

# Characterizing resonant exoplanetary systems with photodynamical modelling

Marylyn Rosenqvist

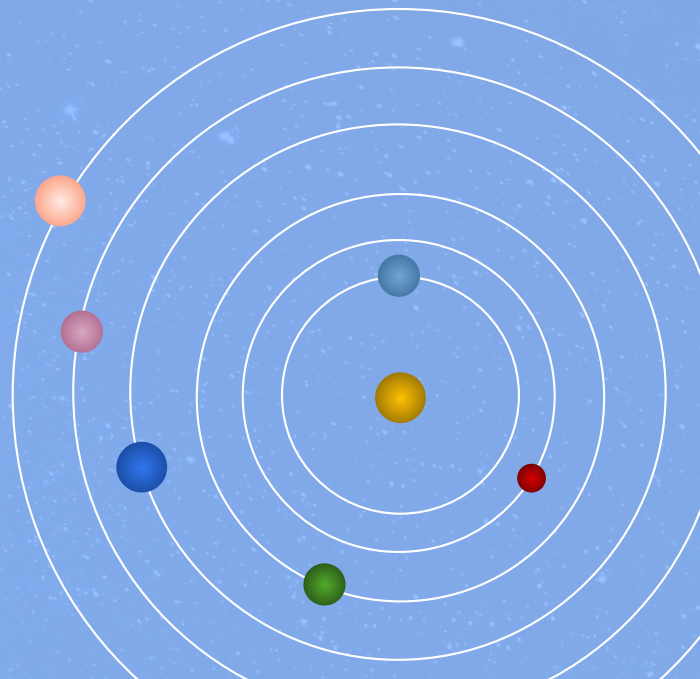
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# Resonant systems

$$\frac{P_2}{P_1} = \frac{k}{k - q} \quad q=1 \text{ for 1st-order MMR}$$

- ★ Planets in **mean motion resonance (MMR)**: the ratio of orbital periods is close to a rational number (e.g. 2/1, 3/2, 5/3 etc.)
  - Places strong constraints on system architecture and orbital elements

