

A large, blue, hazy planet occupies the left side of the frame. In the upper center, a bright orange star with a sunburst effect is visible against a black background. The planet's surface shows some faint, darker blue spots.

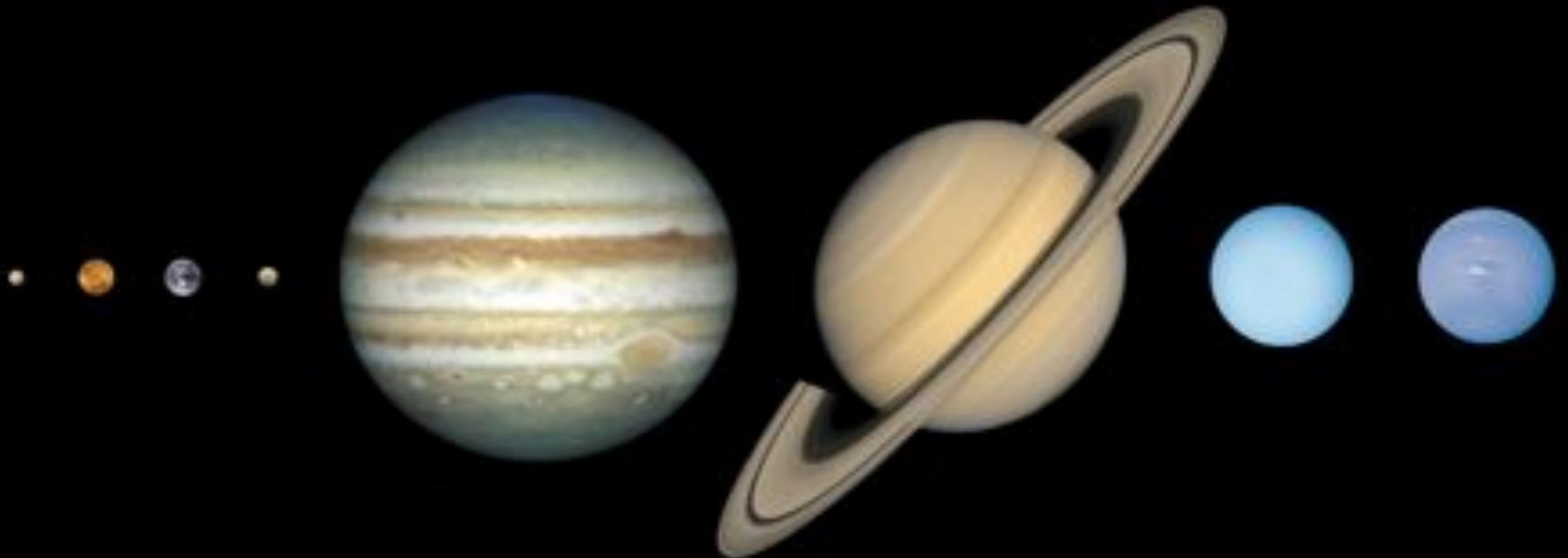
# Spectroscopy of Super-Earths

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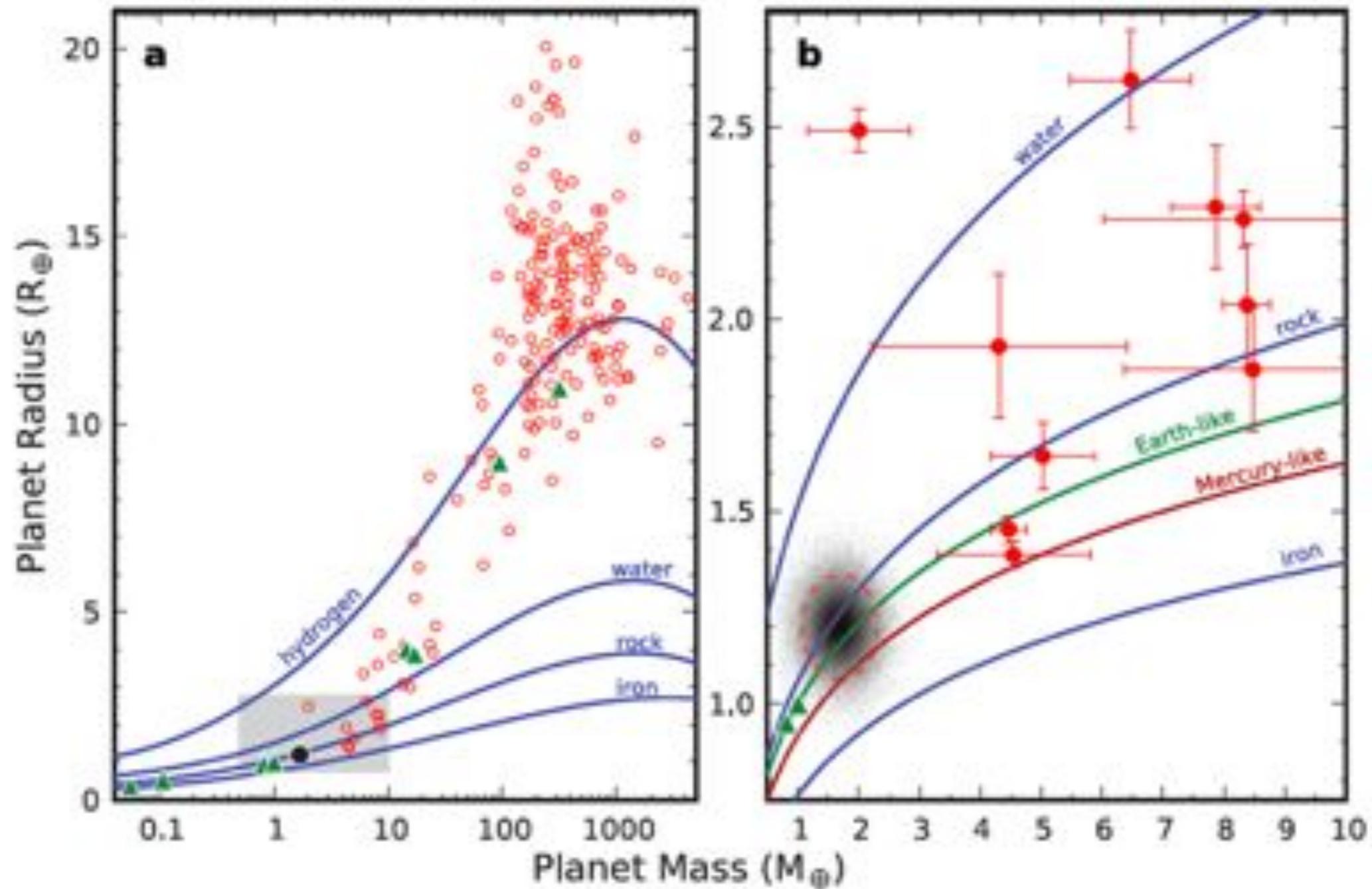
JWST Transit Planning Meeting  
March 11, 2014

