Tidal deformation and tidal decay of WASP-103b

Susana Cristina Cabral de Barros

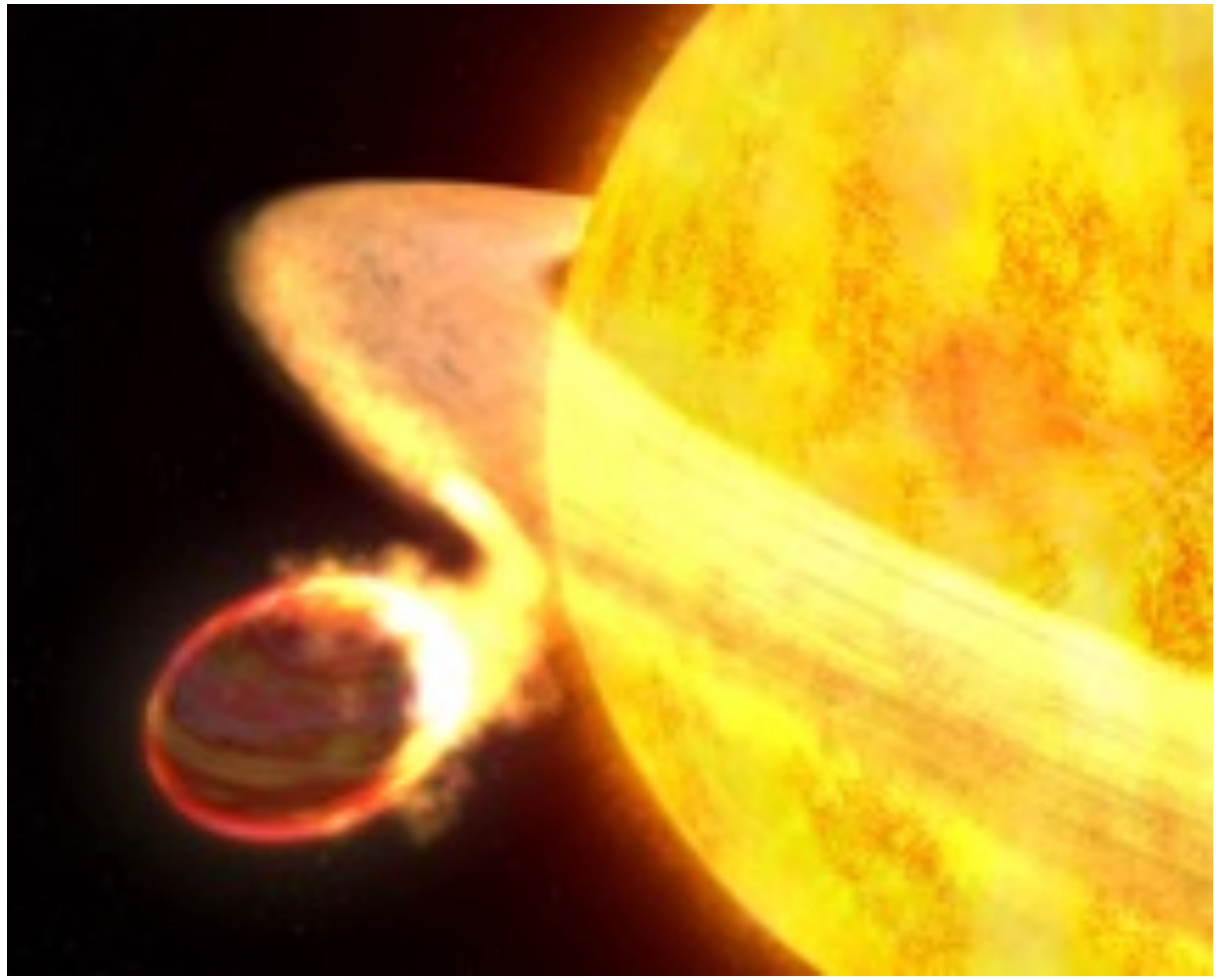
INSTITUTO DE ASTROFÍSICA E CIÊNCIAS DO ESPAÇO

LIneA seminar

Credit: ESA

Outline

- Introduction to exoplanets
- Tidal decay
- Tidal deformation
- Observations of WASP-103b and results
- Future observations



