Multiplanet Systems as Laboratories for Planet Formation

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The Astronomical Journal, 155:48 (12pp), 2018 January https://doi.org/10.3847/1538-3881/aa9ff6

The California-*Kepler* Survey. V. Peas in a Pod: Planets in a *Kepler* Multi-planet System Are Similar in Size and Regularly Spaced*

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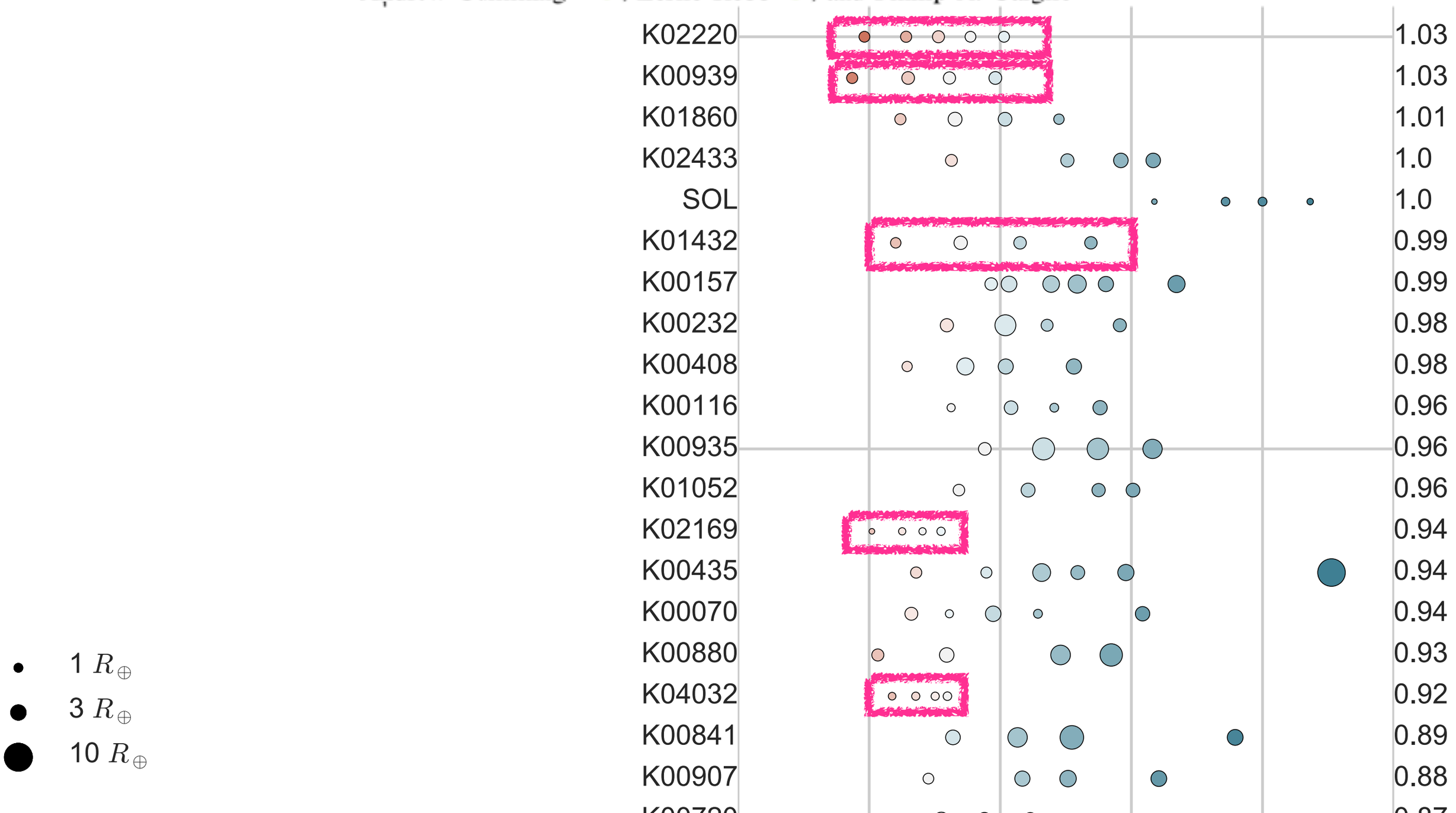
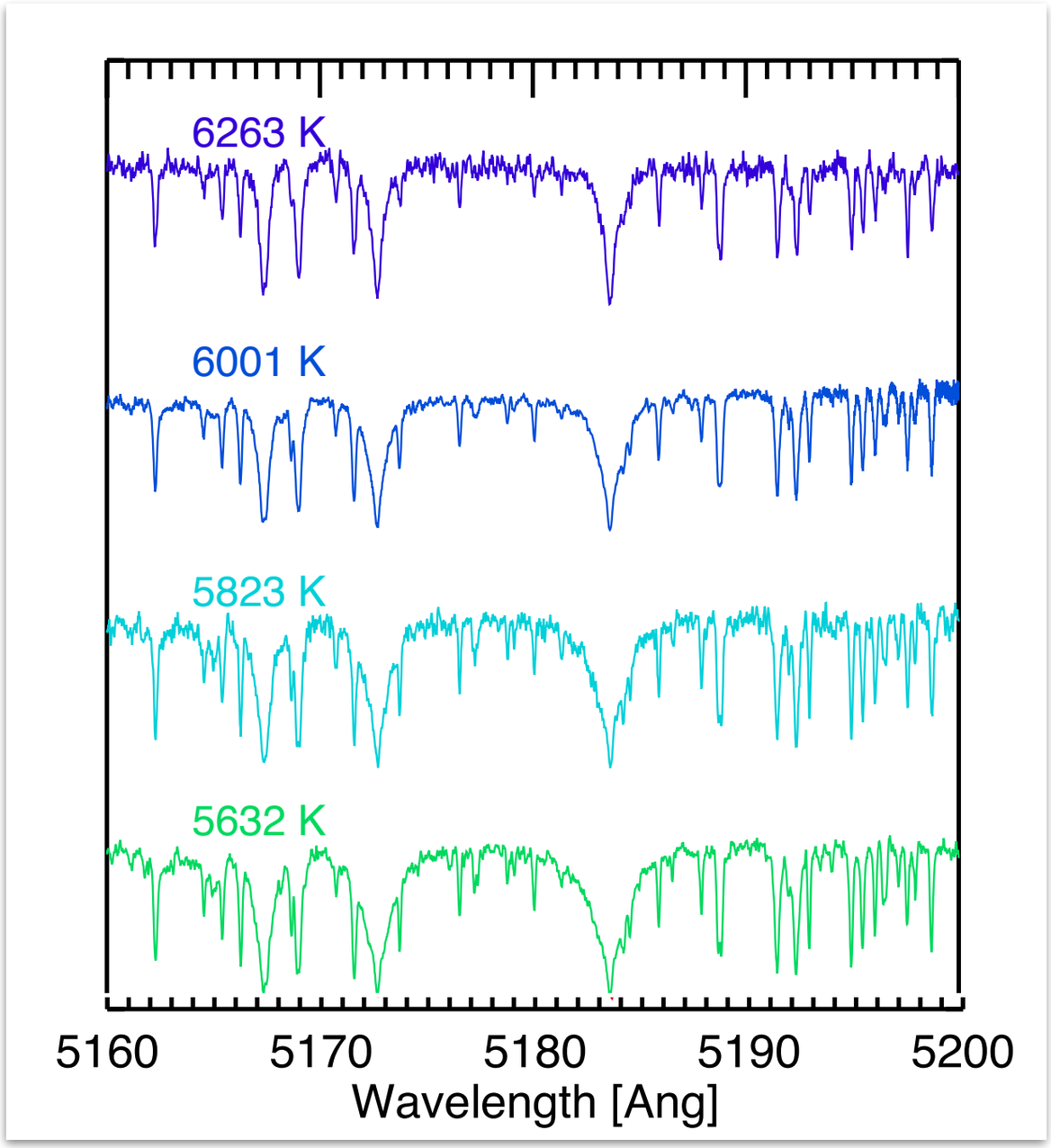
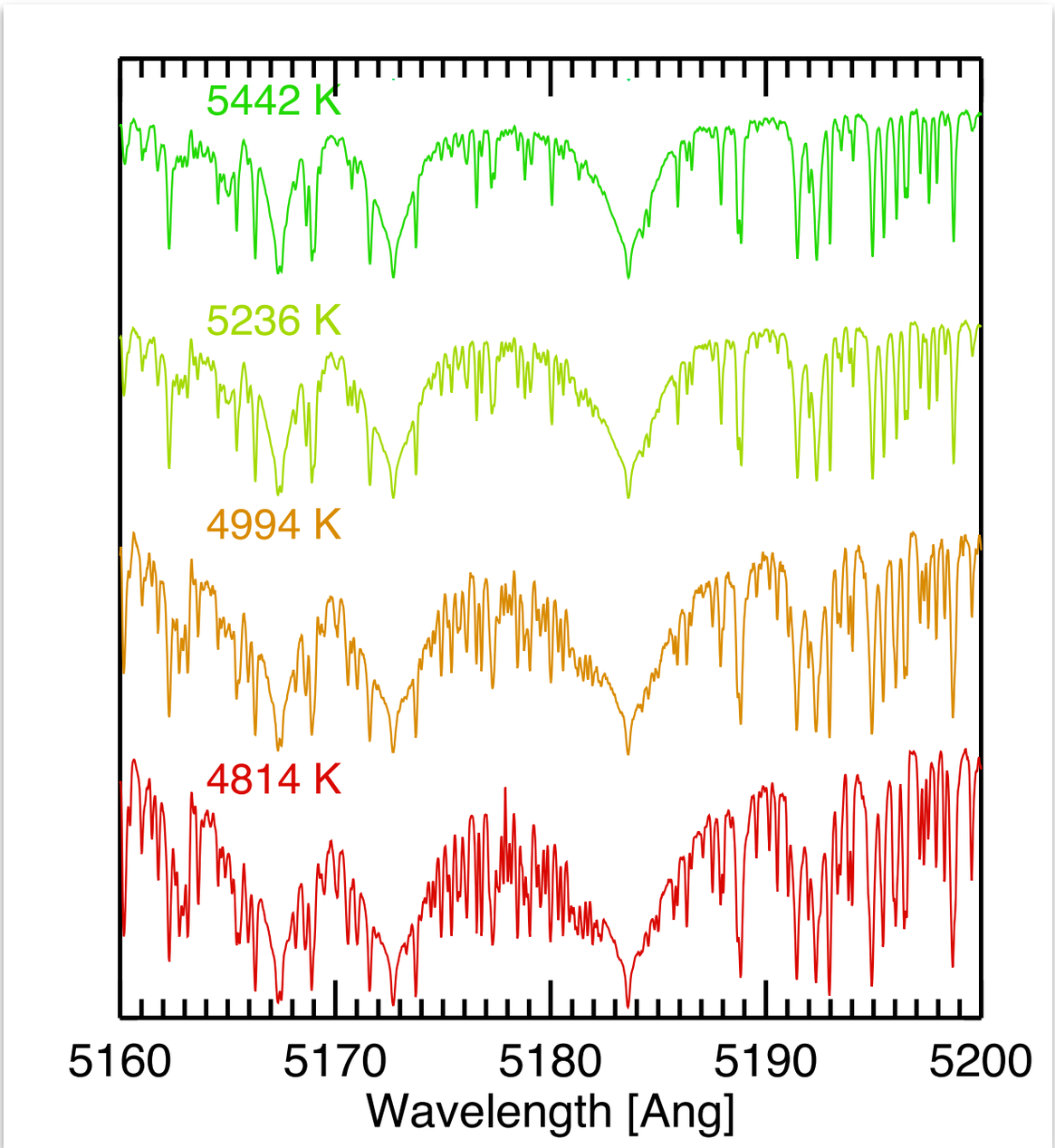


California-Kepler Survey (CKS)

Keck/HIRES Spectra of 1305 Kepler Planet-hosting Stars

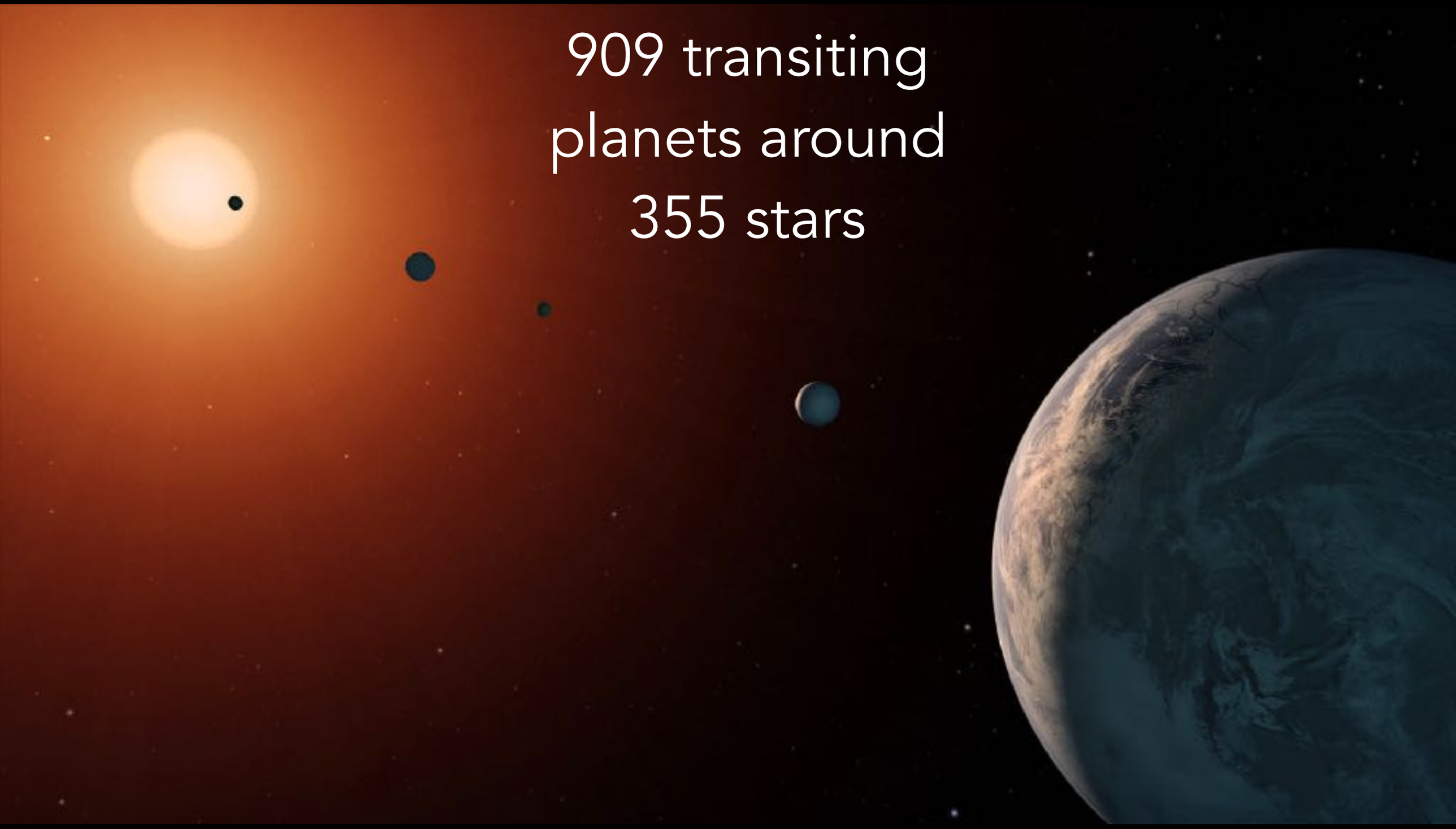
- F,G,K type stars
- R = 60,000; SNR = 45/pixel
- Precision stellar properties: Teff, log(g), [Fe/H], vsini, mass, radius $\sigma(R_\star)/R_\star \approx 10\,\%$



