Exploring the interface between RV and transits

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SDO/HMI 20120606_041559_UTC


PRIMER
ratios
Doppler
Rossiter
useful
overall
radius
usually
nontransiting
therefore
Examples
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TTVs
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Mass
Also
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think
companions
study
Evolutionary
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period
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accuracy
Let
even
computer
assume
understand
planet
far
intensity
density
RVs
fact
data
p-modes
Now
orbit
Show
away
give
know
calculate
gravitational
shift
Recognize
transit
uncertainty
in-plane
2/3
SURFACE
compared
inference
though
long
planets
accelerating
degeneracy
parameter
Measure
stable
star
photometric
Transits
gravity
ie
transits
masses
something
velocity
willing
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get
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RV
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Rossiter-McLaughlin
also
practice
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two
activity
transiting
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better
Age
principle
parallax
photometry
circular
conjunction
mapping
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Teff
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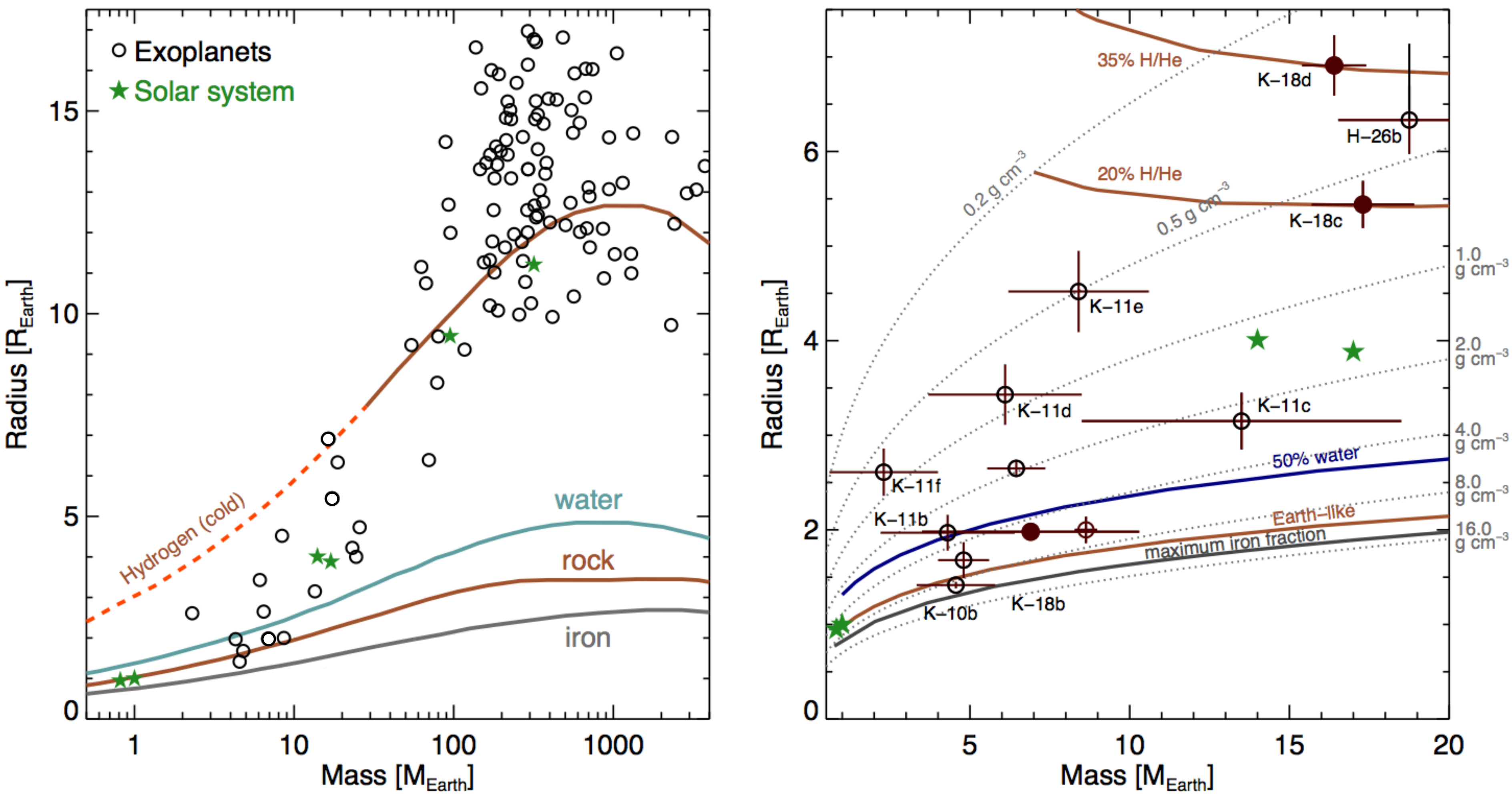
still
periods
Kepler
eccentric
help
factor
surface
order
gained
bring
fraction

wordle.net

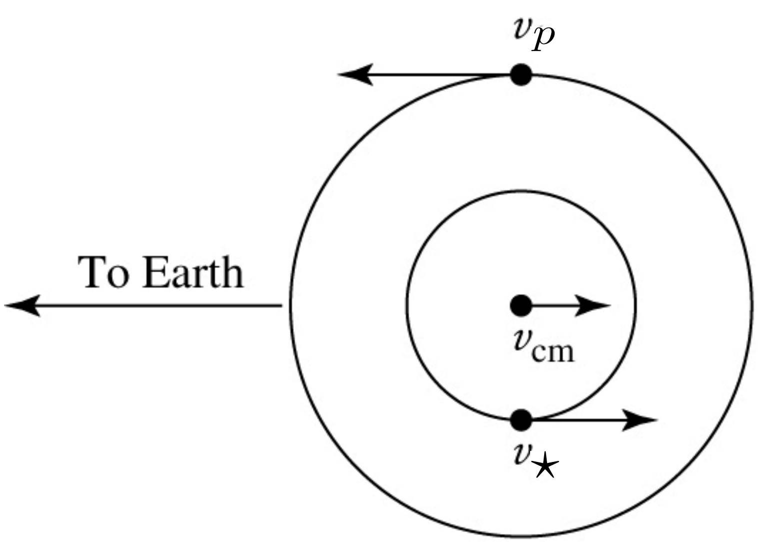
- Measure planet masses
- Detect non-transiting companions
- Survey with different selection function
- Measure stellar obliquity (RM effect)

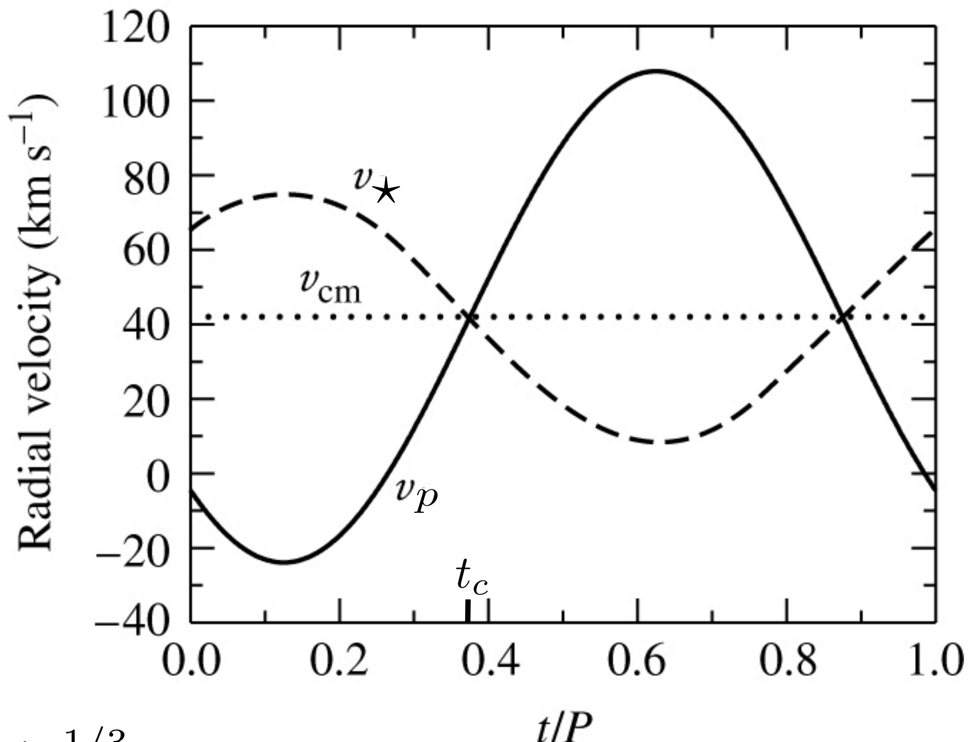
Measure planet masses



Cochran et al. (2012)

Circular orbit





$$v_\star = \frac{2\pi a_\star}{P}$$

$$a_\star = \frac{m_p}{m_\star + m_p} a$$

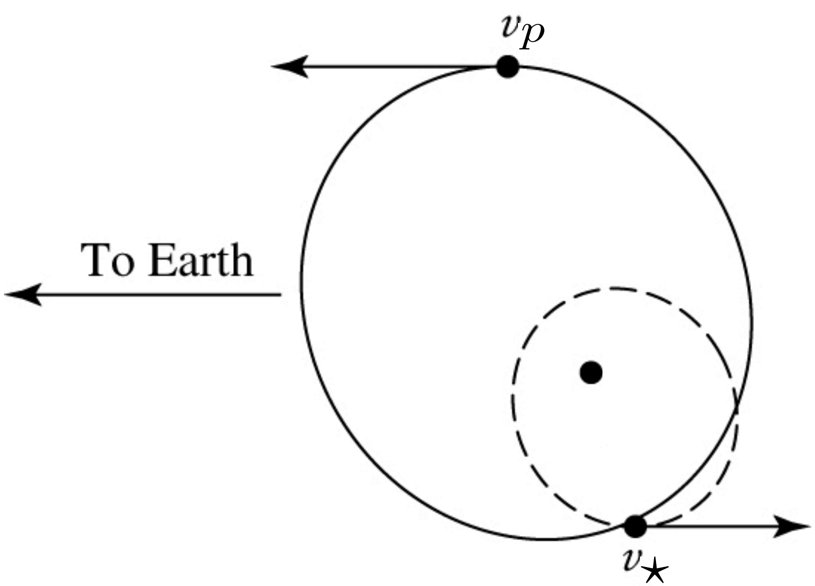
$$\frac{G(m_\star + m_p)}{a^3} = \left(\frac{2\pi}{P}\right)^2$$

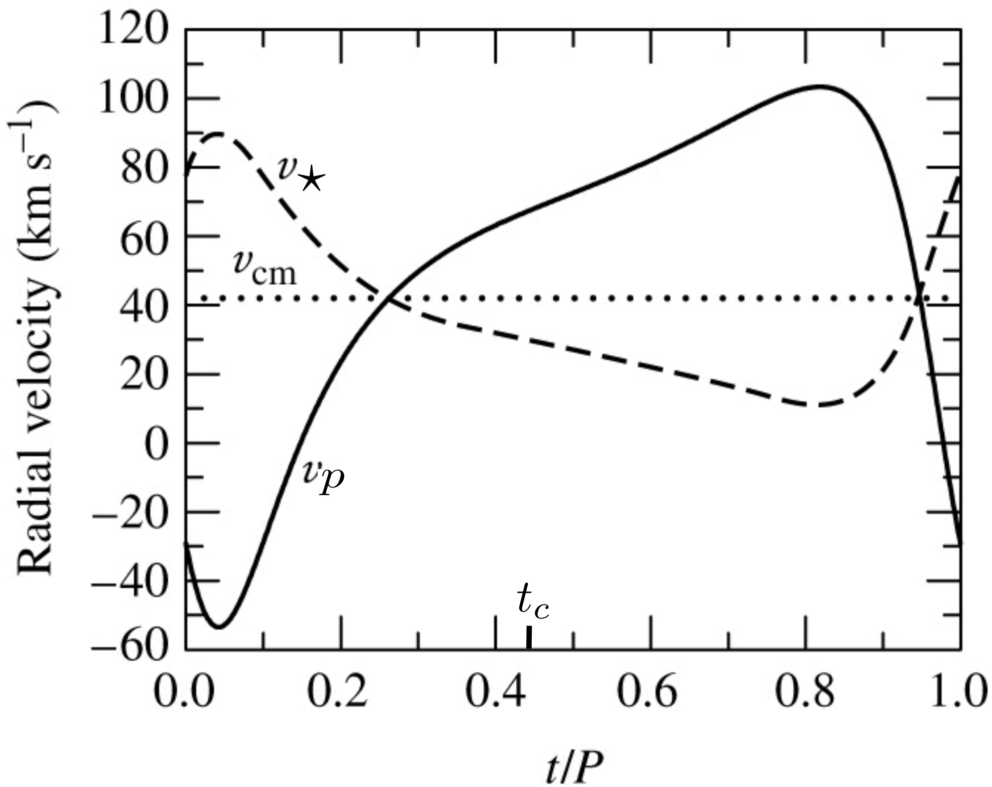
$$v_\star = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{m_p}{(m_\star + m_p)^{2/3}}$$

$$\mathrm{RV}_\star(t) = -\left(\frac{2\pi G}{P}\right)^{1/3} \frac{m_p \sin I}{(m_\star + m_p)^{2/3}} \sin\left[\frac{2\pi(t - t_c)}{P}\right]$$

4 parameters: Offset, Period, Phase, Amplitude

Eccentric orbit





$$\mathrm{RV}_\star(t) = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{m_p \sin I}{(m_\star + m_p)^{2/3}} \frac{1}{\sqrt{1-e^2}} \{\cos[f(t)+\omega] + e\cos\omega\}$$

see, e.g., chap. 2 of *Exoplanets* (2010)

6 parameters: Offset, Period, Phase, Amplitude, e, ω

Radial velocity variations

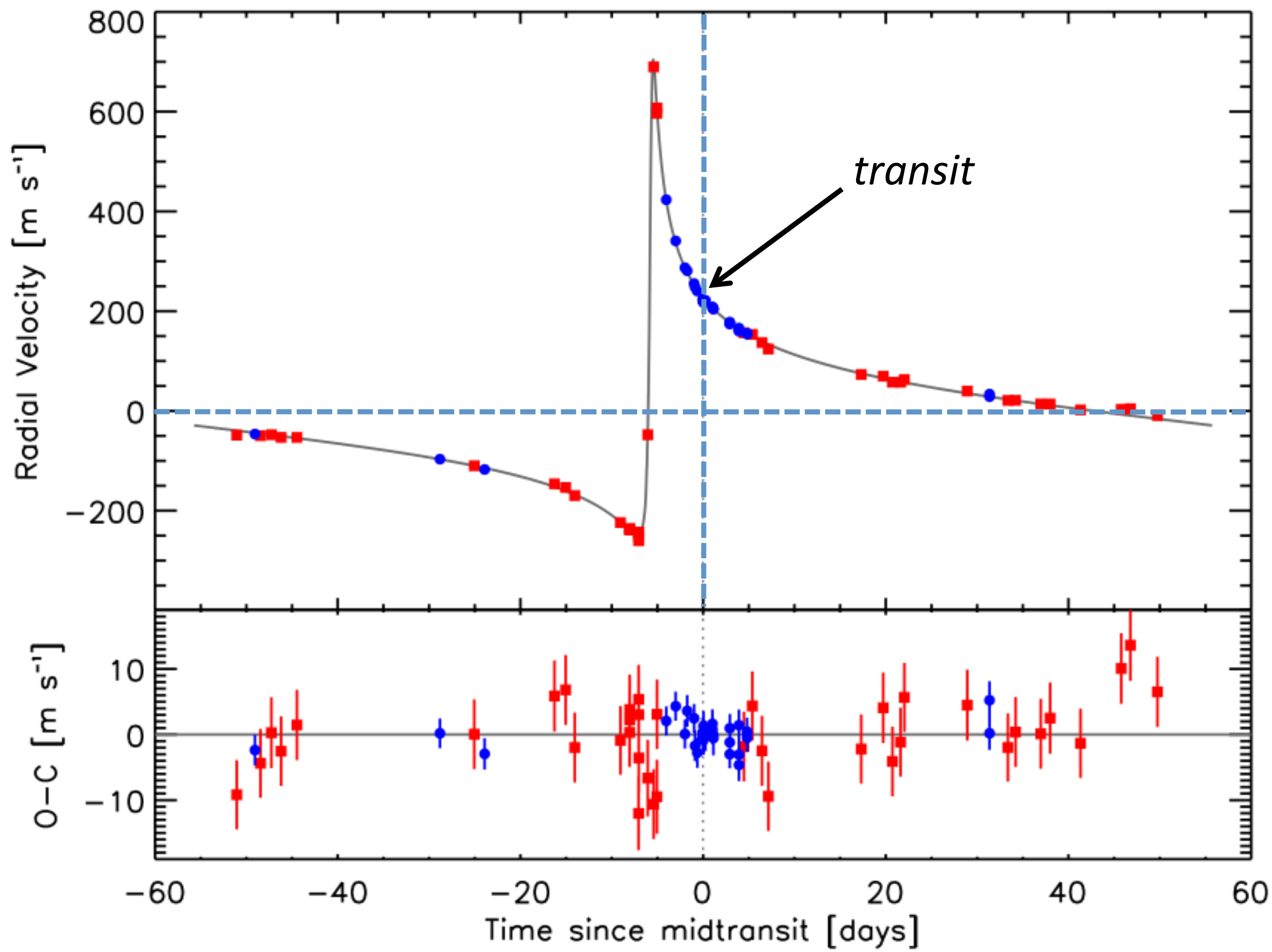
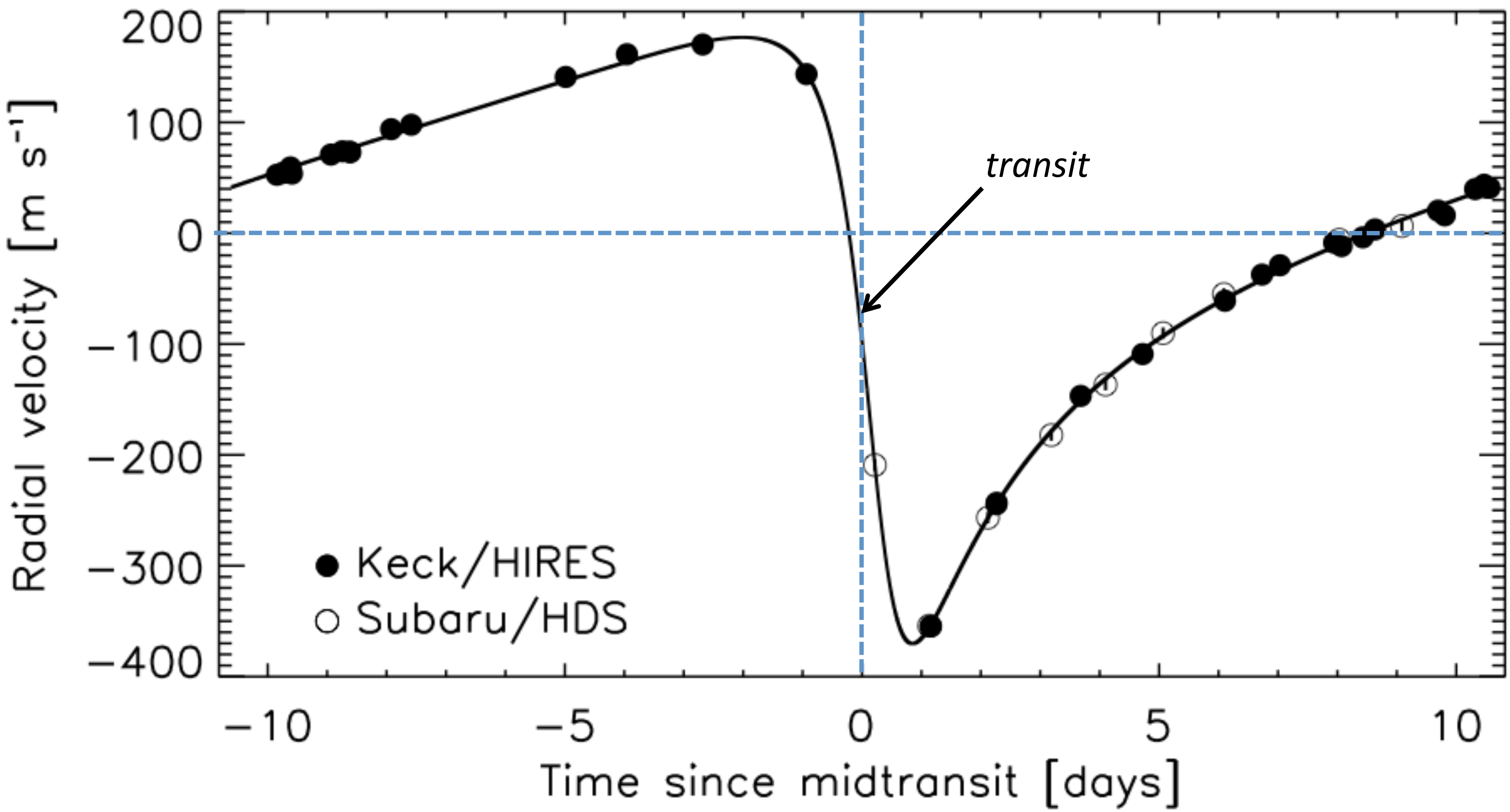


