Detecting tidal deformation and tidal decay

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Detection and Dynamics of Exoplanets

Credit: ESA

Outline

- Tidal decay
- Recent results

- Tidal deformation
- Recent results

- Future perspectives

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

Why study star-planet interactions?

SHAPE PLANETARY EVOLUTION

IMPACT PLANET RADIUS & ORBITS & SPIN-ORBIT ALIGNMENT

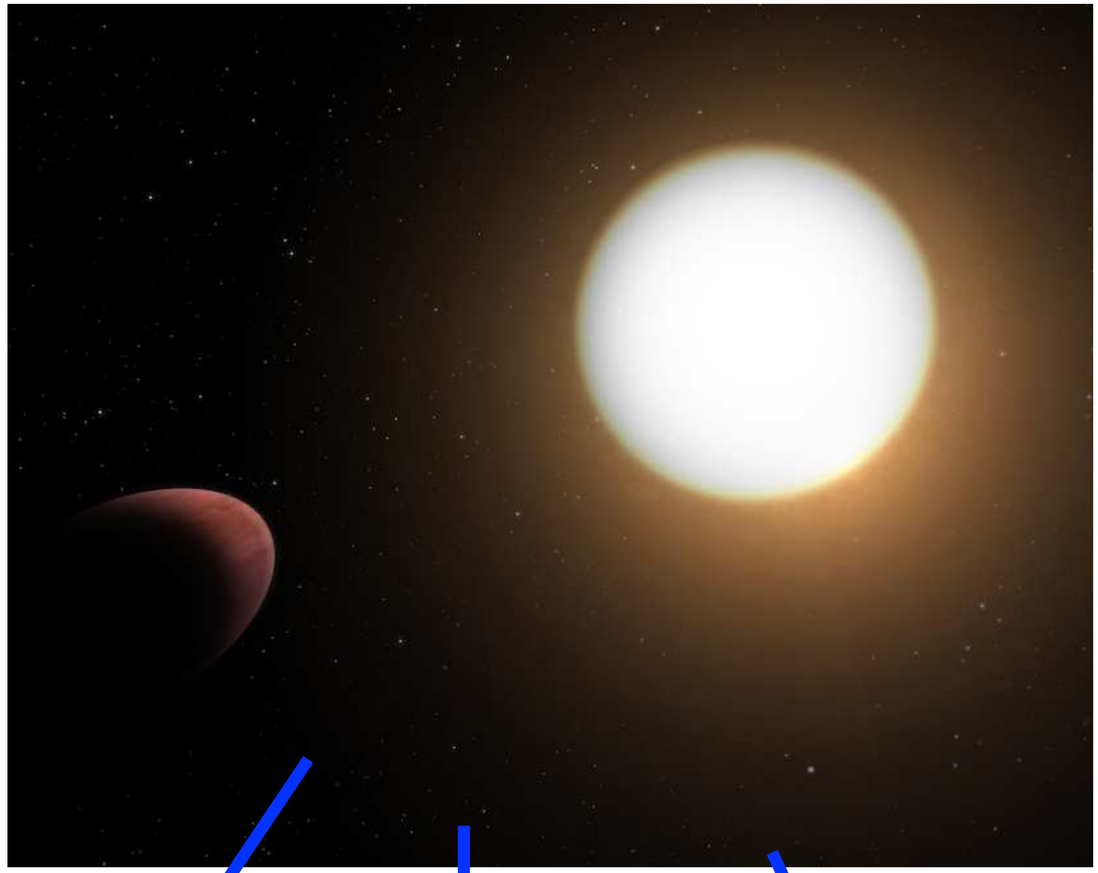
PROBE INTERIORS (DEFORMATION)

CONSTRAIN STELLAR PHYSICS (DECAY)

DETAILED VIEW OF PLANETARY SYSTEMS LINKING DYNAMICS + STRUCTURE

Why now?

ULTRA-SHORT HOT-JUPITERS ARE THE BEST TARGETS

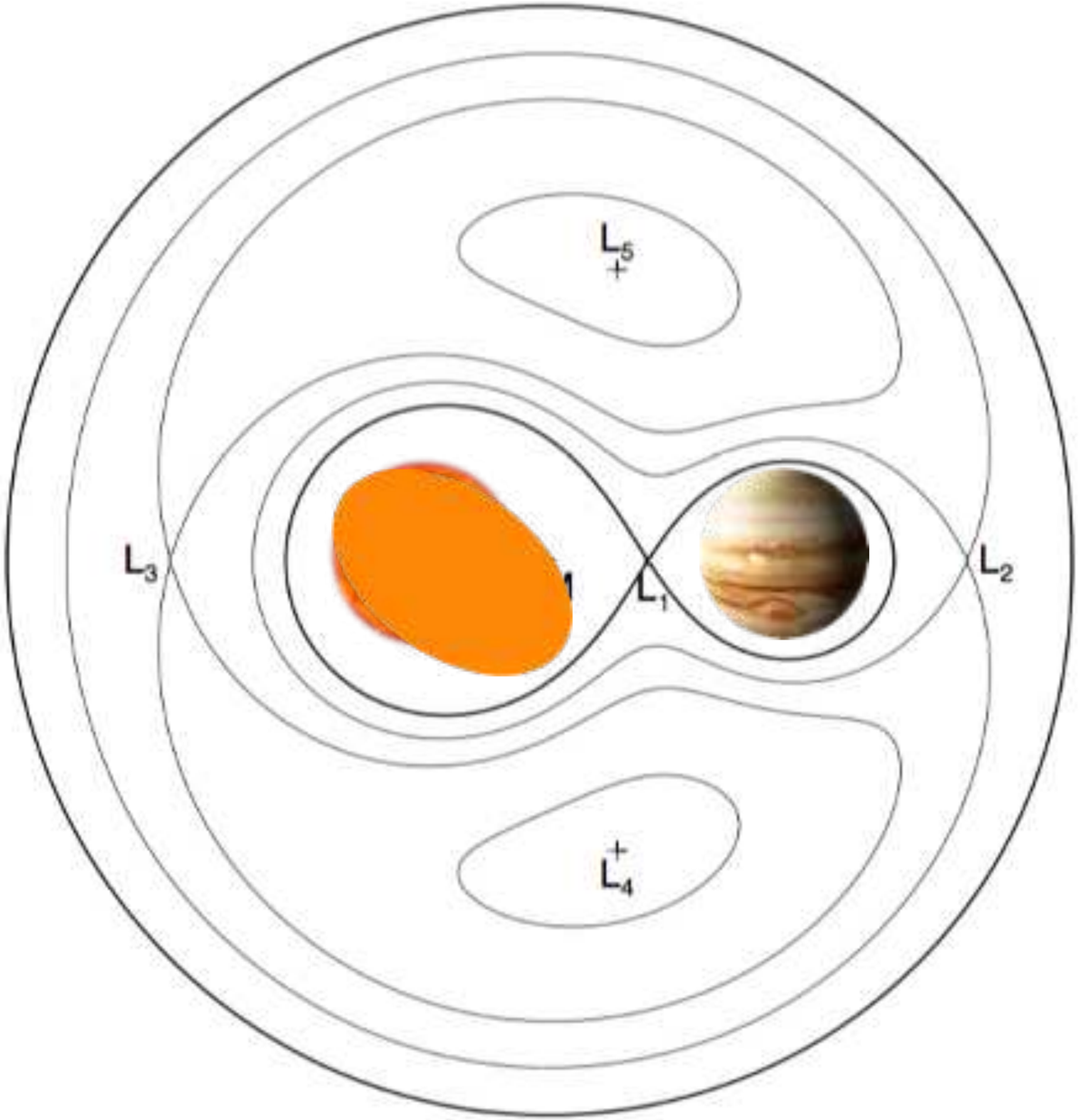


Deformation

Decay

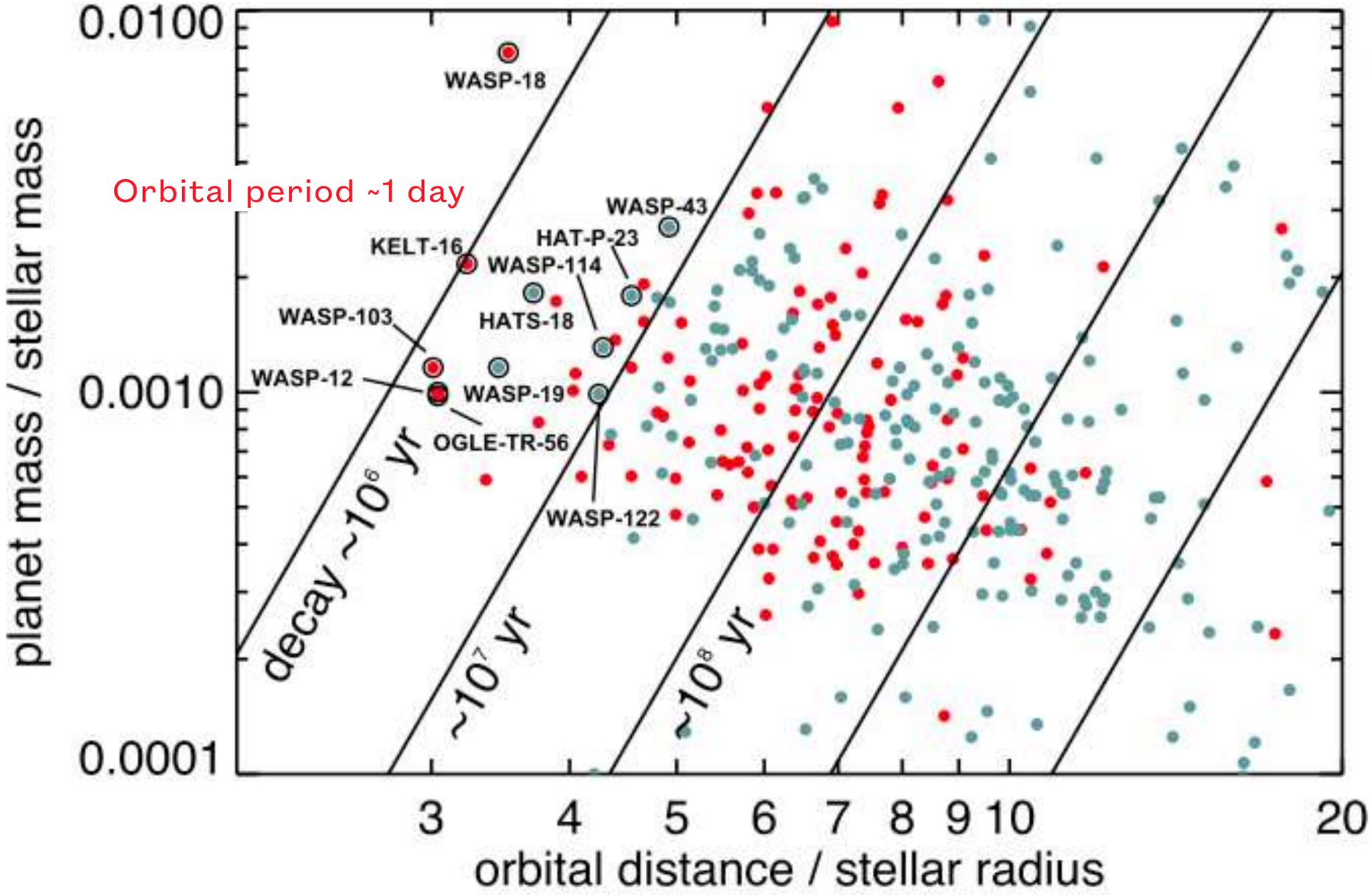
Spin-orbit alignment

Tidal decay



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 in general - **leads transfer of angular momentum from the planetary orbit to the stellar angular momentum.**
- **Shrinkage of the orbit** and eventual tidal disruption of the planet.
- Depends on **tidal quality factor Q.**



Orbital period ~1 day

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

Brighter than 14.5

Assume

$$Q'_* = 10^6$$

Teff > 6000K - radiative envelopes - expect slower tidal dissipation Q'_* $10^5 - 10^6$

Teff < 6000 K - convective envelopes - expect faster tidal dissipation Q'_* $10^7 - 10^8$

Patra et al 2020

Recent insights

Large uncertainty in $Q'_* = 10^5 - 10^8$

May depend on stellar structure (Teff and age)

May vary over time (e.g. due to spin orbit synchronisation)

Accounting for precession

Precession mimics decay (WASP-4b)

