Determining the Host Stars of Planets in Binary Star Systems

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TEXAS ADVANCED COMPUTING CENTER

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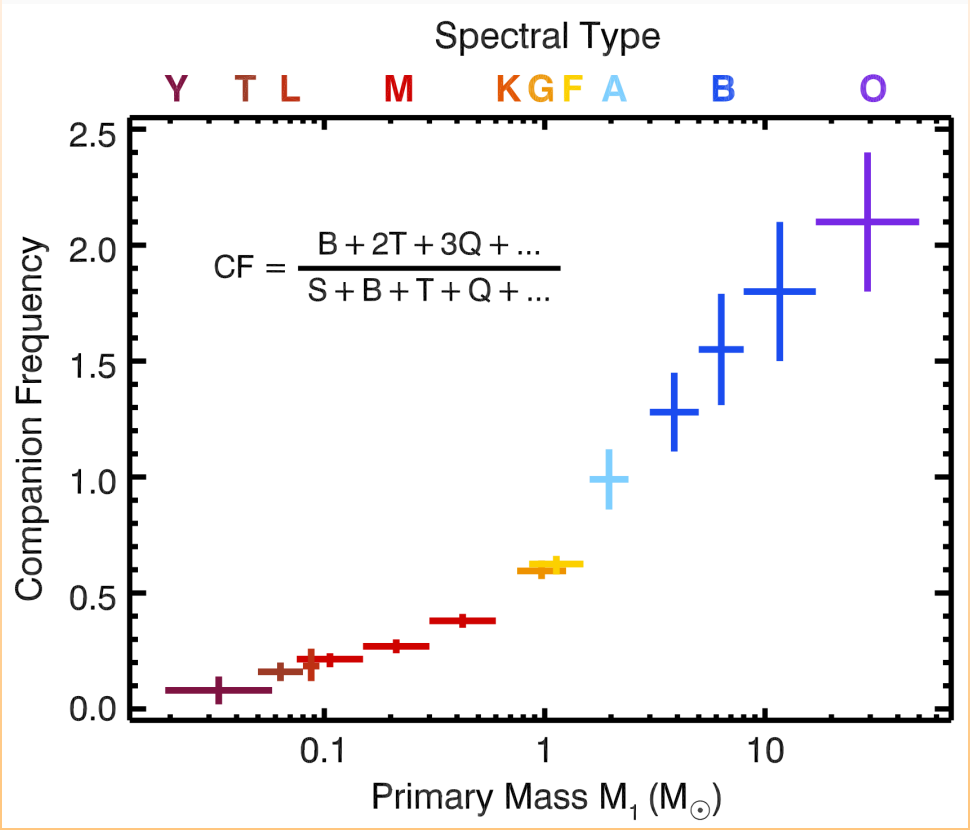
UC SANTA CRUZ

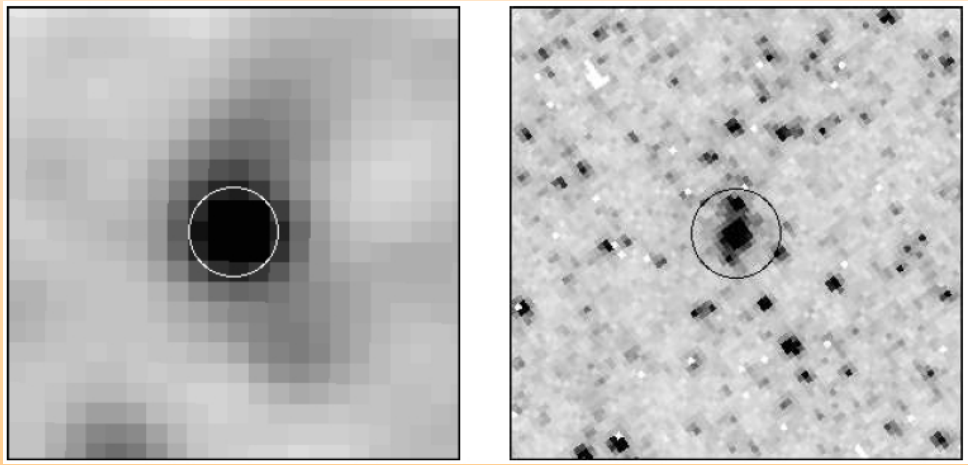
Binary Stars



(Offner et al. 2022)

- Roughly half of all Sun-like stars are in binaries
- Most exoplanet research focuses on single stars
- Binary stars have fewer planets on average: **planet formation is different in binaries**

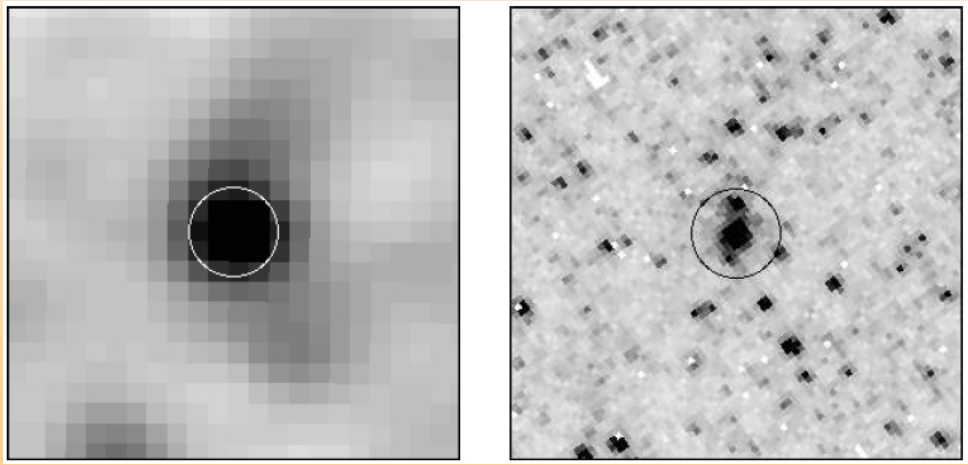
Binaries as Planet Hosts



(Mochejska et al. 2001)

