The Rossiter-McLaughlin Effect

B. Scott Gaudi

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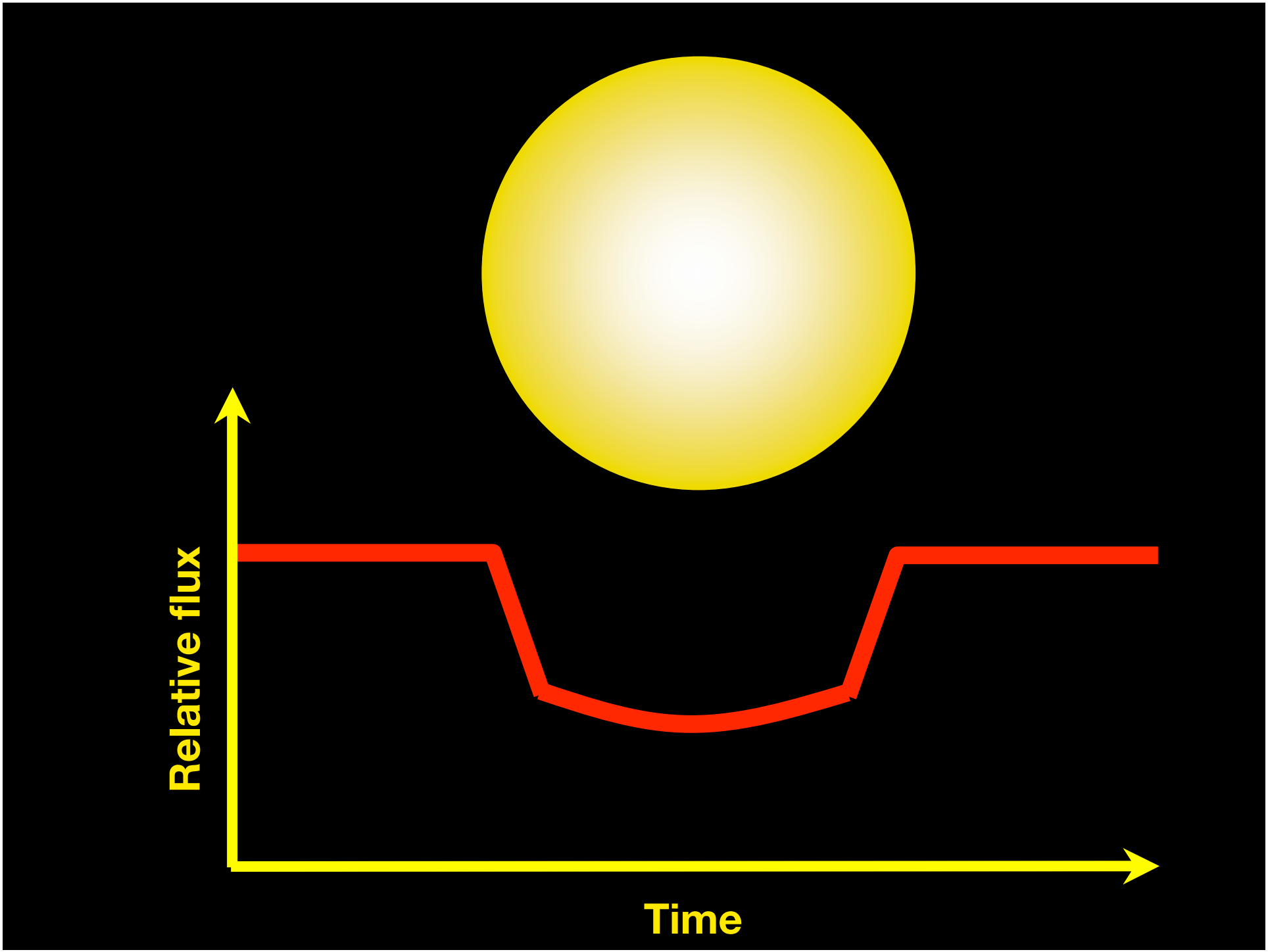
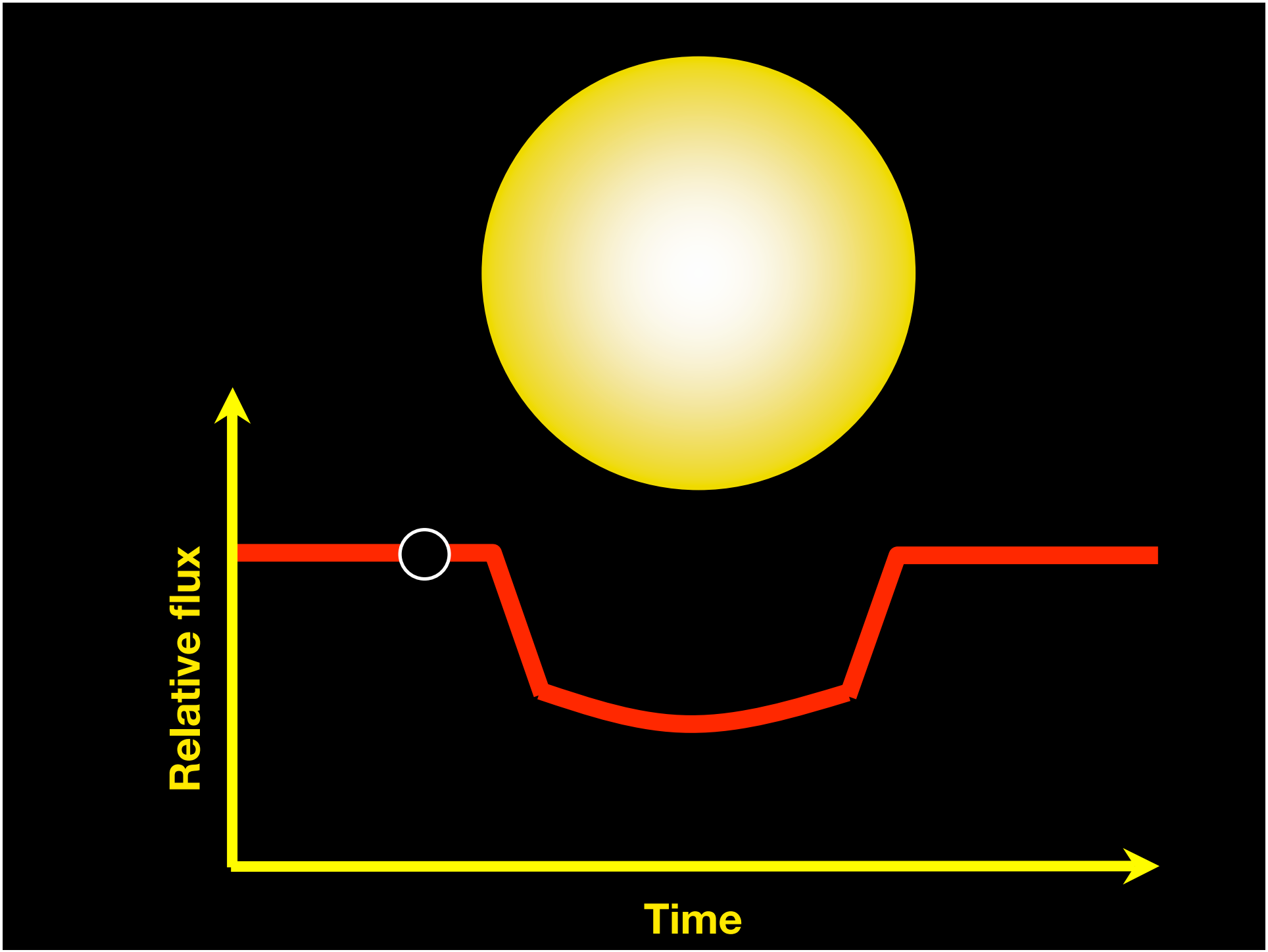
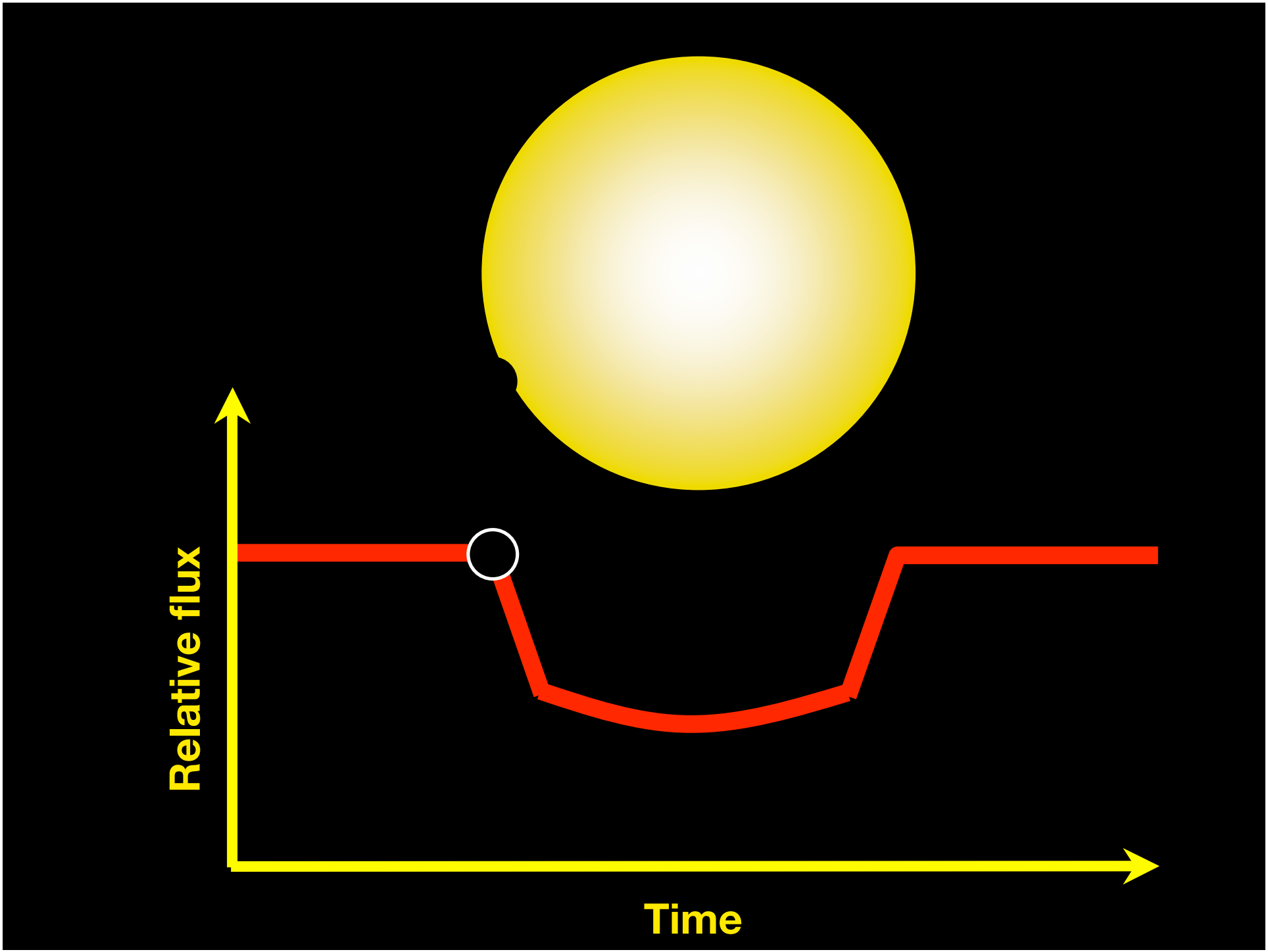
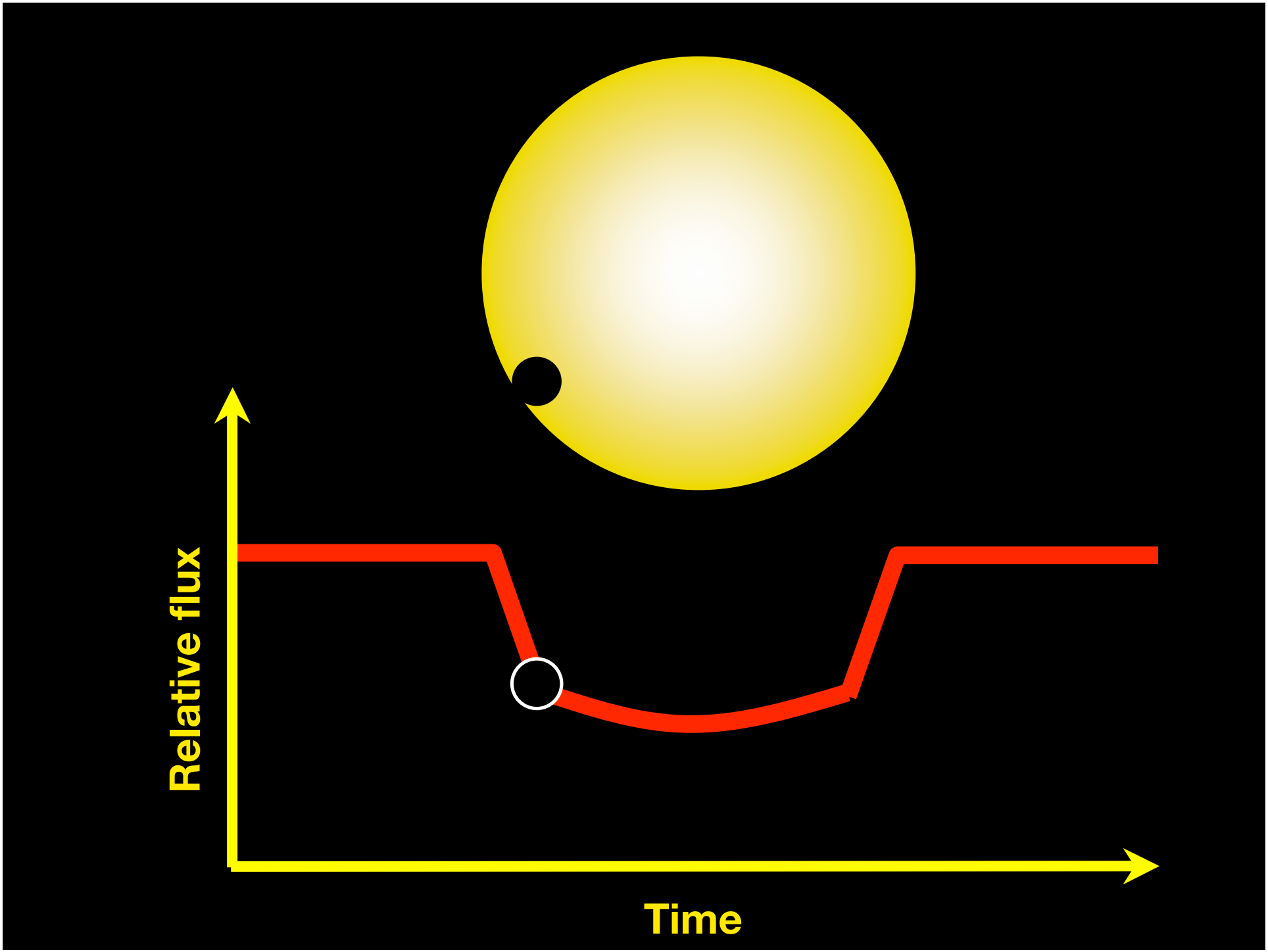
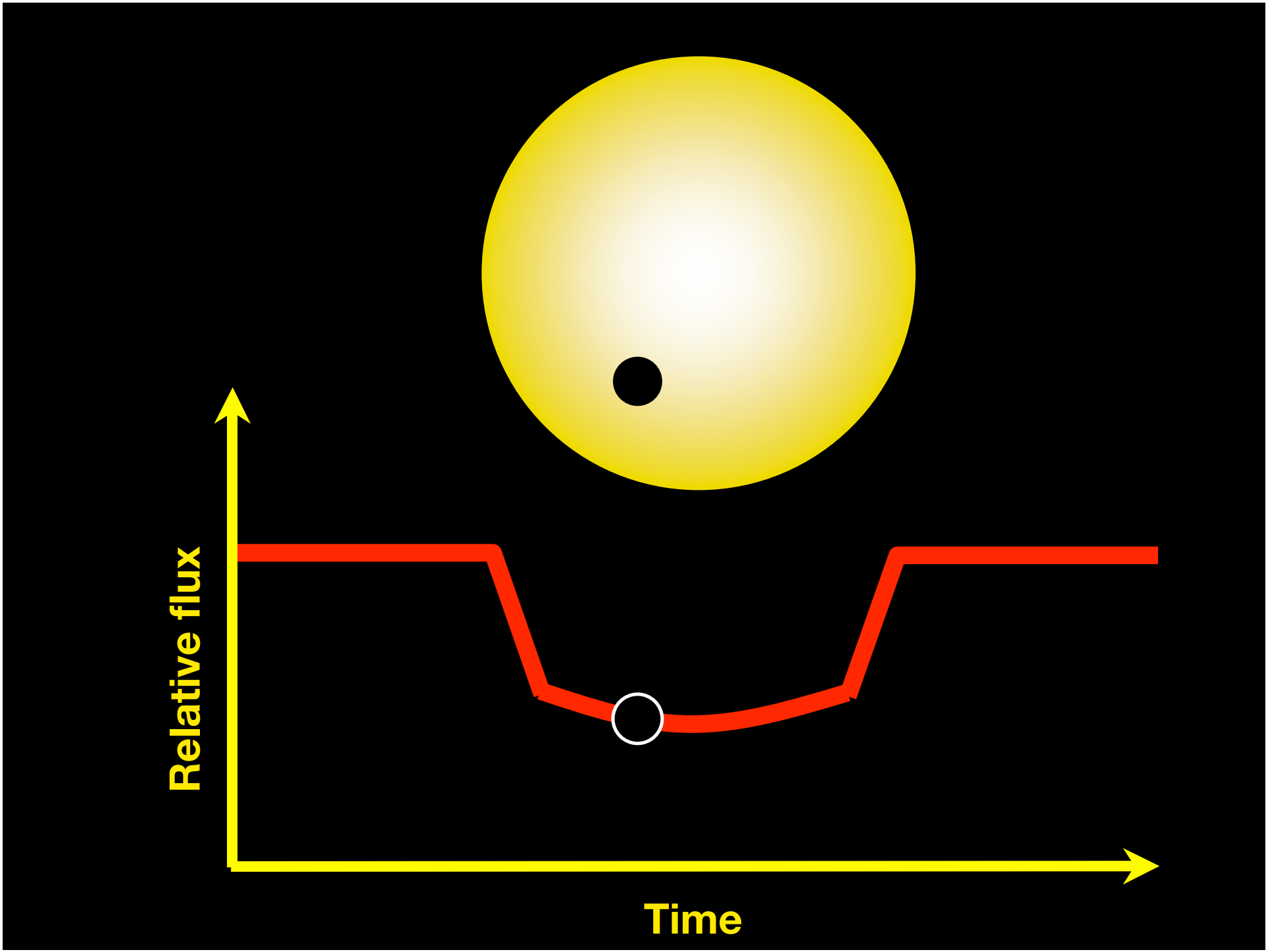
(special thanks to Josh Winn)