# Why Super-Earths?

- Most common type of planet
- No solar system analogs
- Diverse bulk properties

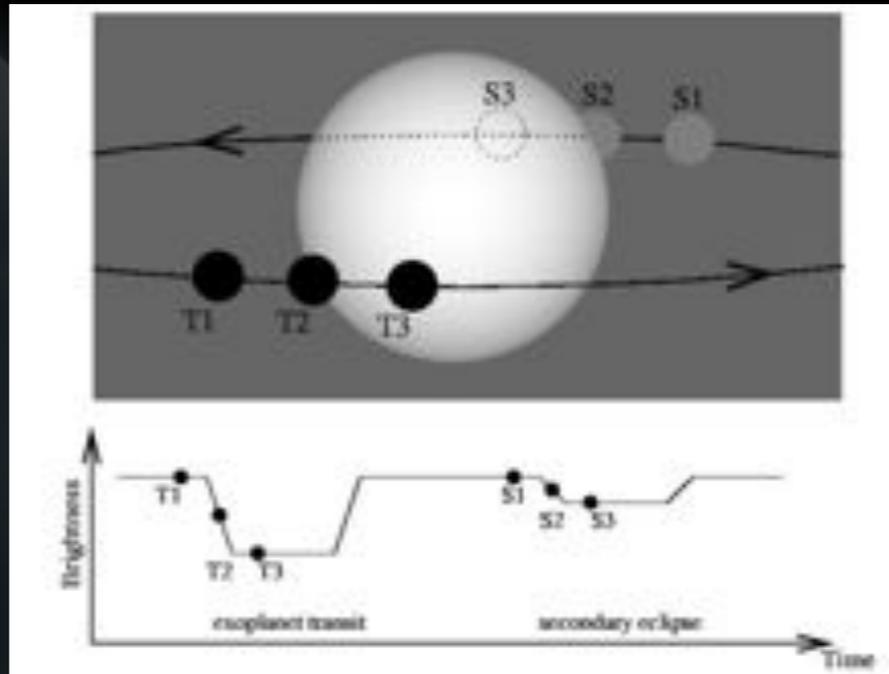
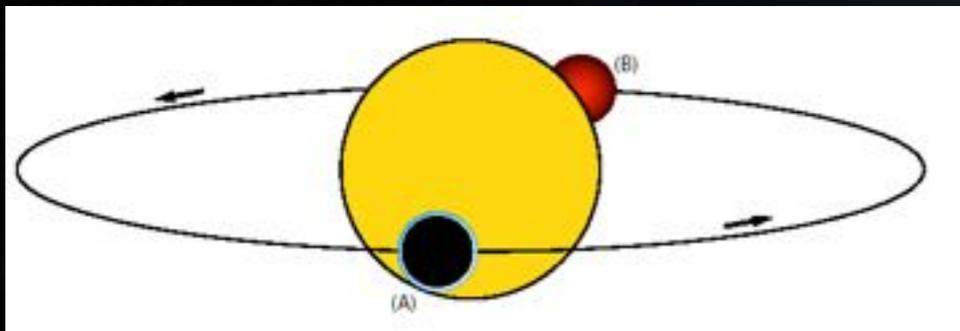


# Super-Earths – a Diverse Population of Planets



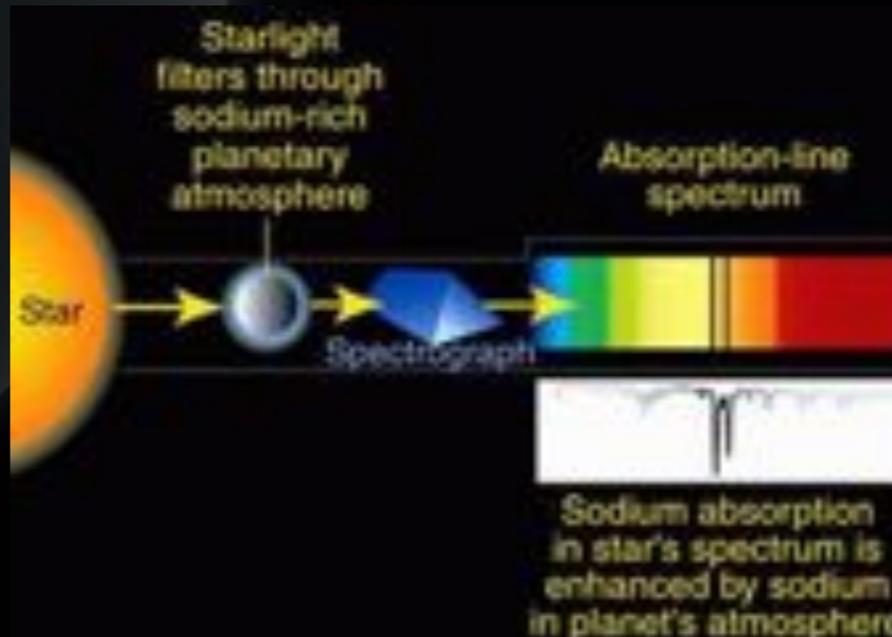
# Transmission vs. Emission Spectroscopy

Emission



- Composition
- Atmospheric structure (T-P profile)
- Global energy budget
- Clouds

Transmission



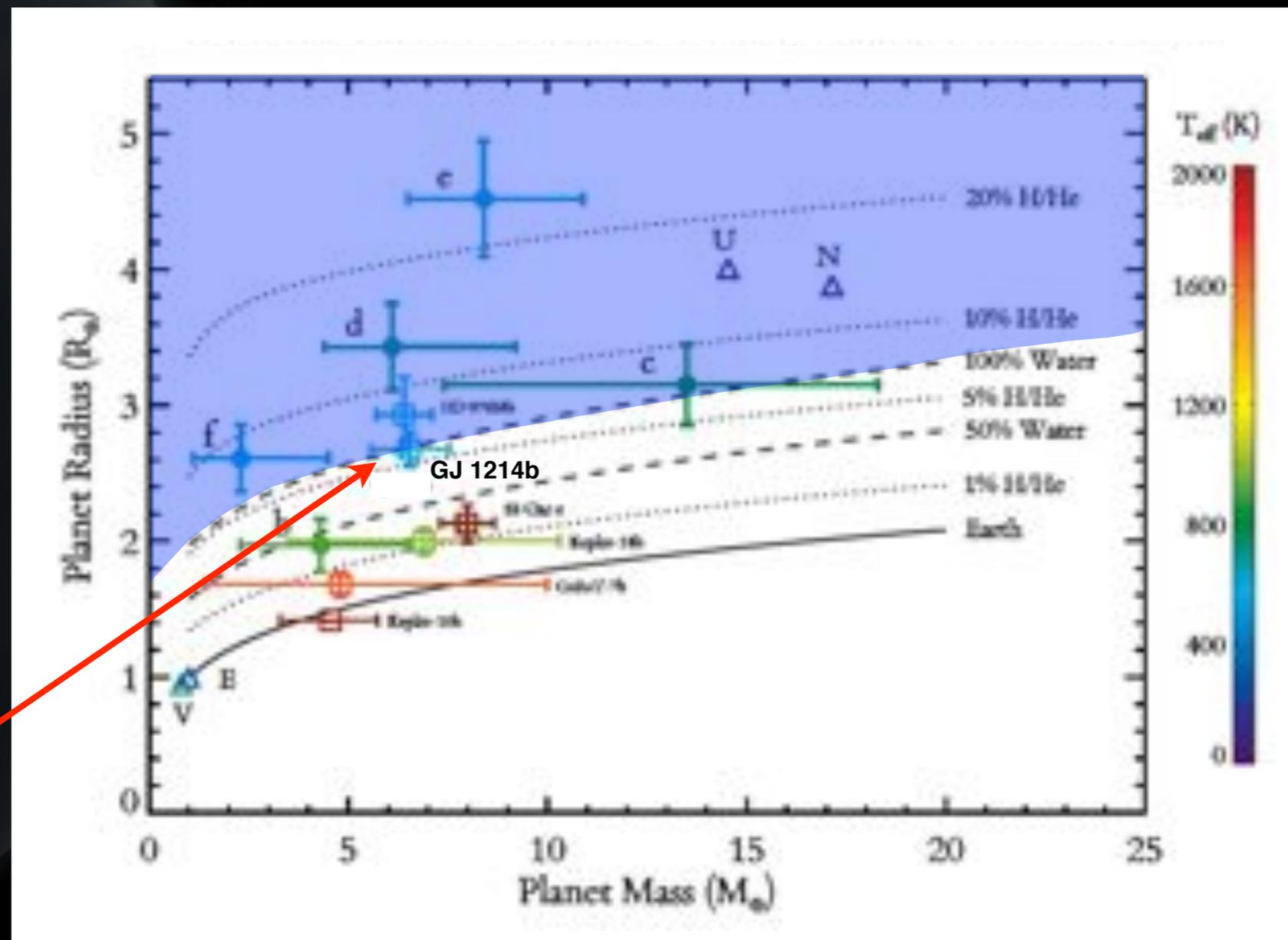
- Composition
- Scale height
- Clouds
- Planetary mass (?)

# Lessons Learned to Date: GJ 1214b - A Transiting Super-Earth with a Thick Atmosphere

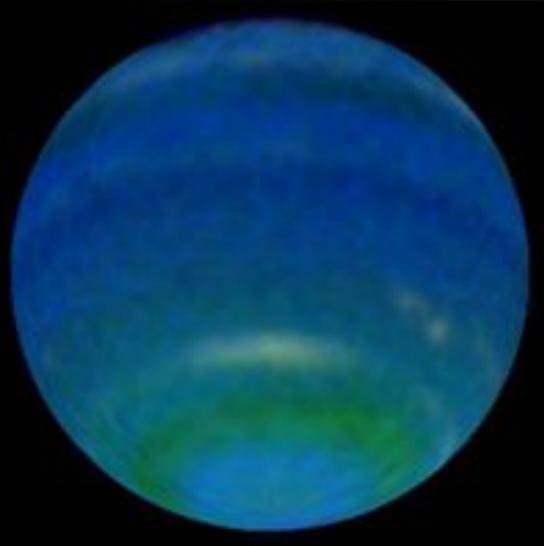
## GJ 1214b:

- $M_{pl} = 6.6 M_{\oplus}$
- $R_{pl} = 2.7 R_{\oplus}$
- $\rho = 1.9 \text{ g/cm}^3$
- $P = 1.58 \text{ days}$
- $T_{eq} \approx 550 \text{ K}$

Planet is too big to be explained without the presence of a significant atmosphere!



