Mapping the structure of the planetary 2/1 mean motion resonance

The TOI-216, K2-24 and HD27894 systems

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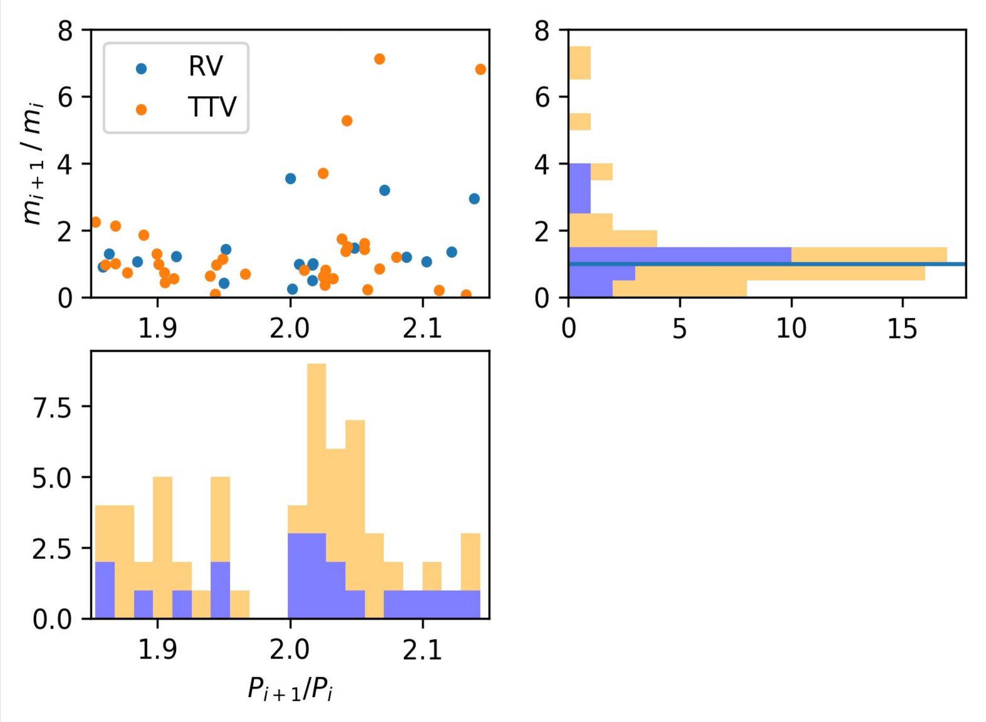
Introduction

Mean motion resonances (MMR) are a frequent phenomenon among extrasolar planetary systems. Current observations indicate that many systems have planets that are close to or inside the 2/1 MMR, meaning the orbital period of one of the planets is twice that of the other. Analytical attempts to describe this particular MMR have limitations due to the many degrees of freedom of the system, which can only be reduced to integrable approximations in a few specific cases. There have been several successful approaches using semi-analytical or semi-numerical methods, yet these are not sufficient to completely understand the resonant dynamics.

In this work, we propose to apply a well-established numerical method to assess the global portrait of the resonant dynamics. It consists of constructing dynamical maps that indicate underlying resonant structures and various systems' behaviors that can be expected in different regions of the phase space and for different values of model parameters.