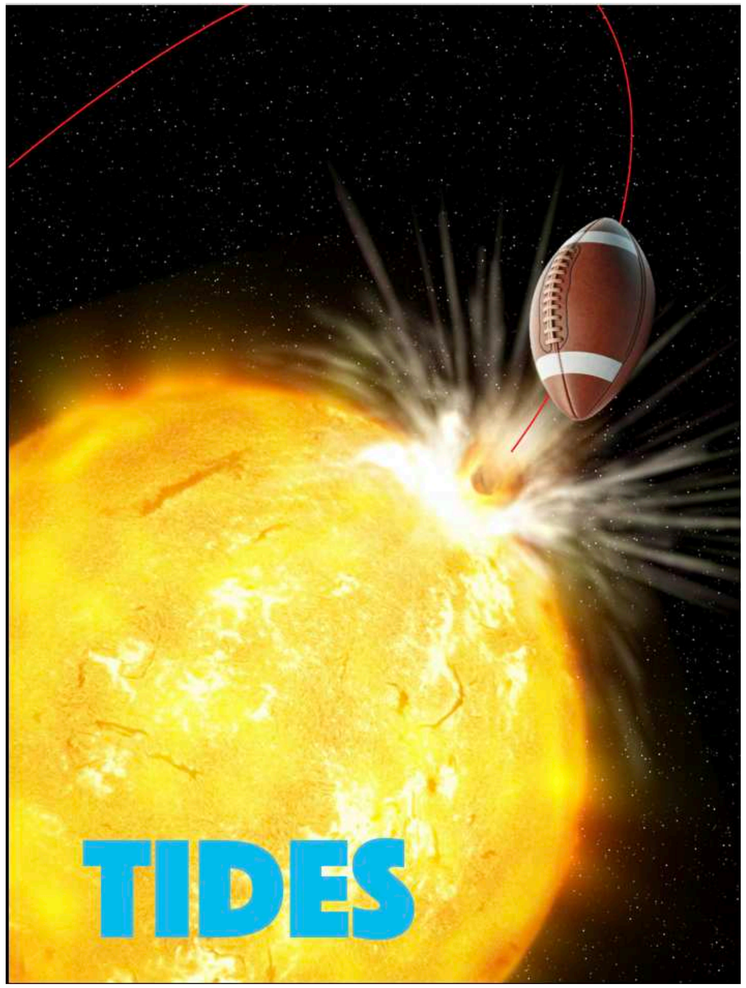
Requires long baselines and occultation timing

Accounting for magnetic effects

Magnetic-enhanced dissipation might be needed to explain WASP-12b

CHEOPS TIDES program

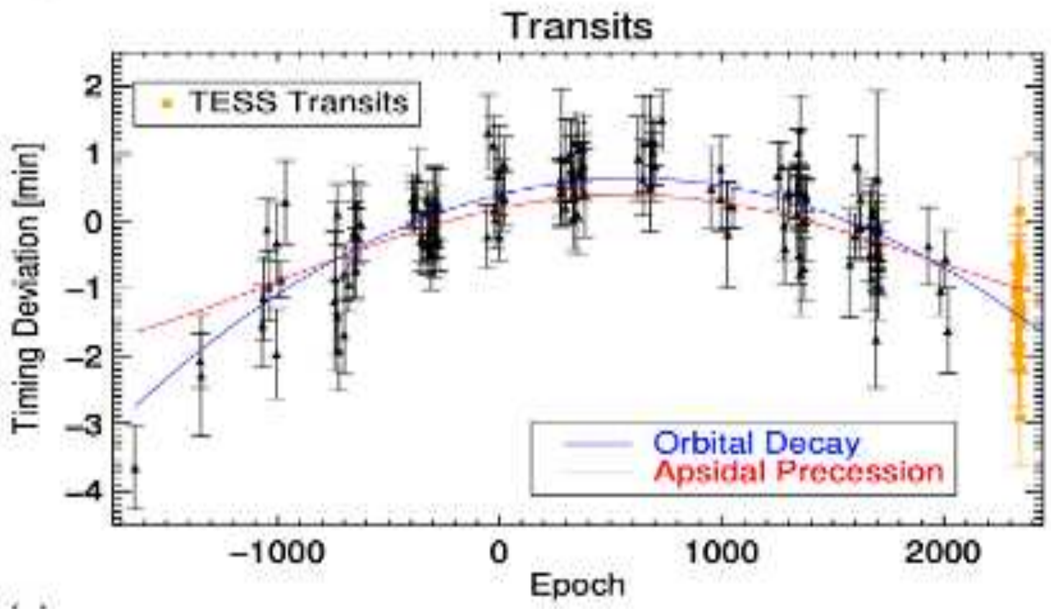
Since the launch of CHEOPS (2019) I am leading the TIDES program to measure tidal decay and deformation for the best targets observable by CHEOPS

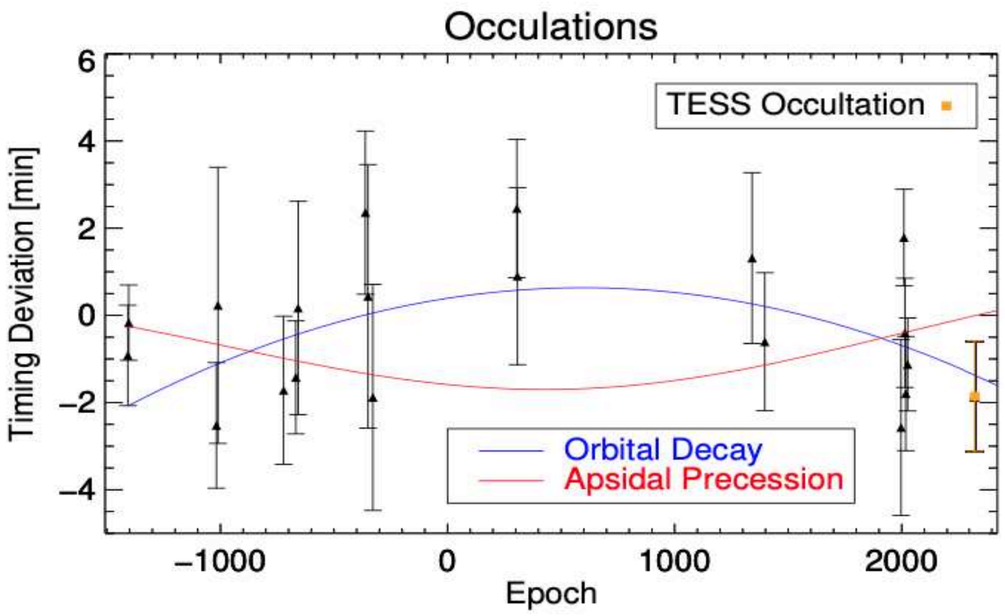


Key questions:

- Does Q'_* depend on stellar mass? other factors?
- Can we differentiate Q'_* regimes observationally?
- Can we mesure the tidal deformation and use it to constrain the planetary internal structure?

