Title: The Hycean Paradigm in Exoplanet Habitability - VIRTUAL

Speakers: Nikku Madhusudhan

Series: Colloquium

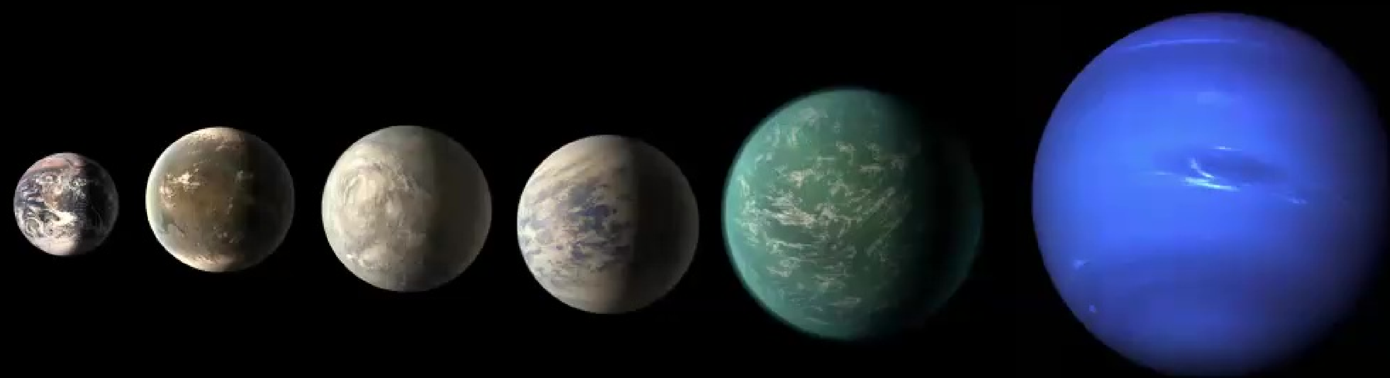
Date: November 22, 2023 - 2:00 PM

URL: https://pirsa.org/23110069

Abstract: Atmospheric characterisation of habitable-zone exoplanets is a major frontier of exoplanet science. The detection of atmospheric signatures of habitable Earth-like exoplanets is challenging due to their small planet-star size contrast and thin atmospheres with high mean molecular weight. Recently, a new class of habitable sub-Neptune exoplanets, called Hycean worlds, have been proposed, which are expected to be temperate ocean-covered worlds with H2-rich atmospheres. Their large sizes and extended atmospheres, compared to rocky planets of the same mass, make Hycean worlds significantly more accessible to atmospheric spectroscopy. Several temperate Sub-Neptunes have been identified in recent studies as candidate Hycean worlds orbiting nearby M dwarfs that make them highly conducive for transmission spectroscopy with JWST. Recently, we reported the first JWST spectrum of a possible Hycean world, K2-18 b, with detections of multiple carbon-bearing molecules in its atmosphere. In this talk, we will present constraints on the atmospheric composition of K2-18 b and on the temperature structure, clouds/hazes, atmospheric extent, chemical disequilibrium and the possibility of a habitable ocean underneath the atmosphere. We will discuss new observational and theoretical developments in the characterisation of candidate Hycean worlds, and their potential for habitability. Our findings demonstrate the unprecedented potential of JWST for characterising Hycean worlds, and temperate sub-Neptunes in general, and open a new era of atmospheric characterisation of habitable-zone exoplanets with JWST.

Zoom link https://pitp.zoom.us/j/98012554989?pwd=b0pCYkIvYmd2Y2hueUExQXBNVG8vZz09

The Hycean Paradigm in Exoplanet Habitability



Nikku Madhusudhan

Institute of Astronomy, University of Cambridge

Collaborators: Savvas Constantinou, Anjali Piette, , Subhajit Sarkar, Mans Holmberg, Julianne Moses, Frances Rigby, Edouard Barrier, Matt Nixon

Image Credits: NASA

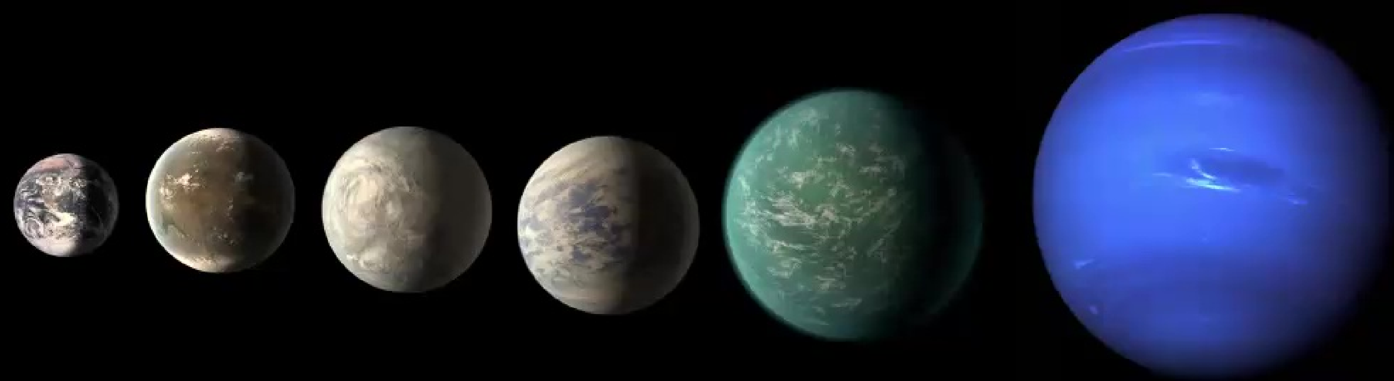
Perimeter Institute
22 November 2023

Requirements for Biosignature Detection in an Earth-twin

1. Detection of a true Earth-twin
2. Observational capability for biosignature detection

Image Credits: NASA

Harnessing Exoplanet Diversity



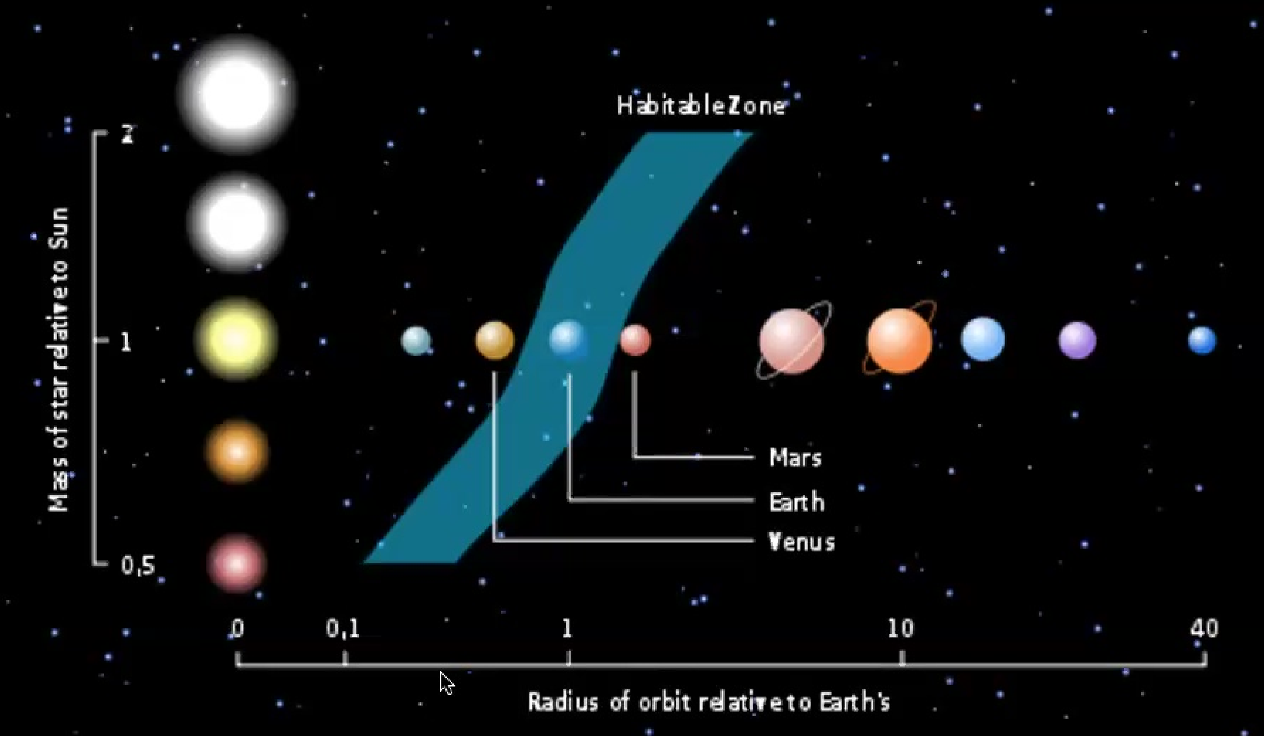
1. Which currently known exoplanets are potentially habitable?
2. Which of them are conducive for atmospheric observations?
3. What are the possible biosignatures that may be detectable?

Image Credits: NASA

Outline

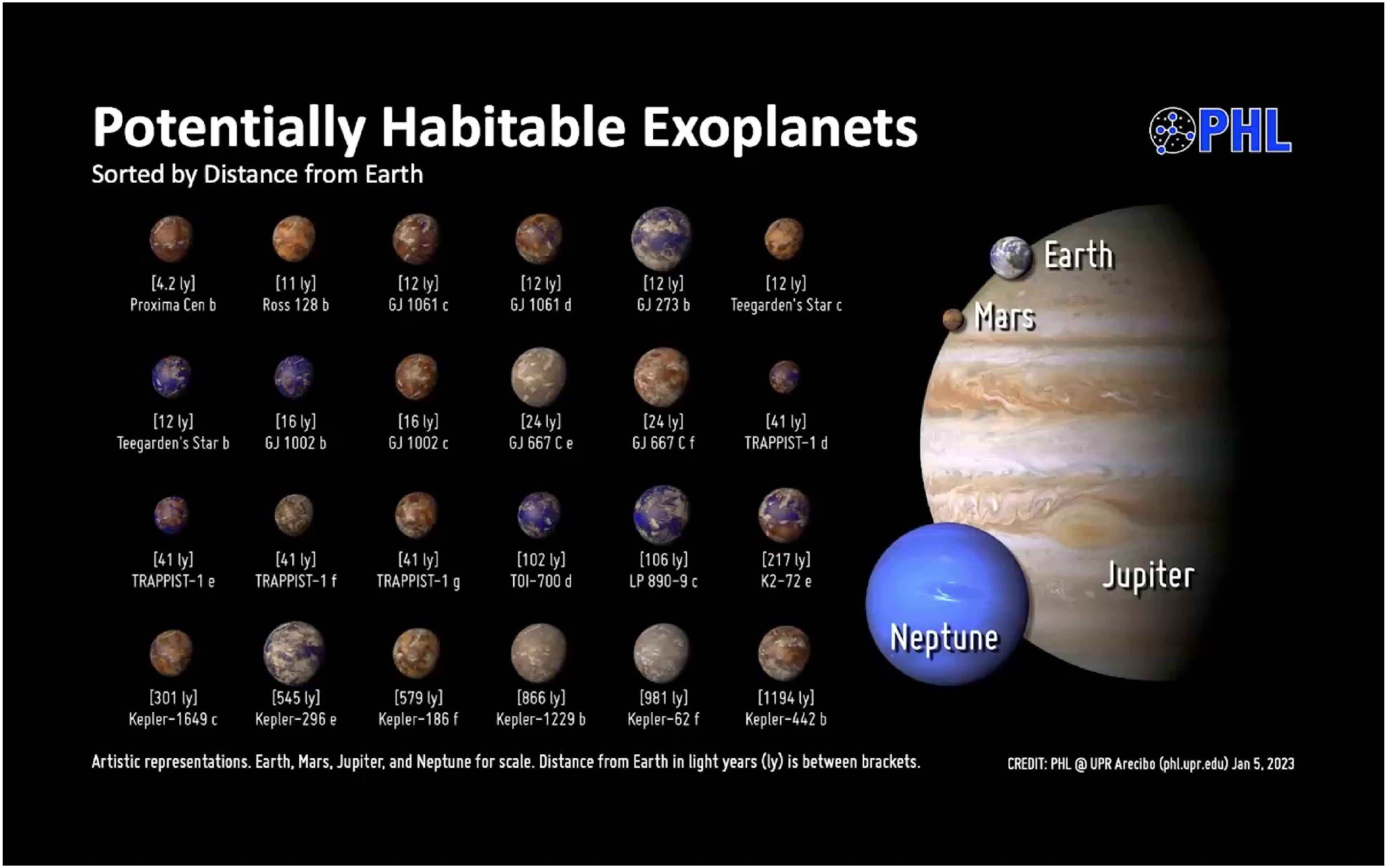
1. Exoplanet Habitability
2. The Hycean Paradigm
3. Biosignatures and Detectability
4. K2-18b: A Case Study
5. Future Outlook

The Classical Habitable Zone

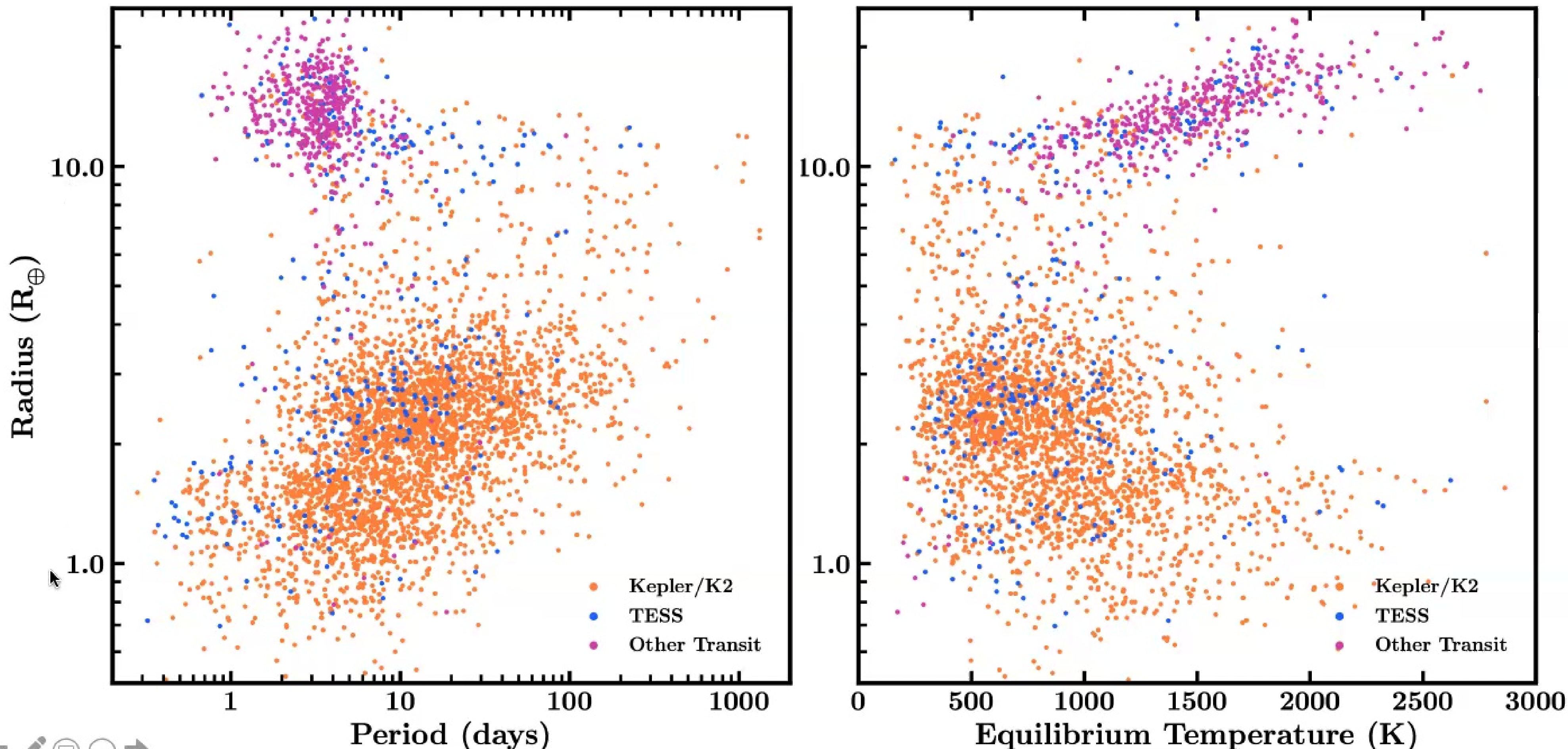


Kasting et al. 1993; also see Selsis et al. 2007, Kopparapu et al. 2013

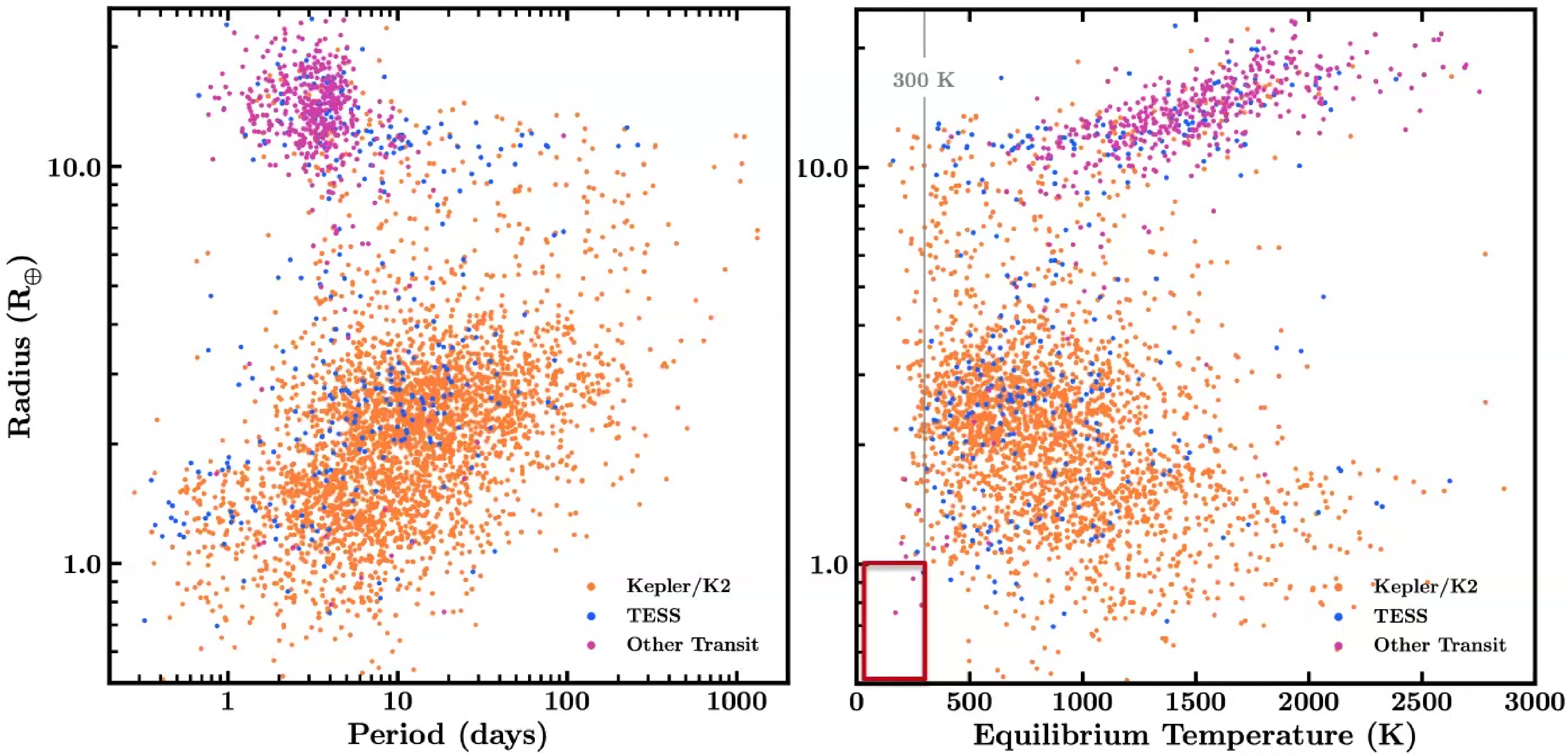
Image Credits: Astrobiology Magazine


Potentially Habitable Exoplanets
Sorted by Distance from Earth
PHL
[4.2 ly] Proxima Cen b
[11 ly] Ross 128 b
[12 ly] GJ 1061 c
[12 ly] GJ 1061 d
[12 ly] GJ 273 b
[12 ly] Teegarden's Star c
[12 ly] Teegarden's Star b
[16 ly] GJ 1002 b
[16 ly] GJ 1002 c
[24 ly] GJ 667 C e
[24 ly] GJ 667 C f
[41 ly] TRAPPIST-1 d
[41 ly] TRAPPIST-1 e
[41 ly] TRAPPIST-1 f
[41 ly] TRAPPIST-1 g
[102 ly] TOI-700 d
[106 ly] LP 890-9 c
[217 ly] K2-72 e
[301 ly] Kepler-1649 c
[545 ly] Kepler-296 e
[579 ly] Kepler-186 f
[866 ly] Kepler-1229 b
[981 ly] Kepler-62 f
[1194 ly] Kepler-442 b
Earth
Mars
Jupiter
Neptune
Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth in light years (ly) is between brackets.
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Jan 5, 2023

