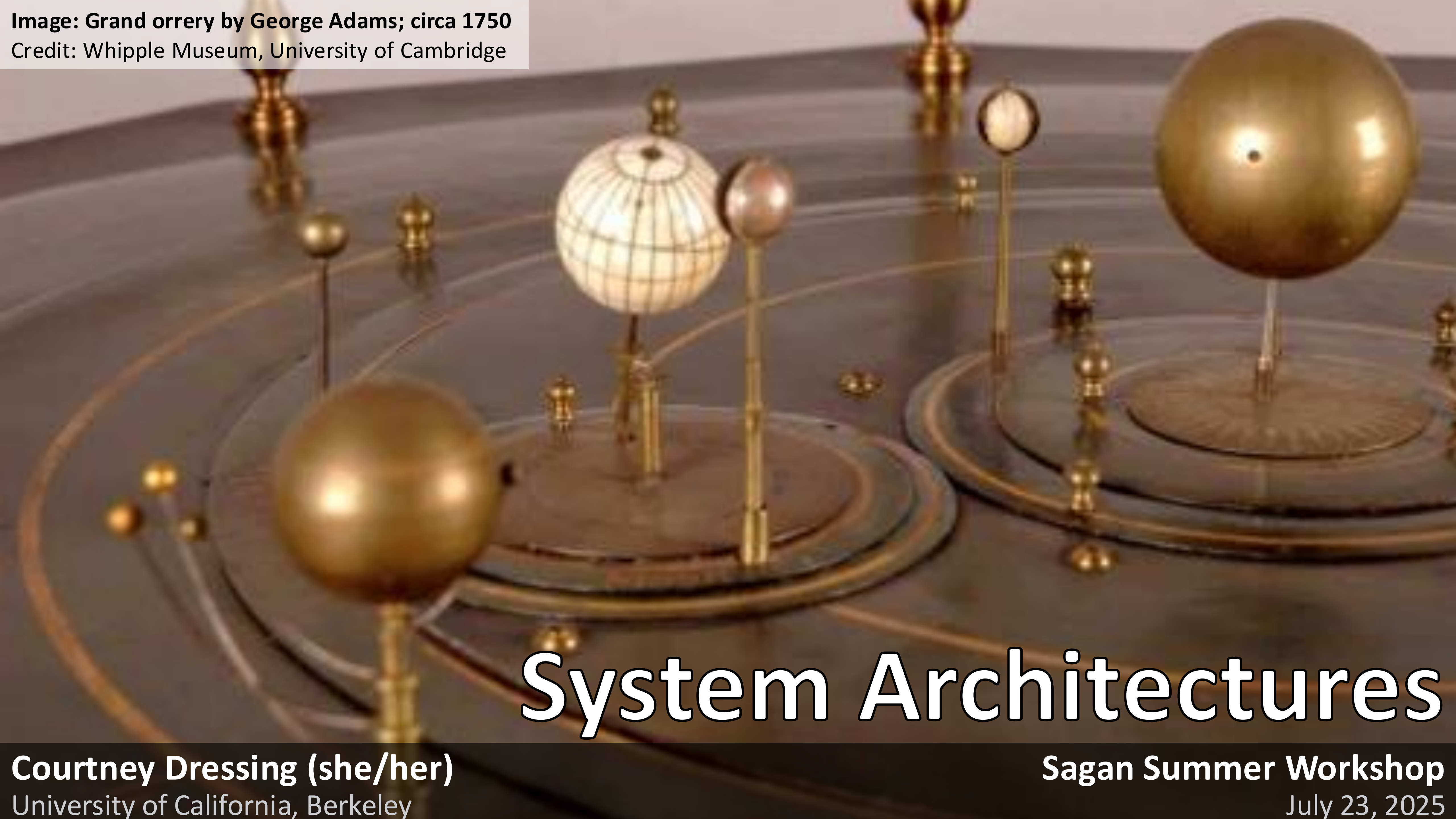
Image: **Grand orrery by George Adams; circa 1750**
Credit: Whipple Museum, University of Cambridge

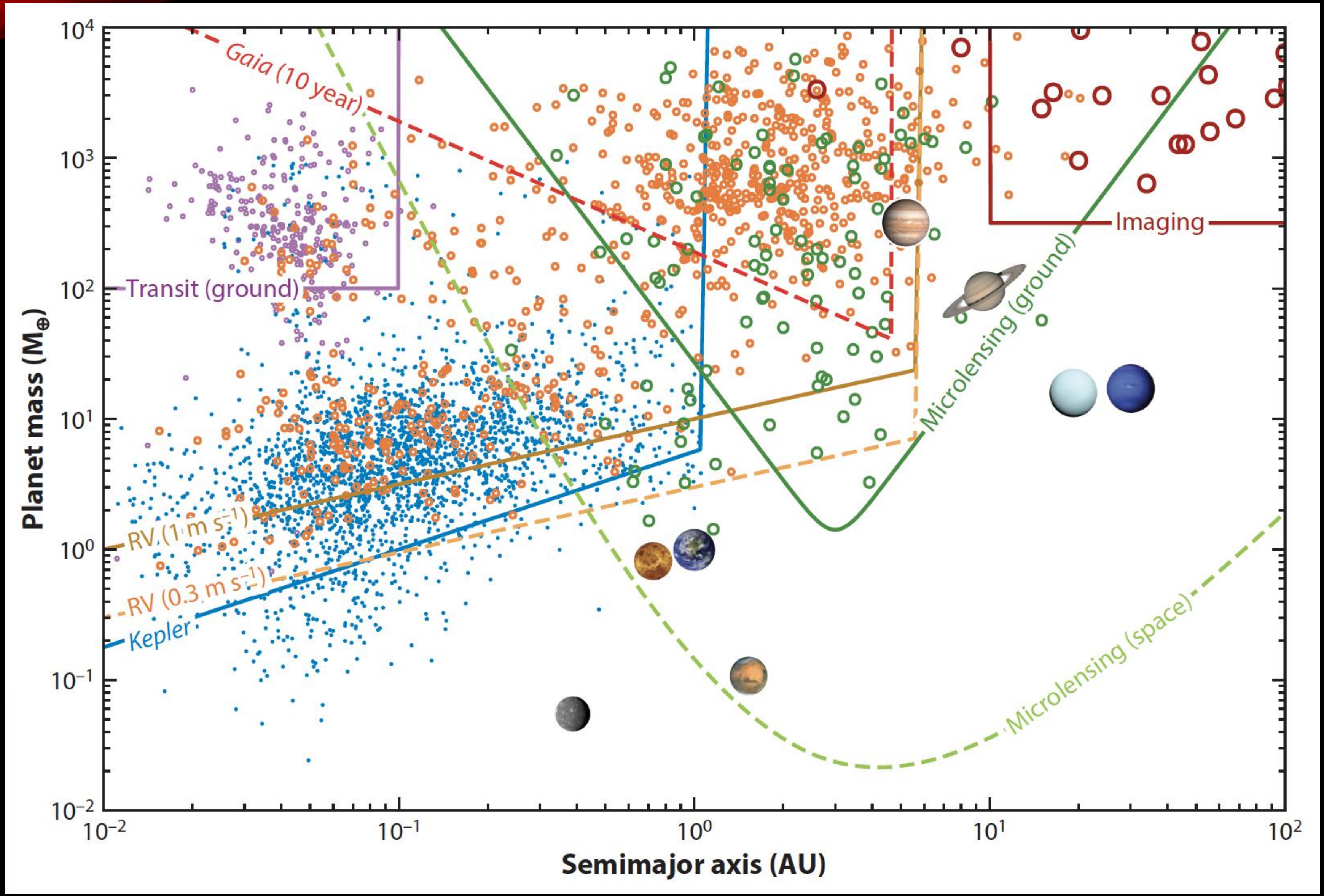


System Architectures

Courtney Dressing (she/her)
University of California, Berkeley

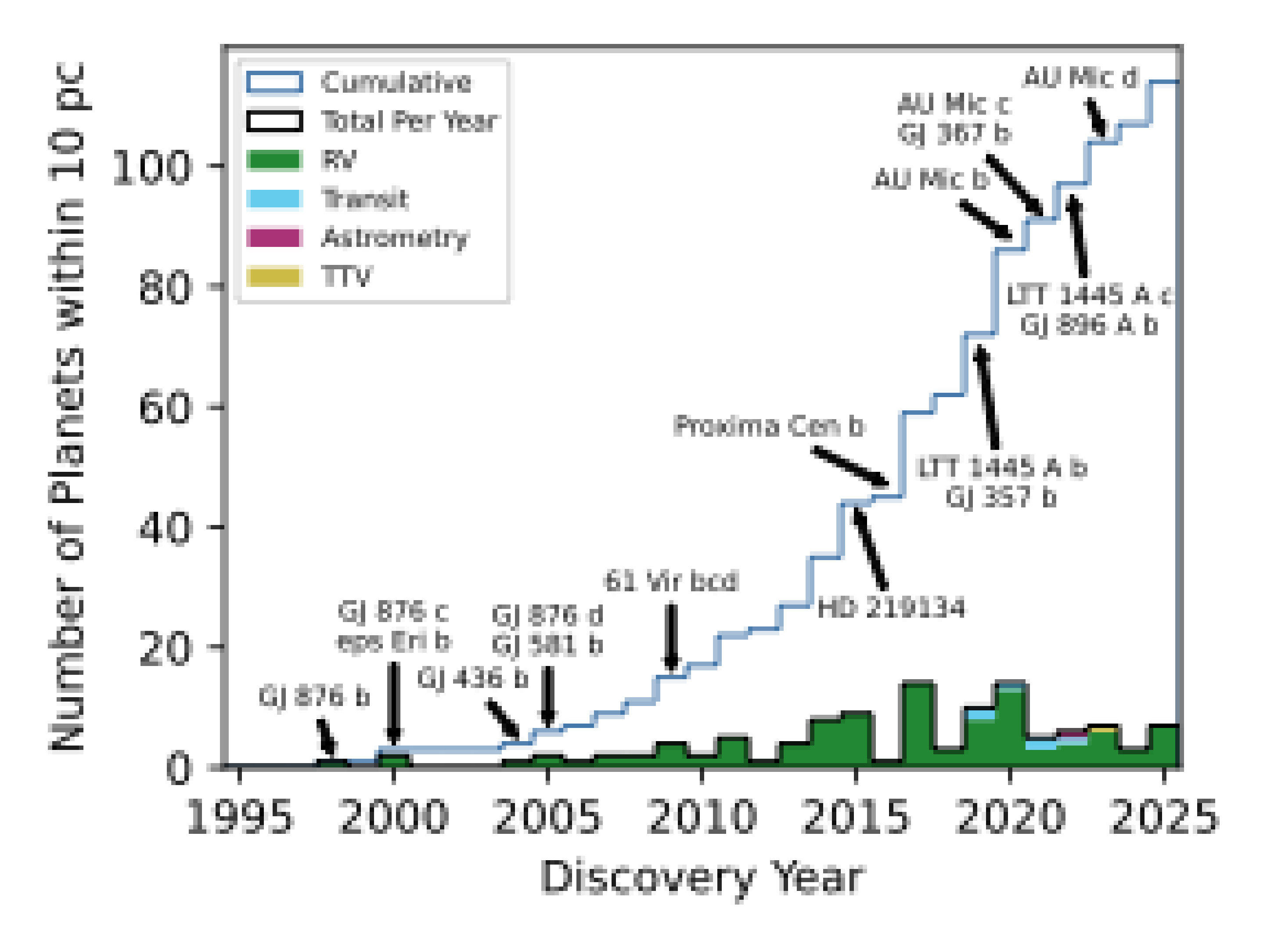
Sagan Summer Workshop
July 23, 2025

Reminder: Detecting Planets Is Hard



Zhu & Dong (2021)

The Planet Census is Incomplete



Dressing (in prep) using data from the NASA Exoplanet Archive

What Are the Properties of Nearby Planetary Systems, And How Well Have They Been Searched for Planets?

- See in-person poster 21 by Caleb Harada

PAPER II (THIS WORK)

Harada et al. (2025)
[in revision]

Analyzing ***all* publicly-available (E)PRV observations** of SPORES-HWO stars to place limits on undetected planets, refine properties of known planets, search for new planet candidates, and identify false positives.

Example HWO Precursor Science Drivers:

- *Massive planets orbiting in the habitable zone (HZ) can preclude long-term dynamical viability of exo-Earths (e.g., Kane et al. 2024), which informs target prioritization for the HWO exo-Earth survey.*
- *Non-detections of HZ exoplanets by (E)PRV place upper mass limits on planets imaged by HWO and hence inform HWO's onboard astrometry requirements.*

Key Science Questions:

- *Are exoplanet systems that host detectable biospheres similar to the Solar System in terms of their overall system architectures?*
- *Is there a particular planetary system architecture (and hence planet formation/ evolutionary pathway, which tends to produce Earth-like planets, or are there many possible evolutionary routes that can lead to habitability?*

SPORES-HWO. II. COMPANION MASS LIMITS FOR FUTURE EXO-EARTH SURVEY TARGET STARS FROM >30 YEARS OF PRECISION RADIAL VELOCITY MONITORING

CALEB K. HARADA[1,*], COURTNEY D. DRESSING[1], & STEPHEN R. KANE[2]
[1]University of California, Berkeley, USA; [2]University of California, Riverside, USA; *NSF Graduate Research Fellow

Definitions

What is a Planetary System?

- Working definition for this talk: **a gravitationally-bound collection of multiple objects including at least one planet**

- Example systems:
  - A single star with ≥ 1 planet
  - A single star with ≥ 1 planet AND additional substellar companions (e.g., brown dwarfs, dwarf planets, small bodies)
  - A stellar binary in which planets orbit one or both stars
  - Three or more stars with planets orbiting one, some, or all stars
  - One or more brown dwarfs with planets orbiting one, some, or all brown dwarfs
  - A collection of gravitationally bound planets, moons, or planetesimals without any bound stars or brown dwarfs

Planets Orbiting Black Holes Are An Extreme Type of Planetary System

- See the remote poster by Alaa Salah Afifi

Formation of Second-Generation Exoplanets in Resonant Fallback Disks Around Black Holes

Author : Alaa Salah Afifi

2025 Sagan Summer Workshop Silver Jubilee: Exoplanet Demographics

Affilation : Kepler space University

Conclusion

Fallback disks can be planet factories and after cosmic death, too. This essay theorizes life-bearing worlds could have been born in places we never would have thought.

Sagan-Inspired Insight "Even in their deaths, stars seed life again. We are star stuff and so might new worlds created from black holes be.".

An Isolated, Single Free-Floating Planet is ***NOT*** a System…

- **See in-person poster 15 by William DeRocco**

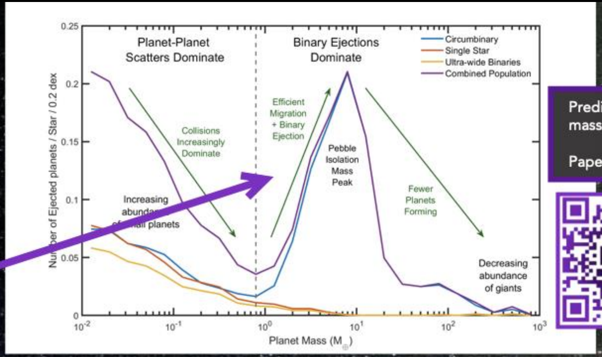
Free-Floating Planets in the Era of Roman

William DeRocco (University of Maryland)
Contact: derocco@umd.edu

Predicting the Galactic population of free-floating planets from realistic initial conditions

DeRocco & Coleman. 2025 MNRAS 537 3 2303–2312.

Motivation: What kind of distribution of FFP masses should Roman expect to see?
Methods: Dedicated ab initio simulations of system evolution from initial planet formation all the way through ejection for a wide variety of stellar systems.
Key Result: Circumbinary ejections dominate at Neptune masses. Strong non-monotonic feature near pebble isolation mass in these systems — simple power-law extrapolation is *not* sufficient!



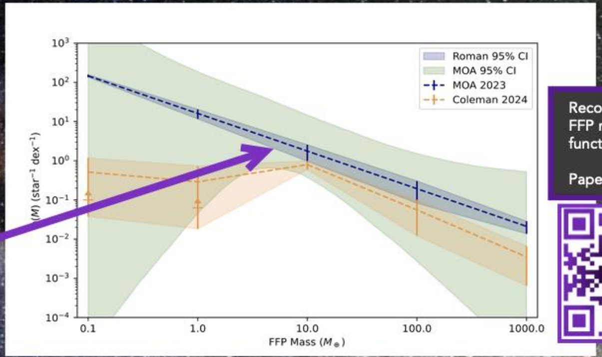
Predicted FFP mass function [3]

Paper link:

Reconstructing the Free-floating Planet Mass Function with the Roman Space Telescope

DeRocco et al. 2025 AJ under review, arxiv: 2505.00092.

Motivation: How can Roman leverage statistics to discover unique features in the FFP distribution?
Methods: Large-scale simulations of Roman survey data to produce Bayesian framework for FFP mass function reconstruction.
Key Result: Roman will be able to discriminate between multiple hypothesized mass functions!



Reconstructed FFP mass function [4]

Paper link:

…but Free-Floating Planets Might Interfere with Planetary Systems

- **See remote poster by Shreesham Pandey**

Rogue Planets Sculpting Exoplanetary Demographics

Dynamical, Biochemical, and Zoological Impacts

Shreesham Pandey[1], Diva Pandey[2]

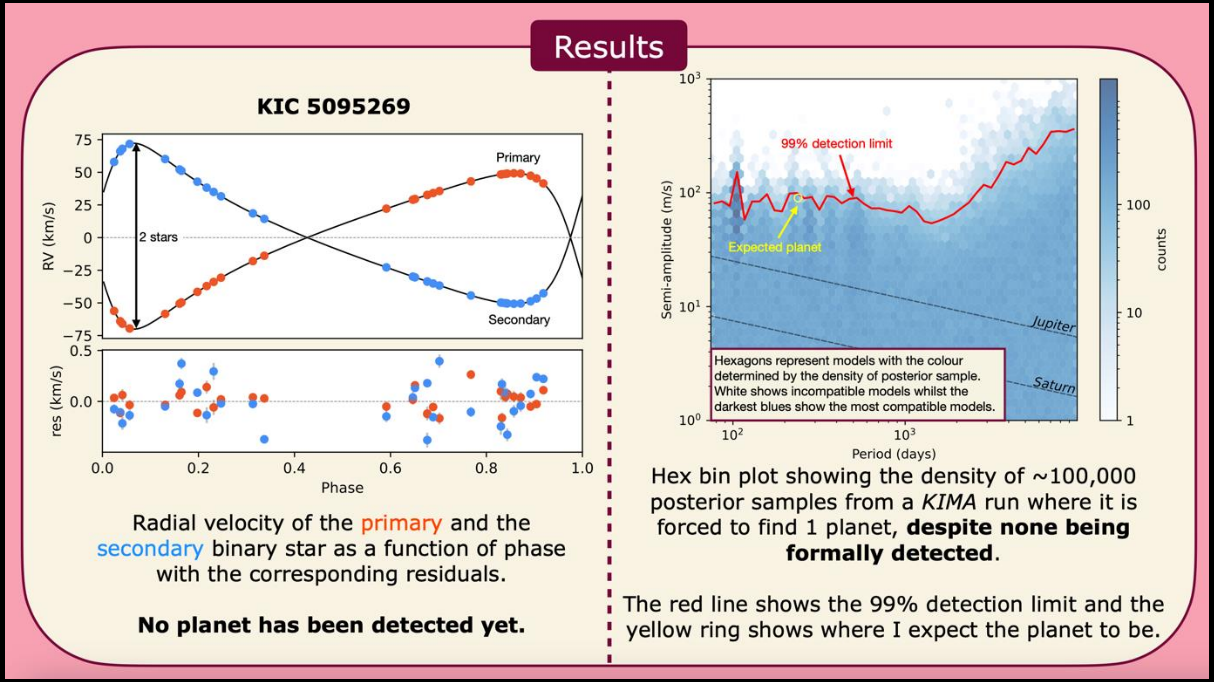
[1]Department of Physics, Kirori Mal College, University of Delhi, Delhi, India
[2]Department of Zoology, Institute of Science, Banaras Hindu University, Varanasi, India

Key Finding

Rogue planets, defined as free-floating planetary-mass objects with masses ranging from 0.1 to 10 Jupiter masses ($M_{\rm Jup}$) and an estimated population of 10^9 to 10^{11} in the Milky Way, are celestial bodies that lack a stable orbit around a star. This study investigates how these rogue planets reshape exoplanetary systems by integrating dynamical interactions, biochemical processes, and zoological potential. Utilizing data from 5,921 confirmed exoplanets, sourced from missions like Kepler, TESS, and radial velocity (RV) surveys, we explore their orbital perturbations, chemical contributions, and potential to support life. The findings aim to guide the Habitable Worlds Observatory (HWO), which targets 13,214 stars for future observations, by providing a comprehensive framework for understanding these impacts.

Some Planetary Systems Have More Than One Star

- See in-person poster 2 by Aleyna Adamson



Determining Which Star In A Multistar System Hosts A Planet Can Be Challenging

- See in-person poster 8 by Nathanael Burns-Watson

Determining The Host Stars of Planets in Binary Star Systems

TACC
TEXAS ADVANCED COMPUTING CENTER
The University of Texas at Austin
Department of Astronomy
College of Natural Sciences
Nathanael Burns-Watson[1], Kendall Sullivan[2], Adam L. Kraus[1]
[1]The University of Texas at Austin, [2]University of California Santa Cruz
UC SANTA CRUZ

A lot of planets remain ambiguous:
Are Circumsecondary Planets More Common than Expected?

Results: 15 total planets, 5 unambiguously circumprimary, the rest are ambiguous

Burns-Watson, Sullivan, & Kraus

We (Tentatively) Confirm that **The Radius Gap is Filled in for Planets in Binaries**

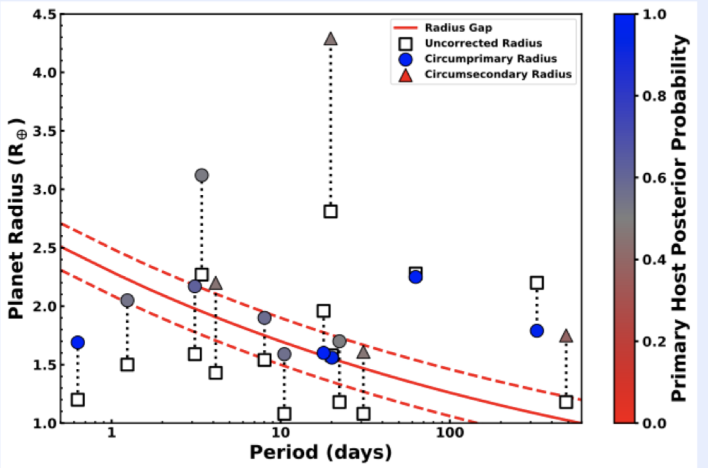


Figure 3: Radius versus period for the planets analyzed in this work. The empty squares are the uncorrected radii reported by the Kepler team (Thompson et al. 2018). The closed points are the corrected radii, color-coded by host star posterior probability. Planets with a higher circumprimary probability are marked with circles, and the circumprimary radius is used as the corrected radius. Similarly, a higher circumsecondary probability is marked with a triangle, and the circumsecondary radius is used.

What is Architecture?

1) Merriam-Webster offers the following definitions:
2) the art or science of building
   a) *Specifically*, the art or practice of designing and building structures and especially **habitable ones**
3) formation or construction resulting from or as if from a conscious act
4) a unifying or coherent form or structure
5) architectural product or work
6) a method or style of building
7) the manner in which the components of a computer or computer system are organized and integrated

What is Planetary System Architecture?

