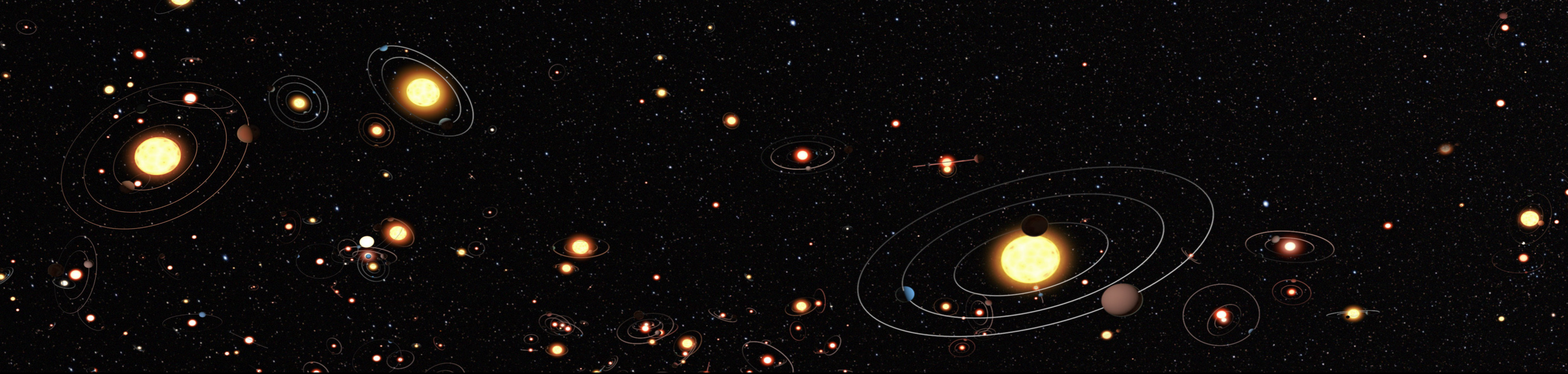

Exoplanet Demographics Beyond *Kepler*

Giant Planets detected with Radial Velocity & Young Planets with TESS

Rachel B. Fernandes

Collaborators:

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THE UNIVERSITY OF ARIZONA
COLLEGE OF SCIENCE
LUNAR & PLANETARY LABORATORY

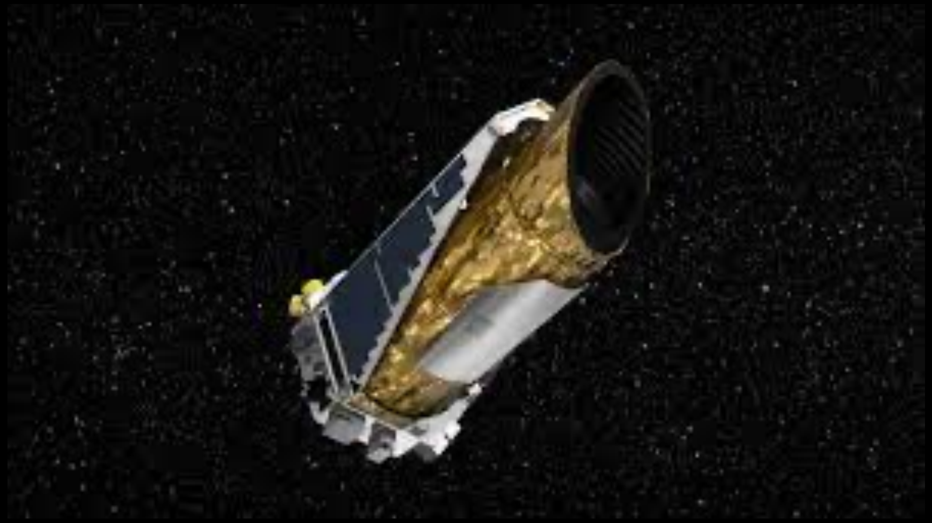
ALIEN EARTHS

May 14, 2021

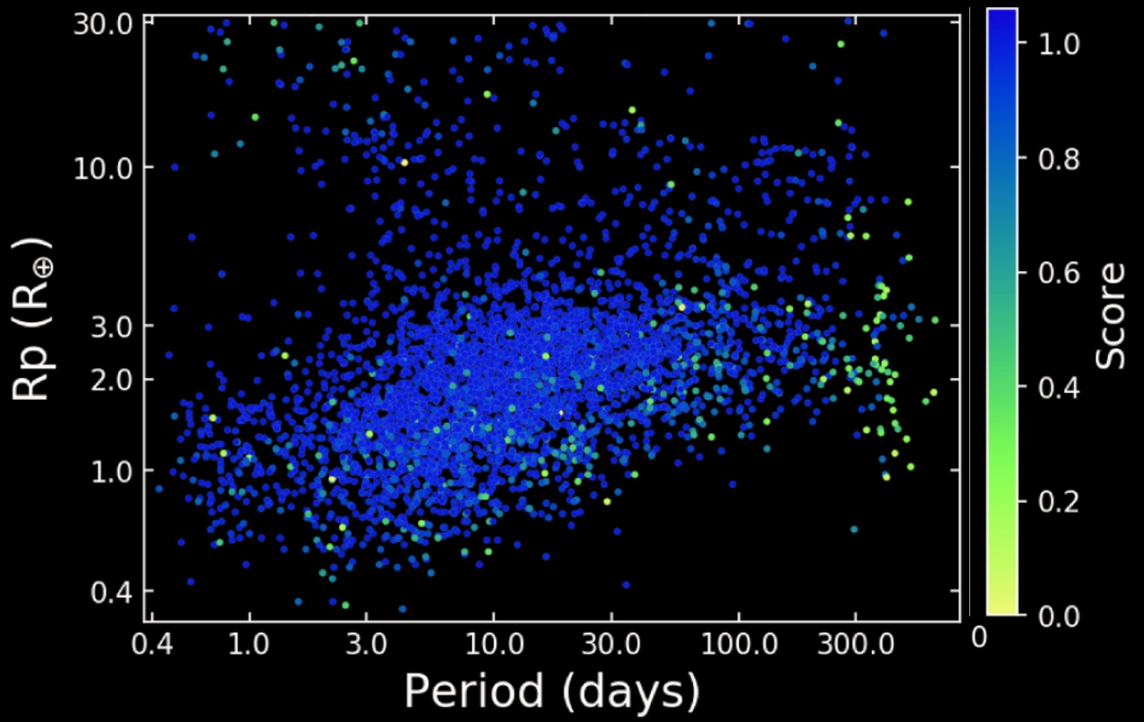
Exoplanet Explorers

The *Kepler* Mission

- Mission Goal: To detect Earth-sized planets in the habitable zone (HZ) of a Sun-like star (SpTy: FGK)
- Lifetime: March 2009-May 2013
- Constellations: Cygnus, Lyra and Draco
  - Greater concentration of FGK stars



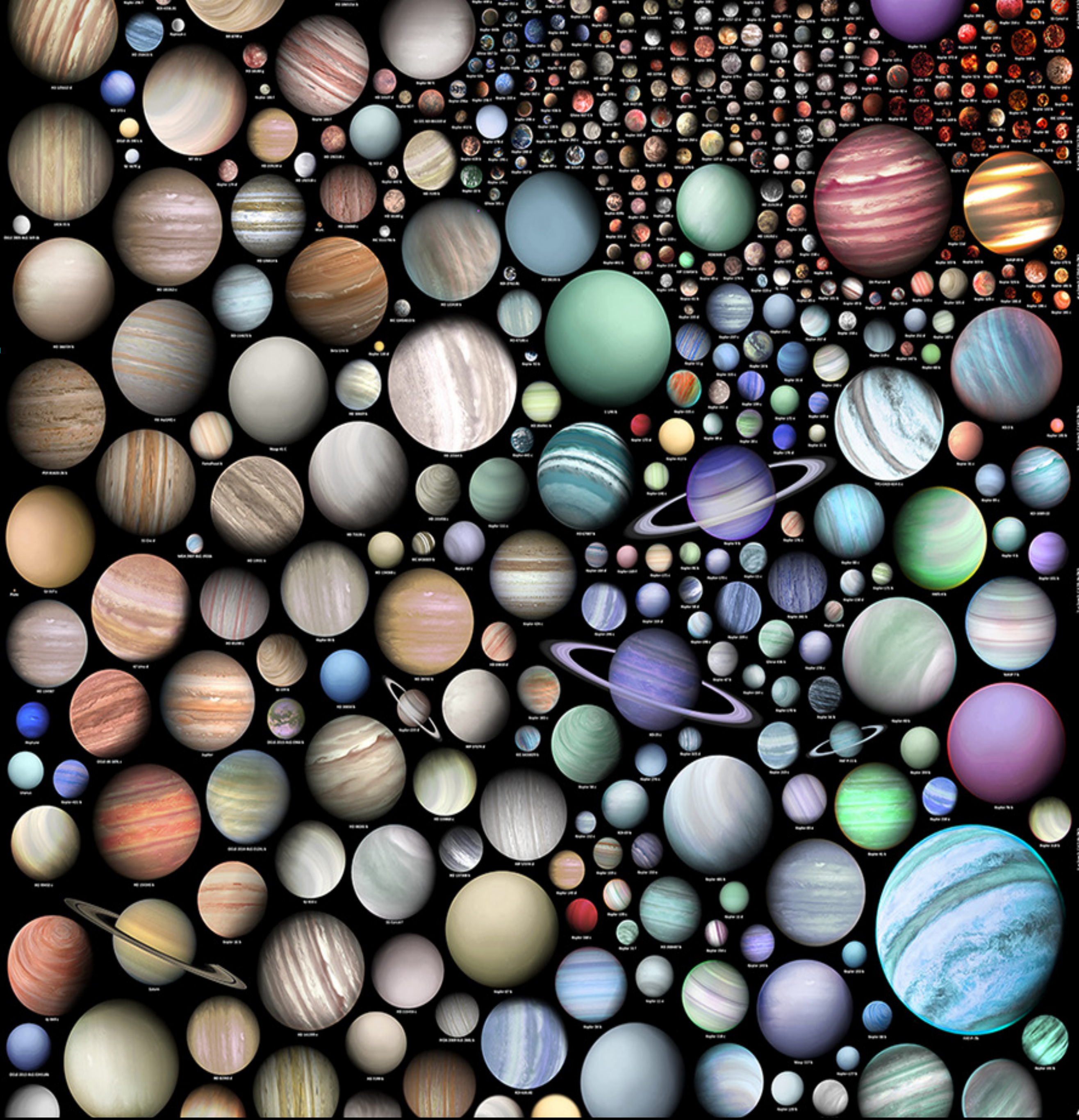
nasa.gov



Thompson et al. 2017 using Kepler dr25

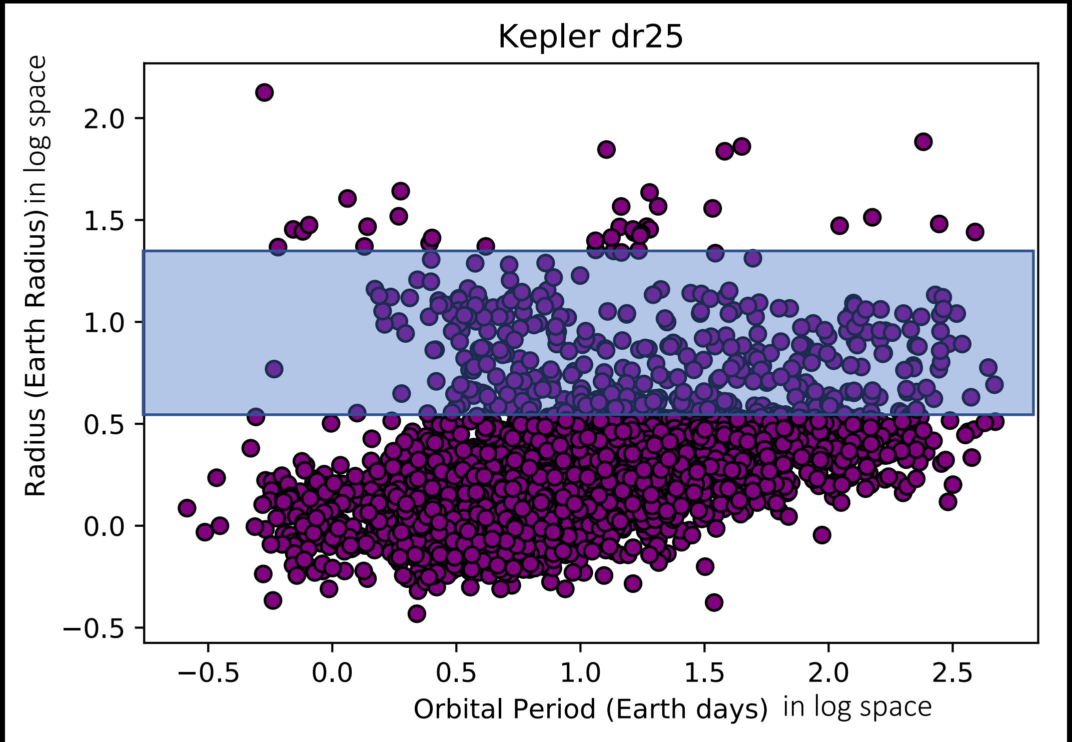
Giant Planets Detected with Radial Velocity

