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WHAT IS A SUB-NEPTUNE?

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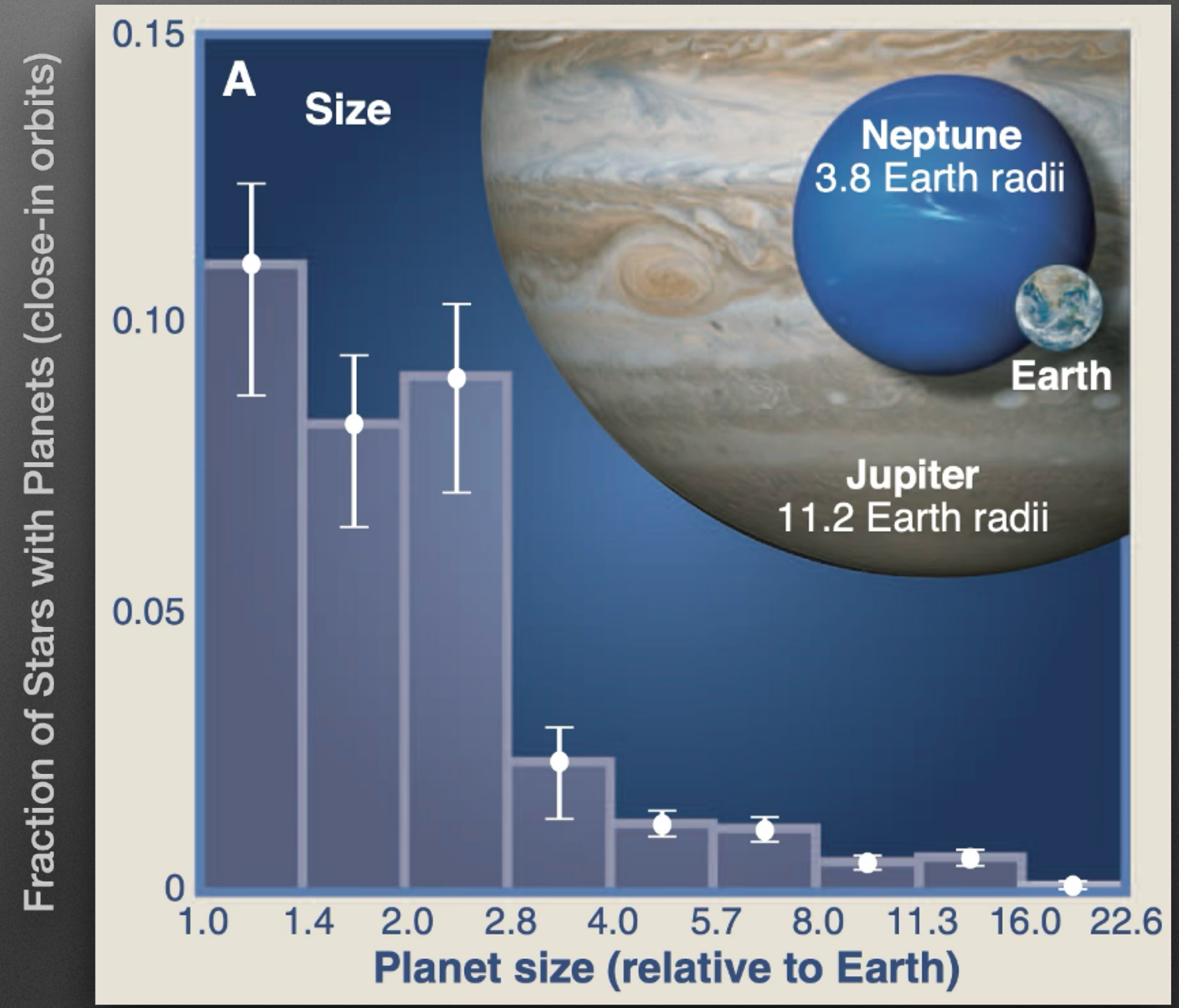
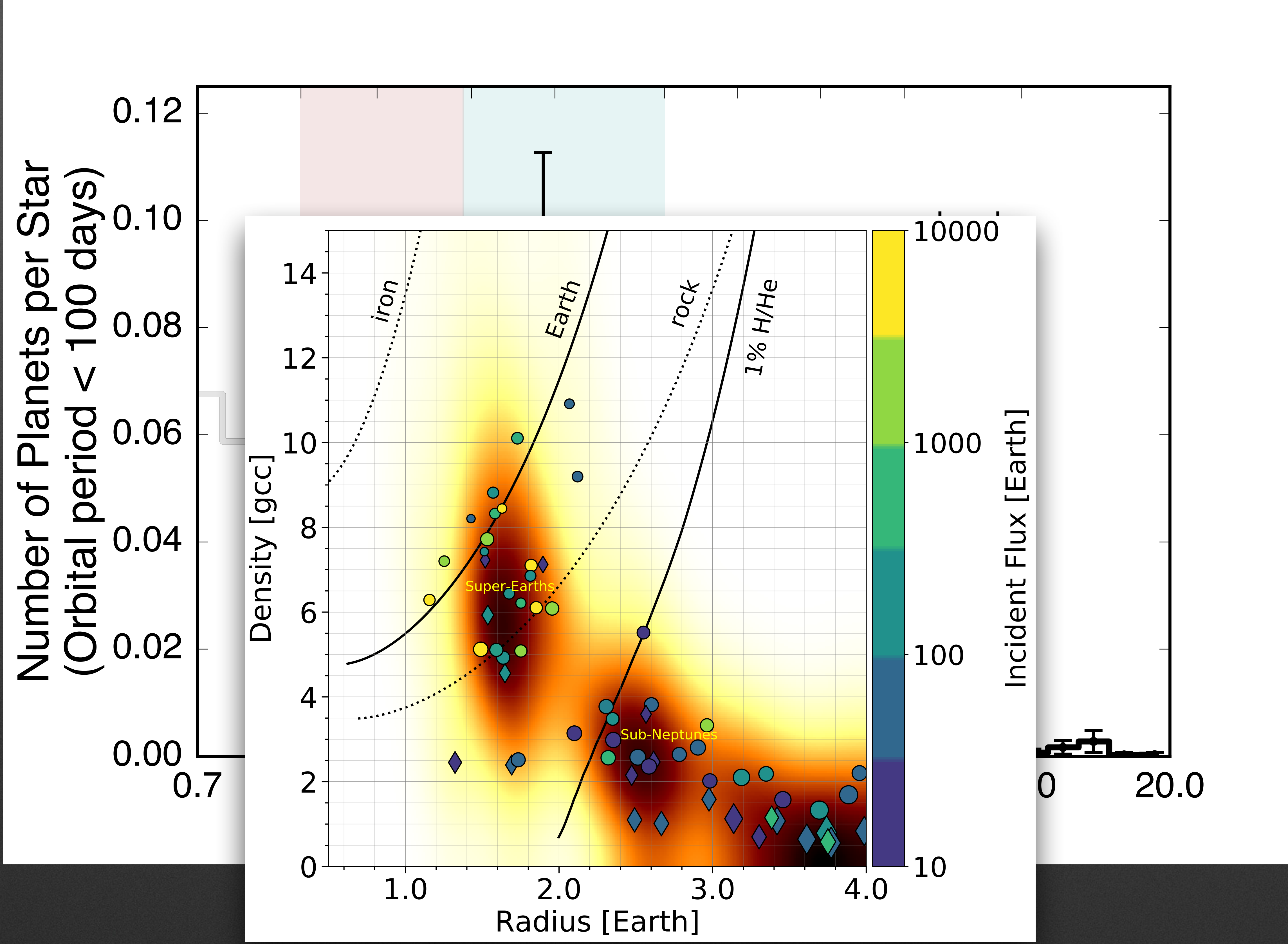
Why ask the question?

- Kepler showed us that planets with radii between that of Earth and Neptune are extremely common
- But there is no example in our Solar System
- They likely span a range of sizes, masses, and likely compositions
- What actually defines them — radius? mass? atmosphere? formation history?
- Understanding them is key to planet formation, evolution, and habitability



