CHEOPS
CHARACTERISING EXOPLANET SATELLITE

UNIVERSITÉ DE GENÈVE

TOI-178

Discovery and characterisation of the system

A. Leleu, Y. Alibert, N. Hara, M. Hooton, T. Wilson and many others!

CHEOPS WORKSHOP VI - 2022

PlanetS

Credit ESO : L. Calcada

Many contributing authors and consortia

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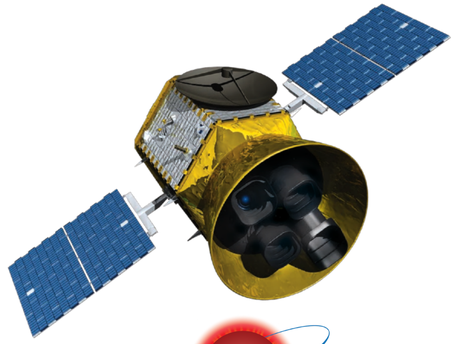
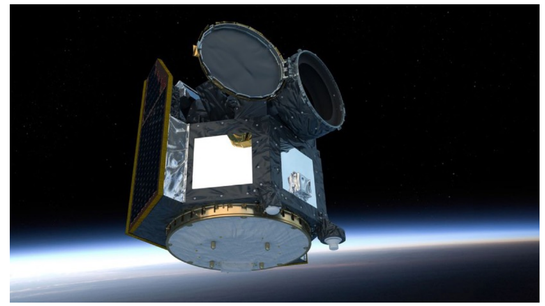


TESS



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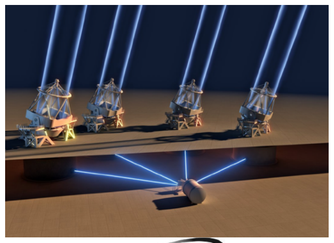


espresso

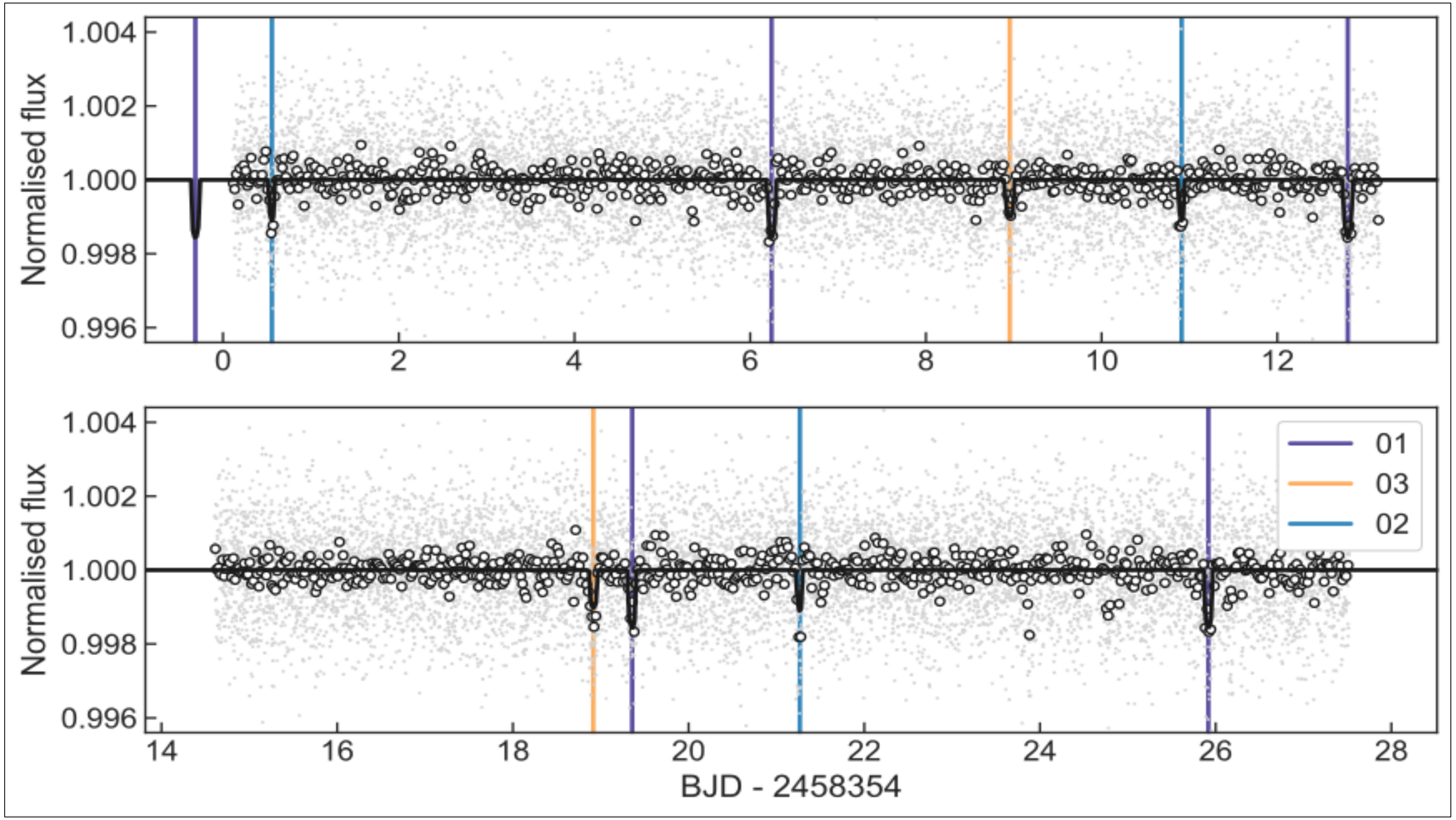
SPECULOOS
Search for habitable Planets EClipsing ULtra-cOOl Stars

NGTS

TESS pipeline's solution for TOI-178 - TESS sector 2

Identical solution favoured in Leleu (2019+)

Parameter	Value
Star (TOI-178)	
m_0 (M_{sun})	0.643 ± 0.075
R_0 (R_{sun})	0.70 ± 0.15
Planet 1 (TOI-178.02)	
P_1 (day)	10.3542 ± 0.0032
T_1 (BTJD)	1354.5522 ± 0.0041
R_1 (R_e)	3.7 ± 1.5
Planet 2 (TOI-178.03)	
P_2 (day)	9.9559 ± 0.0051
T_2 (BTJD)	1362.9533 ± 0.0035
R_2 (R_e)	2.3 ± 2.7
Planet 3 (TOI-178.01)	
P_3 (day)	6.5581 ± 0.0013
T_3 (BTJD)	1360.2423 ± 0.0024
R_3 (R_e)	2.8 ± 1.1



Trojan exoplanets?

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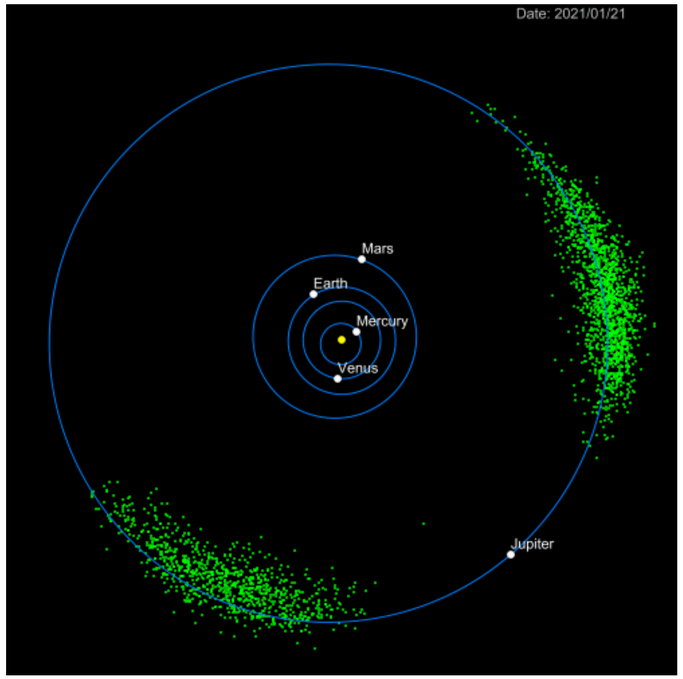
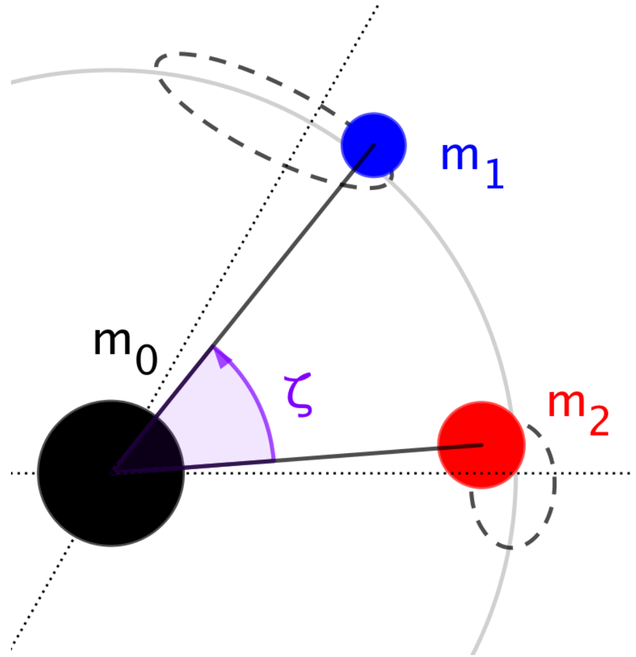
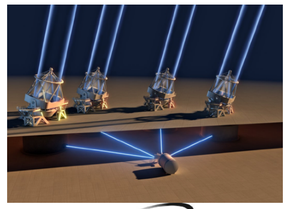




TOI-178 in Spring 2020

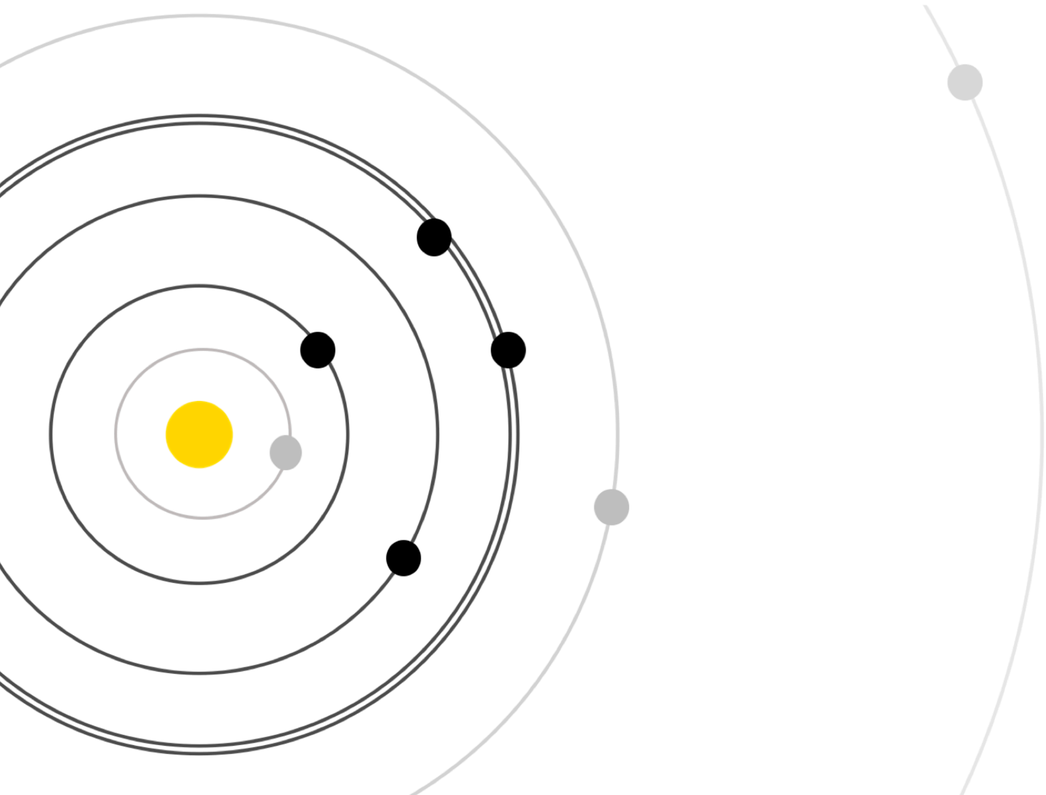
SPECULOOS
Search for habitable Planets EClipsing ULtra-cOOl Stars

NGTS



espresso

Close to a 2:1/3:2/1:1/3:2 resonant chain



Best fit (TESS+ESPRESSO) solution

Period [d]	Mass[Mearth] (ESPRESSO)	Radius[Rearth] (TESS)
1.91?		
3.24	4.2	1.6
6.55	3.7	2.7
10.18 (10.3 TESS instantaneous)	16.4	2.67
10.18 (9.96 TESS instantaneous)	13.7	2.32
15.28 ?	8.38	-
~43.6 ?	9.6	-

Hints in TESS + ESPRESSO

low density?

TESS + ESPRESSO

Only in ESPRESSO (activity residuals?)

