

A decade of monitoring HIP 41378, a transiting multi-planetary system

Salomé Grouffal

Post-doc at IPAG

A decade of monitoring the HIP 41378's planetary system

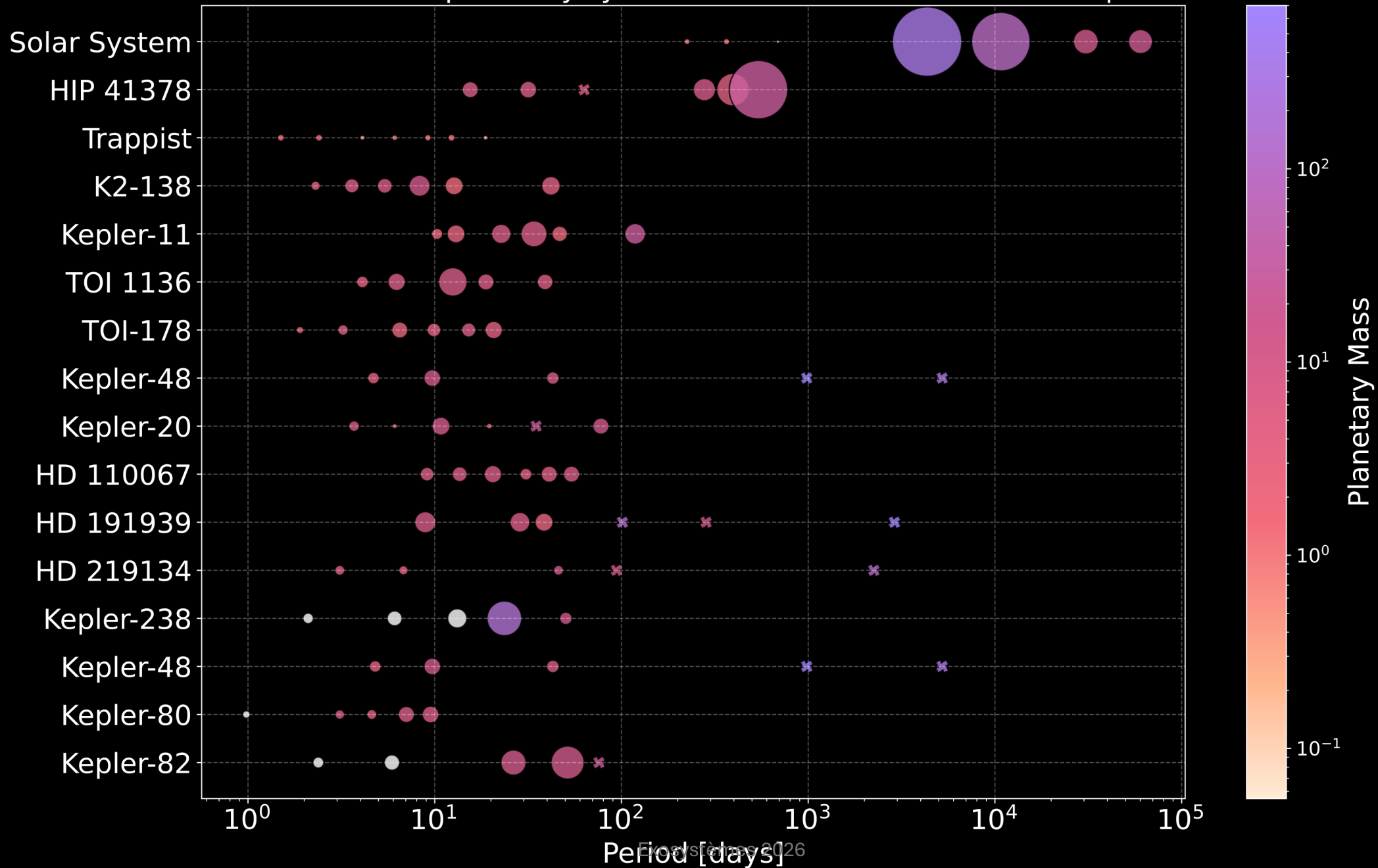
Masses and orbital periods of 6 planets and an extra planet candidate

S. Grouffal^{1,2}, A. Santerne^{1,2}, X. Dumusque³, B. Akınanmi³, T. Guillot⁴, N. C. Hara¹, A. Leleu³, L. Malavolta^{5,7}, M. Saillenfest⁶, D. J. Armstrong^{8,11}, S. C. C. Barros^{17,18}, D. Bayliss⁸, A. S. Bonomo²², D. J. A. Brown^{8,11}, A. Collier Cameron²³, M. Cretignier⁹, I. J. M. Crossfield¹⁰, F. Dai¹⁹, M. Damasso²², O. Demangeon¹⁷, P. Figueira²⁶, P. Leonardi⁵, A. F. Martínez Fiorenzano²⁷, M. López-Morales¹⁶, E. Molinari¹², A. Mortier²⁵, L. D. Nielsen¹³, H. P. Osborn^{14,15}, E. Petigura²⁴, K. Rice^{20,21}, N. C. Santos^{17,18}, A. Sozzetti²², S. Sulis¹, S. Udry³, and C. Watson²⁸

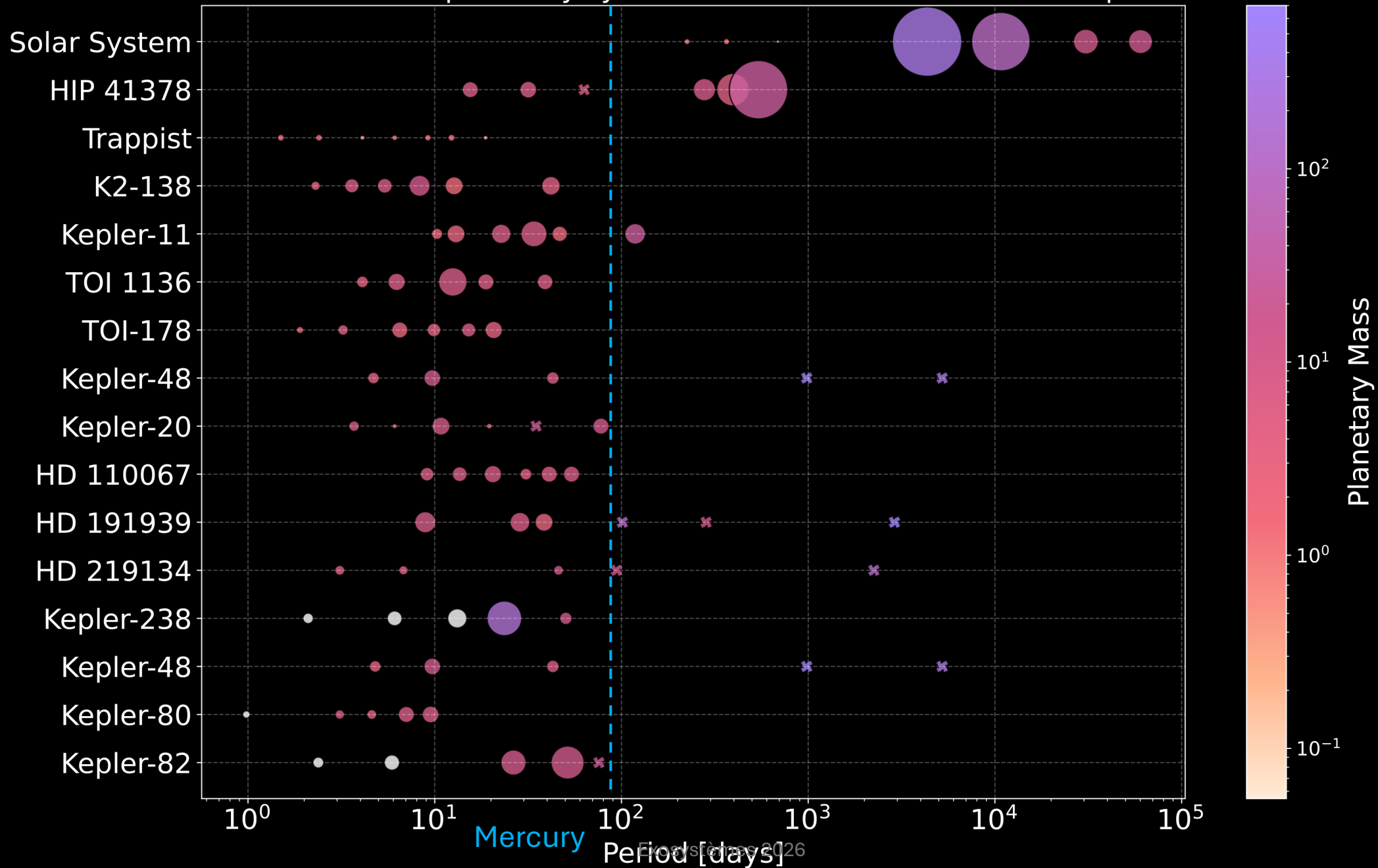
Accepted in A&A



Well characterised planetary systems with more than 5 confirmed planets



Well characterised planetary systems with more than 5 confirmed planets



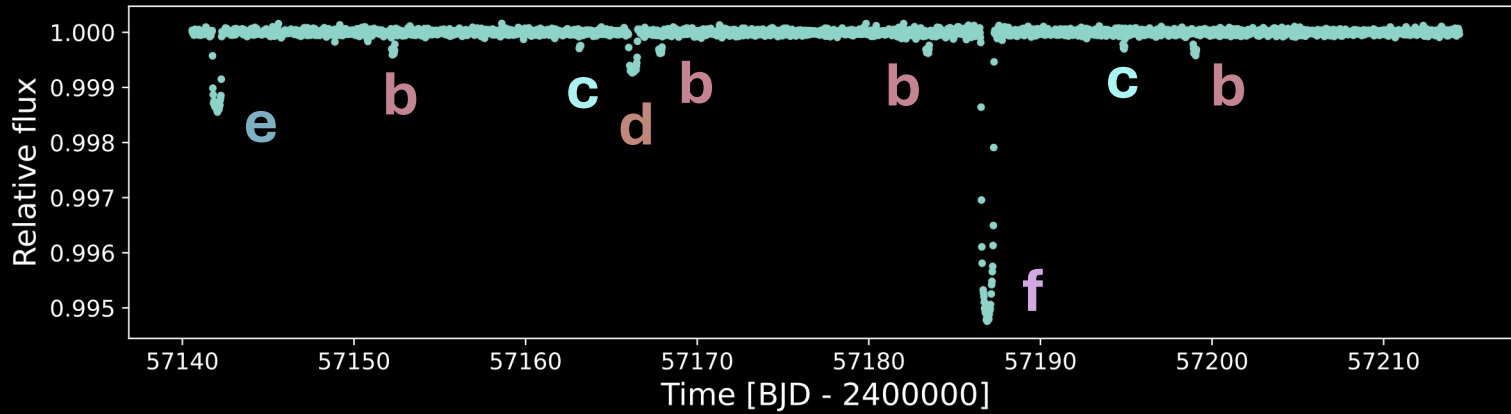
Discovery in 2015 with K2



2015

~ 70 days of observation

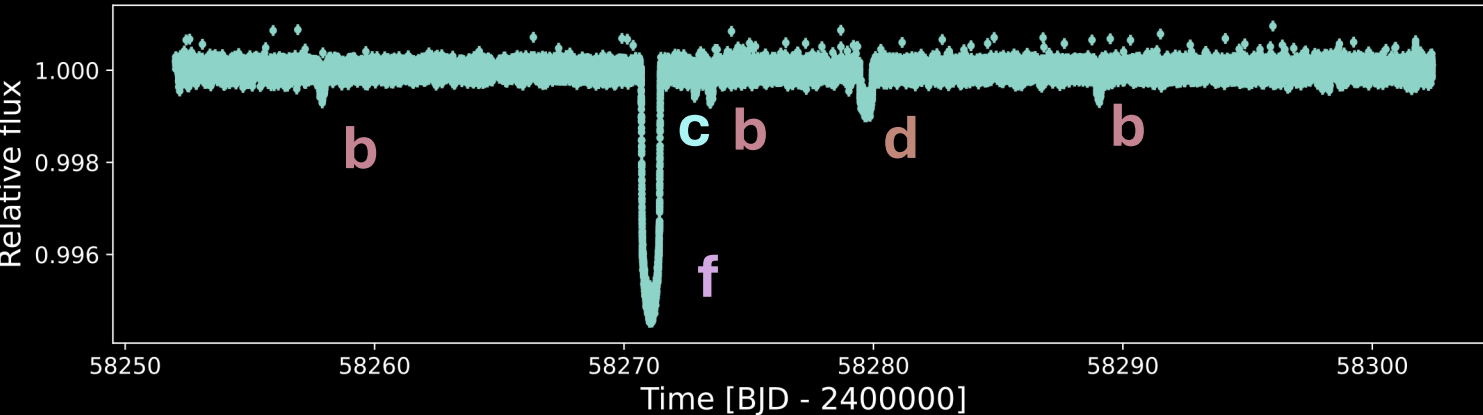
K2-C5



Adapted from Vanderburg et al. (2016)

2018

K2-C18



~ 50 days of observation

Adapted from Becker et al. (2019), Berardo et al. (2019)

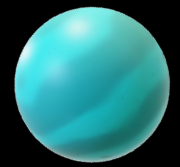
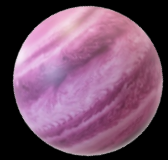
	Period [d]	Radius [R_{\oplus}]	Transit duration [hours]
Planet b	15.57208 $\pm 2 \times 10^{-5}$	2.595 \pm 0.036	5.14 \pm 0.03
Planet c	31.70603 $\pm 6 \times 10^{-5}$	2.727 \pm 0.060	3.11 \pm 0.05
Planet d	?	3.54 \pm 0.06	12.67 \pm 0.06
Planet e	?	4.92 \pm 0.09	13.1 \pm 0.1
Planet f	?	9.2 \pm 0.1	19.018 \pm 0.008

The system with transits



F-type star
 $R_* = 1.3 R_{\odot}$
 $M_* = 1.2 M_{\odot}$
Age = 2.07 Gyr

Planet b
15 days

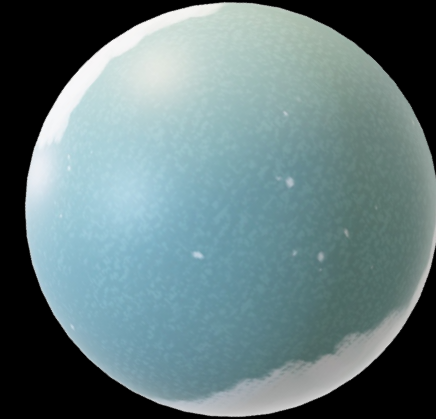


Planet c
31 days

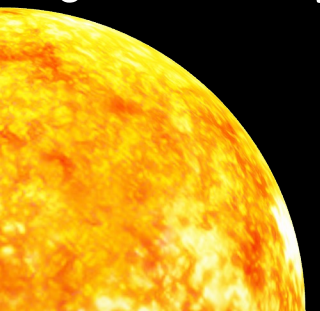
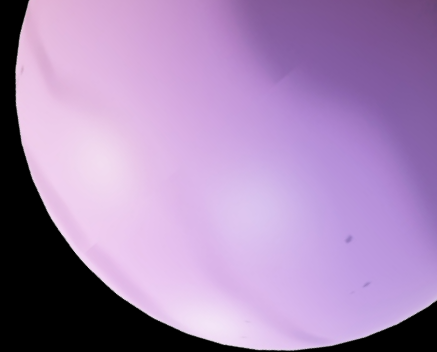
Planet d
? days



Planet e
? days



Planet f
? days

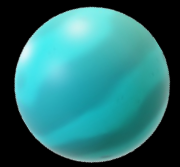
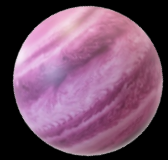


The system with transits

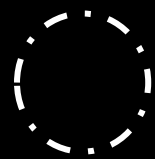


F-type star
 $R_* = 1.3 R_{\odot}$
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Age = 2.07 Gyr

Planet b
15 days



Planet c
31 days



Planet g
60 days?

