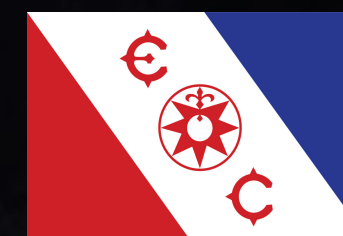
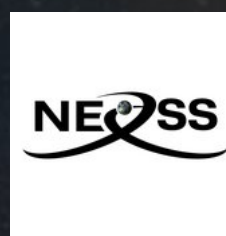
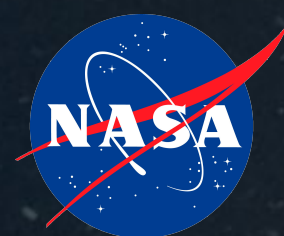




Future Exploration of Key Planetary Processes and Trends in the Sub-Neptune Population

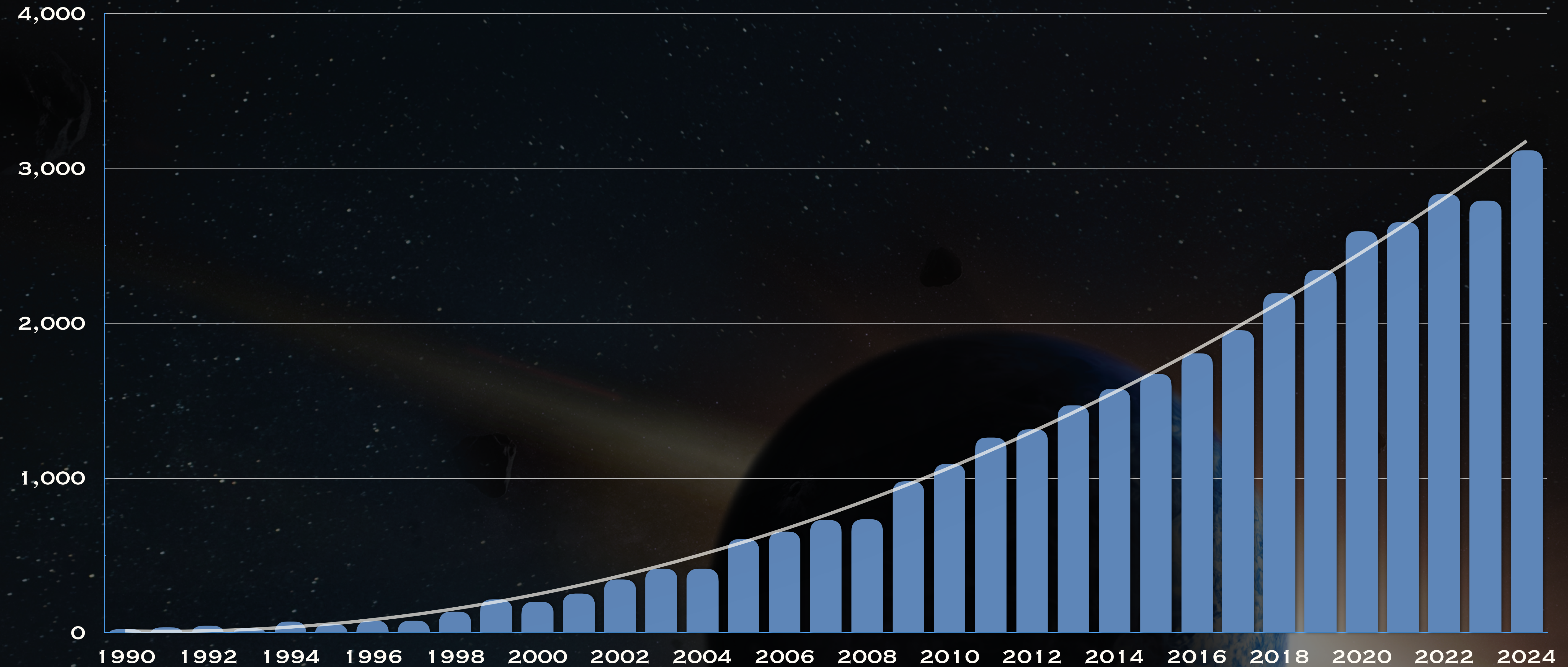
Dániel Apai

Steward Observatory and Lunar and Planetary Laboratory



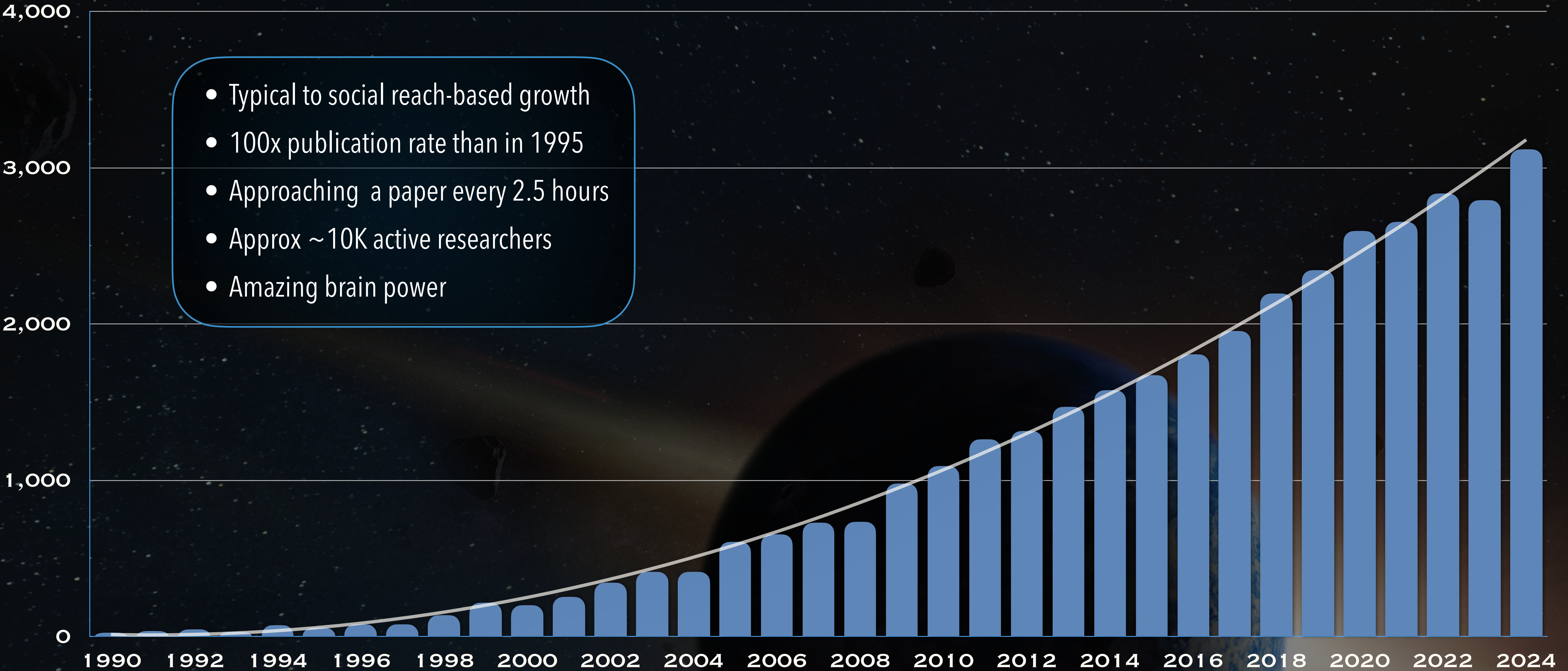
1 EXOPLANET DISCOVERY, DATA AND INFORMATION

REFEREED PAPERS ON EXOPLANETS FROM NASA ADS: QUADRATIC GROWTH

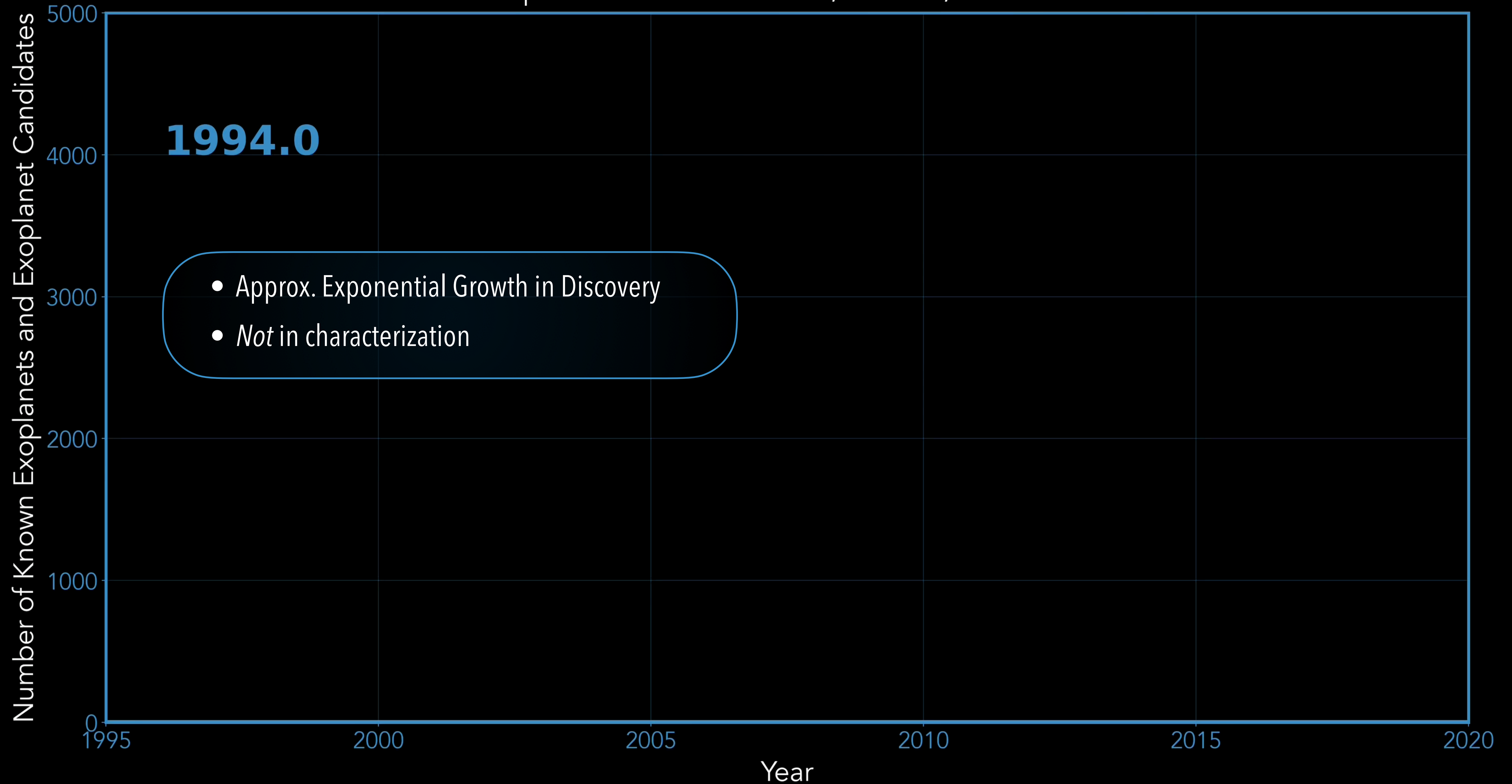


REFEREED PAPERS ON EXOPLANETS FROM NASA ADS: QUADRATIC GROWTH

- Typical to social reach-based growth
- 100x publication rate than in 1995
- Approaching a paper every 2.5 hours
- Approx ~10K active researchers
- Amazing brain power