In Search of Habitable Exoplanets



In Search of Habitable Exoplanets



The Trappist-1 System

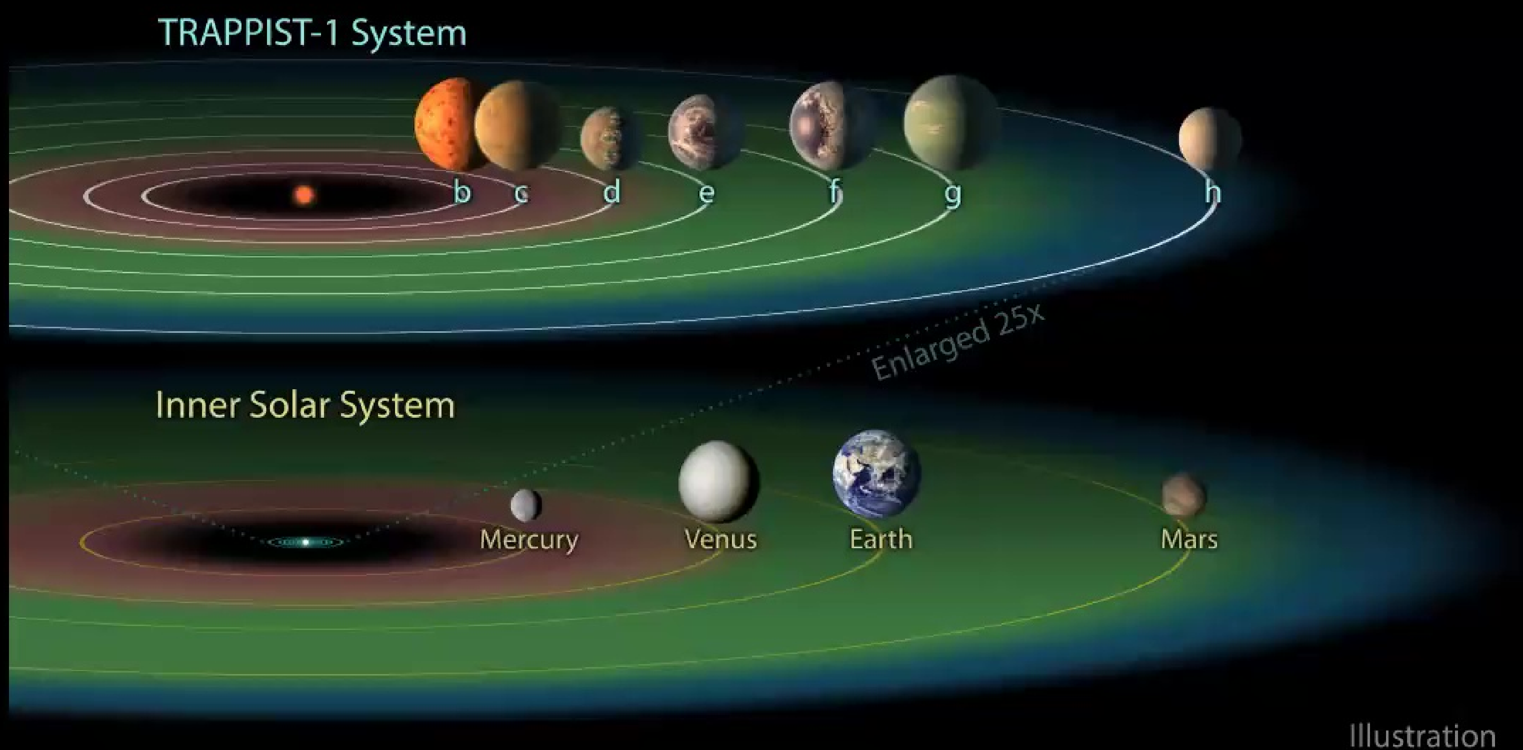
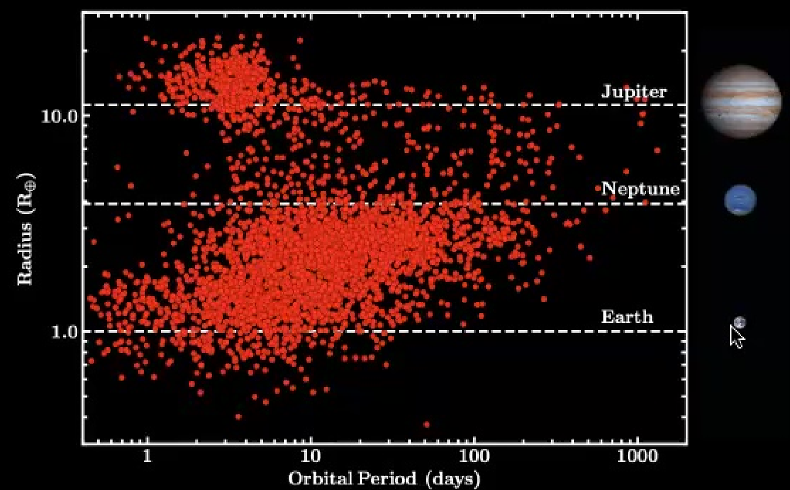


Image credits: NASA

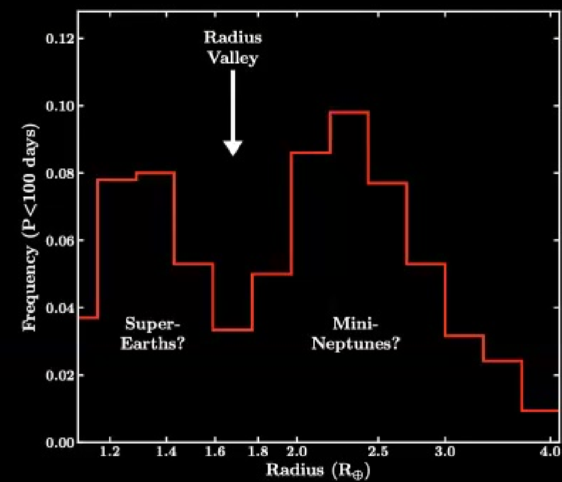
Gillon et al. 2017

New Frontier: The Sub-Neptune Regime

Sub-Neptunes dominate the exoplanet population but have no analogue in the Solar system



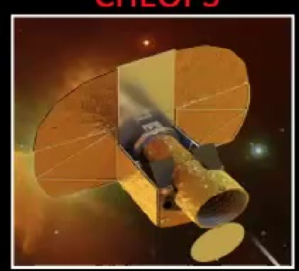
NASA Exoplanet Archive



Fulton et al. 2017

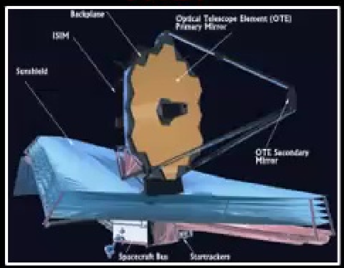
TESS

CHEOPS



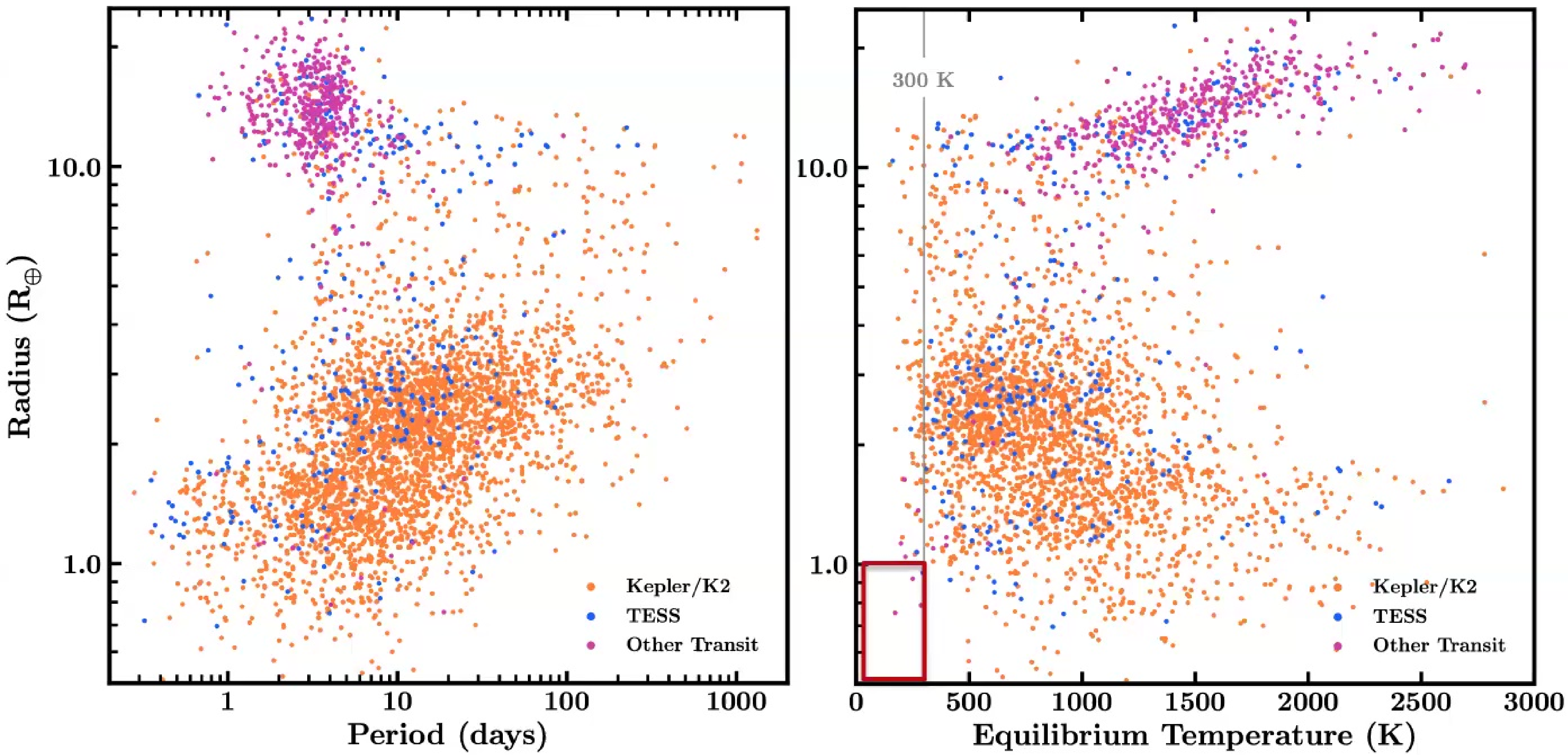
HST

JWST



What are the limits on planet mass, radius, and temperature for habitability?

In Search of Habitable Exoplanets



Outline

1. Exoplanet Habitability
2. The Hycean Paradigm
3. Biosignatures and Detectability
4. K2-18b: A JWST Case Study
5. Future Outlook

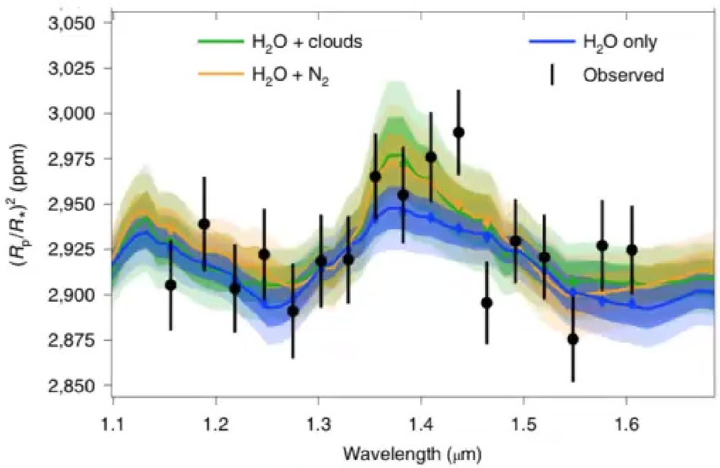
The Sub-Neptune K2-18 b

A Habitable-zone Sub-Neptune transiting a M2.5 V star

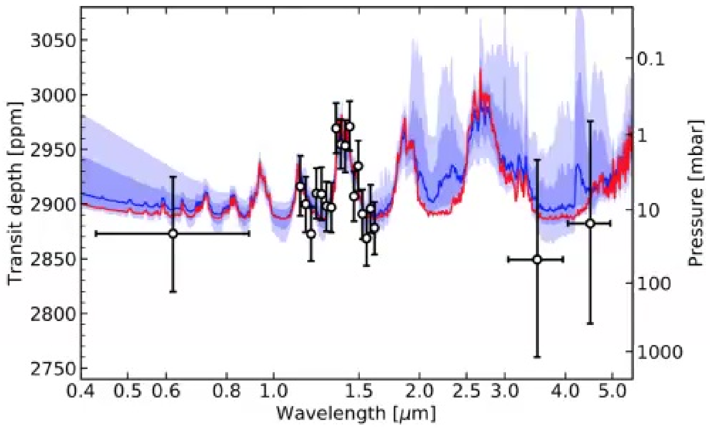
P = 33 day, transit depth = 0.3% (Montet et al. 2015)
M_p = 8.63 ± 1.35 M_E (Cloutier et al. 2019)
R_p = 2.61 ± 0.08 R_E (Benneke et al. 2019)
T_{eq} = 250-300 K, Earth-like insolation
No analogue in the solar system.

Image Credits: NASA, ESA, CSA, STScI

Constraints on Atmospheric Composition



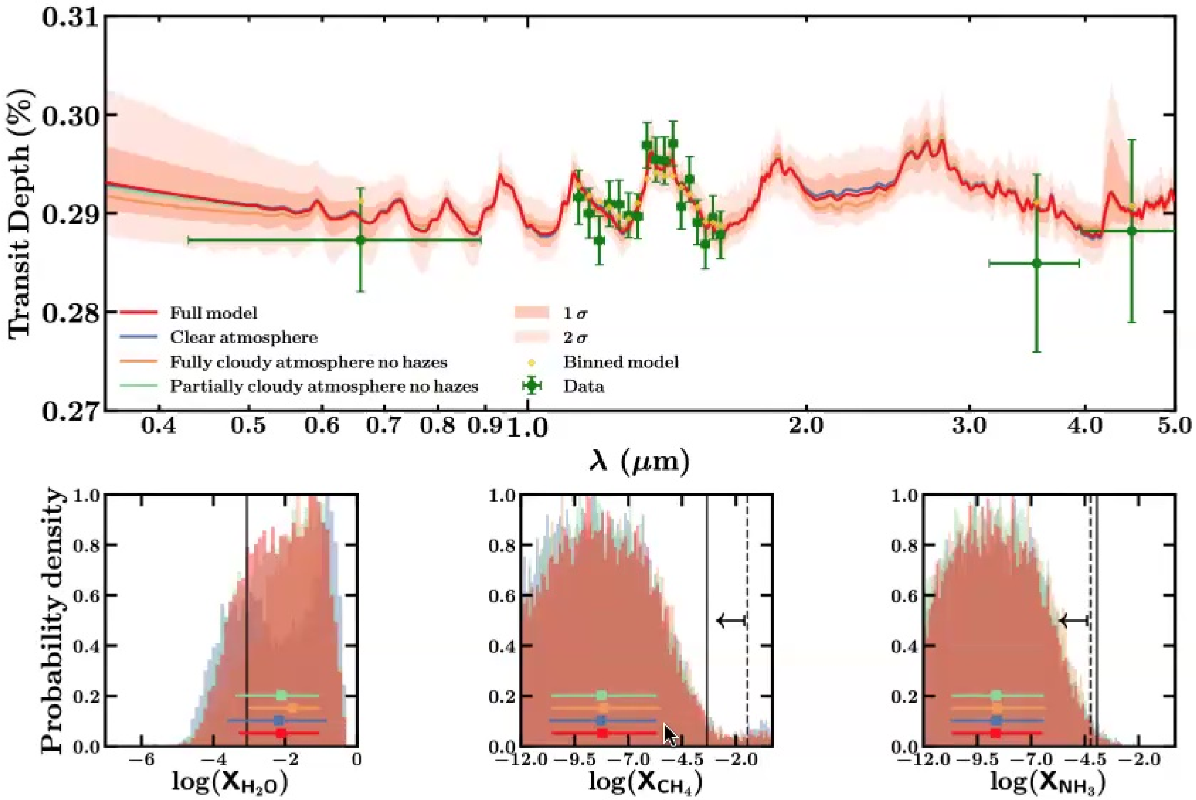
Tsiaras et al. 2019



Benneke et al. 2019

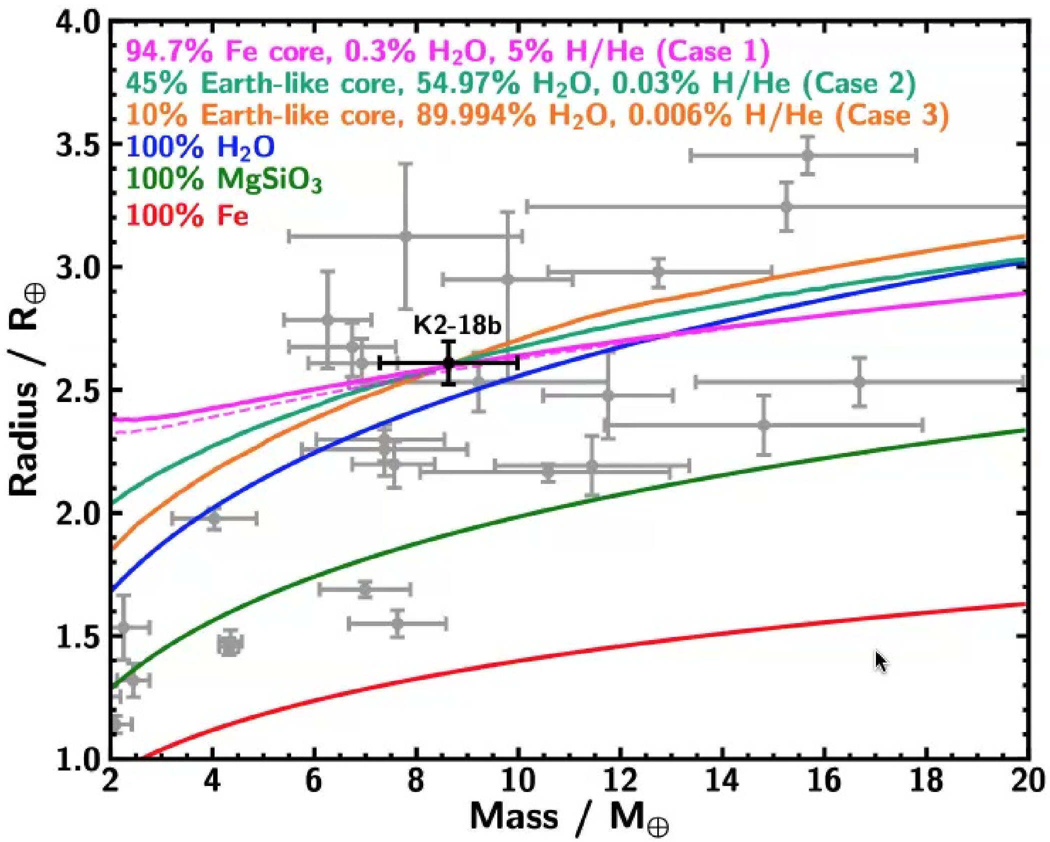
Constraints on Atmospheric Composition

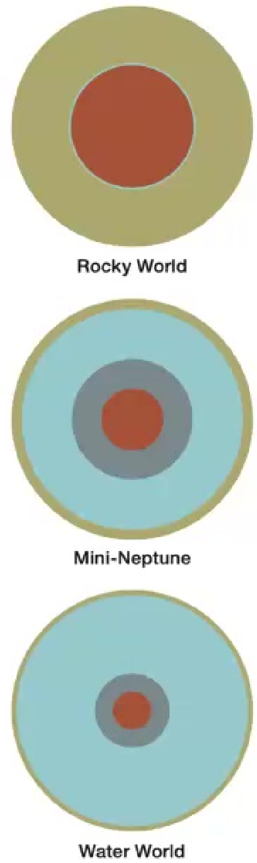
H_2-rich atmosphere with strong molecular absorption