Planet d
? days



Planet e
? days



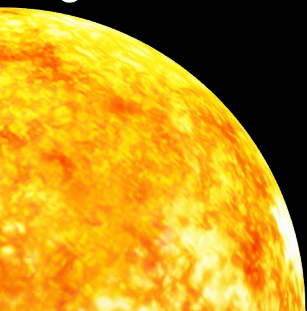
Only 1 transit



2 non-consecutive transits

Planet f
542 days

2 non-consecutive transits

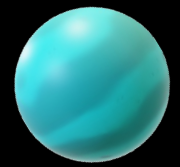


The system with transits

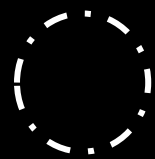


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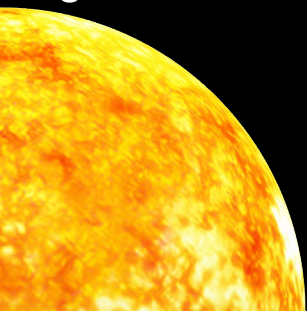
Planet f
542 days



2 non-consecutive transits


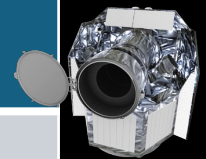
2 non-consecutive transits

Long-period planets :
Few transits + require long RV baseline
+ very long transit duration



What is the orbital period of HIP 41378 d?



Possible periods	TESS observations 	Tentative observation in 2019 and 2022	CHEOPS non observation 
1113.4465	✓	✗	
556.7233	✓	✗	
371.1488	✓	✗	
278.3616	✓	✓	
222.6893	✗	✗	
185.5744	✓	✗	
159.0638	✗	✗	
139.1808	✗	✓	
123.7163	✗	✗	
111.3447	✗	✗	
101.2224	✗	✗	

What is the orbital period of HIP 41378 d?

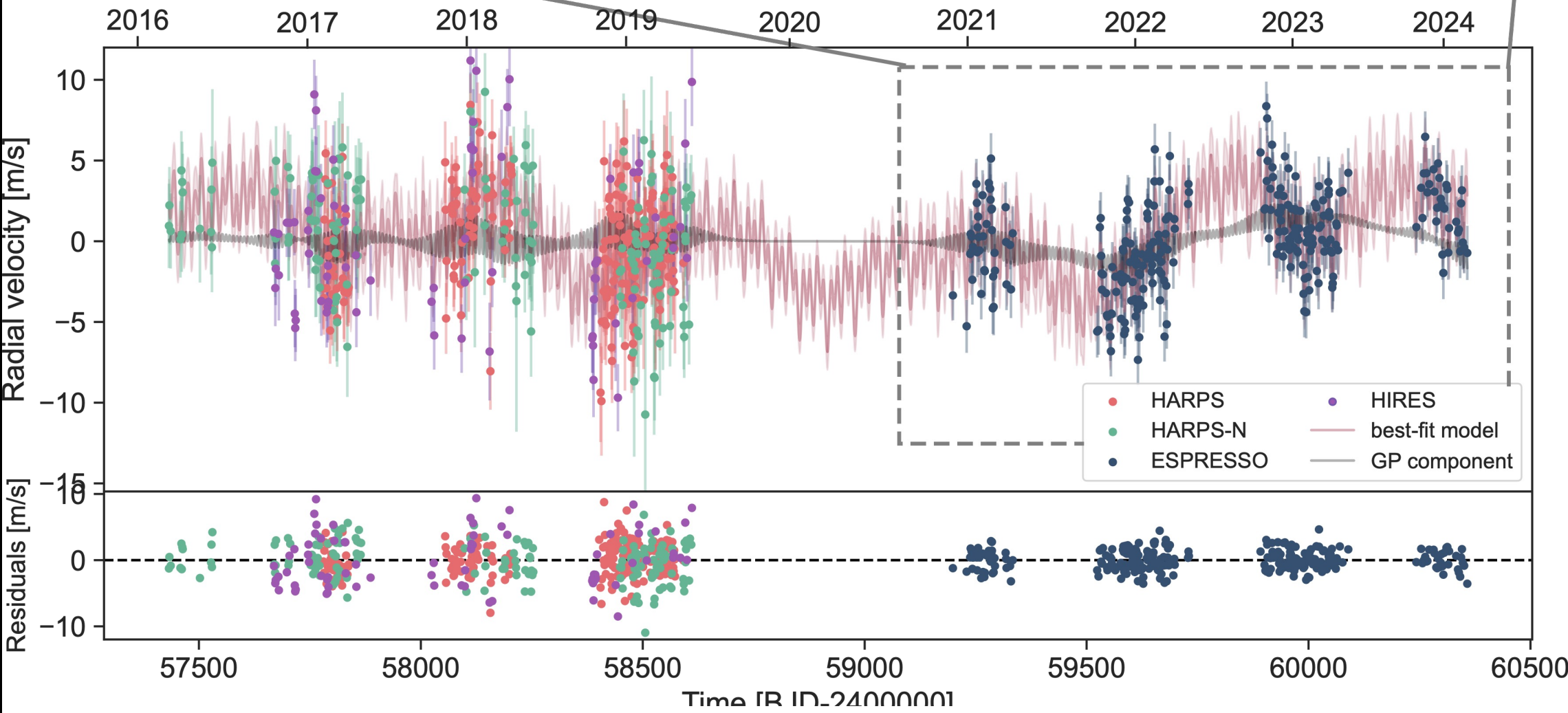


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139.1808	✗	✓	✗
123.7163	✗	✗	✓
111.3447	✗	✗	✗
101.2224	✗	✗	✓

Masses and periods of the planets with RVs



720 epochs in total (272 ESPRESSO)

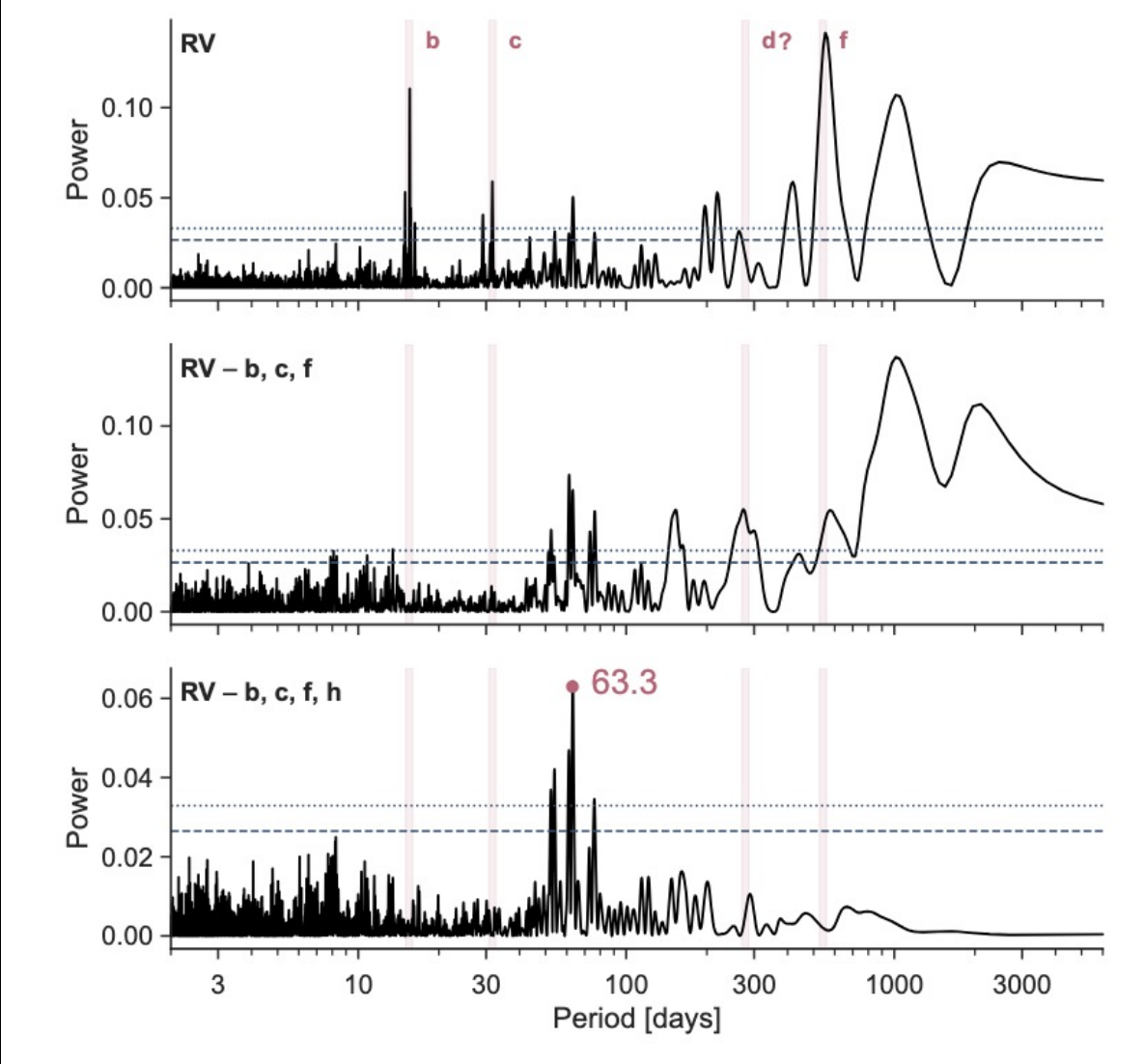


A decade of monitoring the HIP 41378's planetary system (Grouffal et al. accepted)

What are the orbital periods of planet d and e?



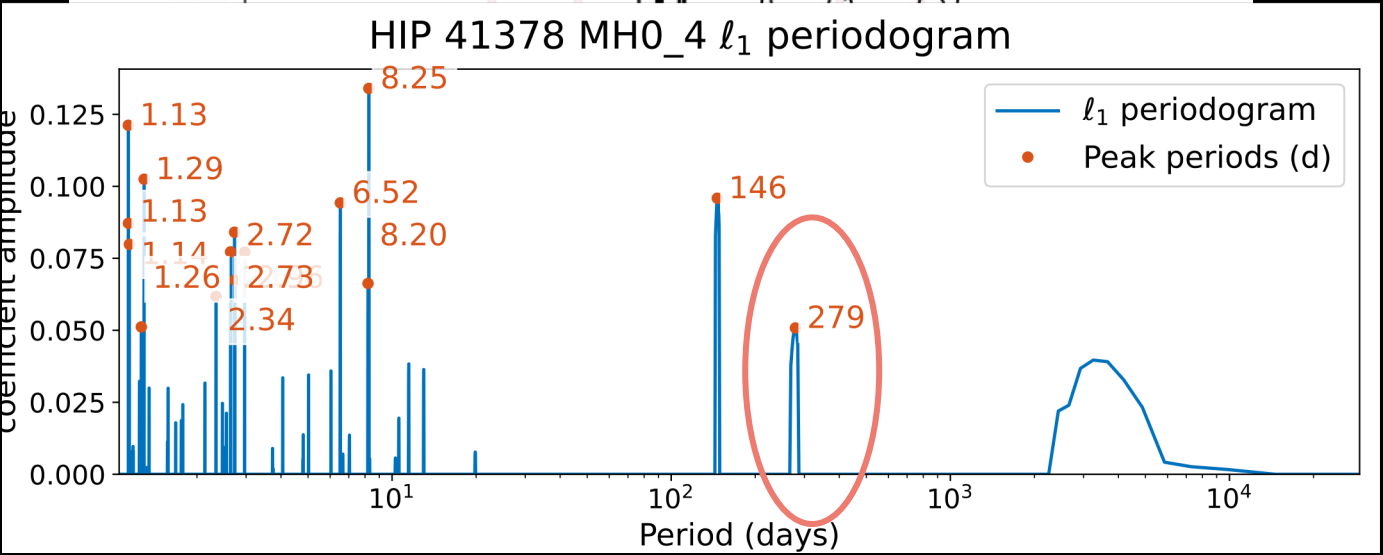
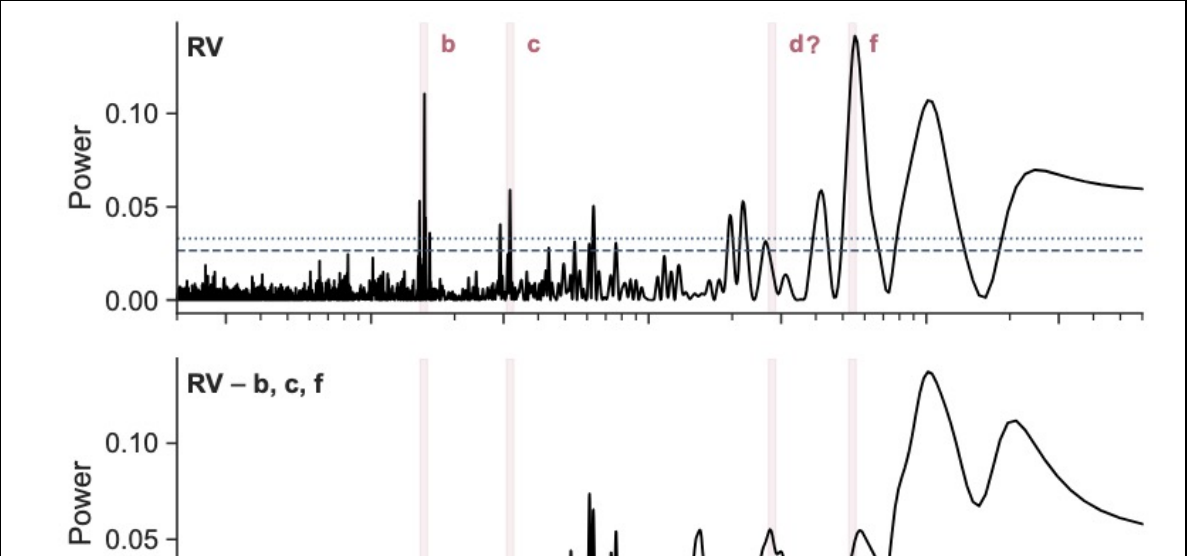
Classical periodogram
→ no sign of planets d after removing planets b, c, g and candidate h



What are the orbital periods of planet d and e?



