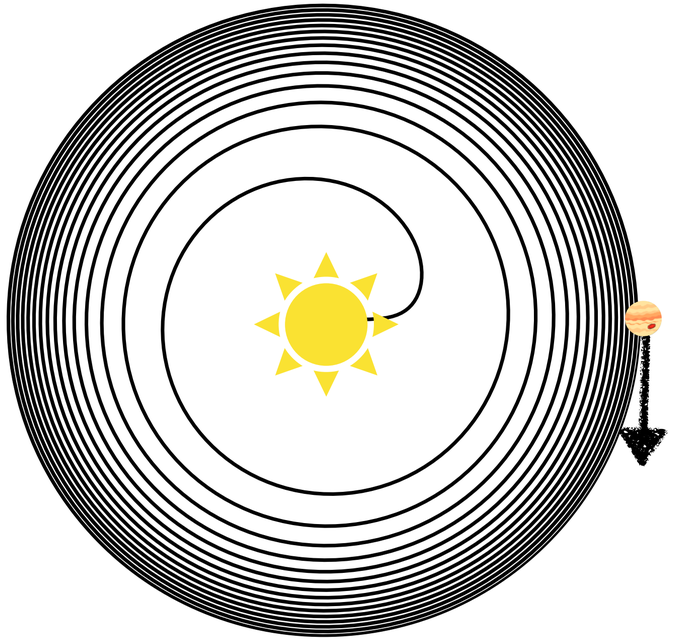
Bouma+2019, *AJ, 157, 217*

WASP-4b Arrived Early for the TESS Mission

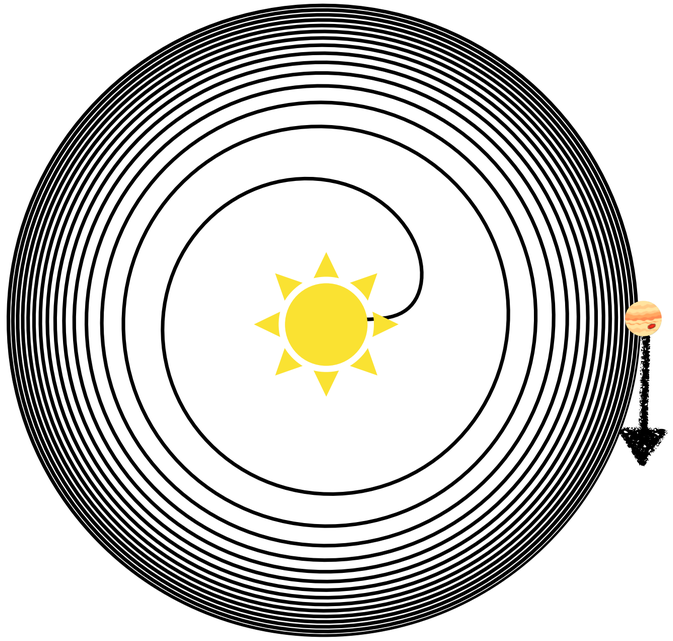
Luke Bouma, Josh Winn,
& a broad team of TESS contributors.

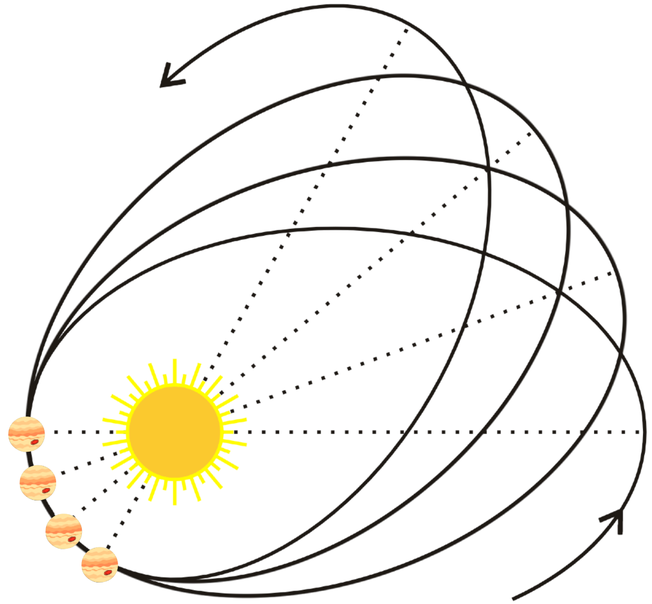
TSC I, July 30, 2019.

tidal decay



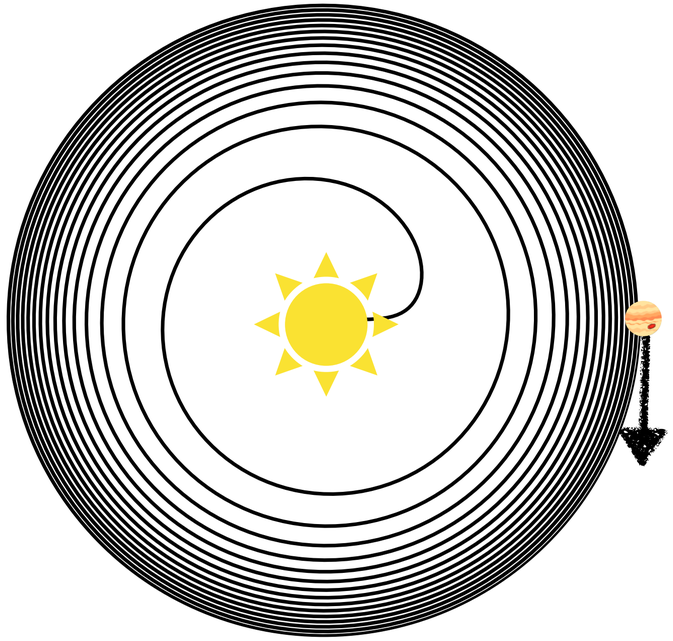
tidal decay

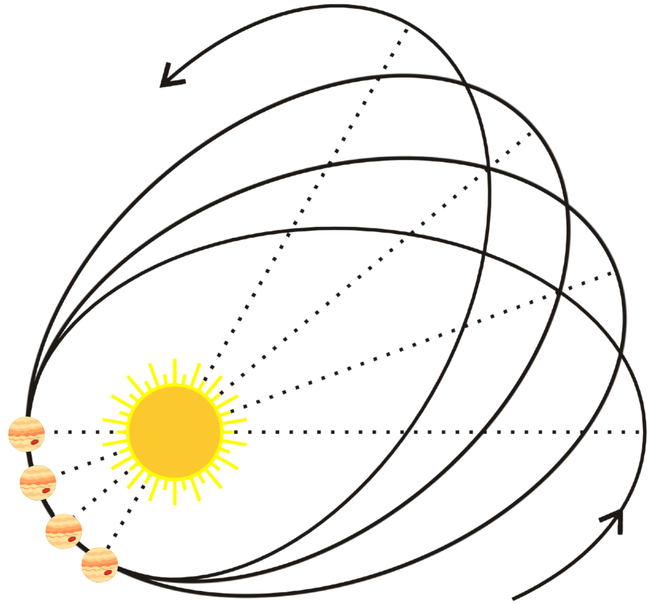




apsidal precession

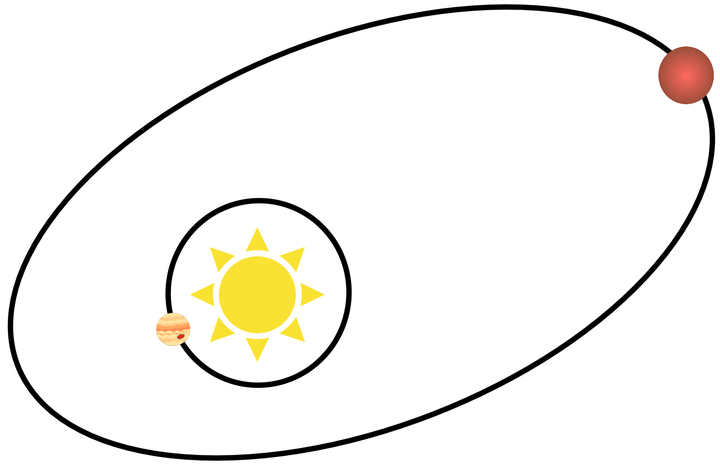
tidal decay



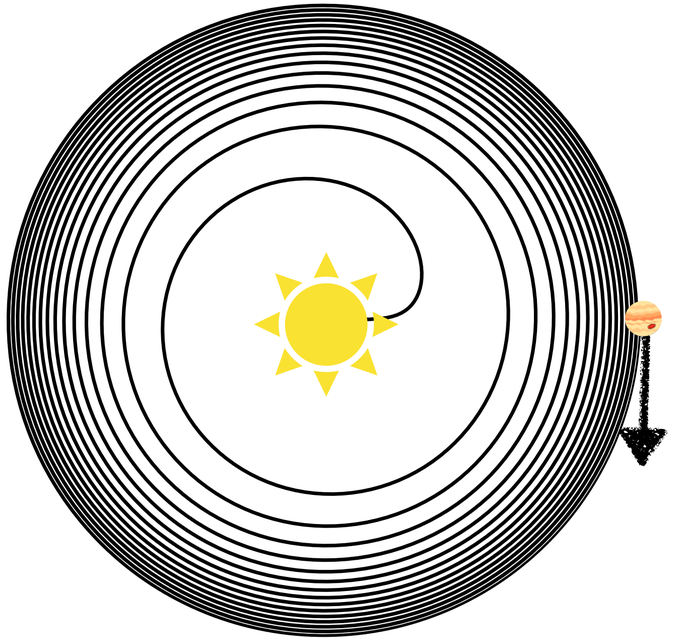


apsidal precession

outer companions

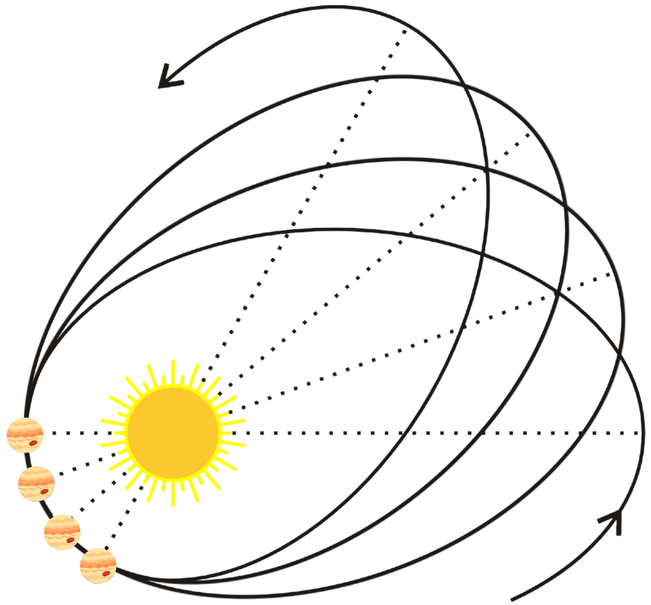


tidal decay



$$\frac{1}{\tau_{\rm a}} = \underbrace{\frac{|\dot{a}|}{a}}_{\textit{measure}} = \underbrace{\frac{9\pi}{Q'_\star}}_{\textit{infer}} \underbrace{\left(\frac{R_\star}{a}\right)^5 \left(\frac{M_{\rm p}}{M_\star}\right) \left(\frac{1}{P}\right)}_{\textit{known}}$$

Reviews: Mazeh 08, Ogilvie 14. Tidal stability: Levrard+09; Matsumura+10. Merger scenarios: Metzger+12.

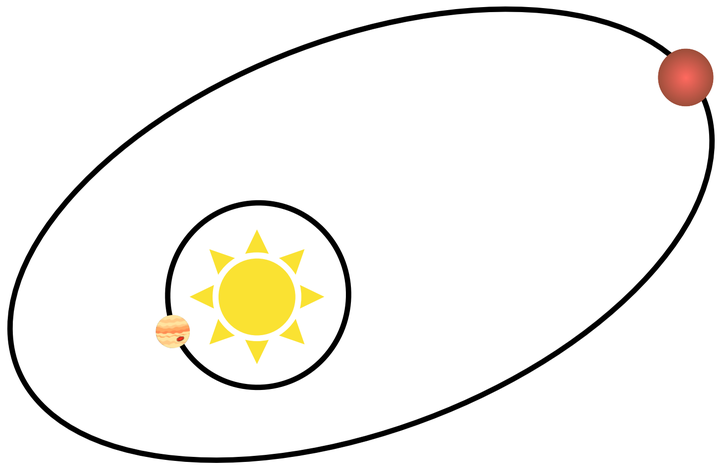


apsidal precession

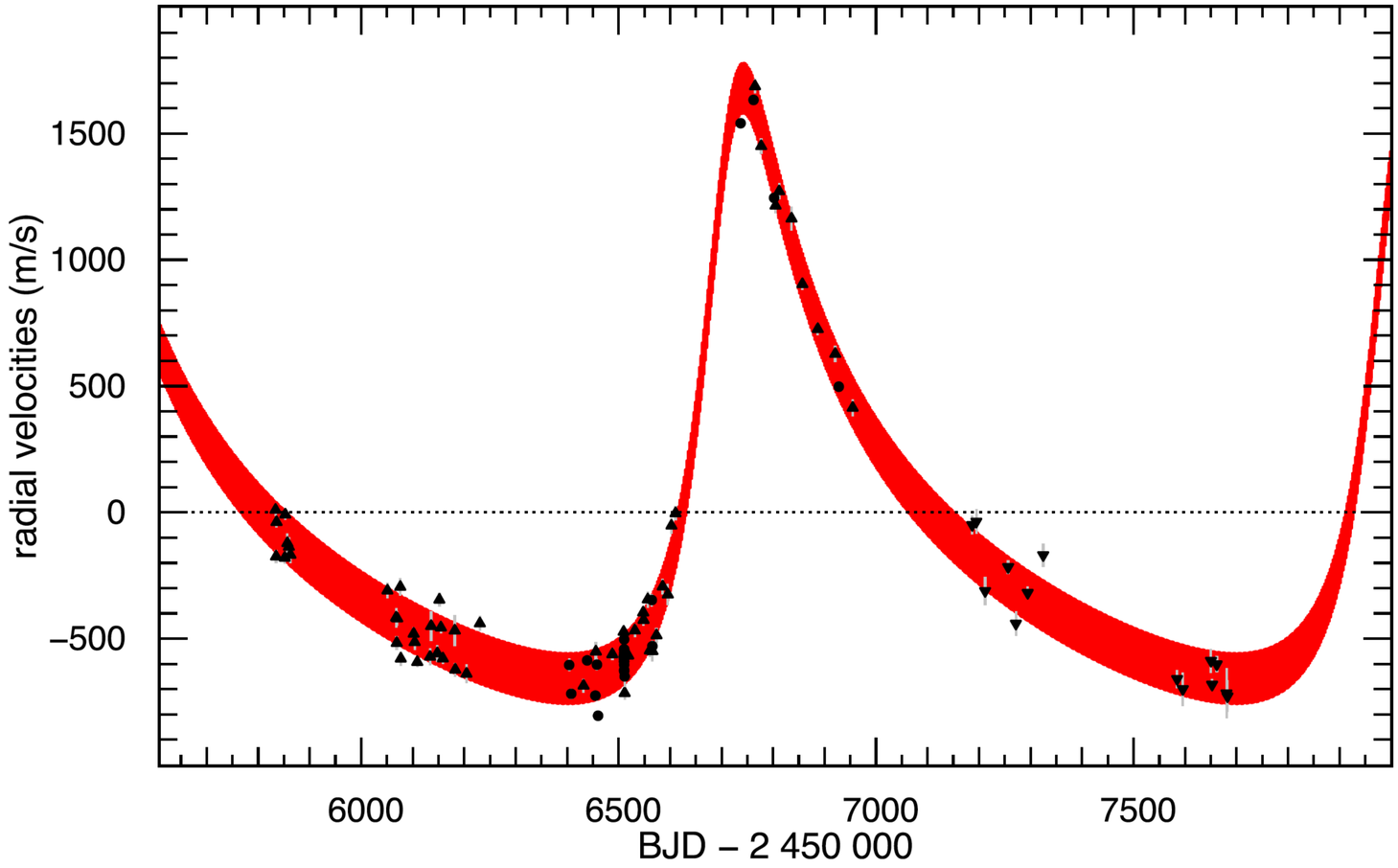
$$\underbrace{\dot{\omega}_{\rm total}}_{\textit{measure}} \propto \underbrace{k_{2,\rm p}}_{\textit{infer}} \underbrace{M_\star^{3/2} M_p^{-1} R_p^5 a^{-13/2}}_{\textit{known}}$$

