Are planetary systems like “peas in a pod”?

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Tsinghua Astro Student Seminar

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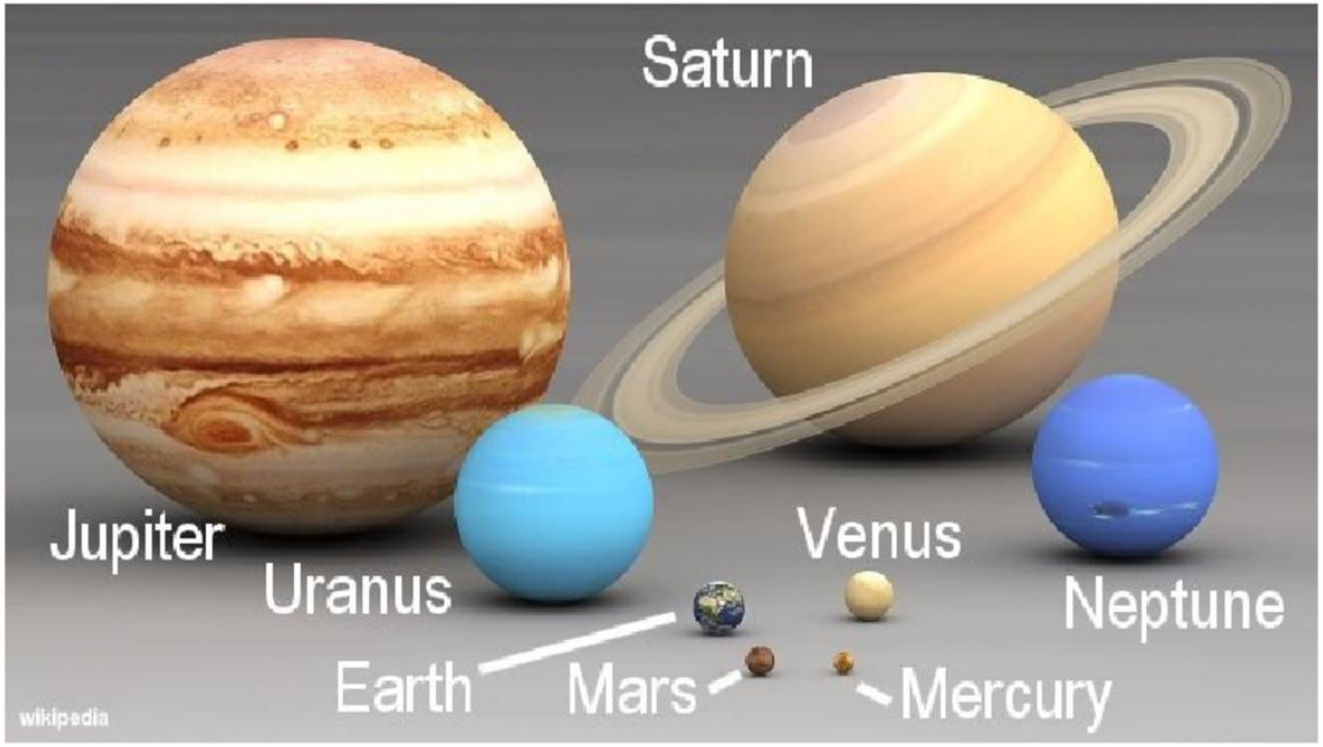
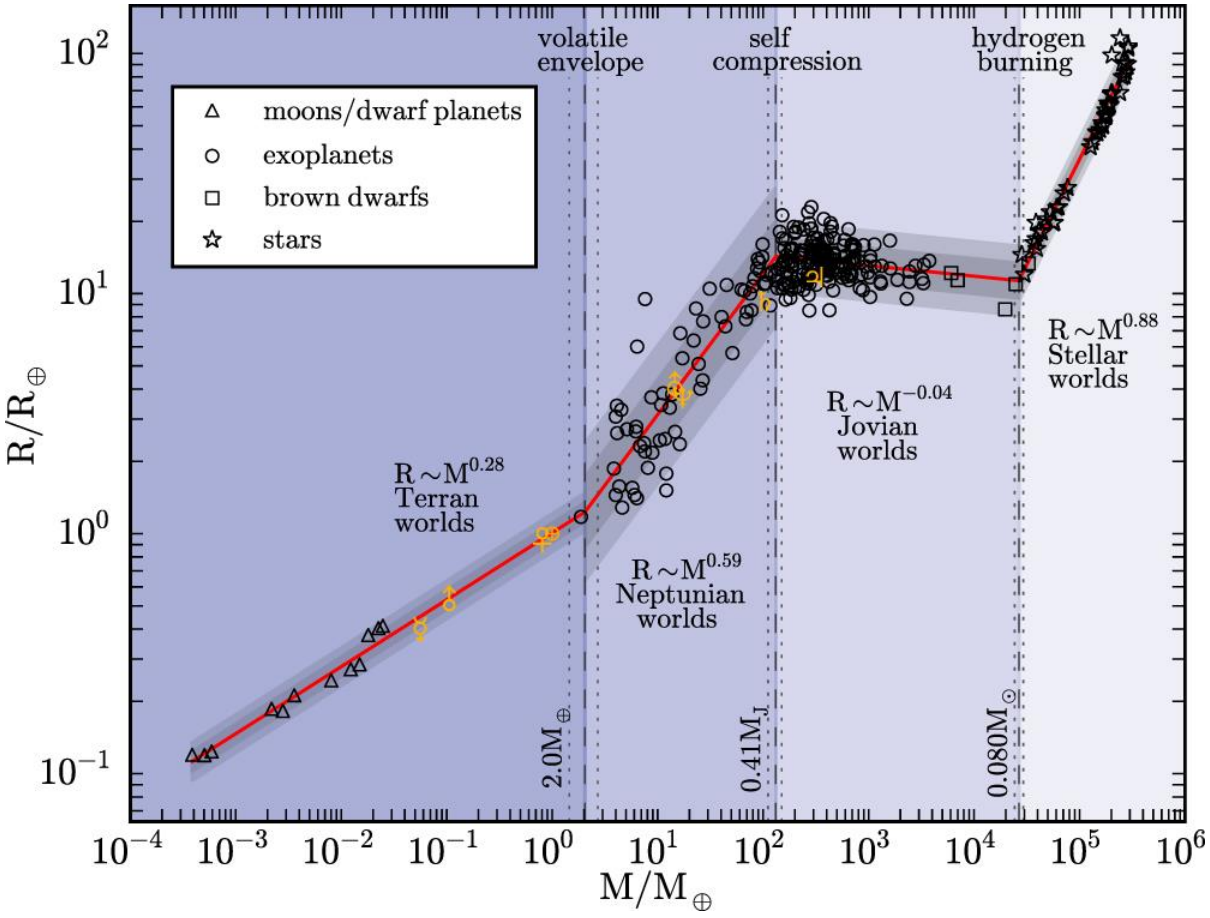
Outline

- “Peas in a pod” in Kepler multi-planet systems
- Potential observational bias(es)
- Summary

