# Exploring New Worlds: Exoplanet Discoveries, Challenges, and Future Frontiers

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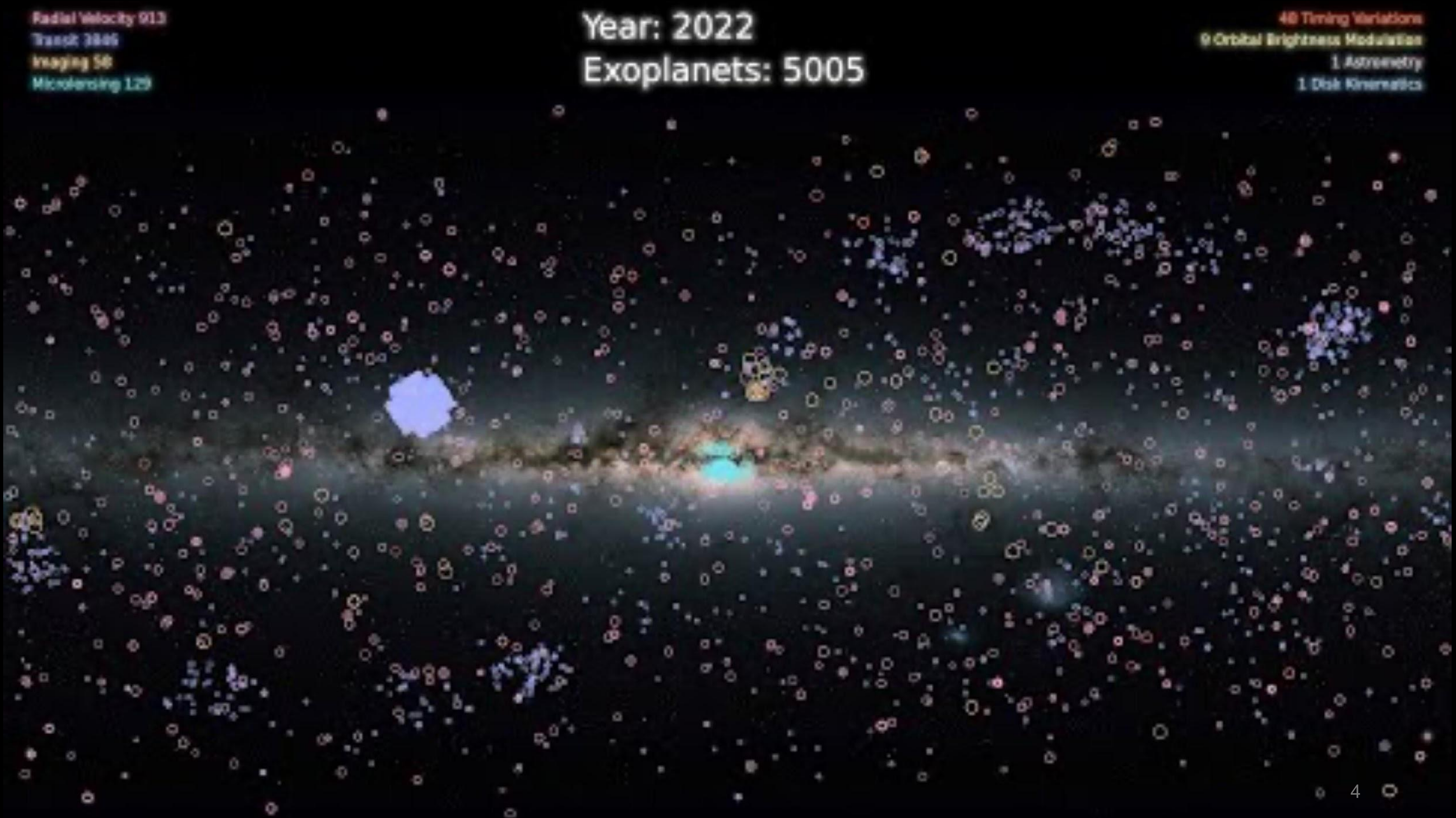
# Short Course Topics

- A brief history of exoplanet discovery
- Earth Cousins: The current search for habitable worlds
- Earth Twins: How to find, identify and characterize them
- Challenges
- Future

# A Brief History of Exoplanet Discovery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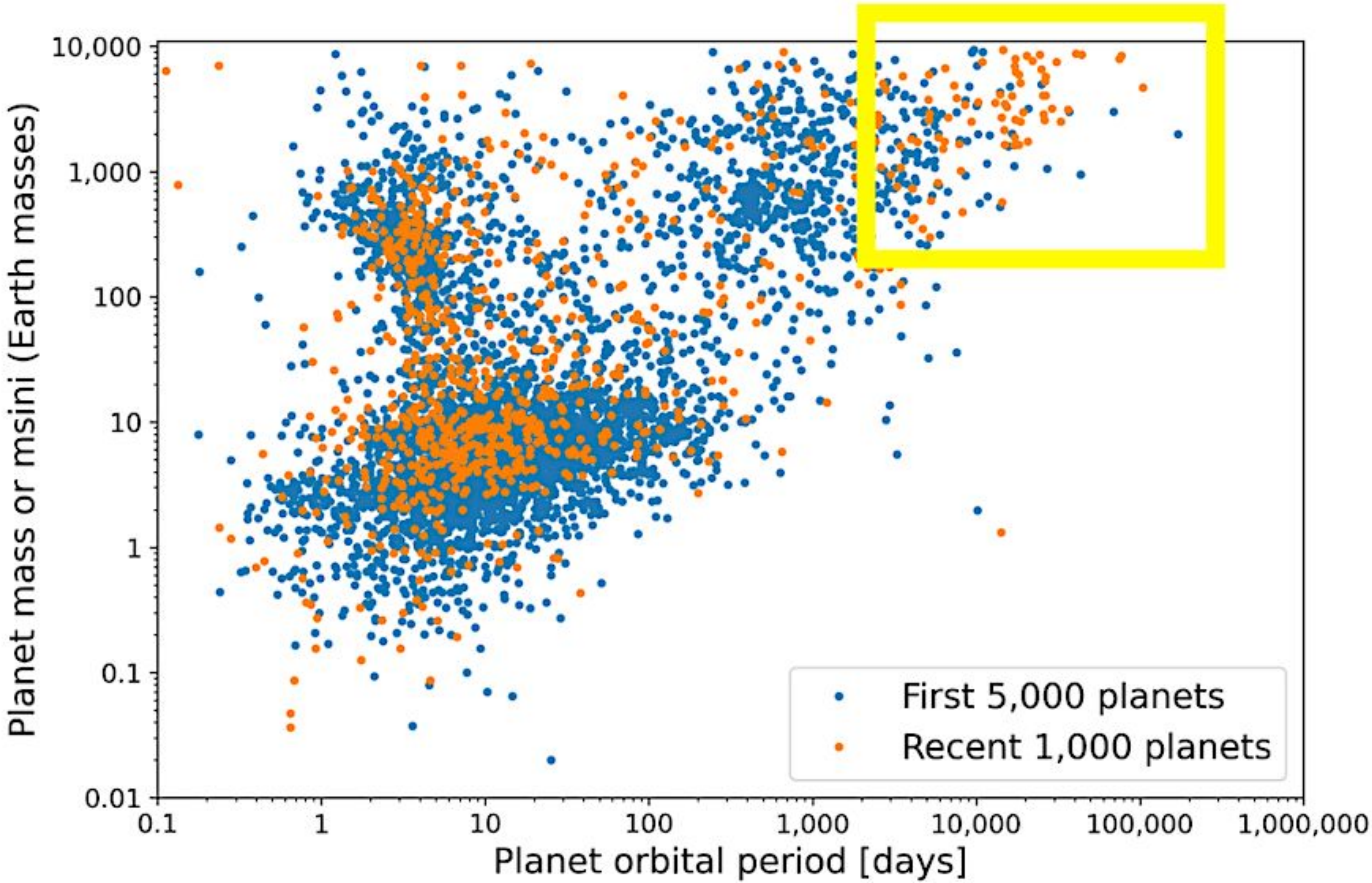
Transit 3846
Imaging 58
Microlensing 129
Year: 2022
Exoplanets: 5005
48 Timing Variations
9 Orbital Brightness Modulation
1 Astrometry
1 Disk Kinematics


