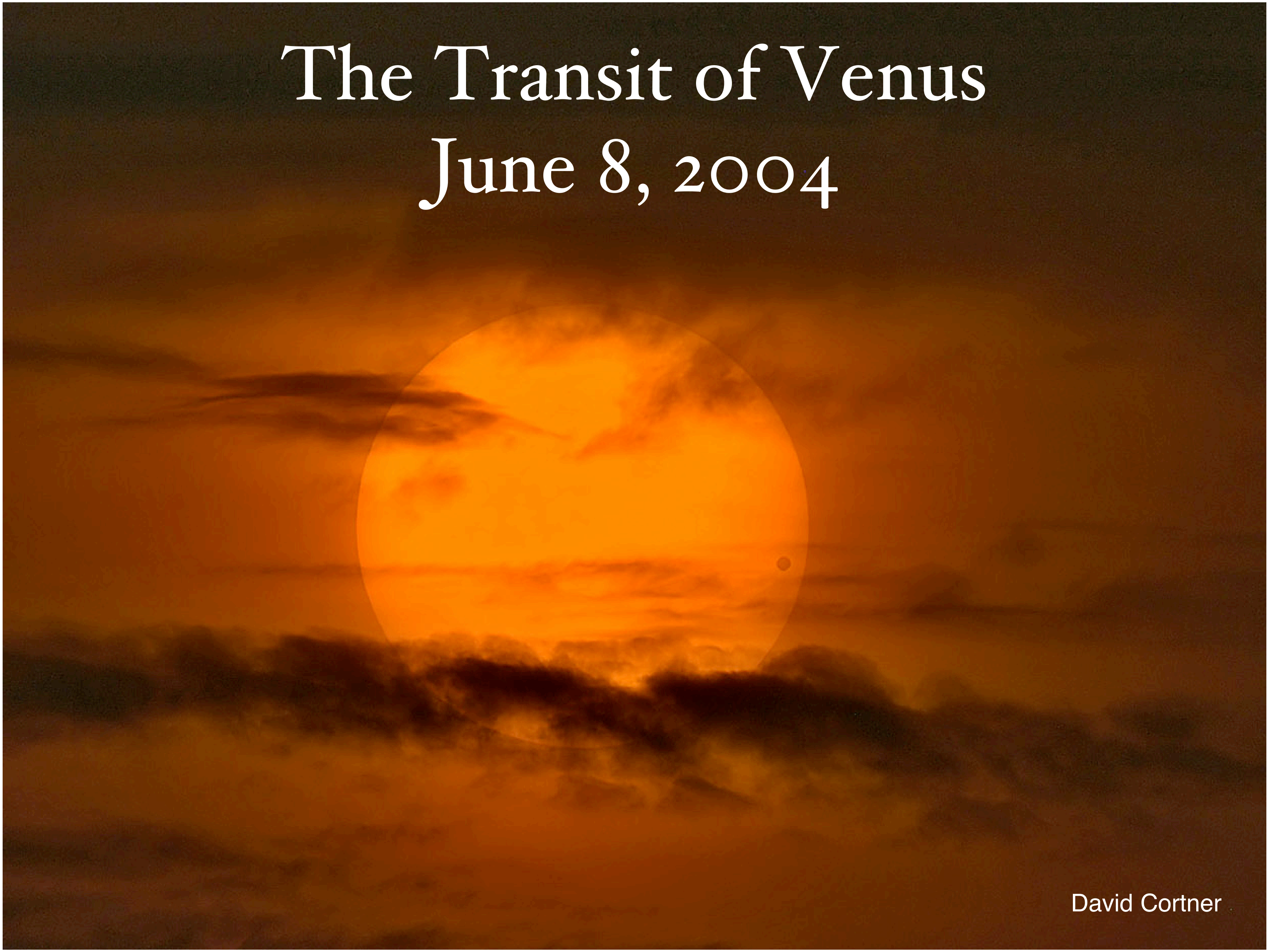
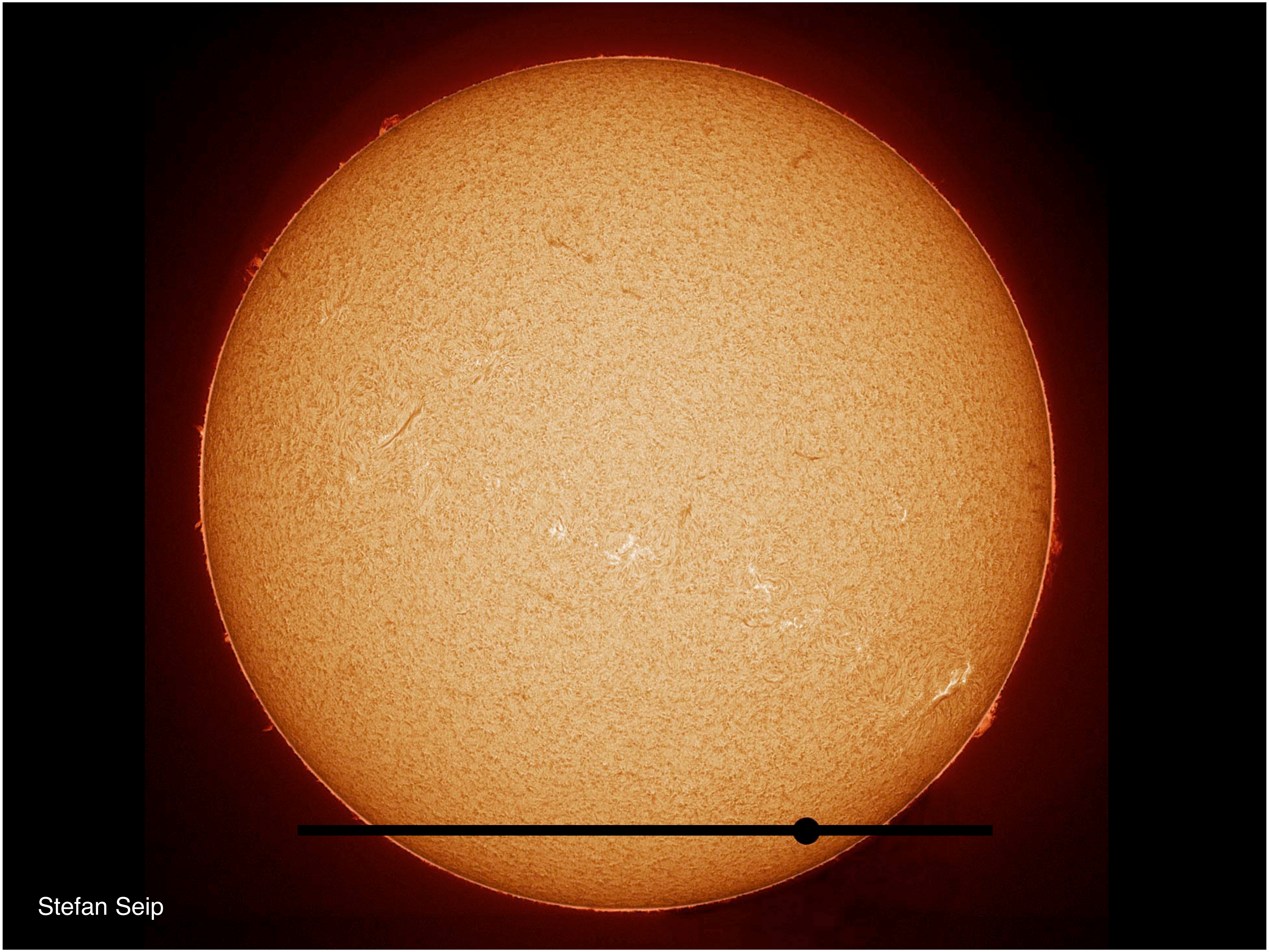
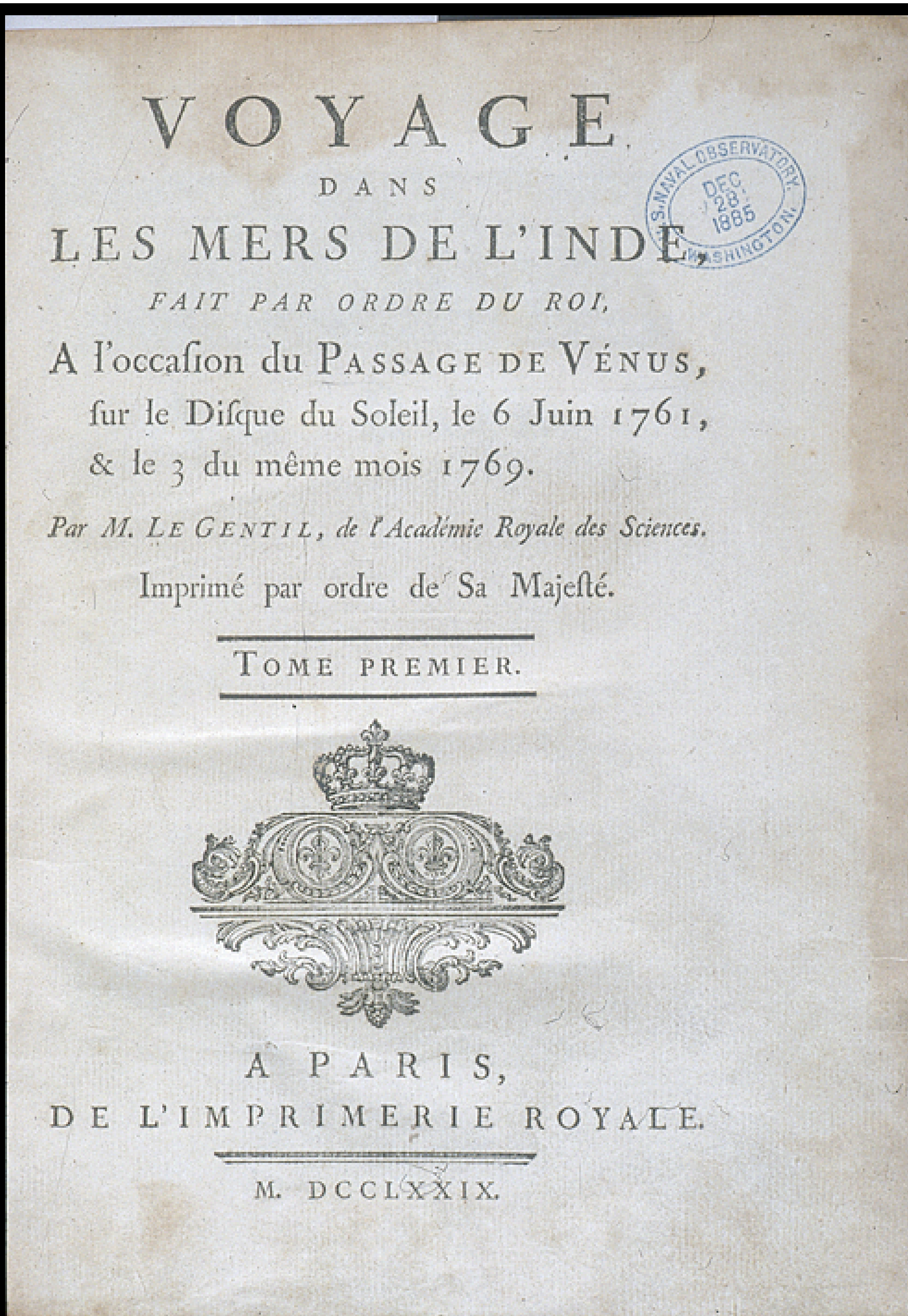

The Transit of Venus
June 8, 2004
David Cortner


Stefan Seip



VOYAGE

DANS

LES MERS DE L'INDE,

FAIT PAR ORDRE DU ROI,

A l'occaſion du PASSAGE DE VÉNUS,

ſur le Diſque du Soleil, le 6 Juin 1761,

& le 3 du même mois 1769.

Par M. LE GENTIL, de l'Académie Royale des Sciences.

Imprimé par ordre de Sa Majeſté.

TOME PREMIER.

A PARIS,

DE L'IMPRIMERIE ROYALE.

