

What happens when a planet goes unseen?

Establishing TTV mass robustness criteria for systems with non-transiting perturbers

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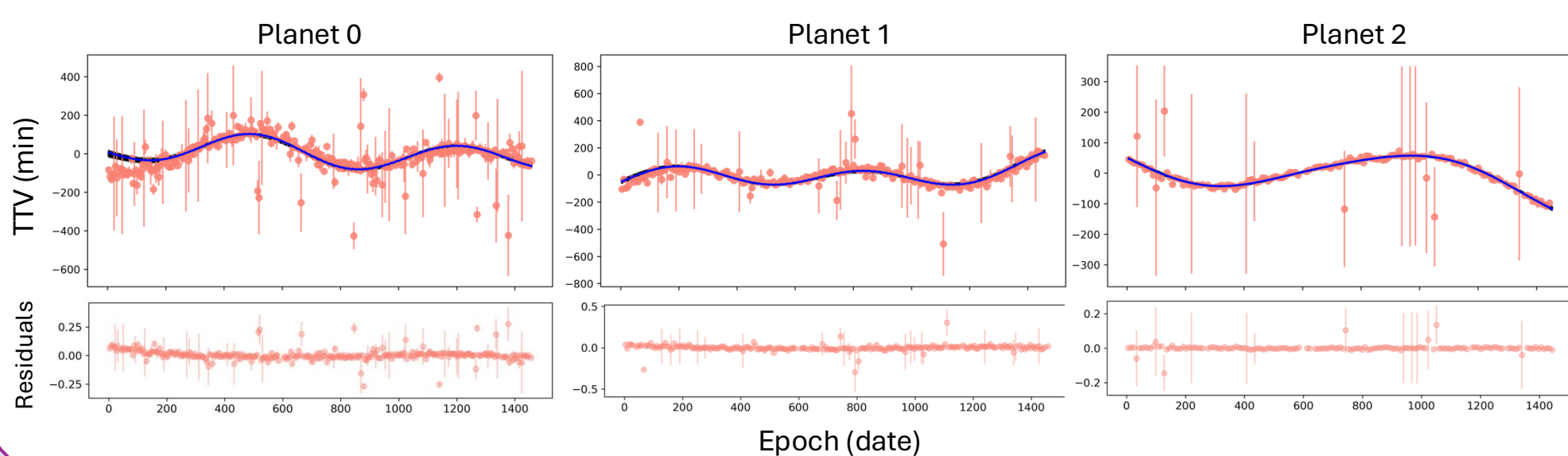
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Context

- **Transit Timing Variations (TTVs)** provide an excellent resource to probe the dynamics of **resonant exoplanet systems** and characterize the **masses of transiting planets**. However, the accuracy of solutions to TTV analysis can be affected by **non-transiting planets (NTPs)** in the system, biasing the masses recovered for the transiting planets.
- As part of the *Geneva Resonant State Workshop (GRSW)*, participants carried out a **data challenge** to identify and develop criteria for tackling the **difficulties of TTV analysis**. The challenge showed that existing **robustness criteria** [1] based on mass and eccentricity priors work well for systems without NTP. However, they were unable to consistently identify the effect of NTP(s), which can lead to masses that appear robust despite being **far from the correct solution**.
- With this in mind, we started developing and present here a series of checks to **ensure accuracy of the masses** of transiting planets regardless of the presence of a NTP in the system.