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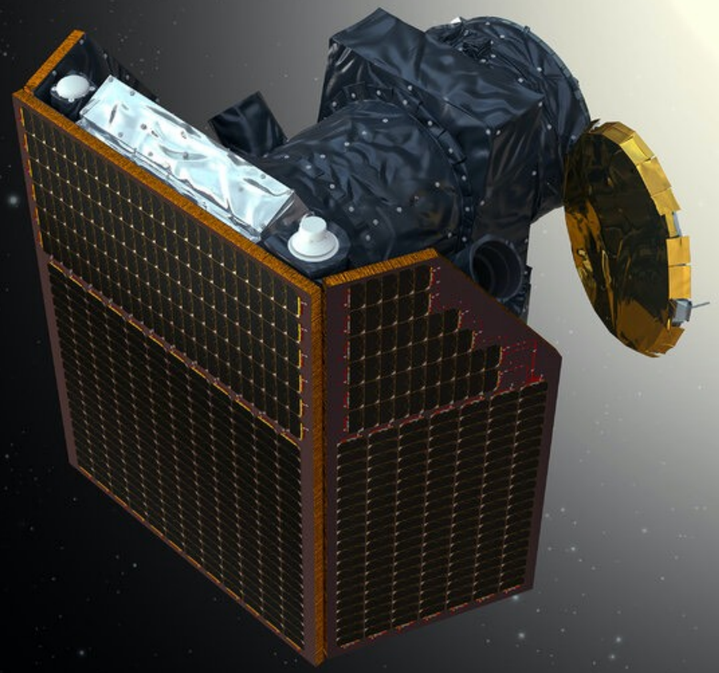
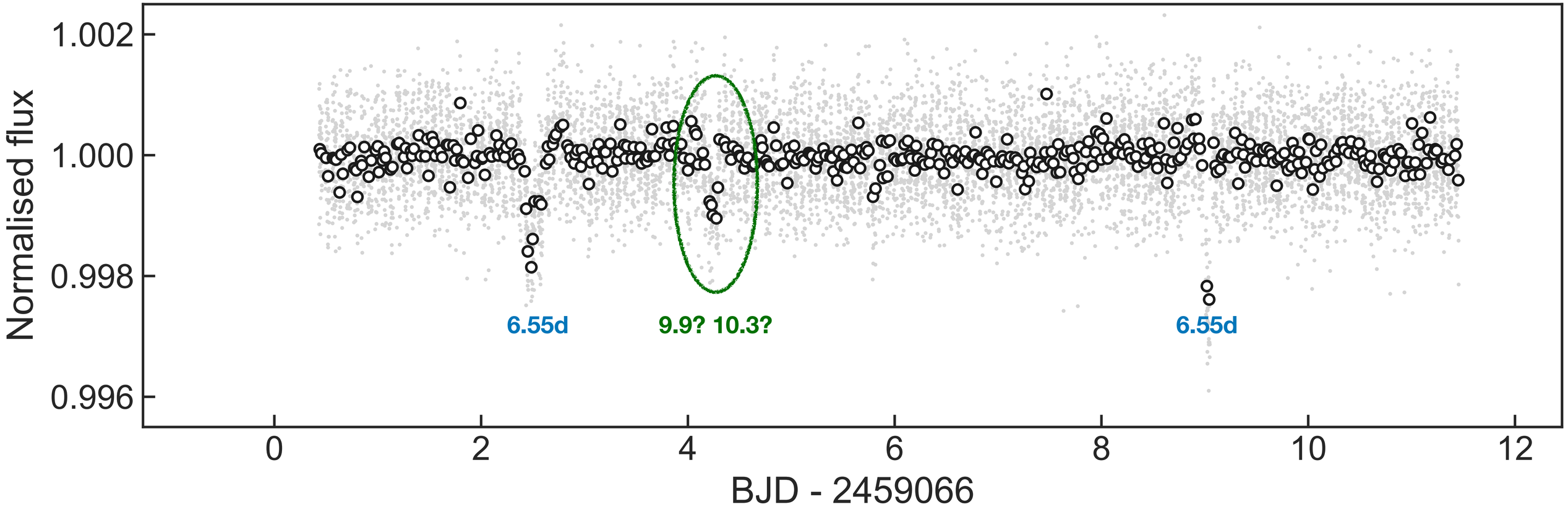
CHARACTERISING EXOPLANET SATELLITE

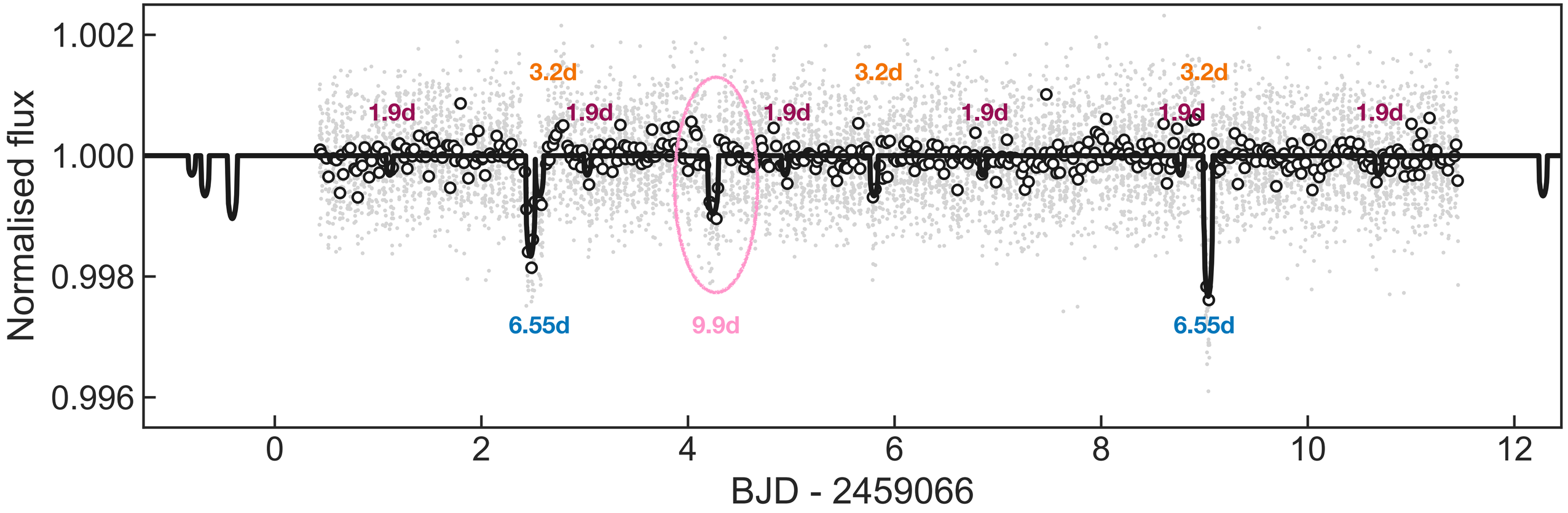


CHEOPS - August 2020

11d visit

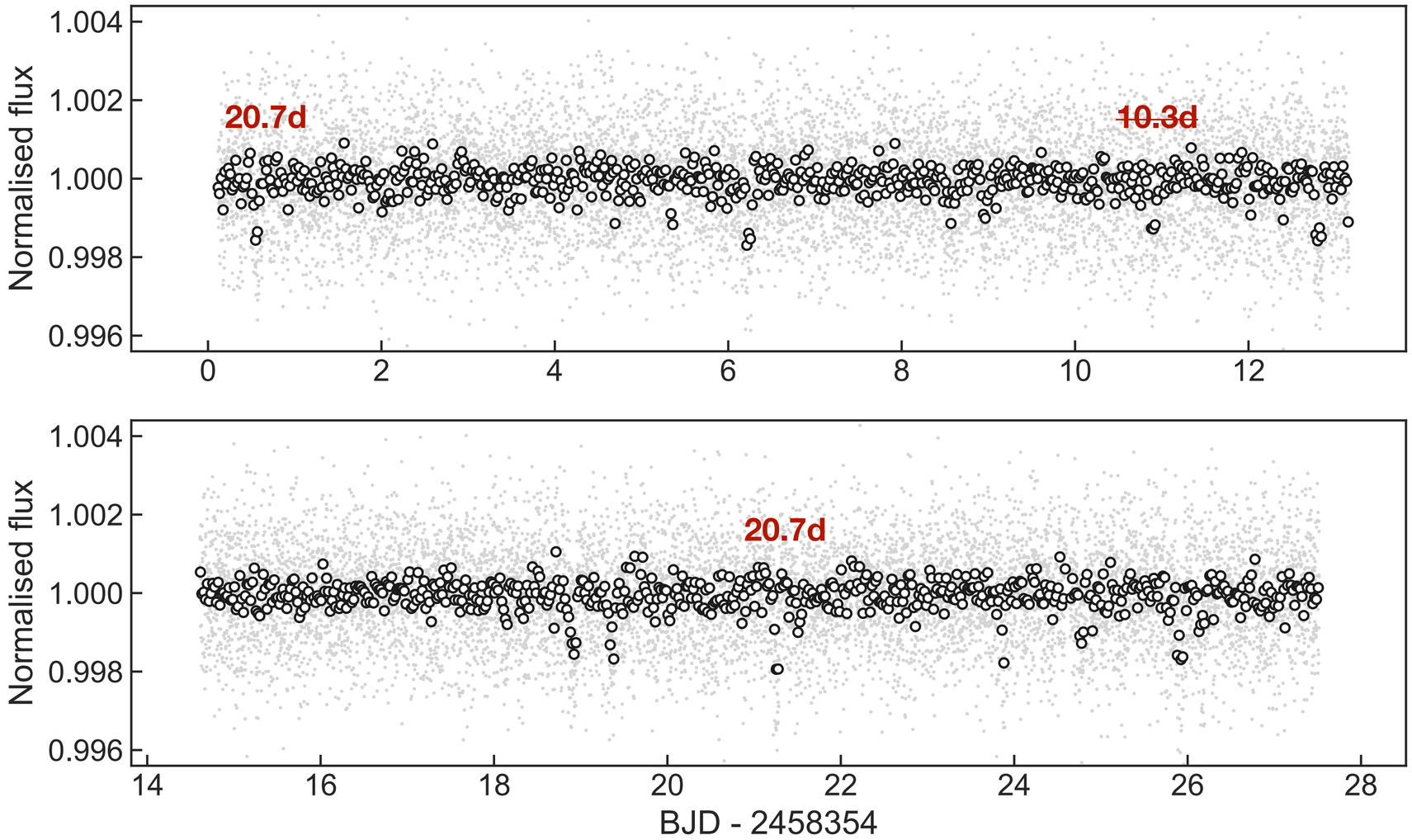


CHEOPS - August 2020



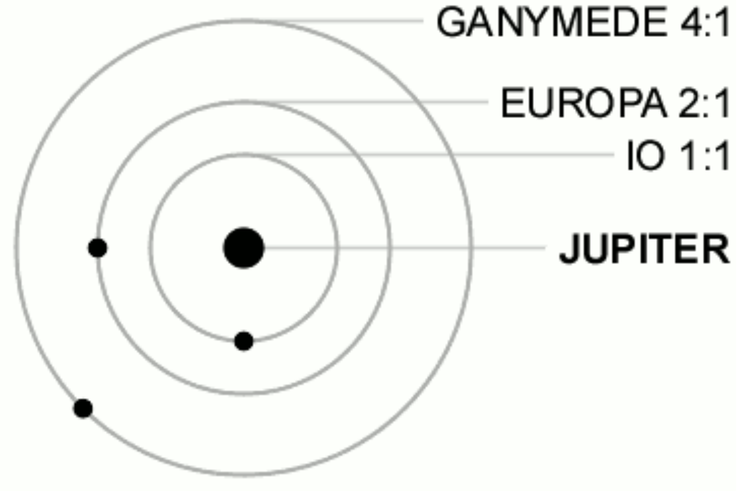
- After trial of 25 models, the favoured solution was : 1.9d, 3.2d, 6.5d, 9.9d and 20.7d

