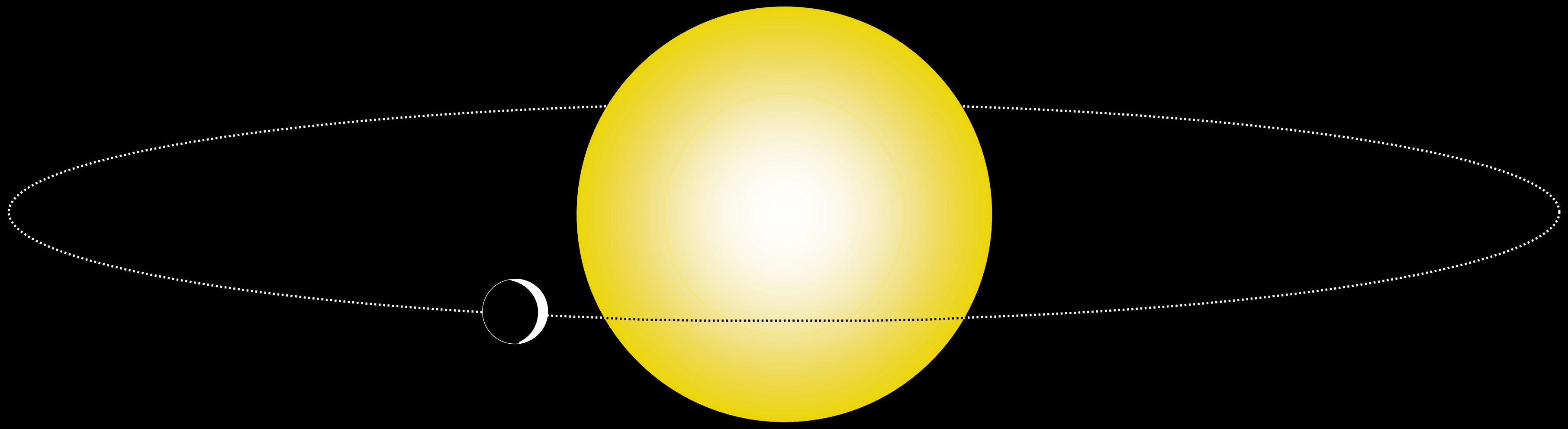
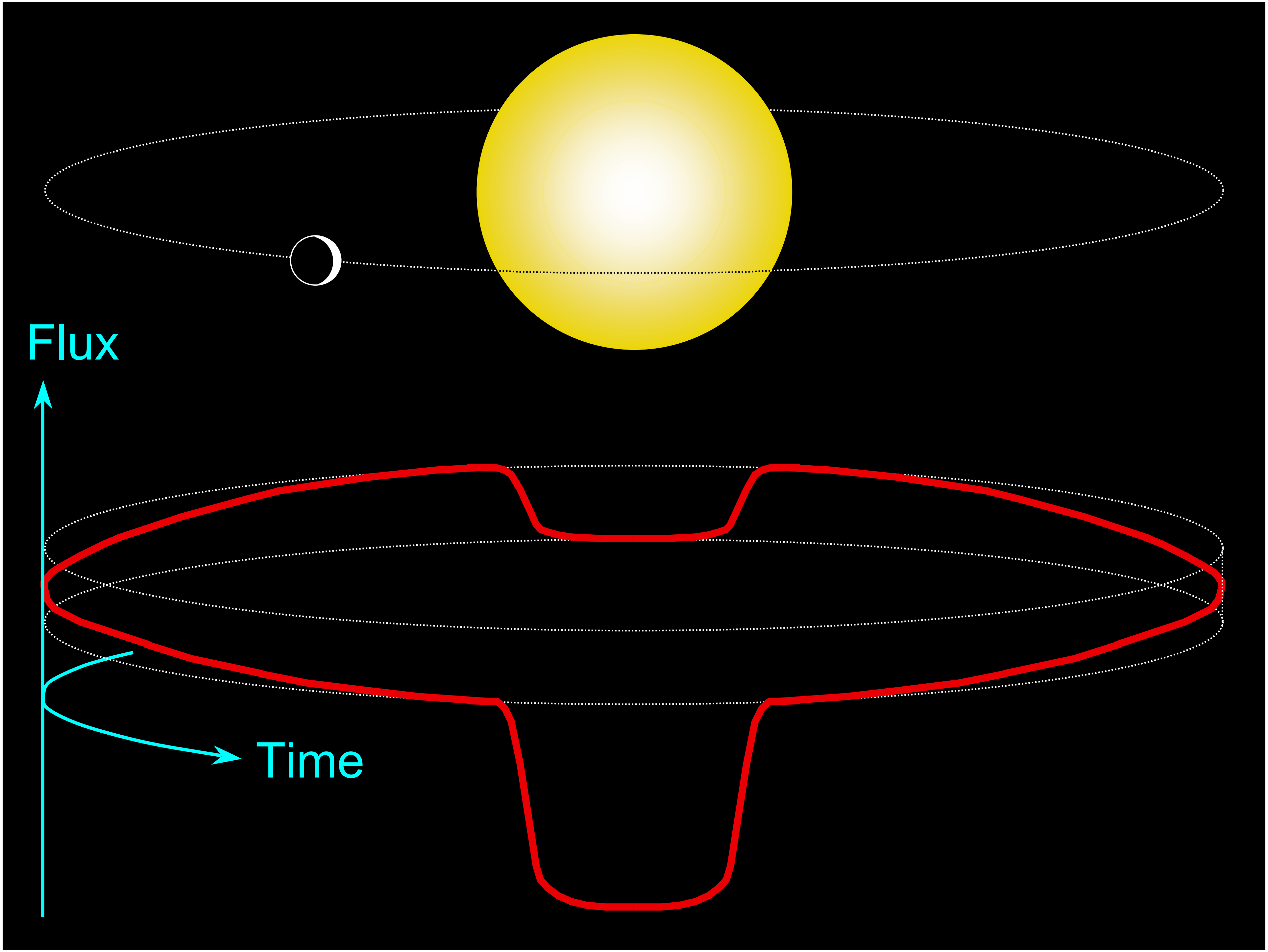
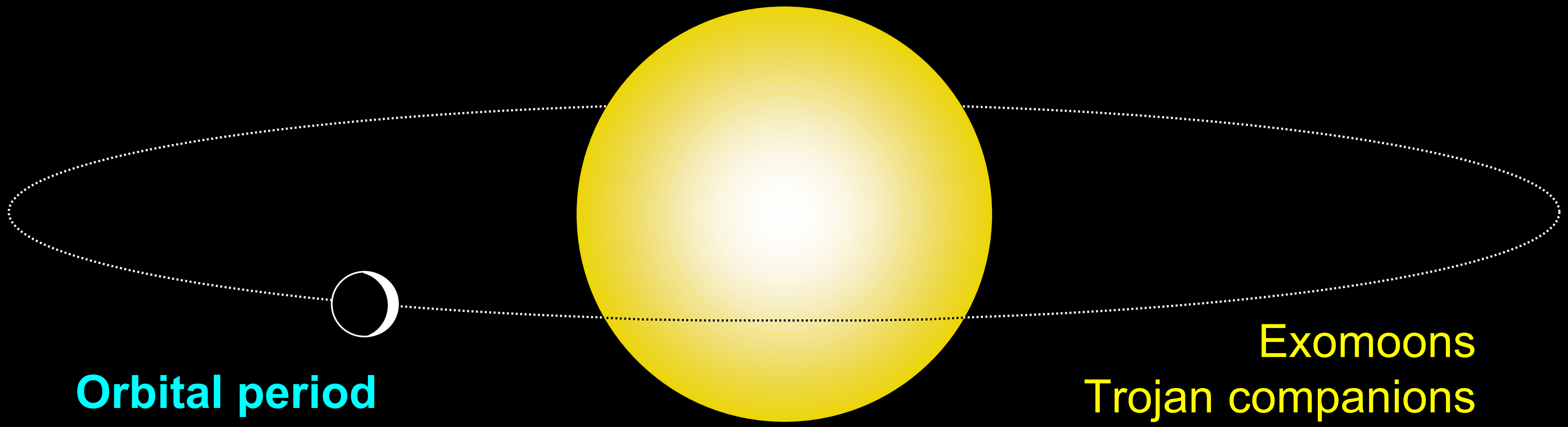


Patterns and puzzles in the transit observables

Josh Winn
Massachusetts Institute of Technology

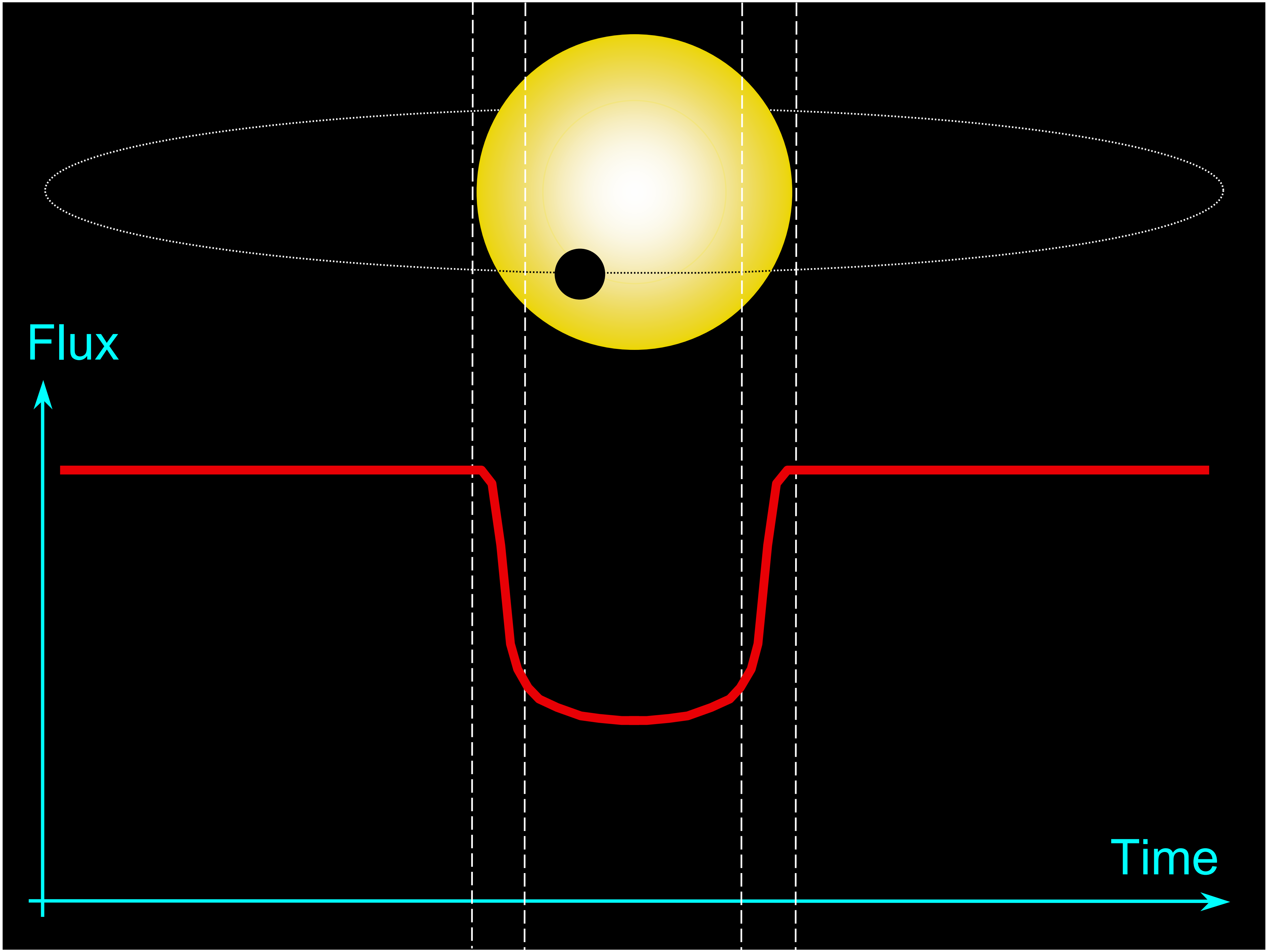
Josh Carter, Simon Albrecht (MIT); John Johnson (Caltech);
Andrew Howard, Geoff Marcy (Berkeley); Dan Fabrycky,
Matt Holman (CfA); Norio Narita (NAOJ)

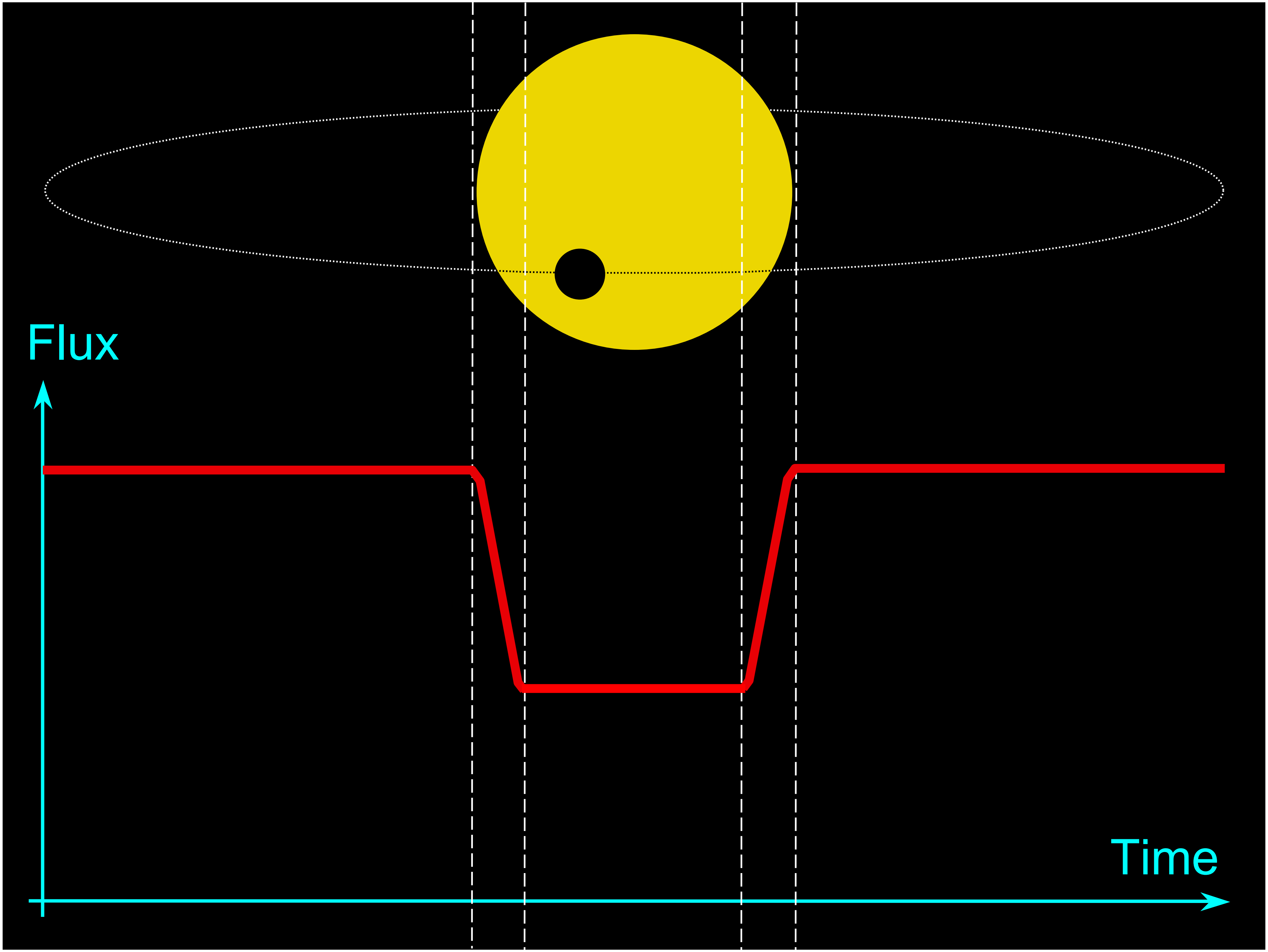

Flux
Time

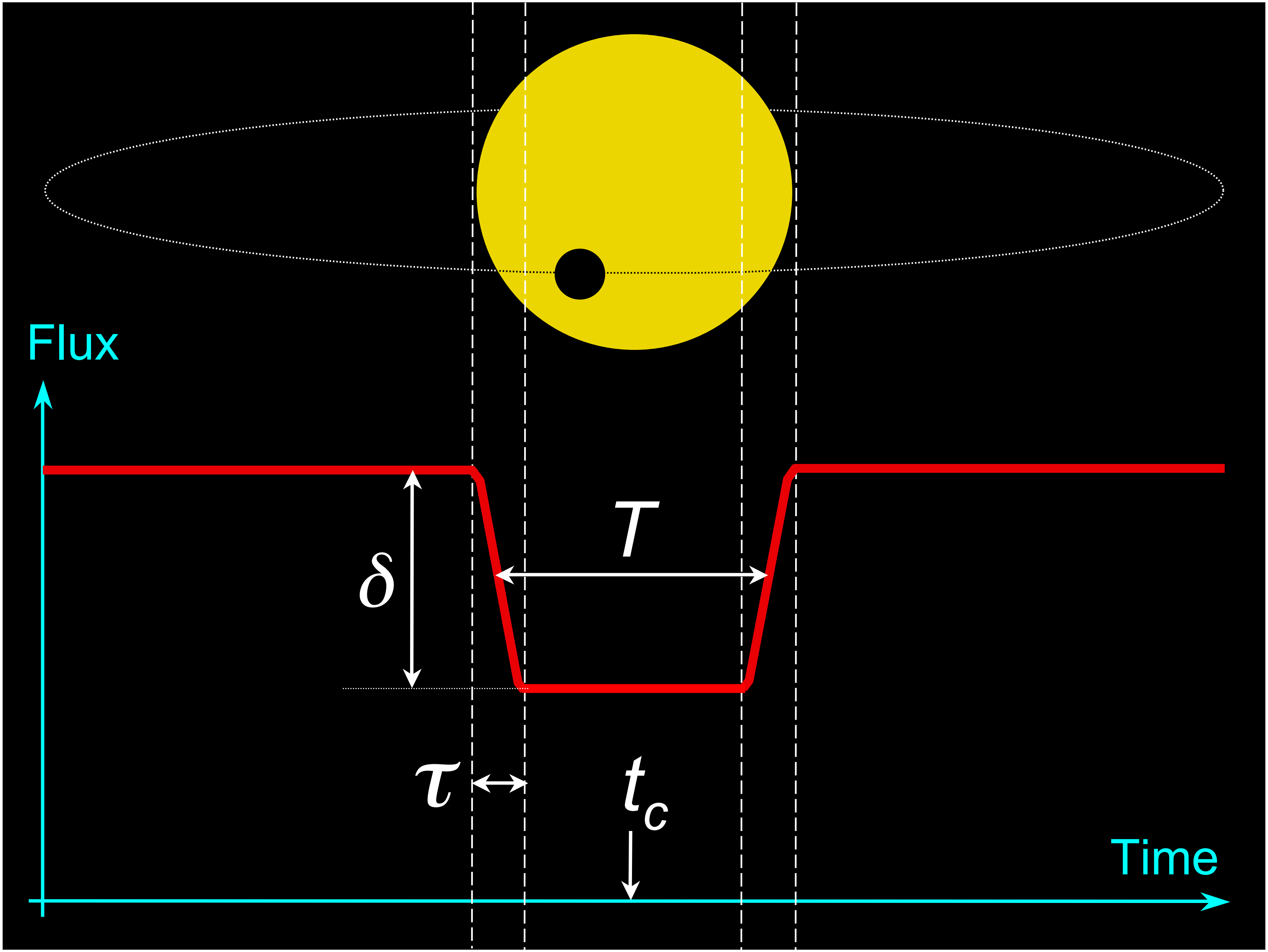


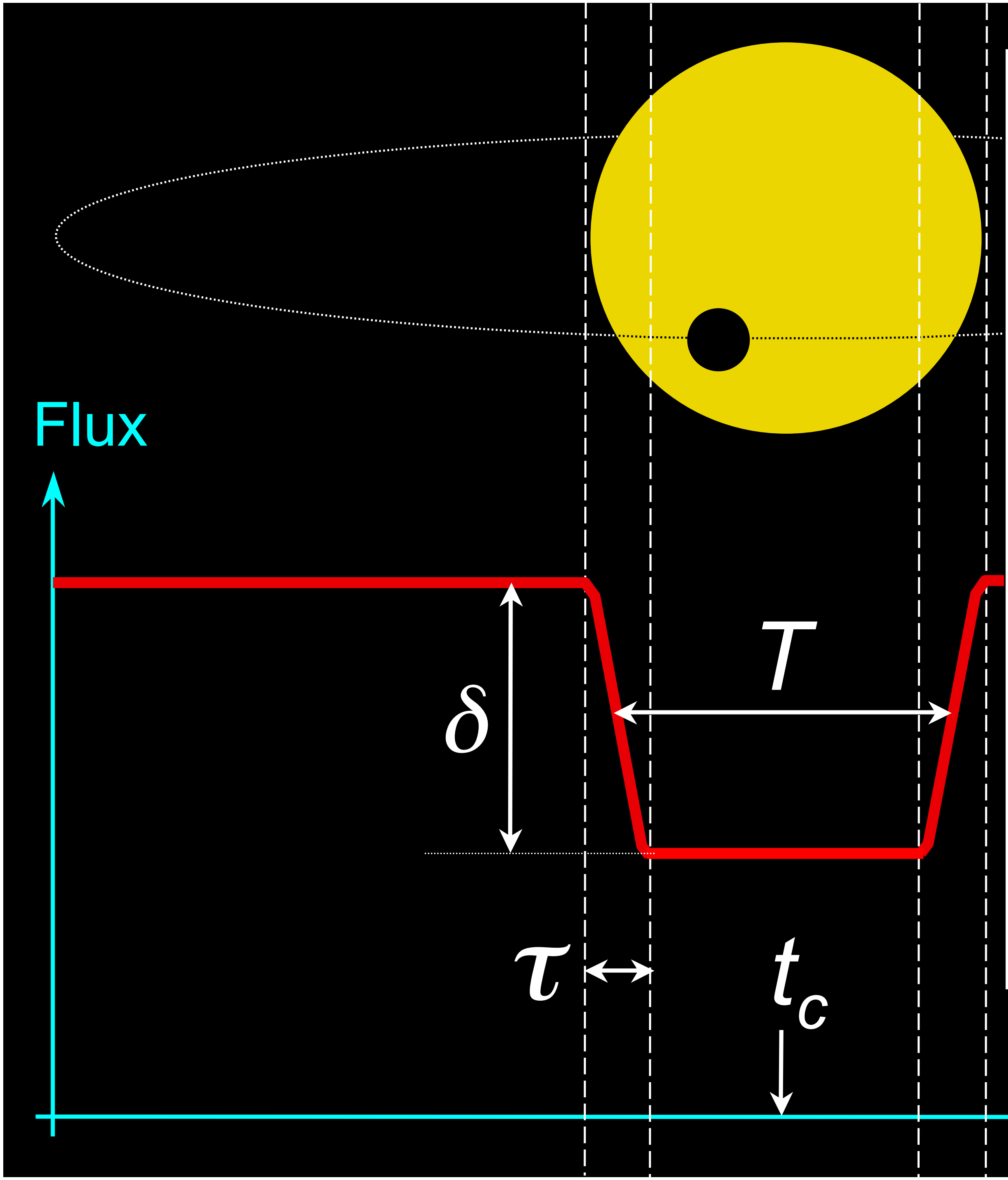
- **Orbital period**
- **Orbital eccentricity**
- ***Planet mass***
- ***Planet radius***
- ***Stellar obliquity***
- **Star spots**
- **Stellar limb darkening**
- **Planetary emission spectrum**
- **Planetary absorption spectrum**
- **Planetary phase function**
- **Radiative time constant**
- Stellar gravity brightening
- Planetary reflectance spectrum
- Mutual orbital inclinations
- Planet-planet interactions

- Exomoons
- Trojan companions
- Moons and rings
- ***Planetary apsidal motion constant***
- ***Planetary oblateness***
- Relativistic precession
- Orbital decay
- Yarkovksy effect
- Planetary magnetic field
- Variations in stellar radius
- Parallax effects
- Stellar differential rotation
- Planetary rotation rate
- Planetary wind speed
- Planetary aurorae
- Artificial planet-sized objects


Flux
Time


Flux
Time


Flux
T
δ
τ
t_c
Time



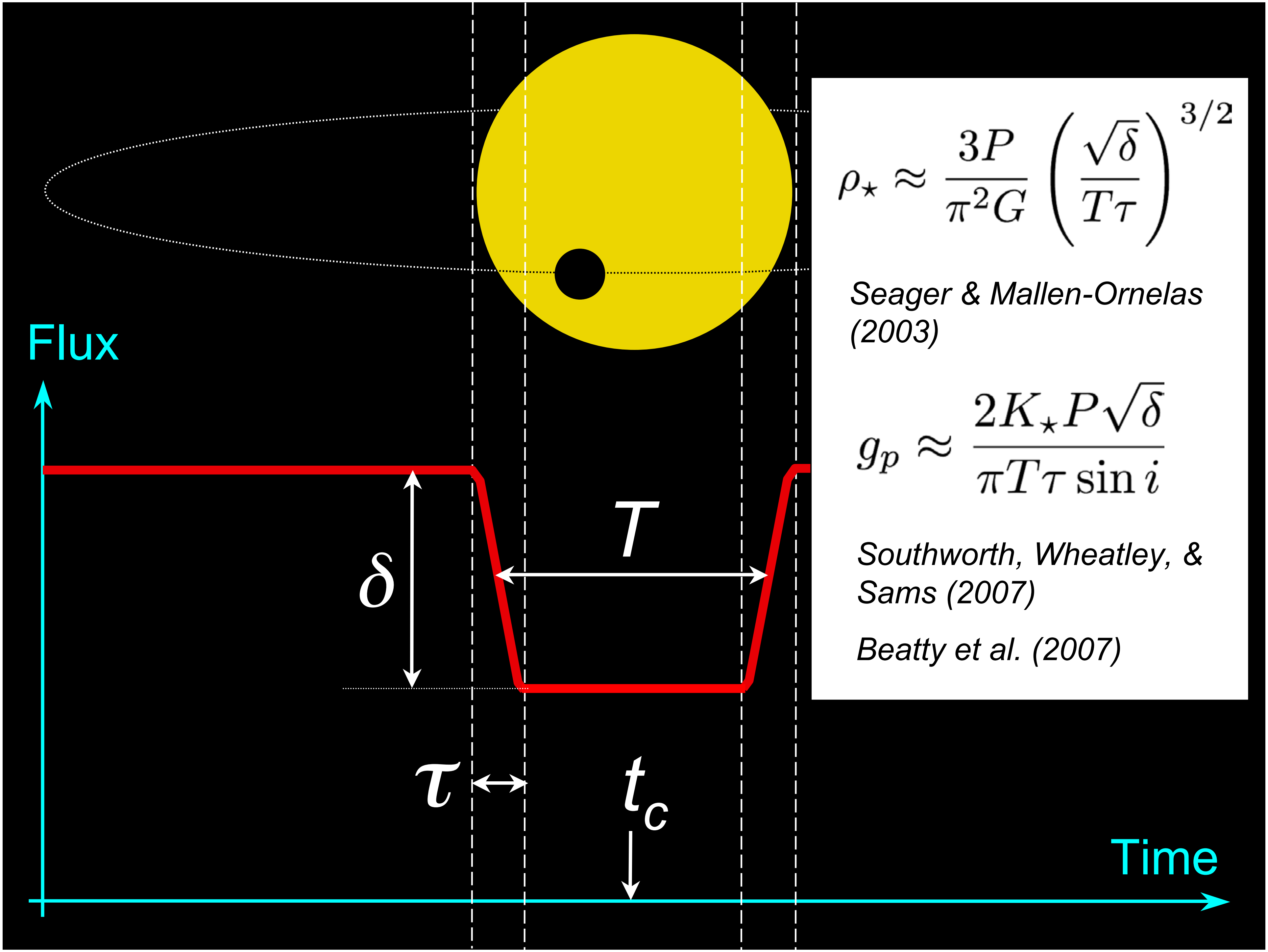
$$\left(\frac{R_p}{R_\star}\right)^2 \approx \delta$$

$$b^2 \approx 1 - \sqrt{\delta}\,\frac{T}{\tau}$$

$$\left(\frac{R_\star}{a}\right)^2 \approx \frac{\pi^2}{\sqrt{\delta}}\,\frac{T\tau}{P^2}$$

Seager & Mallen-Ornelas (2003)

Carter, Yee, Eastman, et al. (2008)



$$\rho_\star \approx \frac{3P}{\pi^2 G}\left(\frac{\sqrt{\delta}}{T\tau}\right)^{3/2}$$

Seager & Mallen-Ornelas (2003)

