Atmospheric Structure: Gas Giants, Sub-Neptunes, and Super-Earths

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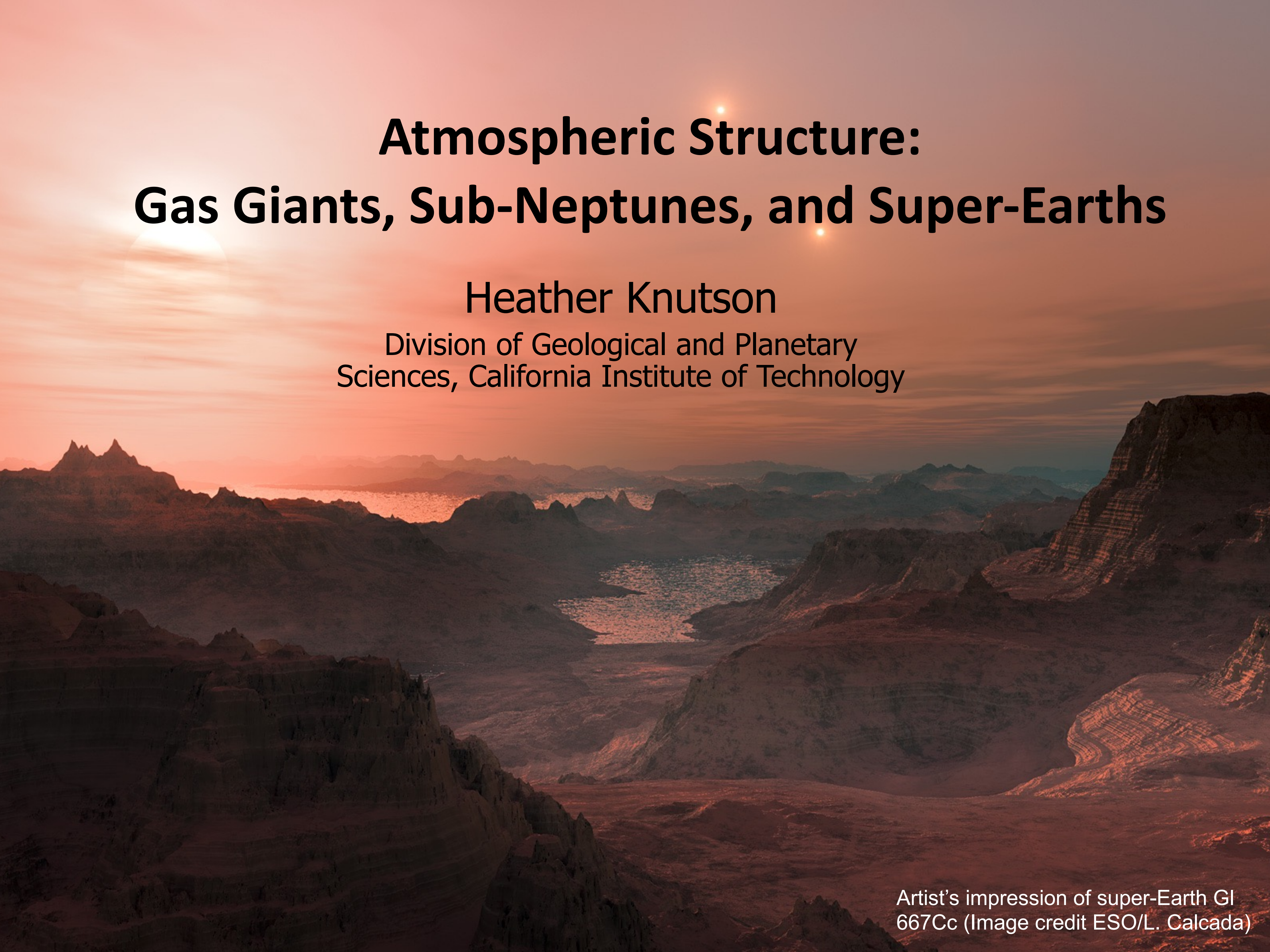
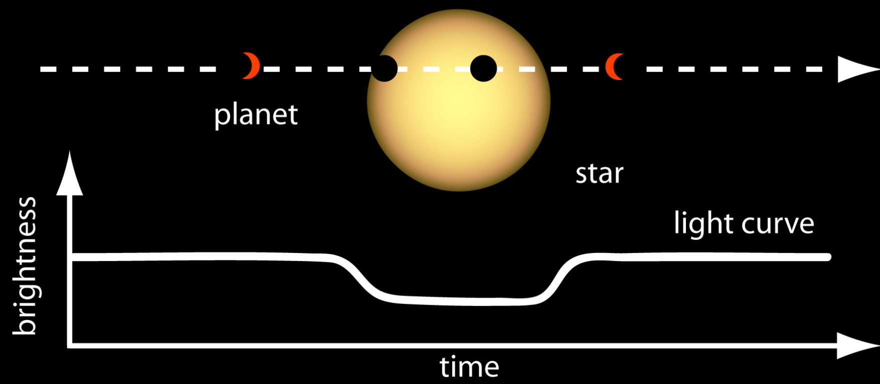
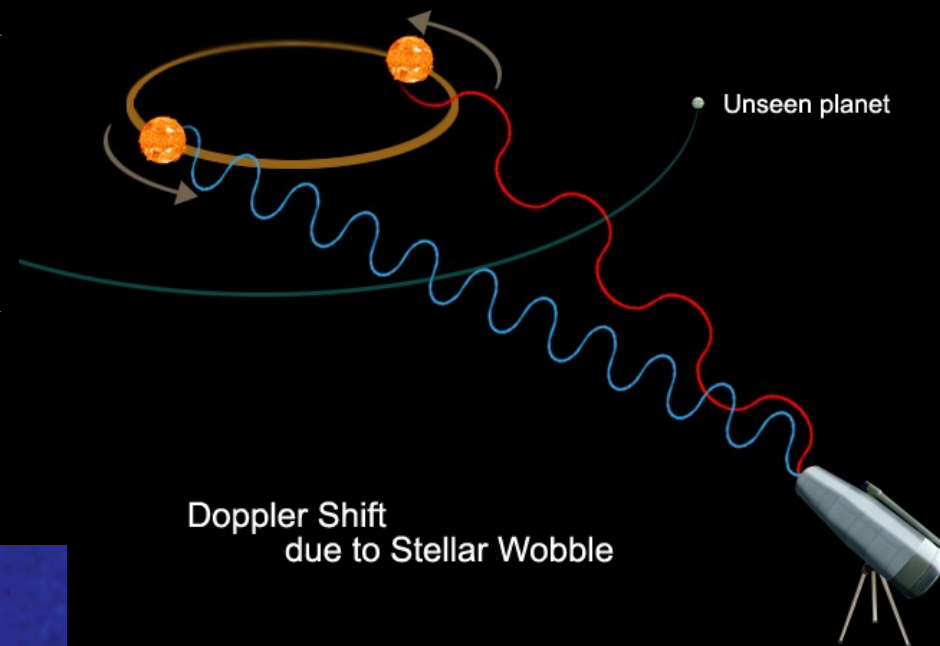


Artist's impression of super-Earth Gl 667Cc (Image credit ESO/L. Calcada)

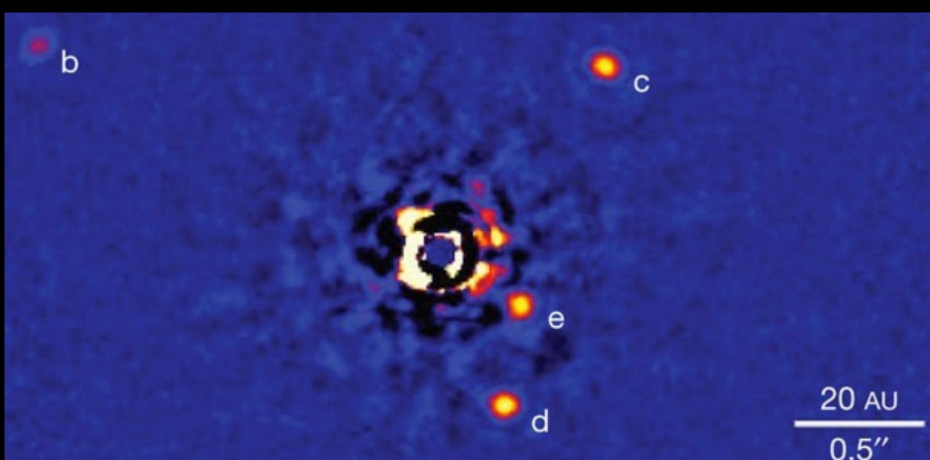
Three Techniques for Detecting and Characterizing Exoplanets



1. **Transits** tell us the planet radius.



2. **Radial velocity** tells us the planet mass.