TESS sector 2

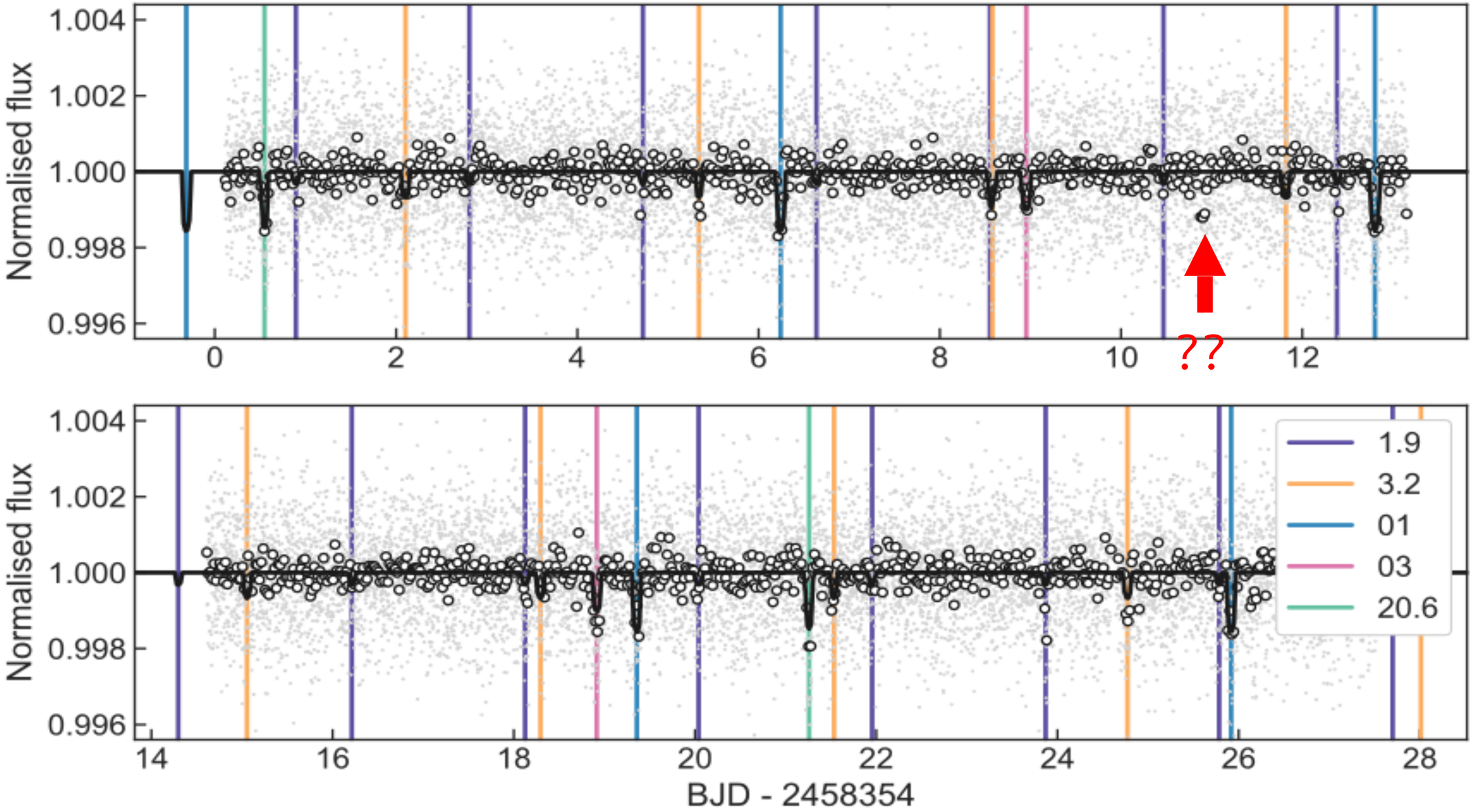


Chain of Laplace resonances

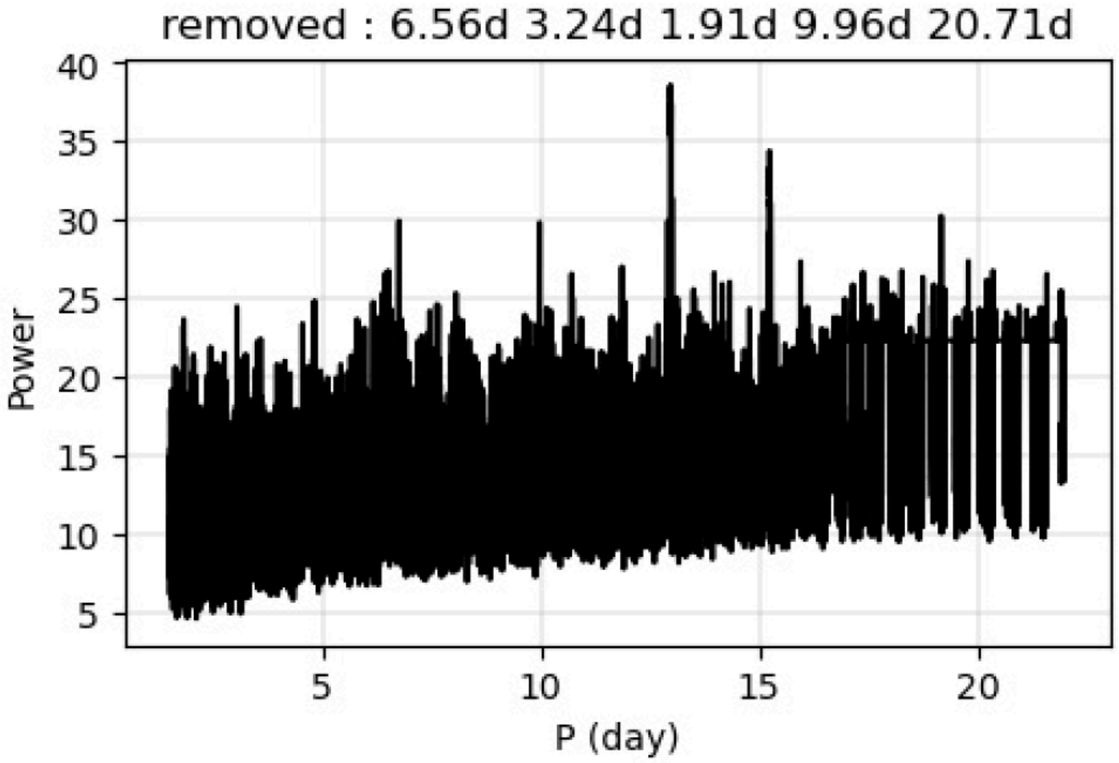
- Orbital periods of 1.9d, 3.23d, 6.55d, 9.9d and 20.7d
- Laplace relation : $(k+q)/P_{\text{mid}} = k/P_{\text{in}} + q/P_{\text{out}}$
- 18:9:6:3 resonant chain



Additional planet in the resonant chain?



BLS on the TESS+NGTS+CHEOPS residuals

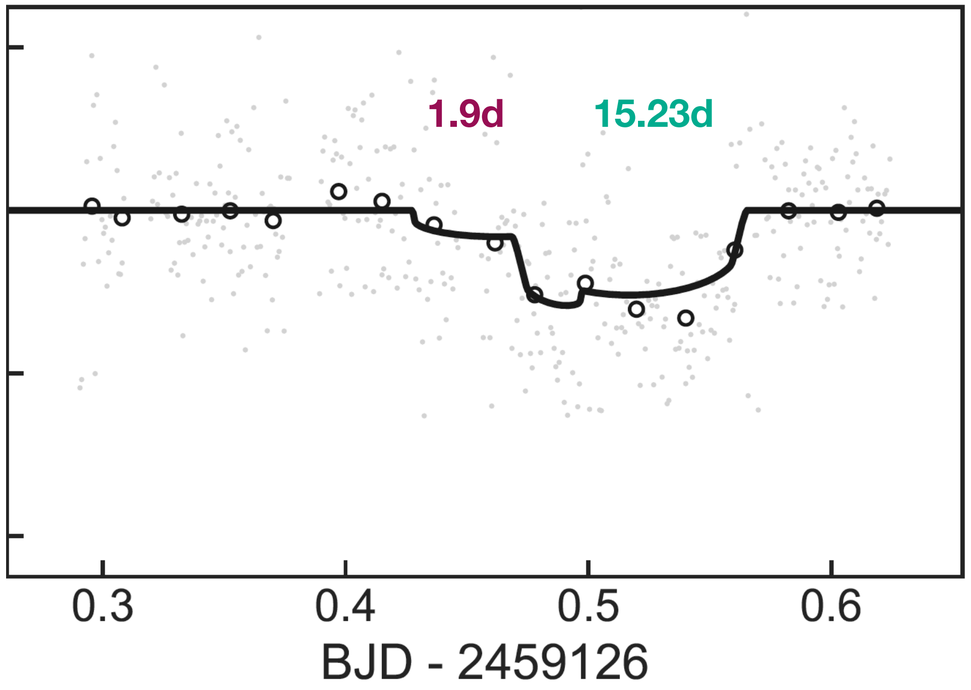


BLS shows peaks at ~12.9d and ~15.23d
With predicted transits uncertainties of ~1 day
due to a 2 year error propagation

Laplace resonance : $(k+q)/P_{\text{mid}} = k/P_{9.9} + q/P_{20.7}$
Yield two possible periods: P = 13.4527 d, or P = 15.2318 d

Observation planed the 3rd of October 2020

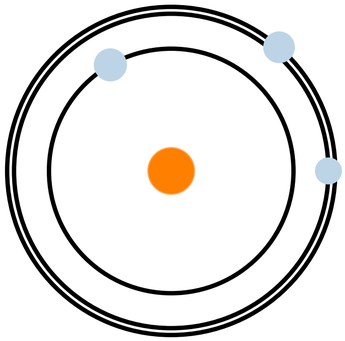
Confirmation of the 15.23d planet by CHEOPS



- Predicted period of **15.2318** d, confirmed period of **15.231915**d +/- 0.0001

Follow-up effort required to solve the architecture

Co-orbital candidates
(Leleu+ 2019)



SPECULOOS
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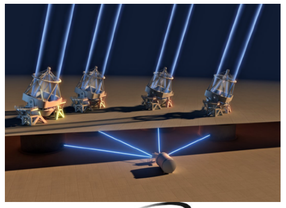
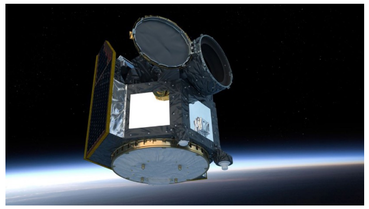


espresso



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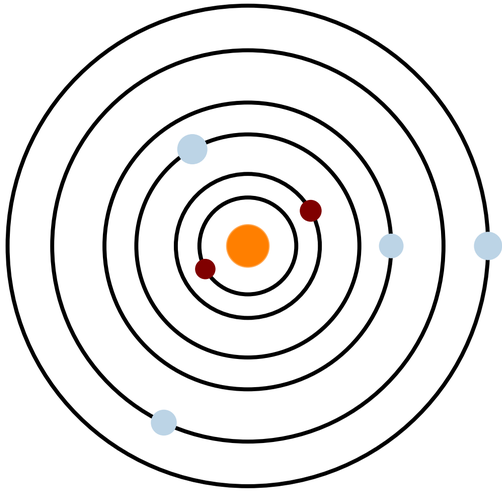
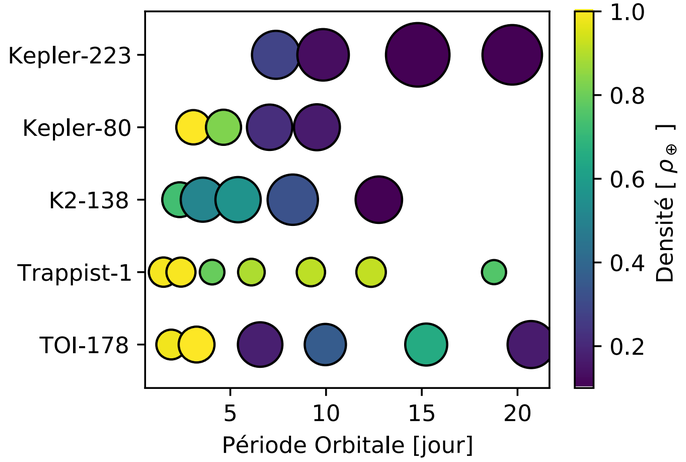
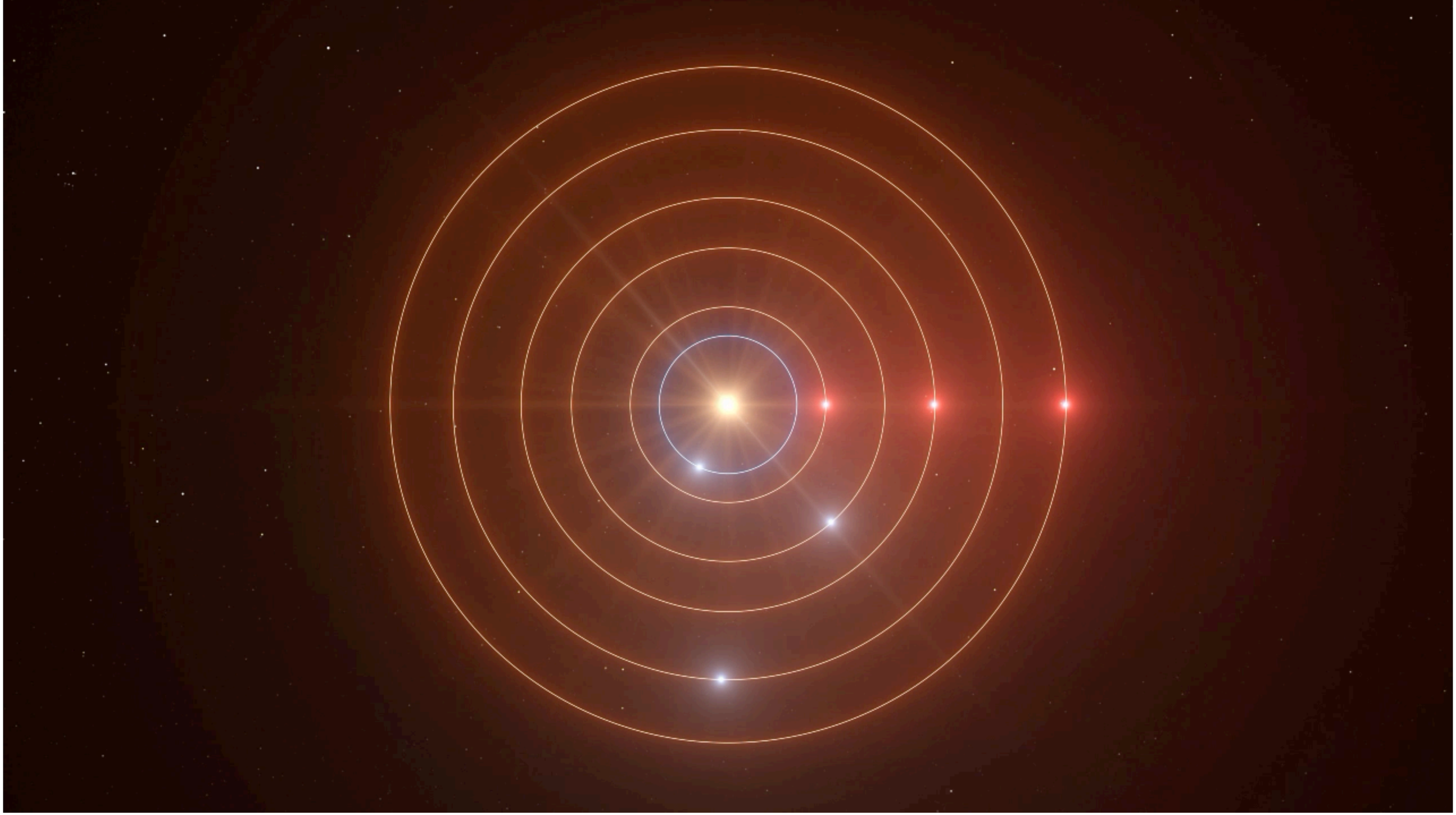
(11 continuous days
+ 2 x 6h)