See: Ragozzine & Wolf 09.

outer companions

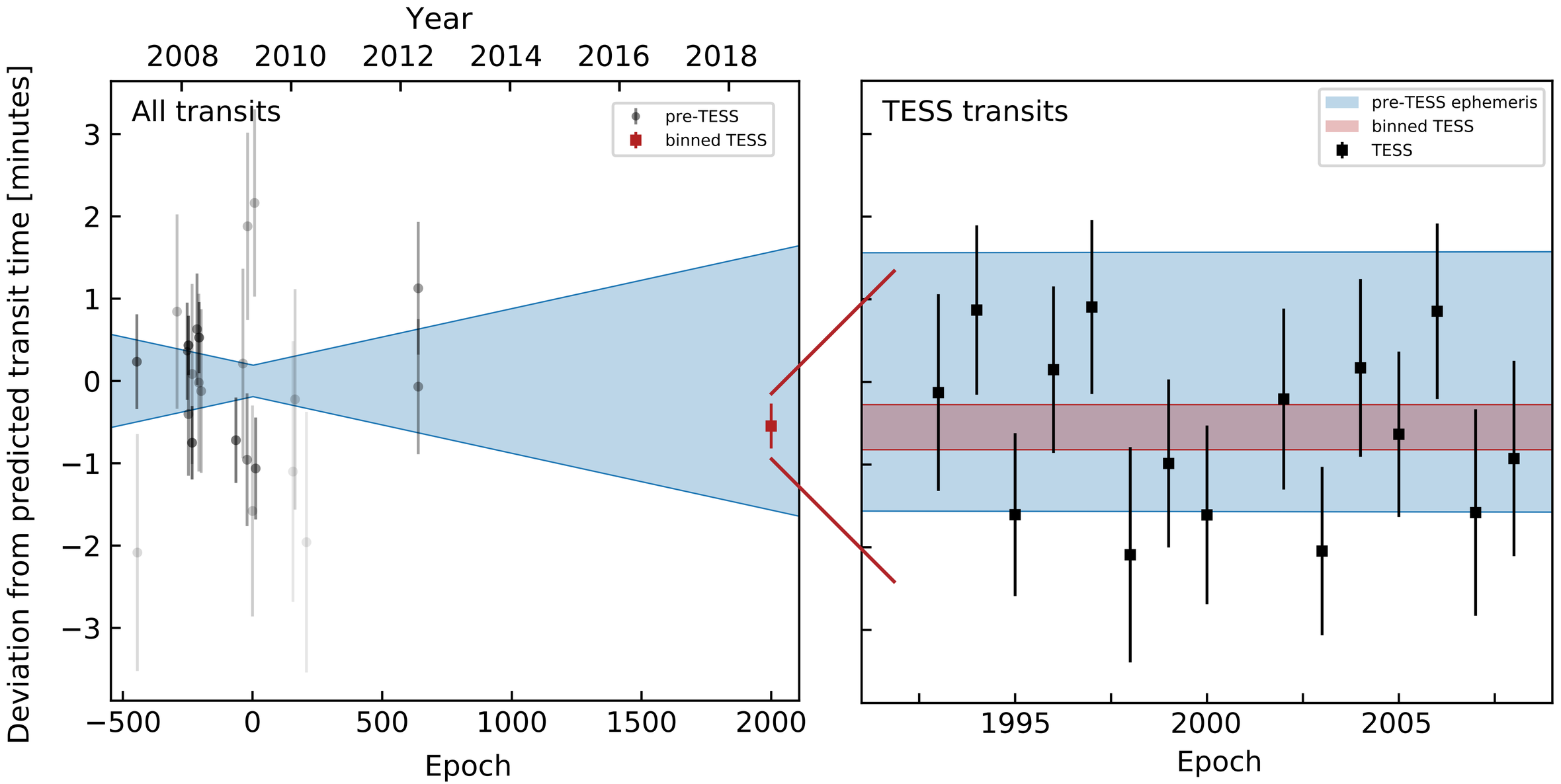


infer $(M_{\rm outer}, a_{\rm outer}, e_{\rm outer})$

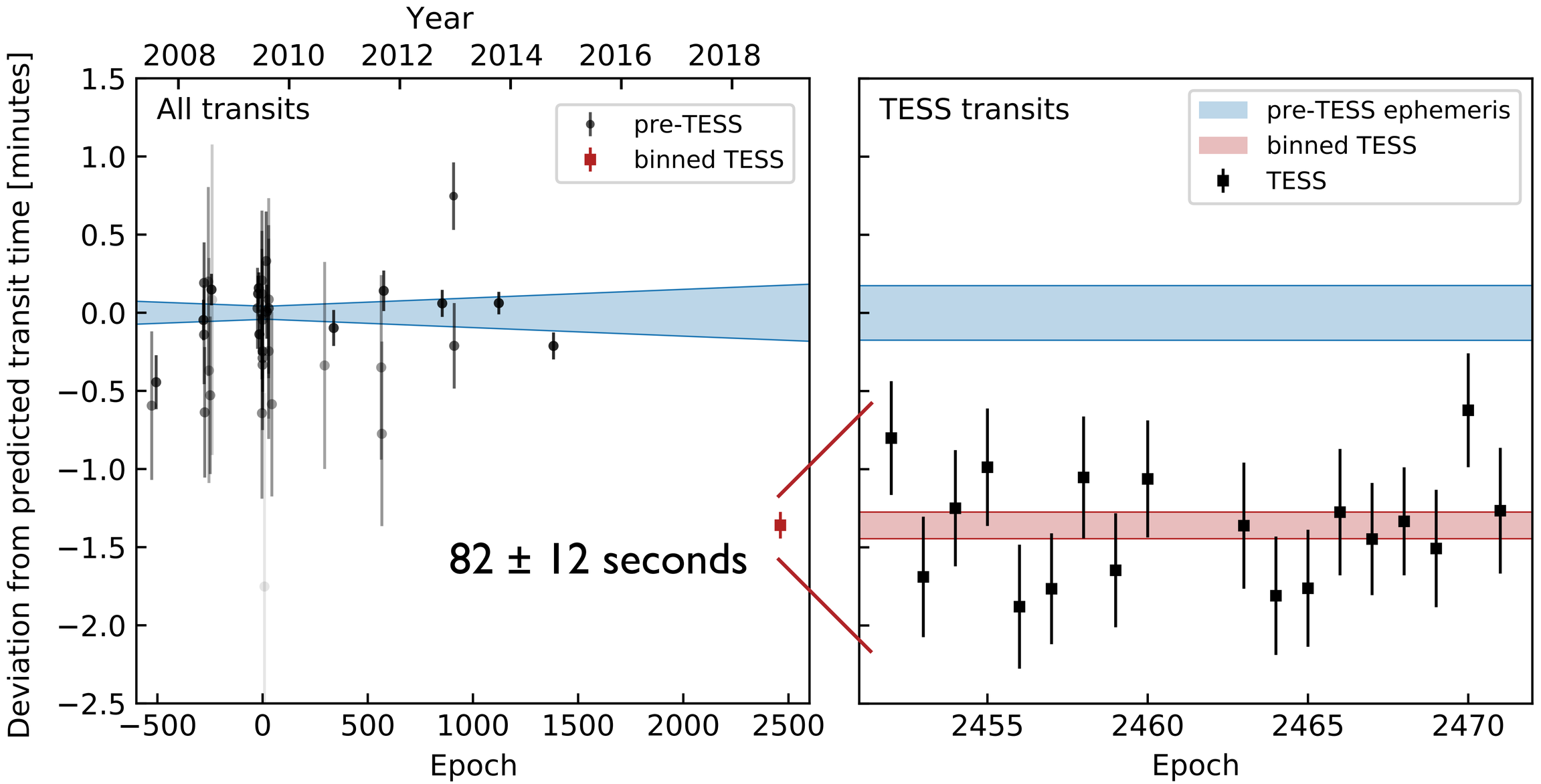


WASP-81: Triaud+17.

We are measuring transit times of close-in hot Jupiters for which many pre-TESS observations exist.

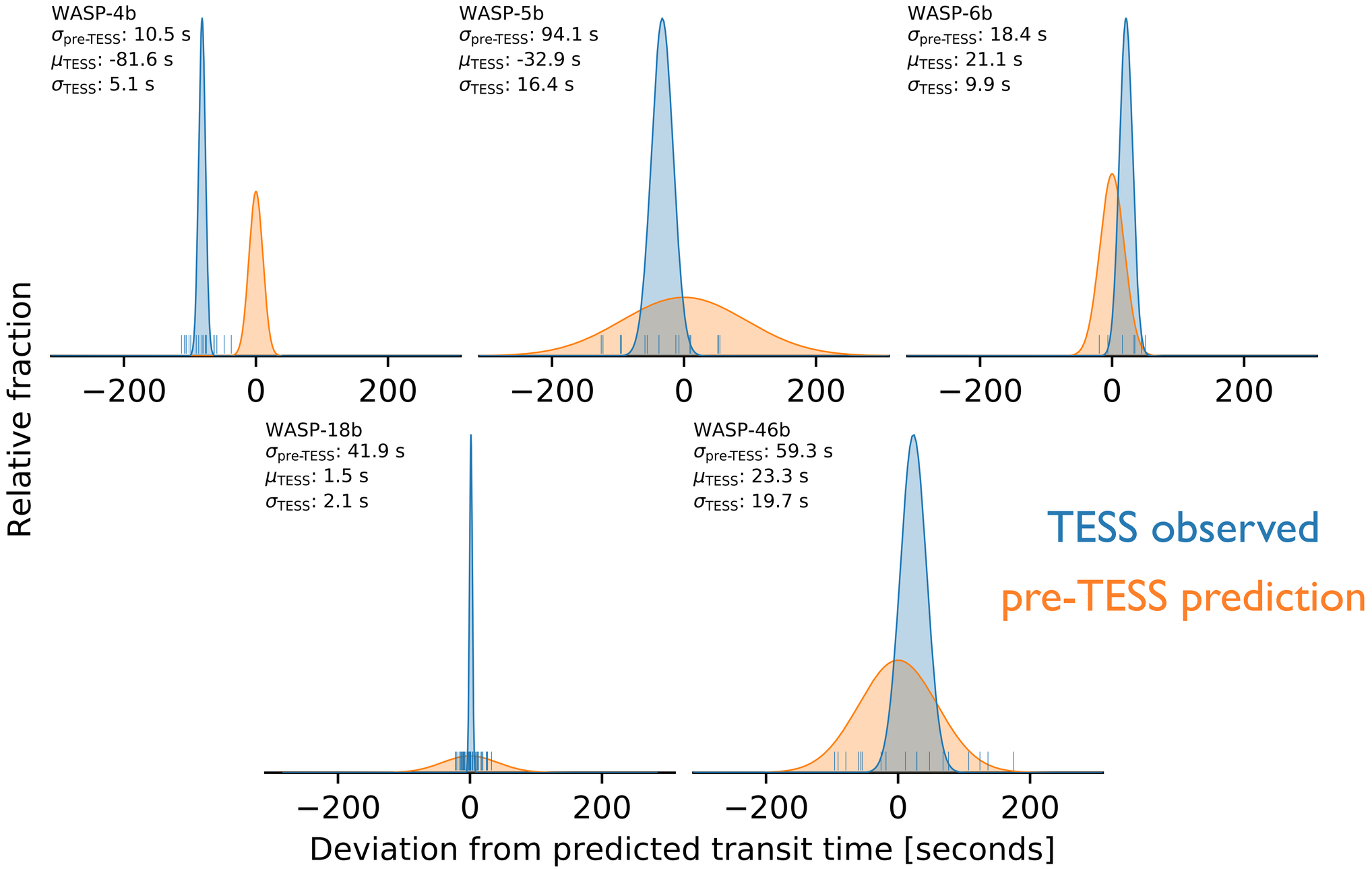

Year
2008
2010
2012
2014
2016
2018
All transits
pre-TESS
binned TESS
Deviation from predicted transit time [minutes]
3
2
1
0
−1
−2
−3
−500
0
500
1000
1500
2000
Epoch
TESS transits
pre-TESS ephemeris
binned TESS
TESS
1995
2000
2005
Epoch