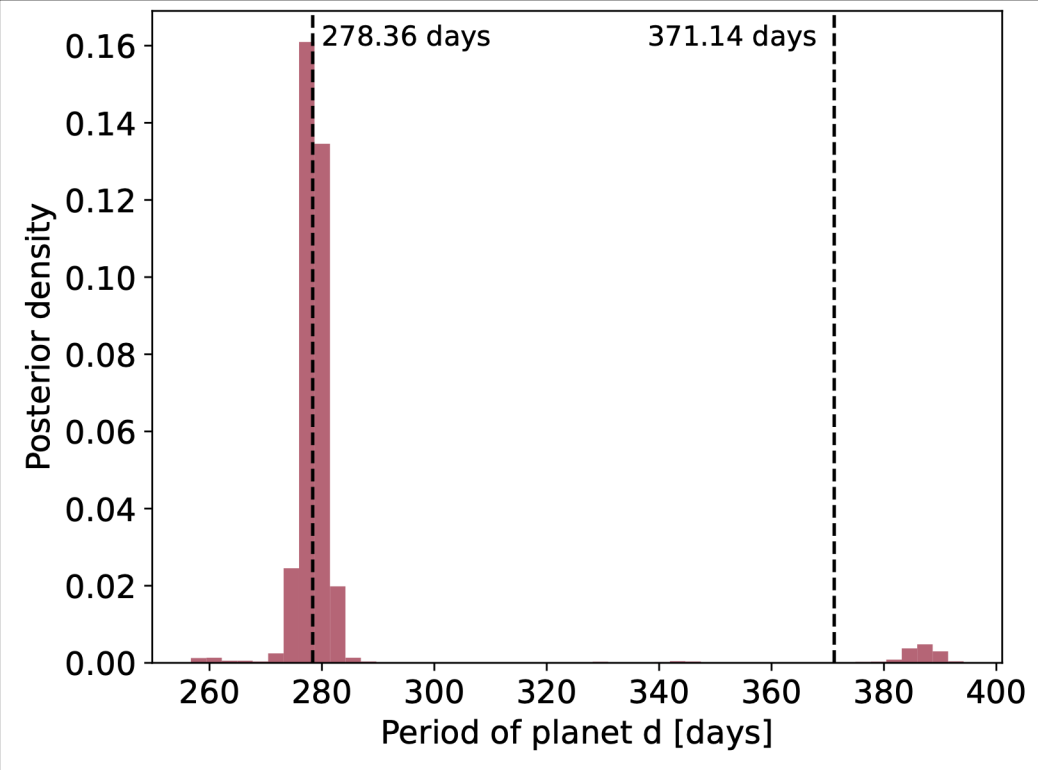
Classical periodogram
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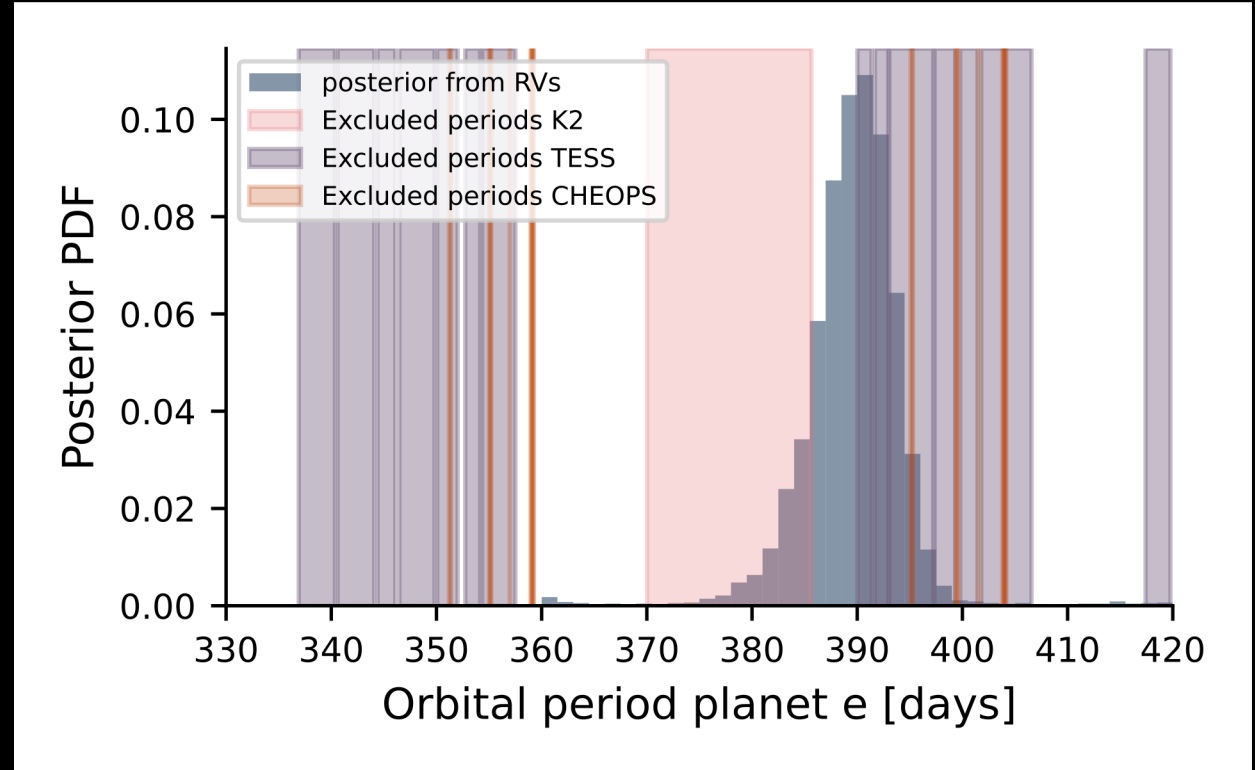
What are the orbital period of planet d and e?



Planet d 278 days

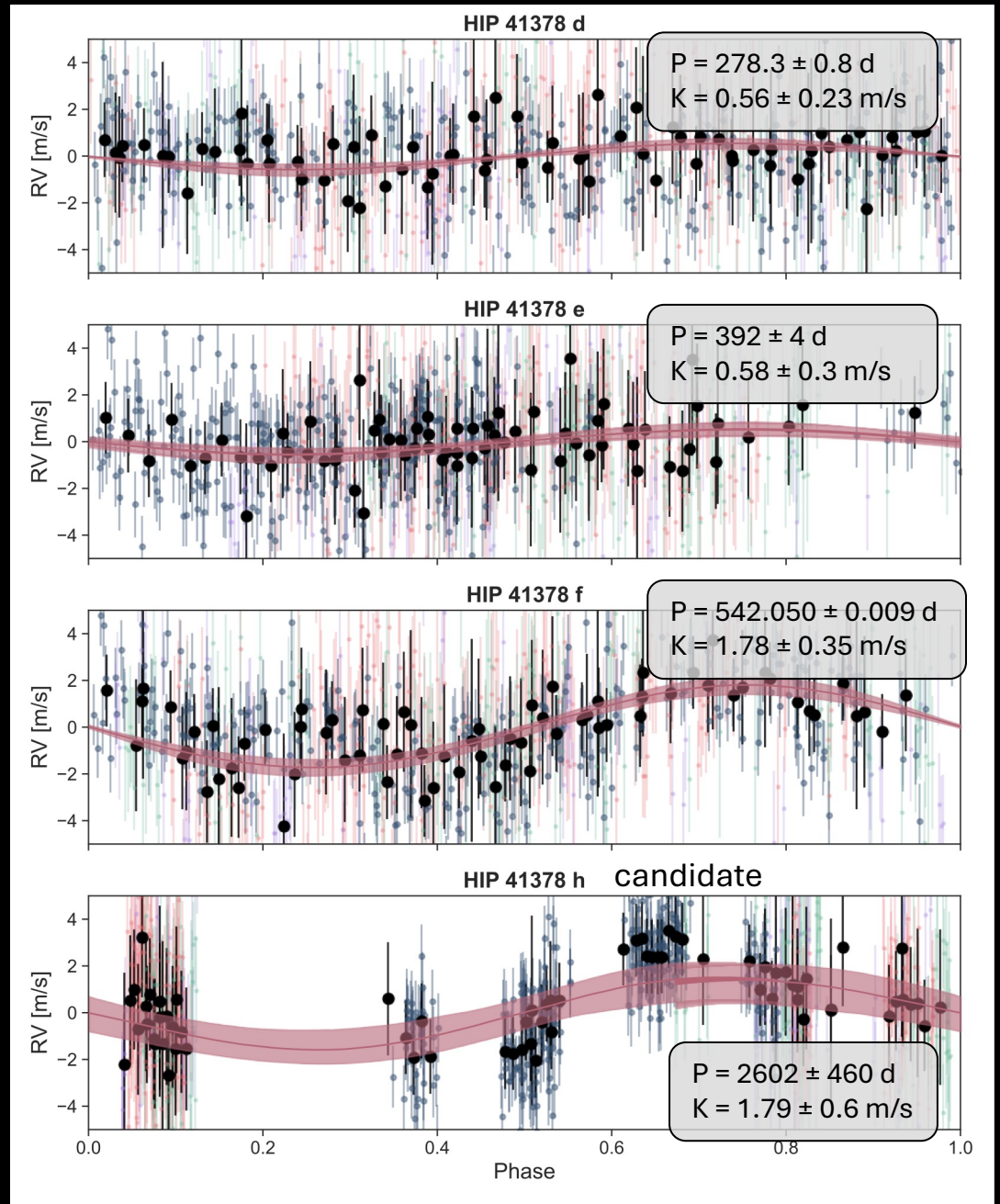
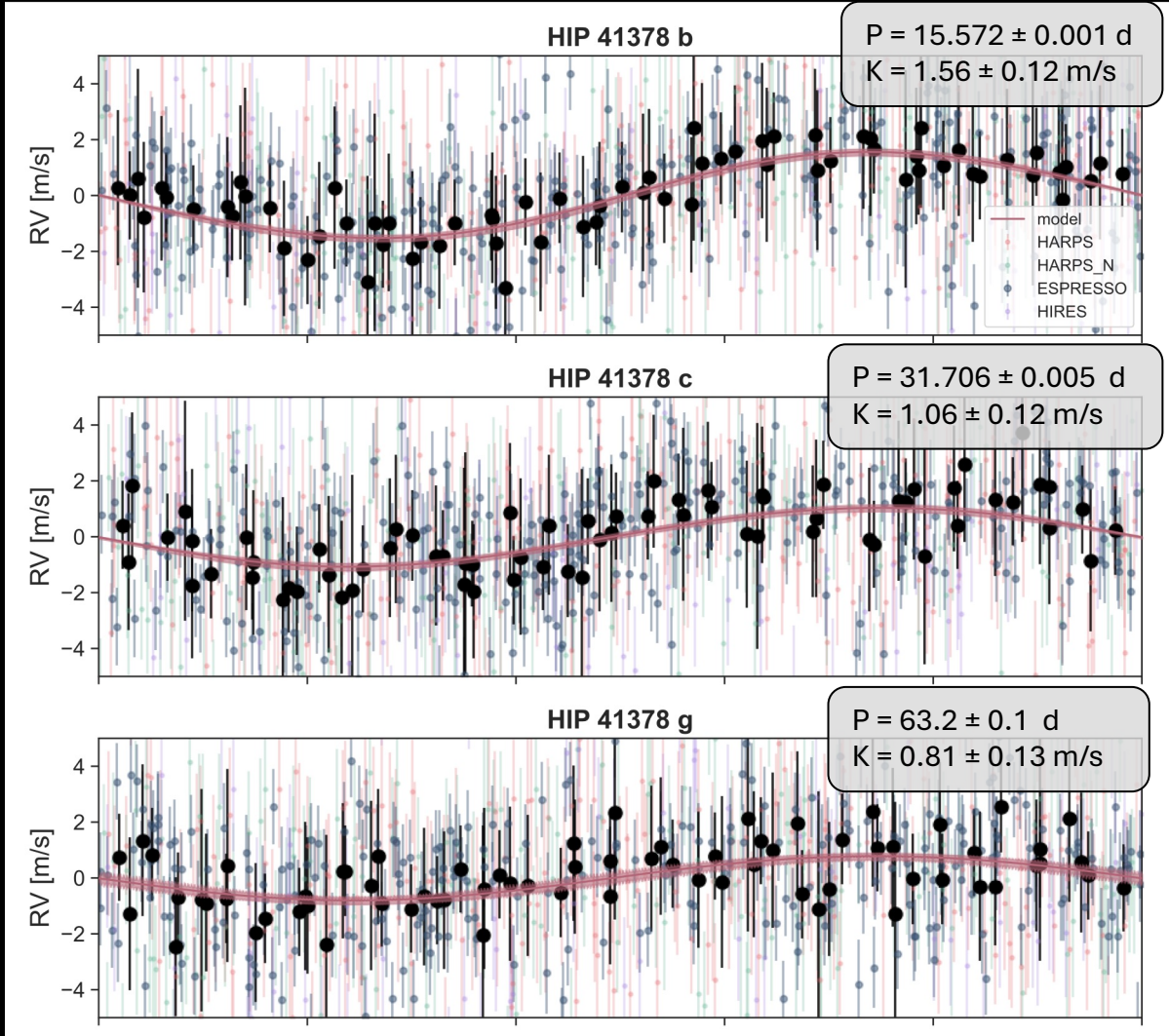


Planet e ~387 days



All the analysis with nested sampling, mcmc, model comparison... in the paper (or PhD thesis)

Phase plots



The system before RVs



Planet b
15 days

$$\rho = 2.17 \pm 0.28 \text{ g.cm}^{-3}$$



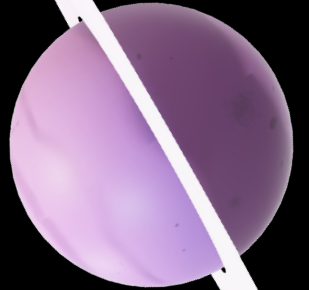
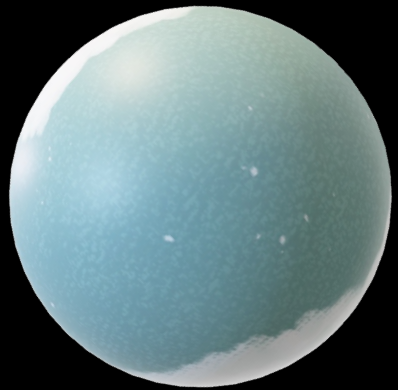
Planet c
31 days

$$\rho = 1.19 \pm 0.30 \text{ g.cm}^{-3}$$

Planet d
278 days?
 $\rho = ?$



Planet e
? days
 $\rho = ?$



Planet f
542 days

$$\rho = 0.09 \pm 0.02 \text{ g.cm}^{-3}$$

Planet g
60 days?

The system now



Planet b
15 days
 $\rho = 2.11^{+0.17}_{-0.15} \text{ g.cm}^{-3}$



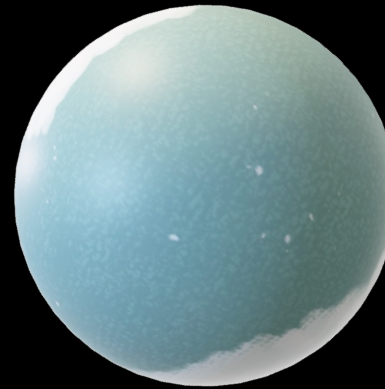
Planet c
31 days
 $\rho = 1.86^{+0.21}_{-0.23} \text{ g.cm}^{-3}$

Planet g
63.11 days
 $m = 5.3 \pm 0.9 M_{\oplus}$

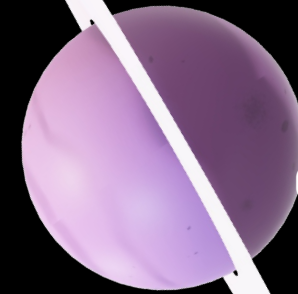
Planet d
278 days
 $\rho = 0.91^{+0.23}_{-0.29} \text{ g.cm}^{-3}$