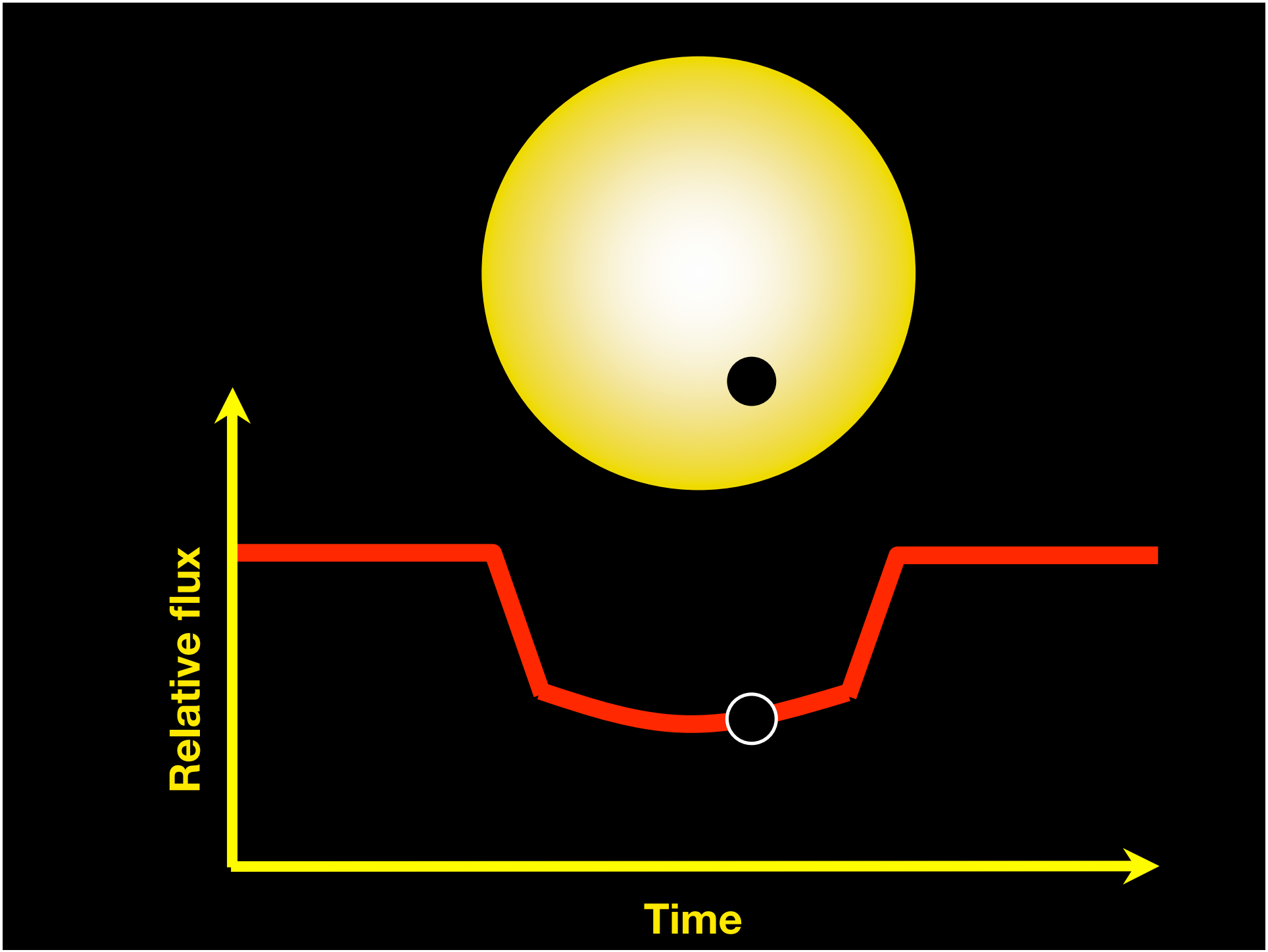

Relative flux
Time

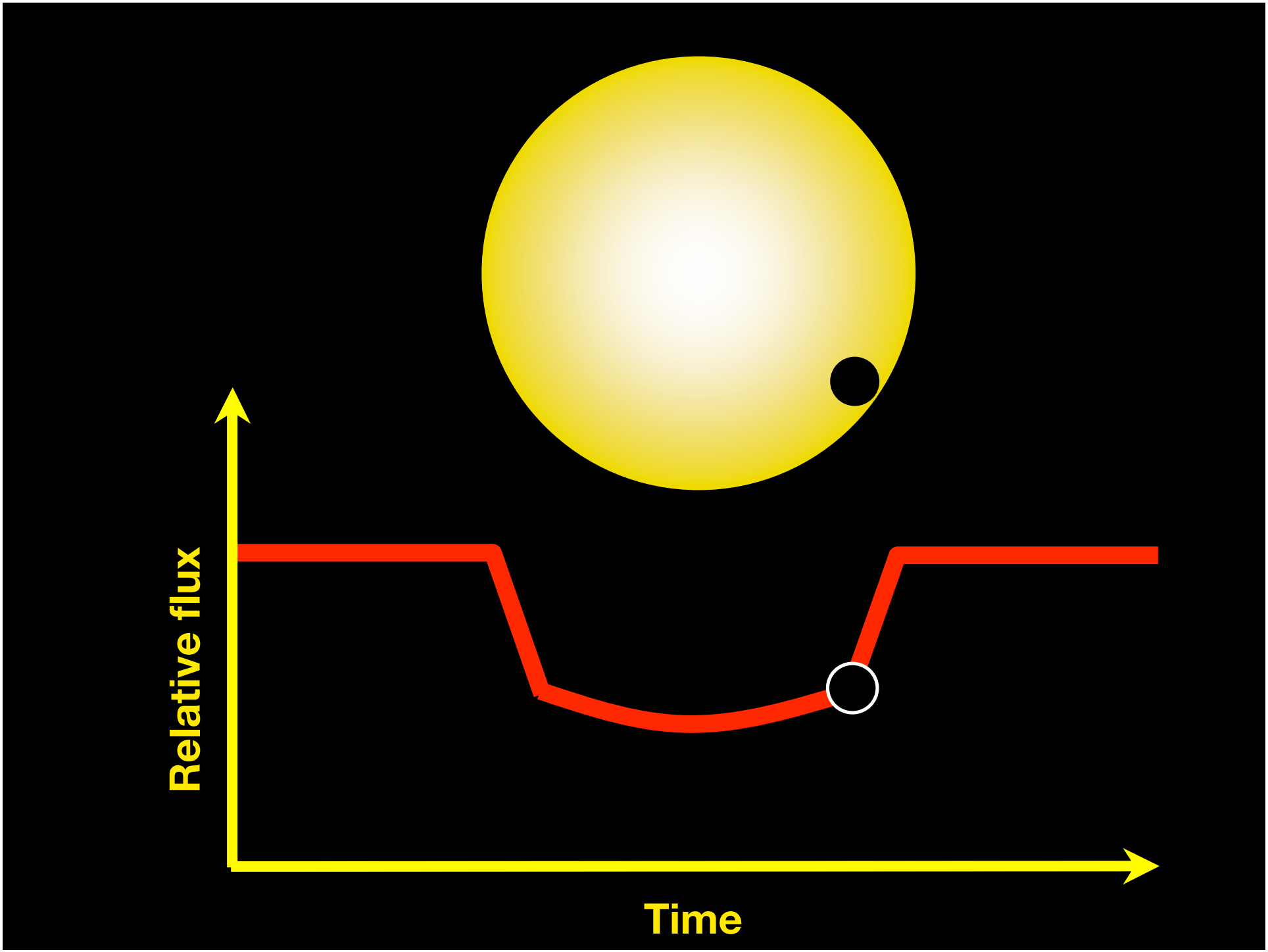

Relative flux
Time

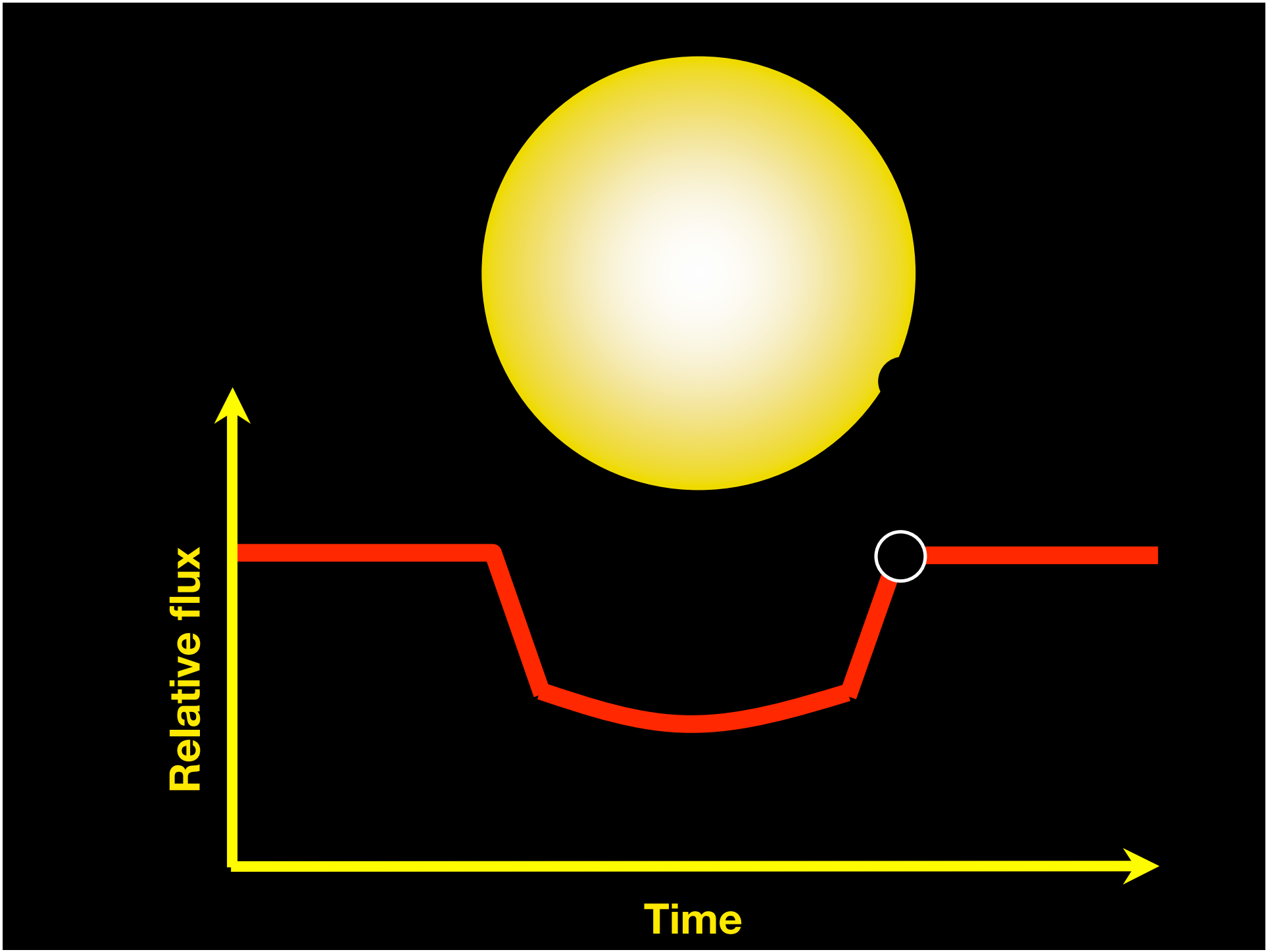

Relative flux
Time

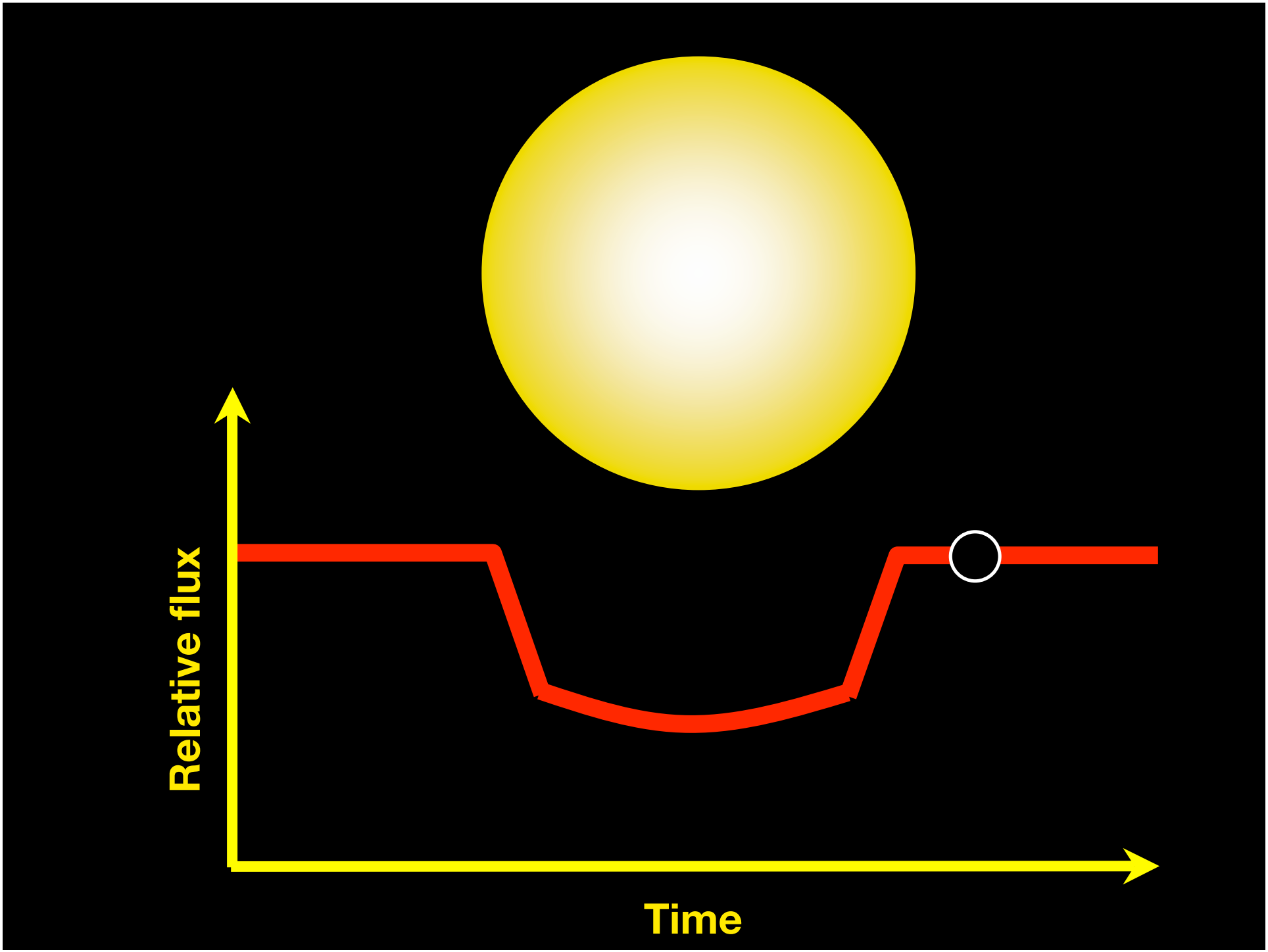

Relative flux
Time

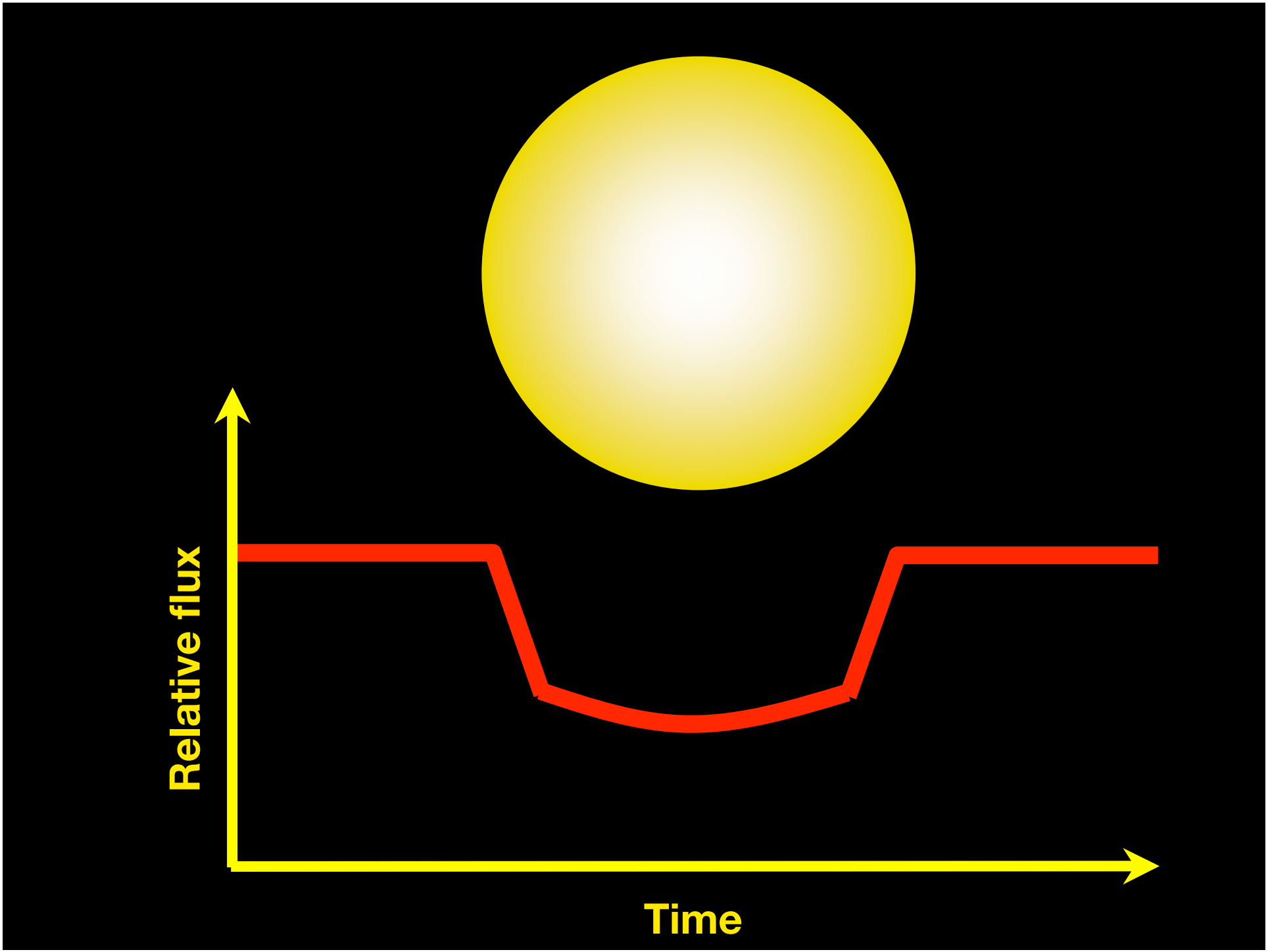

Relative flux
Time

