Human Health and Performance for a Mission to Mars: How NASA Does It How NASA Should Do It

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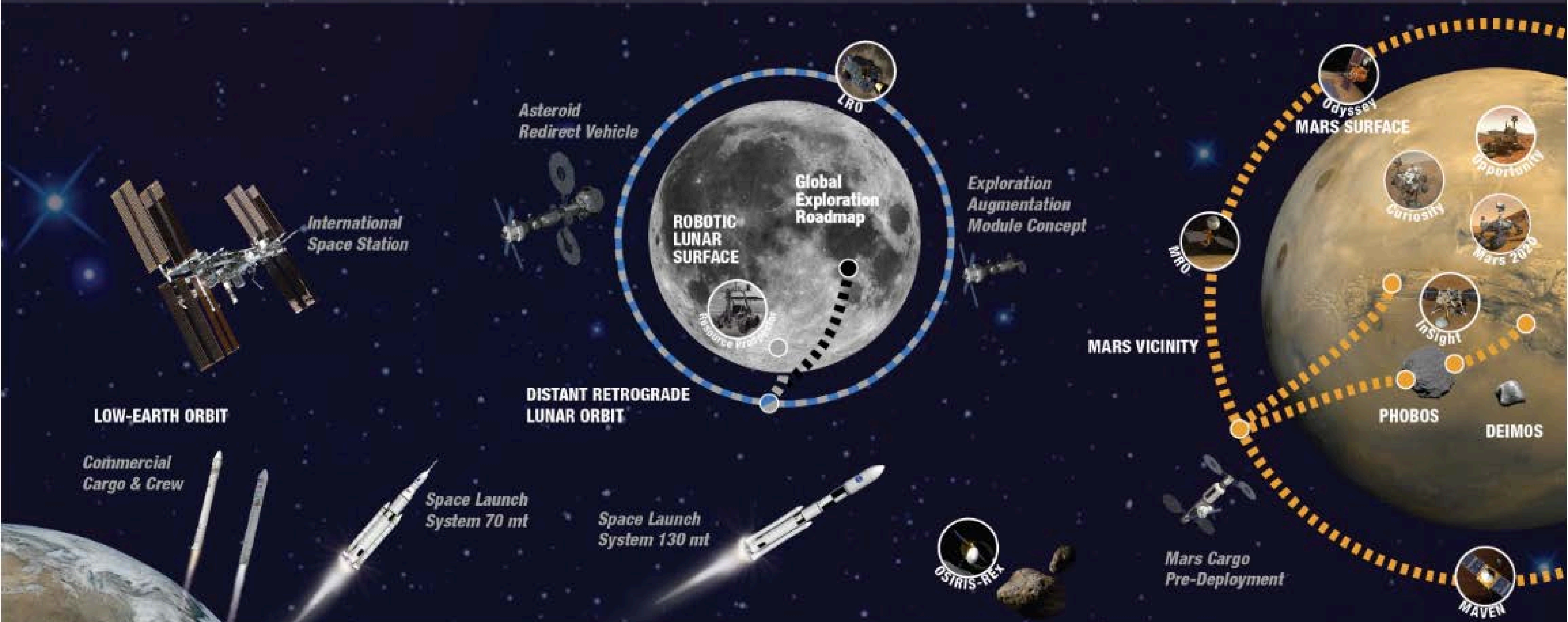
I. NASA & HRP overview

EVOLVABLE MARS CAMPAIGN

A Pioneering Approach to Exploration

EARTH RELIANT | **PROVING GROUND** | **EARTH INDEPENDENT**



THE TRADE SPACE

Across the Board | Solar Electric Propulsion • In-Situ Resource Utilization (ISRU) • Robotic Precursors • Human/Robotic Interactions • Partnership Coordination • Exploration and Science Activities

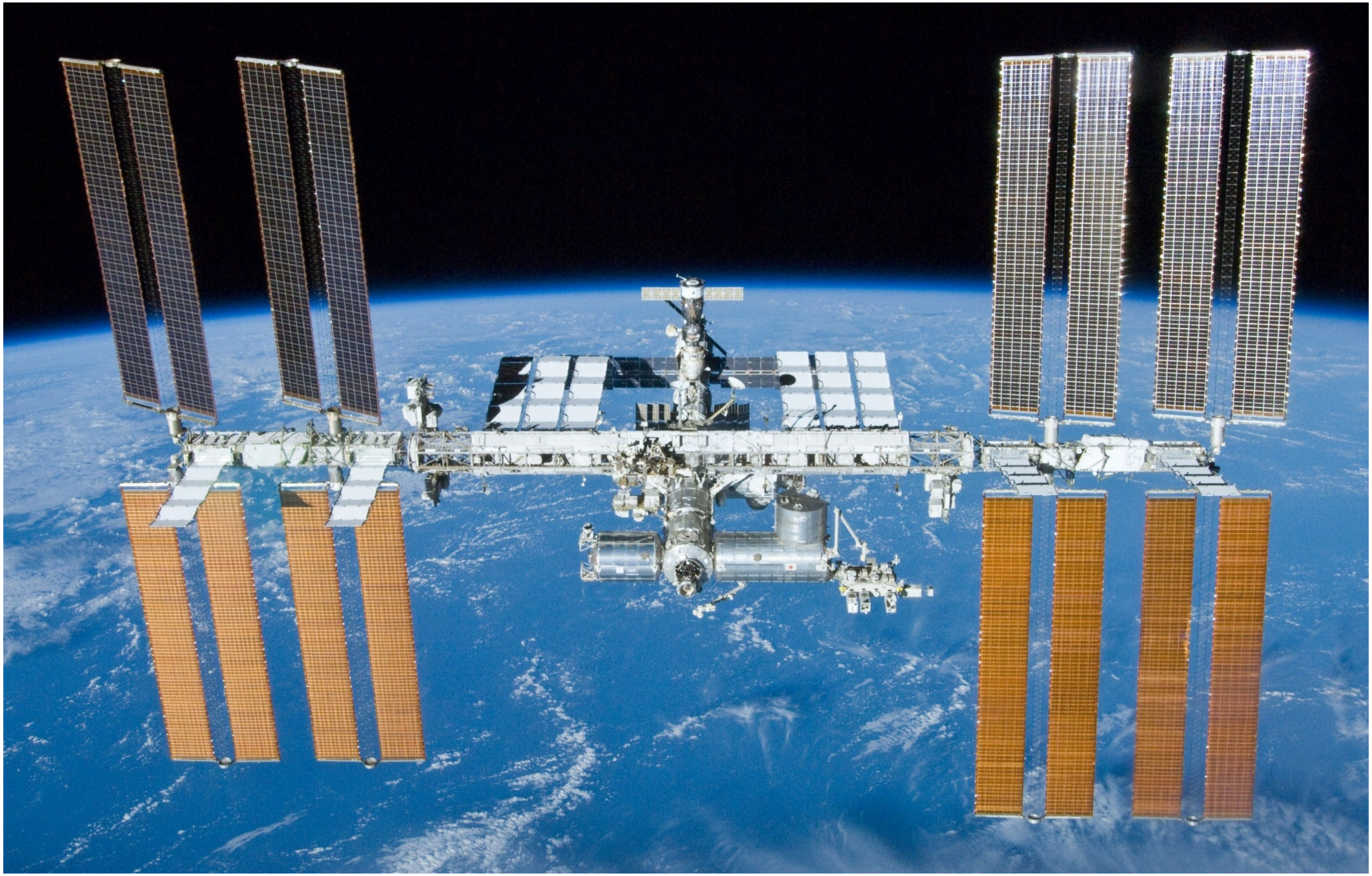
Cis-lunar Trades

- Deep-space testing and autonomous operations
- Extensibility to Mars
- Mars system staging/refurbishment point and trajectory analyses

Mars Vicinity Trades

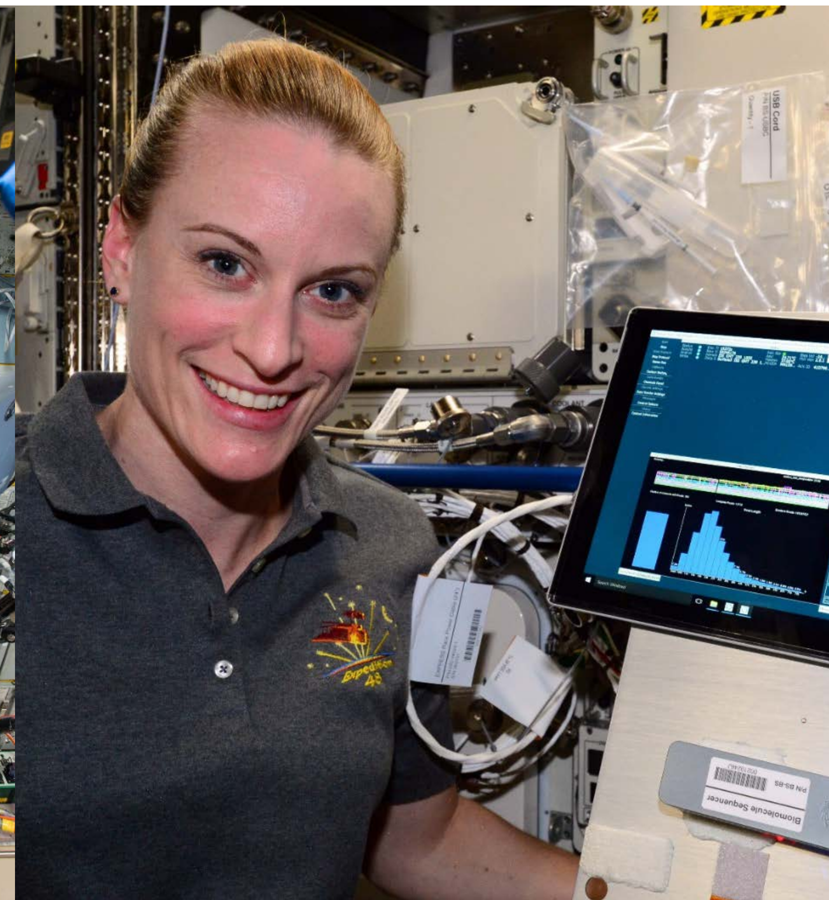
- Split versus monolithic habitat
- Cargo pre-deployment
- Mars Phobos/Deimos activities
- Entry descent and landing concepts
- Transportation technologies/trajectory analyses

ISS is a Test Bed



Human Experiments

Human Experiments



Health and Performance Risks by Hazard

Altered Gravity

1. Spaceflight-Induced Intracranial Hypertension / Vision Alterations
2. Renal Stone Formation
3. Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Space Flight
4. Bone Fracture due to spaceflight Induced changes to bone
5. Impaired Performance Due to Reduced Muscle Mass, Strength & Endurance
6. Reduced Physical Performance Capabilities Due to Reduced Aerobic Capacity
7. Adverse Health Effects Due to Host-Microorganism Interactions
8. Urinary Retention*
9. Orthostatic Intolerance During Re-Exposure to Gravity*

Concerns

1. Concern of Clinically Relevant Unpredicted Effects of Medication
2. Concern of Intervertebral Disc Damage upon and immediately after re-exposure to Gravity

Radiation

1. Risk of Space Radiation Exposure on Human Health

Distance from Earth

1. Adverse Health Outcomes & Decrements in Performance due to inflight Medical Conditions
2. Ineffective or Toxic Medications due to Long Term Storage