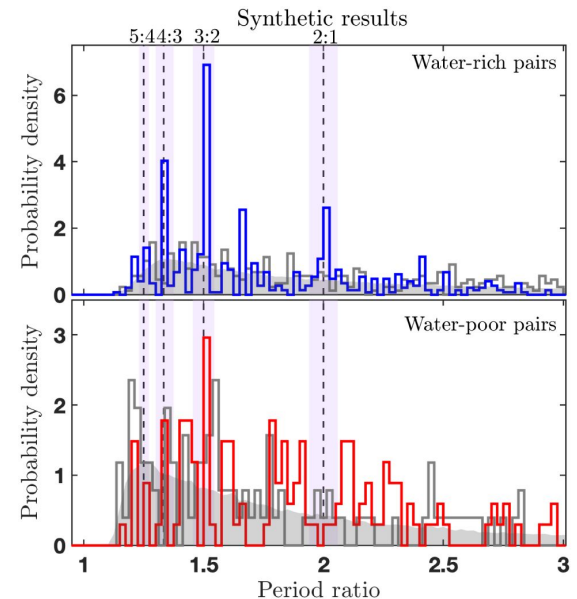
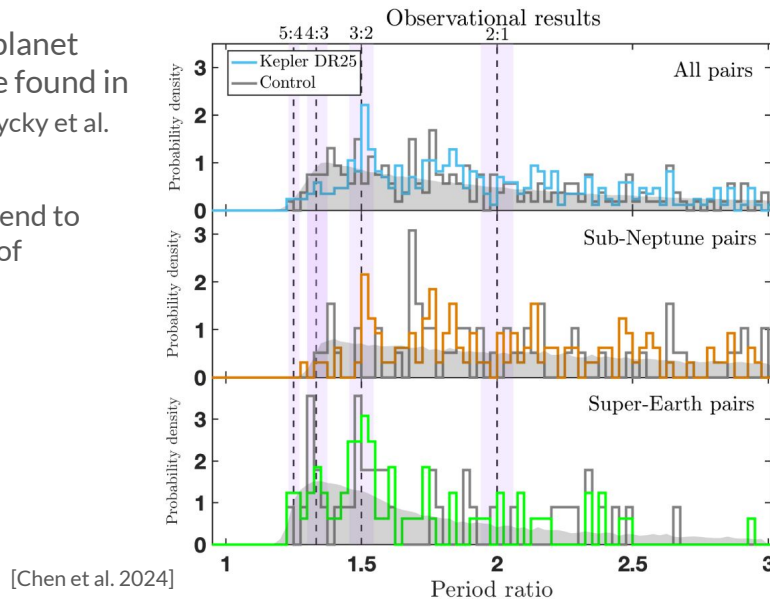
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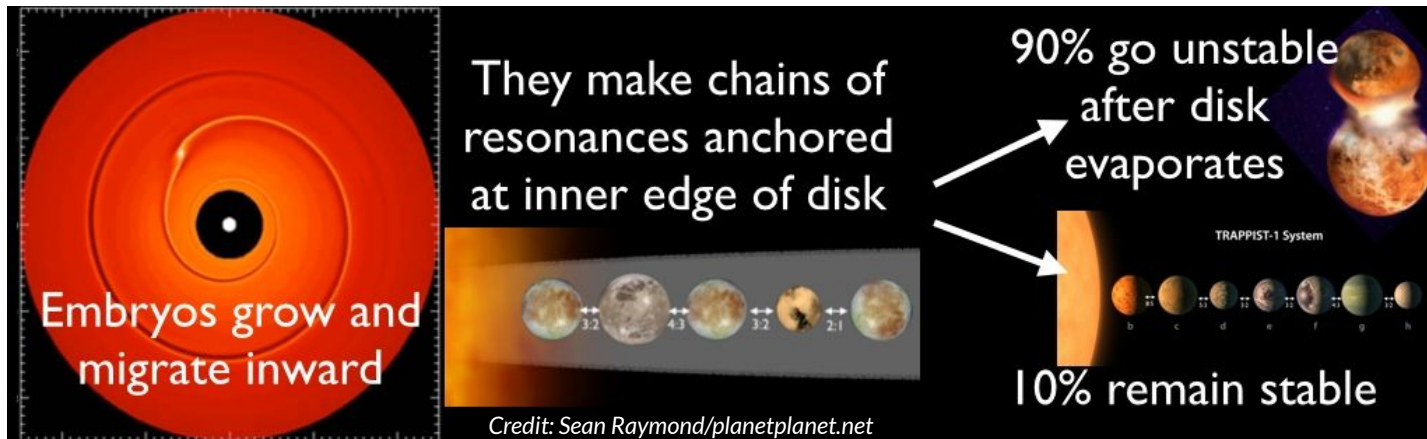
- ★ Simulations predict more planet pairs in resonance than are found in observed systems [e.g. Fabrycky et al. 2016, Chen et al. 2024]

- Observed pairs also tend to cluster slightly wide of resonance



# Formation of resonant chains

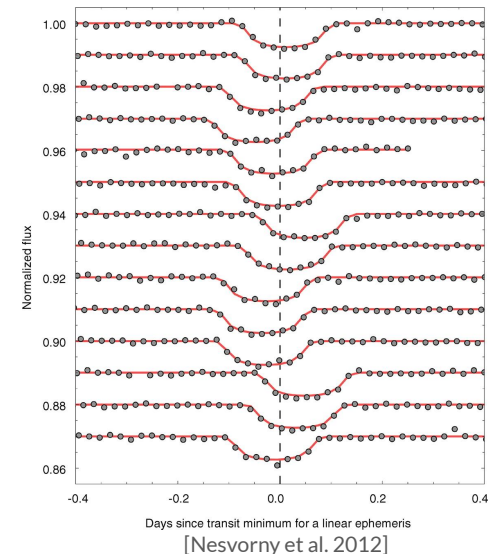
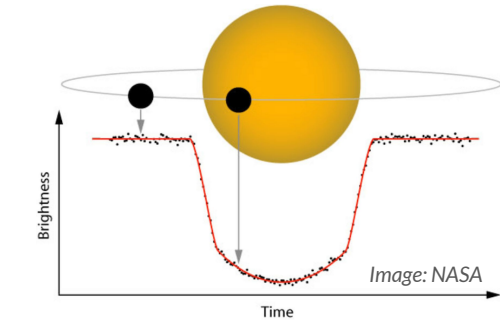
- ★ **“Breaking the chains” theory:** exoplanets migrate into resonant chains during formation, but most chains break after gas disk dissipation [Izidoro et al. 2017, Bean et al. 2021]
  - Surviving chains preserve the early conditions of planet formation
  - Comparison of observed vs simulated systems allow us to study the **formation and evolution pathways** of planets [e.g. Goldberg & Batygin 2023]



