# Architectures of Exoplanetary Systems: A Multi-planet Model for Reproducing the Radius Valley and Intra-system Size Similarity of the Kepler Planets


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Origins Seminar
Steward Observatory/LPL
University of Arizona
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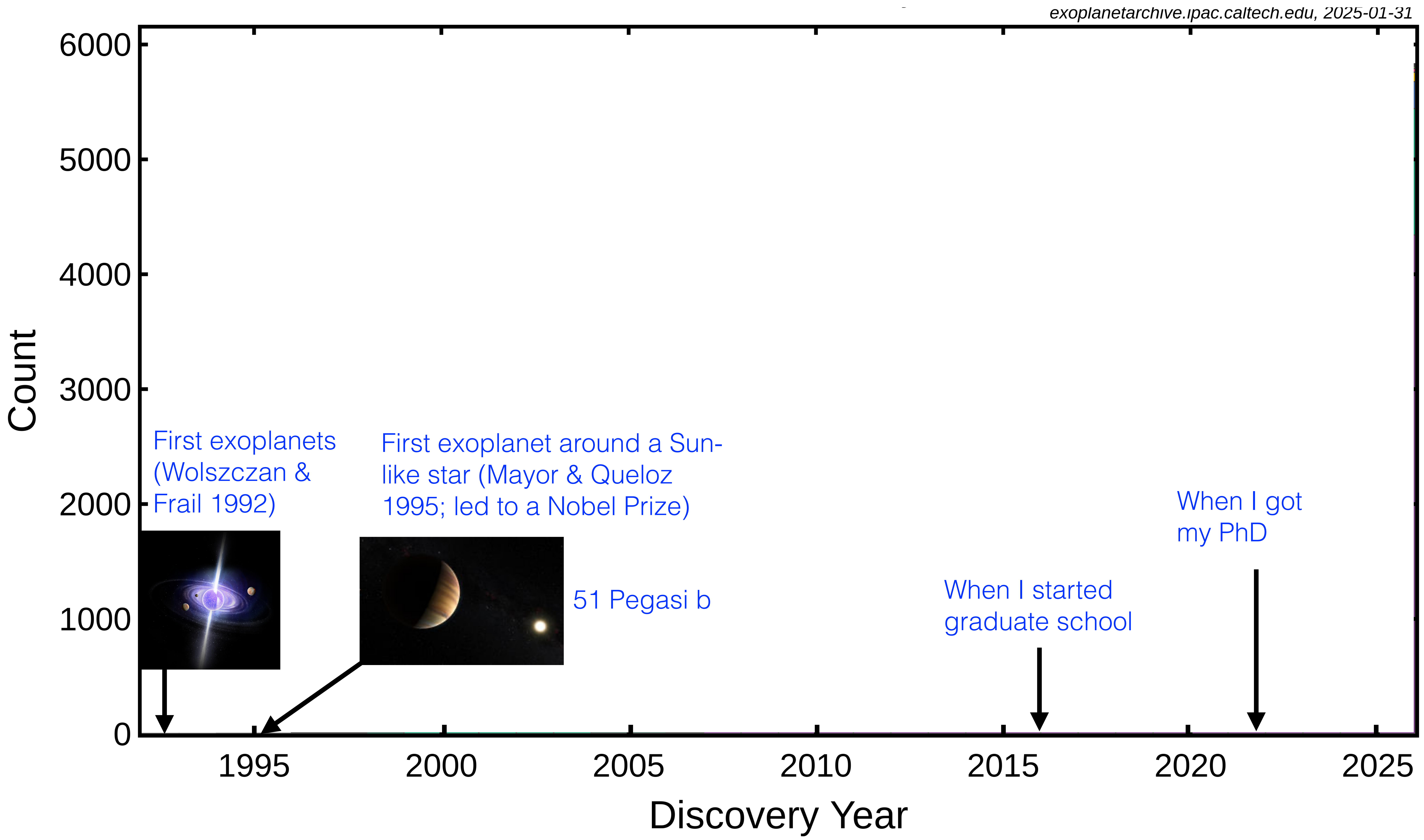
# The first exoplanets were discovered just about three decades ago



# The number of known exoplanets has exploded in the past decade

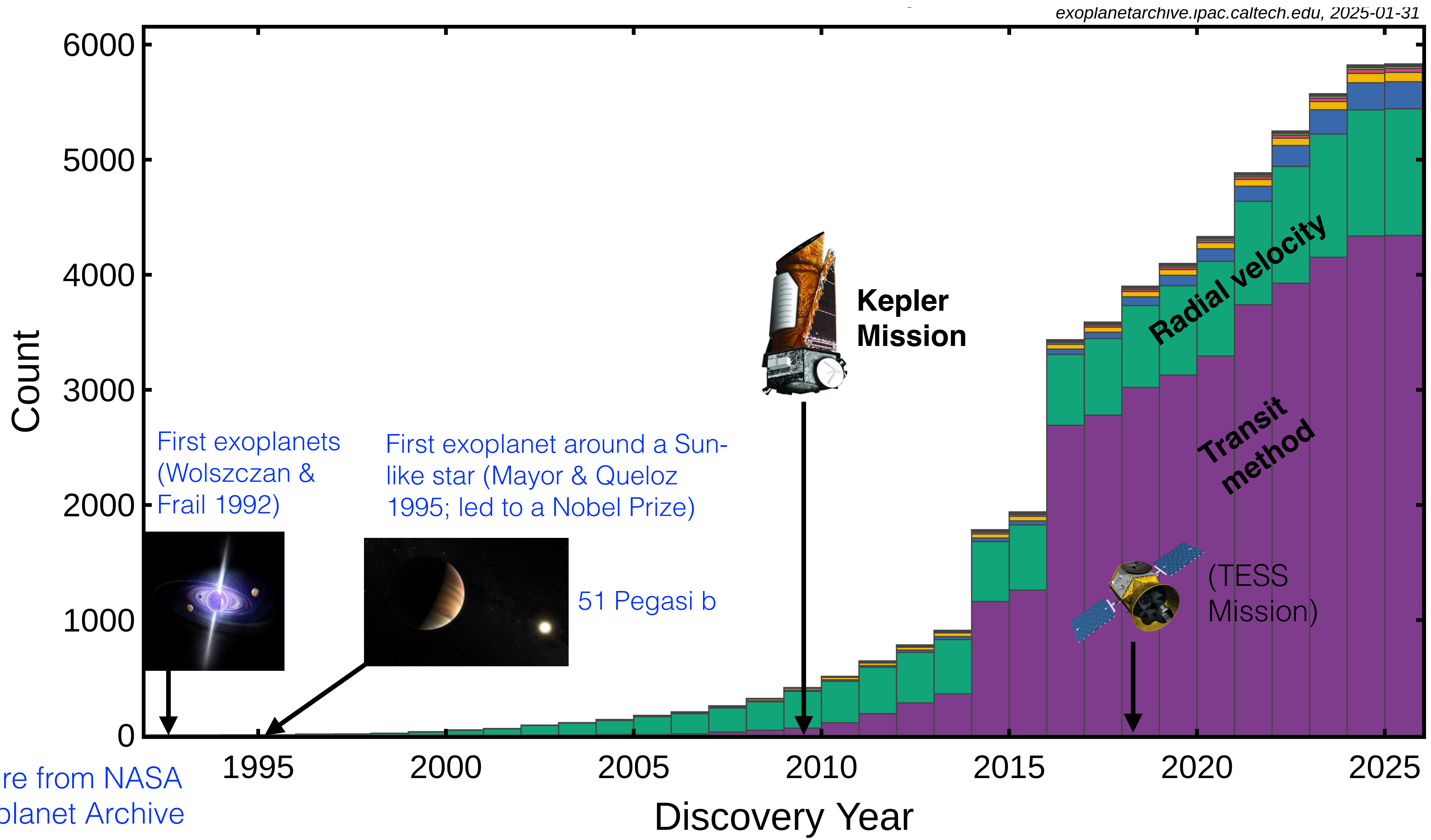
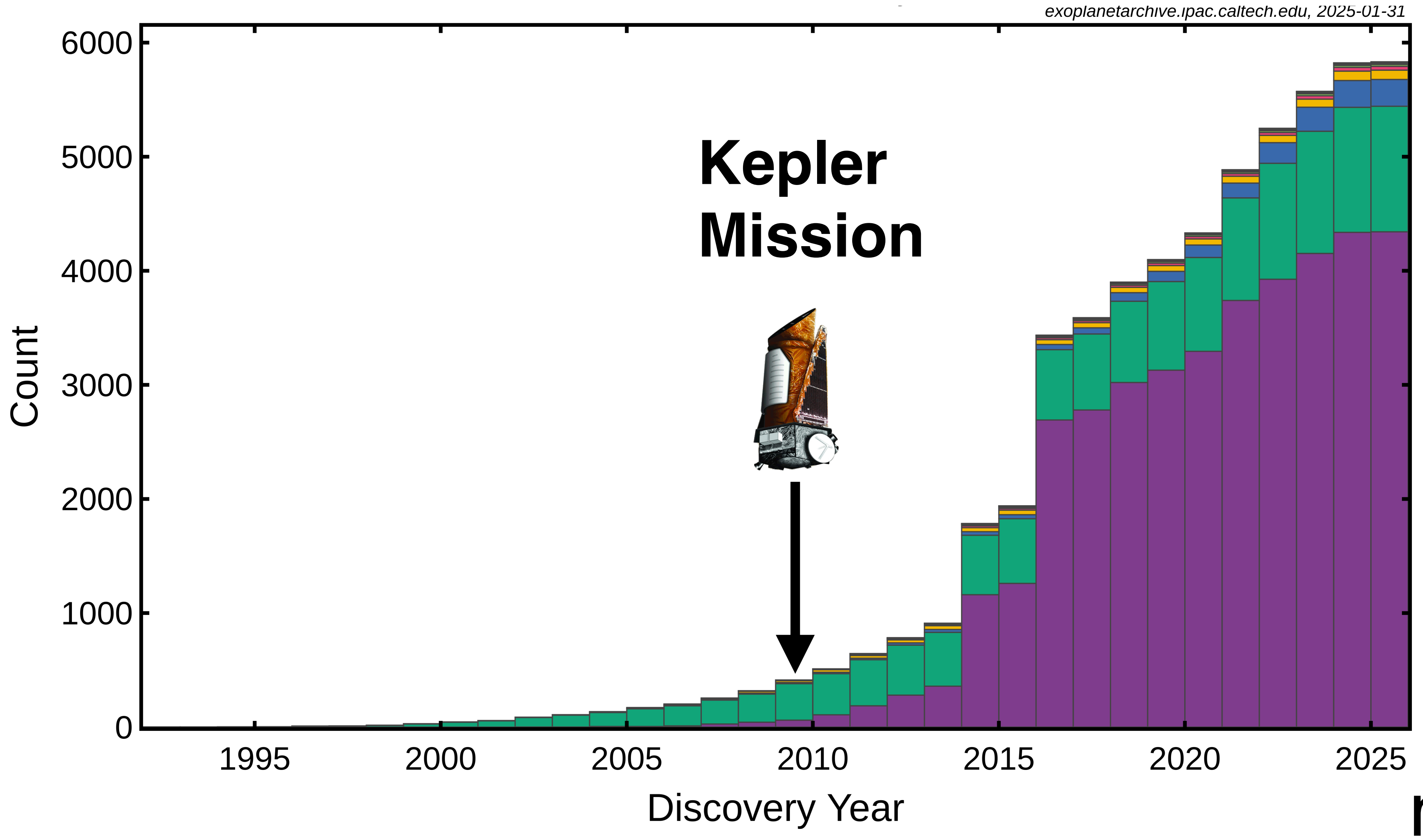
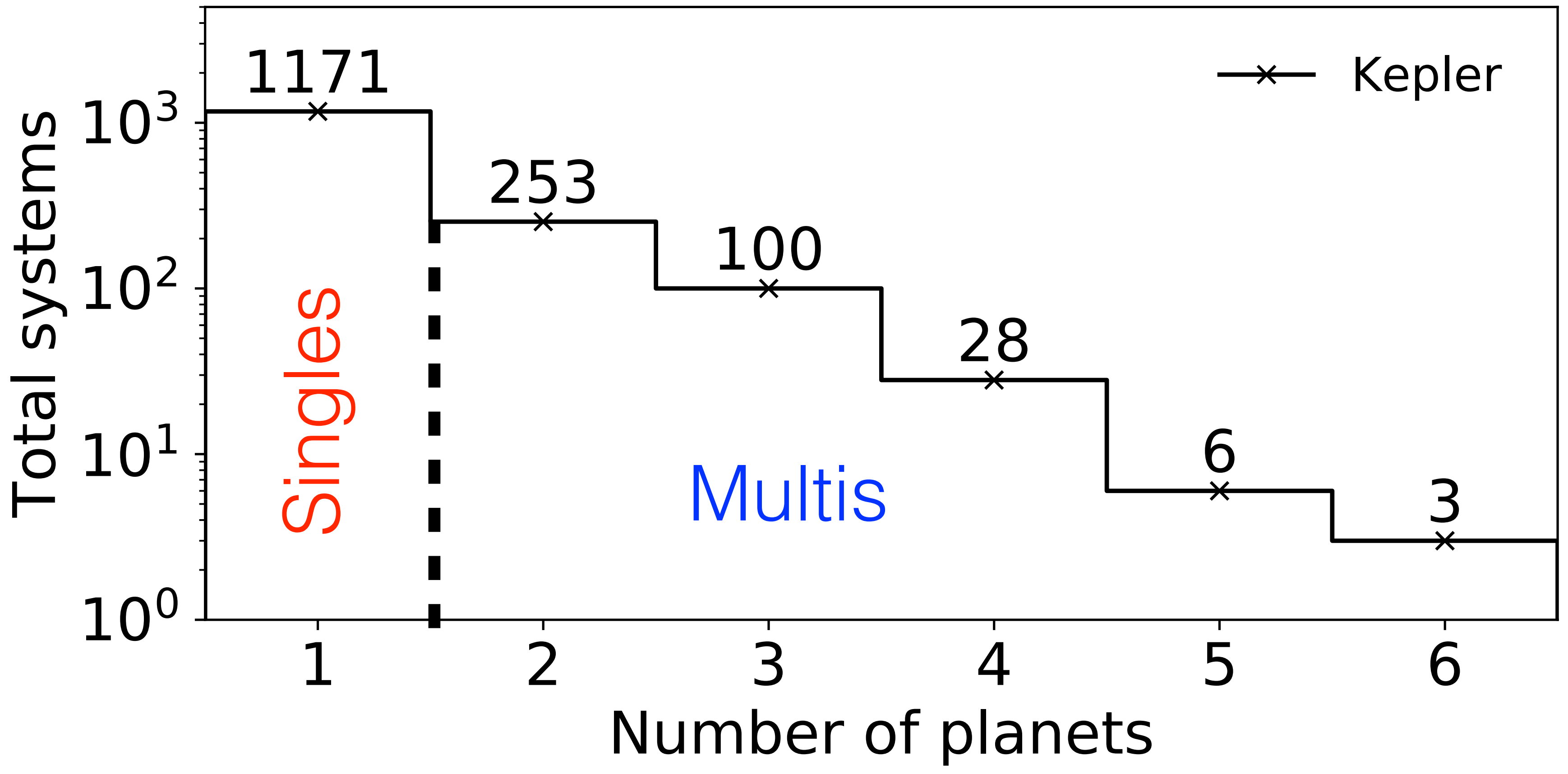



Figure from NASA Exoplanet Archive

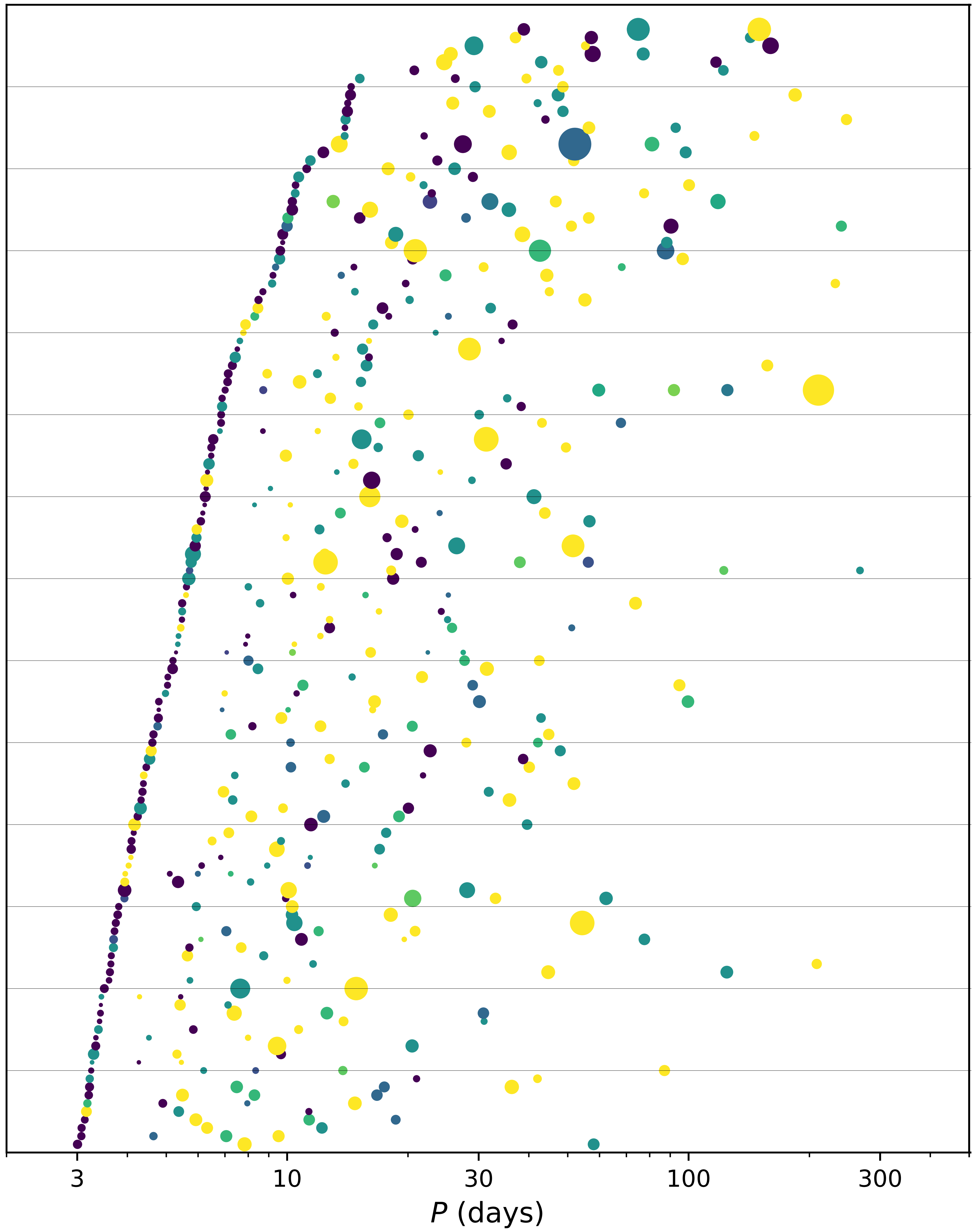
# Kepler's multi-transiting systems are extremely informative to study



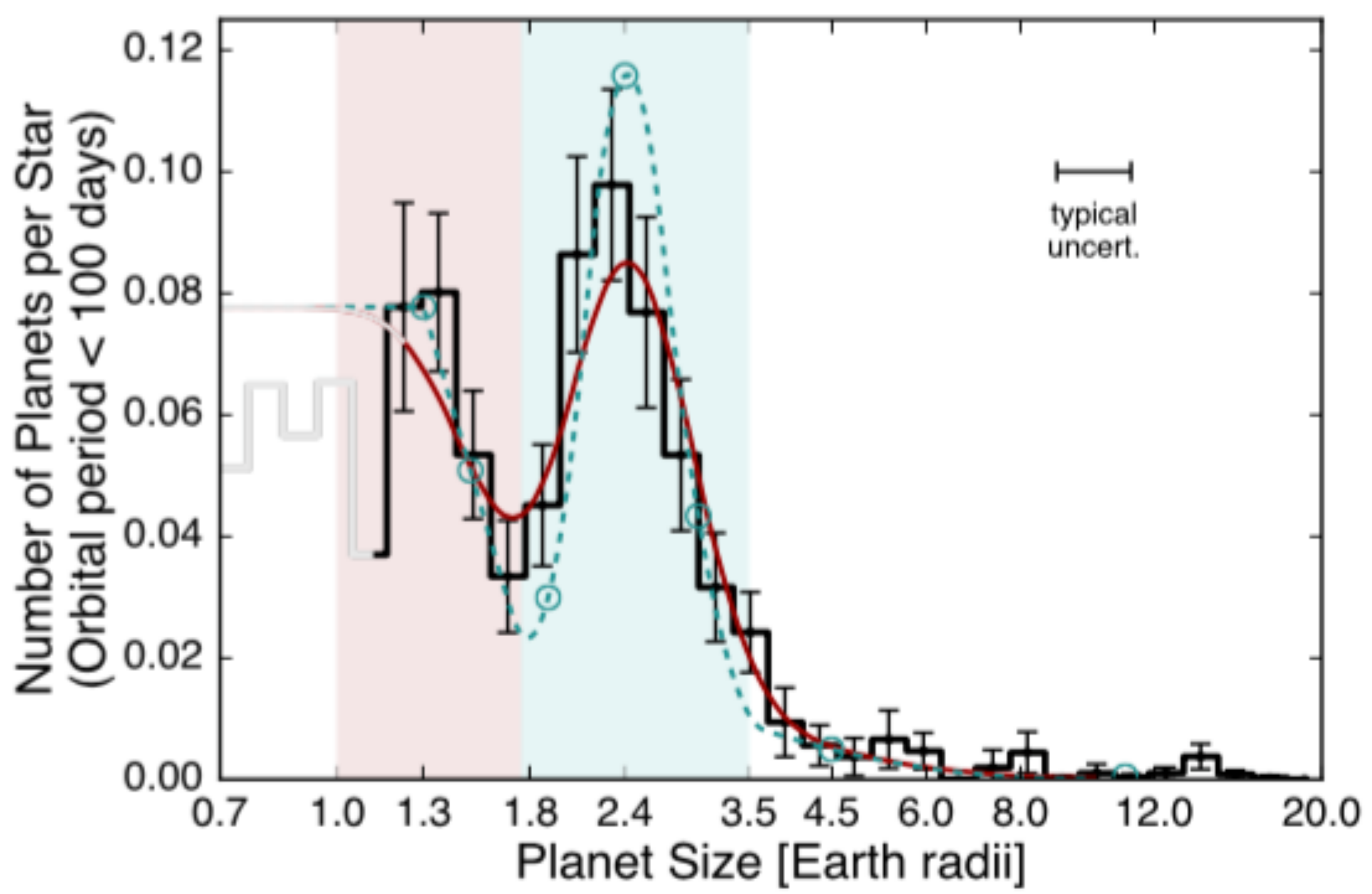

Many planets are in multi-transiting systems!

Kepler systems with 3+ planets



# The observed distribution of planet sizes revealed two distinct patterns

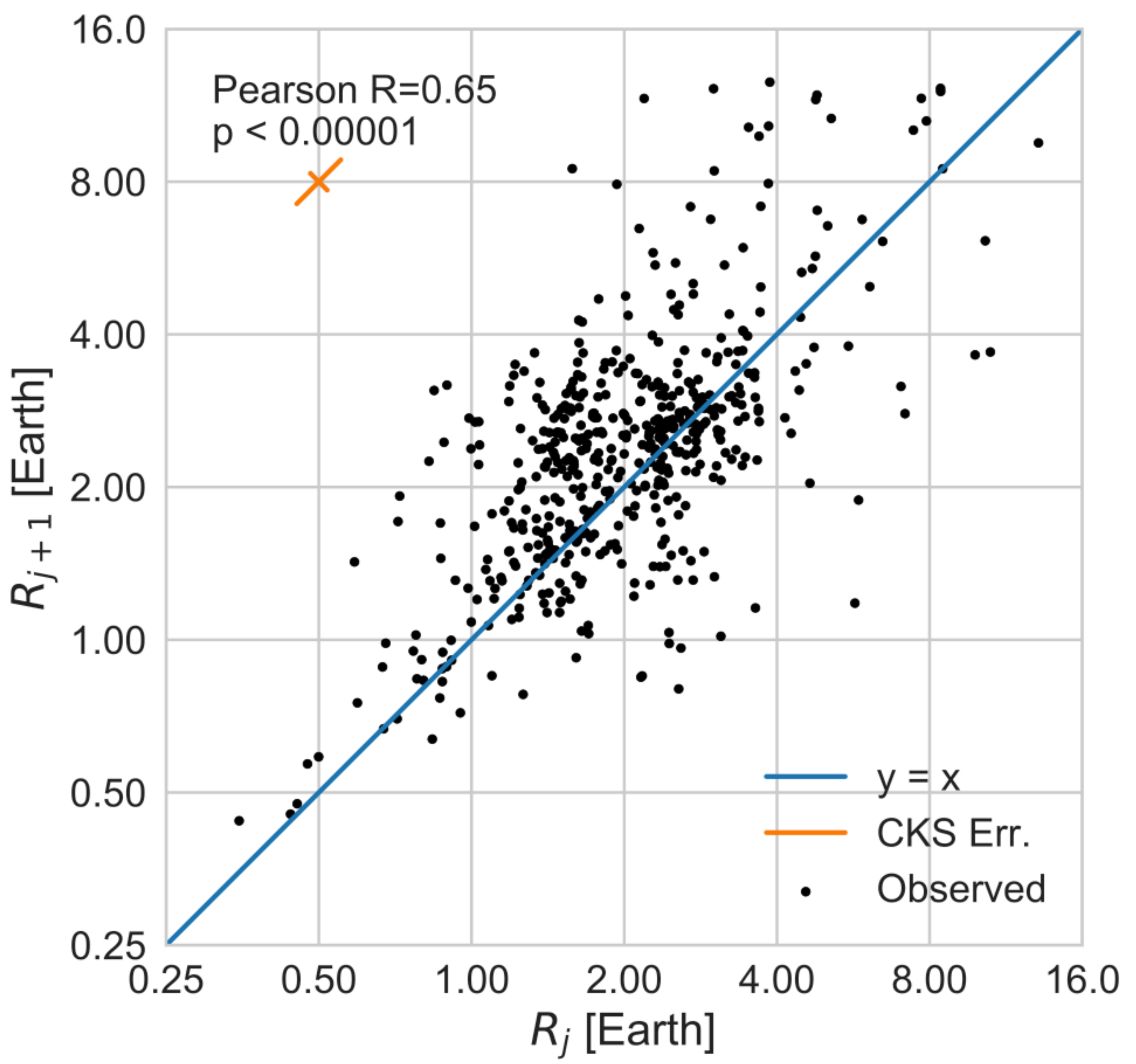
A “radius valley”




Owen & Wu (2013)
Lopez & Fortney (2013)
**Fulton et al. (2017)**
Van Eylen et al. (2018)
Ginzburg et al. (2018)
Gupta & Schlichting (2019, 2020)
Loyd et al. (2020)
Rogers et al. (2021)
Izidoro et al. (2022)
Lee et al. (2022)
Ho & Van Eylen (2023)
Berger et al. (2023)
…

Separates **“super-Earths”** (rocky planets) from **“sub-Neptunes”** (planets with some gaseous envelope)

A preference for size similarity



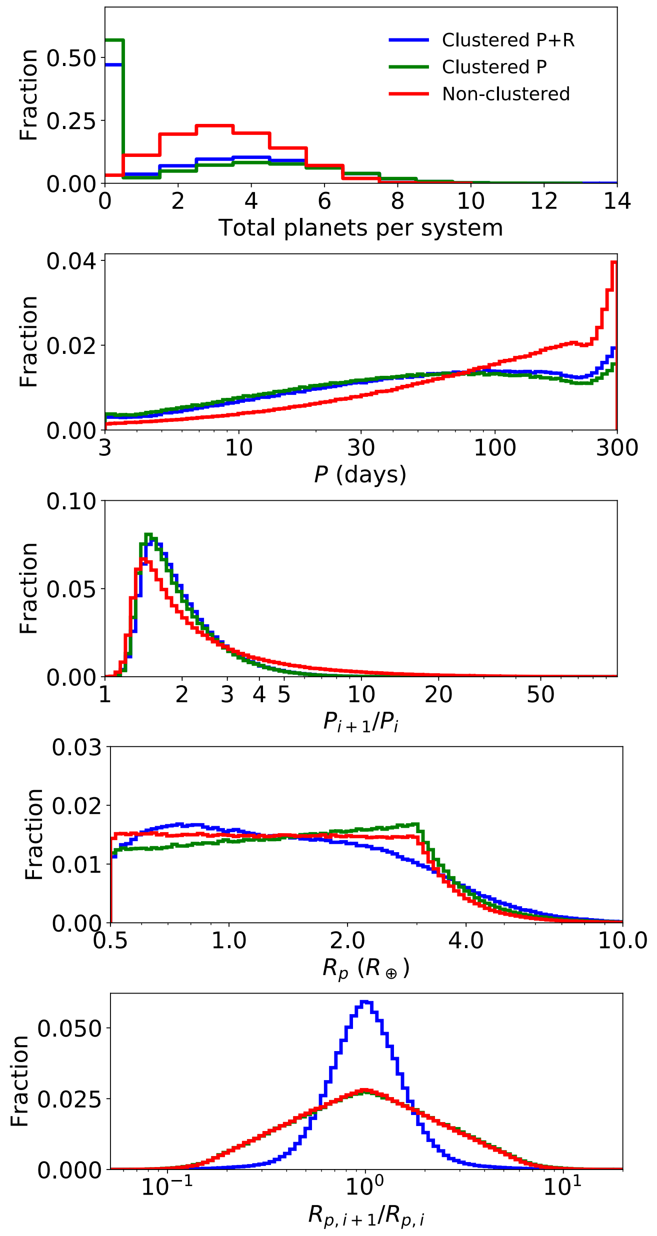

**Weiss et al. (2018)**
Millholland et al. (2017)
He et al. (2019)
Zhu et al. (2019)
Weiss & Petigura (2019)
Murchikova & Tremaine (2020)
Gilbert & Fabrycky (2020)
He et al. (2020)
Mishra et al. (2021)
Millholland & Winn (2021)
Goyal & Wang (2022)
…

Also known as **“peas-in-a-pod”** (correlated sizes and spacings of planets in the same system)

