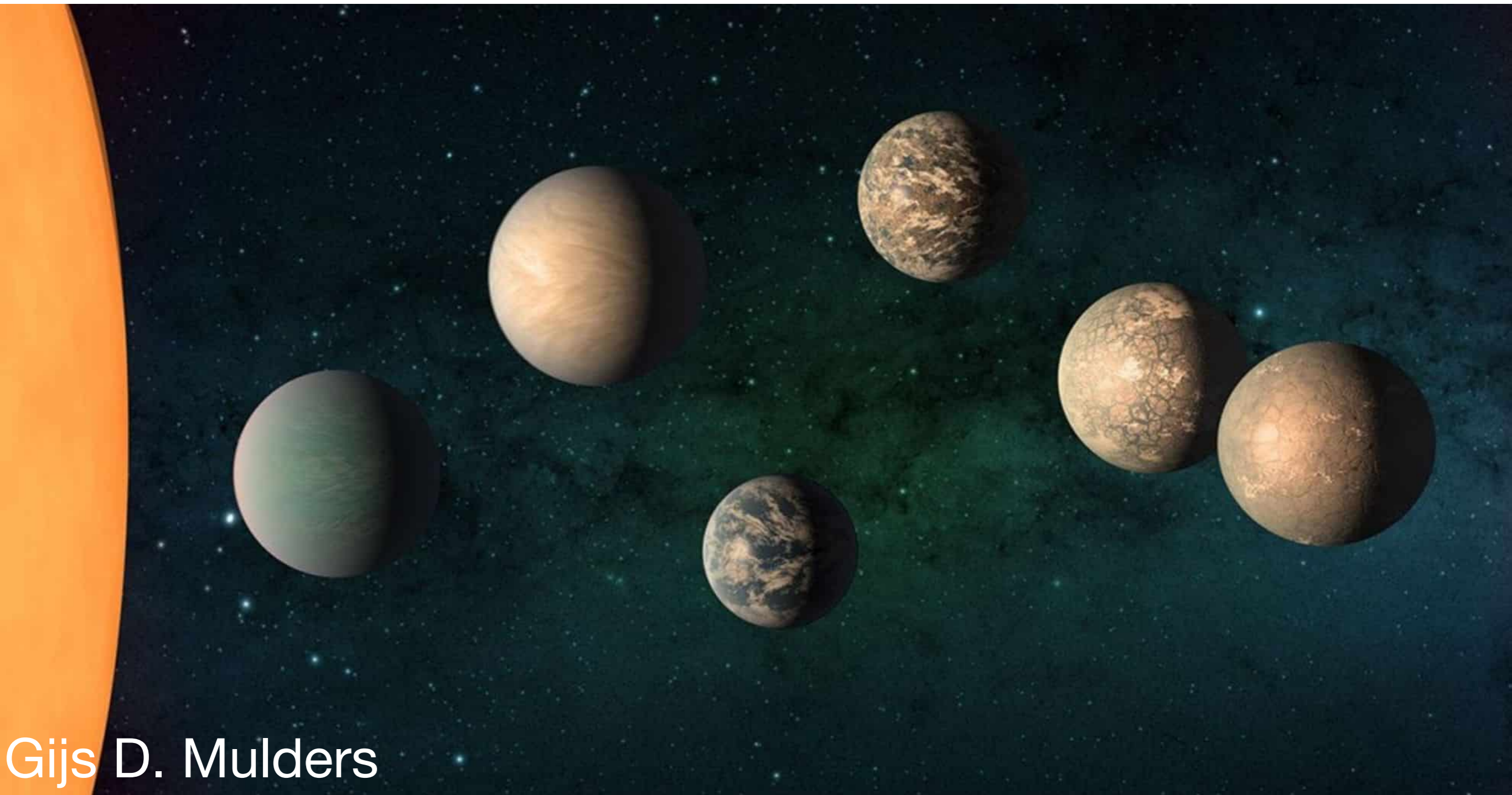


# Demographics of sub-Neptunes at Short Orbital Periods, and out to the Habitable Zone



Gijs D. Mulders

Assistant Professor  
Pontificia Universidad Católica De Chile  
[gijs.mulders@uc.cl](mailto:gijs.mulders@uc.cl)



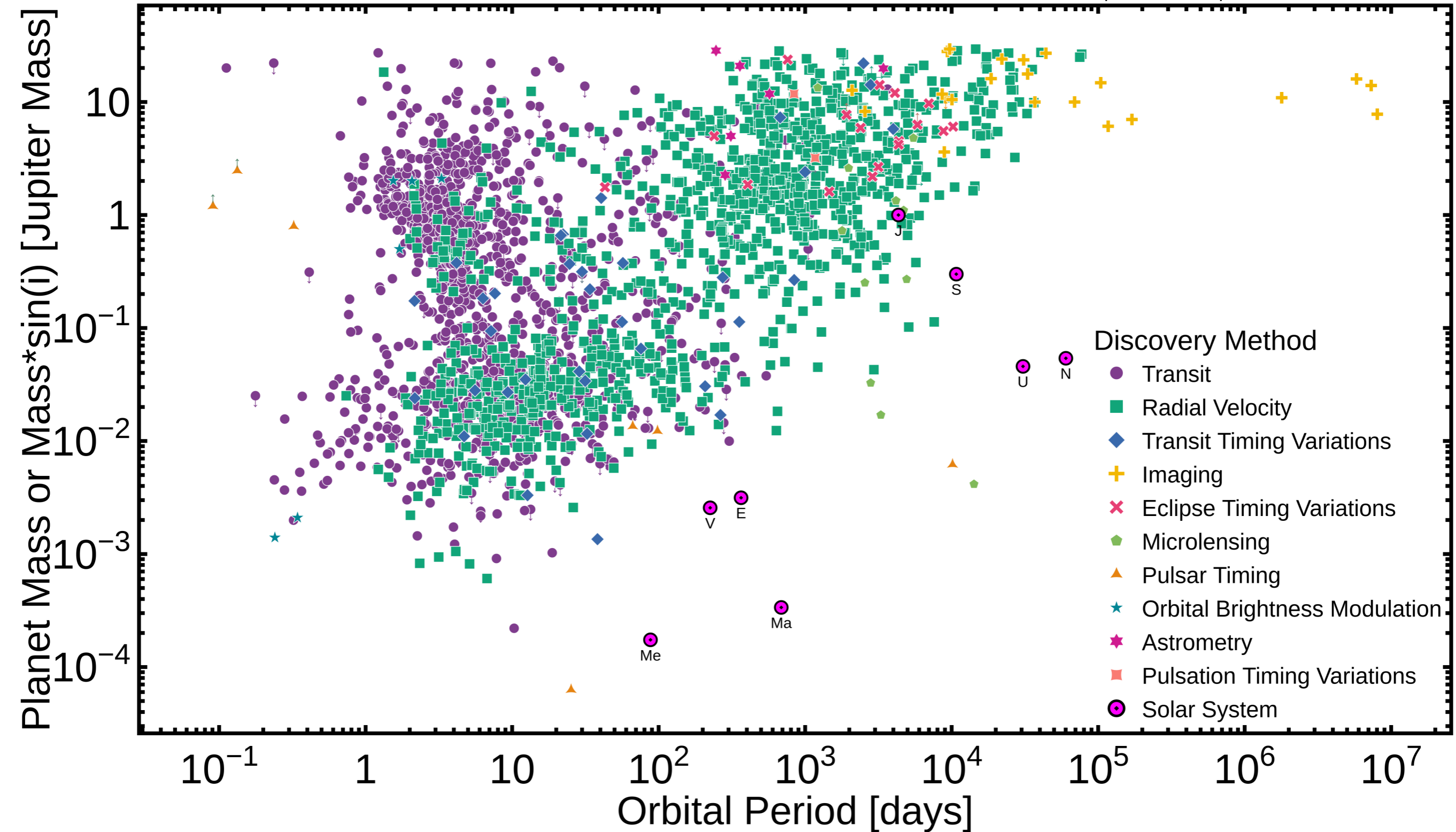
PONTIFICIA  
UNIVERSIDAD  
CATÓLICA  
DE CHILE



# Exoplanets: a diverse population

Planet Mass or Mass\* $\sin(i)$  vs Orbital Period

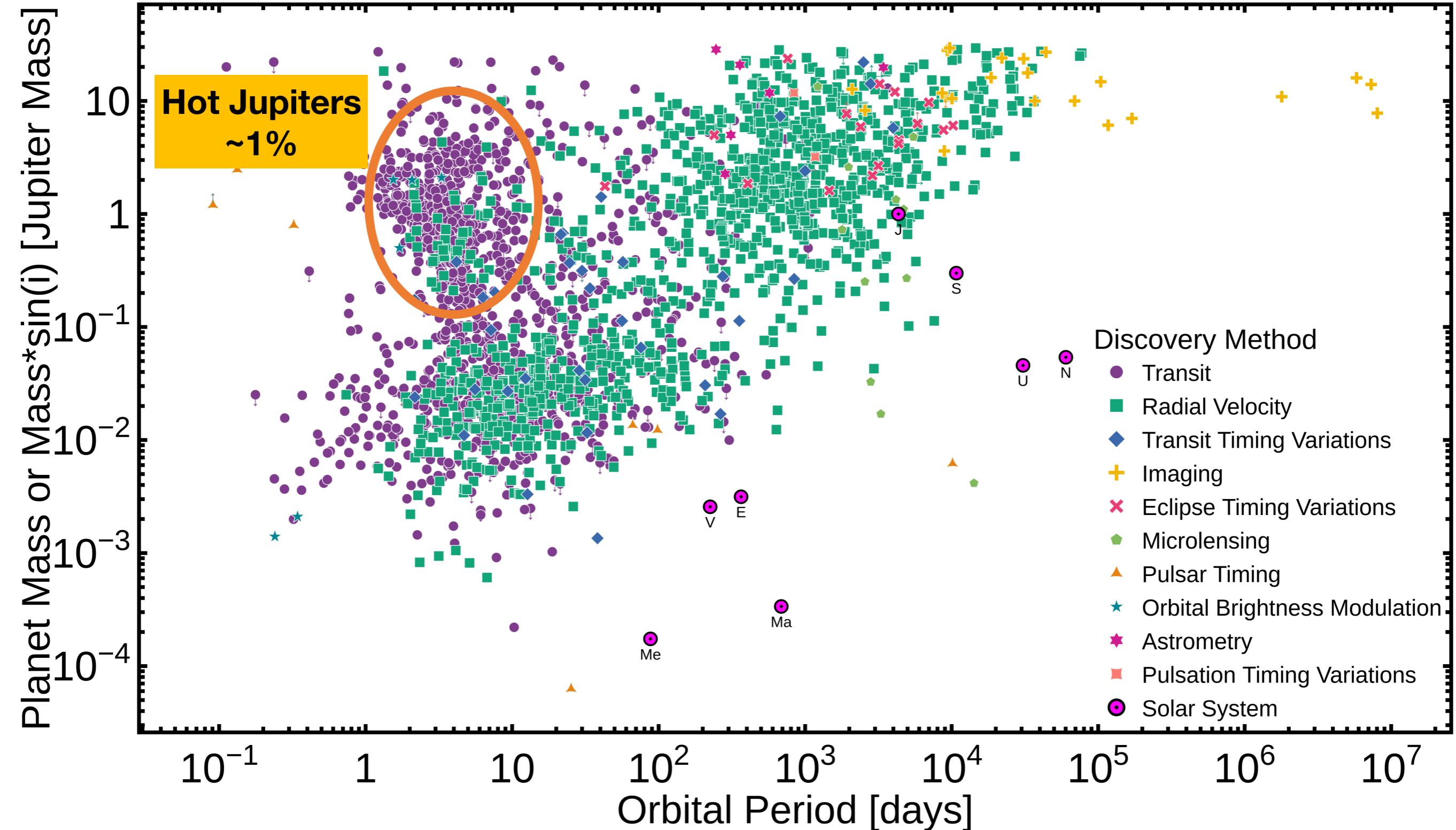
*exoplanetarchive.ipac.caltech.edu, 2026-01-22*



# Exoplanets: a diverse population

Planet Mass or Mass\* $\sin(i)$  vs Orbital Period

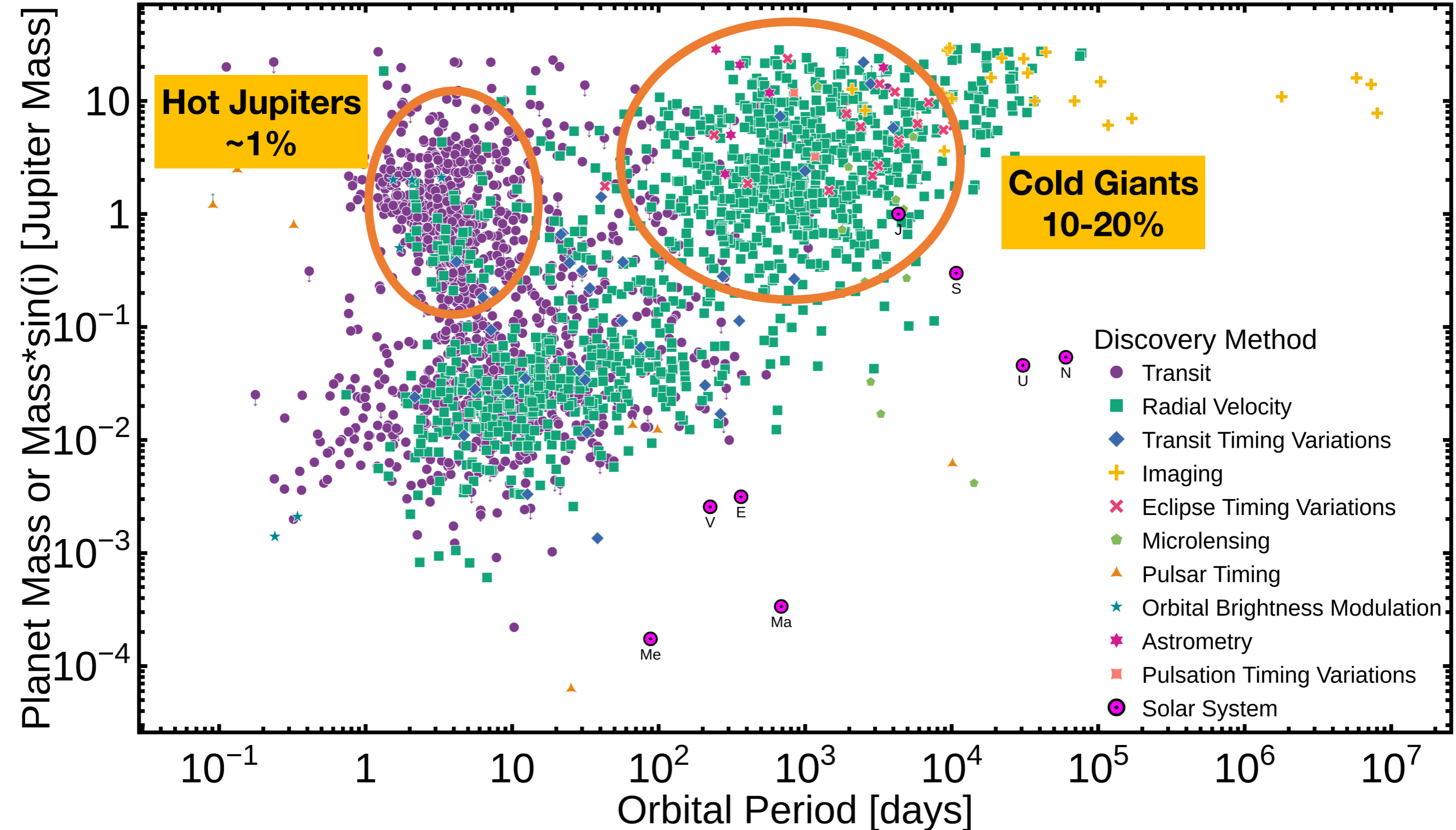
*exoplanetarchive.ipac.caltech.edu, 2026-01-22*



# Exoplanets: a diverse population

Planet Mass or Mass\* $\sin(i)$  vs Orbital Period

*exoplanetarchive.ipac.caltech.edu, 2026-01-22*



**Hot Jupiters**  
~1%

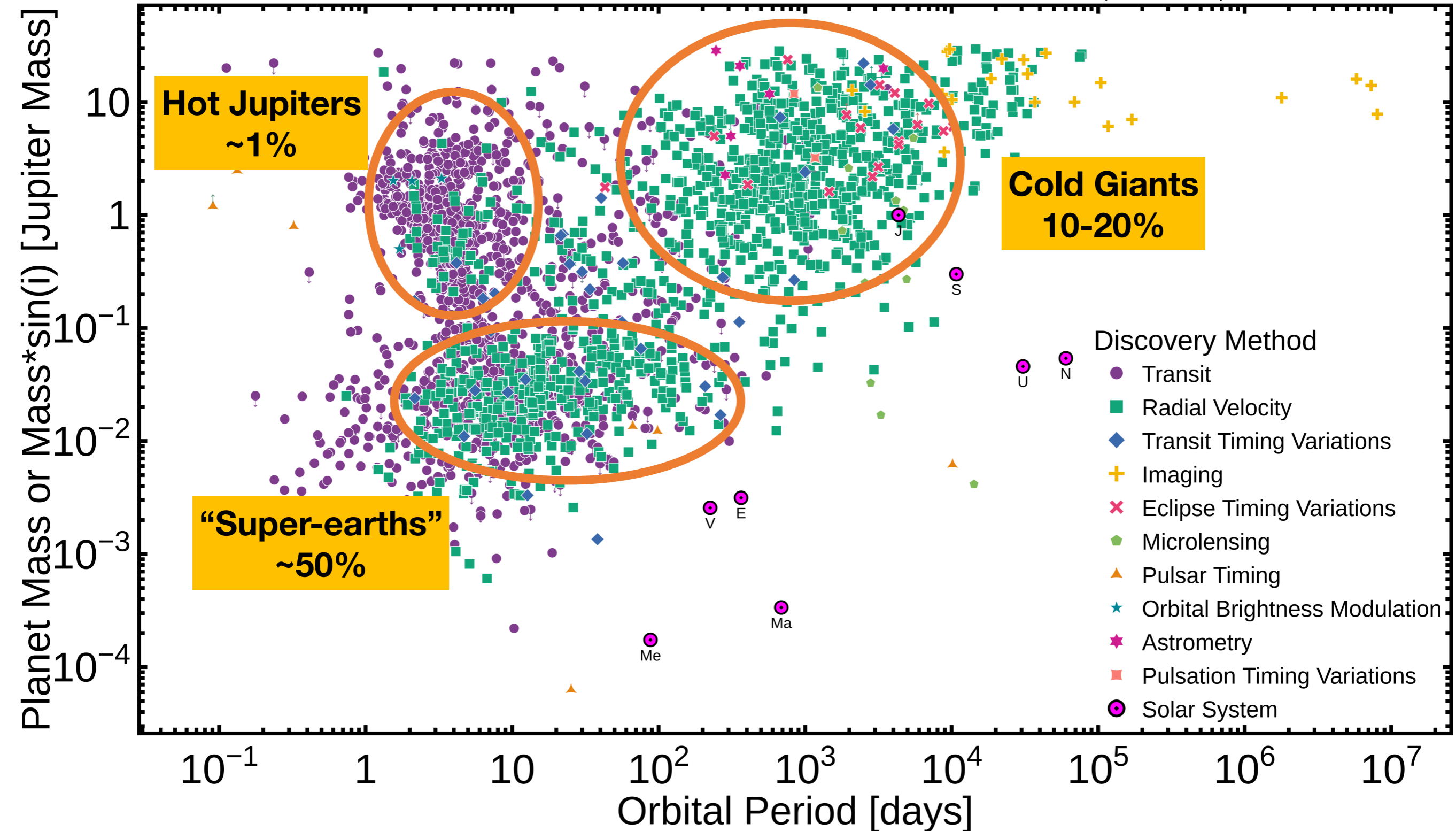
**Cold Giants**  
10-20%

- Discovery Method
- Transit
  - Radial Velocity
  - Transit Timing Variations
  - Imaging
  - Eclipse Timing Variations
  - Microlensing
  - Pulsar Timing
  - Orbital Brightness Modulation
  - Astrometry
  - Pulsation Timing Variations
  - Solar System

# Exoplanets: a diverse population

Planet Mass or Mass\* $\sin(i)$  vs Orbital Period

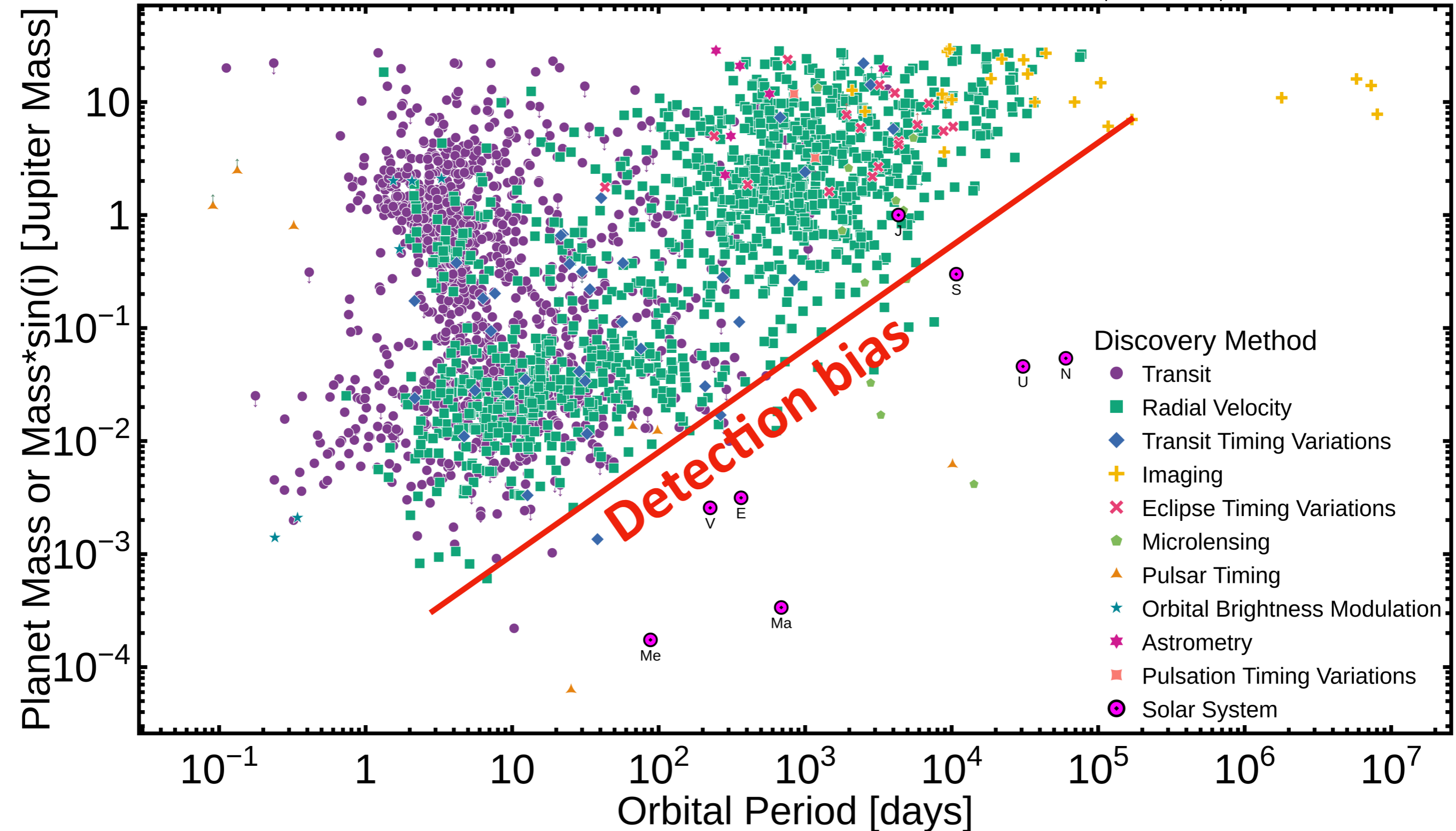
*exoplanetarchive.ipac.caltech.edu, 2026-01-22*



# Exoplanets: a diverse population

Planet Mass or Mass\* $\sin(i)$  vs Orbital Period

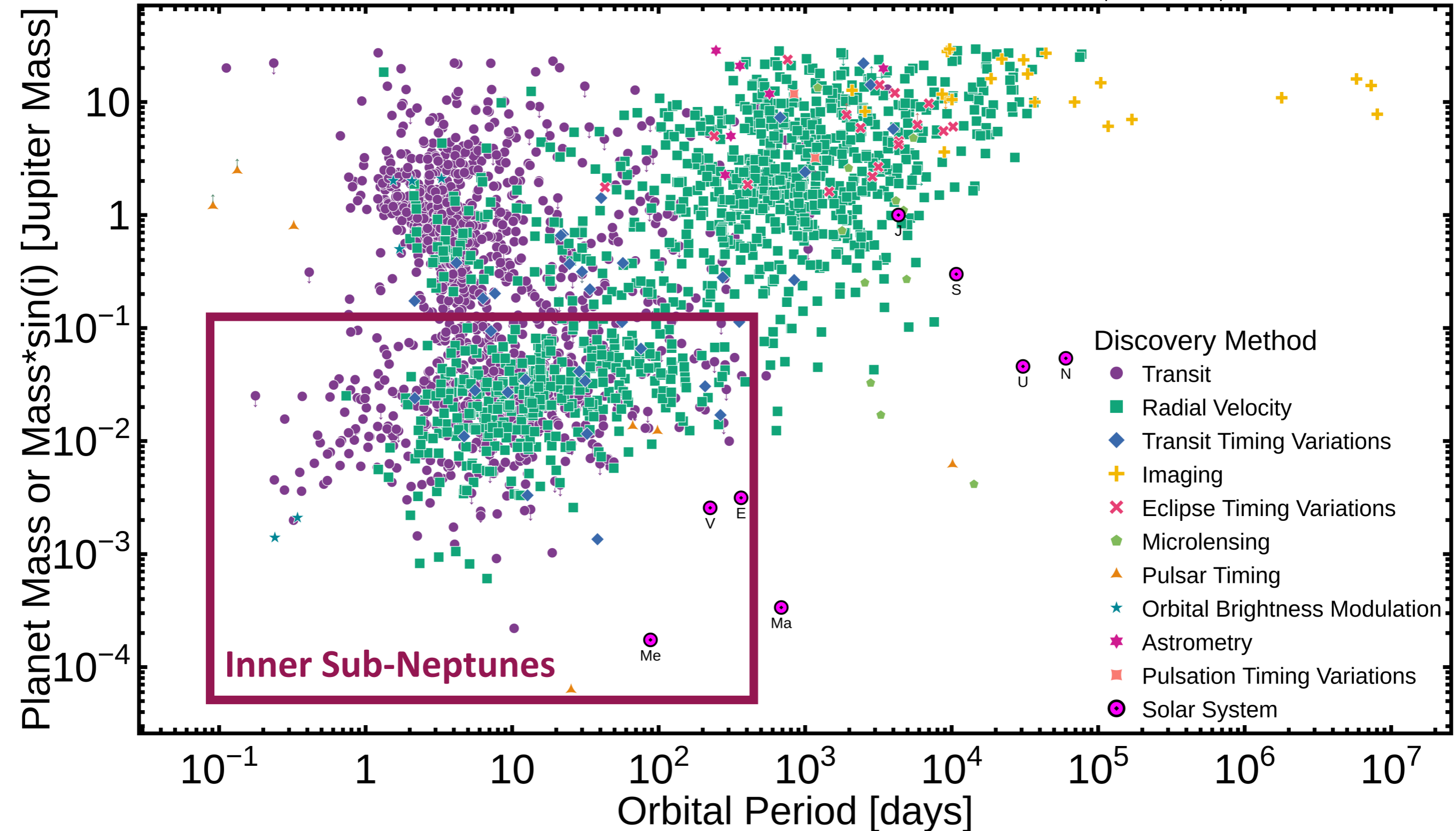
*exoplanetarchive.ipac.caltech.edu, 2026-01-22*



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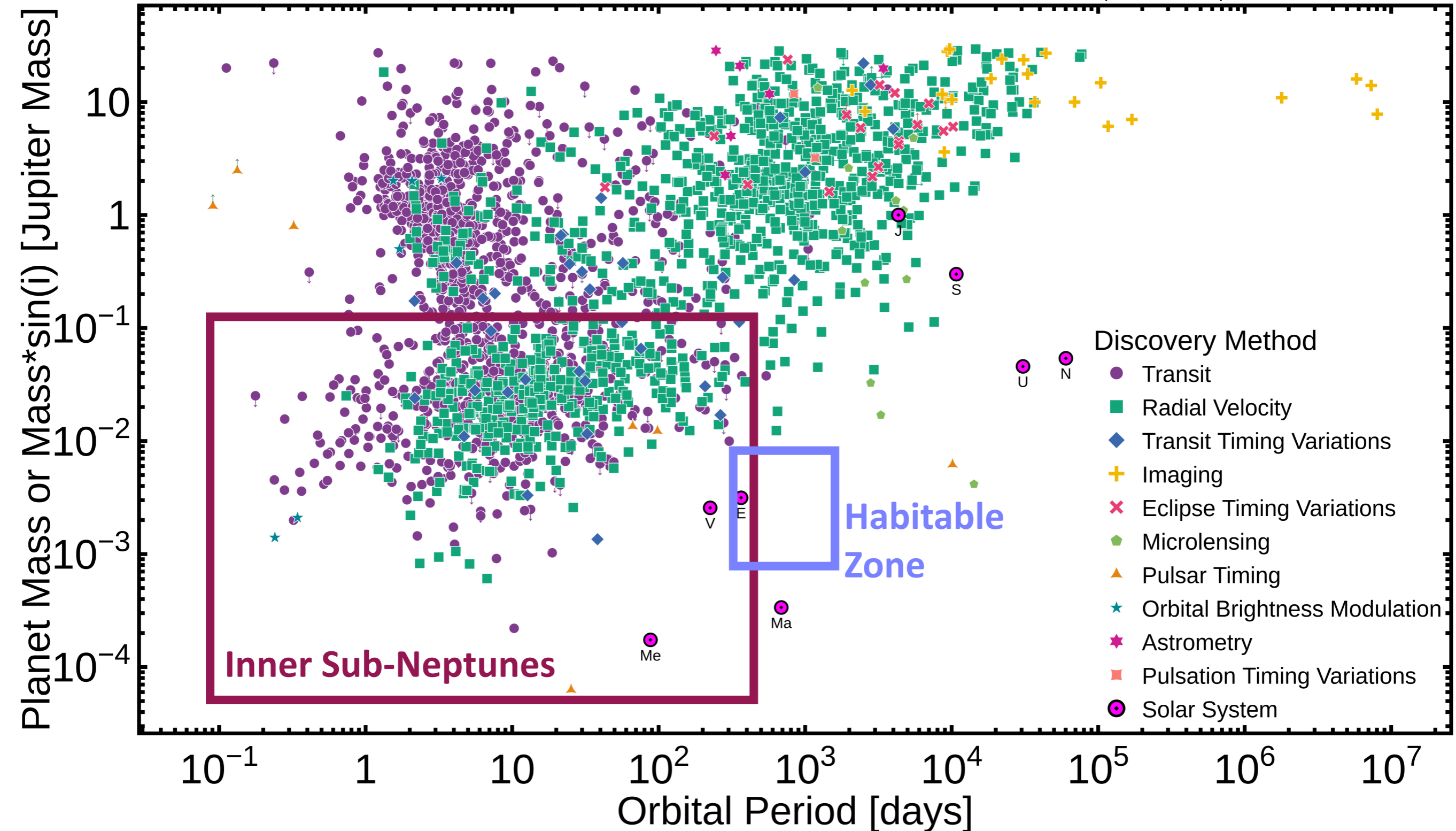
*exoplanetarchive.ipac.caltech.edu, 2026-01-22*



# Exoplanets: a diverse population

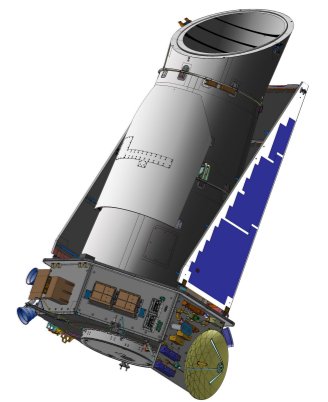
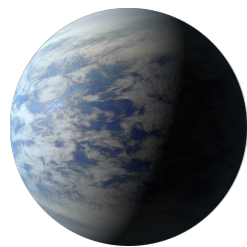
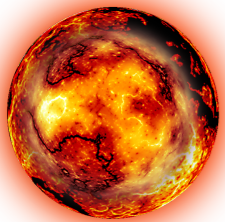
Planet Mass or Mass\* $\sin(i)$  vs Orbital Period

*exoplanetarchive.ipac.caltech.edu, 2026-01-22*

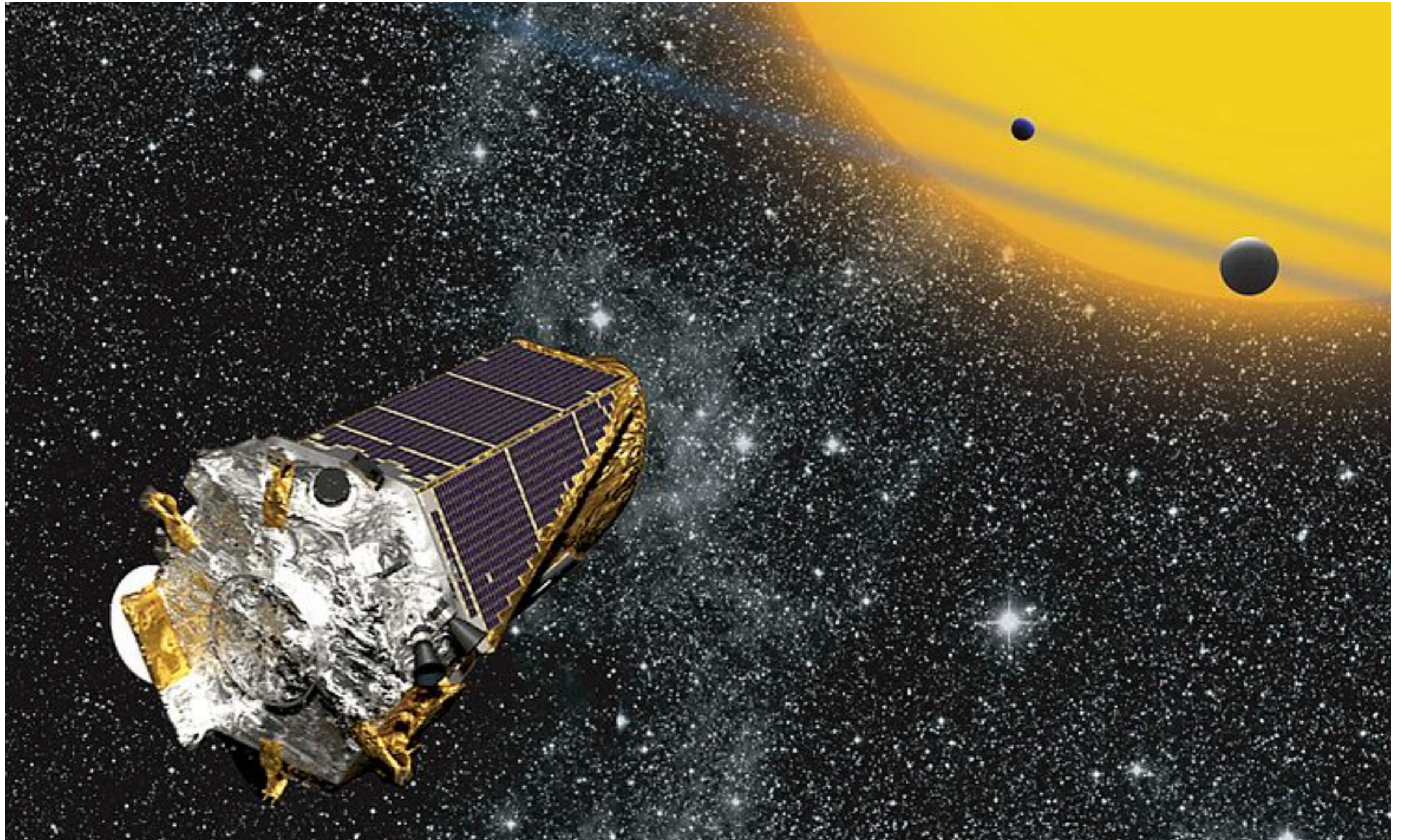


# Transiting Sub-Neptunes

(super-Earths / mini-Neptunes)

