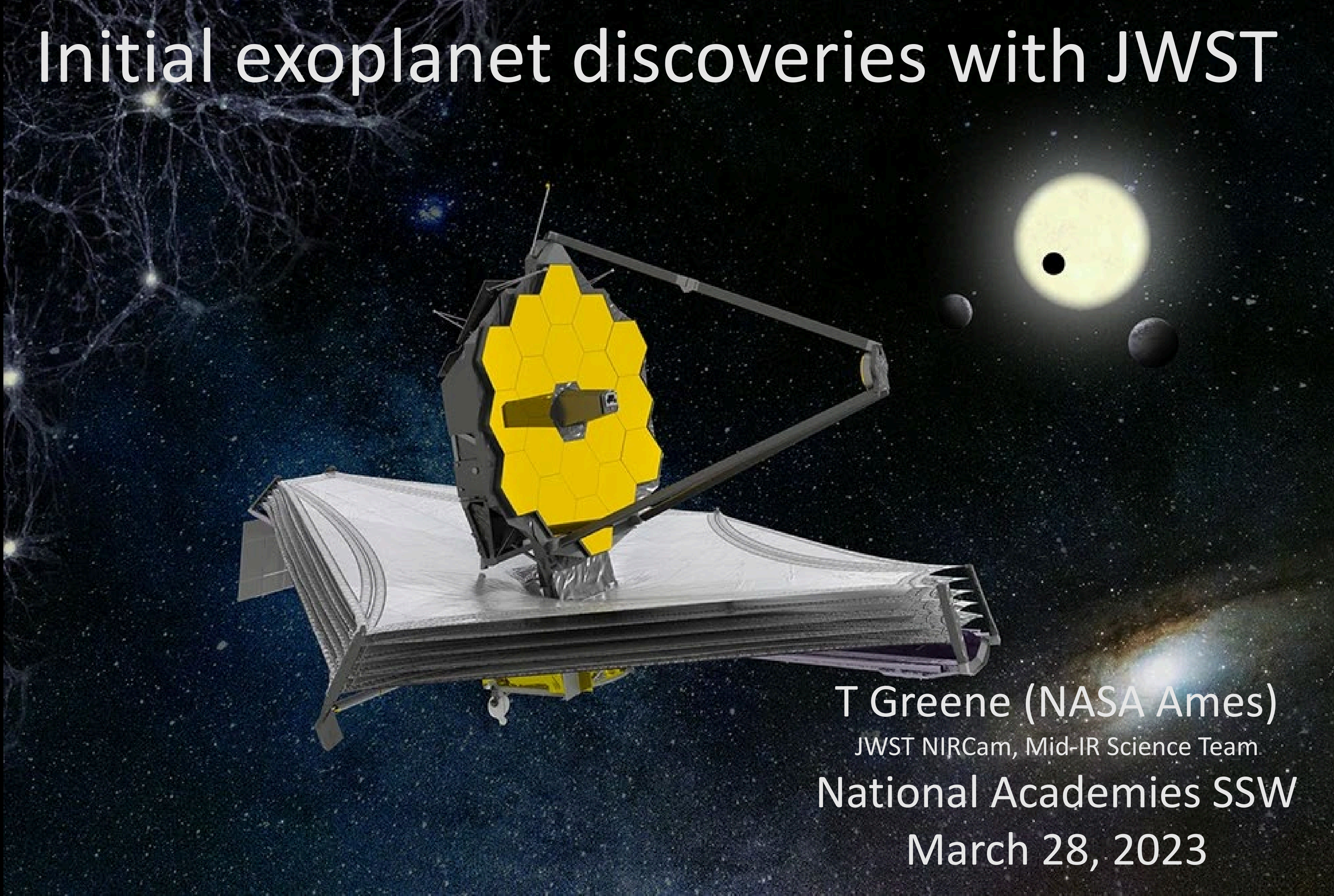
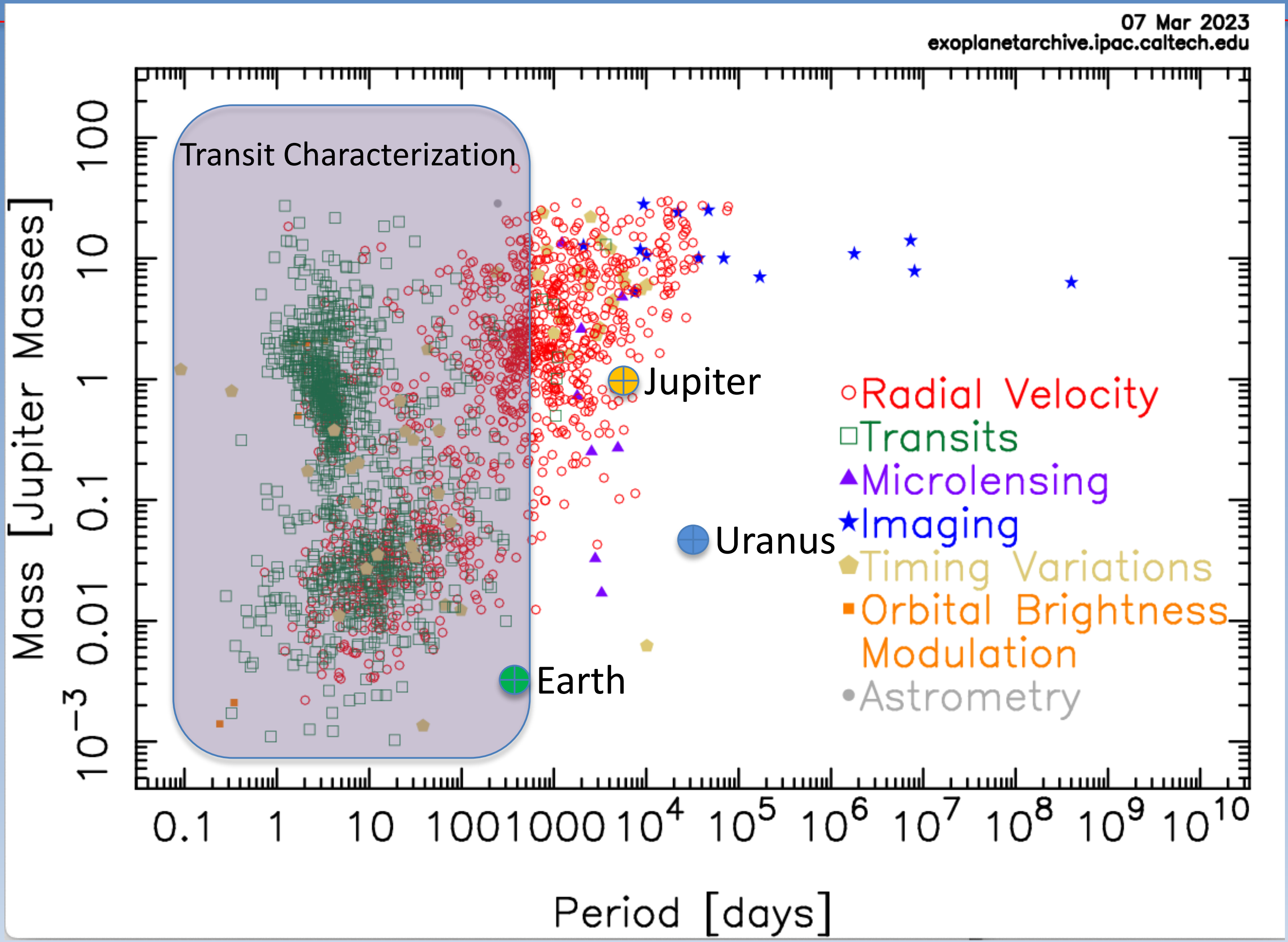
Initial exoplanet discoveries with JWST