NASA / ESA / G. Bacon, STScI / C. Haswell, OU

Lucky transits

WASP

HAT

TRES

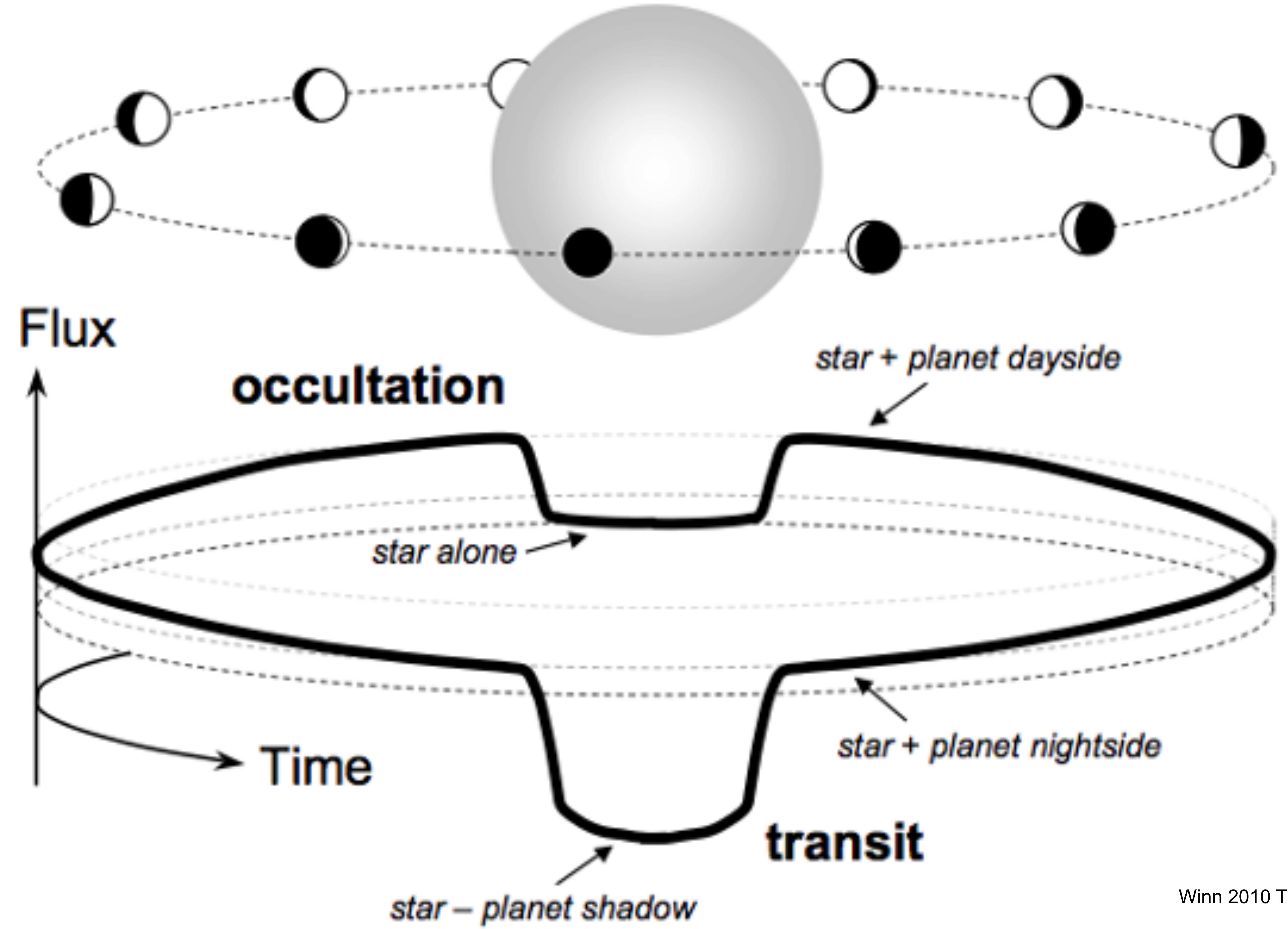
XO

MEarth

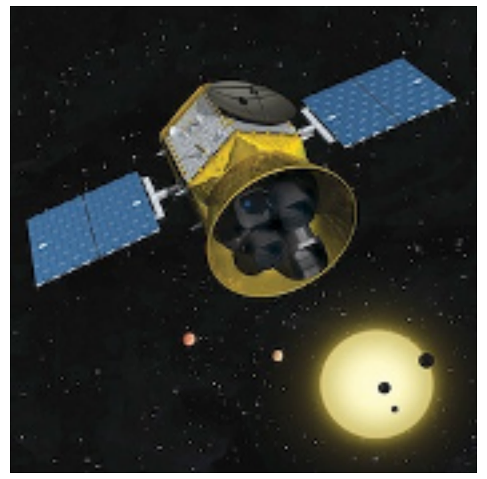
KELT

MASCARA

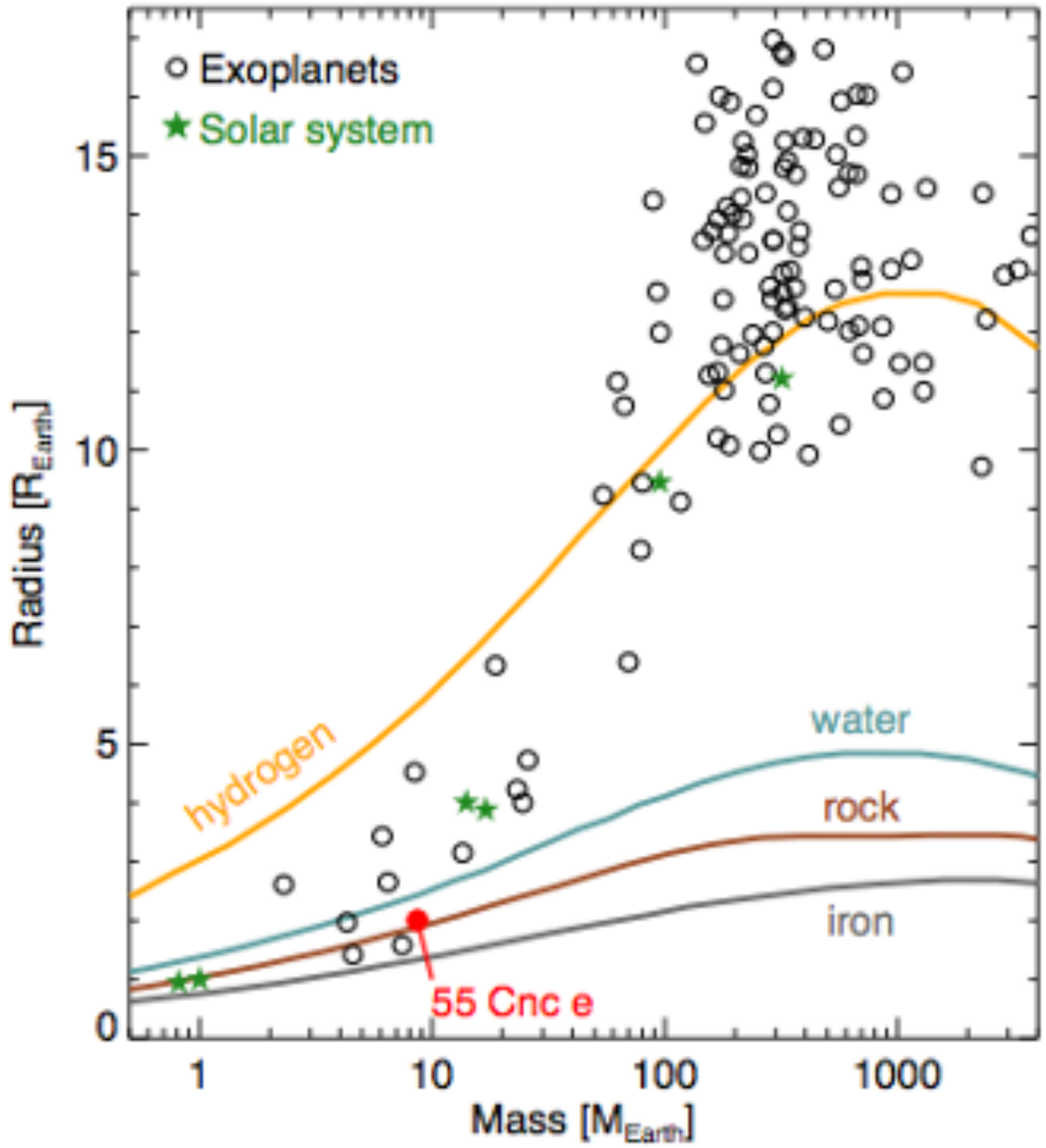
NGTS



Winn 2010 Transits and Occultations

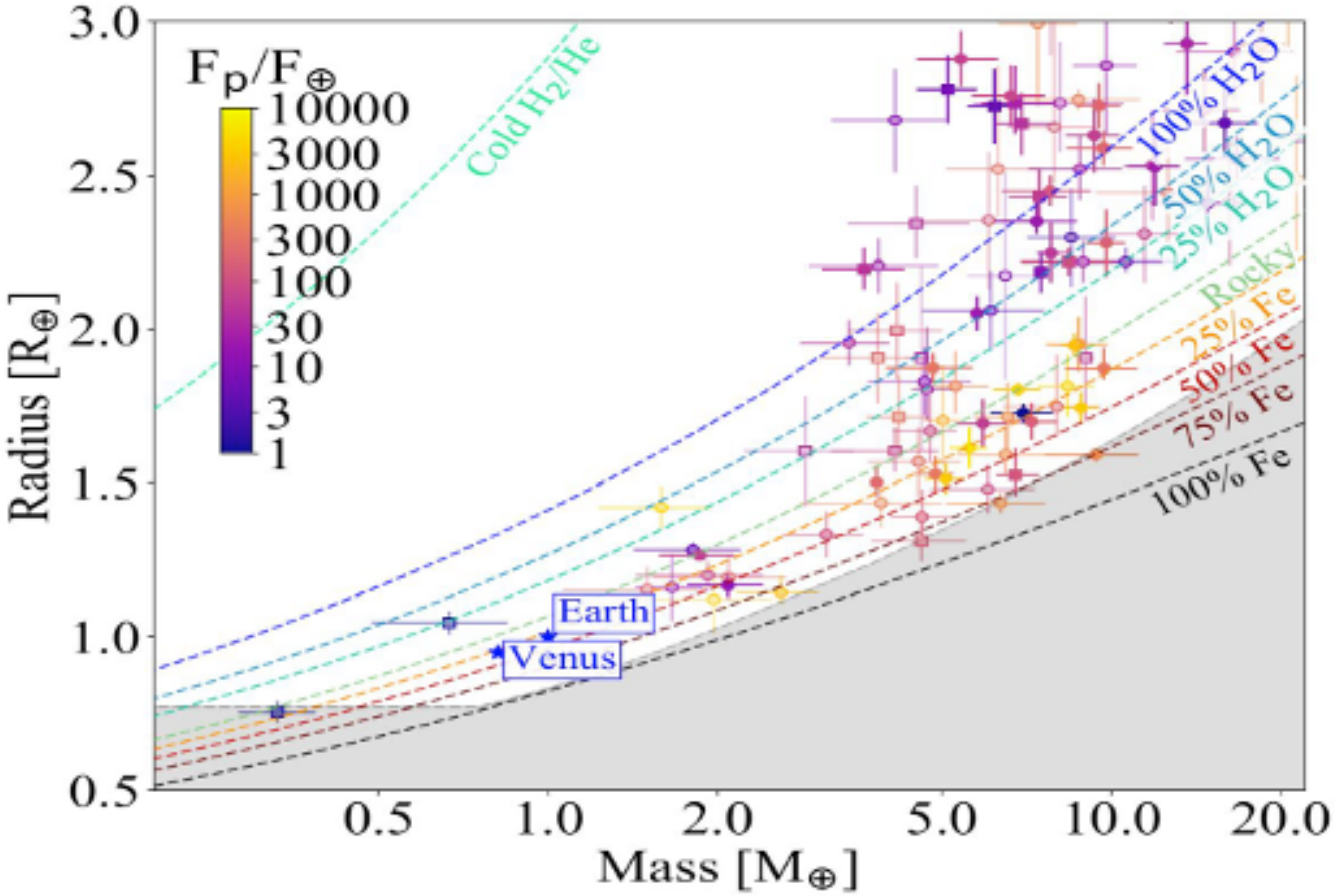


Diversity of compositions



Winn et al. 2011,ApJ, 737, 18

Small planets well characterised



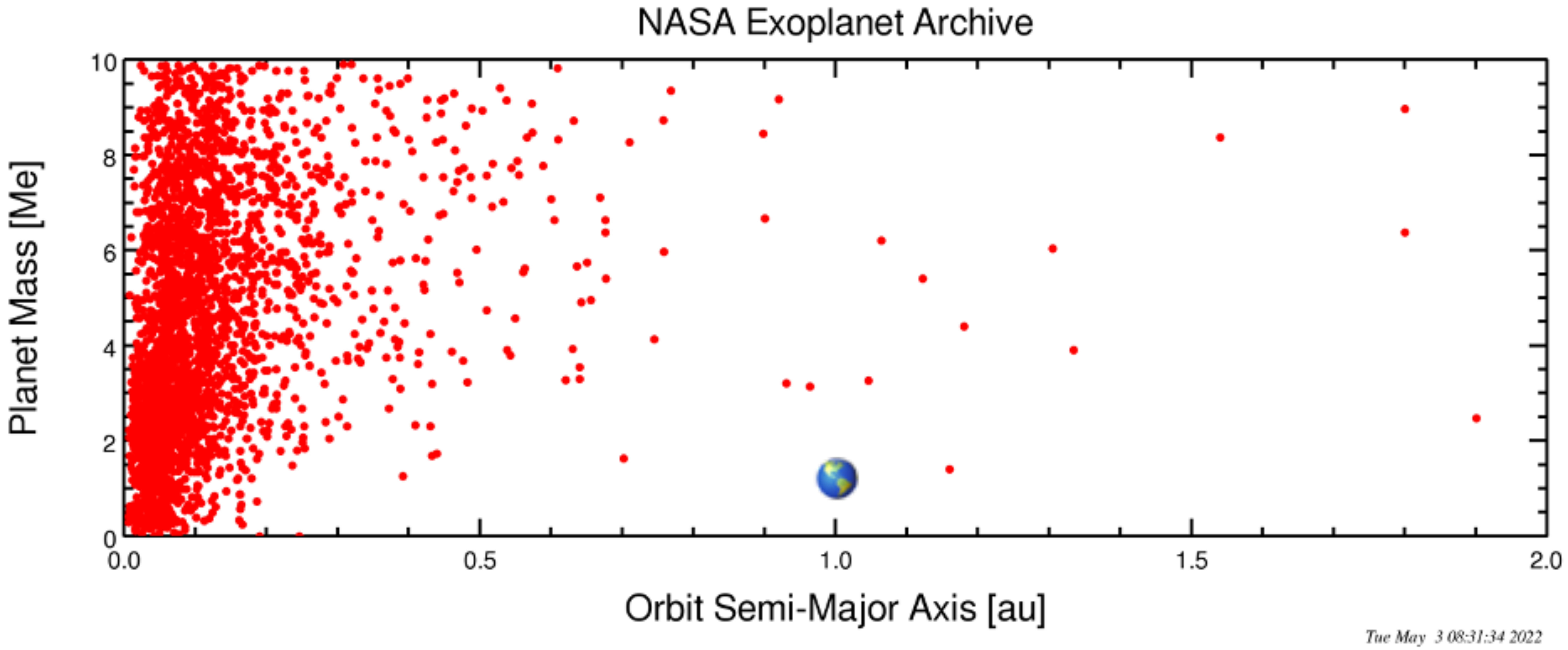
Radius & mass 30%

Circles – RVs
Squares – TTVs

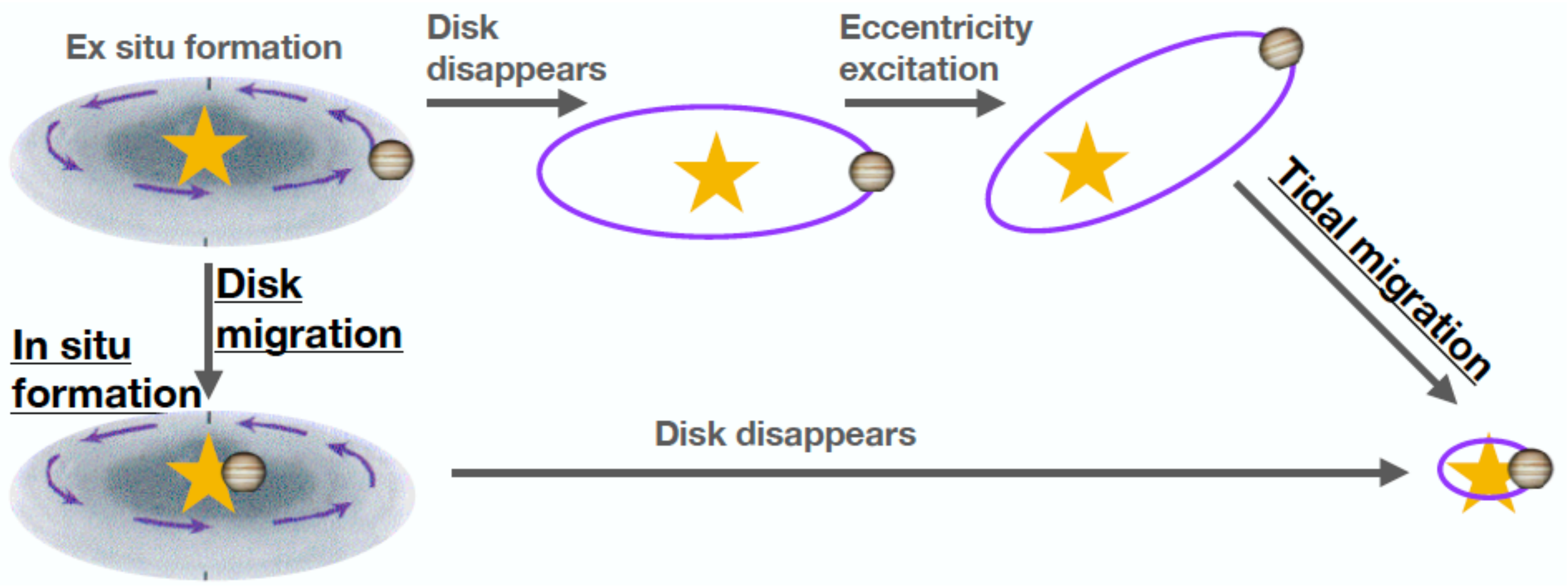
Transparency ∝ erros

Exoplanet.eu

Earth-Like planets around Sun-like stars



Hot Jupiters



In situ formation

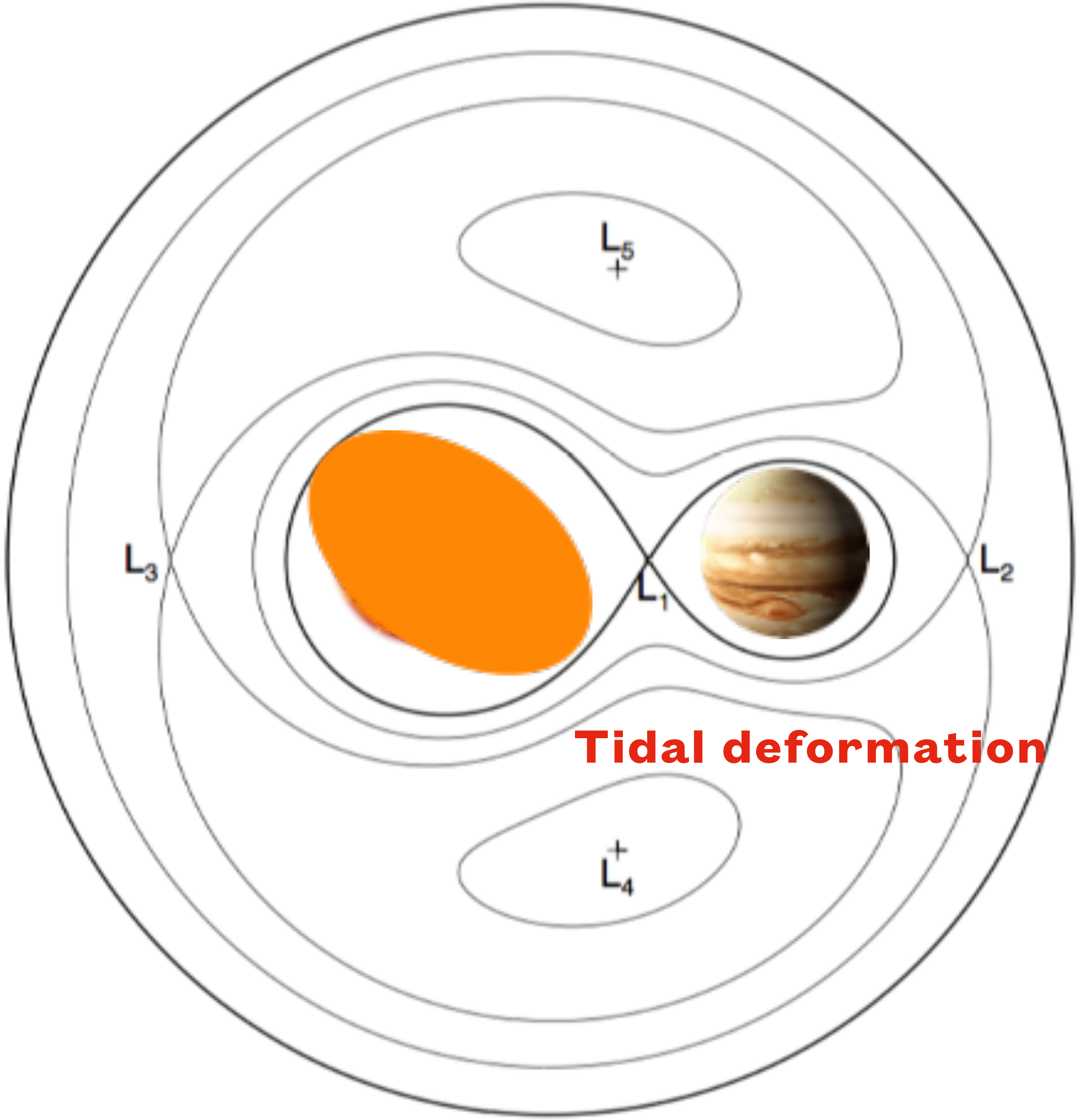
Migration:

- Through the disc- type 1 or type 2
- Kozai star-planet scattering or Kozai planet-planet scattering

Tidal interaction with the host star decreases the orbital period. In some cases aligns the stellar spin with the planet orbital plane

Tidal star planet interaction shapes planetary systems

Equipotentials



Tidal deformation

Tidal forces tend to:

- circularise planetary orbits
- synchronise the **planetary** rotation with the orbital period
- synchronise the **stellar** rotation with the orbital period. Not complete - depends on tidal quality factor Q.

Tidal decay

CHEOPS Feature.characterisation

- One of the science programs of the GTO of CHEOPS is Feature.Characterisation which I am leading. It includes:
- Measuring tidal deformation and tidal decay
- Searching for moons and rings
- Measuring the spin orbit angle through the measurement of the gravity darkening in some stars

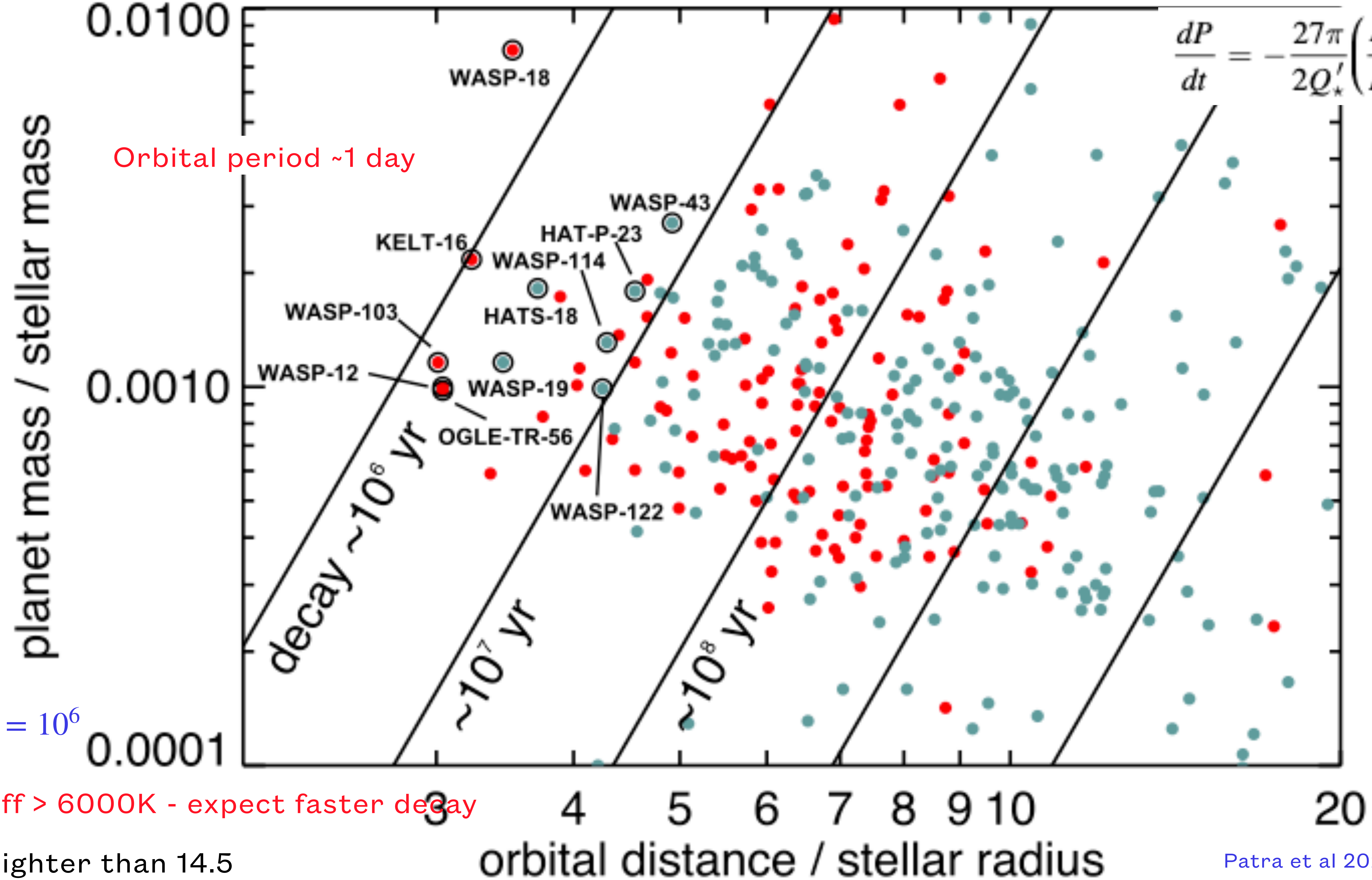
- 2 targets for tidal deformation
- 7 targets for tidal decay

Tidal decay

- In hot Jupiters the synchronisation of the **stellar** rotation with the orbital period leads transfer of angular momentum from the planetary orbit to the stellar angular momentum.
- This leads to shrinkage of the orbit and eventual tidal disruption of the planet.
- Measuring the tidal decay allows to constrain the stellar **tidal quality factor Q'** which is critical to constrain stellar models. It would also help to better understand the hot Jupiter population and its evolution (e.g. Jackson et al. 2008; Hamer & Schlaufman 2019
- From binaries $Q'_* = 10^6 - 10^7$
- Statistical studies of the ensemble of known hot Jupiters majority had $Q'_* \sim 10^8$ and small group had $Q'_* \sim 10^7$

$$\frac{dP}{dt} = -\frac{27\pi}{2Q'_\star}\left(\frac{M_p}{M_\star}\right)\left(\frac{R_\star}{a}\right)^5,$$