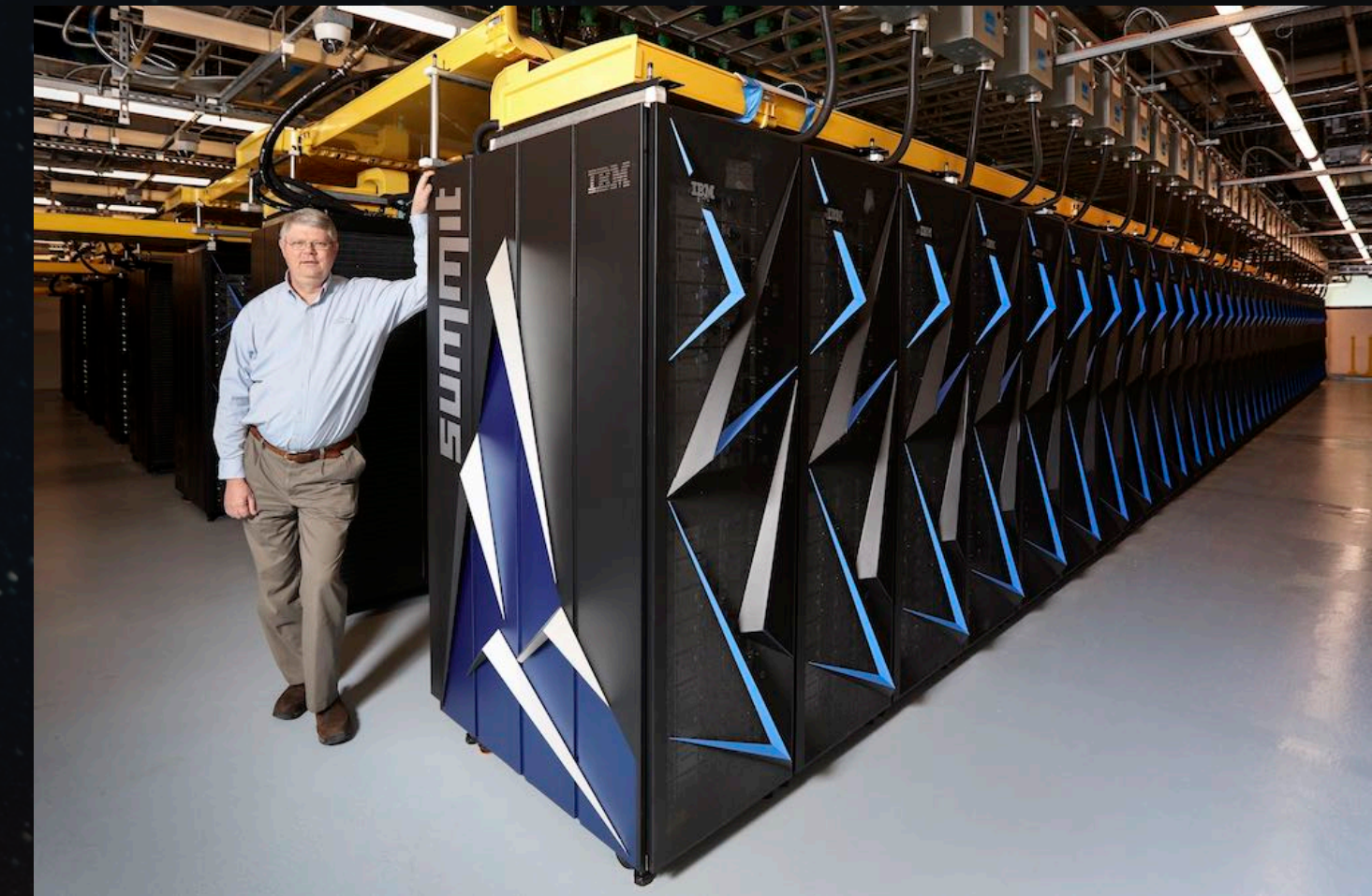


Exoplanet Candidates: Past, Present, and Future



MOORE'S LAW

- Continued exponential increase in computing performance
- Impact on detector capabilities
- Impact on parallel, time-resolved studies of objects
- Impact on Data processing, analysis
- Impact on Numerical Simulations
- Impact on Instrument control (e.g., AO systems)
- Impact on Machine Learning
- ML-based scientific literature interpretation
- AI Astronomers, AI-HI Teams, AI-guided (led?) research



DATA, INFORMATION, AND KNOWLEDGE

- Data ~ Result of measurement
- Information ~ Unexpected data
- Knowledge ~ Ability to explain and predict



INITIALLY

- No/little data
- Every new data point = new information = new knowledge

MATURE FIELD

- Lots of data available
- Good models
- Very difficult to increase knowledge

DATA, INFORMATION, AND KNOWLEDGE

- Data ~ Result of measurement
- Information ~ Unexpected data
- Knowledge ~ Ability to explain and predict



EXOPLANET HYPERINFLATION

- Vast number of planets
- Information value of a Hot Jupiter discovery:
- 1995: Unique data/info/knowledge, Nobel prize
- 2025: ~1 out 20,000 papers
- Information value hyperinflation ~ 30% !



2 CLIFF OF COMPLEXITY





A person in a yellow shirt and blue shorts stands on the edge of a dark, rocky cliff. The background is a vast, hazy canyon under a sunset sky with orange and purple hues. A waterfall is visible on the right side of the canyon.

CLIFF OF COMPLEXITY

- Arguably, planets are the most complex “astrophysical” objects
 - Extreme planets are often dominated by one process
 - Most planets are not extreme
 - Cooler planets are chemically more complex
- Working in a high-dimensional parameter space
- We will learn less and less from single planets
- Capability-driven Questions → Hypothesis-driven capability
- What is the required sample size?

A person in a yellow shirt and blue shorts stands on the edge of a dark, rocky cliff. They are looking out over a vast, deep canyon with layered rock walls. The sky is a mix of orange, yellow, and blue, indicating sunset or sunrise. The overall mood is contemplative and awe-inspiring.

CLIFF OF COMPLEXITY

- Arguably, planets are the most complex “astrophysical” objects
 - Extreme planets are often dominated by one process
 - Most planets are not extreme
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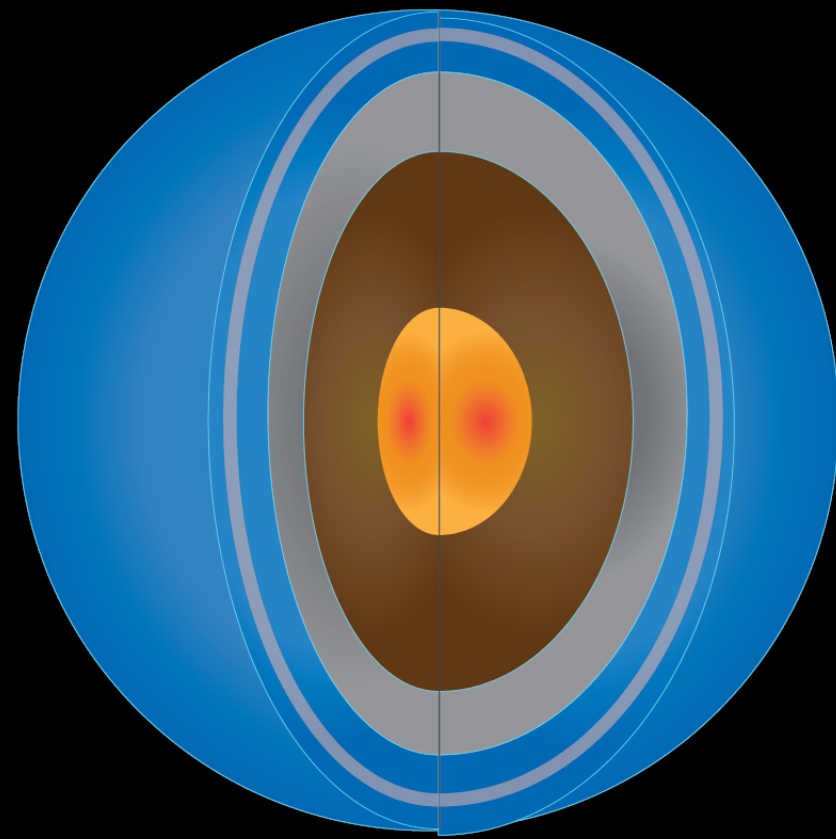
EVEN HUGE AMOUNTS OF DATA MAY NOT BE ENOUGH

- Human Genome Project (\$3B)
- Highly Detailed Maps of Mars
- Very deep cosmology surveys

3 THE NATURE OF SUBNEPTUNES



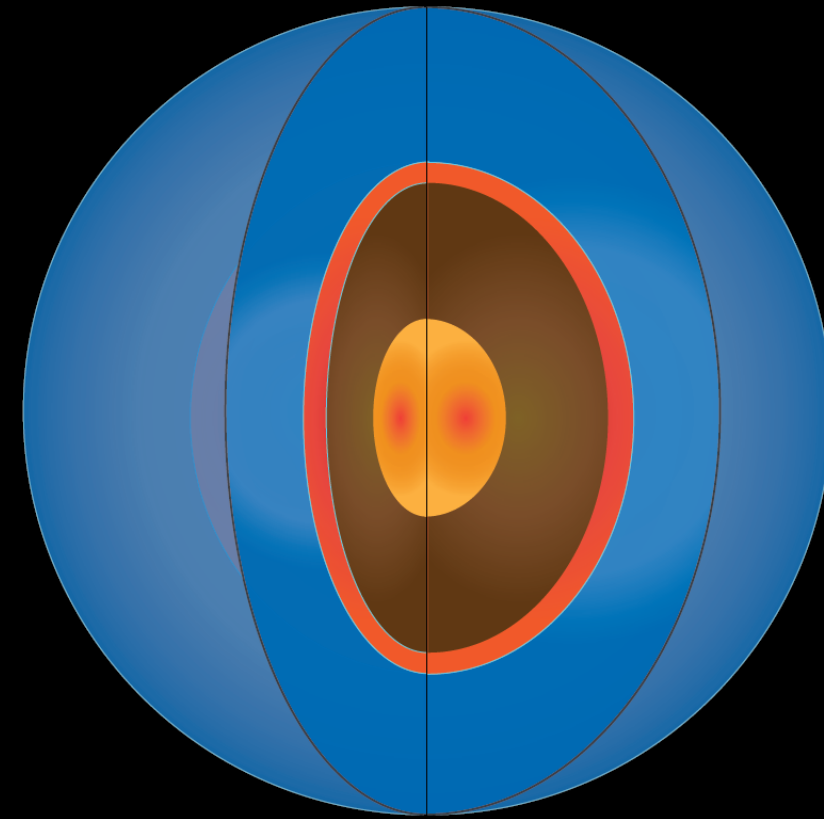
Potential Diversity in Sub-Neptunes and Super-Earths