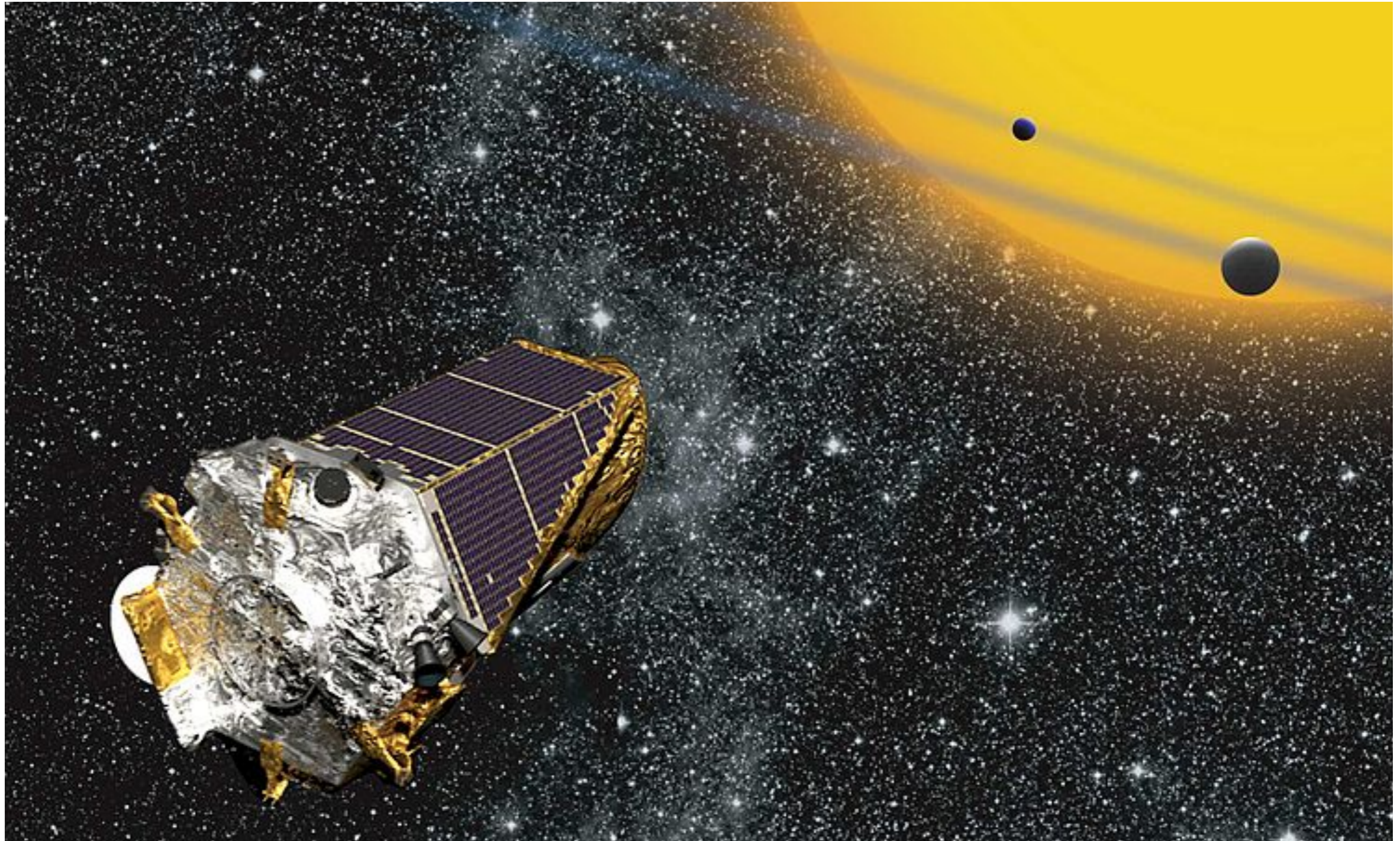


# Kepler Transit Survey



**Homogenous survey of ~200.000 stars**

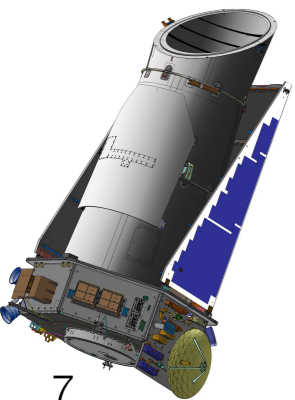
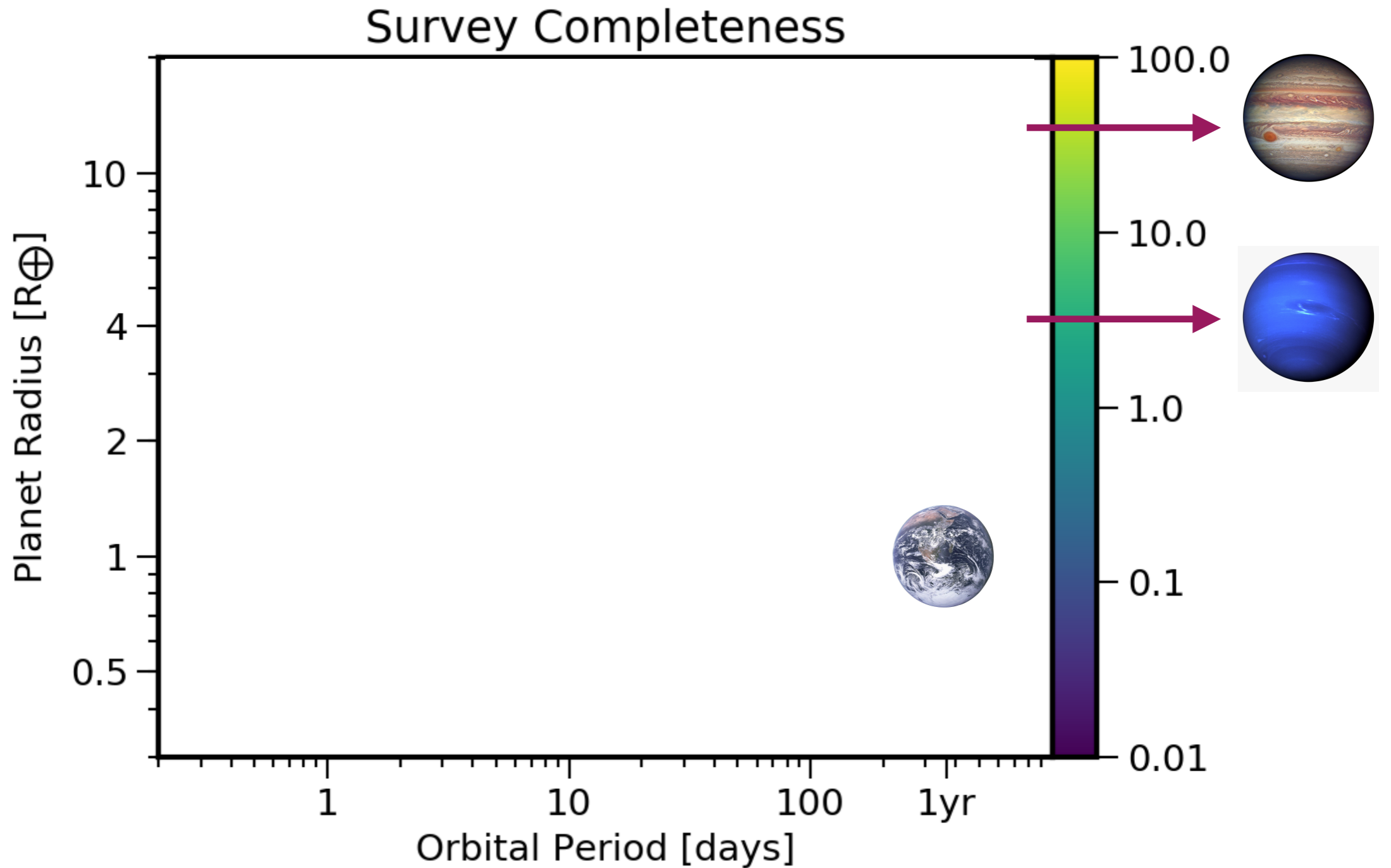
# Kepler Transit Survey



**Homogenous survey of ~200.000 stars**

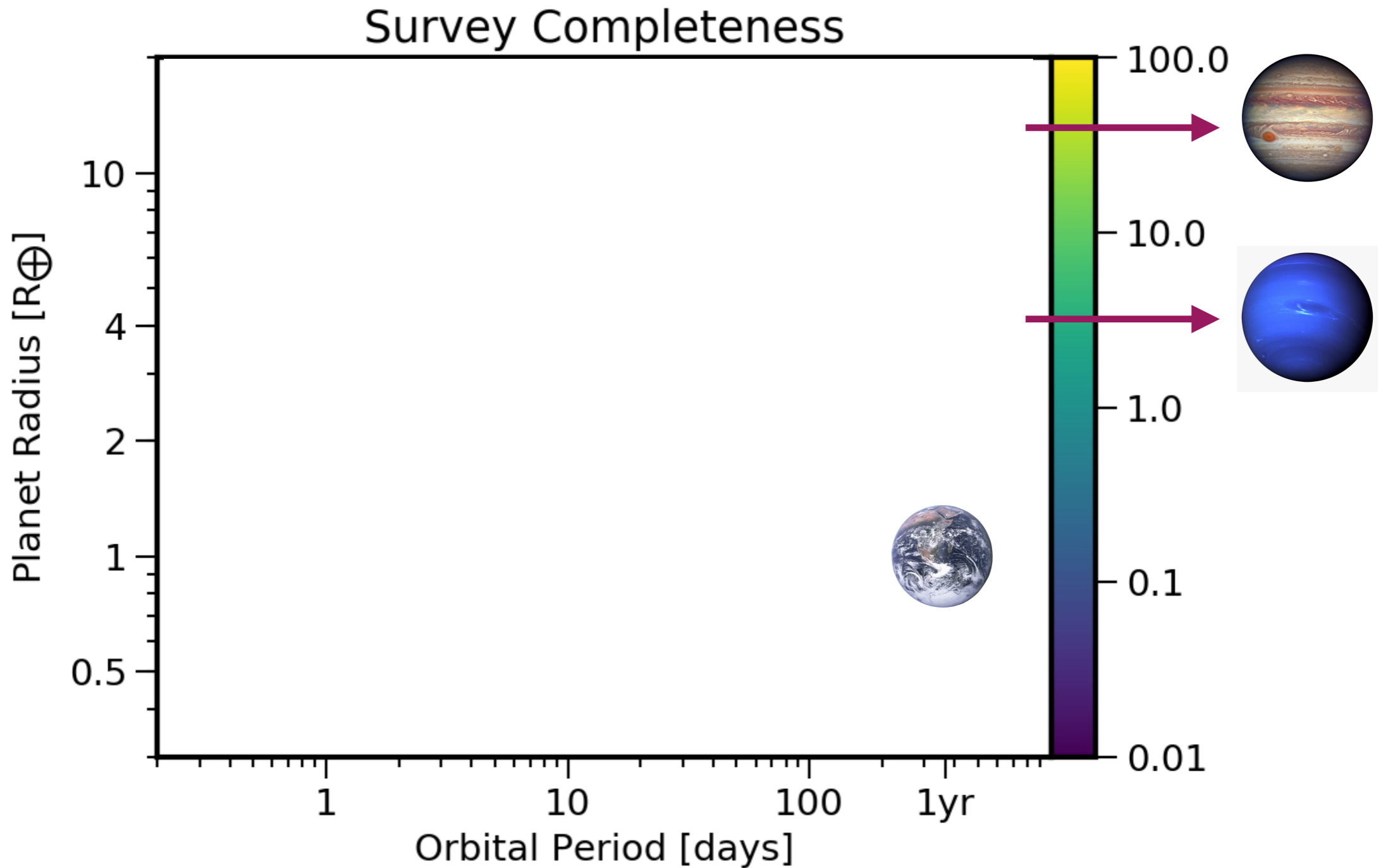
Goal: Measure Frequency of Earth-size planets  
in Habitable Zone of sun-like stars

# Kepler Exoplanets



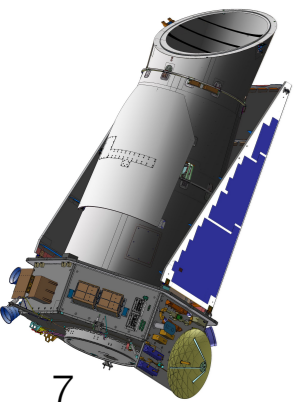
Data from: Thompson+ 2018, Berger+2019

# Kepler Exoplanets

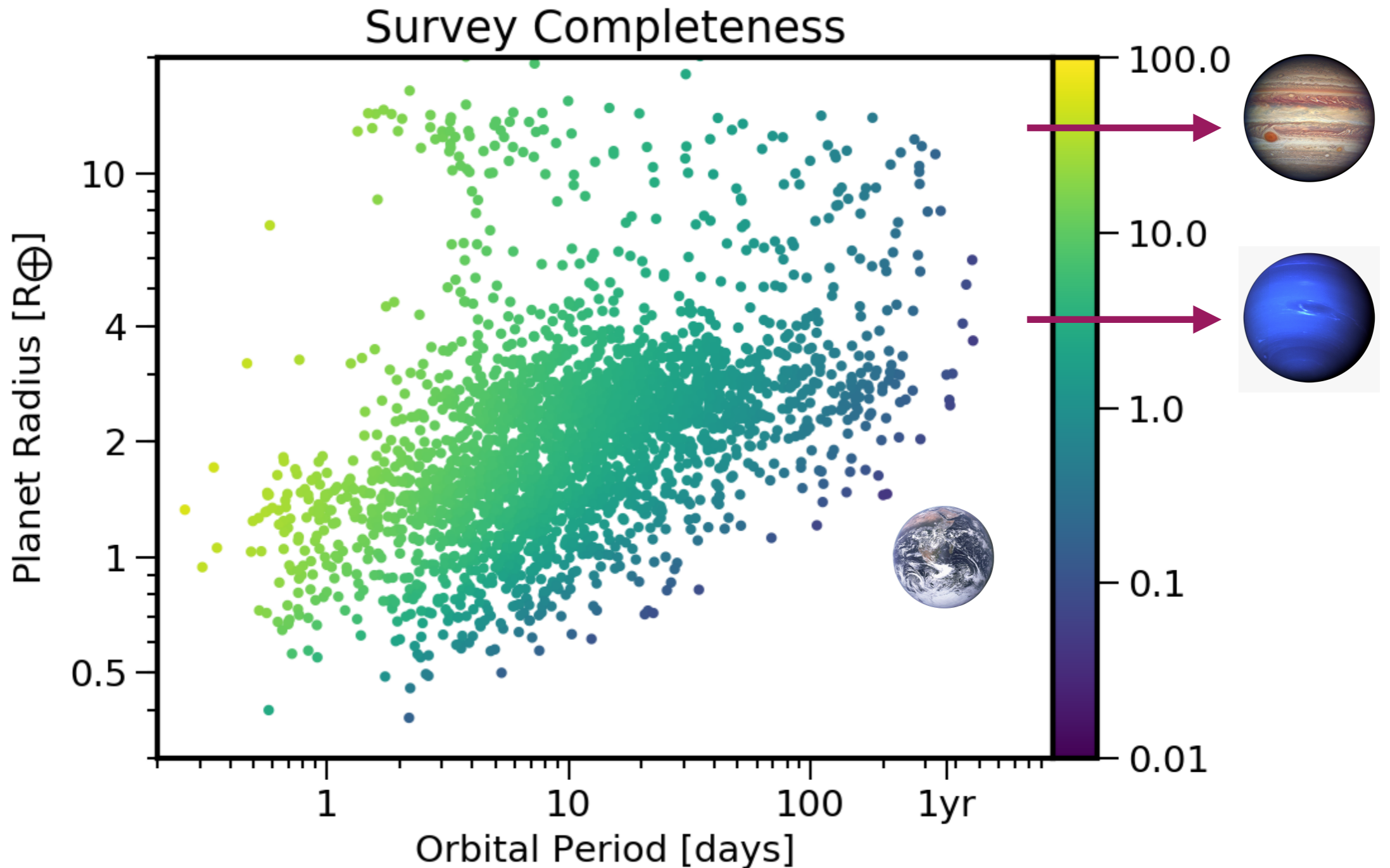


**Transit Probability ~1-10%**

Data from: Thompson+ 2018, Berger+2019



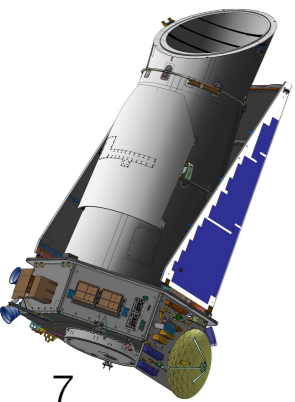
# Kepler Exoplanets



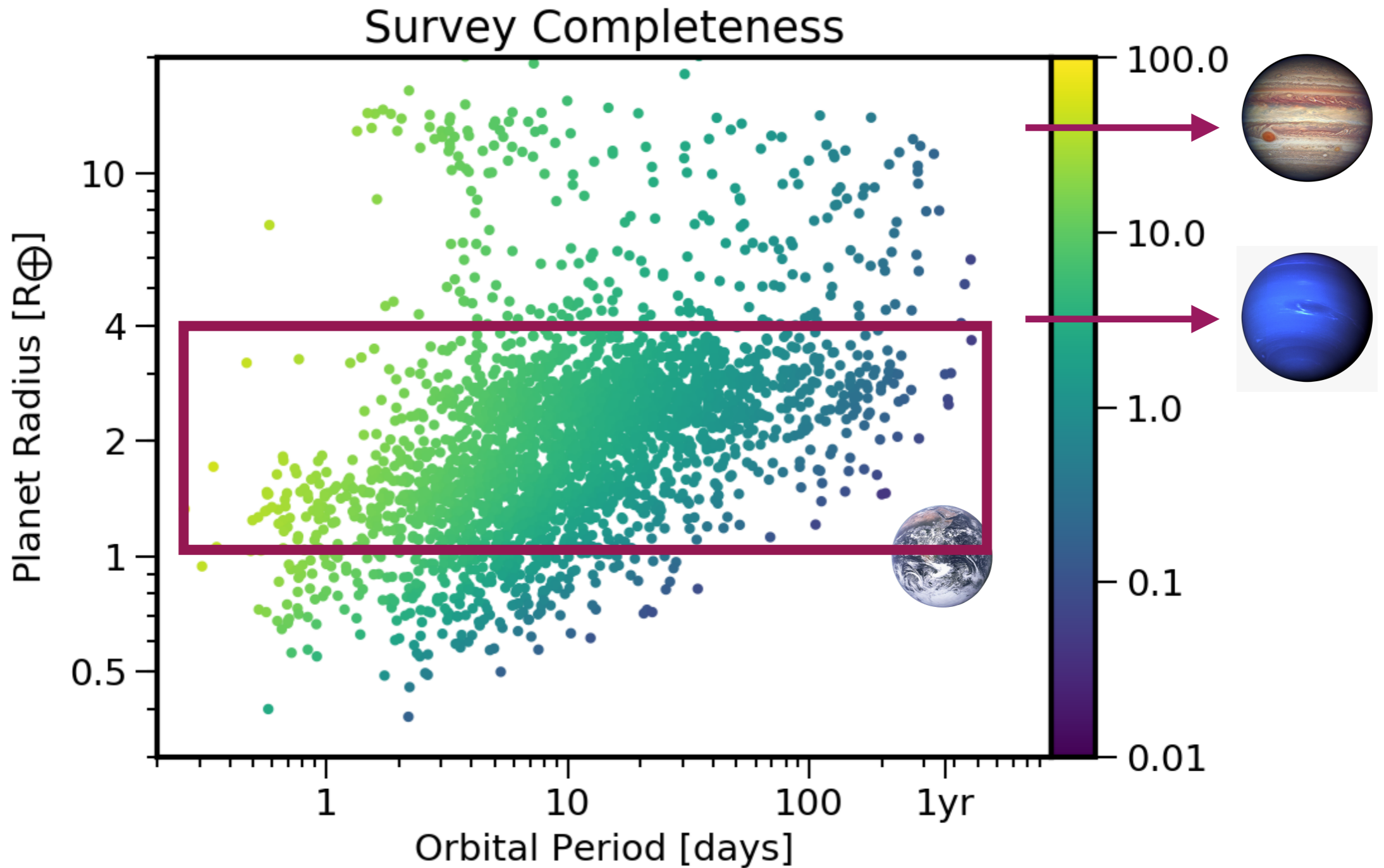
**Transit Probability ~1-10%**

**~4000 planet candidates**

Data from: Thompson+ 2018, Berger+2019

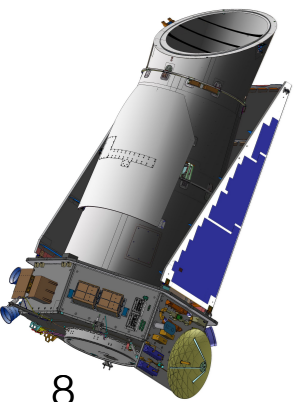


# Kepler Exoplanets

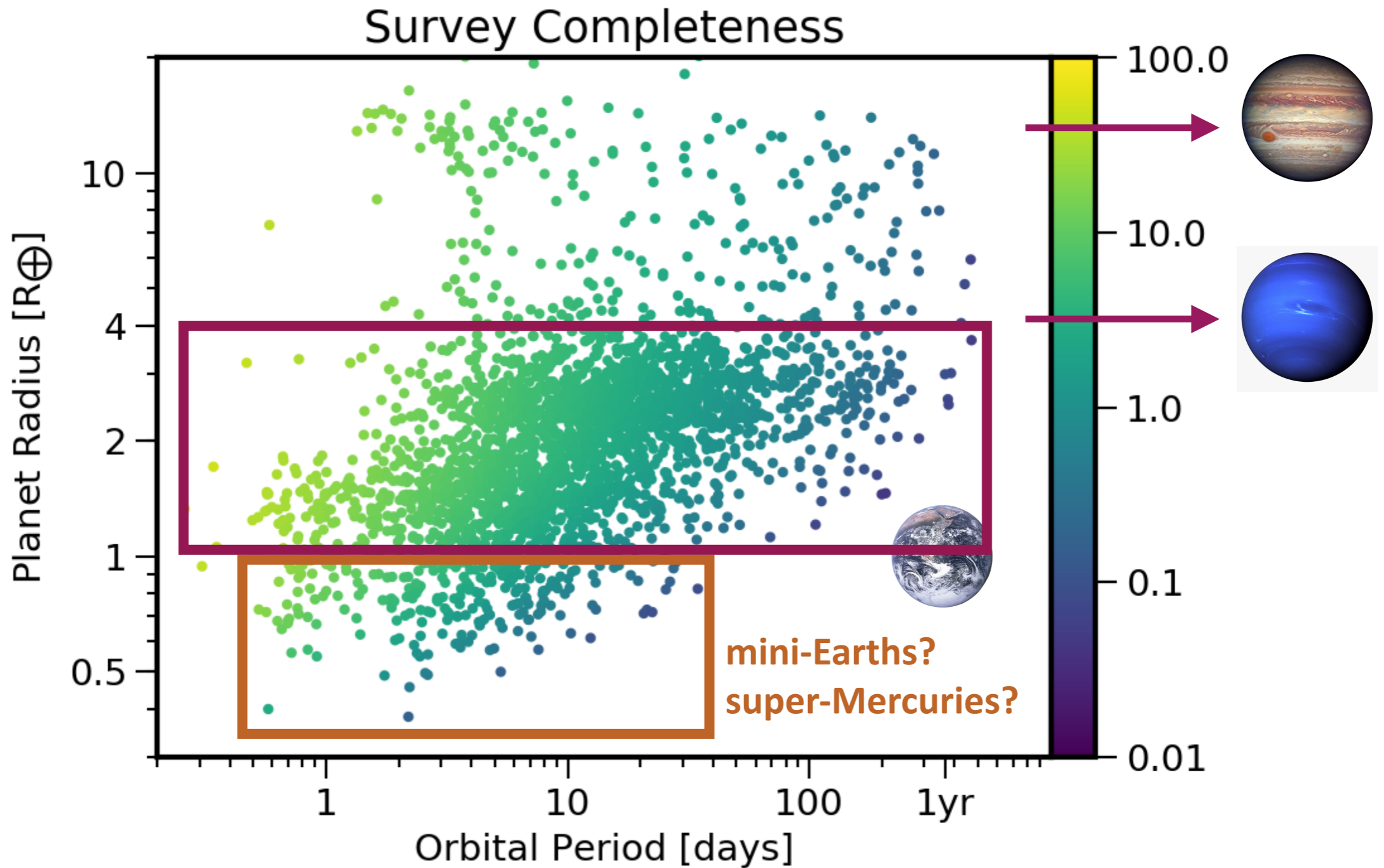


**Super-Earths or mini-Neptunes (1-4  $R_E$ )**

Data from: Thompson+ 2018, Berger+2019

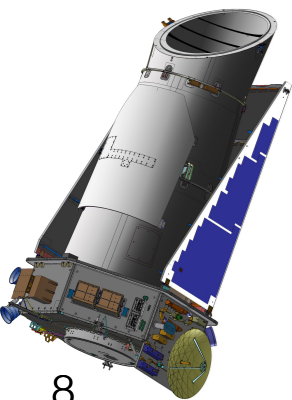


# Kepler Exoplanets

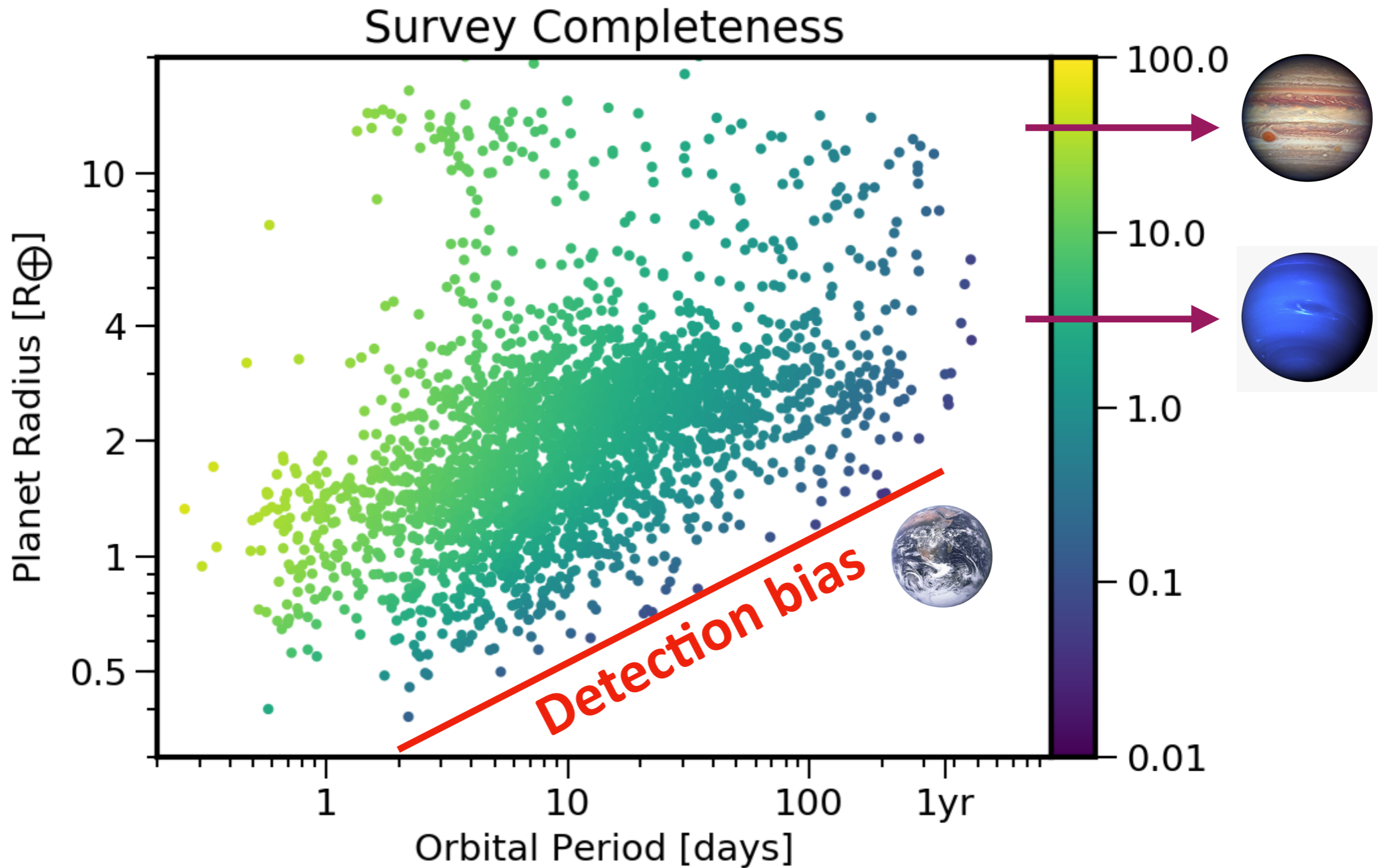


**Super-Earths or mini-Neptunes (1-4  $R_E$ )**

Data from: Thompson+ 2018, Berger+2019

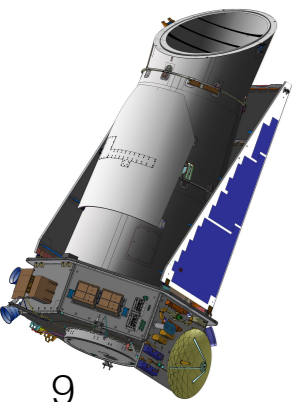


# Kepler Exoplanets



**Super-Earths or mini-Neptunes (1-4  $R_E$ )**

Data from: Thompson+ 2018, Berger+2019



# How many sub-Neptunes are there?

(Planet occurrence rate calculation)

# How many sub-Neptunes are there?

Accounting for detection bias:

Completeness correction

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$$f = \frac{N_{\text{planets}}}{N_{\text{stars}}}$$

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Accounting for detection bias:

Completeness correction

Planet Occurrence Rate:

$$f = \frac{N_{\text{planets}}}{N_{\text{stars}}} \frac{1}{\text{Completeness}}$$

# How many sub-Neptunes are there?

Accounting for detection bias:

Completeness correction

Planet Occurrence Rate:

$$f = \frac{N_{\text{planets}}}{N_{\text{stars}}} \frac{1}{\text{Completeness}}$$

Geometric Factor  
(transit probability)



# How many sub-Neptunes are there?

Accounting for detection bias:

Completeness correction

Planet Occurrence Rate:

$$f = \frac{N_{\text{planets}}}{N_{\text{stars}}} \frac{1}{\text{Completeness}}$$



Geometric Factor  
(transit probability)

Planet Size Factor  
(detection efficiency)

# How many sub-Neptunes are there?

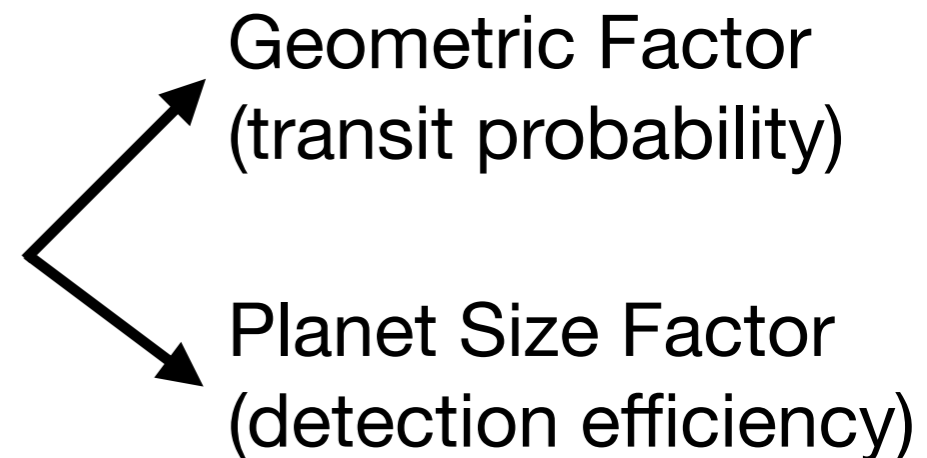
Accounting for detection bias:

Completeness correction

Planet Occurrence Rate:

$$f = \frac{N_{\text{planets}}}{N_{\text{stars}}} \frac{1}{\text{Completeness}}$$

$$f = \frac{N_{\text{planets}}}{N_{\text{stars}}} \frac{1}{C(P, R_P)}$$



# How many sub-Neptunes are there?

Accounting for detection bias:

Completeness correction

Planet Occurrence Rate:

$$f = \frac{N_{\text{planets}}}{N_{\text{stars}}} \frac{1}{\text{Completeness}}$$

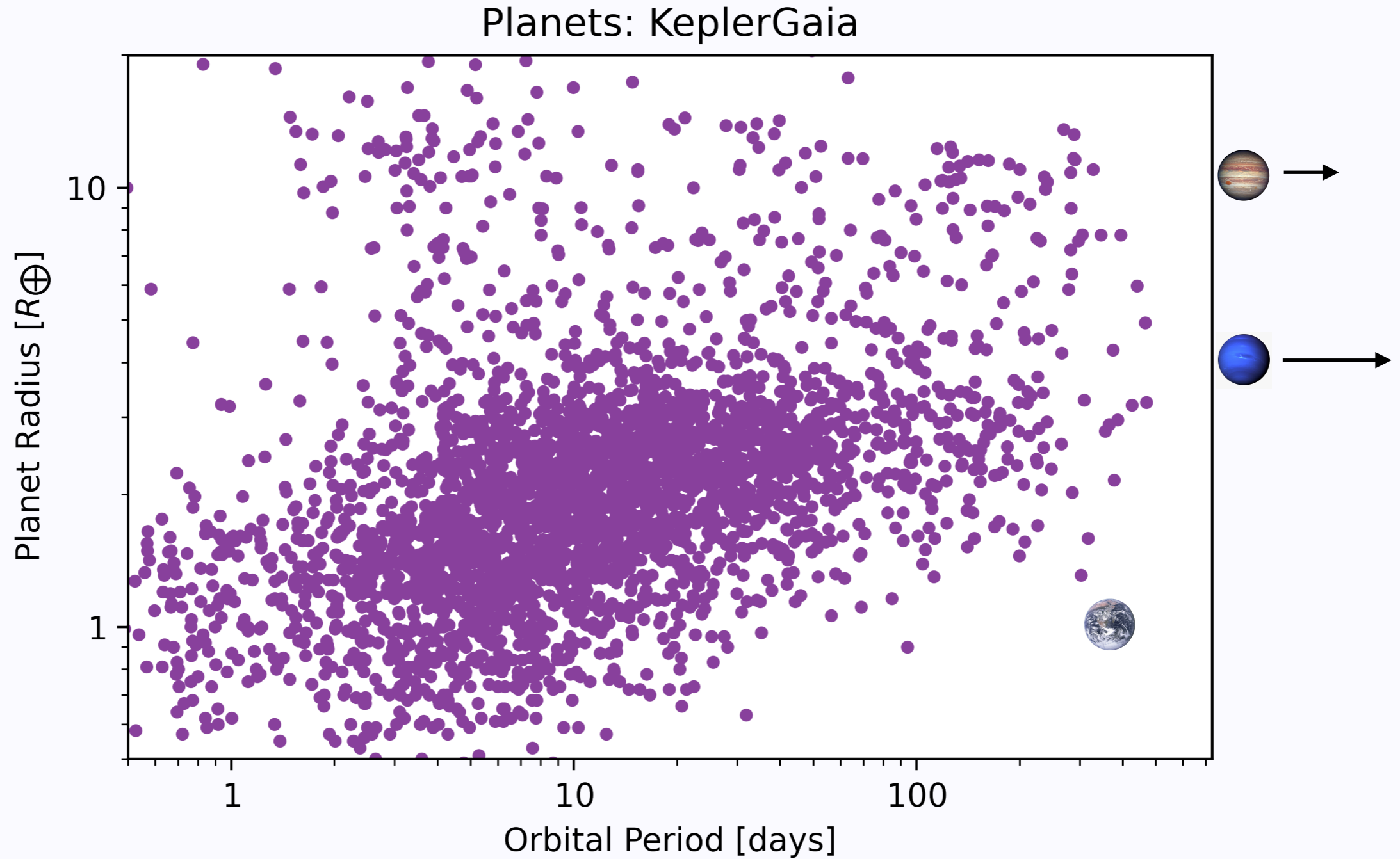
Geometric Factor  
(transit probability)