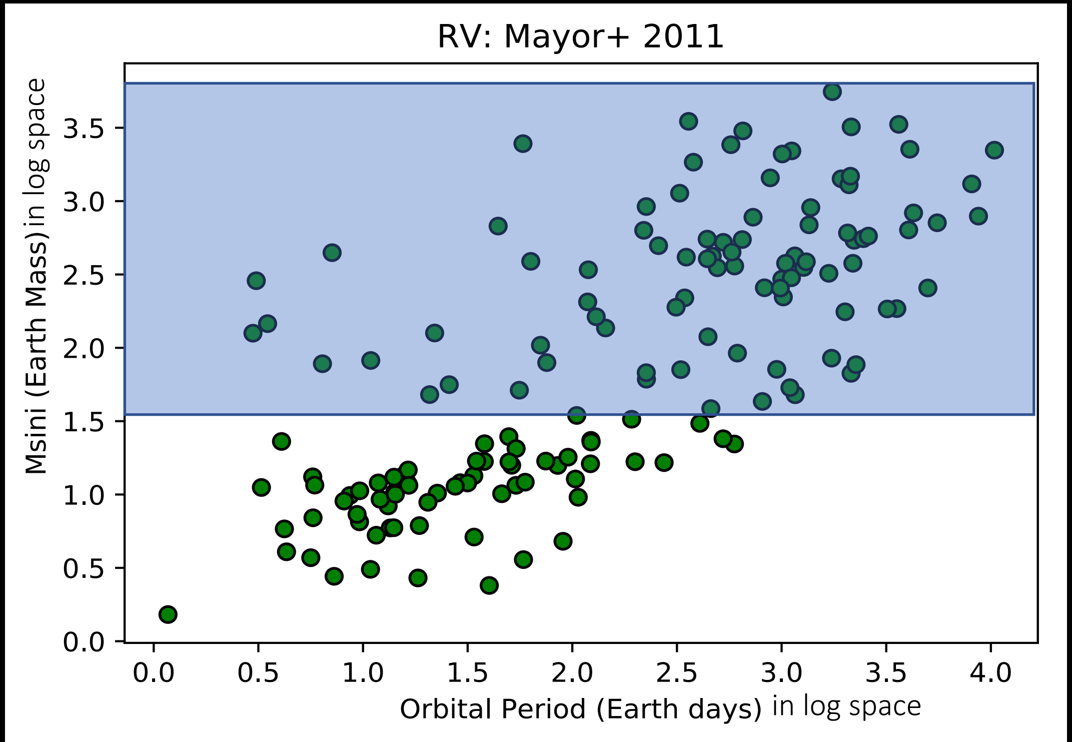
- How different are the *Kepler* and radial velocity (RV) Giant Planet (GP) distributions?
- What is GP distribution across all orbital separations?
- Is there really a break/turnover at larger orbital separations as predicted by planet formation models?



Martin Vargic

Data: *Kepler* and Radial Velocity (RV)





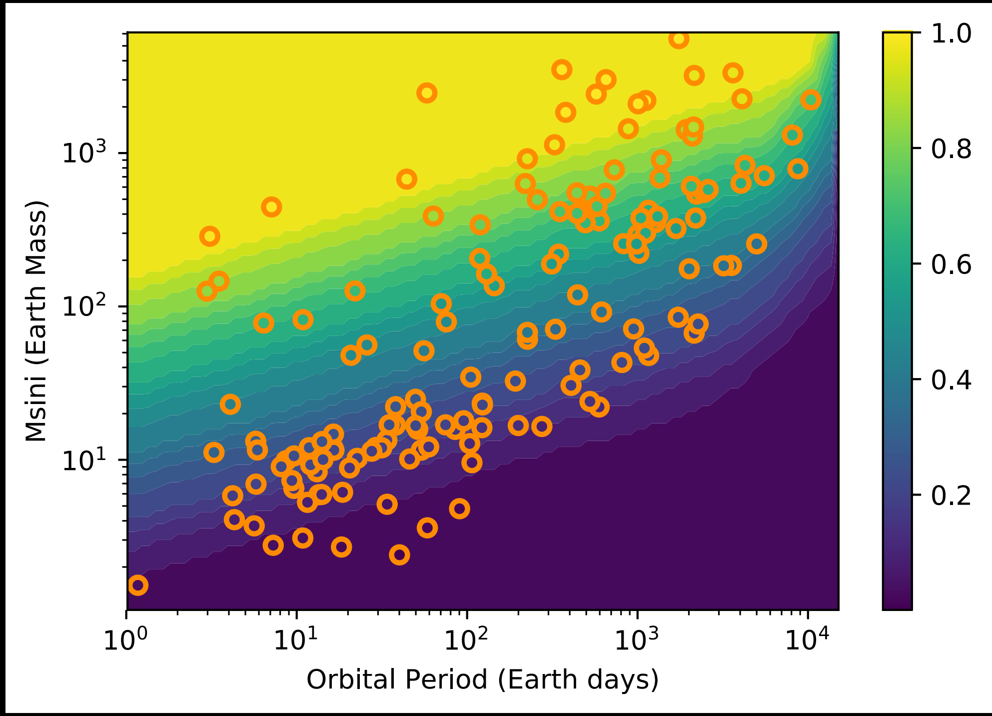
- Method: Transit
- Measures radius
- Close in planets (<480 days)
- GP: 5 – 20 $R_\oplus$

- Method: Radial Velocity (RV)
- Measures mass (more specifically msin*i*)
- Wide orbital range (out to 10,000 days)
- GP: 30 – 6000 $M_\oplus$ (0.1 – 20 M_J)

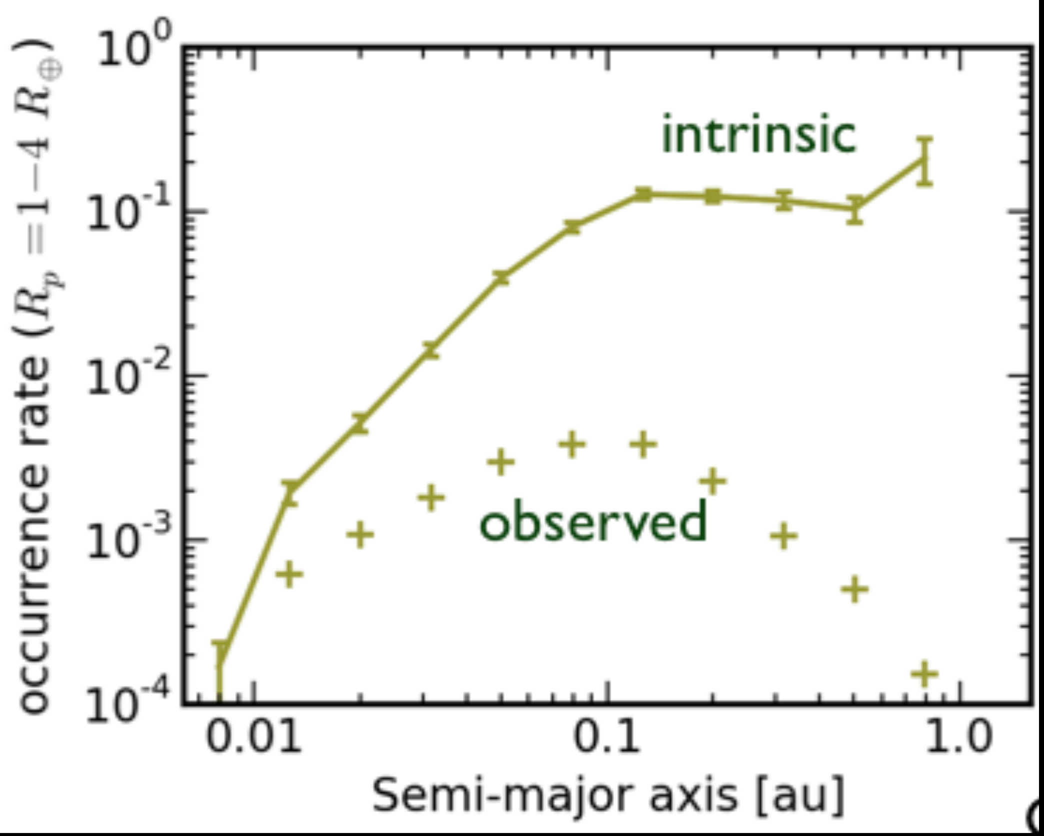
Occurrence Rate Calculations

$$\eta_{bin} = \frac{1}{n_*} \sum_j^{n_p} \frac{1}{comp_j}$$

Where n_* is the number of stars and $comp_j$ is the survey completeness evaluated at the radius/*m*sin*i* and orbital period of each planet in the bin.



Fernandes+ 2019; Kyle Pearson

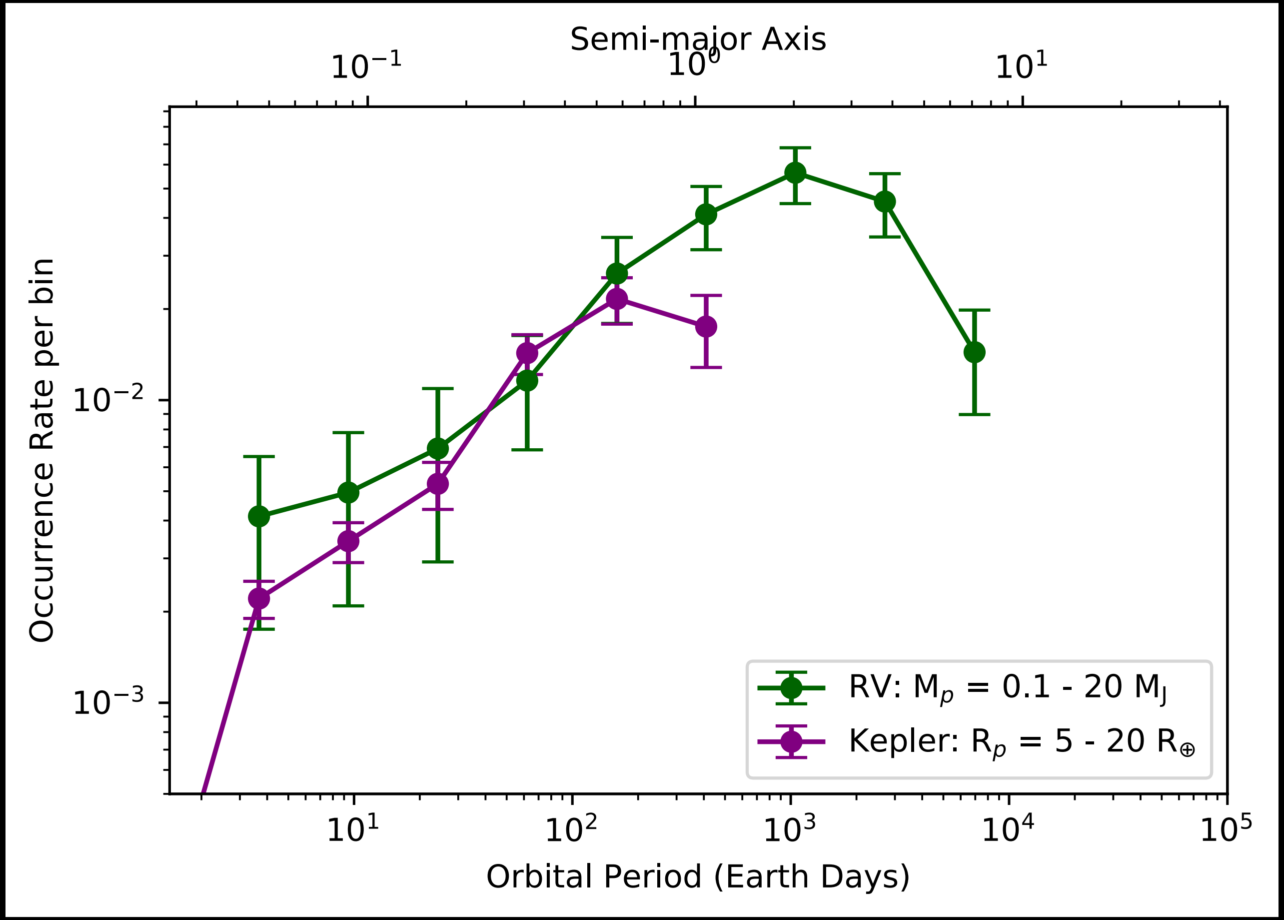


Gijs Mulders

Importance of Completeness:
Observed distribution vs. Intrinsic distribution of exoplanets

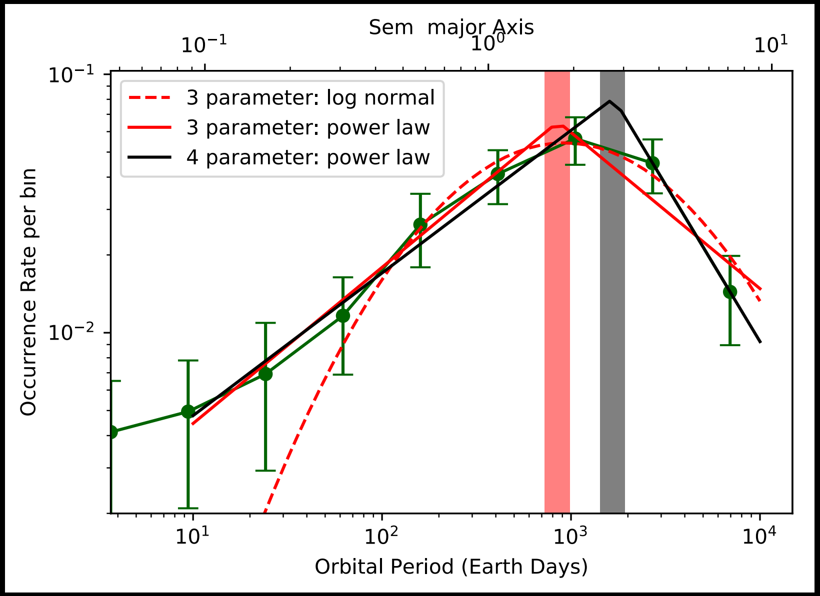
Result 1: RV vs *Kepler*

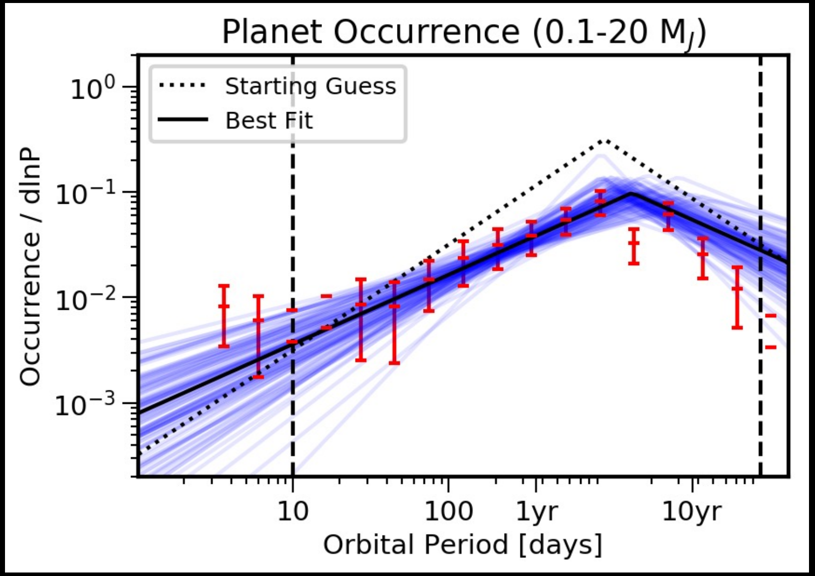
- GP occurrence rate increases as a function of orbital period (consistent with previous results).
- RV and *Kepler* curves are the same within errors
  - RV can be used as an extension of *Kepler*

