Exomoon Detection with Targeted JWST Observations

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overview

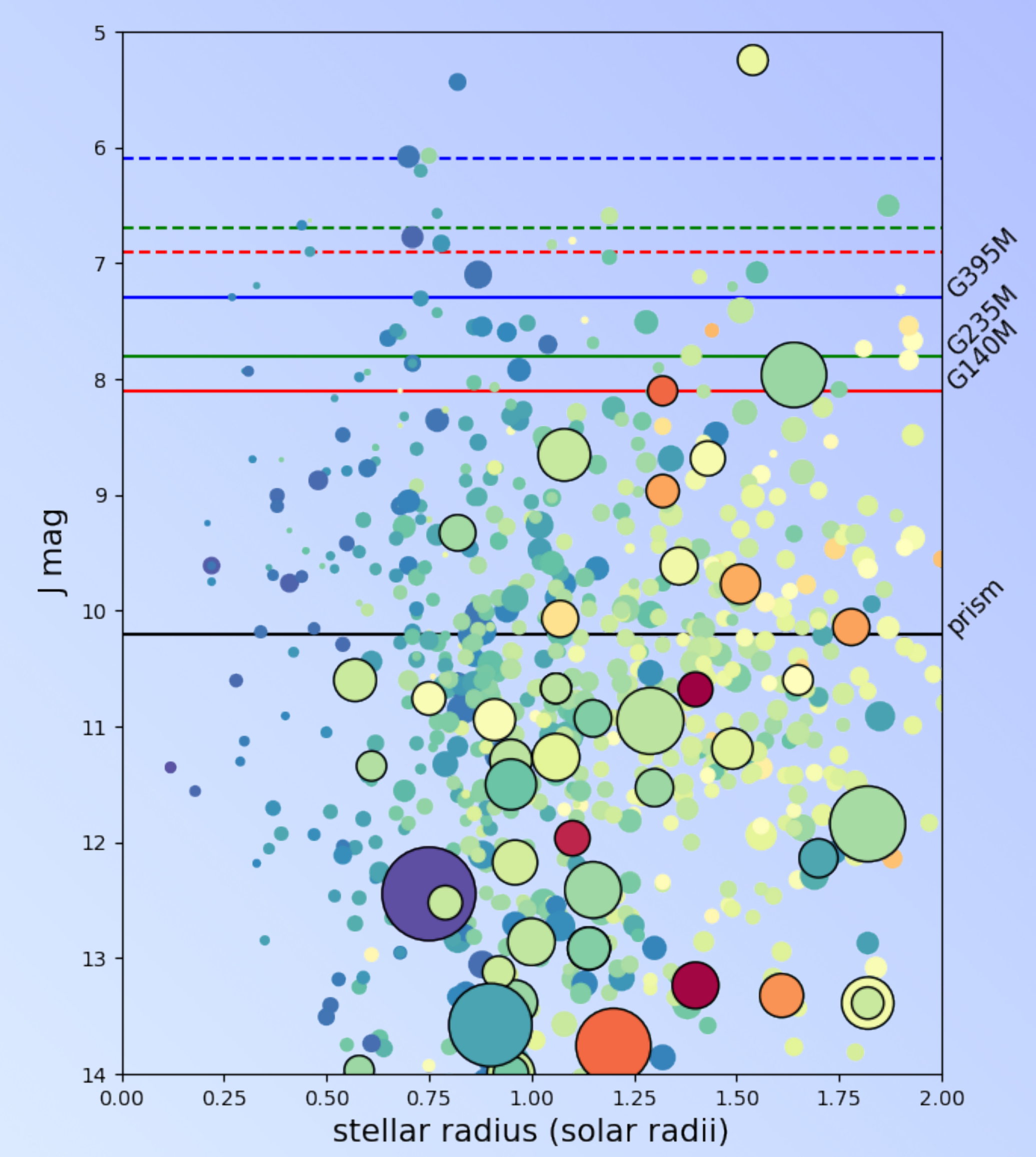
Exomoon transit detection is a technical challenge, due to the small depth of the expected transit signal. Unfavorable geometries and uncertainties about exomoon populations further complicate matters. JWST likely has the photometric precision to enable the detection of the largest exomoons, but even with this revolutionary facility the most likely outcome of a search in any given system is a null detection. We discuss considerations for target selection and outline a framework for deriving constraints on exomoon parameters in the case of a null detection.

target selection

two categories of factors:

(1) those related to the **host star** — these determine the observability of the transit signal. **(brightness, variability, stellar radius)**

