Patterns in Multiplanet Systems as Fossils of Planet Formation

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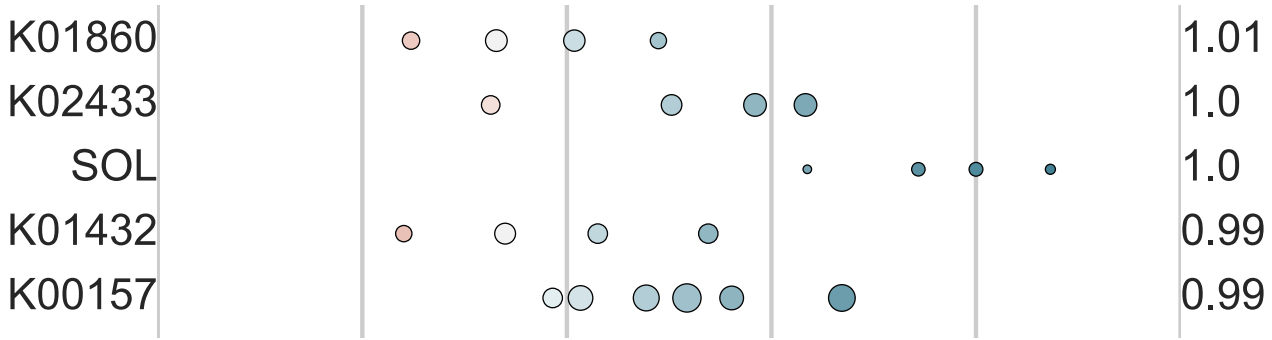


Exoplanets Beyond the Snowline — University of Tokyo

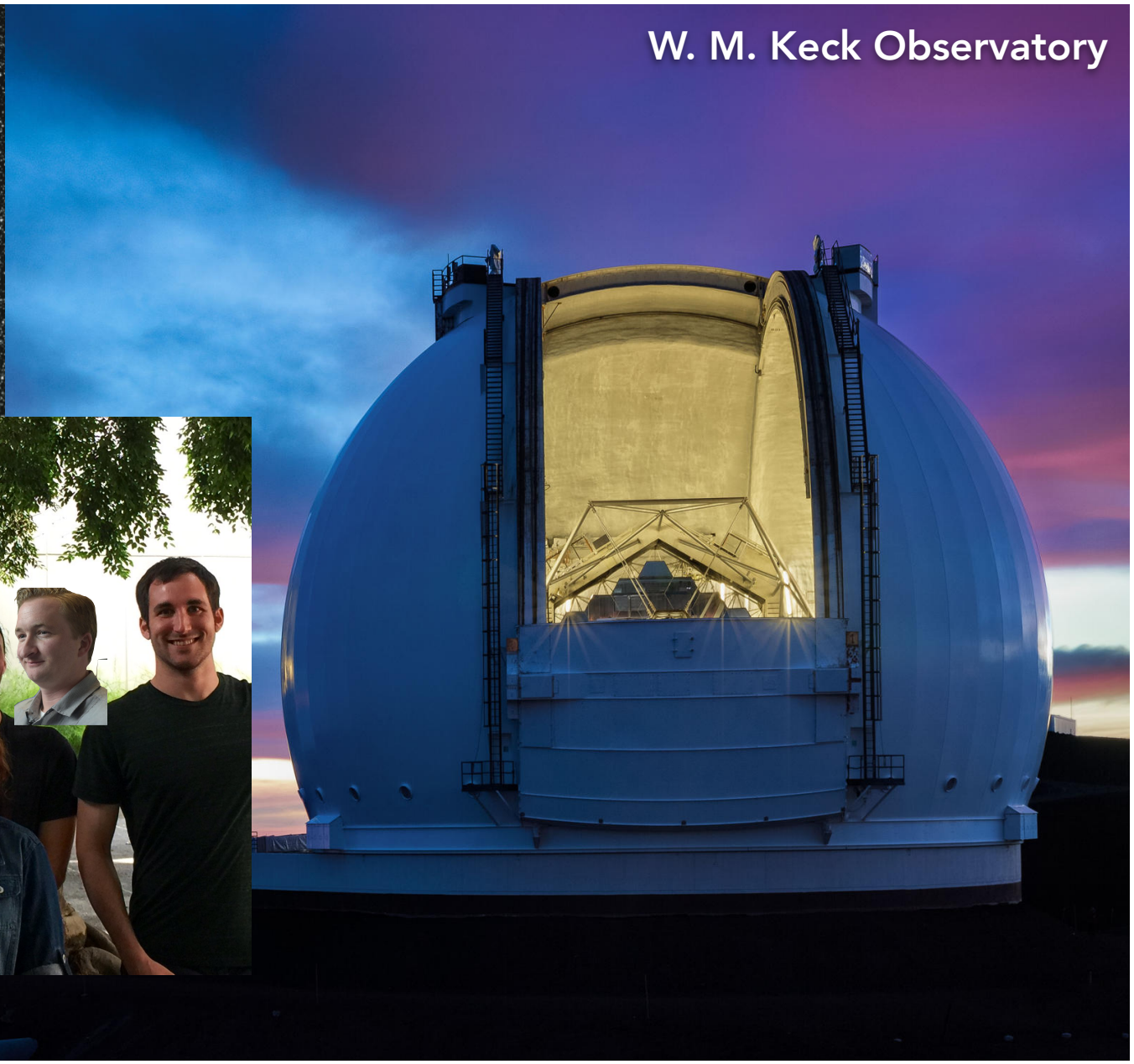
Questions we'd like to answer

- What properties are common in multiplanet systems?
- What do common properties teach us about planet formation?

What properties are common in multiplanet systems?

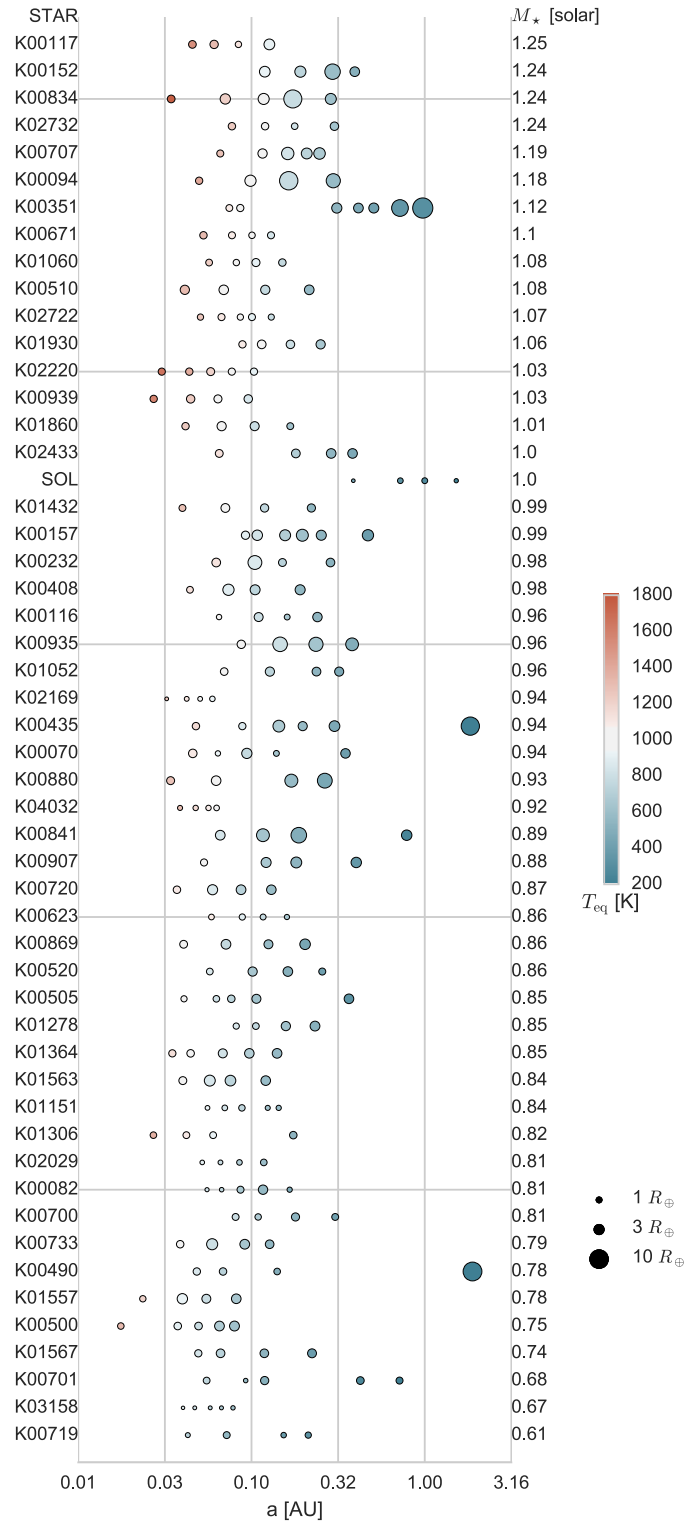
California-Kepler Survey

New exoplanet science from Keck/HIRES Spectra of 1305 Kepler Planet-hosting Stars

