

TESS warm-Jovian exoplanets with strong TTVs

Trifon Trifonov

Landessternwarte, Zentrum für Astronomie der Universität Heidelberg

Detection and Dynamics of Exoplanets
Coimbra, Portugal

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The WINE collaboration team

Nestor Espinoza

Martin Schlecker

HE UNIVERSITY OF ARIZONA

Rafael Brahm (PI)

INSTITUTO MILENIO DE ASTROFISICA

UNIVERSIDAD ADOLFO IBÁÑEZ

Andrés Jordán

Felipe Rojas

Marcelo Tala Pinto

Thomas Henning

Melissa Hobson

Trifon Trifonov

Jan Eberhardt

WINE
The **W**arm **G**iants with **TESS** Collaboration

Logos include: The University of Arizona 'A' logo, Instituto Milenio de Astrofísica logo, Universidad Adolfo Ibáñez logo, and the WINE logo featuring a stylized planet with a ring.

Warm Jovian (WJ) exoplanet – ideal for RV validation

- **Large Radii:** WJs planet pairs have large radii, making their transits easier to detect with the TESS telescope.
- **RV Detectability:** The high masses and short periods (small a) of WJs induce strong RV signals, allowing for mass and eccentricity measurements through ground-based RV observations.

Main goal: Occurance rate, mass and eccentricity distribution of Warm Jovain planets

WINE results so far:

- **11** Warm Jupiters discovered and published by WINE.
- **11** other confirmed Warm Jupiters in prep by WINE.
- WINE has contributed data to the discovery of other **15** WJs.
- **350** active Warm Jupiter candidates under follow-up by WINE.

Tools

- TESSERACT pipeline: generation of light curves from the TESS FFIs, identification of candidates and single transitters.
- CERES: Homogeneous and automatic processing of echelle data.
- ZASPE: Stellar characterization.
- JULIET: Bayesian joint light curve and radial velocity modeling
- SINGLE: Prediction of orbital periods for single
- CHERCAN: Web based tool for managing candidates, observations, and data

The Exo-Striker



- Data modeling
- Long-term stability
- MMR analysis
- and many more!

Available on the GitHub <https://github.com/3fon3fonov/exostriker>

The Exo-Striker: Transit and Radial velocity Interactive Fitting tool for Orbital analysis and N-body simulations

File Edit View Settings Help

RV Transit TTV Activity Sample corr. Orb. Evol.

RVs RVs o-c GLS GLS o-c MLP Window (DFT)

RV [m/s]

BJD [days]

Stellar mass 2.8000
Epoch [JD] 2451853.595
rms [m/s] 10.6376
wrms [m/s] 9.4017
 χ^2 212.3236
 χ^2_{red} 1.1294
lnL -751.2041
BIC 1587.50
AIC 1470.41
N data 204
DOF 188
AMD stable ●

More stat. info

Simplex LM
 Dynamical Keplerian

Initialize Fit

Run MCMC Run Nest.samp.
Run orb. evol RV Auto fit

e,u,Ma h,k,l

Planet param. GP param. Limits and Priors Stellar param. Models param. N-body Plot opt.