Planet Size Factor  
(detection efficiency)

$$f = \frac{N_{\text{planets}}}{N_{\text{stars}}} \frac{1}{C(P, R_P)}$$

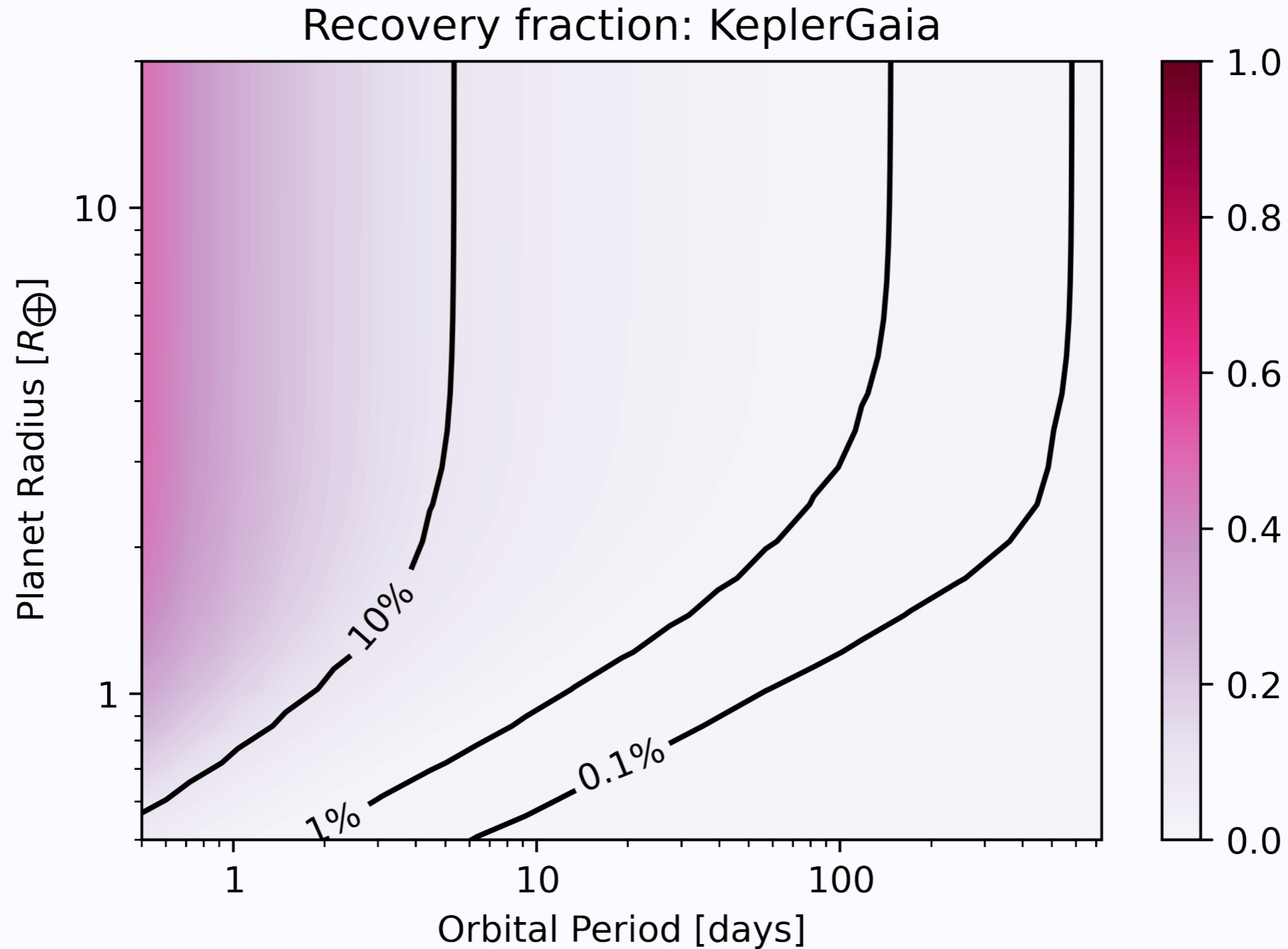
Period and radius  
dependence

# 1. Kepler Planet Occurrence Rate



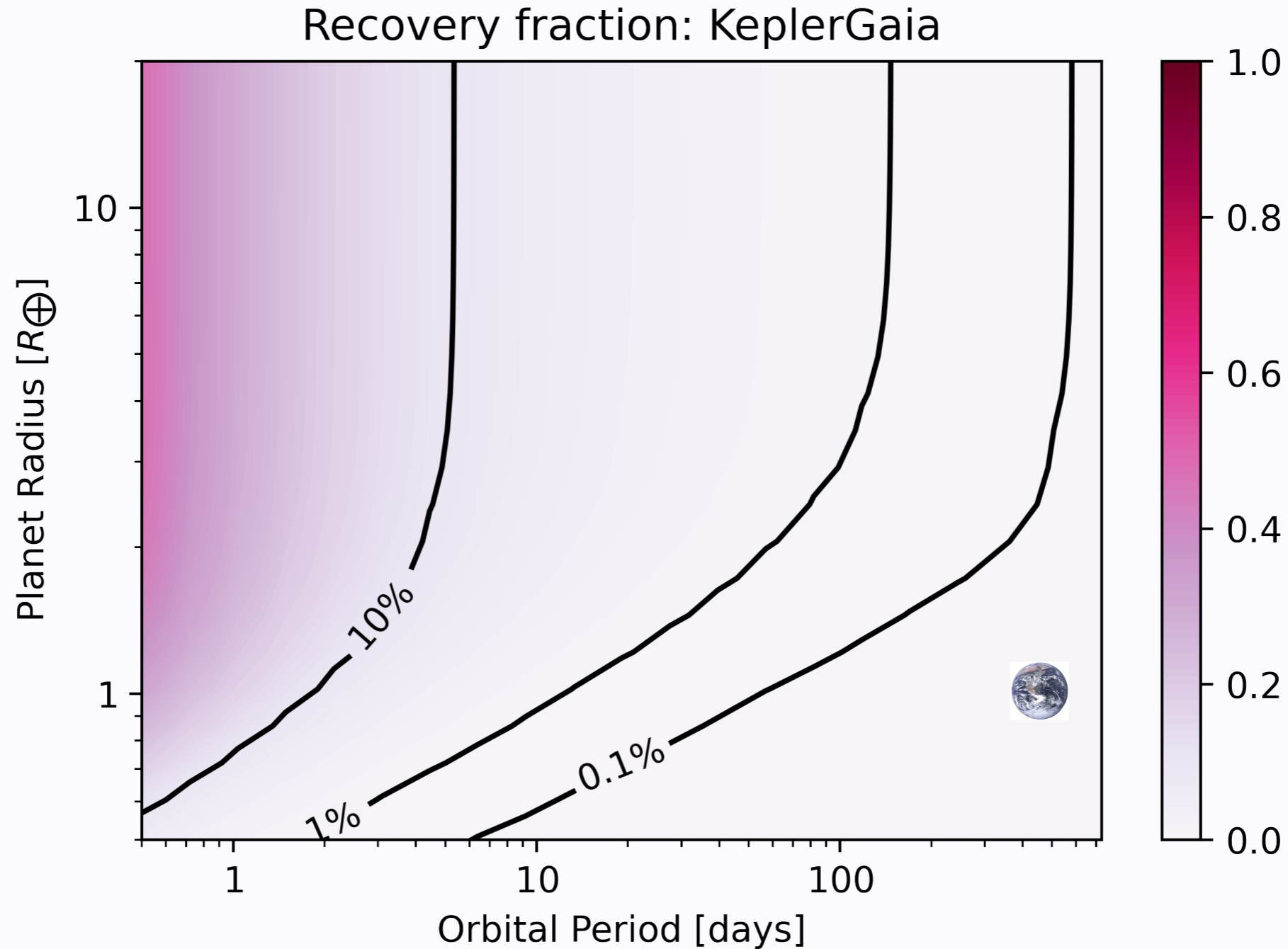
Kepler Planet Candidates (DR25)

# 1. Kepler Planet Occurrence Rate



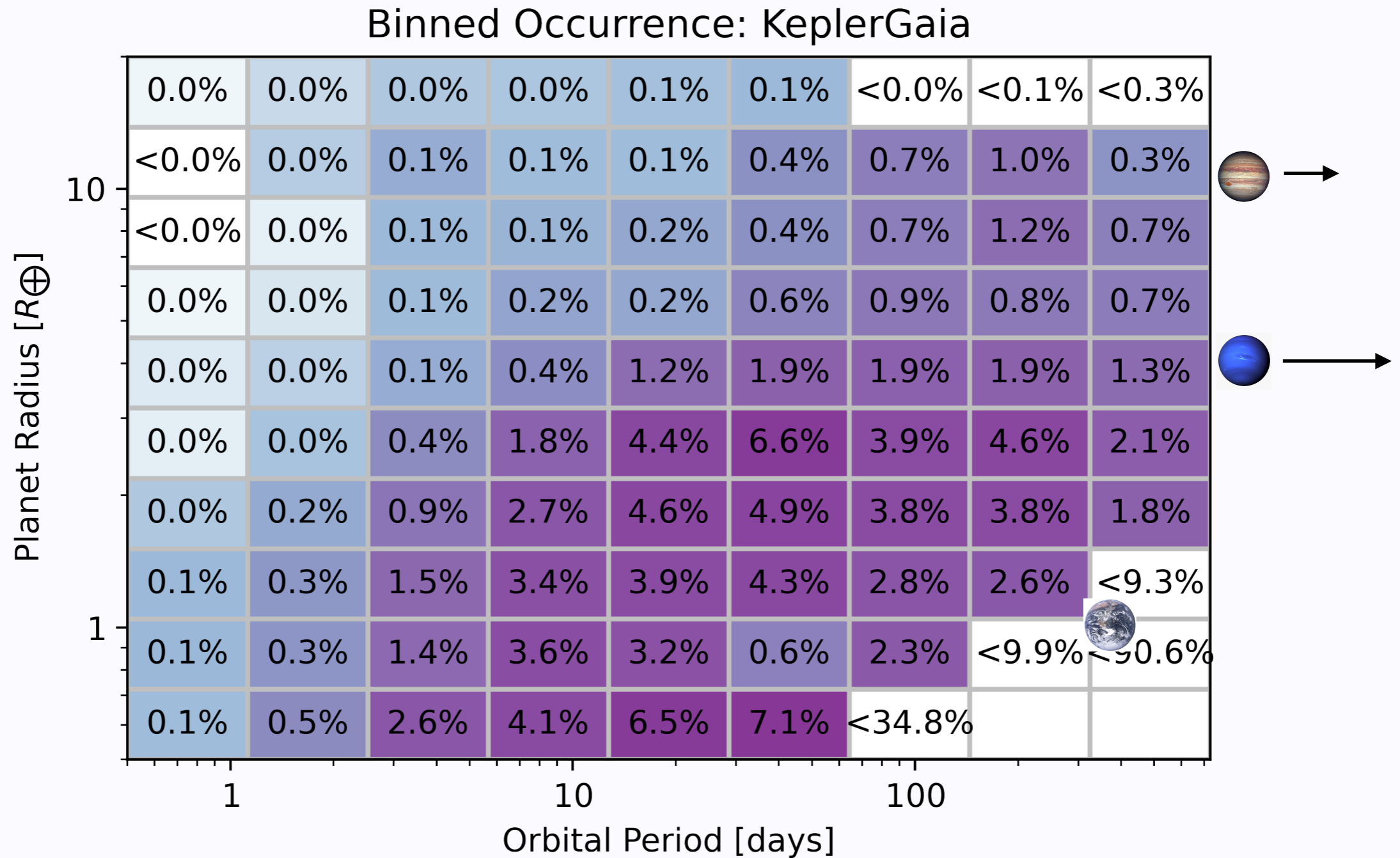
Survey Completeness:  $C(P, R_p)$   
Detection Efficiency + Transit Probability

# 1. Kepler Planet Occurrence Rate



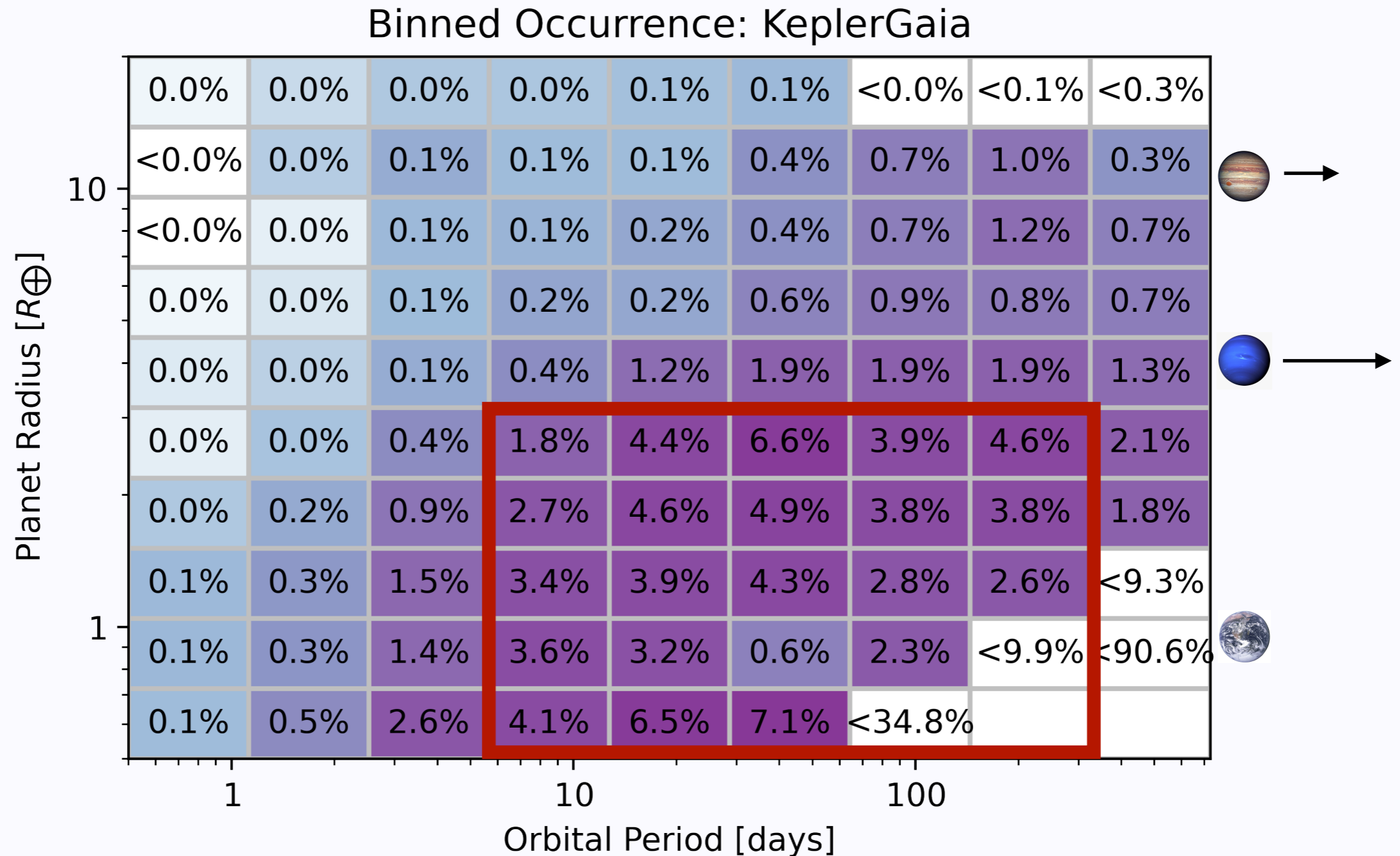
Survey Completeness:  $C(P, R_p)$   
Detection Efficiency + Transit Probability

# 1. Kepler Planet Occurrence Rate



>1.16 Planets per star on average

# 1. Kepler Planet Occurrence Rate



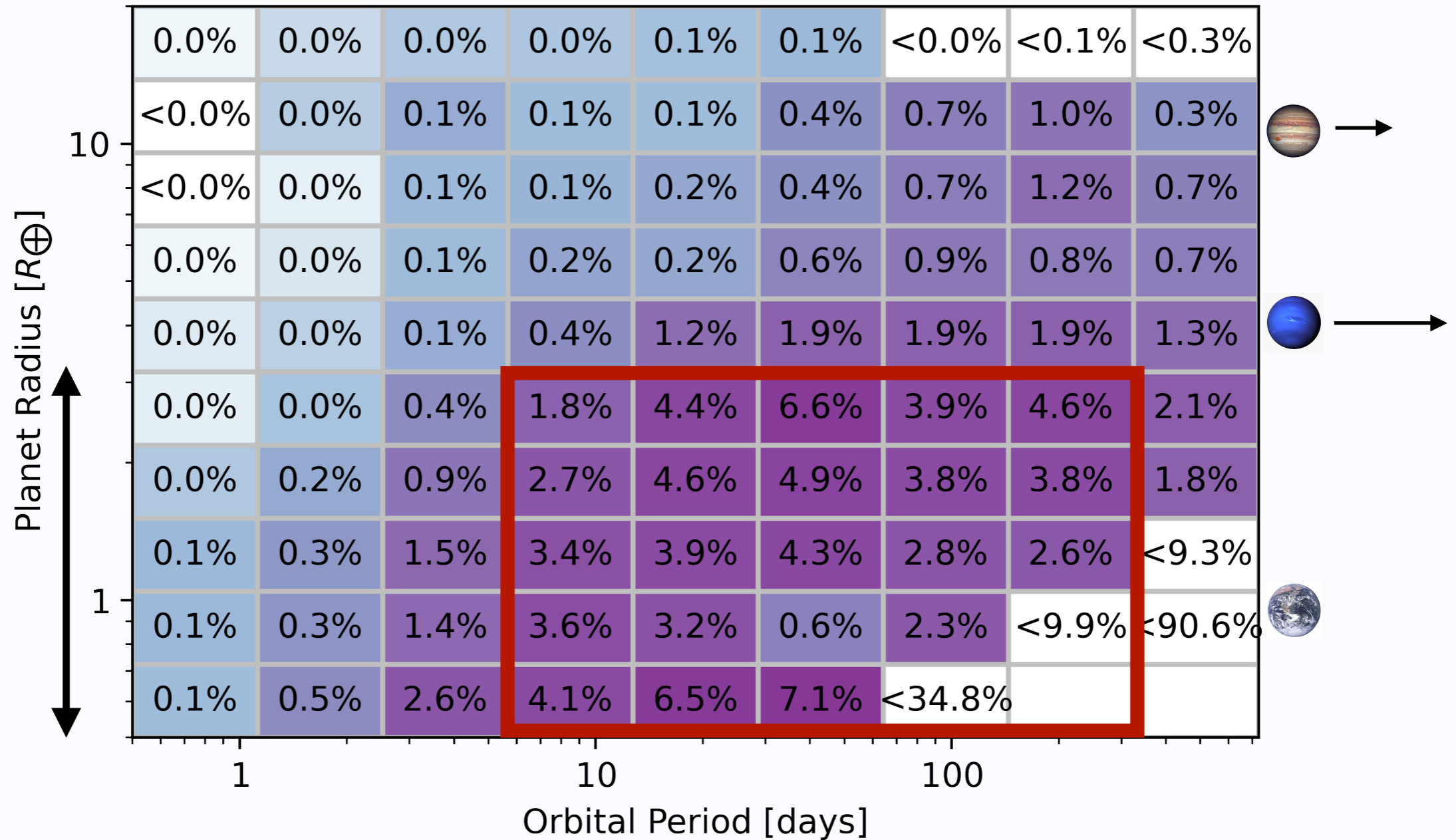
Most common planets, “Sub-Neptunes”

$P > 10$  days

$R < 3 R_{\text{earth}}$

# 1. Kepler Planet Occurrence Rate

Binned Occurrence: KeplerGaia

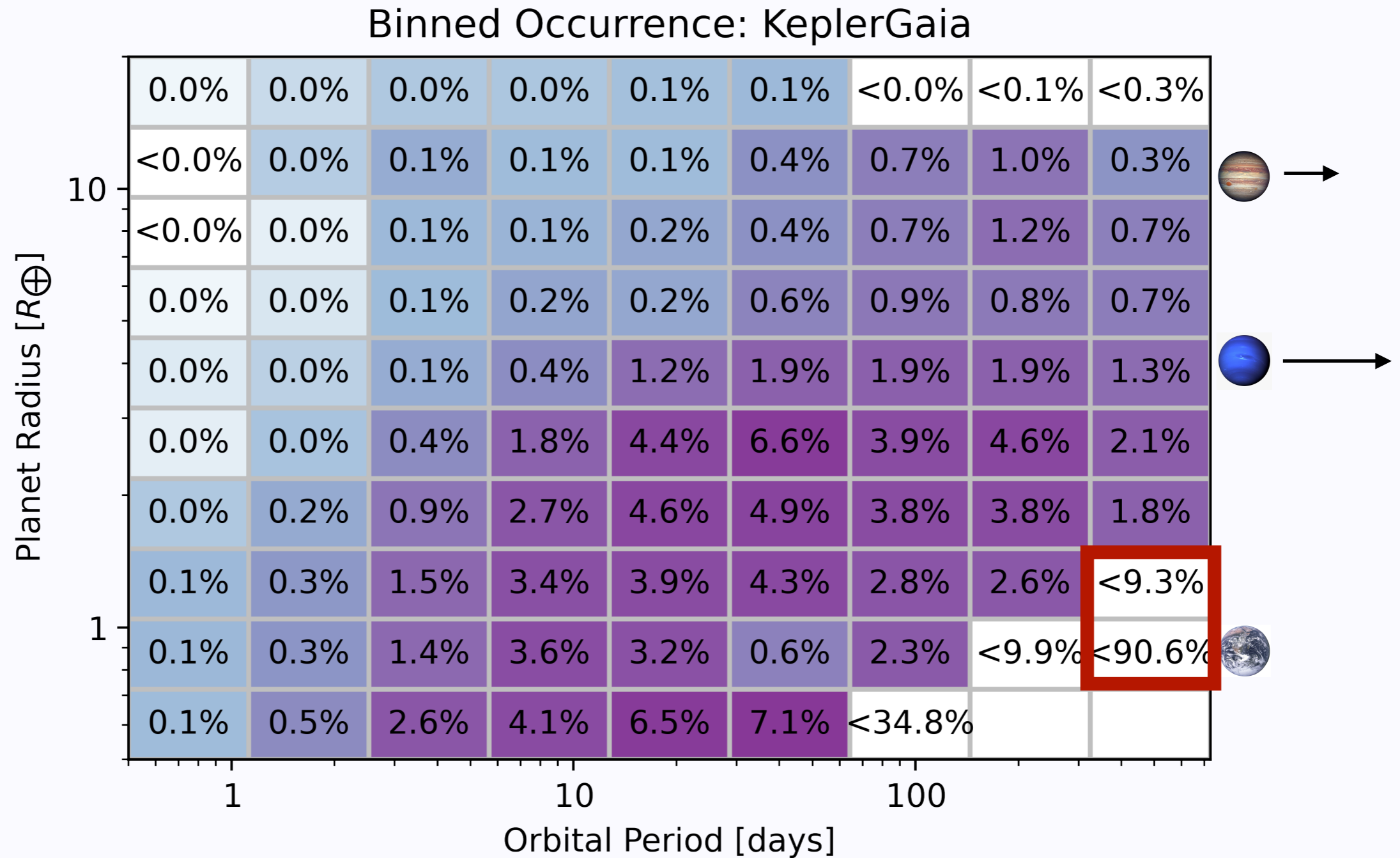


Most common planets, “Sub-Neptunes”

$P > 10$  days

$R < 3 R_{\text{earth}}$

# 1. Kepler Planet Occurrence Rate



What about earth analogues?

# **Occurrence rate of earth analogues**

**(No reliable habitable zone planet detections)**

# Occurrence rate of earth analogues

## (No reliable habitable zone planet detections)

- Need to **extrapolate** in per-radius space  
e.g. Petigura+ 2013, Mulders+2018

# Occurrence rate of earth analogues

(No reliable habitable zone planet detections)

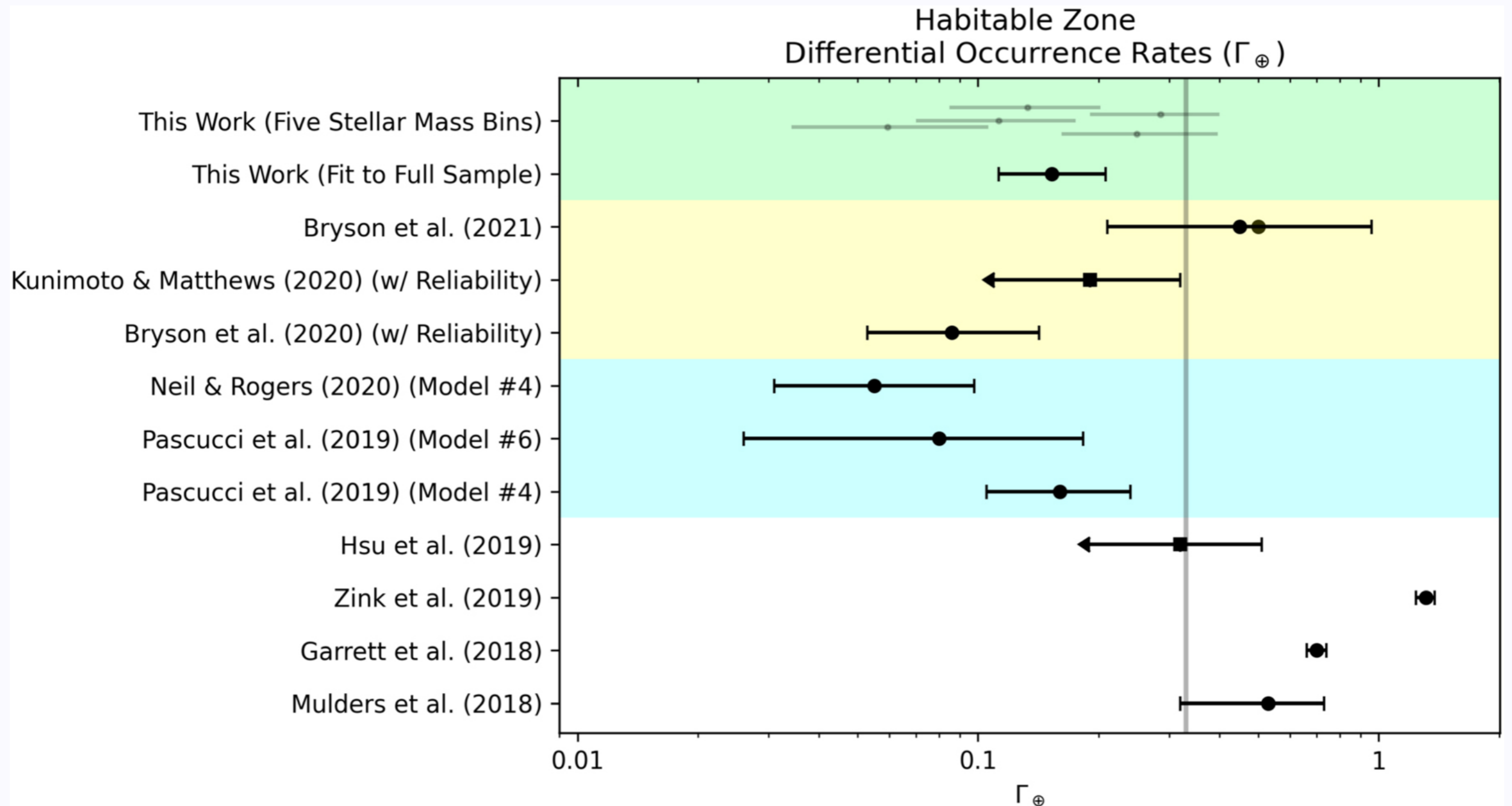
- Need to **extrapolate** in per-radius space  
e.g. Petigura+ 2013, Mulders+2018
- Need to include **less reliable detections**  
and correct for reliability  
e.g. Bryson+ 2020

# Occurrence rate of earth analogues

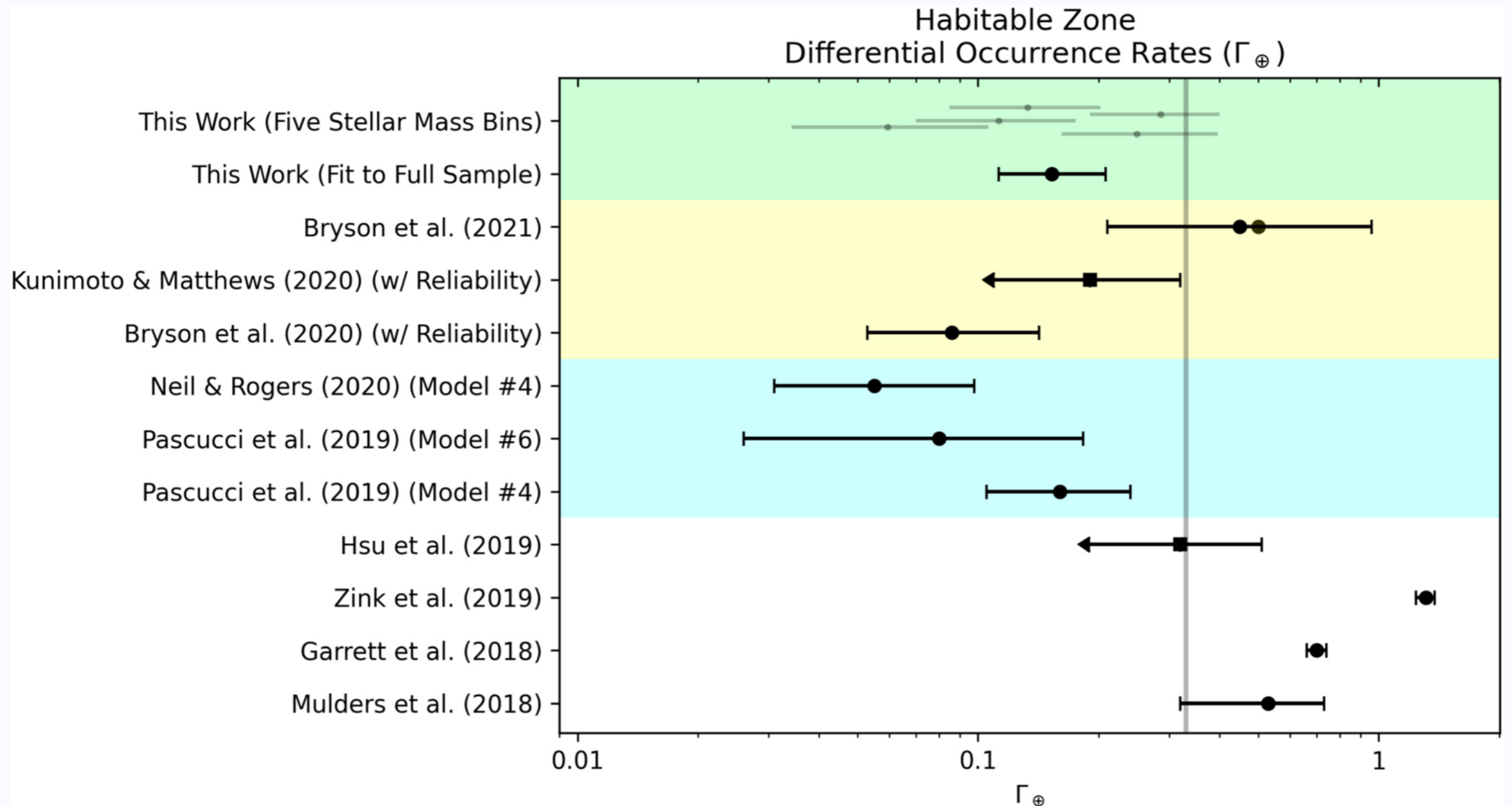
(No reliable habitable zone planet detections)

- Need to **extrapolate** in per-radius space  
e.g. Petigura+ 2013, Mulders+2018
- Need to include **less reliable detections**  
and correct for reliability  
e.g. Bryson+ 2020
- Go to **lower-mass stars** (M/K dwarfs)  
e.g. Dressing & Charbonneau 2015, Bergsten+ 2023