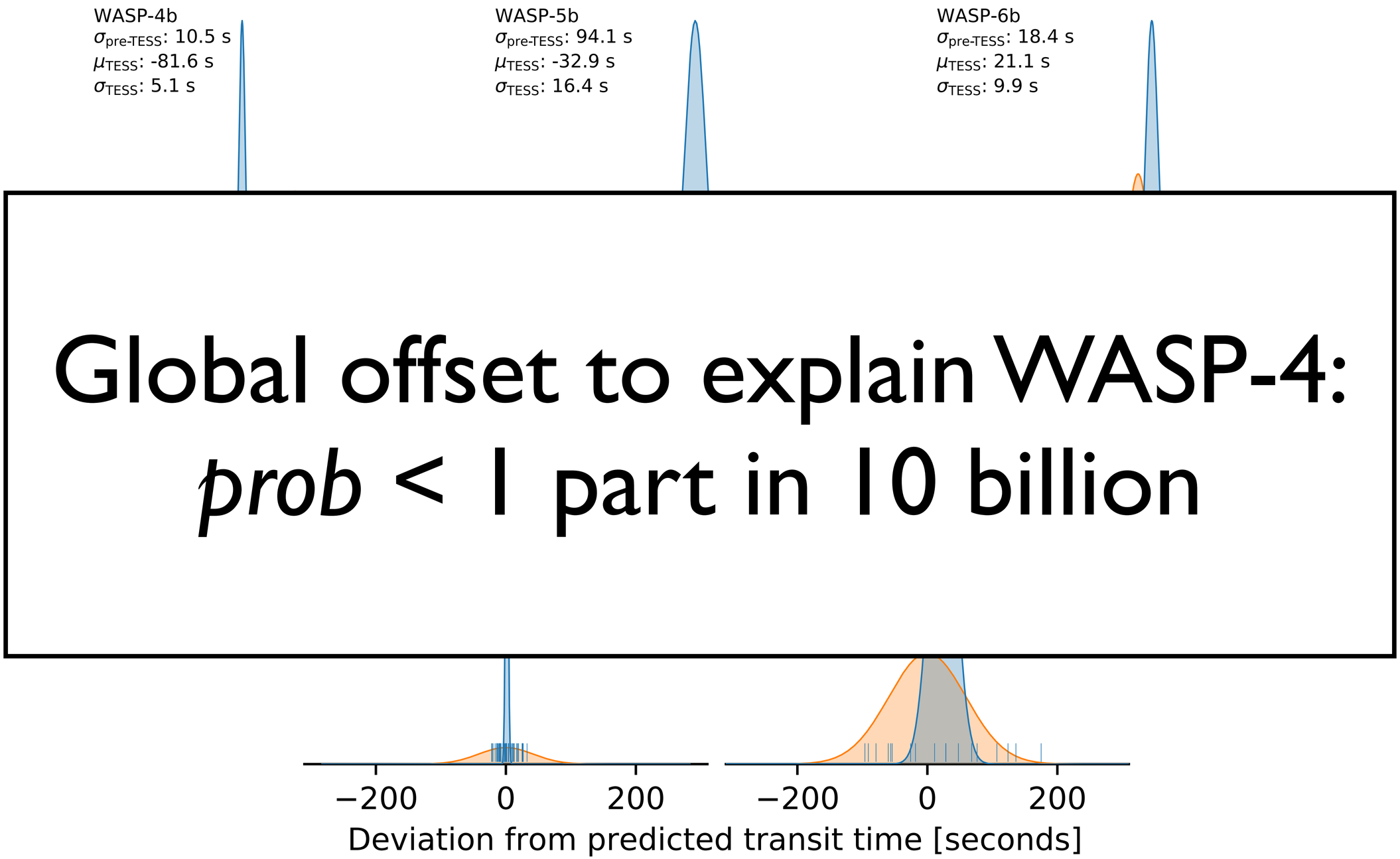
WASP-5b


Year
2008
2010
2012
2014
2016
2018
All transits
pre-TESS
binned TESS
82 ± 12 seconds
Deviation from predicted transit time [minutes]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−500
0
500
1000
1500
2000
2500
Epoch
TESS transits
pre-TESS ephemeris
binned TESS
TESS
2455
2460
2465
2470
Epoch

WASP-4b

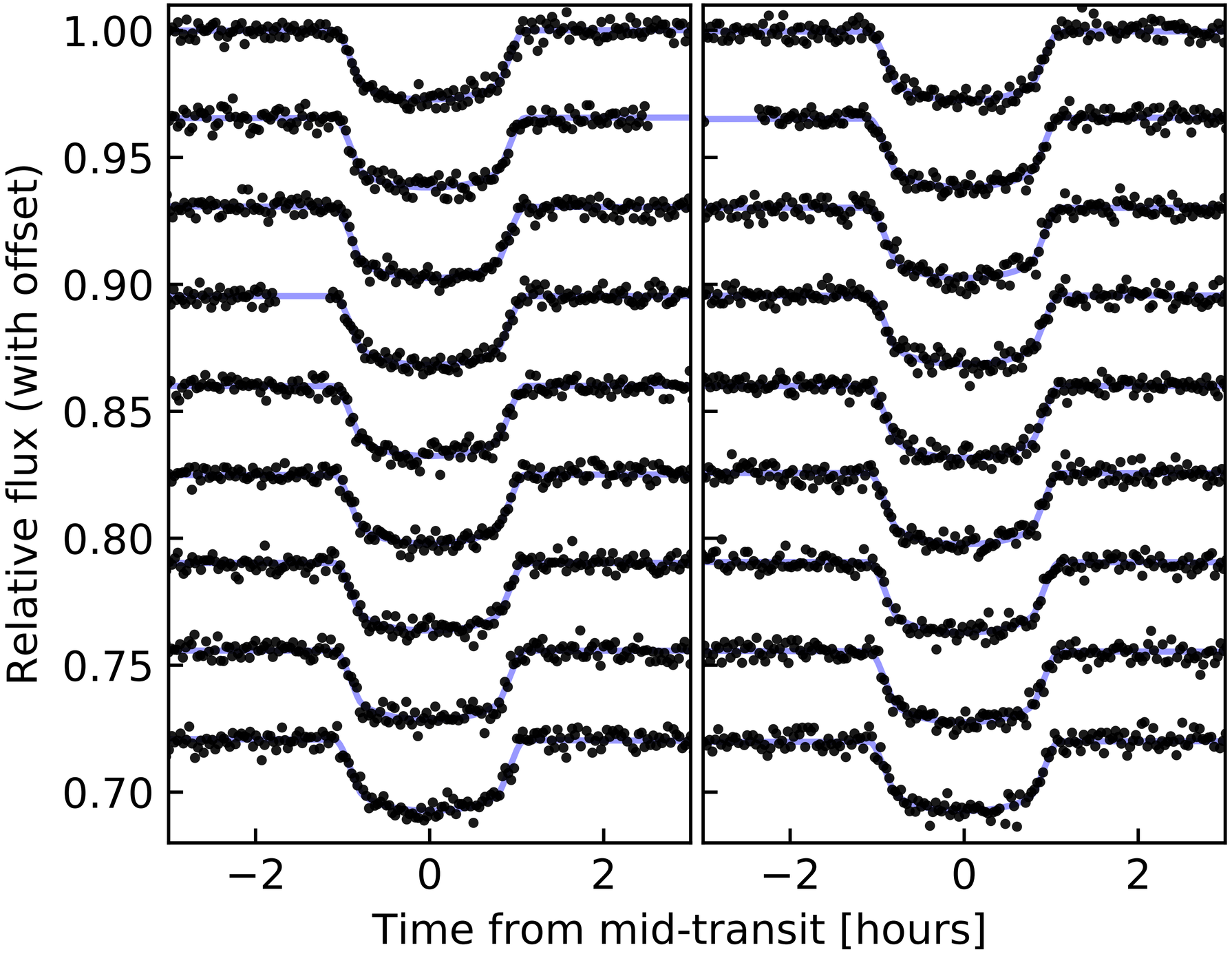
TESS timestamp offset?

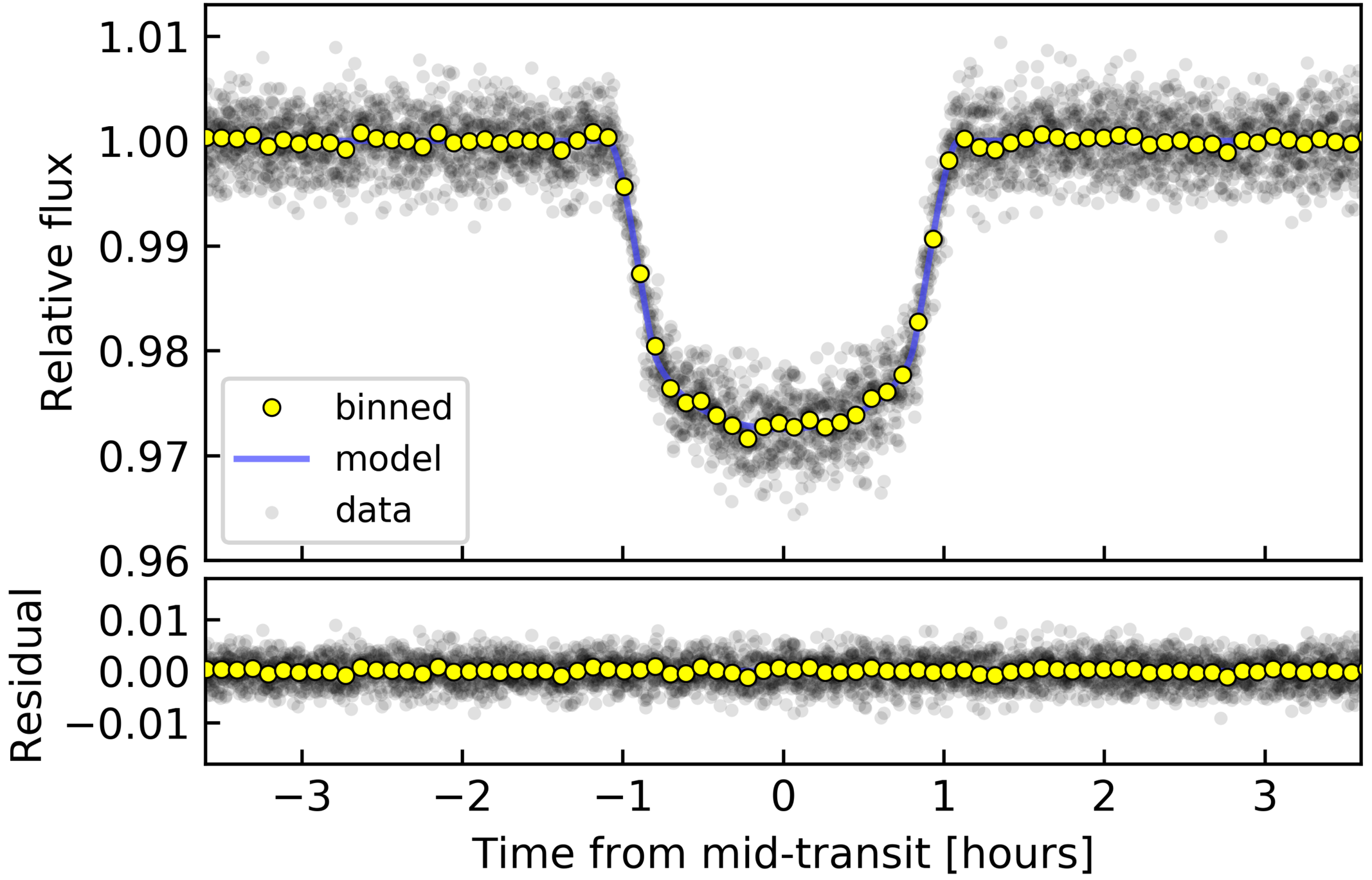

WASP-4b
$\sigma_{\text{pre-TESS}}$: 10.5 s
μ_{TESS}: -81.6 s
σ_{TESS}: 5.1 s
WASP-5b
$\sigma_{\text{pre-TESS}}$: 94.1 s
μ_{TESS}: -32.9 s
σ_{TESS}: 16.4 s
WASP-6b
$\sigma_{\text{pre-TESS}}$: 18.4 s
μ_{TESS}: 21.1 s
σ_{TESS}: 9.9 s
WASP-18b
$\sigma_{\text{pre-TESS}}$: 41.9 s
μ_{TESS}: 1.5 s
σ_{TESS}: 2.1 s
WASP-46b
$\sigma_{\text{pre-TESS}}$: 59.3 s
μ_{TESS}: 23.3 s
σ_{TESS}: 19.7 s
−200
0
200
Relative fraction
Deviation from predicted transit time [seconds]
TESS observed
pre-TESS prediction


WASP-4b
$\sigma_{\text{pre-TESS}}$: 10.5 s
μ_{TESS}: -81.6 s
σ_{TESS}: 5.1 s
WASP-5b
$\sigma_{\text{pre-TESS}}$: 94.1 s
μ_{TESS}: -32.9 s
σ_{TESS}: 16.4 s
WASP-6b
$\sigma_{\text{pre-TESS}}$: 18.4 s
μ_{TESS}: 21.1 s
σ_{TESS}: 9.9 s
Global offset to explain WASP-4:
prob < 1 part in 10 billion
−200
0
200
−200
0
200
Deviation from predicted transit time [seconds]

TESS timestamp offset?

Deformity in light curve?

