International Council on Systems Engineering
A better world through a systems approach

Agile Systems Engineering of an Astronaut Digital Twin to Optimize Resiliency and Performance During Human Space Exploration

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Michael A. Schmidt, & Steve Simske

INCOSE International Symposium 2025 | Ottawa, Canada

The Difficulty of Spaceflight

Imagine a trip to Mars…

34.7 million miles

18 months in space

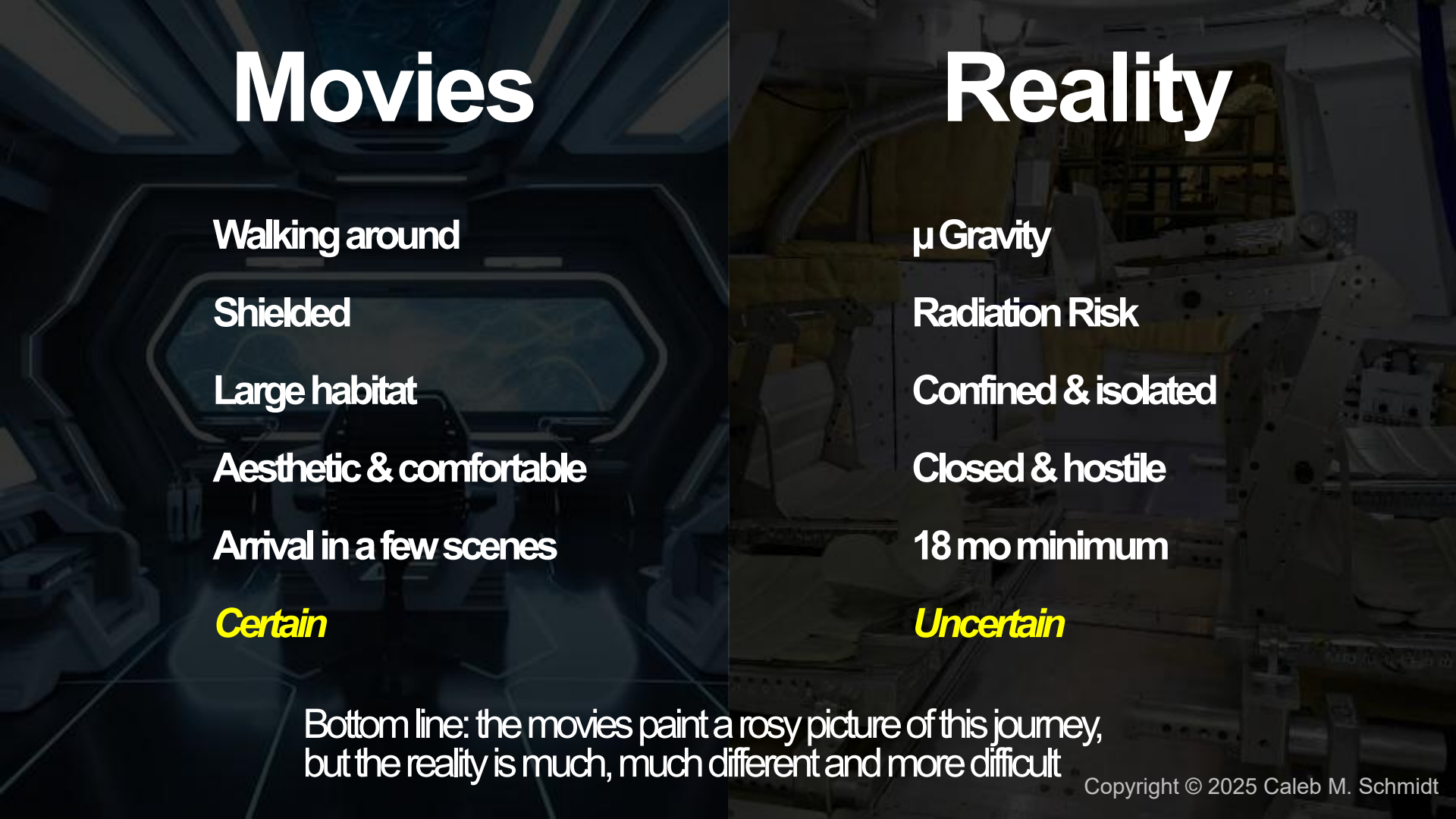
Outbound: 6 mo
Stay: 1 mo
Return: 11 mo

https://www.telegraph.co.uk/news/2017/09/21/plans-2020-chinese-mars-probe-explore-possibility-human-settlement/

Space travel in the Movies

https://www.popsci.com/peek-inside-orion-spacecraft-that-will-fly-us-to-mars/

Reality.



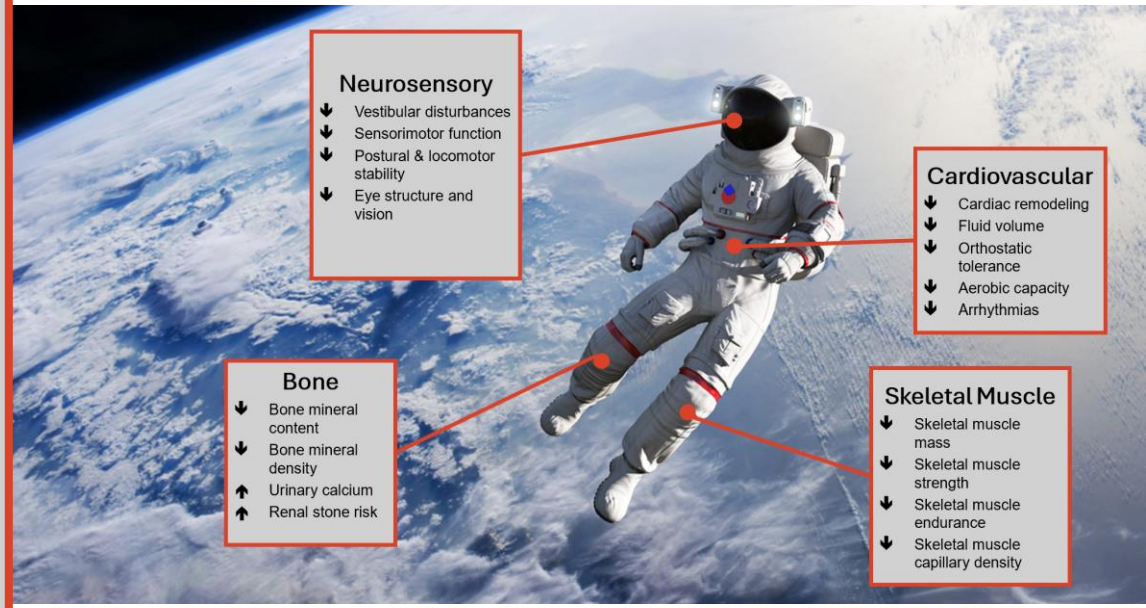
Movies	Reality
Walking around	μ Gravity
Shielded	Radiation Risk
Large habitat	Confined & isolated
Aesthetic & comfortable	Closed & hostile
Arrival in a few scenes	18 mo minimum
Certain	*Uncertain*

Bottom line: the movies paint a rosy picture of this journey,
but the reality is much, much different and more difficult

Human have evolved to exist on Earth

Spaceflight Hazards

- Altered Gravity
- Radiation
- Isolation & Confinement
- Hostile, Closed Environment
- Distance from Earth



SOURCE: NASA/TP-20220015709

Goal: Shifting the Adaptation Curve

Environmental pressures

∨

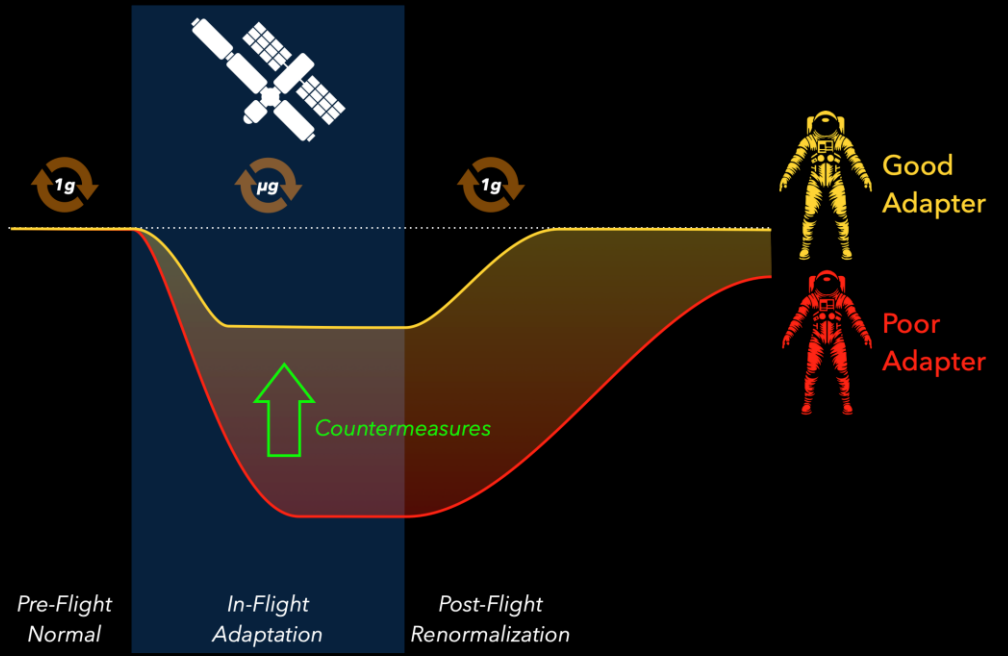
Perturbation

∨

Adaptation

∨

Individual Adaptation Variability



How can we optimize countermeasure application to turn more *poor* adapters into *good* adapters, *reliably*?

