RV – TTV Complementary for transit-survey follow-up

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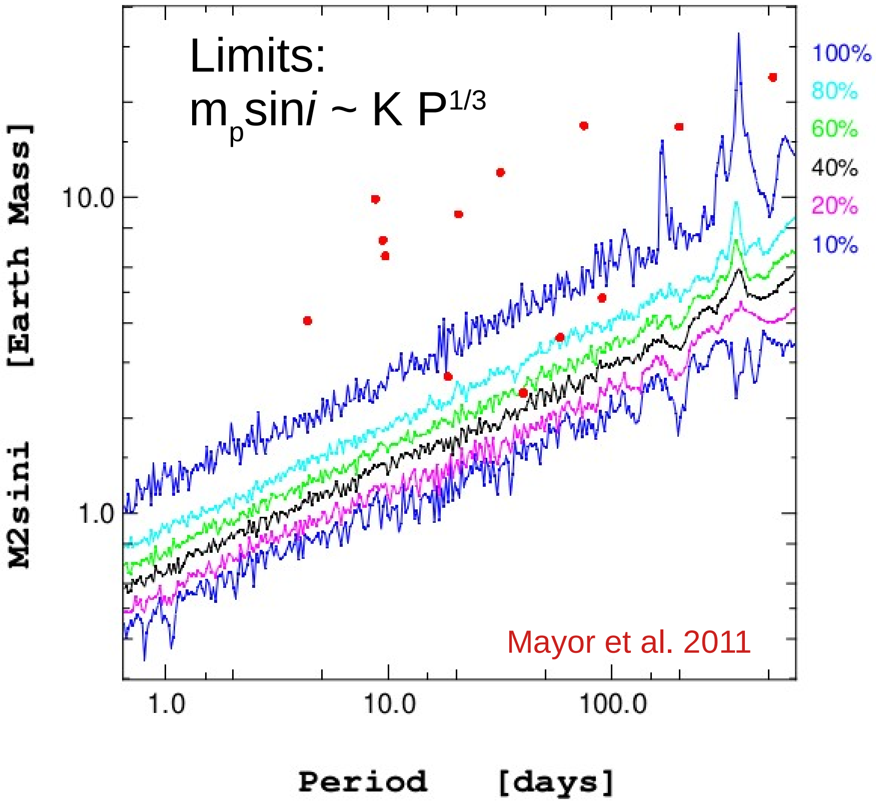
Extremely Differing Detection Limits

RV – Radial Velocity; TTV – Transit Timing Variations



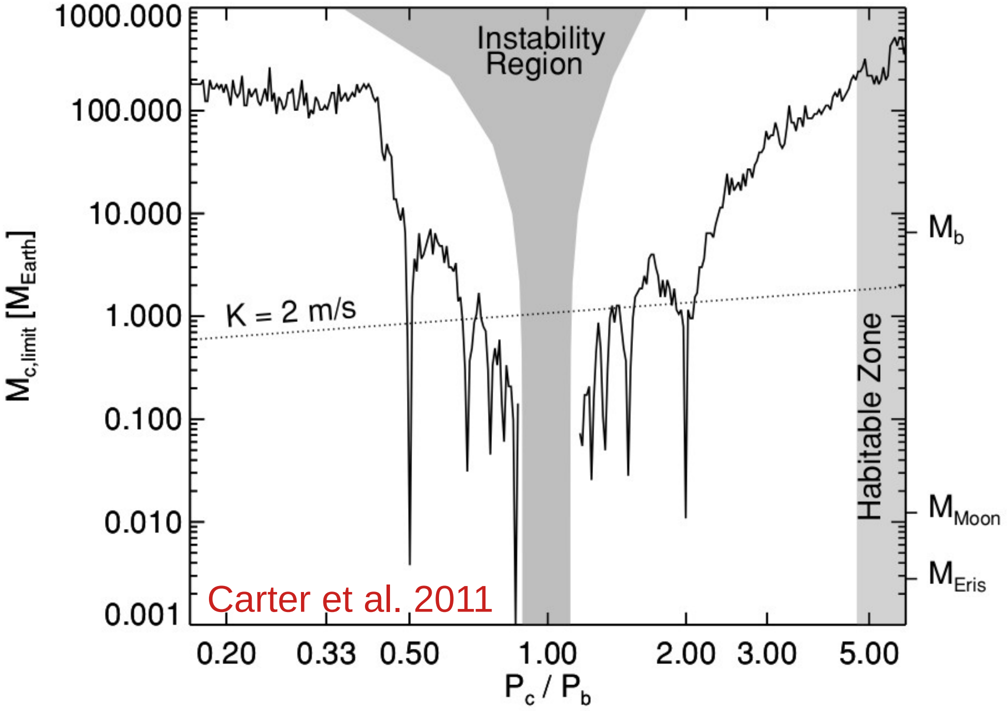


Figure 8. Upper mass limits for a hypothetical perturber as a function of perturber period normalized to the period of GJ 1214b, P_c/P_b.

Usually, either RV *or* TTV will dominate the dynamical mass detection & mass constraint.

