



On the resonant multi-planet system TOI-1408

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AMCM, 20 Aug 2026

TOI-1408: *history*

Planet b:

- initially was a **TESS planet candidate** with orbital period $P_b \simeq 4.42 d$, radius $r_b = 0.700 \pm 0.055 R_{Jup}$;

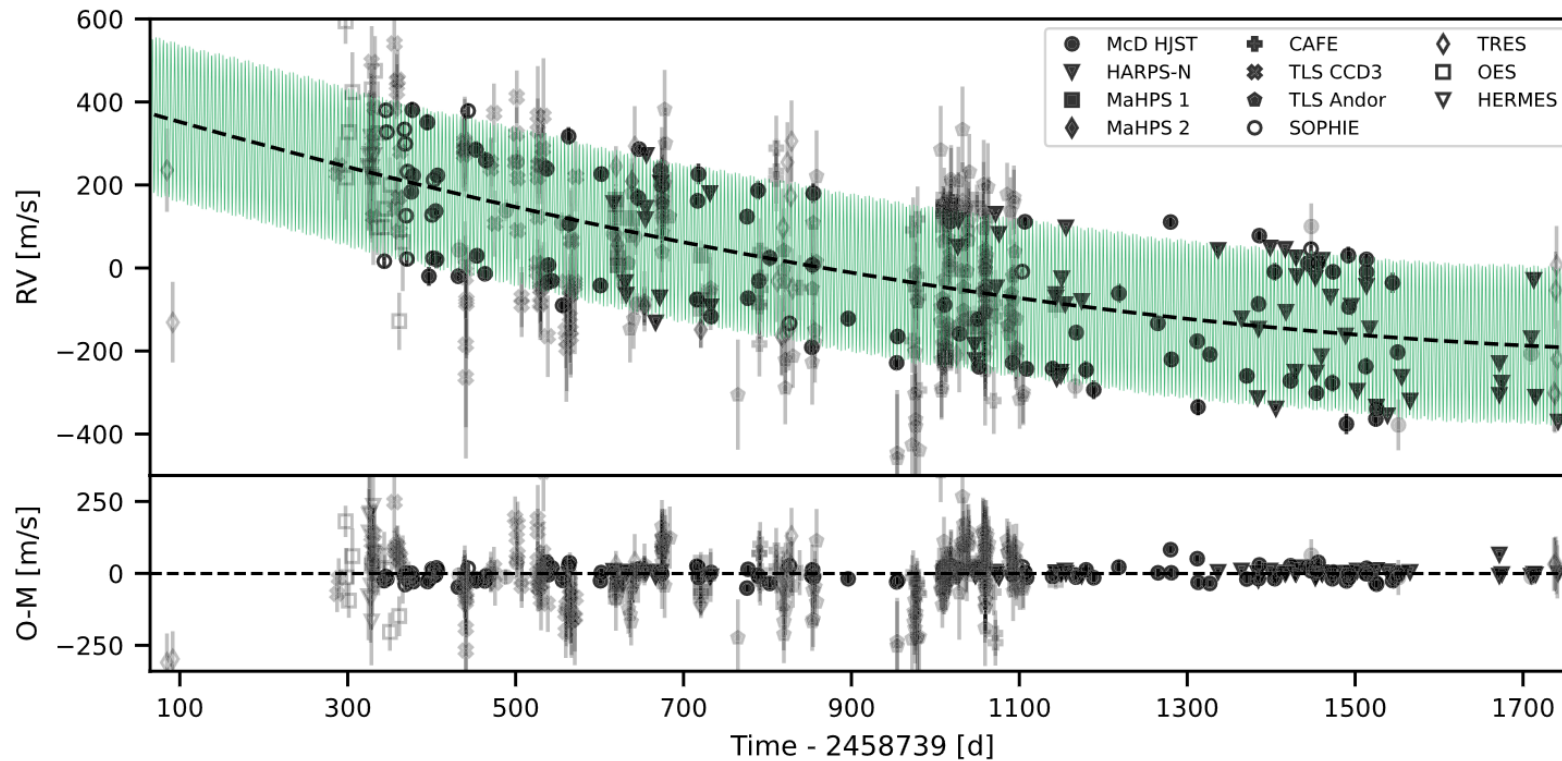
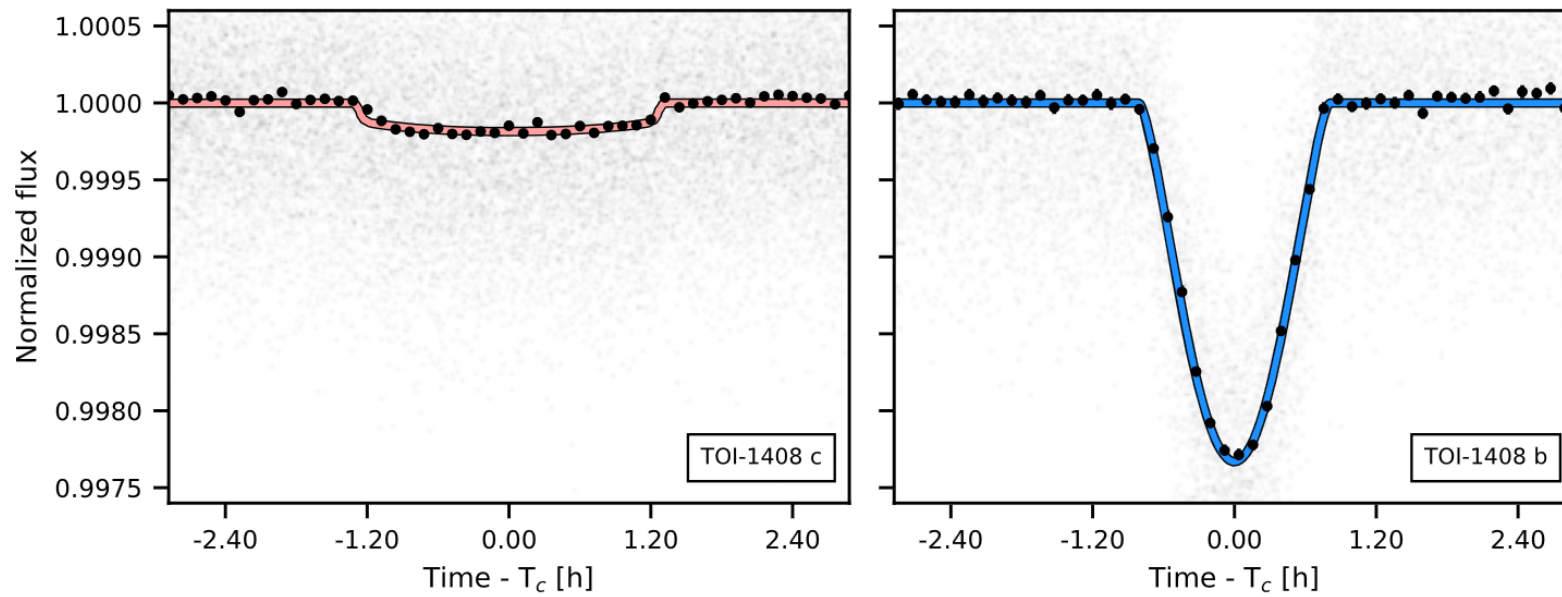
confirmed by **FFOREST Doppler** observations at 6-m BTA SAO RAS (**Galazutdinov**, Baluev, Valyavin et al. **2023**, MNRAS, 525, L111), who provided the first ever **mass** estimation $m_b = (1.69 \pm 0.20) M_{Jup}$ and reported a non-zero orbital **eccentricity** $e_b \simeq 0.25$, but the **radius** appeared ill-fitted because of the near-tangential transit geometry (low limit $r_b > 1 R_{Jup}$).