10,000
1,000
100
10
1
0.1
0.01
Planet mass or msini (Earth masses)
0.1
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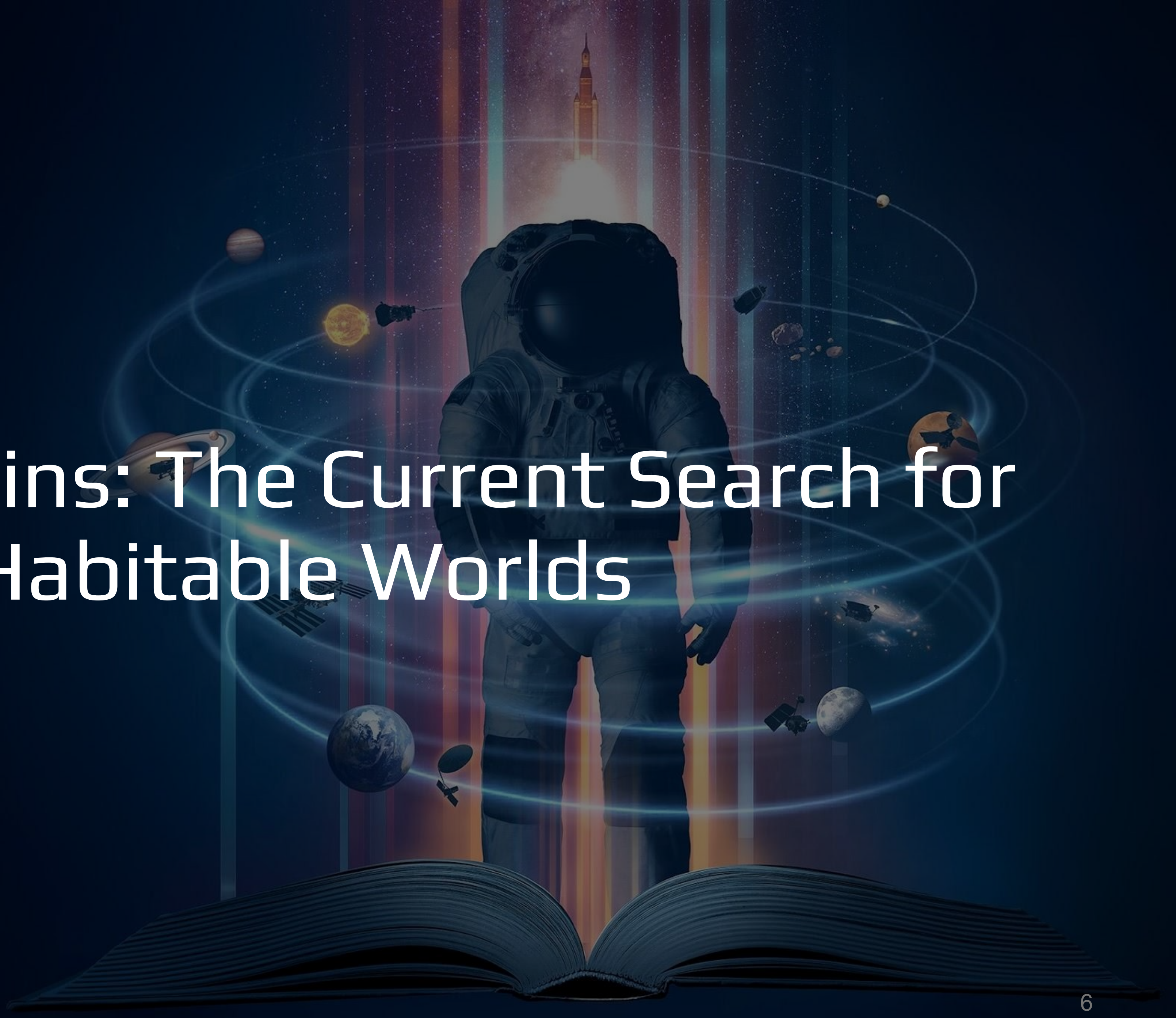
1,000,000
Planet orbital period [days]
First 5,000 planets
Recent 1,000 planets



# Earth Cousins: The Current Search for Habitable Worlds

# Follow the Water: Habitability’s First Principle

- **Water is a biological requirement**
  - Life as we know it depends on water because it makes up most of the mass of living cells and enables essential biochemical processes
  - Liquid water provides a medium where molecules can move, interact, and assemble into complex structures
- **Water is a chemical engine**
  - Water is an exceptional solvent that supports a wide range of reactions, stabilizes biomolecules and enables energy transport
- **Water as a cosmic opportunity**
  - Water is abundant across the universe in interstellar clouds, protoplanetary disks, comets, and planetary systems