# Transit timing variations (TTVs)

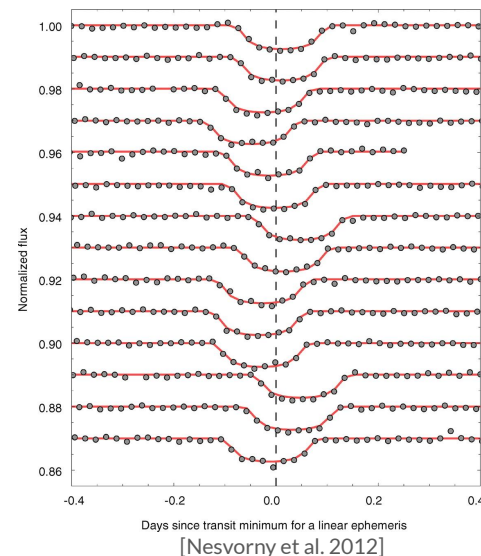
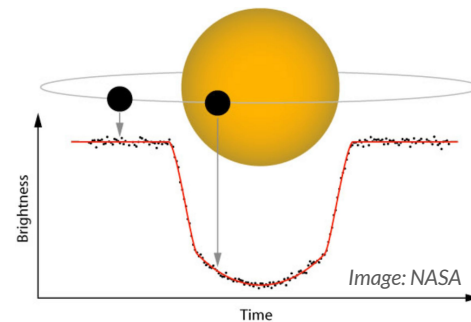
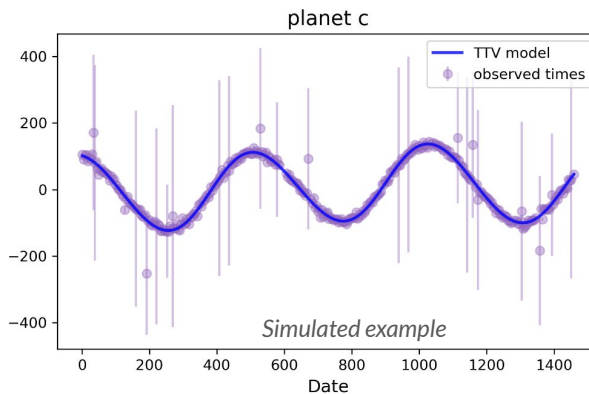
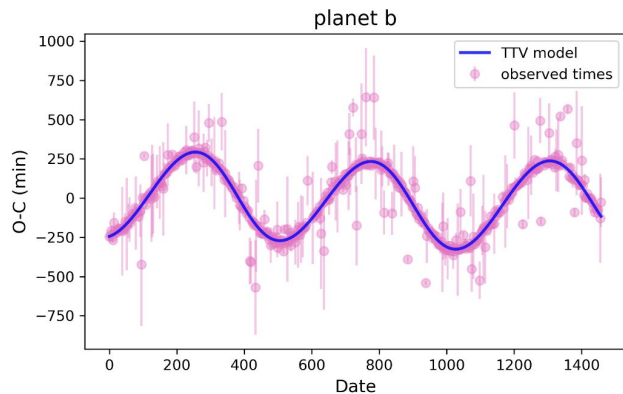
- ★ In non-resonant systems: perturbations between planets cancel out over time
- ★ In (near) resonant systems: strong **planet-planet interactions** accumulate over time, causing orbits to deviate from the Keplerian model
  - Observed (O) transit time occurs earlier/later than the calculated (C) time

*Simulated example*



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  - Observed (O) transit time occurs earlier/later than the calculated (C) time
  - Near-resonant systems induce strong, observable **transit timing variations (TTVs)** [Agol et al. 2005]