- Binaries are almost always unresolved in Kepler (and TESS) imaging
- This means it's not obvious which star a planet in a binary is orbiting
- **How could we figure out the host star?**

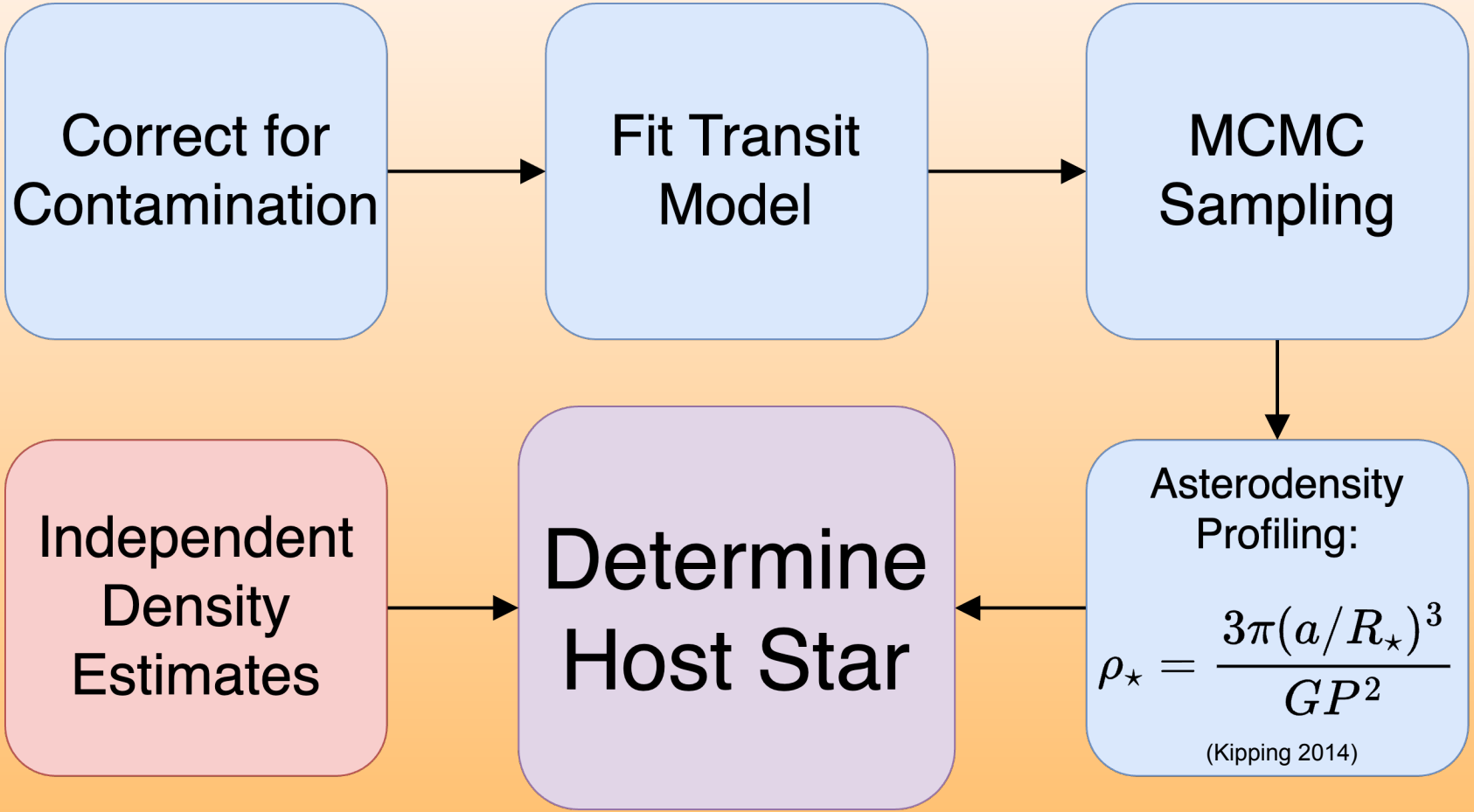
Why Care About the Host Star?



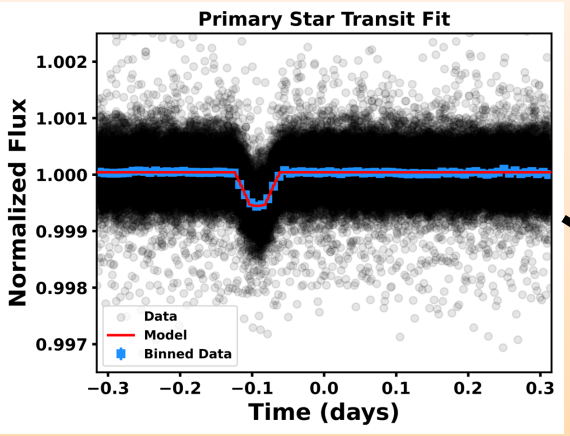
(Mochejska et al. 2001)

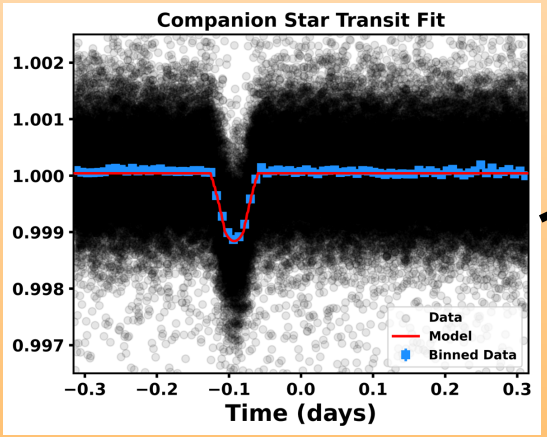
- Host star affects the inferred radius of the planet (Ciardi et al. 2015)
- This affects the demographics of planet radii
- Do more planets form around the primary star or secondary star? Implications for planet formation in binaries