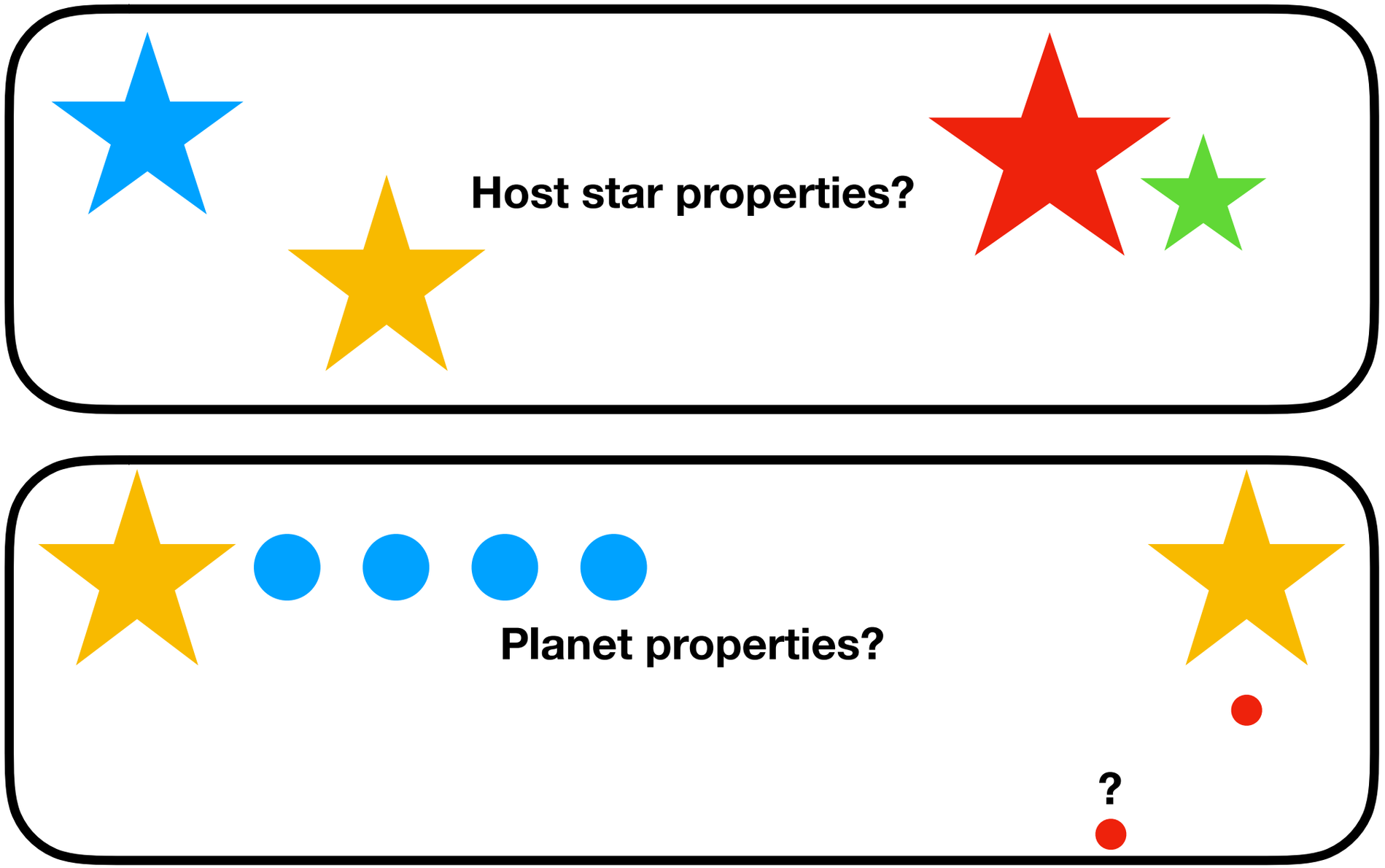


Multi-planet Systems in the California Kepler Survey:

909 transiting
planets around
355 stars

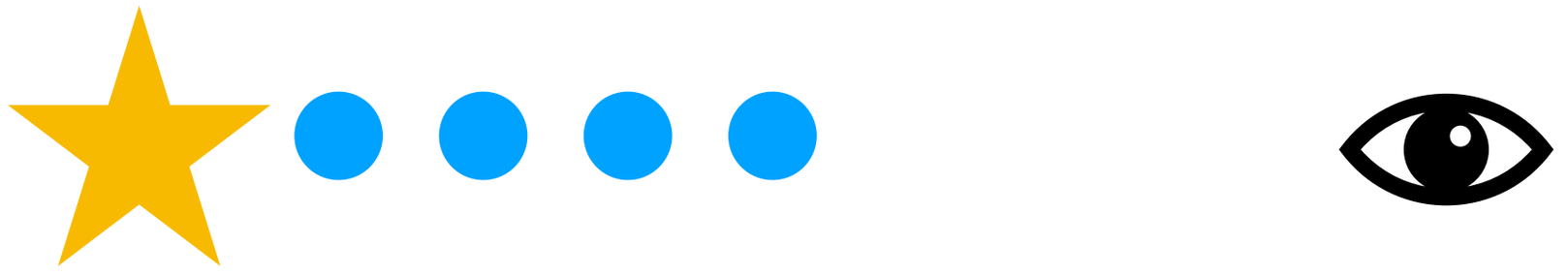


CKS VI: Which Factors Correlate with the Number of Observed Planets?



Weiss+18b

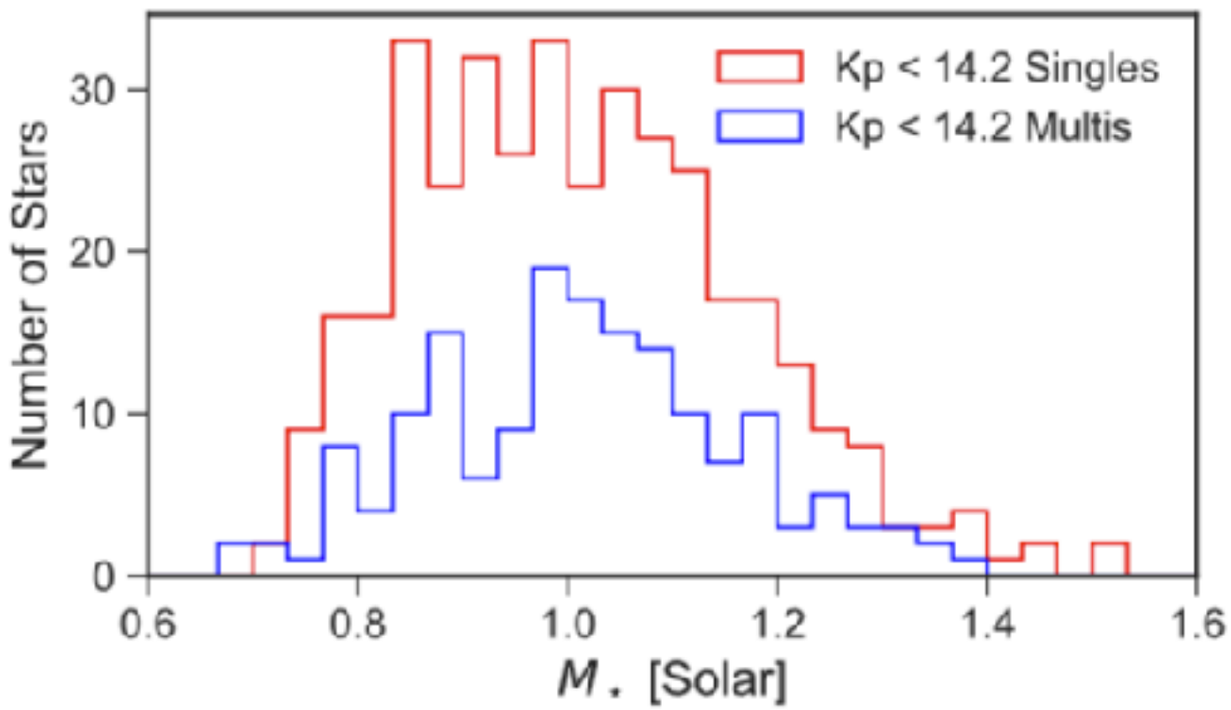
Kepler Multis vs. Singles

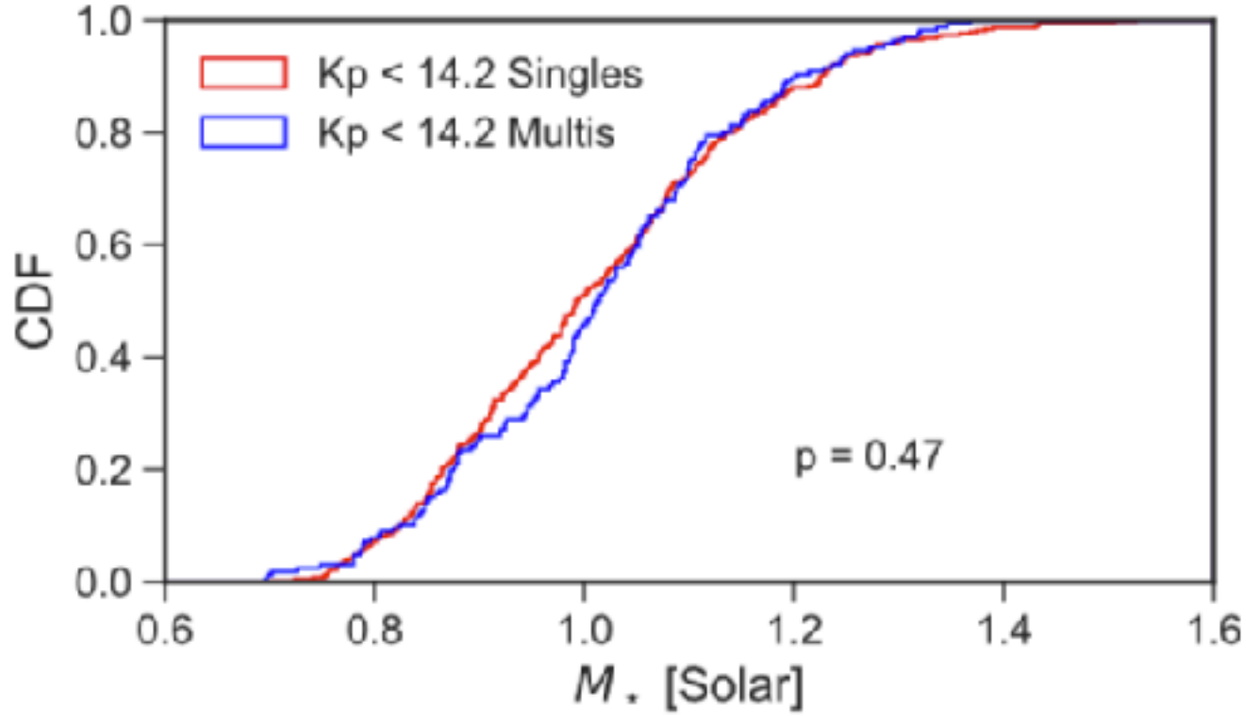


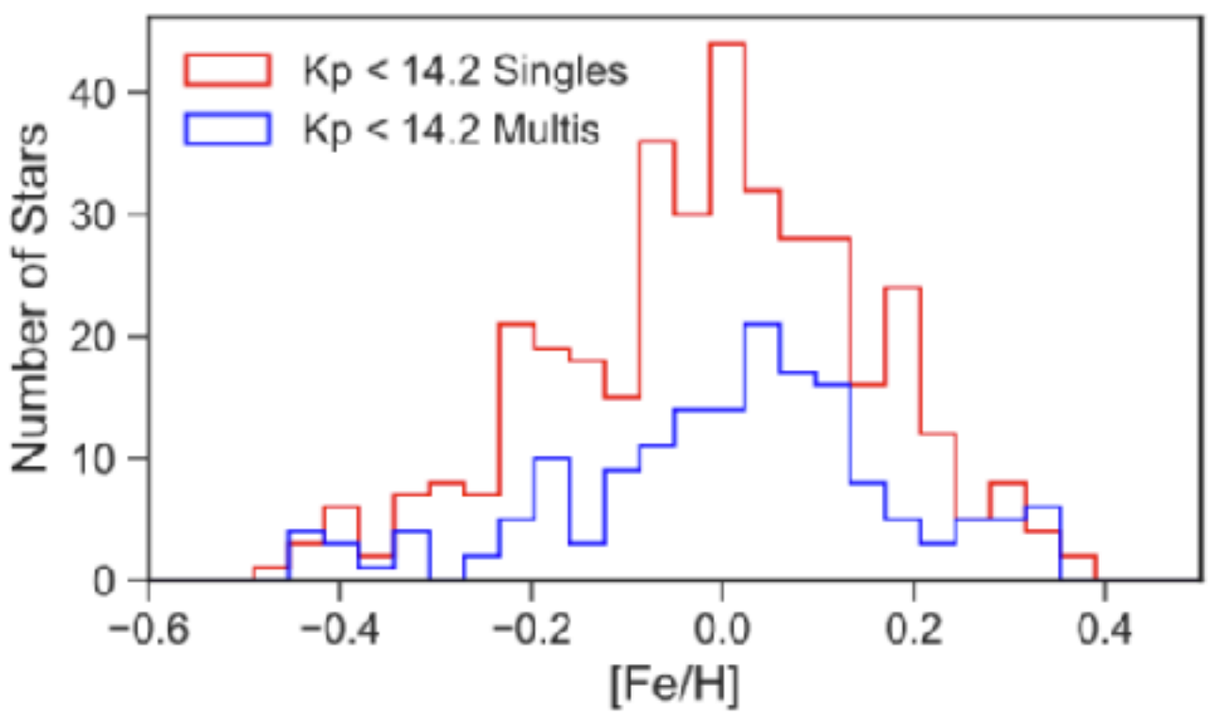
“Multi” = system with multiple observed, transiting planets

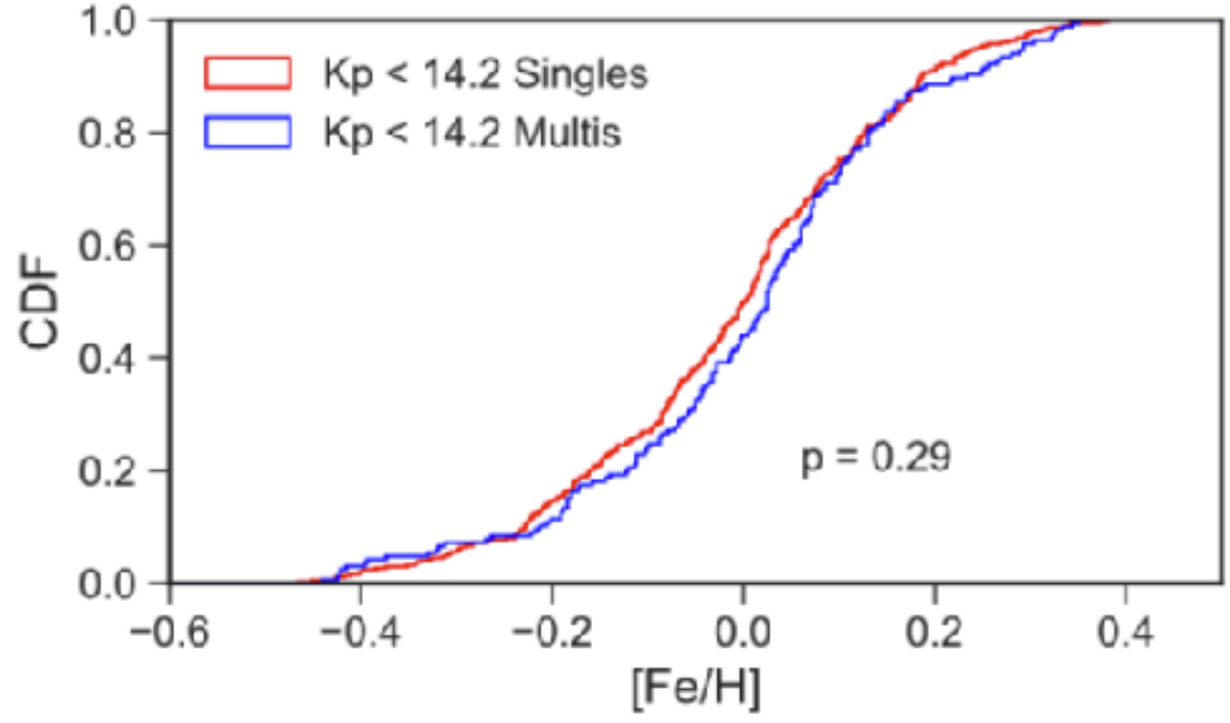
“Single” = system with only one observed, transiting planet

Host star masses, metallicities, and vsini are indistinguishable for singles vs. multis.