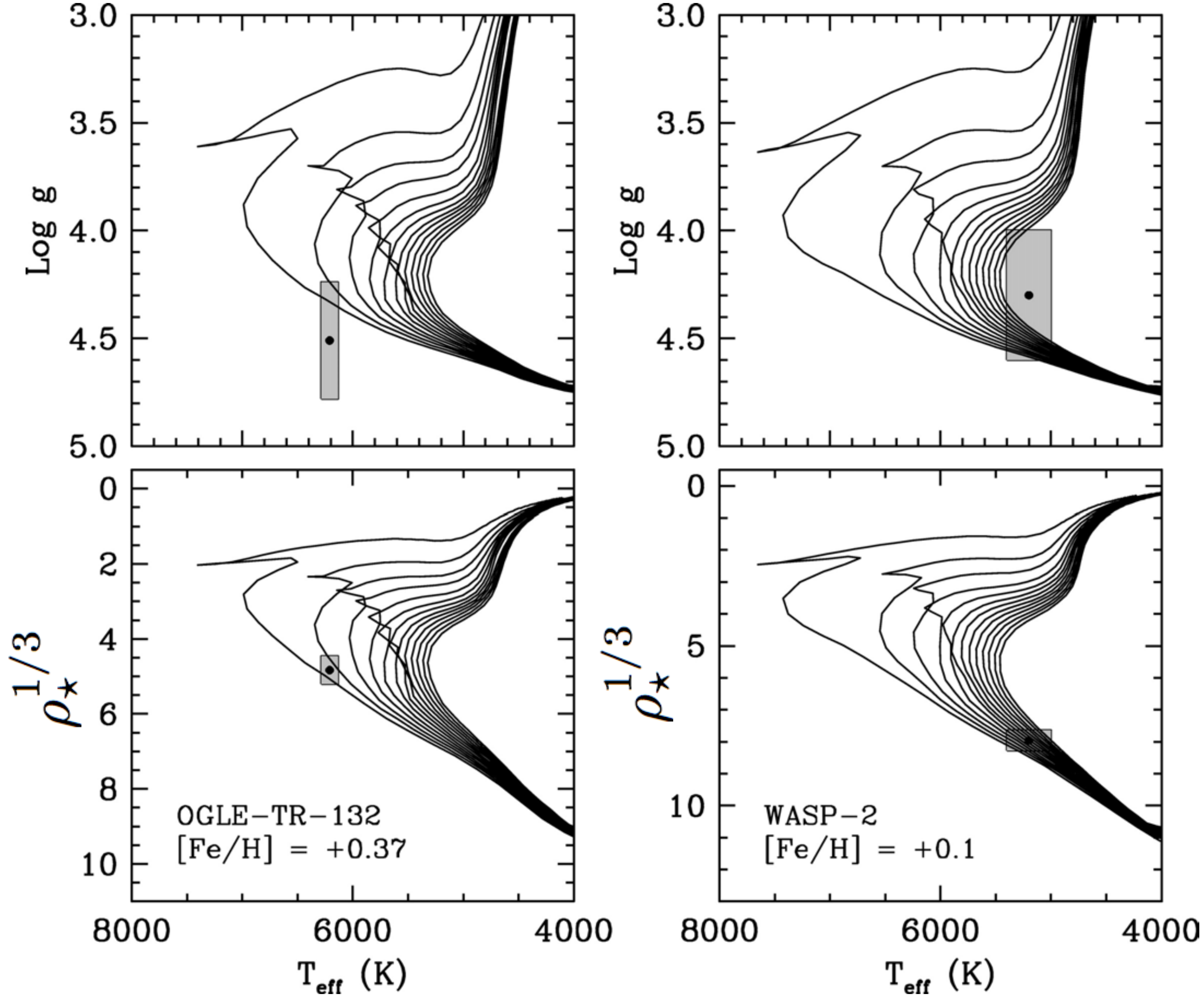
$$g_p \approx \frac{2K_\star P\sqrt{\delta}}{\pi T\tau \sin i}$$

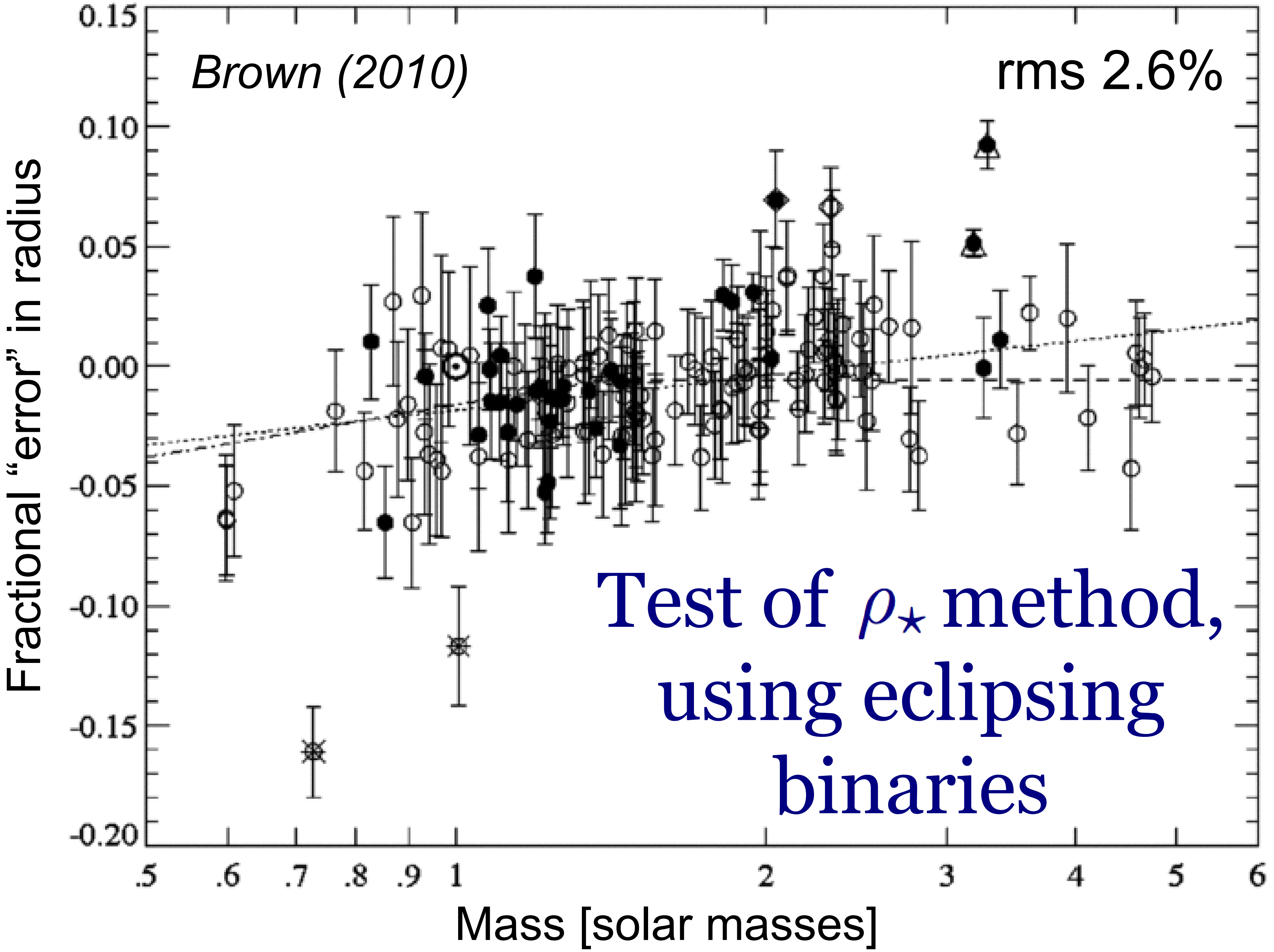
Southworth, Wheatley, & Sams (2007)

Beatty et al. (2007)

Torres et al. (2008)

See also: Pont et al. (2007), Sozzetti et al. (2007)





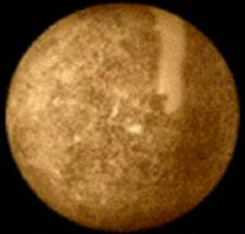
Test of $\rho_\star$ method, using eclipsing binaries

YOUR WEIGHT ON OTHER WORLDS

Ever wonder what you might weigh on Mars or The Moon? Here's your chance to find out.

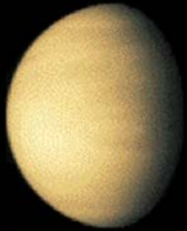
The Planets

MERCURY



Your weight is ______

VENUS

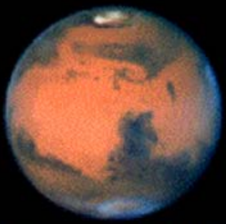


Your weight is ______

THE MOON

Your weight is ______

MARS



Your weight is ______

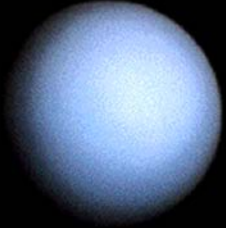
JUPITER

Your weight is ______

SATURN

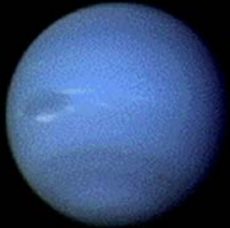
Your weight is ______

URANUS



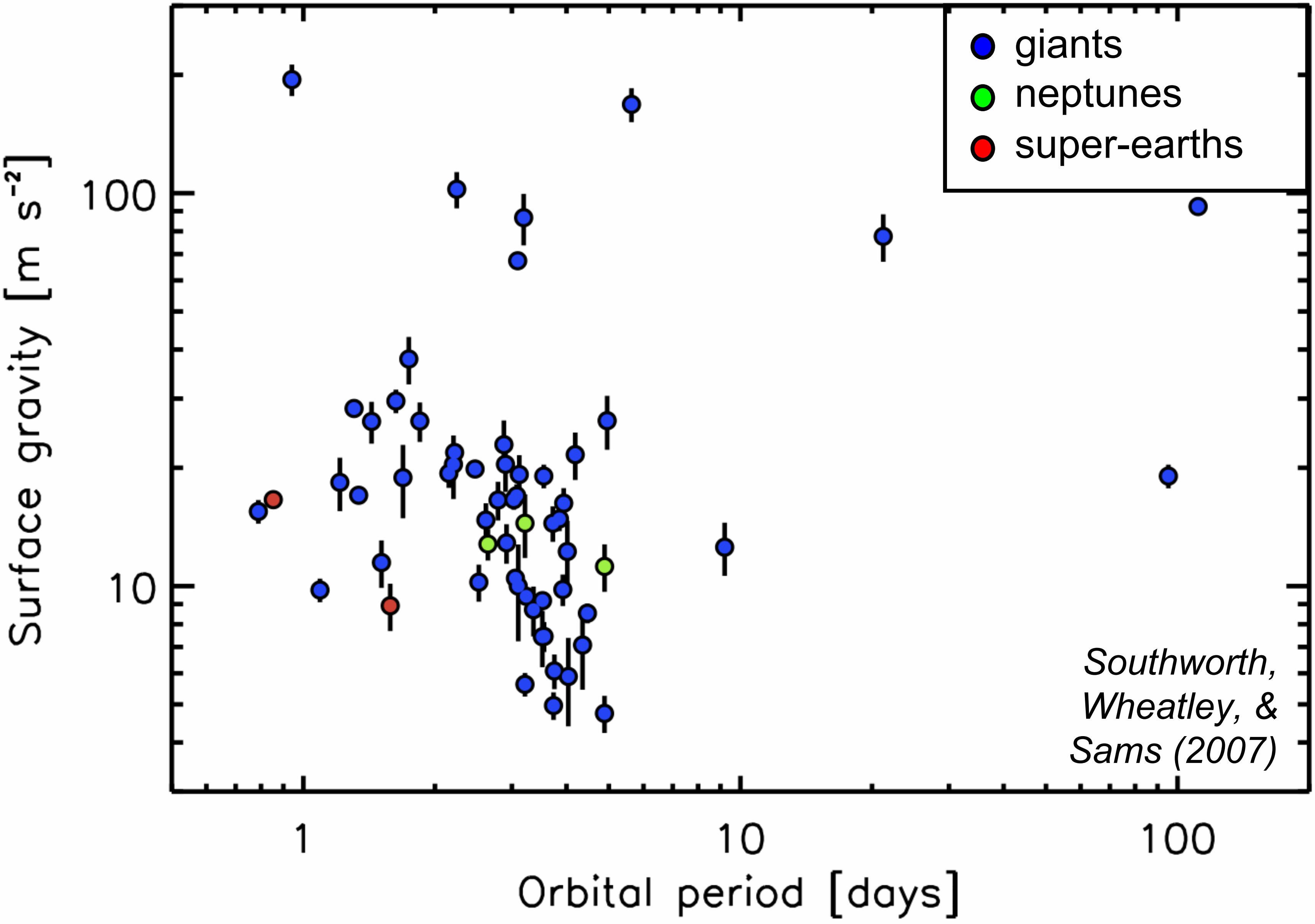
Your weight is ______

NEPTUNE

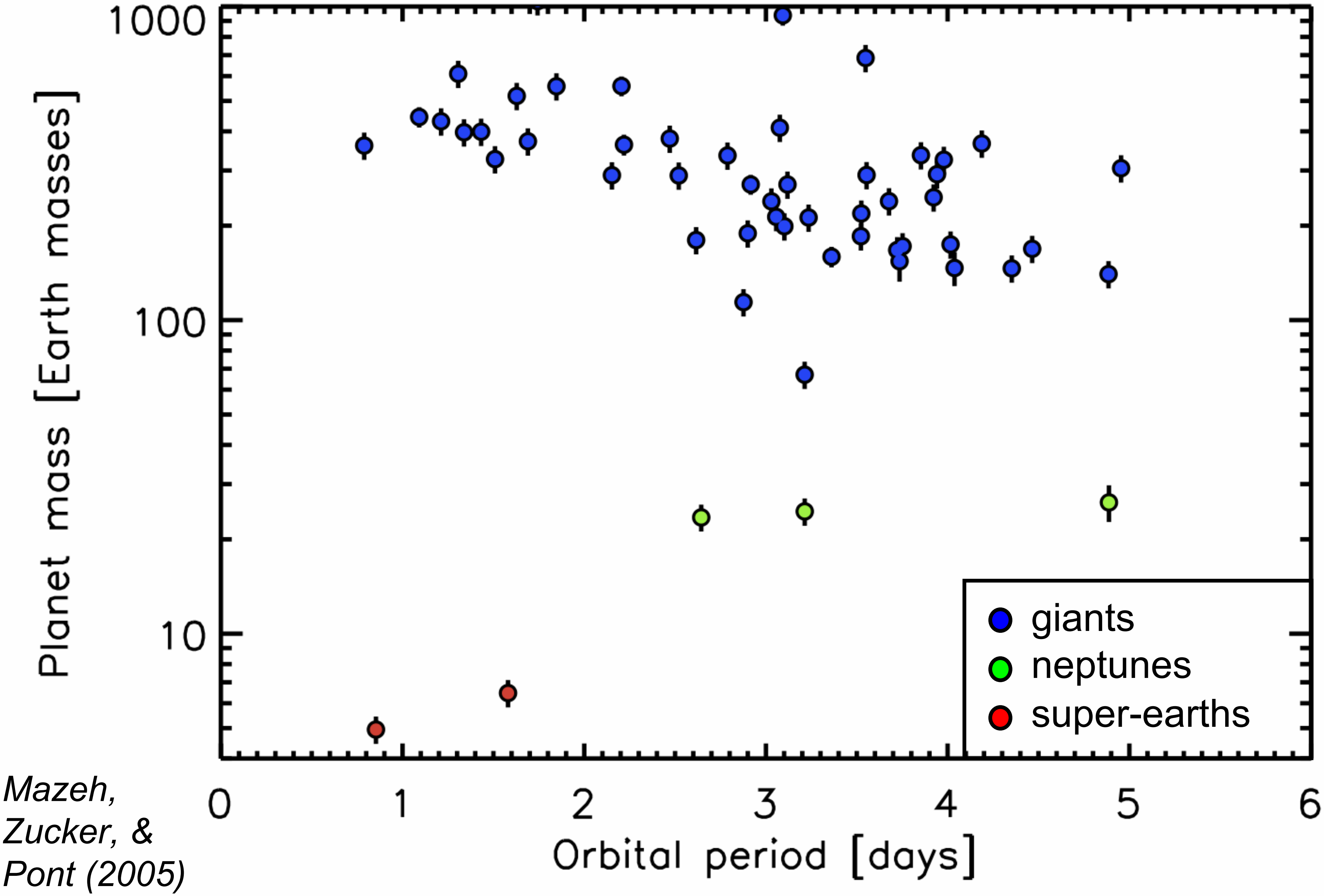


Your weight is ______

The gravity–period correlation

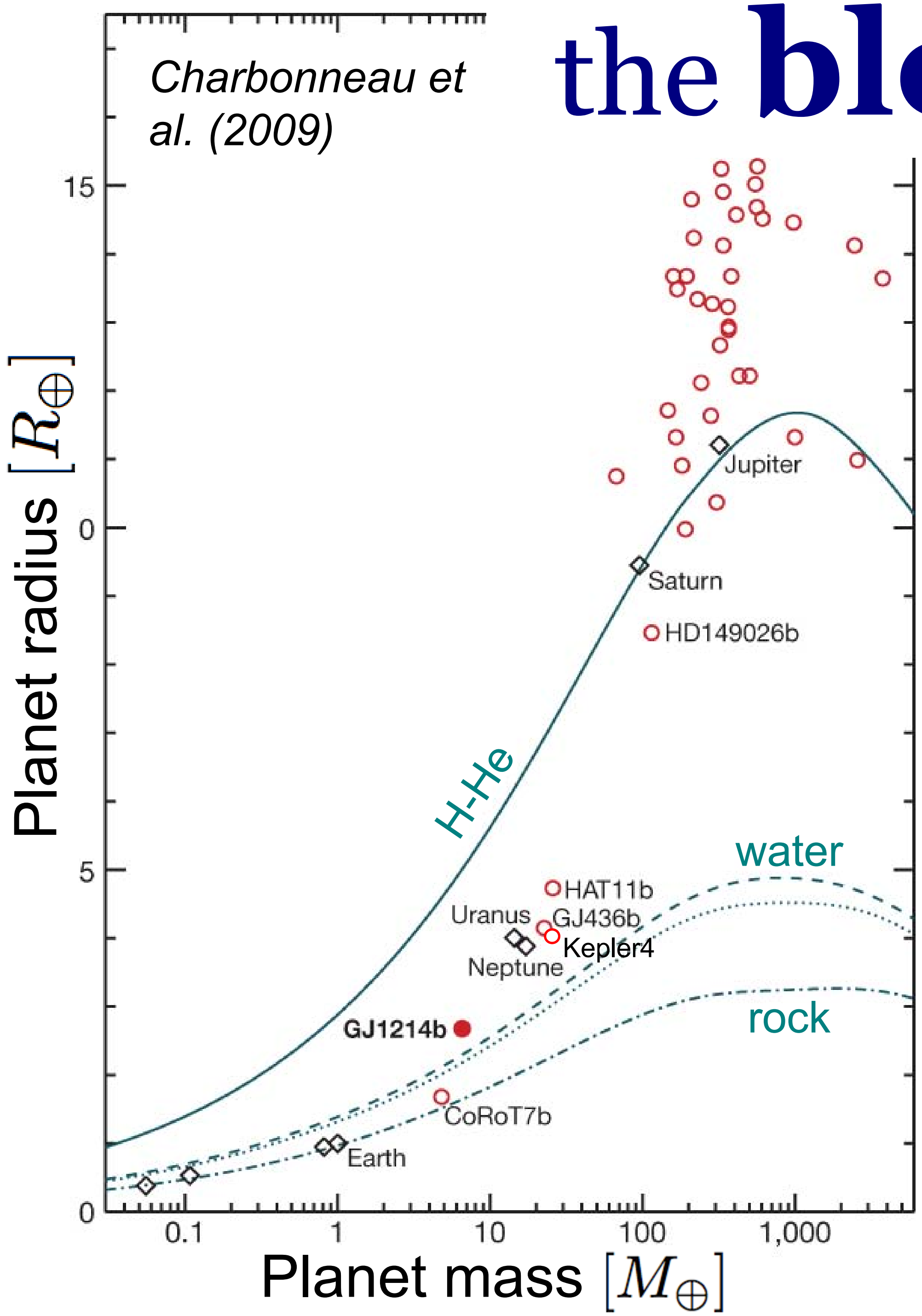


The mass–period correlation



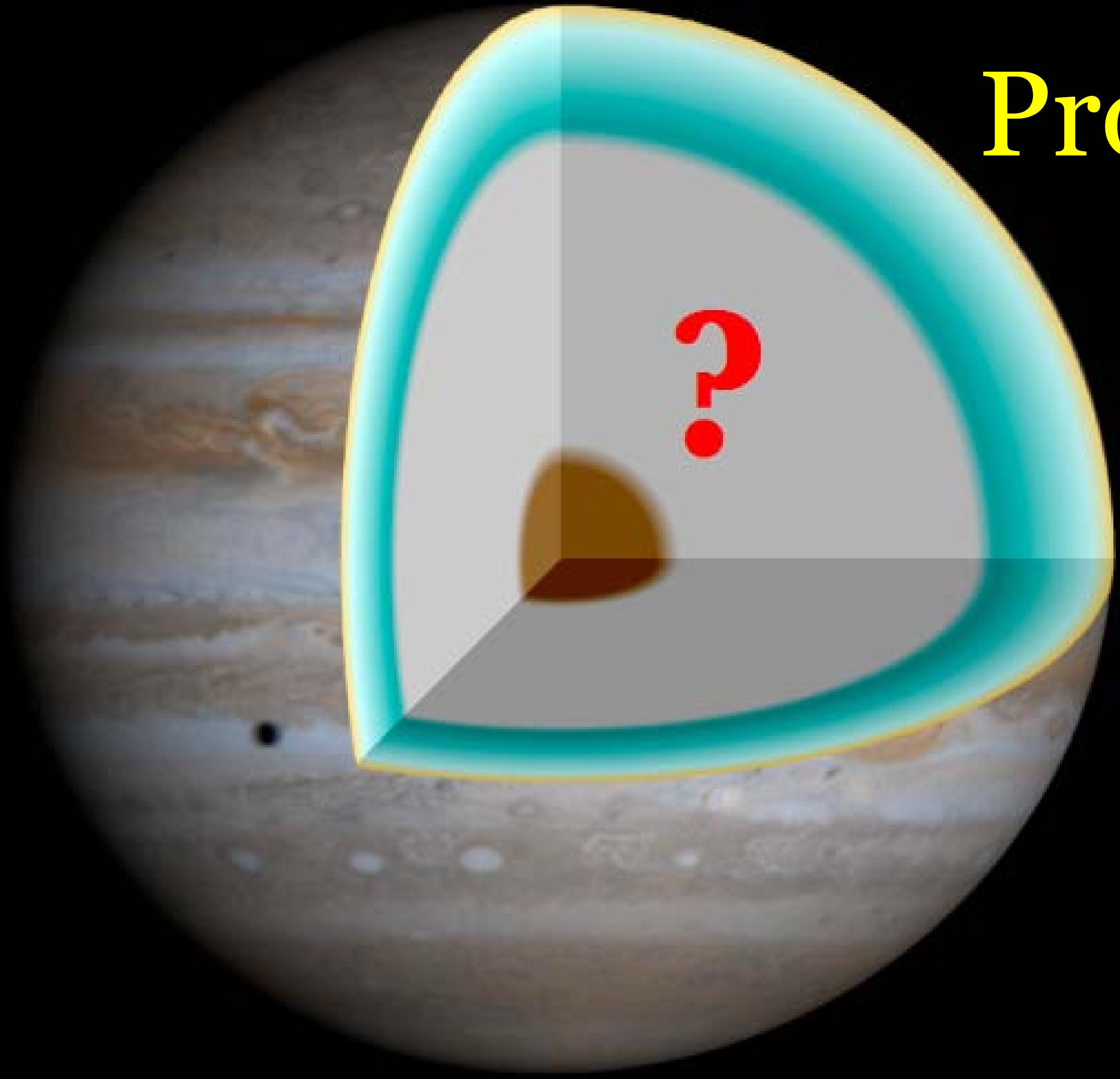
Mazeh, Zucker, & Pont (2005)

the **bloated** planets

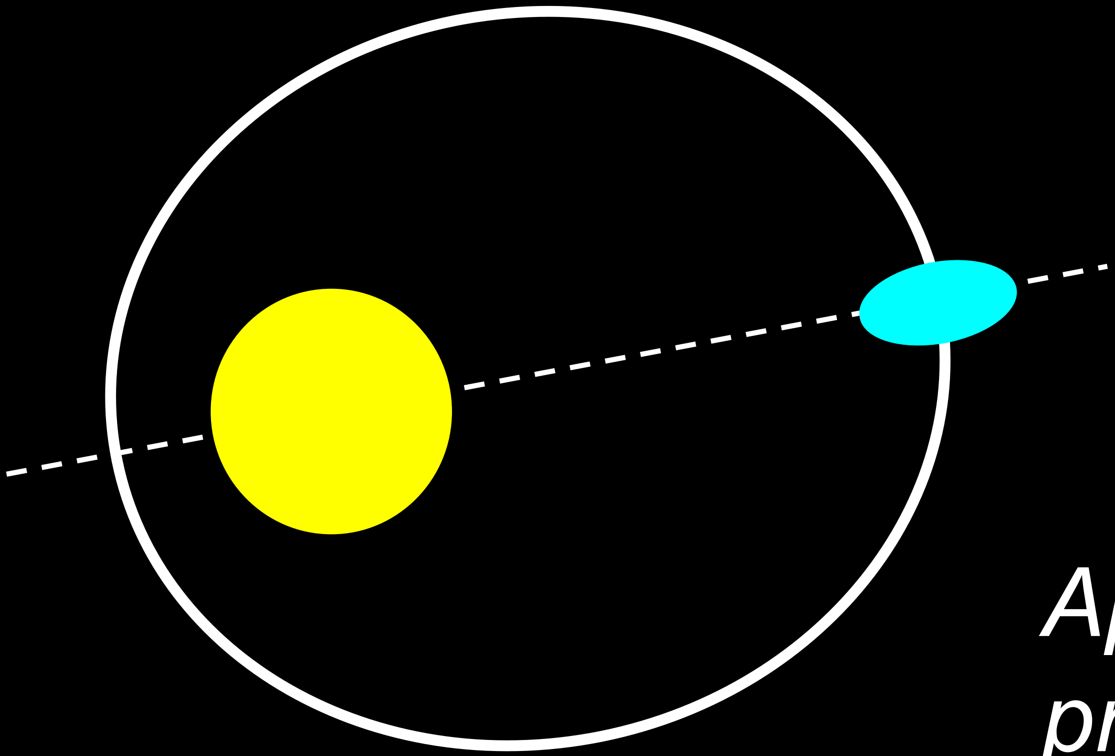

Charbonneau et al. (2009)

- **Early migration** (*Burrows et al. 2000*)
- **Insolation-driven, deeply penetrating gravity waves** (*Showman & Guillot 2002, Guillot & Showman 2002*)
- **Eccentricity tides** (*Bodenheimer et al. 2001, 2003; Liu et al. 2008, Miller et al. 2009, Ibgui & Burrows 2009*)
- **Obliquity tides** (*Winn & Holman 2005, ruled out by Fabrycky et al. 2007, Levrard et al. 2007, Peale 2007)*
- **High atmospheric opacity** (*Burrows et al. 2007*)
- **Inhibited convection of planetary interior** (*Chabrier & Baraffe 2007*)
- **Thermal tides** (*Arras & Socrates 2009, disputed by Goodman 2009*)
- **Dissipation of induced electrical currents** (*Batygin & Stevenson 2010; Perna, Menou, & Rauscher 2010*)

Prospects for probing planetary interiors



Prospects for probing planetary interiors



Ragozzine & Wolf (2009)

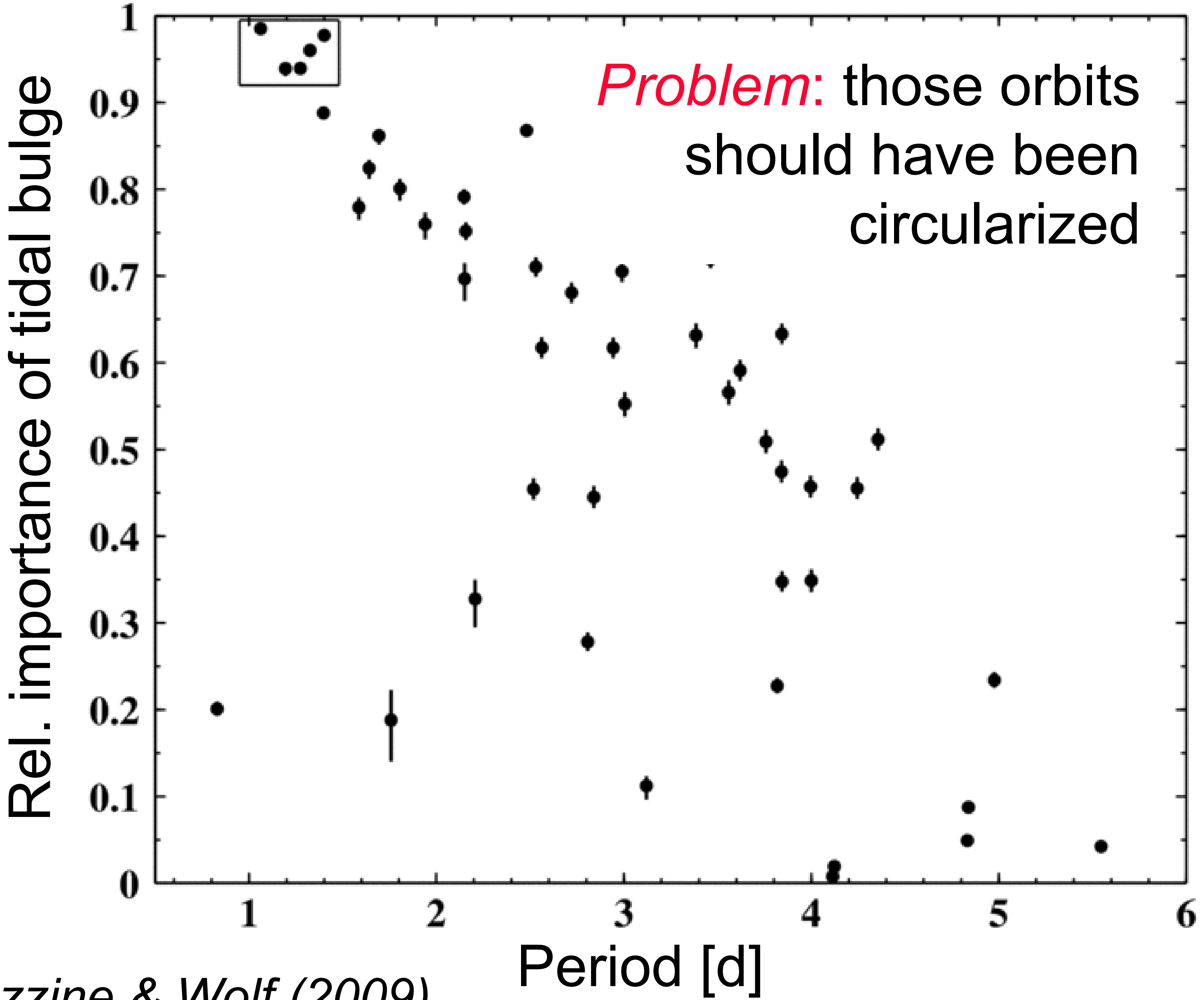
k_2 measurable, through transit / occultation times and durations

Apsidal precession:

General relativity

Tidal bulge

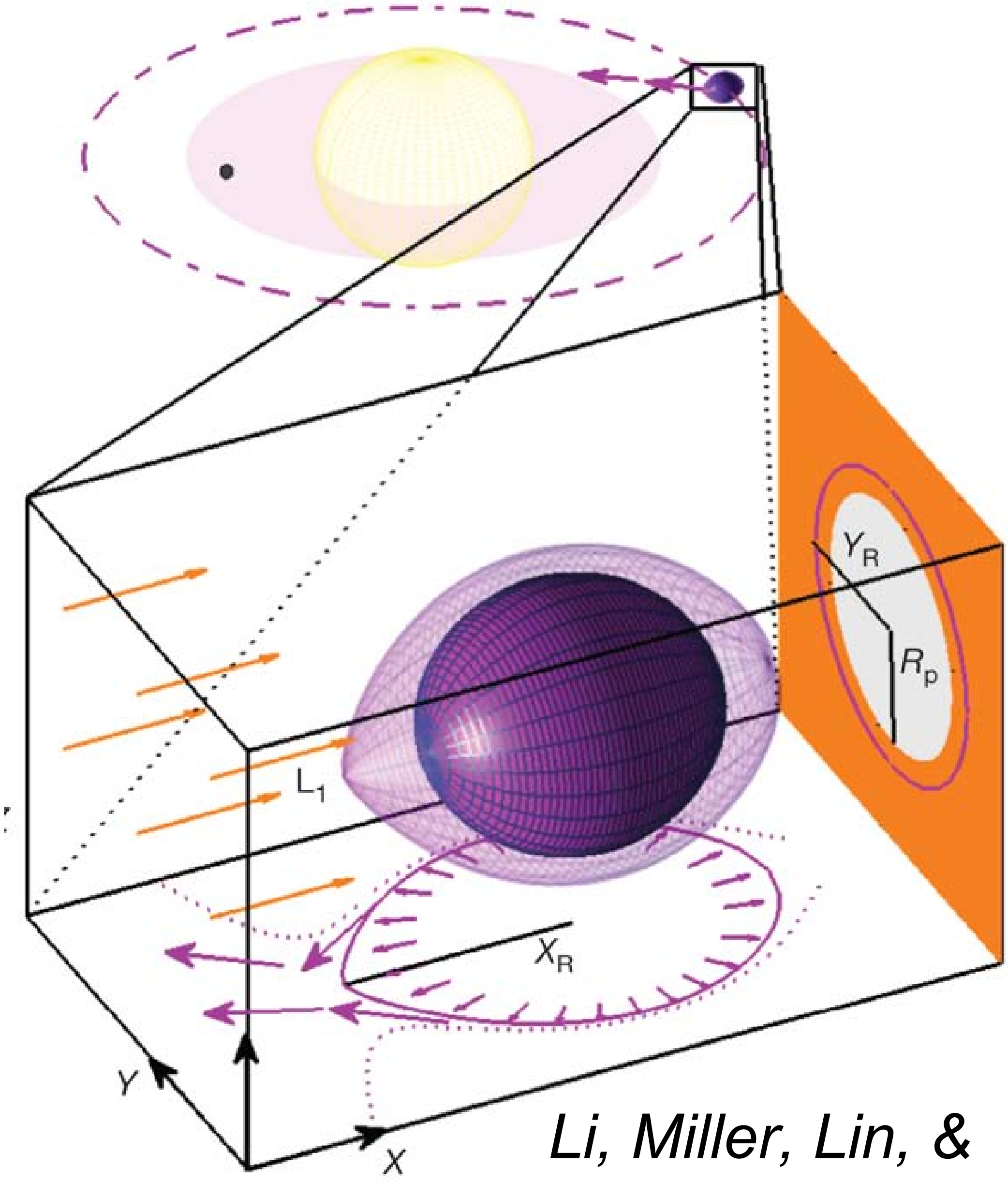
Rotational oblateness



Problem: those orbits should have been circularized

Ragozzine & Wolf (2009)

WASP-12



Li, Miller, Lin, & Fortney (2010)

Found to be eccentric
(e = 0.049 ± 0.015)

Hebb et al. (2009)

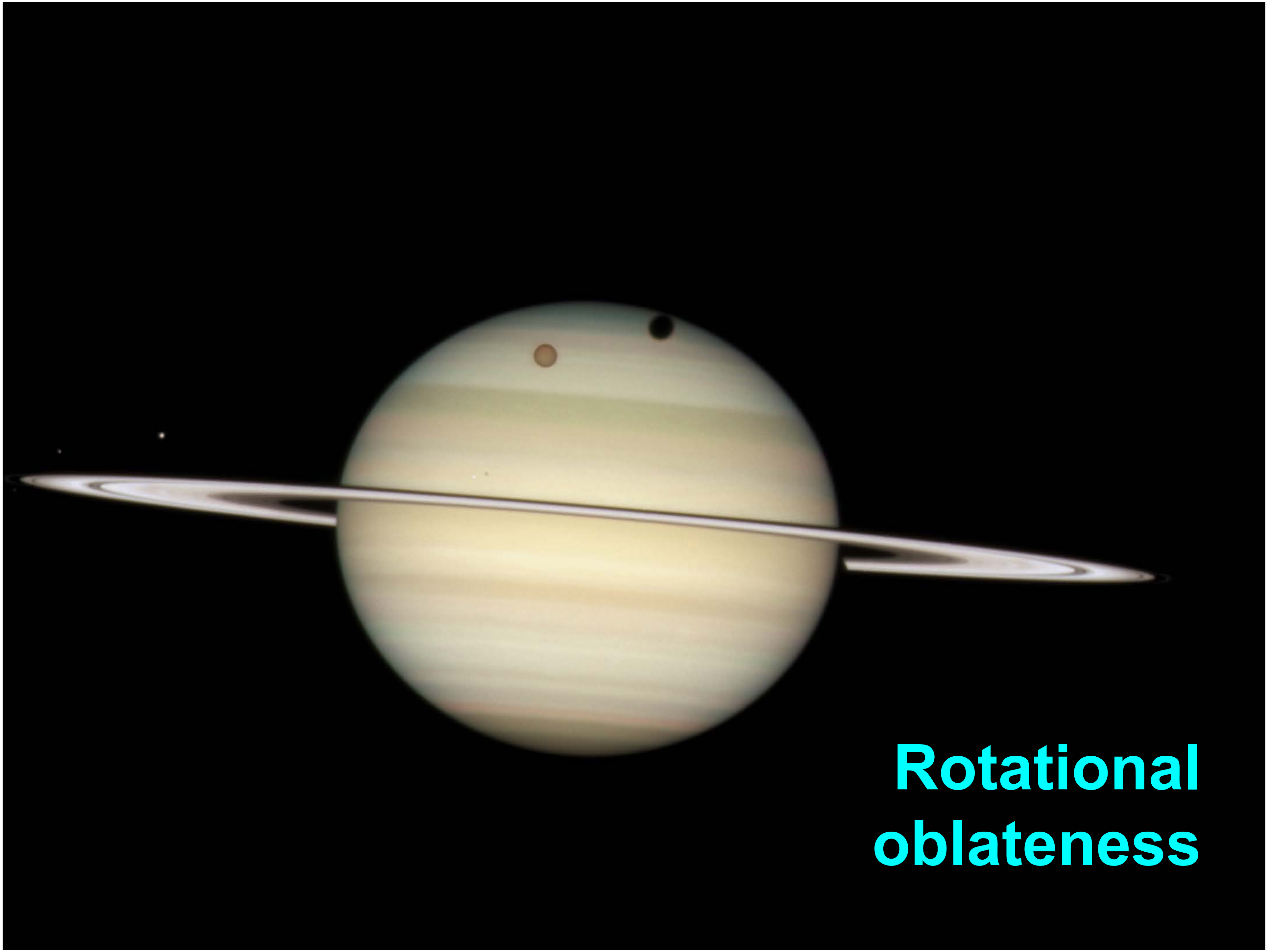
Confirmed eccentricity?
($e\cos\omega$ = 0.0156 ± 0.0035)

Lopez-Morales et al. (2009)

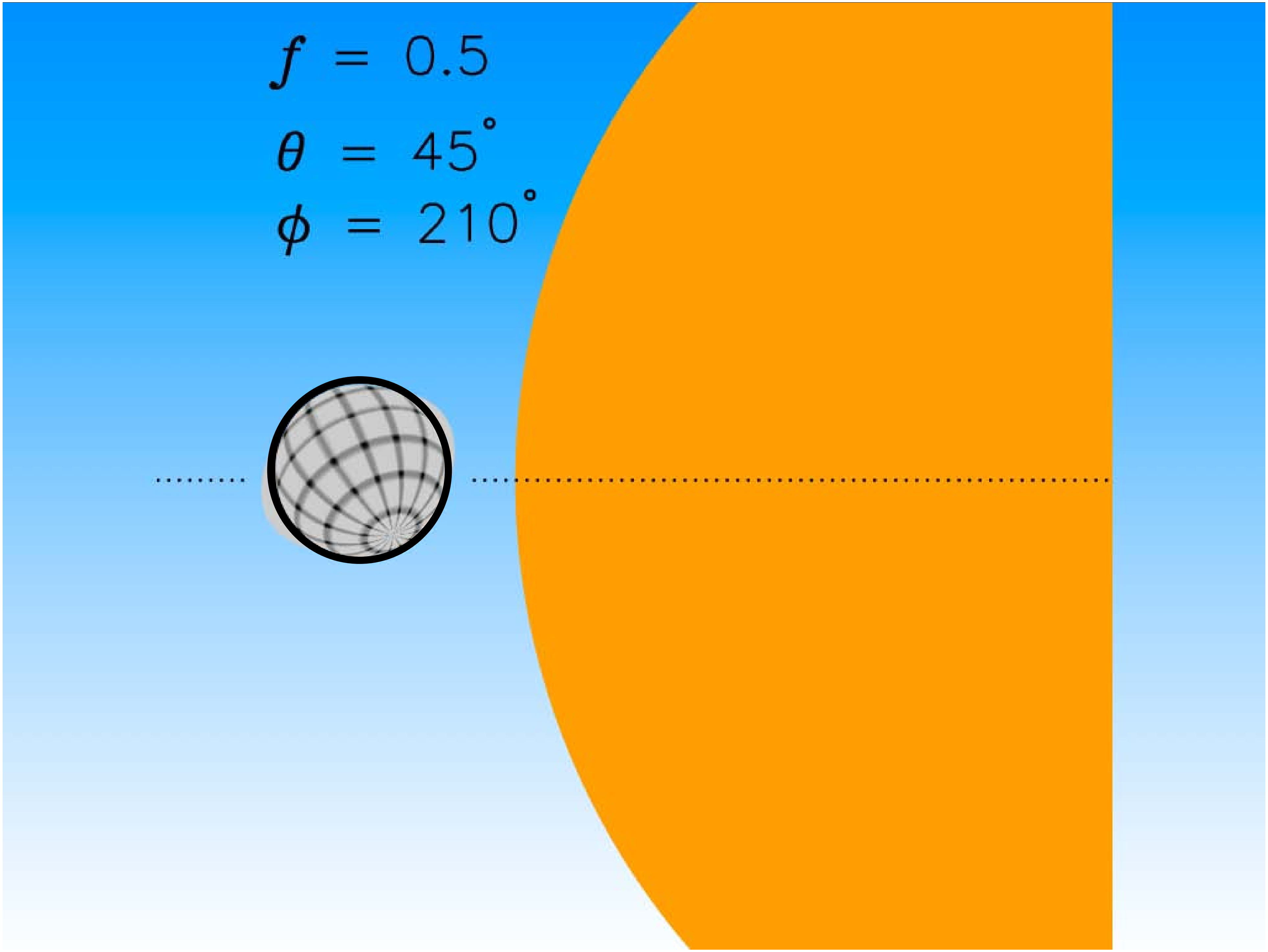
More circular?
($e\cos\omega$ = 0.0019 ± 0.0007)

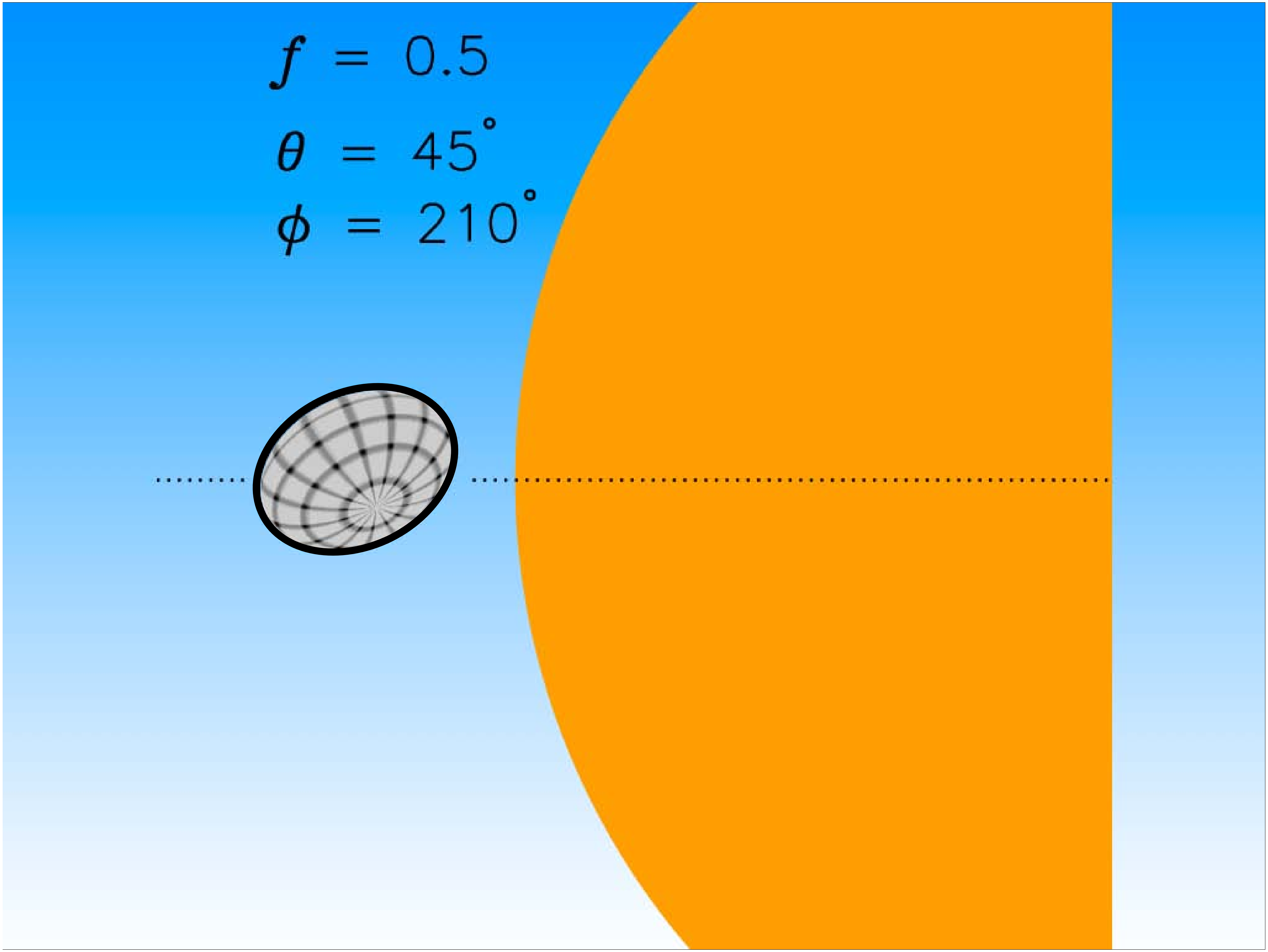
Campo et al. (2010)

$k_2 = 0.15 \pm 0.08$
(very centrally condensed)



Rotational oblateness


$f = 0.5$
$\theta = 45^\circ$
$\phi = 210^\circ$



$f = 0.5$

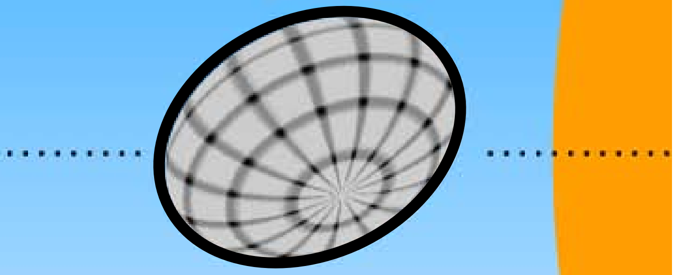
$\theta = 45^\circ$

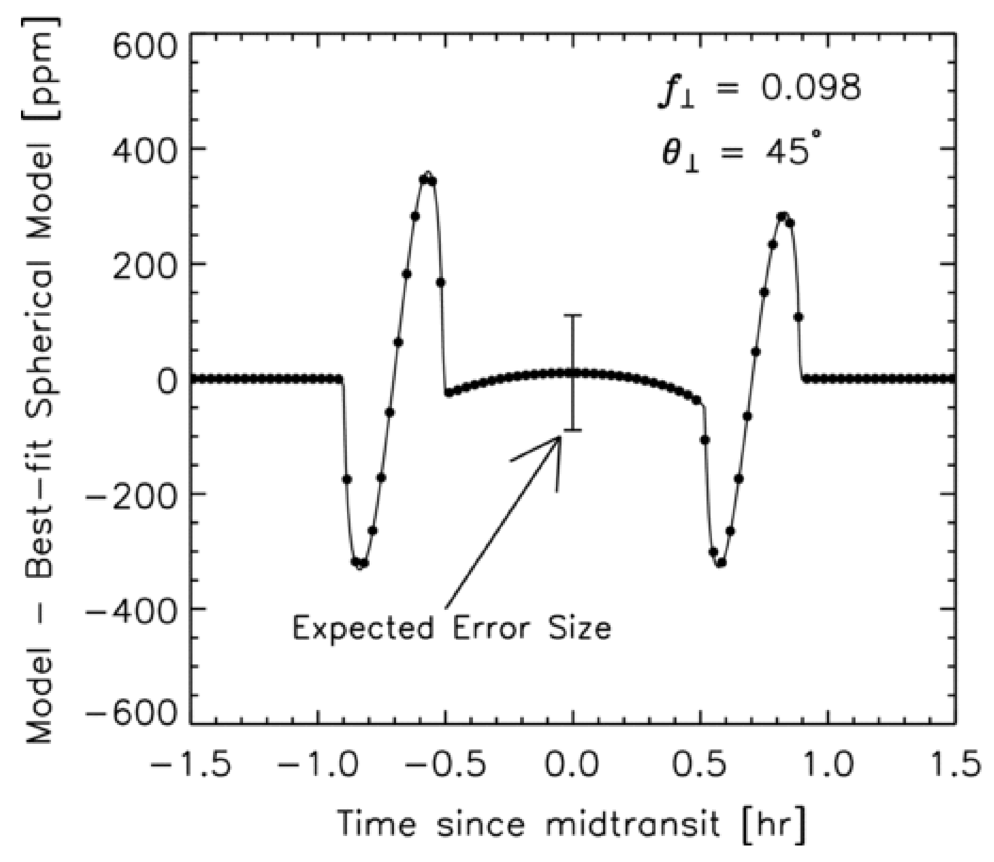
$\phi = 210^\circ$

$f = 0.5$

$\theta = 45^\circ$

$\phi = 210^\circ$



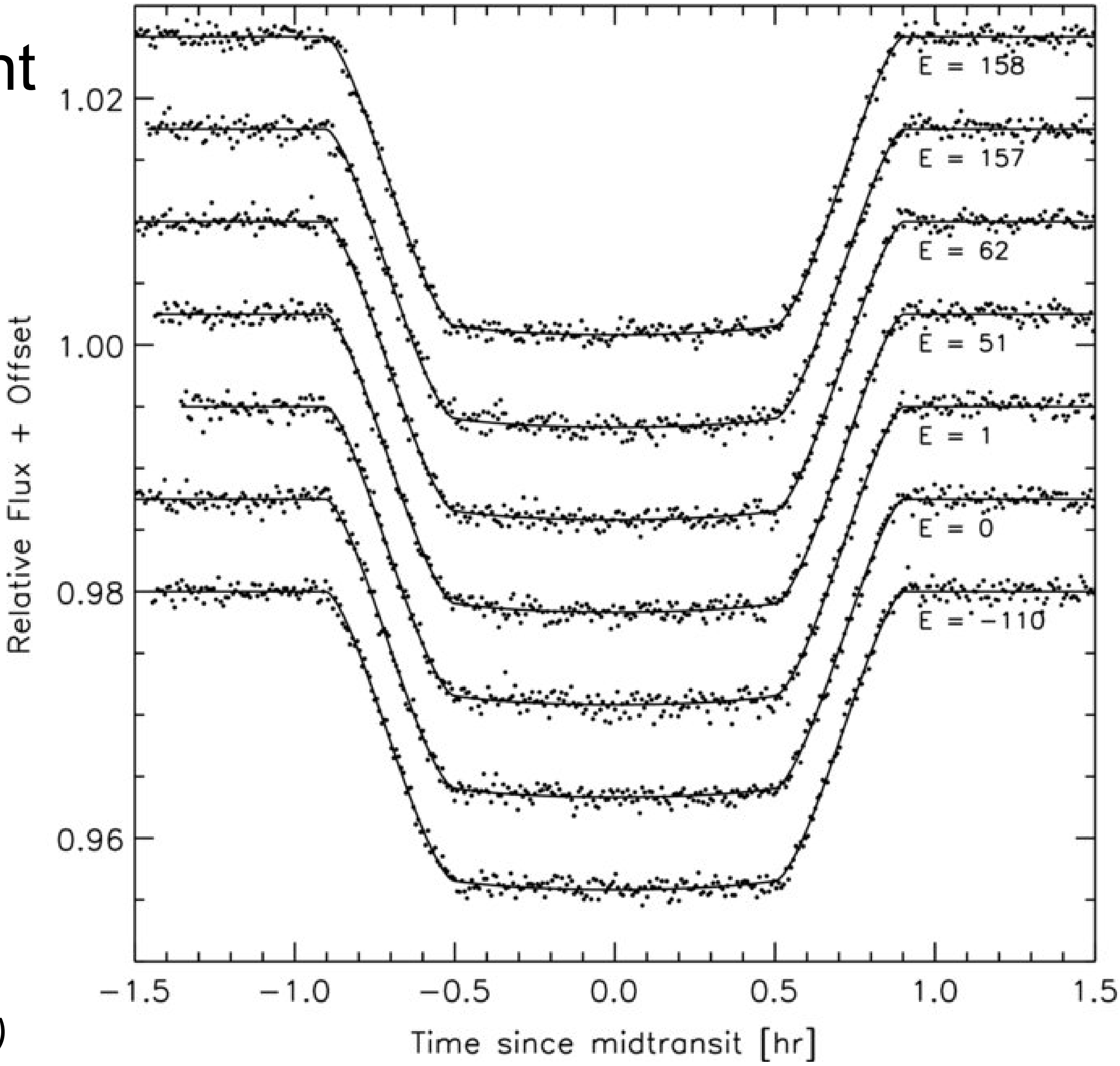


Seager & Hui (2002)

Barnes & Fortney (2003)

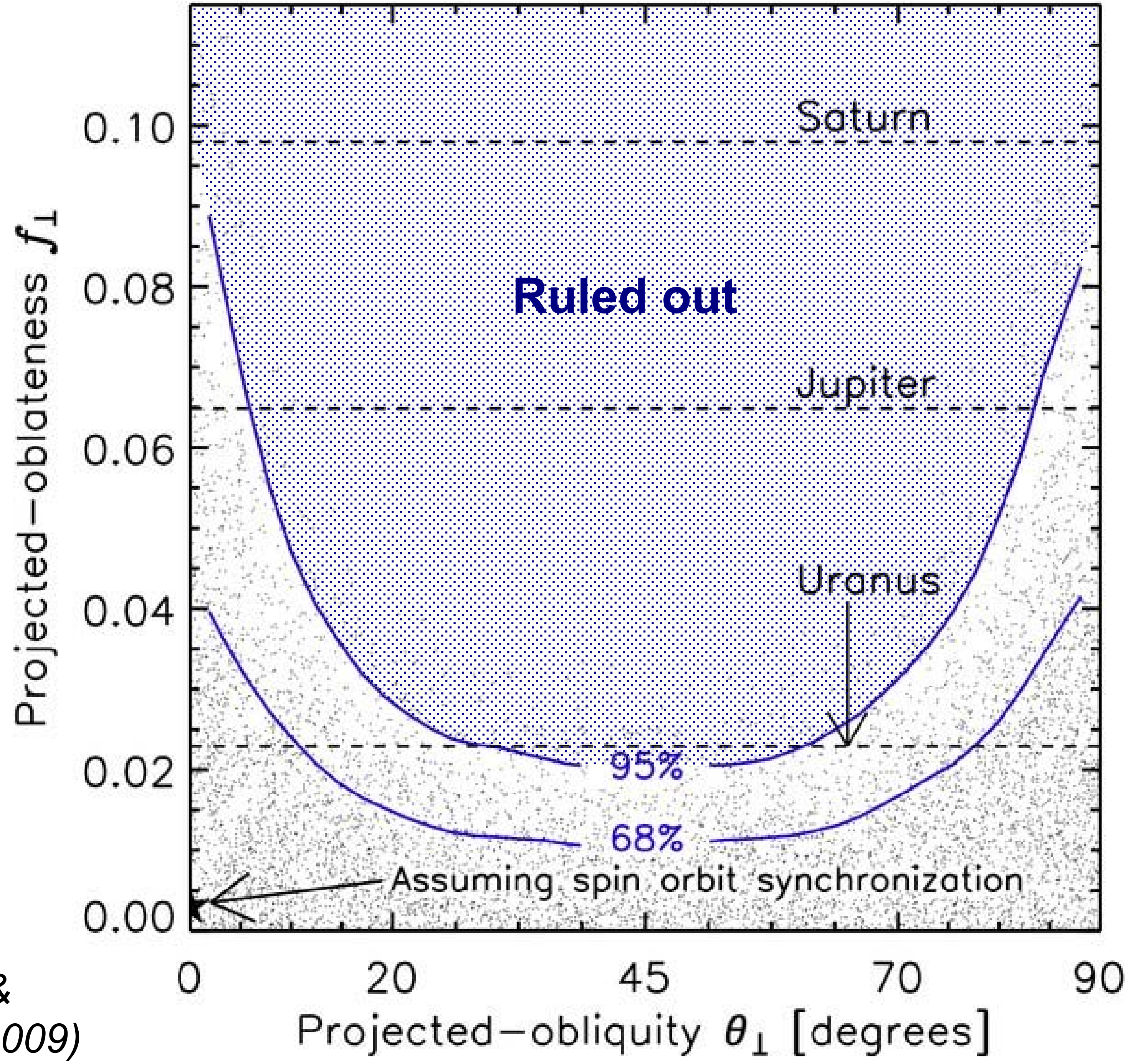
Carter & Winn (2009)

Spitzer light curves of HD 189733 (8 μm)



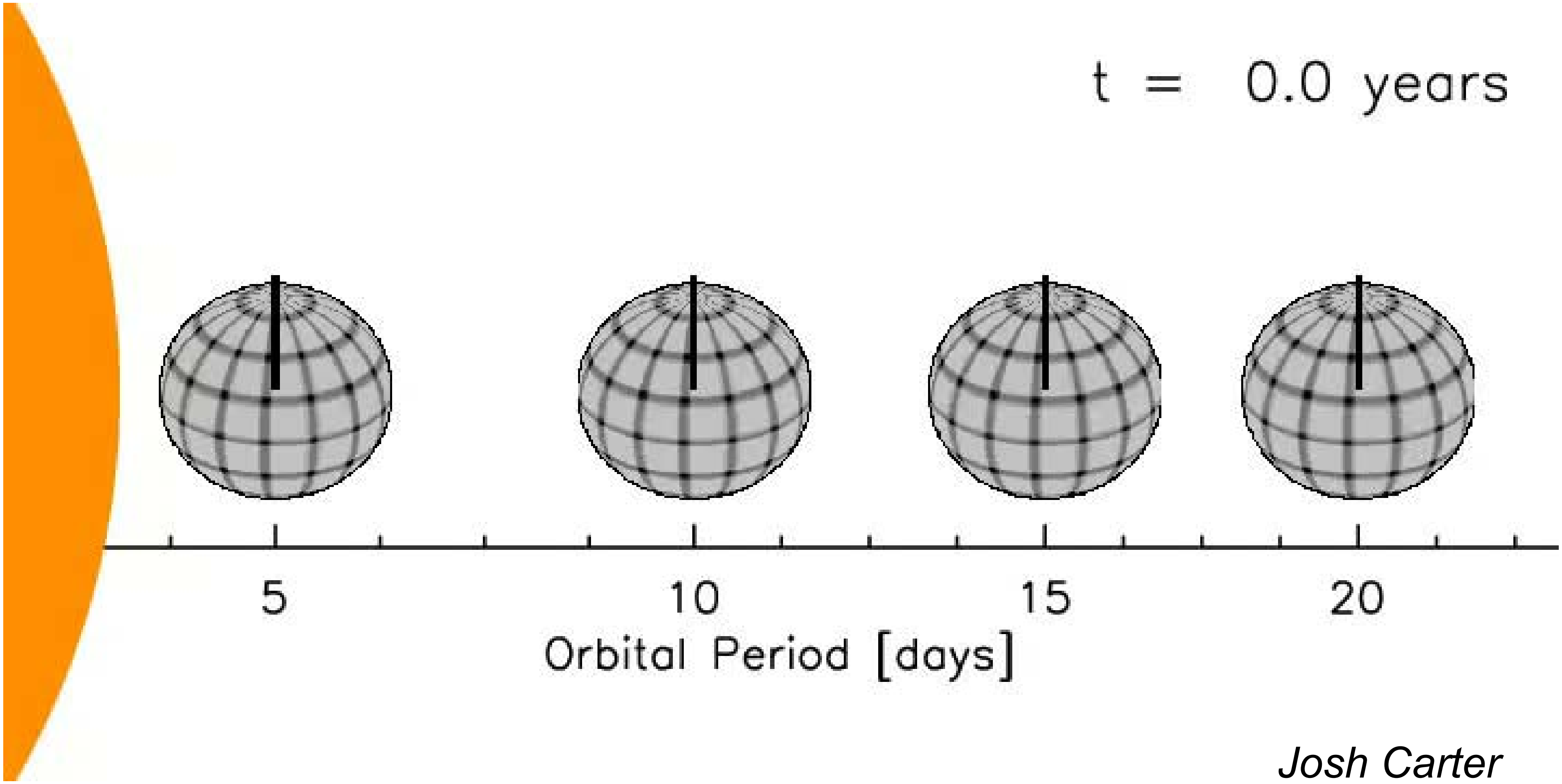
Carter & Winn (2009)

Agol et al. (2010)



Carter & Winn (2009)