**No model has yet to explain both!**

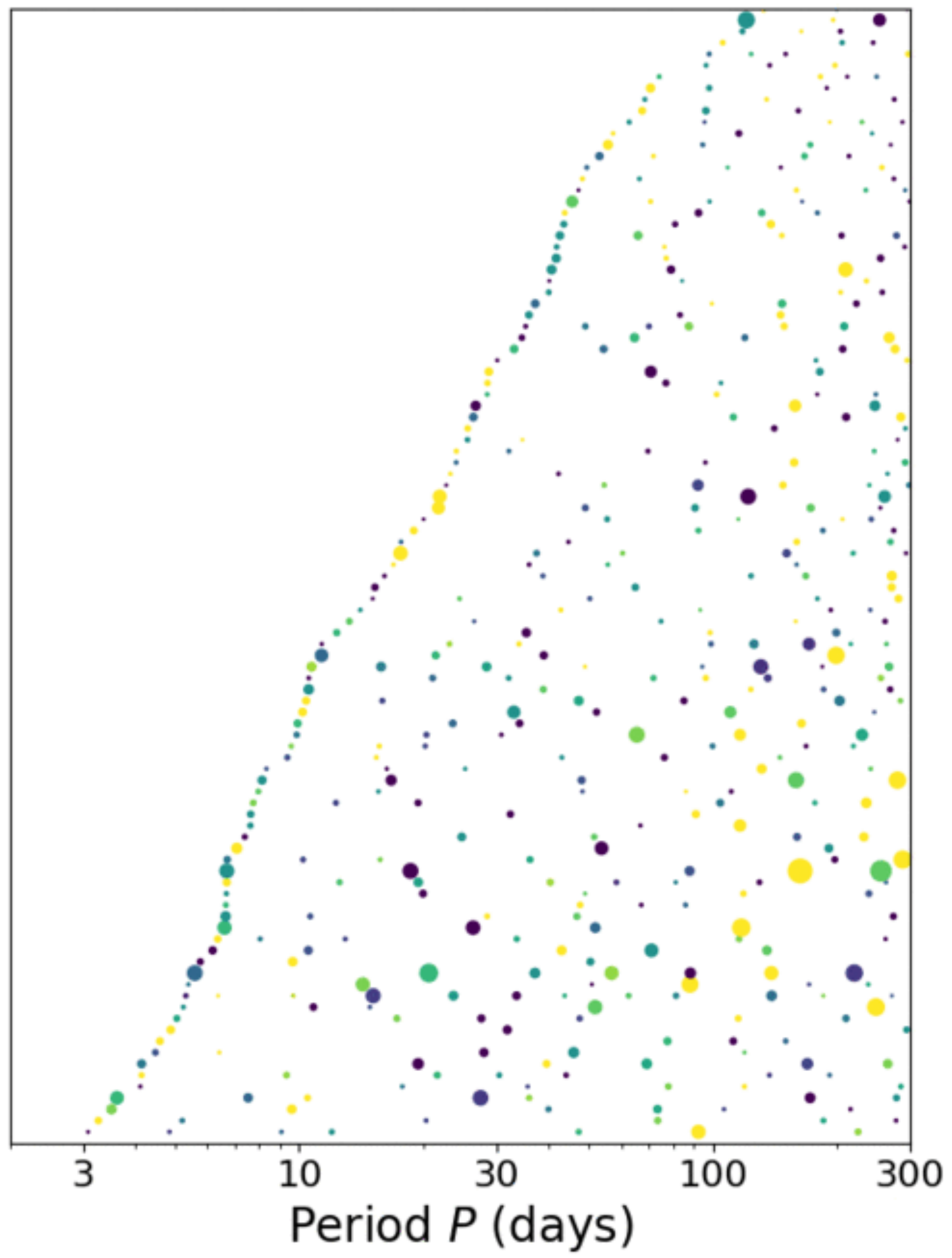
# We forward model the Kepler mission

## 1. Define a model



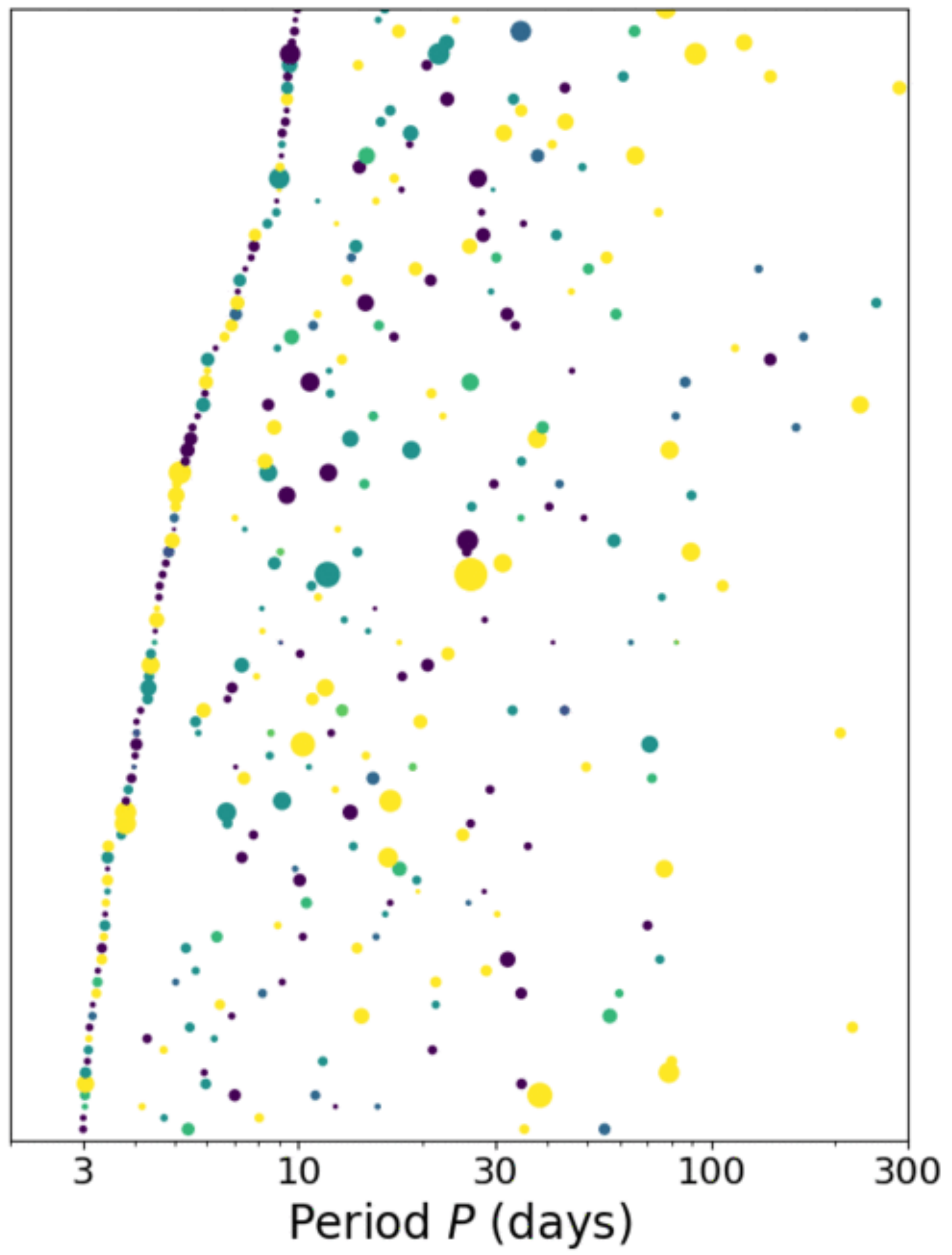

Statistical models that account for correlations in multi-planet systems

## 2. Generate a physical catalog



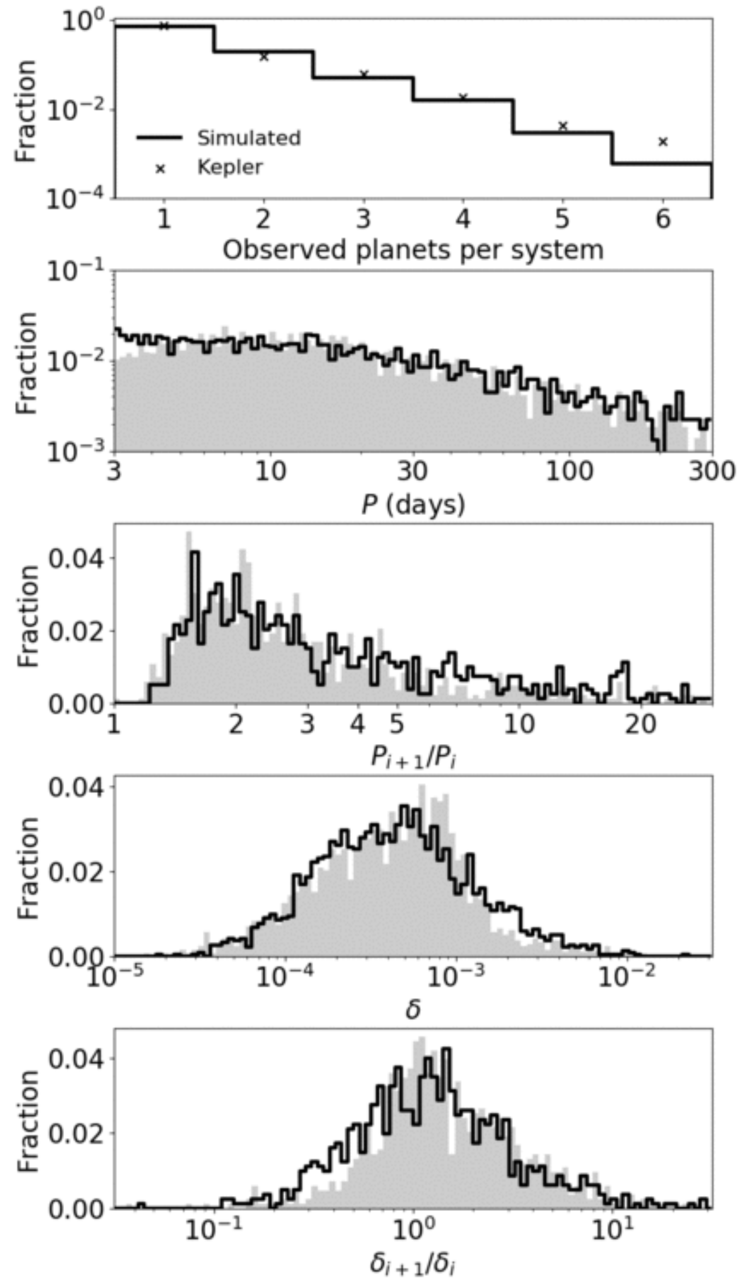

Draw planetary systems from the model assigned to Kepler target stars

## 3. Generate an observed catalog




Simulate the Kepler detection efficiency using ***SysSim***

## 4. Compare with Kepler catalog

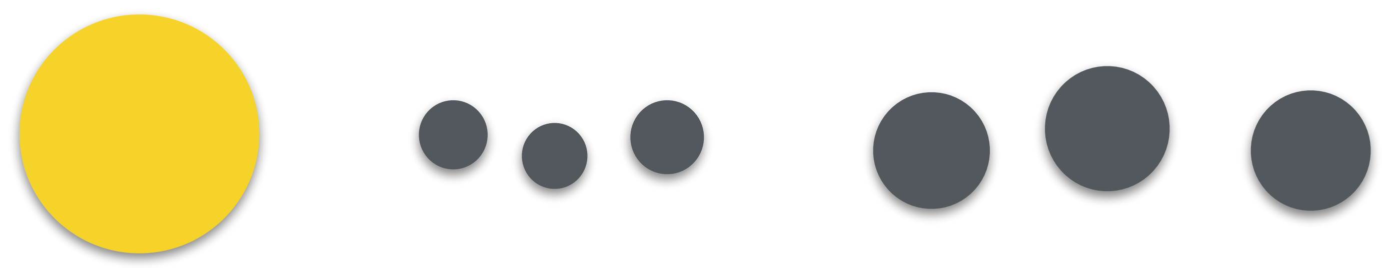



Match Kepler catalog, fitting multiple marginal distributions simultaneously using ABC

*to infer the architectures of all planetary systems*

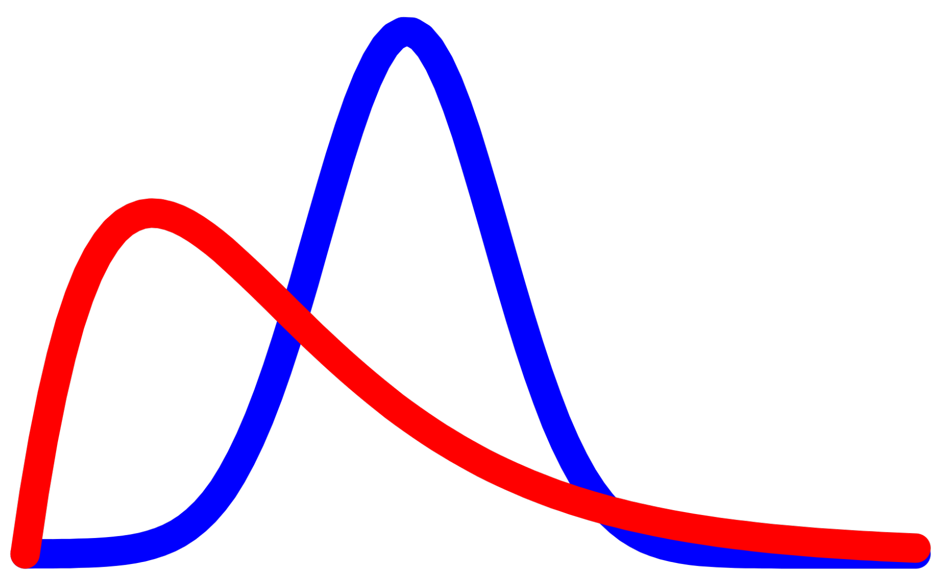
# Forward modeling the Kepler catalog has been extremely insightful for the demographics and architectures of exoplanetary systems…

## Intra-system patterns in planet sizes ~~and spacings~~



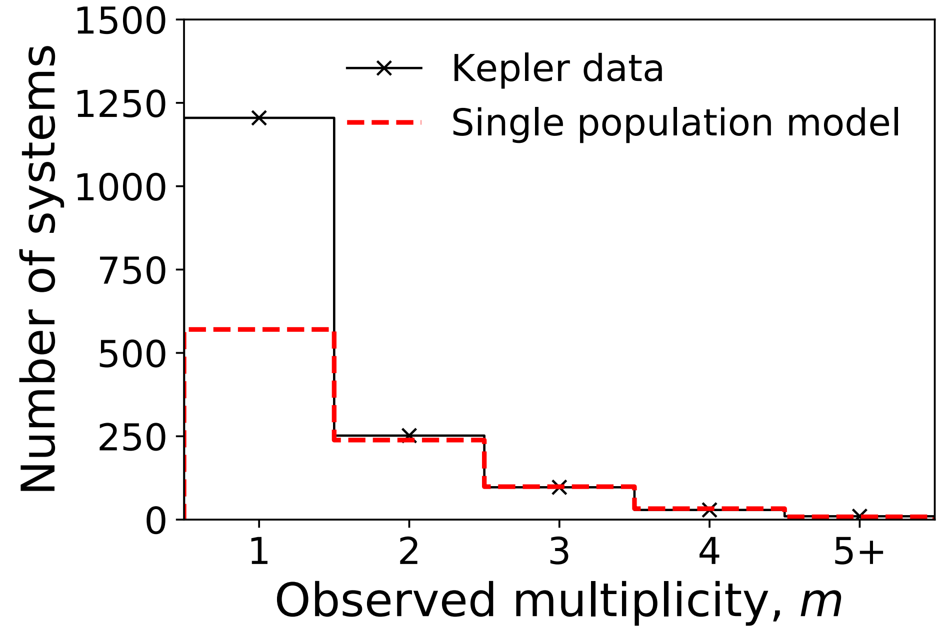
He et al. (2019, 2020, 2021a)
He & Ford (submitted)

## Dependence on stellar type



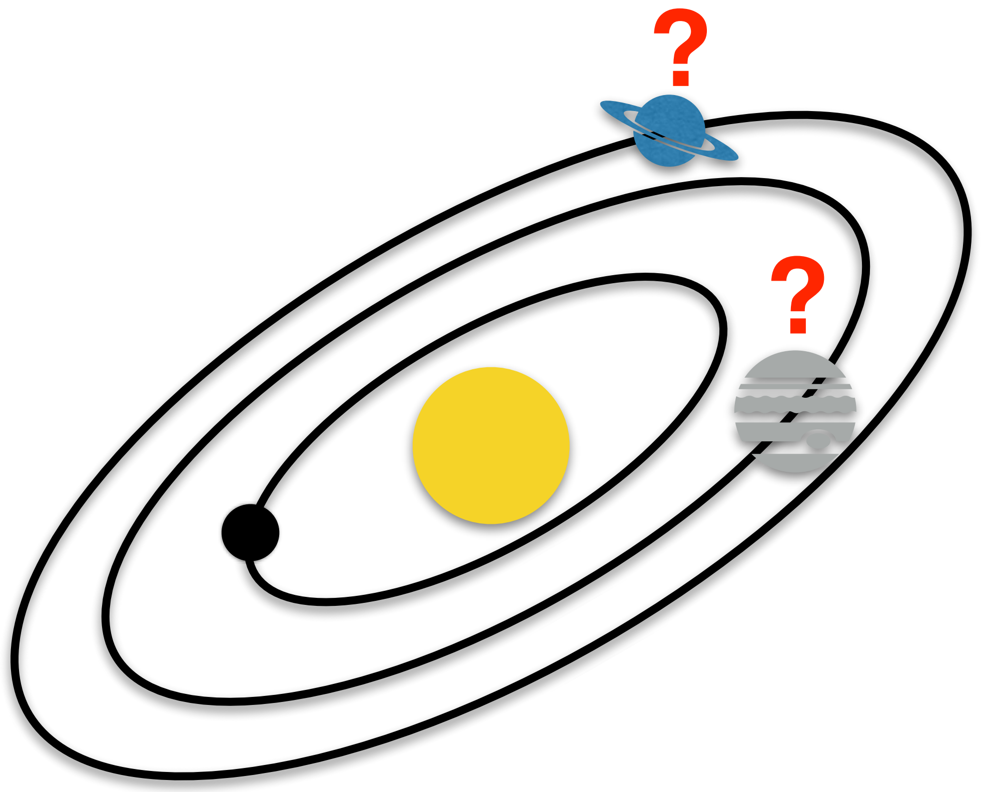
He et al. (2021a)

## Multiplicity and mutual inclinations (“Kepler dichotomy”)



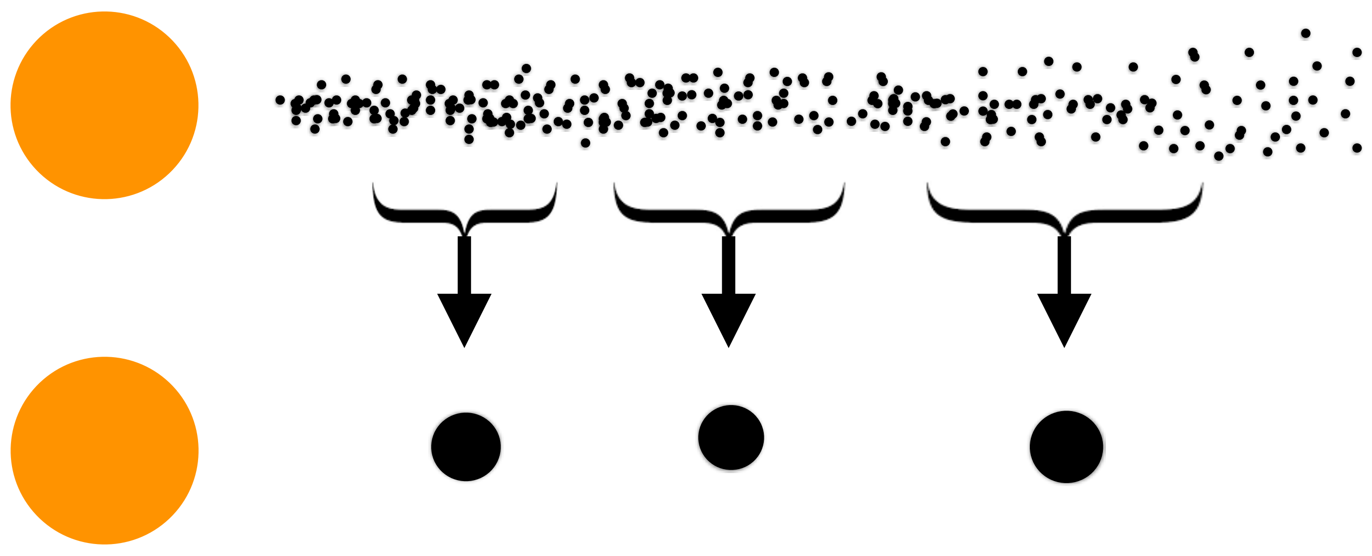

He et al. (2019, 2020)

## Conditional occurrence



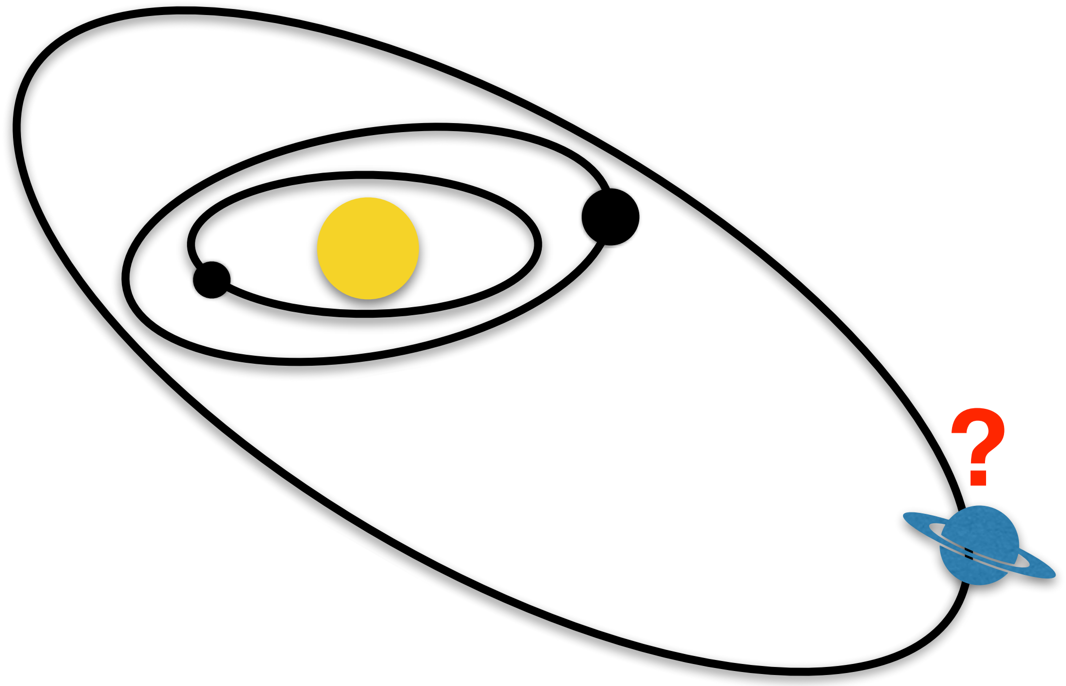

He et al. (2021b)

## Inferring the minimum-mass extrasolar nebula



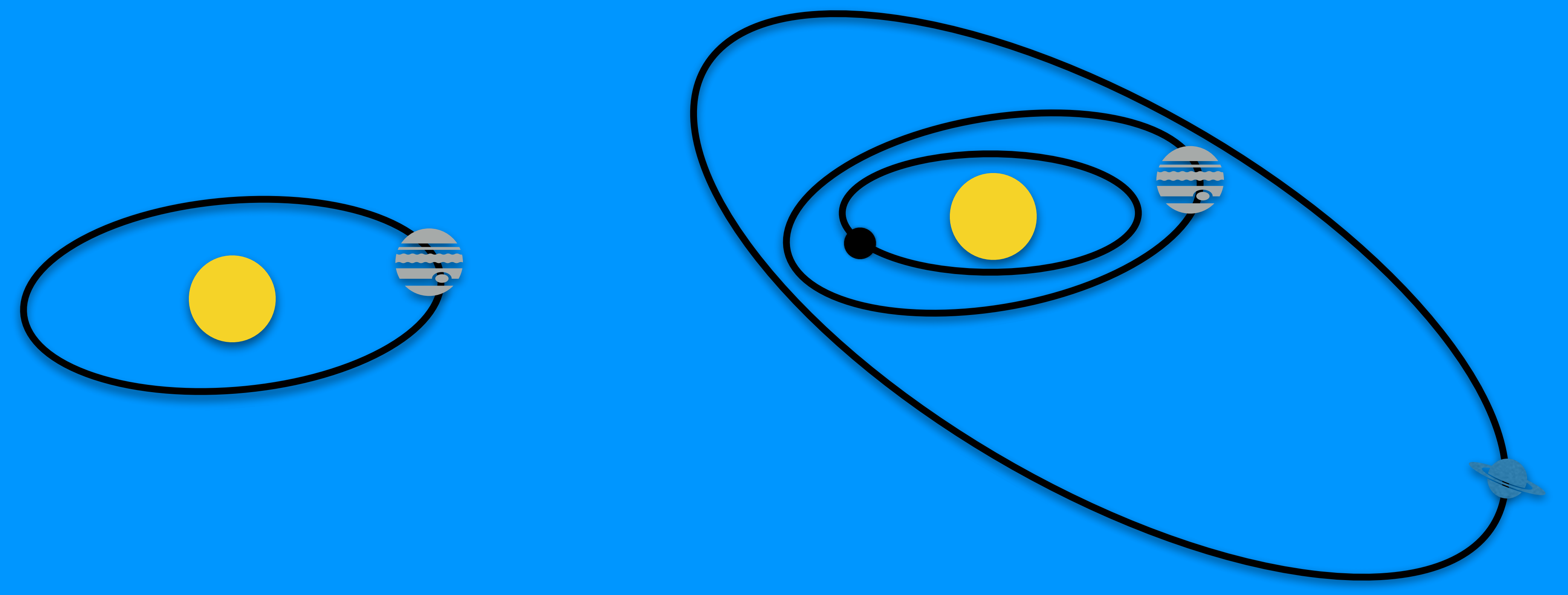
He & Ford (2022)

## Predicting outer giants?

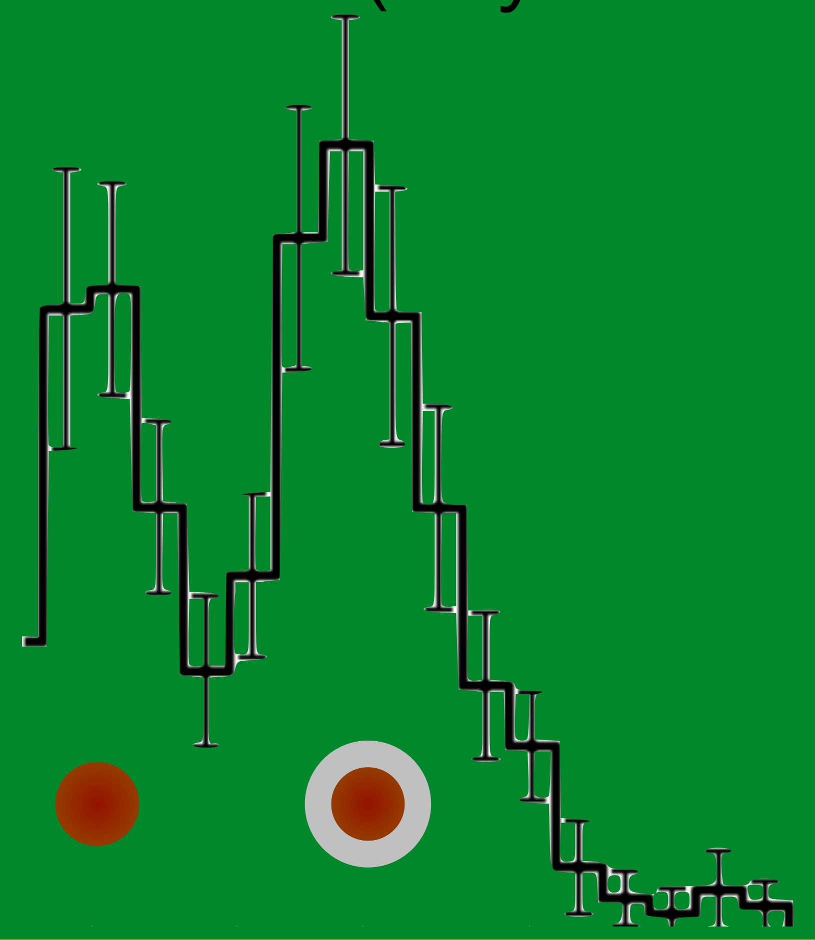



He & Weiss (2023)

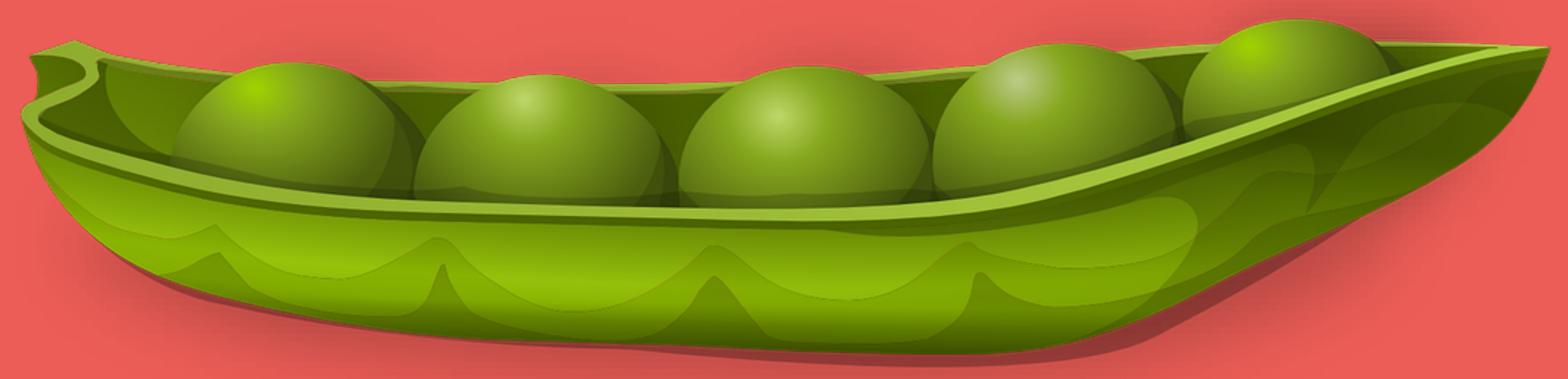
Distribution of multiplicities and mutual inclinations (“Kepler dichotomy”)



Planet radius valley in the context of a multi-planet model (“hybrid model”)