Orbital decay of WASP-12b





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

Orbital decay

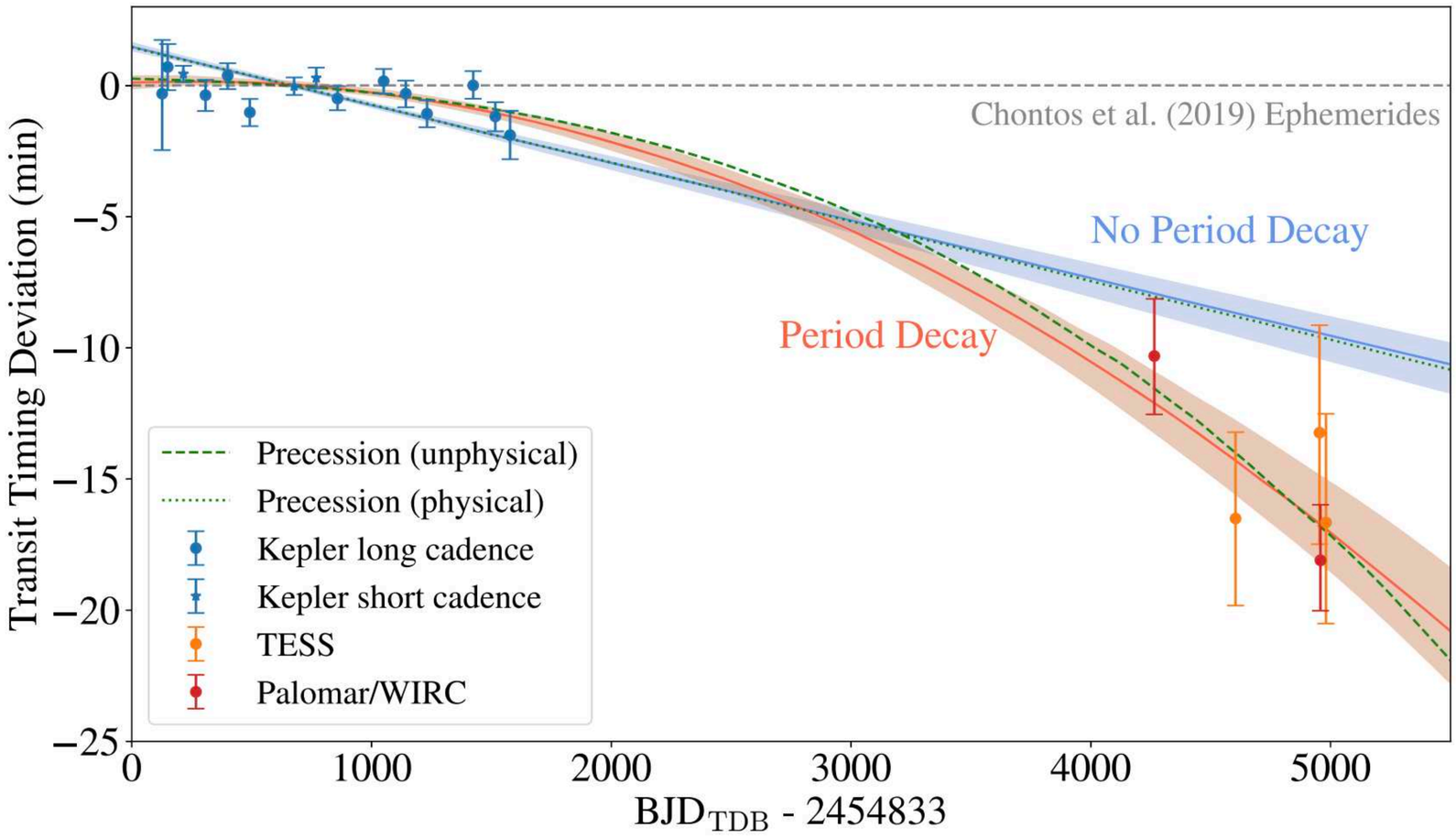
$$Q'_* = 10^5$$

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

Apsidal Precession

Maciejewski et al. 2016, Turner, J. et al. ApJ 2021, Akinsanmi et al. 2024

Orbital decay of Kepler-1658b

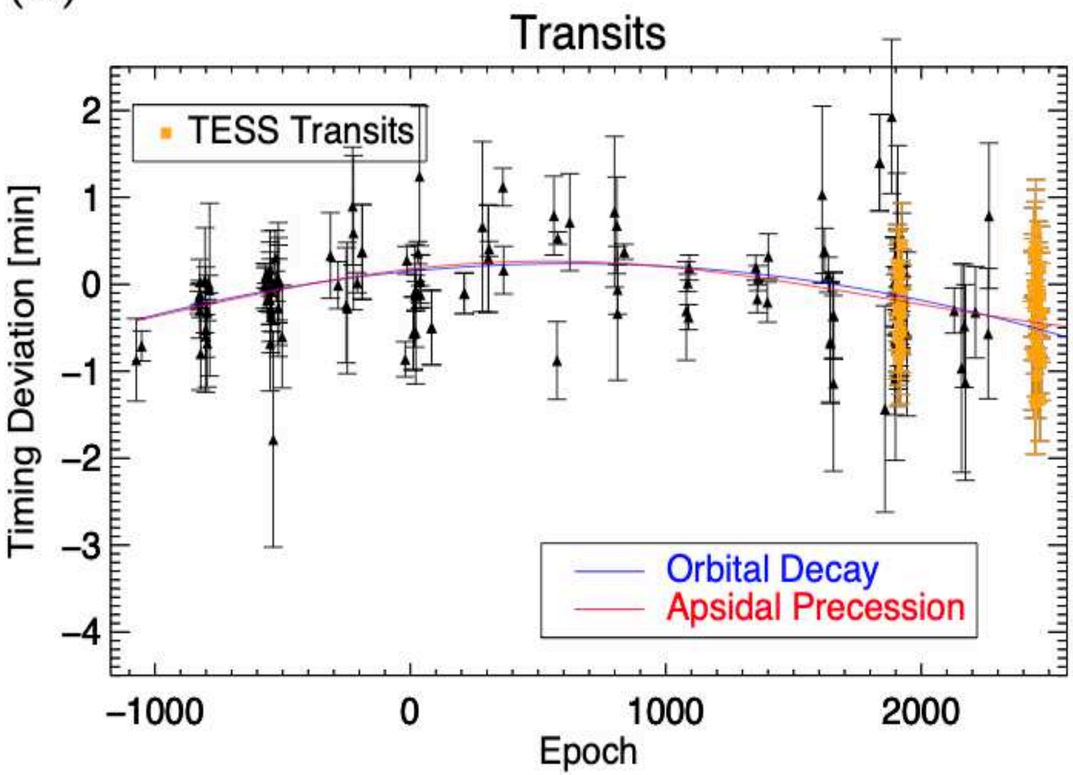


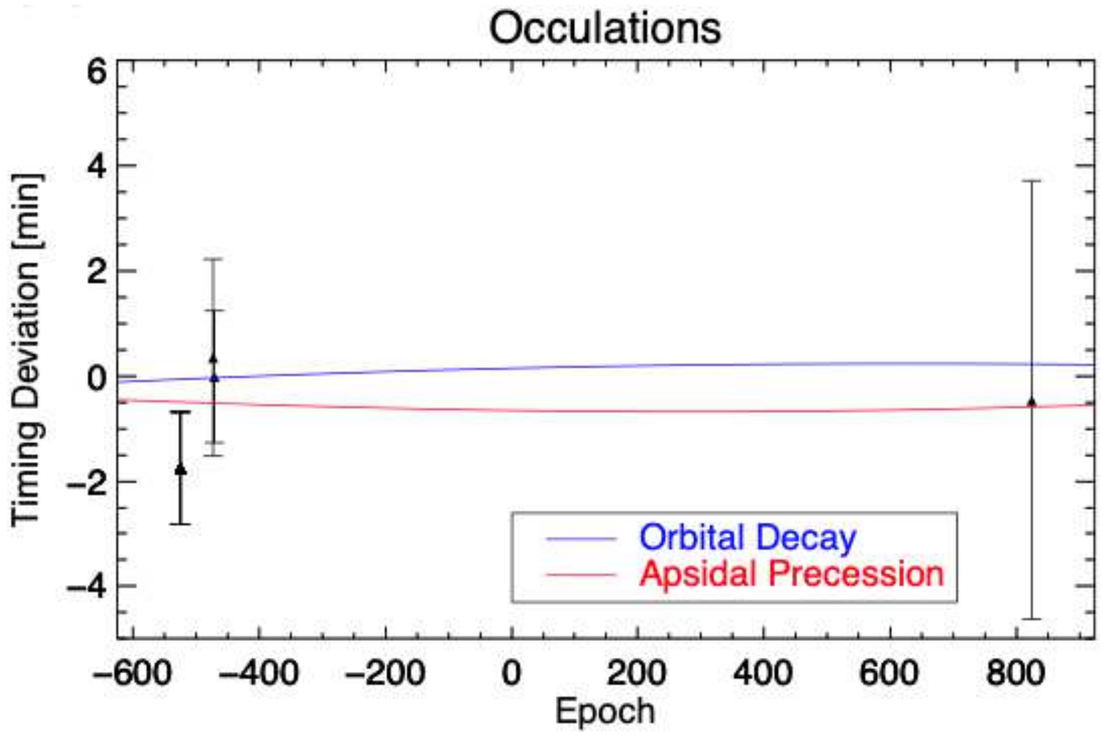
$\dot{P} = -1.31 \pm 0.22 \times 10^{-9}$ days/day

Q = $2.5 \pm 0.10 \times 10^{6}$

Vissapragada 2022

Period decrease of WASP-4b





$$\frac{dP}{dN} = -2.62 \pm 0.49 \times 10^{-10} \text{ days/orbit}$$

$$Q = 5.7 \pm 1.0 \times 10^{4}$$

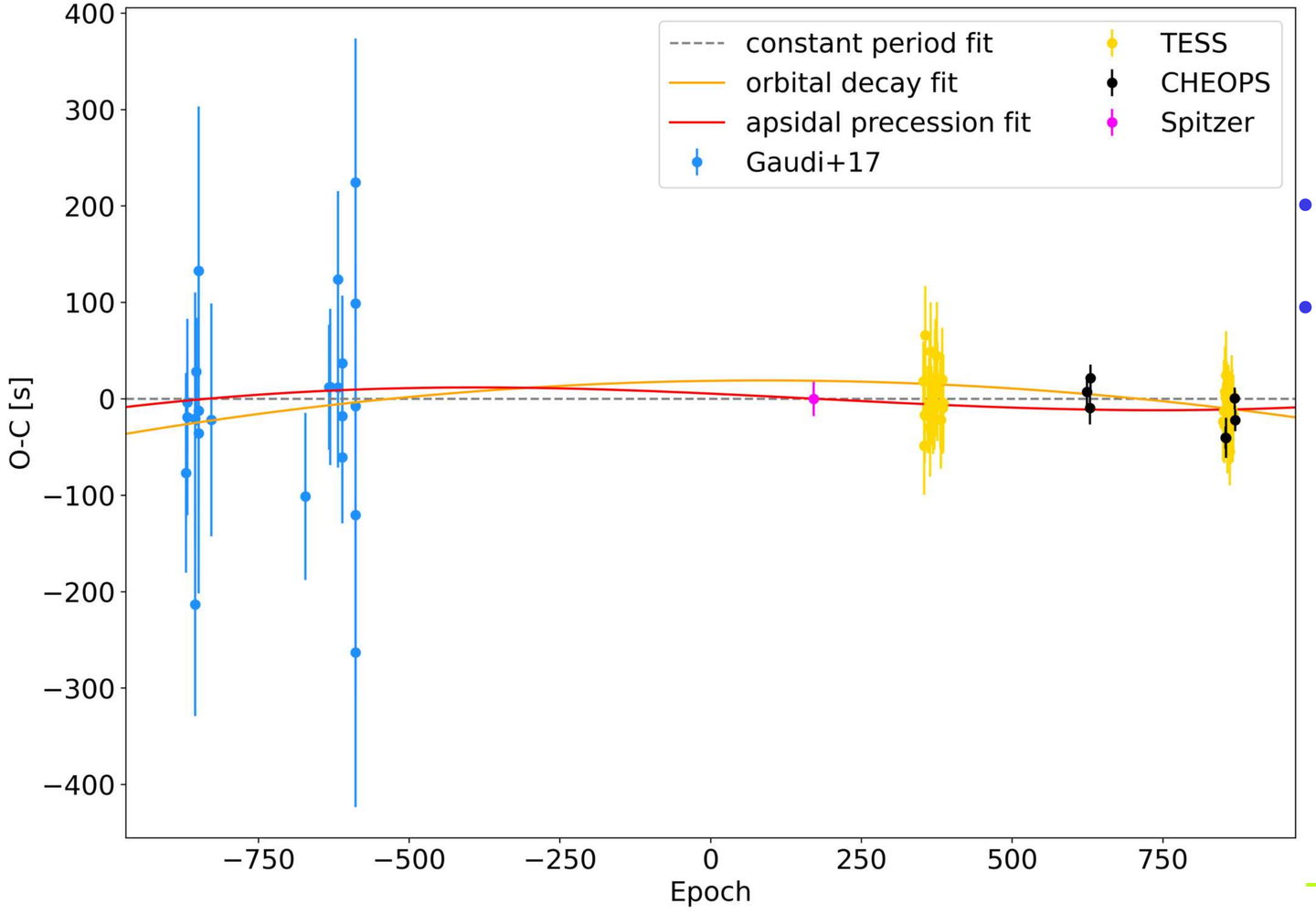
Period ~ 1.3 days

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

Bouma et al. 2020, Turner et al 2021

CHEOPS - Harre et al. 2023

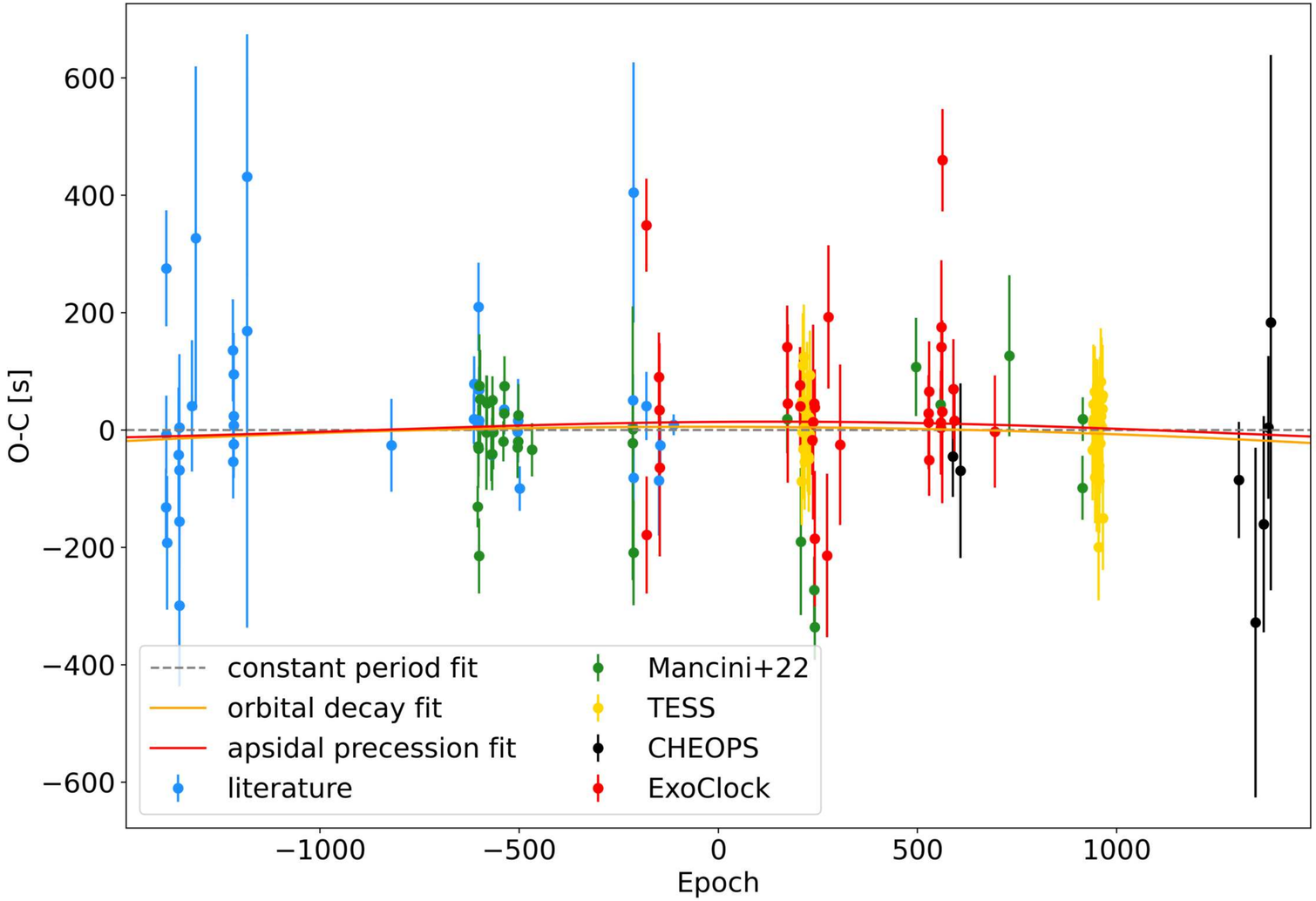
CHEOPS observations KELT-9b



- $\frac{dP}{dN} = -11.4 \pm 5.0 \times 10^{-10}$ days/orbit
- Q > $9.0 \pm 3.7 \times 10^{4}$