Madhusudhan et al. 2020, Data from Benneke et al. 2019

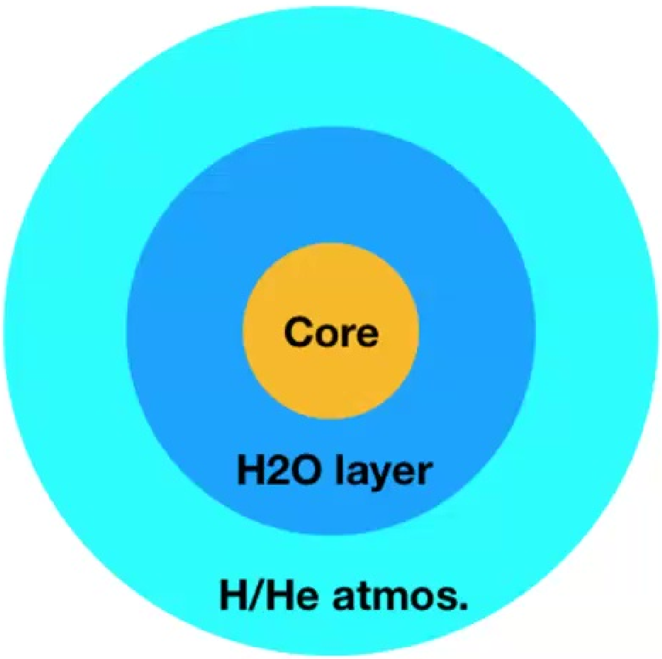
Constraints on Interior Composition

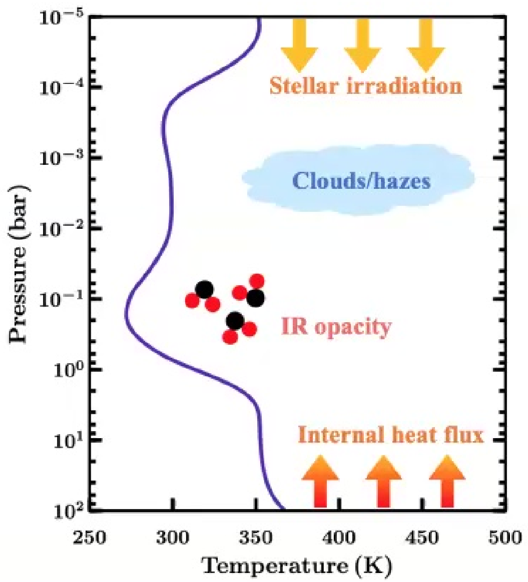




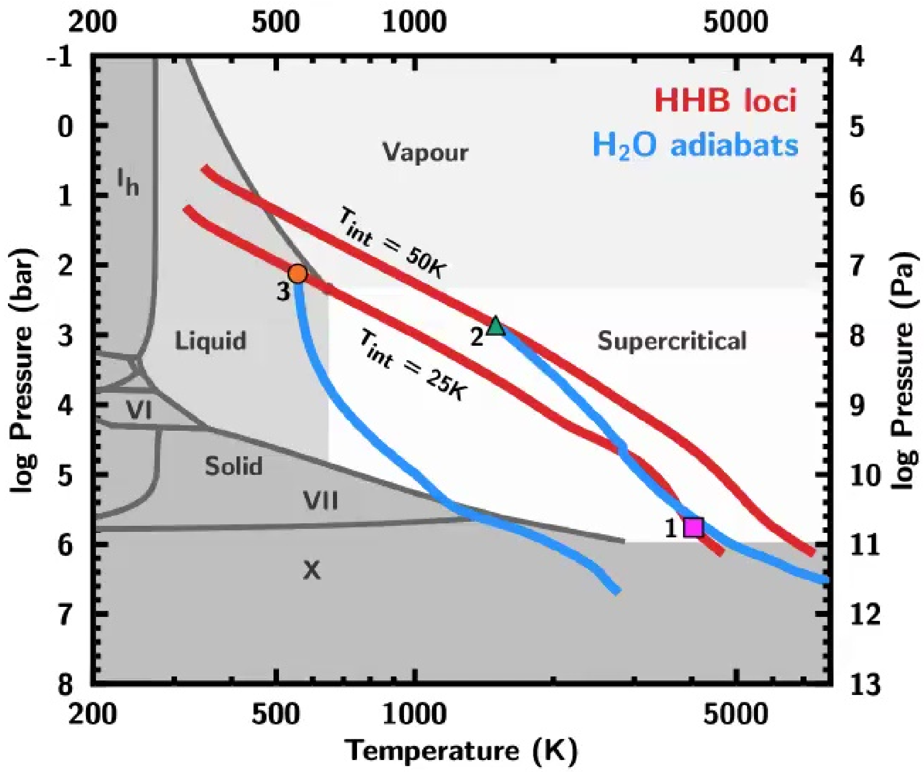
Madhusudhan, Nixon, Welbanks, Piette & Booth 2020

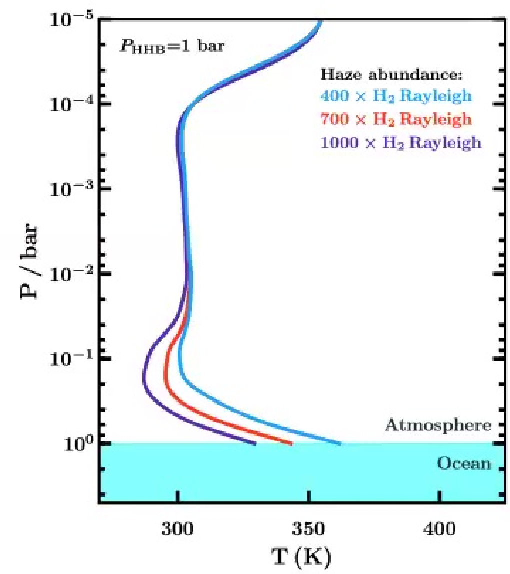
Atmosphere-Interior Coupling





Atmosphere-Interior Boundary

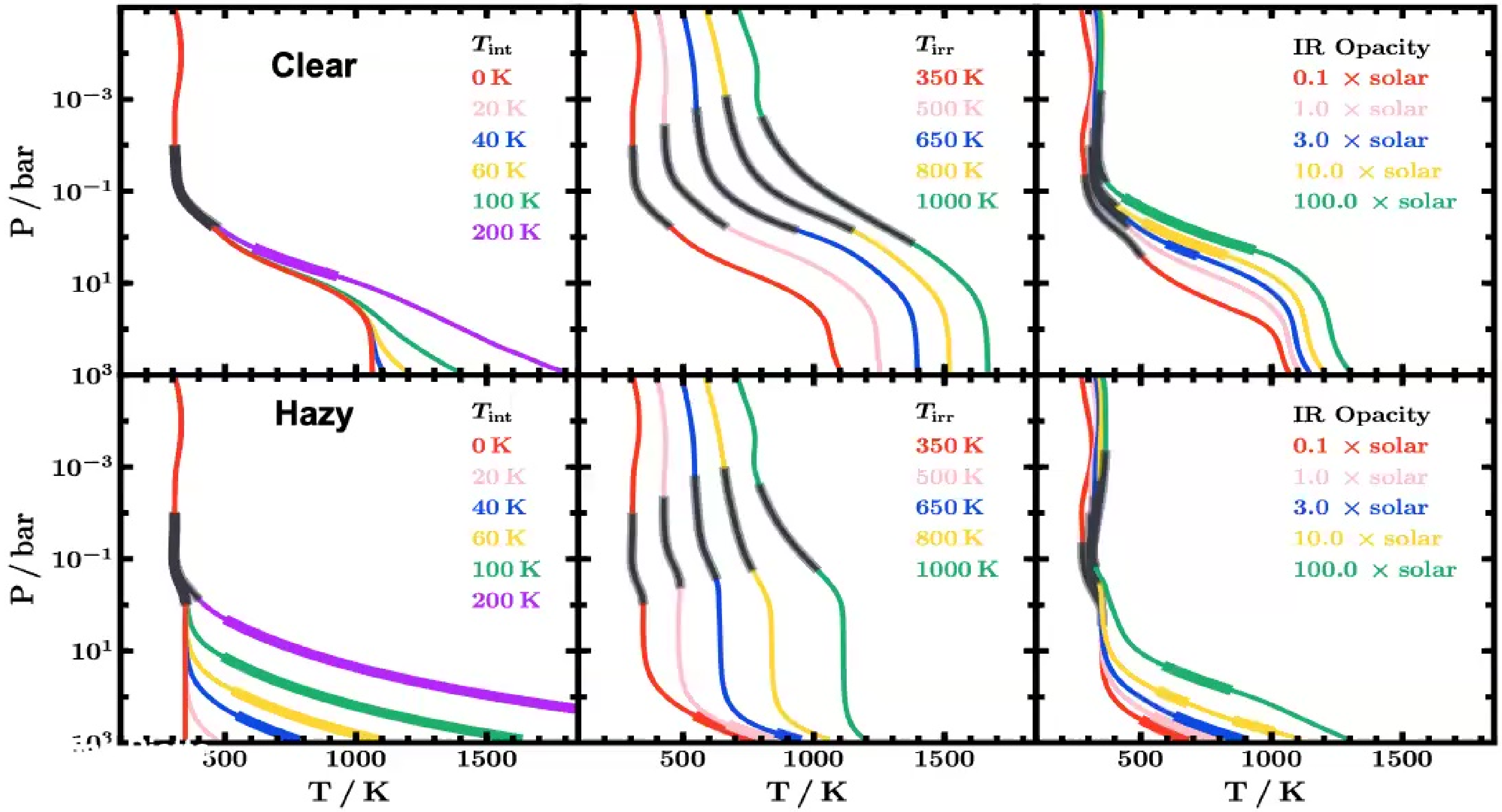




Madhusudhan et al. 2020, Piette & Madhusudhan 2020

Effects of Atmospheric Parameters

Need high albedo for most Hycean candidates

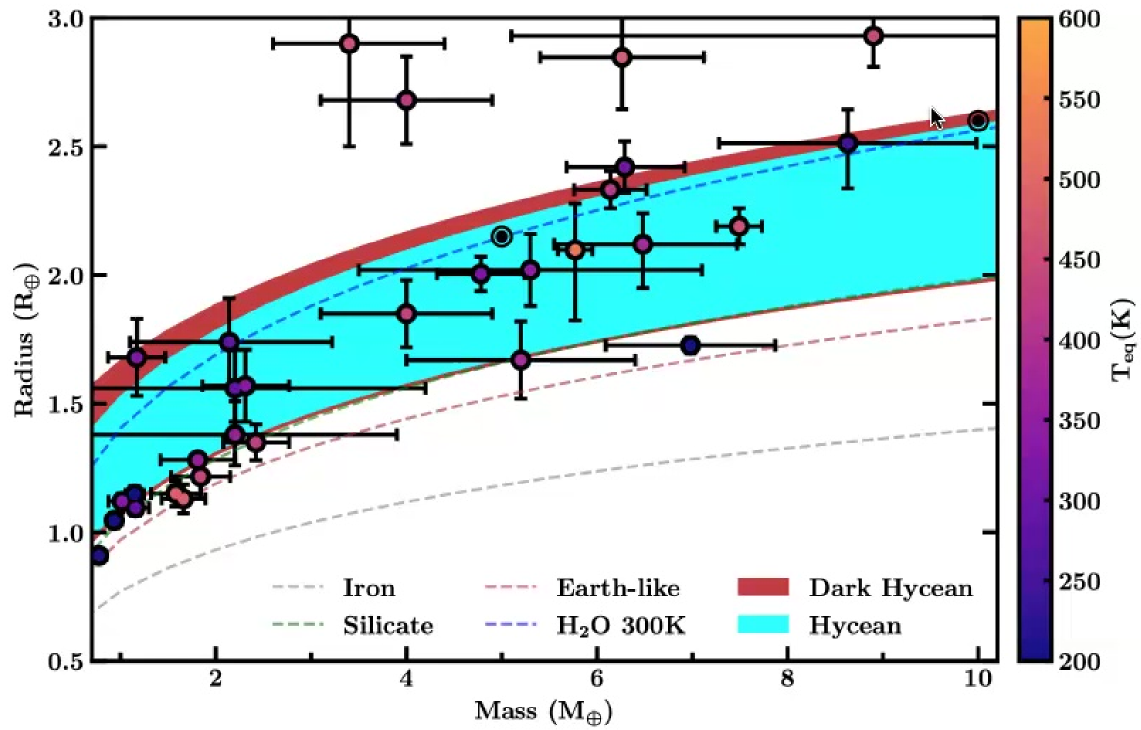


Piette & Madhusudhan 2020

Also see Scheucher et al. 2020, Innes et al. 2023

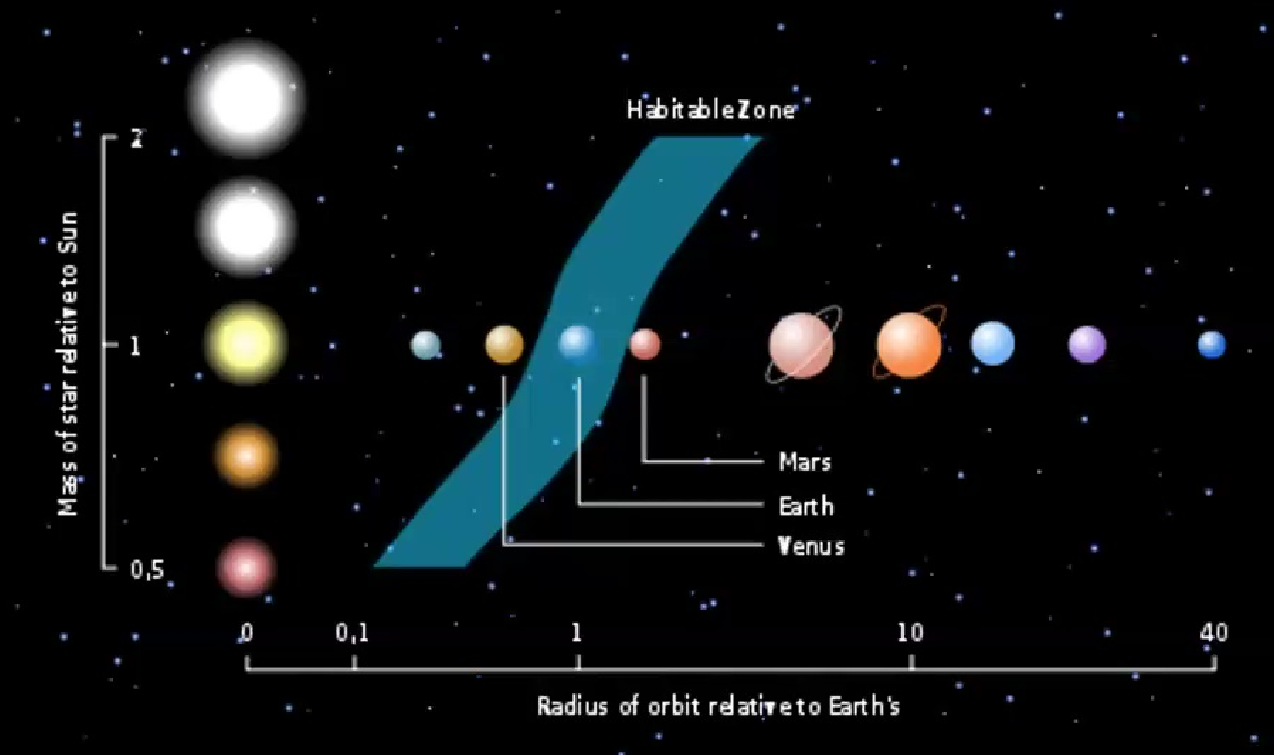

Hycean Worlds
A New Regime in Planetary Habitability
Madhusudhan, Piette and Constantinou 2021