# Occurrence rate of earth analogues

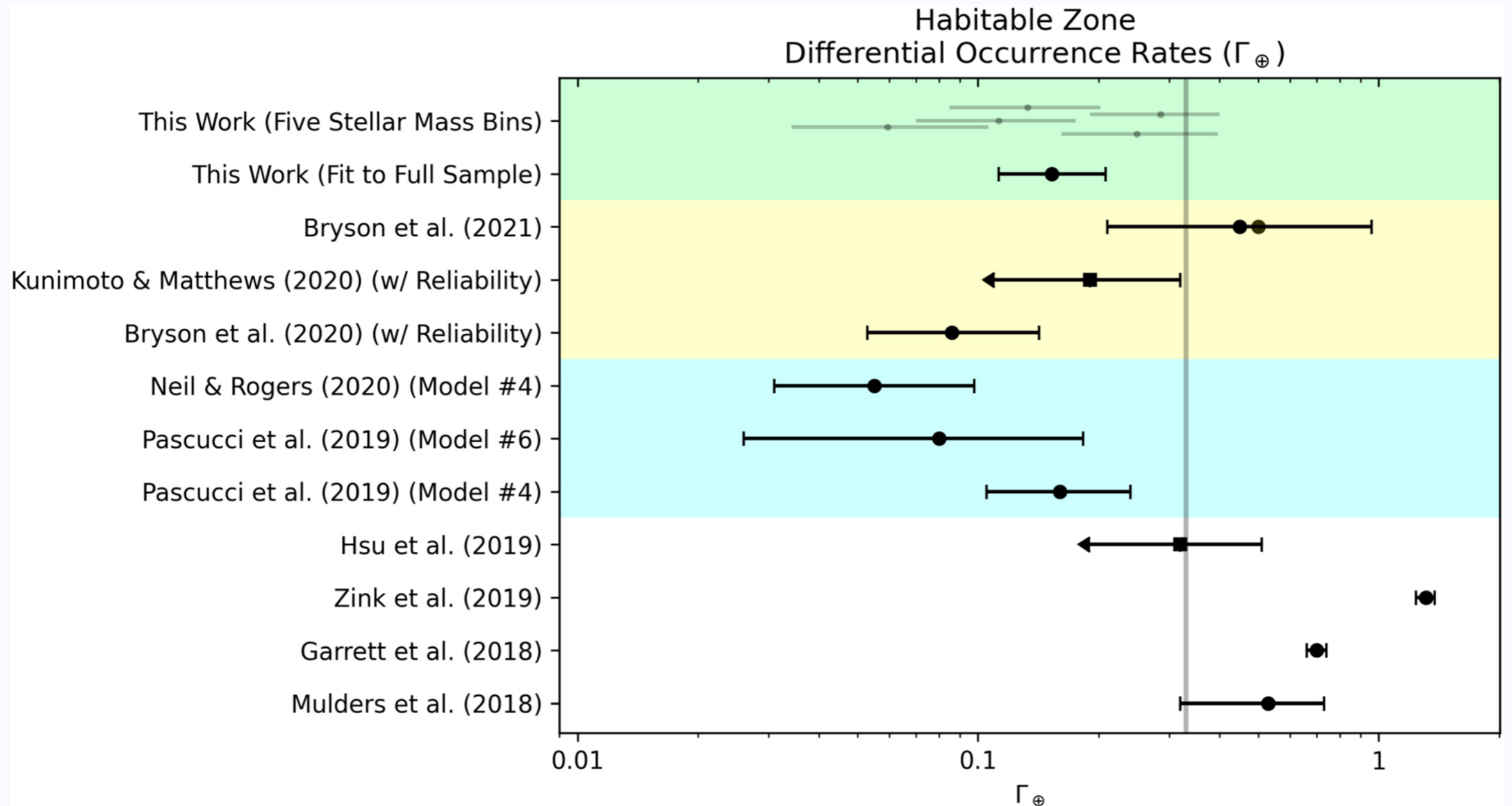


# Occurrence rate of earth analogues



Between 5% and 50%

# Occurrence rate of earth analogues



Between 5% and 50%  
“Consensus” ~10-20%

# Estimating eta-Earth: Caveats

TOPICAL REVIEW • **OPEN ACCESS**

## Are We There Yet? Challenges in Quantifying the Frequency of Earth Analogs in the Habitable Zone

Rachel B. Fernandes, Samson Johnson, Galen J. Bergsten, Sakhee Bhure, Kiersten M. Boley, Alan P. Boss, Steve Bryson, William DeRocco, Jamie Dietrich, Alison Duck ▼ [Show full author list](#)

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[Publications of the Astronomical Society of the Pacific, Volume 137, Number 12](#)

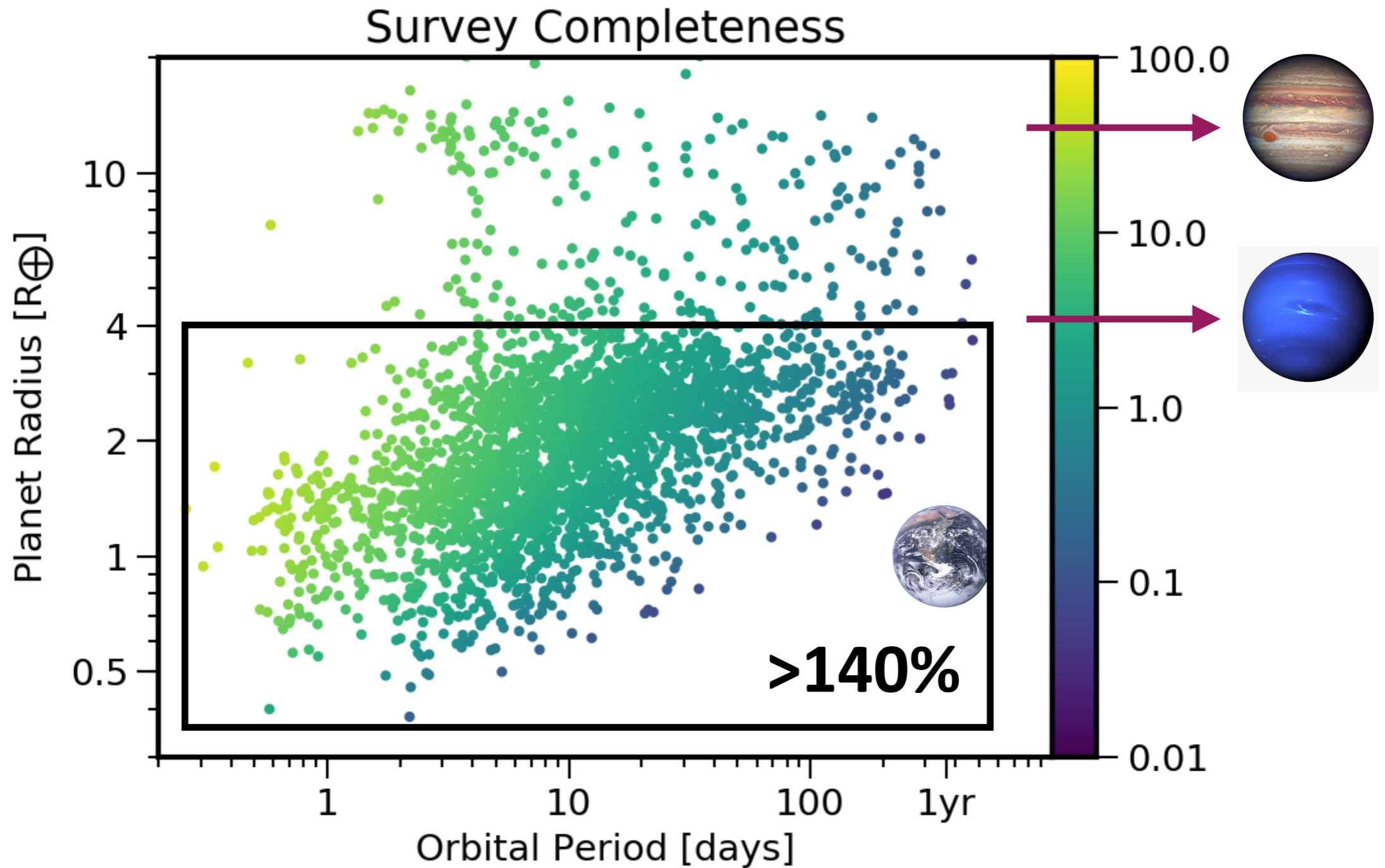
**OPEN ACCESS**

## Why Estimating $\eta_{\oplus}$ is Difficult: A Kepler-Centric Perspective

Steve Bryson, Michelle Kunimoto, Ruslan Belikov, Galen J. Bergsten, Sakhee Bhure, William J. Borucki, Douglas A. Caldwell, Aritra Chakrabarty, Rachel B. Fernandes, Matthias Y. He ▼ [Show full author list](#)

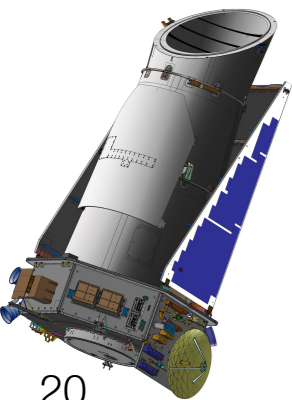
Published 2025 December 17 • © 2025. The Author(s). Published by IOP Publishing Ltd on behalf of the Astronomical Society of the Pacific (ASP).

# Kepler Sub-Neptunes

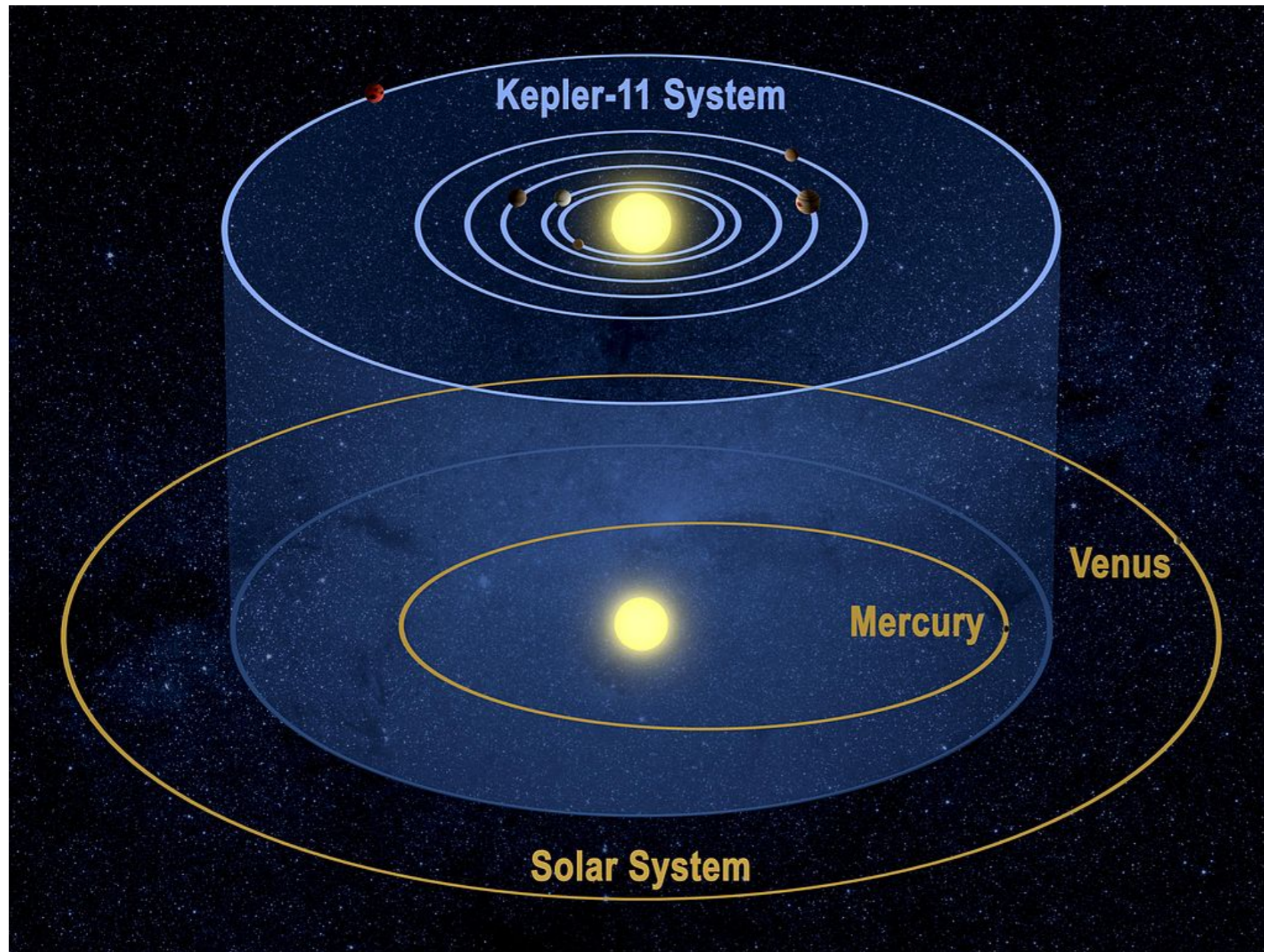


"More planets than stars"

Mulders+ 2018 (data from Thompson+ 2018, Berger+2019)

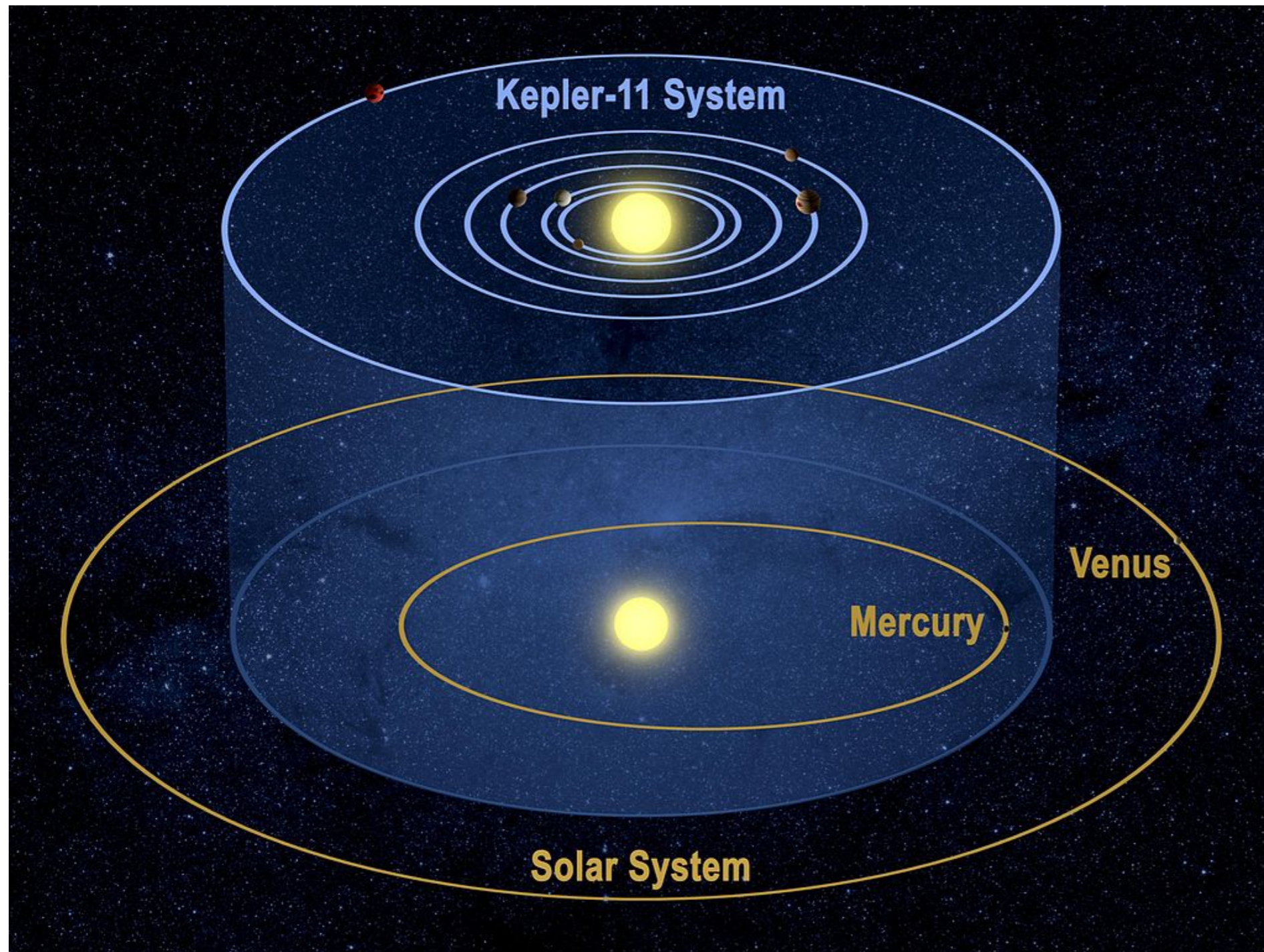


# A new archetype



Multiple super-earths / mini-Neptunes within 1 au

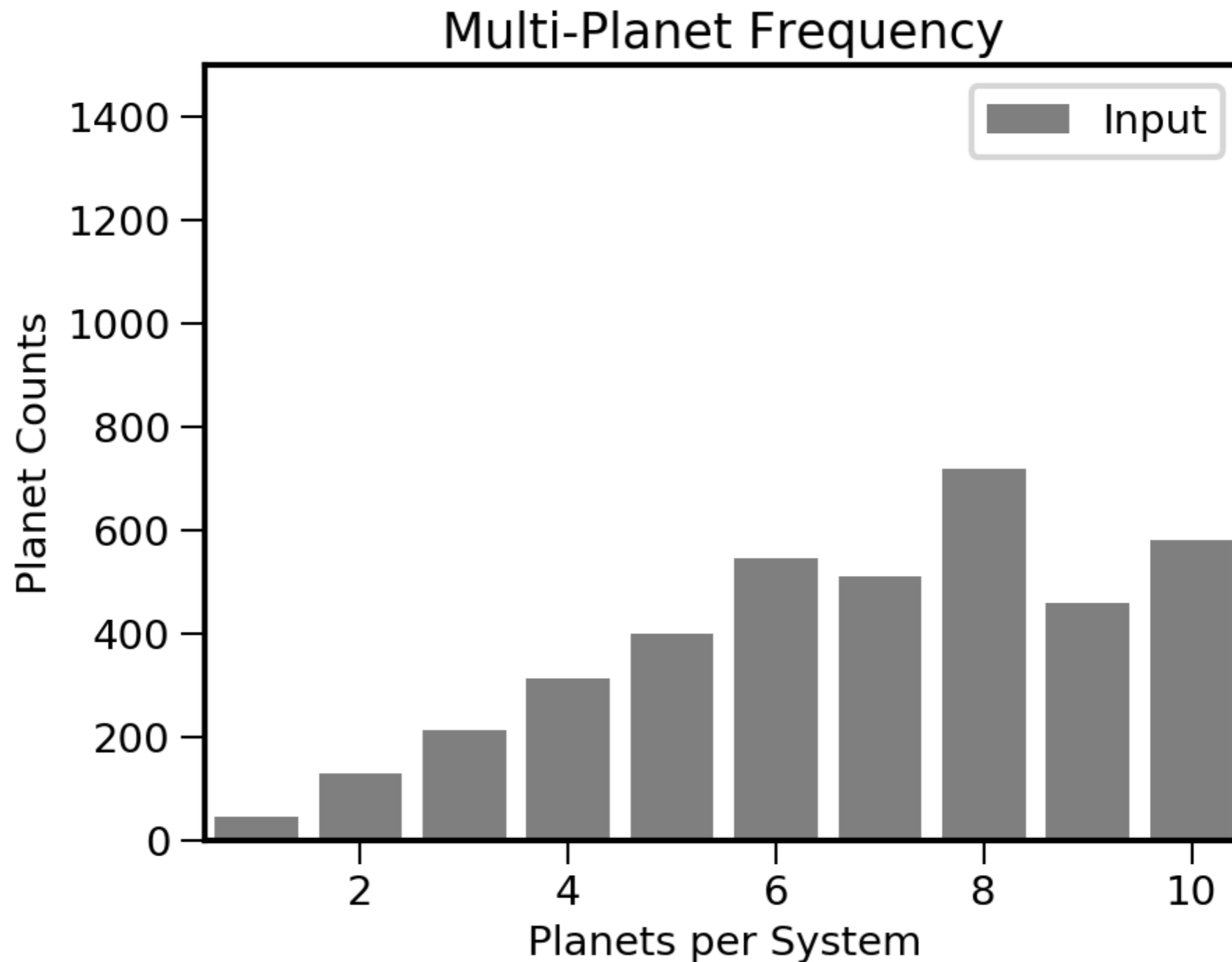
# A new archetype



Peas in a pod  
Weiss+ 2018

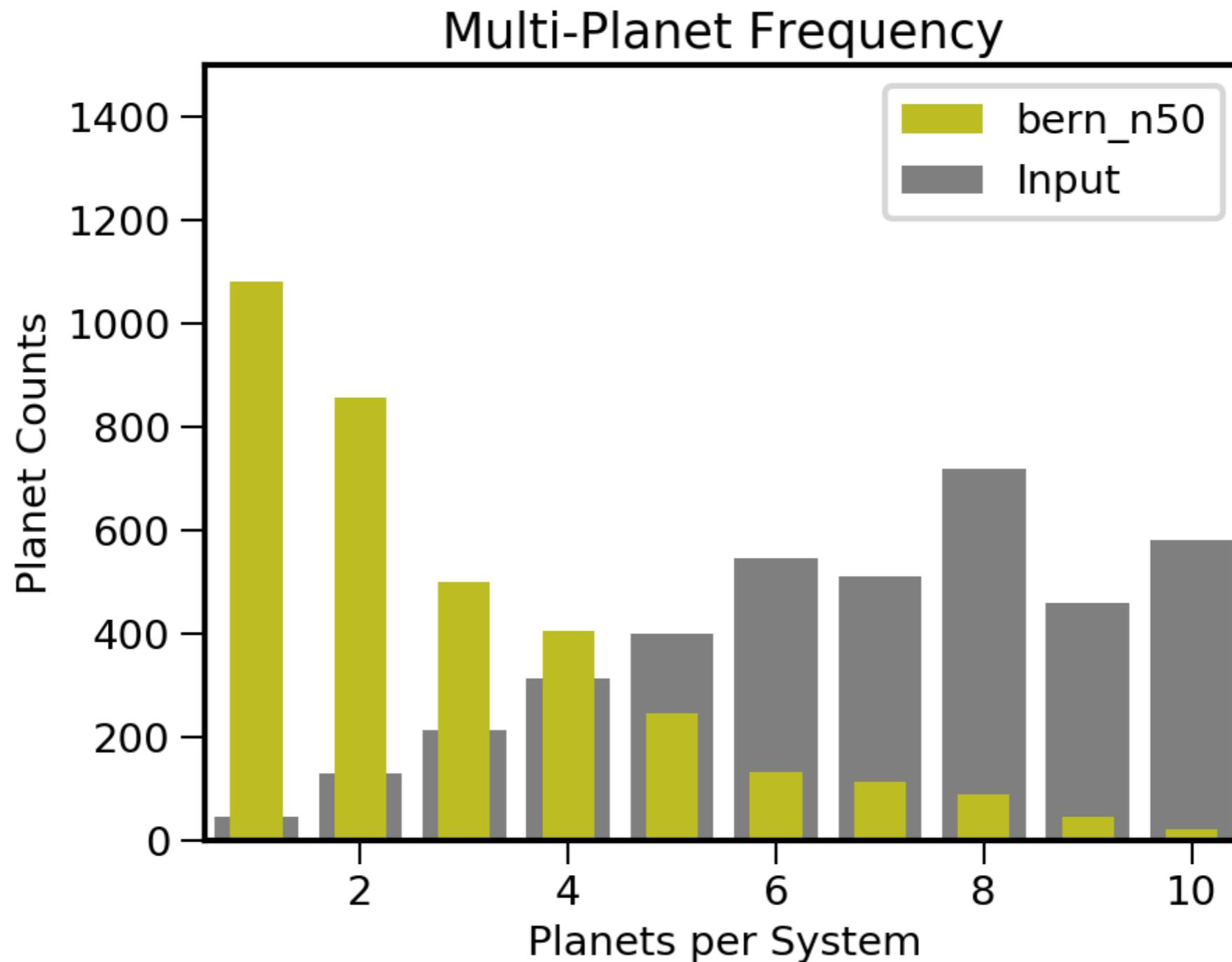
Multiple super-earths / mini-Neptunes within 1 au

# Number of Planets Per System



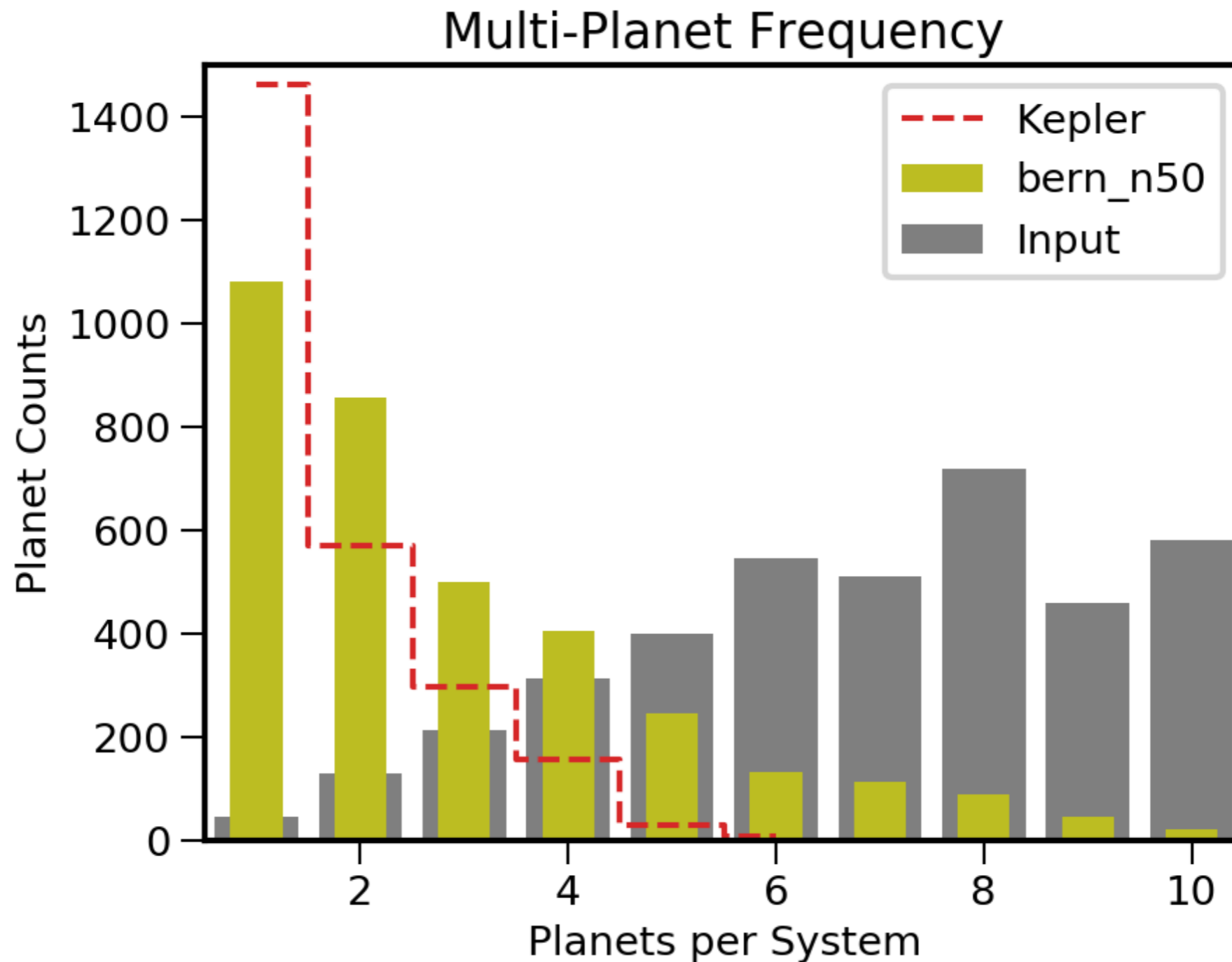
## Bern Model

# Number of Planets Per System



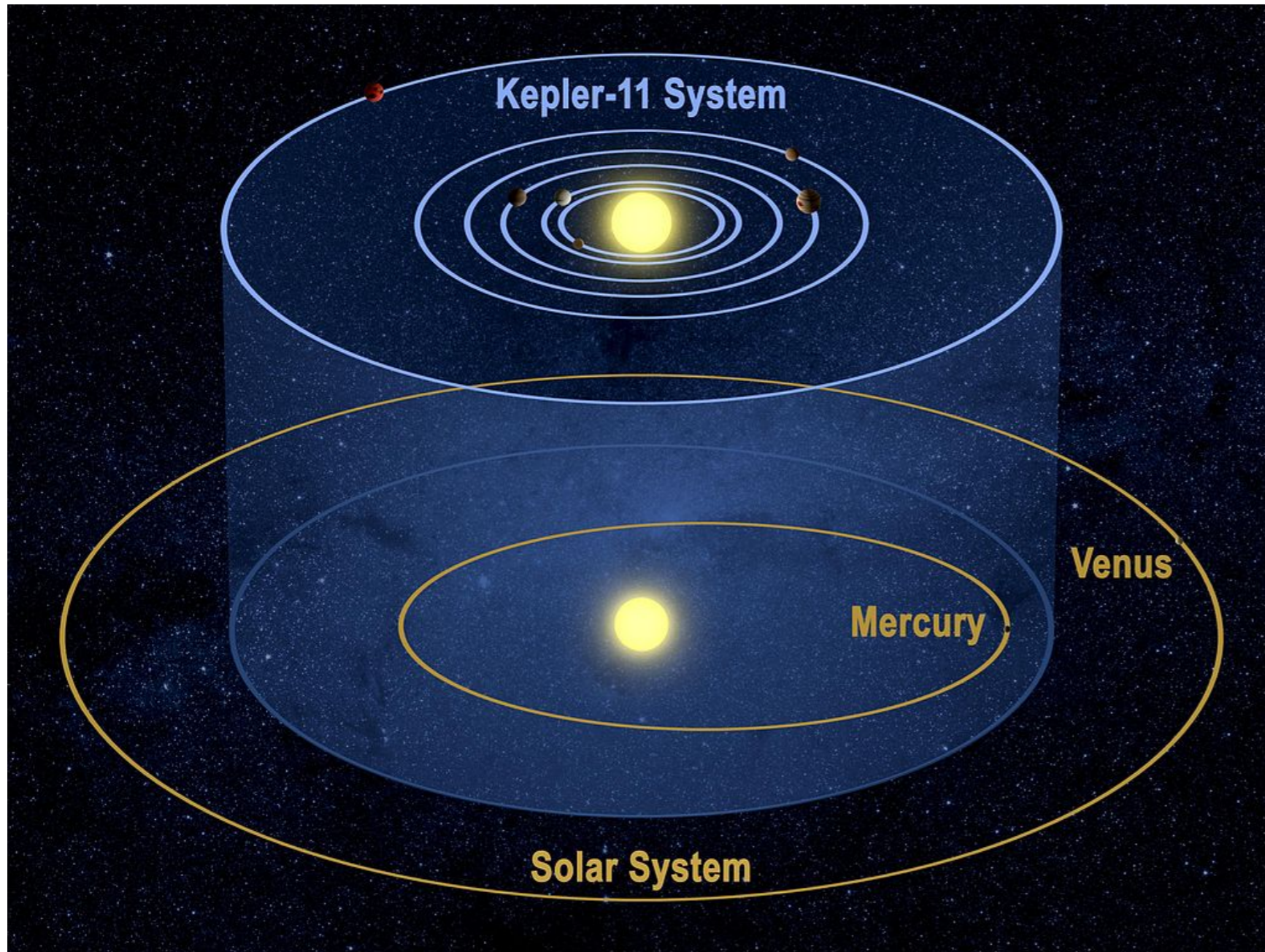
## Simulated Transit Survey

# Number of Planets Per System



## Simulated Transit Survey

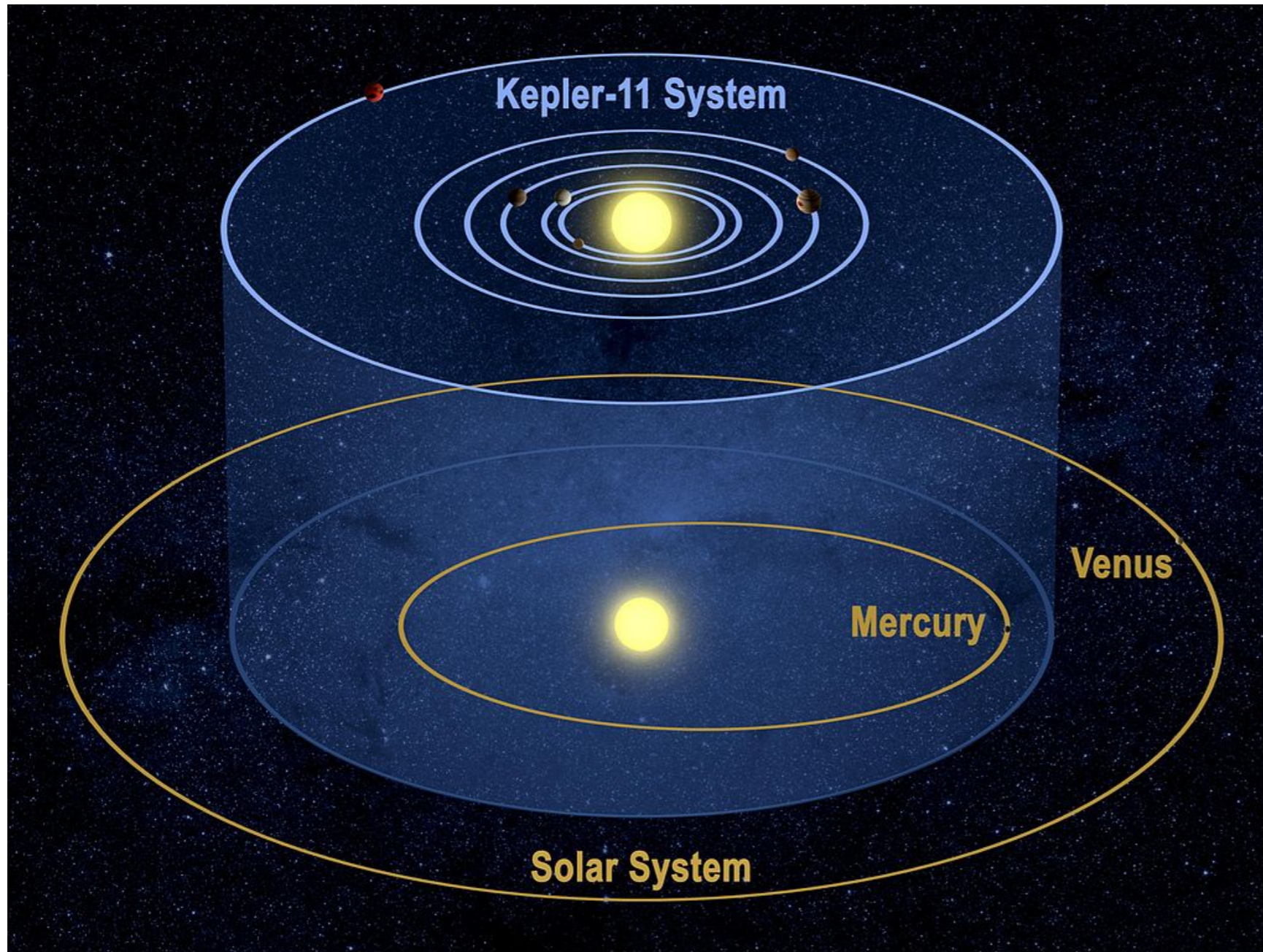
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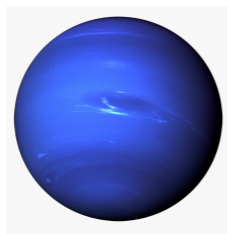
Multiple super-earths / mini-Neptunes within 1 au