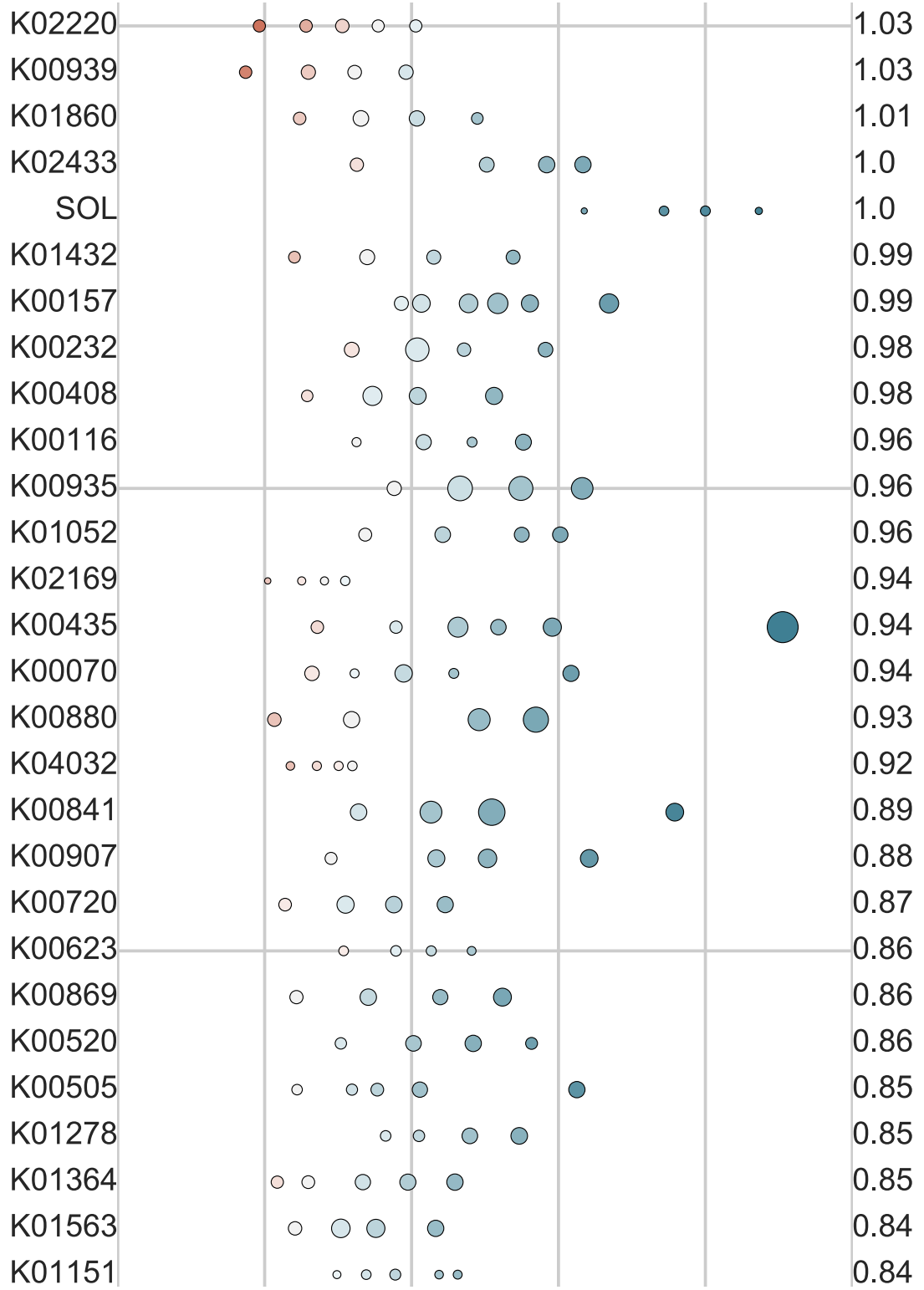


The California Kepler Survey yielded precise parameters for

909 transiting planets in 355 multiplanet systems

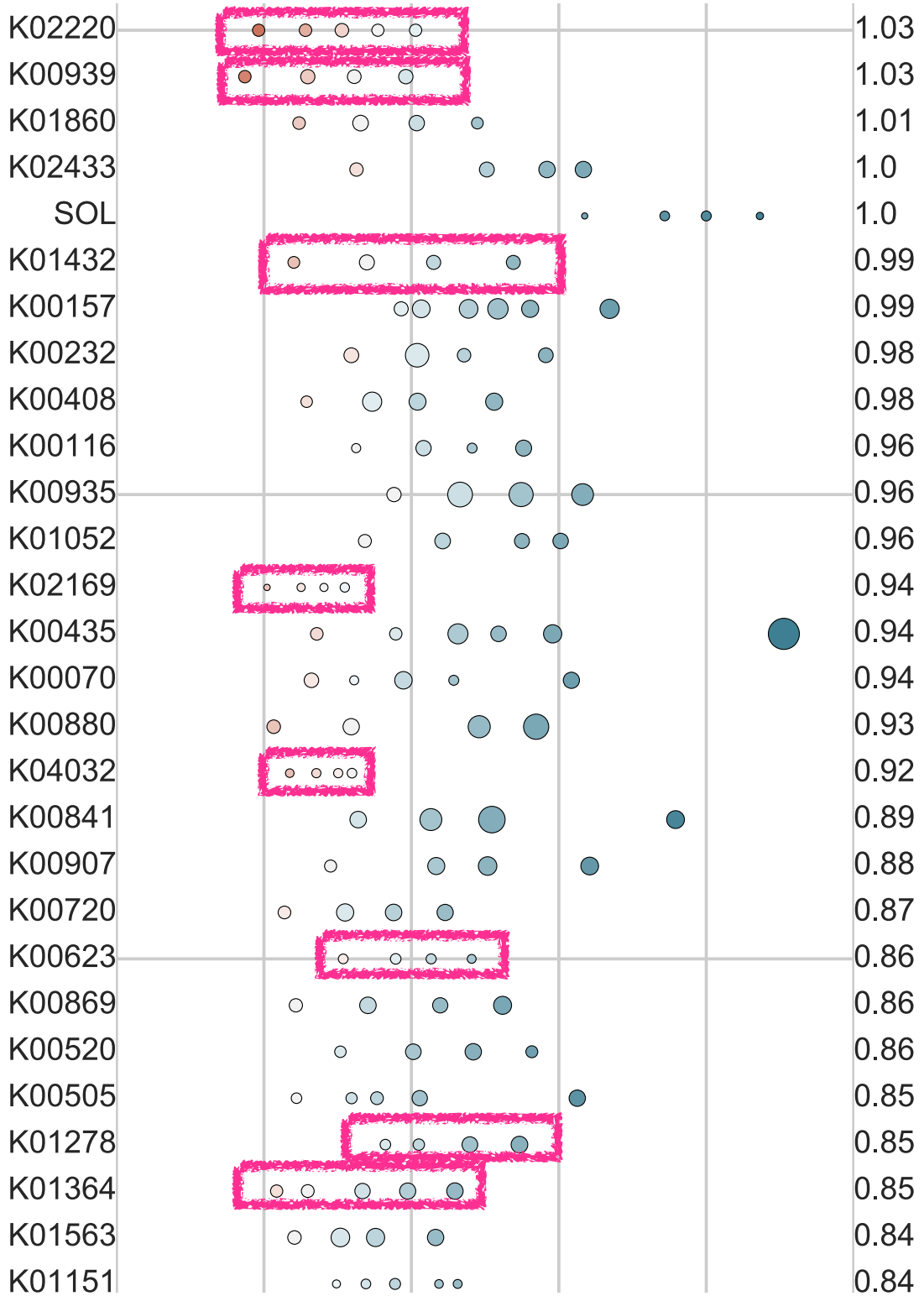


Do you see any patterns?

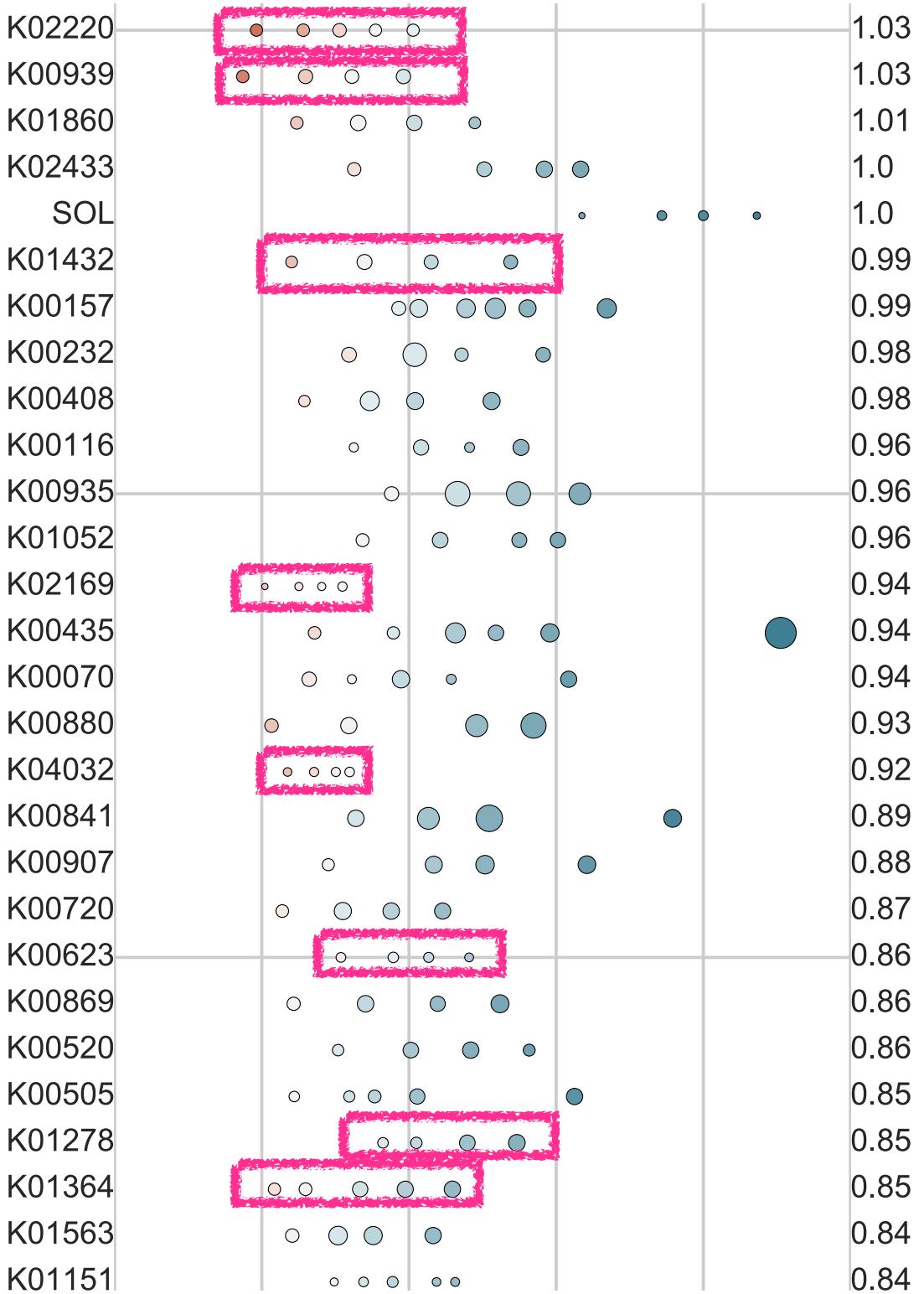


Do you see any patterns?