# 2 Possible Compositions of GJ 1214b



## 1. “Mini-Neptune” Scenario:

Rock / ice interior + hydrogen-dominated atmosphere  
(mostly  $H_2$  + trace  $H_2O$ ,  $CH_4$ , etc.)



## 2. Water World Scenario:

Mostly  $H_2O$  - ice interior + steam atmosphere

# GJ 1214b Transmission & Emission Spectra

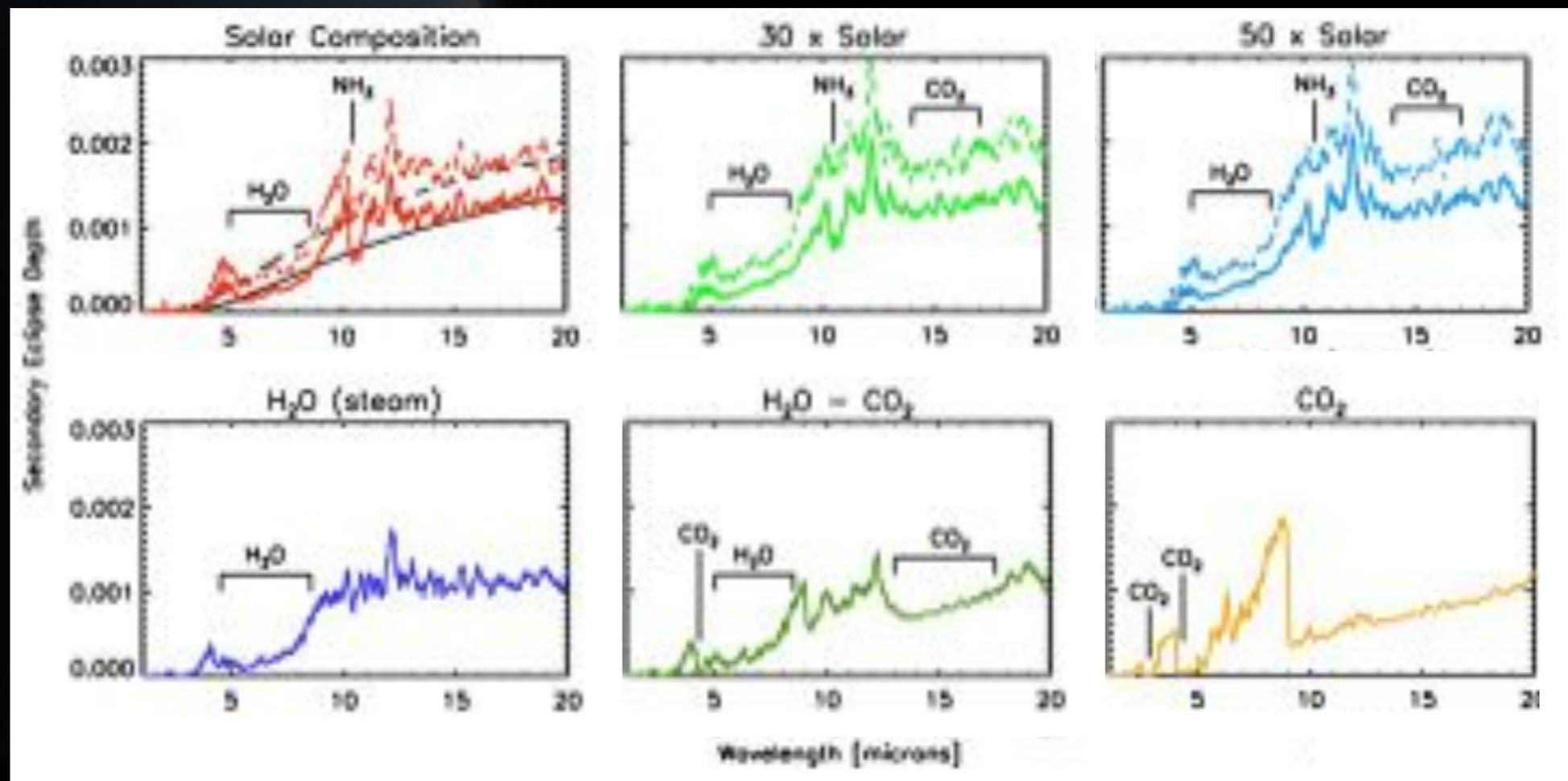
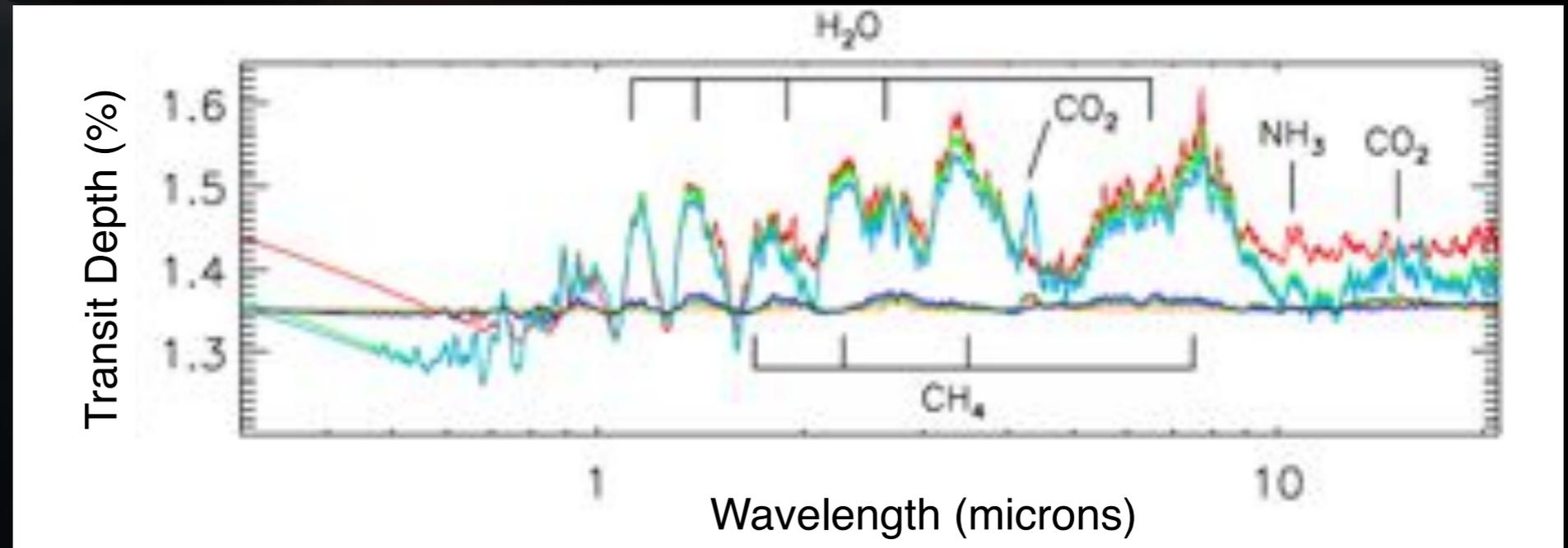
Transmission:

$$\Delta_{\text{depth}} \sim 20H R_{\text{pl}} / R_{*}^2$$

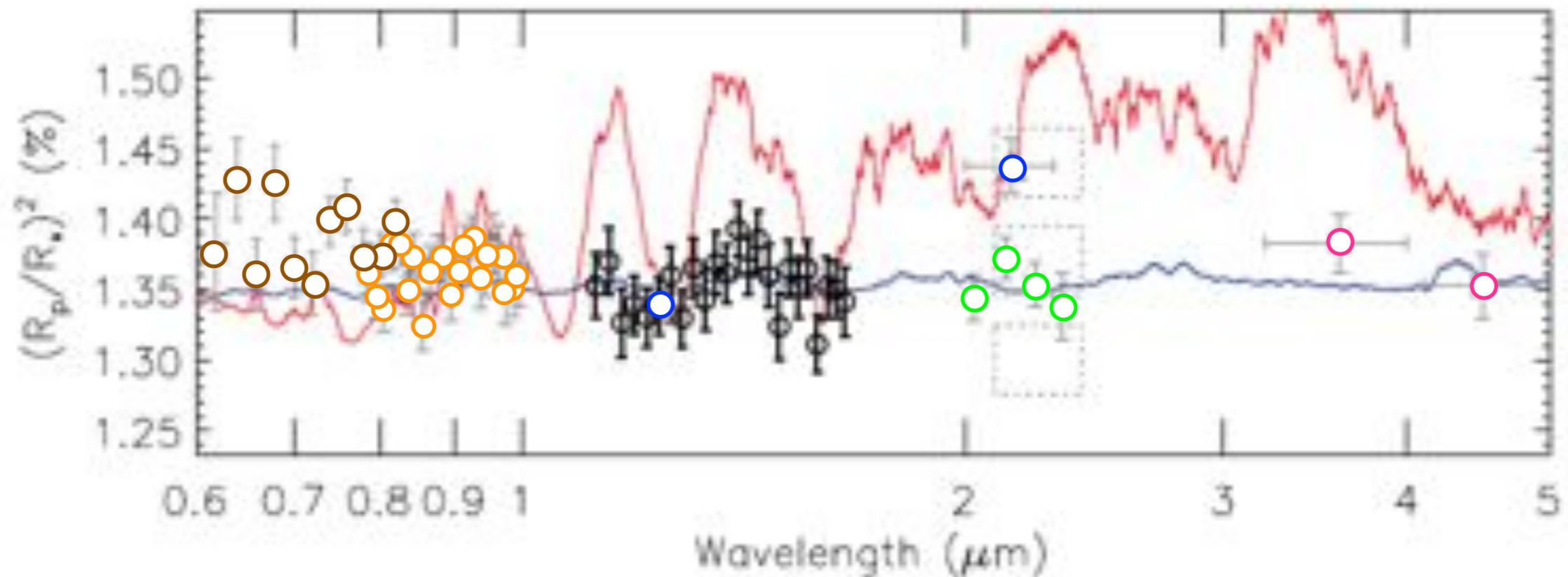
- Solar
- 30 x Solar
- 50 x Solar
- H<sub>2</sub>O
- H<sub>2</sub>O - CO<sub>2</sub>
- CO<sub>2</sub>

Secondary Eclipse:

$$\text{Depth} = \text{Flux}_{\text{pl}} / \text{Flux}_{*}$$



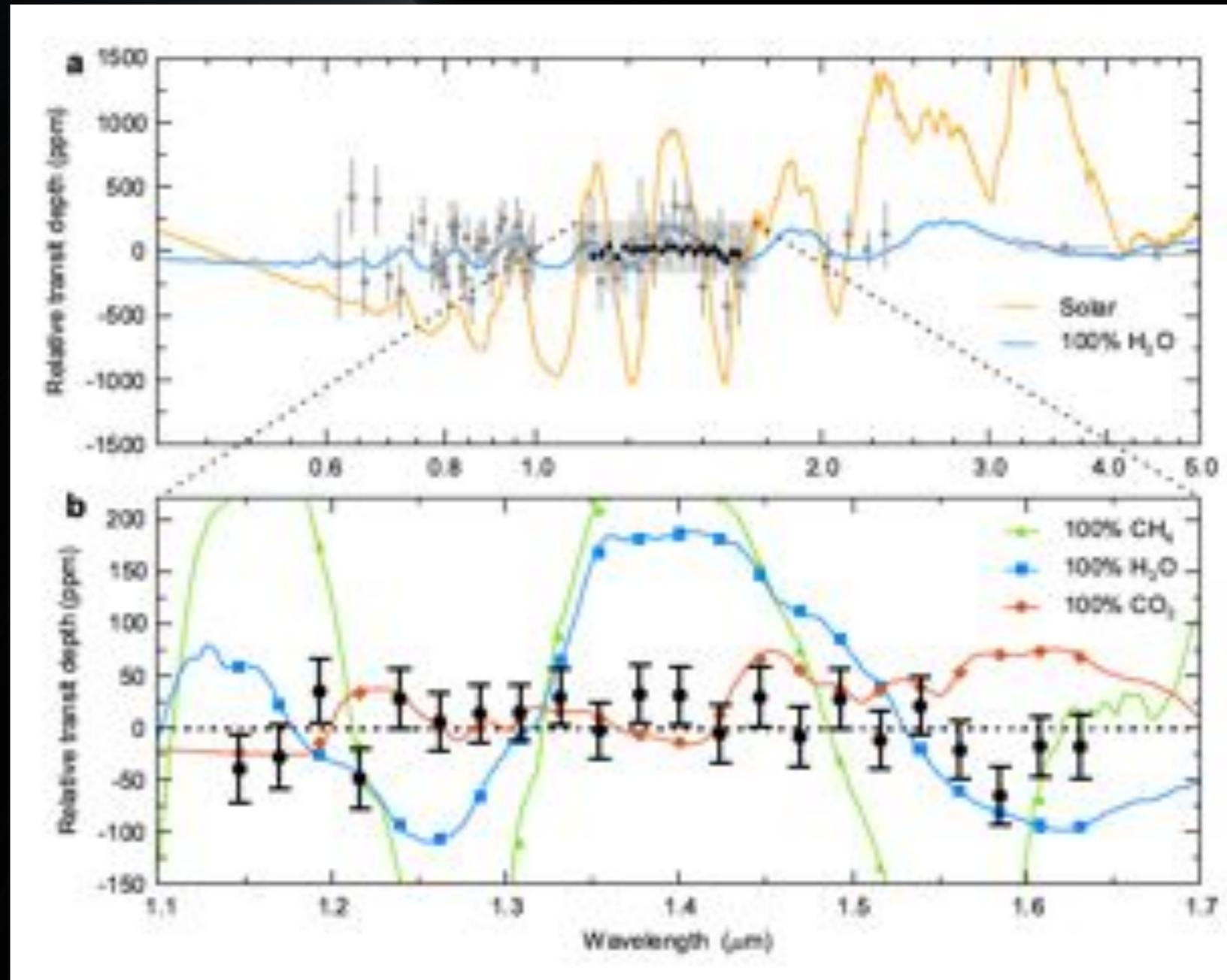
# GJ 1214b – a benchmark Super-Earth



Berta, Charbonneau, Désert, Kempton et al., *ApJ* 2012

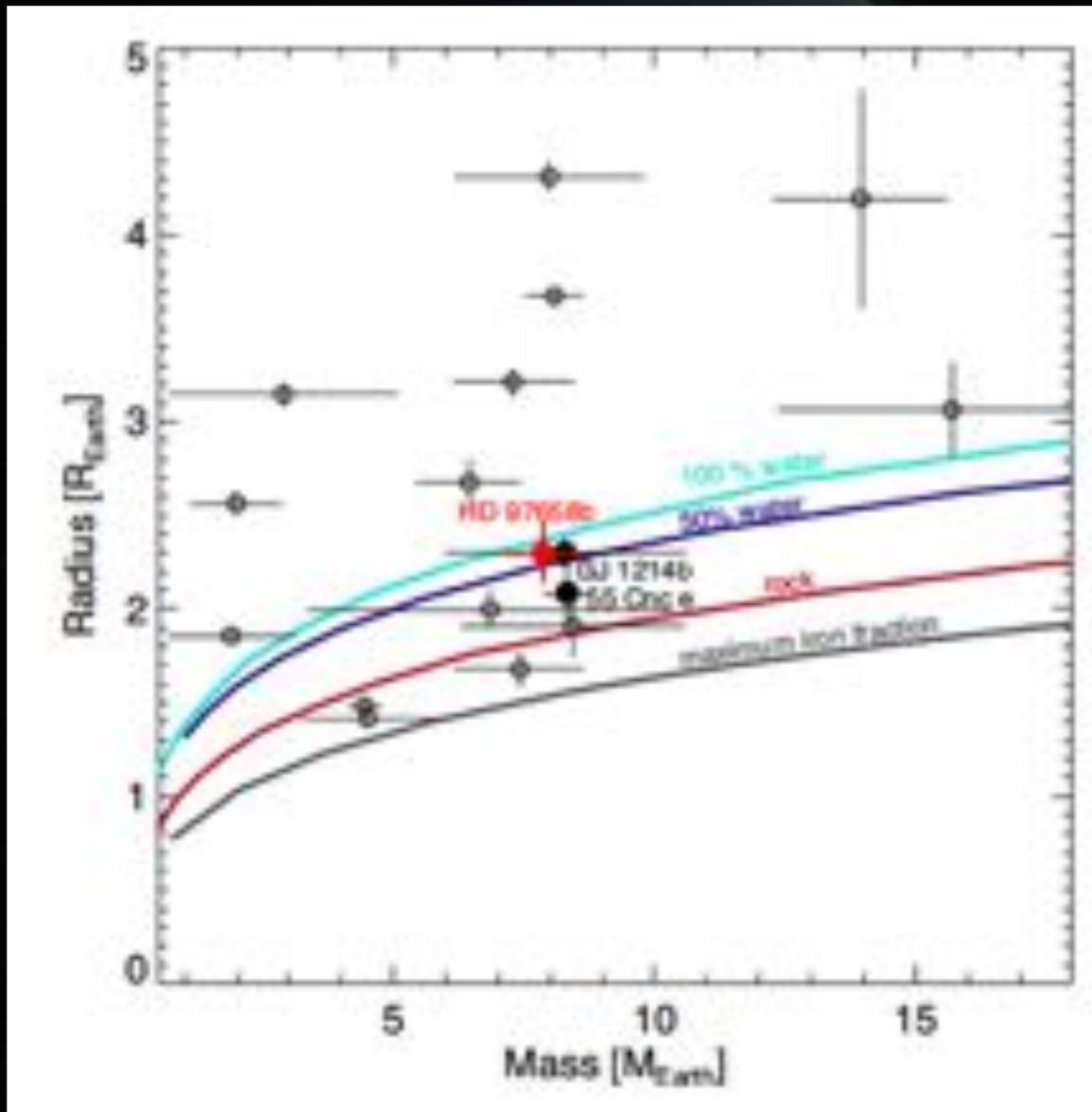
- Solar Composition
- 100% H<sub>2</sub>O
- VLT (Bean et al. 2011)
- VLT (Bean et al. 2010)
- WFC3 (Berta et al.)
- CFHT (Croll et al. 2011)
- Magellan (Bean et al. 2011)
- Spitzer (Désert et al. 2011)
- Keck (Crossfield et al. 2011)