T Greene (NASA Ames)
JWST NIRCam, Mid-IR Science Team

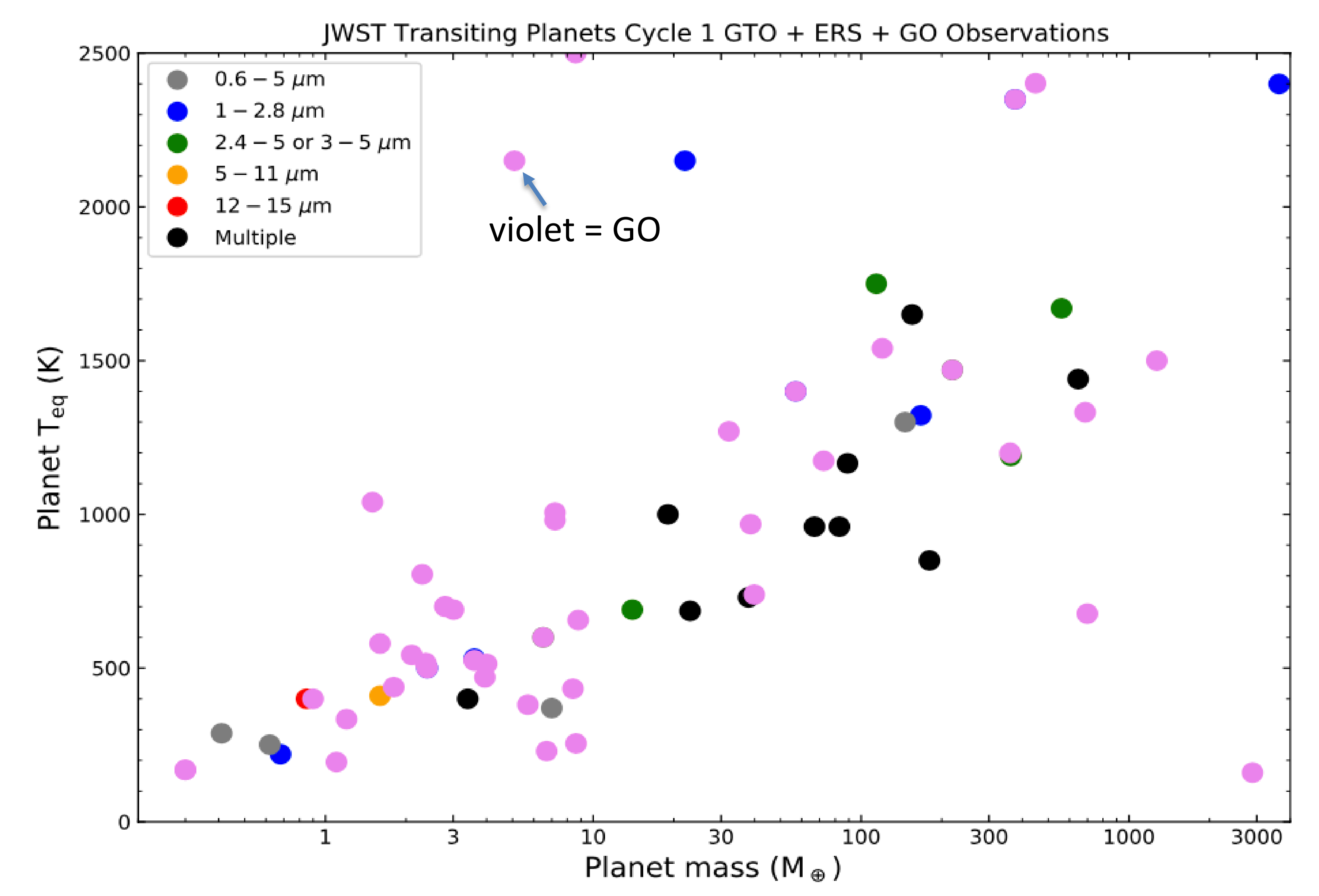
National Academies SSW
March 28, 2023

Current exoplanet census



Outstanding Exoplanet (Atmosphere) issues

- ***We wish to know:***
  - What are their chemical compositions, temperature profiles, and circulations?
    - What causes any departures from chemical equilibrium?
    - What are the compositions, locations, and impacts of clouds?
  - Why are many exoplanets unlike Solar System planets?
    - How and where did the planets form in protoplanetary disks?
    - How do they interact with and are influenced by their stars?
- ***Investigate with transit and secondary eclipse spectra***
  - Observe transmission & emission spectra to probe composition & temperature
    - Need a reasonably complete inventory of atmospheric constituents
  - Compare planet compositions with host star to understand formation process (core or pebble accretion, ablation) and location in disk
  - Observe a large, diverse population to explore range of processes and correlate results with bulk parameters (mass, density, insolation, host star)

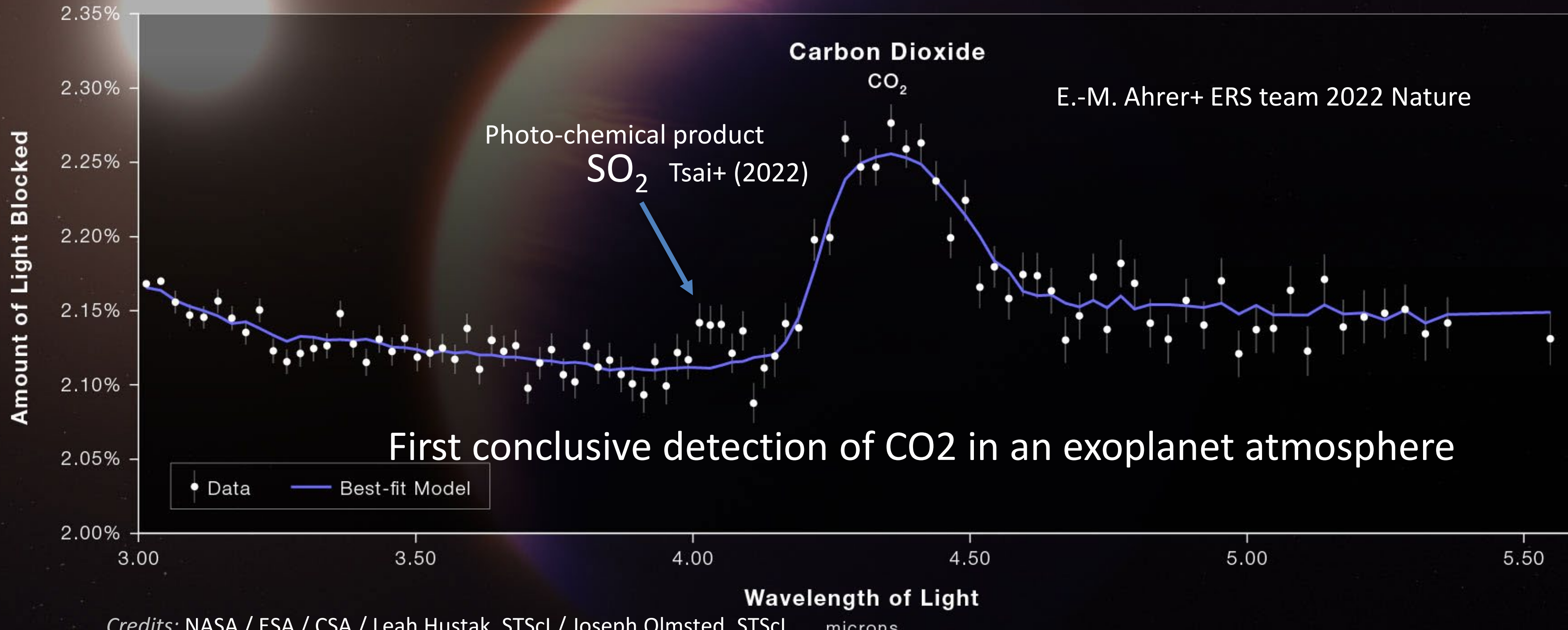

JWST Transiting Planets Cycle 1 GTO + ERS + GO Observations
0.6 – 5 μm
1 – 2.8 μm
2.4 – 5 or 3 – 5 μm
5 – 11 μm
12 – 15 μm
Multiple
violet = GO
Planet T_{eq} (K)
Planet mass ($M_\oplus$)
2500
2000
1500
1000
500
0
1
3
10
30
100
300
1000
3000

HOT GAS GIANT EXOPLANET WASP-39 b

ATMOSPHERE COMPOSITION

NIRSpec | Bright Object Time-Series Spectroscopy

JWST Transiting Exoplanet Early Release Science Program (WASP-39 b hot Saturn mass)