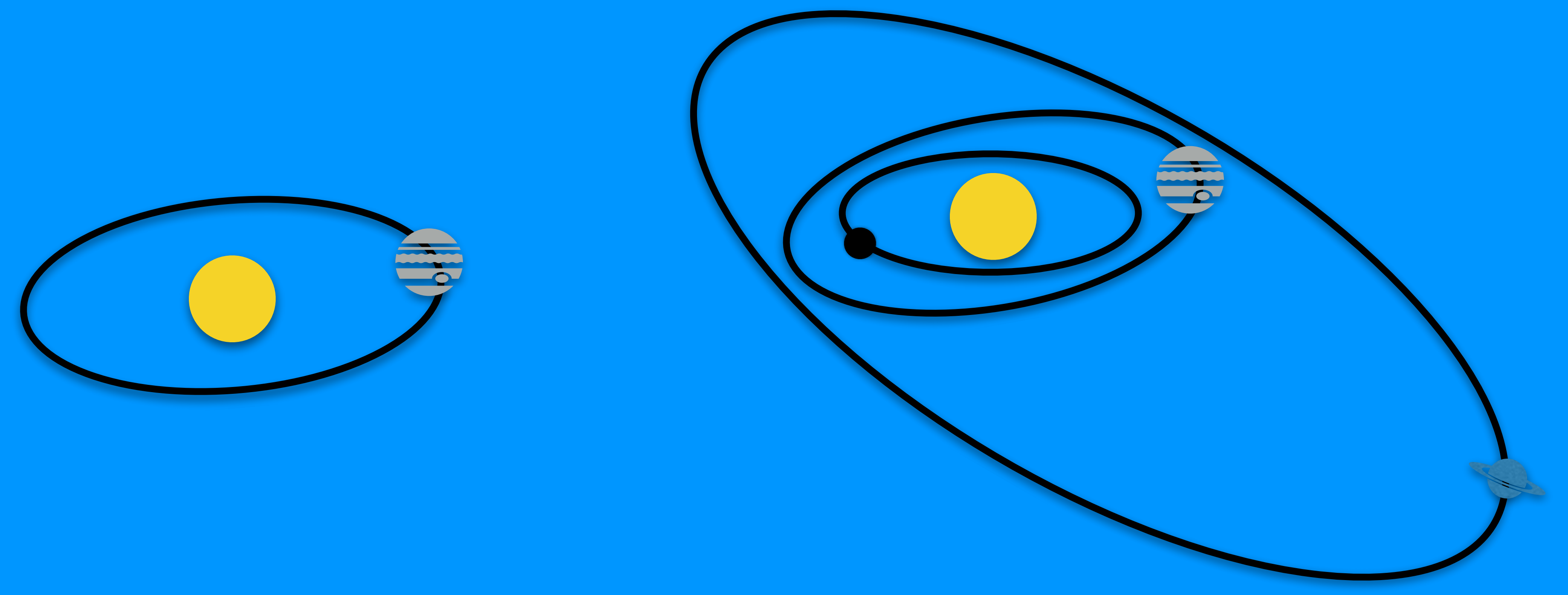


Planet size similarity, ordering, and spacings of multi-planet systems (“peas in a pod”)



Occurrence of Earth-sized planets in the habitable zone (“eta-Earth”)

Distribution of multiplicities and mutual inclinations (“Kepler dichotomy”)



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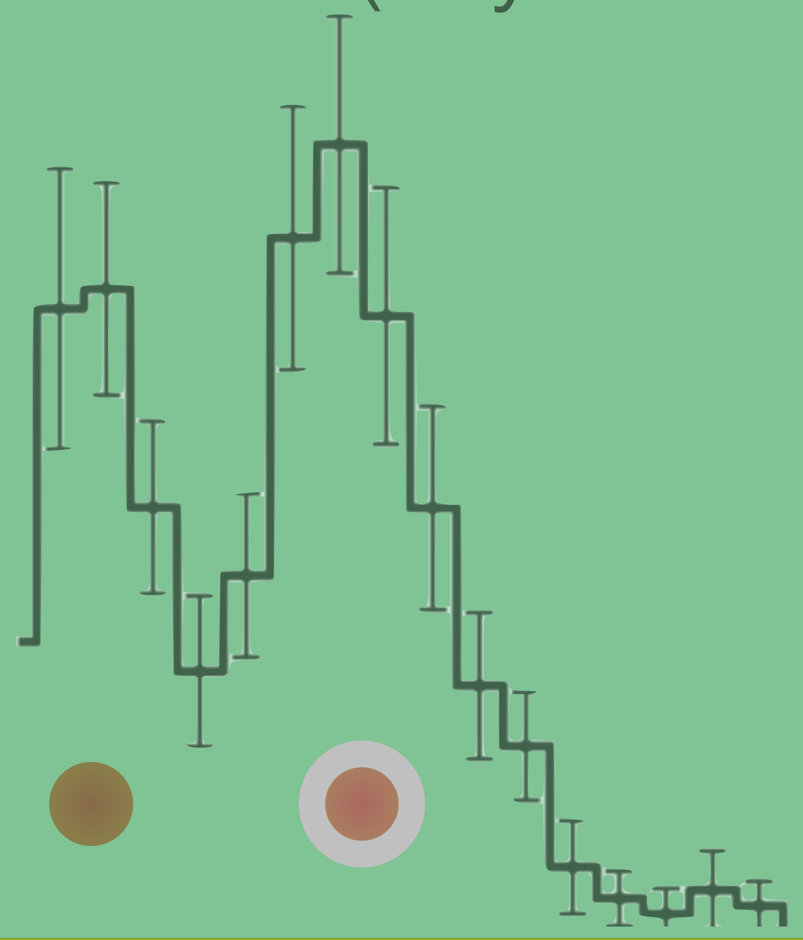

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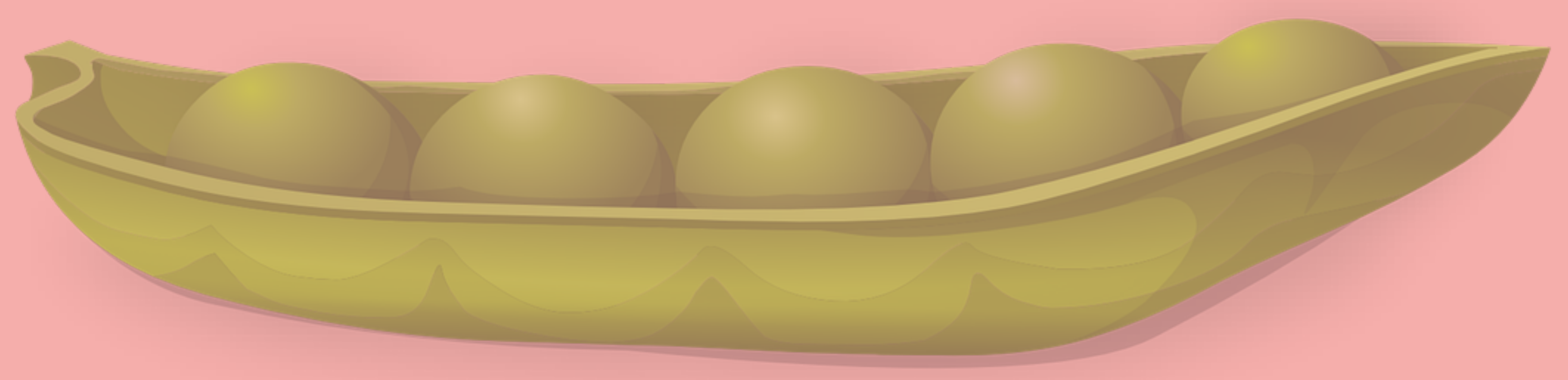

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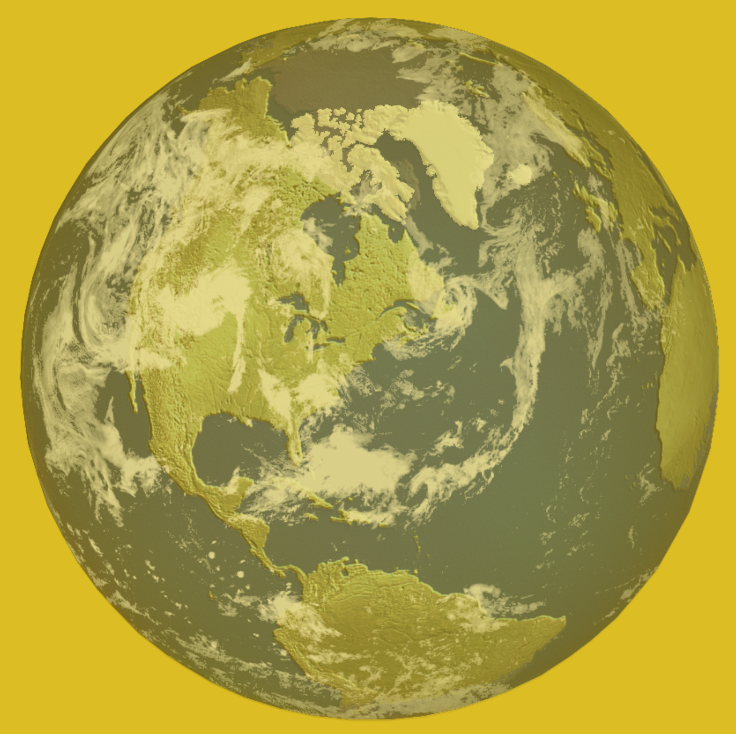
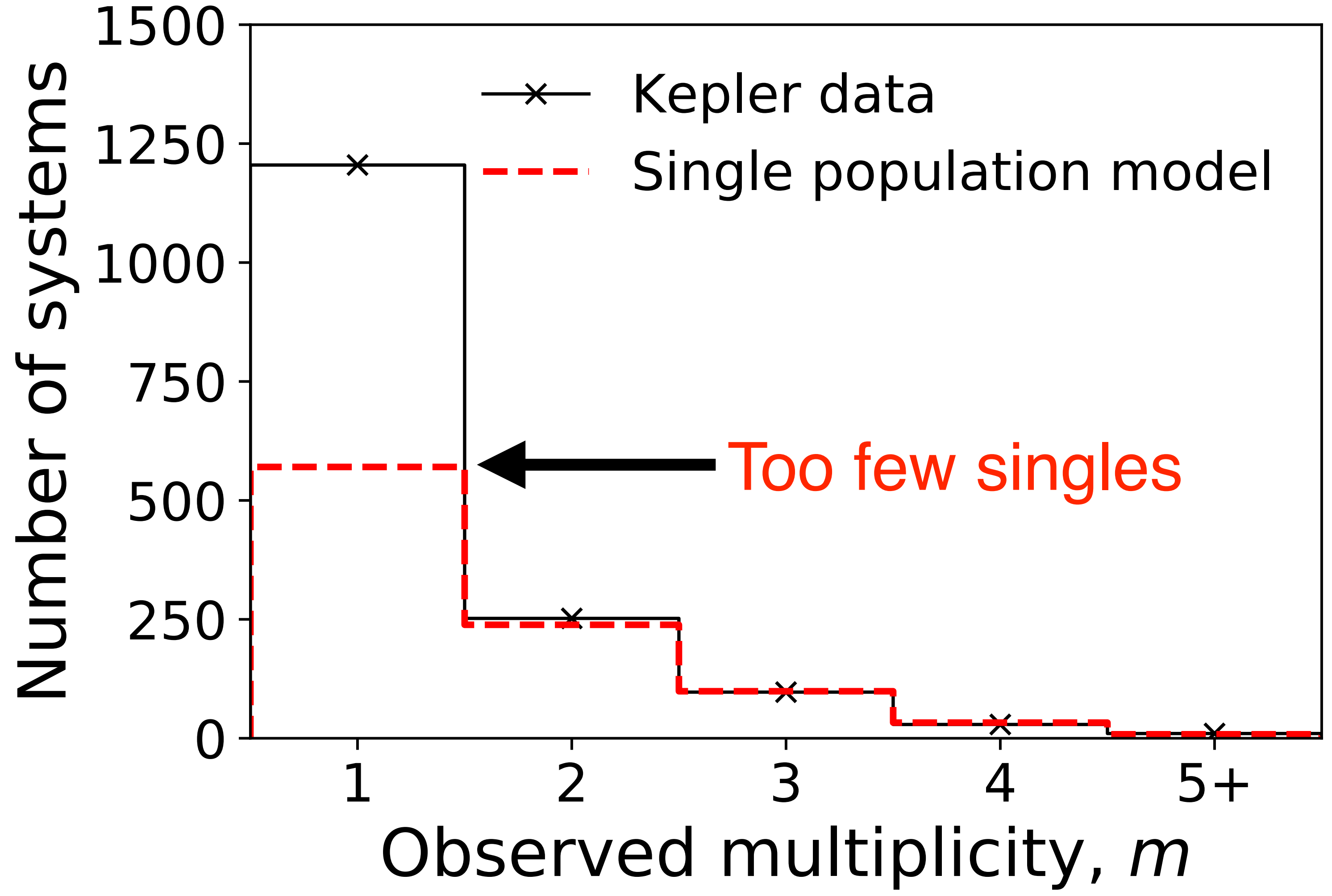


# The Kepler dichotomy: an apparent excess of systems with a single transiting-planet




Single population models can fit rate of observed 2+ systems but under-predict single-transiting planet systems
Lissauer et al. (2011)
Johansen et al. (2012)
Hansen & Murray (2013)
Ballard & Johnson (2016)
Mulders et al. (2018)

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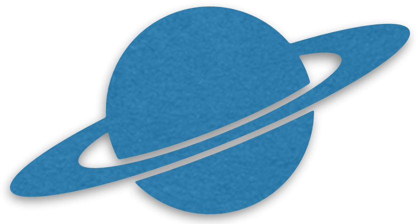
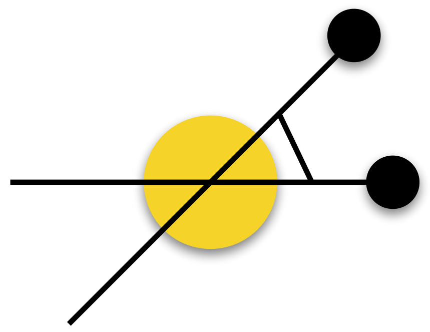
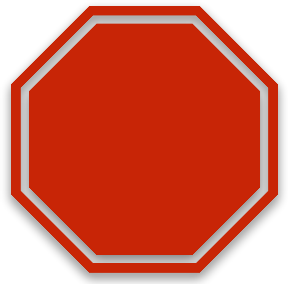


A large fraction of true **single-planet** systems?
Fang & Margot (2012)
Sandford et al. (2019)



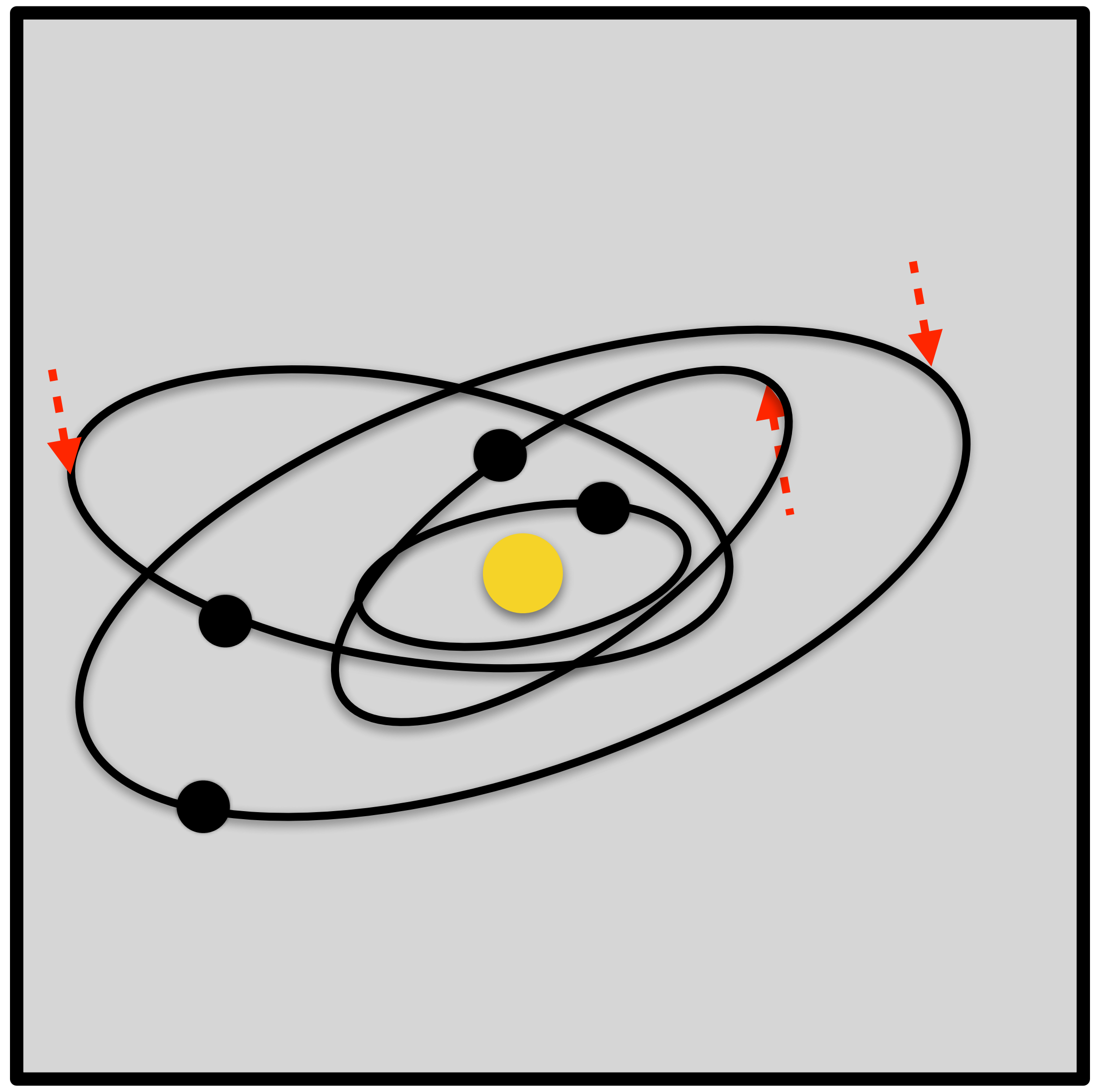
A **high-mutual inclination** population?
Mulders et al. (2018)
He, Ford, & Ragozzine (2019)

A **multiplicity dependent** distribution of inclinations?
Zhu et al. (2018), Yang et al. (2020)
He et al. (2020)

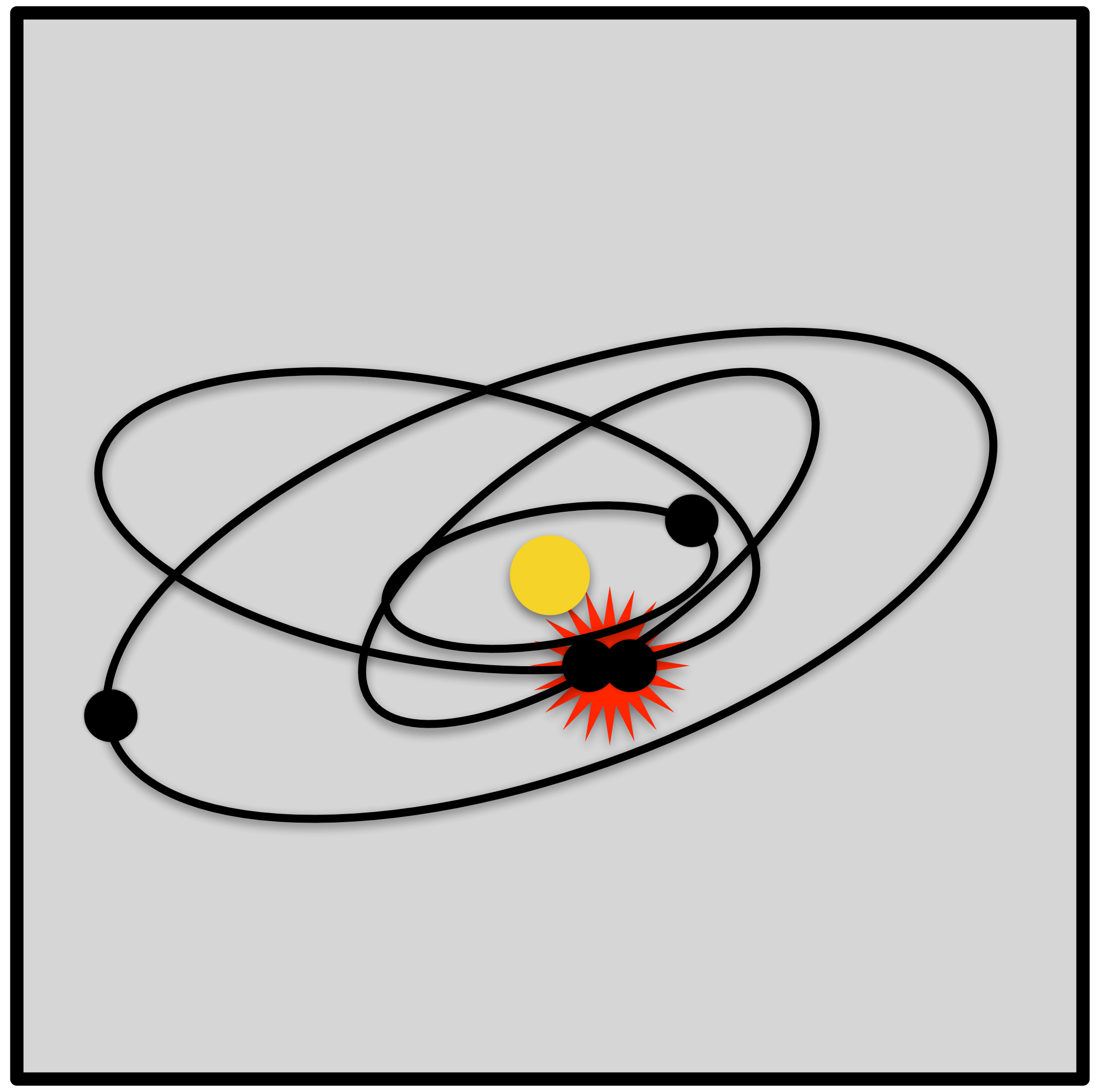


Detection bias?
Zink et al. (2019)

# The AMD stability criteria provides a dynamically motivated constraint on the orbital architectures



Planets **exchange** AMD
(total is conserved)



Collisions **reduce** system
AMD to below a critical value

AMD = angular momentum deficit
(compared to circular, coplanar orbits)

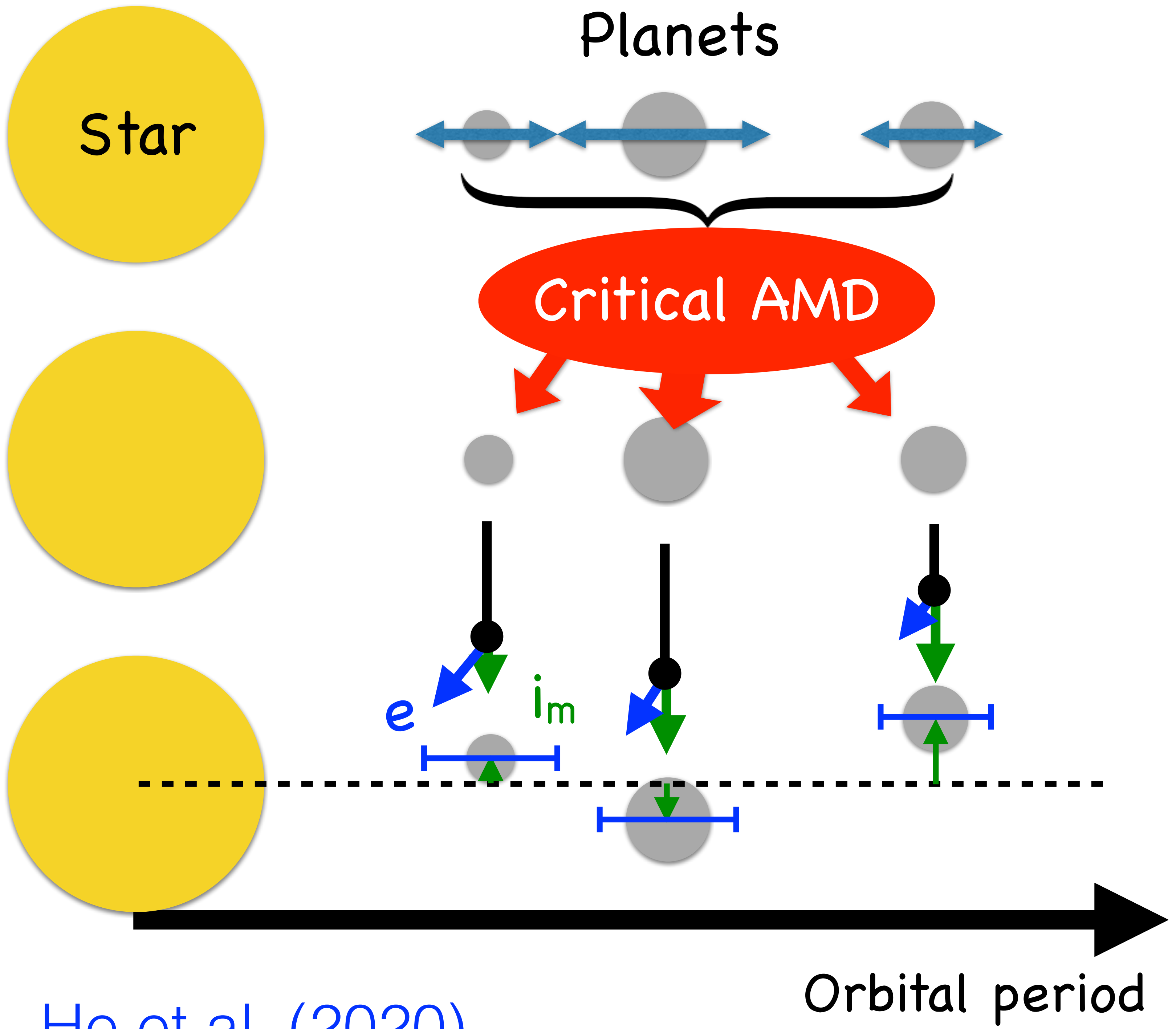
$$= \sum_{k=1}^{N} \Lambda_k \left(1 - \sqrt{1 - e_k^2}\cos i_{m,k}\right),$$

$$\Lambda_k = \mu_k \sqrt{a_k}$$

Laskar (2000)
Laskar & Petit (2017)
Petit, Laskar, & Boue (2017)

**Maximum AMD model:**

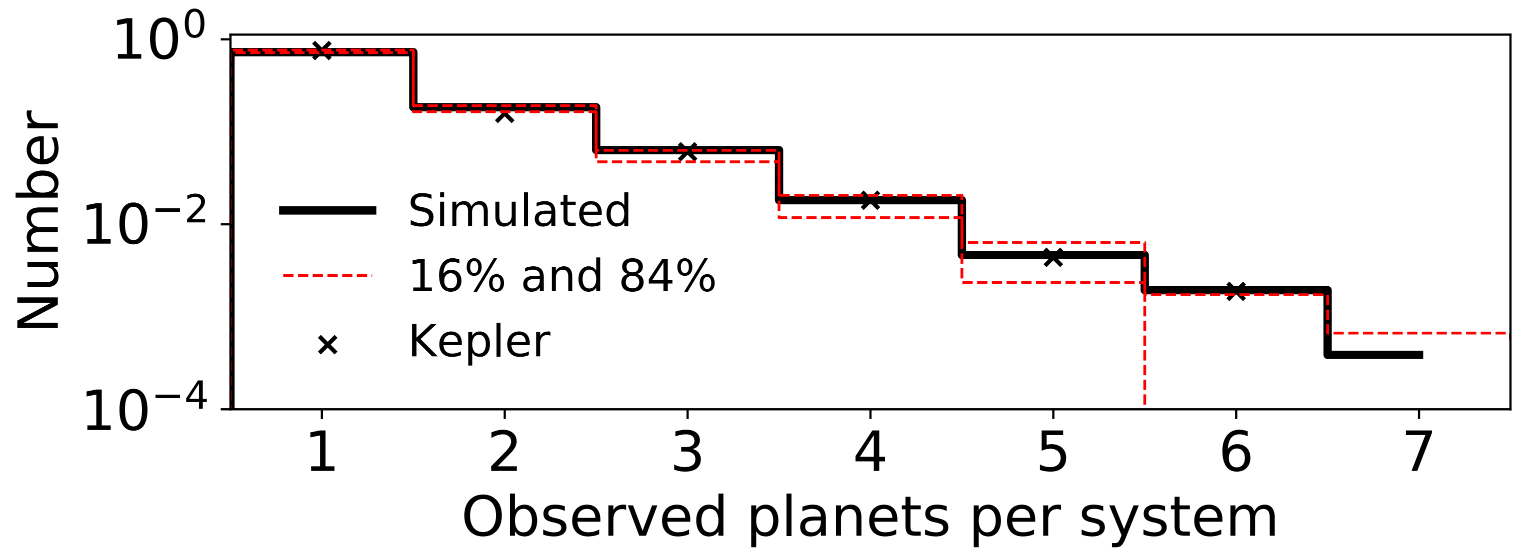
0. Draw clustered periods and sizes
1. Calculate critical AMD of system
2. Distribute AMD among the planets
3. Distribute each planet's AMD among *e* and $i_m$




He et al. (2020)

# The AMD model leads to a multiplicity-dependent distribution of eccentricities and mutual inclinations

## Maximum AMD model



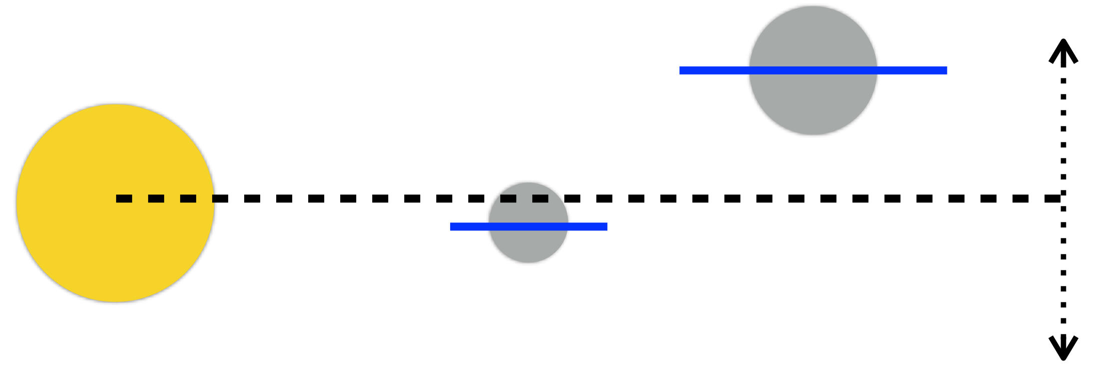

Explains the Kepler "dichotomy" with a single population

A **multiplicity dependent** distribution of mutual inclinations?