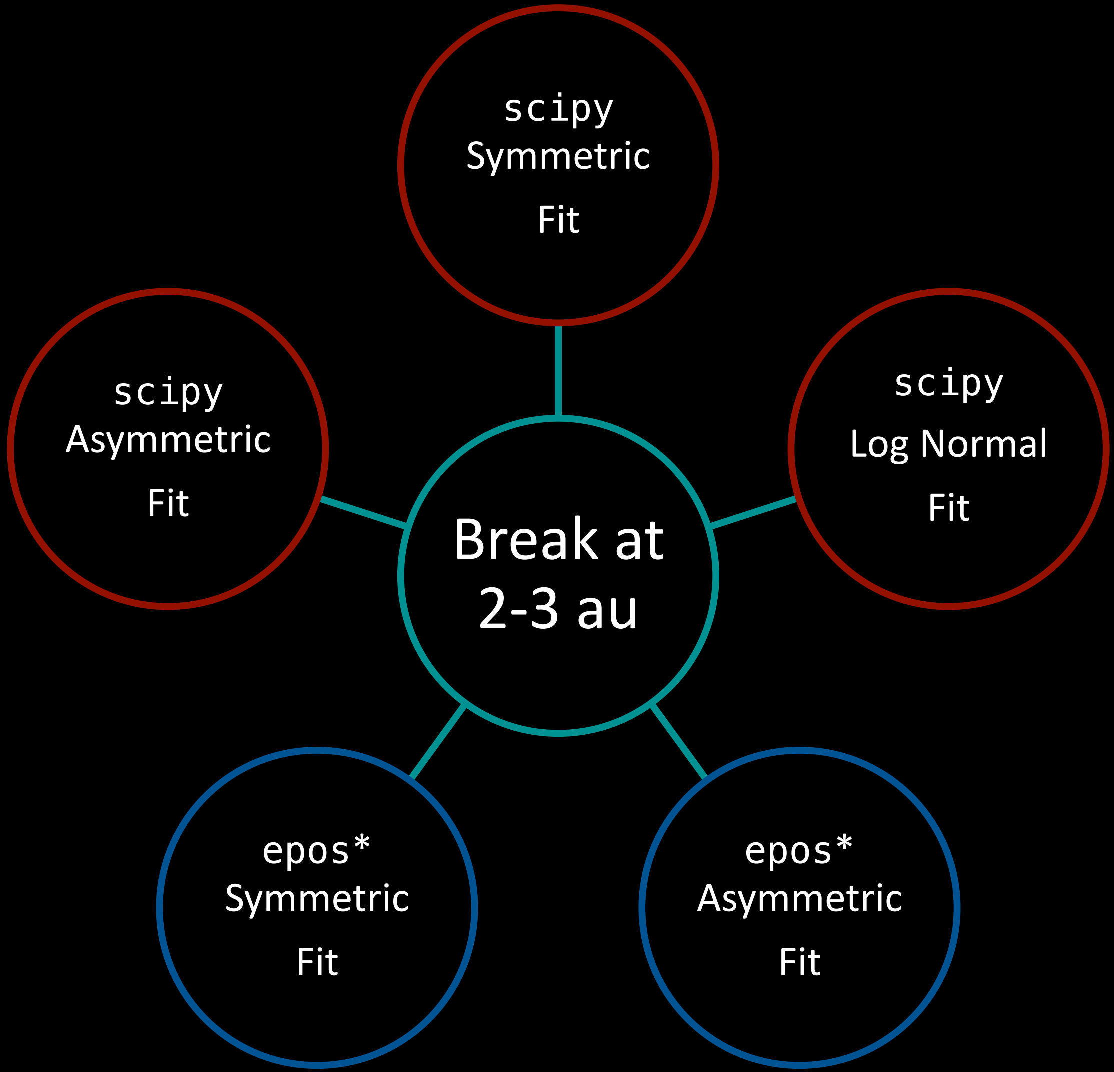


Fernandes+ 2019

Result 2: Turnover at the Snowline

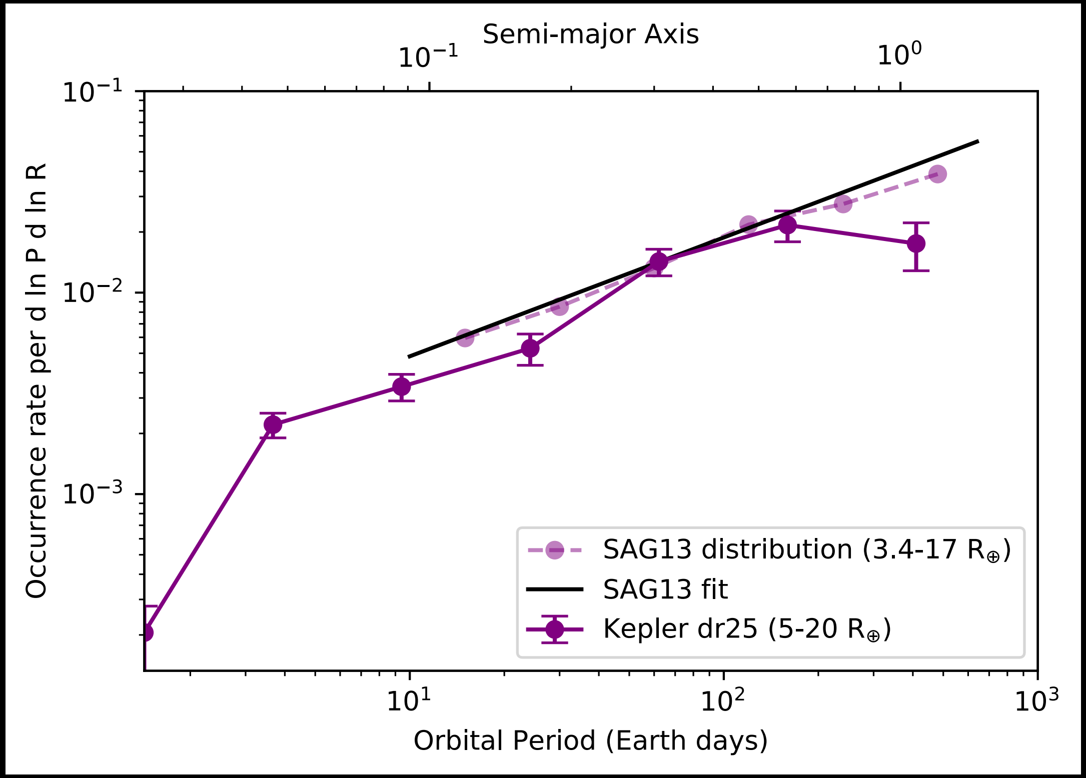


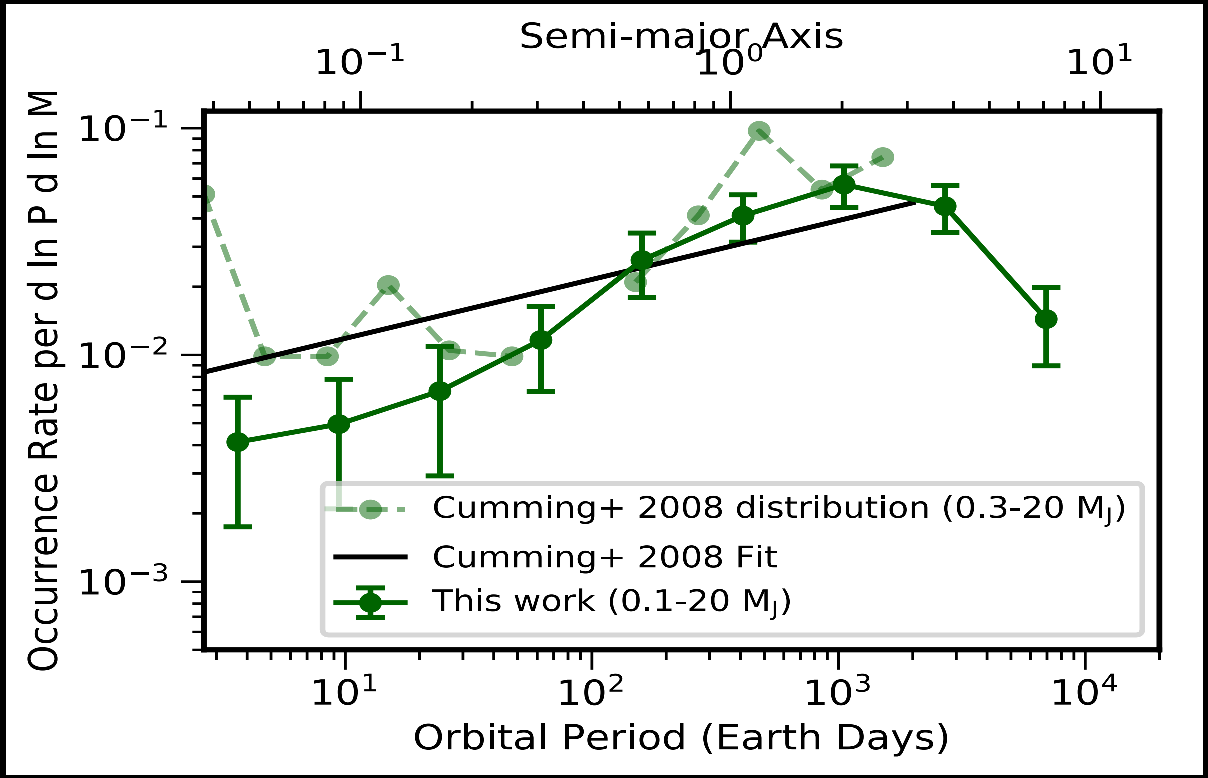




*A Python code to compare synthetic planet populations to the observed planet populations (Mulders+ 2018, 2019; https://github.com/GijsMulders/epos)