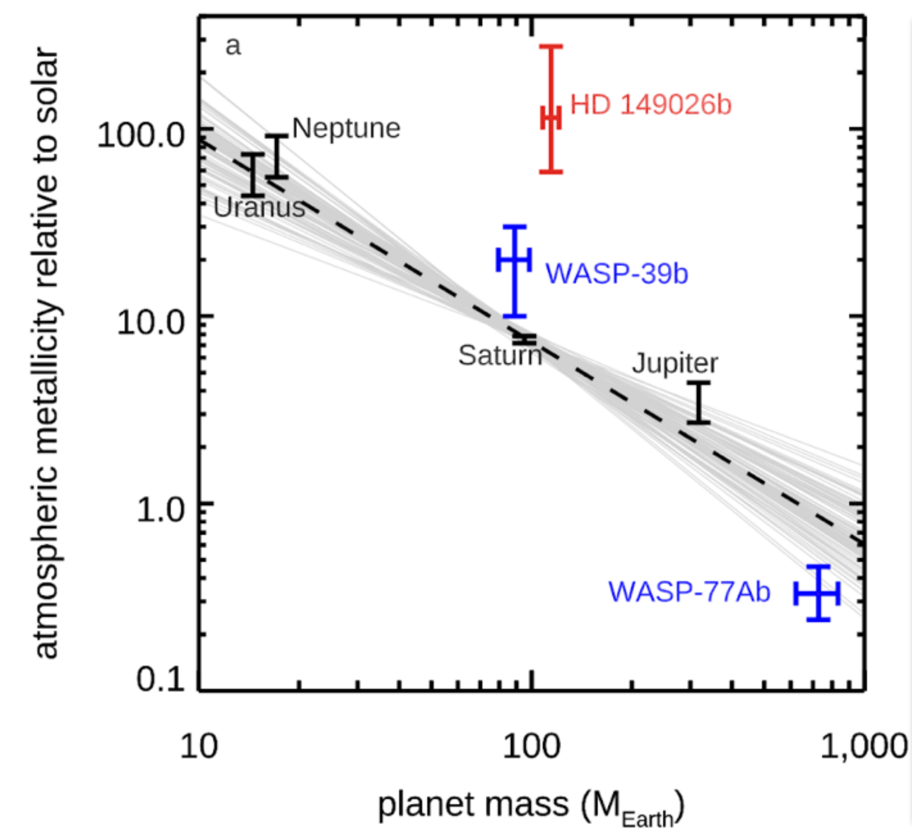


Credits: NASA / ESA / CSA / Leah Hustak, STScI / Joseph Olmsted, STScI.

https://https://www.sci.news/astronomy/webb-carbon-dioxide-wasp-39b-11131.html

WEBB SPACE TELESCOPE

The metal-rich gas giant HD 149026b (Teq = 1700K)



- High C/O = 0.84 implies either a carbon-rich disk or preferential accretion of carbon-rich material

- Can now study the compositions of exoplanets with precision comparable to Solar System ones

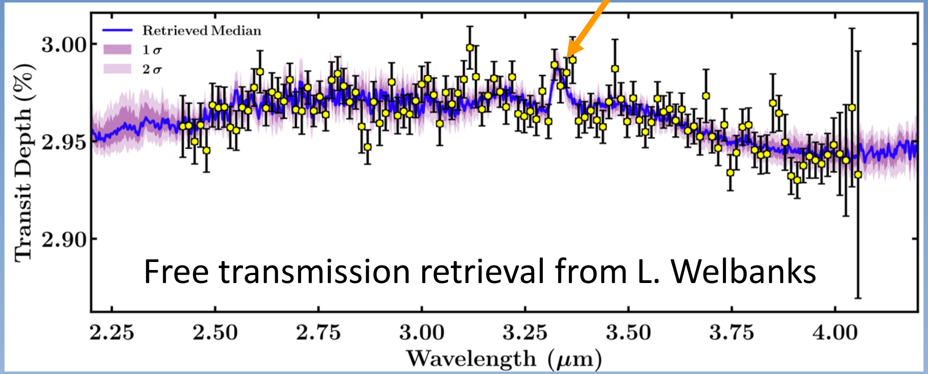
Bean+ 2023 March 27

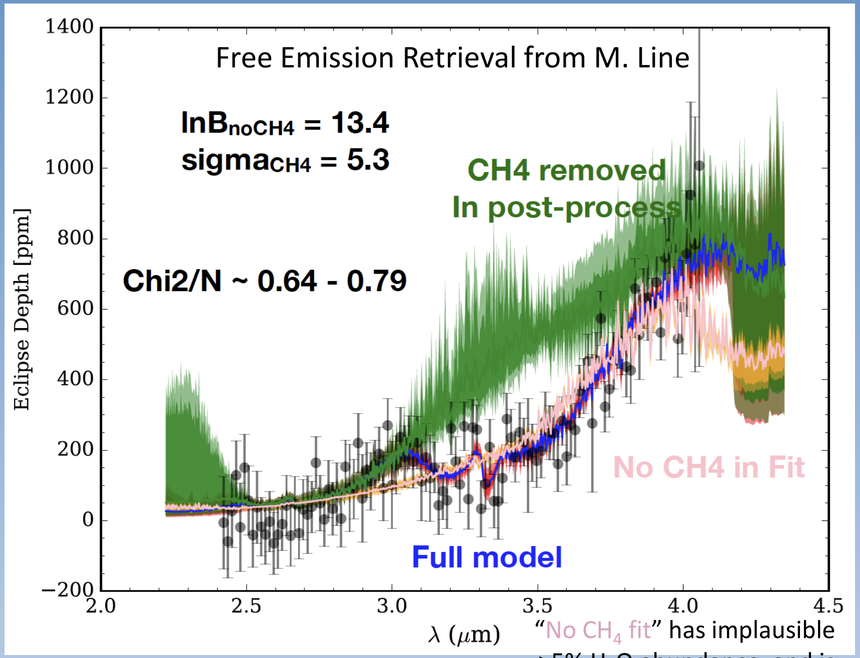
Saturn-like M/H ruled out at >4σ

Work in progress: Definitive detection of methane CH_4

Detected at $>5\sigma$ in both emission and transmission in a T_{eq} = 850 K gas giant

Methane ro-vibrational Q-branch





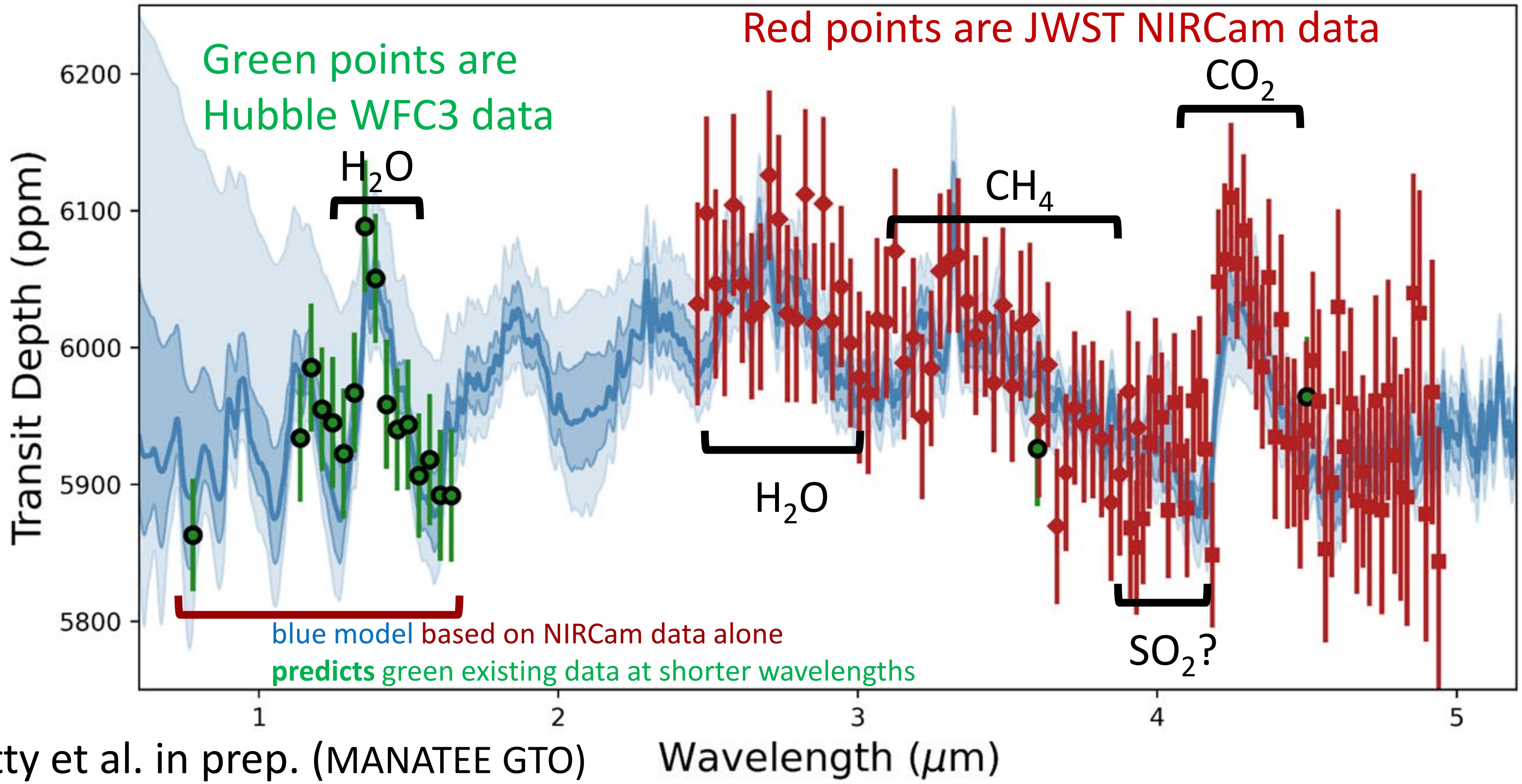
"No CH_4 fit" has implausible >5% H_2O abundance, and is still disfavoured at $>5\sigma$