Planets c and d(?):

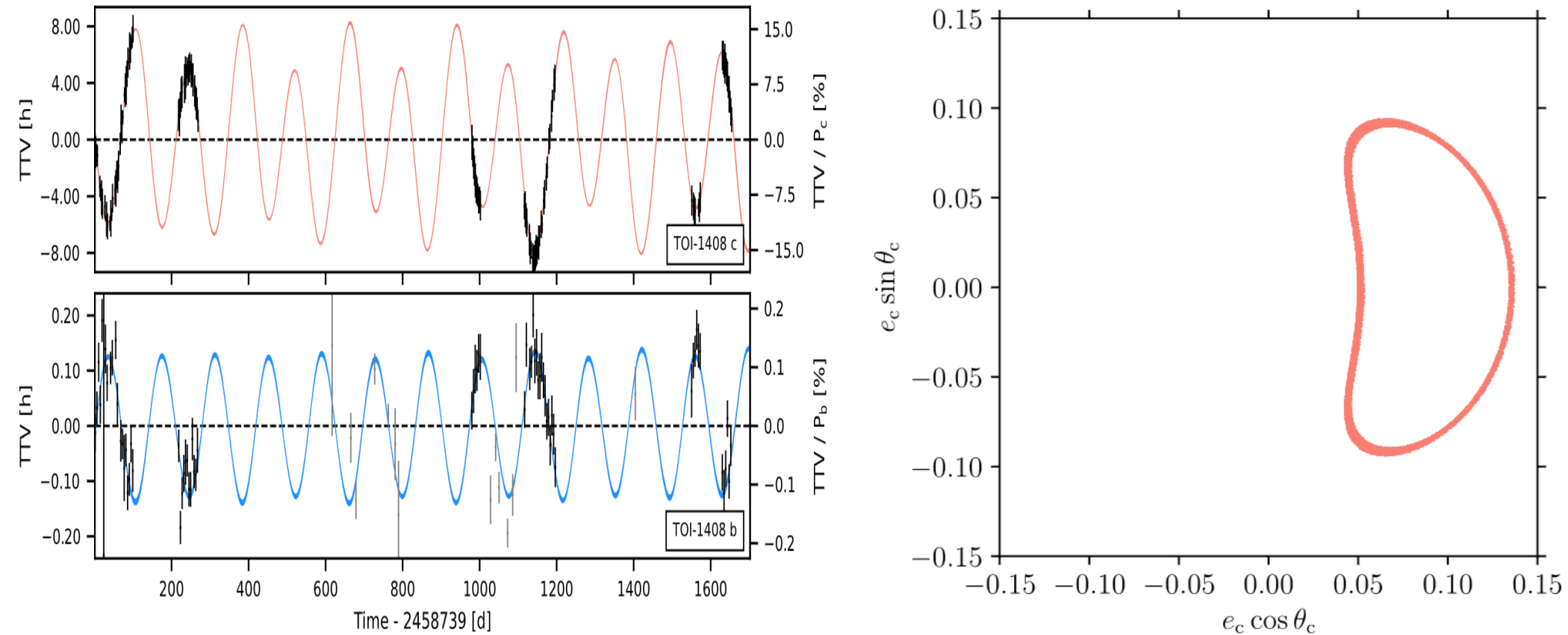
Korth, Chaturvedi, Parviainen et al. (**2024**, ApJ, 971, L28) presented a massive set of new Doppler and ground-based transit observations, acquired at multiple sites, reporting **two planets** orbiting in 2:1 MMR (with **small inner planet** c having $r_c = (2.22 \pm 0.06) R_{\oplus}$) and a long-term nonlinear **Doppler trend** indicating the existence of yet more unseen companion(s).

Multi-planet resonance system

From Korth
et al. (2024)



Perturbed dynamics is directly observable via transit timing variations

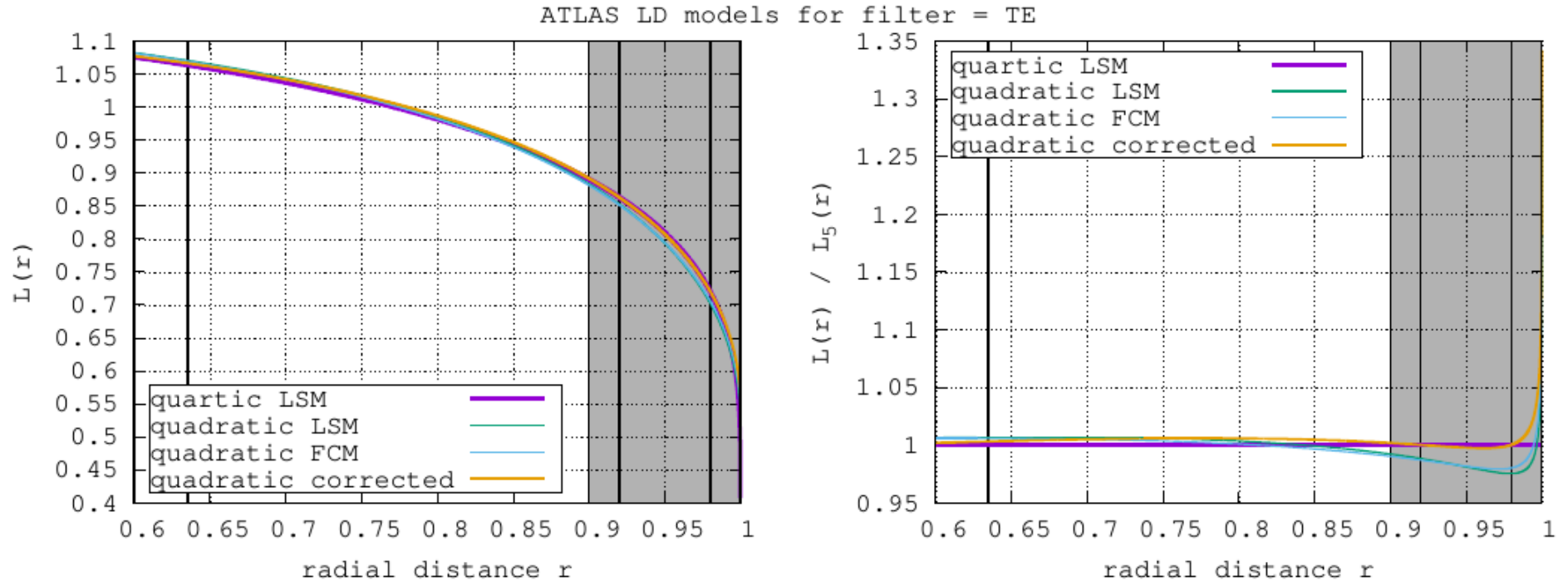


From Korth et al. (2024)

Remaining issues

- 1) **The limb darkening law** should adequately reproduce the near-limb range, because of the near-tangential geometry of the planet b transit.
- 2) **The star's astrophysical mass and radius** assessments appear quite different in Galazutdinov et al. (2023) and Korth et al. (2024). It is necessary to verify how they may affect the derived system parameters.
- 3) **Doppler and photometric noises, possible systematic errors** in the data were not investigated in previous works well enough.
- 4) **More TESS observations** appeared since Korth et al. (2024) which need to be included in the analysis.

1. Limb darkening law



from [Claret & Bloemen \(2011\)](#); [Claret \(2017\)](#):

$$\frac{I_2(r)}{I(0)} = 1 - a(1 - \mu) - b(1 - \mu)^2, \quad \frac{I_5(r)}{I(0)} = 1 - \sum_{k=1}^4 a_k \left(1 - \mu^{\frac{k}{2}}\right),$$

where $\mu = \sqrt{1 - r^2}$ and r is the distance from stellar disc center (assuming $R_{\text{star}} = 1$).

1. Limb darkening law

Filter	a_1	a_2	a_3	a_4	Lev-1 error*	a	b	Lev-2 error*
(uncertainties are level-1, given in brackets)								
TESS	0.516(33)	0.268(85)	-0.137(104)	0.000(43)	0.0048	0.209(8)	0.312(4)	0.0057
Sloan								
u	0.348(55)	0.519(190)	0.209(232)	-0.198(85)	0.0135	0.566(28)	0.239(23)	0.0029
g	0.350(28)	0.684(98)	-0.227(133)	0.013(55)	0.0089	0.458(14)	0.274(9)	0.0050
r	0.448(30)	0.546(86)	-0.329(115)	0.062(48)	0.0066	0.284(10)	0.327(5)	0.0061
i	0.515(33)	0.284(86)	-0.152(107)	0.005(44)	0.0051	0.209(8)	0.315(4)	0.0058
z	0.560(34)	0.080(81)	0.004(95)	-0.049(38)	0.0039	0.160(7)	0.302(4)	0.0054
Johnson-Cousins								
U	0.368(55)	0.431(185)	0.313(223)	-0.232(81)	0.0122	0.582(27)	0.223(22)	0.0025
B	0.348(32)	0.574(112)	0.004(144)	-0.078(57)	0.0092	0.534(16)	0.233(11)	0.0039
V	0.403(29)	0.642(91)	-0.339(122)	0.064(51)	0.0074	0.354(12)	0.311(6)	0.0059
R	0.463(31)	0.488(86)	-0.296(112)	0.052(47)	0.0062	0.262(10)	0.326(4)	0.0061
I	0.535(34)	0.206(86)	-0.090(104)	-0.018(42)	0.0047	0.192(8)	0.312(4)	0.0056
J	0.509(24)	0.296(56)	-0.457(67)	0.174(29)	0.0032	0.066(4)	0.316(2)	0.0067
H	0.730(9)	-0.195(19)	-0.161(19)	0.113(8)	0.0026	-0.006(2)	0.310(3)	0.0073
K	0.556(16)	-0.025(39)	-0.244(49)	0.125(21)	0.0023	0.003(3)	0.264(1)	0.0060
Strömgren								
u	0.313(52)	0.622(176)	0.092(215)	-0.146(80)	0.0143	0.576(27)	0.236(21)	0.0031
v**	0.315(35)	0.810(92)	0.185(165)	-0.155(64)	0.2313	0.895(58)	0.194(15)	0.0034
b**	0.307(26)	0.532(130)	-0.340(130)	0.057(54)	0.0267	0.197(25)	0.274(9)	0.0045
y	0.401(29)	0.646(94)	-0.333(126)	0.060(53)	0.0076	0.361(12)	0.309(6)	0.0058

Notes: * See text for the definition of error measures. ** These lines may be unreliable; see text for a discussion.