**Orbit >50% of FGK stars!**

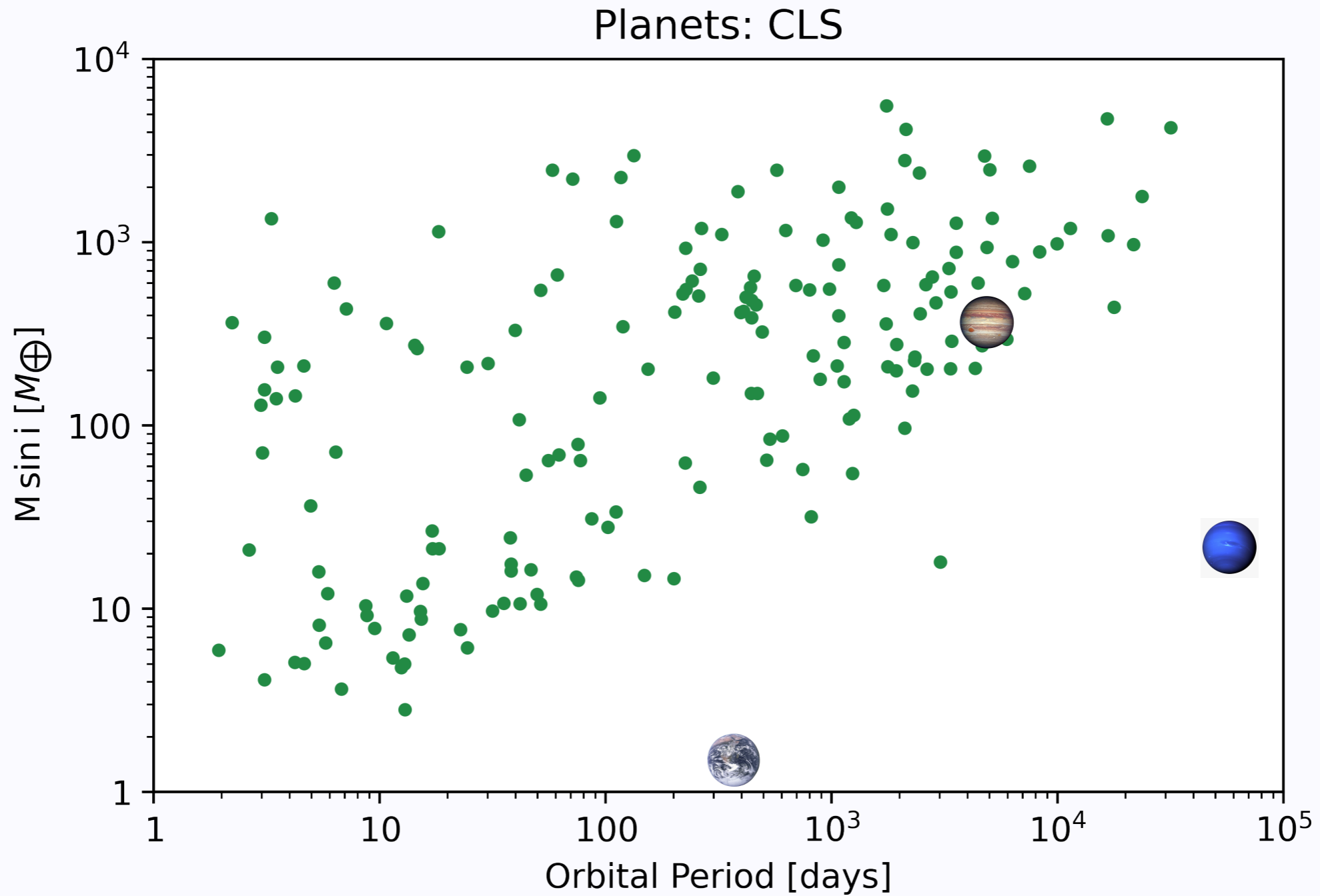
Mulders+ 2018; Zhu+ 2018; He+ 2021

# Radial Velocity Surveys

Cold Giant Planets + mini-Neptunes

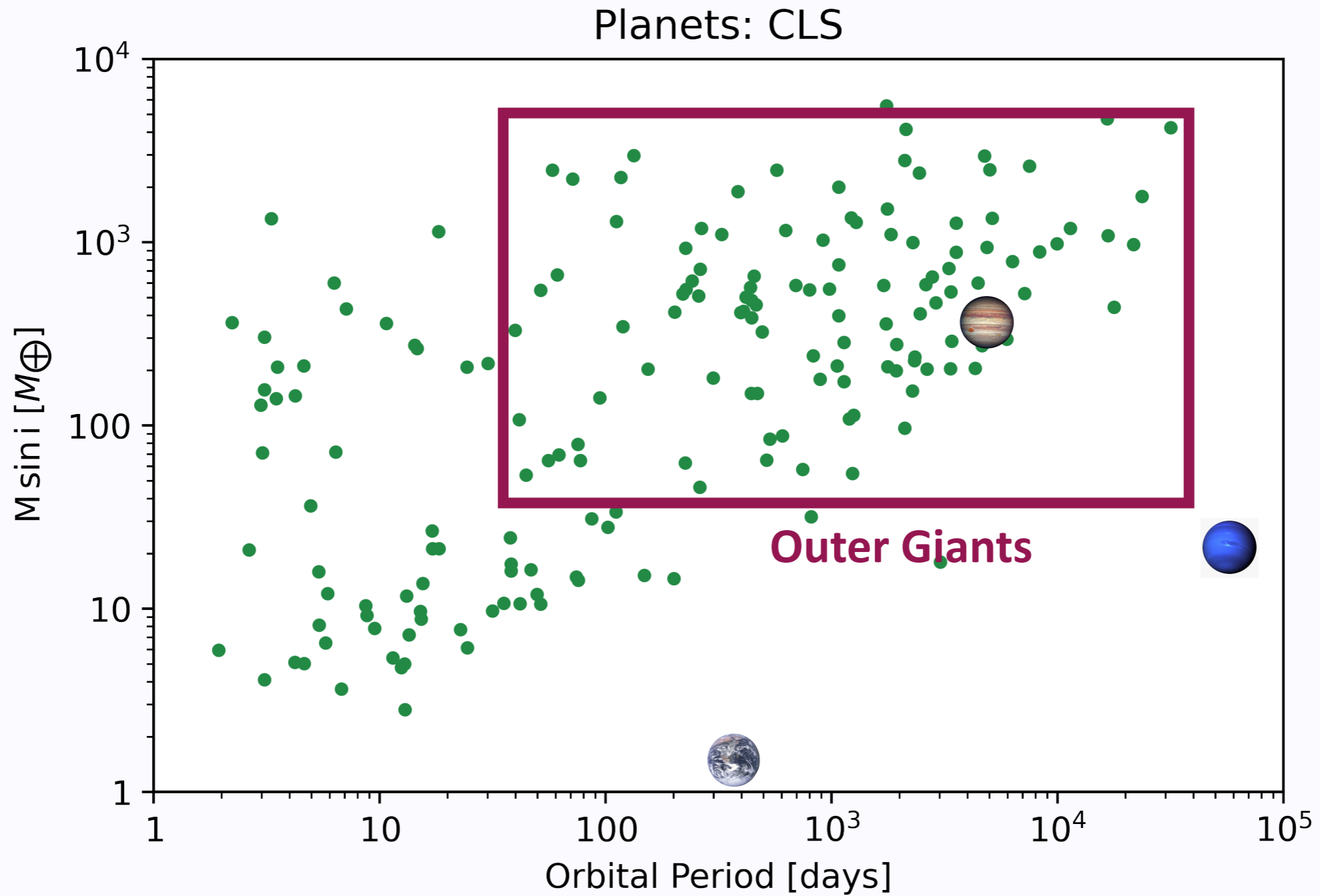


# Radial Velocity



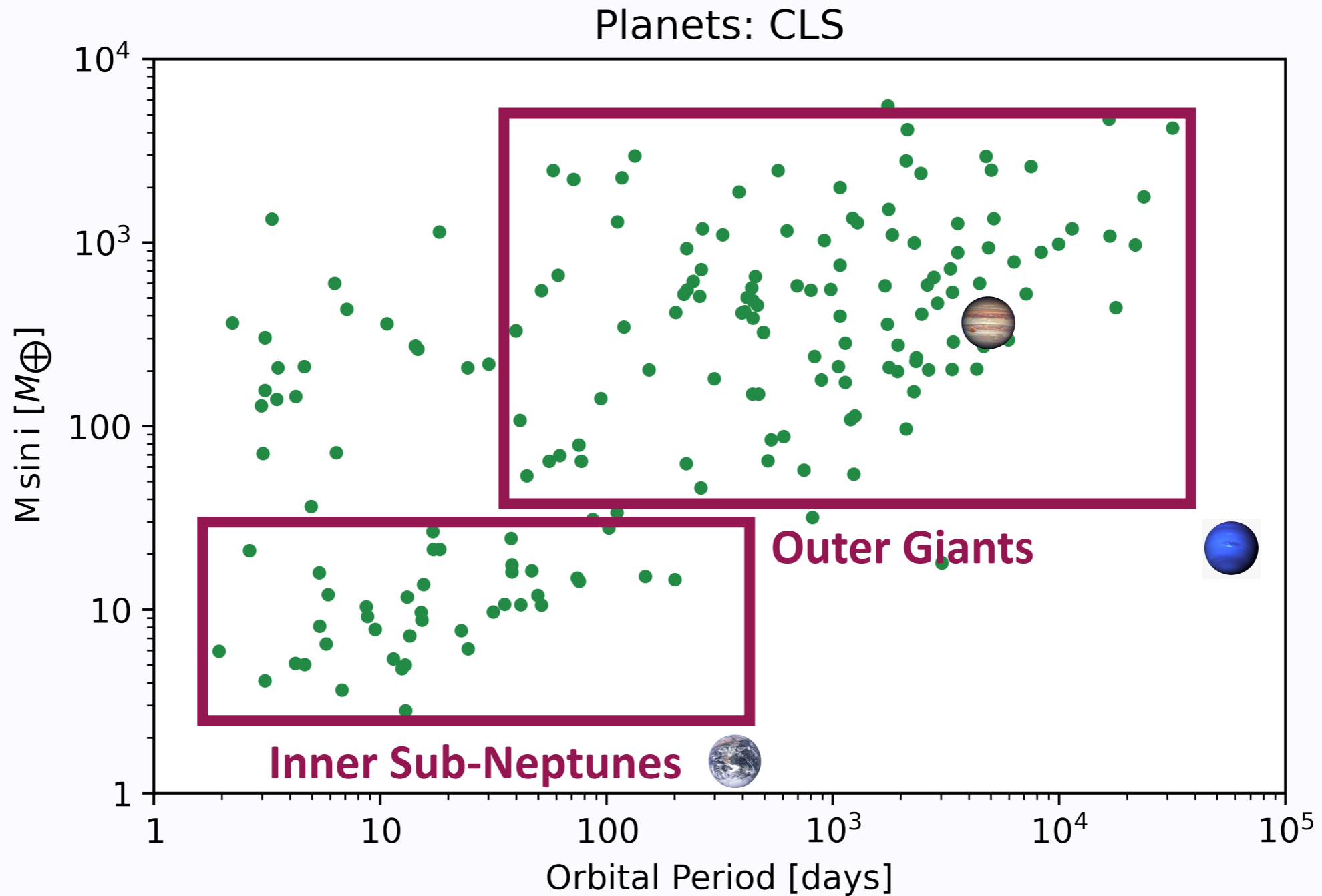
## California Legacy Survey

# Radial Velocity



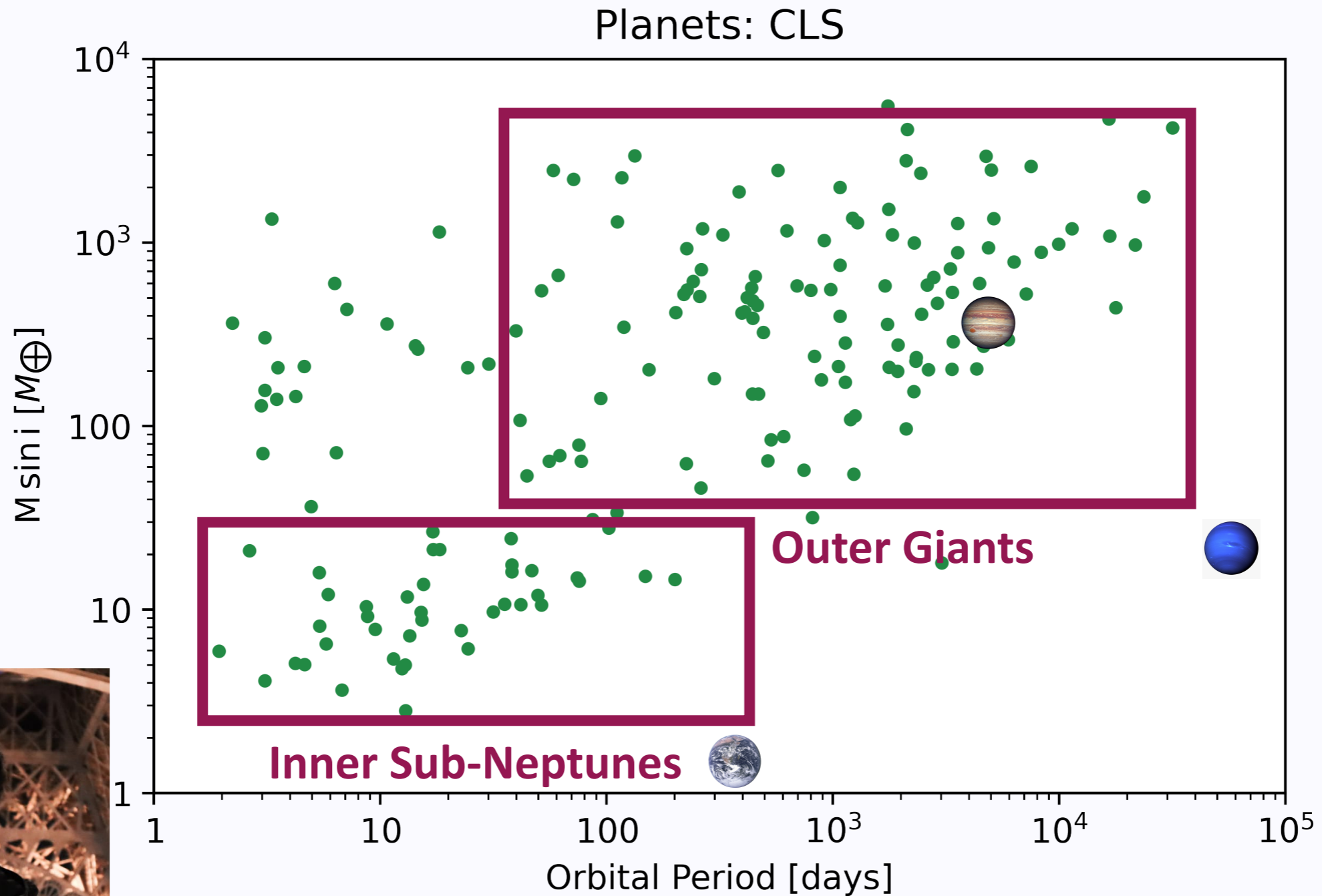
## California Legacy Survey

# Radial Velocity



## California Legacy Survey

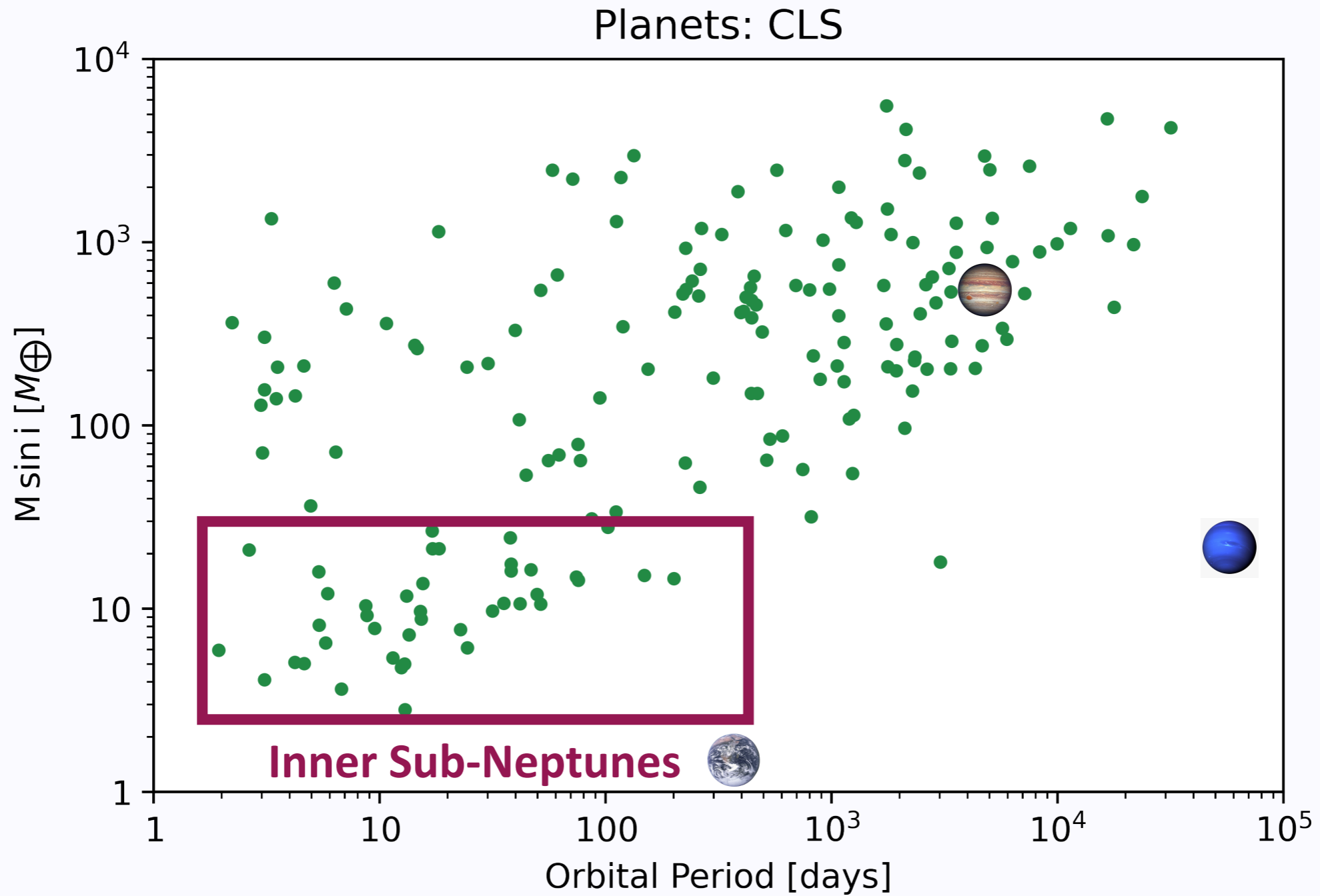
# Radial Velocity



## California Legacy Survey

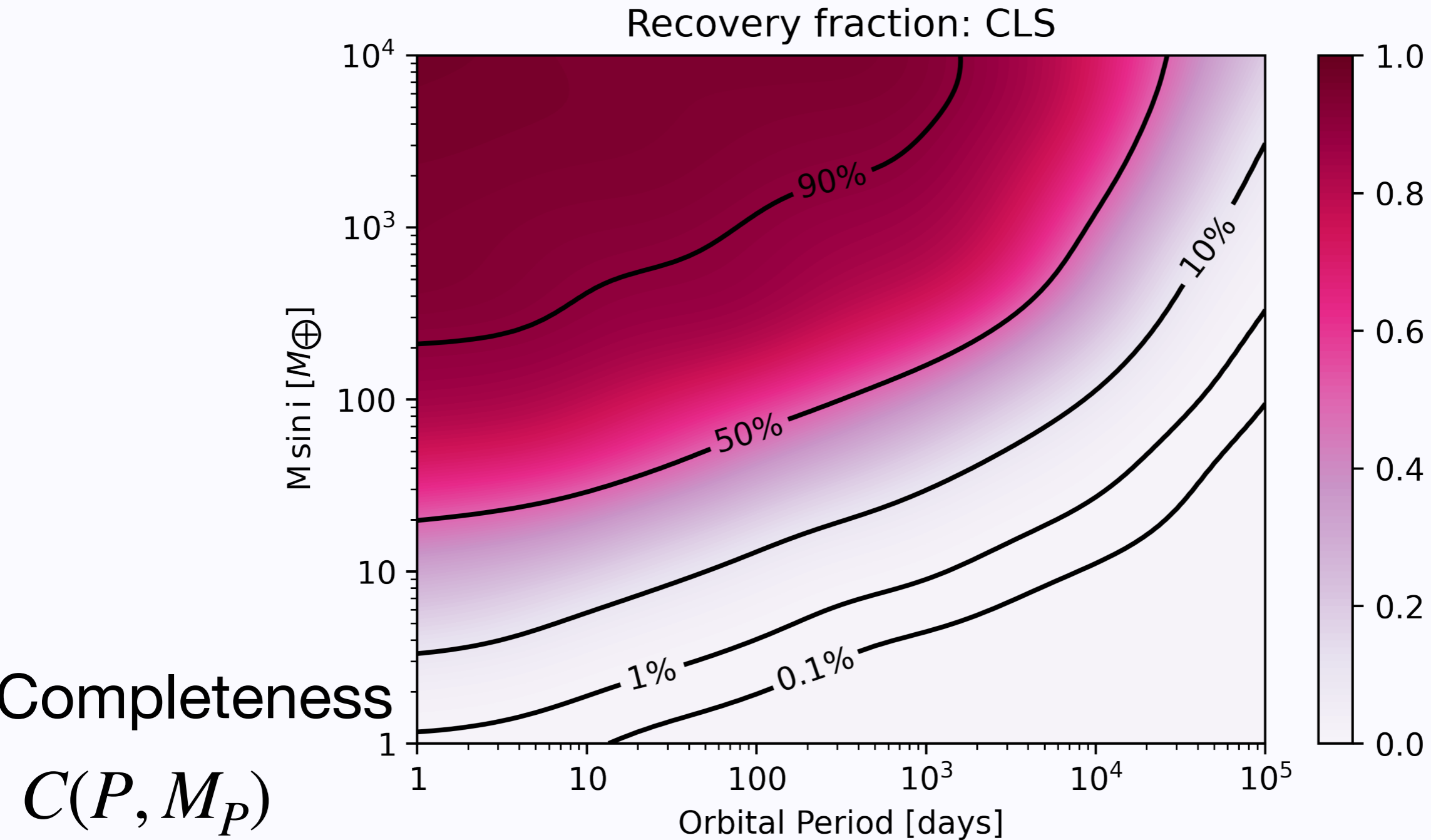
Talk by Etienne Lefevre-Forjan, 3:10 PM

# Radial Velocity



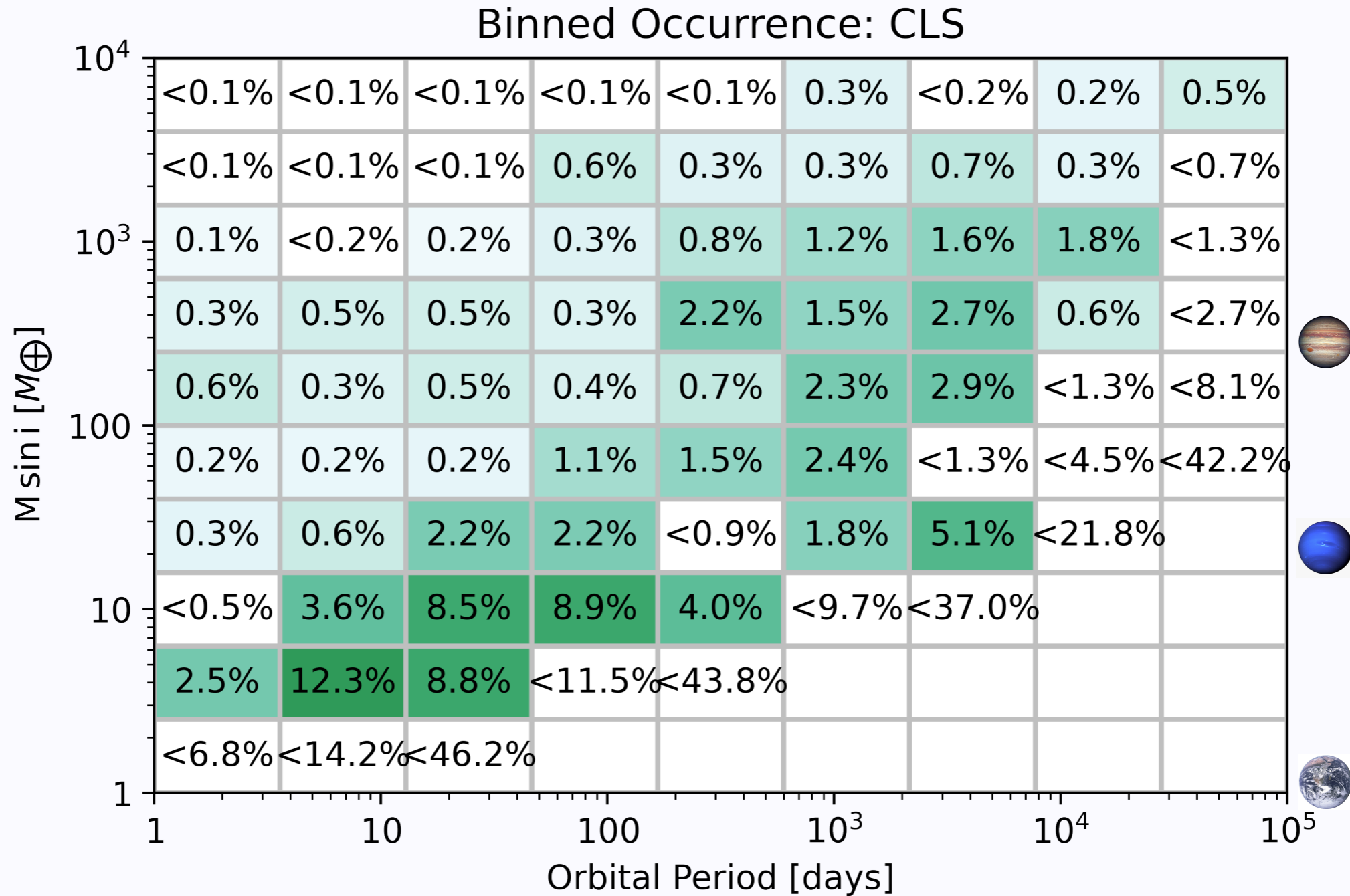
## California Legacy Survey

# Radial Velocity

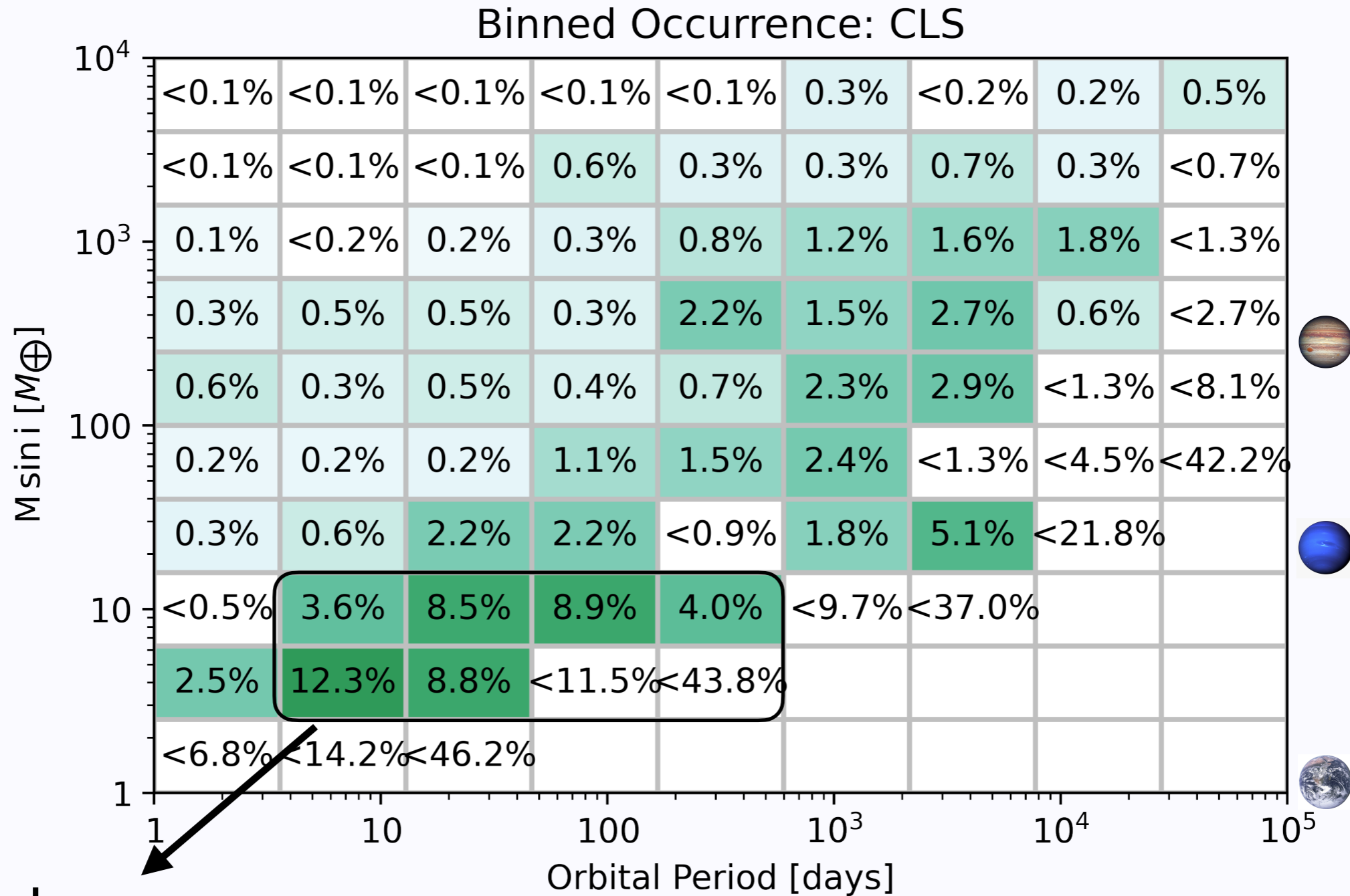


Injection-Recovery Tests wit RadVel

# Radial Velocity



# Radial Velocity

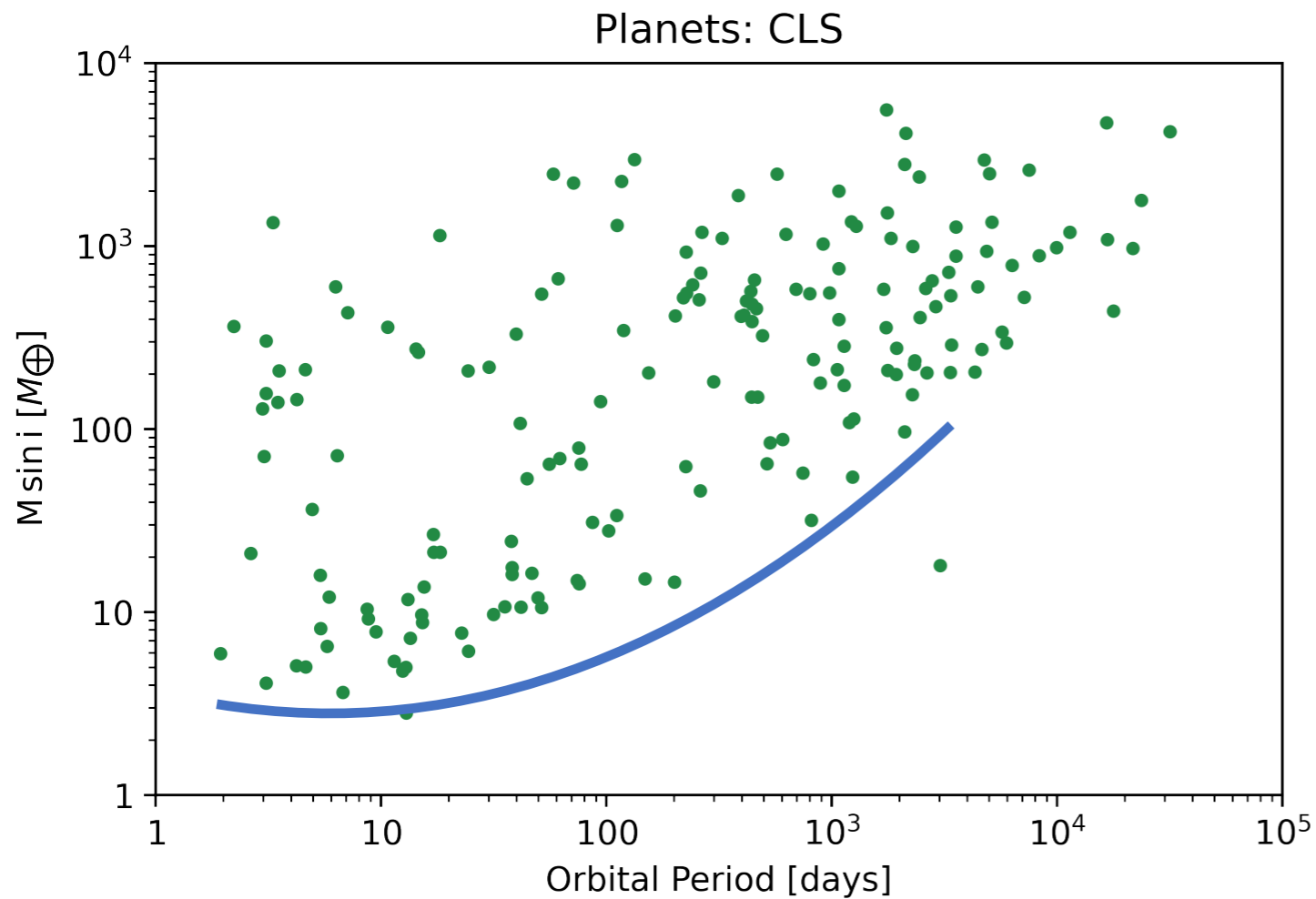


Sub-Neptunes  
(Mini-Neptunes)