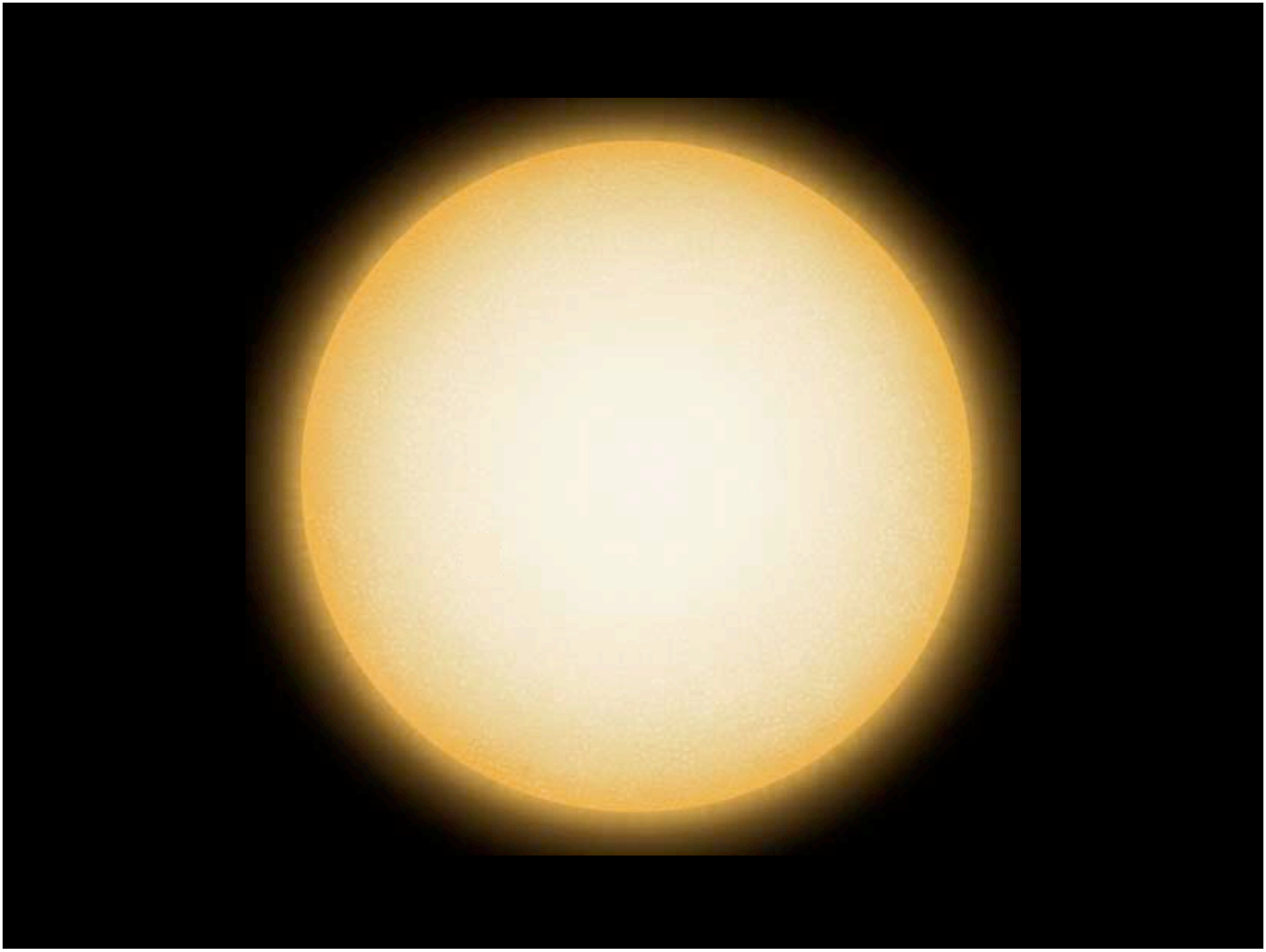

Relative flux
Time

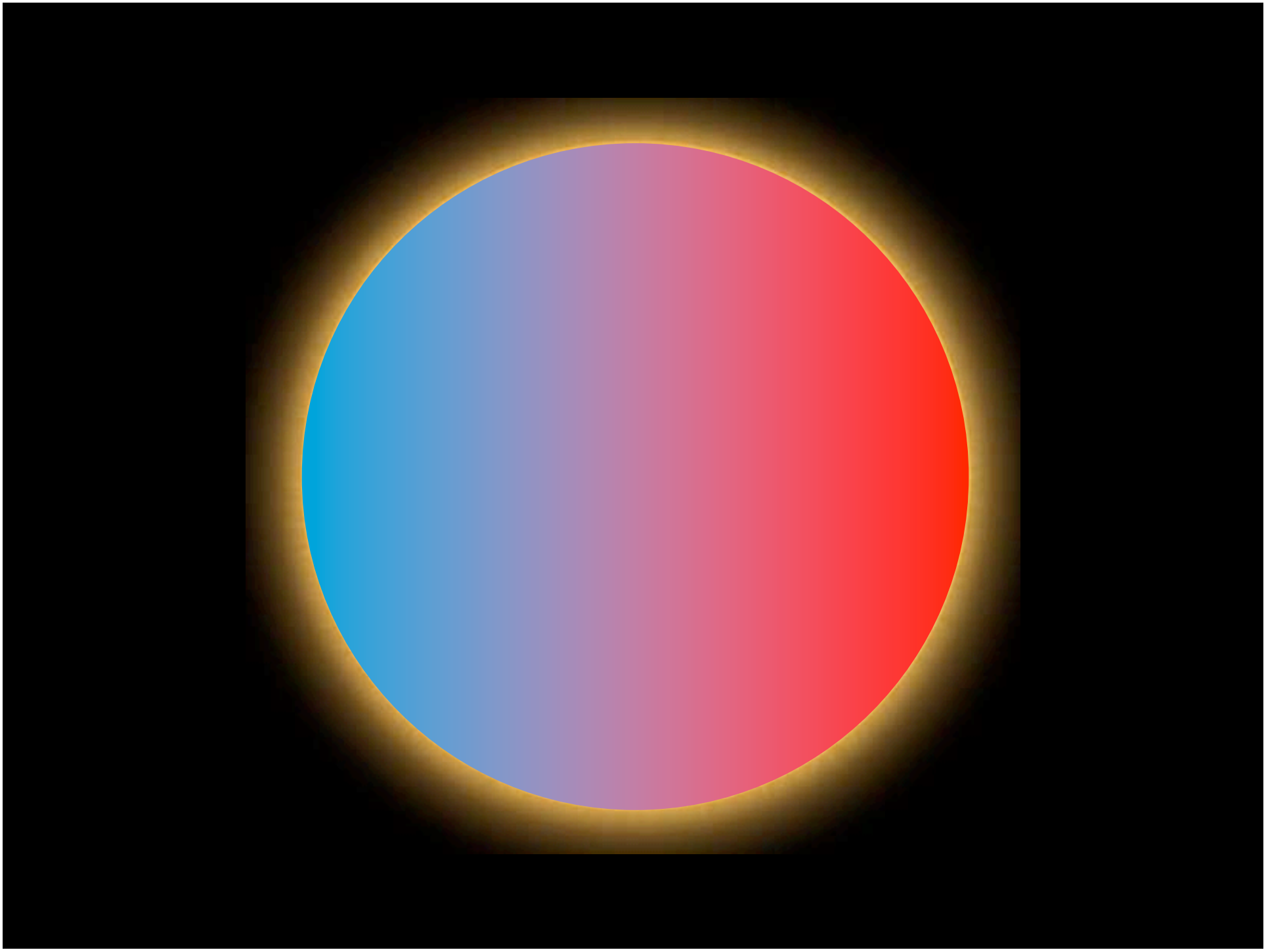

Relative flux
Time

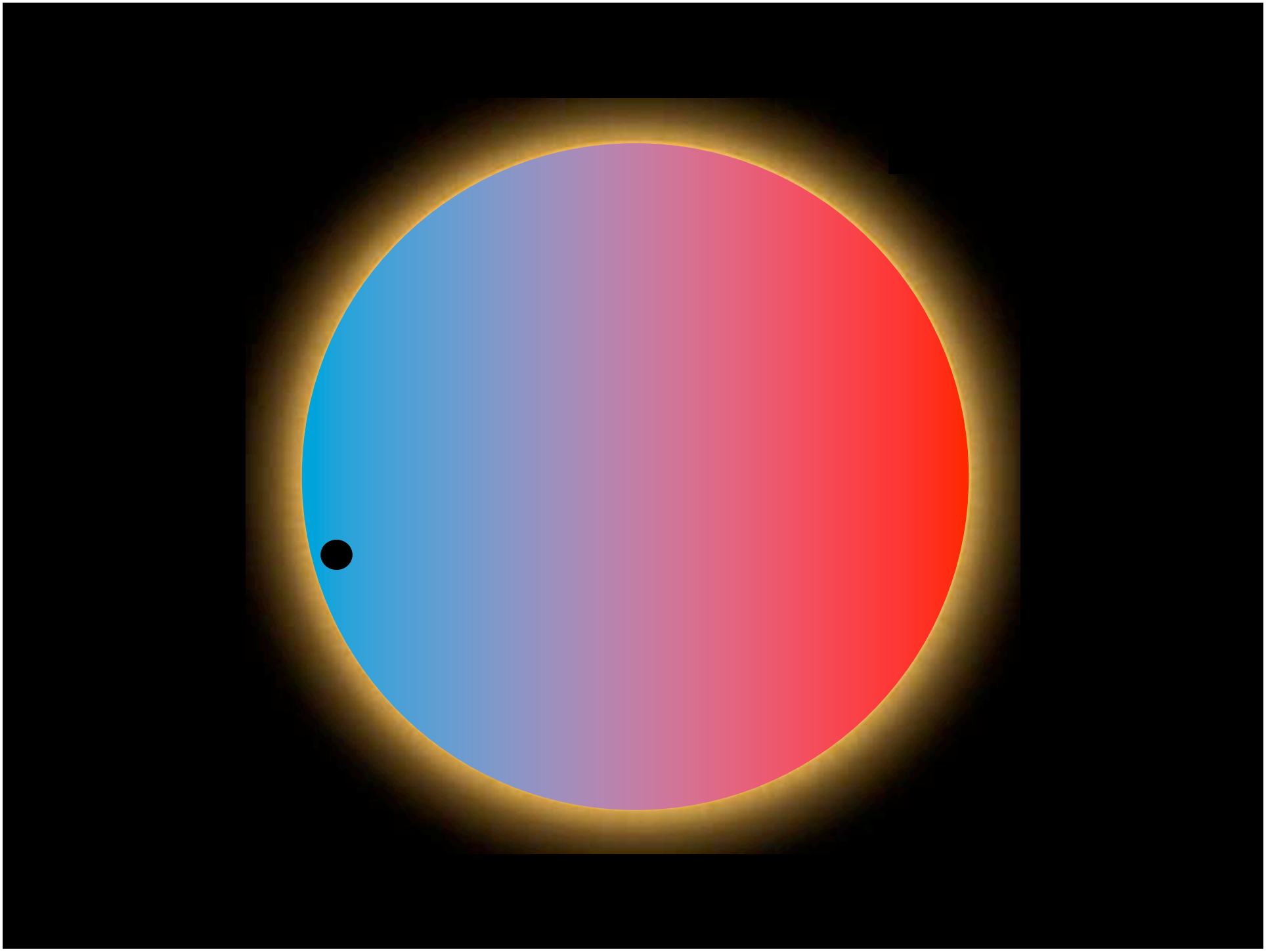

Relative flux
Time

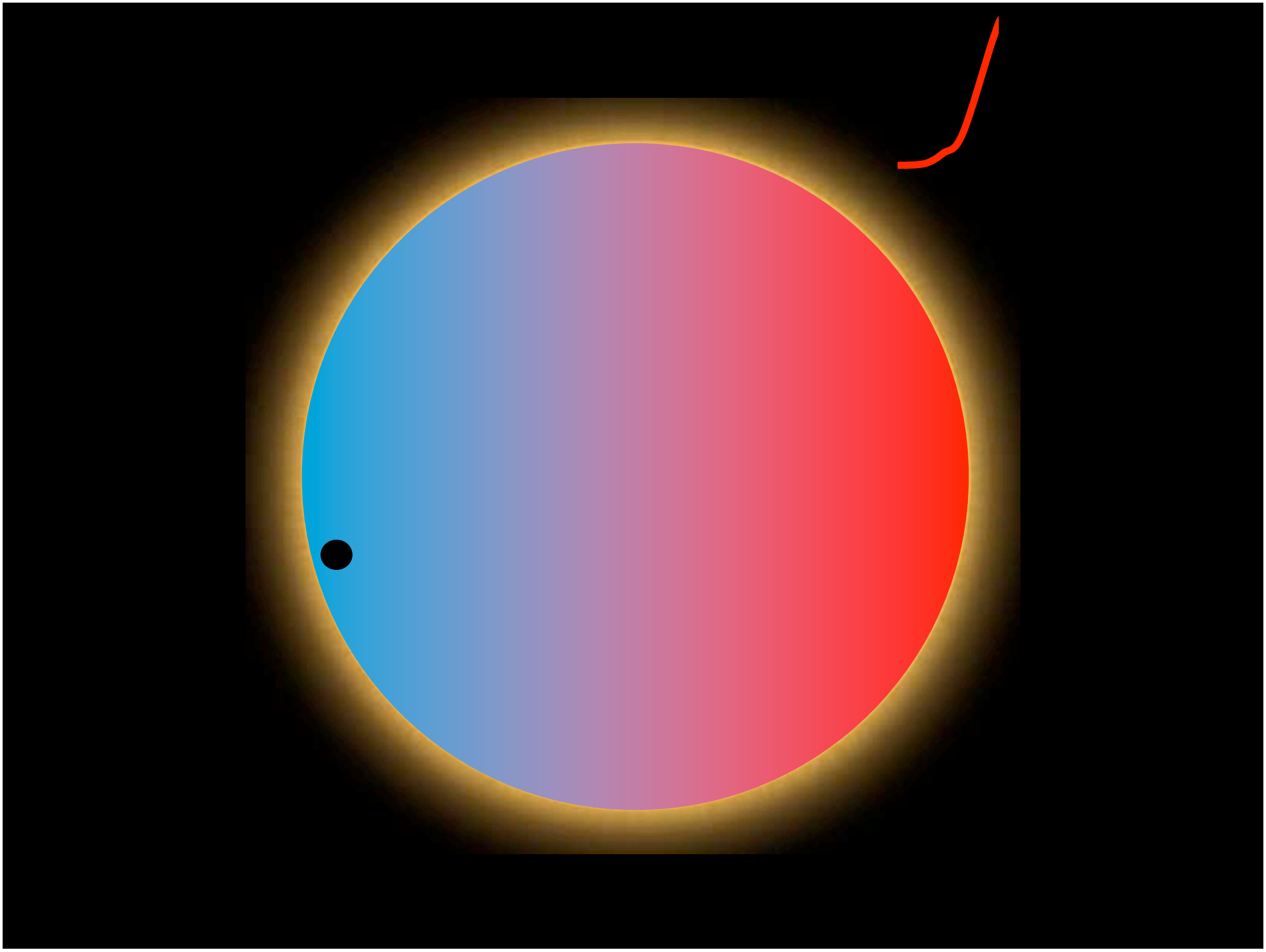

Relative flux
Time

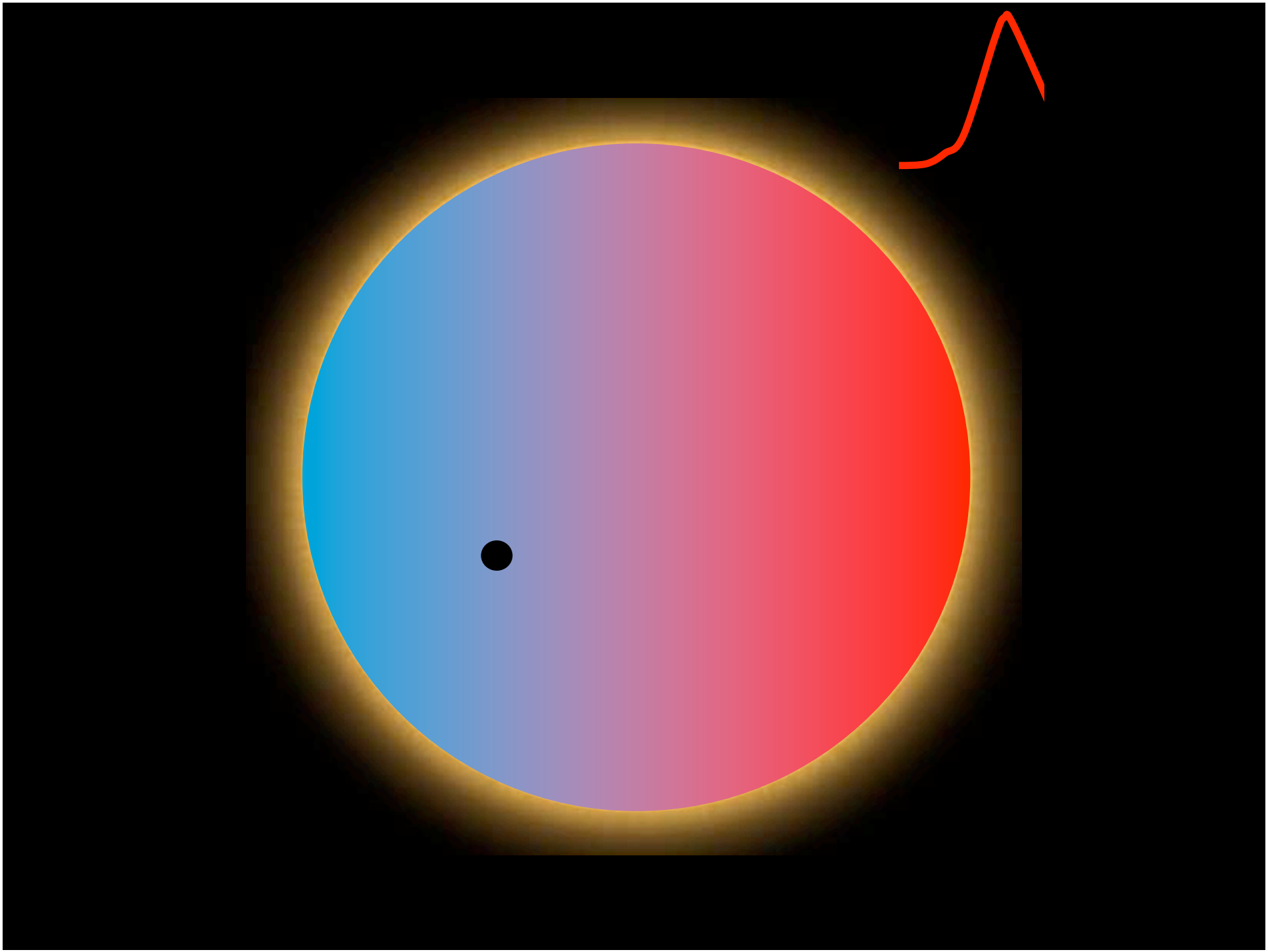

Relative flux
Time

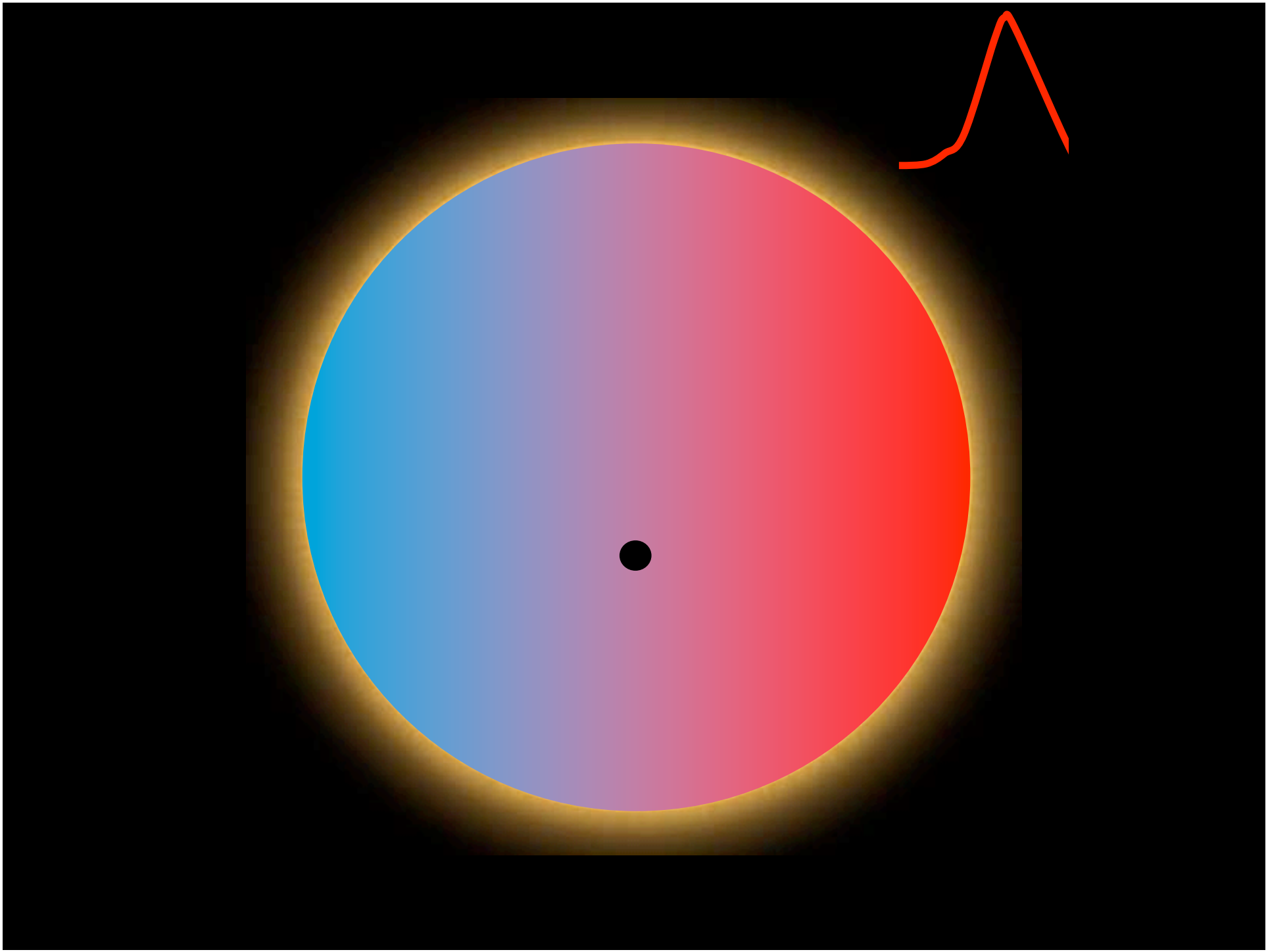