6 planets (Leleu+ 2021)



Systems with chain of Laplace resonances

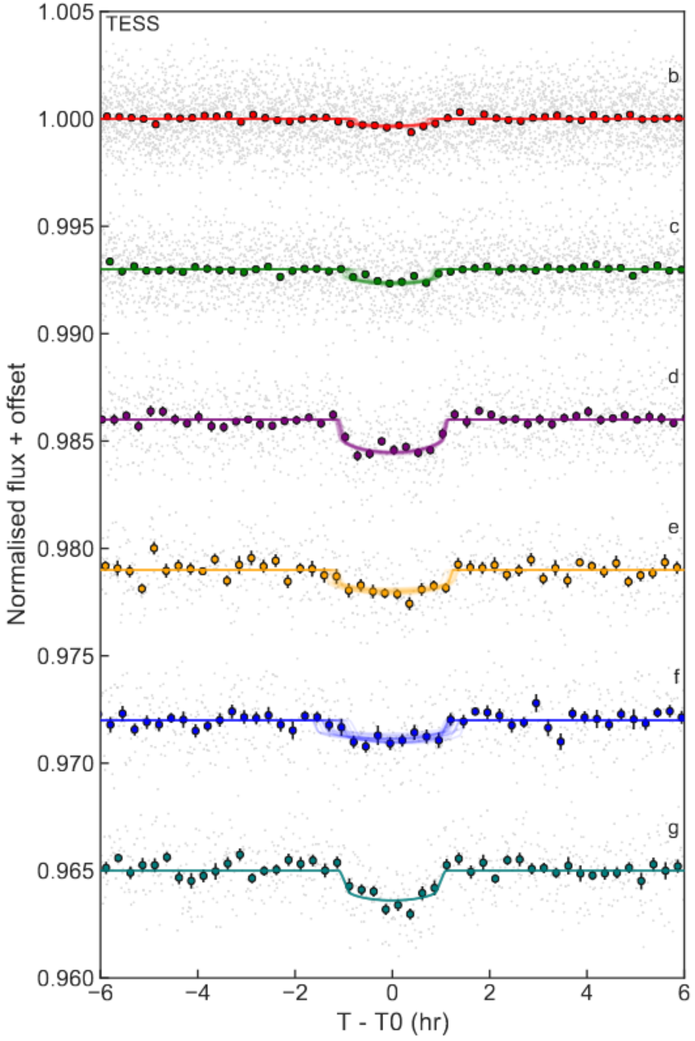


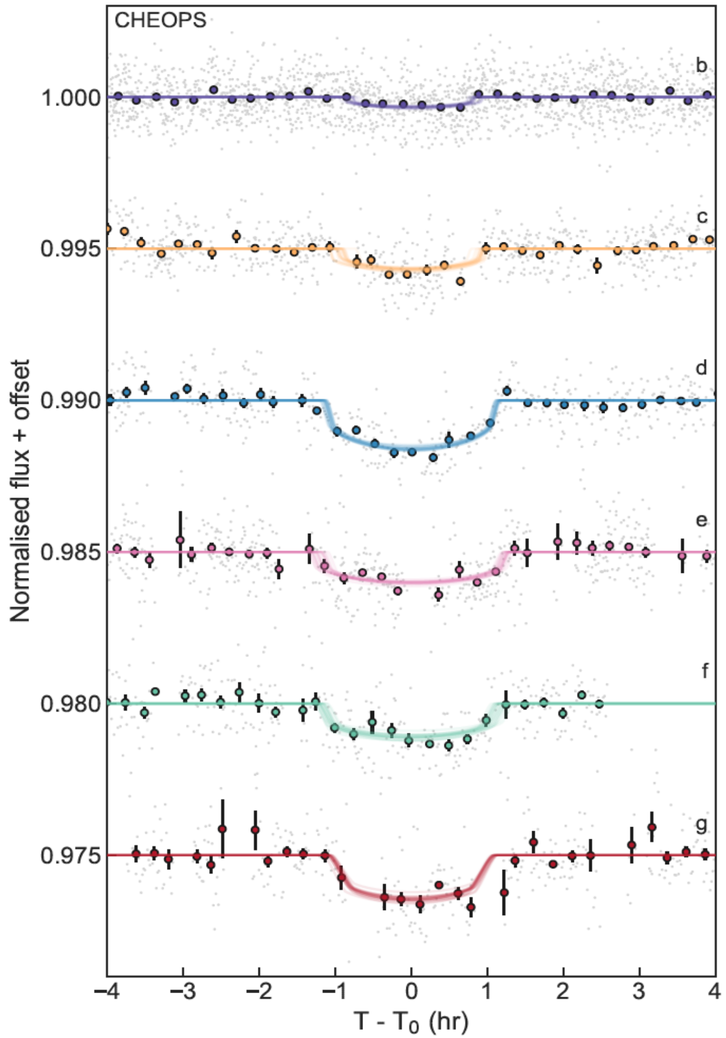


Credit: ESO/L. Calçada

Using CHEOPS to refine radii

Leleu et al (2021)

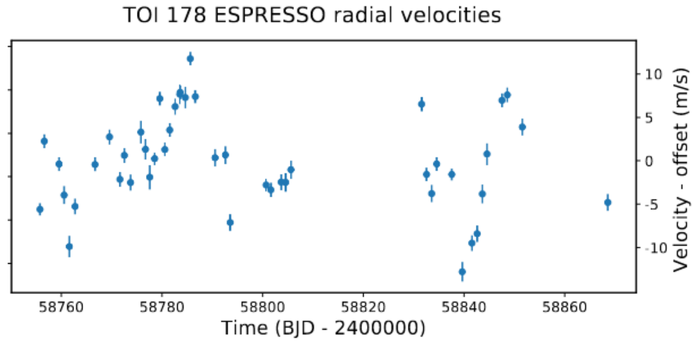


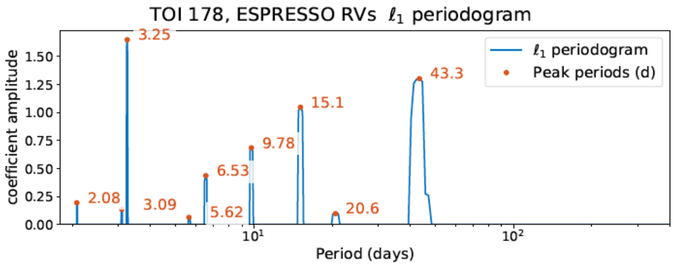


	$R_{\rm p}$ ($R_\oplus$)	$\Delta R_{\rm p}$ (%)
TOI-178 *b* ($P\sim1.91$ *d*) ($T_{\rm eq}\sim1040$ *K*)	$1.152^{+0.073}_{-0.070}$	6.1
TOI-178 *c* ($P\sim3.24$ *d*) ($T_{\rm eq}\sim873$ *K*)	$1.669^{+0.114}_{-0.099}$	5.9
TOI-178 *d* ($P\sim6.56$ *d*) ($T_{\rm eq}\sim690$ *K*)	$2.572^{+0.075}_{-0.078}$	2.9
TOI-178 *e* ($P\sim9.96$ *d*) ($T_{\rm eq}\sim600$ *K*)	$2.207^{+0.088}_{-0.090}$	4.0
TOI-178 *f* ($P\sim15.23$ *d*) ($T_{\rm eq}\sim521$ *K*)	$2.287^{+0.108}_{-0.110}$	4.7
TOI-178 *g* ($P\sim20.71$ *d*) ($T_{\rm eq}\sim470$ *K*)	$2.870^{+0.140}_{-0.130}$	4.5

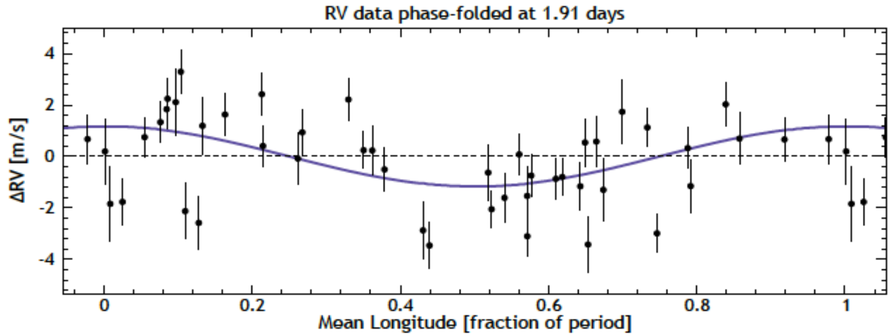
Using ESPRESSO to estimate masses

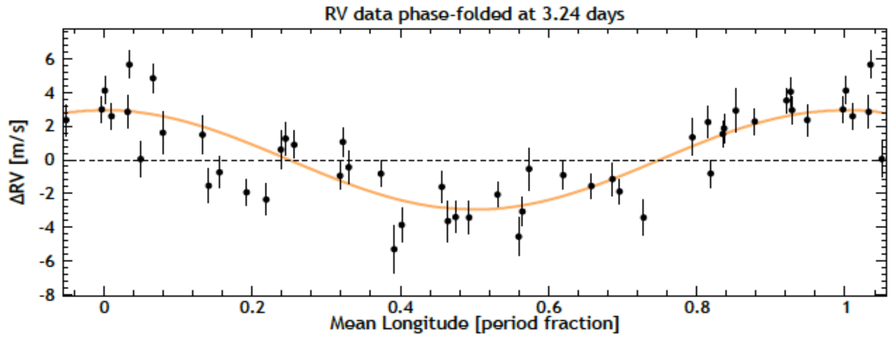
Leleu et al (2021)

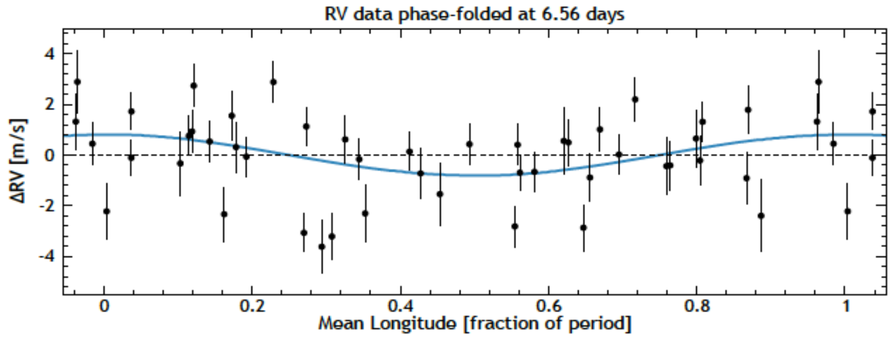


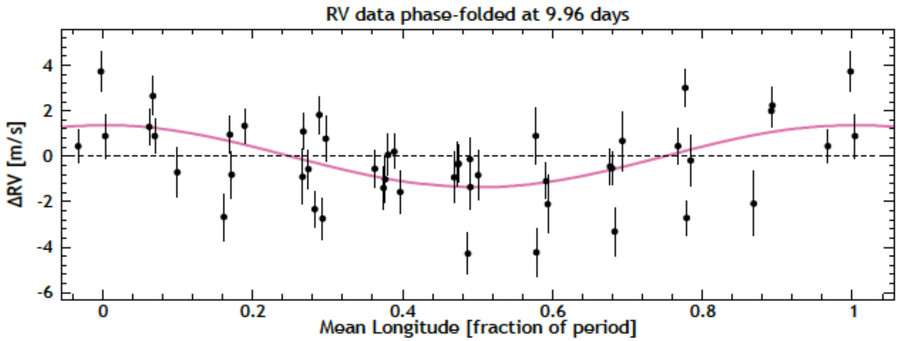


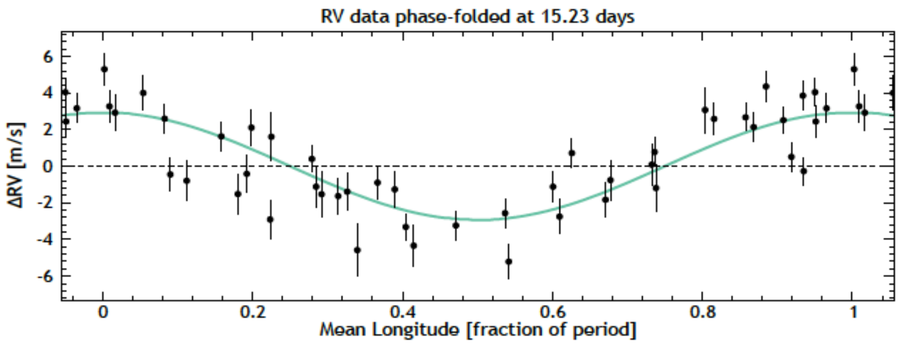
only ~40 RV measurements
but ephemerides constrains
from transits