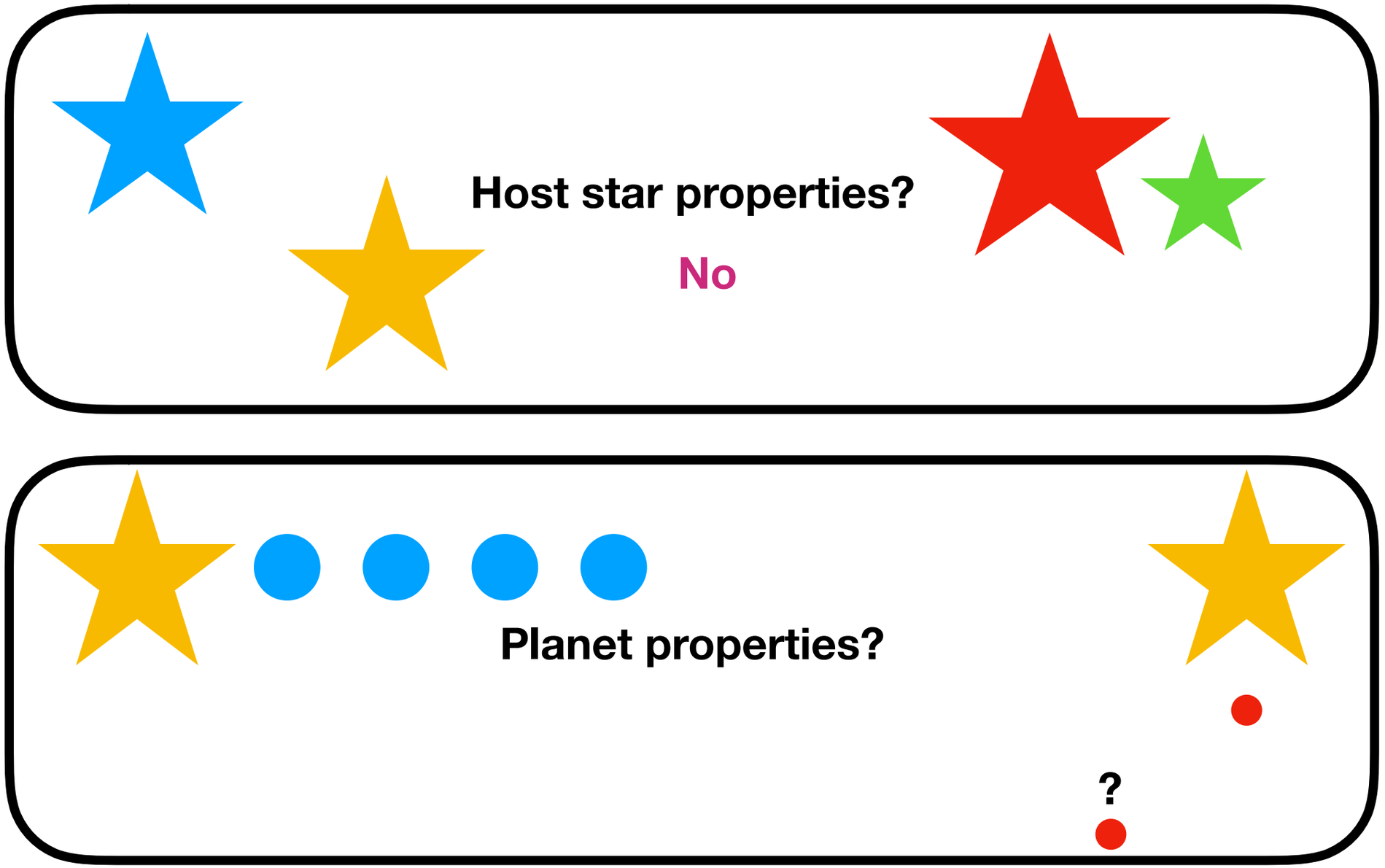






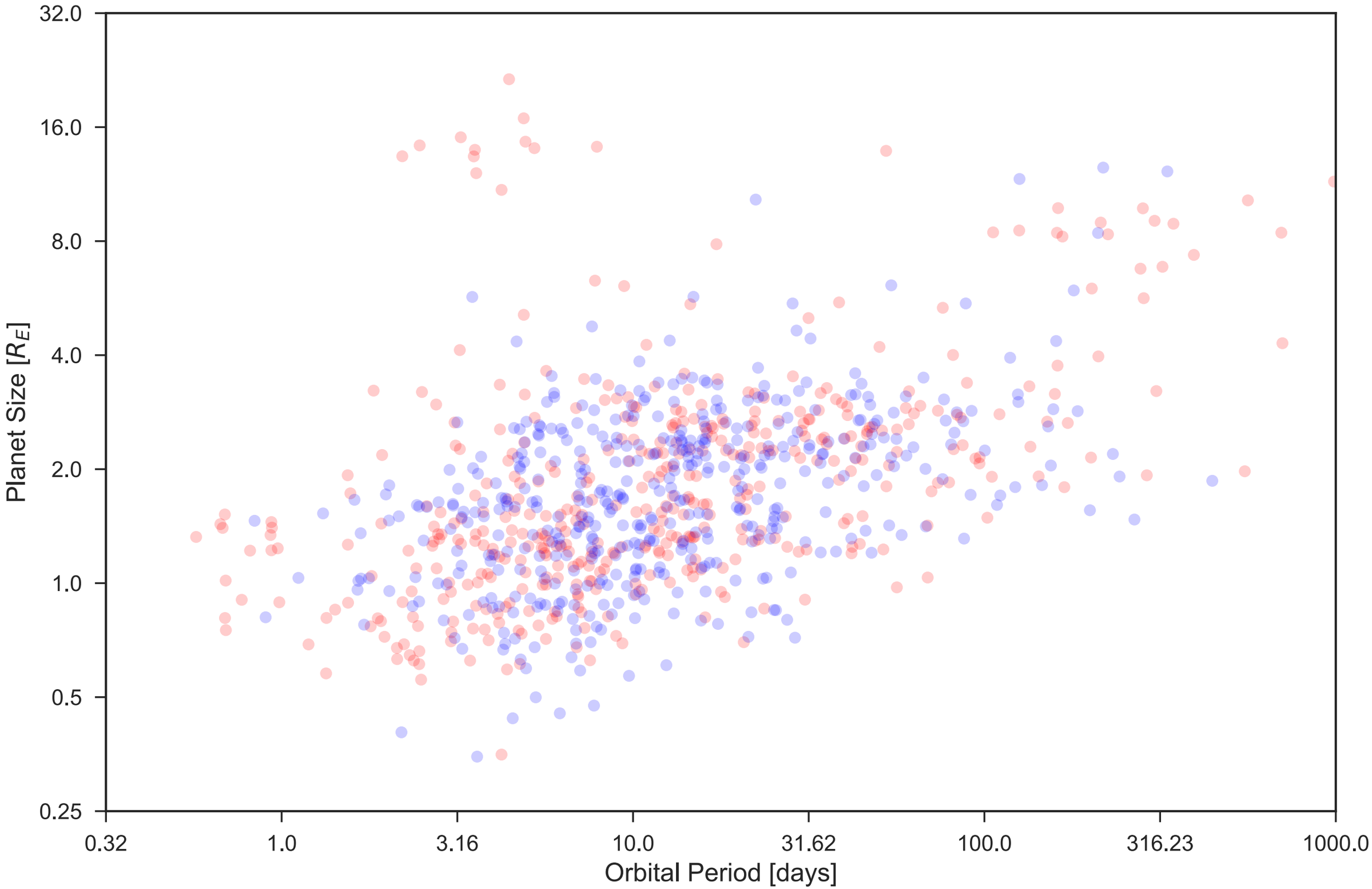
Weiss+18b

Which Factors Correlate with the Number of Observed Planets?



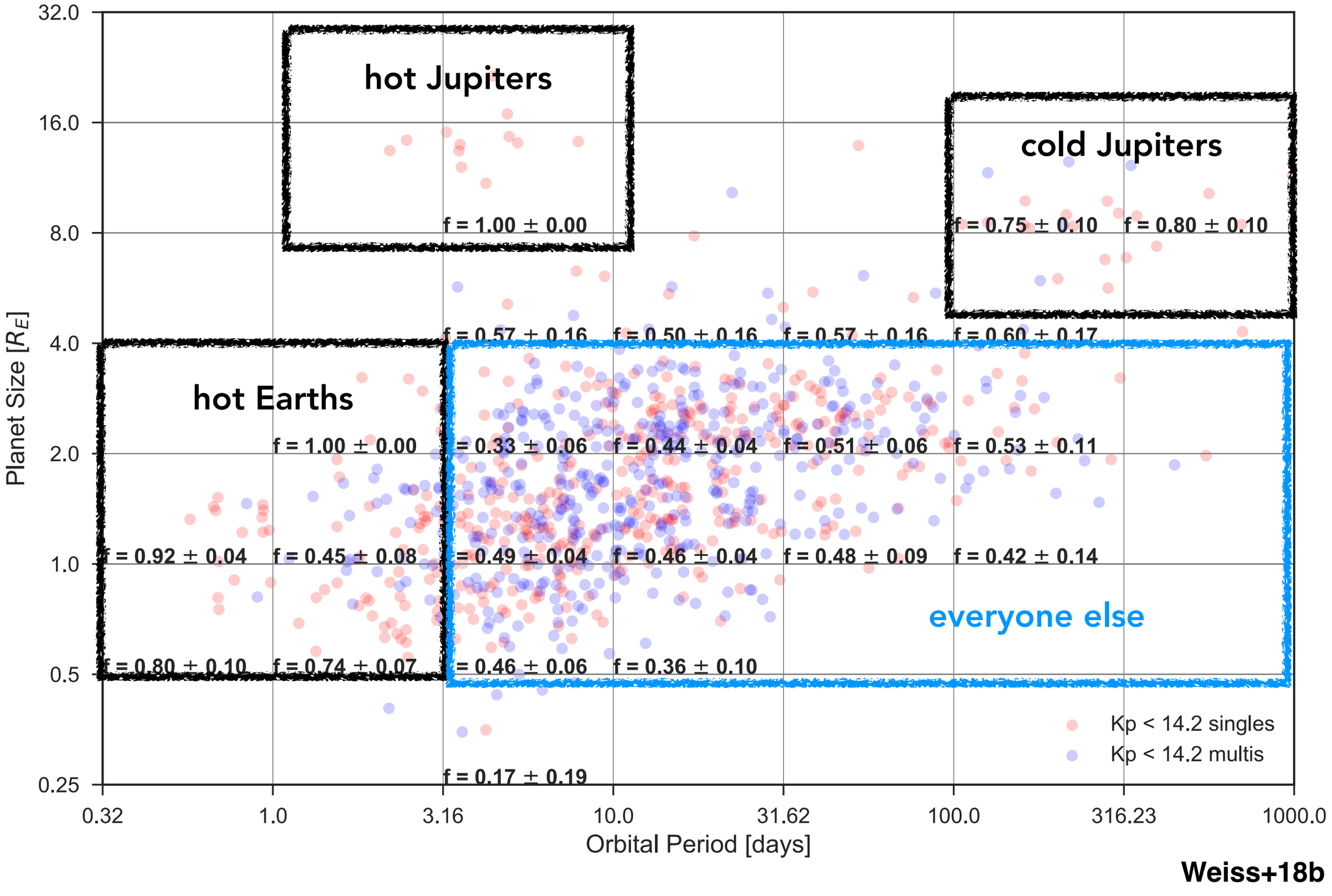
Weiss+18b

Overview of Planets in Multis vs. Singles



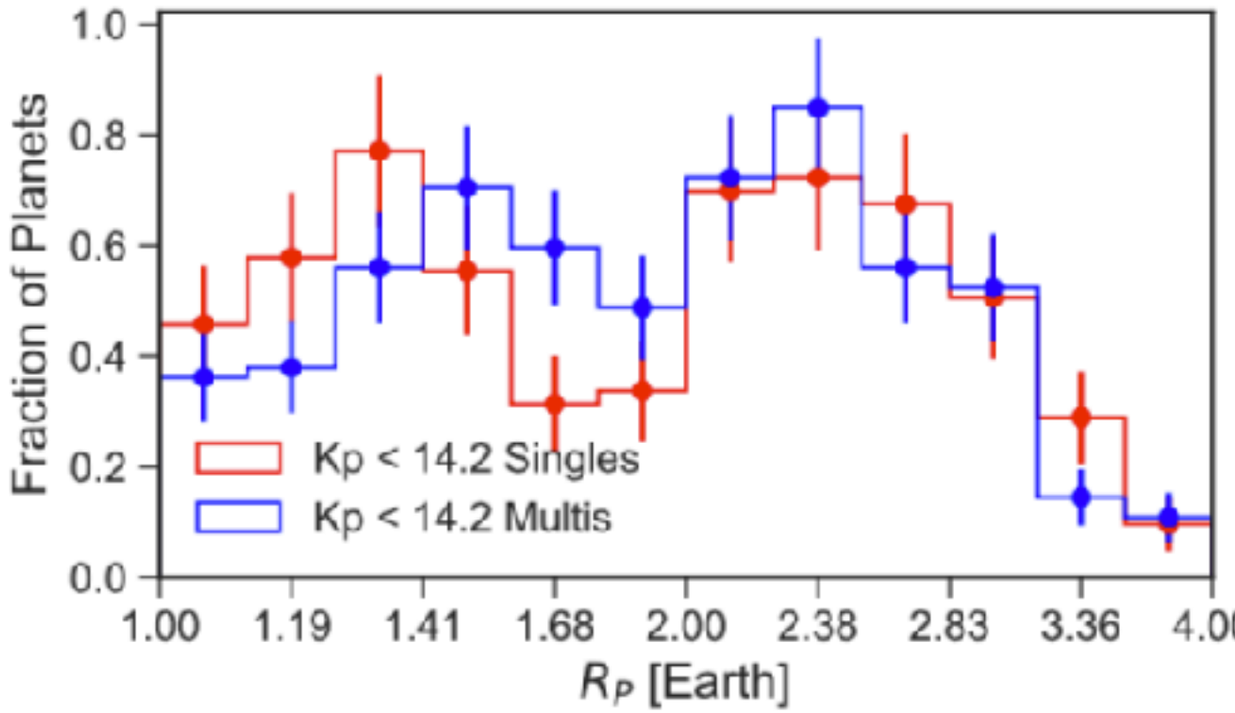
Weiss+18b

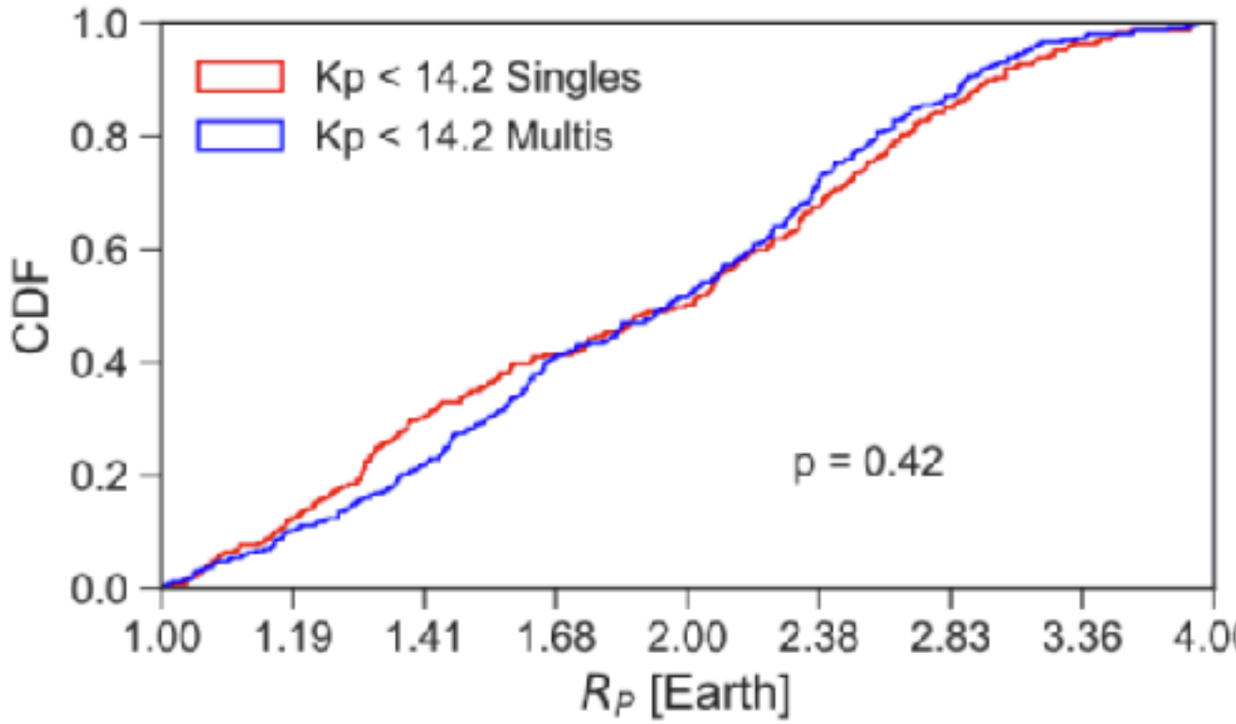
Overview of Planets in Multis vs. Singles