Past Predictions for Direct Imaging





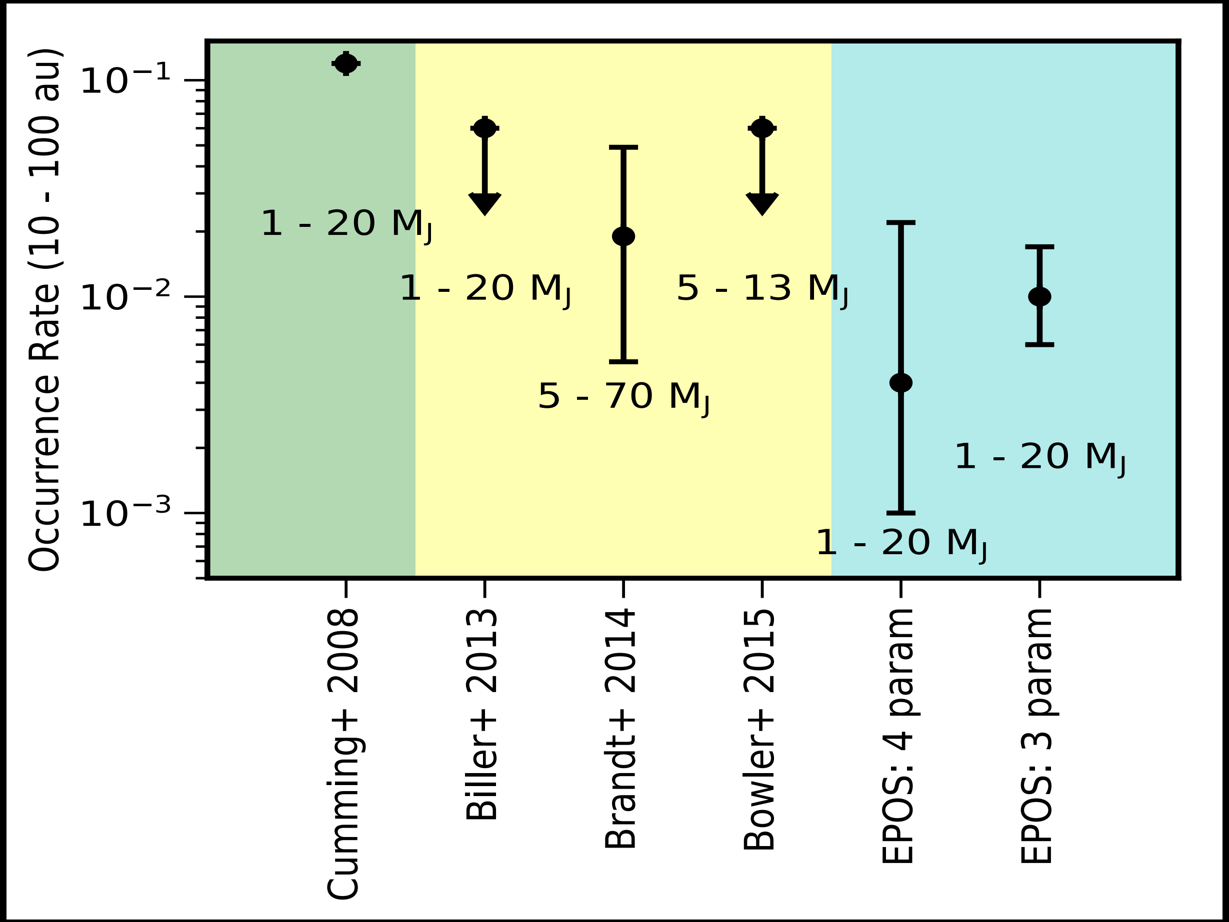
Fernandes+ 2019

Kepler (Kopparapu+ 2018):
Extrapolated rate (within 20 au): 101%

RV (Cumming+ 2008):
Extrapolated rate (10-100 au): 15%

Result 3: Predictions for Direct Imaging

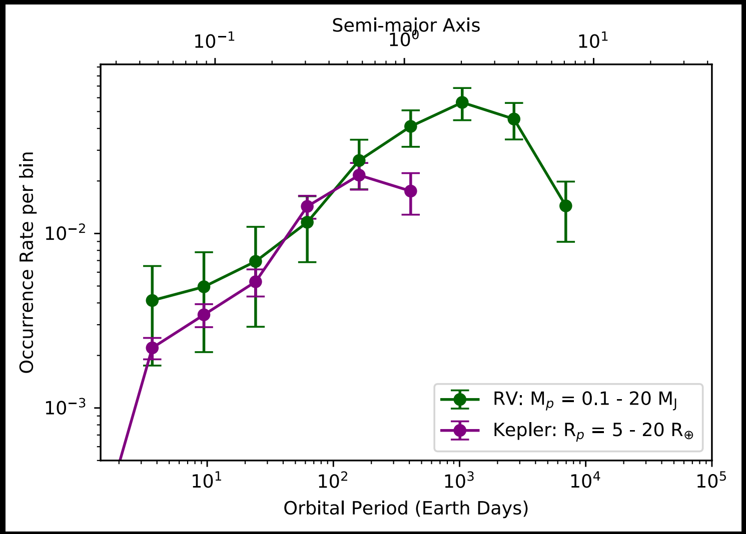
- Extrapolate Broken Power-law instead, using epos
  - Asymmetric : $0.4^{+1.8}_{-0.3}\%$
  - Symmetric : $1.0^{+0.7}_{-0.4}$
- Lower than single power-law extrapolations by orders of magnitude
- Consistent with observed rates (GPIES - Nielsen+ 2019)

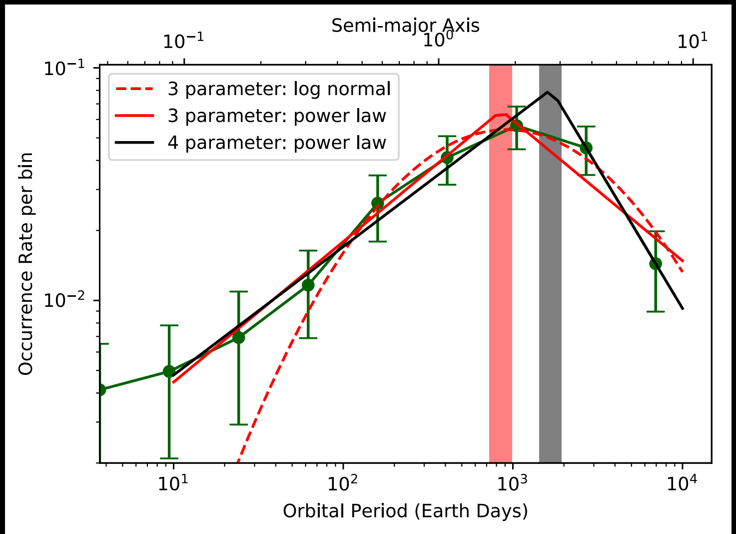


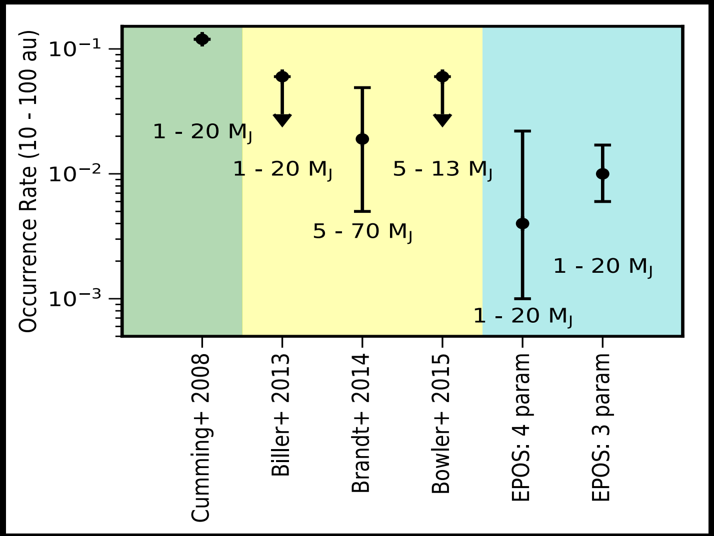
Fernandes+ 2019

Half-way Summary

- What we did:
  - Compared the *Kepler*'s giant planet frequency with that of RV (Mayor+ 2011)
- What we found:
  - The occurrence of *Kepler* and RV as a function of orbital period agree with errors
  - Robust evidence for a break at the snowline (~2-3 au)
  - Extrapolation of this gives more consistent rates when compared to the observed Direct Imaging rates (~1%)







Fernandes+ 2019

Young Planets with TESS

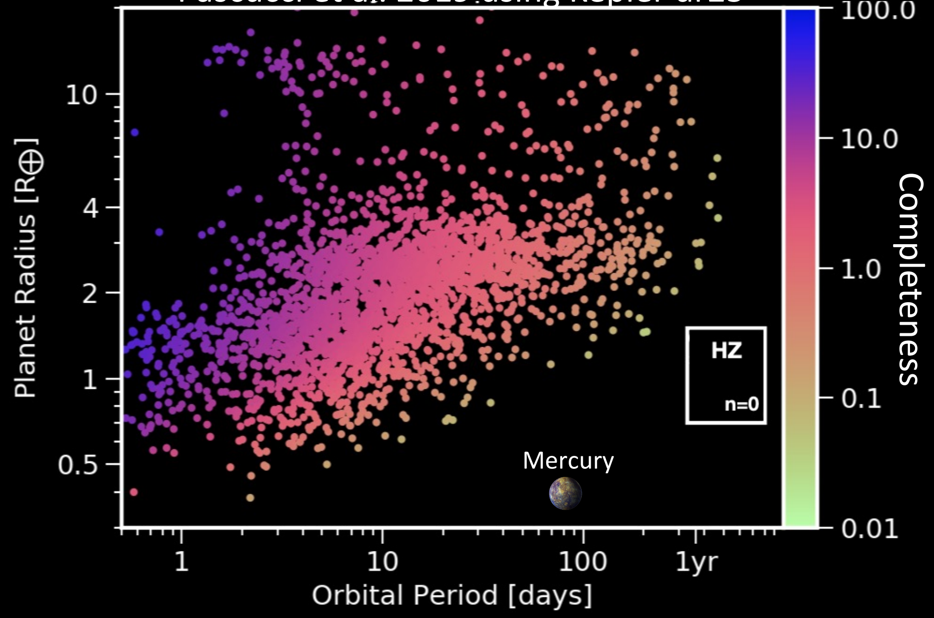
- What does the short-period planet population look like in young clusters?
- How does this young population compare with *Kepler*'s Gyr-old population?
- How can young planets help us refine EtaEarth?

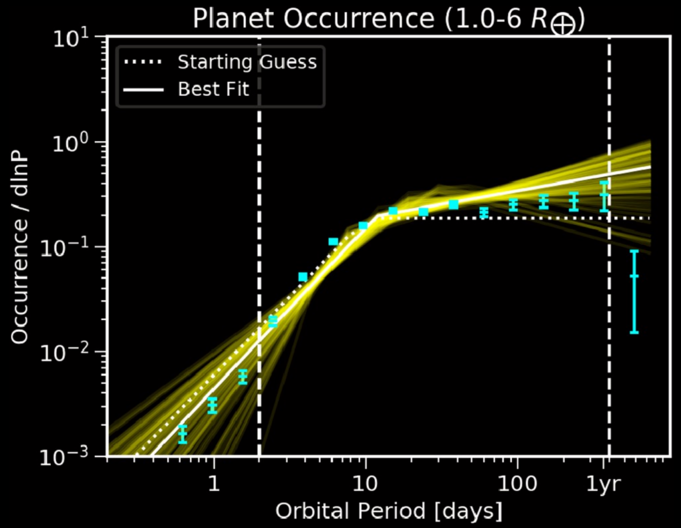
Sam Dietz

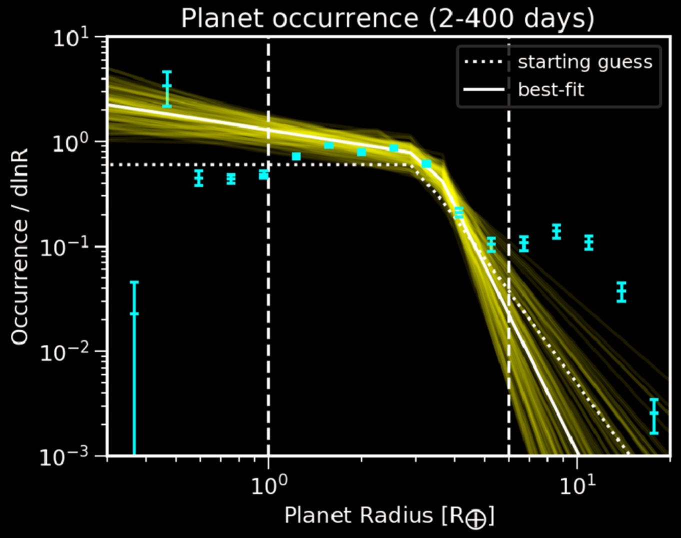
The $\eta_\oplus$ Problem

$\eta_\oplus$: the frequency of Earth-sized planets in the Habitable Zone (0.9 – 2.2 $P_\oplus$; 0.7 – 1.5 $R_\oplus$) of a Sun-like star

Pascucci et al. 2019 using Kepler dr25



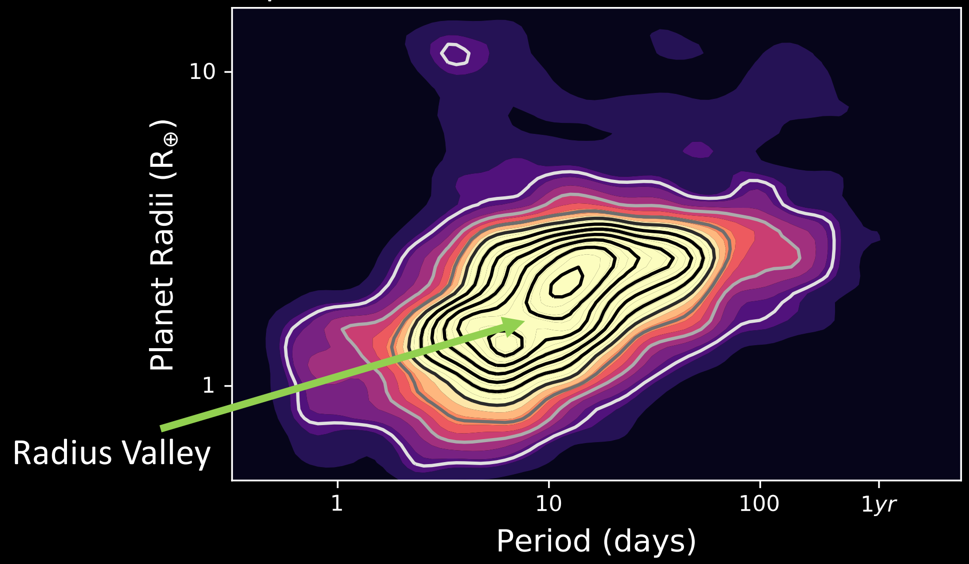




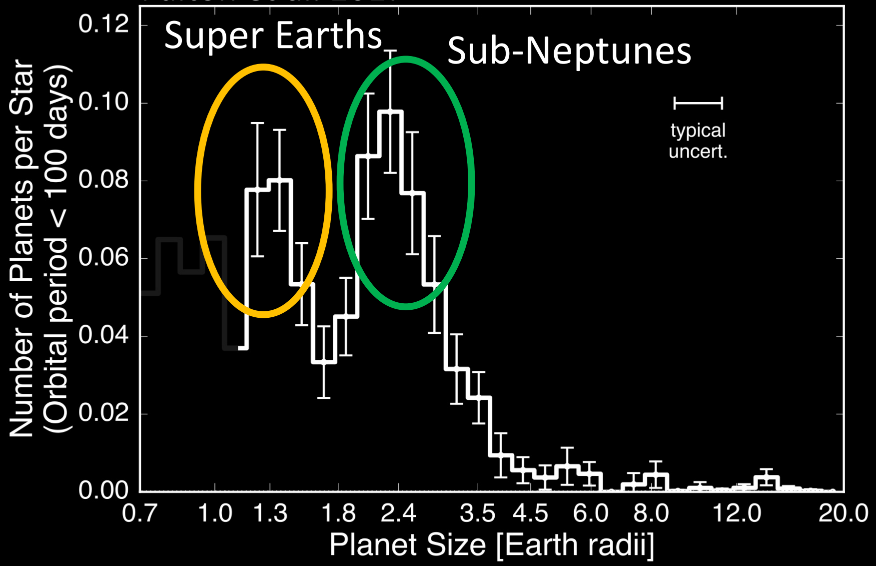
$\eta_\oplus$: 36% (epos; Mulders+ 2018)