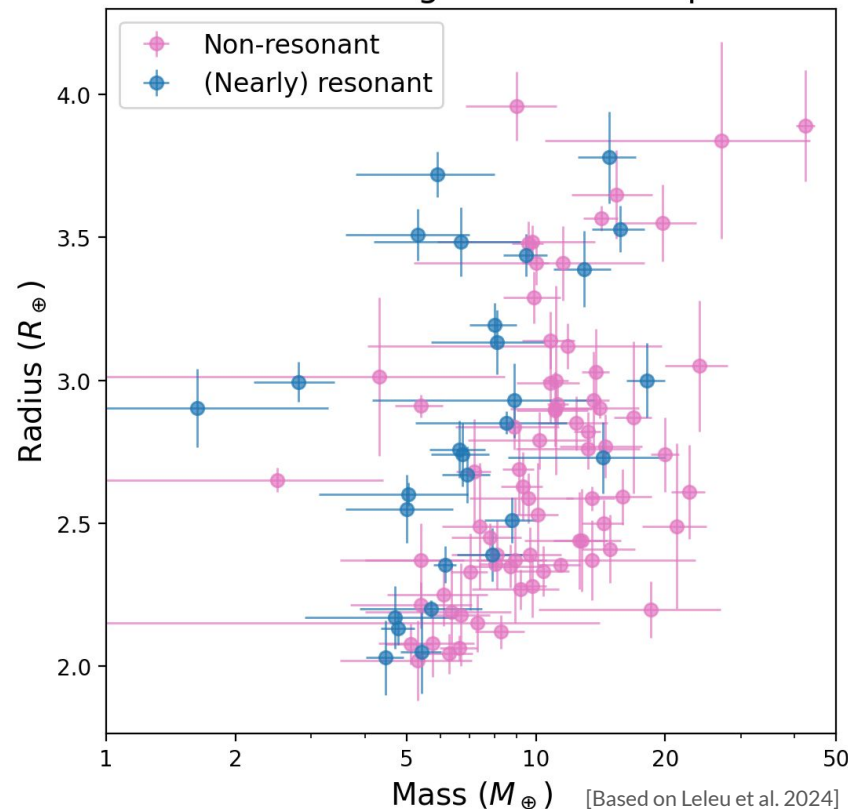
# Densities of resonant planets

- ★ TTV signal of each planet scales with the masses of other bodies in the system [Agol et al. 2005]
  - Allows for **mass measurements** from transit photometry independent of other detection methods e.g. radial velocities (RVs)

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- ★ Combined with radii measured directly from transits, we can determine the **densities of TTV planets**
  - Resonant sub-Neptunes are found to be less dense than non-resonant planets, implying **different formation paths** [Leleu et al. 2024]
- ★ Benefit of analysing near-resonant TTV systems:
  - Comparison of masses determined from RVs vs. TTVs
  - Precise mass measurements from **photodynamical modelling**

Mass-Radius diagram of sub-Neptunes



9.11 d 13.7 d 20.5 d 30.8 d 40.0 d 54.8 d  
 2.2 R<sub>E</sub> 2.4 R<sub>E</sub> 2.8 R<sub>E</sub> 1.9 R<sub>E</sub> 2.6 R<sub>E</sub> 2.6 R<sub>E</sub>