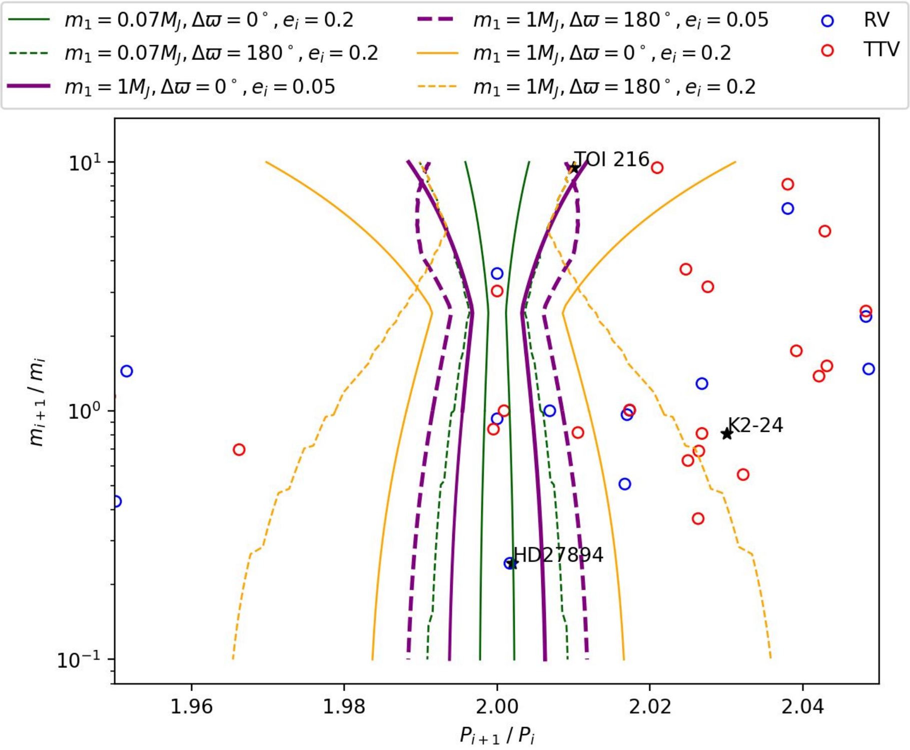


Distribution of known planetary pairs close to the the 2/1 MMR, detected by either radial velocity (RV) or transit timing variations (TTV), in terms of periods and masses. Index i corresponds to the innermost planet, while index i+1 corresponds to the outermost one.

Zoom of the previous plot around the 2/1 MMR, showing the location of the resonant separatrices for three different system configurations, similar to the TOI-216 (green), HD27894 (magenta), and K2-24 (orange). The separatrices has been computed with the semi-analytical model of Gallardo et al. (2021)

Full lines correspond to $\Delta\varpi = 0°$

Dashed lines correspond to $\Delta\varpi = 180°$



Semi-analytical model allows to predict that:

- HD27984 is inside the MMR
- TOI-216 would be in the MMR provided that $\Delta\varpi = 180°$
- K2-24 is not in MMR

Methods

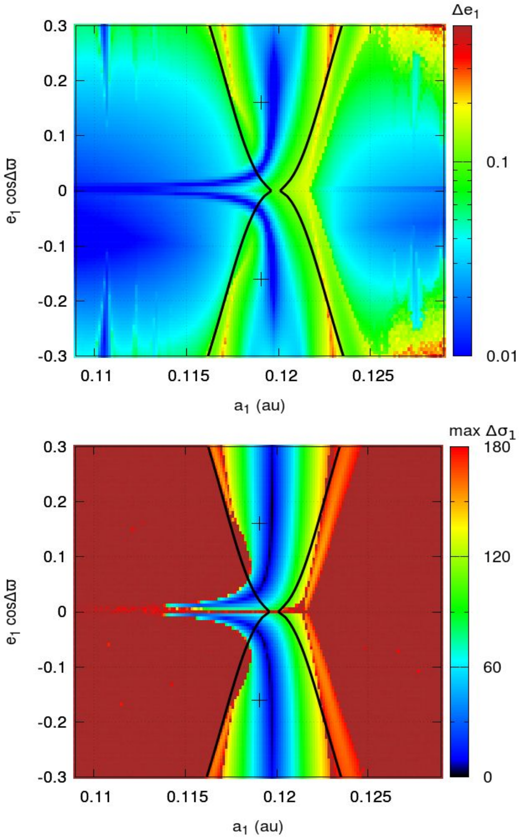
We construct dynamical maps for grids of initial conditions in the plane a_i vs. e_i , such that m_i is the smaller mass in the system. The largest mass of the pair is treated as the perturber, and its orbit through the grid is kept fixed at the actual configuration. We focus on maps that show the maximum amplitude Δe_i in eccentricity, and the maximum amplitude $\Delta\sigma_i$ in the resonant angle $\sigma_i = 2\lambda_2 - \lambda_1 - \varpi_i$, computed over an integration time of 100 years. We analyze three real systems with the following characteristics:

	TOI-216	K2-24	HD27894
m_1 $(M_\oplus)$	18.75	19.0	211.4
m_2 $(M_\oplus)$	178	15.4	51.5
P_1 (days)	17.09	20.89	18.02
P_2 (days)	34.55	42.34	36.07
e_1	0.160	0.06	0.047
e_2	0.0046	< 0.07	0.015
ω_1 (deg)	292	-	-
ω_2 (deg)	190	-	-
$m_\star (M_\odot)$	0.77	1.07	0.8

These three systems map a wide range of mass ratios m_2/m_1

Results: TOI-216

Comparison between the actual TOI-216 system (left), and a fictitious TOI-216 system where the eccentricity of the perturber is set to 0.1 (right).