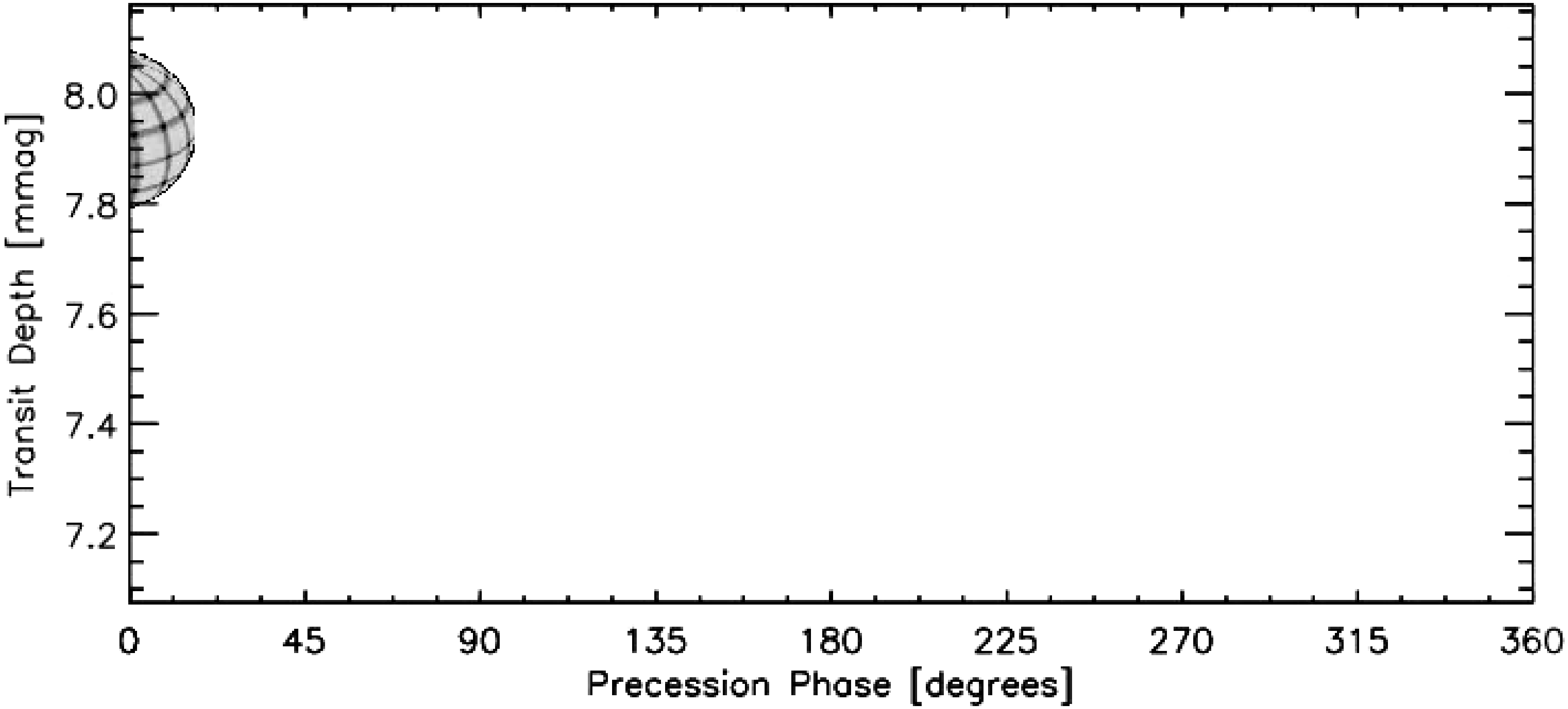
Spin precession



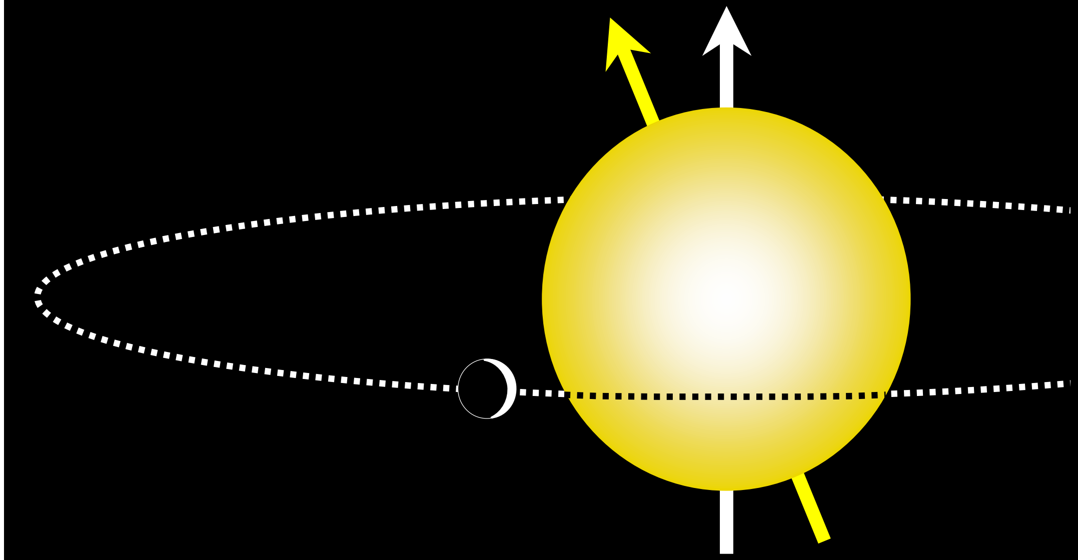
Josh Carter

Transit depth variations

Josh Carter

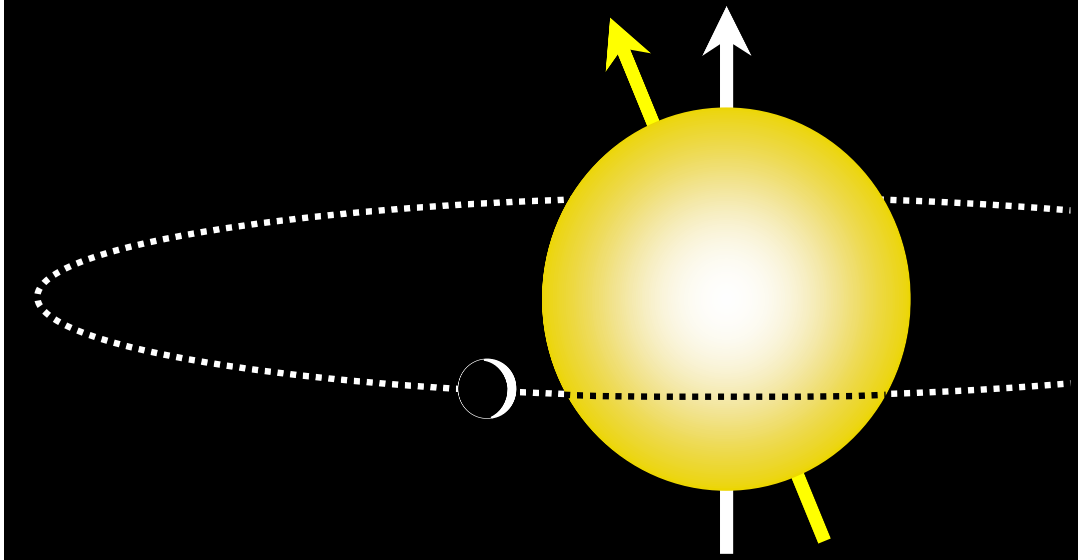


Kepler will measure this effect for giant planets with periods of 15–30 days



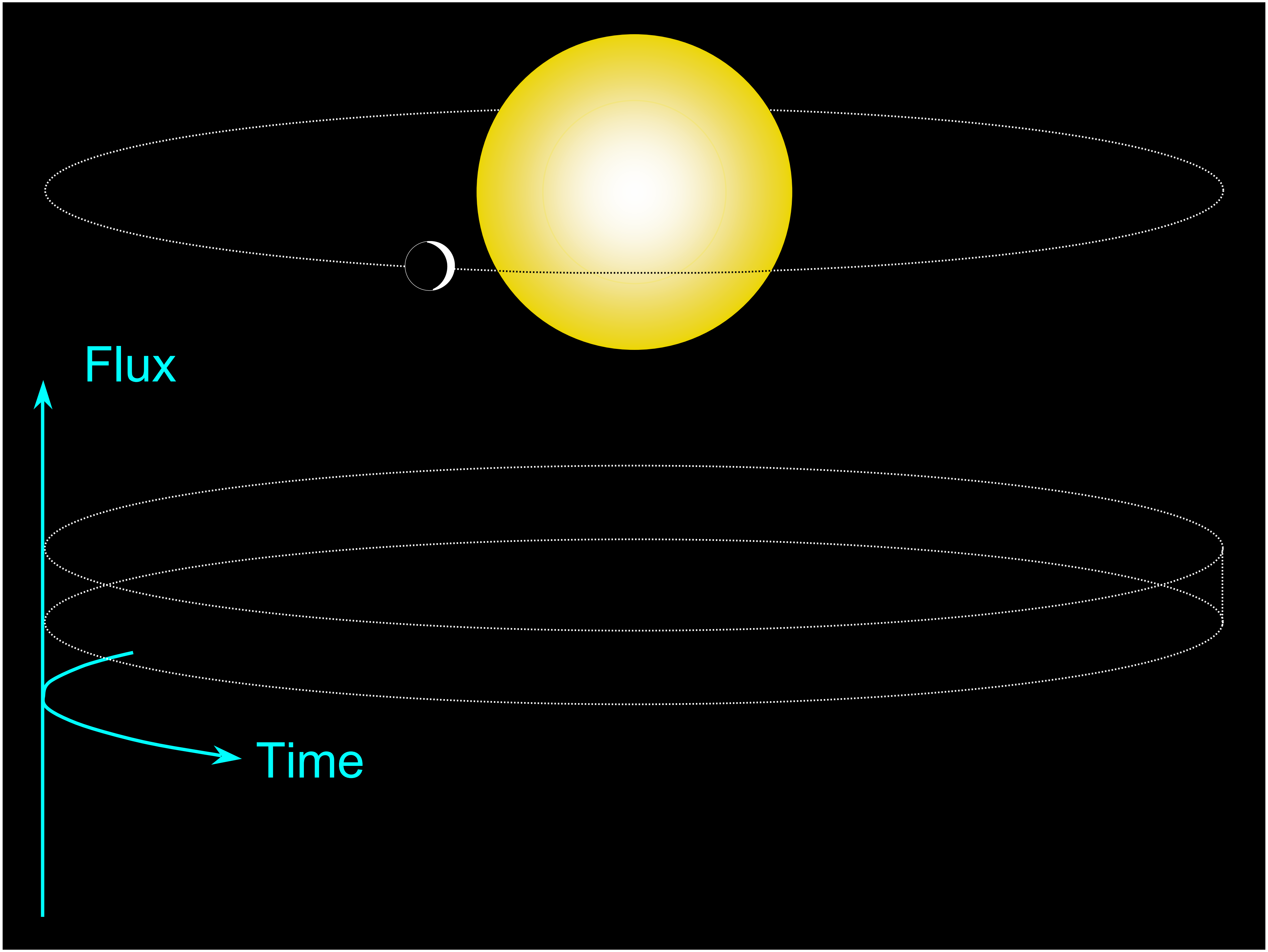
Stellar obliquity

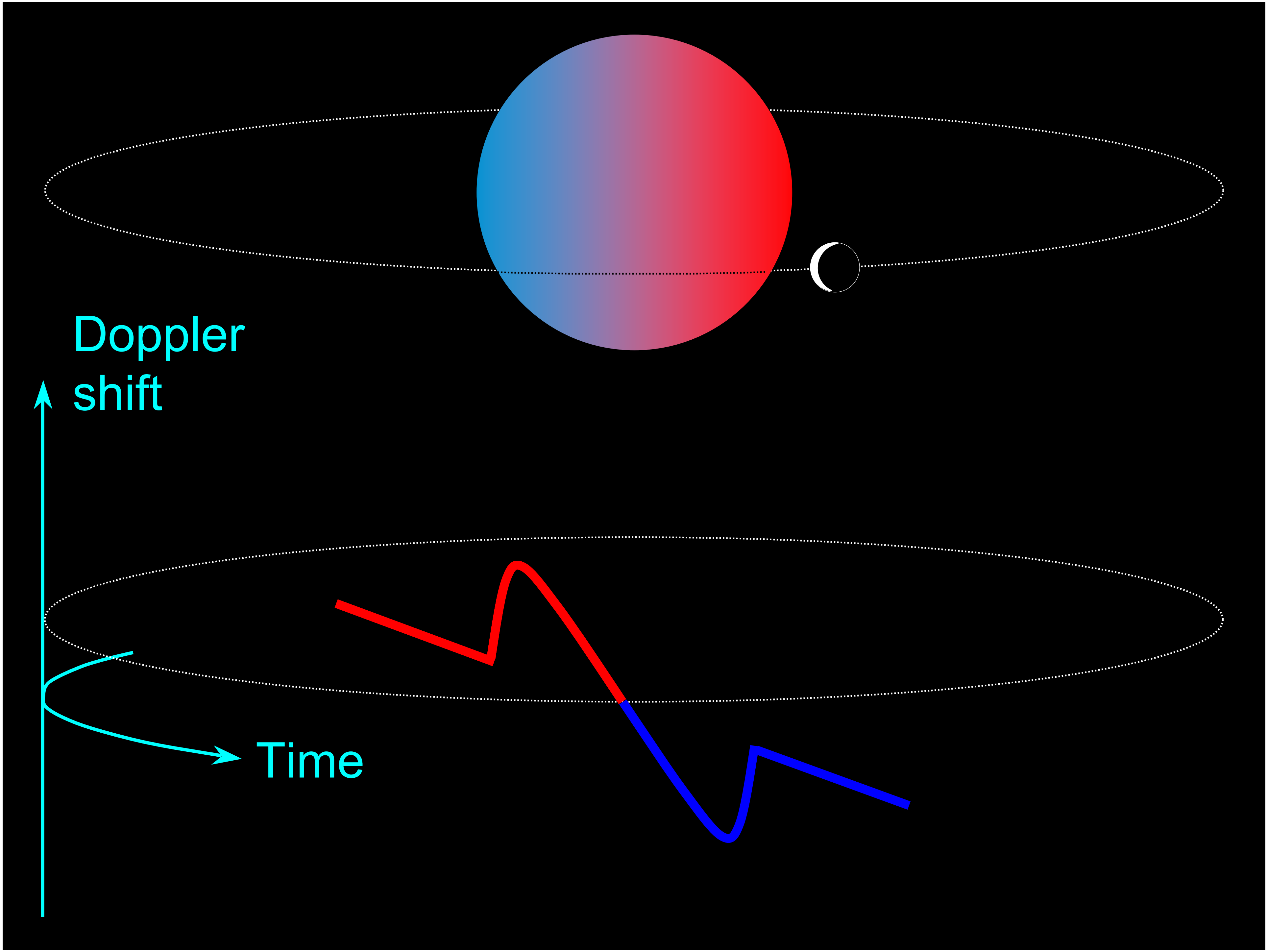
- Sun’s obliquity is 7° — how typical is this?
- Specific reasons to expect misalignment:
  - Whatever perturbs ***eccentricities*** may also perturb ***inclinations***
  - Does orbital ***migration*** perturb ***inclinations***?

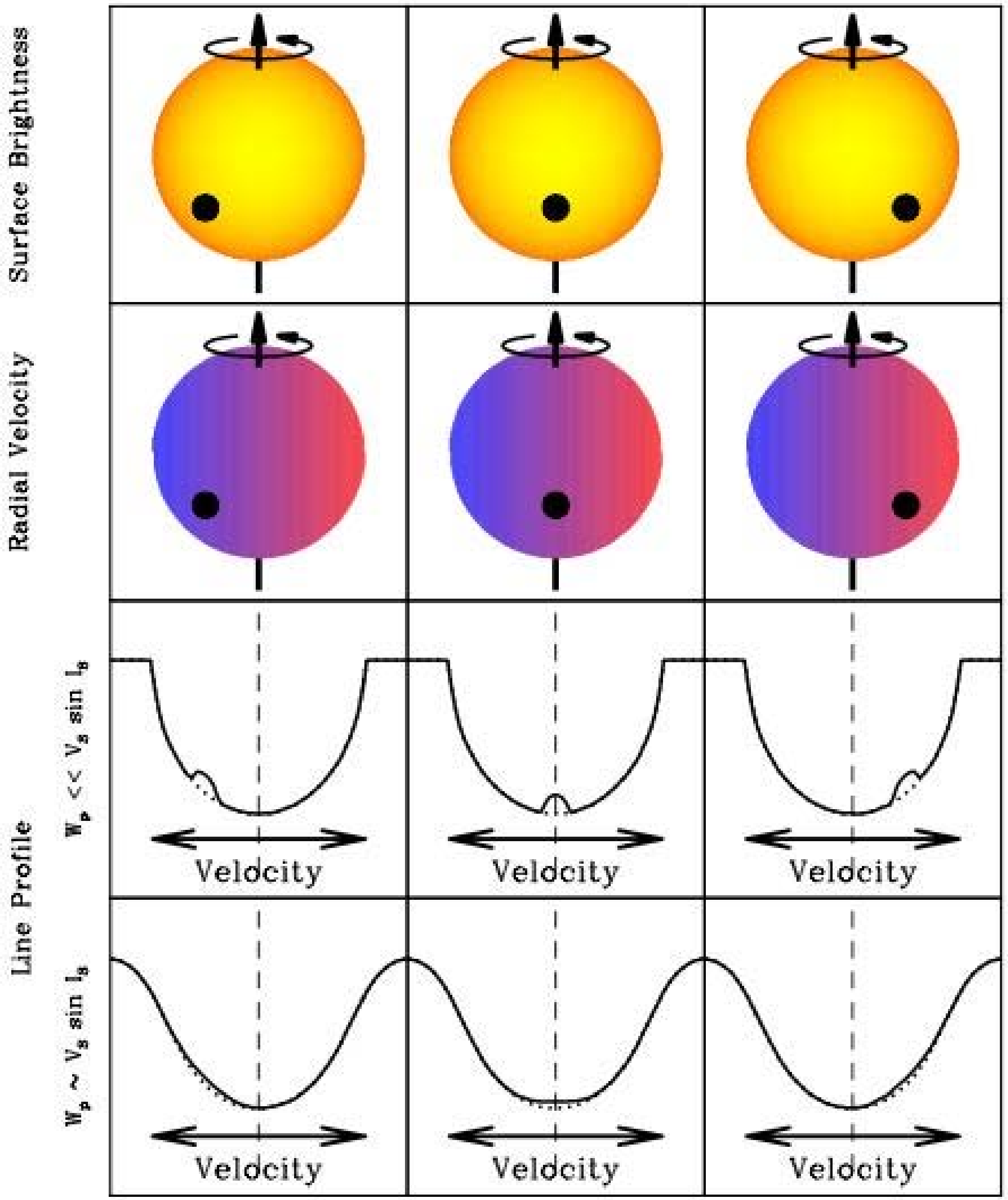


Stellar obliquity

- Disk migration would damp inclinations
  Marzari & Nelson (2009), Cresswell et al. (2007), Lubow & Ogilvie (2001)
- Planet-planet scattering would produce a broad range of final inclinations
  Chatterjee et al. (2008), Nagasawa et al. (2008), Juric & Tremaine (2008)
- Kozai cycles would produce a *very* broad range of final inclinations
  Fabrycky & Tremaine (2007), Nagasawa et al. (2008)

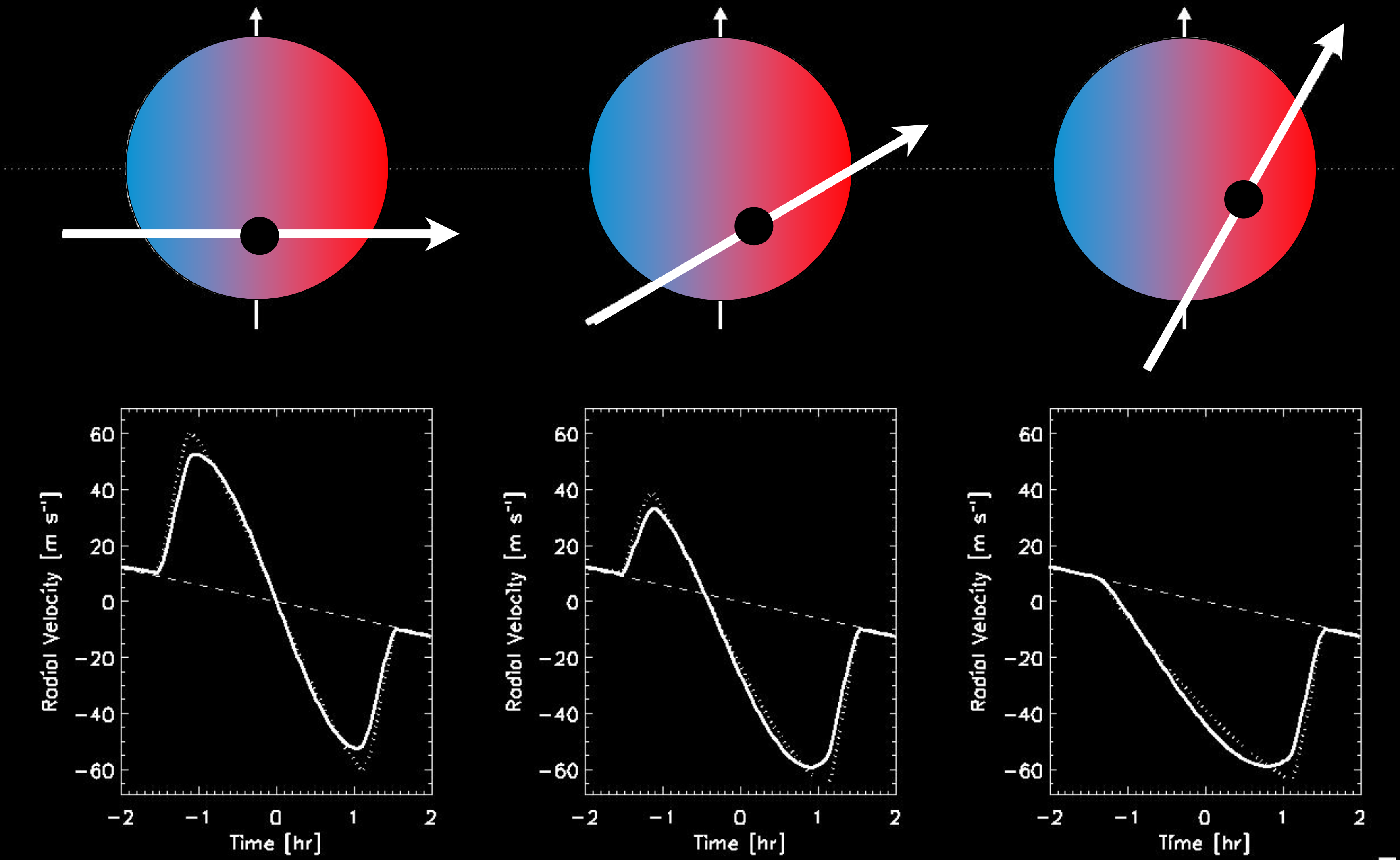

Flux
Time


Doppler shift
Time

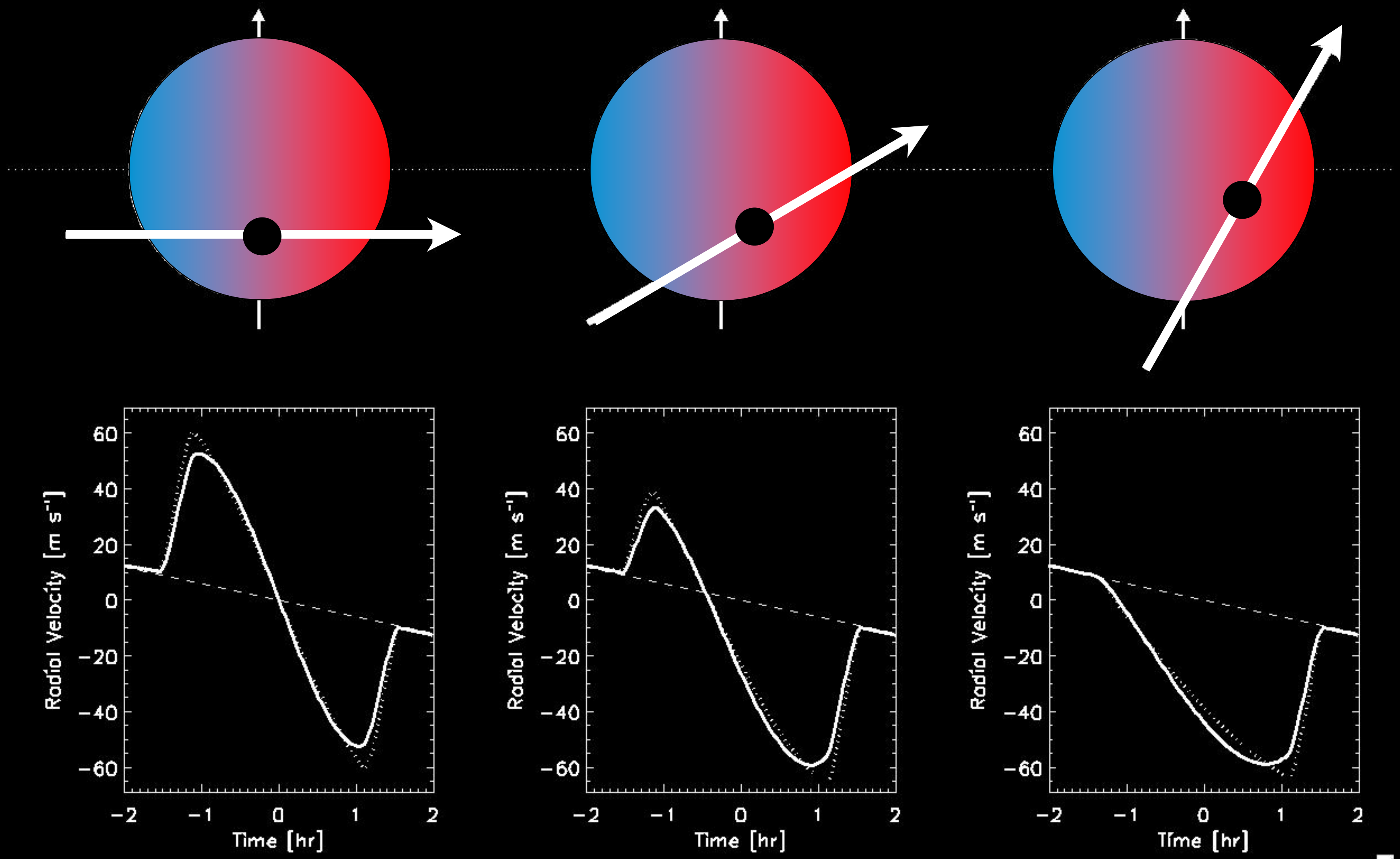


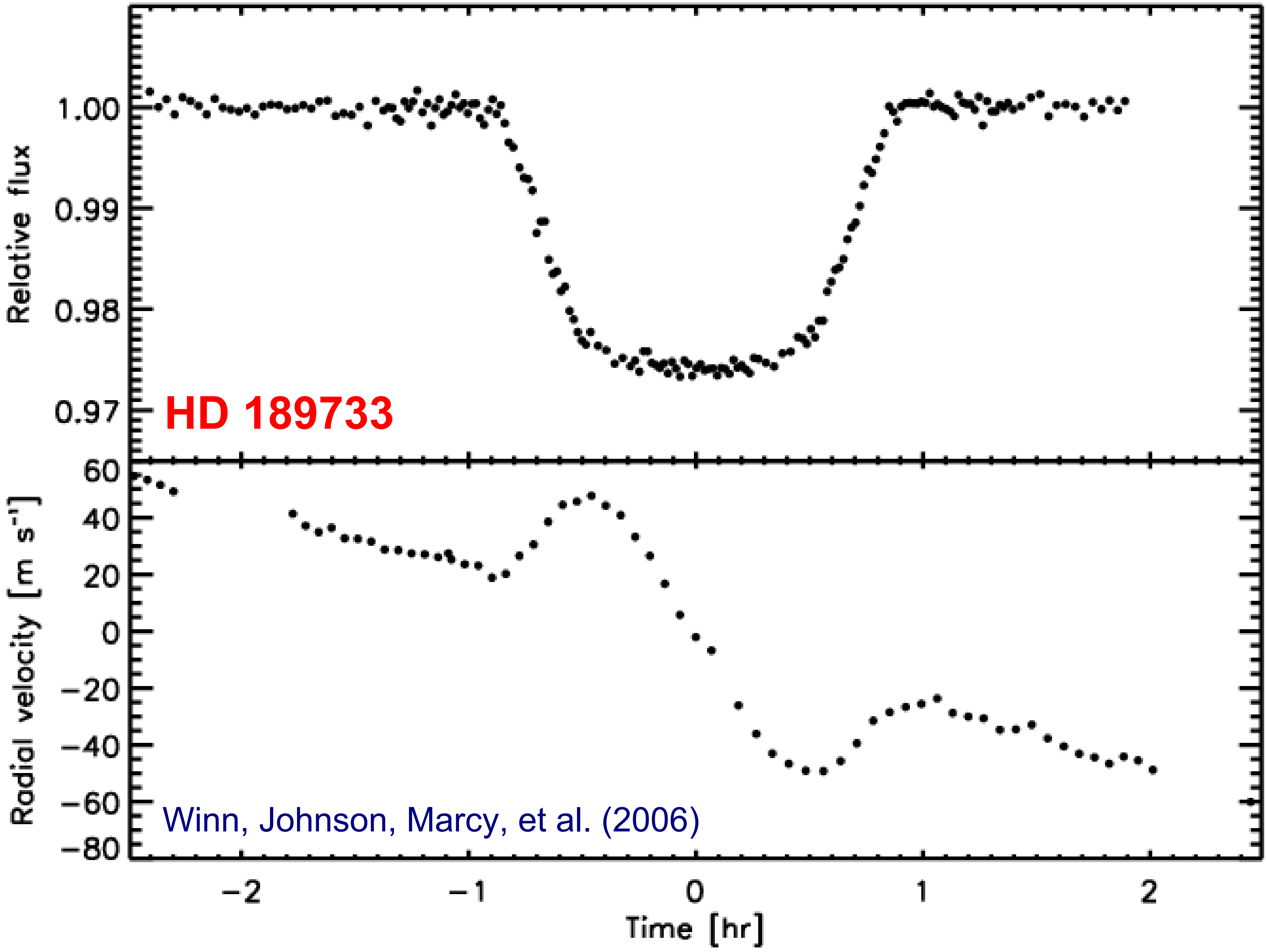
Gaudi & Winn (2007)