RV vs. TTV strength

- As the transit campaign lengthens, TTVs win.
- If targets are brighter, RVs win.
- Kepler: TTV was dominant; RV special cases.
- TESS: RV is dominant; TTV special cases.
- Plato: “just right”! Both need robust programs.

		Transits	Radial Velocities
Basic facts:	Planet number	w/ TTV	
	Masses	w/ TTV	
	Radii		
	Periods (& ratios)		
Dynamical properties:	Eccentricities	w/ TTV	
	Mutual Inclinations	w/ TDV	

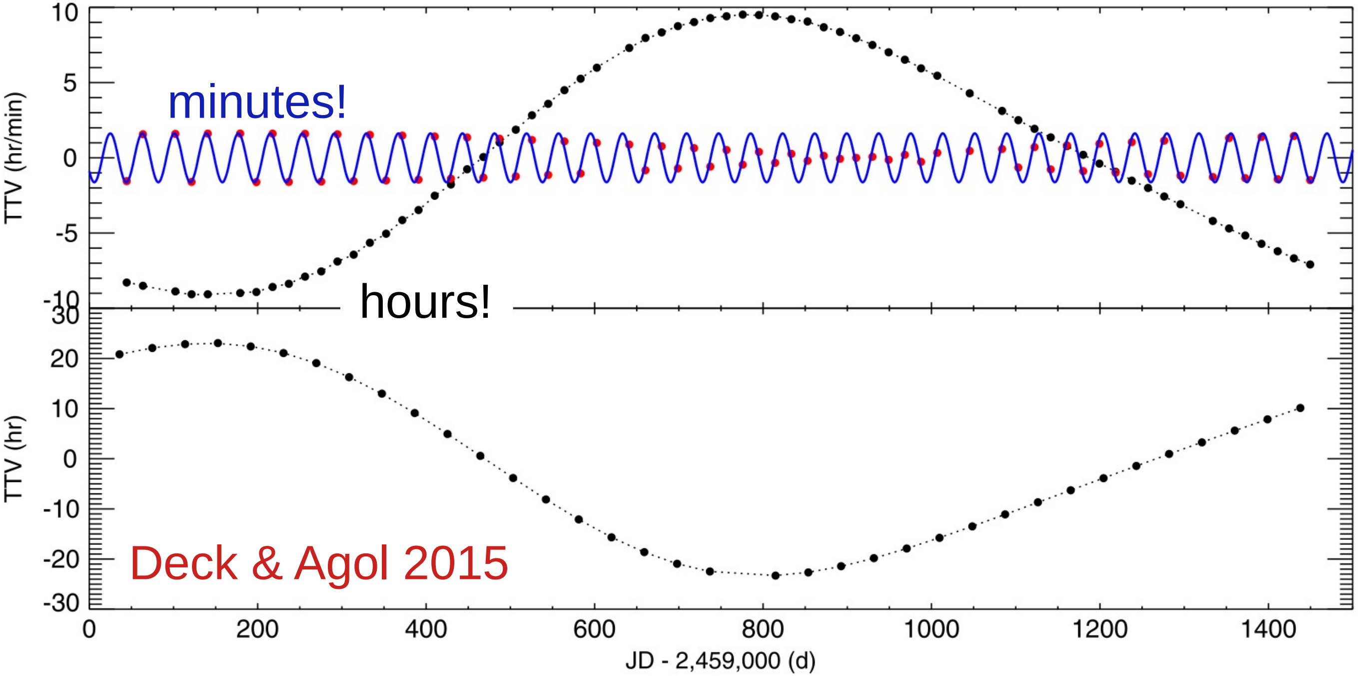
Science Goals:
Mass-Radius measurements (Composition)
Planet Discovery / *Full* Architectures
Resonant dynamics -> Migration Constraints

TTV's Achilles Heel: mass/eccentricity degeneracy

- Detection != Mass Determination
- Mass **determination** can come from "chopping"~ $f(m_p^1, e^0)$