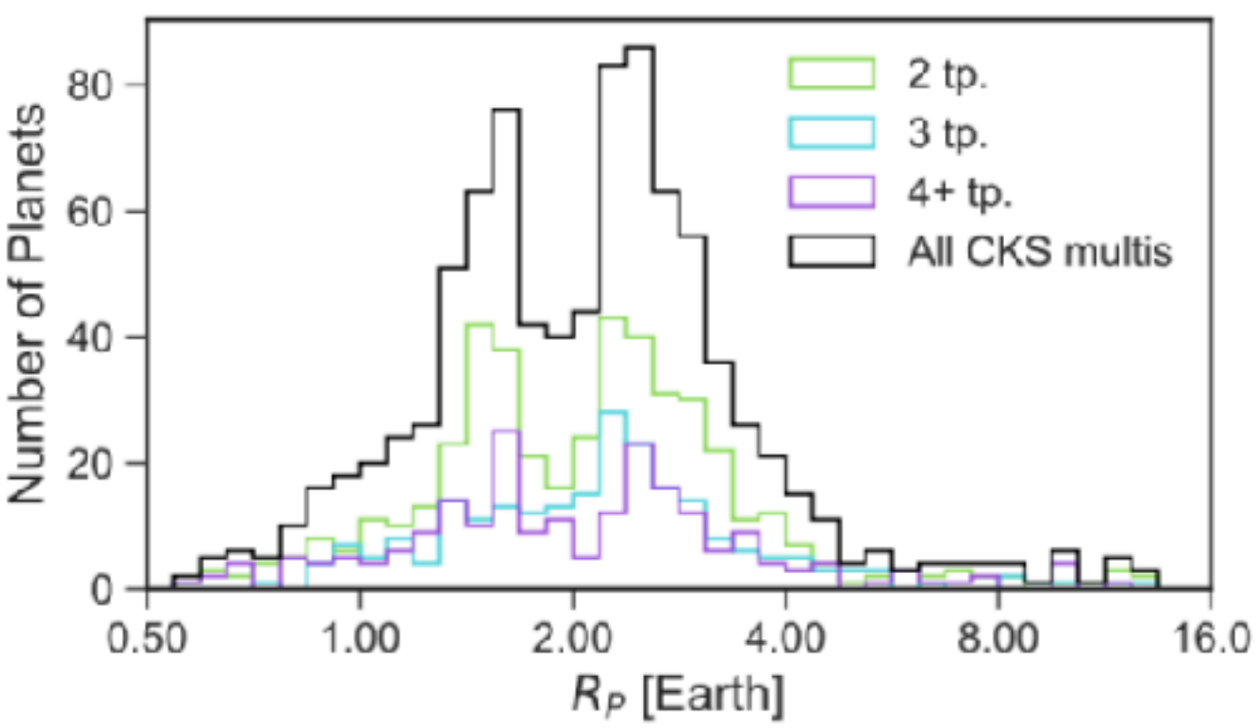


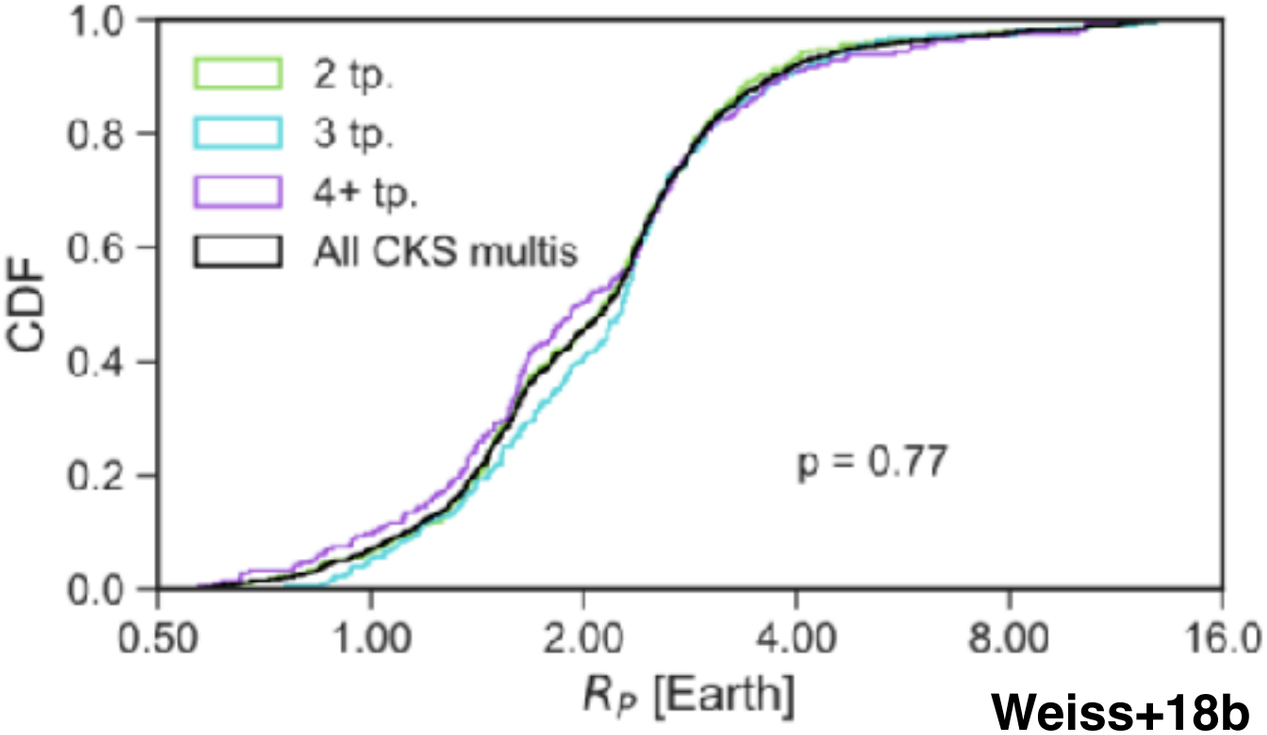
Weiss+18b

The radii of cool (P > 3 days) sub-Neptunes are indistinguishable for singles vs. multis