M. DCCLXXIX.

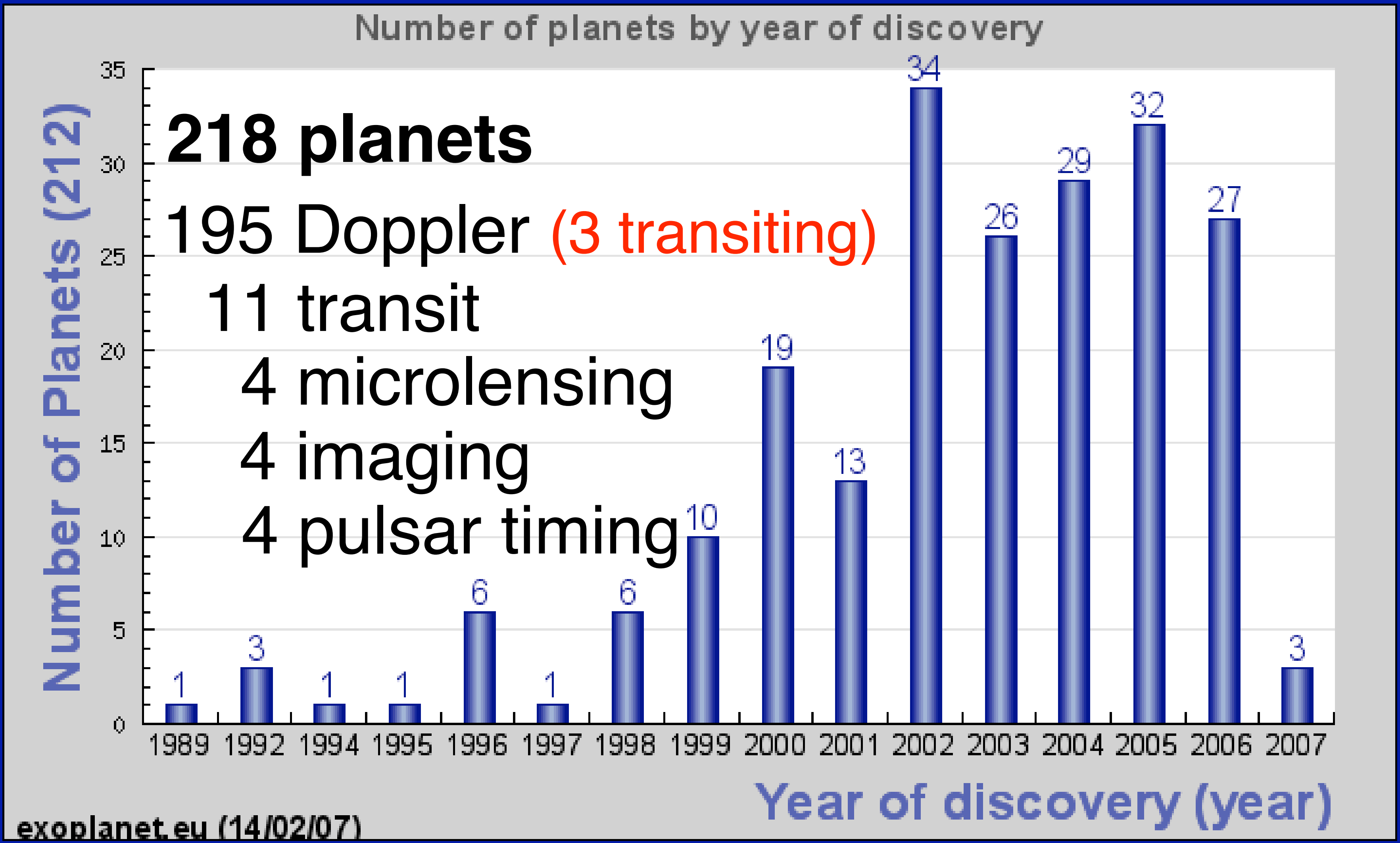
Guillaume Joseph Hyacinthe Jean Baptiste Le Gentil de la Galaisiere

(1725-1792)

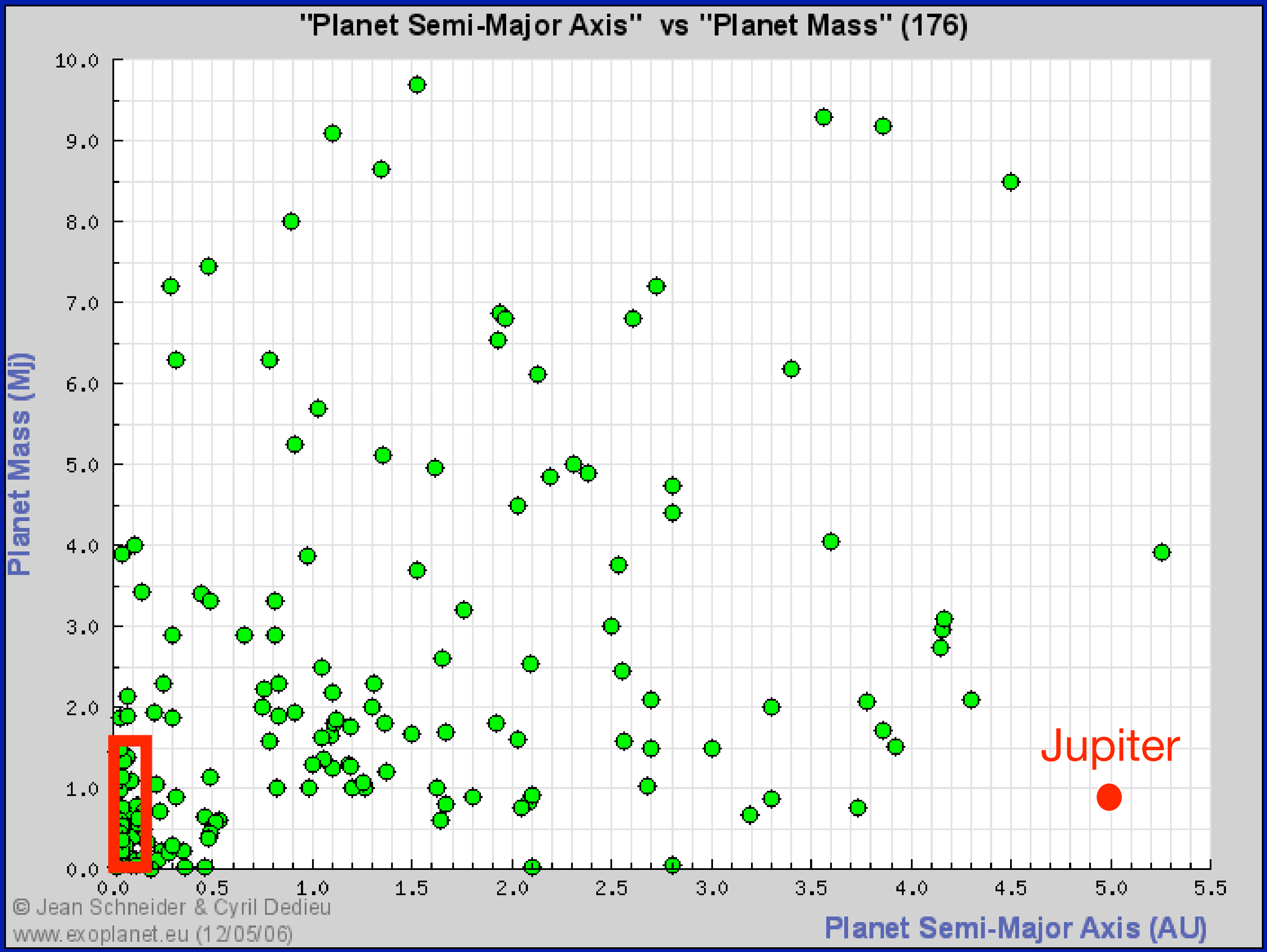
- Destination captured
- Waited 8 years
- Clouded out
- Contracted dysentery
- Shipwrecked
- Declared dead; estate looted