Hycean World

Thin H₂ Atmosphere
Liquid Water Ocean
High-Pressure Ice
Mantle / Core

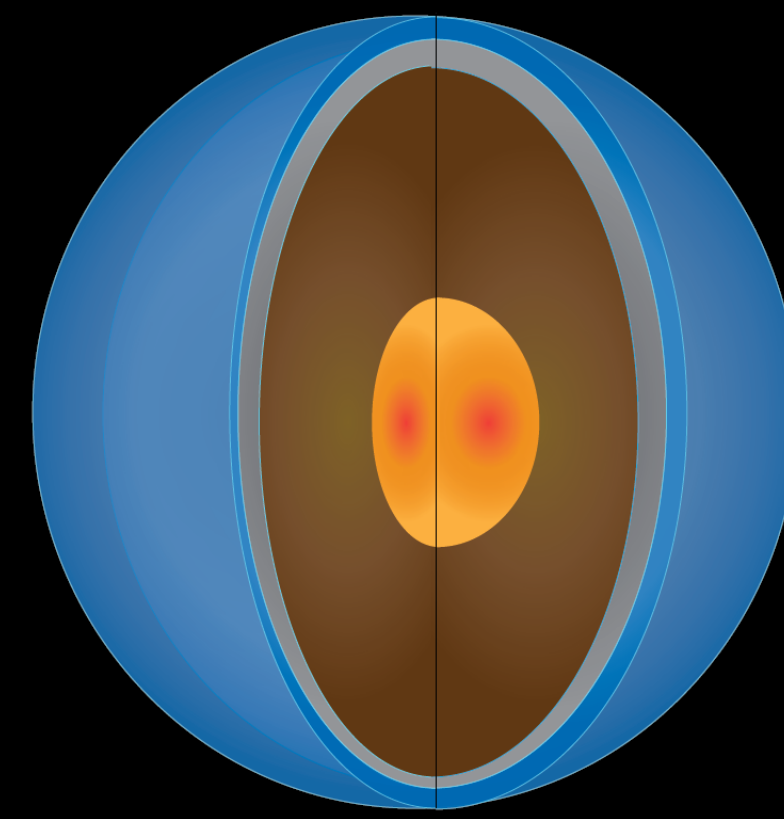
e.g., Hu et al. 21, 25; Innes et al. 23;
Madhusudhan et al. 23



H₂-Rich Sub-Neptune

Massive H₂/H₂O Atmosphere
Magma Ocean?
Mantle / Core

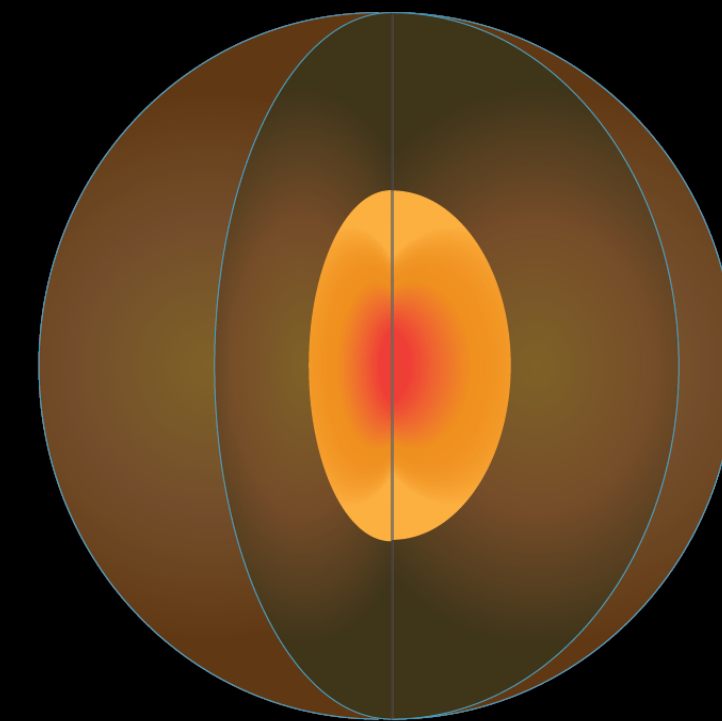
e.g., Hu et al. 25; Tian & Heng 24; Bean,
Raymond, & Owen 20



Aqua Planet

Atmosphere
Global Water Ocean
Silicate Mantle
Solid Core

e.g., Hu et al. 25;



