Searching for Additional Planets in Multi-Planet Systems

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NASA ExoExplorers Science Series
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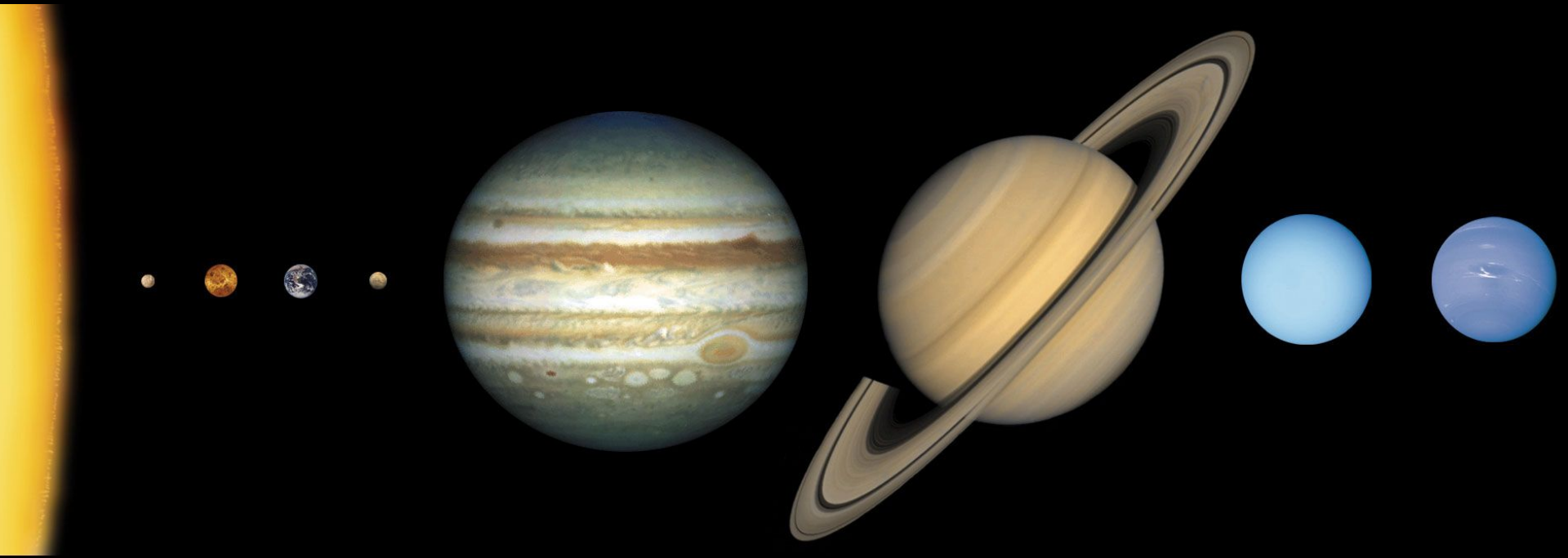
Berkeley
UNIVERSITY OF CALIFORNIA

Is the Solar System unique?



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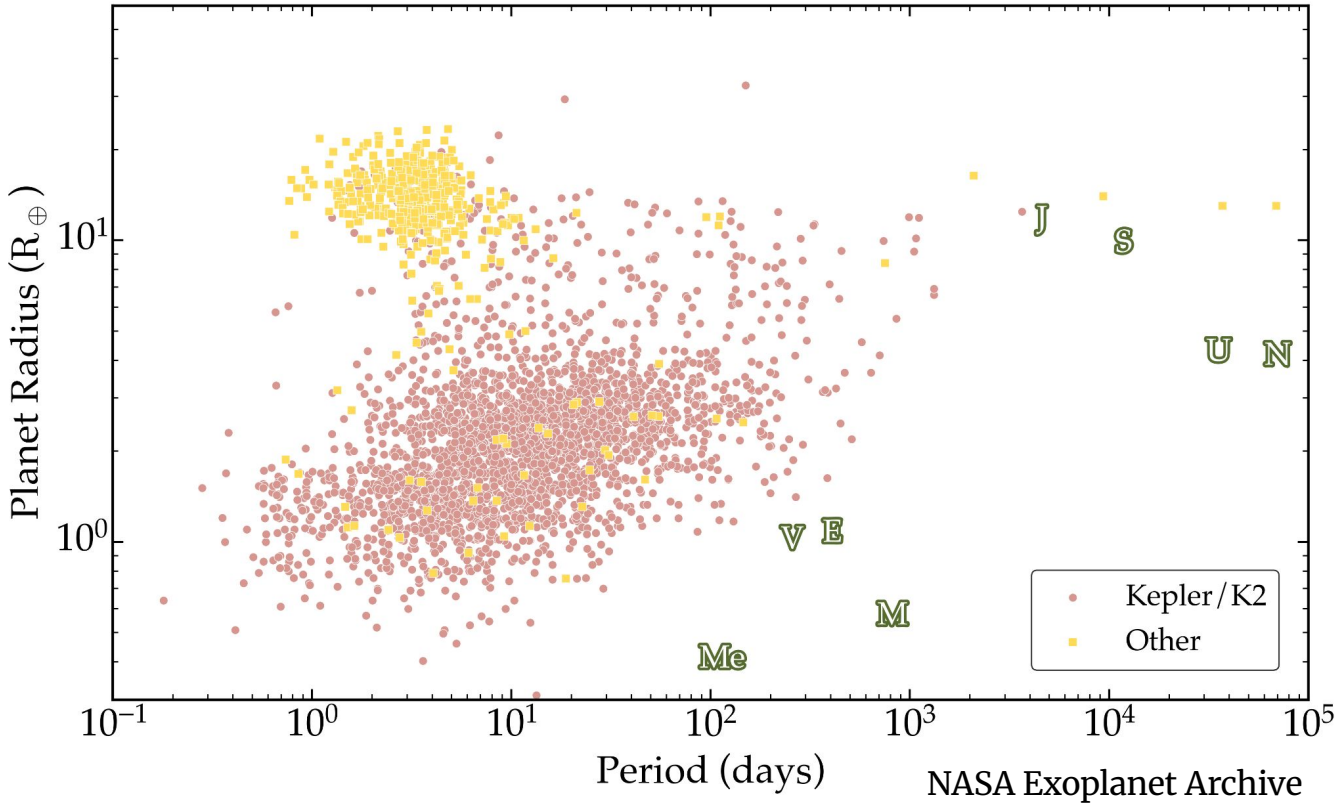
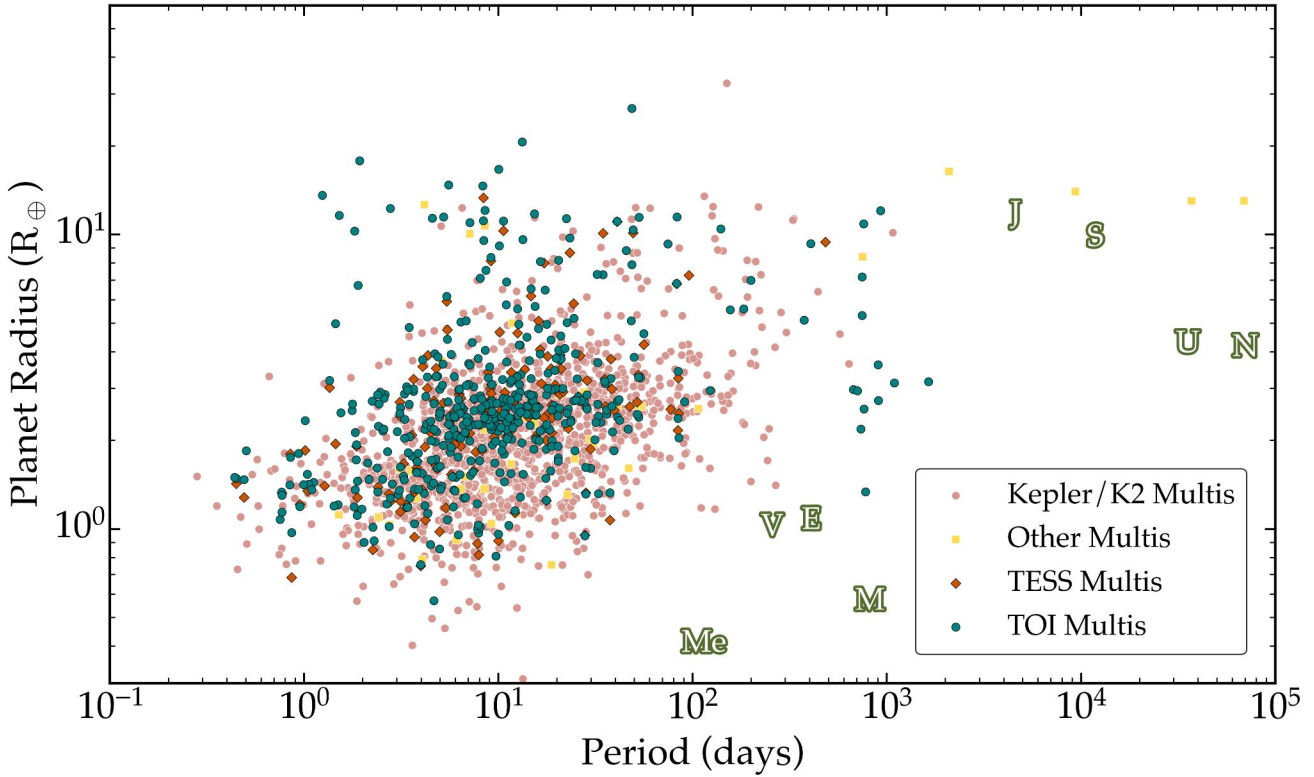
Models of exoplanetary system architectures are largely informed by the Kepler sample



NASA Exoplanet Archive

We can use TESS to test these empirical models

- Currently: 183 multi-planet systems with 369 planet (candidates)



NASA Exoplanet Archive, ExoFOP

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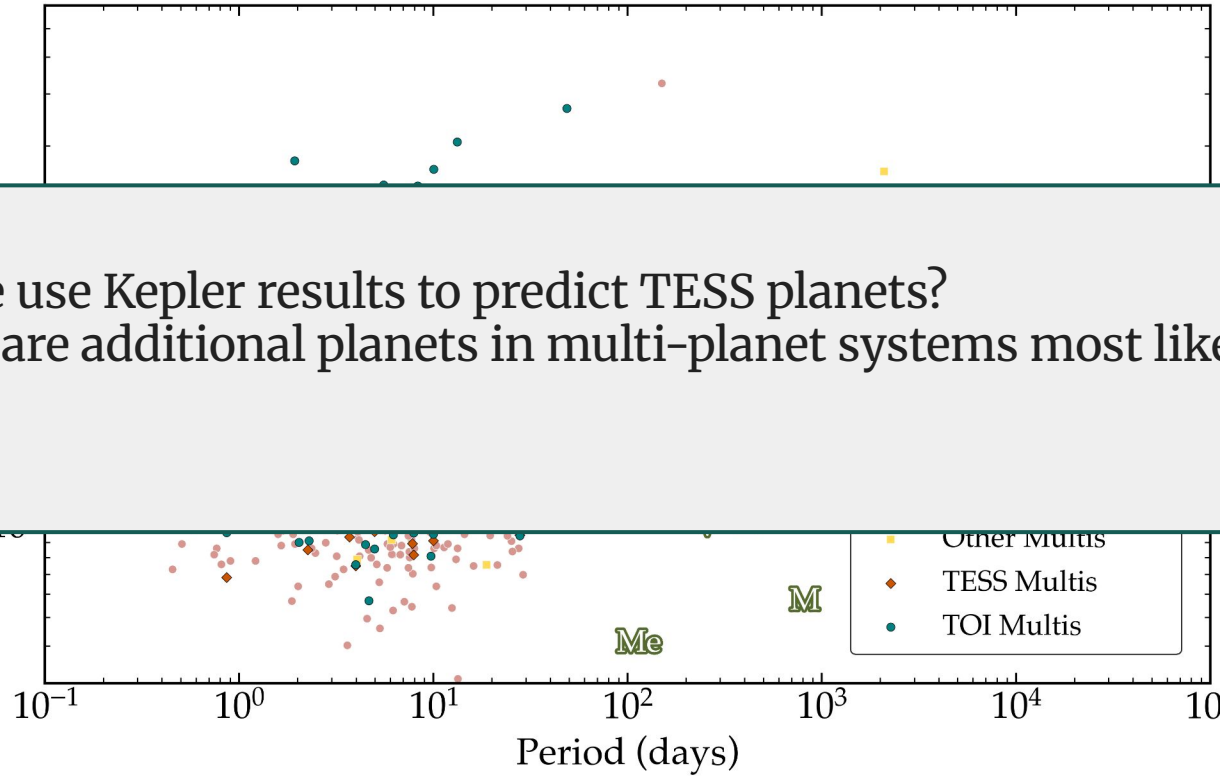


- Can we use Kepler results to predict TESS planets?
- Where are additional planets in multi-planet systems most likely to be found?