Planet e
392 days?
 $\rho = 0.3 \pm 0.1 \text{ g.cm}^{-3}$

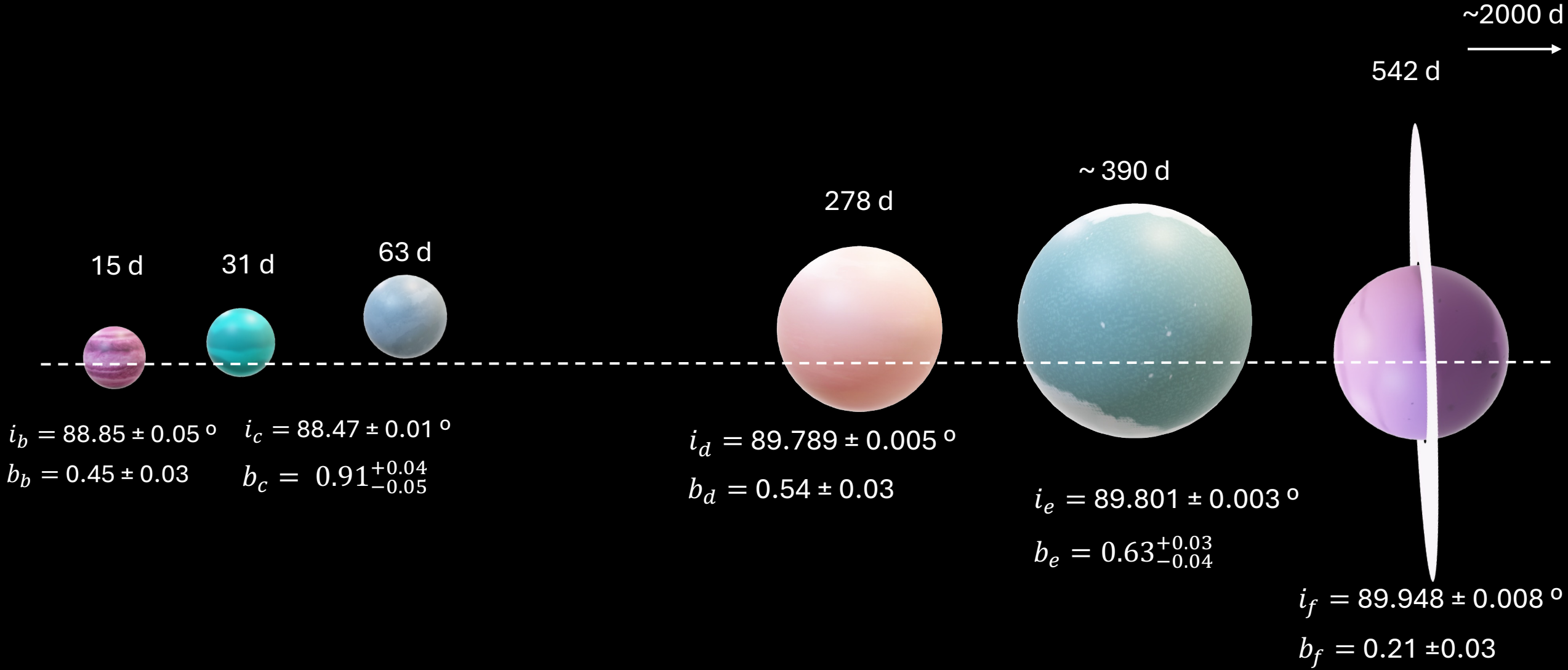


Planet f
542 days
 $\rho = 0.17 \pm 0.02 \text{ g.cm}^{-3}$



Candidate planet h
2000 days?
 $m = 58 \pm 7 M_{\oplus}$

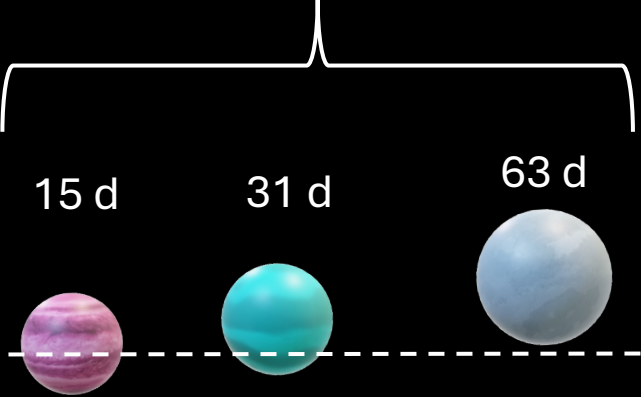
Architecture of the system



Architecture of the system

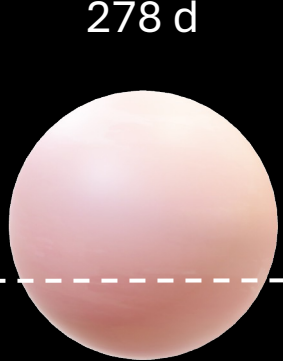


Near 1:2:4 mean motion resonance



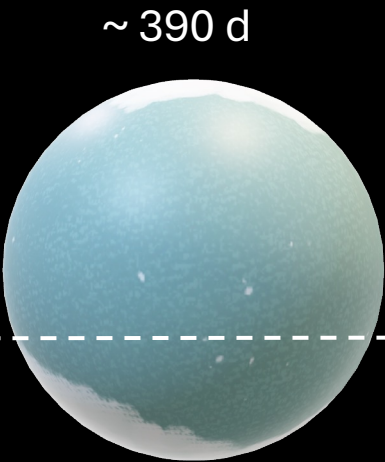
$$i_b = 88.85 \pm 0.05^\circ \quad i_c = 88.47 \pm 0.01^\circ$$

$$b_b = 0.45 \pm 0.03 \quad b_c = 0.91^{+0.04}_{-0.05}$$



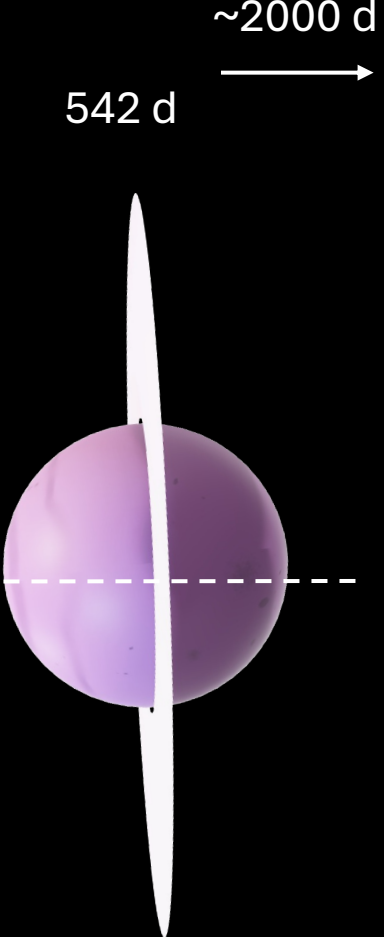
$$i_d = 89.789 \pm 0.005^\circ$$

$$b_d = 0.54 \pm 0.03$$



$$i_e = 89.801 \pm 0.003^\circ$$

$$b_e = 0.63^{+0.03}_{-0.04}$$



$$i_f = 89.948 \pm 0.008^\circ$$

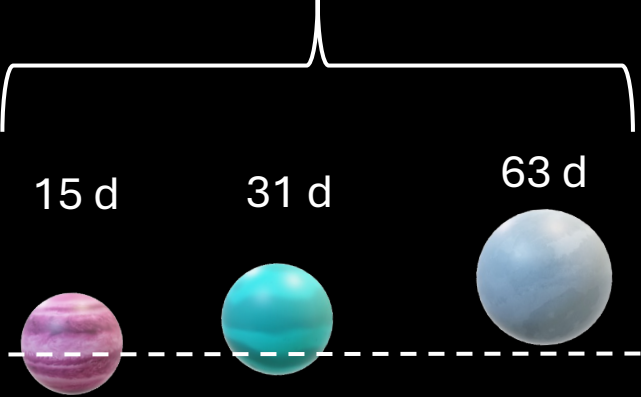
$$b_f = 0.21 \pm 0.03$$

Architecture of the system



Is the system complete ?

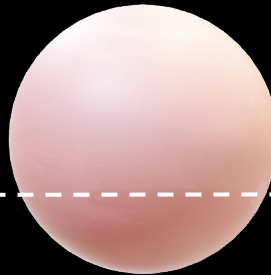
Near 1:2:4 mean motion resonance



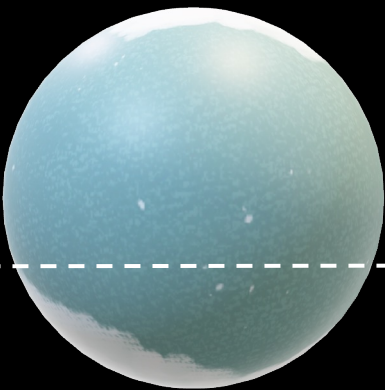
148 d ???



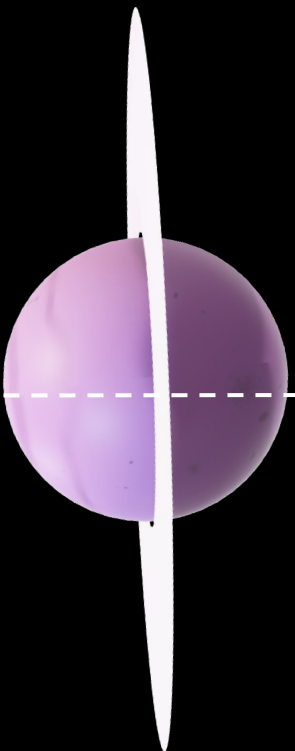
278 d



~ 390 d



542 d



~2000 d



$$i_b = 88.85 \pm 0.05^\circ \quad i_c = 88.47 \pm 0.01^\circ$$

$$b_b = 0.45 \pm 0.03 \quad b_c = 0.91^{+0.04}_{-0.05}$$

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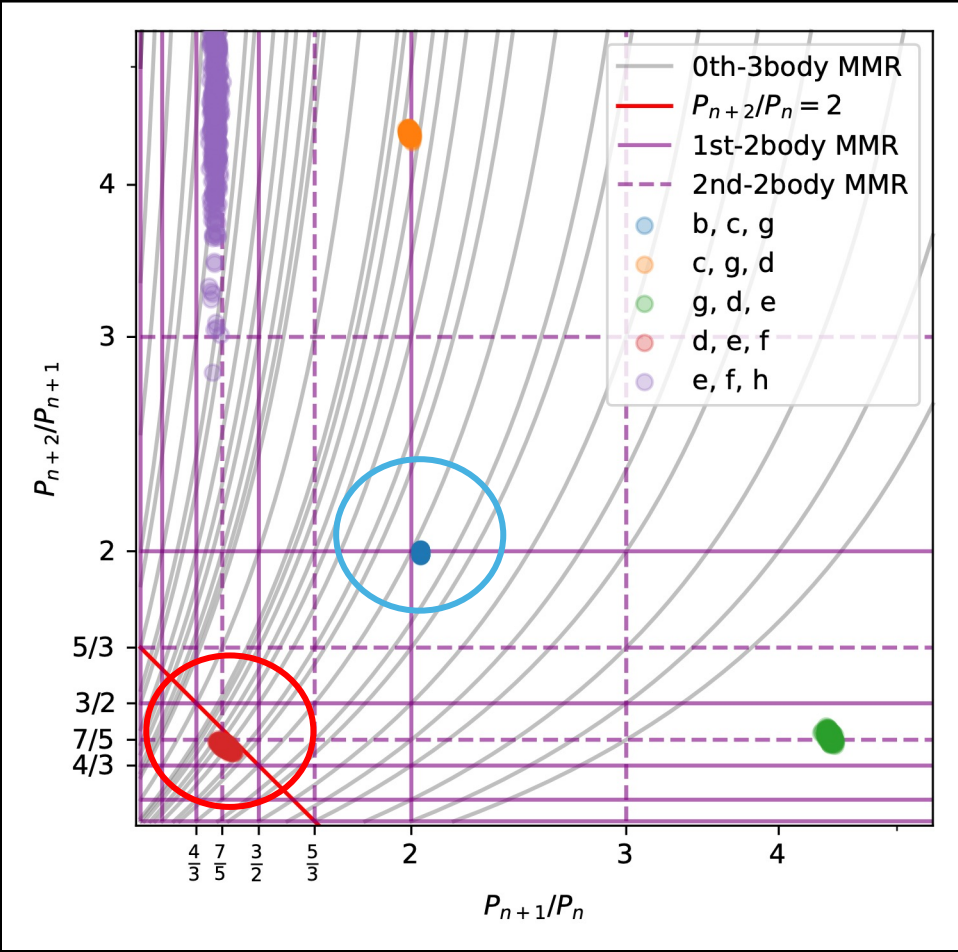
$$i_e = 89.801 \pm 0.003^\circ$$

$$b_e = 0.63^{+0.03}_{-0.04}$$

$$i_f = 89.948 \pm 0.008^\circ$$

$$b_f = 0.21 \pm 0.03$$

Analysis of the resonances

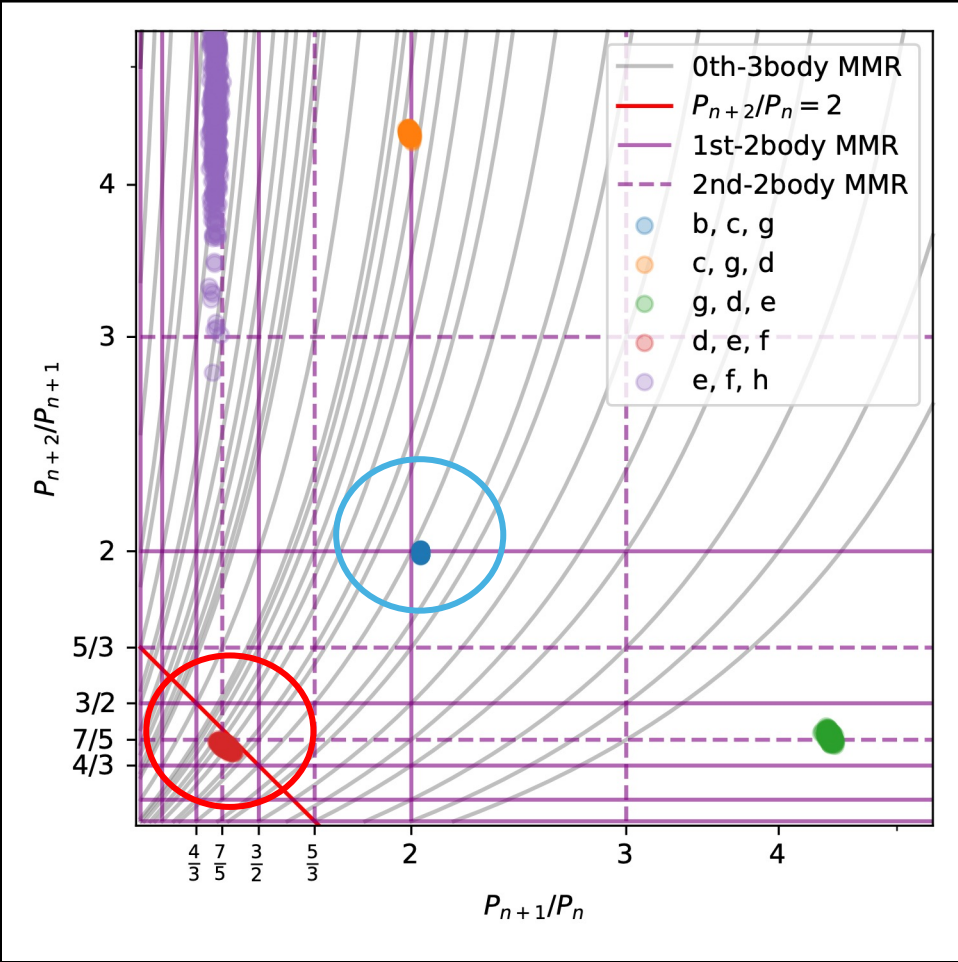


d, e, f close to 7:5 MMR

b, c, g close to 2:1 MMR

Work in collaboration with Adrien Leleu

Analysis of the resonances



Case 1: One additional planet, minimising distance to 2-body MMRs or to 3-body MMRs

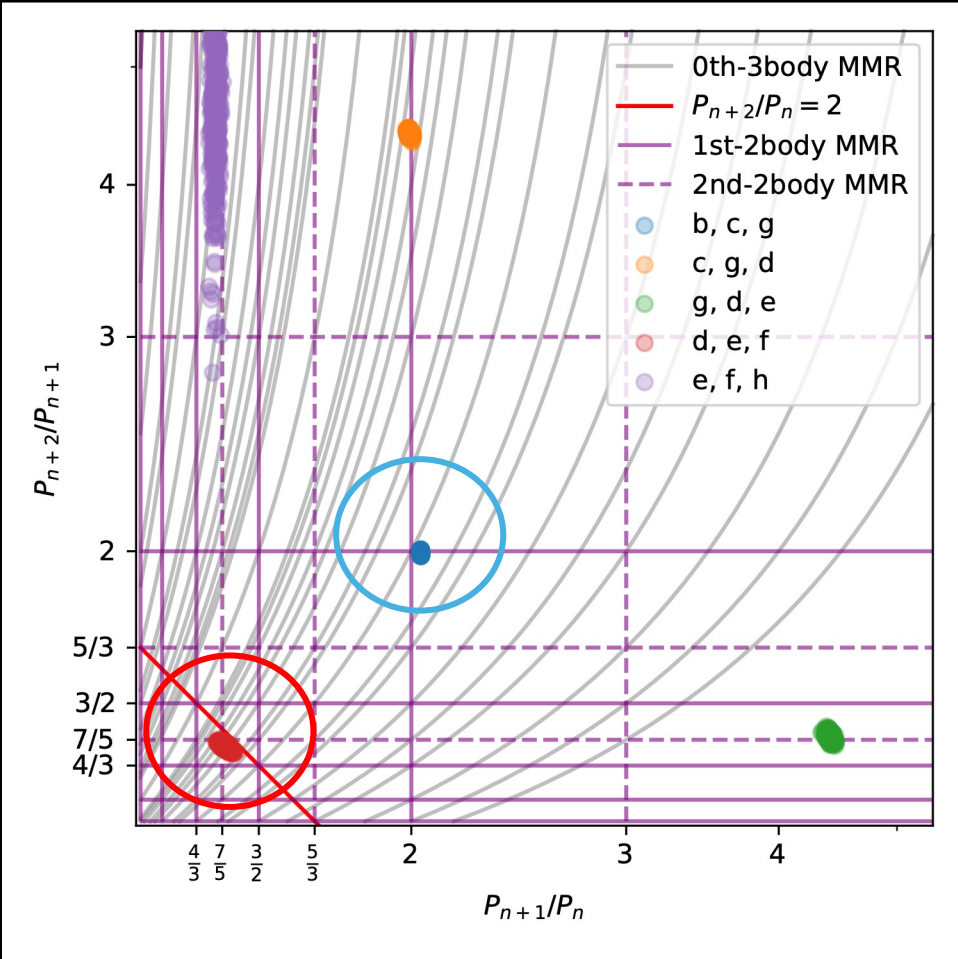
Planets at ~ 188 days or ~148 days

d, e, f close to 7:5 MMR

b, c, g close to 2:1 MMR

Work in collaboration with Adrien Leleu

Analysis of the resonances



Case 1: One additional planet, minimising distance to 2-body MMRs or to 3-body MMRs