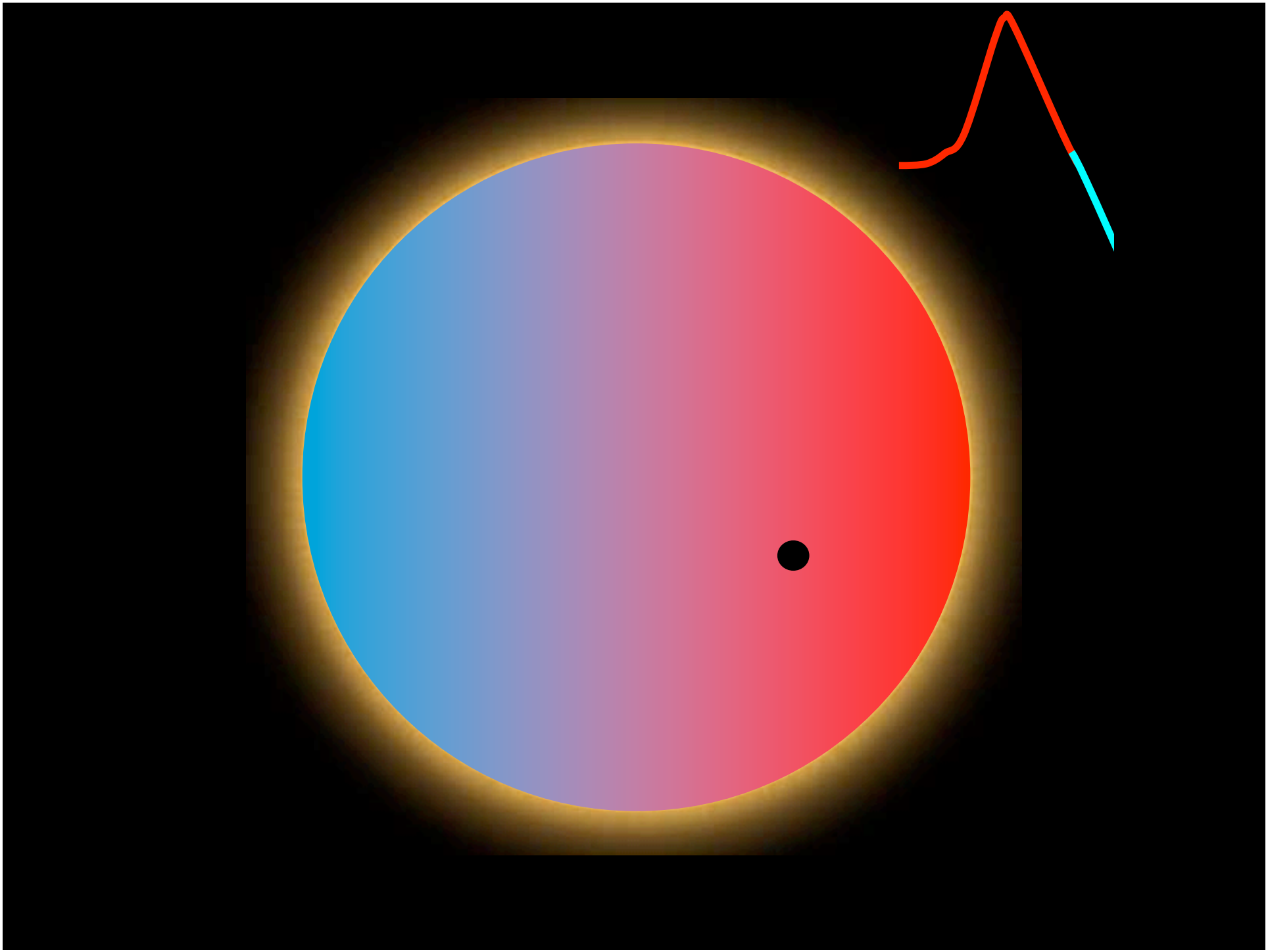


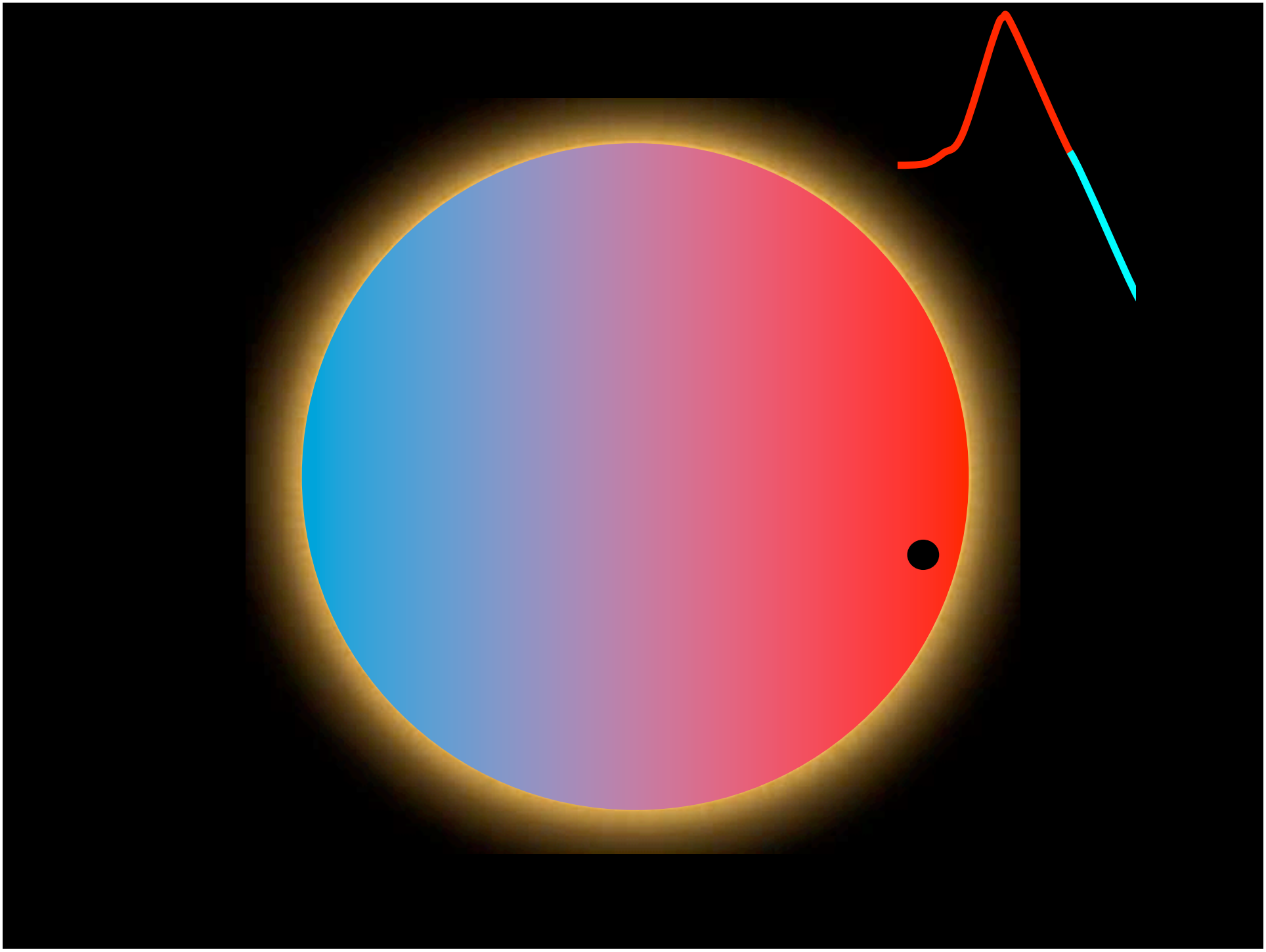


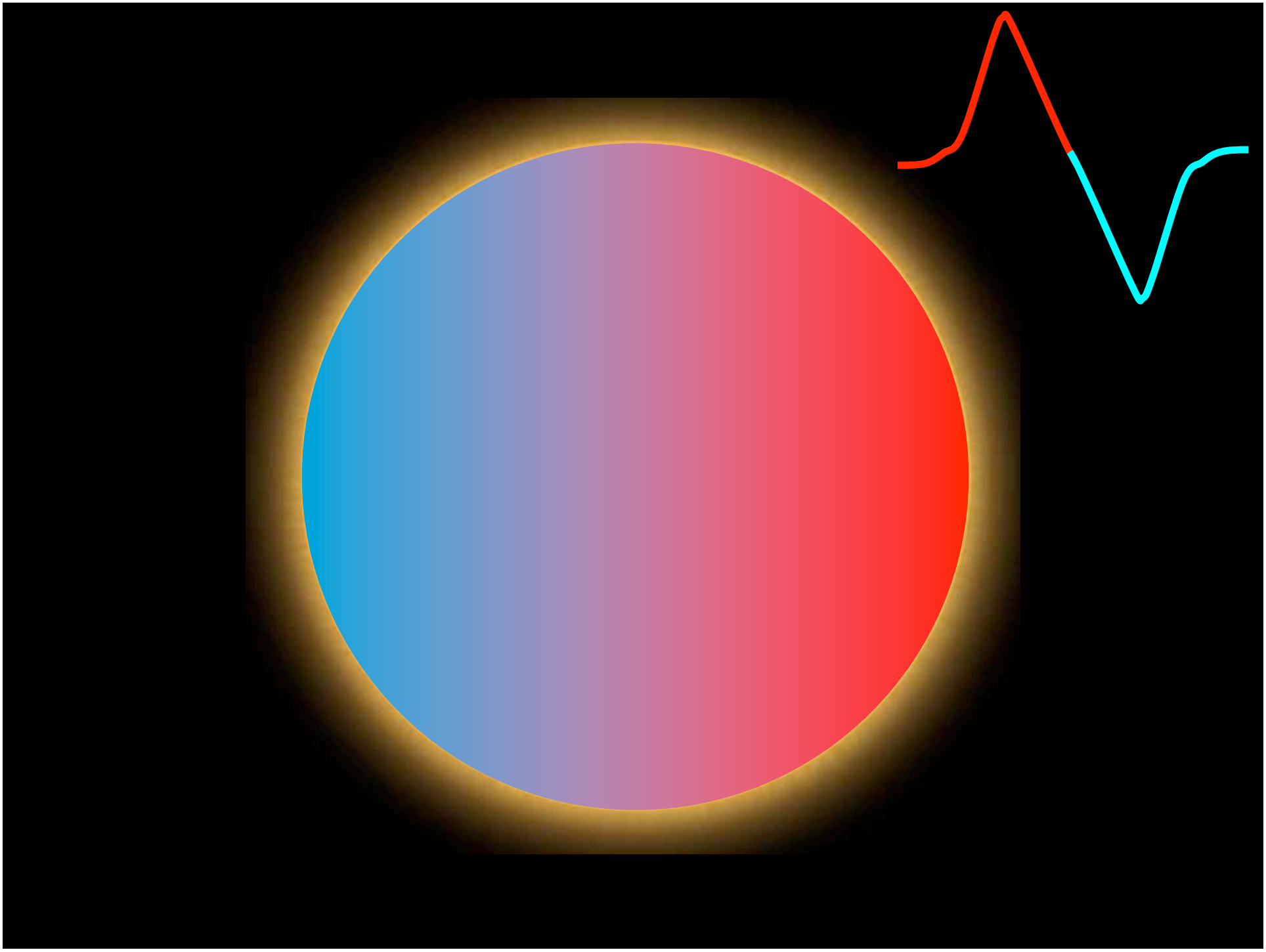


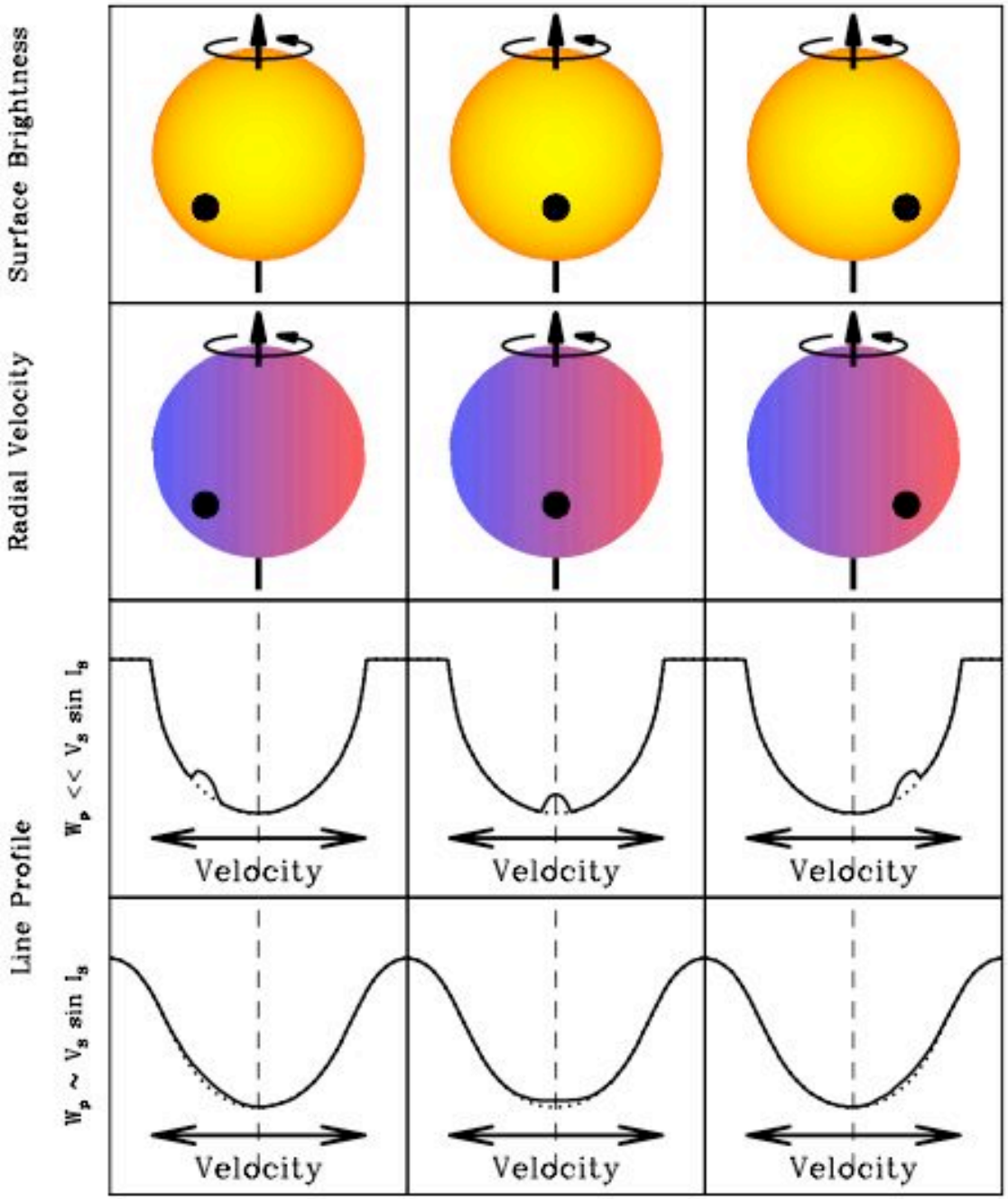








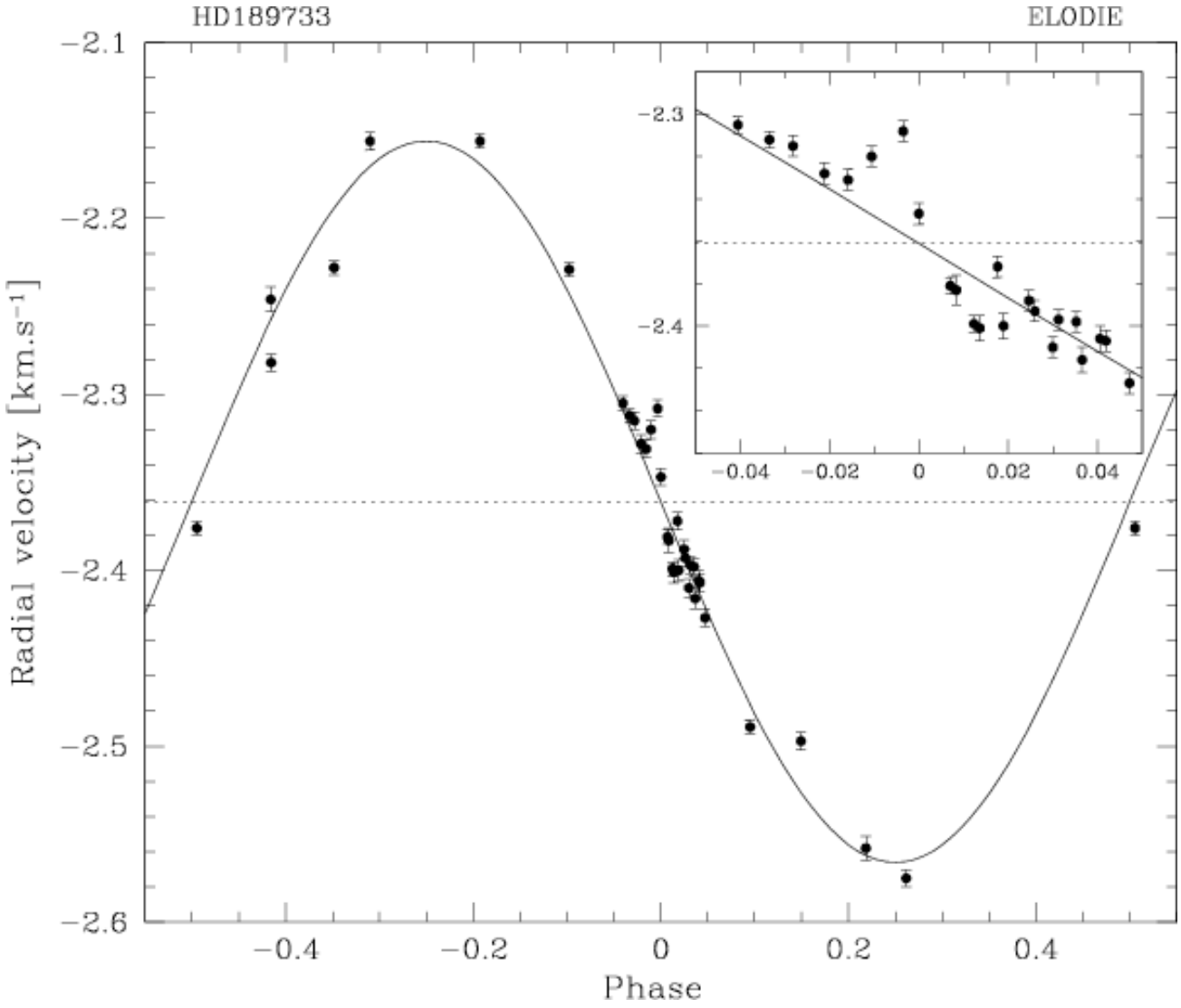




Gaudi &
Winn (2007)

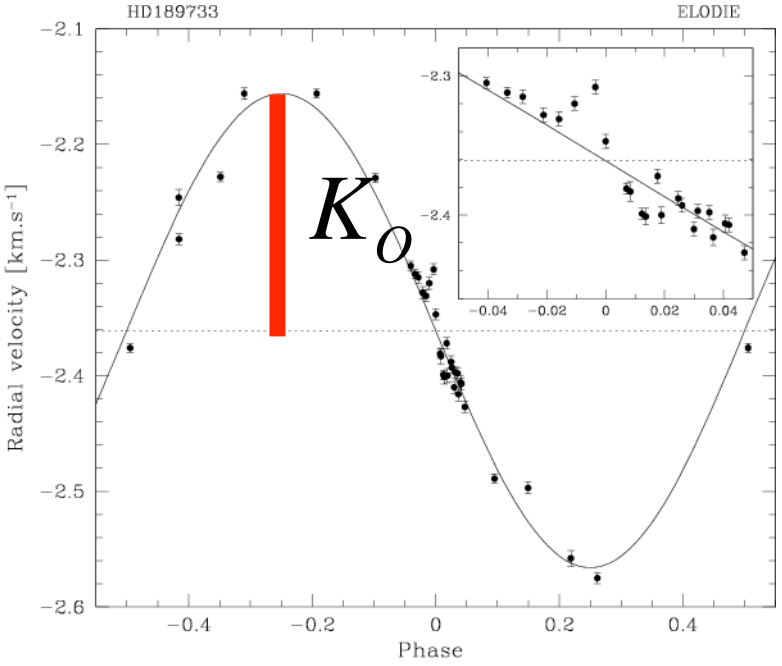
What is the Rossiter-McLaughlin Effect?