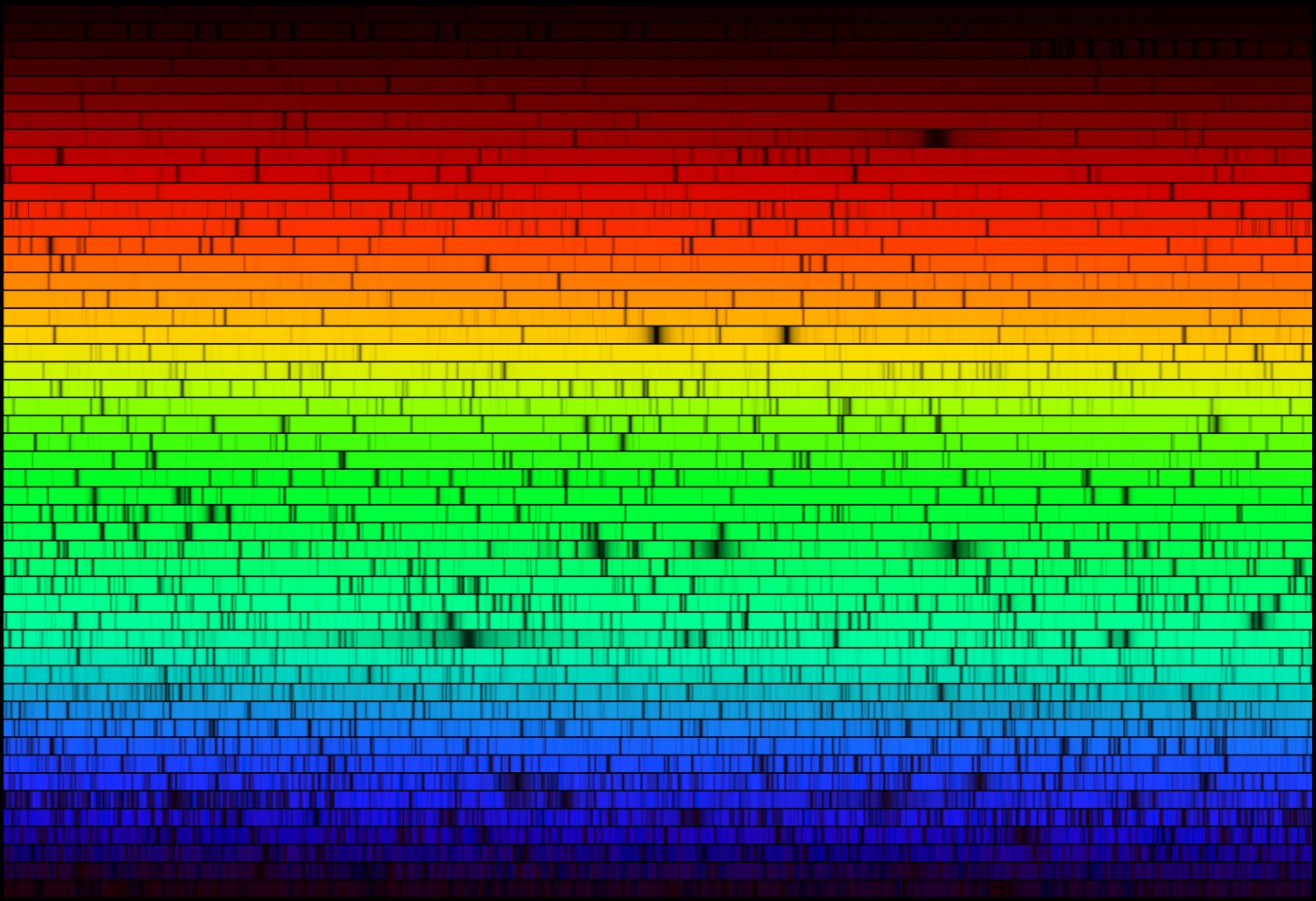
Figure 4. Radial-velocity variation of HD 80606, as a function of orbital phase.

Winn et al. (2009)

Radial velocity variations



Winn et al. (2009)



N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Orders of magnitude

$$\frac{\Delta\lambda}{\lambda} = \frac{K_\star}{c}$$

$$K_\star \approx 140 \text{ m s}^{-1} \left(\frac{m_p \sin I}{M_{\rm Jup}}\right) \left(\frac{m_\star}{M_\odot}\right)^{-2/3} \left(\frac{P}{3 \text{ days}}\right)^{-1/3}$$

$$K_\star \approx 9 \text{ cm s}^{-1} \left(\frac{m_p \sin I}{M_\oplus}\right) \left(\frac{m_\star}{M_\odot}\right)^{-2/3} \left(\frac{P}{1 \text{ year}}\right)^{-1/3}$$

$$R = \frac{\lambda}{\Delta\lambda} \sim 2 \times 10^6 \;\text{ to }\; 3 \times 10^9$$

Gas absorption cell

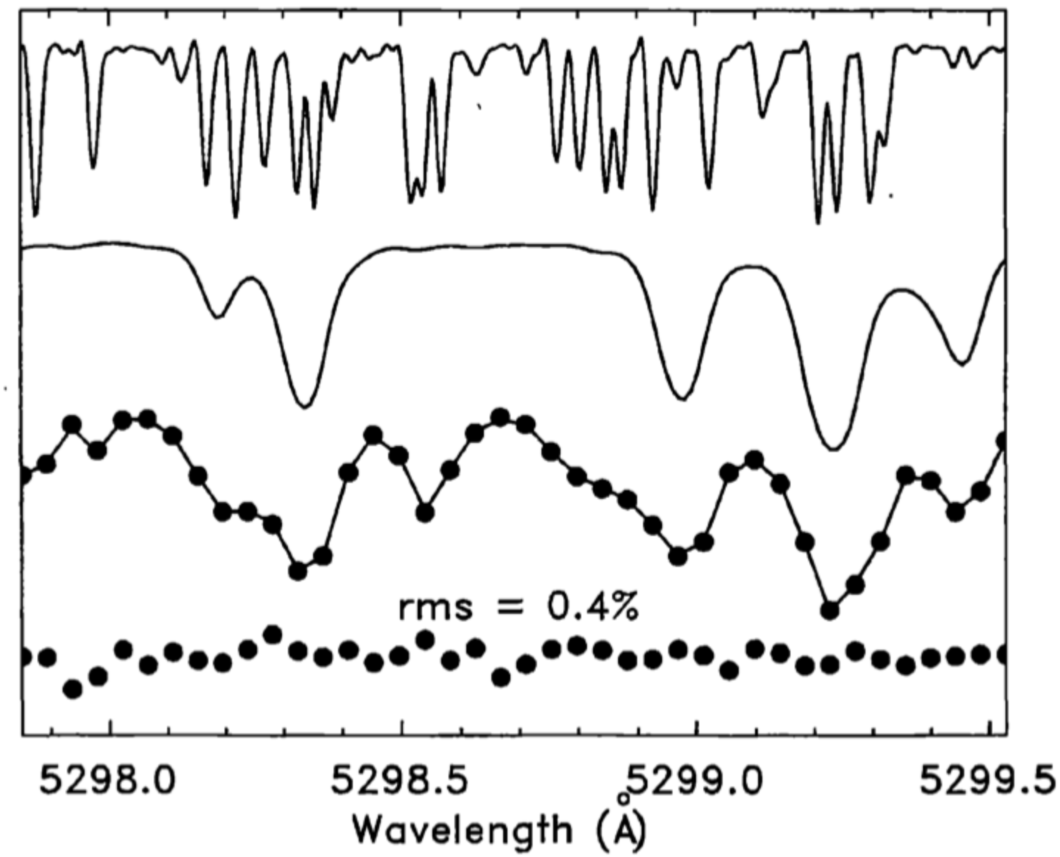
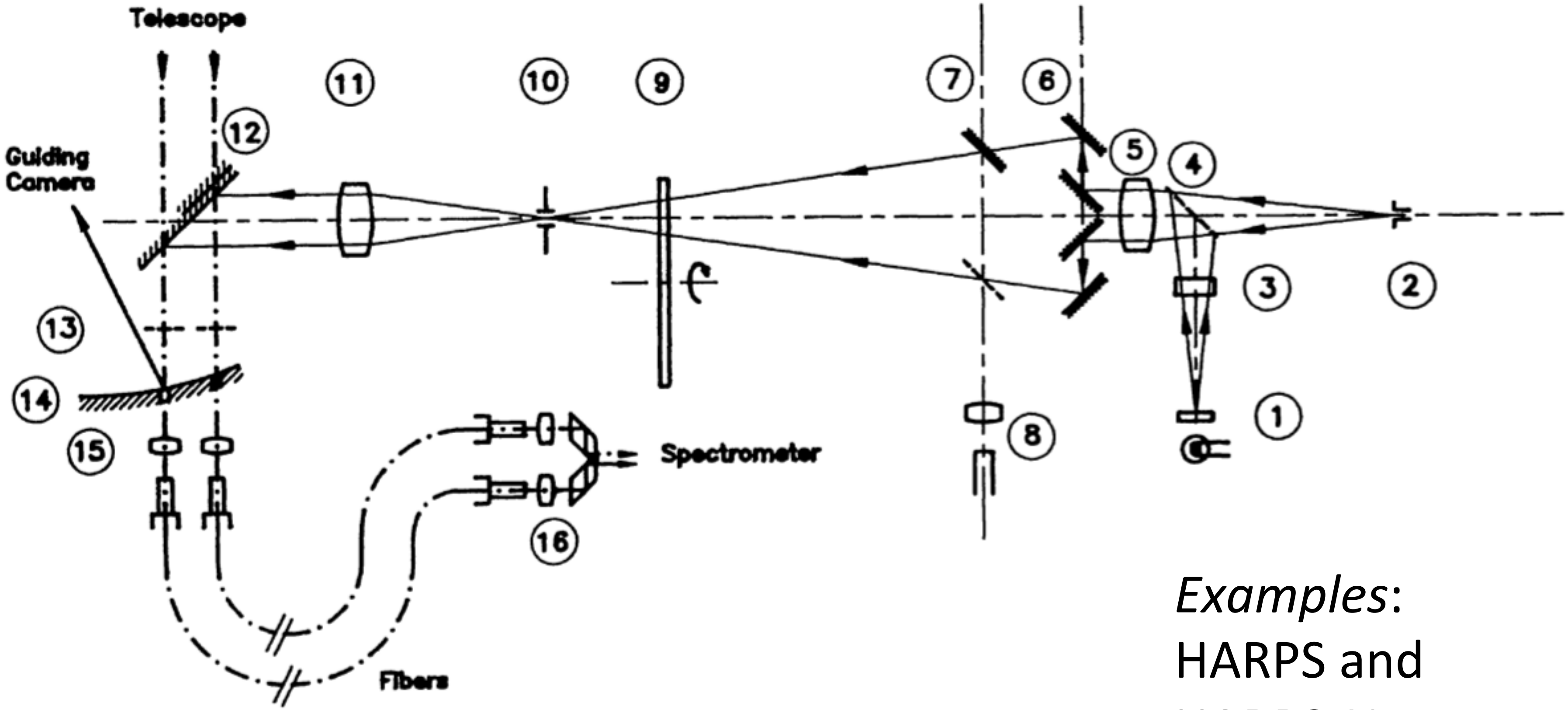


FIG. 1—The modeling process. Top: The template iodine cell spectrum. Second: The template stellar spectrum (τ Ceti, G8 V). Third: The points are an observation of τ Ceti made through the iodine absorption. The solid line is a model of the observation. The model is composed of the template iodine and stellar spectra. The free parameters consist of the spectrograph PSF and the Doppler shift of the template star relative to the template iodine.

Examples:
Keck/HIRES
Magellan/PFS

Butler et al. (1996)

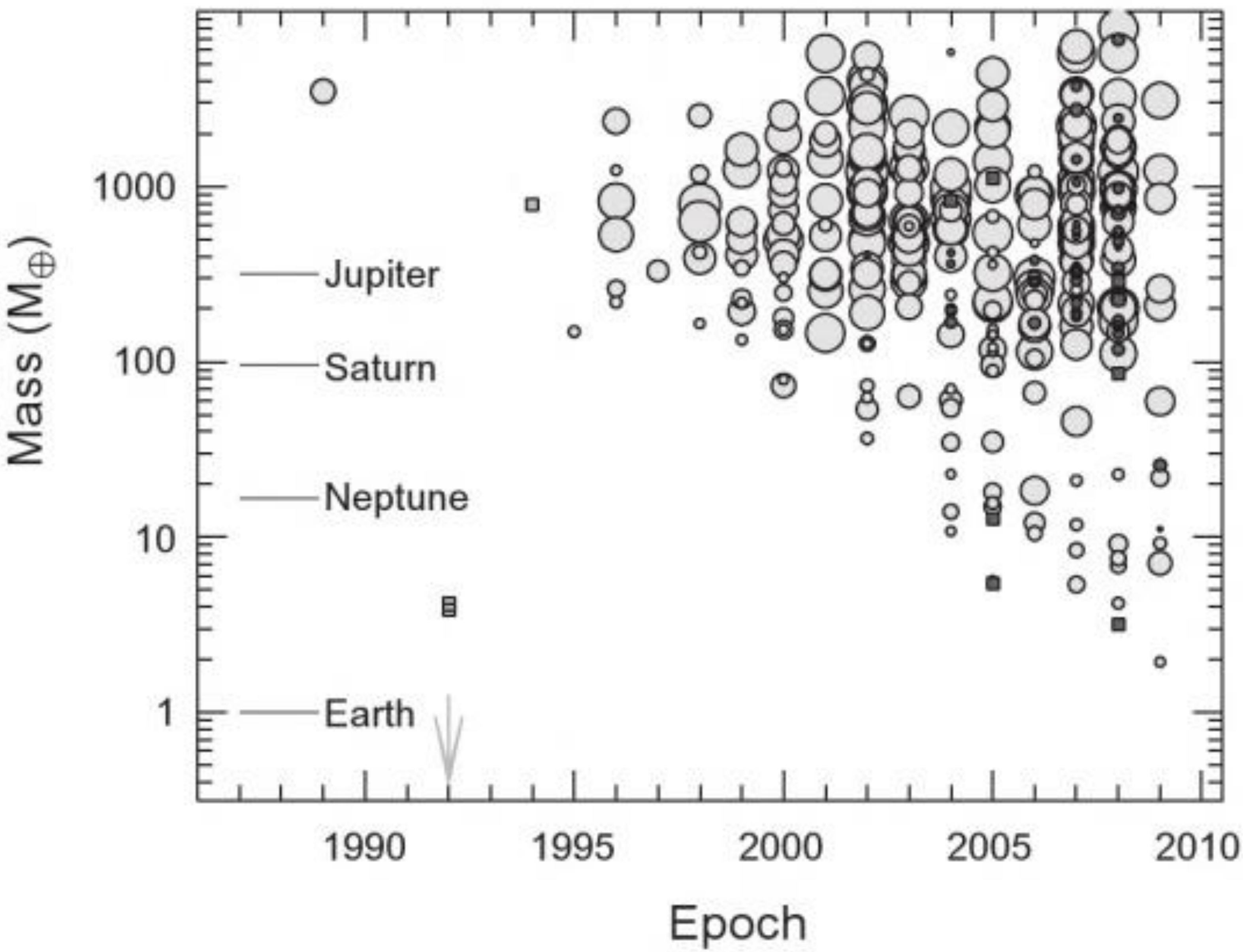
Simultaneous reference



Examples:
HARPS and
HARPS-N

Fig. 4. Optical layout of the calibration system in the front end adaptor: 1) tungsten lamp and diffuser, 2) hollow cathode thorium lamp, 3) colour corrector filter. 4) static beam–splitter, 5) relay achromat, 6) mirrors for beam angular splitting, 7) removal mirror and beam splitting (part of the accelerometry experiment), 8) optical fibre of the Fabry–Perot light (part of the accelerometry experiment), 9) circular wedge 10) pupil, 11) achromat (to put the pupil at infinity), 12) calibration mirror, 13) fibre mask, 14) concave mirror with 2 holes, 15) spectrometer linking fibres and aperture converter, 16) aperture converter optics and rhomboid prisms (to bring the beams closer to the focus of the collimator)

