ASU Complex Adaptive Systems Initiative
Arizona State University

Protecting Astronaut Health: A Grand Challenge for Prolonged Spaceflight and Inter-Planetary Exploration

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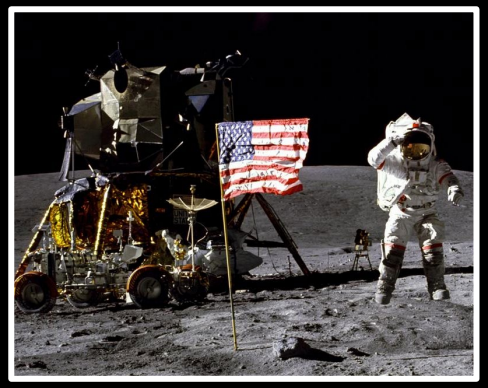
ASU Course LIA 194:
Living in Space: Know Before You Go!
22 March 2024

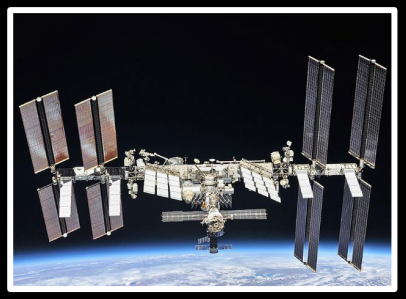
Milestones in Human Exploration of Outer Space

- proving humans can survive in space
  - Soviet cosmonaut, Yuri Gagarin
  - 12 April 1961



- proving humans could land and return from an extra-terrestrial body
  - US astronauts Neal Armstrong and Buzz Aldrin
  - moon landing, 20 July 1969

Expansion of Human Space Travel



- extended survival in low earth orbit (LEO) in orbiting space stations (1973-present)

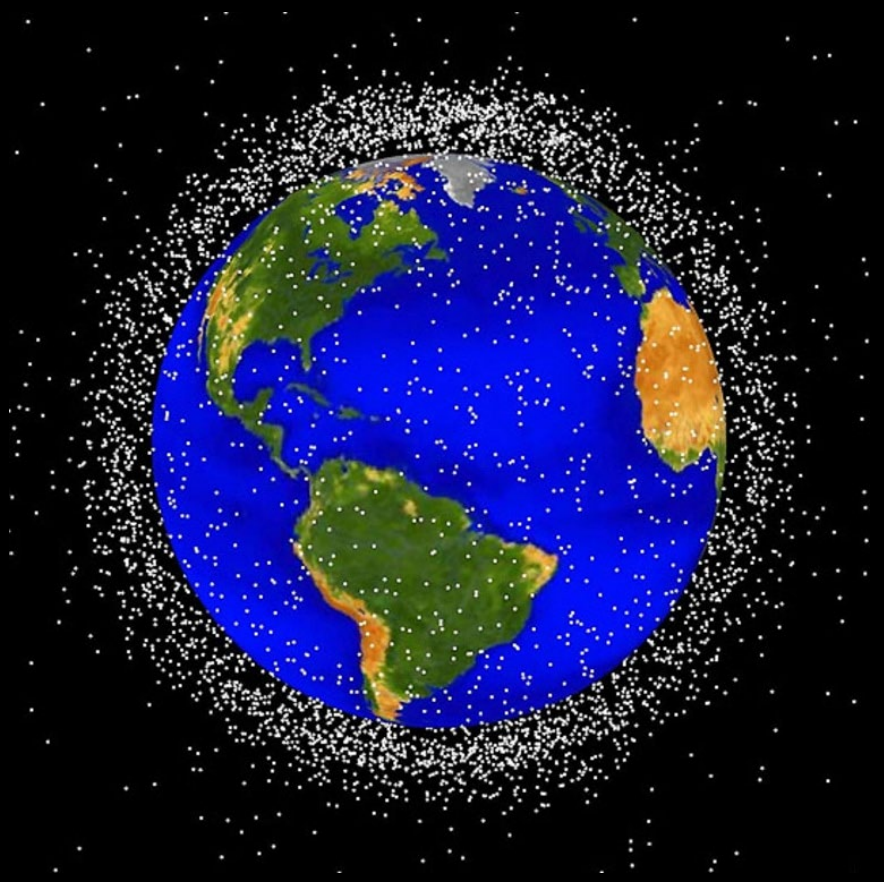
- back to moon
  - Artemis III (2025?)
  - (cis)lunar gateway (?)
  - permanent moon base (?)

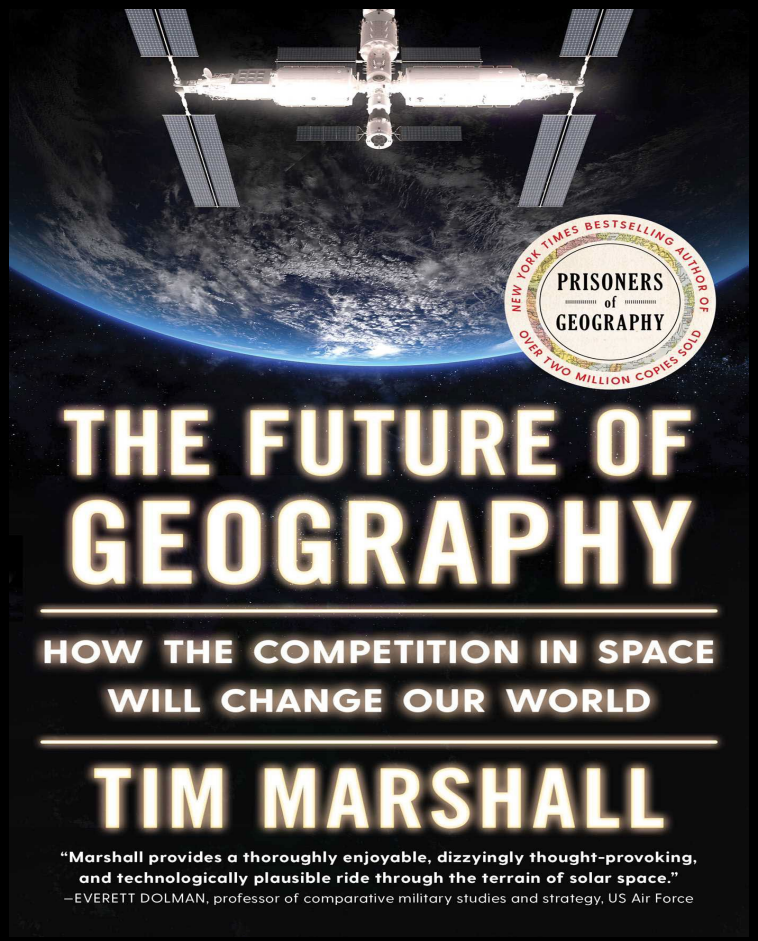
- and beyond (?)

Projected Major Expansion in Space Exploration and Space Commerce

- space-for-military superiority
- space-for-space economy
- space-for-earth economy

Space is Now Becoming An Extension of the Geography of Earth

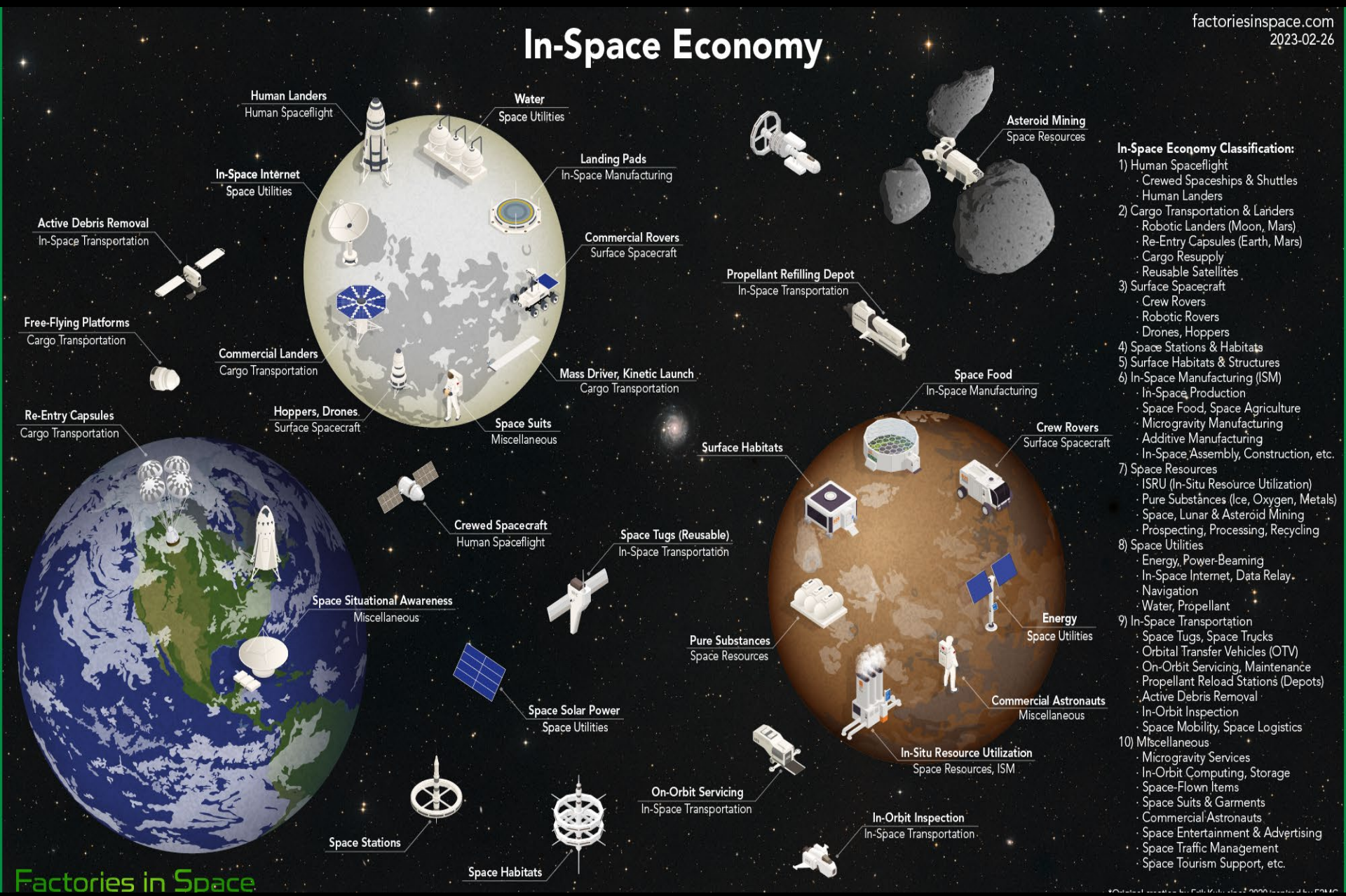




- the idea that space is a global commons to be shared by all humanity is rapidly disappearing

In-Space Economy

factoriesinspace.com
2023-02-26

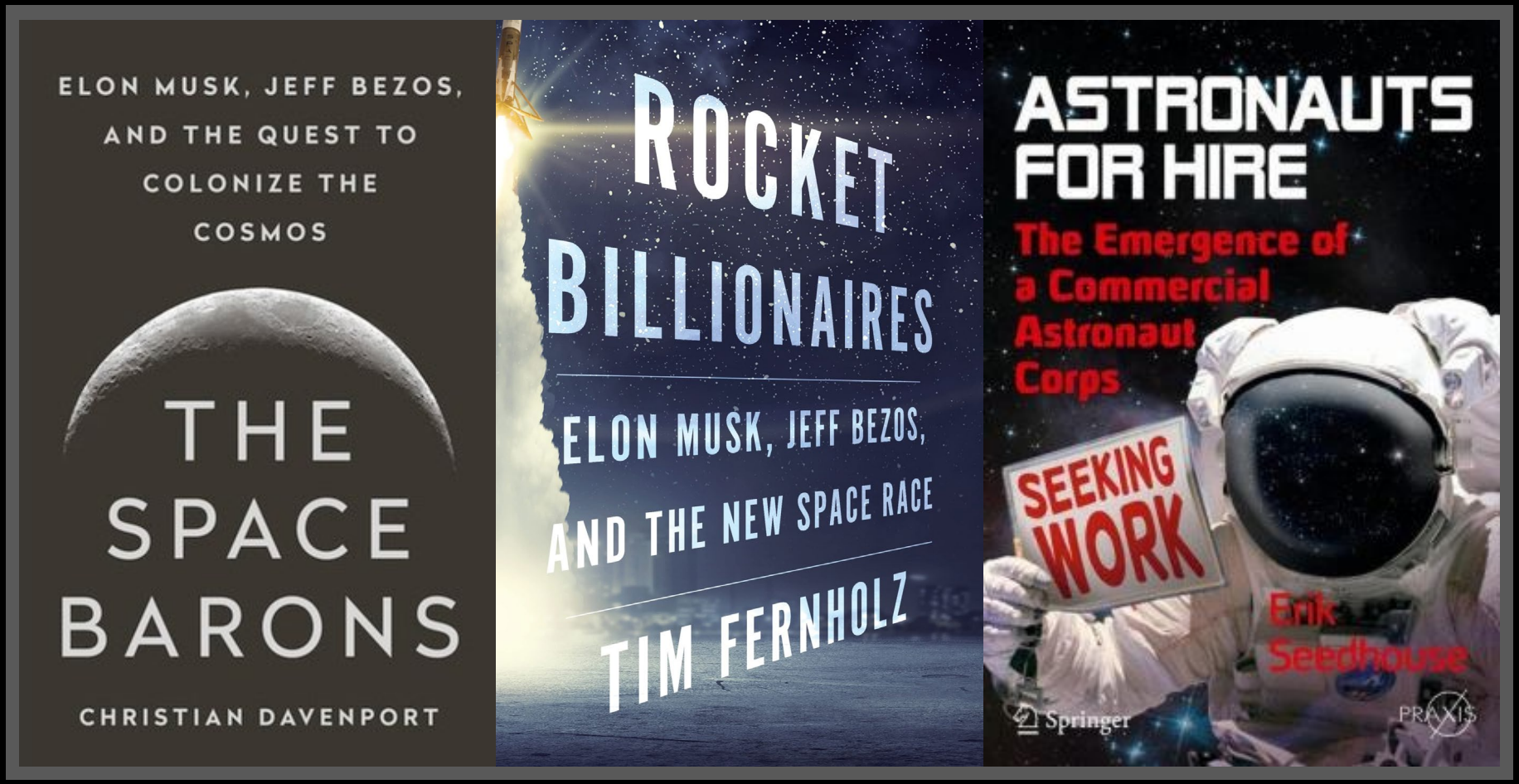


In-Space Economy Classification:

1) Human Spaceflight
   - Crewed Spaceships & Shuttles
   - Human Landers
2) Cargo Transportation & Landers
   - Robotic Landers (Moon, Mars)
   - Re-Entry Capsules (Earth, Mars)
   - Cargo Resupply
   - Reusable Satellites
3) Surface Spacecraft
   - Crew Rovers
   - Robotic Rovers
   - Drones, Hoppers
4) Space Stations & Habitats
5) Surface Habitats & Structures
6) In-Space Manufacturing (ISM)
   - In-Space Production
   - Space Food, Space Agriculture
   - Microgravity Manufacturing
   - Additive Manufacturing
   - In-Space Assembly, Construction, etc.
7) Space Resources
   - ISRU (In-Situ Resource Utilization)
   - Pure Substances (Ice, Oxygen, Metals)
   - Space, Lunar & Asteroid Mining
   - Prospecting, Processing, Recycling
8) Space Utilities
   - Energy, Power-Beaming
   - In-Space Internet, Data Relay
   - Navigation
   - Water, Propellant
9) In-Space Transportation
   - Space Tugs, Space Trucks
   - Orbital Transfer Vehicles (OTV)
   - On-Orbit Servicing, Maintenance
   - Propellant Reload Stations (Depots)
   - Active Debris Removal
   - In-Orbit Inspection
   - Space Mobility, Space Logistics
10) Miscellaneous
   - Microgravity Services
   - In-Orbit Computing, Storage
   - Space-Flown Items
   - Space Suits & Garments
   - Commercial Astronauts
   - Space Entertainment & Advertising
   - Space Traffic Management
   - Space Tourism Support, etc.

Factories in Space

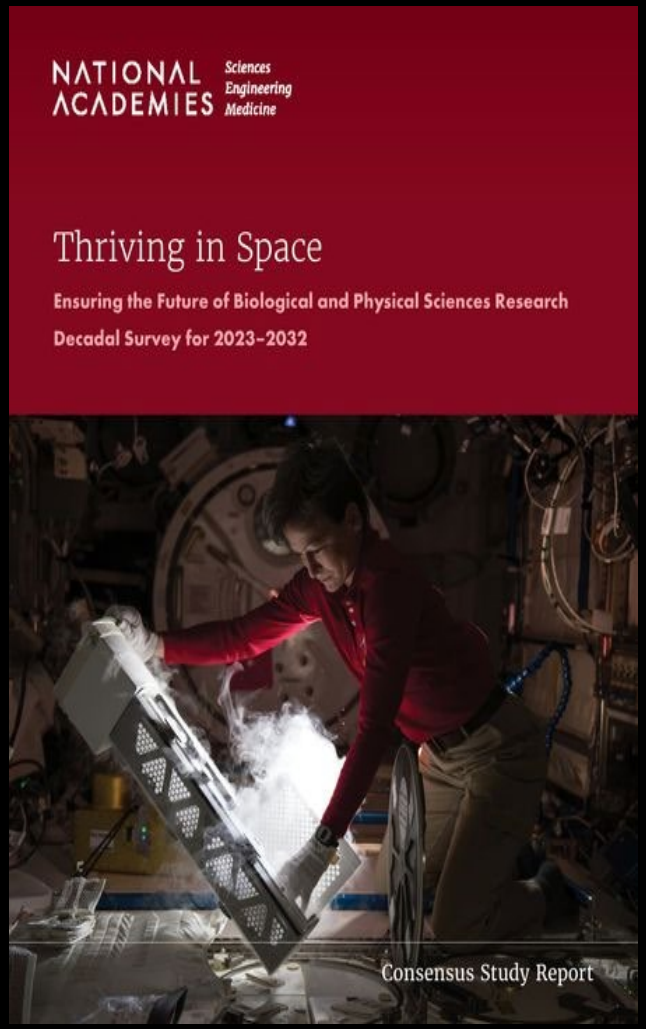
The Rapid Rise of Private Sector Space Commerce and a New Civilian Space Workforce



- "astropreneurs"
- "astrobucks"
- "astronaut homesteaders"
- "astropolitics"


USSF • Google Earth
UNITED STATES
SPACE FORCE
MGN

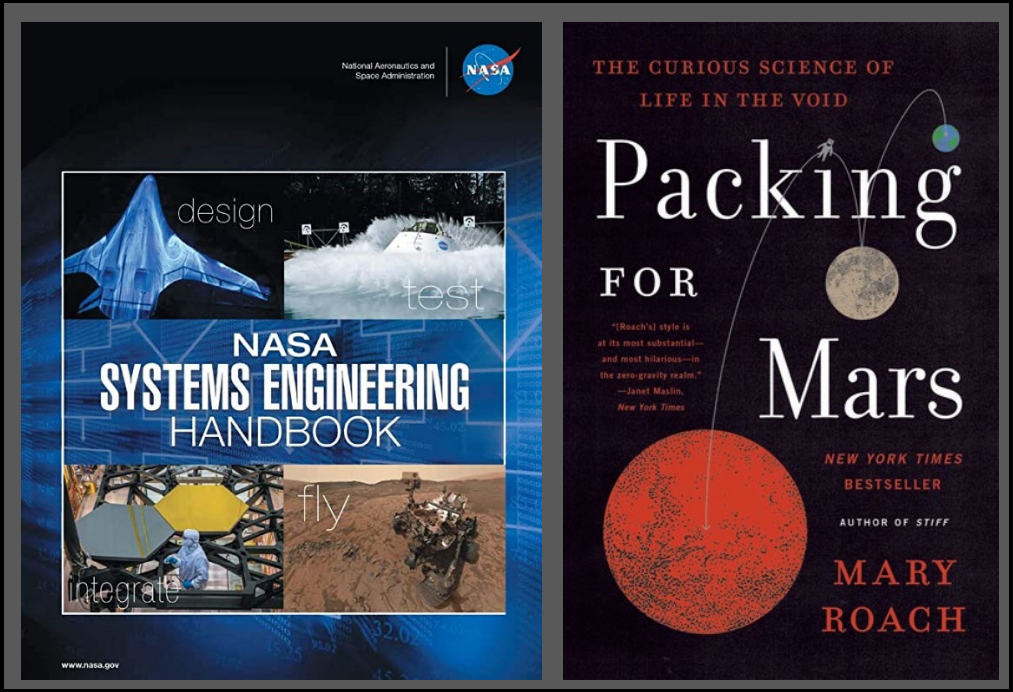
Humans in Space



Humans in Space

- how to thrive in high-risk non-physiological environments for extended periods?
- how to mitigate the short-and long-term adverse health risks from life off-earth?
- how to design and construct sustainable habitats on the moon and beyond?

Humans in Space



- to rocket scientists and engineers, humans are a problem
- humans are a complex, irritating component that comes with wide variation in physical and mental traits creating diverse and often unknown vulnerabilities that could threaten mission success
- everything we take for granted on earth has to be rethought, redesigned, rehearsed
- from the healthiest of the healthy (astronauts) to larger populations with the same multiple health-risks as on earth

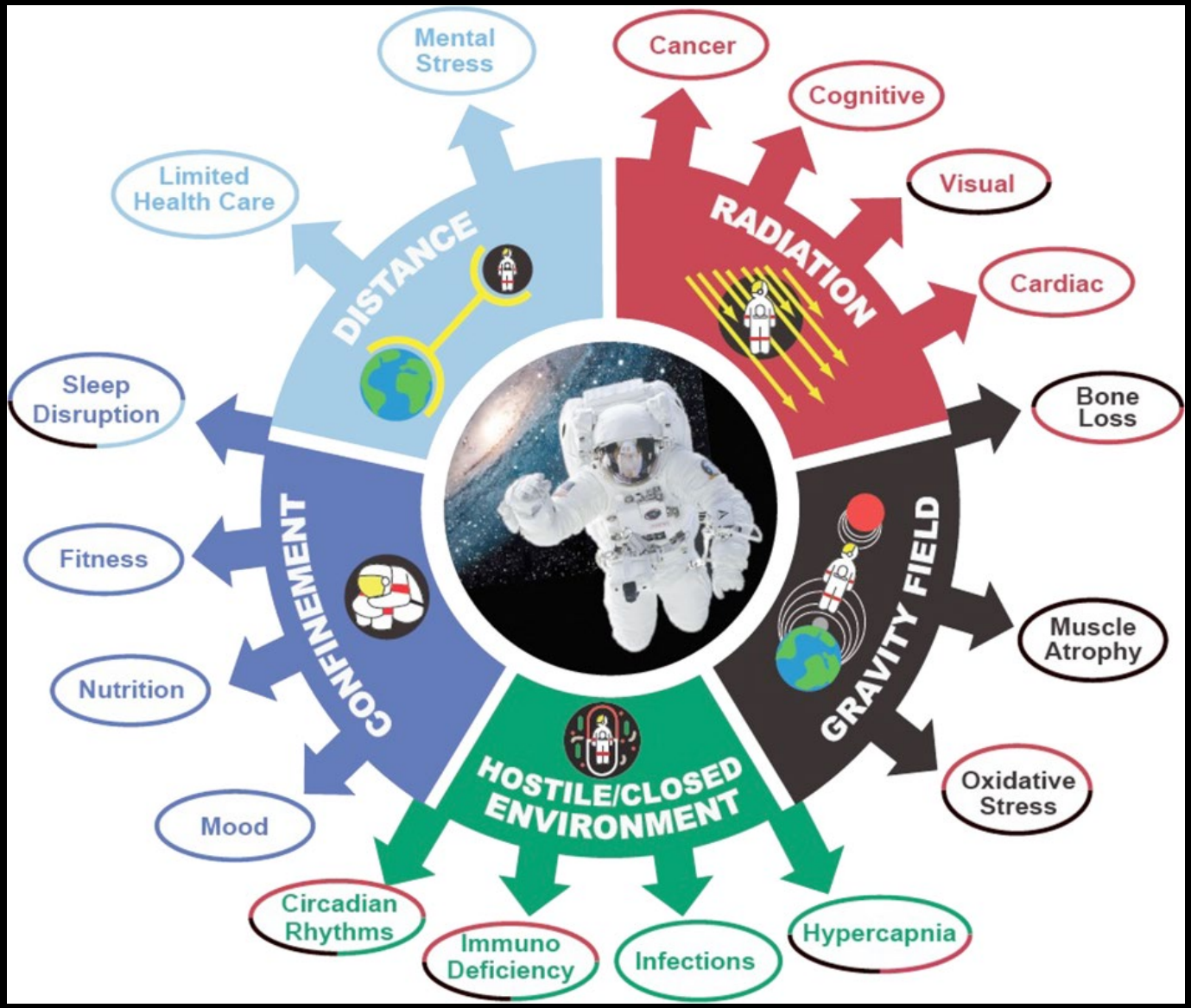
Earth is the Goldilocks Planet

- not too hot
- not too cold
- just right for life

Space-Induced Changes in Different Body Systems

- major knowledge gaps
- small ‘N’ problem: limited number of individuals in space to date
  - LEO environments very different from deep space missions
- need for prolonged follow-up (longitudinal studies)
  - reversible versus irreversible changes
  - additional as yet unknown and unpredicted adverse risks
- eventual need for genetic modification for sustainable health augmentation (non-heritable), enhancement (heritable) in long duration missions and off-earth habitats?
- human reproduction in space