(2) those related to the **host planet** — these *may* influence the likelihood that the system hosts an exomoon, but are generally based on assumptions and/or theoretical predictions. **(Hill radius, mass, orbital geometry)**



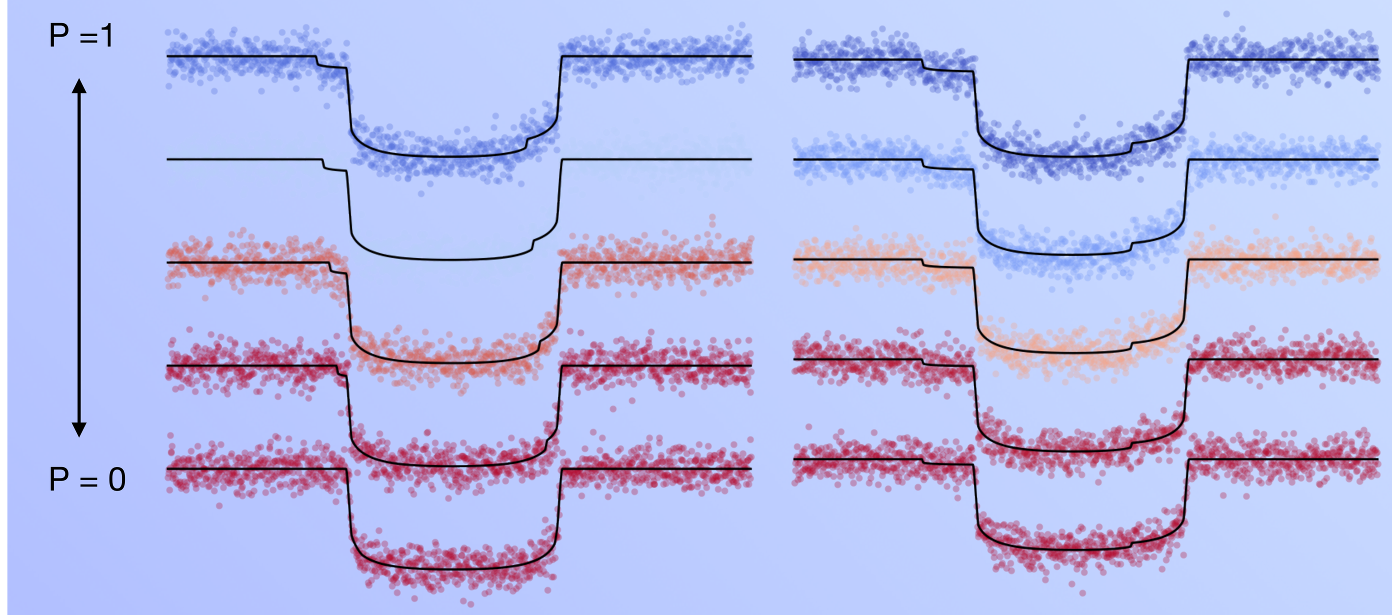
Host magnitude vs. stellar radius for transiting exoplanet systems with mass constraints. Colors indicate the equilibrium temperature of the planet (blue: coldest, red: hottest), and point size is proportional to planetary mass. Solid lines are approximate brightness limits for the NIRSpec medium-resolution dispersers, and dashed lines are for the corresponding high-resolution dispersers. The highest transit SNR for each instrument mode will be achieved for targets on the left side of the plot that sit near, but don't exceed, the brightness limit for a given disperser.

constraints from null detections

Bayesian modeling

$$P(\theta_m, \theta_p | \neg M) \propto [1 - P(M|\theta_m)]\, P(\theta_m|\theta_p) P(\theta_p)$$