Methodology



Test Case: KOI 1300.01

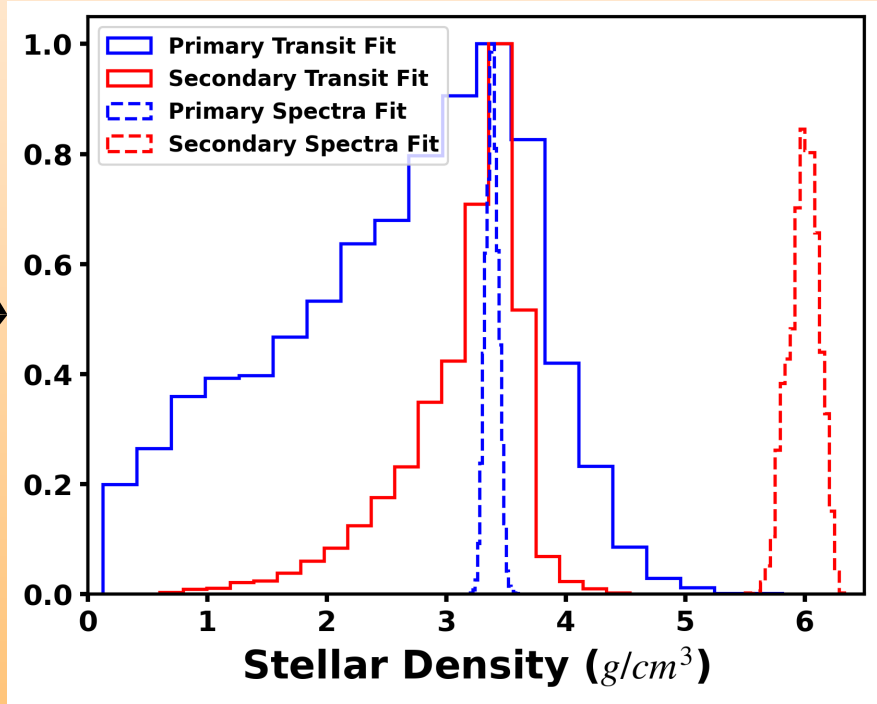




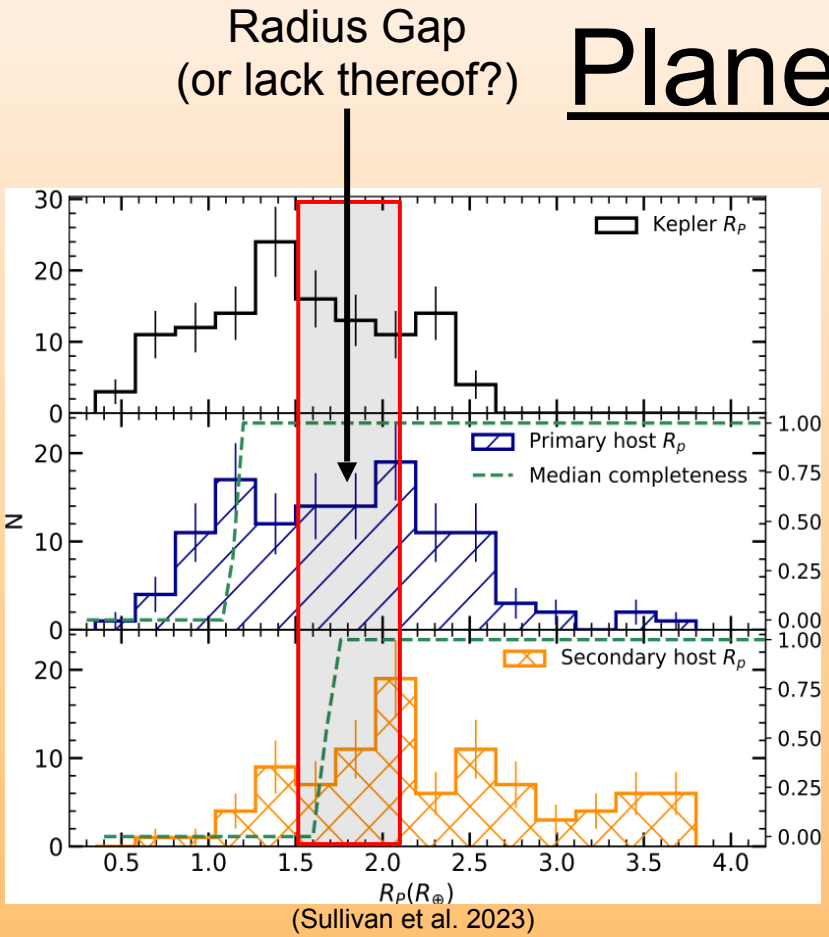
$R_{p,pri} = 1.69R_{\oplus}$

$R_{p,sec} = 3.40R_{\oplus}$

Unambiguous Primary Star Host



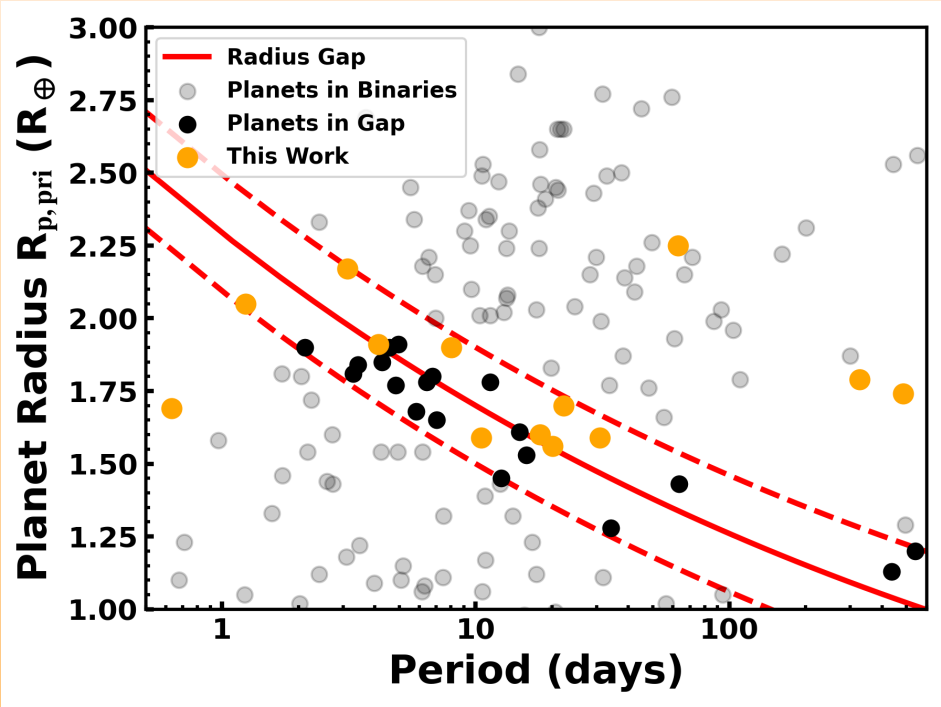
No Radius Gap for Planets in Binaries?



(Sullivan et al. 2023)

- Sullivan et al. (2023) demonstrated that planets in binaries may not show a radius gap
- **But:** This required an assumption that all of the planets are orbiting the primary star

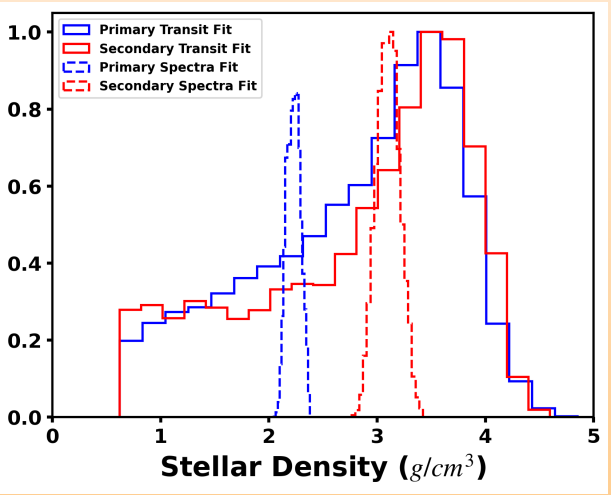
My Project



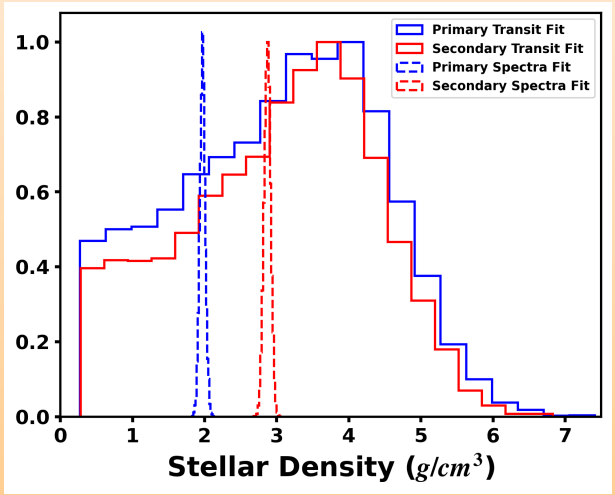