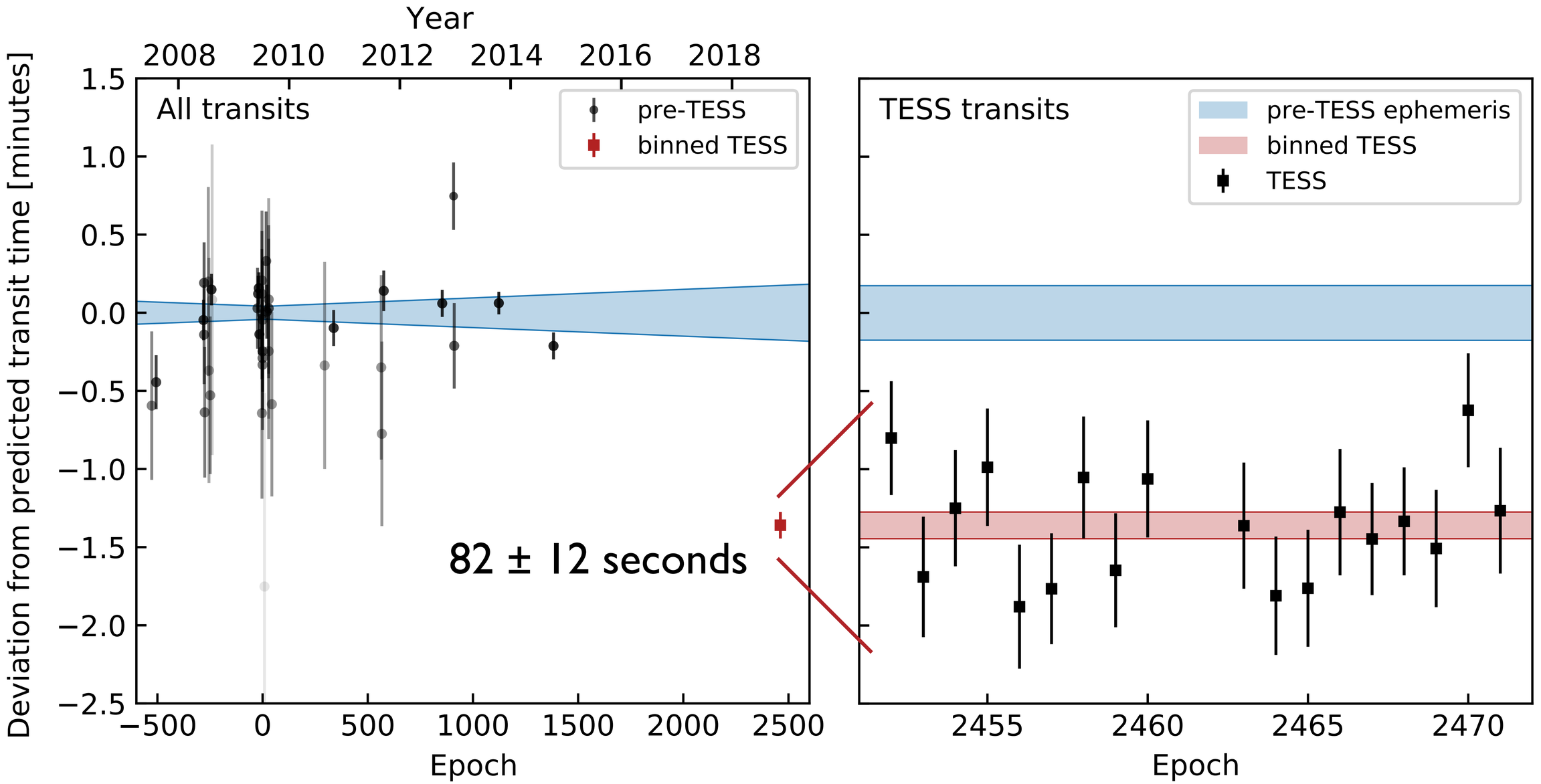

1.00
0.95
0.90
0.85
0.80
0.75
0.70
Relative flux (with offset)
−2
0
2
−2
0
2
Time from mid-transit [hours]

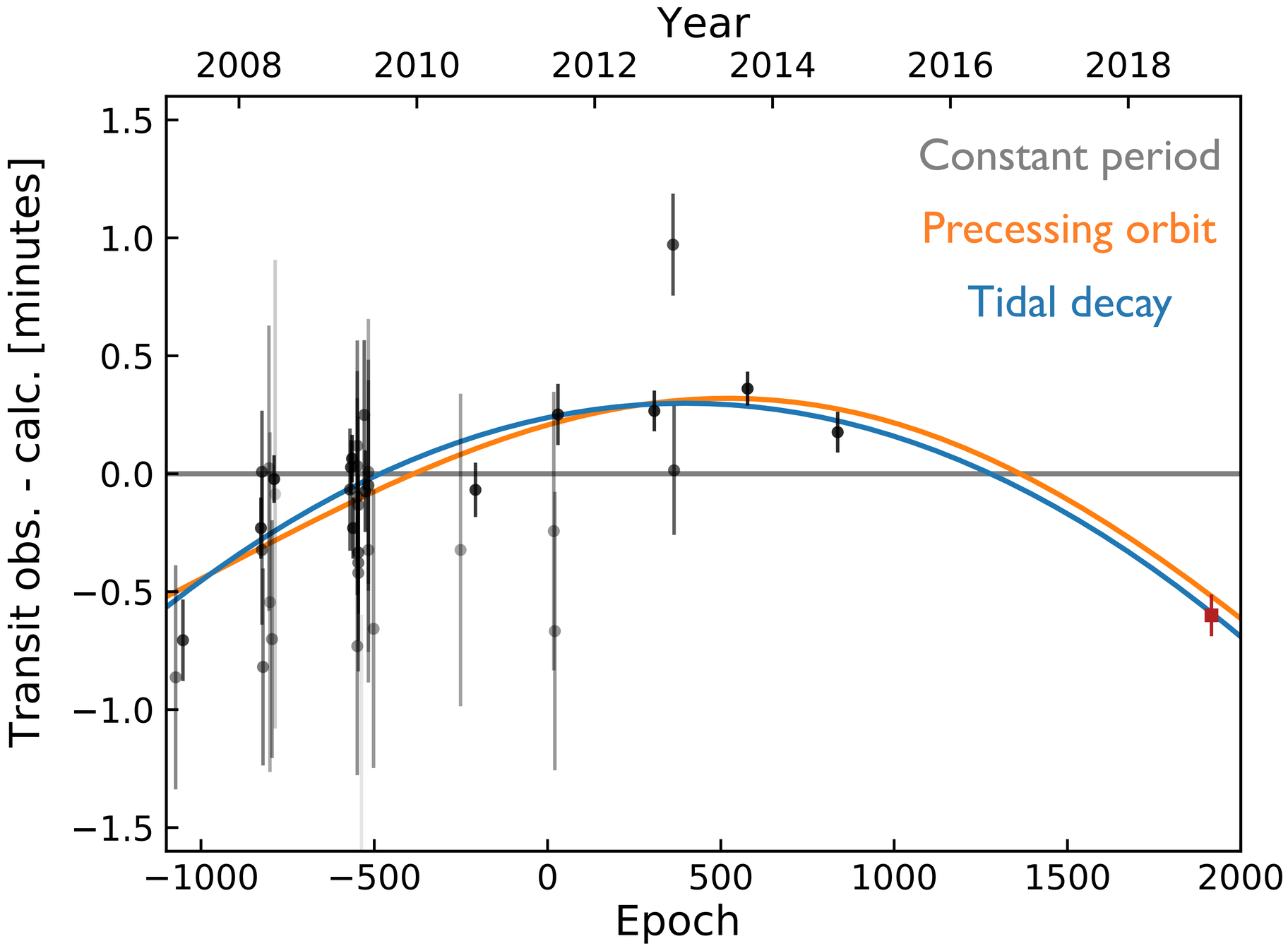

1.01
1.00
0.99
0.98
0.97
0.96
Relative flux
binned
model
data
0.01
0.00
−0.01
Residual
−3
−2
−1
0
1
2
3
Time from mid-transit [hours]

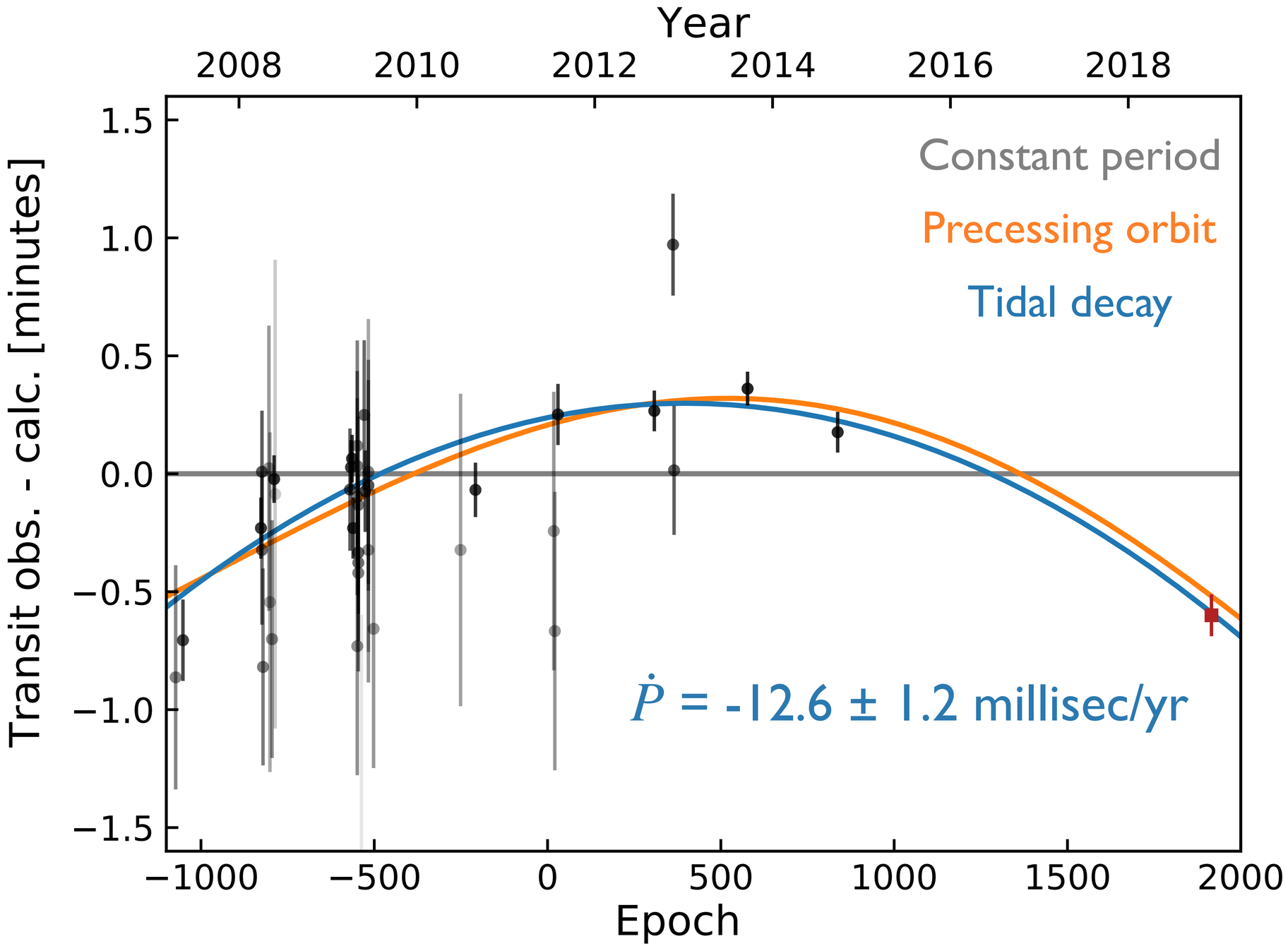
TESS timestamp offset?

Deformity in light curve?

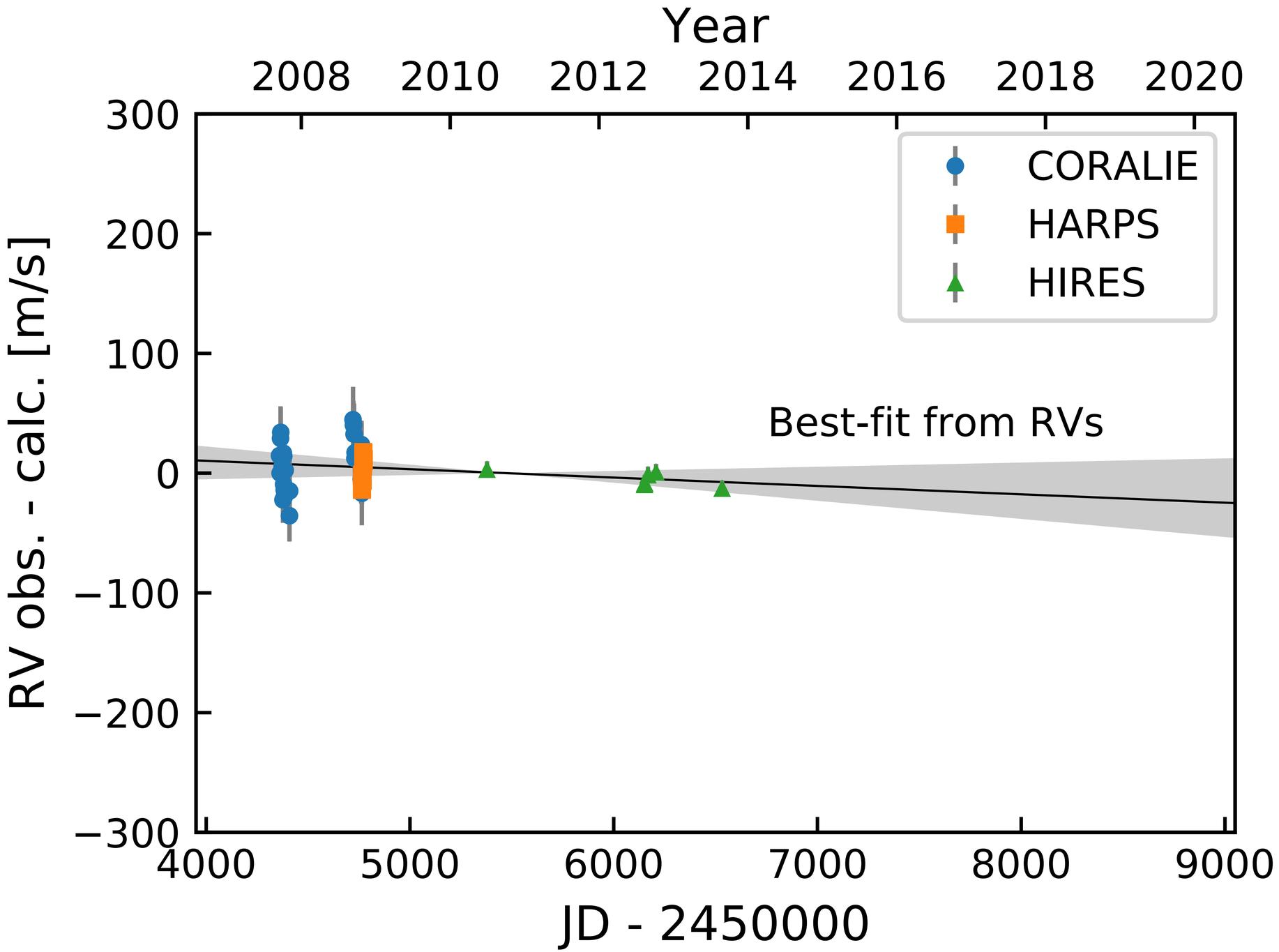
Errors in pre-TESS data?