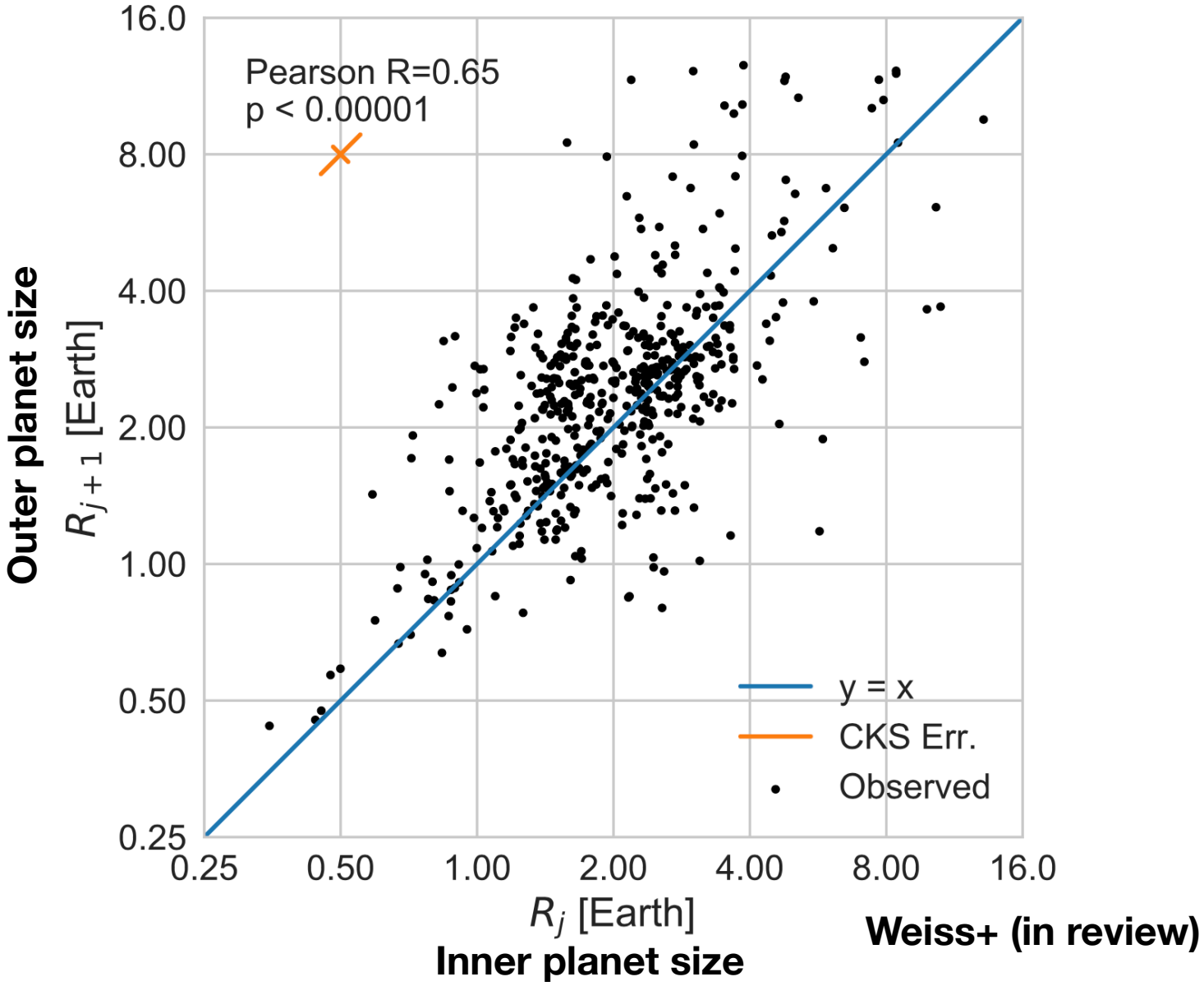
Planets in the same system have similar sizes




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

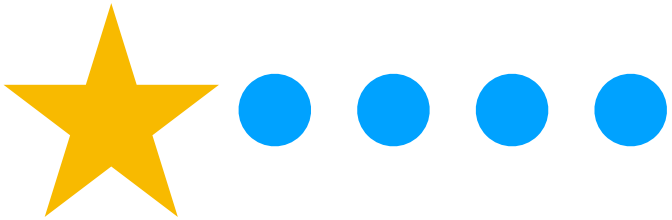

K02220 1.03
K00939 1.03
K01860 1.01
K02433 1.0
SOL 1.0
K01432 0.99
K00157 0.99
K00232 0.98
K00408 0.98
K00116 0.96
K00935 0.96
K01052 0.96
K02169 0.94
K00435 0.94
K00070 0.94
K00880 0.93
K04032 0.92
K00841 0.89
K00907 0.88
K00720 0.87
K00623 0.86
K00869 0.86
K00520 0.86
K00505 0.85
K01278 0.85
K01364 0.85
K01563 0.84
K01151 0.84

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

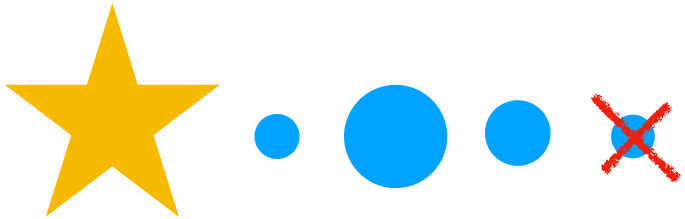


Test Null Hypothesis with Bootstrap Trials

Observed system:



Possible bootstrap system:

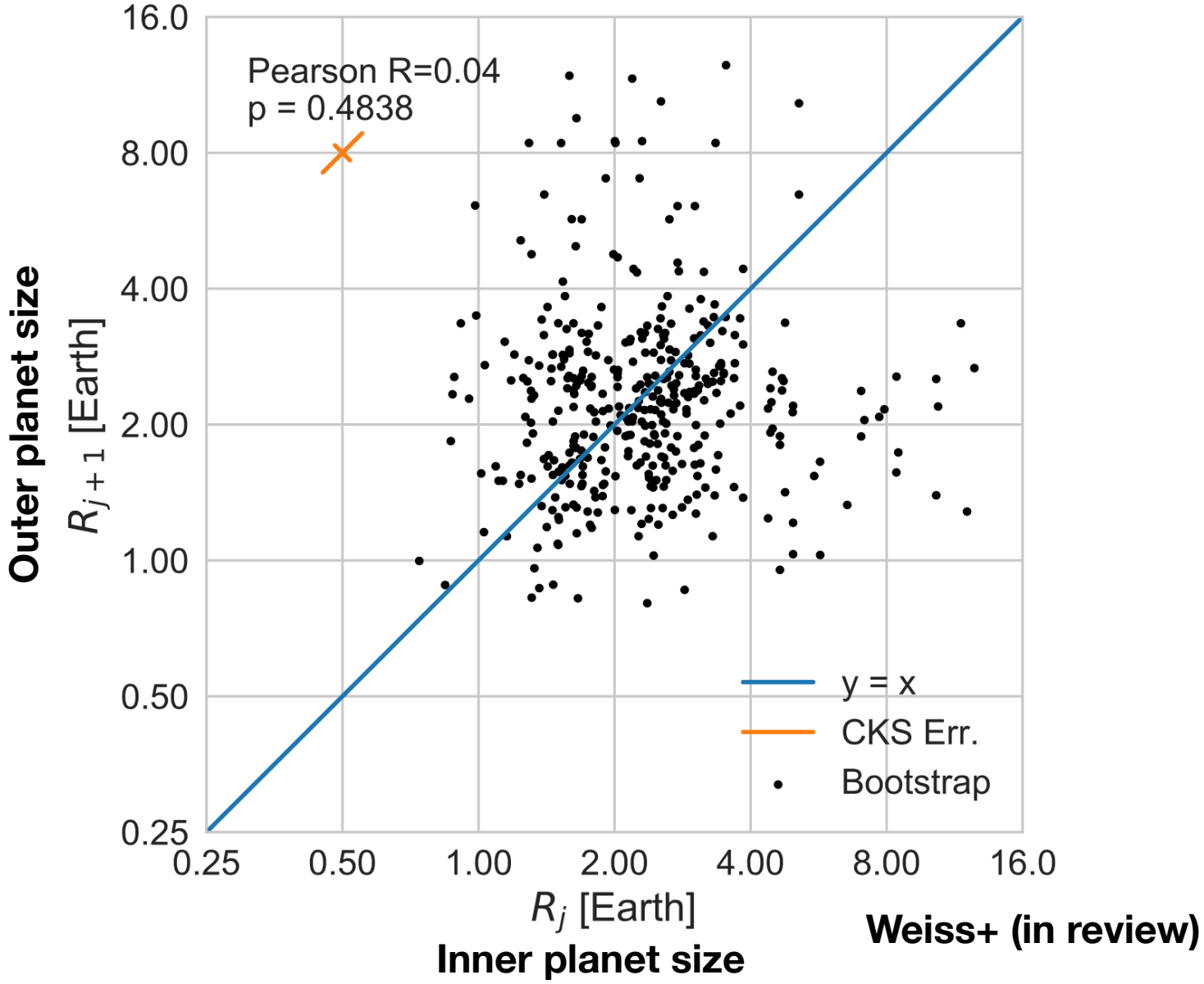


Star, number of planets, orbital periods are preserved

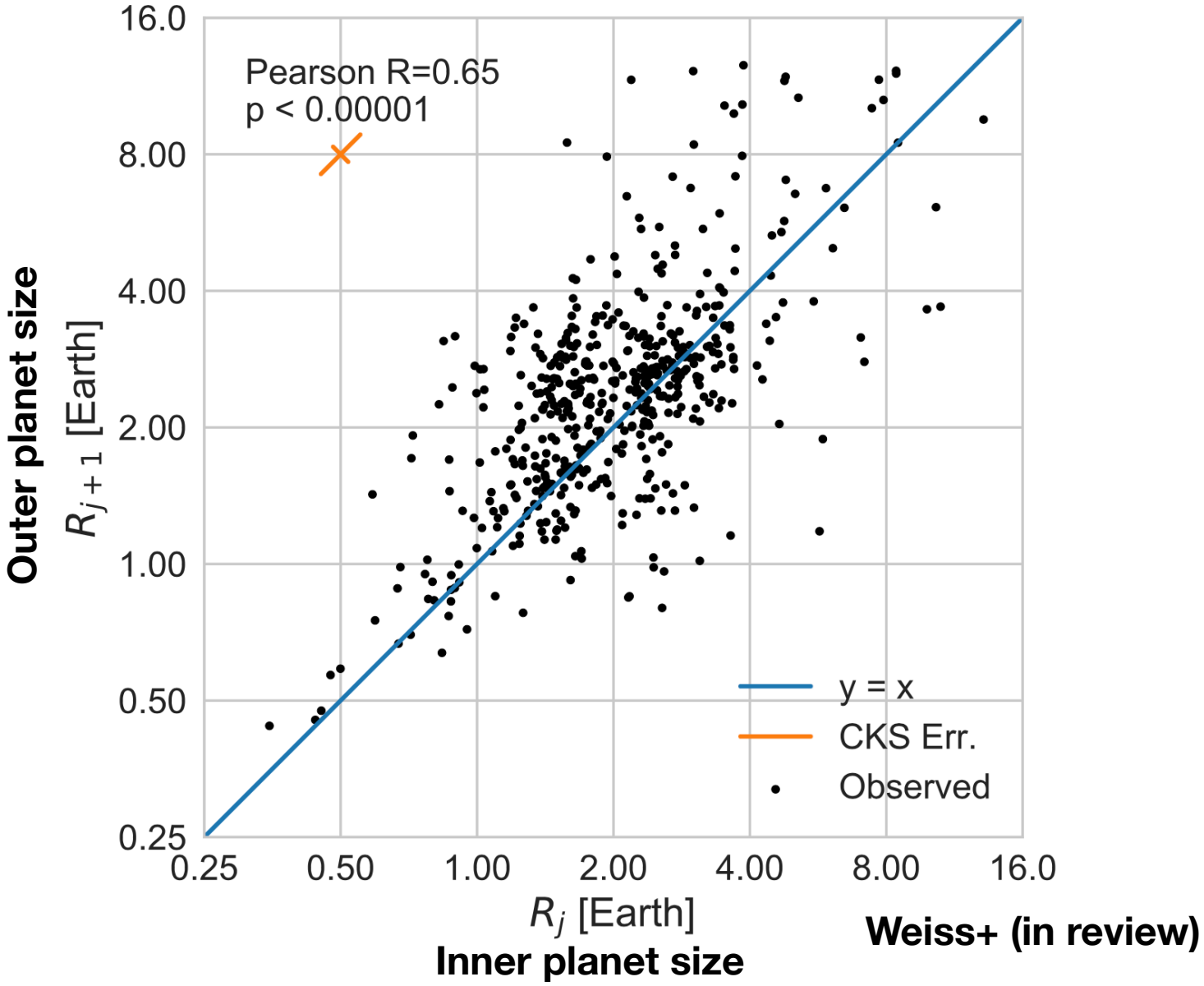
Planet size is drawn at random

Only detectable planets are counted

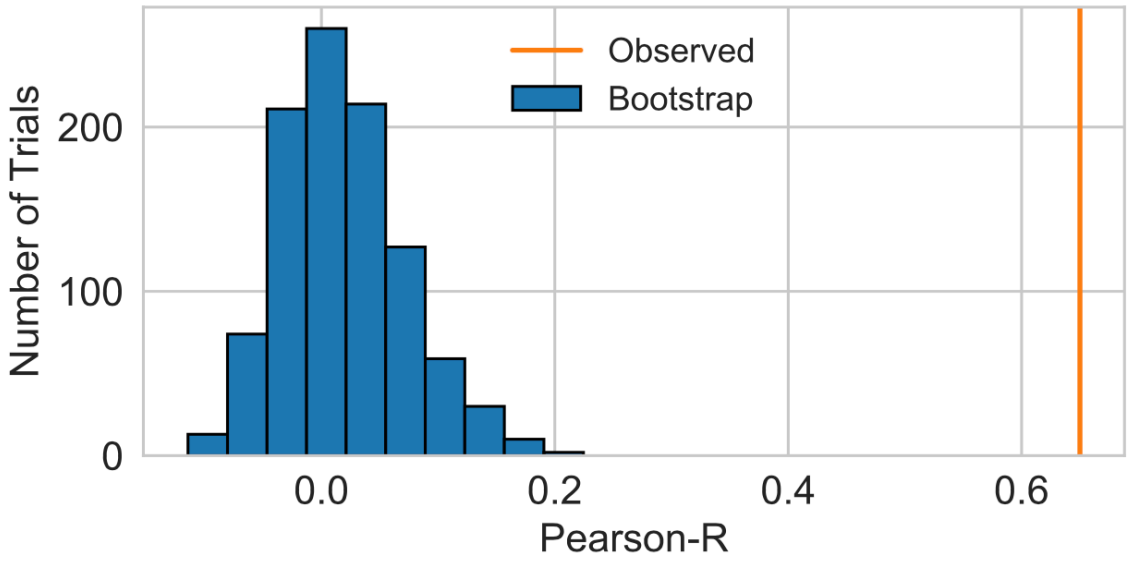
One example bootstrap trial: no correlation between planet sizes

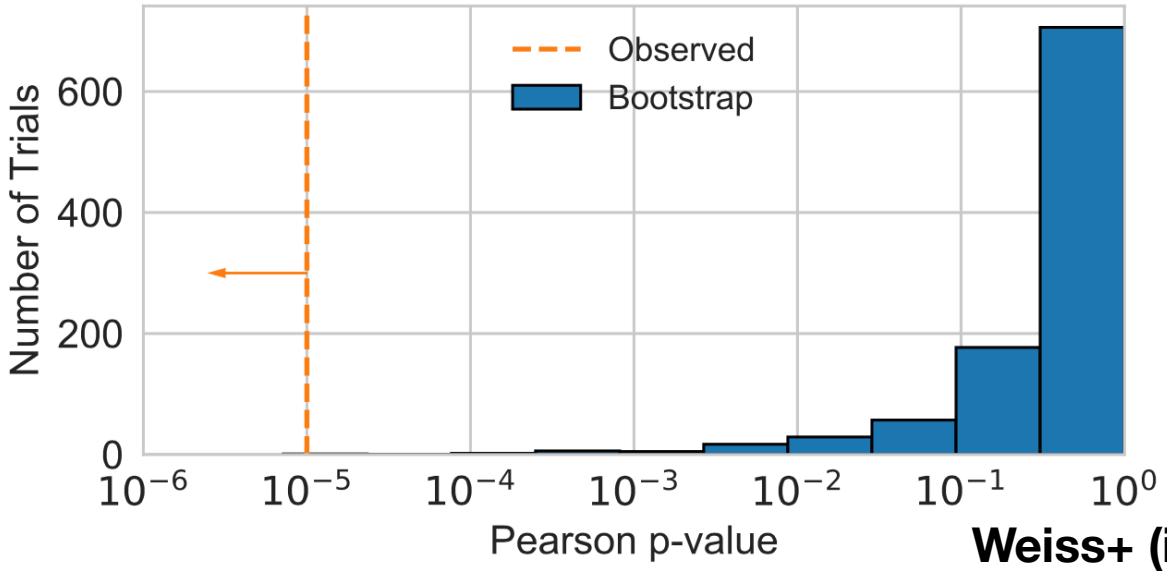


The sizes of pairs of planets in the same system are correlated.