The Population of Small, Short-period Planets

Kepler dr25



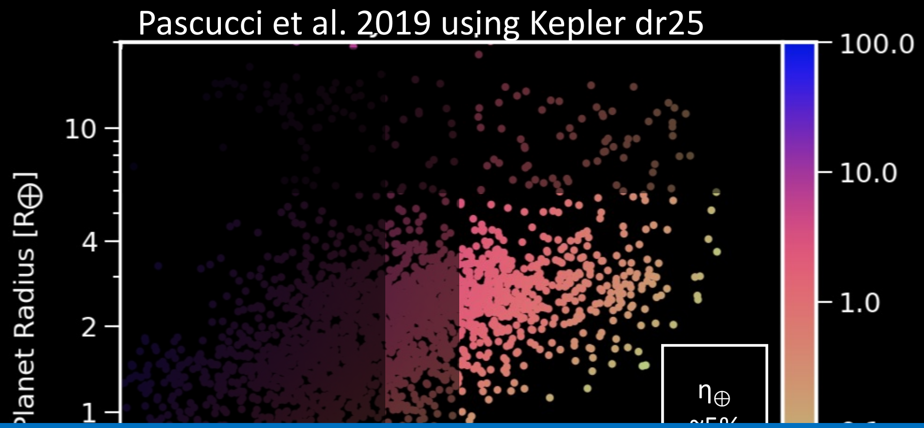
Fulton et al. 2017



Possible explanations:

- XUV Photoevaporation (Owen+Wu 2013, 2017)
- Core-powered Mass Loss (Gupta+Schlichting 2019, 2020)

Impact of Stripped Cores on $\eta_{\oplus}$

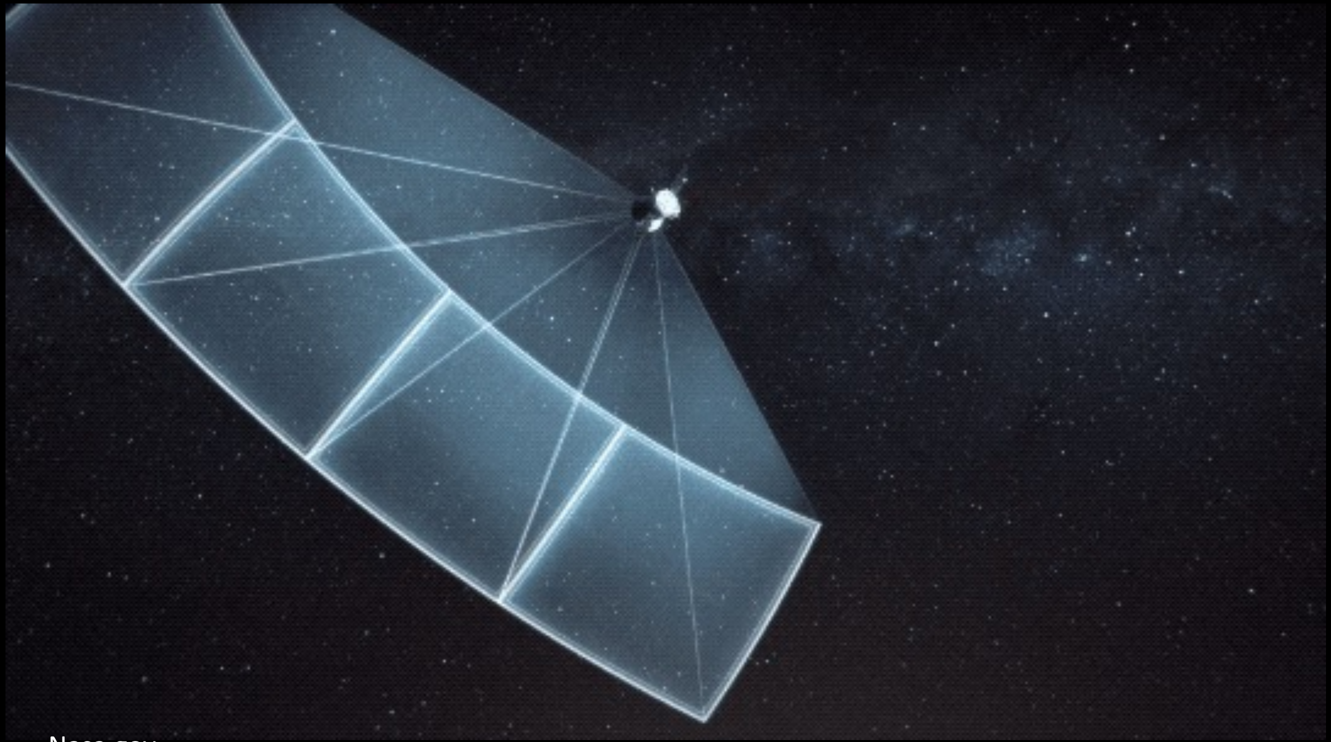


How do we quantify this contamination by the stripped cores of once sub-Neptunes?

The population of short-period small (<1.8 $R_{\oplus}$) planets maybe contaminated by the stripped cores of once sub-Neptunes and hence is not representative of planets that formed like Earth

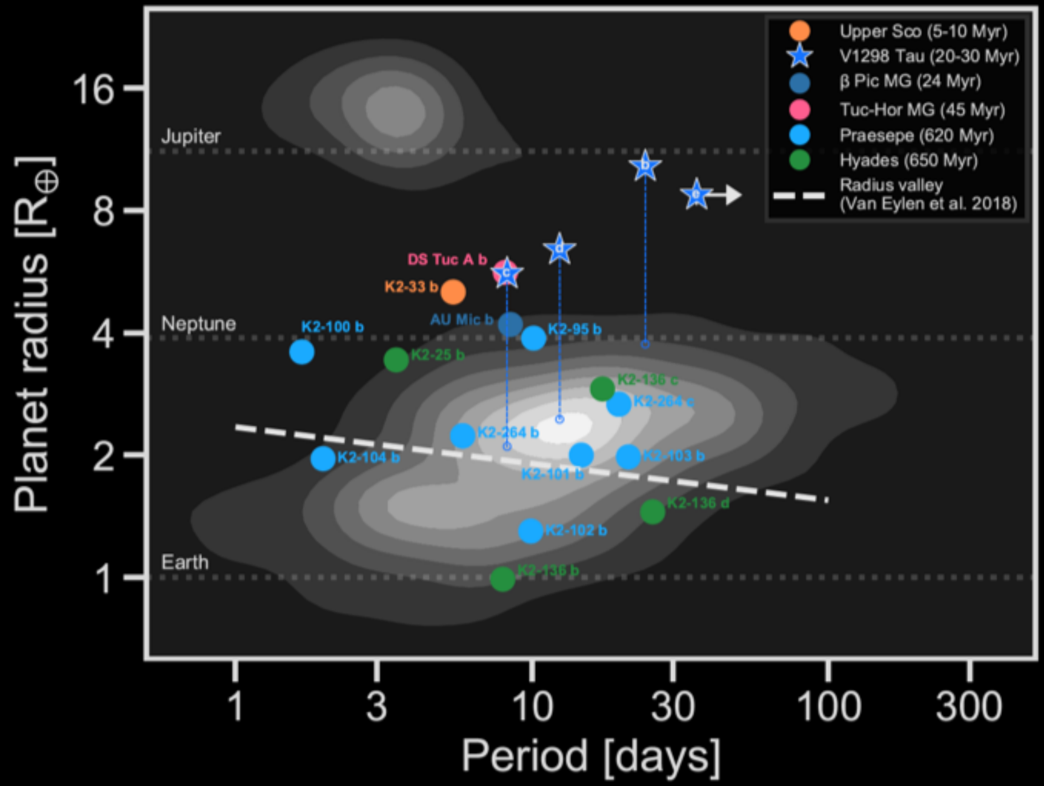
A Possible Solution…

With the Transiting Exoplanet Sky Satellite (TESS) mission, we now have the unique opportunity to detect planets around stars in young clusters and associations, providing a sample much closer in time to the primordial short-period planet population.



Nasa.gov

David, T. et al. 2019



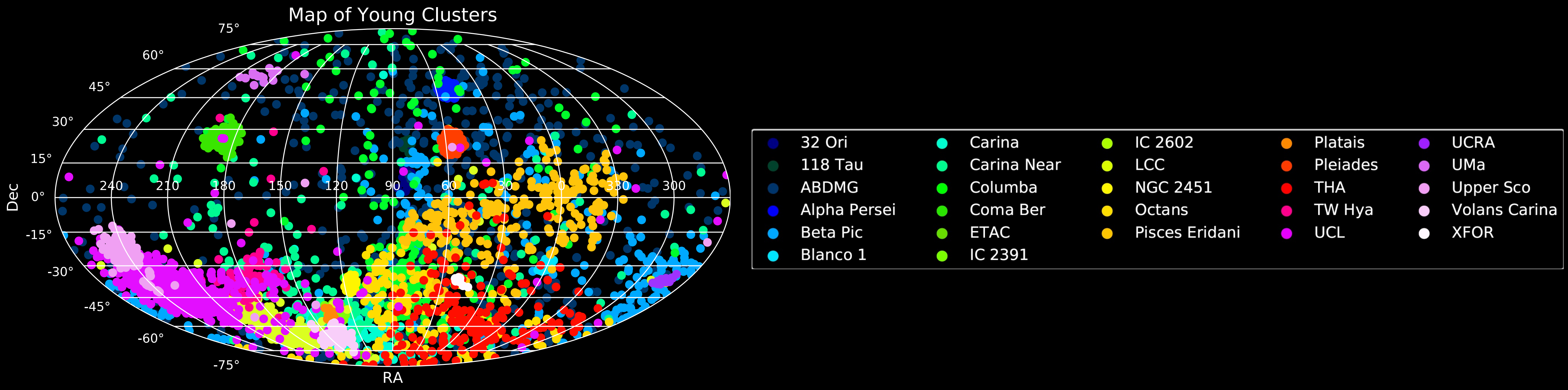
Detections of young planets with K2+TESS fill the gaps in Kepler's radius-period plane

Our Sample of Young Stellar Clusters

- Age: 10 Myr – 1 Gyr
- Distance: < 200 pc

⇒ 8370 stars from 27 young clusters and moving groups

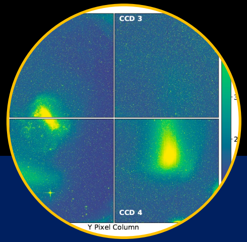
(Gagné et al. 2018 and *Gaia* DR2 (Babusiaux et al. 2018))



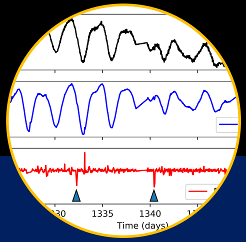
Finding Planet Candidates

pterodactyls

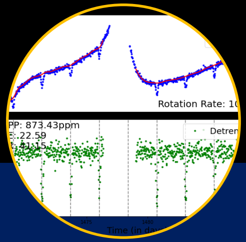
Python Tool for Exoplanets: Really Outstanding Detection and Assessment of Close-in Transits around Young Local Stars



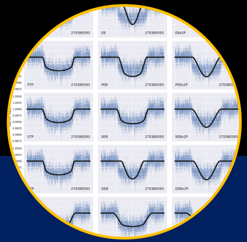
Extract Light Curves from Full Frame Images using eleanor (Feinstein+ 2019)



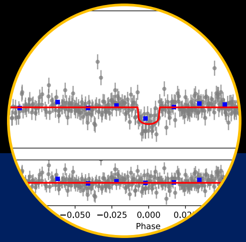
Detrend Light Curves using a penalized spline from Wōtan (Hippke+ 2019)



Search for Planets using TLS (Hippke+Heller 2019)

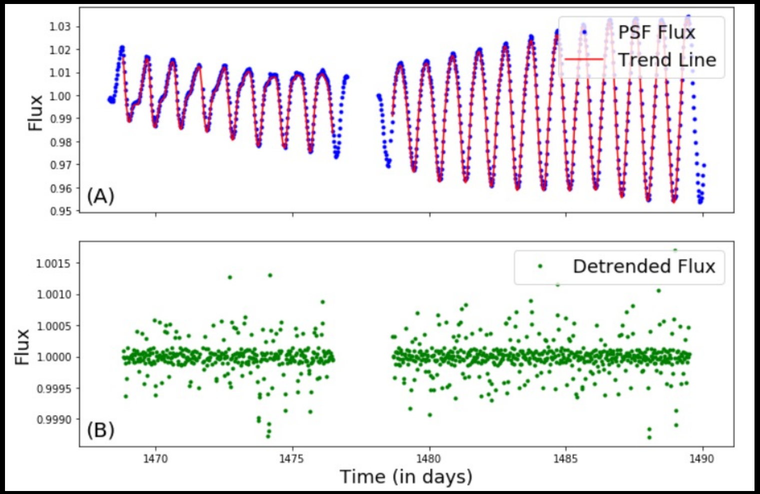


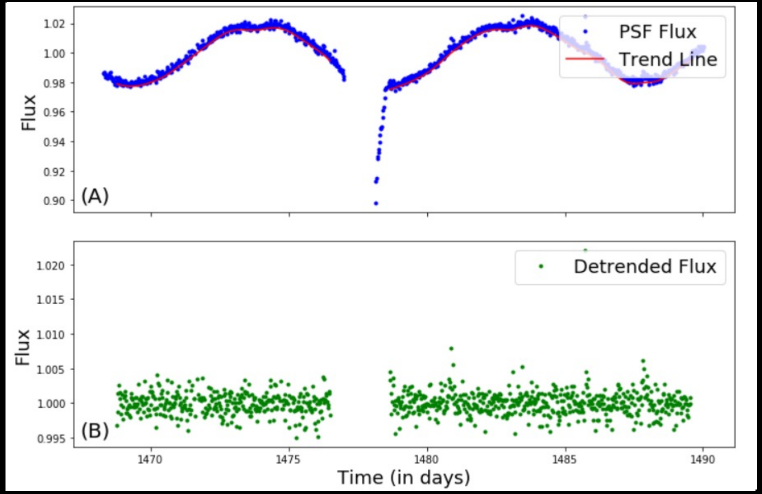
Vet exoplanet candidates using triceratops (Giacalone et al. 2020)