Planets 1-3 Planets 4-6 Planets 7-9

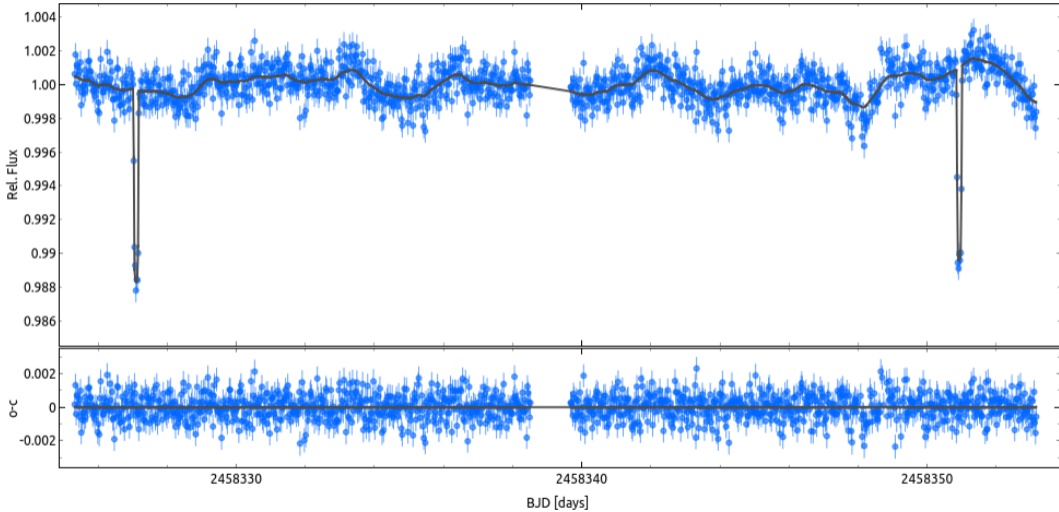
Planet 1	Planet 2	Planet 3
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<input checked="" type="checkbox"/> K [m/s] 288.29568259 +/- 0.424	<input checked="" type="checkbox"/> 176.63716043 +/- 0.314	<input type="checkbox"/> 50.00000000 +/- 0.000
<input checked="" type="checkbox"/> e 0.12421479 +/- 0.007	<input checked="" type="checkbox"/> 0.18001955 +/- 0.011	<input type="checkbox"/> 0.00000000 +/- 0.000
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<input checked="" type="checkbox"/> Ma 236.22706028 +/- 0.355	<input checked="" type="checkbox"/> 222.10464166 +/- 0.190	<input type="checkbox"/> 0.00000000 +/- 0.000
<input type="checkbox"/> incl [deg] 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000
<input type="checkbox"/> Ω [deg] 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000
<input type="checkbox"/> $\dot{\omega}$ [deg/yr] 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000
<input type="checkbox"/> t_0 [d] 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000
<input type="checkbox"/> $R_{H\alpha}/R_*$ 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000
<input type="checkbox"/> a_{in} [au] 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000	<input type="checkbox"/> 0.00000000 +/- 0.000
<input type="checkbox"/> m [M_{Jup}] 1.811	6.004	0.000
<input type="checkbox"/> t_{in} [d] 22.749	25.265	0.000
	2451314.966	0.000

RV data Transit data TTVs Activity Limits and Priors

Offsets and jitters RV trend Data options

	Offset [m/s]	Jitter [m/s]
X hpb8048.vels	-49.27725 +/- 0.637	7.09387 +/- 0.519
X sb8048_sato12.w	0.71014 +/- 0.383	8.06206 +/- 0.440
X p88048_crires.v	982.20295 +/- 0.331	0.02621 +/- 0.223
X data 4	0.00000 +/- 0.000	0.00000 +/- 0.000
X data 5	0.00000 +/- 0.000	0.00000 +/- 0.000
X data 6	0.00000 +/- 0.000	0.00000 +/- 0.000
X data 7	0.00000 +/- 0.000	0.00000 +/- 0.000
X data 8	0.00000 +/- 0.000	0.00000 +/- 0.000
X data 9	0.00000 +/- 0.000	0.00000 +/- 0.000
X data 10	0.00000 +/- 0.000	0.00000 +/- 0.000

A typical example of TESS light curve revealing a WJ



Rather short baseline of ~ 27 days per Sector.