- Working definition for this talk: **the arrangement of one or more planets and other astronomical bodies in a gravitationally-bound collection of objects**
- **Example metrics:**
  - **Number of stars, brown dwarfs, planets, and other objects**
  - **Spacing between objects**
  - **Hierarchical structure (or lack thereof)**
  - **Distribution of mass**
  - **Mutual inclinations**
  - **Eccentricities**
  - **Extent of similarity in various components**

There Are Many Ways to Classify Planetary Systems

- See in-person poster 26 by Alex Howe

A Classification of the Architectures of Planetary Systems

Alex Howe[1], Juliette Becker[2], & Fred Adams[3]

[1]Catholic University of America/NASA Goddard, [2]University of Wisconsin-Madison, [3]University of Michigan

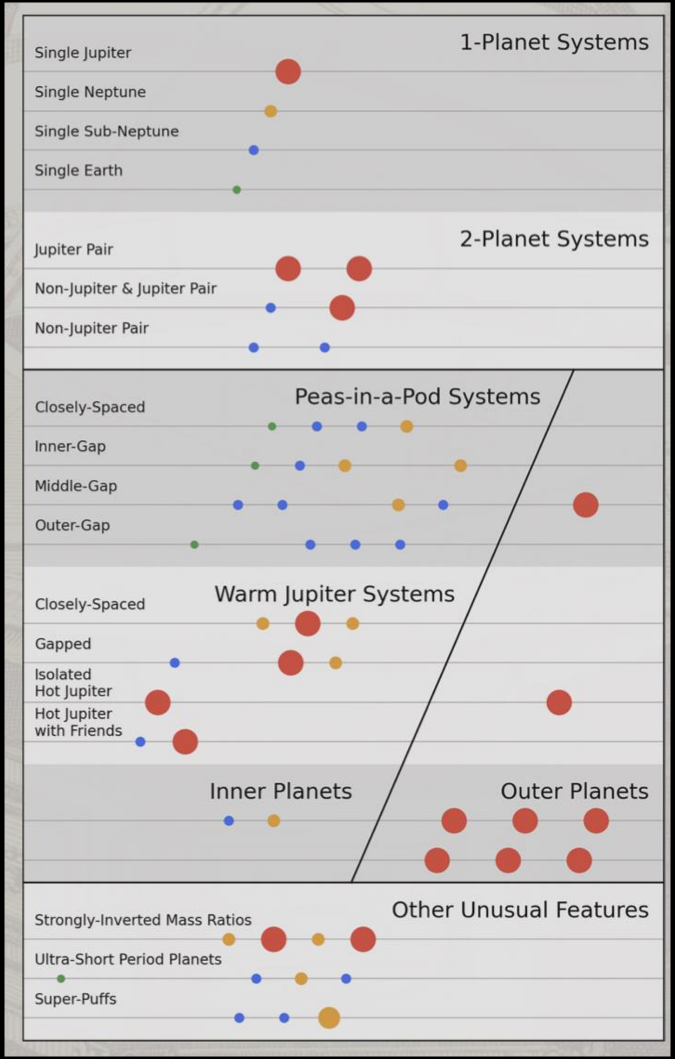
Papers

Architectures I (the classification system):
Howe, Becker, Stark, & Adams, *AJ* **169**, 149

Architectures II (host star properties):
Howe, Becker, & Adams, submitted to *PASP*

Architectures III (eccentricities and inclinations):
Howe, Becker & Adams, in prep.

Acknowledgements



There Are Also Frameworks for Classifying Planets Within Systems

- See in-person poster 41 by Eva Plávalová

ExoClass & SysClass: A Compact Code for Classifying Exoplanets and Planetary Systems

E. Plávalová

The Mathematical Institute of the Slovak Academy of Sciences, Štefániková 49, Bratislava, Slovakia
Email: plavalova@komplet.sk, plavalova@mat.savba.sk

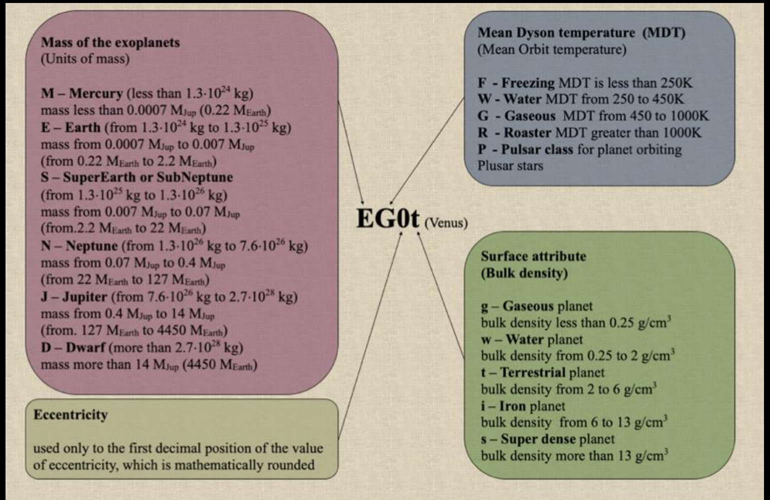


Figure 1: Summary of the ExoClass system, showing physical ranges used to classify planetary mass, temperature, eccentricity, and surface. This framework enables rapid comparison and cataloging across diverse exoplanet populations.

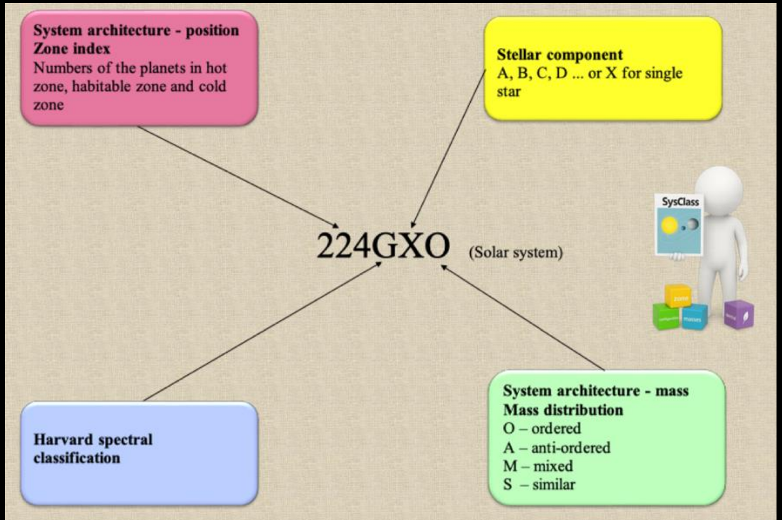
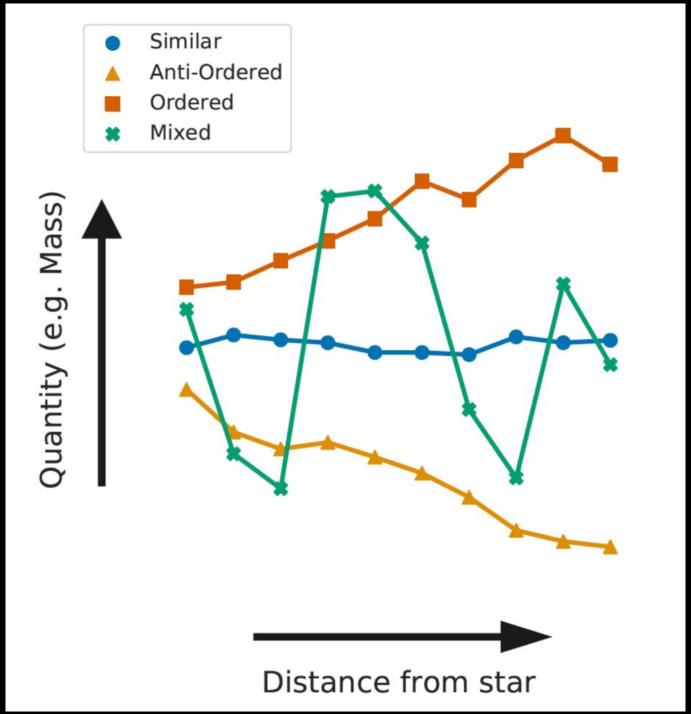
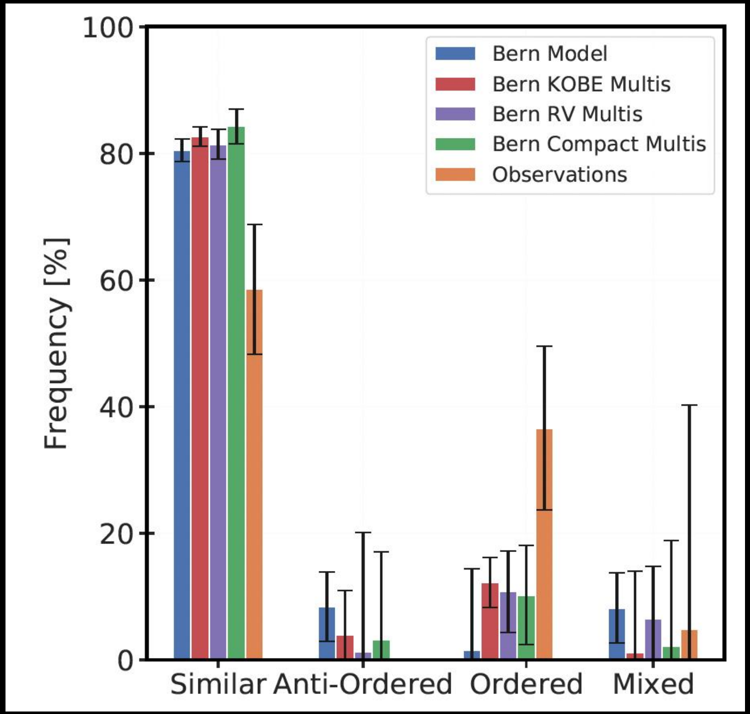


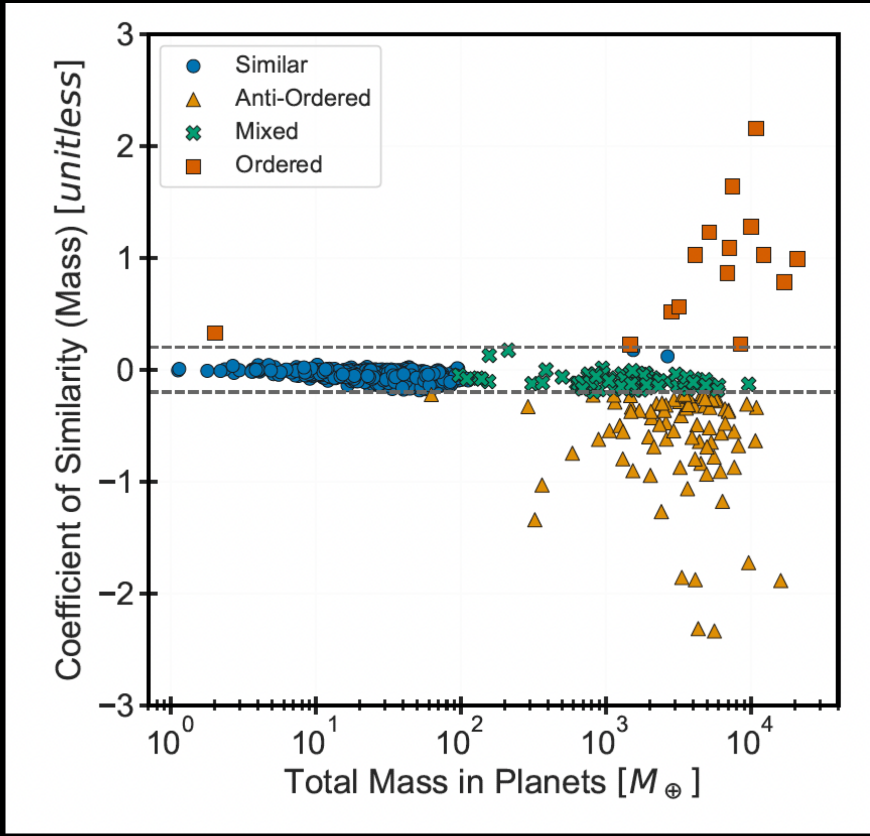
Figure 2: The SysClass code describes planetary systems using four parameters: zone index (number of planets in hot, habitable, and cold zones), stellar spectral class, stellar multiplicity, and planetary mass distribution (similar, ordered, anti-ordered, or mixed).

Planetary Systems Can Also Be Classified By How Planet Properties Change With Distance From The Host Star

- Example: Mishra et al. (2023) proposed four categories of systems
  - **Similar:** the quantity is roughly the same for all planets
  - **Anti-Ordered:** The quantity decreases with increasing distance
  - **Mixed:** The quantity both increases and decreases with increasing distance
  - **Ordered:** The quantity increases with increasing distance

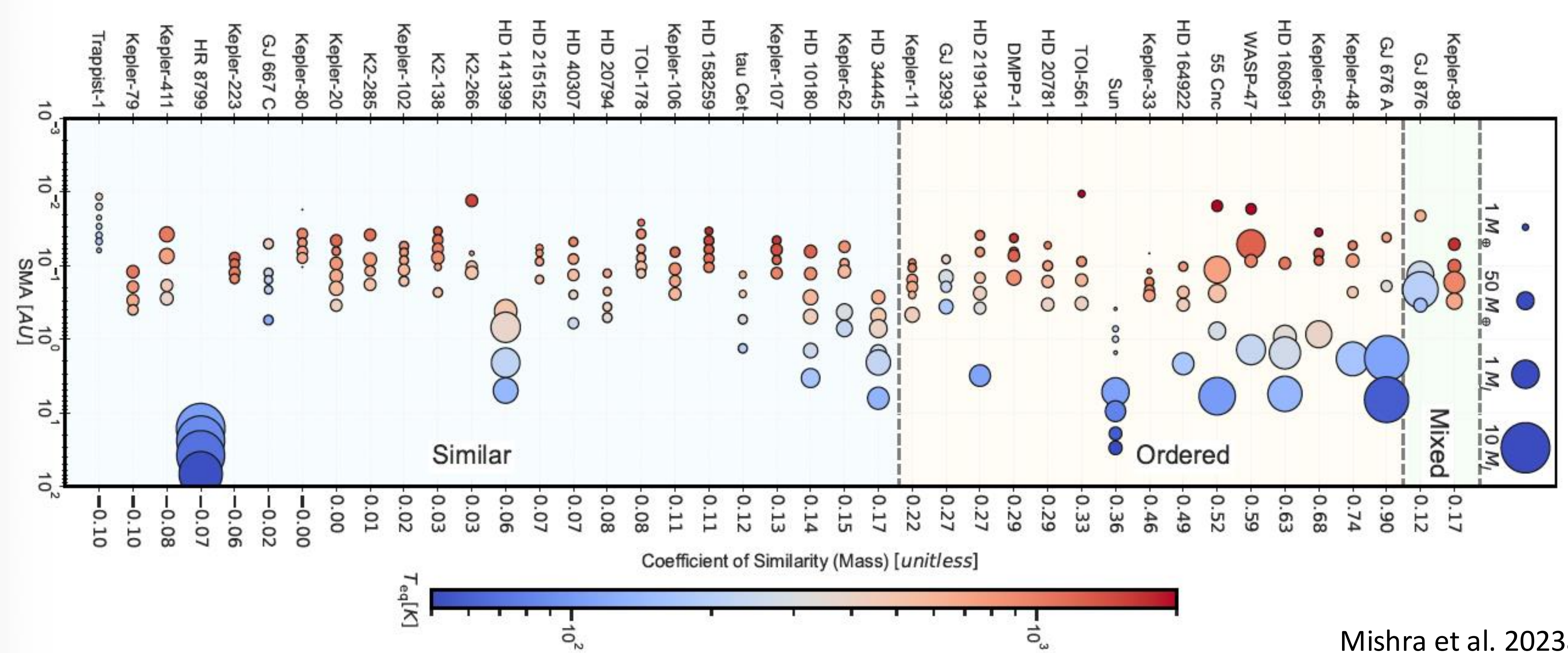






Figures from Mishra et al. 2023a

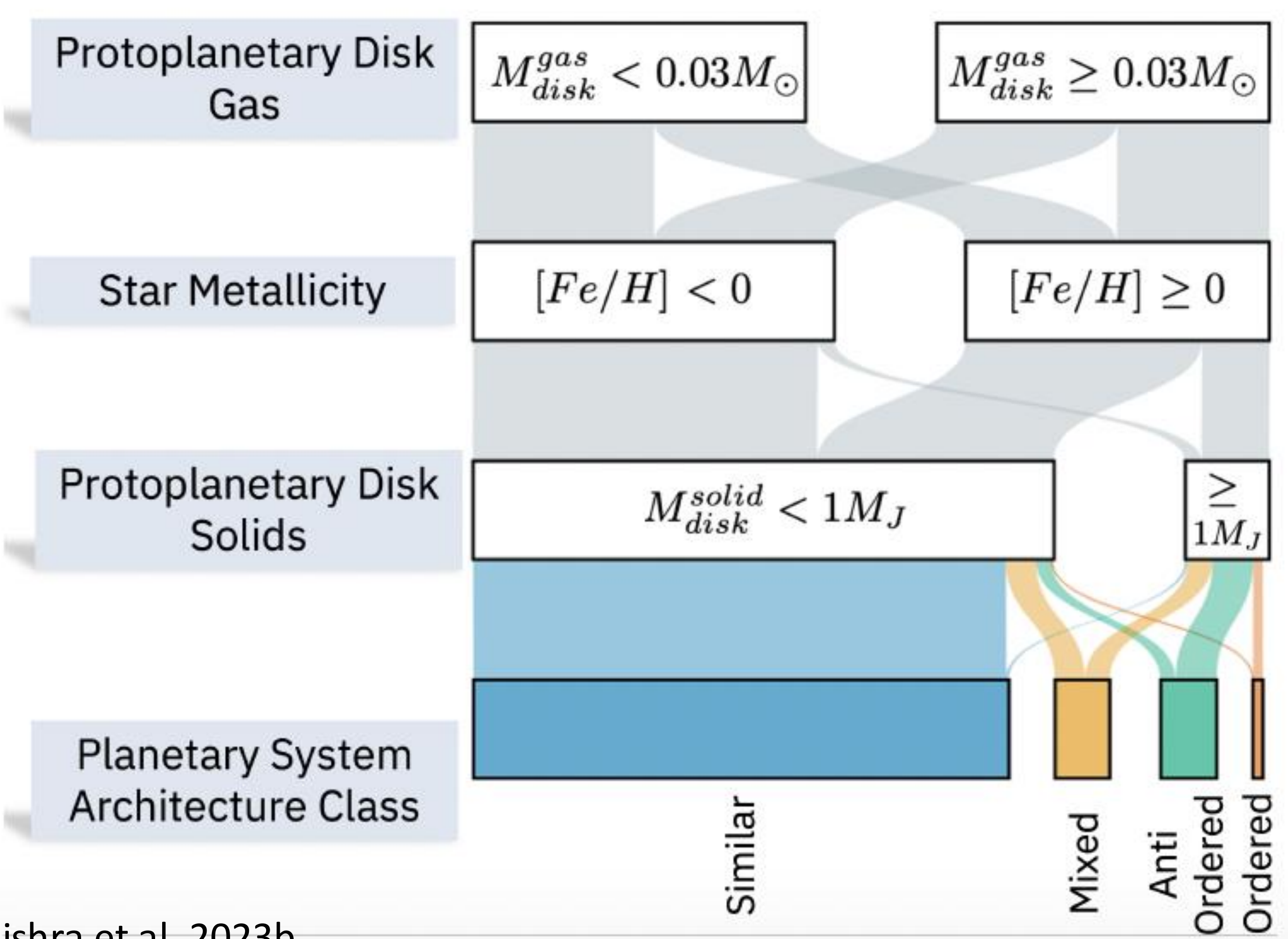
Most Detected Systems Have “Similar” Architectures



Mishra et al. 2023a

Simulations Suggest That Similar Architectures Are The Most Likely Outcome of Planet Formation

- Nearly all systems formed from disks with < 1 M_J of solids are **similar.**
- **Anti-ordered** and **ordered** systems are more likely for systems with metal-rich host stars.
- **Mixed** systems are more likely at intermediate metallicities than at low or high metallicities
- With increased dynamical interactions, **mixed**, **anti-ordered**, and **ordered** architectures are more likely.



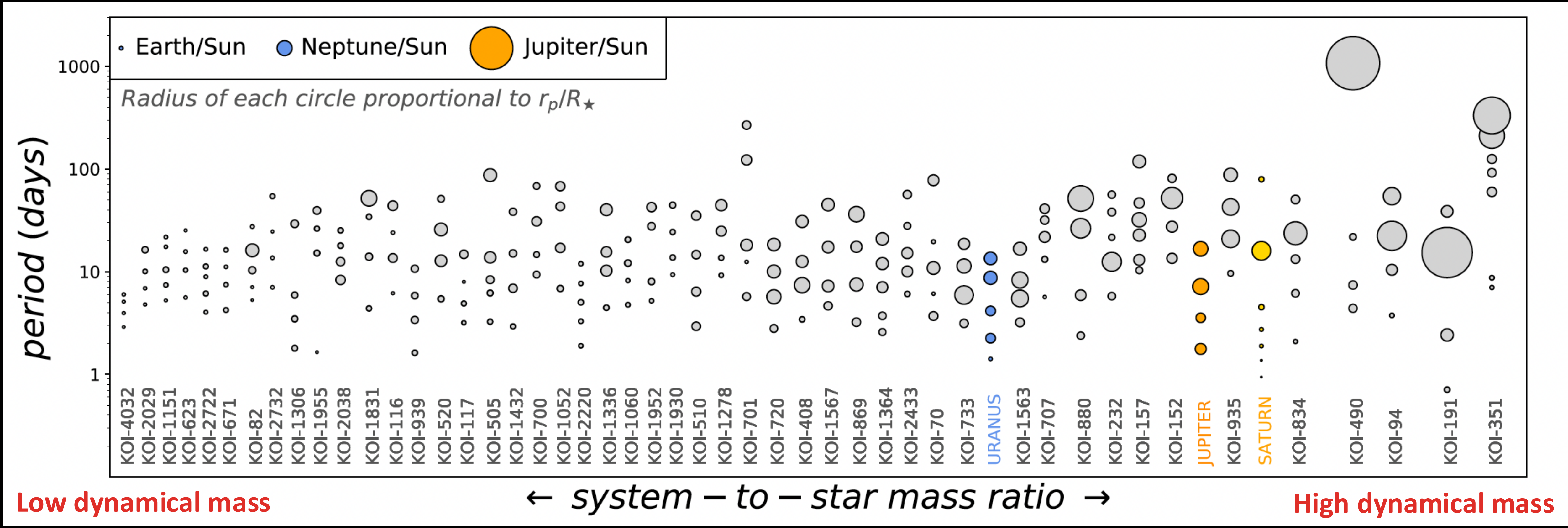
Mishra et al. 2023b

Gilbert & Fabrycky (2020) proposed a classification system inspired by information theory

They identified **seven** key metrics

G&F Metric 1: Dynamical Mass

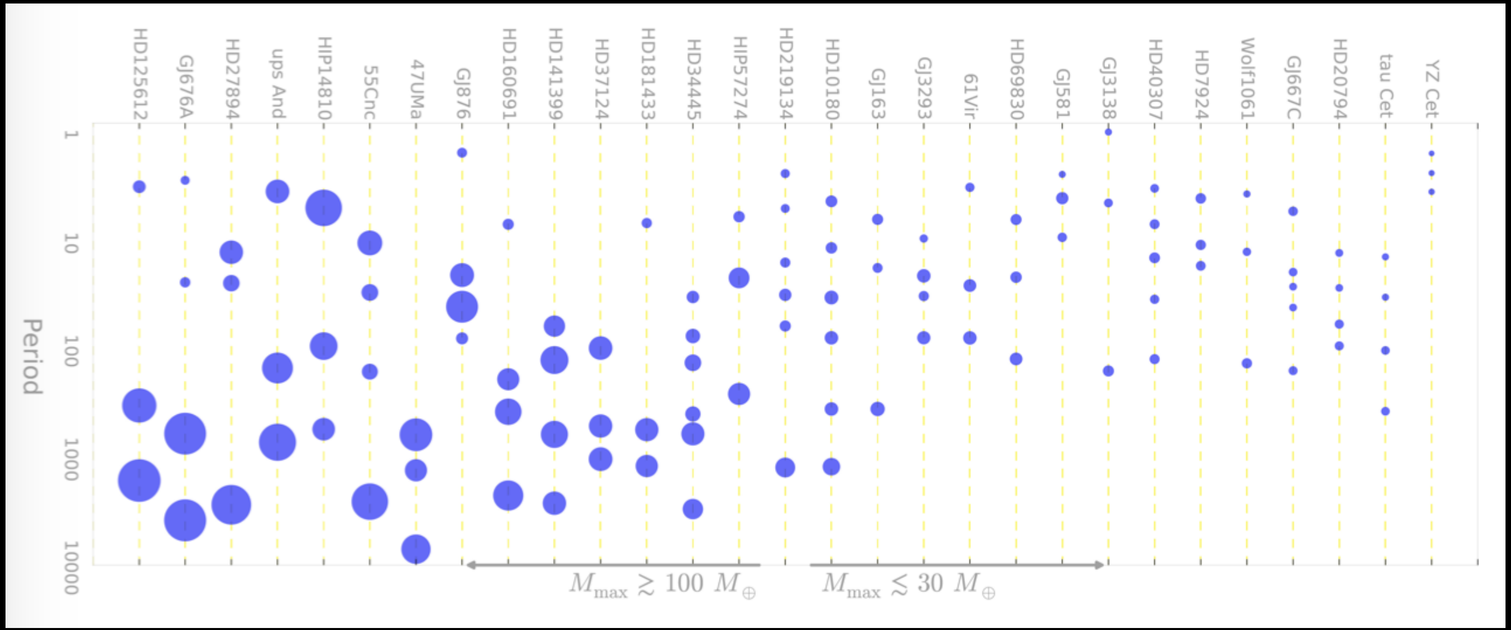
- How much mass is in planets compared to the host star?