- Performing asterodensity analysis on planets that would be in the radius gap if they are orbiting the primary star
- 15 total planets across 10 binary systems analyzed so far
- Binaries are <2” in angular separation
- Will enough of these planets move out of this range for a gap to appear?

Ambiguity is Common

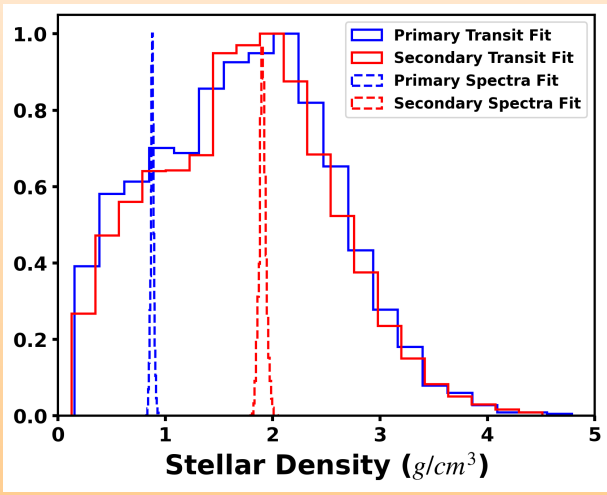
1700.01:



2580.01:



3120.01:



Using Bayes' Theorem

Note:
A has 2 possibilities: primary or secondary host
B is what we observe

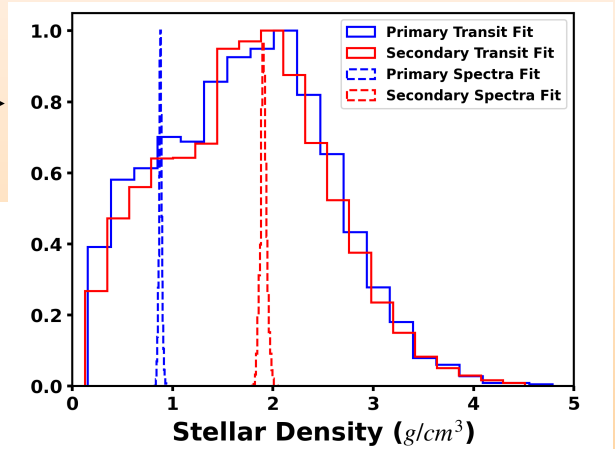
$$P(A|B) = P(A) \times \frac{P(B|A)}{P(B)}$$