The Transits of Exoplanets

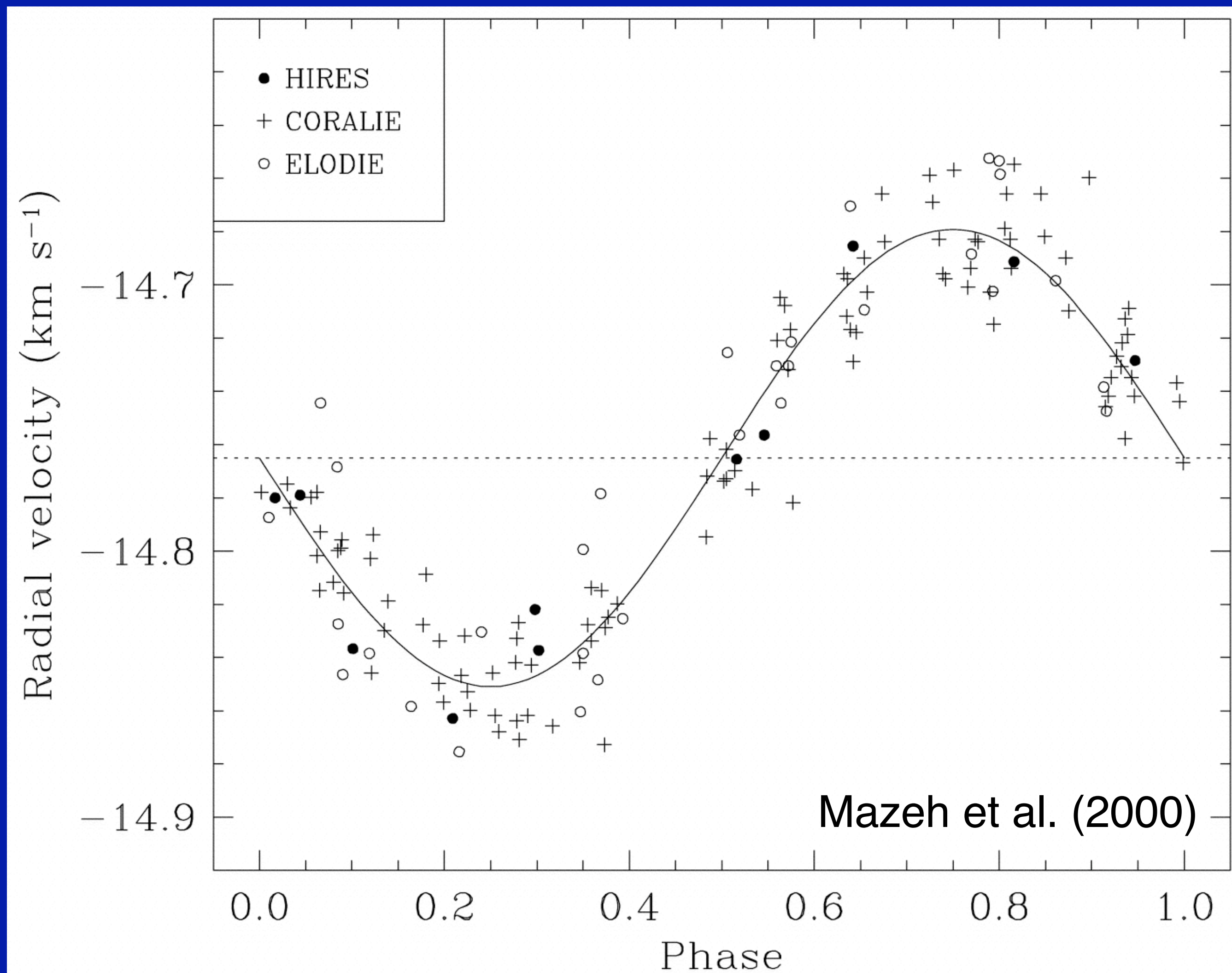
Exoplanet discoveries



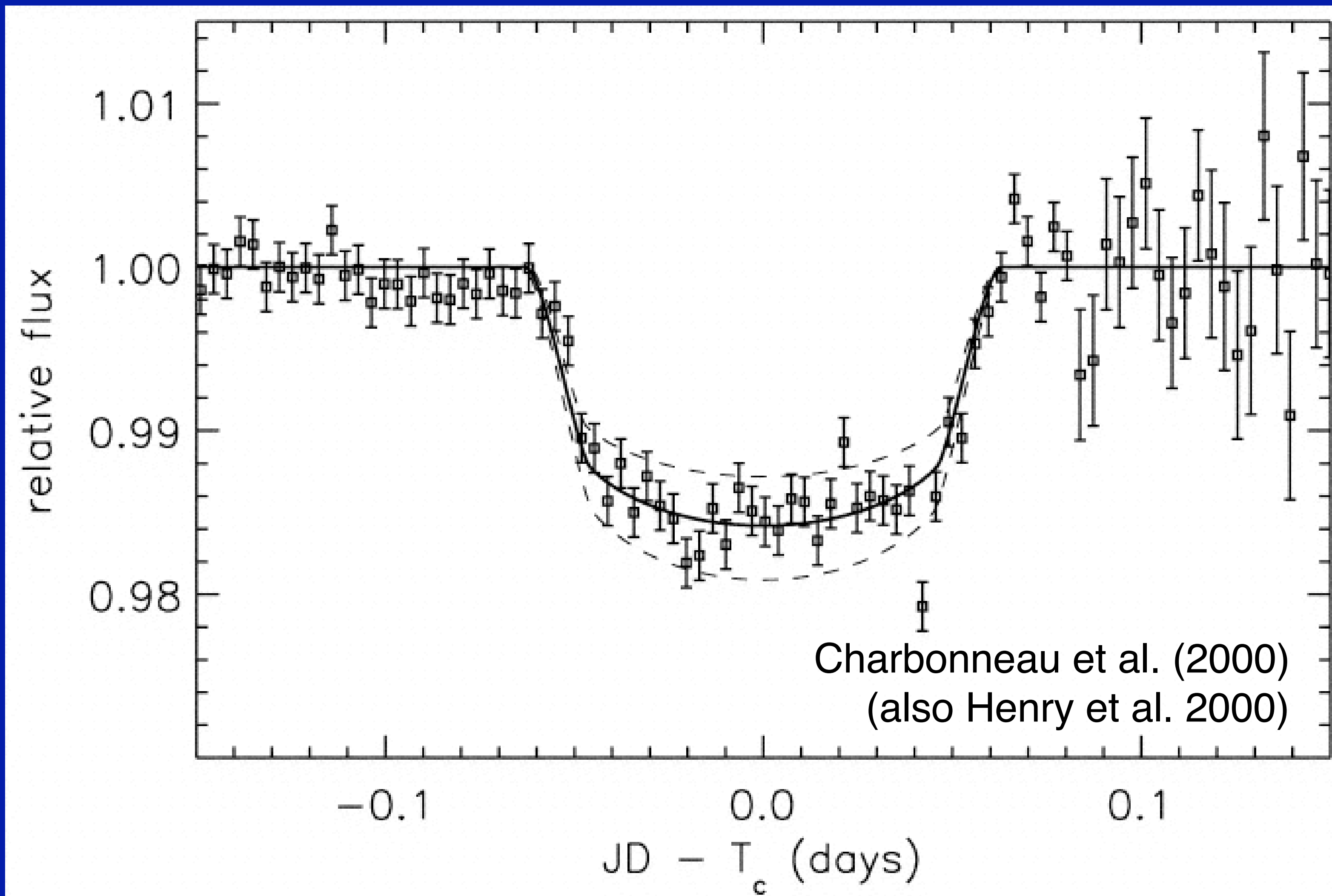
The “hot Jupiters”



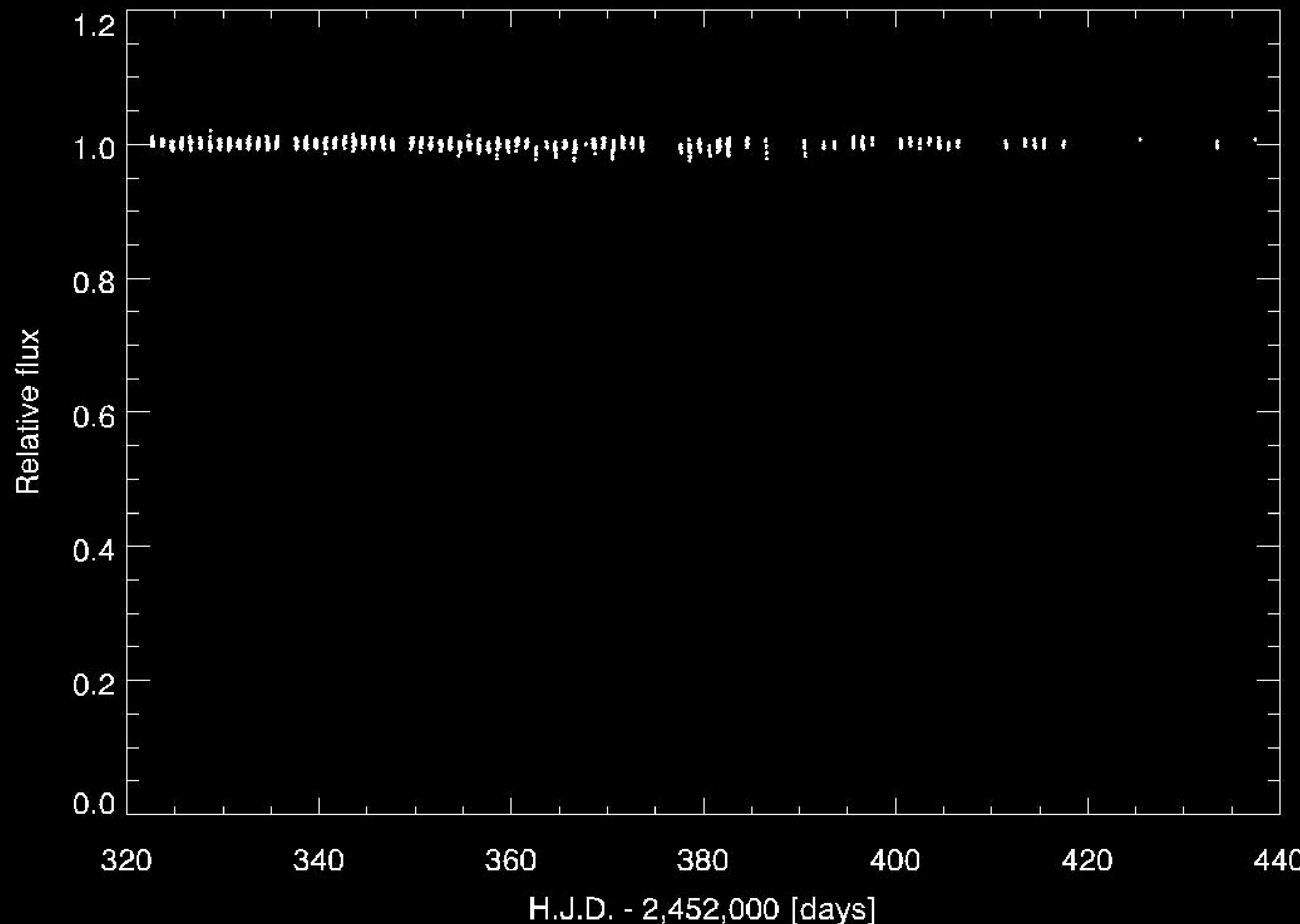
Detect the Doppler shift...