Gilbert & Fabrycky (2020)

G&F Metric 2: Mass Partitioning

- How much do the masses of individual planets vary?
  - *Inspired by Millholland et al. (2017) and Wang (2017)*



Circle size = planet mass

Figures from Songhu Wang 2017 Res. Notes AAS 1 26

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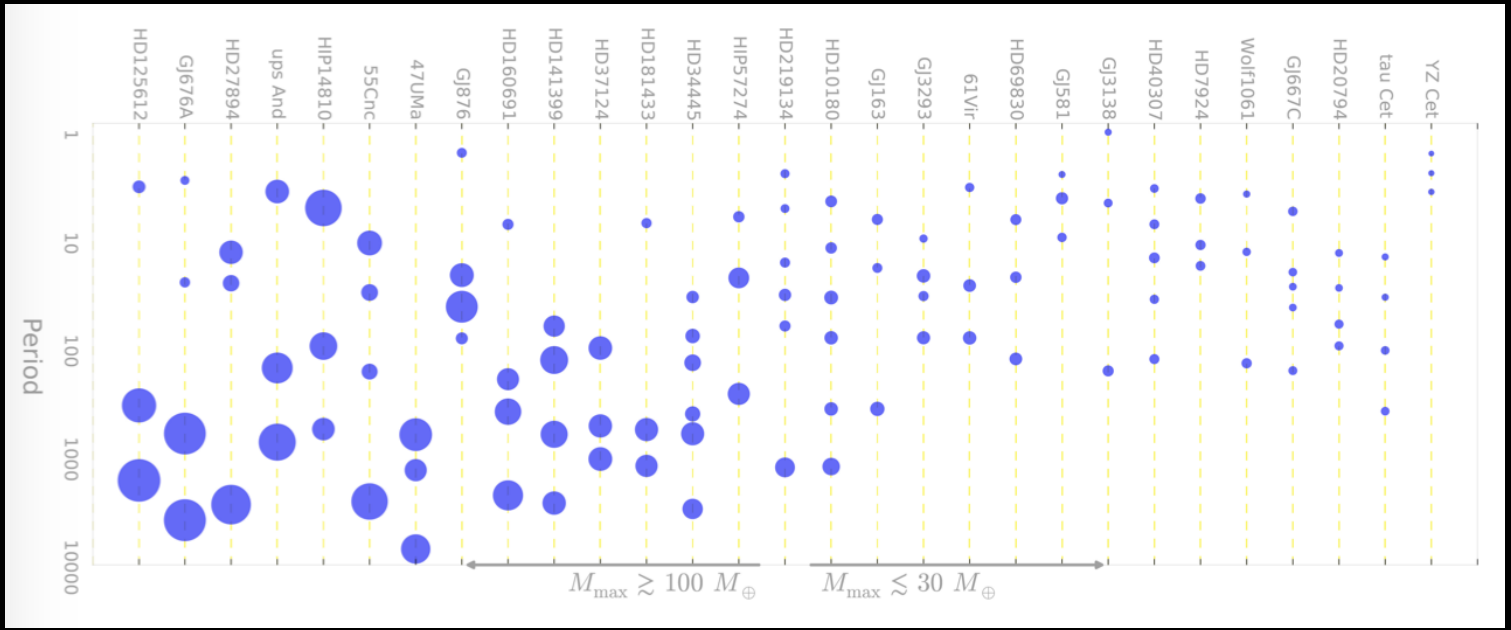

$$\mathcal{D} = \sum_{i=1}^{N_{sys}} \sqrt{\frac{\sum_{j=1}^{N_{pl}} (M_j - \overline{M})^2}{N_{pl} - 1}}$$

intra-system mass dispersion

Circle size = planet mass

Figures from Songhu Wang 2017 Res. Notes AAS 1 26

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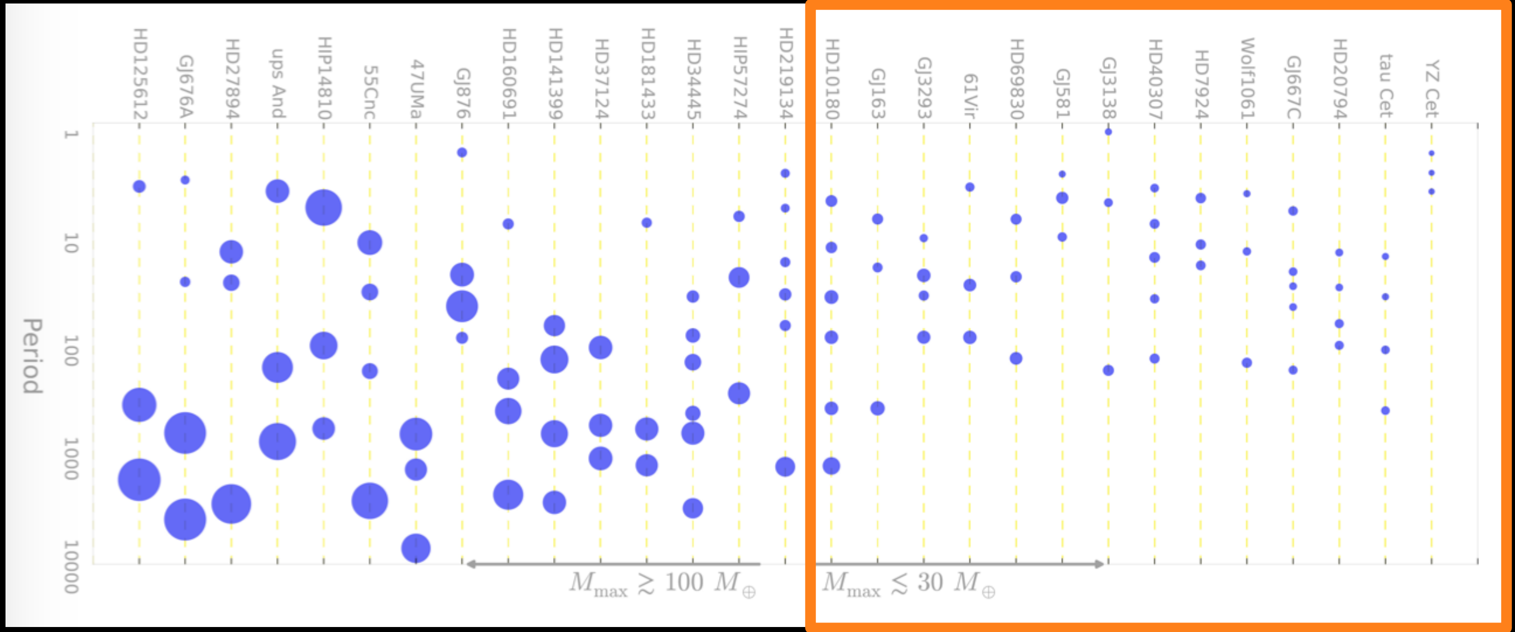

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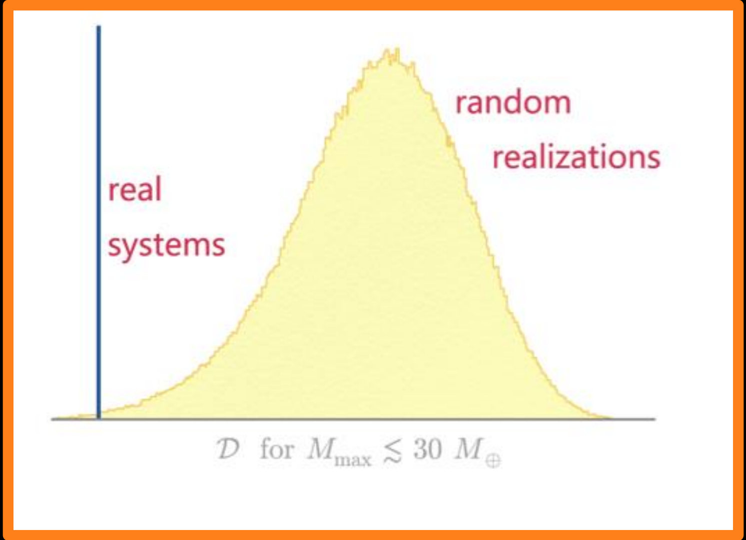

Systems with less massive planets tend to have *__very low__* mass dispersions

Figures from Songhu Wang 2017 Res. Notes AAS 1 26

G&F Metric 2: Mass Partitioning

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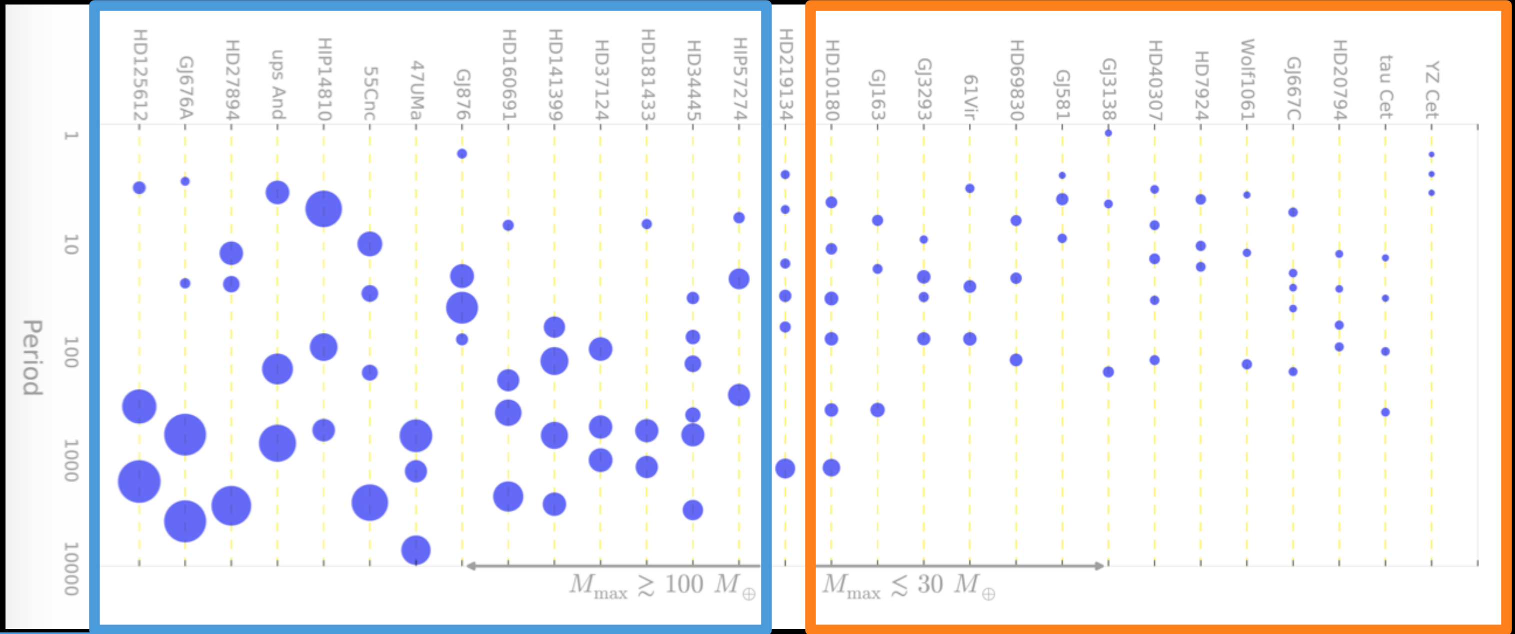
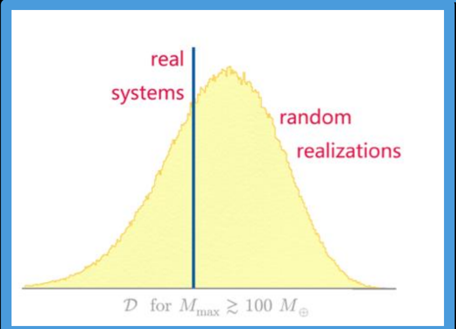
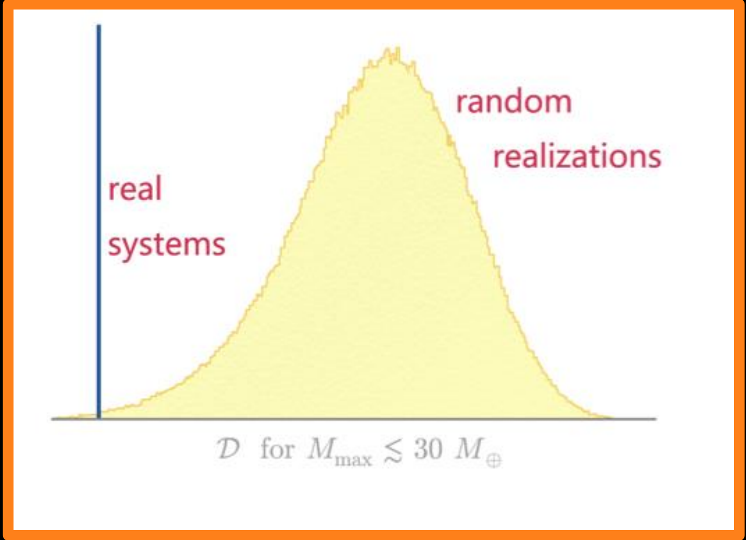


Circle size = planet mass



Systems with massive planets tend to have *high* mass dispersion



Systems with less massive planets tend to have *very low* mass dispersions

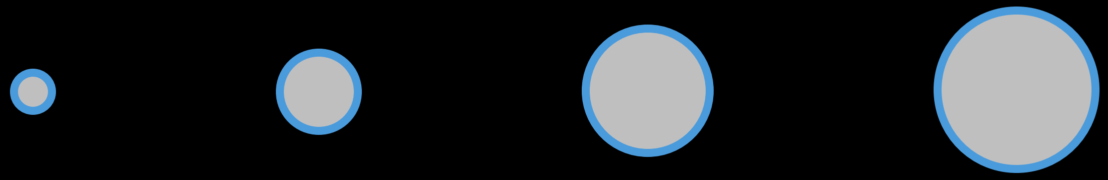
Figures from Songhu Wang 2017 Res. Notes AAS 1 26

G&F Metric 3: Monotonicity

- To what extent are the planets ordered by size?

G&F Metric 3: Monotonicity

- To what extent are the planets ordered by size?
  - ***Monotonicity > 0****: planets generally ordered by* ***<u>increasing</u>*** *size*



G&F Metric 3: Monotonicity

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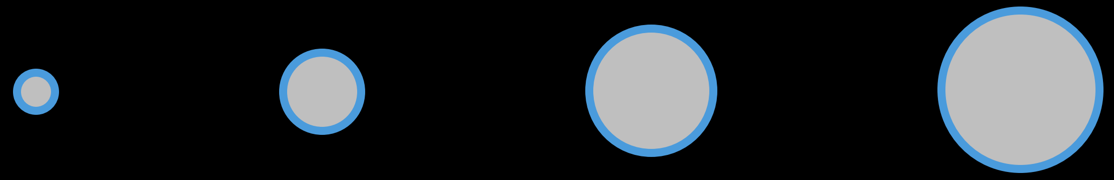

  - ***Monotonicity ≈ 0**: no evidence that planets are ordered by size*

G&F Metric 3: Monotonicity

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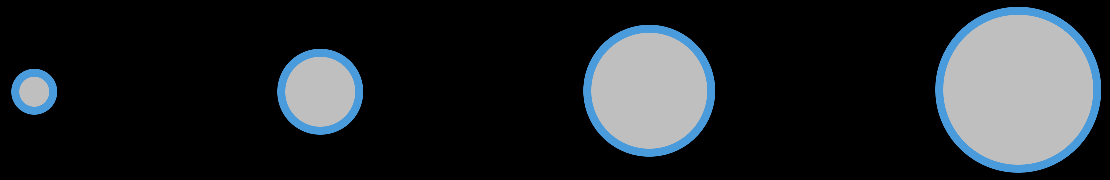

  - ***Monotonicity ≈ 0****: no evidence that planets are ordered by size*

  - ***Monotonicity < 0****: planets generally ordered by* ***__decreasing__*** *size*

G&F Metric 3: Monotonicity

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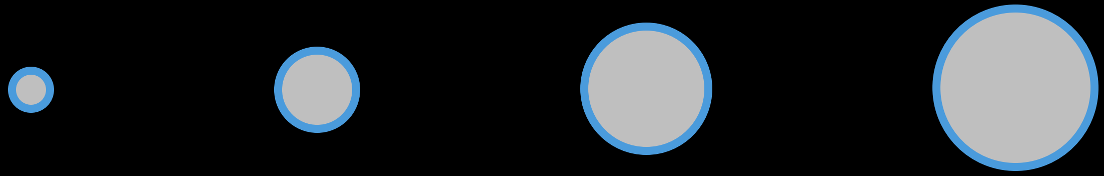

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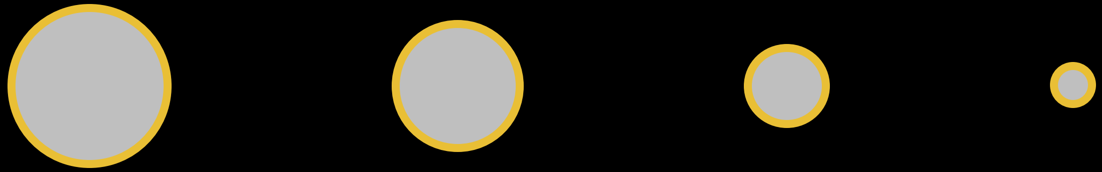
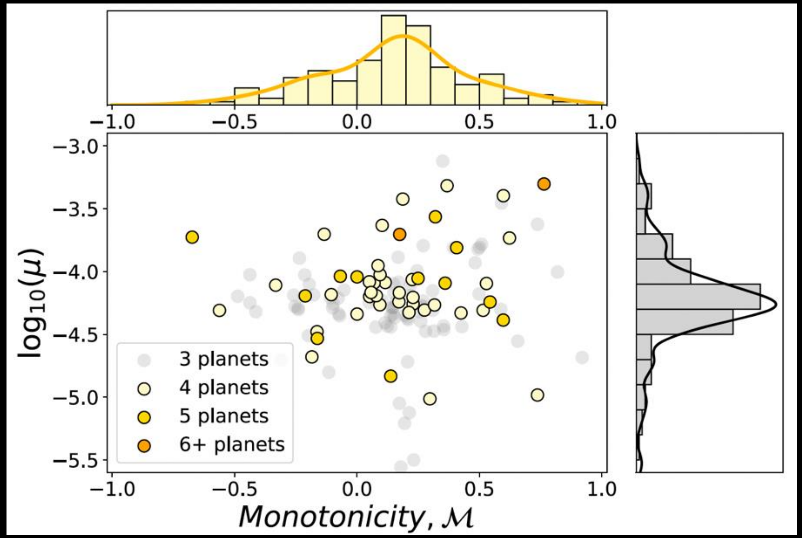
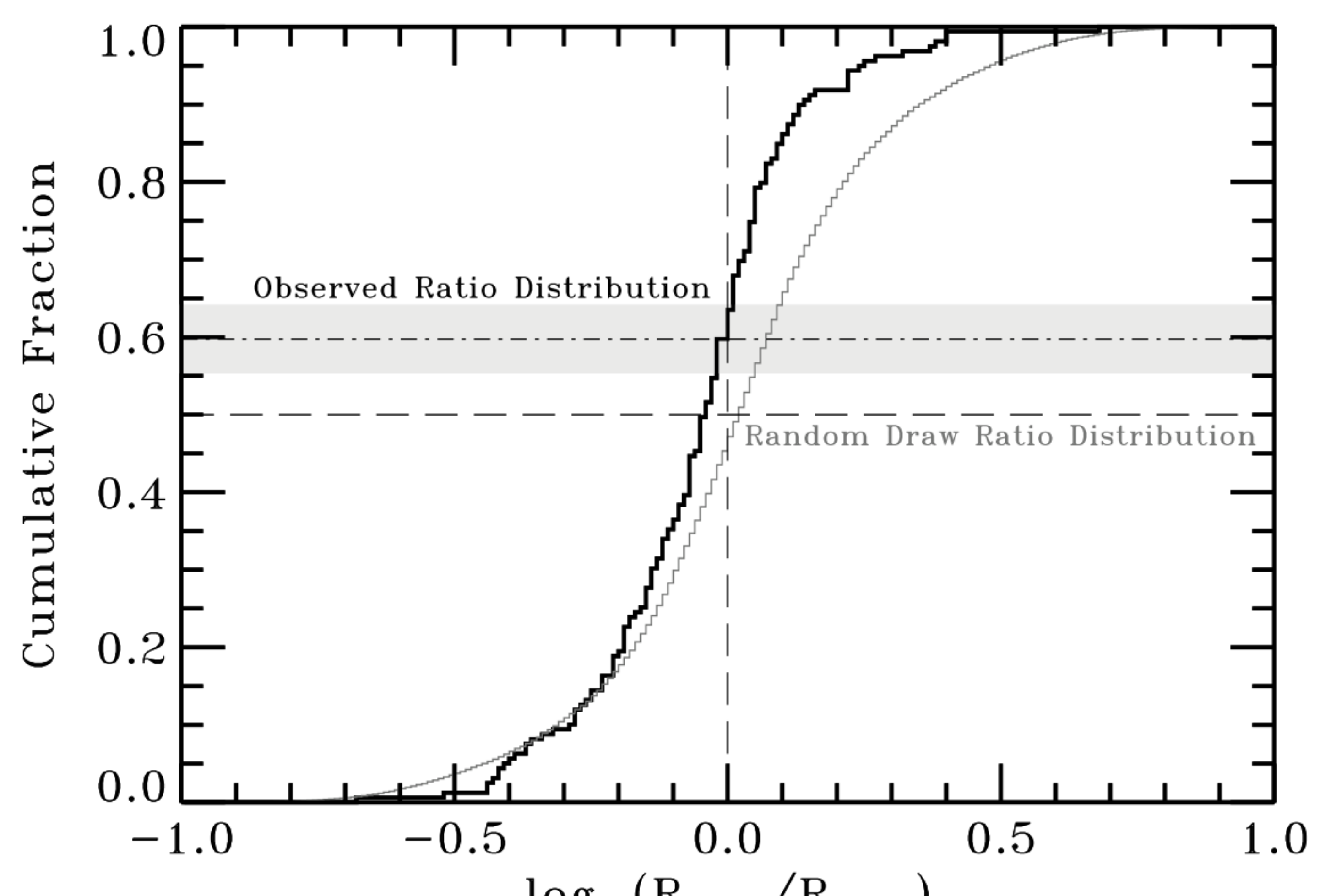