Orbital period ~1 day



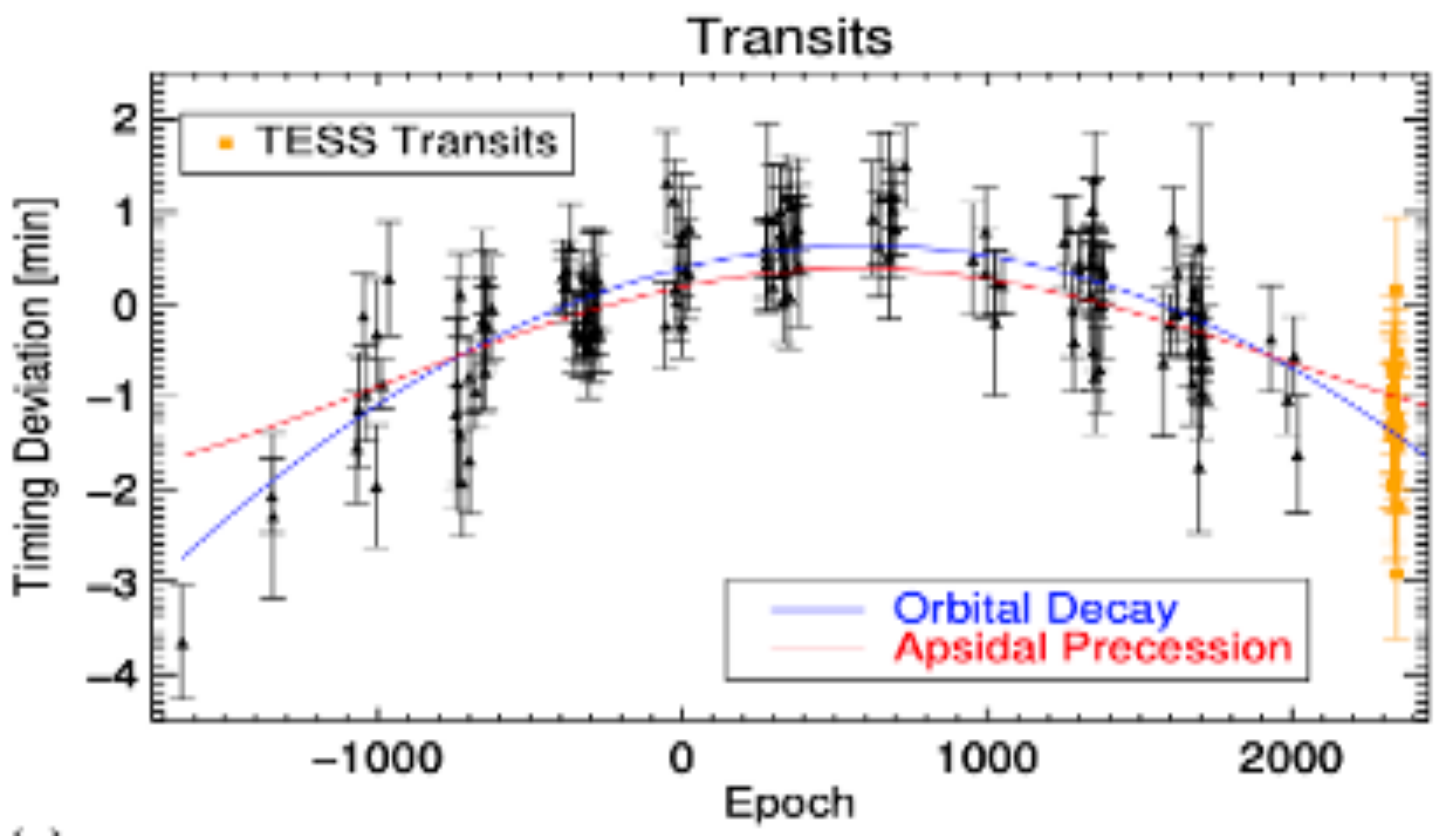
$Q'_* = 10^6$

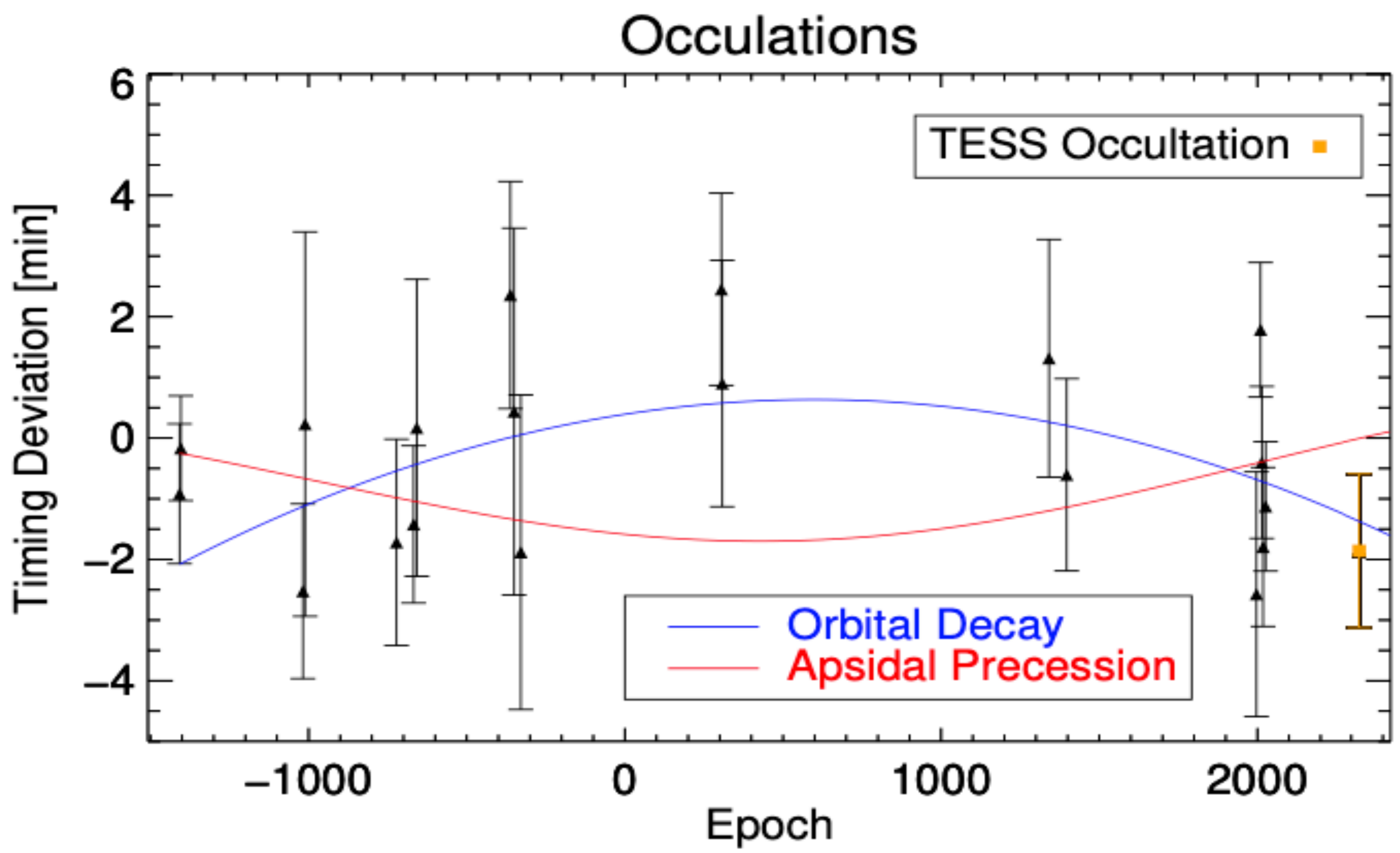
Teff > 6000K - expect faster decay

Brighter than 14.5

Patra et al 2020

Orbital decay WASP-12b





$$T_{\text{mid}} = T_0 + P \times E + P\dot{P} \times \frac{E(E-1)}{2},$$

Orbital decay

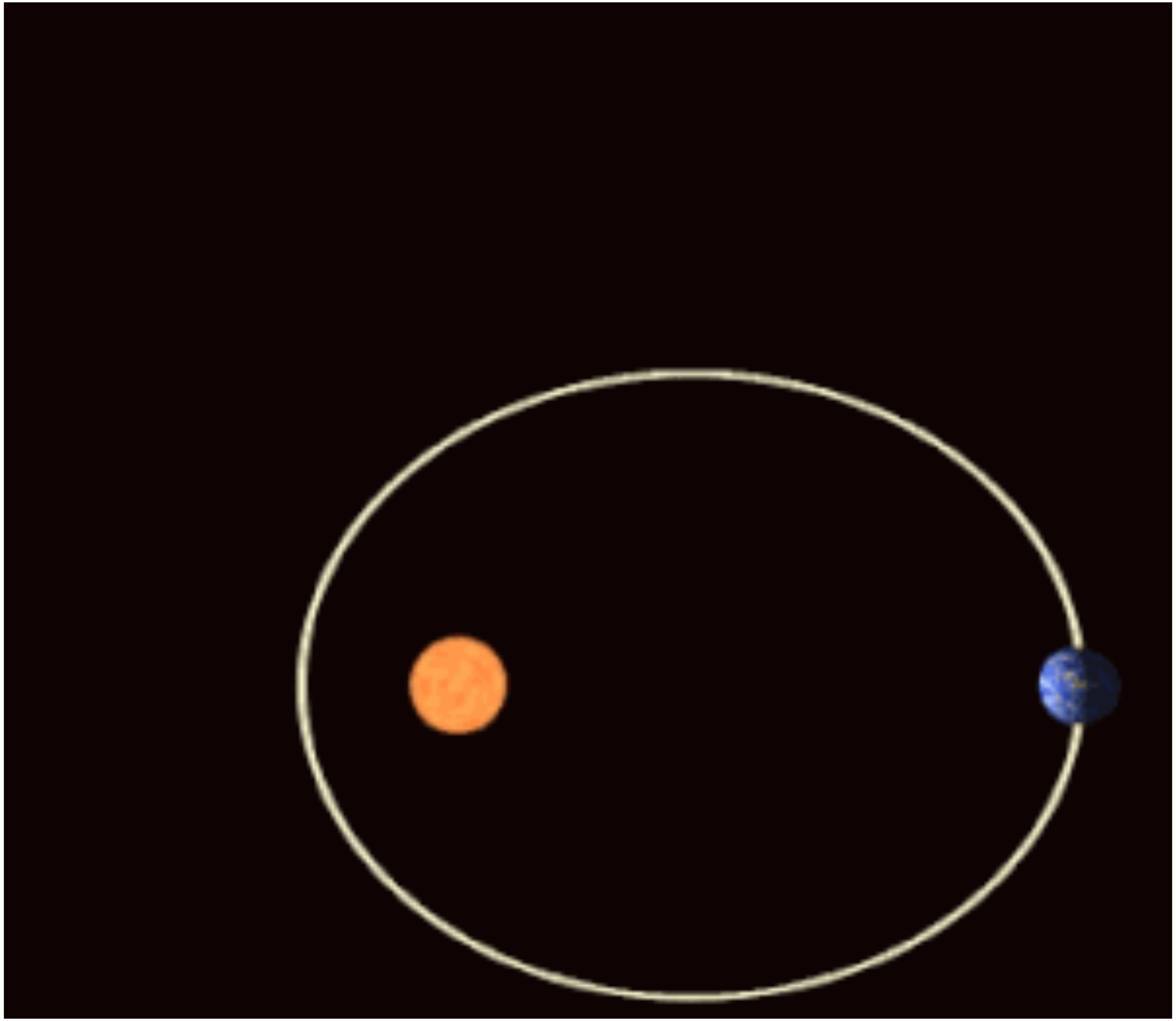
$$Q'_* = 10^5$$

$$T_{\text{mid}} = T_0 + P_{\text{s}} \times E - \frac{e\,P_{\text{a}}}{\pi} \times \cos\omega,$$

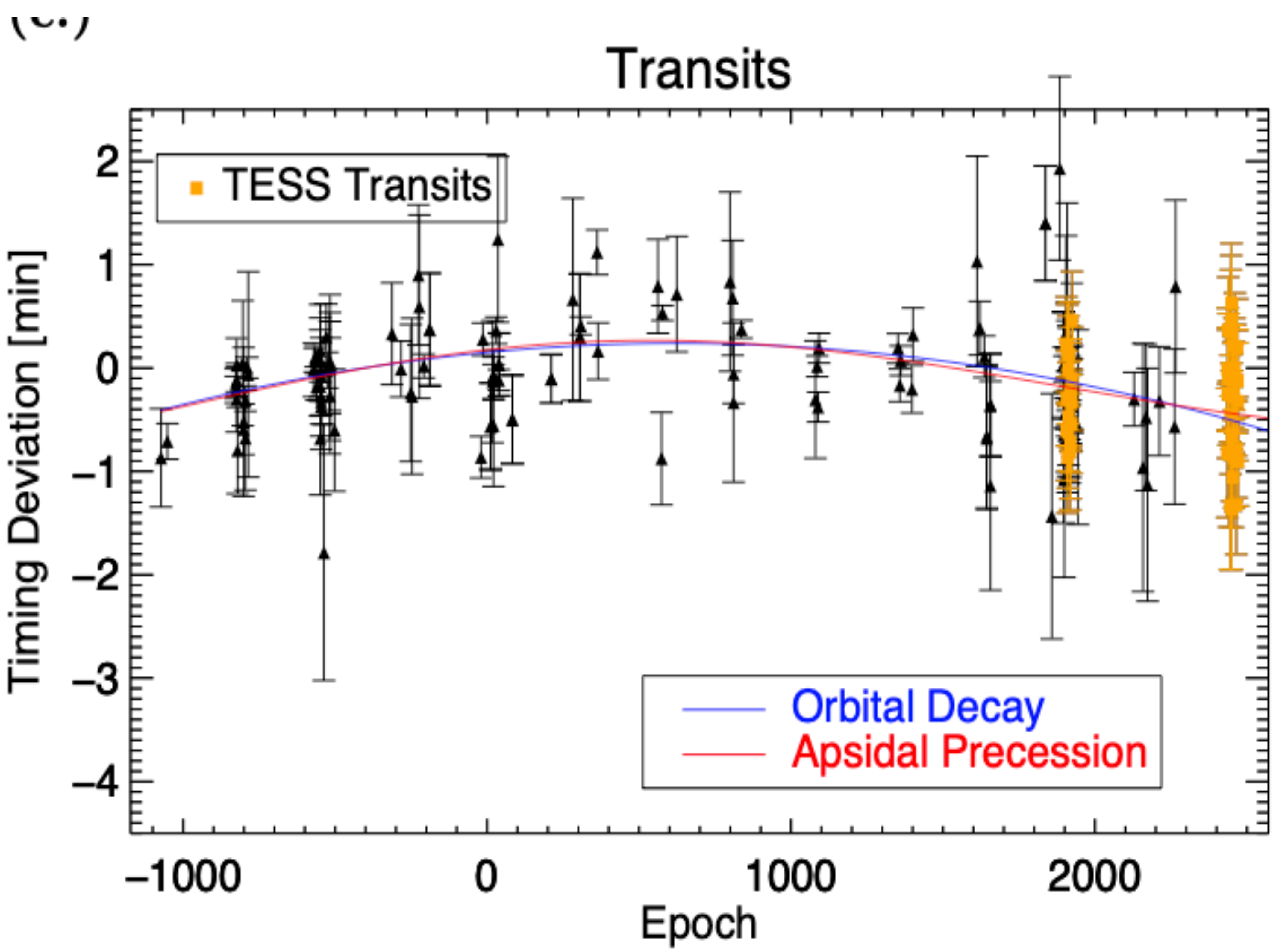
Apsidal Precession

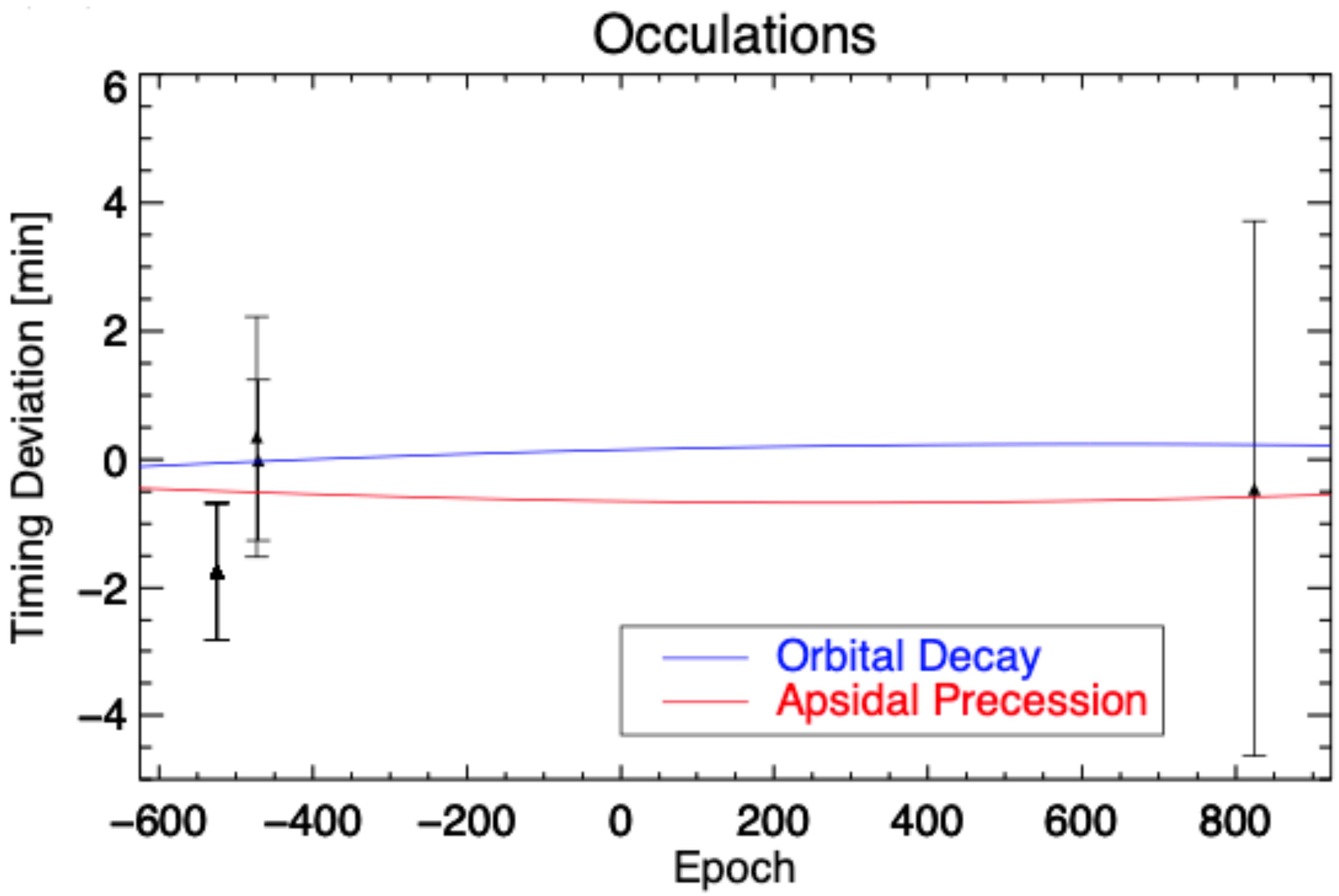
Maciejewski et al. 2016, Turner, J. et al. ApJ 2021