# The Habitable Zone Defined

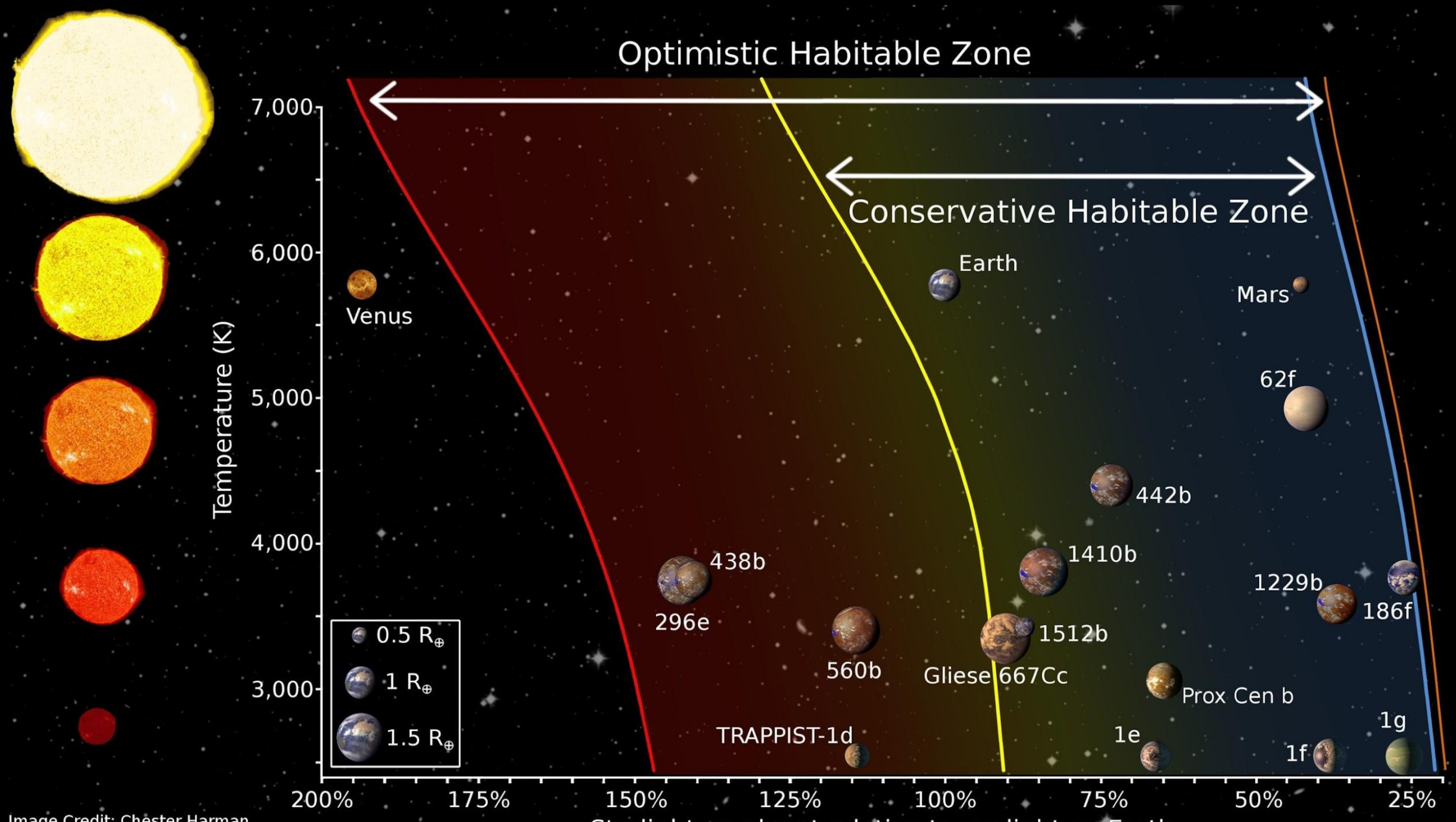


Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

Science

# An Earth-Sized Planet in the Habitable Zone of a Cool Star

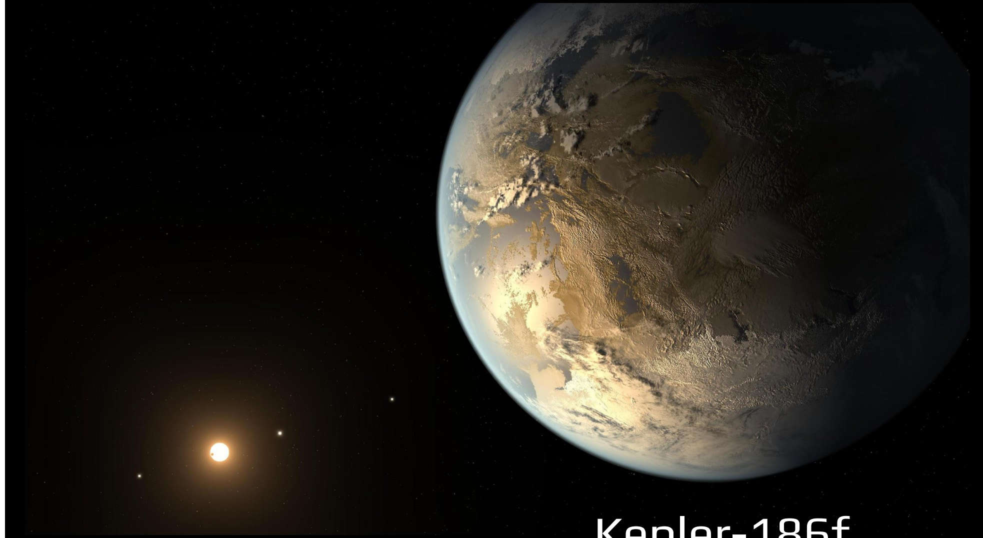
ELISA V. QUINTANA, THOMAS BARCLAY, SEAN N. RAYMOND, JASON F. ROWE, EMELINE BOLMONT, DOUGLAS A. CALDWELL, STEVE B. HOWELL, STEPHEN R. KANE, DANIEL HUBER, [...] , AND FRANCK SELSIS +13 authors Authors Info & Affiliations

*SCIENCE* • 18 Apr 2014 • Vol 344, Issue 6181 • pp. 277-280 • DOI: 10.1126/science.1249403

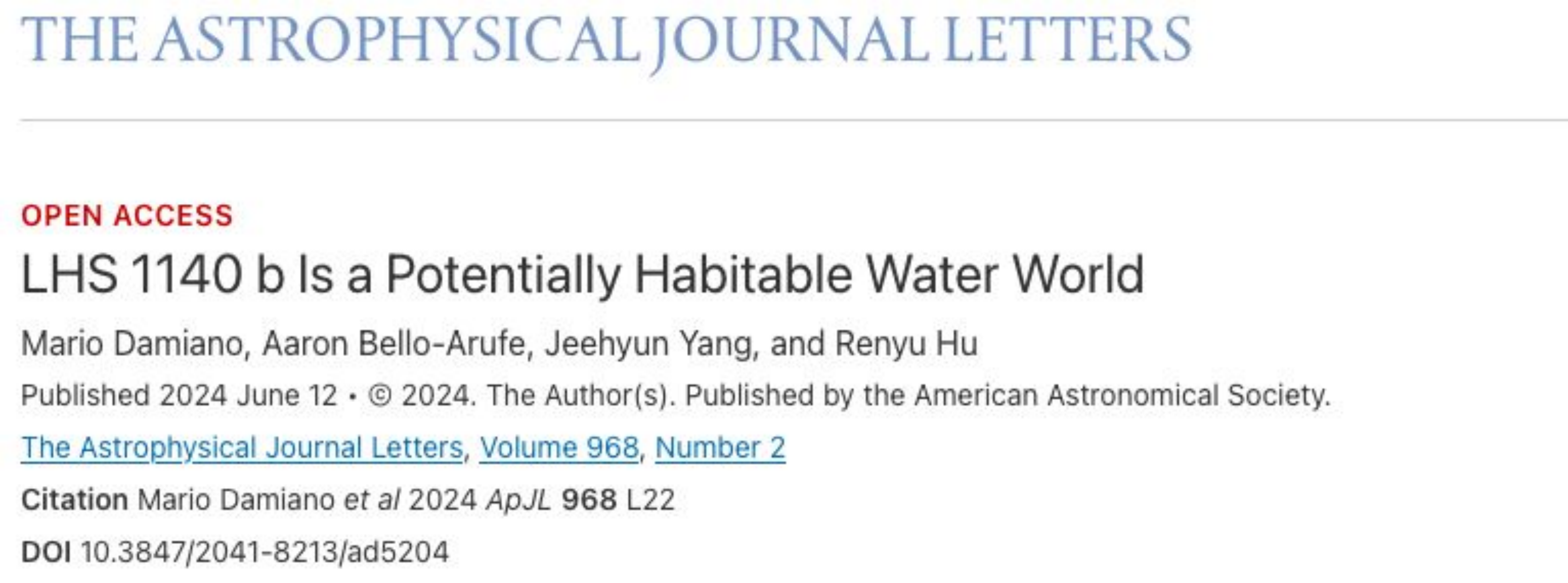
## Abstract

The quest for Earth-like planets is a major focus of current exoplanet research. Although planets that are Earth-sized and smaller have been detected, these planets reside in orbits that are too close to their host star to allow liquid water on their surfaces. We present the detection of Kepler-186f, a 1.11 ± 0.14 Earth-radius planet that is the outermost of five planets, all roughly Earth-sized, that transit a 0.47 ± 0.05 solar-radius star. The intensity and spectrum of the star's radiation place Kepler-186f in the stellar habitable zone, implying that if Kepler-186f has an Earth-like atmosphere and water at its surface, then some of this water is likely to be in liquid form.

Elisa Quintana



Kepler-186f



THE ASTROPHYSICAL JOURNAL LETTERS

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## LHS 1140 b Is a Potentially Habitable Water World

Mario Damiano, Aaron Bello-Arufe, Jeehyun Yang, and Renyu Hu

Published 2024 June 12 • © 2024. The Author(s). Published by the American Astronomical Society.

The Astrophysical Journal Letters, Volume 968, Number 2

**Citation** Mario Damiano *et al* 2024 *ApJL* **968** L22

**DOI** 10.3847/2041-8213/ad5204

Mario Damiano

THE ASTROPHYSICAL JOURNAL LETTERS

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## New Constraints on DMS and DMDS in the Atmosphere of K2-18 b from JWST MIRI

Nikku Madhusudhan, Savvas Constantinou, Måns Holmberg, Subhajit Sarkar, Anjali A. A. Piette, and Julianne I. Moses

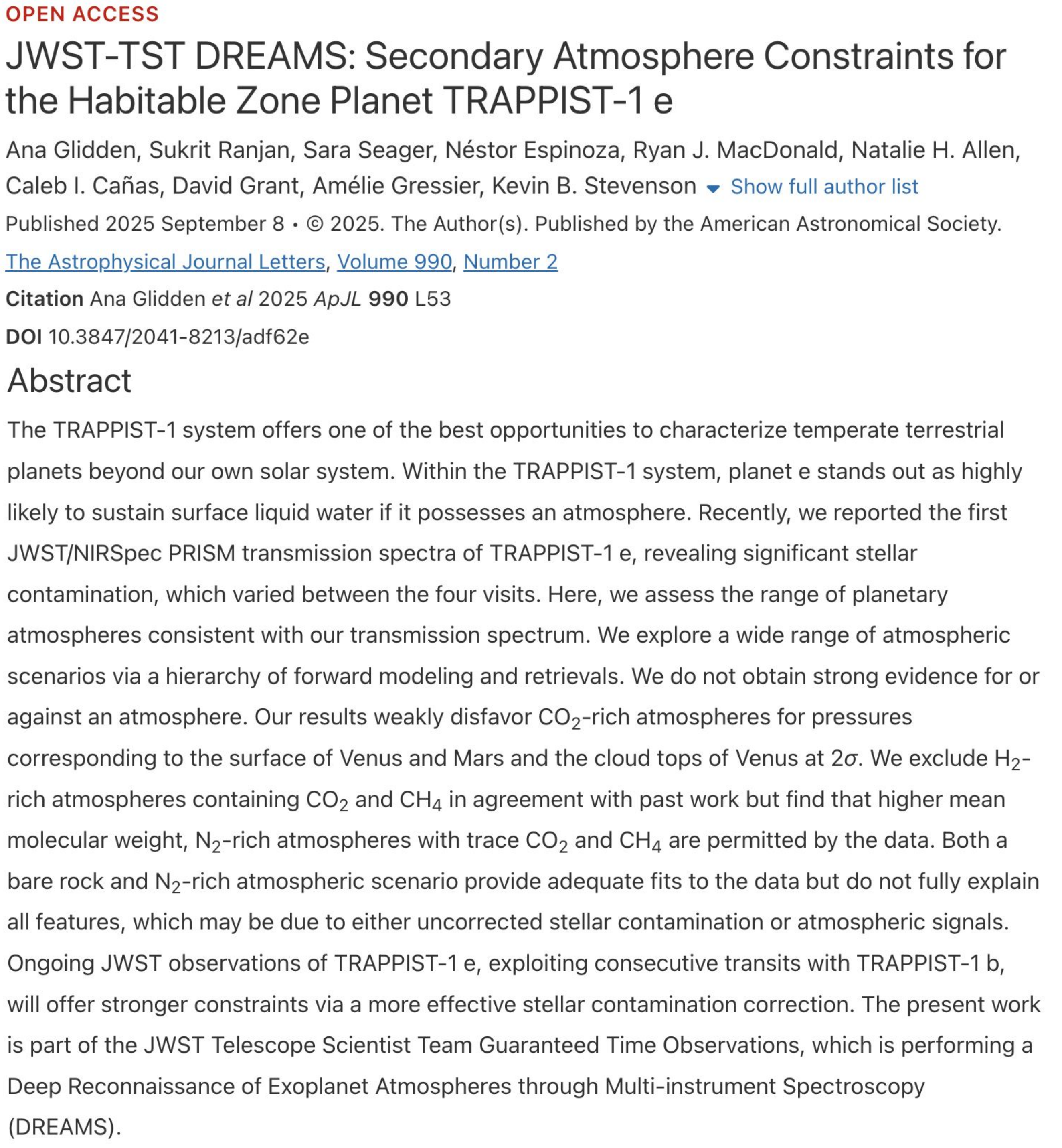
Published 2025 April 17 • © 2025. The Author(s). Published by the American Astronomical Society.