Systems Perspective

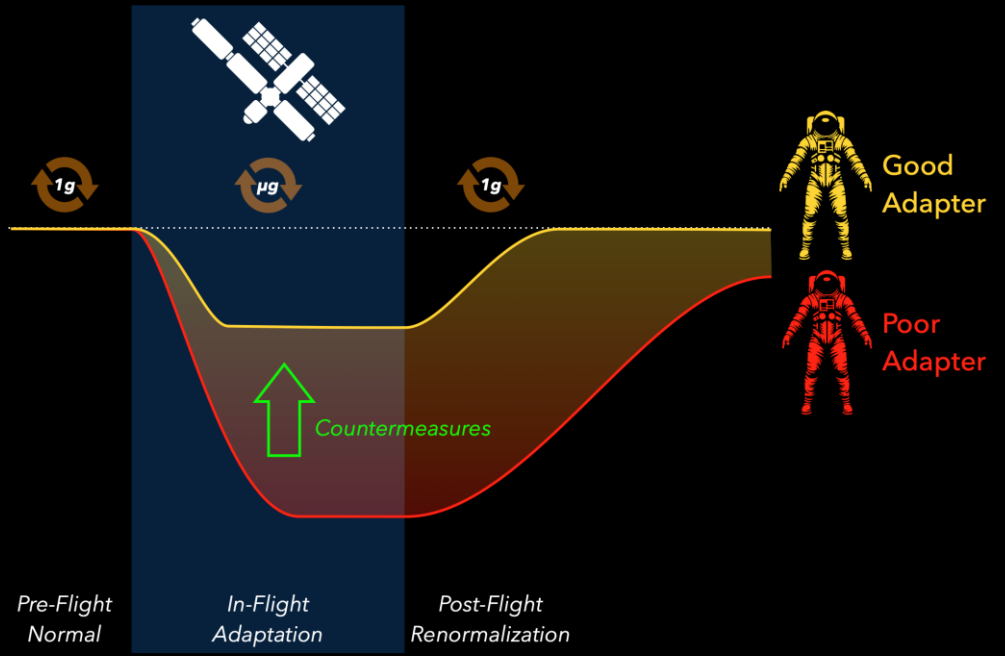
Robust (resist failure)

V

Resilient (recover from)

V

Anti-Fragile (improve after)



Anti-fragility is something beyond resiliency.
It is increased performance in the face of hazardous challenges.

Reality

Plans for this journey are happening now, and it will occur potentially much sooner that many of us realize…

So how can we be ready for human exploration of deep space and what does that entail?

https://www.telegraph.co.uk/news/2017/09/21/plans-2020-chinese-mars-probe-explore-possibility-human-settlement/

The Reality

Ground Truthing the Current State

Factors that Complicate the Problem

Requirements

Aggregated Data

Rapid Innovation

Integrated Framework

Fragmented Data: The NASA DAGs Based On Hard Data

Personal & Environmental Factors Contributing to Allostatic Load

Human System Risks - Personal

- Risk of Performance Decrement and Crew Illness Due to Inadequate Food and Nutrition (**Food and Nutrition Risk**)
- Risk of Adverse Health Event Due To Altered Immune Response (**Immune Risk**)
- Risk of Adverse Health Outcomes and Decrements in Performance Due to Medical Conditions that occur in Mission, as well as Long Term Health Outcomes Due to Mission Exposures (**Medical Risk**)
- Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders (**Behavioral Health Risk**)
- Risk of Spaceflight Associated Neuro-ocular Syndrome (**SANS Risk**)
- Risk of Musculoskeletal Injury and Loss of Function (**Musculoskeletal Risk**)
- Risk of Renal Stone Formation (**Renal Stone Risk**)
- Risk of Radiation Carcinogenesis (**Cancer Risk**)

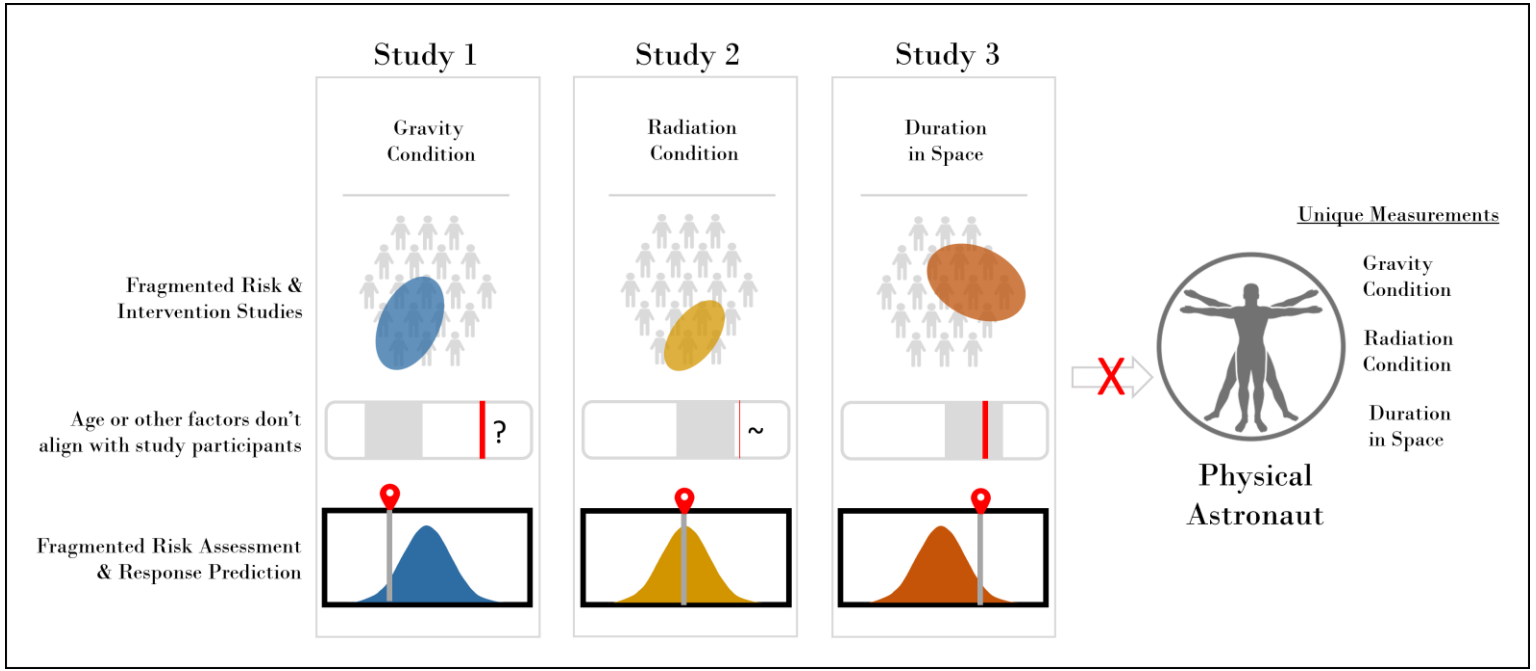
Human System Risks - Personal

- Risk of Cardiovascular Disease and Other Degenerative Tissue Effects from Radiation Exposure (**Cardiovascular Risk**)
- Risk of Acute and Late Central Nervous System Effects from Radiation Exposure (**CNS Risk**)
- Risk of Performance Decrement and Crew Illness Due to Inadequate Sleep (**Sleep Risk**)
- Risk of Adverse Health Effects Due to Altered Microbiome (**Microbiome Risk**)
- Risk of Adverse Health Effects Due to Hypobaric Hypoxia **(Hypobaric Risk**)
- Risk of Adverse Health Effects Due to Inadequate Exercise (**Exercise Risk**)

SOURCE: NASA/TP-20220015709

Fragmented Data: The Reality of the Hard Data

Good for Broad Risk Analysis, Suboptimal for Specific Risk Analysis and Prediction in the Context of Changing Conditions