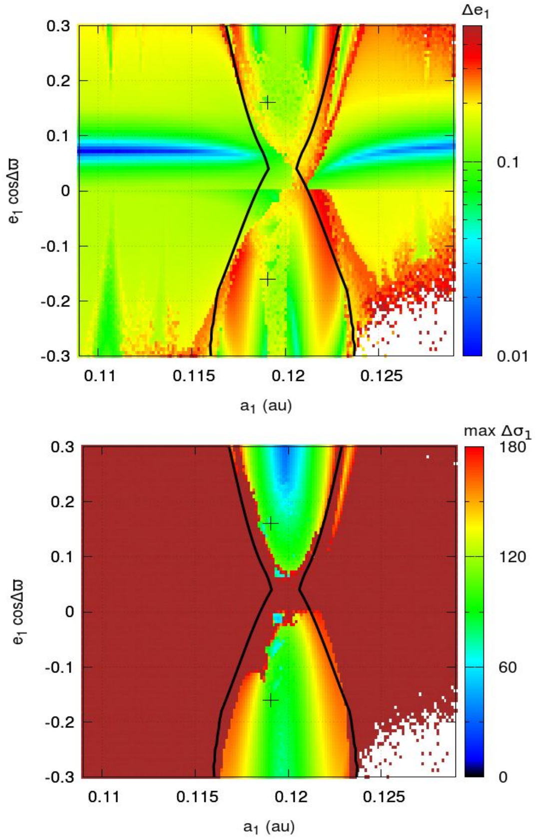
Black lines represent the semi-analytic separatrix.

For low eccentricity of the perturber, we have a structure similar to the RC3BP (V-shape).

For higher eccentricity of the perturber, the libration centers are shifted, and no librations are possible at low eccentricities.

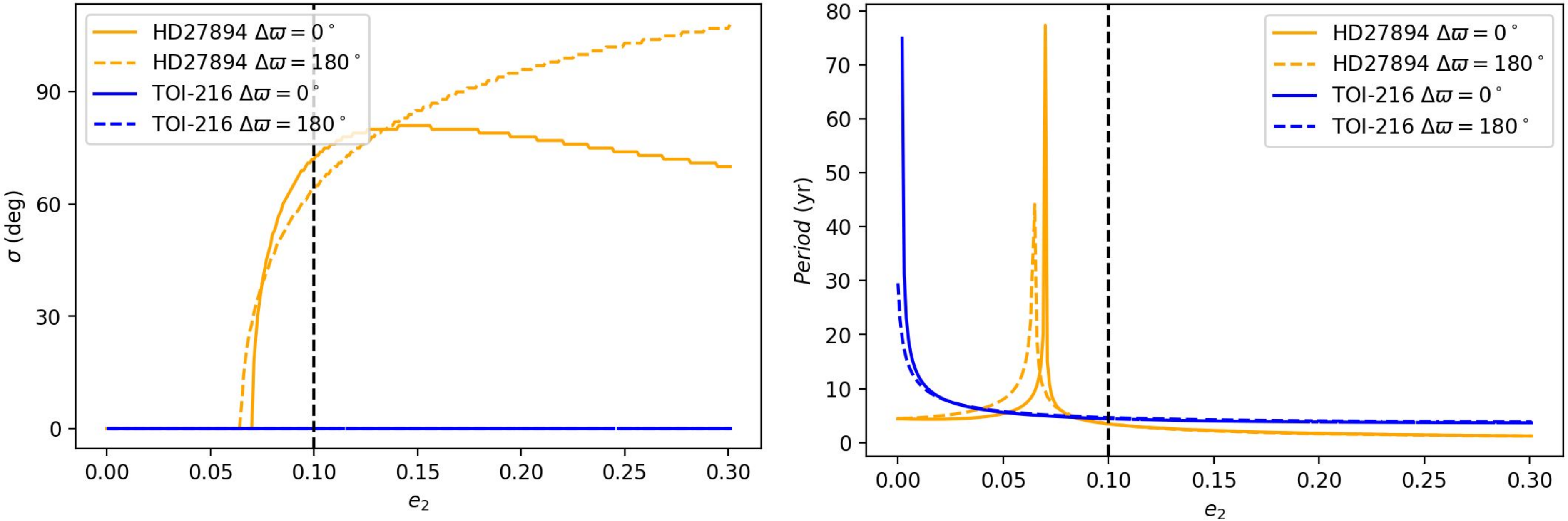
The narrower part of the libration region shifts up according to the perturber's eccentricity.

