Integrated Human Health Risk Assessment: Requirements for Safe Expeditions to Mars

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> ***"Others have said they can go there earlier. Have at it. I want to see that. But when it comes to human life, NASA is going to be very particular, and there are a lot of ifs out there."***

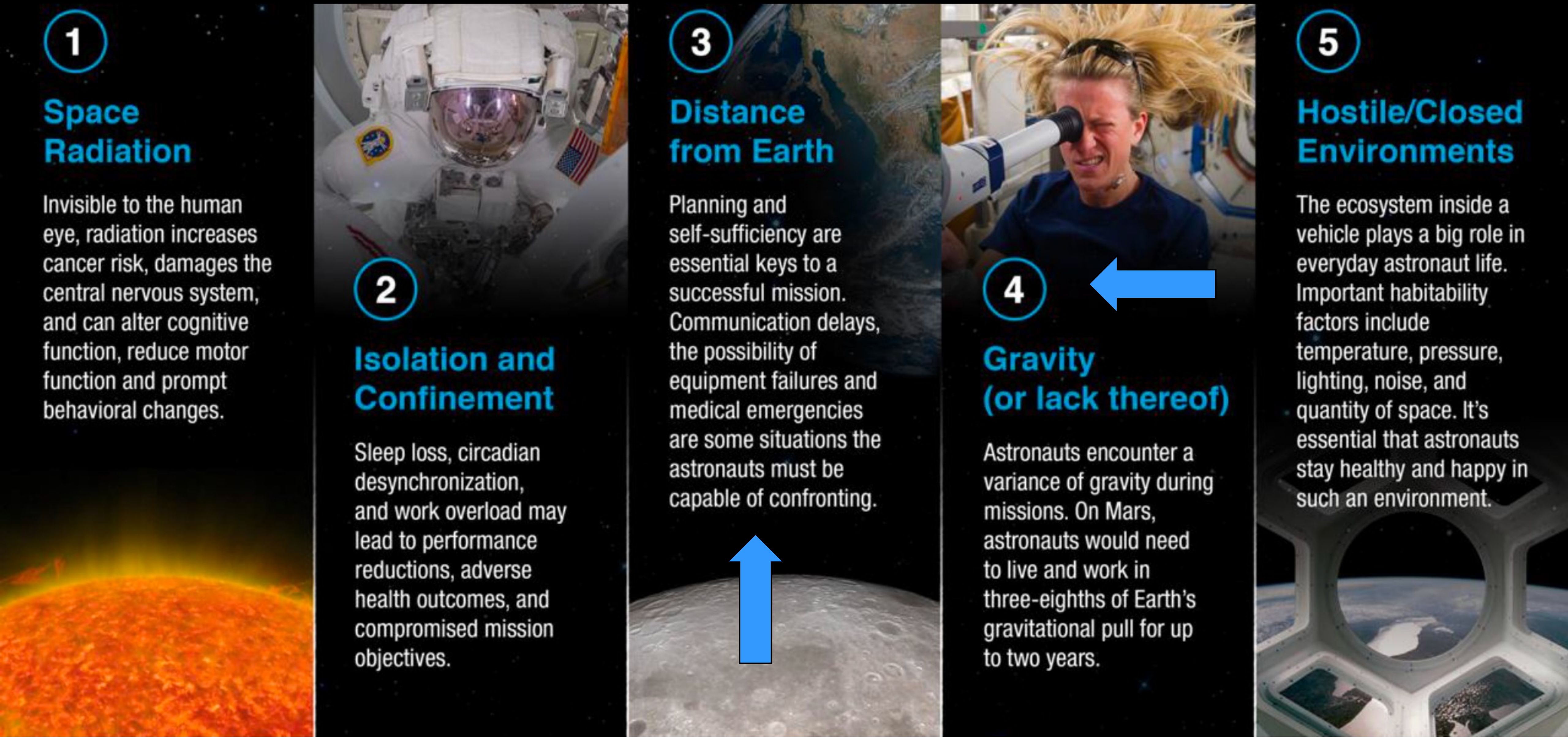
NASA Administrator Bill Nelson, during a Washington Post interview July 21, 2021,
discussing long-term plans by the Agency to **send humans to Mars** in the late 2030s.

- This **NESC assessment** is the *first* of its kind focused on assessing integrated health risks to crew on **missions to Mars**, and the potential engineering solutions required to minimize those risks.

- By using a **systems approach** (rather than individual countermeasures), the assessment team has examined the trade space of a subset of human health hazards and the associated risks to find solutions to mitigate the risks.

- URL: https://ntrs.nasa.gov/citations/20220002905
  Safe Human Expeditions Beyond Low Earth Orbit (Valinia et. al.), February 2022

Hazards of Human Spaceflight



1

Space Radiation

Invisible to the human eye, radiation increases cancer risk, damages the central nervous system, and can alter cognitive function, reduce motor function and prompt behavioral changes.

2

Isolation and Confinement

Sleep loss, circadian desynchronization, and work overload may lead to performance reductions, adverse health outcomes, and compromised mission objectives.

3

Distance from Earth

Planning and self-sufficiency are essential keys to a successful mission. Communication delays, the possibility of equipment failures and medical emergencies are some situations the astronauts must be capable of confronting.

4

Gravity (or lack thereof)

Astronauts encounter a variance of gravity during missions. On Mars, astronauts would need to live and work in three-eighths of Earth's gravitational pull for up to two years.

5

Hostile/Closed Environments

The ecosystem inside a vehicle plays a big role in everyday astronaut life. Important habitability factors include temperature, pressure, lighting, noise, and quantity of space. It's essential that astronauts stay healthy and happy in such an environment.