Isolation & Confinement

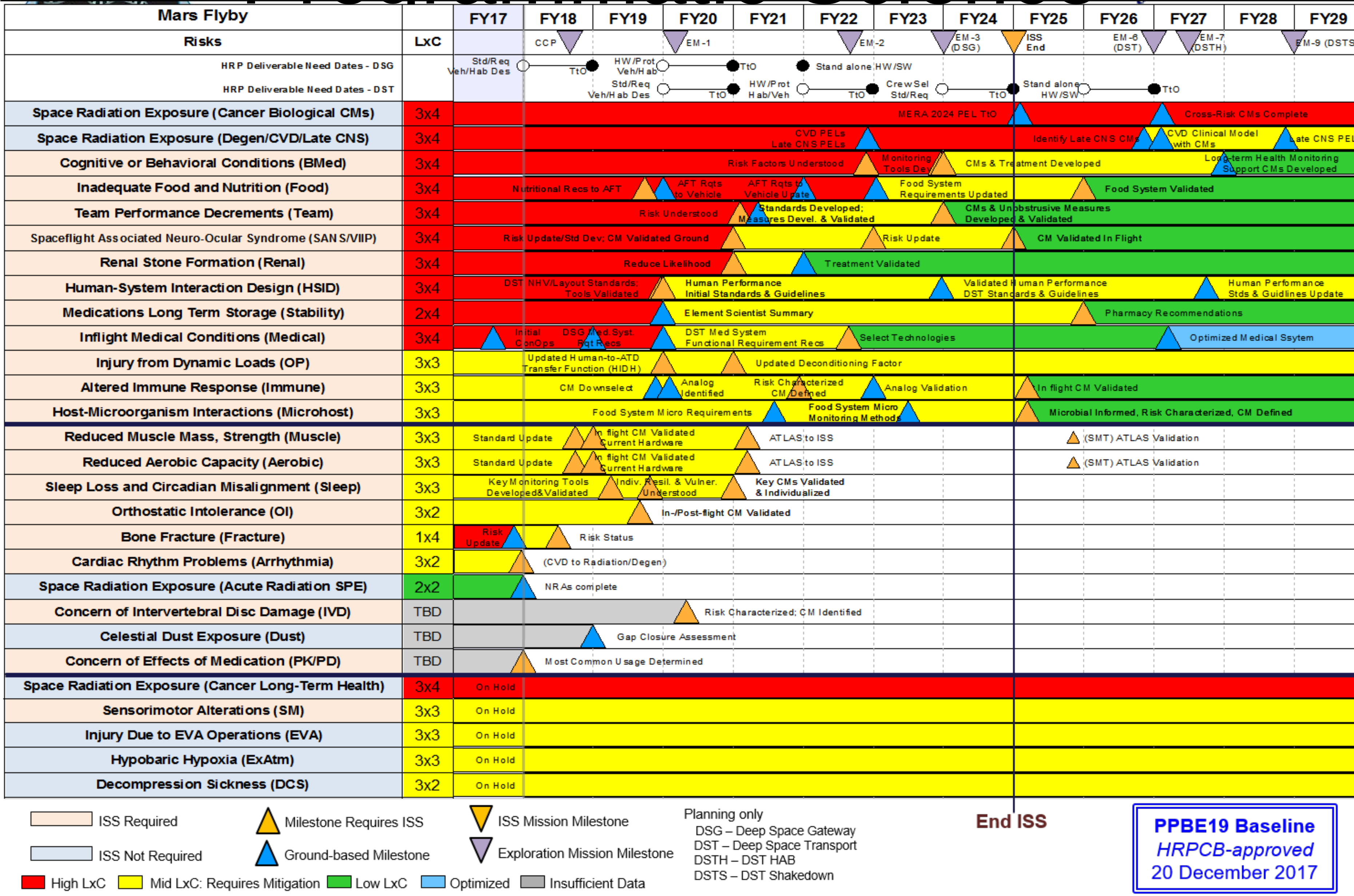
1. Adverse Cognitive or Behavioral Conditions & Psychiatric Disorders
2. Performance & Behavioral health Decrements Due to Inadequate Cooperation, Coordination, Communication, & Psychosocial Adaptation within a Team

Hostile & Closed Environment

1. Acute and Chronic Carbon Dioxide Exposure
2. Performance decrement and crew illness due to inadequate food and nutrition
3. Injury from Dynamic Loads
4. Injury and Compromised Performance due to EVA Operations
5. Adverse Health & Performance Effects of Celestial Dust Exposure
6. Adverse Health Event Due to Altered Immune Response
7. Reduced Crew Performance Due to Hypobaric Hypoxia
8. Performance Decrements & Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, & Work Overload
9. Reduced Crew Performance Due to Inadequate Human-System Interaction Design
10. Decompression Sickness
11. Toxic Exposure*
12. Hearing Loss Related to Spaceflight*

HRP Integrated Path to Risk Reduction

PPBE19 Baseline

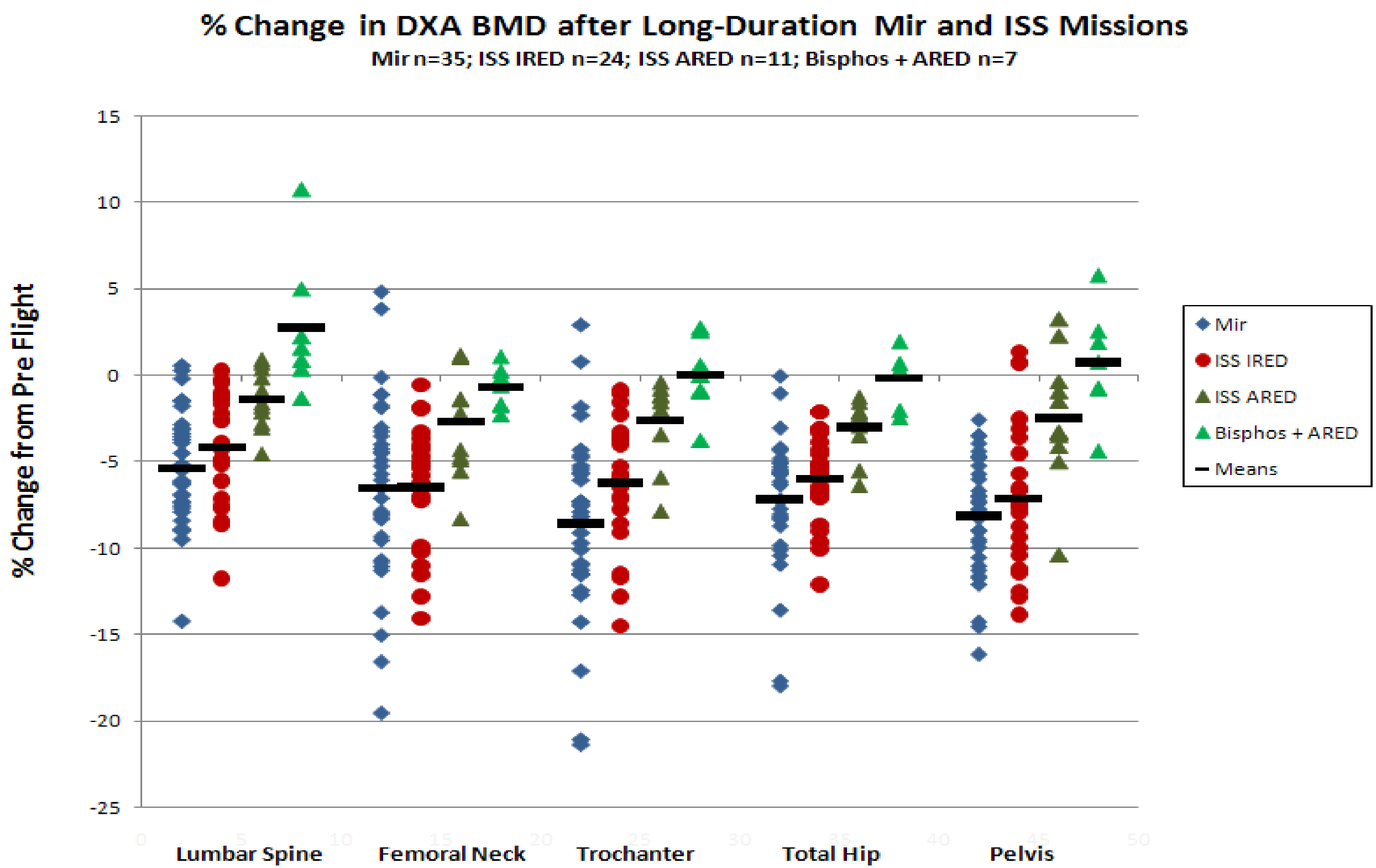


PPBE19 Baseline
HRPCB-approved
20 December 2017

II. Science issues in detail

The Problem

Bone Density Changes



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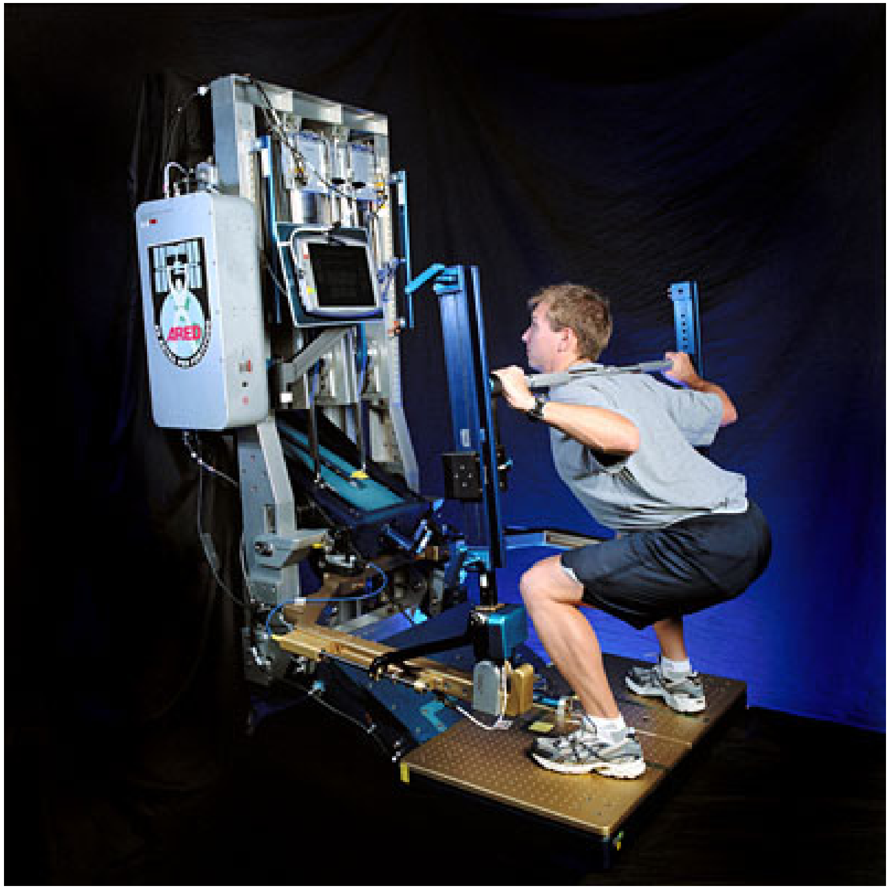
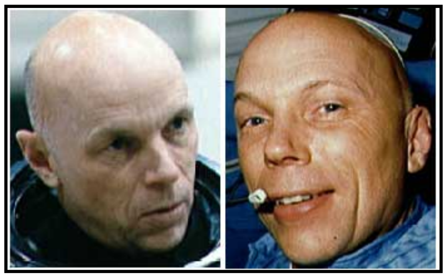


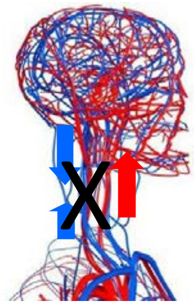
Effective but too big to take to Mars

ISS Locomotion Pre/Post

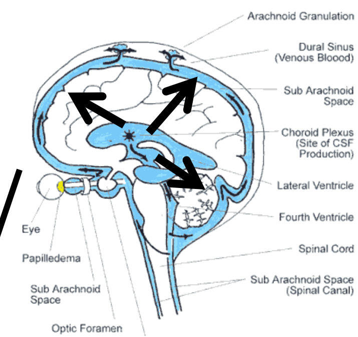
Visual Impairment / Intracranial Pressure