The actual system (black cross) is locked in the MMR, with $\Delta\varpi \approx 100^{\circ}$.



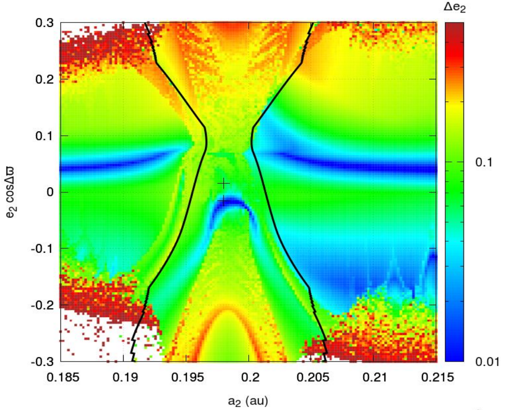
Results: HD27894

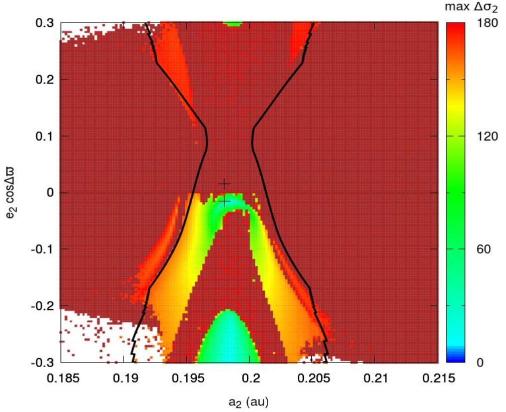
For this system, the perturber is the inner planet, therefore we may expect to have asymmetric librations. The following figure shows the prediction of the libration centers and periods using the semi-analytical model, in comparison with TOI-216.



Results: HD27894

Comparison between the actual HD27894 system (left) and a fictitious HD27894 system, where the masses of both planets have been re-scaled by a factor of 20 (right).





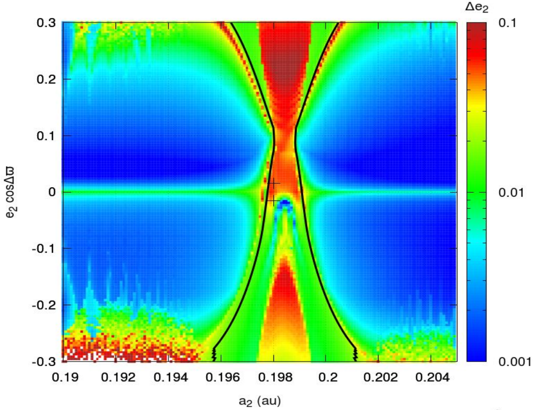
Black lines represent the semi-analytic separatrix.

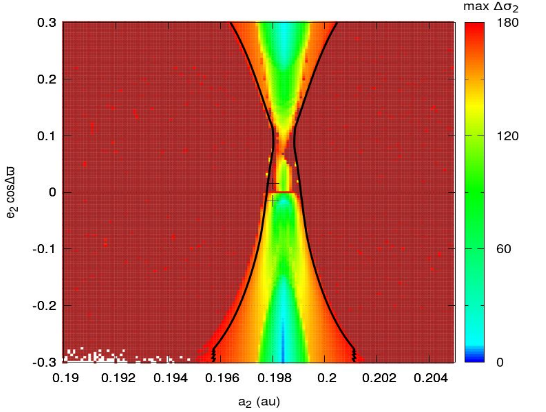
The maps are computed for a variable value of σ, following the analytic prediction of the libration center (see previous slide).