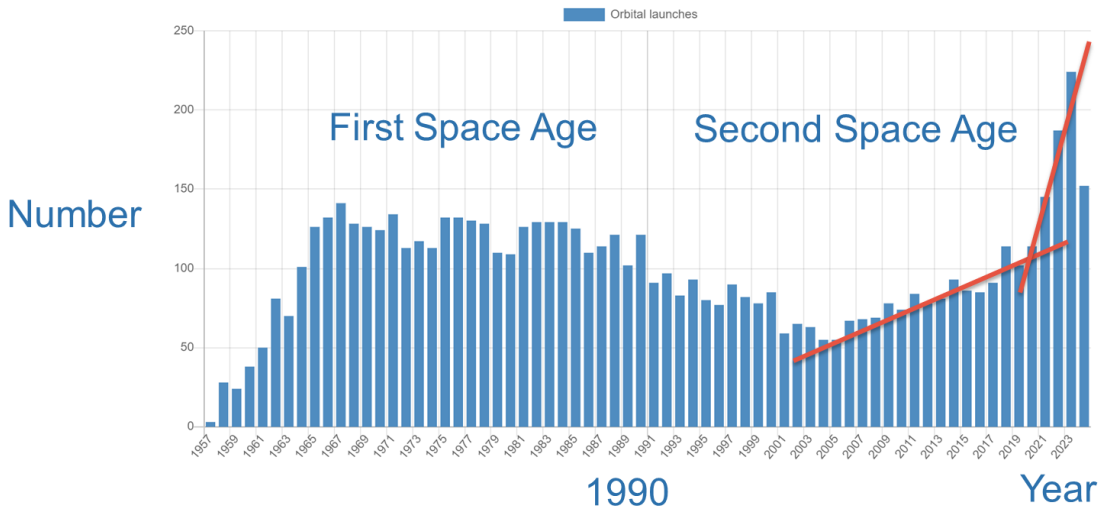


SOURCE: AstronautDigitalTwin.com

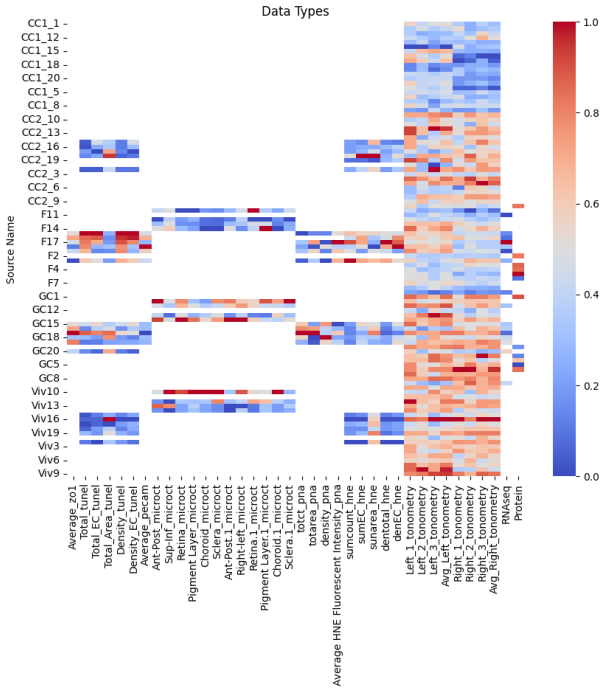
The Need for Rapid Innovation

Open Science for Life in Space

Finding and Leveraging the Right Data



SOURCE: Space Stats Online

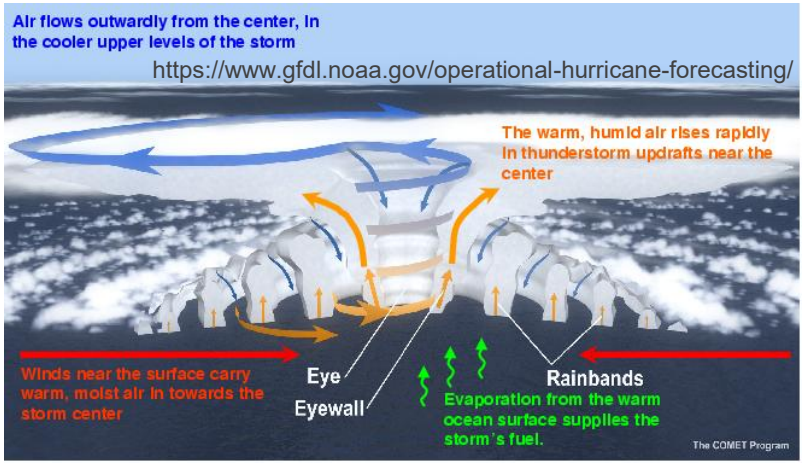


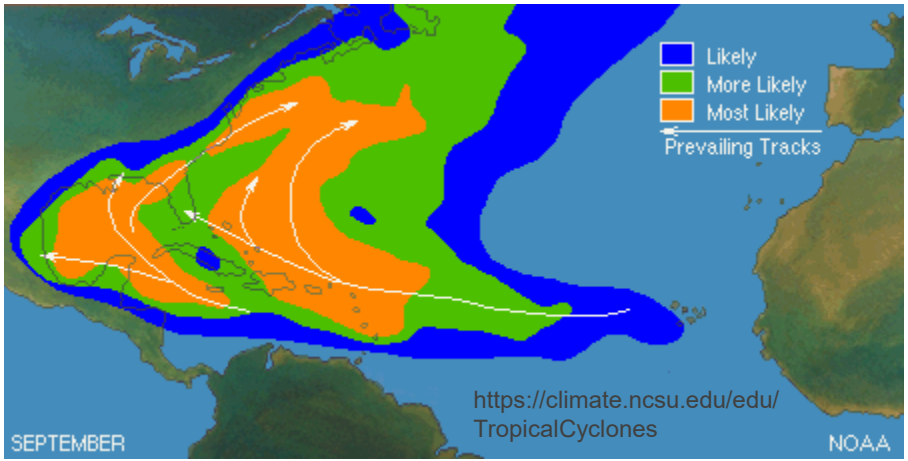
Transparent, Dynamic, Predictive Framework

ML/AI Approaches (like GANs, VAEs, Diffusion models): Lack transparency of decision making and require complete datasets (e.g., imputation)

Models (like NASA DAGs): lack positive & negative feedback and longitudinal predictability

The Hurricane Analogy



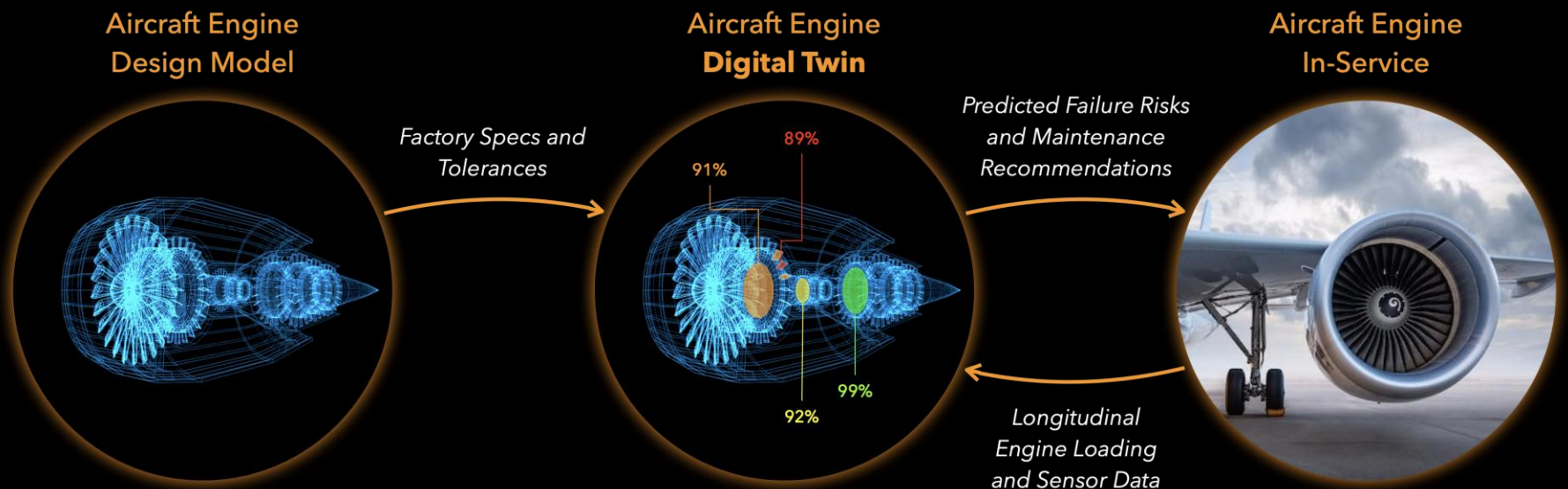


Dynamics | Variability | Predictive

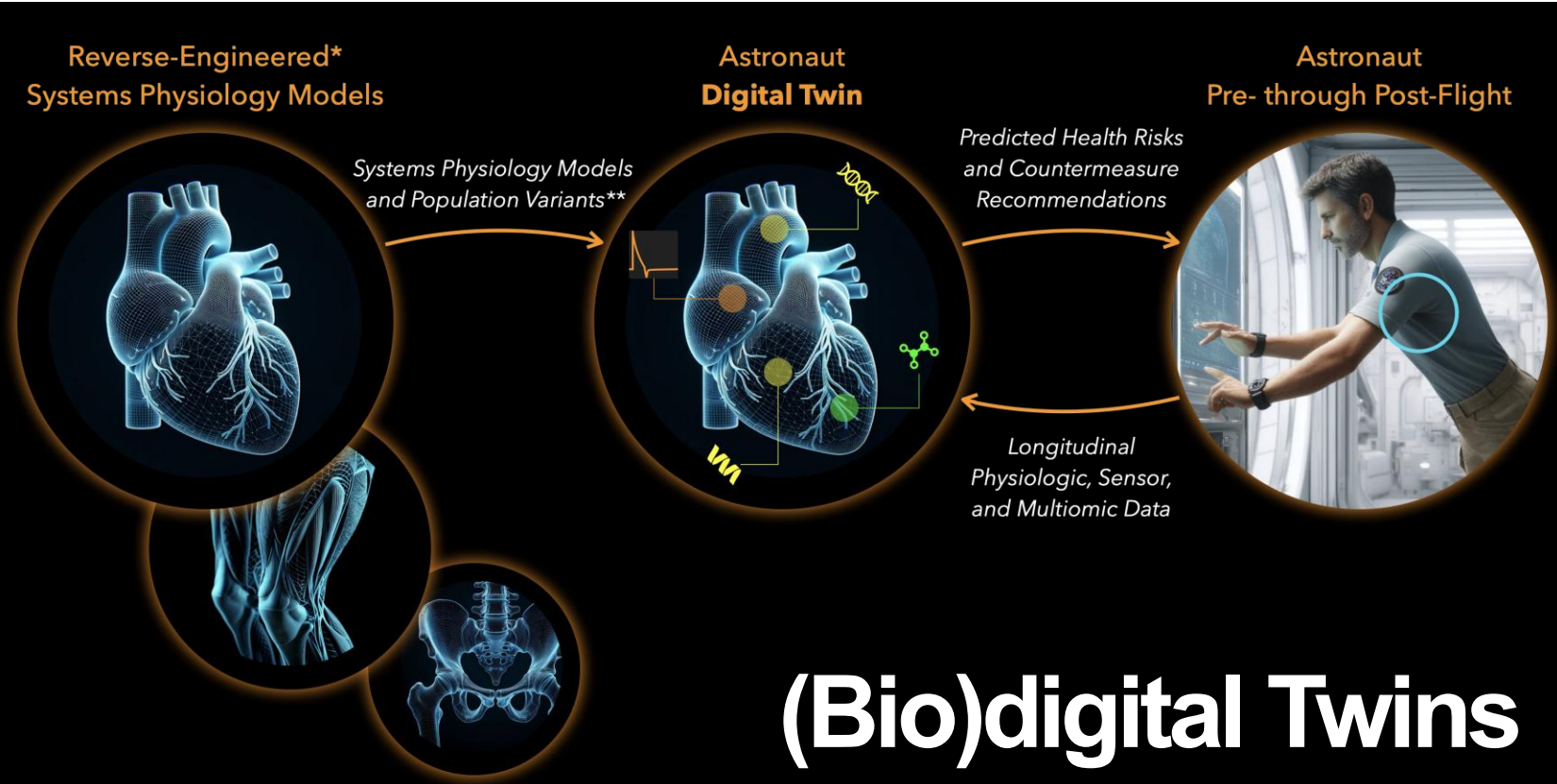
The Approach

Our view on how best to solve these problems for a sustainable, iterative, innovative approach