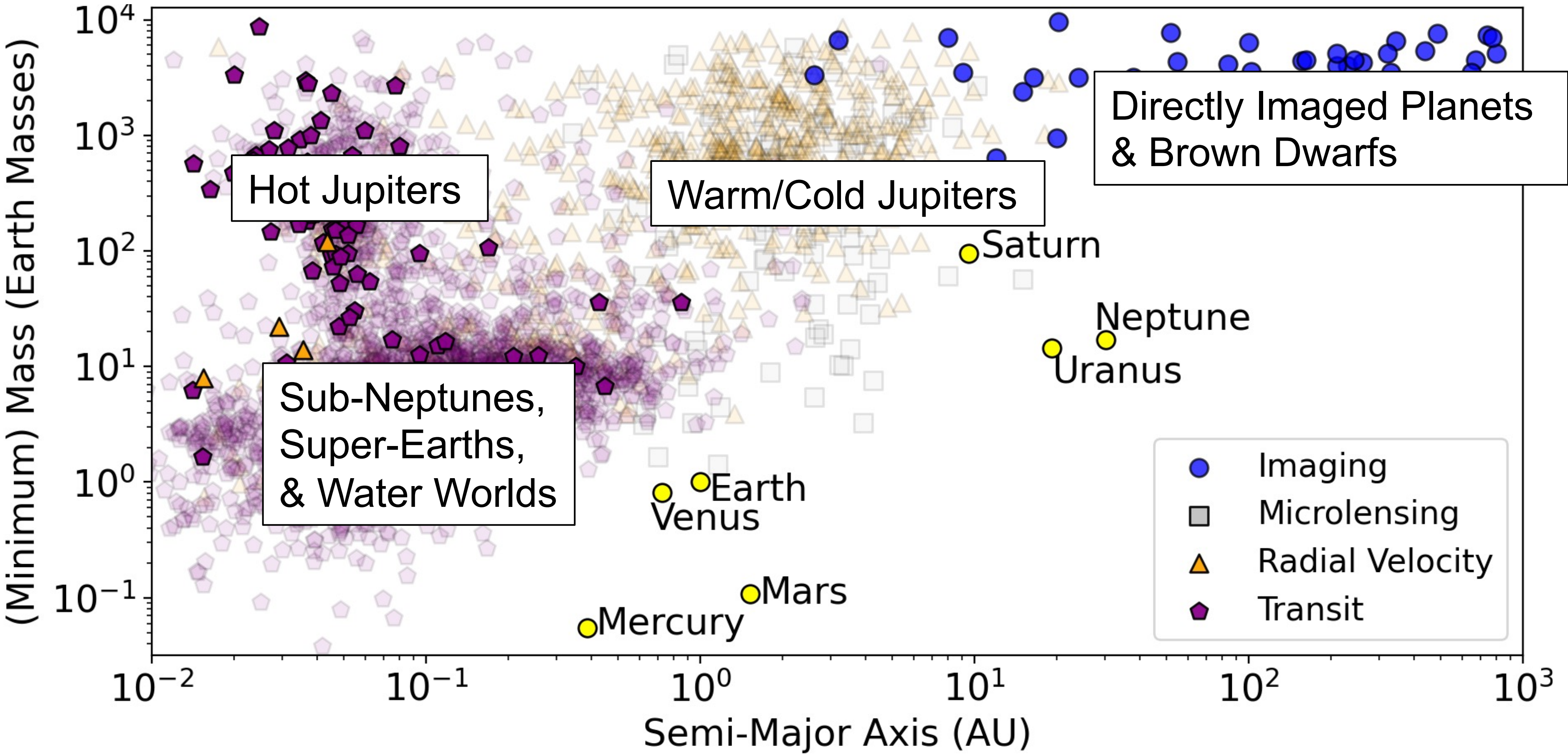


3. **Direct Imaging** tells us the planet's luminosity.

Image credits: NASA and Marois et al. (2010)

Exoplanet Demographics

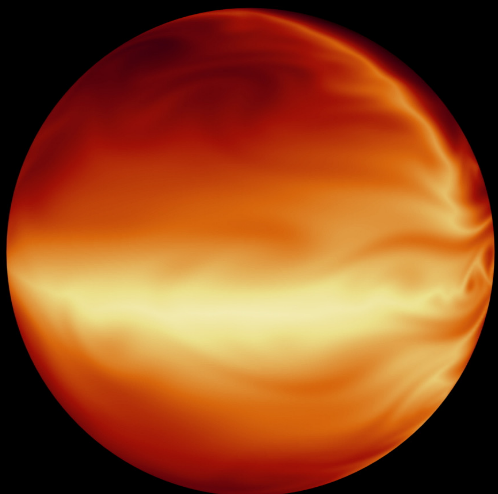
~10,000 planets and planet candidates
~200 with spectroscopic atmosphere observations

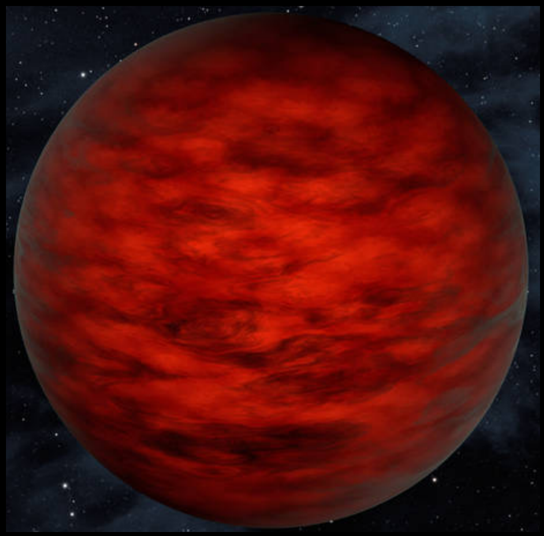


For latest exoplanet data, see the NASA Exoplanet Archive. Figure from Currie et al. (2022)

Exoplanet Demographics

How common is each type of planet?





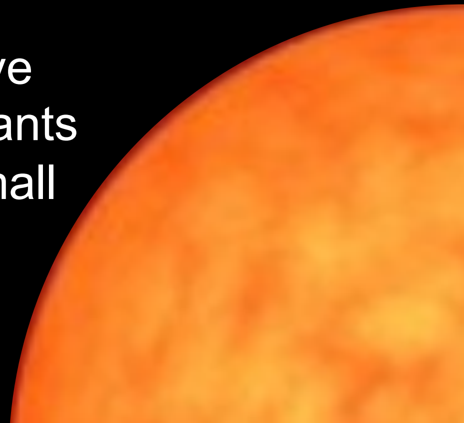
Hot Jupiters:
1% of Sun-like stars

Warm/Cold Jupiters:
10% of Sun-like stars

Directly Imaged Planets:
10% of stars > 1.5 M_{Sun}

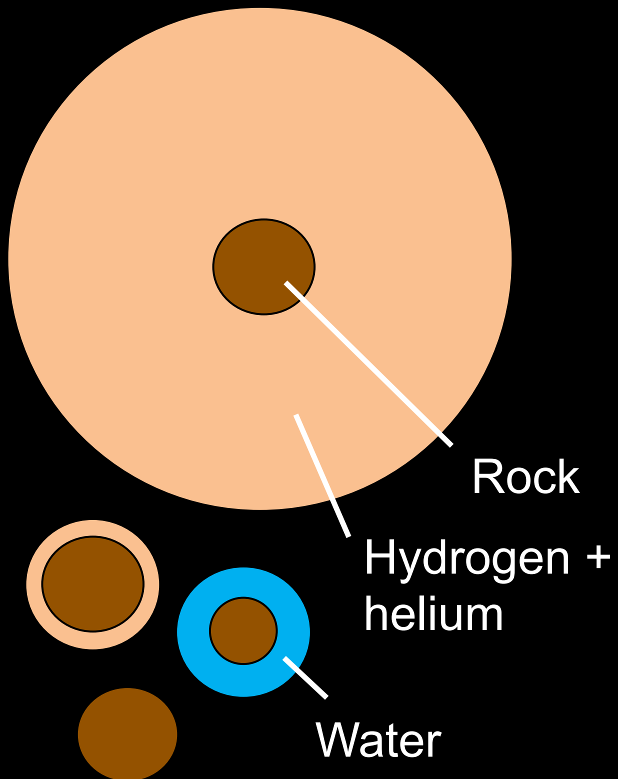
Sub-Neptunes, Super-Earths, & Water Worlds:
50% of Sun-like stars

M dwarfs have **fewer** gas giants and **more** small planets.



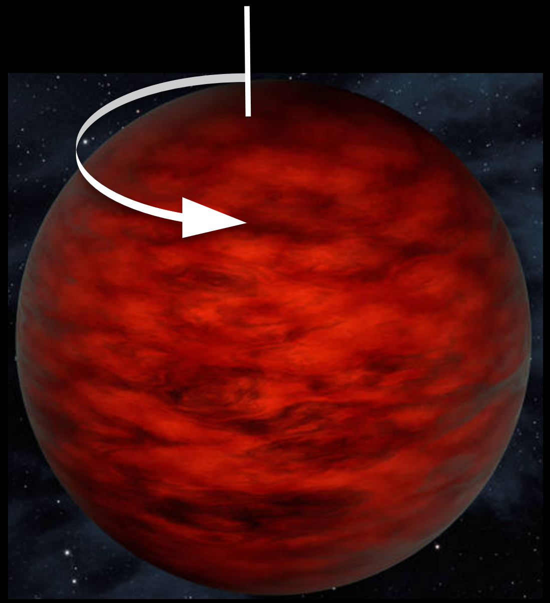
Order-of-magnitude occurrence rates from He+19, Nielsen+19, Hsu+20, Fulton+21, & Bryant+23

Key Atmospheric Properties



What is the atmosphere made of, and how much is there?

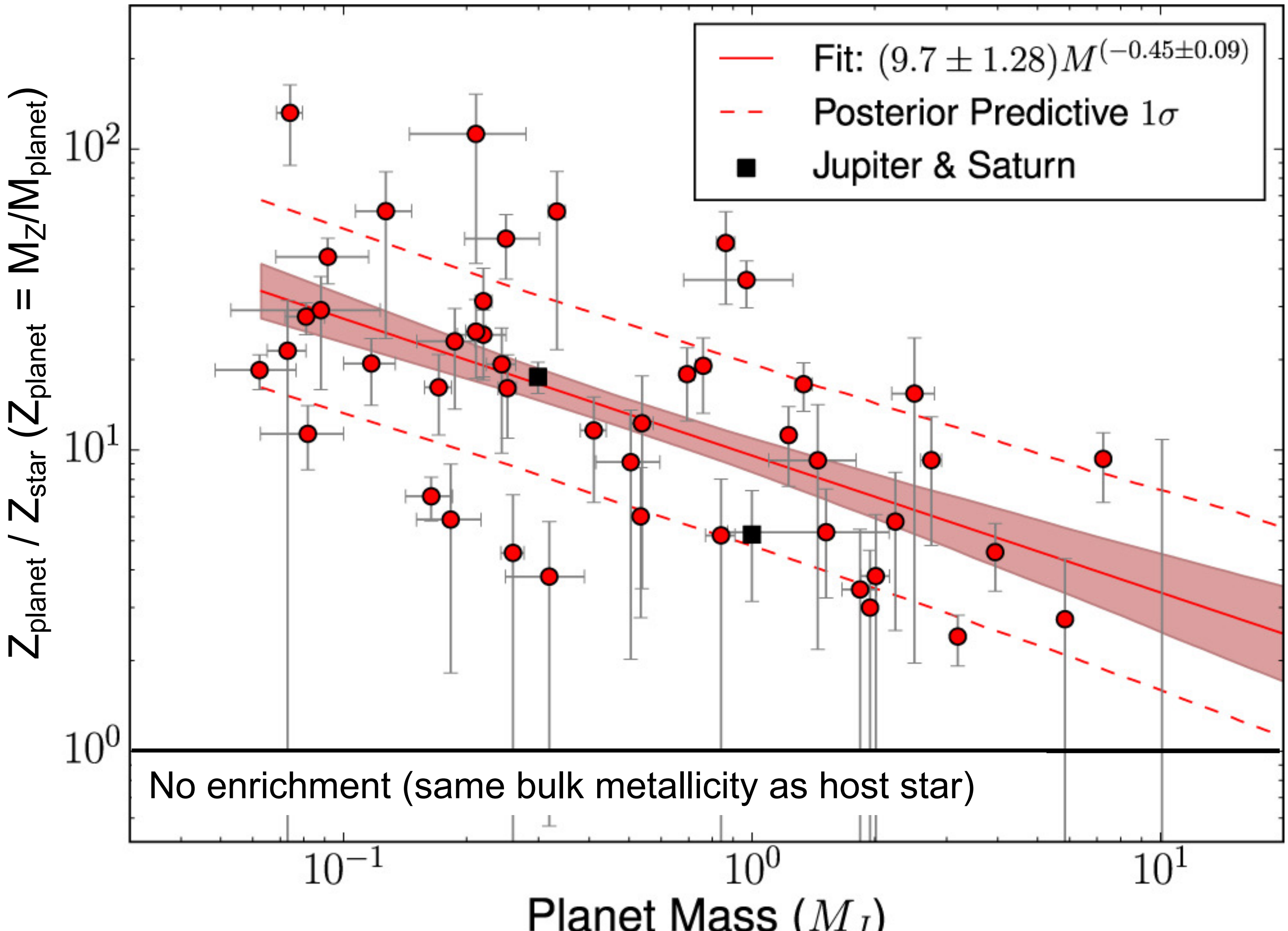
How hot is it? Is it internally or externally heated?