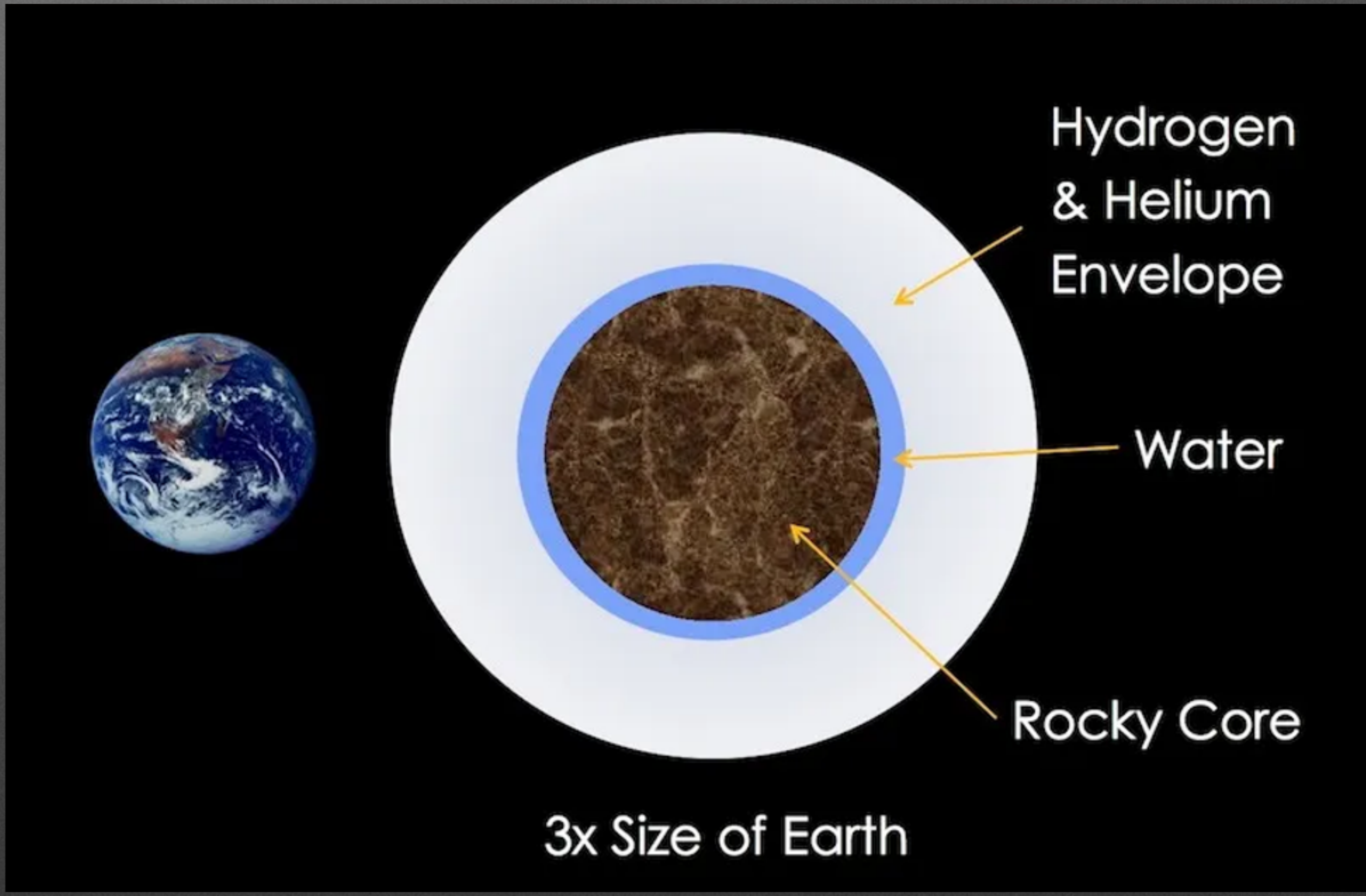
Howard et al. (2013)

The Radius Gap



Working Definition

- Planets with radii ~1.7 to ~4 Earth radii
- Masses typically between ~3 and ~20 Earth masses
- Lower density than rocky planets — must have volatiles (gas and/or ices)
- Could include failed gas giants, water worlds, or anything between



Plausible Explanations for the Gap

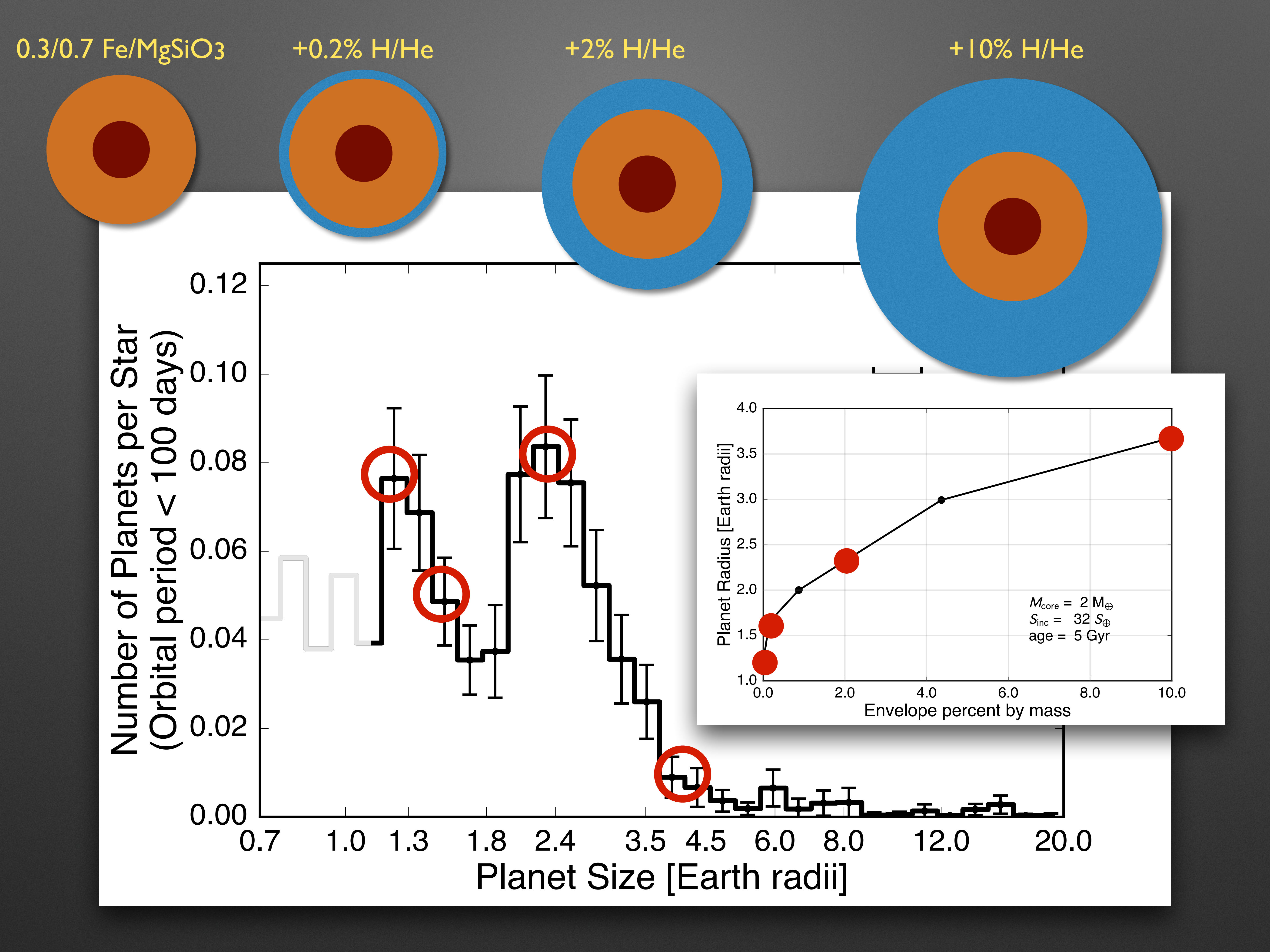
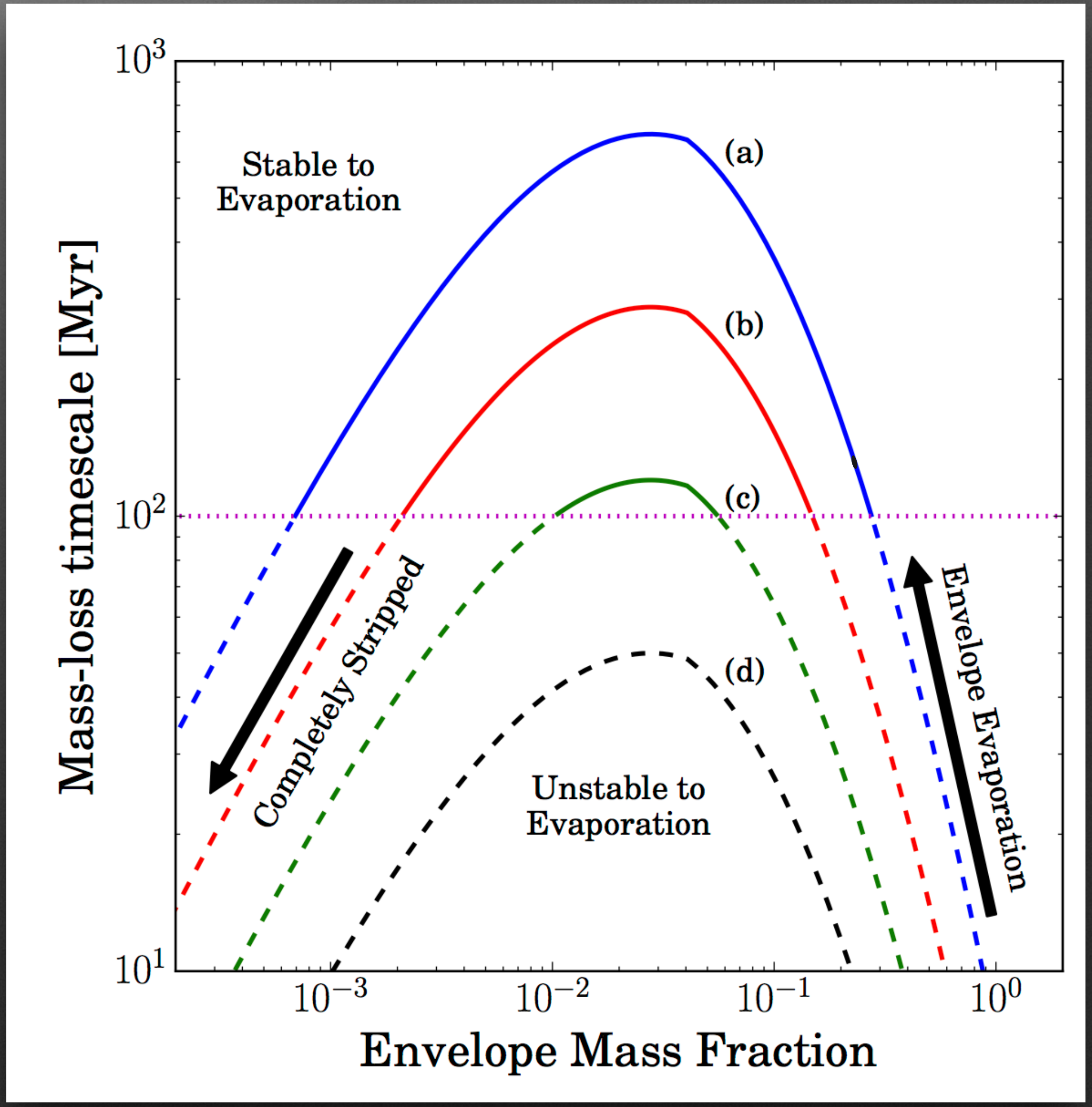
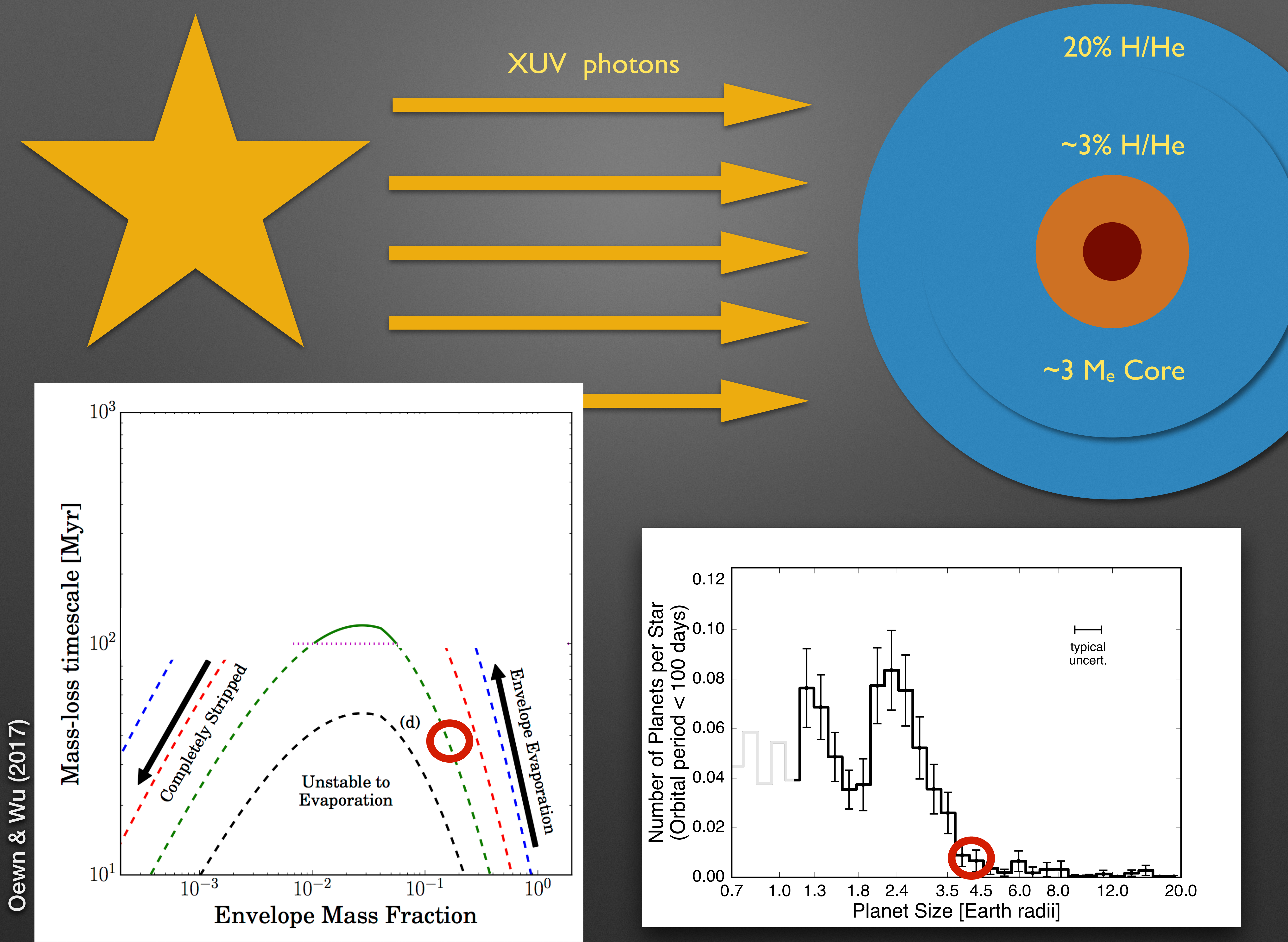