Altered Health in LEO Environments



https://www.nature.com/articles/s41526-021-00143-x

Space Adaption Syndrome:
Humpty Dumpty Head, Chicken Legs

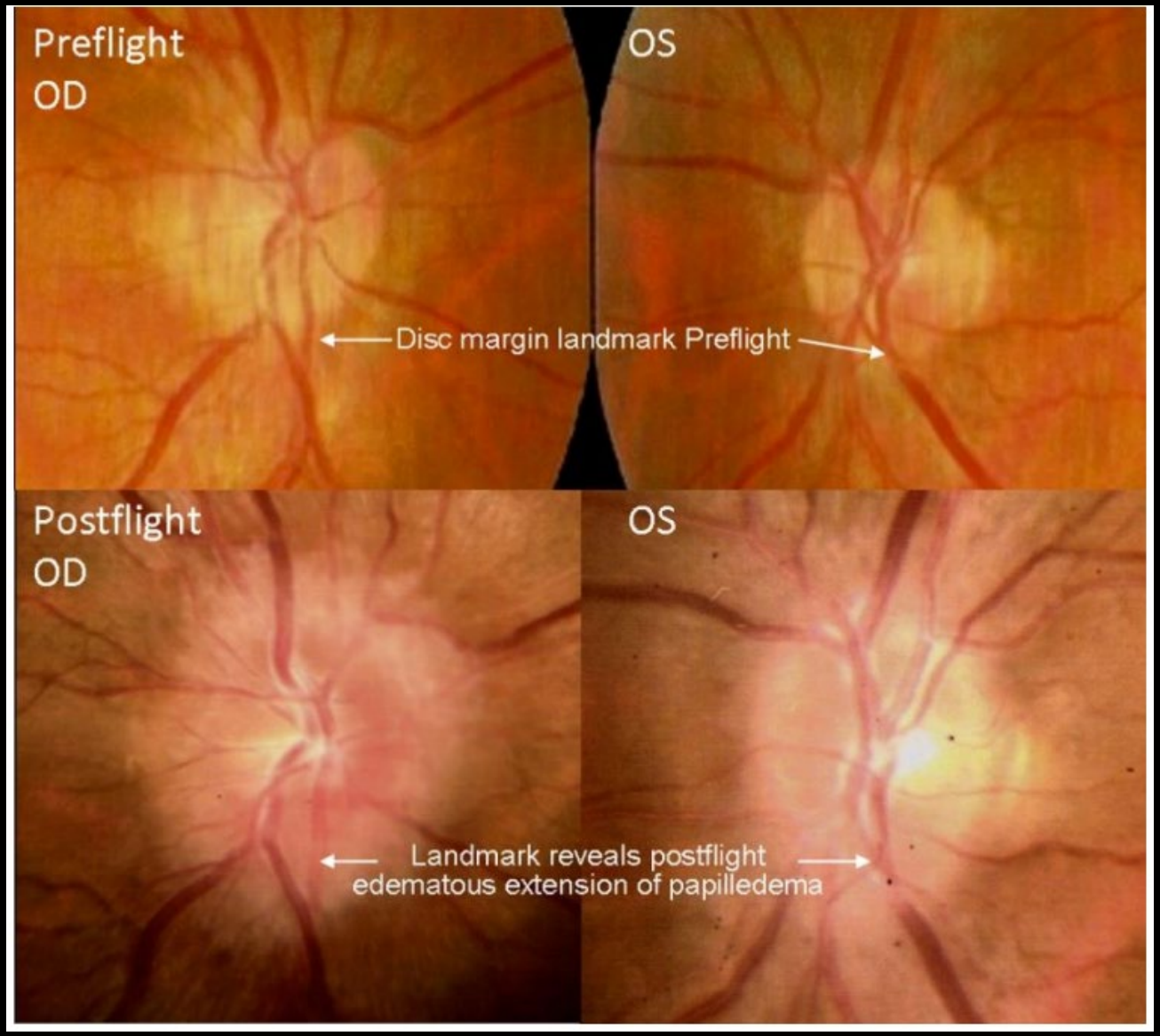
- increased cranial pressure (ICP) due to body fluid redistribution in reduced gravity
- “The full-head sensation never completely goes away. It feels like standing on your head 24 hours a day.”

  Scott Kelly

The Cephalad Fluid Shift: Humpty Dumpty Head, Chicken Legs

- shift of body fluids towards the head and upper torso
- compensatory cardiovascular responses
  - suppression of renin-angiotensin-aldosterone axis
  - release of atrial natriuretic peptide
  - increased salt and water excretion
  - reduction in blood volume (10-20%)
- decreased renal erythropoietin secretion
  - anemia
- reduction in red blood cell mass
- loss of ventricular mass (cardiac atrophy)
- decreased sensitivity of the carotid-cardiac (vagal) baroreflex
- decreased blood pressure and elevation of cardiac output
- increase in risk of blood clots (carotid)

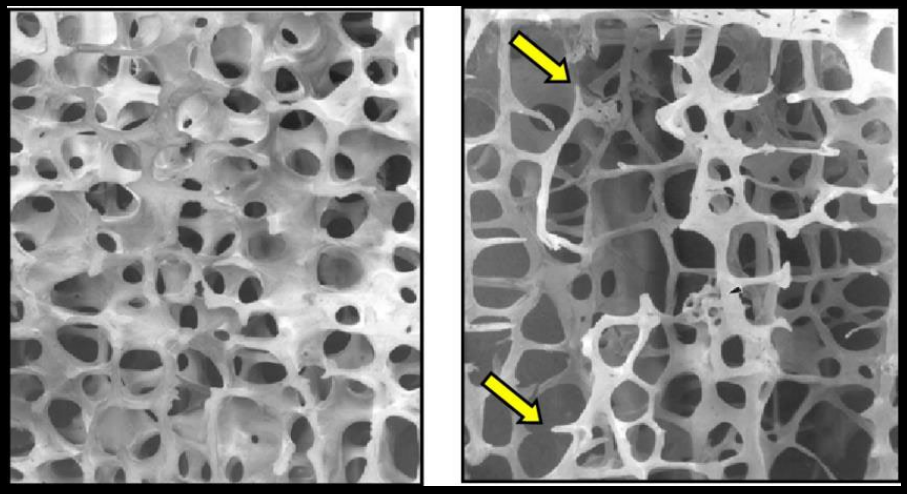
SANS:
Spaceflight-Associated Neuro-Ocular Syndrome



https://humanresearchroadmap.nasa.gov/evidence/reports/SANS.pdf

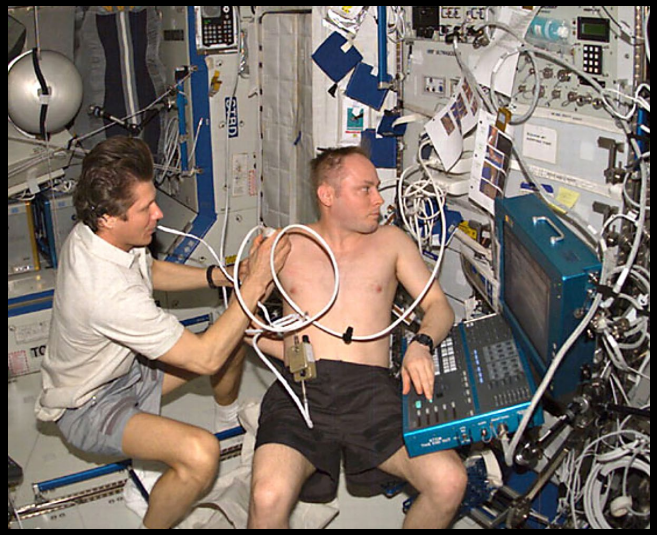
In-Mission Ophthalmic Monitoring

Bone-Loss in Microgravity



- bones of legs, pelvis and lower back lose 20 times as much mass as upper body bones
- loss of bone mineral density/month
  - femur (1.6%), pelvis (1.4%), lower spine (1.1%)
  - whole body (0.35%)
- much higher demineralization than osteoporotic bone loss in post-menopausal women on earth
- urinary excretion of excess calcium (hypercalciuria)
  - predisposition to renal/bladder stones high levels of hydration

On-Station Exercising to Mitigate Bone and Muscle Atrophy



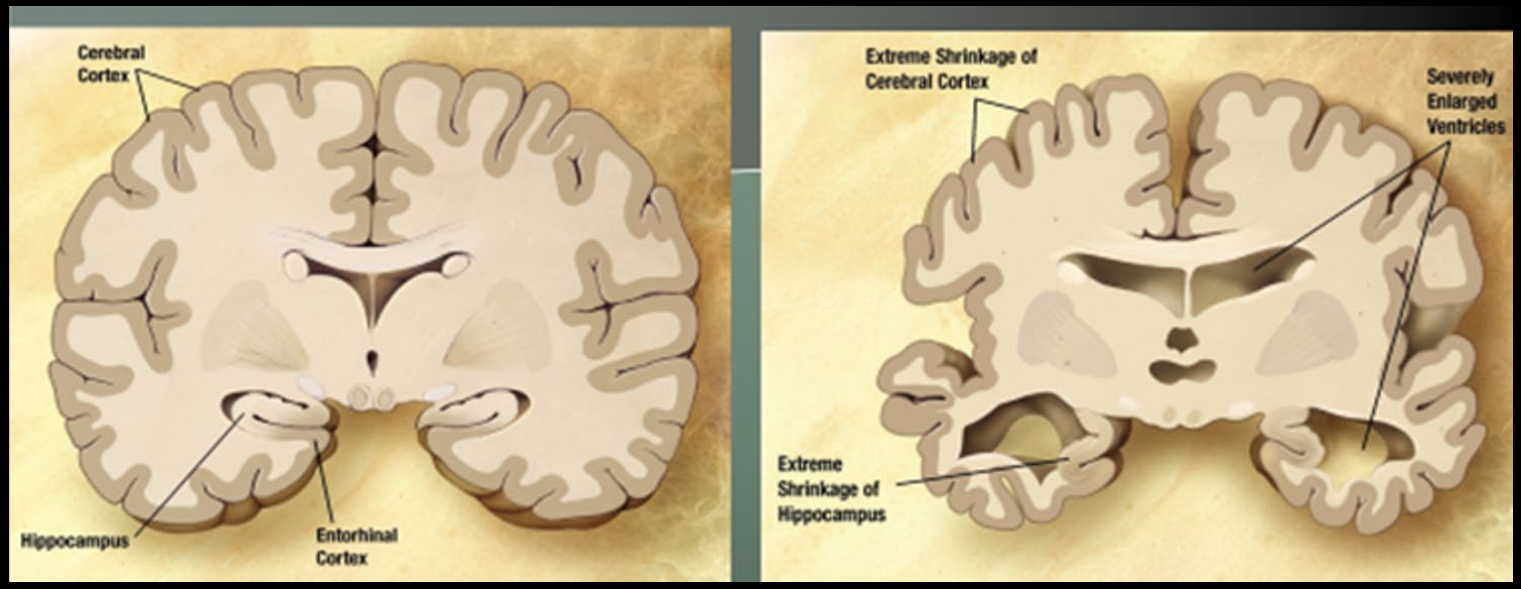
Disrupted Sleep in Reduced Gravity: Altered Circadian Rhythms

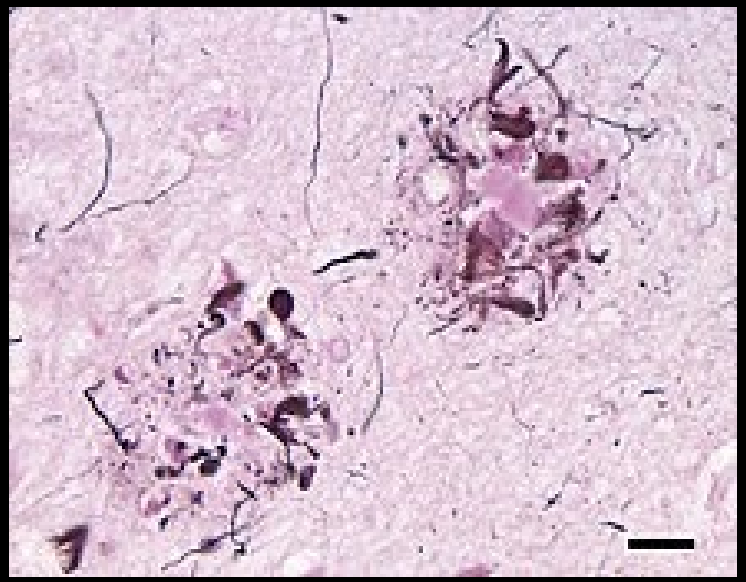
https://www.standard.co.uk/tech/astronauts-struggle-to-sleep-a4555931.html