1. Headward fluid shift

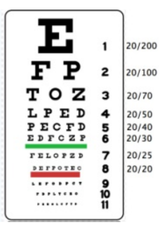




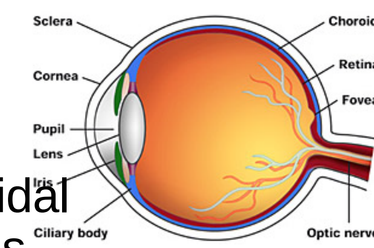
2. Increased ICP



3. Elevated ICP transmitted to eye and optic nerve

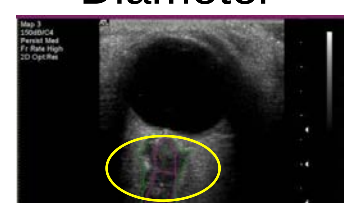


Hyperopic Shifts



+ICP

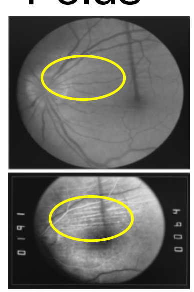
Increased Optic Nerve Sheath Diameter



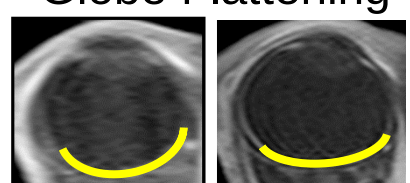
Altered Blood Flow

Scotoma

Choroidal Folds



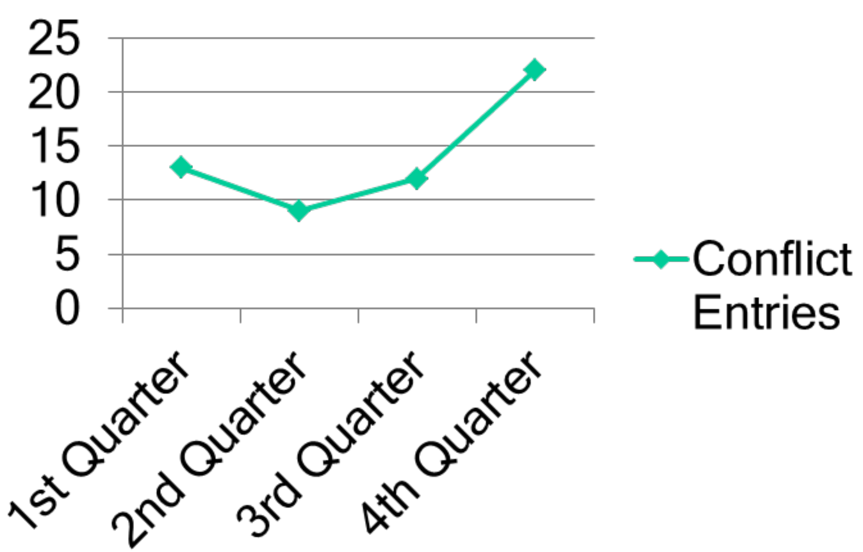
Globe Flattening

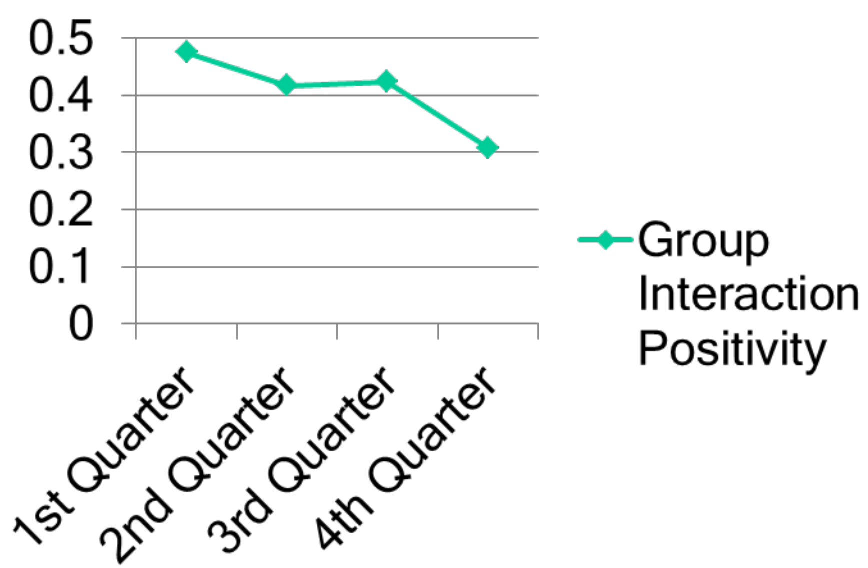


Optic Disc Edema

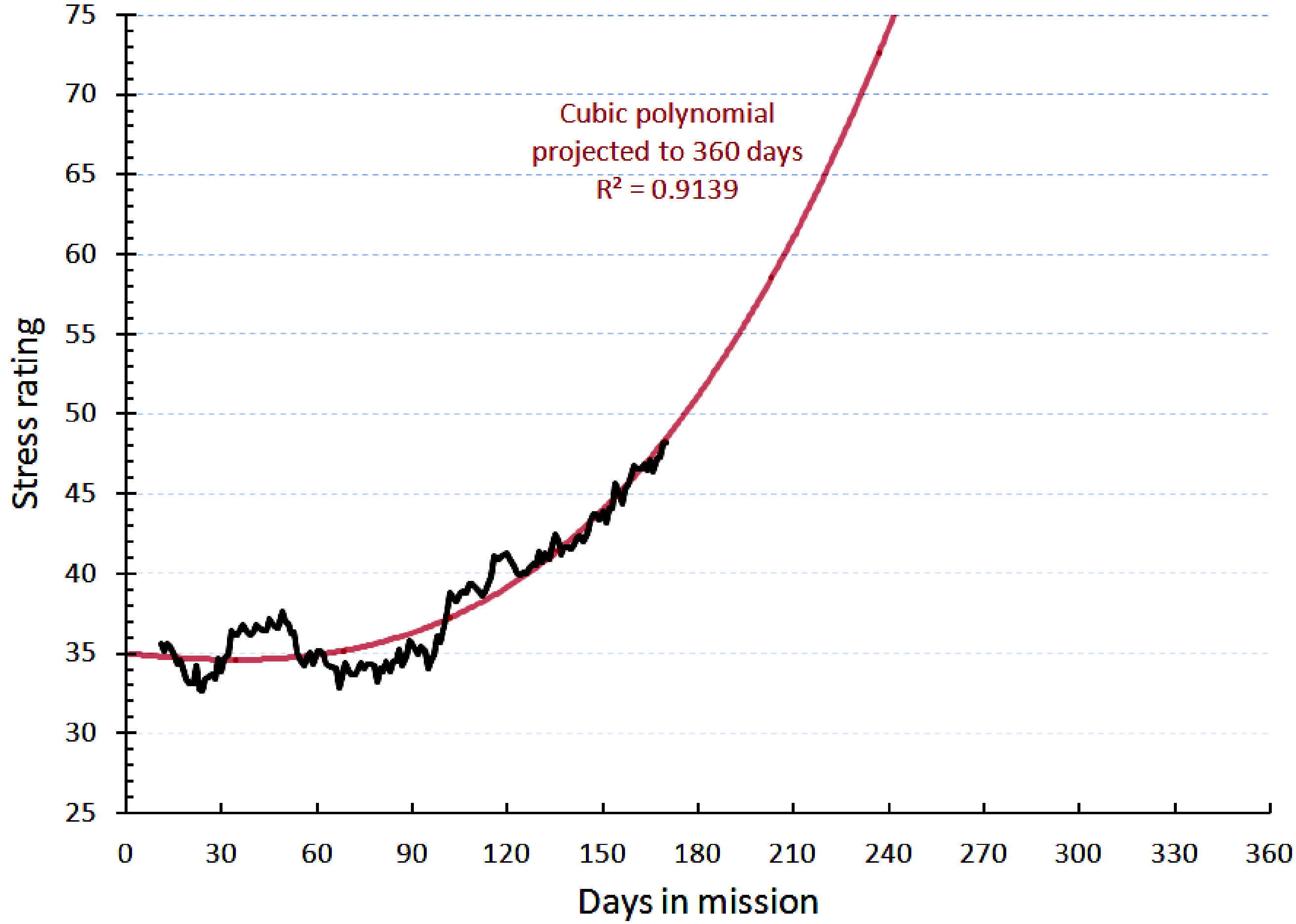
Interpersonal Conflicts

- ISS Journal entries on conflict by mission quarter
- ISS Group Interaction Positivity Ratings by mission quarter (244 entries)





VAS Stress Rating



Even if stress is compensated and does not affect overt performance, it may produce adverse physiological changes (cardiac & immune).

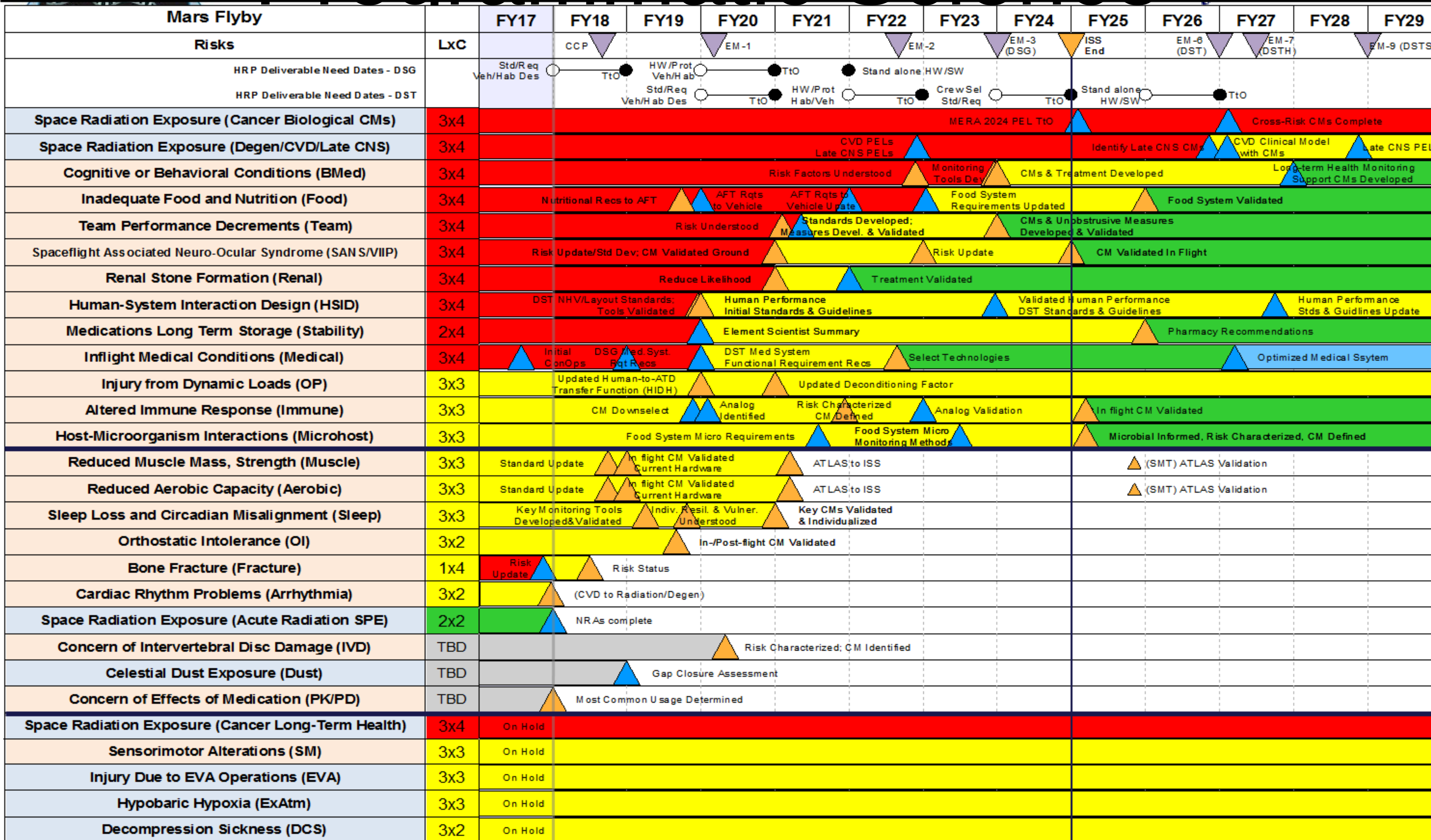
Human Exploration Research Analog
HERA

- Analog for isolation, confinement and remoteness

✓ Behavioral health and performance assessments
✓ Communication and autonomy
✓ Human factors evaluations
✓ Medical capabilities assessments and operations