Human System Risk Posture Summary – Risks by Hazard

(as of November 2021)

Human Spaceflight Risks	Low Earth Orbit (Short)	Low Earth Orbit (Long)	Lunar Orbital (Short)	Lunar Orbital (Long)	Lunar Orbital + Surface (Short)	Lunar Orbital + Surface (Long)	Mars (Preparatory)	Mars (Planetary)
	< 30 D	30 D - 1 Y	< 30 D	30 D - 1 Y	< 30 D	30 D - 1 Y	< 1 Y	730-1224D
Distance from Earth								
* Human Systems Integration Architecture (HSIA) Risk ^{5x5}	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥
* Medical Conditions Risk ^{5x5}	🟩	🟨	🟨	🟥	🟨	🟥	🟥	🟥
* Food and Nutrition Risk	🟩	🟩	🟩	🟨	🟩	🟨	🟥	🟥
* Pharm Risk	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟥
Isolation and Confinement								
* Behavioral Risk ^{5x5}	🟩	🟨	🟩	🟨	🟨	🟨	🟥	🟥
* Team Risk	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥
Altered Gravity								
* Sensorimotor Risk ^{5x5}	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟨
* Bone Fracture Risk ^{5x5}	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟥
* Cardiovascular Risk ^{5x5}	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟥
* Renal Stone Risk	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥
* SANS Risk	🟩	🟨	🟩	🟨	🟩	🟨	🟨	🟥
Crew Egress Risk ^{5x5}	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥
* Microhost Risk	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Urinary Retention Risk	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
* Aerobic Risk	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨
* Muscle Risk	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨
Venous Thromboembolism (VTE) Concern	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Hostile Closed Environment								
* EVA Risk	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟥
* Dynamic Loads Risk	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟥
Carbon Dioxide (CO2) Risk ^{5x5}	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟨
Toxic Exposure Risk ^{5x5}	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
* Immune Risk	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
* Sleep Risk	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Decompression Sickness (DCS) Risk	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨
Hypoxia Risk (LTH)	🟩	🟨	🟩	🟨	🟩	🟨	🟨	🟨
* Dust Risk	⬜	⬜	🟩	🟩	🟩	🟨	⬜	⬜
Electric Shock ^{5x5}	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨
Hearing Loss (LTH)	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨
Radiation								
* Radiation Carcinogenesis Risk (LTH)	🟩	🟨	🟩	🟨	🟩	🟨	🟨	🟨
Non-Ionizing Radiation Risk	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Notes:

Risk posture data managed, controlled and approved by the HMTA/Human System Risk Board (HSRB)

*HSRB Risks for which HRP has active research (per Human Research Roadmap)

Data are for in-mission operations unless otherwise noted for Long-Term Health (LTH)

Risk text color:

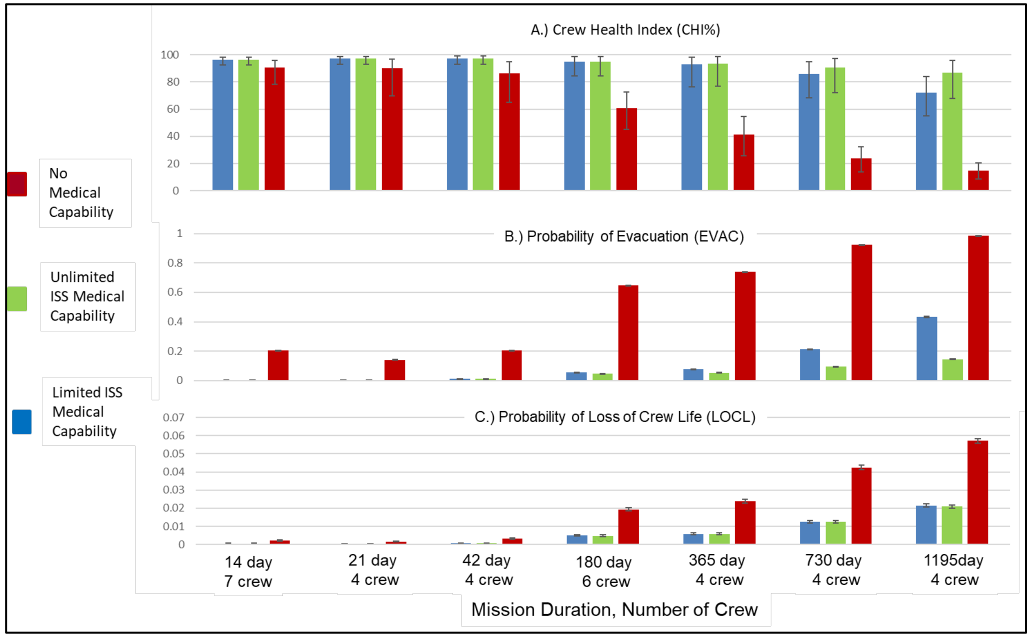
- **Current risk ratings**
- **Risk ratings under HSRB review**

Risk colors:

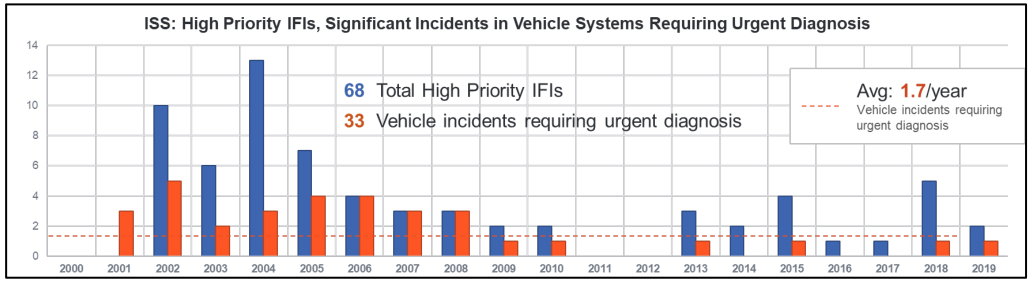
🟥 High LxC
🟨 Mid LxC
🟩 Low LxC

^{5x5} item - Risk has been updated using 5x5 LxC scale (remaining risks use previous 3x4 scale)