- Importance: Measuring CH_4 informs carbon inventory and formation processes
- We knew CH_4 is underabundant in warm planets $T_{eq} < 1000$ K but this is best detection
- We can now constrain vertical mixing and probe accretion processes

Bell et al. in prep. 2023
MANATEE GTO program

Work in progress: Composition of mini-Neptunes

Most common planets in the galaxy but unlike any in our Solar System

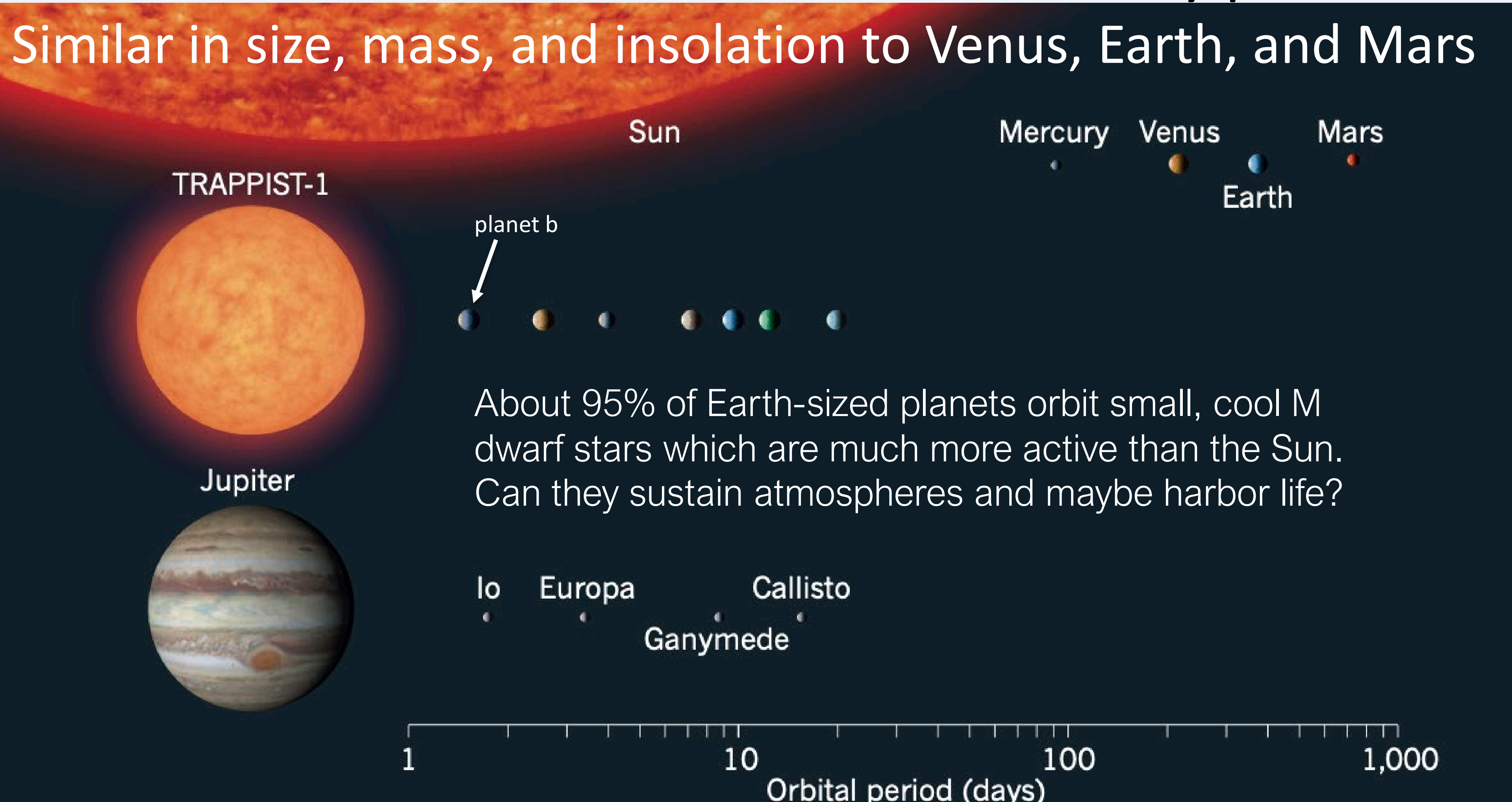


Beatty et al. in prep. (MANATEE GTO)

Before JWST we only knew of H_2O – now we have carbon and sulfur molecules

TRAPPIST-1 is an M dwarf star with 7 rocky planets:

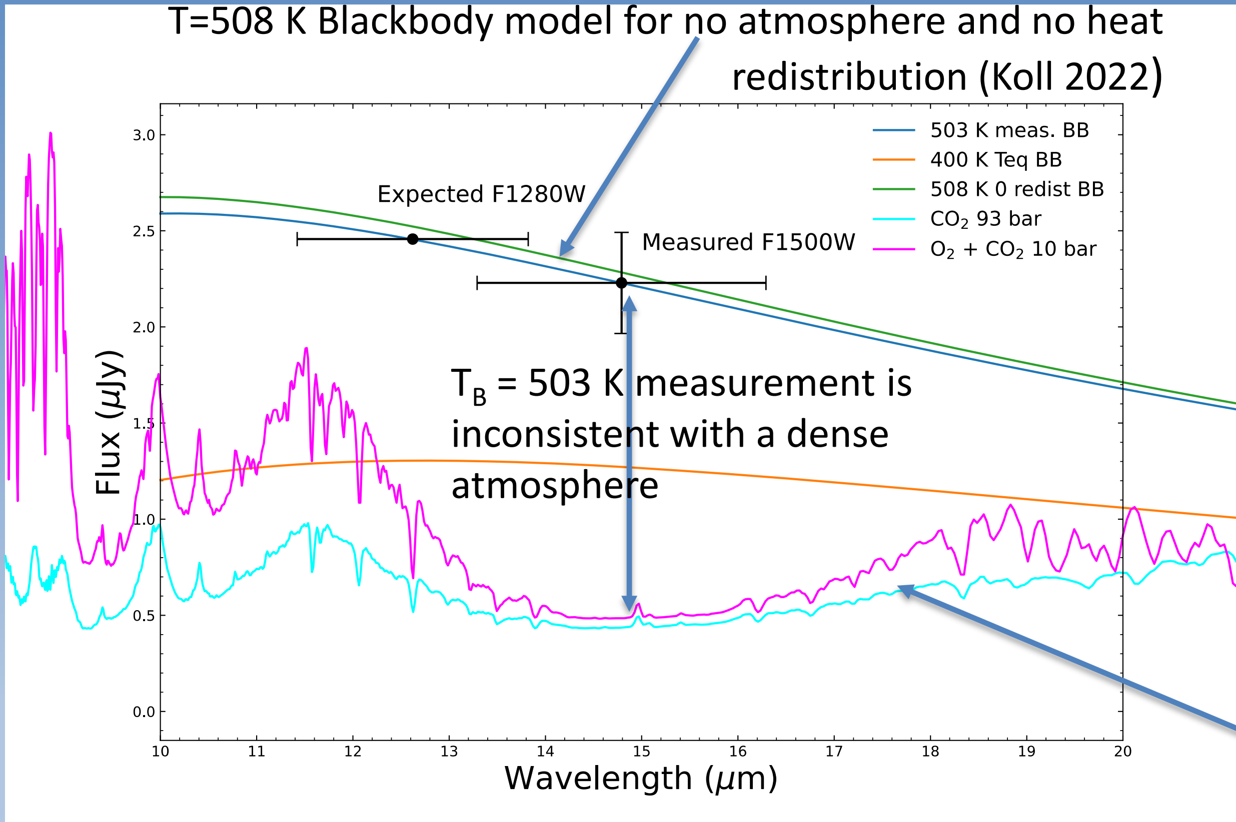
Similar in size, mass, and insolation to Venus, Earth, and Mars