HRP Integrated Path to Risk Reduction

PPBE19 Baseline



ISS Required

ISS Not Required

Milestone Requires ISS

Ground-based Milestone

ISS Mission Milestone

Exploration Mission Milestone

High LxC | Mid LxC: Requires Mitigation | Low LxC | Optimized | Insufficient Data

Planning only
- DSG – Deep Space Gateway
- DST – Deep Space Transport
- DSTH – DST HAB
- DSTS – DST Shakedown

PPBE19 Baseline
HRPCB-approved
20 December 2017

But…

- There are shortcomings to the conventional <u>segregated</u> approach
  - The subsystems *interact* with each other
  - The body subsystems *interact* with other mission factors
  - *Interactions* can lead to resilience or its lack
- Biggest risk: the one we haven't thought of
  - Likely will be related to unanticipated *interaction*
  - How to address this? (not done well…)

III. Integration

Space Flight Effects on Human Body

- Most systems affected
  - Sensorimotor, Cardiovascular, Muscle, Bone, Immune
- Different time courses and magnitudes
- Consequences for health *and* performance (physical *and* behavioral)
- Responses commonly explored individually
- Systems interact in ways we do not yet understand

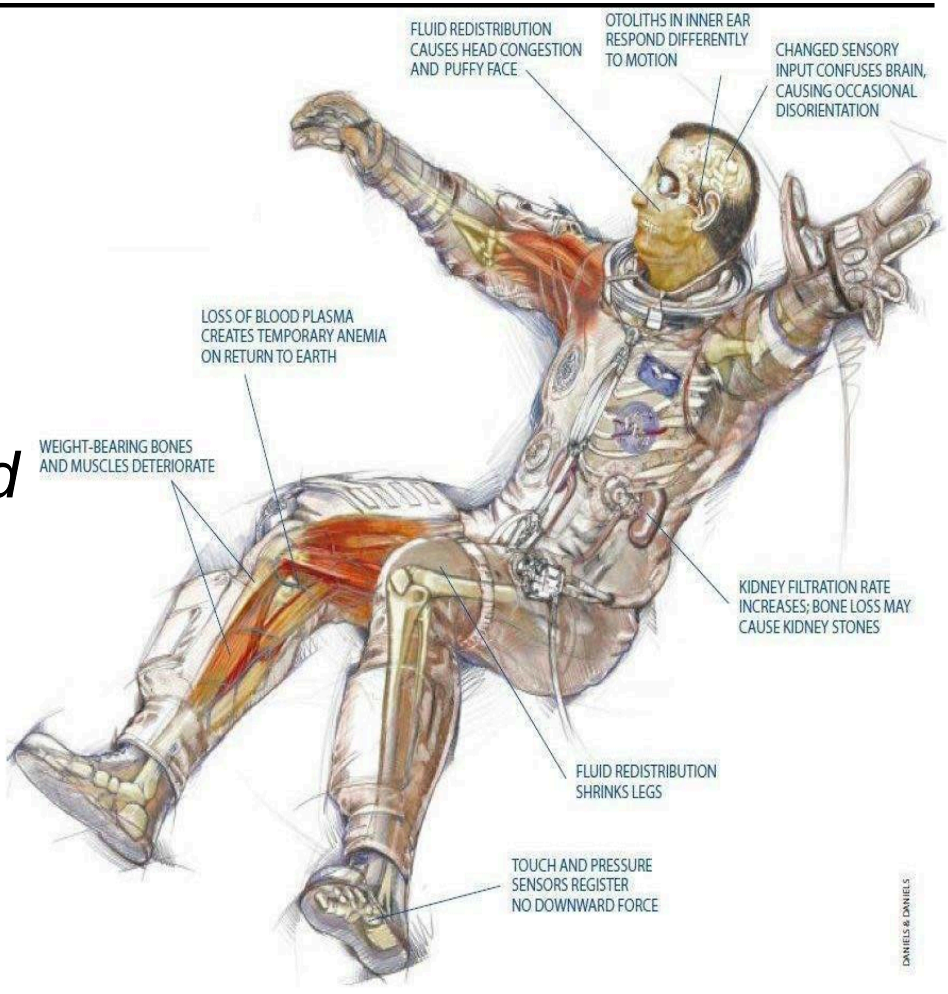


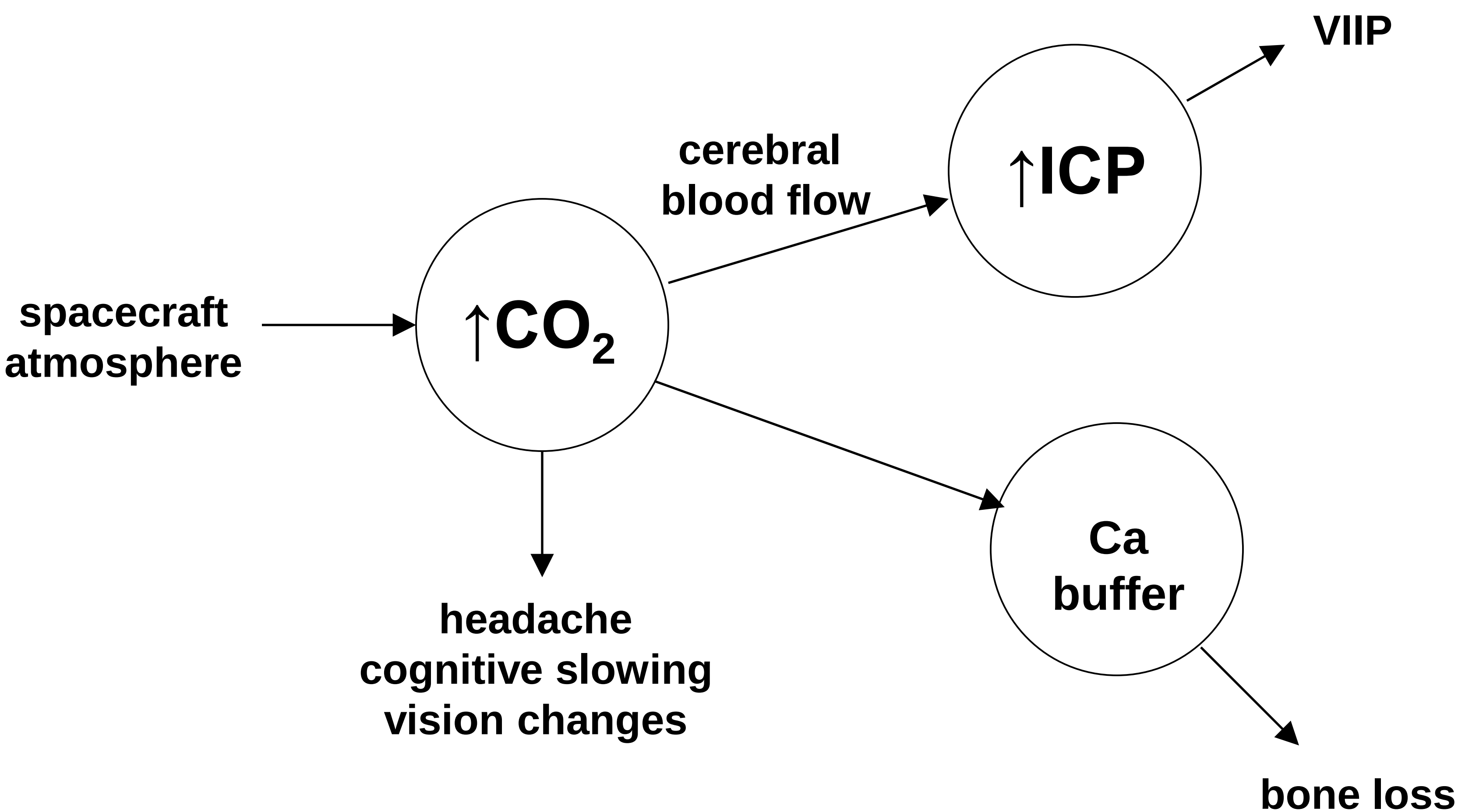
Image from: http://zerog2002.de/bodyreactions.html

Need an Integrated Approach

Meeting the health-related challenges of human space exploration requires that one abandon any model of the human body that has the muscles, bones, heart and brain acting independently. Body parts will not travel on exploration missions. Instead, the individual space traveler's body must be viewed realistically, with all parts connected and fully interacting.

White & Averner (2001) Humans in space. *Nature* 409:1115-1118.

Interaction Example: Spacecraft CO_2 Level



Systematic Approach

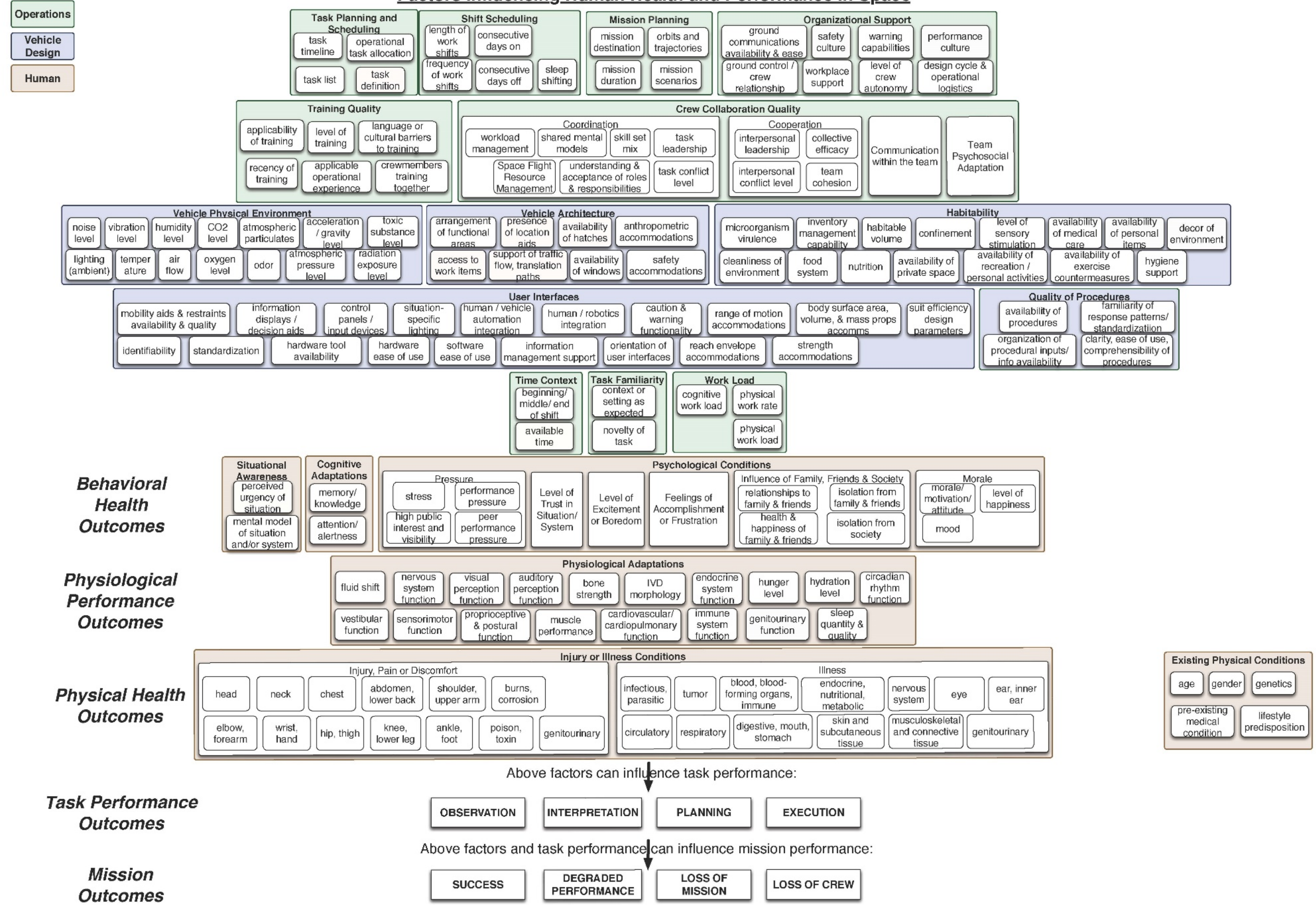
- Need framework to systematically identify interactions
  - Include multiple levels
    - Physiology, Psychology, Behavior, Performance
    - Mission control and planning
    - Vehicle and habitat
  - Prioritize based on connectivity

- Unexpected events when mission duration increases
  - Could tracking of interactions have predicted visual impairment?
  - What is next??!!