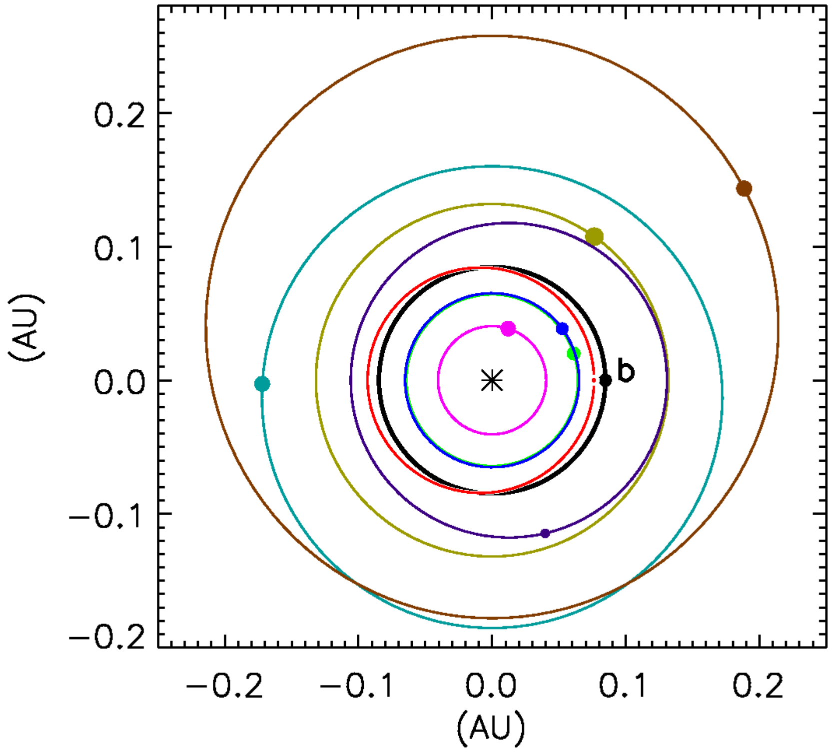
Kepler-9

- Near-2:1 giant planets
- TTV determined m_b/m_c
- Originally RV roughly measured $(m_b+m_c)/m_*$ (Holman+2010)
- Eventually TTV "chopping" & harmonics determined m_c/m_* (Deck&Agol 2015)
- RV confirms: Borsato+2019



Truly resonant planets don't have this degeneracy, but long P_{TTV} (Nesvorný&Vokrouhlický 2016)

Lots of possible perturber orbits for TTV detection of Kepler-19c (Ballard+2011)



Possible orbits:

Mean motion resonances:

<2:3

>2:3

<2:1

Higher-order resonances:

<1:3

<5:3

<3:1

>4:1

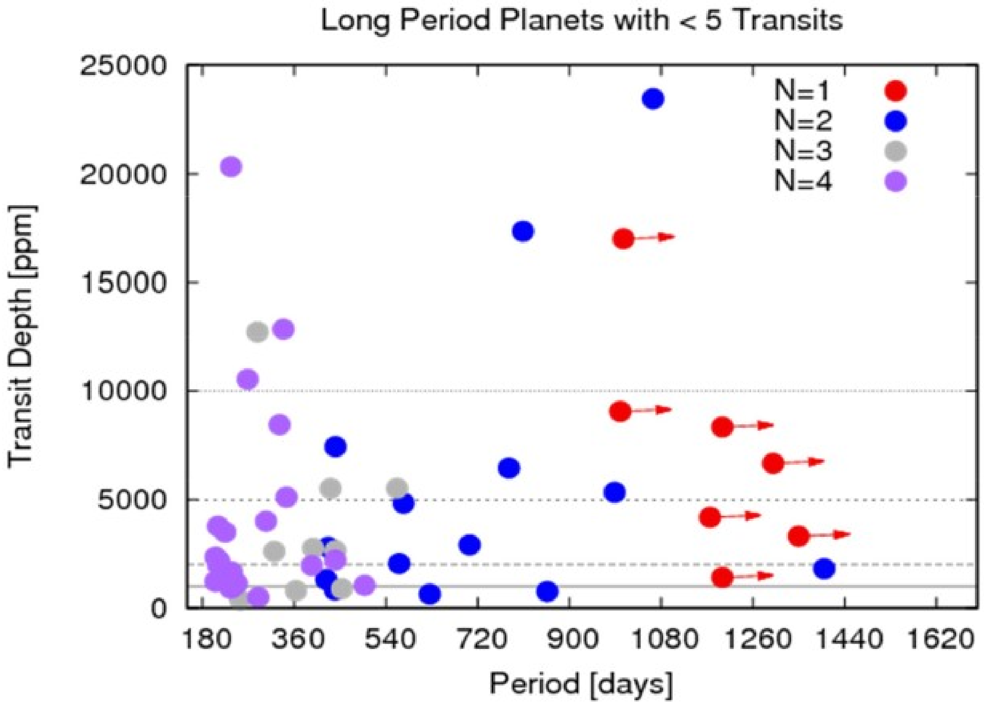
Co-orbital planet?

Distant retrograde satellite? 1:1

RV solved it! P_2/P_1=3.08±0.03 (Malavolta+2017)