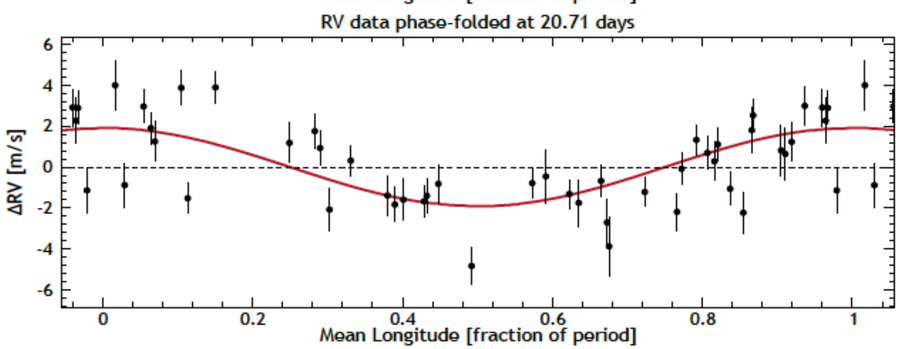






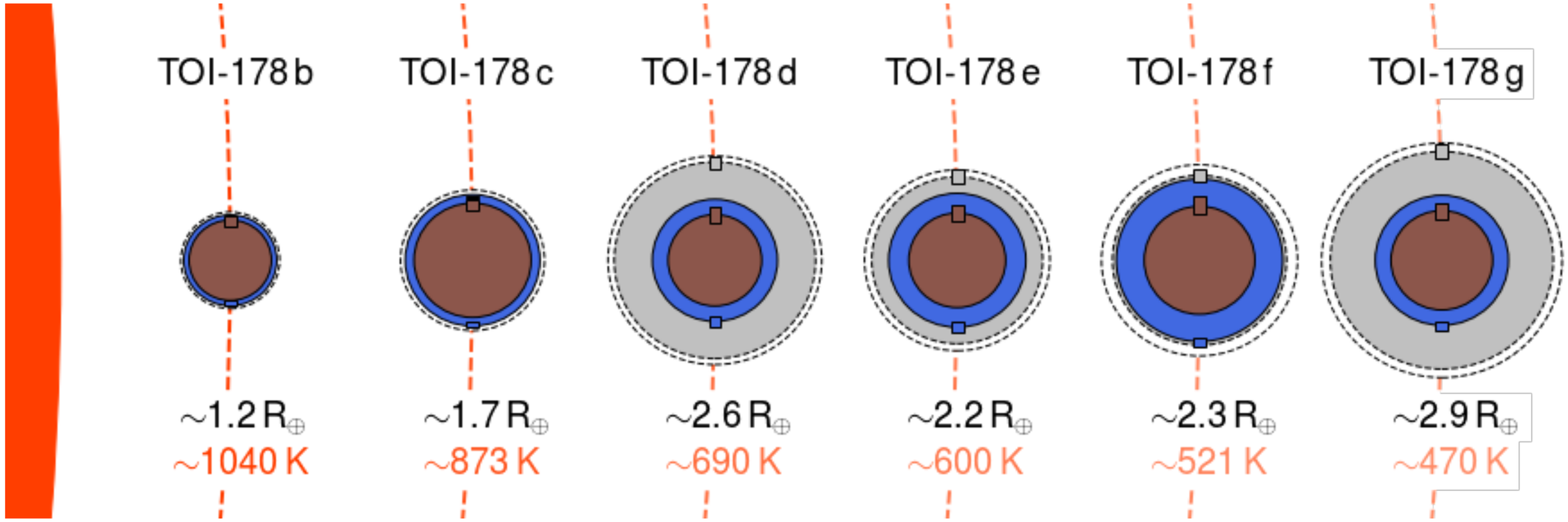






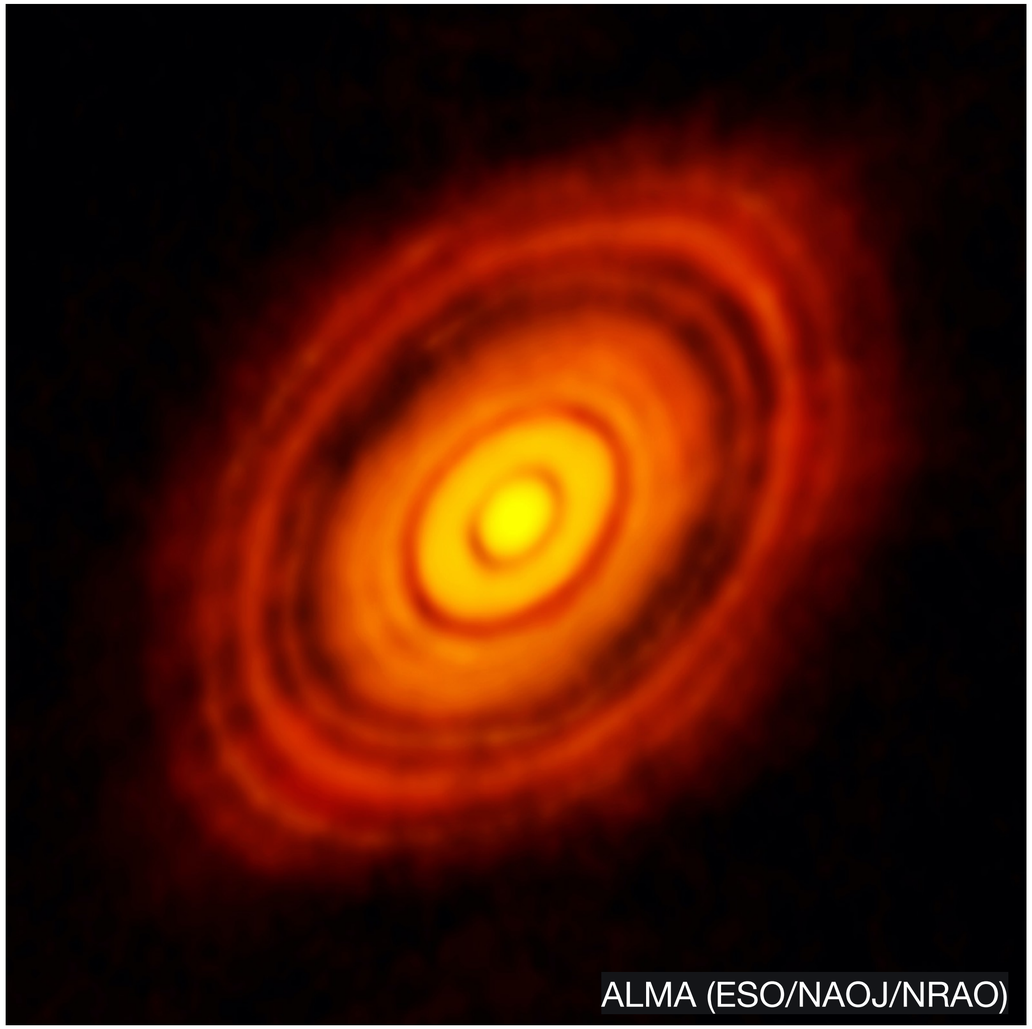
Combining the *CHEOPS*+*TESS* radii with ESPRESSO masses show large density variations

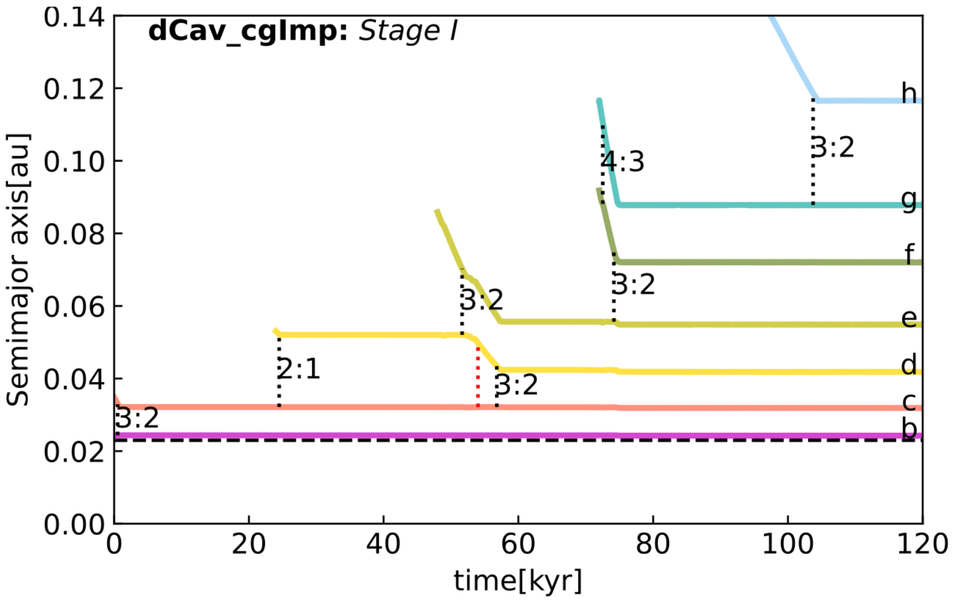
Leleu et al (2021)



Chain of resonances as witness of the early stages of planet formation.

Formation of long resonant chains



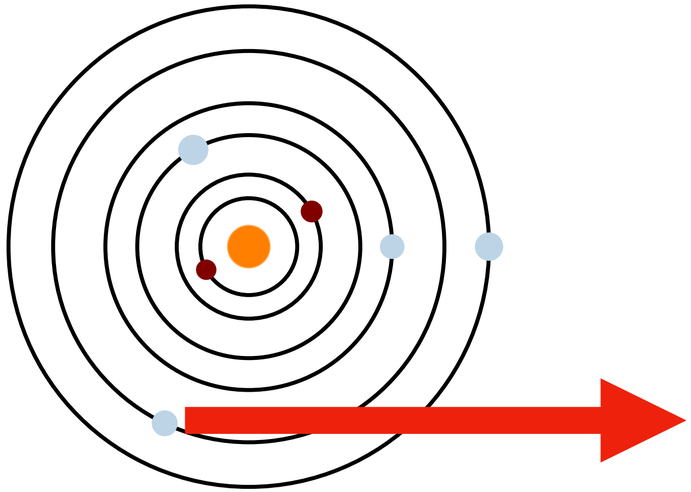


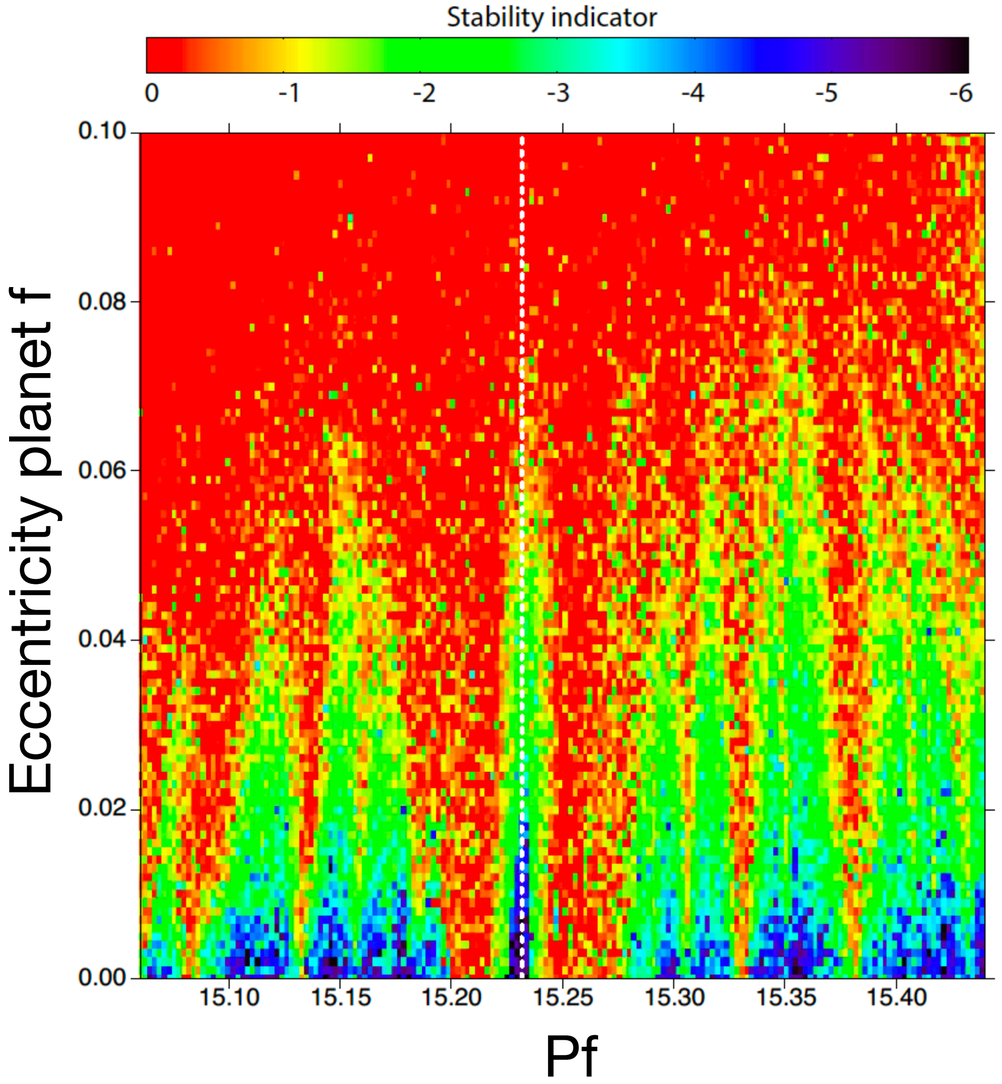
Formation
of Trappist-1
(Hang & Ormel 2021)