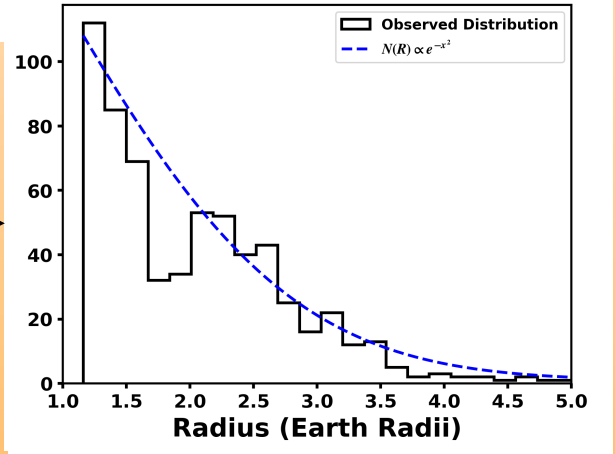
posterior | prior | likelihood | marginal

Normalized Afterward

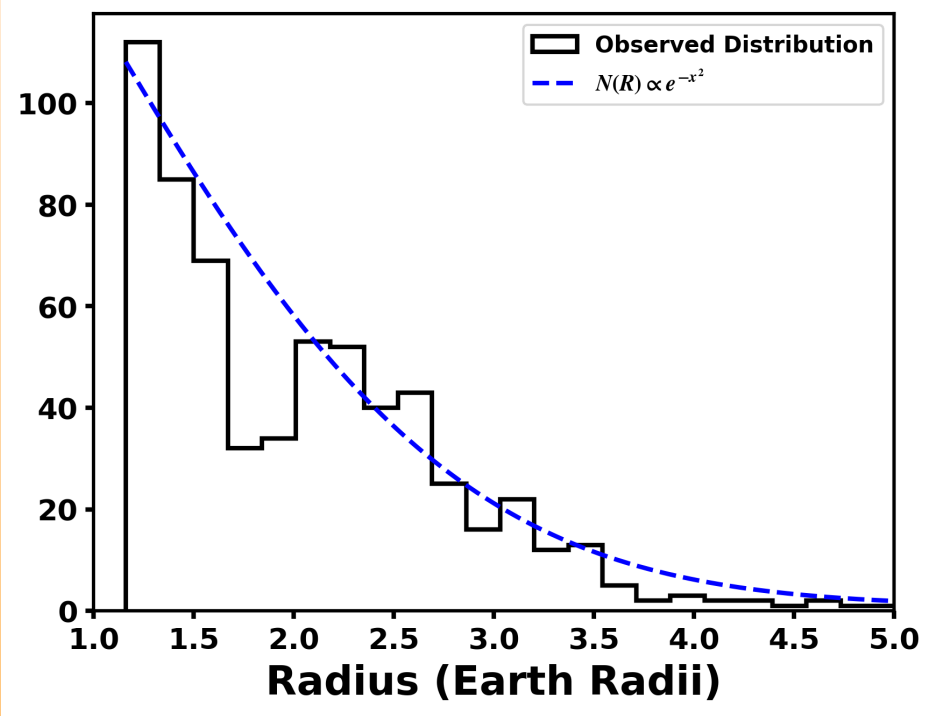
Probability that the planet is hosted by the primary or secondary star