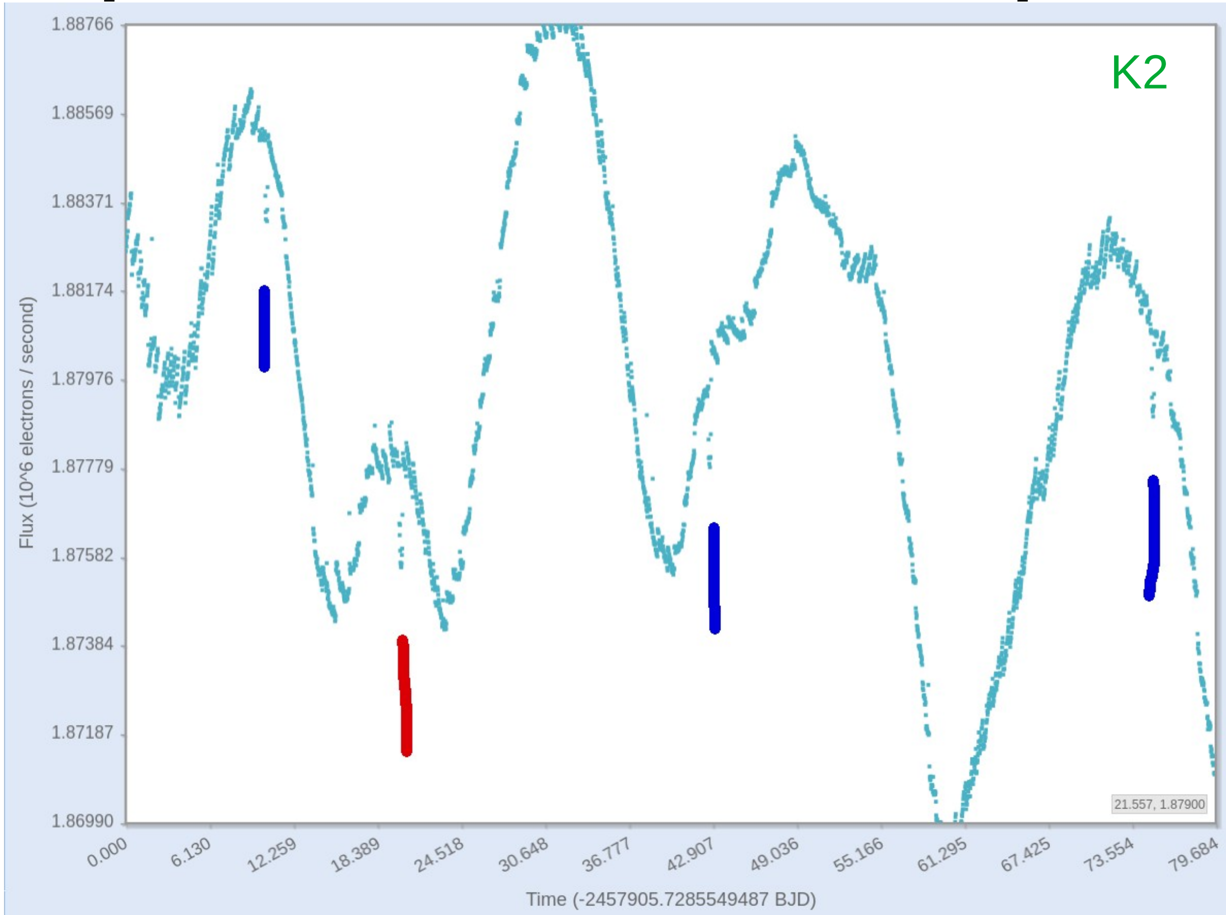
Getting more basic for the HZ: Follow-up Near the Survey Length

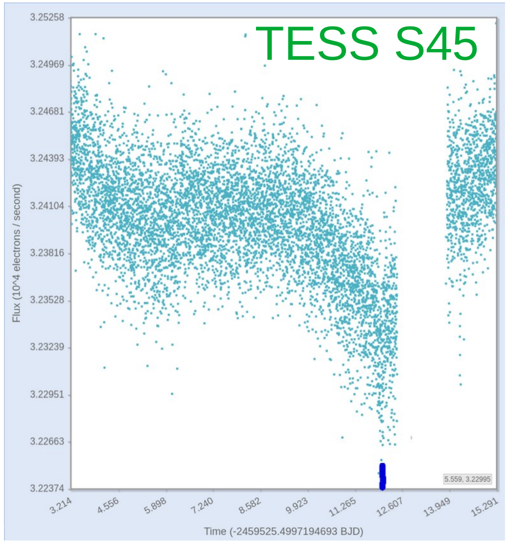
- Plato will find mono- and 2- transit candidates. → Science of the habitable zone.
- Kepler's 1-4 transit candidates shown to the right, after the 1460 day survey. Need to confirm transit periods near the survey length!
- Can do by RV (but multiplanets will confuse us)
- Can do with Photometry (likely poorer precision)