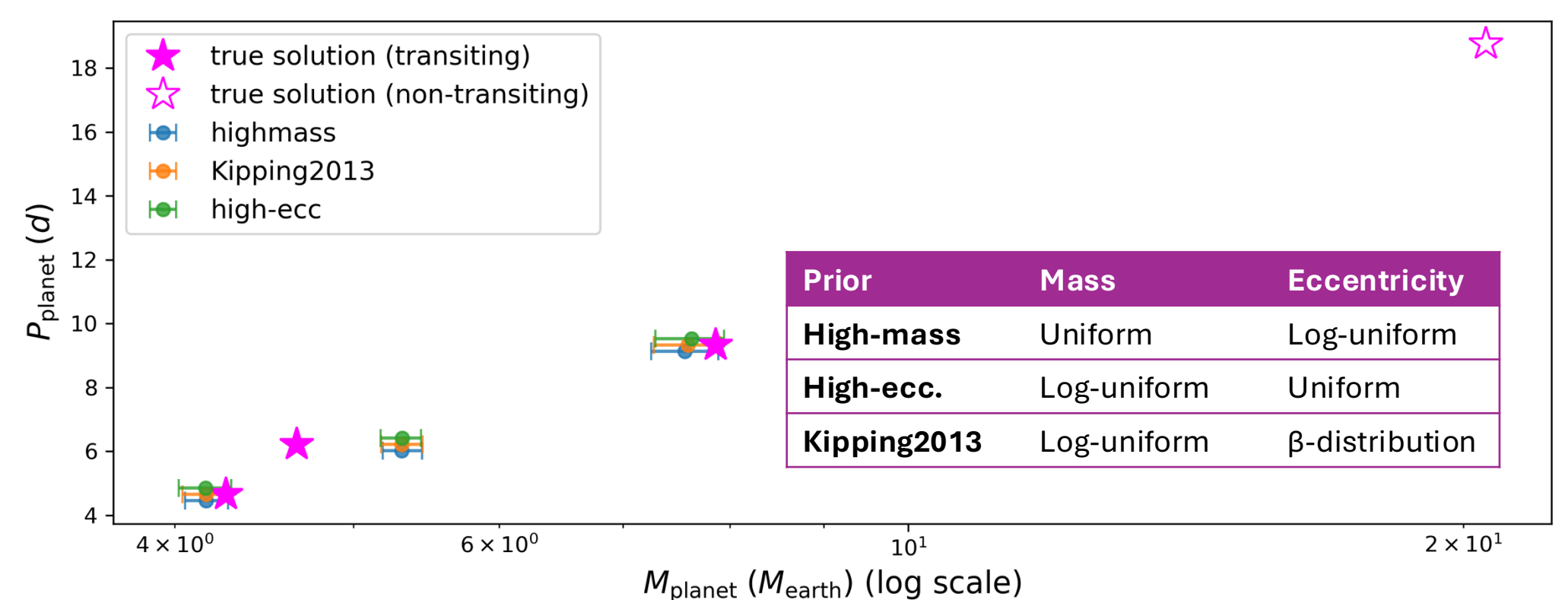
Data

- The simulated dataset consists of **pre-extracted transit timings** from 15 resonant systems:
 - 10 systems without NTPs (23 planets).
 - 3 systems with an outer NTP (9 planets).
 - 1 system with a NTP in the middle of the resonant chain (4 planets).
 - 1 system with a NTP co-orbiting a transiting planet (4 planets).
- **Mass posteriors and orbital parameters** were sampled with an MCMC sampler in an N-body integration using *TTVFast* [2].
- **Case study:** 4-planet resonant chain with an **outer NTP** (black curve = 3-planet model)