# GJ 1214b – a benchmark Super-Earth

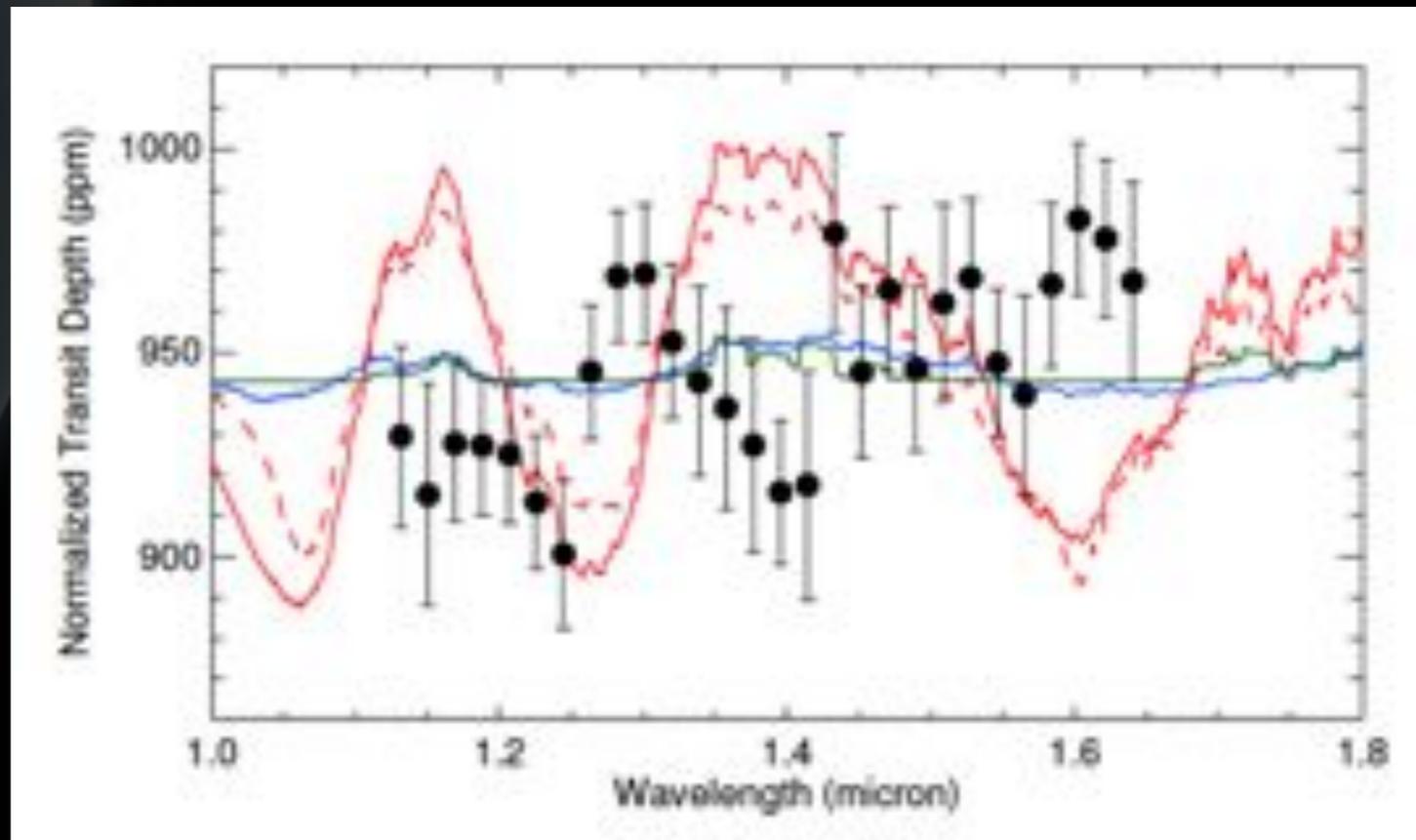


Kreidberg et al., *Nature* 2013

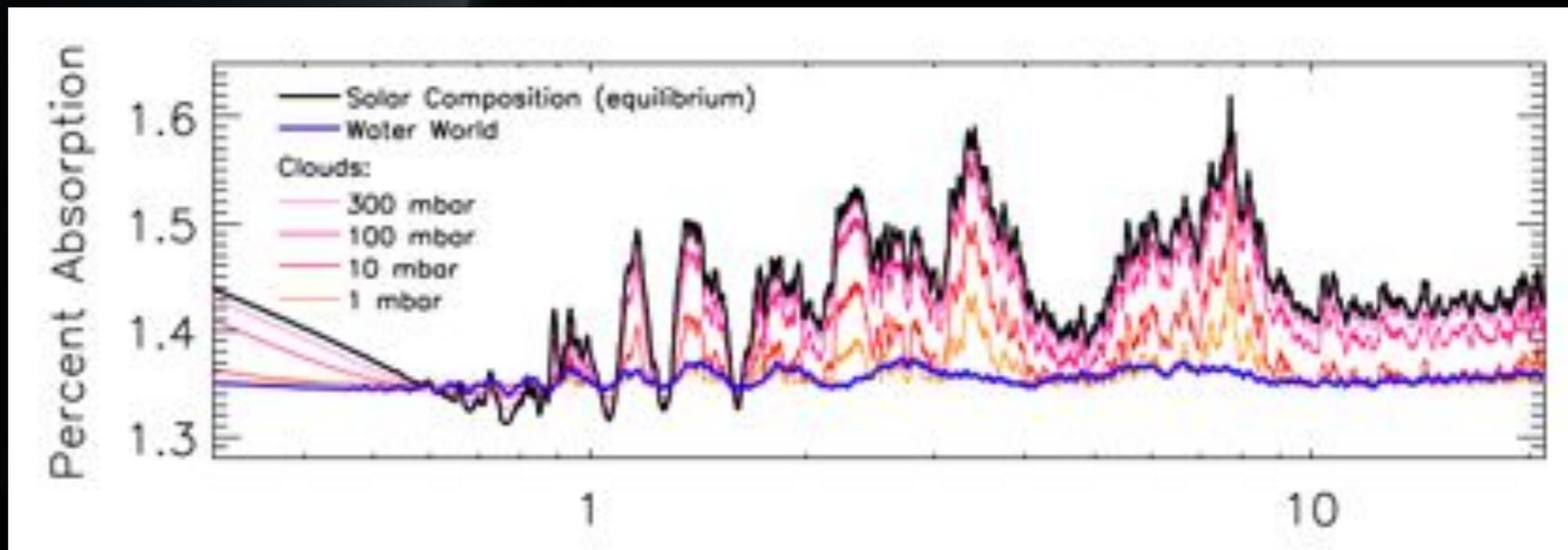
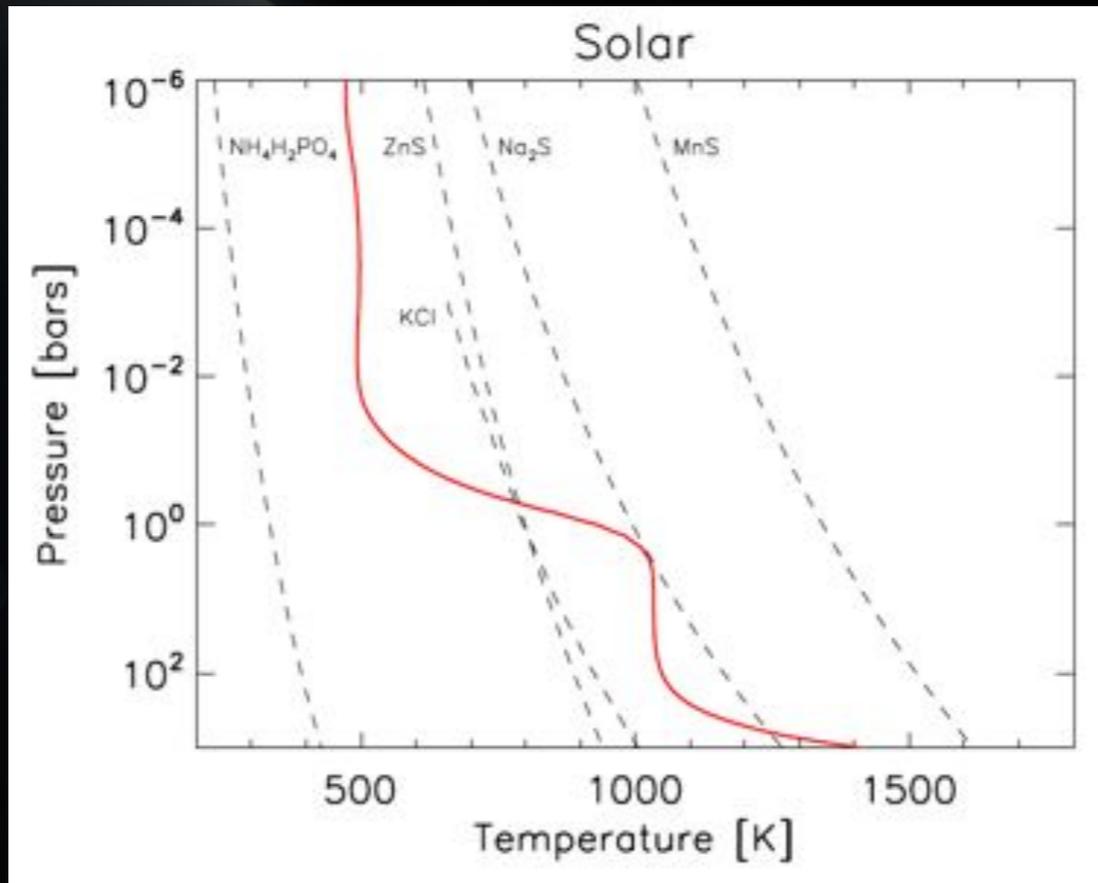
# HD 97658b – A Second Benchmark Super-Earth



- $M_{\text{pl}} = 7.9 M_{\oplus}$
- $R_{\text{pl}} = 2.3 R_{\oplus}$
- $\rho = 3.4 \text{ g/cm}^3$
- $P = 9.49 \text{ days}$
- $T_{\text{eq}} \approx 700 \text{ K}$



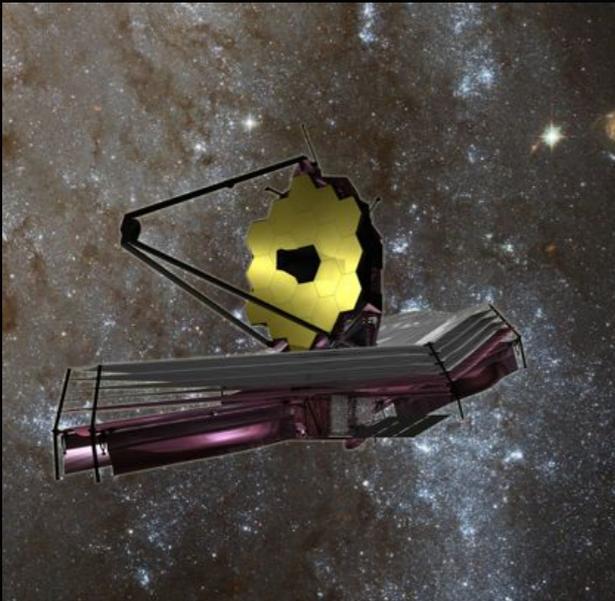
# Clouds?