# HD 110067 / TOI-1835

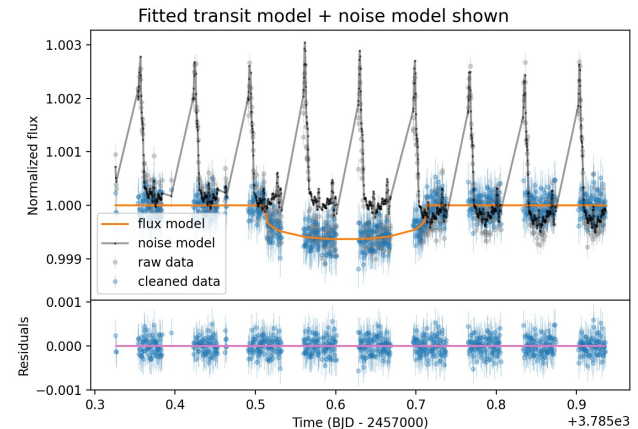
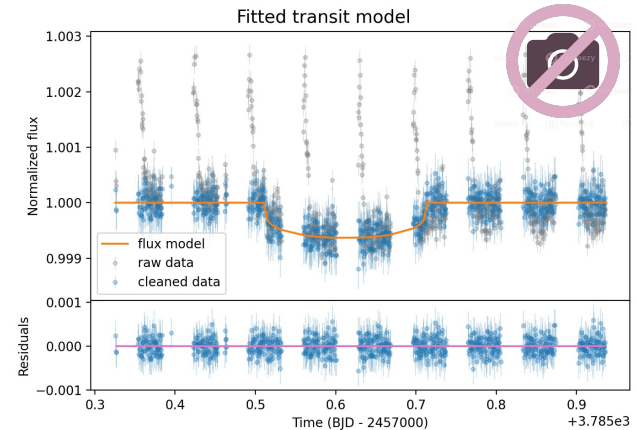
- ★ Resonant chain of 6 sub-Neptunes around 8 Gyr K star
- ★ Two innermost planets first detected with **TESS** (sectors 23, 49)
  - Total of 6 planets confirmed with follow-up **CHEOPS** observations [Luque et al. 2023]
- ★ One of only 4 known transiting resonant chains bright enough for RV follow-up observations
  - Planetary masses not constrained with existing RVs
- ★ Aim: combine photometric data with new **HARPS-N** data in a joint TTV-RV analysis to constrain masses and orbital parameters [Rosenqvist et al. in prep.]
  - Ongoing CHEOPS GTO programme for TTV follow-up
  - Ongoing RV programme with VLT/**ESPRESSO**
  - Ongoing **JWST** programme for atmospheric characterisation



Source	Luque et al. 2023
Sp. T	K0.0 V
T <sub>eff</sub> (K)	5266±64
R <sub>*</sub> (R <sub>⊙</sub> )	0.788±0.008
M <sub>*</sub> (M <sub>⊙</sub> )	0.798±0.042
Metallicity (dex)	-0.20±0.04 [Fe/H]
L <sub>*</sub> (log <sub>10</sub> (L <sub>⊙</sub> ))	---
log g (log <sub>10</sub> (cm/s <sup>2</sup> ))	4.54±0.03
Age (Gyr)	8.10±4.00
ρ <sub>*</sub> (g/cm <sup>3</sup> )	---
v sin i (km/s)	2.5±1.0

# Transit extraction

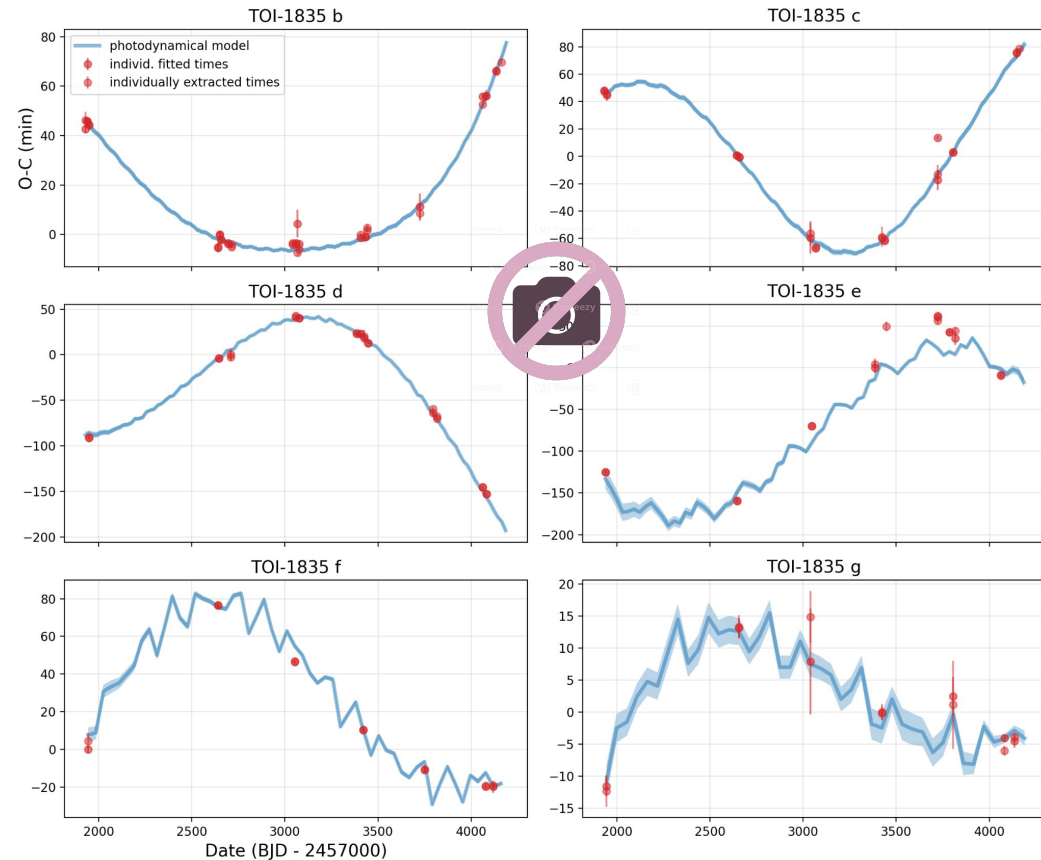
- ★ Extract each transit light curves based on known Keplerian periods and transit epochs  $T_0$
- ★ Fit for each individual time of transit mid-point  $T_i$ 
  - Transit model with [batman](#) [Kreidberg 2015]
- ★ MCMC with Scaled Adaptive Metropolis sampler [samsam](#) [Delisle et al. 2018]
  - Strength: at each step the proposal is randomly generated around the previous point using the covariance matrix of all preceding points [Haario et al. 2001]
- ★ Simultaneous noise modelling with [linmarg](#) [Leleu et al. 2023]
  - Model instrumental systematics + stellar activity as a combination of co-trending basis vectors and B-splines (in time and the spacecraft roll angle)
  - Compute the likelihood marginalized over linear noise detrending parameters