0.3/0.7 Fe/MgSiO3
+0.2% H/He
+2% H/He
+10% H/He
Number of Planets per Star
(Orbital period < 100 days)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]
Planet Radius [Earth radii]
Envelope percent by mass
M_{core} = 2 $M_\oplus$
S_{inc} = 32 $S_\oplus$
age = 5 Gyr

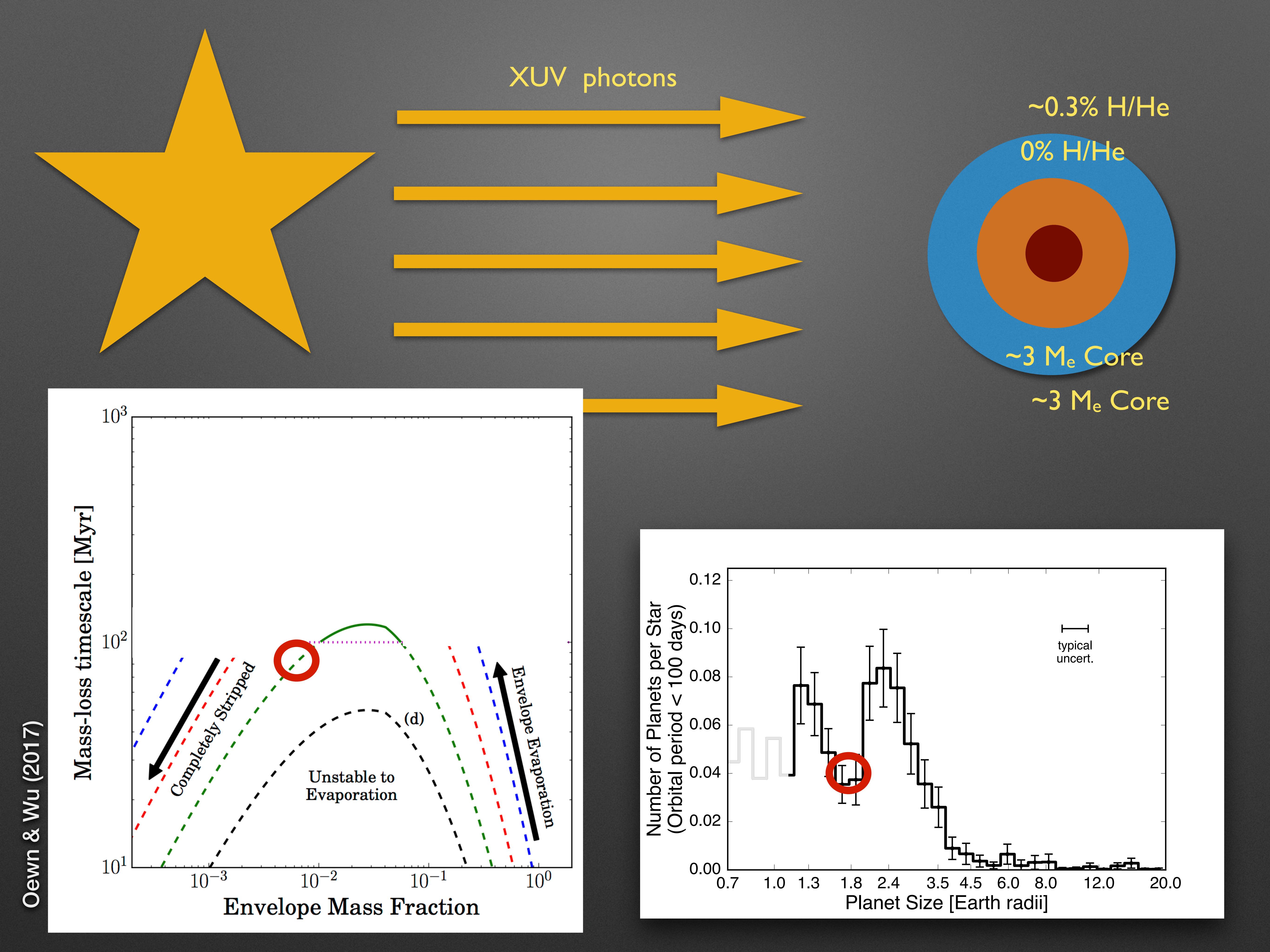
Photo-Evaporation

- **Predicted by Theory**
  - Owen & Wu (2013)
  - Lopez & Fortney (2013)
  - Jin et al. (2014)
  - Chen & Rogers (2016)
- **Explanation**
  - High energy XUV photons emitted during star's first 100 Myr erodes envelopes
  - Most sub-Neptunes are ~3% H/He by mass
    - 3% H/He envelopes have longest mass loss timescale
    - Planets are "herded" into two typical sizes