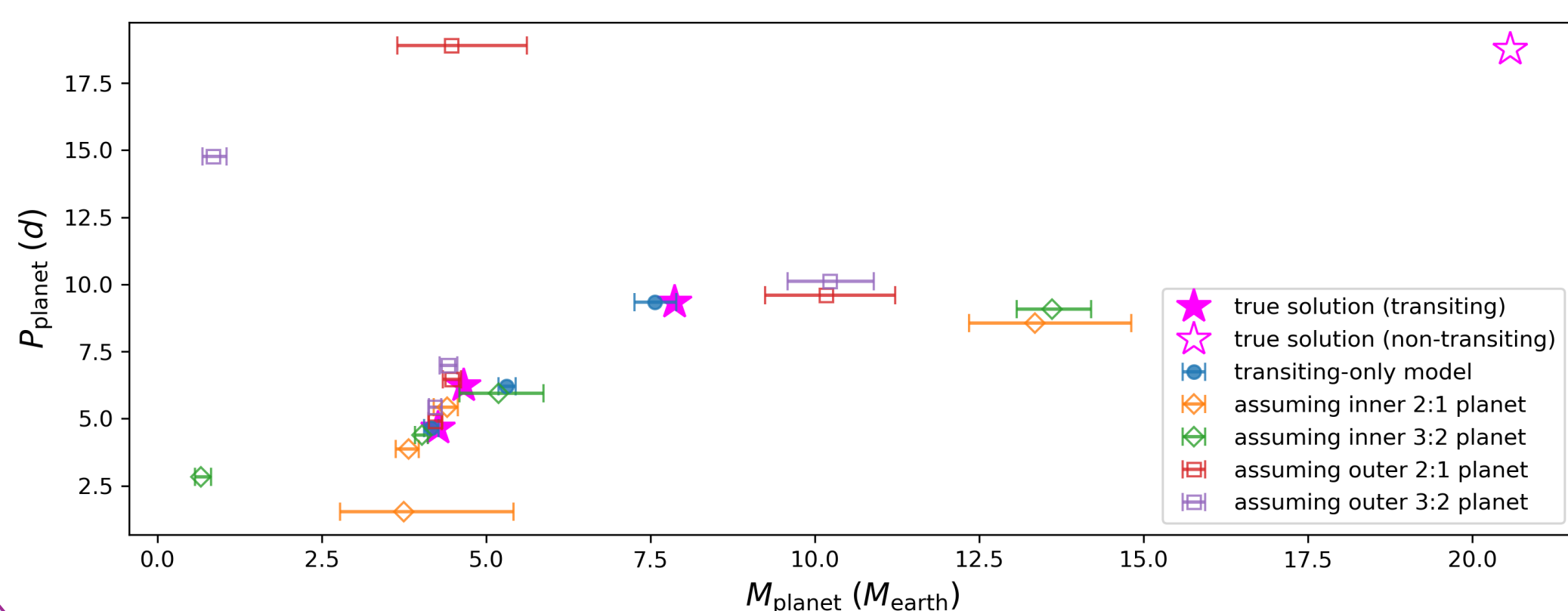
① Mass-eccentricity criteria

- The first robustness test compares the **mass posteriors** obtained from models fitted with different sets of mass and eccentricity priors to check for signs of **mass-eccentricity degeneracy** [1,3].
- Taking the median mass from the Kipping fit as the reference point, the robustness is quantified as the **largest difference from the median mass** between prior sets, divided by the Kipping error.