The Holt-Schlesinger Effect

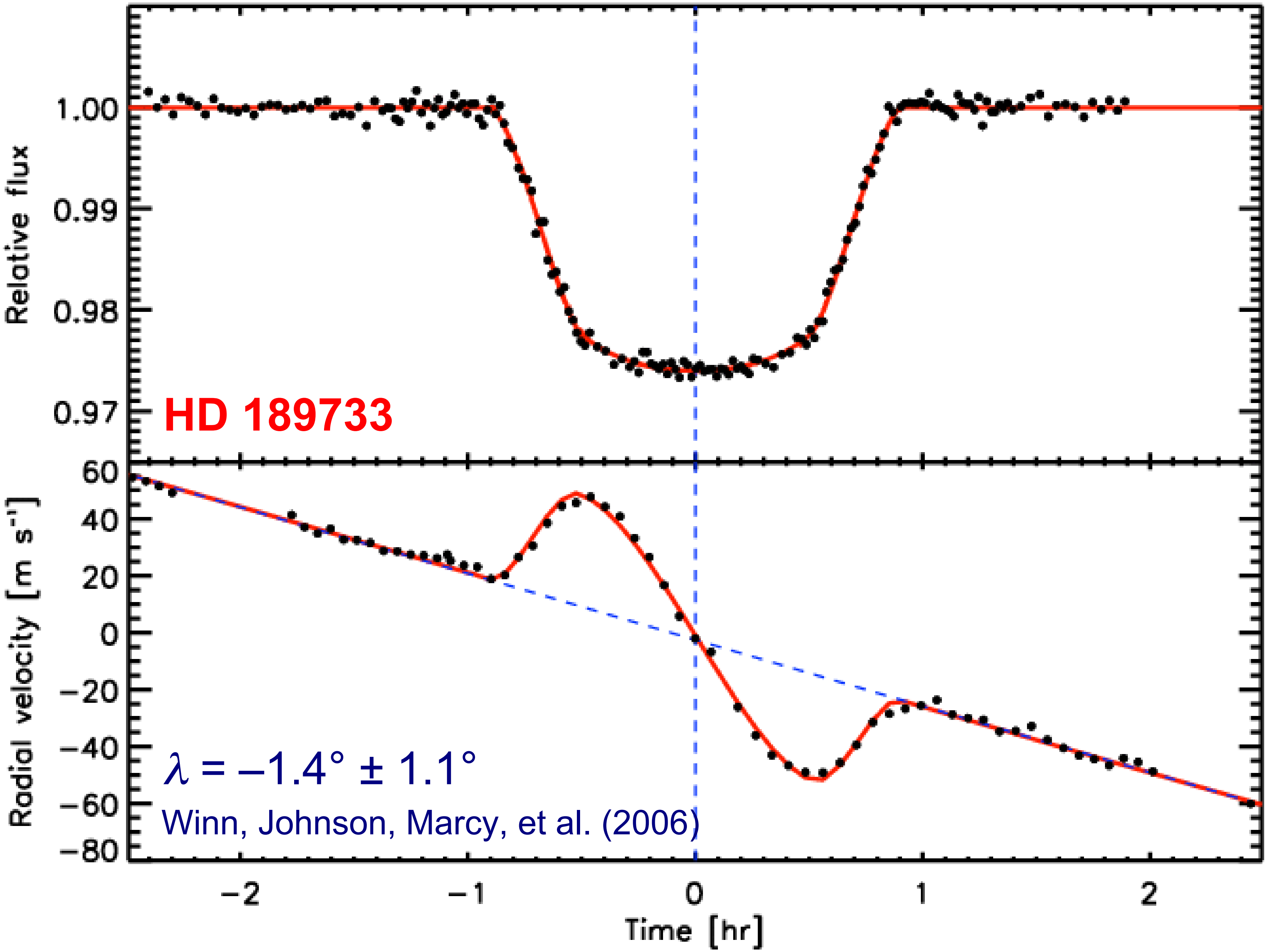


The Rossiter-McLaughlin Effect





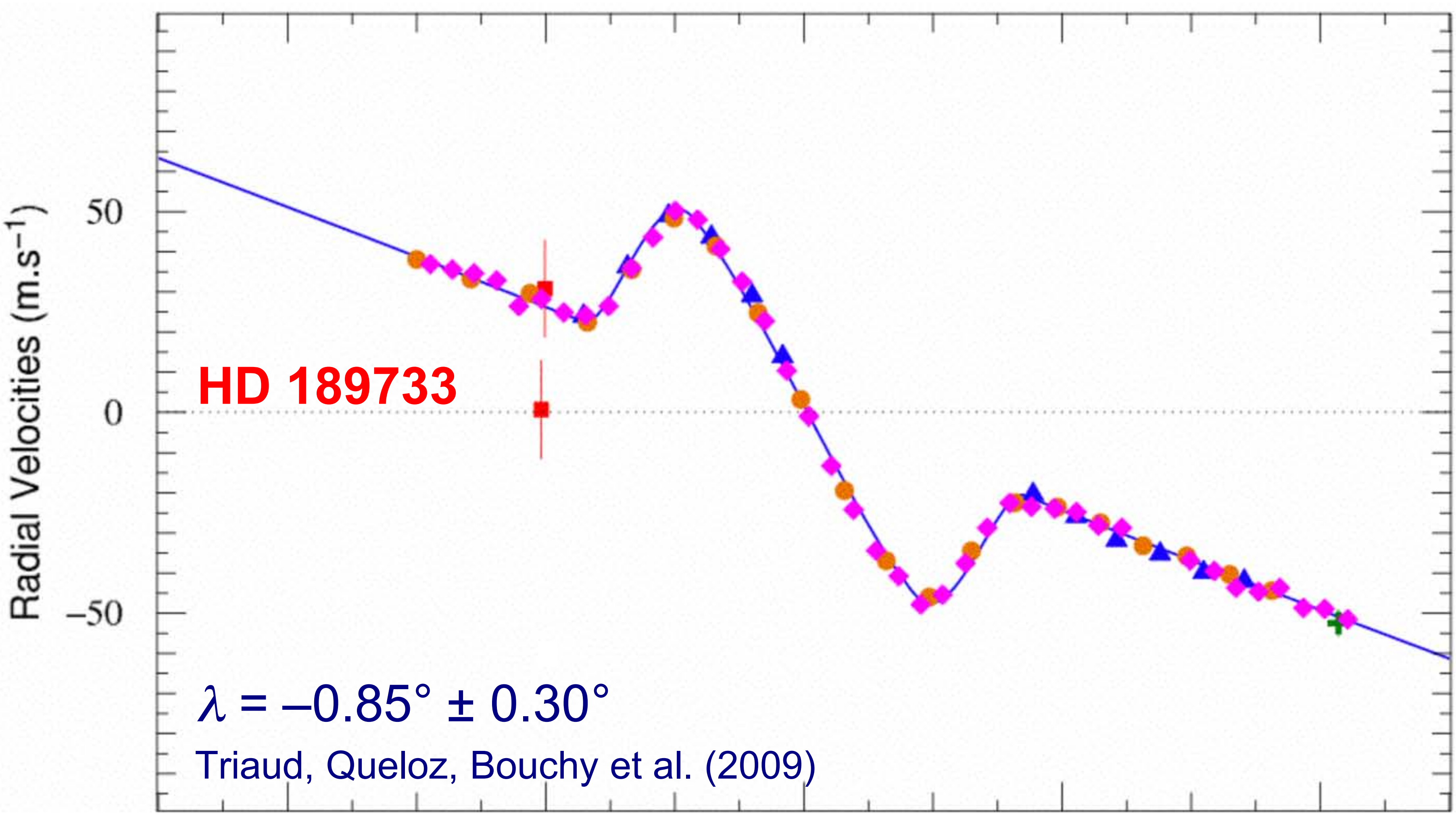
Winn, Johnson, Marcy, et al. (2006)



HD 189733

$\lambda = -1.4° \pm 1.1°$

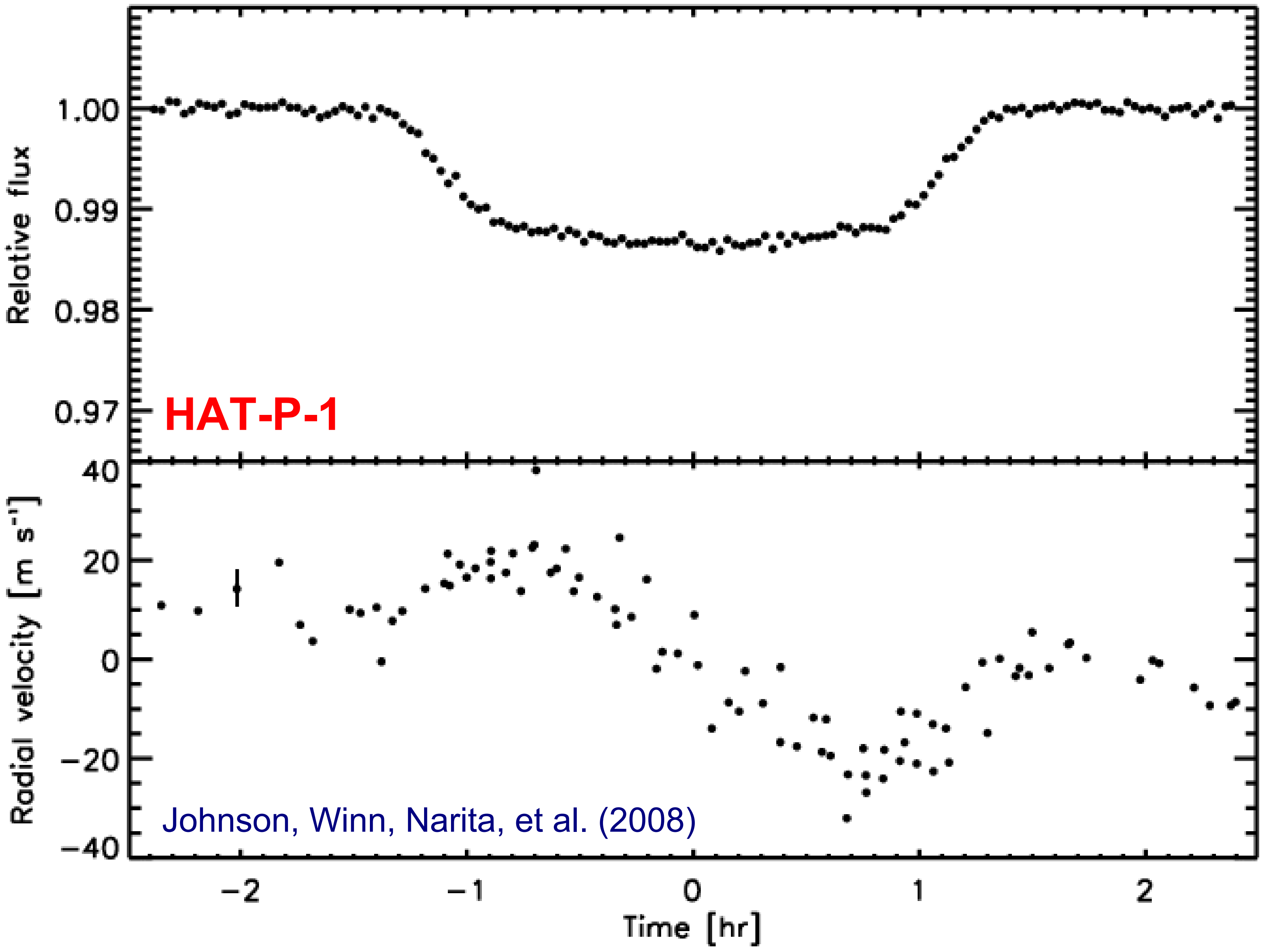
Winn, Johnson, Marcy, et al. (2006)



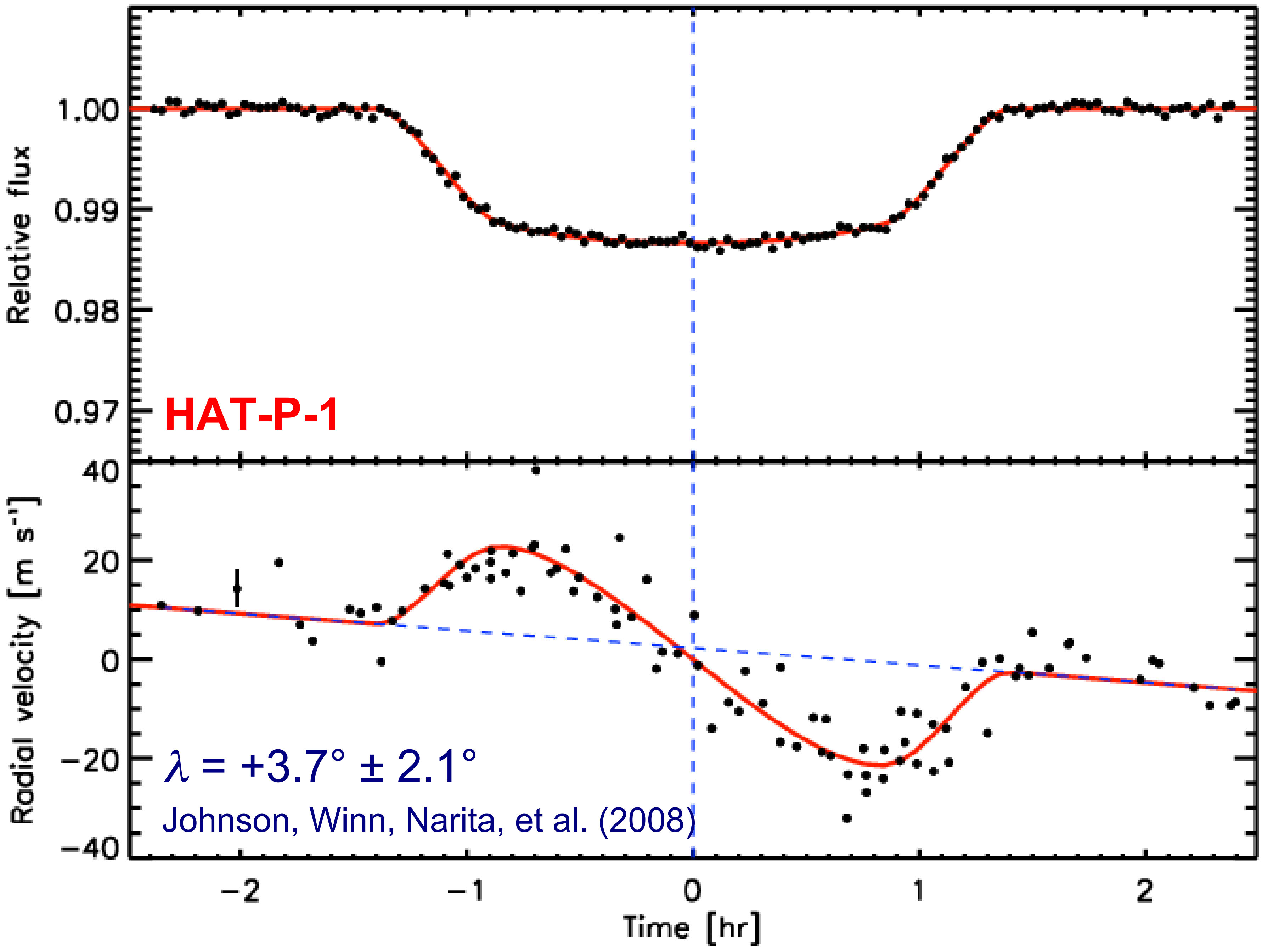
HD 189733

$\lambda = -0.85° \pm 0.30°$

Triaud, Queloz, Bouchy et al. (2009)



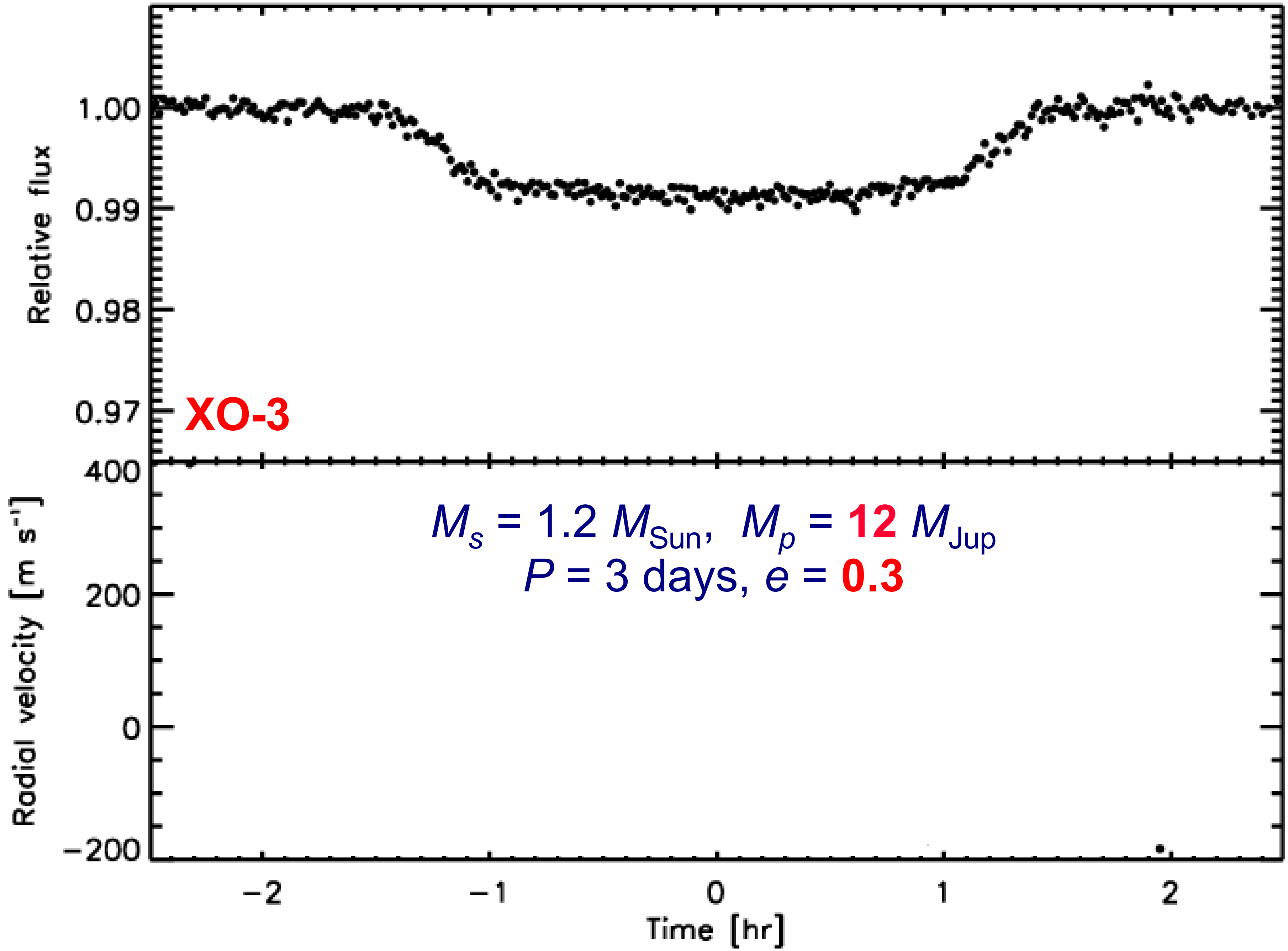
Johnson, Winn, Narita, et al. (2008)



HAT-P-1

λ = +3.7° ± 2.1°

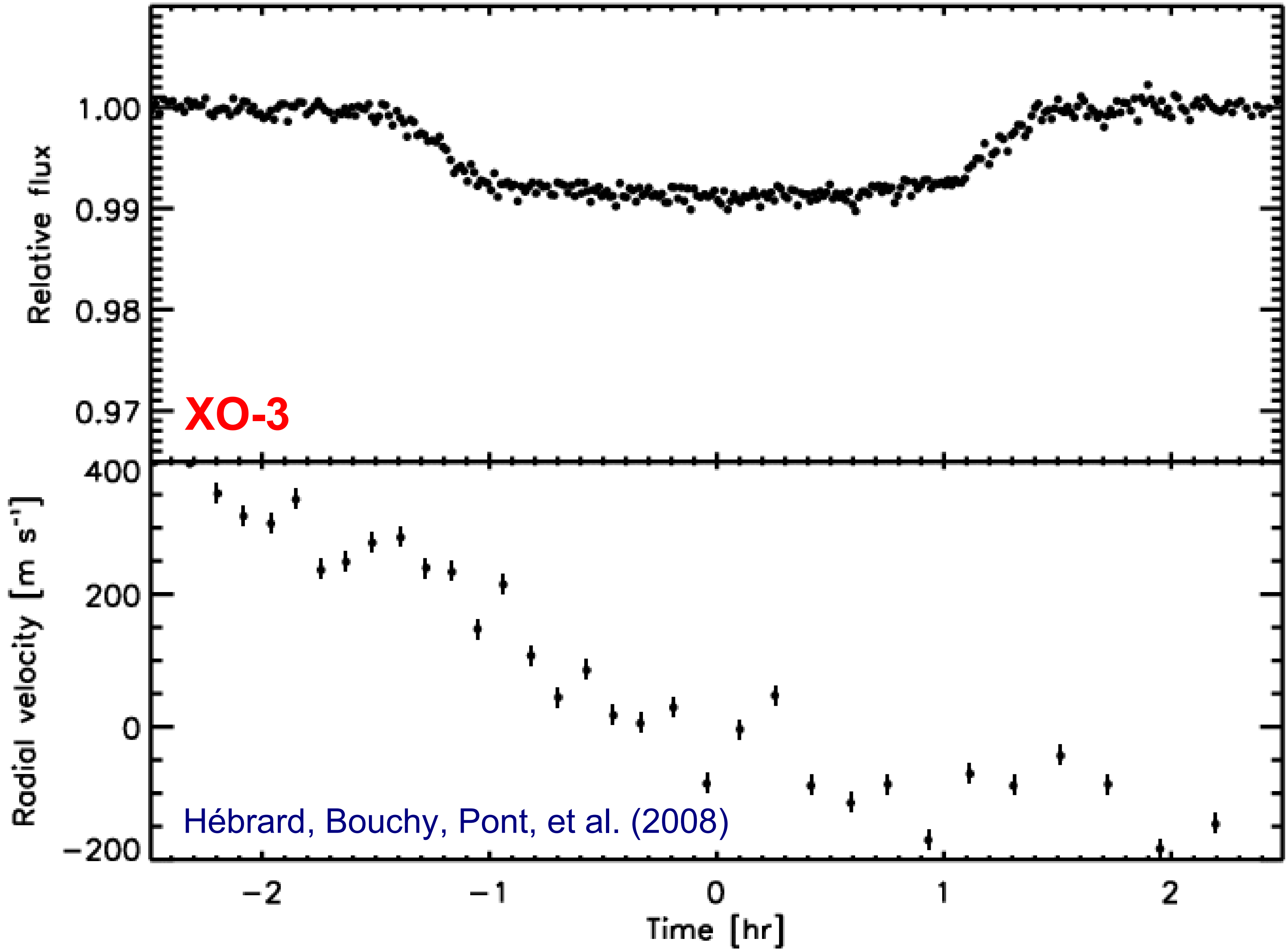
Johnson, Winn, Narita, et al. (2008)



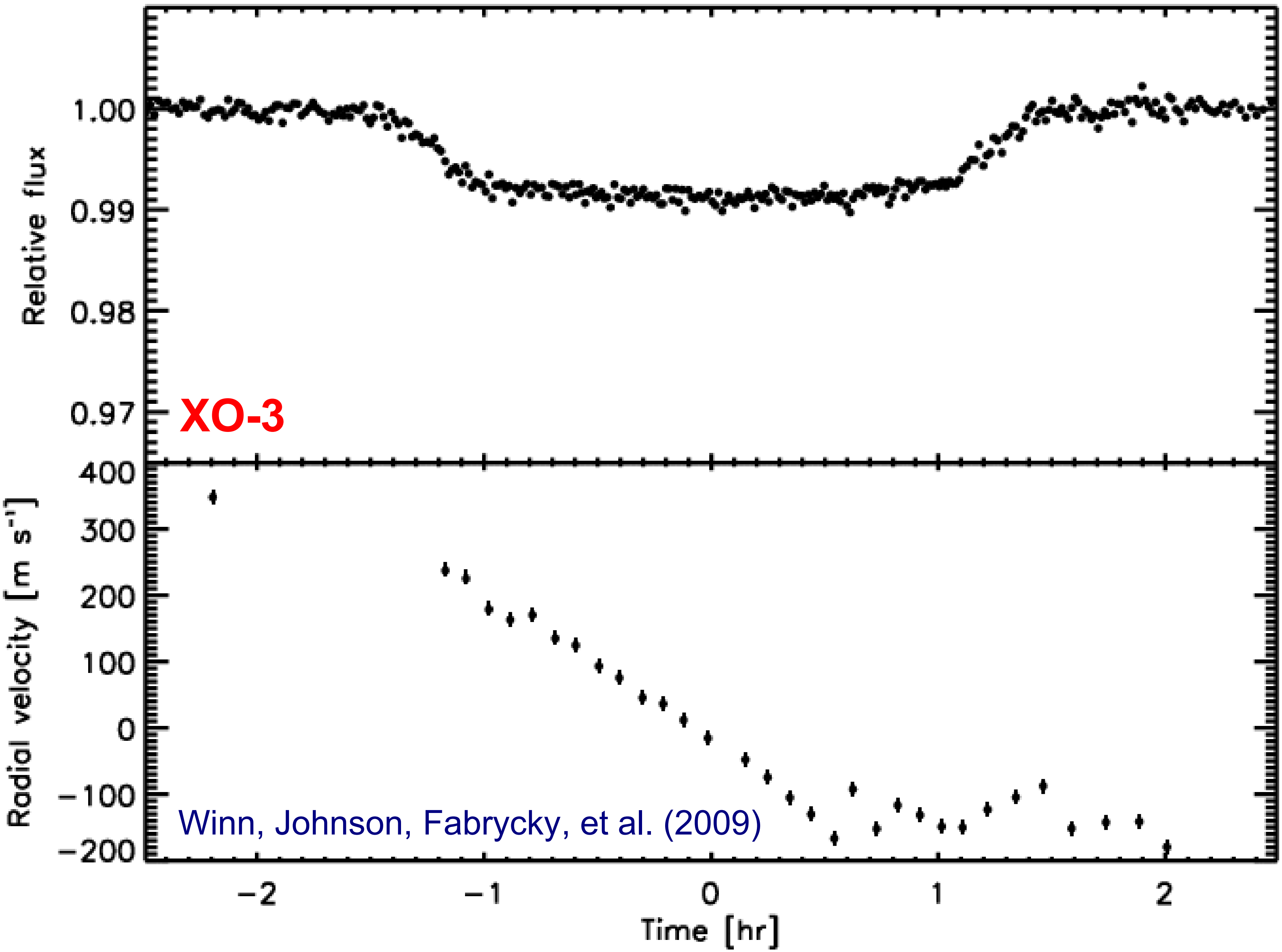
XO-3

$M_s = 1.2\ M_{\mathrm{Sun}}$, $M_p =$ **12** M_{Jup}

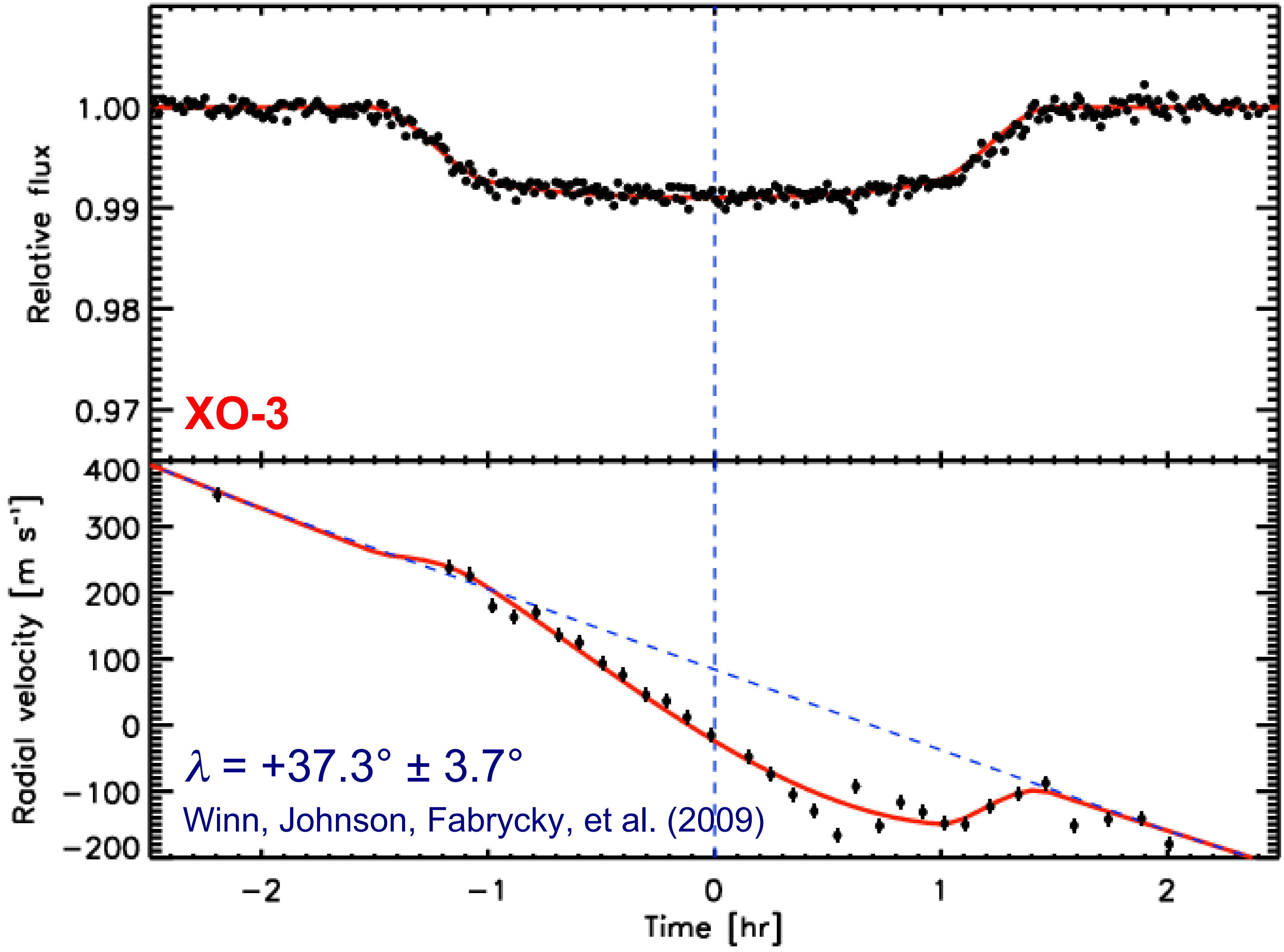
$P = 3$ days, $e =$ **0.3**



Hébrard, Bouchy, Pont, et al. (2008)