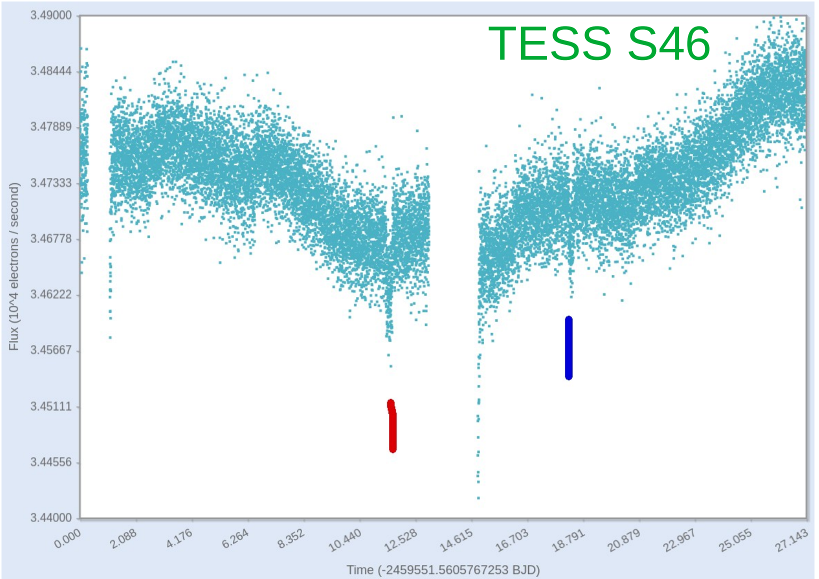
Fabrycky+2013 arXiv:1309.1177

Example: TOI-5696
2 planets, 2 telescopes



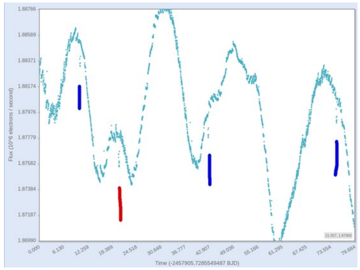


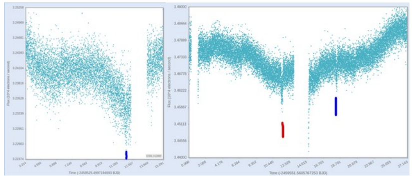
5 transits
2 transits



TOI-5696.01
2-transit example over a data gap

2 transits





1637.27days

Gap >> likely period.
Gap could be 27, 26, 25, 24… 1 periods long.
Short transit duration argues for >~20.

RV can distinguish between aliases. Highly constrained to discrete periods and known transit phase.

See, e.g. Osborne et al. 2022

RV/TTV Complementary Summary

- For individual systems, one of them wins.
- For a long-stare survey of bright targets, both follow-up capabilities are important!
- TTV often *detects* a perturber, without *measuring* its mass
- Determining actual periods is a more basic task, which will be very important for Plato's HZ science goal!

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Chopping Signal – Deck & Agol 2015

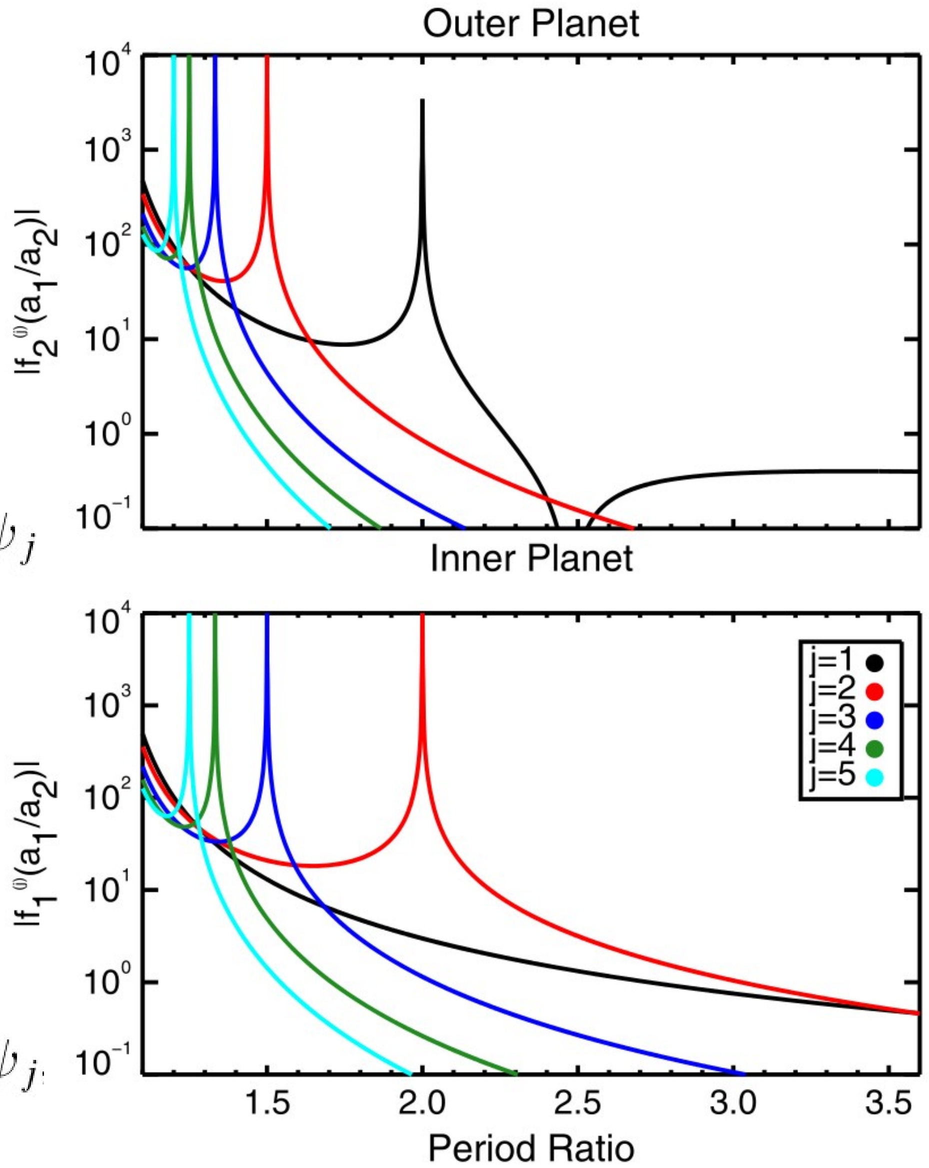
$$\psi_j = j\psi = j(\lambda_1 - \lambda_2)$$