About 95% of Earth-sized planets orbit small, cool M dwarf stars which are much more active than the Sun. Can they sustain atmospheres and maybe harbor life?

Snellen 2017 Nature

TRAPPIST-1 b: JWST MIRI 15 μm measurement



- Measured λ = 15 μm apparent brightness temperature T_B = 503+26/-27 K
- Most consistent with no atmosphere and no redistribution of stellar heating
- Tenuous P ~ 0.1 bar atmosphere without CO_2 also possible

10-100 bar CO_2 and O_2+CO_2 atmospheres (Lincowski+ 2018; Lustig-Yaeger+ 2019)

T Greene, T Bell, E Ducrot, A. Dyrek, P-O Lagage, J Fortney (2023 March 27)

TRAPPIST-1 b JWST MIRI 15 μm brightness temperature T_B

TRAPPIST-1 b dayside brightness temperature and models

Table 1: TRAPPIST-1 b Observations and Model Comparison

Atmospheric Model	Ref.	P_{surf} (bar)	Predicted T_B [1] (K)	Difference (σ) [2]
96.5% CO_2	[23]	10, 92	290	-6.7
95% O_2 + 0.5 bar CO_2	[23]	10, 100	303	-6.4
Isotropic T_{eq}	[1]	N/A	400	-3.6
Gray $\tau = 1.0$	[25]	1	445	-2.1
Gray $\tau = 0.1$	[25]	0.1	495	-0.3
0 redistribution	[32]	0	508	0.2
0 redistrib. + internal	[19]	< 0.1	534	1.2

1. T_B in MIRI F1500W filter, when applicable.
2. Difference between predicted and observed $\lambda = 15$ μm flux in units of measured σ.

T Greene, T Bell, E Ducrot, A. Dyrek, P-O Lagage, J Fortney (2023 March 27)

Implications for M-star planetary systems

- TRAPPIST-1 b suggests that the high initial brightness and frequent flaring of M stars may erode the atmospheres of their planets
- However, TRAPPIST-1 receives 4 times as much stellar flux as Earth and more than Venus
- Other TRAPPIST-1 planets at greater distances from the star may have retained atmospheres
- Knowing this is important for understanding the habitability of Earth-size planets in the cosmos

Thank you

Probe planet formation via C/O abundance

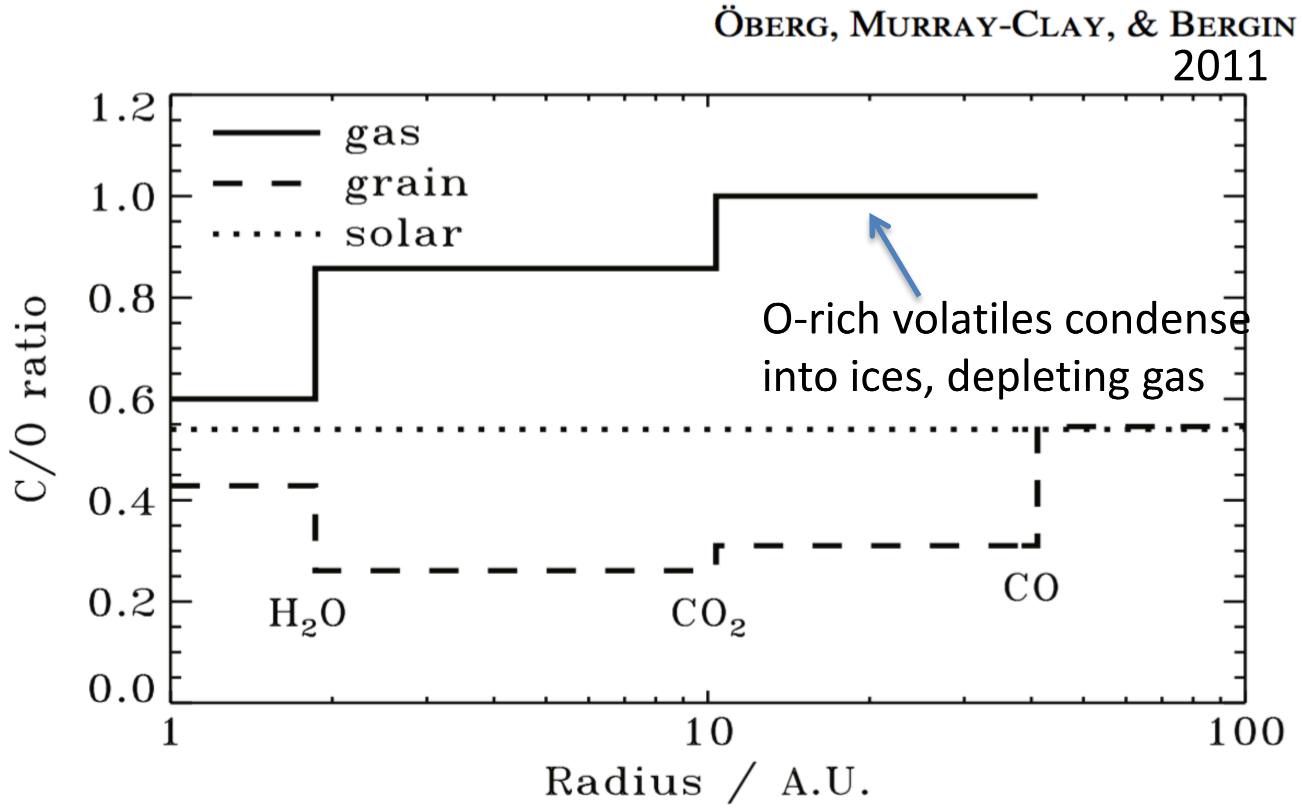
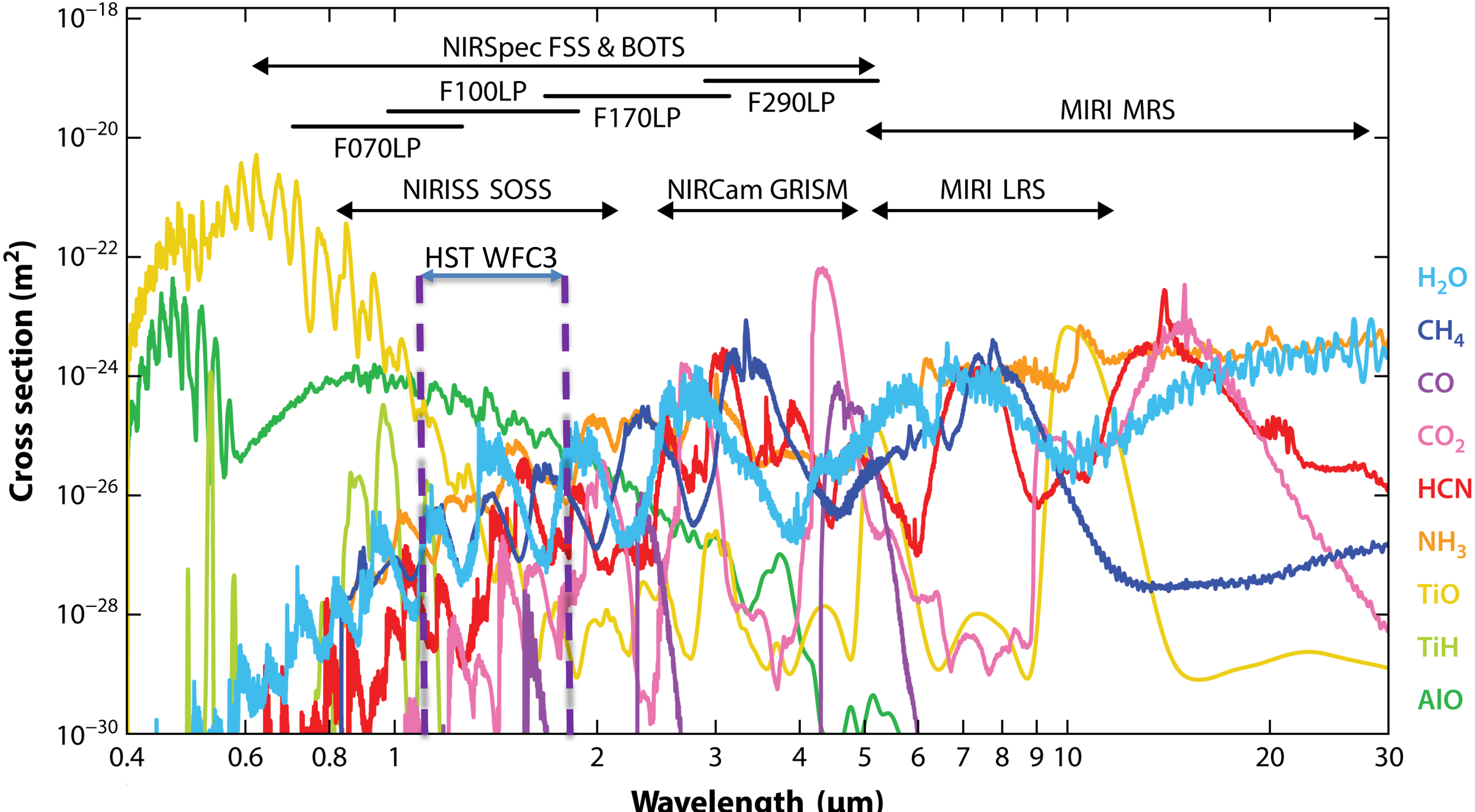