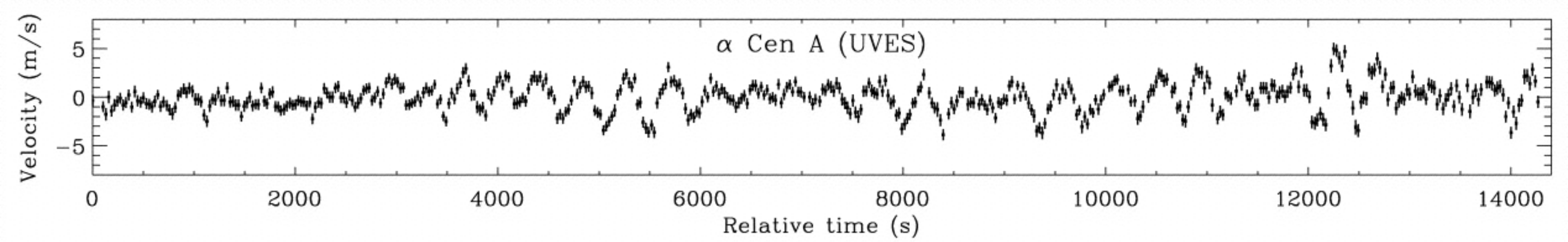
Baranne et al. (1996)

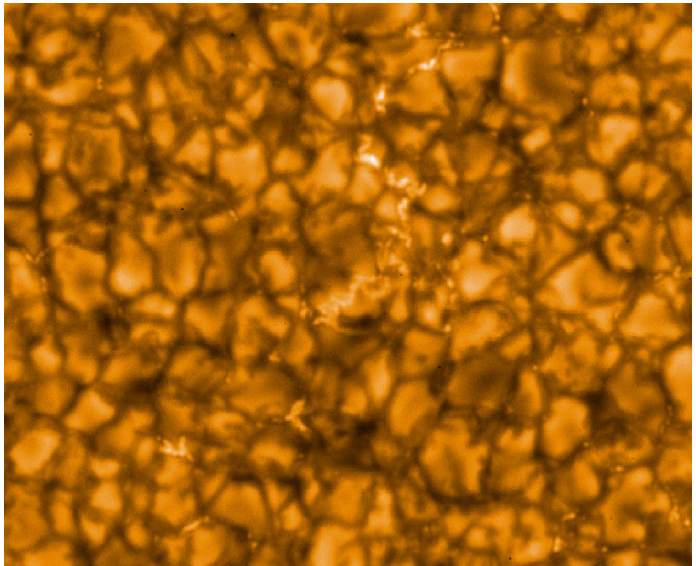


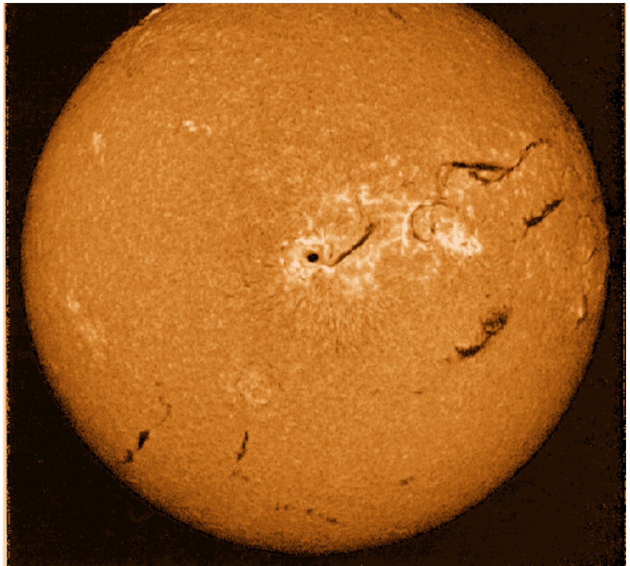
Lovis & Fischer (2010)

Stellar radial-velocity noise

Acoustic oscillations	minutes
Granulation	hours
Spots and plages	days
Long-term magnetic cycles	years

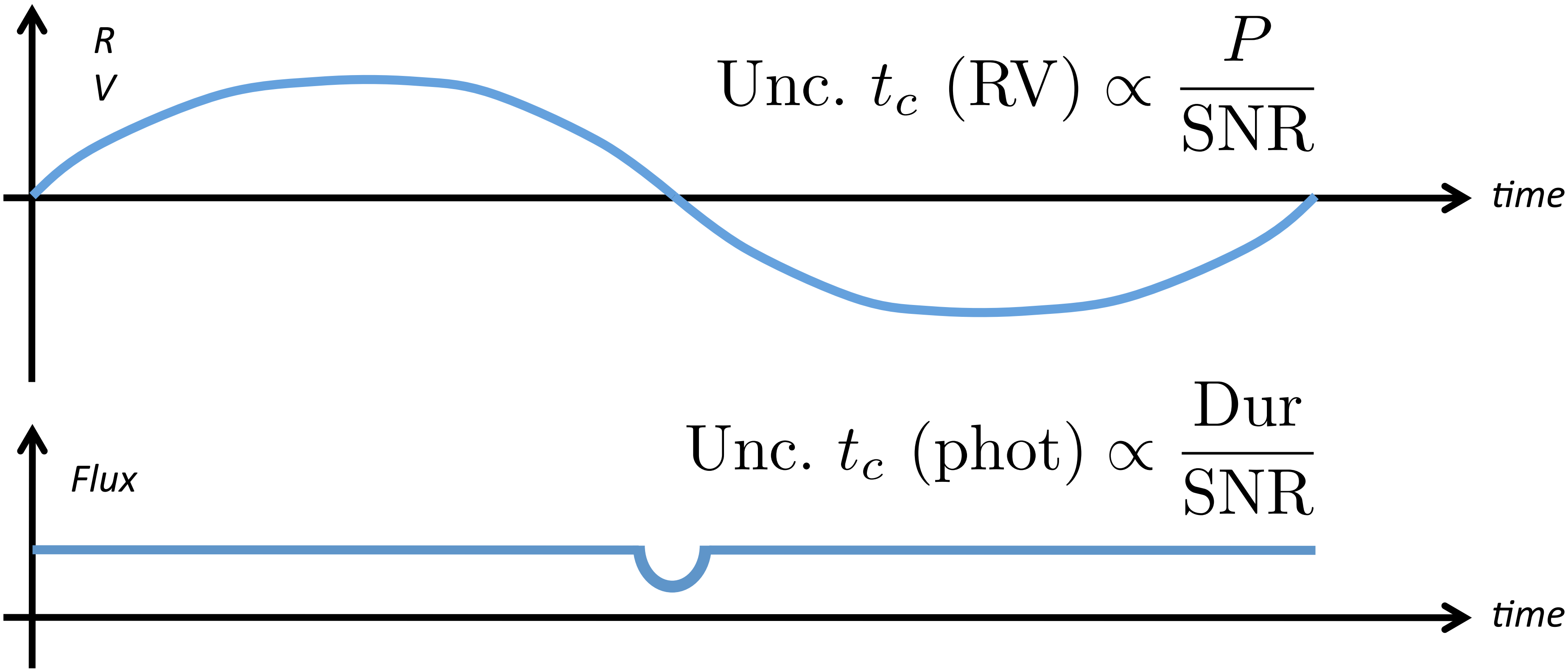






Transits help RV analysis

$$p_{\mathrm{tra}} = \frac{R_\star}{a}$$



$$\text{Unc. } t_c \text{ (RV)} \propto \frac{P}{\mathrm{SNR}}$$

$$\text{Unc. } t_c \text{ (phot)} \propto \frac{\mathrm{Dur}}{\mathrm{SNR}}$$

6 parameters: Offset, Period, Phase, Amplitude, e, ω

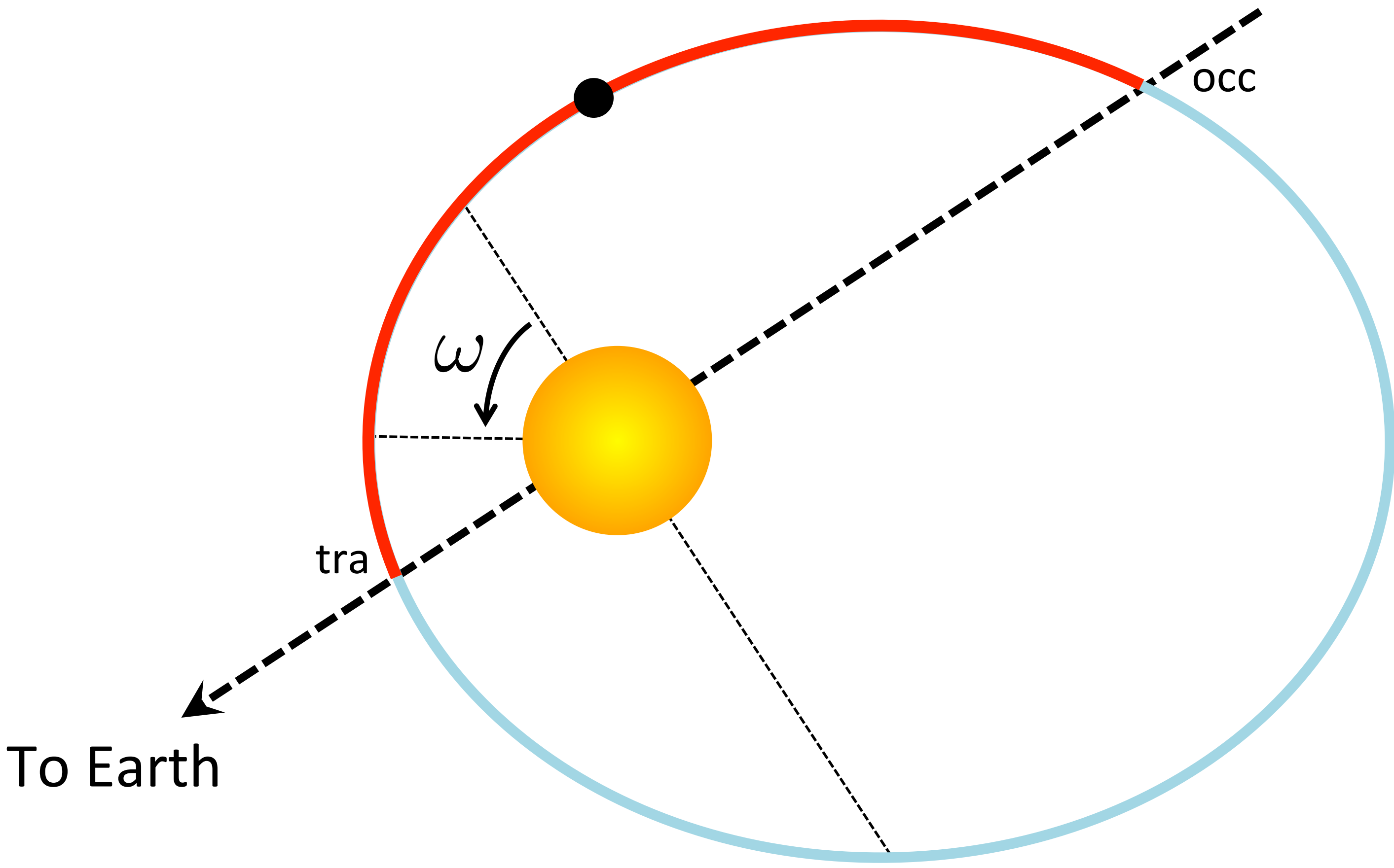
with transits

4 parameters: Offset, *[Period]*, *[Phase]*, Amplitude, e, ω

circular orbit

2 parameters: Offset, *[Period]*, *[Phase]*, Amplitude, *[e]*, *[ω]*

Eccentricity



$$\Delta t_c \approx \frac{P}{2}\left[1 + \frac{4}{\pi} e \cos\omega\right] \qquad \frac{T_{\rm occ}}{T_{\rm tra}} \approx \frac{1 + e\sin\omega}{1 - e\sin\omega}$$

Stellar mean density

Light curves: time, time^{-1}, dimensionless

$$G = 6.673 \times 10^{-11}\ \mathrm{kg}^{-1}\ \mathrm{m}^3\ \mathrm{s}^{-2}$$

$$\frac{1}{G} = 1.16\ (\mathrm{g\ cm}^{-3})\ \mathrm{hr}^2$$ ← We expect to learn something with units g cm^{-3}

$$\rho_\star + \delta^{3/2}\rho_p = \frac{3\pi}{GP^2}\left(\frac{a}{R_\star}\right)^3$$

$$\frac{a}{R_\star} \approx \frac{\delta^{1/4}}{\pi}\,\frac{P}{\sqrt{T\tau}}\,\frac{\sqrt{1-e^2}}{1+e\sin\omega}$$

Transit light curves + (e,ω) + Kepler's 3rd law → Stellar mean density

Planetary surface gravity

Light curves: time, time^{-1}, dimensionless

$$c = 2.9979 \times 10^{10}\ \mathrm{cm\ s^{-1}}$$ ← We expect to learn something with units cm, cm s^{-2}

$$g_p \equiv \frac{GM_p}{R_p^2} = \frac{2\pi}{P}\ \frac{\sqrt{1-e^2}\ K_\star}{(R_p/a)^2 \sin i}$$

Southworth et al. (2007)

Transit light curves + (e, ω) + K_* + Kepler's 3rd law → Planetary surface gravity

YOUR WEIGHT ON OTHER WORLDS

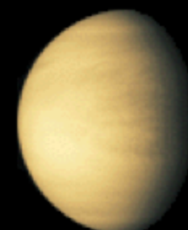
Ever wonder what you might weigh on Mars or The Moon? Here's your chance to find out.

The Planets

MERCURY

Your weight is

VENUS

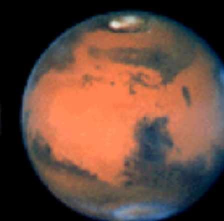


Your weight is

THE MOON

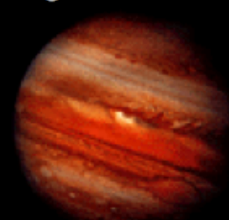
Your weight is

MARS



Your weight is

JUPITER

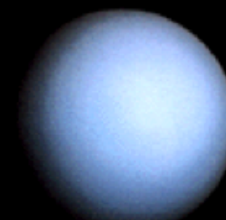


Your weight is

SATURN

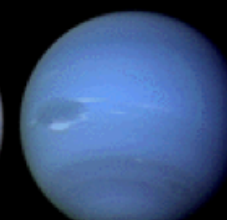
Your weight is

URANUS



Your weight is

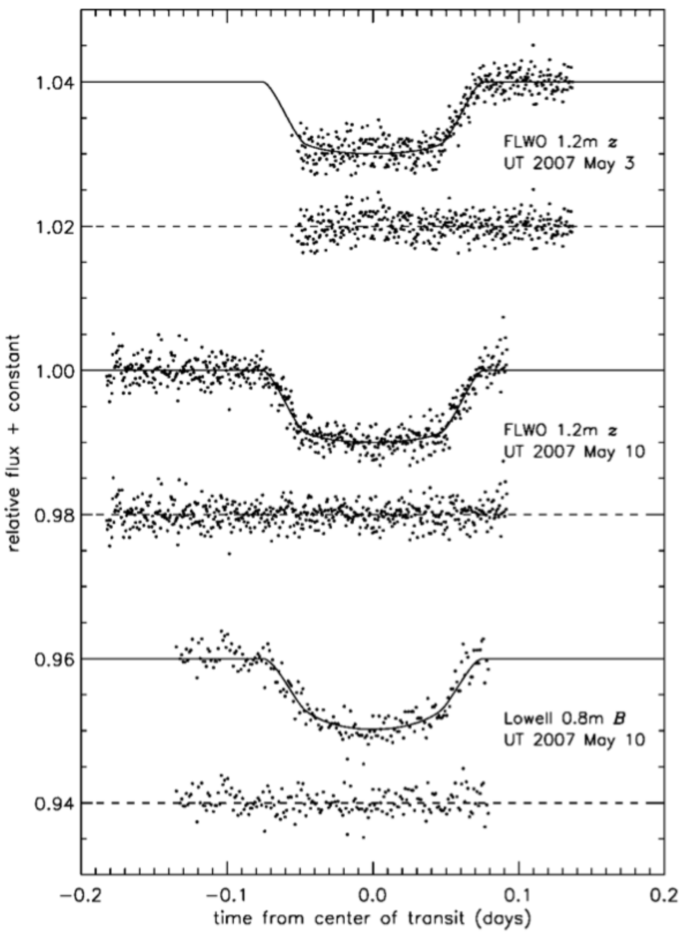
NEPTUNE



Your weight is

Case study: TrES-4

Mandushev et al. (2007)



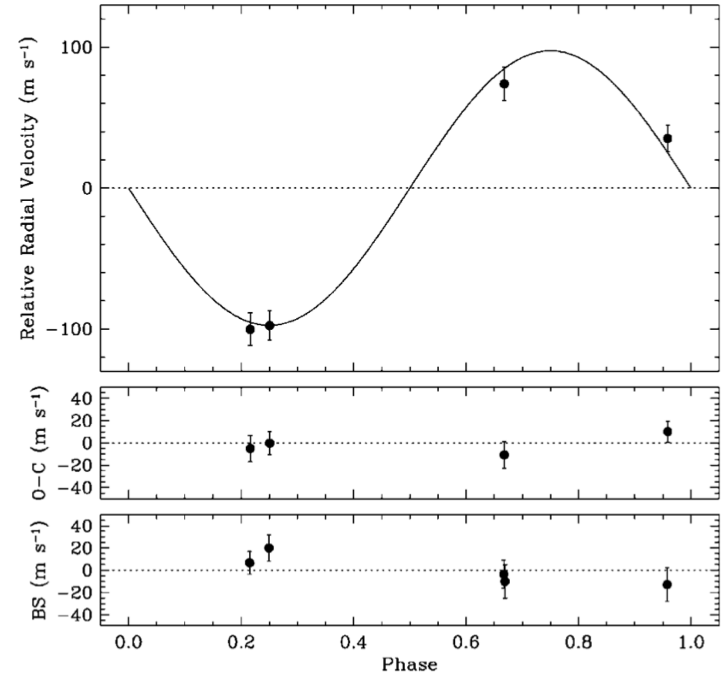
Optical spectrum

Stellar atmosphere models

T_{eff}, Z

Stellar evolution models

M_*, R_*



P, t_c

R_p/R_*

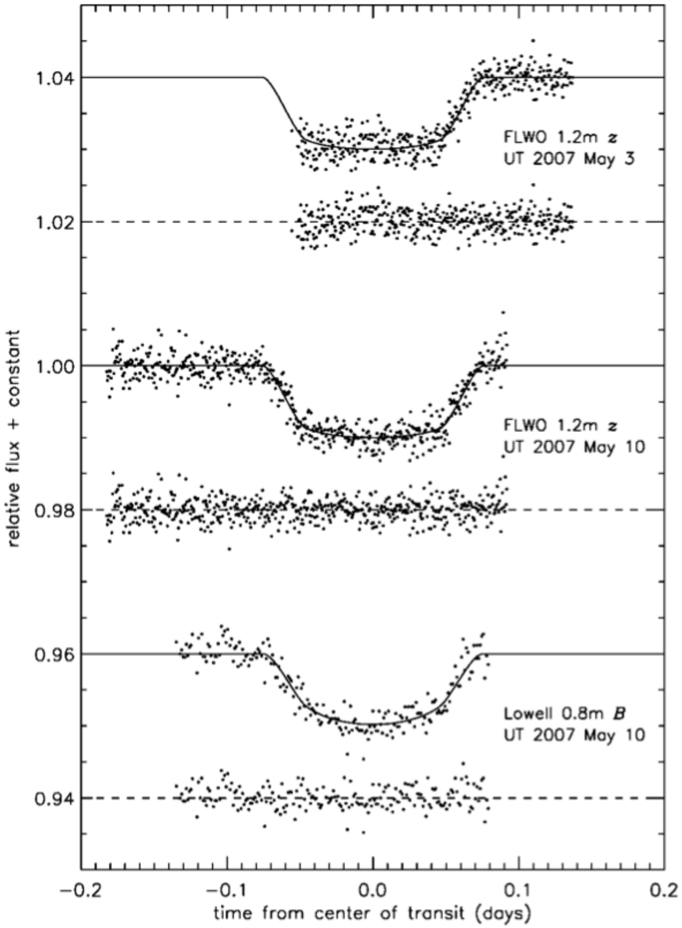
b, Duration

assume $e = 0$

$\rho_\star$

Case study: TrES-4

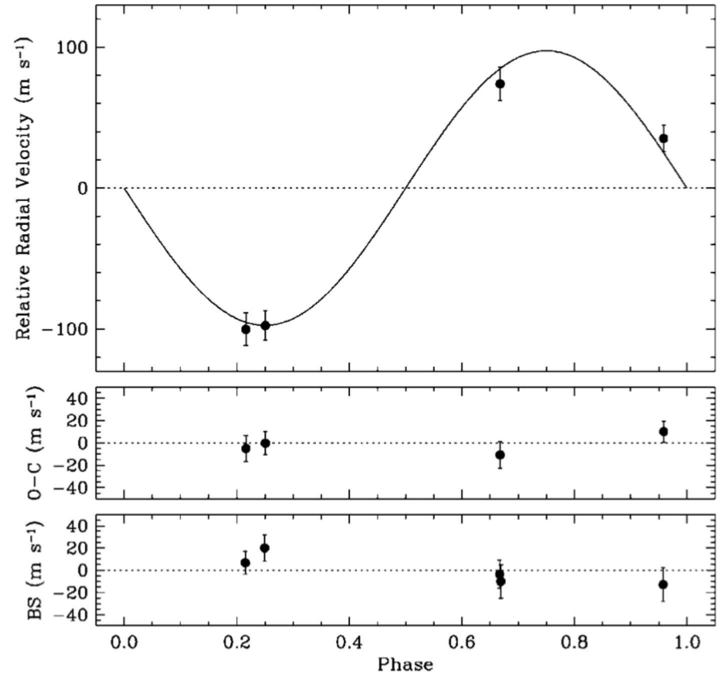
Mandushev et al. (2007)