**Super-Earth
Bare Core**

Silicate Mantle
Solid Core

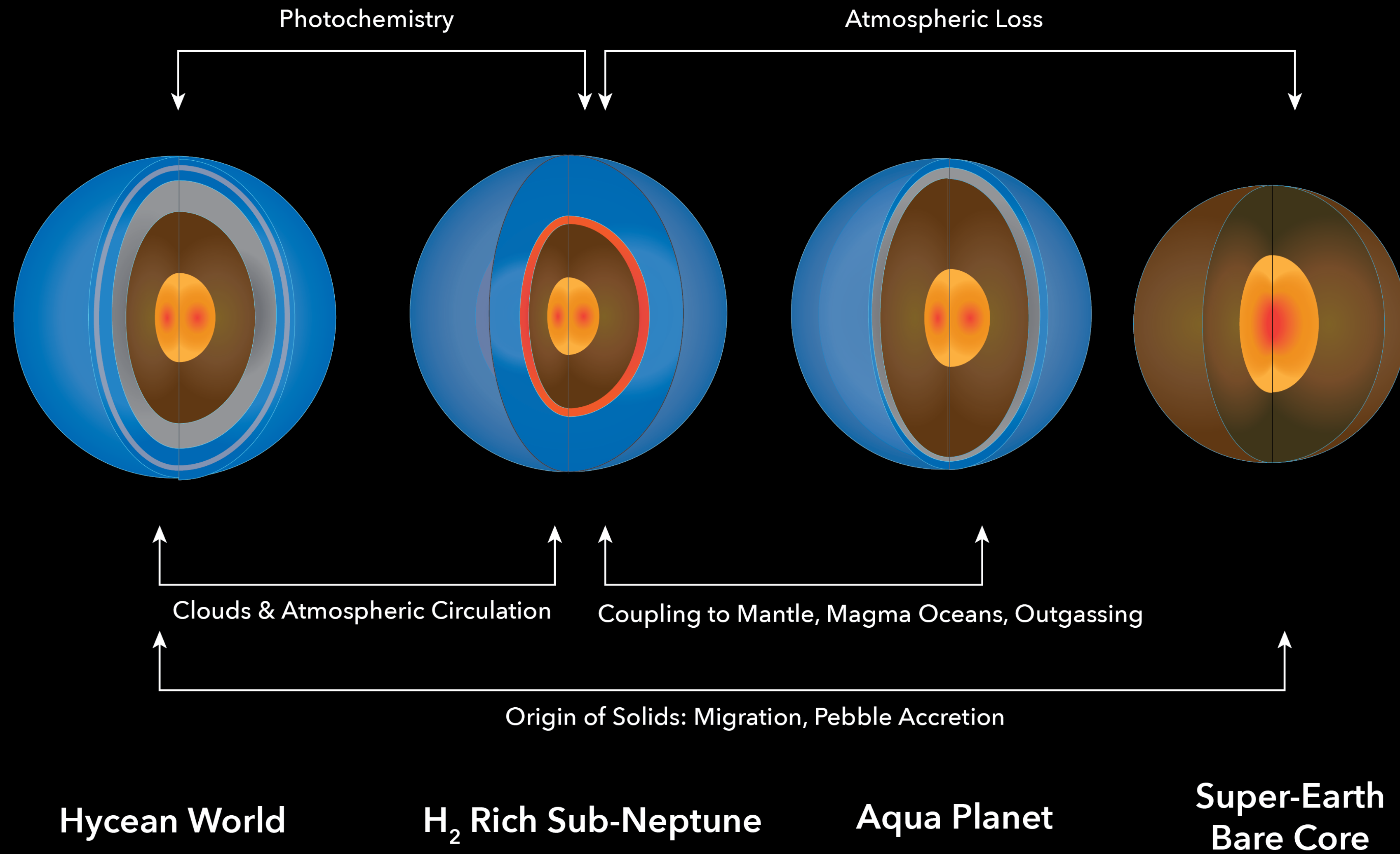
Wu 2019

4 PROCESSES THAT SHAPE SUB-NEPTUNES



KEY PROCESSES

Processes Shaping Sub-Neptunes



5 CONSTRAINING PROCESSES

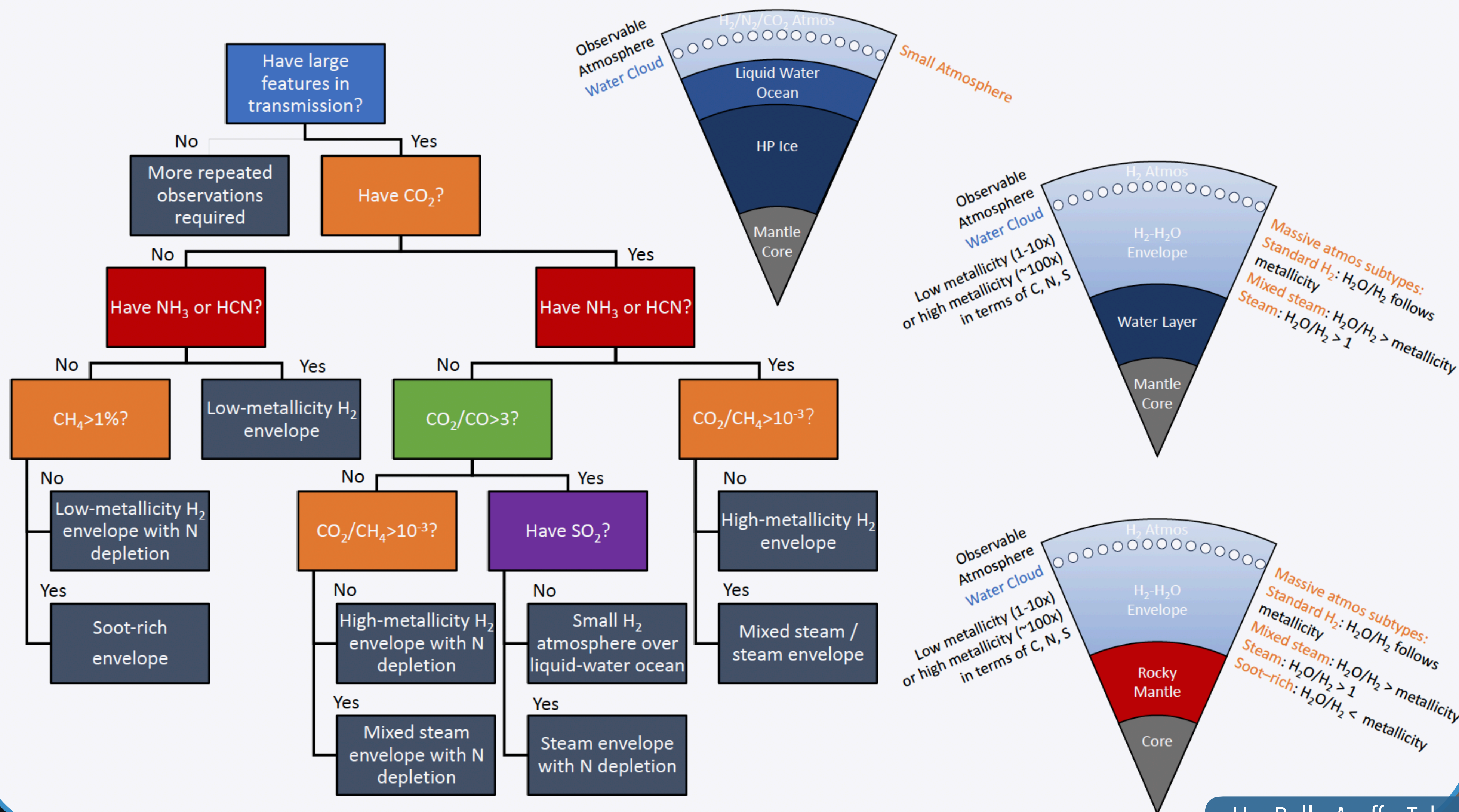


WHICH INTERESTING HYPOTHESES ARE TESTABLE?

Use the scientific method to identify science questions that are answerable

Required sample sizes, measurements, and instrument capabilities can be determined

PROPOSED ROADMAP TO INFERRING INTERNAL STRUCTURE



LIKELY CONNECTIONS

Processes	Property	Likely Correlate with	Example Refs
Photochemistry	UV Irradiation, T_{eff}	Albedo, Gas-phase Abundances, Thermal Emission	Hu et al. 21; Kempton+23; Reed +24
Atmospheric loss	Planet Size, Density	Age, Irradiation, Core Mass, Composition	e.g., Owen & Wu 2017; Fulton+17; Gupta & Schlichting 19; Fernandez+25
Condensate Clouds	T_{eff} , Circulation	Infrared Color, Albedo	Hu+19; Kempton+23
Atmos–Oceans Coupling	H ₂ O Abundance, T_{eff}	Planet Radius, Density, Irradiation	Hu+19; Tsai+21; Dorn & Lichtenberg 21
Migration/Accretion	Semi-major axis, Irradiation	Envelope Mass, Density, Age, Orbital Architecture	Johansen & Lambrechts ; Bitsch+21; Ida & Lin 10; Rogers+11
Outgassing from Core/Mantle	Atm Composition	Planet Radius, Density, Irradiation, Stellar Abundances	Grewal+ 21; Tian & Heng 24; Kite+19
Coupling to Magma oceans	Atm Composition, Transit Radius	T_{eff} , Density, Irradiation, Age	Dorn & Lichtenberg 21; Schlecker+24;
Atmospheric Dynamics	Irradiation, Rotation Period	P-Dependent Albedo/Intensity/Color Evolution	Innes & Pierrehumbert 22; Kempton+23

THE DIAGNOSTIC POWER OF EXOPLANET MISSIONS

Which exoplanet surveys will deliver more information?

- Number of planets \neq science yield
see also Bean et al. 2017, Checlair et al. 2019, 2021, Bixel & Apai 2020
- Hypothesis Testing instead of Merely Sample Size
- Framework for such assessment was lacking
- The missing tool to build statistically sound science cases

Bixel & Apai 2021; Schlecker et al. 2023; Hardegree-Ullman et al. 2023



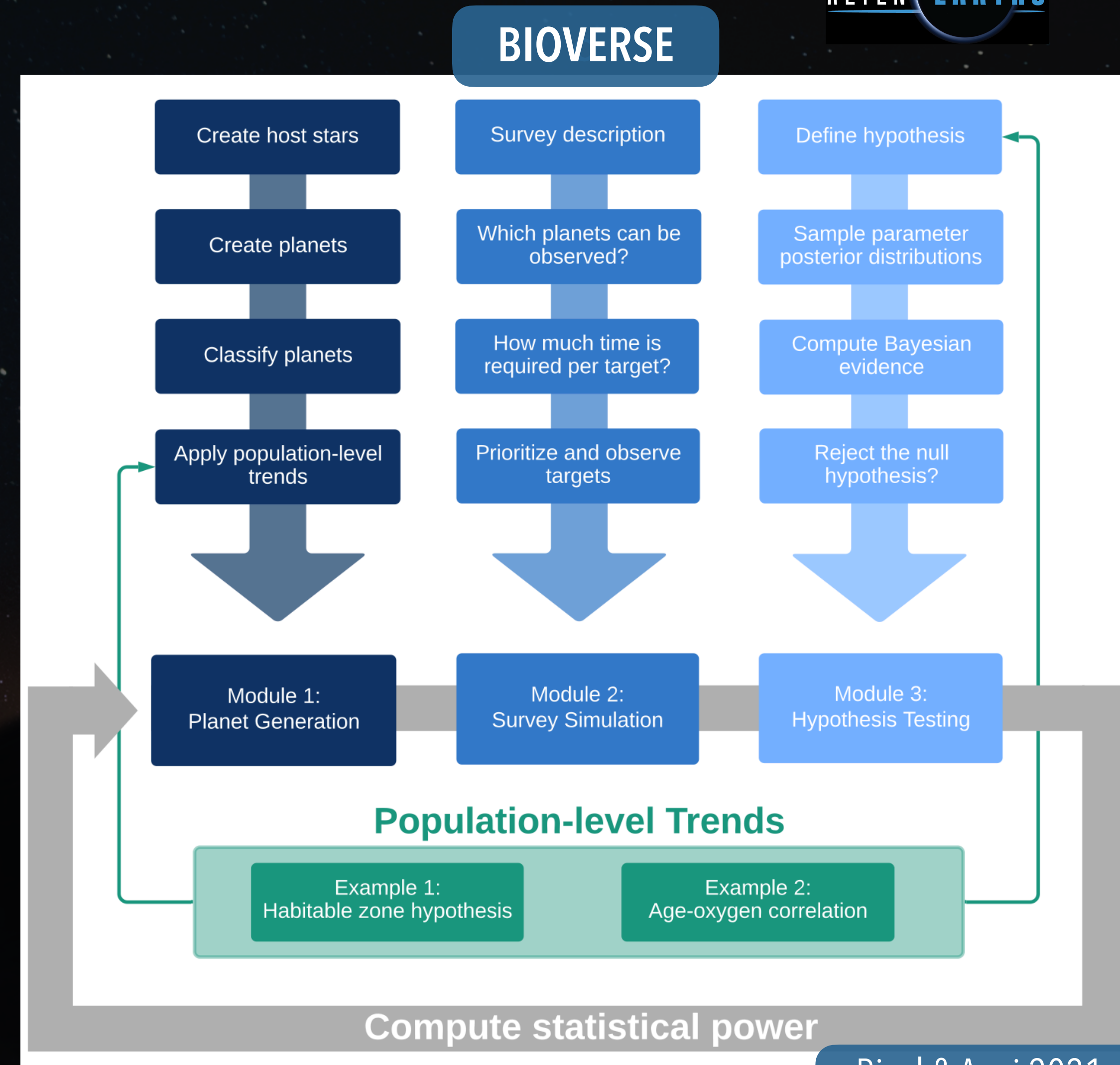
Alex Bixel



Kevin Hardegree-Ullman



Martin Schlecker



Bixel & Apai 2021

<https://github.com/danielapai/bioverse>

THE DIAGNOSTIC POWER OF EXOPLANET MISSIONS

- Bixel & Apai 2020, 2021
Oxygenation lifetime
Presence of Habitable Zone through Water Vapor detection (transits and high-contrast imaging)
- Hardegree-Ullman, Apai et al. 2023
ELT's High Spectral Resolution Spectroscopy of Transiting Exoplanets Hypotheses on Oxygen in Exo-Earth Candidates
- Hardegree-Ullman, Apai et al. 2025
ELT's High Dispersion High Contrast Spectroscopy: Hypotheses on Oxygen in Exo-Earth Candidates
- Schlecker, Apai et al. 2023
Magma Oceans' Imprint on Planet size Distribution: Observable Discontinuity Discontinuity at HZ's Inner Edge
- Schlecker, Apai et al. 2025
Testing UV-Driven Biogenesis in Exoplanet Biosignature Patterns



Alex Bixel



Kevin Hardegree-Ullman



Martin Schlecker

6 SURVEYS AND MISSIONS: QUESTIONS AND HYPOTHESES

Approximate Timeline for Key Exoplanet Missions and ELTs



HST

JWST

Pandora

PLATO

ROMAN

ARIEL

E-ELT

GMT

TMT

HWO Sci. & Tech Def.