Owen and Wu (2017)

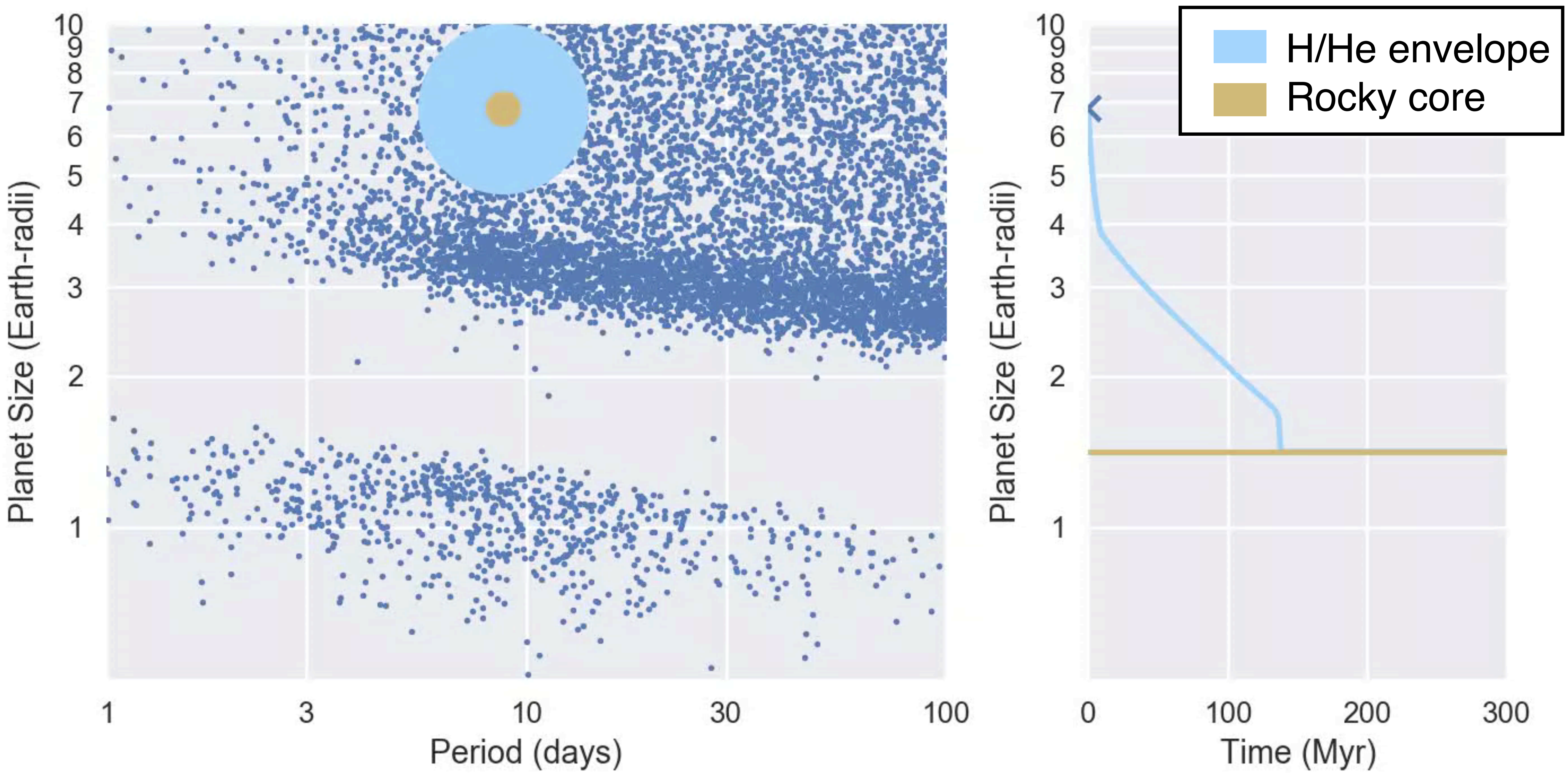

XUV photons
20% H/He
~3% H/He
~3 Mₑ Core
Mass-loss timescale [Myr]
Envelope Mass Fraction
Completely Stripped
Envelope Evaporation
Unstable to Evaporation
(d)
Oewn & Wu (2017)
Number of Planets per Star (Orbital period < 100 days)
Planet Size [Earth radii]
typical uncert.


XUV photons
~0.3% H/He
0% H/He
~3 Me Core
~3 Me Core
Oewn & Wu (2017)
Mass-loss timescale [Myr]
Envelope Mass Fraction
Completely Stripped
Envelope Evaporation
Unstable to Evaporation
(d)
Number of Planets per Star (Orbital period < 100 days)
Planet Size [Earth radii]
typical uncert.

Photoevaporation Creates Radius Gap

Planets are converted into either

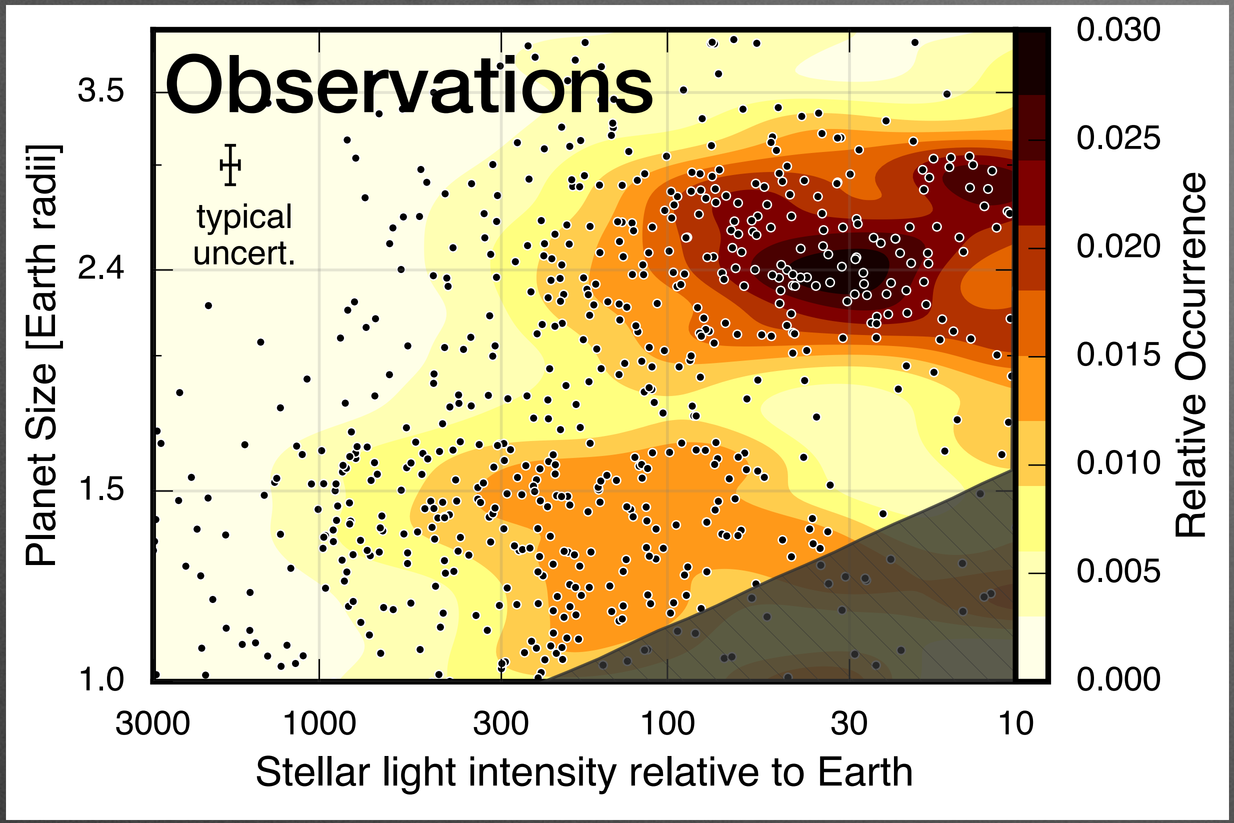
- ~2–3 R_E sub-Neptunes (rocky core with ~3% envelope)
- < 1.5 R_E super-Earths (rocky core with no envelope)