Depends on angular offset

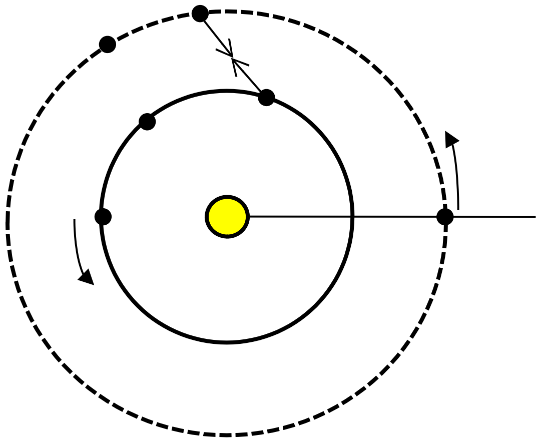
$$\delta t_2 = \frac{P_2}{2\pi}\frac{m_1}{M_\star}\sum_{j=1}^{\infty} f_2^{(j)}(\alpha)\sin\psi_j$$

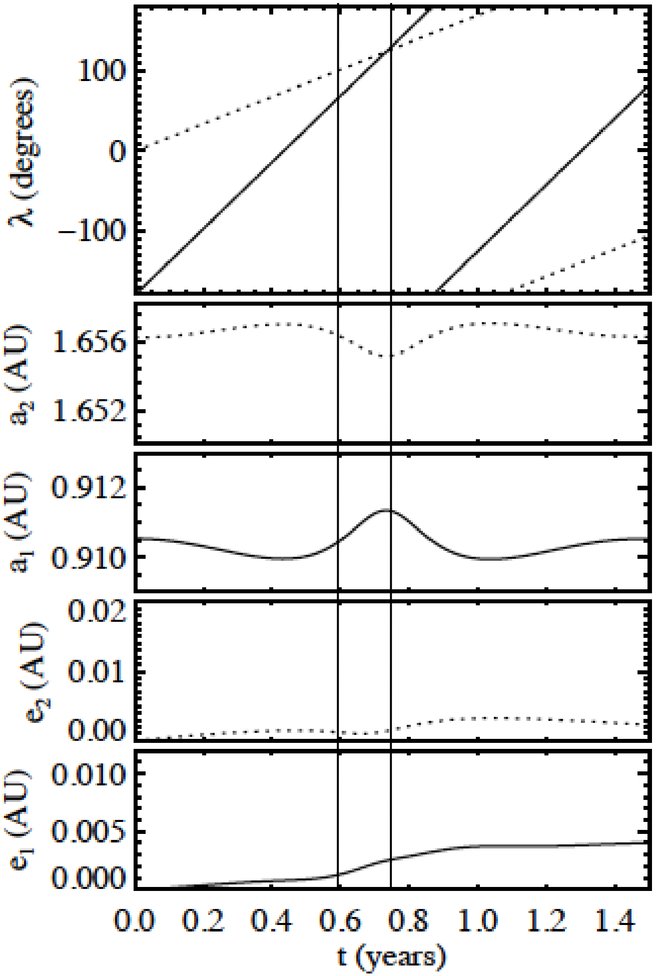
Resonant spikes, but varies by <~10x between 1.2< P_2/P_1 < 2 (where most interacting planets lie)

$$\delta t_1 = \frac{P_1}{2\pi}\frac{m_2}{M_\star}\sum_{j=1}^{\infty} f_1^{(j)}(\alpha)\sin\psi_j$$