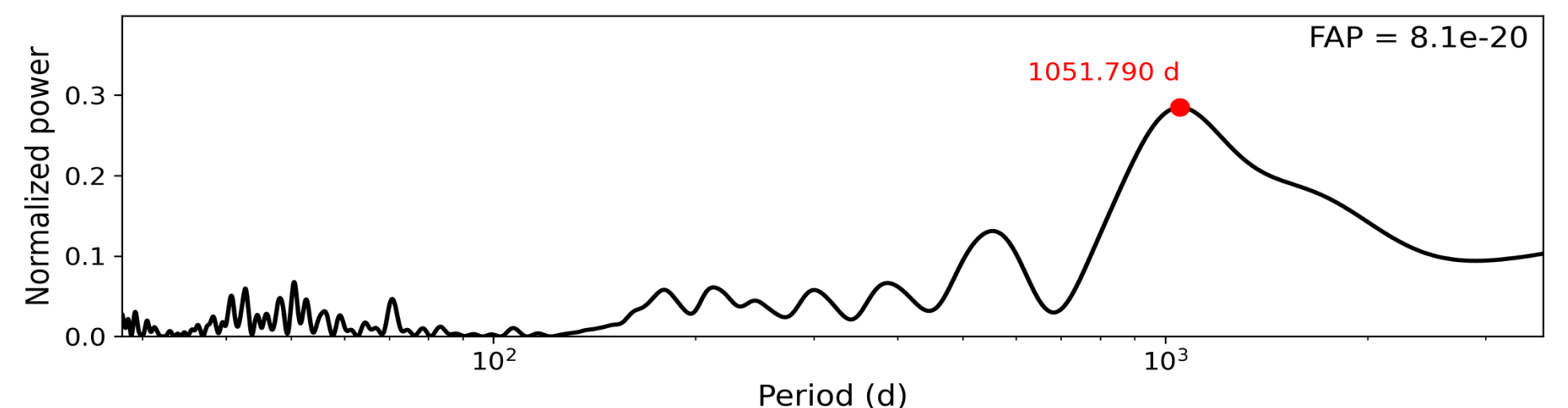
② NTP injection criteria

- The next test studies how **injecting a NTP** affects the masses recovered for the transiting planets.
- A new model is initialized from the high-mass fit of the system, with a planet added at **2:1 or 3:2 period ratio** with the inner or outer transiting planet. The **new fit** is done with the same set of priors.
- Similar to the mass-eccentricity criteria, we compute the **distance between the original and new median masses** of each planet, taking the **resonant case** which leads to the largest difference.

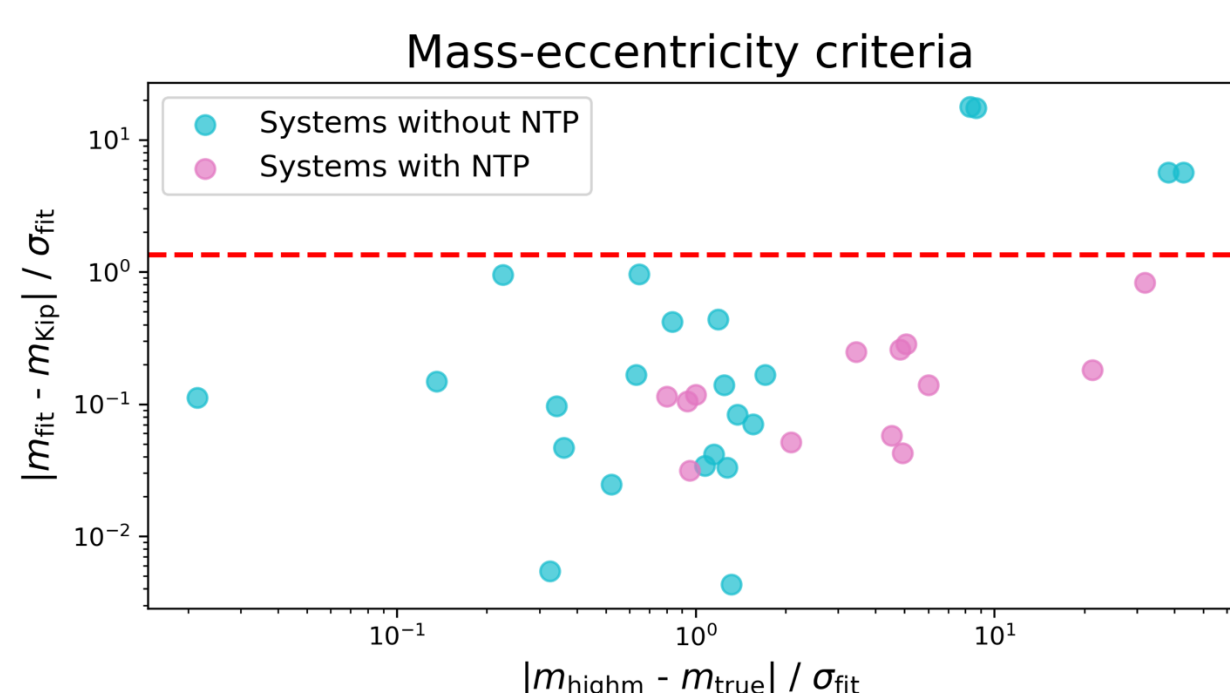


③ Residual FAP criteria

- Finally, to check for **temporal correlation** in the best-fit residuals, we perform a periodogram analysis to compute the analytical **False Alarm Probability (FAP)** [4].
- The FAP values of each planet is calculated before and after a NTP is added to the model.
- Assuming that a **low FAP value** arises from **periodicities caused by a NTP**, we expect an improvement in the model to give a large change in $\log(\text{FAP})$.