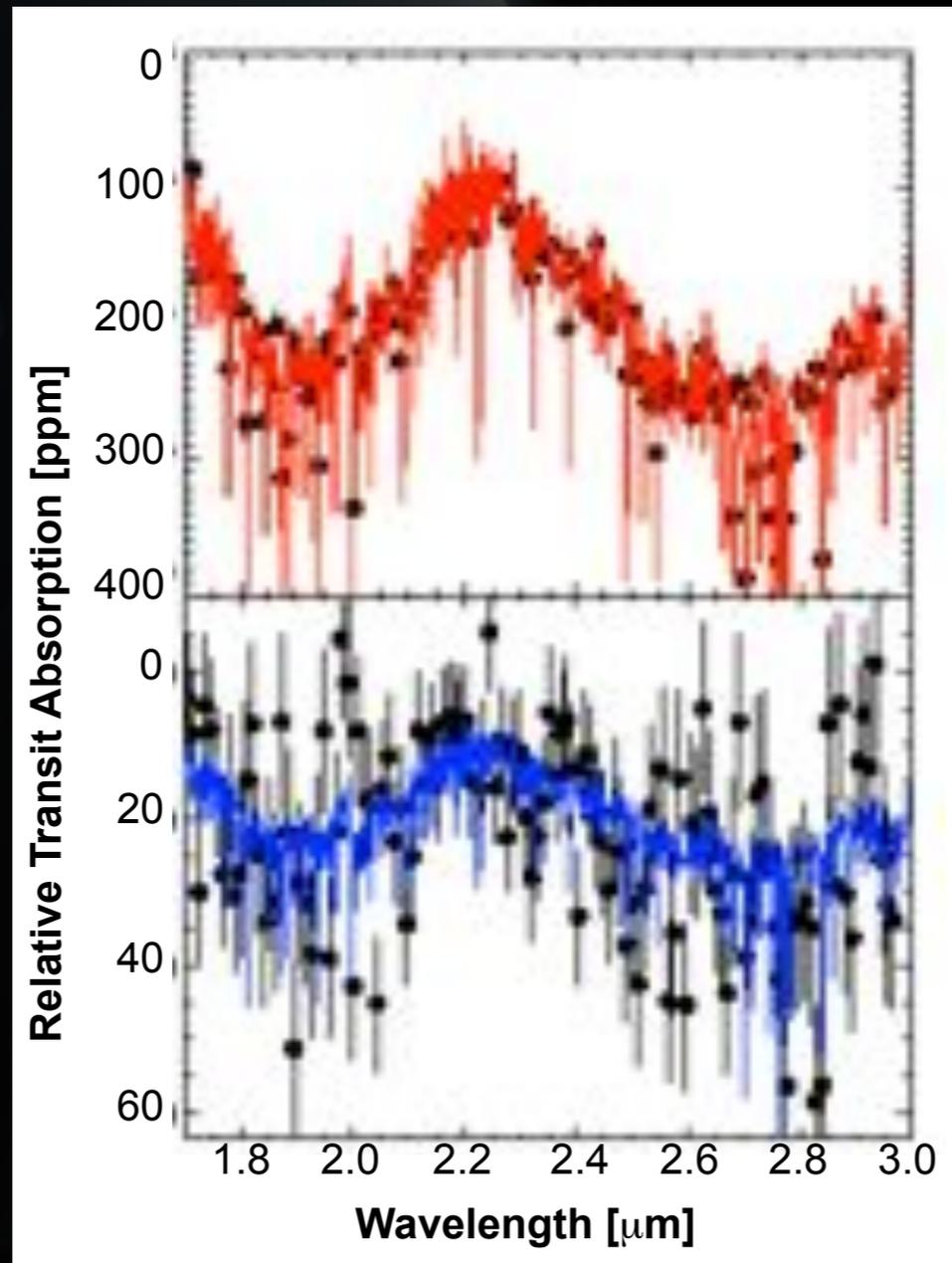
# Observing Super Earth Atmospheres

- Signals of several to 100 ppm → JWST

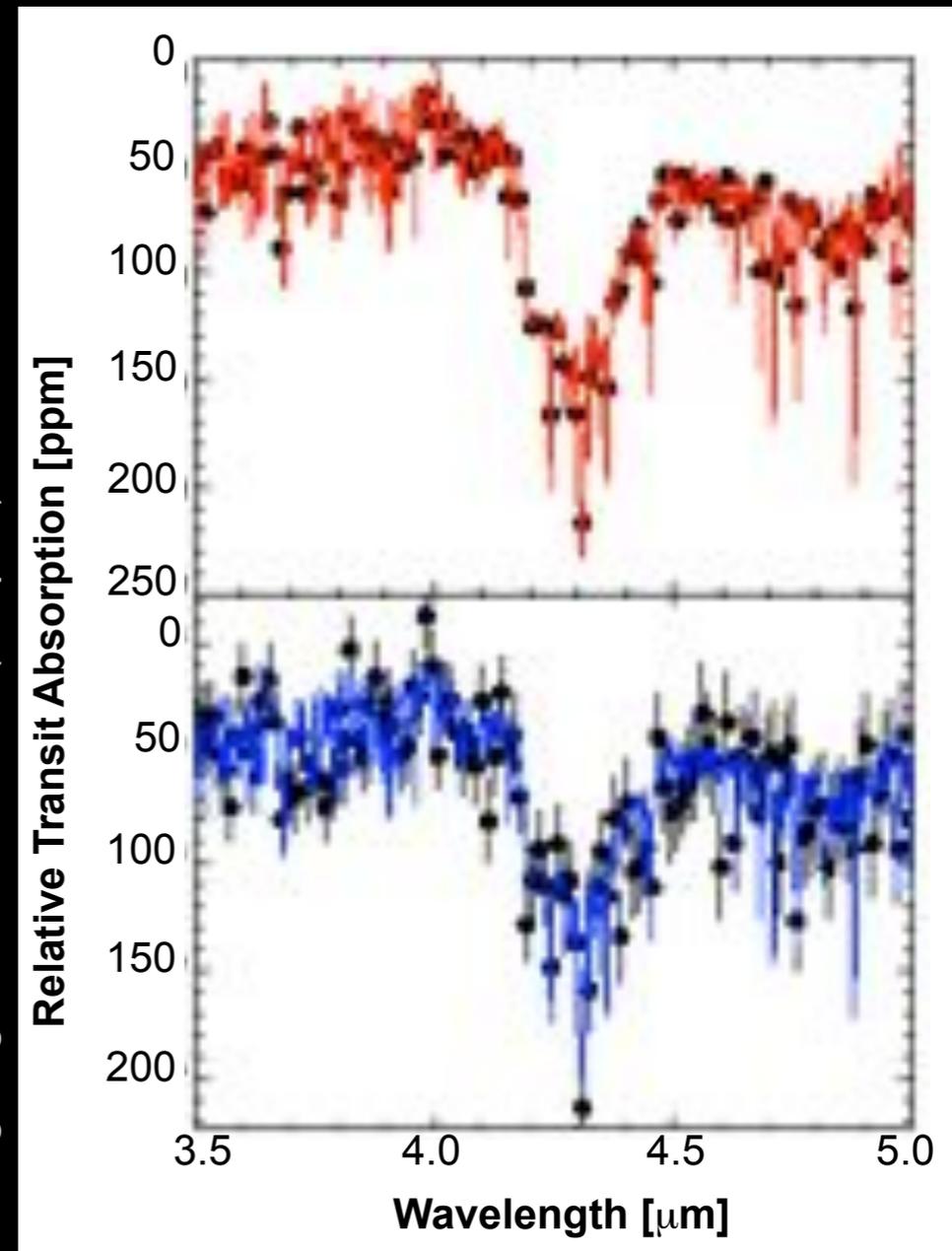
JWST



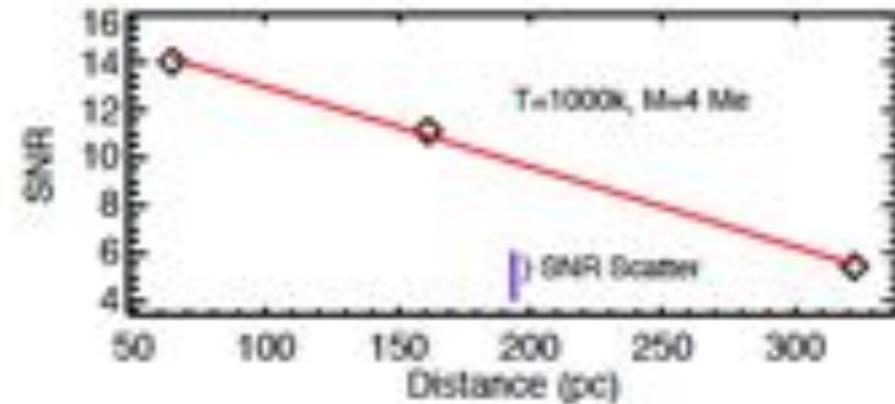
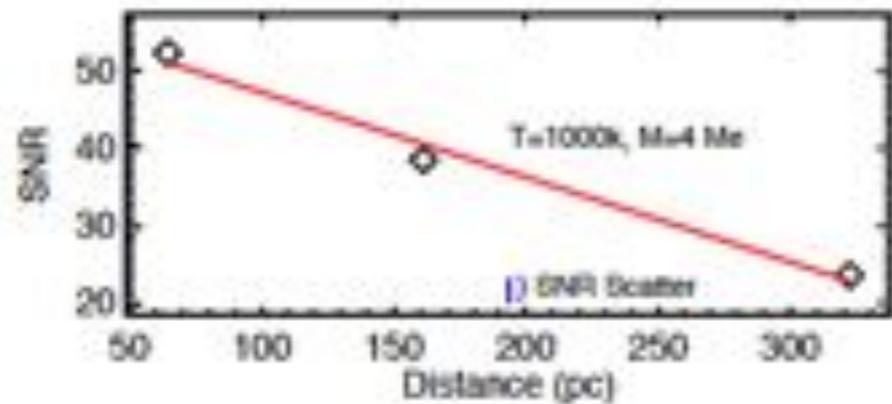