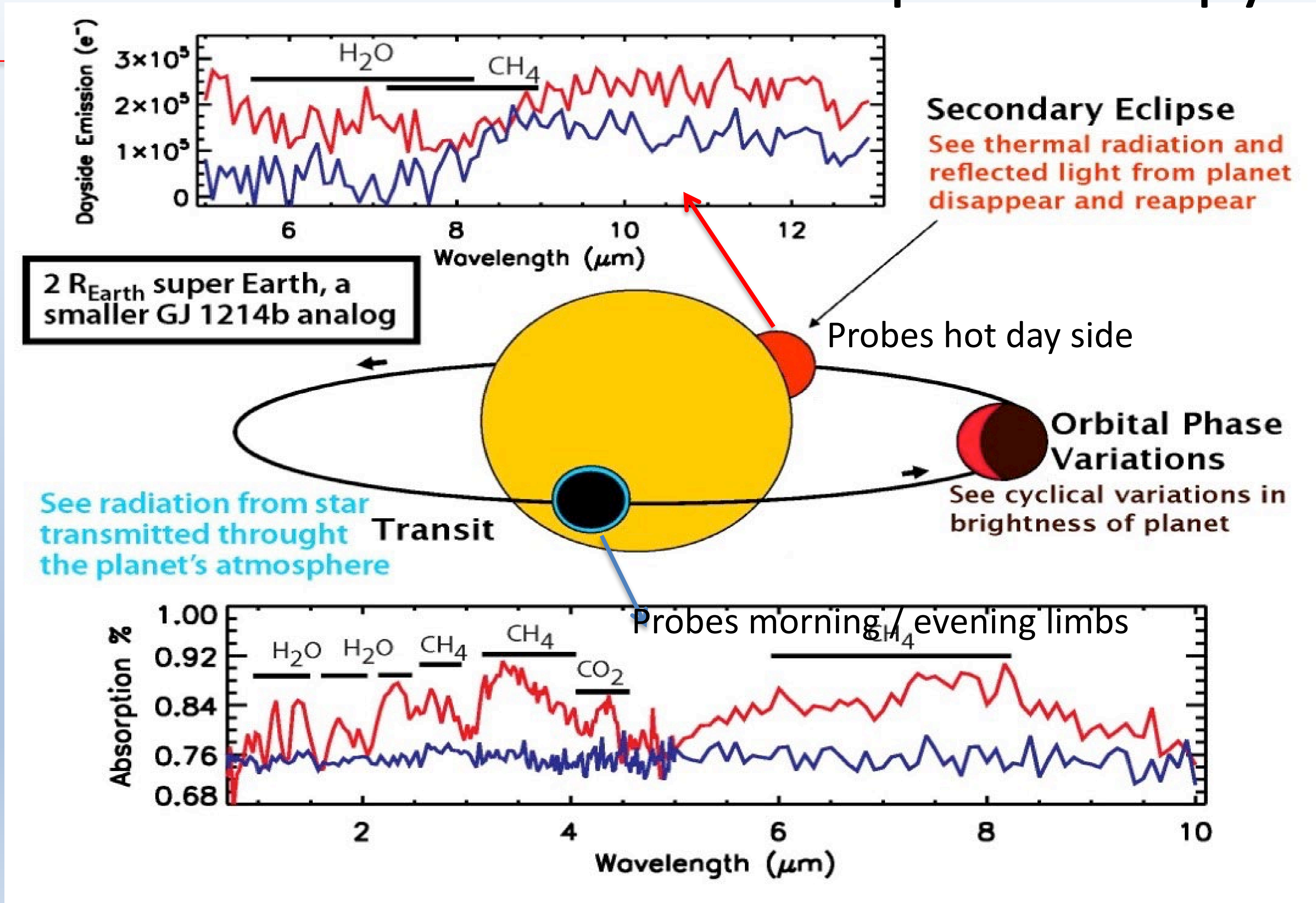
Figure 1. C/O ratio in the gas and in grains, assuming the temperature structure of a "typical" protoplanetary disk around a solar-type star (T_0 is 200 K and $q = 0.62$). The H_2O, CO_2, and CO snowline are marked for reference.

JWST spectral coverage of molecular features



Madhusudhan N. 2019.
Annu. Rev. Astron. Astrophys. 57:617–63

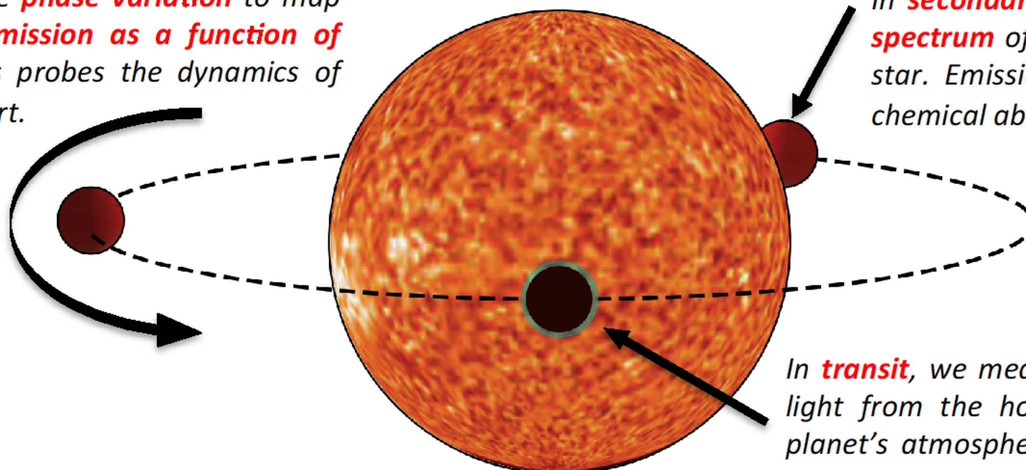
Transmission & Emission Spectroscopy



Probing Exoplanet Atmospheres With Transits

*We observe the **phase variation** to map the planet's **emission as a function of longitude**. This probes the dynamics of energy transport.*