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

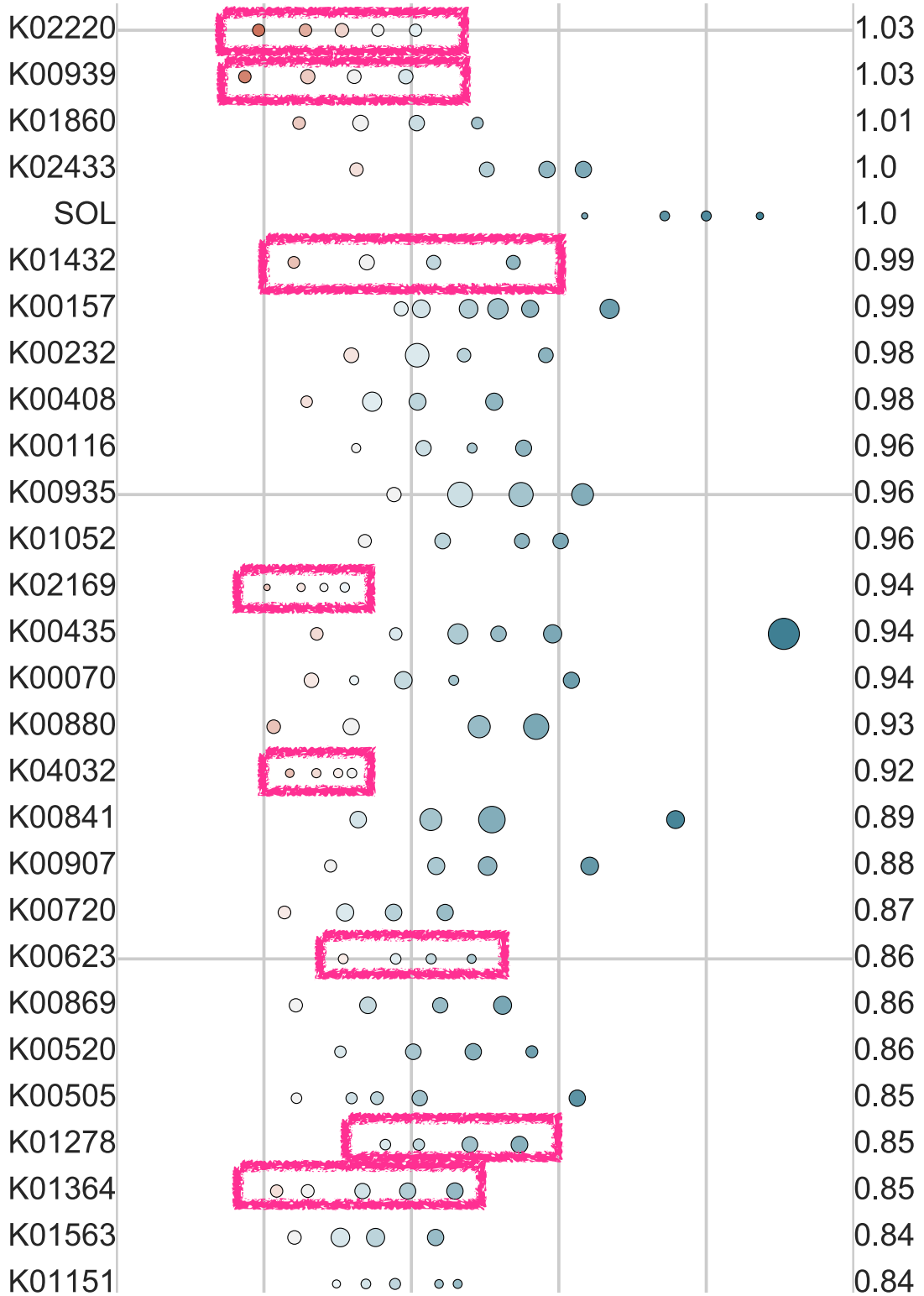




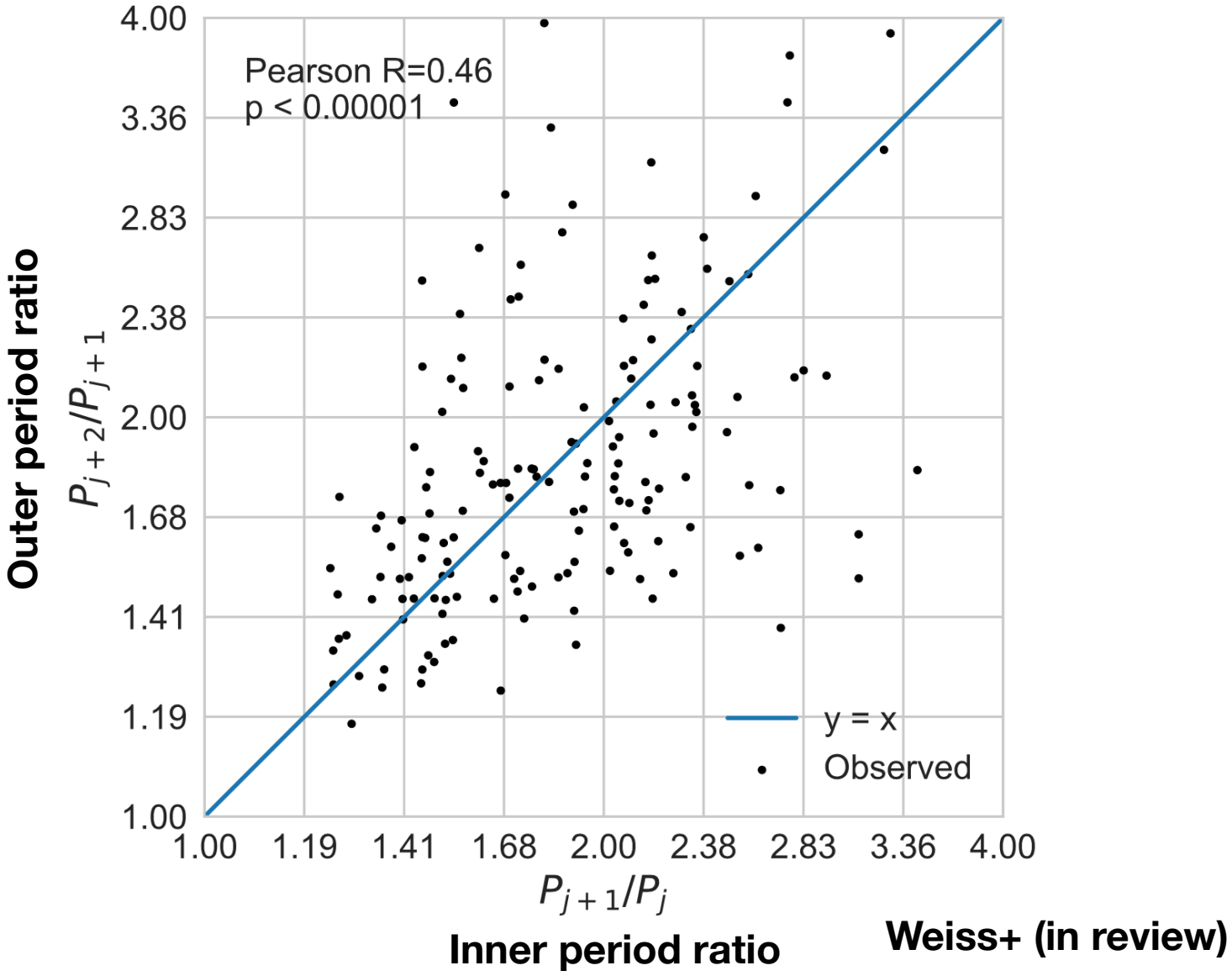
Weiss+ (in review)

Do you see any patterns?

Planets in the same system have regular spacing

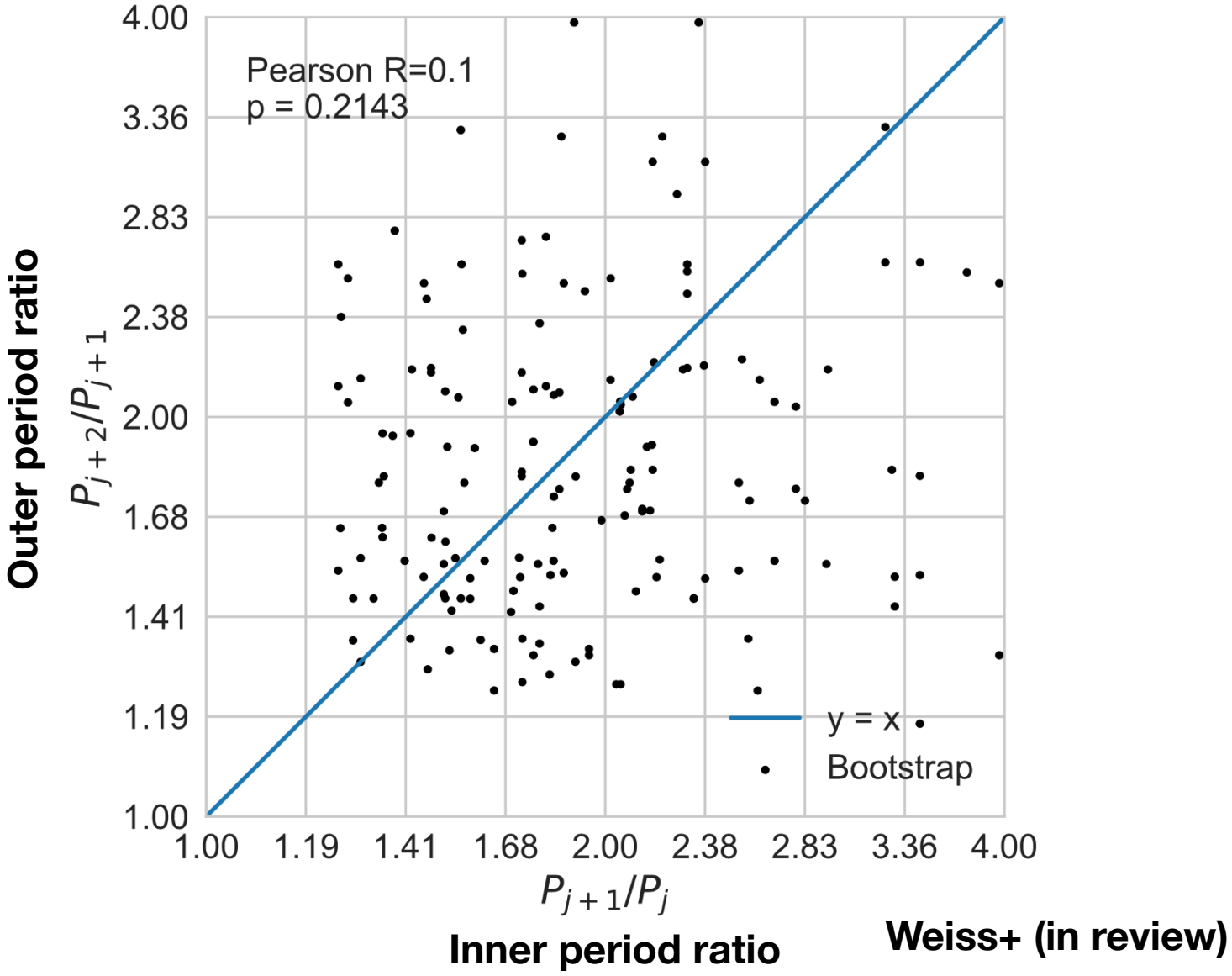


The orbital period ratios of planets in the same system are correlated.