# TTV analysis

## 1. TTV modelling

- ★ Model the TTVs to sample for masses and orbital elements
- ★ Compute predicted timings with [TTVFast](#) [Deck et al. 2015]



[Rosenqvist et al. in prep.]

# TTV analysis

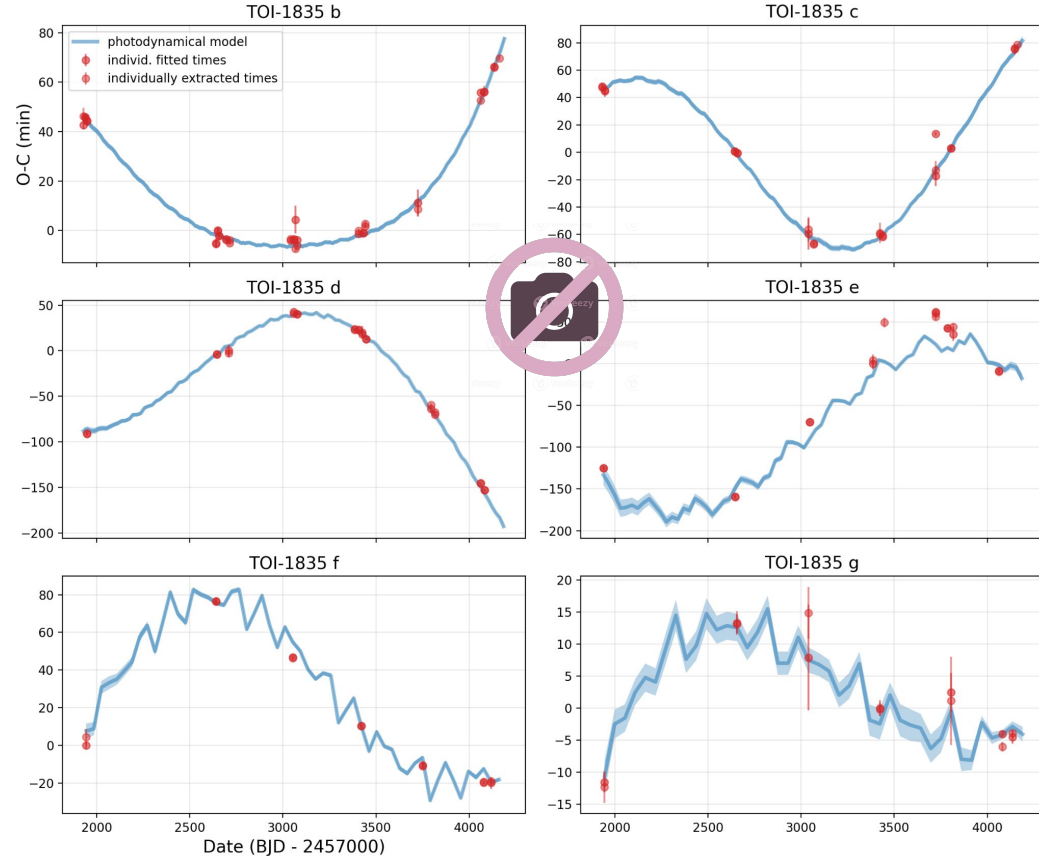
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## 2. Photodynamical modelling