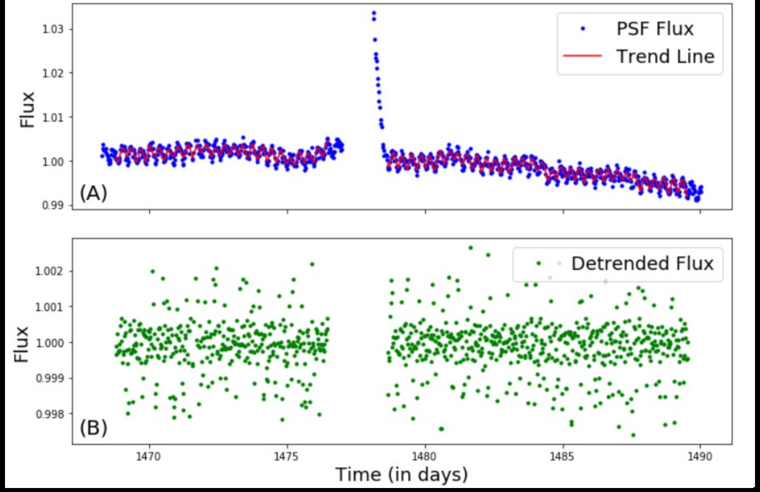


Fit phase-folded light curve using EXOTIC (Zellem et al. 2020)

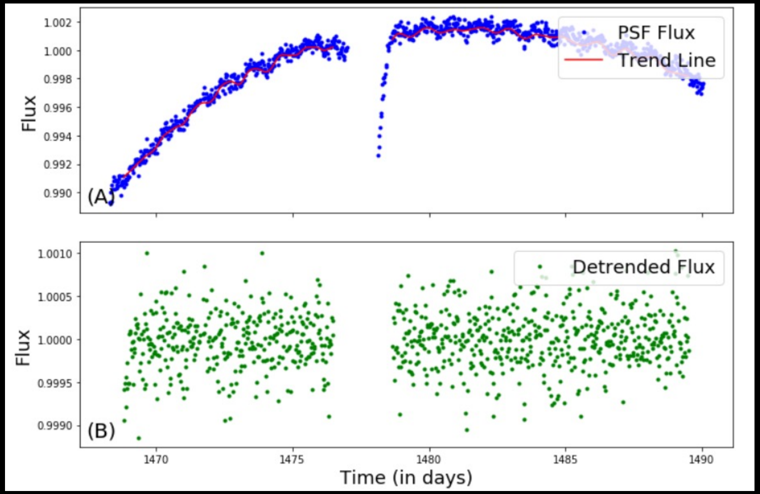
Detrending Light Curves of Young Stars

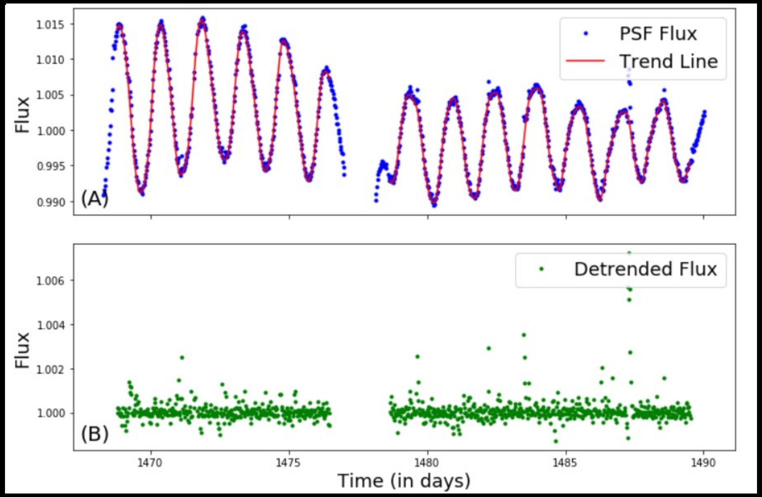


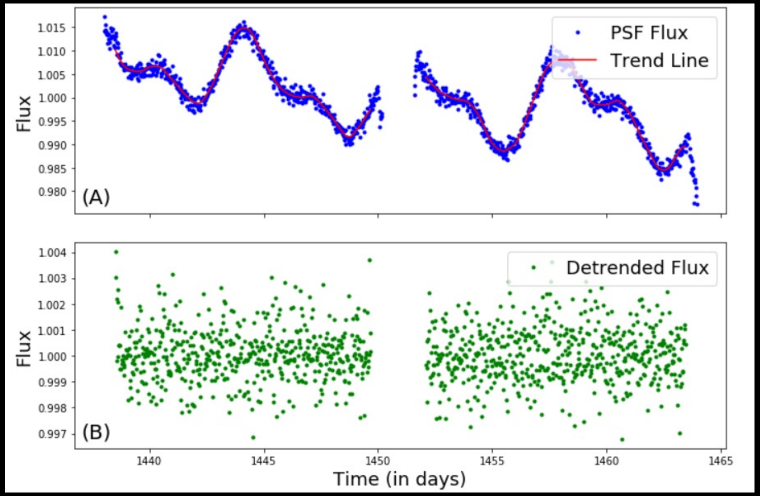




Penalized Spline With Knot Optimization Based on Stellar Rotation Rates



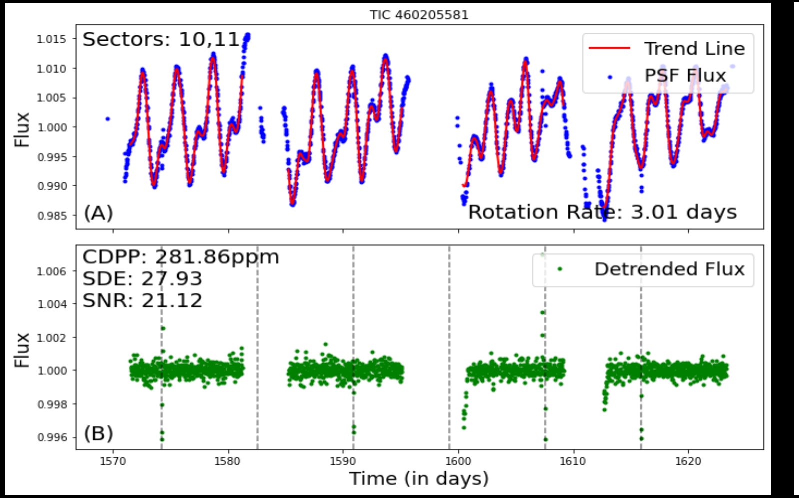


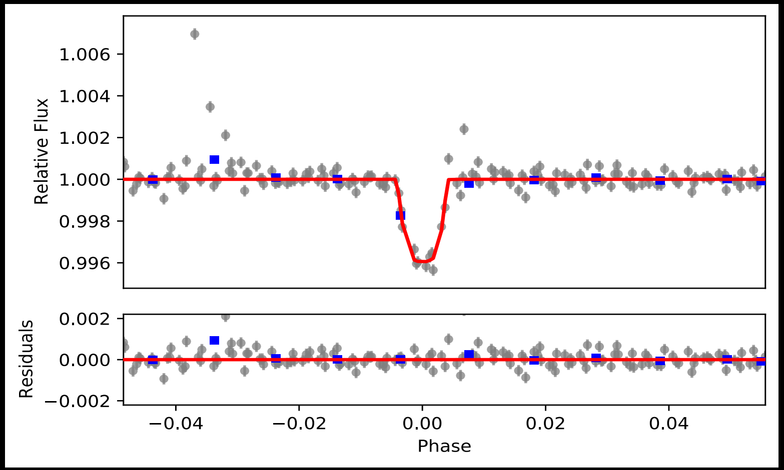


Result 1a: Recovery of Known Planets

Nardiello et al. 2020

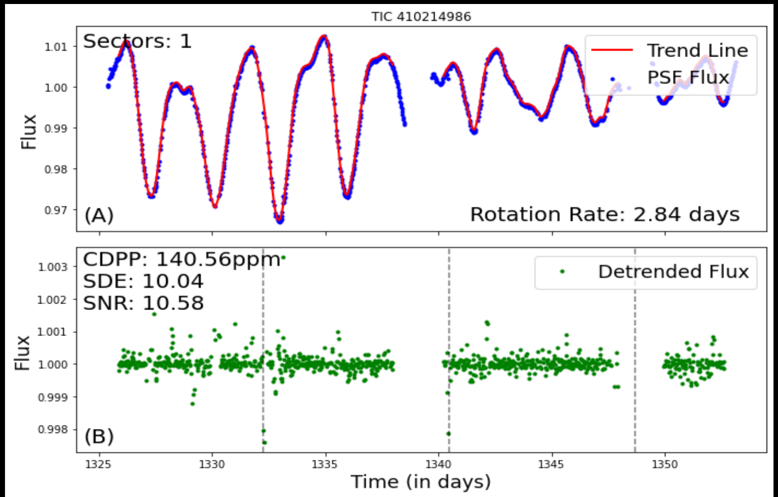
Cluster: IC 2602
Radius: 7.2 $R_\oplus$
Period: 8.3 days

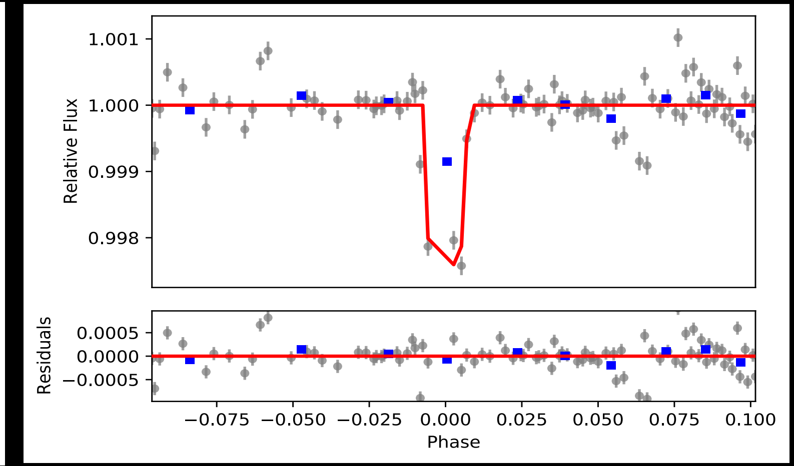




Newton et al. 2019

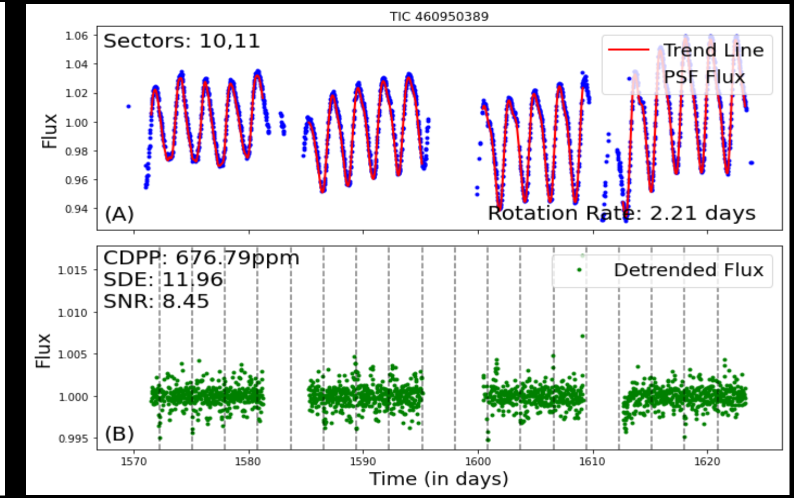
Cluster: THA
Radius: 5 $R_\oplus$
Period: 8.2 days