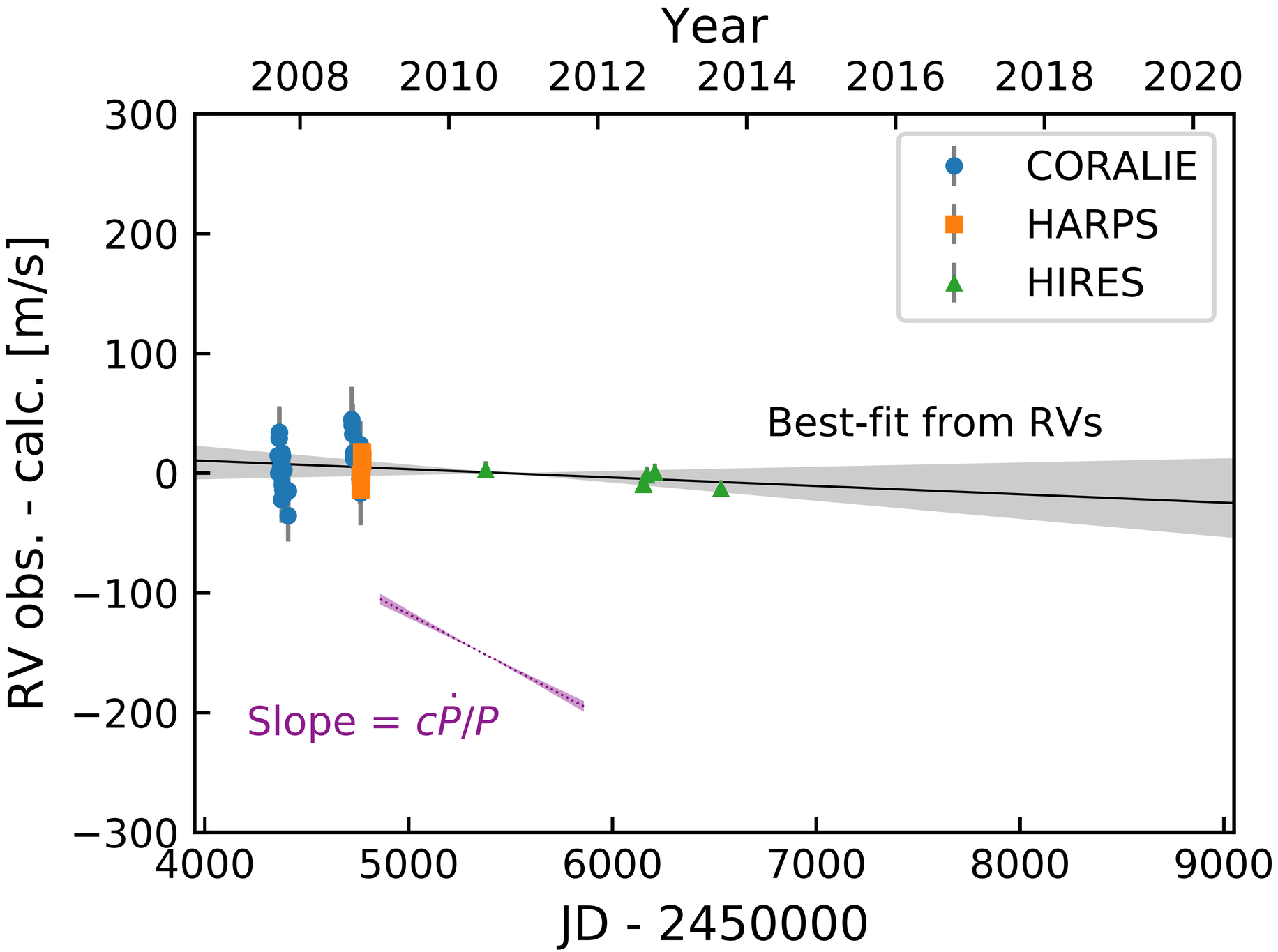

Year
2008
2010
2012
2014
2016
2018
All transits
pre-TESS
binned TESS
82 ± 12 seconds
Deviation from predicted transit time [minutes]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−500
0
500
1000
1500
2000
2500
Epoch
TESS transits
pre-TESS ephemeris
binned TESS
TESS
2455
2460
2465
2470
Epoch


Year
2008
2010
2012
2014
2016
2018
Constant period
Precessing orbit
Tidal decay
Transit obs. - calc. [minutes]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1000
−500
0
500
1000
1500
2000
Epoch


Year
2008
2010
2012
2014
2016
2018
Constant period
Precessing orbit
Tidal decay
$\dot{P}$ = -12.6 ± 1.2 millisec/yr
Transit obs. - calc. [minutes]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1000
−500
0
500
1000
1500
2000
Epoch

$$\frac{\dot{P}}{P} = \frac{\dot{v}_{\mathrm{r}}}{c}$$


Year
2008
2010
2012
2014
2016
2018
2020
300
200
100
0
−100
−200
−300
RV obs. - calc. [m/s]
CORALIE
HARPS
HIRES
Best-fit from RVs
4000
5000
6000
7000
8000
9000
JD - 2450000


Year
2008
2010
2012
2014
2016
2018
2020
300
200
100
0
−100
−200
−300
RV obs. - calc. [m/s]
CORALIE
HARPS
HIRES
Best-fit from RVs
Slope = $c\dot{P}/P$
4000
5000
6000
7000
8000
9000
JD - 2450000

A constant period was ruled out.

We could not distinguish between
(a) tidal decay,
(b) apsidal precession,
(c) line of sight acceleration due to an outer companion.

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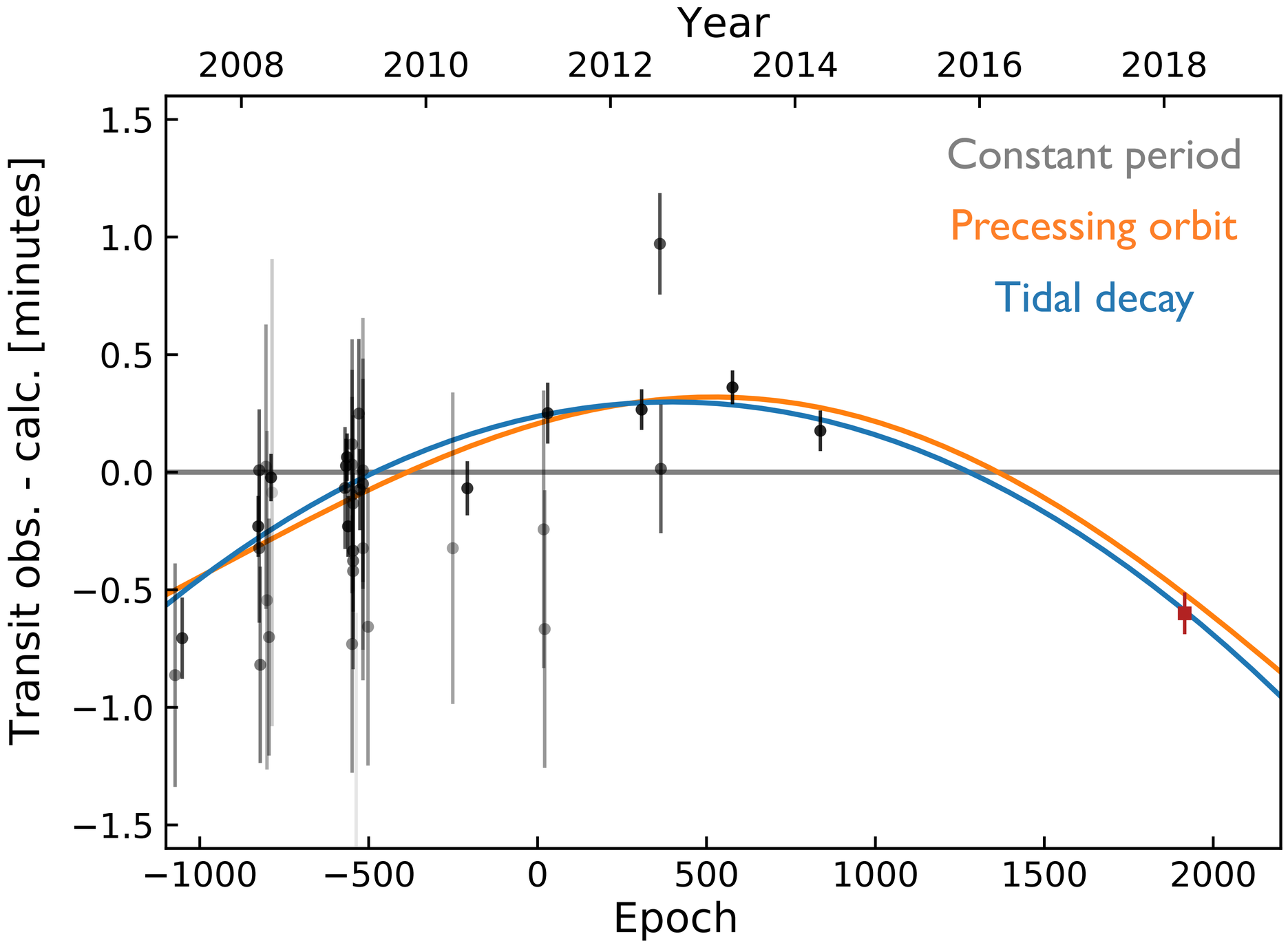
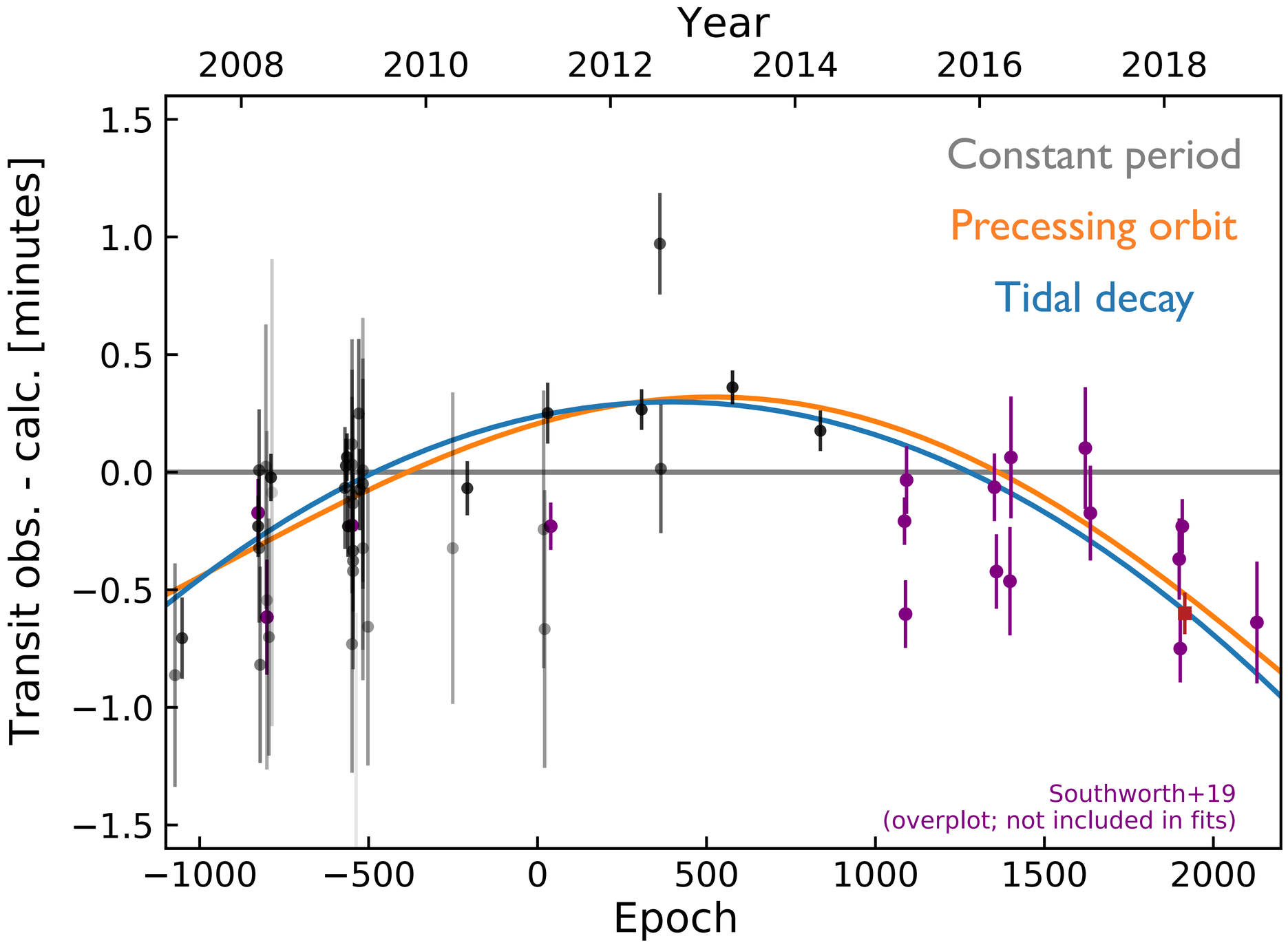
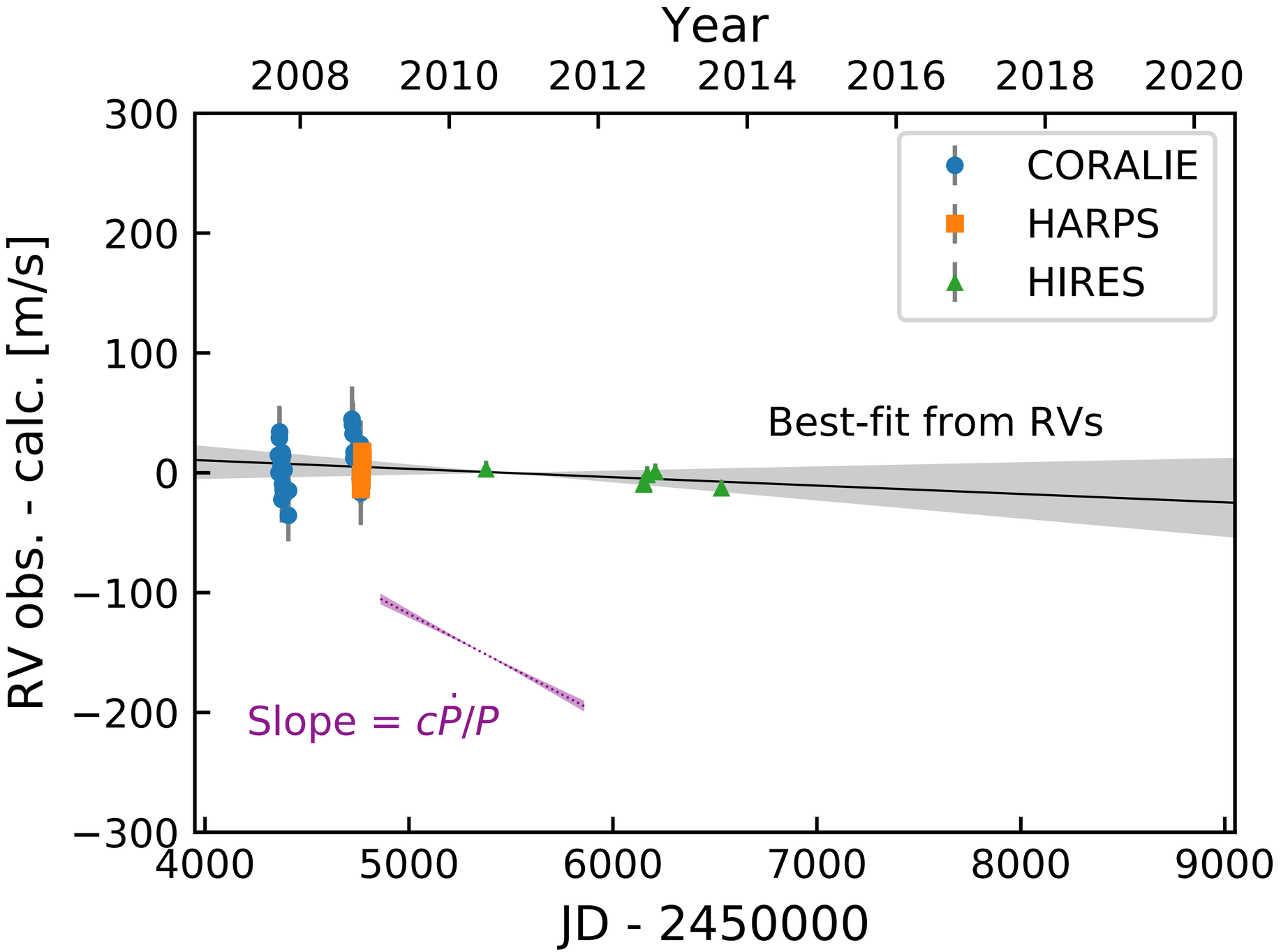
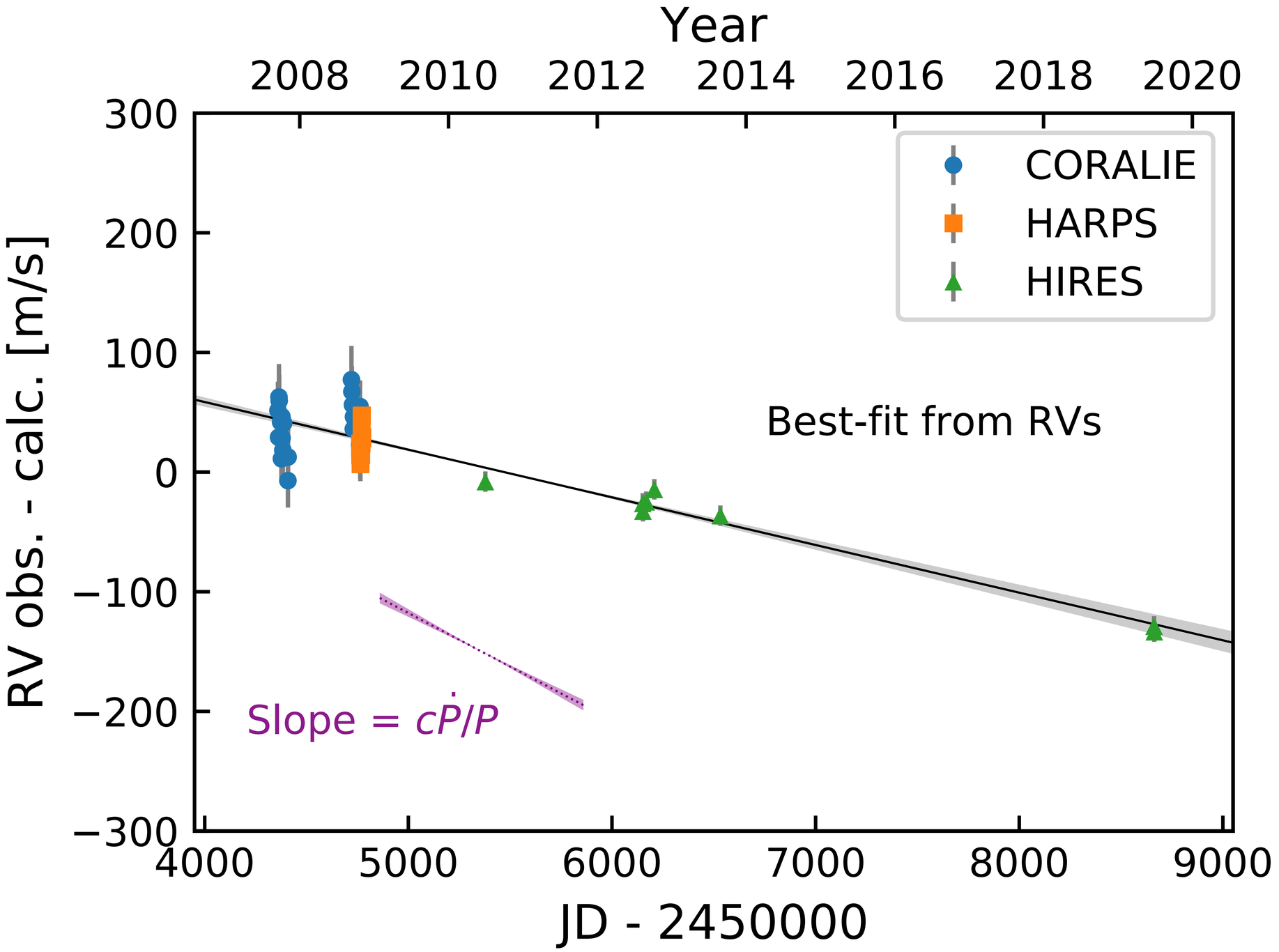
Since publishing, there have been two important developments.