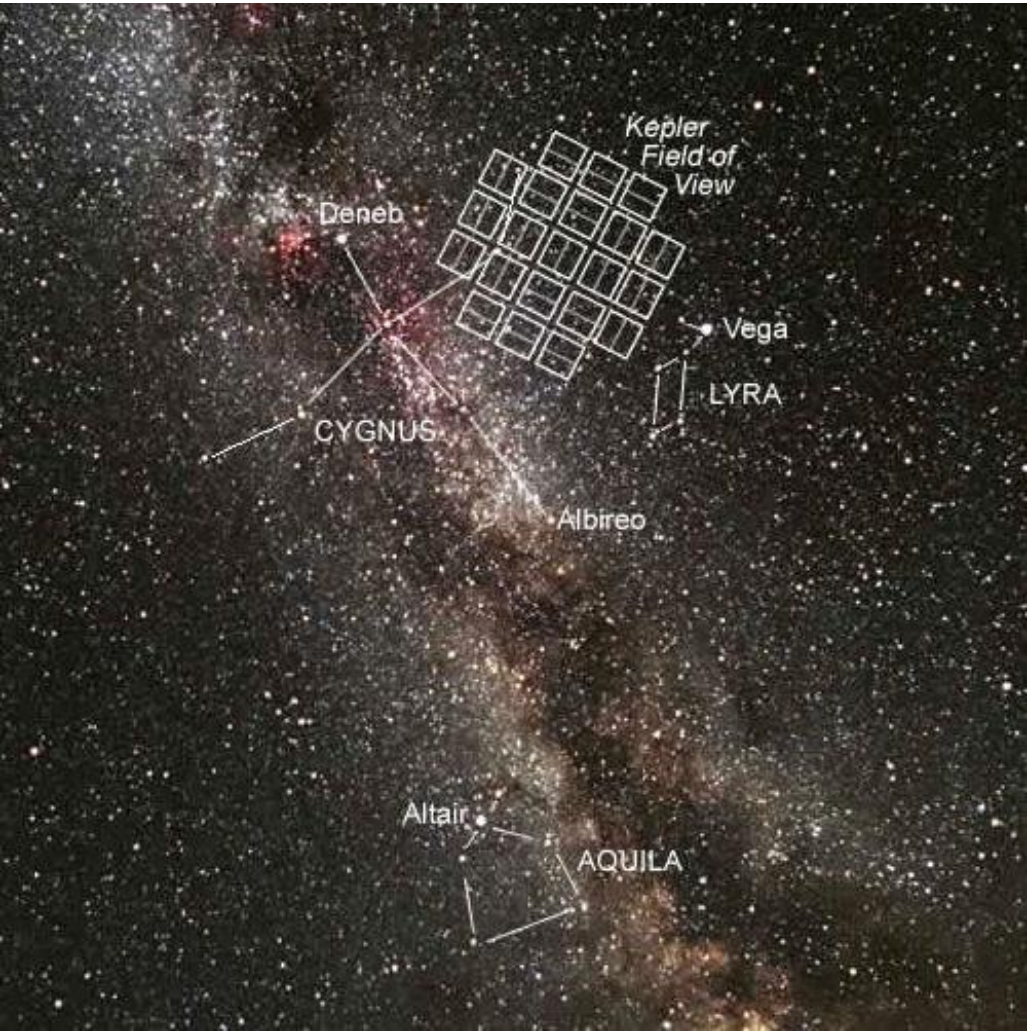
Solar system diversity

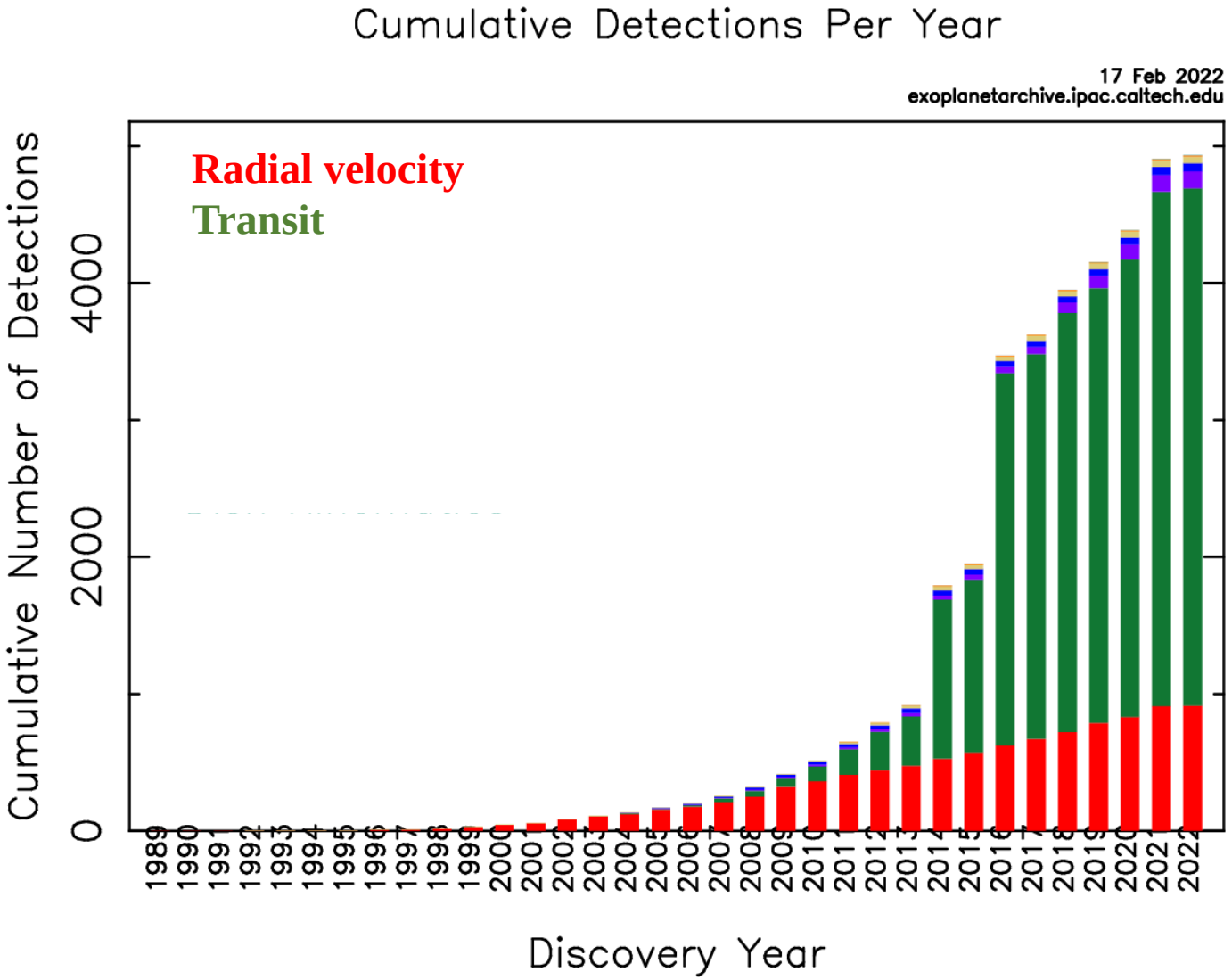


Chen & Kipping (2017)