Baselining In-Mission Mars Risk



Antonsen et al. Accepted NPJ Microgravity Oct 2021



IMM estimates suggest:

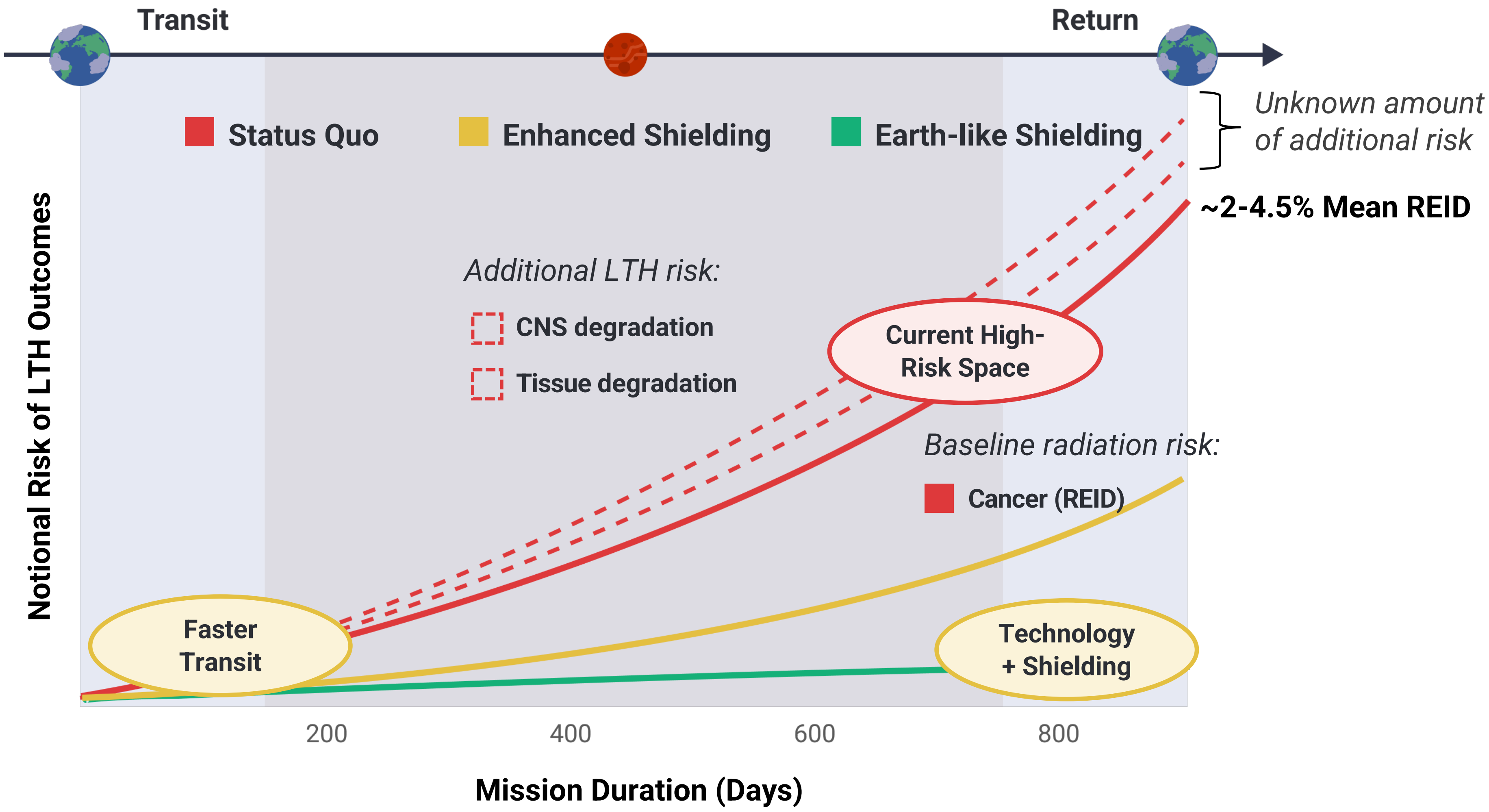
- ❖ **At least a 1:90 likelihood of Loss of Crew Life for a 730-day Mars mission due to medical risk alone**
  - This is comparable to the Space Shuttle total Loss of Crew risk at the end of the program
  - This is an underestimate
  - Depends on mission duration and effectiveness of the Crew Health and Performance System

The ISS experience suggests:

- ❖ At least 1.7 high-consequence events requiring immediate intervention occurred per year
- ❖ Around 3 to 4 high-consequence events requiring immediate intervention per year occurred in the first 6 years
- ❖ Appropriately responding to these types of events in a Mars mission will be significantly harder without real-time communications

Notional Risk Trends: Radiation Exposure

Showing Current Risk Space and Domains that illustrate Potential Improvements in LTH Outcomes from Radiation Exposure