Apsidal precession



Orbital decay WASP-4b



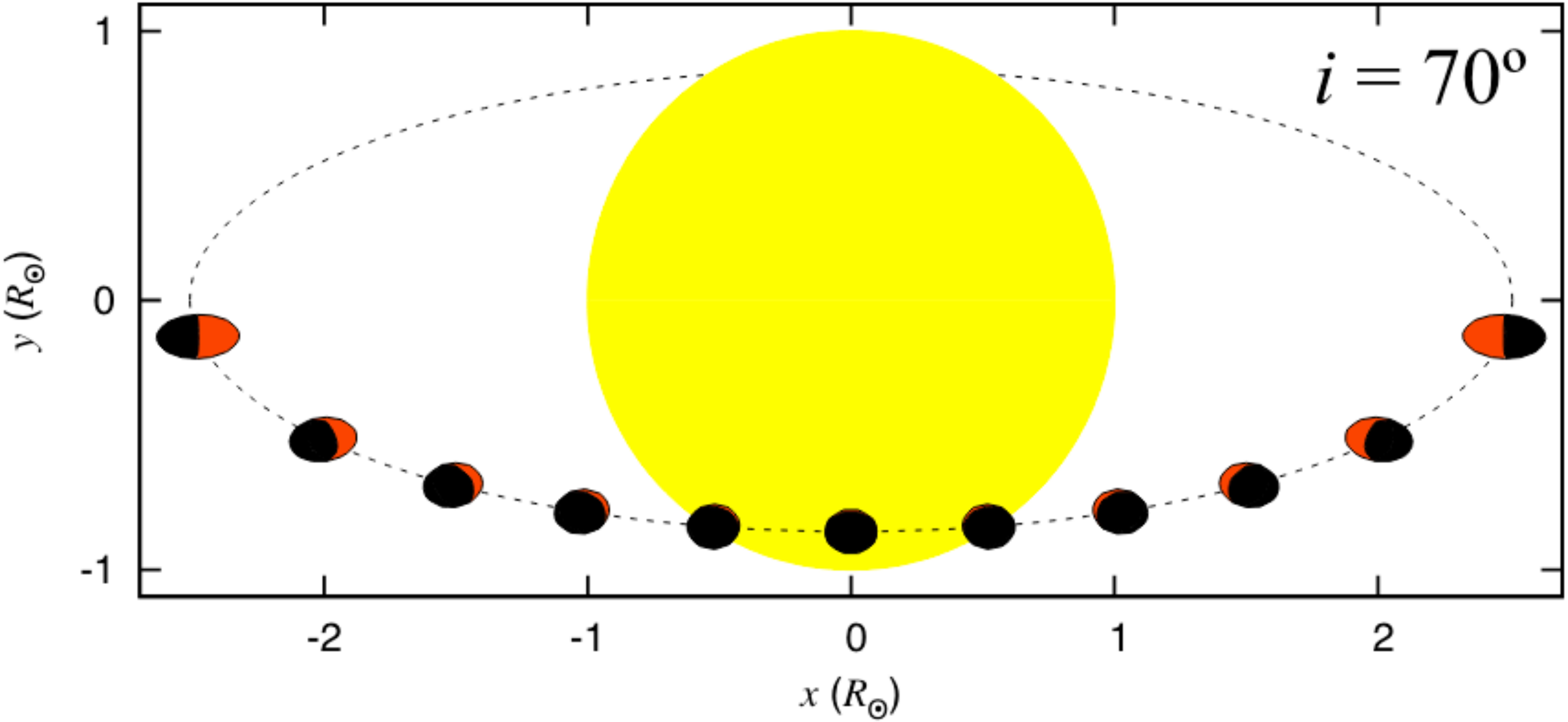


Period ~ 1.3 days

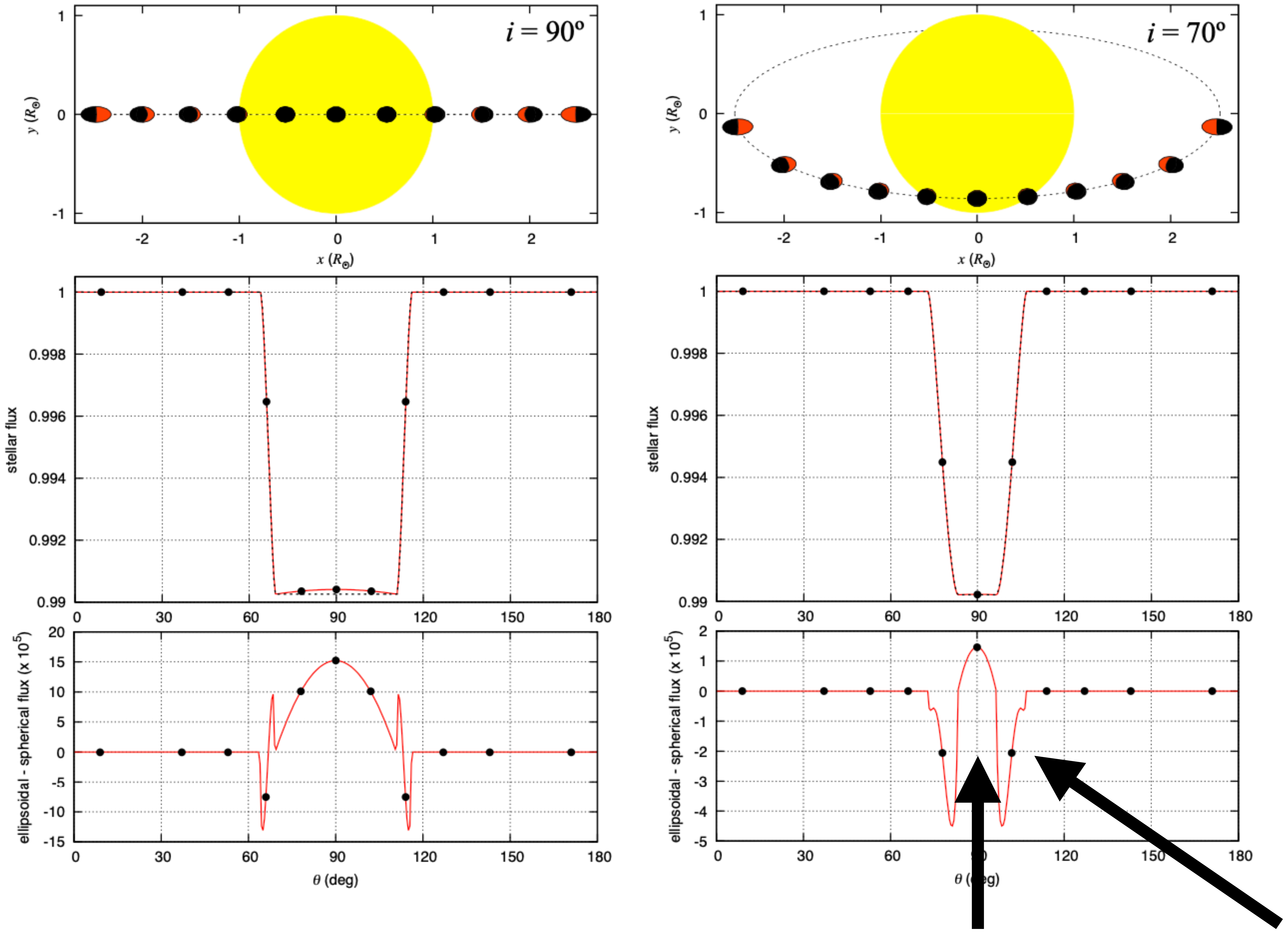
$Q'_* = 5 \times 10^4$ —> Can be due to other effects

Bouma et al. 2020, Turner et al 2021

Tidal deformation



Tidal deformation



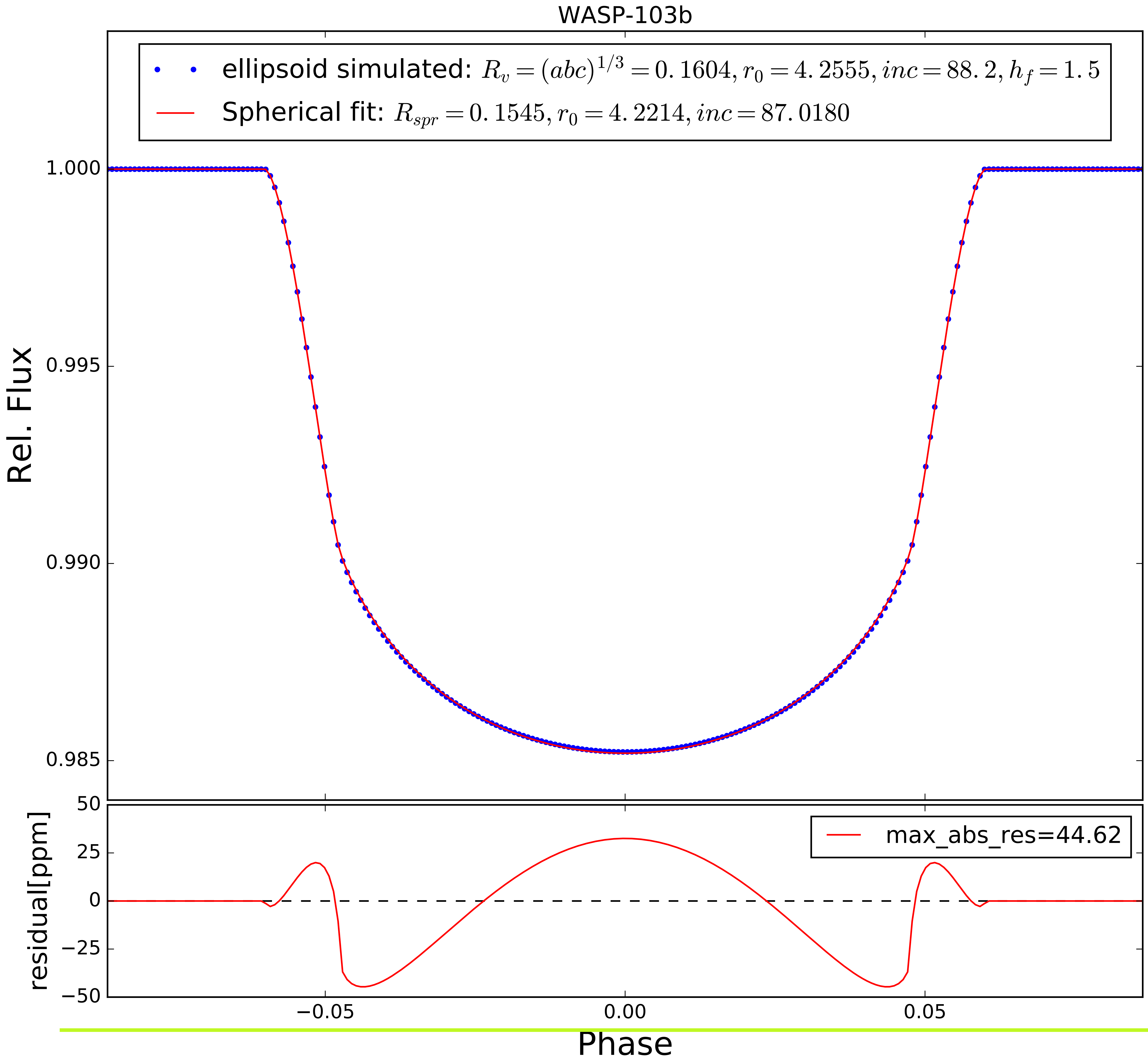
Correia, A. A&A, 2014

Tidal Bulge

Rotation

- Strong tidal forces deforme the shape of ultra Hot Jupiter into ellipsoids.
- The deformation of the three axis is related to a single parameter - Love number
- The Love number measures the distribution of mass within the planet giving insight into the planet internal structure.

Seager & Hui 2002; Barnes & Fortney 2003



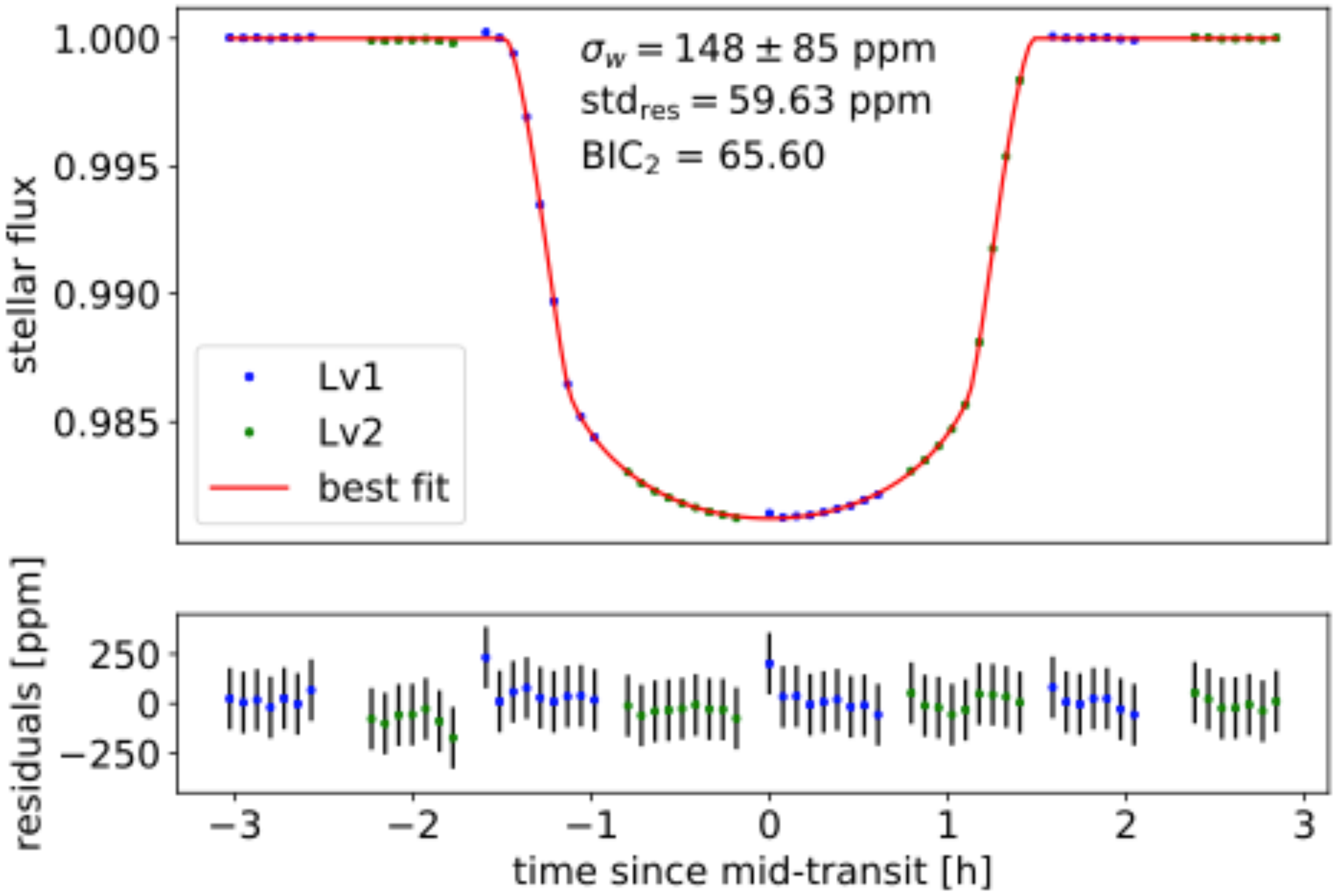
Model

- Implemented the parametrisation of Correia 2014 using the ELLC transit code.
- Signature of the tidal deformation is defined as the difference between the best spherical fit to the data and the best ellipsoidal model fit.
- Assuming hf =1.5 —>293 CHEOPS, ~100 PLATO or 1 JWST transits are needed
- Assumed a large LD error and a smaller radius ratio