Year
2008
2010
2012
2014
2016
2018
Constant period
Precessing orbit
Tidal decay
Transit obs. - calc. [minutes]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1000
−500
0
500
1000
1500
2000
Epoch


Year
2008
2010
2012
2014
2016
2018
Transit obs. - calc. [minutes]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Constant period
Precessing orbit
Tidal decay
Southworth+19
(overplot; not included in fits)
−1000
−500
0
500
1000
1500
2000
Epoch



New RVs from CPS (Howard, Knutson, Isaacson, & friends)



New RVs from CPS (Howard, Knutson, Isaacson, & friends)

Hot Jupiter timing studies can reveal period changes due to *(a)* tidal decay, *(b)* apsidal precession, & *(c)* outer companions.

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This is extremely unlikely to be a TESS timestamp offset (corroborated by Southworth+2019).

Hot Jupiter timing studies can reveal period changes due to *(a)* tidal decay, *(b)* apsidal precession, & *(c)* outer companions.

WASP-4b arrived early, and has a shrinking period.

This is extremely unlikely to be a TESS timestamp offset (corroborated by Southworth+2019).

The extended RV baseline suggests an outer companion might explain the timing variations.

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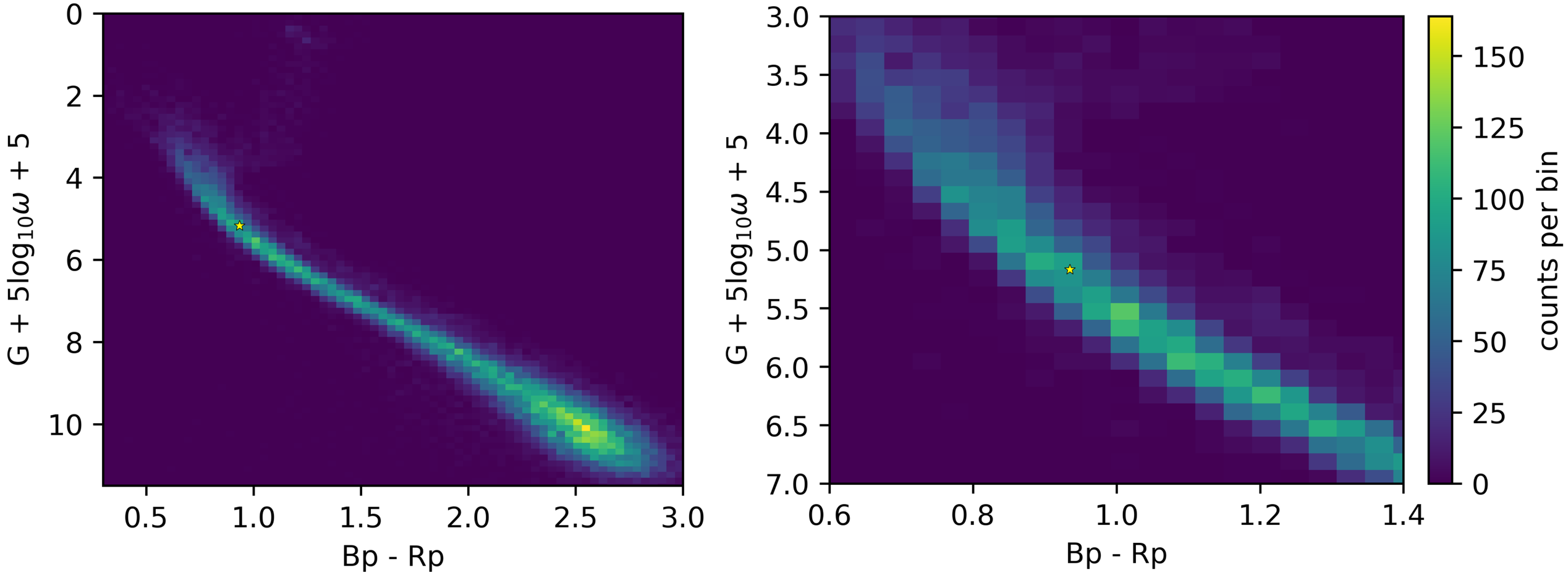
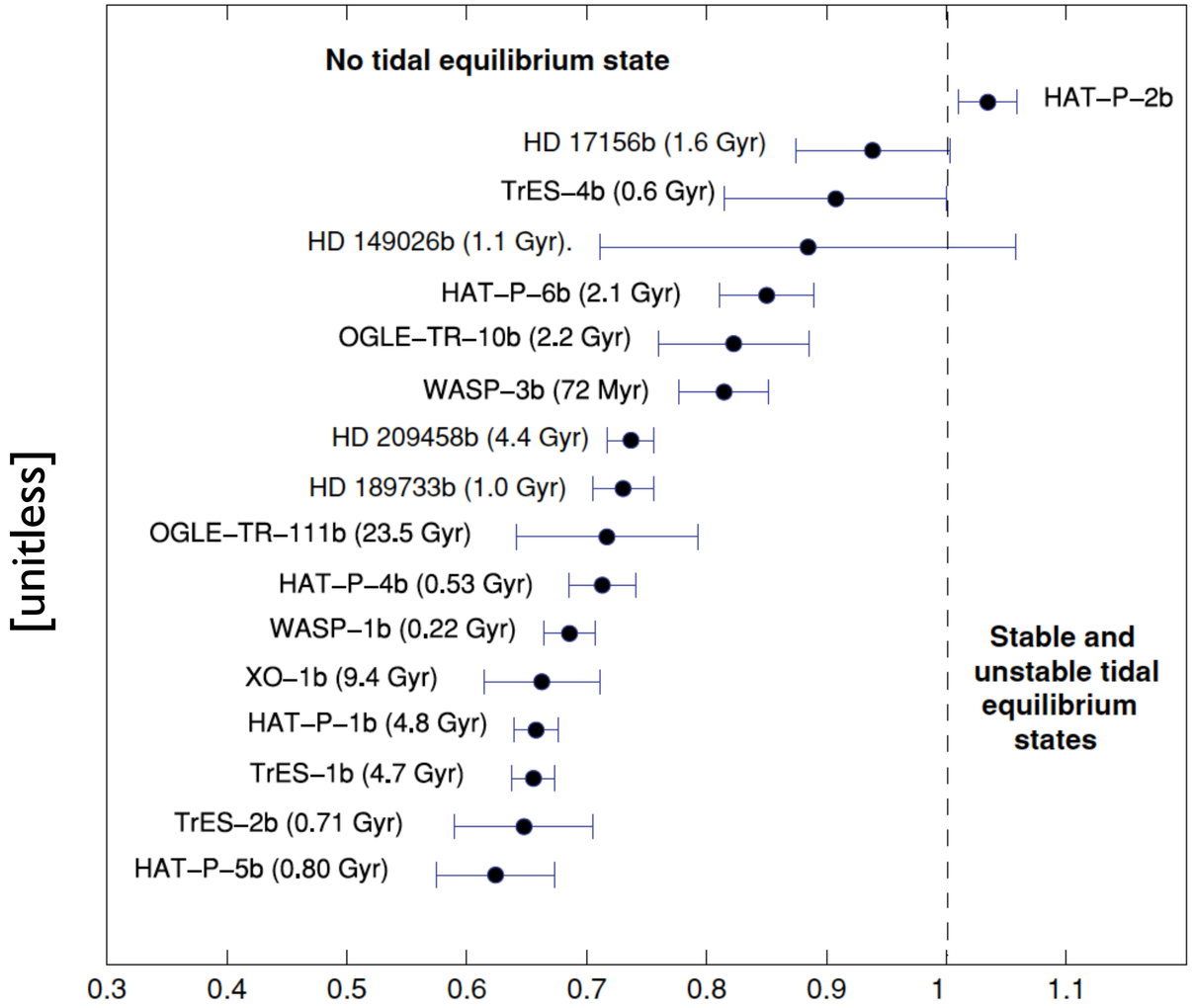
bonus

No obvious indications of photometric binarity



Counts from Gaia-DR2, requiring
* parallax SNR>20 * measured parallax within 0.2 mas of WASP-4's (3.71 mas)
* galactic latitude within 10 degrees of WASP-4's (-68 degrees latitude).

Most hot Jupiters are expected to be unstable to tidal decay.