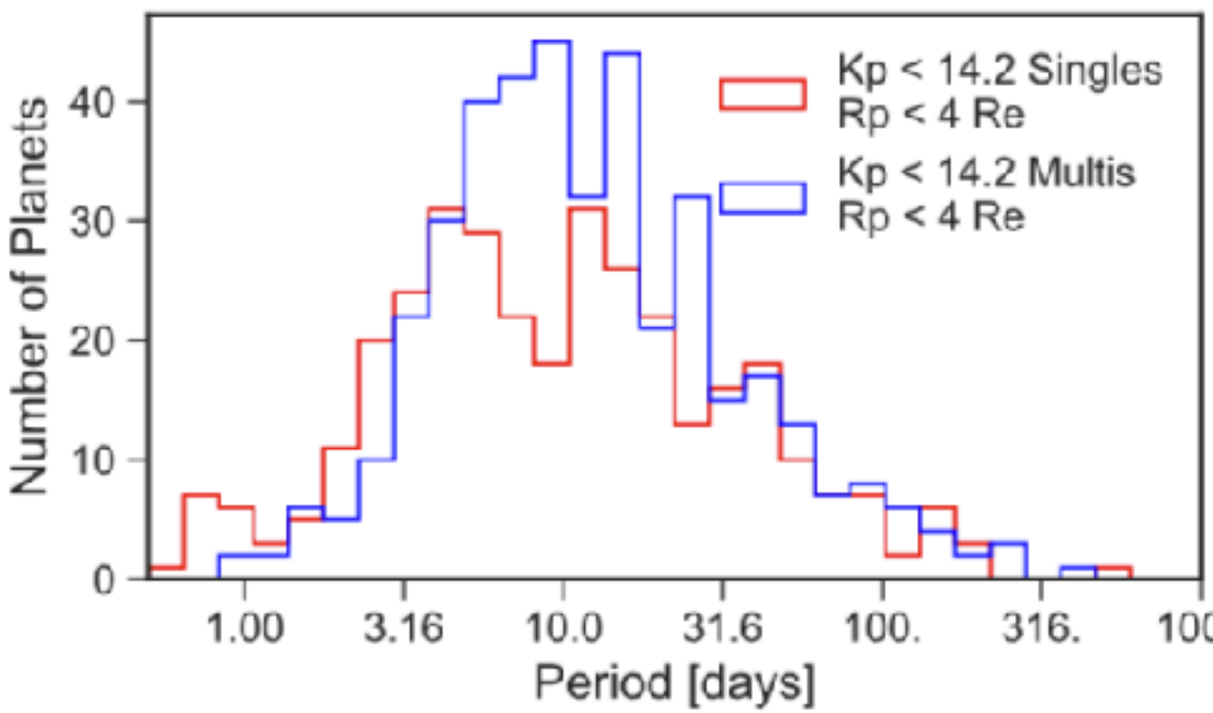


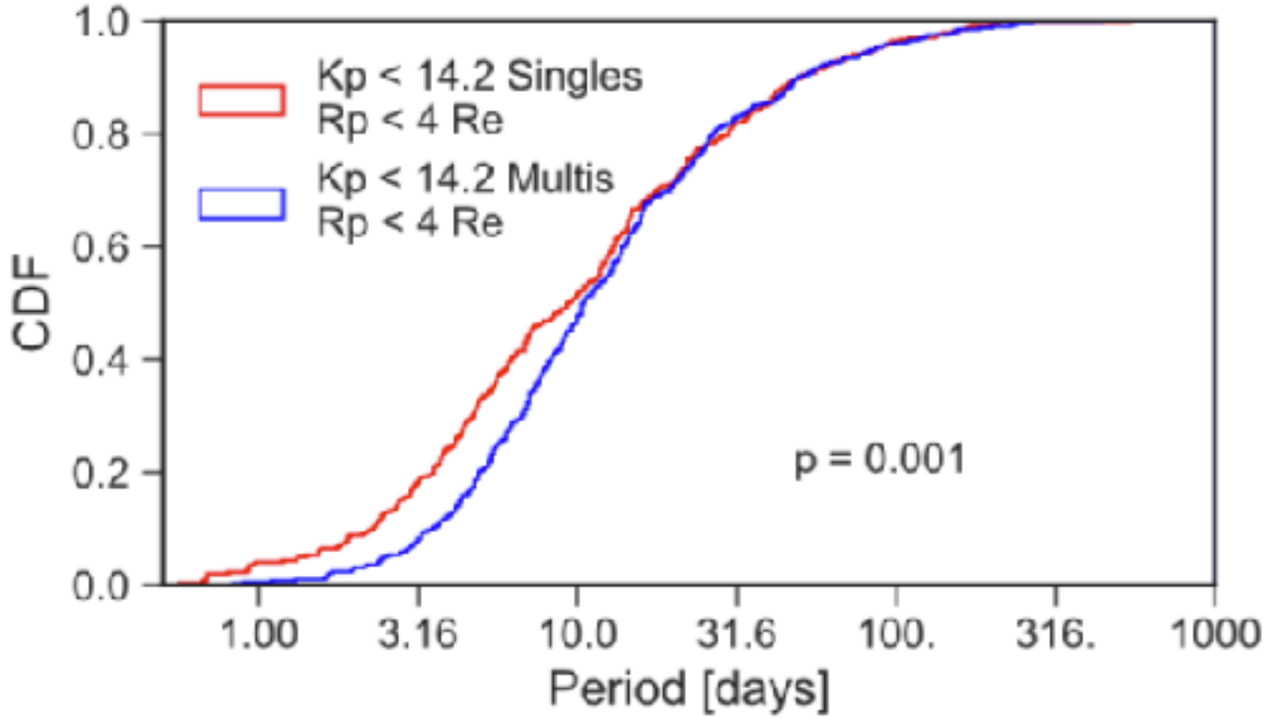


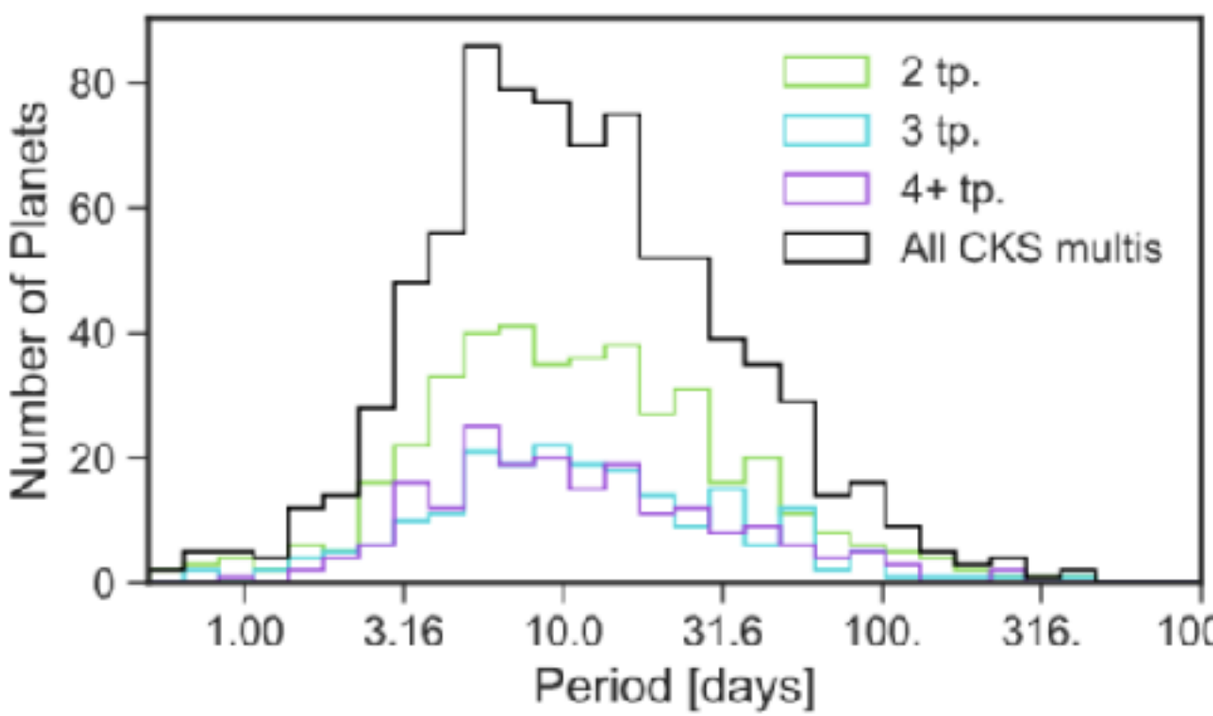


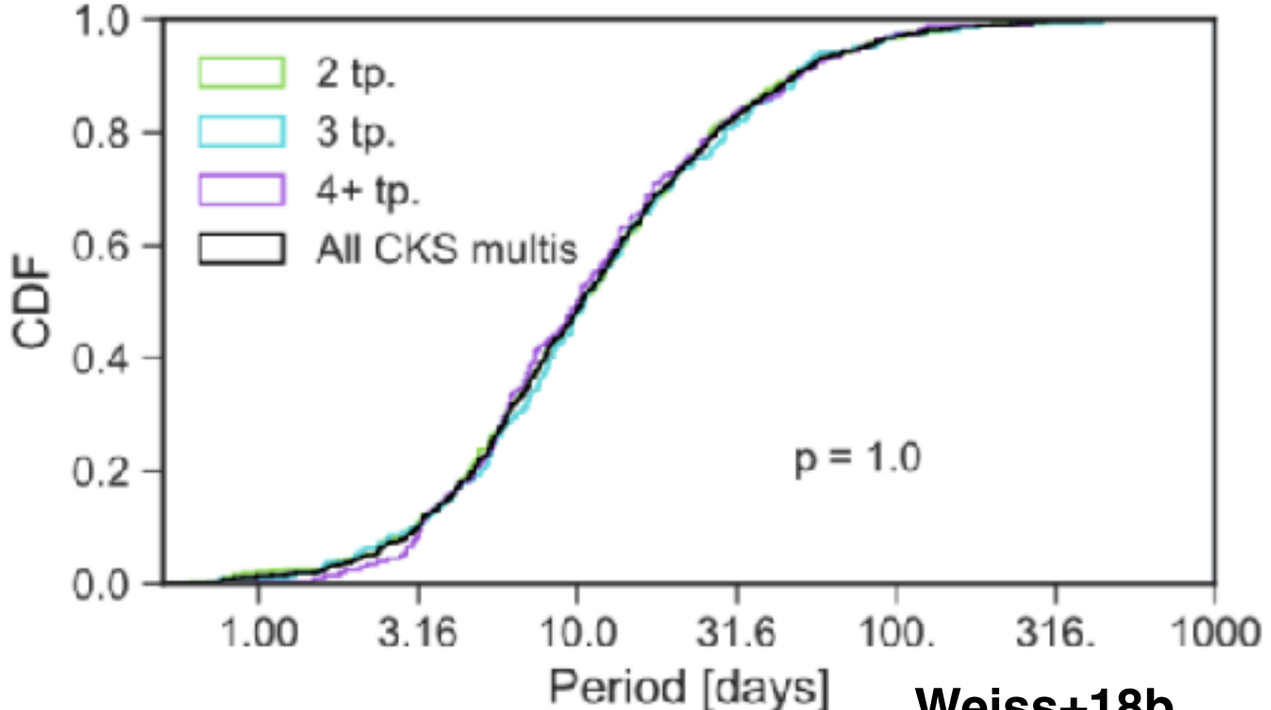
Weiss+18b

There is an excess of singles with P < 3 days (p=0.001)









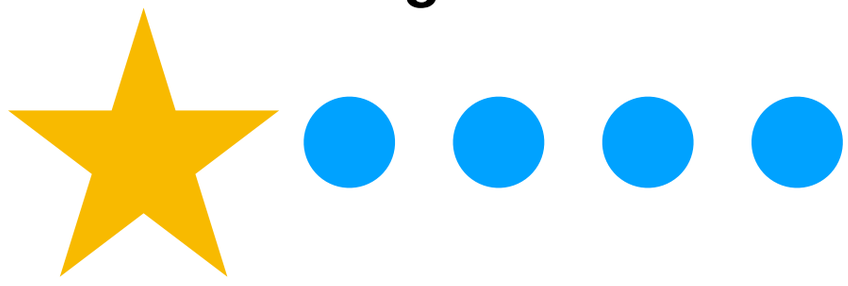
Weiss+18b

What Factors Correlate with the Number of Observed Planets?

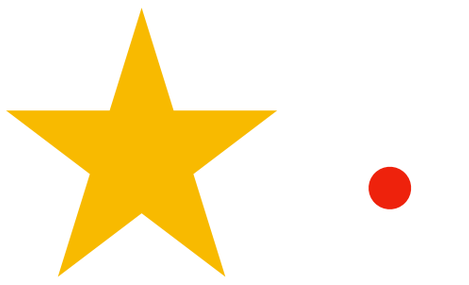
CKS VI. Kepler Multis and Singles have Similar Planet and Stellar Properties Indicating a Common Origin

Weiss+18b

arxiv.org/abs/1808.03010



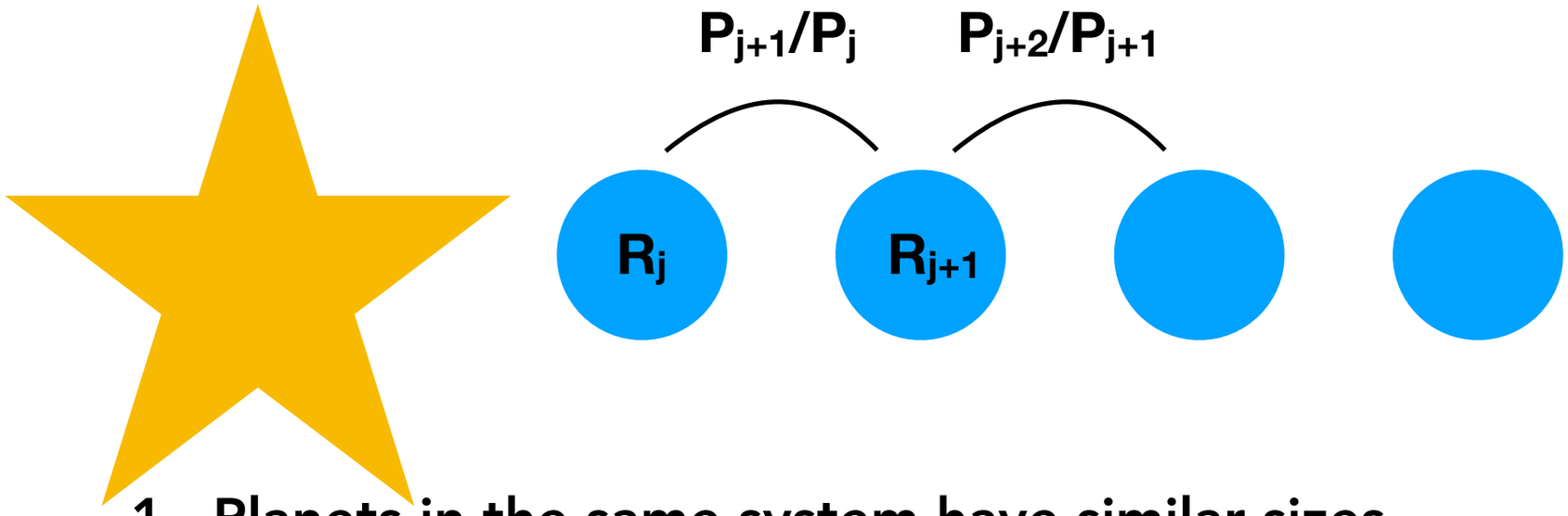
“Multi” = system with multiple observed, transiting planets



“Single” = likely a former multi in which the planets have been scattered to high mutual inclinations

Other supporting evidence from Xie+16, Van Eylen+18, Dai+18

Five Patterns to Reproduce in Population Synthesis:



1. **Planets in the same system have similar sizes**
2. **Planets in the same system have regular orbital spacing**
3. **Underlying relation between period ratio and planet sizes**
4. **Singles and multis have indistinguishable stellar properties**
5. **Planet sizes in singles and multis have similar radius distributions with a gap at 1.8 Earth radii**

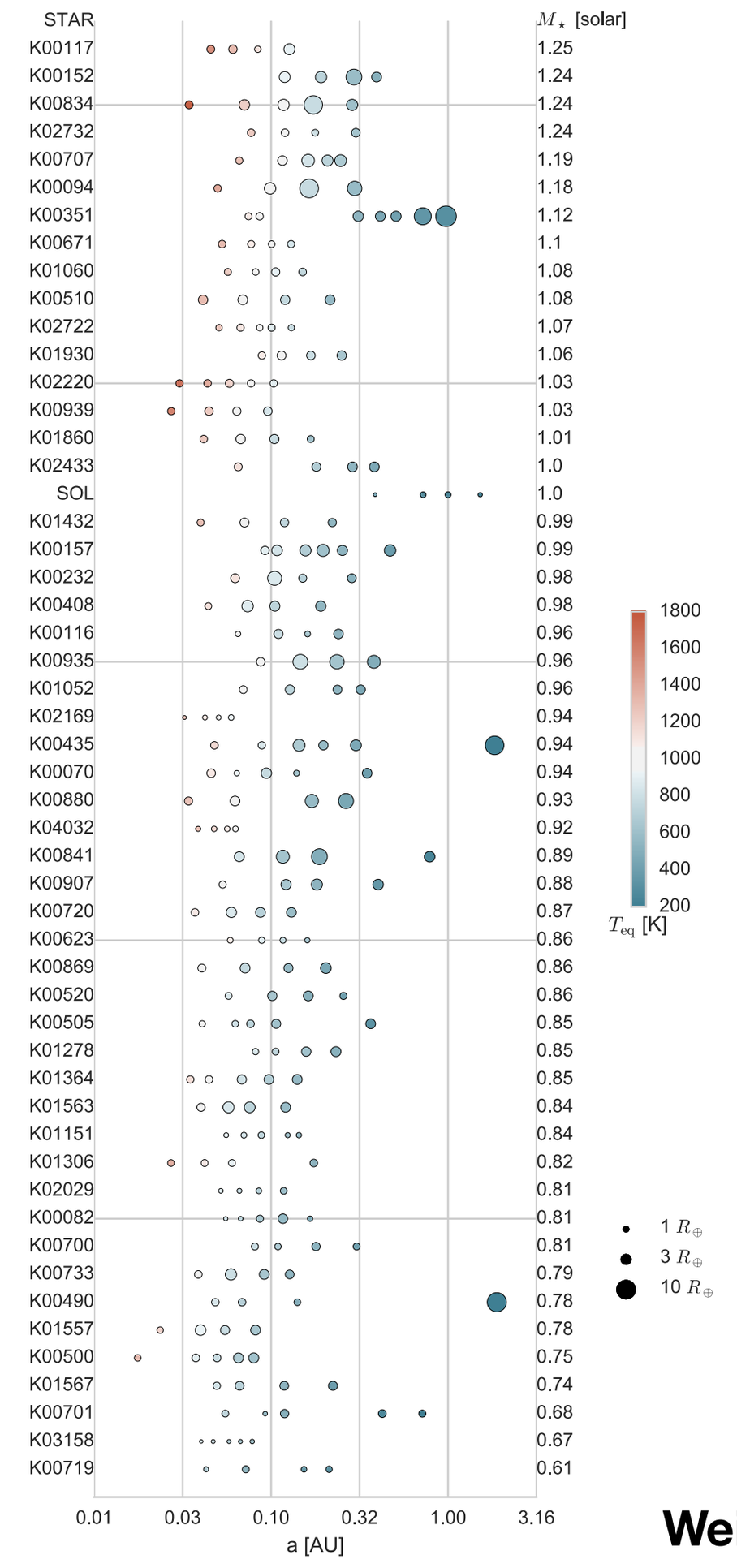
Multiplanet systems: Tharrr be treasure!

Weiss+18a,b

Bonus content

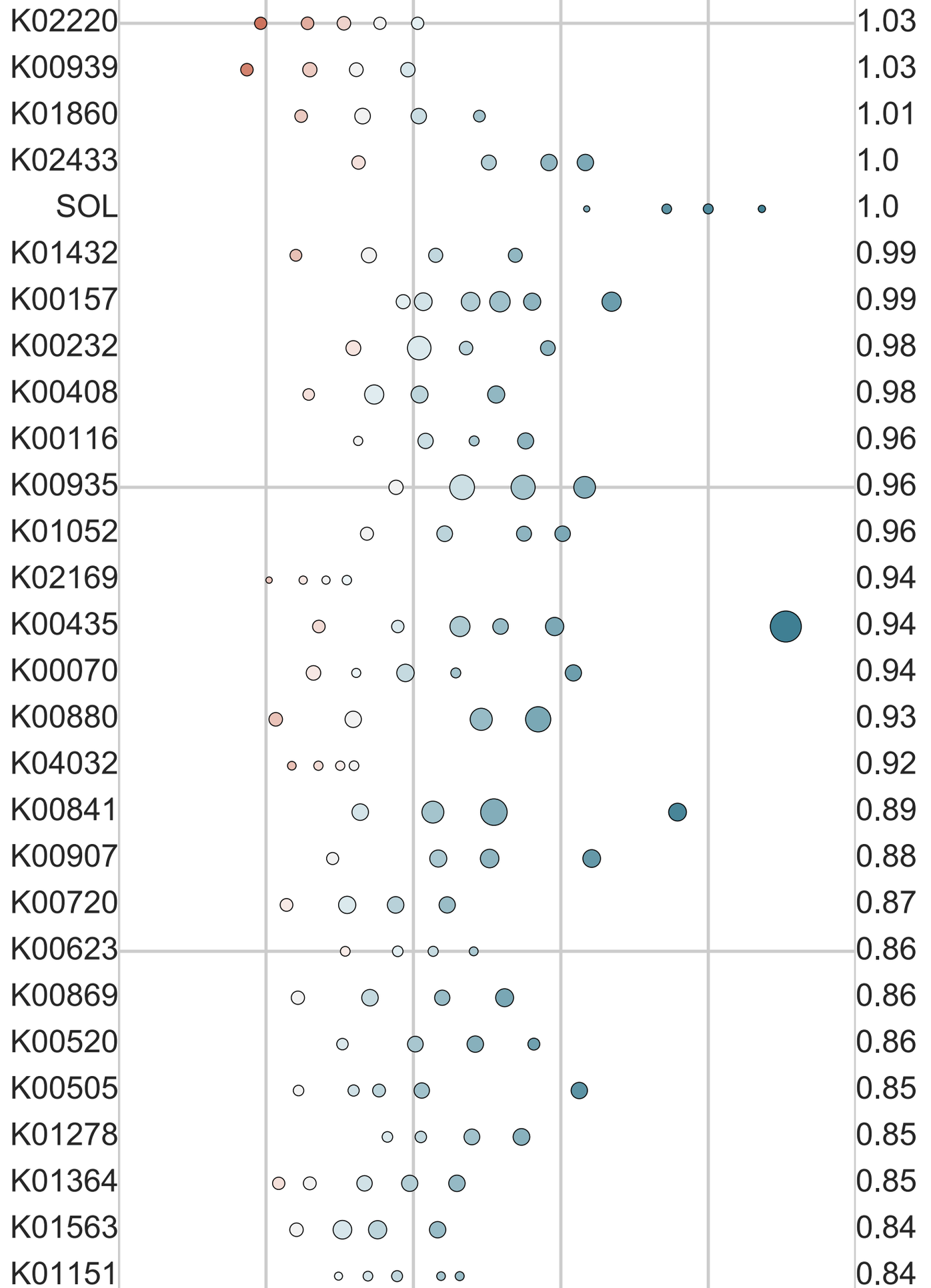
CKS V.

What are some fundamental properties in multis?



Weiss+18

Do you see any patterns?