Based on T_{eff} , $\log g$, and $[\text{Fe}/\text{H}]$ estimations by **Galazutdinov, Korotin, Poklad, Kazanina, Valyavin (2026, ApJ, submitted)** which were derived from the public HARPSN spectra.

2. *Star astrophysical (spectrum-derived) mass and radius*

- **Star mass M_*** is important because it **directly affects the dynamics** of the system (e.g. through scaling various secular periods).
- **Star radius R_*** directly affects the planet radii, and **implicitly affects the dynamics** through setting an absolute scale on the semimajor axes.
- **Whenever dynamical perturbations are directly observed**, M_* and R_* can be estimated from Doppler RV data and transit photometry (in combination), without resorting to astrophysical spectrum modelling.
- However, **in case of TOI-1408 this is partly broken** because of degeneracies caused by near-tangential transit geometry. Astrophysical estimations of M_* and R_* still may be useful because they may improve the accuracy of orbital parameters.
- In this work we test **newer estimations** by Galazutdinov et al. (2026, in press): $M_* = (1.35 \pm 0.04) M_\odot$ and $R_* = (1.50 \pm 0.05) R_\odot$. These were derived from the same HARPSN spectra as in (Korth et al., 2024), and appear similar but have larger (and more realistic) uncertainties thanks to combining multiple stellar models.

3. *Noises and systematic errors*

1) **Doppler data often revealed correlated noise.** We applied Gaussian Process (GP) models, using the following correlation functions:

$$k(t_i - t_j) = \sigma_{\text{white}}^2(s) \delta_{ij} + \sigma_{\text{red}}^2 \exp\left(\frac{|t_i - t_j|}{\tau_{\text{red}}}\right),$$

(except HARPSN data)

$$k(t_i - t_j) = \sigma_{\text{white}}^2(s) \delta_{ij} + \frac{\sigma_{\text{red}}^2}{1 + \frac{(t_i - t_j)^2}{\tau_{\text{red}}^2}},$$

(for HARPSN data)

Significant correlated noise was revealed in 6 Doppler datasets out of 12 available; the remaining datasets were modelled as usual white noise.

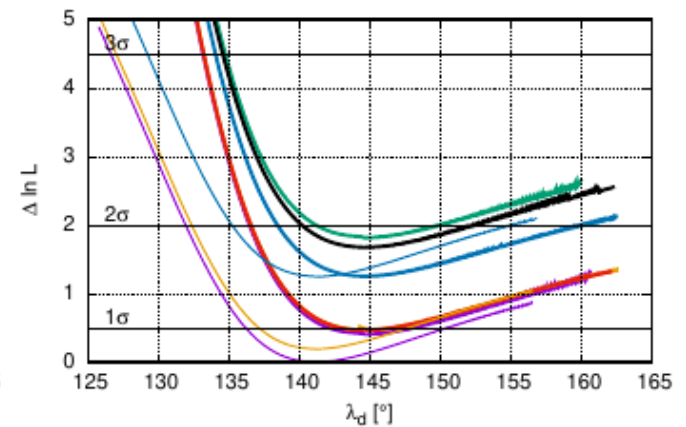
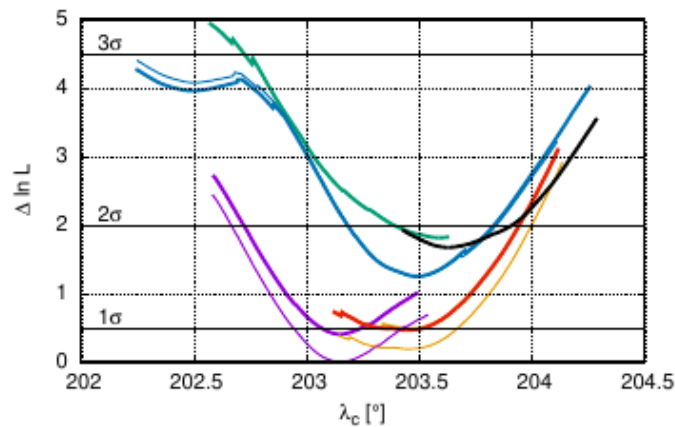
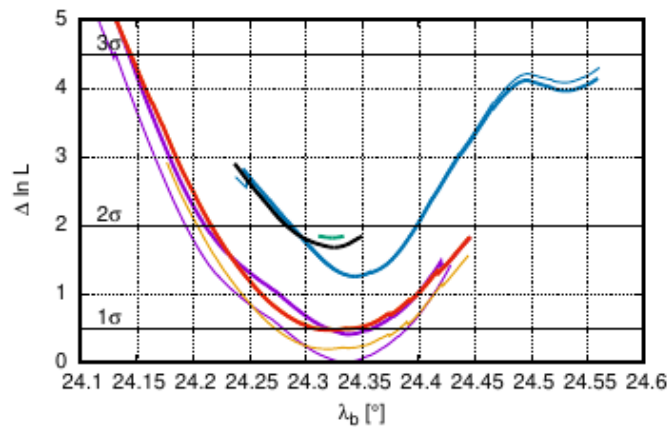
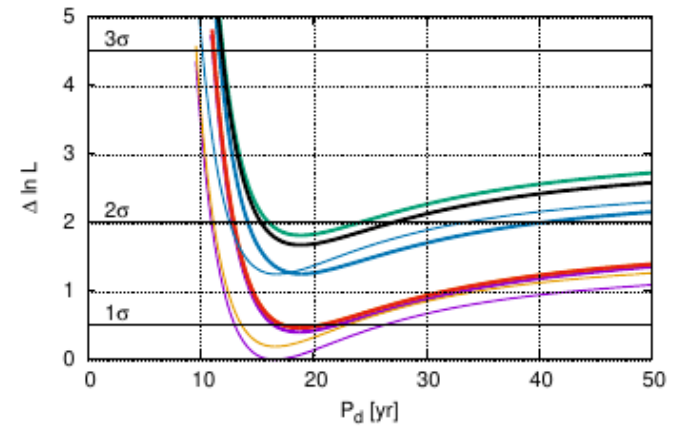
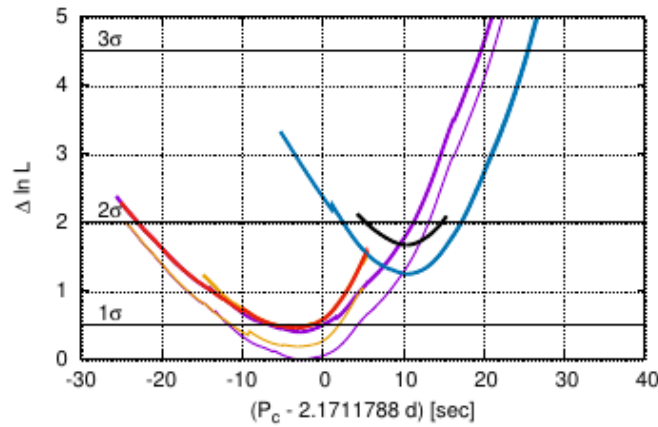
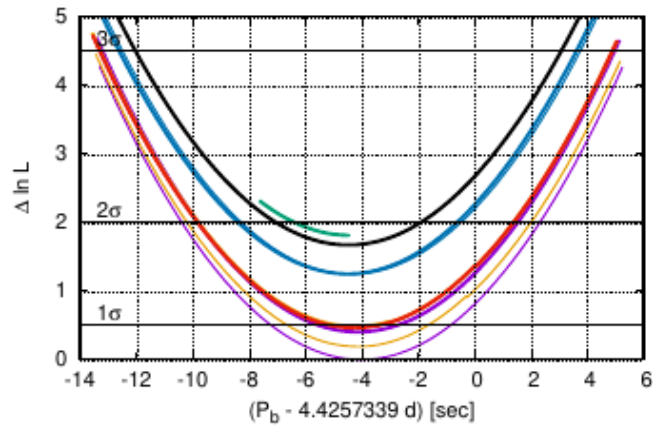
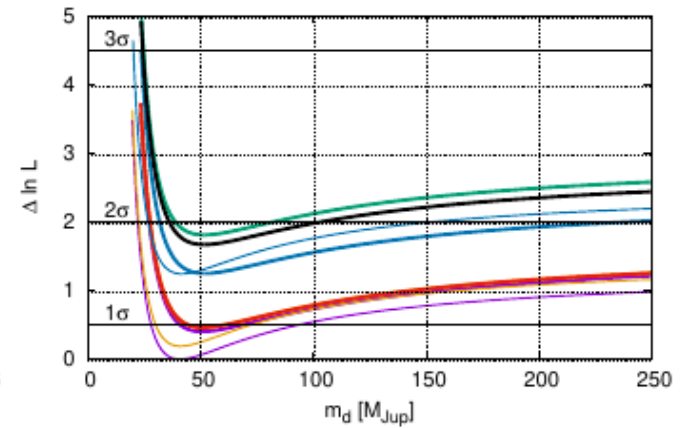
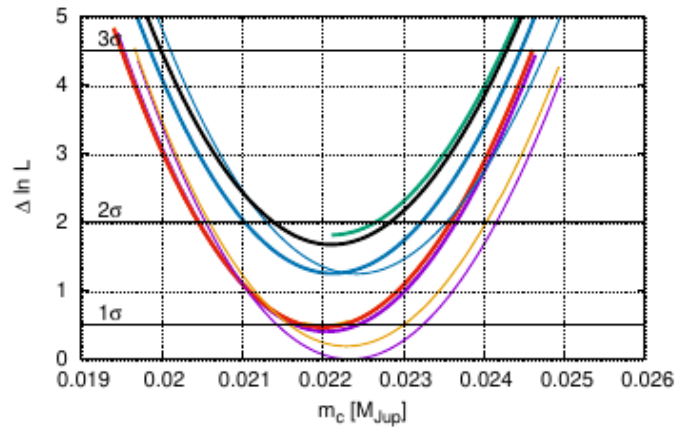
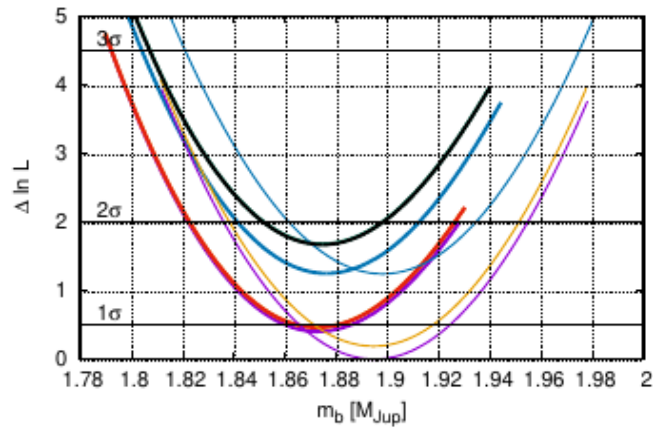
2) **TESS photometry** didn't reveal significant correlated noise **on the time scale of a single transit** (although we revealed a noise excess in the time range from ~1 d to ~10 d). We modelled all transit curves as white noise plus polynomial trends to take into account variations beyond the timescale of 1 d.