Using a fixed value of σ to construct the map does not allow to detect the libration region.

For the actual high masses, no libration center can be identified in the maps, due to the strong short period variations
(see next slide).

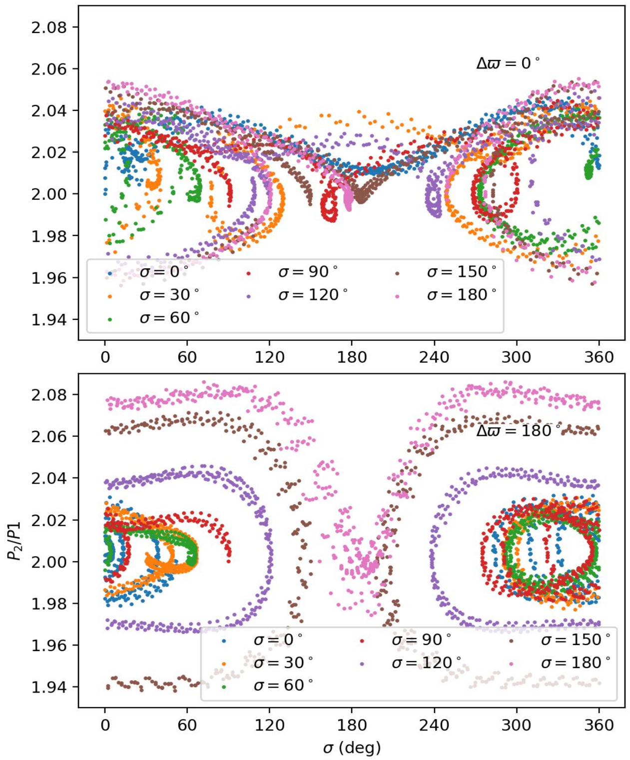
The actual system would only be resonant if $\Delta\varpi \approx 180^{\circ}$.





Results: HD27894

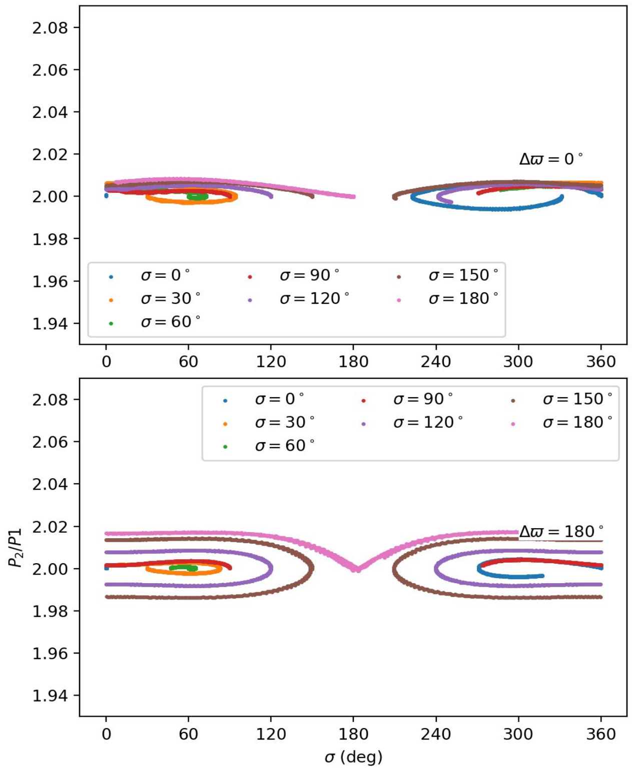
Comparison between the actual HD27894 system (left) and a fictitious HD27894 system, where the masses of both planets have been re-scaled by a factor of 20 (right).



Top and bottom panels show initial conditions for Δϖ = 0º, 180º, respectively.

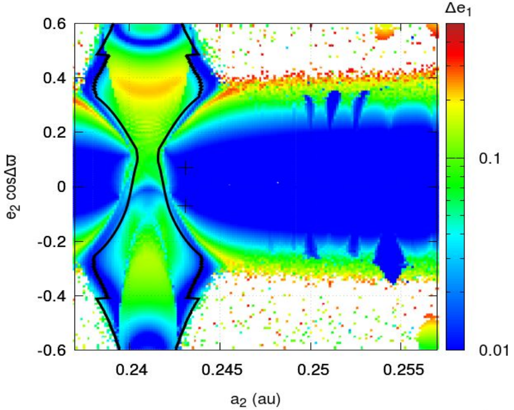
Orbits correspond to total integration time of 10 years (left) and 20 years (right).