NASA Exoplanet Archive, ExoFOP

Planetary system architectures encode the results of planet formation & evolution

Period Ratio Model

Mulders et al. 2018

Clustered Period Model

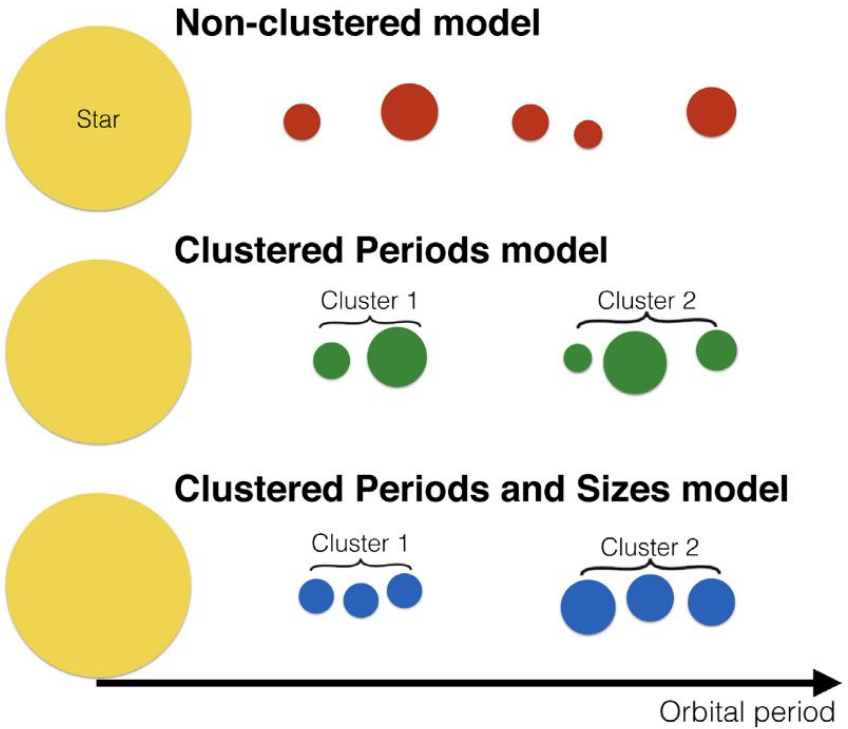
He et al. 2019

Kepler Empirical Model #1 - Period Ratio Model (PRM)

- Introduced in Mulders et al. (2018)
- Innermost planet period distribution peaks at ~10d
  - Inner edge of protoplanetary disk acting as a trap that halts migration (Lee & Chiang 2017, Izidoro et al. 2017)
- Outer planets are evenly spaced in log-period space
  - “Peas-in-a-pod” architecture also seen in masses and radii (Millholland et al. 2017, Weiss et al. 2018)

Kepler Empirical Model #2 - Clustered Period Model (PCM)

- Introduced by He et al. (2019)
- Planets are grouped in period and radius space.
- The location of each cluster is drawn from a power law for period, and from a broken power law for radius (Youdin 2011, Howard et al. 2012).



He et al. 2019

Are models of planetary system architectures predictive as well as descriptive?

Period Ratio Model

Mulders et al. 2018

Clustered Period Model

He et al. 2019

- If a model is descriptive but not predictive, we have *overfit* the data

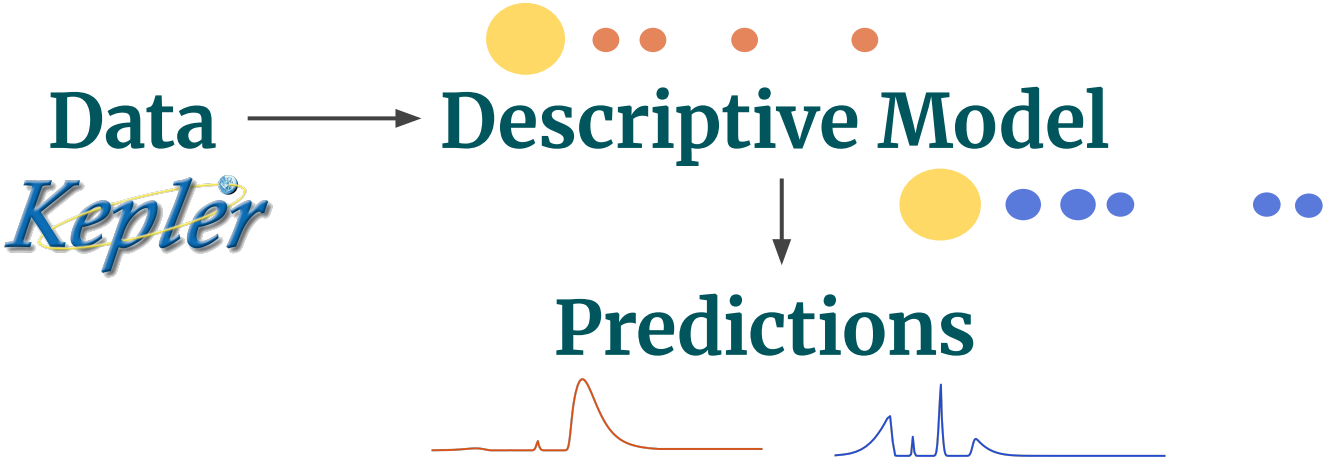
Do Kepler models accurately predict additional planets in TESS systems?

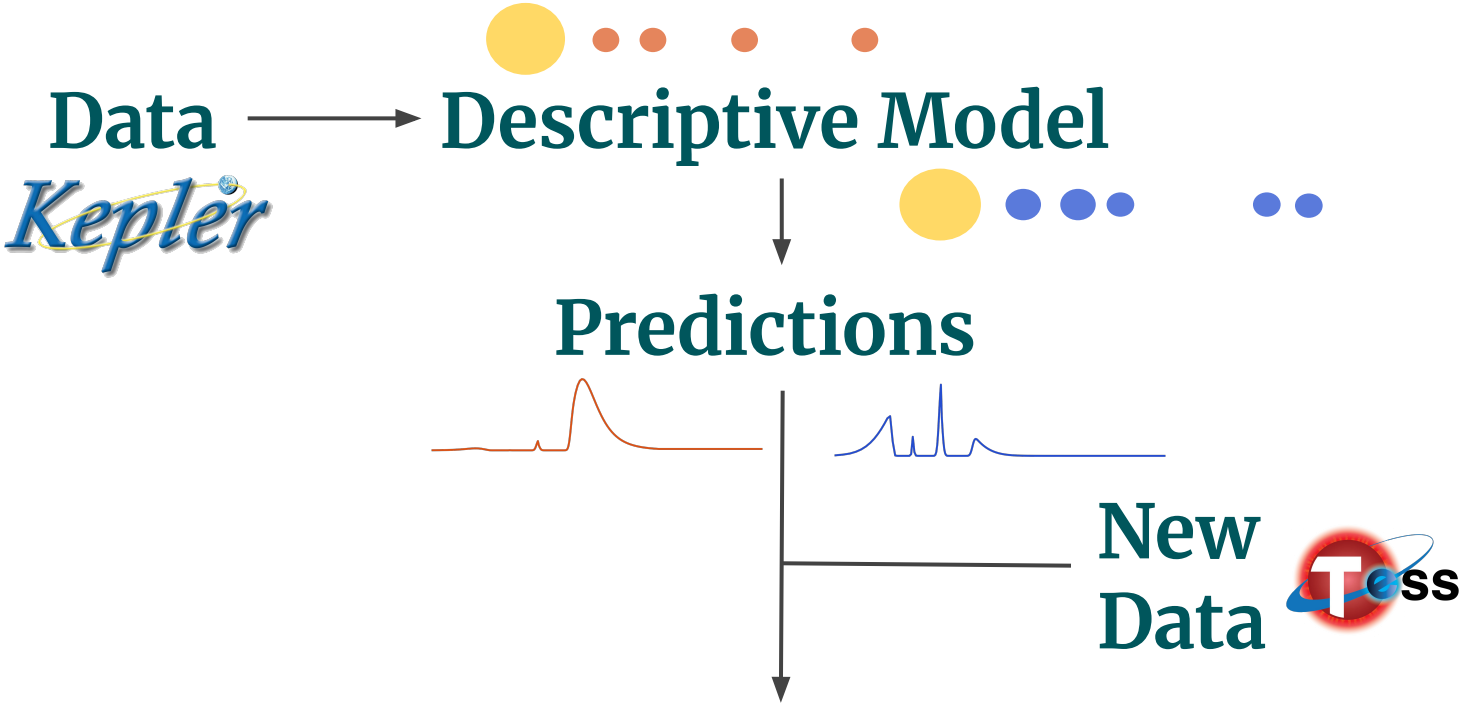
- DYNAMITE (Dietrich & Apai 2020)
  - 52 TESS multi-planet systems known in 2020
  - Integrate over empirical independent probability density functions in period, radius, and inclination to return a posterior probability distribution
  - Predict additional planet in each system
- Use additional TESS observations (2020-2024) to evaluate the accuracy of each model

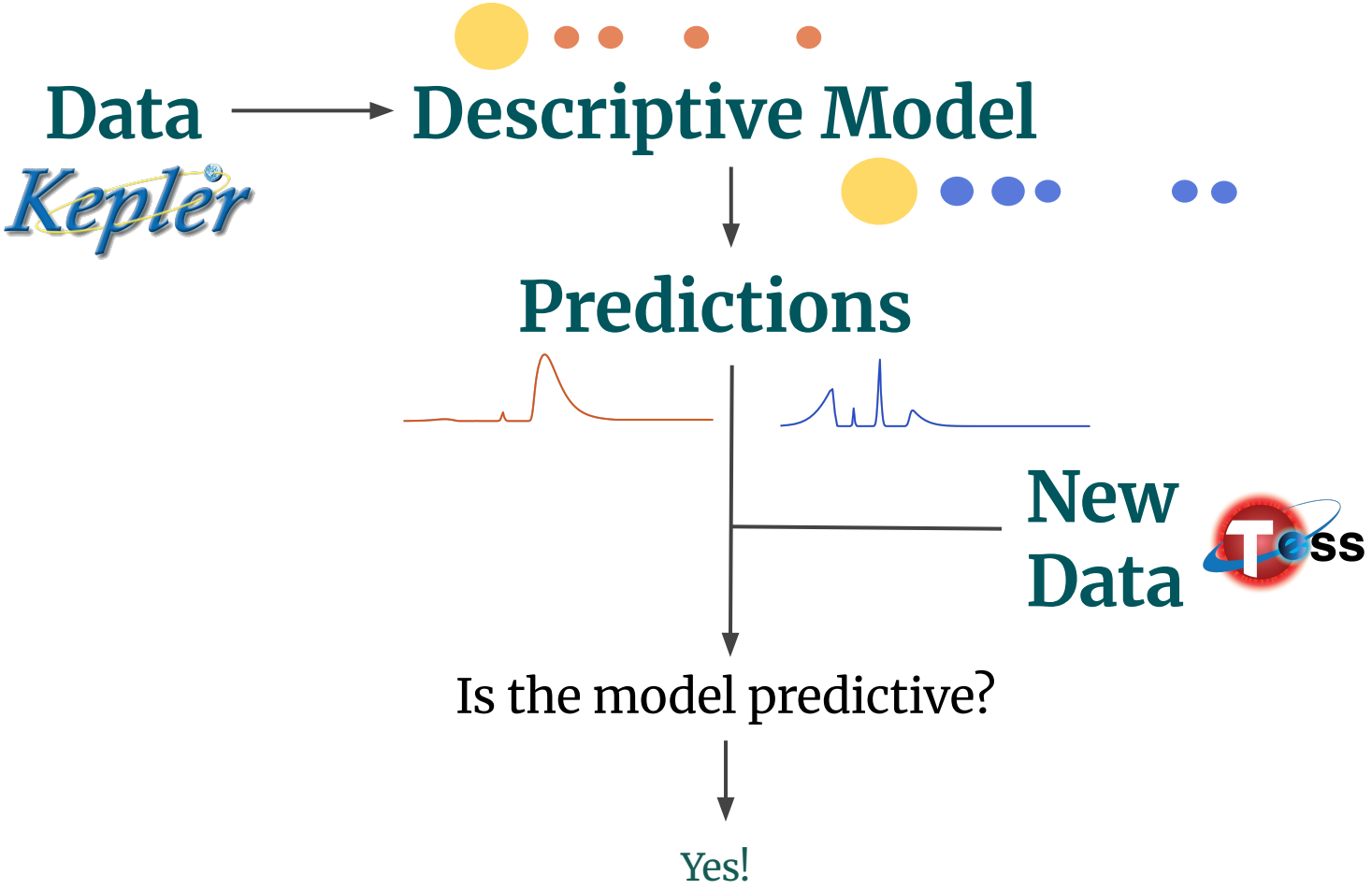
Period Ratio Model (PRM)