Akinsanmi, Barros et al A&A 2019

Tidal deformation

WASP-121



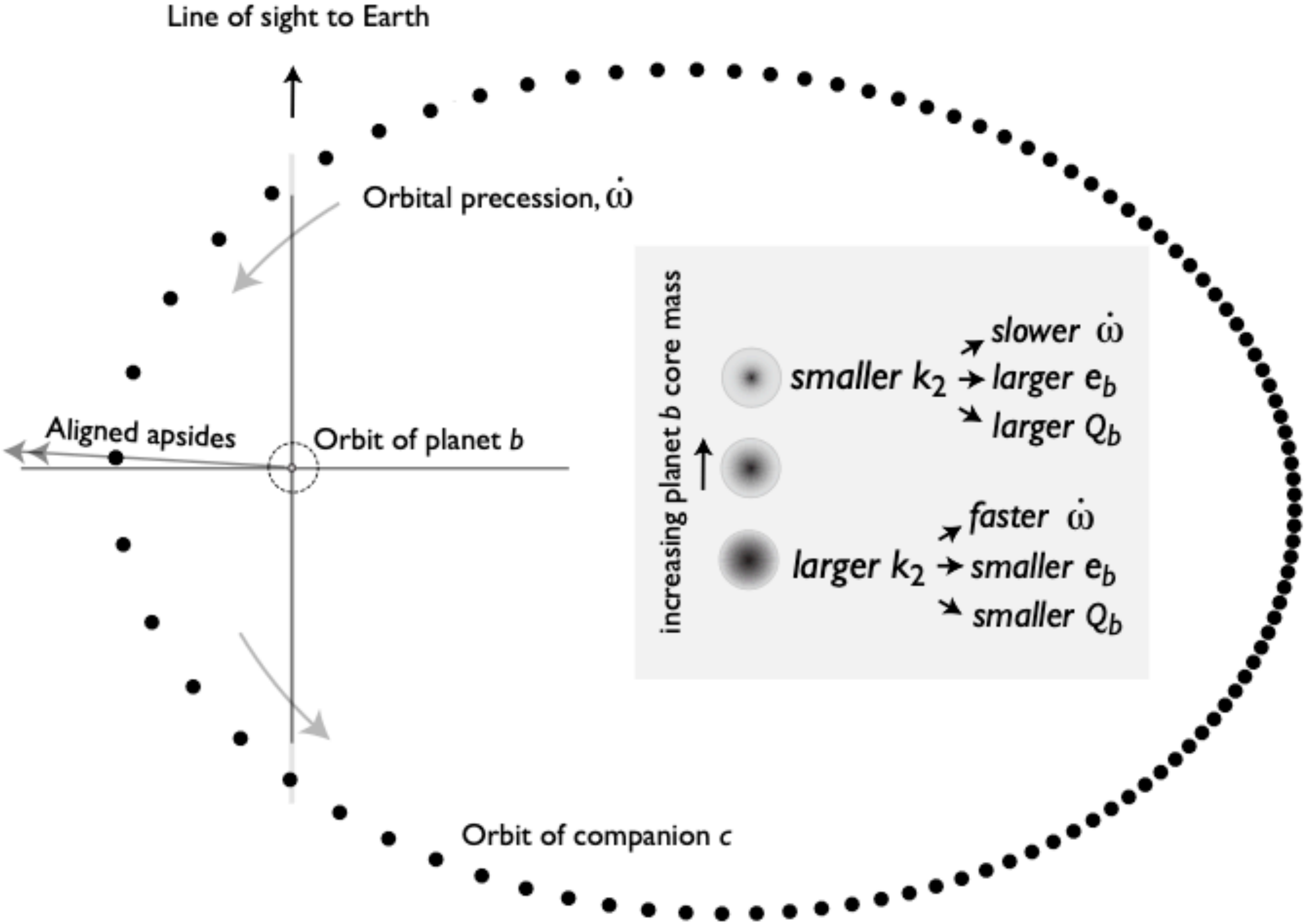
Best measurement of the Love number

2 HST transits

$h_f = 1.39 \pm 0.8 - < 2\sigma$

Hellard et al. 2019

Love number from planet-planet interaction - HAT-P-13b



Batygin et al 2009

$h_f < 1.425$

$0 < M_{core} < 120\,M_\oplus$

Batygin et al 2009

$M_{core} < 27\,M_\oplus$

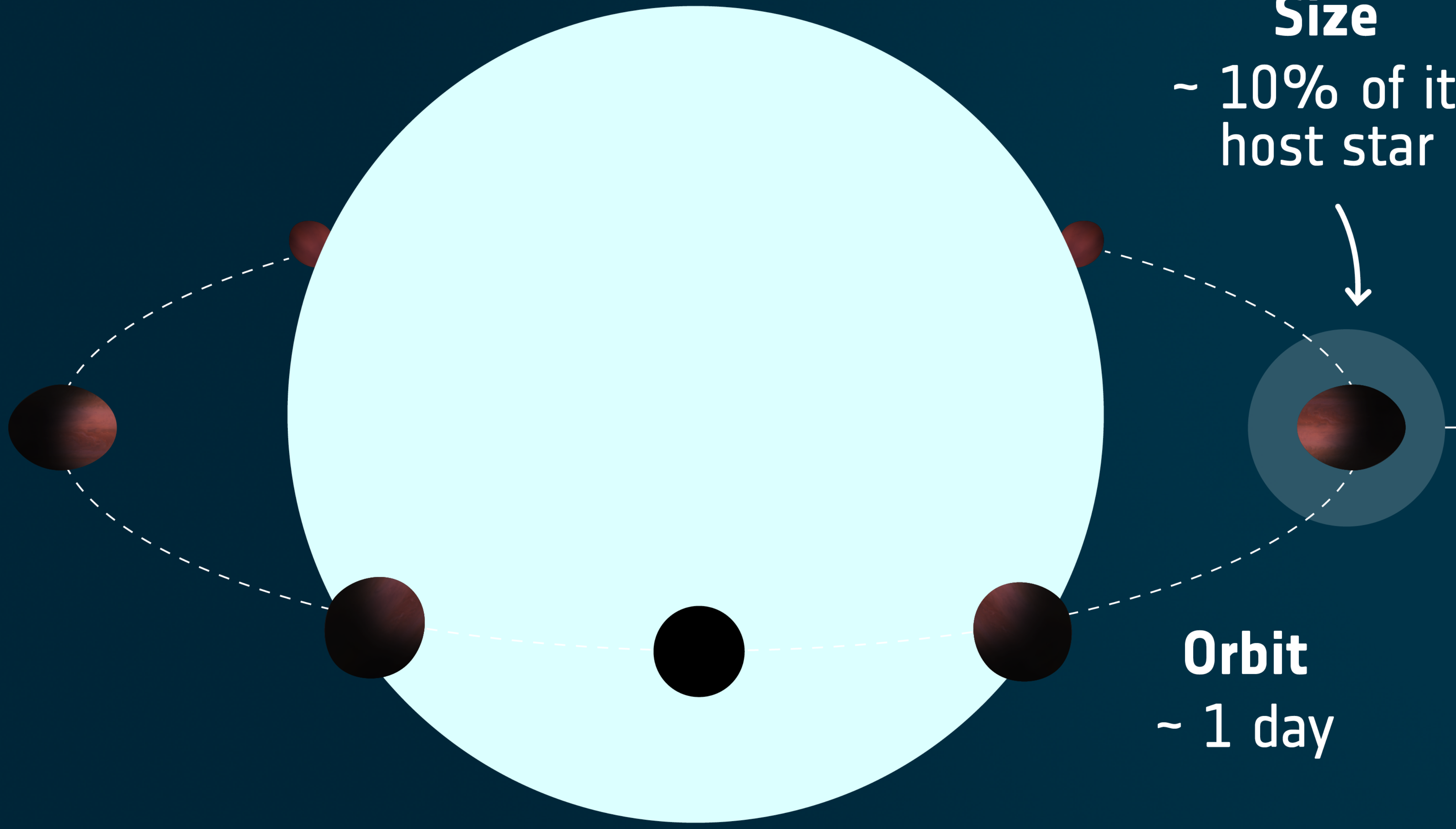
the envelope and bulk metallicity 1-11 times stellar metallicity
Kramm et al 2012

$h_f = 1.31^{+0.08}_{-0.05}$
$M_{core}\ \ 11\,M_\oplus$
Buhler et al 2006

CHEOPS REVEALS A RUGBY BALL-SHAPED EXOPLANET

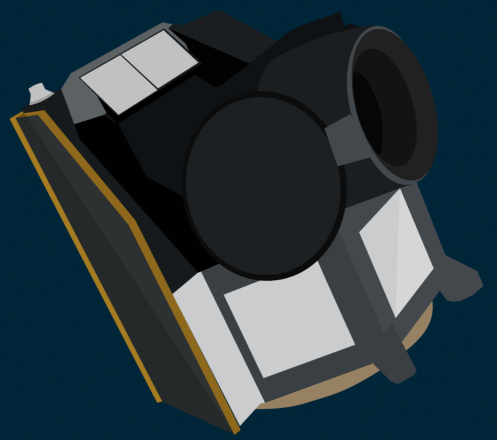
ESA's exoplanet mission **Cheops** has revealed that an exoplanet orbiting its host star within a day has a deformed shape more like that of a rugby ball than a sphere. **This is the first time that the deformation of an exoplanet has been detected**, offering new insights into the internal structure of these star-hugging planets.

WASP-103
Host star



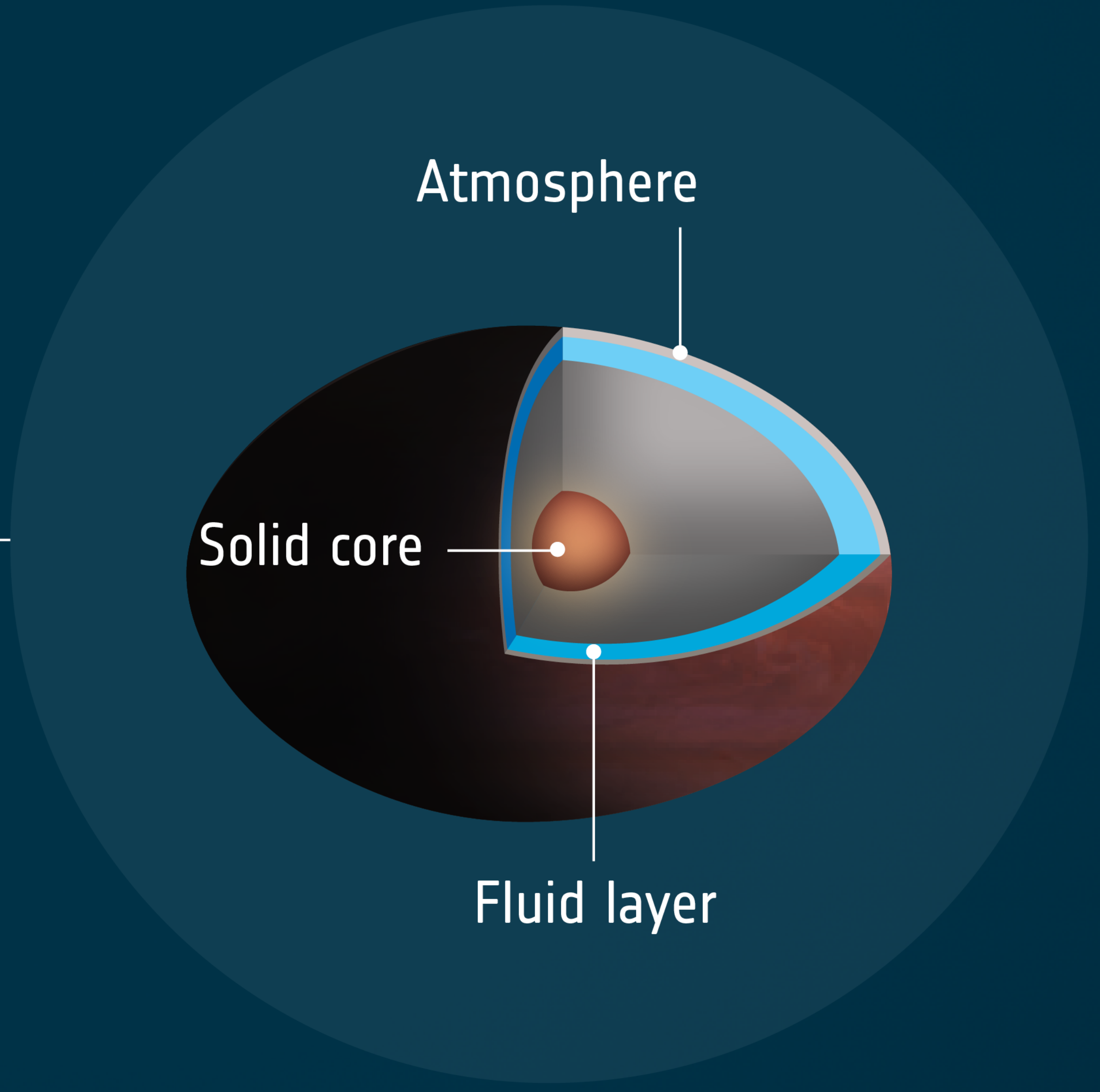
Size
~ 10% of its host star

Orbit
~ 1 day



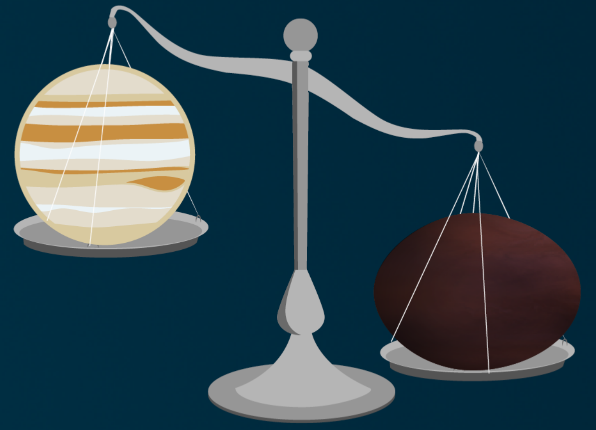
Cheops spotted a small difference in the typical transit light curve, caused by the deformation of the planet