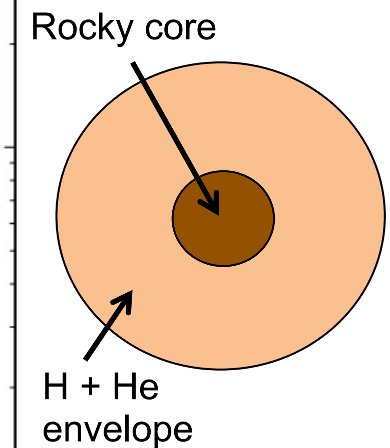


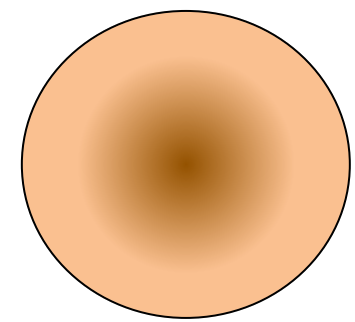
How rapidly does it rotate? Is it tidally locked?

Image credits: NASA/JPL-Caltech

Giant Planets Are Enriched in Heavy Elements



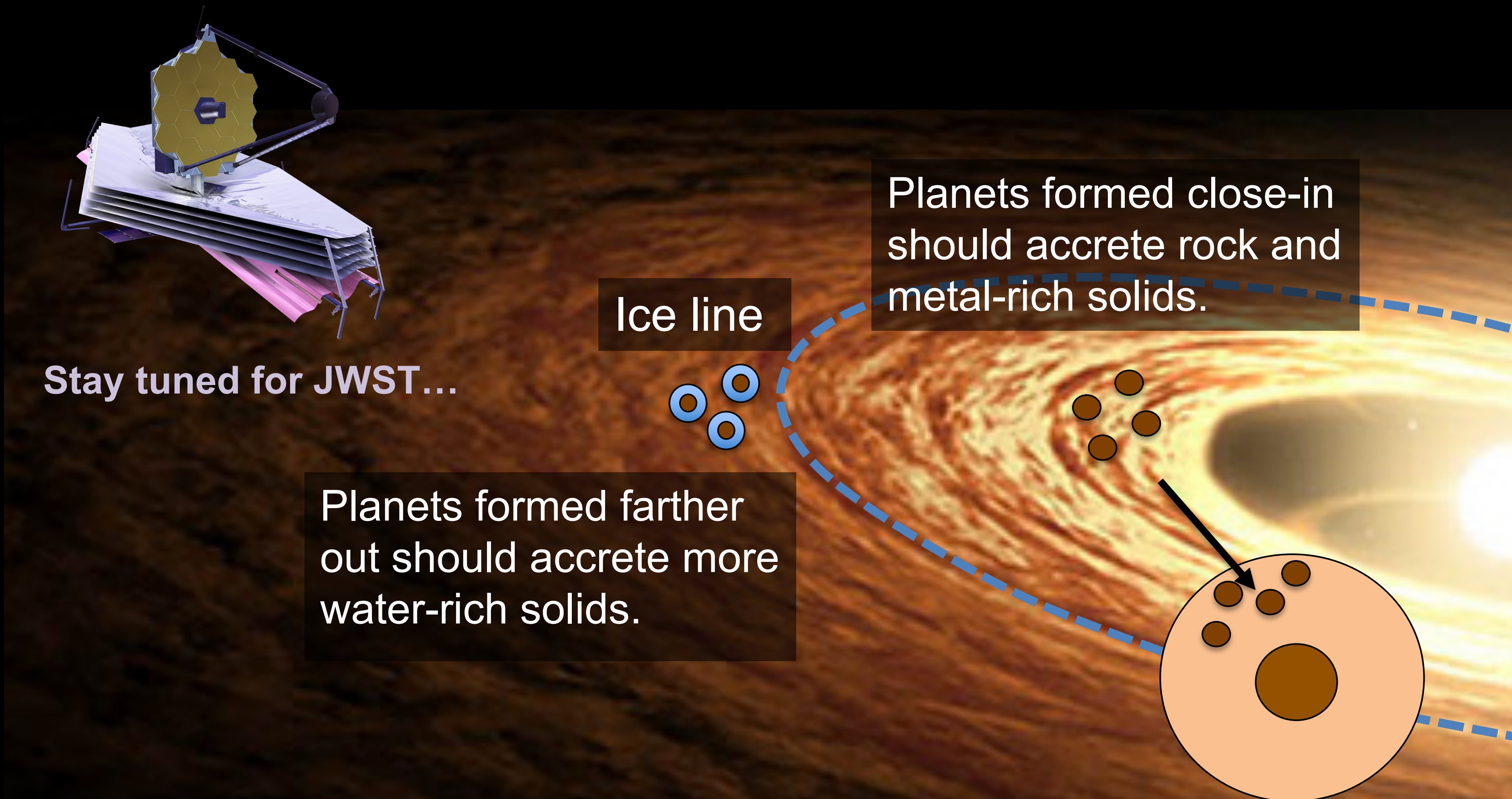




How are these elements distributed, & which elements are enriched?

Thorngren et al. (2016), Thorngren & Fortney (2019).
For Jupiter’s fuzzy core, see review by Helled et al. (2022).

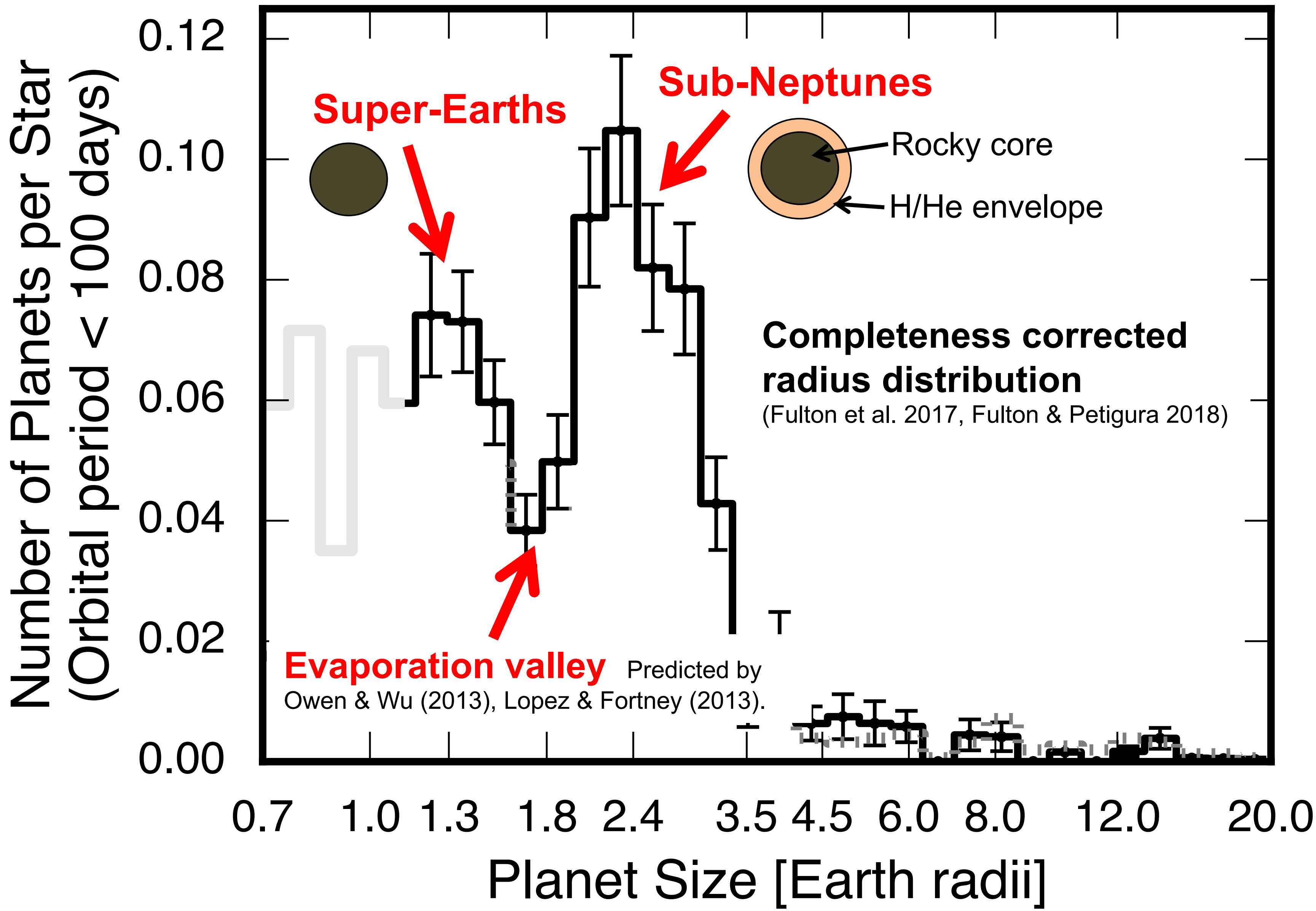
Elemental abundances of hot Jupiter envelopes can tell us about their formation locations.