Harre et al. 2023

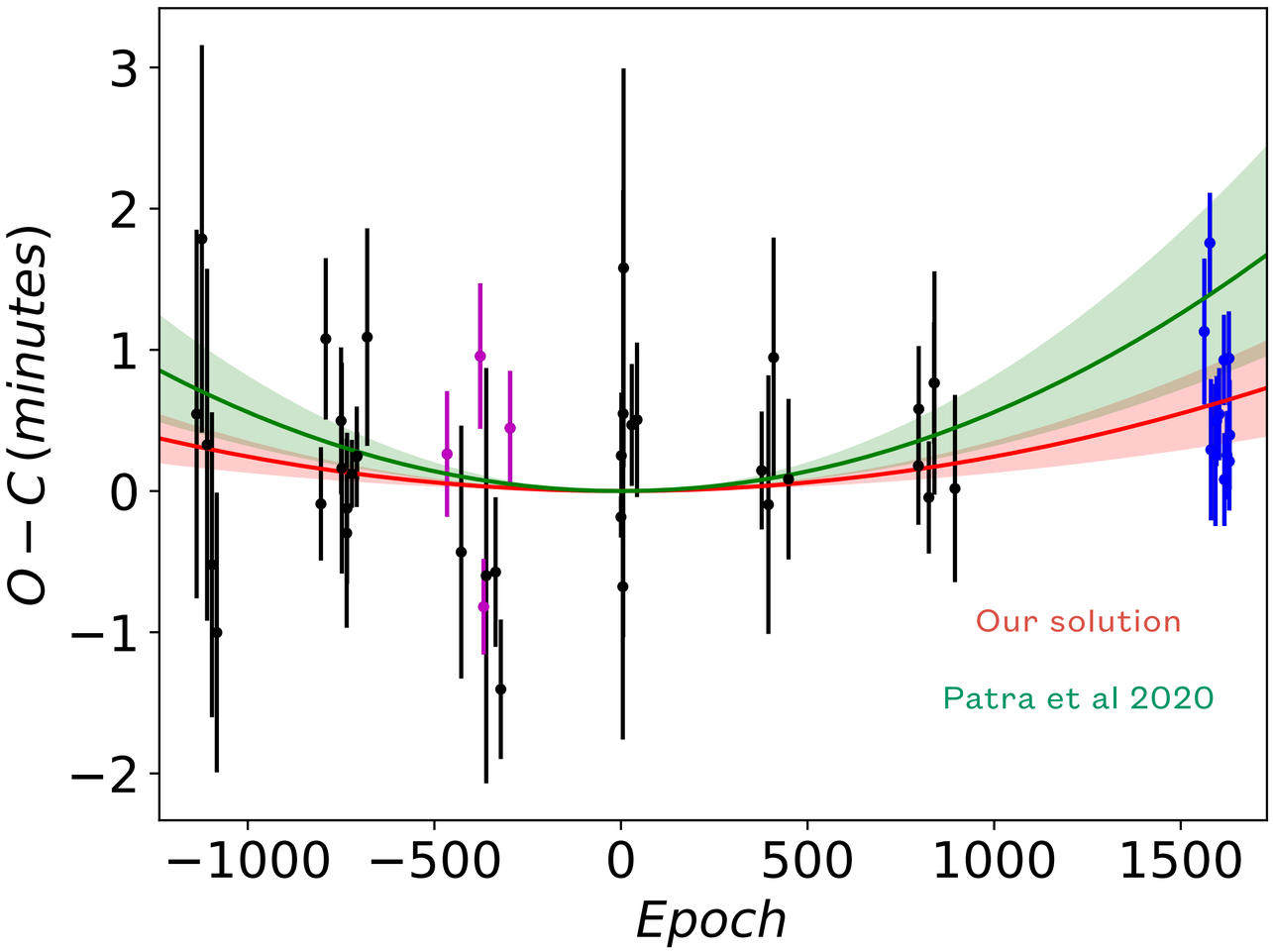
CHEOPS observations KELT-16b



- $\frac{dP}{dN} = -2.7 \pm 3.8 \times 10^{-10}$ days/orbit
- Q > $2.1 \pm 0.9 \times 10^{5}$

Harre et al. 2023

CHEOPS observations WASP-103b



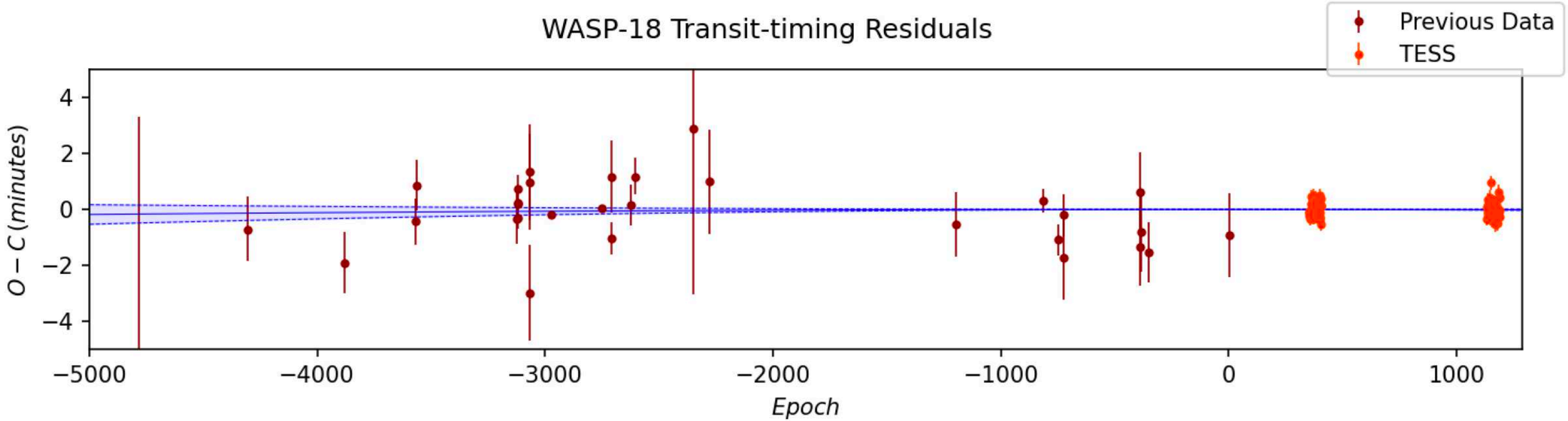
Literature values from Maciejewski et al. 2008

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

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

Barros et al. 2022

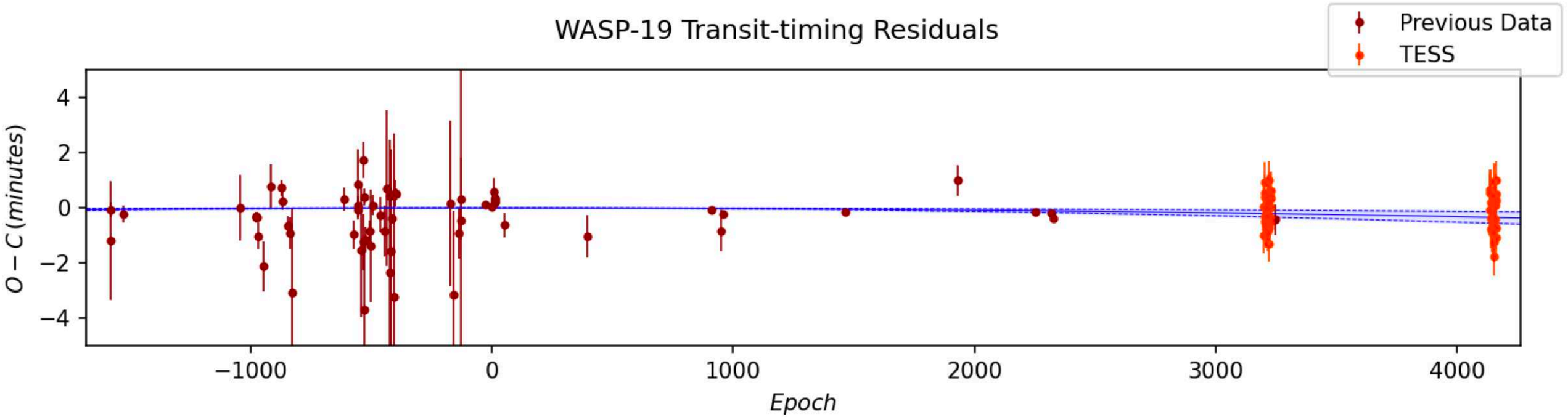
TESS observations of WASP-18b



- $\dot{P} = -0.11 \pm 0.21 \times 10^{-10}$ days/day
- Q > $1.42 \pm 0.34 \times 10^{7}$ at $3\,\sigma$ (99.7% confidence interval)

Rosario et al. 2022

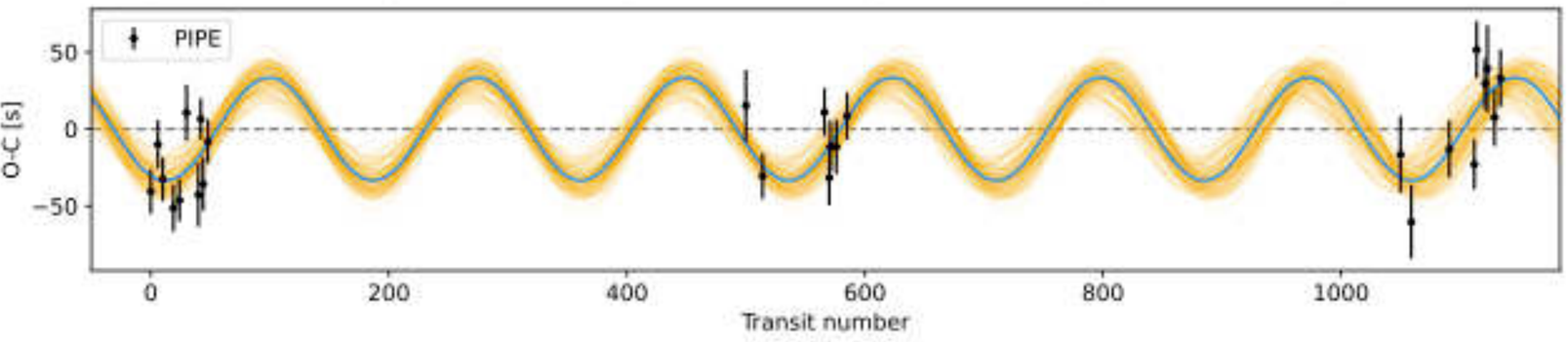
TESS observations of WASP-19b



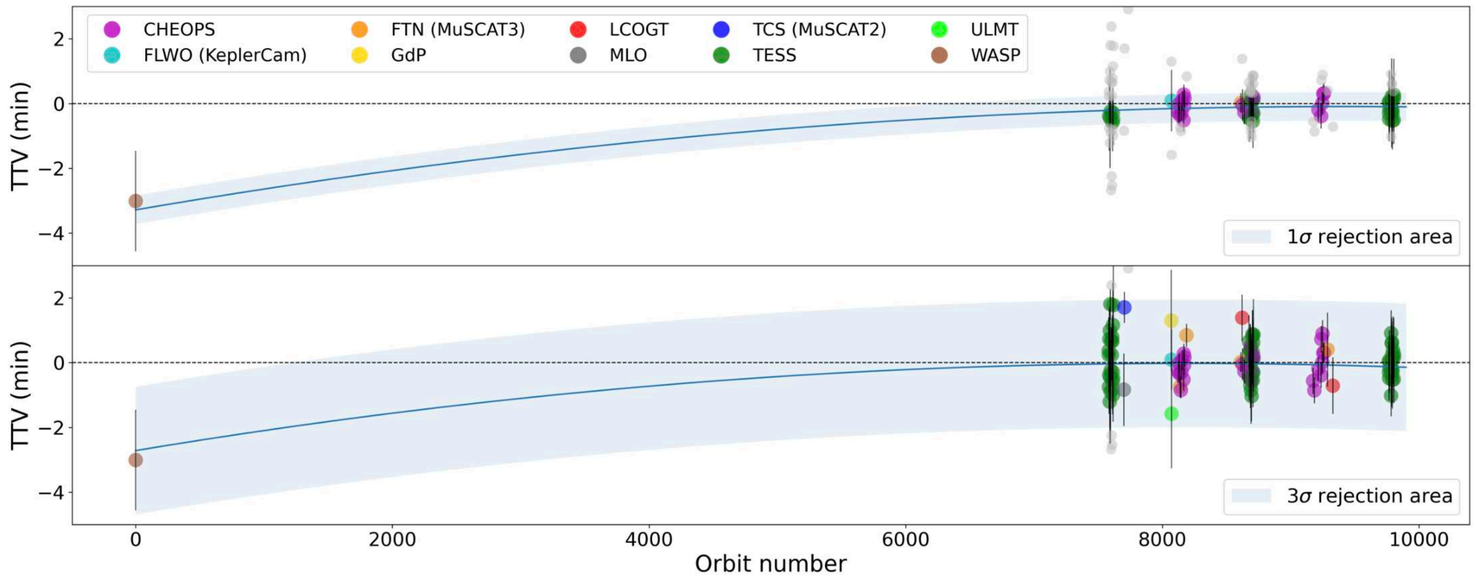
- $\dot{P} = -0.35 \pm 0.22 \times 10^{-10}$ days/day
- Q > $1.26 \pm 0.10 \times 10^{6}$