1 $R_\oplus$

3 $R_\oplus$

10 $R_\oplus$

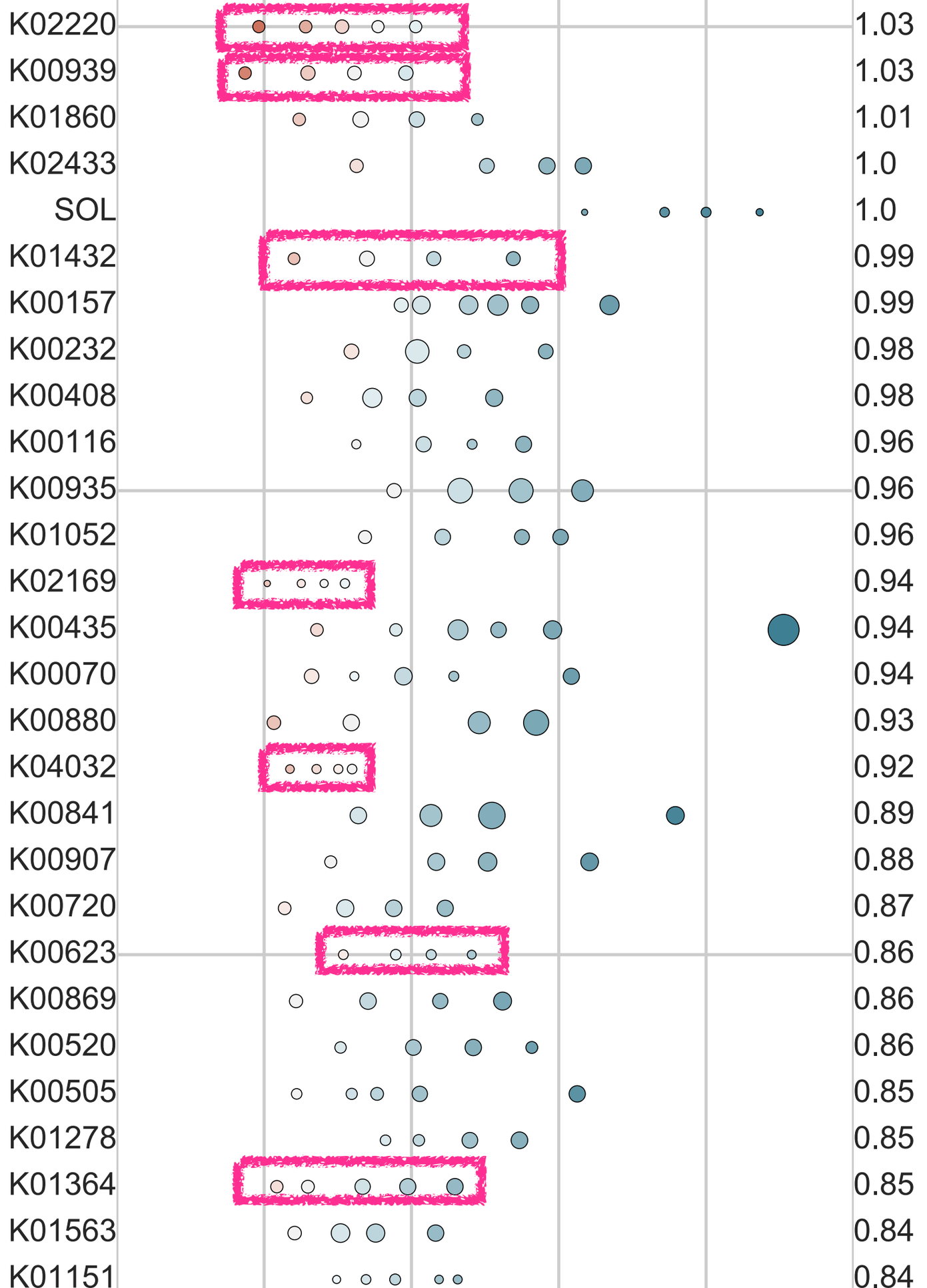
Do you see any patterns?

Planets in the same system often have similar sizes

1 $R_\oplus$

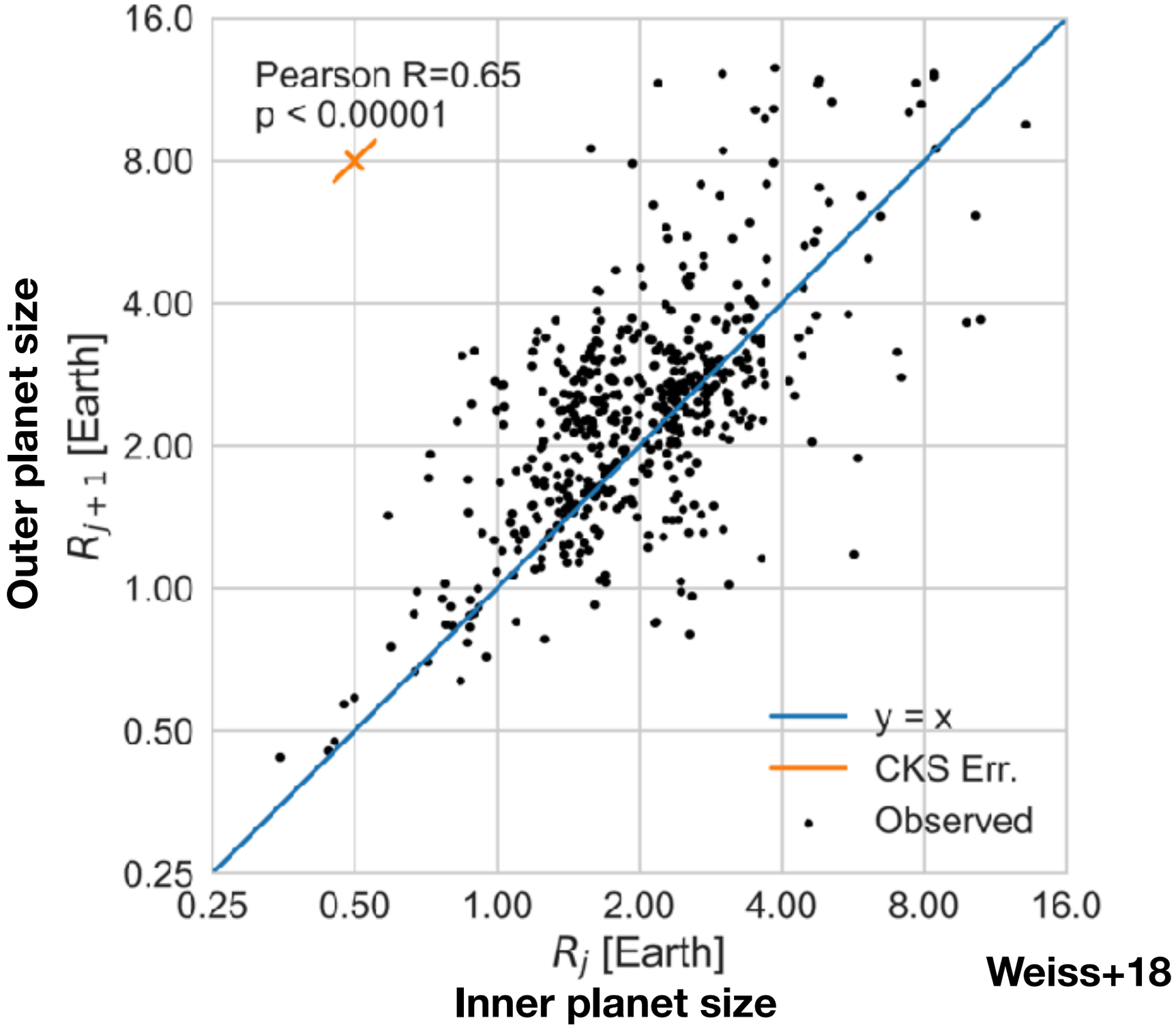
3 $R_\oplus$

10 $R_\oplus$



CKS V. “Peas in a Pod”
Weiss et al. (2018)

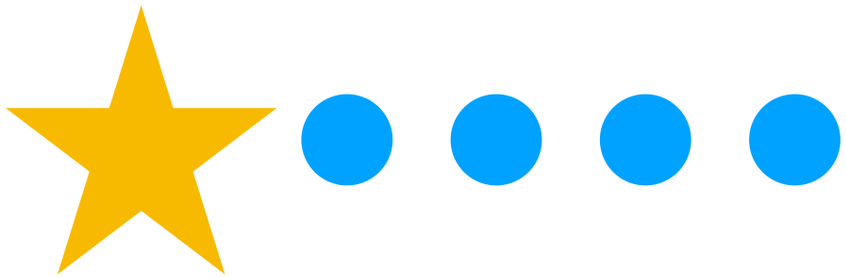
The sizes of planets in the same system are correlated (504 pairs)



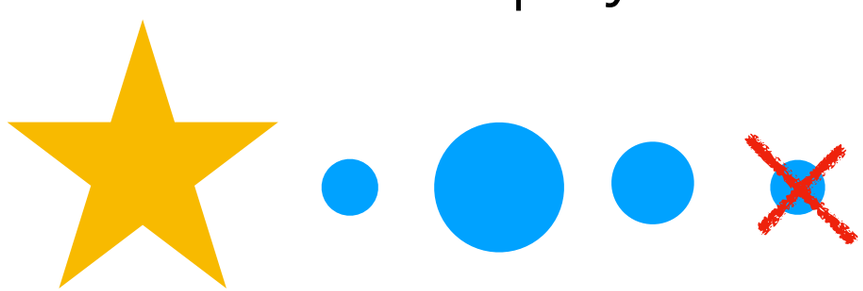
Weiss+18

Test Null Hypothesis with Bootstrap Trials

Observed system:



Possible bootstrap system:

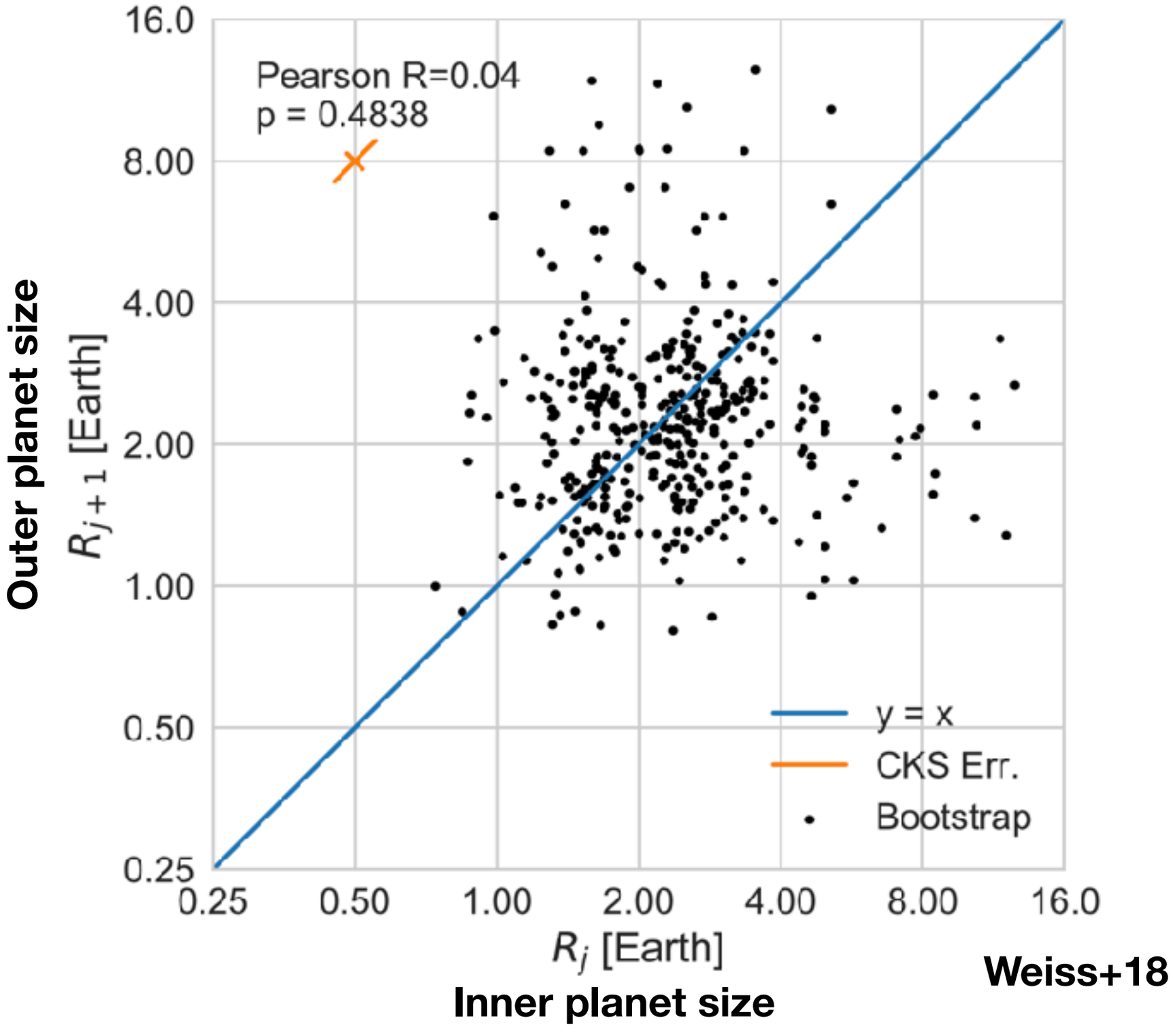


Star, number of planets, orbital periods are preserved

Planet size is drawn at random

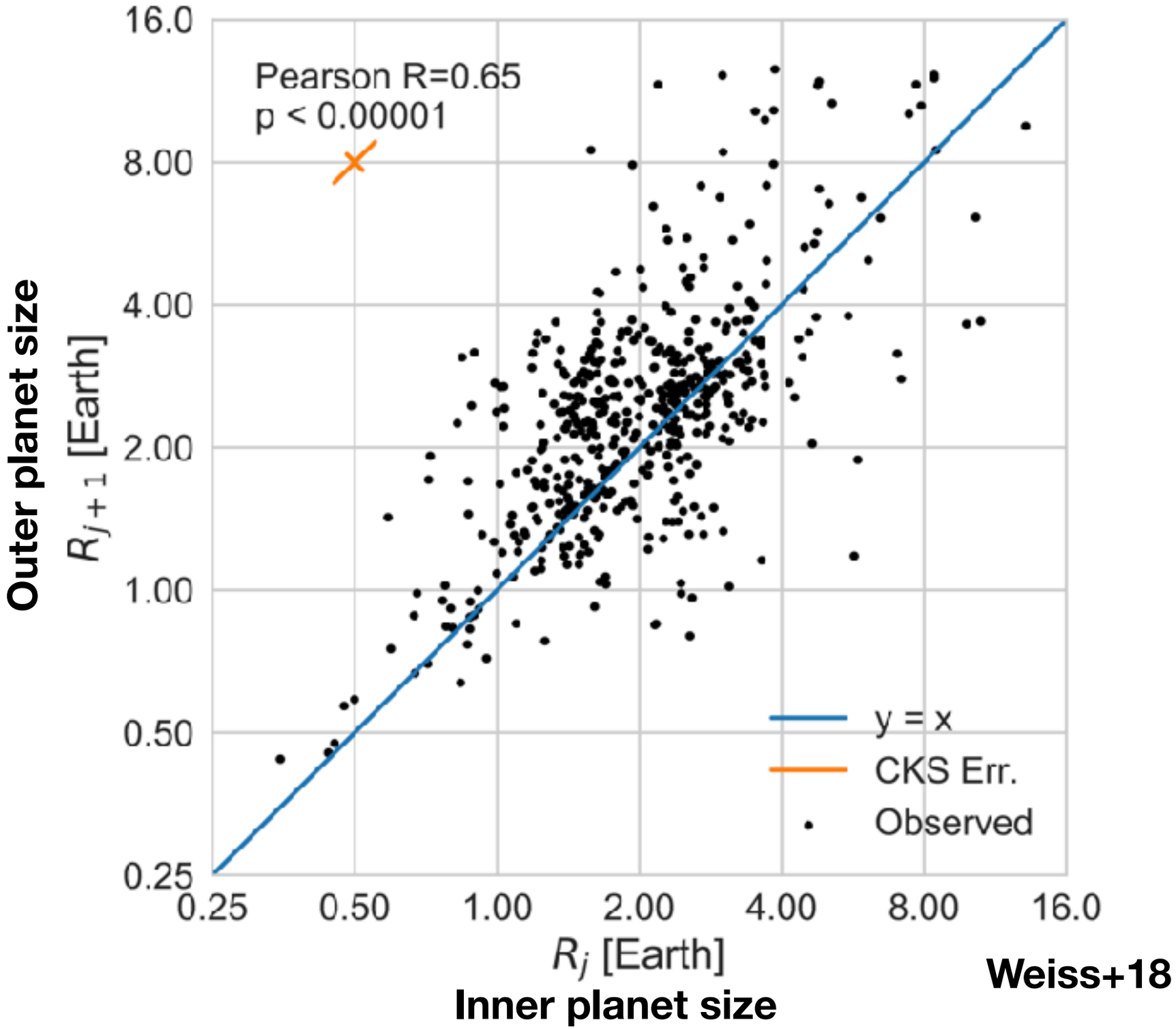
Only detectable planets are counted

One example bootstrap trial: no correlation between planet sizes

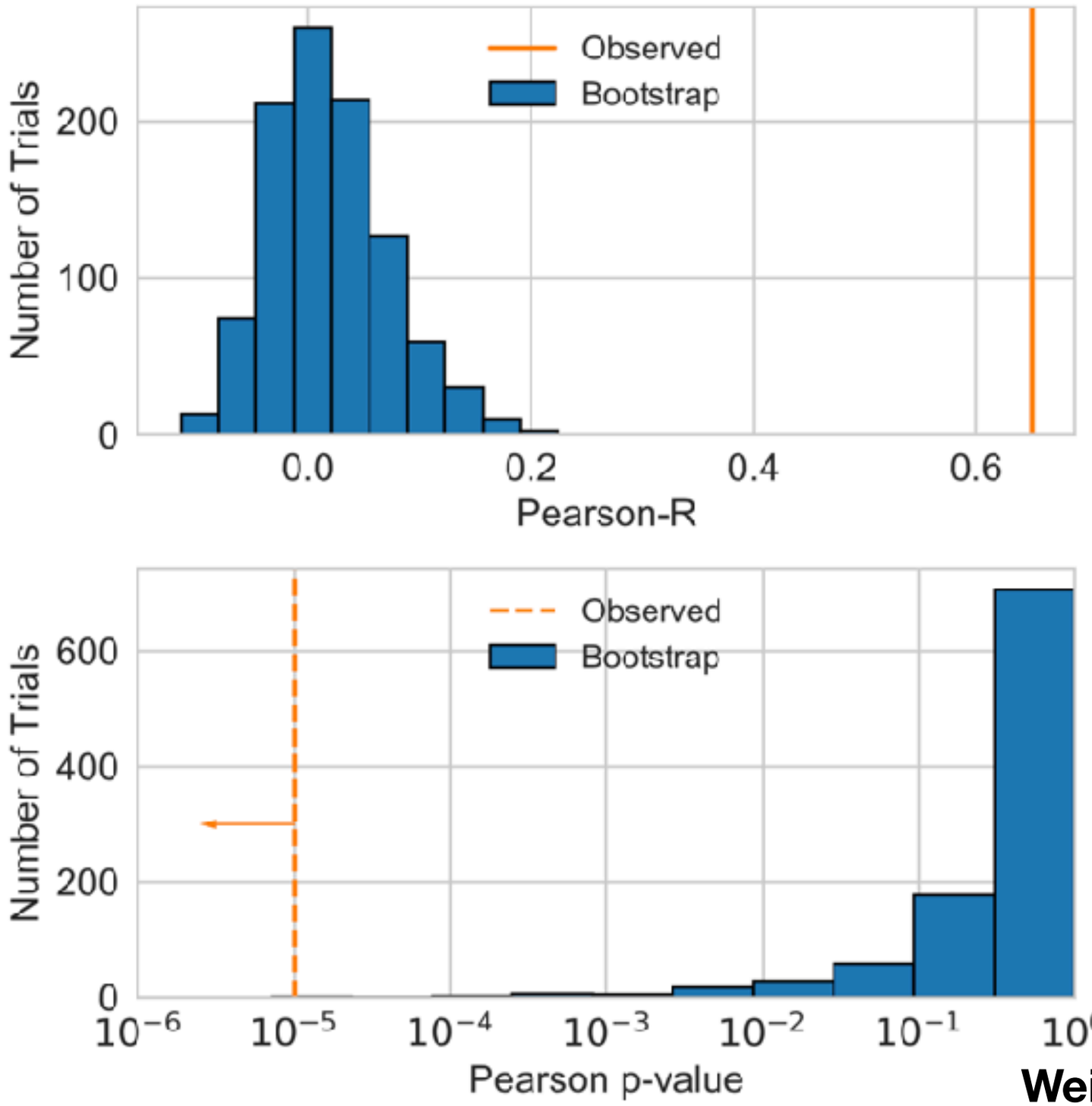


Weiss+18

The sizes of pairs of planets in the same system are correlated.



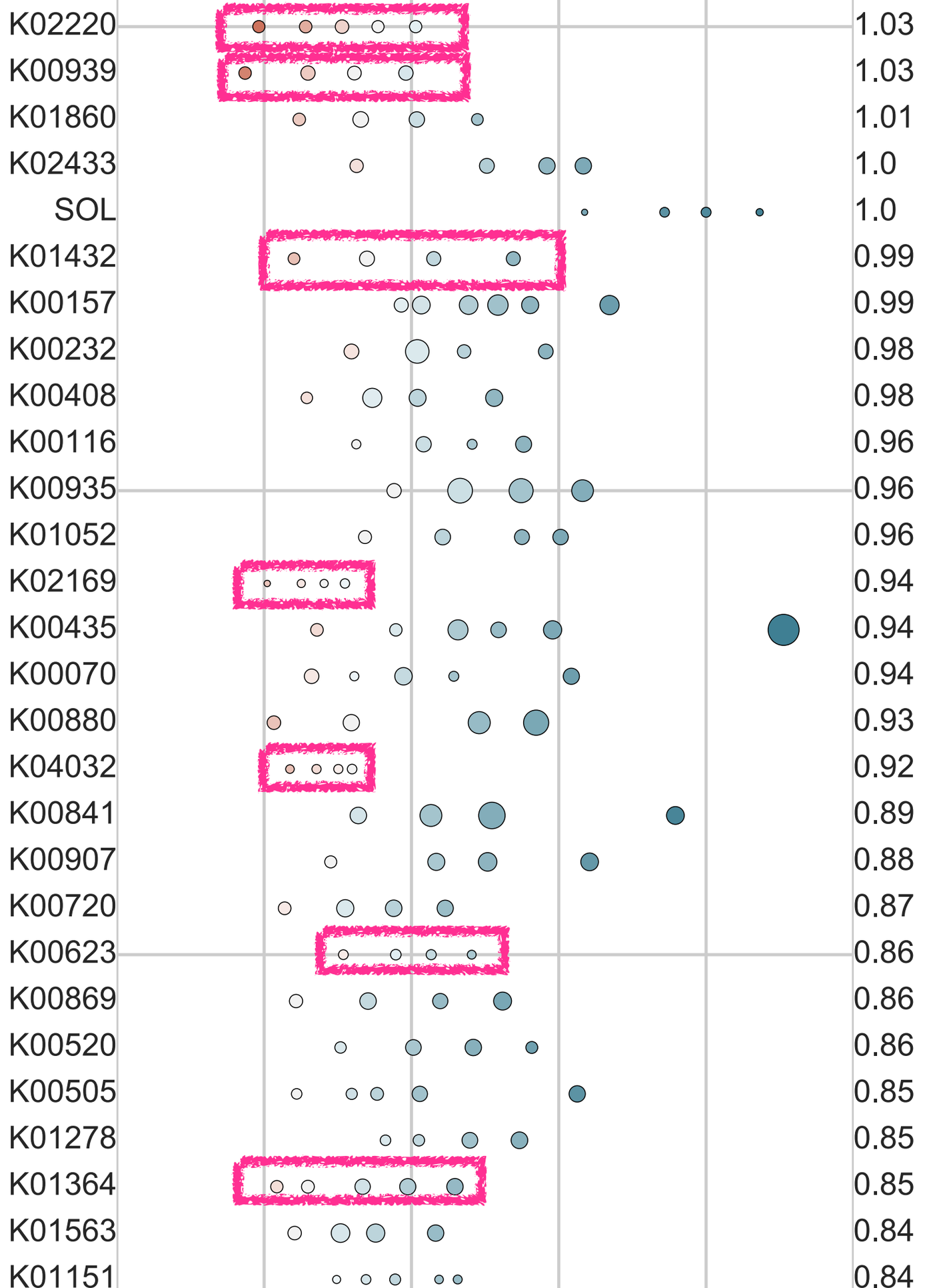
1000 bootstrap trials: the planet size correlation is not reproduced with a null hypothesis + detection biases



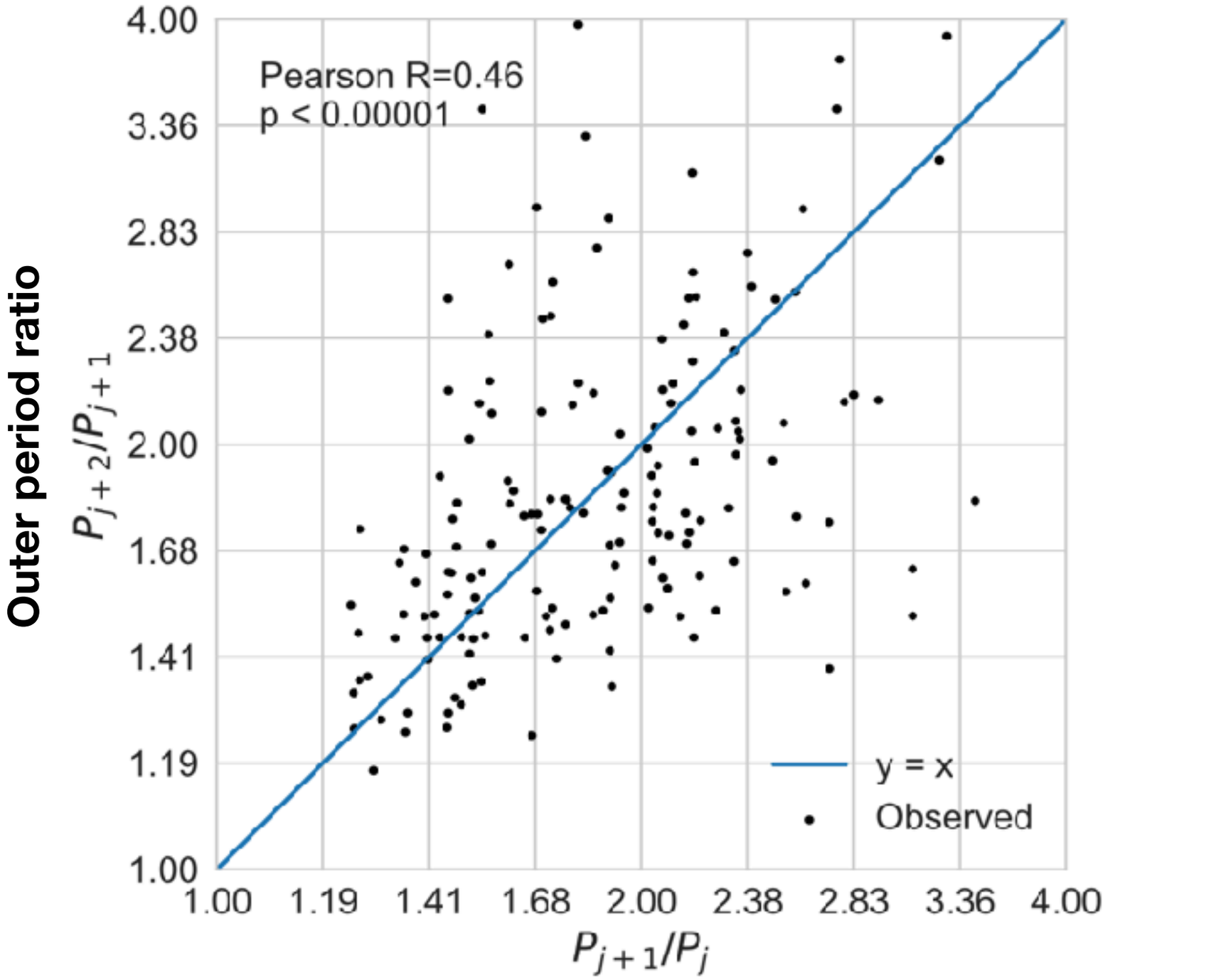
Weiss+18

Do you see any patterns?

Planets in the same system have regular spacing



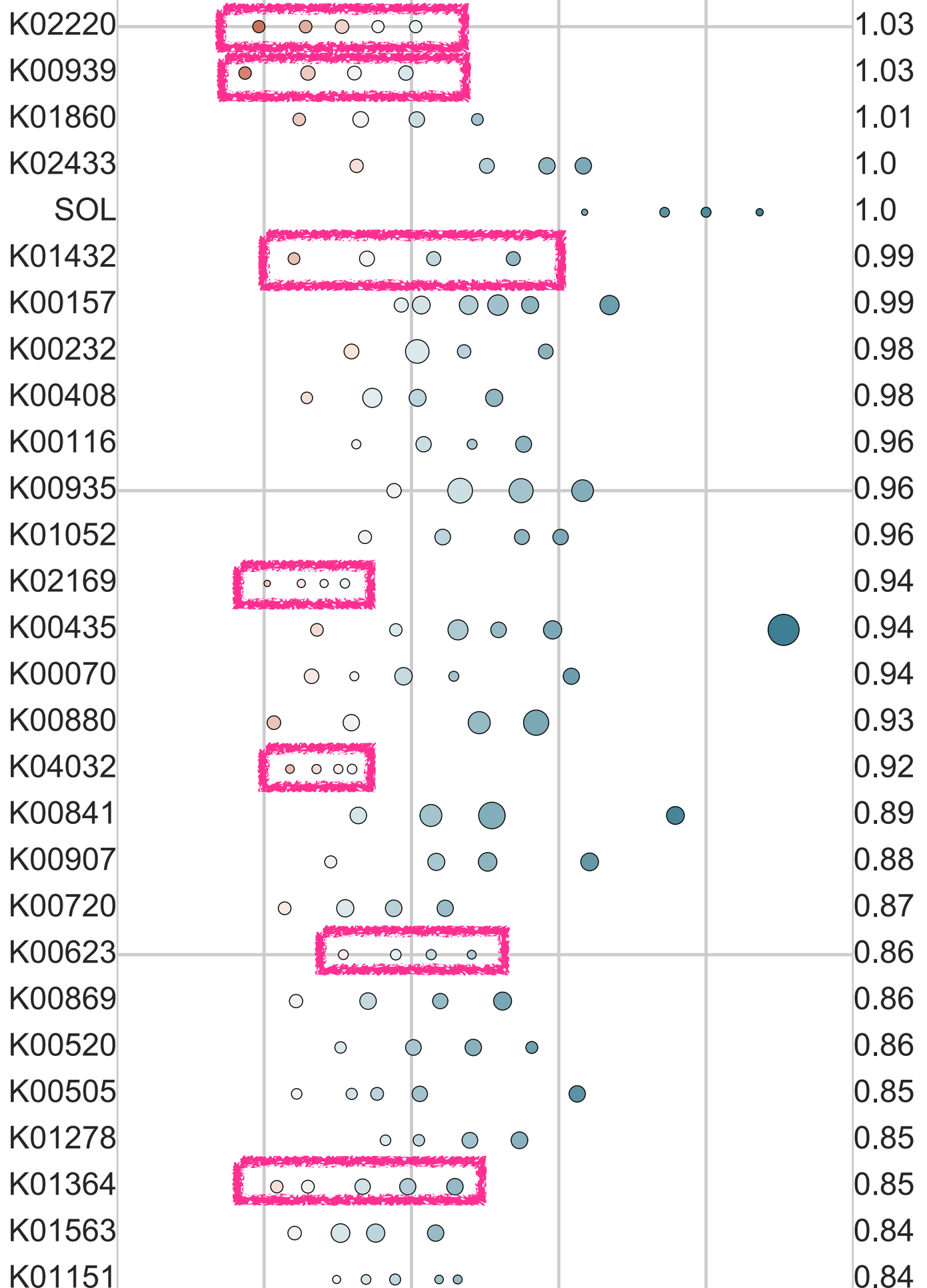
The orbital period ratios of planets in the same system are correlated (165 pairs)