3) Some **ground-based photometry** from Korth et al. (2024) revealed suspicious systematic variations and was removed from the analysis. The remaining lightcurves were modelled as white noise.

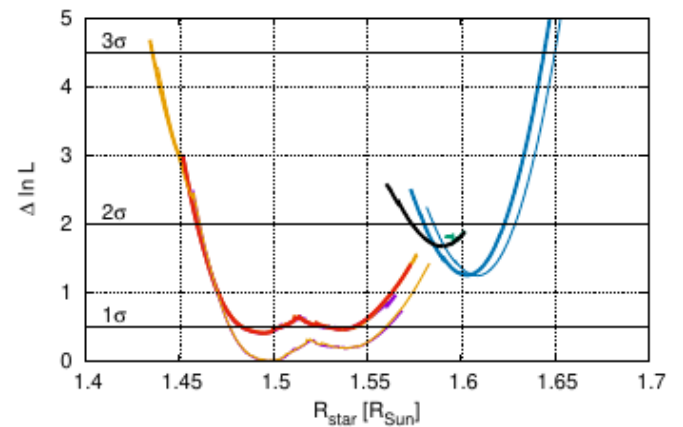
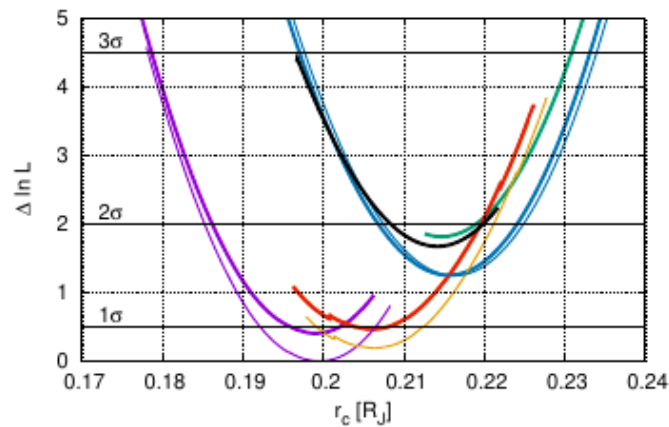
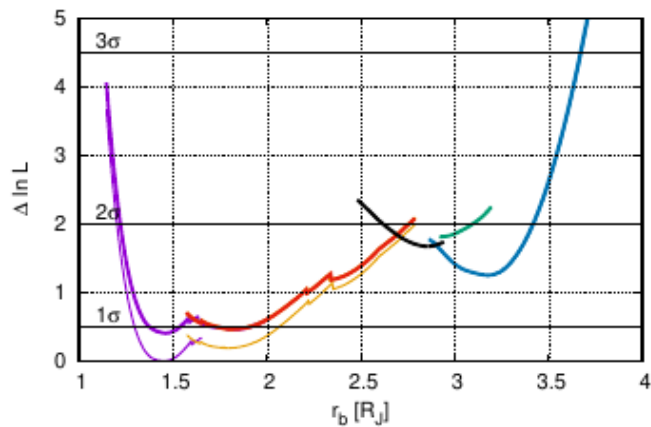
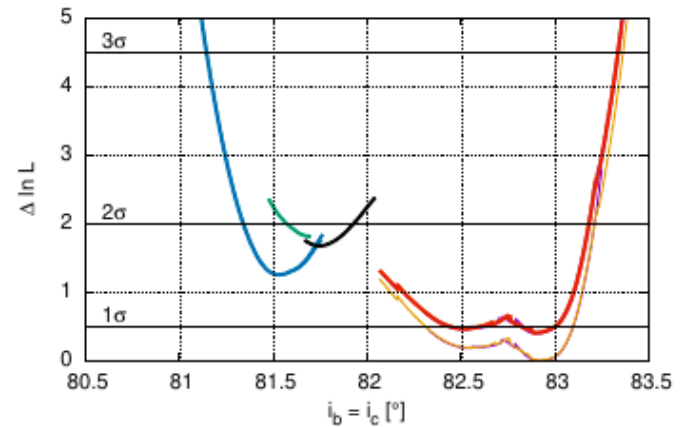
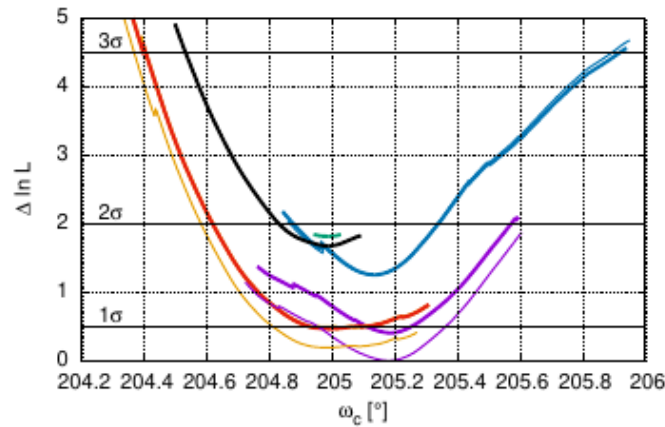
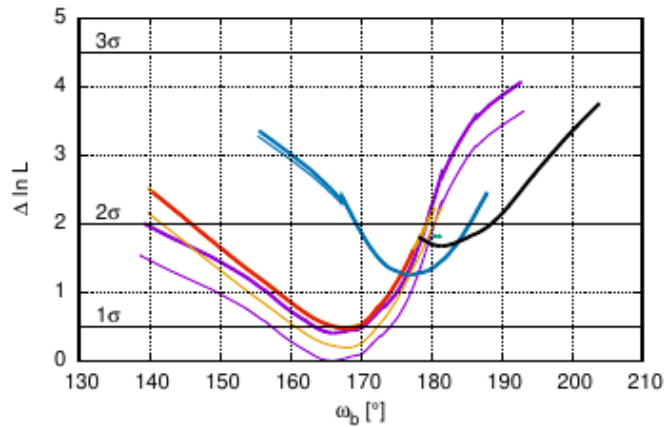
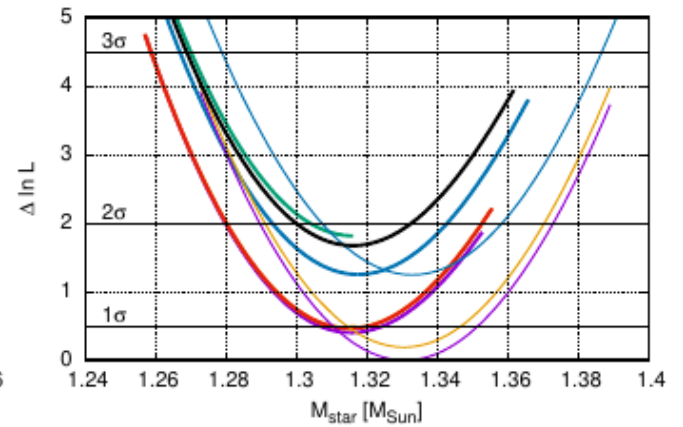
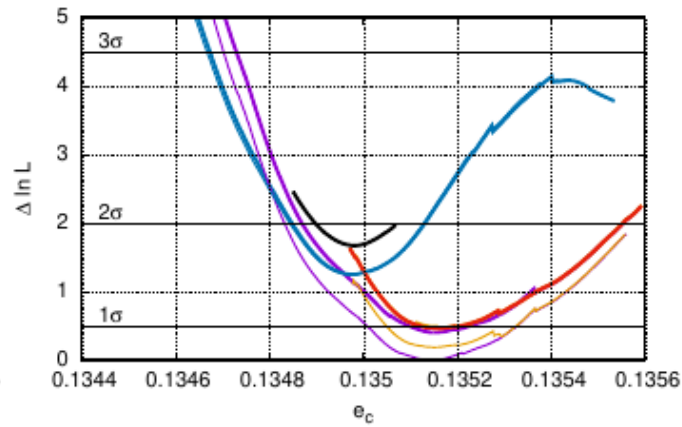
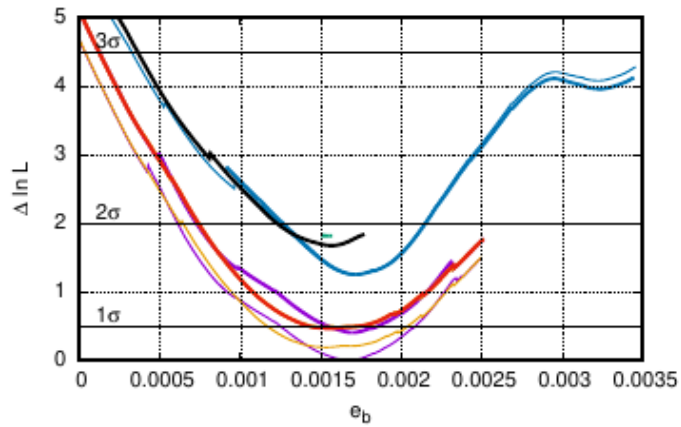
The analysis