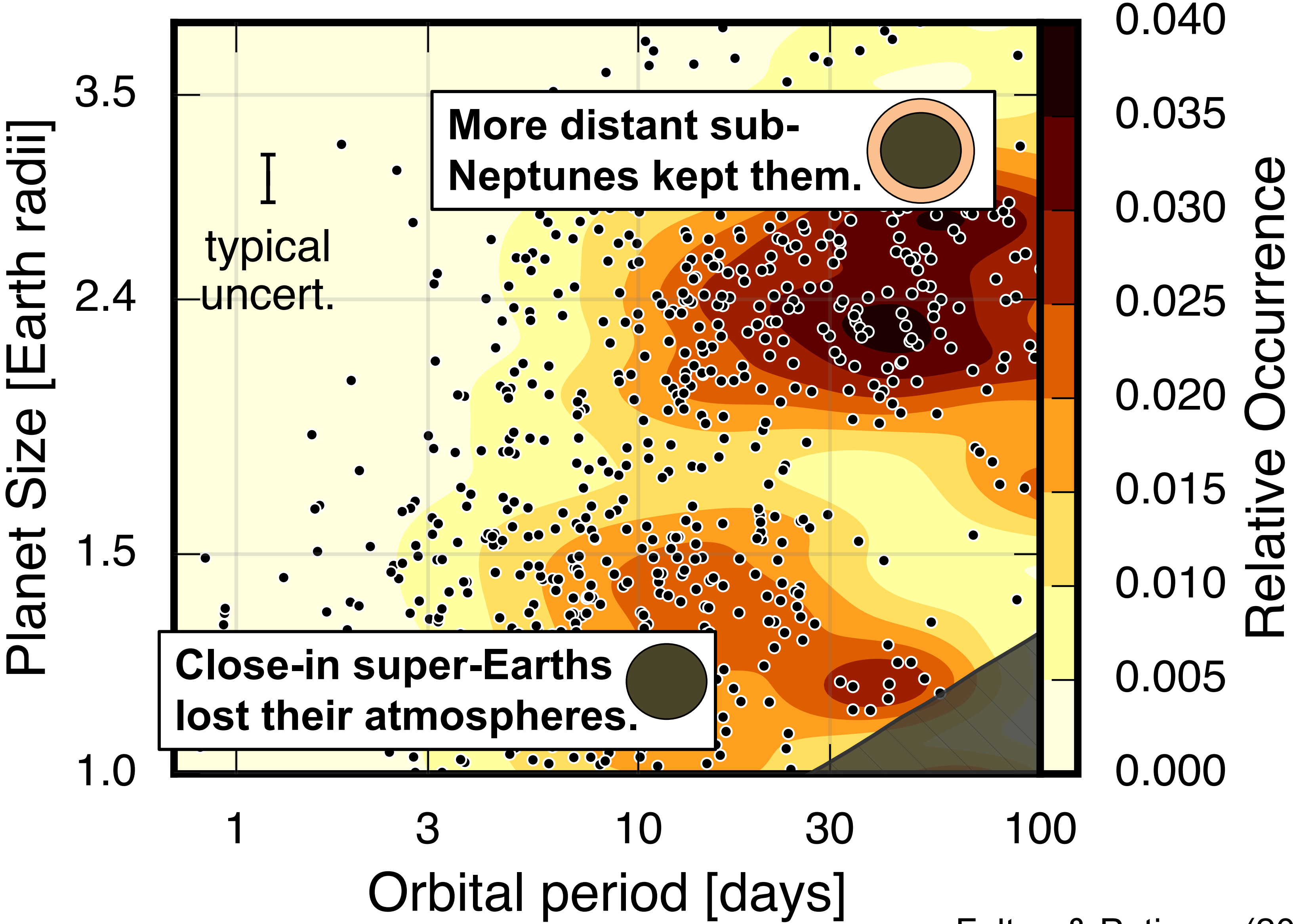
Complications: 3D, time-evolving disk structure, small solids can migrate too (e.g., Oberg+11, Madhusudhan+19 Eistrup+22, + many more…)

Image credit: NASA/JPL

What are the bulk compositions of sub-Neptune-sized planets?

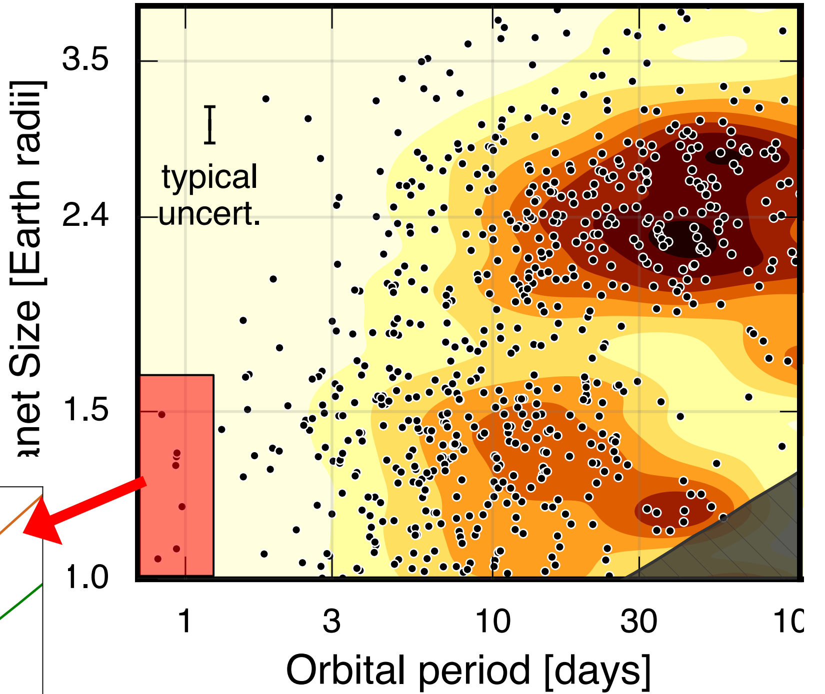


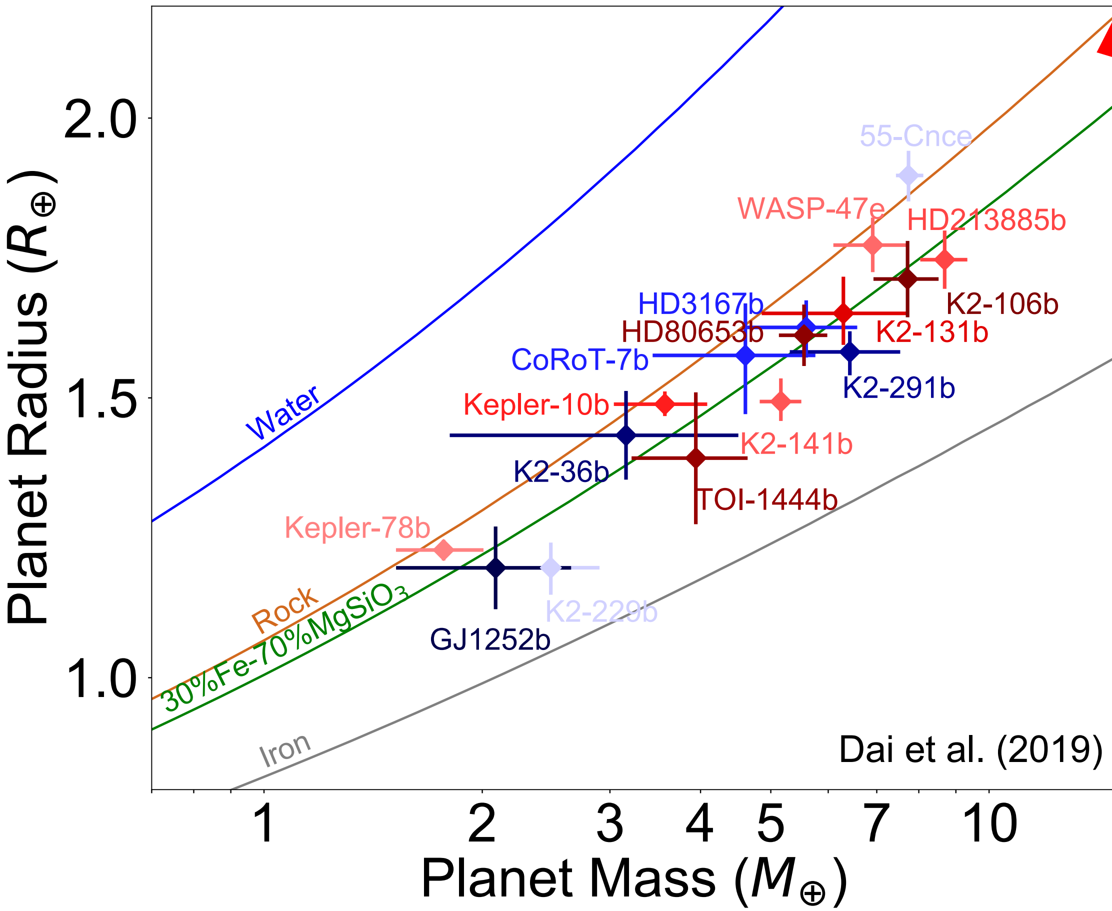
The Evaporation Valley In Two Dimensions

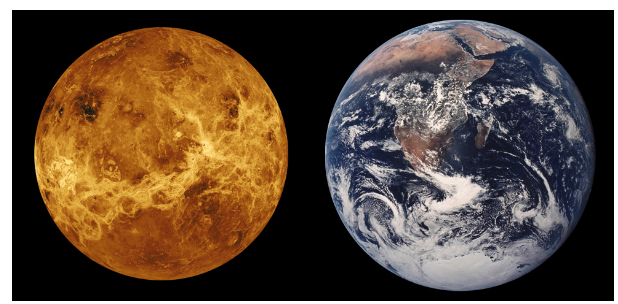


Fulton & Petigura (2018)

Sanity check: close-in super-Earths have Earth-like bulk densities.