Engineered Digital Twins



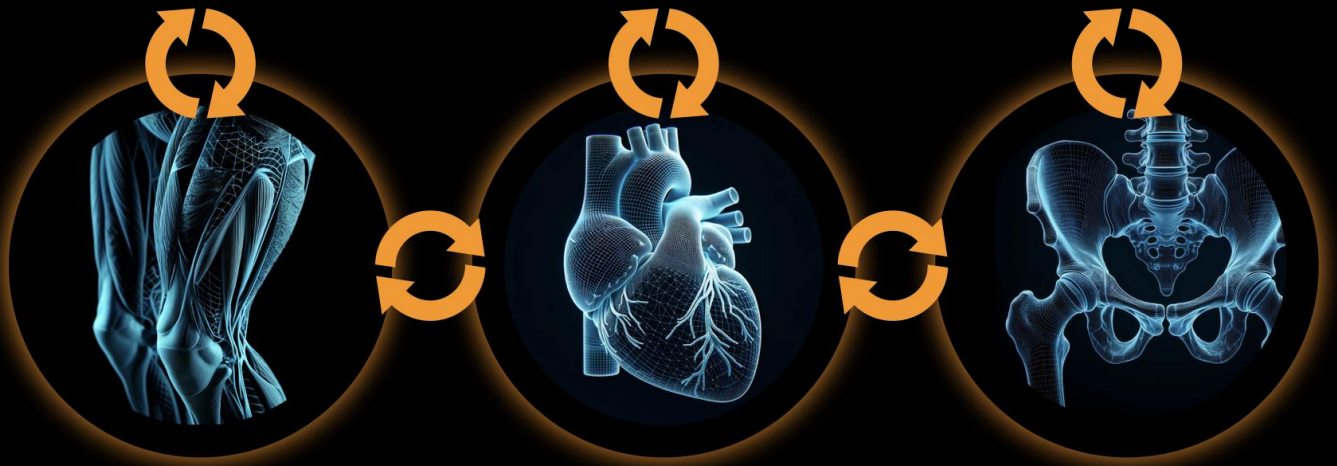
SOURCE: AstronautDigitalTwin.com



(Bio)digital Twins

SOURCE: AstronautDigitalTwin.com

Objective 1: Seed Astronaut



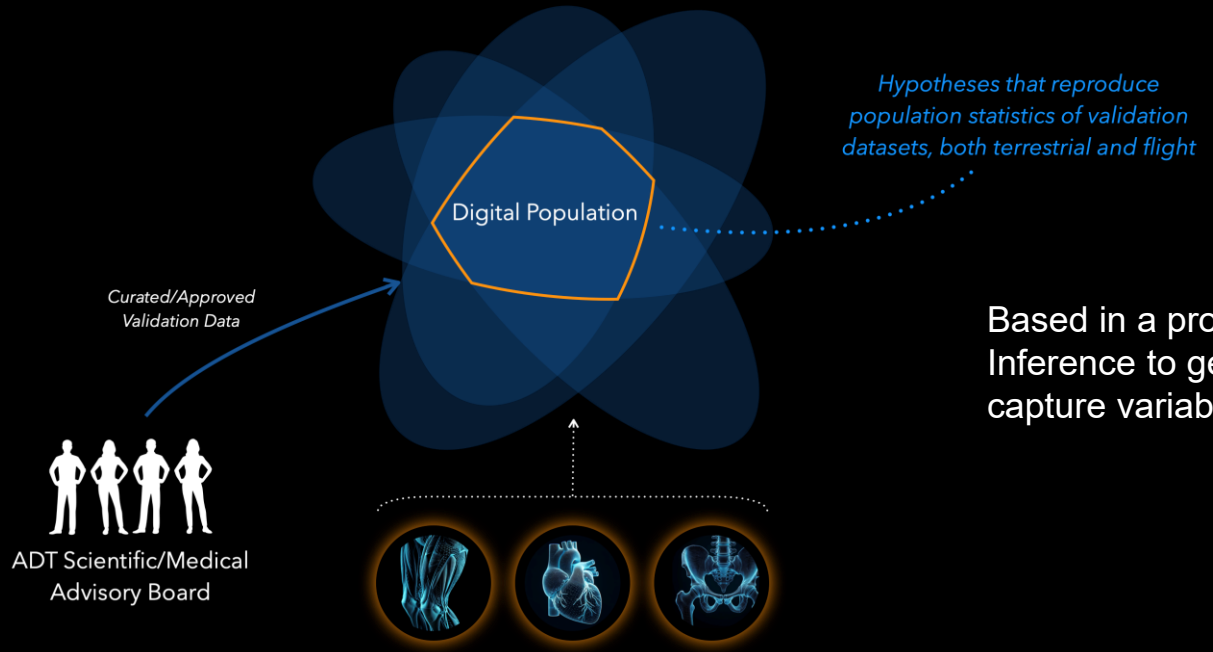
Based in systems differential equations and feedback in control systems

Variations in **Dynamic Equilibrium** result from numerous factors:

- Population variants
  - Genetics
  - Aging
  - Nutrition
  - Lifestyle/cumulative physiologic state
- **Gravity & other spaceflight pressures**

SOURCE: AstronautDigitalTwin.com

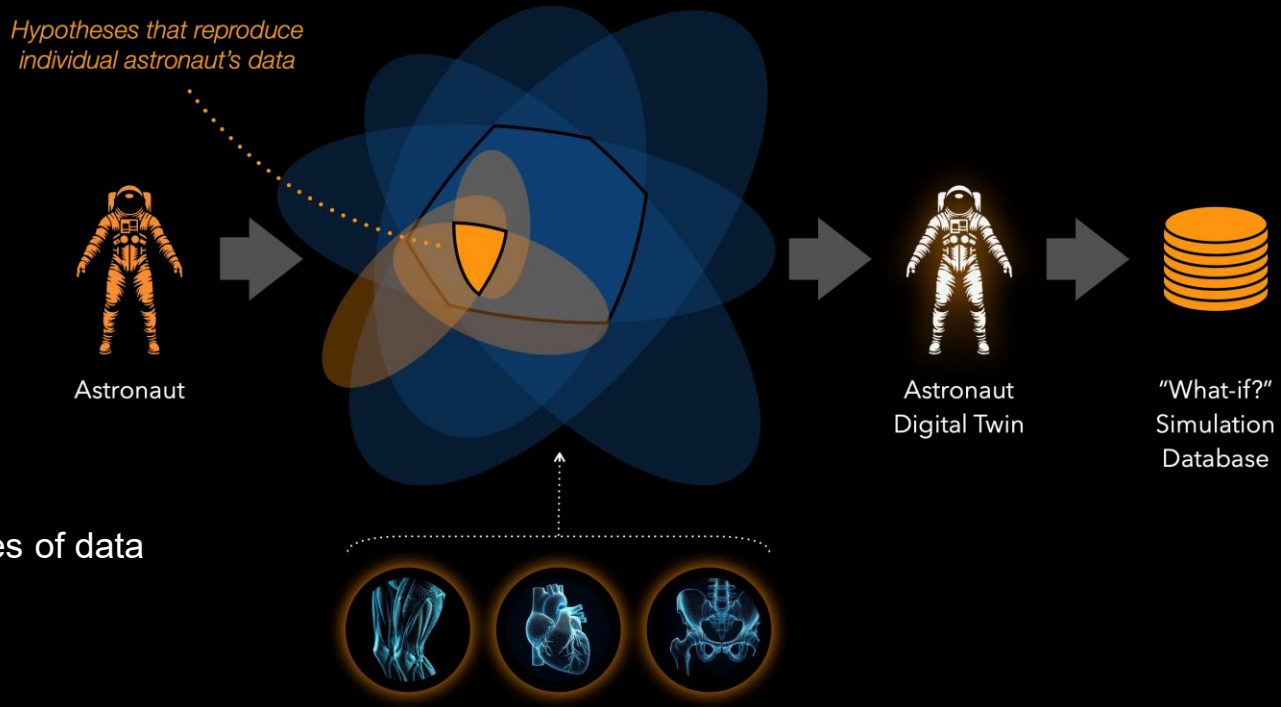
Objective 2: Digital Astronaut Population



Based in a probabilistic layer of Bayesian Inference to generate counterfactuals and capture variability in population