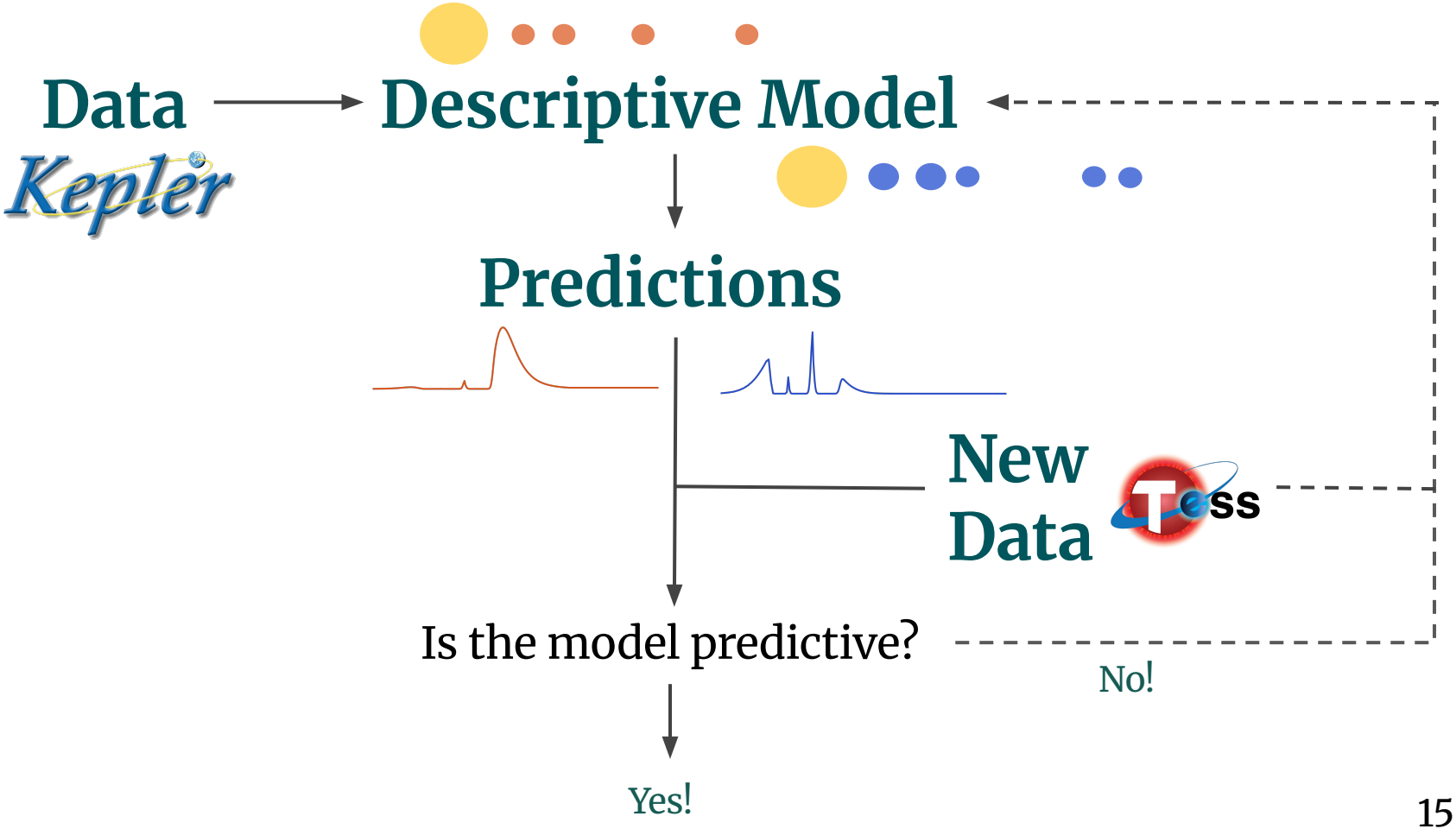
Clustered Period Model (PCM)

Data → Descriptive Model

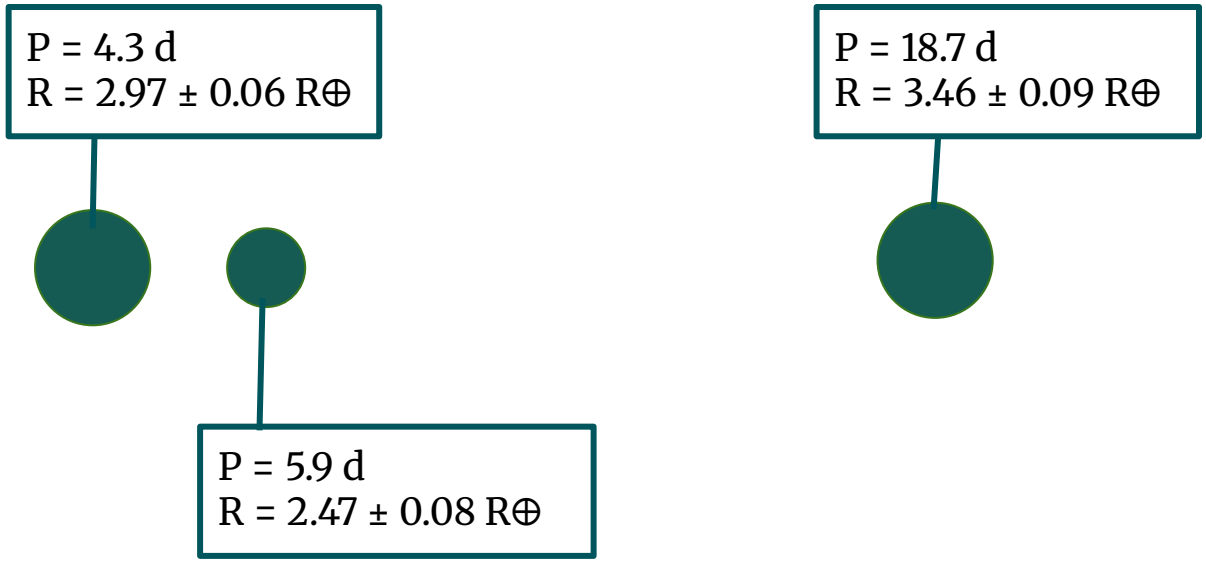

Data
Descriptive Model
Kepler
Predictions


Data
Kepler
Descriptive Model
Predictions
New
Data
TESS
Is the model predictive?


Data
Kepler
Descriptive Model
Predictions
New
Data
TESS
Is the model predictive?
Yes!


Data
Kepler
Descriptive Model
Predictions
New
Data
TESS
Is the model predictive?
No!
Yes!