- ★ Model **N-body interactions** together with ideal transit light curve on the full photometric data set
- ★ More computationally heavy but provides **better constraints** on TTVs and more precise errors [Leleu et al. 2023]



[Rosenqvist et al. in prep.]

# Mass robustness check

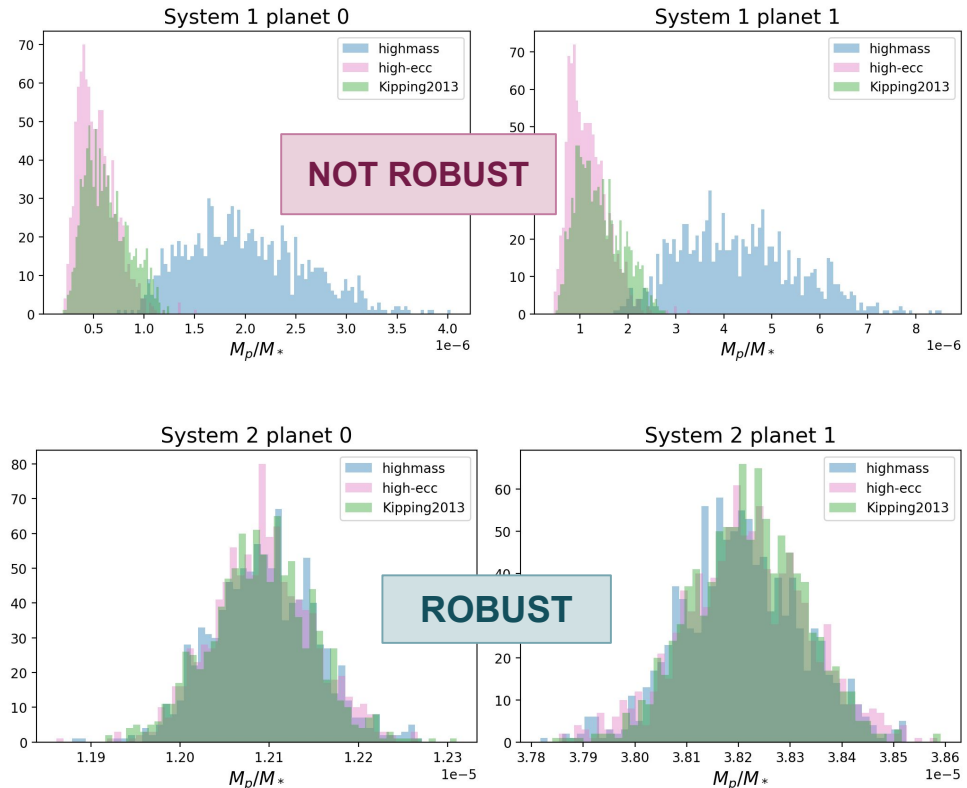
- ★ Different systems can give rise to similar TTVs
  - TTV signals may be dominated by different components of the planet-planet interactions that are difficult to distinguish from each other
  - Degeneracy in mass and eccentricity [Boué et al. 2012, Lithwick, Xie & Wu 2012, Hadden & Lithwick 2016]
  
- ★ Assess the **mass-eccentricity degeneracy** in a system using different choices of priors [Hadden & Lithwick 2017, Leleu et al. 2023]
  - Draw mass (and eccentricity) posteriors towards opposite extremes of the degeneracy

Type	Mass prior	Eccentricity prior
High-mass	Uniform	Log-uniform
Low-mass (high-ecc)	Log-uniform	Uniform
Kipping2013	Log-uniform	Empirical beta-distribution