The Astrophysical Journal Letters, Volume 983, Number 2

**Citation** Nikku Madhusudhan *et al* 2025 *ApJL* **983** L40

**DOI** 10.3847/2041-8213/adc1c8

Nikku Madhusudhan



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# JWST-TST DREAMS: Secondary Atmosphere Constraints for the Habitable Zone Planet TRAPPIST-1 e

Ana Glidden, Sukrit Ranjan, Sara Seager, Néstor Espinoza, Ryan J. MacDonald, Natalie H. Allen, Caleb I. Cañas, David Grant, Amélie Gressier, Kevin B. Stevenson ▾ Show full author list

Published 2025 September 8 • © 2025. The Author(s). Published by the American Astronomical Society.

The Astrophysical Journal Letters, Volume 990, Number 2

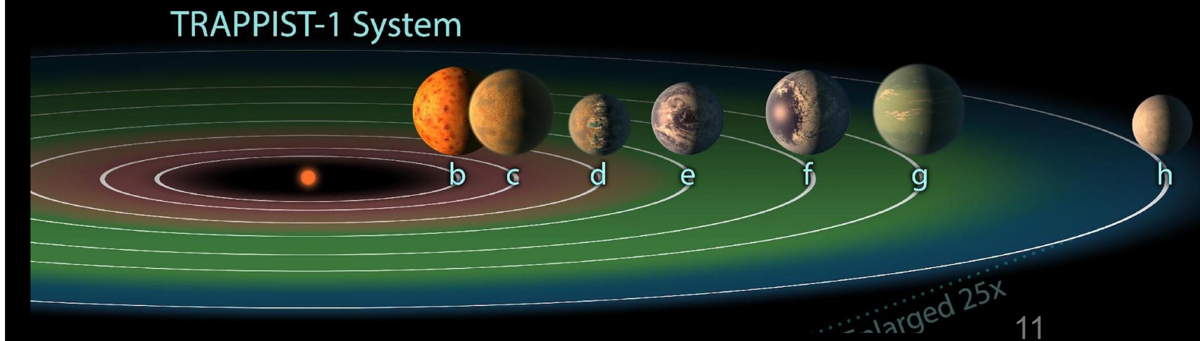
**Citation** Ana Glidden *et al* 2025 *ApJL* **990** L53

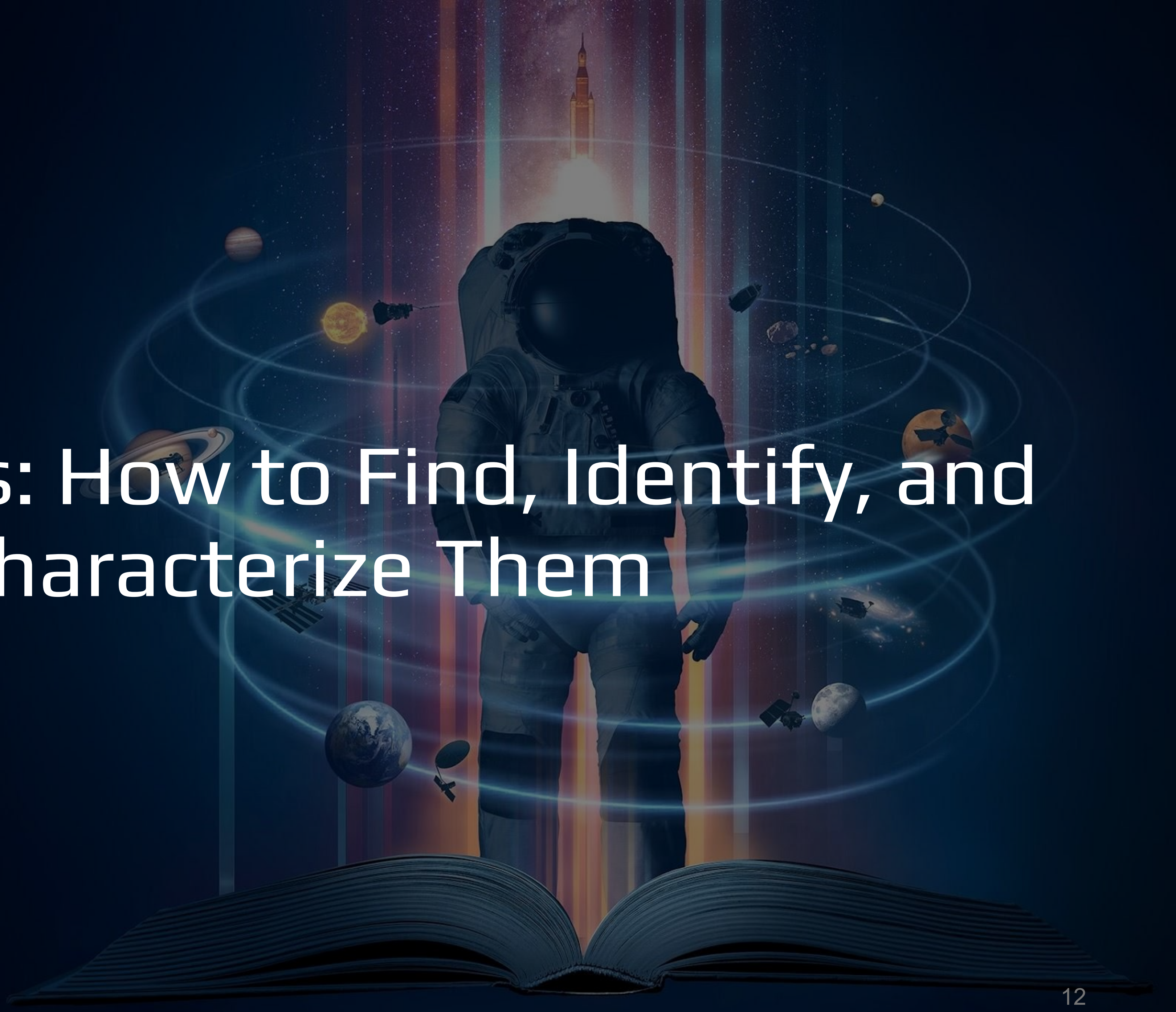
**DOI** 10.3847/2041-8213/adf62e

## Abstract

The TRAPPIST-1 system offers one of the best opportunities to characterize temperate terrestrial planets beyond our own solar system. Within the TRAPPIST-1 system, planet e stands out as highly likely to sustain surface liquid water if it possesses an atmosphere. Recently, we reported the first JWST/NIRSpec PRISM transmission spectra of TRAPPIST-1 e, revealing significant stellar contamination, which varied between the four visits. Here, we assess the range of planetary atmospheres consistent with our transmission spectrum. We explore a wide range of atmospheric scenarios via a hierarchy of forward modeling and retrievals. We do not obtain strong evidence for or against an atmosphere. Our results weakly disfavor $CO_2$-rich atmospheres for pressures corresponding to the surface of Venus and Mars and the cloud tops of Venus at $2\sigma$. We exclude $H_2$-rich atmospheres containing $CO_2$ and $CH_4$ in agreement with past work but find that higher mean molecular weight, $N_2$-rich atmospheres with trace $CO_2$ and $CH_4$ are permitted by the data. Both a bare rock and $N_2$-rich atmospheric scenario provide adequate fits to the data but do not fully explain all features, which may be due to either uncorrected stellar contamination or atmospheric signals. Ongoing JWST observations of TRAPPIST-1 e, exploiting consecutive transits with TRAPPIST-1 b, will offer stronger constraints via a more effective stellar contamination correction. The present work is part of the JWST Telescope Scientist Team Guaranteed Time Observations, which is performing a Deep Reconnaissance of Exoplanet Atmospheres through Multi-instrument Spectroscopy (DREAMS).