- We used the **maximum-likelihood approach** with GP models for the correlated noise (as detailed above).
- The planetary system was assumed **coplanar**.
- The system motion was modelled by integrating the N-body task with the **16-order implicit Gauss-Everhart-type scheme** (initially based on Avdyushev (2010, Vych.Tekhn. 15, 31–46)).
- All computations were done using C++ command-line software **PlanetPack** (Baluev 2013, 2018).

Multiple extrema of the likelihood

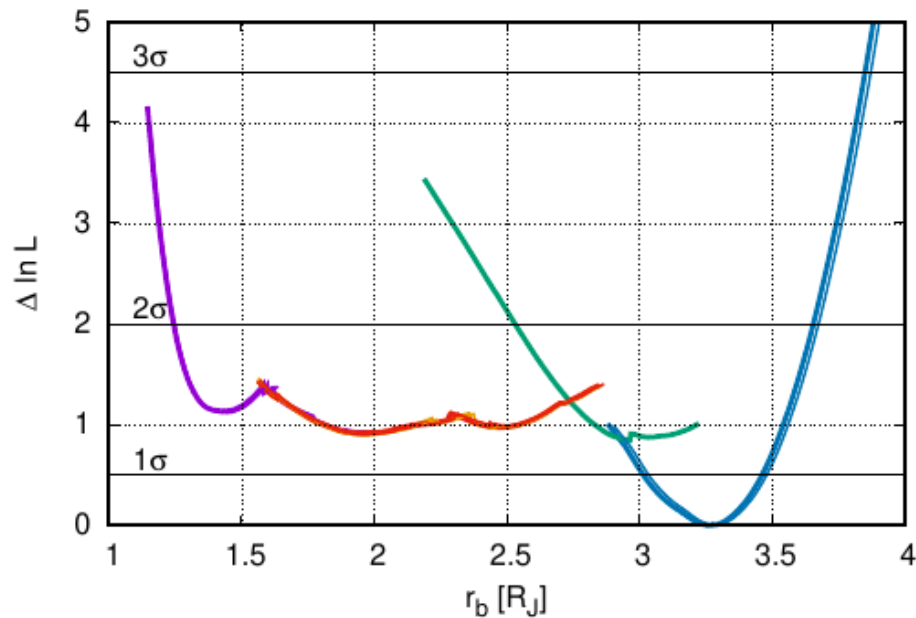


Multiple extrema of the likelihood

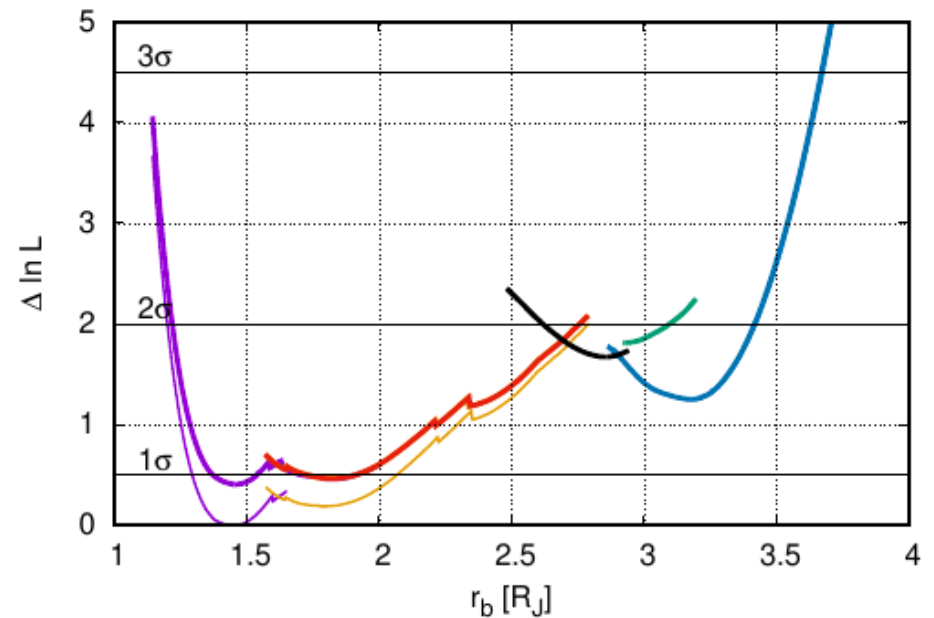


The effect of star mass and radius

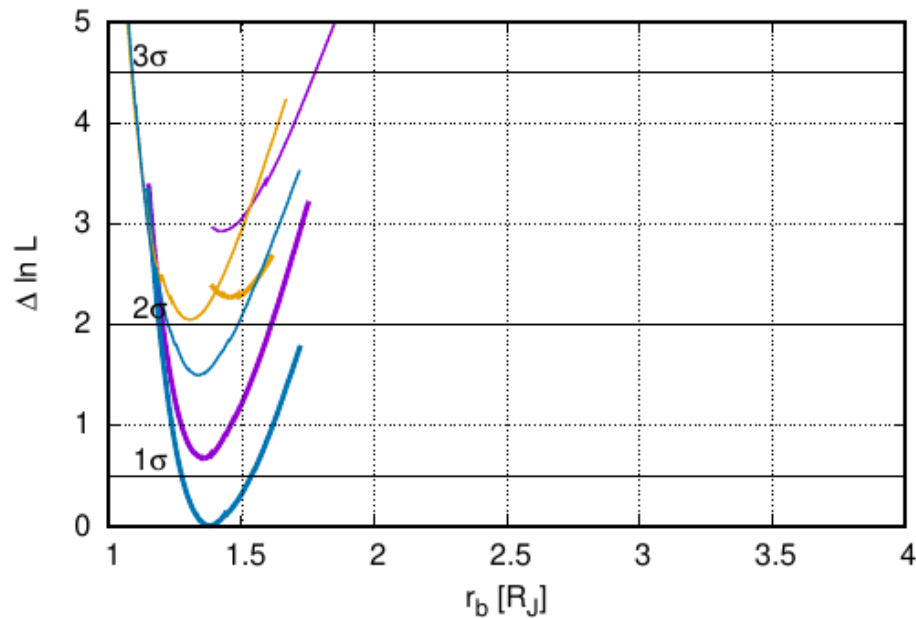
no M_* , R_* penalty



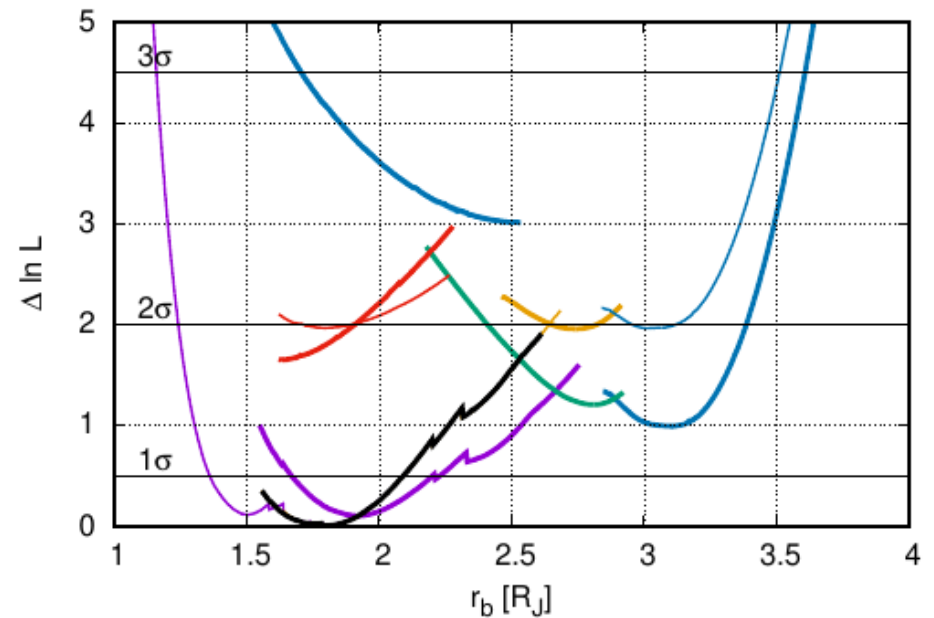
M_* , R_* correlation = 0



M_* , R_* correlation = +0.9



M_* , R_* correlation = -0.9



Conservative parametric estimates

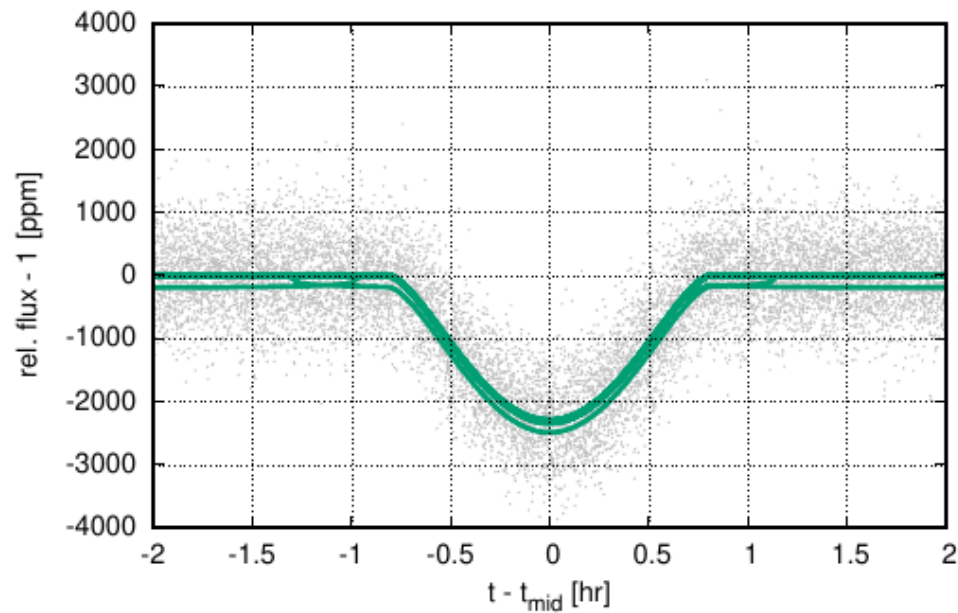
- We finally retracted from using any prior estimates for $M_\star$ and $R_\star$ (since their distribution is important but not known in full).
- Instead of that we constructed a „conservative“ model with pessimistic uncertainties by assuming that the true solution may belong (with equal probability) to any of the likelihood extrema:

parameter	planet b	planet c	“planet” d