Gilbert & Fabrycky (2020)

Longer Period Planets Tend to Be Larger

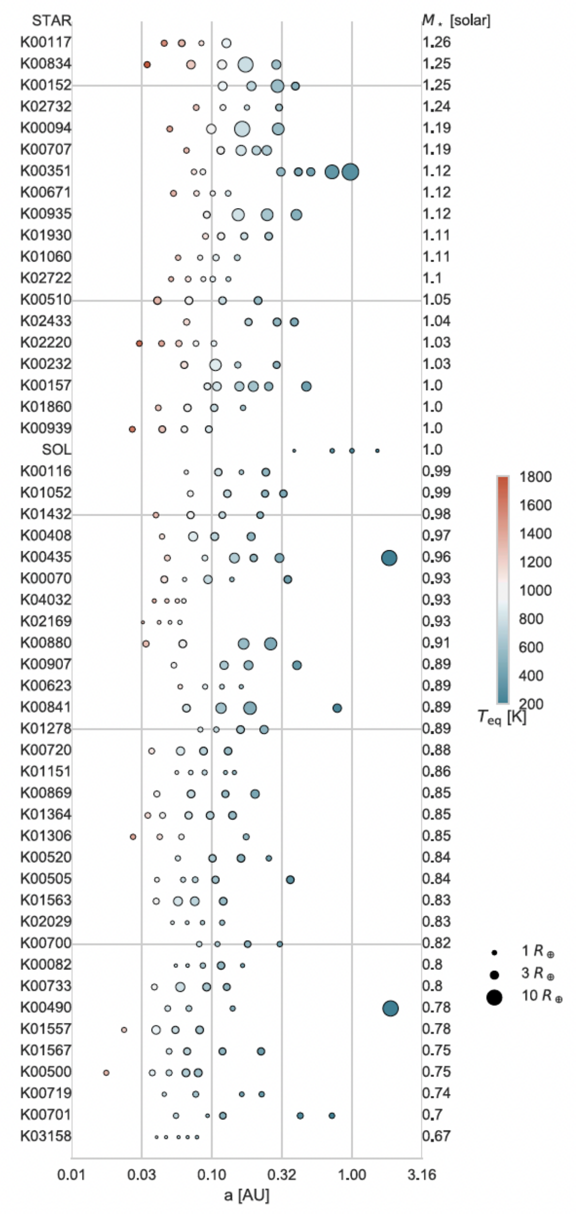
- In systems in which at least one planet is at least as large as Neptune, Ciardi et al. (2013) found that **larger planets tend to have longer orbital periods**.
  - True even after correcting for detection biases
  - Trend is **NOT** seen for systems in which all planets are smaller than Neptune



Ciardi et al. (2013)

Compact Systems Resemble Peas in a Pod

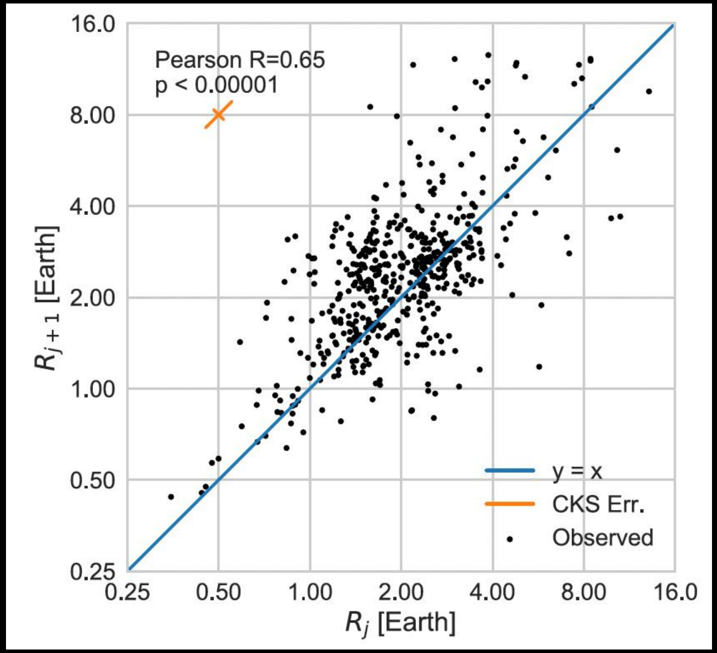
Compact Systems Resemble Peas in a Pod

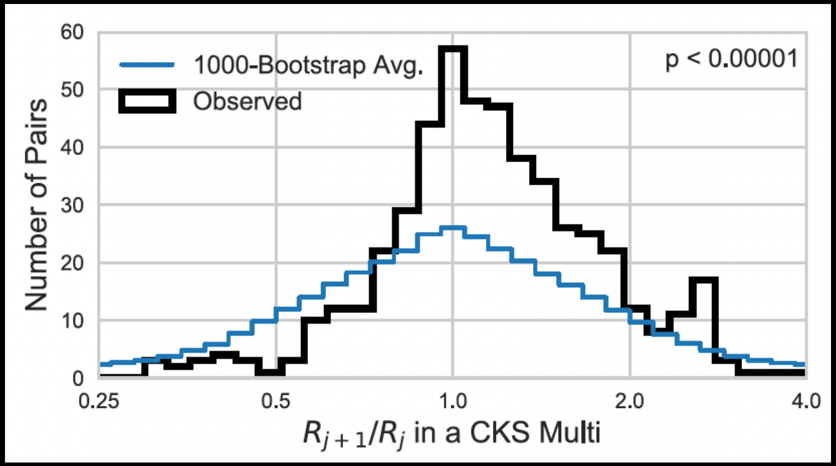


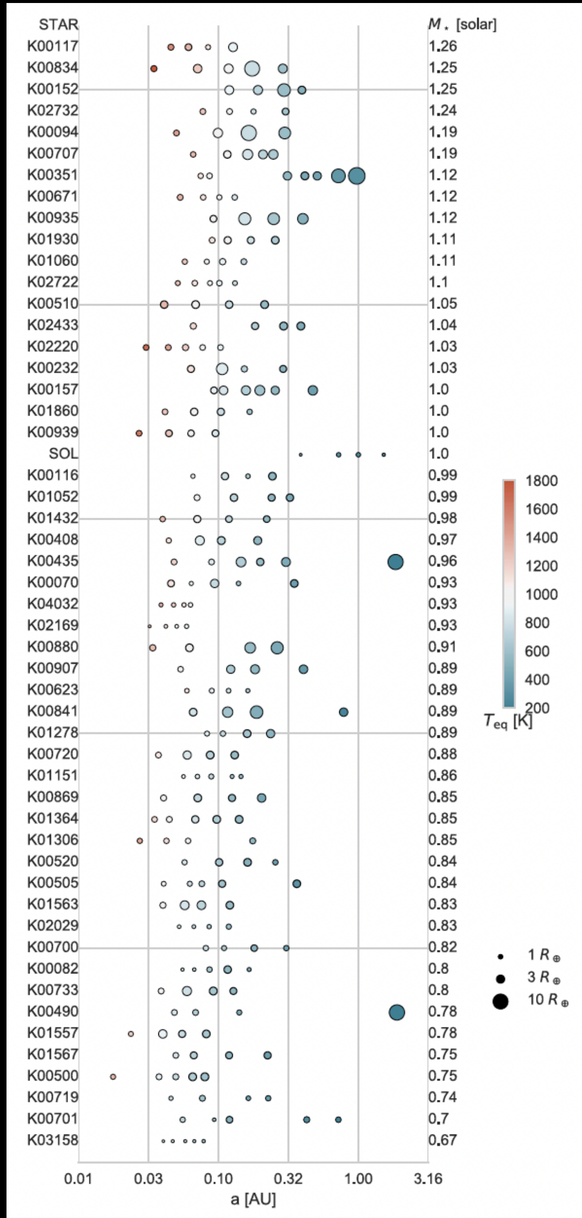
Figures from Weiss et al. (2018)

Compact Systems Resemble Peas in a Pod

- Radii of neighboring planets are correlated.
- For systems with 3+ planets, the period ratios of adjacent planet pairs are correlated.
- Smaller planets tend to have closer spacing.
- Systems with more planets tend to be more packed.

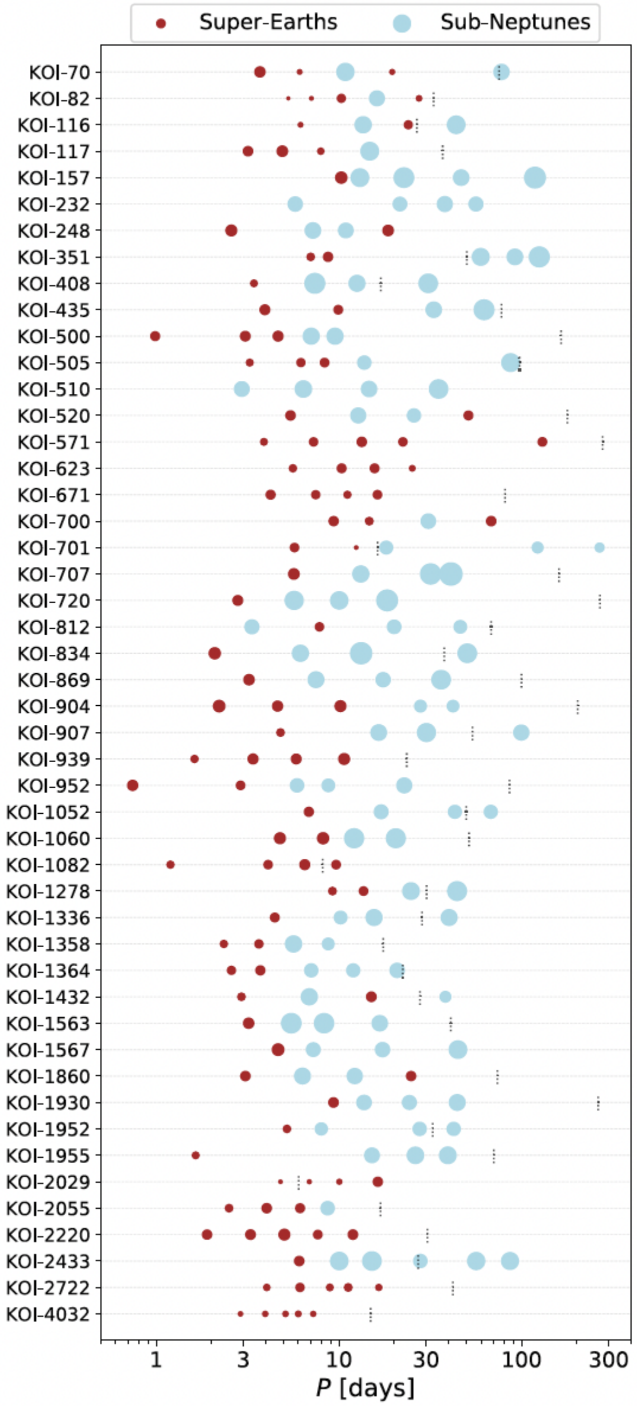






Figures from Weiss et al. (2018)

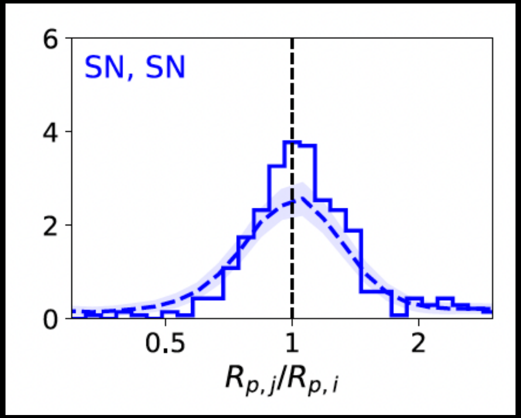
"Split Peas in a Pod"

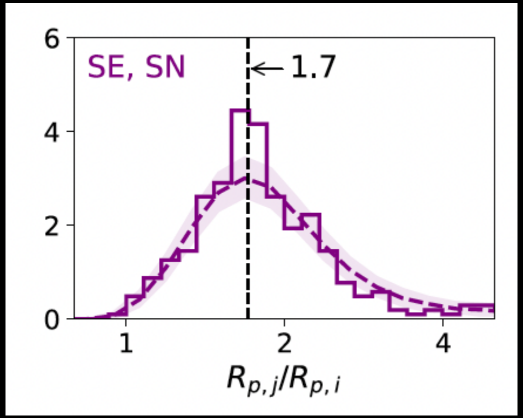


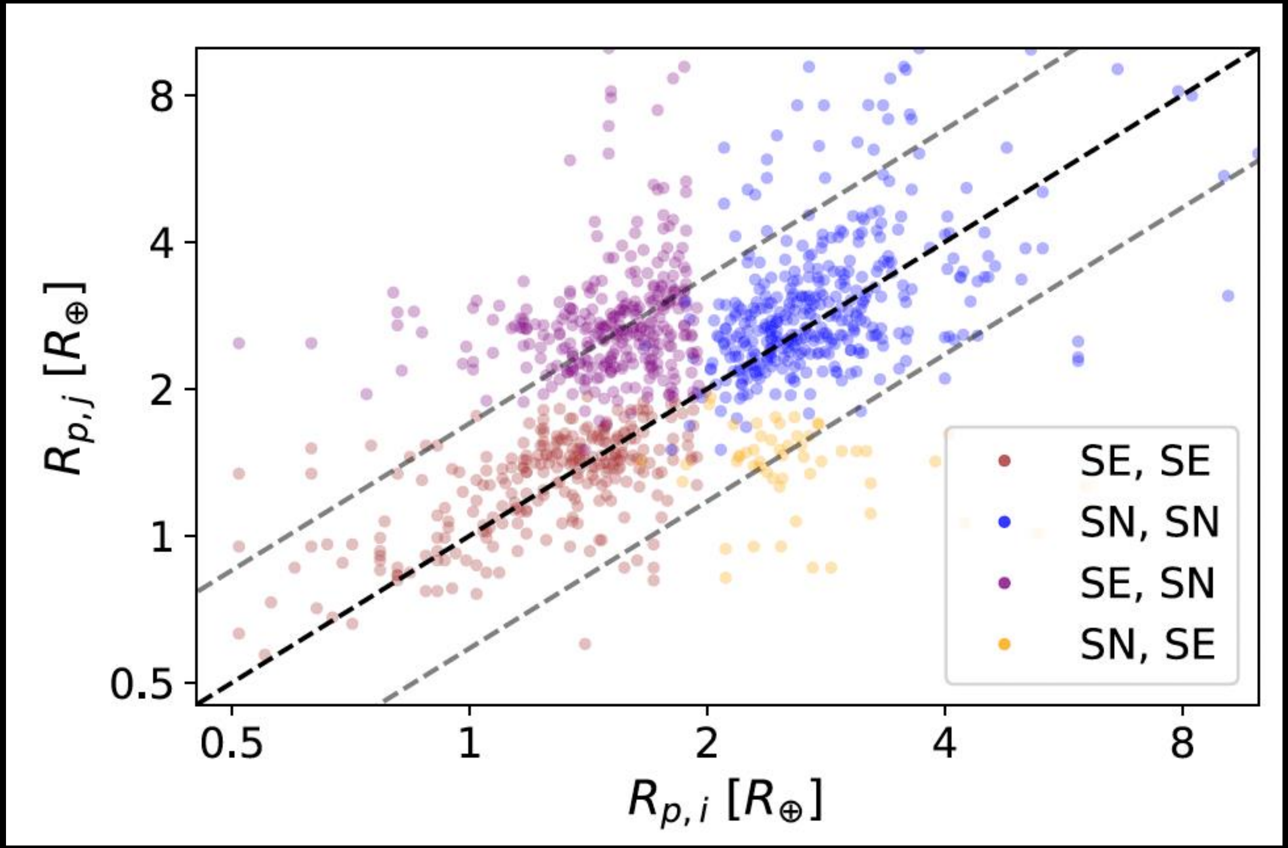
Figures from Millholland & Winn (2021)

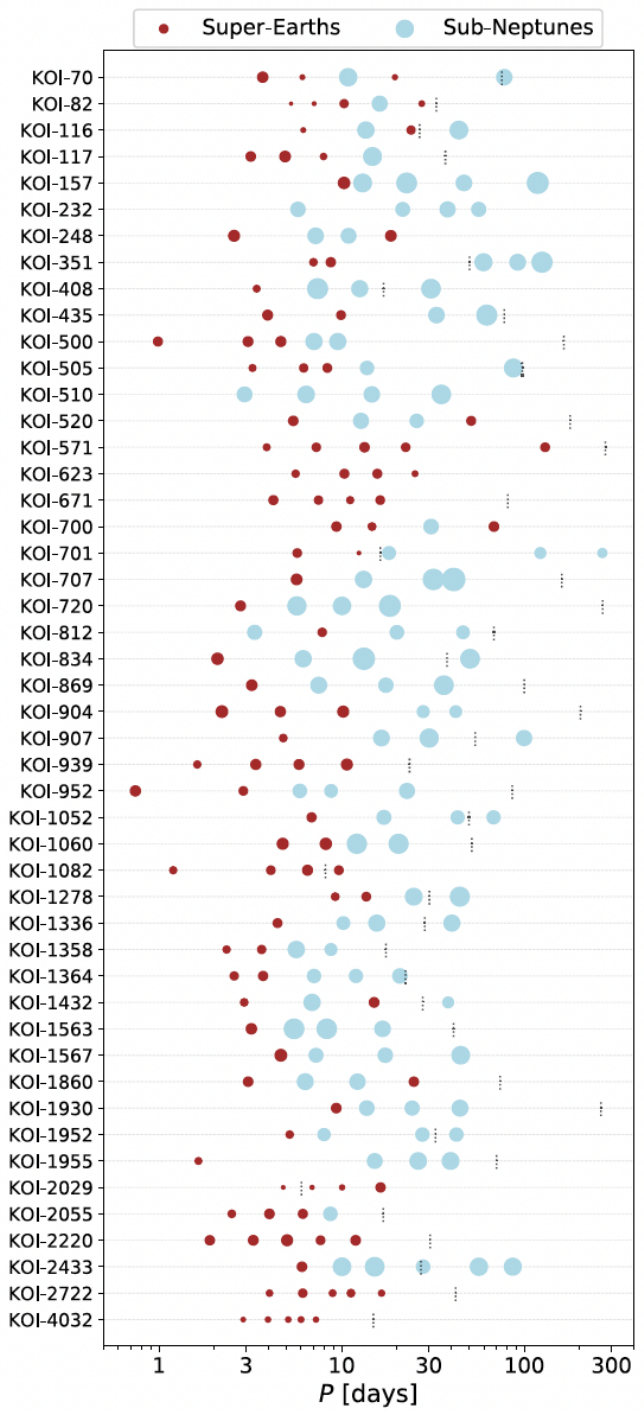
"Split Peas in a Pod"

- Compact systems with both Super-Earths and Sub-Neptunes show planet size correlations within planet classes
- Within a system, sub-Neptunes tend to be 1.7 times larger than Super-Earths