Capture in 2-body MMRs

$$(k+q)/P_{\text{out}} = k/P_{\text{in}}$$

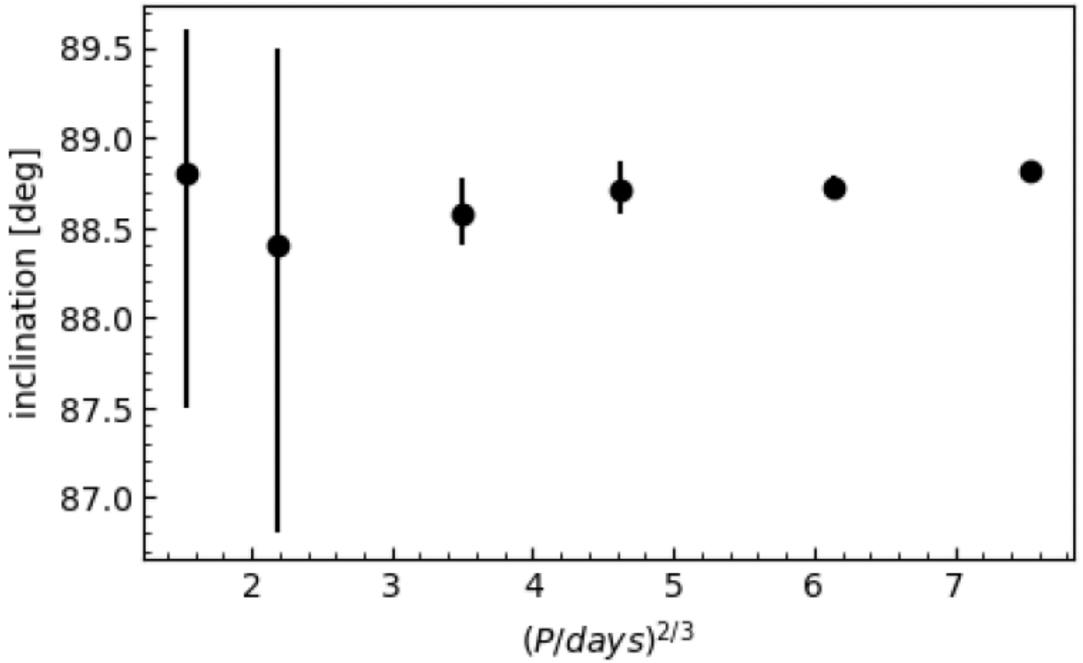
Laplace resonant chain - a fragile configuration

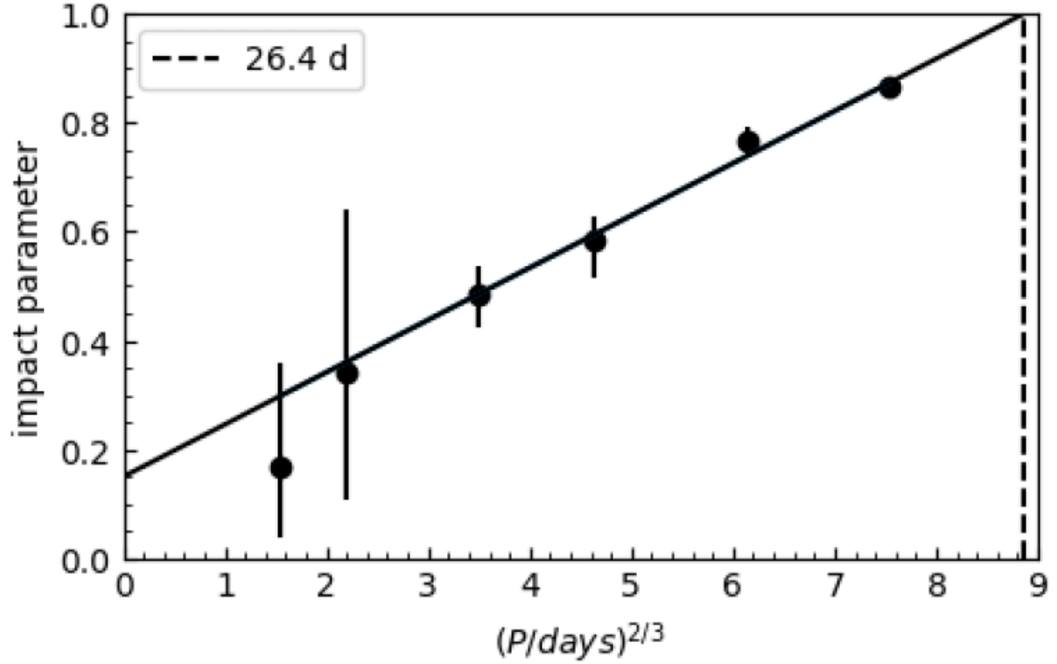




Planet f (15.2d) of TOI178
Leleu et al (2021)

TOI178 - A very flat system

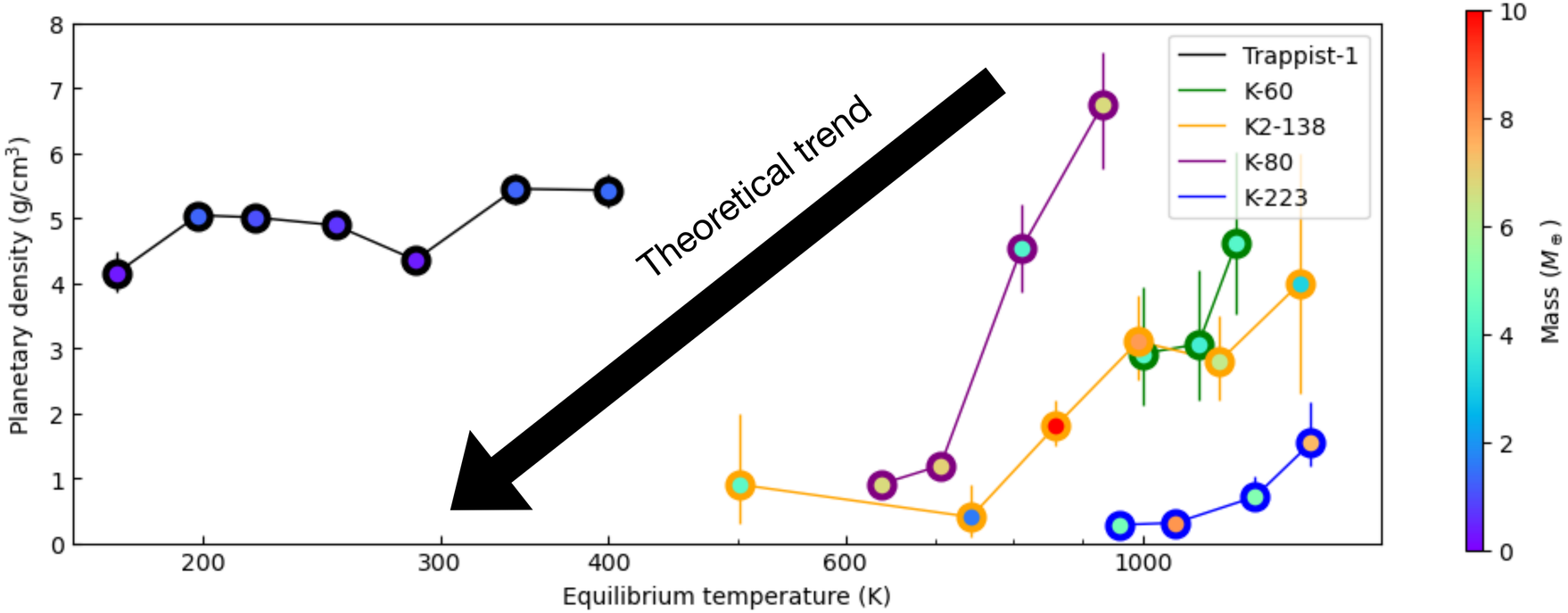


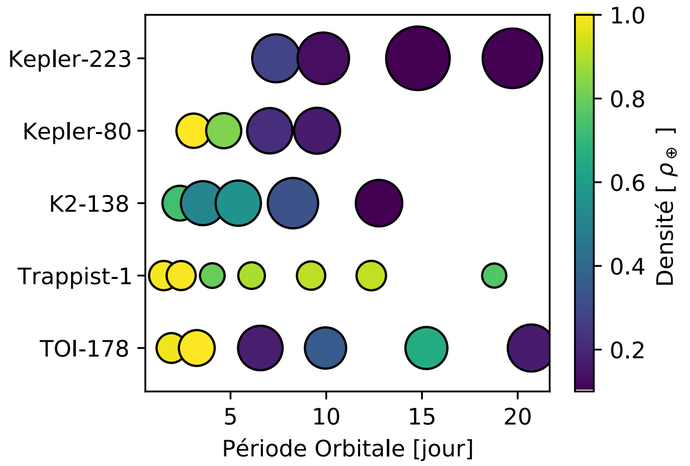


Similar result for Trappist-1 (Agol+ 2021)

Density repartition in the systems

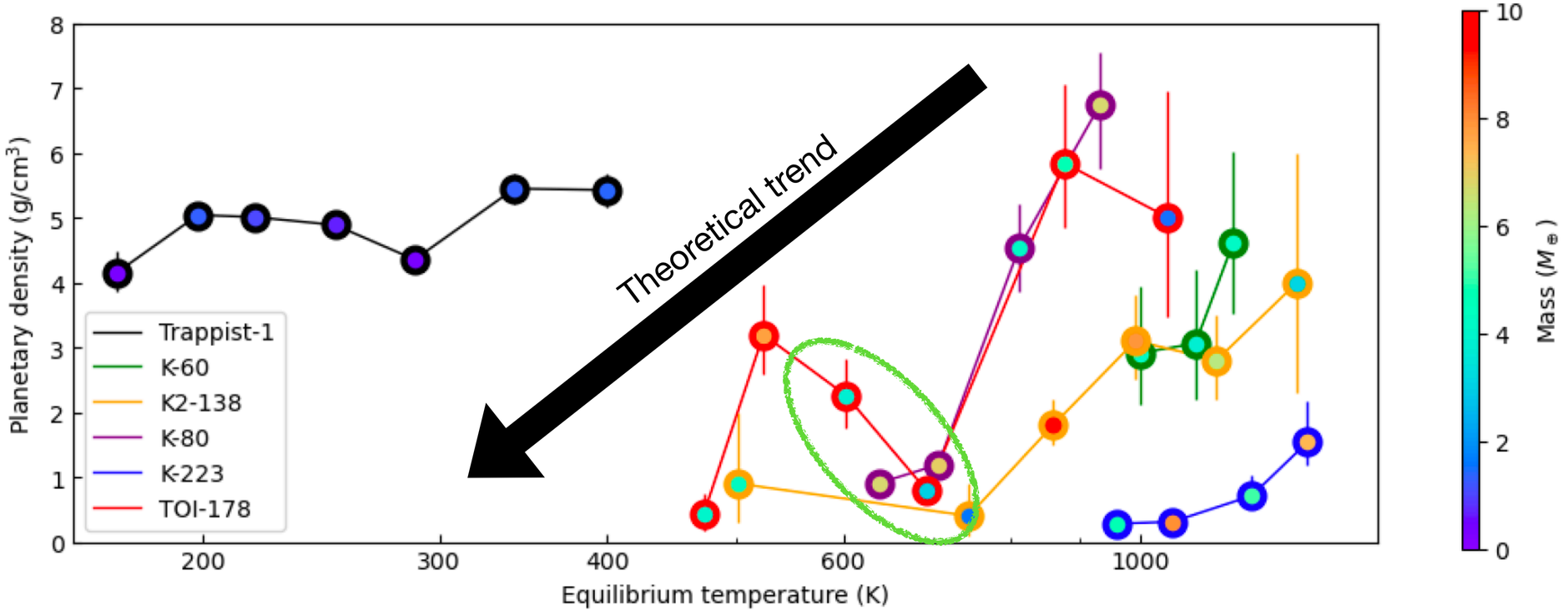
comparaison to other systems in Laplace resonant chain



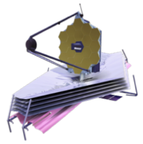


Large density variations

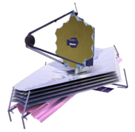
comparaison to other systems in Laplace resonant chain



- Large density variations at odds with the fragile ordered architecture.