m, M_{Jup}	$1.881 \begin{pmatrix} +0.070 \\ -0.060 \end{pmatrix}$	$0.0222 \begin{pmatrix} +0.0019 \\ -0.0017 \end{pmatrix}$	$48 \begin{pmatrix} +\infty \\ -25 \end{pmatrix}$
r, R_{Jup}	$2.3 \begin{pmatrix} +1.2 \\ -1.1 \end{pmatrix}$	$0.209 \begin{pmatrix} +0.020 \\ -0.023 \end{pmatrix}$	
P, d	$4.425684 \begin{pmatrix} +0.000069 \\ -0.000069 \end{pmatrix}$	$2.17121 \begin{pmatrix} +0.00021 \\ -0.00031 \end{pmatrix}$	$6600 \begin{pmatrix} +\infty \\ -2500 \end{pmatrix}$
$\lambda, ^\circ$	$24.33 \begin{pmatrix} +0.11 \\ -0.12 \end{pmatrix}$	$203.43 \begin{pmatrix} +0.81 \\ -0.71 \end{pmatrix}$	$144 \begin{pmatrix} +\infty \\ -11 \end{pmatrix}$
e	$0.00162 \begin{pmatrix} +0.000090 \\ -0.000093 \end{pmatrix}$	$0.13508 \begin{pmatrix} +0.00049 \\ -0.00031 \end{pmatrix}$	
$\omega, ^\circ$	$172 \begin{pmatrix} +27 \\ -34 \end{pmatrix}$	$205.06 \begin{pmatrix} +0.51 \\ -0.46 \end{pmatrix}$	
$i, ^\circ$	$82.21 \begin{pmatrix} +0.99 \\ -0.95 \end{pmatrix}$		
$M_\star, M_\odot$	$1.321 \begin{pmatrix} +0.049 \\ -0.042 \end{pmatrix}$		
$R_\star, R_\odot$	$1.556 \begin{pmatrix} +0.082 \\ -0.098 \end{pmatrix}$		

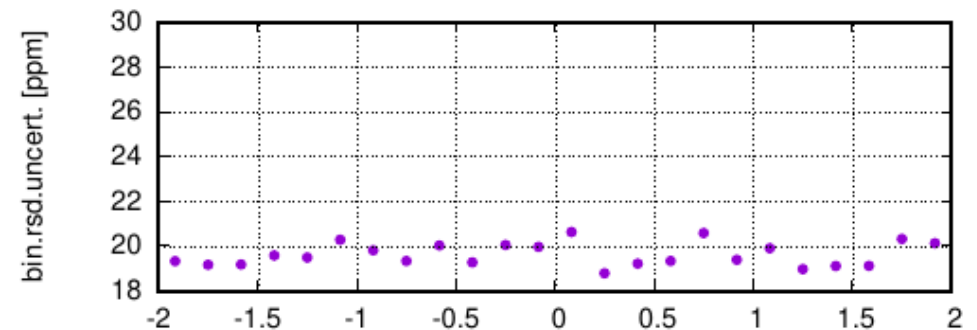
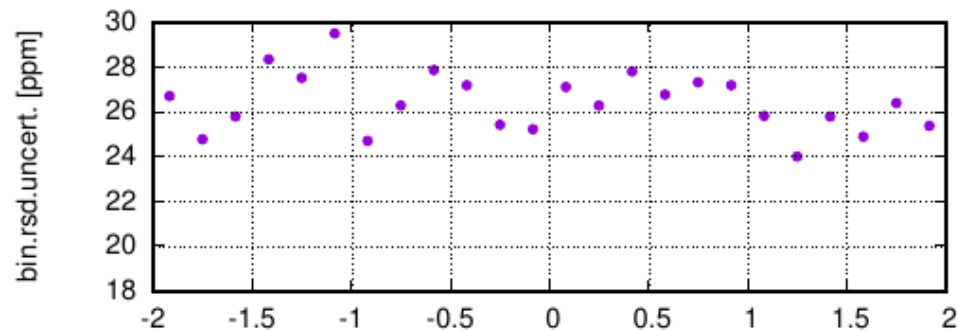
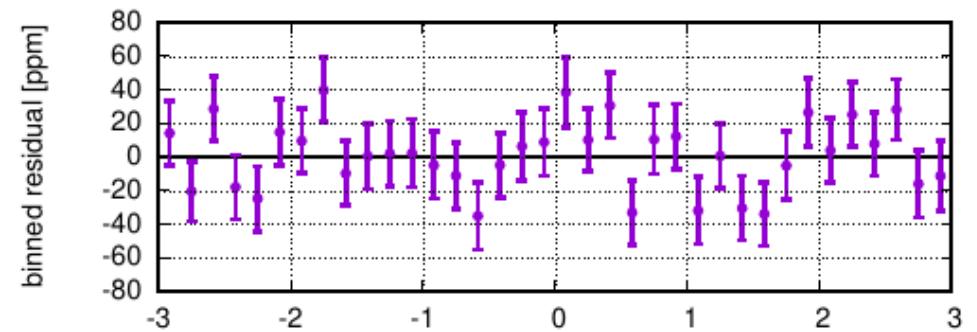
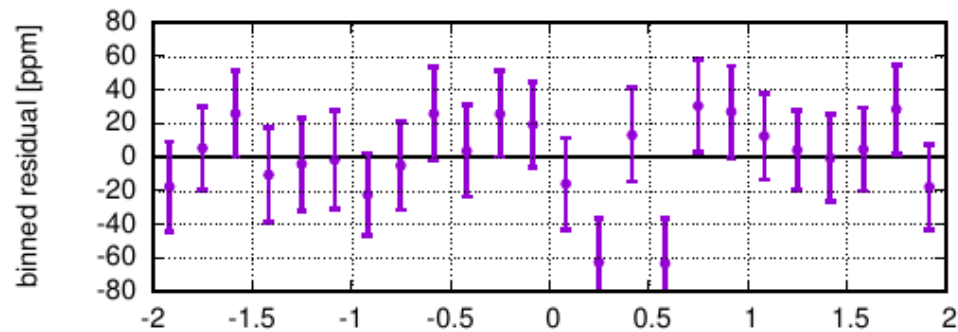
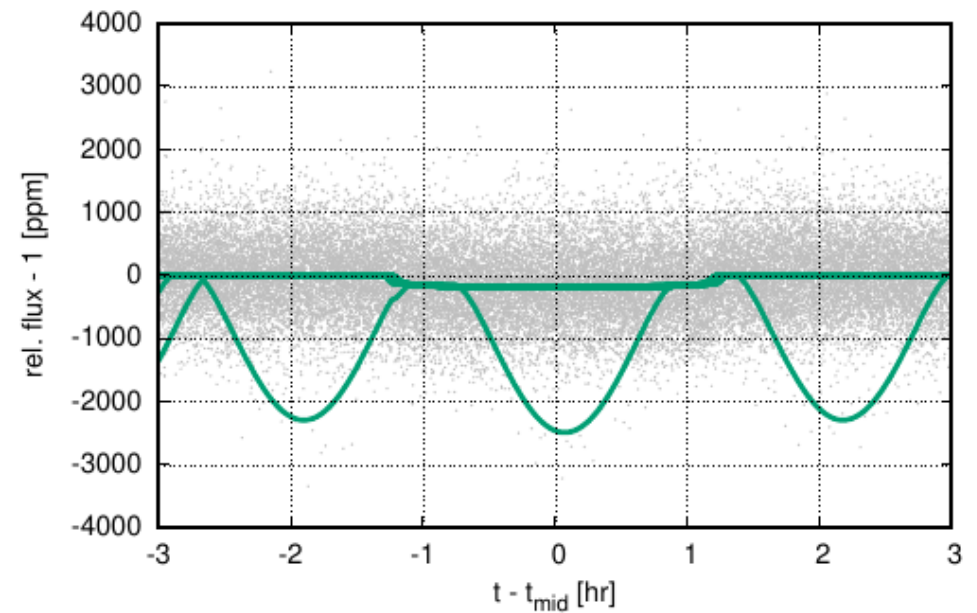
(osculating epoch $T_0 = 2459987.815534$ BJD_{TDB}, Jacobi coordinates)