The power of WINE is in its Doppler follow up strategy

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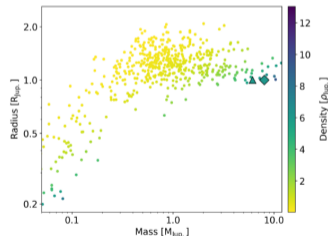
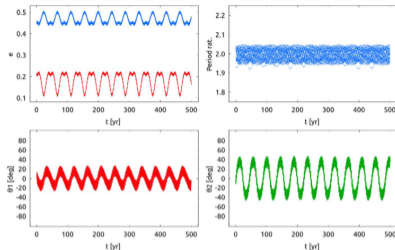
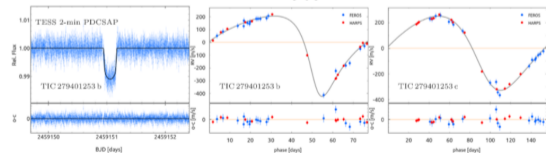
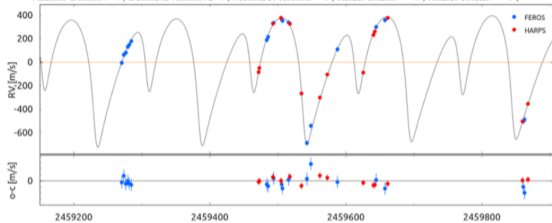
OPEN ACCESS

<https://doi.org/10.3847/2041-8213/acbd4f>



A 2:1 Mean-motion Resonance Super-Jovian Pair Revealed by TESS, FEROS, and HARPS*

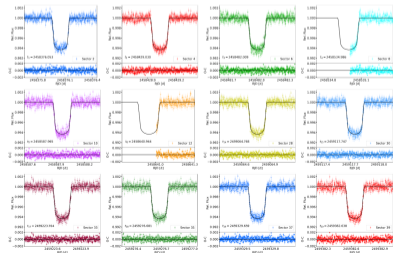
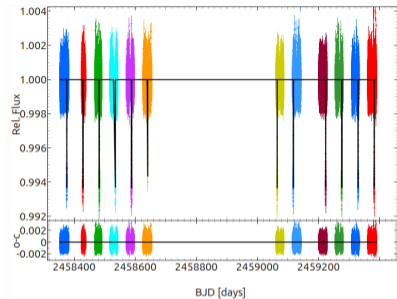
Vladimir Bozhilov¹, Desislava Antonova¹, Melissa J. Hobson^{2,3}, Rafael Brahm^{3,4,5}, Andrés Jordán^{3,4,5}



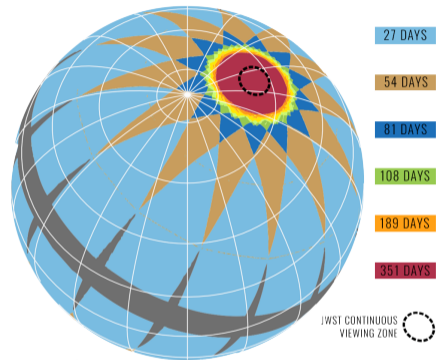
Even with one transit event, WINE RVs reveals interesting exoplanet systems!

$P_b \sim 11.91$ days, $M_b \sim 0.93 M_{JUP}$, $P_c \sim 24.75$ days, $M_c \sim 0.19 M_{JUP}$

TESS multi-sector data; ideal for a TTV search

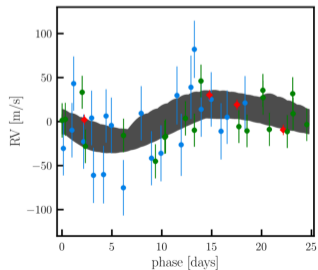
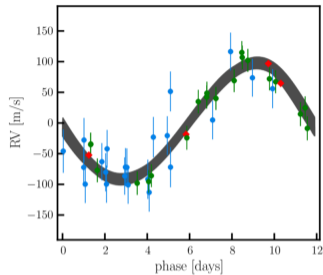
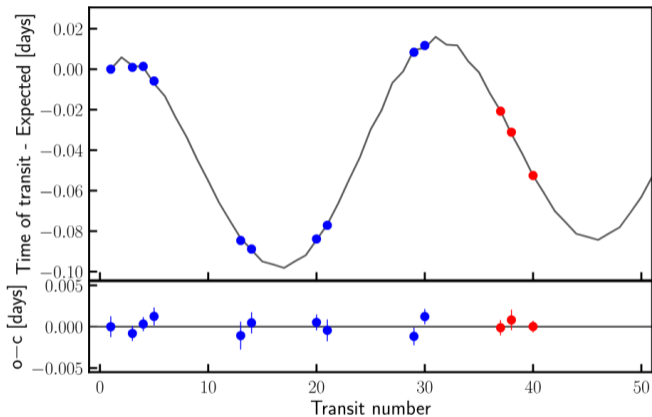