What do we measure?



What do we measure?

$$V(t) = V_O(t) + V_R(t) + V_0$$



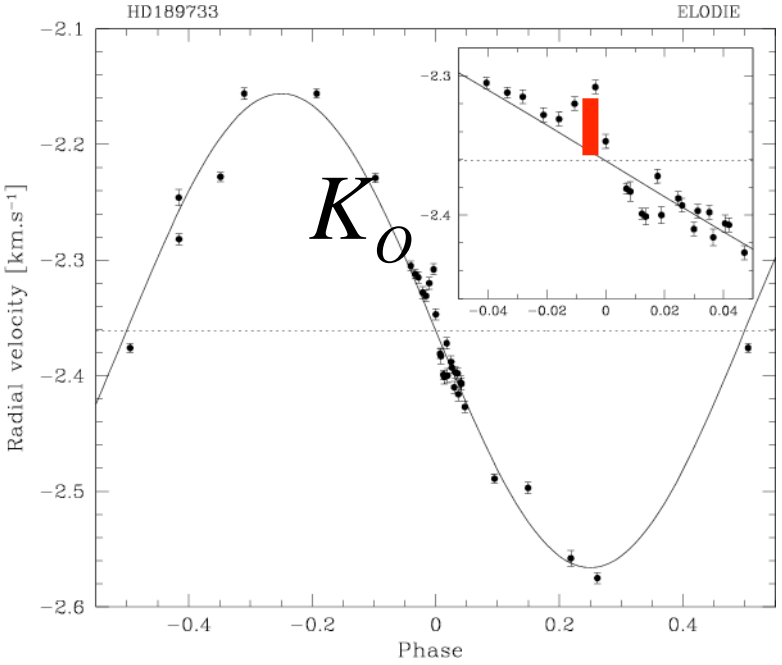
Doppler

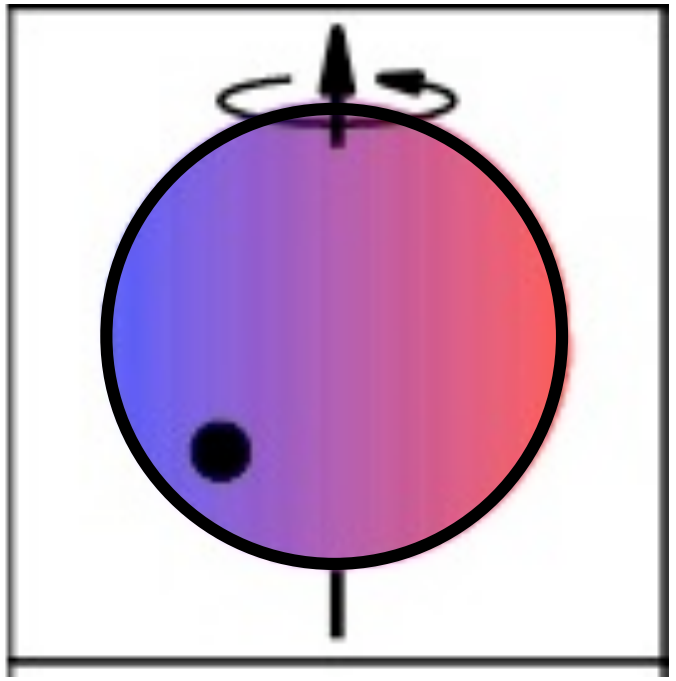
$$V_O(t) = K_O\{\cos[f(t) + \omega] + e\cos\omega\}$$

$$K_O = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{m\sin i}{(M+m)^{2/3}}(1-e^2)^{-1/2}$$

What do we measure?

$$V(t) = V_O(t) + V_R(t) + V_0$$

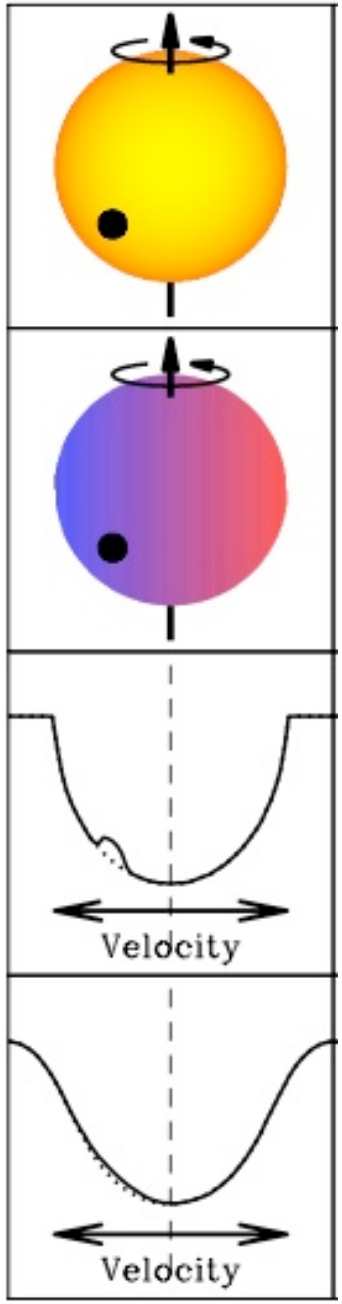


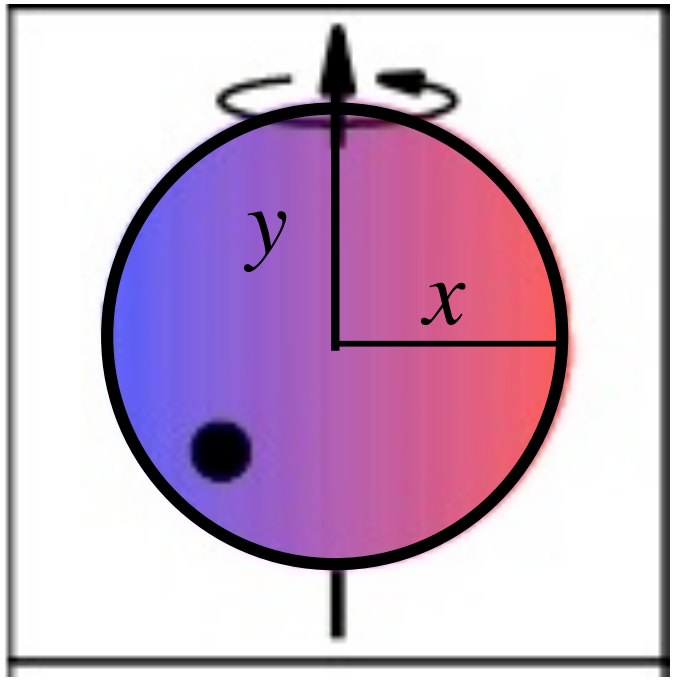


"Anomalous RV"

What exactly is the RM effect?

- Change in line shape
- *Not* a Doppler shift
- Cross-correlation measures line centroids
- Some methods attempt to correct for line shape variations





$$V(x,y) = xV_* \sin I$$

Centroid approximation

$$V_R = V_* \sin I \frac{\int\int xS(x,y)dxdy}{\int\int S(x,y)dxdy}$$

$$\gamma = \frac{r}{R}$$

$$V_R = V_* \sin I \frac{\gamma^2}{1-\gamma^2} g(t; x_p, y_p, \gamma, u_1, \ldots) \equiv K_R g(t)$$

Ohta et al 2005

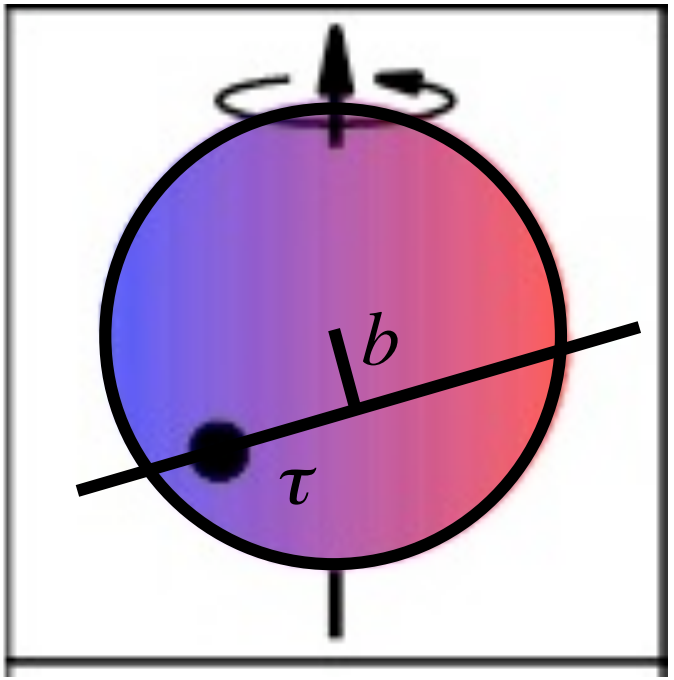
Gimenez 2006

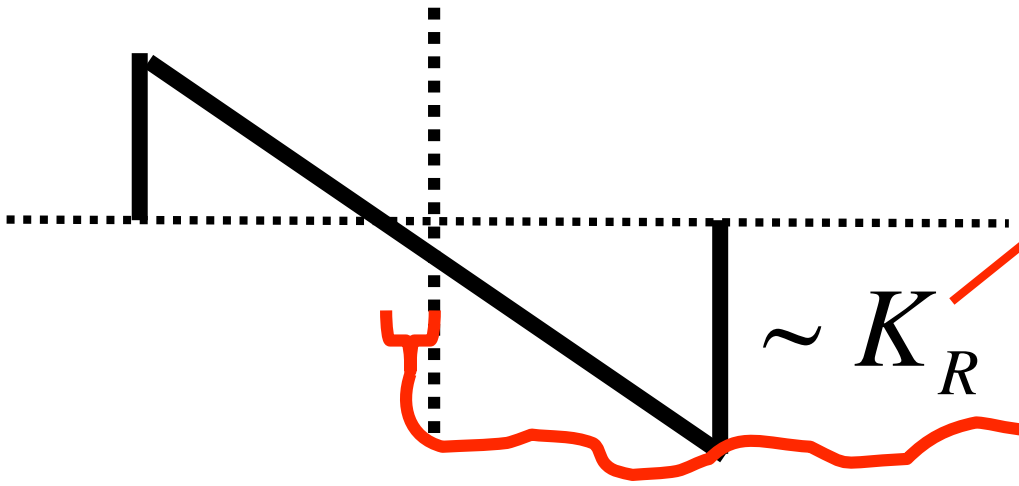
No limb-darkening, complete transit

$$V_R = K_R g(t)$$

$$g(t) = x(t) = \tau \cos\lambda - b \sin\lambda$$

where $\tau = \dfrac{t - t_{tra}}{T}$

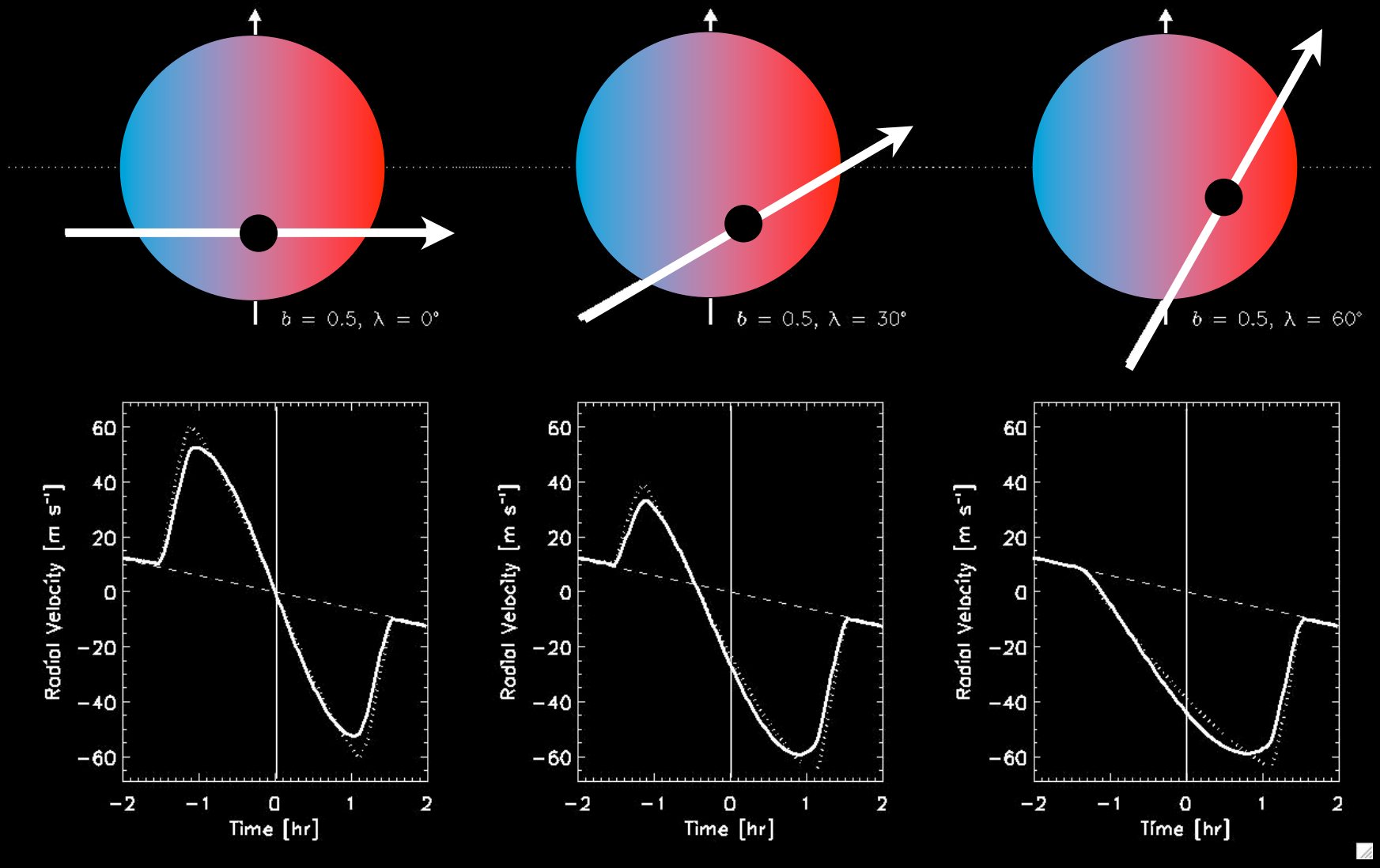




$$K_R = V_* \sin I \frac{\gamma^2}{1 - \gamma^2}$$

$$\frac{t_{rot} - t_{tra}}{T} \sim b \tan\lambda$$

Measuring spin-orbit alignment



Ohta, Taruya, & Suto 2005; Gaudi & Winn 2007

Parameters

Specified by the photometric transit:

- Duration
- Ingress/Egress Time
- Impact Parameter
- Limb Darkening
- Planet/Star Radius Ratio

Additional Parameters Required for RM Effect

- λ (Spin-Orbit alignment)
- $V_* \sin I$ (can also be constrained from spectrum)

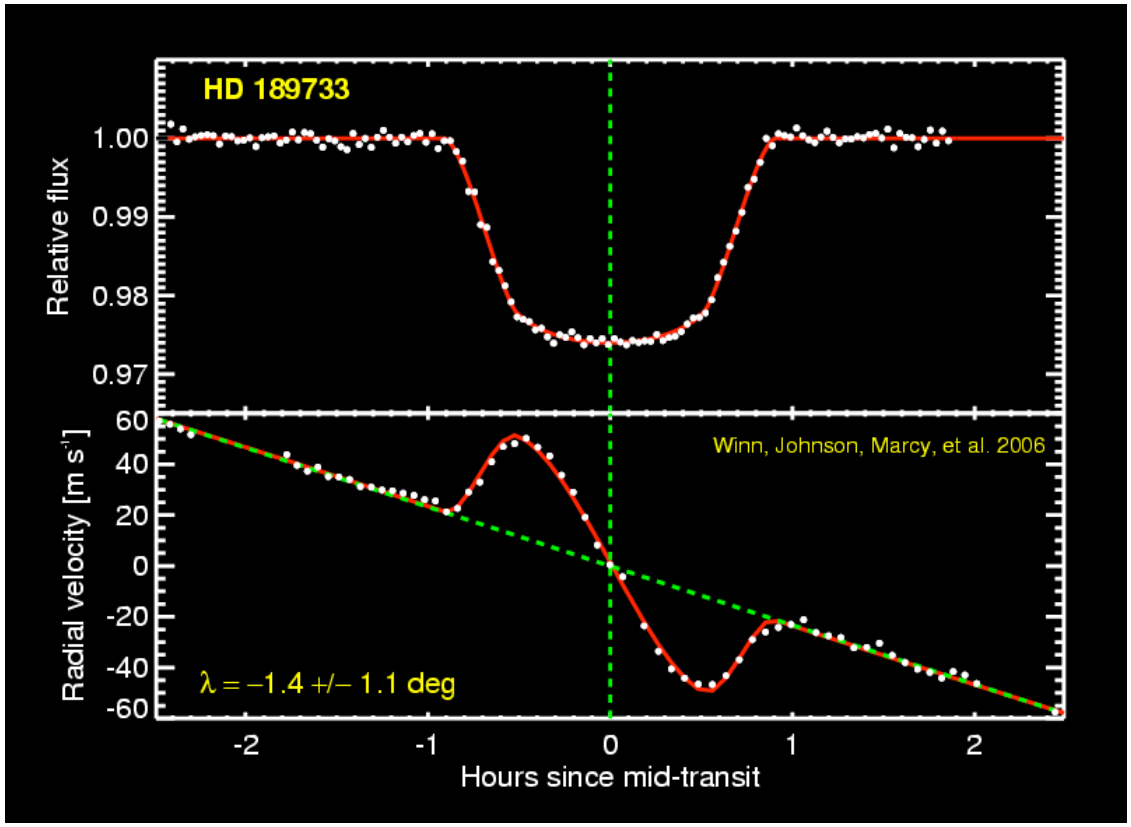
Total S/N

$$\frac{S}{N} \approx Q_R \left[\tfrac{1}{3}(1 - 4b^2)\cos^2\lambda + b^2 \right]^{1/2}$$

where

$$Q_R = \frac{\sqrt{N}}{\sigma} K_R$$

$$\frac{S}{N} \approx 50$$



Measurement Uncertainties

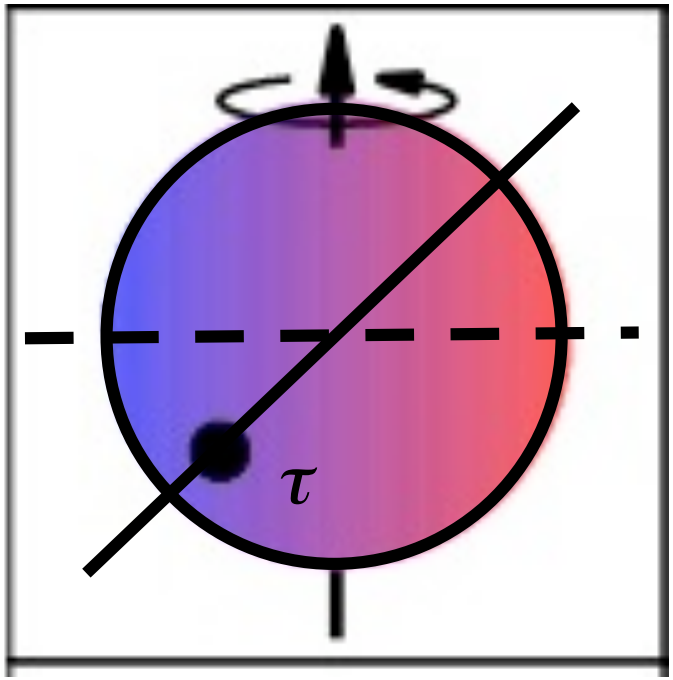
$$\sigma_\lambda \approx Q_R^{-1}\left[\frac{(1-b^2)\cos^2\lambda + 3b^2\sin^2\lambda}{b^2(1-b^2)}\right]^{1/2}$$