Planetary transits

TOI-1408 b (+some c) transit

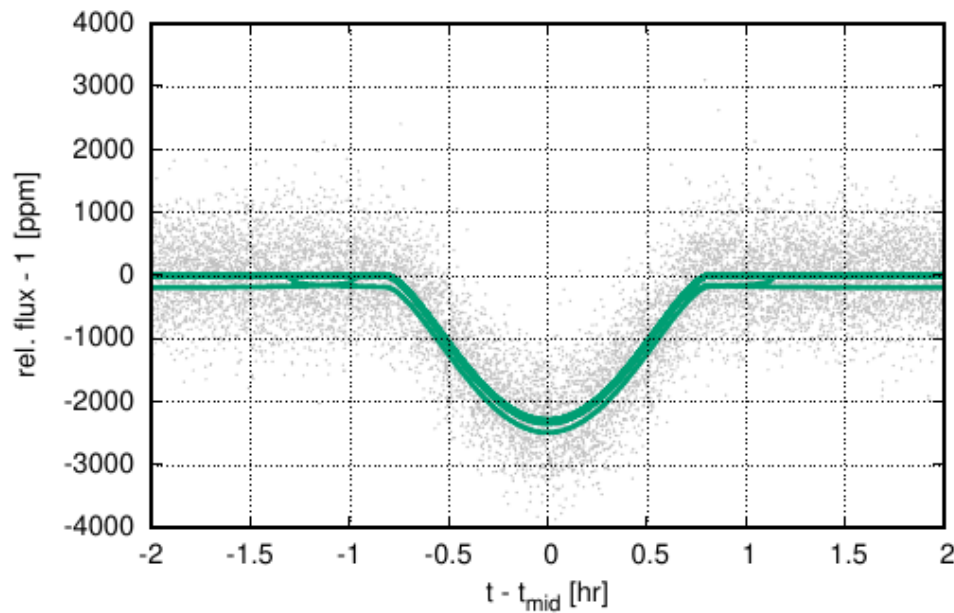


TOI-1408 c (+some b) transit

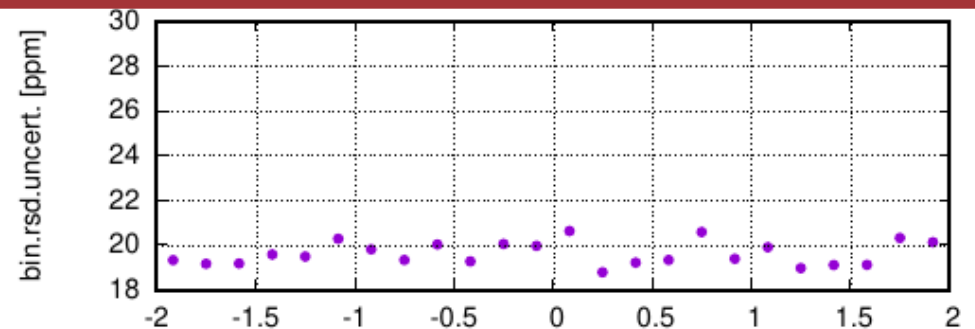
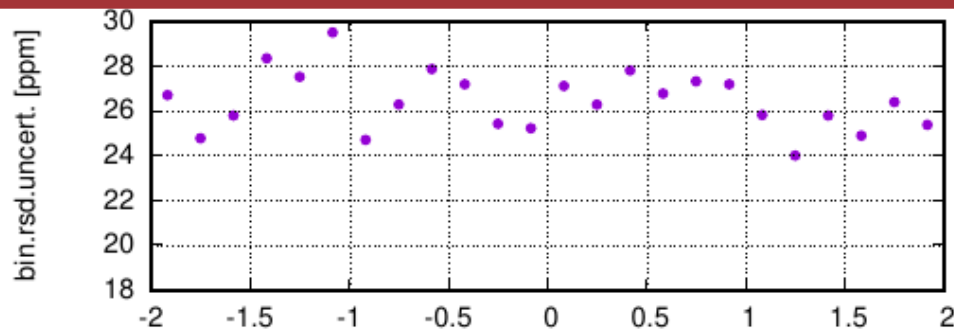
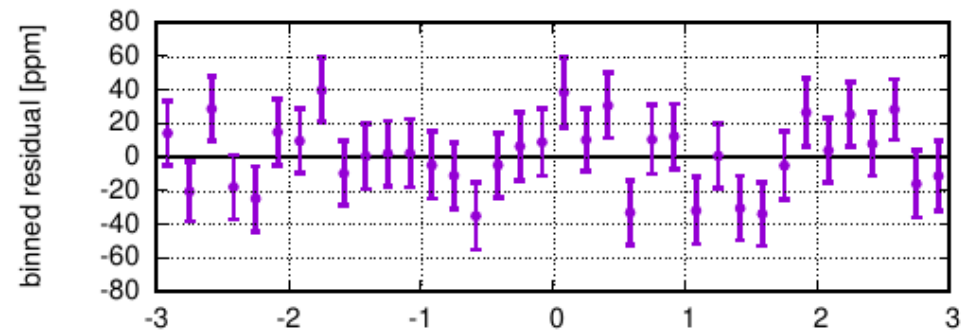
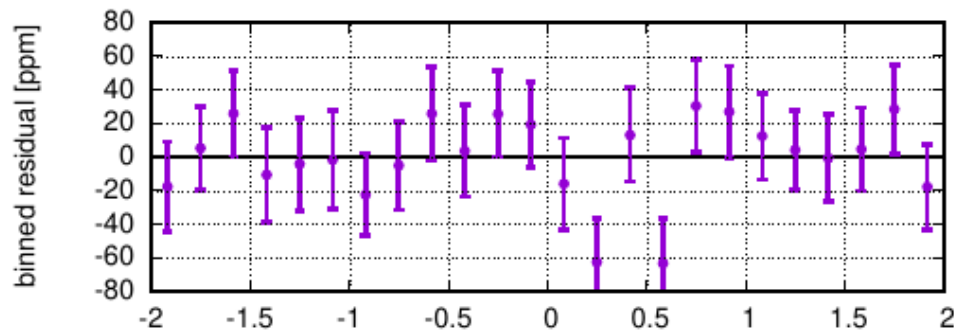
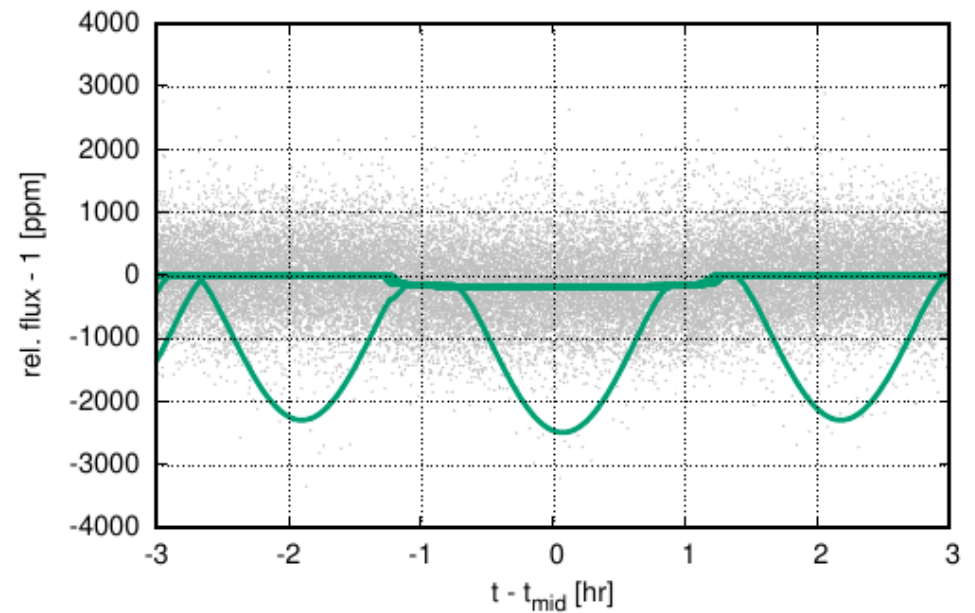