Ana Glidden





# Earth Twins: How to Find, Identify, and Characterize Them

# Finding Potential targets: Exoplanetary Yield Calculations

Stars in the local volume

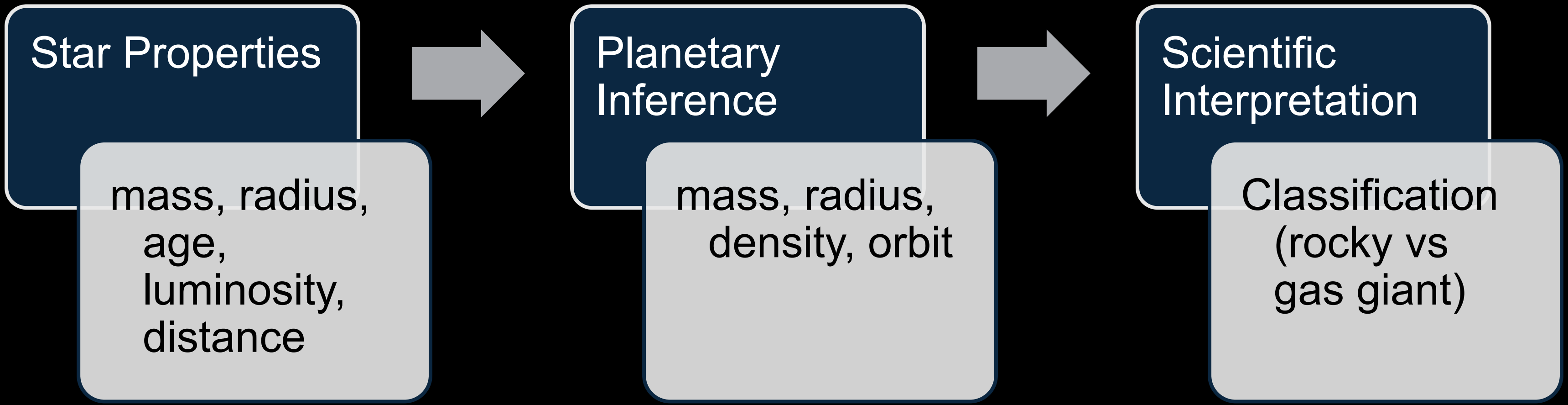
Stars observable by the mission

Stars with detectable HZs

Expected ExoEarth yield

# The Major Axes for Identifying Potential Earth-like targets

1. Stellar properties (type, brightness, activity)
2. Planetary Physical Properties (radius, mass, density)
3. Orbital Distance (stellar insolation, HZ orbital region)



**Star Properties**

mass, radius, age, luminosity, distance

**Planetary Inference**

mass, radius, density, orbit

**Scientific Interpretation**

Classification (rocky vs gas giant)

# Step 1: Characterizing the Stellar Context

- **Planet measurements depend on stellar measurements.**
- Stellar mass, radius, age, luminosity, distance are all properties that need to be understood to properly infer planetary properties
- Planetary properties are usually inferred as quantities relative to the host star

# Step 2: Constraining Bulk Planetary Properties (Mass)

- **Mass** - Important for constraining atmospheric properties like scale height, escape rates, long-term climate stability
  - **Radial Velocity** - measuring the doppler shift of spectral lines from host starlight as it wobbles about the center of mass. This is used to obtain minimum mass estimates
  - **Transit Timing Variations** - obtaining the mass by observing how planets perturb each other causing transits to occur early or late relative to a constant period model. The magnitude of these shifts encodes masses and eccentricities of the interacting planets
  - **Astrometry** - measuring the star's proper motion on the sky where the amplitude of this motion can provide mass estimates and yields the full 3D orbital configuration.

# Step 2: Constraining Bulk Planetary Properties (Radius)

- **Radius** – Crucial for understanding and identifying the transitions between rocky and non-rocky planets
  - **Transits** - As the planet passes in front of the host star and causes a decrease in stellar brightness the depth of level of occultation will correlate with the size of the planet. But requires precise characterization of the host star to be precise.
  - **Direct imaging** - the planetary radius can be inferred from the reflected spectrum if the orbit is sufficiently know (radius – phase angle degeneracy)
- **Density can then be inferred from radius and mass estimates**

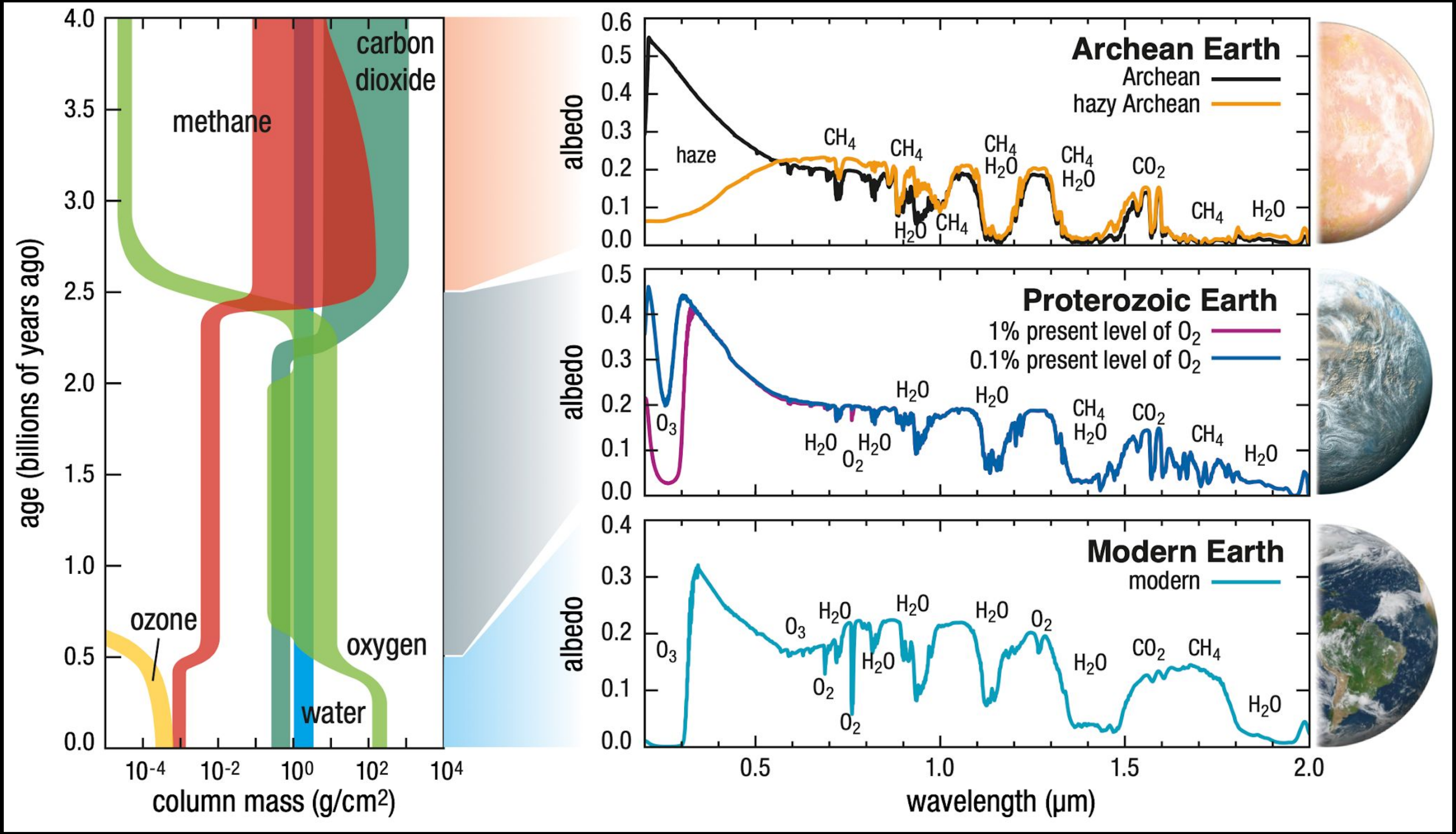
# Step 3: Constraining the Orbital Distance