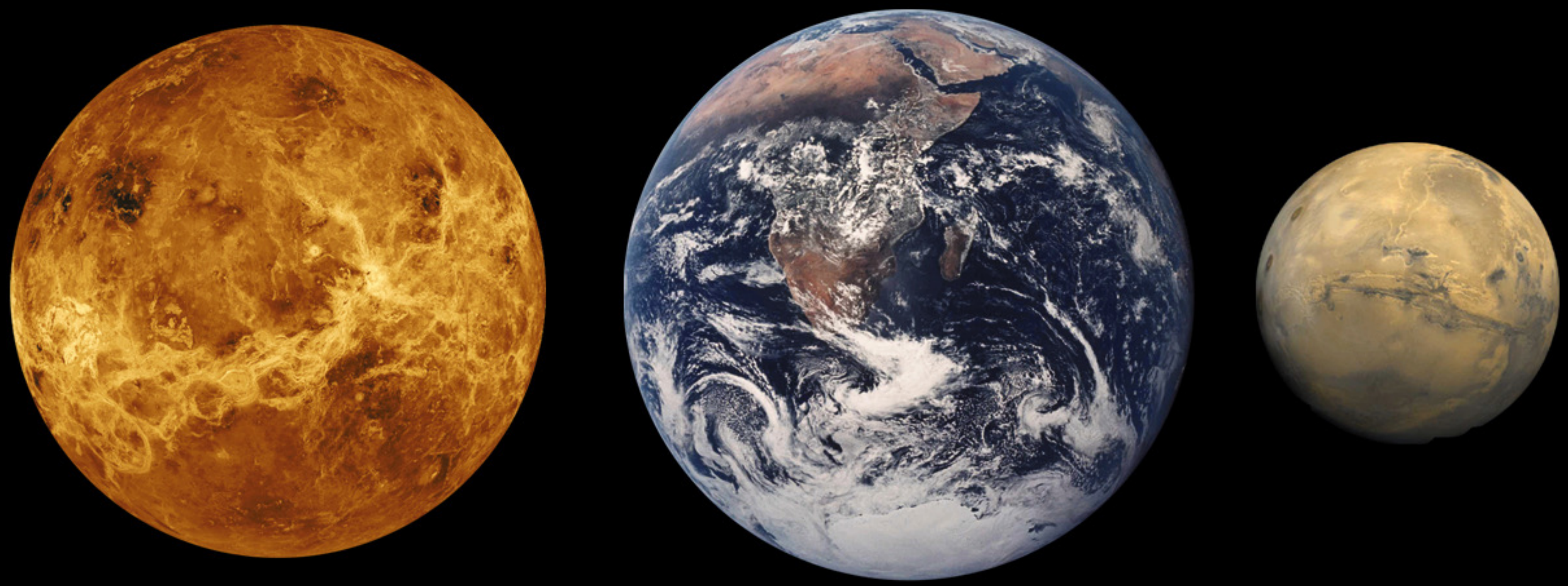






Earth & Venus atmospheres are only ~1% of their radii.

What are the typical atmospheric compositions of rocky exoplanets?



Initial outgassed atmospheres depend on compositions of accreted solids, are modified by surface processes + mass loss.

Likely dominated by C, N, O, S, & (sometimes) H; see review by Wordsworth & Kreidberg (2022)

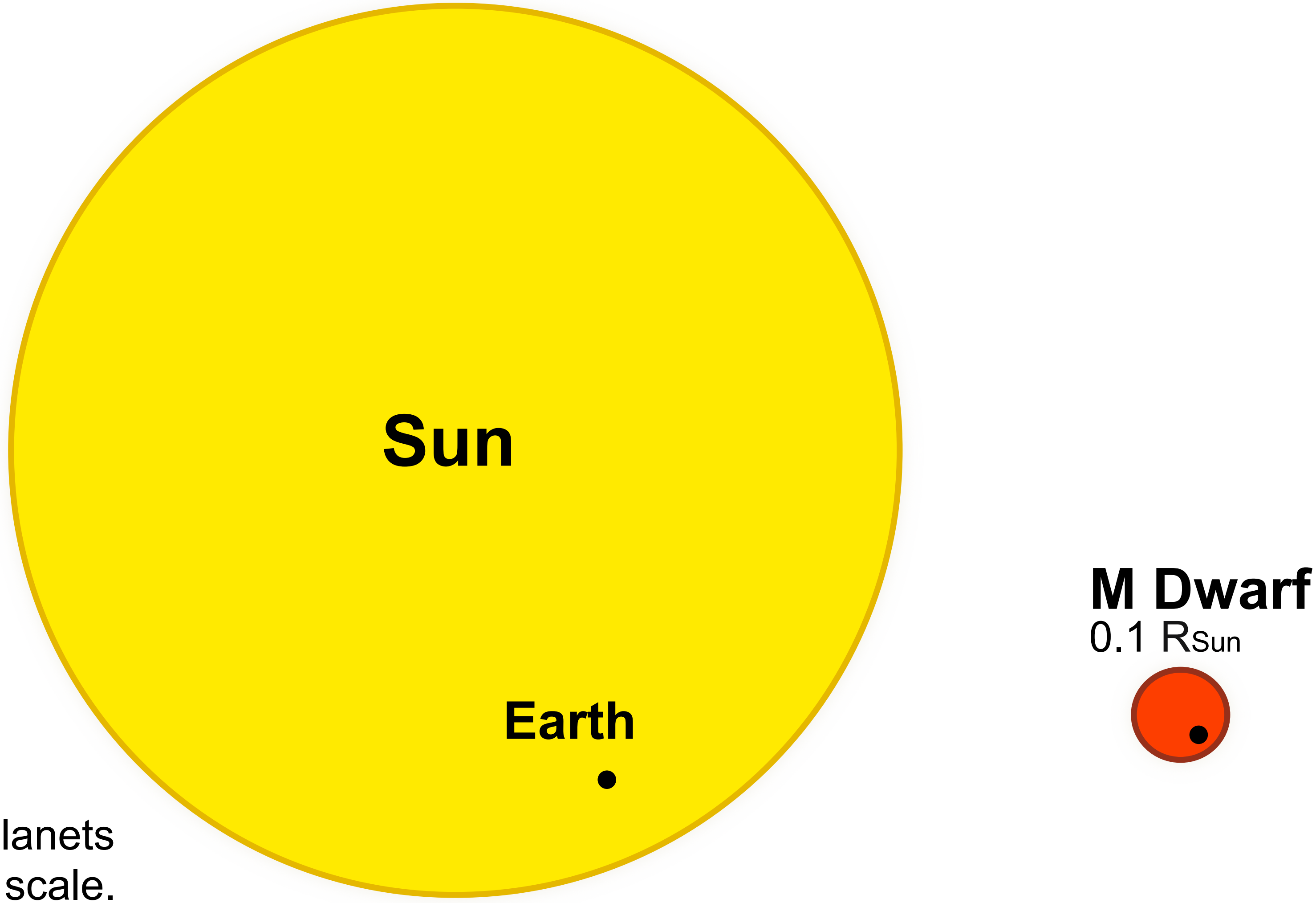
Small Planets are Challenging To Study

We've mostly observed planets this size

We would like to study planets this size

Jupiter's area is 120 times greater than the Earth's, and it has over 300 times the Earth's mass.