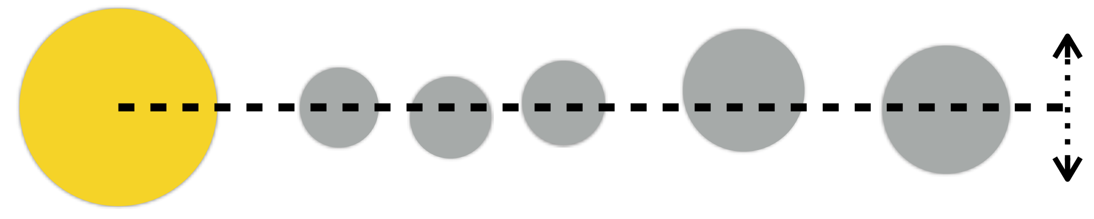
Zhu et al. (2018)

Yang, Xie, Zhou (2020)

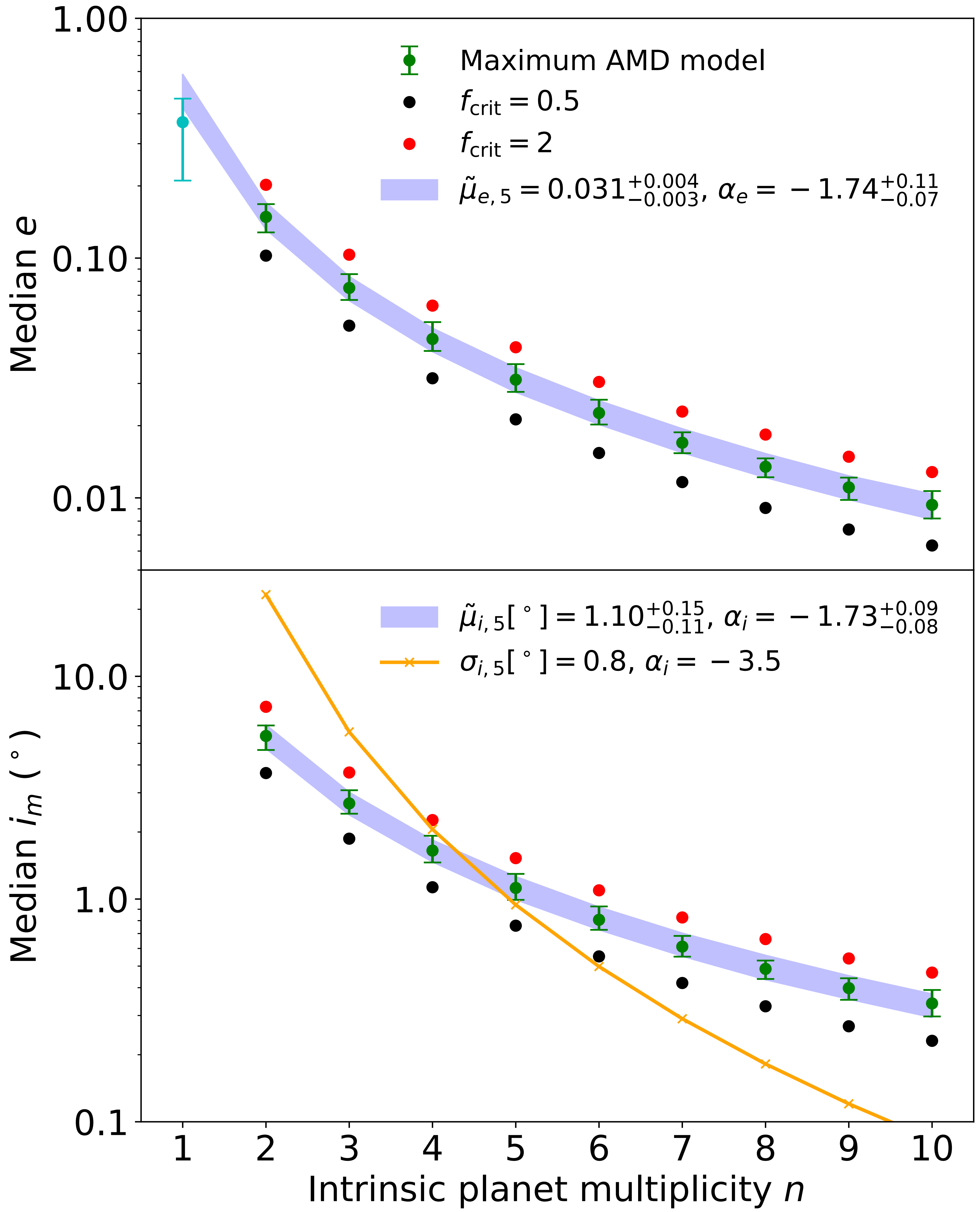
He et al. (2020)



Fewer planets = higher $i_m$, e



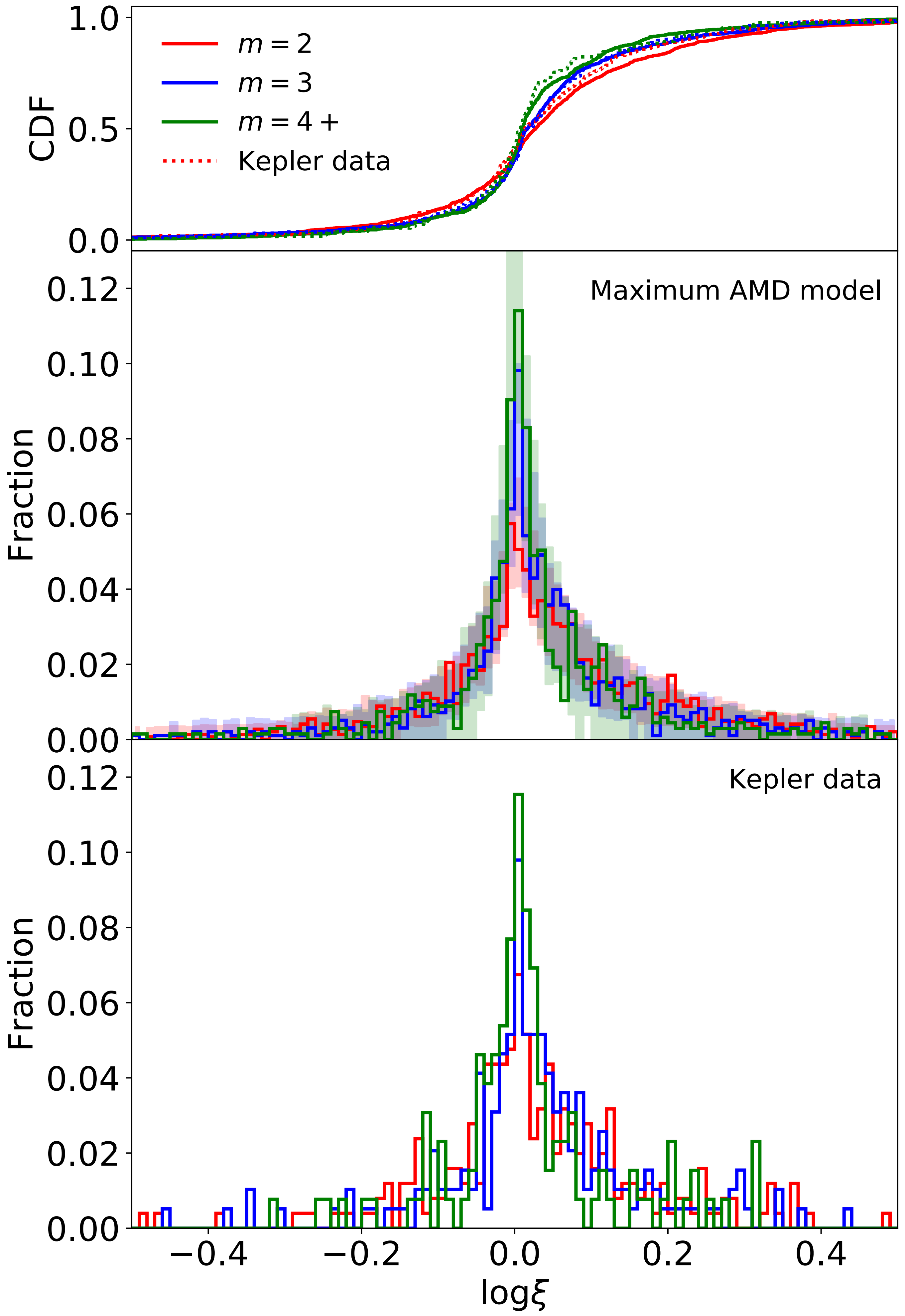
More planets = lower $i_m$, e



# There is observed evidence for the increase in orbital excitations with decreasing multiplicity

Period-normalized transit duration ratios

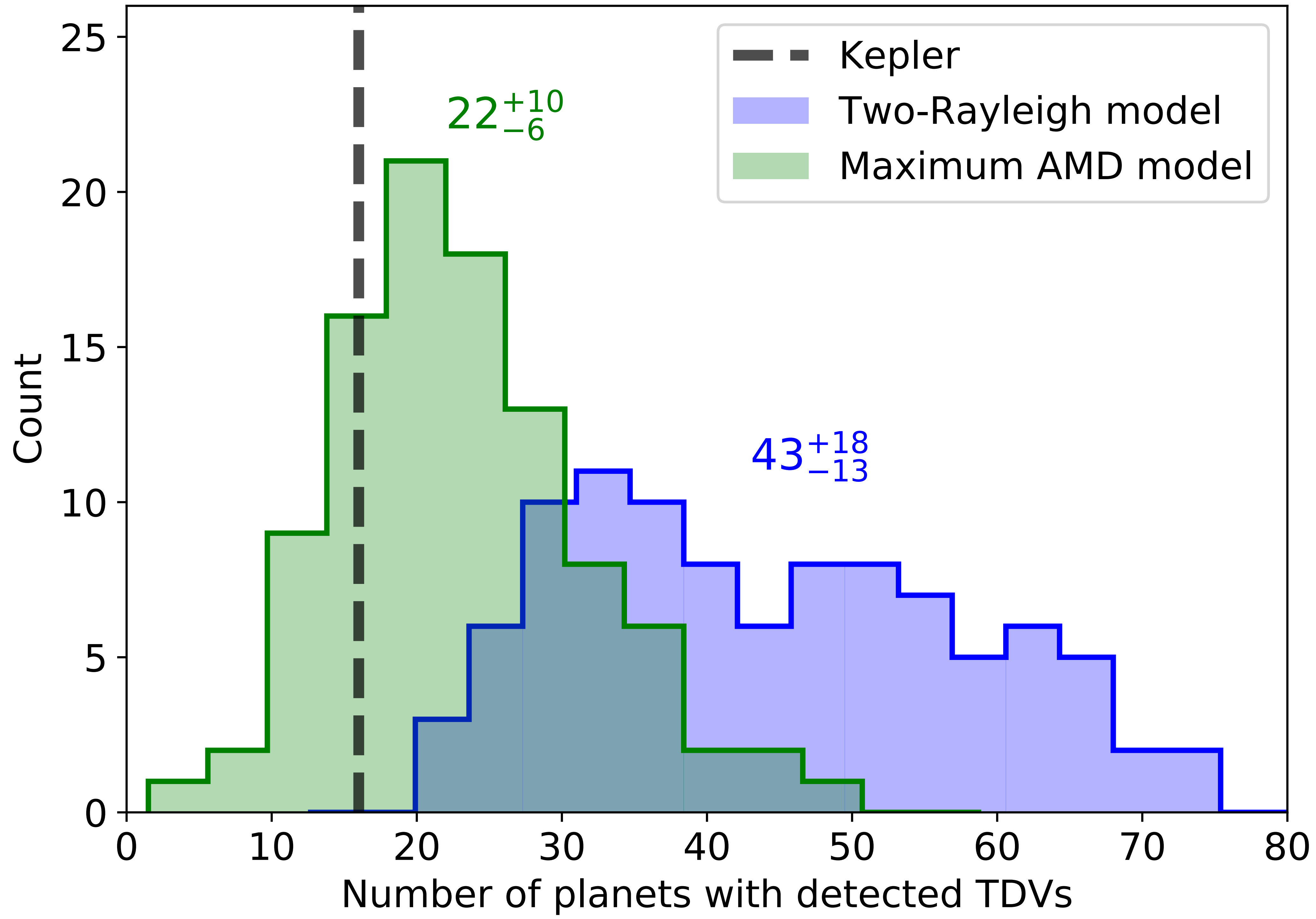
$$\xi = \left(\frac{t_{\rm dur,in}}{t_{\rm dur,out}}\right)\left(\frac{P_{\rm out}}{P_{\rm in}}\right)^{1/3}$$




Model predicts more **peaked** (lower *e*) and more **skewed** (lower $i_m$) distribution for higher multiplicity (m)

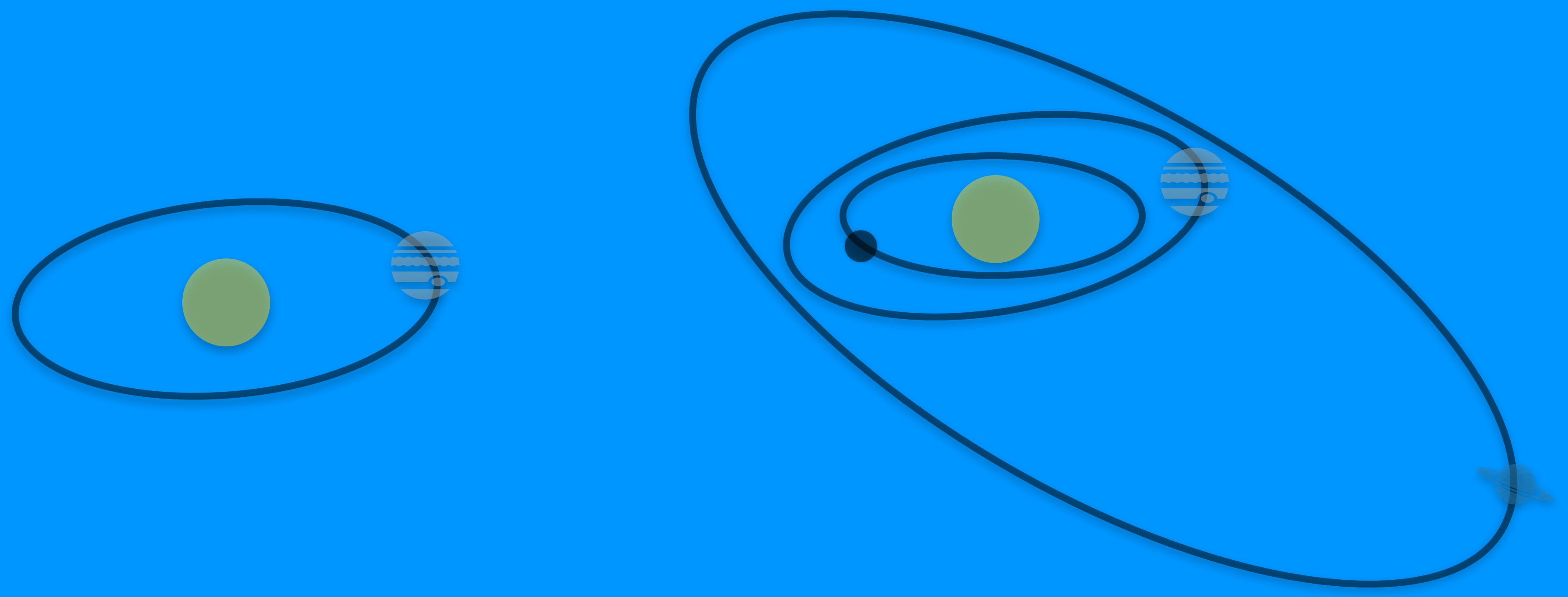
We see this in the data!

**TDVs = transit duration variations**

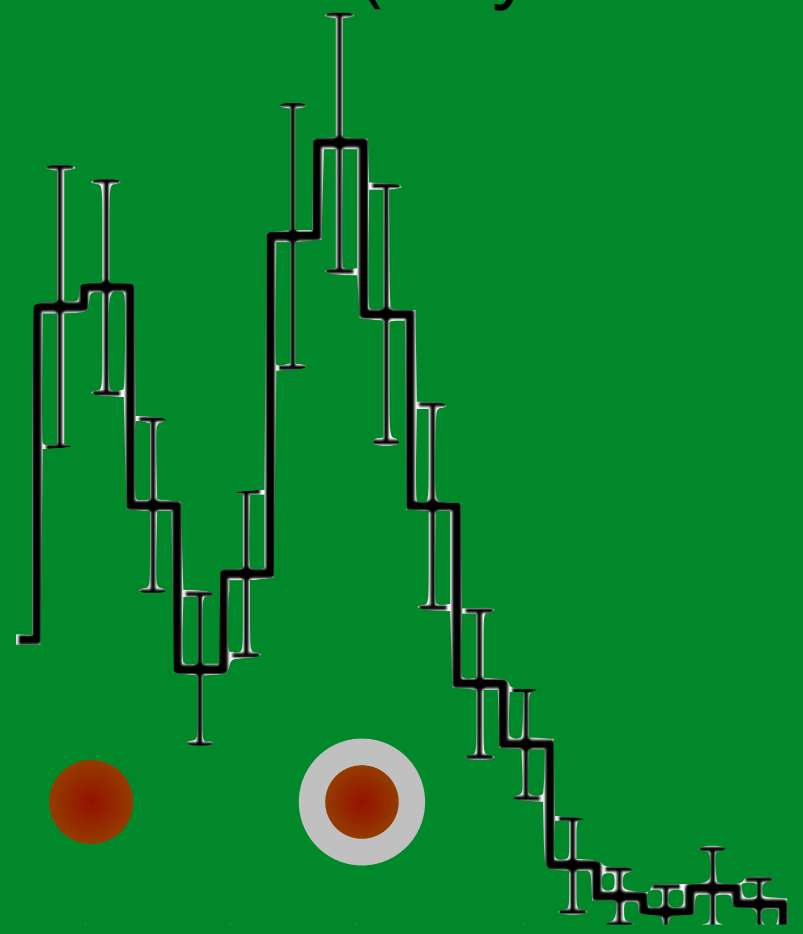



Millholland, He et al. (2021)

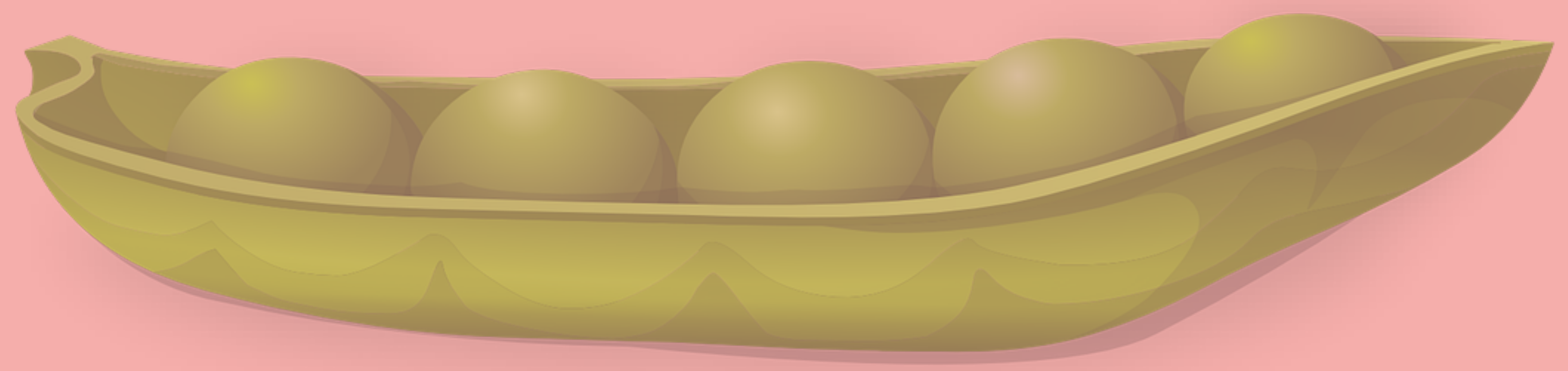
Distribution of multiplicities and mutual inclinations ("Kepler dichotomy")



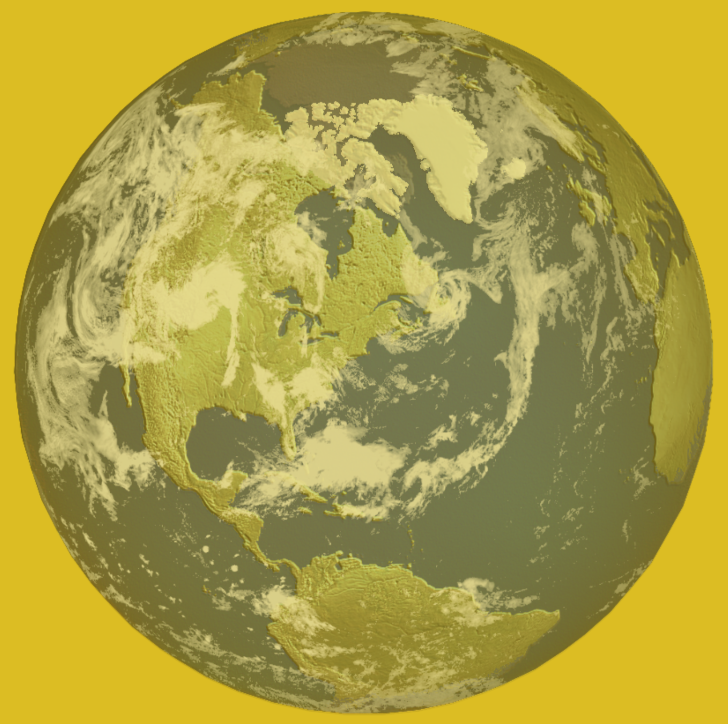
Planet radius valley in the context of a multi-planet model ("hybrid model")



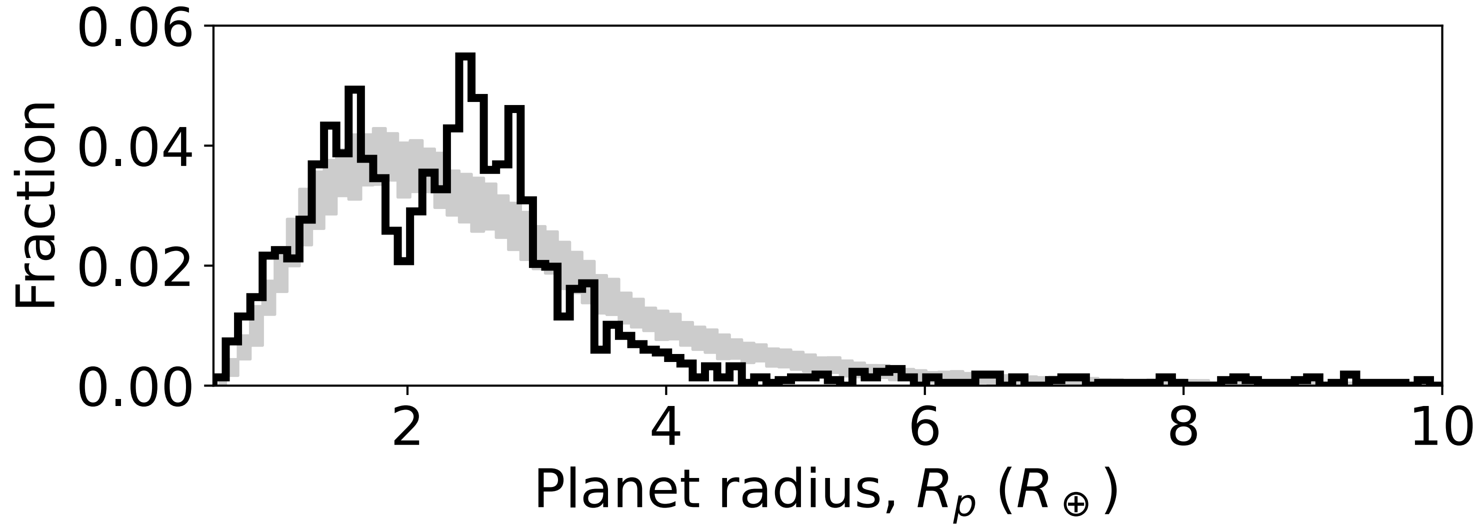
Planet size similarity, ordering, and spacings of multi-planet systems ("peas in a pod")



Occurrence of Earth-sized planets in the habitable zone ("eta-Earth")



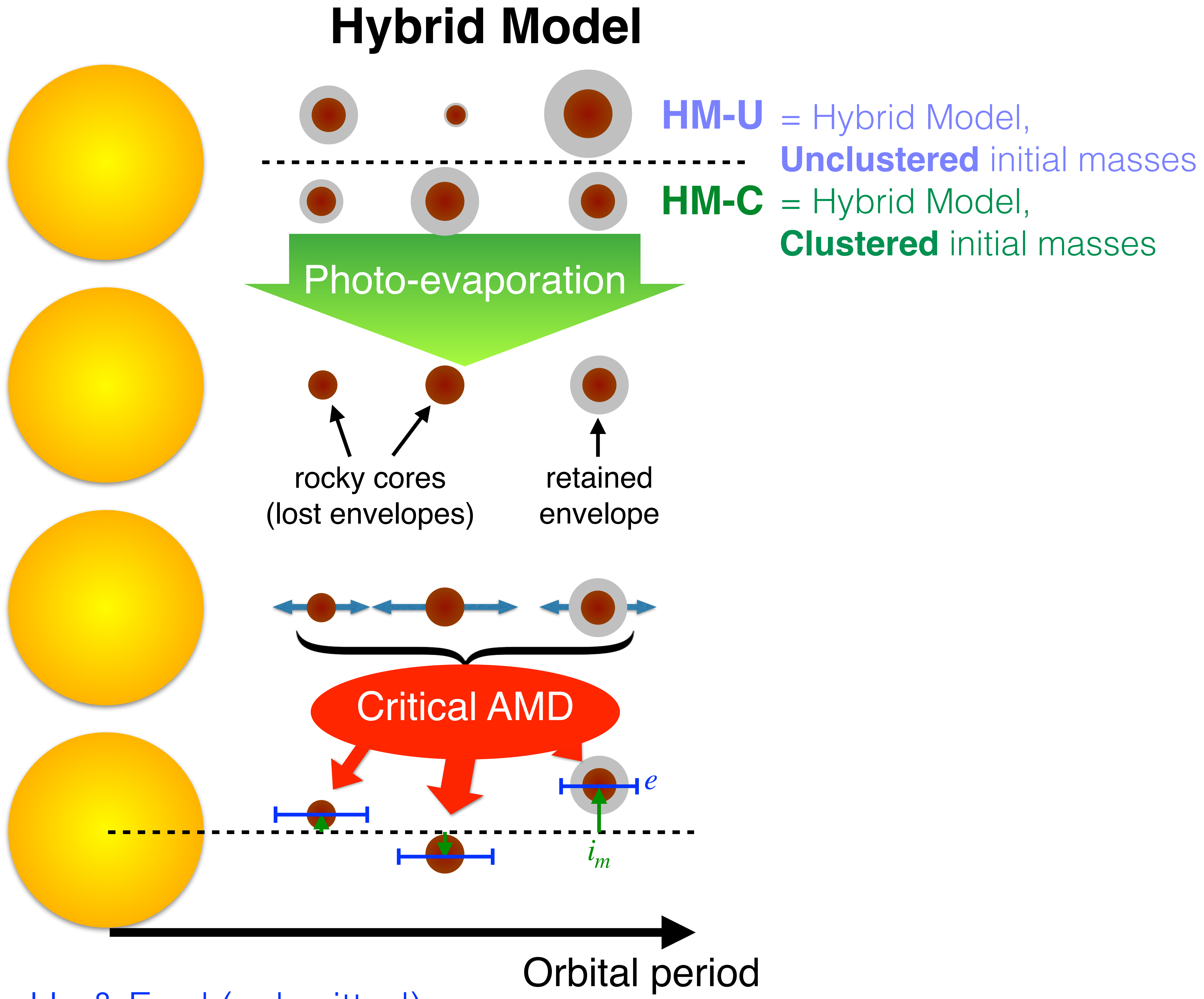
# We construct a "hybrid model" between the clustered AMD model (He et al. 2020) and a joint mass-radius-period model (Neil & Rogers 2020)




The previous AMD model **(hereafter H20)** cannot reproduce any radius valley

**+**

Neil & Rogers (2020) **(hereafter NR20)** proposed a joint mass-radius-period model and incorporated a prescription for envelope mass-loss driven by photoevaporation (Lopez et al. 2012)




He & Ford (submitted)

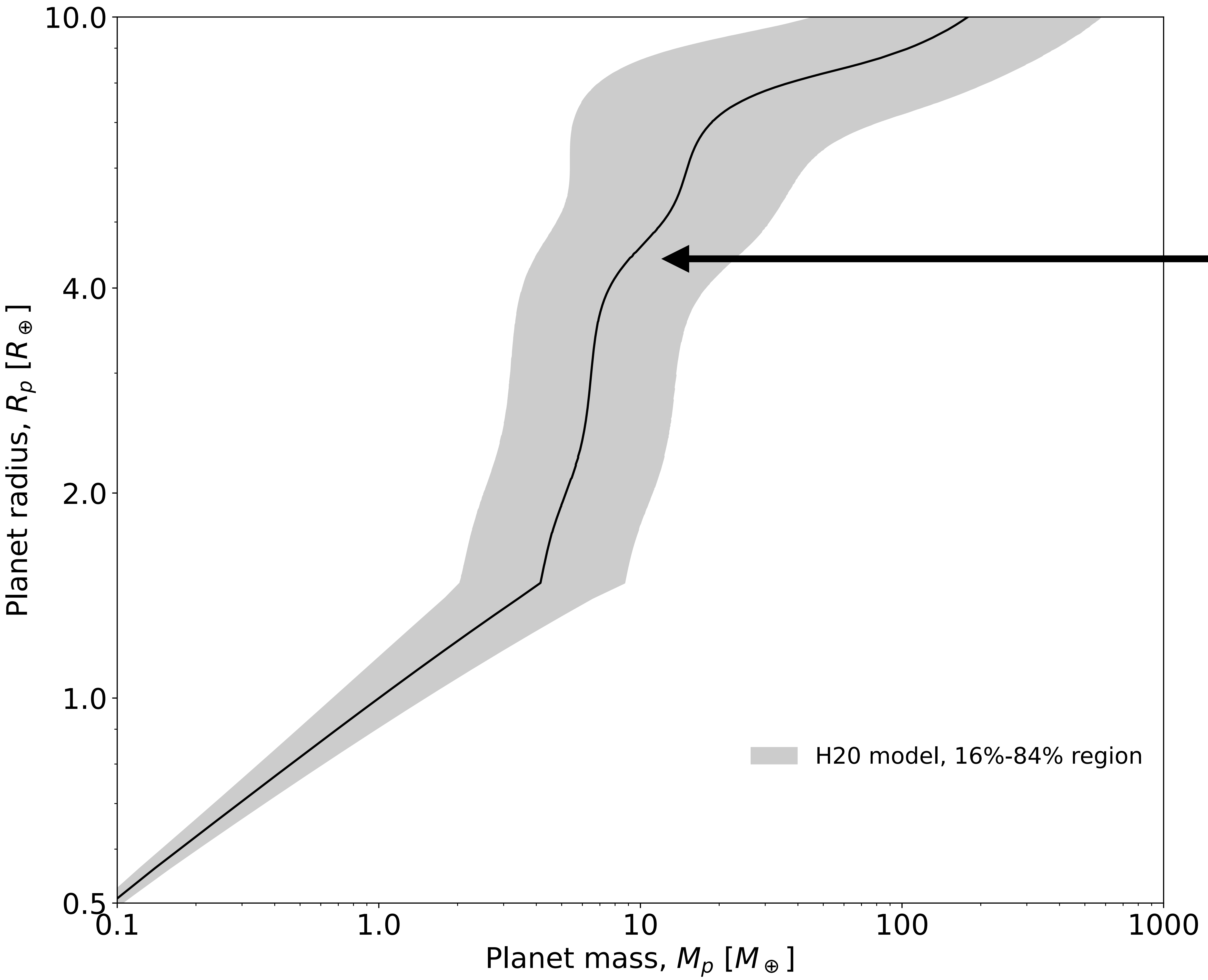
# We replace the mass-radius relation with a radius-mass relation

H20 uses a combination of:

Non-parametric, probabilistic mass-radius relation fit to TTV planets (Ning et al. 2018)