Rosario et al. 2022

Period variation of TOI - 2109b

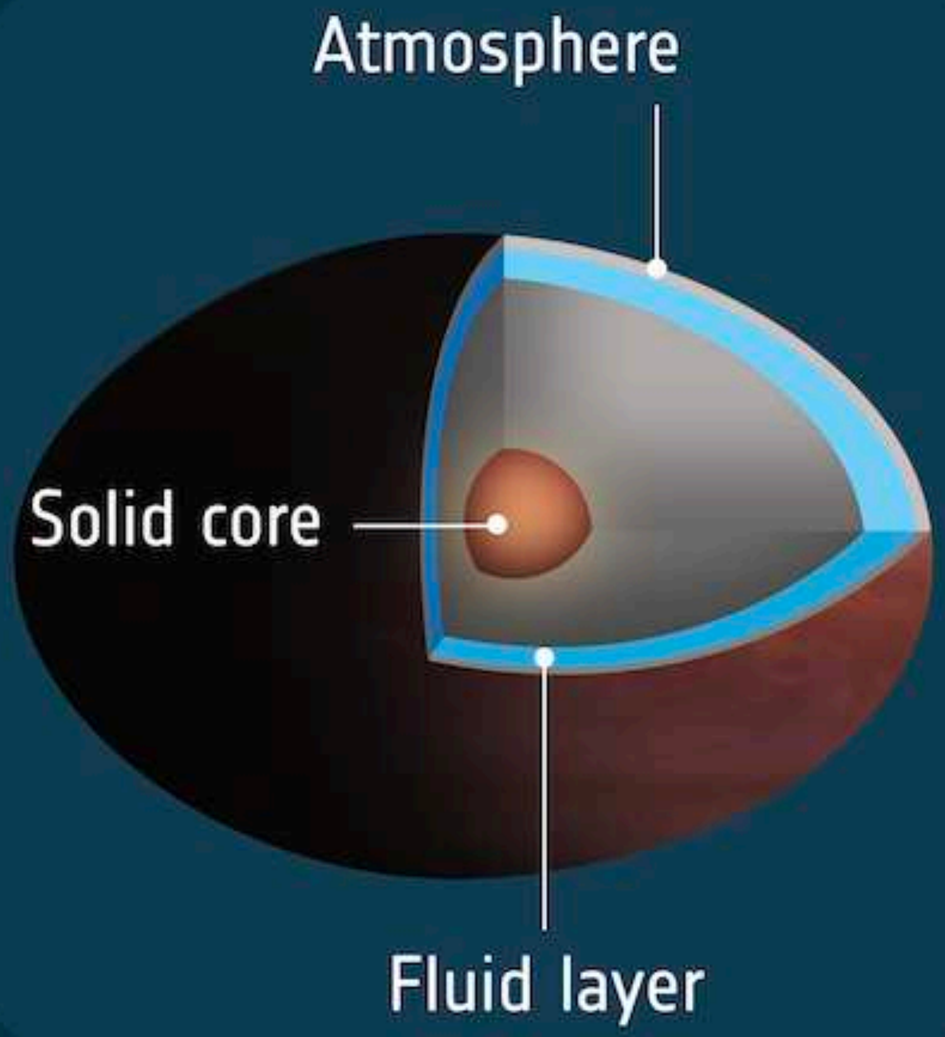


Harre et al 2024
dP/dt = (–1.32 ± 1.63) ms yr–1
Q′⋆ > 1.6 ×10^7
eccentricity —> apsidal precession

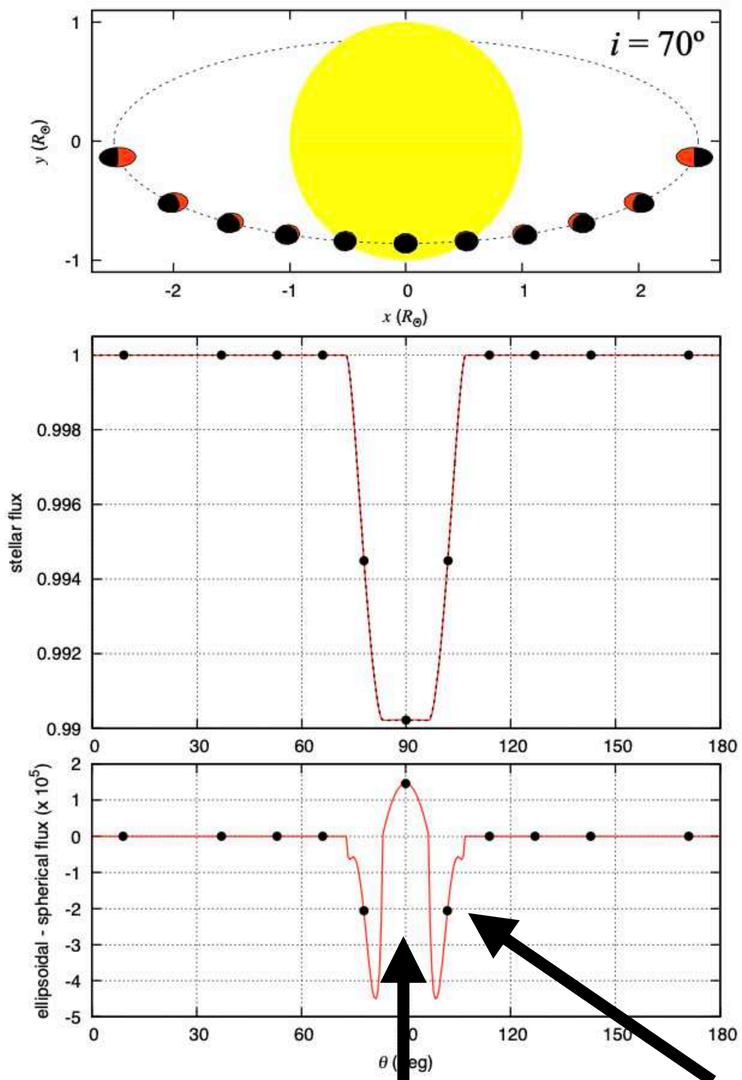


Alvarado-Montes 2025
dP/dt = (–2.62 ±1.29) ms yr–1
Q′⋆ > 3.7 ×10^7
Related to the star internal structure —> young star.
If older star theory predicts more efficient tides Q′⋆ ~ 10^4

Tidal deformation



Tidal deformation



Rotation

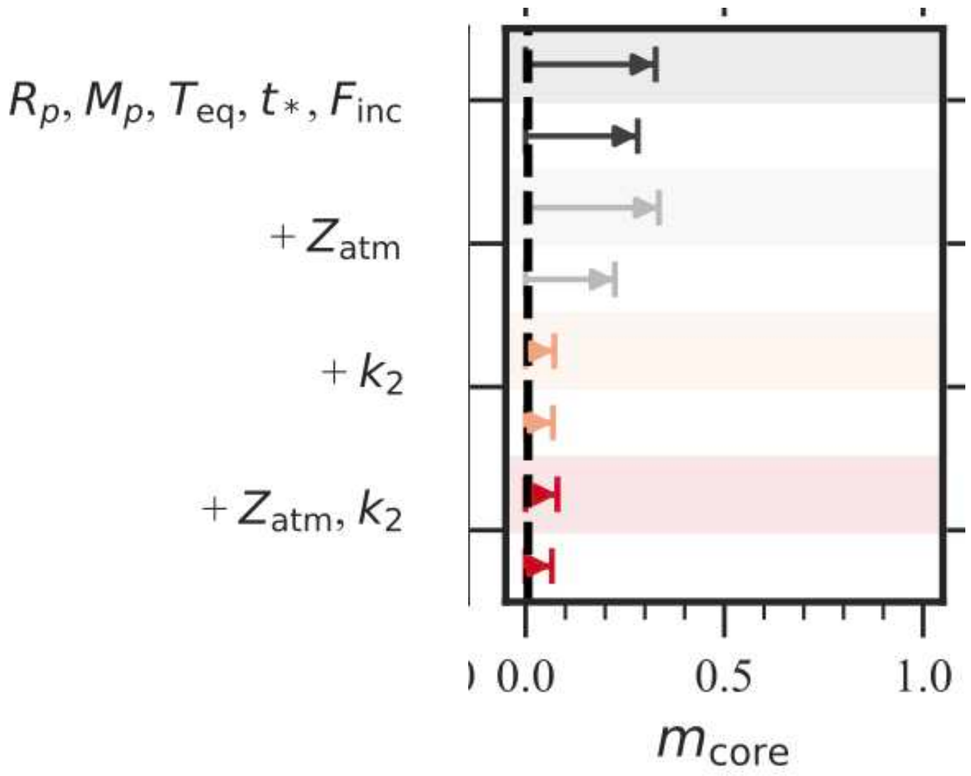
Tidal Bulge

Correia, A. A&A, 2014

- Strong tidal forces deforme the shape of ultra Hot Jupiter into ellipsoids. Some planets fill 90% of their Roche Lobe
- The deformation of the three axis is related to a single parameter - Love number (Correia 2014)
- The Love number measures the distribution of mass within the planet giving insight into the planet internal structure. It is an extra observable to lift the degeneracy of planetary interior models.
- Planetary differentiation depends on the size of particles that were accreted during formation - it can distinguish between accretion by pebbles and accretion by planetesimals. Hence, it can improve our understanding of planetary core accretion

Seager & Hui 2002; Barnes & Fortney 2003

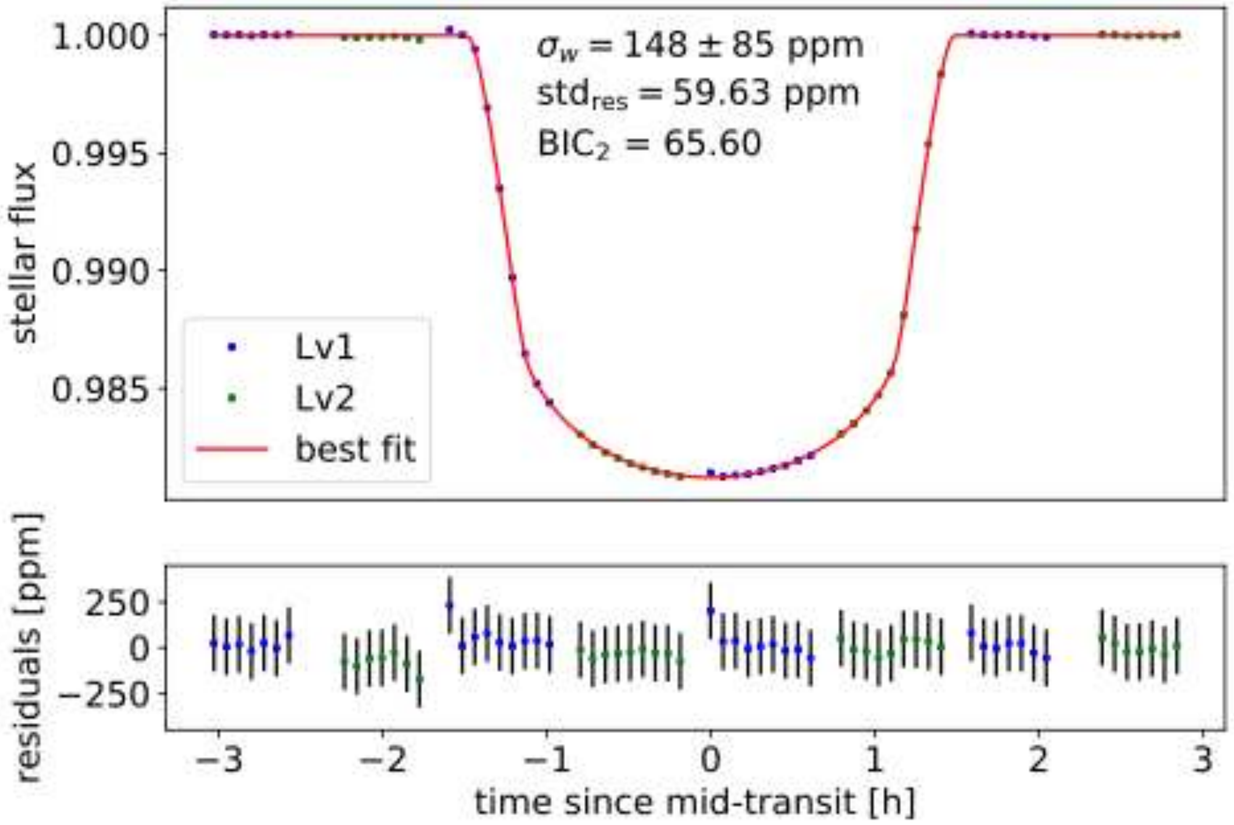
Constraining the interior structure



van Dijk & Miguel 2025

- Including k_2 narrows the uncertainty on the core mass from ~33% to ~7% of parameter space.
- Precision better than 40% is needed for meaningful core constraints.
- Confirms theoretical link between interior structure and Love number (e.g. Kramm+ 2011, Wahl+ 2021).