Optical spectrum

Stellar atmosphere models

T_{eff}, Z



M_*, R_*

K_*

P, t_c

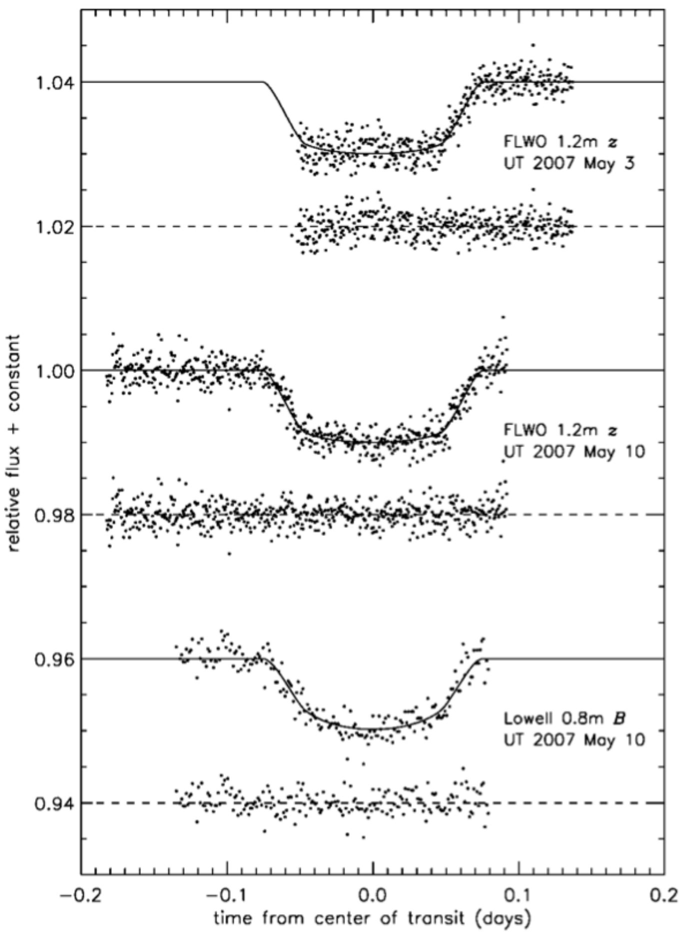
R_p/R_*

b, Duration

assume $e = 0$

Case study: TrES-4

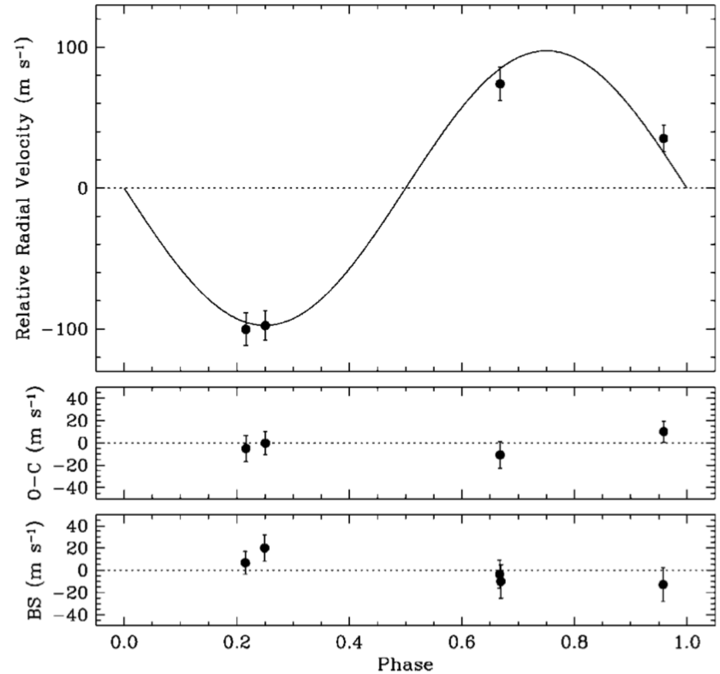
Mandushev et al. (2007)



Optical spectrum

Stellar atmosphere models

T_{eff}, Z



M_*, R_*

K_*

P, t_c

R_p/R_*

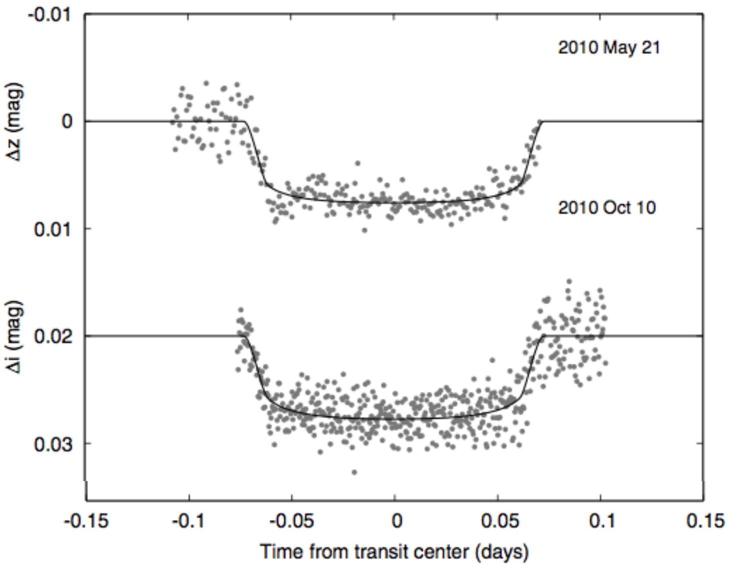
b, Duration

assume $e = 0$

M_p, R_p

Case study: HAT-P-34

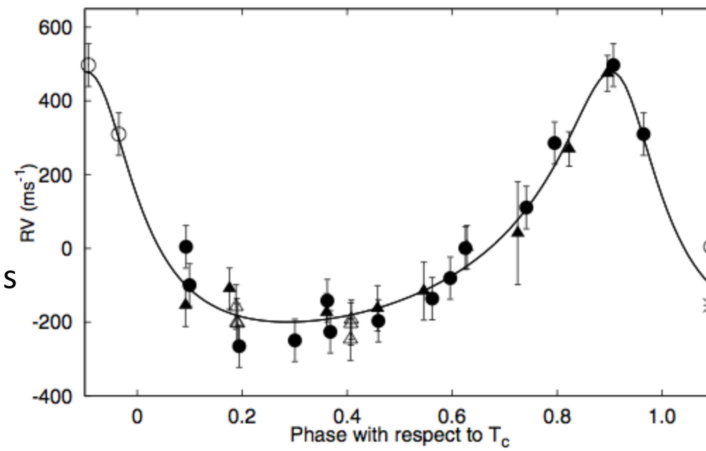
Bakos et al. (2012)



Optical spectrum

Stellar atmosphere models

$T_{\rm eff}, Z$



P, t_c

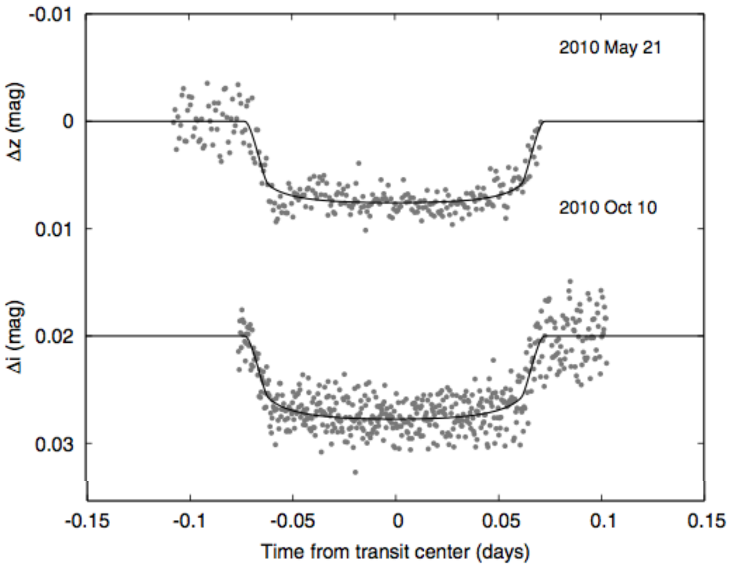
R_p/R_*

b, Duration

K_*, e, ω

Case study: HAT-P-34

Bakos et al. (2012)



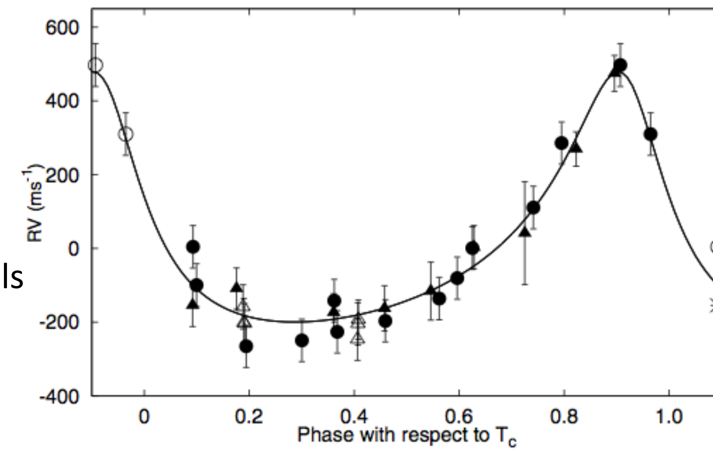
Optical spectrum

Stellar atmosphere models

T_{eff}, Z

Stellar evolution models

M_*, R_*



P, t_c

R_p/R_*

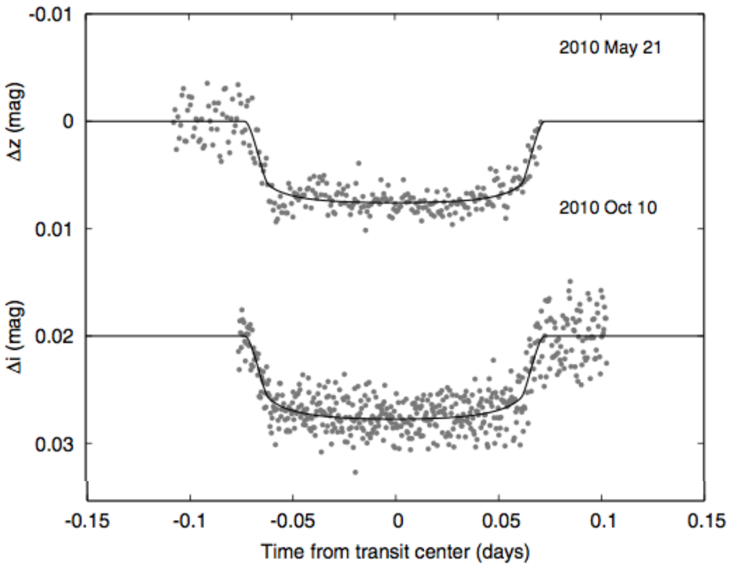
b, Duration

K_*, e, ω

$\rho_\star$

Case study: HAT-P-34

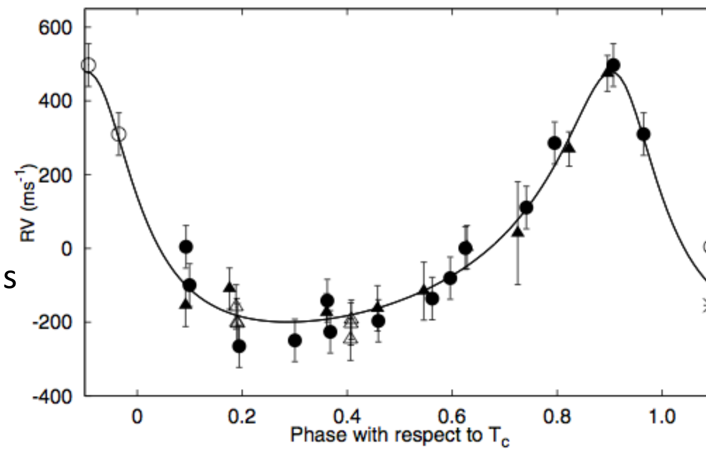
Bakos et al. (2012)