+

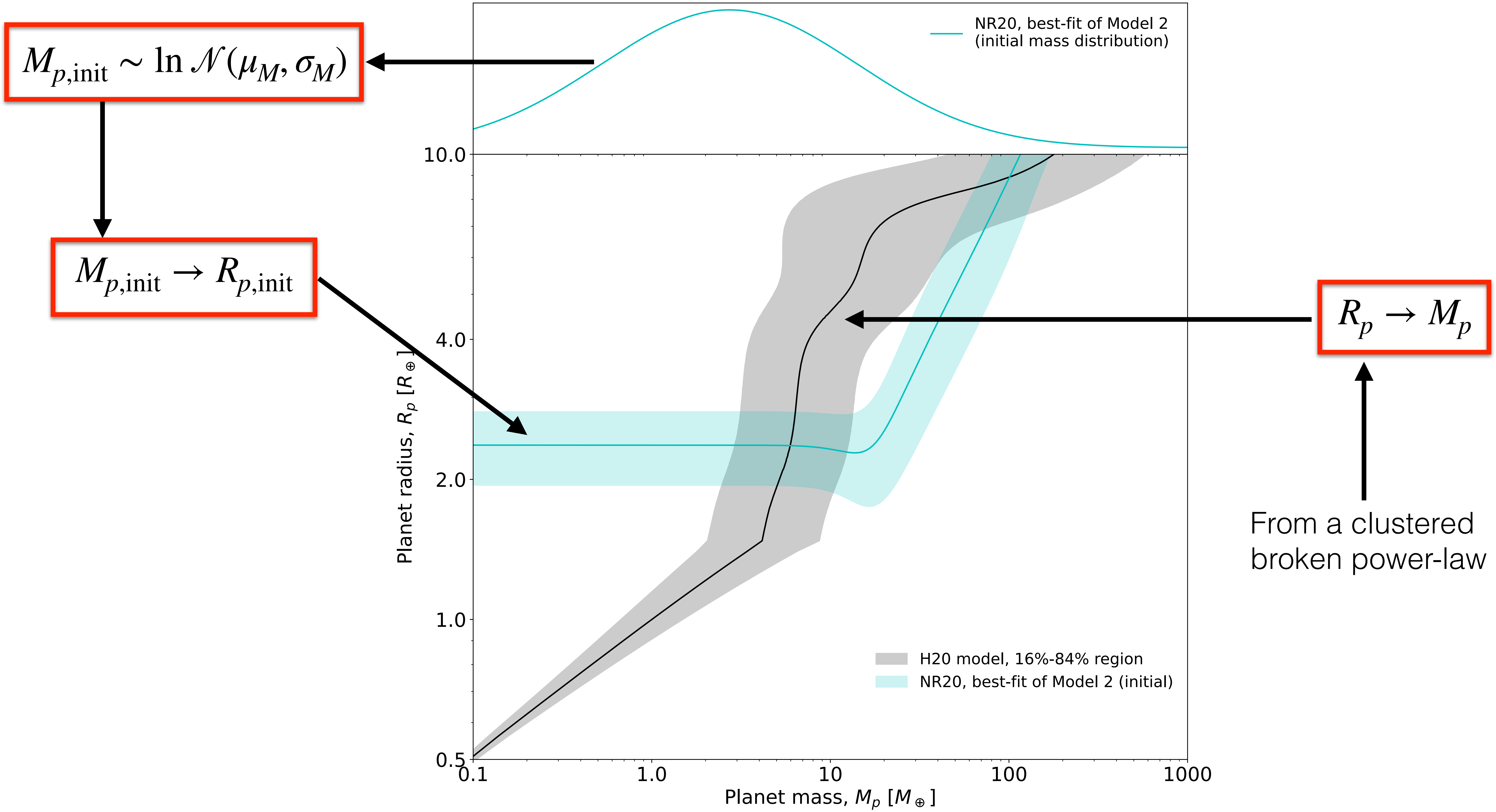
"Earth-like rocky" relation (Zeng et al. 2019)




$R_p \rightarrow M_p$

From a clustered broken power-law

# We replace the mass-radius relation with a radius-mass relation



# Photoevaporation-driven atmospheric mass loss as radius-mass relations

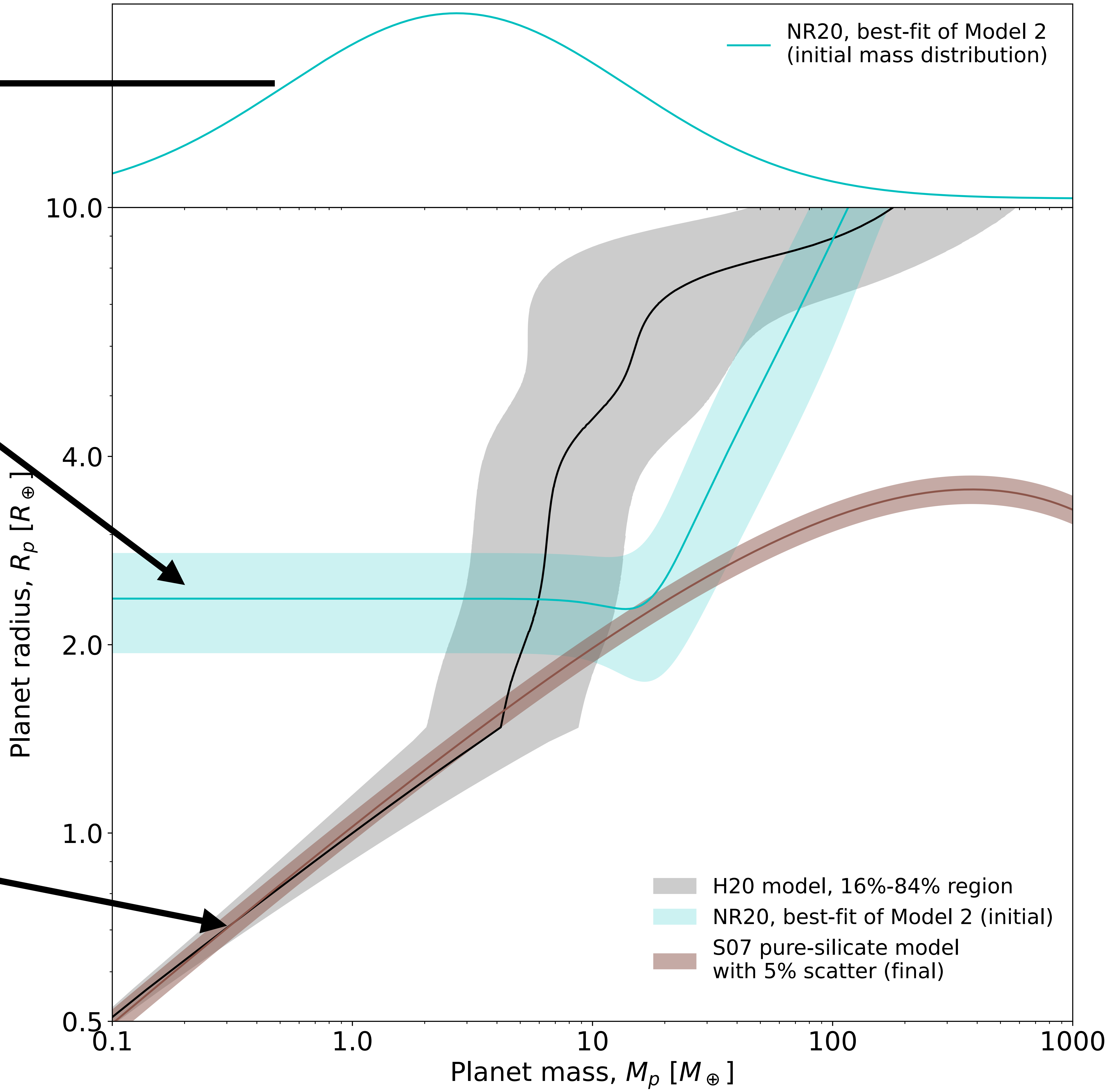
$M_{p,\mathrm{init}} \sim \ln \mathcal{N}(\mu_M, \sigma_M)$

$M_{p,\mathrm{init}} \rightarrow R_{p,\mathrm{init}}$

A fraction of the mass is assumed to be in the gaseous envelope ($M_{\mathrm{env}}$)

$M_{p,\mathrm{final}} \rightarrow R_{p,\mathrm{final}}$

(For planets that have lost their envelopes to photoevaporation)




Mass-loss timescale and probability due to photo evaporation (Lopez et al. 2012, NR20):

$$t_{\mathrm{loss}} = \frac{G M_{\mathrm{env}}^2}{\pi \epsilon R_{p,\mathrm{init}}^3 F_{\mathrm{XUV,E100}}} \cdot \frac{F_\oplus}{F_p}$$

$$p_{\mathrm{loss}} = 1 - \min\left(\alpha_{\mathrm{ret}} \frac{t_{\mathrm{loss}}}{\tau}, 1\right)$$

# We model planet size similarity in the form of clustered initial planet masses

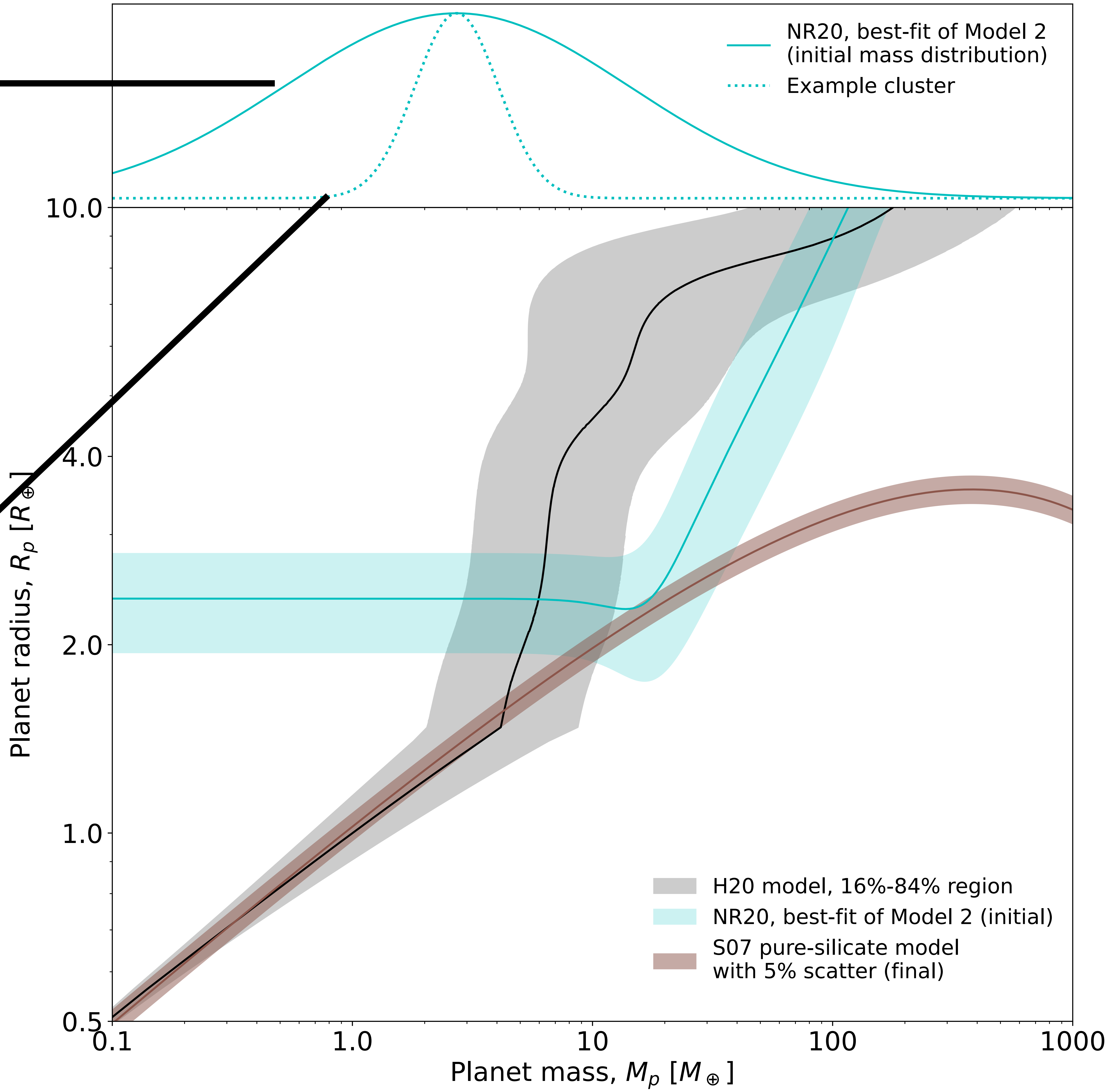
$$M_{p,\text{init}} \sim \ln\mathcal{N}(\mu_M, \sigma_M)$$

Unclustered initial masses

$$\mu_{M,c} \sim \ln\mathcal{N}(\mu_M, \sigma_M)$$
$$M_{p,\text{init}} \sim \ln\mathcal{N}(\mu_{M,c}, \sigma_{M,c})$$

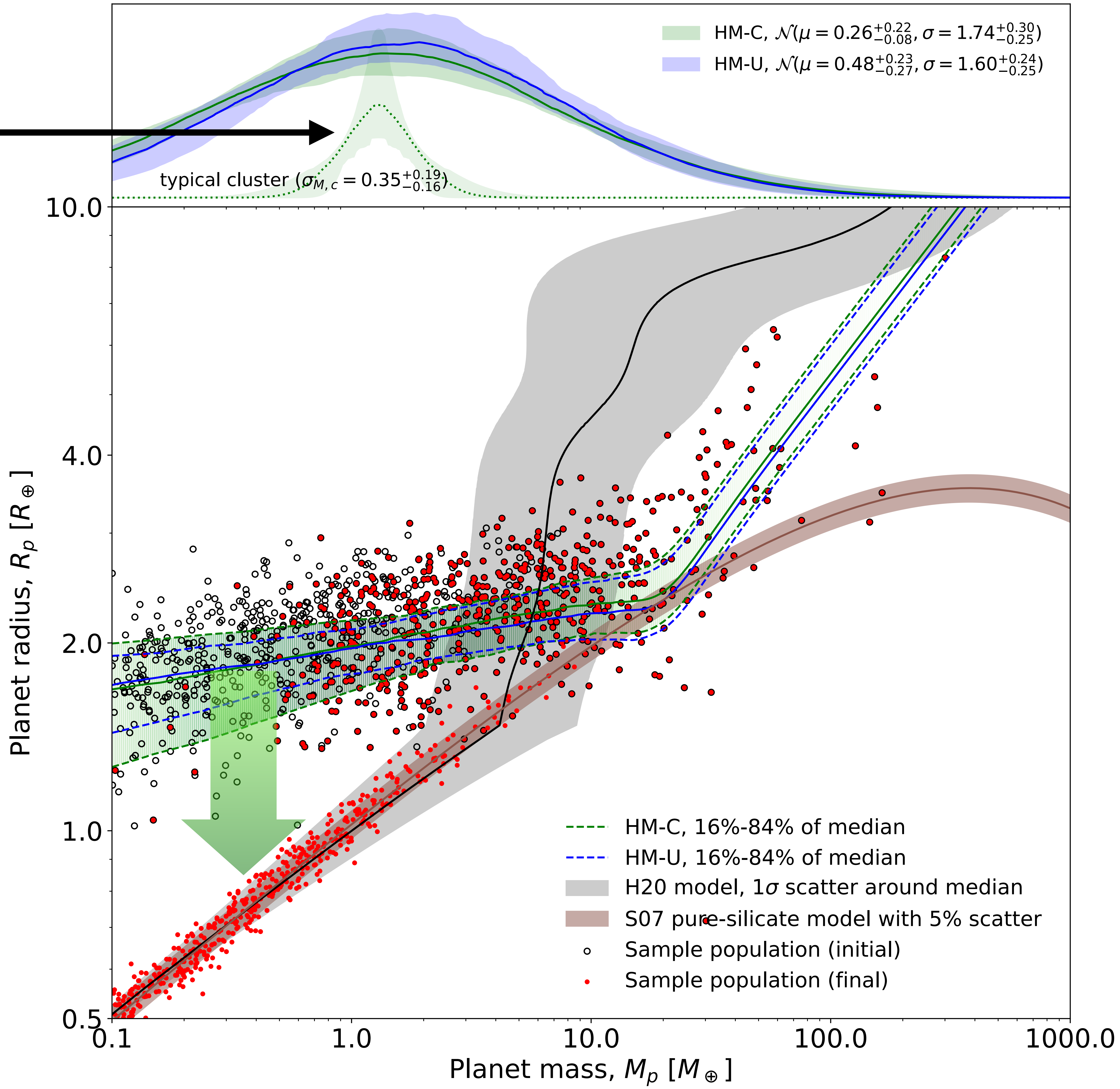
Clustered initial masses
(a lognormal distribution is
drawn for each planet cluster)

$\sigma_{M,c} < \sigma_M$
**implies strong clustering**



# We test two versions of the hybrid model: with vs. without clustered initial planet masses

In HM-C, the cluster width is narrow, implying strongly clustered initial masses



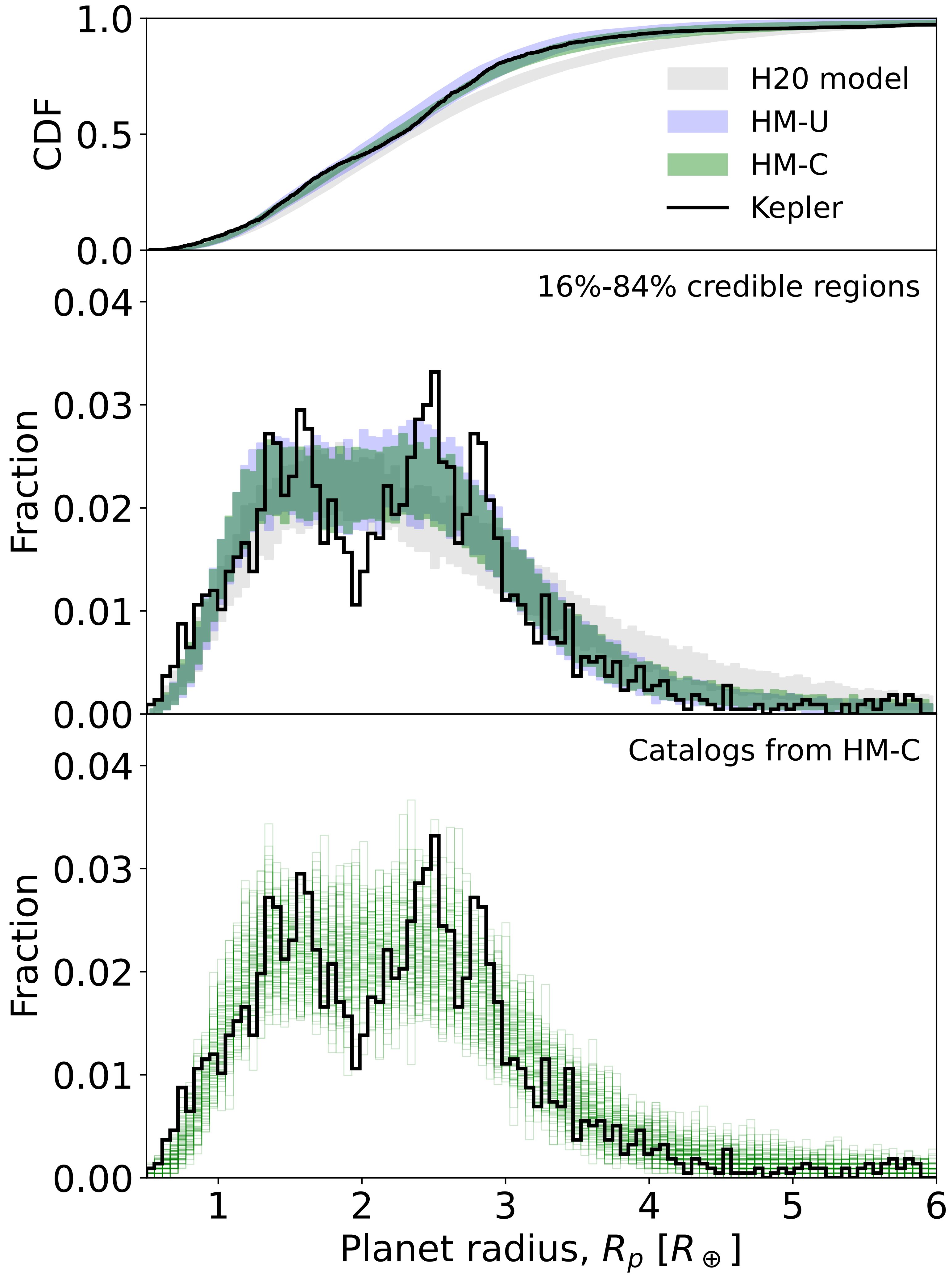

HM-U = Hybrid Model, **Unclustered** initial masses

HM-C = Hybrid Model, **Clustered** initial masses

Less massive planets tend to lose their atmospheres (also a function of orbital period, not visible on this plot)

He & Ford (submitted)

# Do the hybrid models produce a planet radius valley?

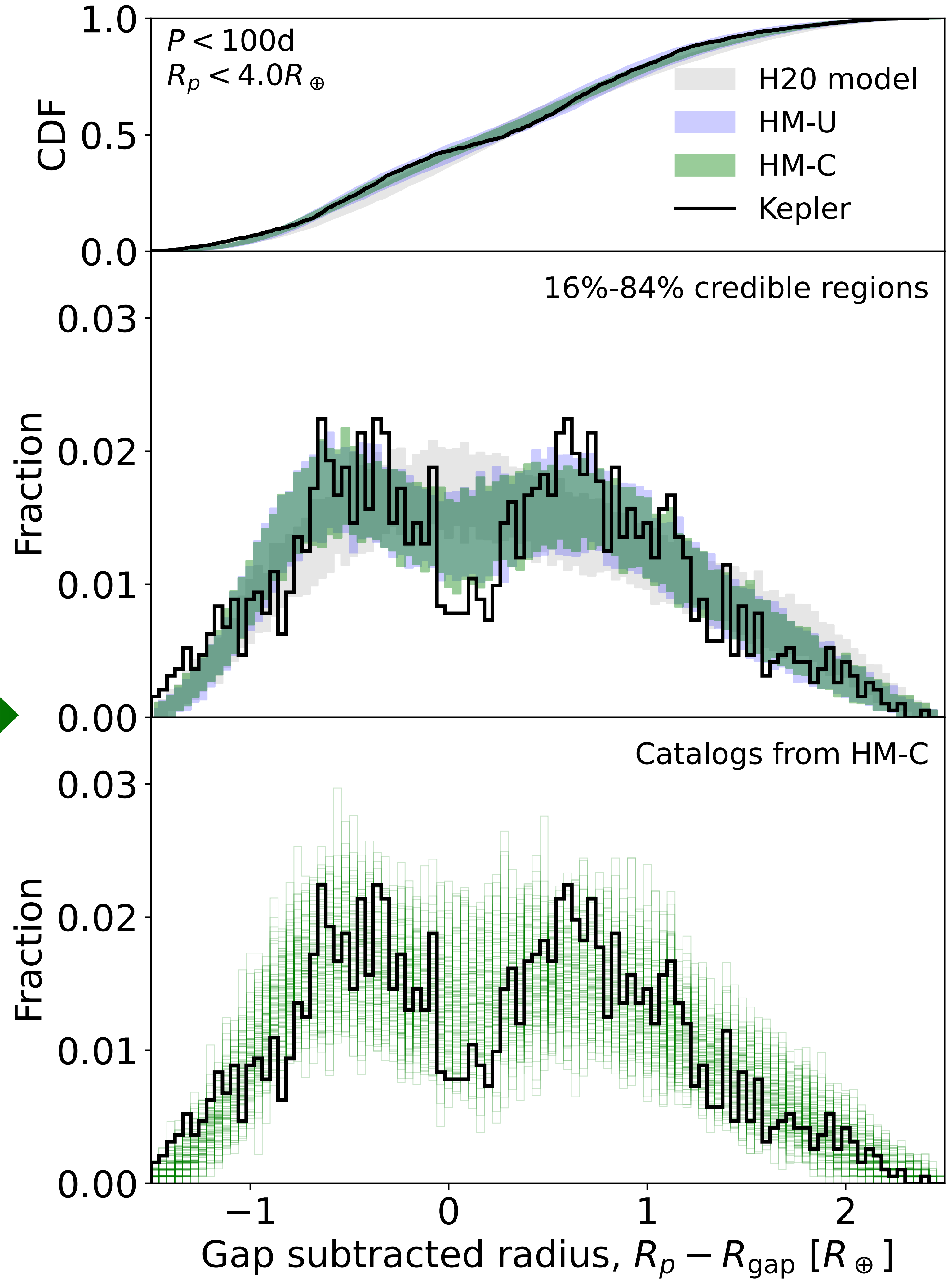



- The hybrid models are capable of producing a radius valley, but our distance function is not very sensitive
- Results for HM-U and HM-C are similar

Subtracting the location of valley:

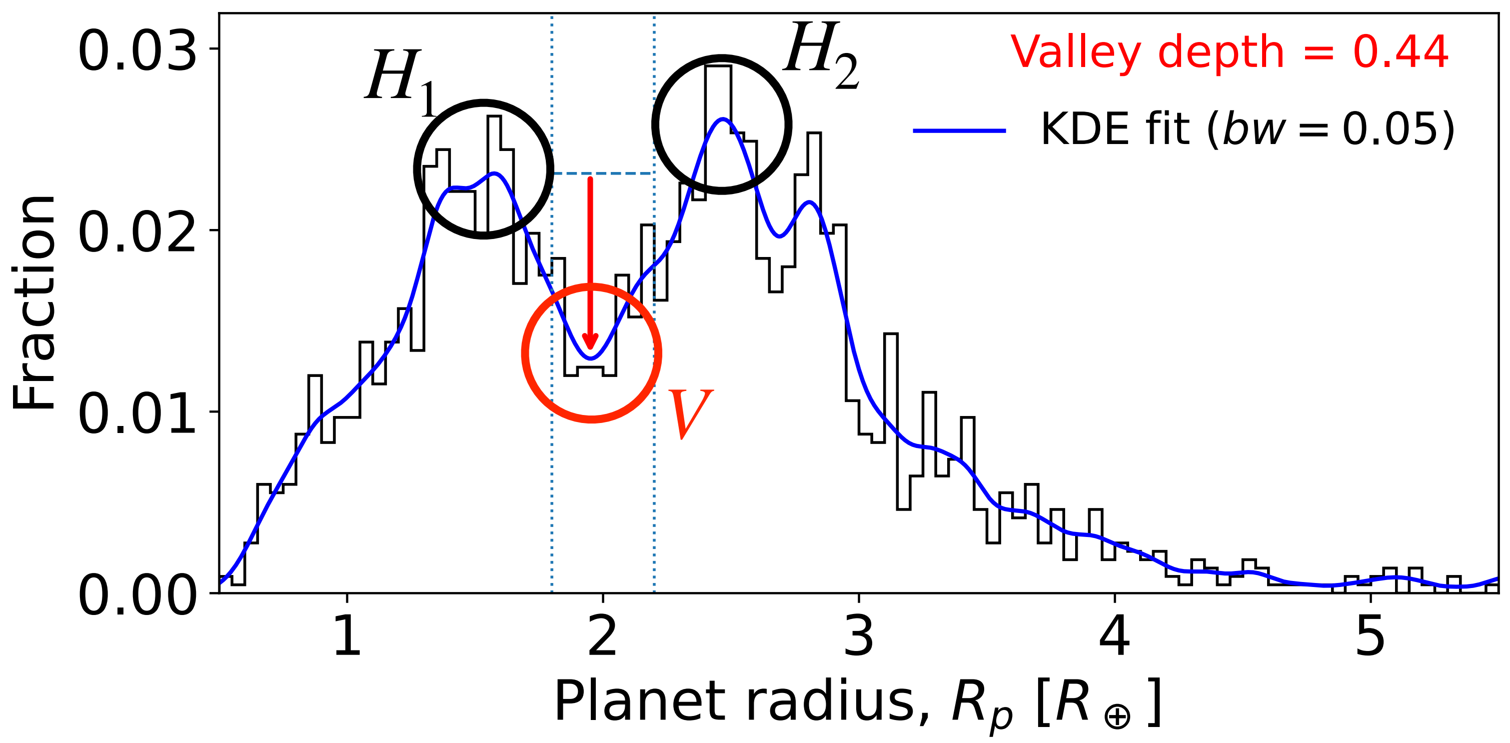
$$R_{\rm gap} \equiv (2.40R_\oplus)P^{-0.10}$$

(best-fit of Van Eylen et al. 2018)