Planets at ~ 188 days or ~148 days

Case 2: Two additional planets for a complete chain of resonance

solution	1	2	3	4	5	6
P_x [d]	126.4	126.4	105.3	105.3	84.3	84.3
P_y [d]	210.7	168.5	210.7	140.4	168.5	140.4

d, e, f close to 7:5 MMR

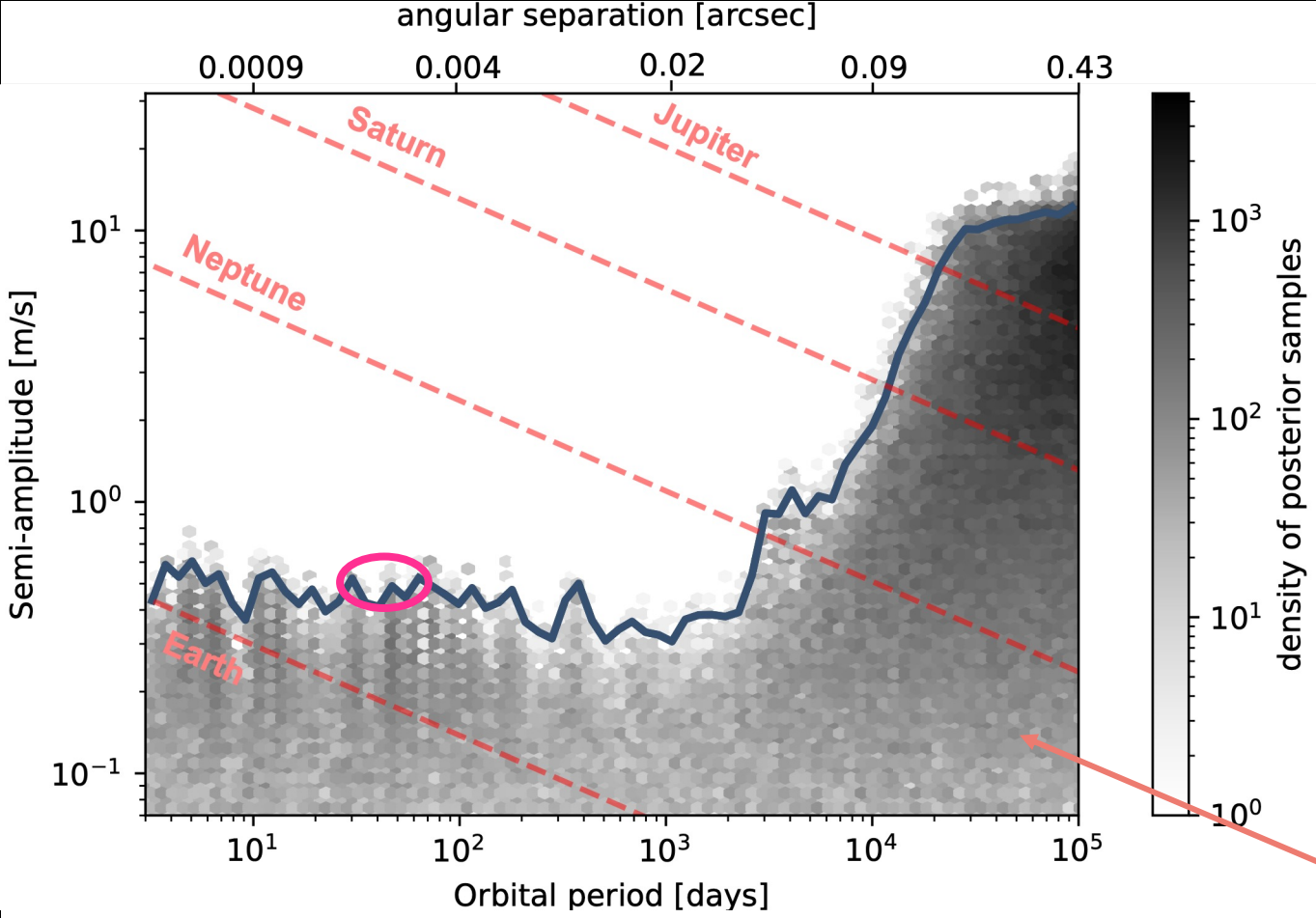
b, c, g close to 2:1 MMR

Work in collaboration with Adrien Leleu

System's completeness



More massive planets beyond 1.5 AU?

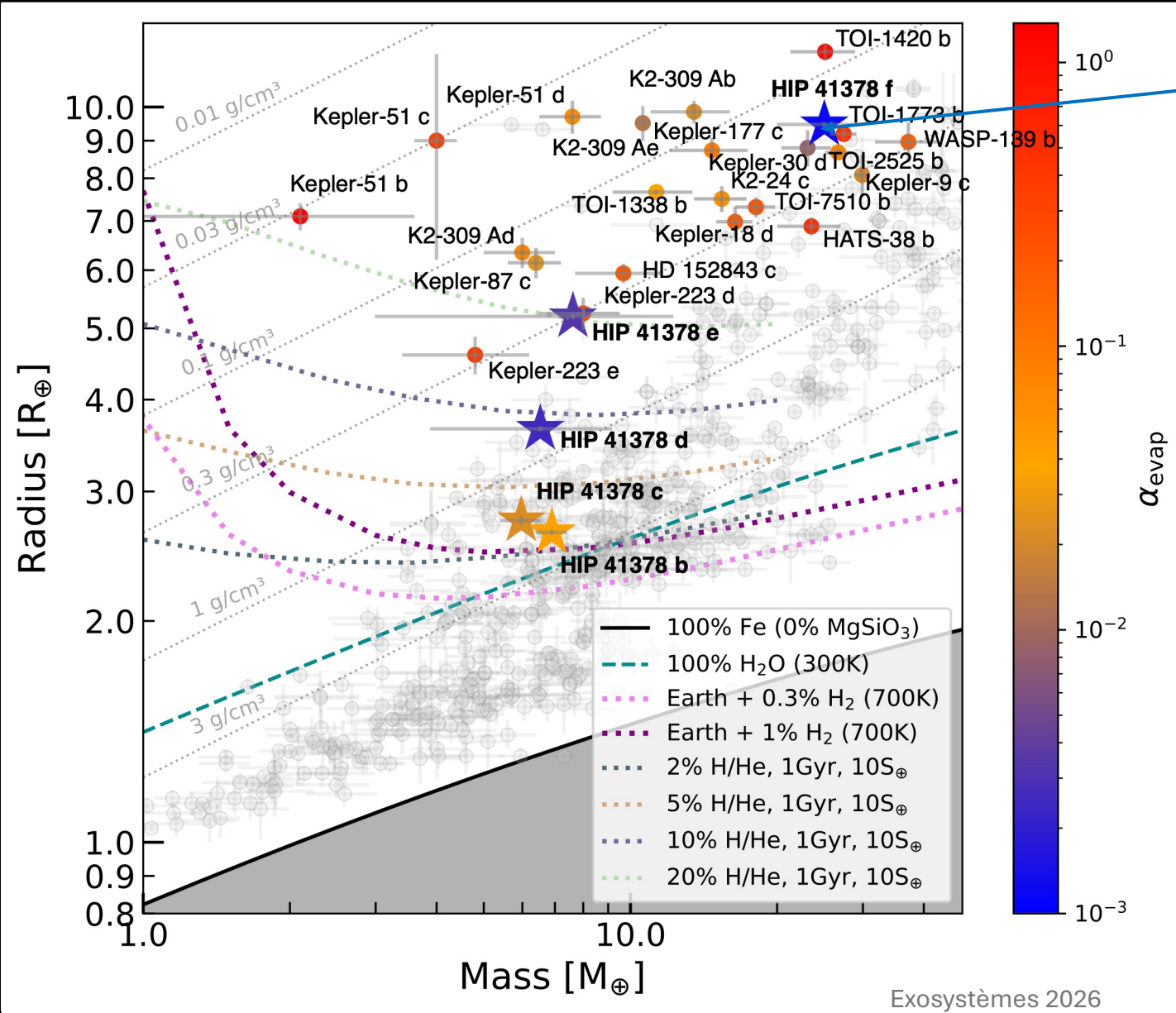


Jupiter-mass planets compatible if period exceed 55 years

Future instruments like HWO or PCS could reveal additional planets in the outer part of the system

Grey zone : parameters still compatible with Rv observations

The low density of HIP 41378 f

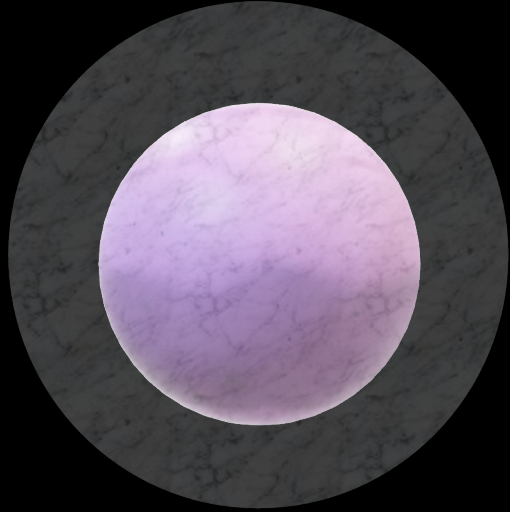


$$\rho_f = 0.17^{+0.03}_{-0.04} \text{ g.cm}^{-3}$$

mass loss parameter α_{evap}
 magnitude of mass loss due to XUV radiation

$$\alpha_{evap} = \frac{E_{UV}}{E_{bind}}$$

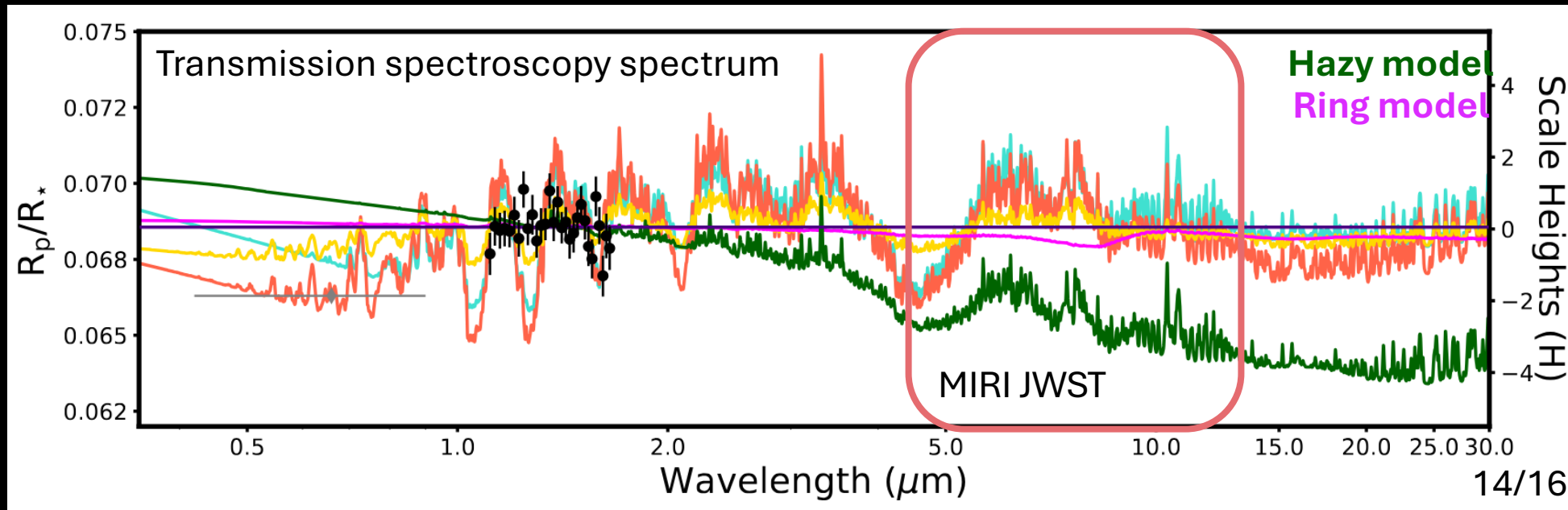
The very low density of HIP 41378 f



High-altitude
photochemical hazes?



The First Near-infrared Transmission Spectrum of HIP 41378 f, A Low-mass Temperate Jovian World in a Multiplanet System (Alam et al. 2022 incl. Grouffal, published in MNRAS)

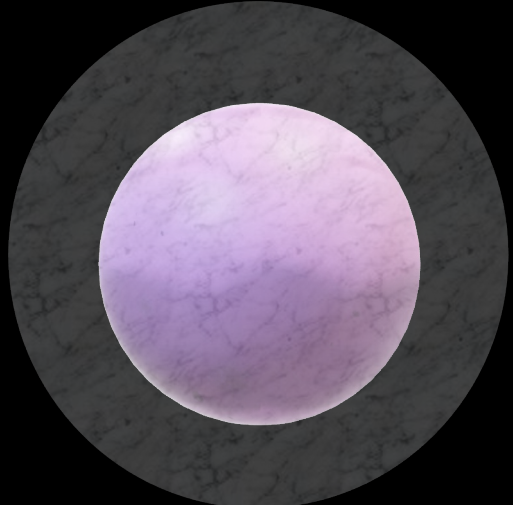


The very low density of HIP 41378 f

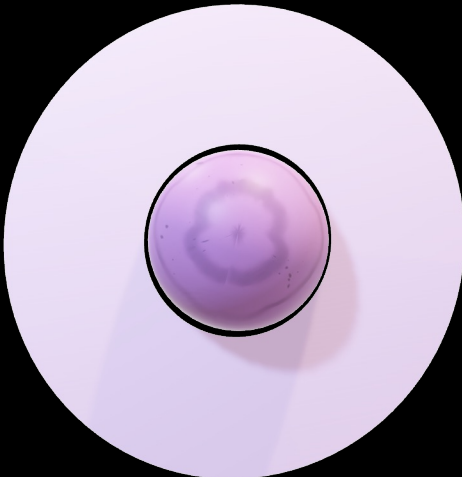


Circumplanetary rings ?