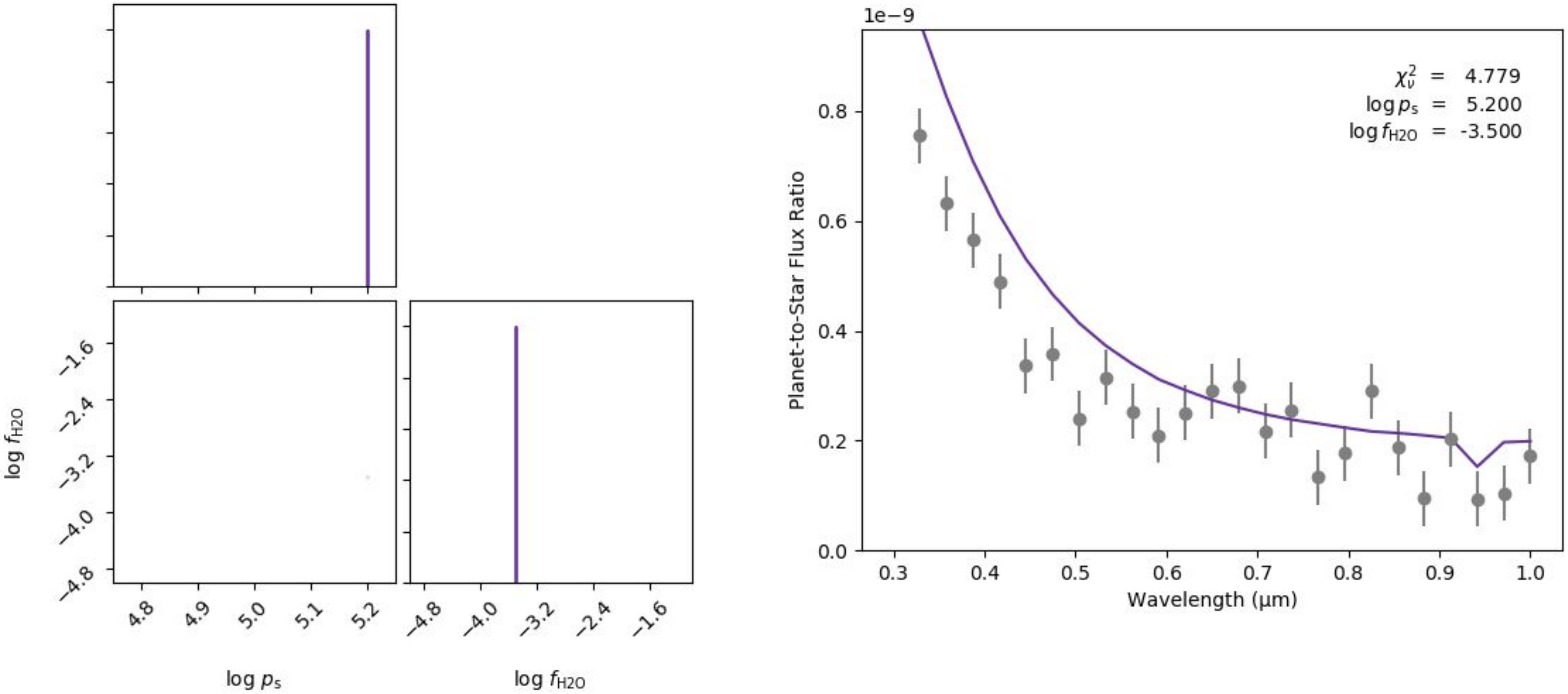
- **Orbital Distance** – Tightly tied to inferences of habitability and setting the stellar flux the planet receives
  - **Transits** - Measuring the time between transits in order to constrain the orbital period to which the orbital distance can be backed out using Kepler's 3rd law ($P^2 \sim a^3$)
  - **Astrometry** - 3D orbital configuration and mapping
  - **Direct Imaging -** Directly observing the orbital separation because we're resolving the star and planet as separate point sources ideally.

# Developing ExoEarth Characterization Strategies

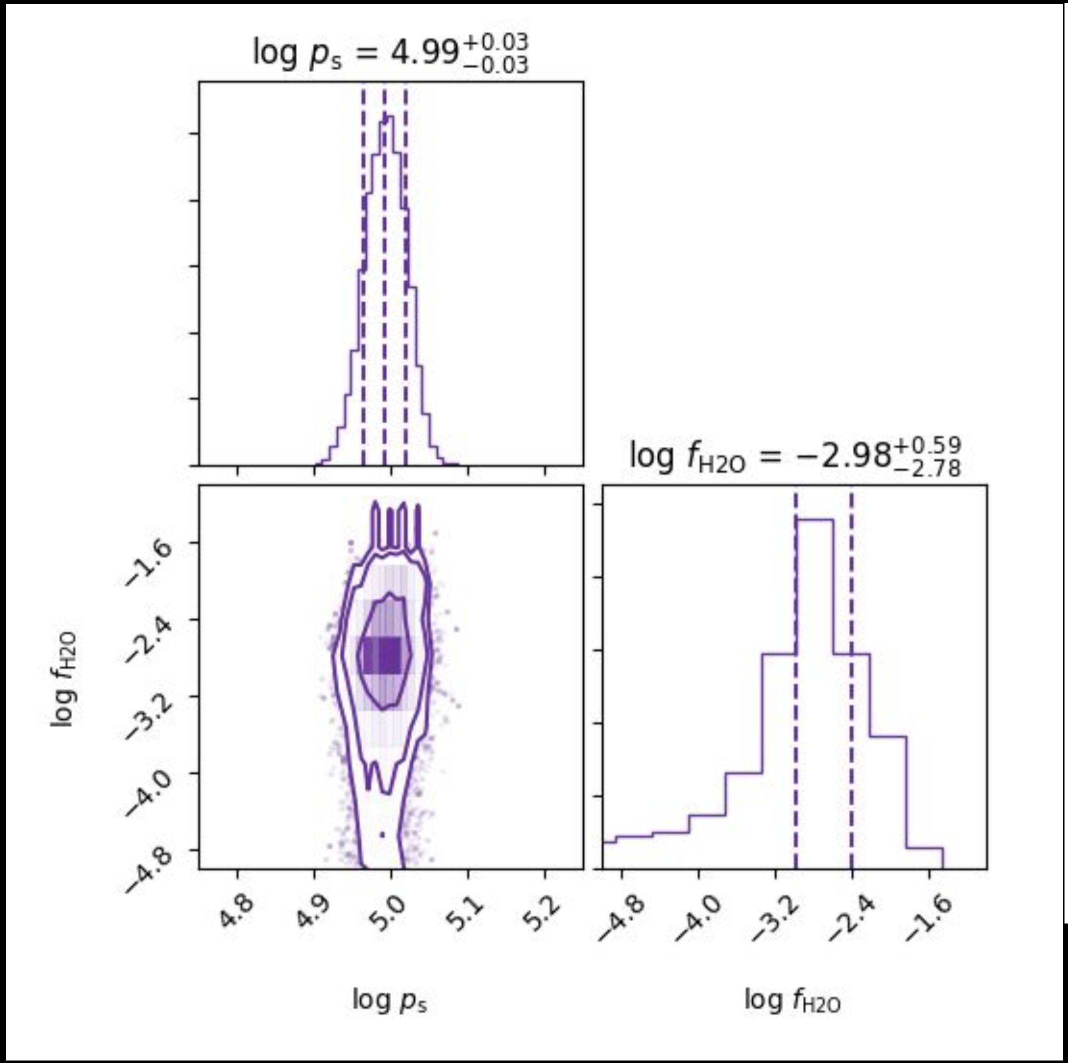
- **Scientific Goal**: Determine which atmospheric compositions and climate states could be inferred from observations of Earth-like exoplanets
- **Current Challenge**: We have no direct observations of true ExoEarths to date (only Earth observations, e.g., EPOXI data)
- **Strategy**: Use simulated atmospheres and synthetic data to evaluate how different observing approaches recover key atmospheric properties
- **Impact**: These results guide instrument requirements and trade studies for next generation missions