Contributing Factor Map

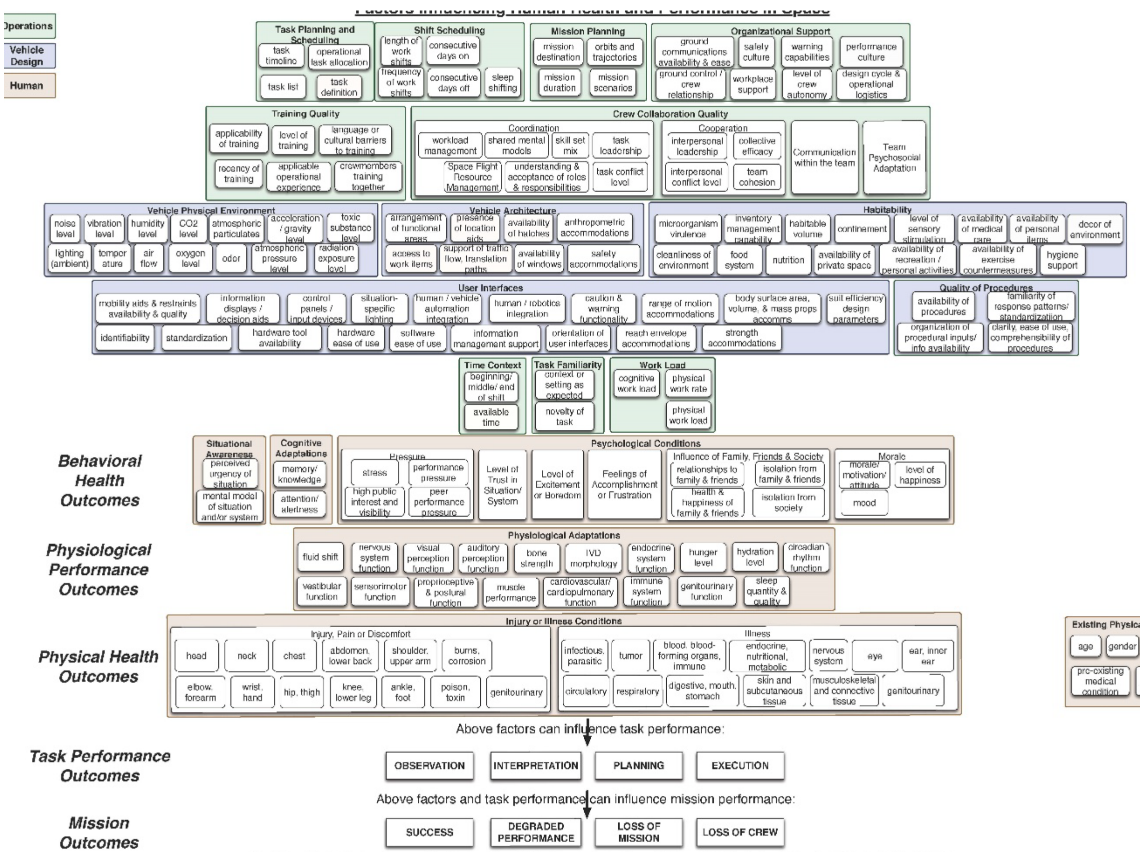
Factors Influencing Human Health and Performance in Space

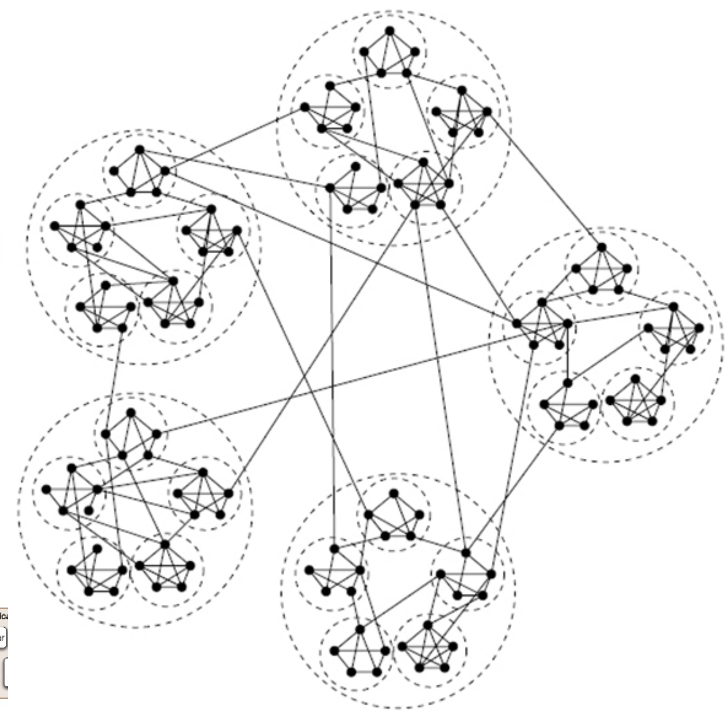
9/5/13



Adapted from Mindock, J., *Development and Application of Spaceflight Performance Shaping Factors for Human Reliability Analysis.* University of Colorado, Boulder, CO, 2012.

It’s a Network

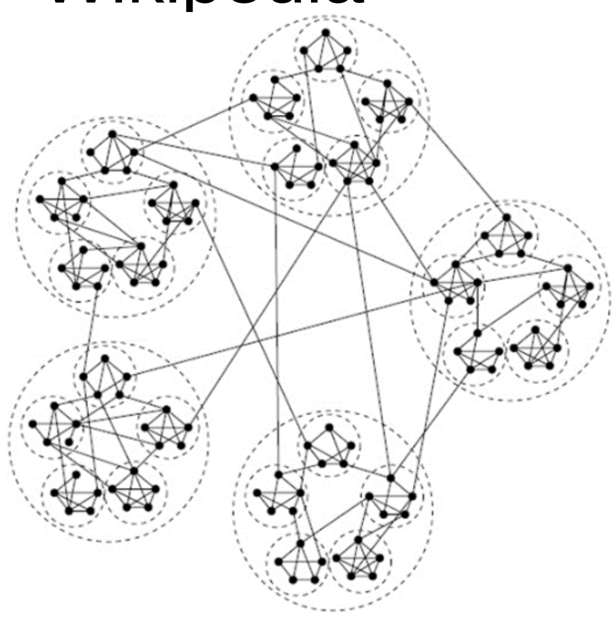




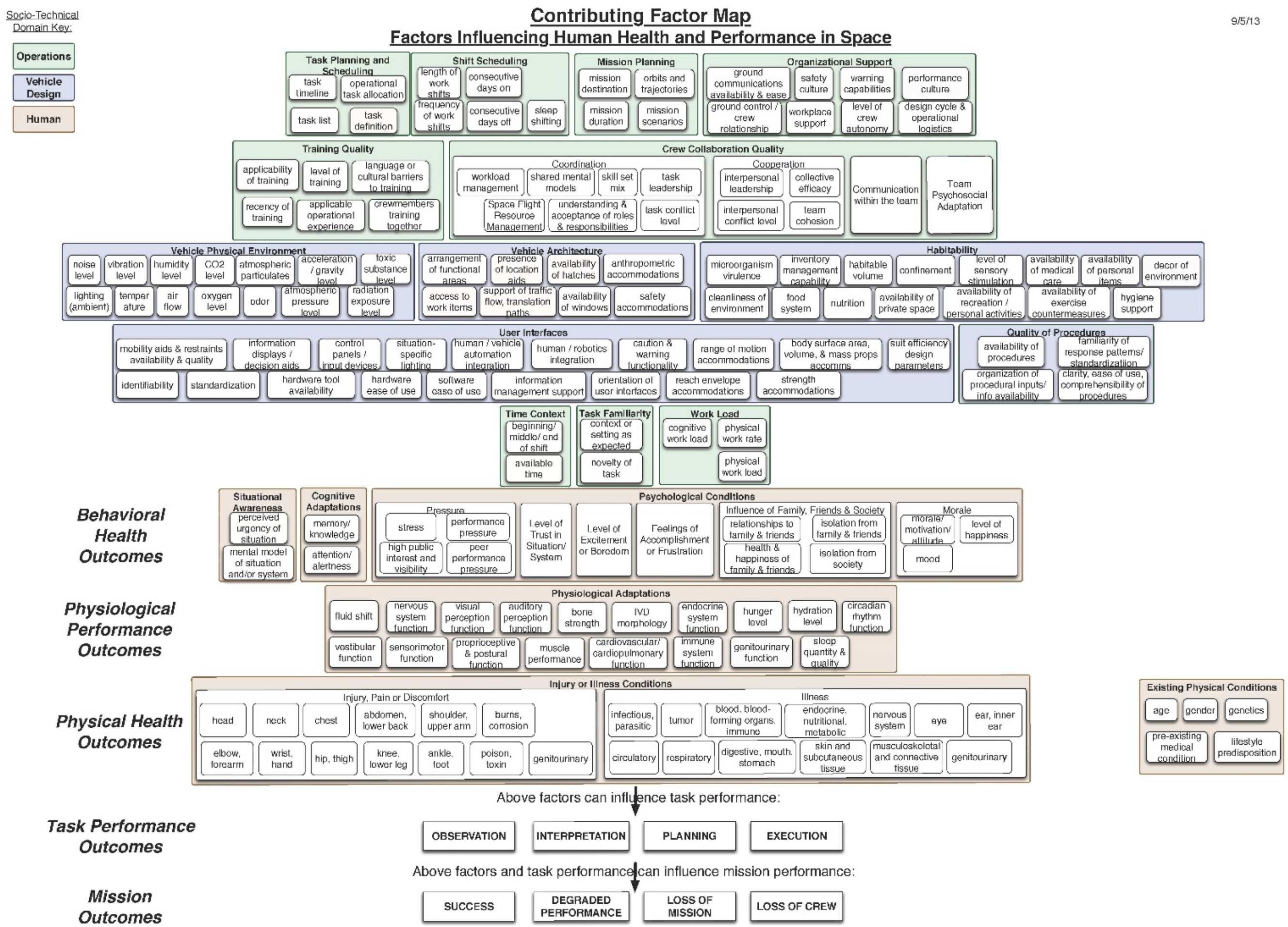
IV. Digression on Complex Networks

SWN

- “A **small-world network** is a type of mathematical graph in which most nodes are not neighbors of one another, but the neighbors of any given node are likely to be neighbors of each other and most nodes can be reached from every other node by a **small** number of hops or steps.” – Wikipedia
  - Watts DJ, Strogatz SH (1998) Collective dynamics of ‘small-world’ networks. Nature 393:440-2.
  - >30,000 citations