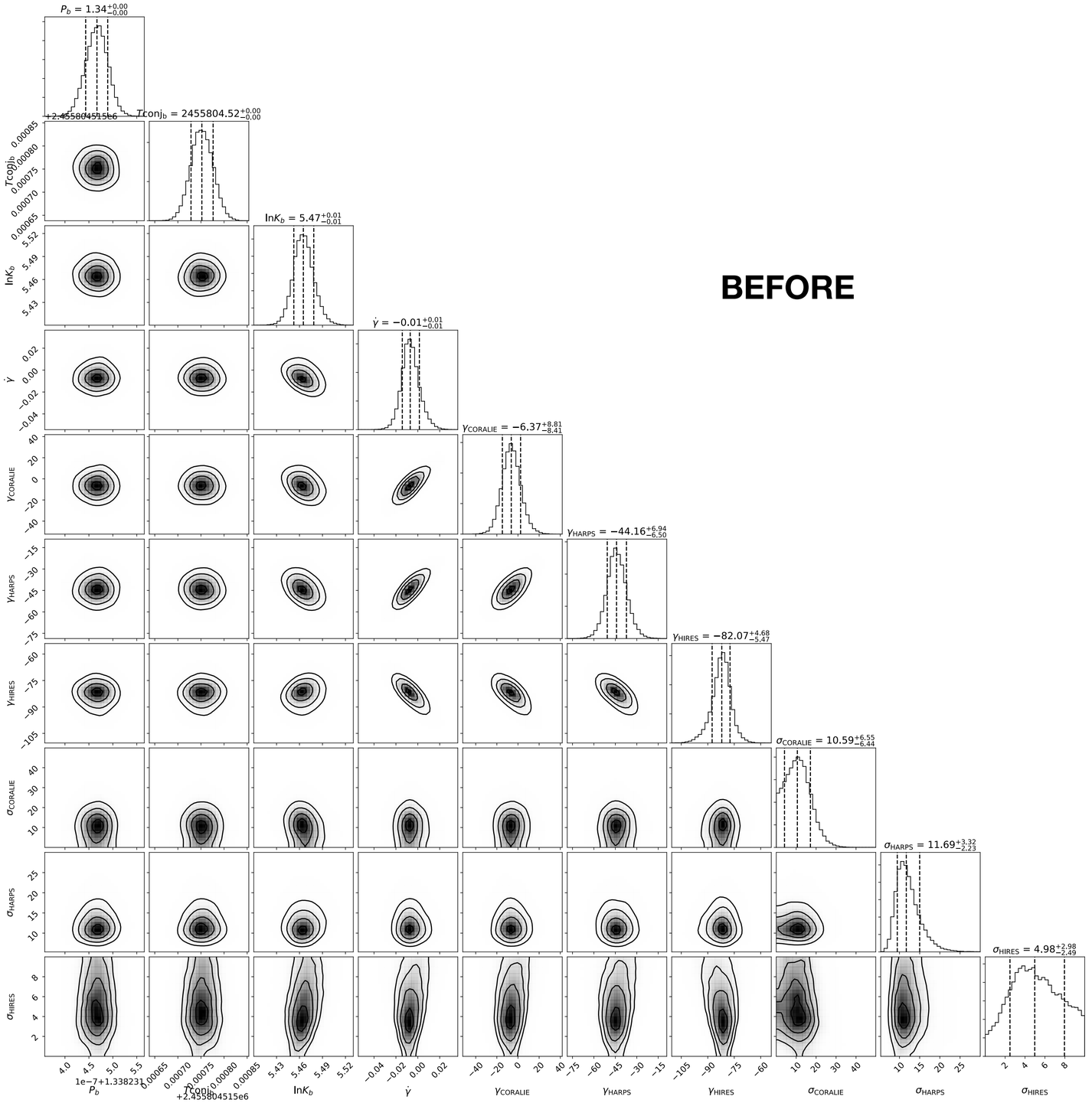
(Orbital angular momentum) / (3 × total spin angular momentum)

Counselman '73; Hut '80; Levrard+09; Matsumura+10.

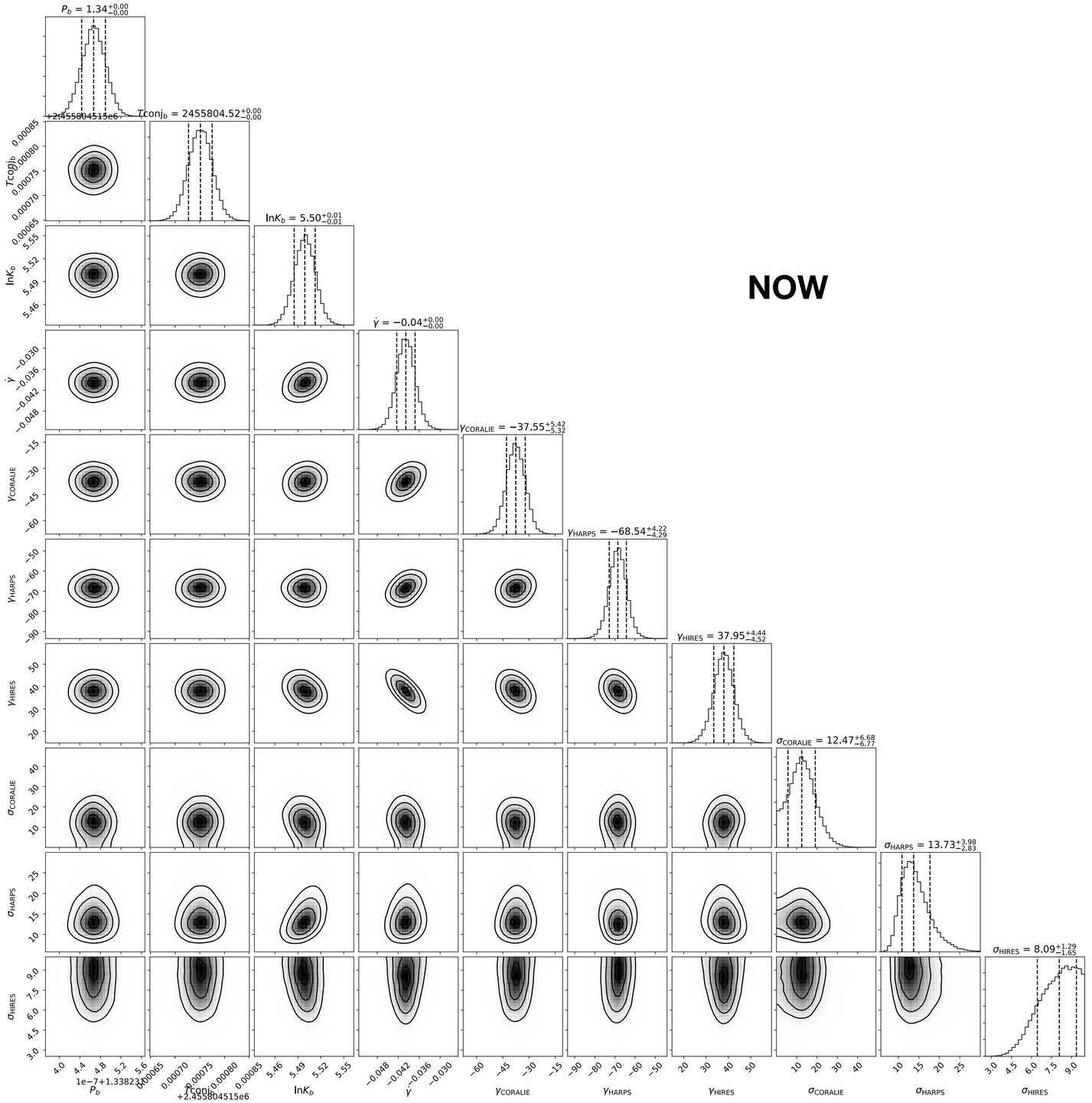
Table 1. Selected system parameters of WASP-4b

Parameter	Value	68% Confidence Interval	Comment
Transit/RV parameters:			
$R_p/R_\star$	0.15201	+0.00040, −0.00033	A
i [deg]	89.06	+0.65, −0.84	A
$a/R_\star$	5.451	+0.023, −0.052	A
$u_{\rm linear}$	0.382	—	A
$u_{\rm quad}$	0.210	—	A
K [m s^{-1}]	241.1	+2.8, −3.1	B
Stellar parameters:			
$T_{\rm eff}$ [K]	5400	±90	C
$\log g_\star$ [cgs]	4.47	±0.11	C
[Fe/H]	−0.07	±0.19	C
$F_{\rm bol}$ [erg cm^{-2} s^{-1}]	2.802×10^{-10}	$\pm 0.076 \times 10^{-10}$	D
A_V [mag]	0.03	+0.02, −0.01	D
π [mas]	3.7145	0.0517	F
$R_\star$ [R$_\odot$]	0.893	±0.034	E
$\rho_\star$ [g cm^{-3}]	1.711	+0.022, −0.048	E
$M_\star$ [M$_\odot$]	0.864	+0.084, −0.090	E
T magnitude	11.778	±0.018	G
Planetary parameters:			
a [AU]	0.0226	+0.0007, −0.0008	E
M_p [M$_{\rm Jup}$]	1.186	+0.090, −0.098	E
R_p [R$_{\rm Jup}$]	1.321	±0.039	E

NOTE— (A) From phase-folded TESS lightcurve (§ 2.2). Orbital periods are in Table 4. The limb darkening parameters were allowed to float around the Claret (2017) prediction, but were unconstrained. (B) Triaud et al. (2010). (C) From HARPS spectra (Doyle et al. 2013). (D) Stassun et al. (2017). (E) This work, see § 2.3. (F) Gaia Collaboration et al. (2018). (G) Stassun et al. (2018).


$P_b = 1.34^{+0.00}_{-0.00}$
$Tconj_b = 2455804.52^{+0.00}_{-0.00}$
$\ln K_b = 5.47^{+0.01}_{-0.01}$
$\dot{\gamma} = -0.01^{+0.01}_{-0.01}$
$\gamma_{CORALIE} = -6.37^{+8.81}_{-8.41}$
$\gamma_{HARPS} = -44.16^{+6.94}_{-6.50}$
$\gamma_{HIRES} = -82.07^{+4.68}_{-5.47}$
$\sigma_{CORALIE} = 10.59^{+6.55}_{-6.44}$
$\sigma_{HARPS} = 11.69^{+3.32}_{-2.23}$
$\sigma_{HIRES} = 4.98^{+2.98}_{-2.49}$
1e−7+1.338231
+2.455804515e6
P_b
$Tconj_b$
$\ln K_b$
$\dot{\gamma}$
$\gamma_{CORALIE}$
γ_{HARPS}
γ_{HIRES}
$\sigma_{CORALIE}$
σ_{HARPS}
σ_{HIRES}

BEFORE


$P_b = 1.34^{+0.00}_{-0.00}$
$T\mathrm{conj}_b = 2455804.52^{+0.00}_{-0.00}$
$\ln K_b = 5.50^{+0.01}_{-0.01}$
$\dot{\gamma} = -0.04^{+0.00}_{-0.00}$
$\gamma_{\mathrm{CORALIE}} = -37.55^{+5.42}_{-5.32}$
$\gamma_{\mathrm{HARPS}} = -68.54^{+4.22}_{-4.29}$
$\gamma_{\mathrm{HIRES}} = 37.95^{+4.44}_{-4.52}$
$\sigma_{\mathrm{CORALIE}} = 12.47^{+6.68}_{-6.77}$
$\sigma_{\mathrm{HARPS}} = 13.73^{+3.98}_{-2.83}$
$\sigma_{\mathrm{HIRES}} = 8.09^{+1.29}_{-1.65}$
1e−7+1.338231
+2.455804515e6
P_b
$T\mathrm{conj}_b$
$\ln K_b$
$\dot{\gamma}$
$\gamma_{\mathrm{CORALIE}}$
γ_{HARPS}
γ_{HIRES}
$\sigma_{\mathrm{CORALIE}}$
σ_{HARPS}
σ_{HIRES}

NOW

$$t_{\mathrm{tra}}(E) = t_0 + PE,$$

$$t_{\mathrm{tra}}(E) = t_0 + PE + \frac{1}{2}\frac{\mathrm{d}P}{\mathrm{d}E}E^2,$$

$$t_{\mathrm{tra}}(E) = t_0 + P_{\mathrm{s}}E + \frac{eP_{\mathrm{a}}}{\pi}\cos\omega,$$

$$\omega(E) = \omega_0 + \frac{\mathrm{d}\omega}{\mathrm{d}E}E,$$

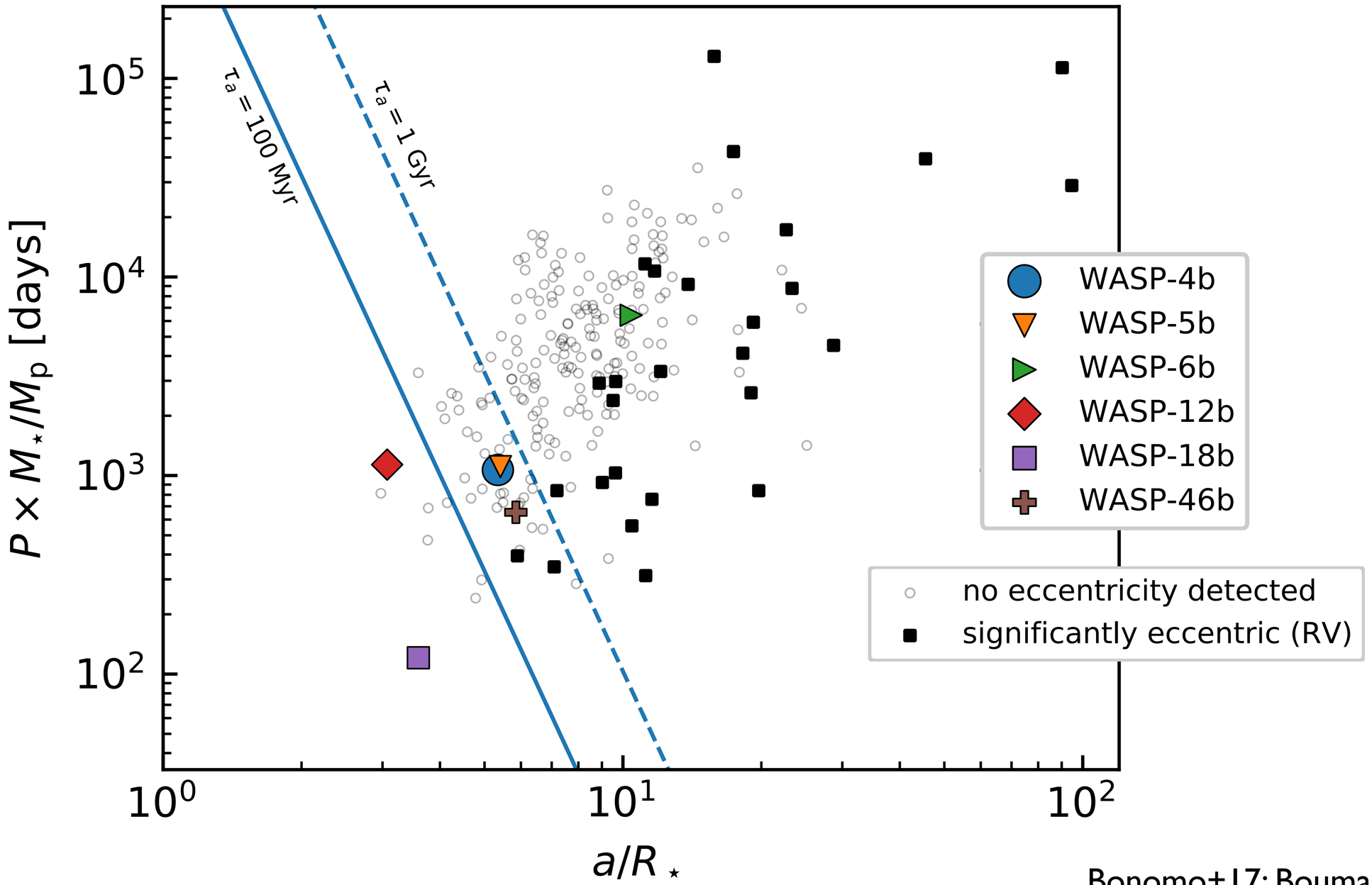
$$P_{\mathrm{s}} = P_{\mathrm{a}}\left(1 - \frac{1}{2\pi}\frac{\mathrm{d}\omega}{\mathrm{d}E}\right)$$