Akinsanmi et al. 2020

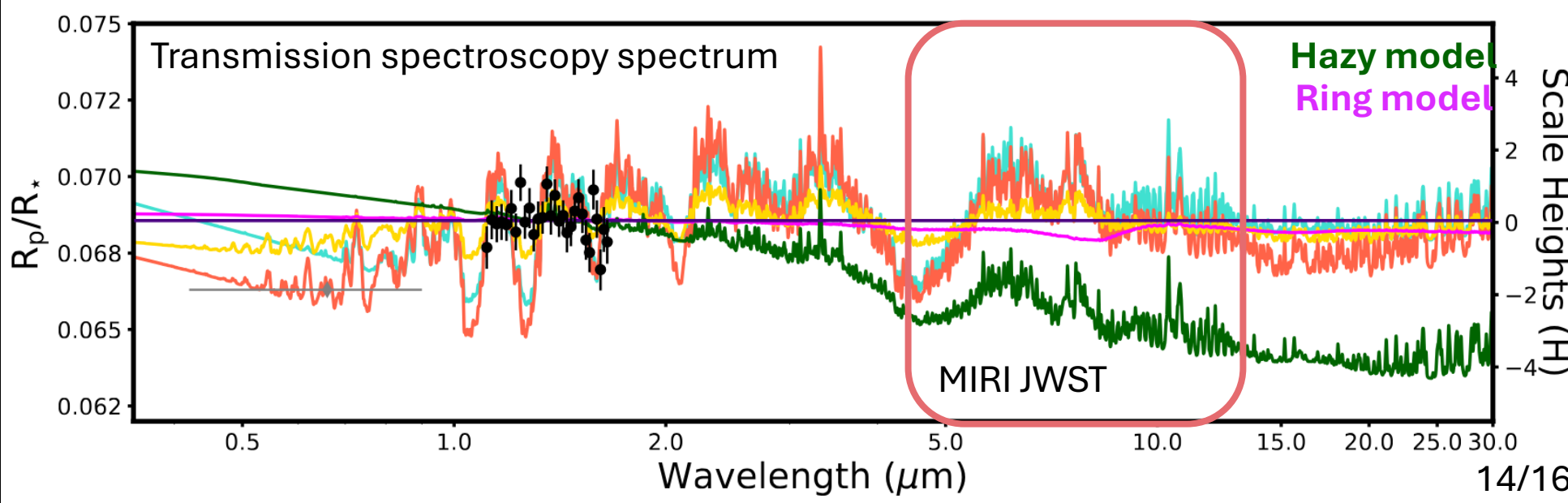


OR

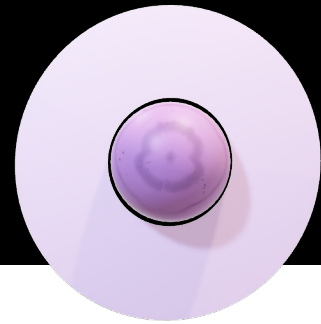


The First Near-infrared Transmission Spectrum of HIP 41378 f, A Low-mass Temperate Jovian World in a Multiplanet System (Alam et al. 2022 incl. Grouffal, published in MNRAS)

High-altitude photochemical hazes?



Rings for HIP 41378 f ?



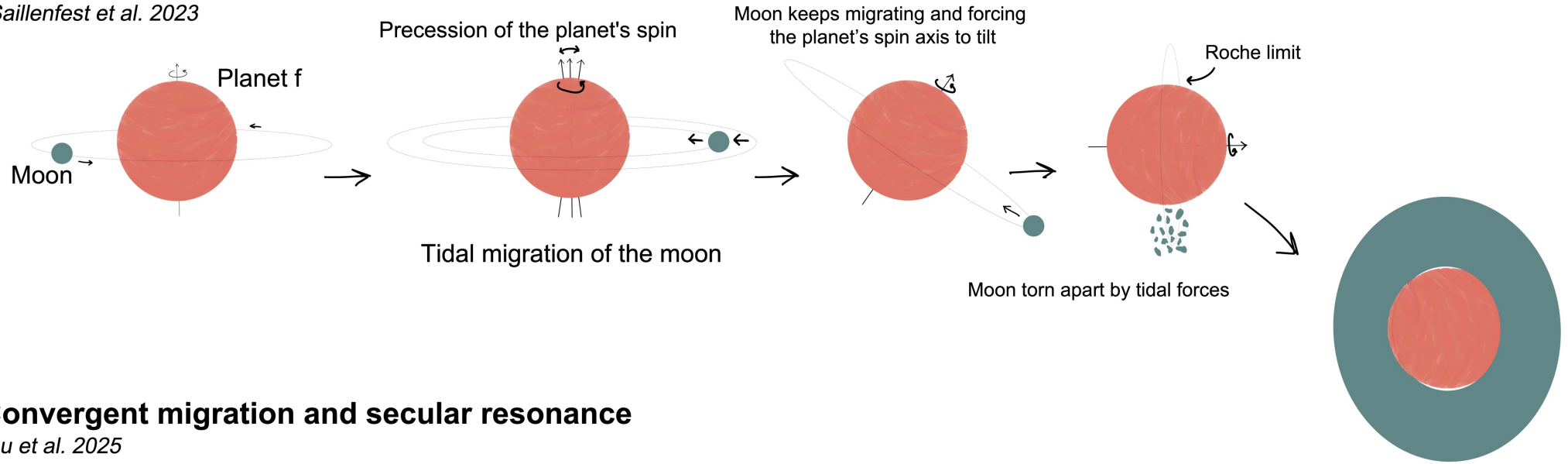
$$R_{true} = 3.9 R_{\oplus}$$

$$\rho = 2.3 \text{ g.cm}^{-3}$$

$$R_{ring} = 2.4 R_{true}$$

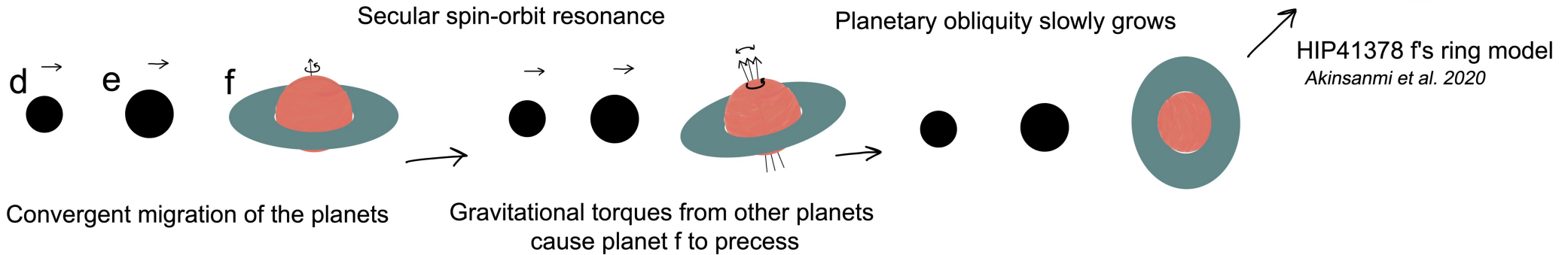
Tilt from moon migration

Saillenfest et al. 2023



Convergent migration and secular resonance

Lu et al. 2025



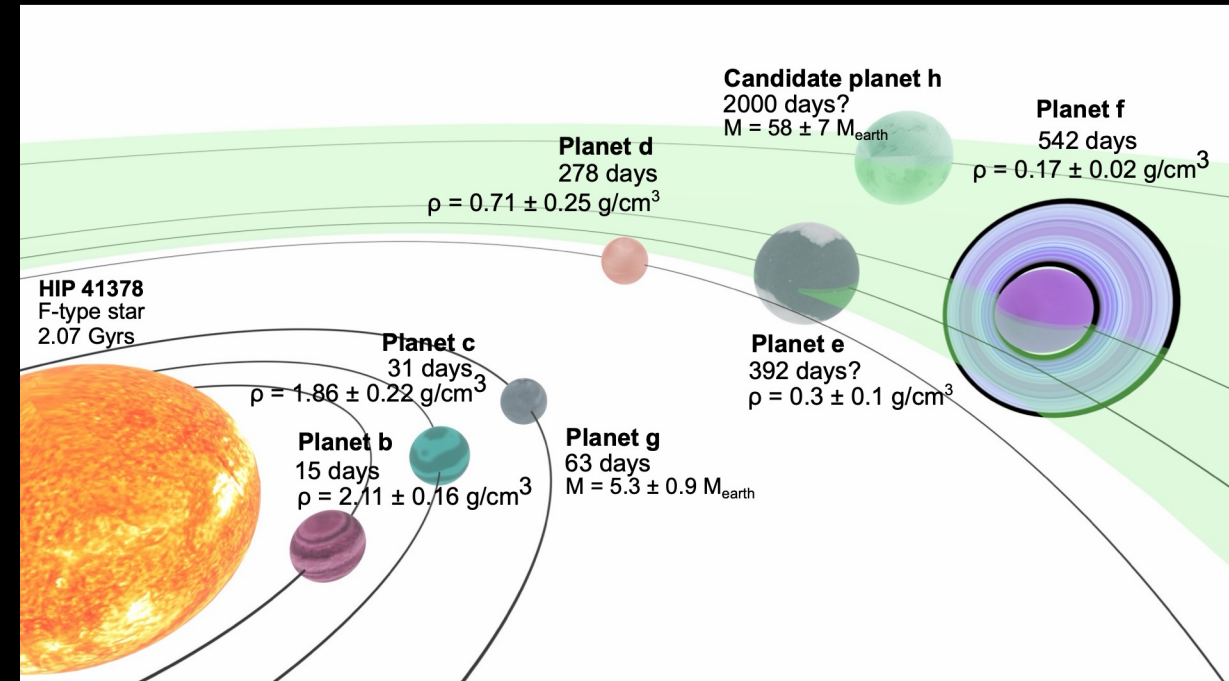
Conclusion



This system is a testbed for the PLATO mission and long-period planets detection

Stay tuned...

HIP 41378 f has not revealed all its secrets

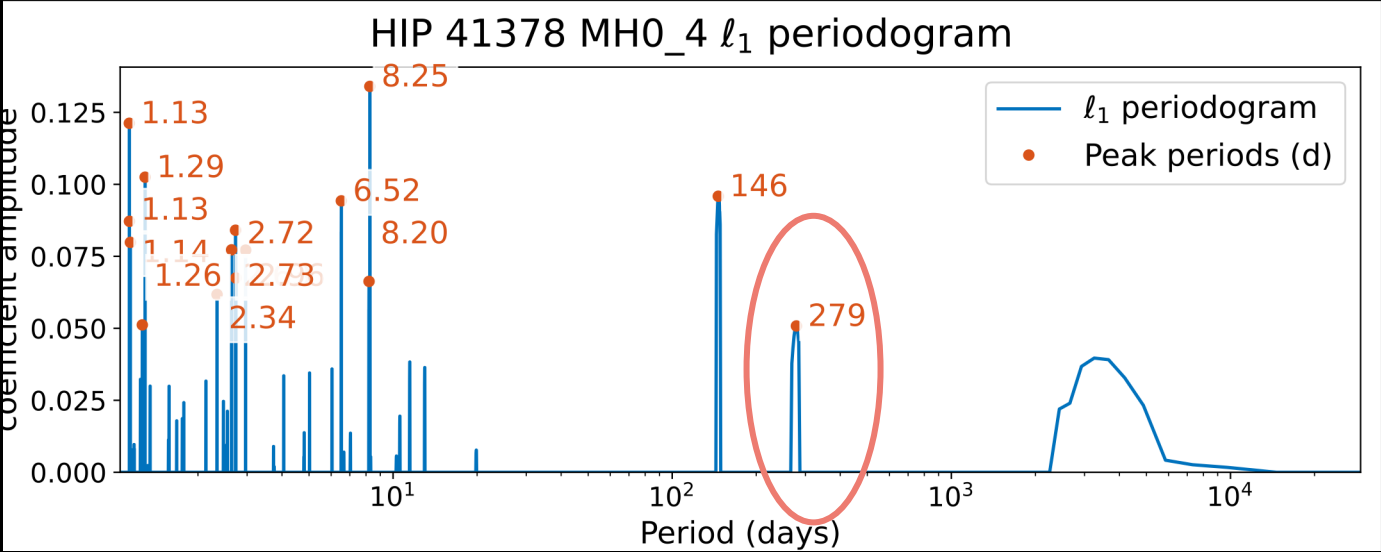


Annexes

What is the orbital period of planet d?



Every test converges toward a planet with an orbital period of 278 days



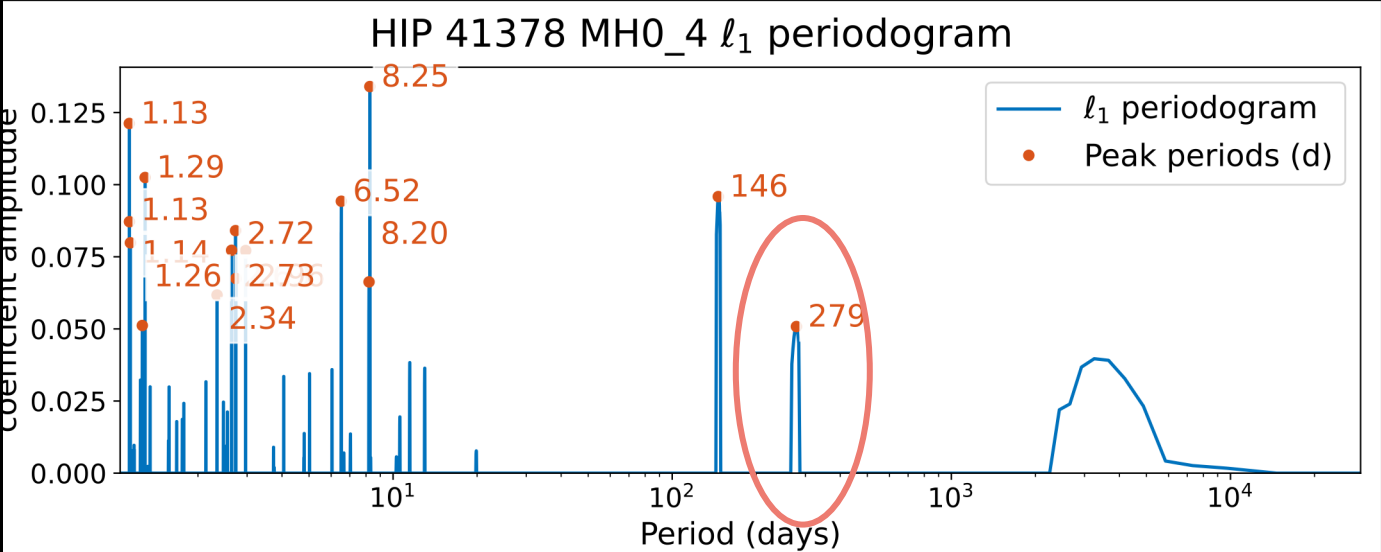
l_1 periodogram after removing planets b, c, g, f and h

Work in collaboration with Nathan Hara

What is the orbital period of planet d?