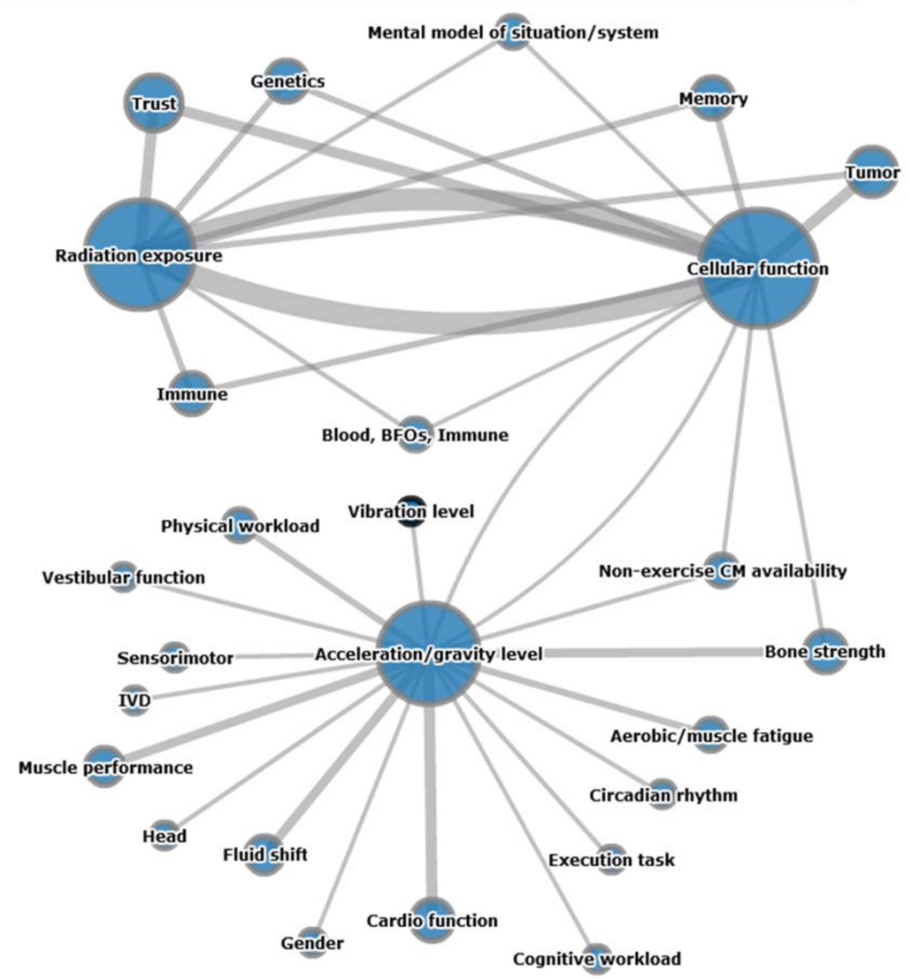
Populating the Nodes



Adapted from Mindock, J., *Development and Application of Spaceflight Performance Shaping Factors for Human Reliability Analysis.* University of Colorado, Boulder, CO. 2012.

Populating the Links

Visualize links between topics covered by NASA Human Research Program based on publication records



Network Approach

- Explicit recognition of interconnectedness
  - Lacking in biomedical research
  - Need to span domains
- Can draw on results from network theory and complexity
- Networks have **emergent properties**
  - Hopelessness of understanding details
  - Common features regardless of details

Resilience Functions

LETTER

doi:10.1038/nature16948

Universal resilience patterns in complex networks

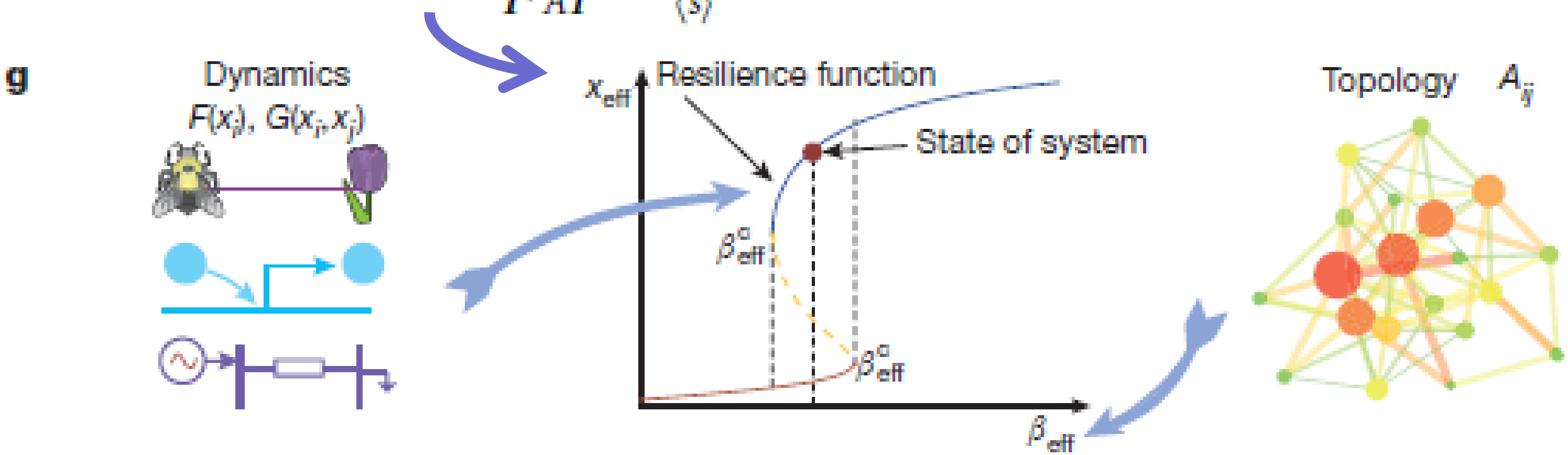
Jianxi Gao[1]*, Baruch Barzel[2]* & Albert-László Barabási[1,3,4,5]

Resilience Functions

Consider a system consisting of N components (nodes) whose activities $\boldsymbol{x} = (x_1, \ldots, x_N)^\top$ follow the coupled nonlinear equations[12,13]

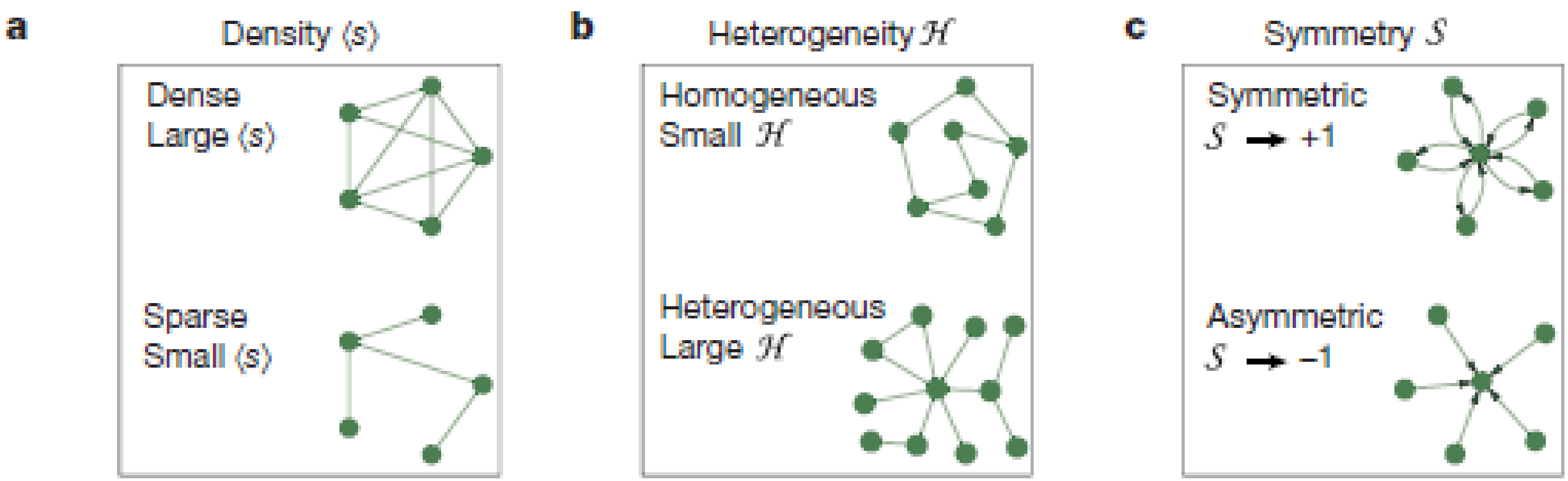
$$\frac{\mathrm{d}x_i}{\mathrm{d}t} = F(x_i) + \sum_{j=1}^{N} A_{ij} G(x_i, x_j) \quad (4)$$

$$x_{\mathrm{eff}} = \frac{\boldsymbol{1}^\top A \boldsymbol{x}}{\boldsymbol{1}^\top A \boldsymbol{1}} = \frac{\langle s^{\mathrm{out}} x \rangle}{\langle s \rangle}$$



Resilience Functions

$$\beta_{\mathrm{eff}} = \langle s \rangle + \mathcal{S}\mathcal{H}$$



Connectivity (topology) determines resilience

Density

Heterogeneity

Symmetry

Resilience Functions

- Function depends on dynamics not topology
- Location along the resilience function depends on topology
- Some networks are more resilient than others
  - depends on Density, Heterogeneity, Symmetry
- Resilience function
  - effective state as function of effective topology
- Can have critical points and bifurcations to undesired states
- Establish resilience – stay away from a bad critical point
- But how to define desired and undesired effective states?

HUMAN RESEARCH PROGRAM

Controllability

JOHNS HOPKINS MEDICINE
SCHOOL OF MEDICINE

ARTICLE

doi:10.1038/nature10011

Controllability of complex networks

Yang-Yu Liu[1,2], Jean-Jacques Slotine[3,4] & Albert-László Barabási[1,2,5]

- Controllability = ability to steer system to desired states
- Depends on topology not dynamics
  - Degree distribution: number of incoming and outgoing links per node

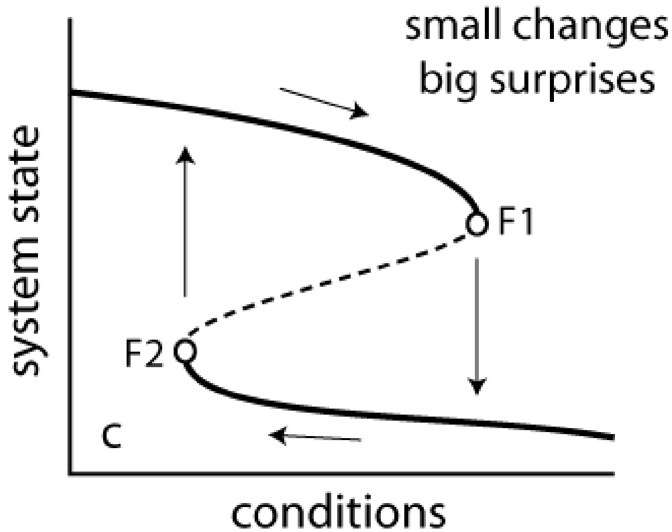
Early Warning

Vol 461|3 September 2009|doi:10.1038/nature08227 nature

Early-warning signals for critical transitions

Marten Scheffer[1], Jordi Bascompte[2], William A. Brock[3], Victor Brovkin[5], Stephen R. Carpenter[4], Vasilis Dakos[1], Hermann Held[6], Egbert H. van Nes[1], Max Rietkerk[7] & George Sugihara[8]

Complex dynamical systems, ranging from ecosystems to financial markets and the climate, can have tipping points at which a sudden shift to a contrasting dynamical regime may occur. Although predicting such critical points before they are reached is extremely difficult, work in different scientific fields is now suggesting the existence of generic early-warning signals that may indicate for a wide class of systems if a critical threshold is approaching.