Sleep Disorders and Dreaming in LEO

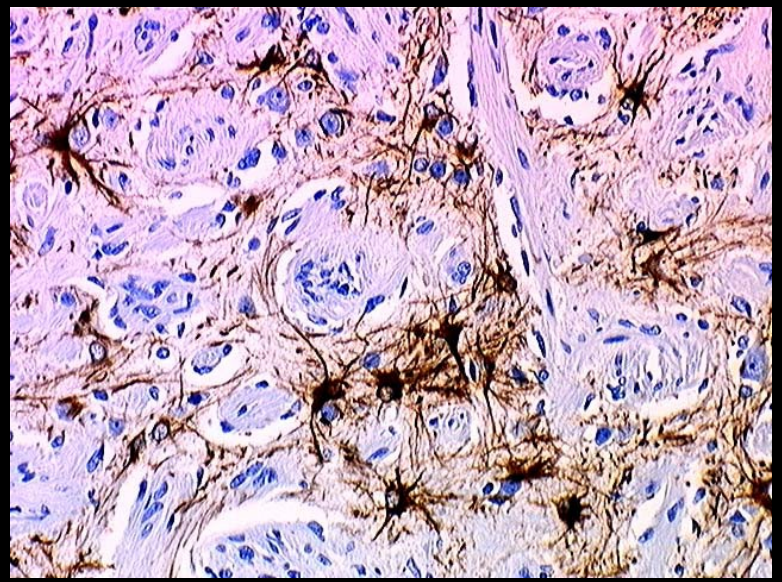
- among most common perturbations
- dissatisfaction with depth and duration of sleep
- 75% astronauts use sleeping pills
- disruption of five stages of sleep and cascading neurohormonal alterations
  - pineal gland, hypothalamus and pituitary functions
  - increased secretion of growth hormone
- adverse impact on cognitive and emotional behaviors
  - decision making, reasoning, irritability
  - complex spectrum of emotional responses, including overt clinical psychiatric conditions

Alzheimer's Disease and Neurodegeneration: Beta-Amyloid and TAU Neurotoxic Proteins



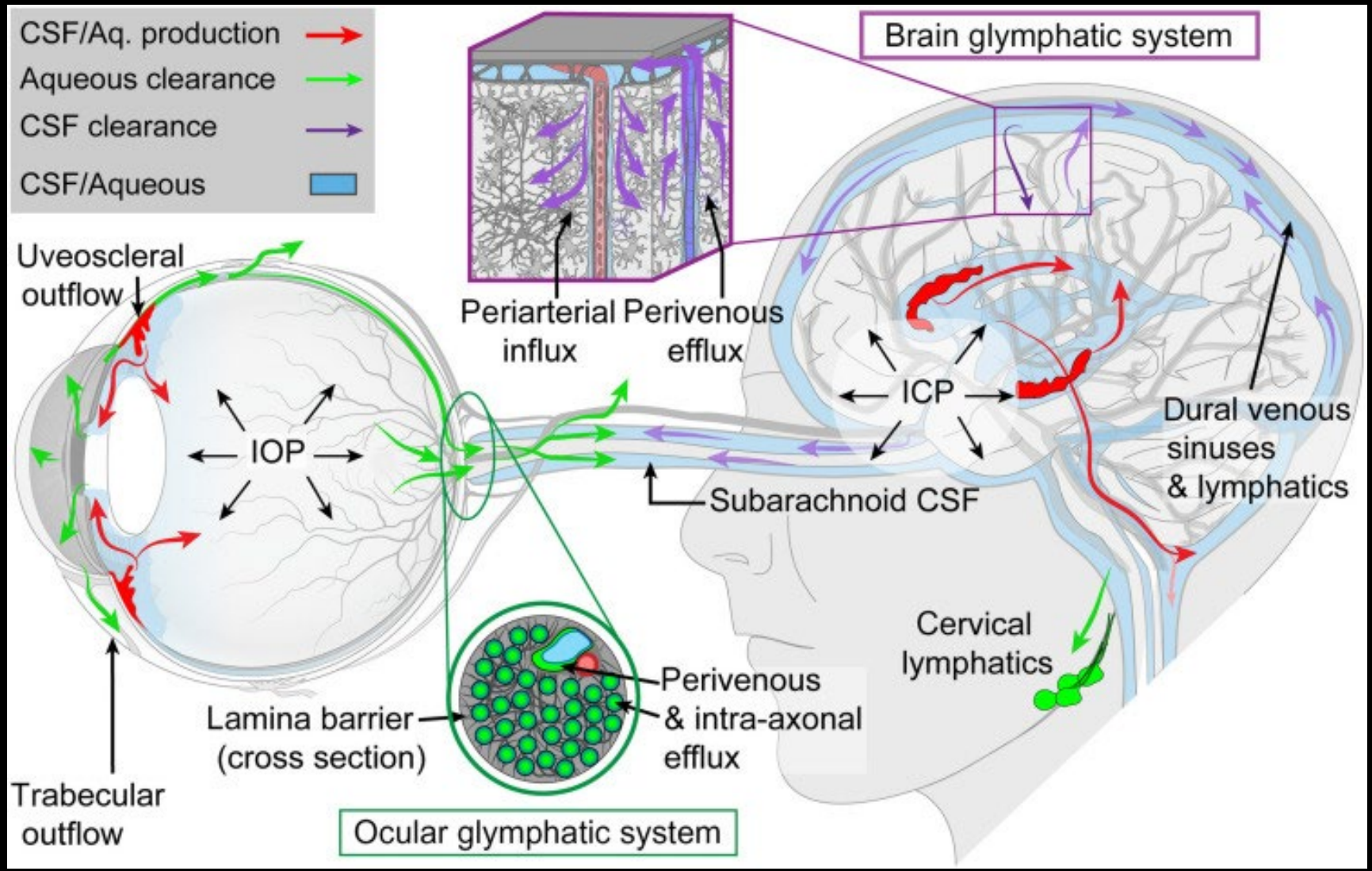


Beta - Amyloid Plaques



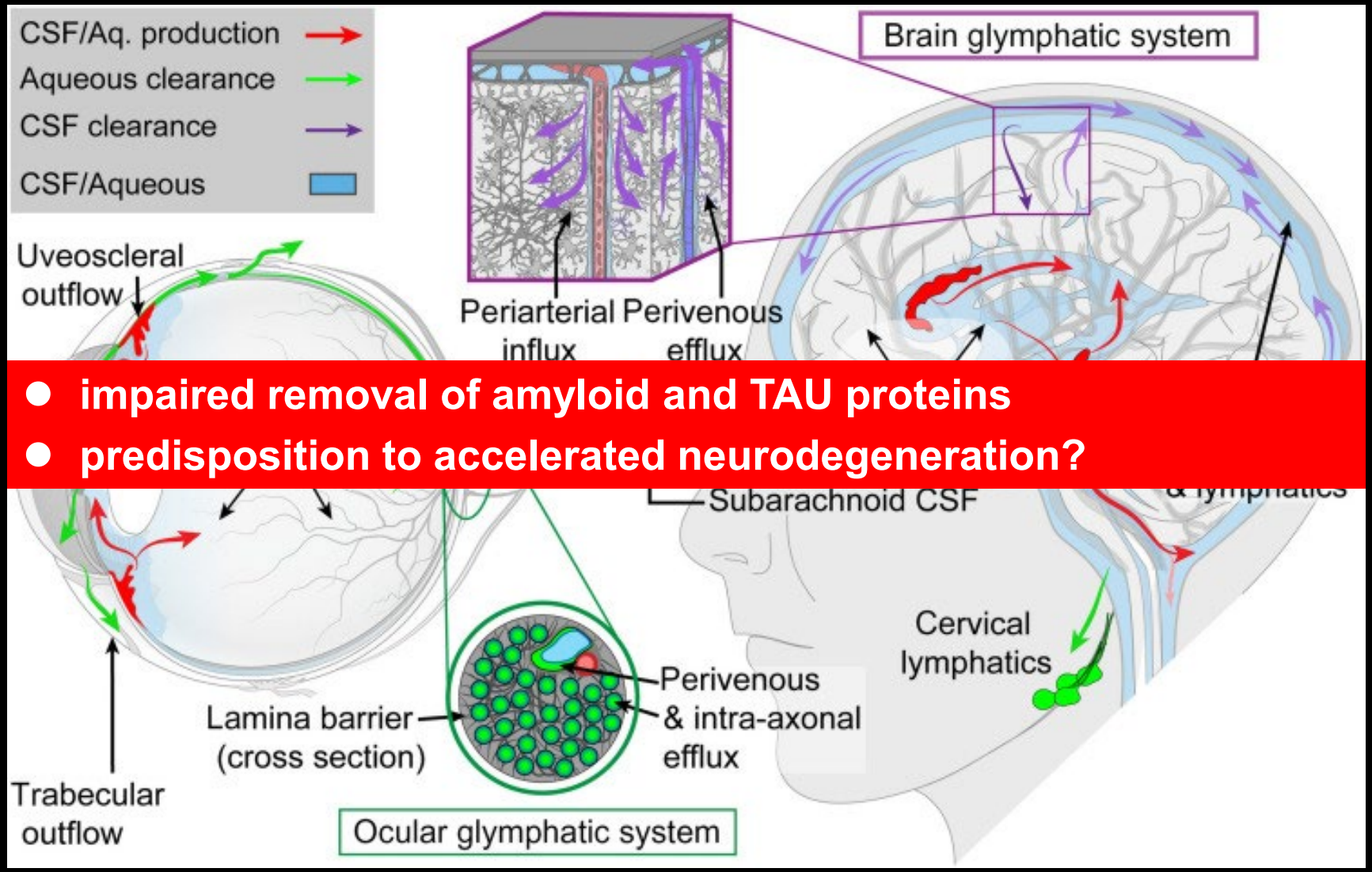
TAU - Neurofibrillary Tangles

The Glymphatic System (Ocular and CNS)



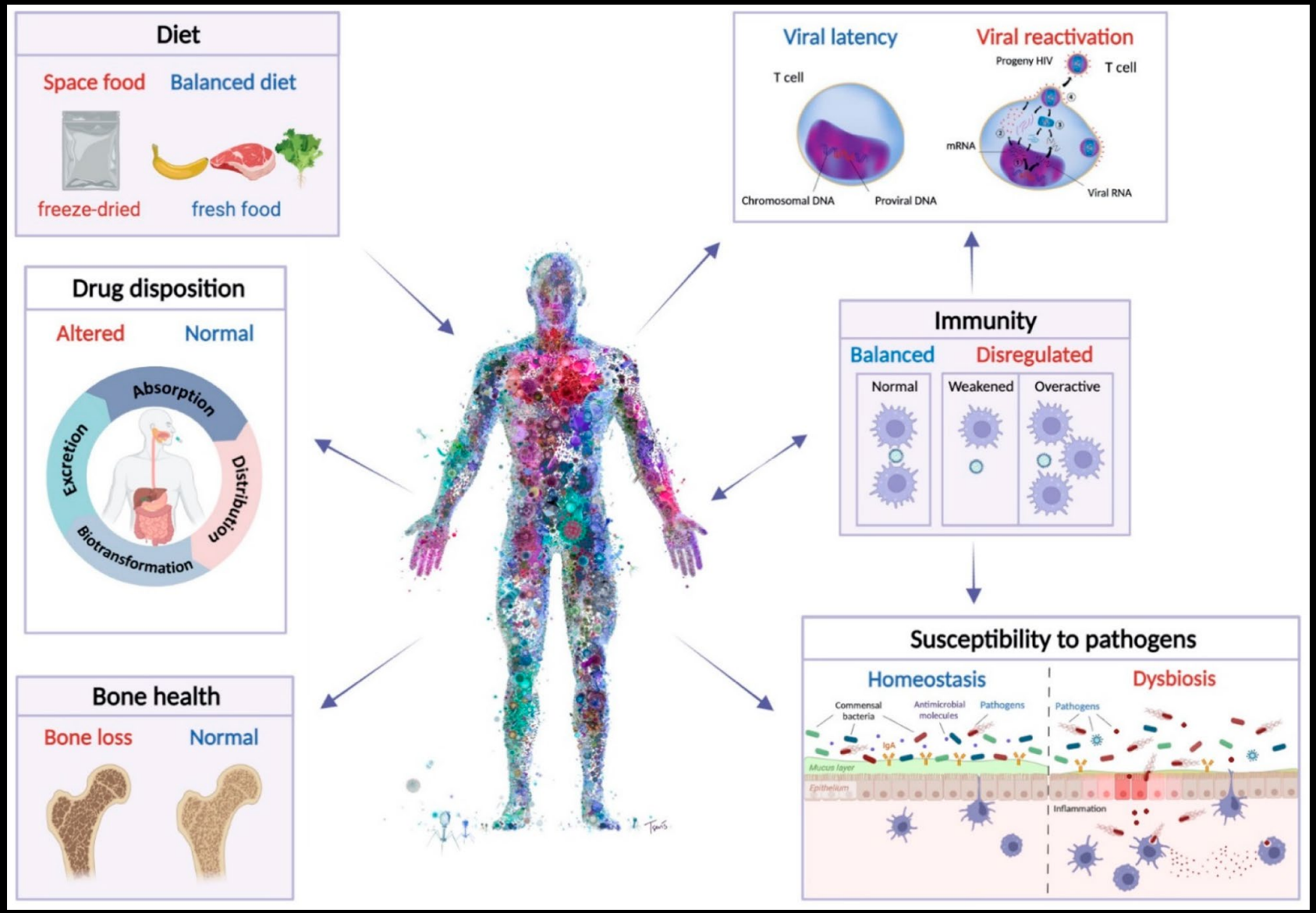
Eye and Brain(2022) doi.10.2147/EB.S354710

Glympathic Drainage of Brain Metabolic Waste Products: Impaired Clearance with Increased IOP/ICP and Sleep Disturbance



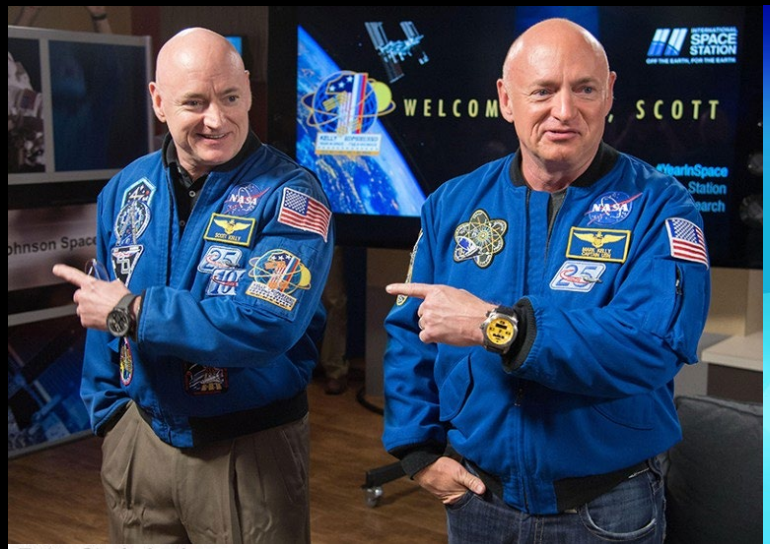
- impaired removal of amyloid and TAU proteins
- predisposition to accelerated neurodegeneration?