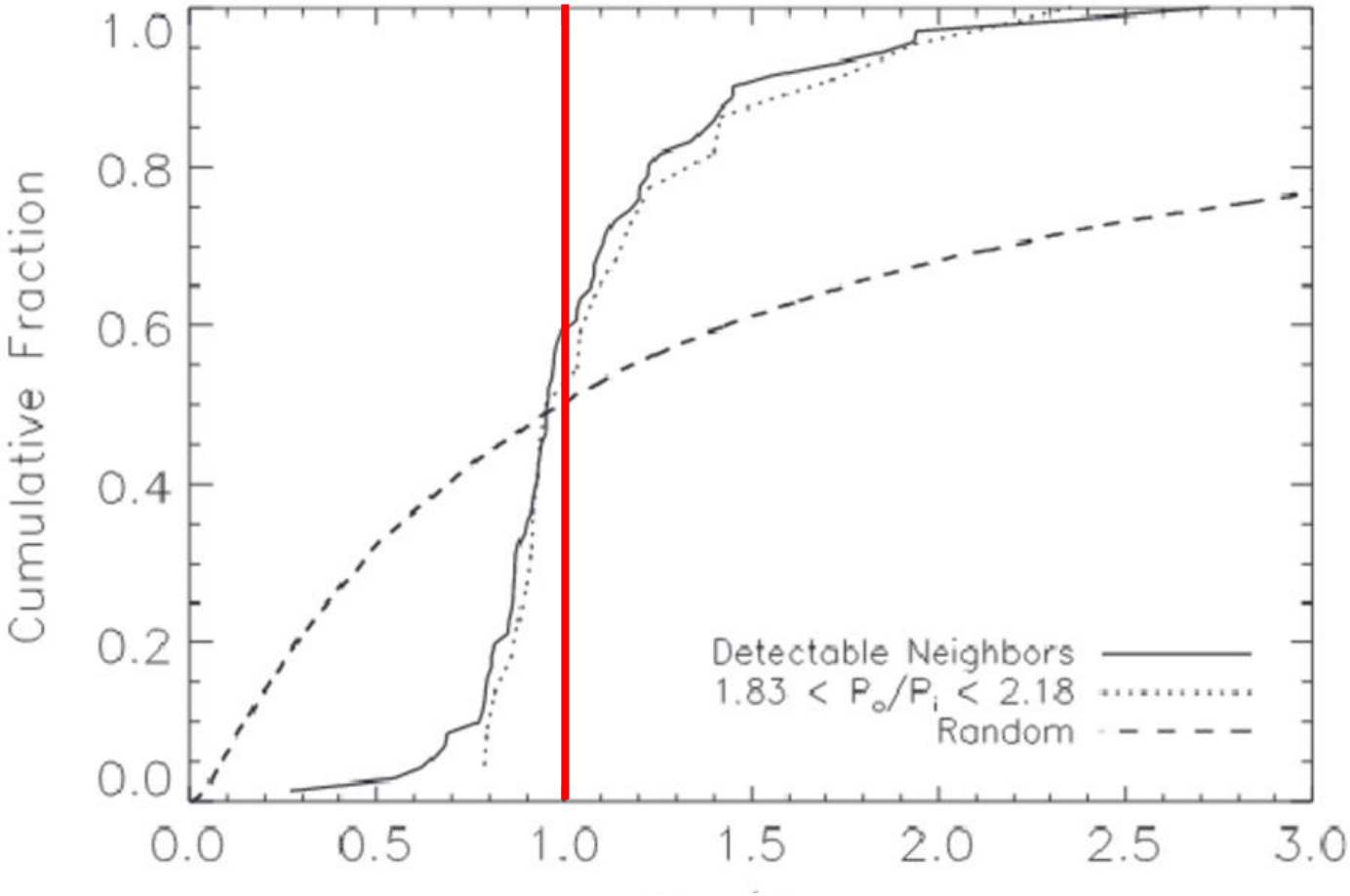
Kepler's revolution

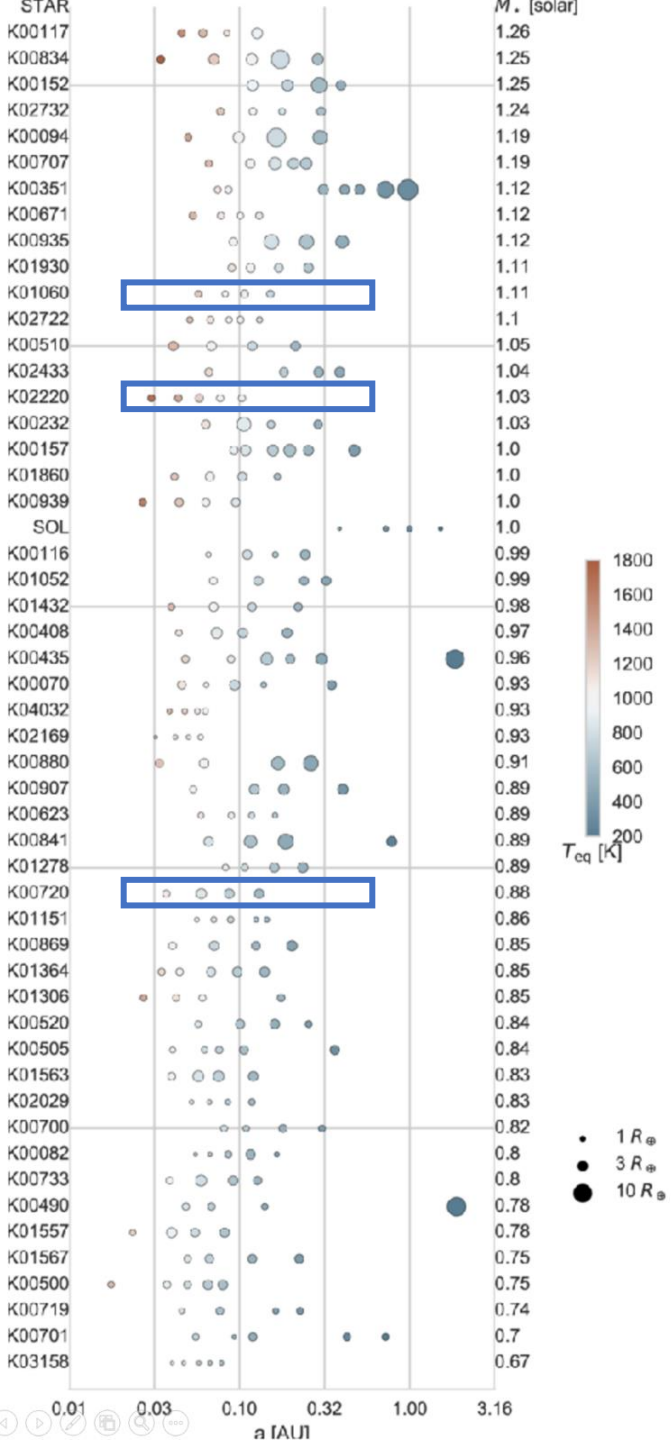




Similar sizes in Kepler planets?

- Transit detects planet-to-star radius ratio.
- Adjacent Kepler planets tend to have similar sizes (Lissauer et al. 2011, Ciardi et al. 2012).

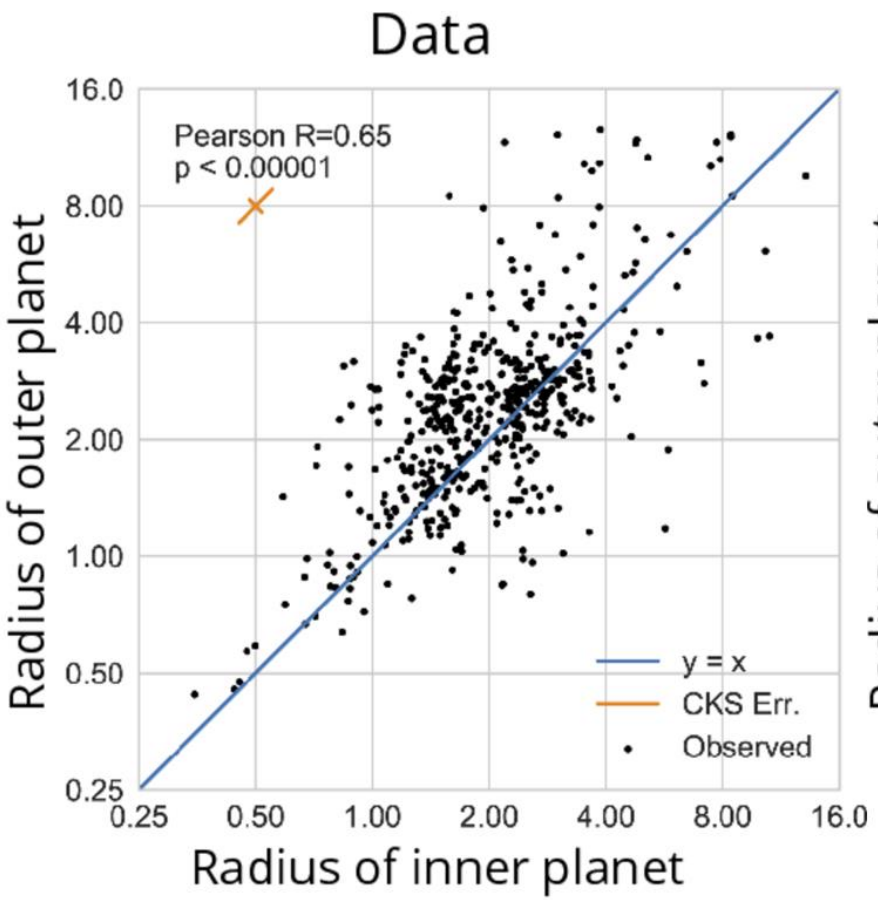


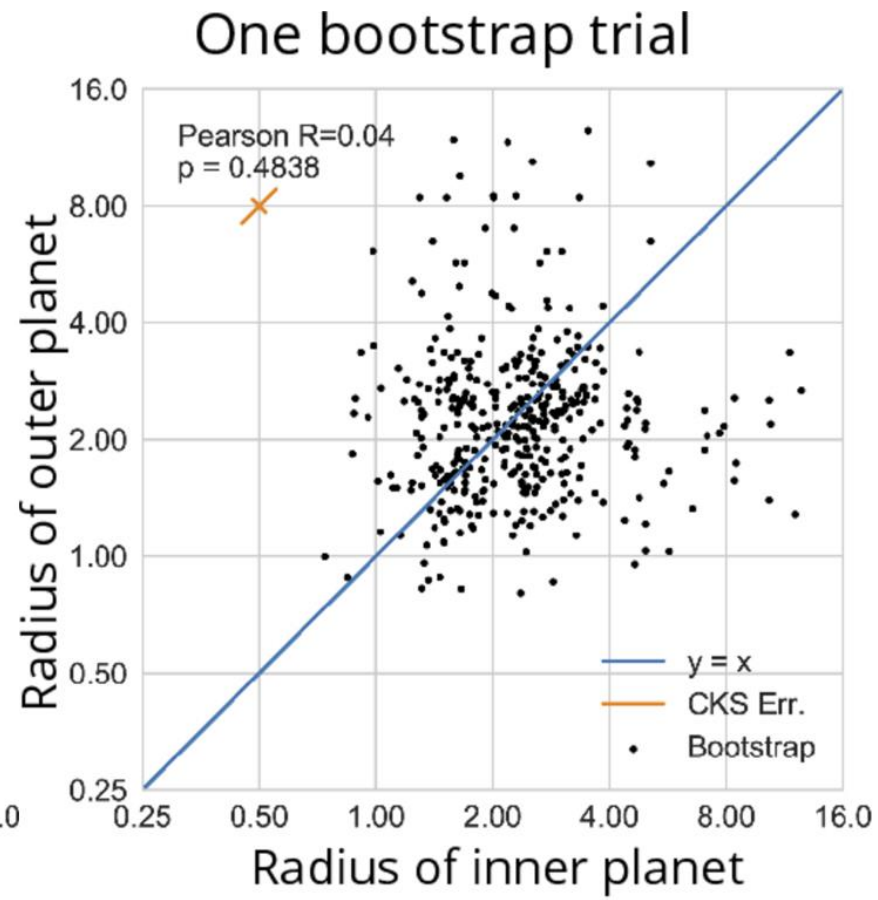


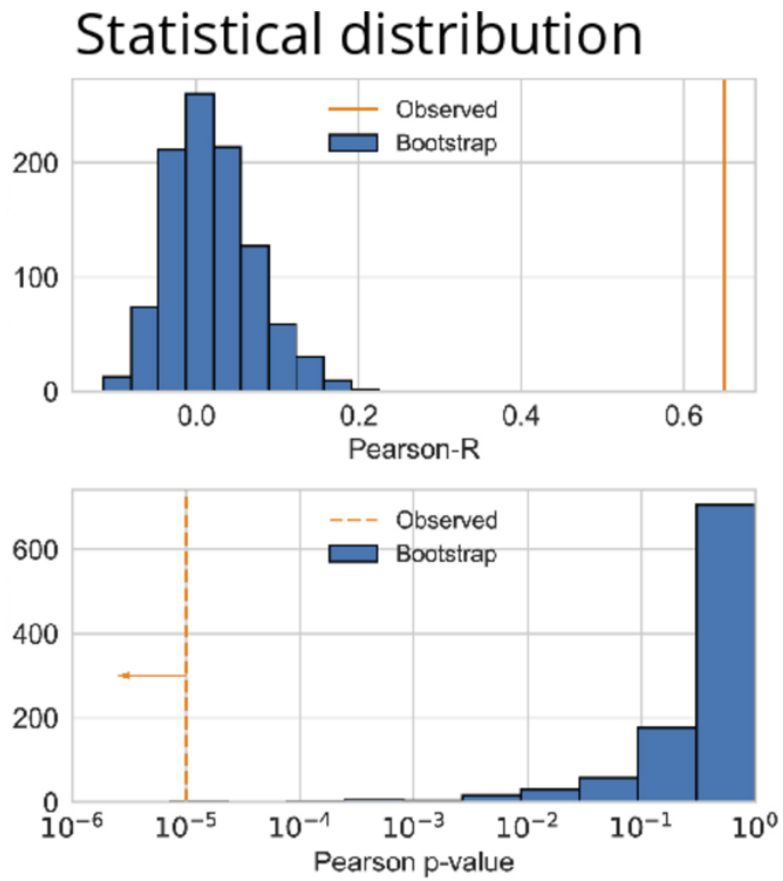
Peas in a pod?