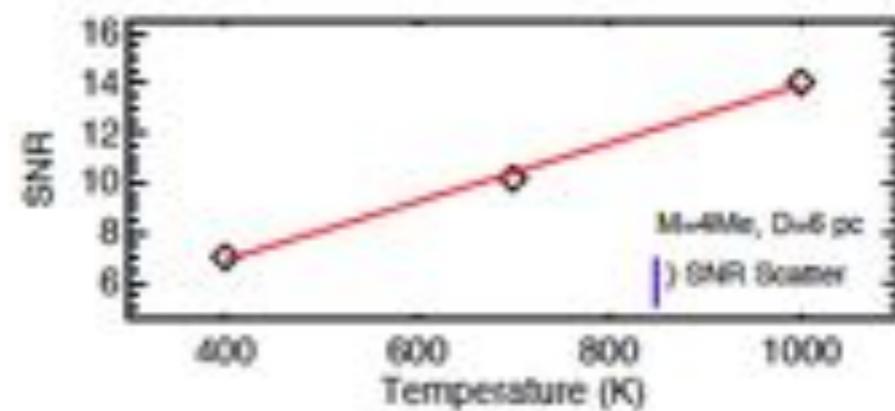
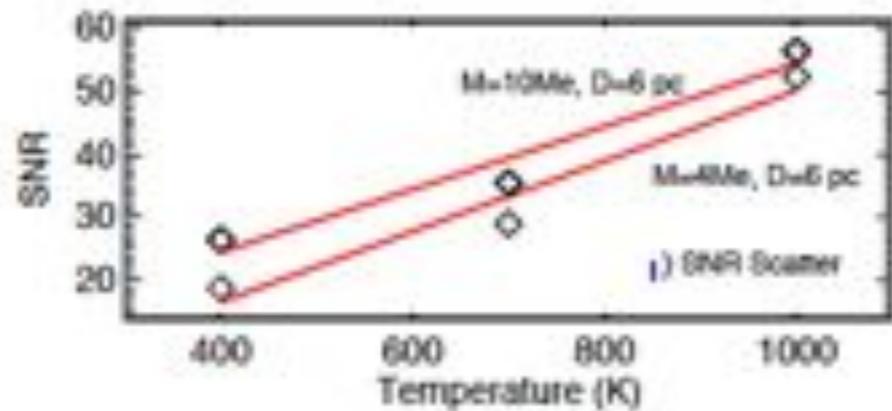
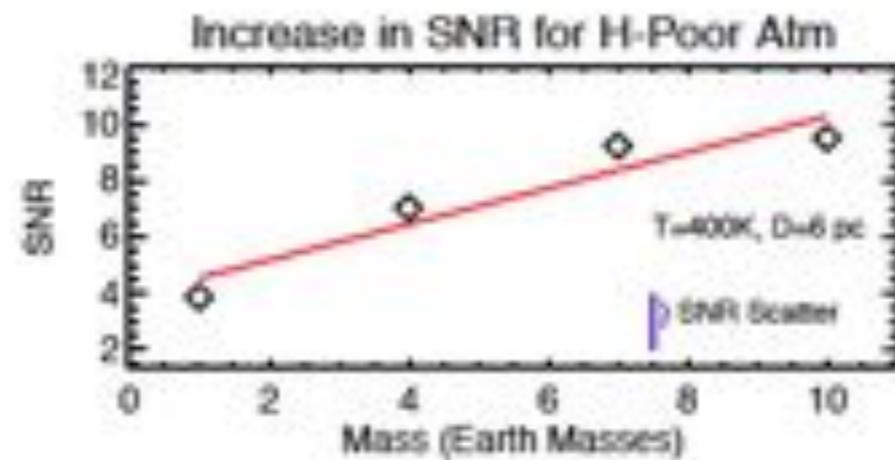
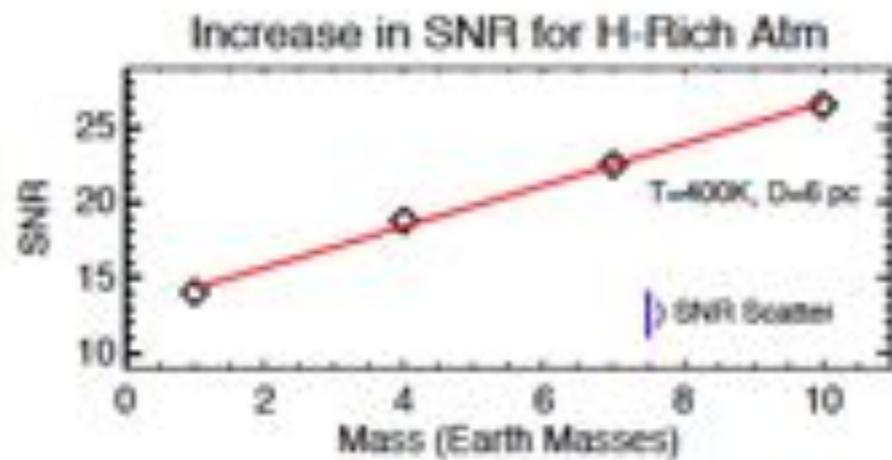
— Hot super-Earth  
— Habitable super-Earth