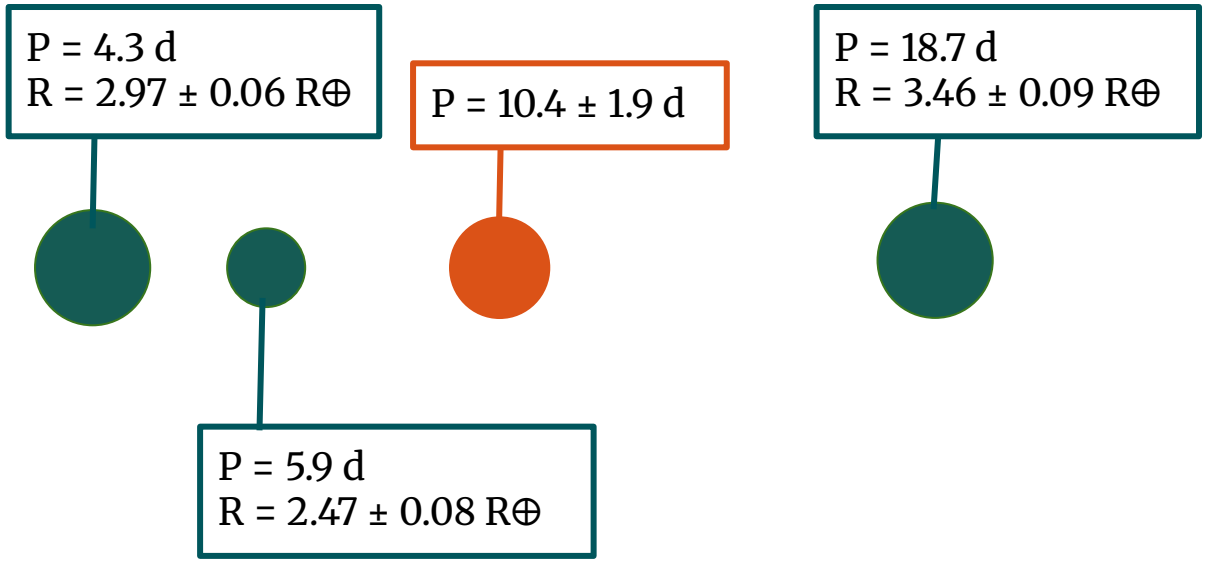
TOI-1246



Turtelboom et al. 2022

Period Ratio Model

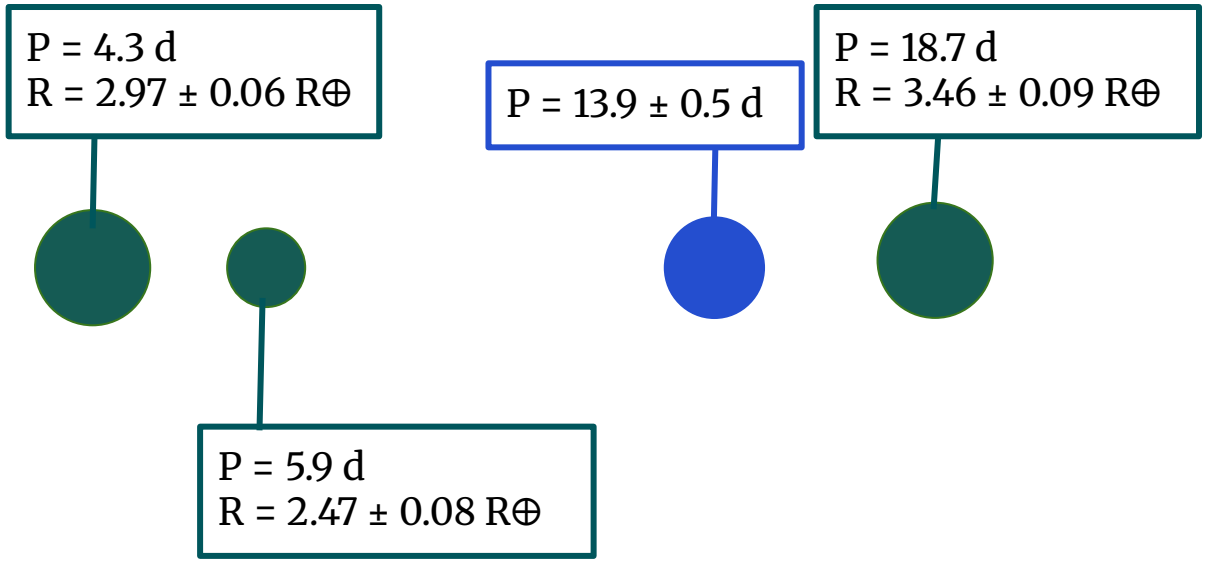
2020



Turtelboom et al. 2022

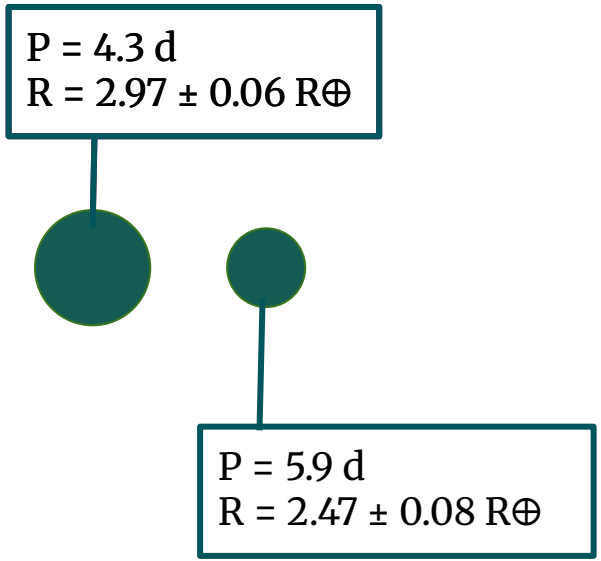
Clustered Period Model

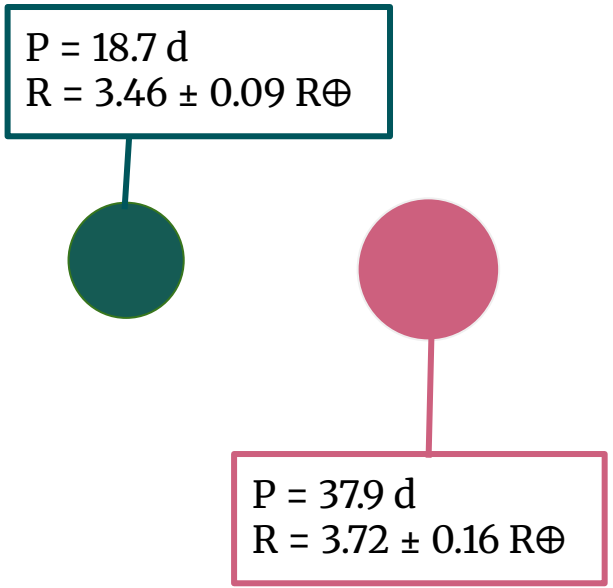
2020



Turtelboom et al. 2022

More data → neither model was accurate





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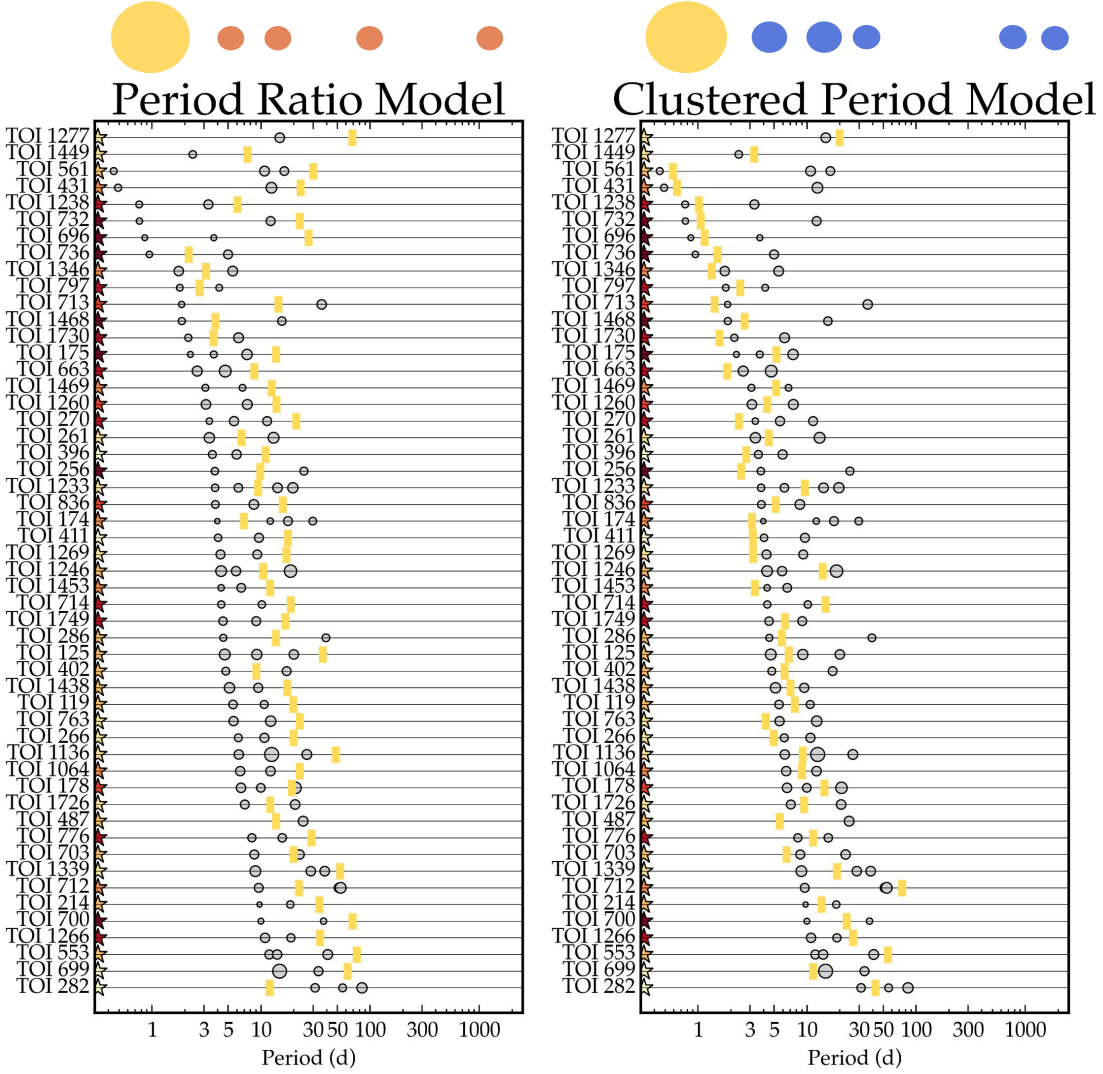


In 2020, TESS had discovered 52 multi-planet systems hosting 119 planet (candidates).

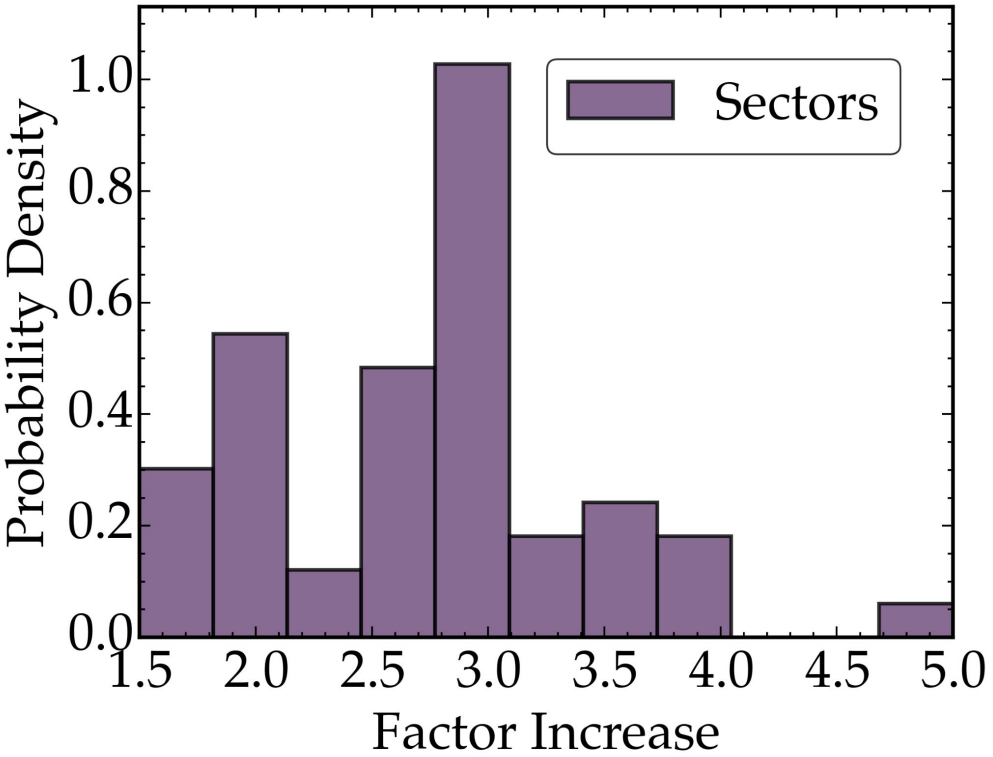
Dietrich & Apai (2020) predicted an additional planet in each system for both the PRM and PCM.

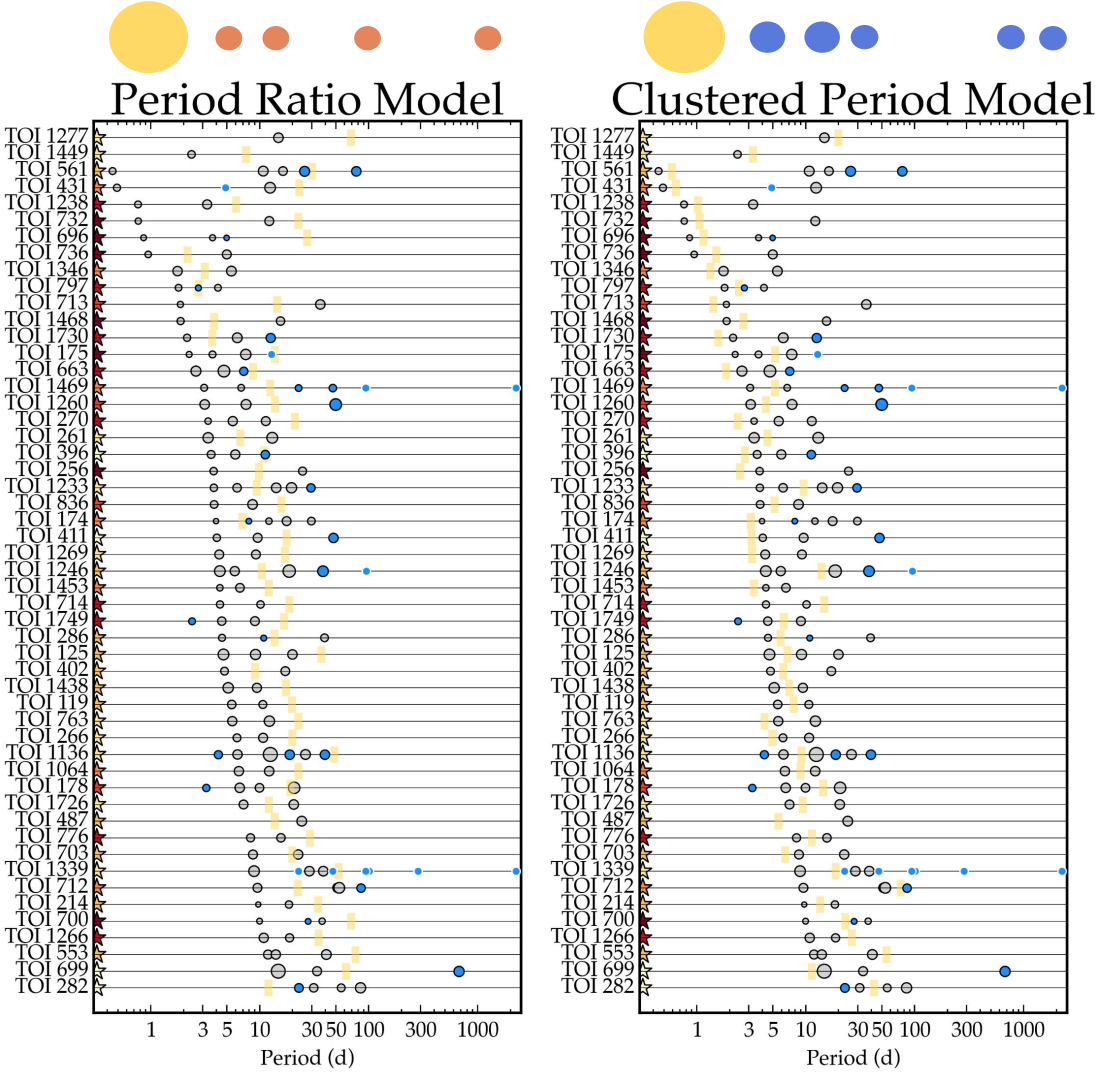
= known planets in 2020

= predicted additional planets

Since 2020, TESS has re-observed its full field of view

- All 52 systems have an extended TESS baseline
- 22/52 systems have 31 new planet candidates