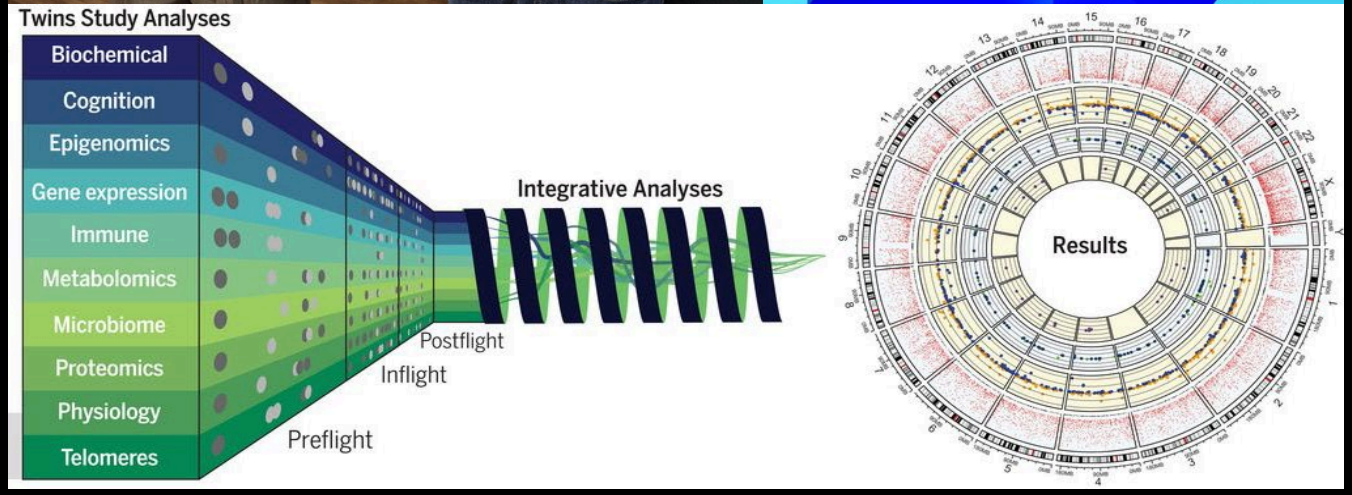
Impact of Spaceflight-induced Microbiome Changes and Altered Immune Functions



Life 2022, *12*(4), 495; https://doi.org/10.3390/life12040495

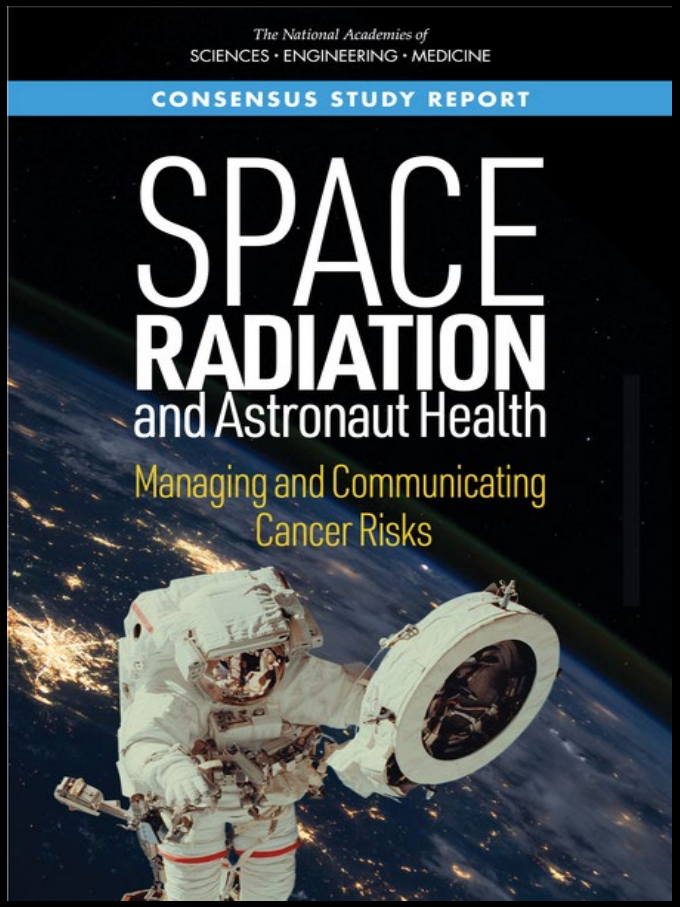
The NASA Twins Study: Comprehensive MultiOmics Profiling of Extended Spaceflight Duration in LEO (One Year)





https://www.science.org/doi/10.1126/science.aau8650 (2019)

Radiation:
The Omnipresent Health Risk in Space Flight

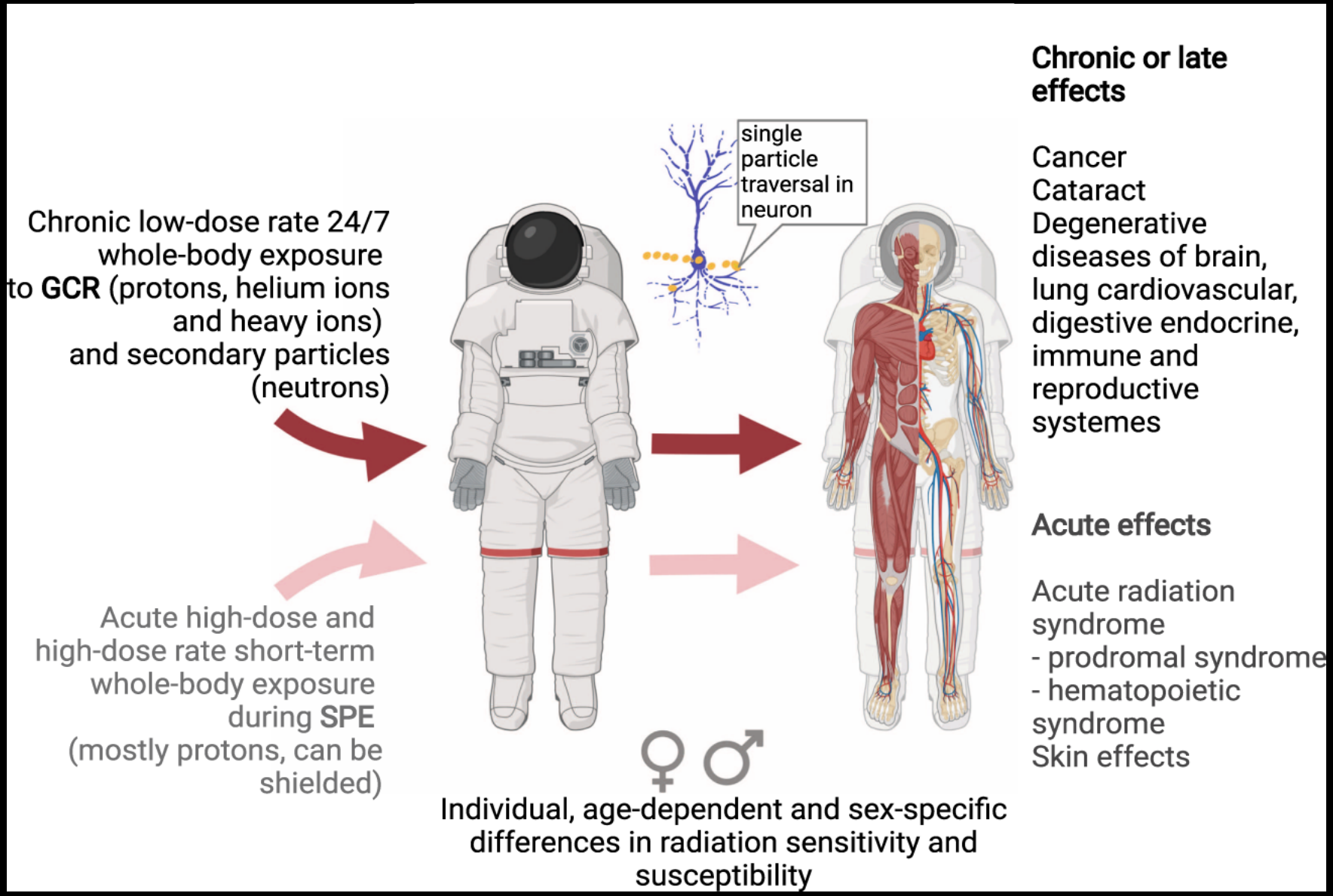


doi.org/10.17226/26155 (2021)

Commander Moonkin Campos:
Artemis I return 1/10/2023

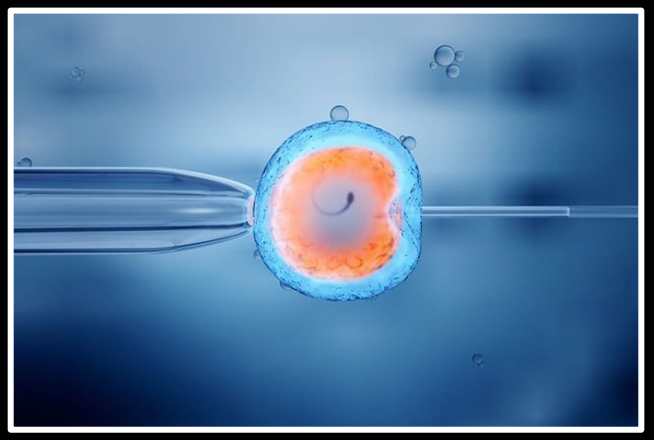
- **due to lack of atmosphere on the moon's surface radiation levels are 200X higher than on earth**

Radiation Risk Exposure in Space:
GCR = Gamma Cosmic Rays SPE = Solar Particle Events



https://www.nature.com/articles/s41526-023-00262-7 (2023)

Space-Acquired Radiation Mutation Damage to Gametes and Enhanced Risk of Fetal Abnormalities (Teratogenicity)



- cryogenic storage of astronaut eggs/sperm harvested before mission for IVF use on return (or loss of life of donor on mission)
- analogous situation to use of IVF for donors facing high dose cancer chemotherapy

Do You Want to Apply?

"Men wanted for hazardous journey.
Low wages, bitter cold,
long hours of complete darkness.
Safe return doubtful.
Honour and recognition in
event of success."

1907 Recruitment Advertisement for Sir Ernest Shackleton's Antarctica Expedition

qualified. M. L. Barker, 1408 Chapman Bldg.

MEN WANTED

for hazardous journey, small wages, bitter cold, long months of complete darkness, constant danger, safe return doubtful, honor and recognition in case of success.

Ernest Shackleton 4 Burlington st.

MEN—Neat-appearing young men of pleasing personality, between ages ... and 40 to work

"Men wanted for hazardous journey.
Low wages, bitter cold,
long hours of complete darkness.
Safe return doubtful.
Honour and recognition in
event of success."

https://www.smithsonianmag.com/smart-news/shackleton-probably-never-took-out-an-ad-seeking-men-for-a-hazardous-journey-555237

Psychological Fragility Induced by Isolation and Confinement

- people don't anticipate how much they miss the natural world until they can't access it

Getting Along:
The Psychological and Sociological Aspects of Space Travel

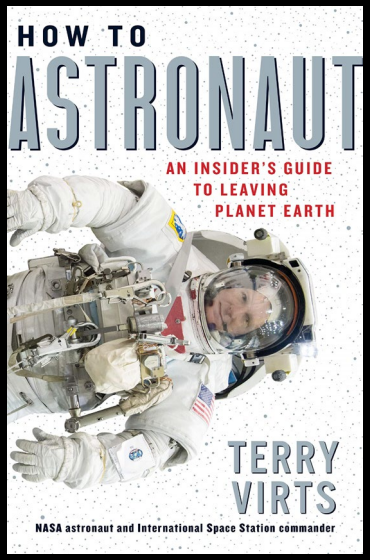
- sustaining resilient mental health as critical component for longer duration missions (individuals, groups)
- complex interplay between physical, sensory and cognitive events in high risk/high stress environments
- major investment by space agencies in screening candidates (and future space workforce employers)
  - individual resiliency/vulnerability
  - group dynamics and trust
  - will genetic determinants be identified that can be used to select individuals with optimal resiliency traits?