Mission Implementation

HWO

Nautilus Sci. & Tech

Mission Implementation

Nautilus

2020

2025

2030

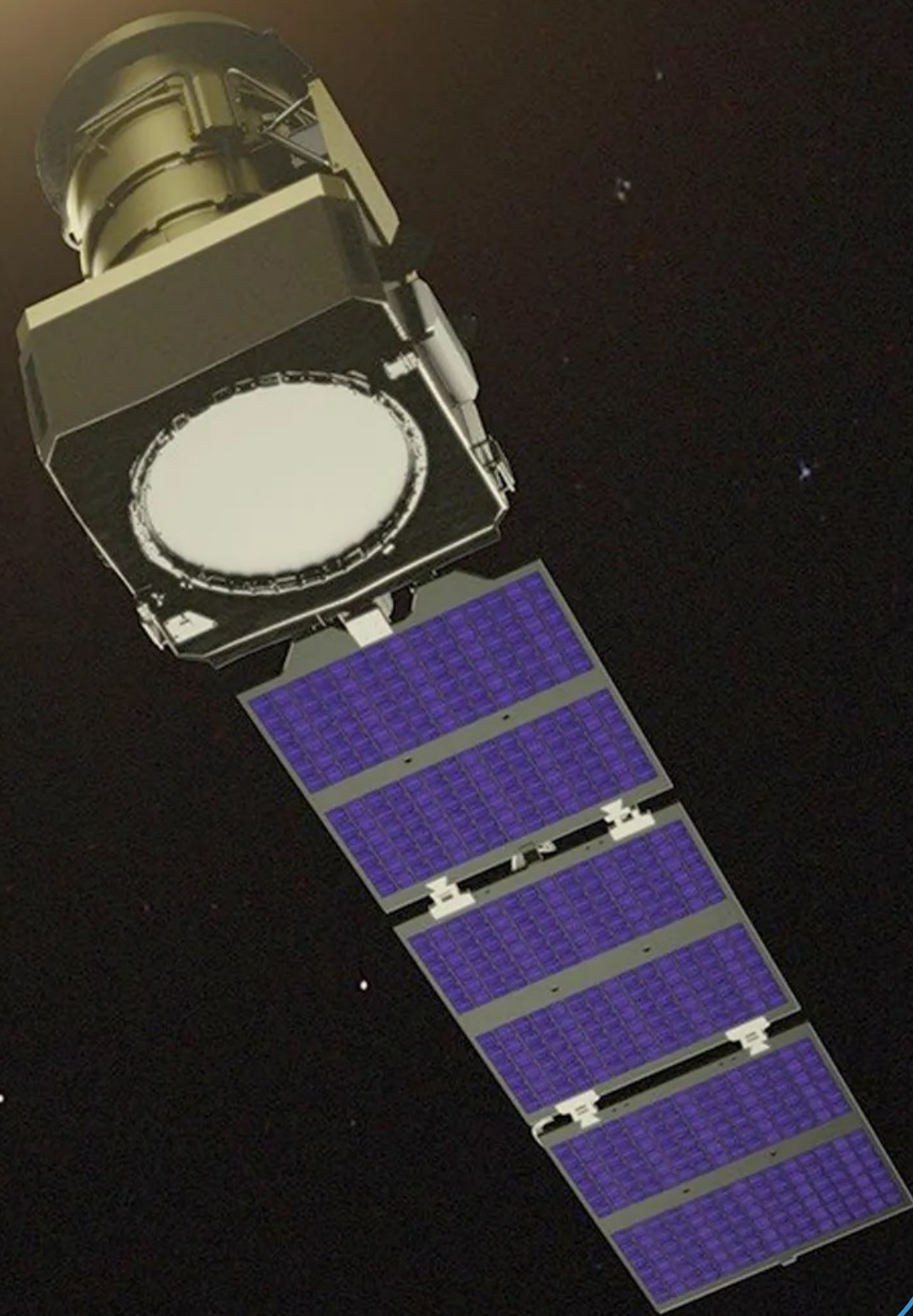
2035

2040

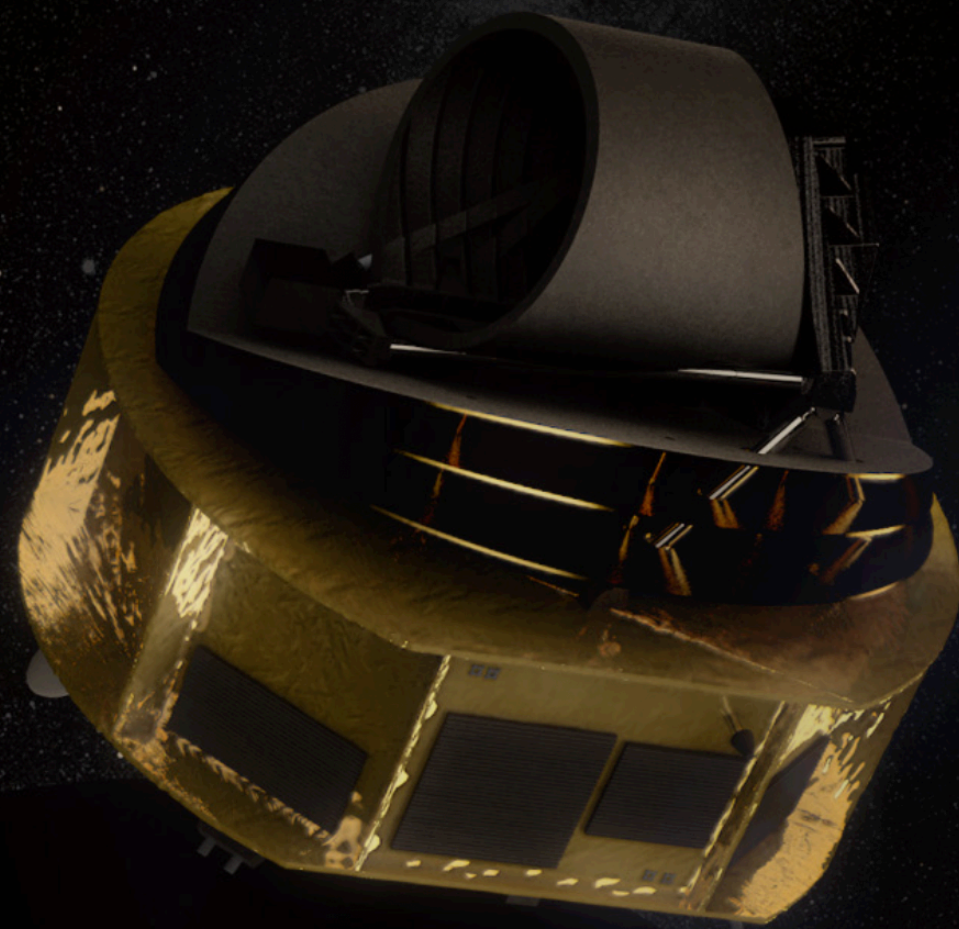
2045

2050

PANDORA



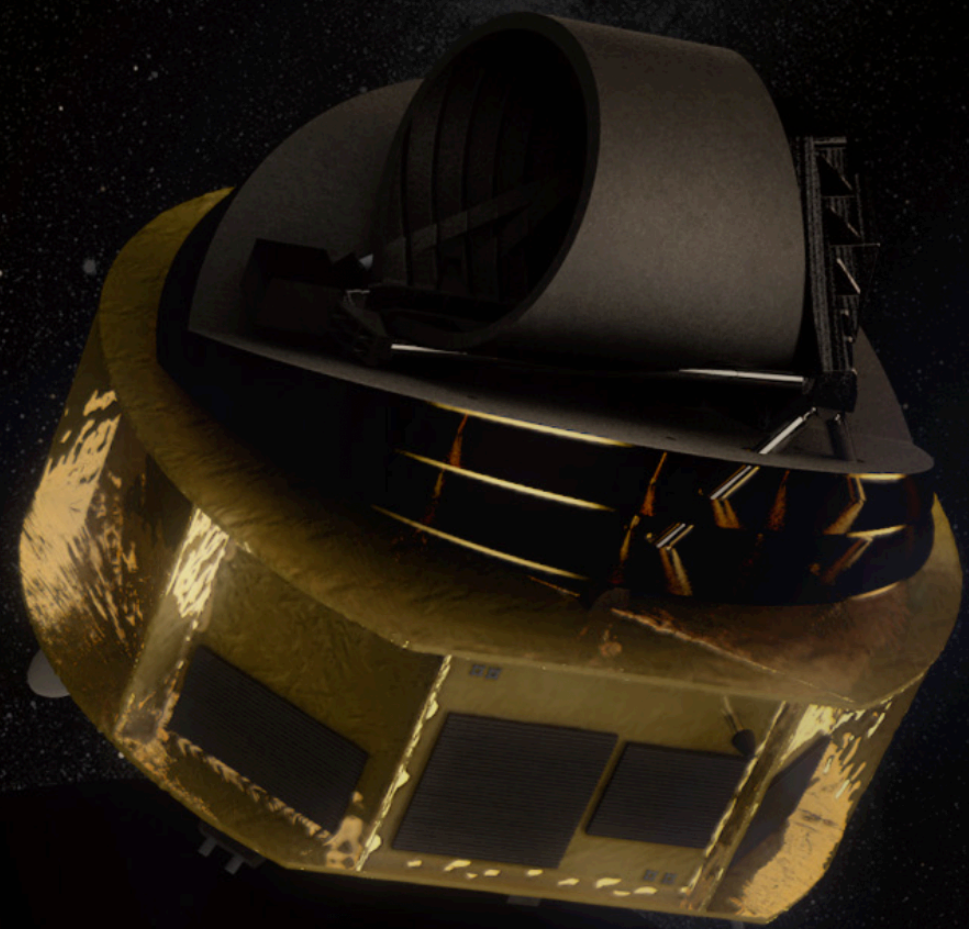
ARIEL



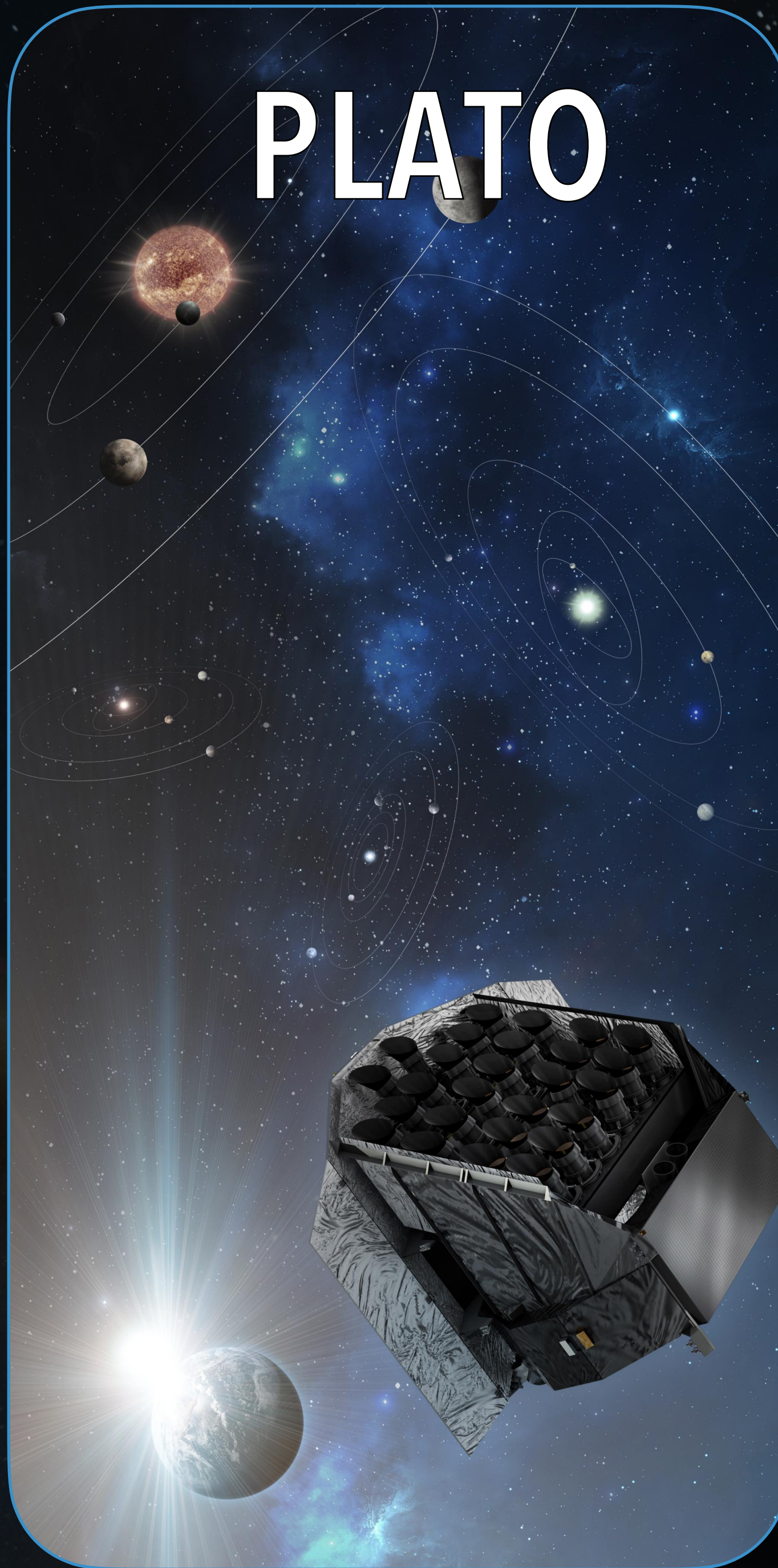
PLATO



ARIEL



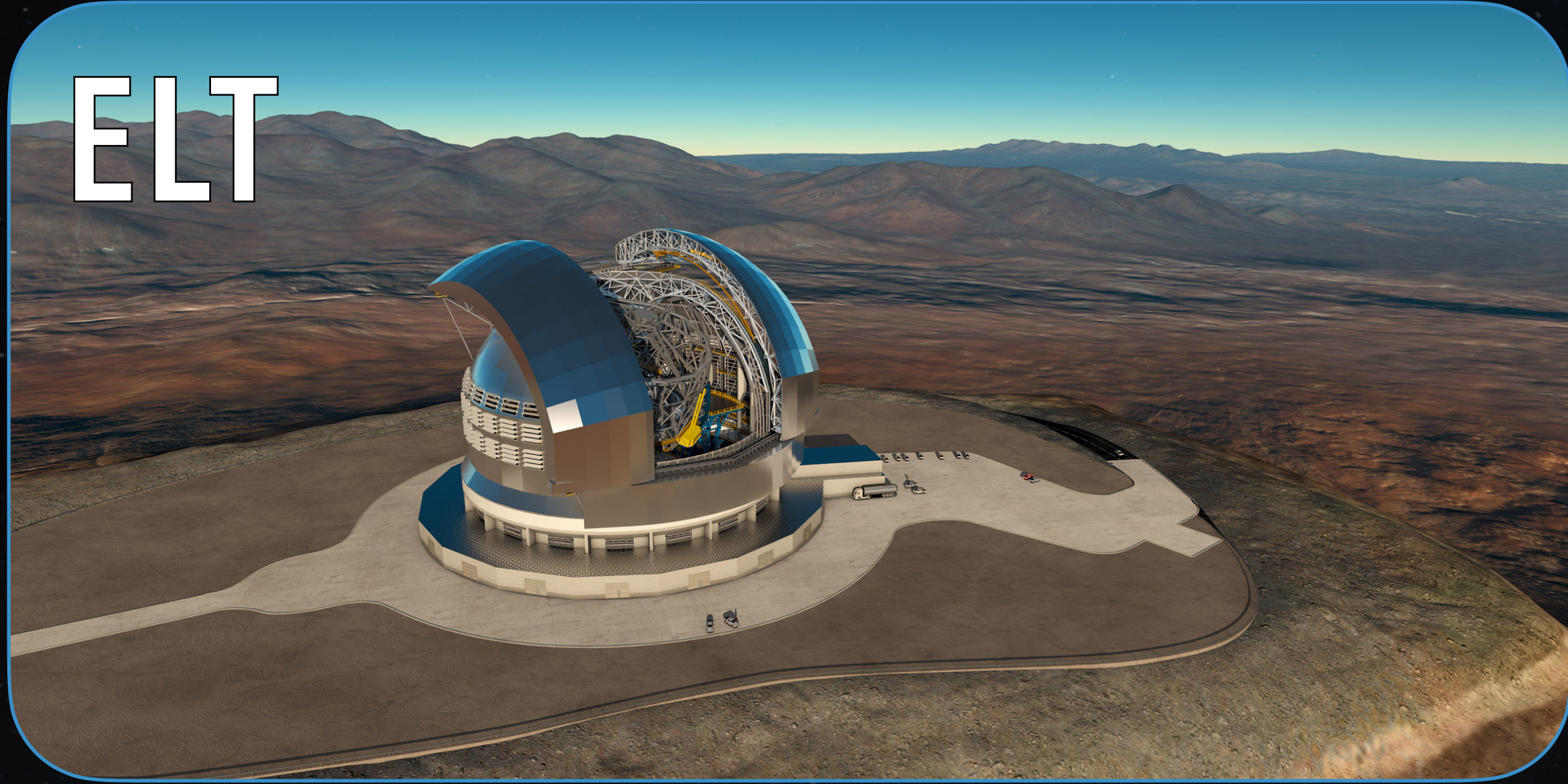
PLATO



ROMAN