WASP-103b
Planet

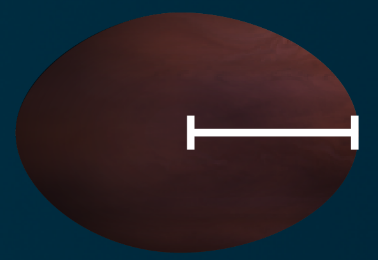


Internal structure
Likely very similar to that of Jupiter

Mass
1.5 x Jupiter



Radius
2 x Jupiter



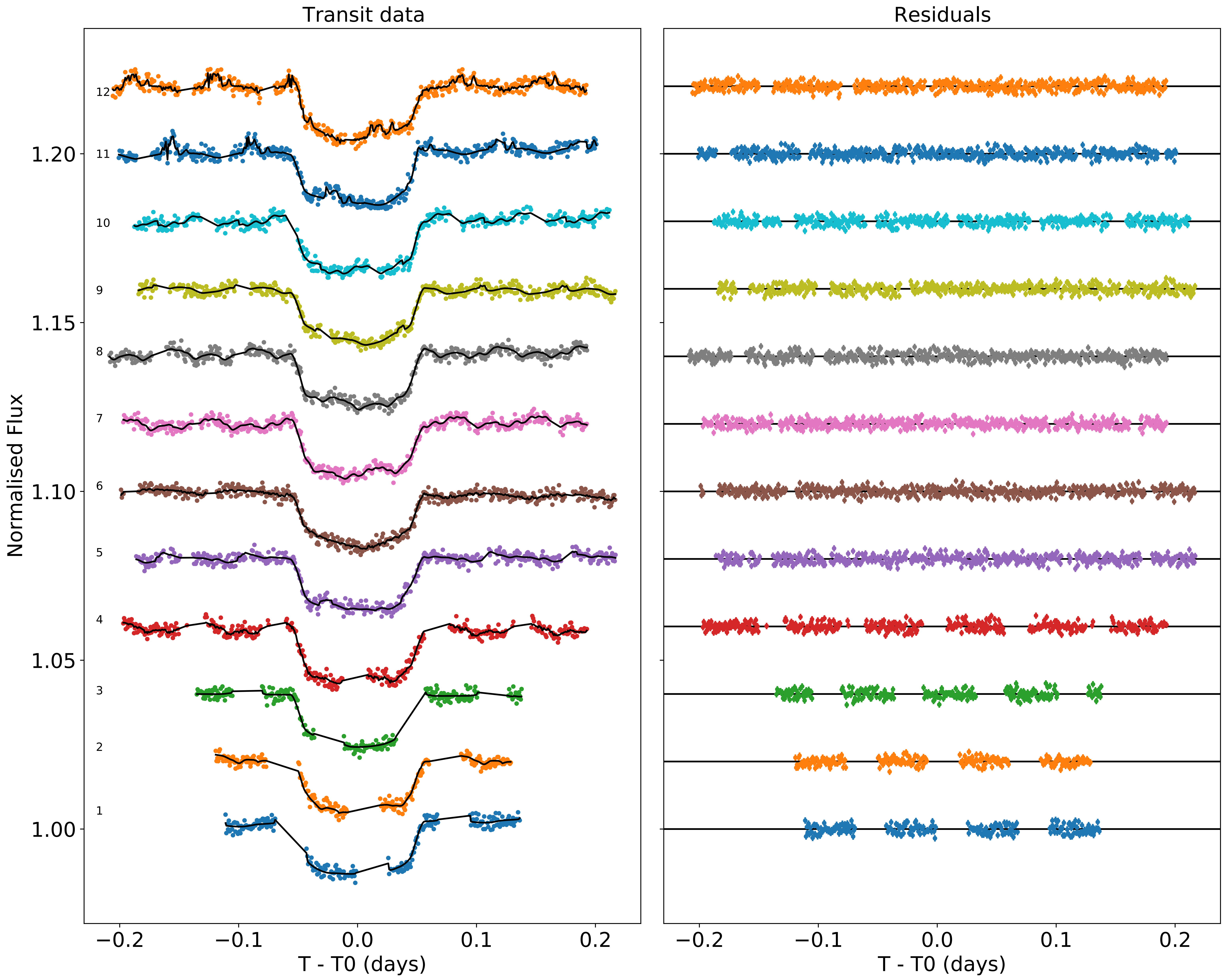
Temperature
20 x hotter than Jupiter

#CHEOPS

Credit: ESA

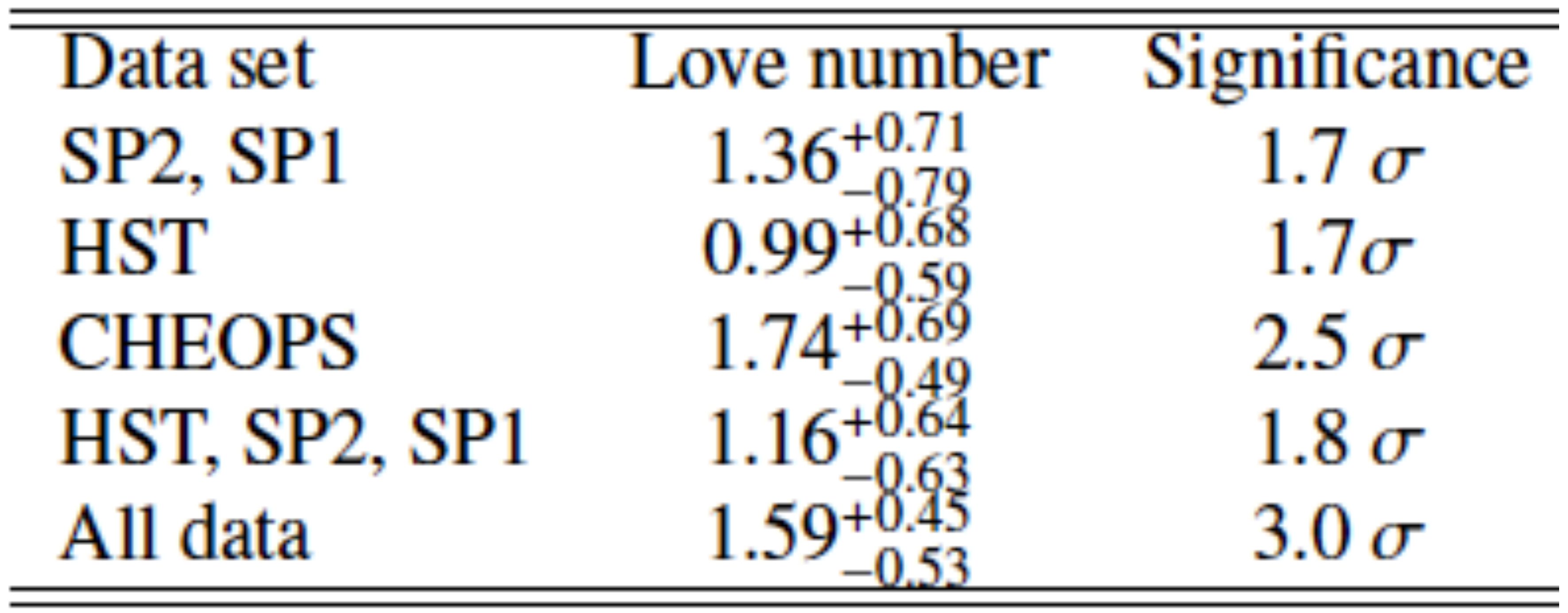
Credit: ESA

CHEOPS data

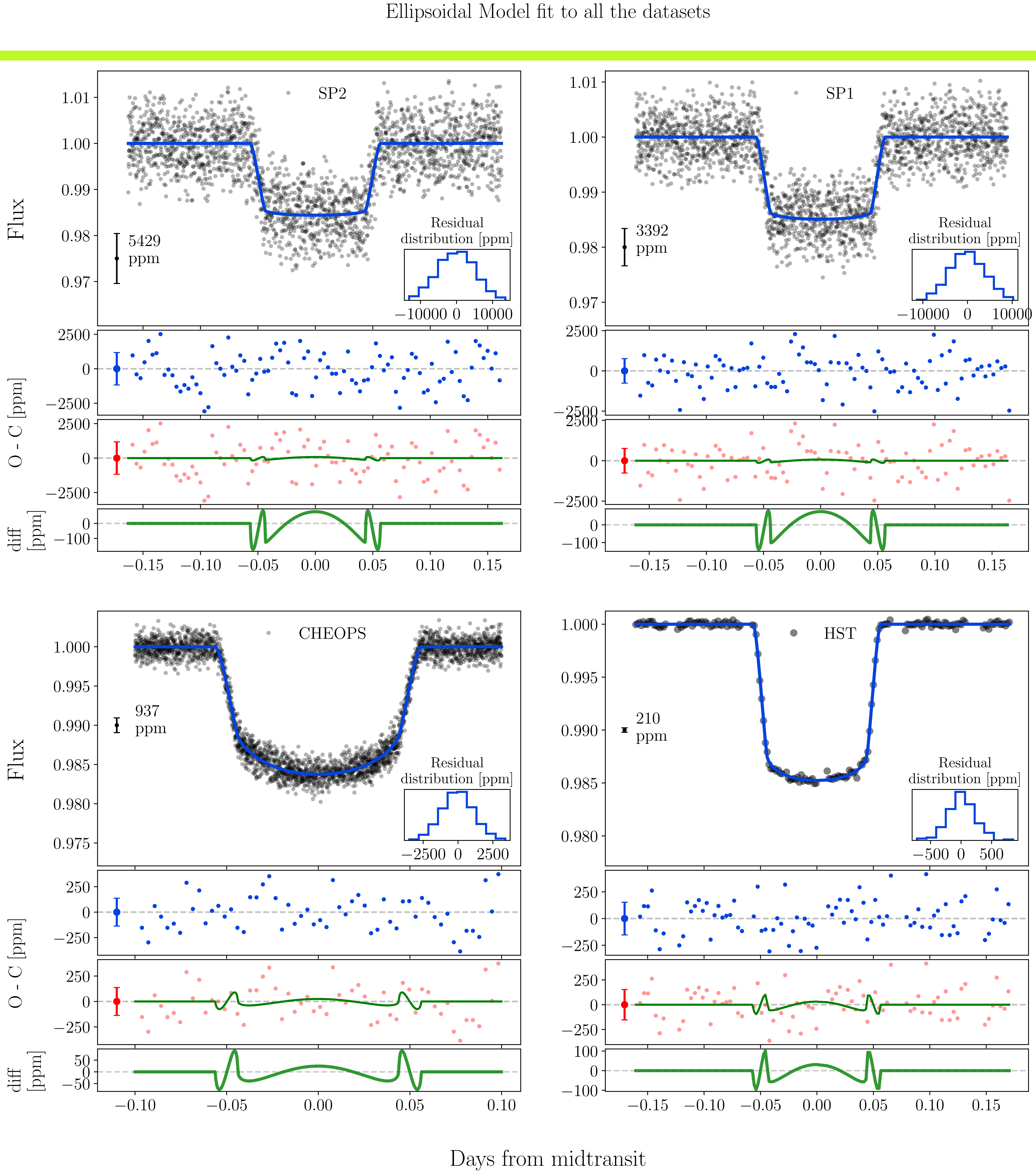


Systematics corrected with a multi-dimensional Gaussian constrained by instrumental parameters: roll angle, position of the star in CCD, target contamination and background

Combination



Data set	Love number	Significance
SP2, SP1	$1.36^{+0.71}_{-0.79}$	1.7 σ
HST	$0.99^{+0.68}_{-0.59}$	1.7σ
CHEOPS	$1.74^{+0.69}_{-0.49}$	2.5 σ
HST, SP2, SP1	$1.16^{+0.64}_{-0.63}$	1.8 σ
All data	$1.59^{+0.45}_{-0.53}$	3.0 σ

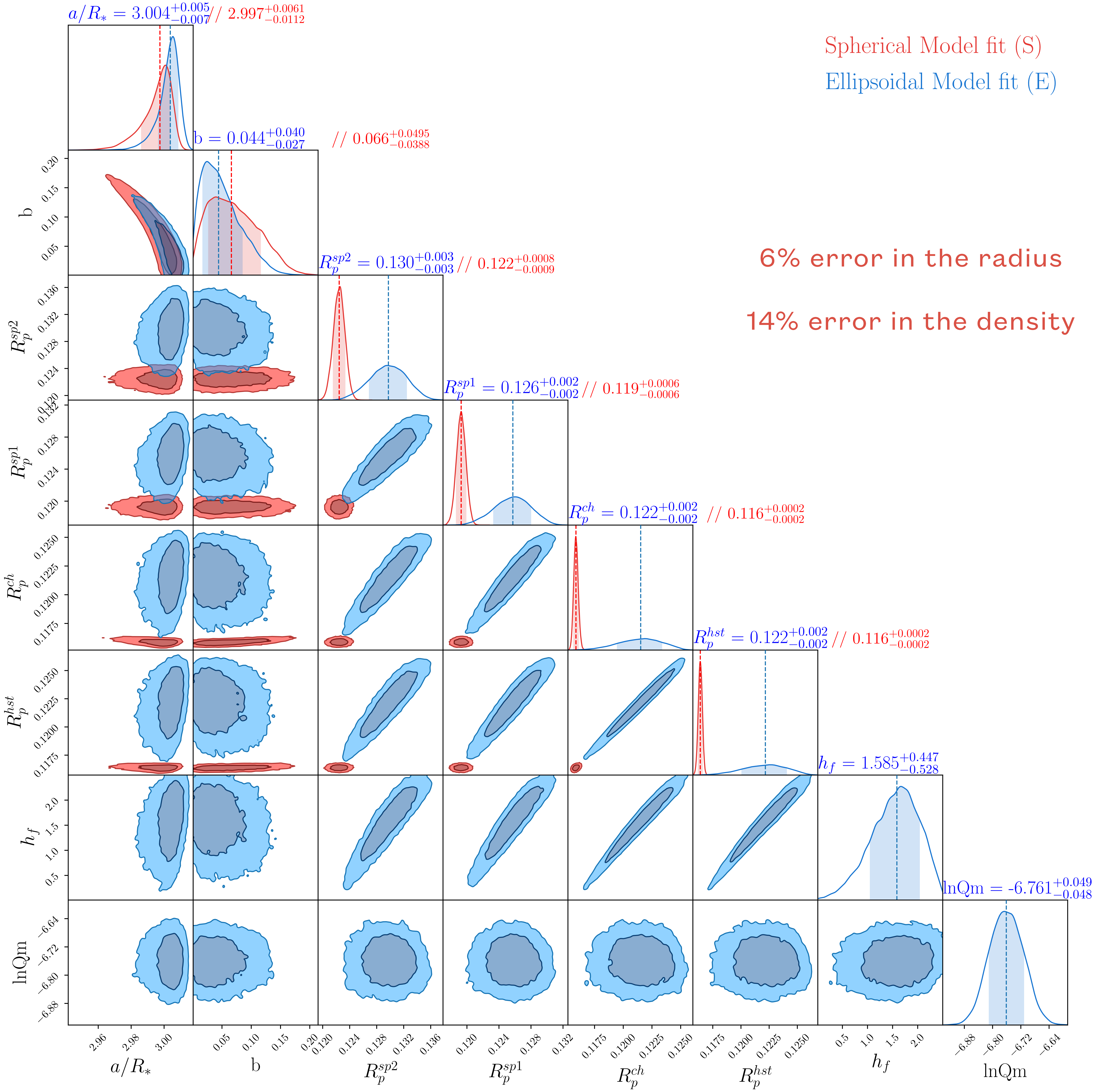



Difference between the ellipsoidal and spherical model fits to the datasets
Flux difference [ppm]
Days from midtransit
SP2
SP1
CHEOPS
HST
0
−100
0
−100
50
0
−50
100
0
−100
−0.10
−0.05
0.00
0.05
0.10
−0.10
−0.05
0.00
0.05
0.10

Results

Assuming a power-2 limb darkening law we estimated the Love number, $h_f = 1.59^{+0.45}_{-0.53}$. This is the first time that a 3σ detection of the Love number has been achieved directly from the analysis of the deformation of the transit light curve. Possible due to:

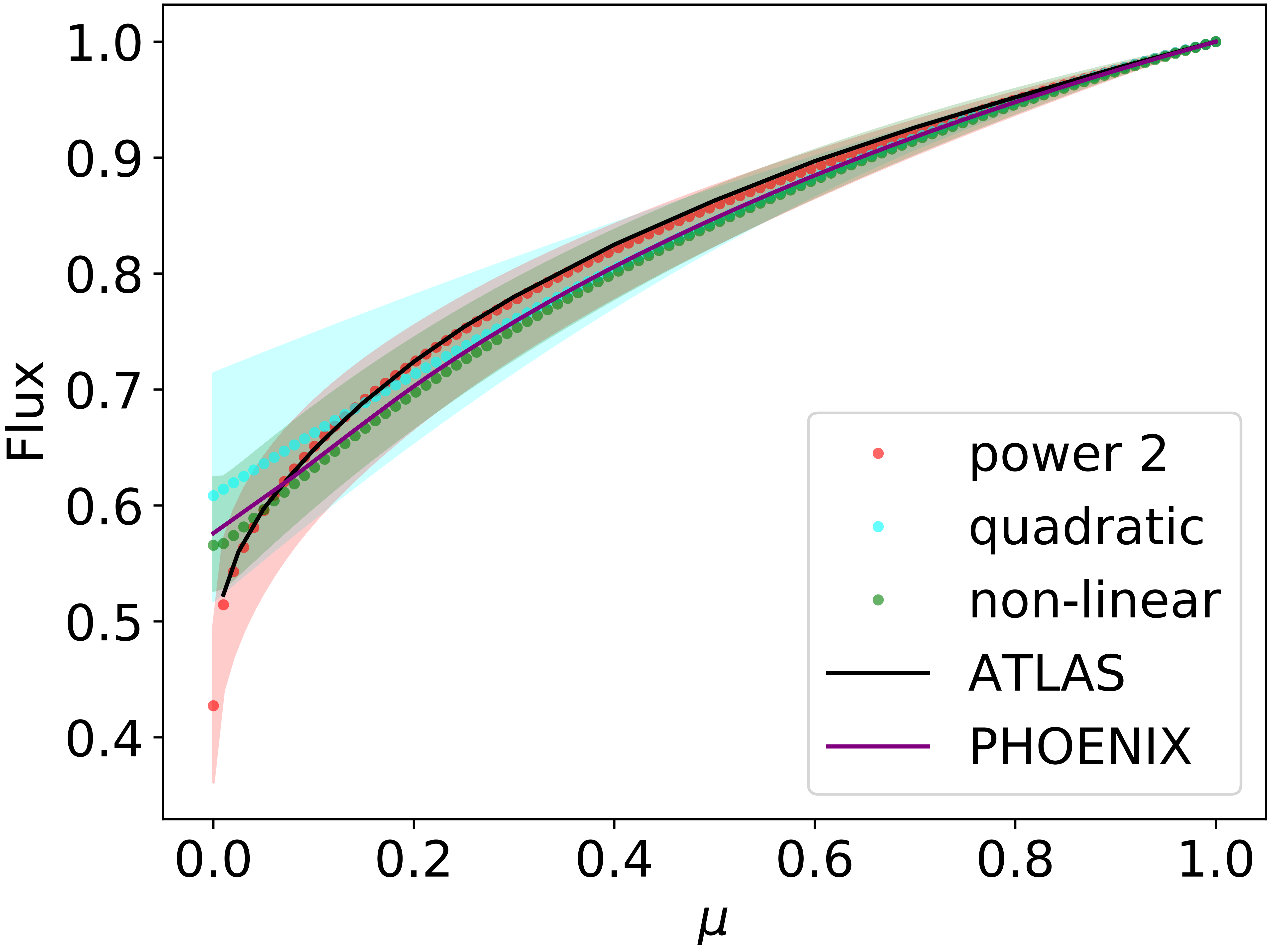
- Combination of several high precision transits
- Improvement of the model
- Strong limb darkening constrains