TESS 2-YEAR SKY COVERAGE MAP



- **Strong dynamical signals:** Massive WJ pairs produce large TTVs, ideal for dynamical modeling.
- **TTV + RV synergy:** Joint analysis constrains physical and orbital parameters, aiding planet formation studies.

The first WINE-TTV system: TOI-2202 (Trifonov et al. 2021)

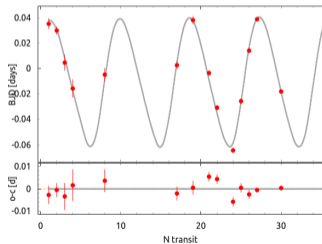
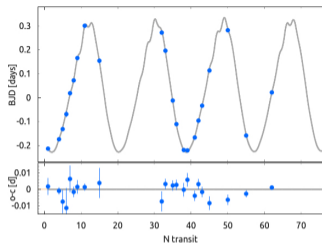
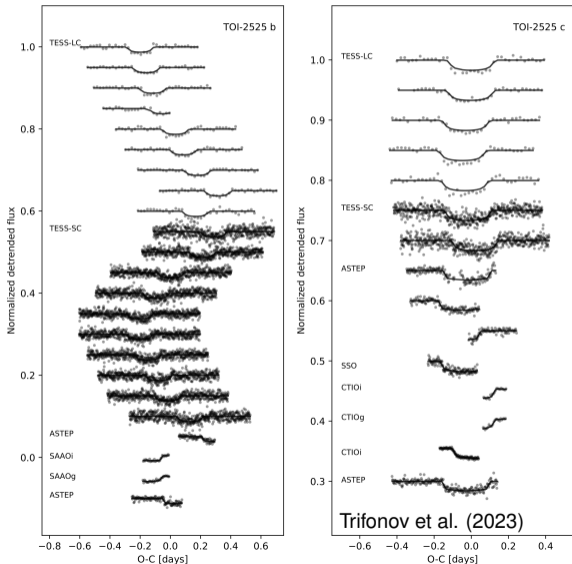


A pair of WJ near the 2:1 MMR around a K-dwarf

$P_b \sim 11.91$ days, $M_b \sim 0.93 M_{\text{Jup}}$

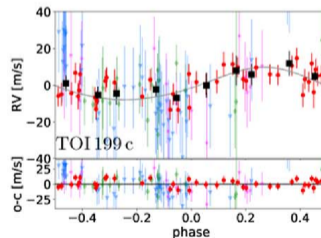
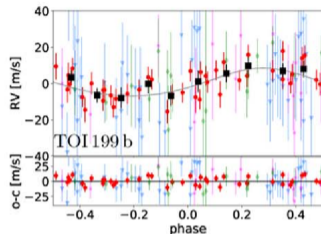
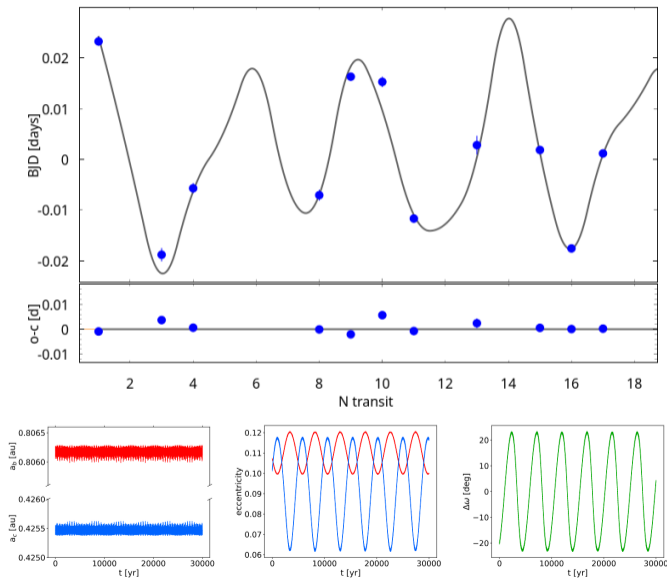
$P_c \sim 24.75$ days, $M_c \sim 0.19 M_{\text{Jup}}$