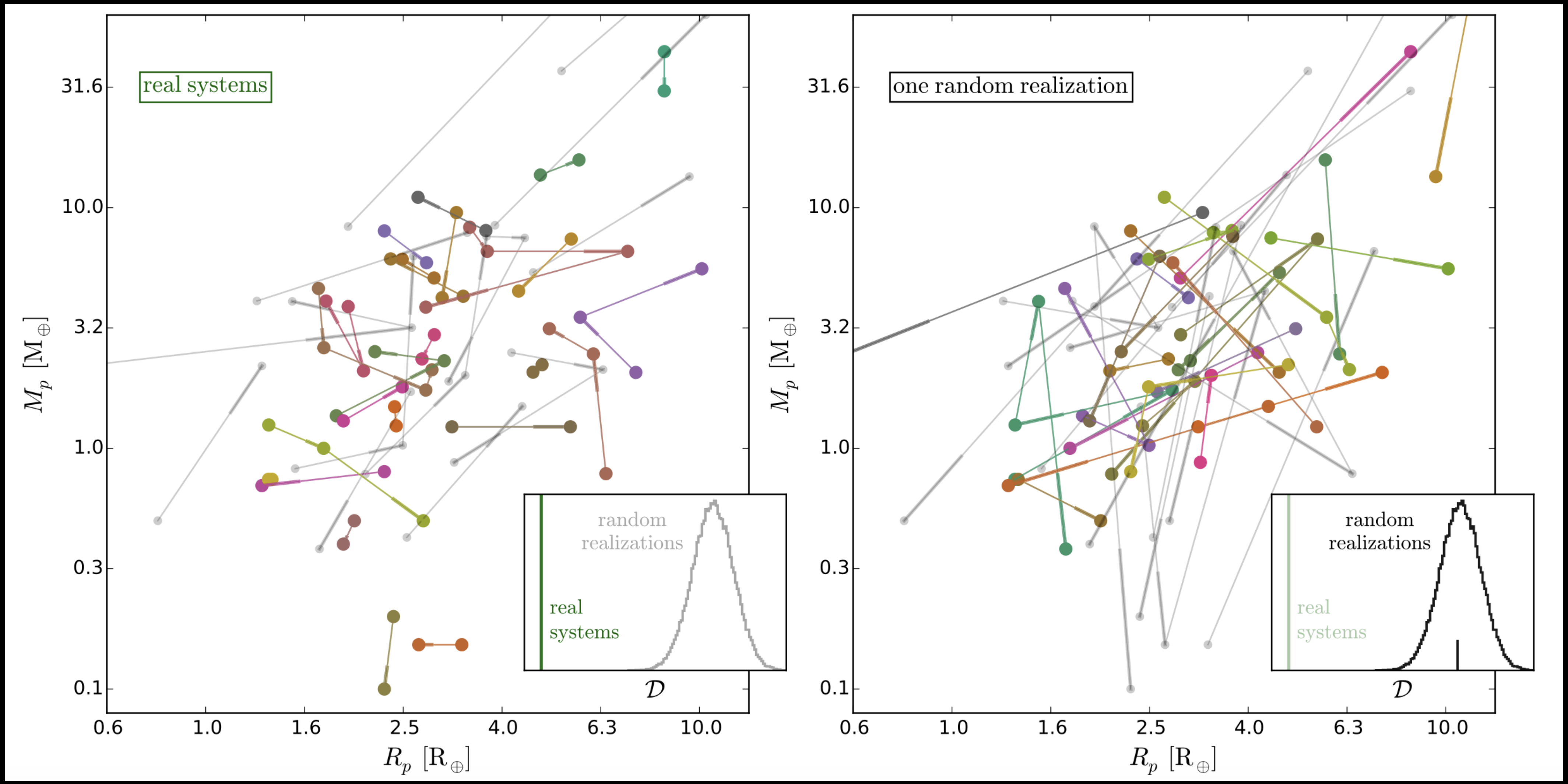






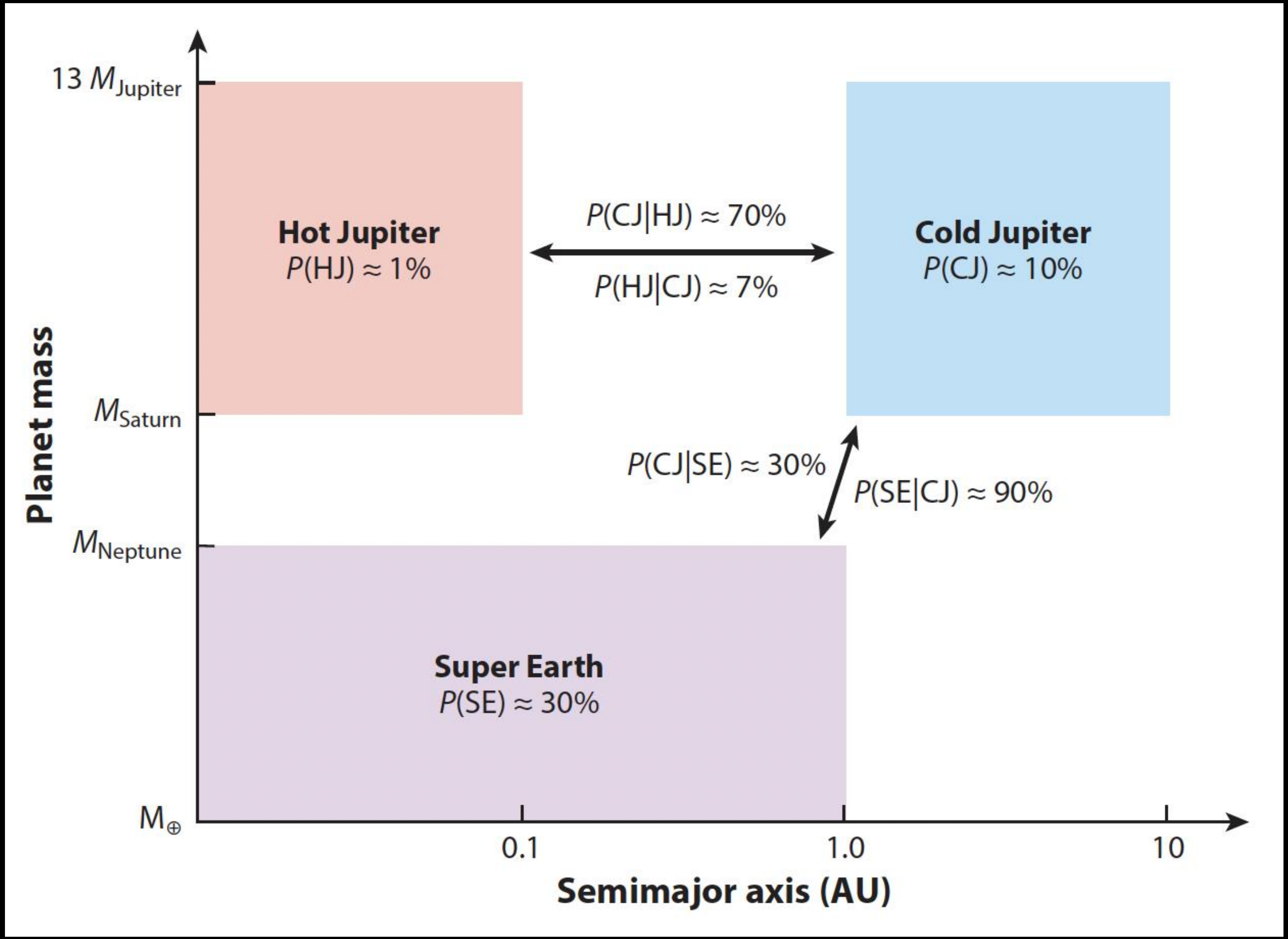
Figures from Millholland & Winn (2021)

Planets in Compact Multis Also Tend to Have Similar Masses



Masses and radii for transiting planets with masses measured from transit timing variations. Figure from Millholland et al. (2017)

Cold Jupiters May Point Towards Hot Super Earths



Zhu & Dong (2021)

- Roughly 1/3 of hot super Earths are in systems with cold Jupiters
- Most systems with Hot Jupiters also have cold Jupiters
- Nearly all systems with cold Jupiters also host inner super-Earths

See also Knutson et al. (2014), Bryan et al. (2016, 2019), Huang et al. (2016), Uehara et al. (2016), Dawson & Johnson (2018), Zhu & Wu (2018), Herman et al. (2019), Masuda et al. (2020)

How Does The Frequency of Outer Gas Giants Depend on the Properties of Inner Planets?

- **See in-person poster 7 by Joshua Bromley**

Gas Giants and Their Friends

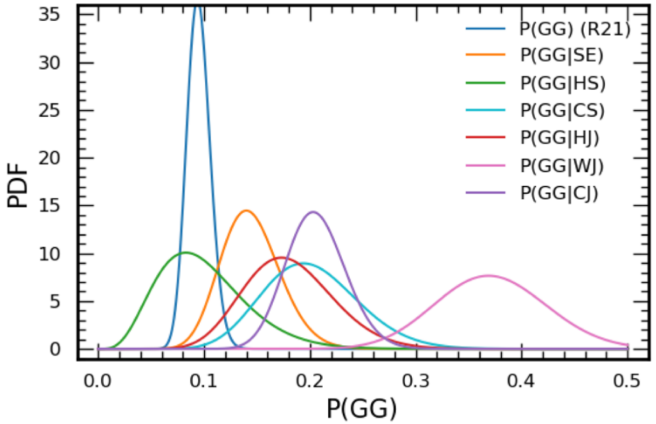
How Gas Giant Properties Vary with Inner Companions

Joshua Bromley[1], Marta L. Bryan[1,2]

1) Department of Astronomy, University of Toronto 2) Department of Chemical & Physical Sciences, University of Toronto Mississauga

David A. Dunlap Department of Astronomy & Astrophysics
UNIVERSITY OF TORONTO

We compute the occurrence rate of gas giants around different types of inner planets. We compare these rates to the occurrence rate of gas giants around field stars taken from Rosenthal et. al. 2021 (R21) [8].



The typical star has a 9% chance of hosting a gas giant. Hot sub-Saturn systems have a similar likelihood. For super Earth, hot Jupiter, and cold Jupiter and sub-Saturn systems, it improves to 15-20%. For a warm Jupiter systems, it is 37%. We see that for almost all types of inner companions, their systems are **more likely to have a gas giant than the typical star.**

How Can Systems Form Planets Interior to Hot Jupiters?

- See in-person poster 38 by Devansh Mathur

Investigating the Formation of Planets Interior to in situ Hot Jupiters

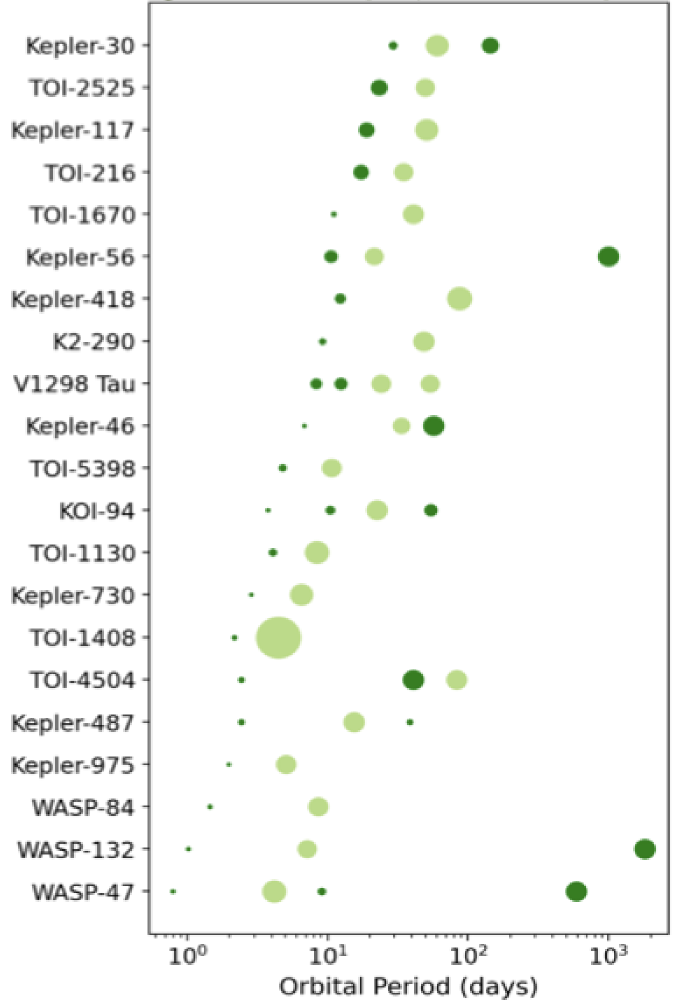
Devansh Mathur & Dr. Juliette Becker
Department of Astronomy, University of Wisconsin - Madison

Results

- **Effect of Planetary Embryo Surface Density**
  - Our simulations suggest that a hot Jupiter core likely formed beyond 0.4 – 0.16 AU, depending on disk model, to supply enough solids for inner planet formation. See **Figure 2**.
  - We find that higher surface densities consistently yield more massive planets, with frequent growth to ≥ 1 Earth mass. See **Figure 5**.
  - Our results show no evidence of growth suppression at high densities, indicating low relative velocities and efficient accretion even in crowded disks. See **Figure 2**.
  - Our simulations confirm that the initial inner disk mass budget is a key driver in determining the formation of detectable super-Earths.

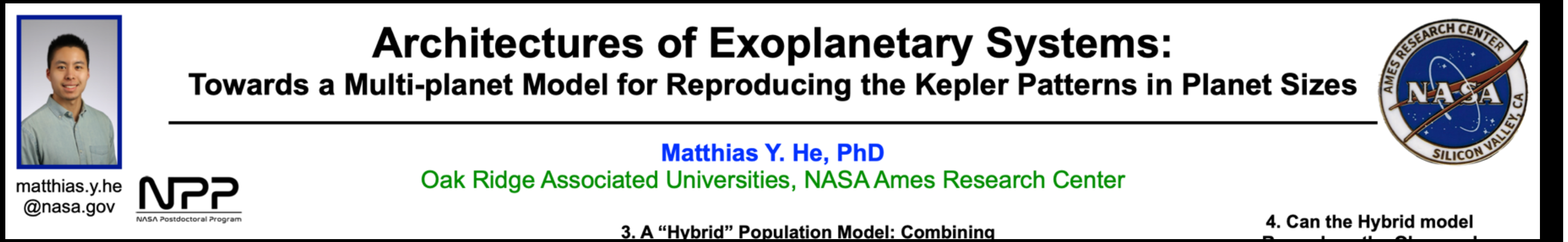
- **Effect of the Hot Jupiter's Orbital Position**
  - We find that inner planet formation is most efficient when the hot Jupiter is at ~ 0.04–0.05 au. See **Figure 4**.
  - Our simulations show that the mass of the companion planet becomes insensitive to hot Jupiter position beyond ~0.10 au (warm Jupiter regime). See **Figure 4**.
  - We observe that the survival rates of embryos increase with larger hot Jupiter orbital distances. See **Figure 6**.
  - In the closest-in cases (<0.06 AU), our simulations show that only ~20% of embryos survive, indicating strong dynamical disruption.
  - At wider orbits (>0.08 AU), our results show that more embryos survive and grow, pointing to reduced loss through collisions or ejections. See **Figure 6**.

Figure 1: Observed hot Jupiter systems with inner companions.



System Architectures Hold Clues to the Physics Of Planet Formation & Evolution

- See in-person poster 23 by Matthias He


Architectures of Exoplanetary Systems:
Towards a Multi-planet Model for Reproducing the Kepler Patterns in Planet Sizes

Matthias Y. He, PhD
Oak Ridge Associated Universities, NASA Ames Research Center
matthias.y.he
@nasa.gov

NPP
NASA Postdoctoral Program

3. A "Hybrid" Population Model: Combining

4. Can the Hybrid model

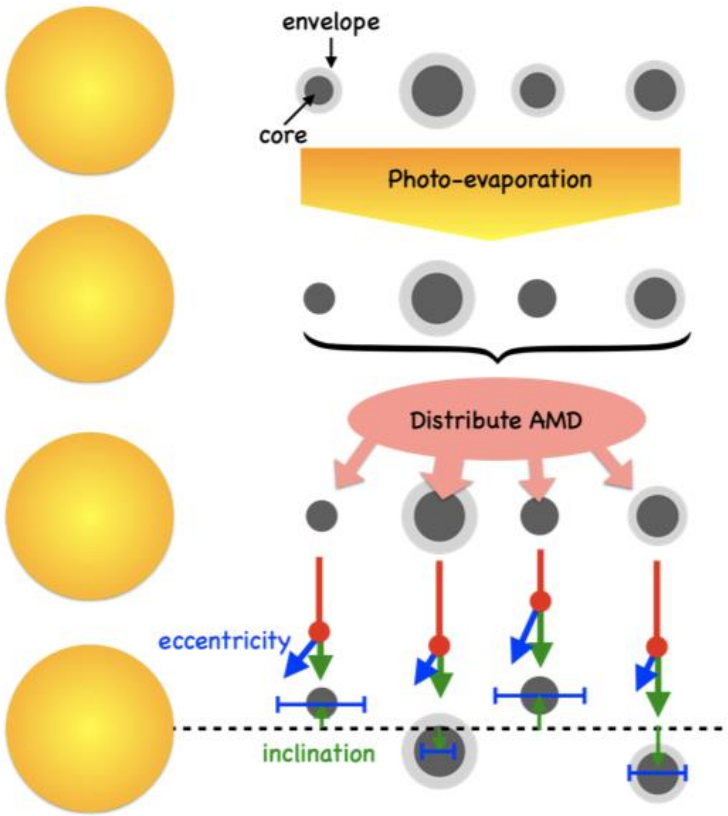


Fig. 4: Cartoon illustration of the hybrid model. The initial masses and radii are drawn from a broken power-law (blue curve in Fig. 3), and the photoevaporation mass-loss timescale is computed to determine which planets lose their atmospheres, following NR20. The final orbital architectures are drawn in a way to ensure mutual Hill radii stability and angular momentum deficit (AMD) stability, following H20.

G&F Metric 4: Characteristic Spacing

- What is the typical separation between planets?

$$\mathcal{S} \equiv \text{mean}(\Delta_{\text{H}}),$$

Characteristic spacing

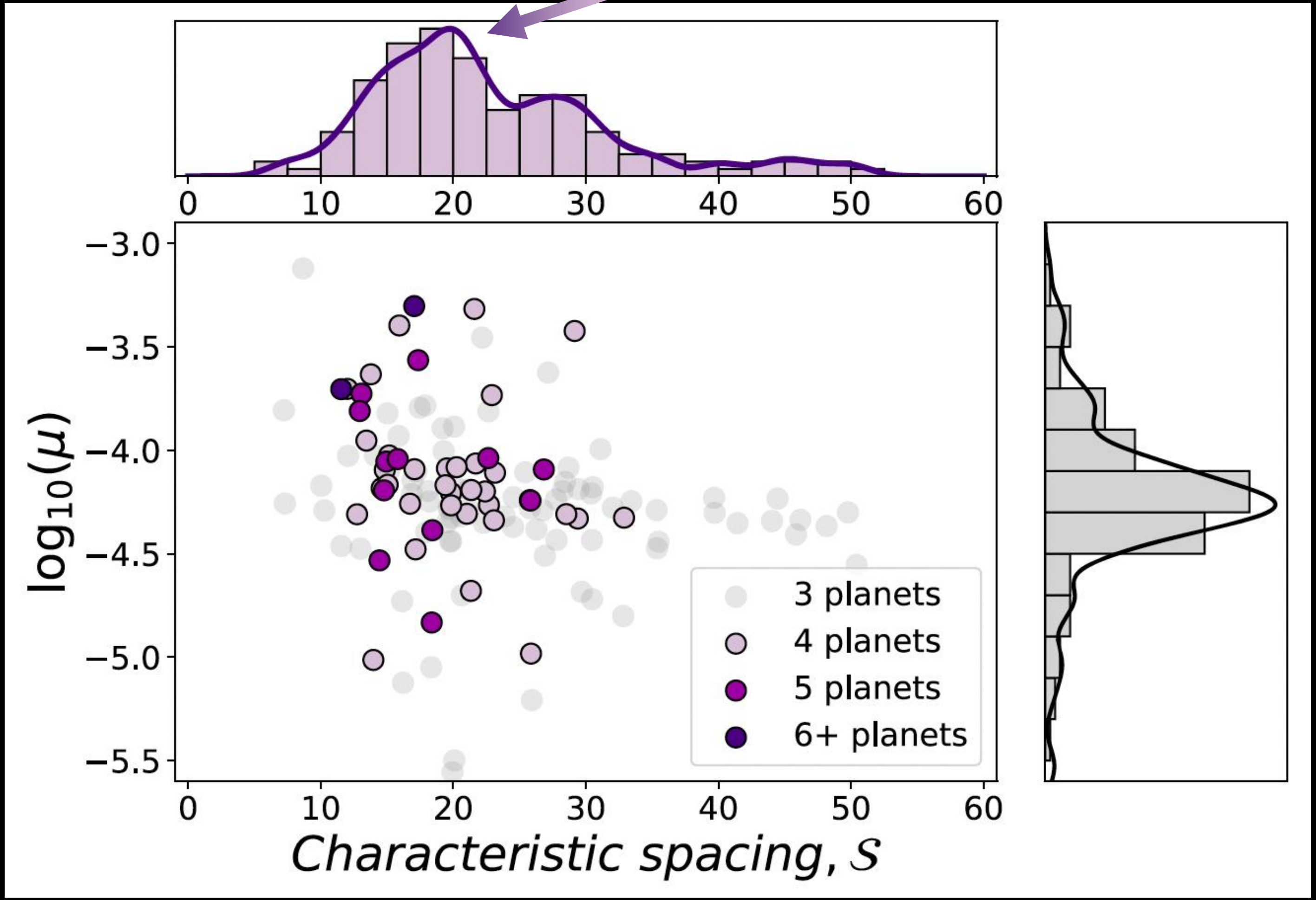
$$\Delta_H = (a' - a)/r_H$$

Scaled separation

$$r_H = \left(\frac{m' + m}{3M_\star}\right)^{1/3}\left(\frac{a' + a}{2}\right)$$

Mutual Hill radius

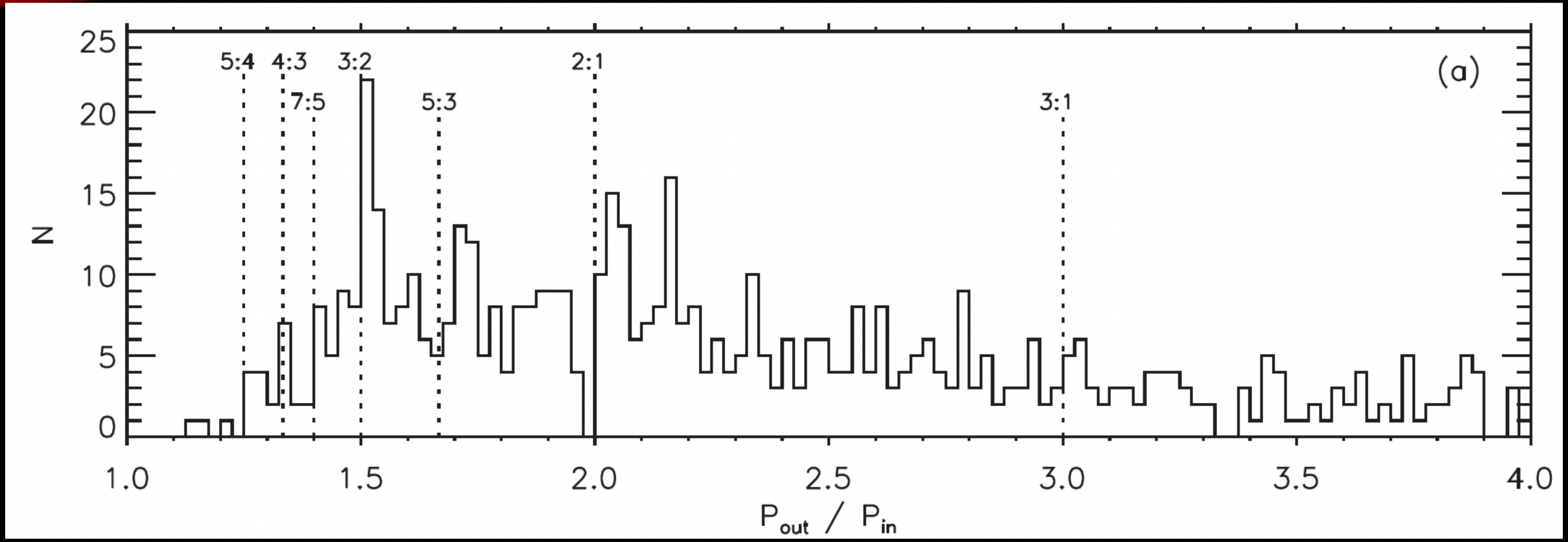
Typical separation ≅ 20 Hill radii



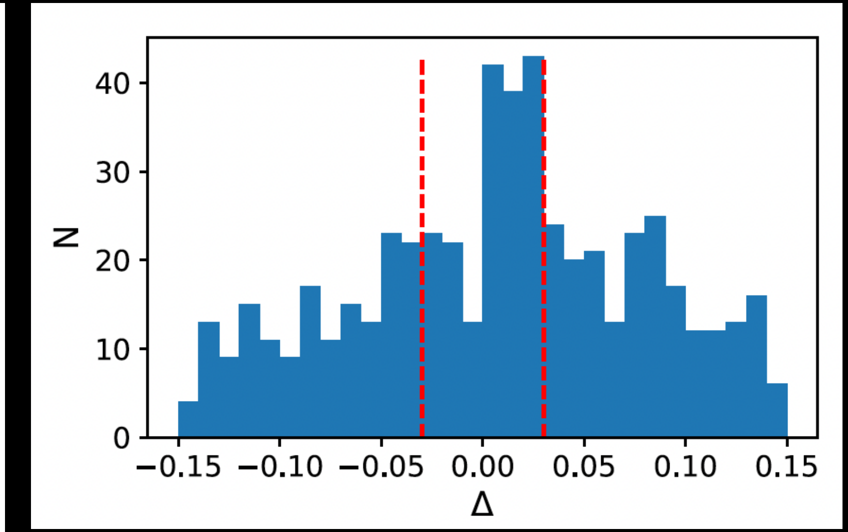
Gilbert & Fabrycky (2020)

Consistent with Lissauer+2011, Fang & Margot 2012, Pu & Wu 2015, Dawson+2016, Weiss+2018

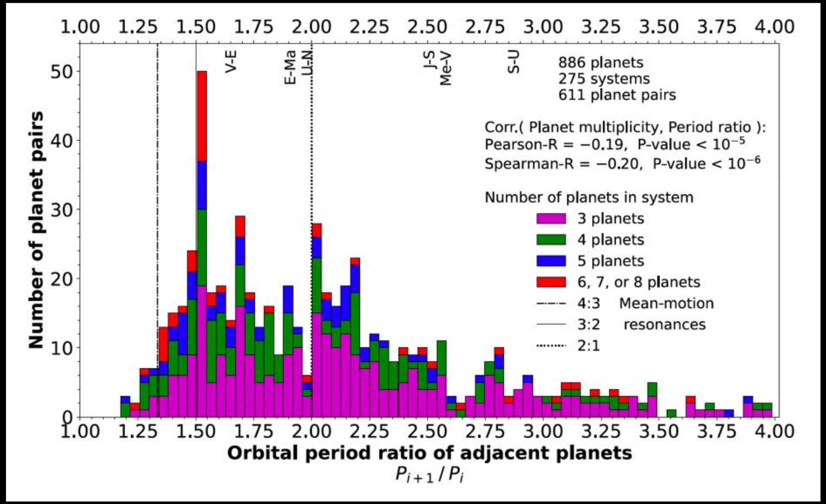
There is an Excess of Planets Just Wide of Resonance



Fabrycky et al. (2014)



Jiang et al. (2020)



Muresan et al. (2024)

- There are clear peaks in the distribution of period ratios for adjacent planets.
- Systems just wide of resonance are much more common than those just narrow of resonance.