Planetary transits

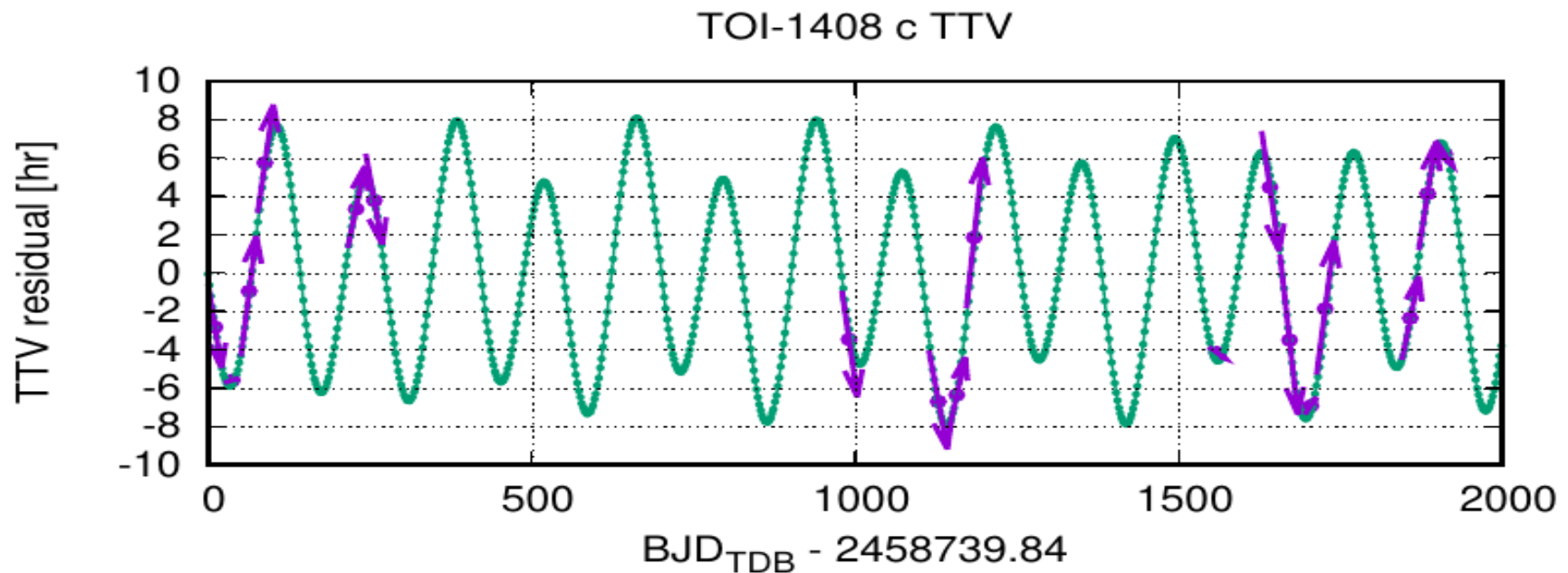
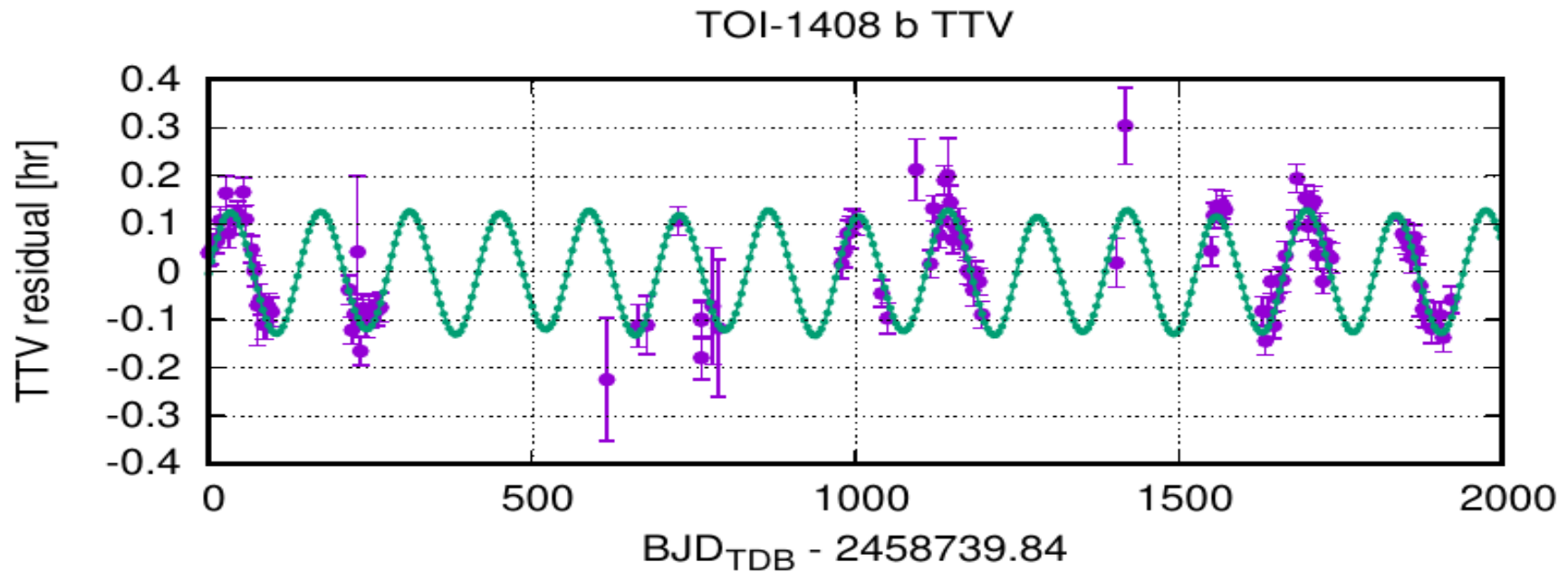
TOI-1408 b (+some c) transit



TOI-1408 c (+some b) transit



Transit timing variations



Conclusions

- Qualitatively, **our analysis confirms** the main results by Korth et al. (2024) regarding TOI-1408: two planets in a 2:1 MMR and a third distant companion with unconstrainable mass and orbital period.
- However, many parametric **uncertainties appear considerably larger**, in particular the planet radius r_b still remains ill-fitted, residing in a wide domain $(1.2-3.6) R_{Jup}$.
- **Astrophysical estimations of the star mass and radius** may, in theory, help to reduce parametric uncertainties of the fit, however their distribution must be known well and in full, including e.g. the correlation between them (which is currently not the case).
- The third long-period companion appears too massive to be a planet (under an assumption that there is just a single such companion).
- In this work we did not consider in details the dynamics of TOI-1408. For a few of our likelihood maxima we verified that this dynamics remains nearly the same as in Korth et al. (2024), but the effect of increased parametric uncertainties still needs to be considered in details.
- Full details of this work will be published in *Research in Astronomy & Astrophysics (RAA)*.

Thank you for attention!