Notional Risk Trends: Altered Gravity Exposure

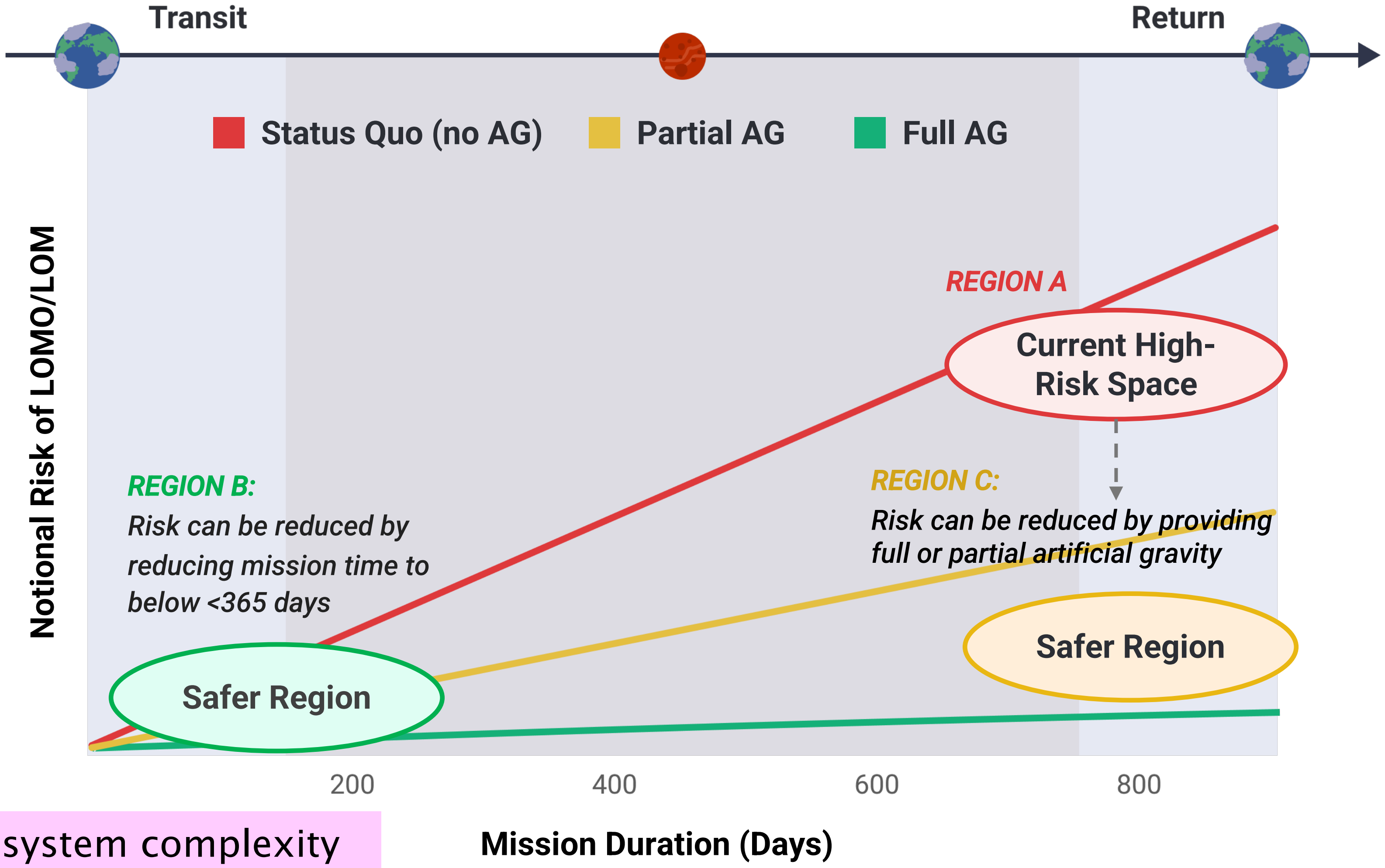
Notional Risk Trends showing Current Risk Space and Domains that illustrate Potential Improvements in In-mission Risks due to Altered Gravity Exposure

Human system risks affected by altered gravity in-mission:

- SANS
- Sensorimotor alterations
- Bone fracture
- Cardiovascular
- Aerobic capacity
- Muscle strength
- Venous thromboembolism
- Urinary retention
- Renal stone
- MicroHost
- Immune
- Sleep
- Dynamic loads
- EVA injury
- Crew egress

Human system risks affected by altered gravity for LTH:

- SANS
- Bone fracture



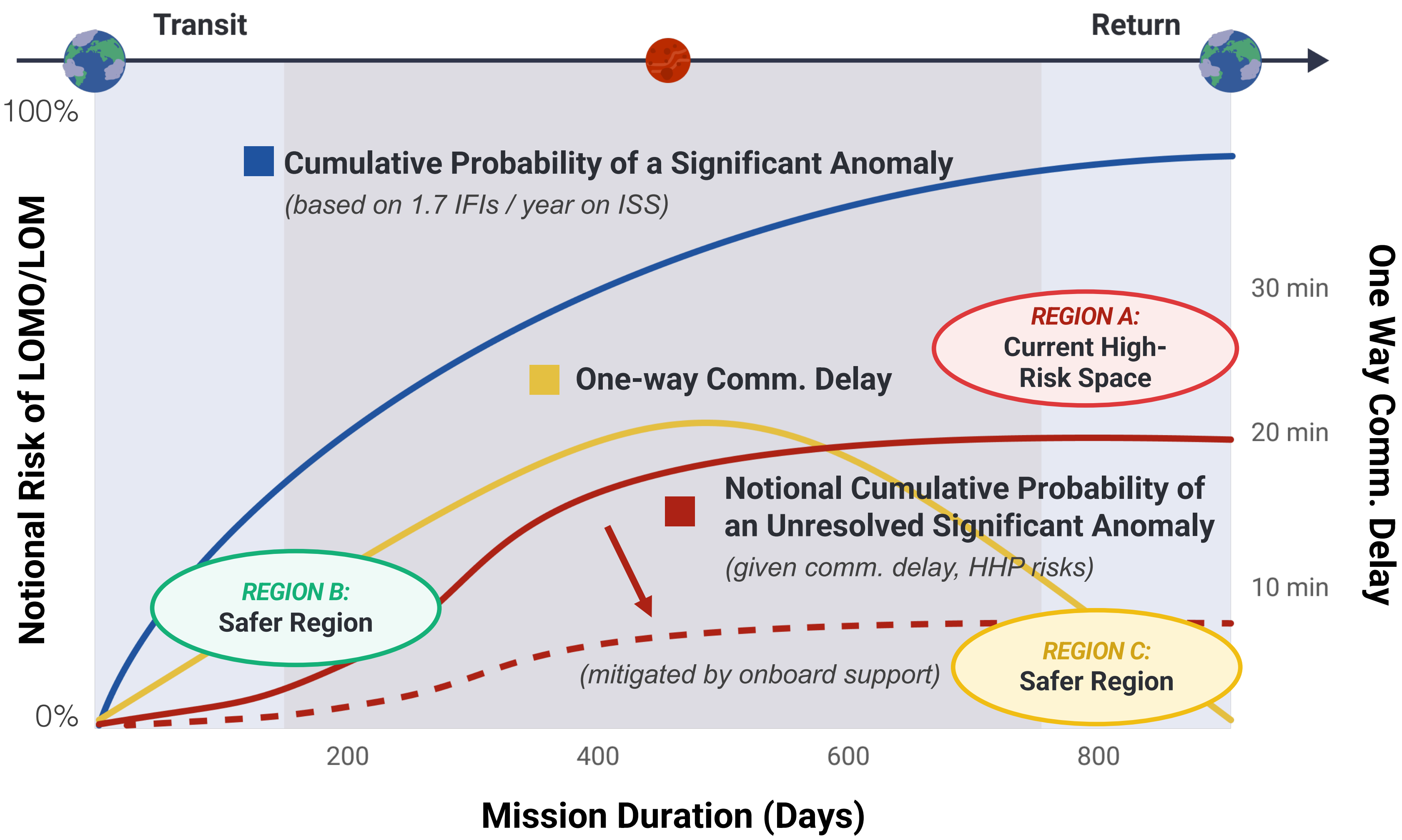
But – HSIA Risk increases with increased system complexity