The Hycean Mass-Radius Plane



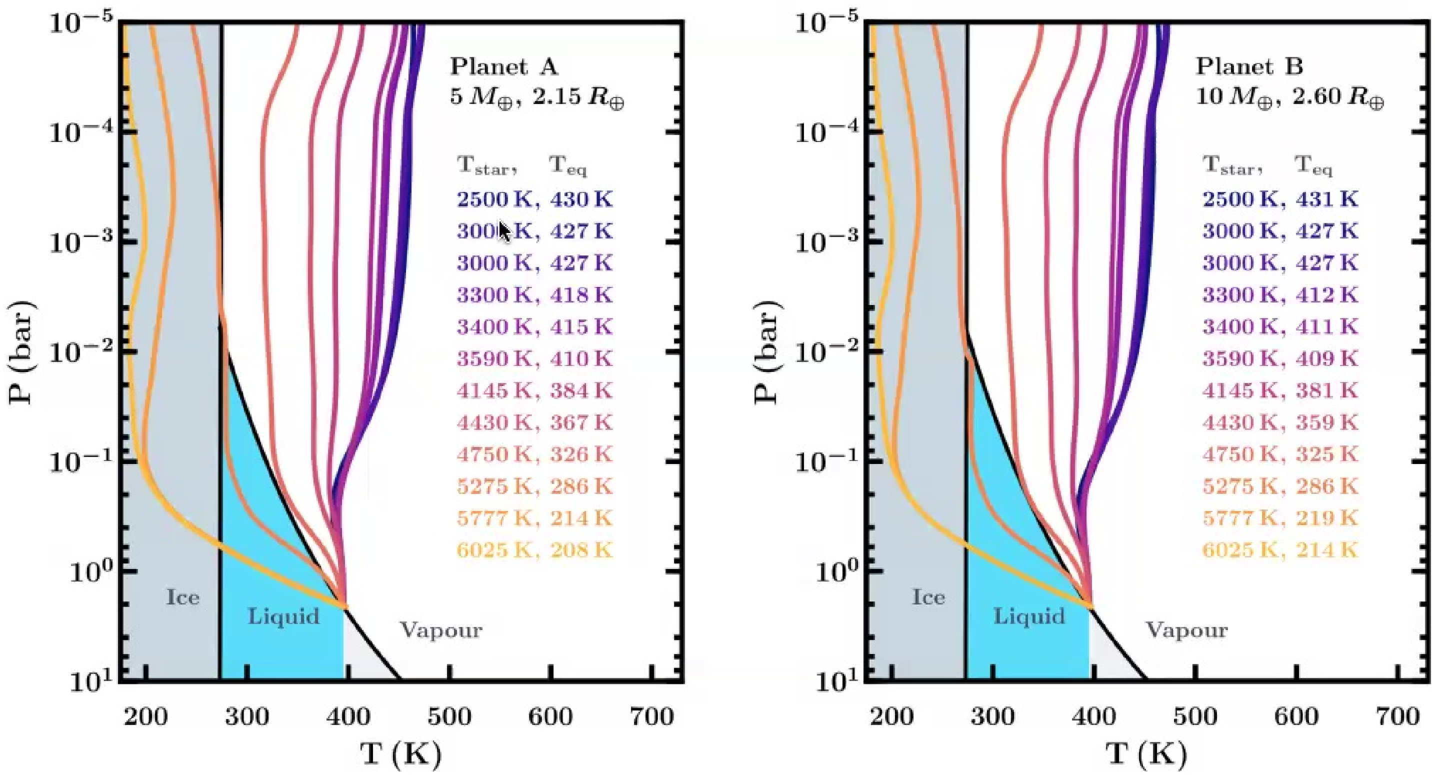
Madhusudhan, Piette & Constantinou 2021

The Classical Habitable Zone



Kasting et al. 1993; also see Selsis et al. 2007, Kopparapu et al. 2013

Temperature Structures

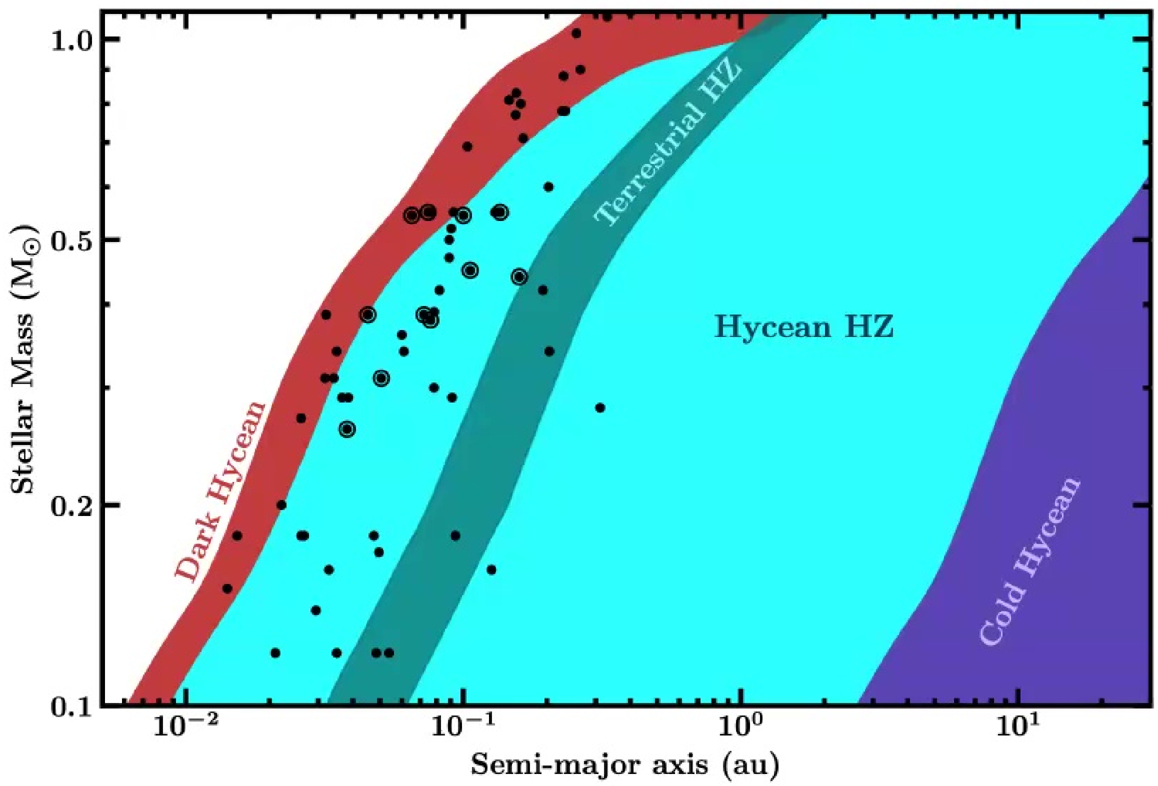


Madhusudhan et al 2021

Self-consistent Models using GENESIS

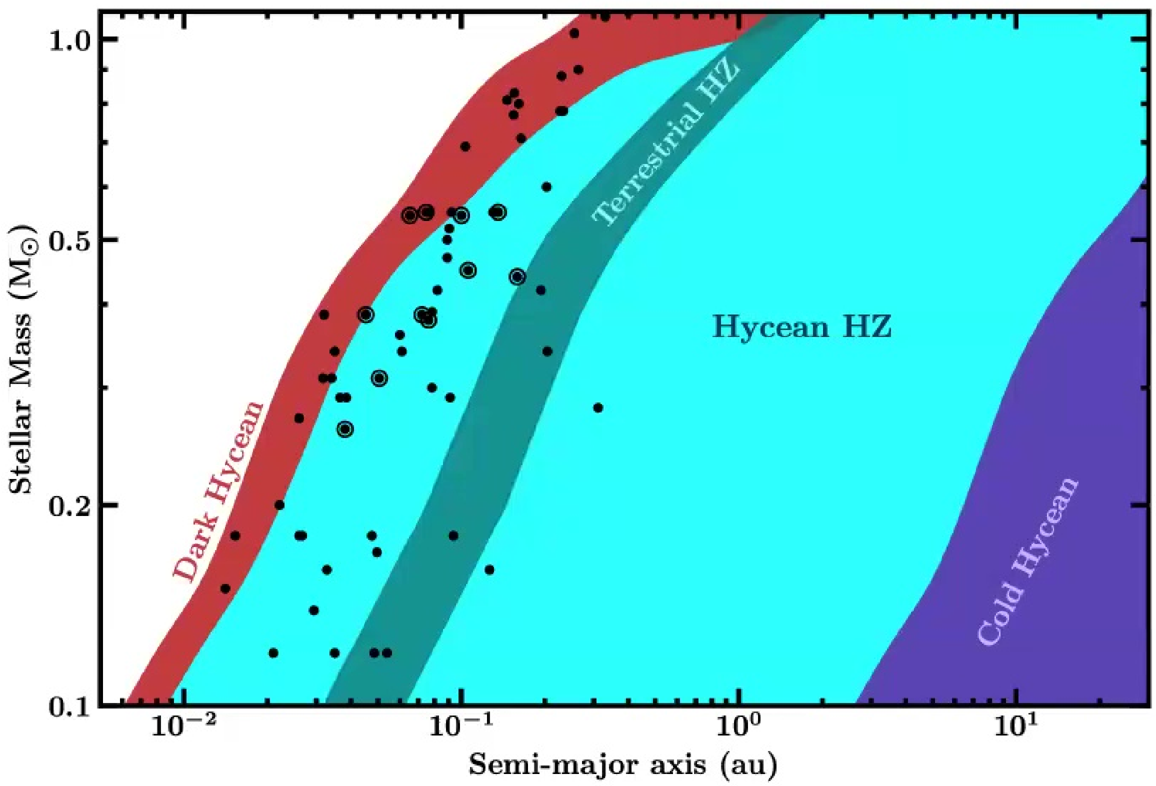
(Gandhi & Madhusudhan 2017, Piette and Madhusudhan 2020)

The Hycean Habitable Zone



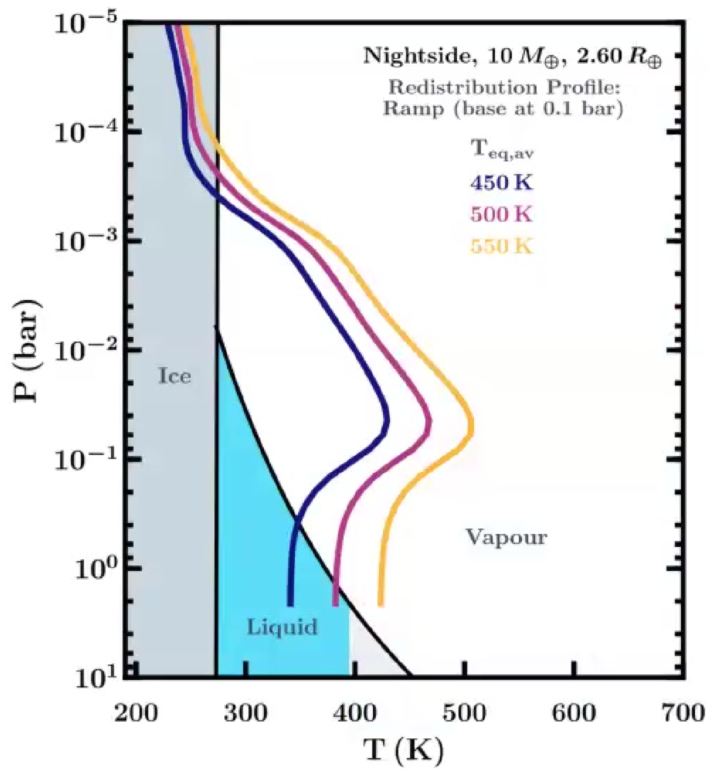
Madhusudhan et al 2021

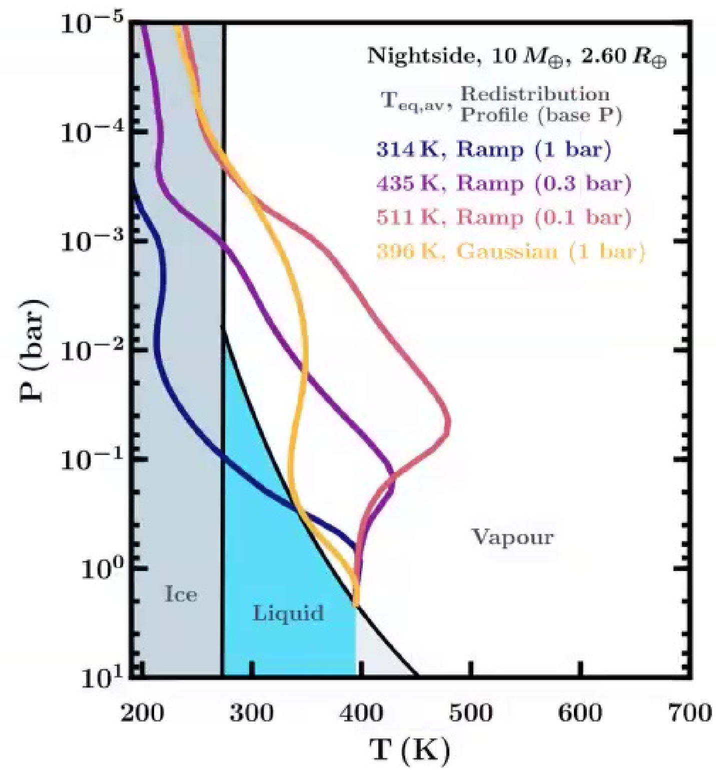
The Hycean Habitable Zone



Madhusudhan et al 2021

Dark Hycean Temperature Structures





Madhusudhan et al 2021
Self-consistent Models using GENESIS
(Gandhi & Madhusudhan 2017, Piette and Madhusudhan 2020)

Hycean Candidates

Properties of Promising Hycean Candidates and Their Host Stars

Name	$M_P/M_\oplus$	$R_P/R_\oplus$	T_{eq}/K	a/au	$M_\star/M_\odot$	$R_\star/R_\odot$	$T_\star$/K	J mag	V mag	Ref
K2–18 b	8.63 ± 1.35	$2.51^{+0.13}_{-0.18}$	250	0.153	0.44	0.45	3590	9.8	13.5	1, 2
K2–3 c	$2.14^{+1.08}_{-1.04}$	$1.74^{+0.17}_{-0.17}$	286	0.136	0.55	0.55	3500	9.4	12.2	1, 3
TOI-1266 c	$2.2^{+2.0}_{-1.5}$	$1.56^{+0.15}_{-0.13}$	291	0.106	0.45	0.42	3600	9.7	12.9	4
TOI-732 c	$6.29^{+0.63}_{-0.61}$	2.42 ± 0.10	305	0.076	0.38	0.38	3360	9.0	13.1	5
TOI-270 d	4.78 ± 0.46	2.01 ± 0.07	327	0.072	0.39	0.38	3506	9.1	12.6	6
TOI-175 d	$2.31^{+0.46}_{-0.45}$	1.57 ± 0.14	341	0.051	0.31	0.31	3412	7.9	11.7	7, 8
TOI-776 c	5.30 ± 1.80	2.02 ± 0.14	350	0.100	0.54	0.54	3709	8.5	11.5	9
LTT 1445 A b	$2.2^{+1.7}_{-2.1}$	$1.38^{+0.13}_{-0.12}$	367	0.038	0.26	0.28	3337	7.3	11.2	10
K2–3 b	$6.48^{+0.99}_{-0.93}$	$2.12^{+0.12}_{-0.17}$	384	0.075	0.55	0.55	3500	9.4	12.2	1, 3
TOI-270 c	6.14 ± 0.38	2.33 ± 0.07	413	0.045	0.39	0.38	3506	9.1	12.6	6
TOI-776 b	4.00 ± 0.90	1.85 ± 0.13	434	0.065	0.54	0.54	3709	8.5	11.5	9

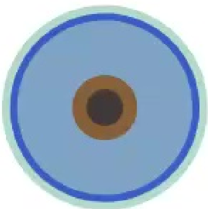
Note. The table lists properties of promising exoplanets that fall within the Hycean boundaries in Figure 1, with $T_{eq} < 500$ K, and whose host stars have $J < 10$. T_{eq} is the equilibrium temperature of the planet assuming full day–night energy redistribution and a Bond albedo of 0.5, as discussed in Section 3.1. The first five columns show the planet properties, and the following five columns show the stellar properties. $M_\star$, $R_\star$, and $T_\star$ are the mass, radius, and effective temperature of the host star, respectively.

References. System properties are derived from (1) Hardegree-Ullman et al. 2020; (2) Cloutier et al. 2019b; (3) Kosiarek et al. 2019; (4) Demory et al. 2020; (5) Nowak et al. 2020; (6) Van Eylen et al. 2021; (7) Kostov et al. 2019; (8) Cloutier et al. 2019a; (9) Luque et al. 2021; (10) Winters et al. 2019.

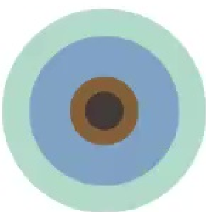
Chemical Probes of the Presence of a Surface

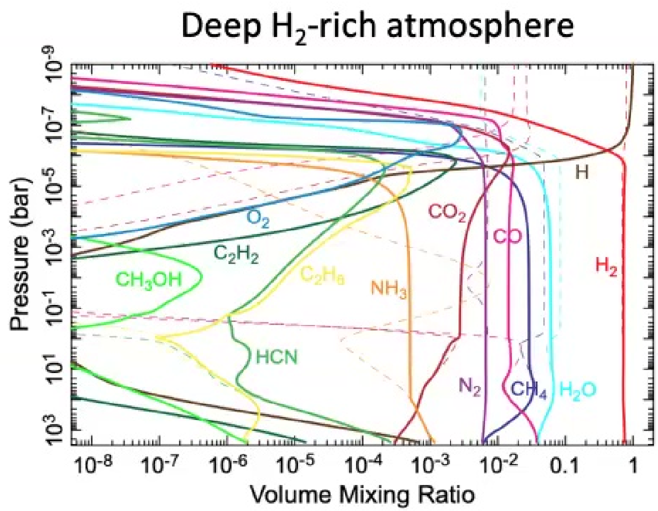
Rocky world

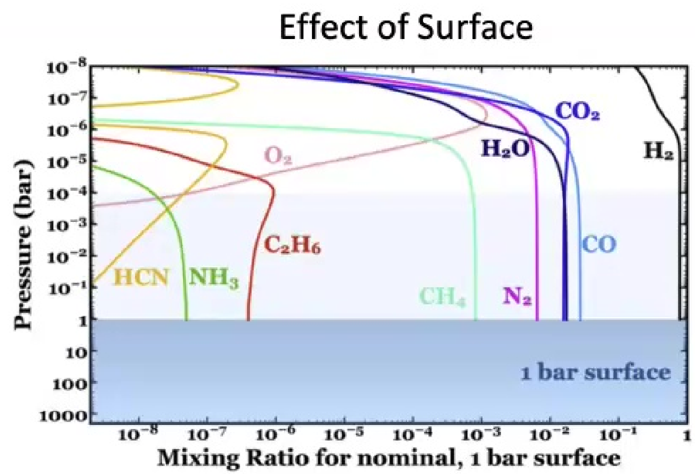
Hycean world



Mini-Neptune







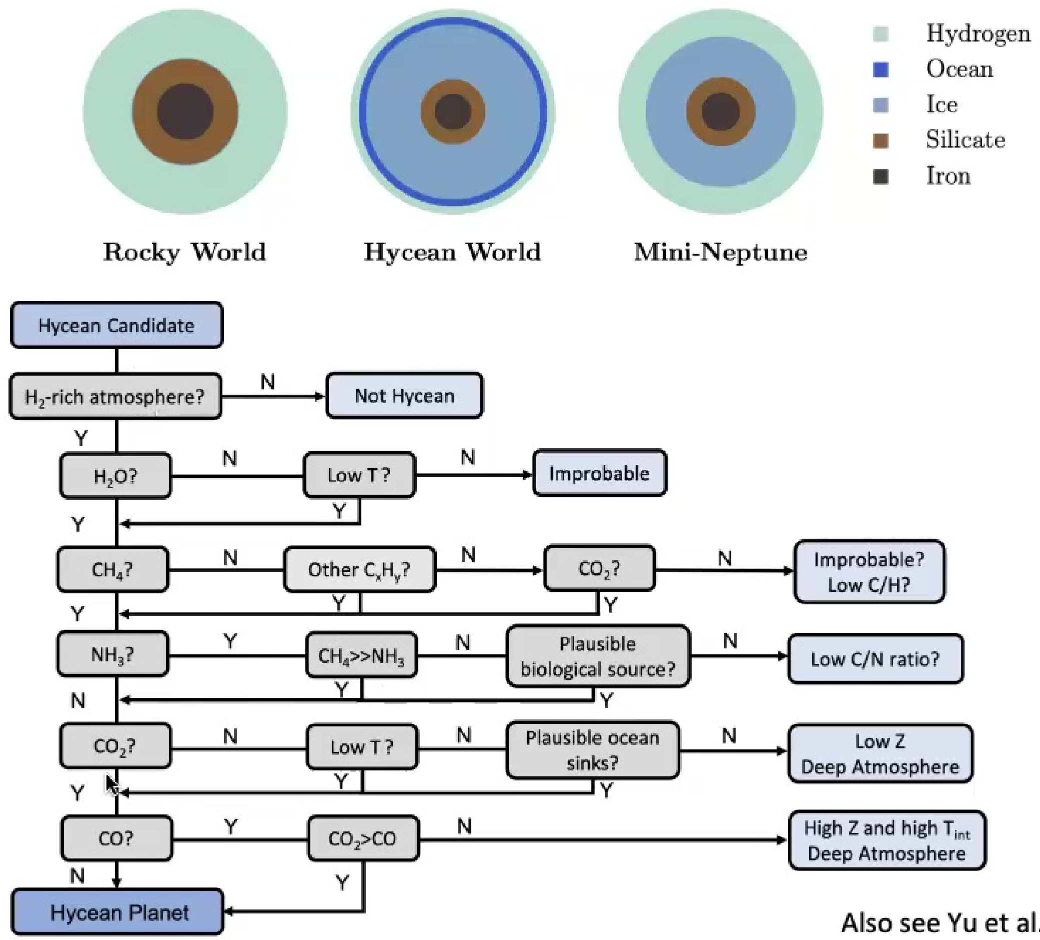
Yu et al. 2021, Hu et al. 2021, Tsai et al. 2021
Madhusudhan et al. 2023