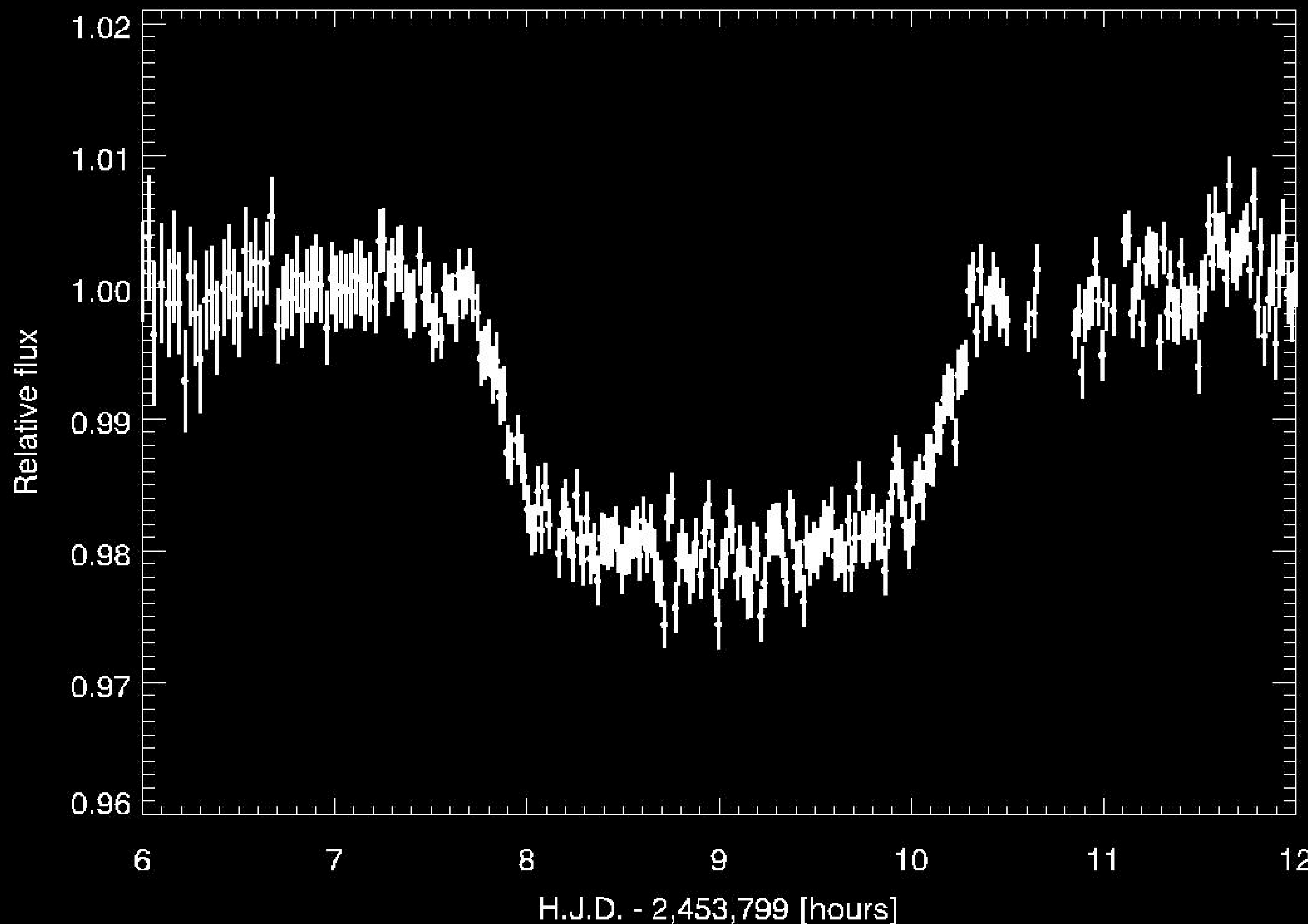
...and then look for transits



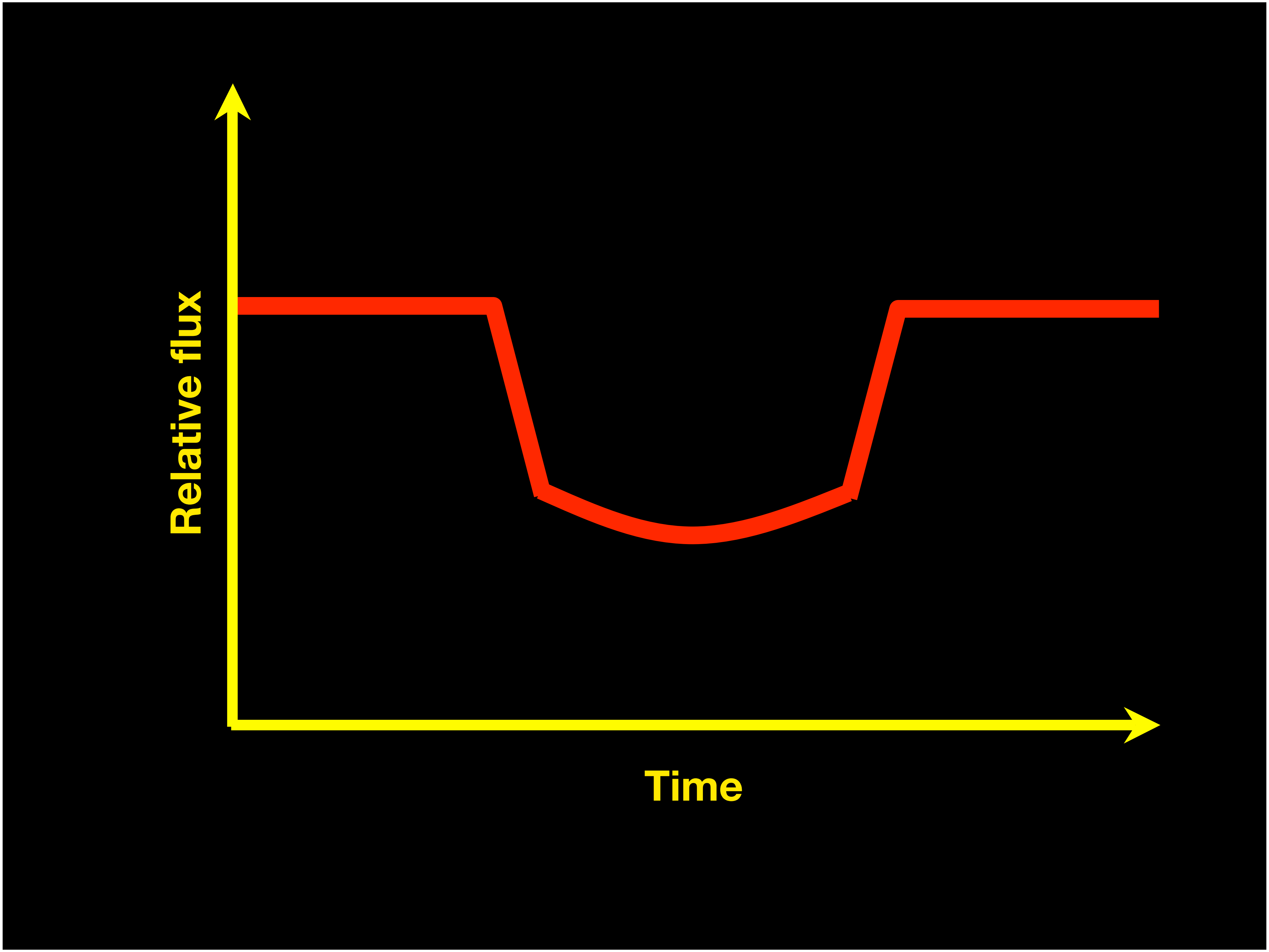

Or, look for the transits first



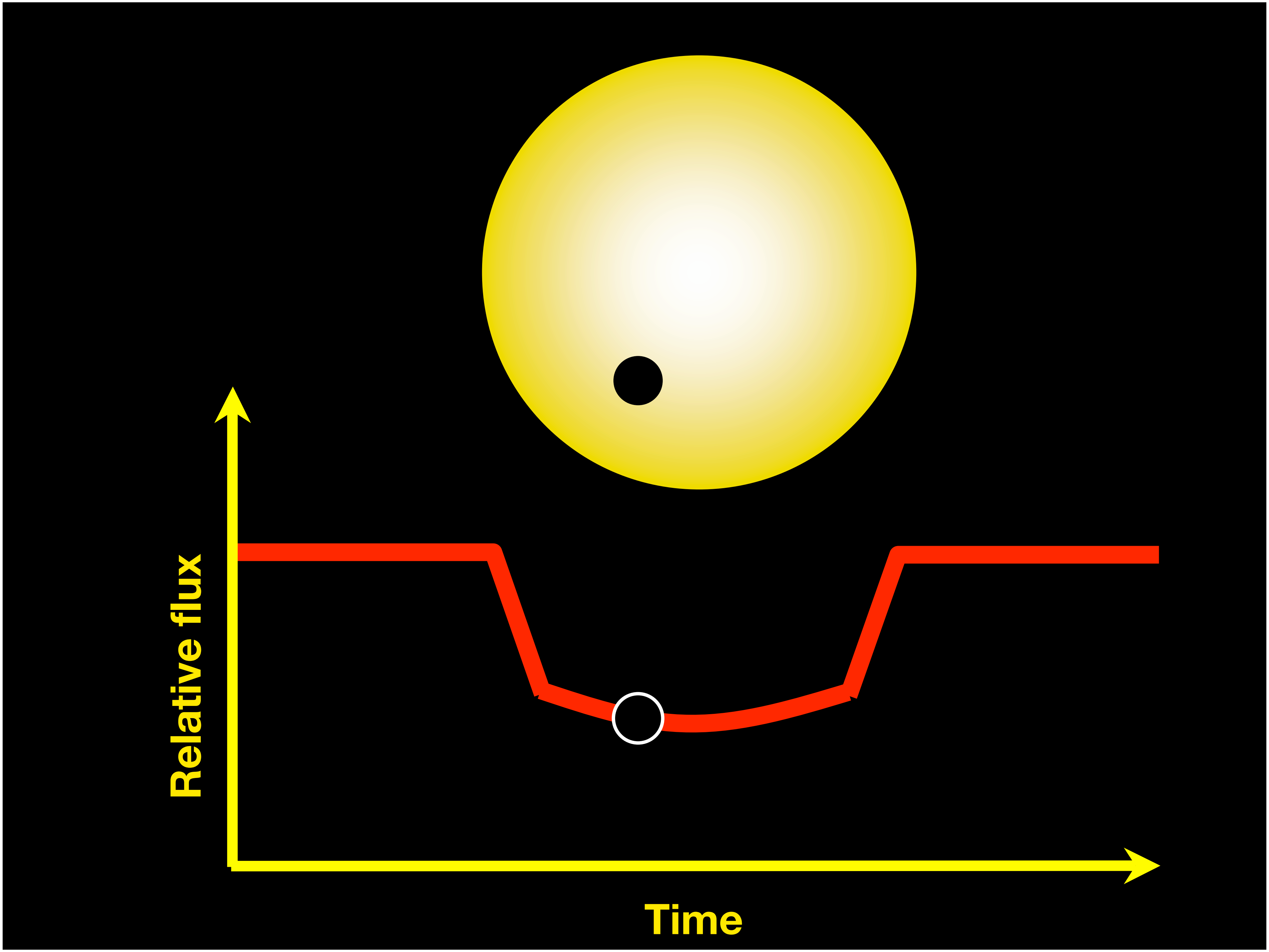
The OGLE collaboration (Udalski et al.)