Mental Health Resiliency in Long Duration Missions in High Risk/High Stress Environments

- anxiety, despondency, depression, withdrawal and isolation
- impulsivity, mania, aggression, violence
- hallucinations
- resentment of workload and acceptance/conformity with critical SOPs needed for mission success
- conflict risk management
- cross-cultural clashes
- "irrational antagonism": emerges after c.6 weeks
  - cumulative intolerance and annoyances at previously innocuous events

Learning to Tolerate Less Than Optimal Living Quarters

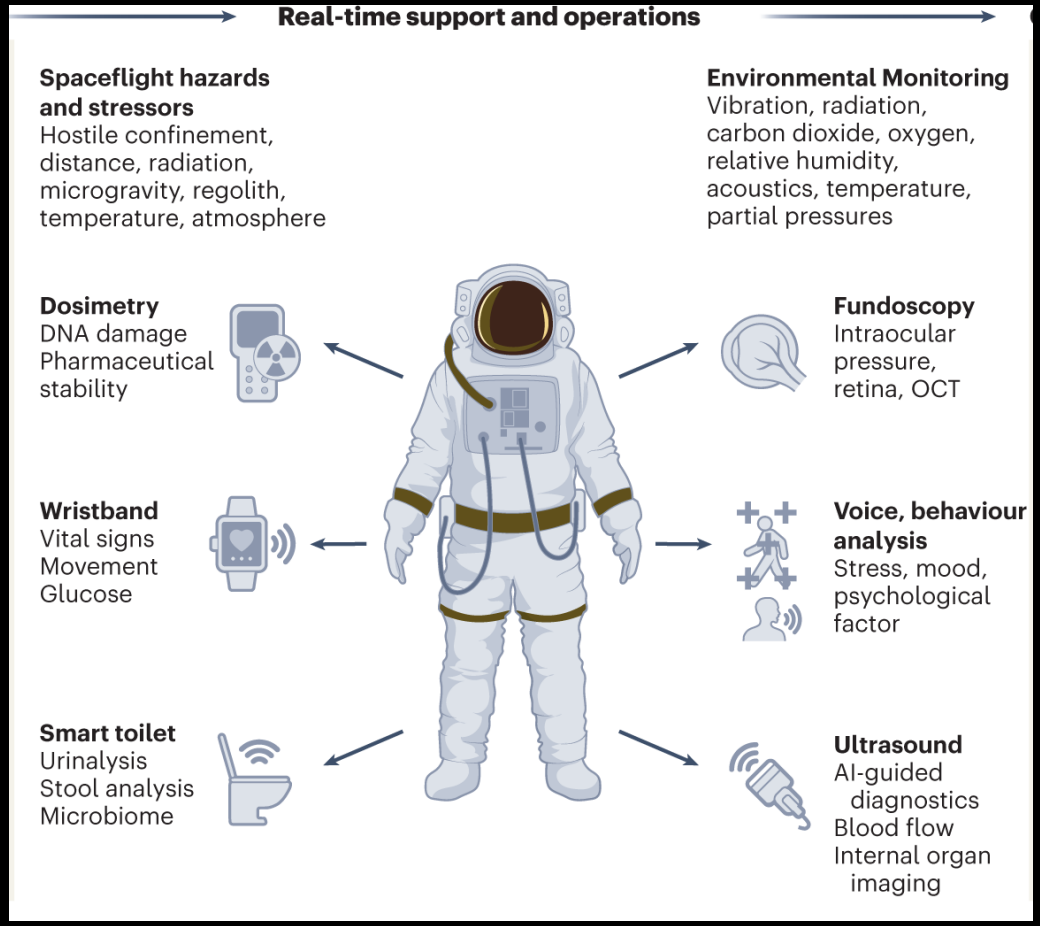
personal hygiene



ISS: smelly, noisy and awash in microbes and crumbs

- everything floats
- the benefits of anosmia

Next-Generation Health Monitoring Assessment for Extended Duration Space Missions



R.T. Scott et. al. (2023) Nat. Mach. Intell. 5,196

Ranking of the Most Likely In-Mission Health Emergencies

- cardiovascular
  - clotting
  - myocardial infarction due to altered myocardial mass
- infections
- trauma, hemorrhage, shock
- acute radiation sickness (Moon and beyond)

individual or multiple cases

Medical Emergencies in Space

- limited medical supplies, equipment and crew training
- limited on-board pharmacy
- limited storage for blood and blood derivatives (35-day shelf-life)
- faster deterioration of medicines and reduced shelf-life versus earth
- rapid evacuation from locations beyond LEO not currently feasible

Returning to Earth: Biological Readaptation

- days
  - impact of sudden postural shifts: fainting, vertigo, nystagmus
- weeks
  - variable persistent balance and walking problems
  - dysconjugate gaze (cross-eyed)
  - back/joint pain as spine/tendons recompress under Earth's gravitation
  - vision
- month to years?
  - restoring muscle and bone mass
  - normal sleep patterns
  - memory and cognitive functions

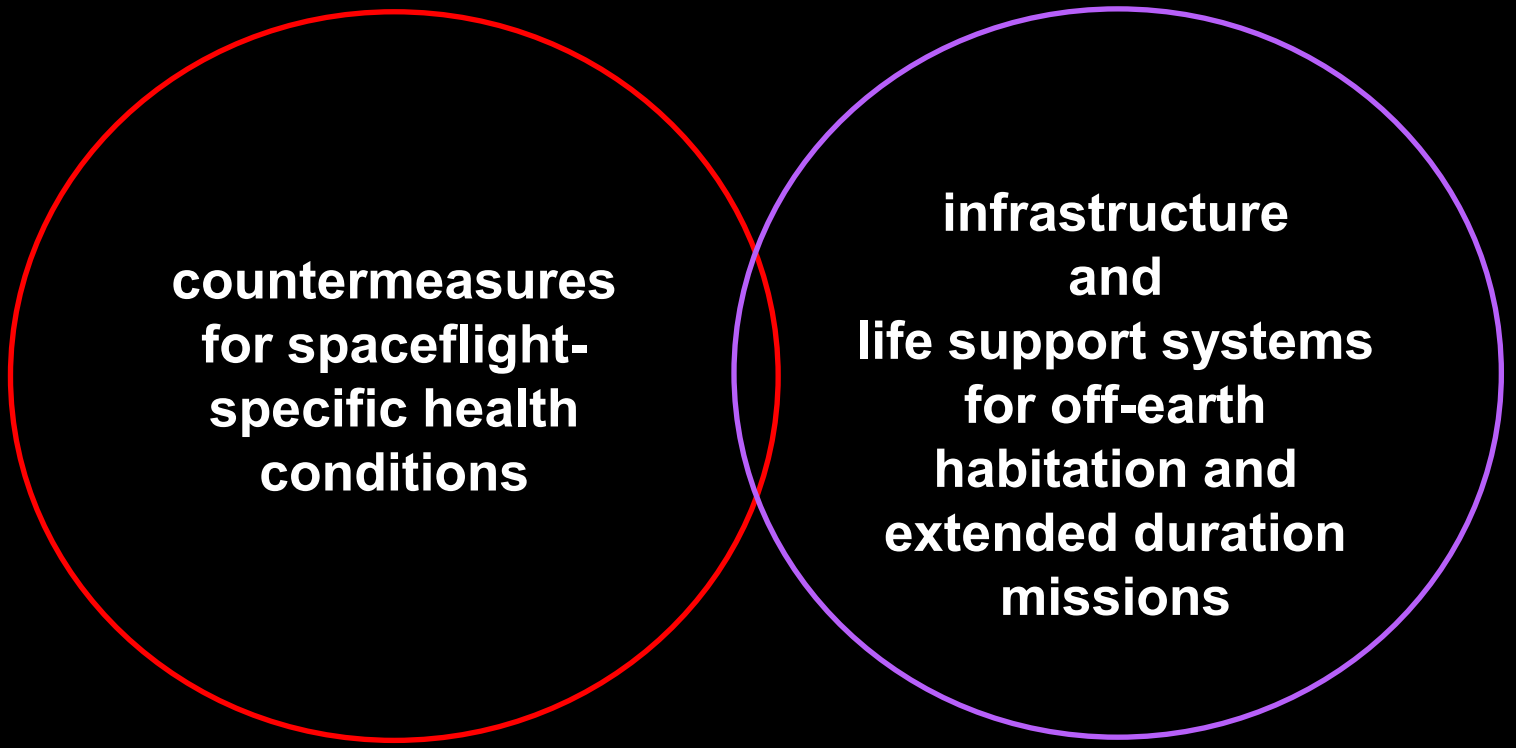
Returning to Earth: Unknown Unknowns

- long-term health effects?
- influence of mission duration and location on risks?
- DNA mutation and cancer predisposition?
- chronic immune dysregulation and persistent subclinical inflammatory states?
  - autoimmunity, susceptibility to infection, cancer
- vision
  - SANS, accelerated cataracts?
- neurodegeneration?
  - impaired brain glymphatic drainage and accumulation of neurotoxic materials

The Elephant in the Room: Unresolved Fundamental Issues in Space Exploration

Dr. Rowena Christiansen Australian Space Biology Symposium rchr@unimelb.edu.au

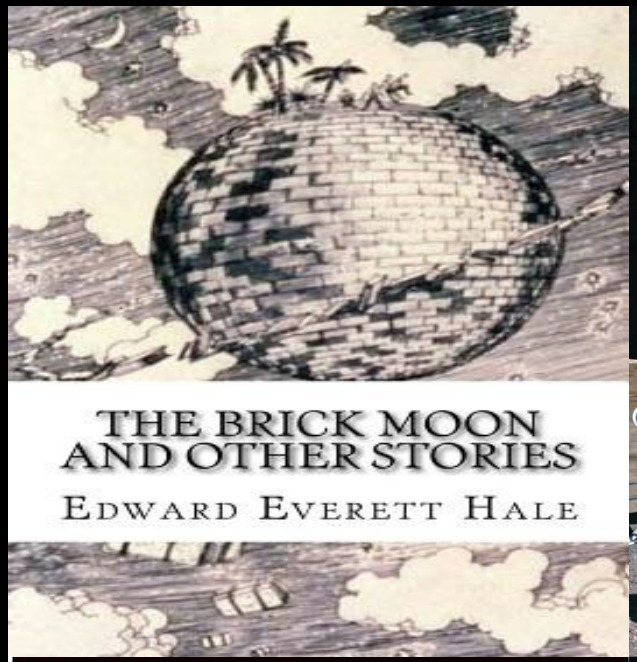
Human Health and Performance in Space

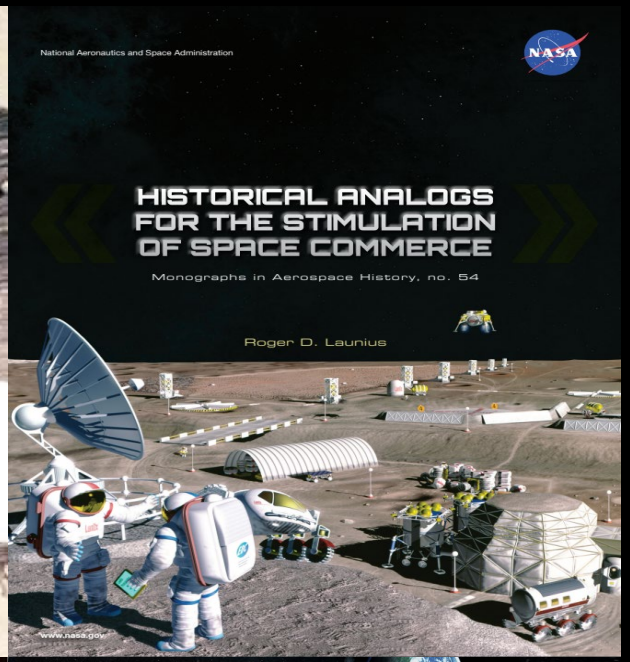


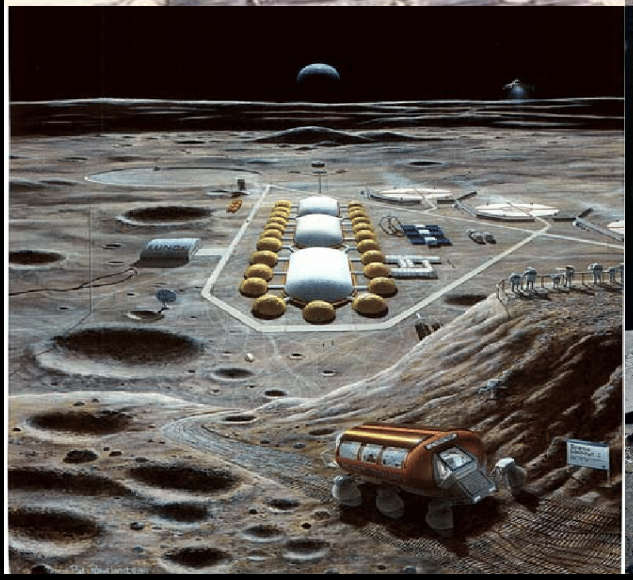
current dependency on terrestrial biomedical interventions