- **Deep H2-rich Atmosphere:** Inconsistent with high CH_4 and CO_2 and low NH_3
- **Shallow H2-rich Atmosphere + Solid Surface:** Inconsistent with Density
- **Shallow H2-rich Atmosphere + Ocean Surface:** Consistent with all data

Presence of Ocean: High H_2O, CO_2, CH_4, Low NH_3, HCN, CO

Composition depends on P-T profile, initial & boundary conditions

Chemical Signatures of Hycean Atmospheres



Madhusudhan et al. 2023a

Also see Yu et al. 2021, Hu et al. 2021, Tsai et al. 2021

Outline

1. Exoplanet Habitability
2. The Hycean Paradigm
3. Biosignatures and Detectability
4. K2-18b: A Case Study
5. Future Outlook

Prominent Biomarkers

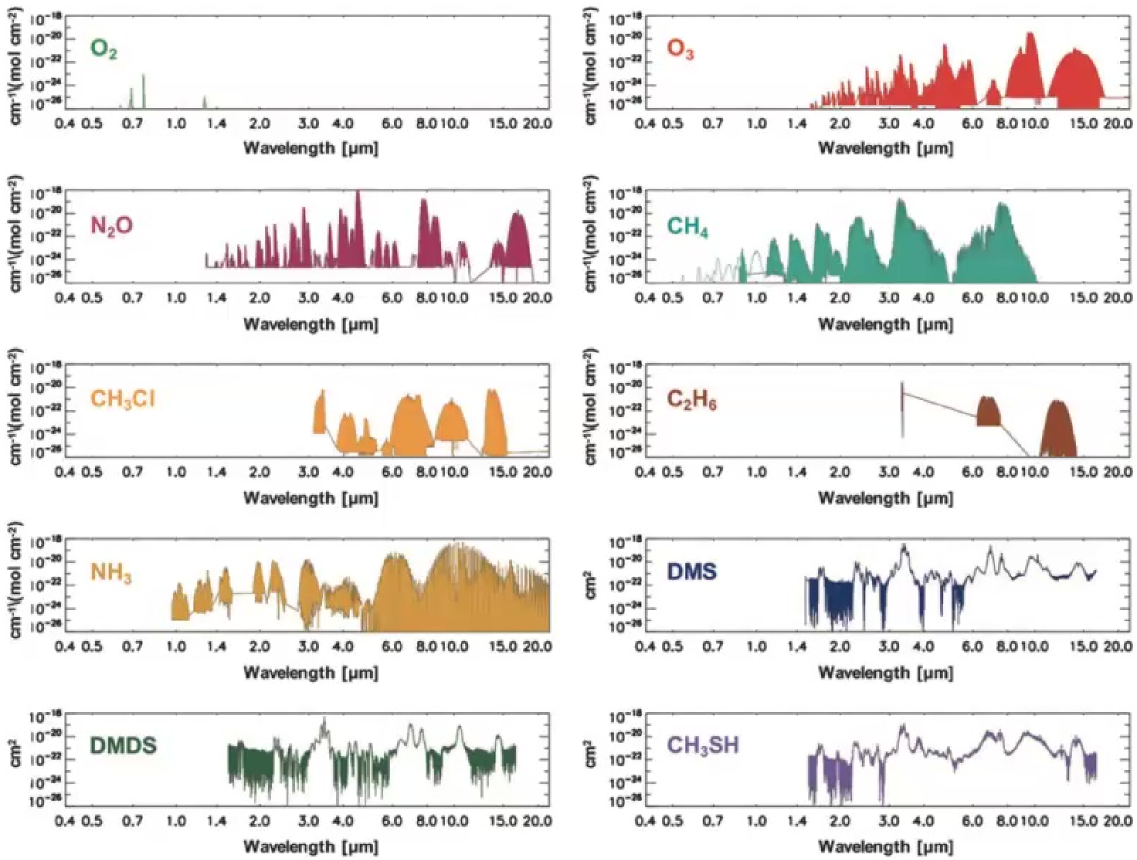
Biosignature	*UV-Visible-NIR band center, μm and (cm^{-1})*	*Visible-NIR band interval, cm^{-1}*	*Thermal IR spectral band center, μm*	*Biogenic source*	*Abiogenic false positive*
O_2	1.58 (6329) 1.27 (7874) 1.06 (9433) **0.76 (13158)** 0.69 (14493) 0.63 (15873) 0.175–0.19 [Schumann–Runge]	6300–6350 7700–8050 9350–9400 **12850–13200** 14300–14600 14750–15900	—	*Photosynthesis*: splitting of water	Cases of water and CO_2 photodissociation and preferential escape of hydrogen, with lack of O_2 sinks
O_3	4.74 (2110) 3.3 (3030) 0.45–0.85 [Chappuis] 0.30–0.36 [Huggins] 0.2–0.3 [Hartley]	2000–2300 3000–3100 10600–22600	>15 (rotation), 14.3, 9.6, 8.9, 7.1, 5.8	*Photosynthesis:* photochemically derived from O_2	As above
CH_4	3.3 (3030) **2.20 (4420)** 1.66 (6005) <0.145 continuum	2500–3200 **4000–4600** 5850–6100	6.5, 7.7	*Methanogenesis*: reduction of CO_2 with H_2, often mediated by degradation of organic matter	Geothermal or primordial methane
N_2O	4.5 (2224) 4.06 (2463) 2.87 (3484) 0.15–0.20 0.1809, 0.1455, 0.1291	**2100–2300** 2100–2800 3300–3500	7.78, 8.5, 16.98	*Denitrification*: reduction of nitrate with organic matter	Chemodenitrification but not truly abiotic on Earth[a]; also strong coronal mass injection affecting an N_2–CO_2 atmosphere[b]
NH_3	4.3 3.0 (3337) 2.9 (3444) 2.25, 2, 1.5, 0.93, 0.65, 0.55, 0.195, 0.155	**2800–3150**	6.1, 10.5	*Ammonification*: Volatilization of dead or waste organic matter	Nonbiogenic, primordial ammonia
$(CH_3)_2S$	3.3 (2997) 3.4 (2925) 0.205, 0.195, 0.145, 0.118	**2900–3100**	6.9, 7.5, 9.7	Plankton	No significant abiotic sources
CH_3Cl	3.3 (3291) 3.4 (2937) 0.175, 0.160, 0.140, 0.122	**2900–3100**	6.9, 9.8, 13.7	Algae, tropical vegetation	No significant abiotic sources (Keppler *et al.*, 2005)
CH_3SH	3.3 (3015) 3.4 (2948) 0.204	**2840–3100**	6.9, 7.5, 9.3, 14.1	Mercaptogenesis: Methanogenic organisms can create CH_3SH instead of CH_4 if given H_2S in place of H_2 (Moran *et al.*, 2008).	No significant abiotic sources
C_2H_6	3.37 (2969) 3.39 (2954) 3.45 (2896) <0.16	**2900–3050**	6.8, 12.15	Photochemically derived from CH_4, CH_3SH, and other biologically produced organic compounds	Could be derived from geothermal or primordial methane

- O_2, O_3, N_2O, CH_4 prominent biomarkers on Earth
- Several secondary biomarkers, less abundant but more robust
- Robustness of a candidate biomarker depends on the environment.
- Secondary biomarkers more promising for H_2-rich atmospheres

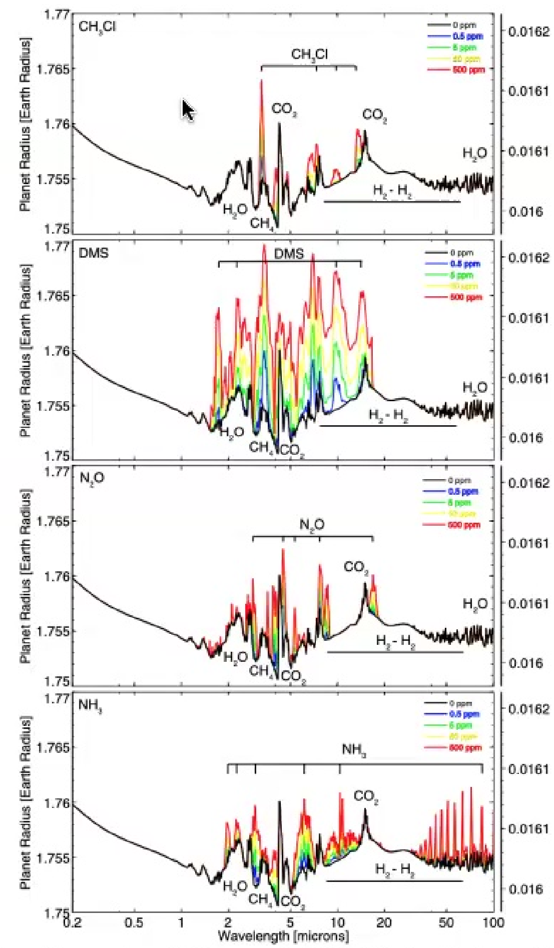
Need for molecular absorption data for biomarkers in non-terrestrial environments

Catling et al. 2018, also see Segura et al. 2005, Domagal-Goldman et al. 2011, Seager et al. 2013,2016

Biosignature Spectral Contributions

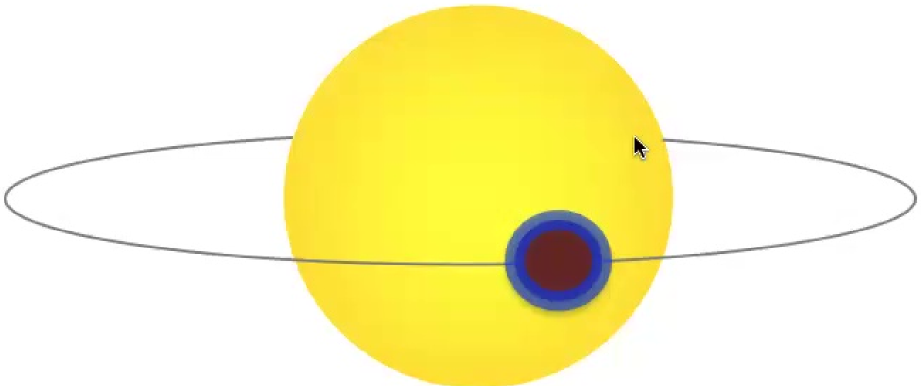


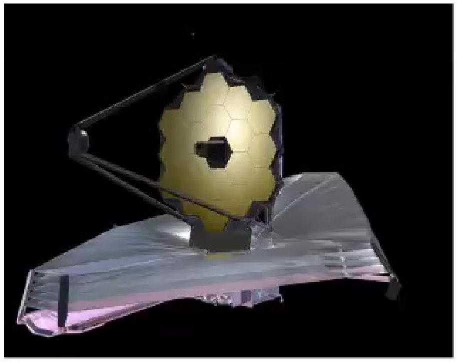
Schwieterman et al. 2018

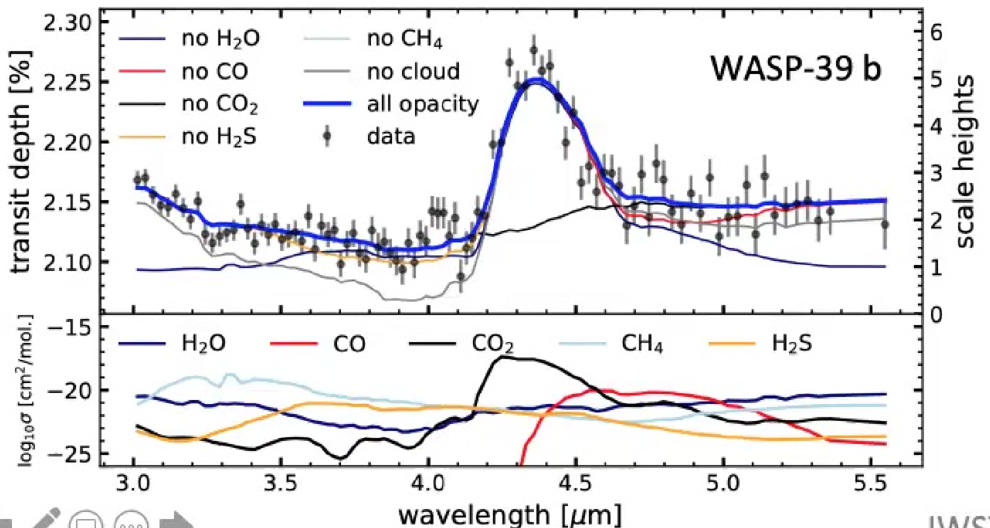


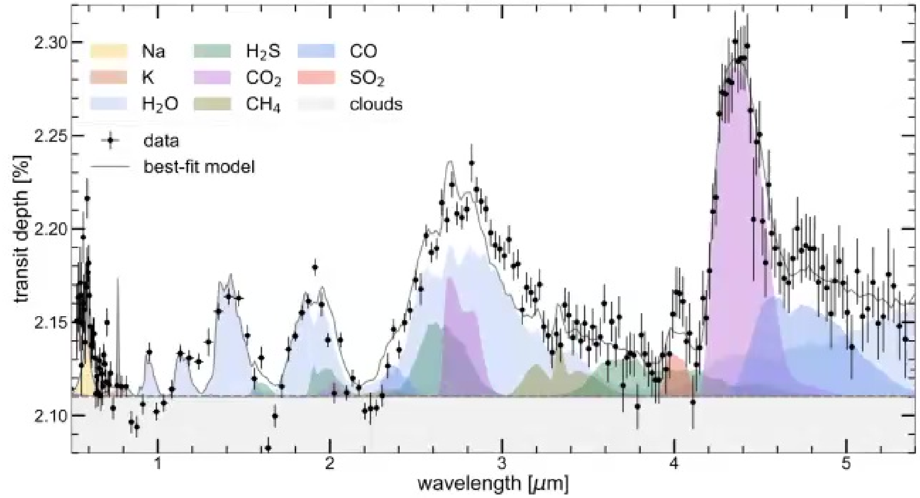
Seager et al. 2013

Transit Spectroscopy of Exoplanets with JWST





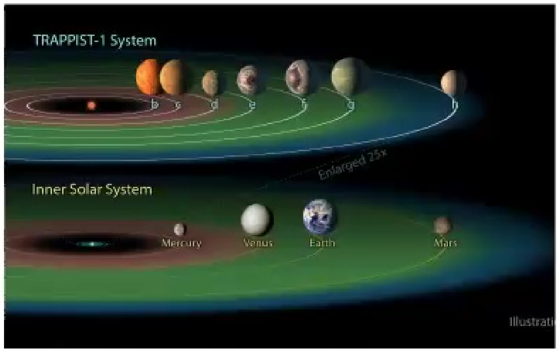




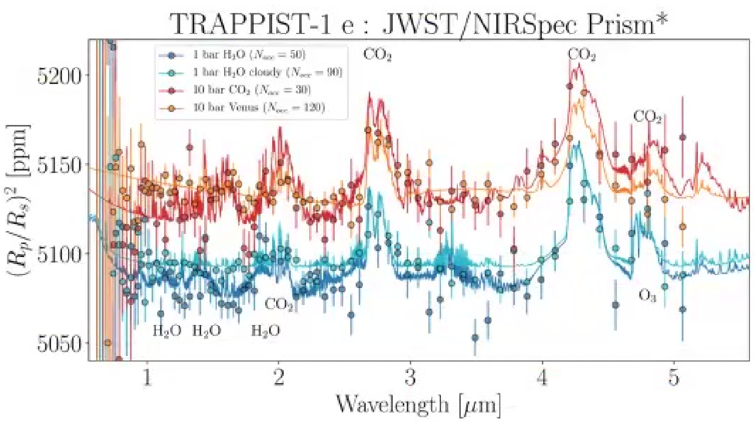
JWST Transiting Exoplanet ERS Team 2023, Rustamkulov et al. 2023

Biosignature Detectability: Trappist-1 with JWST

O_3 in Trappist-1 Planets (Earth-size planets)

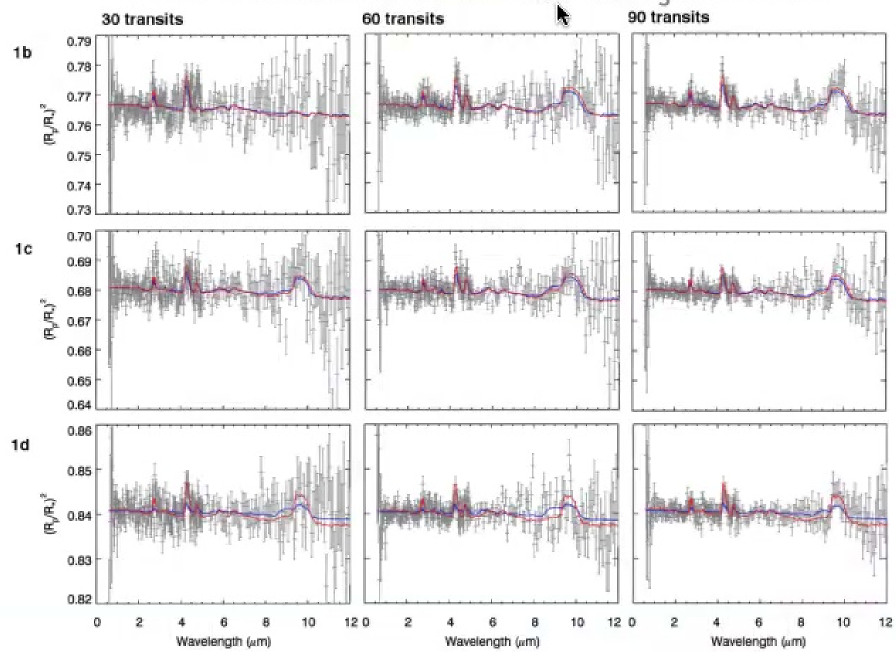


Credits: NASA JPL Gillon et al. 2017



Lustig-Yaeger et al. 2019

Need several tens of transits for O_3 detection

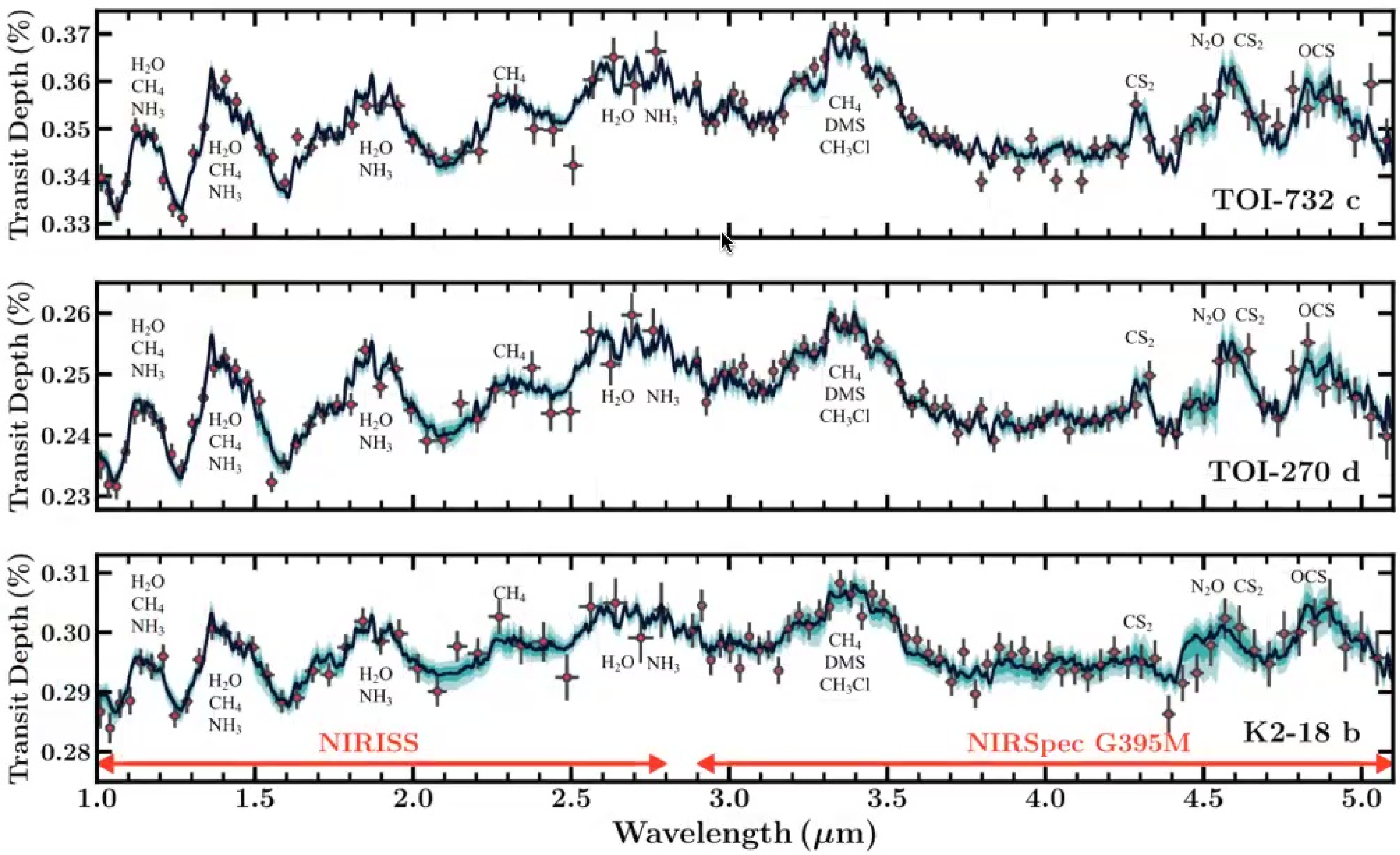


Barstow & Irwin 2016

Biosignature detection in trappist-1 planets will require 100s of hours of JWST time investment