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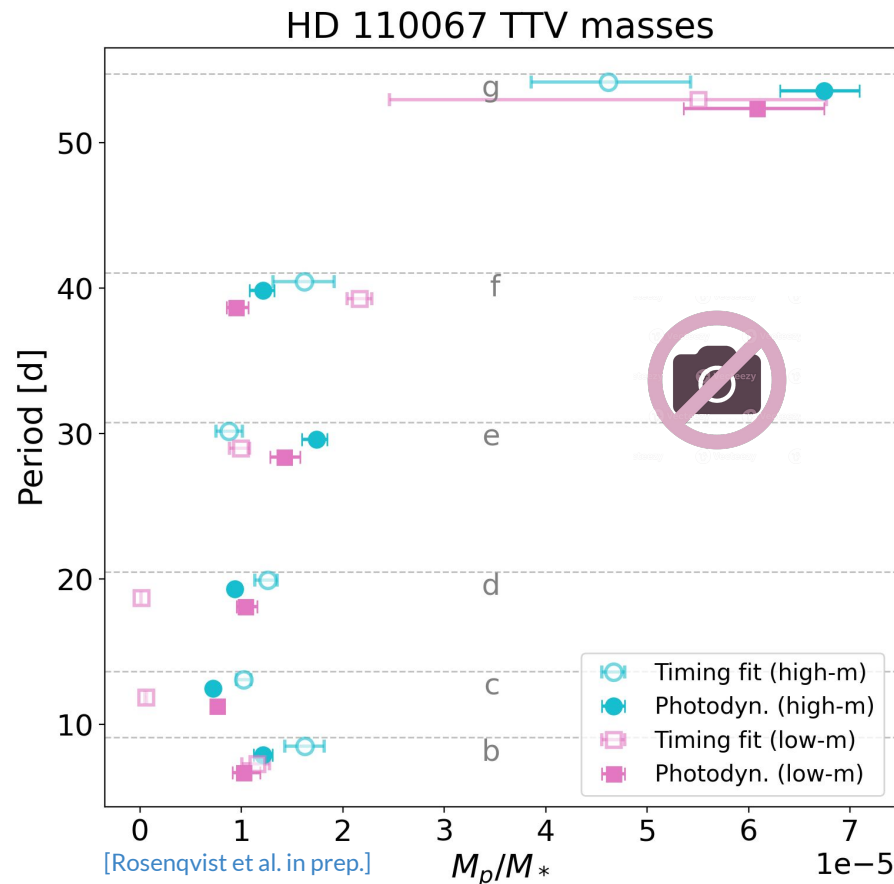
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# Preliminary results

- ★ TTV signal only constrains the **mass ratios** between planets and between each planet and star [Agol et al. 2005, Nesvorný & Vokrouhlický 2016]
  - In individual timing fit: assume stellar parameters from [Luque+ 2023]
  - In photodynamical model: also fit for stellar radius and density, allowing to derive the **stellar mass** and convert the mass ratios
- ★ **More precise masses** from photodynamical model
  - But outermost planet not well constrained
- ★ **More robust masses** in photodynamical model
  - But still some dependency on choice of priors
- ★ **Analysis is still ongoing** with new data being gathered



# Challenges

Breaking the **mass-eccentricity degeneracy** requires distinguishing higher-order harmonics or short-period effects of the TTV signal [Nesvorný & Vokrouhlický 2016]

- ★ Require long baselines
- ★ Require dense sampling

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## Next steps

- Analyse RV data for independent mass measurements
- Compare TTV and RV masses (and densities)
- Perform joint RV-photodynamical analysis

# Summary

- ★ Resonant systems are key to understanding the **formation history and dynamical evolution** of exoplanets, by comparing observations with simulations
- ★ Near-resonant planets induce **strong observable transit timing variations (TTVs)** that can be used to precisely determine planetary masses
- ★ **Photodynamical analysis** combining photometry with dynamical simulations to model TTVs is able to recover robust and precise masses
- ★ TTV analysis remains challenged by the **mass-eccentricity degeneracy** and by the effect of **non-transiting perturbers**
- ★ Future work aims to combine photodynamical modelling with **radial velocities** for a more comprehensive analysis

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