- Planets in a Kepler multi-planet system are similar in size and regularly spaced (Weiss et al. 2018, Weiss & Petigura 2020).
  - Also Millholland et al. (2017), He et al. (2020), etc.

Quantifying the detection significance







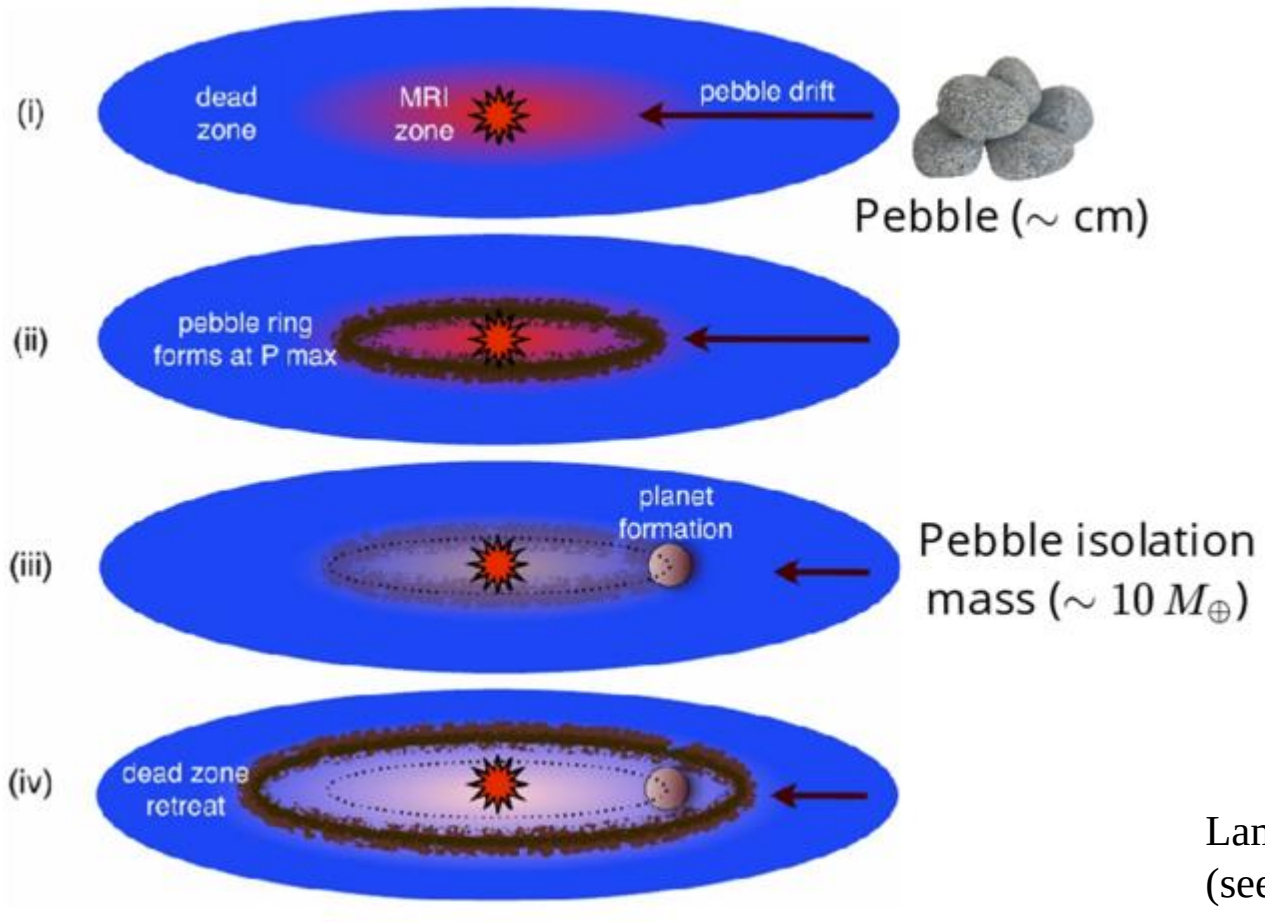
Figures from Weiss et al. (2018)

What the size correlation means?

- Planets “know” about each other.
- Planets “know” about the system they formed in.
- Planets “know” nothing.

Murchikova & Tremaine (2020)

“Peas in a pod” pattern has important implications to theoretical models.