Critical Transitions

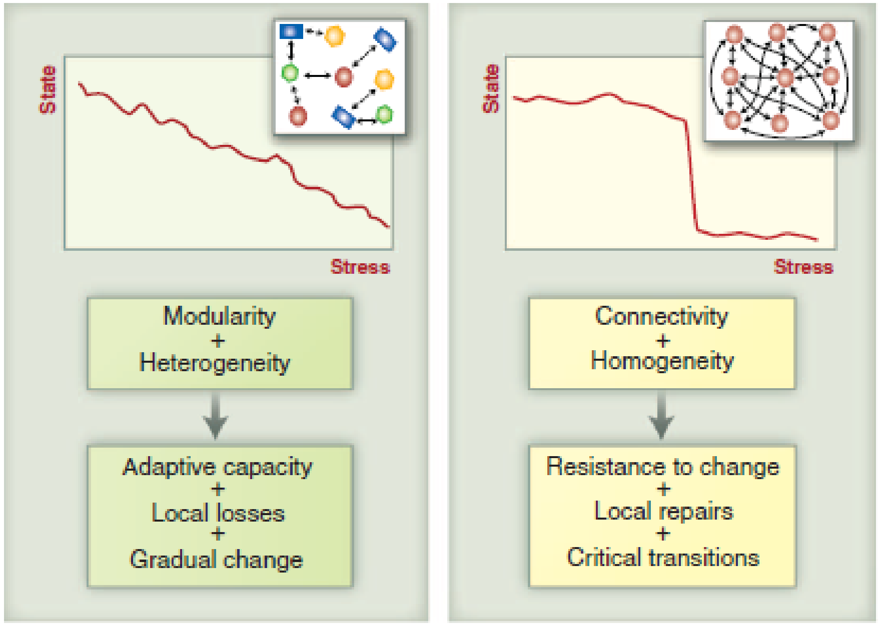


Fig. 1. The connectivity and homogeneity of the units affect the way in which distributed systems with local alternative states respond to changing conditions. Networks in which the components differ (are heterogeneous) and where incomplete connectivity causes modularity tend to have adaptive capacity in that they adjust gradually to change. By contrast, in highly connected networks, local losses tend to be "repaired" by subsidiary inputs from linked units until at a critical stress level the system collapses. The particular structure of connections also has important consequences for the robustness of networks, depending on the kind of interactions between the nodes of the network.

Critical Transitions

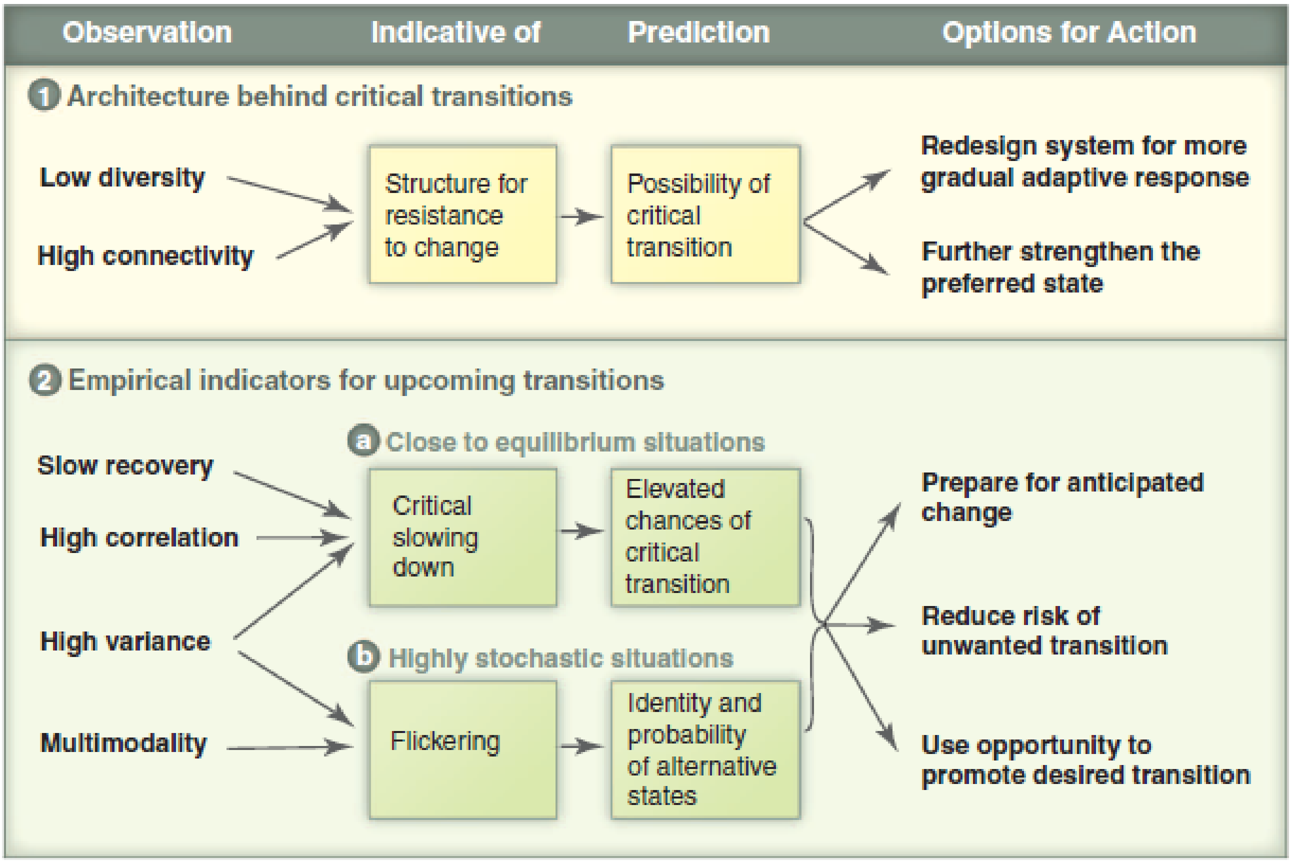


Fig. 4. Different classes of generic observations that can be used to indicate the potential for critical transitions in a complex system.

Early Warning

- Dynamics and imminent breakdown
  - Latent indicators of impending failure
- Critical slowing near transition
  - slower recovery from perturbation
- Increased correlations
  - slowed dynamics, increased memory
- Increased variance
- Use perturbations (natural and artificial) as probes
  - monitor recovery time

Network Approach

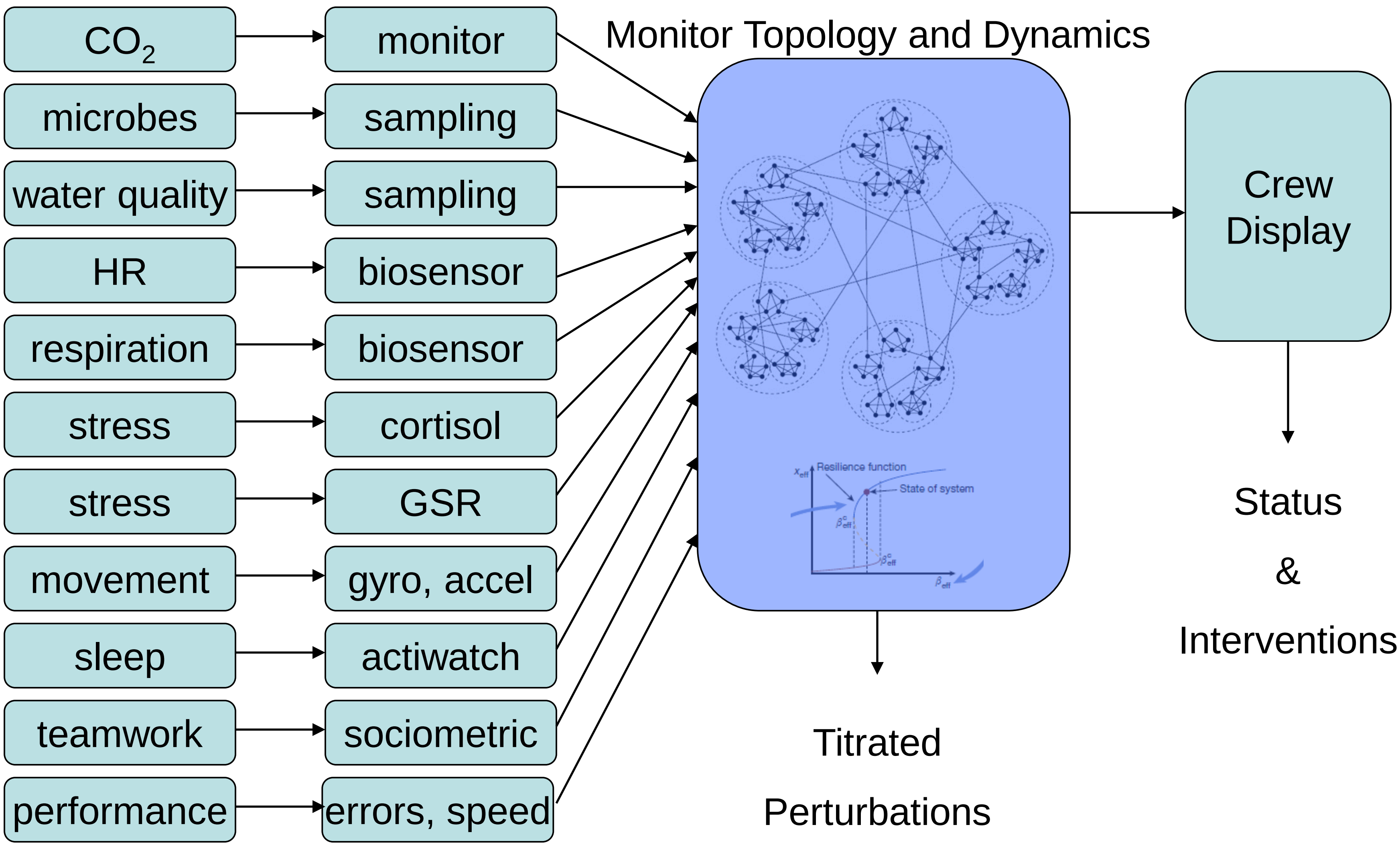
- Explicit recognition of interconnectedness
  - Lacking in biomedical research
  - Need to span domains
- Can draw on results from network theory and complexity
- Networks have **emergent properties**
  - Hopelessness of understanding details
  - Common features regardless of details

V. Back to Space

Human Spaceflight as a Complex System

- Many interacting parts
  - Factors from CFM
  - System of human/vehicle/ops
- Emergent behavior
  - Unanticipated problems (and solutions)
- Resilience/adaptation capabilities
  - Resilience to physiological assaults
  - Resilience of team to operational stressors
- Self-organizing
  - Autonomy from Earth

The Grand Plan
(subset)



Applications

- Spaceflight mission architecture
- Design guidelines
  - Density, Heterogeneity, Symmetry
- Real-time inflight monitoring and intervention
- Identification of cross-disciplinary research opportunities

Advantages

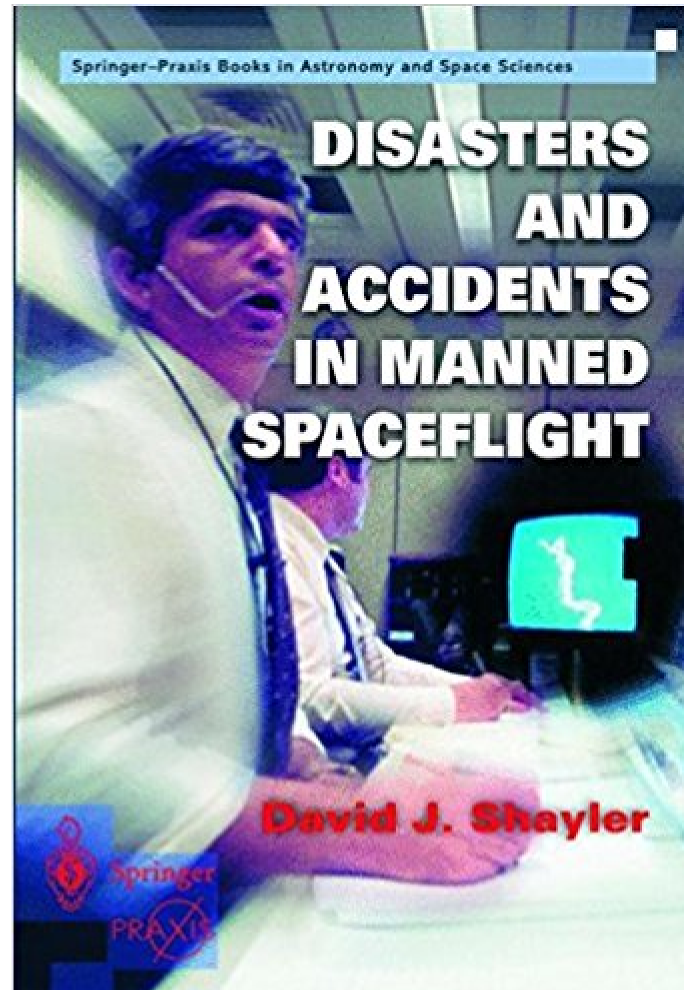
- Autonomy
- Resilience
- Tools to deal with the unexpected
- Detect and intervene before problems become overt
- Possible to control overall system with incomplete knowledge of components

Problems

- Crew acceptability
  - Big Brother
  - Unexpected automation
- How to distinguish undesired changes in state from desired changes due to adaptation?