Equation graphic from Peter Gleeson



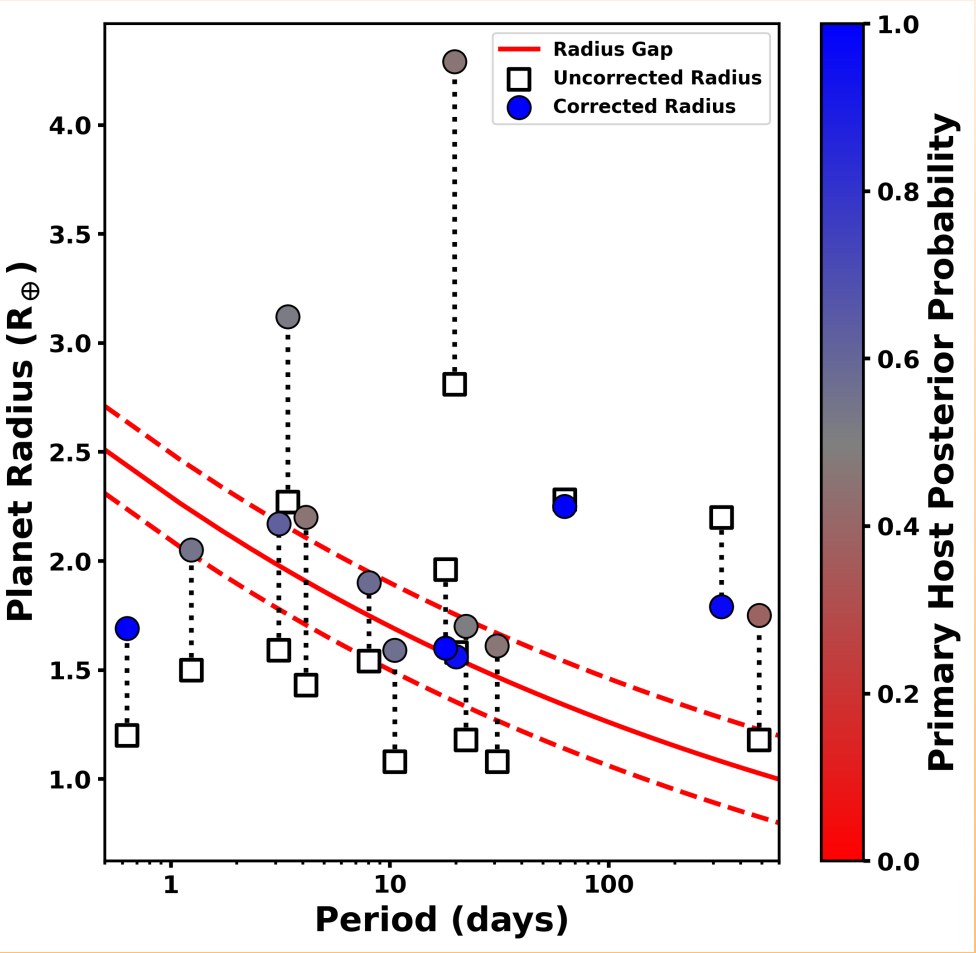


Prior Probabilities



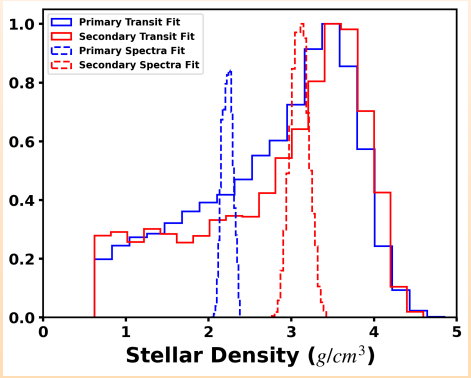
- Planets would have larger radii if they were hosted by the secondary star
- We know that larger planets are less common
- **Prior favors primary hosts by design**
- This bias is consistent with observational and theoretical evidence

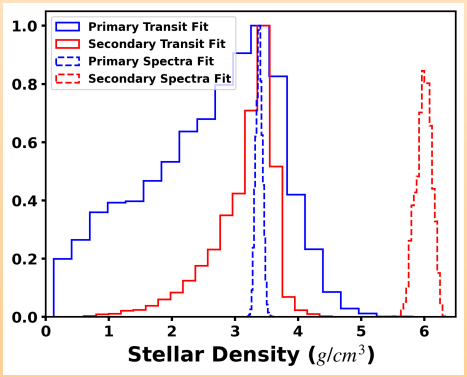
Revised Radii

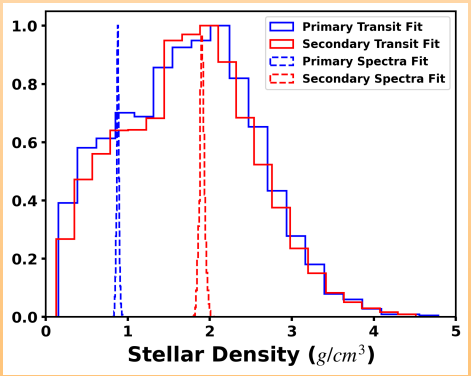


- 15 total planets: 11 more likely (>50%) orbiting primary, 4 orbiting secondary
- 9 radius gap planets: 7 primary, 2 secondary
- 5 planets are >90% for primary, none that high for secondary

Interpreting the Results: Likelihoods

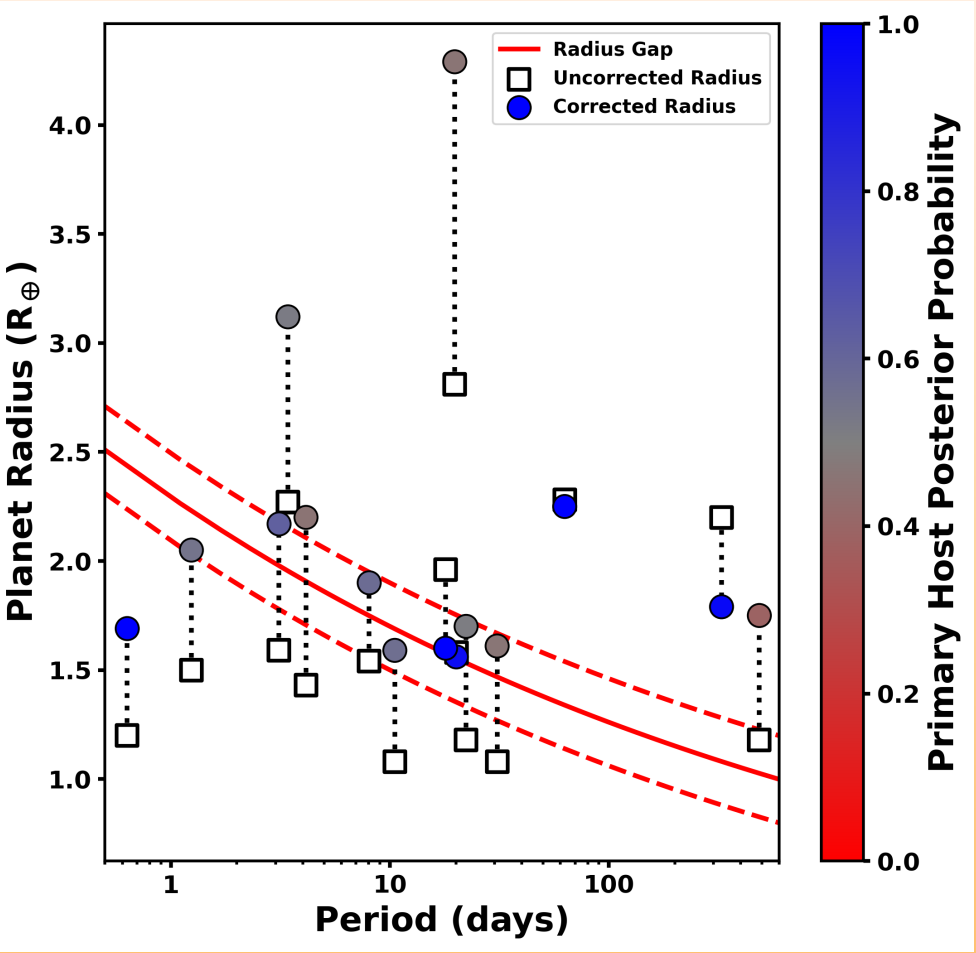






- Density posteriors show a consistent shape: namely a low density tail out to ~0
- This means that **secondary hosts can be ruled out in some cases, but primary hosts never can**