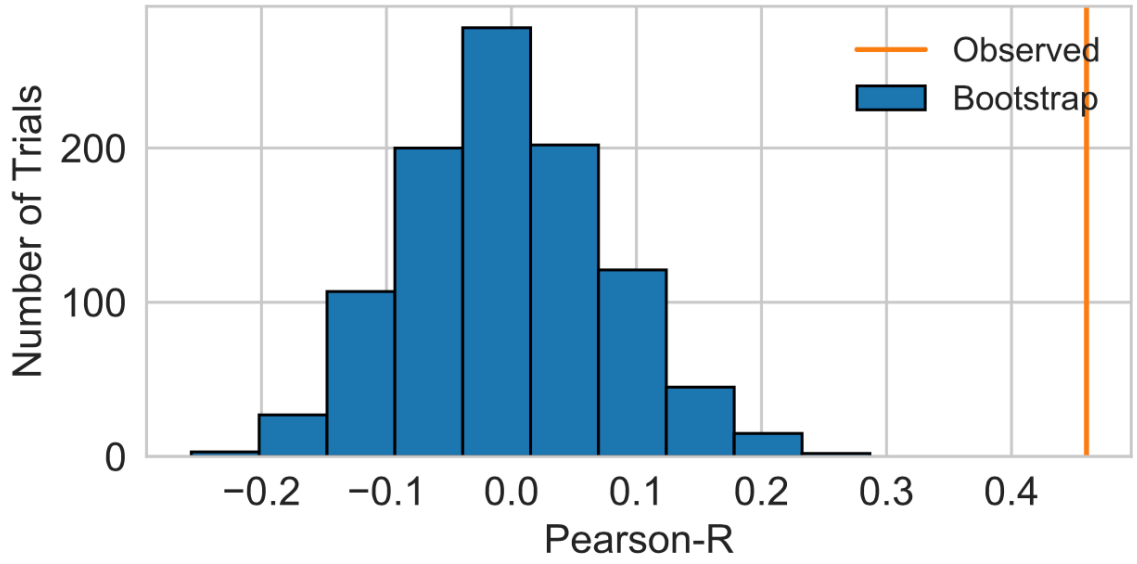


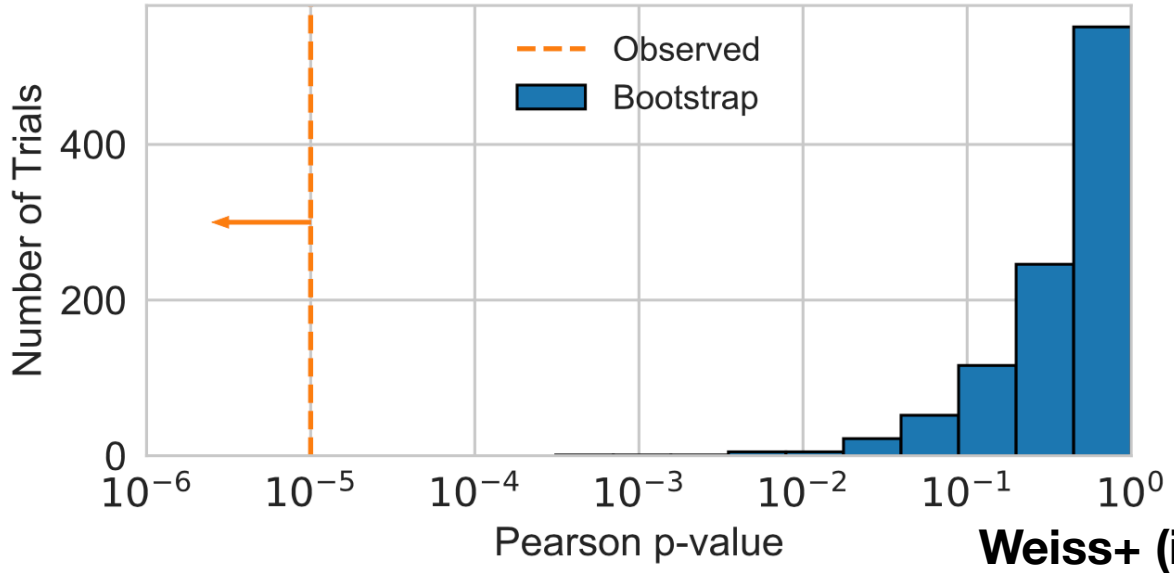
Weiss+ (in review)

One example bootstrap trial: no correlation between planet spacings



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

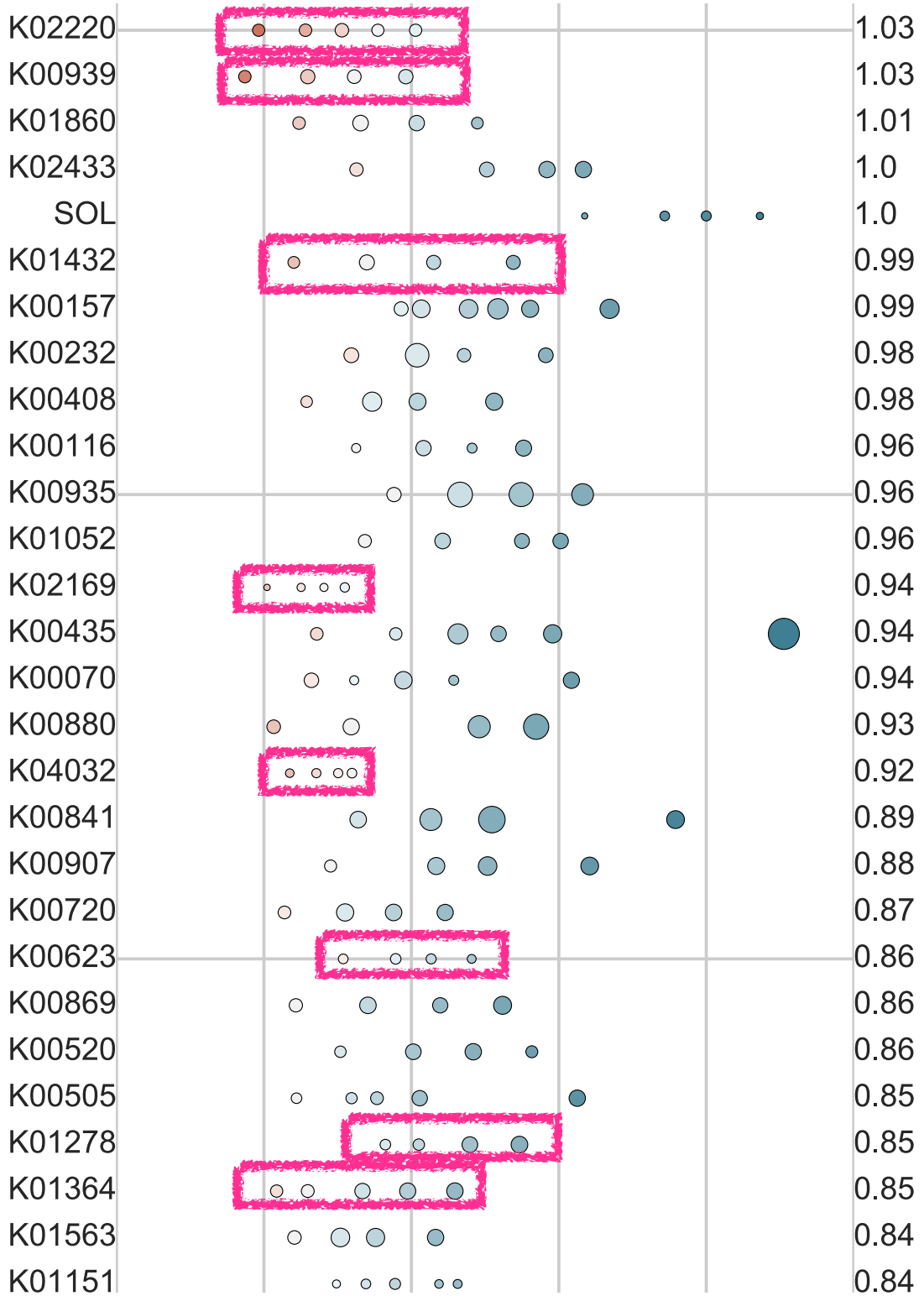




Weiss+ (in review)