Optical spectrum

Stellar atmosphere models

T_{eff}, Z



P, t_c

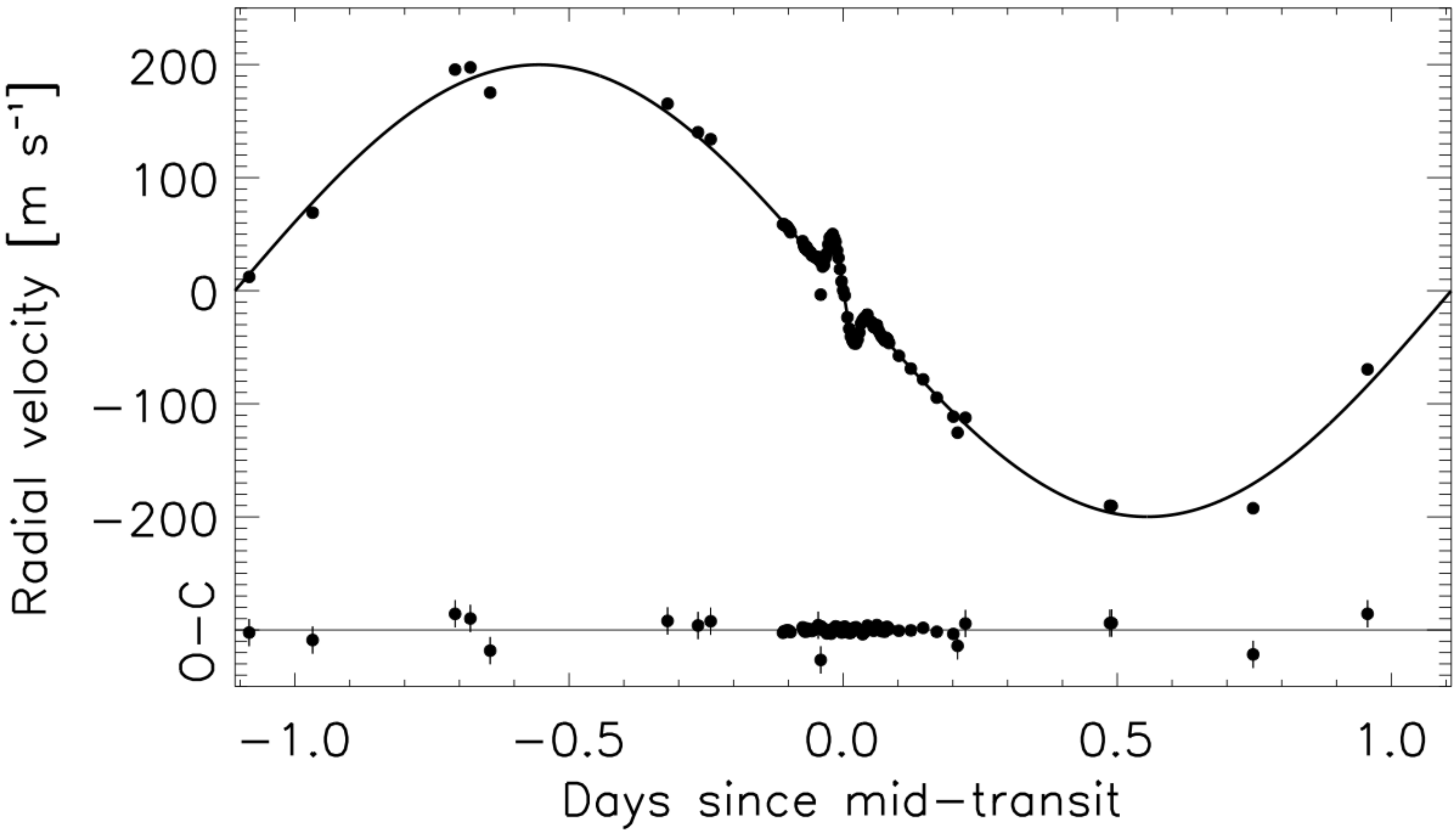
R_p/R_*

b, Duration

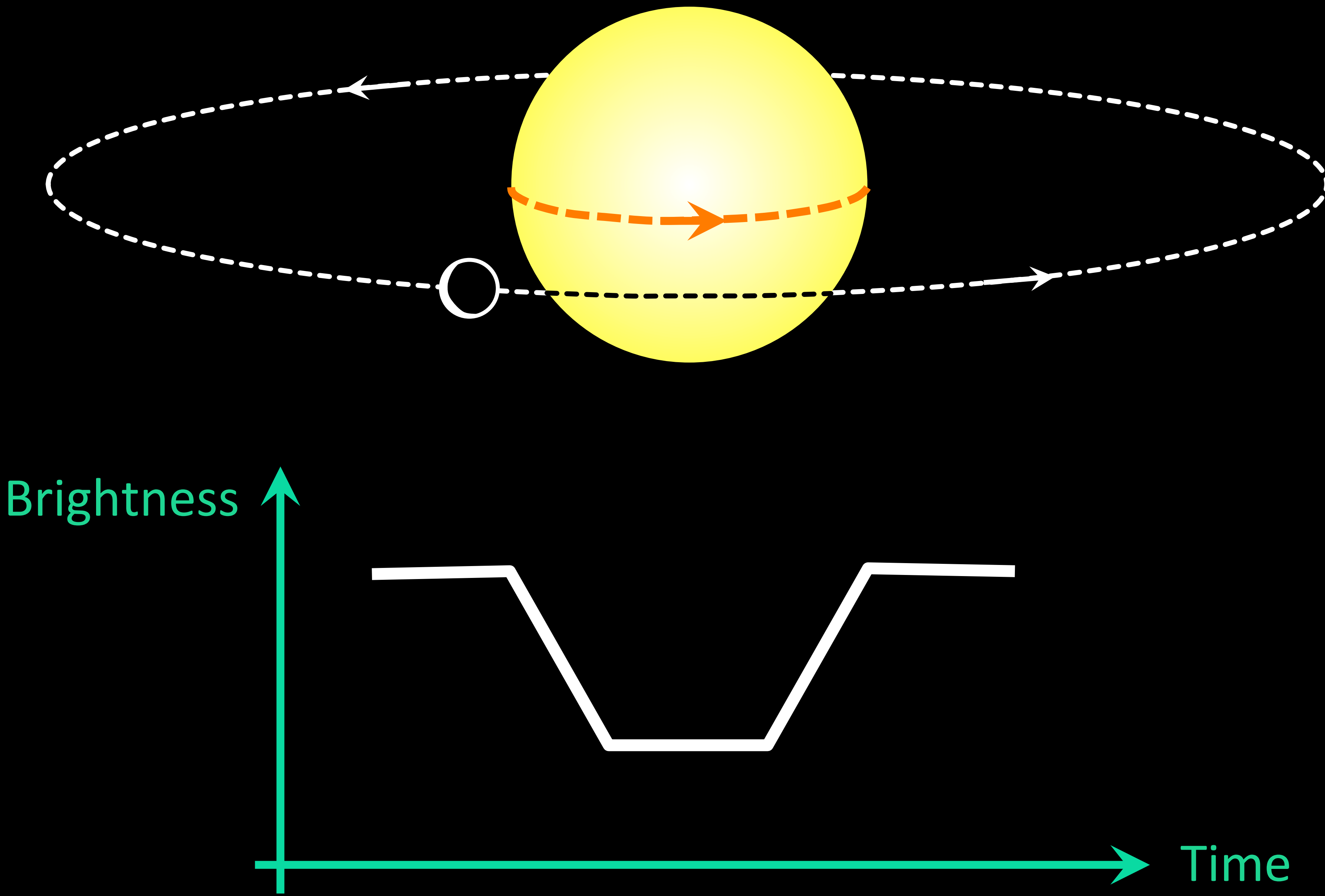
M_*, R_*

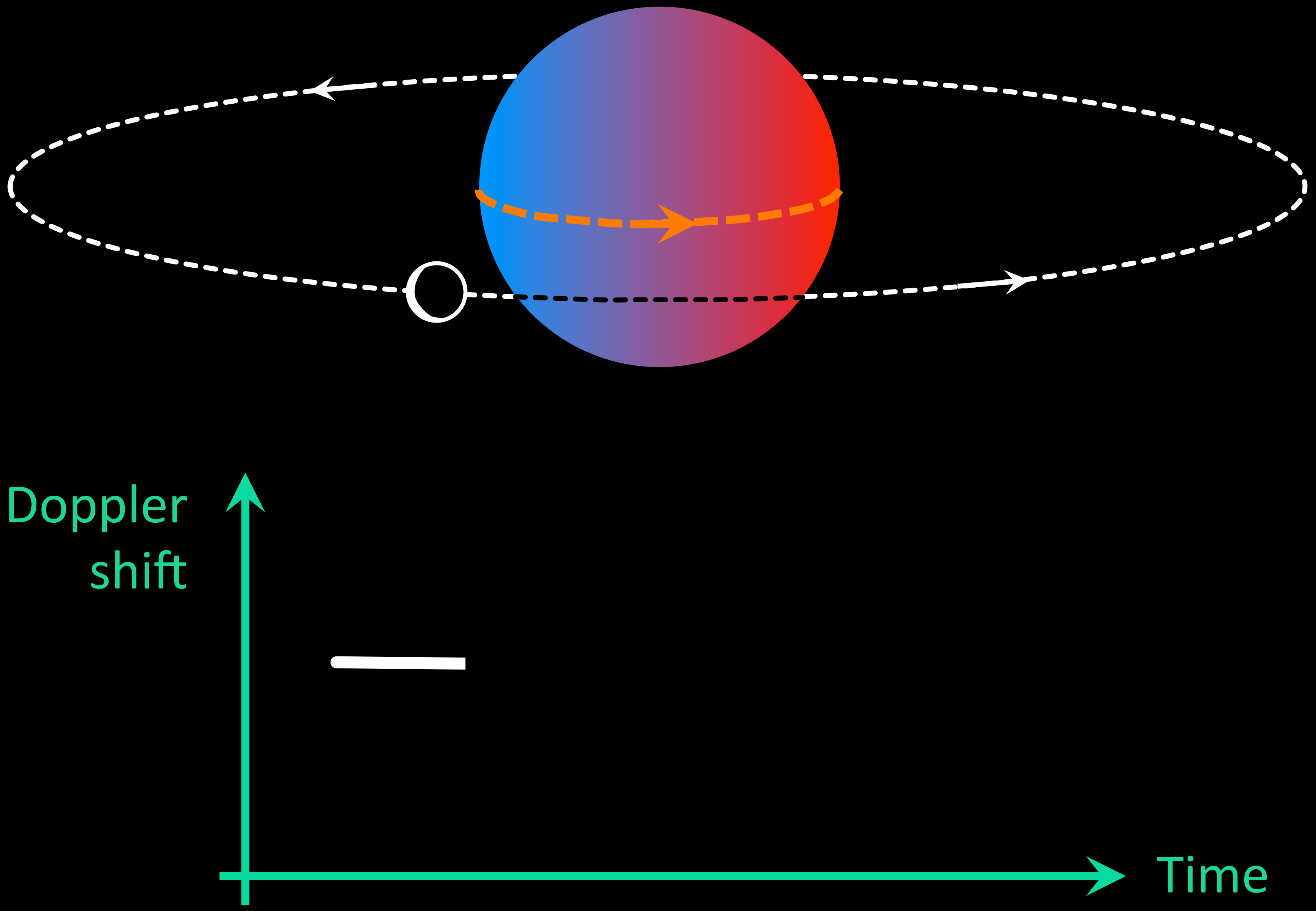
K_*, e, ω

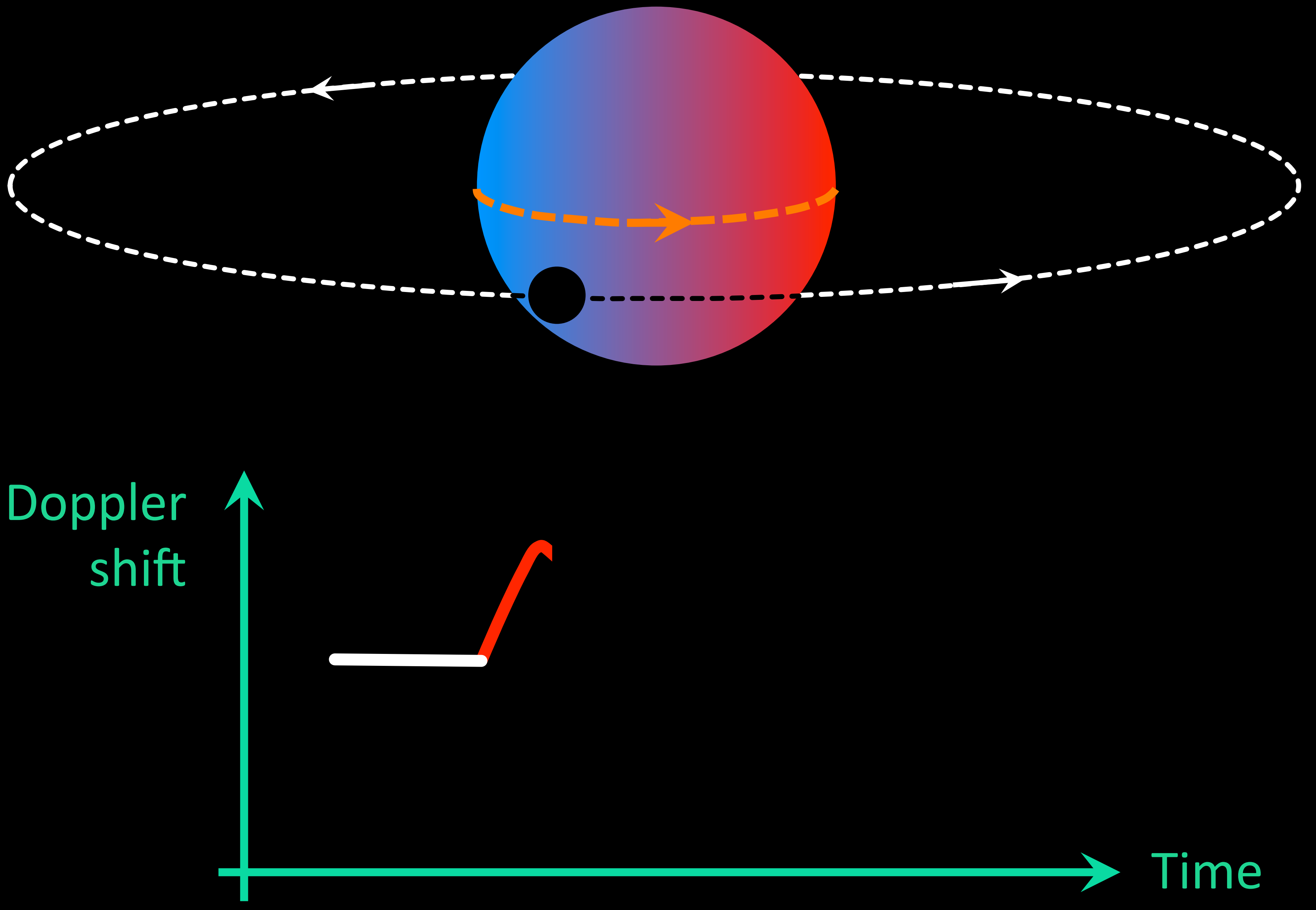
M_p, R_p

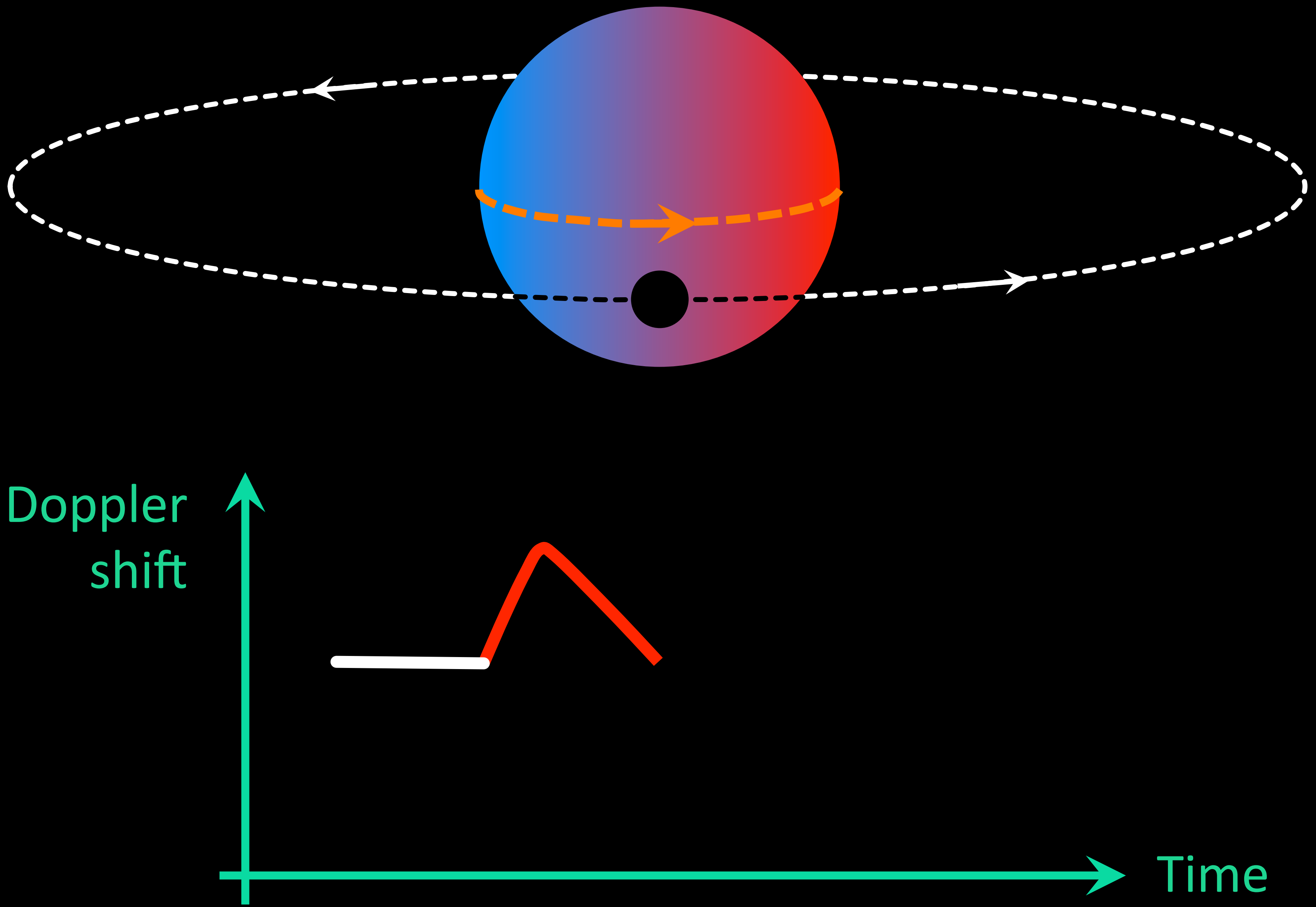


Winn et al. (2006)