Simulation: J. Owen, Animation: E. Petigura

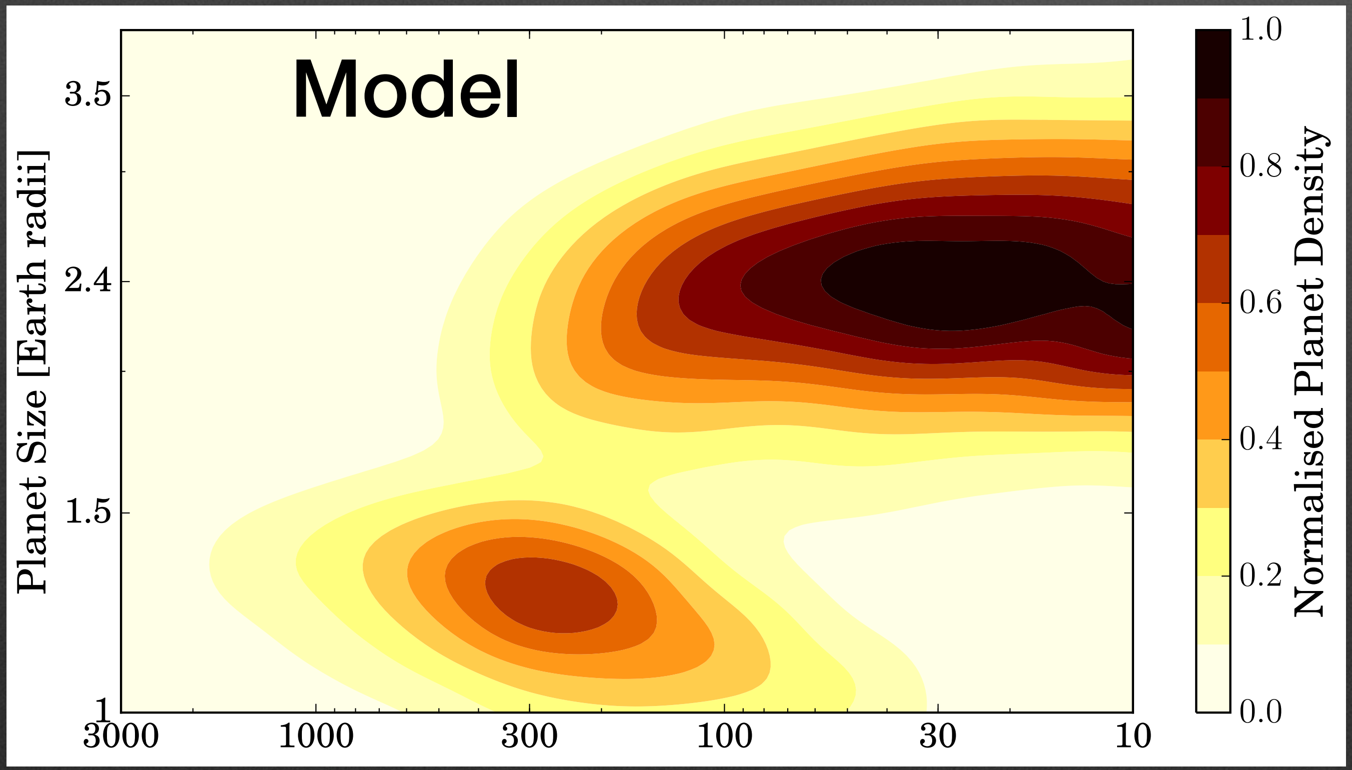
Photoevaporation

Fulton & Petigura (*2018*)

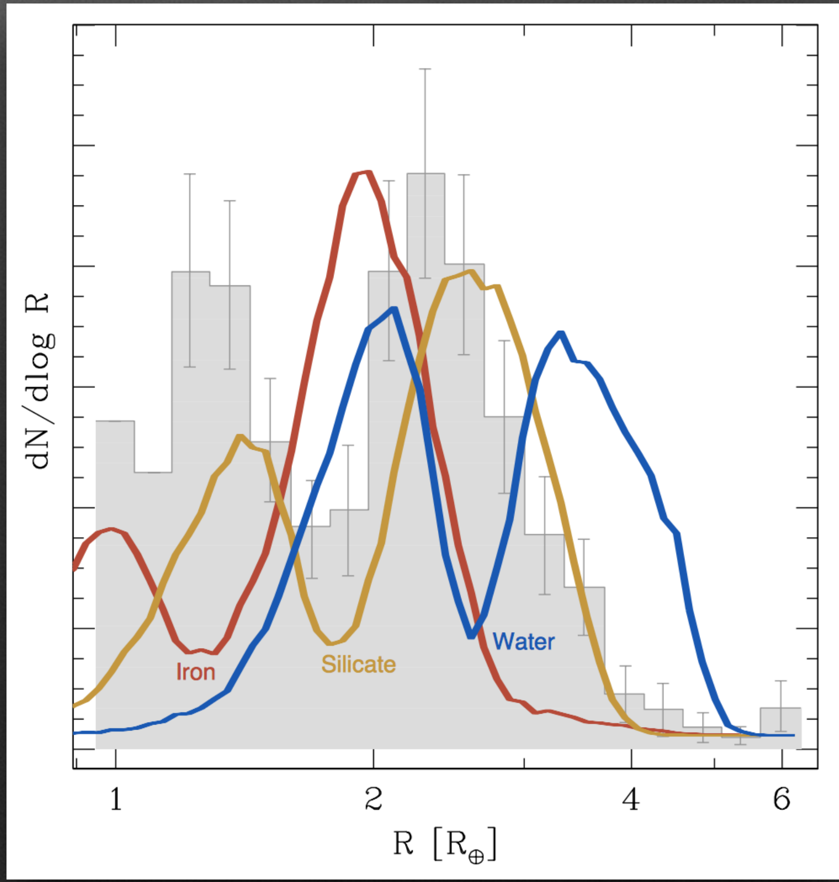


Major Implications

- Earth-density cores (water-poor)
- Large scale migration after 100 Myr is uncommon



Owen & Wu (2017)

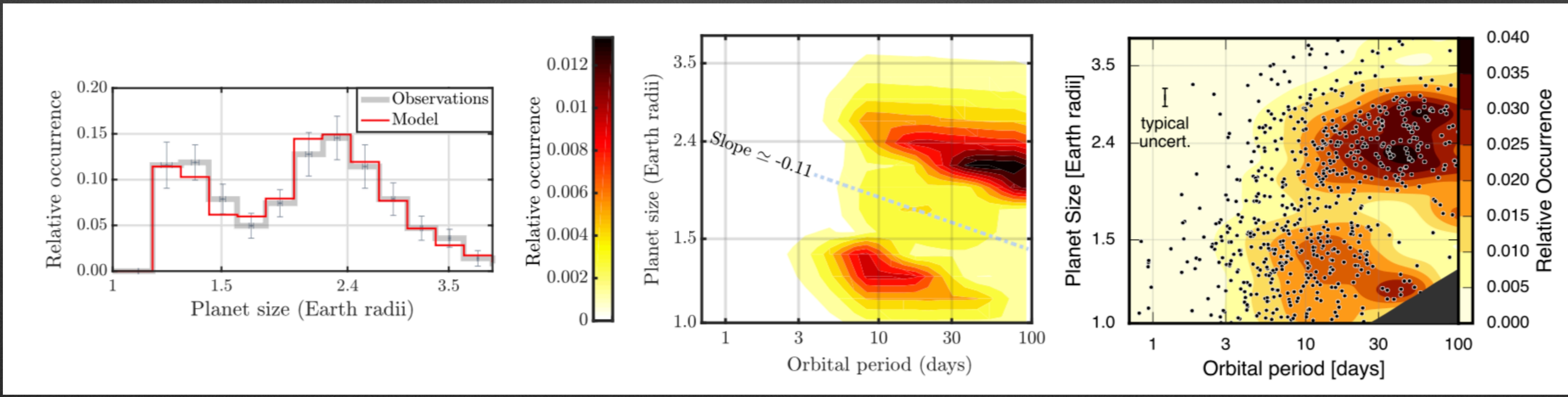


Owen & Wu (2017) Jin & Mordasini (2018)

Other Explanations for the Gap

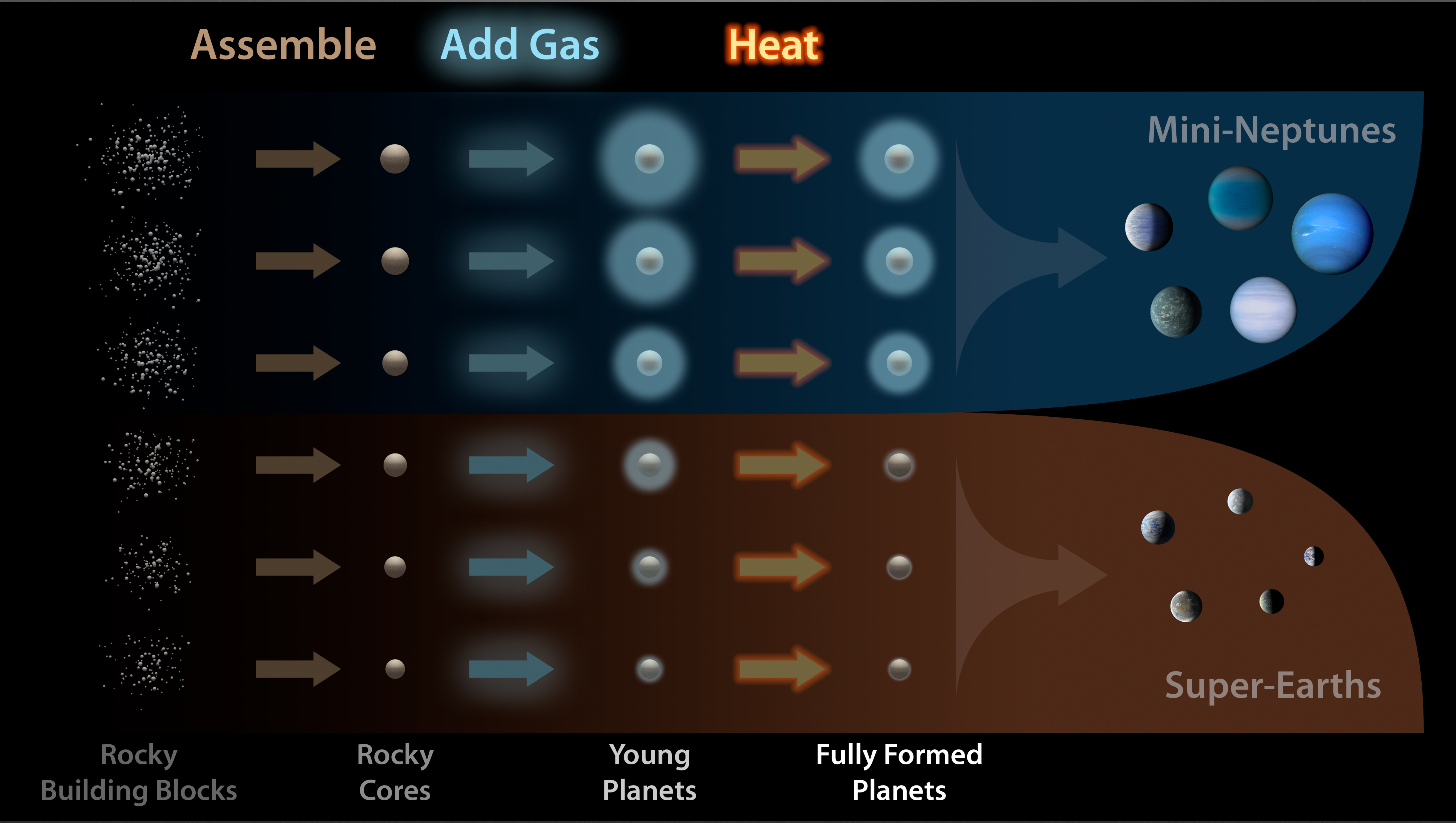
- <u>Impacts</u>
  - Pebble accretion (e.g. Chatterjee & Howard 2018)
  - Giant impacts (e.g. Inamdar & Schlichting 2016; Biersteker & Schlichting 2018)
- <u>Outgassing</u>
  - Outgassing of a few percent by mass (e.g. Dorn et al. 2018)