TOI-2525 – A pair of WJs with a strong TTV signal (Trifonov et al. 2023).



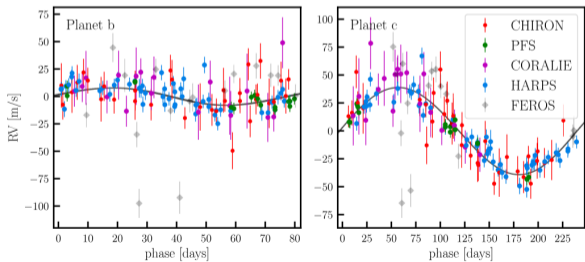
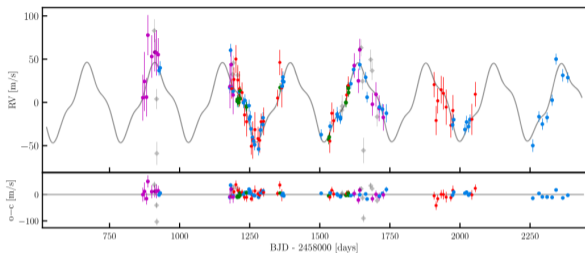
$P_b \sim 23.3$ days, $M_b \sim 0.09 M_{Jup}$
 $P_c \sim 49.3$ days, $M_c \sim 0.71 M_{Jup}$

TOI-199: A pair of WJs, the outer in the HZ (Hobson et al. 2023)



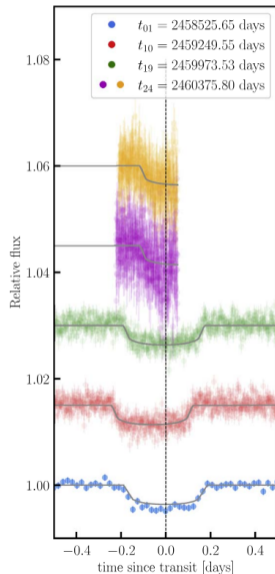
$P_b \sim 105$ days, $M_b \sim 0.17 M_{\text{Jup}}$
 $P_c \sim 274$ days, $M_c \sim 0.28 M_{\text{Jup}}$

TOI-6695: A pair of WJs, close to the 3:1 MMR (Eberhardt et al. 2025)