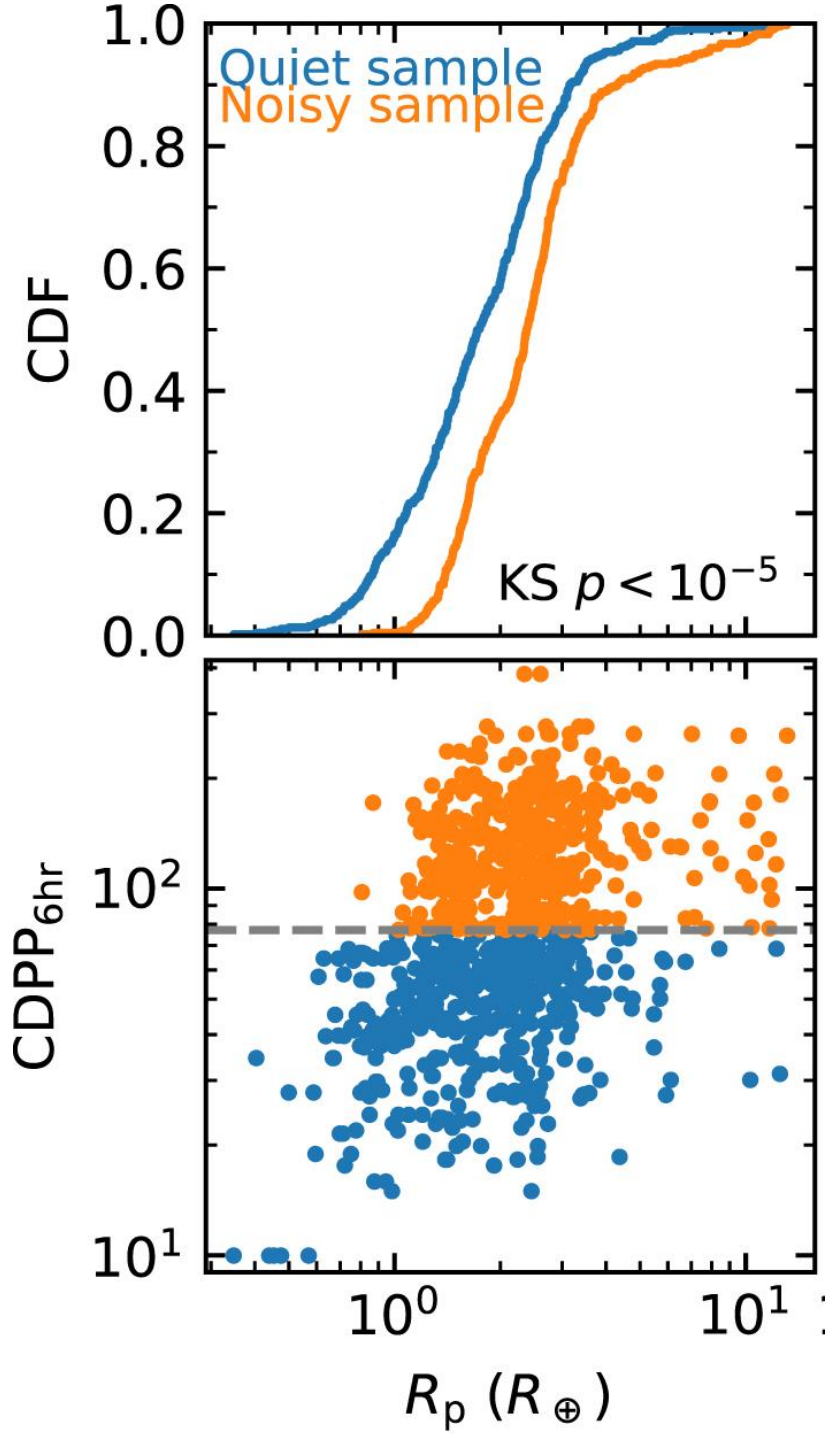


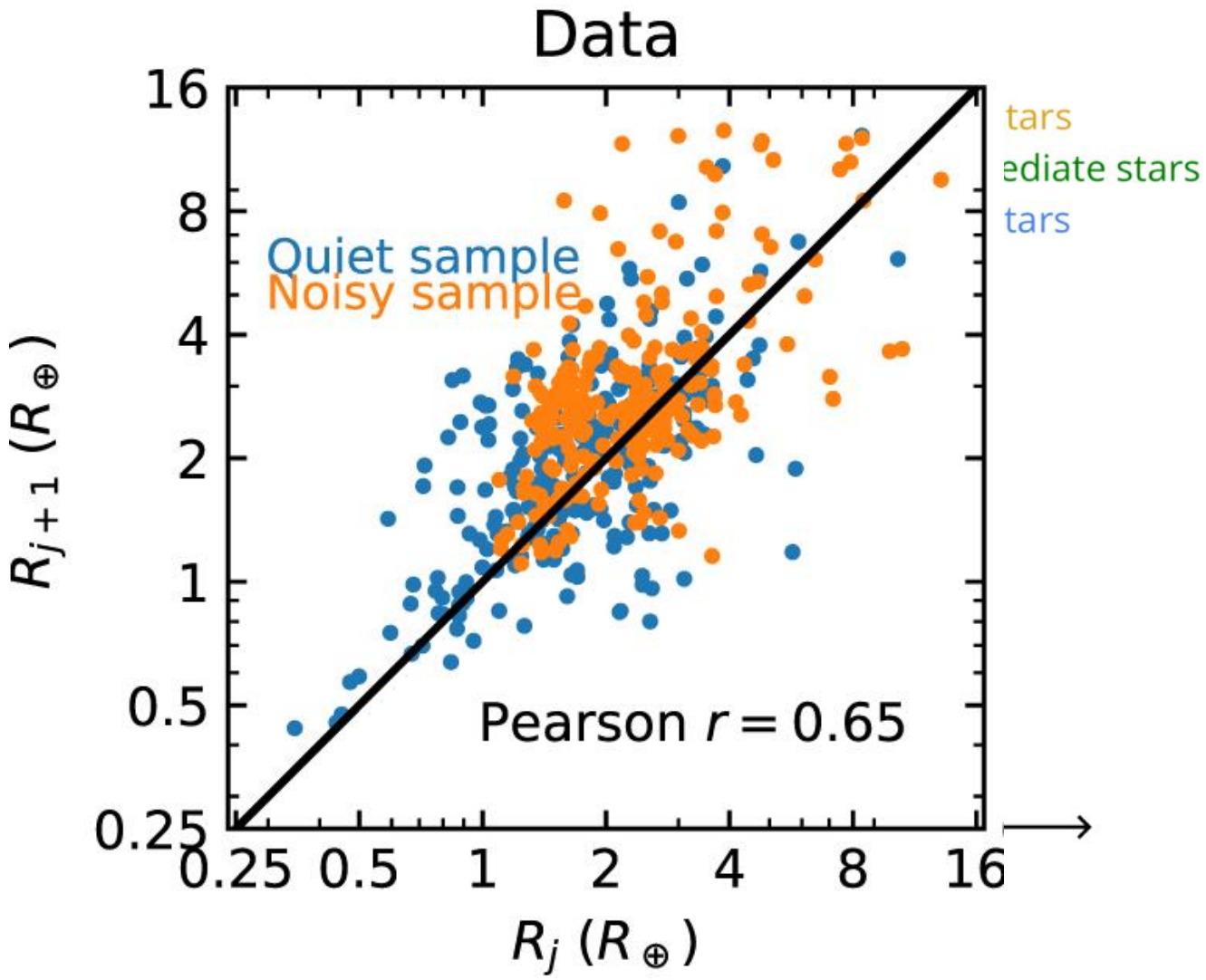
Lambrechts et al. (2014); Liu et al. (2019)
(see Ormel 2017 for a review)

Take-home message

Planets in *Kepler* multi-planet systems appear similar in size, but this “peas in a pod” pattern may just be the consequence of several observational biases.

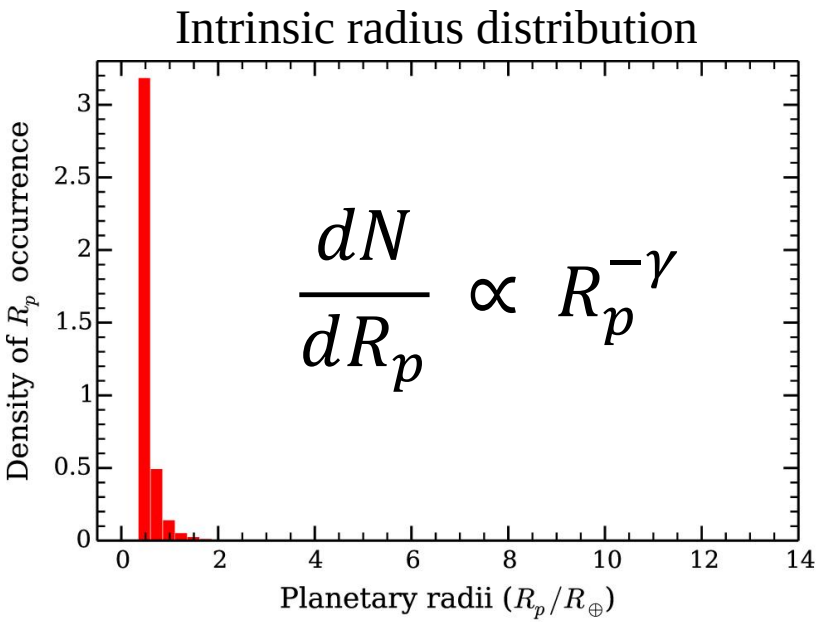
Detection threshold variation

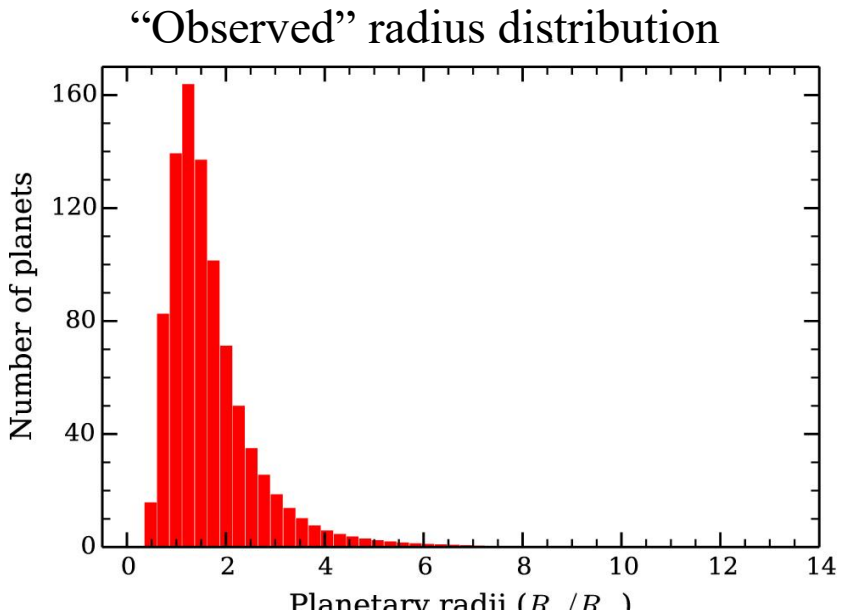


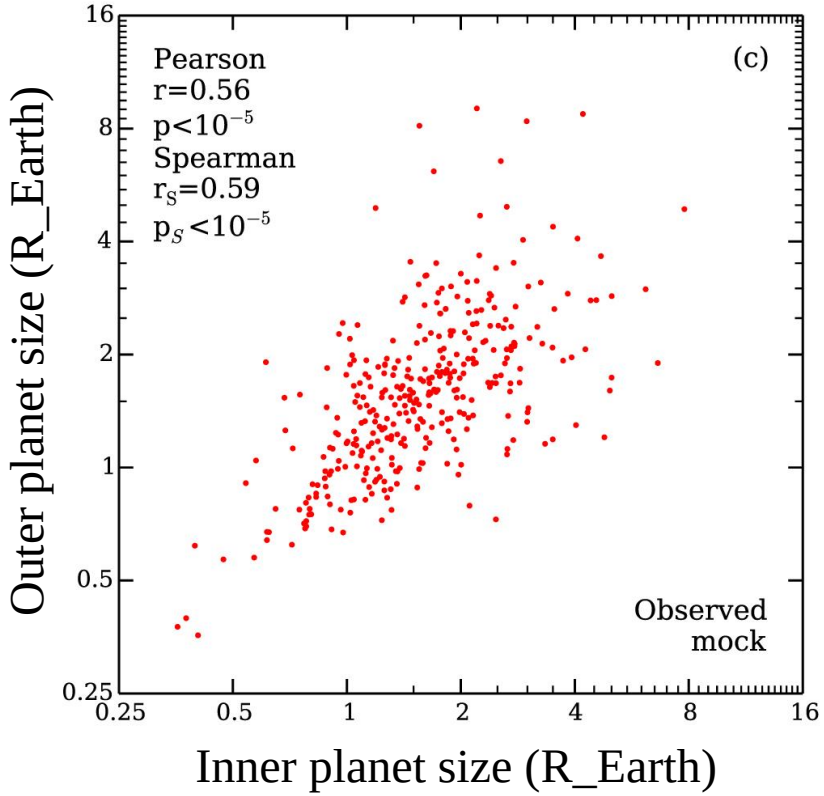


Zhu (2020)