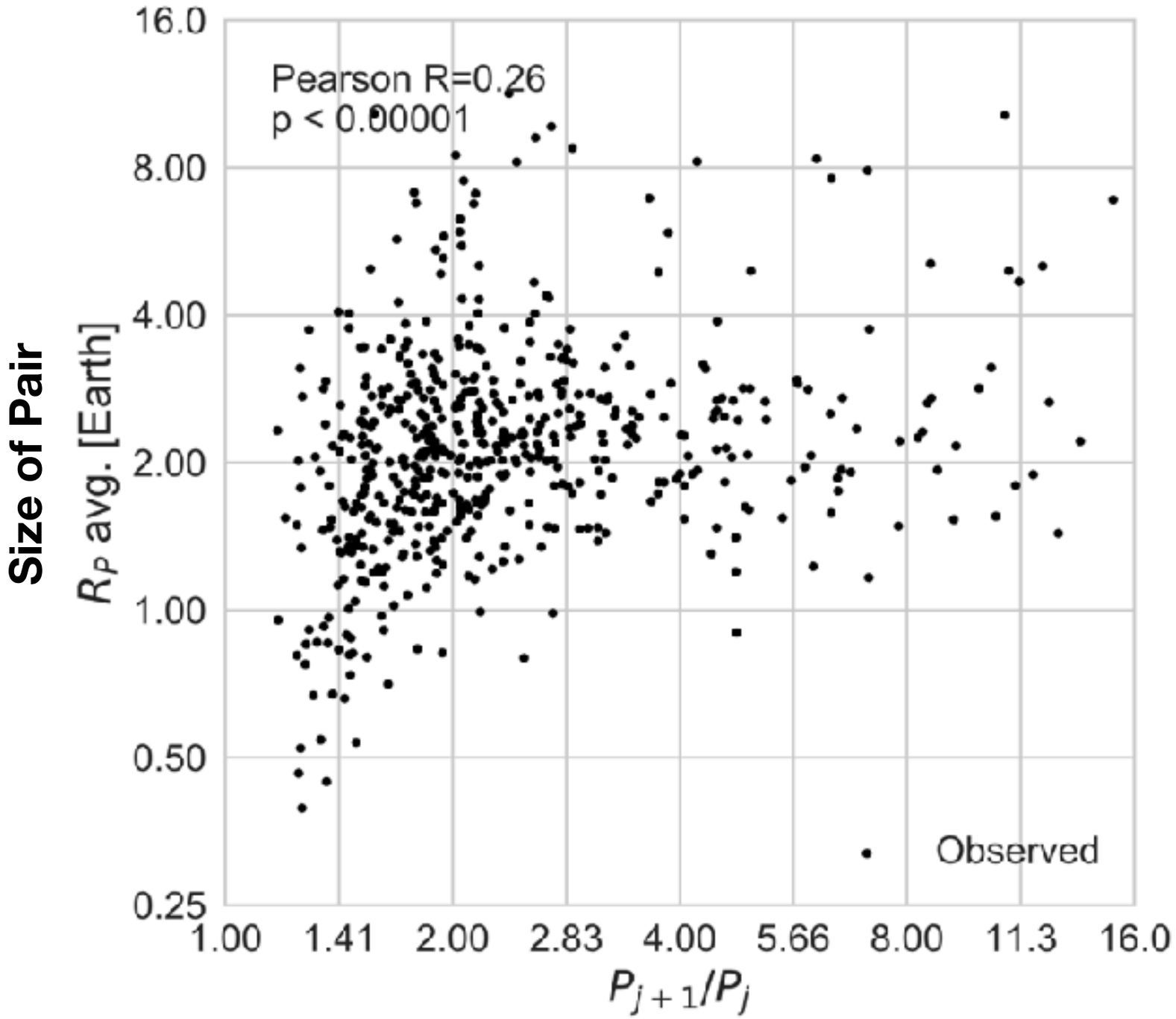
Weiss+18

Do you see any patterns?

Is there a connection between planet size and spacing?

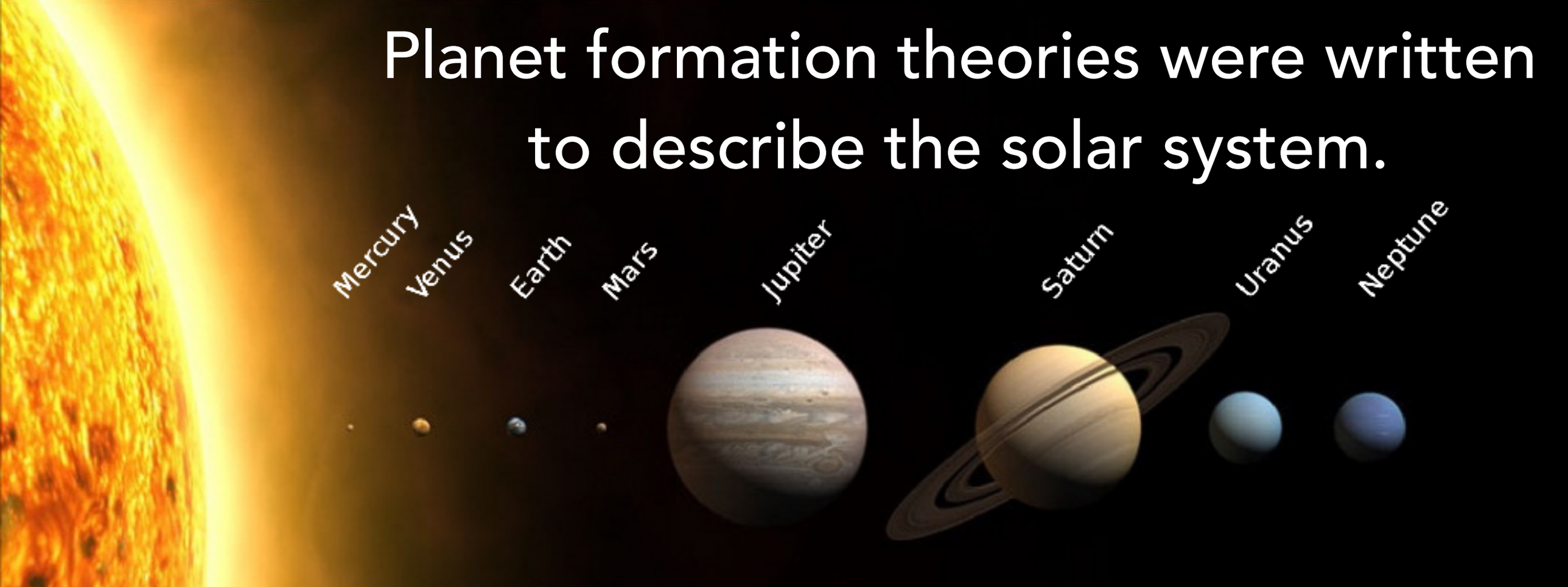


The spacing and size of a pair of planets are correlated



Weiss+18

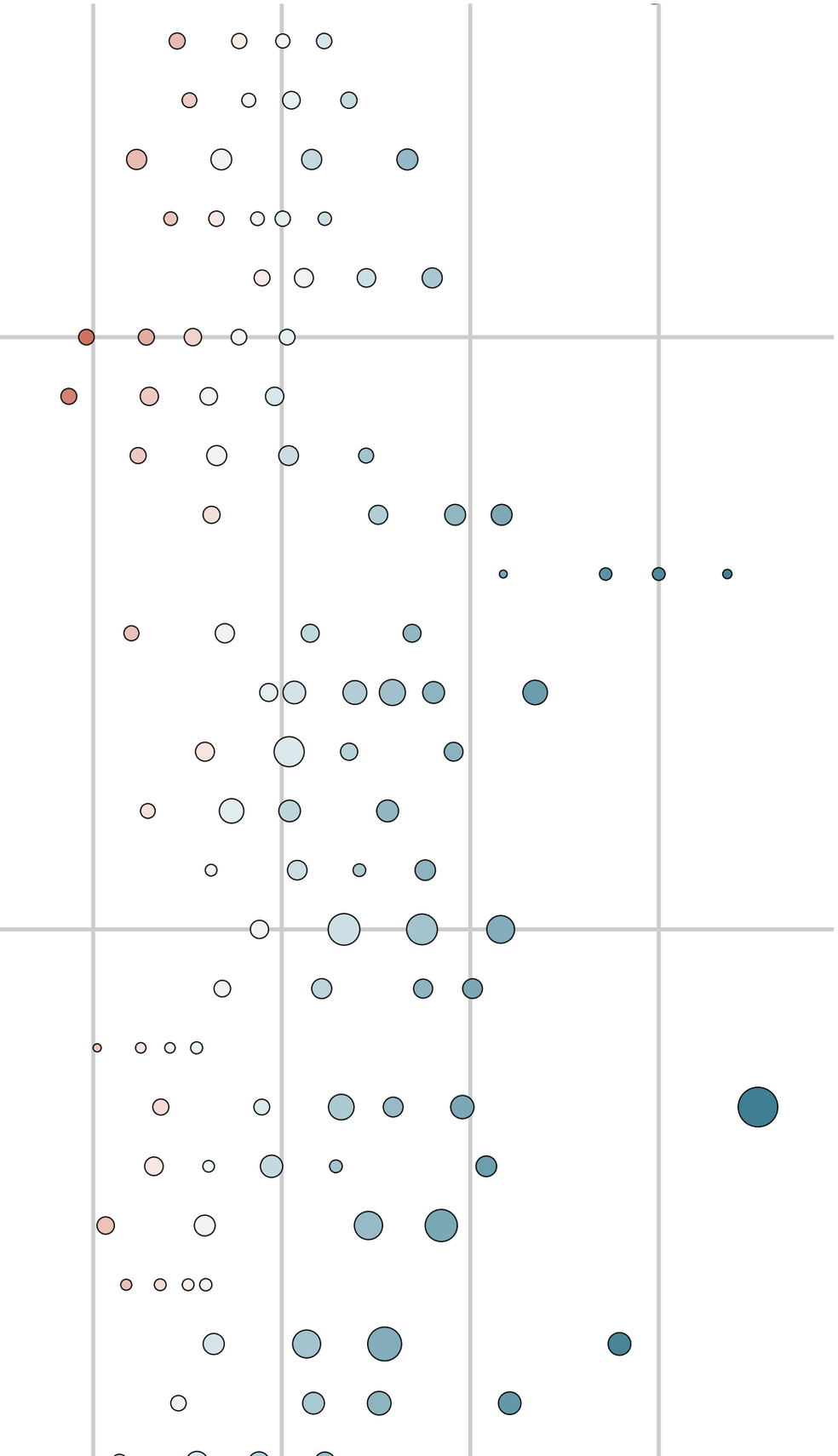
Planet formation theories were written to describe the solar system.

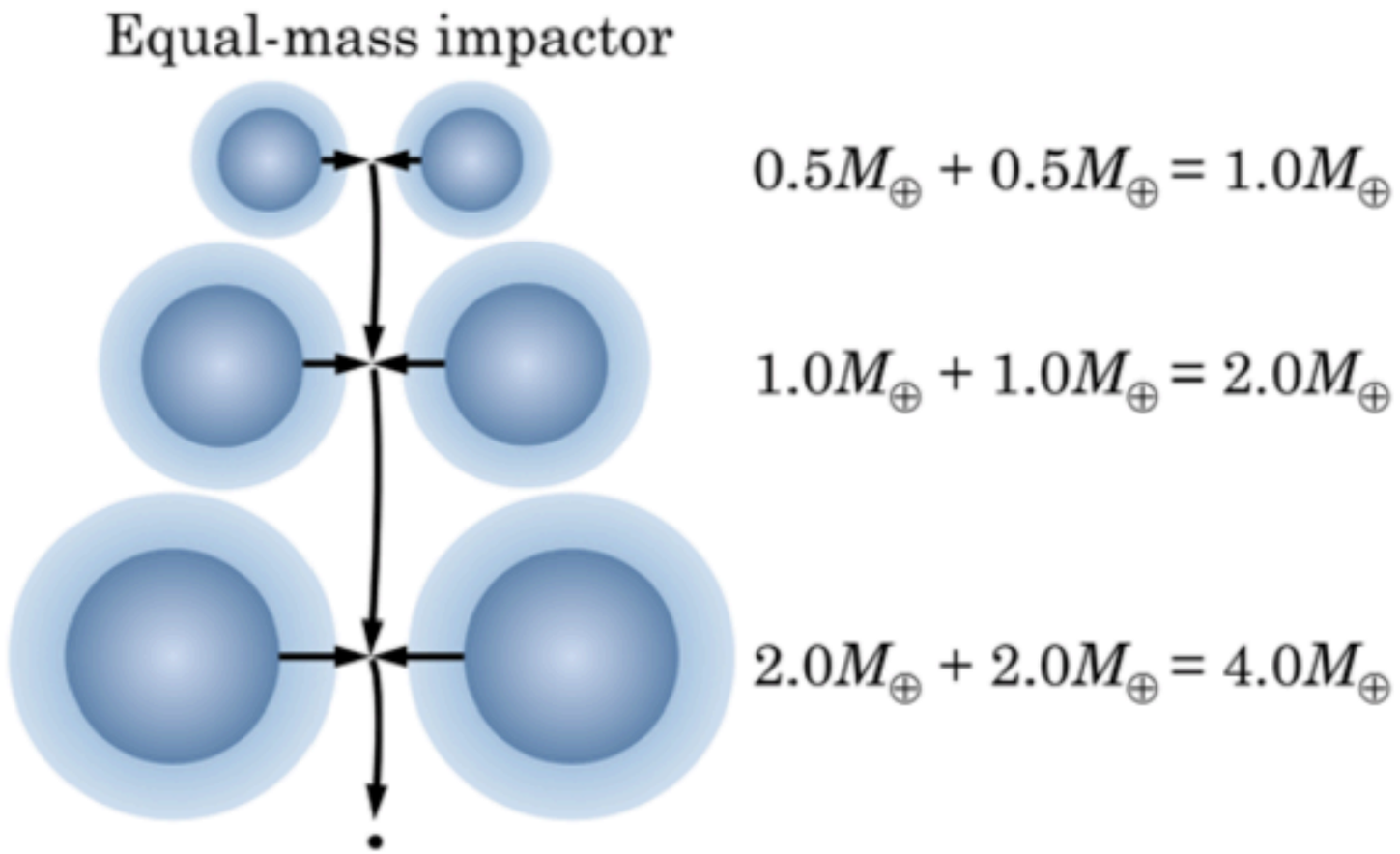


Giant Impacts

needed to make big terrestrial planets *in situ*

Giant impacts diversify planet sizes.





Inamdar & Schlichting 2015

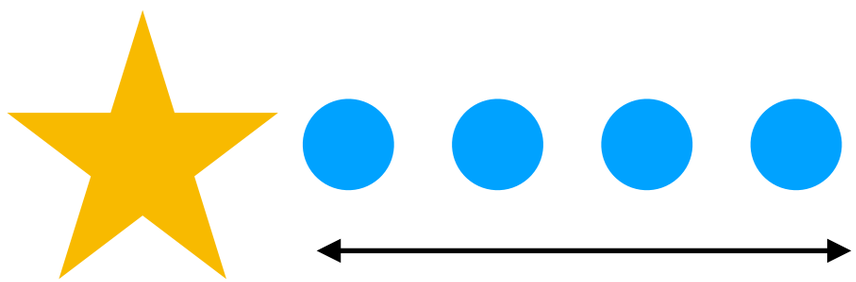
Clues from oligarchic growth

Lissauer & Stewart (1993):

The self-limiting nature of runaway growth strongly implies that massive protoplanets form at regular intervals in semimajor axis.

Kokuba & Ida (1998):

We have shown the oligarchic growth of protoplanets in the post-runaway stage. Protoplanets with the same order masses with the orbital separation larger than about $5r_H$ is the inevitable outcome of planetary accretion in the post-



Kepler multis = aged oligarchs with few giant impacts?