Of the 24 new transiting planets:

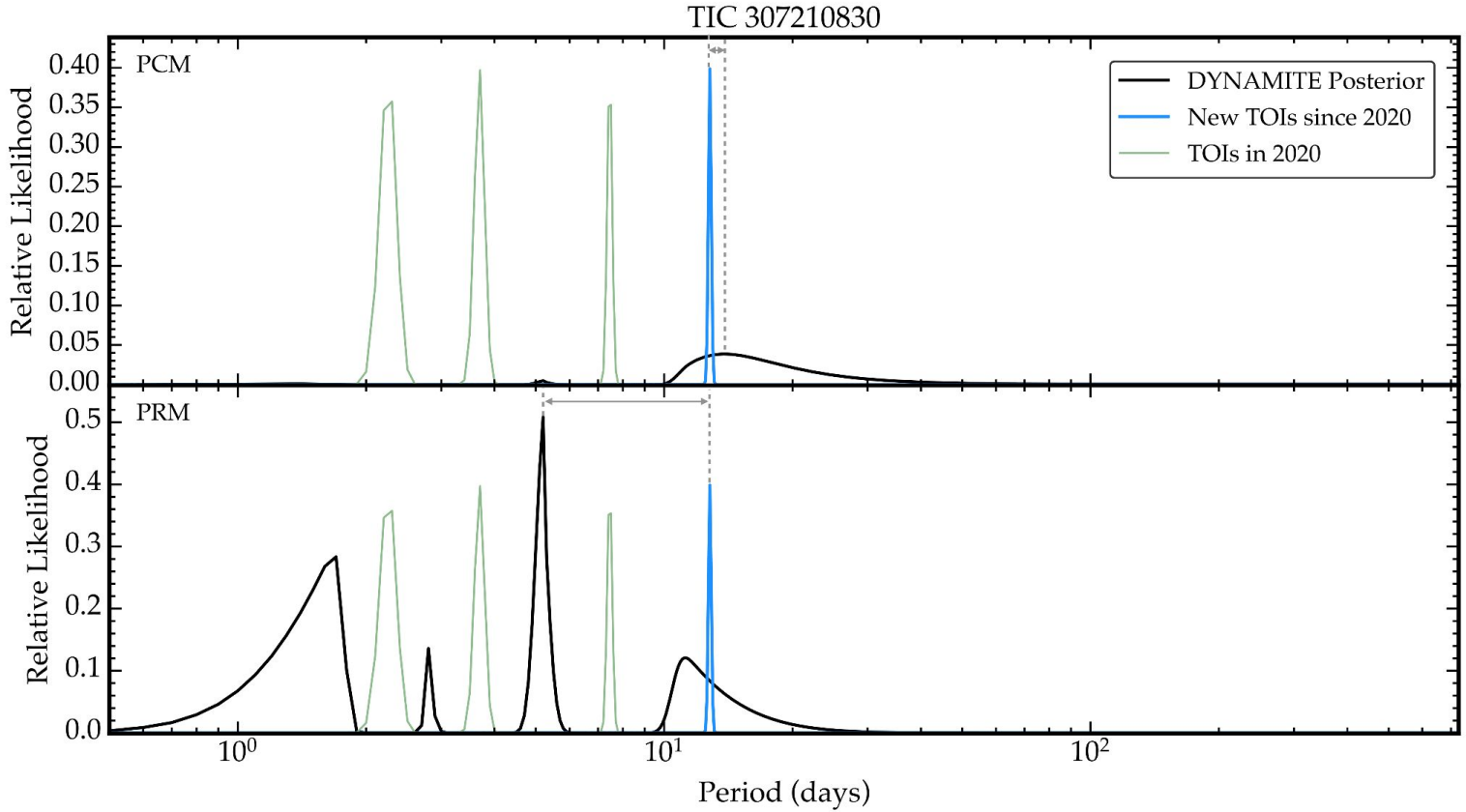
- 4 PCM matches
- 8 PRM matches

= known planets in 2020

= predicted additional planets

= newly discovered planets

What does it mean for a prediction to be accurate?



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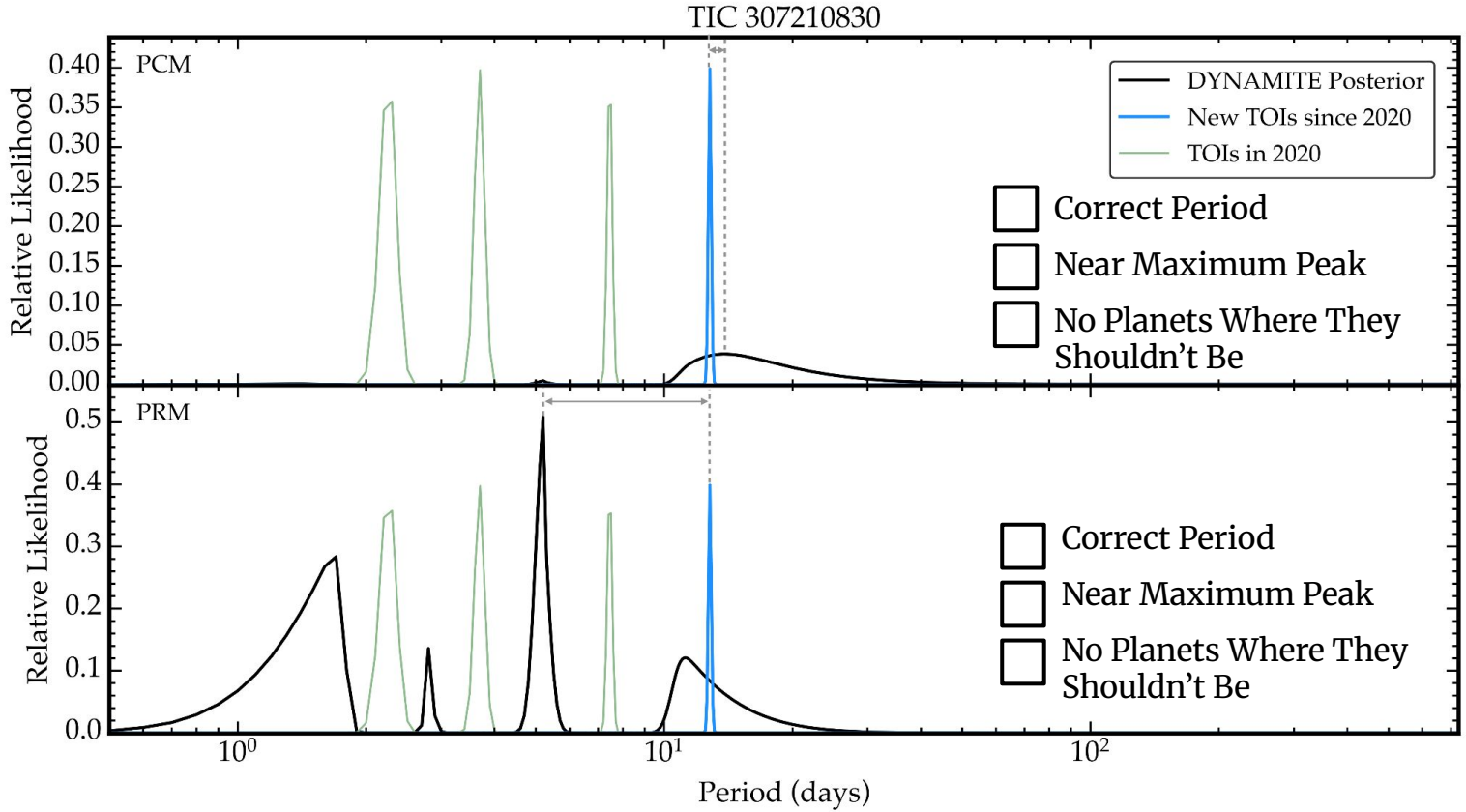

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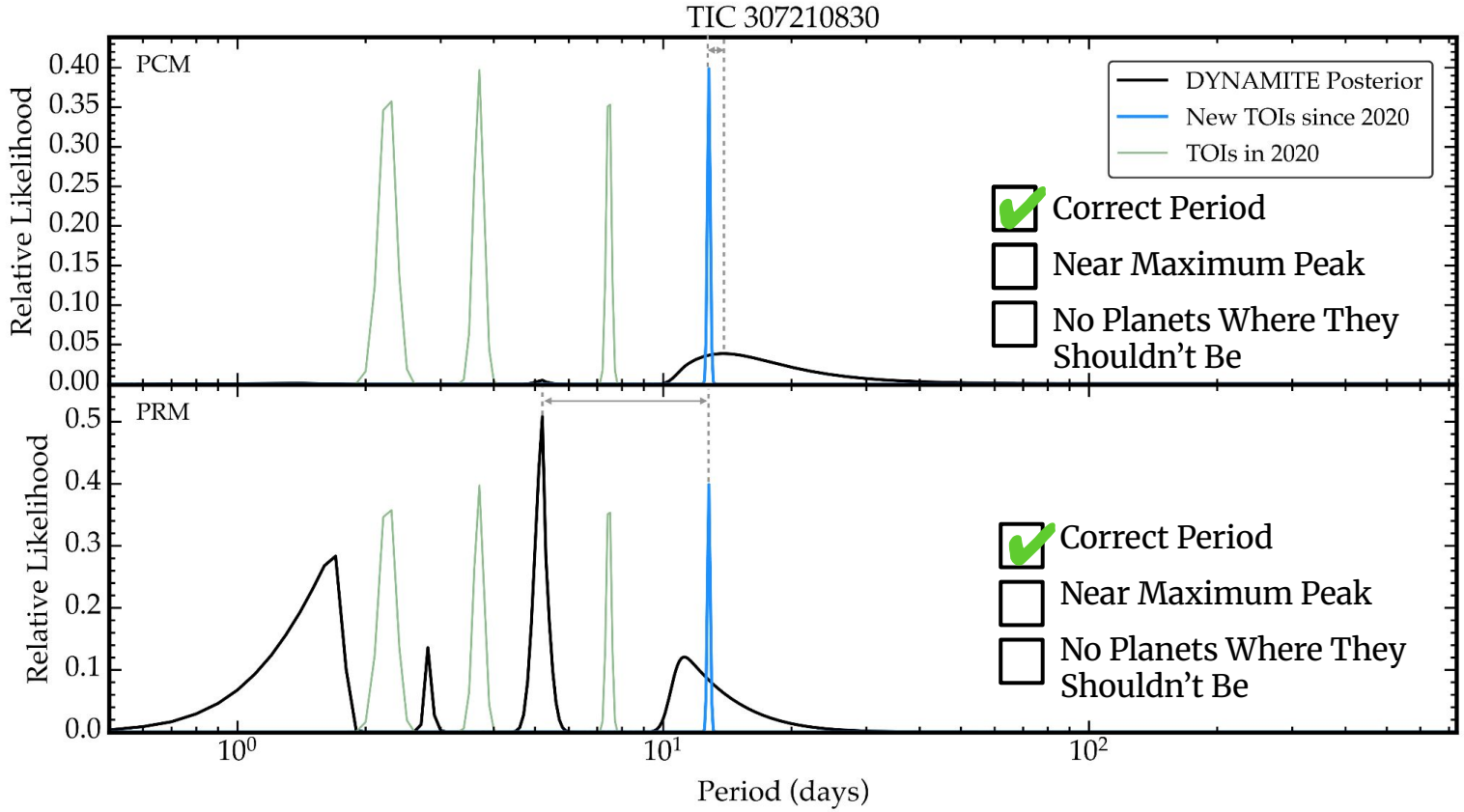