SOURCE: AstronautDigitalTwin.com

Objective 3: Astronaut Digital Twin



Real-time input of multiple types of data
Learns over time

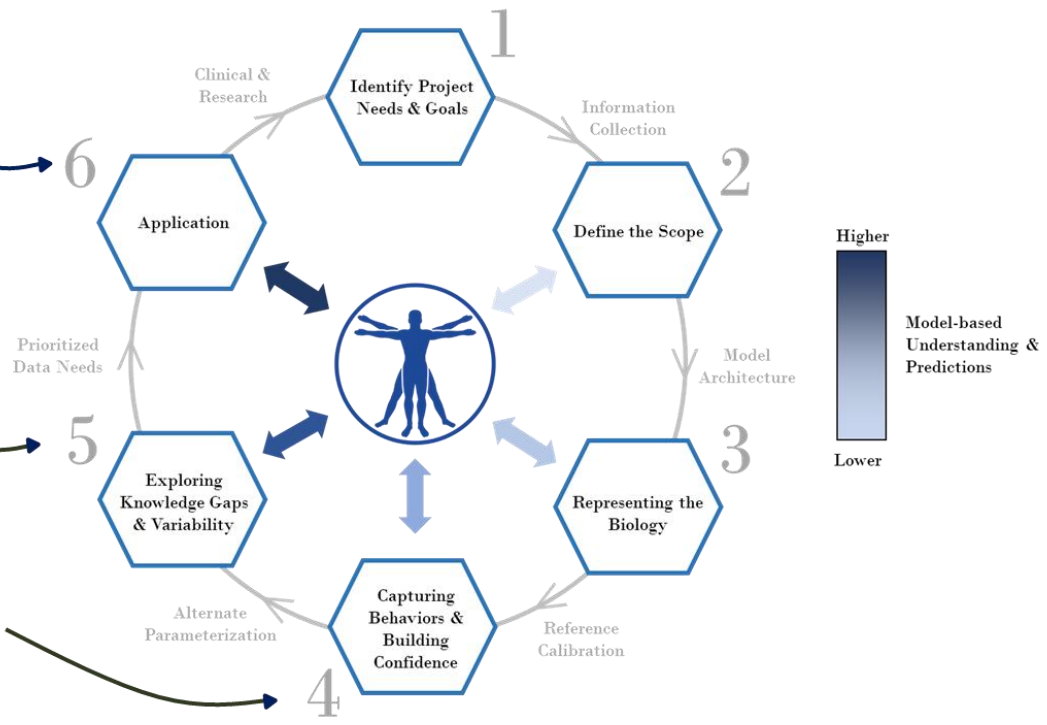
SOURCE: AstronautDigitalTwin.com

Three Objective – Six Stages

Astronaut Digital Twin

Virtual Astronaut Population

Seed Astronaut



Sensitivity Analysis, Testing, & Validation

At Various Stages of Development

- **Seed Astronaut**
  - Parameterization for Homeostatic and Non-homeostatic Solutions
  - Qualitative Mechanistic Validation
- **Astronaut Digital Population**
  - Published Clinical/Spaceflight Data
  - Quantitative Mechanistic Validation
- **Astronaut Digital Twin**
  - Clinical Case Testing Data
  - Can the predictions over time be validated experimentally?

The Need for Agility

Why agility is a central component of our approach

Drivers of the Need to Be Agile

80-20 Rule and the Data

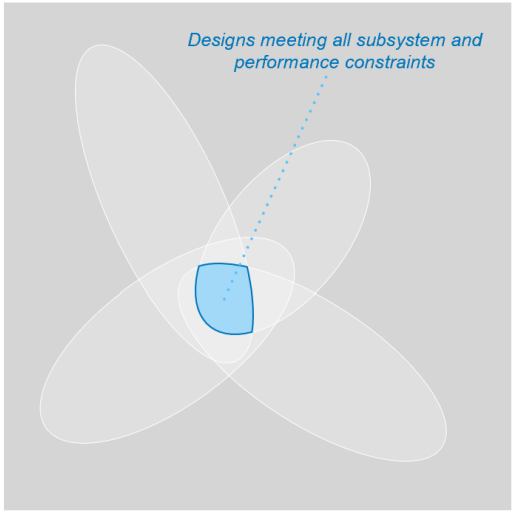
Modularity

Stakeholders

Rapid Innovation

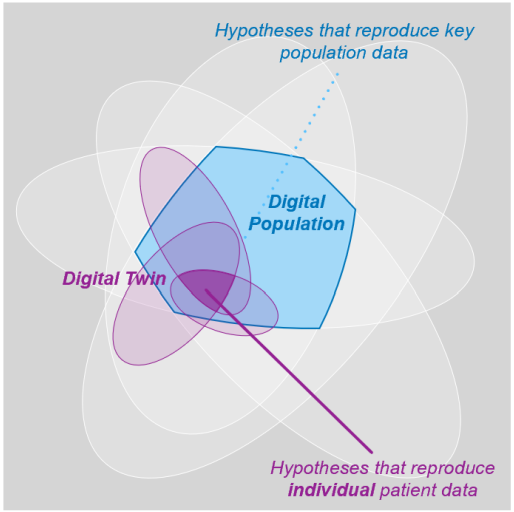
Drivers of the Need to Be Agile: 80-20 Rule

Systems Engineering & Digital Twins



Multi-Dimensional **Design** Space

Biological Digital Twins

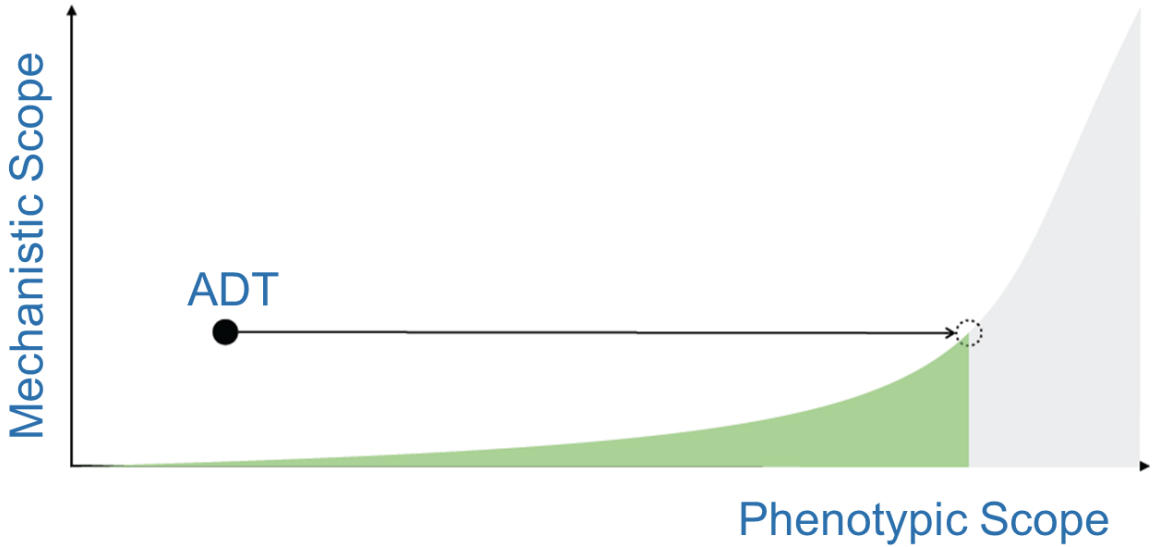


Multi-Dimensional **Hypothesis** Space

SOURCE: AstronautDigitalTwin.com

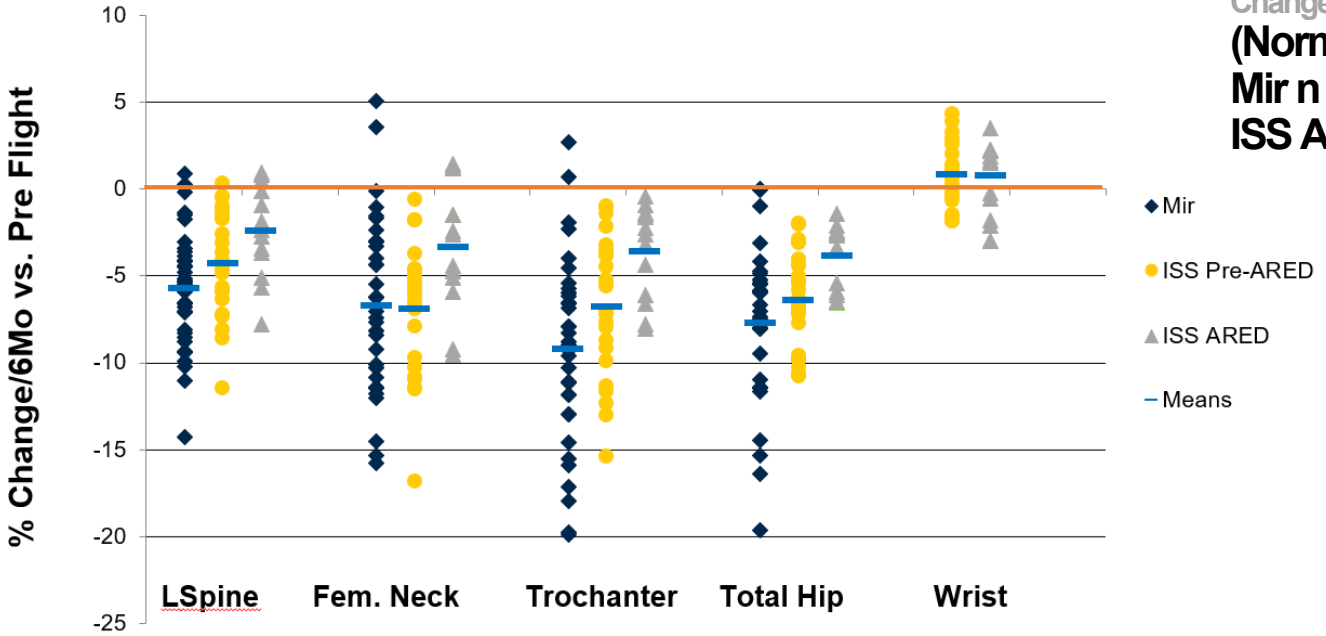
Drivers of the Need to Be Agile: 80-20 Rule