System Architectures Can Be Shaped By Migration

- See in-person poster 29 by Finnegan Keller

Higher-Order Mean-Motion Resonances Can Form in Type-I Disk Migration

School of Earth and Space Exploration
Arizona State University

Finnegan Keller [1, 2, 3] Fei Dai [3, 4, 5] Wenrui Xu [6]

[1]School of Earth and Space Exploration, Arizona State University [2]Department of Physics, Brown University [3]Institute for Astronomy, University of Hawai'i
[4]Division of Geological and Planetary Sciences, California Institute of Technology [5]Department of Astronomy, California Institute of Technology
[6]Center for Computational Astrophysics, Flatiron Institute

- We performed $\sim 6,000$ Type-I simulations of multi-planet systems with initial conditions that mimic the observed *Kepler* sample.
- We found that Type-I migration coupled with a disk inner edge can produce second- and third-order resonances in a manner that is consistent with observations (Figs 2 and 4).
- Planets that end engaged in a higher-order resonance need not begin near the resonance (Figs 1 and 3).
- For further motivation, methods, and findings, see the preprint [30].

PREPRINT

How Does Planet Mass Ratio Affect Period Ratio?

- See in-person poster 36 by Linghong Lin

Resonance Capture and Stability Analysis for Planet Pairs under Type I Disk Migration

Linghong Lin[1], Beibei Liu[1★], and Zekai Zheng[1,2]

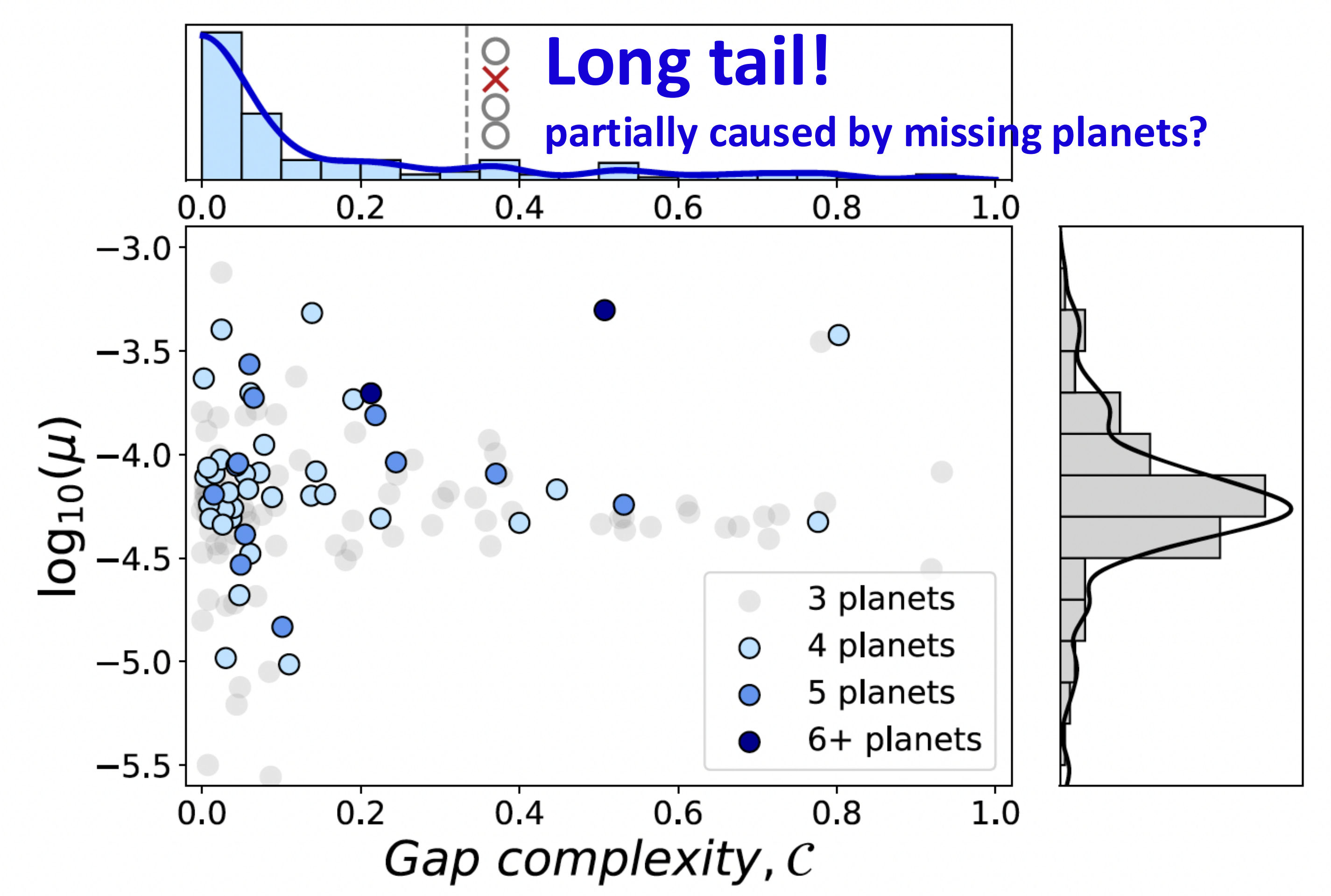
[1] Institute for Astronomy, School of Physics, Zhejiang University, Hangzhou 310027, China
e-mail: [llh_astro; bbliu]@zju.edu.cn
[2] Department of Physics, National University of Singapore, Singapore 117542, Singapore
e-mail: zekai77@u.nus.edu

Article Link: **https://arxiv.org/abs/2501.12650**

G&F Metric 5: Gap Complexity

- How predictable is the relationship between planetary periods?

- In most cases, planet spacing appears very regular
- Planet spacing is more uniform than required by analyses of adjacent planets
- Systems with high ***apparent*** gap complexity might actually have low gap complexity if we could detect all of the planets.



Gilbert & Fabrycky (2020)

Inferences About System Architectures May Be Incorrect When Planets Are Missed

- **See in-person poster 56 by Alexander Thomas**

UNIVERSITY OF NOTRE DAME

Alex Thomas
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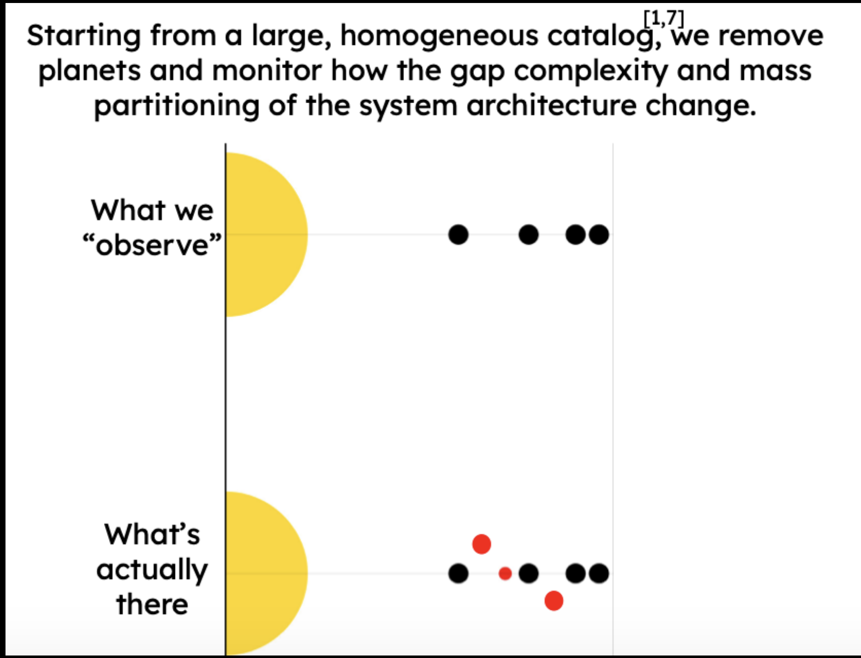
@spacealexspace.bsky.social

Biases From Missing a Small Planet in High Multiplicity Systems

C. Alexander Thomas, Lauren Weiss, Matthias He

Accepted for Publication in Astrophysical Journal Letters



Lead author
Emma Turtelboom
(UC Berkeley → McMaster)

Testing Empirical Models of Exoplanet Systems Based on Kepler Data:

Searching for Additional Planets in TESS Multi-Planet Systems

Emma Turtelboom (UC Berkeley → Herschel Postdoctoral Fellow at McMaster), **Jamie Dietrich** (postdoc at Arizona State University), **Courtney Dressing** (she/her; UC Berkeley), & **Caleb Harada** (grad student at UC Berkeley)

Turtelboom, Dietrich, Dressing, & Harada
(2025, AJ, 170, 3; arXiv:2409.03852)

Work supported by the Packard Foundation & NASA XRP

Key Question:

How Well Do We Understand the Architectures of Multiplanet Systems?

If we have detected some planets in a system, can we successfully predict the properties of additional planets in the system?

Methodology

Use empirical models to make predictions about the likely radii and periods of as-yet-undetected planets in systems that are known to have multiple planets

Collect more observations of those stars

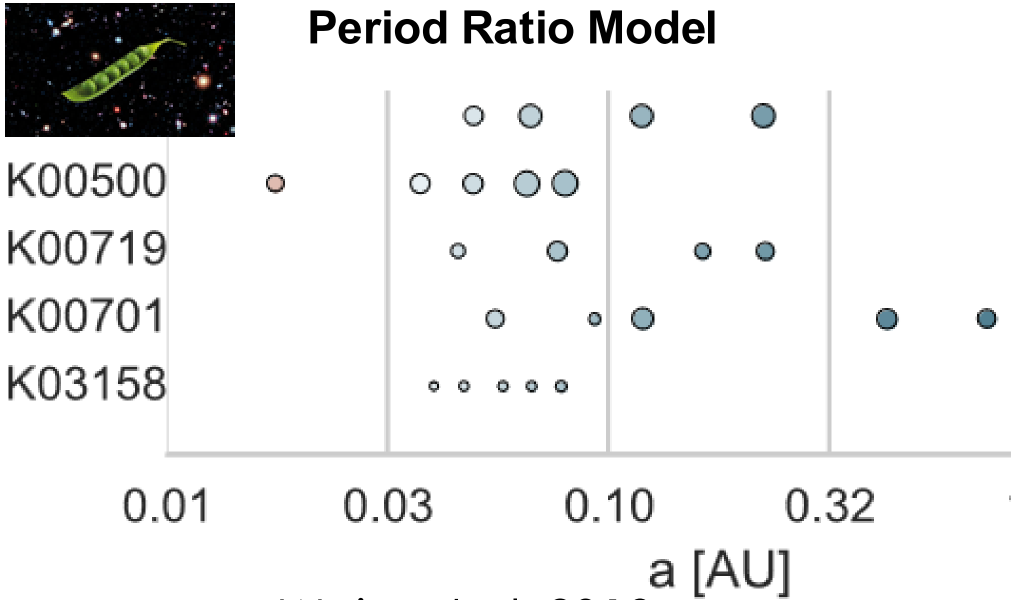
Search the expanded data set for additional planets

Investigate detectability of predicted planets

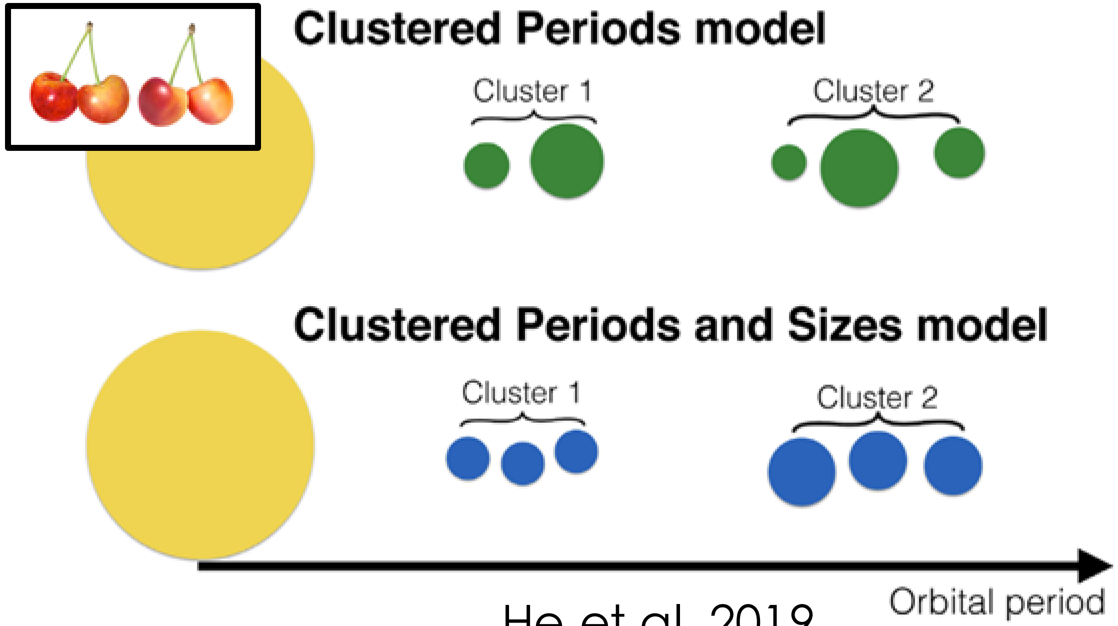
Check whether newly detected planets match predictions

Step 1: Predict Planet Properties

- **Jamie Dietrich** (now at ASU, then at Arizona) developed the **DYNAMITE** package (https://github.com/JamieDietrich/dynamite) to predict system properties and test architectures (Dietrich & Apai 2020, 2021; Dietrich et al. 2022; Basant et al 2022a, 2022b; Dietrich 2024)
- Predicted additional planets in **52 TESS multiplanet systems** using two models for the distribution of planet periods



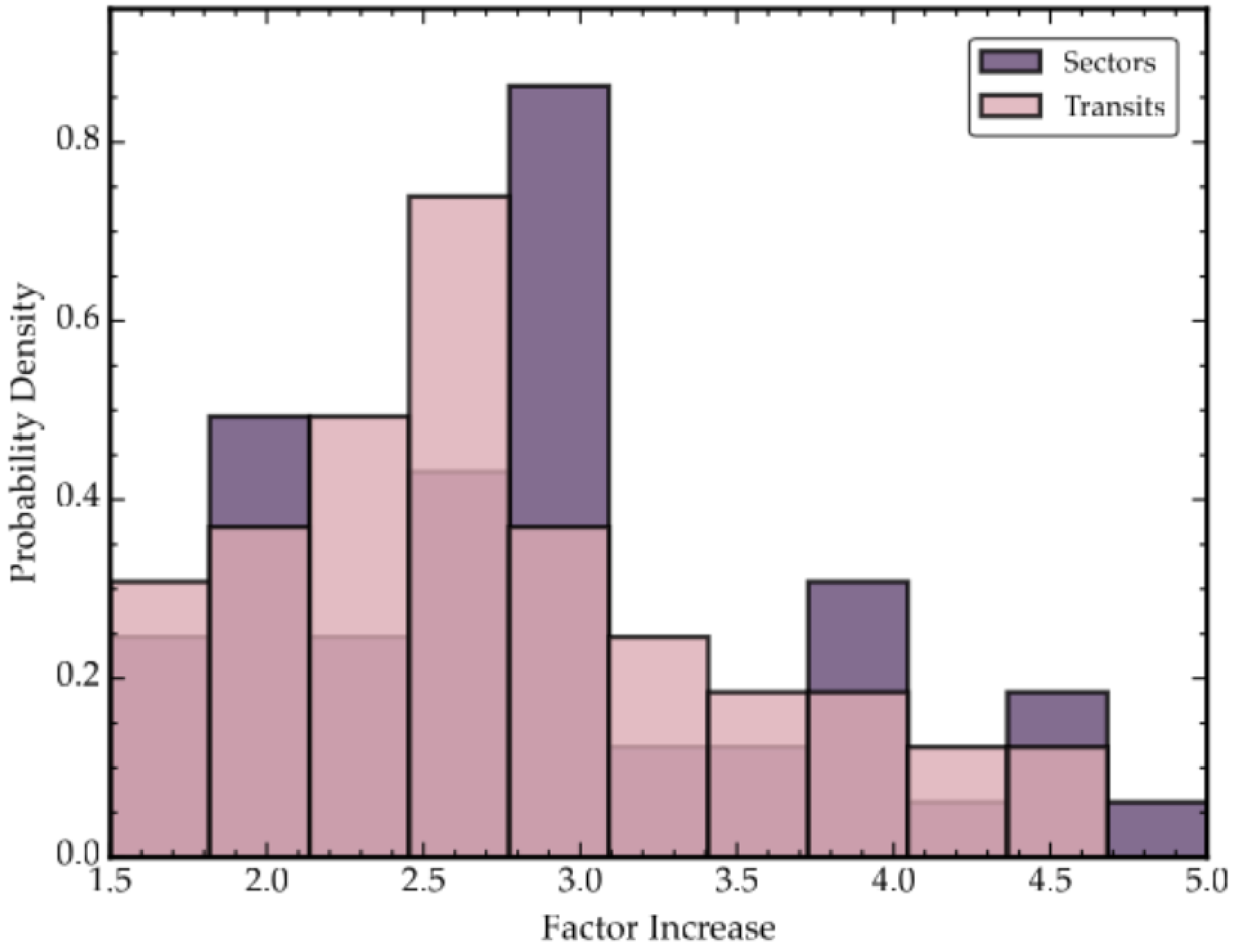
Weiss et al. 2018



He et al. 2019

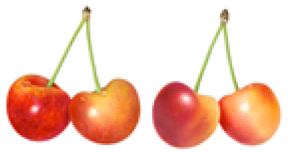
Step 2: Collect More Observations

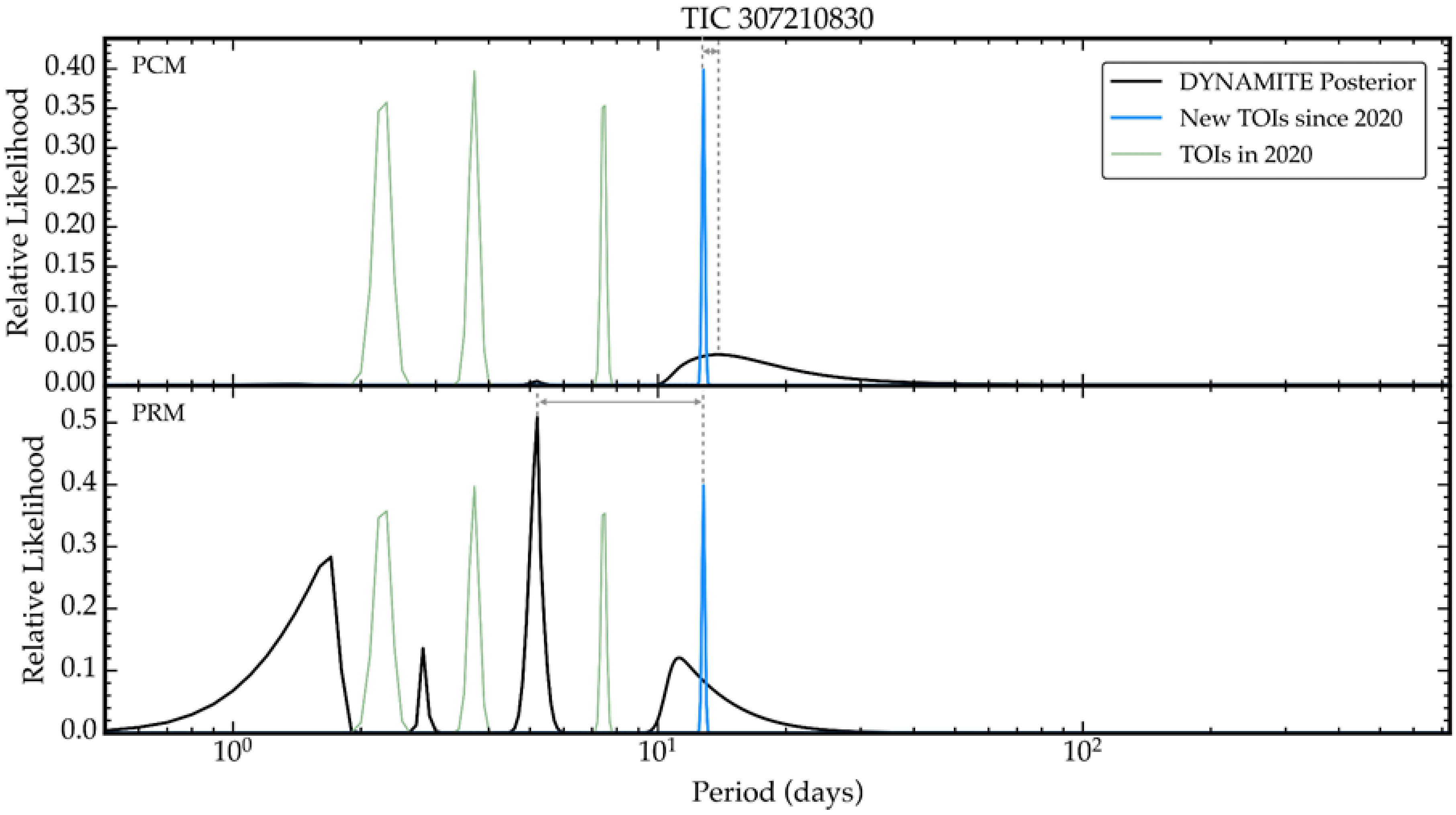
- Between 2020 and 2024, TESS continued to observe the sky
- A typical star in the sample received ***five additional sectors*** of TESS data!
- Most targets had ***at least twice as much data*** in 2024 as in 2020
- The most heavily observed stars had ***six times as many sectors*** of data and ***4.5 times more transits!***



Turtelboom, Dietrich, Dressing, & Harada (2025)