no current demonstration of feasibility of large-scale construction beyond LEO

Human Health in Off-Earth Locations: Moon Base





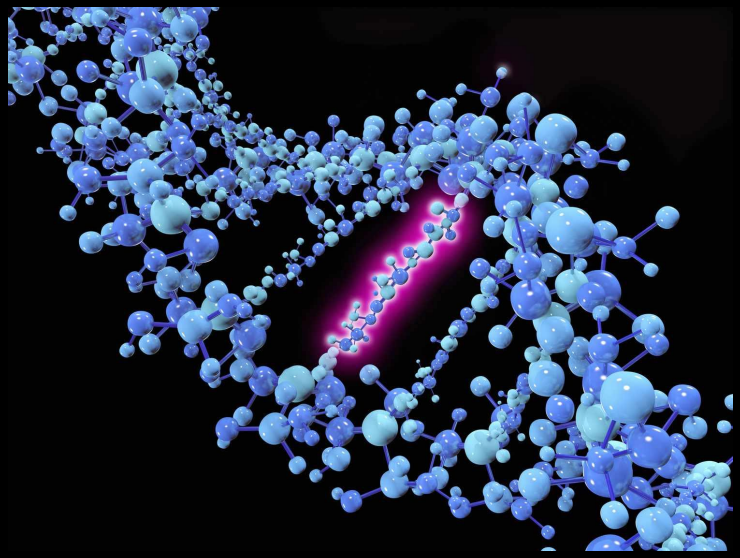


Future Issues in Space Exploration: Construction of New Communities in Space

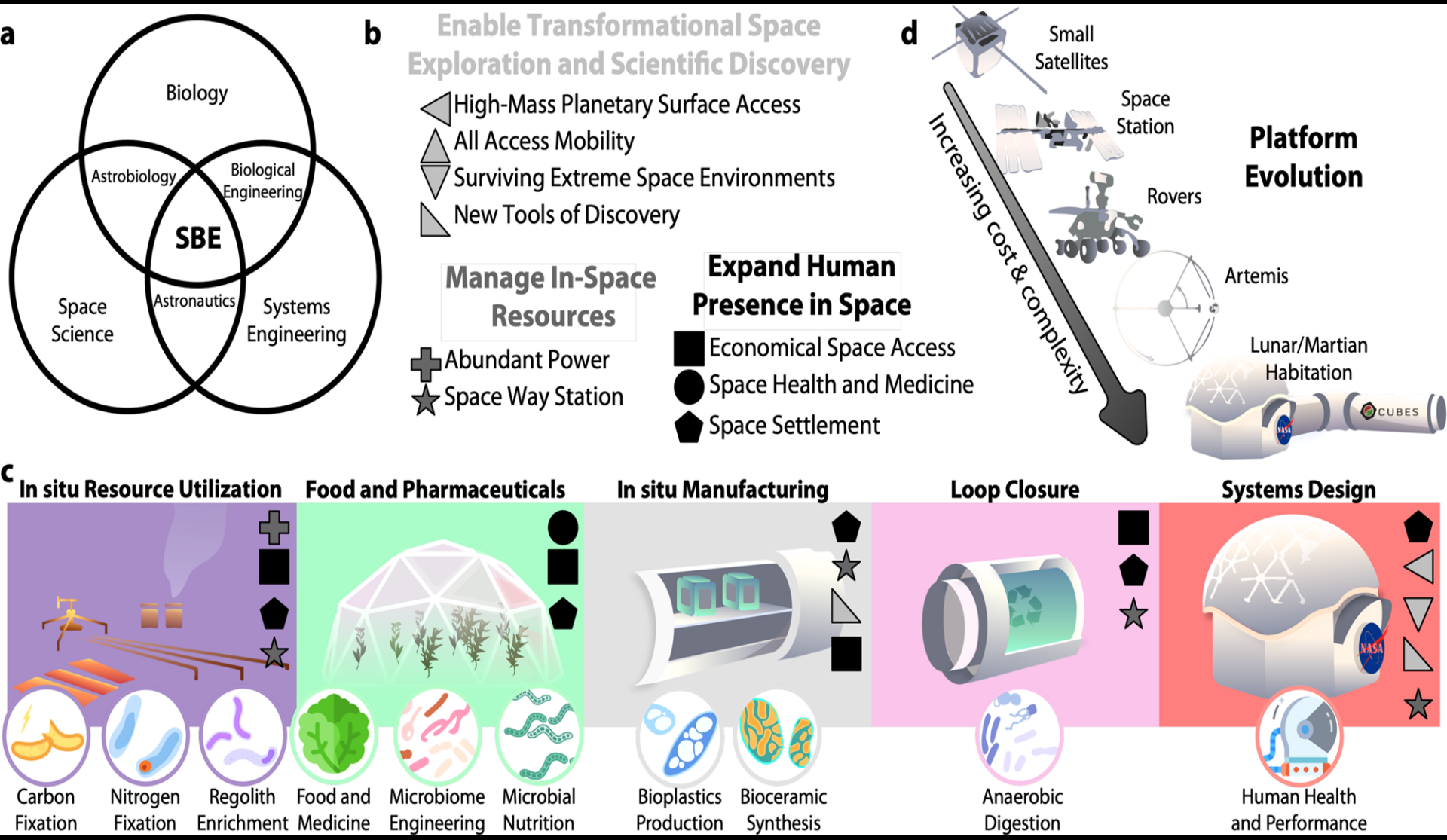
- technical feasibility of large-scale habitat engineering (time-lines)?
- affordability (cost-effectiveness and conflicting societal priorities on earth)?
- role of robotics, autonomous systems and AI versus humans?
- off-earth reproduction, citizenship and nationhood?
- heritable genetic modification for off-earth survival (Homo astrum, Homo ares, Homo astral)?
- hybrid humans: fusion of eugenic genetics and integrated physical devices (Homo cyborgensis)?

Future Issues in Space Exploration: Microbial Biocontamination, Biocontainment and Biosafety Risks

- two-way traffic: from the earth and back-to-earth
- microbial mutation and selection in off-earth locations
  - evolution of 'stress adaptation' phenotypes not present in terrestrial ancestors?
  - new microbial species?
  - need for new classes of antimicrobial drugs?



Overview of Space Bioprocess Engineering Challenges: Technologies, Components, and Platforms

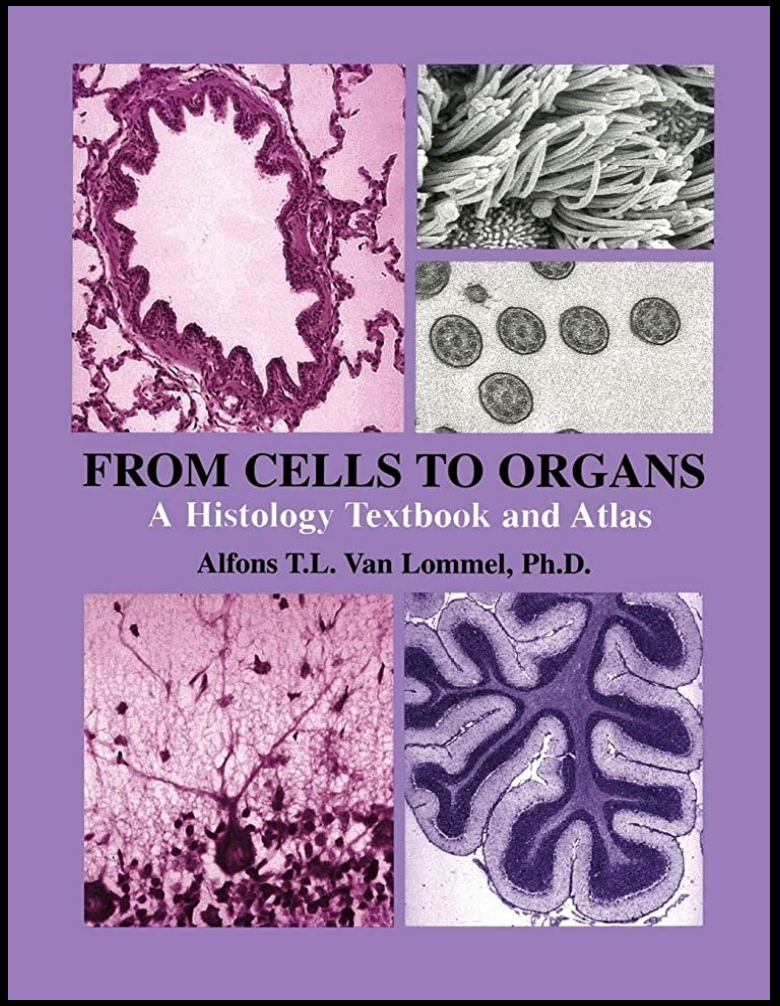


Commun Eng 1, 13 (2022). https://doi.org/10.1038/s44172-022-00012-9

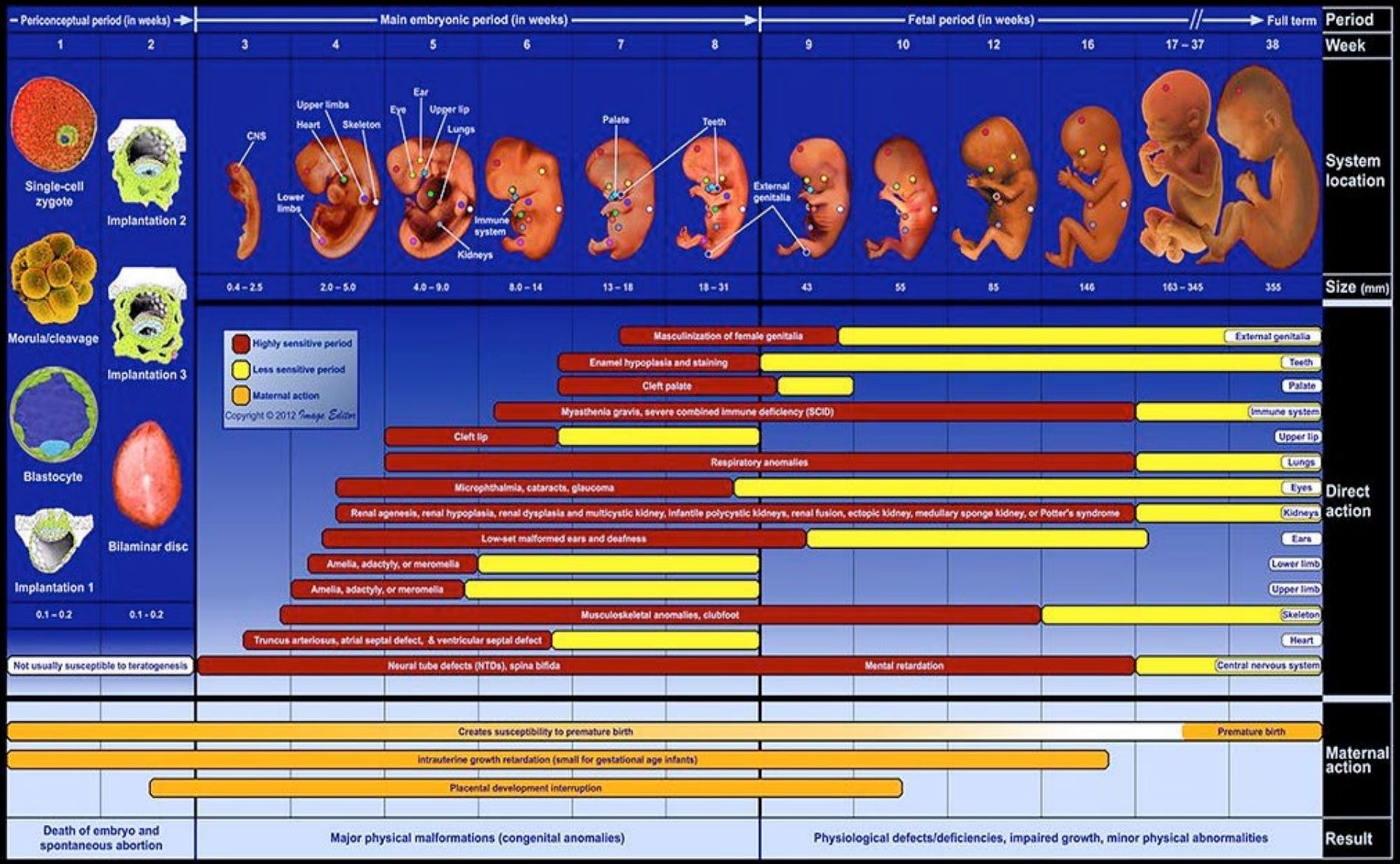
Fundamental Issues in Space Exploration

- feasibility of reproduction in reduced gravity environments?