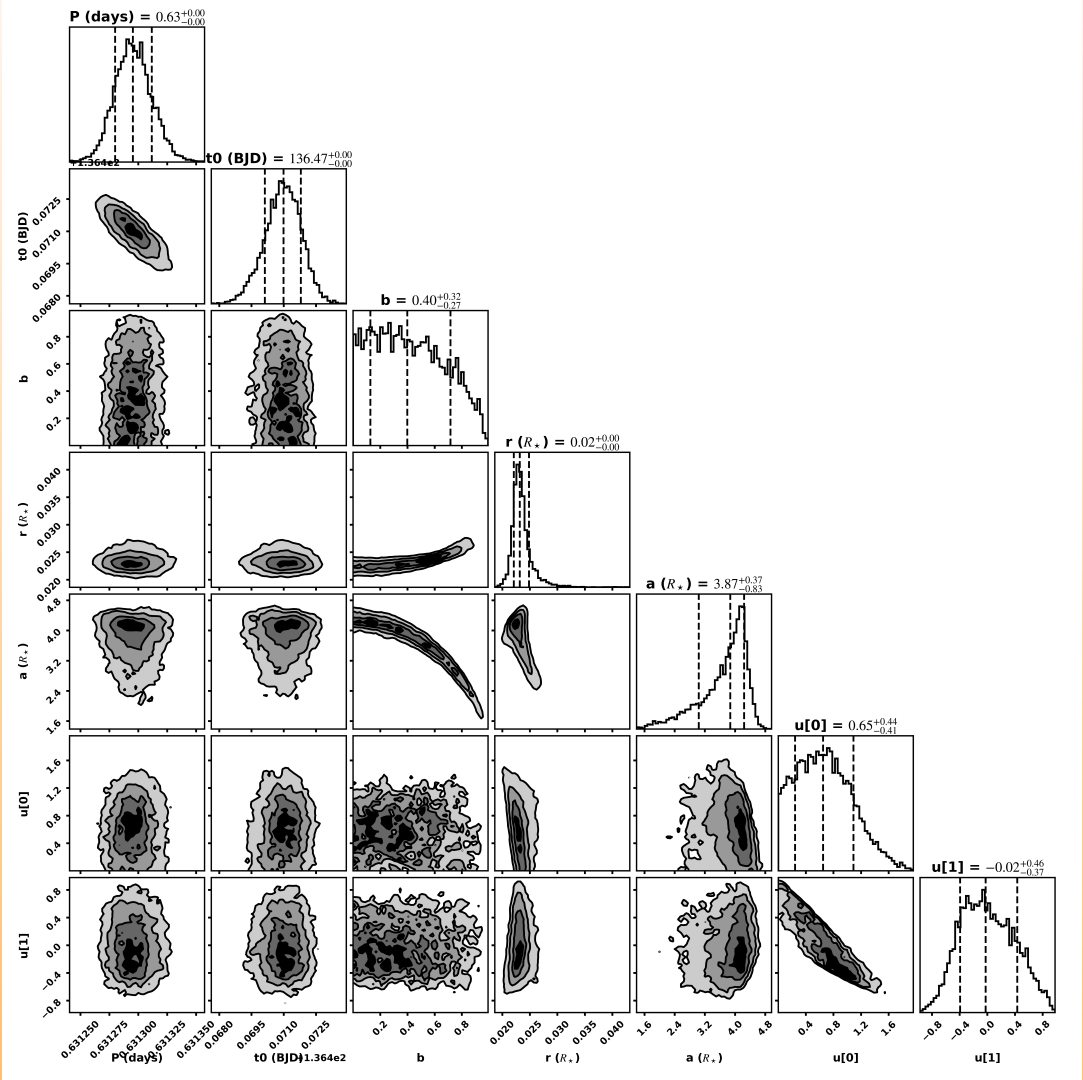
Interpreting The Results: Posteriors



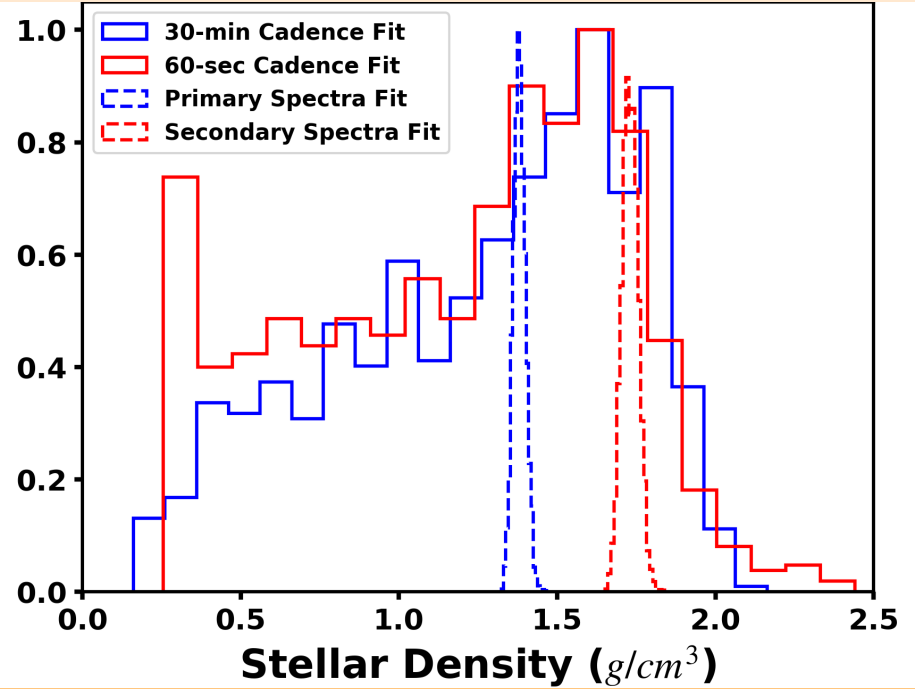
- Bayesian likelihoods show a stronger preference for secondary hosts than the posteriors do
- Even with a prior that is biased against secondary hosts, they can't be ruled out in most cases
- Does this suggest that these planets could really be hosted by the secondary?
  Just a result of low precision?
  Or due to unknown systematics?