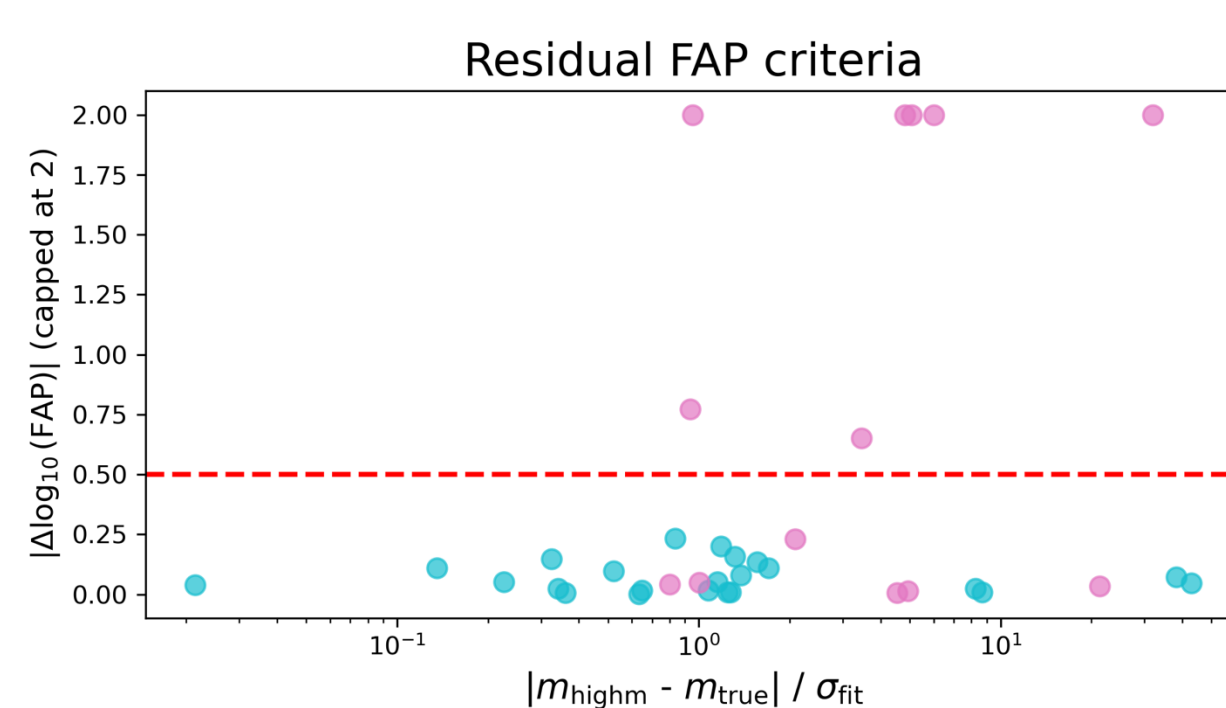