Tidal deformation of WASP-121b



Best measurement of the Love number

2 HST transits

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

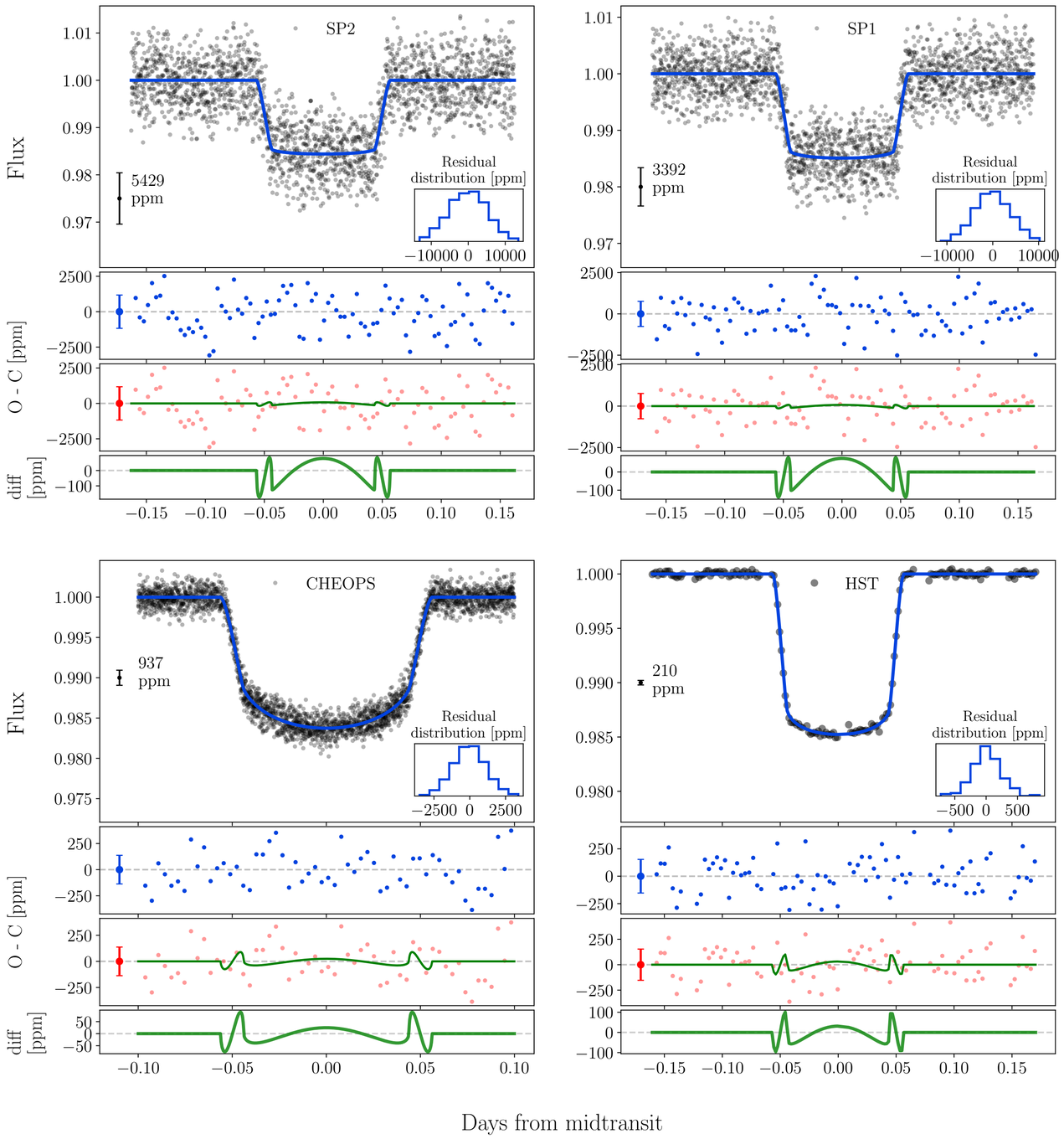
Hellard et al. 2019

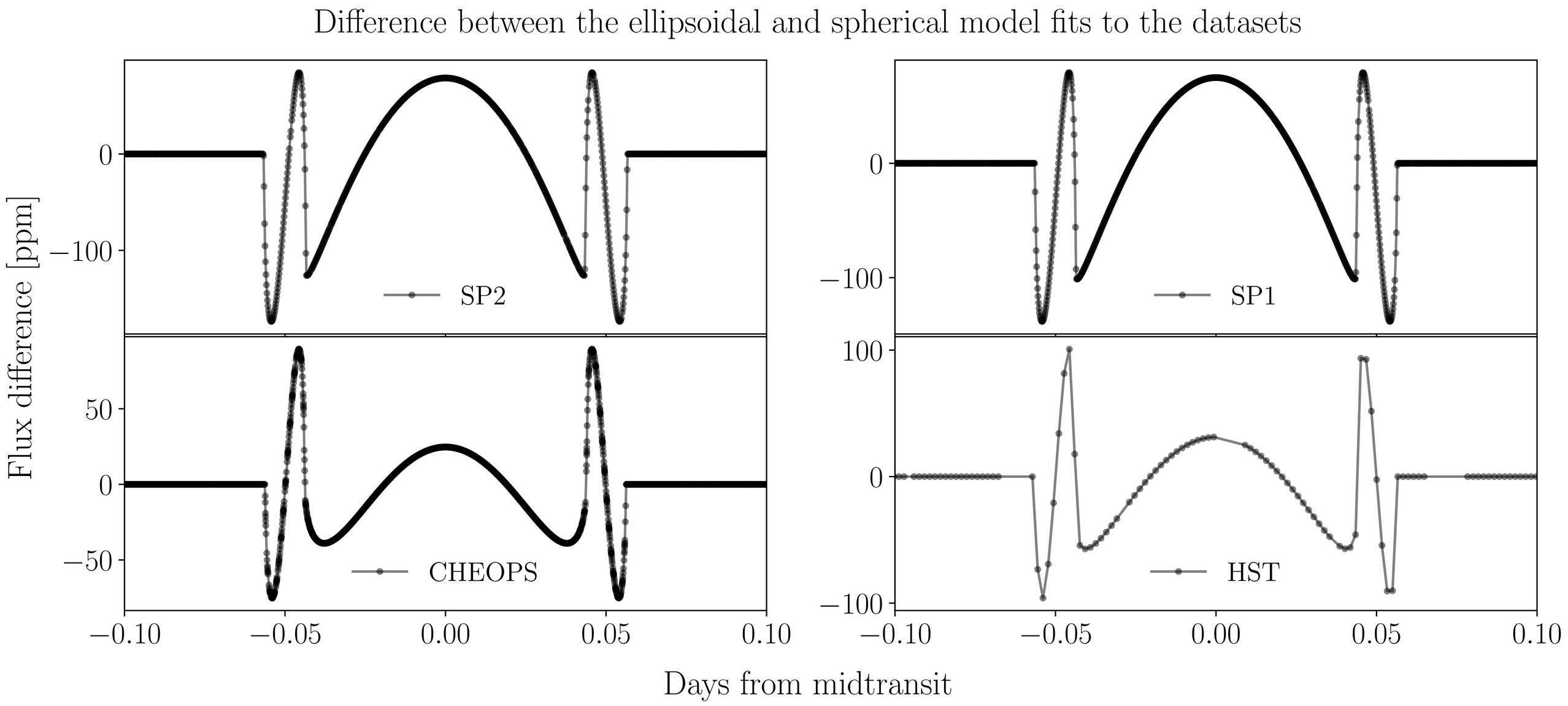
Tidal deformation of WASP-103b

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

Barros et al. 2022

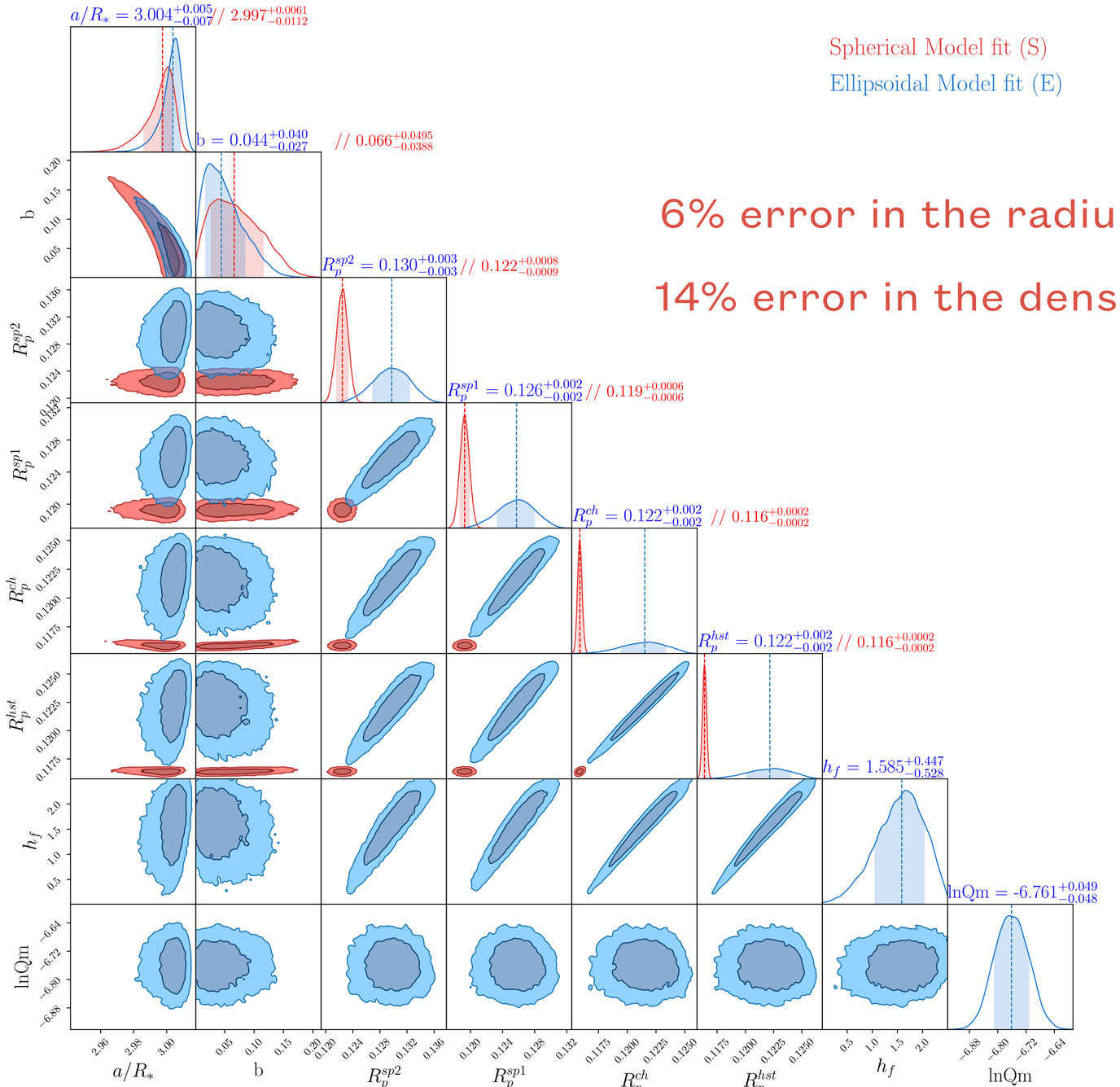
Ellipsoidal Model fit to all the datasets





SIGNATURE STRONGEST IN INFRARED–> JWST

Results



Spherical Model fit (S)

Ellipsoidal Model fit (E)

6% error in the radius (underestimation)

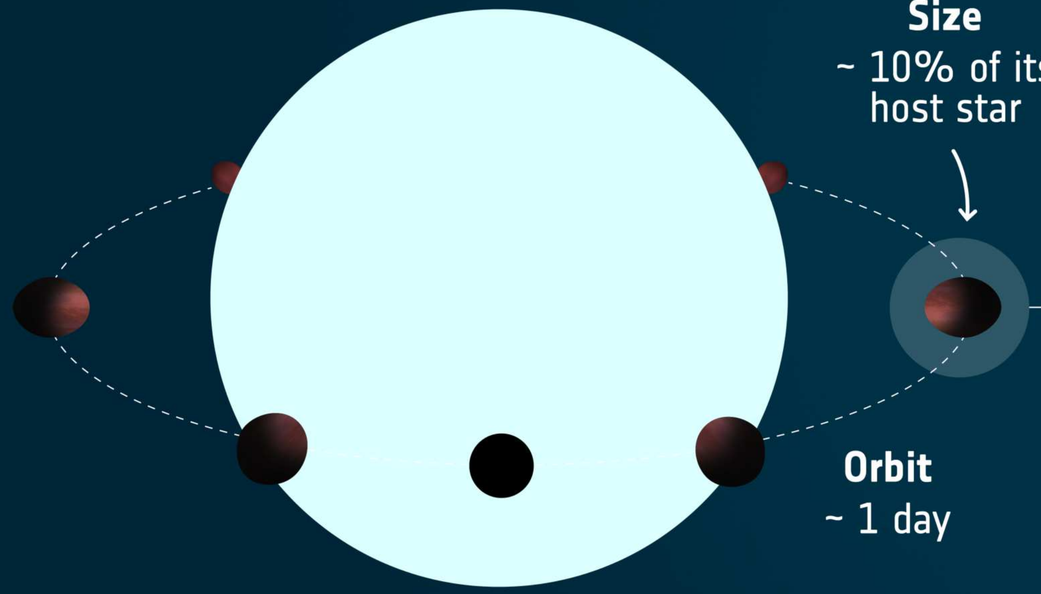
14% error in the density (overestimation)

Barros et al. 2022

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.