6% error in the radius

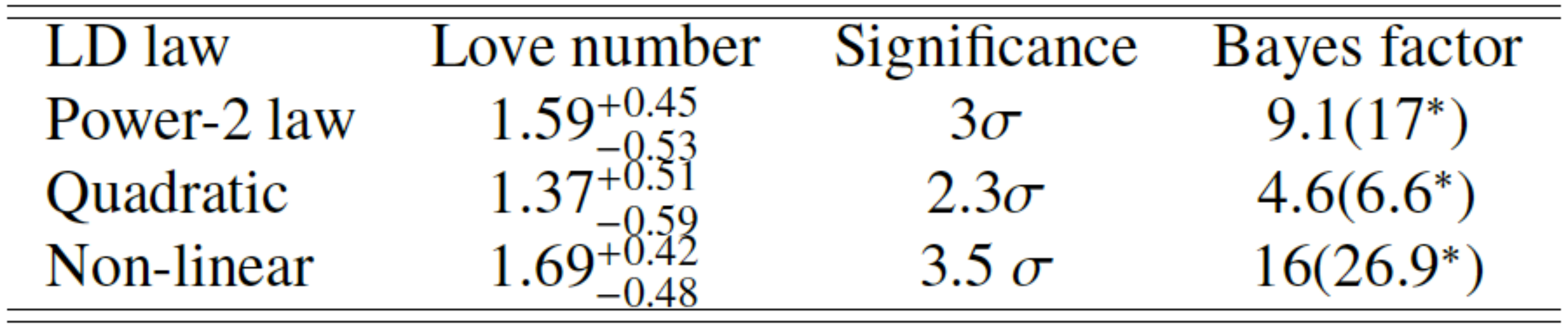
14% error in the density

Limb darkening

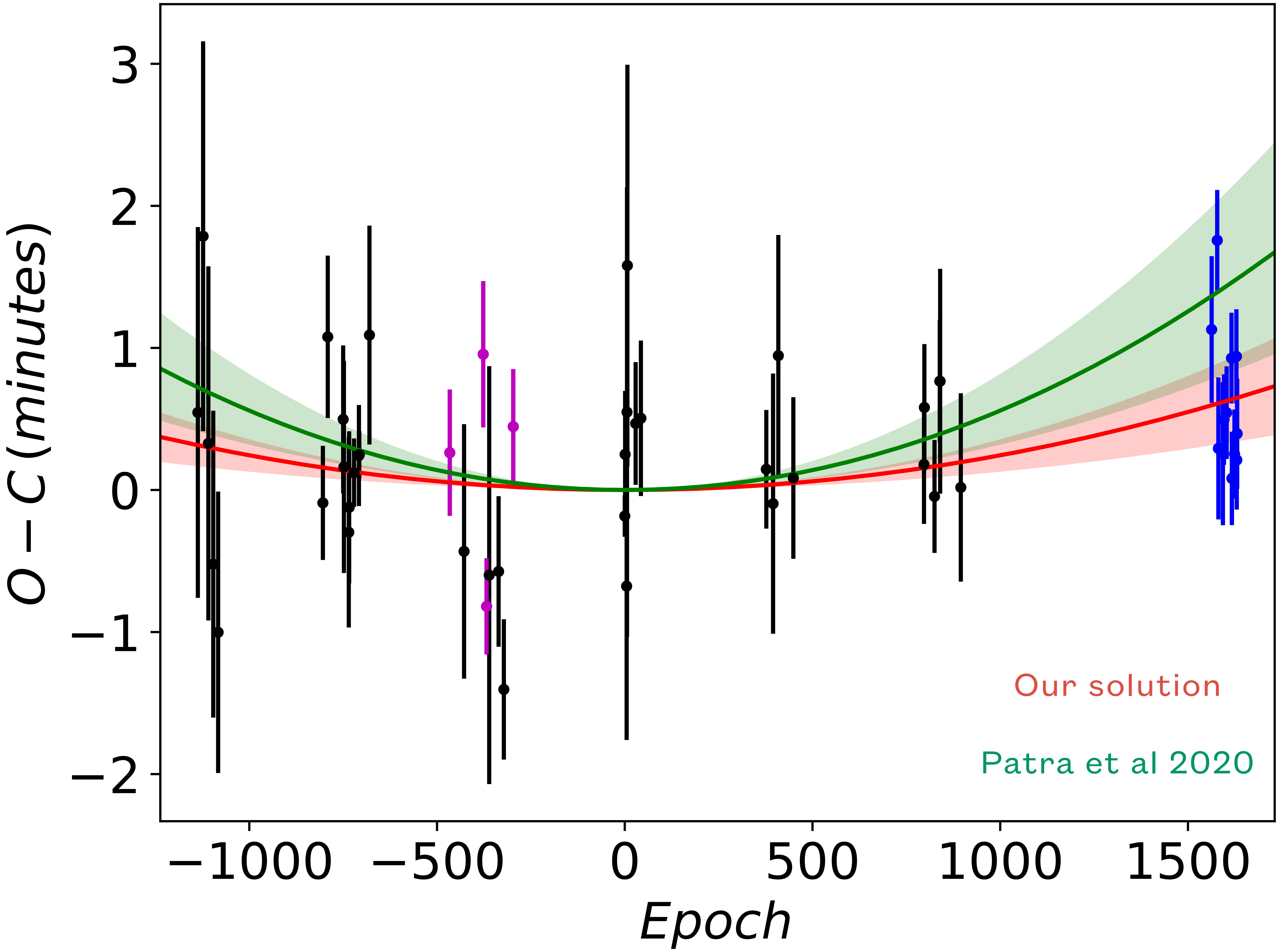


- Wide priors don’t allow to constrain the Love number. Wide priors give too much freedom to the data and don’t account for correlations between the four different colours. In particular for the Spitzer the LD erros should be small.

- Estimate what was the smallest priors that was still reasonable. Used 3 limb darkening laws and 2 stellar intensity profiles increasing the errors to encompass the two limb darkening laws.



LD law	Love number	Significance	Bayes factor
Power-2 law	$1.59^{+0.45}_{-0.53}$	3σ	9.1(17*)
Quadratic	$1.37^{+0.51}_{-0.59}$	2.3σ	4.6(6.6*)
Non-linear	$1.69^{+0.42}_{-0.48}$	$3.5\ \sigma$	16(26.9*)



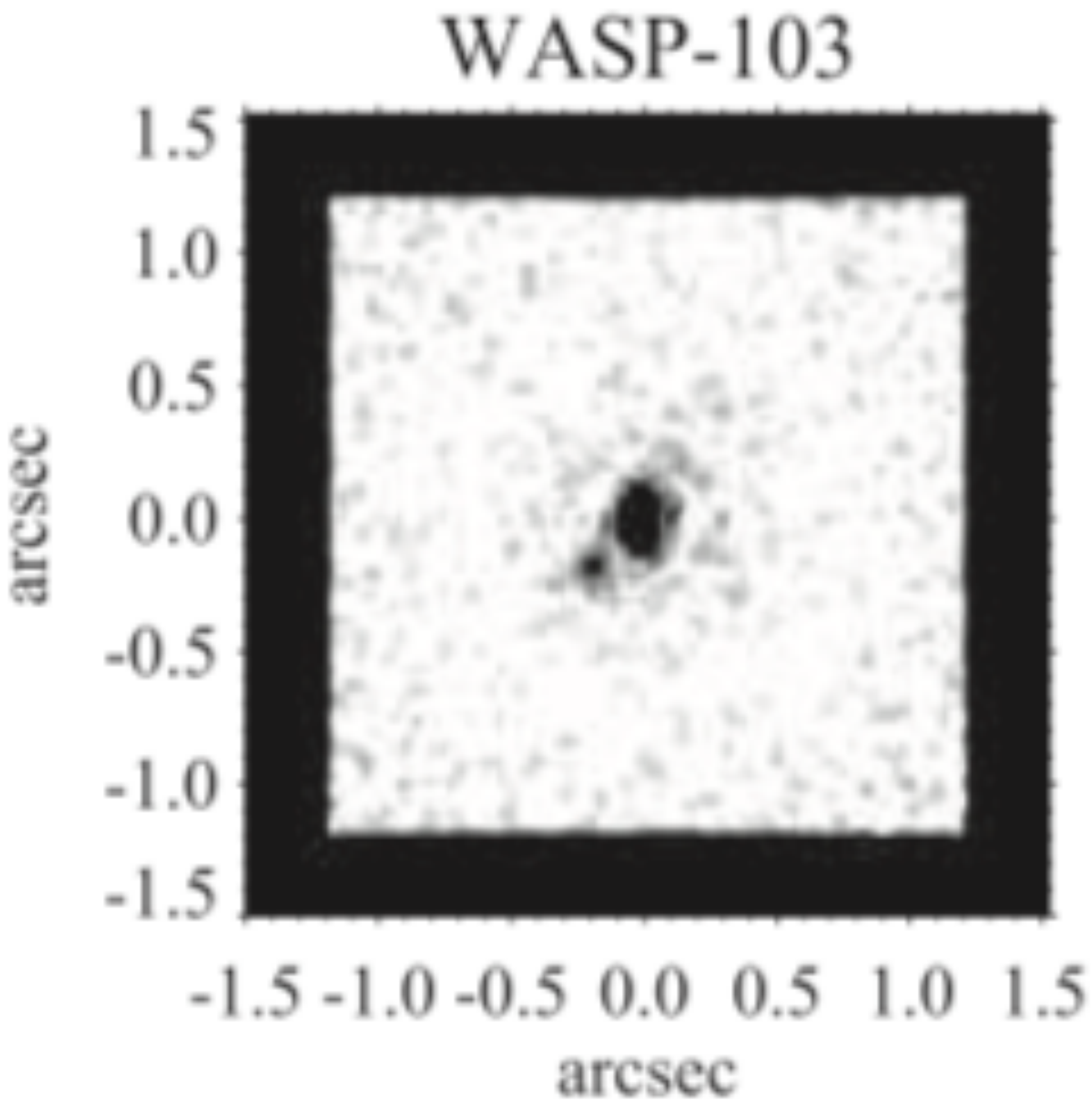
Literature values from Maciejewski et al. 2008

Tidal Decay

- $\dot{P} = 3.5 \pm 1.8 \times 10^{-10}$ days/day
- Q > 1.6×10^{6} at $3\,\sigma$ (99.7% confidence interval)

- RV acceleration due to a companion
- Applegate effect
- Apsidal precession

RV acceleration due to companion



Wollert et al 2012, Ngo et al. 2016

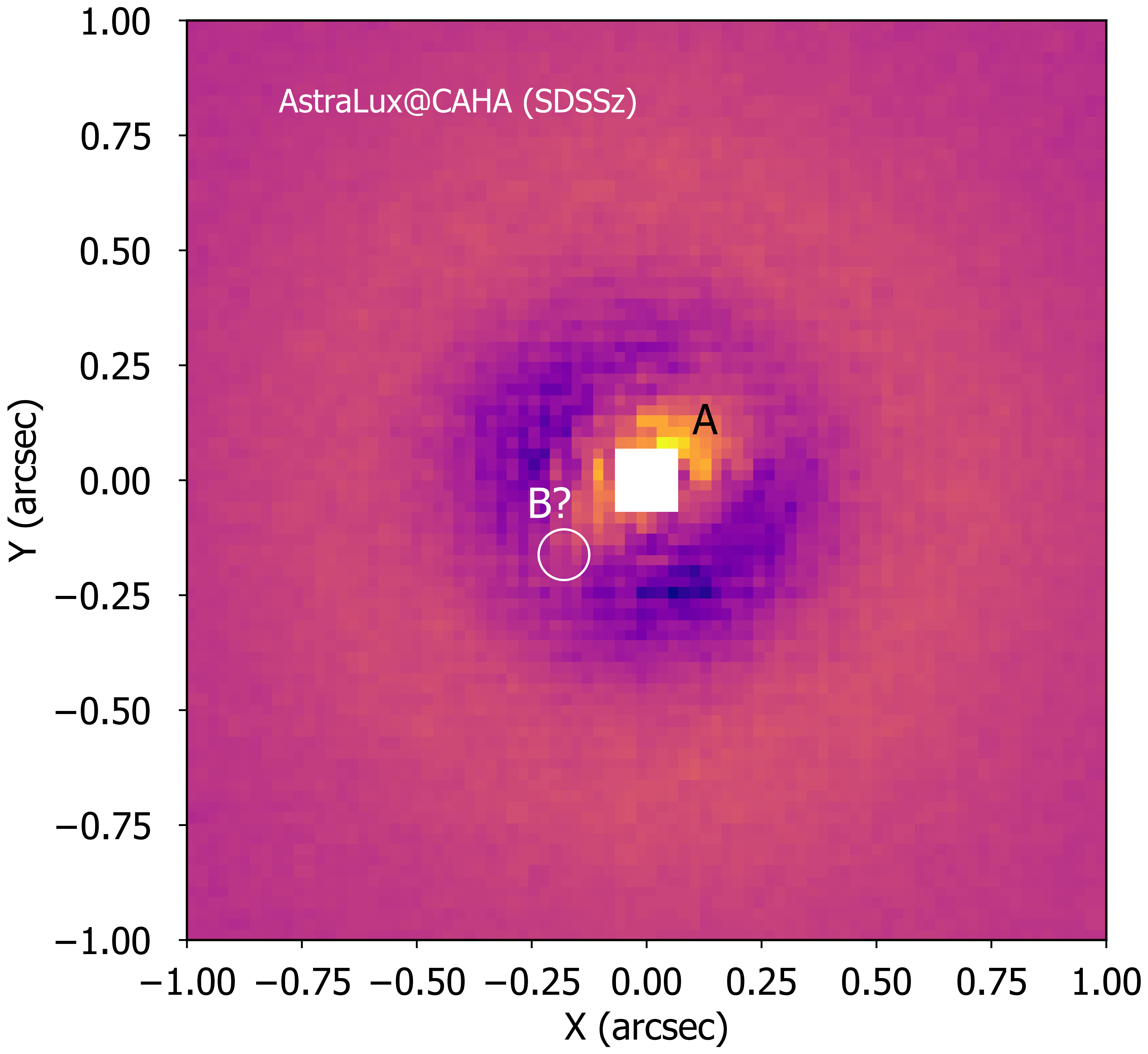
Companion of WASP-103 —> RV acceleration —> transit timing variations due to a change in the light travel time.