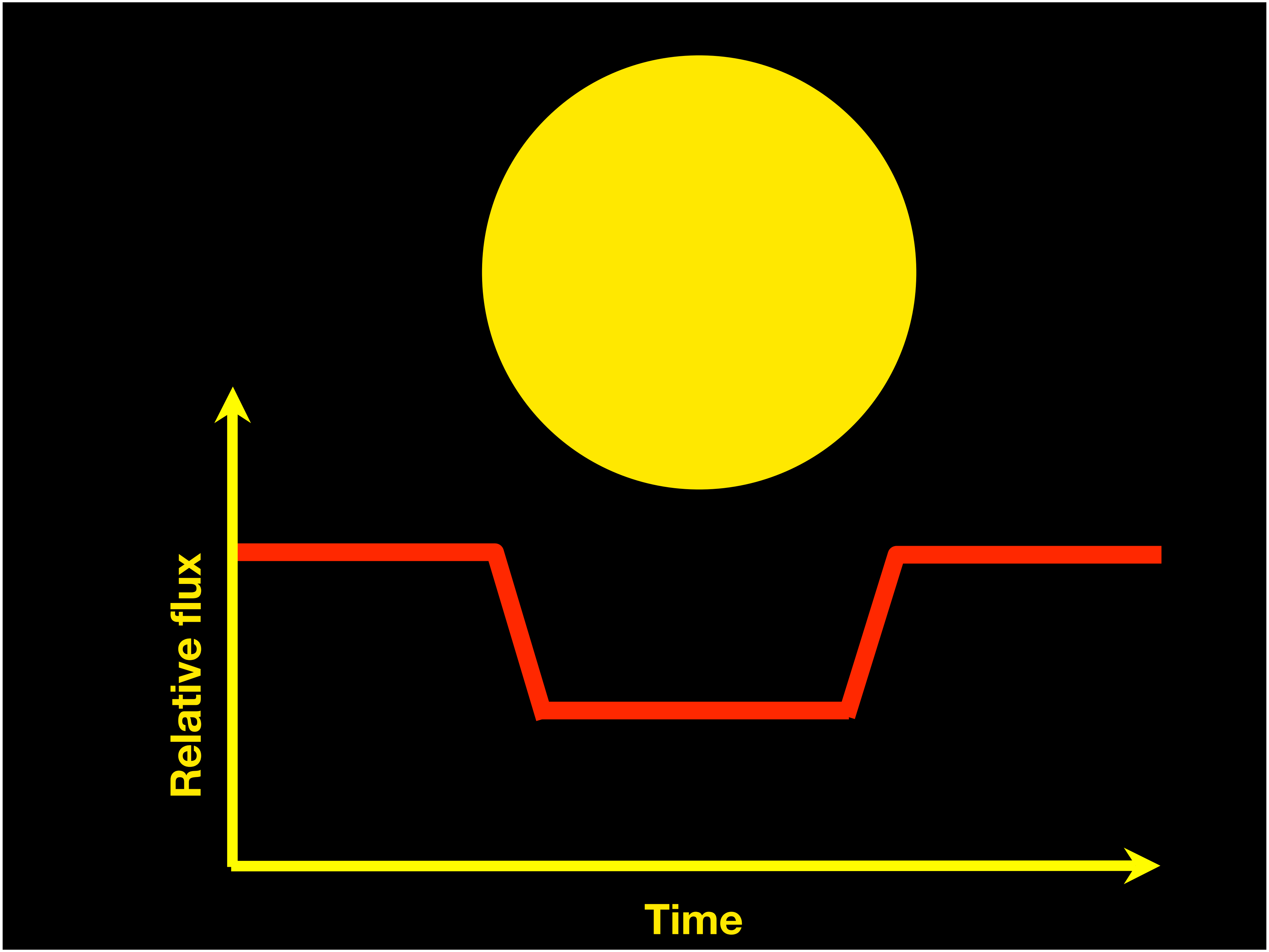


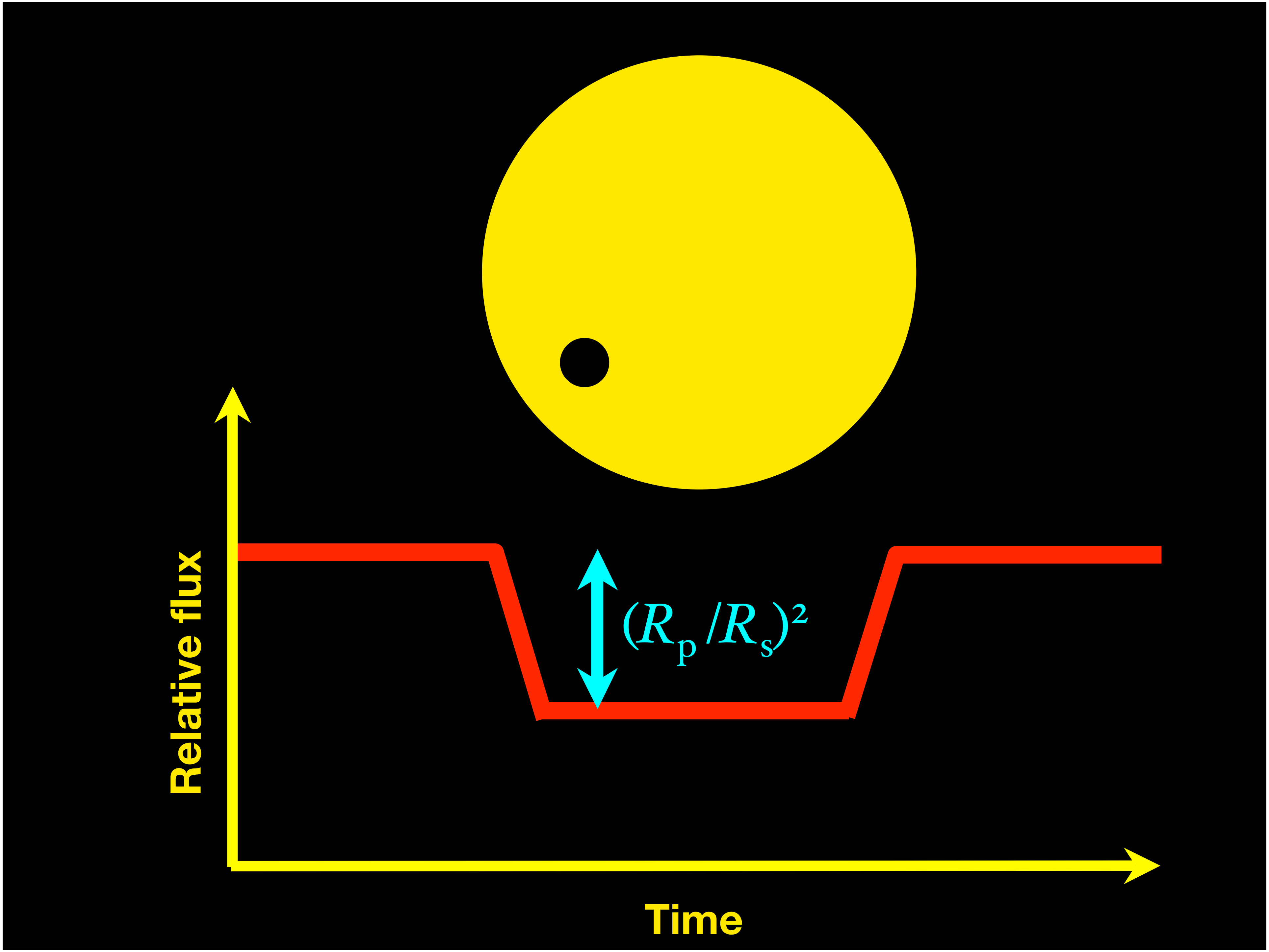
Winn, Holman, & Fuentes (2006)