Case Study

- David J. Shayler
- *Disasters and accidents in manned spaceflight*
- Springer Science & Business Media
- pp 309-342



MIR/Progress Collision

MIR/Progress Collision Contributing Factors I

Precipitating events

- Previous onboard fire
  - flight engineer blamed, initially
  - pre-existing stress from fire
- Later re-use of oxygen candles due to failure of oxygen separator
  - CO_2 scrubber failure and backup use
  - problems with availability and reliability of spares for separator
  - incompatible connectors for gas fittings
- Failure of attitude sensor
  - gravity-gradient mode
  - power reduction
  - increase in temperature
  - reduction in exercise and use of LBNP
- Coolant leak into the module
  - flight engineer allergic eye reaction
- Toilet failure and repair
- Passageways cluttered with equipment
- Earlier failed re-docking of Progress M-33

MIR/Progress Collision Contributing Factors II

Hardware/software issues

- Restricted views from observation windows
- Commander had video image of Mir from Progress POV
- Poor Progress thruster performance

Human factors

- Foale surprised at Russian commander's initial remoteness
- High Cosmonaut workload
  - falling behind in maintenance
  - no free weekend in three months
- Crew cohesion and shared workload
  - Foale offered to do some work
    - Russian reticence to accept assistance
  - Russians shared little with American astronauts

MIR/Progress Collision Contributing Factors III

Implementation issues

- Commander showing signs of stress before docking
- Unclear instructions on what to expect from the docking initiation
- Bad visual reference and lighting on video image
- Had not practiced docking for 130 days
- Poor ground communication impaired real-time assistance

Overarching issues

- Poor information flow
  - crew-ground, crew-crew
- Crew health status
  - fatigue, pressure, workload
- Performance pressure

MIR/Progress Collision Contributing Factors IV

Trend of increasing problems

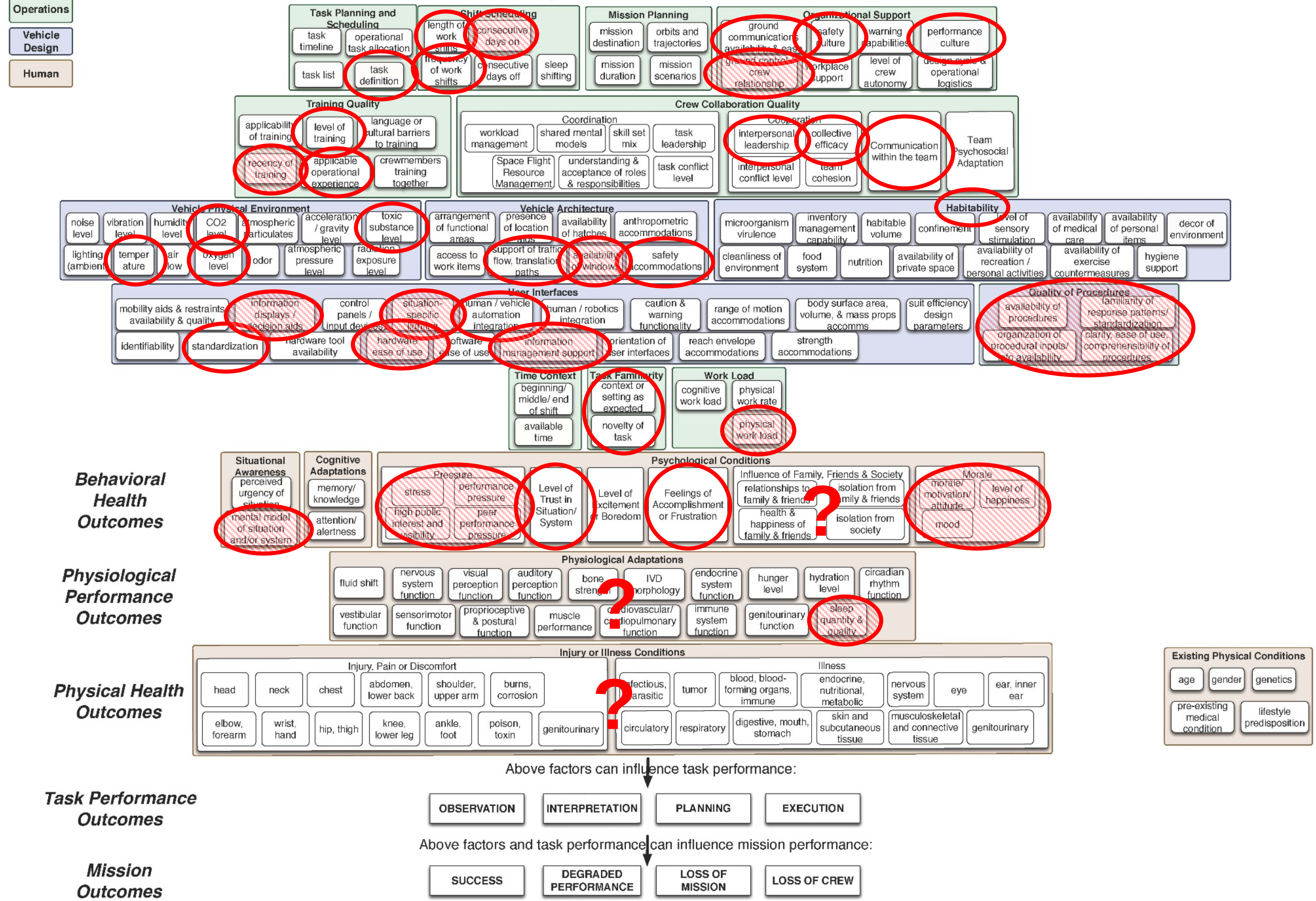
"It was not the fault of one person or element, but a combination of several actions of a variety of people and by different hardware and software." – Shayler p 339

Contributing Factor Map

Factors Influencing Human Health and Performance in Space

9/5/13

Socio-Technical Domain Key:



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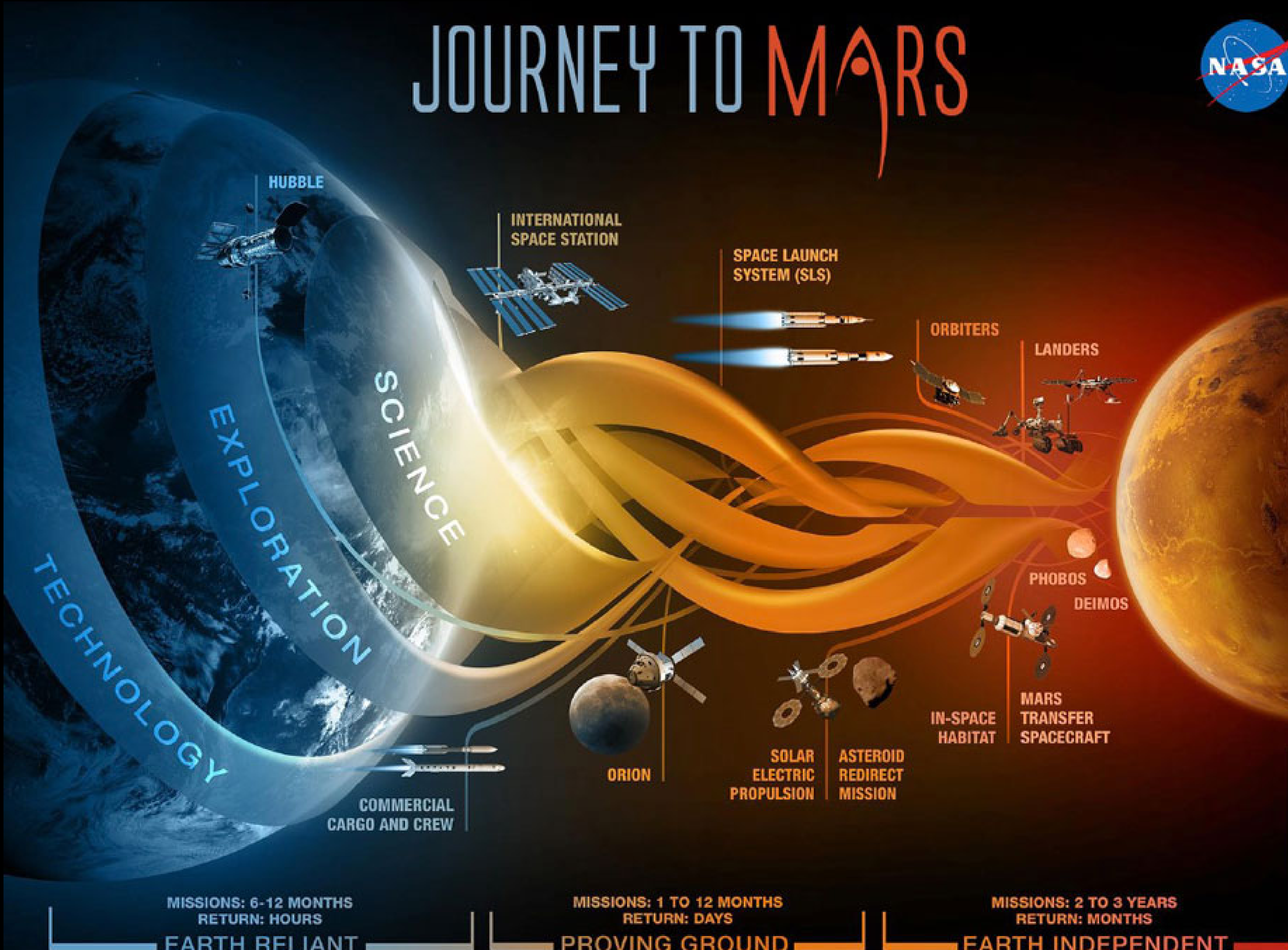
JOURNEY TO MARS
NASA
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
ORION
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
IN-SPACE HABITAT
MARS TRANSFER SPACECRAFT
COMMERCIAL CARGO AND CREW
MISSIONS: 6-12 MONTHS
RETURN: HOURS
EARTH RELIANT
MISSIONS: 1 TO 12 MONTHS
RETURN: DAYS
PROVING GROUND
MISSIONS: 2 TO 3 YEARS
RETURN: MONTHS
EARTH INDEPENDENT