Notional Risk Trends: Reduced Ground Support

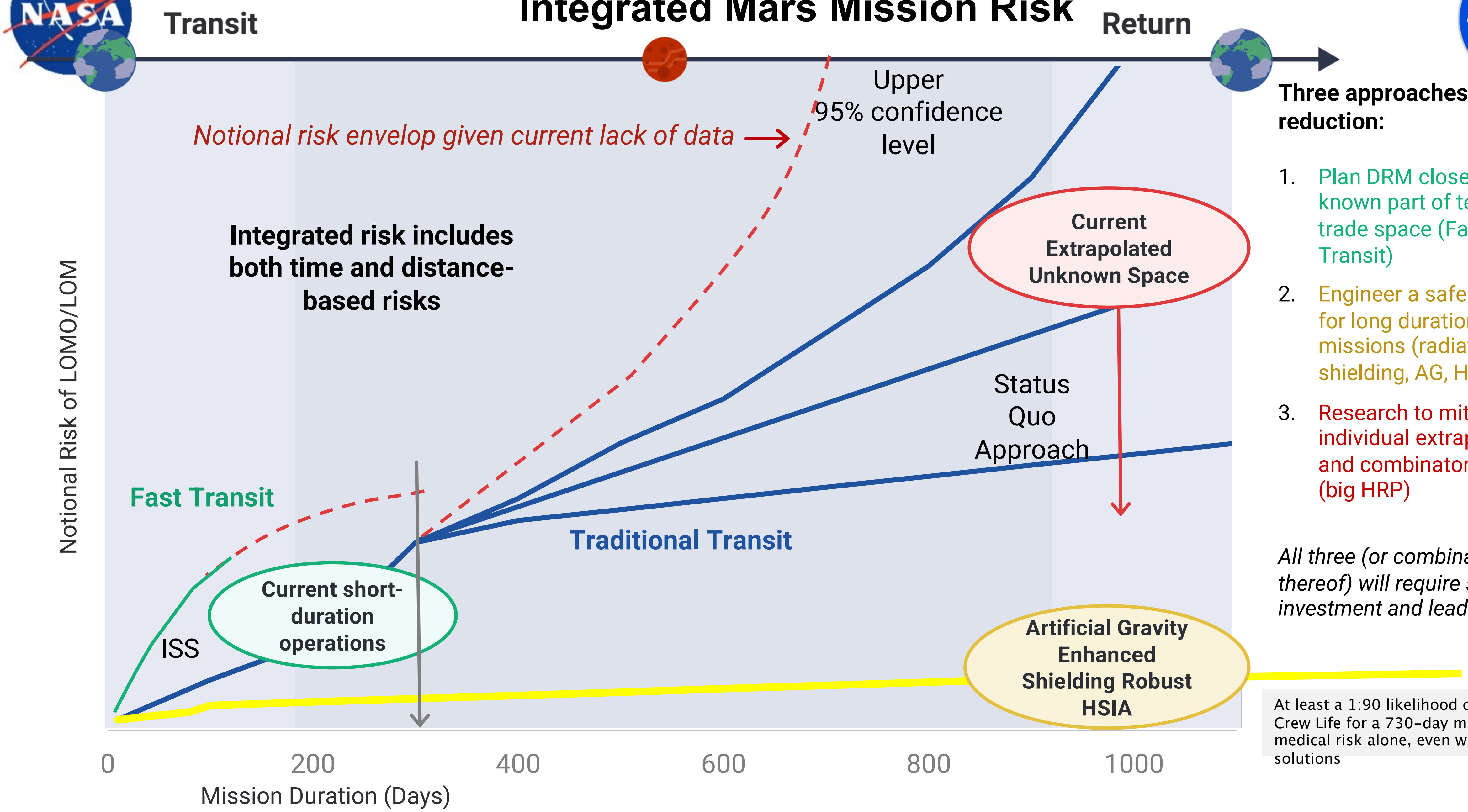
What shapes this risk curve?

- Crew performance degrades with time
- Training effectiveness degrades with time
- System knowledge improves with time
- Spares decrease with time
- Evacuation timeframe improves only at end of mission
- One–way communication time varies with distance from Earth

Notional Risk Trends Due to Inadequate HSIA



Integrated Mars Mission Risk



Notional risk envelop given current lack of data →

Integrated risk includes both time and distance-based risks

Three approaches to risk reduction:

1. Plan DRM closer to known part of temporal trade space (Fast Transit)
2. Engineer a safe harbor for long duration missions (radiation shielding, AG, HSIA)
3. Research to mitigate the individual extrapolated and combinatorial risks (big HRP)

All three (or combinations thereof) will require significant investment and lead time.