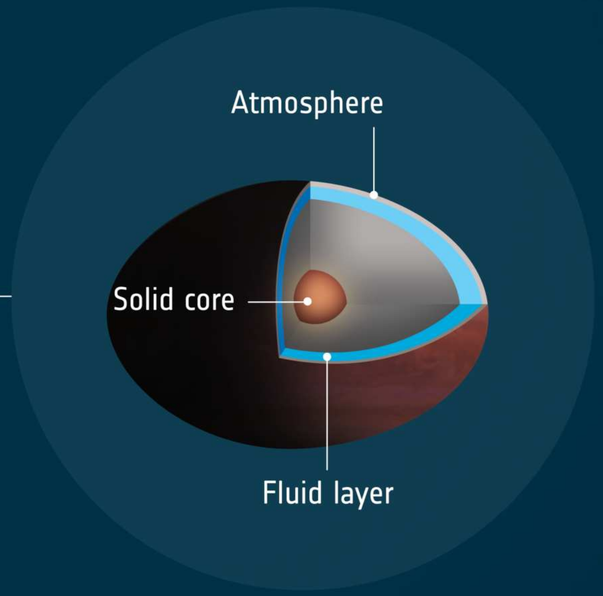
WASP-103
Host star



Size
~ 10% of its host star

Orbit
~ 1 day

WASP-103b
Planet



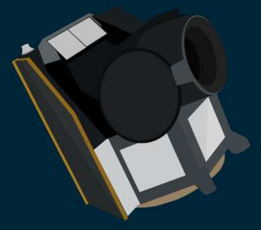
Internal structure
Likely very similar to that of Jupiter

Mass
1.5 x Jupiter

Radius
2 x Jupiter

Temperature
20 x hotter than Jupiter

Teff = 2500



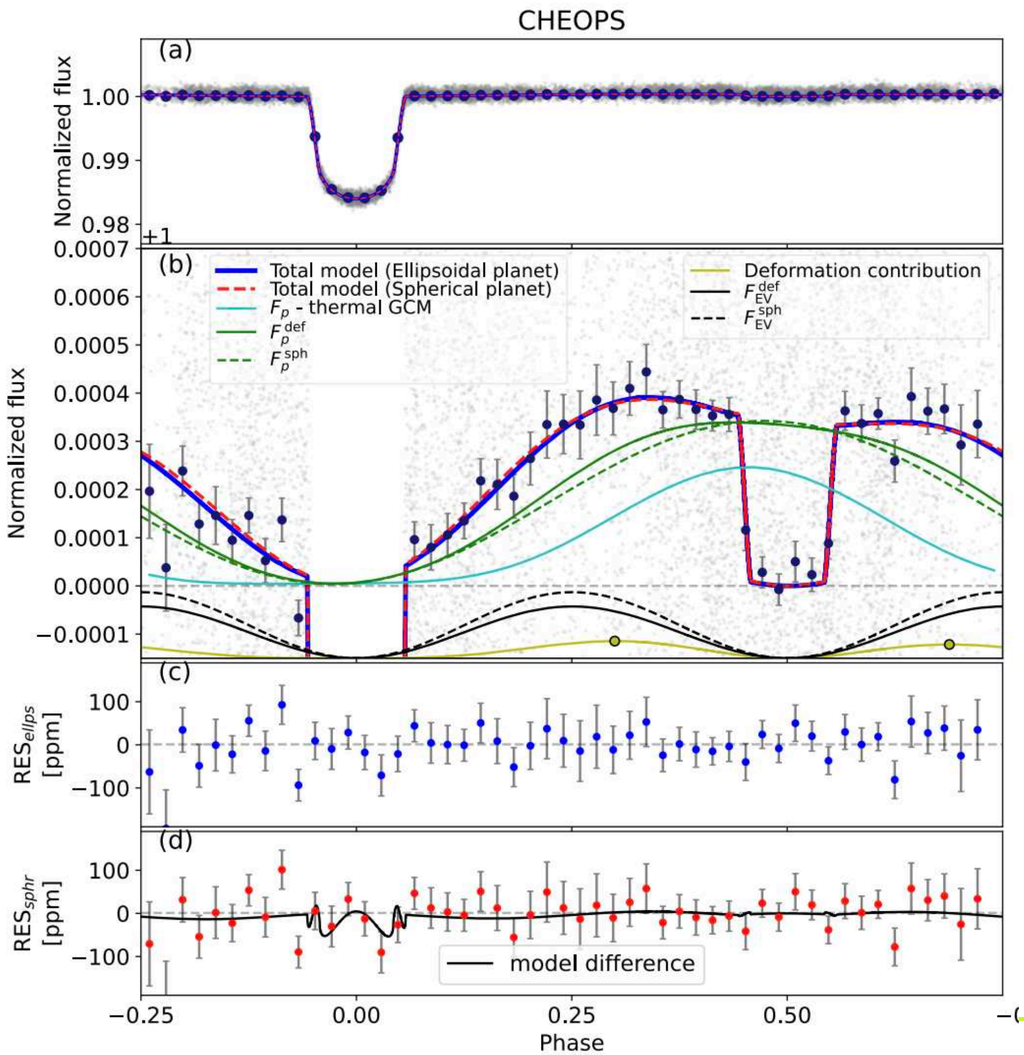
Cheops spotted a small difference in the typical transit light curve, caused by the deformation of the planet