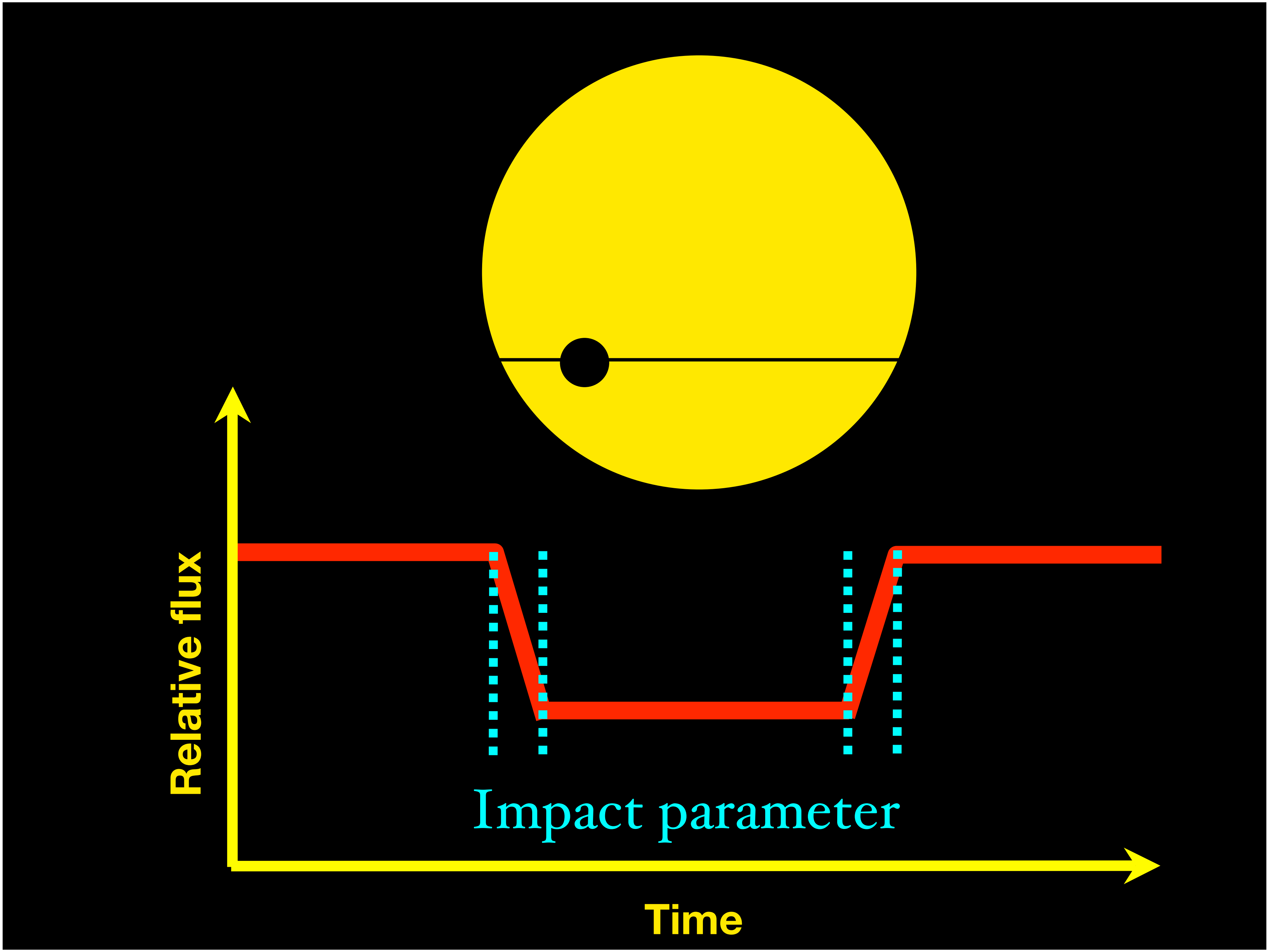


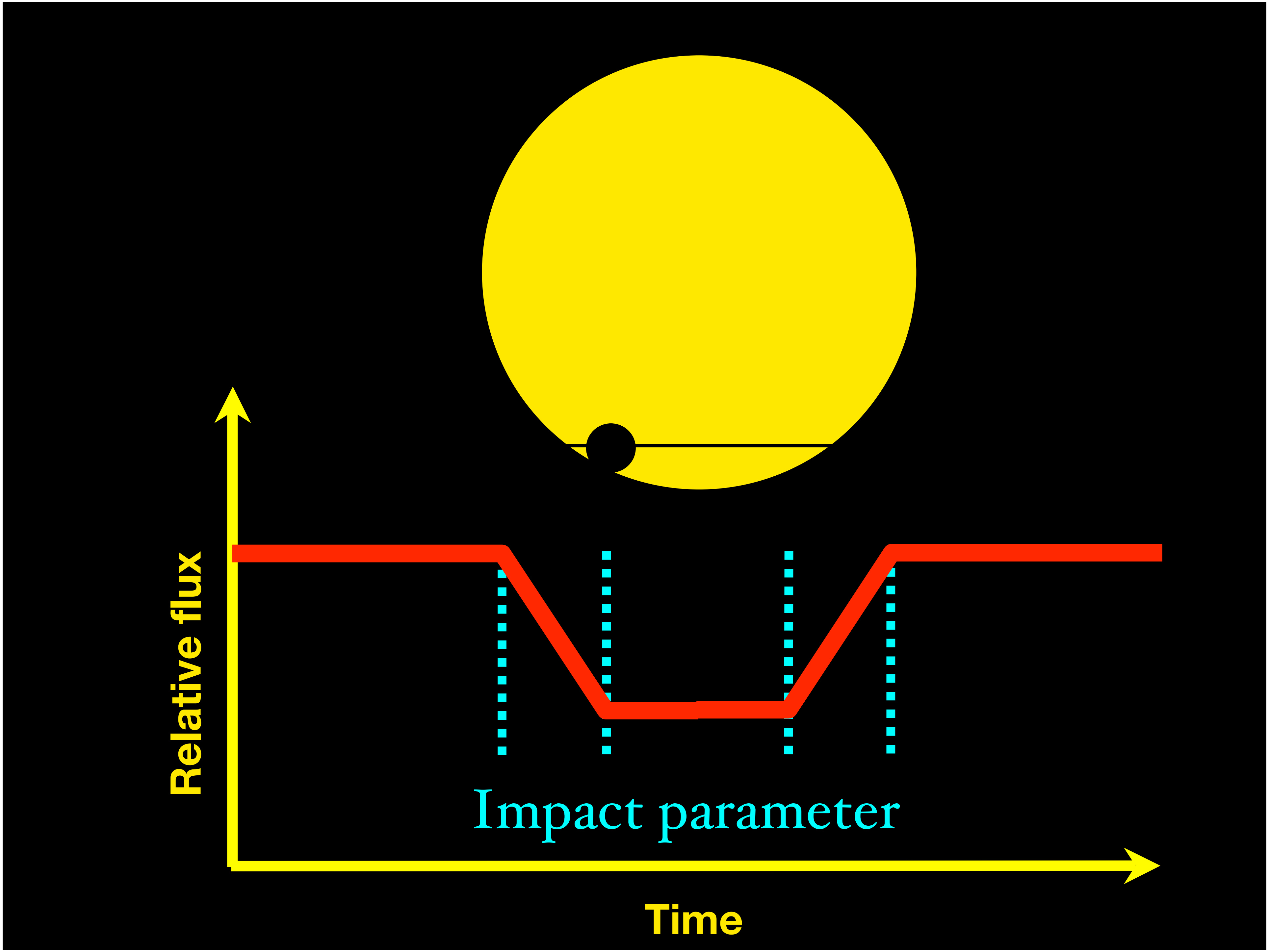
Relative flux
Time

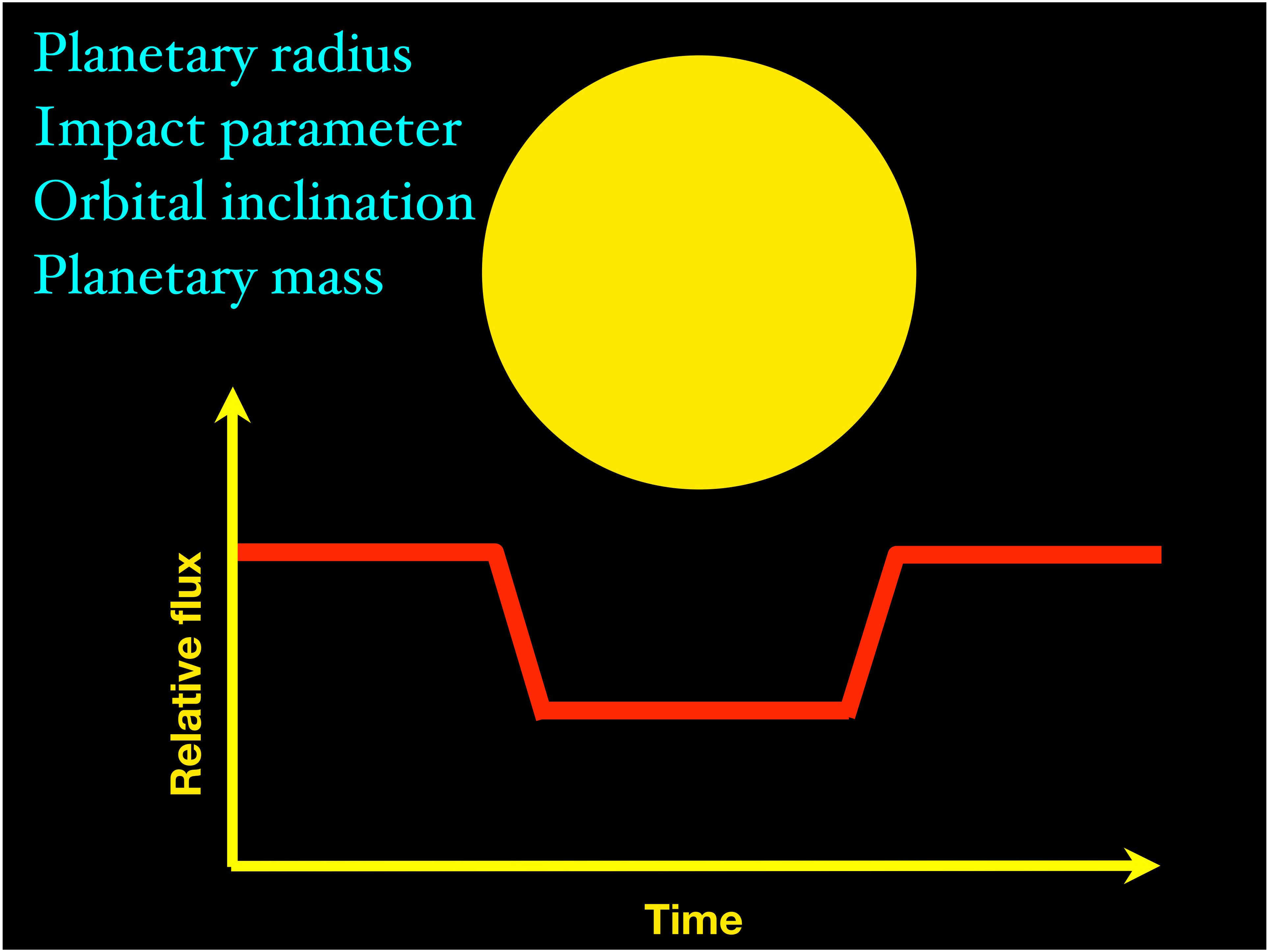

Relative flux
Time


Relative flux
Time

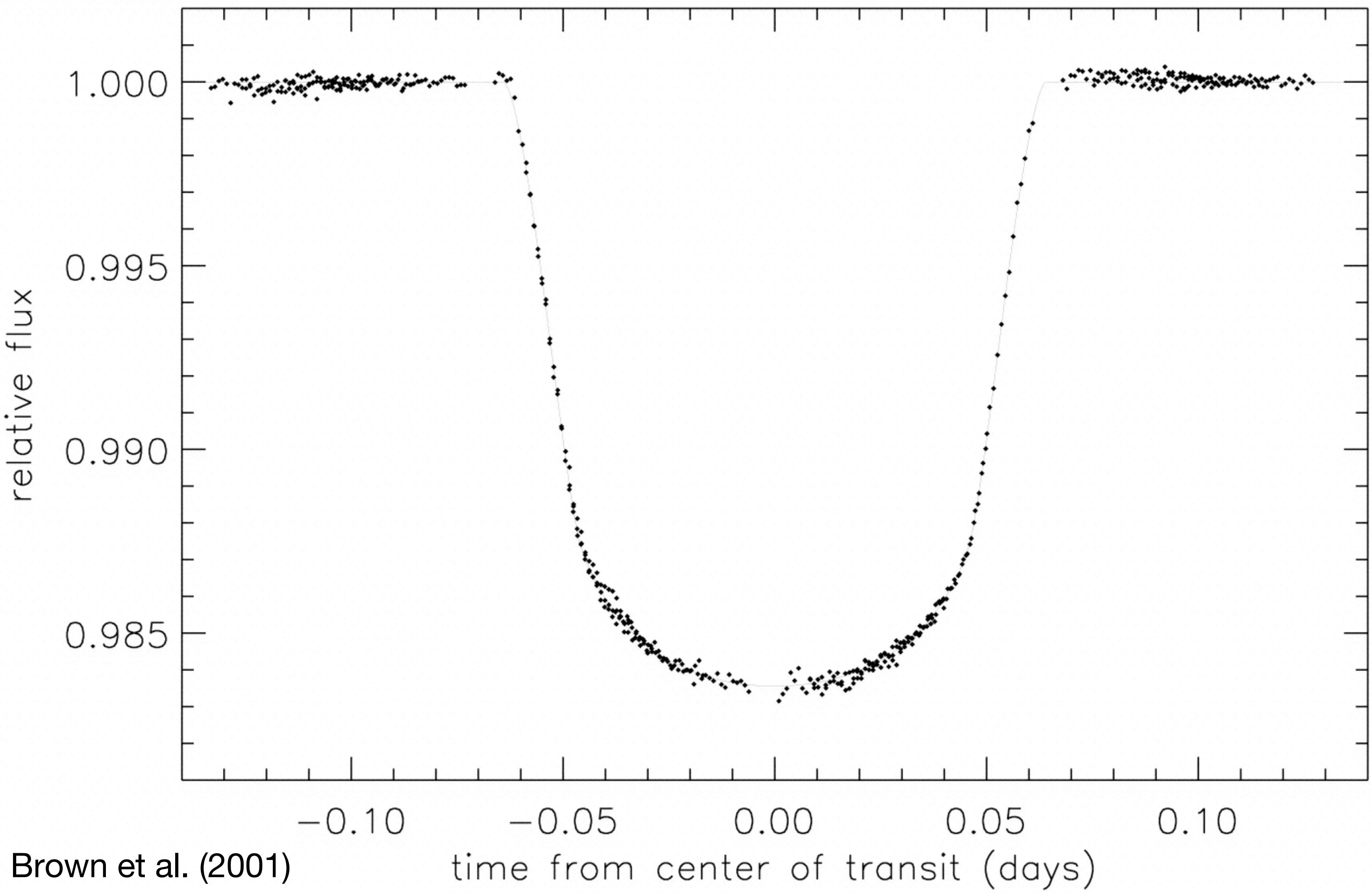

Relative flux
$(R_p/R_s)^2$
Time


Relative flux
Impact parameter
Time


Relative flux
Impact parameter
Time

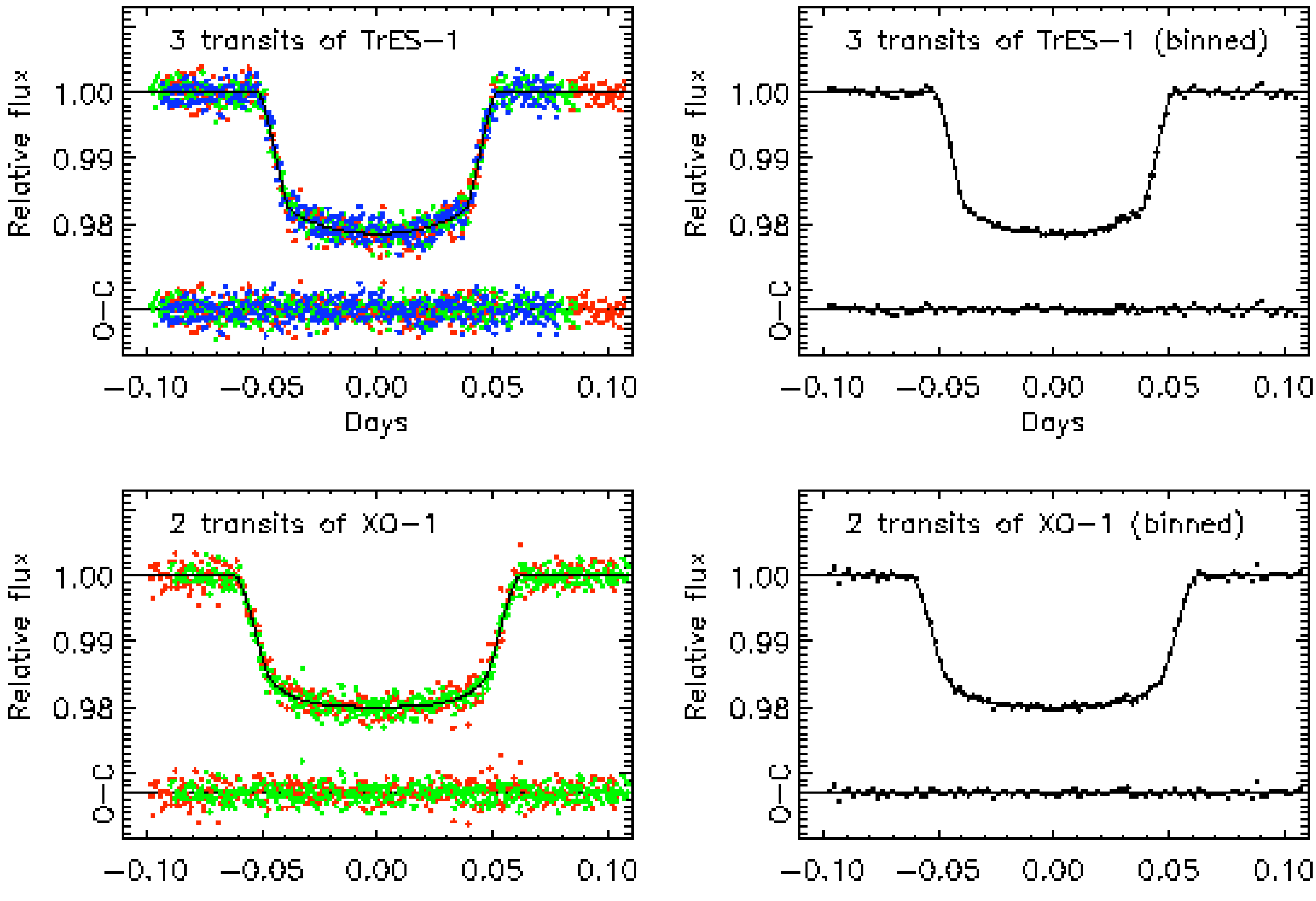

Planetary radius
Impact parameter
Orbital inclination
Planetary mass
Relative flux
Time

Photometry with *HST*

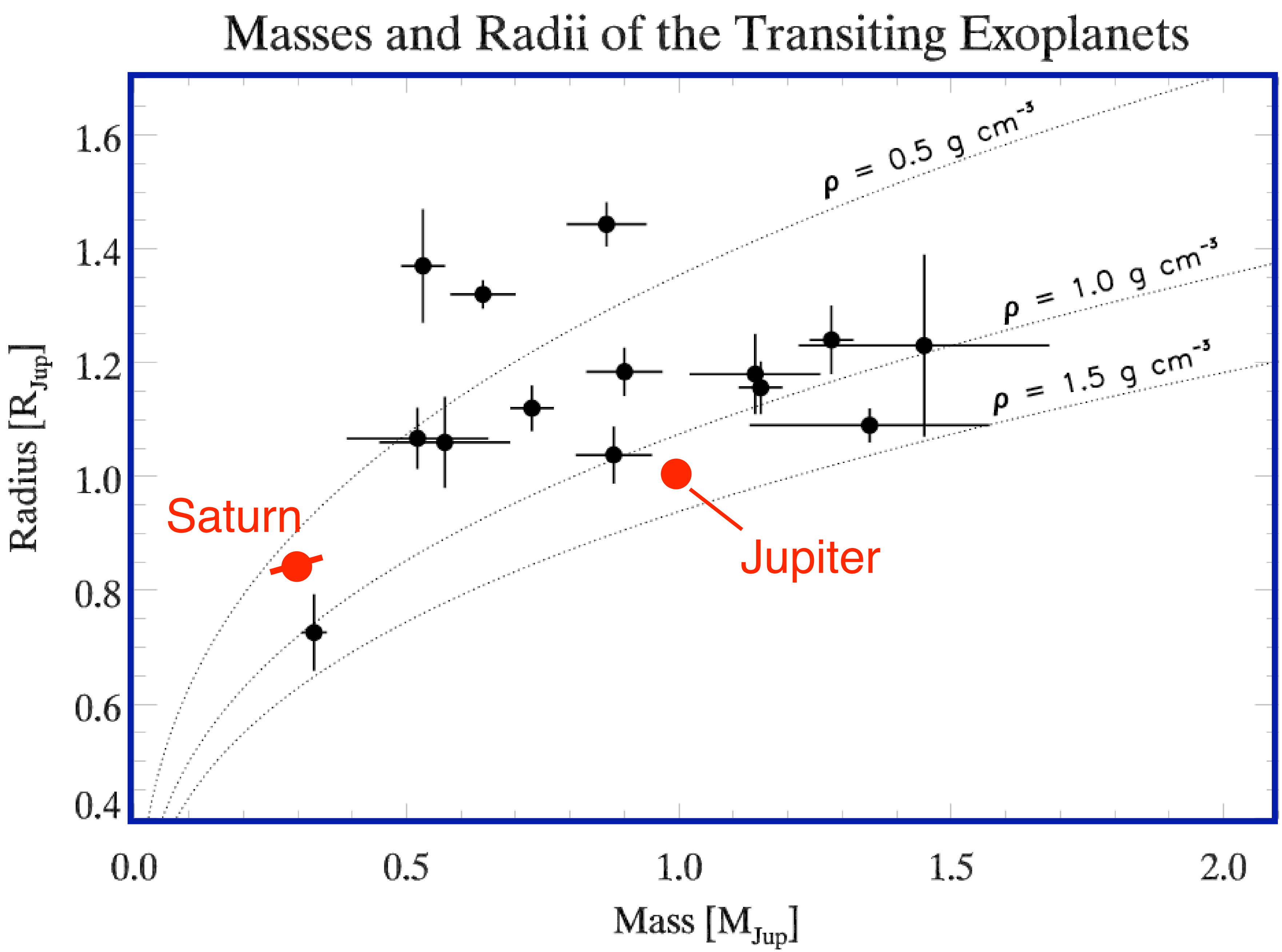


Brown et al. (2001)