This method of modelling is an exercise in dimensionality reduction, while still fully capturing behavior



Drivers of the Need to Be Agile: 80-20 Rule

The Phenotypic Scope of Bone in Space



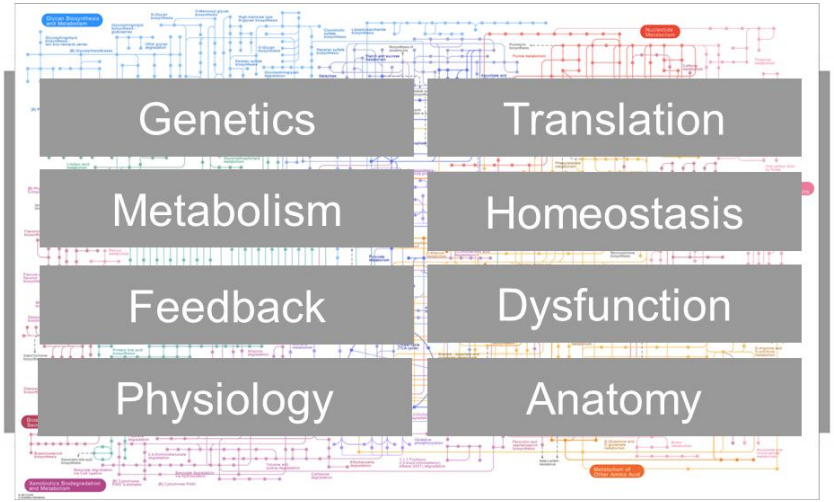
Change in DXA BMD

(Normalized to 6-Month Flight)
Mir n = 35; ISS Pre ARED n = 24; ISS ARED n = 13

SOURCE: English KL, Downs M, Goetchius E, Buxton R, Ryder JW, Ploutz-Snyder R, Guilliams M, Scott JM, Ploutz-Snyder LL. High intensity training during spaceflight: results from the NASA Sprint Study. NPJ Microgravity. 2020 Aug 18;6:21.

Drivers of the Need to Be Agile: 80-20 Rule

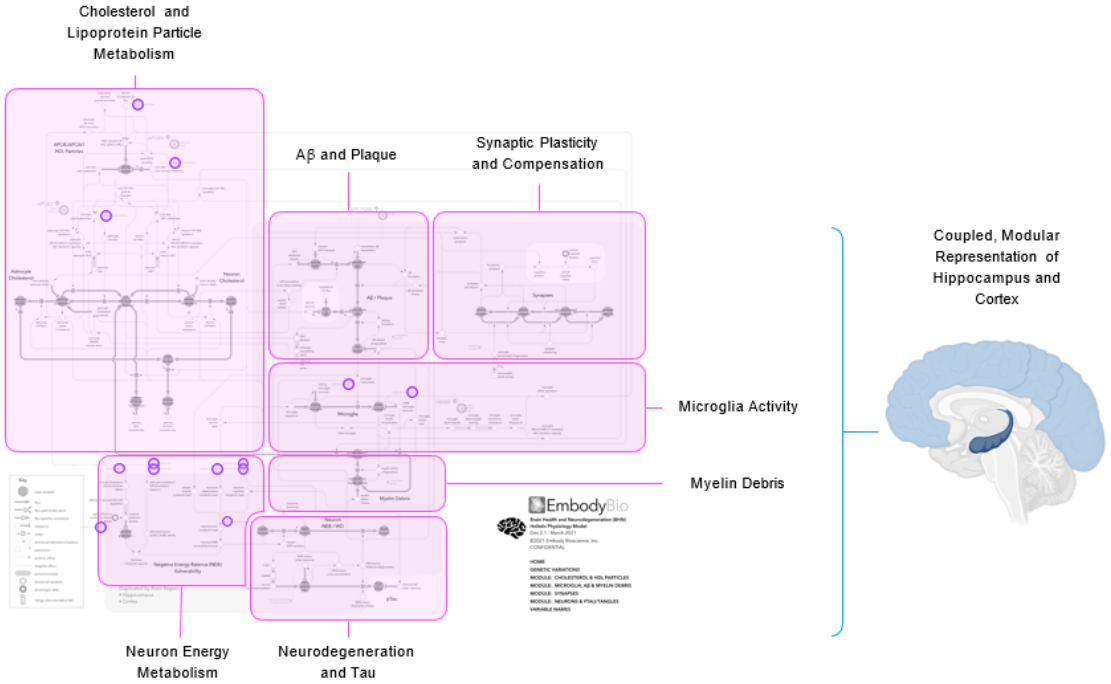
The Mechanistic Scope of All Biological Systems

Input → 

→ Output

Drivers of the Need to Be Agile: Modularity

Modularity within Human Systems and Between Human Systems



ADT Risk & Performance (R&P) Profiles:

Musculoskeletal R&P
Cardiovascular R&P
Radiation R&P
Behavioral R&P
Aggregated R&P
More…

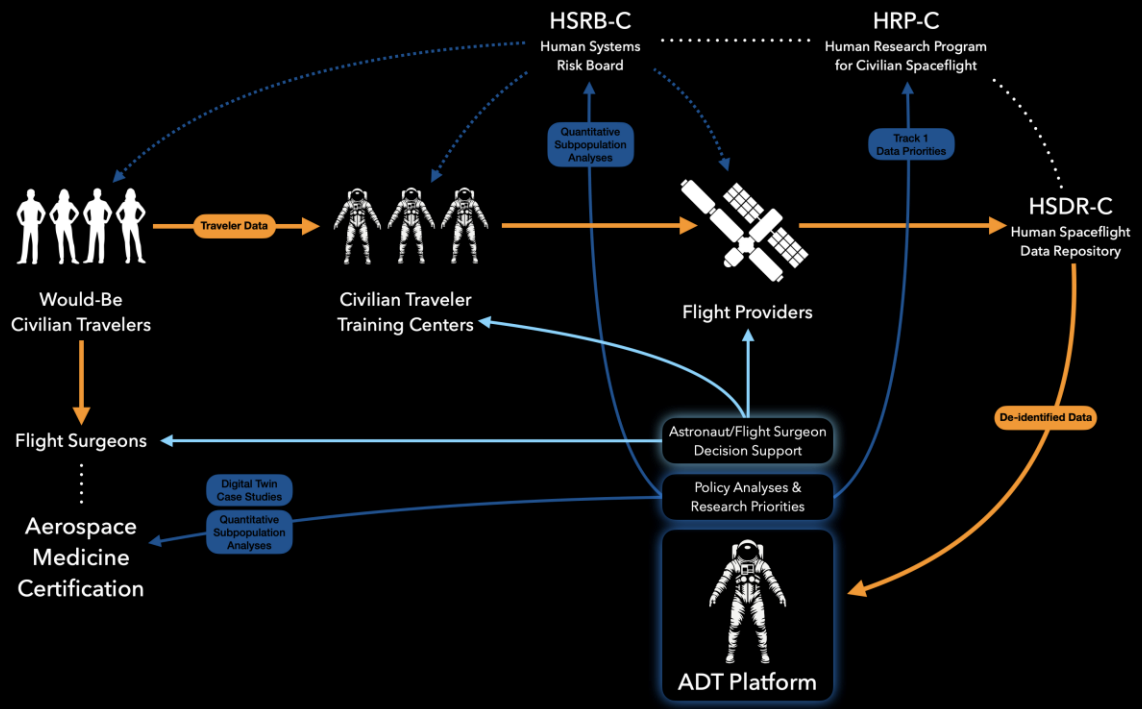
SOURCE: EmbodyBio

Drivers of the Need to Be Agile: The Stakeholder Ecosystem

Target Populations:

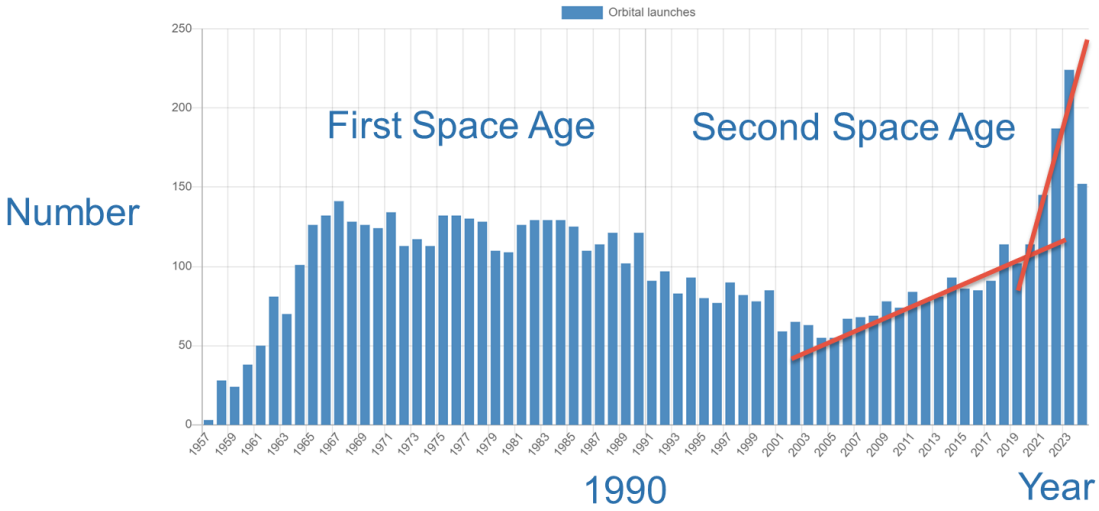
Astronauts
Flight Surgeons
Flight Providers
Researchers
Policy Makers