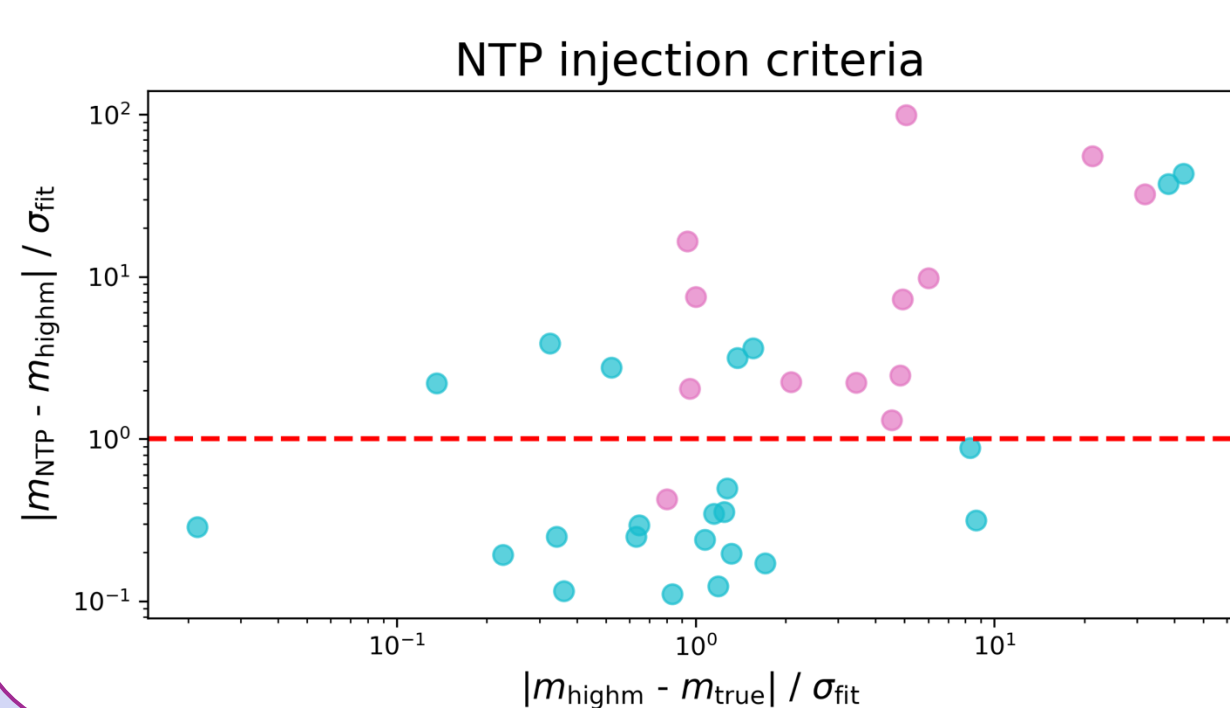