At least a 1:90 likelihood of Loss of Crew Life for a 730-day mission due to medical risk alone, even with these solutions

Integrated Risk Analysis Summary

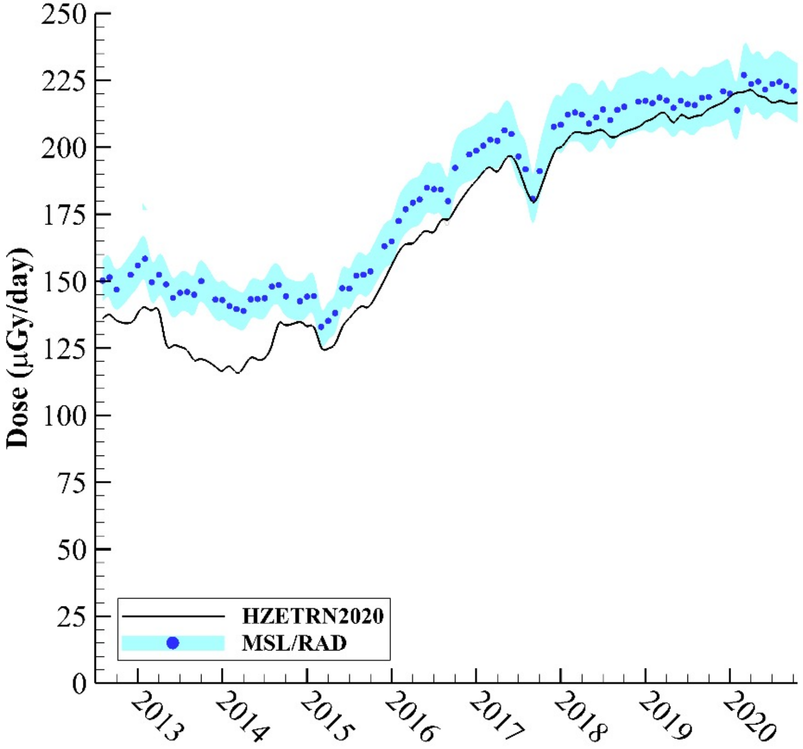
- **Integrated Health Risk Analysis** pointed to:
  - **Game-changing risk reduction** (needs fundamental paradigm shift in approaching the problem and may require decades of research and development (R&D))
    - **Shorter Mars transit durations** – feasibility study with current technology shows promise, approach ensures sustainability
    - **New paradigm for designing Human Systems Integration Architecture (HSIA)** for long missions beyond low Earth orbit (LEO)
    - **Artificial gravity or similar techniques** to reduce microgravity exposure
  - **Incremental risk reduction** – low-hanging fruit, also increases knowledge base and lays a strong foundation
    - Improved radiation monitoring/shielding and timing of missions to Mars
    - Galactic cosmic ray (GCR) reduction/standards

Incremental Risk Reduction

- **GCR - the main radiation health risk and challenge for crew health**
  - Complex mixture of highly energetic particles – everything on the periodic table
  - Highly penetrating throughout the solar cycle
  - Continuous low exposure rate
  - Significant uncertainties in projecting attributable health risks

- **Combined models can reliably predict exposure, but *important gaps remain***
  - **Precise spaceflight measurements of neutrons above 20 MeV**
  - **Ground-based measurements and models for neutron and light ions**
  - **Time-resolved measurements for GCR heavy ions**

Mars surface dose rate:
comparison of model predictions to MSLRAD data



Slaba, *Space Weather* **19**: e2021SW002851; 2021.

Model-calculated mission exposures

	Mission	Duration(2) (days)	Effective dose (mSv)(1)		
			0 g/cm^2	20 g/cm^2	40 g/cm^2
solar maximum	**Artemis II**	10	6.3	5.1	5.3
	Artemis III	30	19.0	15.4	15.8
	Artemis III (surf)	23.5/6.5	17.4	14.1	14.4
	Gateway – 6 mo.	183	116	94	96
	Gateway – 12 mo.	365	232	188	192
	Mars DRM	621/40	405	331	339
	Mars DRM	840	533	432	442
solar minimum	**Artemis II**	10	14.6	10.9	10.7
	Artemis III	30	43.8	32.8	32.1
	Artemis III (surf)	23.5/6.5	39.8	29.9	29.2
	Gateway – 6 mo.	183	267	200	196
	Gateway – 12 mo.	365	533	399	391
	Mars DRM	621/40	929	702	688
	Mars DRM	840	1228	918	899

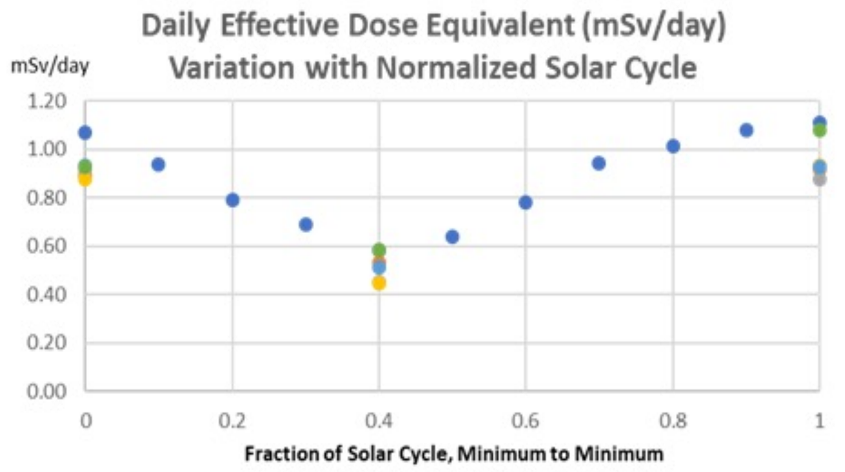
(1) ICRP effective dose is calculated using the approach described by Slaba et al. *Adv. Space Res.* **45**: 866-883; 2010.
(2) X/Y format denotes X days in free space and Y days on the surface.