Biosignature Detectability: Hycean Candidates with JWST

Multiple biomarkers, 4 transits (20-30 hours) for each planet

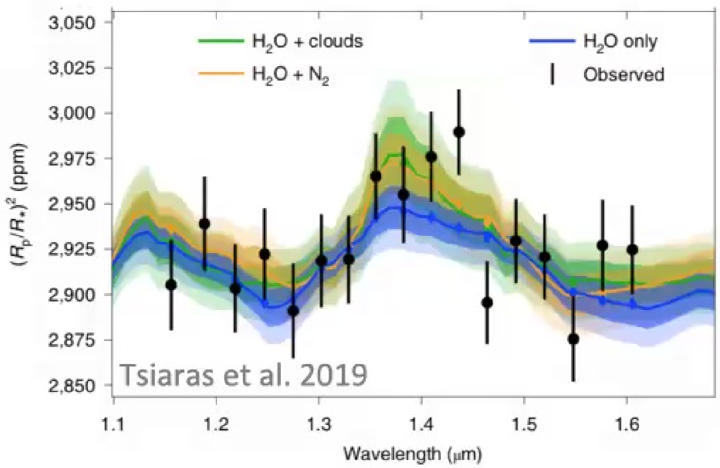


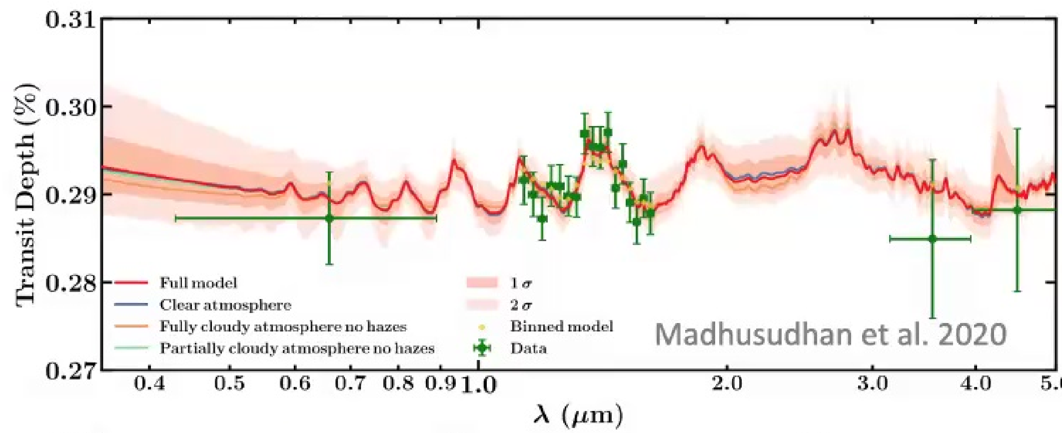
Madhusudhan, Piette & Constantinou 2021

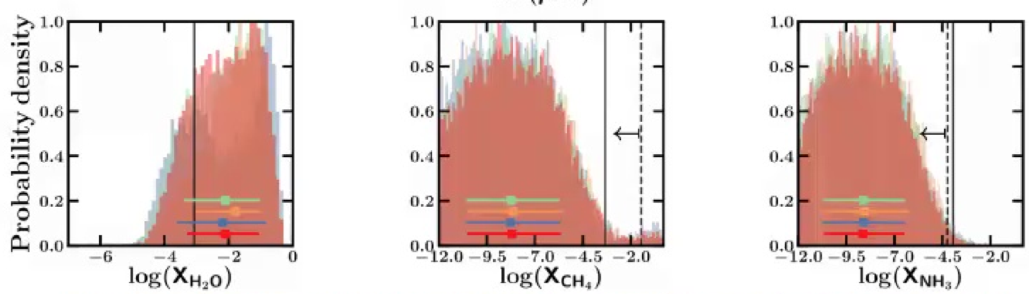
Outline

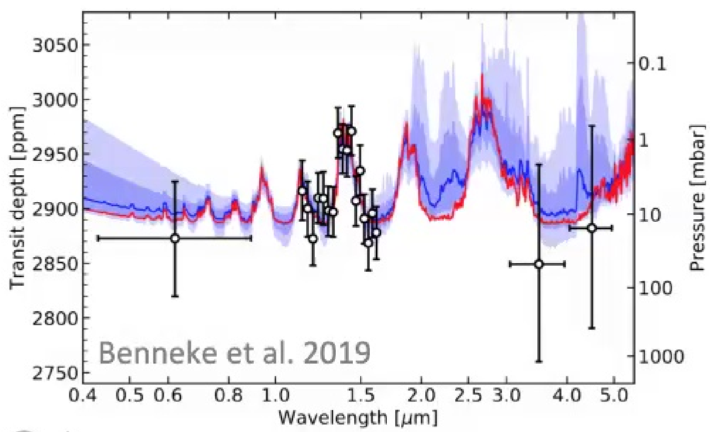
1. Exoplanet Habitability
2. The Hycean Paradigm
3. Biosignatures and Detectability
4. K2-18b: A JWST Case Study
5. Future Outlook

K2-18b: What is the Atmospheric Composition?





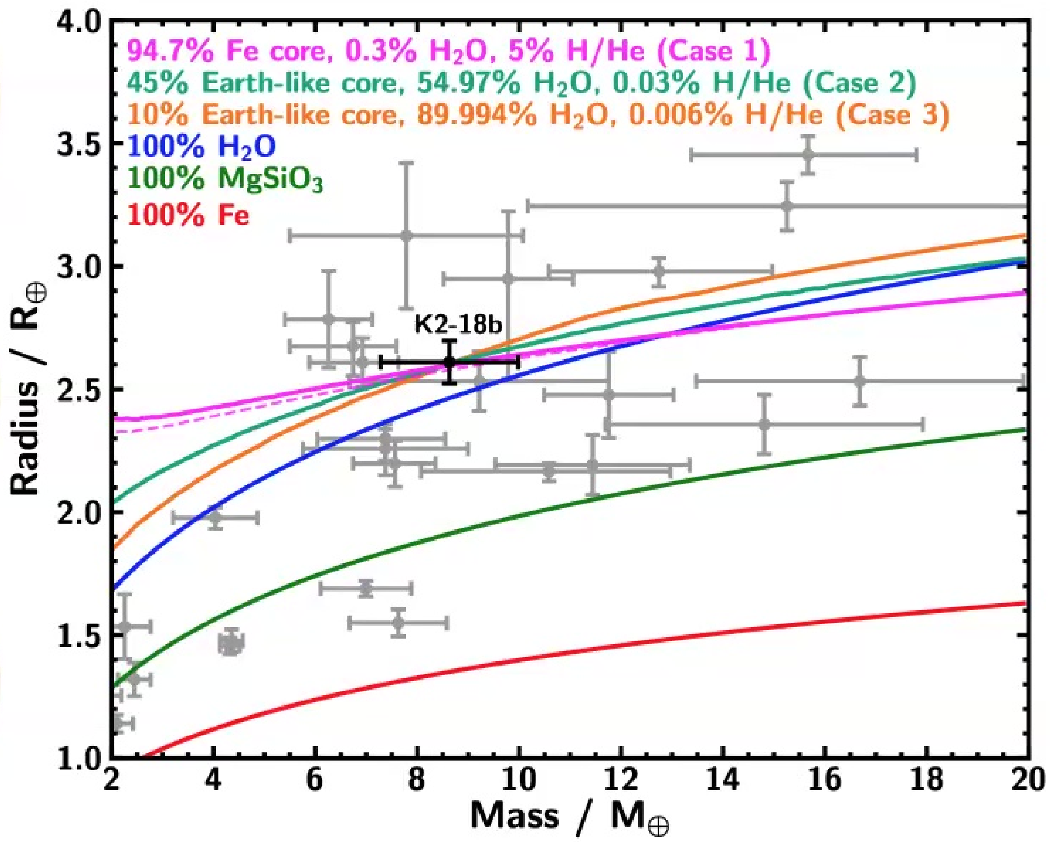




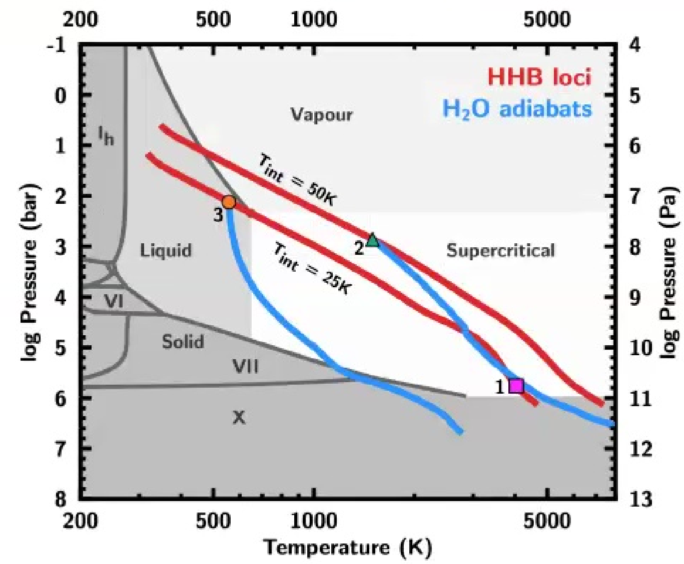
Atmospheric composition inconclusive before JWST

- Degeneracy between H_2O and CH_4 (Blain et al. 2021, Bezard et al. 2022)
- Degeneracy between spectral feature and stellar heterogeneity (Barclay et al. 2021)

K2-18b: What are the Interior and Surface Conditions?



Liquid H_2O at surface possible



Potential habitability depends on albedo, internal temperature, atmospheric composition

Credits: Terri Dube

Madhusudhan et al. 2020

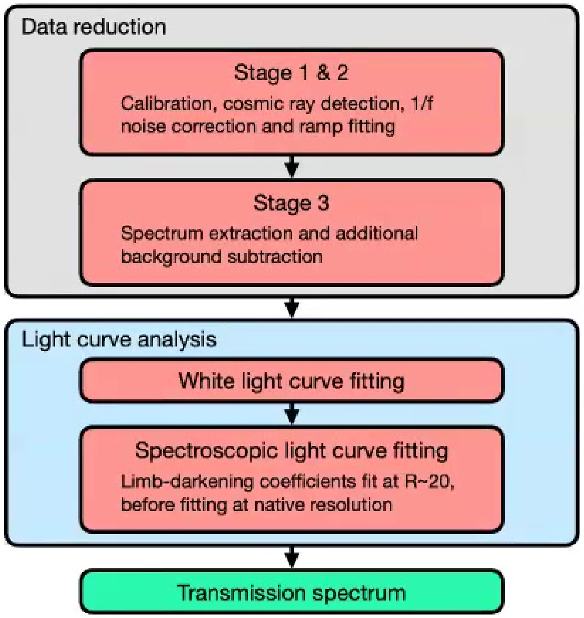
Piette & Madhusudhan 2020, Innes et al. 2023

JWST GO Program 2722

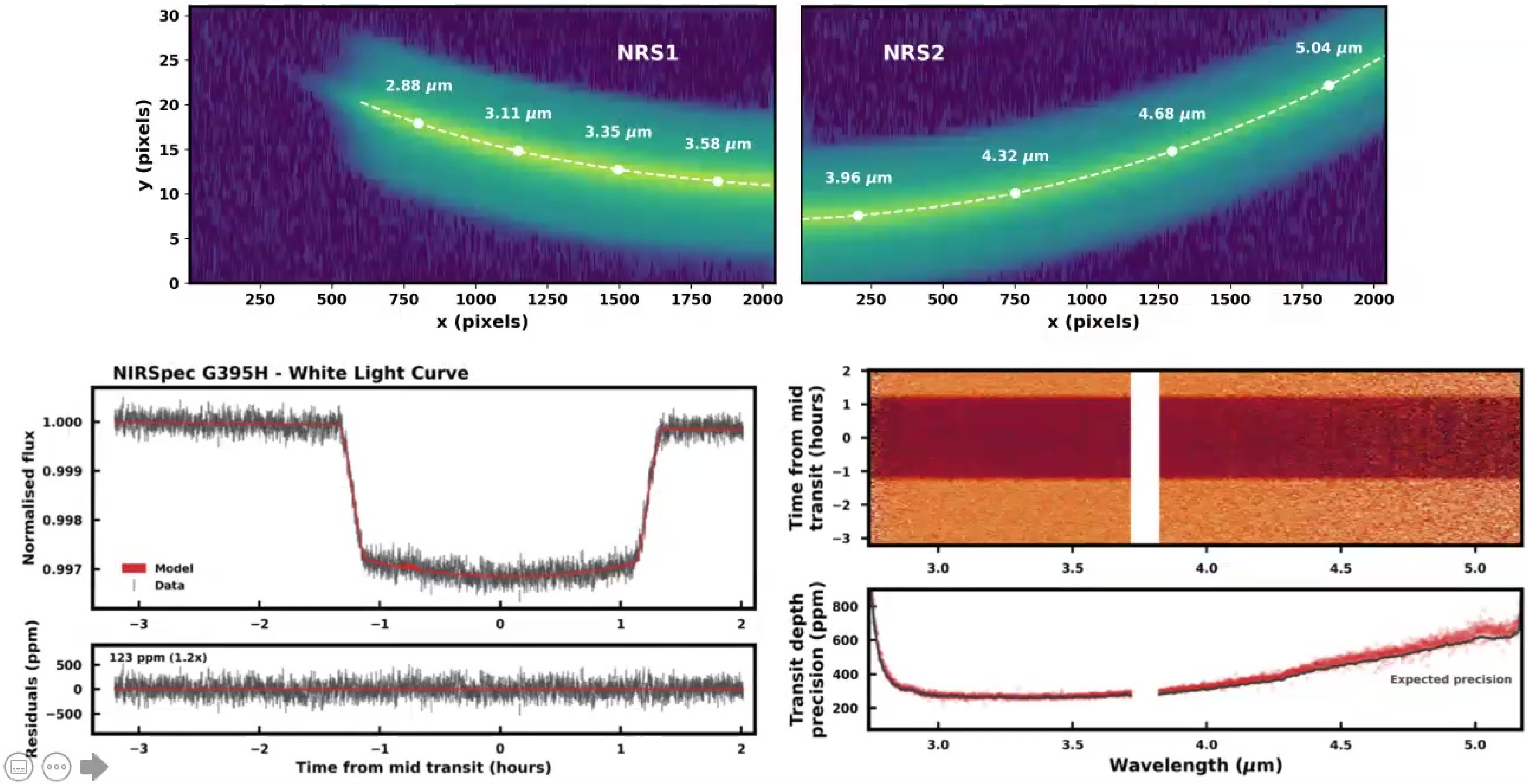
Chemical Disequilibrium in a Temperate Sub-Neptune

We will observe the first signs of chemical disequilibrium in the habitable-zone mini-Neptune K2-18b. We will conduct high-precision transit spectroscopy in the 1-8 μm range with three JWST instruments (NIRISS, NIRSpec and MIRI) and detect prominent molecules such as H_2O, CH_4 and NH_3 along with trace chemicals like CO and CO_2.