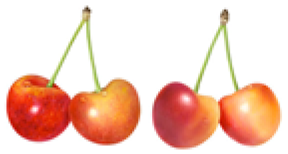
Step 5: Assess Model Predictions

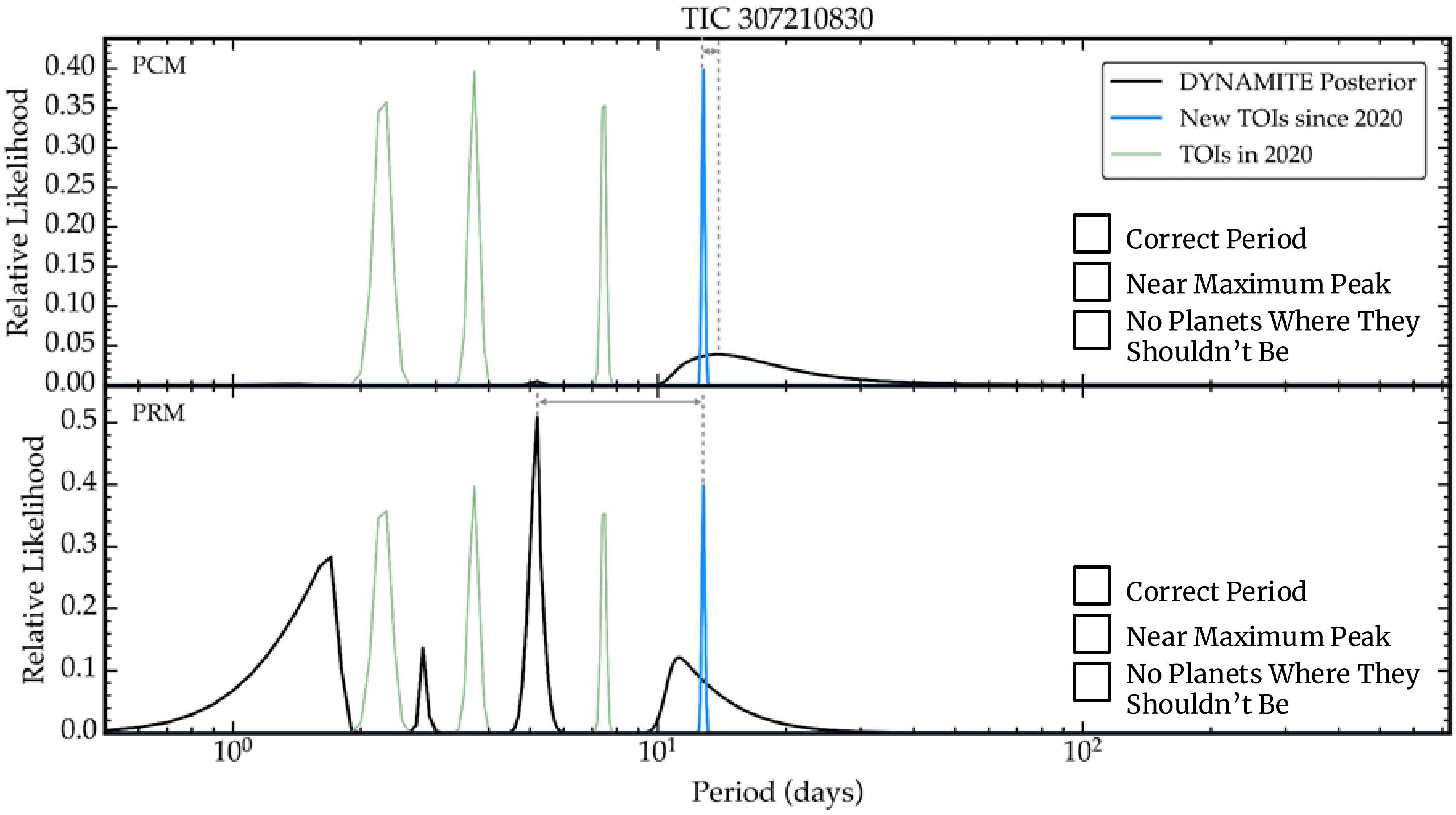




Turtelboom, Dietrich, Dressing, & Harada (2025)

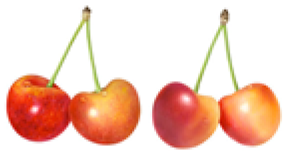
Step 5: Assess Model Predictions

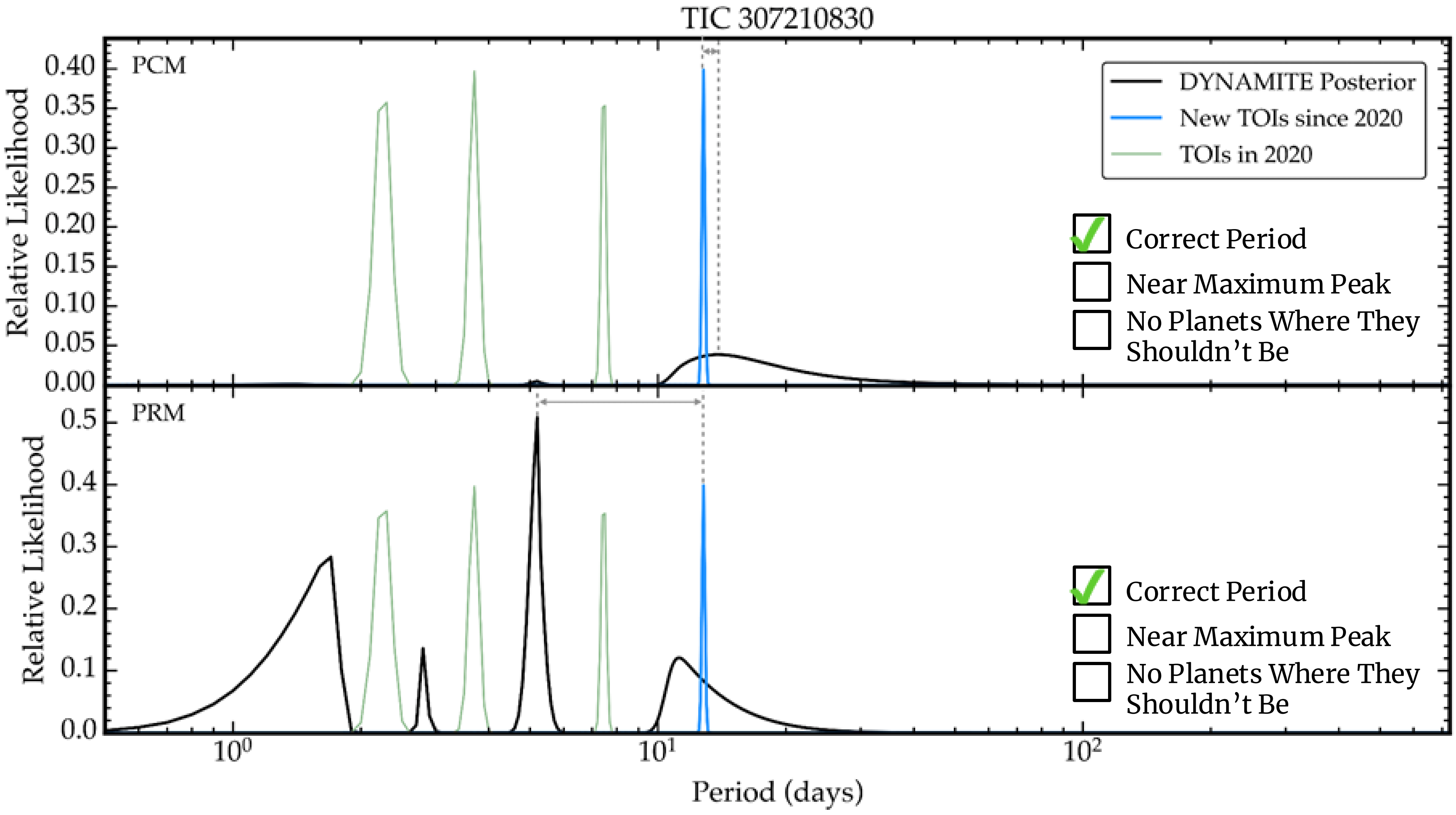




Turtelboom, Dietrich, Dressing, & Harada (2025)

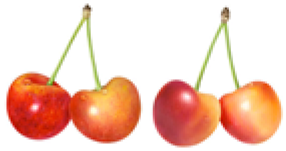
Step 5: Assess Model Predictions

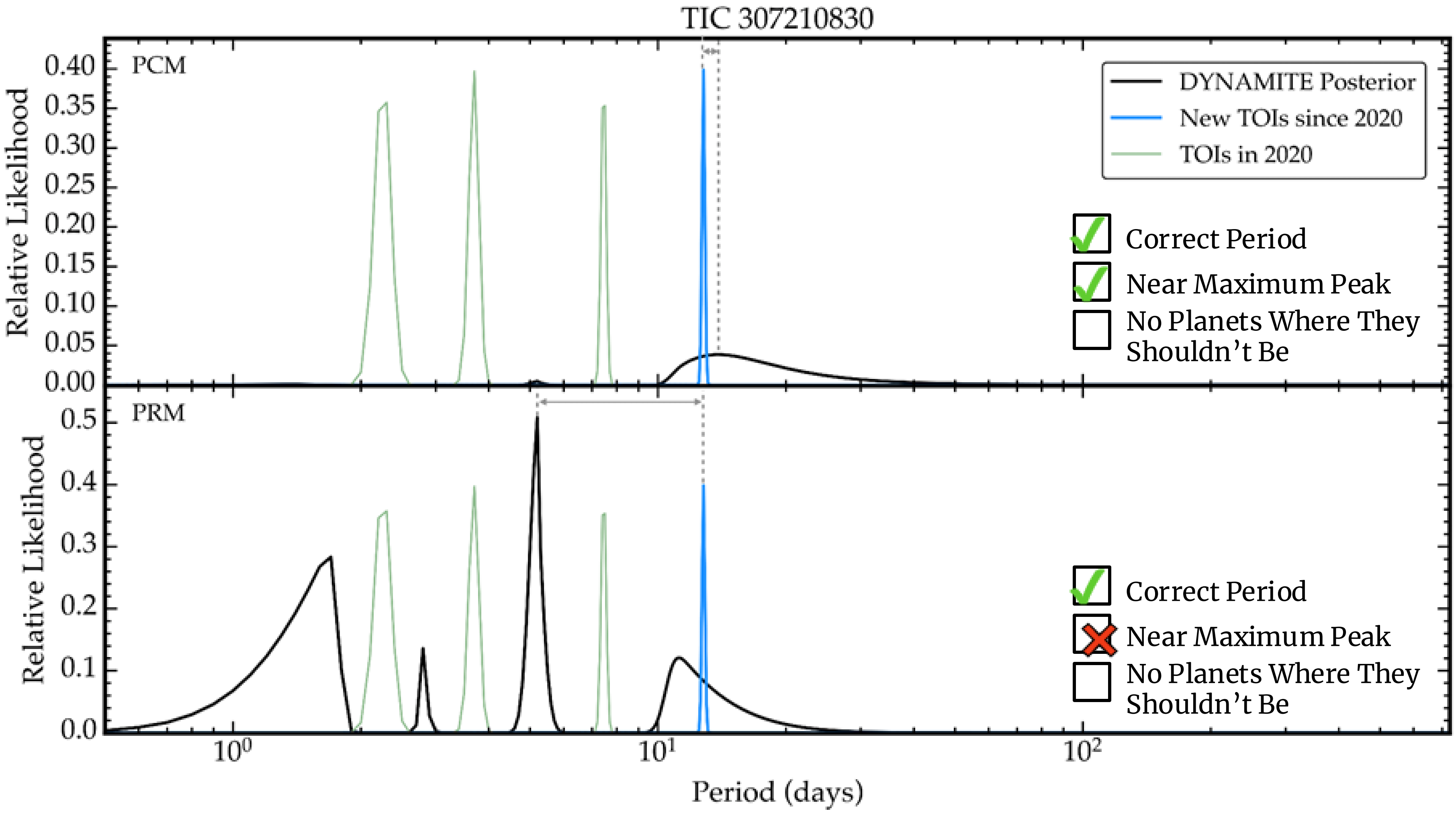




Turtelboom, Dietrich, Dressing, & Harada (2025)

Step 5: Assess Model Predictions

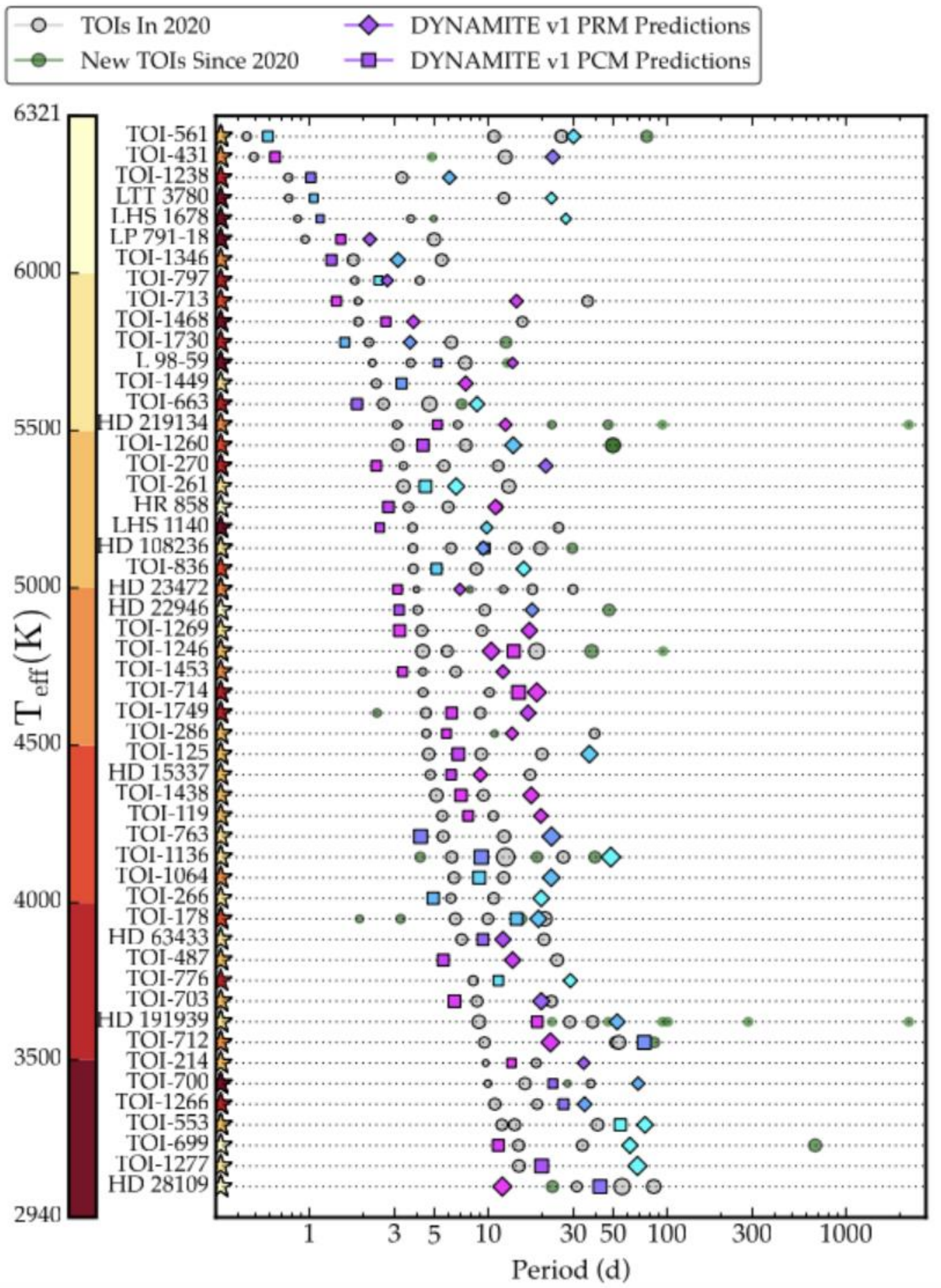




Turtelboom, Dietrich, Dressing, & Harada (2025)

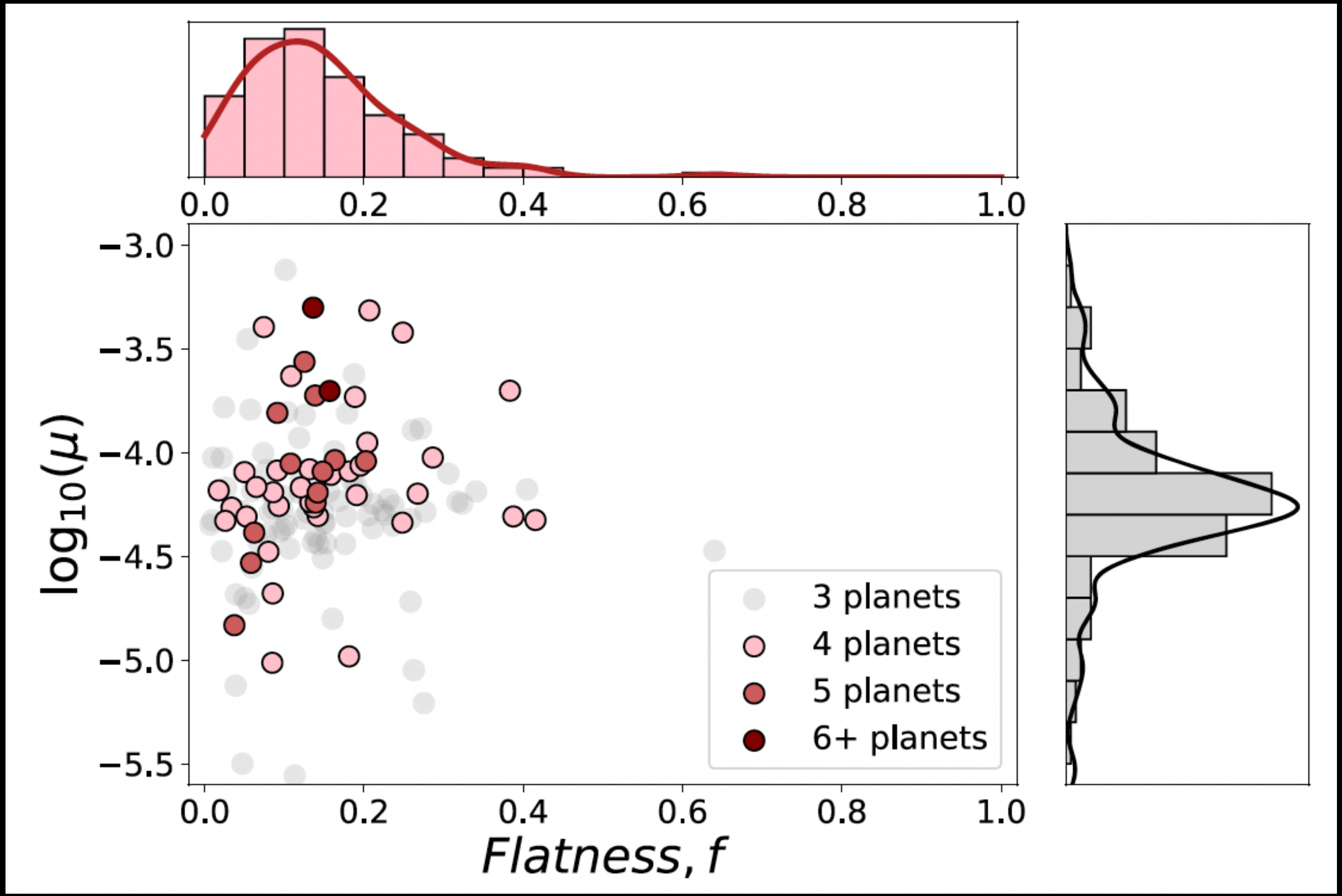
Key Result: ***Neither*** **model accurately predicted additional planets**

- 8 of 25 newly detected planets have >10% period overlap with PRM or PCM predictions
- Using updated predictions from DYNAMITE v3 (Dietrich et al. 2022) that include non-circular orbits & variable inclinations slightly improves predictions (13 matches instead of 8)
- Periods tend to **be closer to primary peak of PRM posteriors** than primary peak of PCM posteriors
- For more details, see **Turtelboom**, Dietrich, Dressing, & Harada (2025, AJ, 170, 3;; **arXiv:2409.03852**)



G&F Metric 6: Flatness

- How similar are the orbital planes of the planets?
  - Most systems are very flat



Gilbert & Fabrycky (2020)

Obliquity Measurements Provide Valuable Information About Architectures

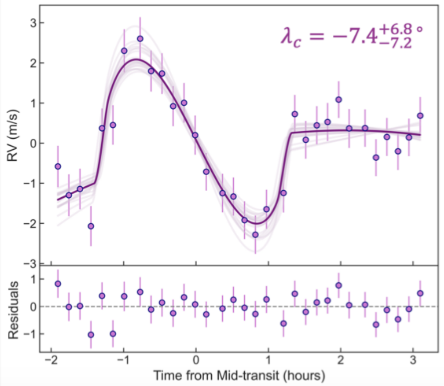
- See in-person poster 62 by Elina Yuchen Zhang

TOI-880: A Dynamically Cold, Aligned, Coplanar Multi-Planet System -- Adding to the Demographic Portrait of Compact, Multi-Transiting Systems

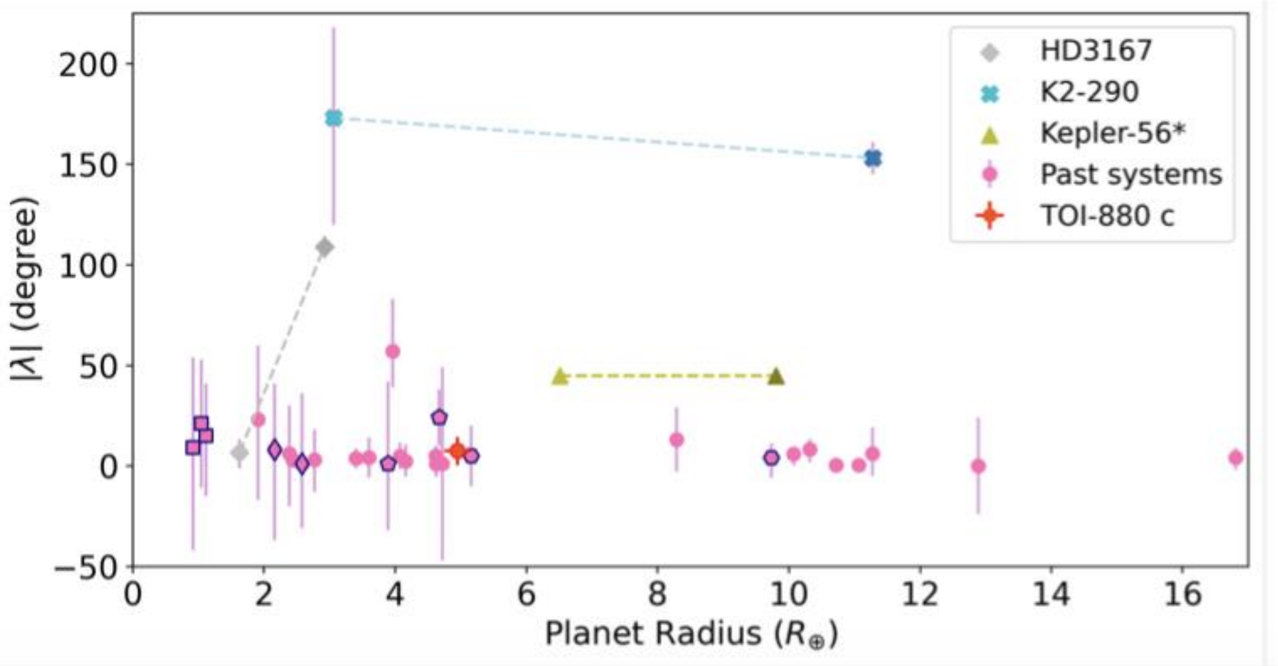
Elina Yuchen Zhang (yuchenzh@hawaii.edu), Fei Dai, Huanyu Teng, *et al.*
Institute for Astronomy, University of Hawai'i at Mānoa

Spin-Orbit Alignment via Rossiter–McLaughlin Effect

- Measured for TOI-880 c using Keck Planet Finder (KPF).
- Sky-projected obliquity:
- $\lambda_c = -7.4^{+6.8}_{-7.2}{}^\circ$, consistent with an aligned, prograde orbit.
- Low $vsini_\star$ and lack of rotational modulation → slow stellar spin → minimal nodal precession.



The RV variations during the transit of TOI-880 c on UTC Jan 20, 2024.