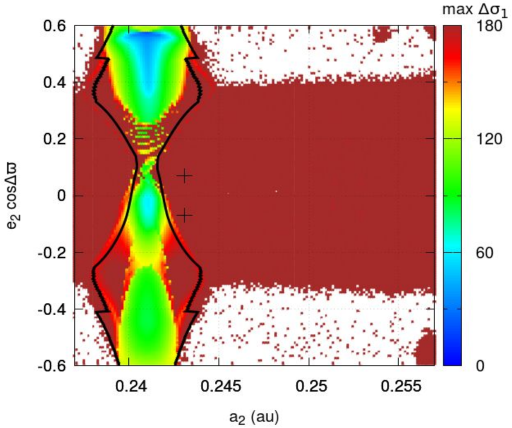
Short period variations with large amplitude destroy the libration region, especially in the top-left panel.



Results: K2-24

The K2-24 system has two planets of similar mass.
We compare the the behavior of the inner planet (left) and the outer planet (right).





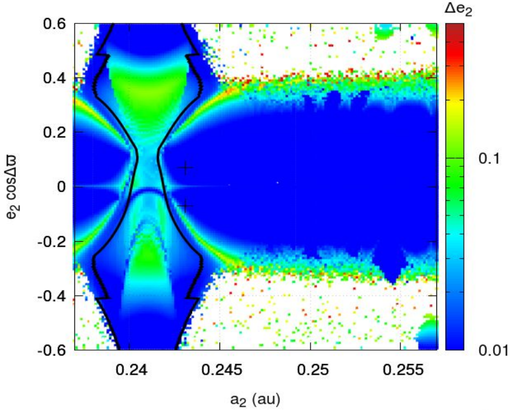
Black lines represent the semi-analytic separatrix. Crosses represent the possible configurations of the actual system.

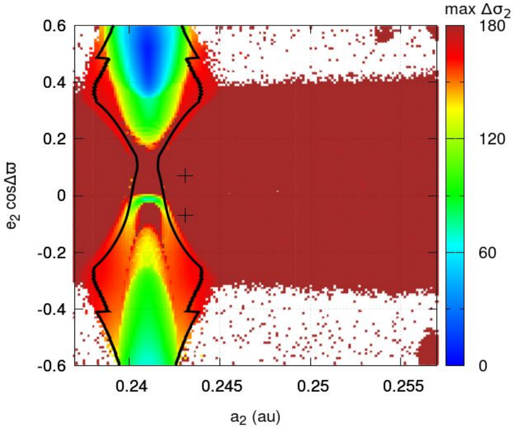
The maps for each planet have been constructed assuming that the other planet is fixed at its actual orbit.

The maps have been constructed for a fixed value of $\sigma = 60°$.

In spite of the small eccentricities of both planets, the resonant portrait differs significantly from the classical RCRBP (V-shape).

In both cases, librations are only observed at very high eccentricities. The actual system is not resonant.





Conclusions

- We are able to validate results from the semi-analytical model of Gallardo et al. (2021), that show that the family of stable resonant points bifurcate from symmetric to asymmetric librations, depending on the planets' masses and eccentricities.
- The semi-analytic separatrices fit very well with the predictions of the dynamical maps.
- For mass ratios $m2/m1 \gg 1$, increasing the eccentricity of the perturber destroys the resonant librations of the perturbed at low eccentricities.
- With the current orbital parameters, the TOI-216 system is captured in the 2/1 MMR, independently of the values of $\Delta\varpi$.
- For mass ratios $m2/m1 \ll 1$, the system may show asymmetric librations, and dynamical maps constructed at a fixed value of $\sigma 2$ do not provide the right portrait of the resonant phase space.
- In this case, the libration amplitude strongly depends on the value of $\Delta\varpi$
- The HD27894 system would be captured in a 2/1 resonant libration state only if $\Delta\varpi \approx 180º$.
- With the current orbital parameters, the K2-24 system is not captured in the 2/1 MMR, independently of the values of $\Delta\varpi$.