0.5 planets per star

# Key Difference: sensitivity

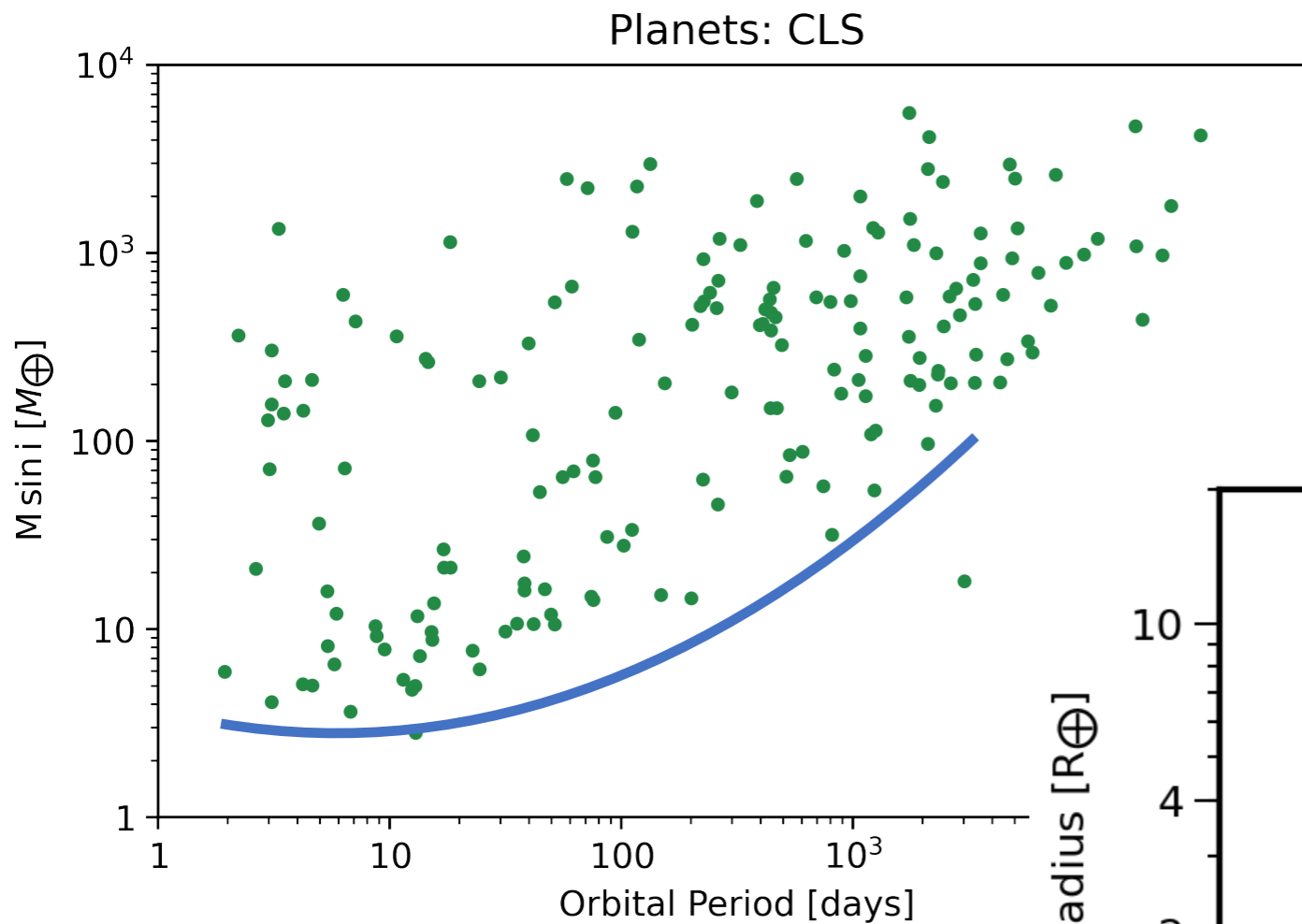
# Key Difference: sensitivity



Sensitive to Super-earths

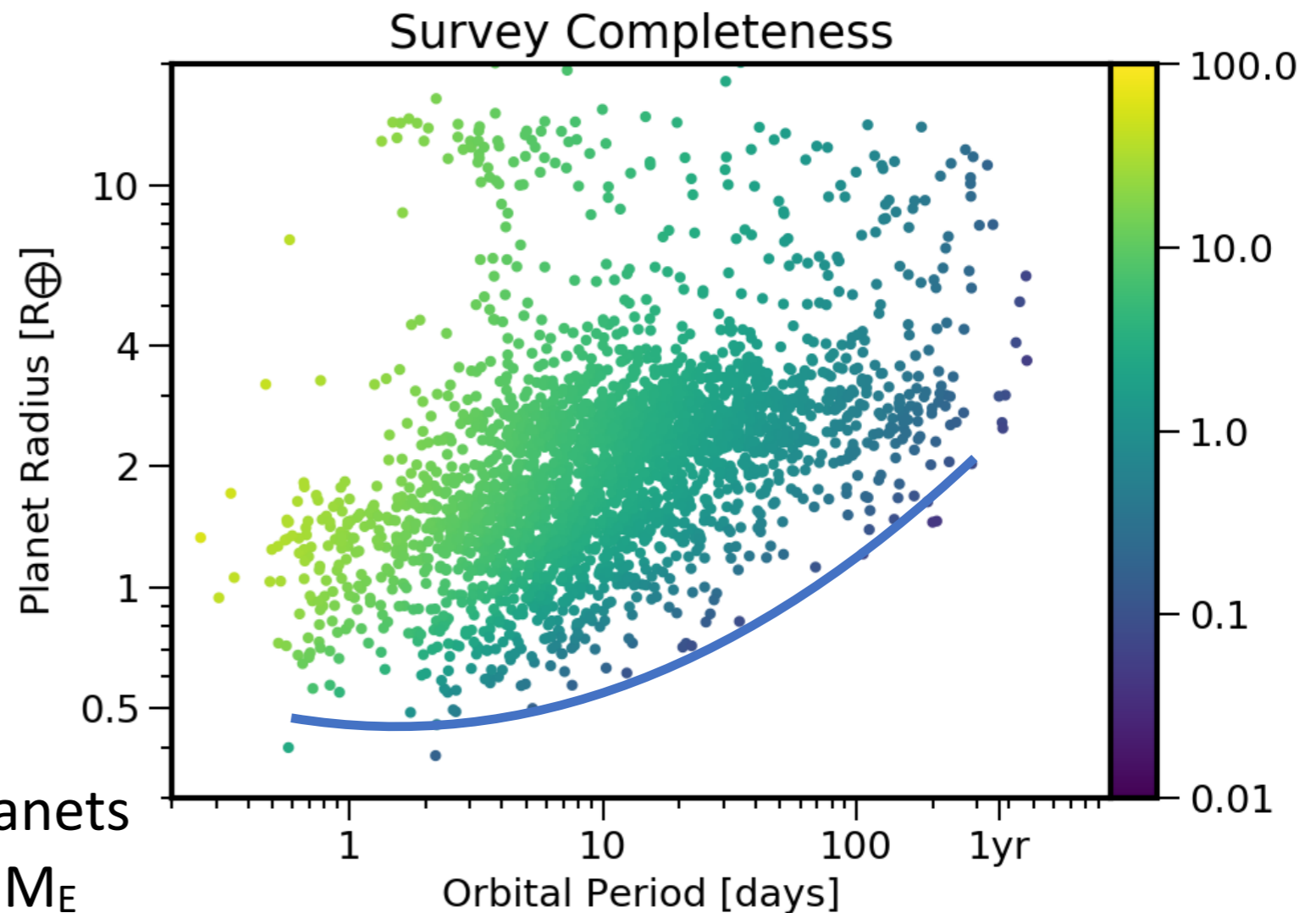
3  $M_E$  at 10 days

# Key Difference: sensitivity

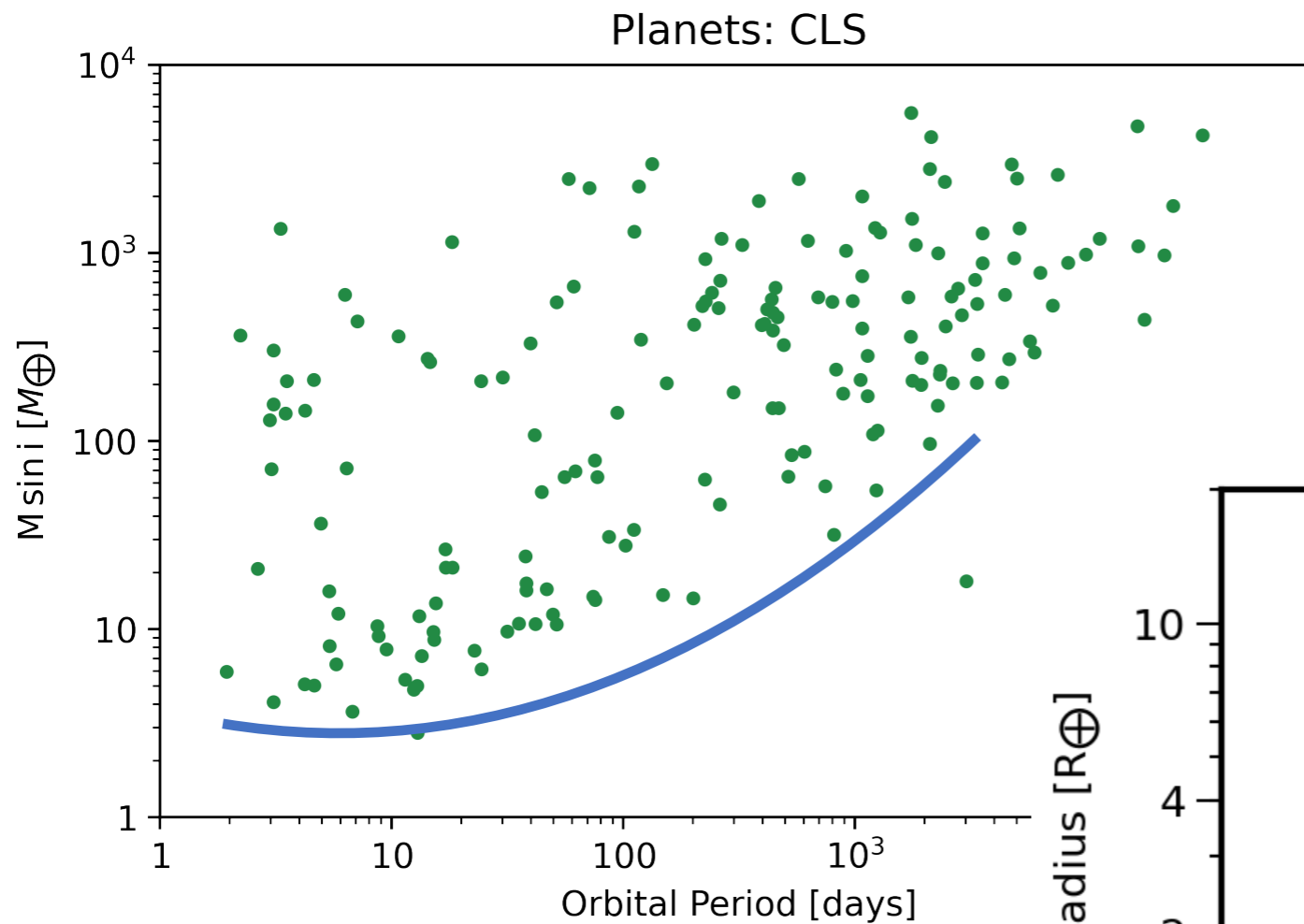


Sensitive to Super-earths  
 $3 M_E$  at 10 days

Sensitive to Mars-sized planets  
 $0.5 R_E$  at 10 days       $\sim 0.1 M_E$



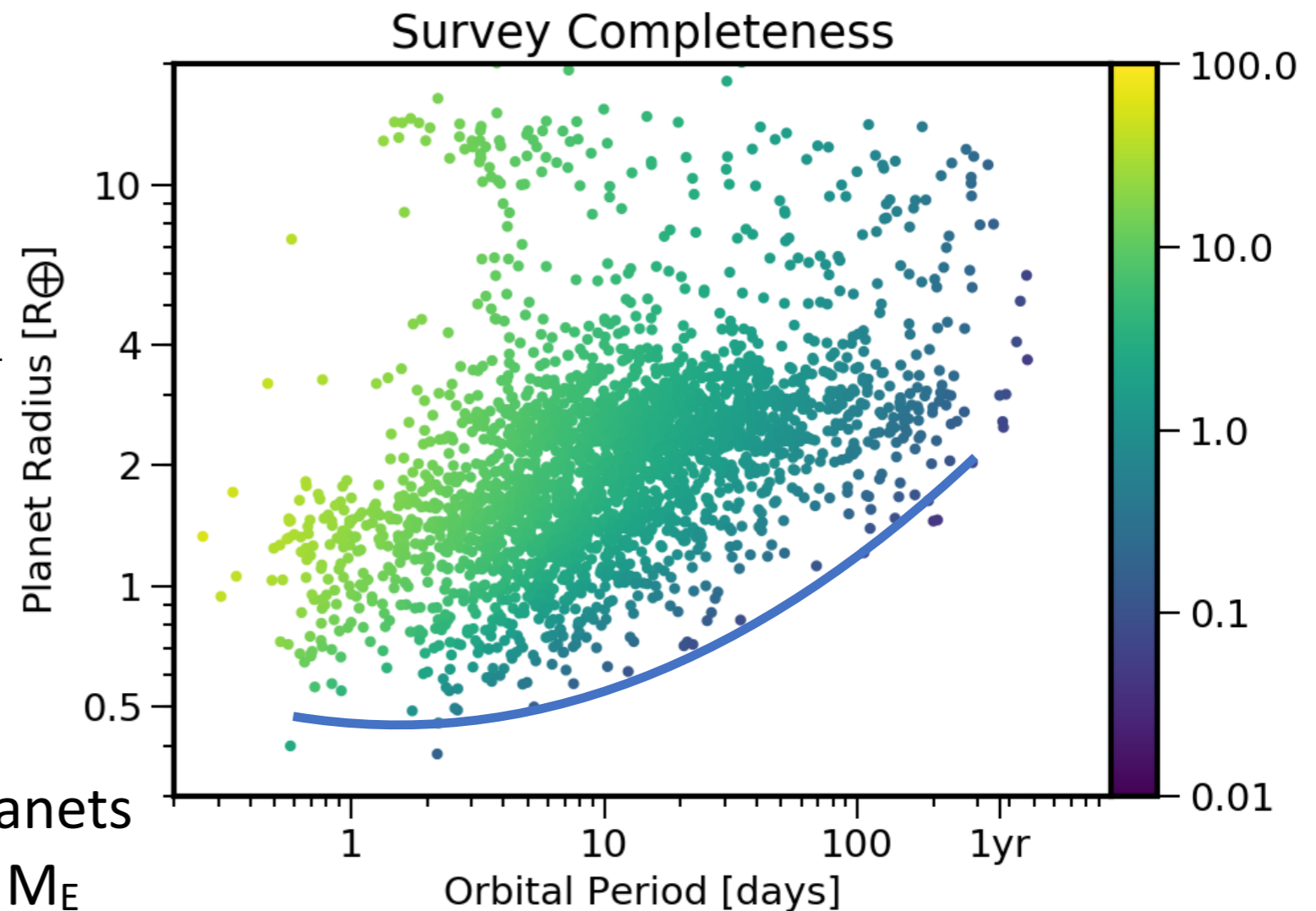
# Key Difference: sensitivity



Half the sub-Neptune population remains undetected!

Sensitive to Super-earths  
3  $M_E$  at 10 days

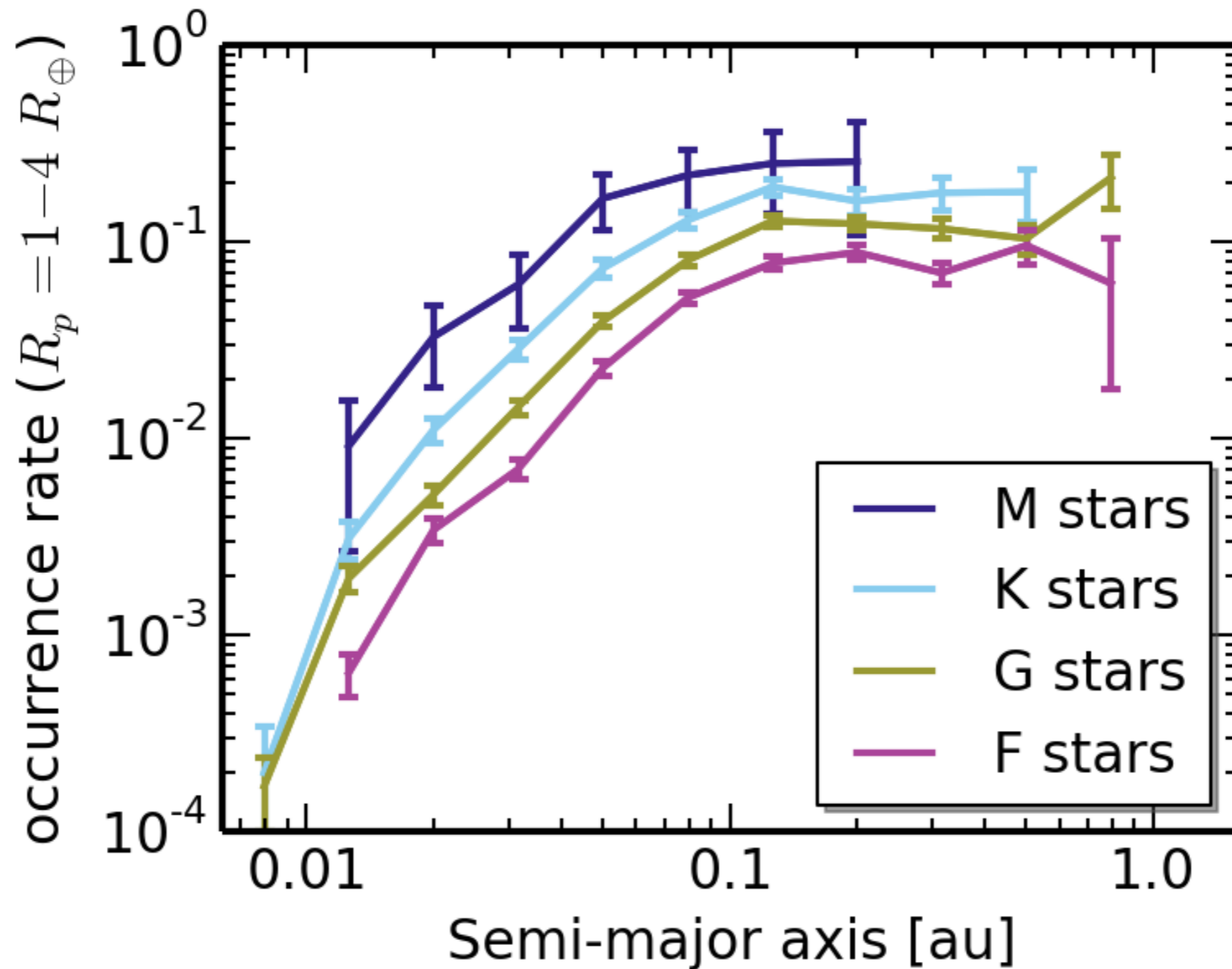
Sensitive to Mars-sized planets  
0.5  $R_E$  at 10 days       $\sim 0.1 M_E$



# Stellar mass dependence

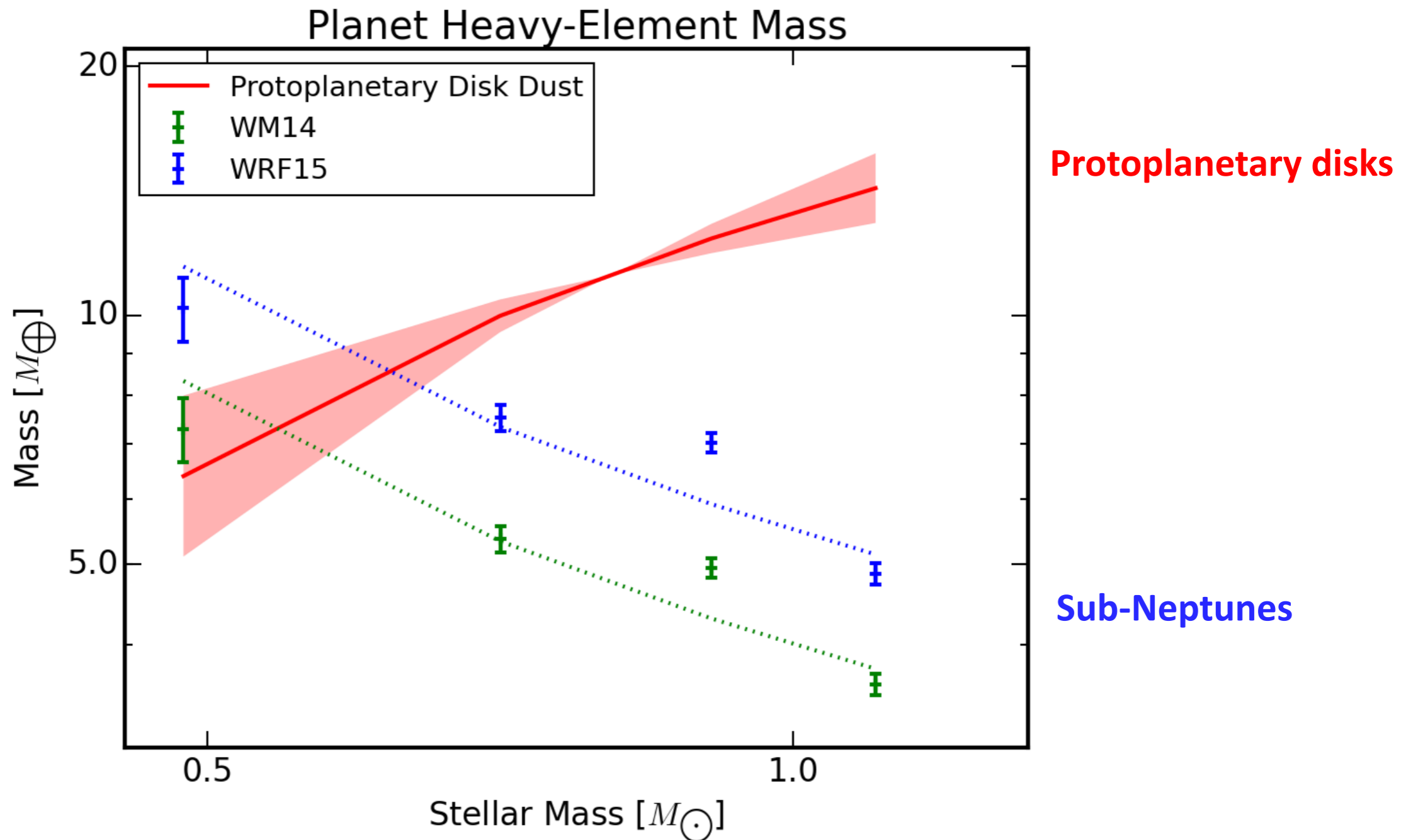


# Stellar Mass Dependence of Sub-Neptunes



More planets around lower mass stars / M dwarfs !

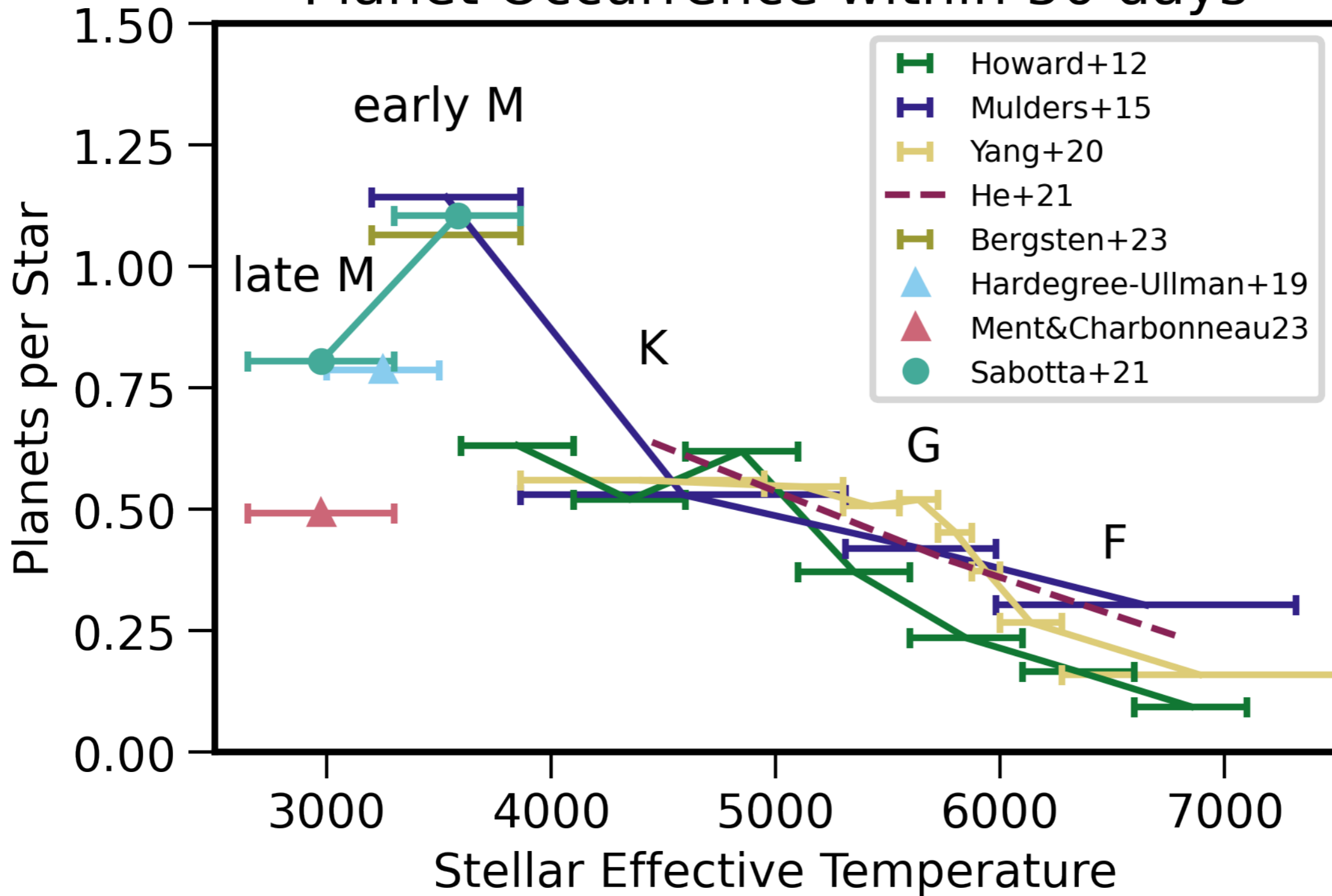
# More solids in planets around M dwarfs



Not an observation bias -> efficiency planet formation or migration/drift

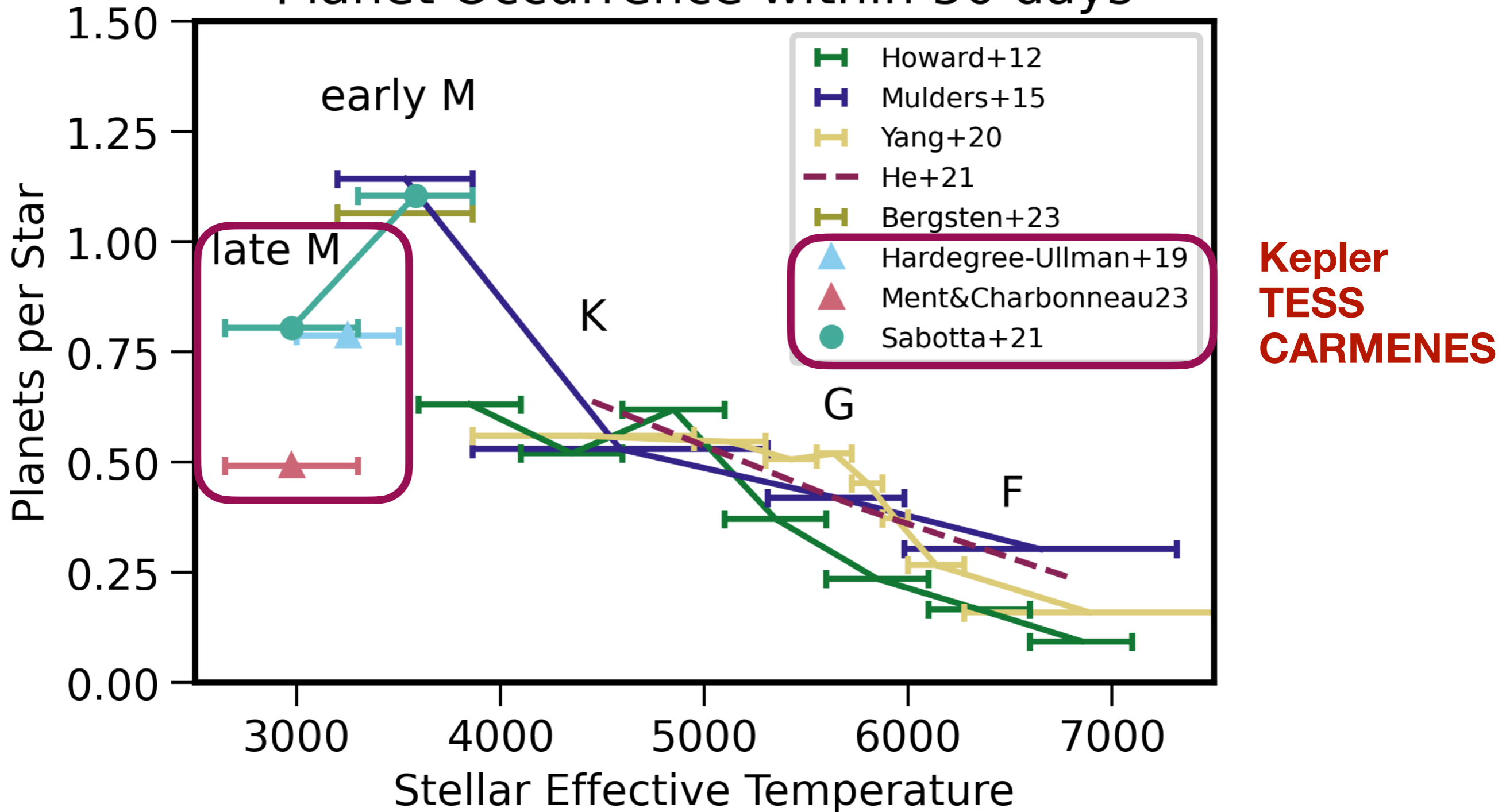
# Stellar Mass Dependence of Sub-Neptunes

Planet Occurrence within 50 days



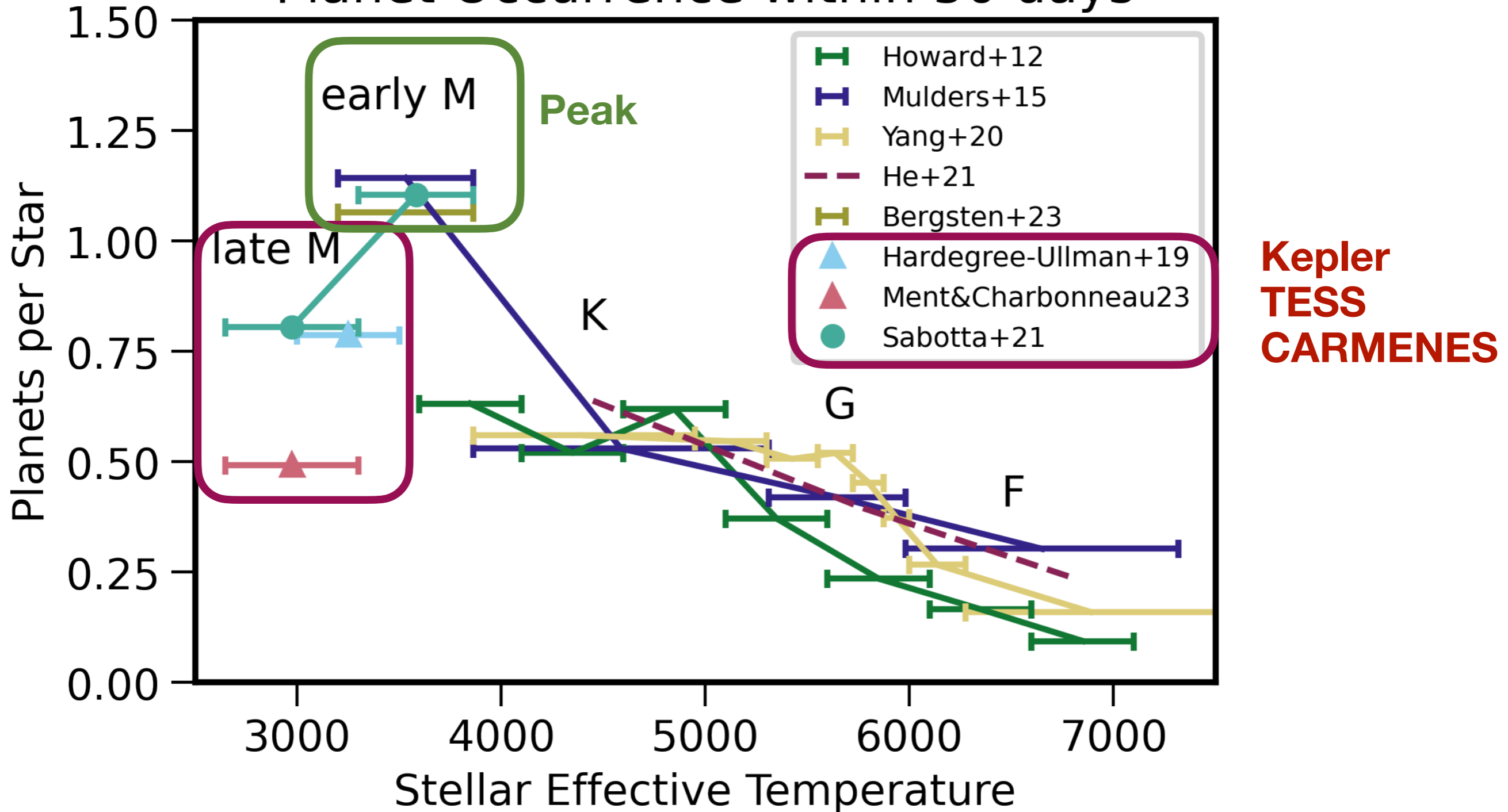
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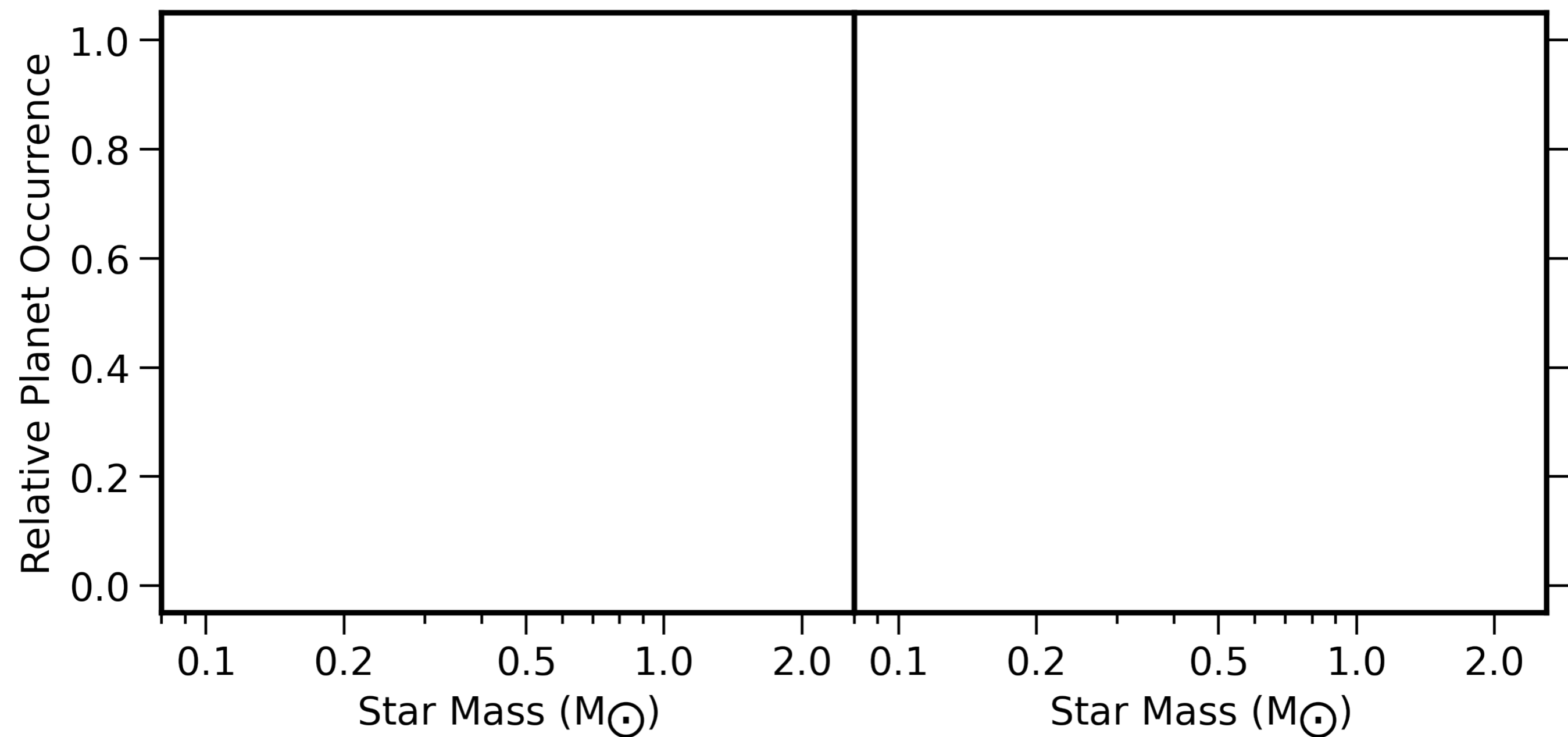