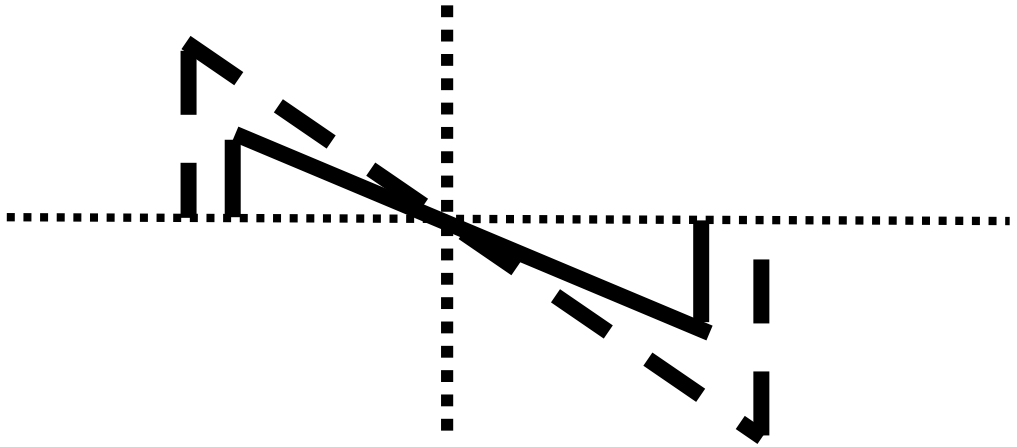
$$\frac{\sigma_{V_* \sin I}}{V_* \sin I} \approx Q_R^{-1}\left[\frac{(1-b^2)\sin^2\lambda + 3b^2\cos^2\lambda}{b^2(1-b^2)}\right]^{1/2}$$

Gaudi & Winn (2007)

Useful for estimating expected uncertainties

Central Transits are bad:





$$V_R = K_R(\tau\cos\lambda - b\sin\lambda) \rightarrow [K_R\cos\lambda]\tau$$

λ is degenerate with $V_*\sin I$

Why Measure the Rossiter-McLaughlin Effect?

Spin-orbit alignment for exoplanets

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- Solar system: alignment is within ~10°

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- How common or unusual is this?

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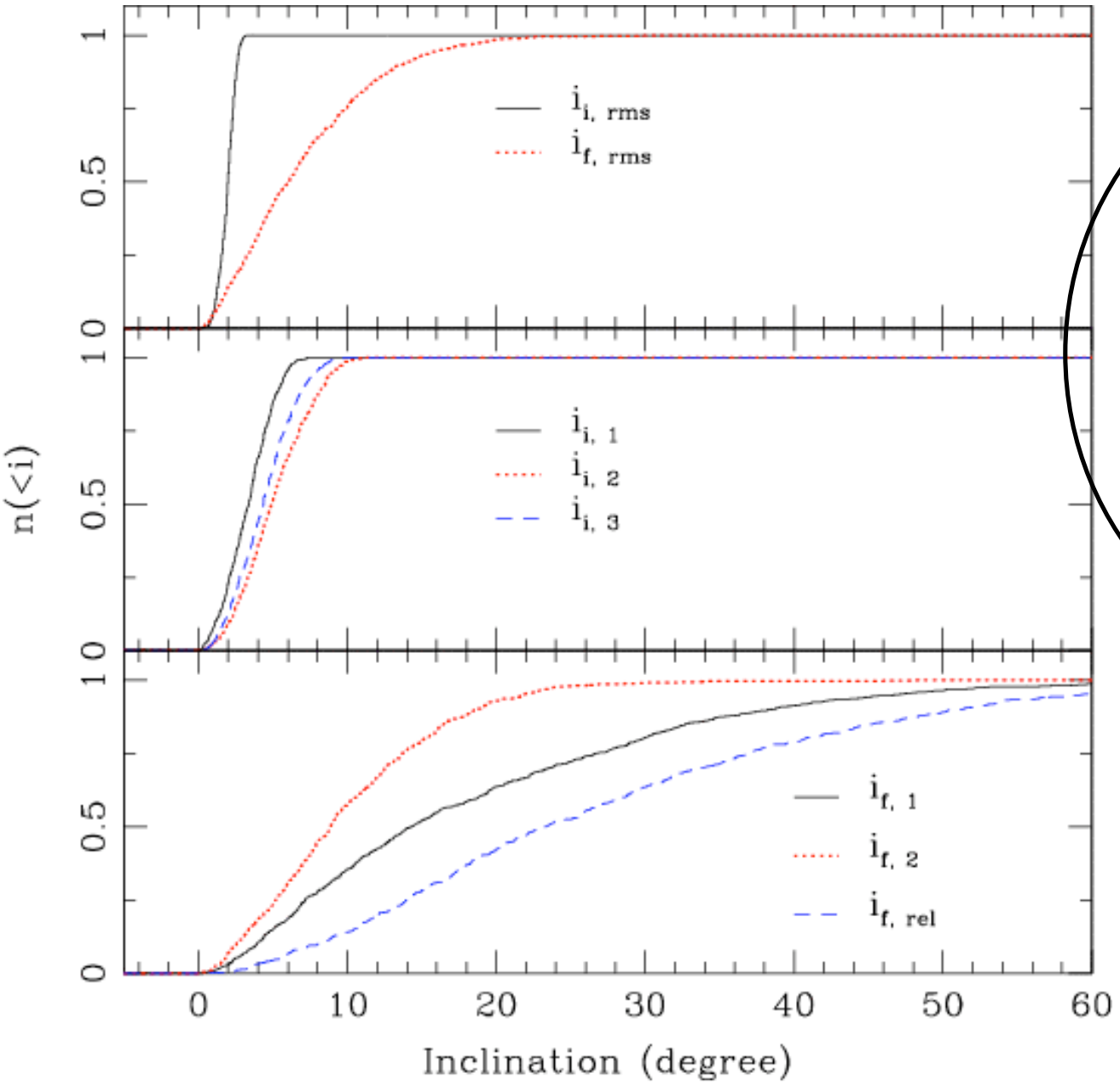
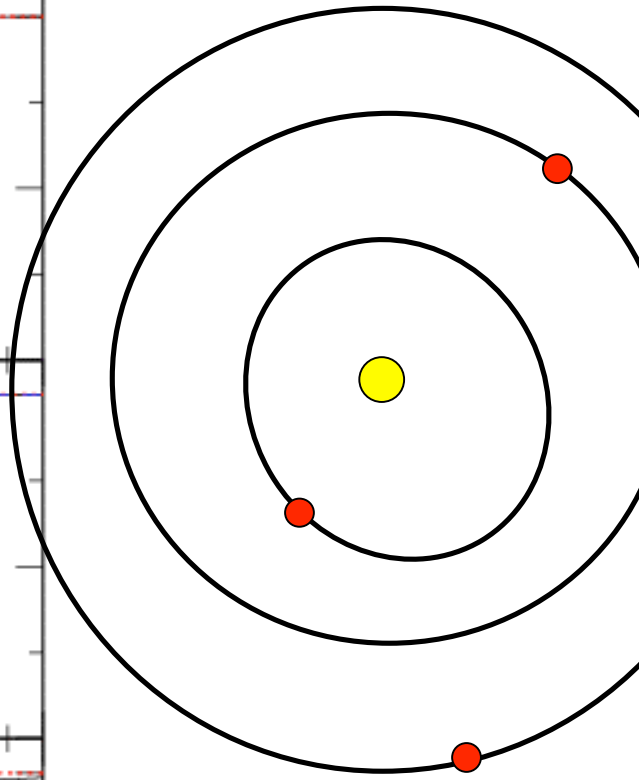
  - Migration (disk interaction *v.* scattering, Kozai)

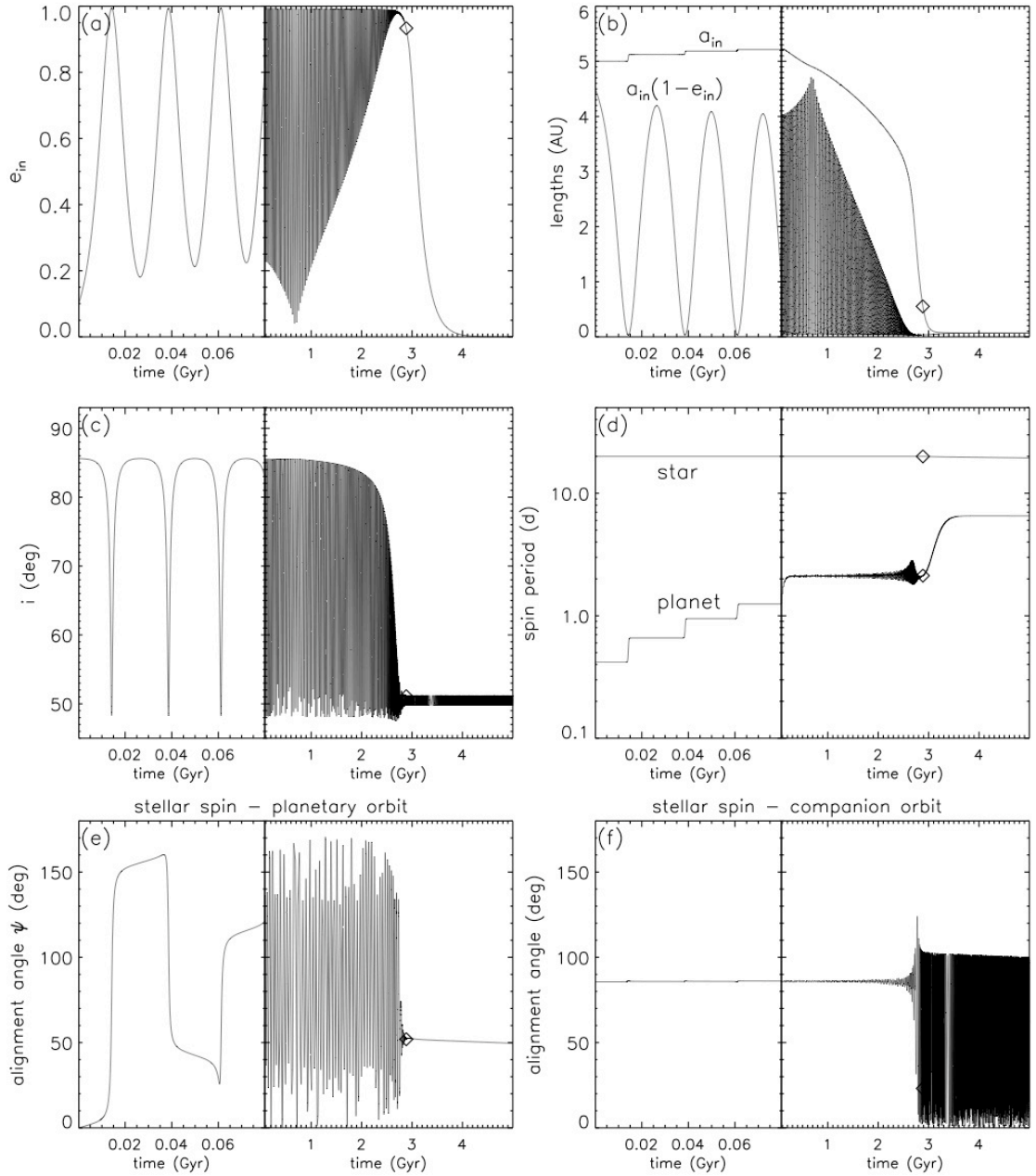
Planet-Planet Scattering





Chatterjee, Ford,
& Rasio (2007)

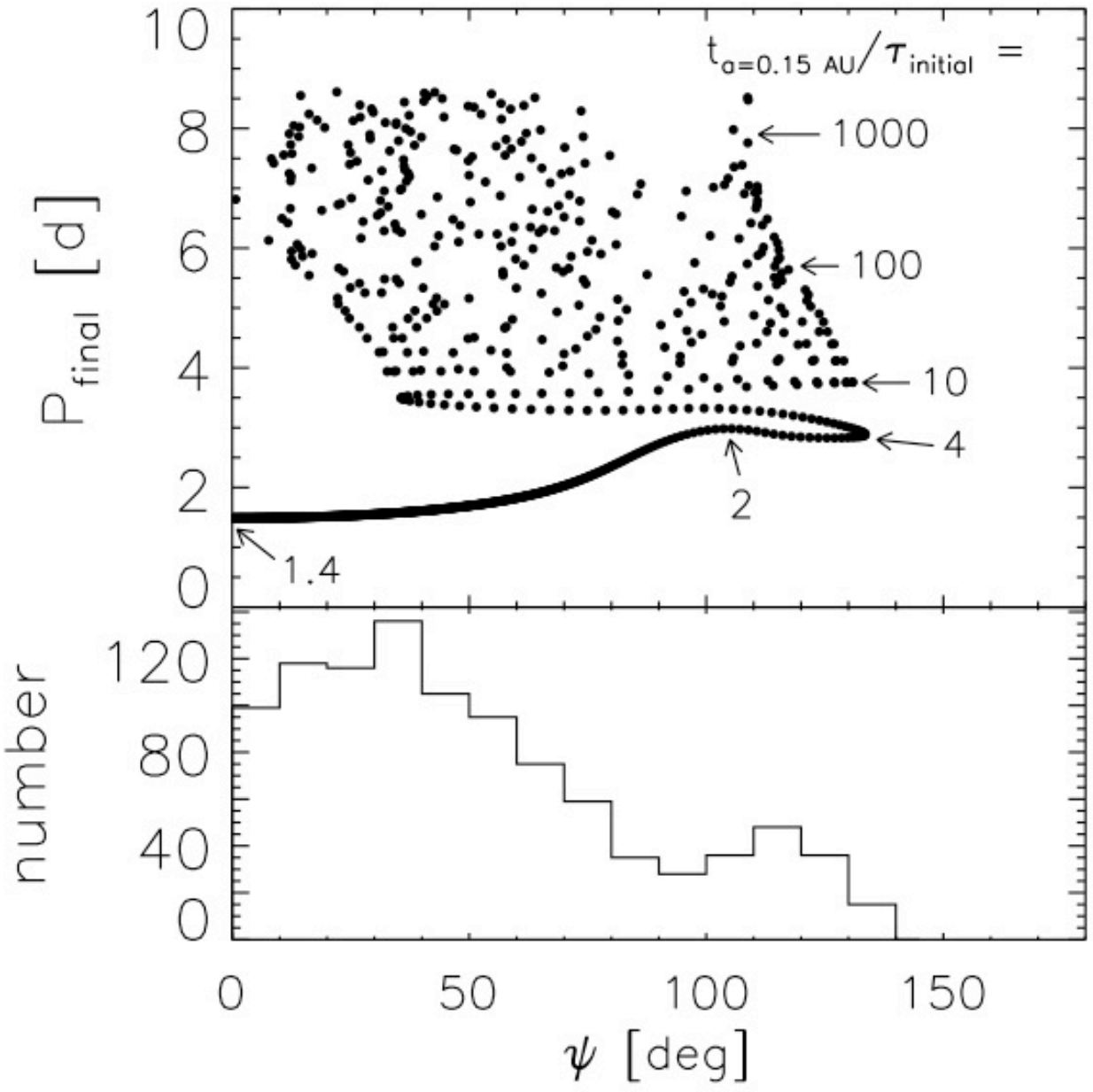
Kozai Oscillations with Tides



Fabrycky &Tremaine (2007)

Wu et al (2007)

Kozai Oscillations with Tides

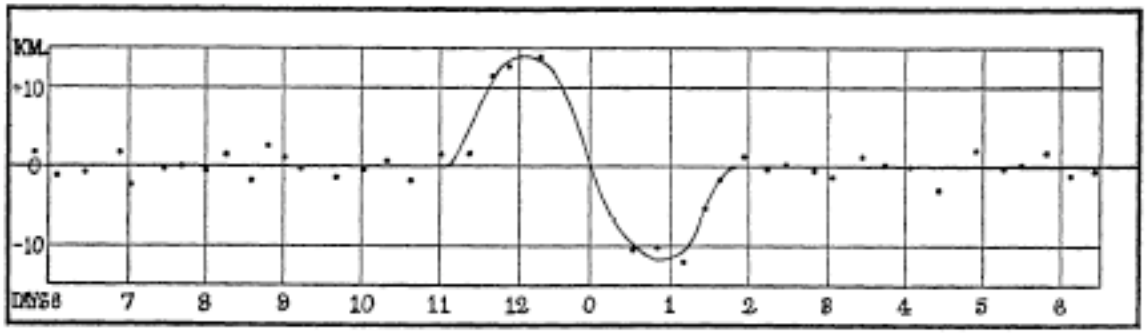


Spin-orbit alignment for exoplanets

- Solar system: alignment is within ~10°
- How common or unusual is this?
- Theoretical reasons to expect misalignment:
  - Whatever perturbs e may also perturb I
  - Migration (disk interaction *v.* scattering, Kozai)
- Fundamental measurement