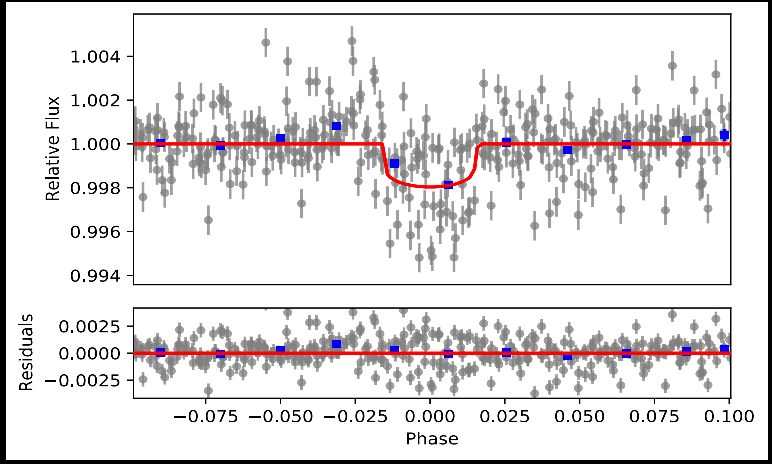




Nardiello et al. 2020

Cluster: IC 2602
Radius: 3.5 $R_\oplus$
Period: 2.8 days

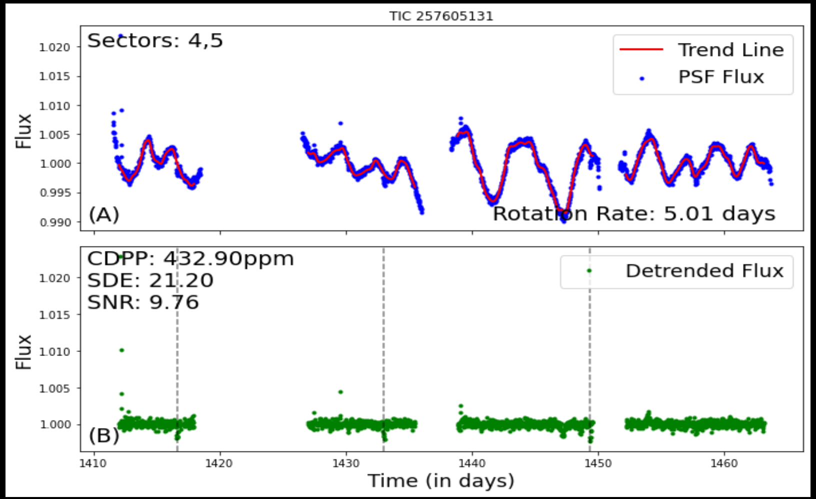


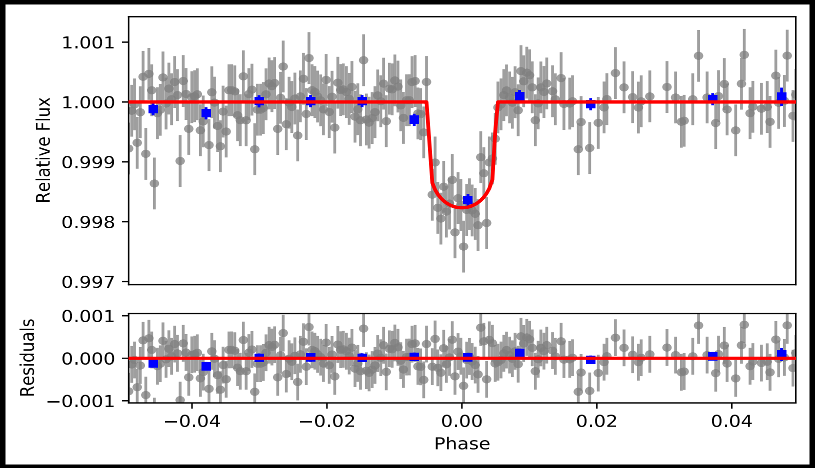


Result 1b: Recovery of Multi-Planet Systems

Newton et al. 2021

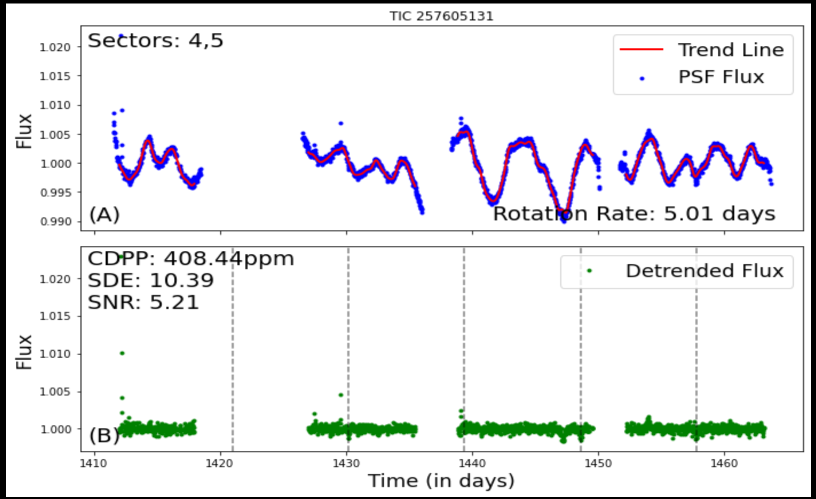
Cluster: Pisces-Eridani
Radius: 3.6 $R_\oplus$
Period: 16.4 days

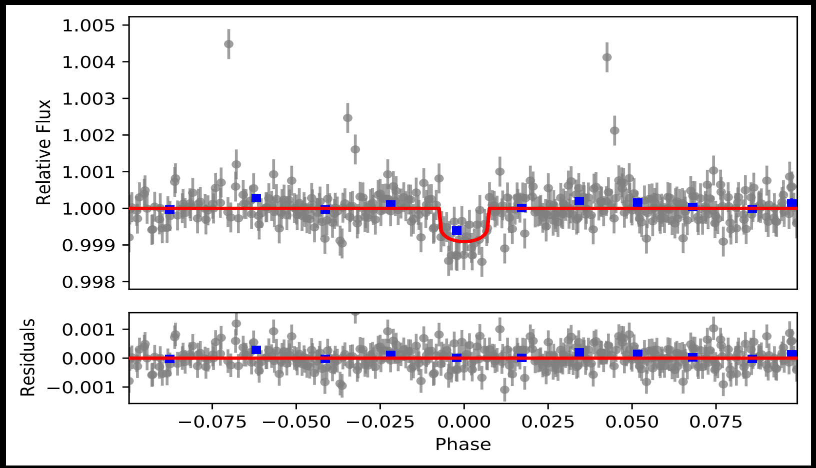




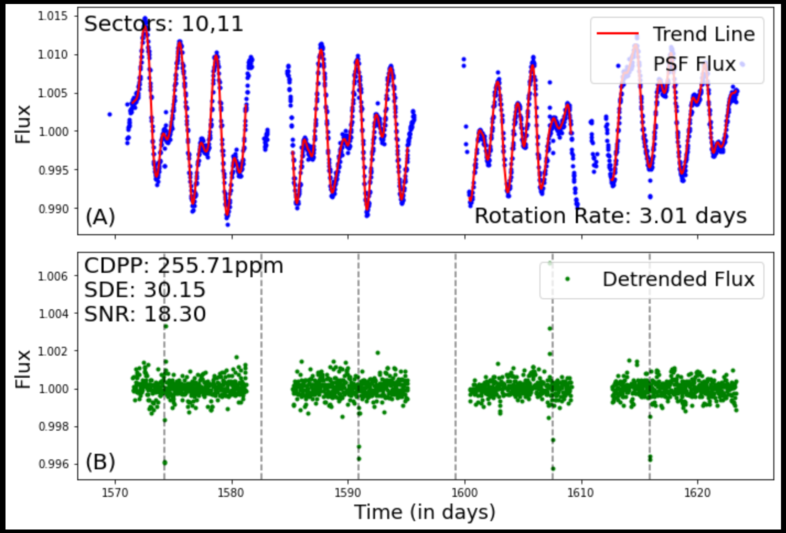
Newton et al. 2021

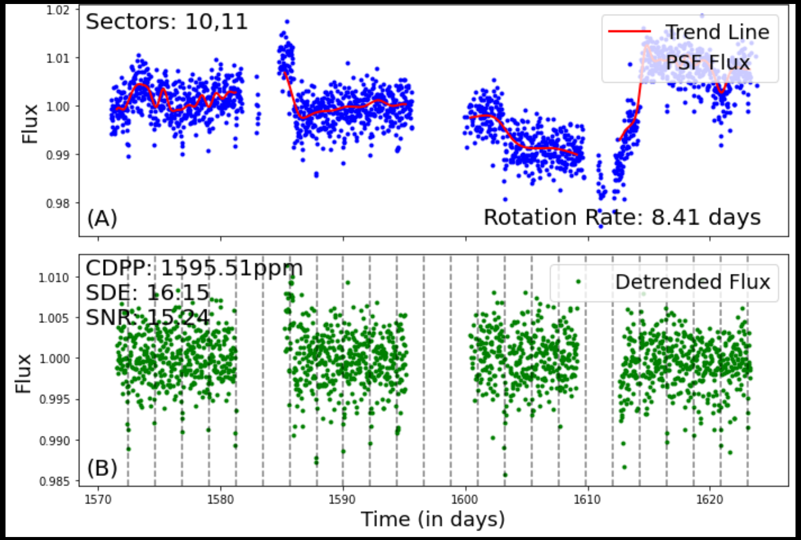
Cluster: Pisces-Eridani
Radius: 2.6 $R_\oplus$
Period: 9.2 days

