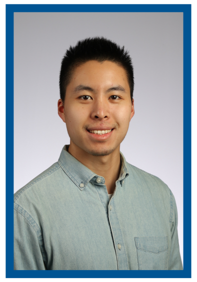
Friends and Foes:

The Conditional Occurrence of Planetary Companions to Transiting Exoplanets and their Impact on Radial Velocity Follow-up Observations



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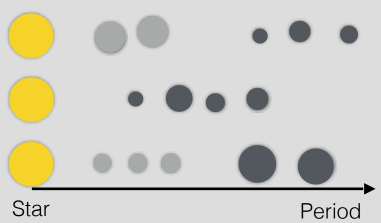
Introduction: Forward modeling planetary system architectures (SysSim)

We develop models for the **intrinsic distribution** of planetary systems that constrain the:

- underlying multiplicity distribution
- clustering in multi-planet systems
- correlations in orbital eccentricities and inclinations



Define statistical models that include correlated planets + stability criteria

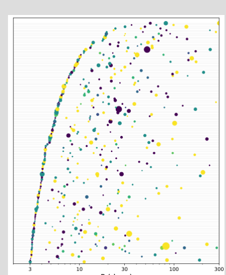
which planets transit and can be detected?

We **forward model the Kepler mission** to account for detection biases (transit probability and detection efficiency) in the observed population.

Calculate which planets would transit and be detected by Kepler

what systems are observed?

Using this framework, we can simulate thousands of Kepler-sized catalogs for intrinsic and observed systems!

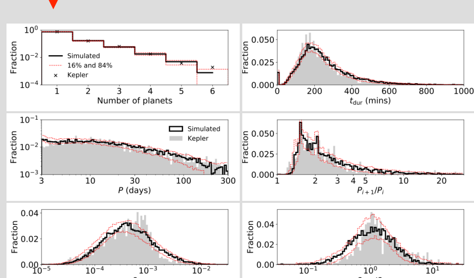


Simulate large catalogs of Kepler-observed planetary systems

how do the simulations compare to the data?

By comparing our simulated observed catalogs to the Kepler catalog, we reproduce the observed distributions of:

- multiplicity and total planets
- periods and period ratios
- depths and depth ratios
- durations and duration ratios
- and many more! (system-level metrics, observed correlations, TDVs, etc.)



Fit to marginal distributions of observed system properties using a distance function, to constrain model parameters

1. *Friends:* what is the distribution of planets conditioned on a known planet?

Our understanding of planetary systems at the population level has improved to the point where we can make predictions about the presence of additional planets in observed systems. By combining our model with the properties of observed planets, we can compute the **conditional occurrence** of planets given a known planet (e.g. from Kepler, TESS, etc).