- <u>Core heating</u>
  - Vazan et al. (2017); Ginzburg et al. (2018); Gupta & Schlichting (2018)
  - Reproduced observations well: gap, rocky cores, slope



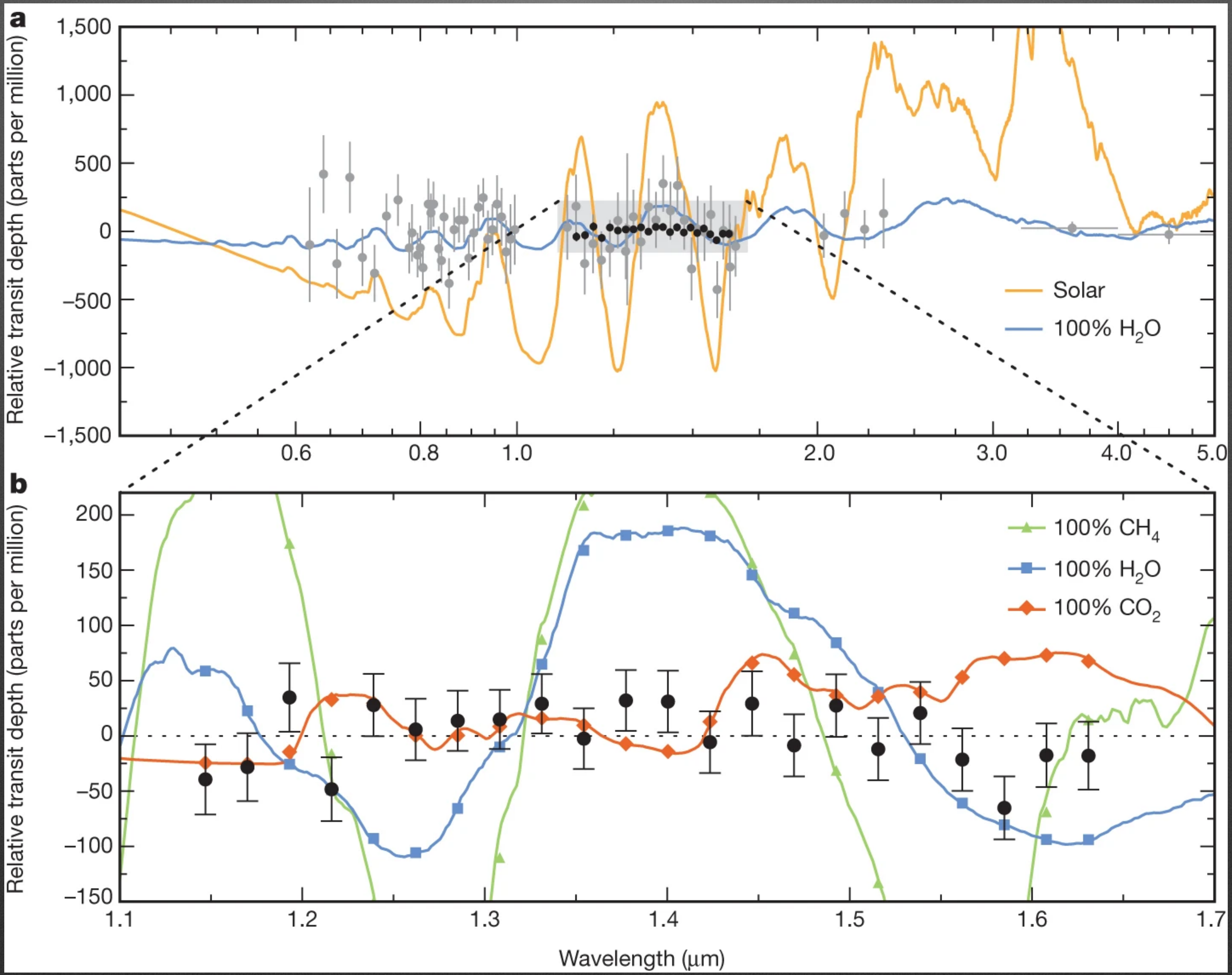
Gupta & Schlichtung (2018)