Winn, Johnson, Fabrycky, et al. (2009)



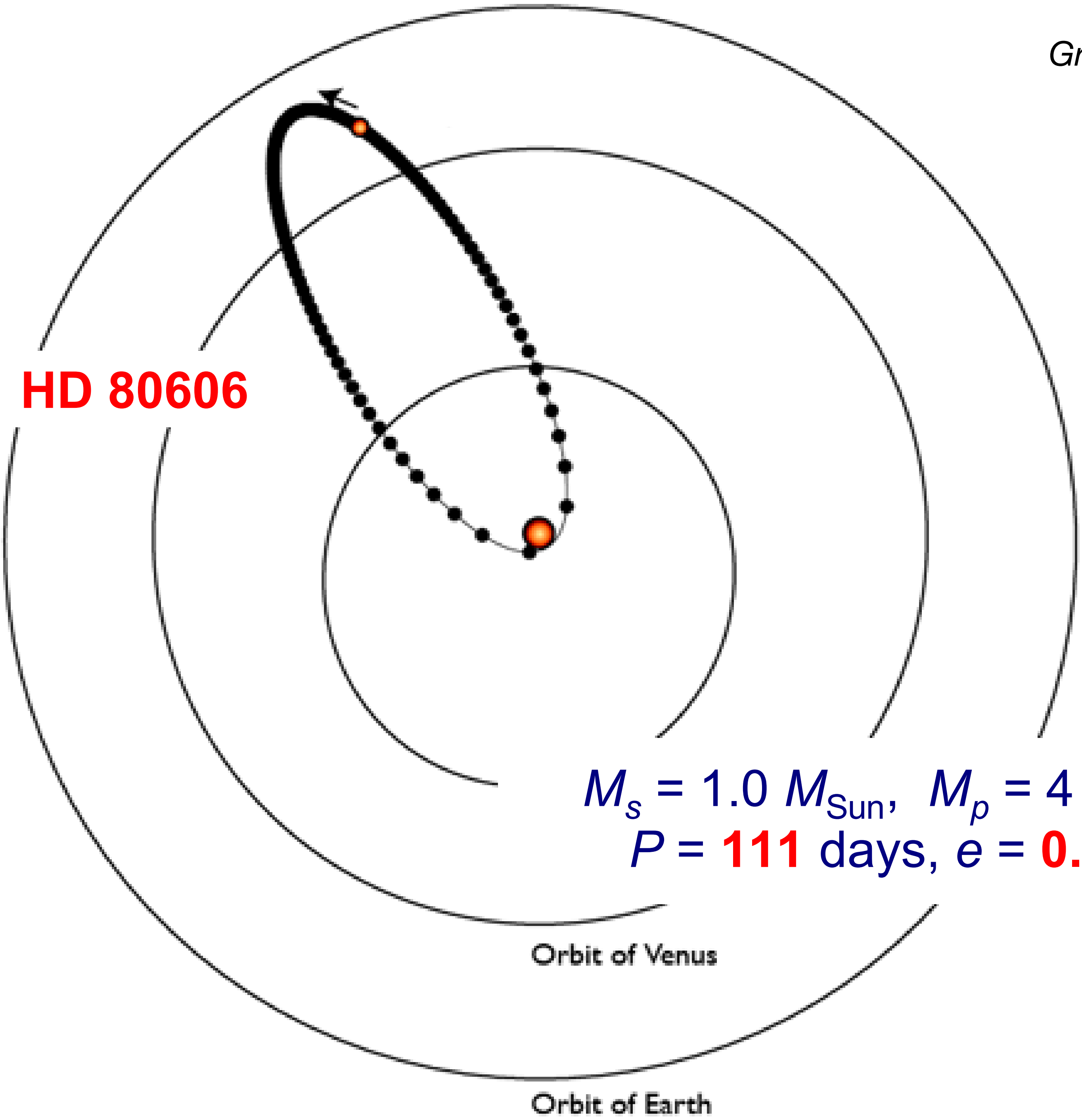
XO-3

λ = +37.3° ± 3.7°

Winn, Johnson, Fabrycky, et al. (2009)

Greg Laughlin

HD 80606



$M_s = 1.0\ M_{\mathrm{Sun}}$, $M_p = 4\ M_{\mathrm{Jup}}$

P = **111** days, e = **0.93**

Moutou et al. (2009)

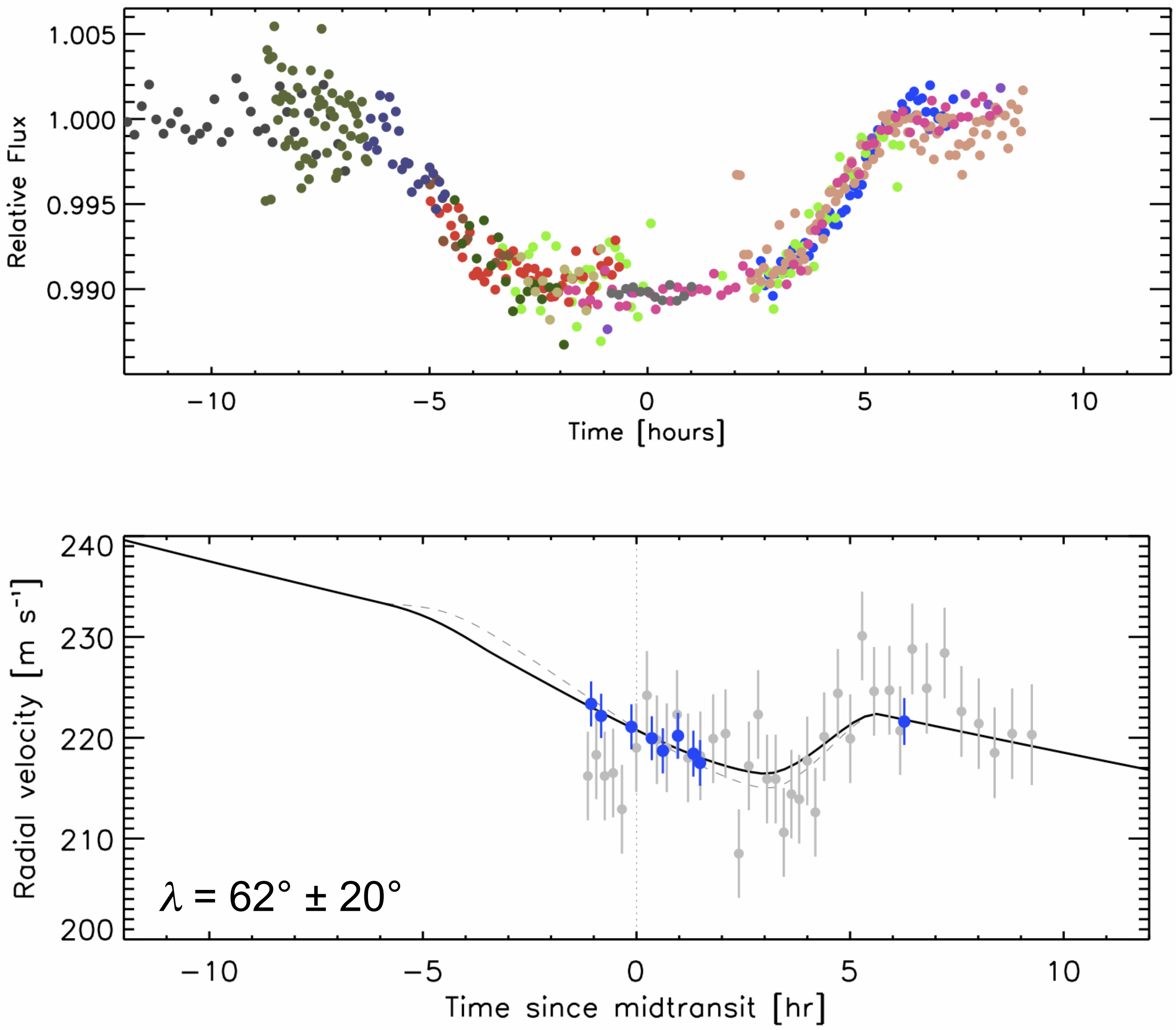
Garcia-Melendo & McCullough (2009)

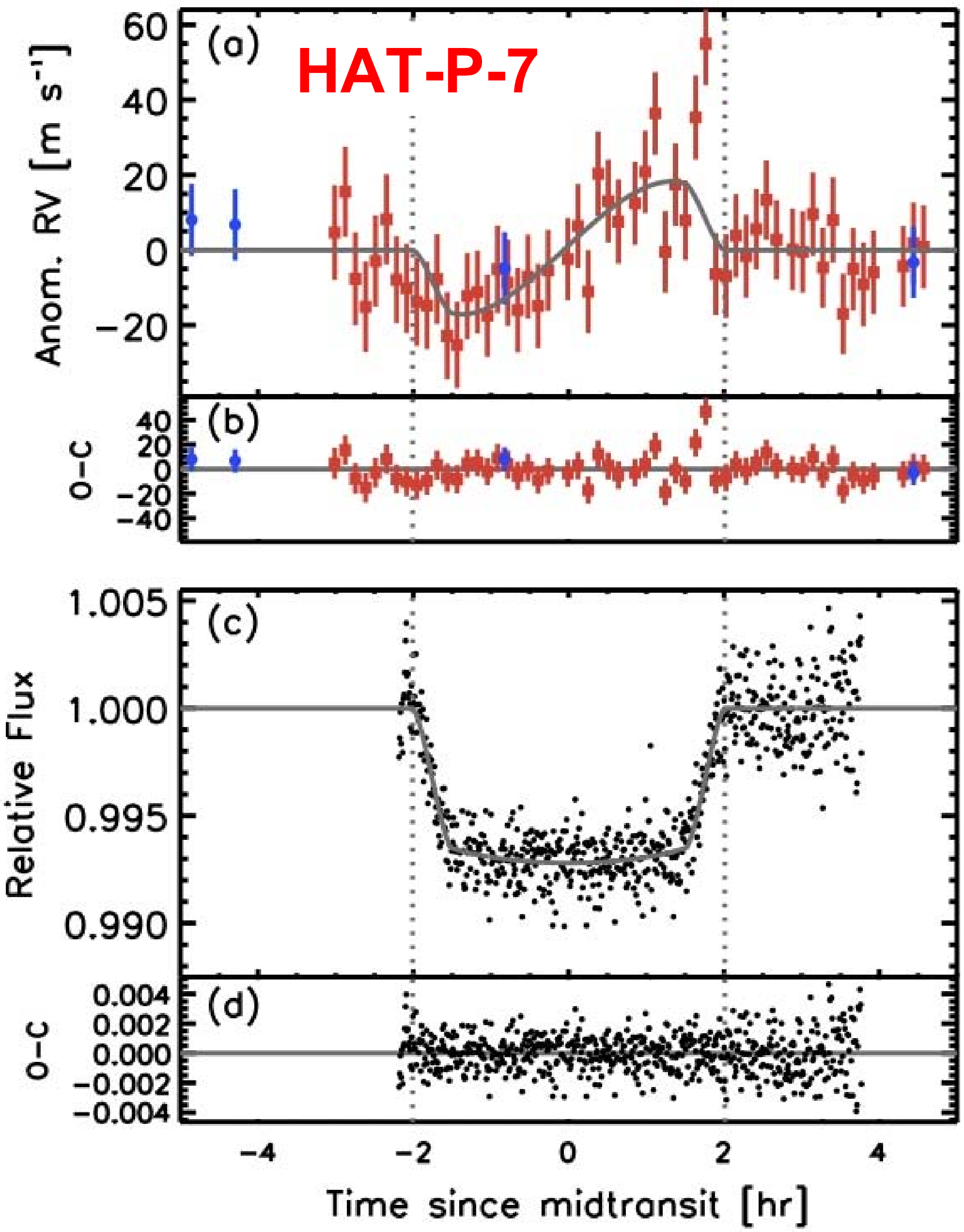
Fossey et al. (2009)

Winn et al. (2009)

Hidas et al. (2010)

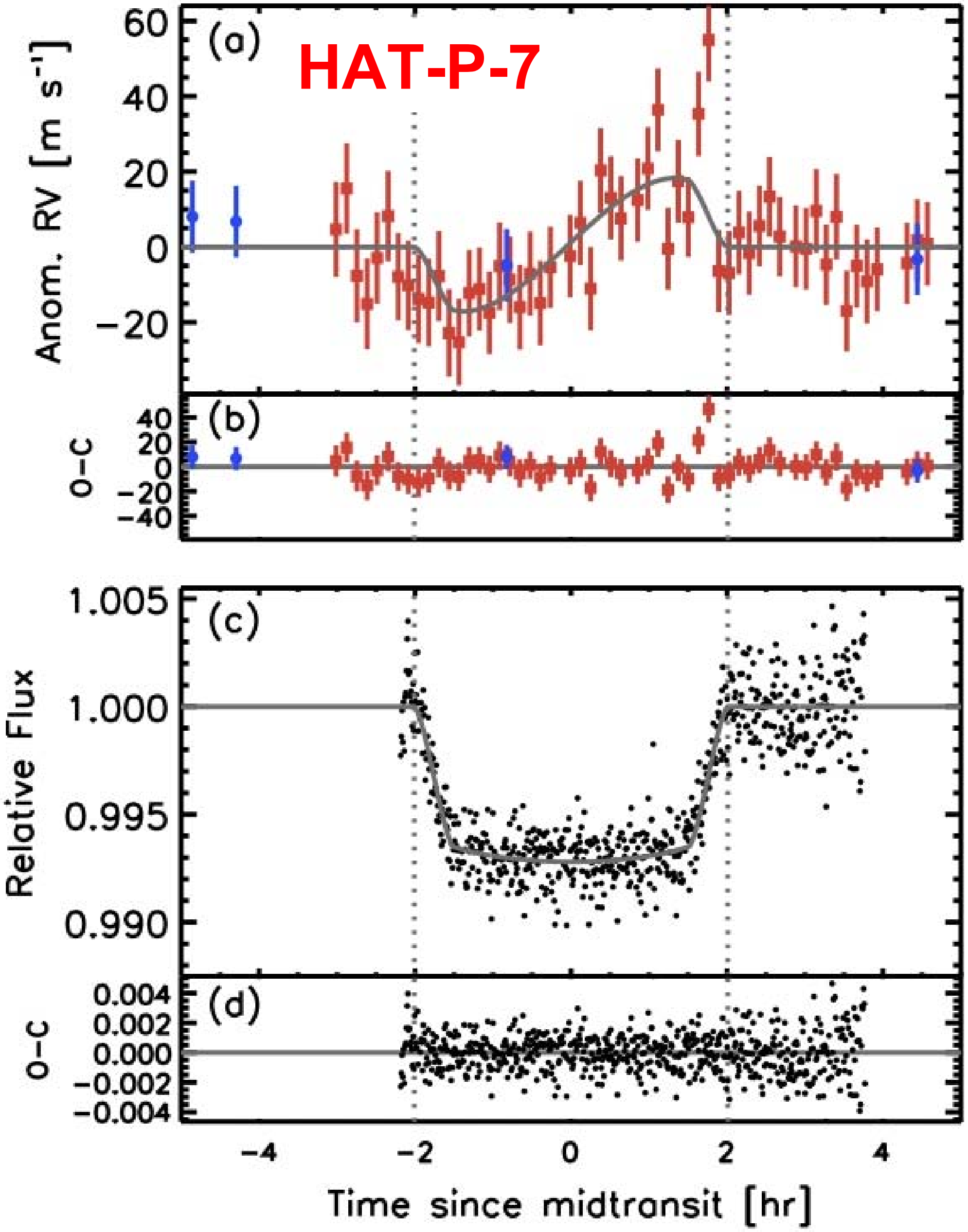
Shporer et al., in prep.

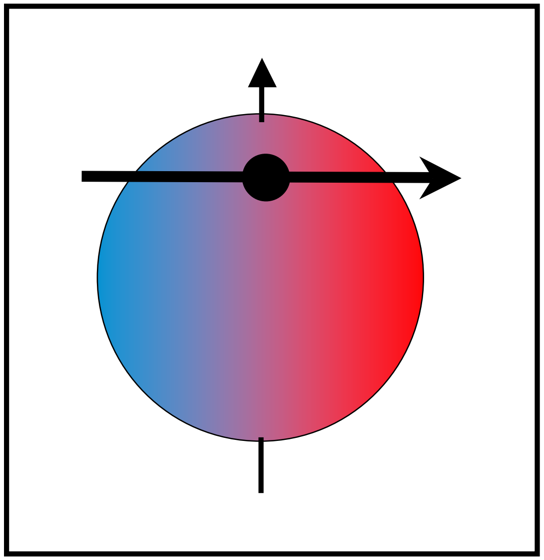




Winn, Johnson, Albrecht
et al. (2009)

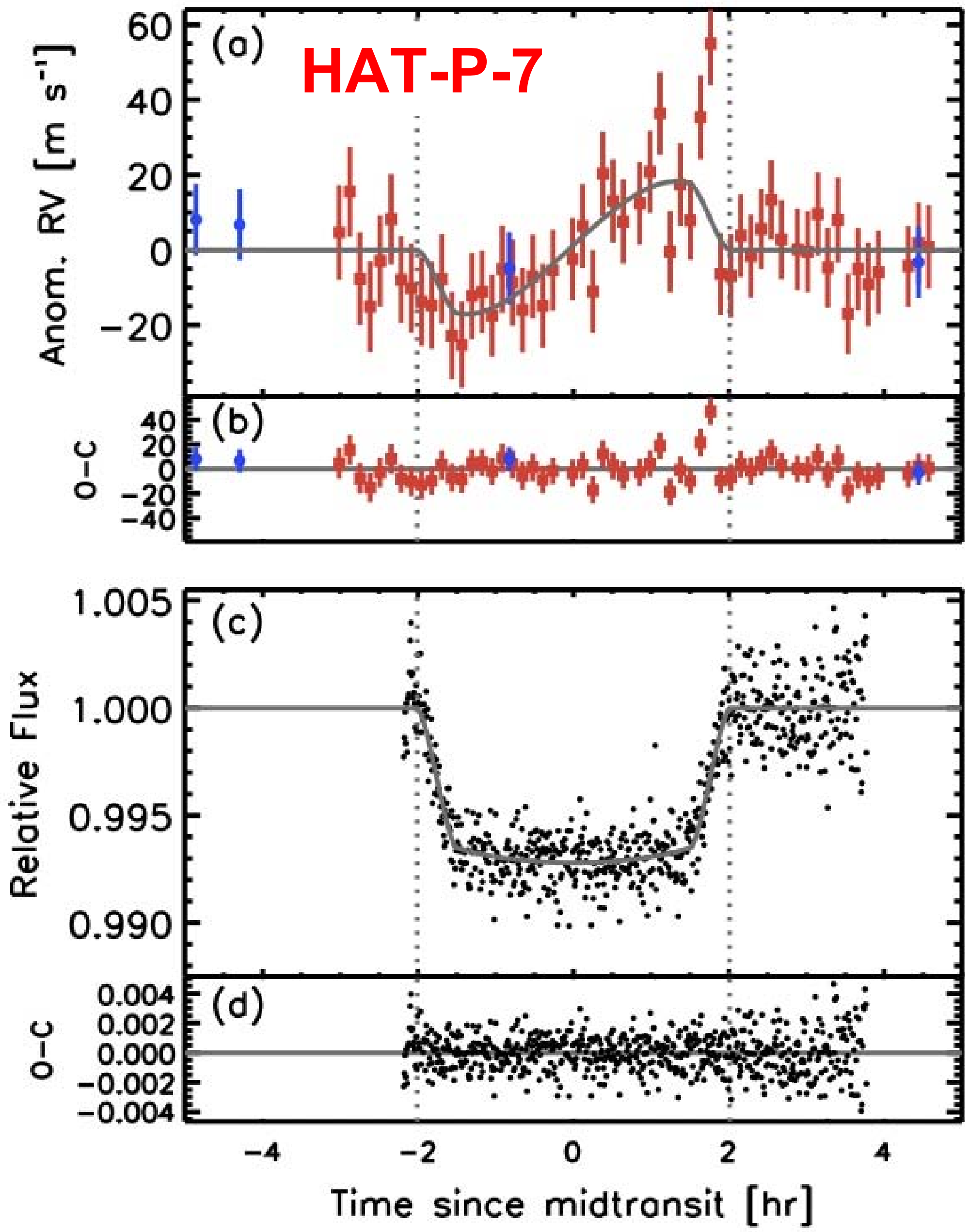
See also Narita, Sato,
Hirano, & Tamura (2009)

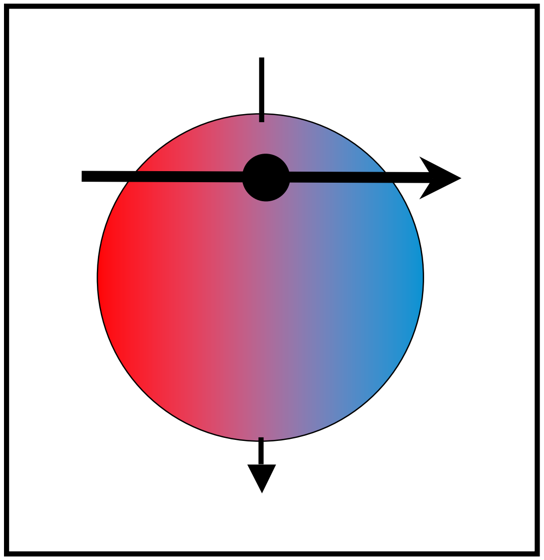




Winn, Johnson, Albrecht
et al. (2009)

See also Narita, Sato,
Hirano, & Tamura (2009)

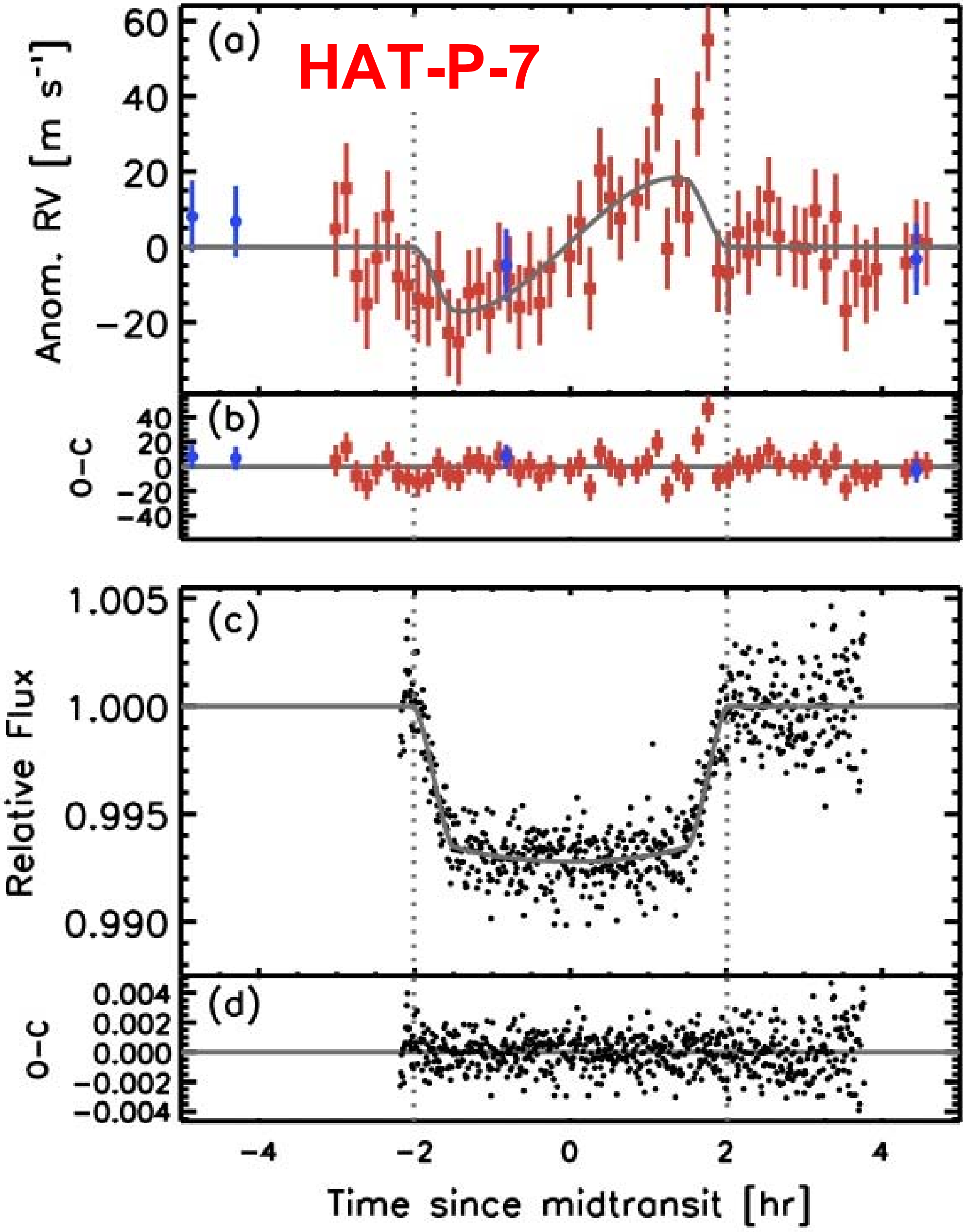




λ = 182.5° ± 9.4°

Winn, Johnson, Albrecht et al. (2009)

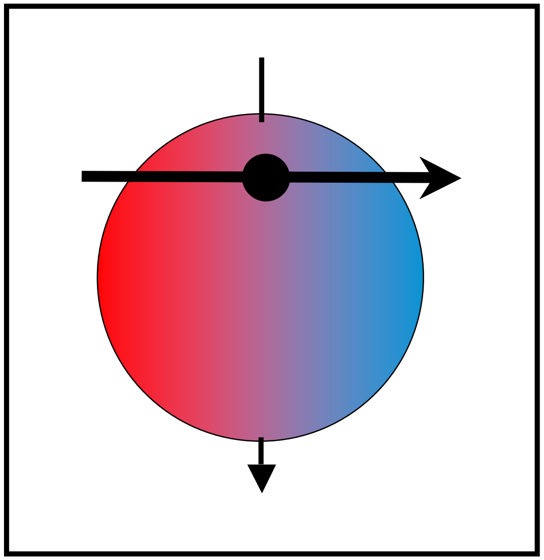
See also Narita, Sato, Hirano, & Tamura (2009)



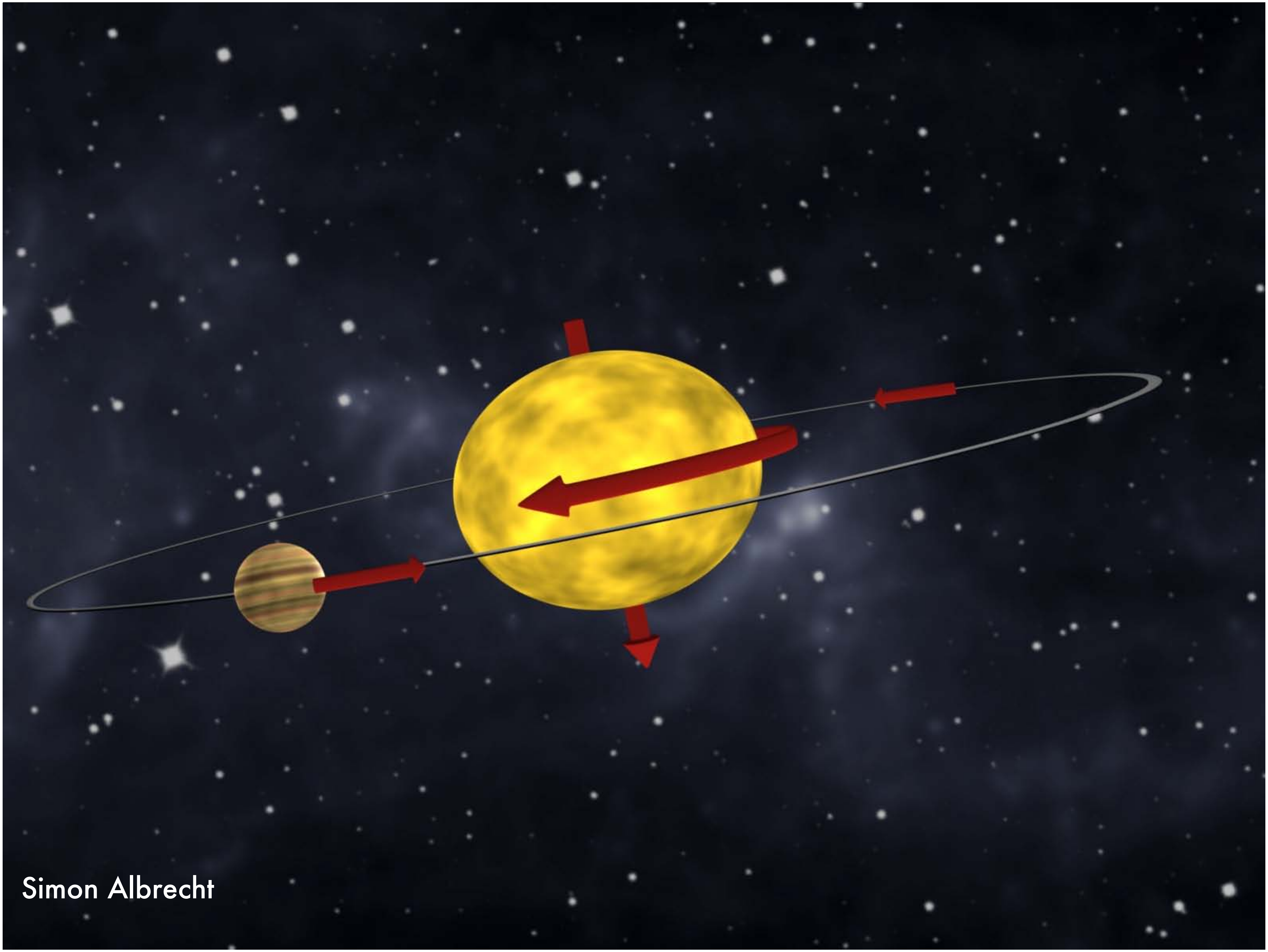
Winn, Johnson, Albrecht et al. (2009)

See also Narita, Sato, Hirano, & Tamura (2009)

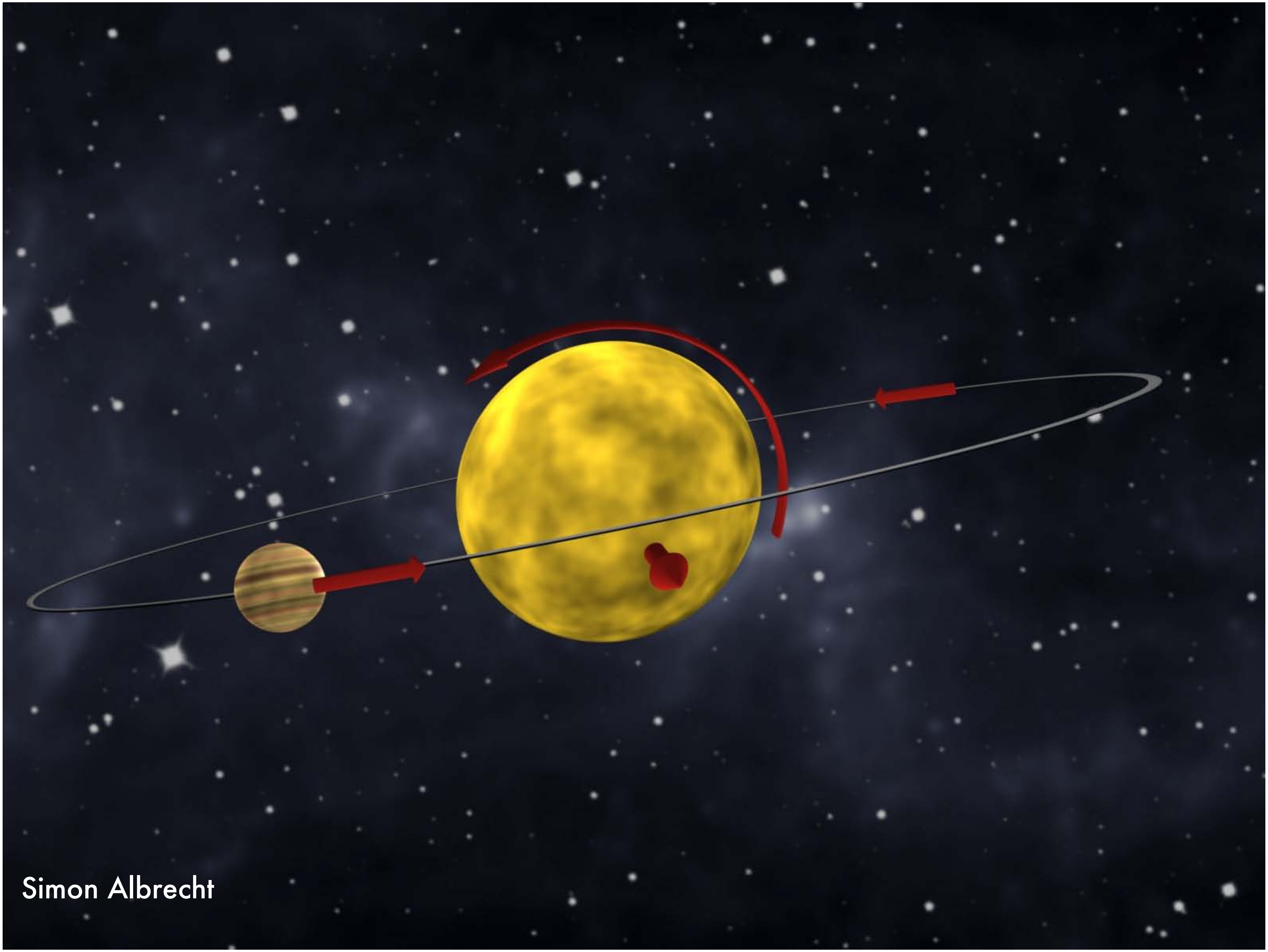
A planet on a retrograde orbit?