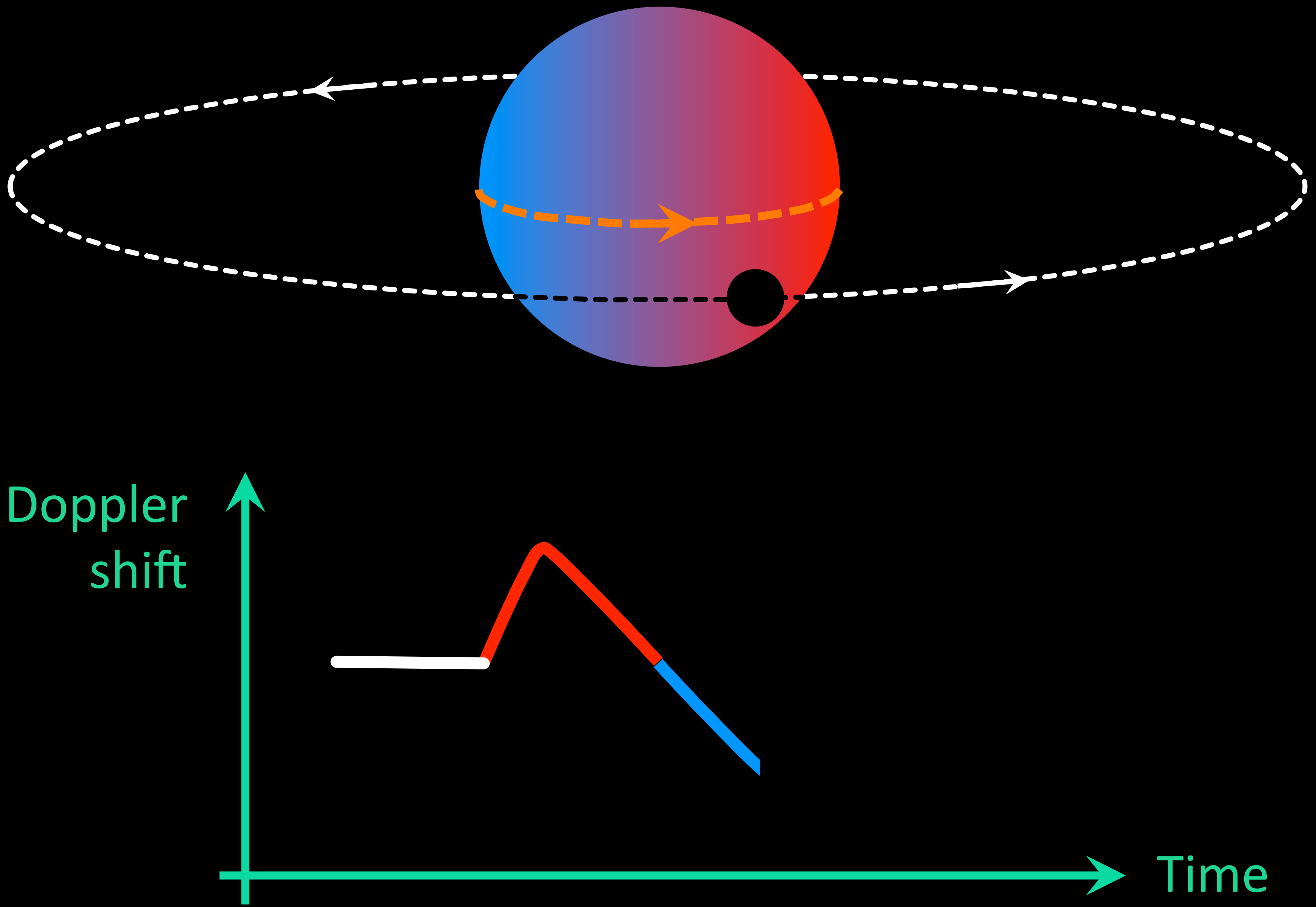

Brightness
Time

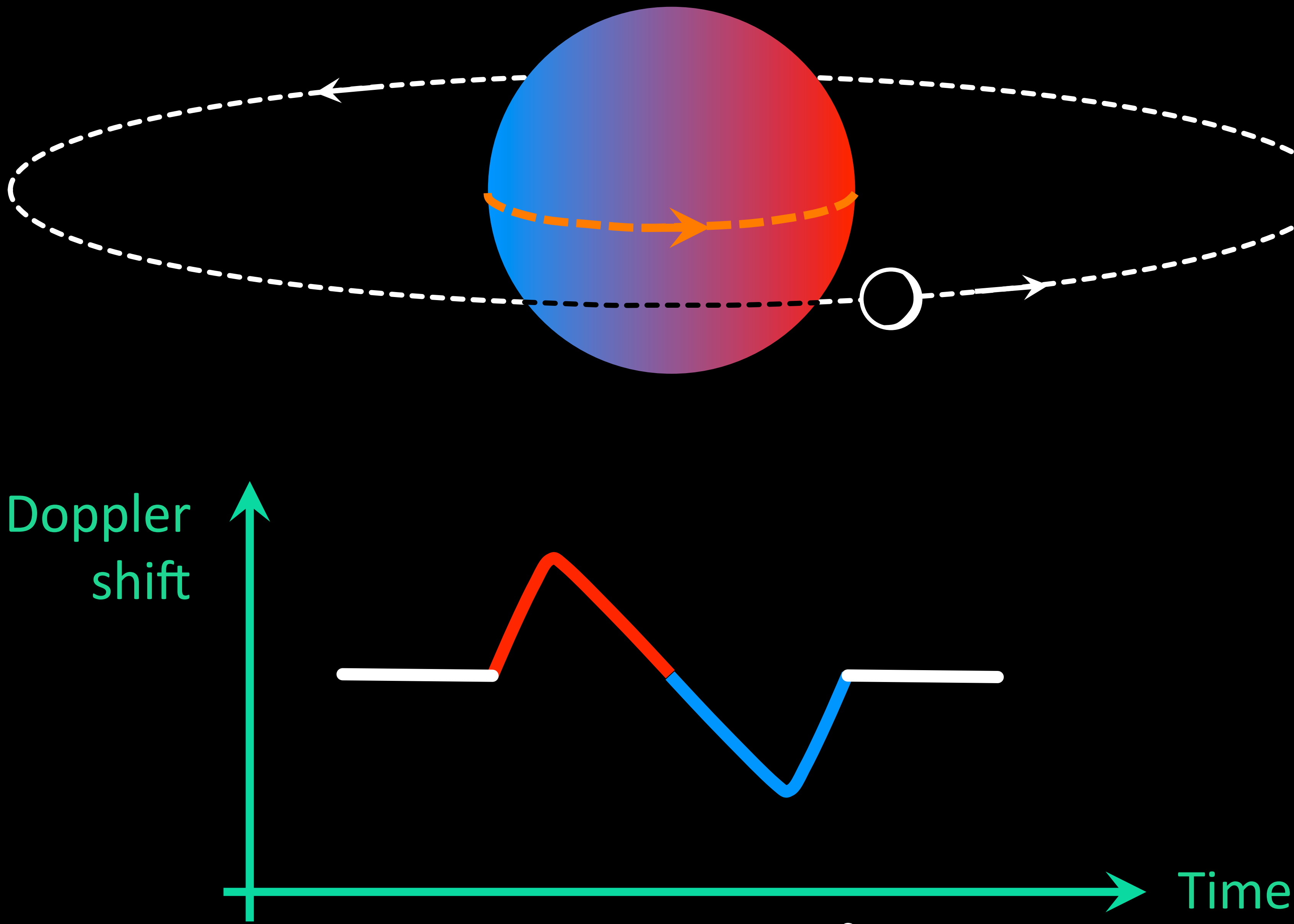

Doppler
shift
Time


Doppler
shift
Time

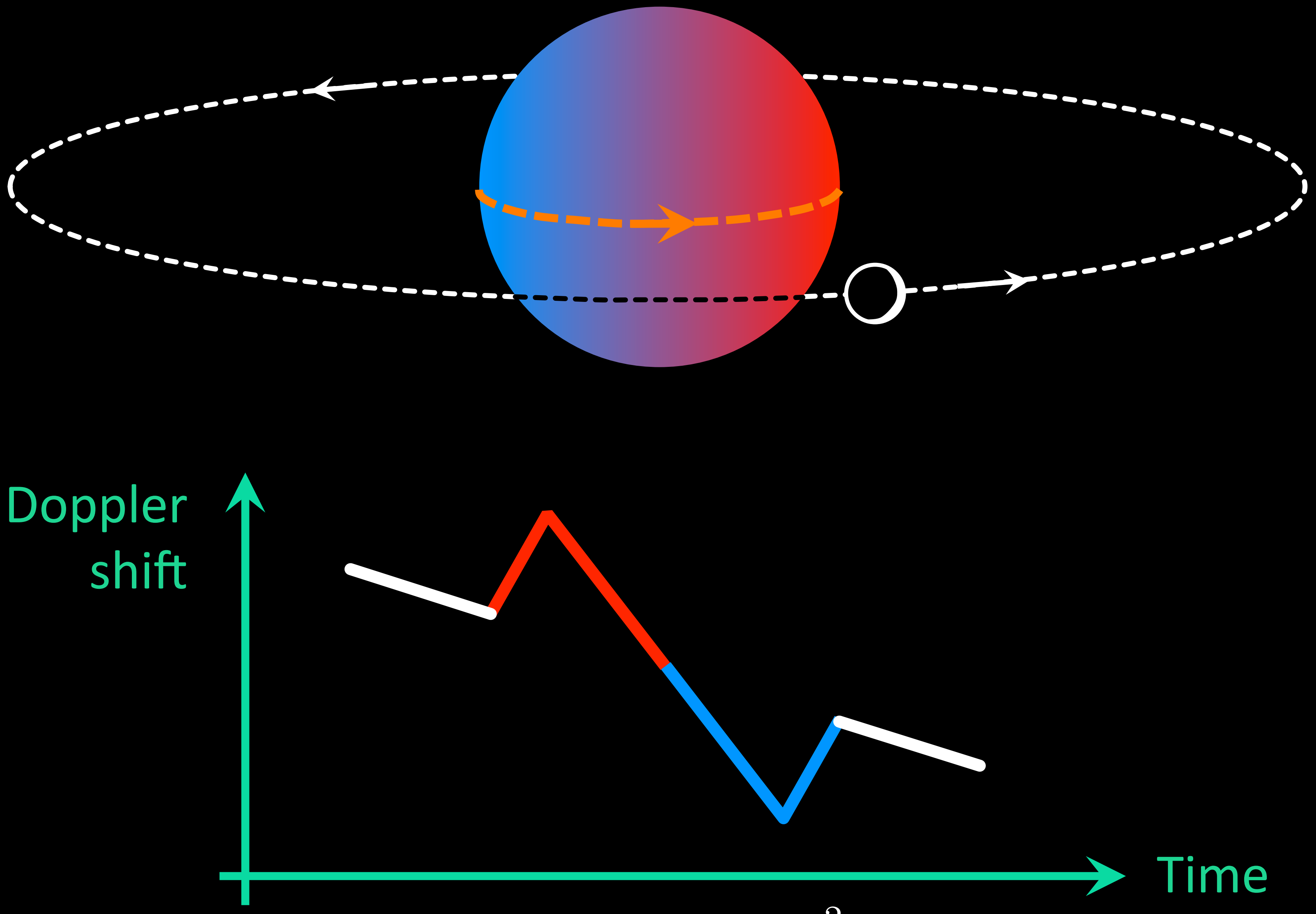


Doppler
shift
Time


Doppler
shift
Time

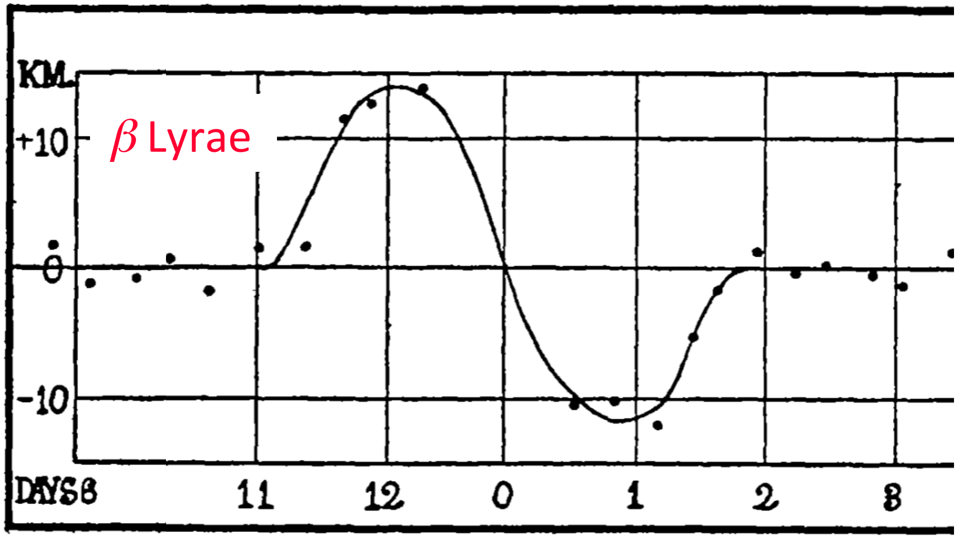


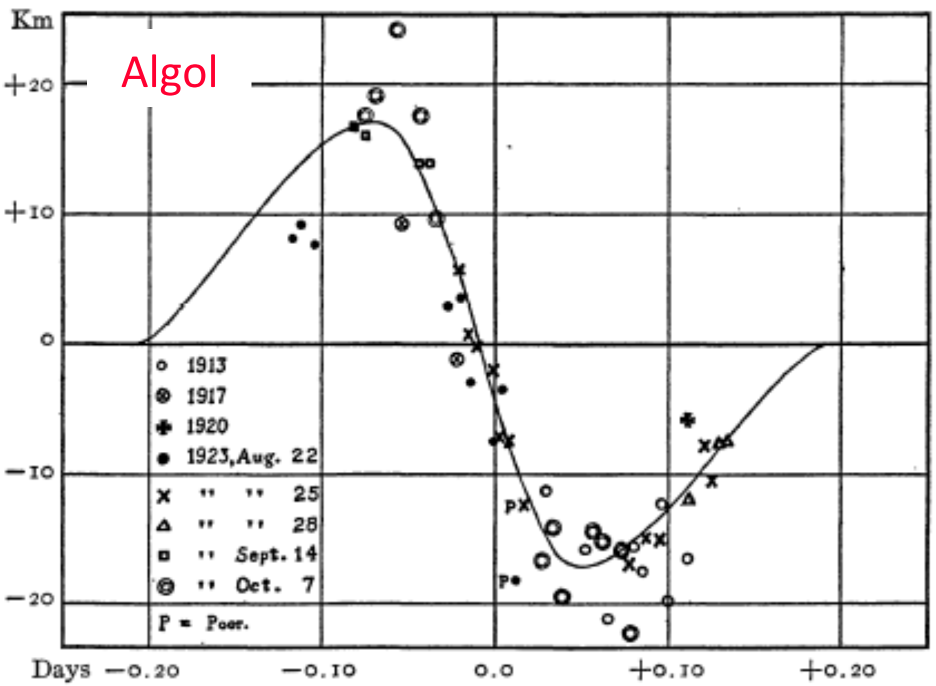
$$\Delta \mathrm{RV} \approx 0.7 \sqrt{1-b^2} \left(\frac{R_p}{R_\star}\right)^2 v_{\mathrm{rot}} \sin I_{\mathrm{rot}}$$



$$\Delta \mathrm{RV} \approx 0.7 \sqrt{1-b^2} \left(\frac{R_p}{R_\star}\right)^2 v_{\mathrm{rot}} \sin I_{\mathrm{rot}}$$

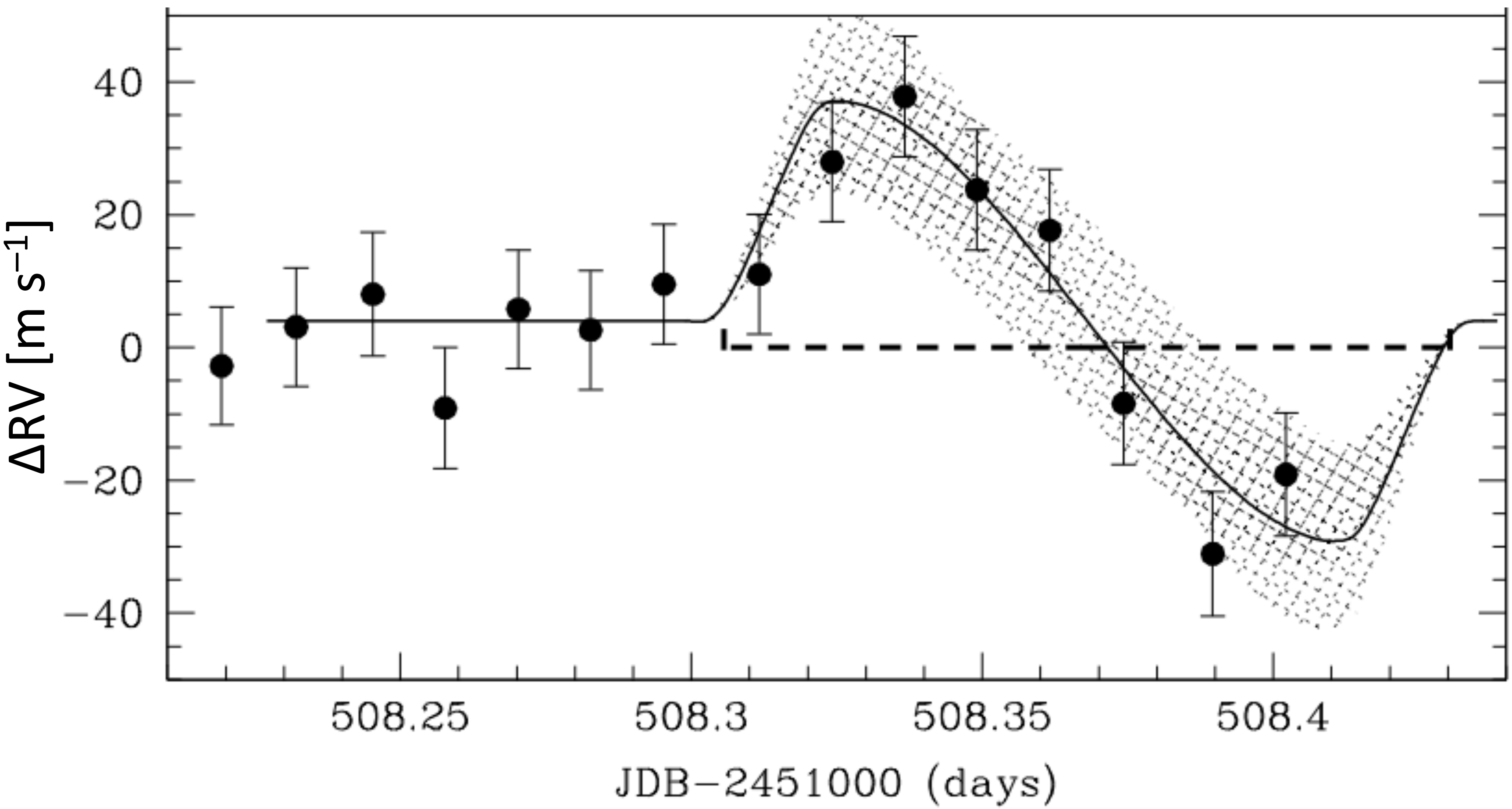
The Rossiter-McLaughlin (RM) effect





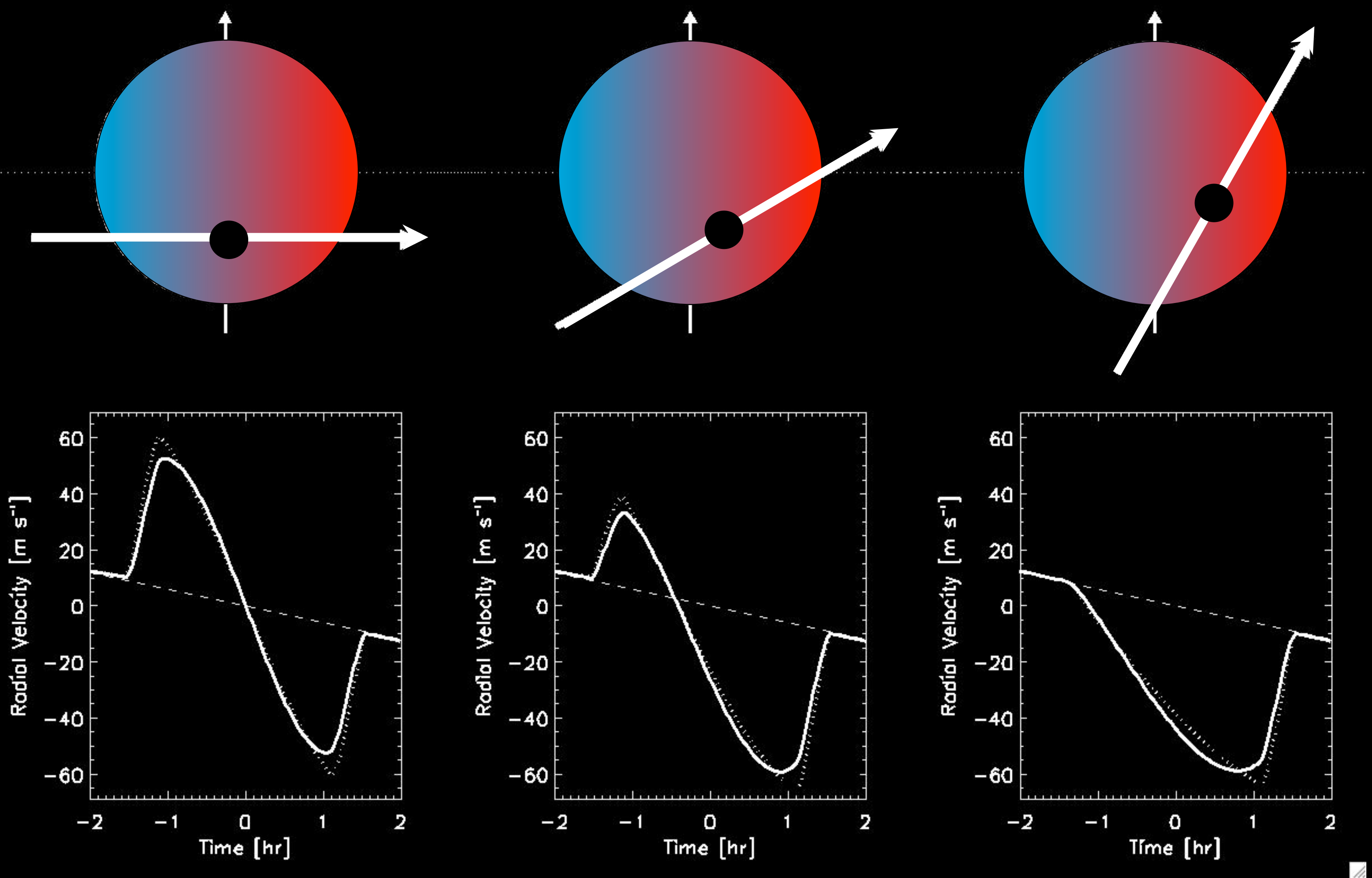
Richard Rossiter (1886-1977)

Dean McLaughlin (1901-1965)