Common Thread

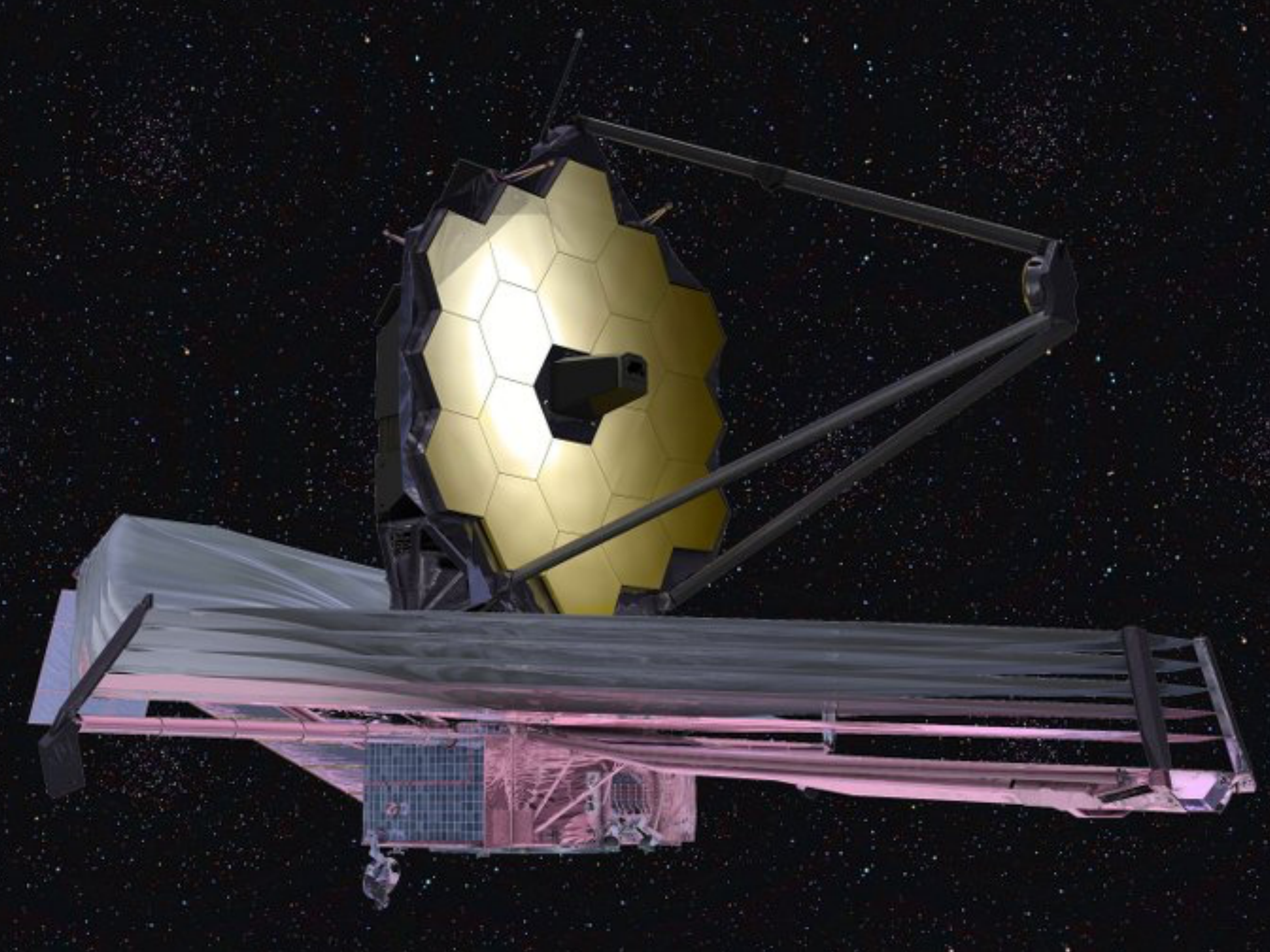


GJ1214b

Radius: 2.7R⊕ Mass: 6.3M⊕

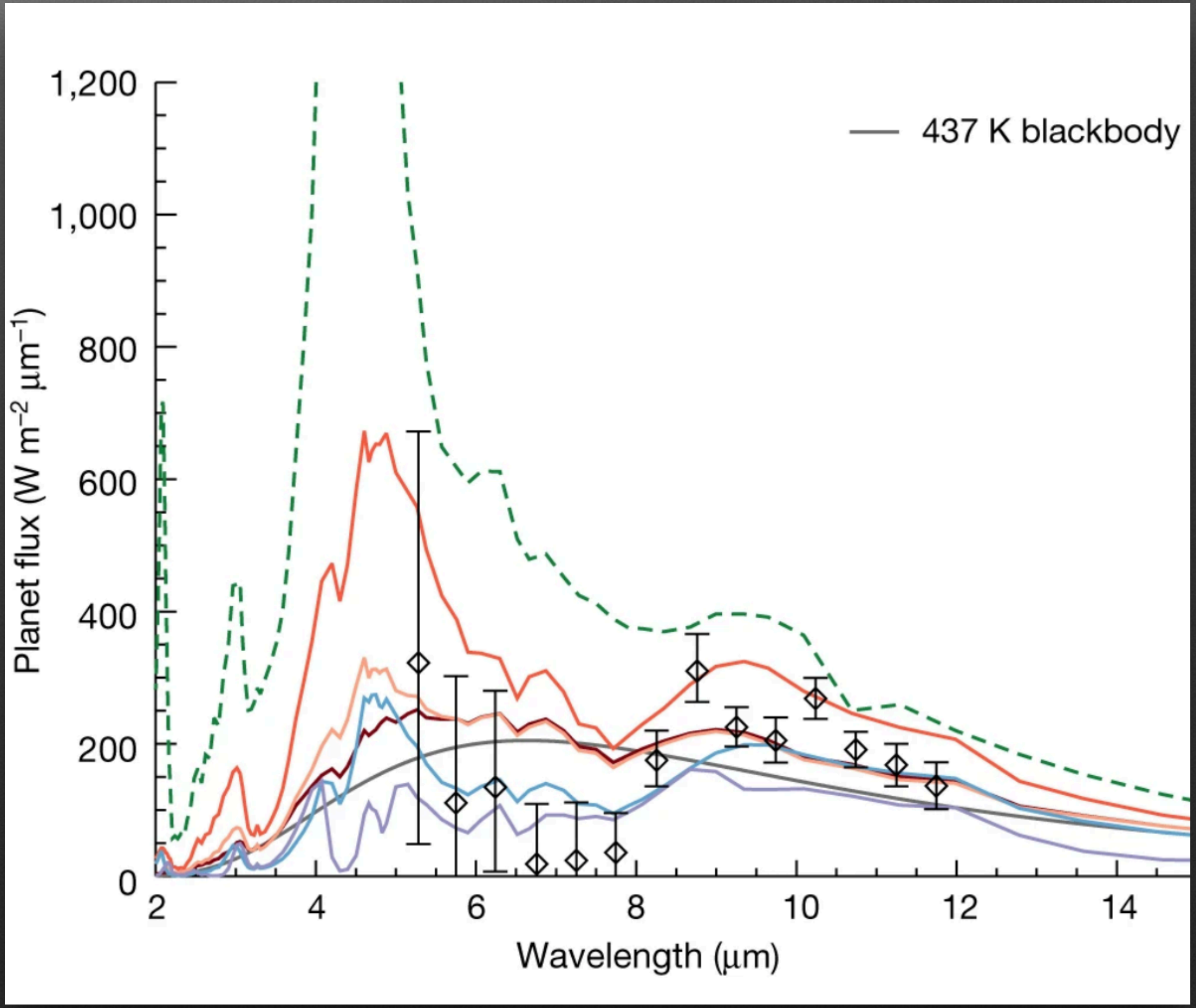


Kreidburg et al. (2014)



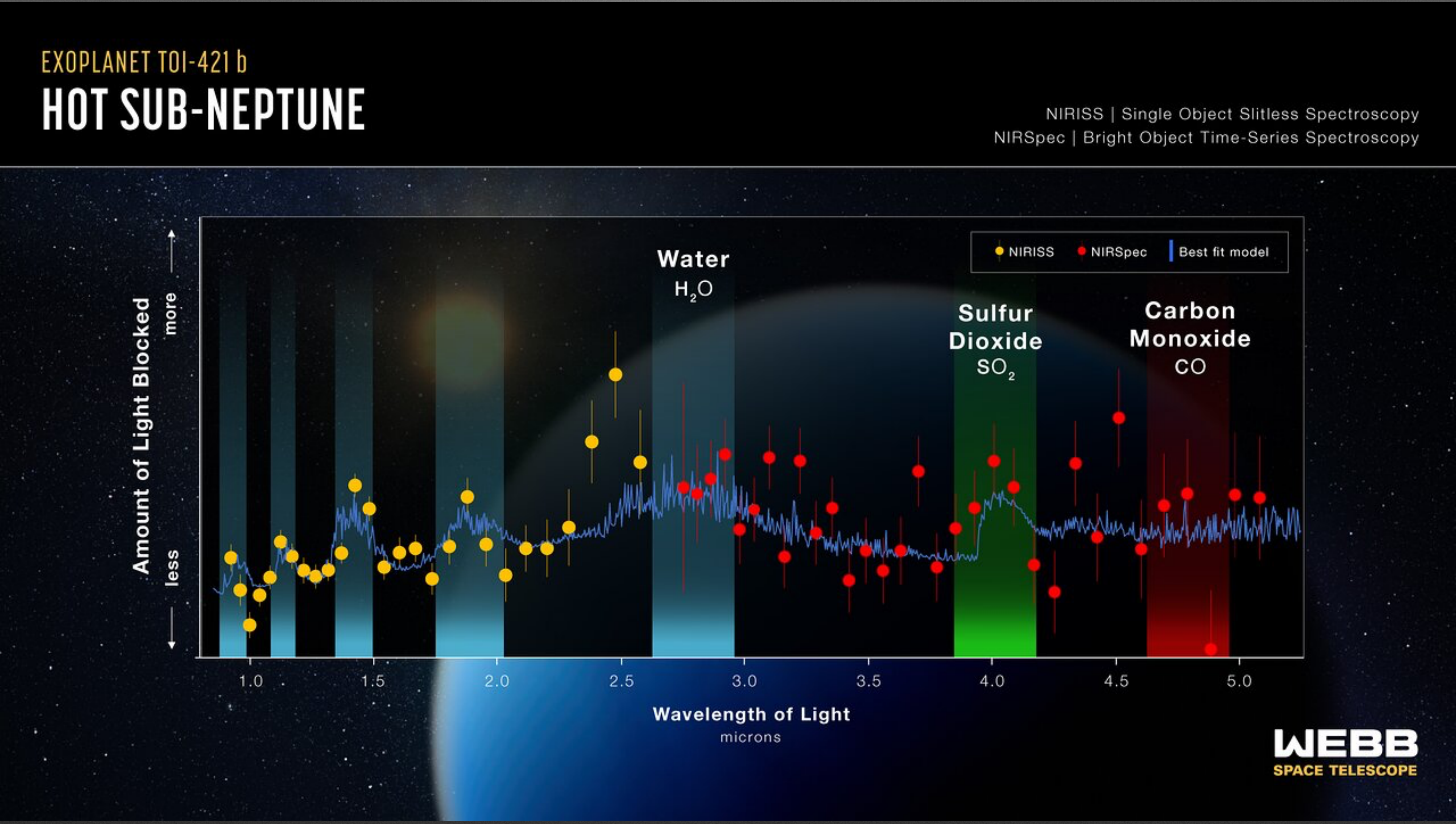
GJ1214b: Water in a Hazy Atmosphere?