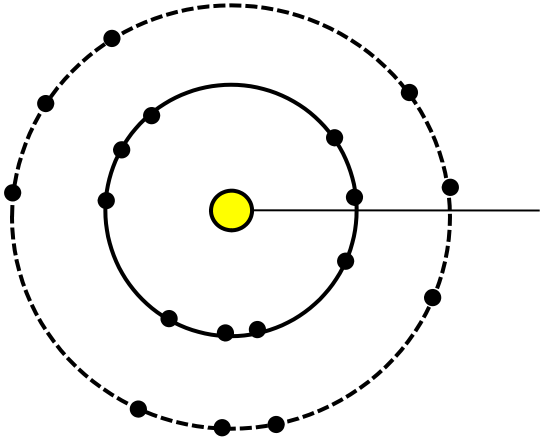


Dynamics: Orbital Timescales

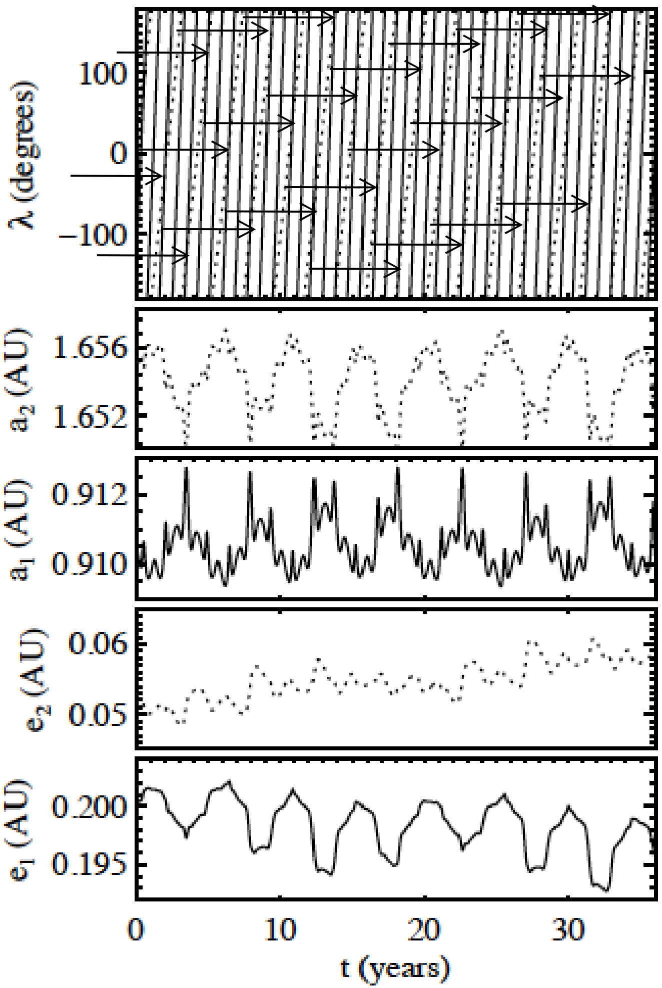




Dynamics: Secular Timescales



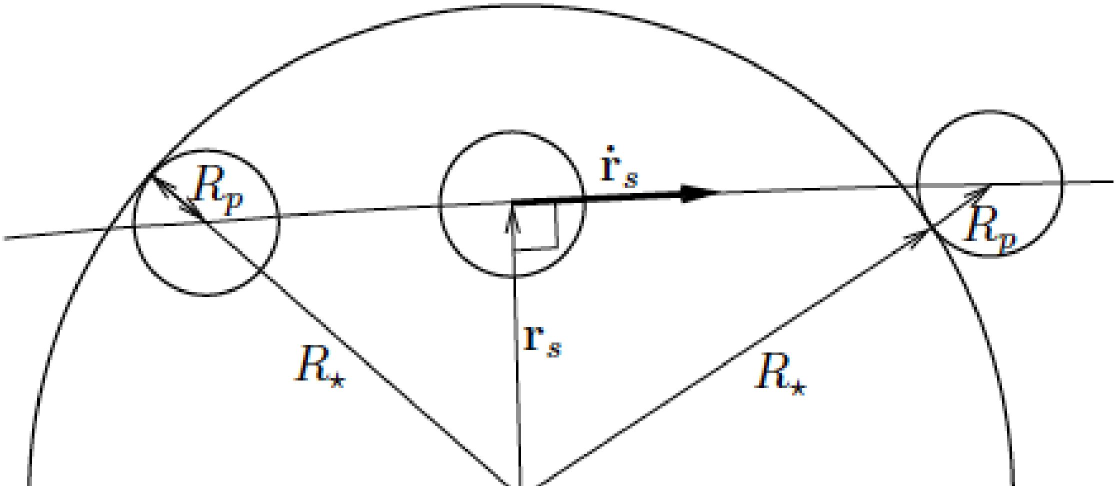
$P_2/P_1 = 2.44$



The Numerical Model

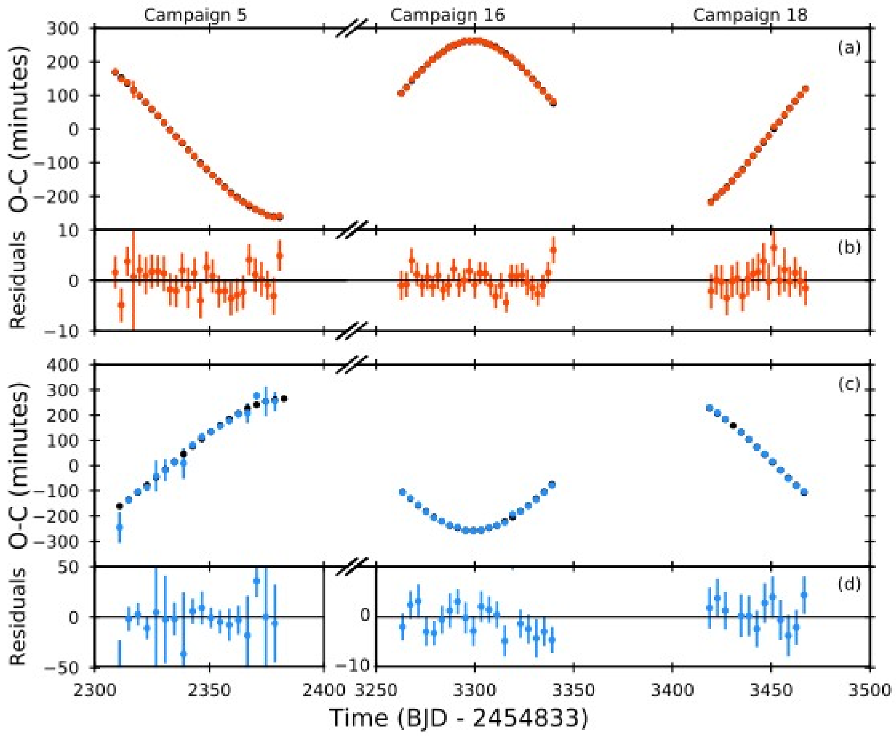
Newton's equations, using high-order Runge-Kutta. Determine **RV** at observation times and **transit** t (mid-time), and b, v (for shapes).