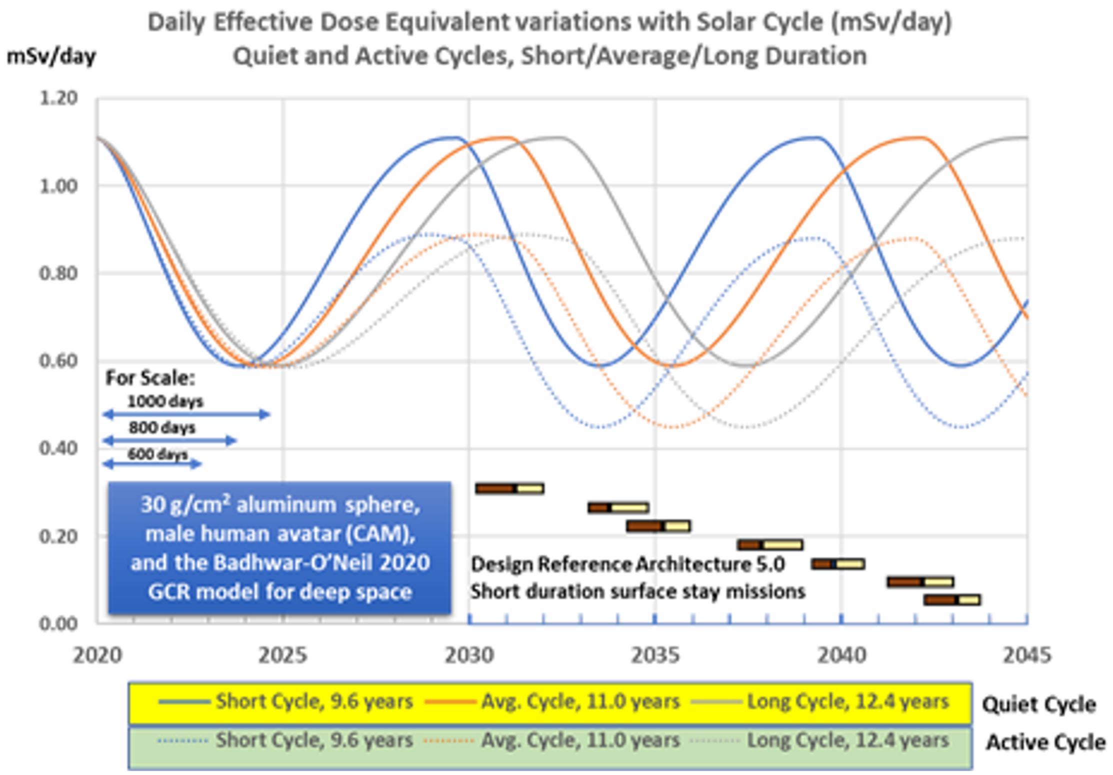
- **NASA PEL is now 600 mSv effective dose**
- **Summary for crew with no prior flight experience**
  - **All crew qualify for Artemis missions**
  - **All crew qualify for Gateway missions**
  - **Certification for Mars DRM depends on mission timing (solar cycle)**
    - **Solar maximum – within PEL**
    - **Solar minimum – exceeds PEL**

GCR Dose Variation with Solar Cycle

- **The energetic GCR ions are so penetrating that large shielding mass is required to mitigate GCR threats to crew health; GCR is a major radiation issue for long-term exploration of deep space**
- **GCR flux varies slowly over solar cycle time scales (about a decade)**
- **The ability to forecast the shielding mass required to protect crew for upcoming missions as a function of phase in the solar cycle will complicate mission planning**
- **Long-range Mars mission planning would benefit from efforts to improve the ability to forecast solar cycle length**
  - Mars missions during solar maximum will substantially reduce crew dose
  - Increased shielding mass is required to keep crew radiation dose within program limits during solar minimum
  - Additional shielding mass reduces payload, impacting overall mission capability

Effective Dose Equivalent (mSv/day)	
1965 Solar Minimum	0.89
1977 Solar Minimum	0.92
1987 Solar Minimum	0.88
1997 Solar Minimum	0.93
2010 Solar Minimum	0.93
2019 Approaching Minimum	1.08
1970 Solar Maximum	0.53
1982 Solar Maximum	0.45
1991 Solar Maximum	0.44
2001 Solar Maximum	0.51


Daily Effective Dose Equivalent (mSv/day) Variation with Normalized Solar Cycle


Daily Effective Dose Equivalent variations with Solar Cycle (mSv/day) Quiet and Active Cycles, Short/Average/Long Duration

30 g/cm² aluminum sphere, male human avatar (CAM), and the Badhwar-O'Neil 2020 GCR model for deep space