Deming, Seager, Winn, Miller-Ricci (Kempton) et al., *PASP*, 2009



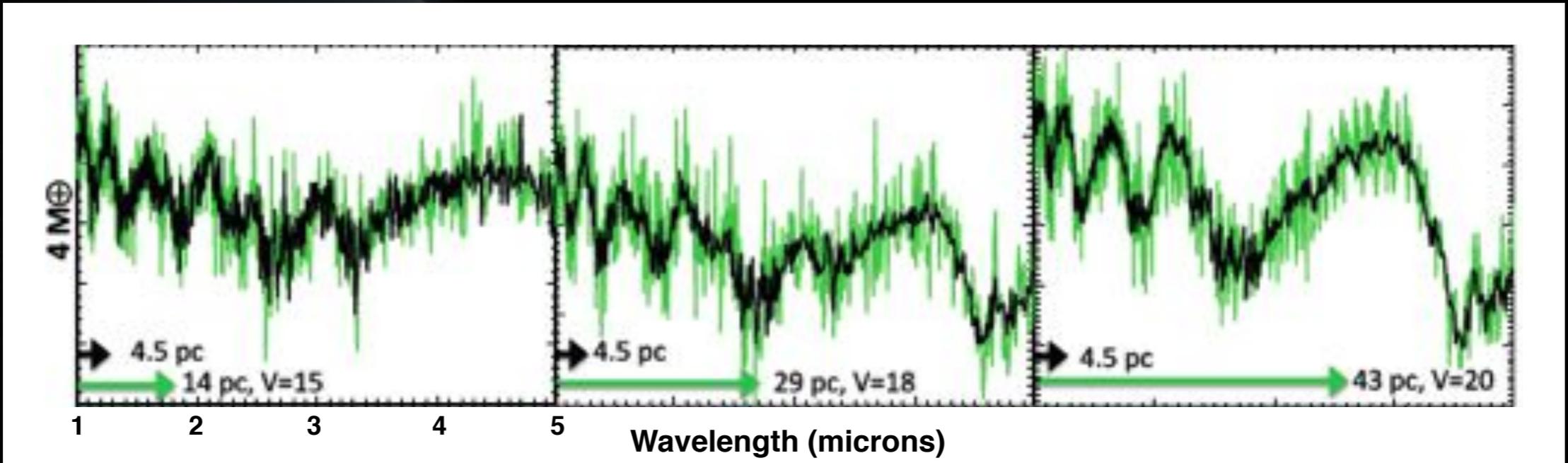
# NIRSpec Simulations



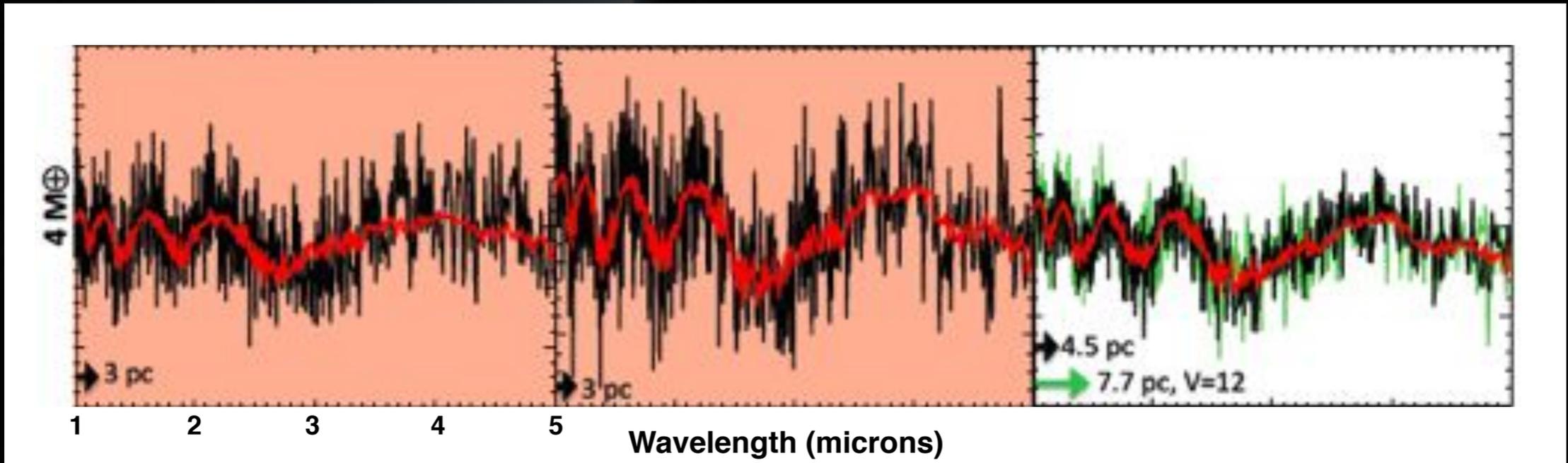
# NIRSpec Simulations

Temperature: 400K 700 K 1000 K

H-Rich



H-Poor



# Some goals for JWST

- Constrain compositions for a diverse set of super-Earths
- Differentiate between planets with clouds and those with high mean molecular weight atmospheres
- Constrain cloud properties
- Classify planets that fall within (and below) the “super-Earth” mass and radius range
- Choose between “low-cost” and “high reward” targets