Reproducing the observed size correlation



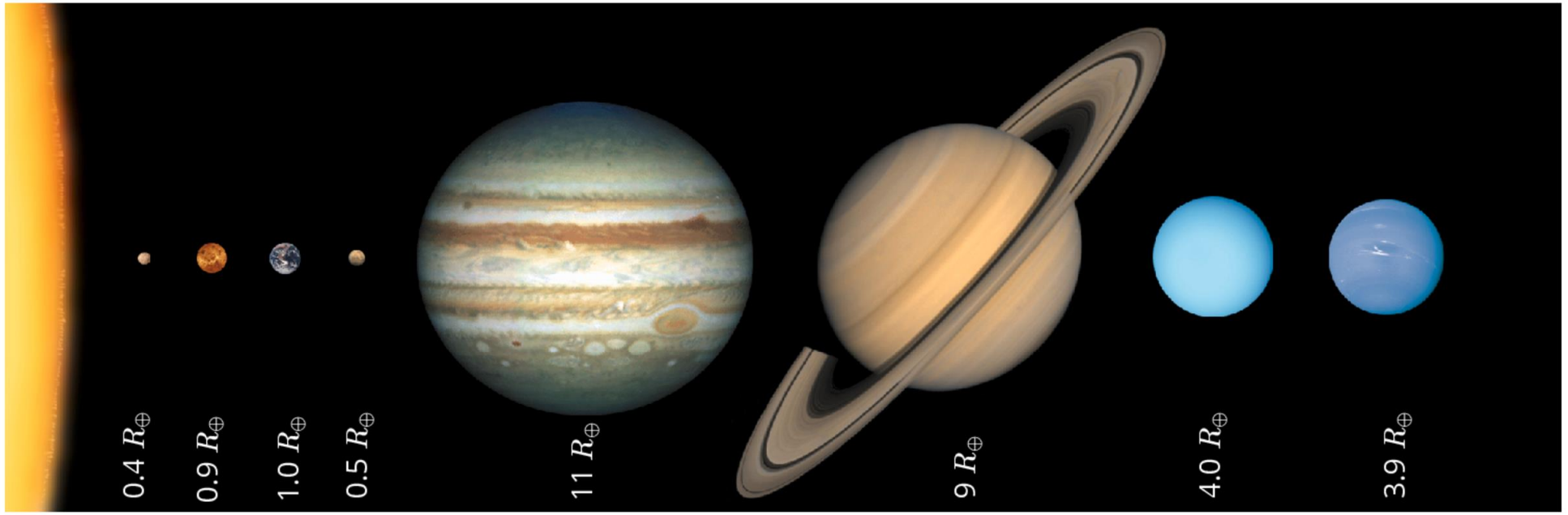




Murchikova & Tremaine (2020), Zhu (2020)

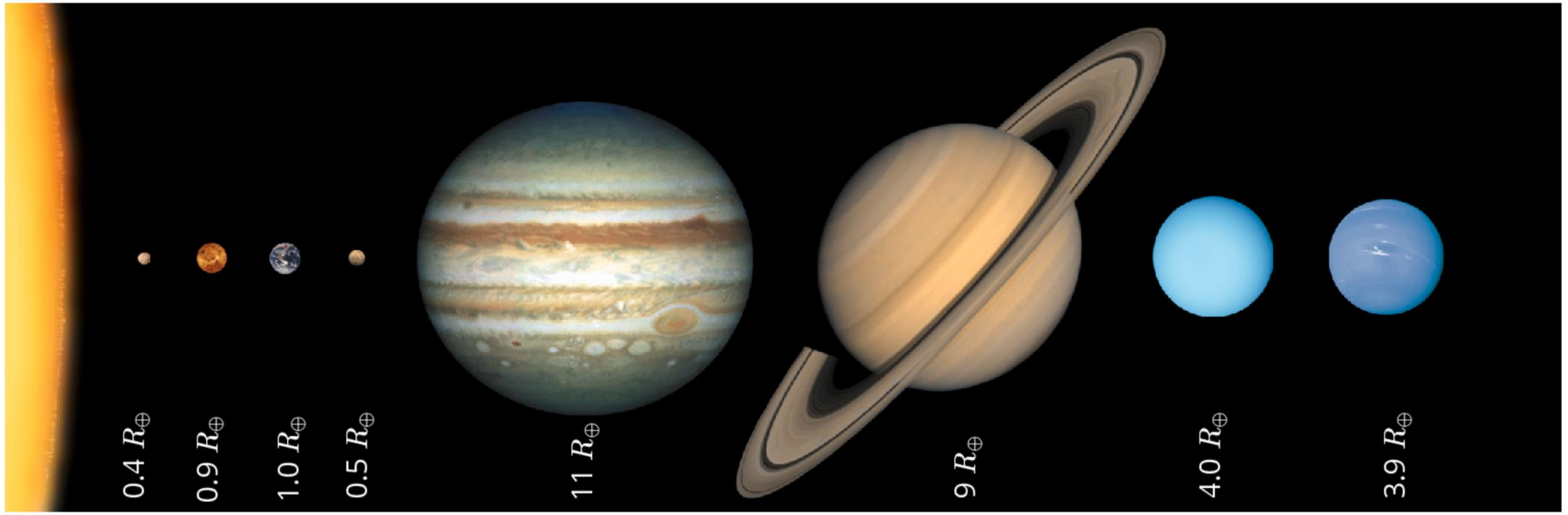
- Variation in detection threshold produces size correlation in pairs of adjacent planets.
- **However, the required size distribution is very steep (r=4).**

Do solar system planets show “peas in a pod”?



Do solar system planets show “peas in a pod”?