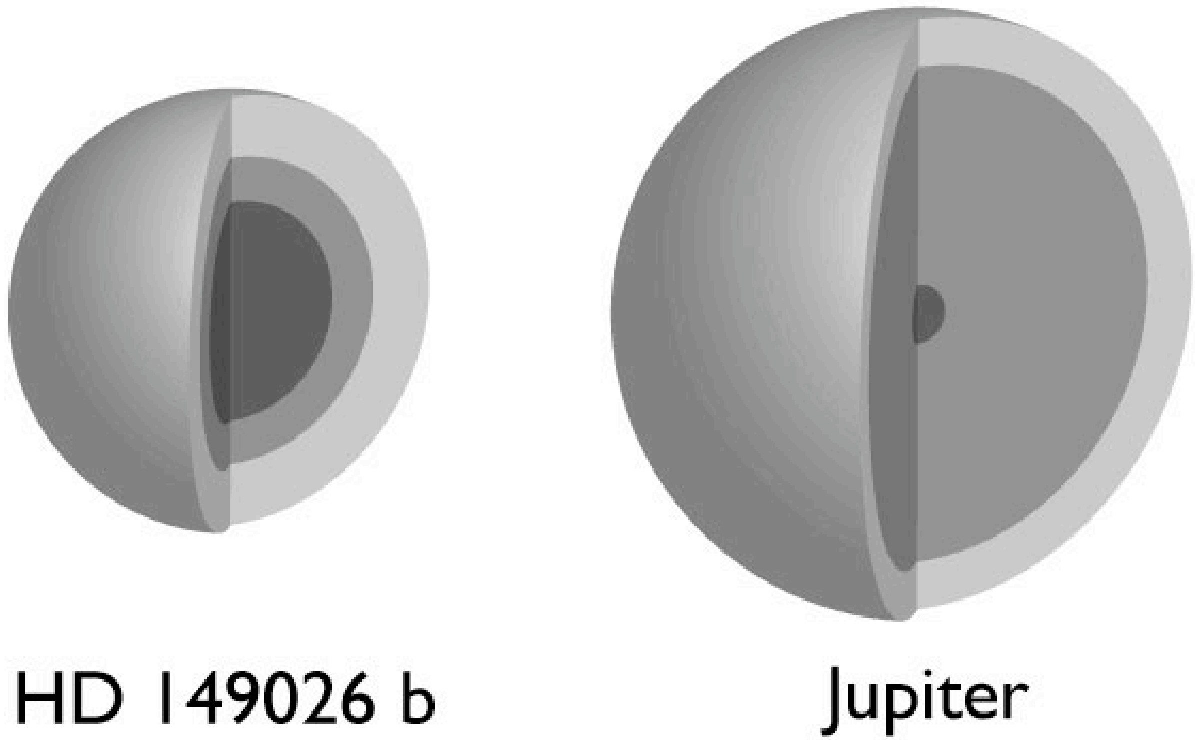
The Transit Light Curve project



Winn, Holman, Roussanova, et al.


Masses and Radii of the Transiting Exoplanets
ρ = 0.5 g cm⁻³
ρ = 1.0 g cm⁻³
ρ = 1.5 g cm⁻³
Saturn
Jupiter
Radius [R_Jup]
Mass [M_Jup]
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.0
0.5
1.0
1.5
2.0

The "super-Neptune" HD 149026



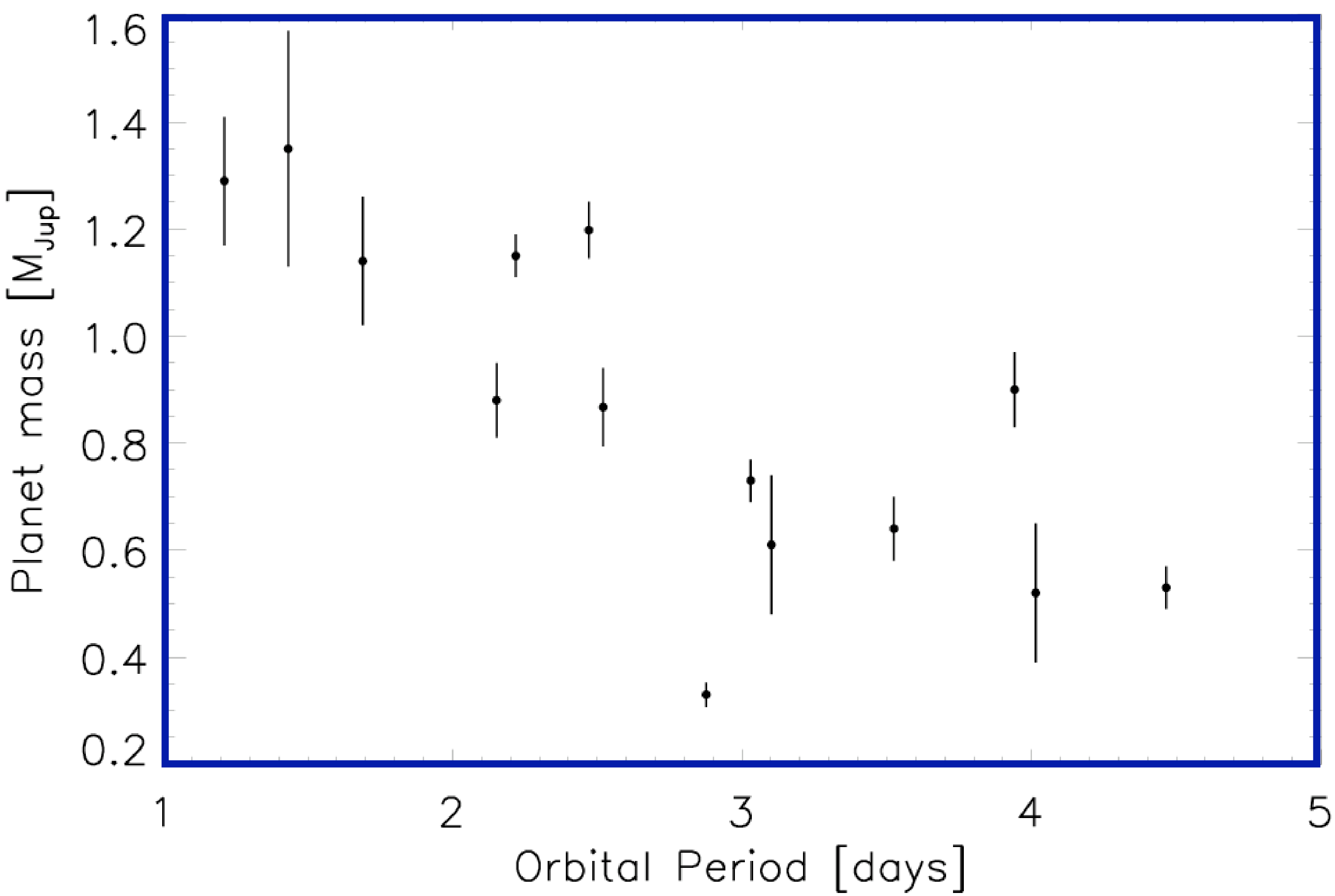
Why did the core not accrete gas efficiently?
Or, if it did, what happened to the envelope?

G. Laughlin

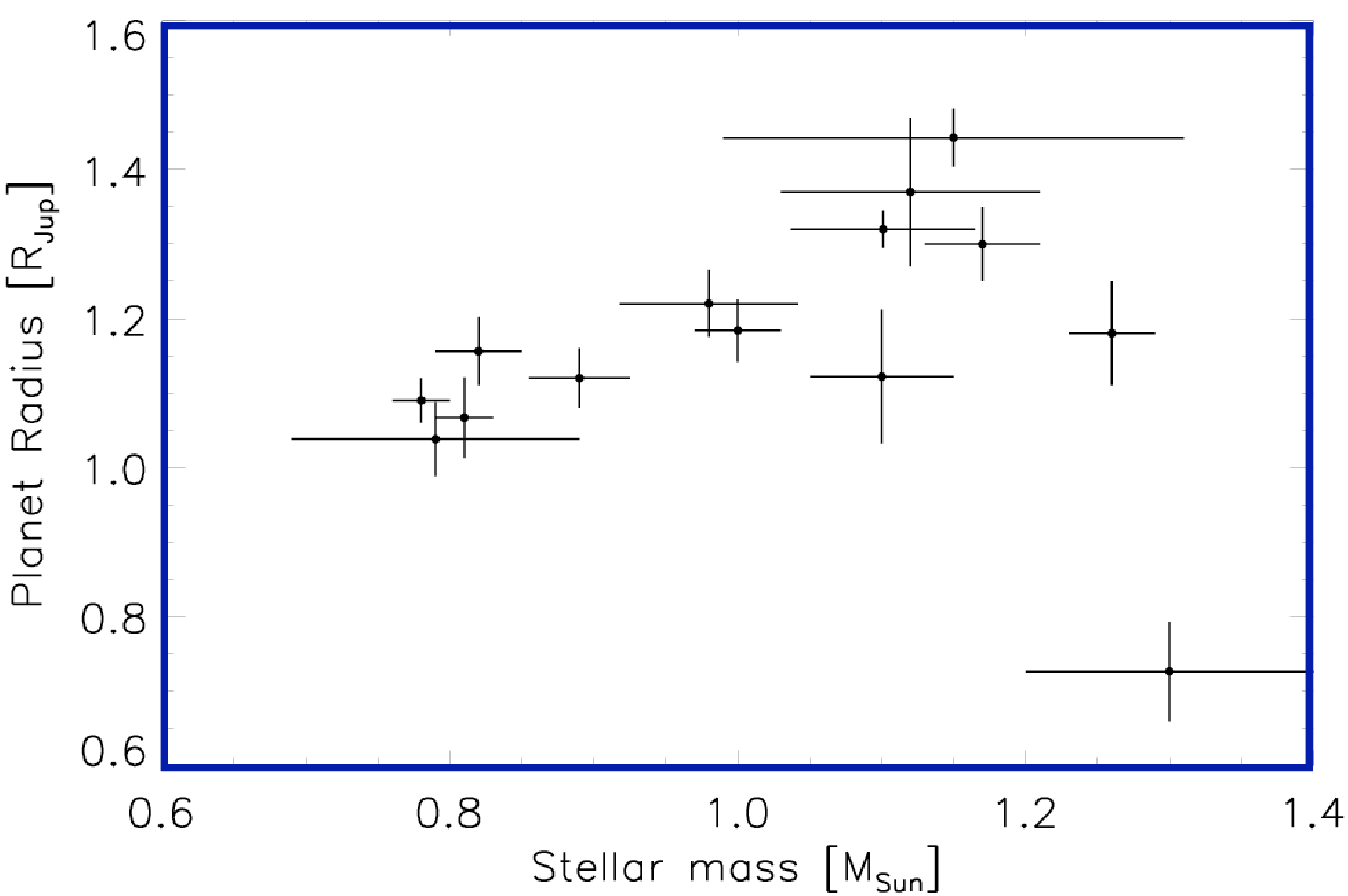
The “bloated” planets

- Early migration (Burrows et al. 2000)
- Insolation-driven, deeply penetrating waves (Showman & Guillot 2002)
- Eccentricity tides (Bodenheimer et al. 2001, 2003)
- Obliquity tides (Winn & Holman 2005)
- Heterogeneity in atmospheric metallicity (Burrows et al. 2007)
- Inhibition of large-scale convection of planetary interiors (Chabrier & Baraffe 2007)