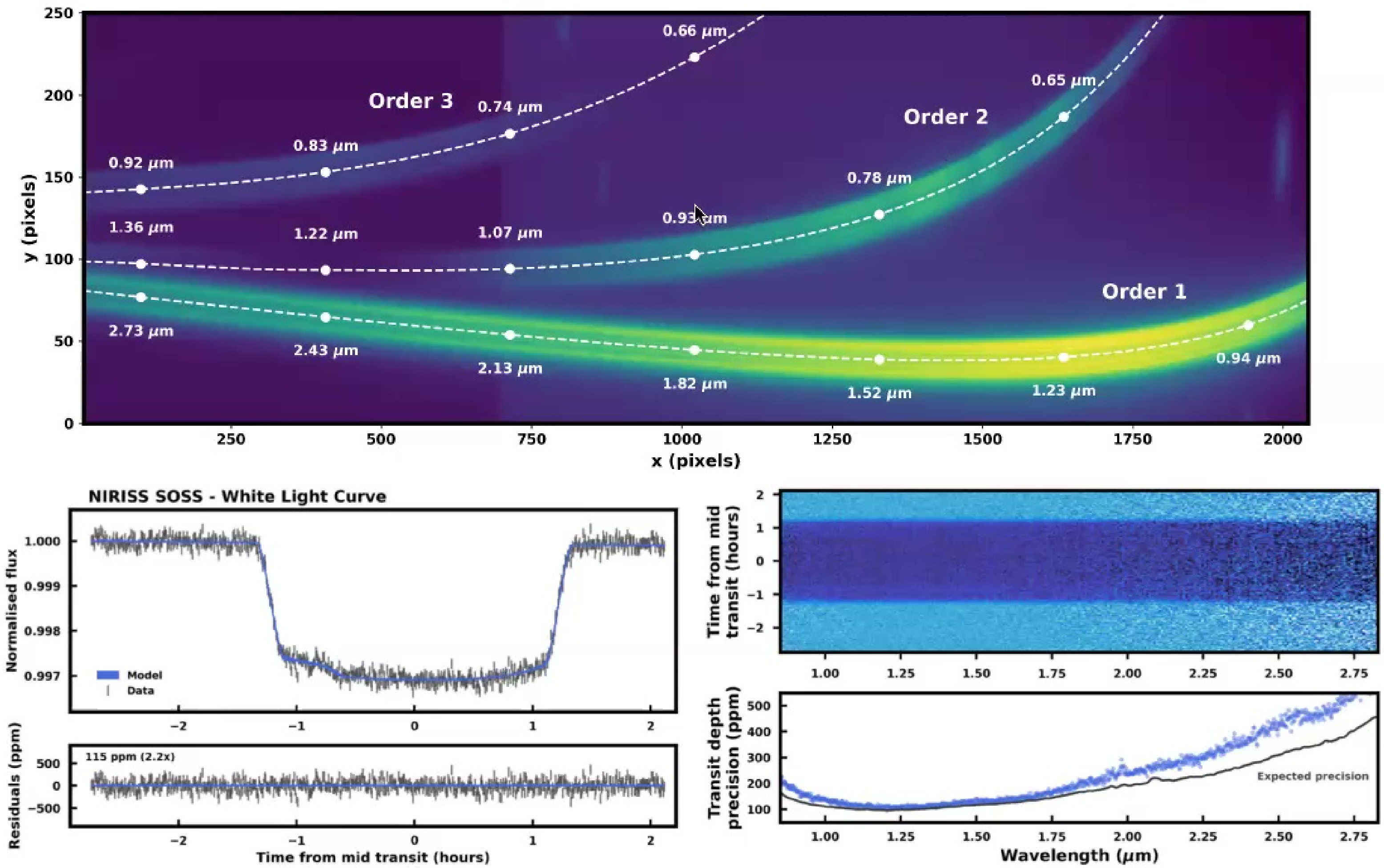
- Source: M2.5V, J = 9.8, d = 38 pc, High proper motion
- Two transits: one each with NIRISS and NIRSpec
- NIRSpec G395H: 2.7-5.2 µm, R~2700
  - Jan 20, 2023, 5.3 hours, separate TA source
- NIRISS SOSS: 0.9-2.8 µm, R~700, 4.9 hours
  - June 1, 2023, 4.9 hours, TA on target
- Successful time-series observations, no HGA move



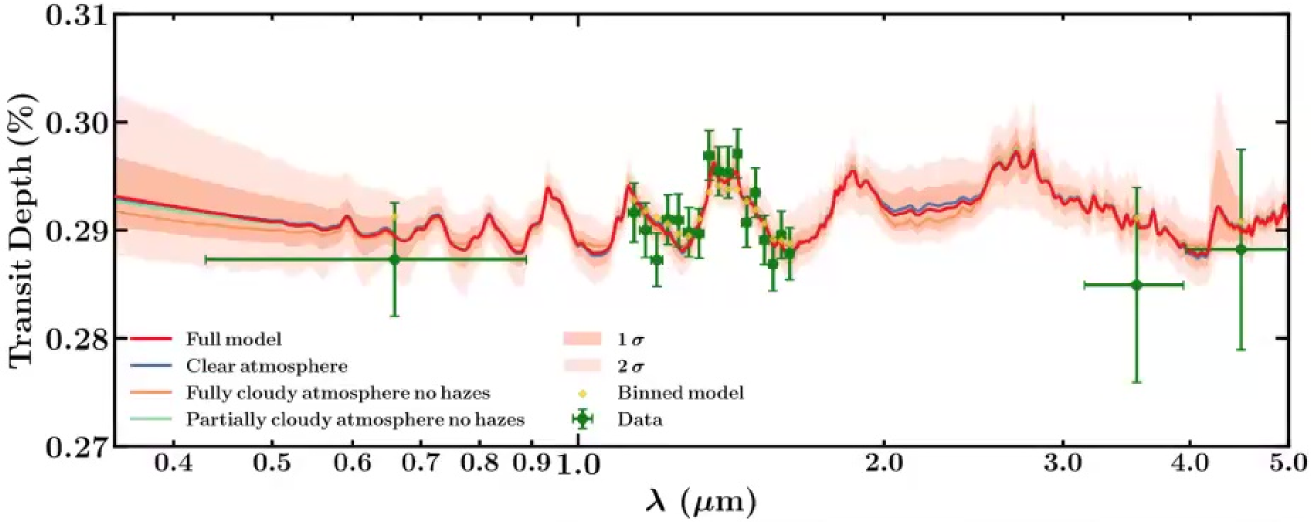
JWST Observations: NIRSpec G395H

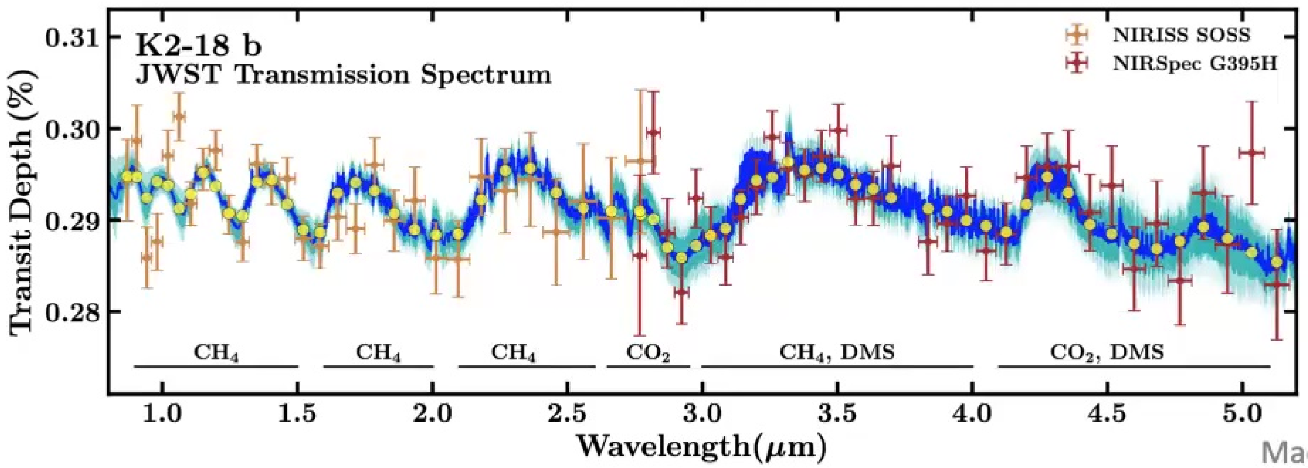


JWST Observations: NIRISS SOSS



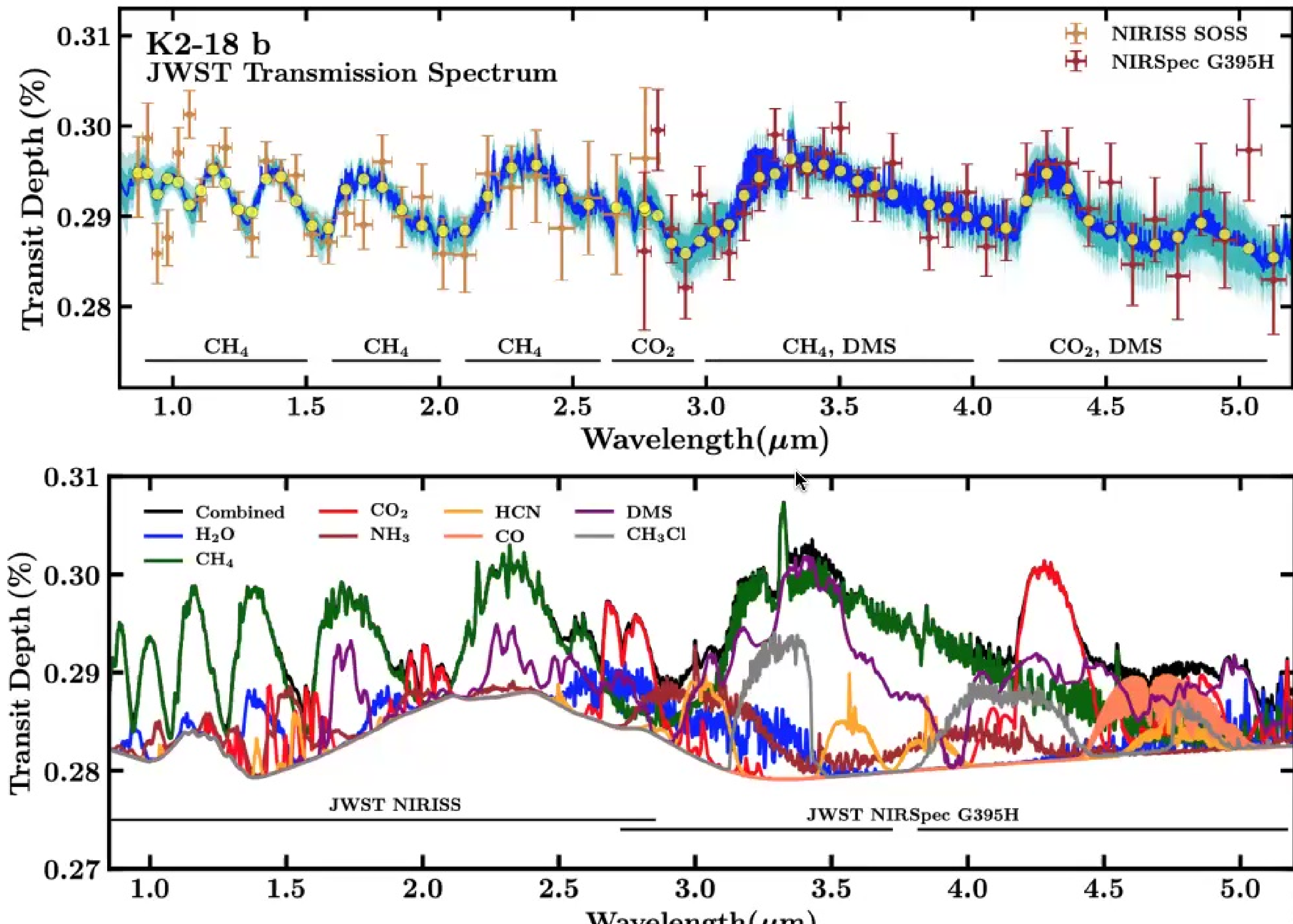
The JWST Spectrum of K2-18 b





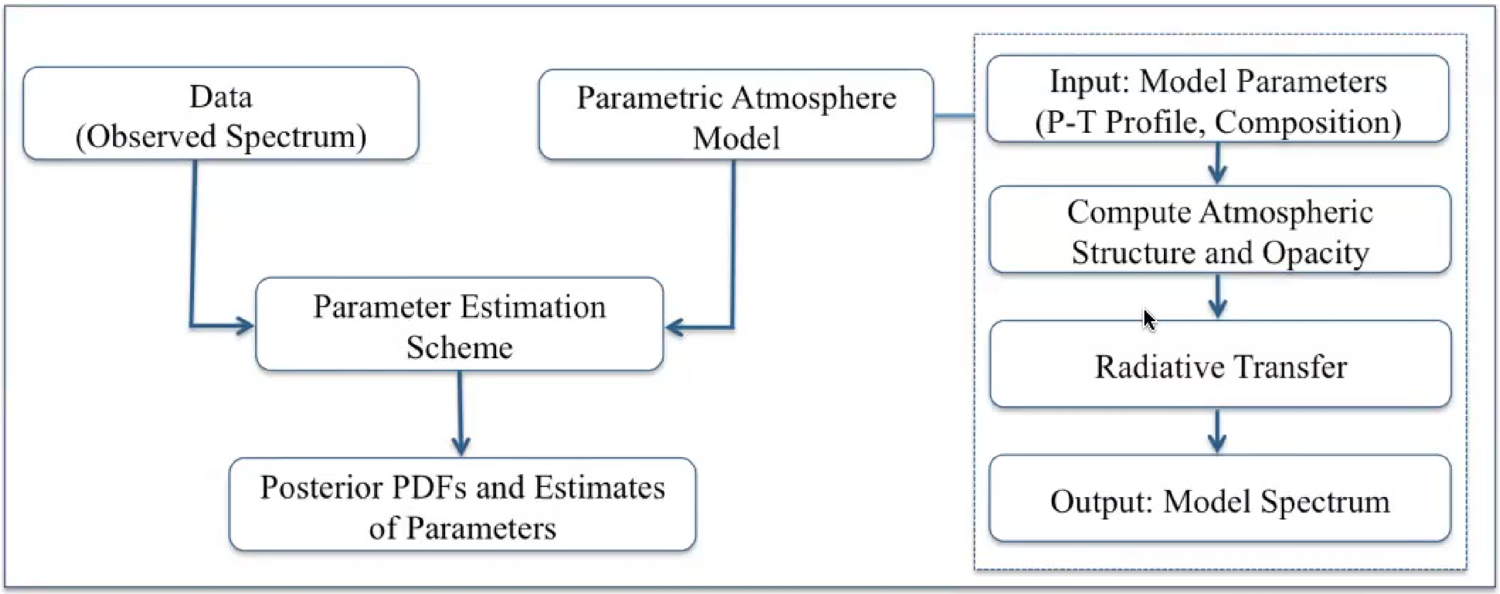
Madhusudhan et al. 2023

Atmospheric Retrieval



Madhusudhan et al. 2023

Atmospheric Retrieval

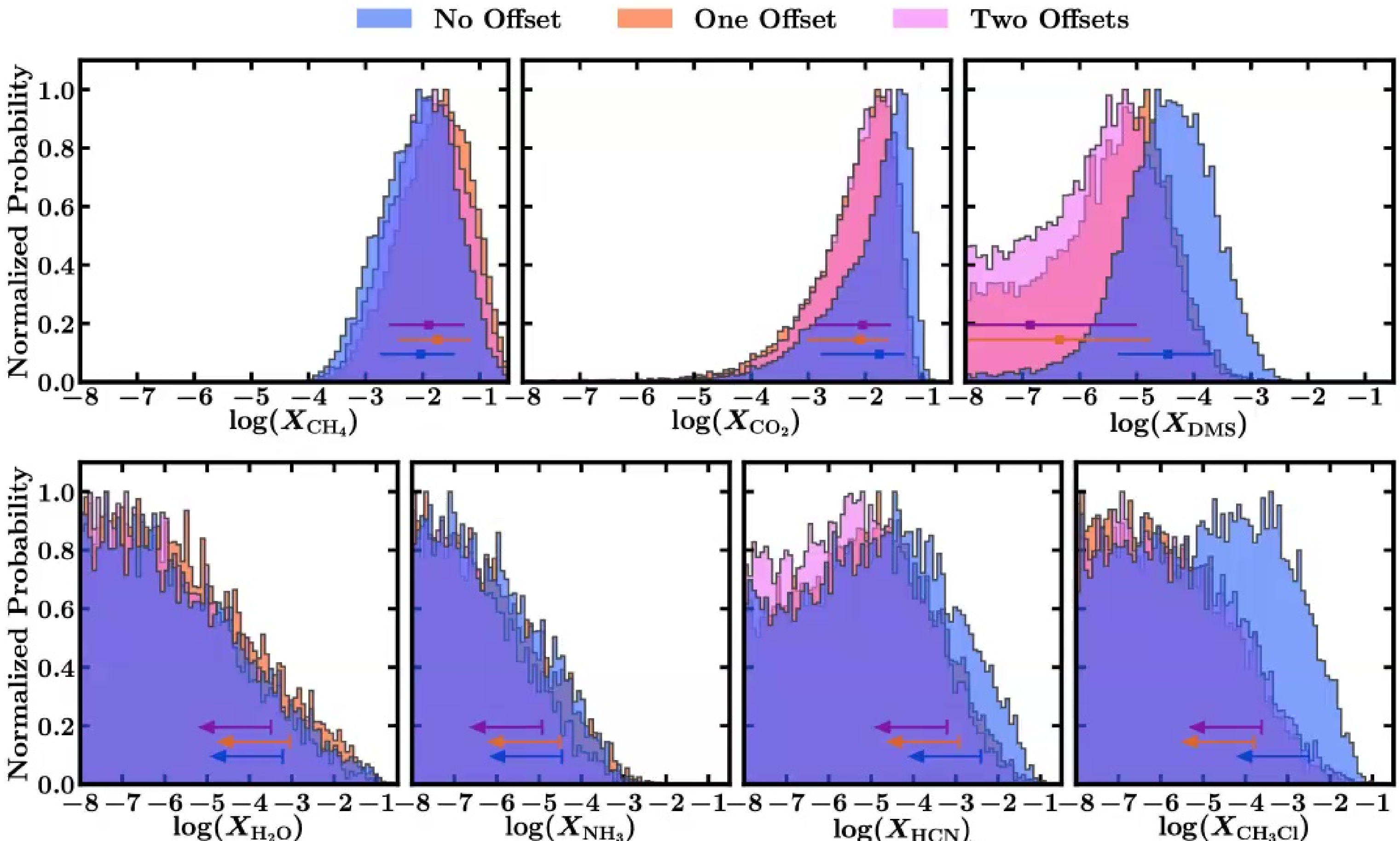


Madhusudhan 2018

Retrieval Considerations

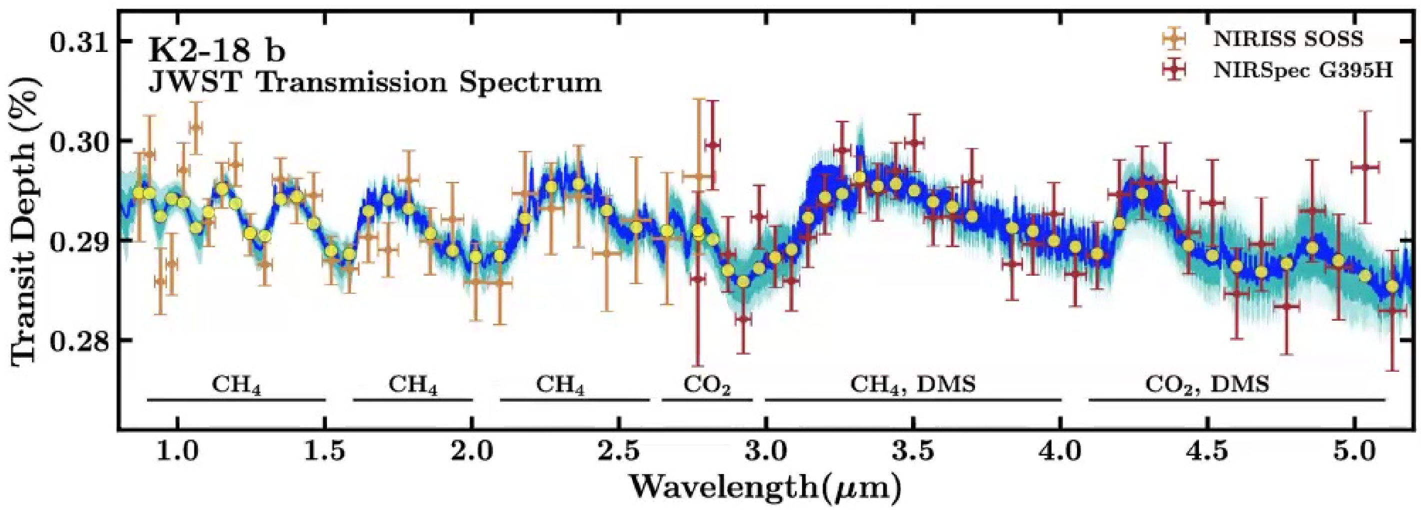
Canonical Model (22 params): 11 nominal molecules, P-T profile, Inhomogeneous Clouds/Hazes, Reference pressure
Other Considerations: Stellar Heterogeneities, other molecules, Mie scattering from multiple aerosols, offsets between datasets
Bayesian Inference: MultiNest, Model comparisons (Detection significances), High-resolution data and models