#CHEOPS

Credit: ESA

Credit: ESA

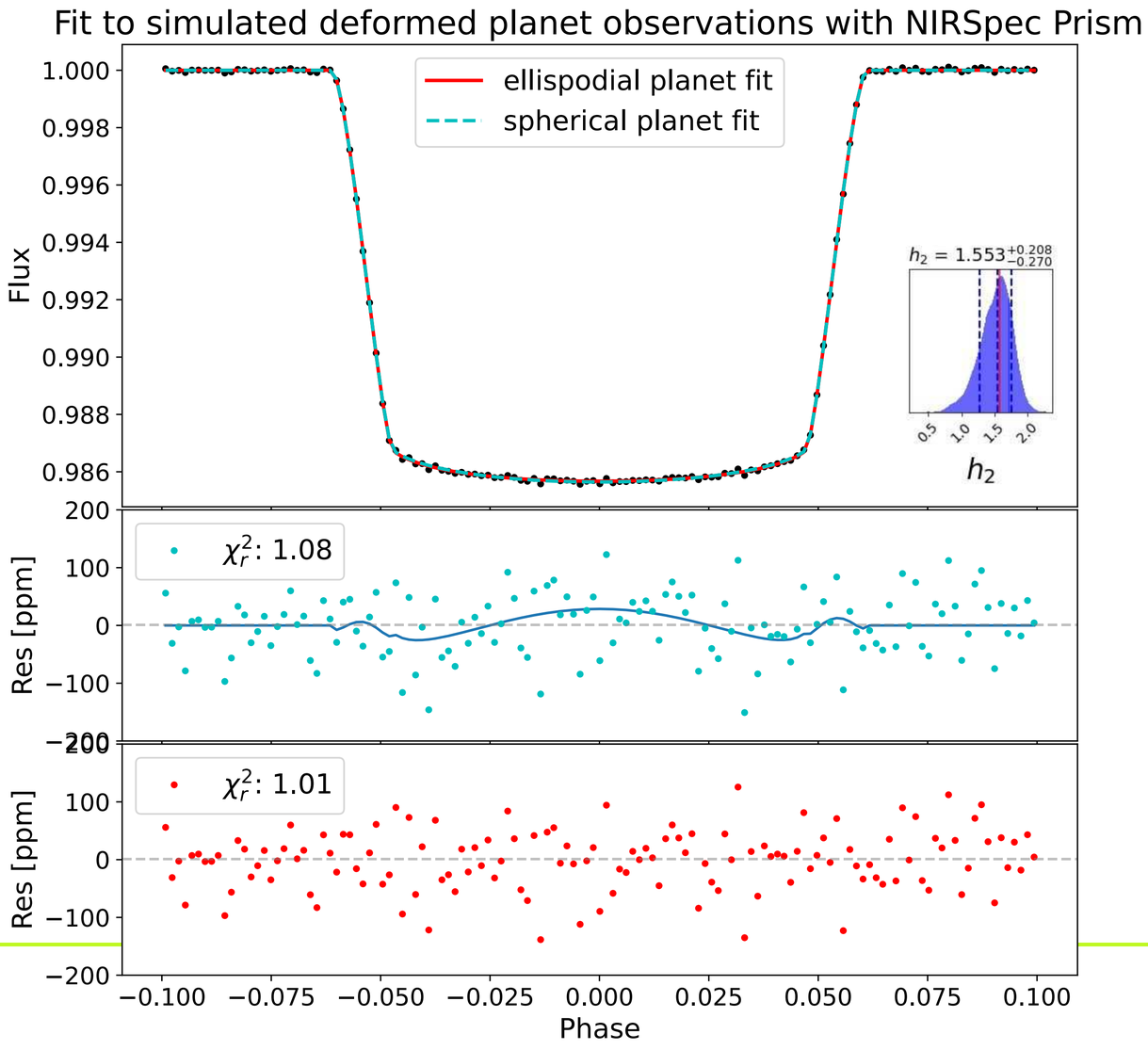
WASP-12b CHEOPS observations



- Spoiler alert for the Talk of Akin
- $h_f = 1.55^{+0.45}_{-0.49}$

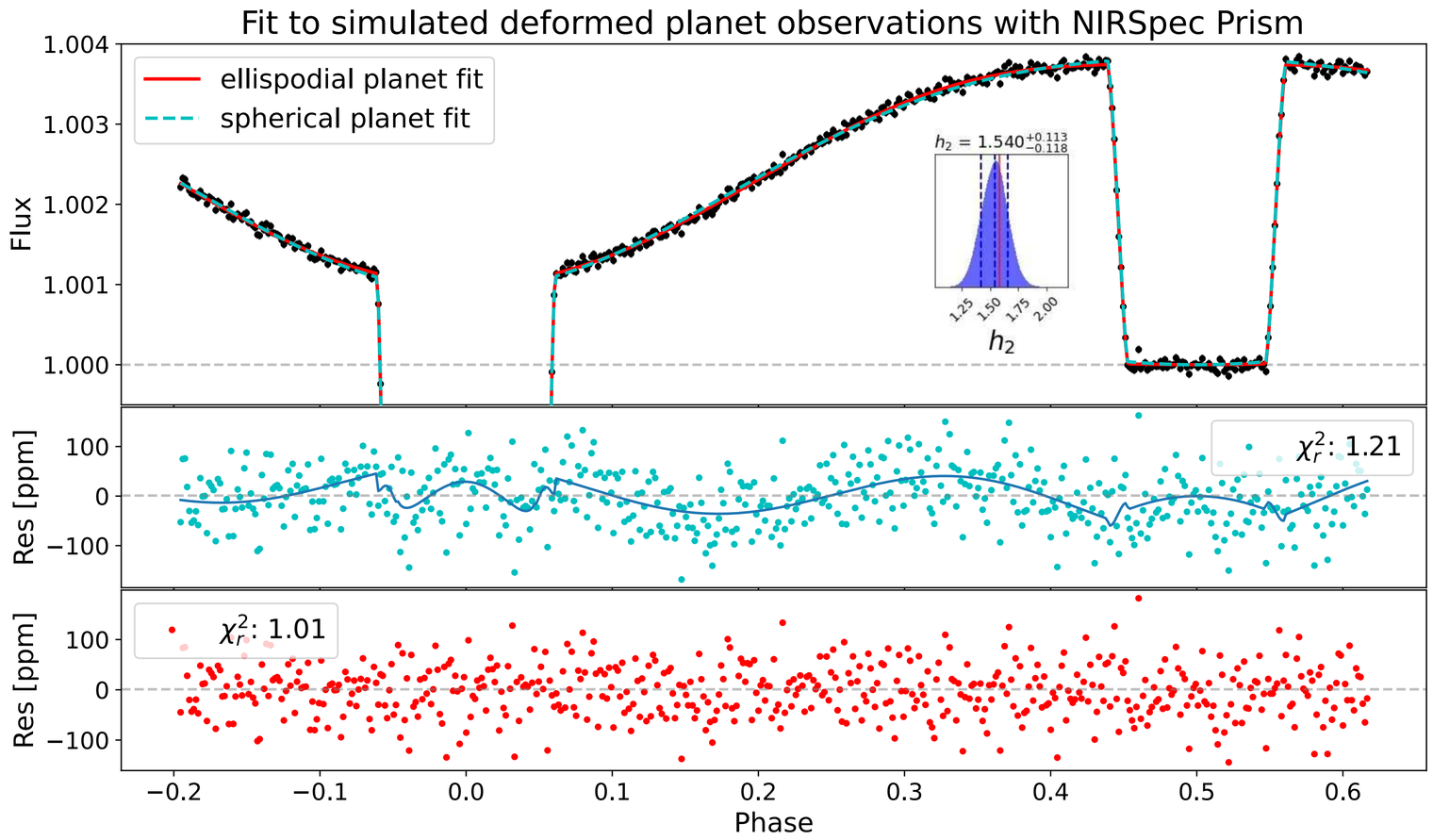
Akinsanmi 2024

WASP-103b JWST observations



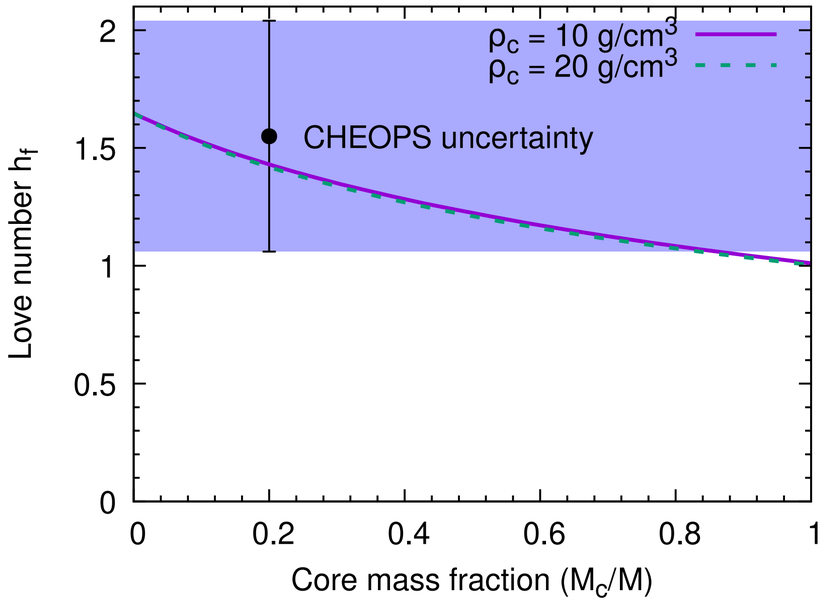
- NIRSPSpec Prism transit observation
- $h_f = 1.55^{+0.21}_{-0.27}$
- 7 sigma precision on the Love number

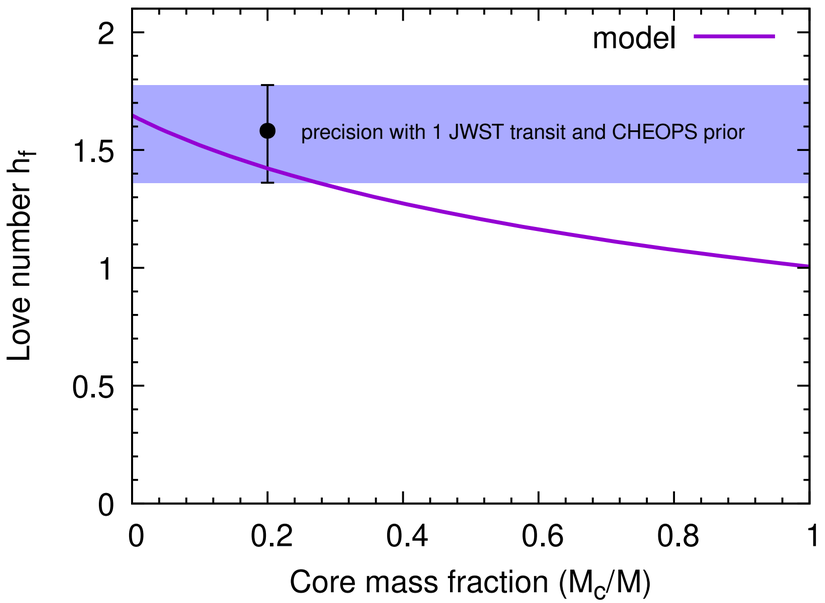
Adding the phase curve

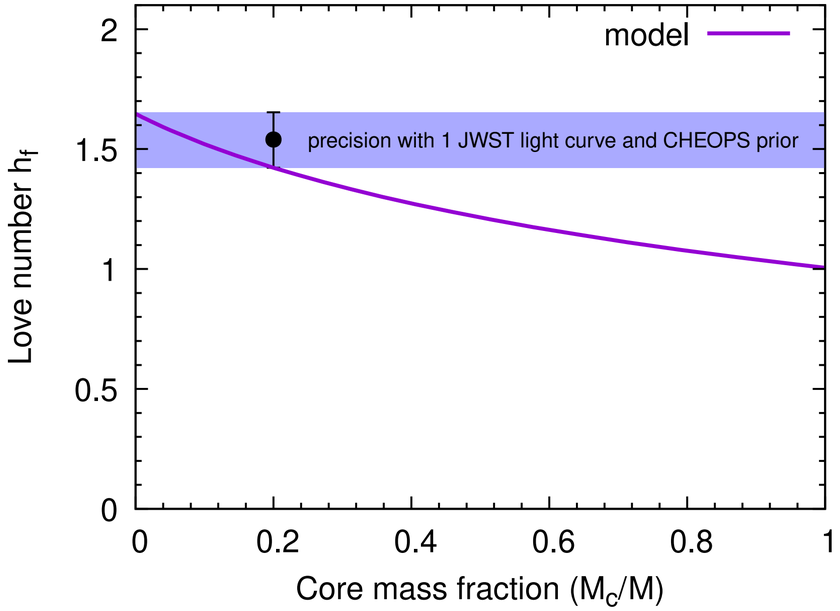


- NIRSPSpec Prism phase curve observation - 76% orbit
- $h_f = 1.54^{+0.11}_{-0.12}$
- 13 sigma precision on the Love number

Constraining the internal structure



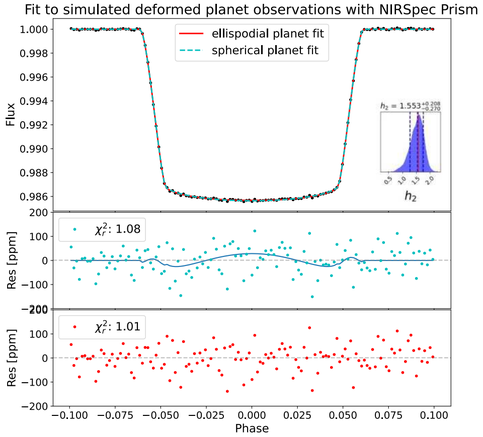


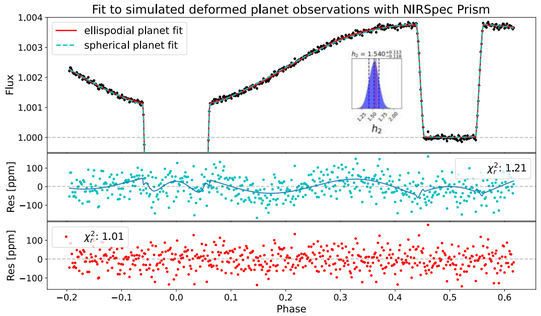


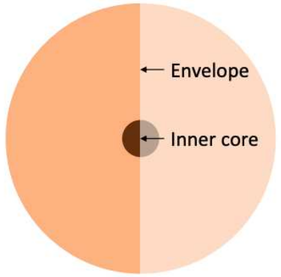
Love number	3 sigma	7 sigma	13 sigma
Core mass	None	0.2	0.1
Fraction			

What's next for Star-Planet interactions

Tidal deformation

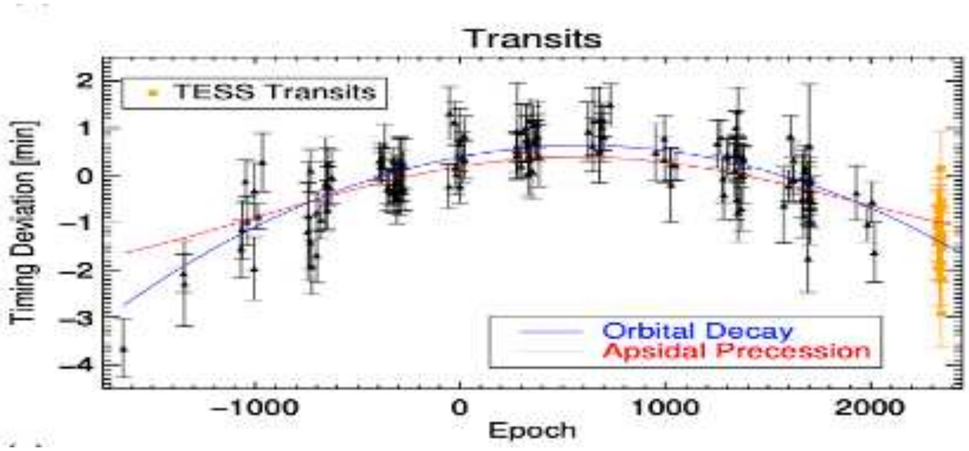


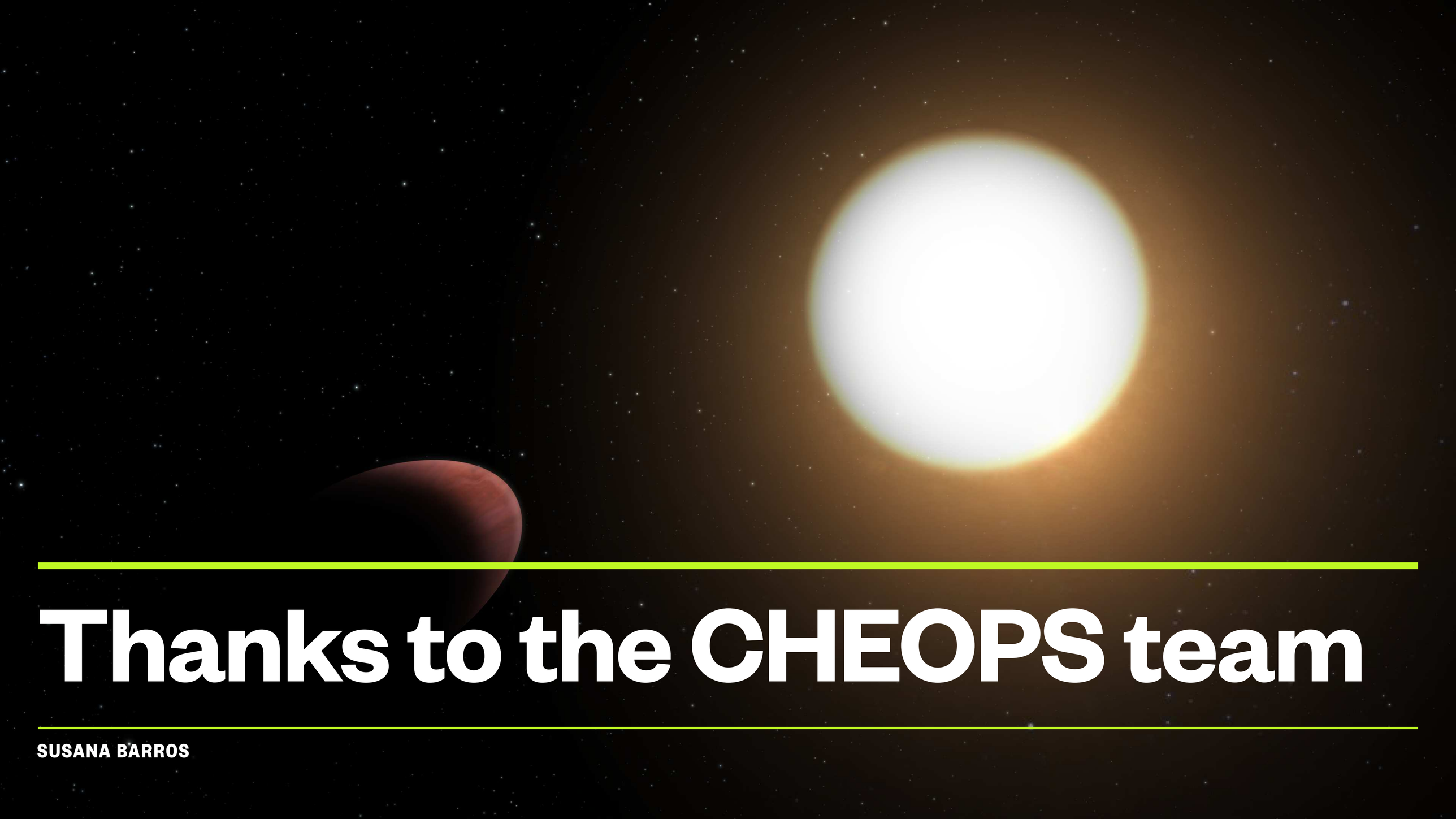




Bloot et al 2023

Tidal decay





Thanks to the CHEOPS team

SUSANA BARROS