The Critical Role of Mechanical Forces in Early Embryonic Development and Life-Long Maintenance of Complex 3D-Tissue and Organ Structures



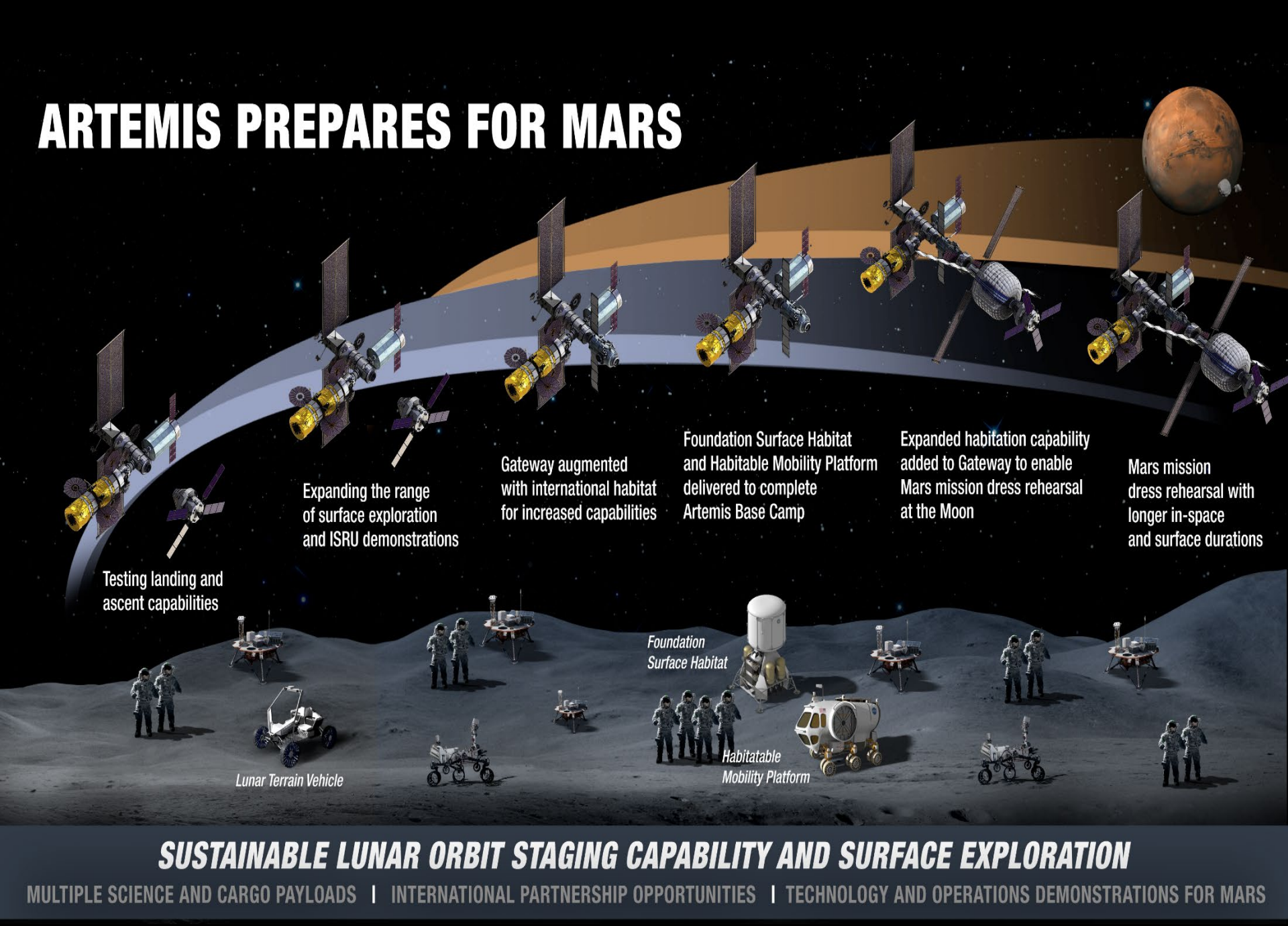
Critical Stages in Human Prenatal Development and Risk of Fetal Abnormalities



https://www.flickr.com/photos/11304375@N07/7178272407

The Moon:
The First Extraterrestrial Location for Human Planetary Exploration

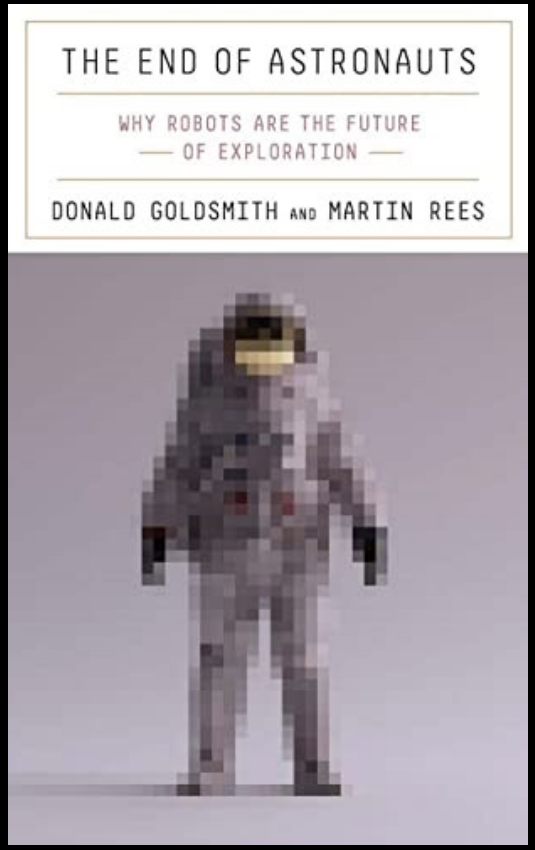
- first or last?
- insurmountable barriers for onward travel?
  - sustainable habitats
  - health, reproduction, genetic modification



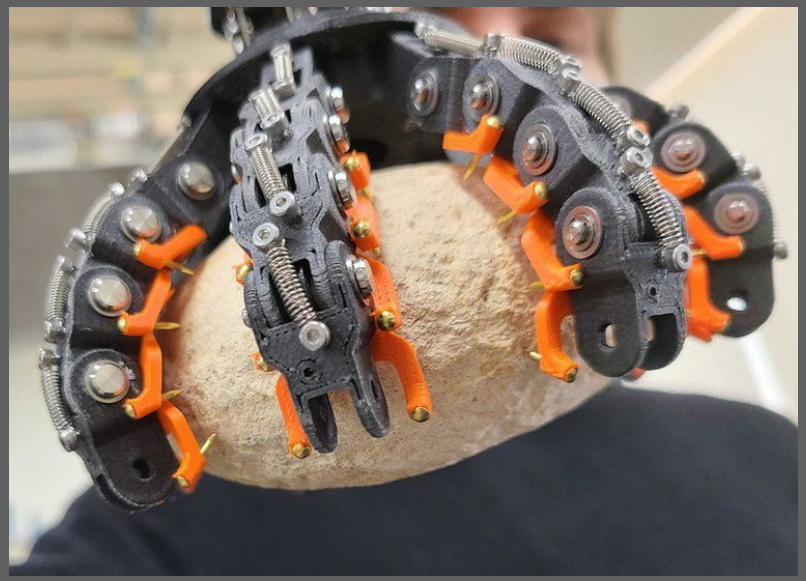
https://www.orbital-velocity.com/news/nasa-details-how-artemis-missions-prepare-us-for-mars

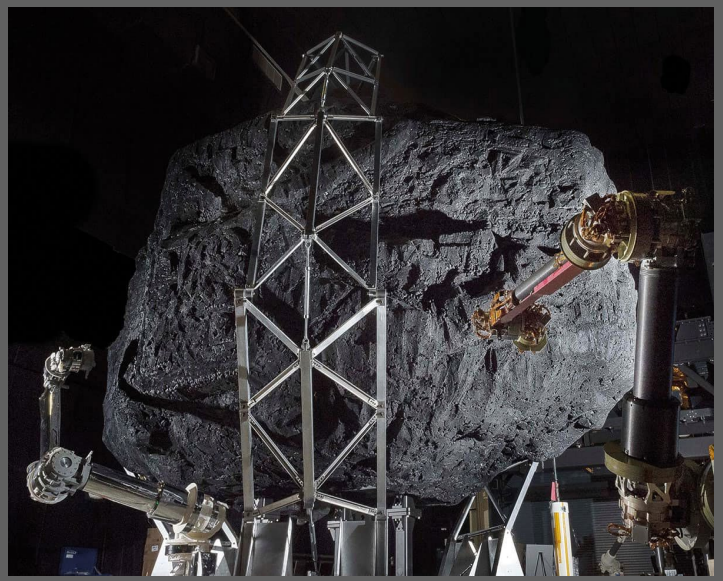
Why Humans?

- technology advances in robotics, autonomous systems and AI will outperform humans and dramatically expand the repertoire of machine-based capabilities to benefit humans on-earth



Robots and Asteroid Mining

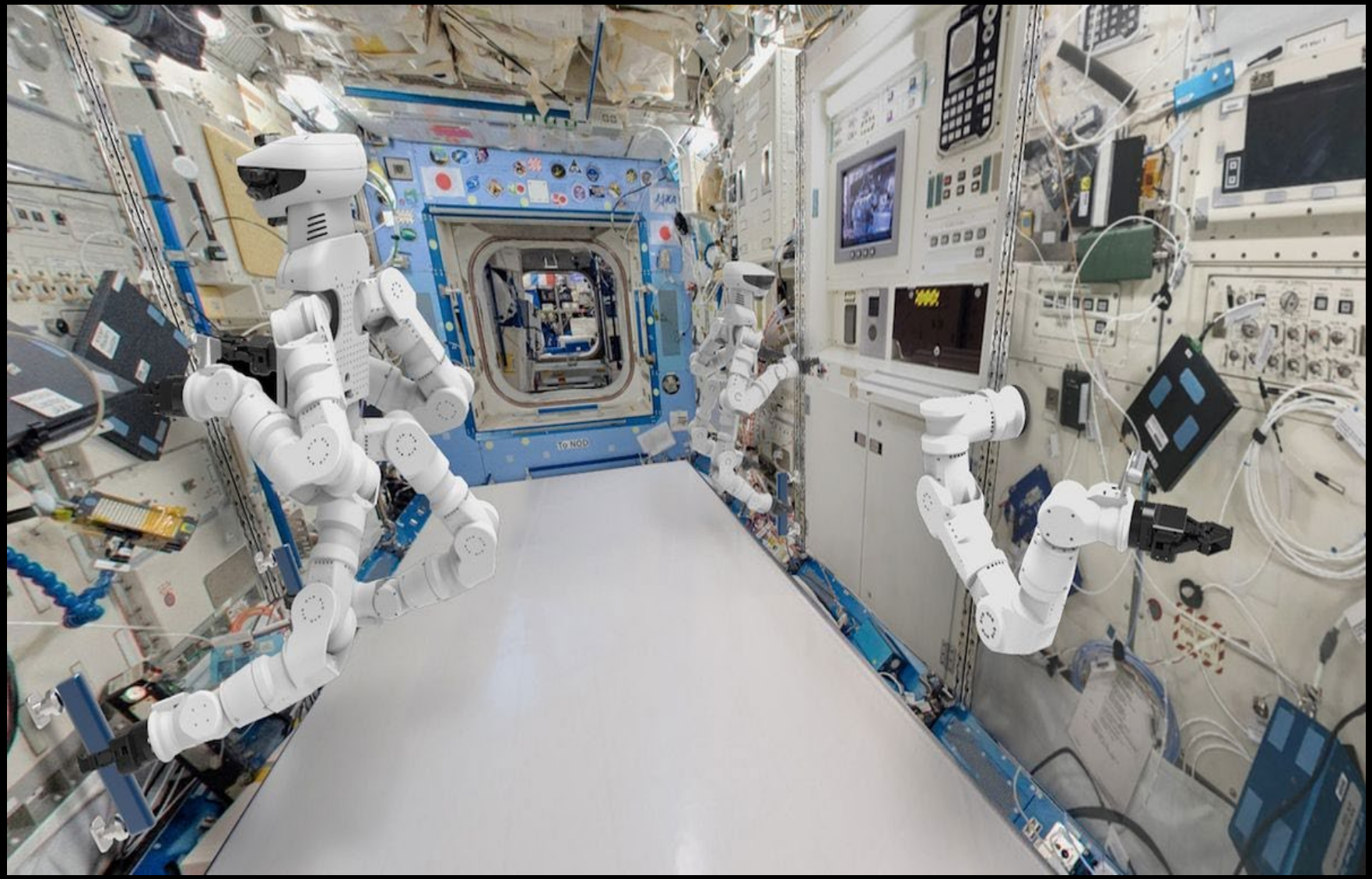




Mining the Moon

- reserves of rare-earth metals, titanium and aluminum
- helium-3 and making nuclear fusion a reality
  - on earth only 0.0001 percent of helium (99% as the isotope helium-4)
  - estimated one ton of helium 3 is equivalent to 50 million barrels of crude oil
- water
  - polar zones and freezing caverns of ice crystals
  - as source of hydrogen and oxygen for rocket fuel and habitation

Next Generation In-Craft Robots



https://www.engineering.com/story/gitai-aims-to-bring-autonomous-robot-workers-to-space

“To confine our attention to terrestrial matters would be to limit the human spirit.”

Stephen Hawking
University of Cambridge

“Curiosity is the essence of human existence.”

Gene Cernan
US Astronaut


Slides Available @
https://casi.asu.edu/presentations