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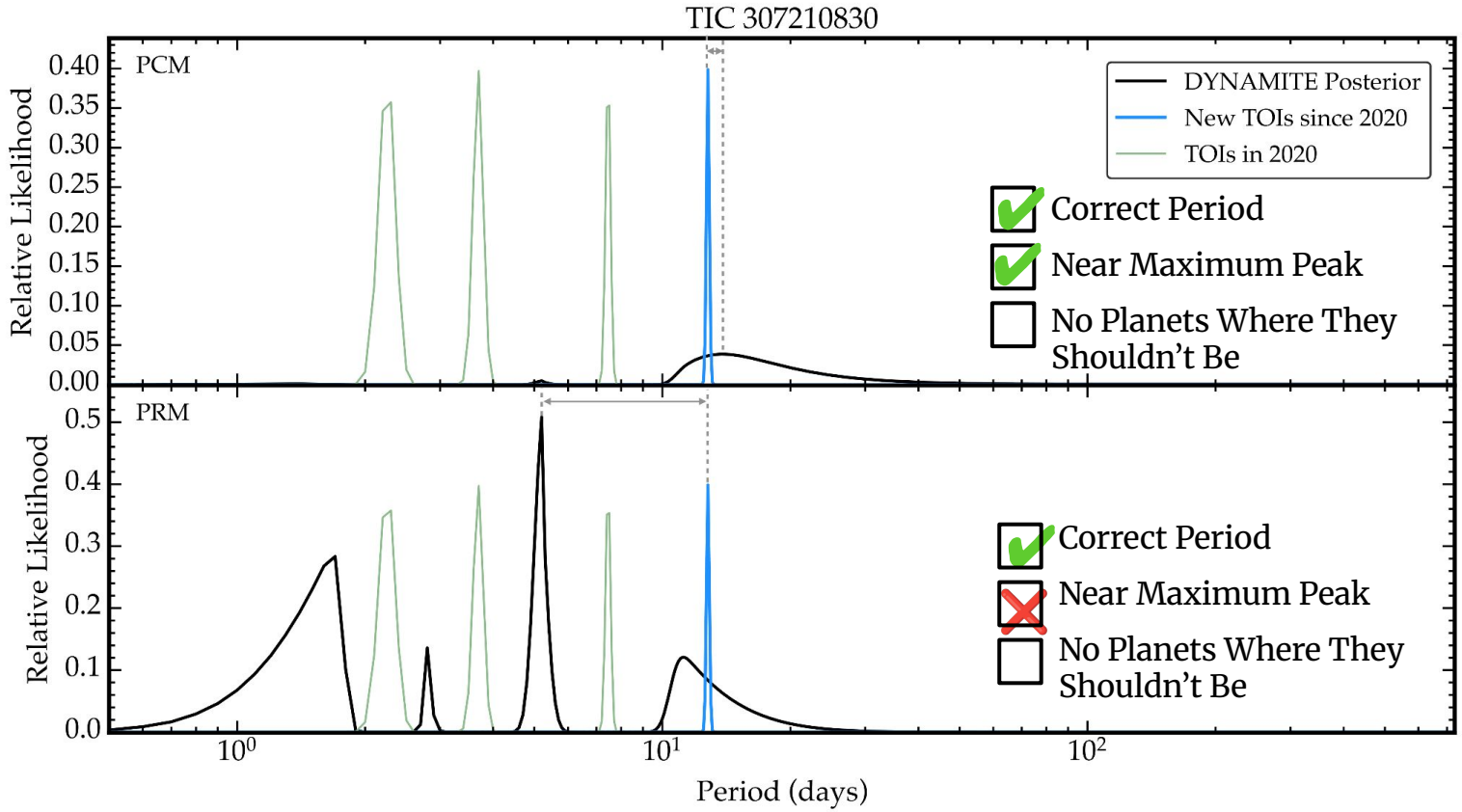
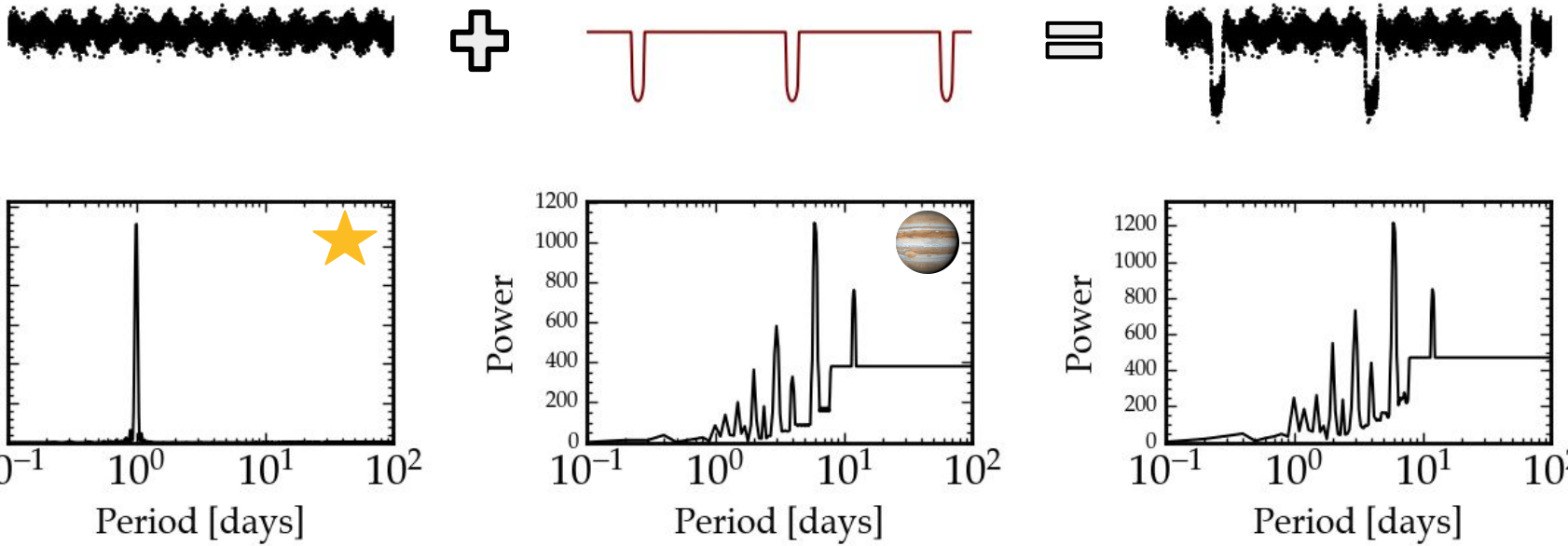


Transit Injection and Recovery quantifies sensitivity to detecting planets



Lomb 76, Scargle 82, Kovacs+02

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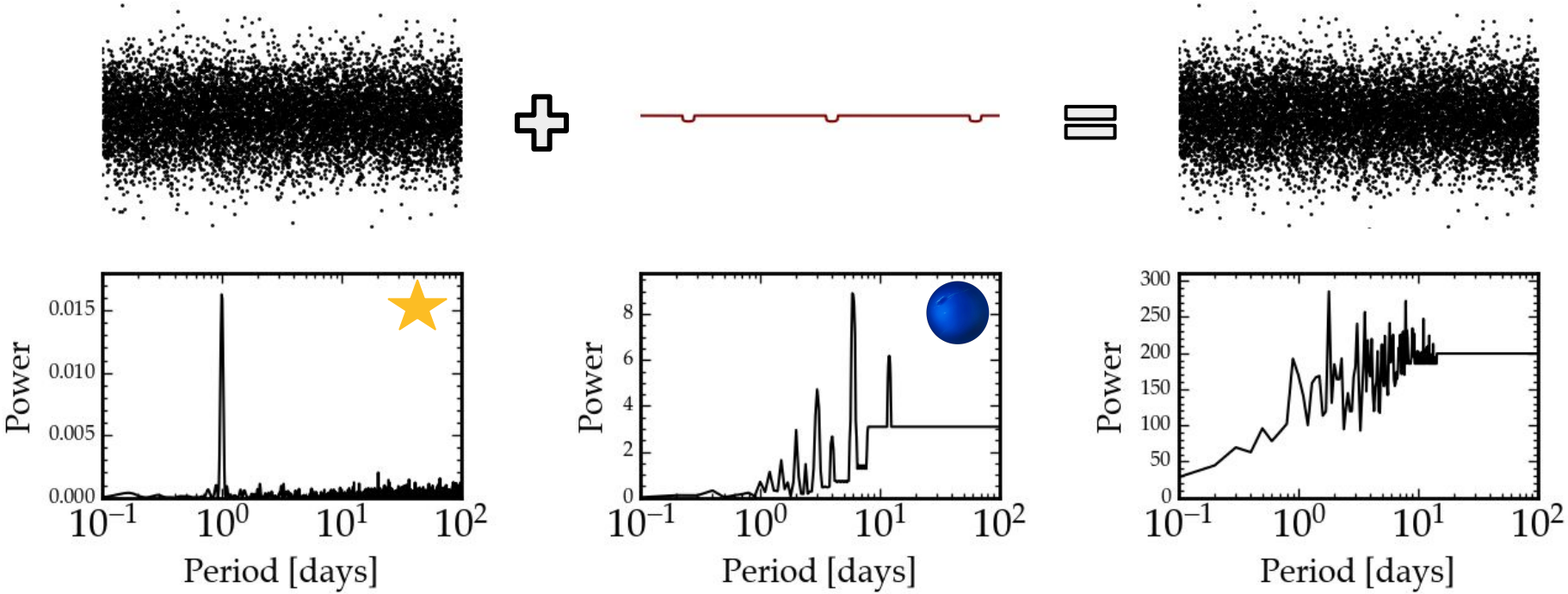