# We need a better way of measuring the strength (depth) of the radius valley

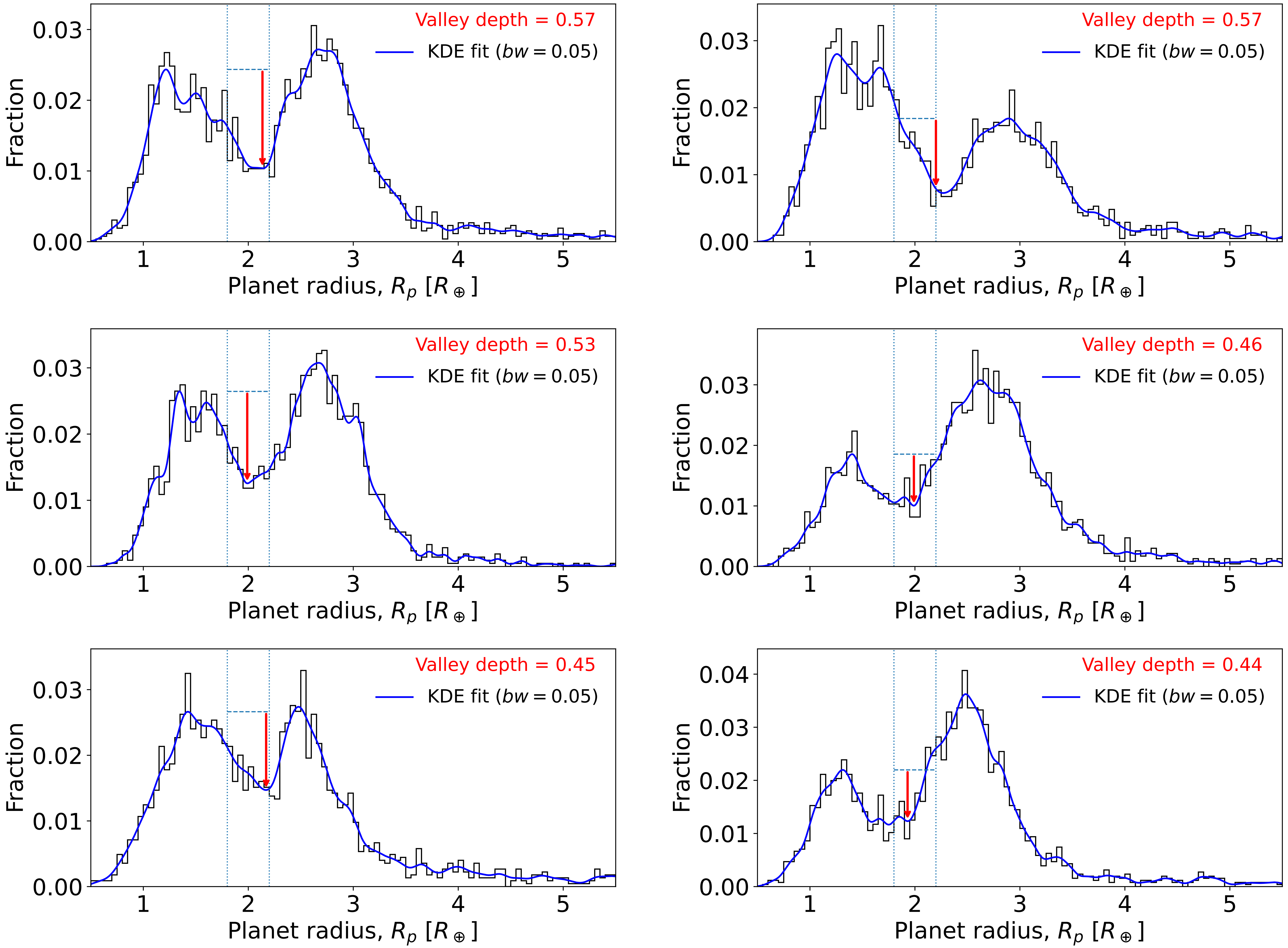
**Kepler catalog**



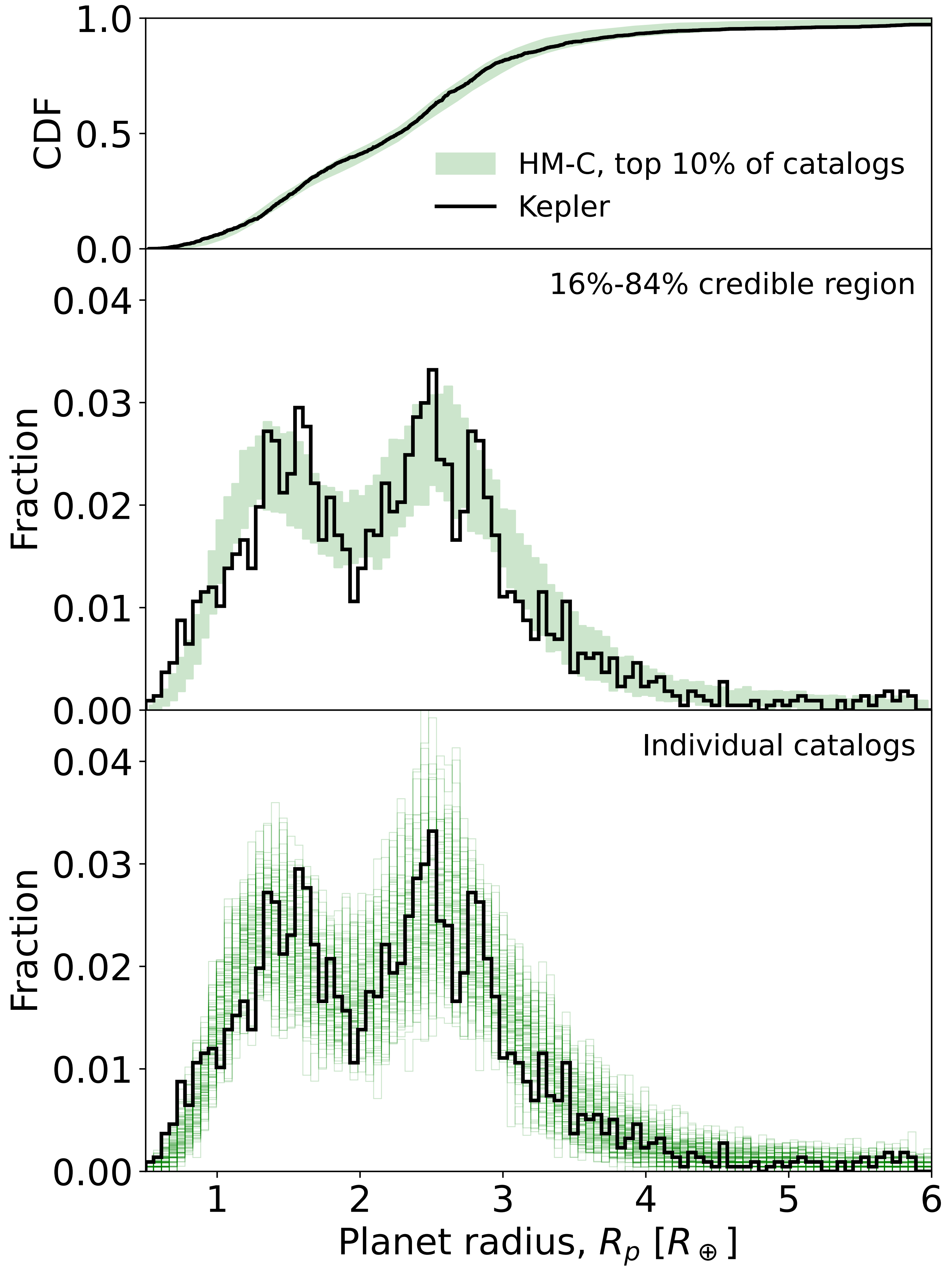

$$\Delta_{\mathrm{valley}} = \frac{H - V}{H}$$

$$H = \min\{H_1, H_2\}$$

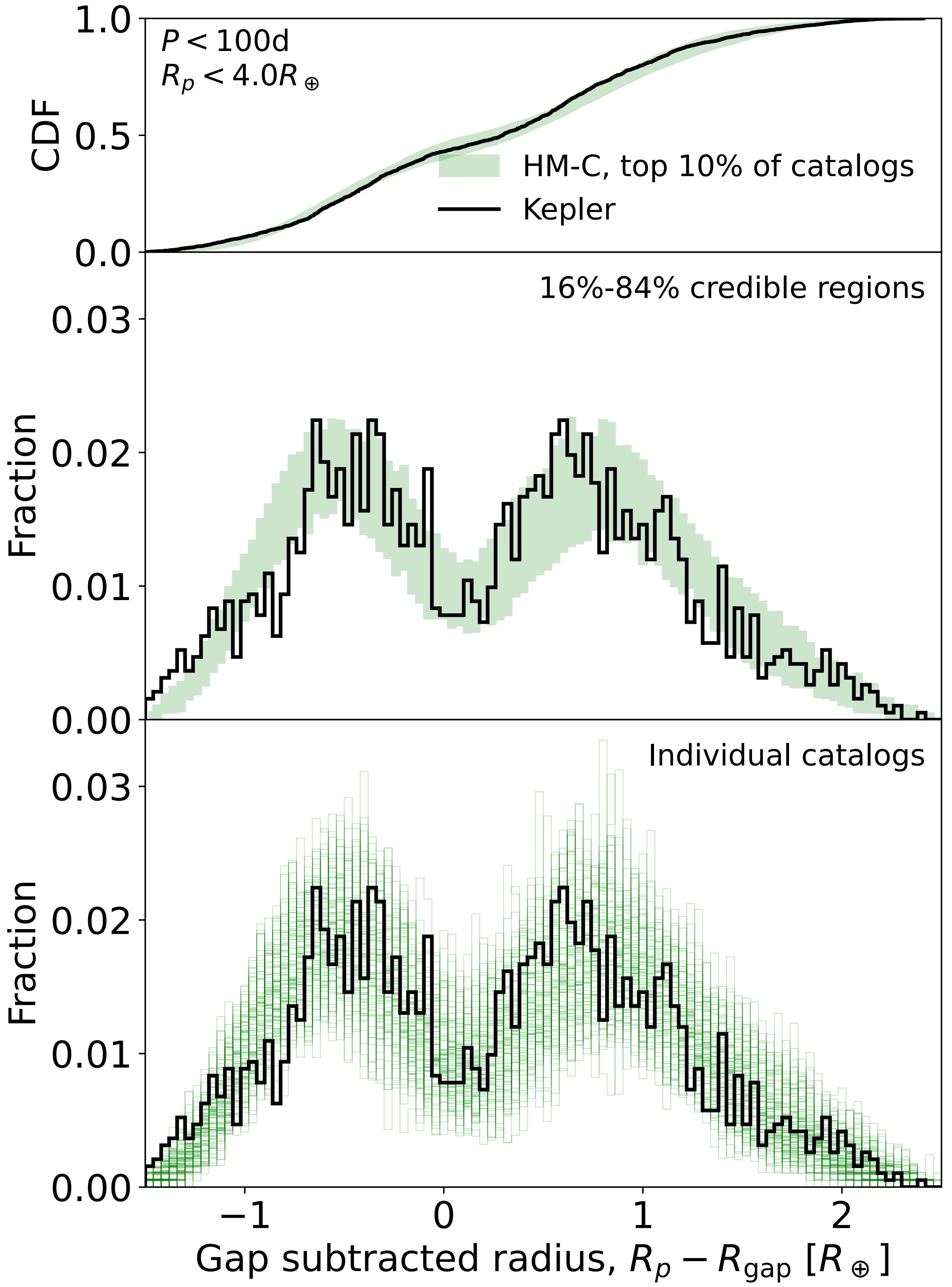
**Simulated catalogs (HM-C)**



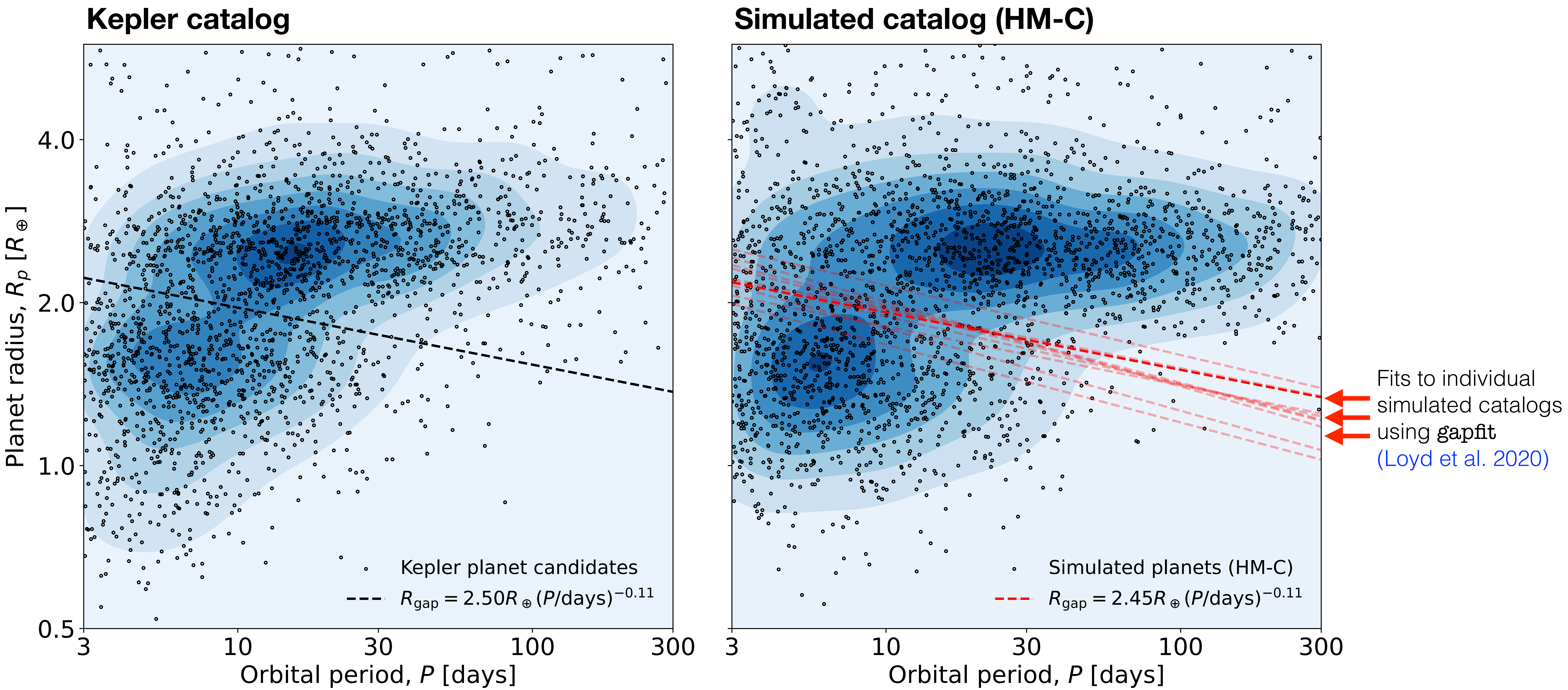
# The hybrid models are capable of producing a planet radius valley like the Kepler data, but requires appropriate model parameters




- The hybrid models with the largest radius valley depths provide very close fits to the Kepler data
- Results for HM-U and HM-C are similar



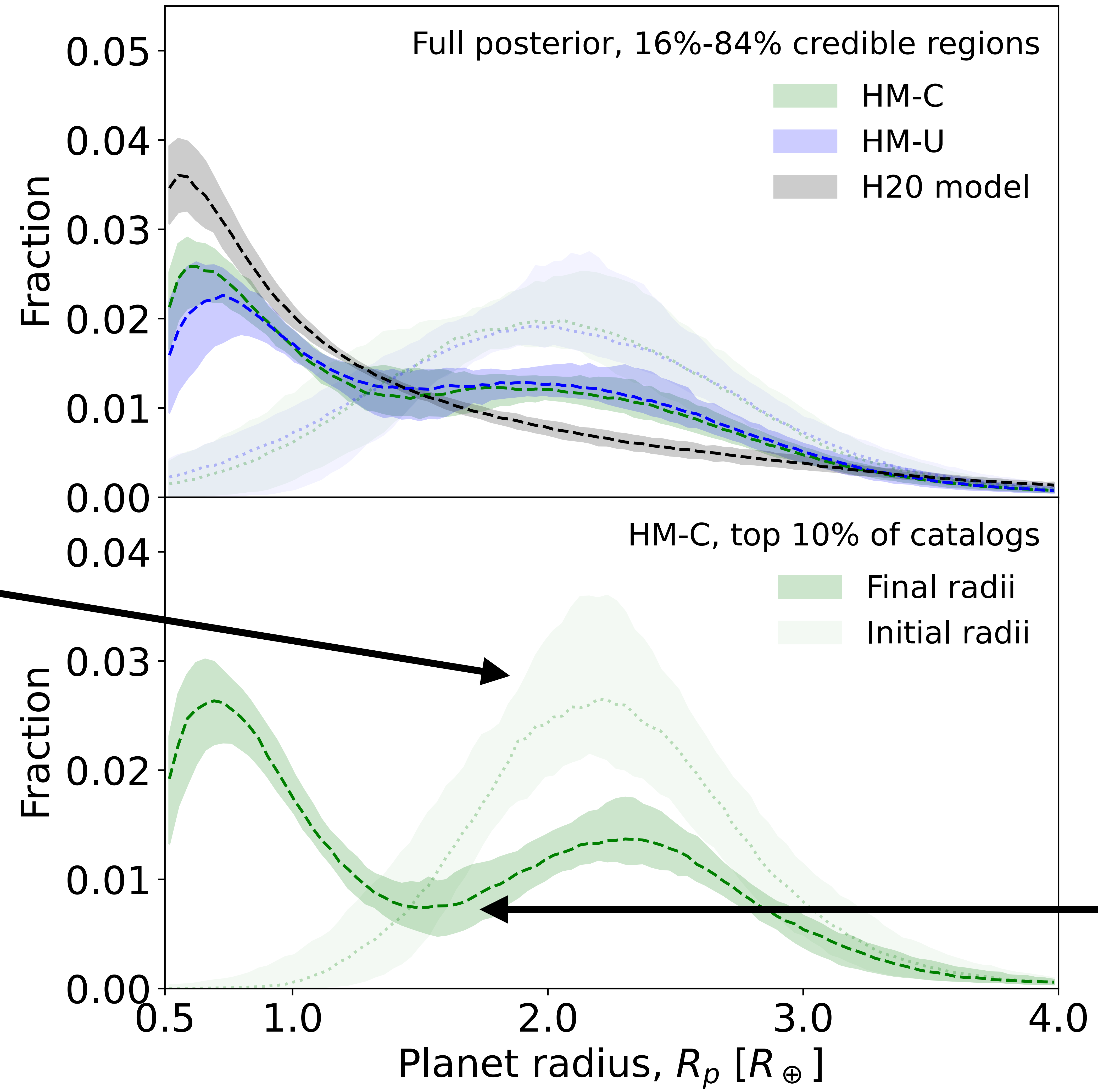
# For simulated catalogs that produce a strong radius valley, its location in period-radius also closely matches that of the Kepler data



# The hybrid models predict a primordial distribution of planet radii (i.e. before photo evaporation) that peaks above $\sim 2R_\oplus$

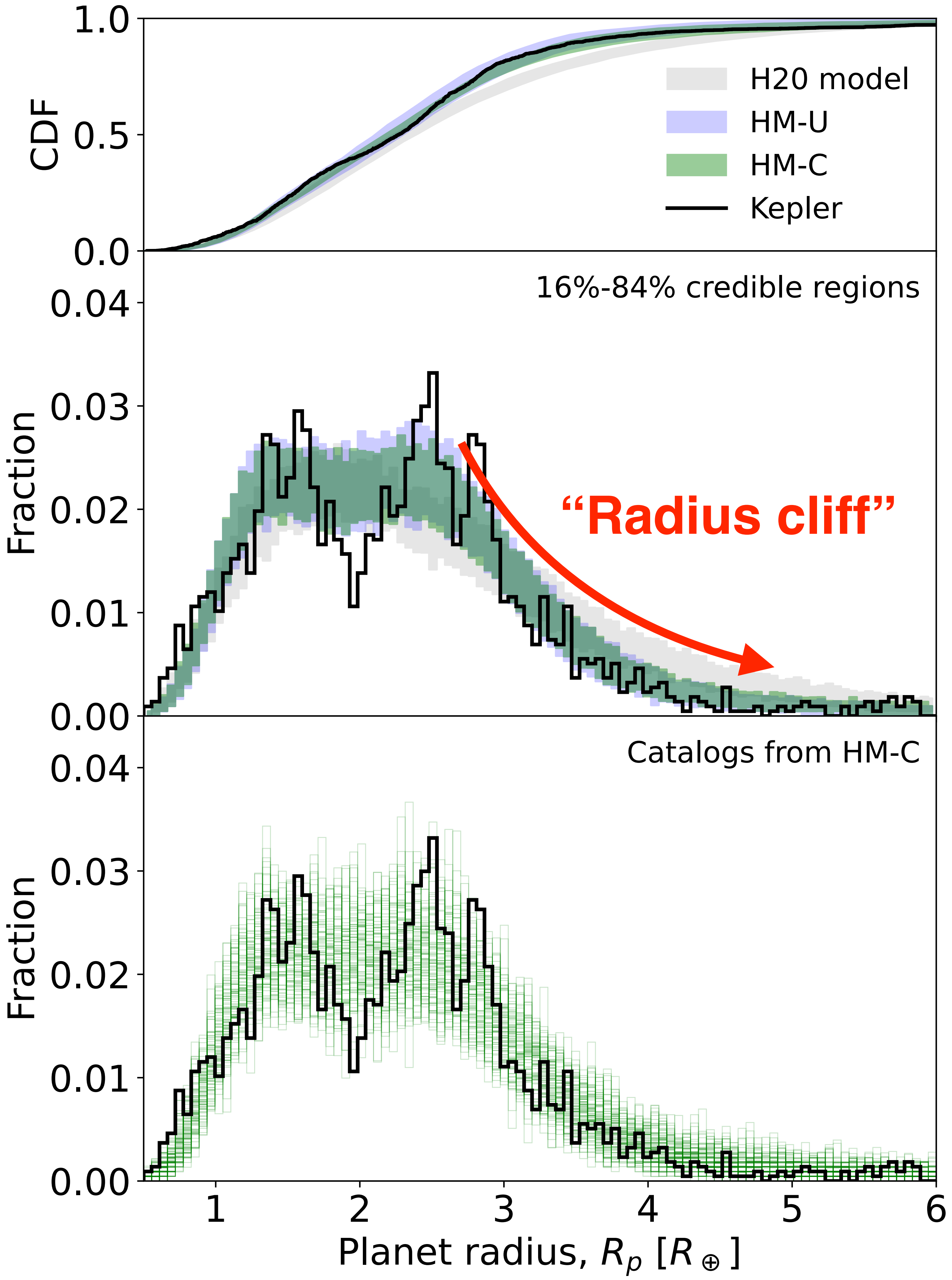
Initial radius distribution is strongly peaked above $\sim 2R_\oplus$

Most small planets are photo-evaporated cores



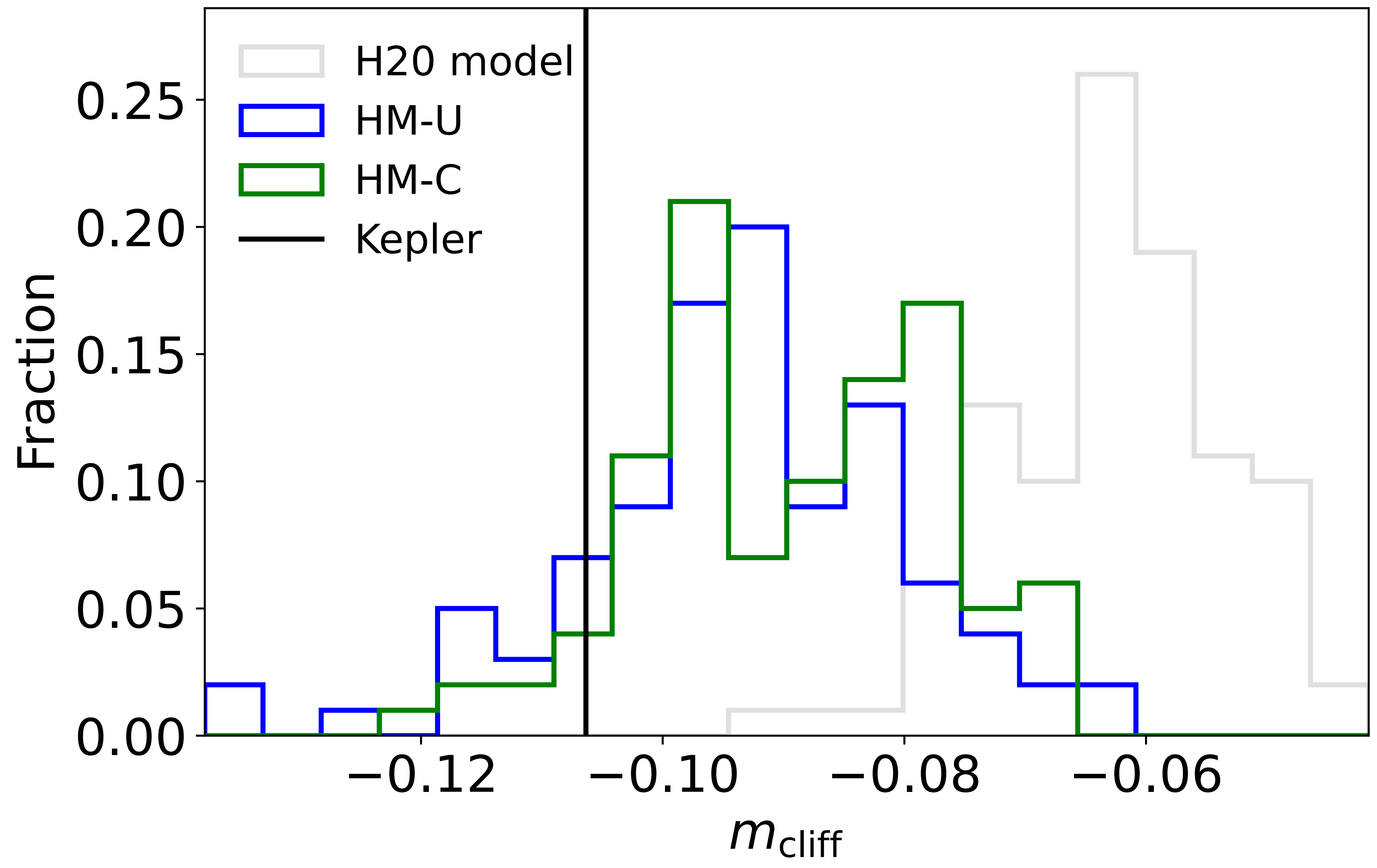

Radius valley also seen in the underlying (final) distribution, but shifted

# The hybrid models also naturally explains the observed “radius cliff”



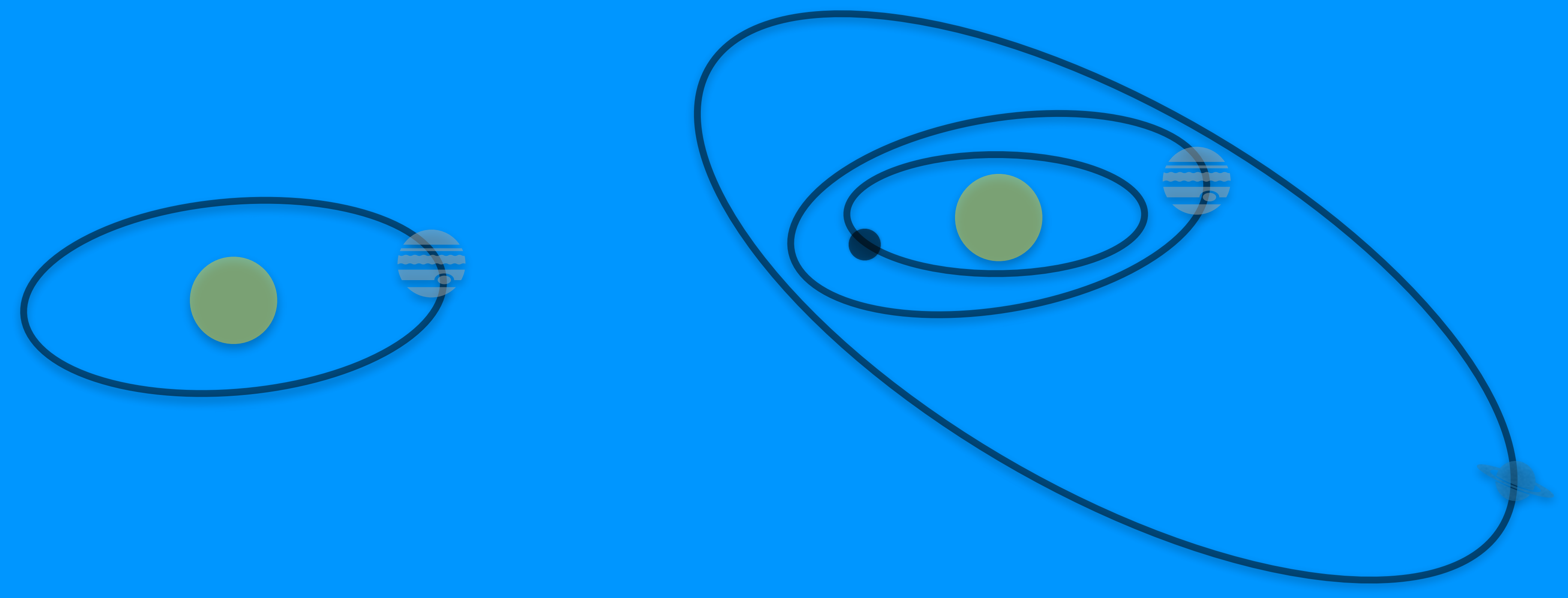

$$f(R_p) = m_{\rm cliff} \log_{10}(R_p) + b$$

Slope of the radius cliff, fit between $2.5 - 5.5 R_\oplus$ (following Dattilo et al. 2023, 2024)

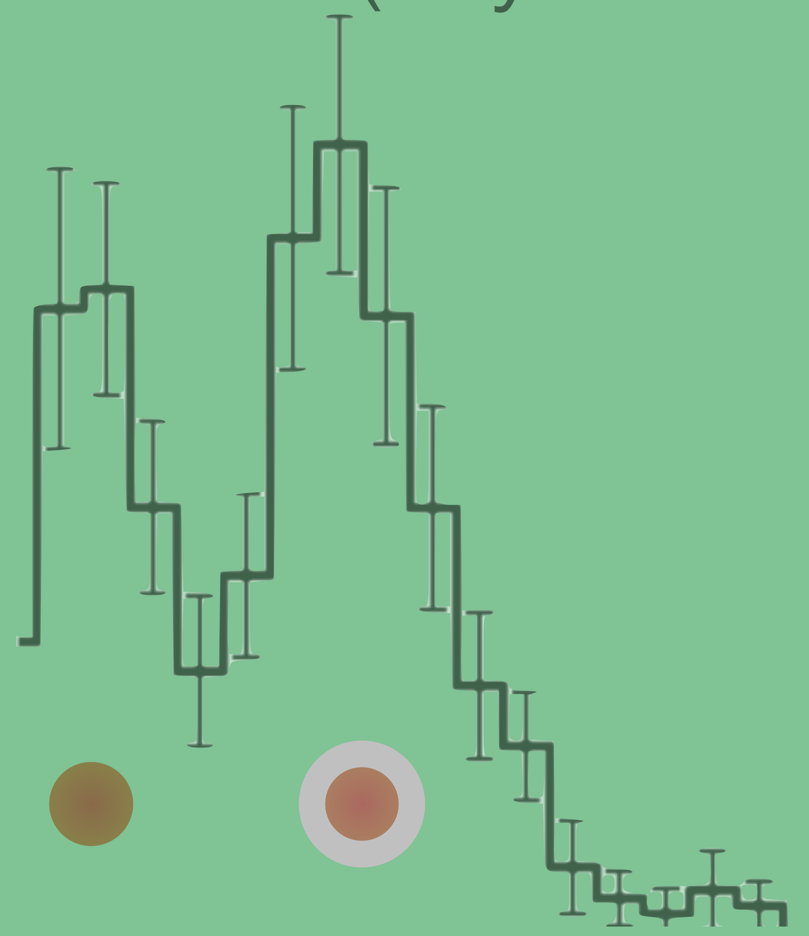



He & Ford (submitted)

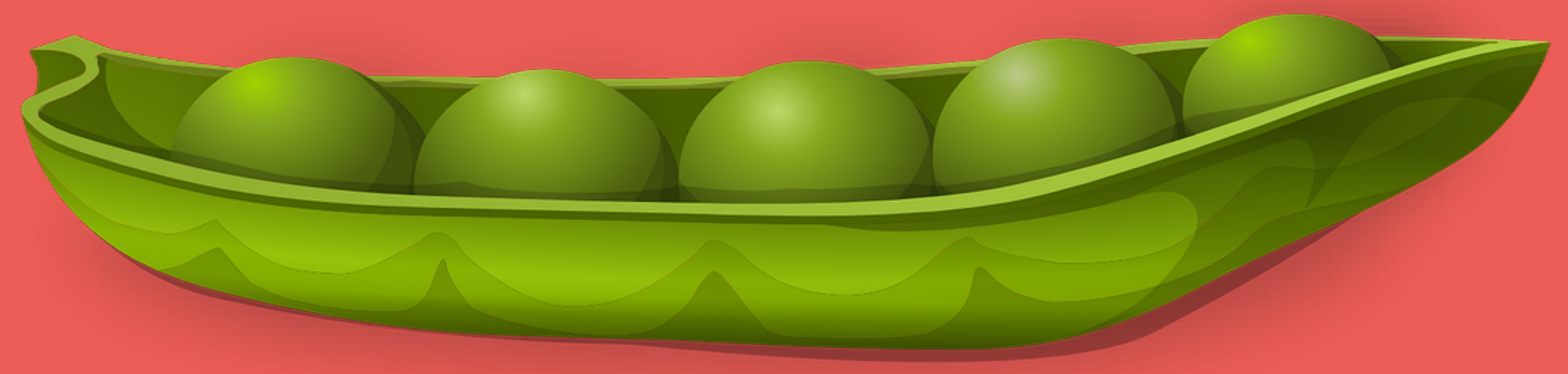
Distribution of multiplicities and mutual inclinations (“Kepler dichotomy”)