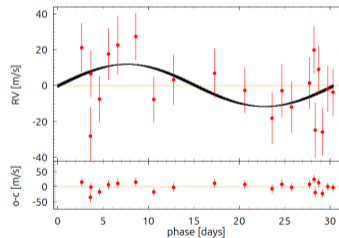
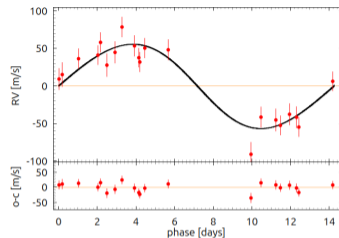
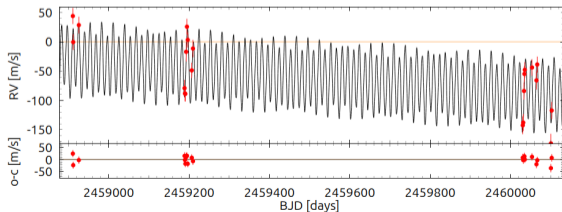
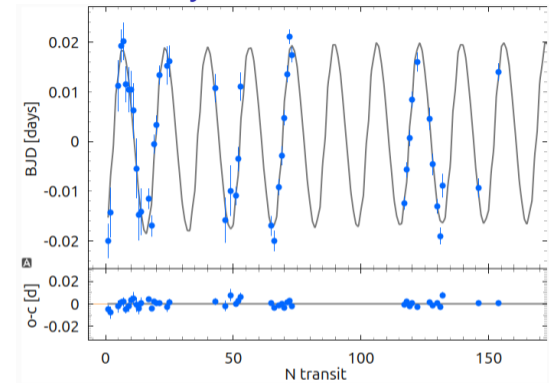


$P_b \sim 80.4$ days, $M_b \sim 0.21 M_{Jup}$

$P_c \sim 242.4$ days, $M_c \sim 1.45 M_{Jup}$

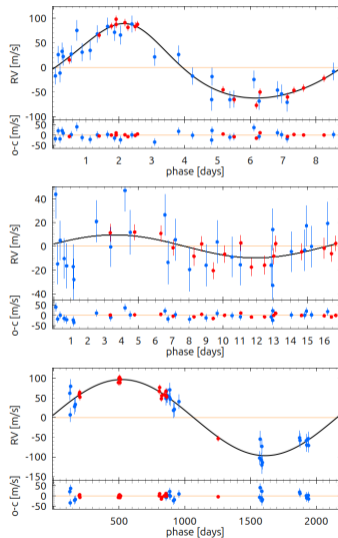
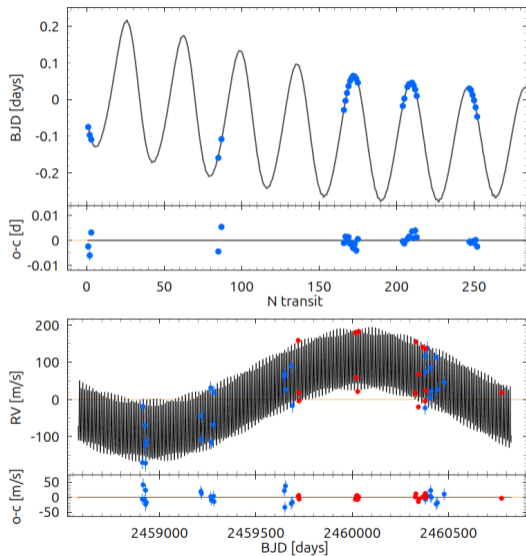


TOI-1232: TTV system near the 2:1 MMR (Mihylov et al. submitted)



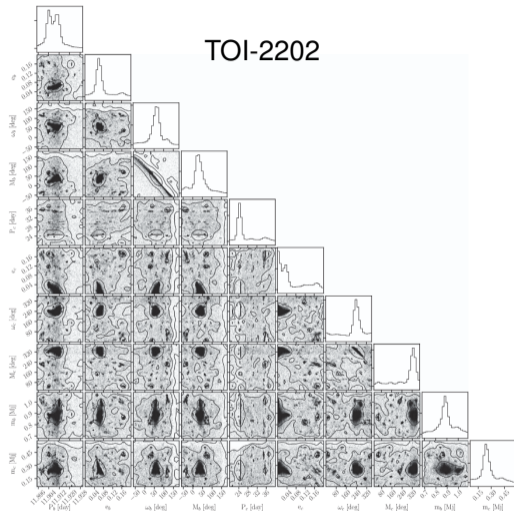
$P_b \sim 105$ days, $M_b \sim 0.17 M_{Jup}$
 $P_c \sim 274$ days, $M_c \sim 0.28 M_{Jup}$

TOI-XXXX: TTV system near the 2:1 MMR (Stefanov et al. in prep.)