λ = 182.5° ± 9.4°

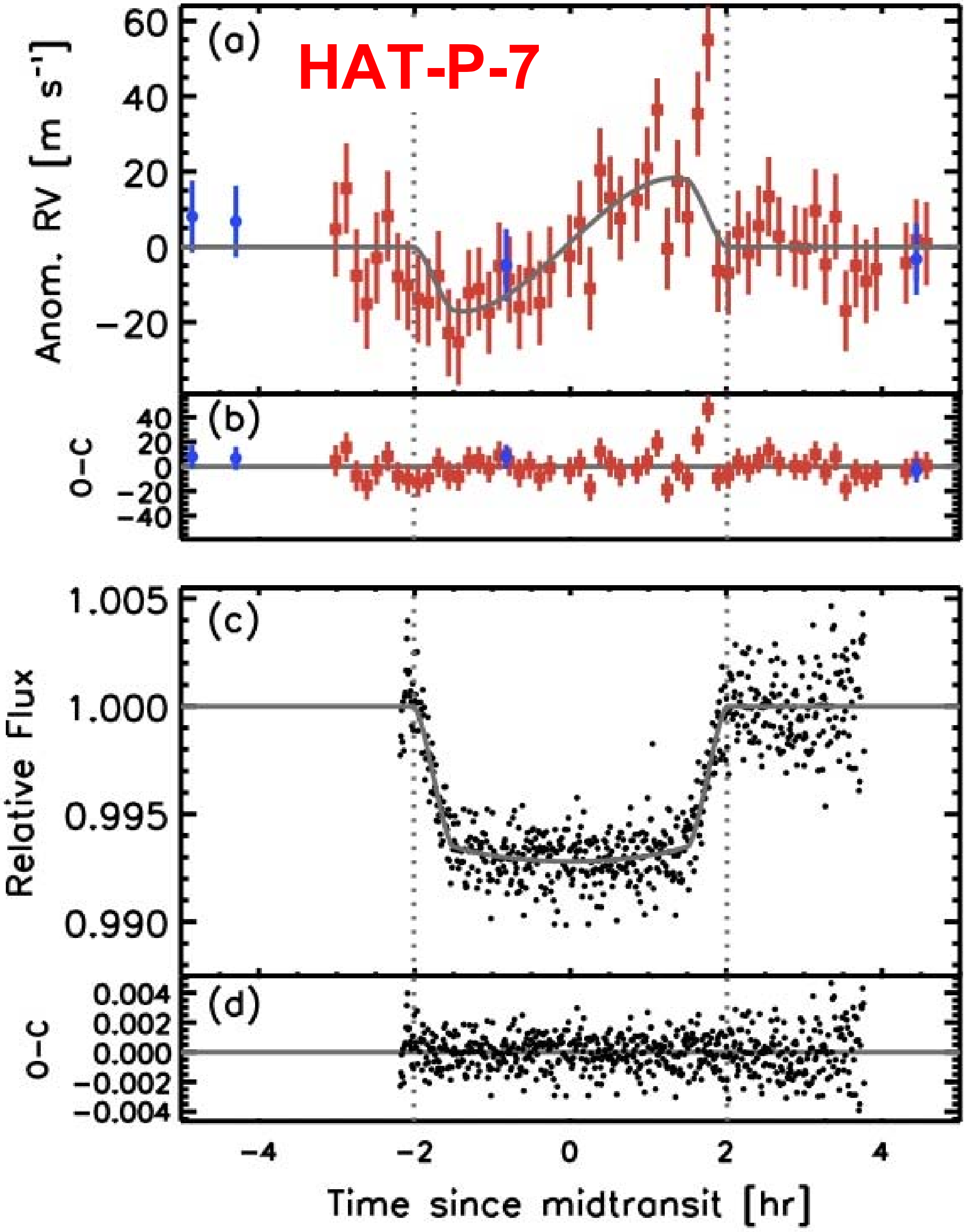


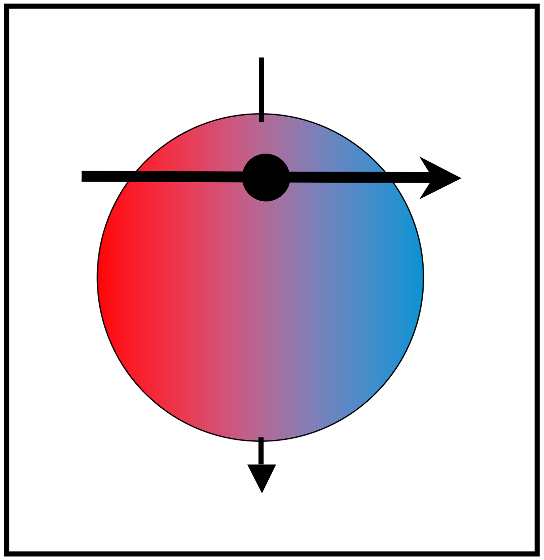
Simon Albrecht



Simon Albrecht

A planet on a retrograde or polar orbit





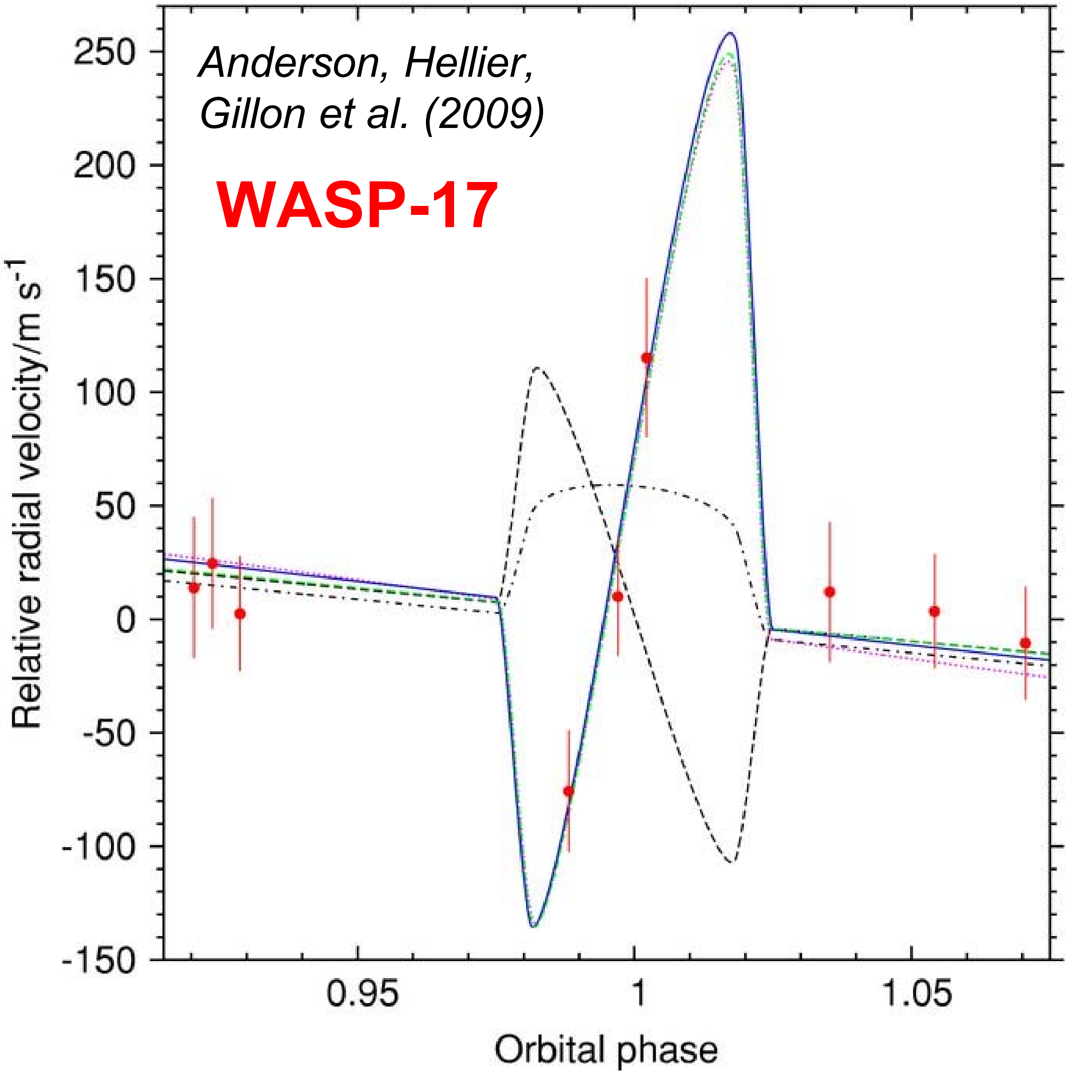
λ = 182.5° ± 9.4°

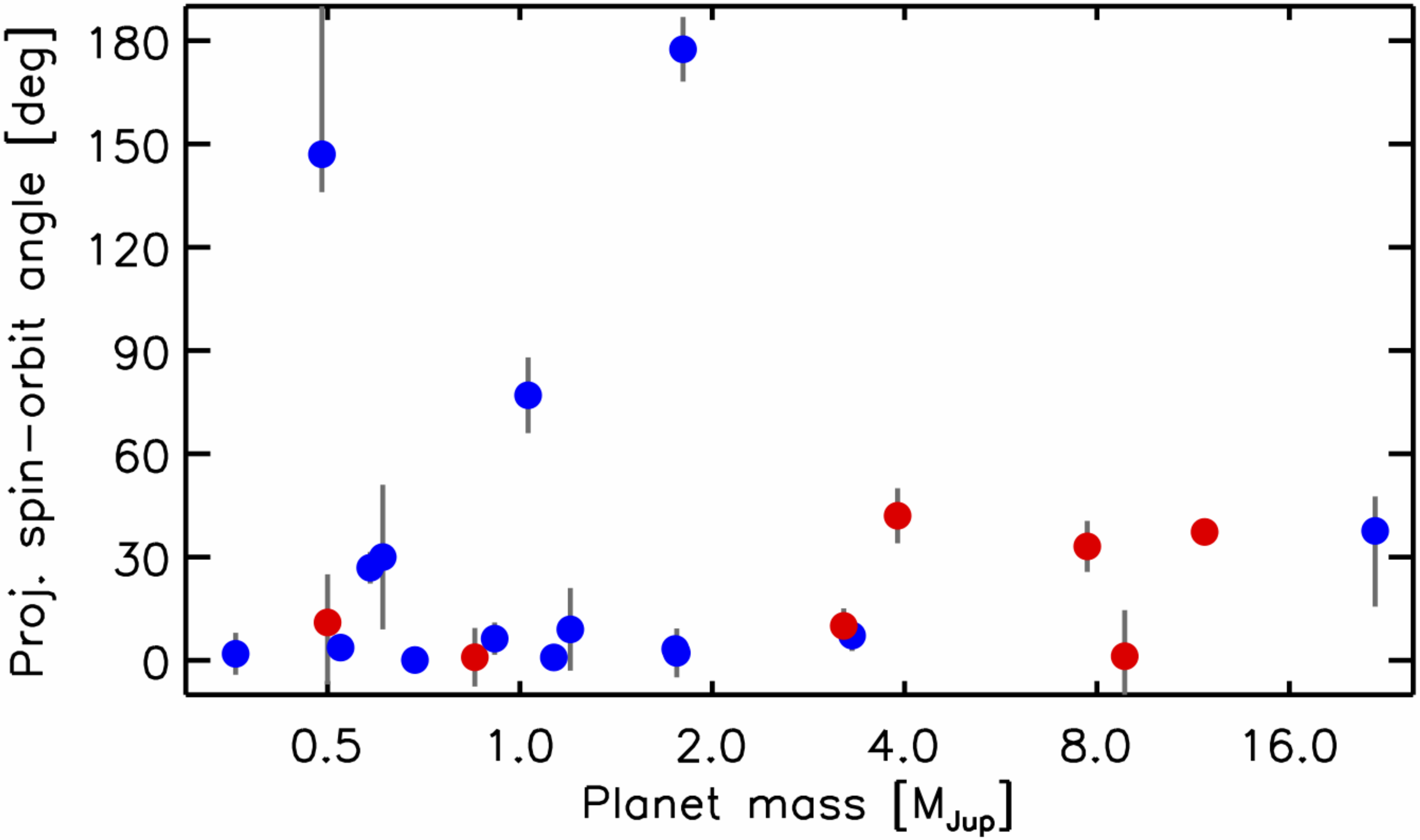
ψ > 86.7°

Winn, Johnson, Albrecht
et al. (2009)

See also Narita, Sato,
Hirano, & Tamura (2009)

More planets on retrograde or polar orbits

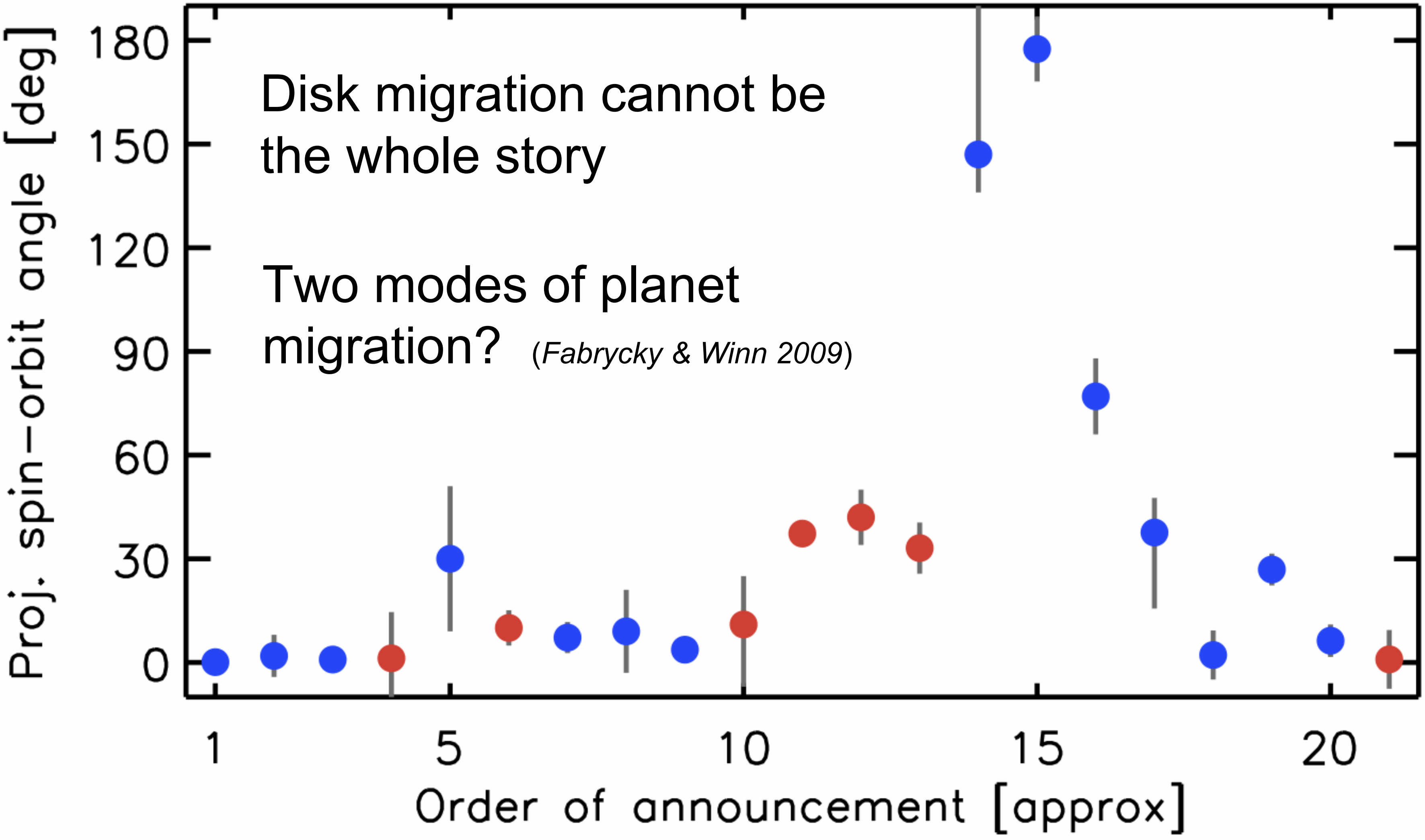



● Circular orbit

● Eccentric orbit

● Circular orbit

● Eccentric orbit

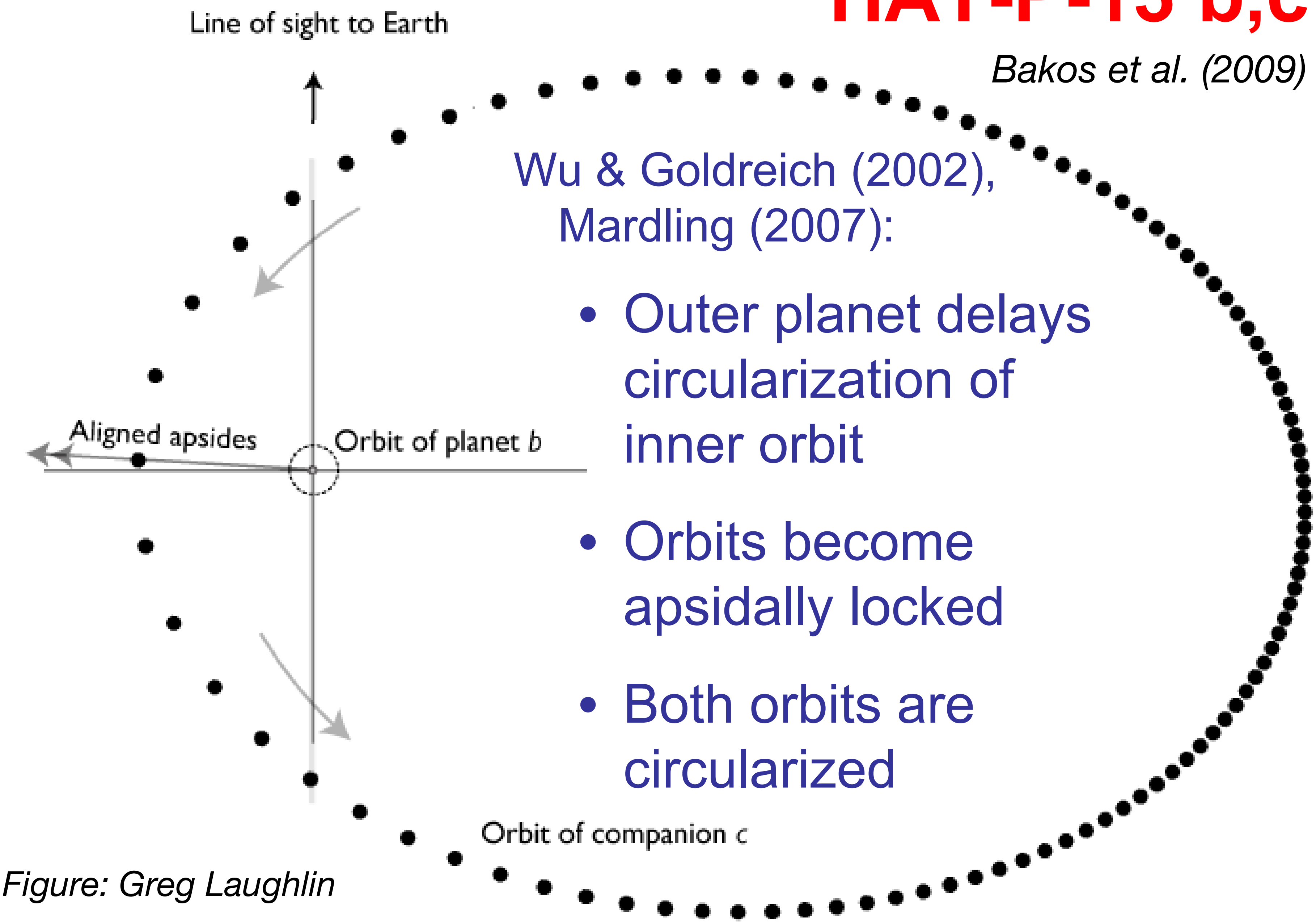


Disk migration cannot be the whole story

Two modes of planet migration? (*Fabrycky & Winn 2009*)

HAT-P-13 b,c

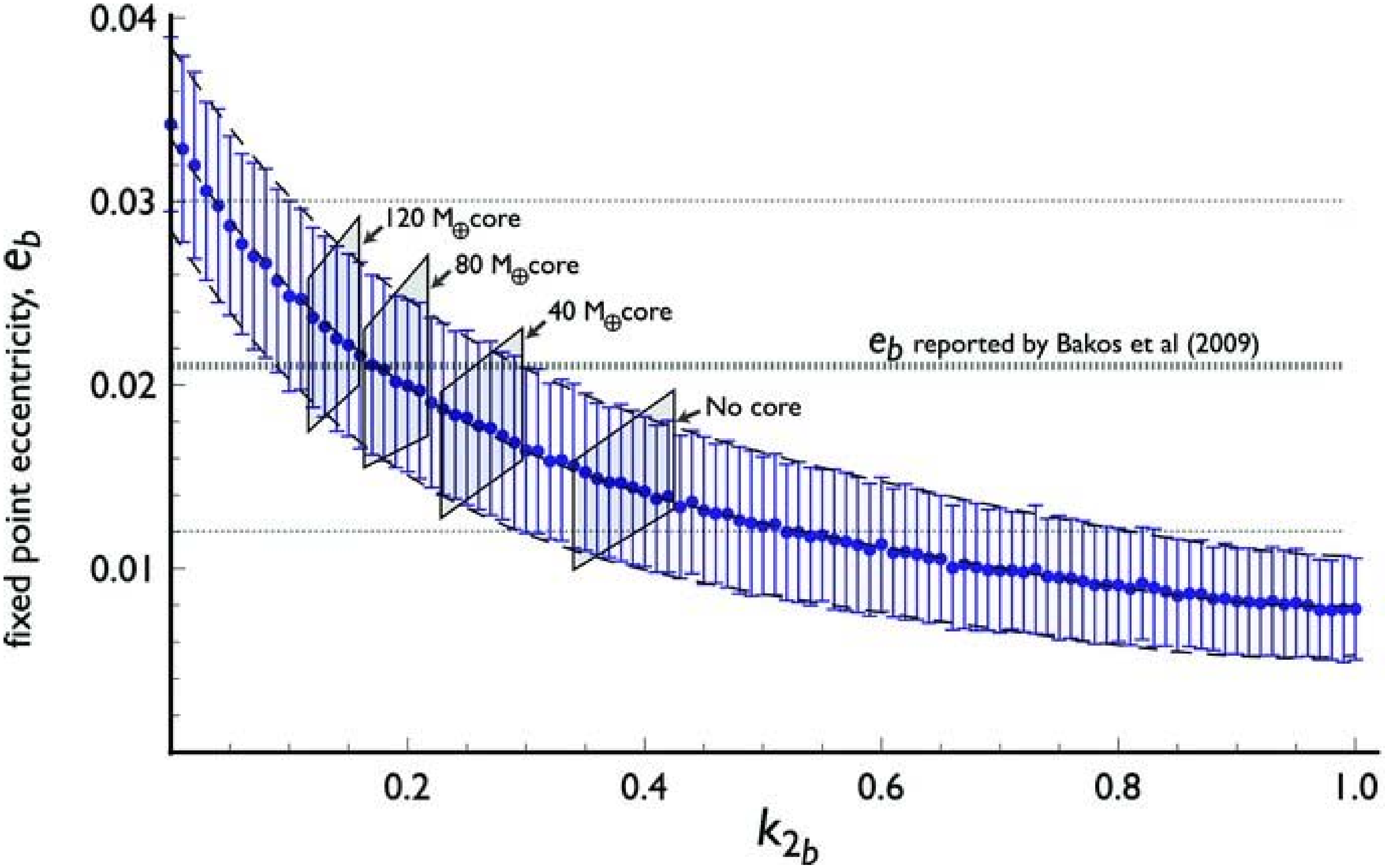
Bakos et al. (2009)



Wu & Goldreich (2002), Mardling (2007):

- Outer planet delays circularization of inner orbit
- Orbits become apsidally locked
- Both orbits are circularized

Figure: Greg Laughlin

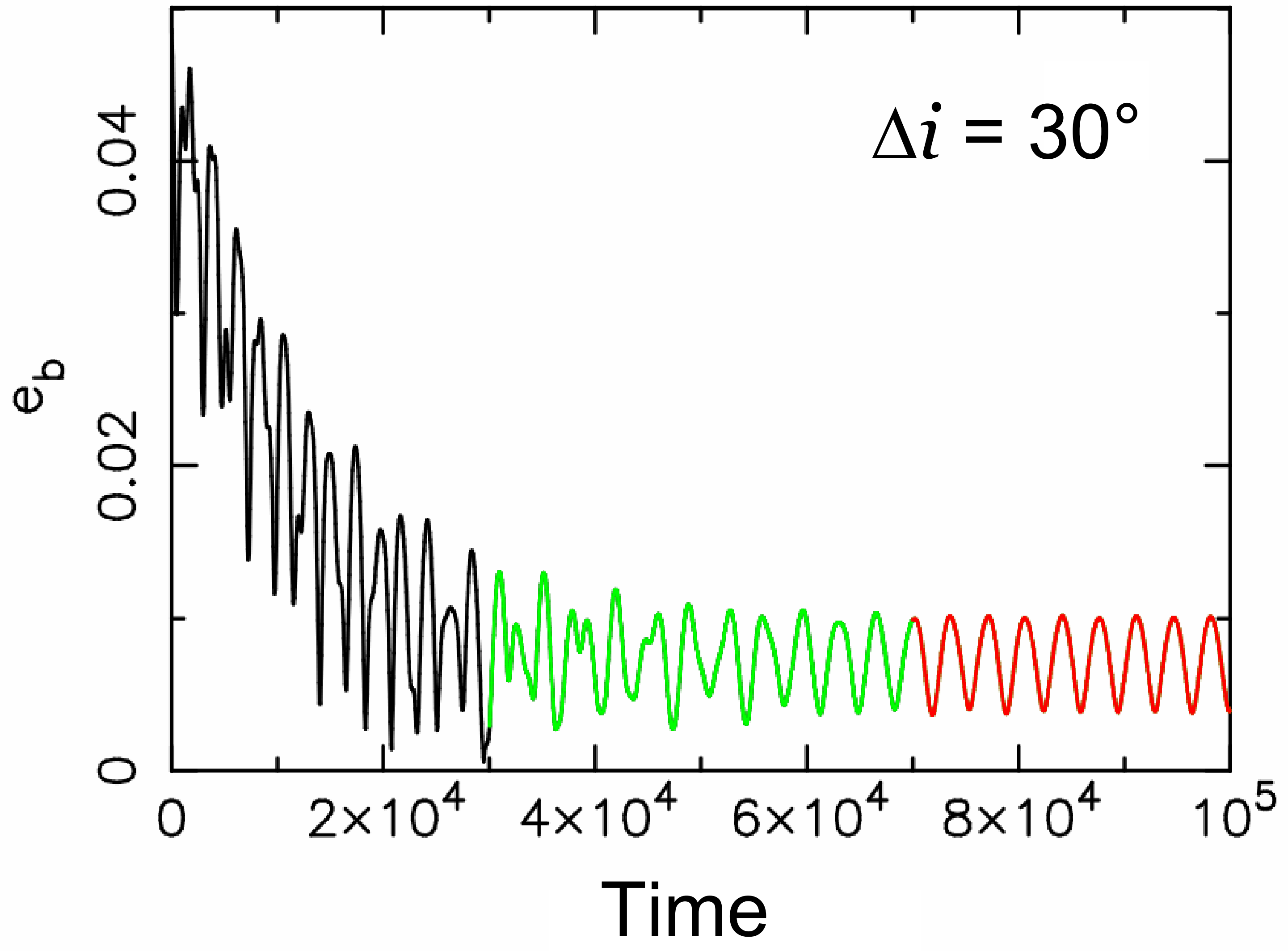


Batygin et al. (2009), Mardling (2010):

- Precession rate of outer orbit can be calculated.
- Precession rate of inner orbit depends on k_2.
- If you assume the rates are equal, you learn k_2.