ELT



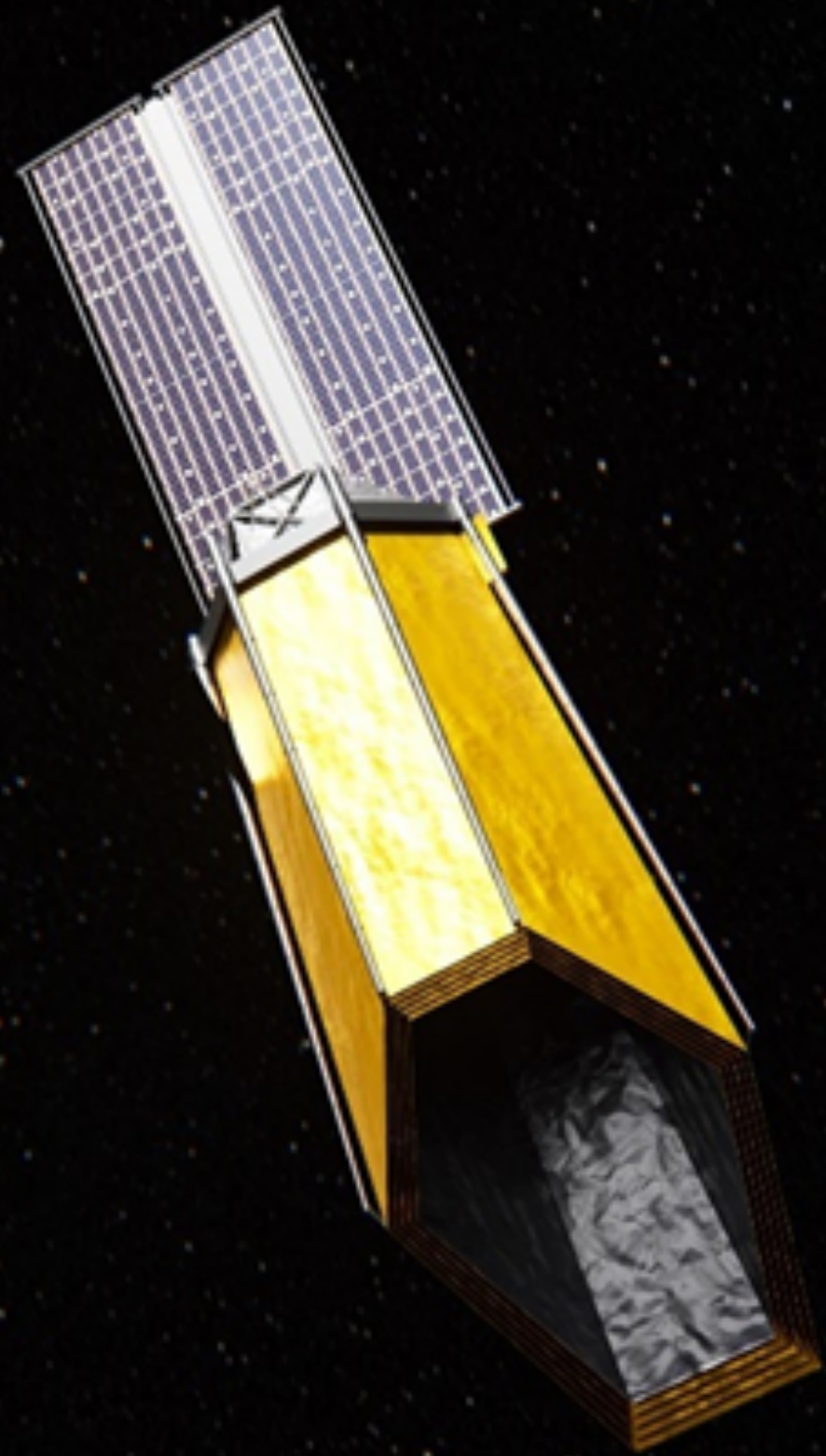
GMT



TMT



HWO



LIFE



NAUTILUS



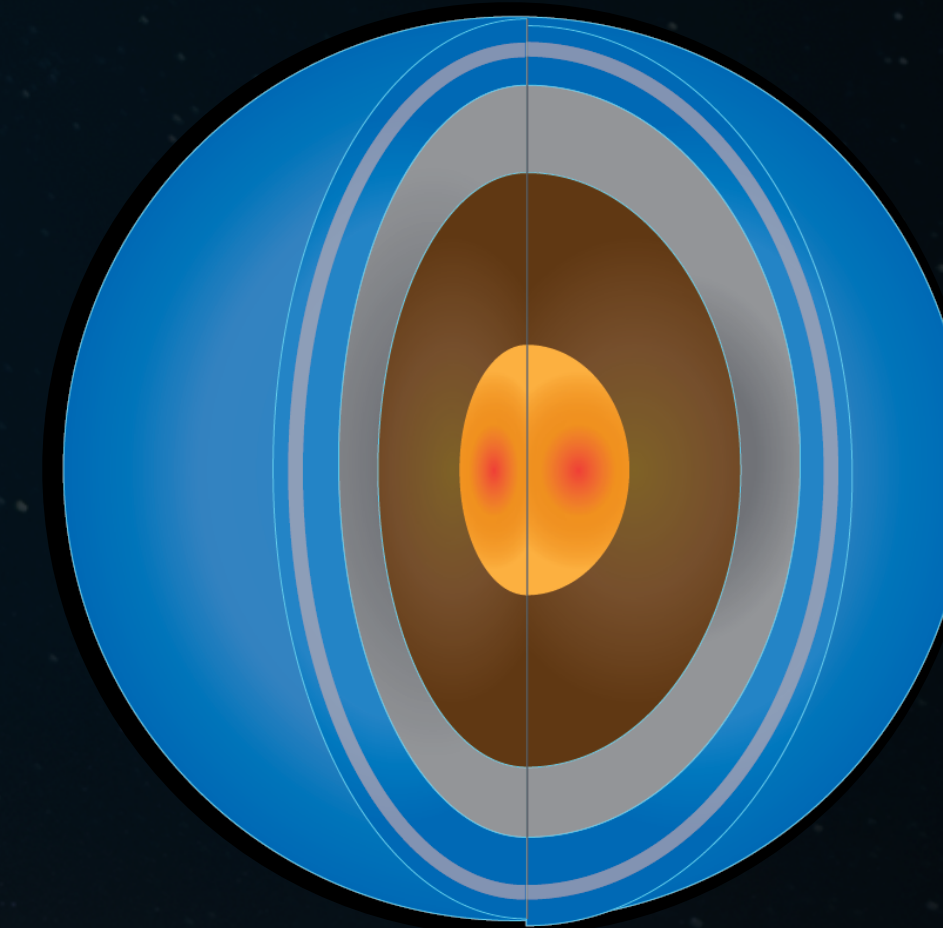


7 SUB-NEPTUNES AND THE SEARCH FOR LIFE



TEMPERATE SUB-NEPTUNES – HYCEAN WORLDS

- Approaching temperate temperature range, surprises may await
- Liquid water oceans? Habitable? (Madhusudhan+2025)
- Aerial life? Proposed for Venus (e.g., Sagan, Seager, ...)