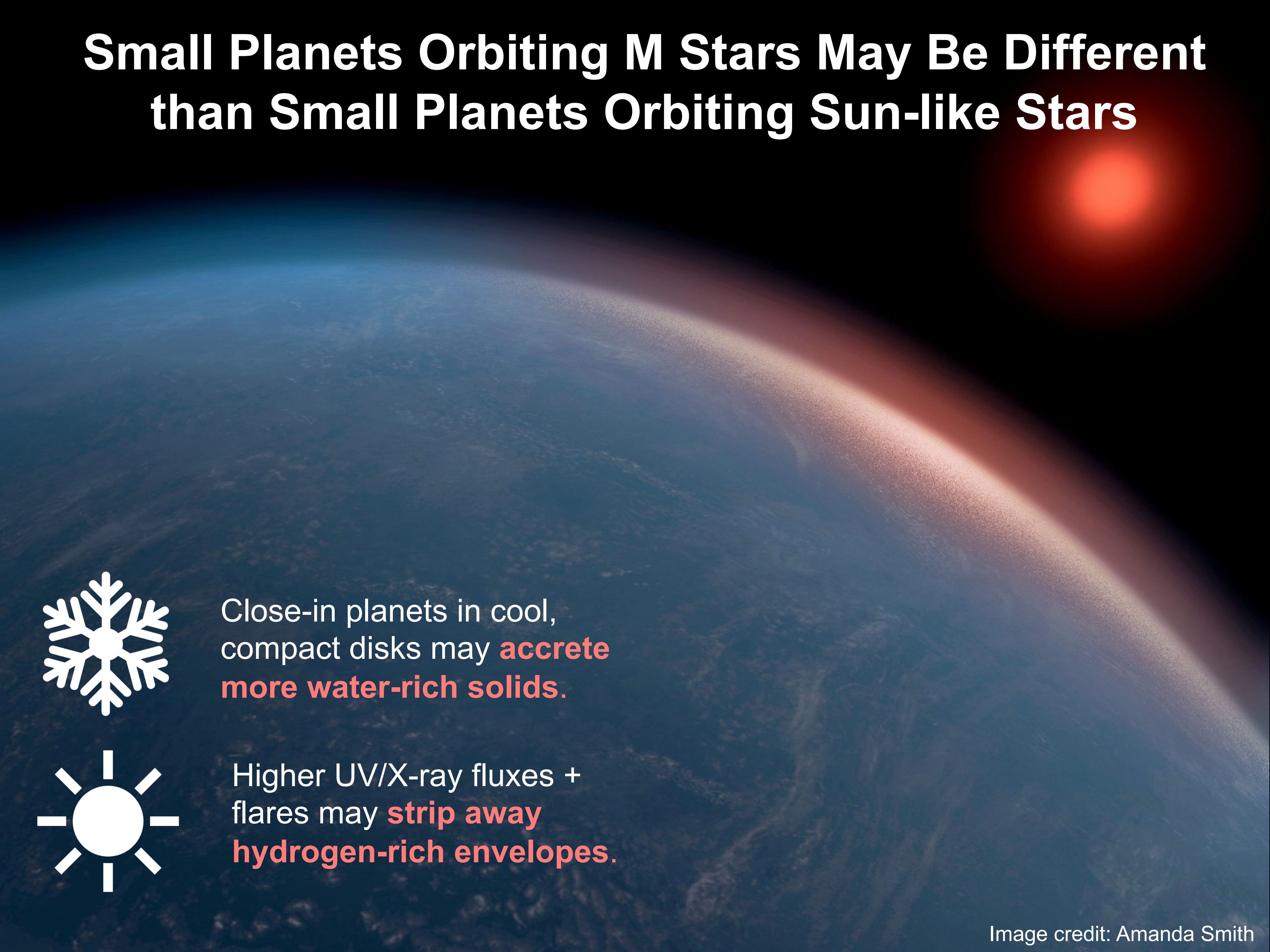
The M Star Opportunity



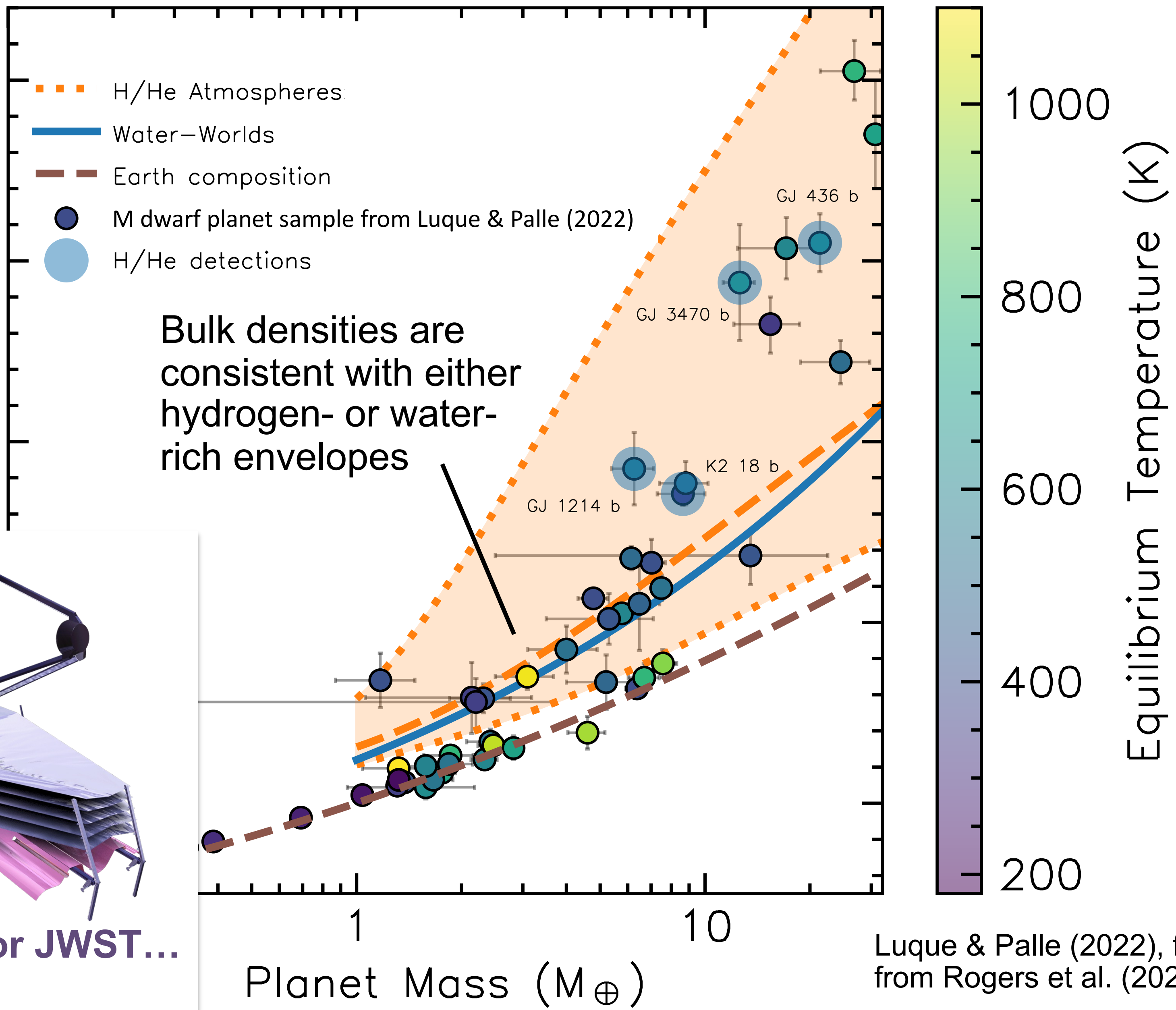
Stars + planets drawn to scale.

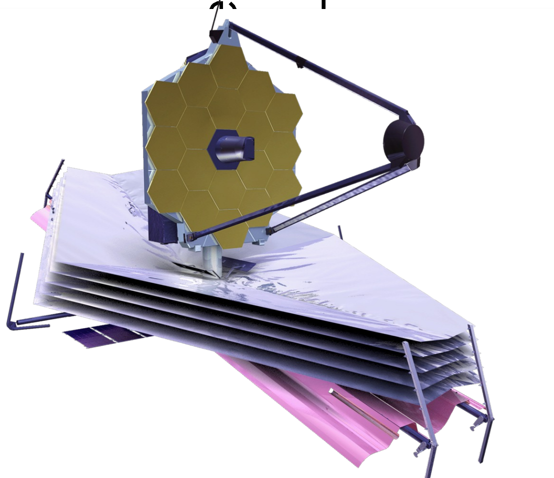
Smaller planets are *much* easier to detect and characterize around small stars.

Figure courtesy Z. Berta


Small Planets Orbiting M Stars May Be Different than Small Planets Orbiting Sun-like Stars
Close-in planets in cool, compact disks may accrete more water-rich solids.
Higher UV/X-ray fluxes + flares may strip away hydrogen-rich envelopes.
Image credit: Amanda Smith

Do Water Worlds Exist, and How Common Are They?

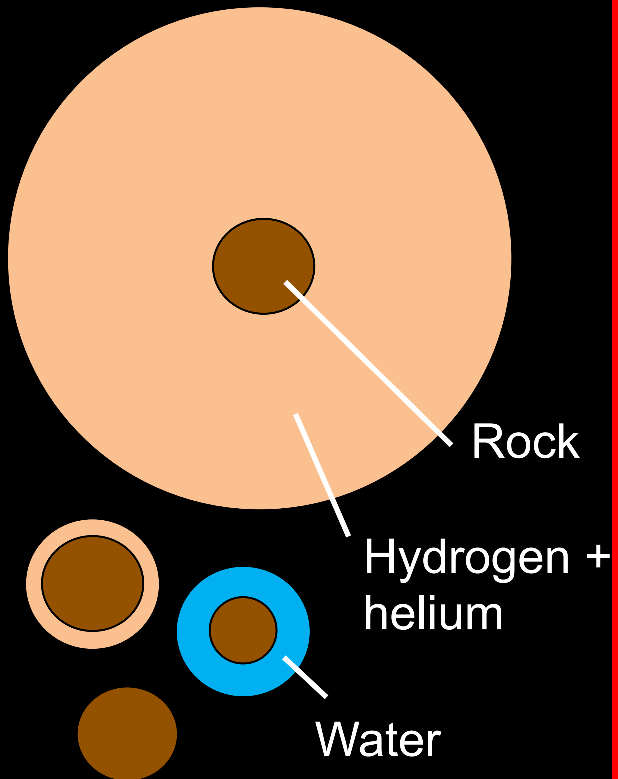




Stay tuned for JWST…

Luque & Palle (2022), figure from Rogers et al. (2023)

Key Atmospheric Properties



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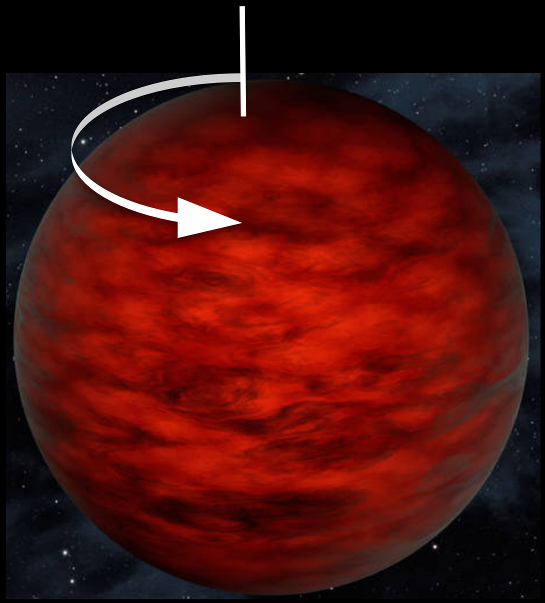
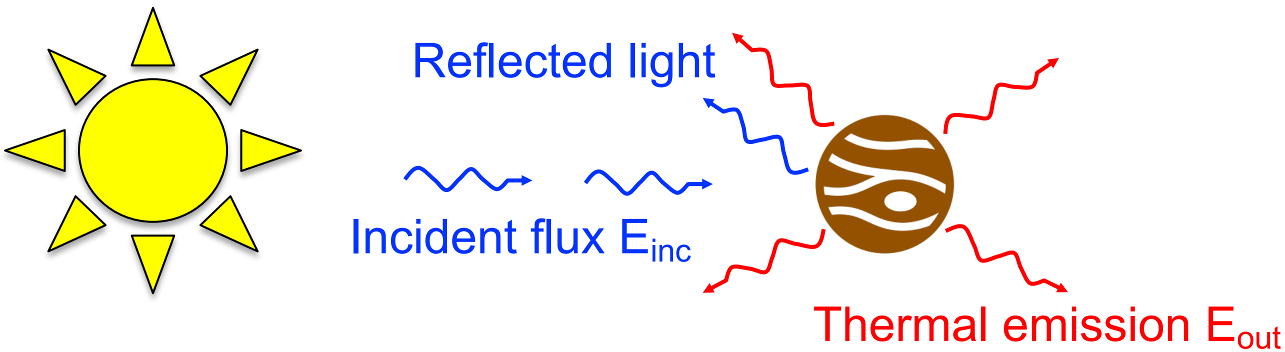
How hot is it? Is it internally or externally heated?



How rapidly does it rotate? Is it tidally locked?