# Comparison with Formation Models

## Planet Formation Models

Outer Planets

Inner Planets

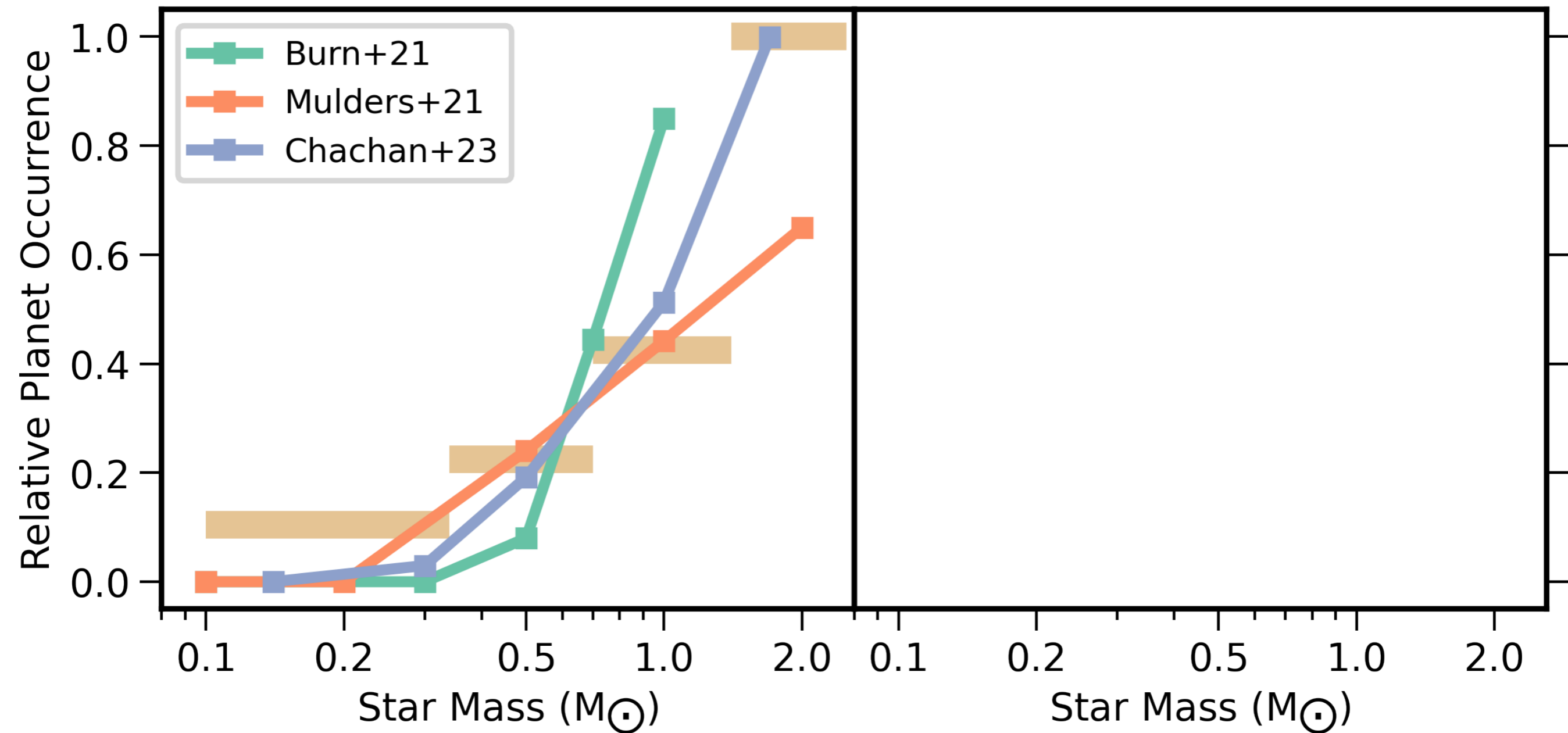


# Comparison with Formation Models

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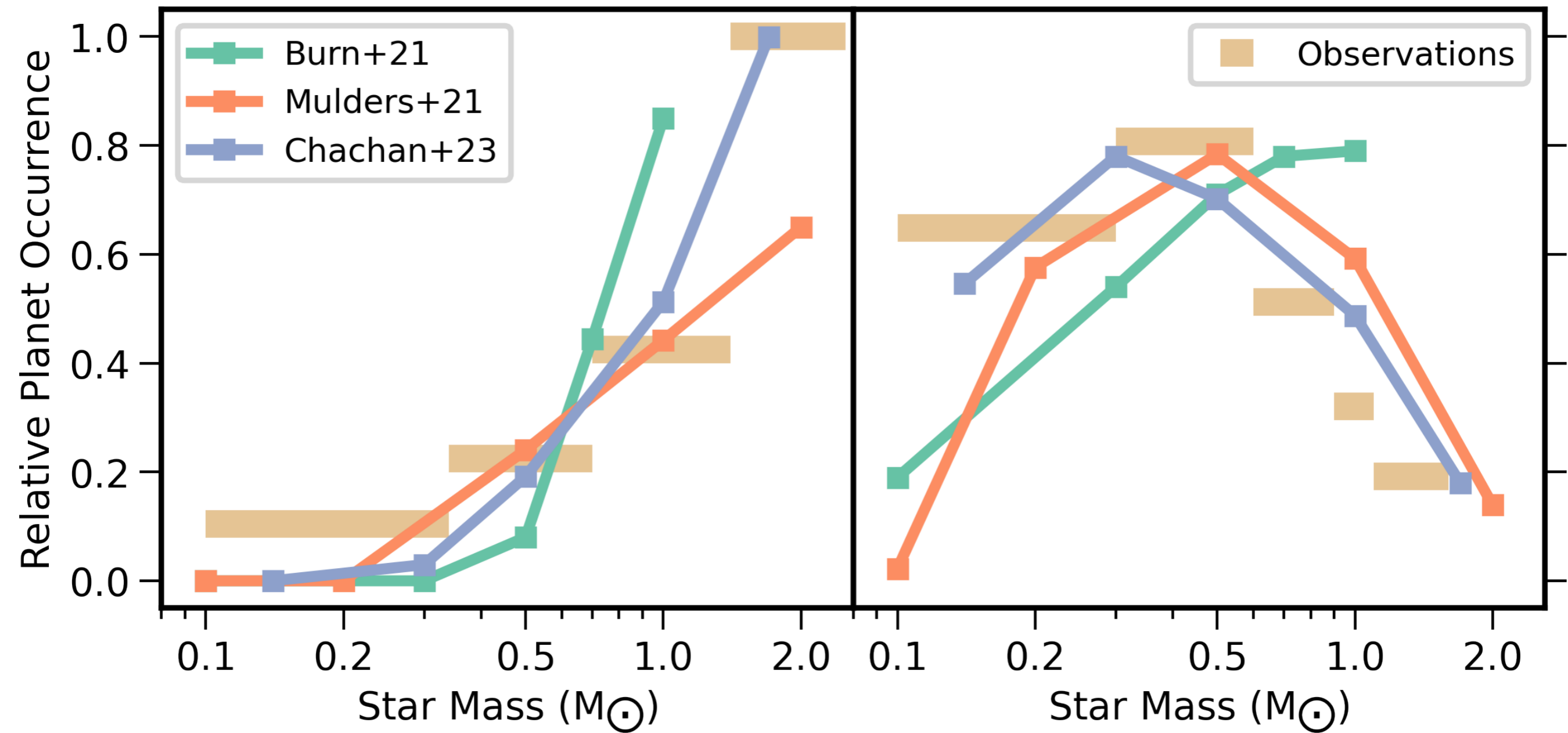


# Comparison with Formation Models

## Planet Formation Models

### Outer Planets

### Inner Planets

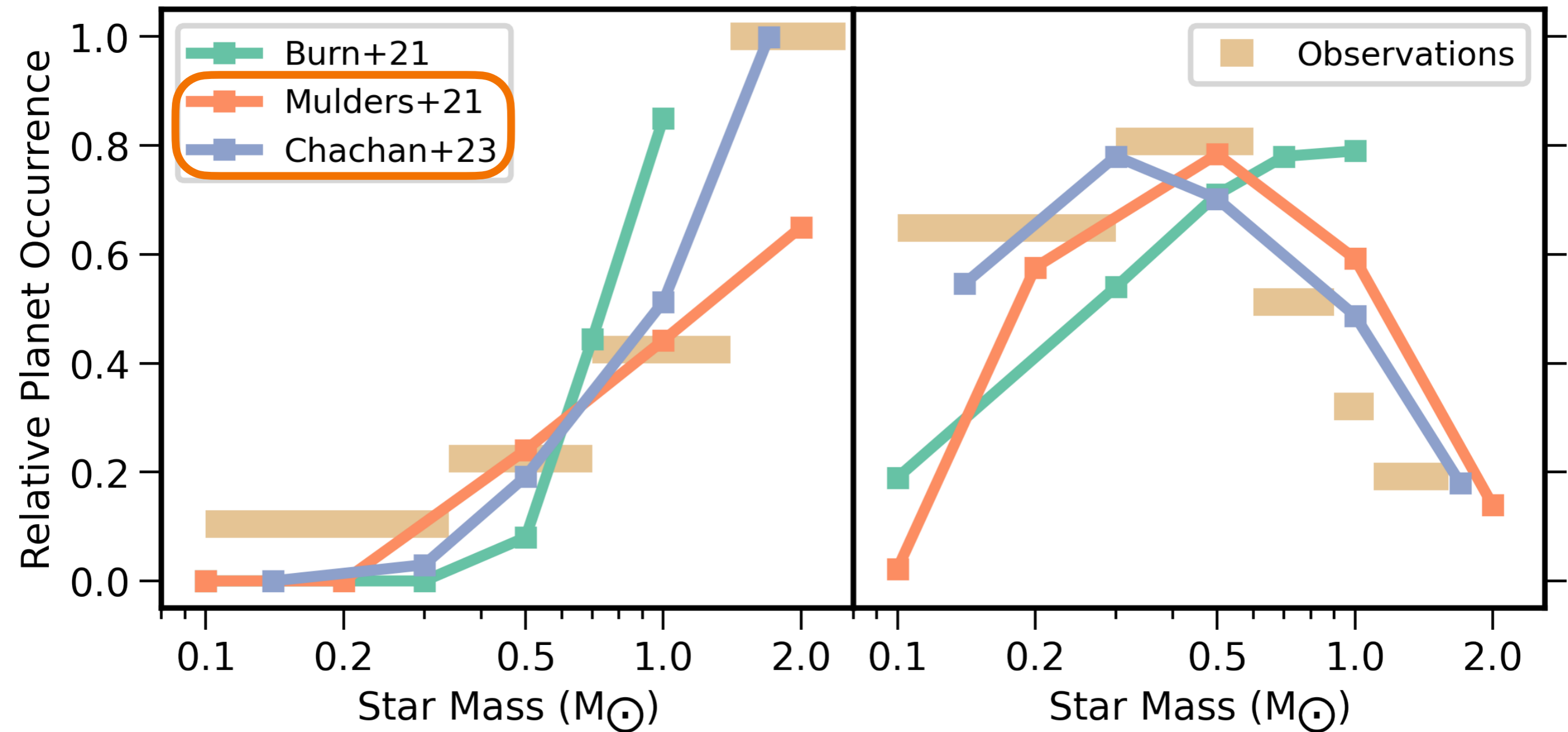


# Comparison with Formation Models

## Planet Formation Models

### Outer Planets

### Inner Planets



Pebble accretion describes data better than planetesimal accretion

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**About ~50% of FGK stars have planetary systems of sub-Neptunes (peas in a pod)  
Planet occurrence rate >100%**

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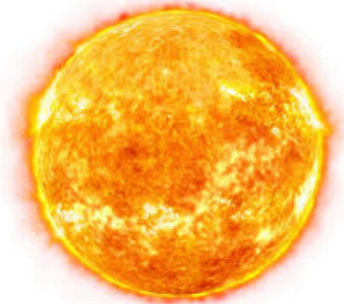


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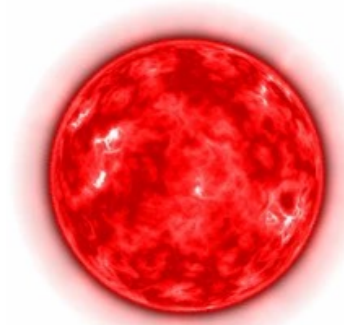


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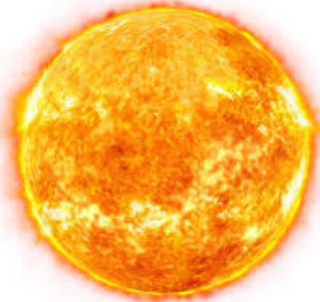


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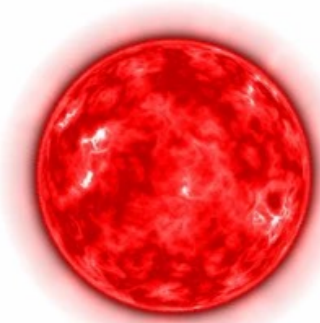


**About ~10% of stars have earth analogues  
(planets similar in size and orbital period as earth)  
But with big uncertainty from extrapolation/reliability**

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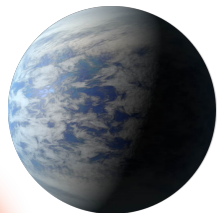
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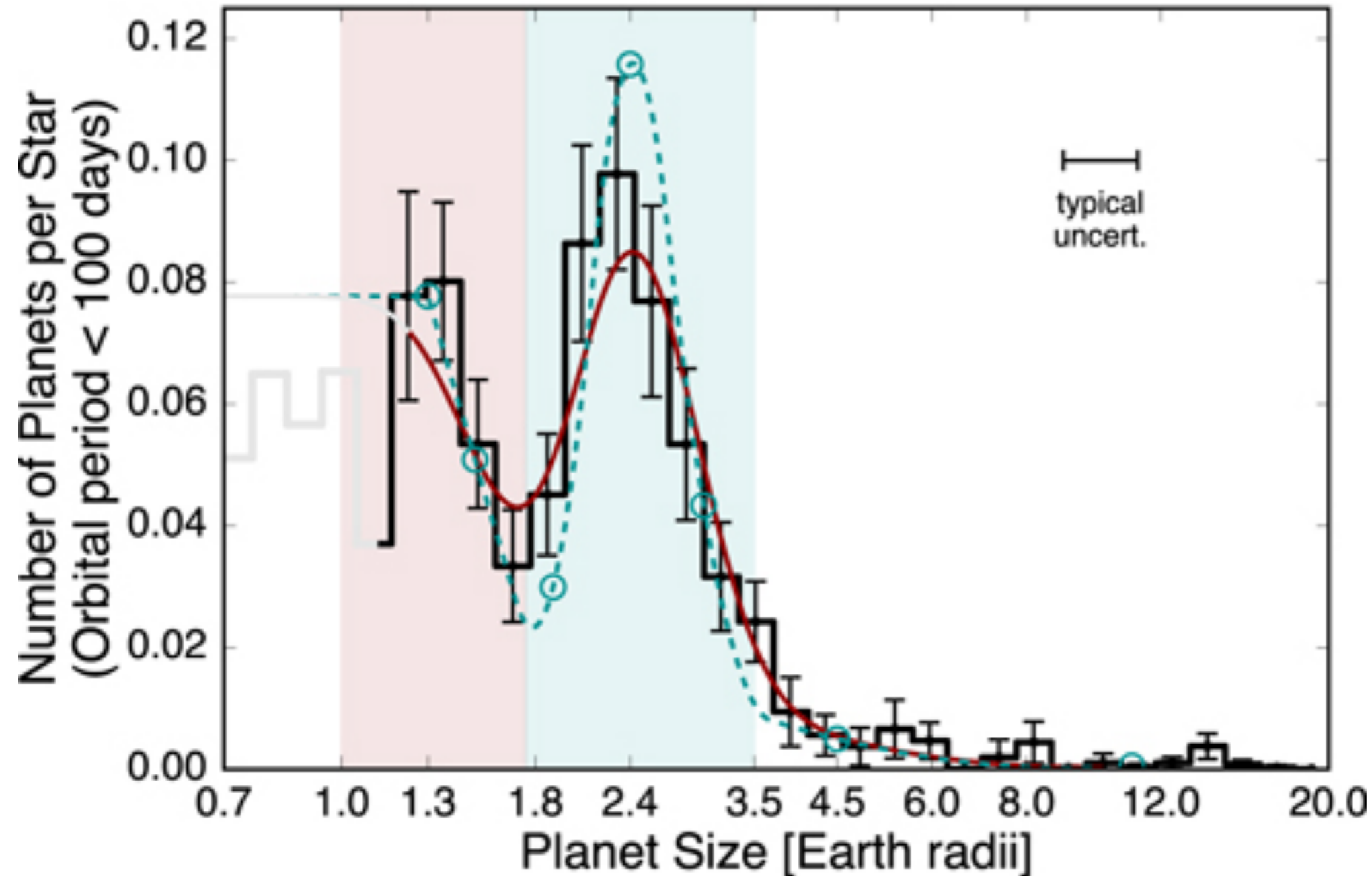


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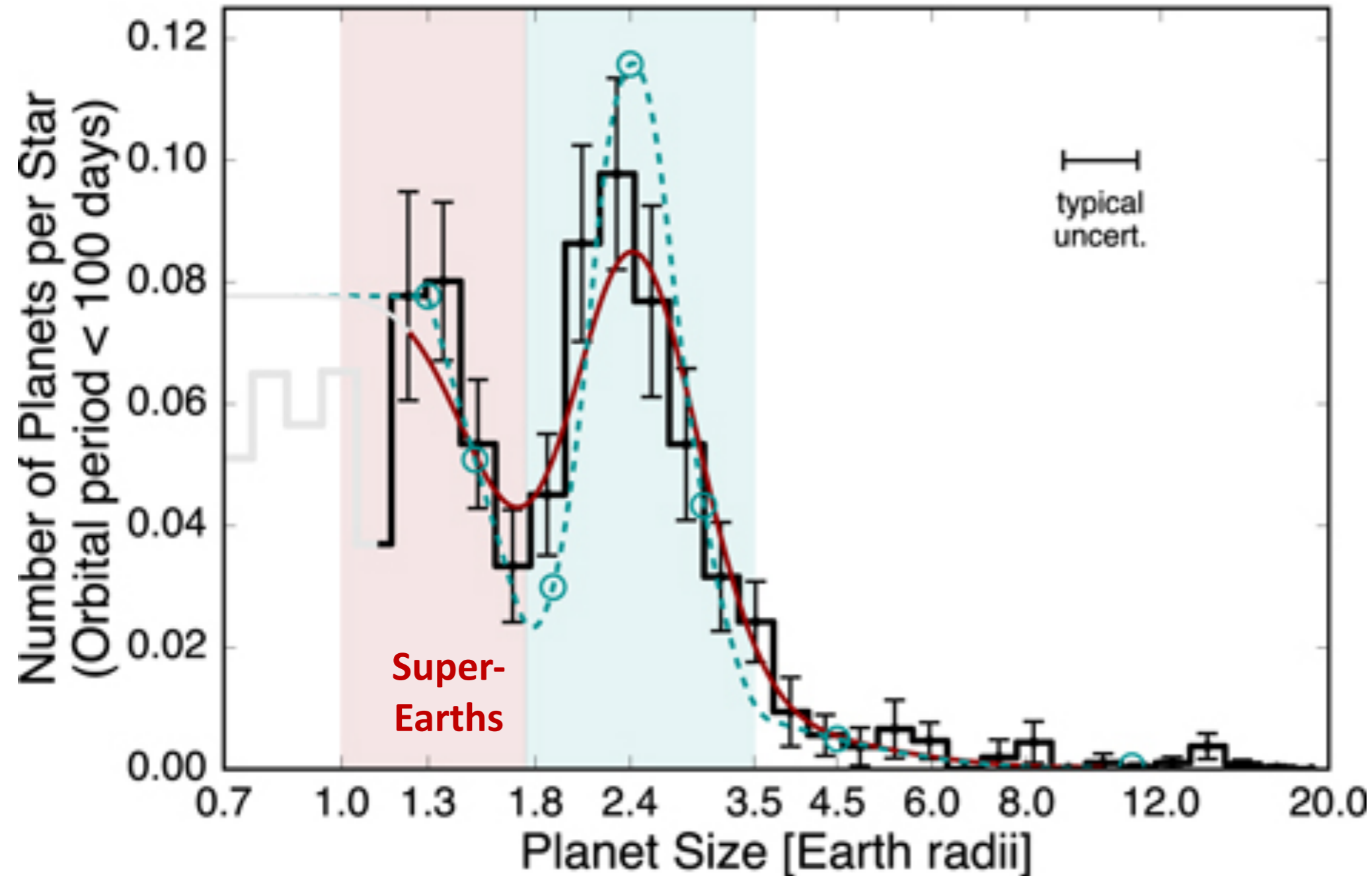


**All surveys have a detection bias in size & period.  
Completeness varies per survey: not all surveys probe entire population of sub-Neptunes**

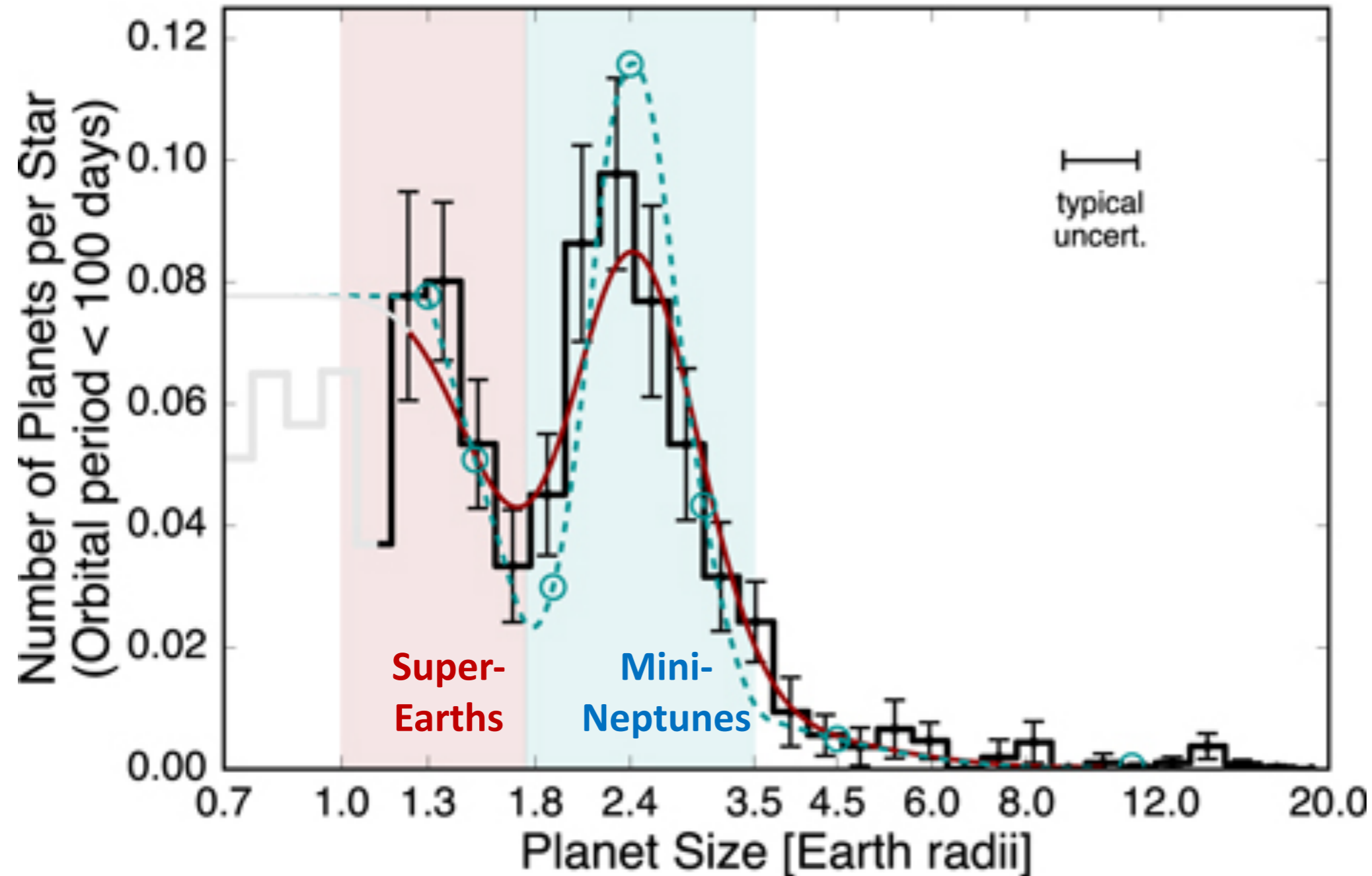
# Exoplanet Radius Distribution



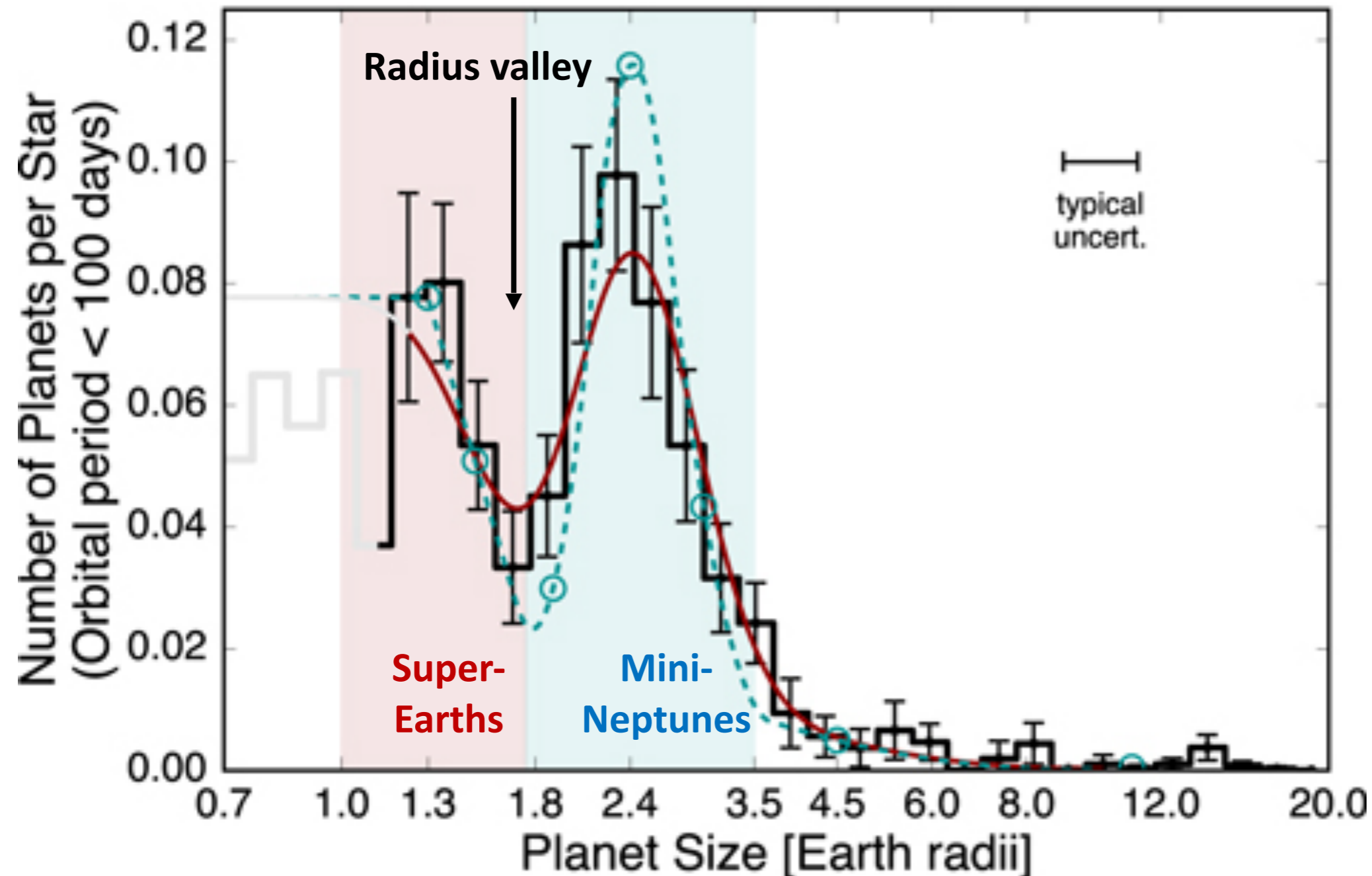
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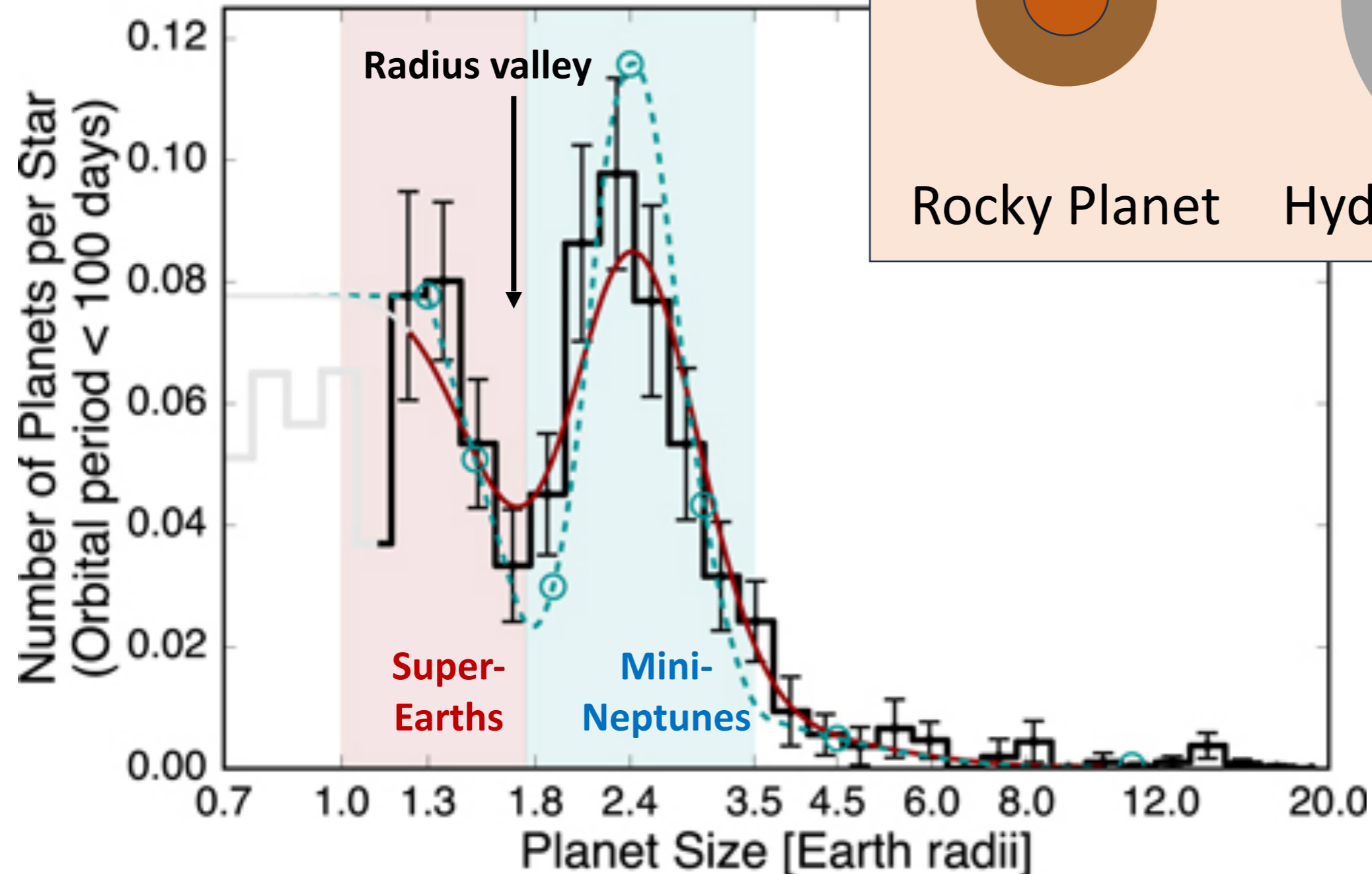
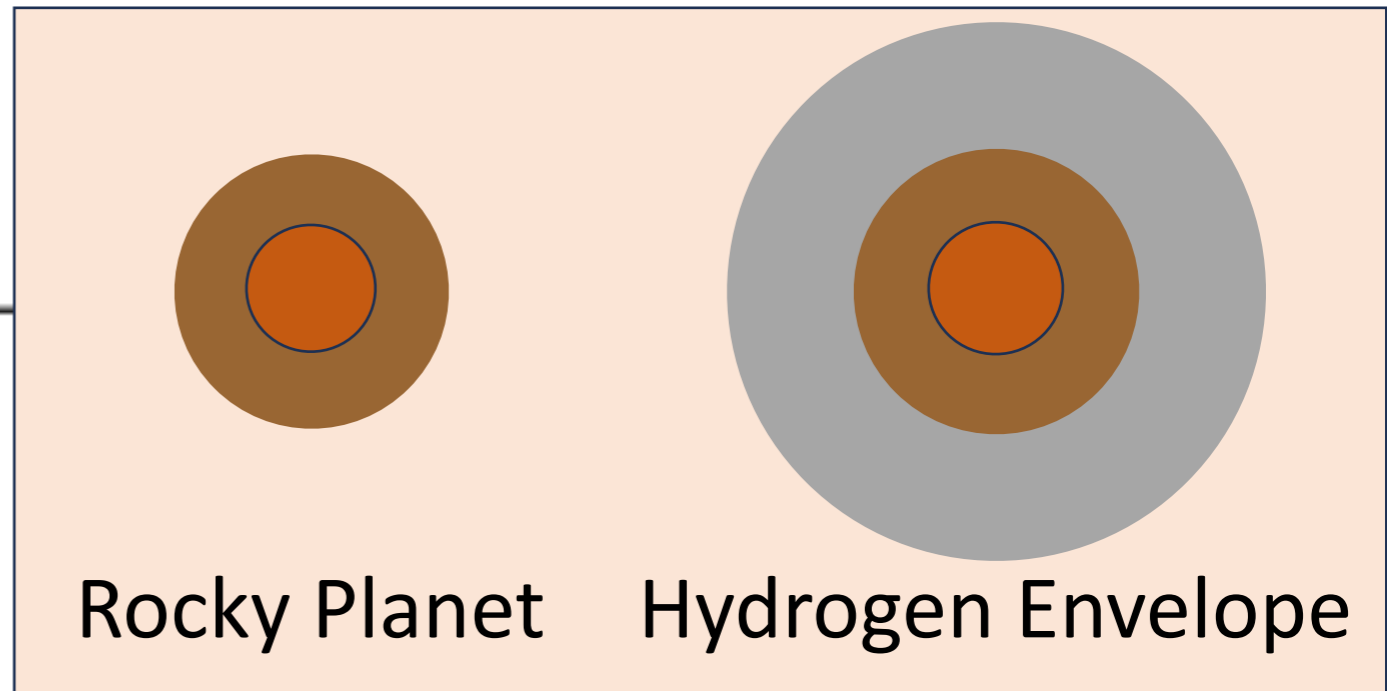
# Exoplanet Radius Distribution