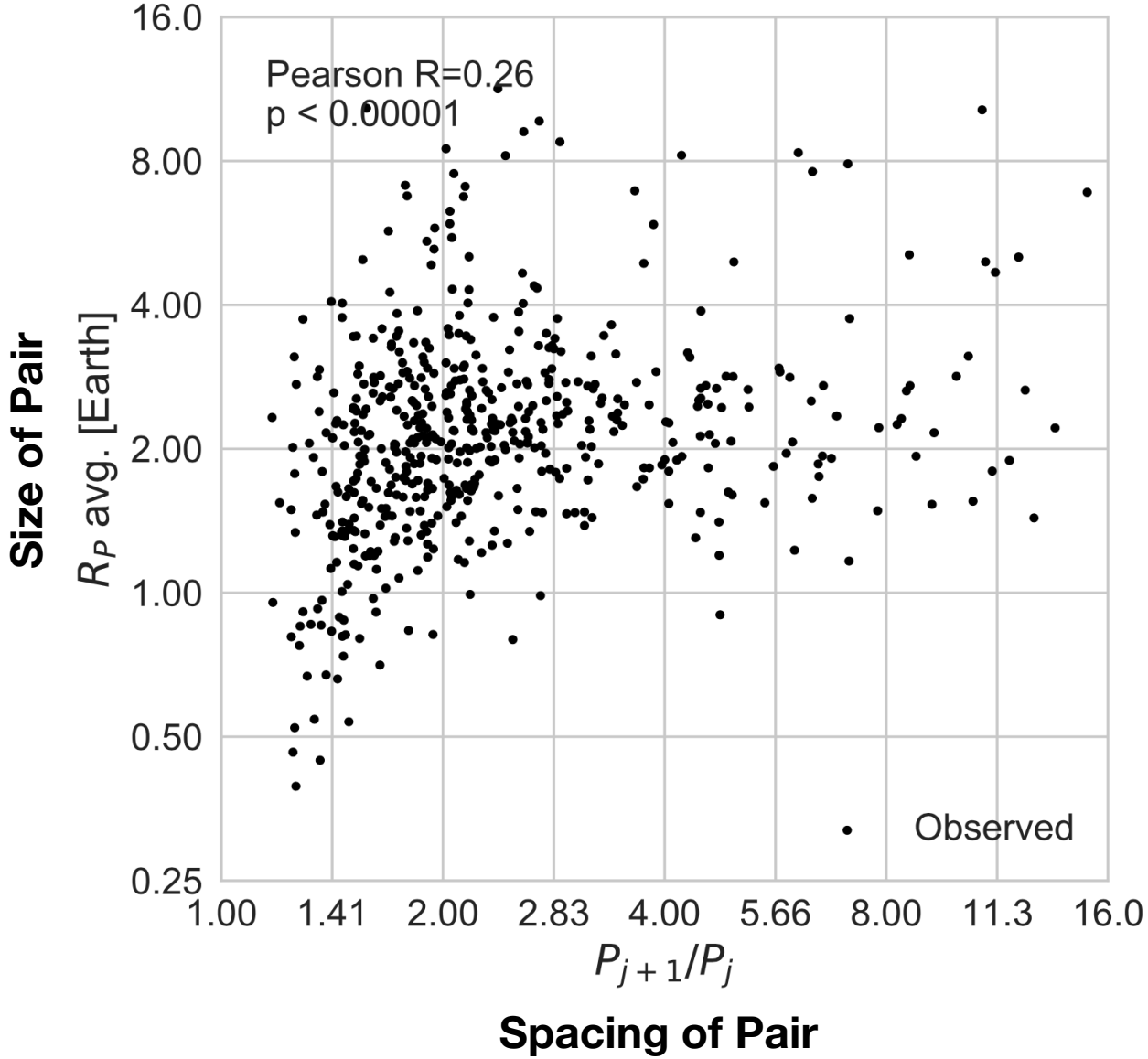
Do you see any patterns?

Is there a connection between planet size and spacing?



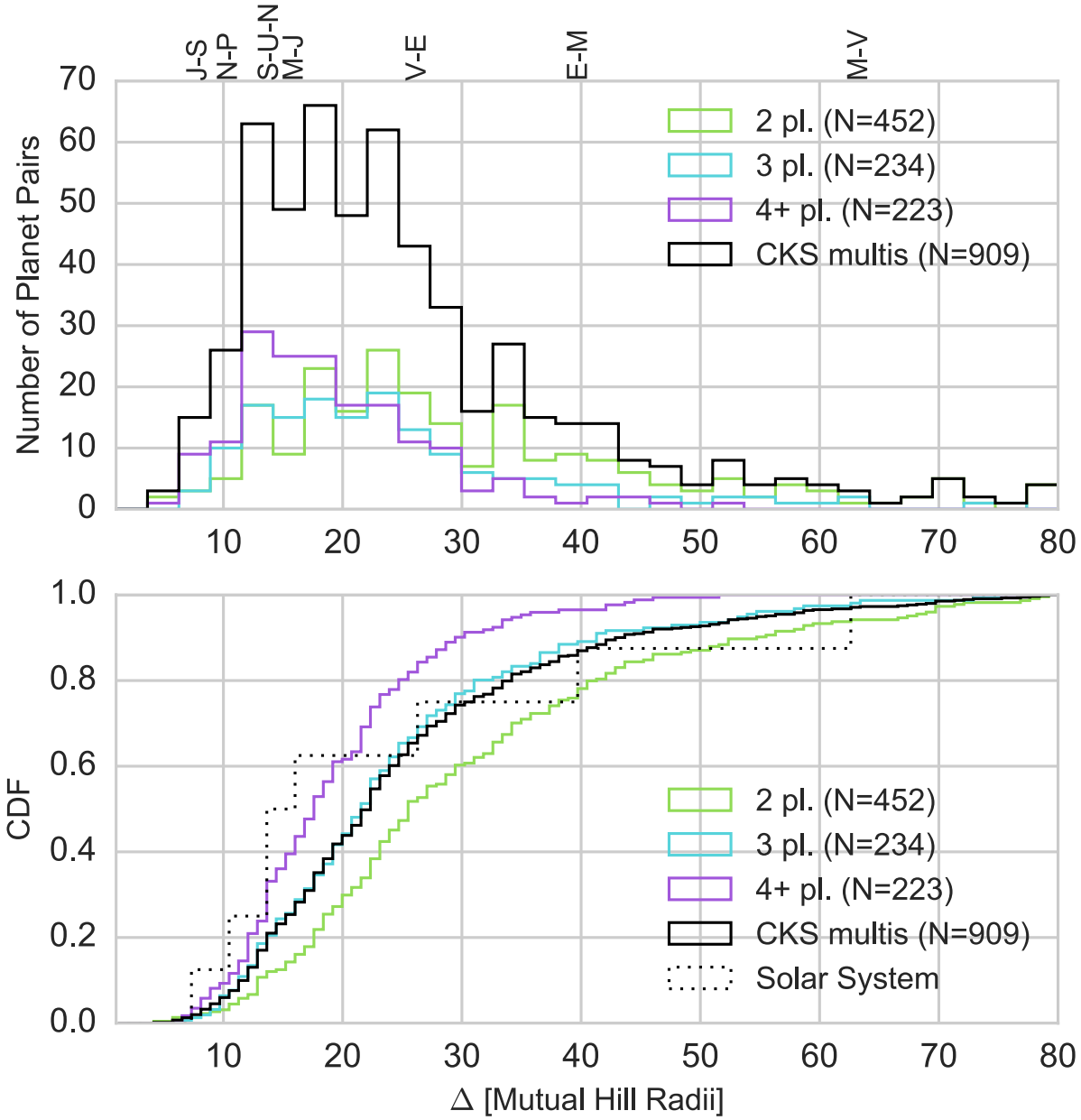
The spacing and size of a pair of planets are correlated

Is size-spacing pattern related to mutual Hill radii?



Weiss+ (in review)

Estimated mutual Hill radii for all planet pairs



Masses estimated with

- Weiss & Marcy 2014
- Weiss et al. 2013

Weiss+ (in review)

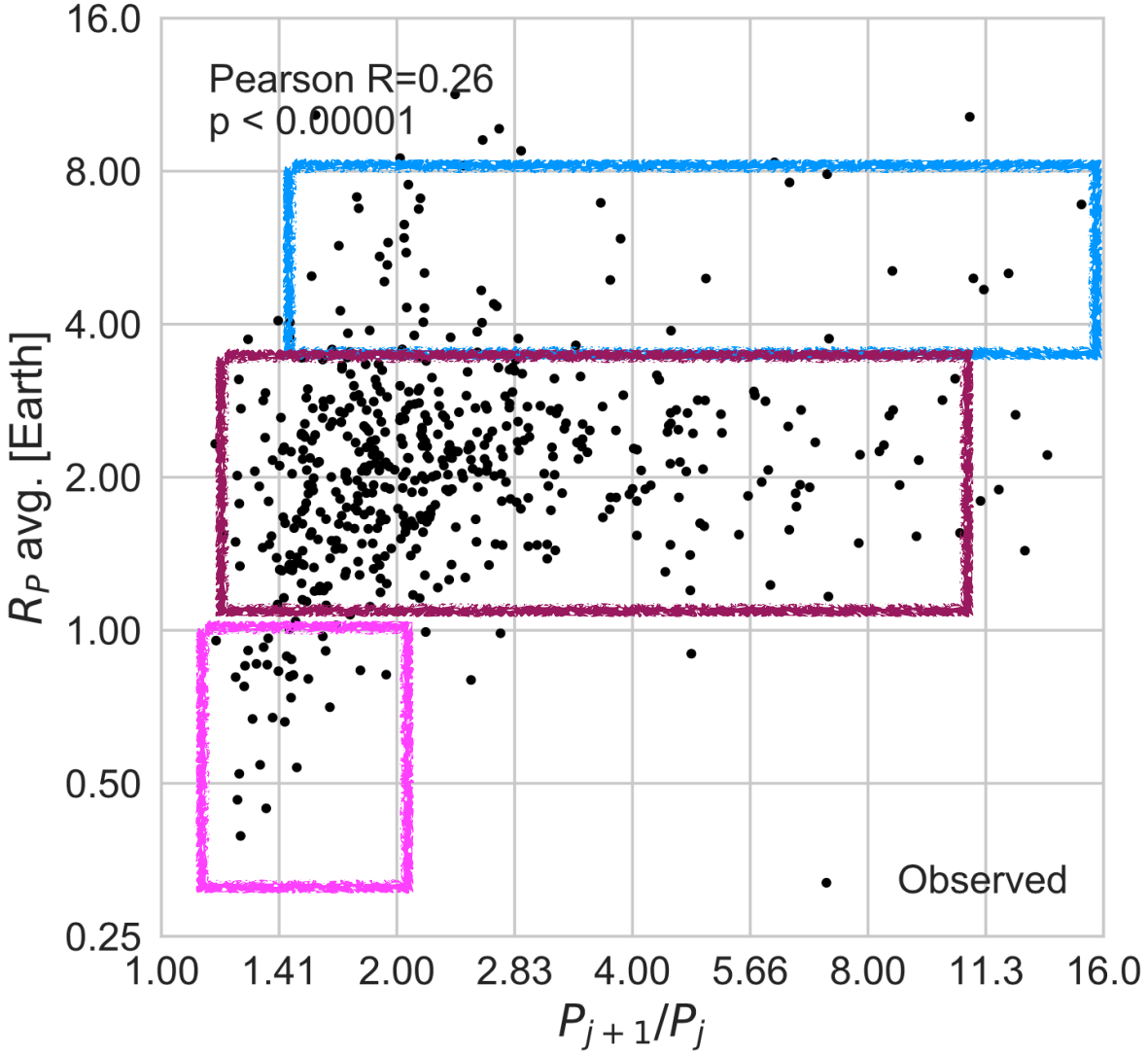
Do mutual Hill radii affect stability?