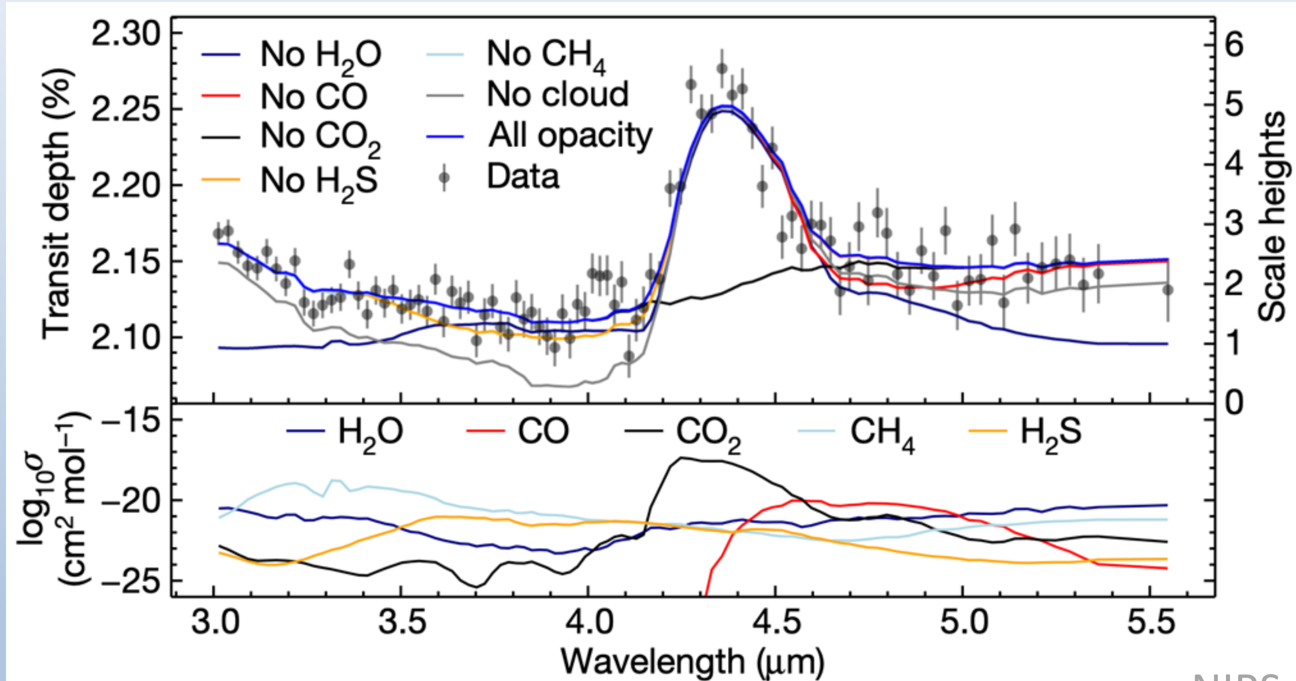
*In **secondary eclipse**, we measure the dayside **emission spectrum** of the planet as its light is blocked by the host star. Emission spectroscopy is sensitive to the absolute chemical abundances and the thermal structure.*



*In **transit**, we measure the **transmission spectrum** of the planet as light from the host star is absorbed by chemical species in the planet's atmosphere. These data are most sensitive to the relative chemical abundances and the presence of cloud or haze particles.*