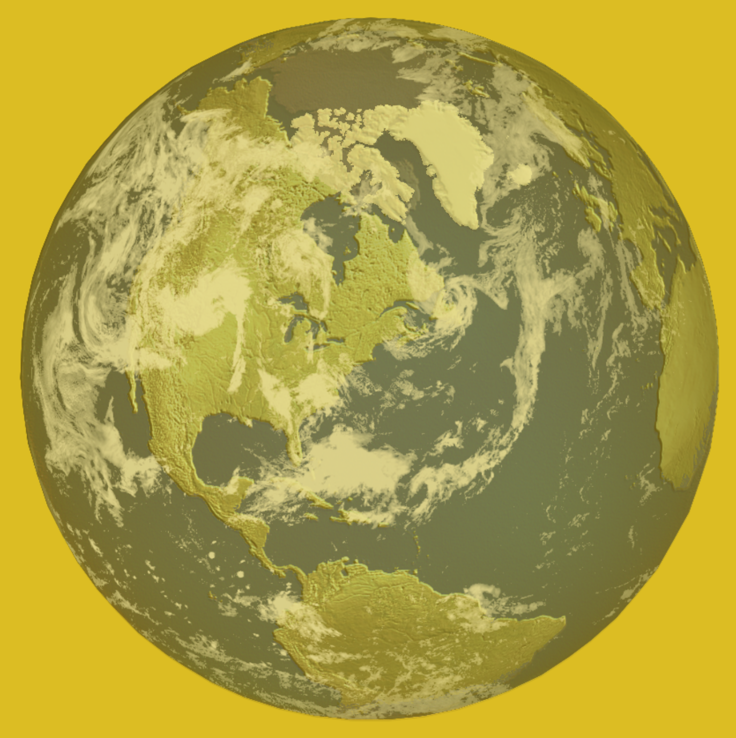
Planet radius valley in the context of a multi-planet model (“hybrid model”)



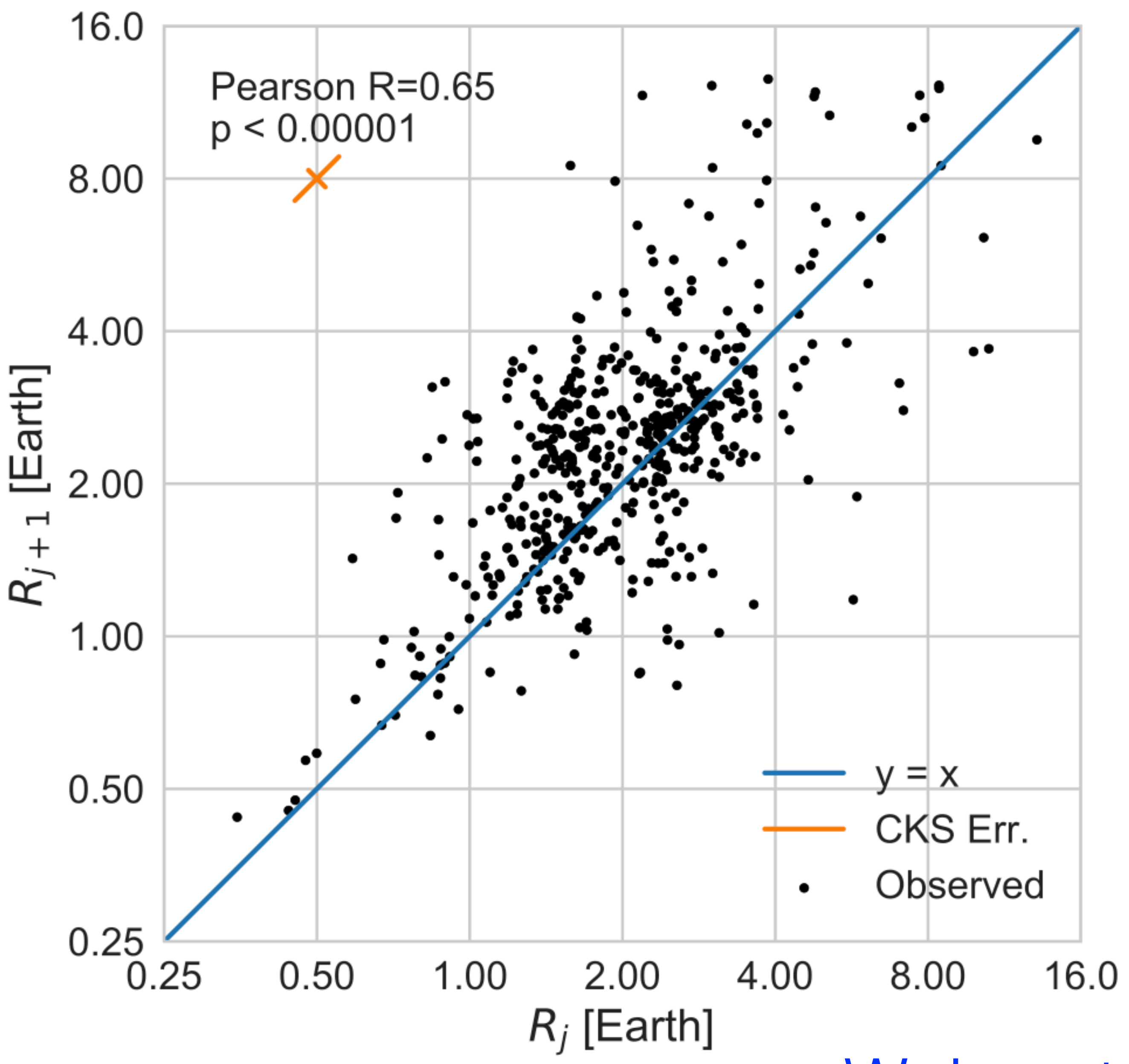
Planet size similarity, ordering, ~~and spacings~~ of multi-planet systems (“peas in a pod”)

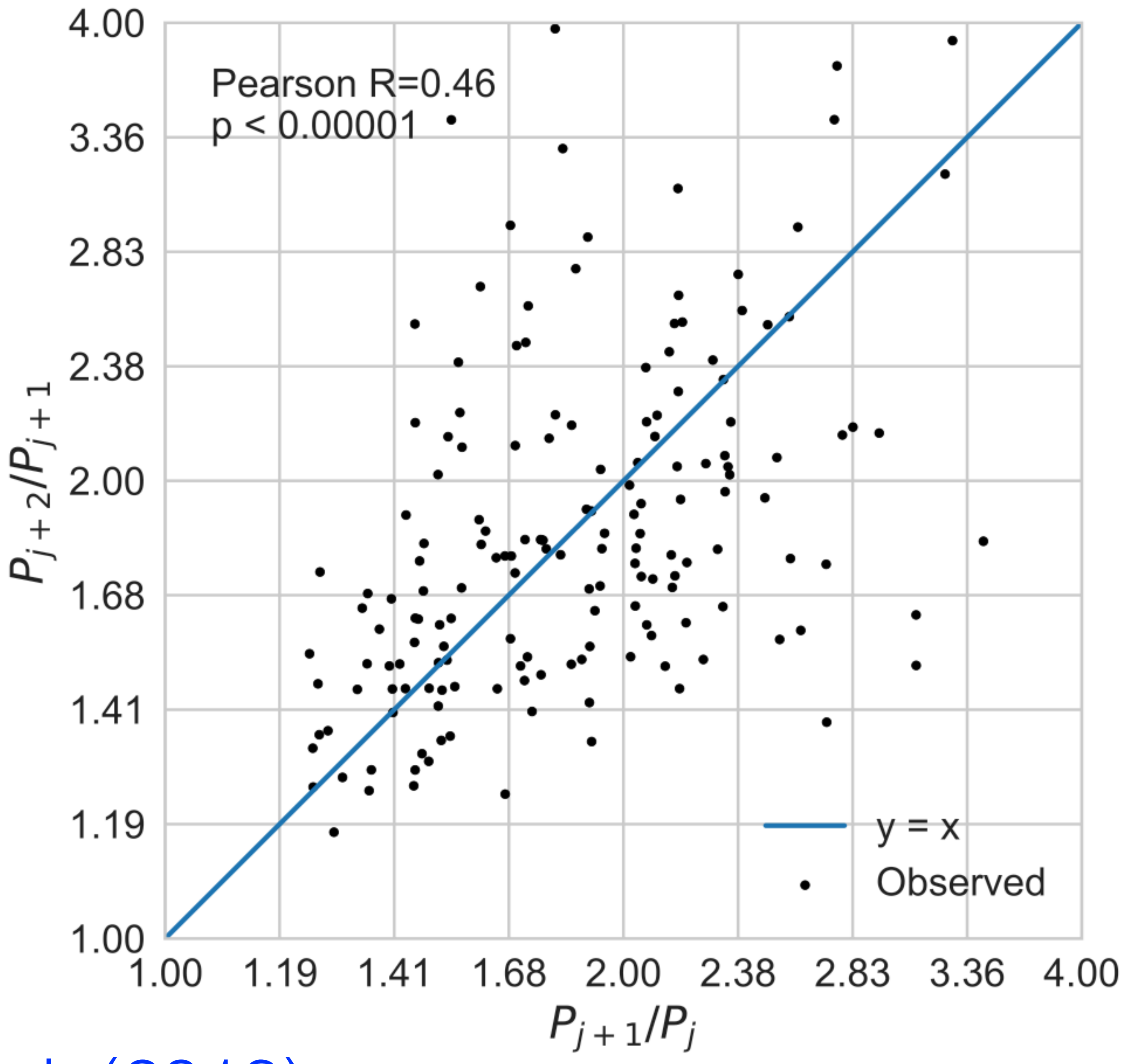


Occurrence of Earth-sized planets in the habitable zone (“eta-Earth”)



# Planets in the same system are more similar in size than planets from different systems

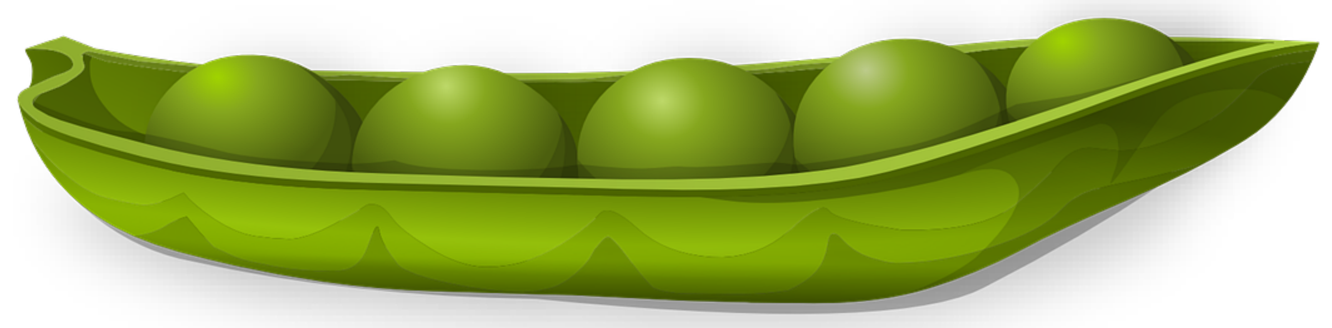



Weiss et al. (2018)

Detection biases may play a role, but forward modeling shows that these patterns are physical

***"Peas in a pod"***

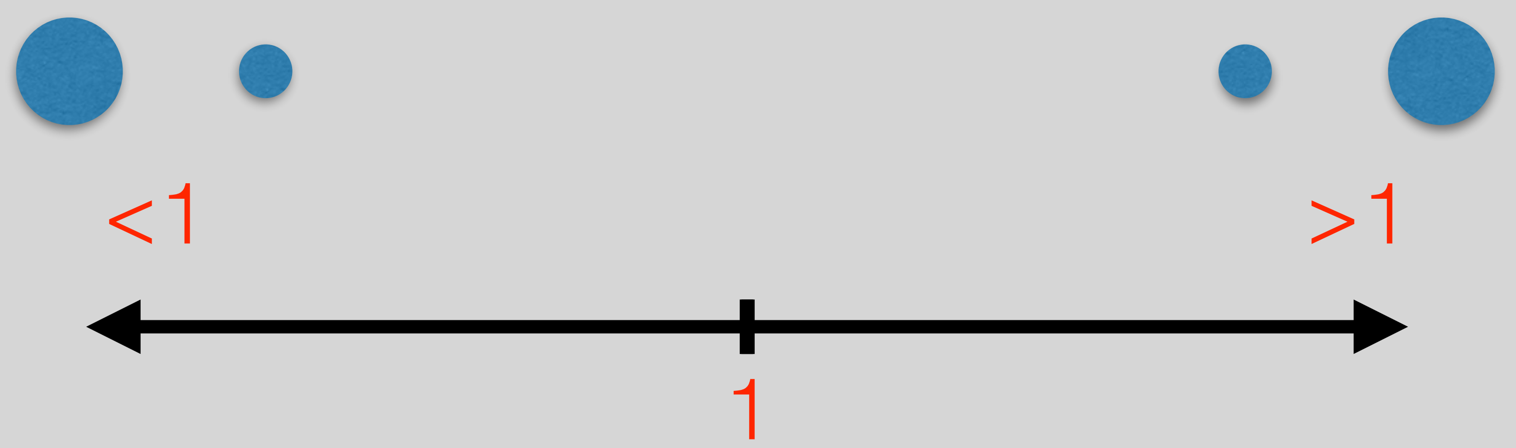


Ciardi et al. (2013)
Millholland et al. (2017)
Zhu et al. (2019)
Weiss & Petigura (2019)
**He et al. (2019, 2020)**
Murchikova & Tremaine (2020)
Gilbert & Fabrycky (2020)
Mishra et al. (2021)
Millholland & Winn (2021)
Goyal & Wang (2022)

The radii of adjacent observed planets are correlated
The period ratios of adjacent observed planet pairs are also correlated

# We fit the distributions of several metrics that capture the system-level patterns in the planet radii

## How similar are adjacent pairs of planets?




transit depth ratio
= (planet radius ratio)²

$$\frac{\delta_{\rm out}}{\delta_{\rm in}} = \left(\frac{R_{p,\rm out}}{R_{p,\rm in}}\right)^2$$

He et al. (2019)

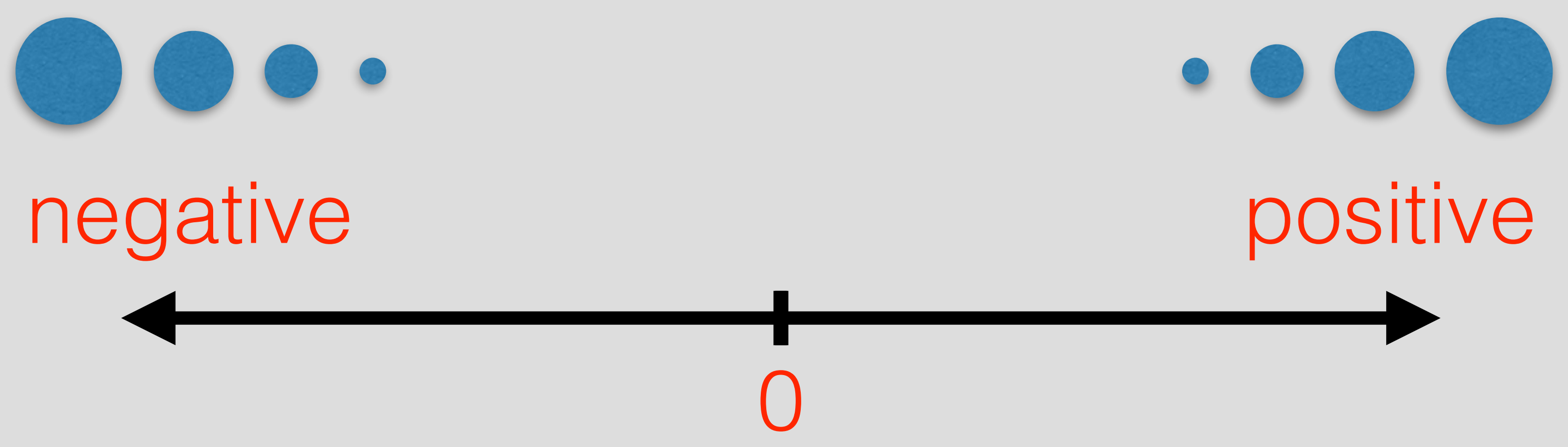
## How similar are planets in the same system?


"radius partitioning"

$$\mathcal{Q}_R \equiv \left(\frac{m}{m-1}\right)\left(\sum_{k=1}^{m}\left(R^*_{p,k} - \frac{1}{m}\right)^2\right),$$

$$R^*_{p,k} = \frac{R_{p,k}}{\sum_{i=1}^{m} R_{p,i}}$$

## How are planets ordered?



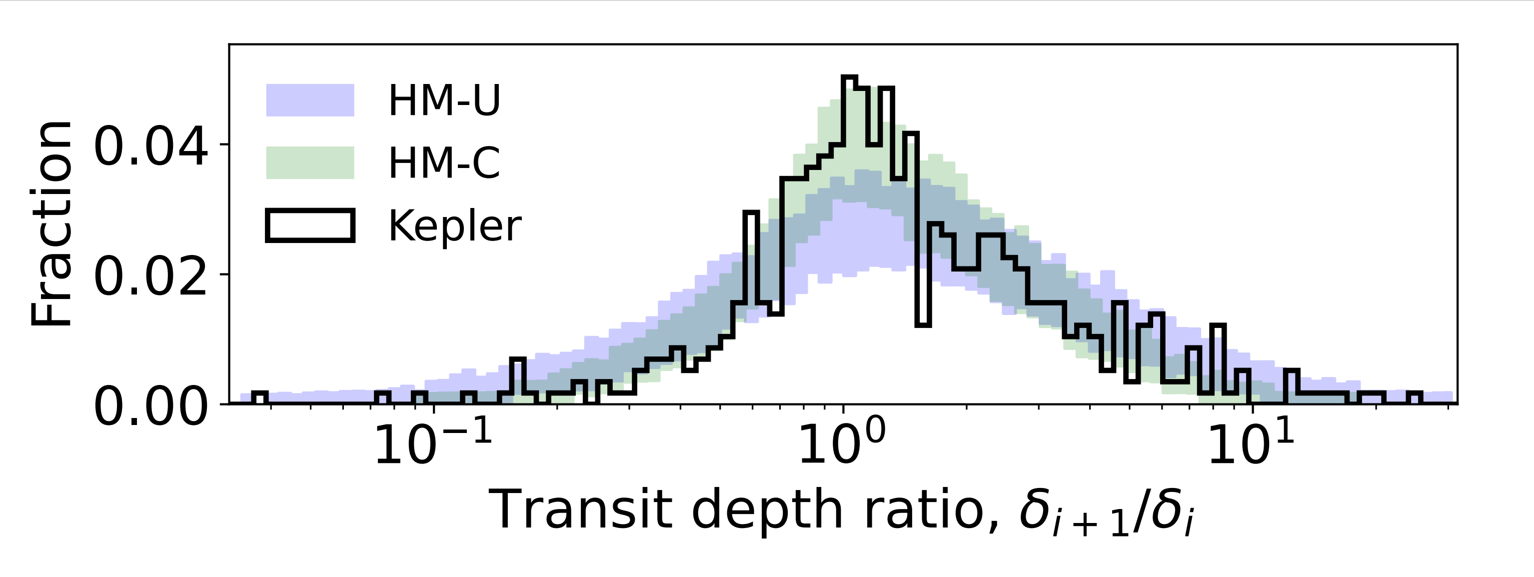

"radius monotonicity"

$$\mathcal{M}_R \equiv \rho_S \mathcal{Q}_R^{1/m}$$

Gilbert & Fabrycky (2020)
He et al. (2020)

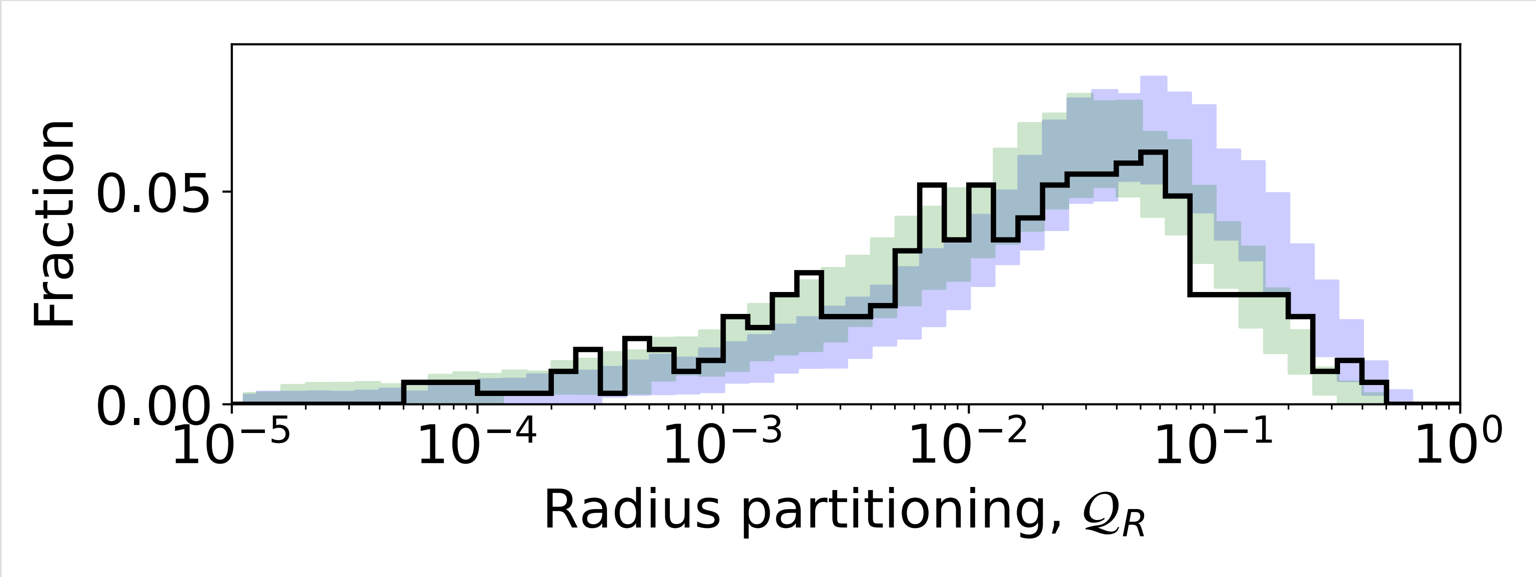
# We find strong evidence for clustering in the underlying planet *mass* distribution, which produces the planet radius correlations

## How similar are adjacent pairs of planets?



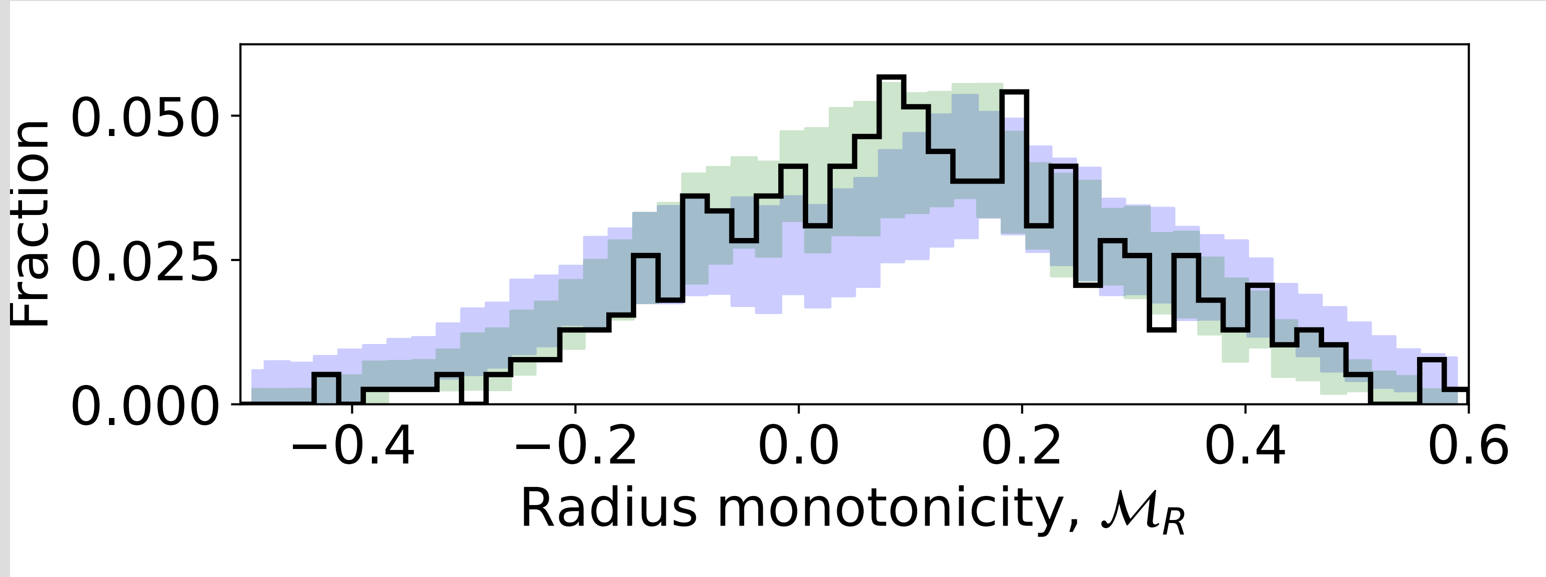

HM-C provides a better fit to the Kepler distribution (especially the strong peak around 1, implying similar planet radii)

## How similar are planets in the same system?




HM-C also provides a better fit here, implying similar planet sizes within the same system

## How are planets ordered?

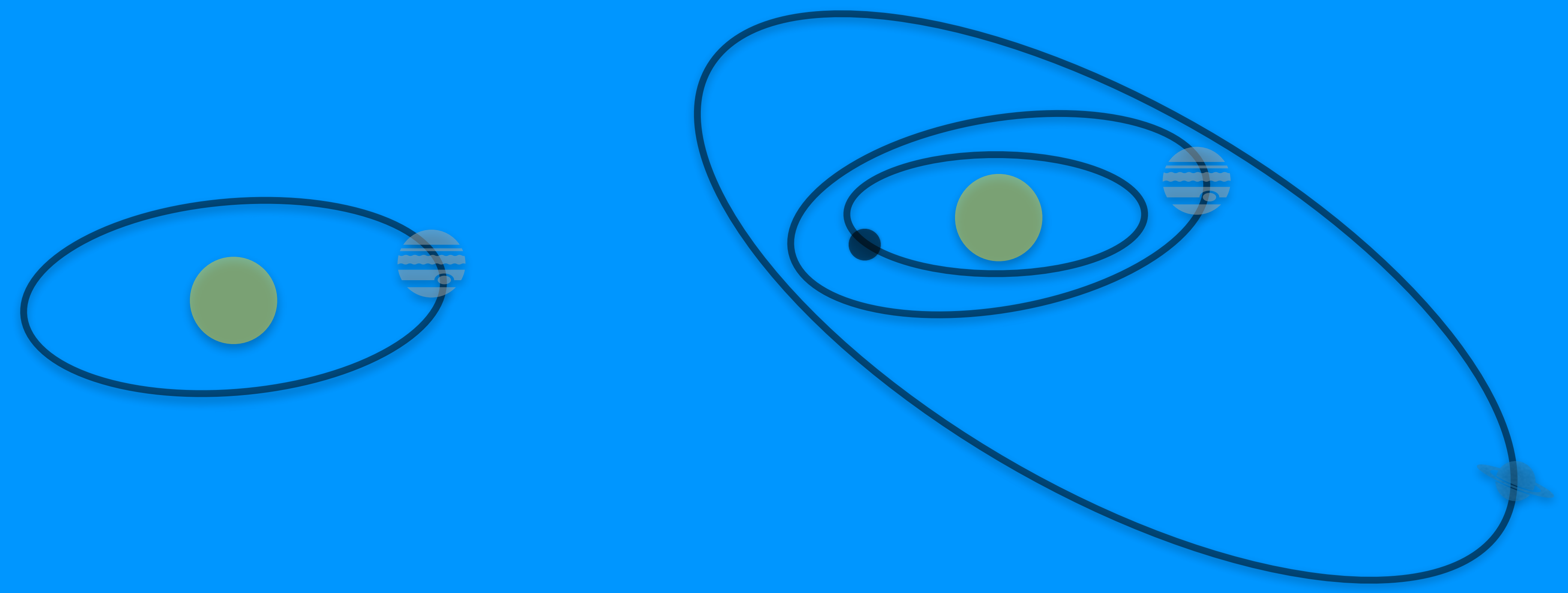



While both models produce more positive than negative values (indicating a preference for increasing sizes towards longer periods), HM-C is again better

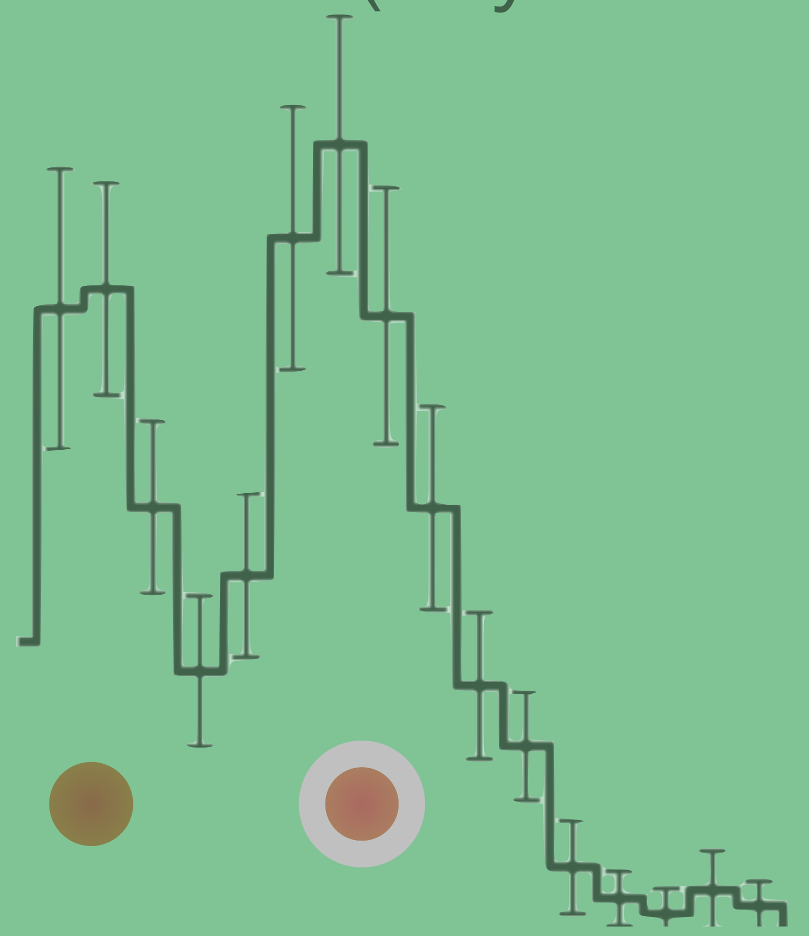
He & Ford (submitted)

**The observed size similarity of planets in multi-planet systems can be fully explained by a clustering in the initial mass distribution**