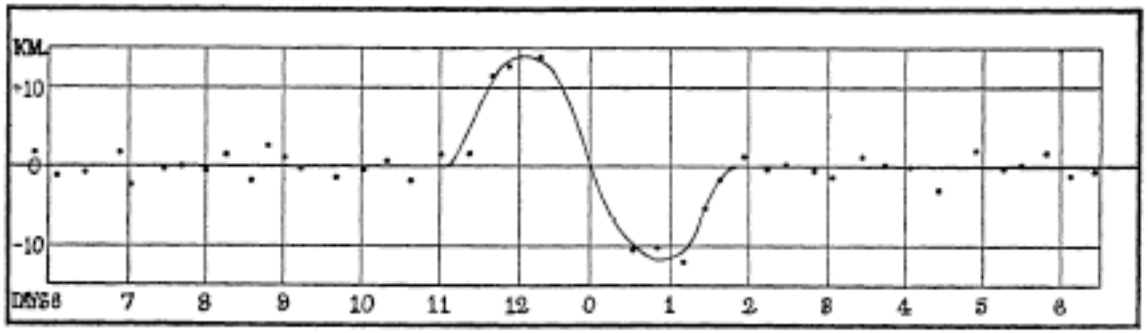
Measurements of the Rossiter-McLaughlin Effect

R. A. Rossiter
(1896-1977)

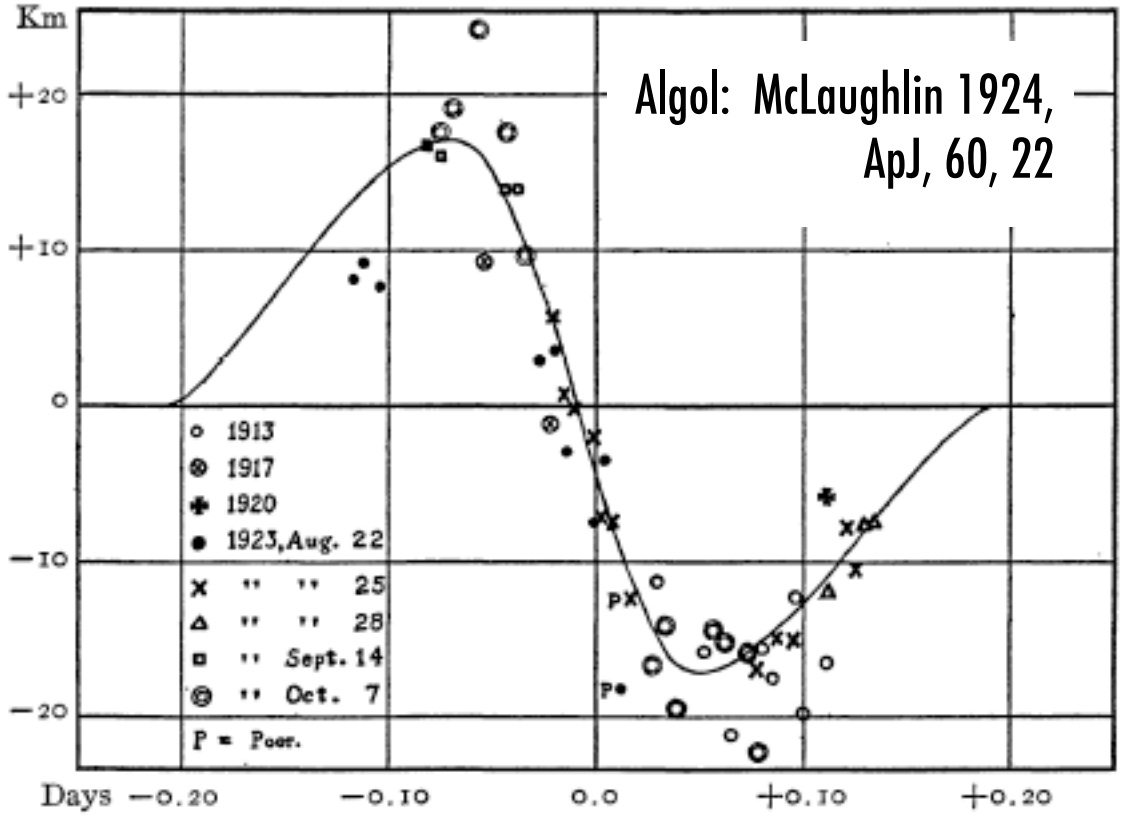


β Lyrae: Rossiter 1924, ApJ, 60, 15

R. A. Rossiter
(1896-1977)



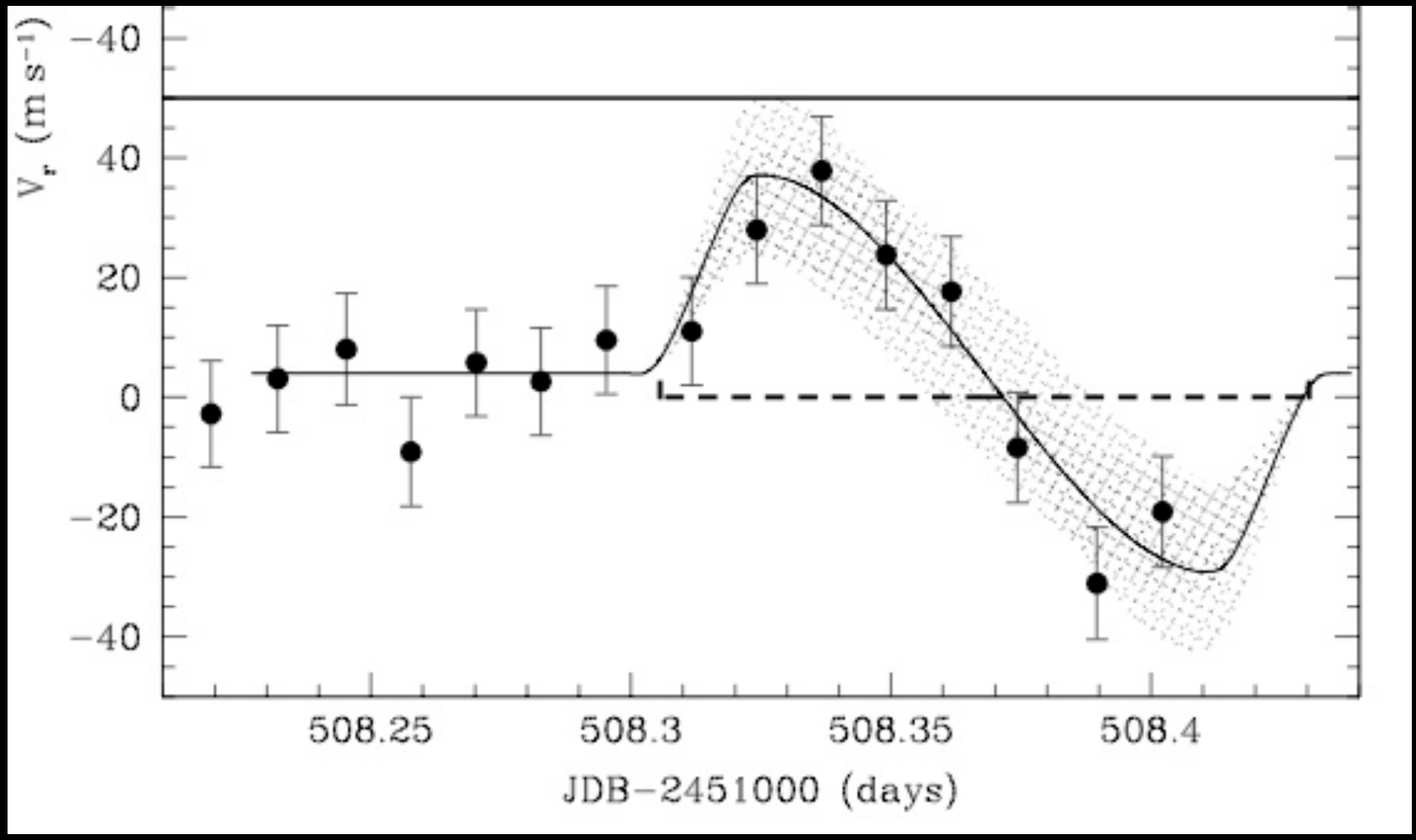
β Lyrae: Rossiter 1924, ApJ, 60, 15



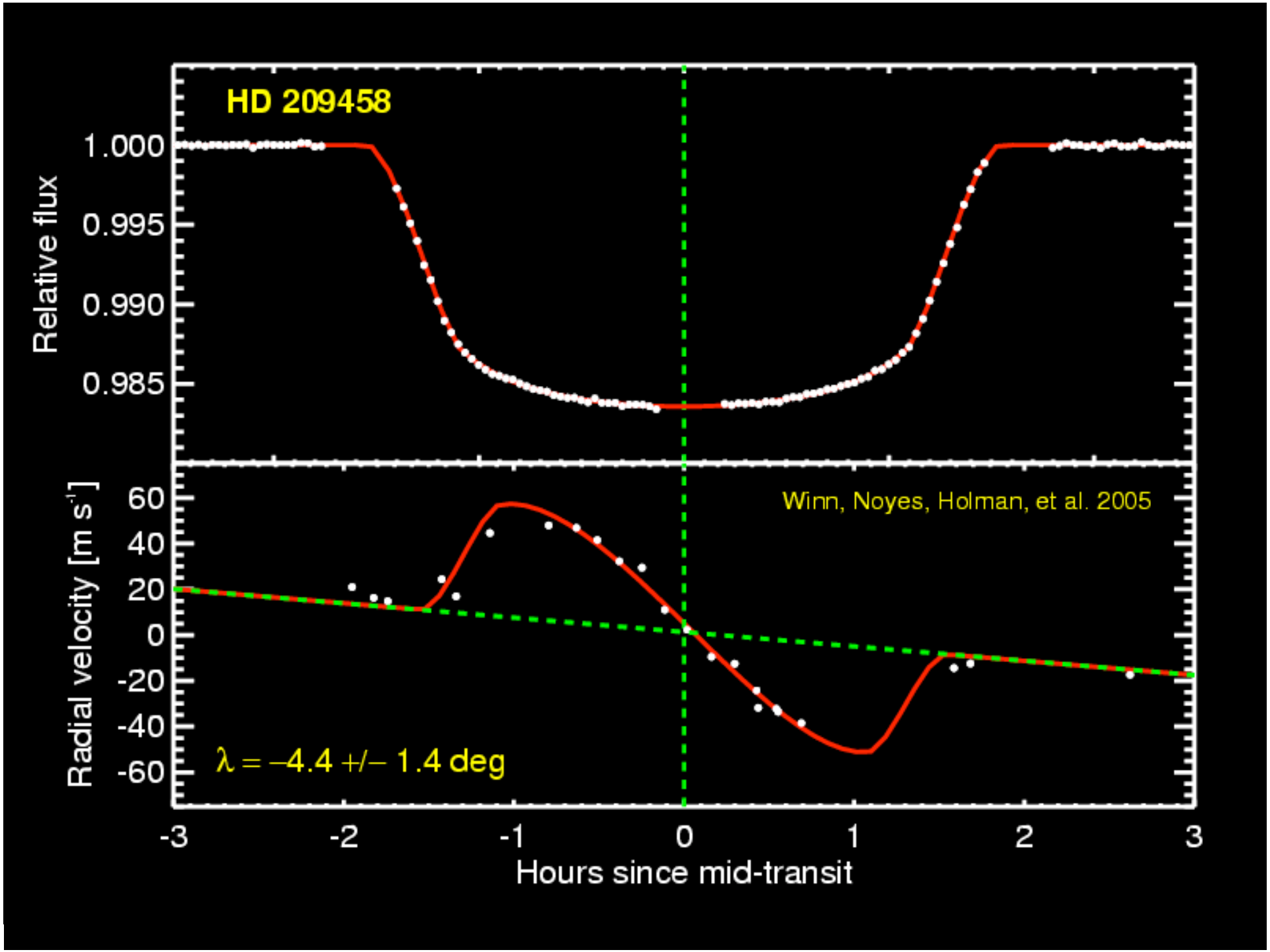
Algol: McLaughlin 1924, ApJ, 60, 22

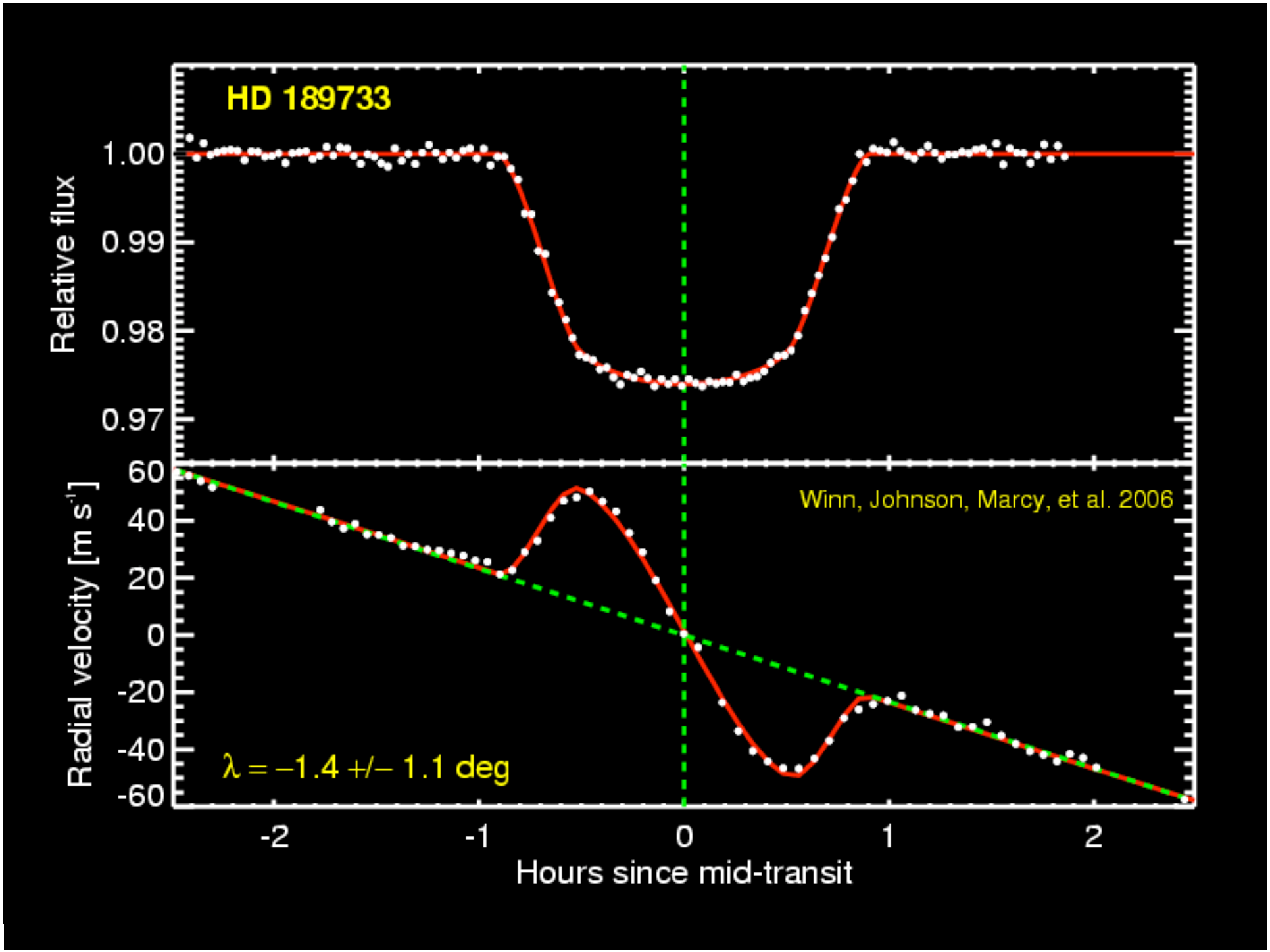
FIG. 1.—Curve of the rotational effect in Algol

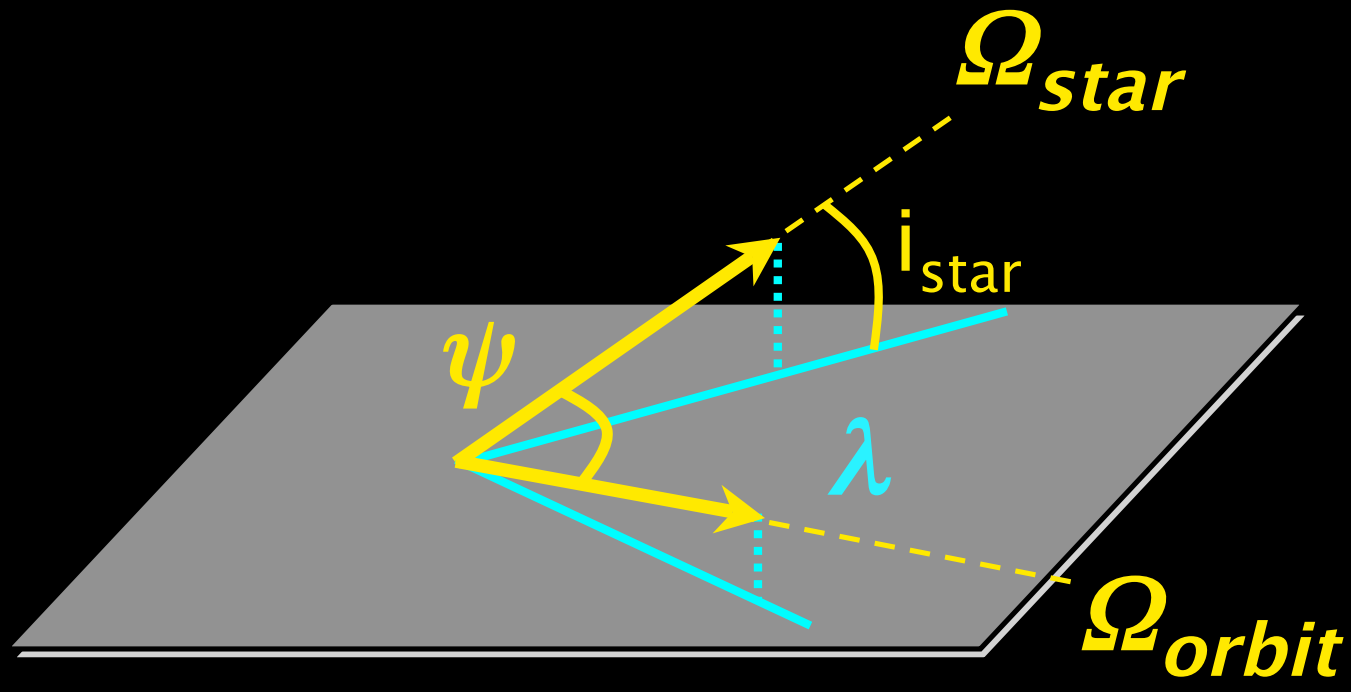
R. A. Rossiter (1896-1977)



Queloz et al 2000


HD 209458
Relative flux
1.000
0.995
0.990
0.985
Radial velocity [m s-1]
60
40
20
0
-20
-40
-60
Winn, Noyes, Holman, et al. 2005
λ = –4.4 +/– 1.4 deg
-3
-2
-1
0
1
2
3
Hours since mid-transit


HD 189733
Relative flux
1.00
0.99
0.98
0.97
Radial velocity [m s-1]
60
40
20
0
-20
-40
-60
Winn, Johnson, Marcy, et al. 2006
λ = –1.4 +/– 1.1 deg
-2
-1
0
1
2
Hours since mid-transit



$\lambda = -1.1 +/- 1.4$ deg (RM effect)

$\sin i_{star} = [v \sin i_{star}] / (2\pi R/P)$

$\psi < 27$ deg (95% conf.)