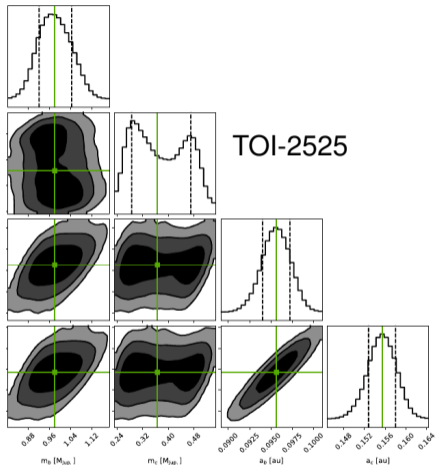


$P_b \sim 8.7$ days, $M_b \sim 0.76 M_{\text{Jup}}$, $P_c \sim 17.2$ days, $M_c \sim 0.1-0.4 M_{\text{Jup}}$, $P_b \sim 2200$ days, $M_b \sim 6.1 M_{\text{Jup}}$

Transit-timing degeneracies



Typical TTV parameter landscape. Strong multimodality makes it difficult to pinpoint the actual solution.



Photodynamical modeling is better, but even then we find posterior multimodality

The WINE-TTV systems up to mid-2025

System	Stellar host	P_b [d]	P_c [d]	$\hat{P}_{\text{rat.}}$	Planet type	resonant
TOI-216	K8V, 0.77 M_{\odot}	17.1	34.5	2.02	Nep,Jup	Yes
TOI-2202	K8V, 0.82 M_{\odot}	11.9	23.8	2.06	Jup,Sat	No
TOI-2525	K8V, 0.85 M_{\odot}	23.3	49.3	2.12	Nep,Jup	No
TOI-6695	G0V, 1.34 M_{\odot}	80.4	242.4	3.02	Sat,Jup	No
TOI-1232	G2V, 1.06 M_{\odot}	14.3	30.3	2.12	Jup,Sat	No
TOI-XXXX	G2V, 1.00 M_{\odot}	8.7	17.2	1.99	Jup,Nep,(+Jup)	No

The WINE-TTV systems up to mid-2025

System	Stellar host	P_b [d]	P_c [d]	$\hat{P}_{\text{rat.}}$	Planet type	resonant
TOI-216	K8V, 0.77 M_{\odot}	17.1	34.5	2.02	Nep,Jup	Yes
TOI-2202	K8V, 0.82 M_{\odot}	11.9	23.8	2.06	Jup,Sat	No
TOI-2525	K8V, 0.85 M_{\odot}	23.3	49.3	2.12	Nep,Jup	No
TOI-6695	G0V, 1.34 M_{\odot}	80.4	242.4	3.02	Sat,Jup	No
TOI-1232	G2V, 1.06 M_{\odot}	14.3	30.3	2.12	Jup,Sat	No
TOI-XXXX	G2V, 1.00 M_{\odot}	8.7	17.2	1.99	Jup,Nep,(+Jup)	No
TIC 279401253	G1V, 1.13 M_{\odot}	76.8	155.3	2.0	Jup,Jup	Yes
TOI-4504	K1V, 0.89 M_{\odot}	40.6	82.5	2.06	(+SE),Jup,Jup	Yes

TOI-4504 – the new King of the TTVs! See talk by Michaela Vítková

Conclusions

- TESS is capable of detecting TTV systems, but mostly sensitive to Warm-massive pairs of exoplanets with a strong TTV signal.
- Degeneracy in mass-eccentricity, eccentricity-eccentricity, and even Period ratio (for non-transiting perturbers) do exist and are strong.
- Photodynamical models and additional RV data are necessary for these TESS TTVs systems.
- The WINE survey is extremely productive.