- *No*, if knowing all planets



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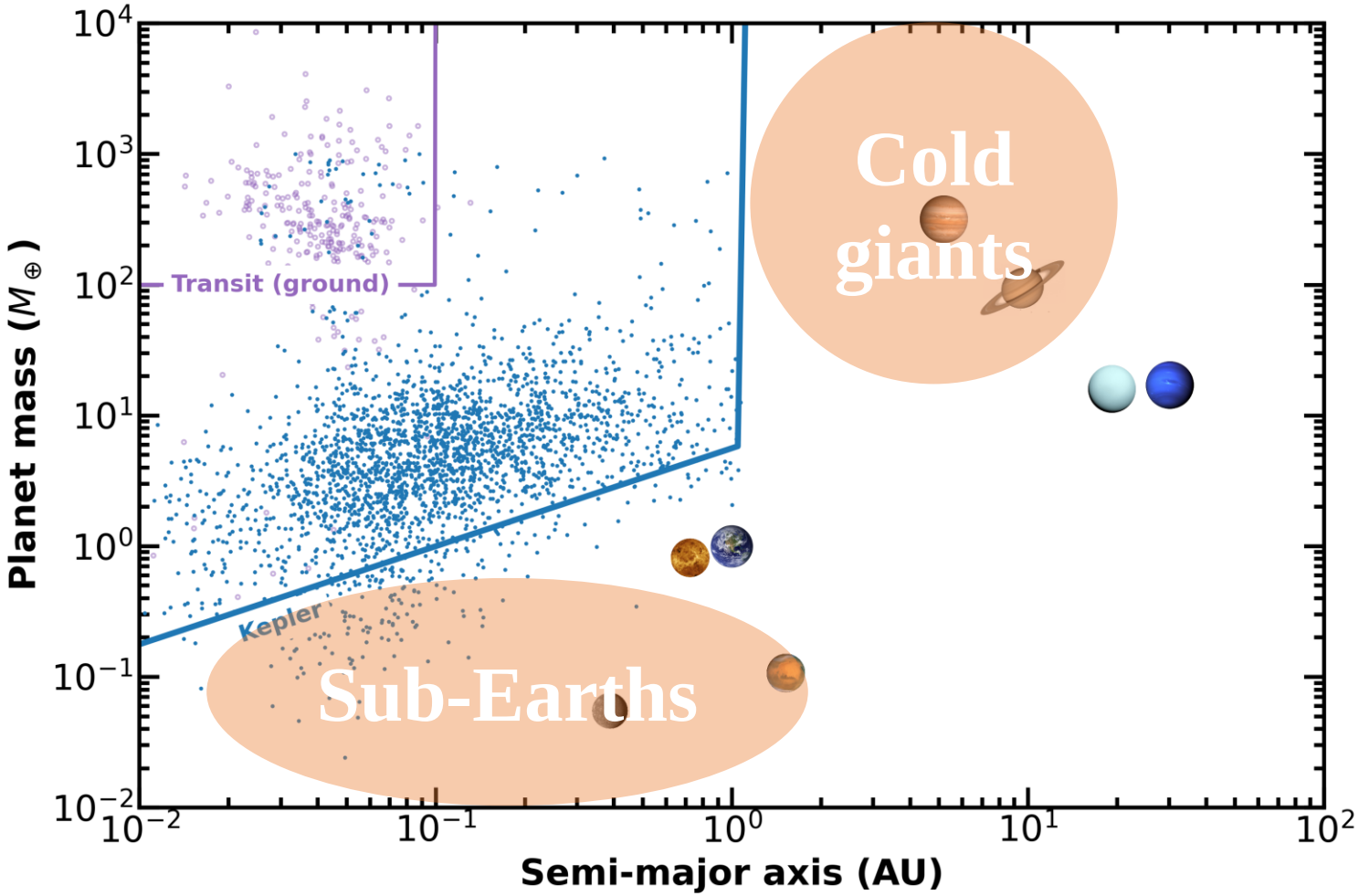
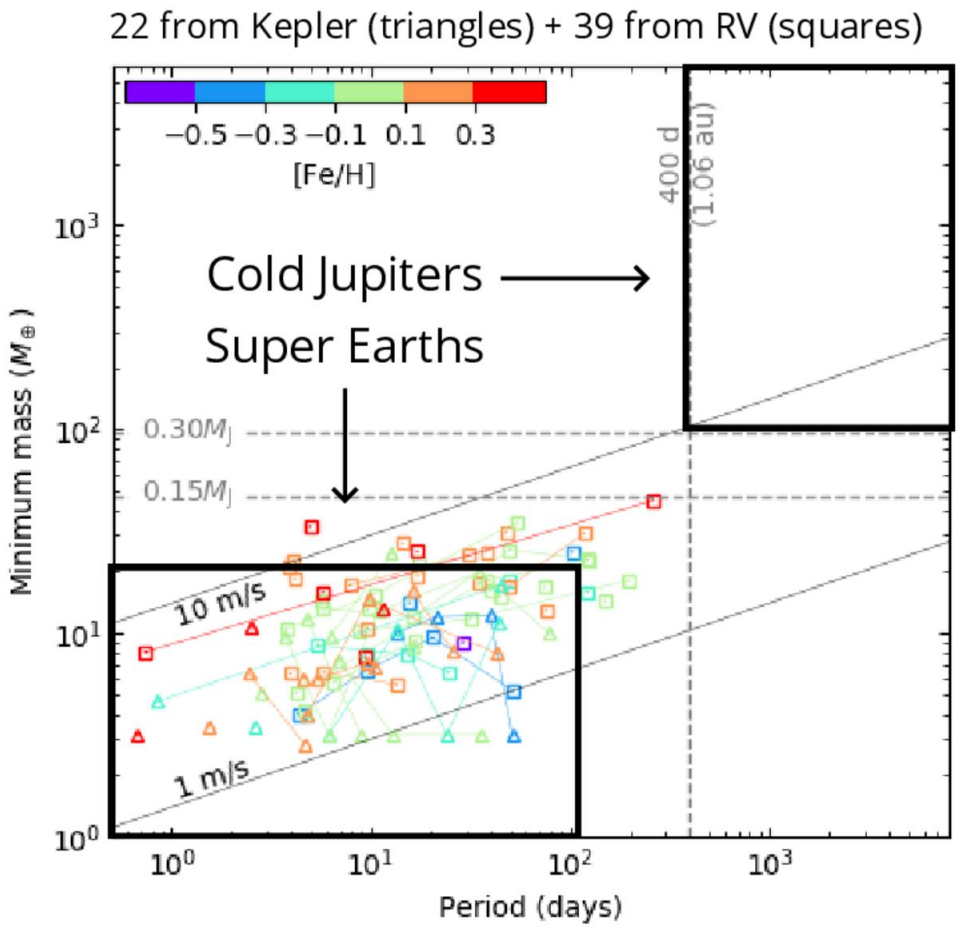
- **Giant planets** are not observable: orbital period too long
- **Mercury** & **Mars** undetectable: too small
- *Yes*, if only Venus & Earth are seen

Solar system in eyes of Kepler



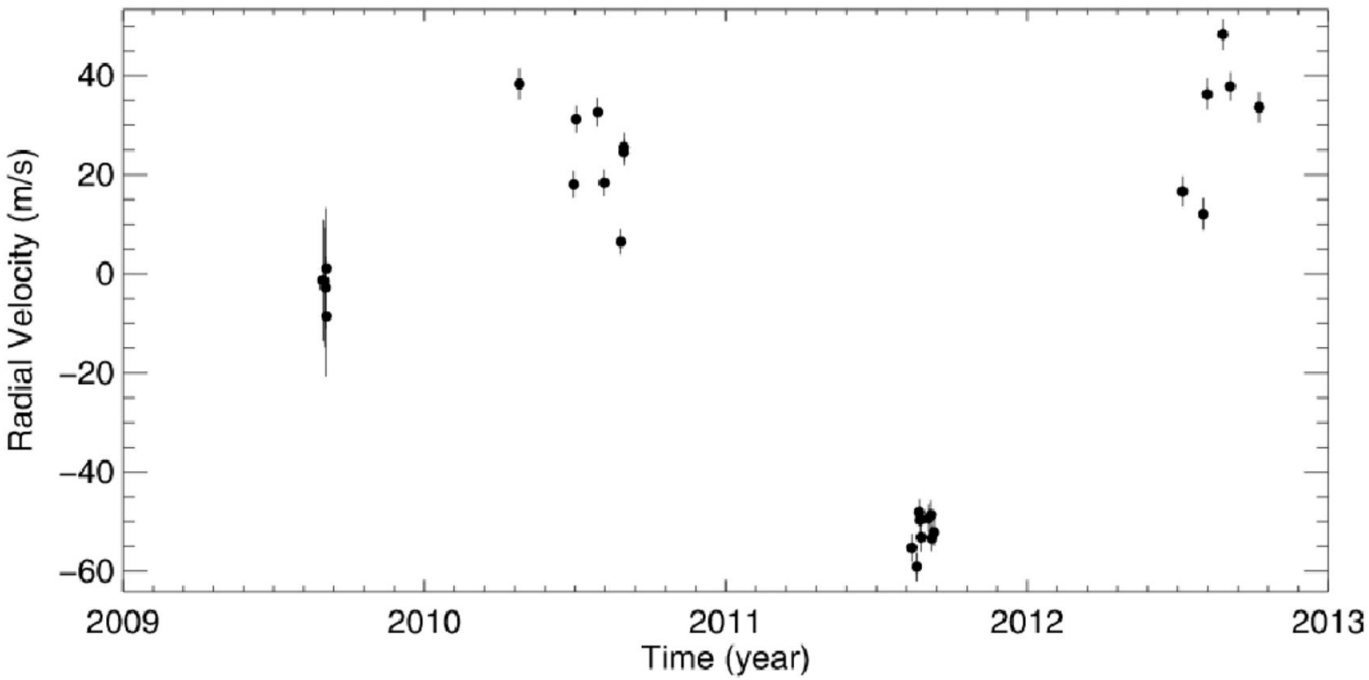
Hidden giants in Kepler-like systems



Zhu & Wu, 2018, AJ, 156, 92

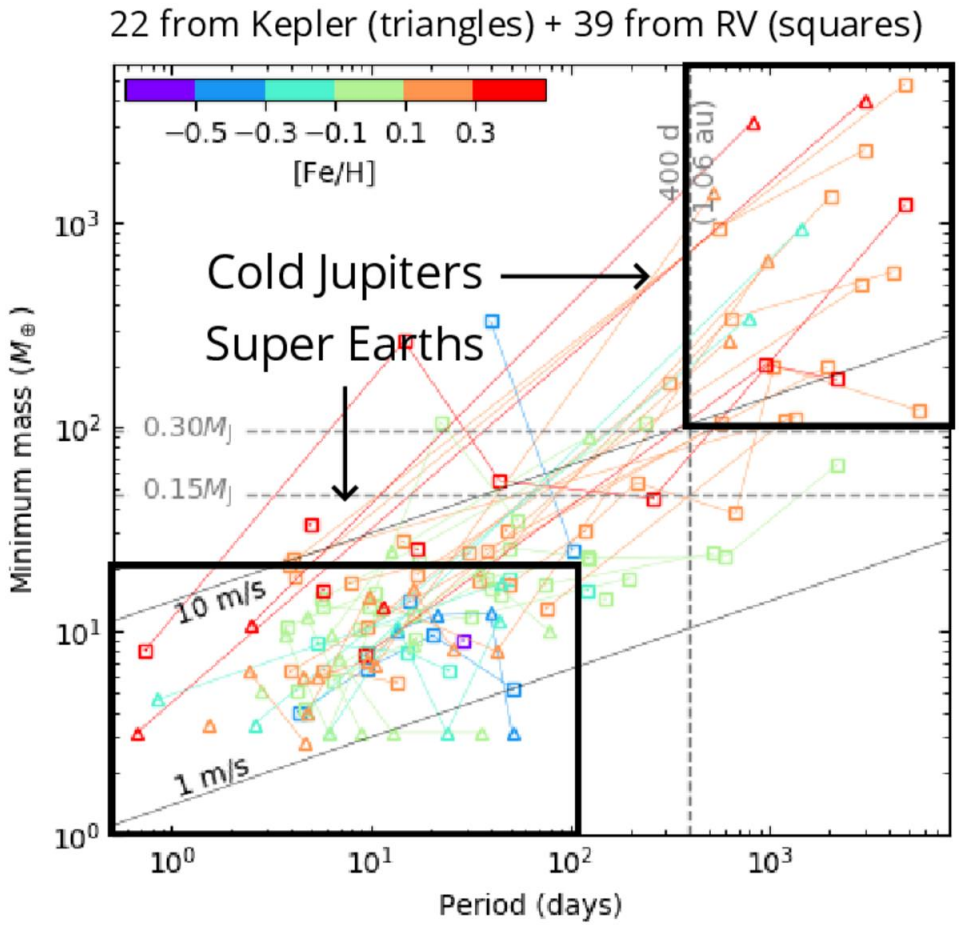
(see also Bryan et al. 2019, Herman, Zhu, & Wu 2019)