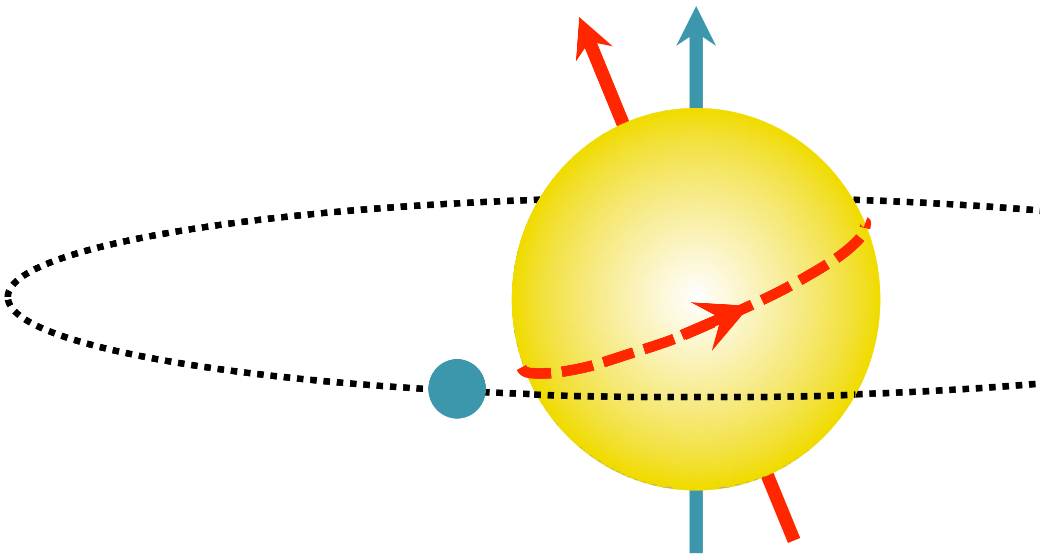


Queloz et al. (2000)

Measuring the stellar obliquity

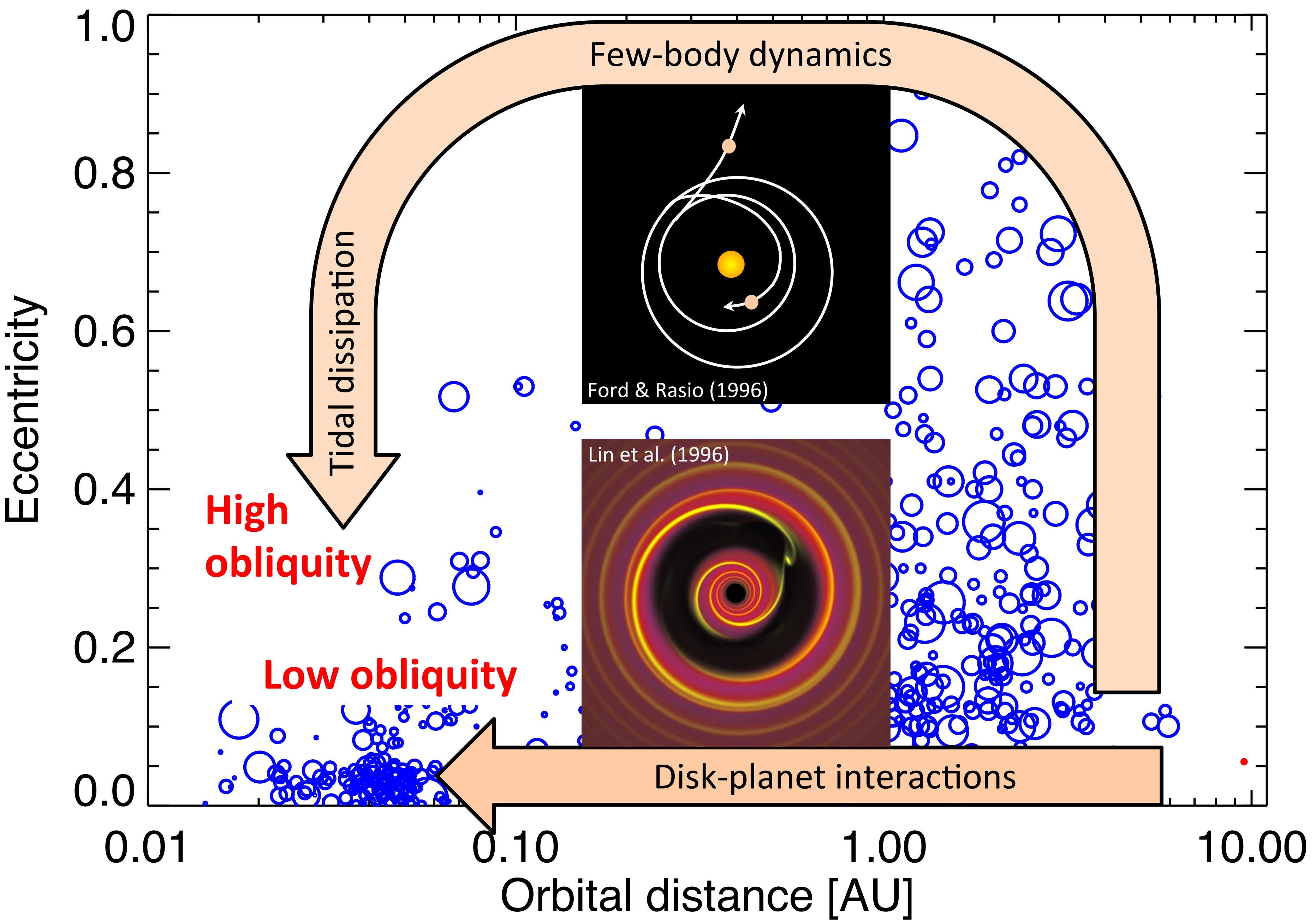


Queloz et al. (2000); Ohta, Taruya, & Suto (2005); Gaudi & Winn (2007)



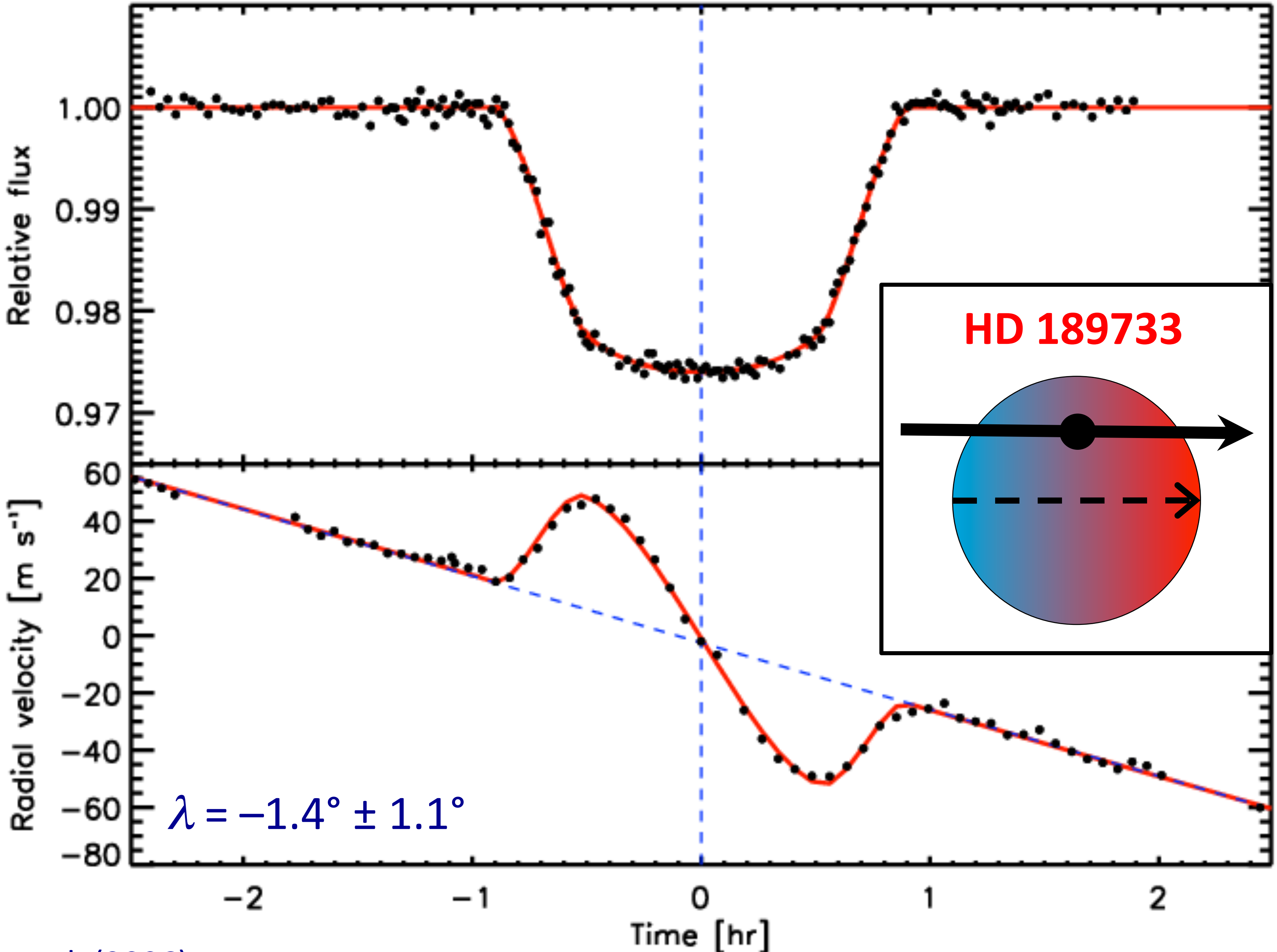
Stellar obliquity

- Sun’s obliquity is 7º — how typical is this?
- Whatever produces ***hot Jupiters*** may also perturb inclinations

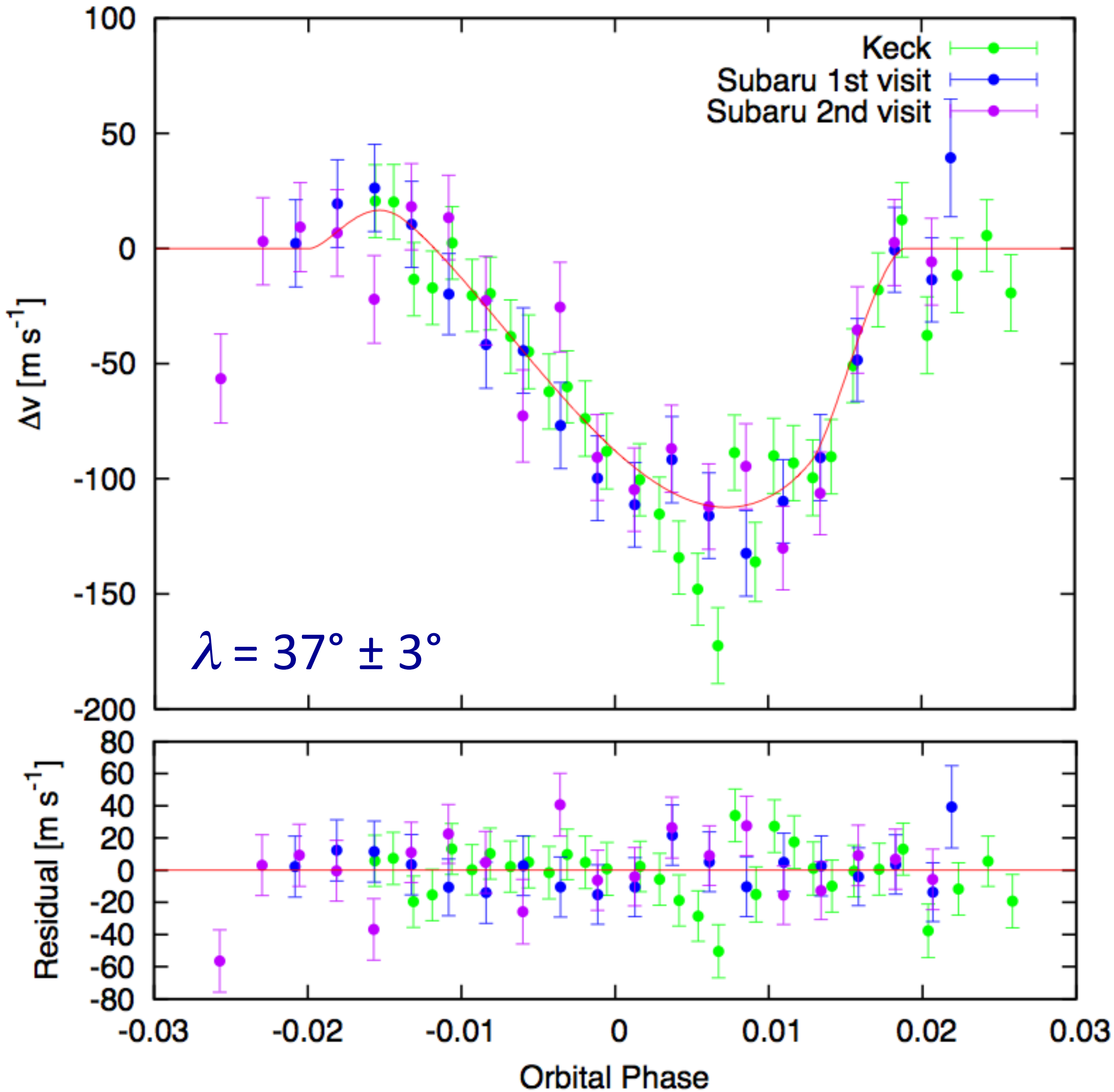


Few-body dynamics
Ford & Rasio (1996)
Tidal dissipation
Lin et al. (1996)
High obliquity
Low obliquity
Disk-planet interactions
Eccentricity
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.10
1.00
10.00
Orbital distance [AU]

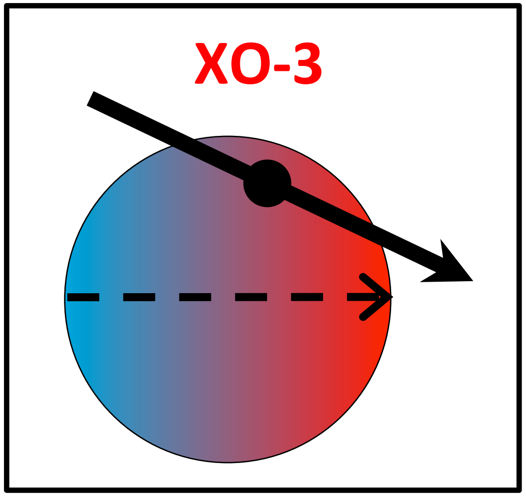
Low obliquity



Winn et al. (2006)

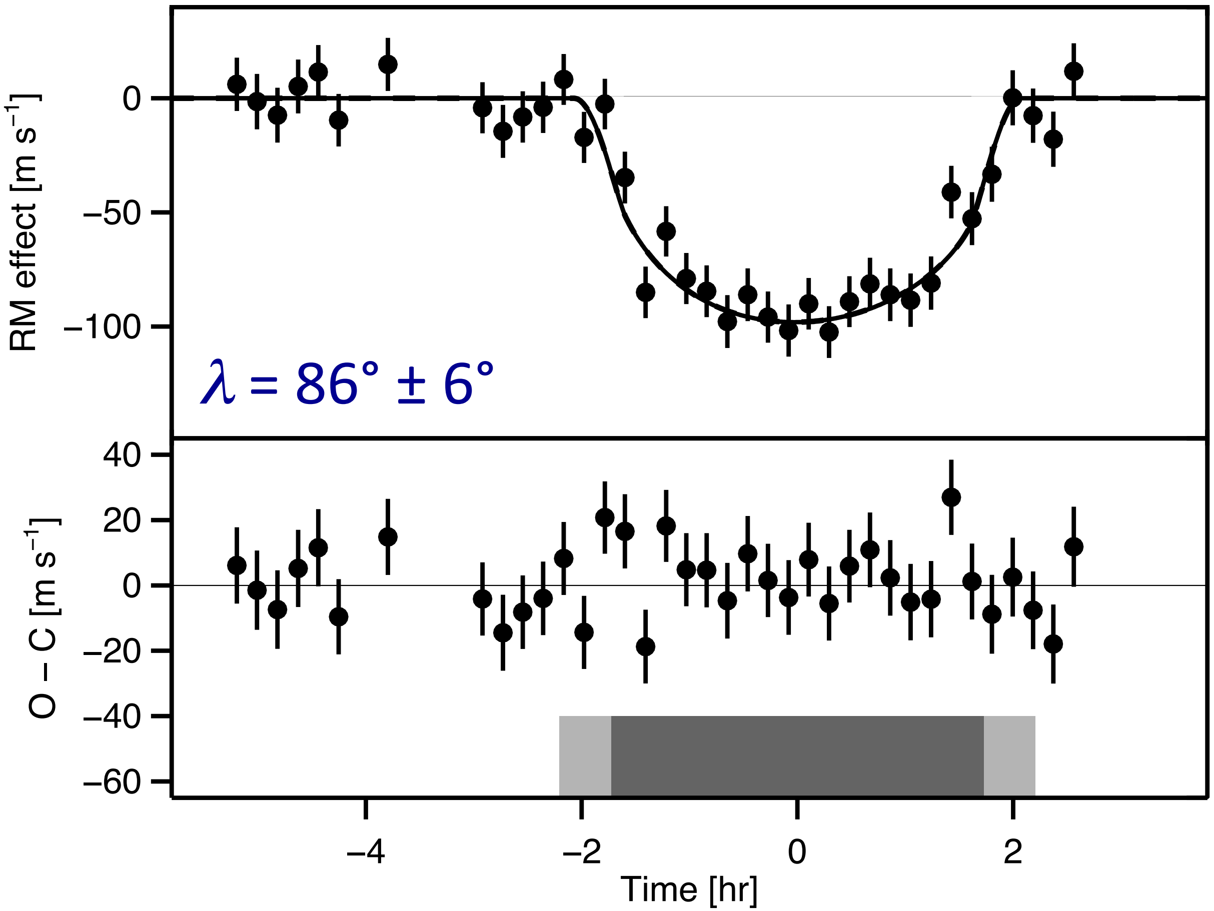


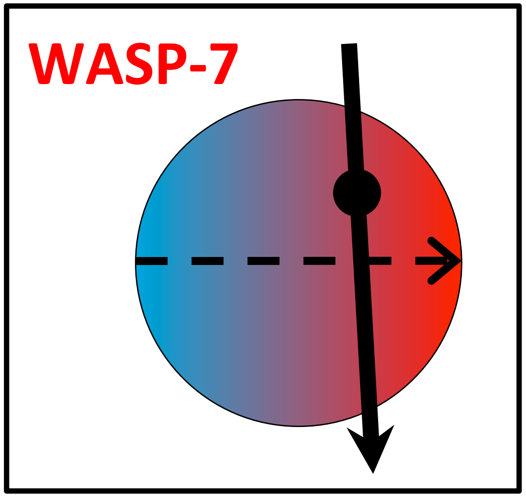
Moderate obliquity



Hirano et al. (2011); see also Hébrard et al. (2008)