Identification of CO_2 in an exoplanet atmosphere

WASP-39b

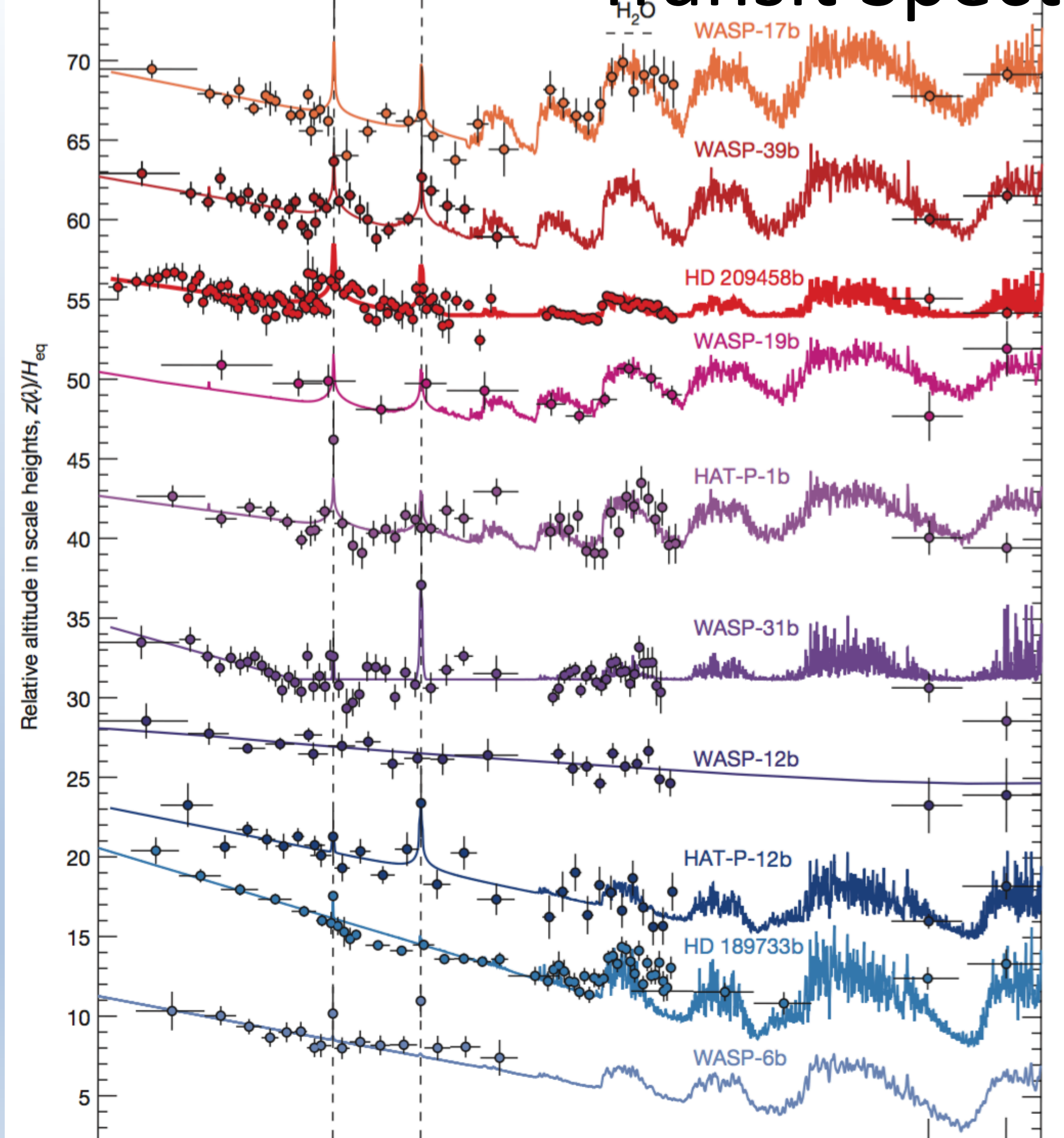


NIRSpec

Best-fit model: M/H = 10x solar, C/O = 0.35, moderate grey cloud opacity

ERS Team 2023, Nature

ransit Spectroscopy Status



Clear atmospheres show spectral features

Clear-to-cloudy hot Jupiter transmission spectra from visible to mid-IR

Smaller planets are difficult to characterize

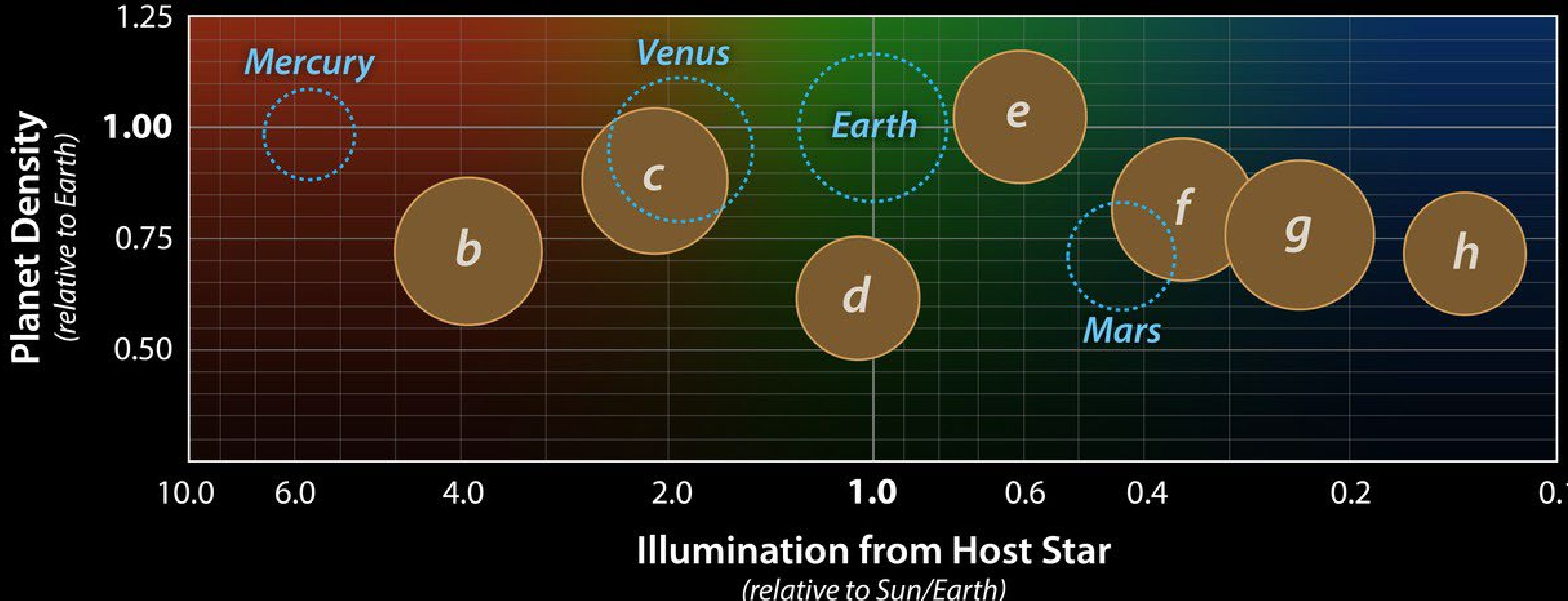
Cloudy or hazy have strong blue scattering slopes and weak spectral features

Meet the Planets: MANATEE GTO Observations

Planet	M_e	Teq K	Geometry	Visits	λ/Mode	Comment
HD 189733 b	360	1190	Emission	1	3.9 – 5 μm	Fiducial HJ; Collab w/J Bean
WASP-80 b	180	850	Emis+ Trans	6	2.4–11 μm	Chemistry, circulation
WASP-69 b	92	960	Emission	3	2.4–11 μm	Warm Saturn
WASP-107 b	~35	740	Trans	2	2.4–5 μm	Weird mass, low gravity
GJ 436 b	22	700	Emission	8	2.4–11 μm	Chemistry: CH_4?
HAT-P-26 b	19	1000	Trans	1	5 –11 μm	Collab w/Telescope team
GJ 3470 b	14	600	Trans	2	2.4–5 μm	Clouds, chemistry: CH_4?
GJ 1214 b	6.3	570	Trans	2	2.4–5 μm	Clouds, chemistry
TRAPPIST-1 b	1.1	400	Emission	5	MIRI 15μm	CO absorption? T_B?

Total time of 215 hours: ~140 hours with NIRCam grism (2.4 – 5μm) and ~75 with MIRI LRS (5 – 10+ μm) + imager (15 μm for TRAPPIST-1 b)

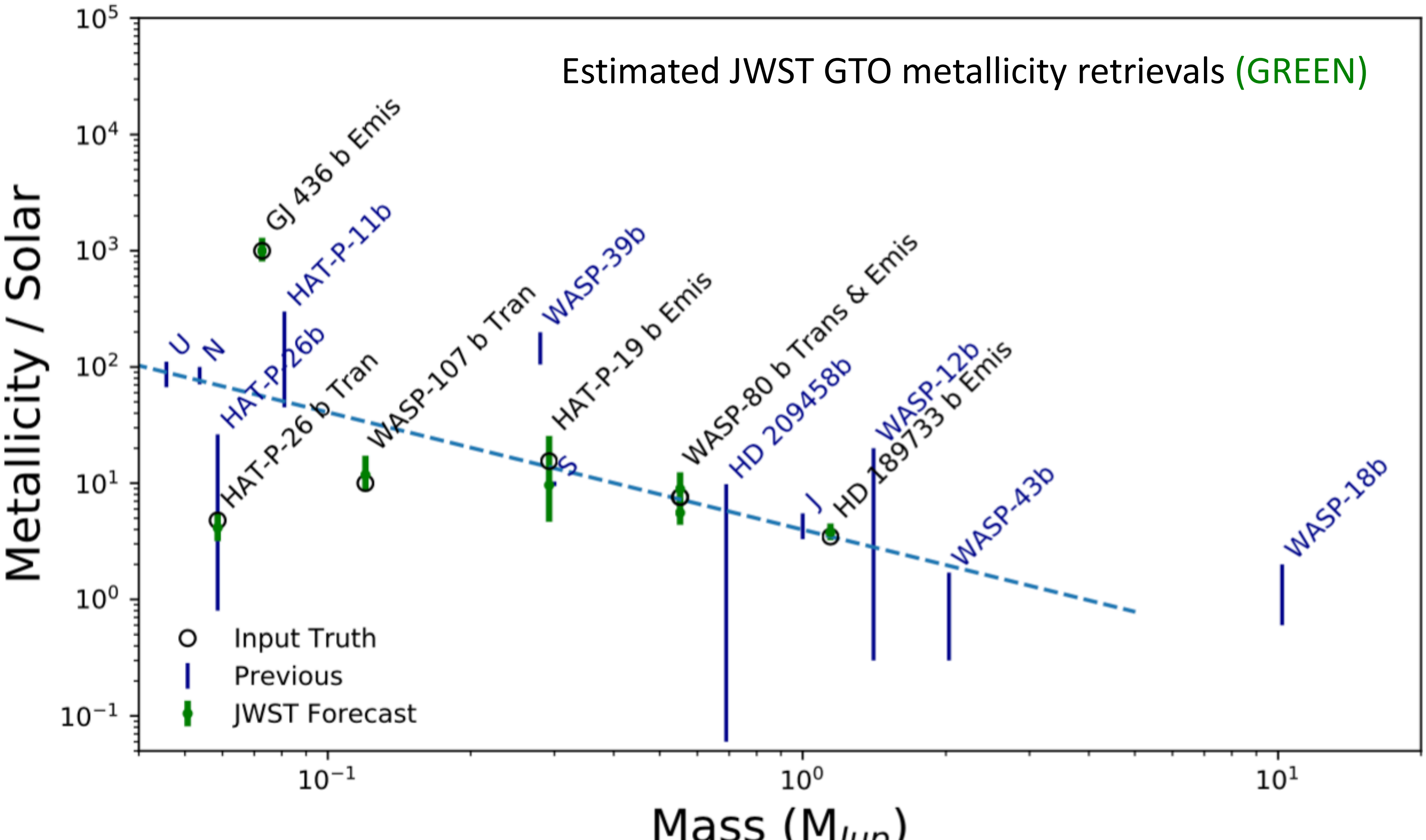
TRAPPIST-1/Solar System Comparison



Great laboratory for studying atmospheres of M dwarf planets:
Its 7 planets have stellar heating commensurate with our Solar System's terrestrial planets

JWST Clear & Cloudy Forecasts

Schlawin+ (2018)



Input metallicities (open circles) for the forward models were assigned to be consistent with literature spectra for the masses < 0.2MJup or the mass

Planet mass-radius relationships