Hot Jupiters In Compact Systems Appear Preferentially Aligned With Their Host Stars

- See in-person poster 42 by Brandon Radzom

Evidence for Primordial Alignment: Insights from Stellar Obliquity Measurements for Giants in Compact Systems

Brandon Radzom[1], Jiayin Dong[2], Malena Rice[3], Xian-Yu Wang[1], Samuel Yee[4,5], Tyler Fairnington[6], Cristobal Petrovich[1], Songhu Wang[1]

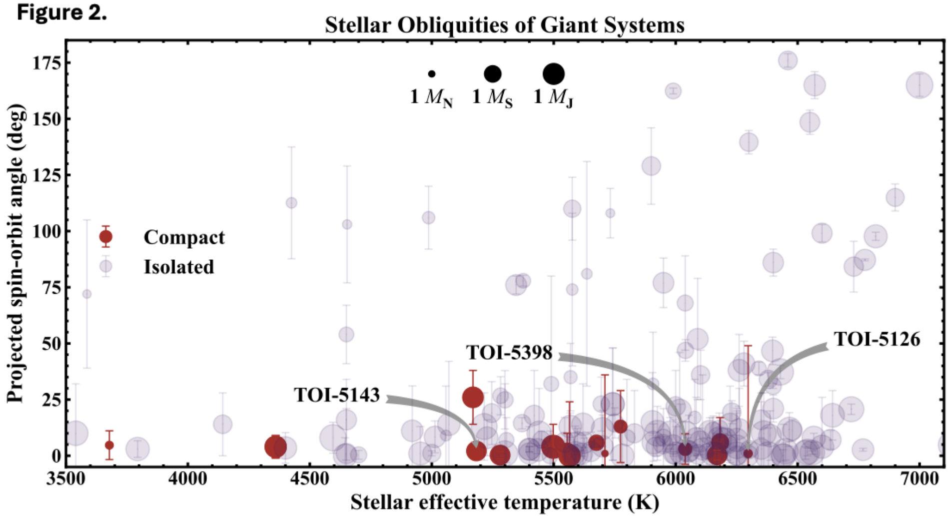
[1]Indiana University, [2]Flatiron Institute – CCA, [3]Yale University, [4]Harvard – CfA, [5]Princeton University, [6]University of Southern Queensland

My Website:

Contact: bradzom@iu.edu

Significant Support for Primordial Alignment

Figure 2.

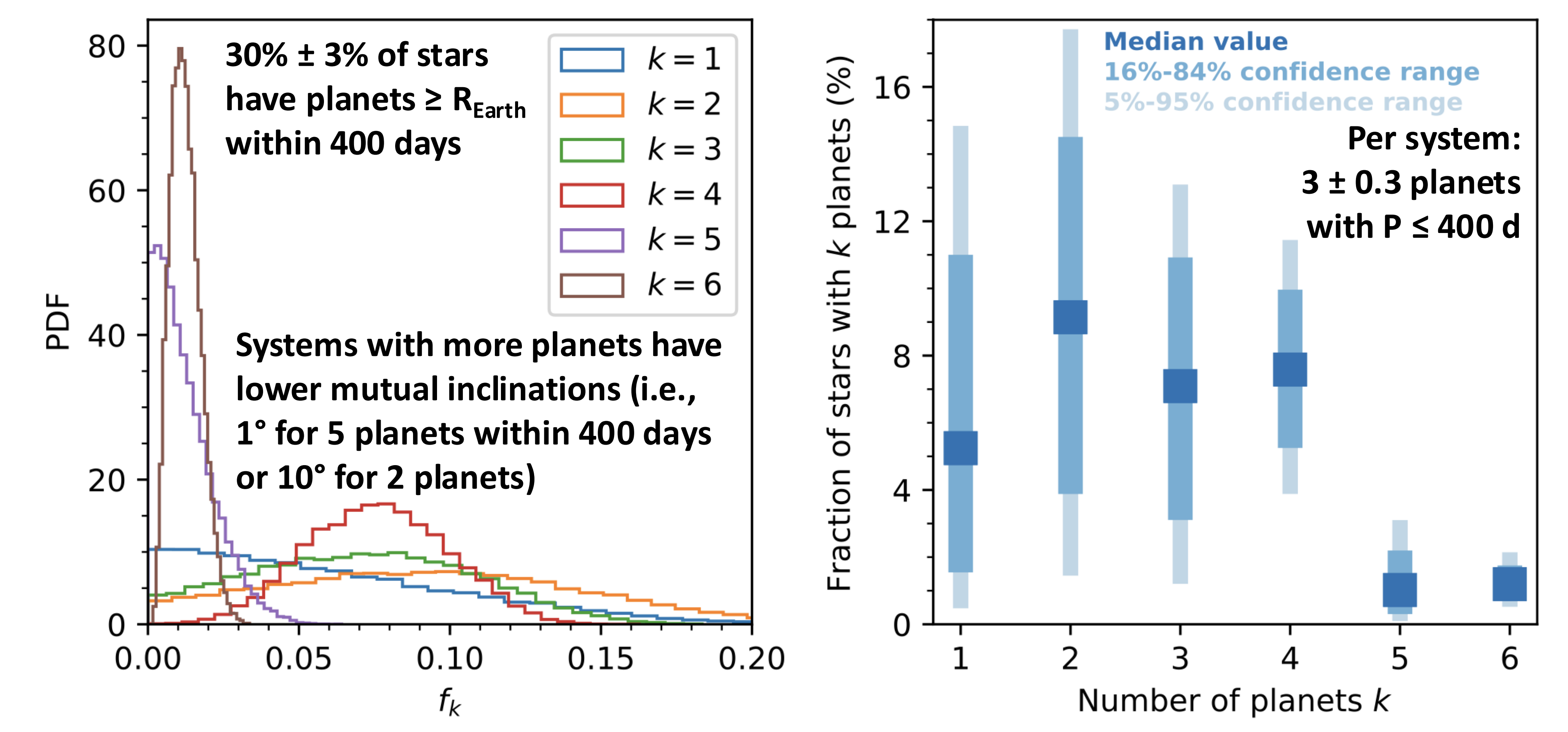


Our measurements for TOI-5126 b and TOI-5398 b enable the first **statistical verification** of the alignment of compact sub-Saturn systems (2.6σ; see also Figure 2)[12]. TOI-5143 c is **only the third** hot Jupiter in a compact system to have its spin-orbit angle measured, and all three are aligned[13].

Together, our results strongly suggest that close-in giants like **hot Jupiters form spin-orbit aligned,** providing renewed support for **violent evolutionary pathways** like high-eccentricity migration **in misaligned systems** while also affirming that giants in **compact systems have** dynamically **quiescent origins,** such as disk migration — even hot Jupiters.

G&F Metric 7: Multiplicity

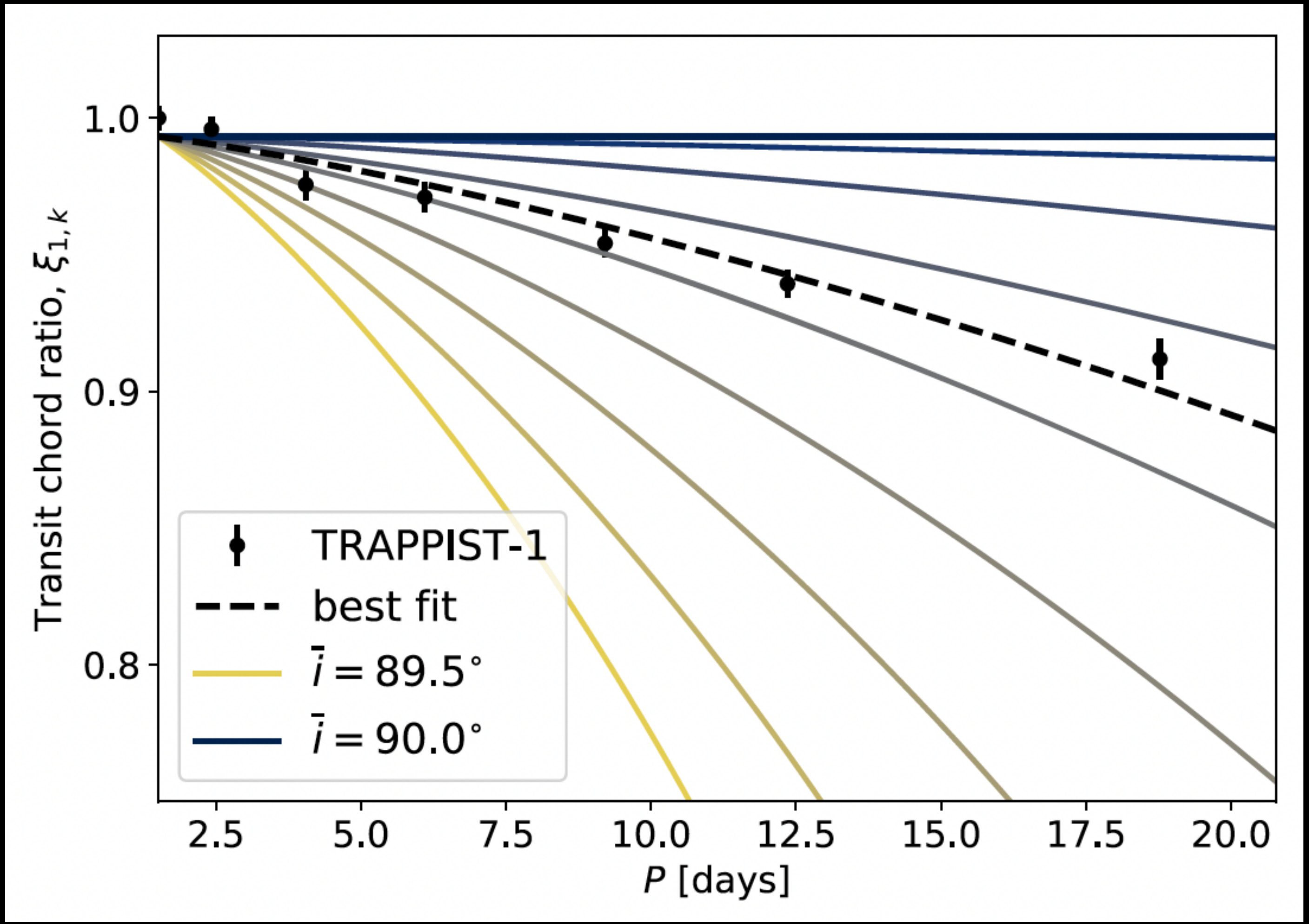
- How many planets are known to exist in the system?



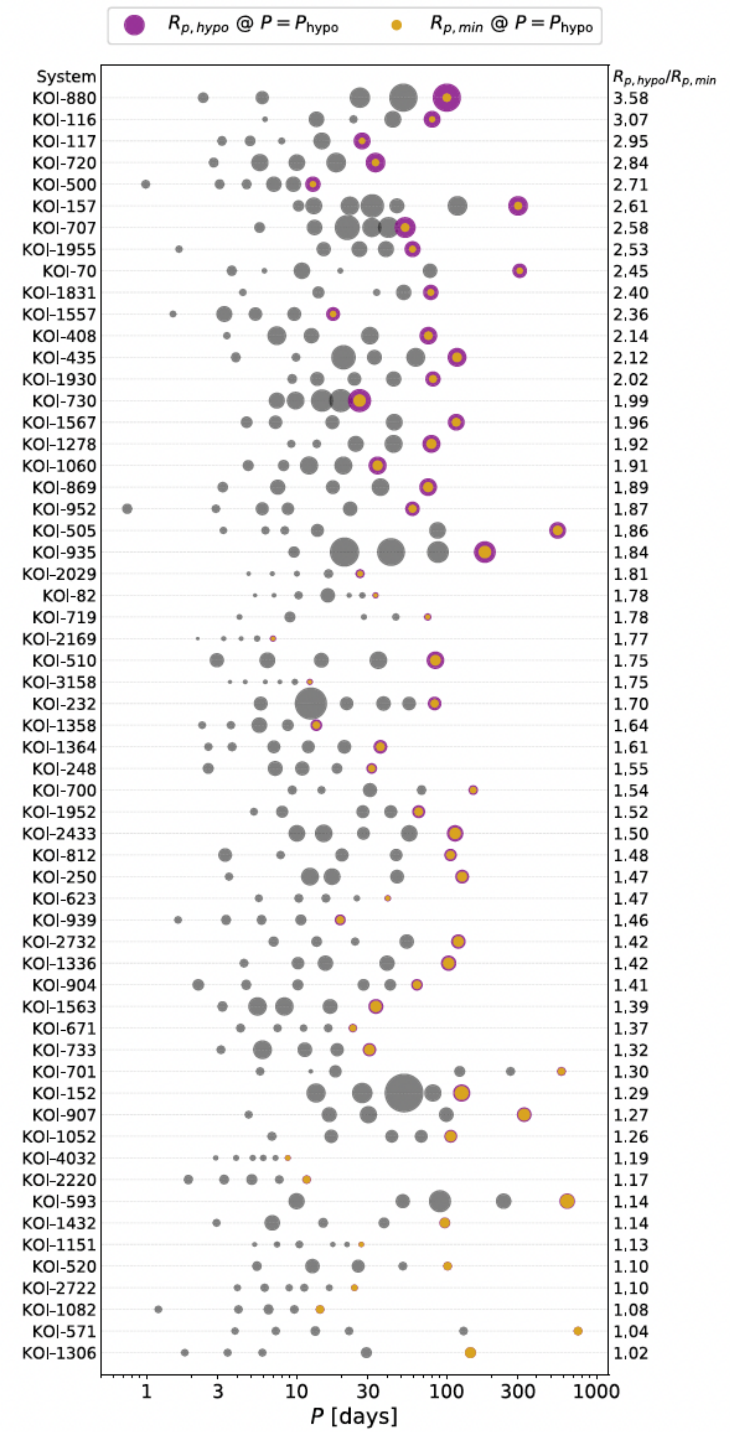
See also Fang & Margot (2012)

Zhu et al. (2018)

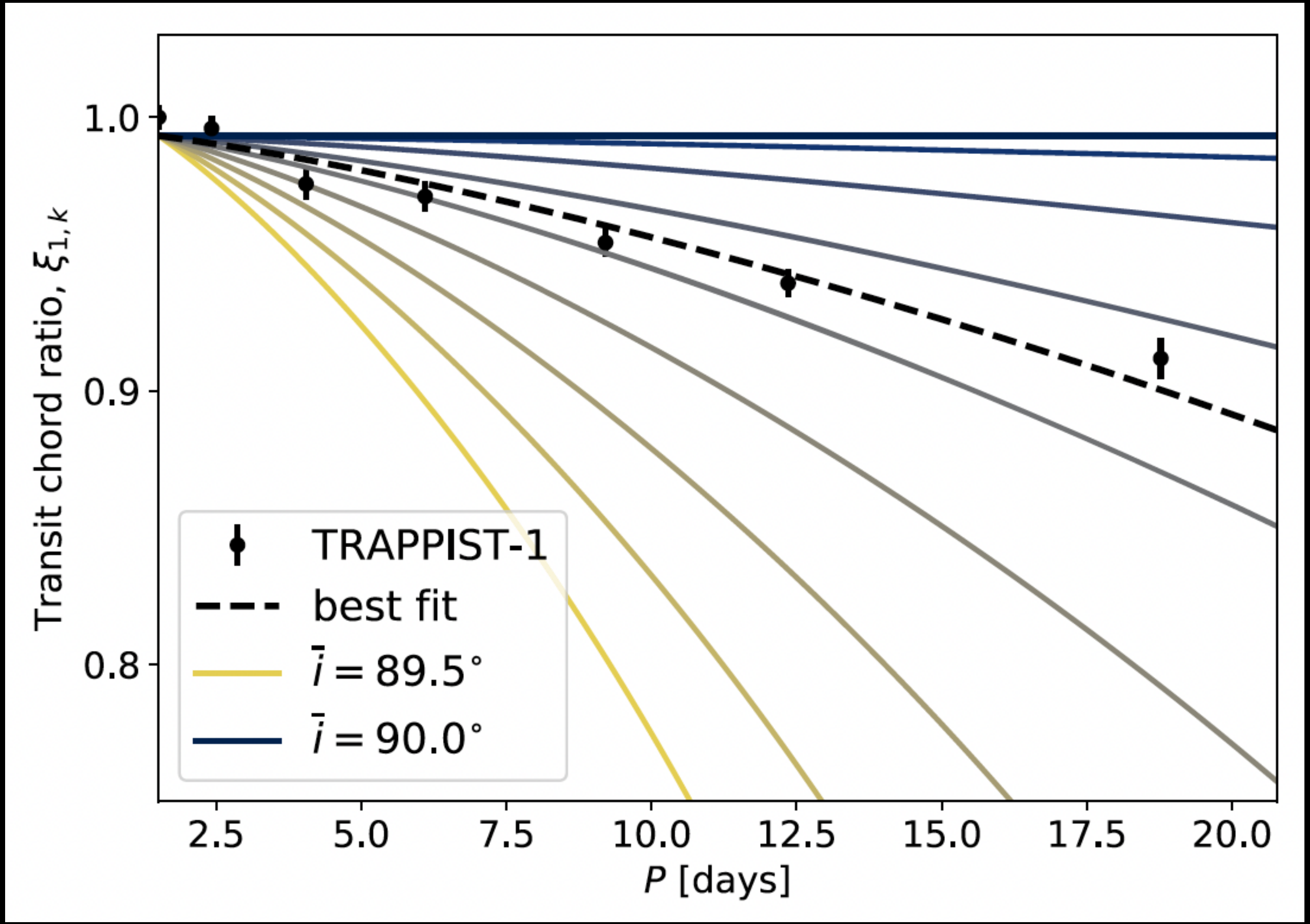
Compact Multis Appear Truncated



Figures from Millholland et al. (2022)



Compact Multis Appear Truncated



Figures from Millholland et al. (2022)

See also Fang & Margot (2013), Pu & Wu (23015), Tió Humphrey & Quintana (2020), Turtelboom et al. (2025)

Future Directions

- Improve measurements of host star properties
- Increase the sample of planets with measured masses
- Refine eccentricity measurements
- Determine obliquities
- Extend searches and combine detection methods to increase search completeness
- Consider a wide variety of planetary systems, not just those around single stars
- Continue measuring abundances in stellar and planetary atmospheres
- Build and expand frameworks to consider full systems and include correlations between system parameters

Stellar Science is Essential

- See in-person poster 17 by Ashley Elliott

One Big Exoplanet Family: A Comprehensive Analysis of the HD 219134 System

Ashley Elliott & Tabetha Boyajian

CHARA · NSF · LSU Department of Physics & Astronomy

METHODS

Stellar Parameters:

★ Used LBOI from the CHARA Array to directly measure the angular diameter of HD 219134
  - Developed `RADPy` to perform a multi-wavelength visibility squared fit

★ Used broadband photometry and spectrophotometry to obtain a bolometric flux with spectral energy distribution fits.

★ From the angular diameter, the temperature, luminosity, and radius are empirically determined.

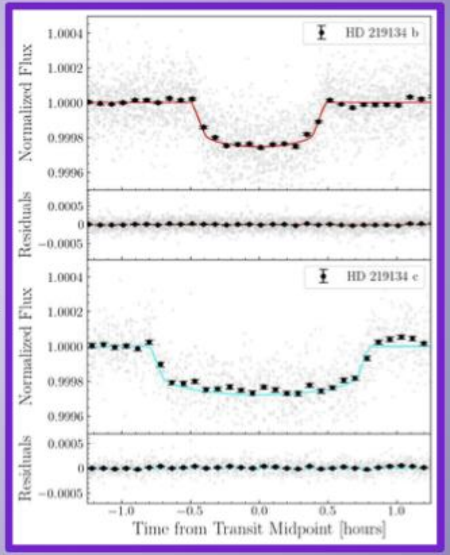
Figure 1:
Spectral Energy Distribution of HD

METHODS

Planet Parameters:

★ Archival data, including ~30 years of radial velocity monitoring and 5 sectors of TESS data

★ Modeling with `ExoFASTv2` with the precise stellar parameters as priors to simultaneously solve for an orbital solution



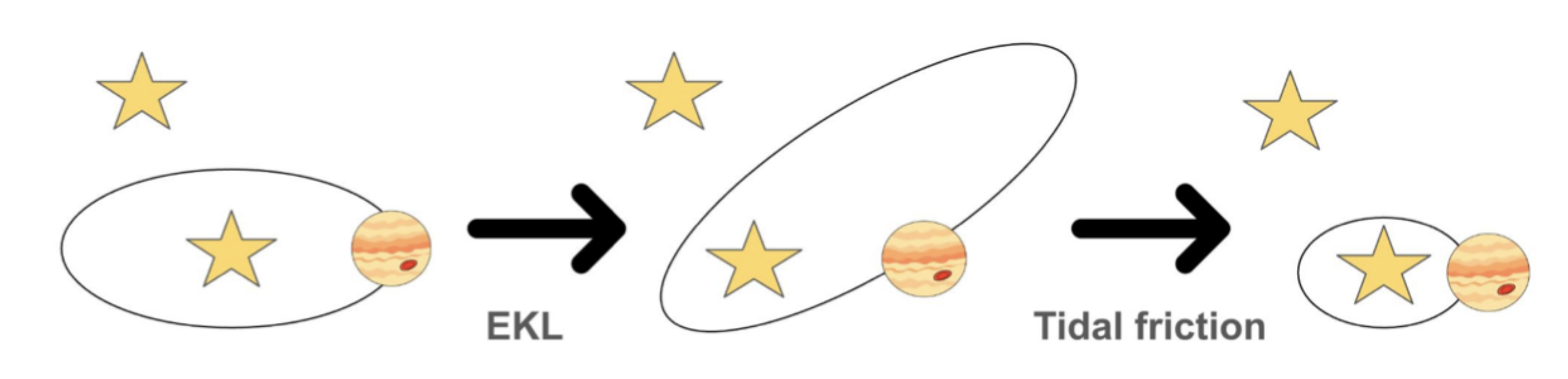
How Do Cold Jupiters Acquire their Eccentricities?

- See in-person poster 60 by Grant Weldon

The Stellar Eccentric Kozai-Lidov Mechanism as a Key Driver of Cold Jupiter Eccentricities

Grant Weldon, Smadar Naoz, Brad Hansen

UCLA



Weldon et al 2025
ApJ Letters

gweldon@astro.ucla.edu

One Set of Metrics For Classifying Planetary Systems

- Gilbert & Fabrycky (2020) proposed a classification system inspired by information theory and identified seven key metrics:
  1. **Dynamical mass:** how much mass is in planets compared to the host star?
  2. **Mass partitioning:** how much do the masses of individual planets vary?
  3. **Monotonicity:** to what extent are the planets ordered by size?
  4. **Characteristic spacing:** what is the typical separation between planets?
  5. **Gap complexity:** how predictable is the relationship between planetary periods?
  6. **Flatness:** how similar are the orbital planes of the planets?
  7. **Multiplicity:** how many planets are known to exist in the system?

Summary of System Architectures

Selected References
Lissauer+2011,Fang & Margot 2012, Fabrycky 2014
Millholland+2017, Wang 2017, Weiss+2018, Gilbert & Fabrycky 2020, Zhu & Dong 2021

1. **Dynamical mass:** planets are much less massive than their host stars
2. **Mass partitioning:** in compact multis, planets tend to have similar masses
3. **Monotonicity:** planets are <u>sometimes</u> ordered by size
   - In compact multis, planets tend to have similar sizes
   - In systems with planets larger than Neptune, exterior planets tend to be larger
4. **Characteristic spacing:** planets tend to be evenly spaced
   - In compact multis, typical separations are roughly 20 mutual Hill radii
5. **Gap complexity:** how predictable is the relationship between planetary periods?
   - Planets spacing is very regular
   - 25% of systems have higher gap complexity, which could be due to missing planets
6. **Flatness:** most systems are very flat
   - ***<u>Some</u>*** evidence that systems with more planets are flatter
7. **Multiplicity:** systems tend to have roughly 3 planets with periods < 400 days
   - High-multiplicity systems seem to be drawn from the same population
   - Single-planet and multi-planet systems can also be explained by the same population

Supplemental Reading

- Fang, J., Margot, J.-L. 2012. Architecture of Planetary Systems Based on Kepler Data: Number of Planets and Coplanarity. *The Astrophysical Journal* 761. doi:10.1088/0004-637X/761/2/92
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