Image credits: NASA/JPL-Caltech

Equilibrium Temperature (Externally Heated Planets)



Most exoplanets are old (>Gyr); this means they are *externally* heated.

Energy balance:

Bond albedo A_B

$$(1\text{-fraction of light reflected})^*E_{inc} = E_{out}$$

Treat planet + star as blackbodies:

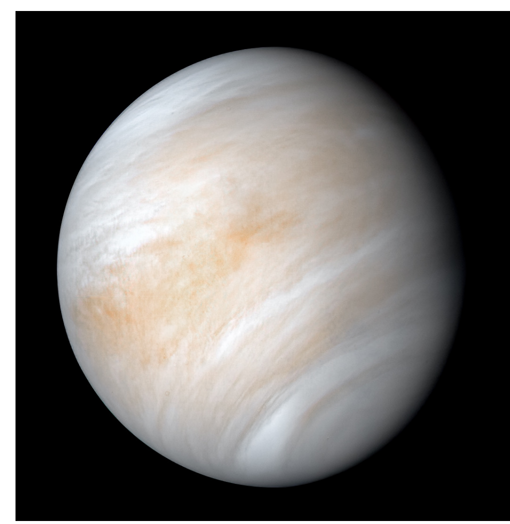
$$(1-A_B)(\cancel{\sigma} T_*^4)(R_*/a)^2(\cancel{\pi R_p^2}) = (4\cancel{\pi R_p^2})(\cancel{\sigma} T_p^4)$$

Solve for the equilibrium planet temperature:

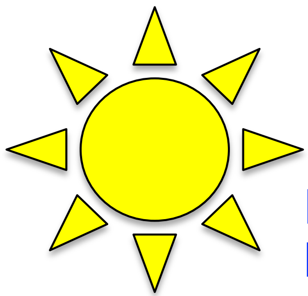
$$T_{eq} = T_p = [(1/4)(1-A_B)]^{1/4}(T_*)(R_*/a)^{1/2}$$

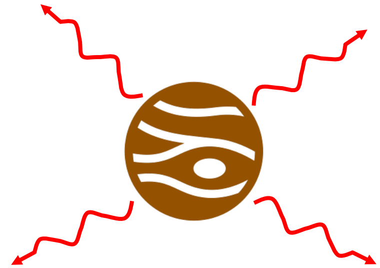
Most hot Jupiters have low (< 0.1) Bond albedos. Need reflective clouds to increase albedo (A_B for Venus is ~0.75).

Atmospheric temperature is controlled by **distance from the star (a)** and **albedo A_B**.



Temperatures of Directly Imaged Planets



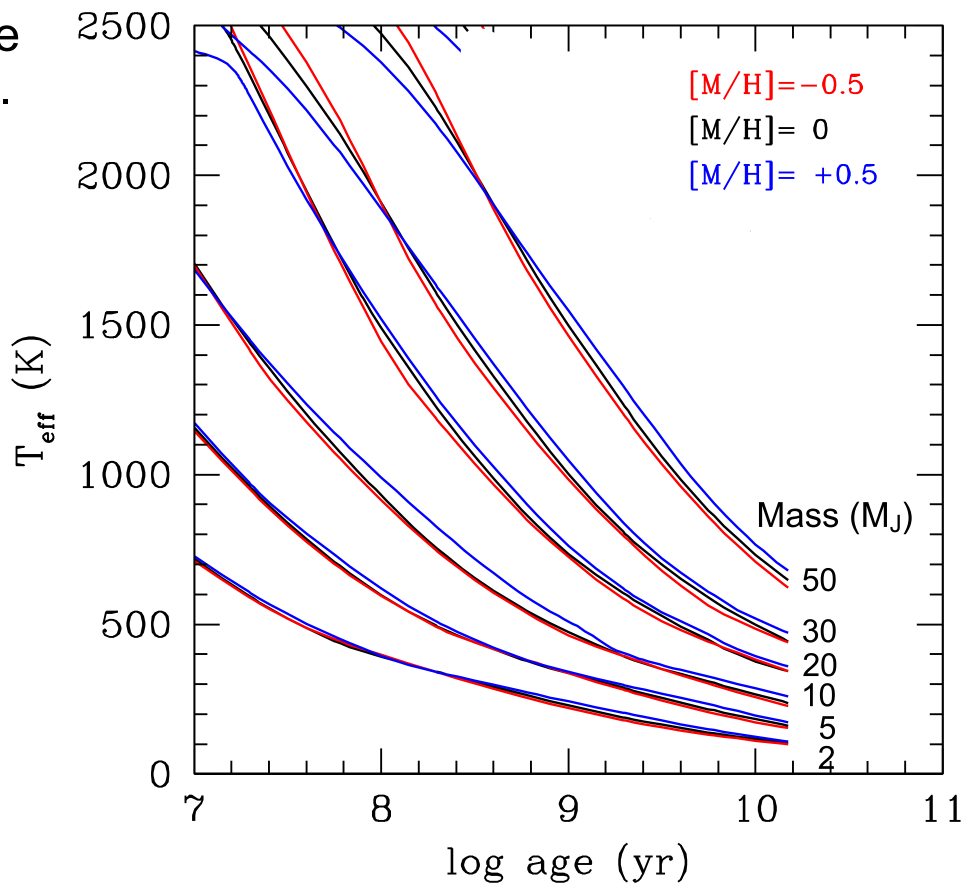


Directly imaged planets (young, hot, wide orbital separations) are *internally* heated.

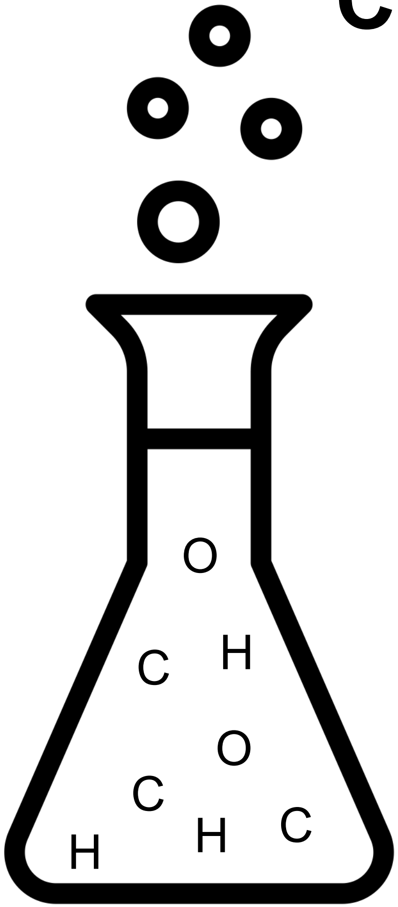
Must **measure temperatures empirically**. T_{eff} is the blackbody temperature needed to match the observed luminosity:

$$4\pi R_p \sigma T_{eff}^4 = \int_0^\infty F_p(\lambda) d\lambda$$

Luminosity is dominated by **leftover heat from formation**, decreases over time. Figure from Marley et al. (2021).

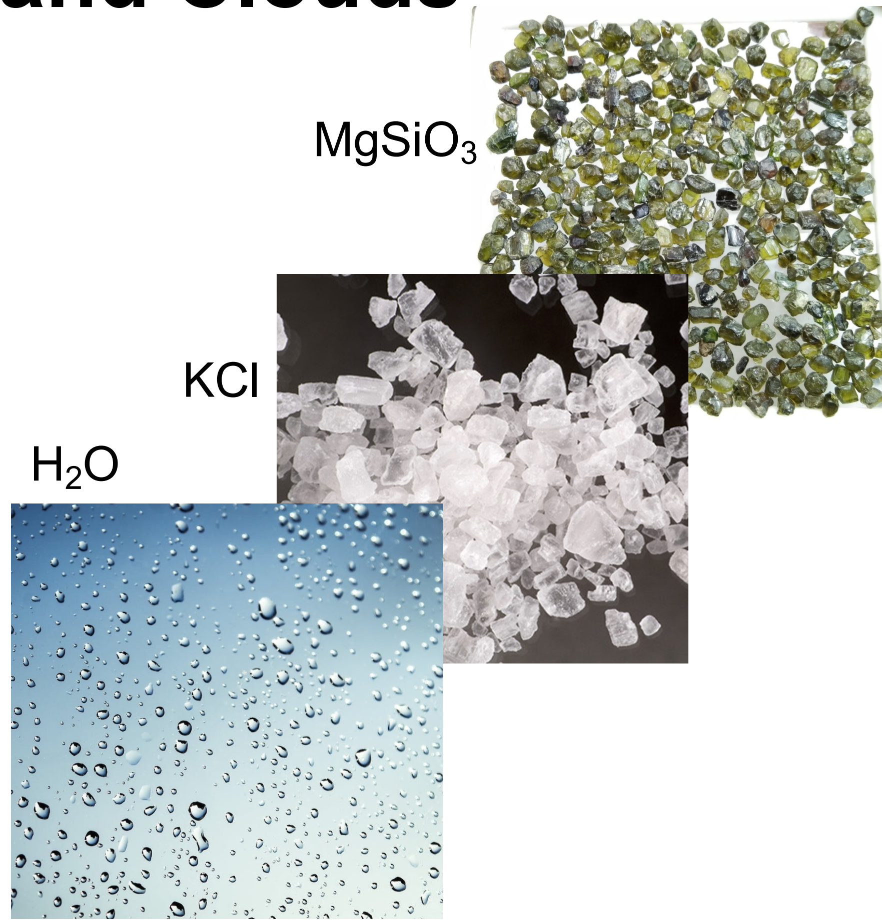


Consequences of Temperature: Chemistry and Clouds



H_2O?
CO_2?
CO?
H_2?
CH_4?