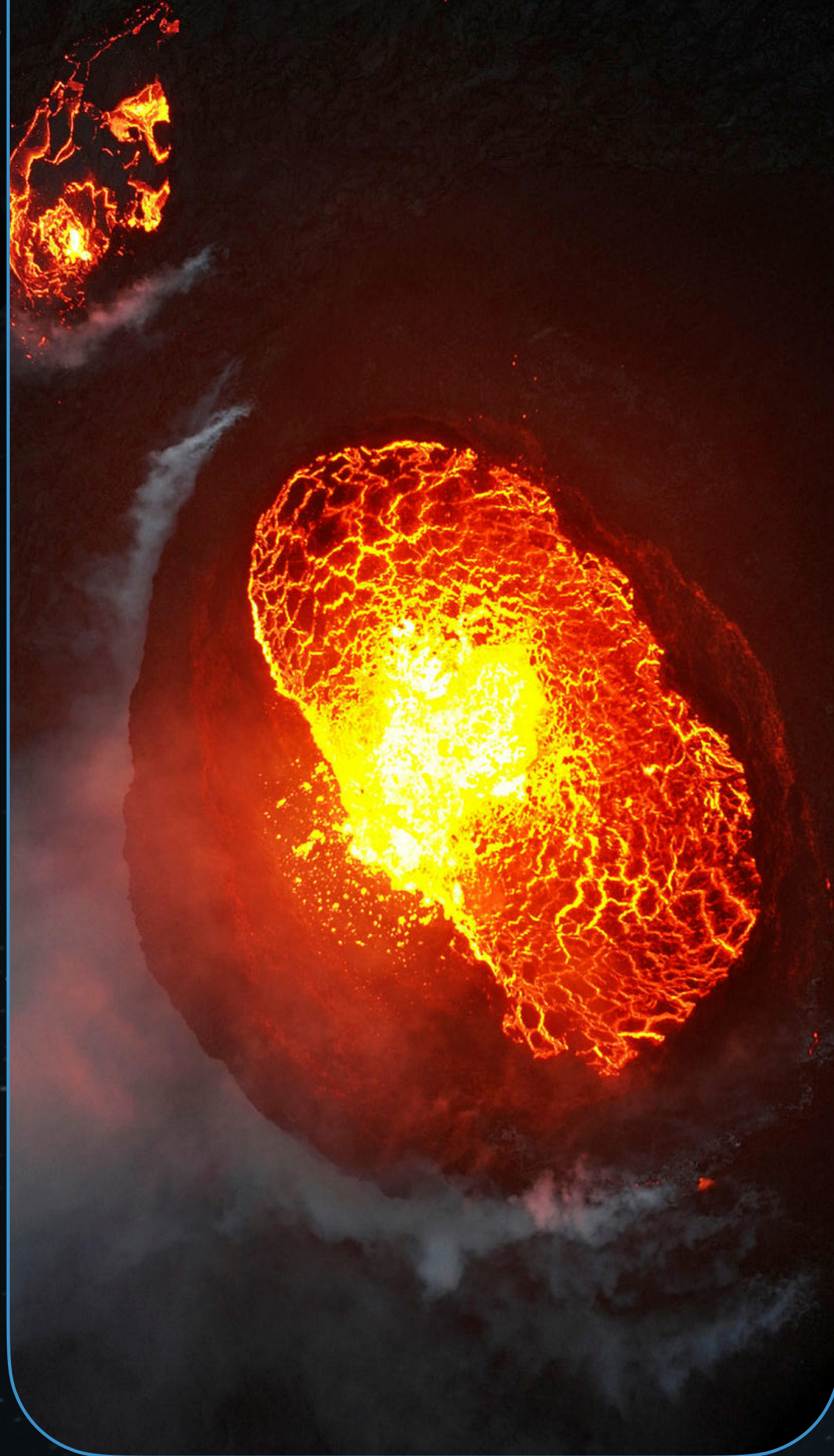
- Thin H₂ atmospheres
- Cold Trap for Water
- Clouds
- Liquid Water ocean
- High-P Ice
- Core/Mantle

KNOWLEDGE TRANSFER

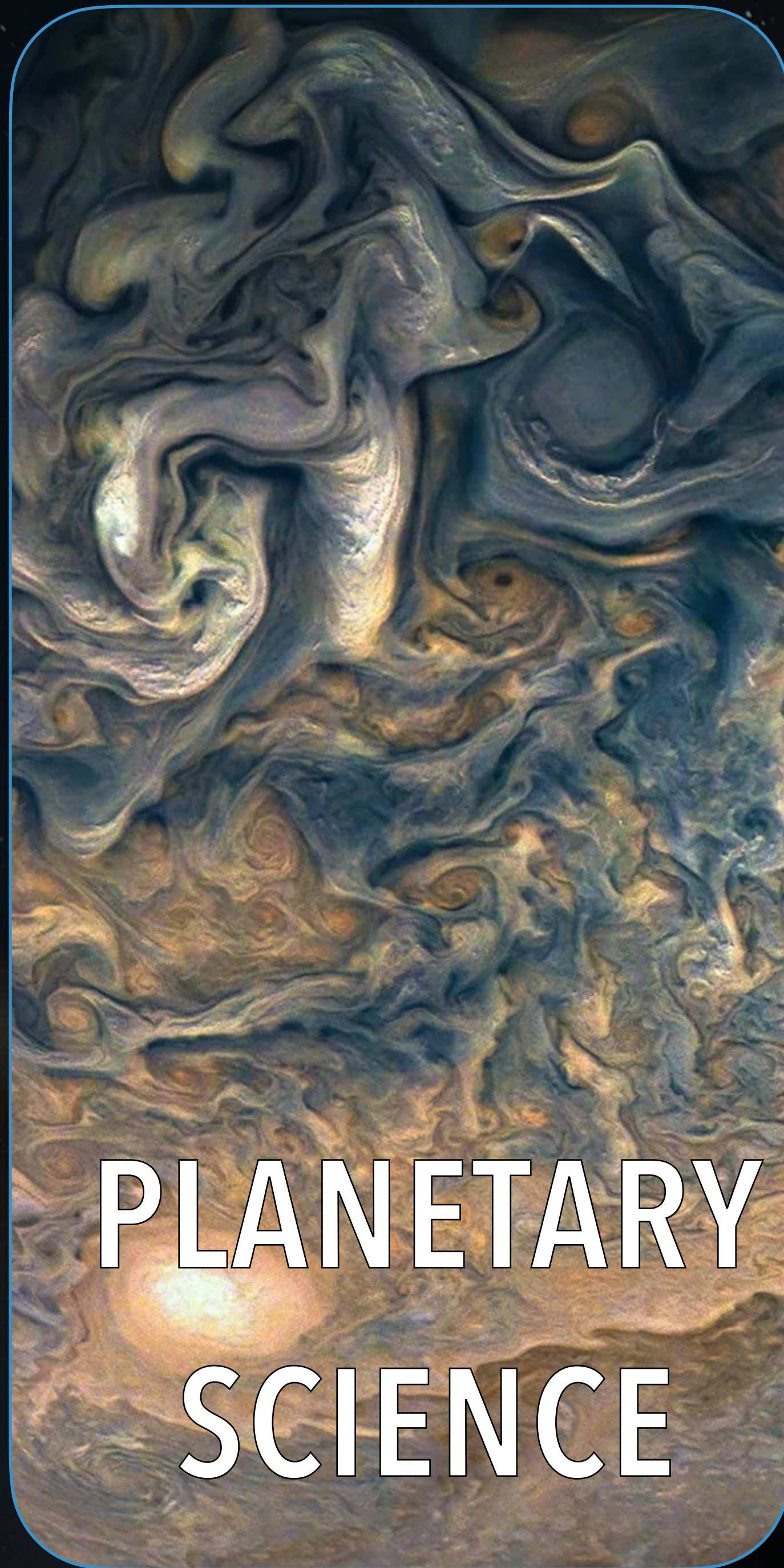
- Likely that path to understanding exo-Earths leads through sub-neptunes and super-earths
- Need for understanding processes over broad parameter ranges and planet types