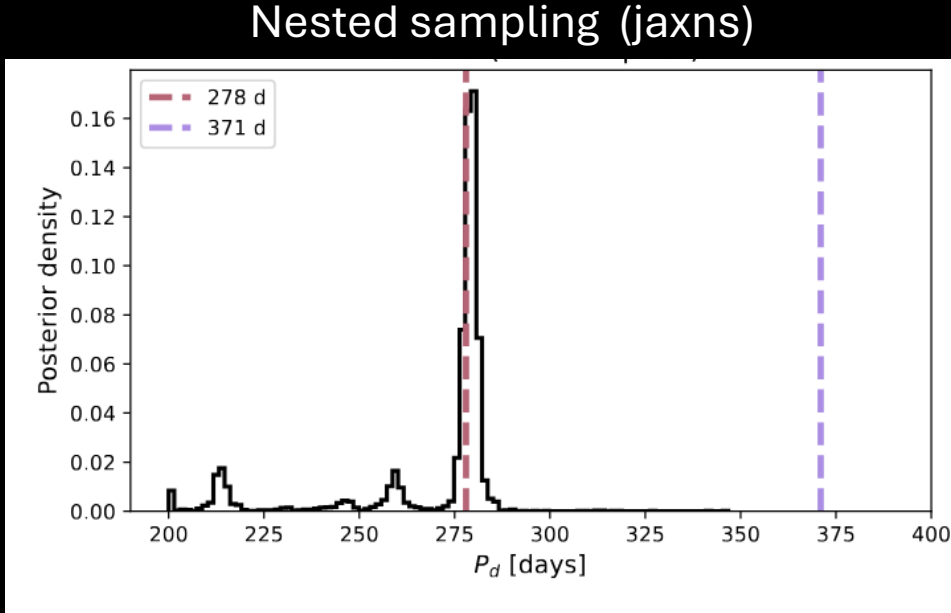
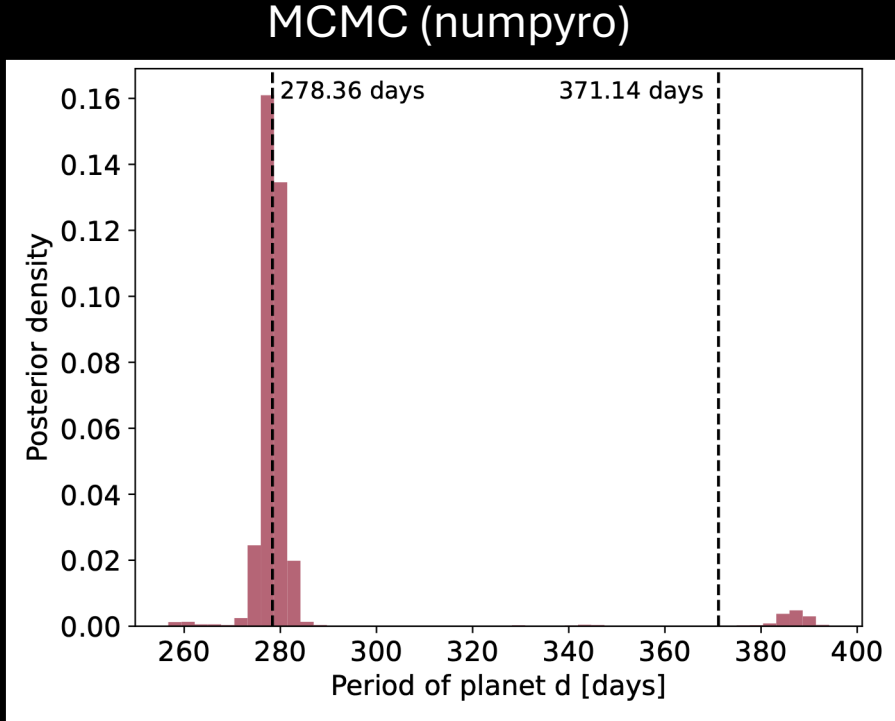


Every test converges toward a planet with an orbital period of 278 days



l_1 periodogram after removing planets b, c, g, f and h

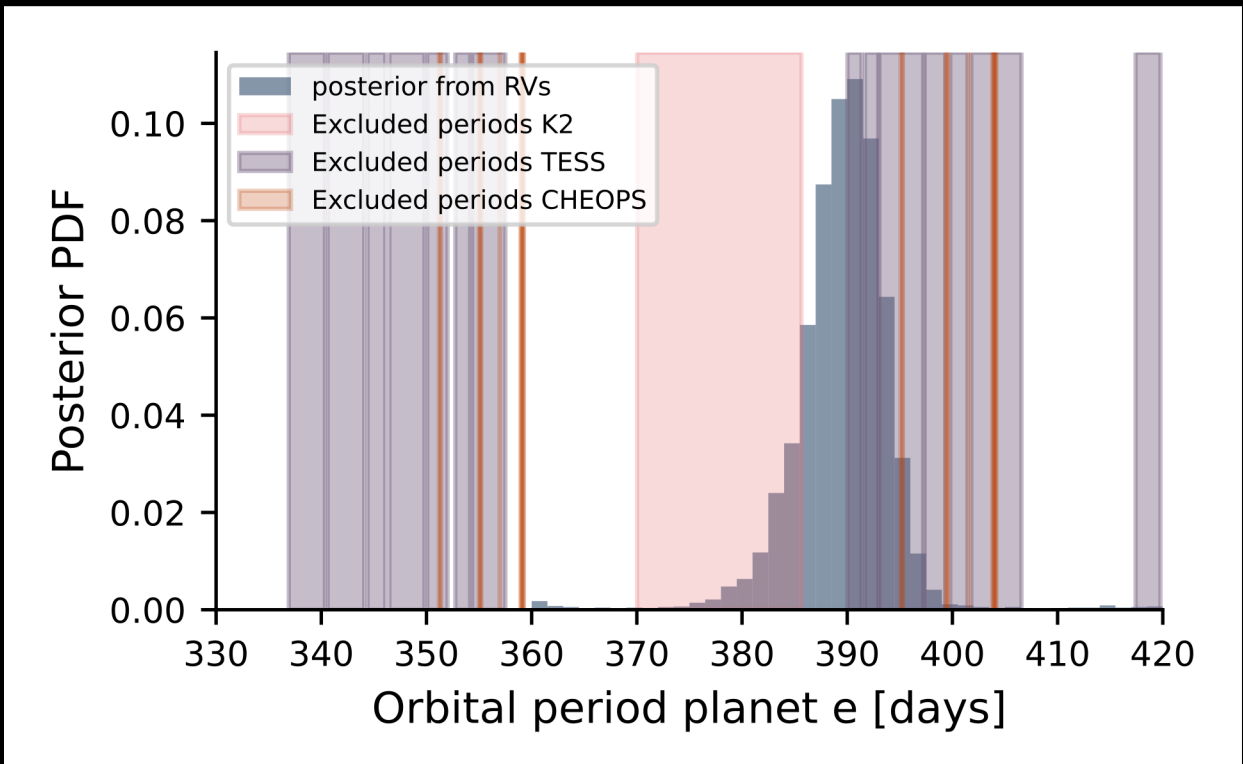
Code to model RV + photometry: jaxoplanet



What is the orbital period of planet e?



MCMC posterior with RV – only analysis

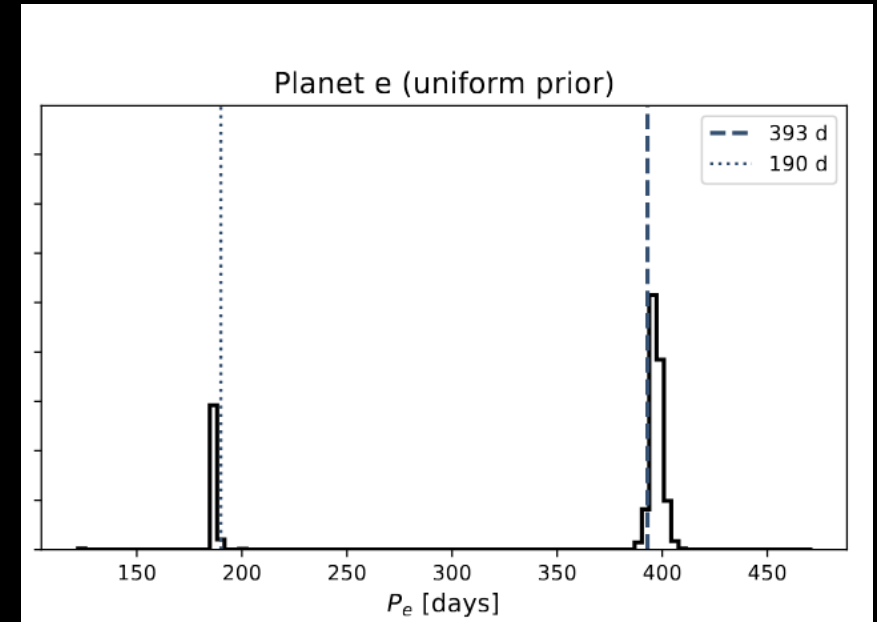
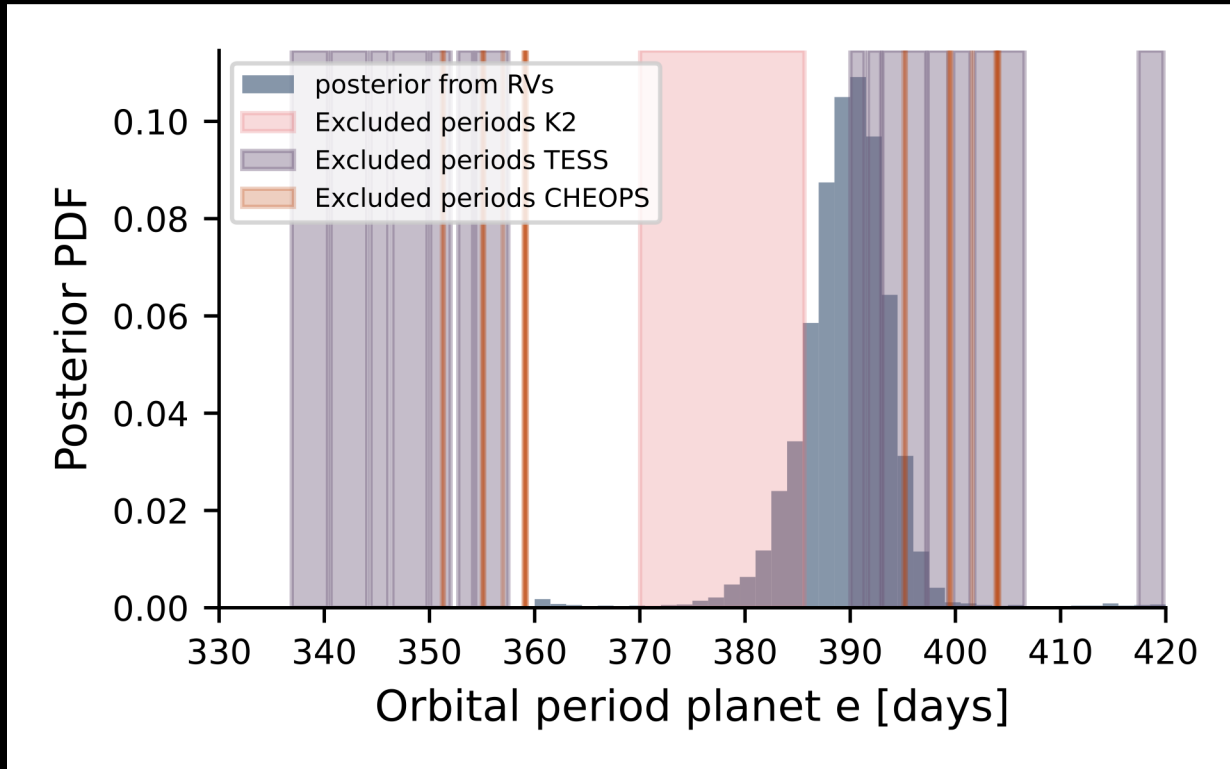


What is the orbital period of planet e?



Nested sampling and model comparison

MCMC posterior with RV – only analysis

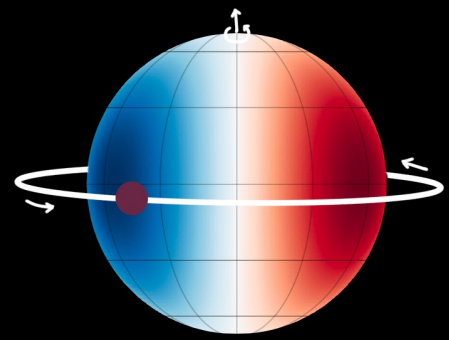
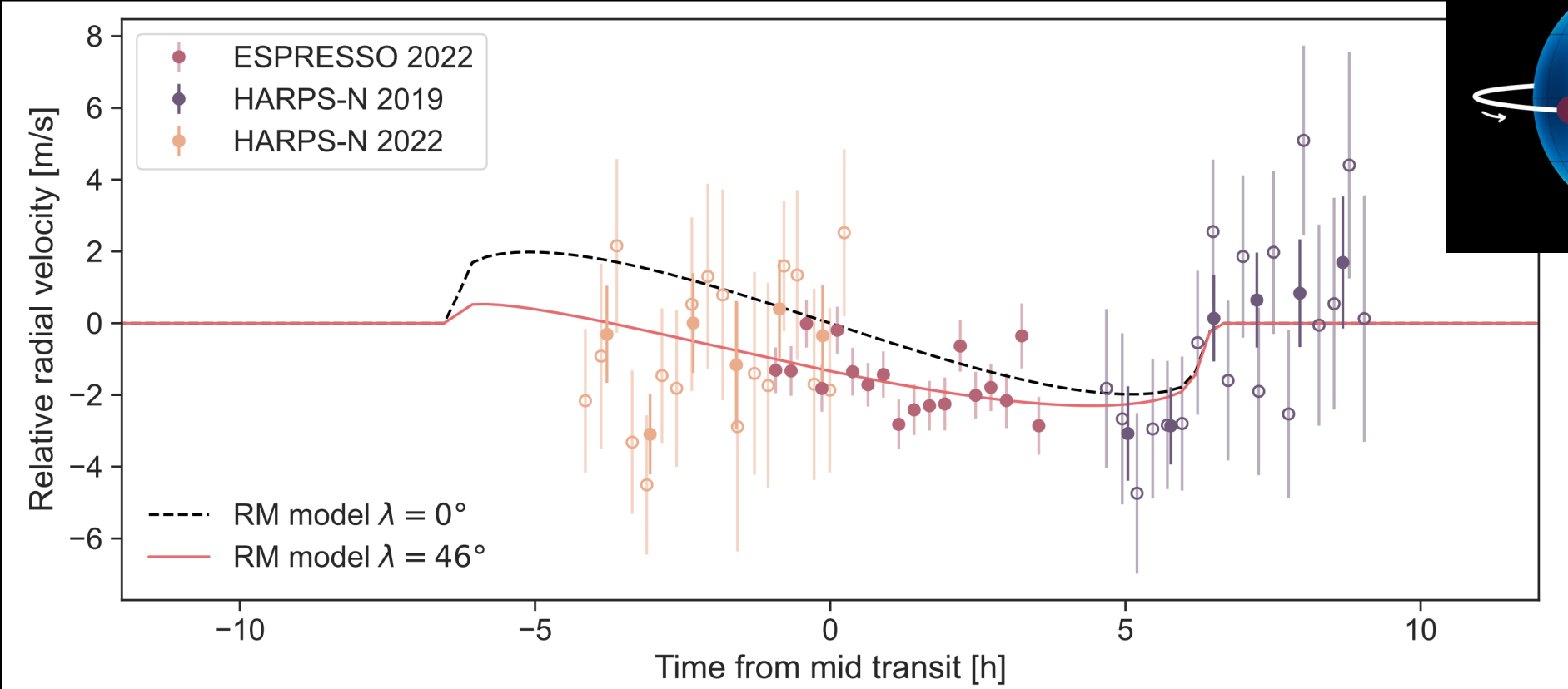


Planet order	$\log Z$	$\Delta \log Z$	ESS
$d - e - f$	8855.93 ± 0.40	0.0	5242
$e - d - f$	8849.43 ± 0.40	-6.50	4960
$d - f - e$	8841.23 ± 0.38	-14.70	4803