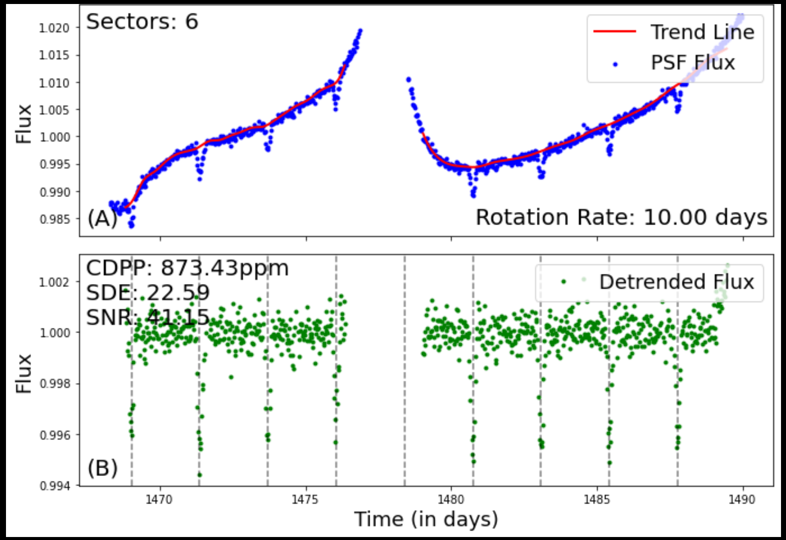


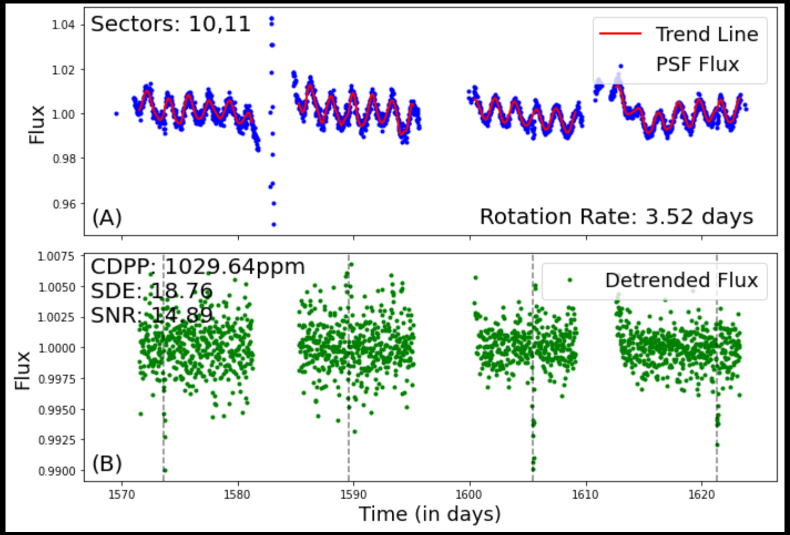


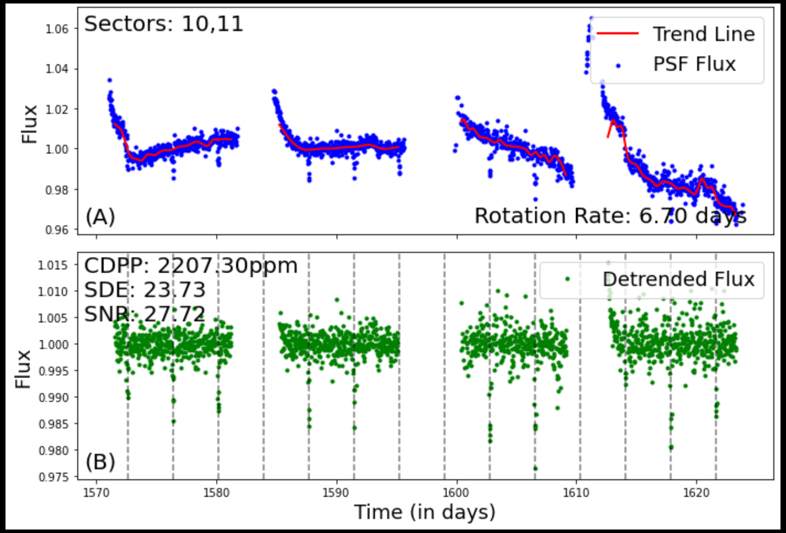
Result 2: New Detections





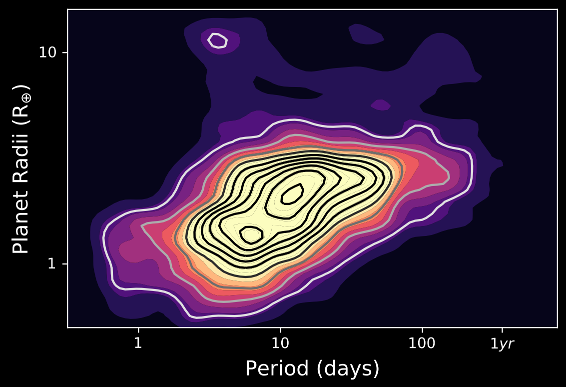


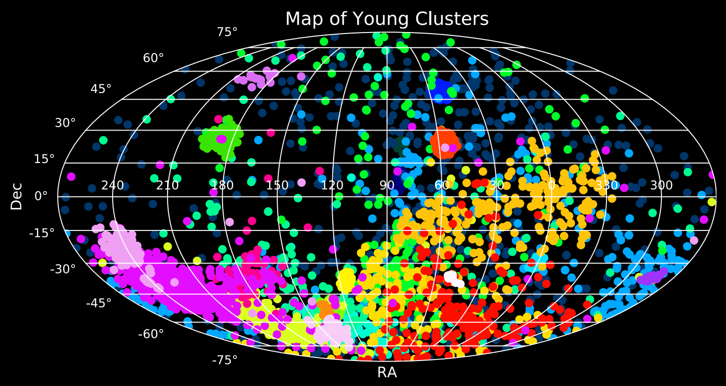




Summary & Future Work

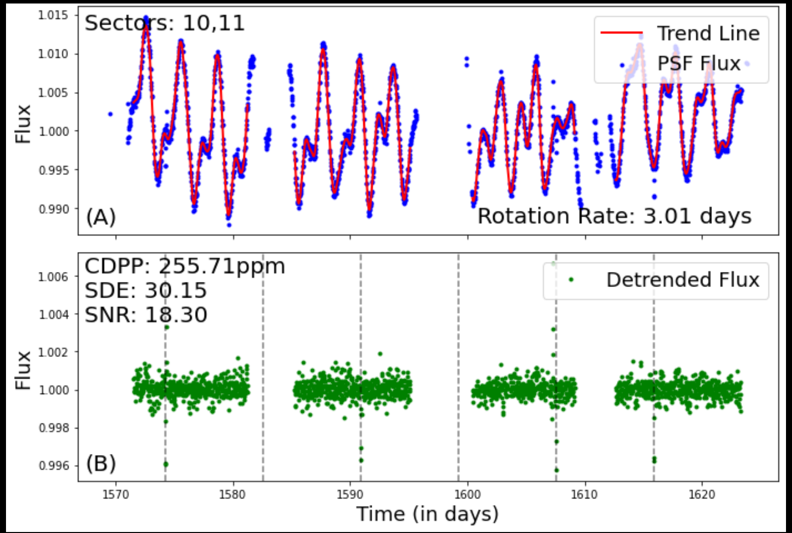
- Many of the short-period Earth-sized planets might be the stripped cores of once sub-Neptunian planets. An extrapolation of this population to the HZ leads to an overestimation of $\eta_\oplus$.





- By measuring the occurrence of yet unstripped short-period sub-Neptunes in young (10-500 Myr) stellar clusters with TESS, we can quantify the contamination of stripped cores in the short-period planet population.

- Our code, `pterodactlys`, has been optimized to be able to detrend young light curves from TESS FFIs.
- <u>Next steps:</u>
    - Search and vet planet candidates in entire sample
    - Community Follow-up of planet candidates
    - Uniform characterization of stars in young clusters
    - Measure occurrence of young Super Earths and sub-Neptunes



Extra Slides

Kepler's Impact of ExoEarth Formation

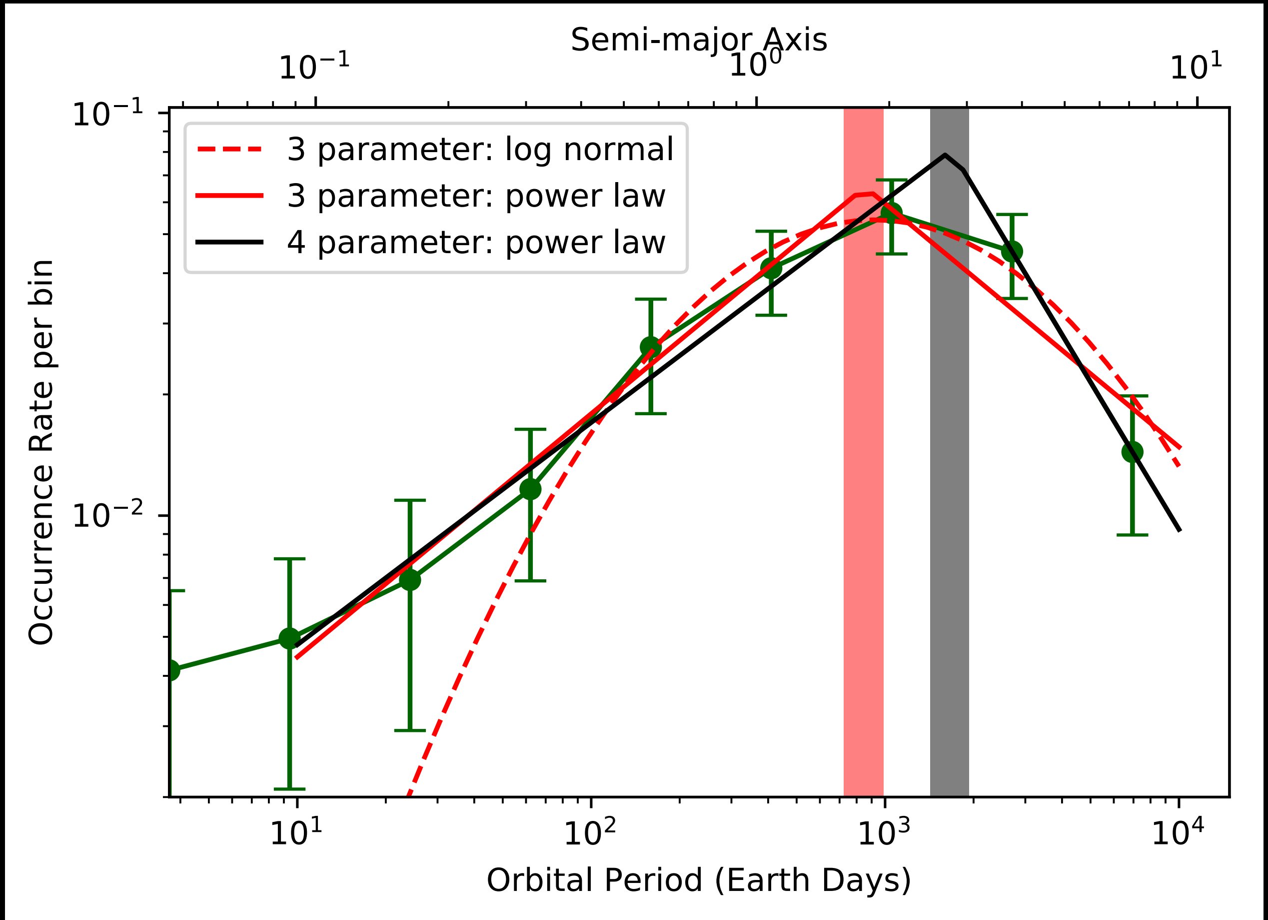
ExoEarths

Form in a gas-poor environment
+ Atmosphere from outgassing

Planets can form with a thick hydrogen atmosphere and then lose it (Stripped Cores)

Result 2: Turnover at the Snowline

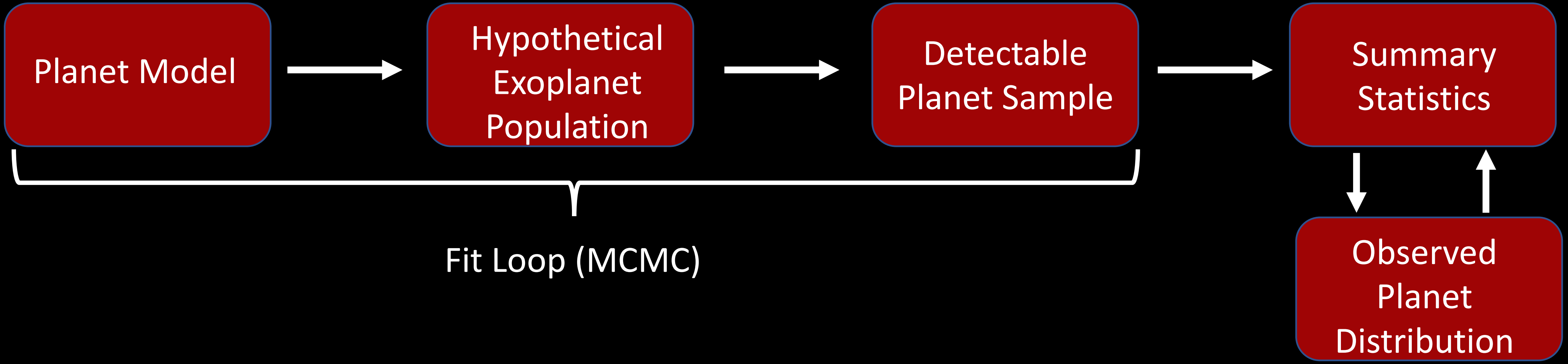
- CRAN segmented:
  - Can the distribution be fit with one or multiple line segments?
- Asymmetric
  - $p_{pre-break} = 0.55^{+0.05}_{-0.05}$
  - $p_{preak} = 1679^{+252}_{-252}$ days
  - $p_{post-break} = -1.21^{+0.24}_{-0.24}$
- Symmetric
  - $p_{pre-break} = -p_2 = 0.57^{+0.09}_{-0.09}$
  - $p_{break} = 855^{+131}_{-131}$ days
- Log normal (Meyer+ 2018)
  - $p_{break} = 919^{+105}_{-105}$



Fernandes+ 2019

Exoplanet Population Observation Simulator (EPOS)

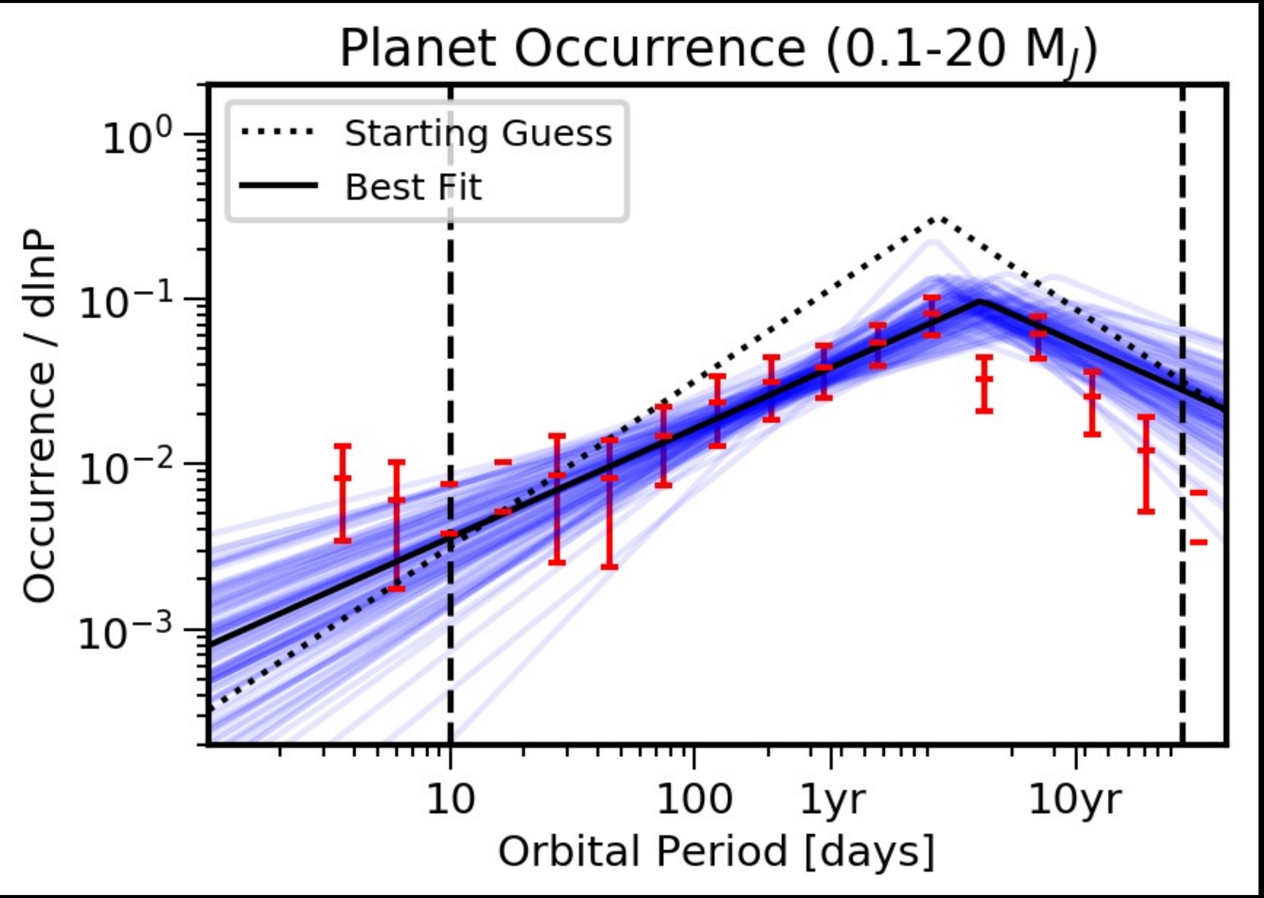
- A Python code to compare synthetic planet populations to the observed planet populations (Mulders+ 2018, 2019)



- Applications: Mulders+ 2018,2019; Kopparapu+2018; Pascucci+2018, 2019; Fernandes+ 2019
- EPOS is available on Github for download: https://github.com/GijsMulders/epos

Exoplanet Population Observation Simulator (EPOS)

- Asymmetric:
  - $p_{pre-break} = 0.70^{+0.30}_{-0.16}$
  - $p_{preak} = \ 2075^{+1154}_{-1202}$ days
  - $p_{post-break} = \ -1.20^{+0.92}_{-1.26}$
- Symmetric:
  - $p_{pre-break} = -p_{post-break} = 0.65^{+0.20}_{-0.15}$
  - $p_{break} = \ 1581^{+894}_{-392}$ days



Fernandes+ 2019