- Reproduce for space travel
  - Genetic screening
  - Active electromagnetic shielding
  - Crystal shielding
  - Faster transit times (e.g. nuclear rockets)
  - Upon arrival, build very thick habitat (water walls) or bury underground

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Steve Smith
Lawrence Townsend
Charles Werneth
John Wilson
Sharon Xiaojing Xu
Cary Zeitlin

THE END

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