Winn, Holman, Henry, et al. (2007)

HD 147506 = HAT-P-2

Bakos et al. (2007)

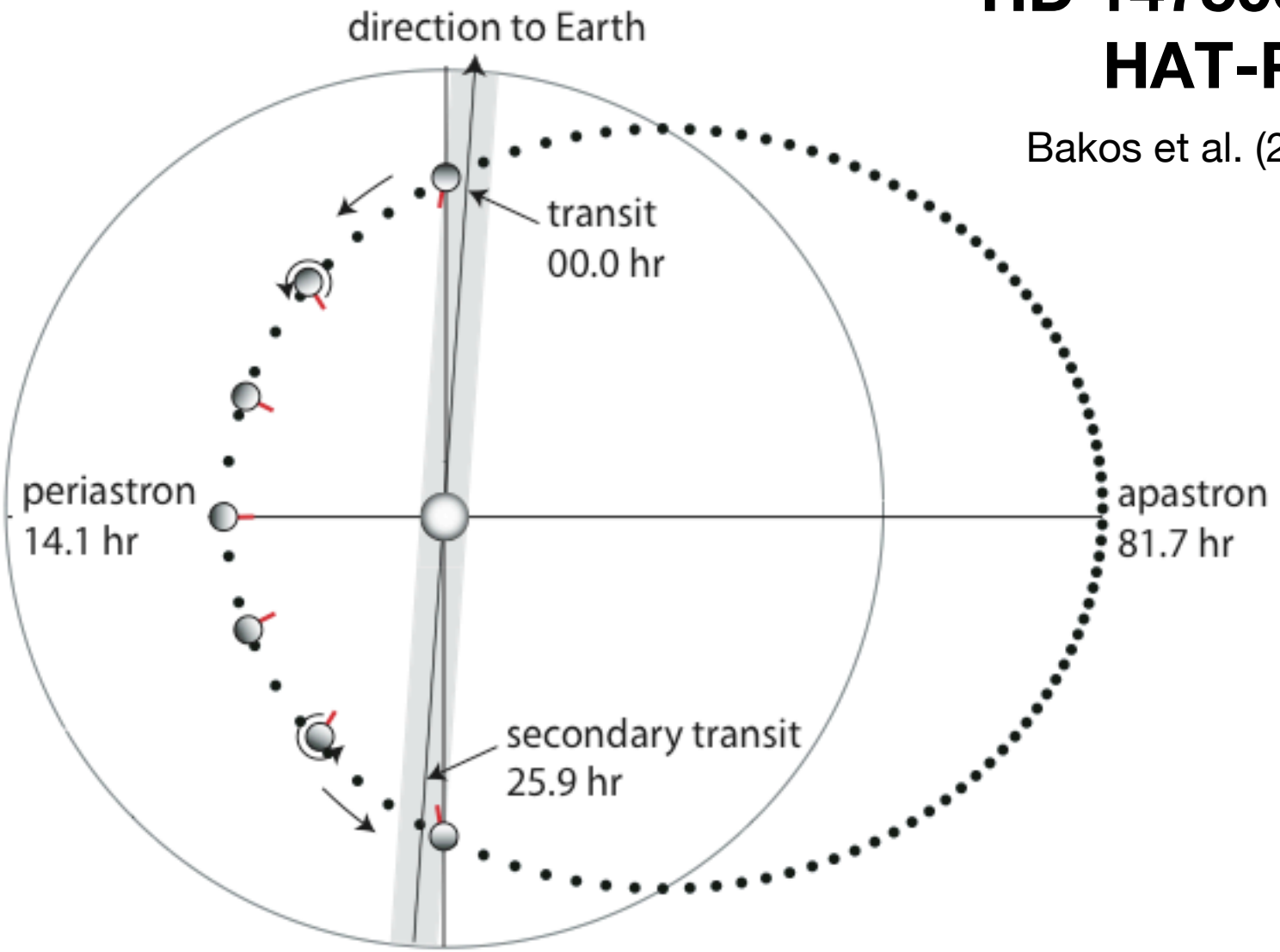
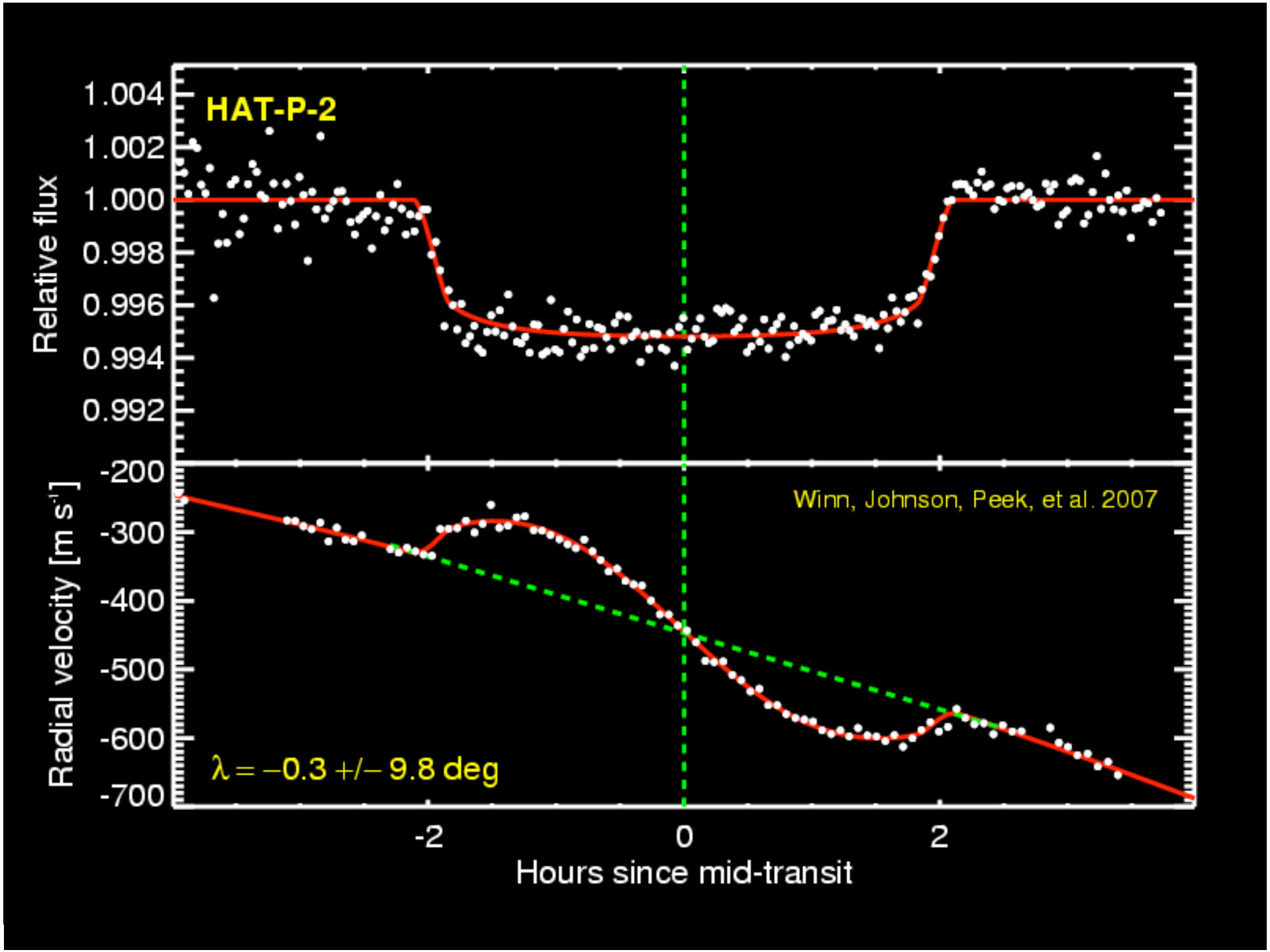
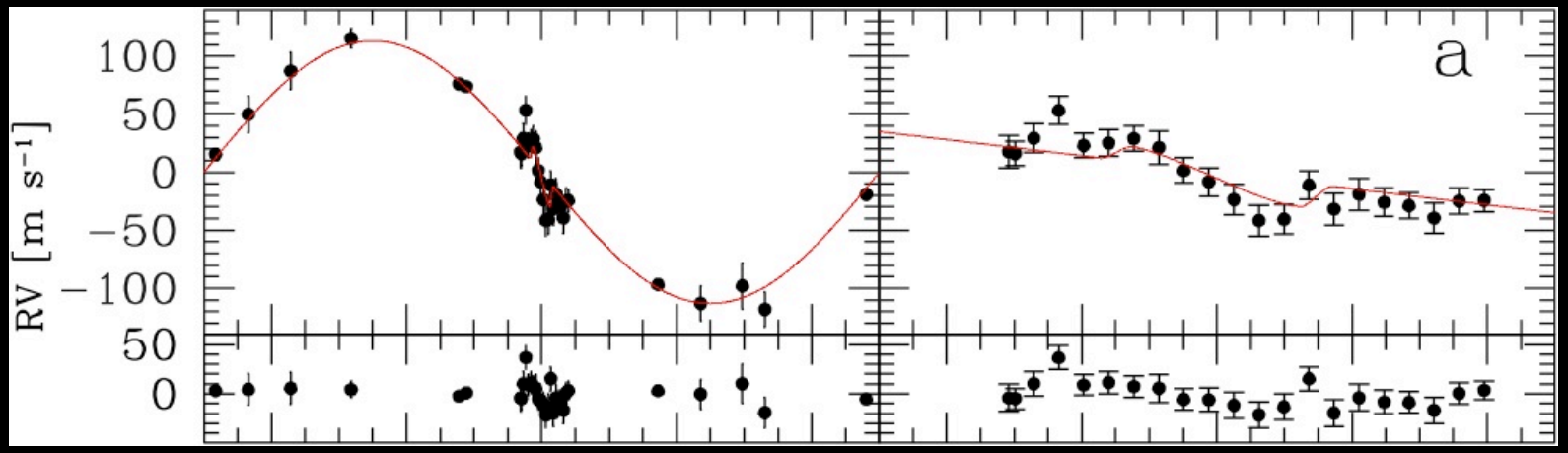
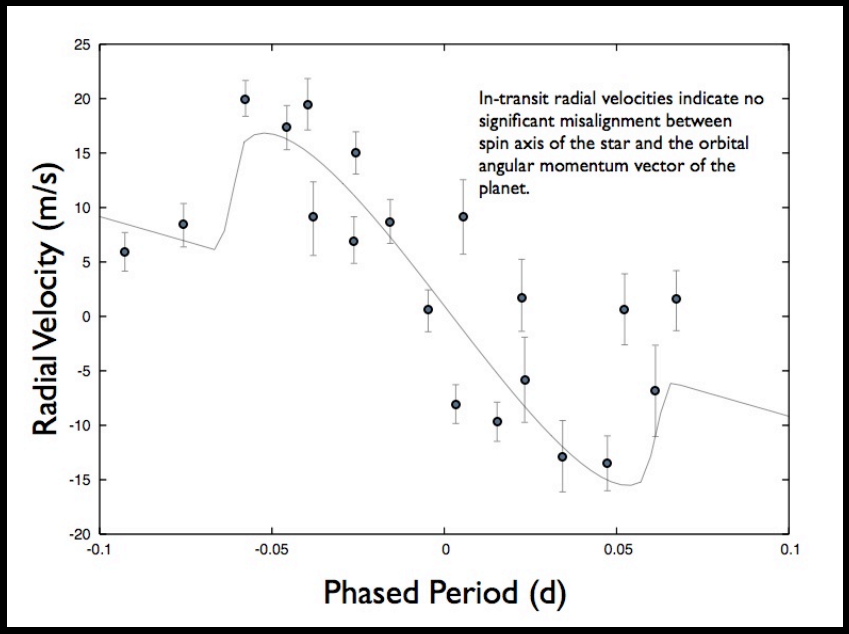


Diagram by G. Laughlin


HAT-P-2
Relative flux
1.004
1.002
1.000
0.998
0.996
0.994
0.992
Radial velocity [m s-1]
-200
-300
-400
-500
-600
-700
Winn, Johnson, Peek, et al. 2007
λ = −0.3 +/− 9.8 deg
-2
0
2
Hours since mid-transit



TrES-1: λ= 30° ±21° (Narita et al 2007)



HD 149026: λ= 12° ±14° (Wolf et al)

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- Random alignments ruled out (>99.9% CL)

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- Migration generally preserves spin-orbit alignment?

Confirming Planets Rossiter-McLaughlin Effect

RM Effect Amplitude

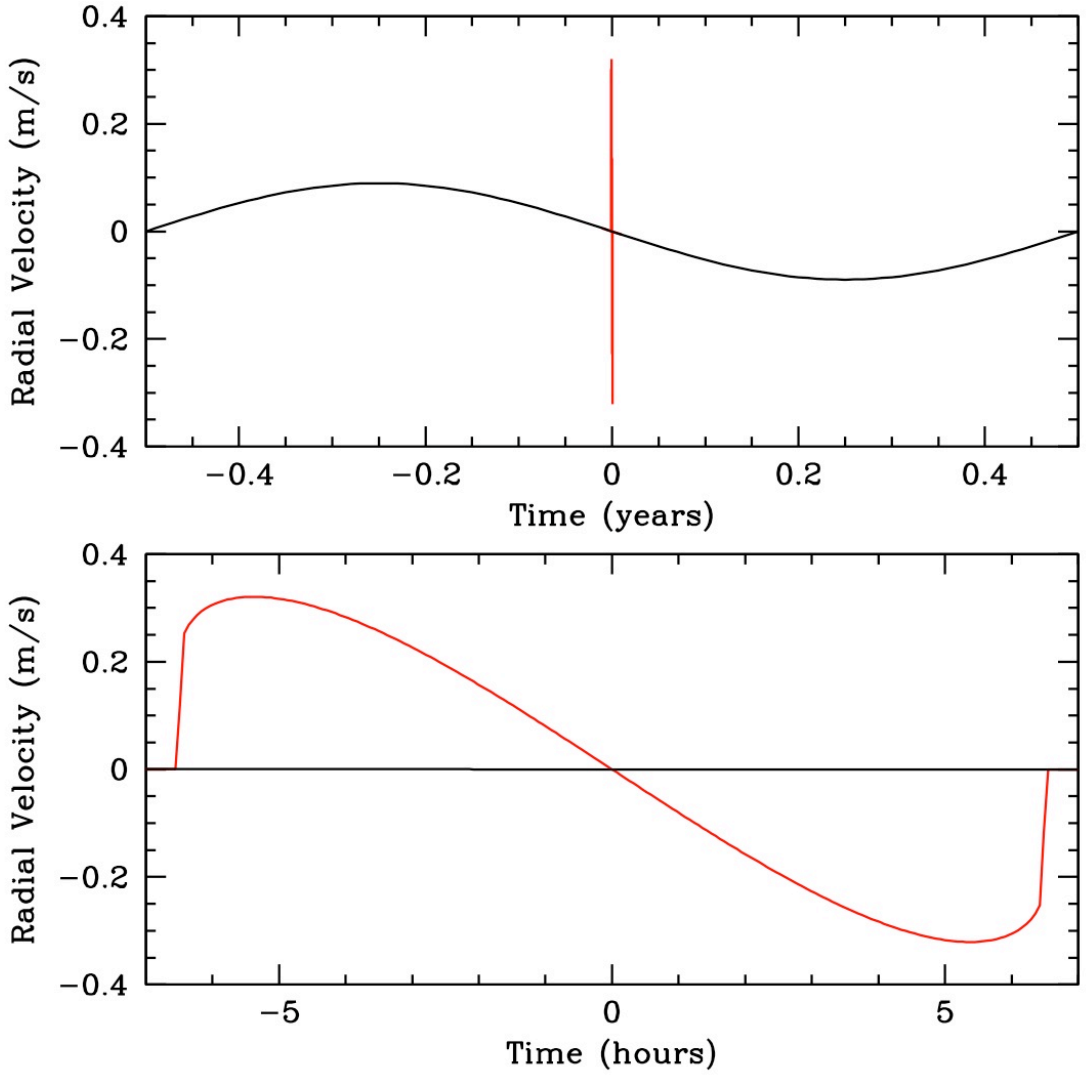
$$\frac{K_R}{K_O} \approx \left(\frac{P}{2\pi G m}\right)^{1/3} V_* \sin I$$

$$\approx 0.3 \left(\frac{m}{M_{Jup}}\right)^{-1/3} \left(\frac{P}{3 \text{ days}}\right)^{1/3} \left(\frac{V_* \sin I}{5 \text{ km/s}}\right)$$

Doppler and RM amplitude of the same order for Hot Jupiters

Larger for less massive planets, or longer period planets

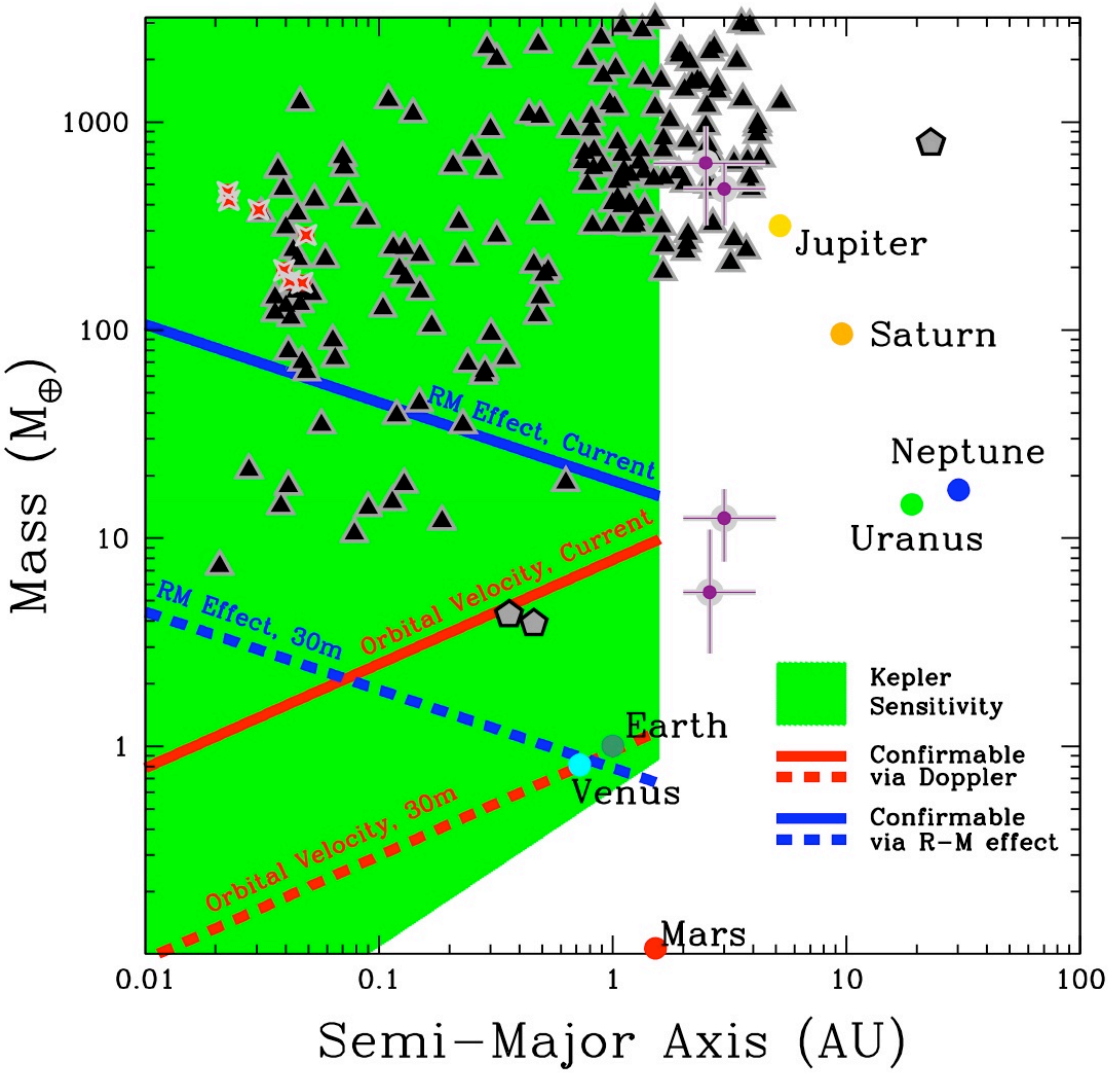
Earthlike Planet



Gaudi & Winn (2007)

Welsh et al (2004)

Confirming *Kepler* Detections



Gaudi & Winn (2007)