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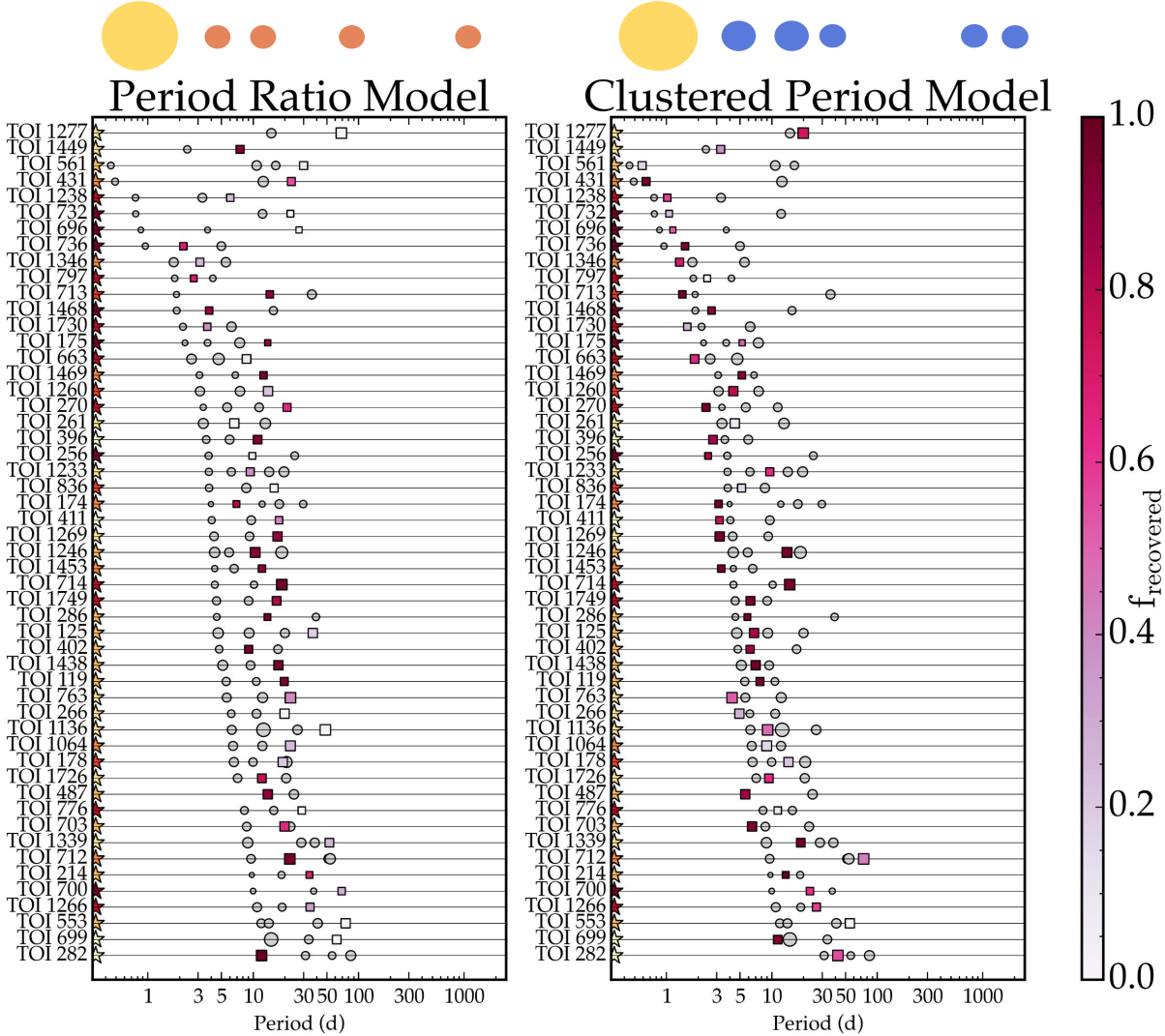

Injection -Recovery tests show that the PCM predictions were more detectable in TESS data.

= known planets in 2020

= predicted additional planets

- The Period Ratio Model describes TESS multi-planet systems more accurately, but the sample is not well-described by *either* model

Multi-planet system architectures are complex and challenging to characterize!

- **Turtelboom et al. 2025, in review** - arxiv:2409.03852
- The Period Ratio Model describes TESS multi-planet systems more accurately, but the sample is not well-described by *either* model
- To improve models of system architectures, we can
  - Study other architecture metrics
    - Planetary system truncation
    - Dynamical packing
  - Add nuance e.g. non-circular orbits
  - Compare observed architectures to predictions from planet formation models

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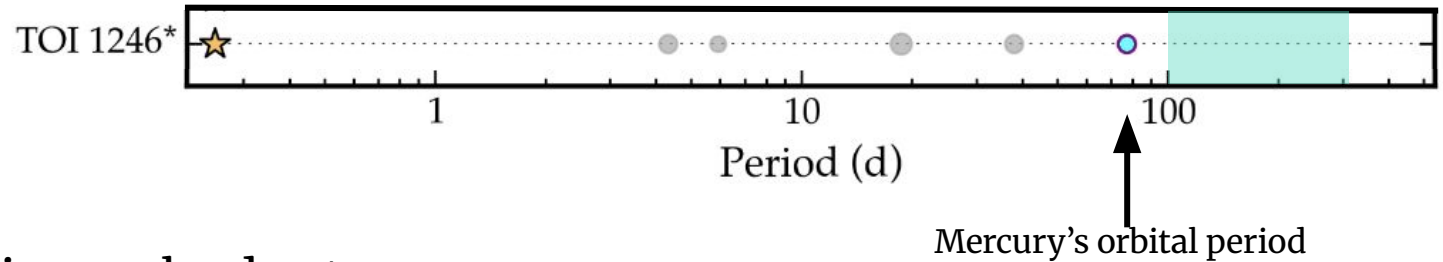
Are Multi-Planet Systems Truncated?

- Kepler high-multiplicity systems are truncated relative to detection biases. There is a dearth of planets between 100-300 days (Millholland et al. 2022).



This may be due to:

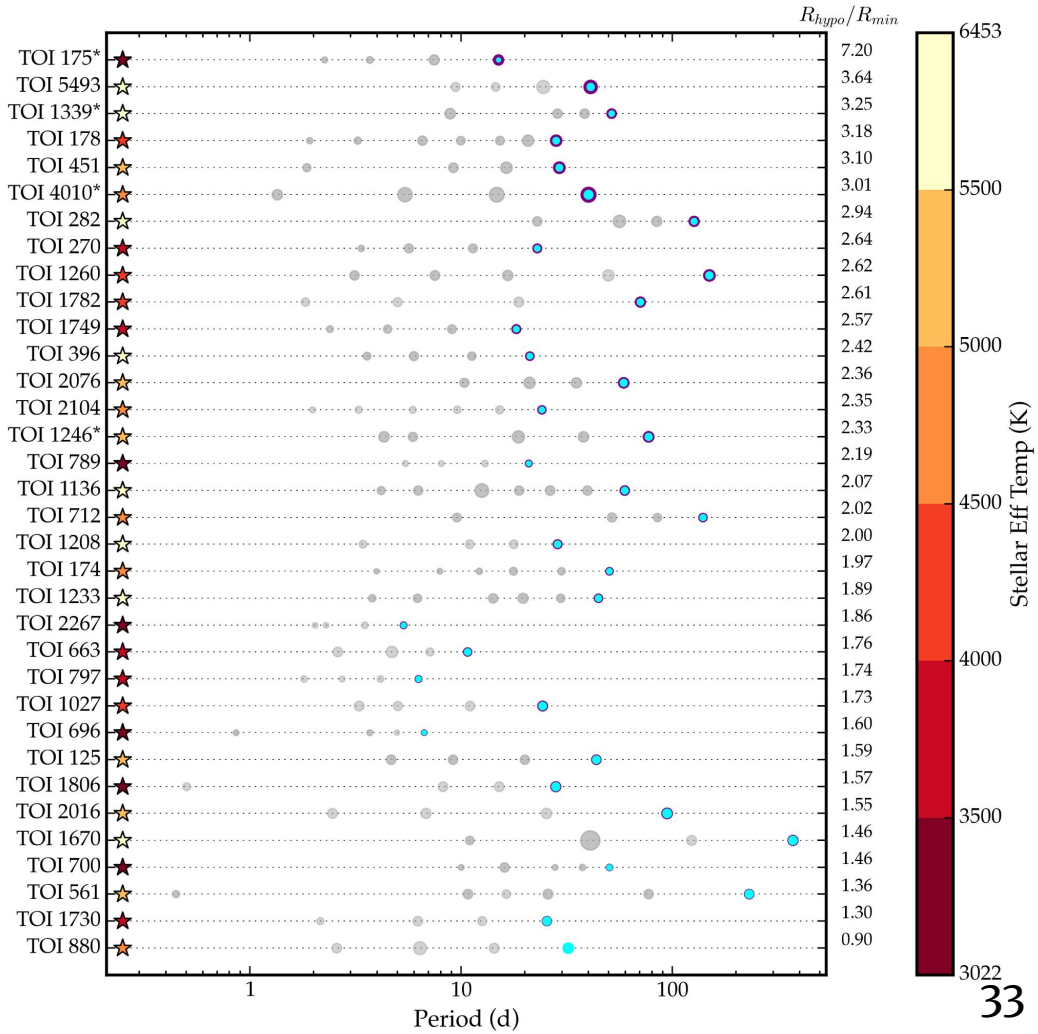
- Change in the underlying occurrence rate
- Breakdown of peas-in-a-pod architecture

Are TESS Multi-Planet Systems Truncated?

The minimum detectable radius is smaller than the radius predicted using peas-in-a-pod in each system.

= known planets

= hypothetical additional planets



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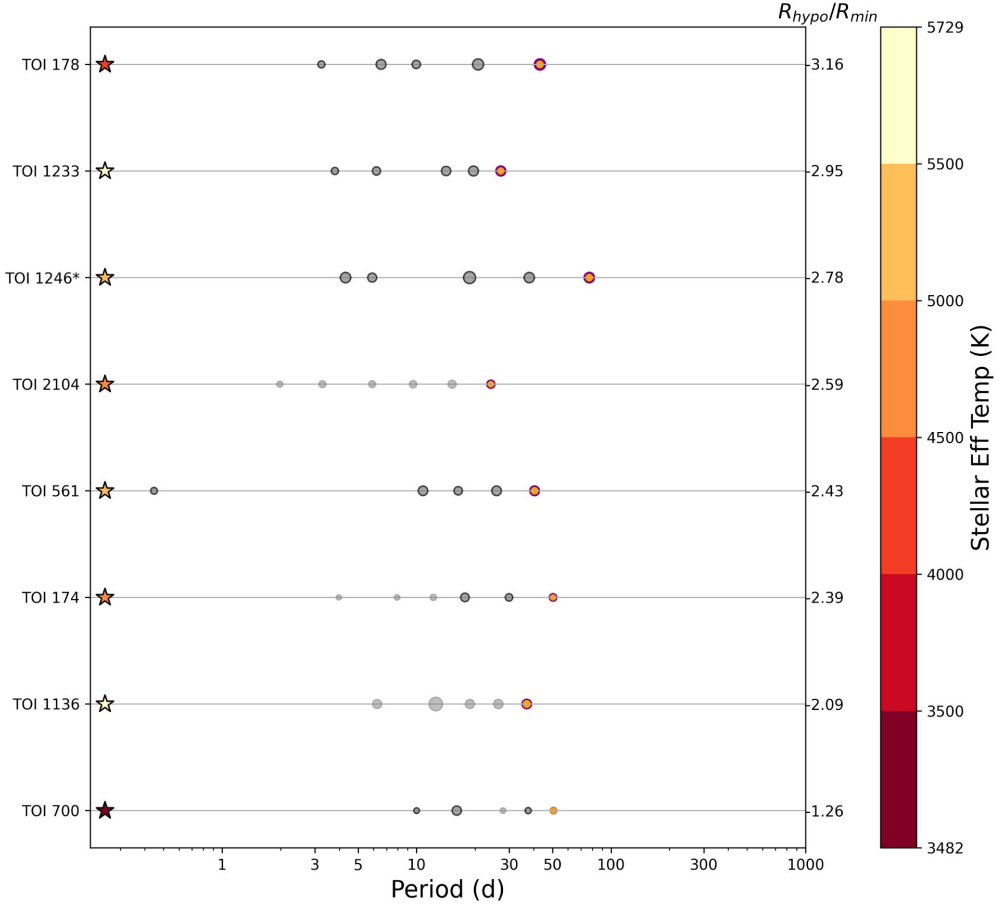
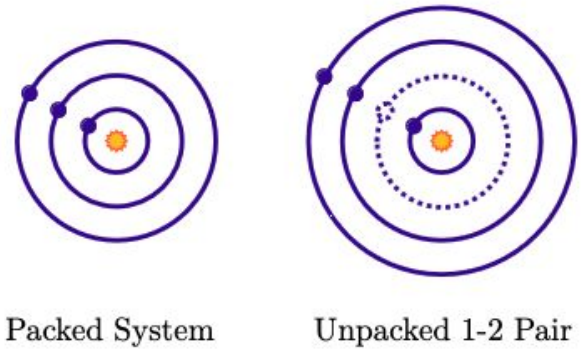


Are TESS Multi-Planet Systems Dynamically Packed?