Design Reference Architecture 5.0 Short duration surface stay missions

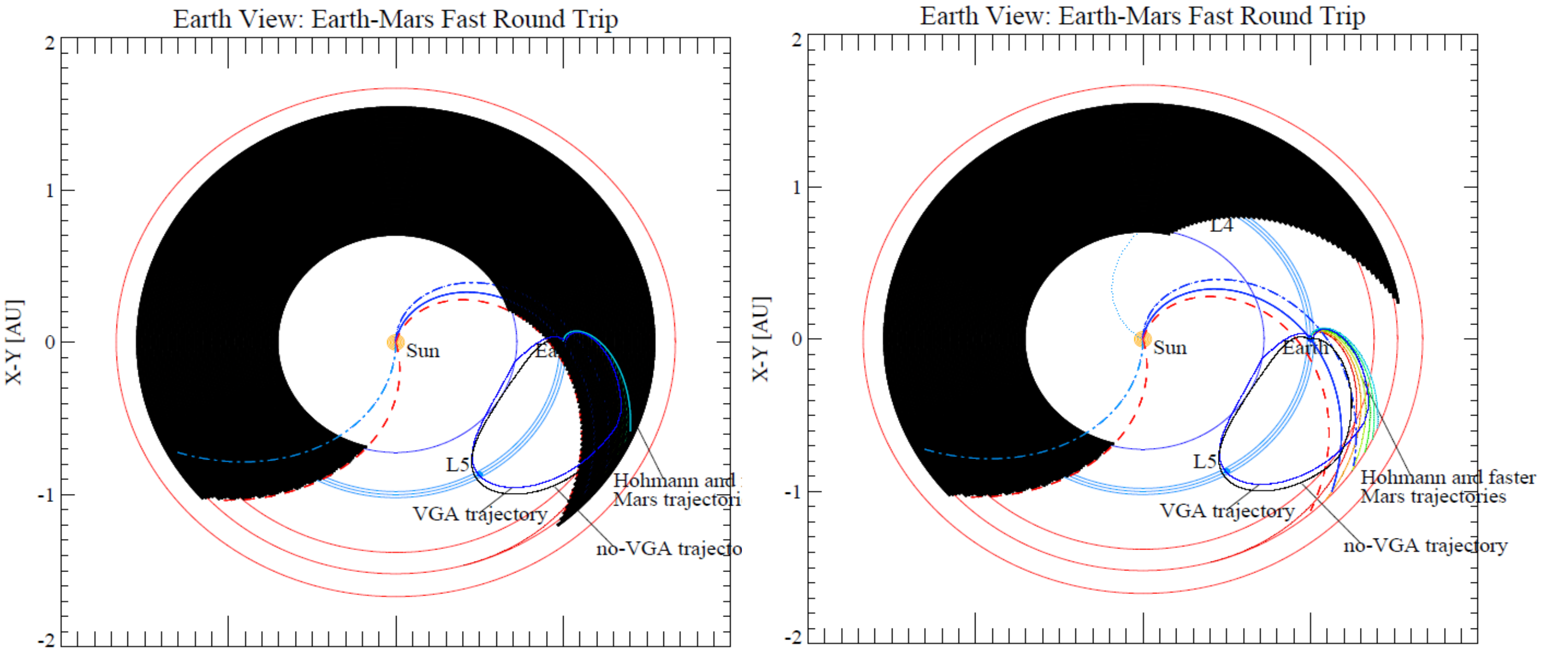
GCR Shielding Standards Needed

- A standard for GCR shielding for human exploration missions beyond LEO is needed
- It is recommended that vehicles and habitat systems provide sufficient protection to reduce exposure from GCRs by 15% compared with free space such that the effective dose from GCR remains below:
  - 1.3 millisieverts per day (mSv/day) for systems in space
  - 0.8 mSv/day for systems on planetary surfaces
- This standard is based on missions during solar minimum (the worst-case scenario); it can be achieved with current aluminum spacecraft structures
- Note: For Mars missions *longer than 600 days*, additional GCR mitigation strategies will be required to meet the newly proposed 600 mSv crew lifetime exposure limit (except for potentially limited opportunities for missions during solar maximum when the overall GCR exposure is the lowest)

Monitoring of SPEs: Sun-Earth L4, L5, Sun-Mars L1 and L4, L5

- Additional space weather monitoring assets (i.e., coronagraphs and particle detector suites) at Sun-Earth Lagrange points L4 and L5 and Sun-Mars L1 and L4/L5 can enable sufficient early warnings for Mars missions during transit and long-term stays on the planet surface
- The Sun-Earth and Sun-Mars L4/L5 assets would also provide a communications relay solution for when the Earth line-of-sight to Mars is behind or close to the Sun, leading to a 2-week blackout period every 2 years

Fast Mars Round Trips and SWx Safety Zones



N. Hatten/NASA GSFC

SWx Safety Zone supported by L1 only

SWx Safety Zone supported by L1 and L4[1]

Improved Space Weather Monitoring at Mars Needed

Additional space weather monitoring assets (solar coronagraph and particle detector suites) at Sun-Earth Lagrange point L4 and Sun-Mars L1 and L4/L5 can enable sufficient early warnings for Mars missions during transit and stay. The Sun-Mars L4/L5 assets would also provide a communications relay solution for when the Earth line of sight to Mars is behind/close to the Sun, leading to a 2-week blackout period every 2 years.

Recommendations for Future Research & Development

Mars Mission Architecture

Investigate fast Mars transit

Benefit: Reduces overall risks and enables sustainability

Radiation Monitoring

Consider adding additional assets: Earth-Sun L4, Mars-Sun L1, L4, L5

Benefit: Improves early SW warning

Human Research

Investigate AG Prescription

Benefit: Will inform game-changing engineering solutions

Spacecraft Shielding

Implement GCR shielding for humans-to-Mars missions

Benefit: Impact future spacecraft designs now

Cross-Cutting

Implement a paradigm shift in Human Systems Integration Architecture (HSIA)

Benefit: Enable Earth-independent operations

Bottom Line

- Our understanding of the **integrated Human System Risks** for Mars missions is in its early stage. We don't have strong quantitative estimates, but we can establish a lower bound and a qualitative picture of how some **engineering solutions** will affect mission risk.
- A **fundamental paradigm shift** is needed to enable **safe, sustainable, and Earth-independent** human expeditions to Mars in the near term.
  - Requires both game-changing (i.e., revolutionary) as well as incremental (i.e., evolutionary) risk-reduction strategies.
- Engineering, human, and medical technical authorities should partner to further explore the integrated human risk trade space to prioritize game-changing technologies and investments needed to significantly reduce the risk on future human Mars missions.

NESC Workshop Participants (September 14-16, 2021)

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Maneesh Arya, NASA
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