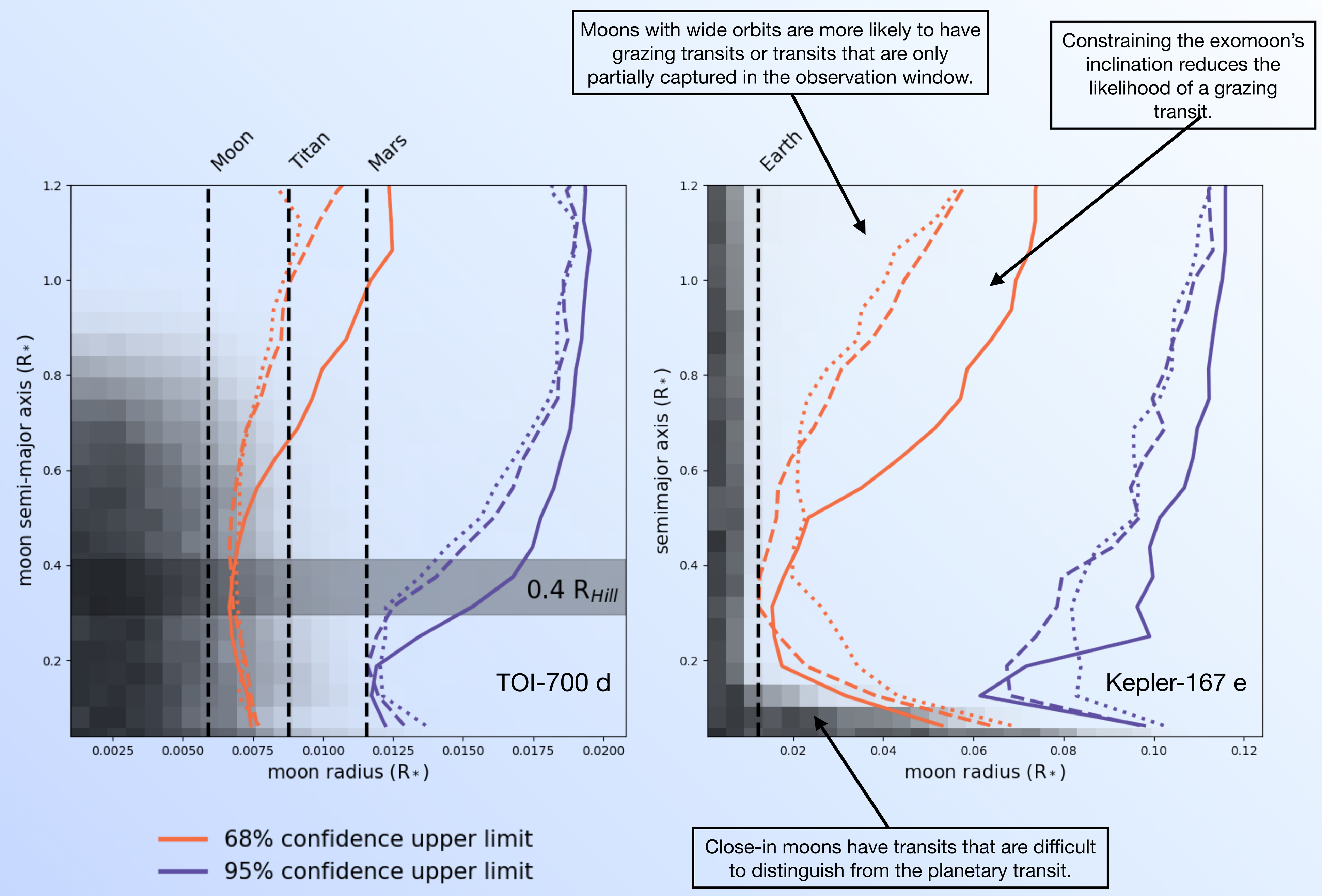
$P(M|\theta_m) =$ probability that the Bayesian information criterion for the planet-only model exceeds that for the moon+planet model by at least 10



change in detection probability with increasing projected planet-moon separation at time of transit

change in detection probability with increasing exomoon radius

analysis for approved Cycle 3 JWST observations of Kepler-167 e (Program 6491; PI Cassese) and TOI-700 d (Program 6193; PI Pass)



Posterior distribution for exomoon semi-major axis and radius for undetectable moons around Kepler-167e **(right)** and TOI-700d **(left).** Orange and purple lines show the 68% (1-sigma) and 95% (2-sigma) confidence upper limits for the radius of exomoons with a given semi-major axis. For the dotted line exomoon orbital inclination has been constrained to within 5° of the planet's orbital plane (approximately the inclination of Earth's Moon's orbit). For the dashed line the inclination is constrained to within 27° of the ecliptic (approximately the inclination of Titan's orbit), and for the solid line it is unconstrained. The underlaying posterior distribution corresponds to the unconstrained inclination case. Note that TOI-700e will also be observed for JWST program 6193. Because the host star is the same, the posterior distribution for planet e very similar to that shown here for planet d.

conclusions

1. Exomoon detection will continue to be challenging, even with JWST. We can maximize the value of null detections by choosing targets that allow us to constrain the parameters of any unseen moons.

2. For purposes of constraining parameters, targets with excessively large Hill radii are less useful, because moons with large orbital separations are frequently undetectable.

3. Baysian modeling of exomoon detection probabilities allows for robust constraints on exomoon properties that account for uncertainties in stellar and planetary parameters.

4. This same modeling framework can also be used to estimate the likelihood of a detection for the purpose of comparing potential targets and observing strategies.