Conclusions and Future Work

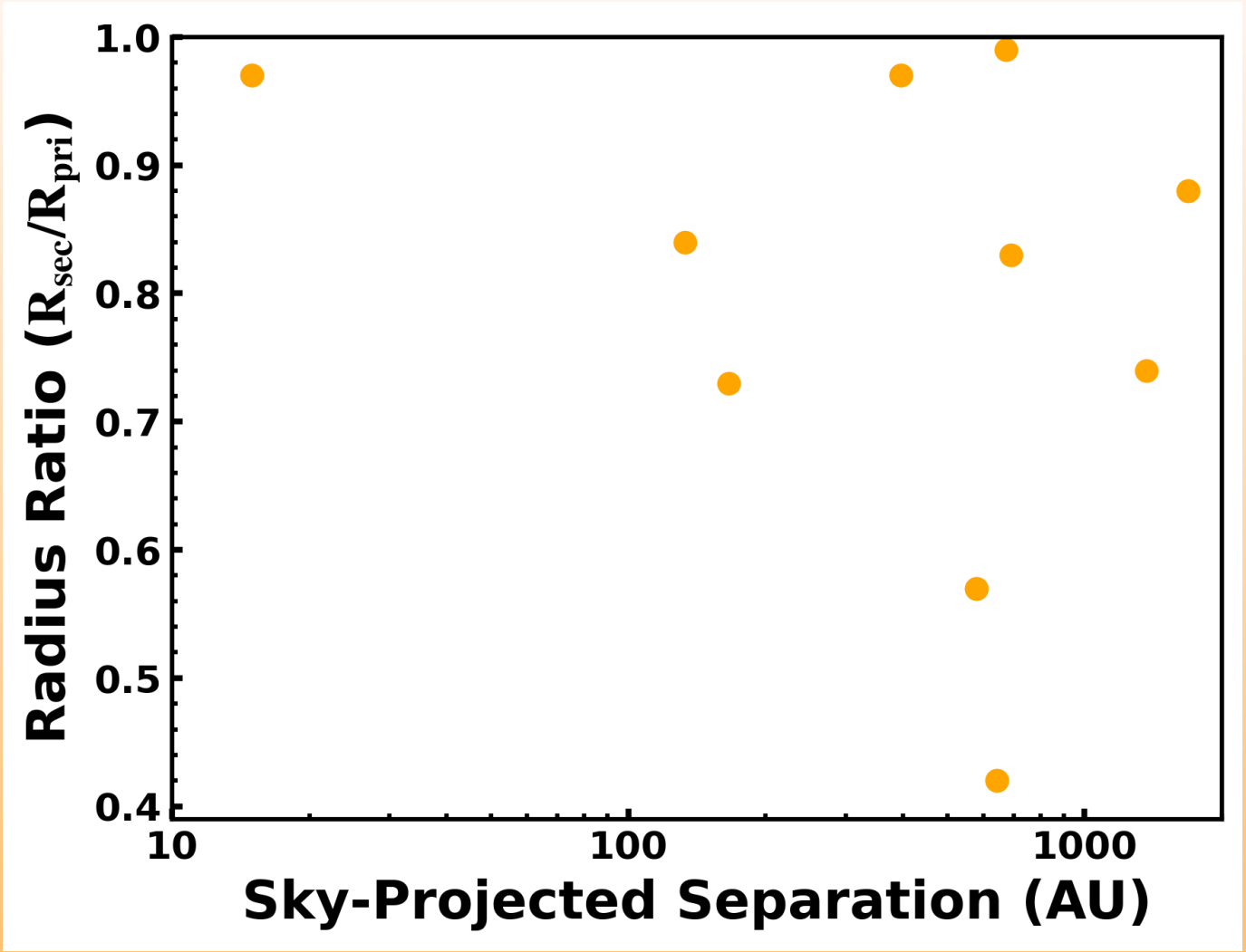
- We have found unambiguous primary hosts for 5 planets so far. The rest have been ambiguous
- Perform analysis for a larger sample of planets and assemble statistics on primary vs secondary star host.
- In multi-planet systems: Are the planets all orbiting the same star or some combination of both? Larger sample helps here too
- Our analysis is SNR-limited: More epochs and higher precision photometry would help
- To achieve more conclusive results, we could combine this work with other techniques to infer the host star (ex: centroid shifts, TTV's, etc.)


P (days) = $0.63^{+0.00}_{-0.00}$
t0 (BJD) = $136.47^{+0.00}_{-0.00}$
b = $0.40^{+0.32}_{-0.27}$
r ($R_\star$) = $0.02^{+0.00}_{-0.00}$
a ($R_\star$) = $3.87^{+0.37}_{-0.83}$
u[0] = $0.65^{+0.44}_{-0.41}$
u[1] = $-0.02^{+0.46}_{-0.37}$
+1.364e2
P (days)
t0 (BJD)
b
r ($R_\star$)
a ($R_\star$)
u[0]
u[1]

Test Case: Fast vs Slow Cadence



- Kepler's default exposure cadence was 30-minutes, but there was a faster 60-second cadence
- Could that yield narrower posteriors by resolving ingress/ egress? Tested this on KOI 284.01
- Found little difference (**we are SNR limited, not cadence limited)** and have continued to use the 30-minute cadence data for uniformity


1.0
0.9
0.8
0.7
0.6
0.5
0.4
Radius Ratio (R_{sec}/R_{pri})
10
100
1000
Sky-Projected Separation (AU)