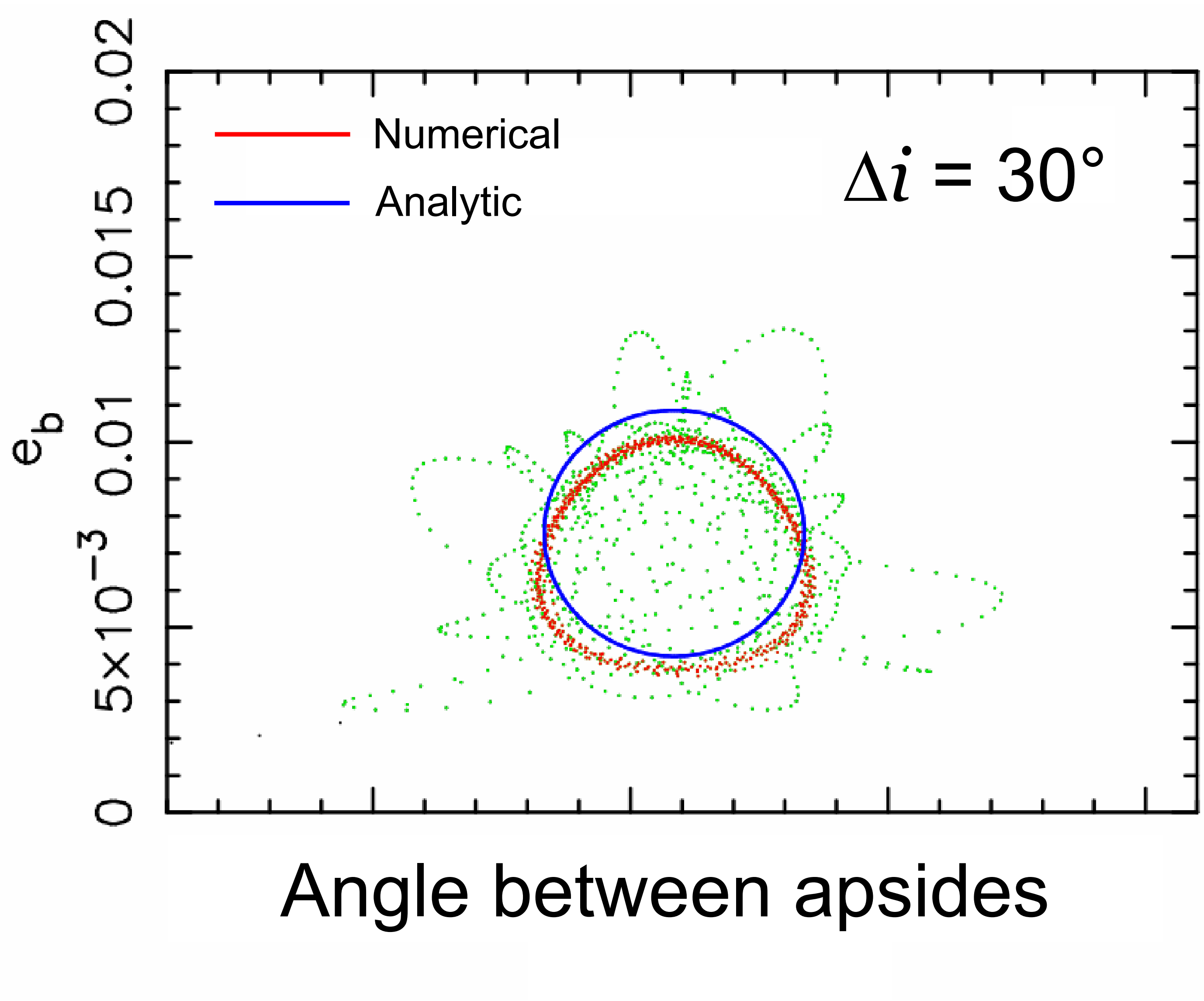
Mardling (2010):

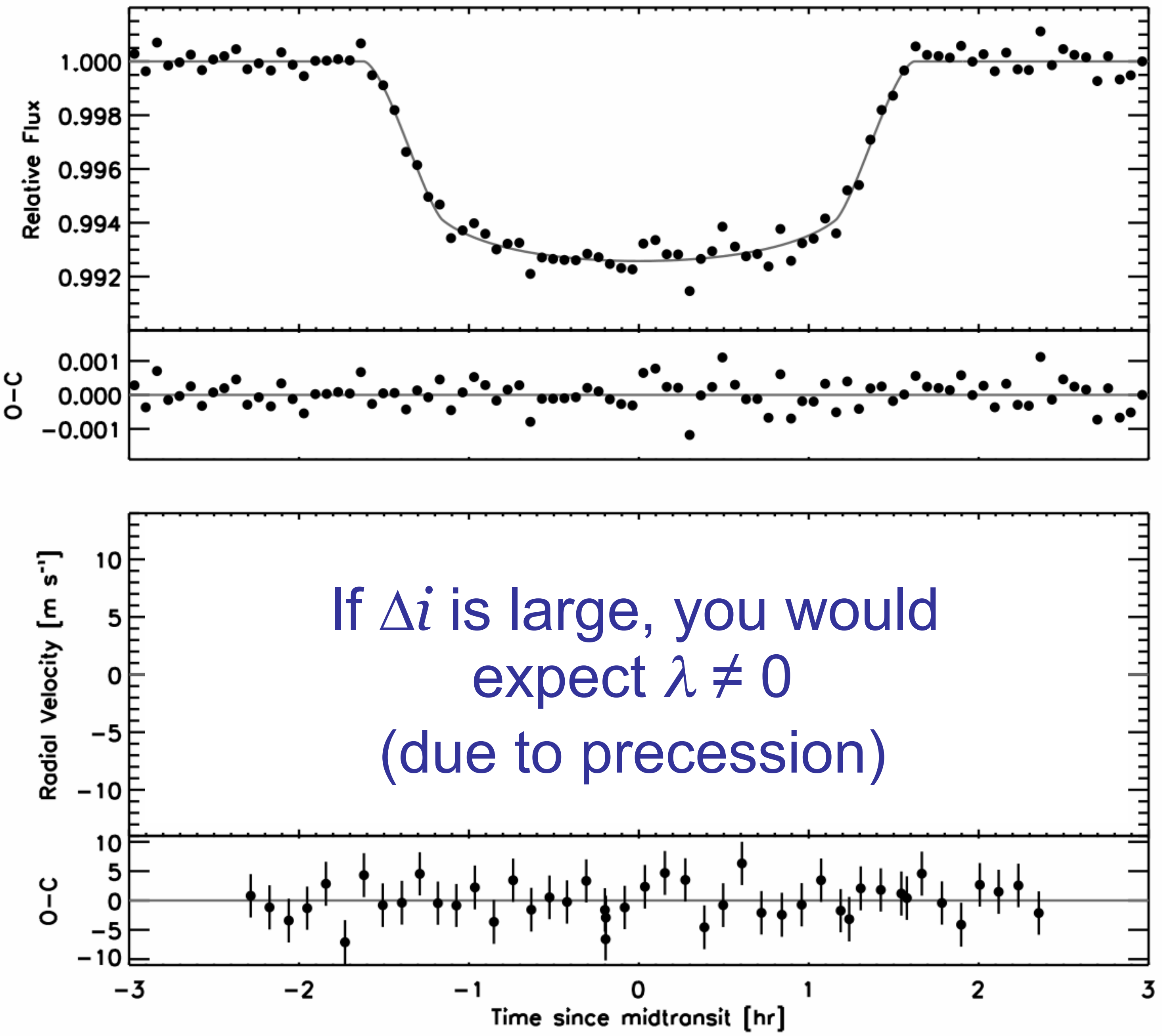
You must also know the ***mutual inclination***.



Mardling (2010):

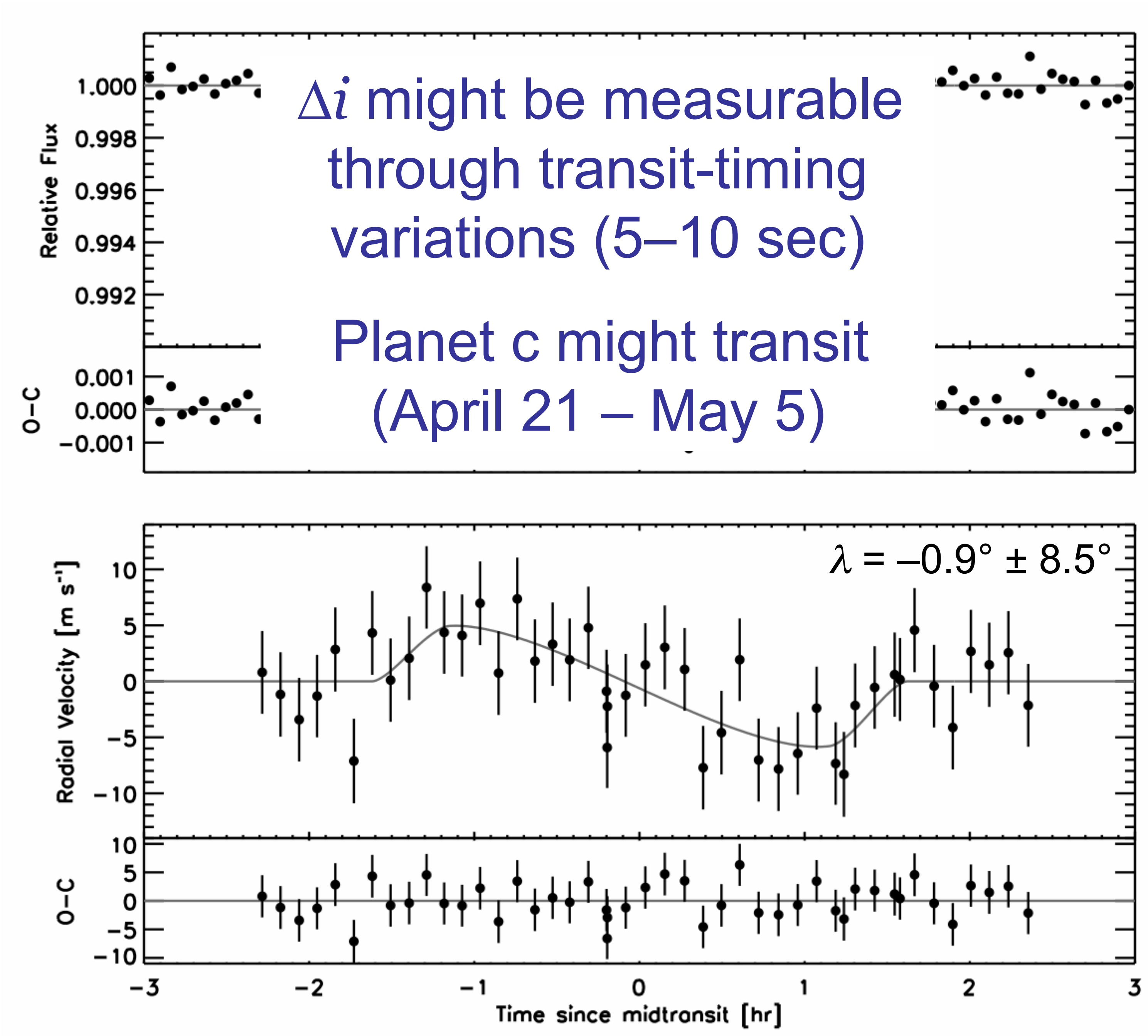
You must also know the ***mutual inclination***.





If Δi is large, you would expect $\lambda \neq 0$ (due to precession)

Bakos et al. (2009); Winn et al. (2010)

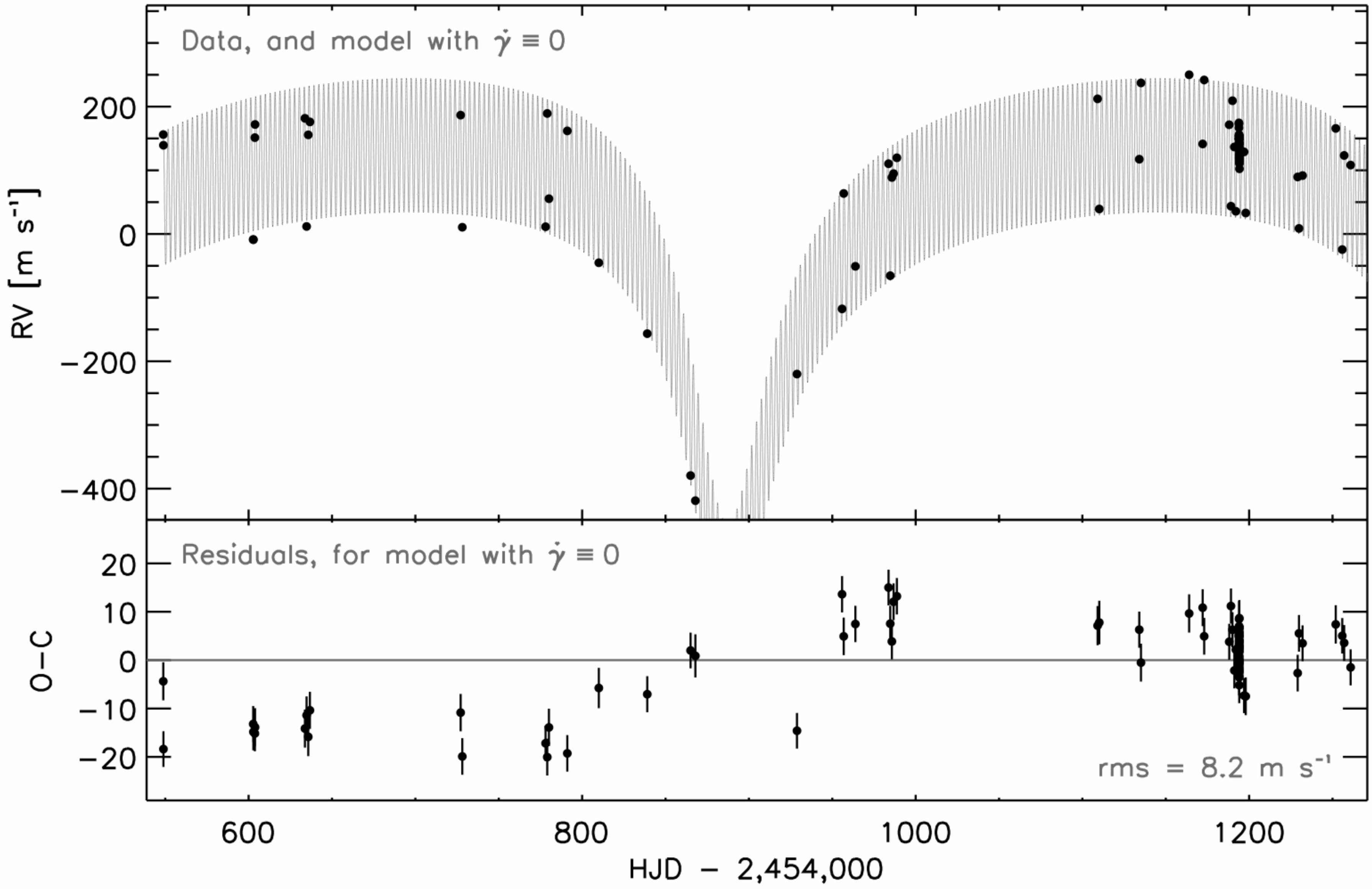


Δi might be measurable through transit-timing variations (5–10 sec)

Planet c might transit (April 21 – May 5)

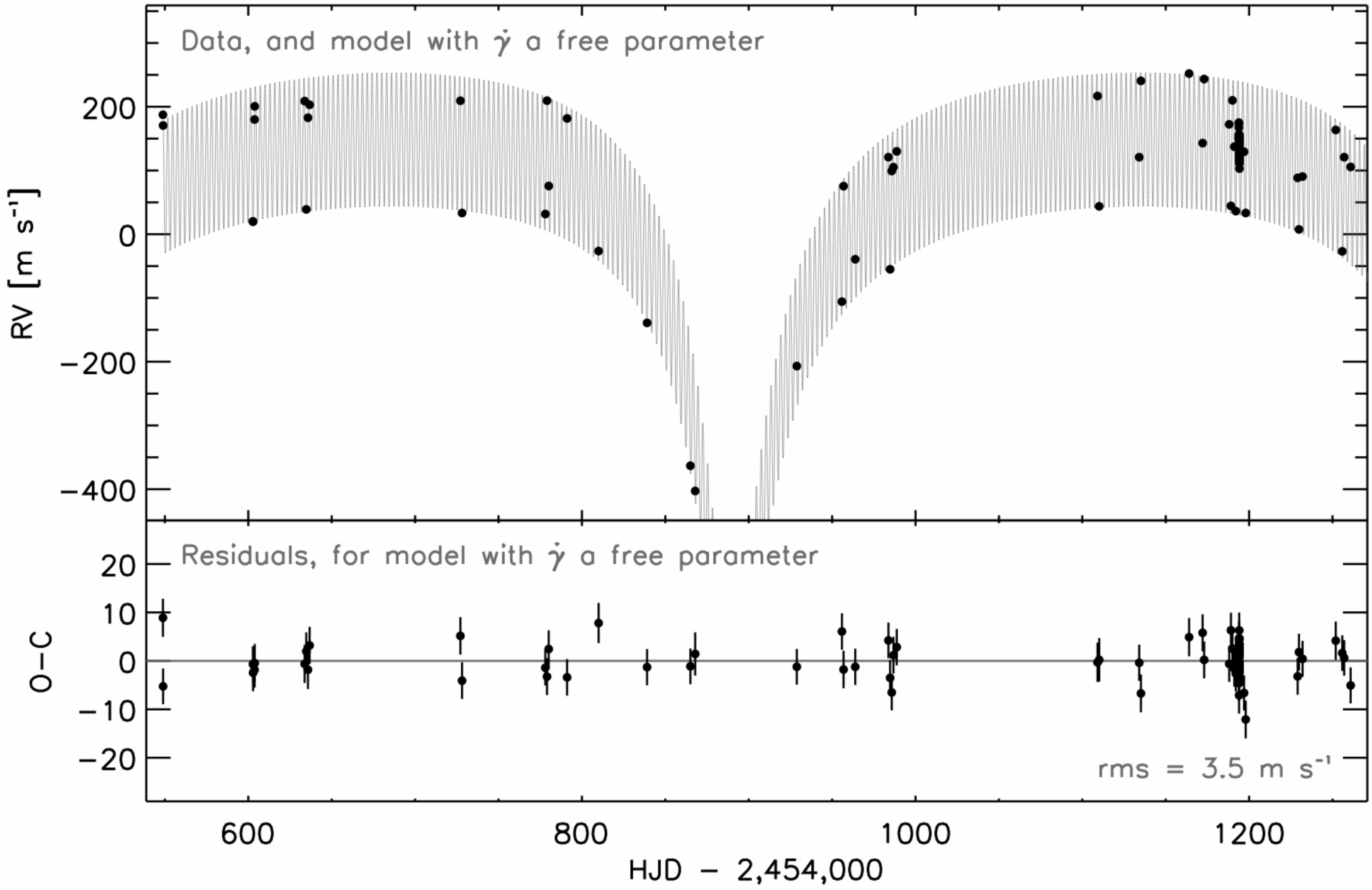
Bakos et al. (2009); Winn et al. (2010)

HAT-P-13 b,c



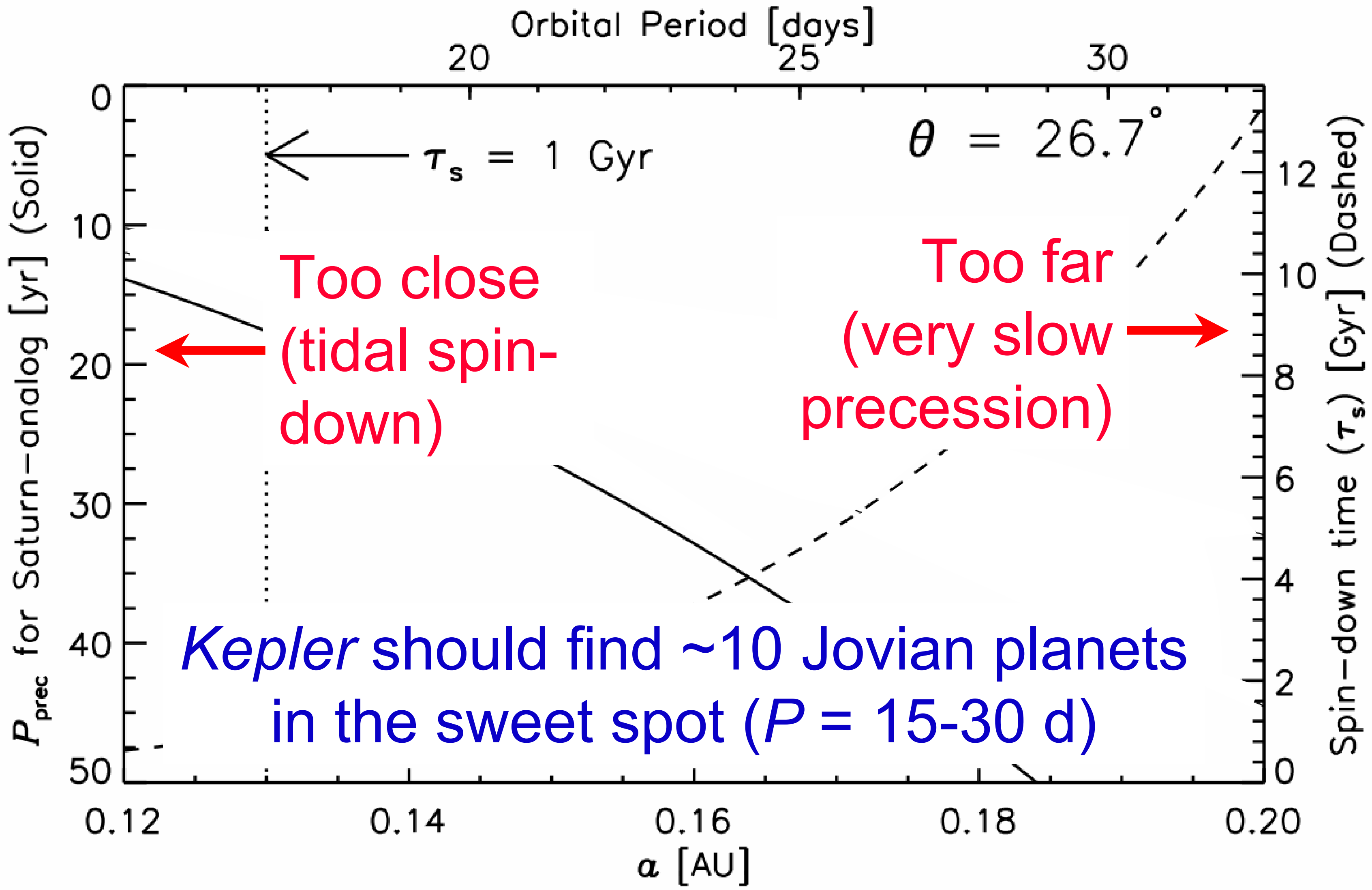
Bakos et al. (2009); Winn et al. (2010)

HAT-P-13 b,c,d



Bakos et al. (2009); Winn et al. (2010)

The “sweet spot” for precession



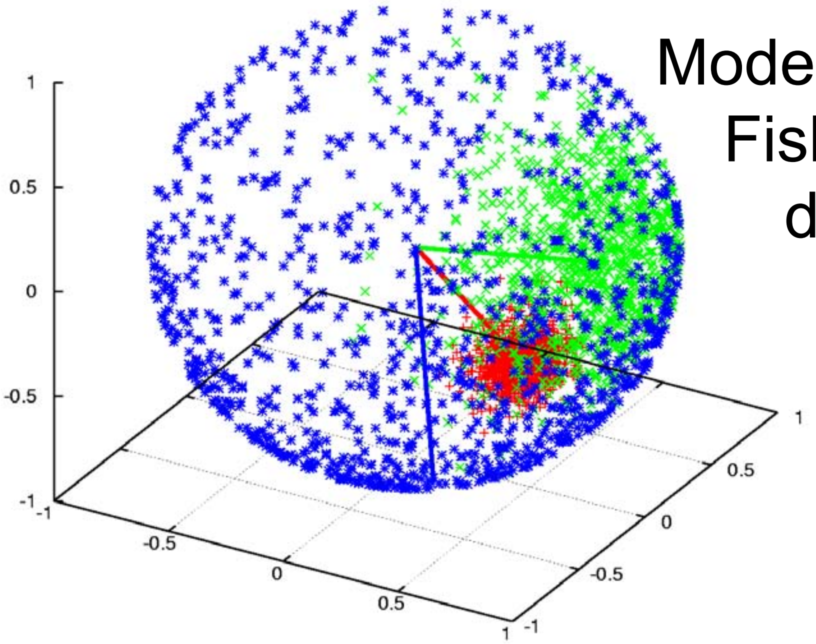
Too close (tidal spin-down)

Too far (very slow precession)

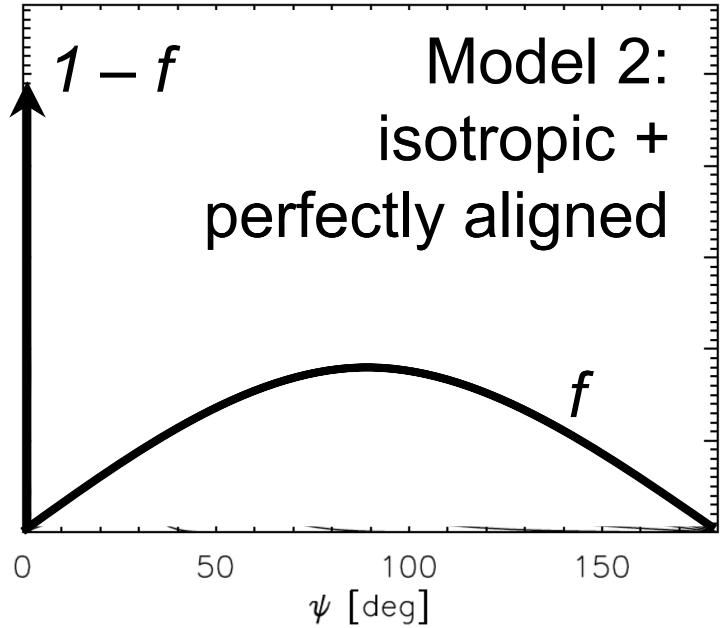
Kepler should find ~10 Jovian planets in the sweet spot (P = 15-30 d)

Carter & Winn (2010)

Ensemble results

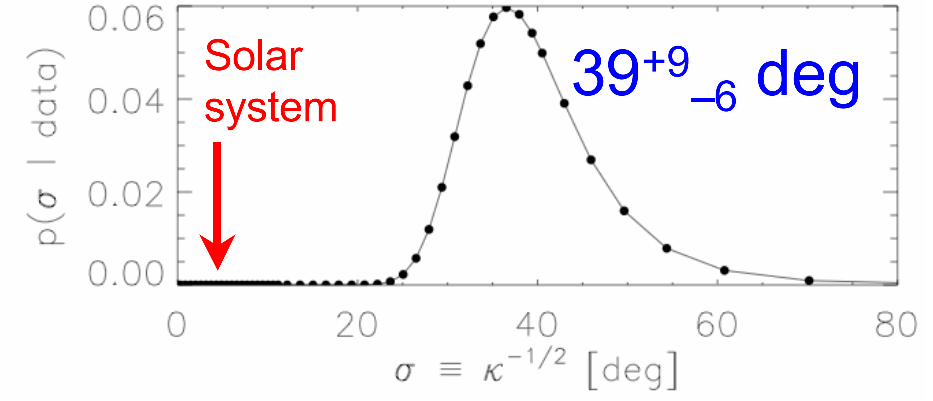


Model 1:
Fisher
dist.



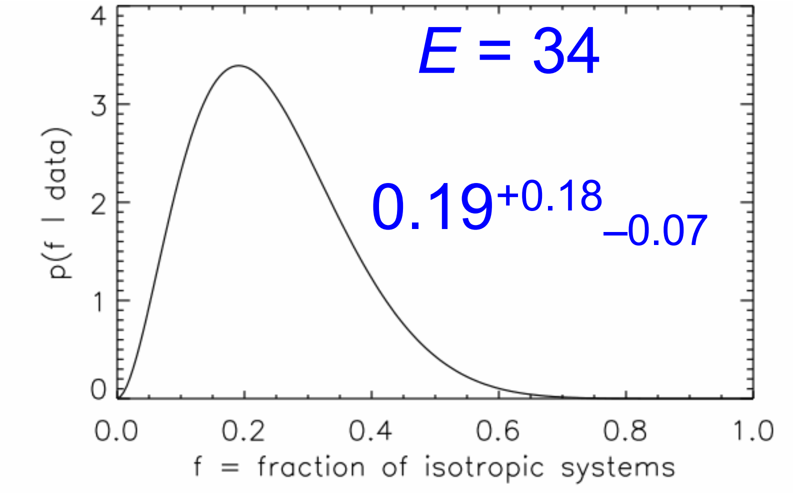
Model 2:
isotropic +
perfectly aligned

$E = 1.1 \times 10^{-5}$



Solar system

39^{+9}_{-6} deg



$E = 34$

$0.19^{+0.18}_{-0.07}$

Fabrycky & Winn (2009)