1. Tidal decay would imply "observing at a special time"

$$\dot{P} = -12.6 \pm 1.2\,\mathrm{ms\,yr^{-1}},$$
$$P/\dot{P} = 9.2\,\mathrm{Myr},$$
$$Q'_\star = (2.9 \pm 0.3) \times 10^4$$

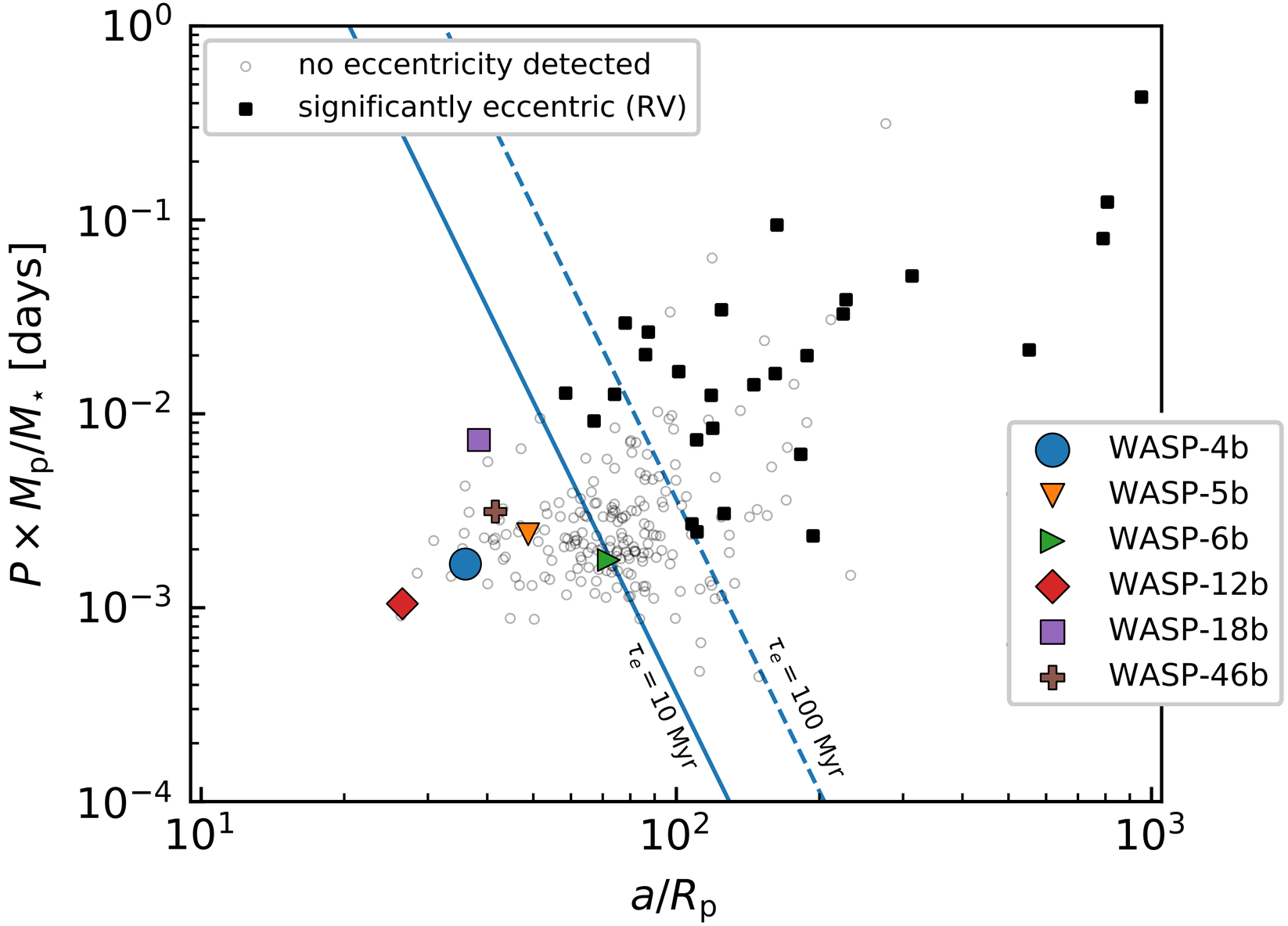
2. Tidal decay (+ equilibrium tidal theory) would imply a surprising amount of friction inside the star.

3. If WASP-4 is decaying, why aren't other hot Jupiters decaying too?



Bonomo+17; Bouma+19 (subm.)

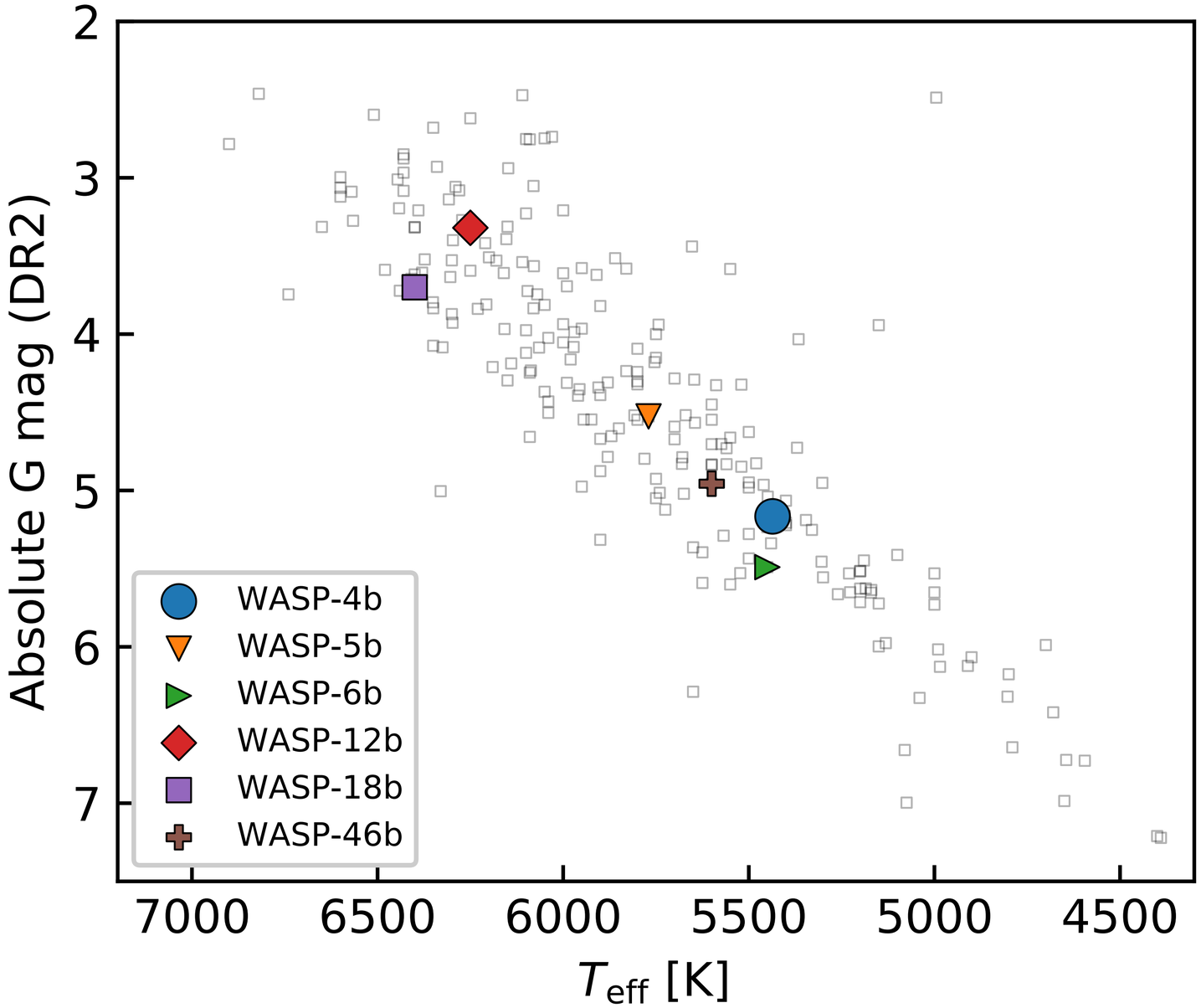
Apsidal precession gives a plausible (but uncertain) Love number. However, the implied eccentricity ($e \approx 10^{-3}$) requires explanation.



Data:
Bonomo+17
Bouma+19 (subm.)

How to stay eccentric:
Mardling 07
Lidov, Kozai 62

WASP-4 is on the M.S., ruling out some tidal decay mechanisms.



$a/R_\star$	5.45 ± 0.03
T_{eff} [K]	5400 ± 90
$M_\star$ [$M_\odot$]	0.864
R_p [R_{Jup}]	1.32 ± 0.04
M_p [M_{Jup}]	1.19 ± 0.09

see Weinberg+17; Bailey & Goodman 19

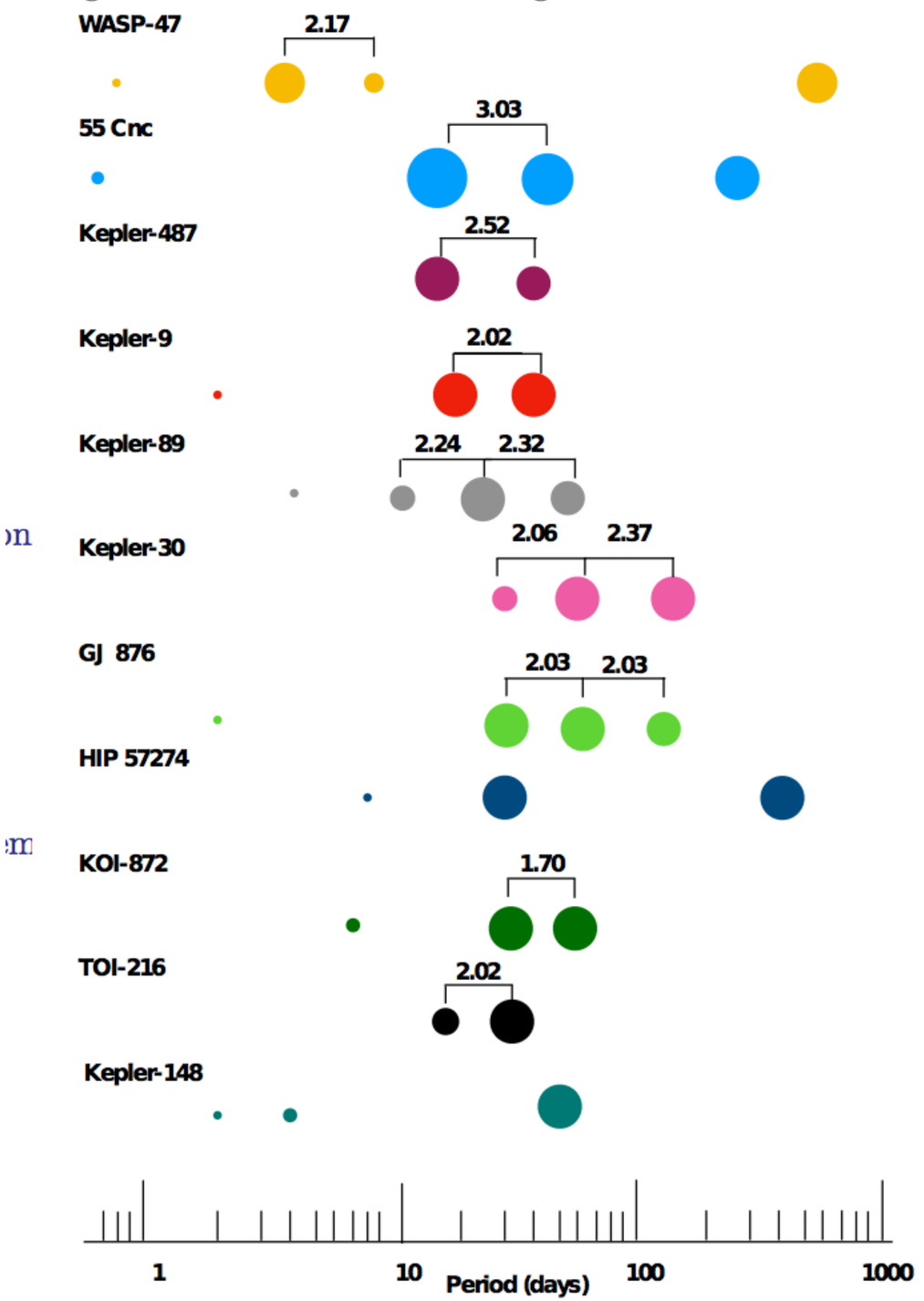


Figure 1. All confirmed exoplanet systems with a warm, large exoplanet (mass greater than 0.25 $M_{\rm Jup}$ or radius greater than 8 Earth radii; orbital period less than 100 days) and one or more companions with a < 100 day orbital period. (The WASP-47 system satisfies this criteria but contains a hot Jupiter.) Sizes shown are roughly proportional to planet size.

Dawson+2019