- Envelope mass fraction ≥8% (H_2O and/or H/He) needed to explain mass/radius
- JWST MIRI phase-curve (mid-IR) shows hints of H_2O absorption features from both dayside & nightside
- Bond albedo ~0.51



Kempton et al. 2023

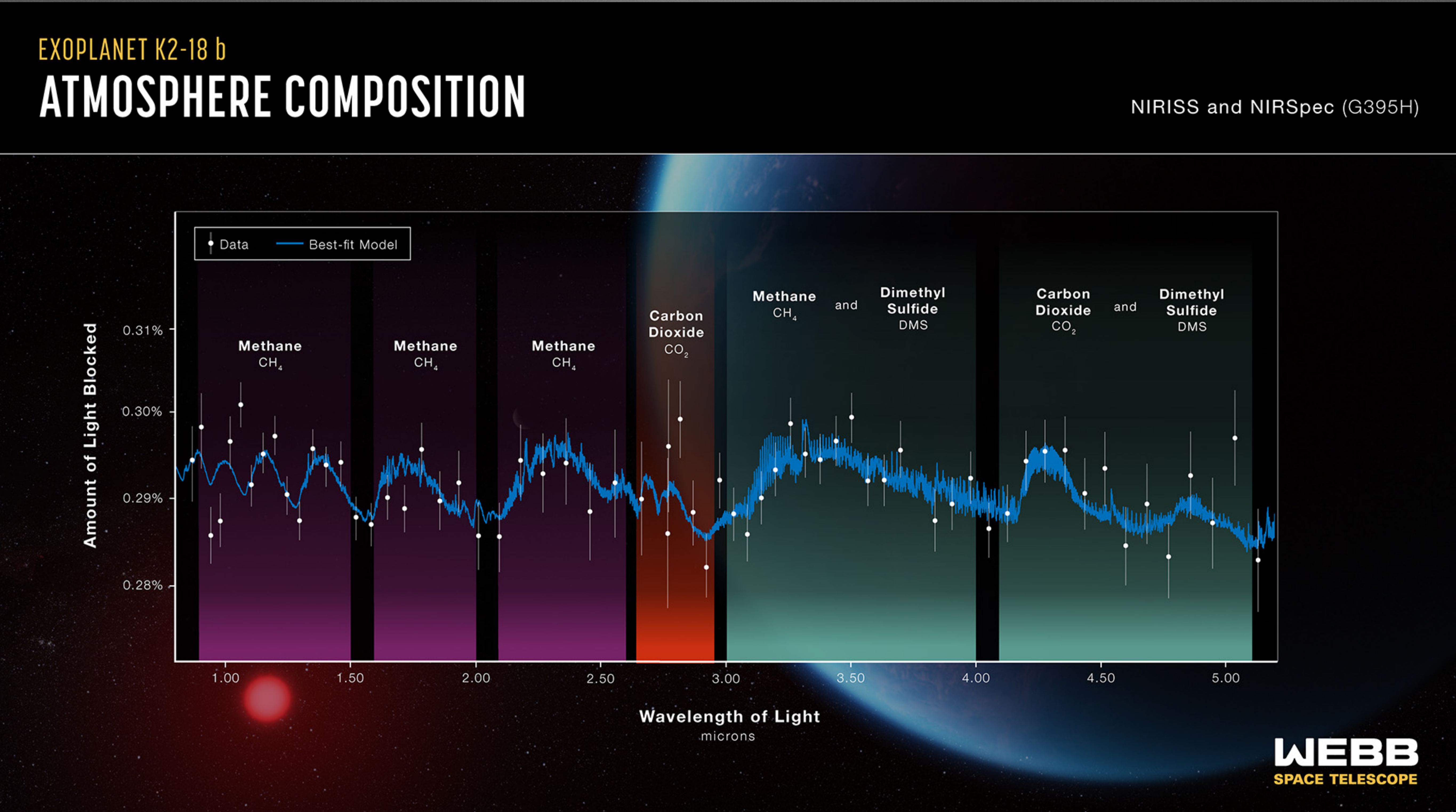
TOI-421b



Davenport et al. 2025

- Radius 2.68 R⊕ Mass 7.2 M⊕

K2-18b

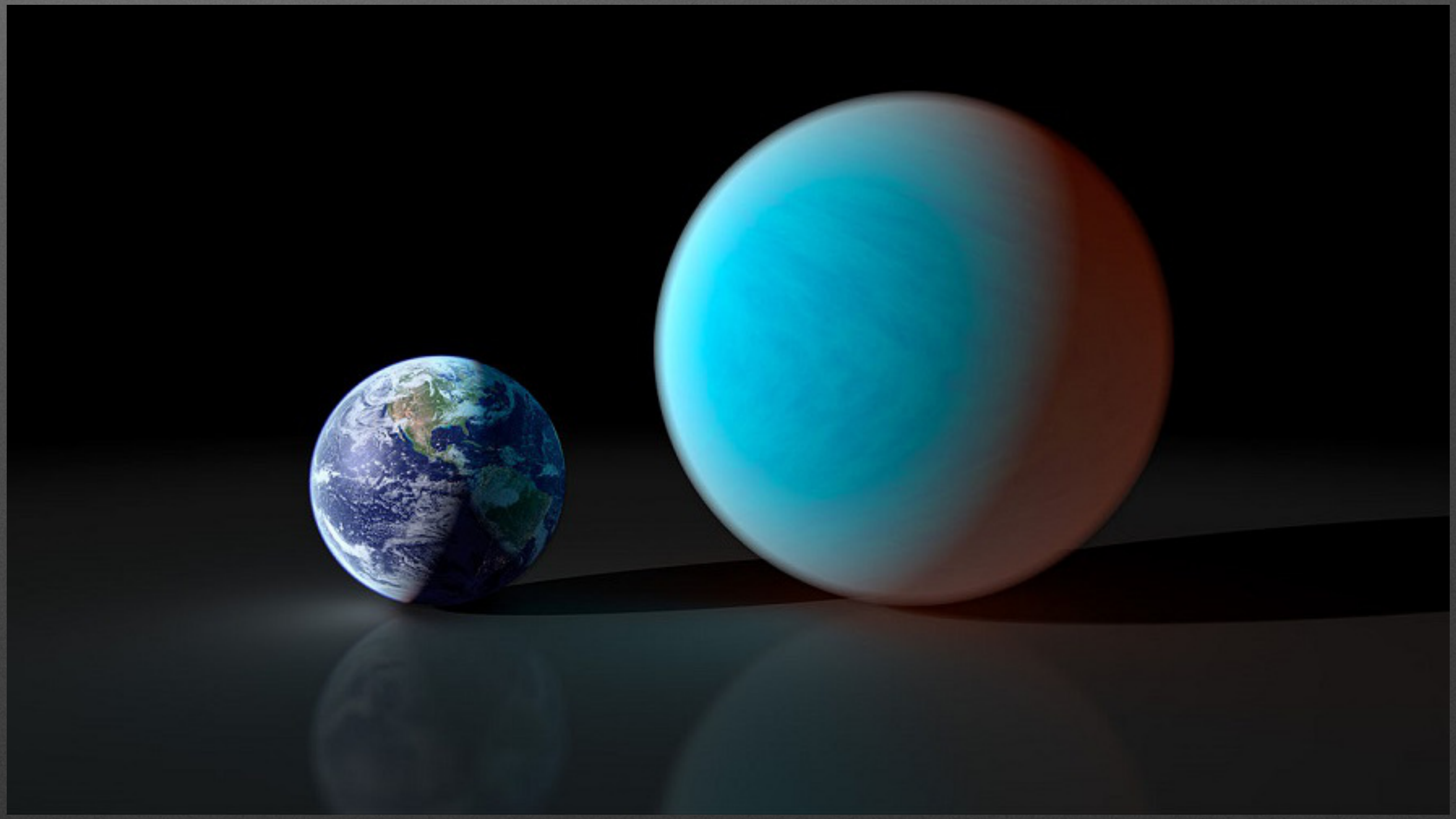


Madhusudhan et al. (2023)

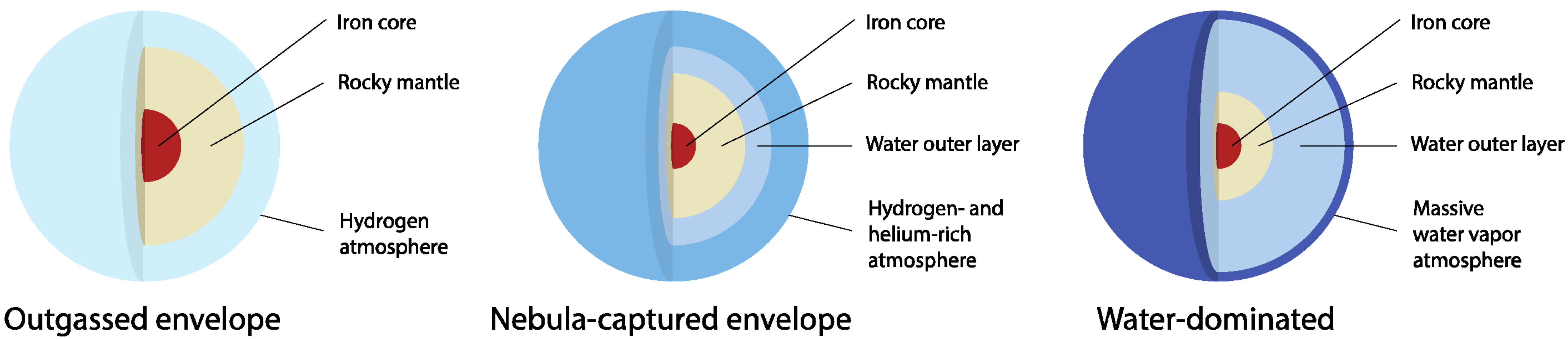
- Radius 2.6 R⊕   Mass 8.6 M⊕

So What Is a Sub-Neptune?

- Radius between 1.7-4.0 $R_\oplus$
- Has a volatile-rich envelope (H/He and/or water)
- Structurally distinct from rocky super-Earths
- Shaped by formation location, gas accretion, and atmospheric loss
- Confirmed by both bulk density and now atmospheric composition



What We Still Don't Know



Seager et al. 2021

- What fraction are water-rich vs. gas-dwarfs?
- Do sub-Neptunes ever host liquid oceans?
- Nature vs. Nurture
- Why does our Solar System lack one?

Summary

- Sub-Neptunes are the most common planets in the galaxy
- The Radius Gap divides two physically distinct populations
- Atmosphere retention/loss is key to their identity
- JWST is just beginning to peel back the haze and measure atmospheric compositions