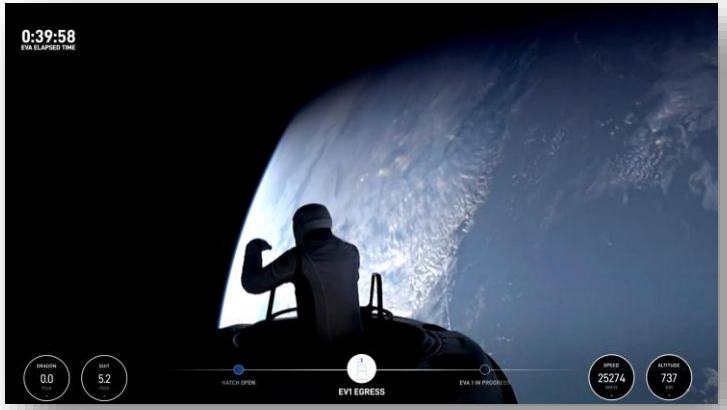
Must be responsive to each and their needs…



Drivers of the Need to Be Agile: The Need for Rapid Innovation

Success in human space exploration rests on the ability to shorten the development cycle, increasing innovation and readily deployable solutions

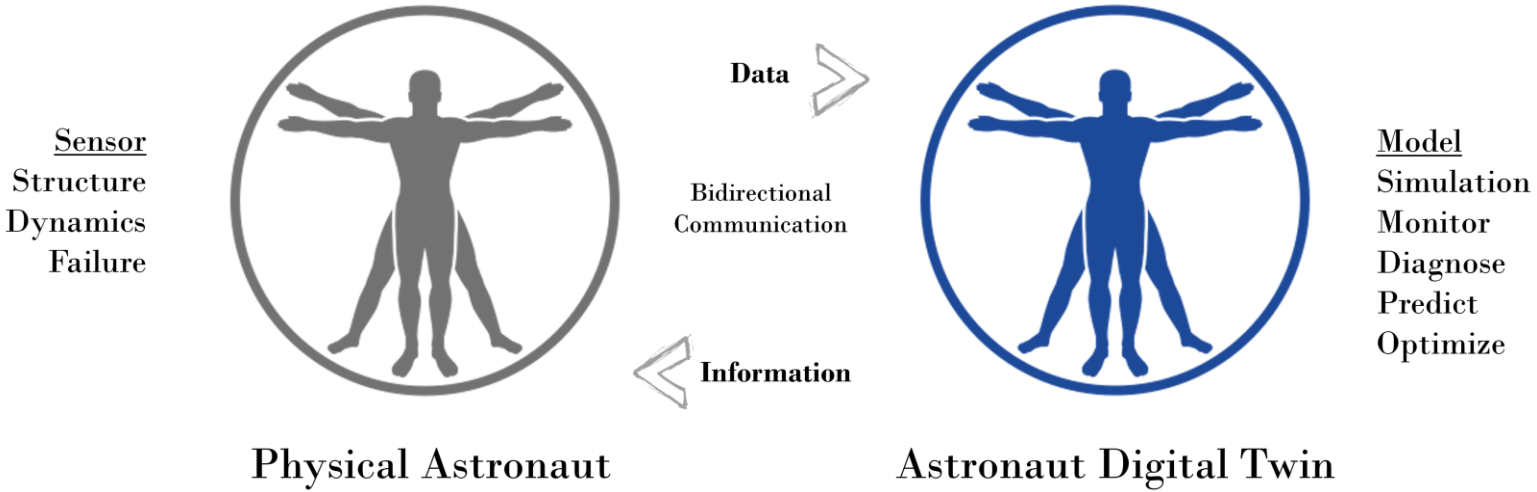




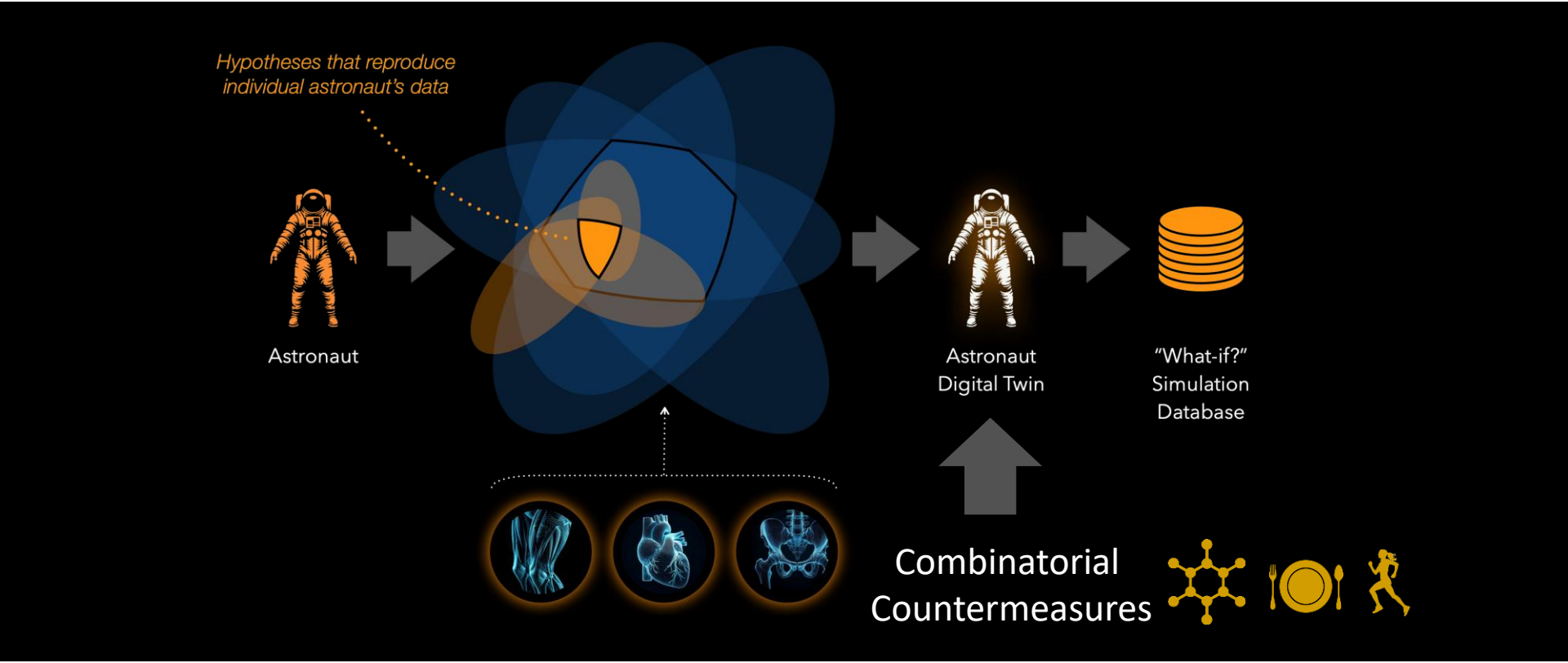
SOURCE: SpaceX Polaris Program

Deployment

Real Time Bidirectional Digital Twin Platform



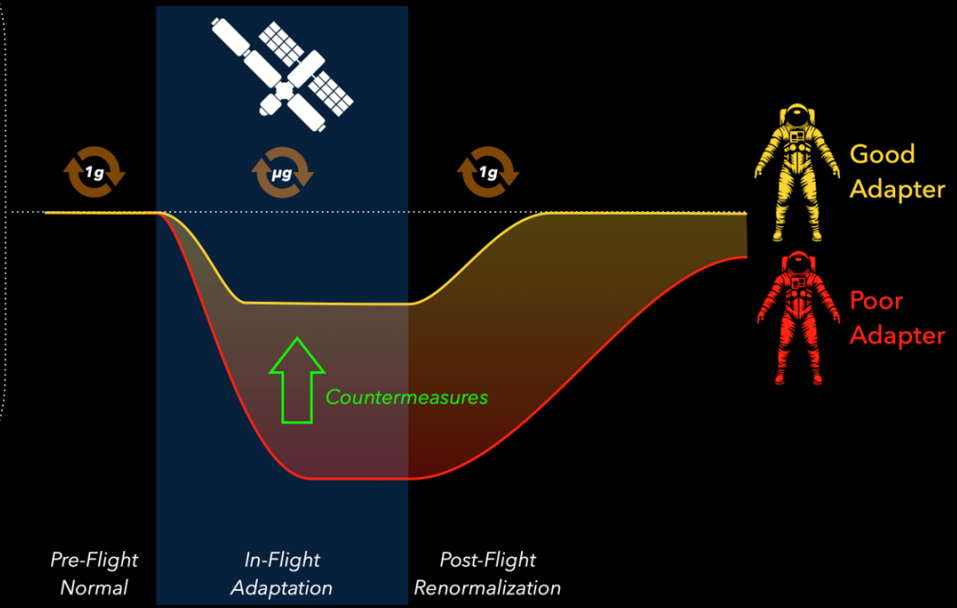
Calibrated Multimodal Countermeasures



Clinical ADT: Optimizing the Adaptation Curve towards Anti-Fragility

Target Populations:

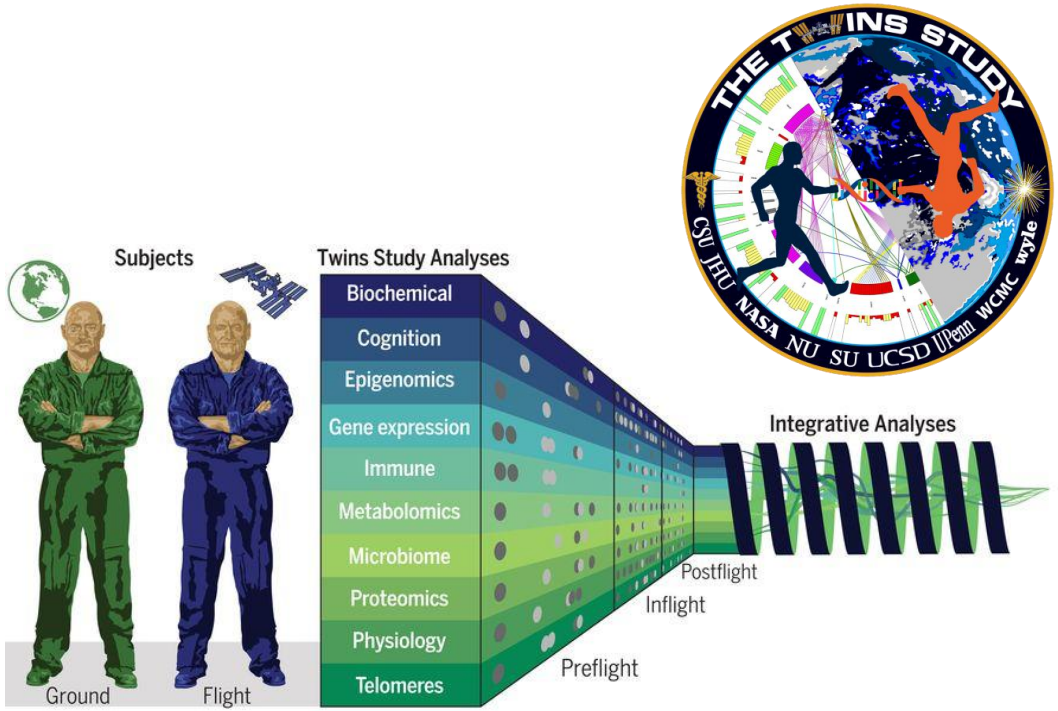
Astronauts
Flight Surgeons
Flight Providers



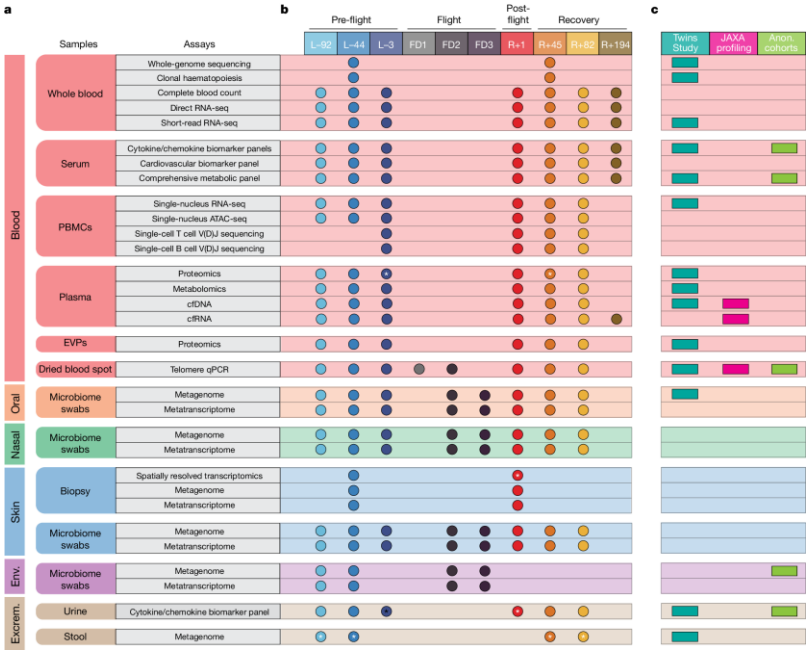
SOURCE: AstronautDigitalTwin.com

Research Application

SOURCE: Garrett-Bakelman et al. The NASA Twins Study: A multidimensional analysis of a year-long human spaceflight. Science. 2019 Apr 12;364(6436):eaau8650.

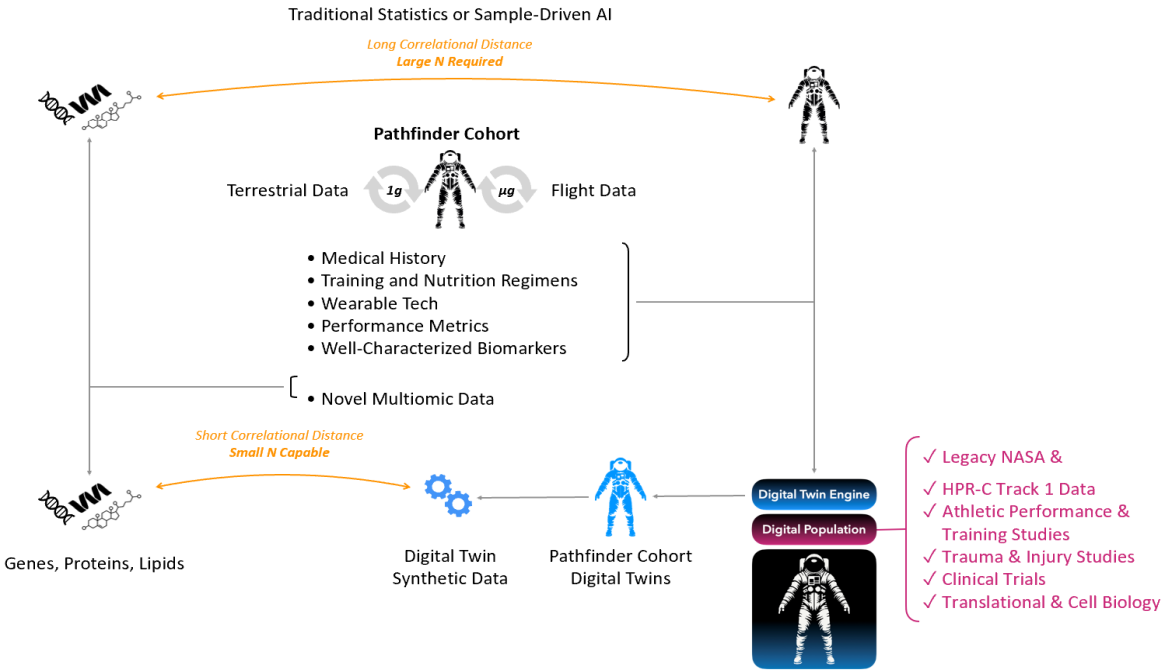


Research Application



SOURCE: Overbey et al. The Space Omics and Medical Atlas (SOMA) and international astronaut biobank. Nature. 2024 Aug;632(8027):1145-1154.

Research Application: Unraveling Deep Biology

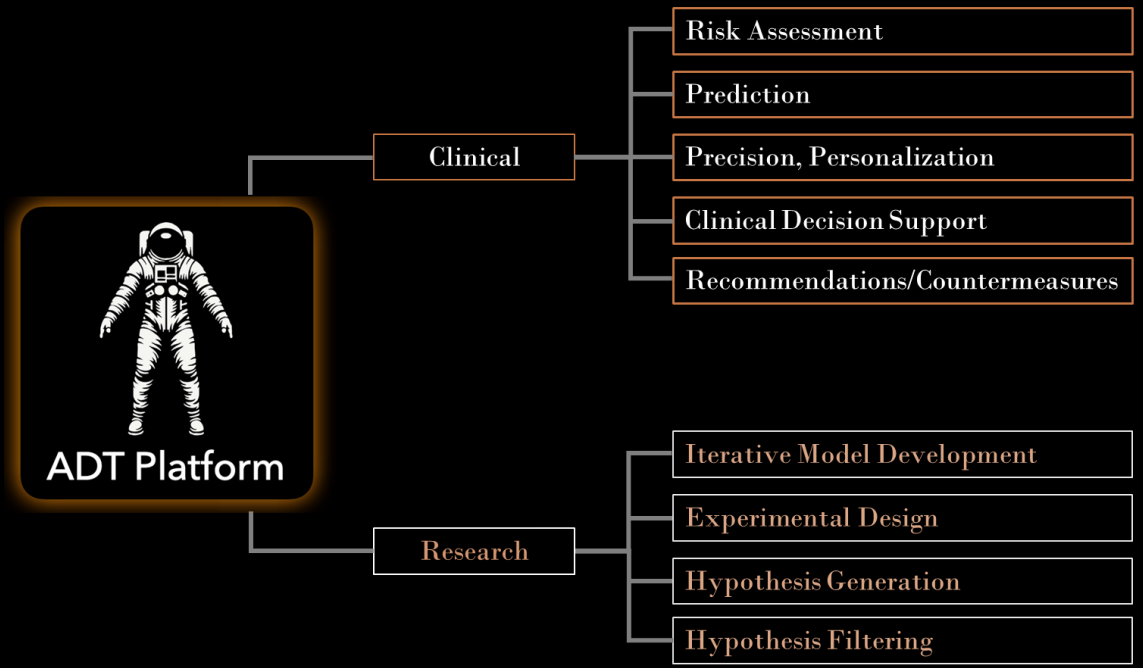


SOURCE: AstronautDigitalTwin.com

Continuum of Deployments

ADT Benefits

- Aggregates Hard Data in a Validated Way
- Decreases Time for Development Cycles, Fostering Rapid Innovation
- Transparent, Dynamic, & Predictive



We believe these capabilities can be leveraged to help support private and public space exploration in a meaningful, responsive way

https://www.telegraph.co.uk/news/2017/09/21/plans-2020-chinese-mars-probe-explore-possibility-human-settlement/

Thank You!

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A better world through a systems approach

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