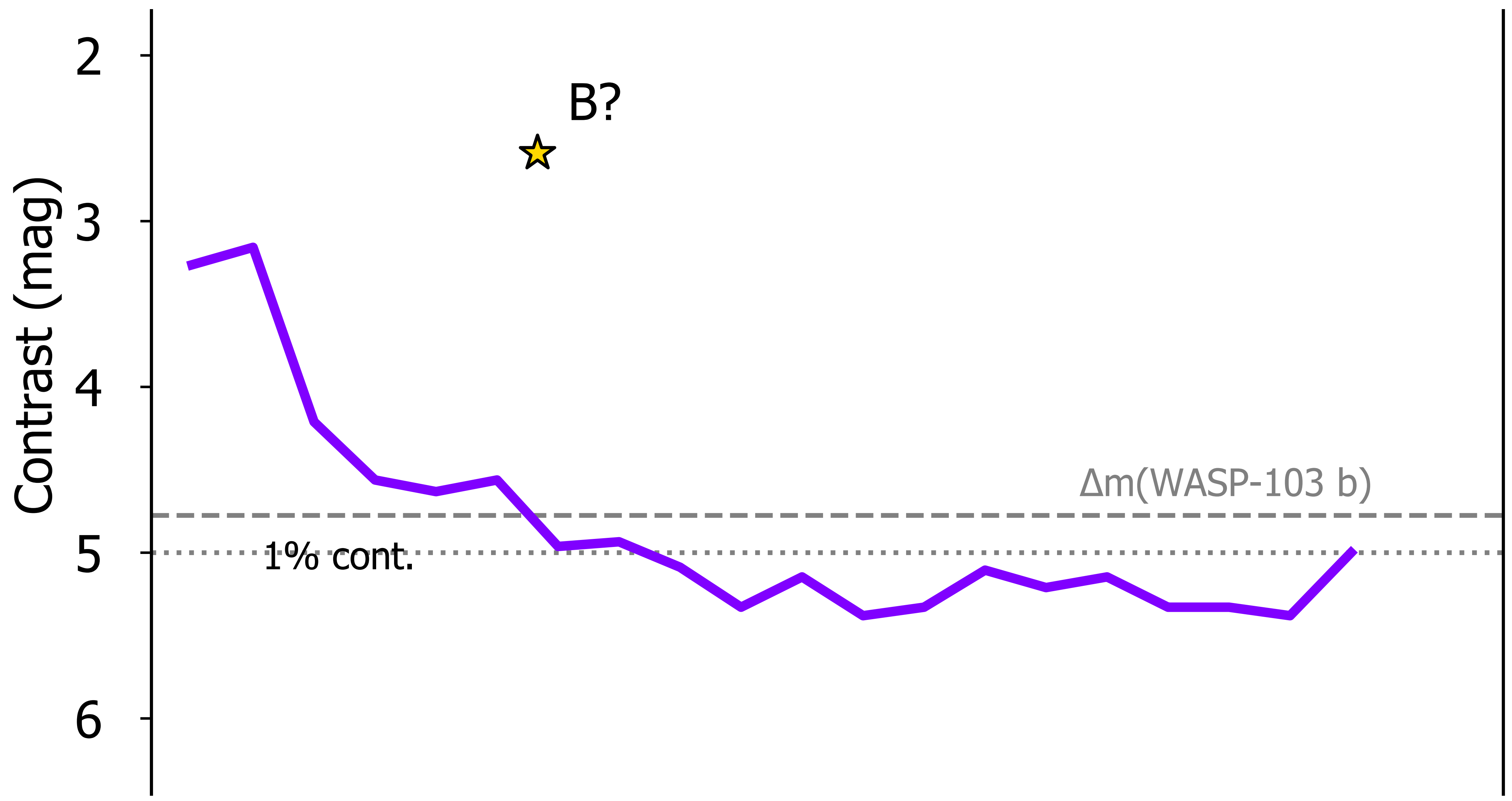
From observed period variation we derive line-of-sight acceleration $a_r = 0.113 \pm 0.058$m/s/day.

From the imaging companion we derive $a_{rad} \leqslant 0.00796 \pm 0.00095$ m/s/day

Cannot be excluded

Further observations with AstraLux





New RV observations also do not show a large offset

Applegate effect

- Variations in the quadrupole moment of the stars driven by stellar activity can lead to variation of the observed eclipse times in binary stars. It happens in the timescale of variation of the stellar dynamos ~11 years.
- We estimated that for WASP-103 the Applegate effect could produce transit timing variations < 38 seconds over the time span of the available observations.

Apsidal precession

- If a planet's orbit is slightly eccentric, then its orbit would be apsidally precessing. For hot Jupiters, the precession timescale is ~ decades.
- The transit times can be explained by a precession rate of $1.10^{+1.9}_{-0.63} \times 10^{-3}$ rad which would imply a Love number of $h_f = 1.35 \pm 0.43$

Future

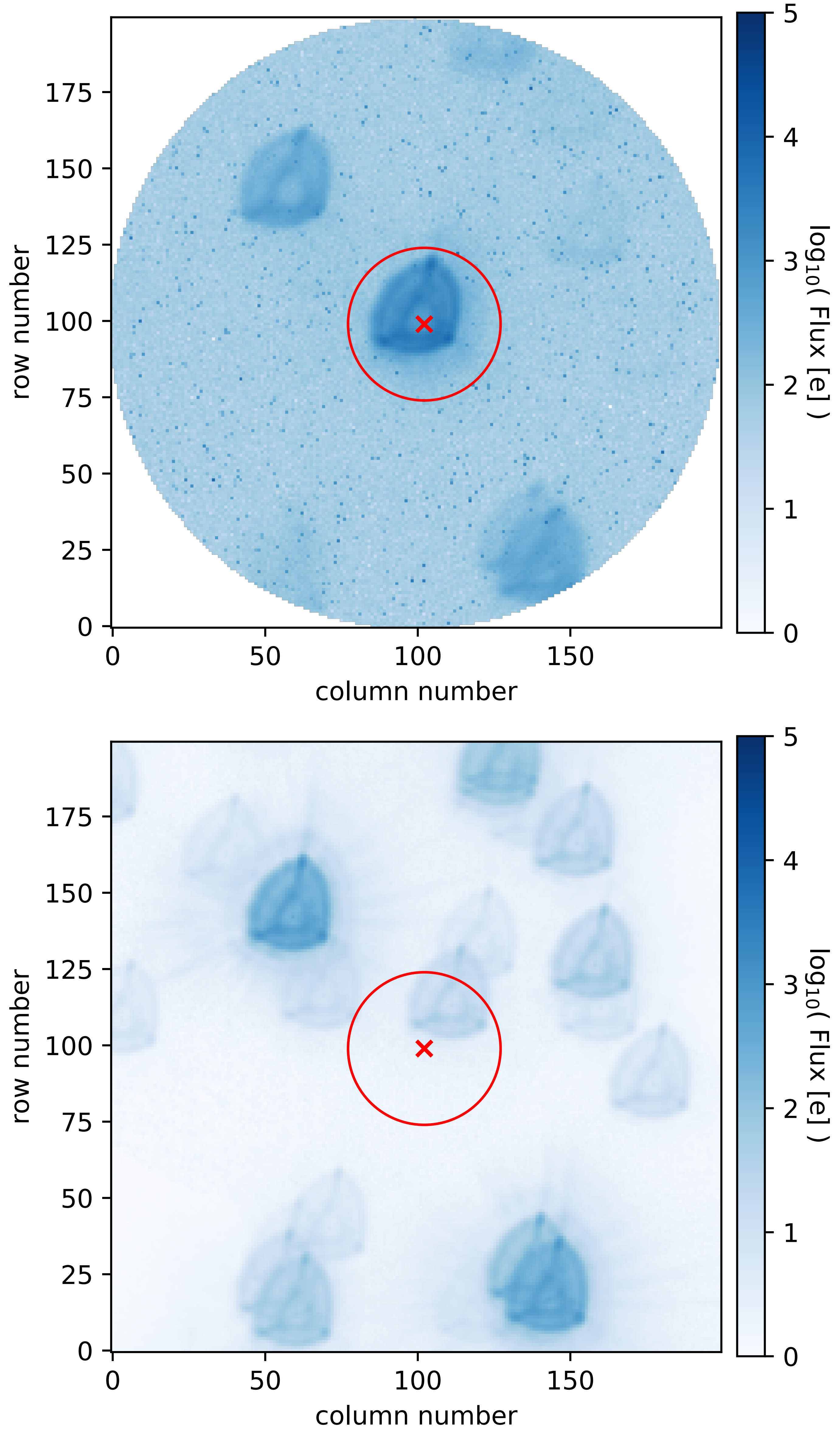
- Longer time span of the monitoring of transit time variation will help us understand the period evolution of the system.
- Other AO observations and GAIA paralaxes will allow to constrain the possible companion.
- Improve the precision of the tidal deformation:

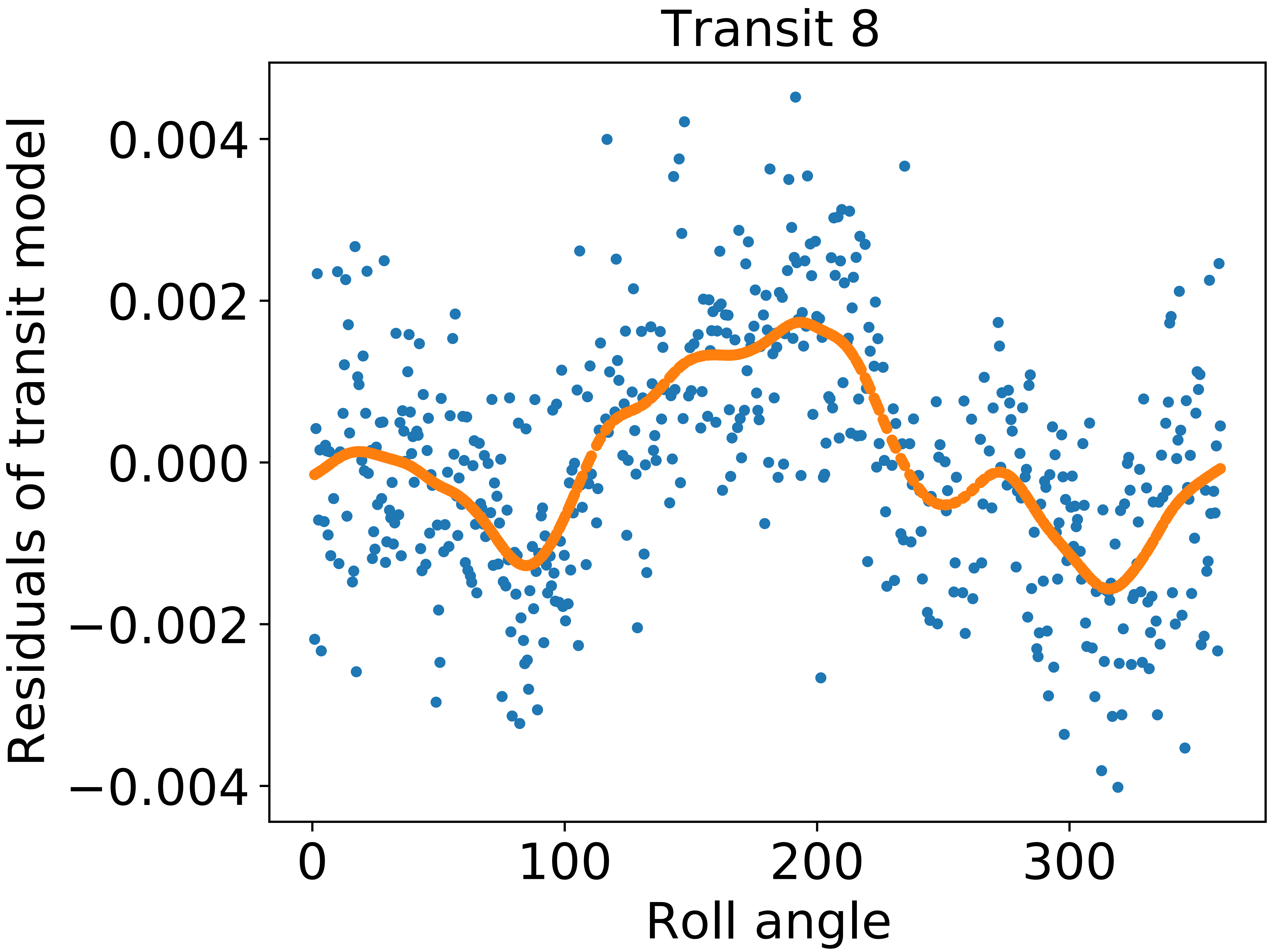
One transit of JWST $h_f = 1.62^{+0.12}_{-0.13}$ 12 sigma - unprecedented constrain on the internal structure of a hot Jupiter planet

48 CHEOPS transits to reach 4 sigma and 72 to reach 5 sigma

Thanks to the CHEOPS team

SUSANA BARROS


row number
column number
log10(Flux [e])
0
25
50
75
100
125
150
175
0
50
100
150
0
1
2
3
4
5


Transit 8
Residuals of transit model
Roll angle
0.004
0.002
0.000
−0.002
−0.004
0
100
200
300

Significance of the detection

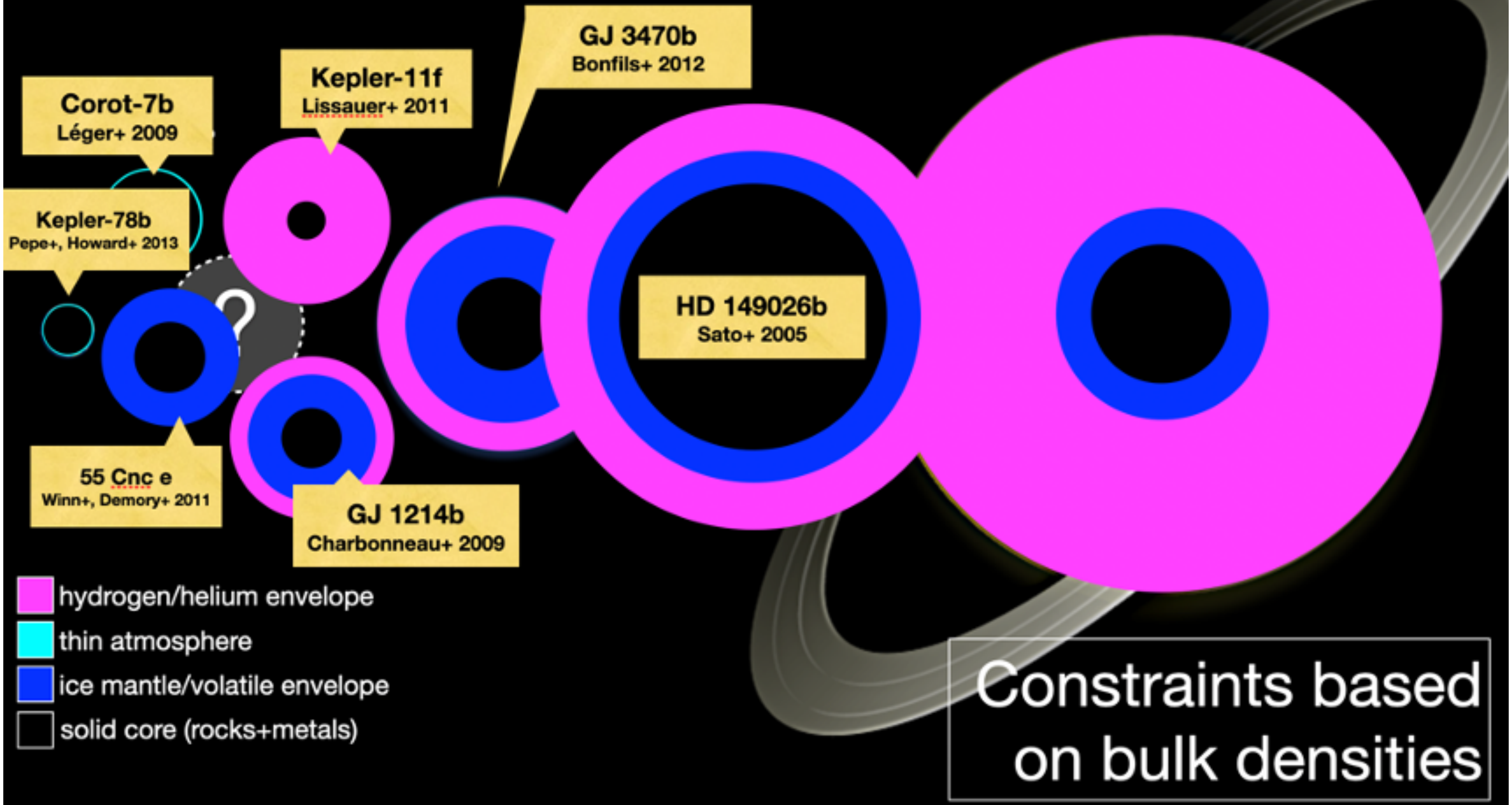
- Bayesian model comparison requires computing the odds ratio between two hypotheses.
  $Odds\ ratio = prior\ odds \times Bayes\ factor$ Is the planet deformed?
- Prior odds strongly favours the ellipsoidal model ~ infinity
- Bayes factor is 9.1 X prior odds —> very strong odds ratio YES

How much the planet deformed?

- Parameter inference should be used instead of model comparison in this case

- Bayes factor as a proxy of which model is favoured by the data. Will require some modifications like not penalising for complexity of the model. This increases the Bayes factor to 17.2. So the ellipsoidal model is 17X more probable then the spherical model.

Composition of exoplanets



Constraints based on bulk densities