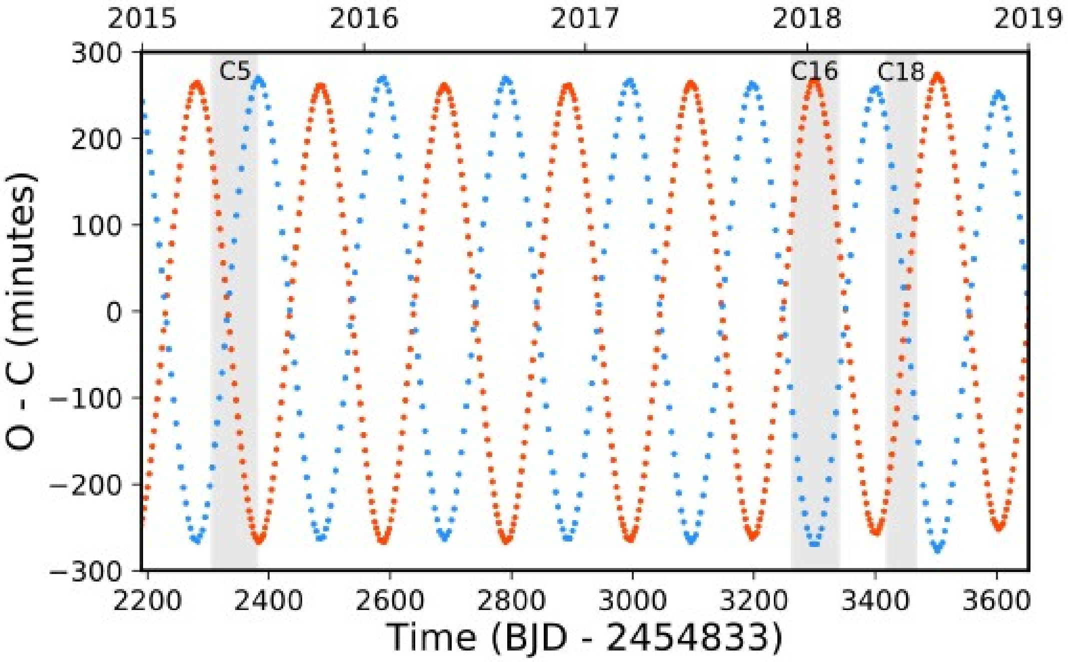
Or, just model the photometry point-by-point ("photodynamics")



Example of Gaps for TTV

- K2 revisited its own fields. TTV analysis of K2-146 (Hamann et al. 2019):





Monotools

- Osborne et al. 2022

model transit lightcurves in cases of multiple transits, duotransits, and monotransits, as well as multiple systems with combina-tions of such candidates, with both radial velocities and transit photometry.

https://github.com/hposborn/MonoTools

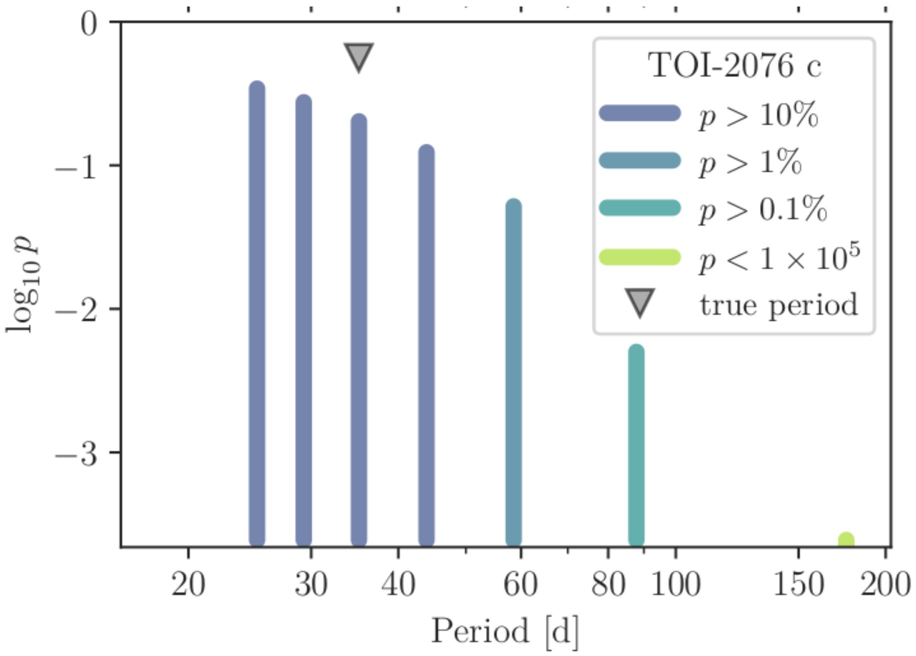


Fig. 1. Marginalised $\log_{10}$ probabilities for each of TOI-2076 c (*upper*) and TOI-2076 d (*lower*) period aliases, as computed by `MonoTools` before CHEOPS observations.