8 INFORMATION BOOST

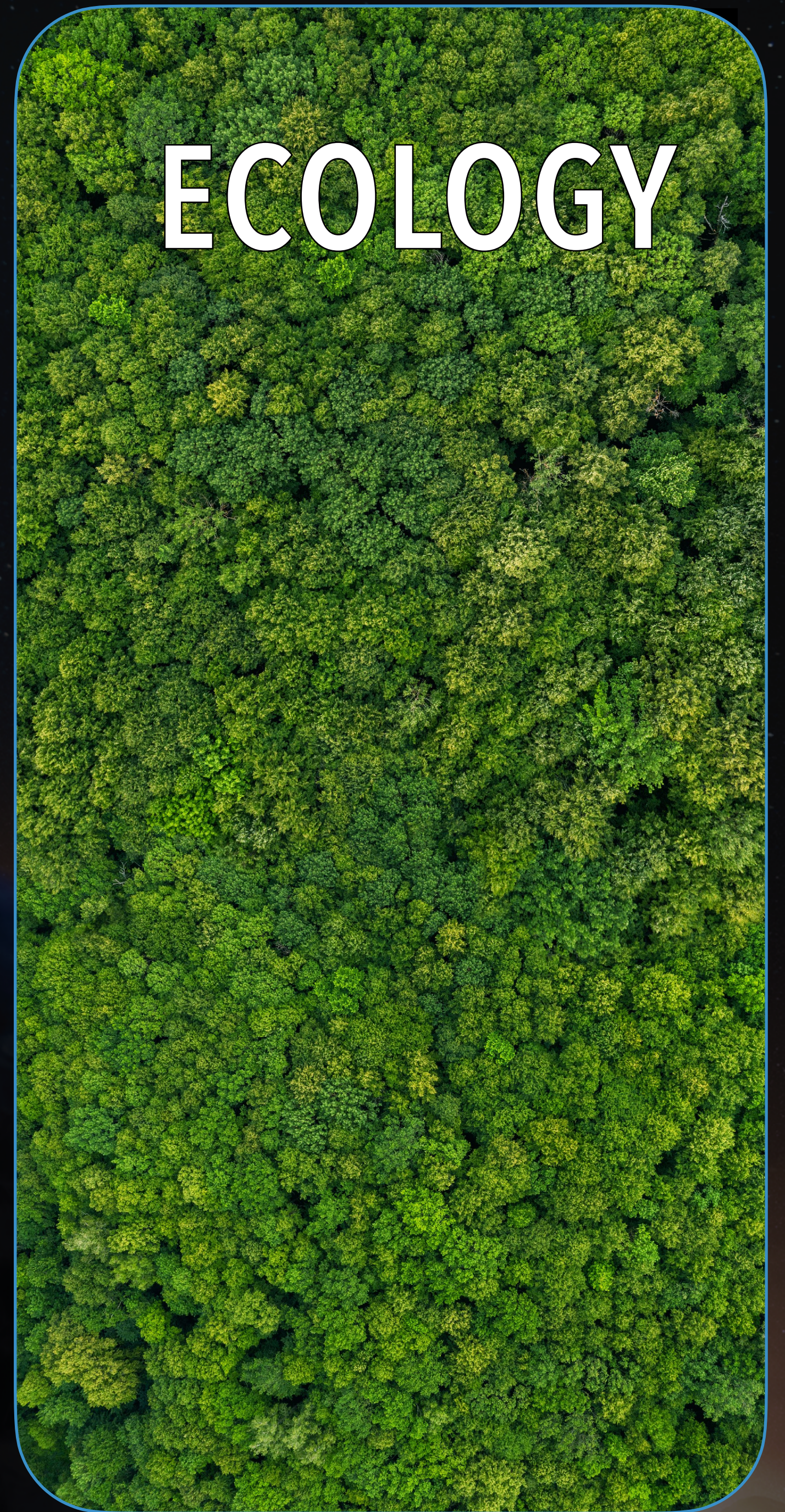
GEOSCIENCES



PLANETARY SCIENCE

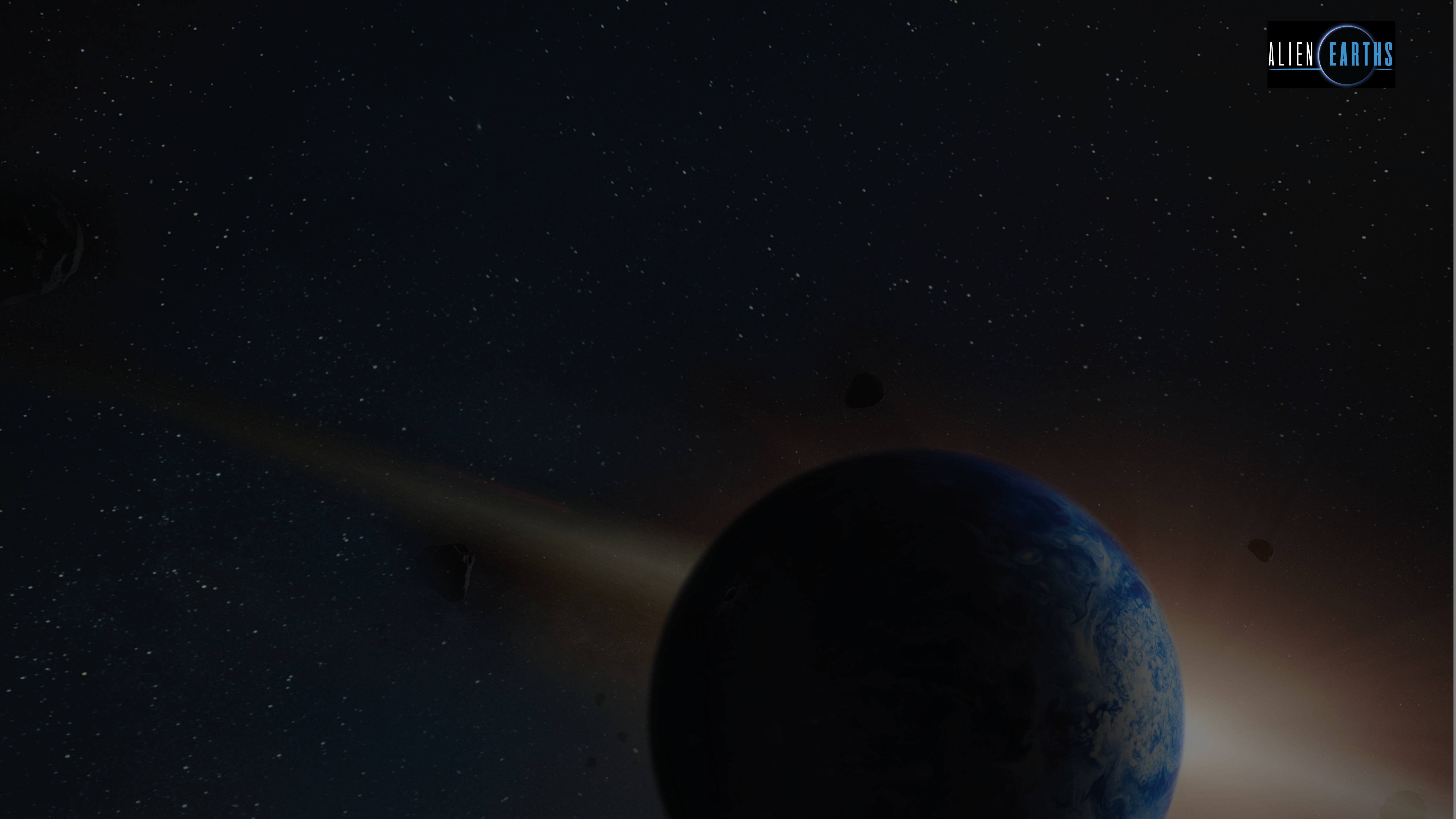


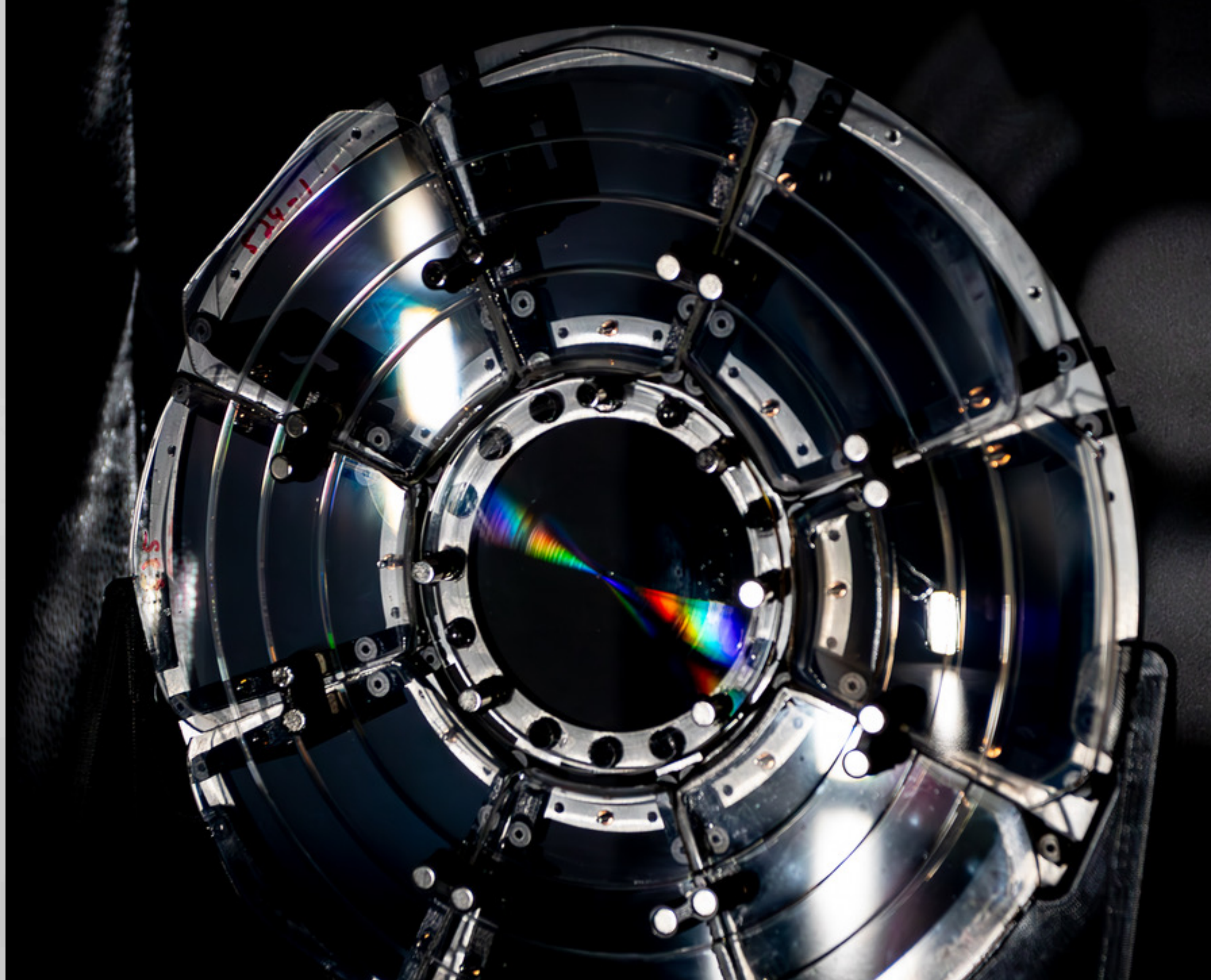
ECOLOGY



FUTURE OF SUB-NEPTUNE STUDIES

- Data vs. Information vs. Knowledge
- Complexity Likely Increases toward Cooler Planets
- Focus on planetary processes rather than sub-types of planets: Integrative vs. Reductionist
- Exoplanet Demographics are Key: Integrative
- 2D → Multi-D demographics: Testing Presence of *Predicted* Trends
- What information do we need? Is the Information enough to tackle complexity?
- We have incredible brain power and need information-rich data, and integrative approach





We invented a powerful technology
Scalable, hybrid lenses that can enable lower-cost, replicated space telescopes



Our goal is to drive down the cost of space telescopes by mass-producing large space optics
Similarly to how car windshields are produced