# Earth is More Than One Planet





Movie credit: Ty Robinson



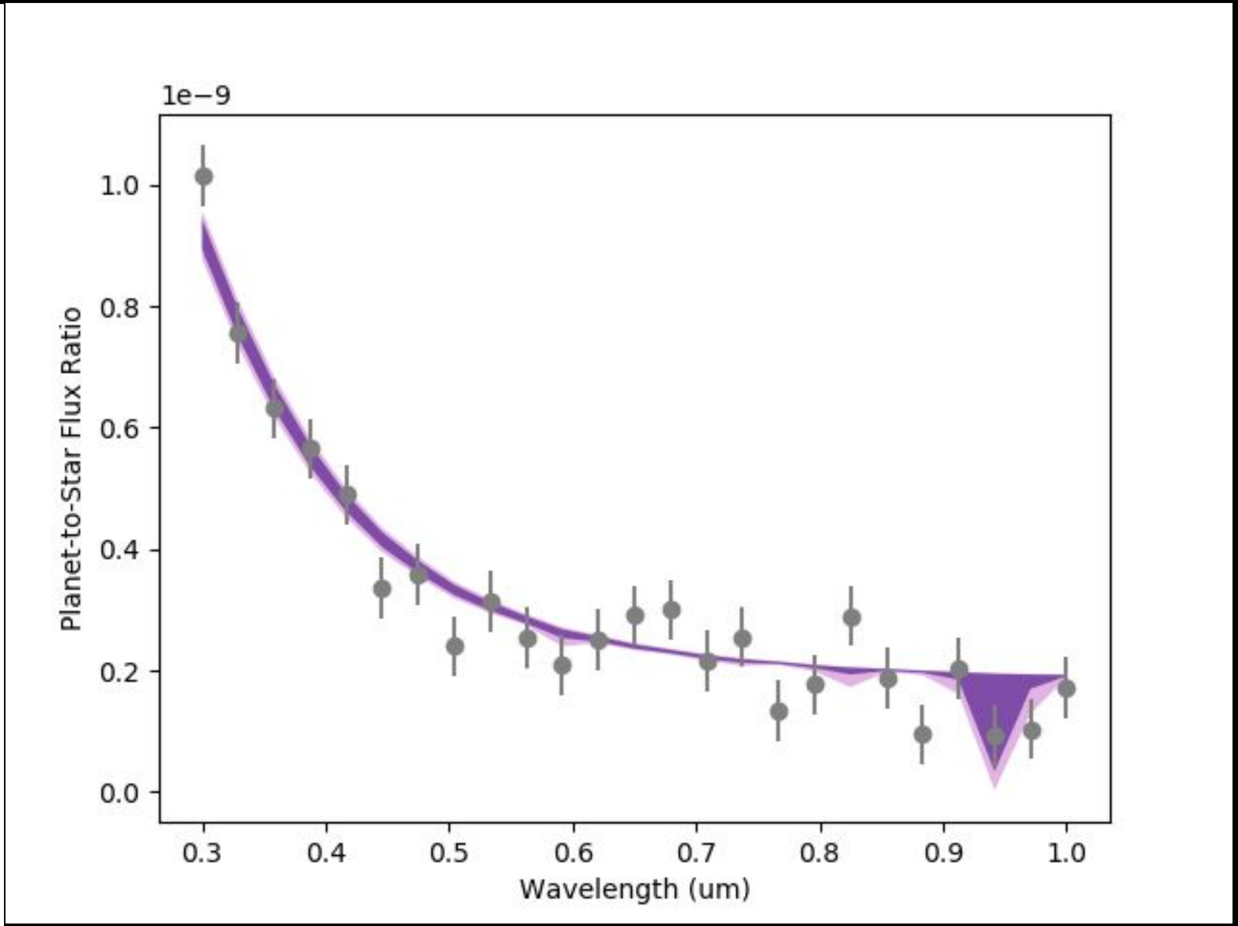
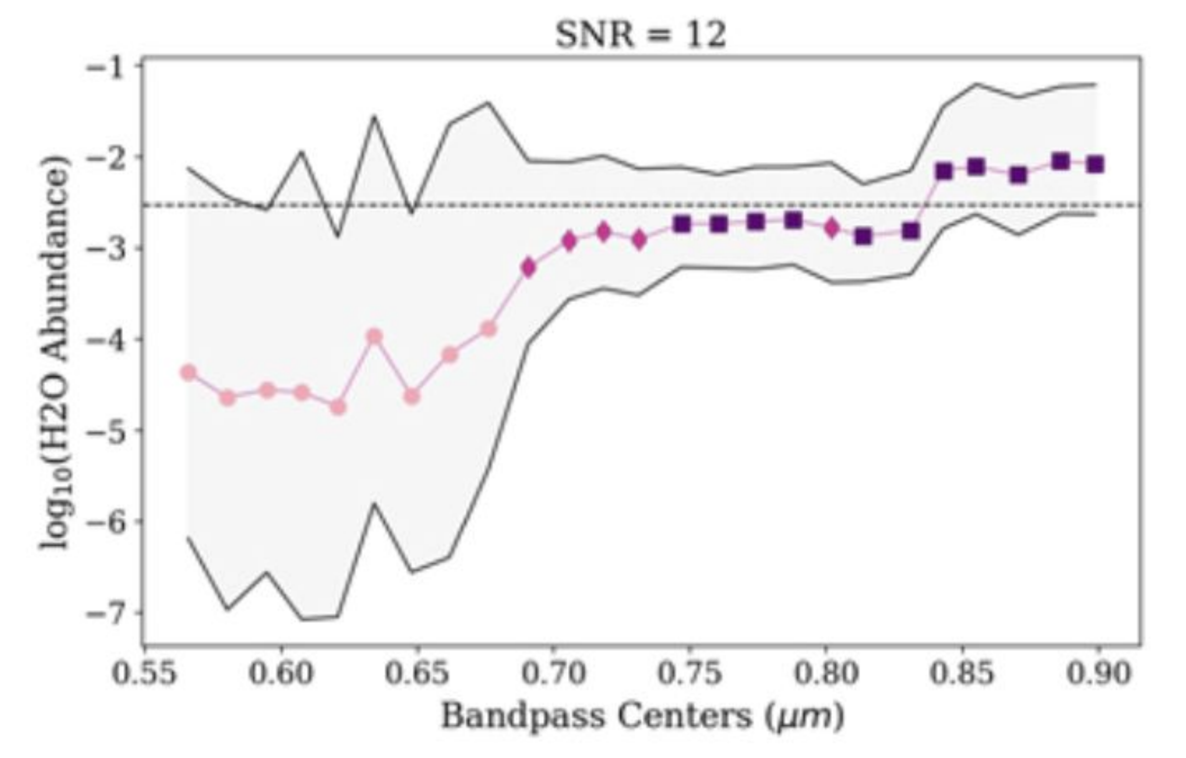
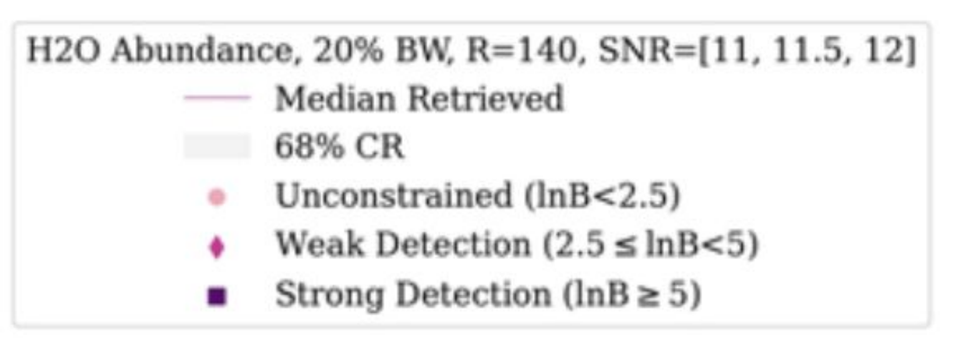