Kepler-48 as an example



Marcy et al. (2014)

Hidden giants in Kepler-like systems



$$P(\mathrm{CJ}|\mathrm{SE}) \approx 33\% \text{ vs. } P(\mathrm{CJ}) = 10\%$$

- **1/3 of Kepler systems have cold Jupiter companions.**
  - >50%, if [Fe/H]>0.

Zhu & Wu, 2018, AJ, 156, 92

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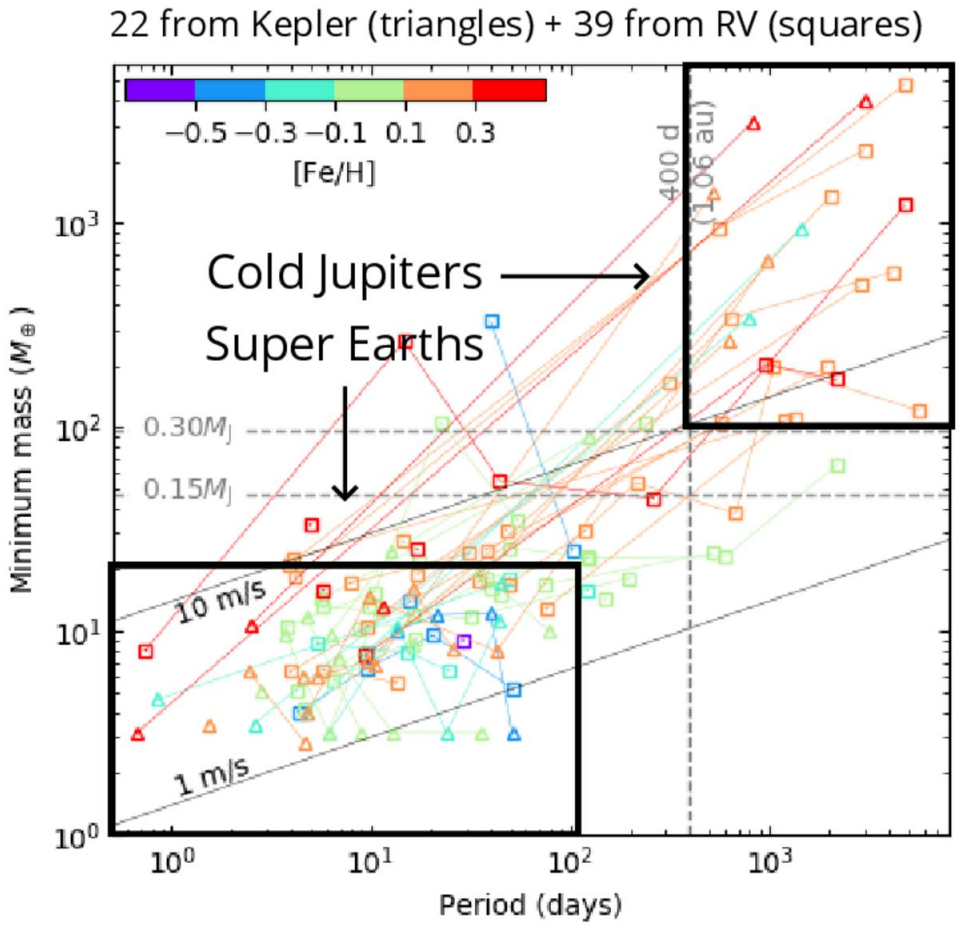

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$$P(\mathrm{SE}|\mathrm{CJ}) \cdot P(\mathrm{CJ}) = P(\mathrm{CJ}|\mathrm{SE}) \cdot P(\mathrm{SE})$$

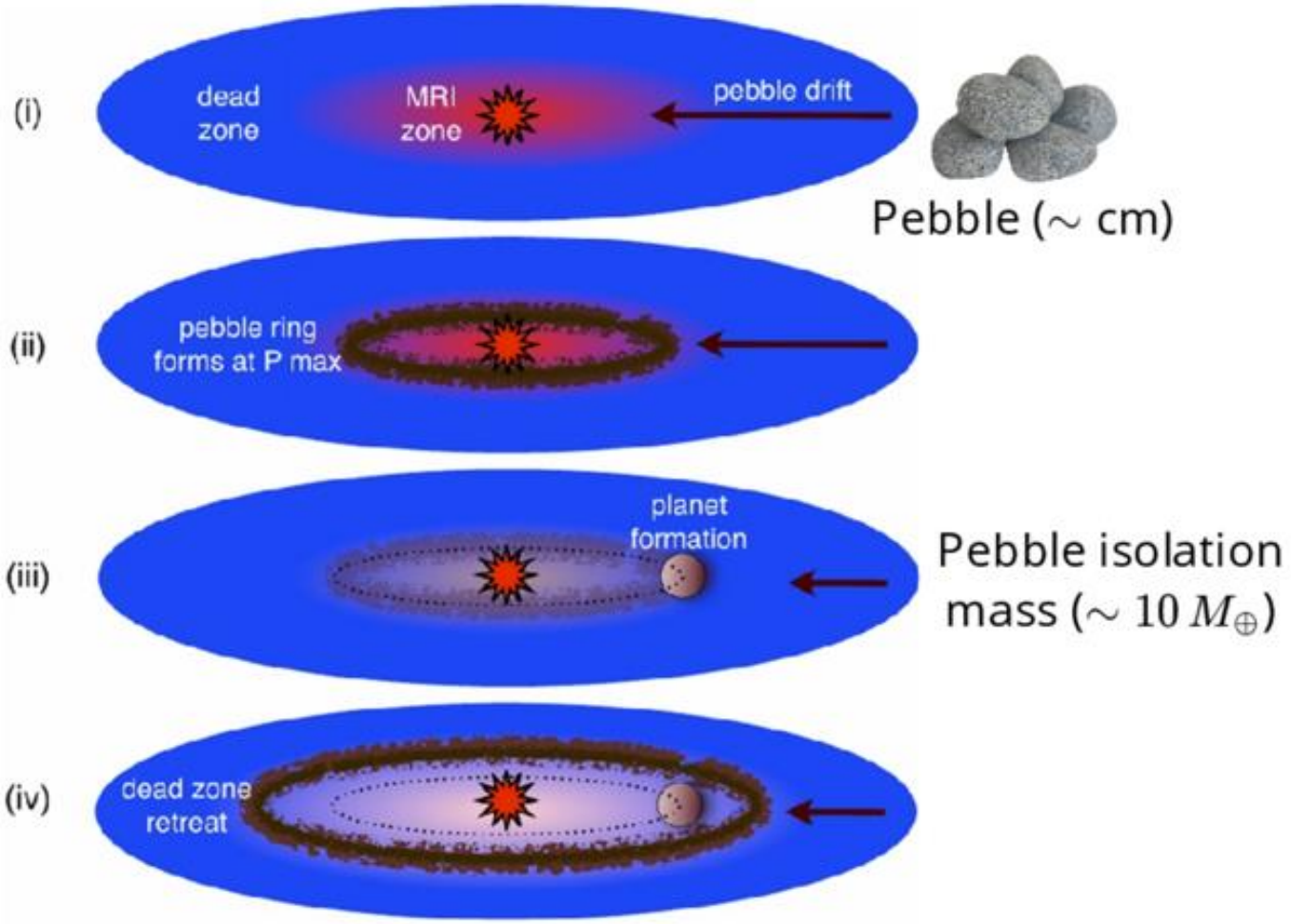
$$\rightarrow P(\mathrm{SE}|\mathrm{CJ}) = 100\%$$

- **Cold Jupiters (almost) always have inner super Earth companions!**

Zhu & Wu, 2018, AJ, 156, 92

(see also Bryan et al. 2019, Herman, Zhu, & Wu 2019)

Coexisting giant planets: theoretical implications



Summary

- **Multi-planet systems from Kepler show “peas in a pod” pattern.**
  - In Kepler’s eyes, so does Solar system.
  - Implications to theoretical models (e.g., pebble accretion).
- **Variation of detection threshold leads to size correlation.**
  - Steep size distribution is required.
- **Kepler systems contain distant giant planets and, possibly, close-in tiny planets.**
  - A Solar system-like architecture?