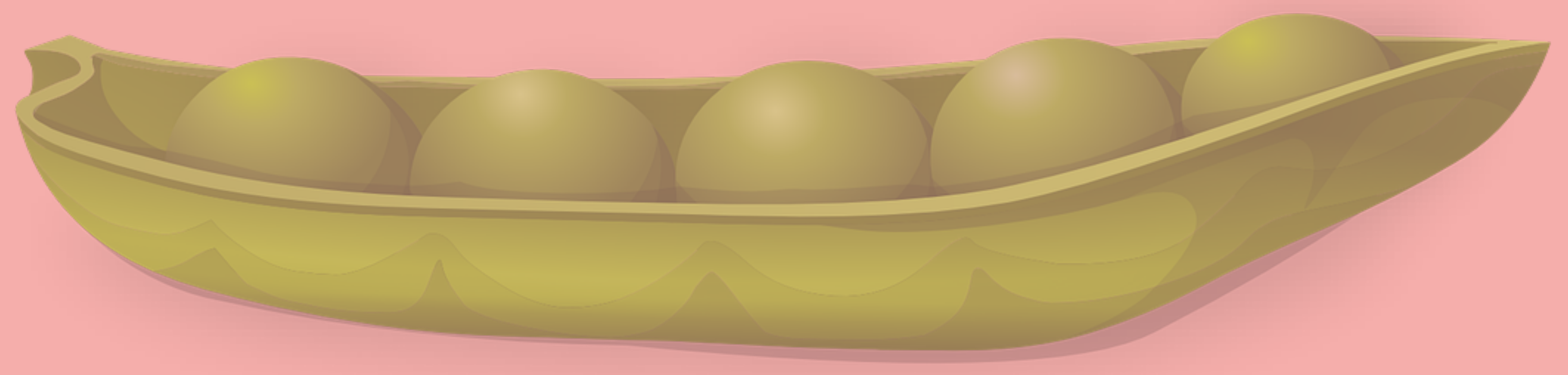
Distribution of multiplicities and mutual inclinations ("Kepler dichotomy")



Planet radius valley in the context of a multi-planet model ("hybrid model")

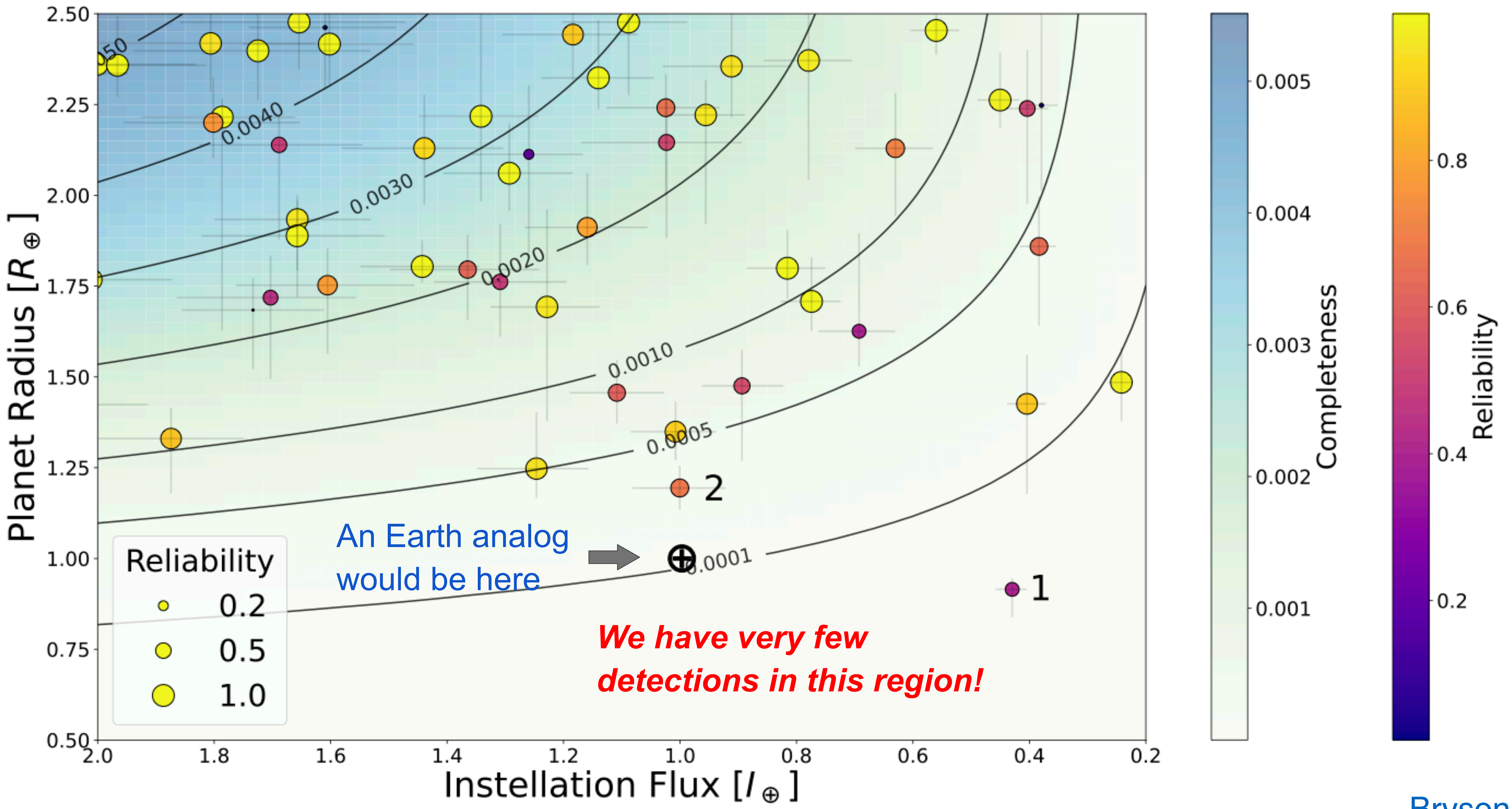


Planet size similarity, ordering, ~~and spacings~~ of multi-planet systems ("peas in a pod")



Occurrence of Earth-sized planets in the habitable zone ("eta-Earth")

# What about the occurrence of Earth-sized rocky planets in the habitable zones of Sun-like stars ($\eta_{\oplus}$)?




Bryson et al. (2021)

# Extrapolating population models based on the inner systems can significantly overestimate $\eta_\oplus$

In abstract of Pascucci et al. (2019):

*"Here, we show that extrapolations relying on the population of small ($<1.8R_\oplus$), short-period (<25 days) planets bias $\eta_\oplus$ to large values. As the radius distribution at short orbital periods is strongly affected by atmospheric loss, we reevaluate $\eta_\oplus$ using exoplanets at larger separations. We find that $\eta_\oplus$ drops considerably, to values of only ~5%-10%."*

| Model # | Fitted $P$ days | Fitted $R$ $R_\oplus$ | Function | $\Gamma_\oplus$ % | $\eta_\oplus$ % |
|---|---|---|---|---|---|
| 1 | 2–400 | 0.5–6 | 2D broken | $59.6^{+21.8}_{-25.4}$ | $40.6^{+14.9}_{-17.3}$ |
| 2 | 2–400 | 0.5–2 | $P$ broken | $78.7^{+43.5}_{-39.2}$ | $53.6^{+29.7}_{-29.7}$ |
| 3 | 12–400 | 0.5–6 | $R$ broken | $17.0^{+7.6}_{-5.6}$ | $11.5^{+5.2}_{-3.8}$ |
| 4 | 12–400 | 1–6 | $R$ broken | $16.0^{+8.0}_{-5.5}$ | $10.9^{+5.5}_{-3.7}$ |
| 5 | 25–400 | 0.5–6 | $R$ broken | $8.6^{+8.9}_{-5.1}$ | $5.9^{+6.0}_{-3.5}$ |
| 6 | 25–400 | 1–6 | $R$ broken | $8.0^{+10.3}_{-5.4}$ | $5.4^{+7.0}_{-3.7}$ |
| 7 | 25–400 | 1–2 | $P$ and $R$ single | $7.8^{+10.3}_{-3.8}$ | $5.3^{+7.0}_{-2.6}$ |

Table 2 of Pascucci et al. (2019)

In abstract of Neil & Rogers (2020):

*"When using models with envelope mass loss to calculate $\eta_\oplus$, we find nearly an order of magnitude drop, indicating that many Earth-like planets discovered with Kepler may be evaporated cores which do not extrapolate out to higher orbital periods."*

| Variable Range | Model 1 | Model 2 |
|---|---|---|
| $0.4 < \frac{R}{R_\oplus} < 30,\ 0.3 < \frac{P}{1\ \mathrm{day}} < 100$ | $1.36^{+0.07}_{-0.06}$ | $1.31^{+0.06}_{-0.06}$ |
| $0.5 < \frac{R}{R_\oplus} < 6,\ 2 < \frac{P}{1\ \mathrm{day}} < 400$ | $2.28^{+0.22}_{-0.18}$ | $1.89^{+0.18}_{-0.13}$ |
| $1.4 < \frac{R}{R_\oplus} < 2.8,\ 0.3 < \frac{P}{1\ \mathrm{day}} < 100$ | $0.43^{+0.02}_{-0.02}$ | $0.47^{+0.03}_{-0.03}$ |
| $2 < \frac{R}{R_\oplus} < 4,\ 0.3 < \frac{P}{1\ \mathrm{day}} < 100$ | $0.30^{+0.01}_{-0.01}$ | $0.45^{+0.02}_{-0.02}$ |
| $50 < \frac{M}{M_\oplus} < 10000,\ 0.3 < \frac{P}{1\ \mathrm{day}} < 11$ | $0.005^{+0.001}_{-0.001}$ | $0.010^{+0.002}_{-0.001}$ |
| $3 < \frac{M}{M_\oplus} < 10,\ 0.3 < \frac{P}{1\ \mathrm{day}} < 50$ | $0.19^{+0.01}_{-0.01}$ | $0.22^{+0.01}_{-0.01}$ |
| $0.8 < \frac{R}{R_\oplus} < 1.2,\ 292 < \frac{P}{1\ \mathrm{day}} < 438$ | $0.076^{+0.016}_{-0.011}$ | $0.008^{+0.003}_{-0.002}$ |
| $0.8 < \frac{R}{R_\oplus} < 1.2,\ 292 < \frac{P}{1\ \mathrm{day}} < 438,\ 0.5 < \frac{M}{M_\oplus} < 2.0$ | $0.055^{+0.011}_{-0.009}$ | $0.005^{+0.003}_{-0.002}$ |

Table 2 of Neil & Rogers (2020) (partial)

No mass loss (Model 1) — With mass loss (Model 2)

# Extrapolating population models based on the inner systems can significantly overestimate $\eta_\oplus$

**Table 2.** Occurrence rates ($\eta$) of various planet types for each model, and comparisons to previous literature values.

| | Planet bounds | H20 model | HM-U | HM-C | NR20* | Other literature value/reference | |
|---|---|---|---|---|---|---|---|
| Full simulation range → | $R_p = 0.5$-$10$, $P = 3$-$300$ | $2.49^{+0.37}_{-0.28}$ | $2.53^{+0.19}_{-0.20}$ | $2.49^{+0.23}_{-0.13}$ | – | – | – |
| | $R_p = 2$-$4$, $P = 3$-$100$ | $0.34^{+0.03}_{-0.03}$ | $0.43^{+0.06}_{-0.04}$ | $0.42^{+0.05}_{-0.03}$ | $0.45^{+0.02}_{-0.02}$ | $0.37^{+0.02}_{-0.02}$ | Fulton et al. (2017)[a] |
| Planets spanning valley → | $R_p = 1.4$-$2.8$, $P = 3$-$100$ | $0.46^{+0.04}_{-0.03}$ | $0.60^{+0.06}_{-0.05}$ | $0.58^{+0.03}_{-0.05}$ | $0.47^{+0.03}_{-0.03}$ | $0.43^{+0.02}_{-0.02}$ | Fulton et al. (2017)[a] |
| | $R_p = 0.75$-$1.4$, $P = 3$-$100$ | $0.54^{+0.07}_{-0.08}$ | $0.54^{+0.07}_{-0.07}$ | $0.55^{+0.04}_{-0.04}$ | – | – | – |
| Hot sub-Saturns/Jupiters → | $M_p = 50$-$1000$, $P = 3$-$11$ | $0.002^{+0.001}_{-0.001}$ | $0.006^{+0.006}_{-0.003}$ | $0.008^{+0.006}_{-0.004}$ | $0.010^{+0.002}_{-0.001}$ | – | – |
| | $M_p = 3$-$10$, $P = 3$-$50$ | $0.29^{+0.02}_{-0.02}$ | $0.23^{+0.02}_{-0.02}$ | $0.22^{+0.02}_{-0.01}$ | $0.22^{+0.01}_{-0.01}$ | $0.12^{+0.04}_{-0.04}$ | Howard et al. (2012) |
| | $M_p = 1$-$3$, $P = 3$-$50$ | $0.23^{+0.02}_{-0.03}$ | $0.27^{+0.05}_{-0.03}$ | $0.27^{+0.03}_{-0.02}$ | – | – | – |
| | $R_p = 0.75$-$2.5$, $P = 50$-$300$ | $0.87^{+0.16}_{-0.13}$ | $0.98^{+0.11}_{-0.11}$ | $0.91^{+0.13}_{-0.12}$ | – | $0.77^{+0.12}_{-0.12}$ | Burke et al. (2015) |
| $\eta_♀$ (Venus-like planets) → | $R_p = 0.8$-$1.2$, $P = 180$-$270$[†] | $0.081^{+0.030}_{-0.016}$ | $0.038^{+0.010}_{-0.009}$ | $0.035^{+0.018}_{-0.014}$ | – | $0.075^{+0.225}_{-0.062}$ | Burke et al. (2015) |
| | $R_p = 0.8$-$1.2$, $P = 180$-$270$, $M_p = 0.65$-$0.98$[†] | $0.022^{+0.008}_{-0.005}$ | $0.006^{+0.004}_{-0.002}$ | $0.006^{+0.003}_{-0.002}$ | – | – | – |
| Not $\eta_\oplus$, but a similar quantity (Earth-like composition planets at slightly shorter periods) → | $M_p = 0.1$-$4$, $P = 180$-$300$, $R_p = (0.9$-$1.1)R_{si}$[‡] | $0.21^{+0.09}_{-0.05}$ | $0.075^{+0.042}_{-0.027}$ | $0.079^{+0.038}_{-0.023}$ | – | – | – |

NOTE—The units for the planet bounds are: $R_p$ [$R_\oplus$], $M_p$ [$M_\oplus$], and $P$ [days].

* "Model 2" of NR20; their values include periods down to 0.3 days.

[a] Includes all periods less than 100 days.

[†] These bounds correspond to approximately within 20% of Venus ($P_♀ = 224.7$ days and $M_♀ = 0.815 M_\oplus$).

[‡] $R_{si}$ is the radius, as a function of planet mass, given by the pure-silicate model (Equation 28; Seager et al. 2007).

He & Ford (submitted)

# We can also differentiate between occurrence rates ($\eta$) and the fractions of stars with planets ($f_{\rm swp}$) in the hybrid models

For small planets in large period ranges, $f_{\rm swp}$ is generally lower than $\eta$ by up to ~50%

A similar drop in $f_{\rm swp}$ of Venus and Earth-like composition planets at these periods

**Table 3.** Fractions of stars with various planet types ($f_{\rm swp}$) for each model, and comparisons to previous literature values.

| Planet bounds | H20 model | HM-U | HM-C | Other literature value/reference | |
|---|---|---|---|---|---|
| $R_p = 0.5\text{-}10,\ P = 3\text{-}300$ | $0.84^{+0.05}_{-0.07}$ | 0.87* | 0.87* | – | – |
| $R_p = 2\text{-}4,\ P = 3\text{-}100$ | $0.23^{+0.03}_{-0.02}$ | $0.34^{+0.03}_{-0.02}$ | $0.30^{+0.02}_{-0.02}$ | $0.24^{+0.02}_{-0.02}$ | Petigura et al. (2013)[a] |
| $R_p = 1.4\text{-}2.8,\ P = 3\text{-}100$ | $0.30^{+0.02}_{-0.02}$ | $0.42^{+0.03}_{-0.03}$ | $0.37^{+0.02}_{-0.02}$ | $0.33^{+0.01}_{-0.01}$ | Petigura et al. (2013)[a] |
| $R_p = 0.75\text{-}1.4,\ P = 3\text{-}100$ | $0.34^{+0.03}_{-0.04}$ | $0.36^{+0.04}_{-0.03}$ | $0.33^{+0.02}_{-0.02}$ | – | – |
| $M_p = 50\text{-}1000,\ P = 3\text{-}11$ | $0.002^{+0.001}_{-0.001}$ | $0.006^{+0.006}_{-0.003}$ | $0.007^{+0.005}_{-0.004}$ | $0.009^{+0.004}_{-0.004}$ | Mayor et al. (2011)[b] |
| $M_p = 3\text{-}10,\ P = 3\text{-}50$ | $0.22^{+0.02}_{-0.01}$ | $0.19^{+0.02}_{-0.02}$ | $0.15^{+0.01}_{-0.01}$ | – | – |
| $M_p = 1\text{-}3,\ P = 3\text{-}50$ | $0.18^{+0.02}_{-0.02}$ | $0.22^{+0.03}_{-0.03}$ | $0.17^{+0.03}_{-0.02}$ | – | – |
| $R_p = 0.75\text{-}2.5,\ P = 50\text{-}300$ | $0.55^{+0.07}_{-0.07}$ | $0.63^{+0.04}_{-0.05}$ | $0.58^{+0.05}_{-0.05}$ | – | – |
| $R_p = 0.8\text{-}1.2,\ P = 180\text{-}270$[†] | $0.079^{+0.029}_{-0.016}$ | $0.038^{+0.010}_{-0.009}$ | $0.035^{+0.017}_{-0.014}$ | – | – |
| $R_p = 0.8\text{-}1.2,\ P = 180\text{-}270,\ M_p = 0.65\text{-}0.98$[†] | $0.022^{+0.008}_{-0.005}$ | $0.006^{+0.004}_{-0.002}$ | $0.006^{+0.003}_{-0.002}$ | – | – |
| $M_p = 0.1\text{-}4,\ P = 180\text{-}300,\ R_p = (0.9\text{-}1.1)R_{\rm si}$[‡] | $0.19^{+0.08}_{-0.05}$ | $0.073^{+0.039}_{-0.026}$ | $0.073^{+0.033}_{-0.020}$ | – | – |

NOTE—The units for the planet bounds are: $R_p$ [$R_\oplus$], $M_p$ [$M_\oplus$], and $P$ [days].

*The uncertainties are not reported here because they are exceedingly low, due to fixing the parameters for the overall fraction of stars with planets in these models (see discussion at the end of §2.3.2).

[a] Includes periods down to 5 days.

[b] Includes all periods less than 11 days, and the mass bounds are in $M_p \sin i$.

# I am working to reprocess the original Kepler pipeline at NASA Ames, with the goal of delivering a new planet catalog and improving $\eta_\oplus$

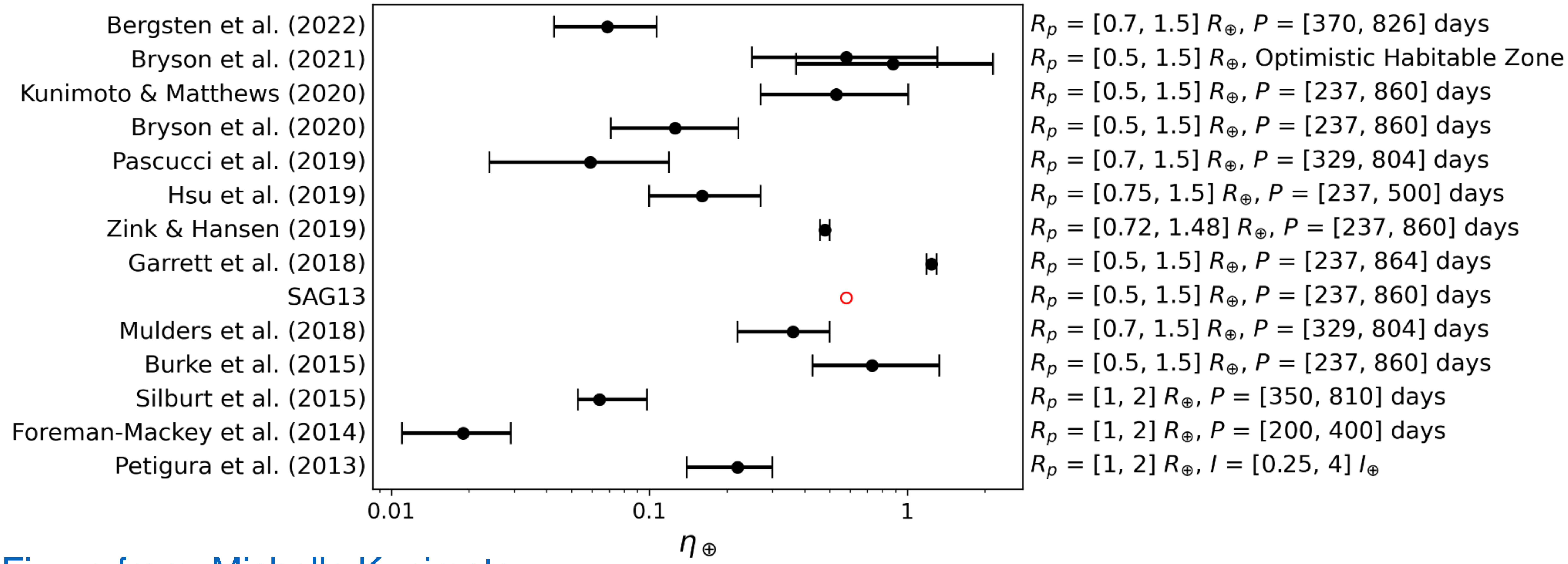
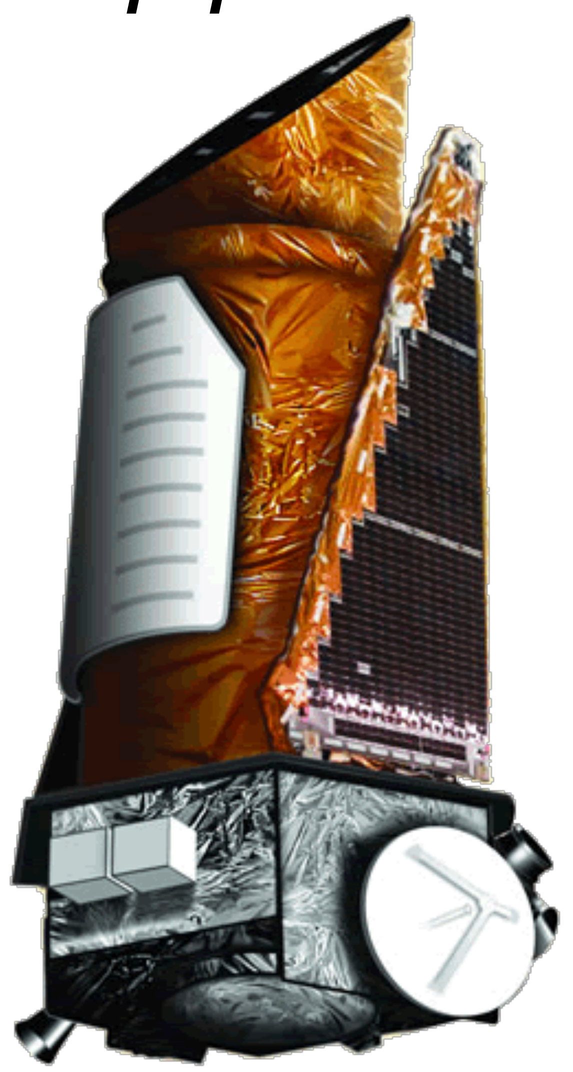



Figure from: Michelle Kunimoto

See also: Fernandes et al. (2025), Bryson et al. (2025)

*This means rewriting and improving the original pipeline code!*

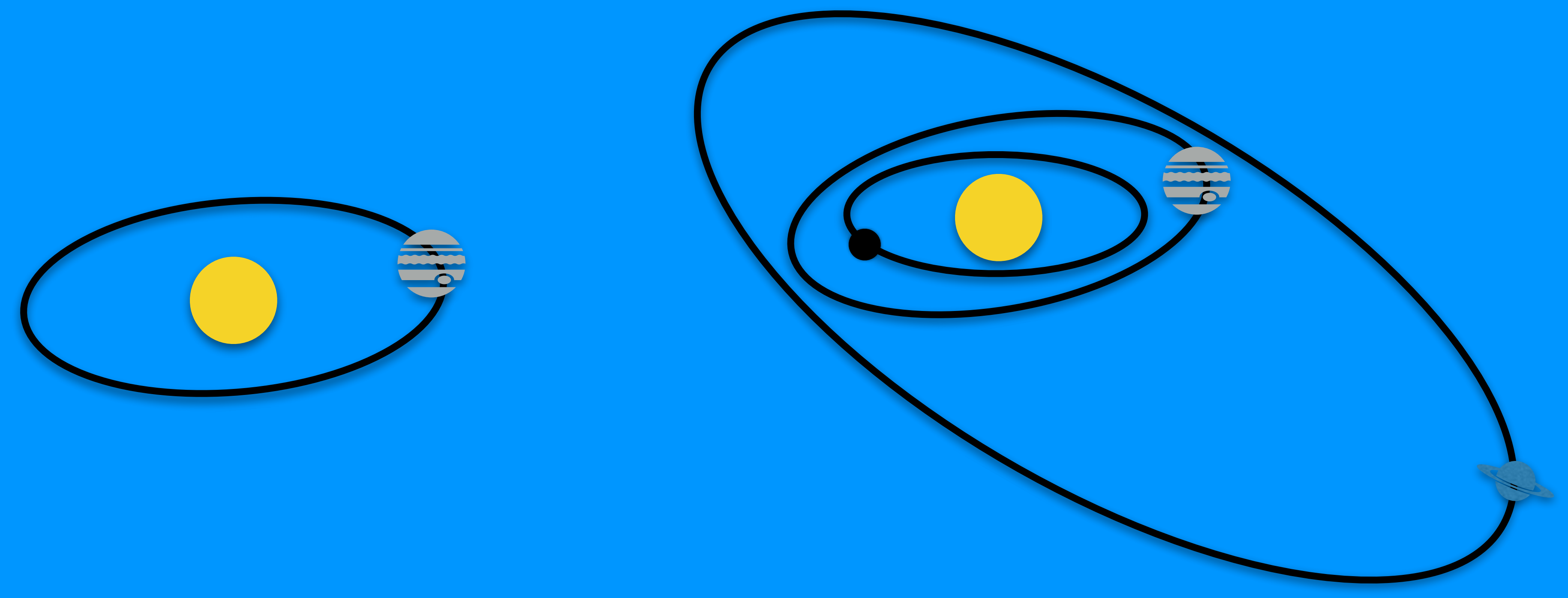


The number of rocky habitable planets per star ($\eta_\oplus$) is a critical input for the design of the Habitable Worlds Observatory (aims to detect 25 such planets)

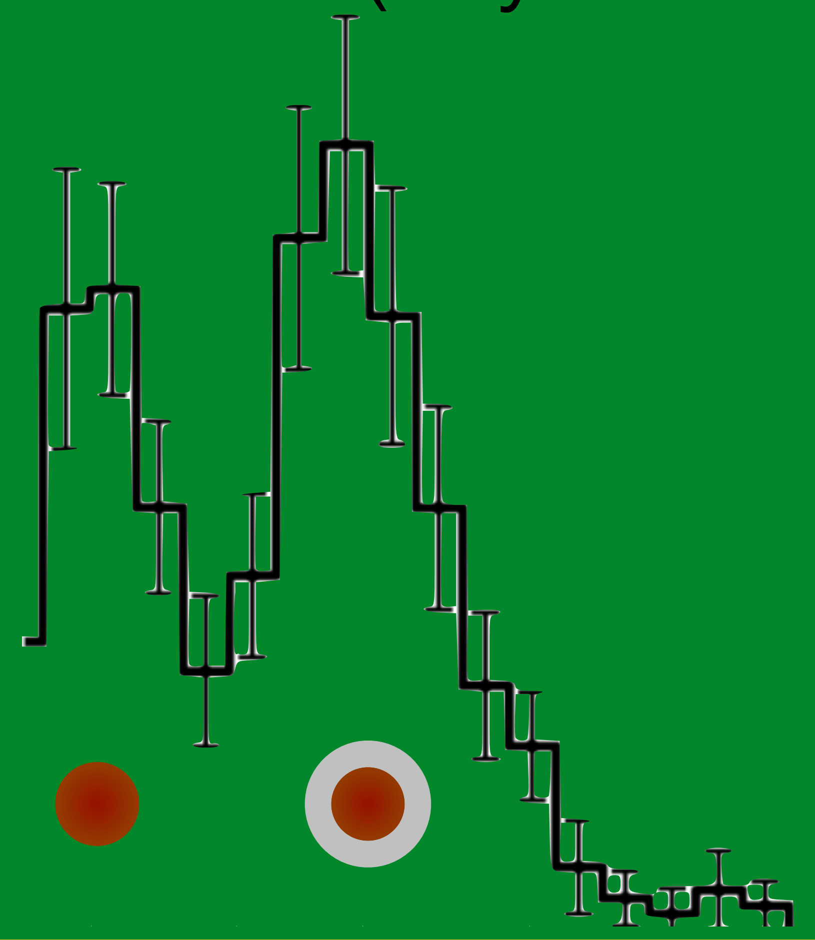
PI's: Steve Bryson, Jon Jenkins, and Douglas Caldwell (original Kepler team members); Aritra Chakrabarty (NPP), and other collaborators

Summary

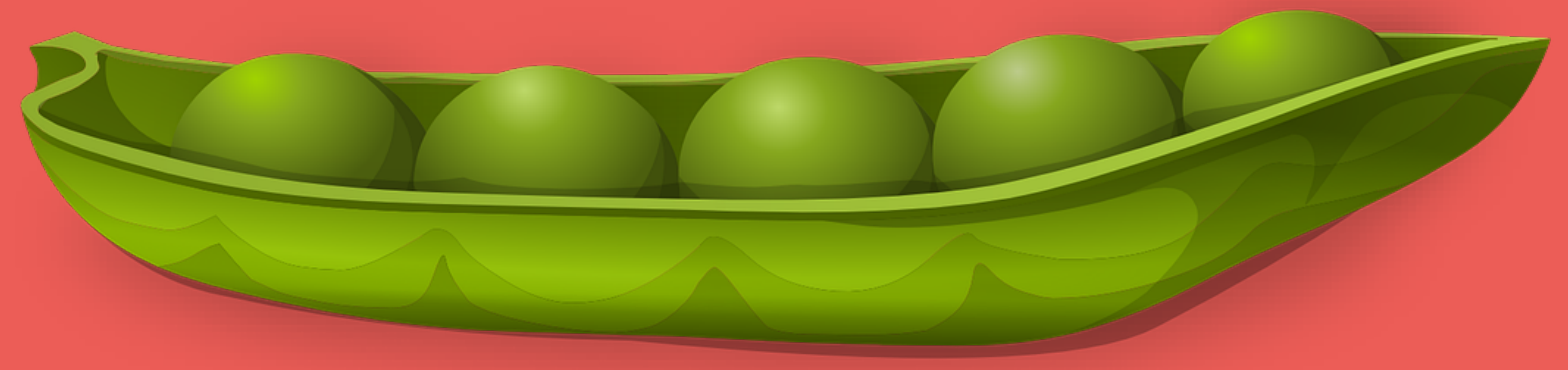
Distribution of multiplicities and mutual inclinations (“Kepler dichotomy”)



Planet radius valley in the context of a multi-planet model (“hybrid model”)



Planet size similarity, ordering, and spacings of multi-planet systems (“peas in a pod”)



Occurrence of Earth-sized planets in the habitable zone (“eta-Earth”)