Atmospheric Retrieval



Madhusudhan et al. 2023

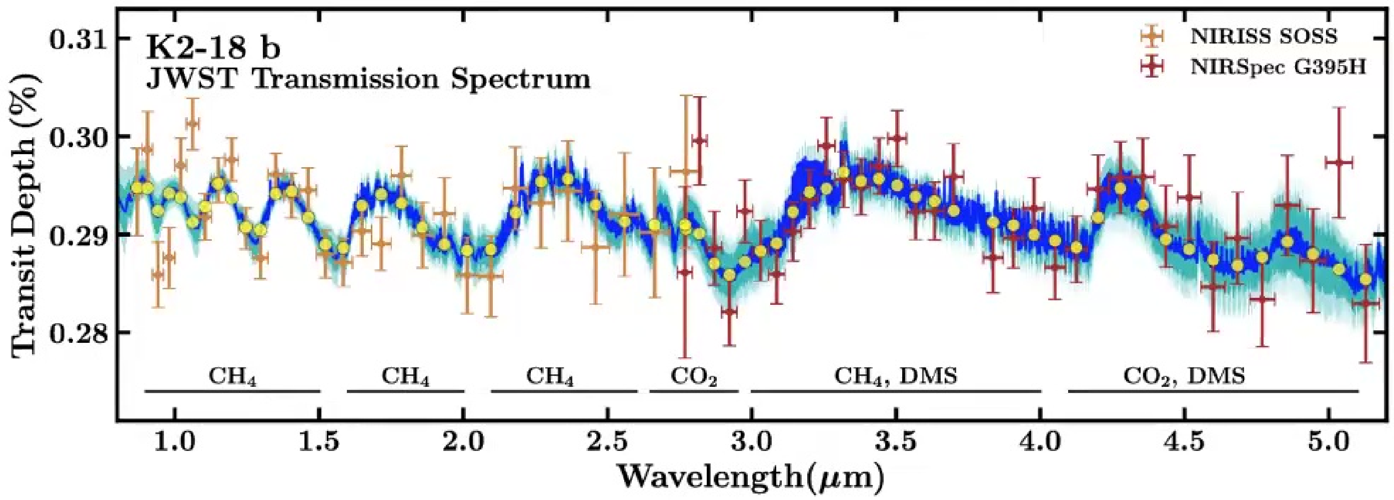
Atmospheric Retrieval



Cases	CH_4	CO_2	DMS	H_2O	NH_3	CH_3Cl	CO	HCN
No offset	$-2.04^{+0.61}_{-0.72}$ (4.7σ)	$-1.75^{+0.45}_{-1.03}$ (2.9σ)	$-4.46^{+0.77}_{-0.88}$ (2.4σ)	<-3.21	<-4.46	<-2.50	<-3.00	<-2.41
1 offset	$-1.74^{+0.59}_{-0.69}$ (5.0σ)	$-2.09^{+0.51}_{-0.94}$ (2.9σ)	$-6.35^{+1.59}_{-3.60}$ ($\sim1\sigma$)	<-3.06	<-4.51	<-3.80	<-3.50	<-2.92
2 offsets	$-1.89^{+0.63}_{-0.70}$ (5.0σ)	$-2.05^{+0.50}_{-0.84}$ (3.2σ)	$-6.87^{+1.87}_{-3.25}$ (–)	<-3.49	<-4.93	<-3.62	<-3.19	<-3.21

Madhusudhan et al. 2023

Atmospheric Composition

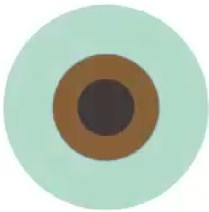


- H_2-rich with high abundance (>1%) of CH_4 and CO_2
- Non-detections of H_2O, NH_3, and CO
- Marginal evidence for DMS, potential biomarker
- Evidence for Clouds/Hazes and Low stratospheric temperatures

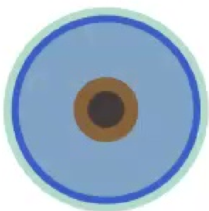
Madhusudhan 2023

Chemical Probes of the Presence of a Surface

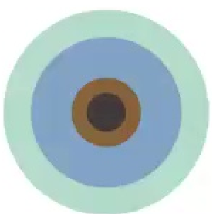
Rocky world



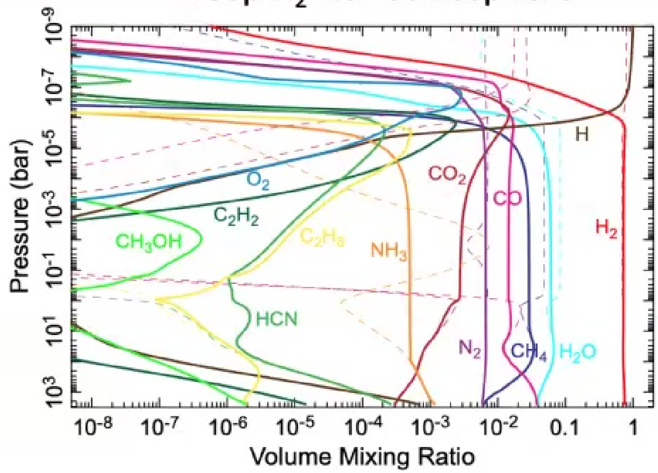
Hycean world



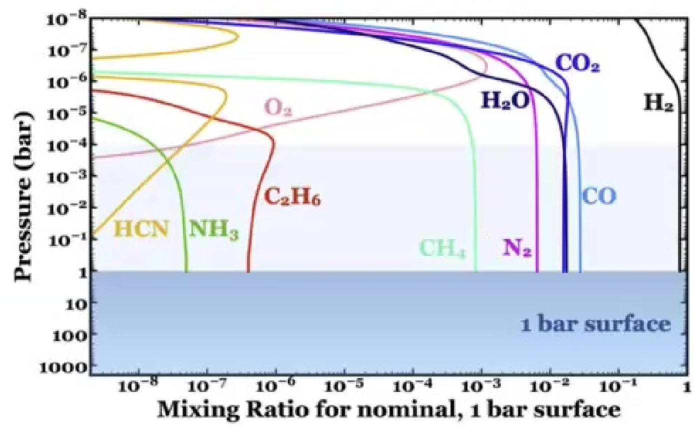
Mini-Neptune



Deep H_2-rich atmosphere



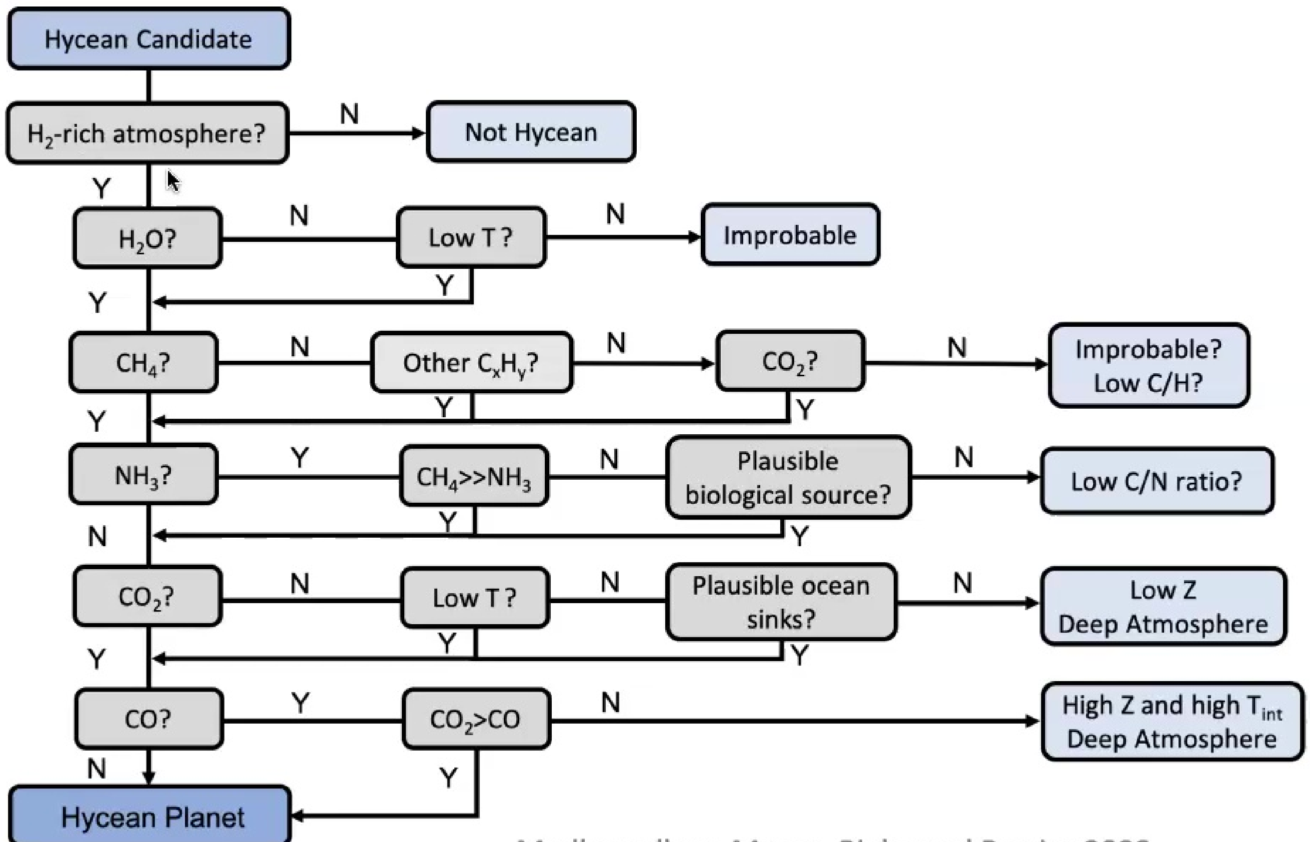
Effect of Surface

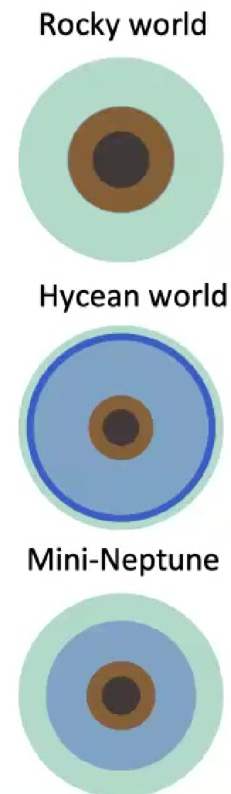


Yu et al. 2021, Hu et al. 2021, Tsai et al. 2021
Madhusudhan et al. 2023

- **Deep H2-rich Atmosphere:** Inconsistent with high CH_4 and CO_2 and low NH_3
- **Shallow H2-rich Atmosphere + Solid Surface:** Inconsistent with Density
- **Shallow H2-rich Atmosphere + Ocean Surface:** Consistent with all data

Chemical Diagnostics of Hycean Atmospheres





Madhusudhan, Moses, Rigby and Barrier 2023

Yu et al. 2021, Hu et al. 2021, Tsai et al. 2021

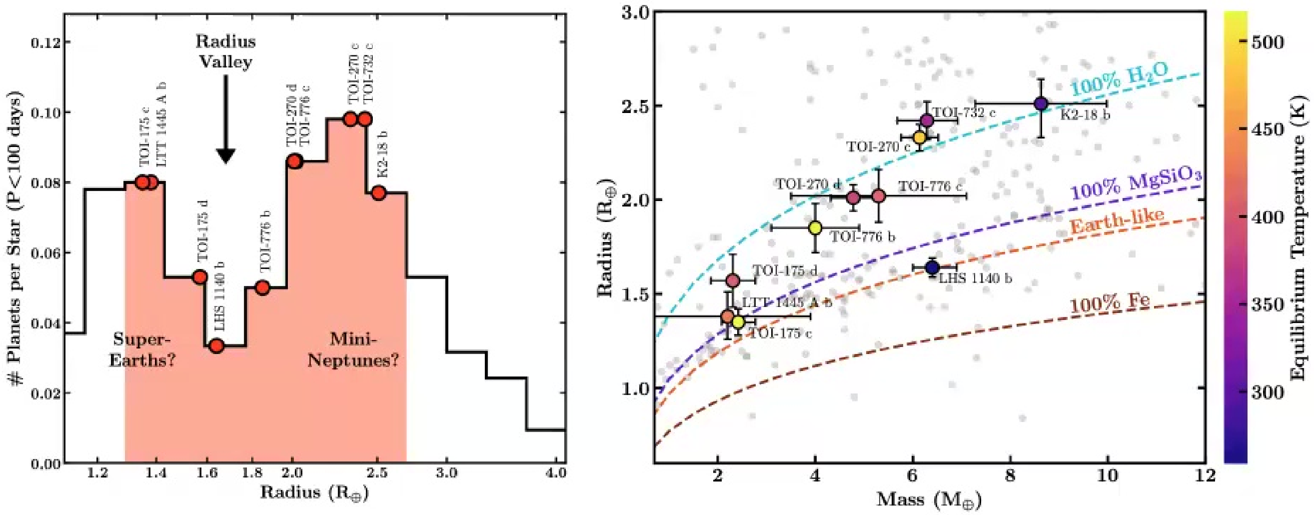
Conclusions

- First detection of CH_4 and CO_2 in a habitable-zone exoplanet
  - Resolution to missing methane problem in a temperate exoplanet
- High CH_4 and CO_2 and Low NH_3 consistent with Hycean world
  - Composition inconsistent with mini-Neptune or rocky world
  - New theoretical work needed for alternate explanations
- Potential inference of DMS, possible biomarker molecule
  - More modeling and observations needed for robustness
  - New theoretical work needed to establish biological activity
- Pathway to explore exoplanet habitability with JWST
  - Hycean worlds to expand and accelerate the search for life


K2-18 b: A Possible Hycean World
A New Era in Exoplanet Science

Atmospheric Reconnaissance of Nearby (<40 pc) Hycean Candidates

Over 200 hours of JWST time allocated in Cycles 1 and 2 for diverse science



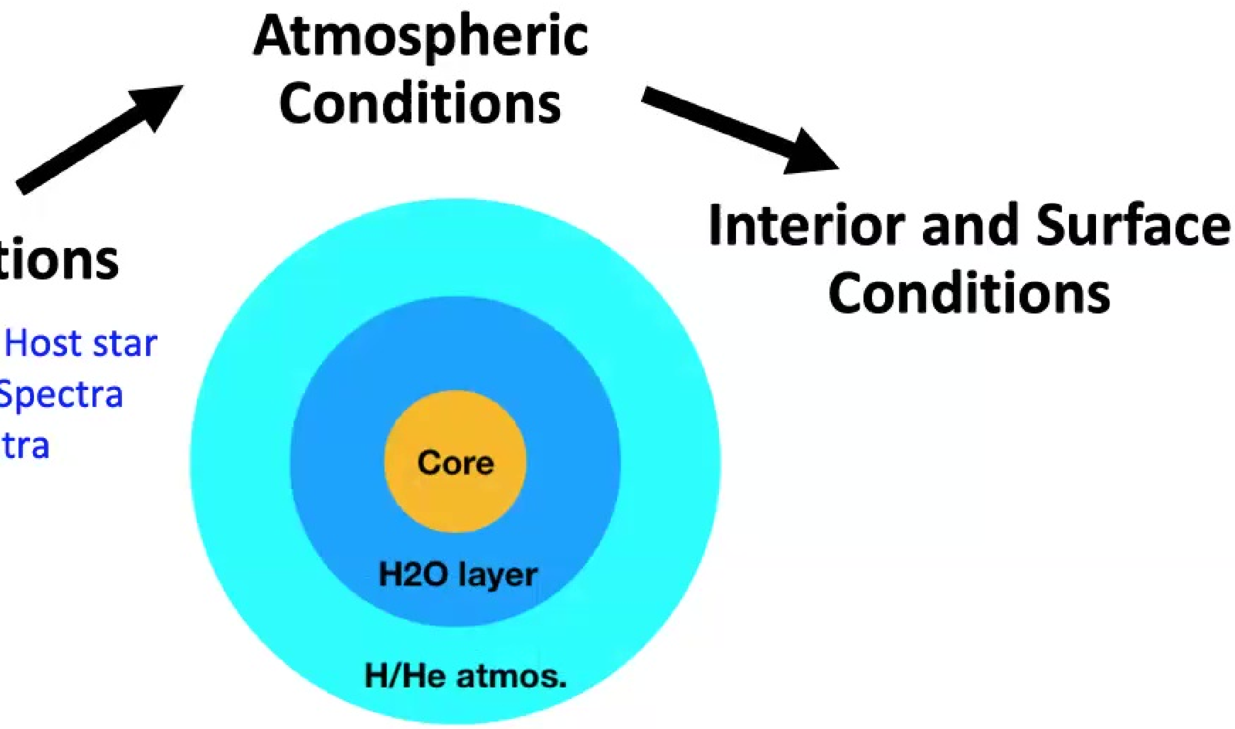
Name	R_p (R⊕)	M_p (M⊕)	T_{eq} (K)	M_* ($M_\odot$)	T_{eff} (K)	K mag	Approved Observations
K2-18 b	$2.51^{+0.13}_{-0.18}$	8.6 ± 1.3	297	0.444	3590	8.9	HST, JWST
LHS 1140 b	1.64± 0.05	$6.4^{+0.5}_{-0.4}$	259	0.191	3216	8.8	HST, JWST
LTT1445 Ab	$1.38^{+0.13}_{-0.12}$	$2.2^{+1.7}_{-2.1}$	433	0.257	3337	6.5	HST
TOI-175 c	1.35 ± 0.07	$2.4^{+0.3}_{-0.3}$	517	0.312	3412	7.1	HST, JWST
TOI-175 d	1.57 ± 0.14	$2.3^{+0.5}_{-0.4}$	409	0.312	3412	7.1	HST, JWST
TOI-270 c	2.33 ± 0.07	6.1 ± 0.4	489	0.386	3506	8.25	HST
TOI-270 d	2.01 ± 0.07	4.8 ± 0.5	387	0.386	3506	8.3	HST, JWST
TOI-732 c	$2.42^{+0.10}_{-0.10}$	$6.3^{+0.6}_{-0.6}$	353	0.401	3331	8.2	JWST
TOI-776 b	1.85 ± 0.13	4.0 ± 0.9	513	0.544	3709	7.6	JWST
TOI-776 c	2.02 ± 0.14	5.3 ± 1.8	414	0.544	3709	7.6	JWST

A Holistic Approach

Coupled Atmosphere-Interior-Surface Constraints

Observations

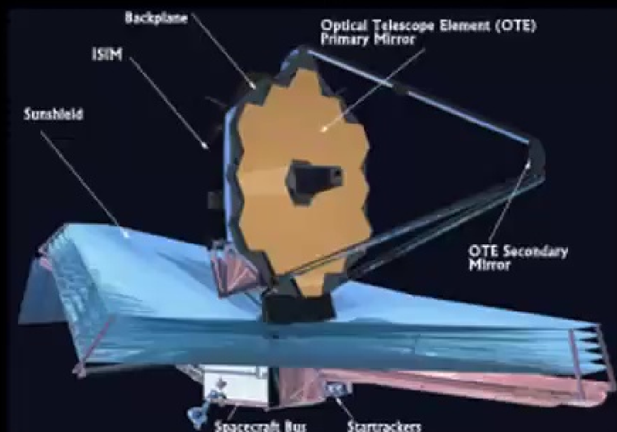
- Mass, Radius, Host star
- Transmission Spectra
- Emission Spectra



The Promise of this Decade

Launch pad in the search for life

The James Webb Space Telescope



Credits: NASA/ESA/CSA

Extremely Large Telescopes on Ground

Credits: ESO

Credits: NASA