39 **Radius valley splits exoplanets in two distinct populations (Fulton+17)**

# Exoplanet Radius Distribution

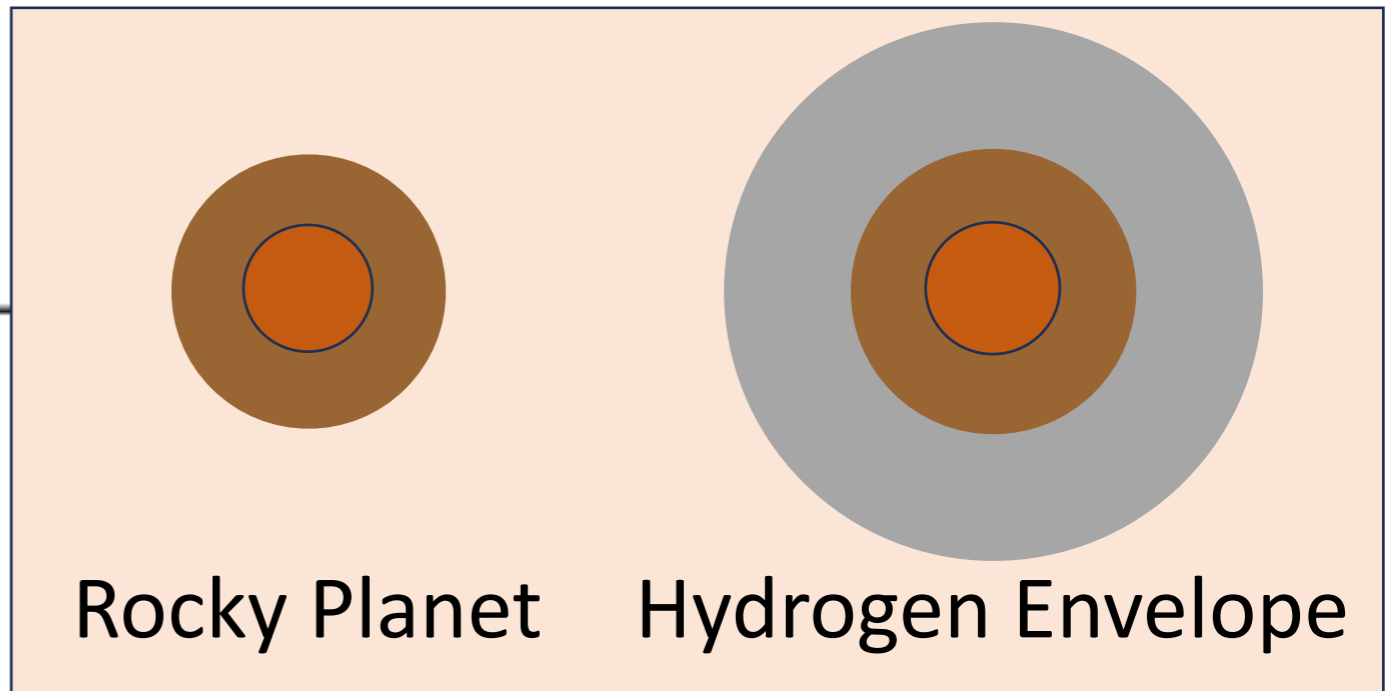
Origin: photo-evaporation  
(Owen & Wu 2017)



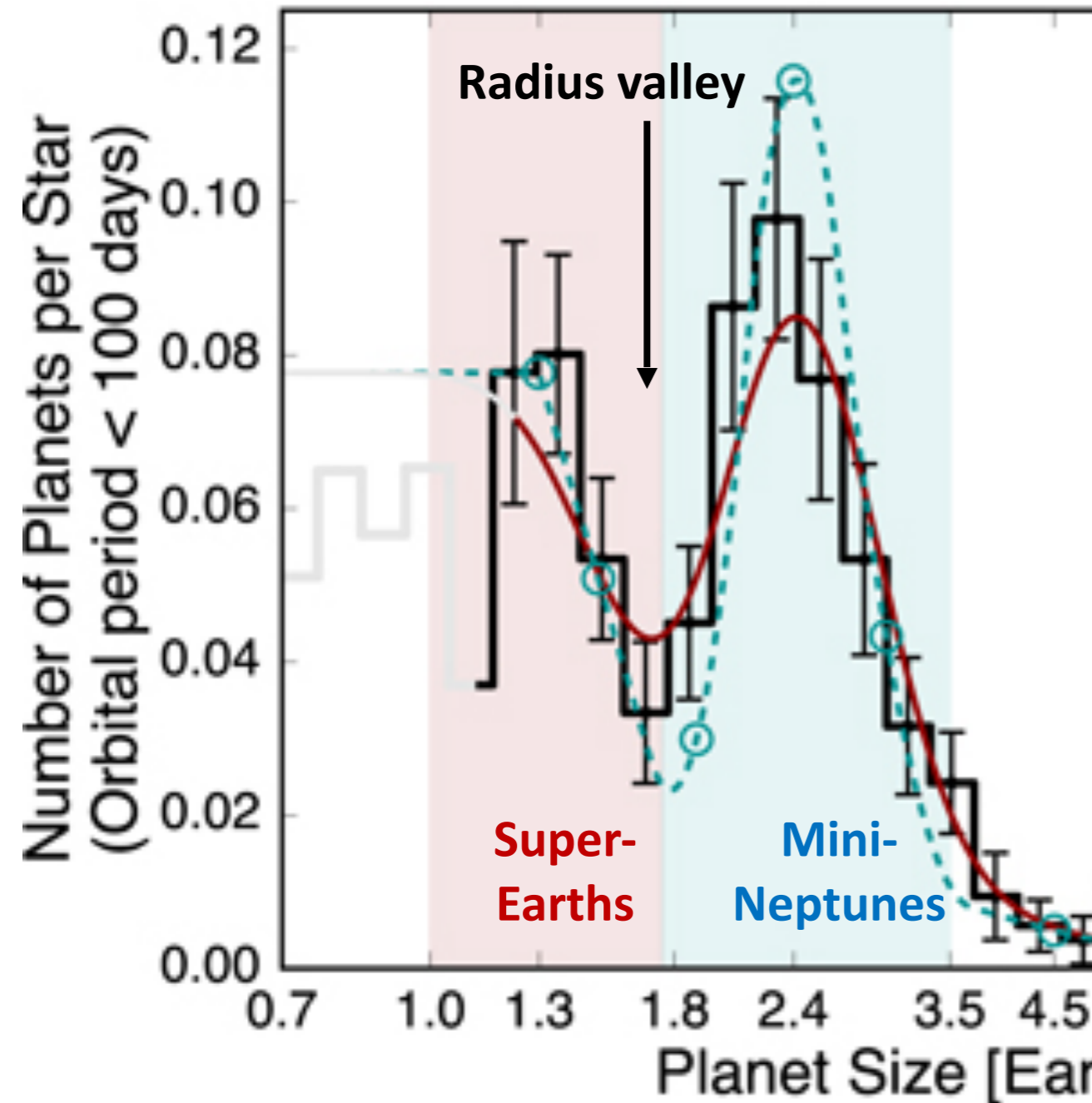
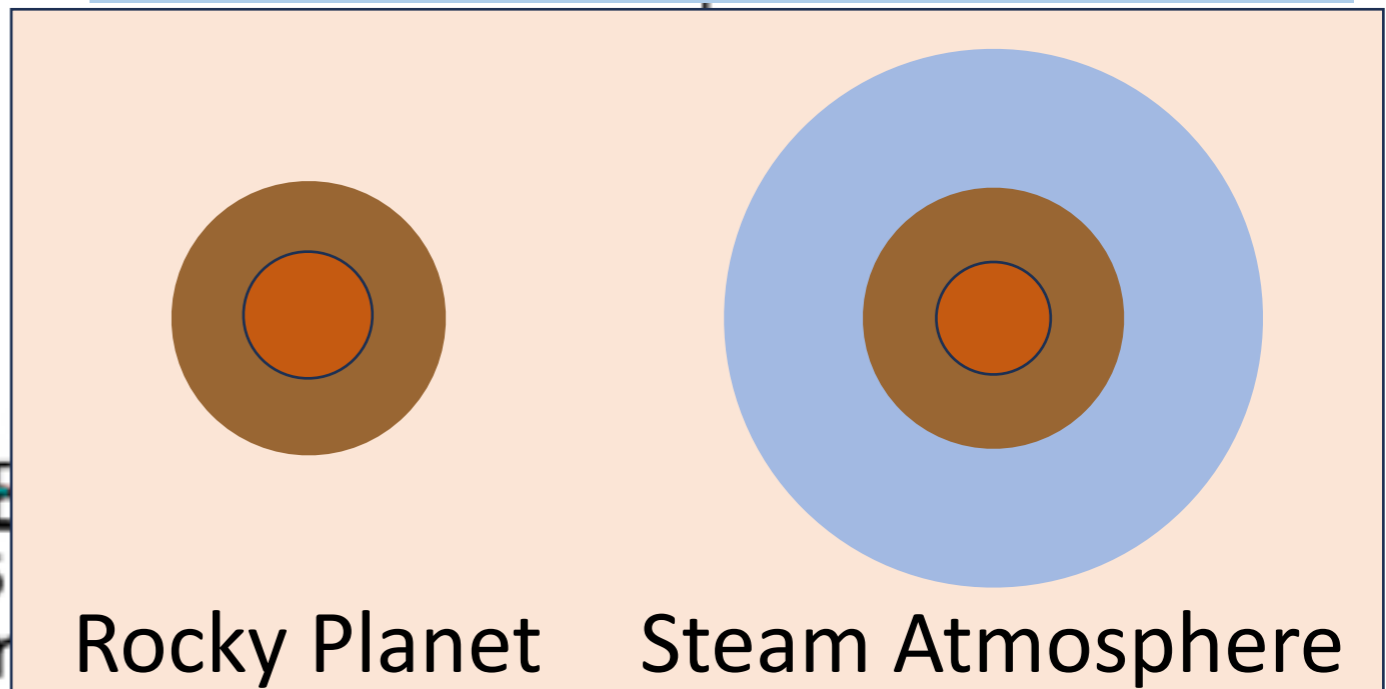
<sup>39</sup>Radius valley splits exoplanets in two distinct populations (Fulton+17)

# Exoplanet Radius Distribution

Origin: photo-evaporation  
(Owen & Wu 2017)



Origin: Migrated waterworlds  
Burn+ 2024; Chakrabarty+ 2026

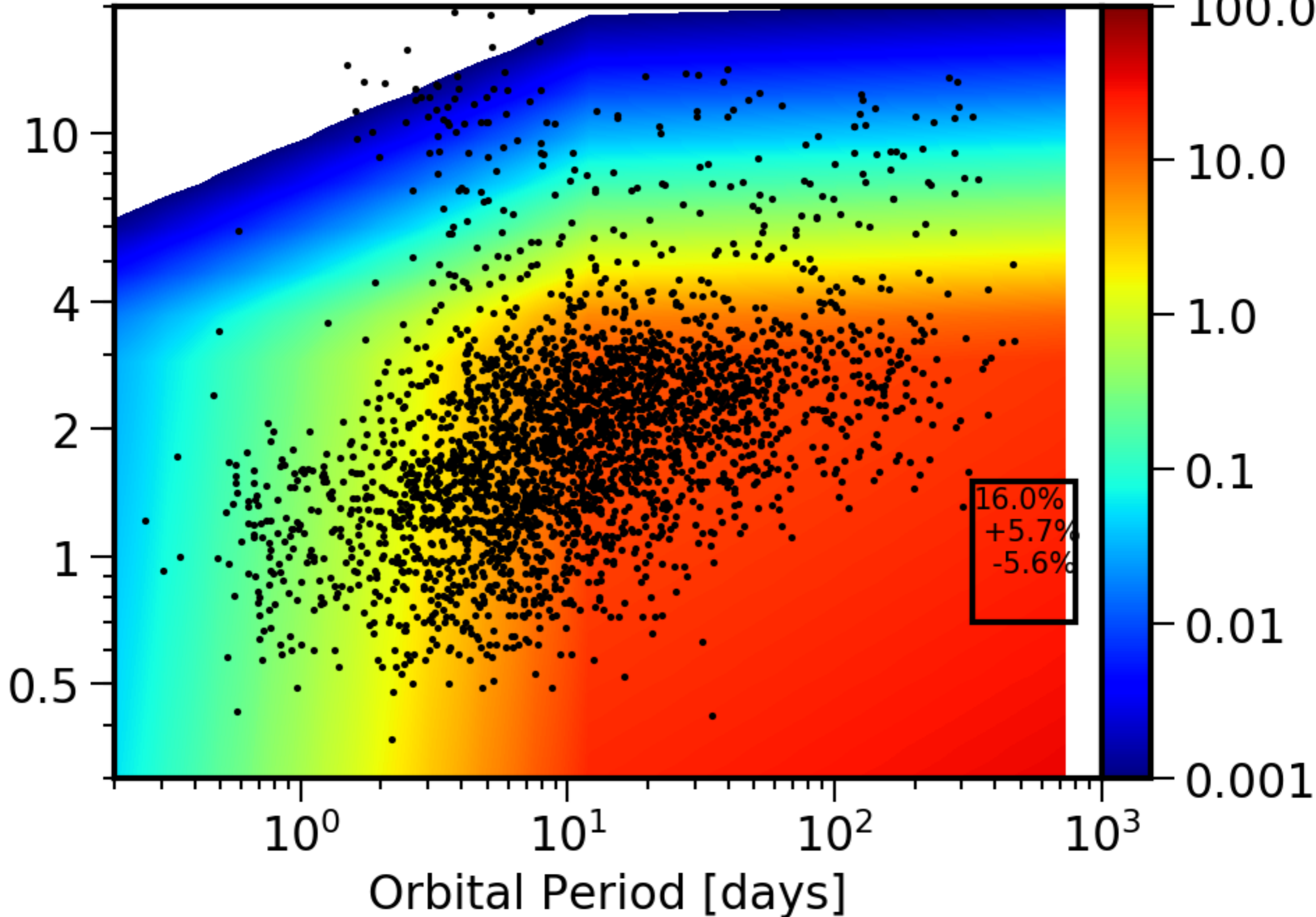


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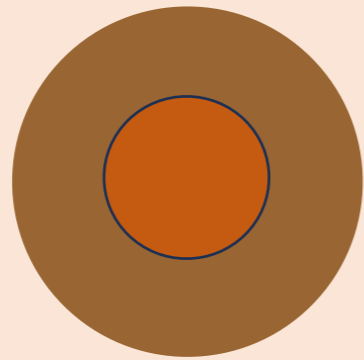
# Backup slides

# Occurrence (dlnR dlnP)

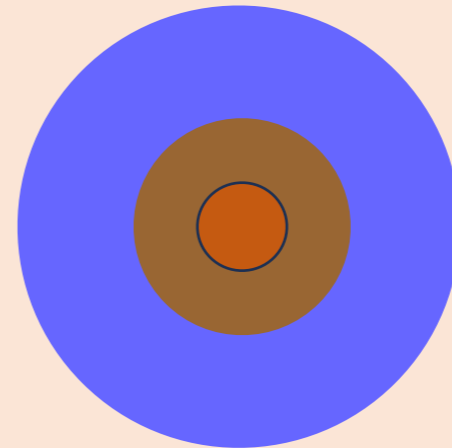
$M [M_{\oplus}]$



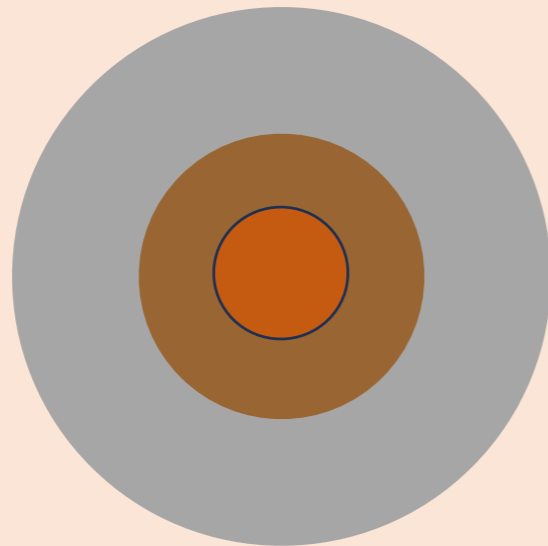
# Classic Scenario: Liquid Water



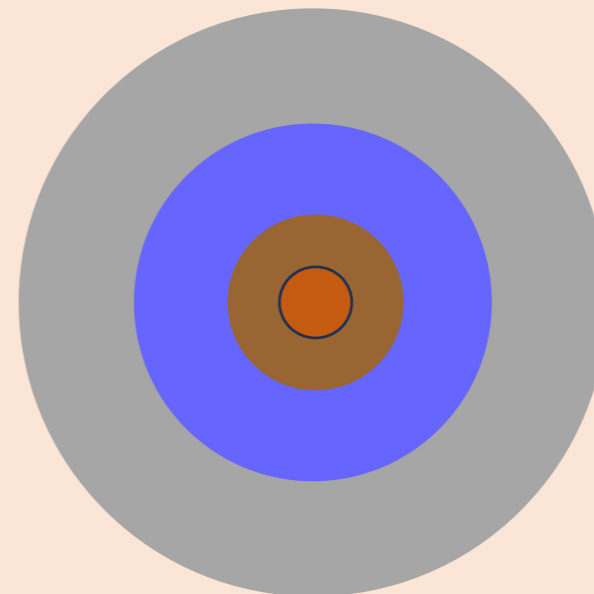
Rocky Planet



Water World

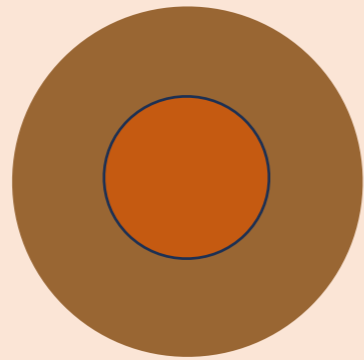


Mini-Neptune (?)

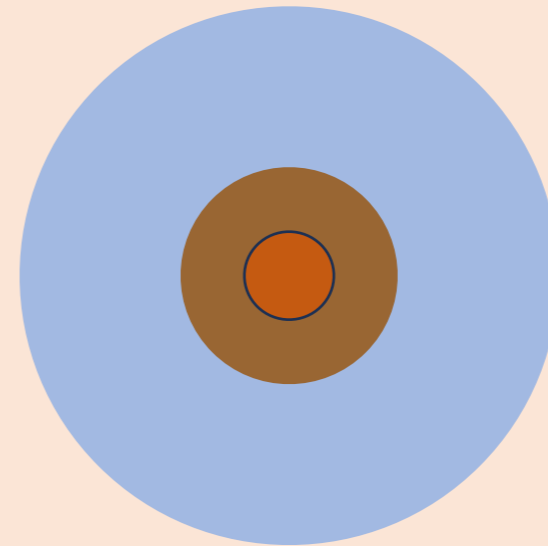


Hycean?

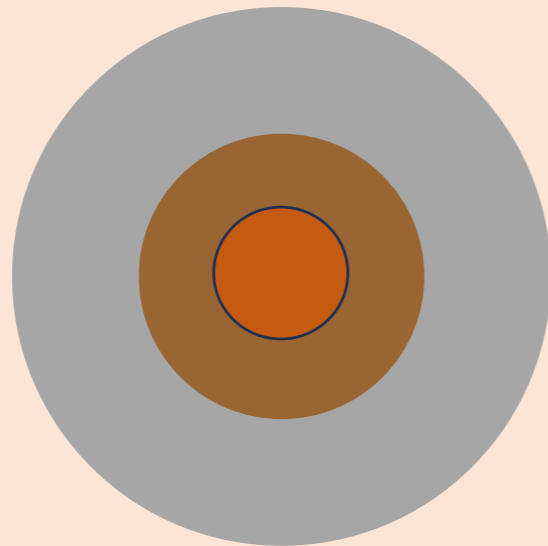
# Alternative Scenario: Steam Worlds



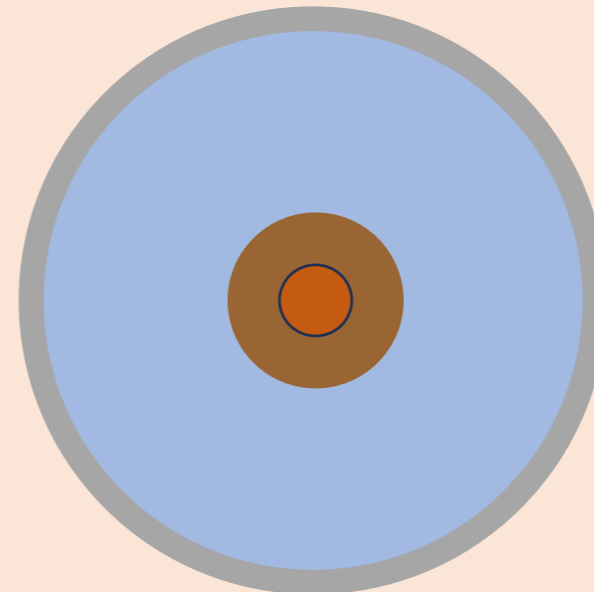
Rocky Planet



Steam World

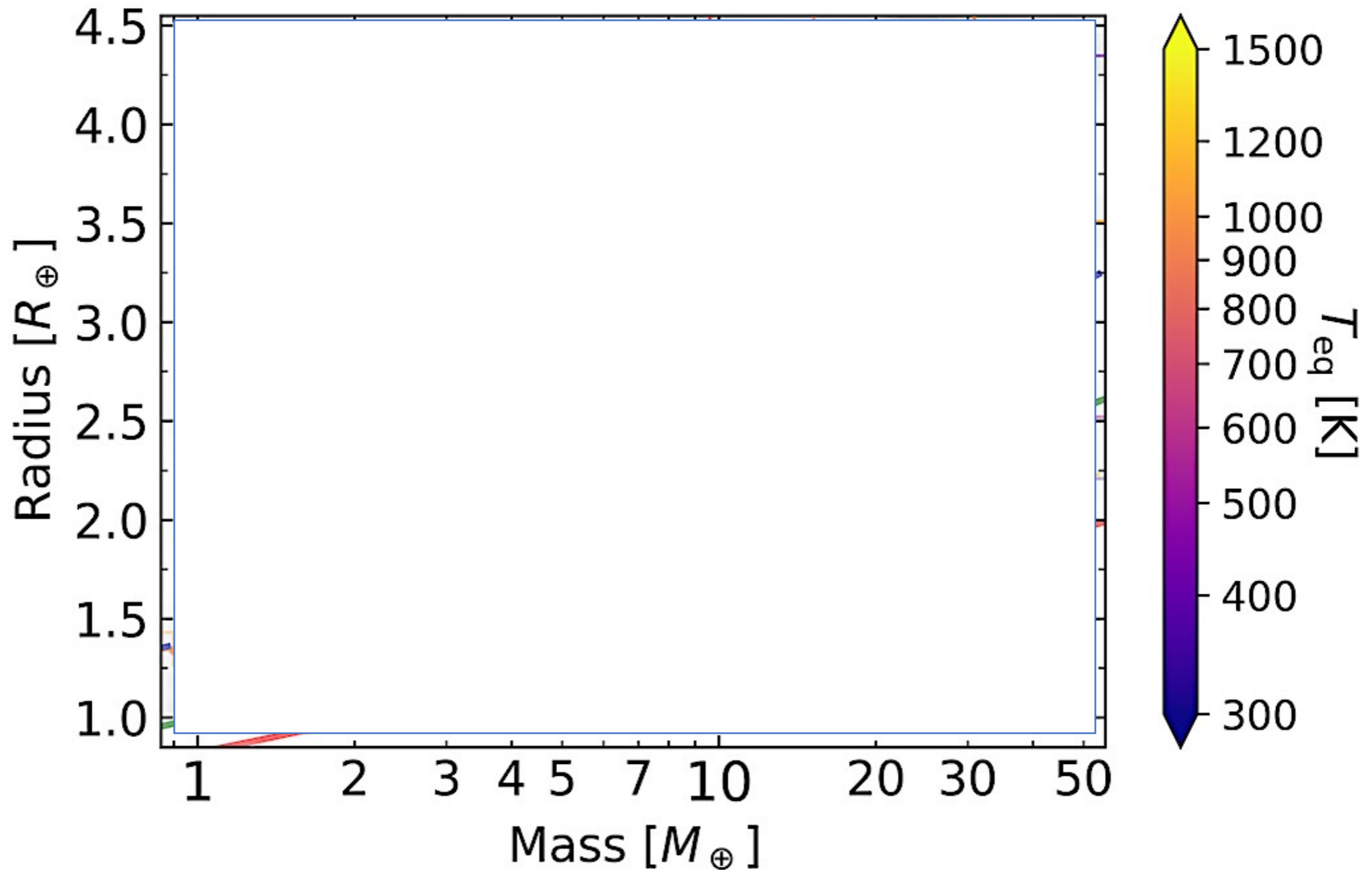


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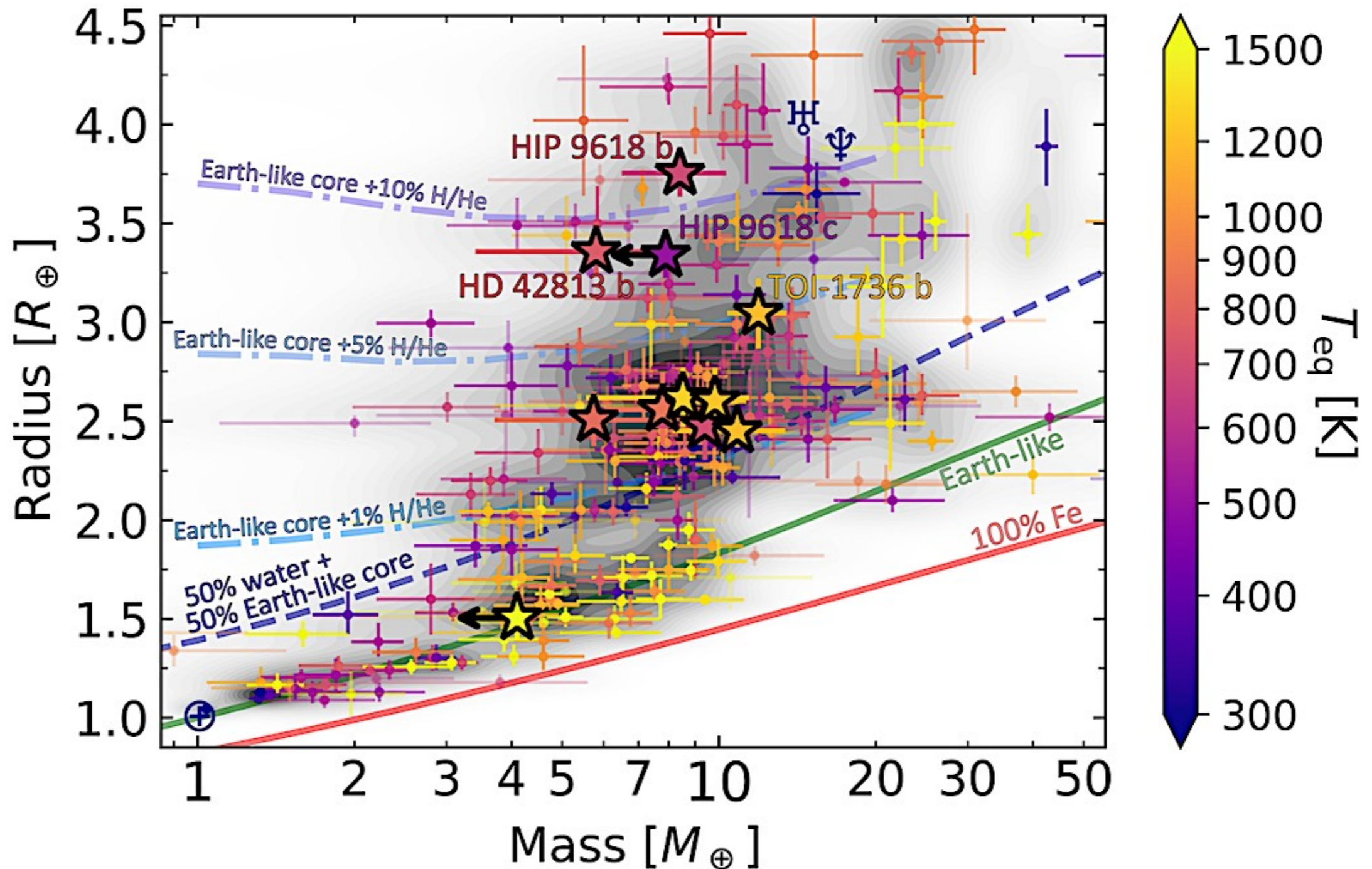


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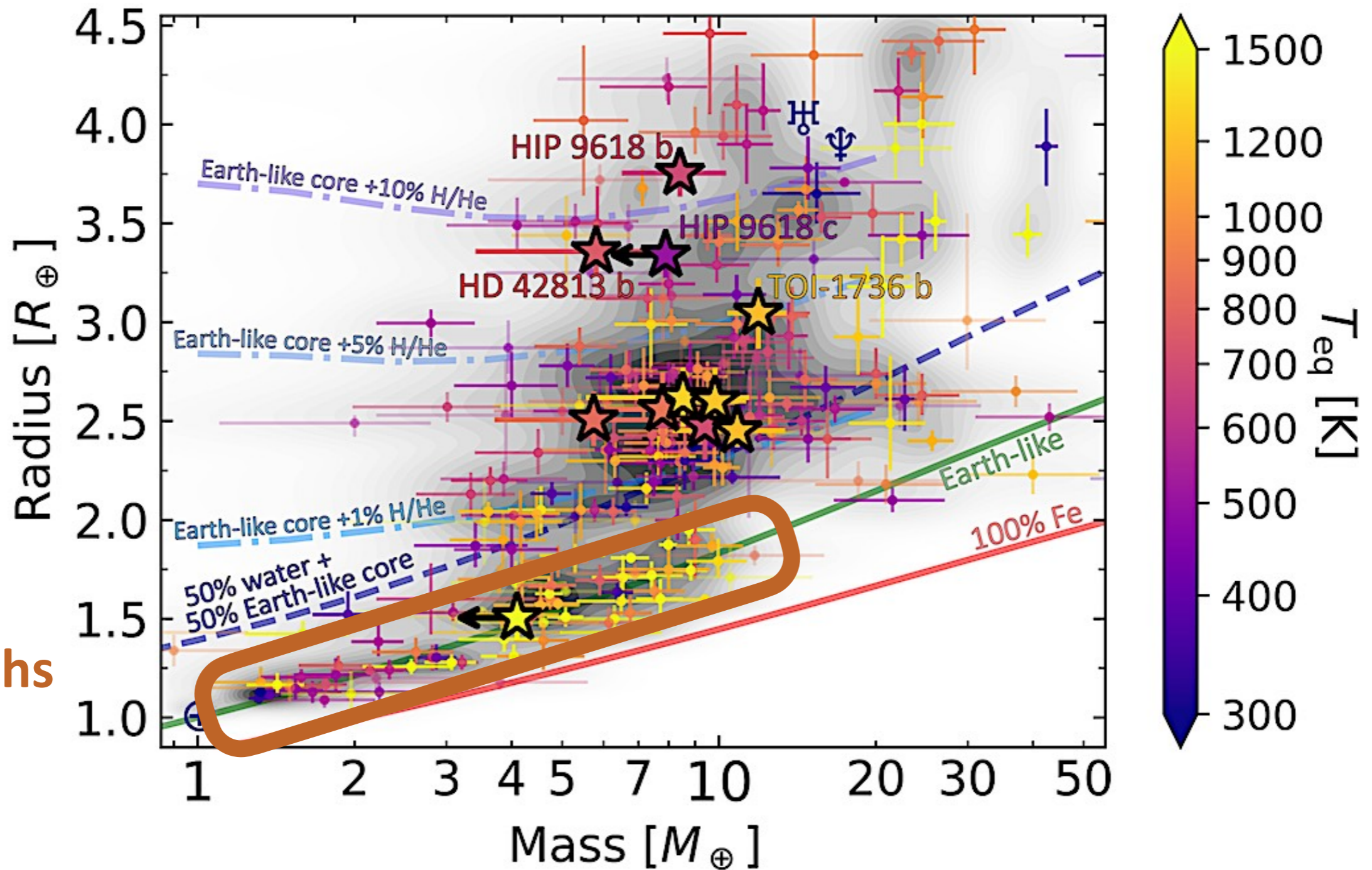
# Exoplanet Mass Radius Diagram



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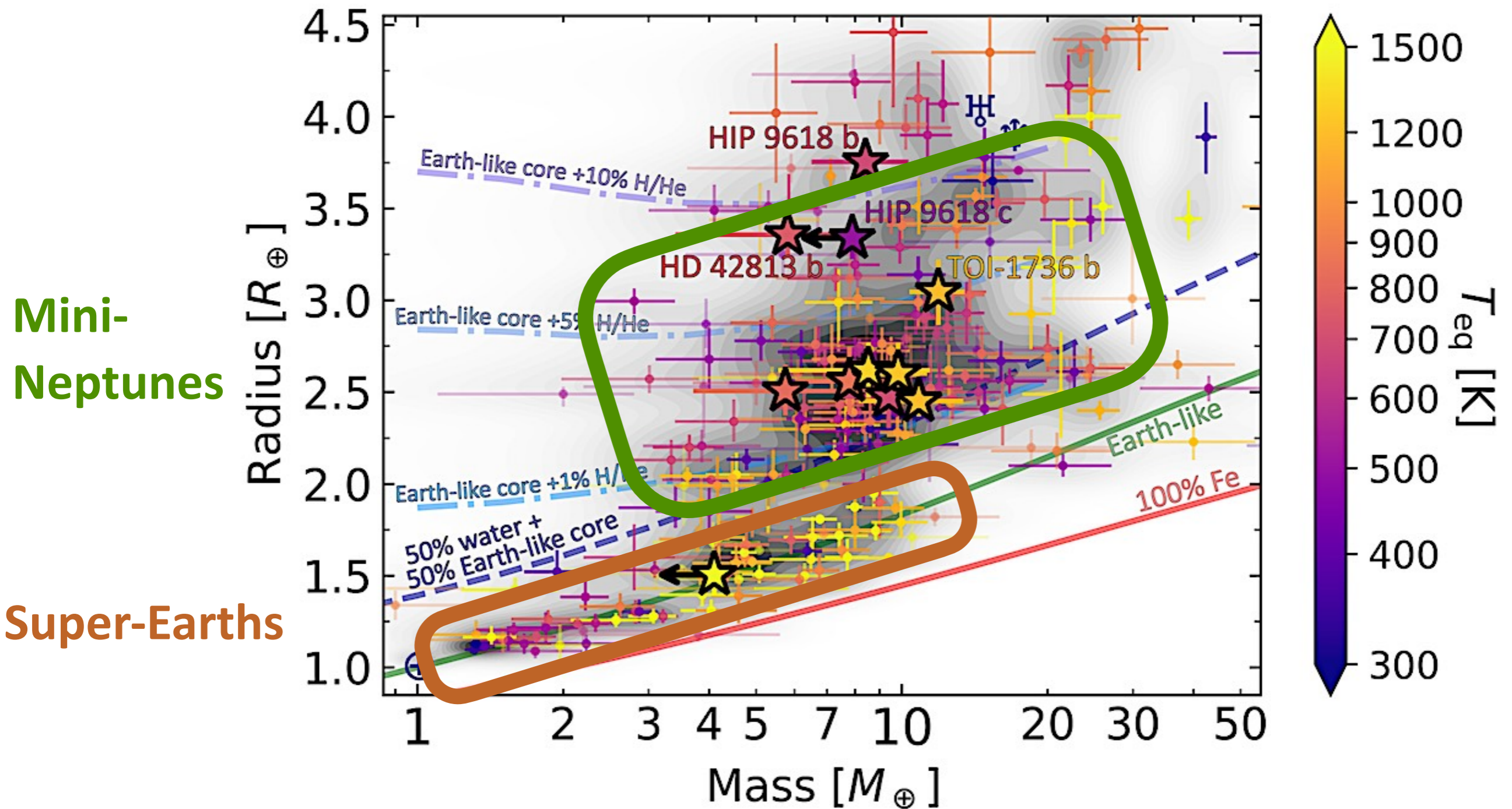


# Exoplanet Mass Radius Diagram



Super-Earths

# Exoplanet Mass Radius Diagram



# Alternative Scenario: Steam Worlds