Kepler multi-planet systems appear to be mostly dynamically packed assuming some stability criteria

Δ_{crit} = 8, 10, 12.3, or 21.7 R_{Hill}

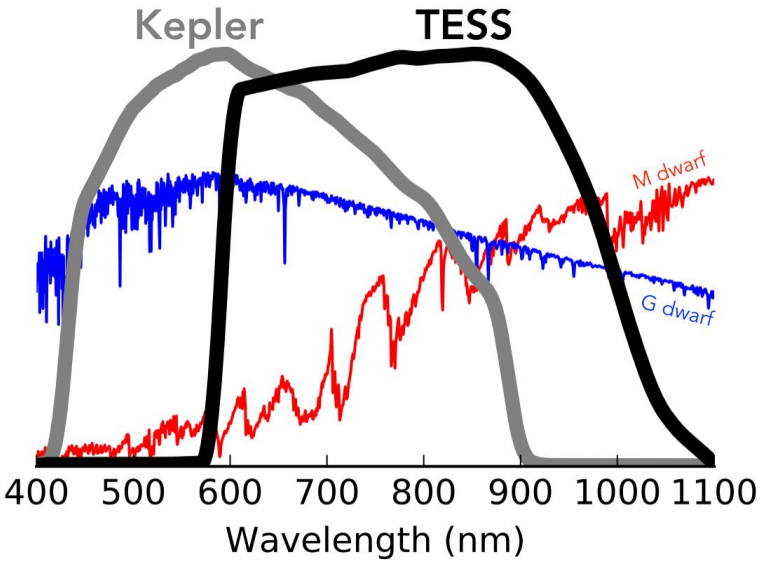
(He et al. 2019, Pu & Wu 2015, Fang & Margot 2013)



Tió Humphrey & Quintana 2020

Kepler vs. TESS

- TESS has
  - Redder bandpass
  - Brighter targets
  - All-sky survey design
  - Shorter average baseline
  - Larger pixels (21” vs. 4”)
  - More sensitive to cool stars



Zach Berta-Thompson with data from Sullivan+2015

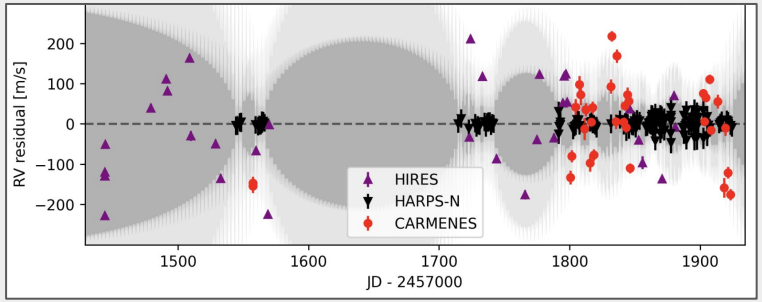
Are TESS Multi-Planet Systems Dynamically Packed?

Kepler systems are dynamically packed for stability criteria spacing of ~10 RH for circular orbits and ~12 RH for e~0.02 (Pu & Wu 2015). Long term numerical integration. Only 6 systems with Npl > 4

Fang & Margot 2013 found that >31%, >35% and >45% of 2, 3, 4-planet systems are dynamically packed for Kepler P<200d and 1.5-30 Re, assuming stability criteria of 21.7 RH on ~Gyr timescales. Suggest formed even tighter and then spaced by dynamical instability. - accounted for transit geometry and sensitivity limits by simulating systems + applying detection biases.

He+19 finds stability criteria of 8 RH needed to reproduce period ratio distribution. Did full simulated catalog too.

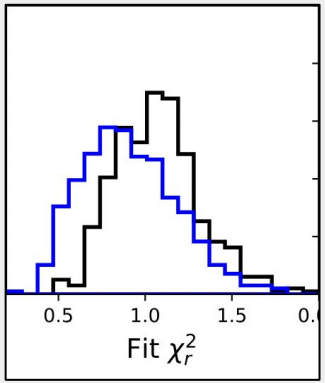
RV Models using Gaussian Process
(Blunt et al. 2023)



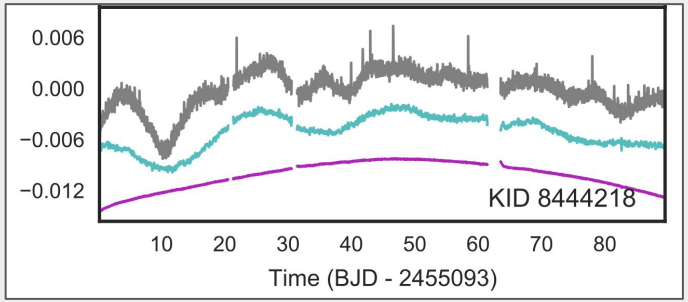
Previous works have studied the impact of overfitting on multiple types of analysis

Atmospheric Retrievals
(Ih & Kempton 2021)

Blue = Correlated noise
Black = Gaussian noise

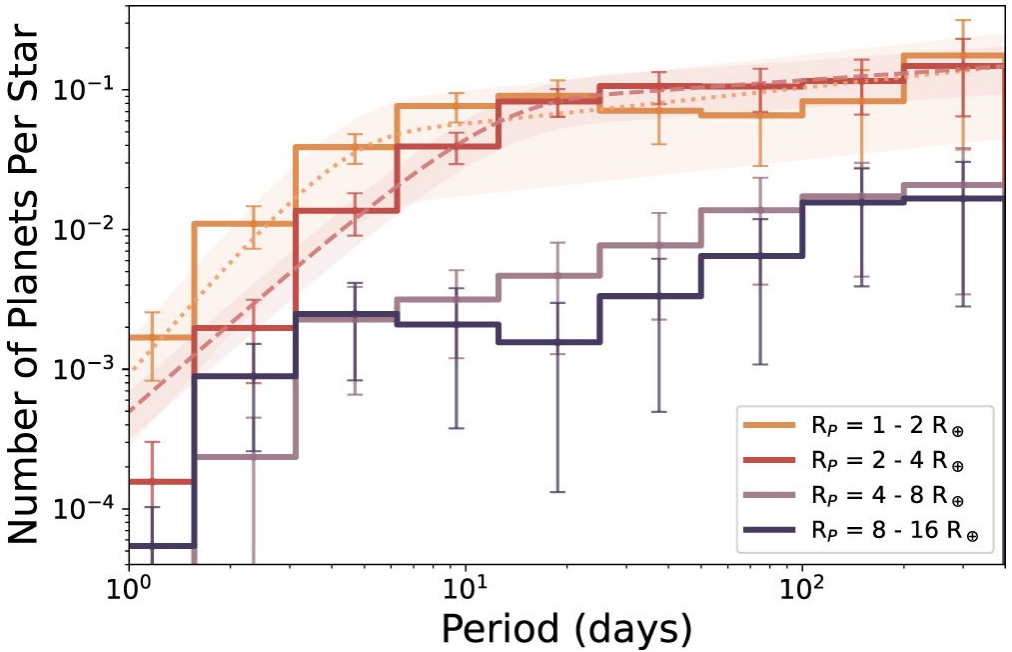


Detrending photometric light curves
(Aigrain et al. 2017)



(In)dependent probability distributions

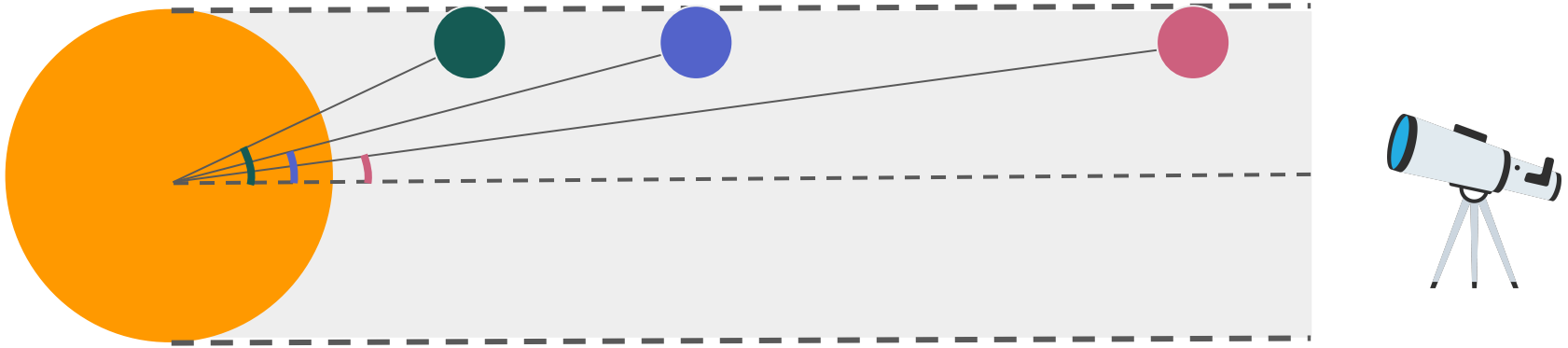
- ➔ Longer-period planets tend to be larger (Helled+16, Carrera+18)
- ➔ Weak correlation of tighter spacing in flatter systems (Gilbert & Fabrycky 20)
- ➔ For <4 $R_\oplus$, the period distributions of planets are ~independent of radius (Howard+12, Dattilio+23)



Dattilio+23

Predict an additional planet in all 52 systems under two period models

- ➔ DyNAMITE (Dietrich+20)
- ➔ Integrate over independent probability density functions in (P, R, i) space
- ➔ Predict additional planet in each system for each model with a corresponding period, radius, and geometric transit probability



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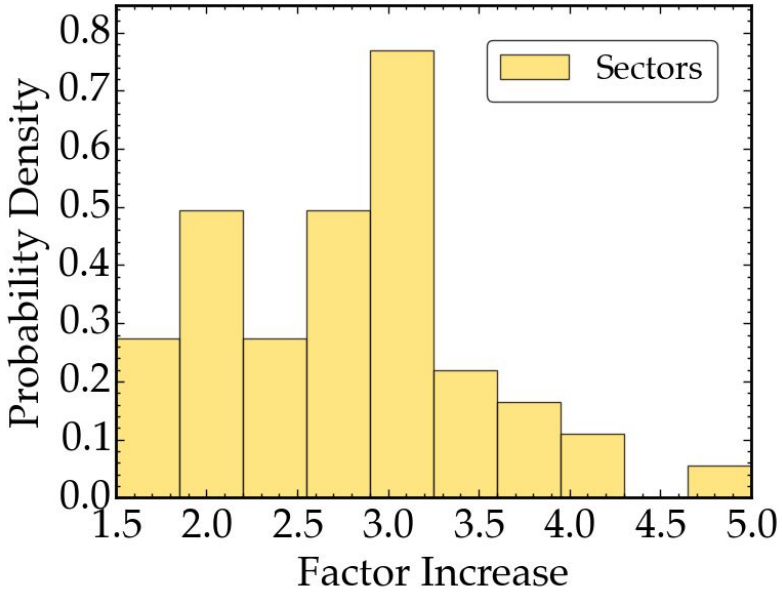

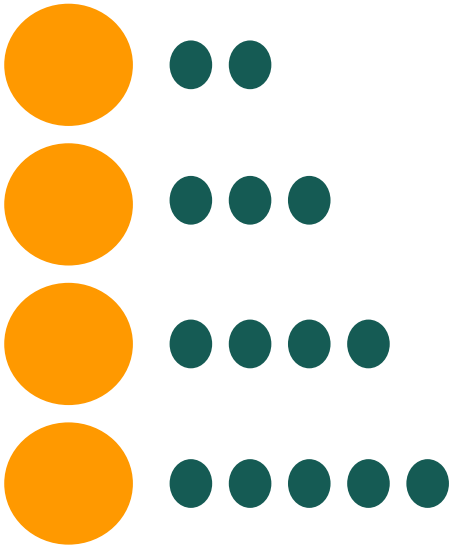

2020	2023
37	30
11	21
8	14
0	1