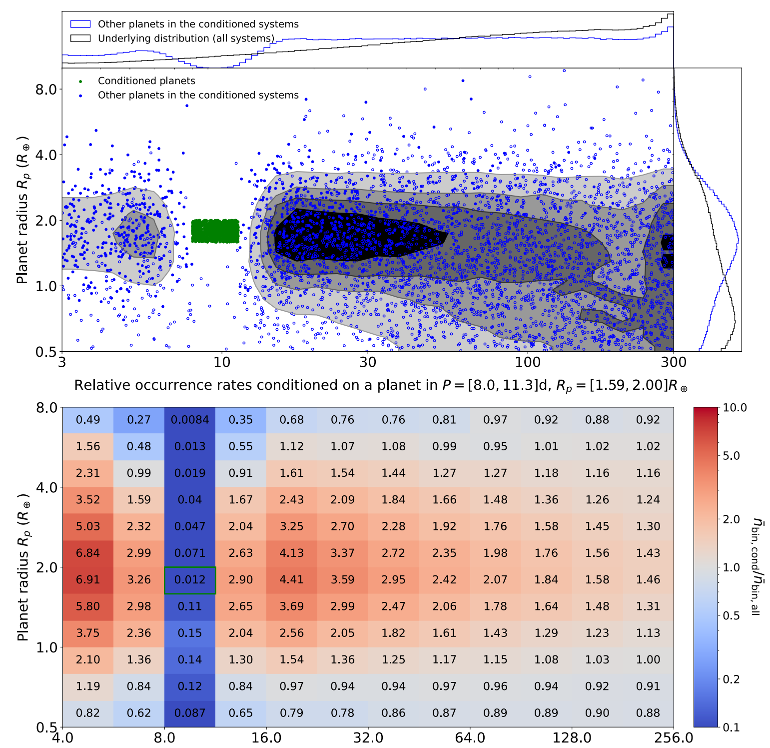


Fig. 1: Distribution of planets conditioned on a super-Earth around 10d **(top)**. Occurrence rates in these systems, relative to the overall occurrence rates as predicted by our population model **(bottom)**. There is a lack of planets at periods very close to the known planet (green box) due to orbital stability, but an **enhanced occurrence** both interior and exterior (period ratios of ~2) for planets with similar sizes due to clustering.

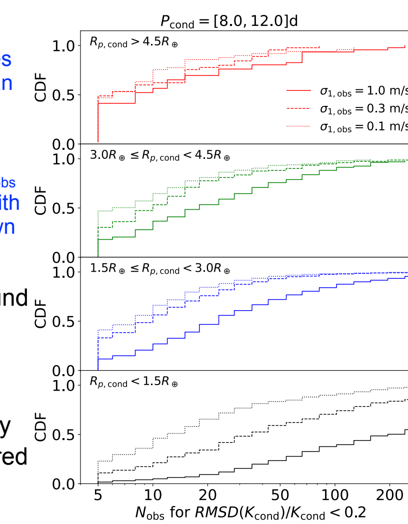
2. *Foes:* how do unseen planets affect RV measurements of a transiting planet?

In the RV follow-up of transiting planets (to measure their masses), unseen planetary companions can add a source of **systematic error** if unmodeled.

We **determine the minimum number of RV observations** (N_{obs}) needed to accurately measure the transiting planet's K (K_{cond}), assuming a single-planet model in which its orbit is fully known. This is then compared to simulations of N_{obs} in the ideal case, when there are no additional planets.

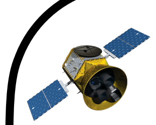
Fig. 2: Number of observations (N_{obs}) needed to measure the semi-amplitudes (K_{cond}) of transiting planets to better than 20% accuracy, for various levels of RV single-measurement precision ($\sigma_{1,obs}$).

The panels show the distributions of N_{obs} for various sizes of transiting planets with orbital periods between 8-12 days drawn from our model.



Small (1-2 Earth radii) planets around 10-day periods, common amongst TESS planet candidates, with K comparable to the single-measurement RV precision typically require ~100 observations, compared to only ~60 in the ideal case.

3. Applications to follow-up of TESS planets



While almost ~2250 TOIs have already been discovered from the TESS primary mission (Guerrero et al. 2021), the majority of TOIs do not have any mass measurements.

Our code can be used to optimize RV follow-up of TOIs by:

Estimating the number of observations needed to accurately constrain TOI planet masses

Informing the time-span and cadence of observations

Evaluating the probability of having additional detectable planets

Also see poster by **Arvind Gupta** for RV follow-up of TESS single-transit planet candidates

4. Summary and to read more

Population models can be used to predict the conditional occurrence and properties of additional planets in systems with a known transiting planet. However, these additional planets can also pose a unique challenge in the characterization (mass measurements) of the known planets with RVs.

In our paper, we also explore:

- prospects for measuring the mass of Venus-like analogs
- whether there are any patterns to the types of planets that have the greatest effects on the number of RV observations

Paper: https://arxiv.org/abs/2105.04703 (under review)
Code: https://github.com/ExoJulia/SysSimExClusters

References

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9. **He, Ford, & Ragozzine (2021b), submitted to AAS Journals**

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