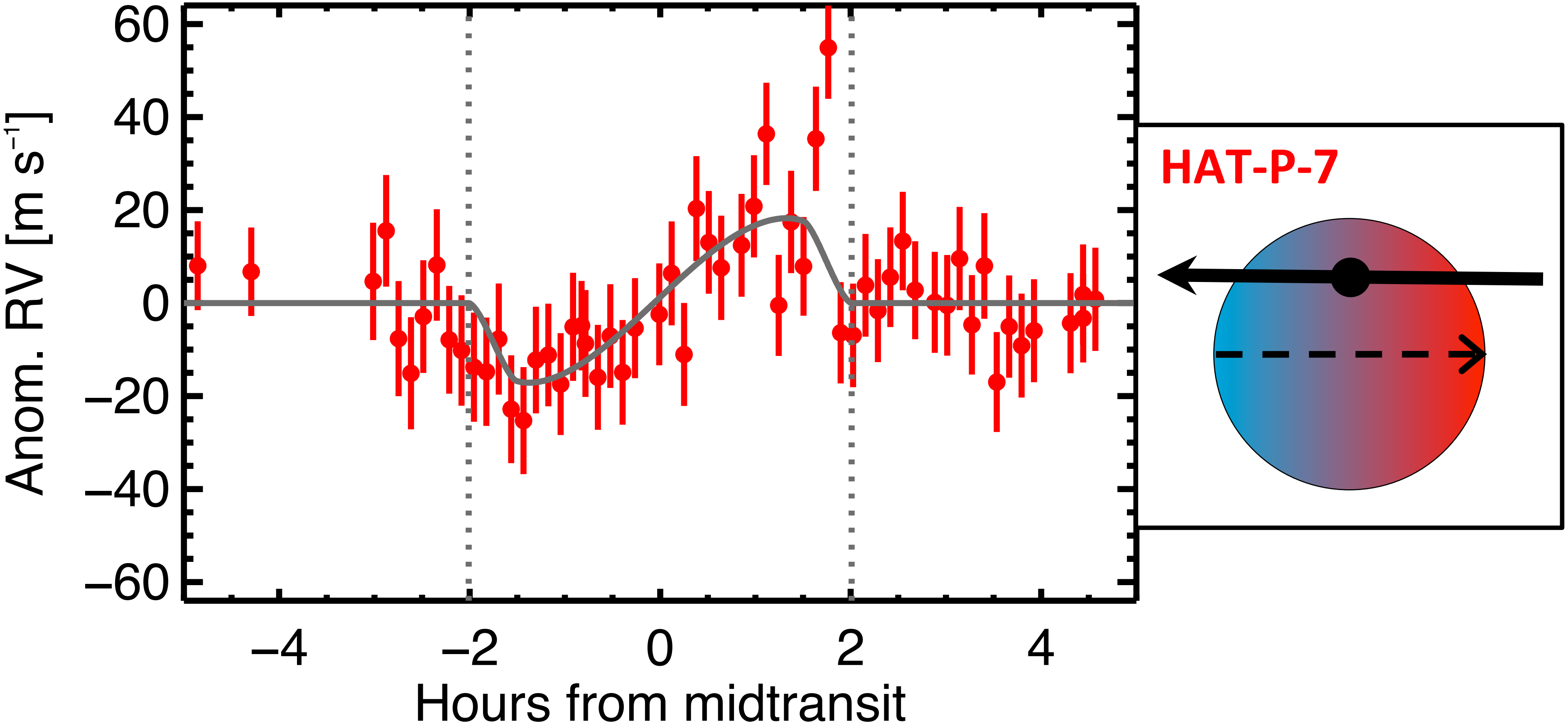
High obliquity



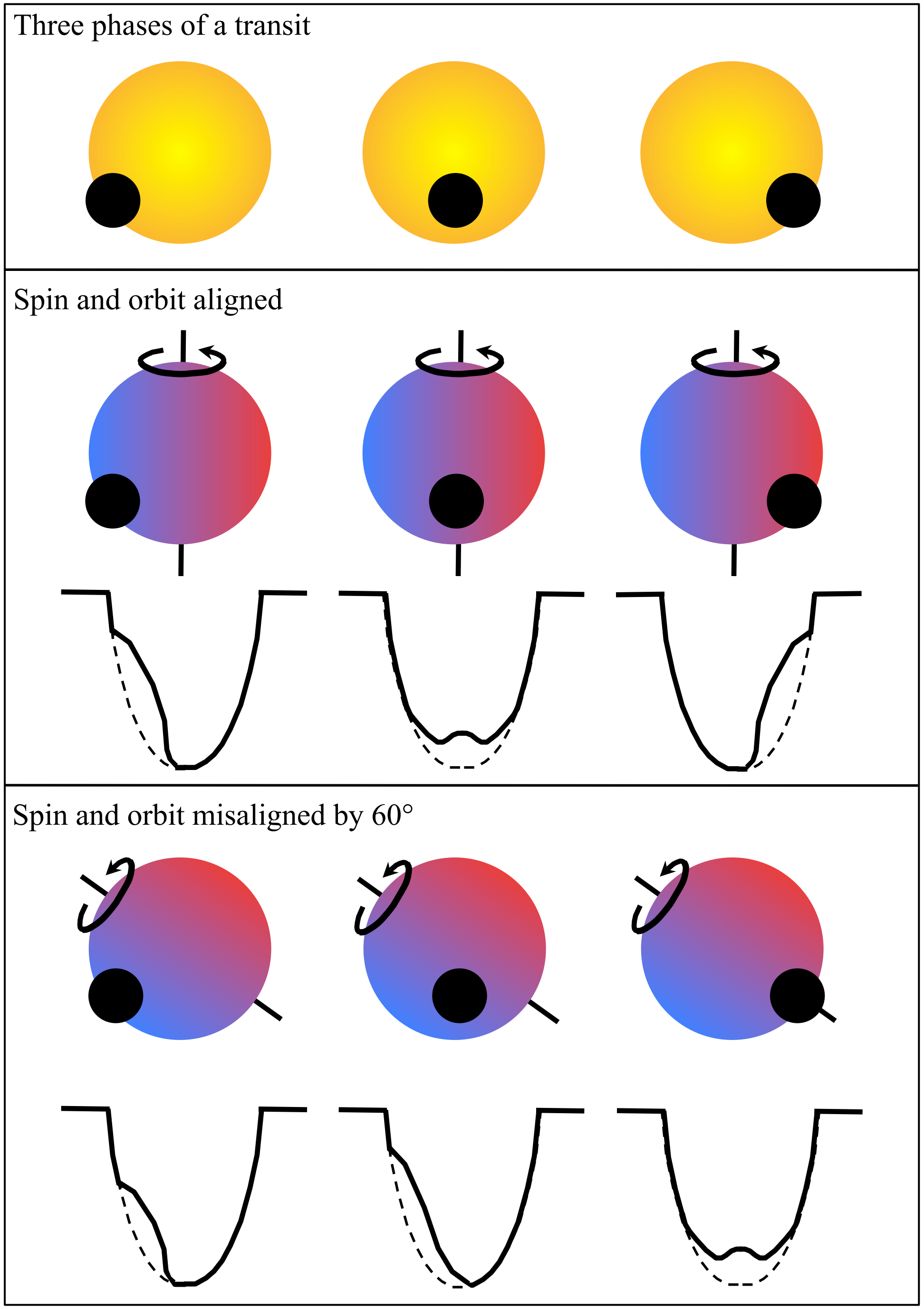


Albrecht et al. (2011)

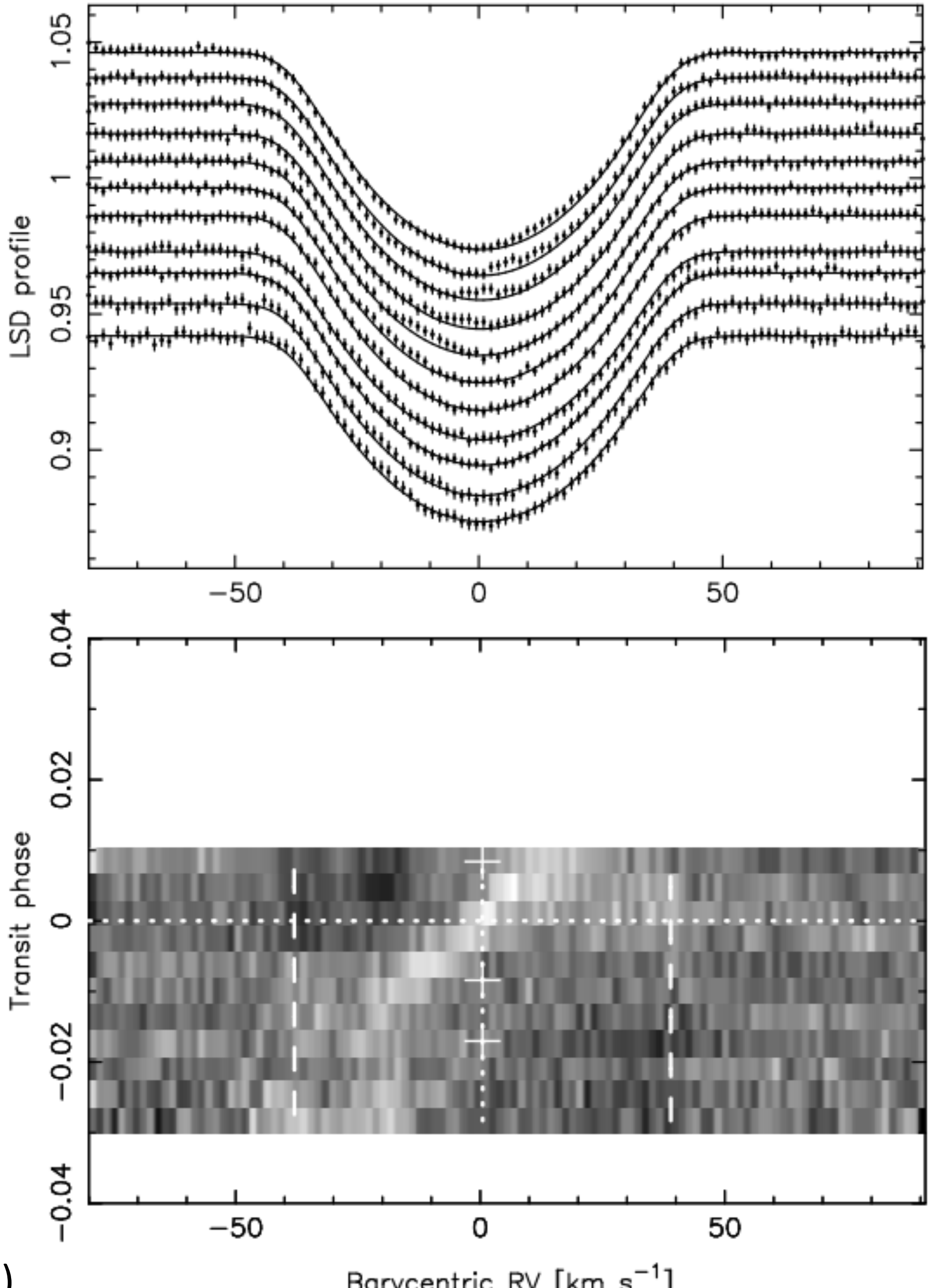
Retrograde



Winn et al. (2009)

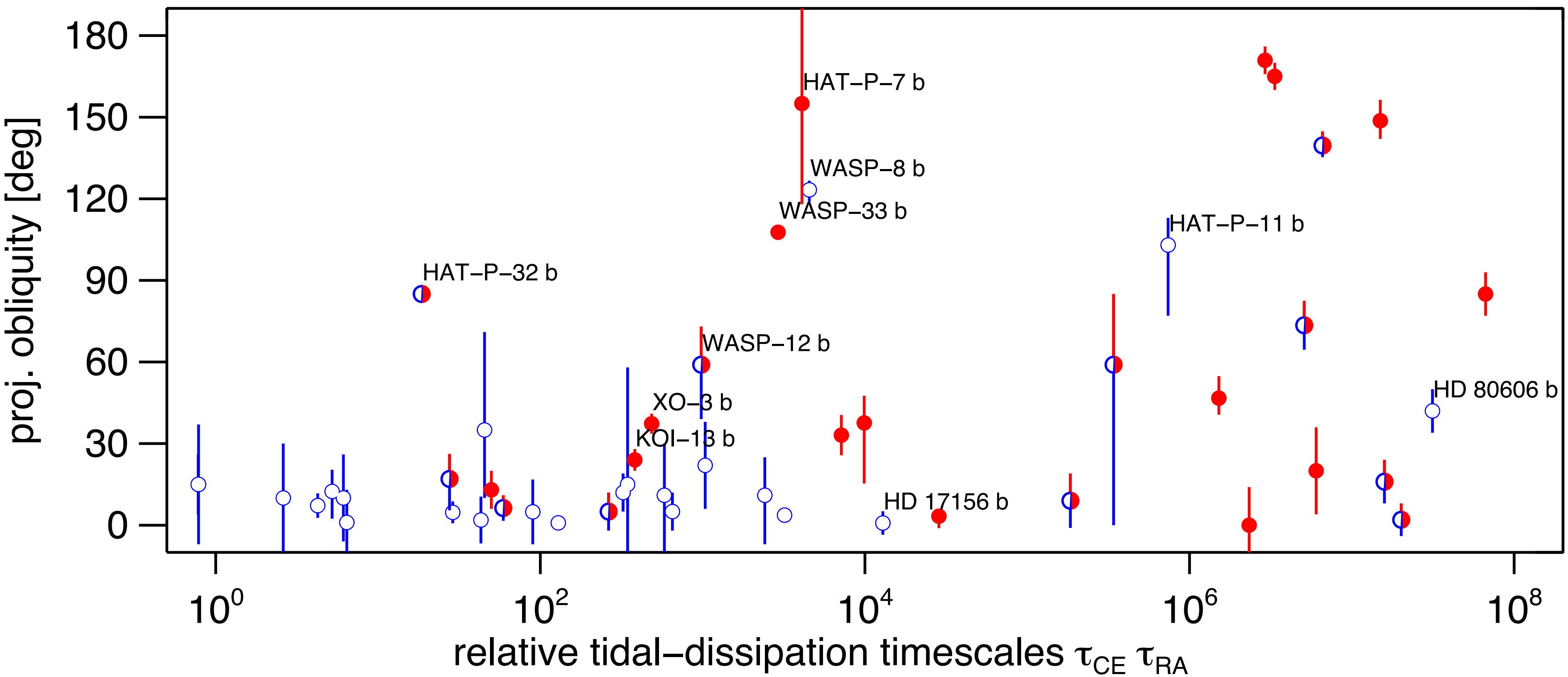


Gaudi & Winn (2007)



Gandolfini et al. (2012)

Obliquities of hot-Jupiter hosts



convective envelope

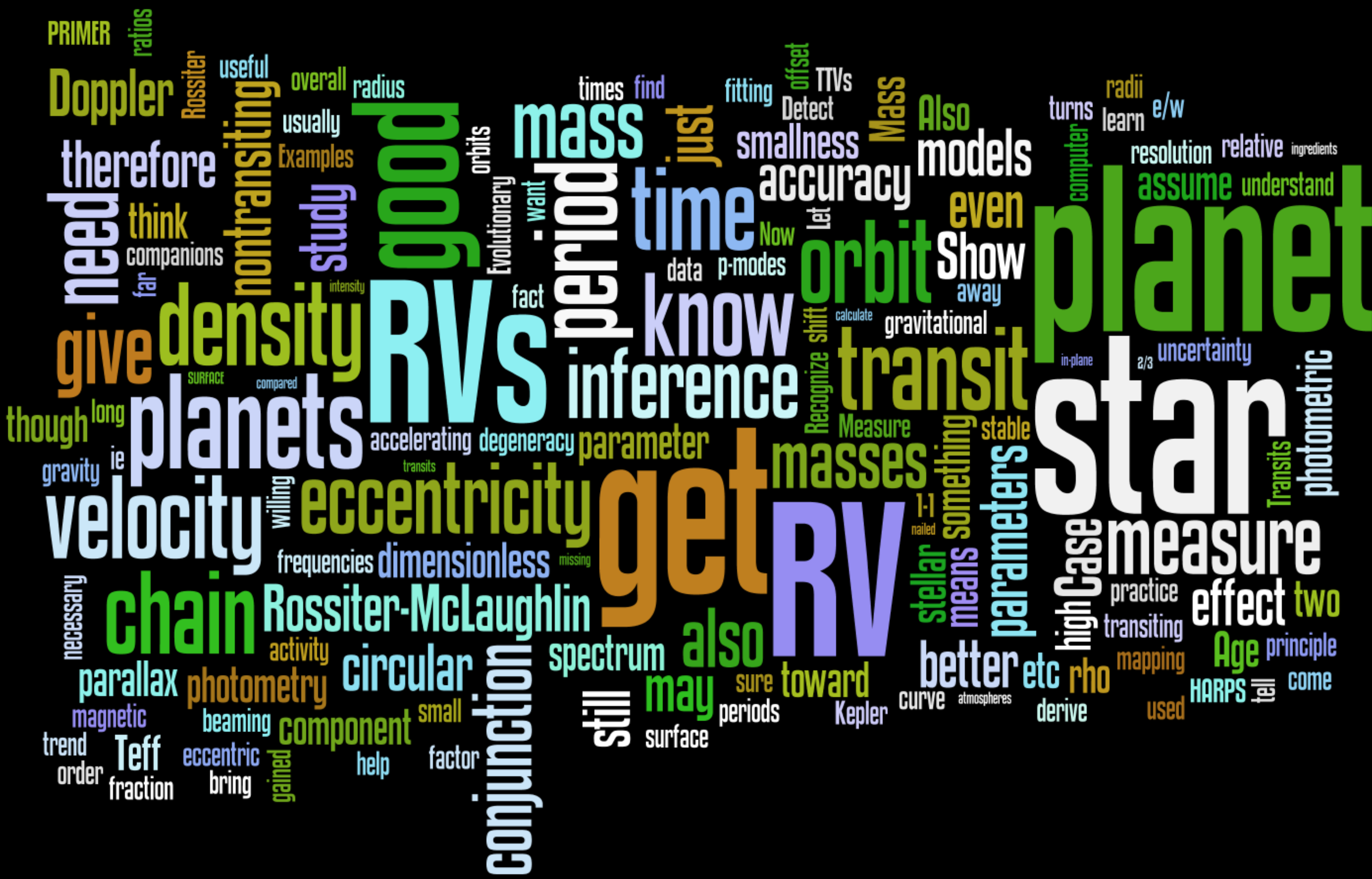
radiative envelope

not sure

$$\frac{1}{\tau_{CE}} = \frac{1}{10 \cdot 10^9 \mathrm{yr}} q^2 \left(\frac{a/R_\star}{40} \right)^{-6}$$

$$\frac{1}{\tau_{RA}} = \frac{1}{0.25 \cdot 5 \cdot 10^9 \mathrm{yr}} q^2 (1+q)^{5/6} \left(\frac{a/R_\star}{6} \right)^{-17/2}$$

Albrecht et al. (2012)



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fitting
offset
TTVs
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accuracy
Also
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