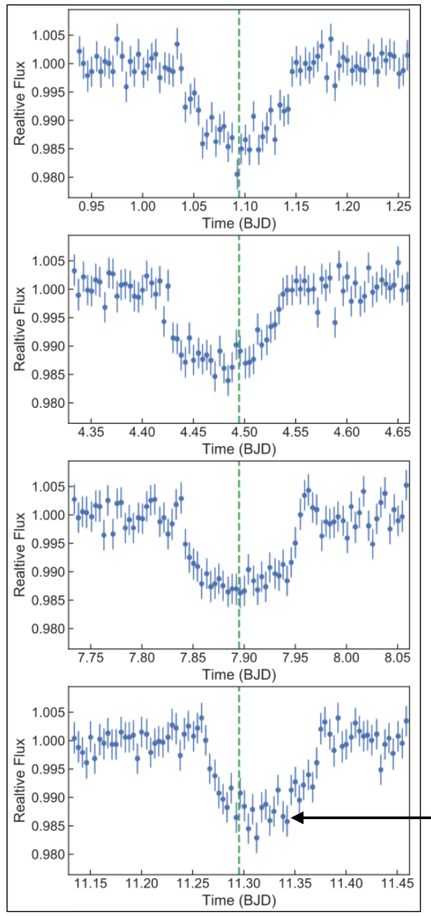
Selected for JWST GO Cycle 1 observations of TOI178 b, d and g; PI: Hooton



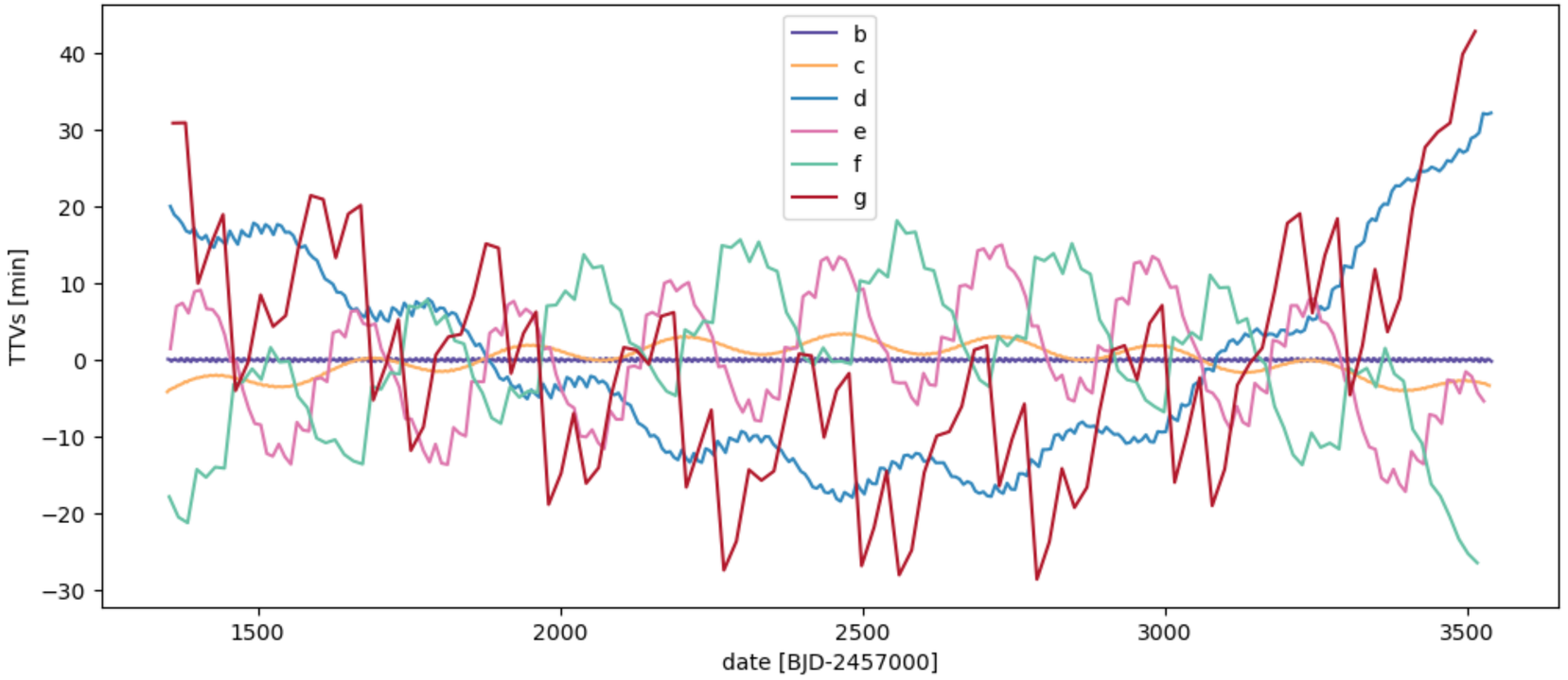
The resonant architecture of TOI-178

Transit Timing Variations - TOI178

transit timing for unperturbed planet



shift due to planet-planet interactions



Kepler-223 (Mills+ 2016)

Table 1 | Kepler-223 system parameters

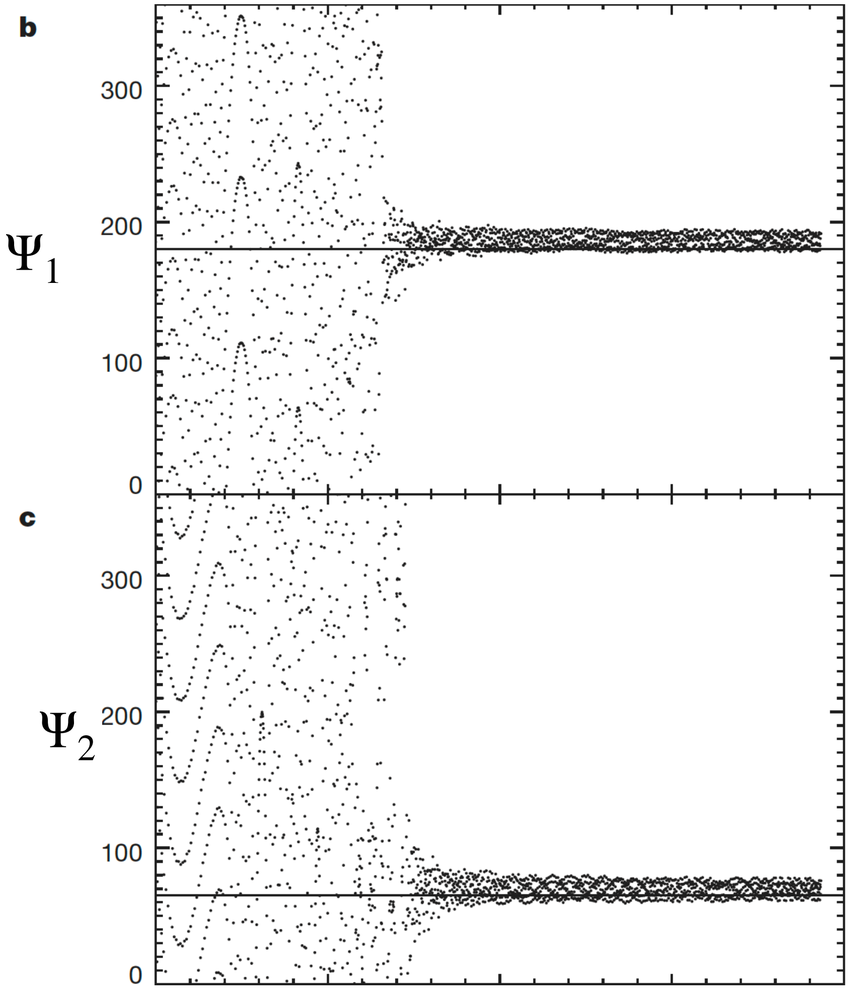
Parameter name	DEMCMC result			
Spectroscopic stellar mass, $M_\star$ ($M_\odot$)	$1.125^{+0.094}_{-0.073}$			
Stellar radius, $R_\star$ ($R_\odot$)	$1.72^{+0.07}_{-0.14}$			
	Kepler-223 b	Kepler-223 c	Kepler-223 d	Kepler-223 e
Orbital period, P (d)	$7.38449^{+0.00022}_{-0.00022}$	$9.84564^{+0.00052}_{-0.00051}$	$14.78869^{+0.00030}_{-0.00027}$	$19.72567^{+0.00055}_{-0.00054}$
Eccentricity, e	$0.078^{+0.015}_{-0.017}$	$0.150^{+0.019}_{-0.051}$	$0.037^{+0.018}_{-0.017}$	$0.051^{+0.019}_{-0.019}$
Inclination, $\lvert i - 90\rvert$ (°)	$0.0^{+1.8}$	$0.0^{+1.3}$	$2.06^{+0.26}_{-0.32}$	$2.00^{+0.21}_{-0.27}$
Mass, M ($M_\oplus$)	$7.4^{+1.3}_{-1.1}$	$5.1^{+1.7}_{-1.1}$	$8.0^{+1.5}_{-1.3}$	$4.8^{+1.4}_{-1.2}$
Radius, R ($R_\oplus$)	$2.99^{+0.18}_{-0.27}$	$3.44^{+0.20}_{-0.30}$	$5.24^{+0.26}_{-0.45}$	$4.60^{+0.27}_{-0.41}$
Density, ρ (g cm^{-3})	$1.54^{+0.63}_{-0.35}$	$0.71^{+0.33}_{-0.20}$	$0.31^{+0.12}_{-0.07}$	$0.28^{+0.12}_{-0.08}$

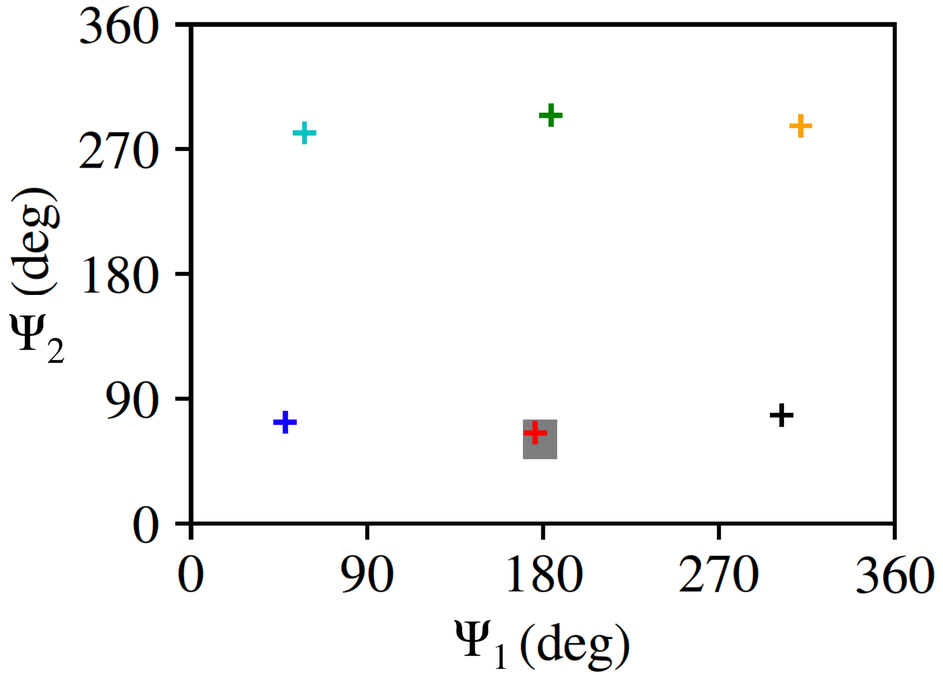
Laplace angles - Kepler-223 (Mills+ 2016)

Mean Longitude : $\lambda_j = \lambda_{j,0} + t\frac{2\pi}{P_j}$

Laplace Relation : $(k+q)/P_{\text{mid}} \sim k/P_{\text{in}} + q/P_{\text{out}}$

Laplace Angles : $\Psi_i = p\lambda_i - (p+q)\lambda_{i+1} + q\lambda_{i+2}$

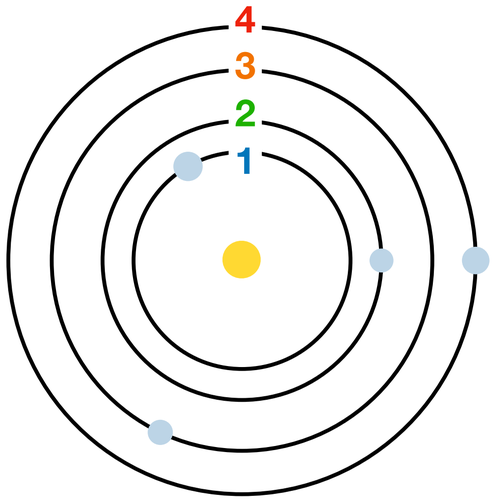




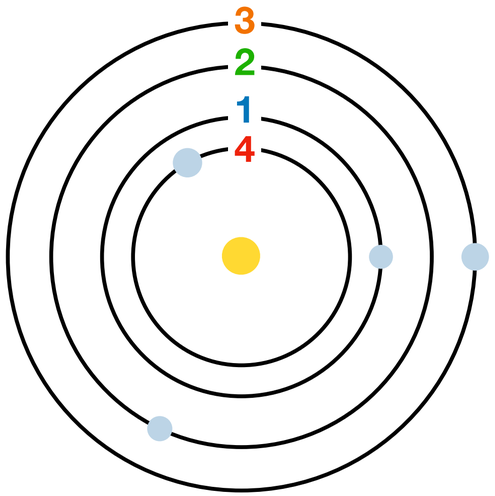
6 possible equilibria (Delisle 2017)

Capture order - Kepler-223 (Delisle 2017)

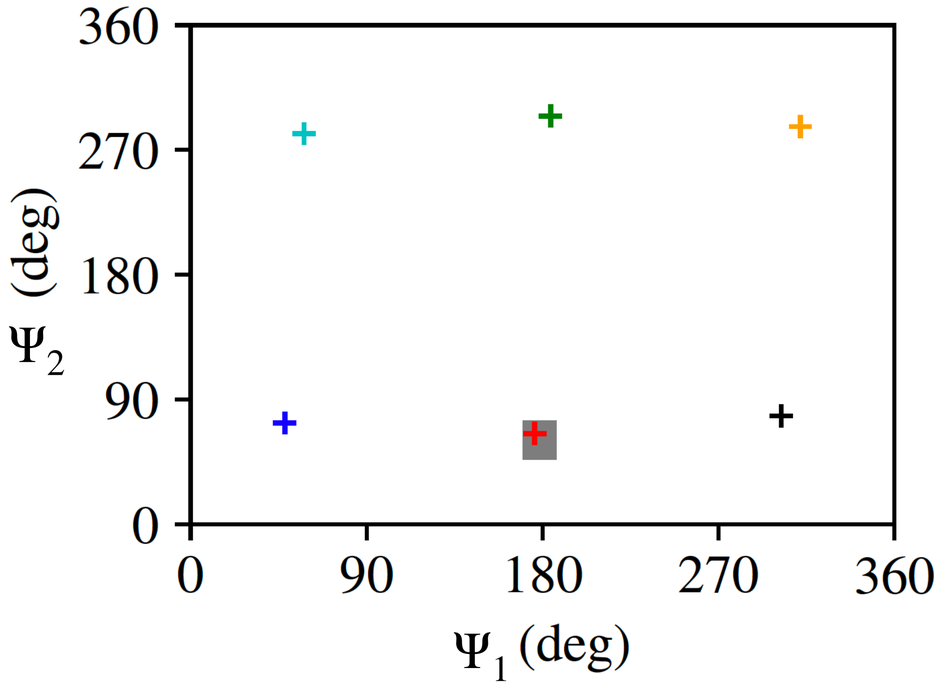
Laplace Angles : $\Psi_i = p\lambda_i - (p+q)\lambda_{i+1} + q\lambda_{i+2}$