10-50 mutual Hill radii apart

10-50 mutual Hill radii apart

>20 mutual Hill radii apart

Hill instability does not affect the smallest planets



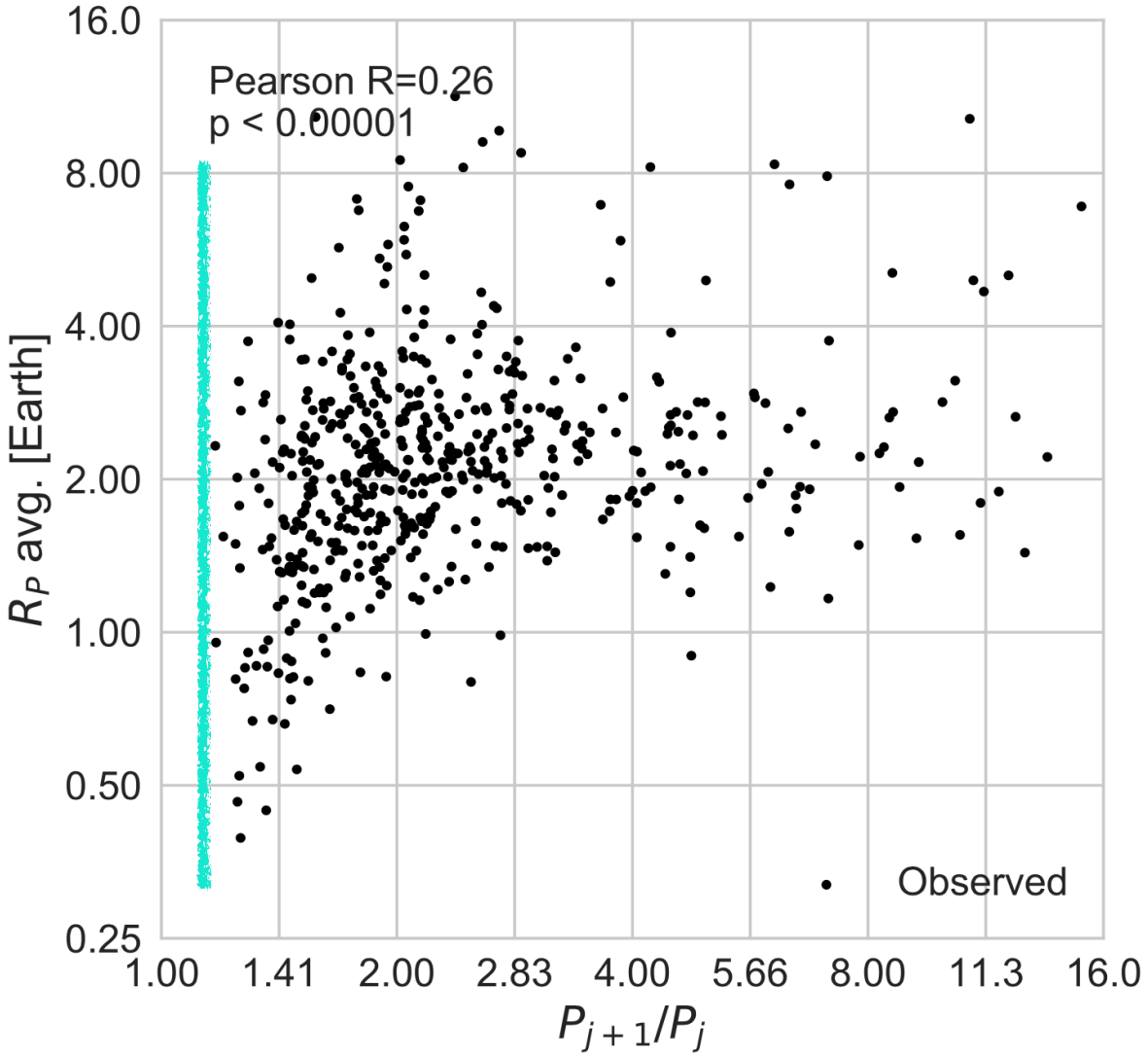
Weiss+ (in review)

How close can two planets be?

P_2/P_1 always > 1.2

Lagrange instability occurs before Hill instability for R < ~1 R_E?

(Deck+13)



Weiss+ (in review)

What do these patterns teach us about planet formation?

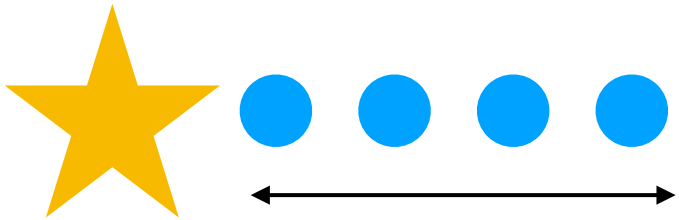
Theories of oligarchic growth

Lissauer & Stewart (1993):

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

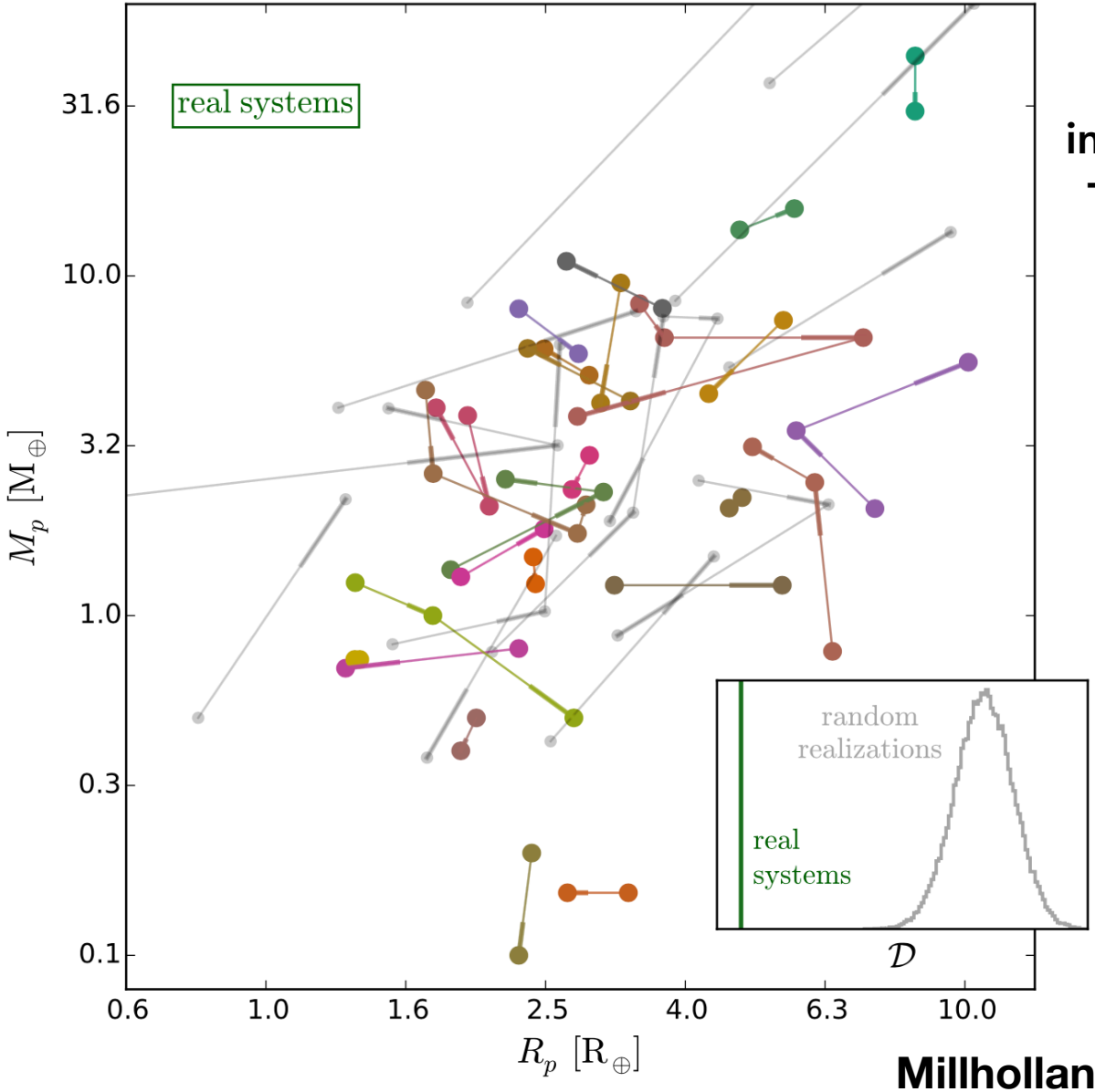
Kokuba & Ida (1998):

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?

Planets in the same system have similar sizes *and masses*

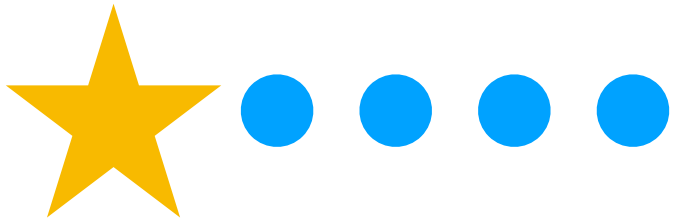


in 37 systems with TTV-determined masses

Millholland+17

Questions we have addressed

- What properties are common in multi-planet systems?



sizes

separations

masses

similar within a planetary system

- What do common properties teach us about planet formation?

Similar masses & separations were predicted in oligarchic growth