Figure credit: Ty Robinson

# Optimized bandpasses for $H_2O$ Detection in Reflected Light

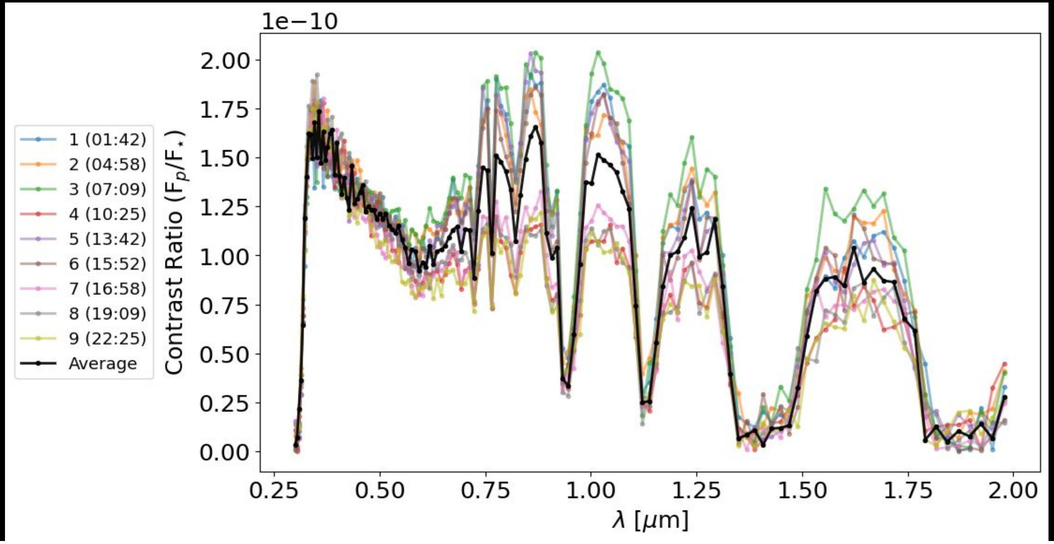


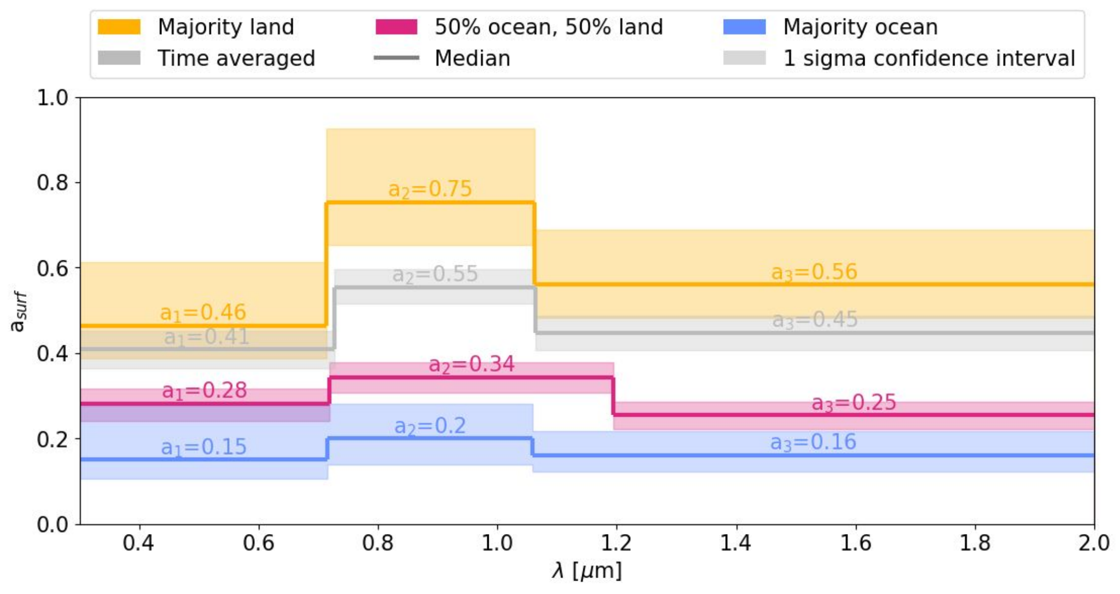


Latouf et al., 2023

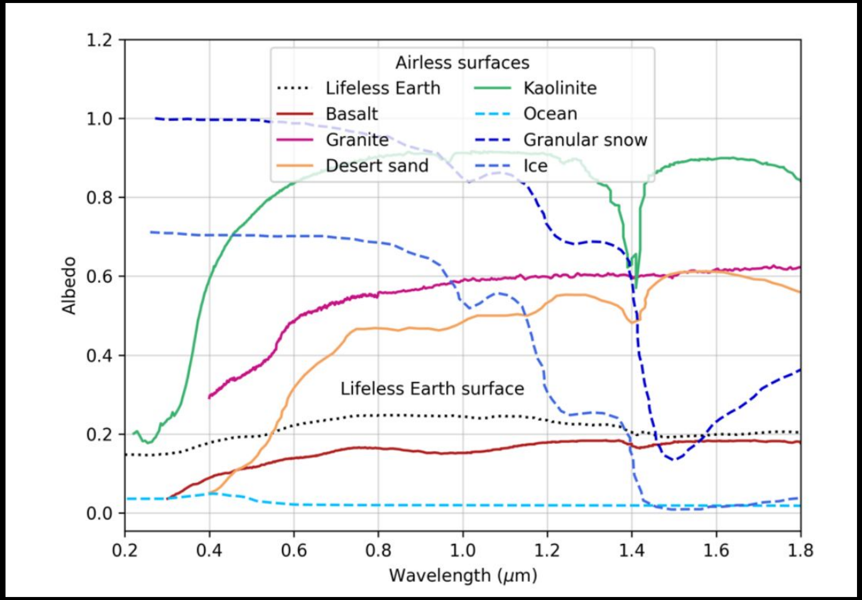
Natasha Latouf

# Beyond just atmospheres

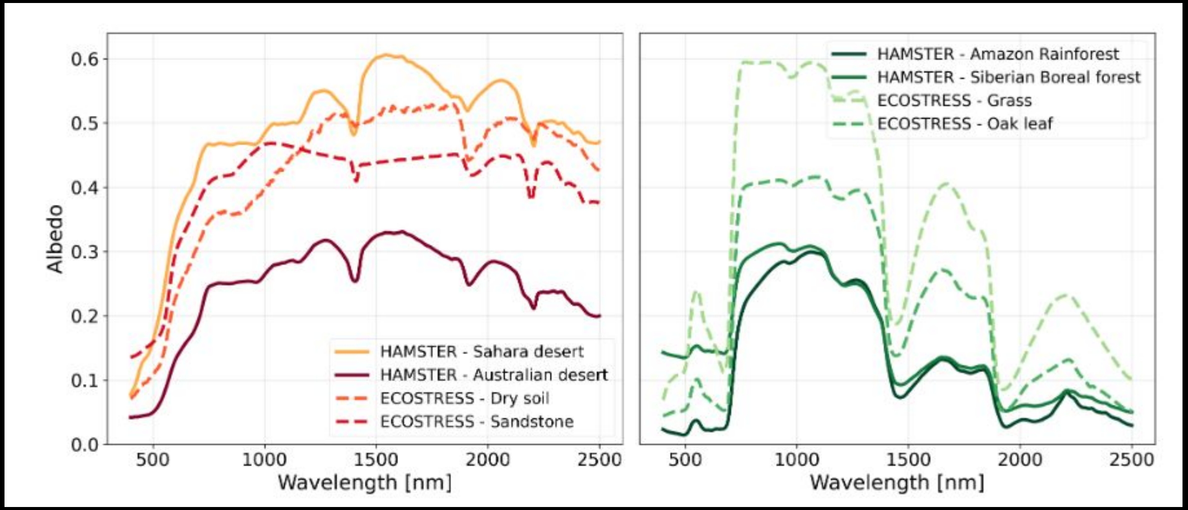




Burr, Damiano, & Hu in review



Ulses et al. 2025



Roccetti et al.

# Challenges

# Observational Challenges

- **Radial Velocity** – ExoEarths produce extremely weak Doppler signals, easily overwhelmed by stellar activity and instrument systematics
- **Astrometry** – Detecting Earth mass planets requires sub-micro arcsecond precision, demanding extreme spacecraft stability
- **Direct Imaging** – Earth analogs are 10 billion times fainter than their host stars, requiring $10^{-10}$ contrast and exquisite starlight suppression

# Future Advancements

- **Deeper contrast and stability** – From advanced coronagraphs and starshades to isolate faint Earth-like planets
- **Space observatories built for biosignature detection** – Like HWO and LIFE which are being designed with biosignature detection and detailed characterization of temperate terrestrial planets as core science goals
- **Ground based apertures** – Providing high dispersion spectroscopy and synergy with space missions for characterization