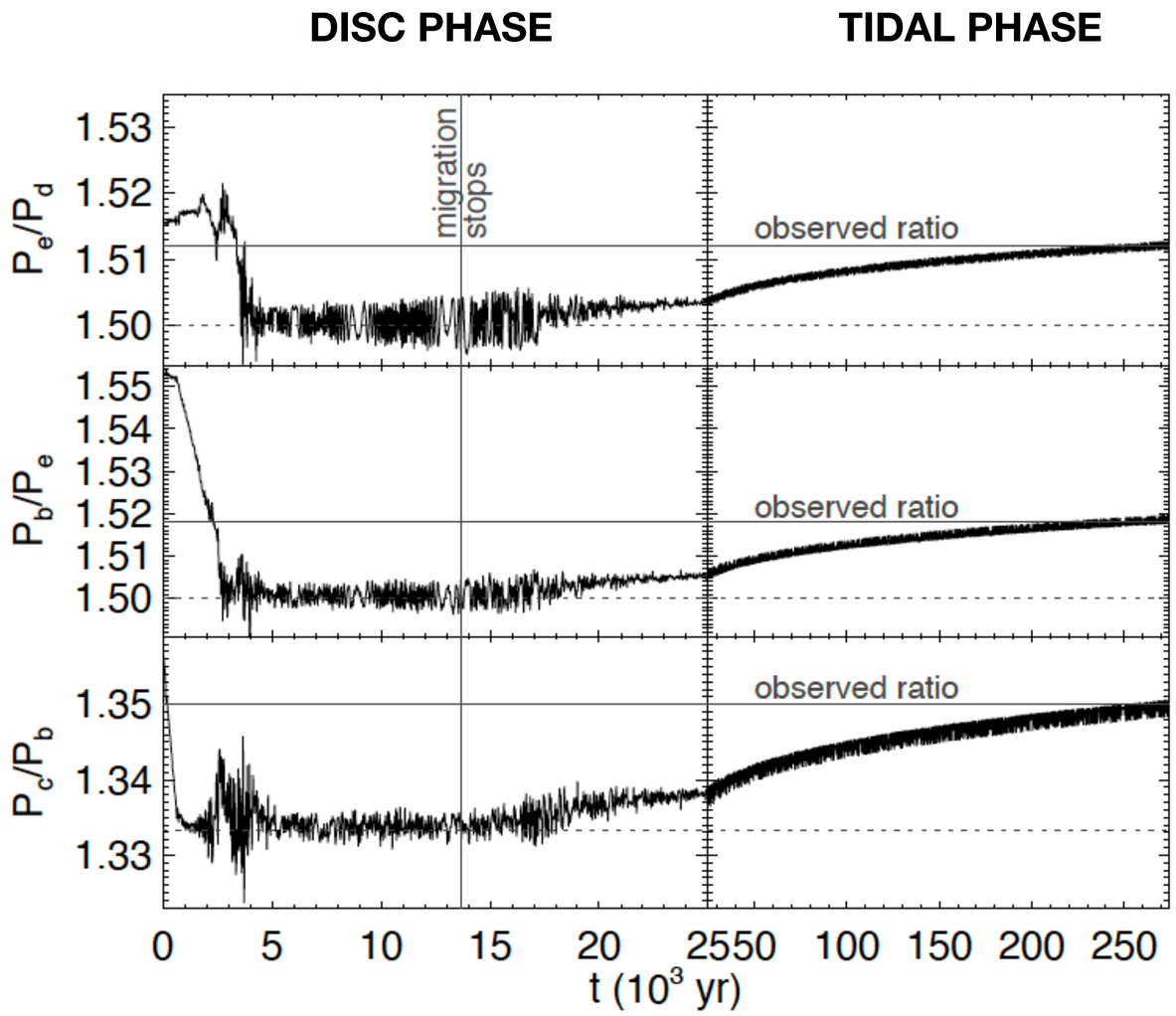
Equilibrium probability: 4%



Equilibrium probability: 52%



Formation of long resonant chains - Kepler-80 (MacDonald+ 2016)



During tidal phase, the pairs move away from 2-body MMRs

$$(k+q)/P_{\text{out}} = k/P_{\text{in}}$$

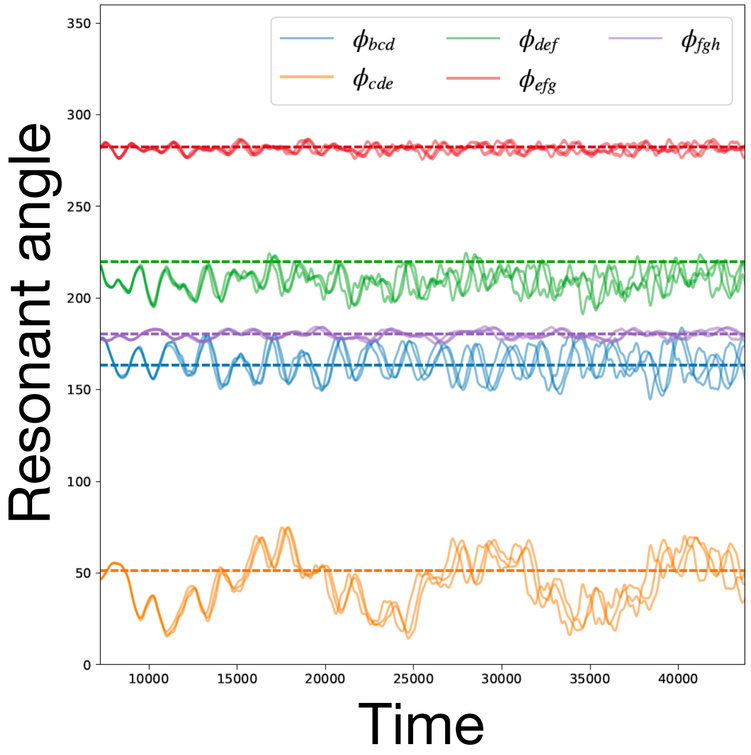
But the 3-body MMRs (Laplace) hold

$$(k+q)/P_{\text{mid}} = k/P_{\text{in}} + q/P_{\text{out}}$$

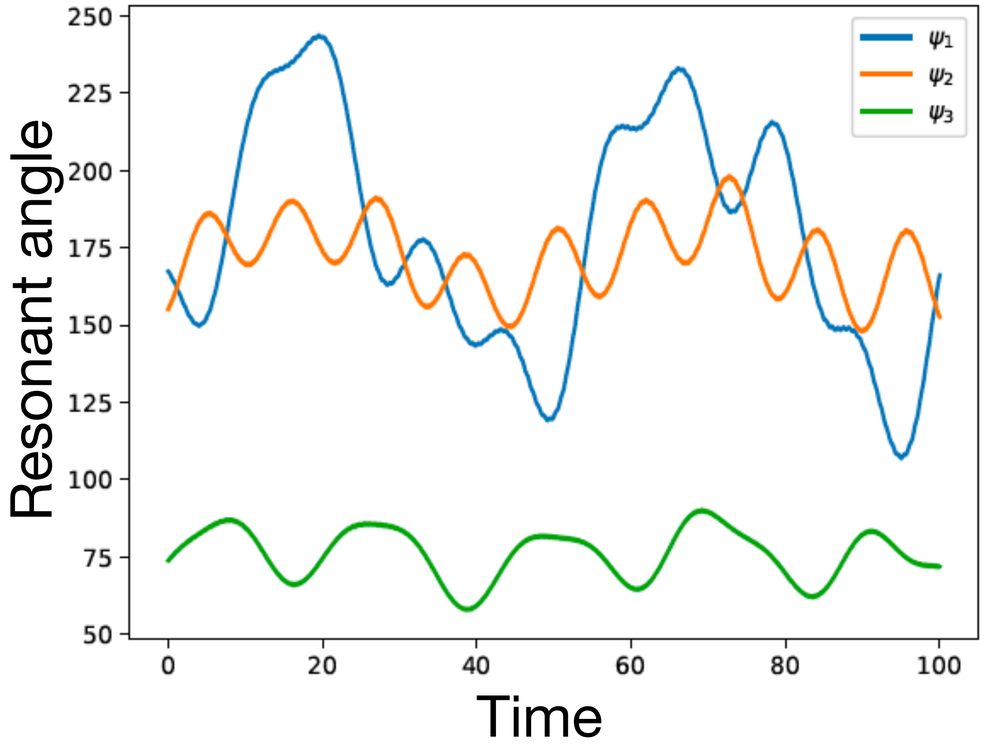
Amplitude of resonant angles, eccentricities, and tides

$$\Psi_i = p\lambda_i - (p+q)\lambda_{i+1} + q\lambda_{i+2}$$

- Trappist-1 (Agol+ 2021)
  - All planets in the chain.
  - Surprising period ratios (Pc/Pb~8/5).



- TOI-178 (Leleu+ 2021)
  - Inner planet out of the chain.
  - Larger libration of the inner resonance.

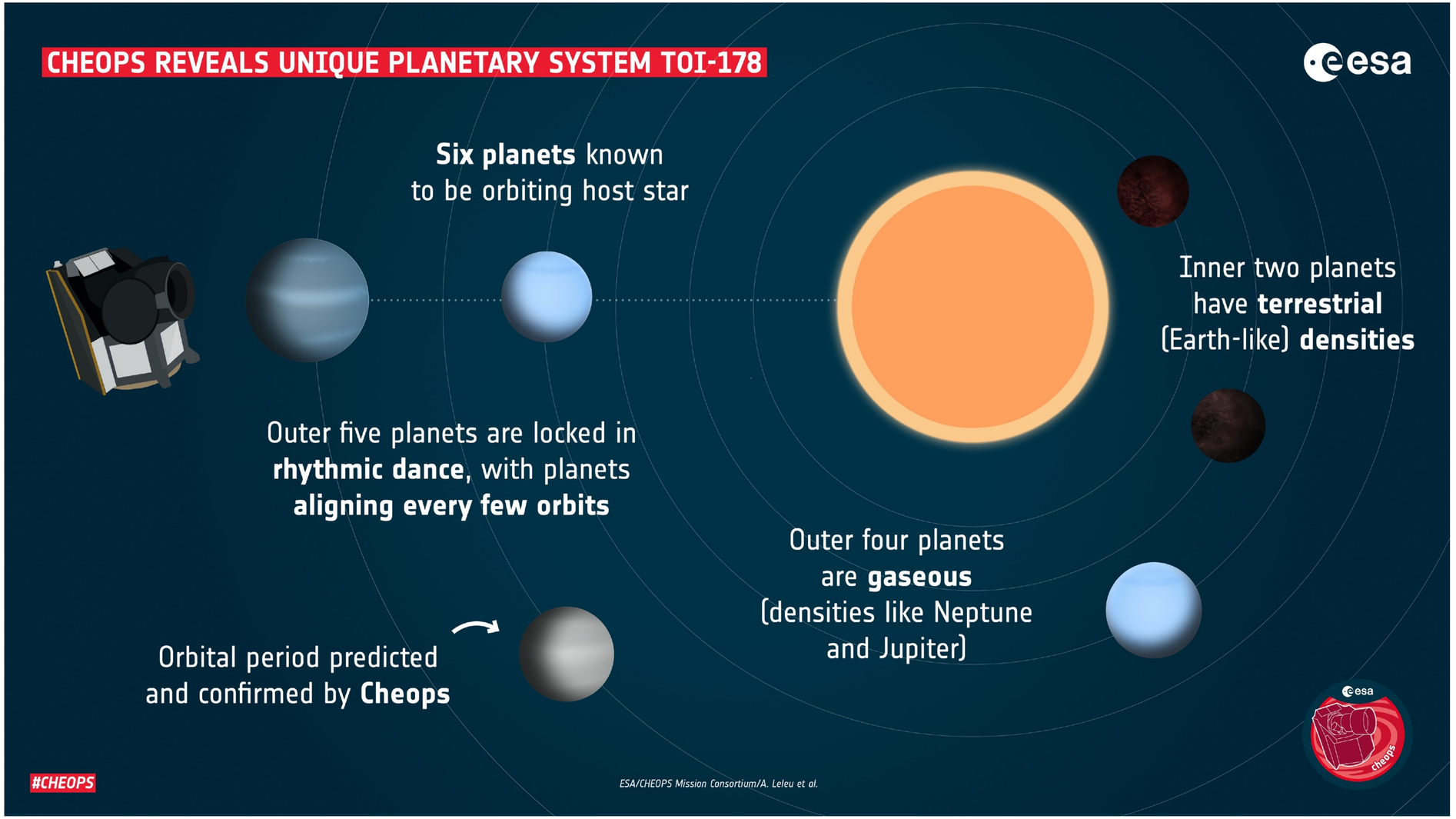


Minute architecture differences constrain the formation and evolution of resonant chains

Many thanks!

TOI-178 is a golden target for the study of formation and evolution of planetary systems.

TOI-178 - credit : ESA



A. Leleu, Y. Alibert, N. Hara, M. Hooton, T. Wilson et al (2021)