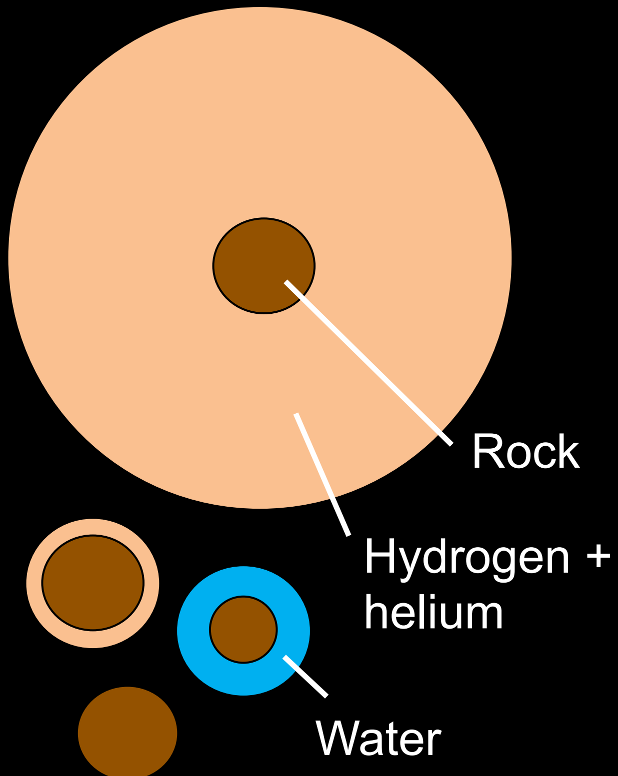
Temperature (and pressure) determines the **atmospheric chemistry**.



It also determines what **types of clouds** can condense.

See reviews by Moses (2013), Marley & Robinson (2015), Gao et al. (2021).

Key Atmospheric Properties



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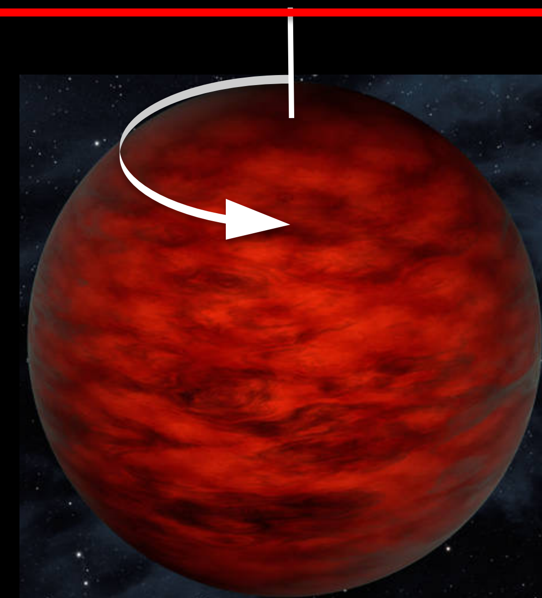
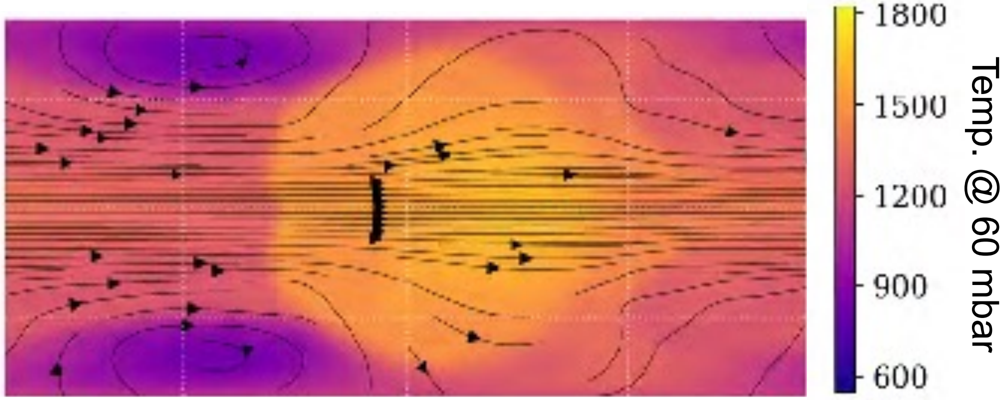


How rapidly does it rotate? Is it tidally locked?

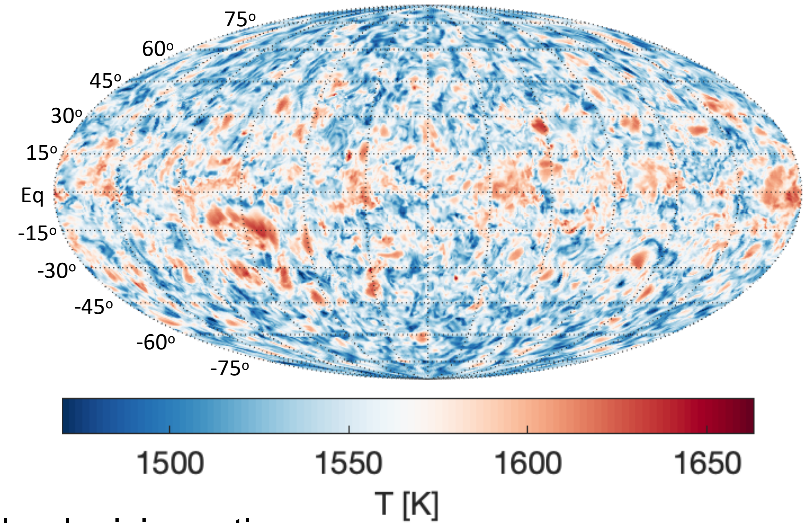
Image credits: NASA/JPL-Caltech

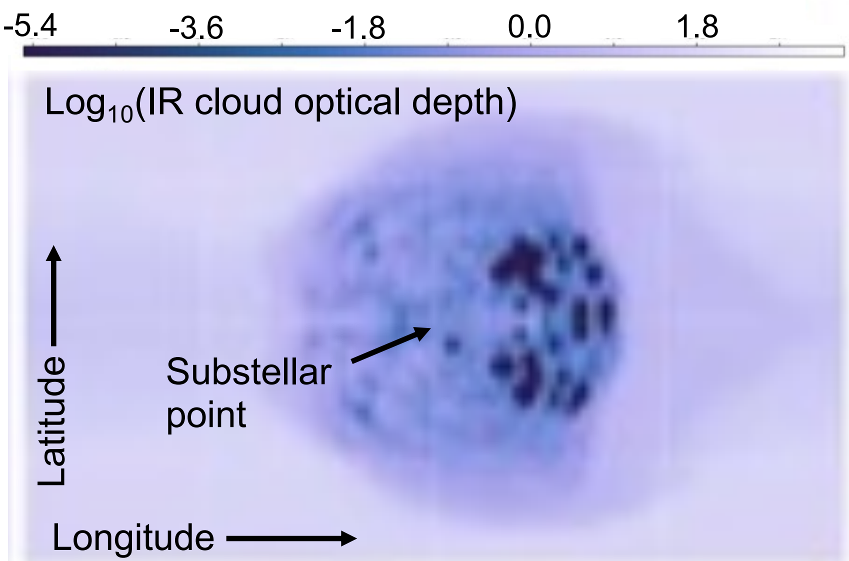
Atmospheres in 3D

Close-in planets are predicted to be *tidally locked* (P_{rot} ~ days).

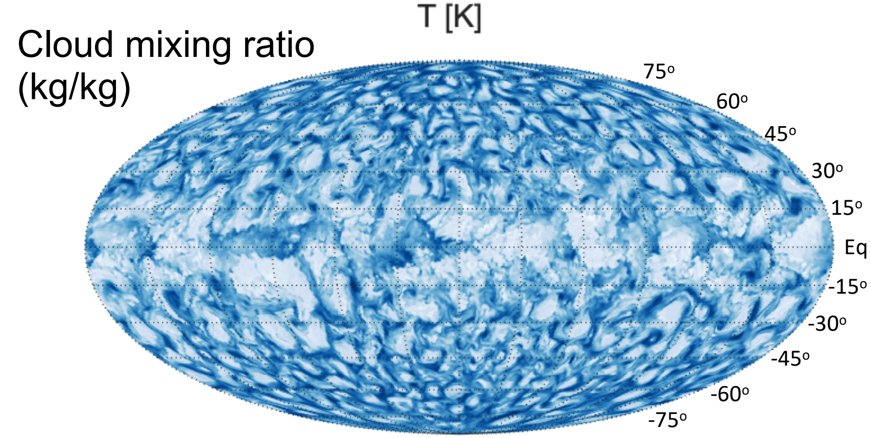


More distant planets are *rapidly rotating* (P_{rot} ~ hours).



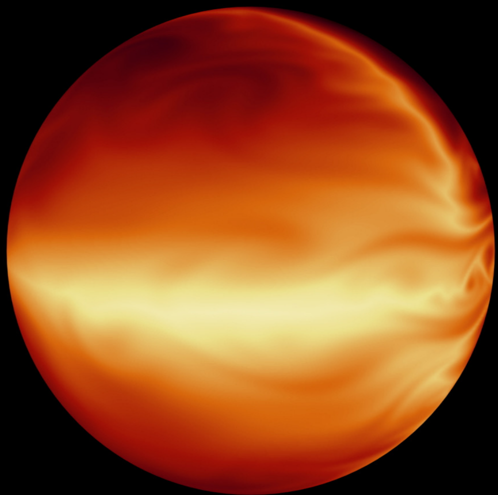


Hemisphere-scale atmospheric features
(T_{eq}=1800 K planet, Roman & Rauscher 2021).



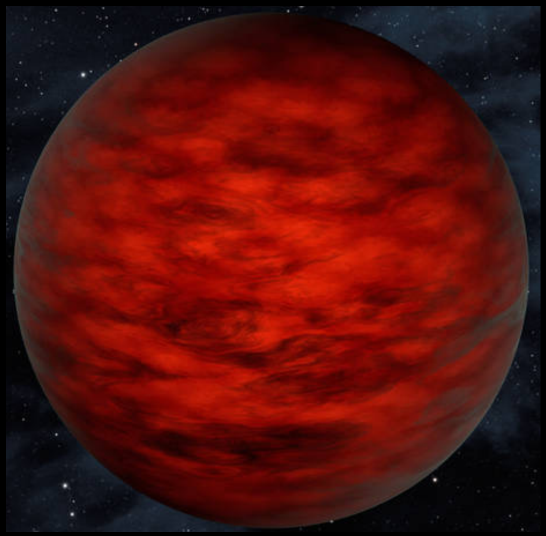
Smaller scale atmospheric features
(Isolated T_{eff}=1500 K brown dwarf with a 5 hr rotation period, Tan & Showman 2021)

Conclusions: A Diversity of Atmospheres



Hot Jupiters

Warm/Cold Jupiters



Directly Imaged Planets

Sub-Neptunes,
Super-Earths, &
Water Worlds

Image credits: NASA/JPL-Caltech