Combined criteria

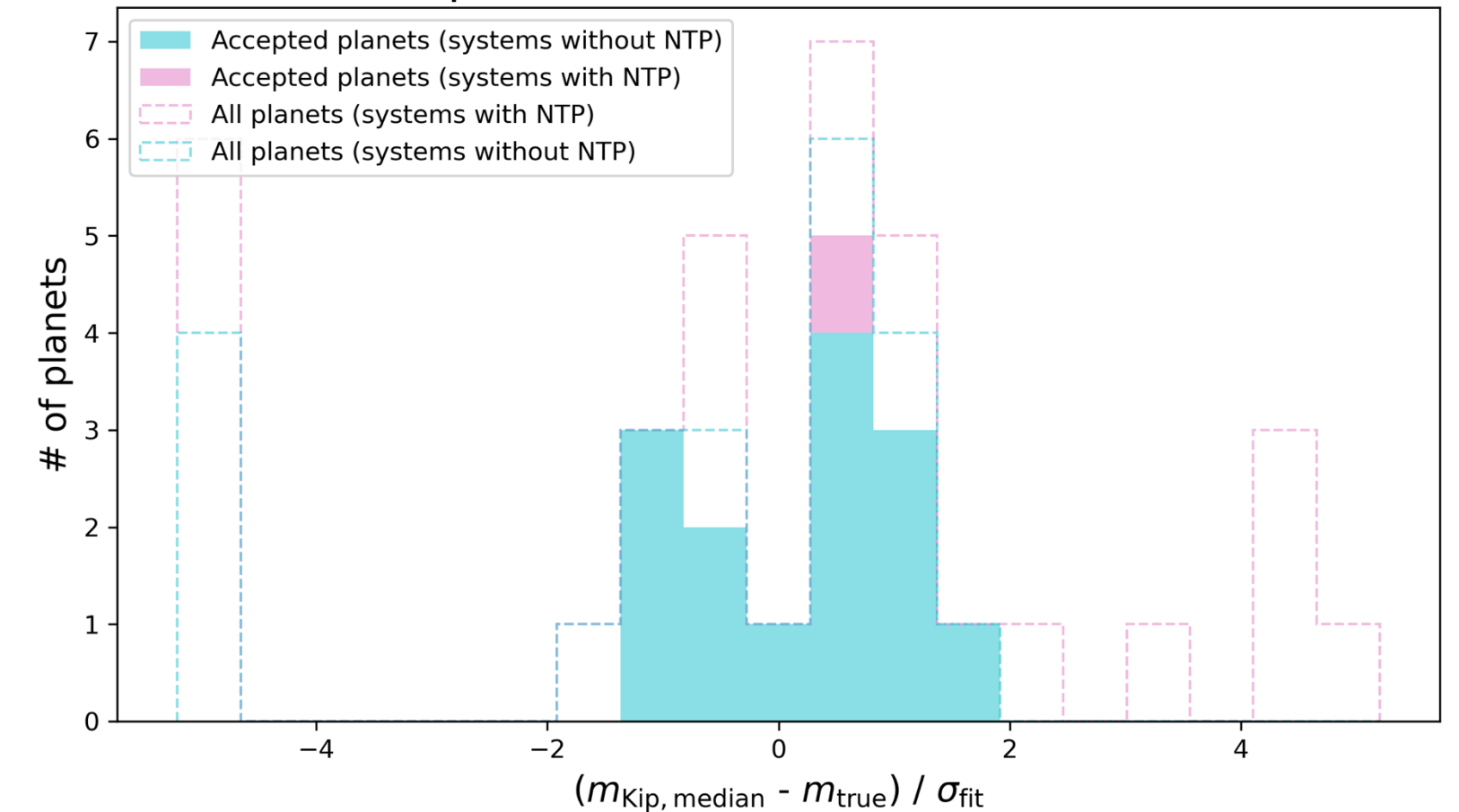


After performing the **checks for all planets** in both types of systems (with and without NTP), we can represent each metric as a function of the **distance from the true solution** $|m_{fit,highm} - m_{true}| / \sigma_{fit,highm}$ and define the following robustness criteria:

- ① **Mass-eccentricity:** $|m_{fit,other} - m_{Kip}| / \sigma < 1.35$ [5]
- ② **NTP injection:** $|m_{NTP} - m_{highm}| / \sigma < 1$
- ③ **Residual FAP:** $|\Delta \log_{10}(\text{FAP})| < 0.5$



Planets which pass criteria vs. distance from true solution



Conclusion

- Mass-eccentricity degeneracy and NTPs unaccounted for by the model can generate **large outliers** in masses retrieved for transiting planets.
- Our three criteria are able to **identify systems** with a non-transiting perturber, and reject all masses which are **far from the solution**.
- Applying the robustness criteria also **improves the distribution** of the distances from mass solutions, going from $(\mu_{all}, \sigma_{all}) = (0.41, 4.26)$ towards a **Gaussian distribution**: $(\mu_{pass}, \sigma_{pass}) = (0.17, 0.87)$.
- However, two planets from a robust system without NTPs are rejected by the criteria, calling for **further refinement** of the method.

References

[1] Hadden & Lithwick (2017) AJ 154, 5; [2] Deck et al. (2014) ApJ 787, 132; [3] Boué et al. (2012) MNRAS 422, 1; [4] Delisle, Hara & Ségransan (2020), A&A 635, A83; [5] Leleu et al. (2023) A&A 669, A117



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