The orbital period of HIP 41378 d

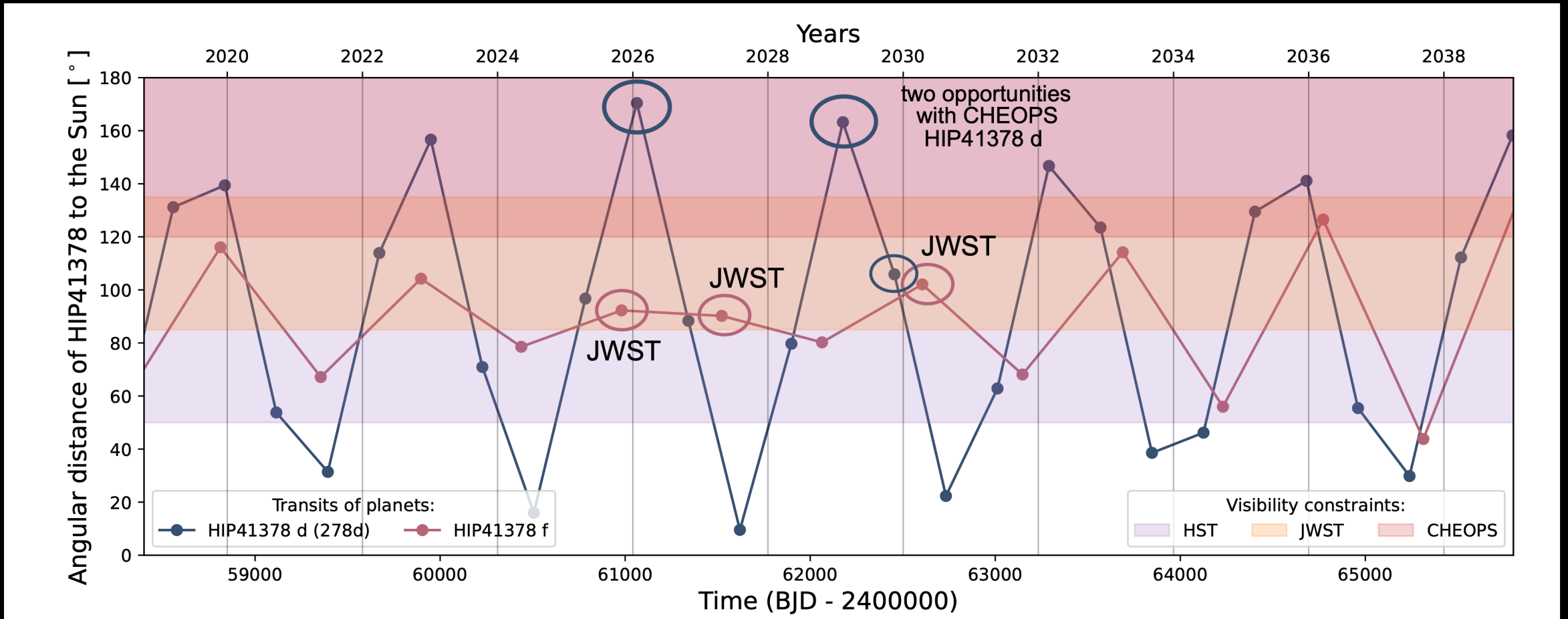


Rossiter-McLaughlin detection of the 9-month period transiting exoplanet HIP41378 d (Grouffal et al. 2022, published in A&A)



Tentative detection of the planet d is compatible with 278 days of orbital period

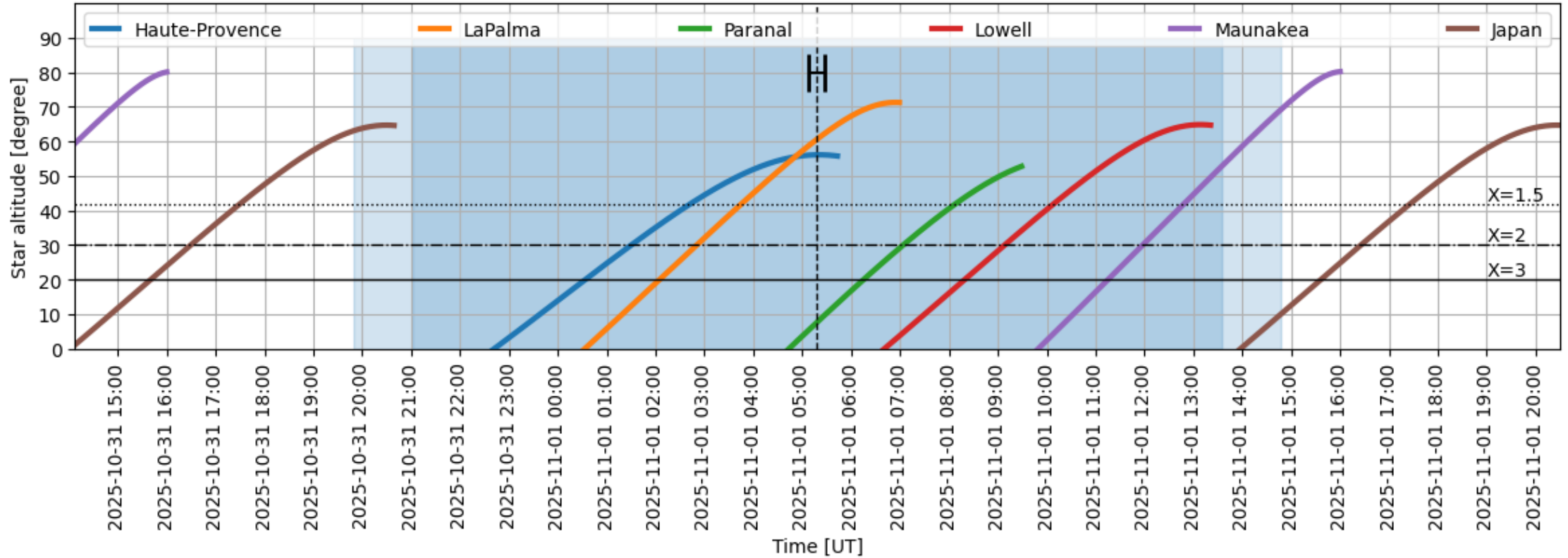
Observability HIP 41378



Observability HIP 41378



Visibility of HIP41378 during the transit of planet f on 2025-11-1



Could we directly image planet in the future?

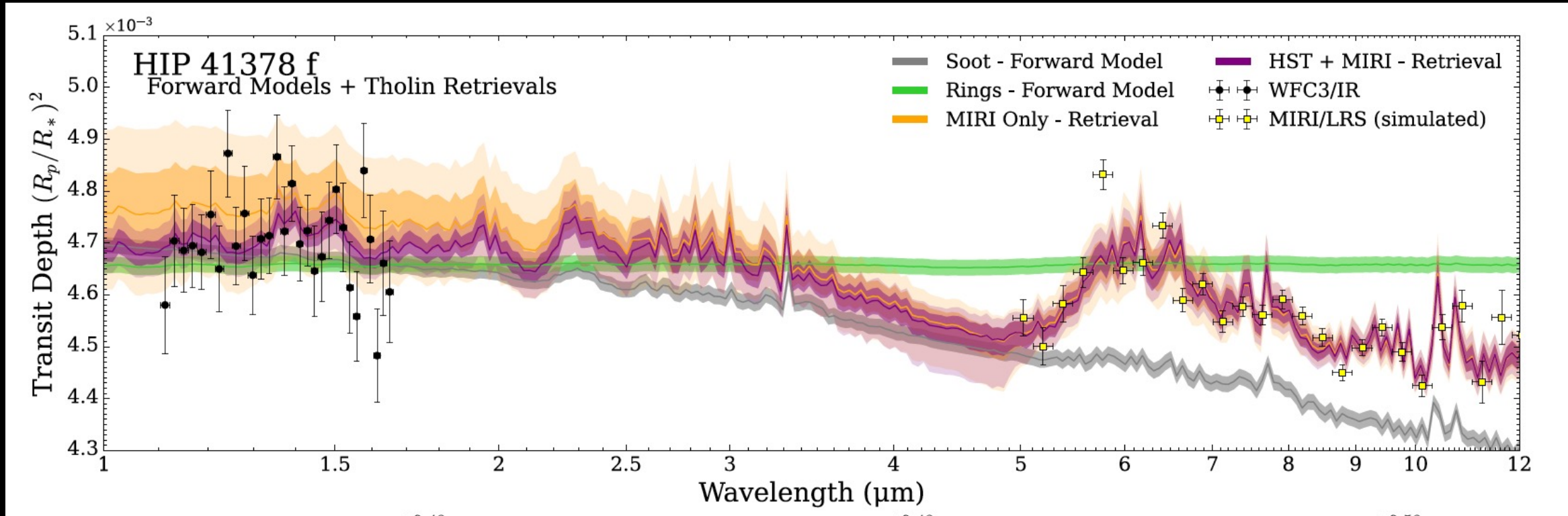


$$\frac{F_p}{F_*} \approx A_g \left(\frac{R_p}{a} \right)^2 \phi \quad \text{Reflected light contrast}$$

Albedo	Contrast
0.04 (very dark)	1.6×10^{-9}
0.20 (moderate)	8×10^{-9}
0.50 (high)	2.0×10^{-8}

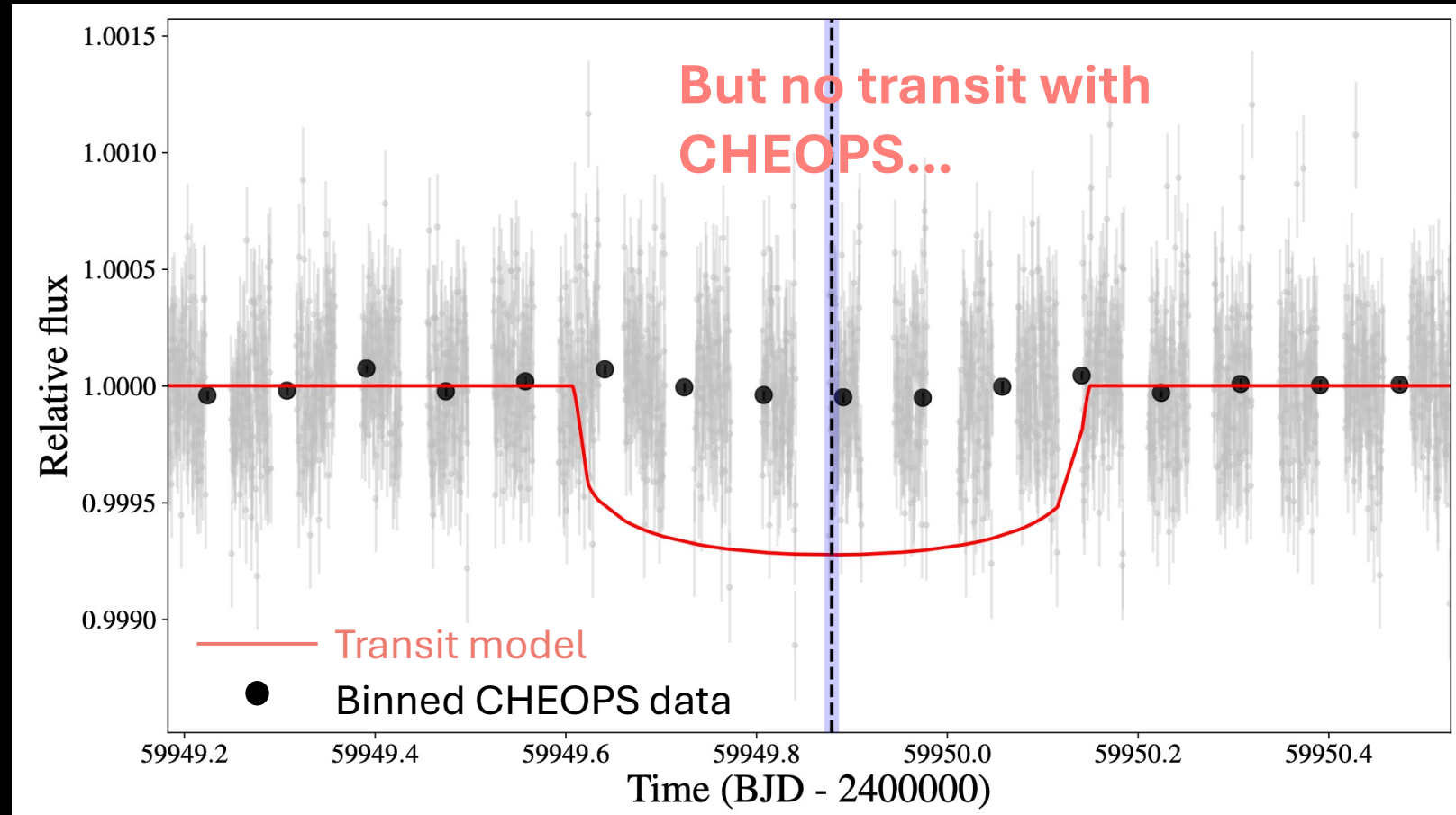
Plausible detection if we achieve the precision expected for PCS

Limit for PCS below 15 mas: $\approx 10^{-8}$

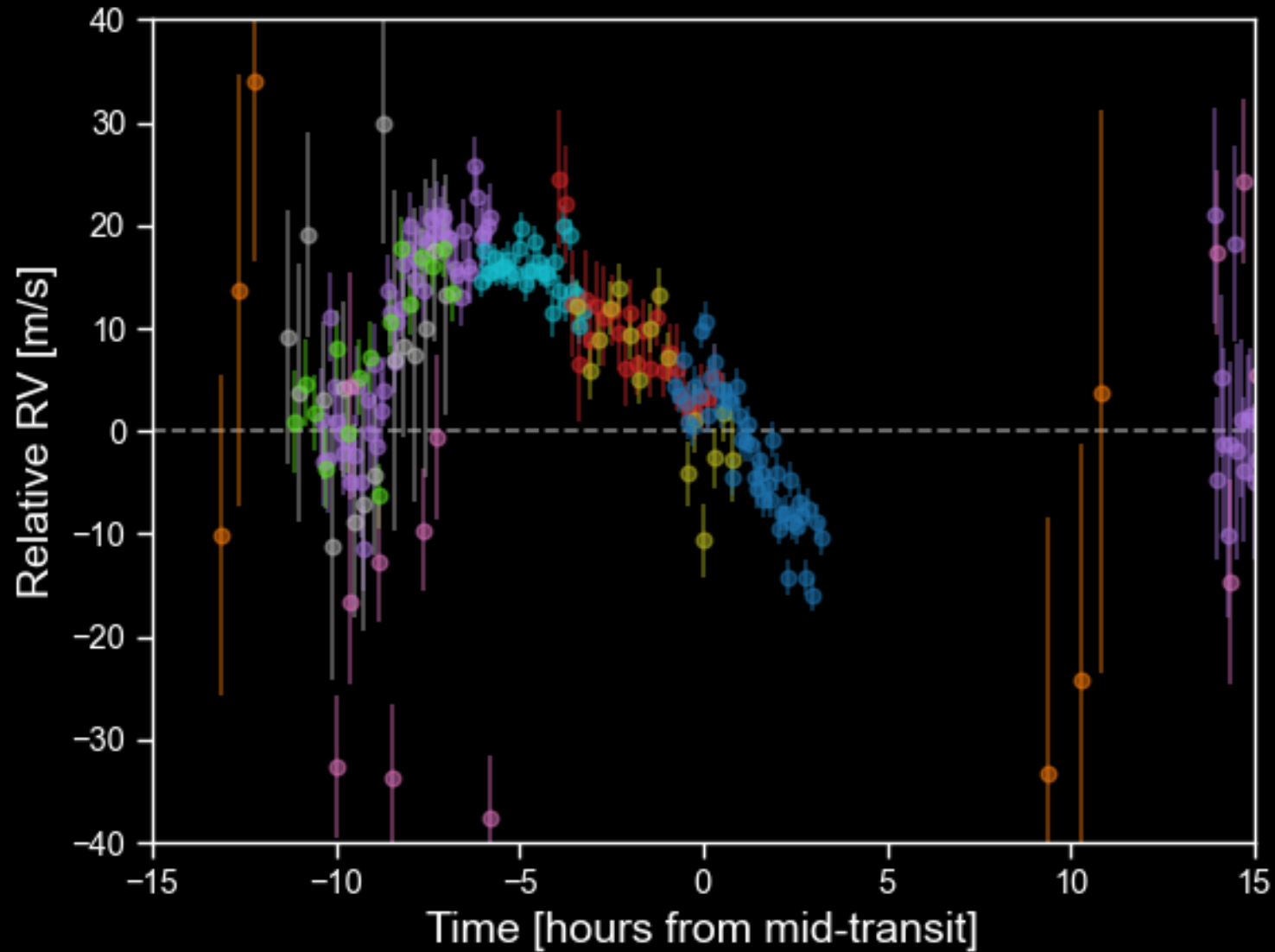


Alam, proposal JWST

The orbital period of HIP 41378 d



Rossiter-McLaughlin effect: transit follow-up



CARMENES

HARPS-N

MAHPS

ESPRESSO

NEID

EXPRES

HIRES

HERMES

PARAS

Transit Timing Variations



The external system

Prediction of future transits considering TTVs and mean-motion resonance between the planets