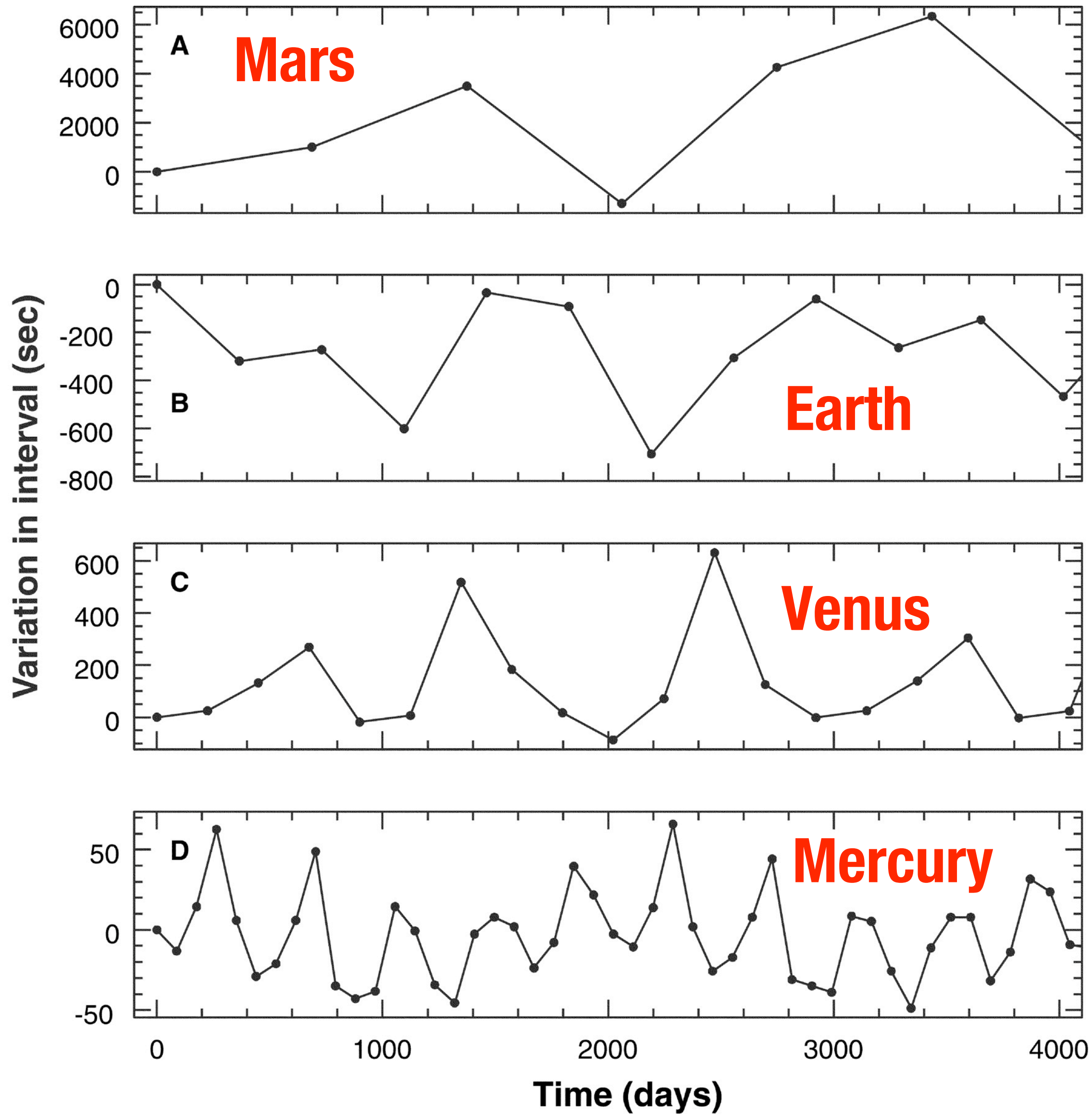
Unexplained correlations



Unexplained correlations

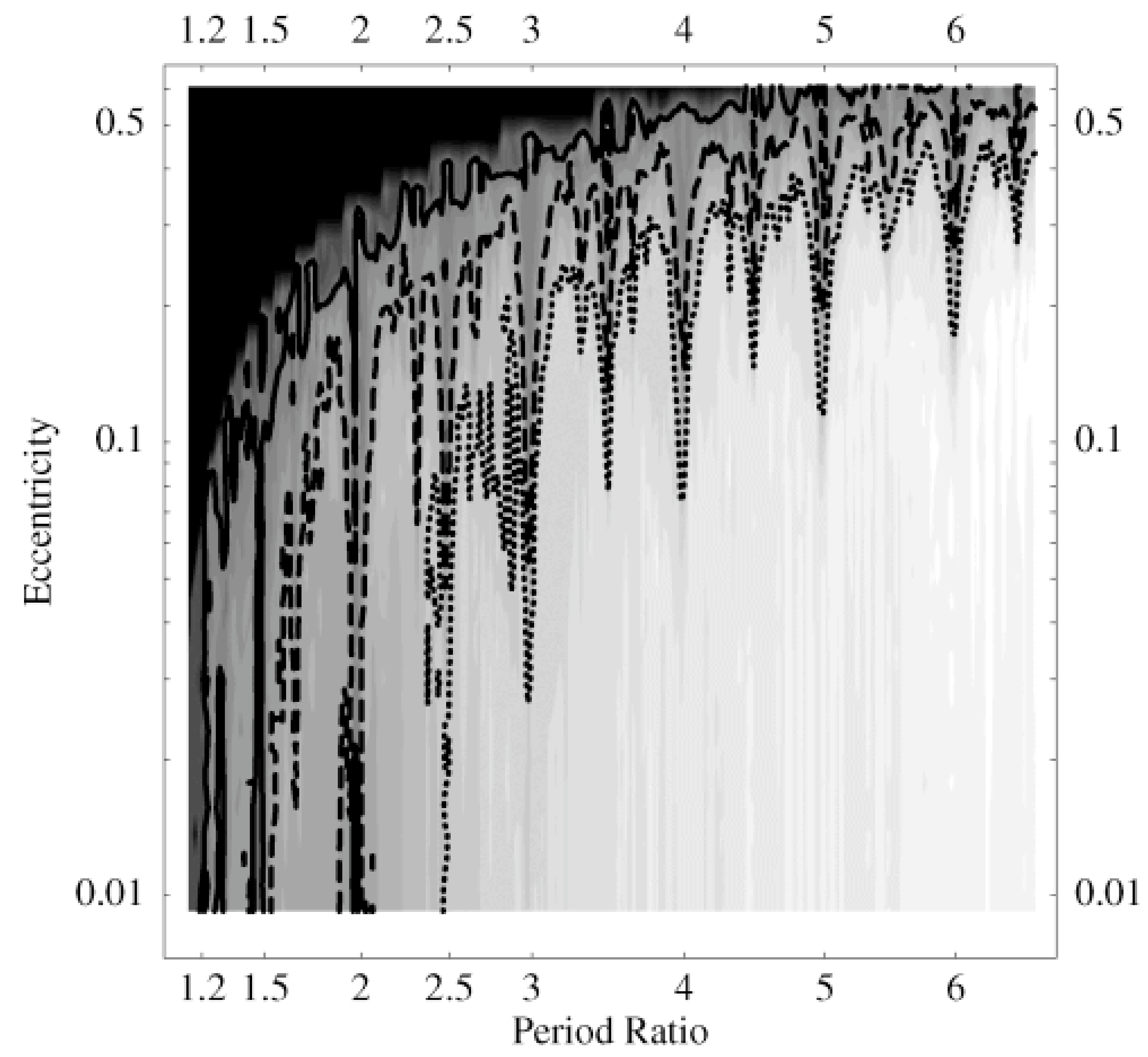


Transit timing variations

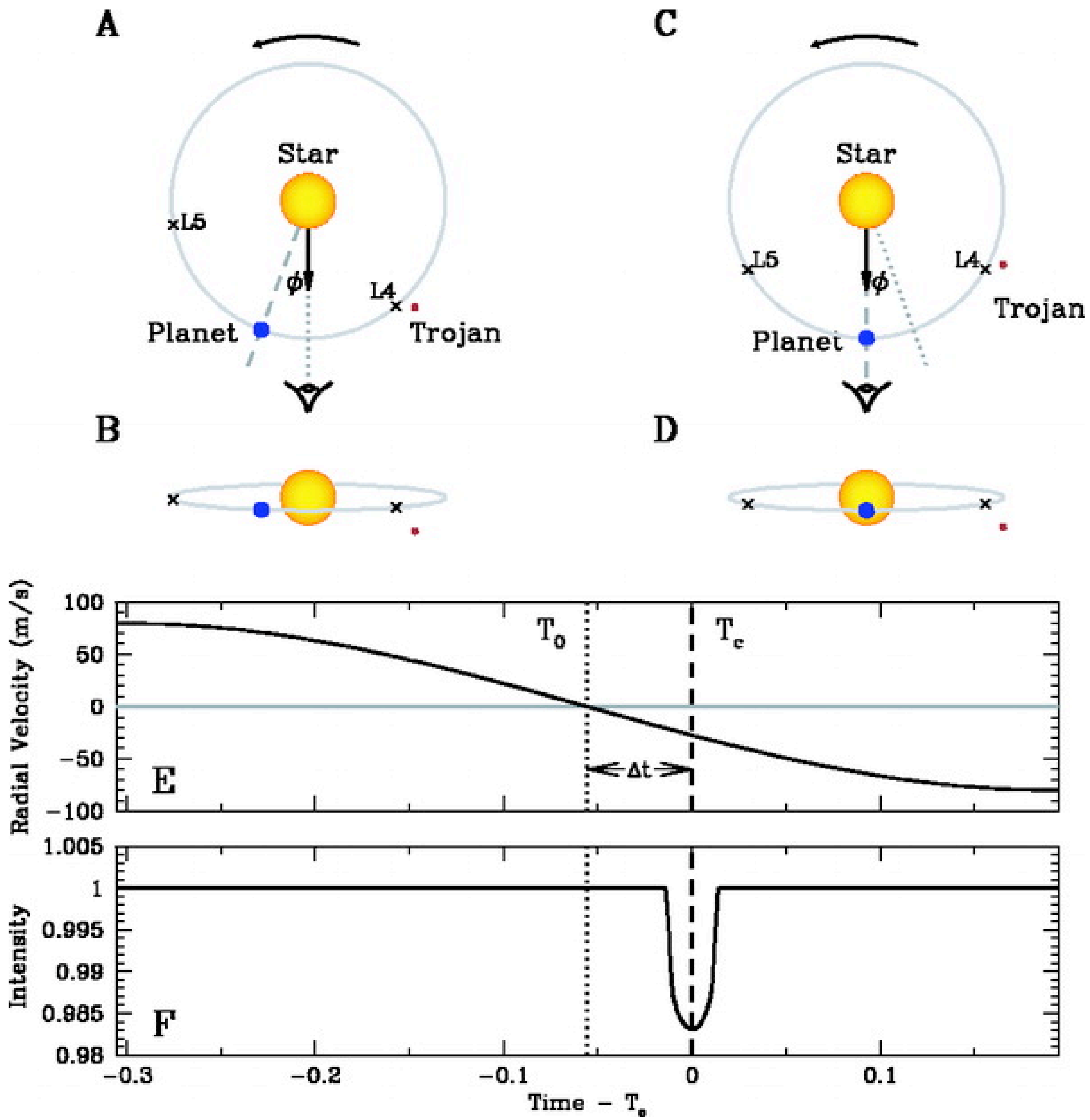


Holman & Murray (2005)

Transit timing variations

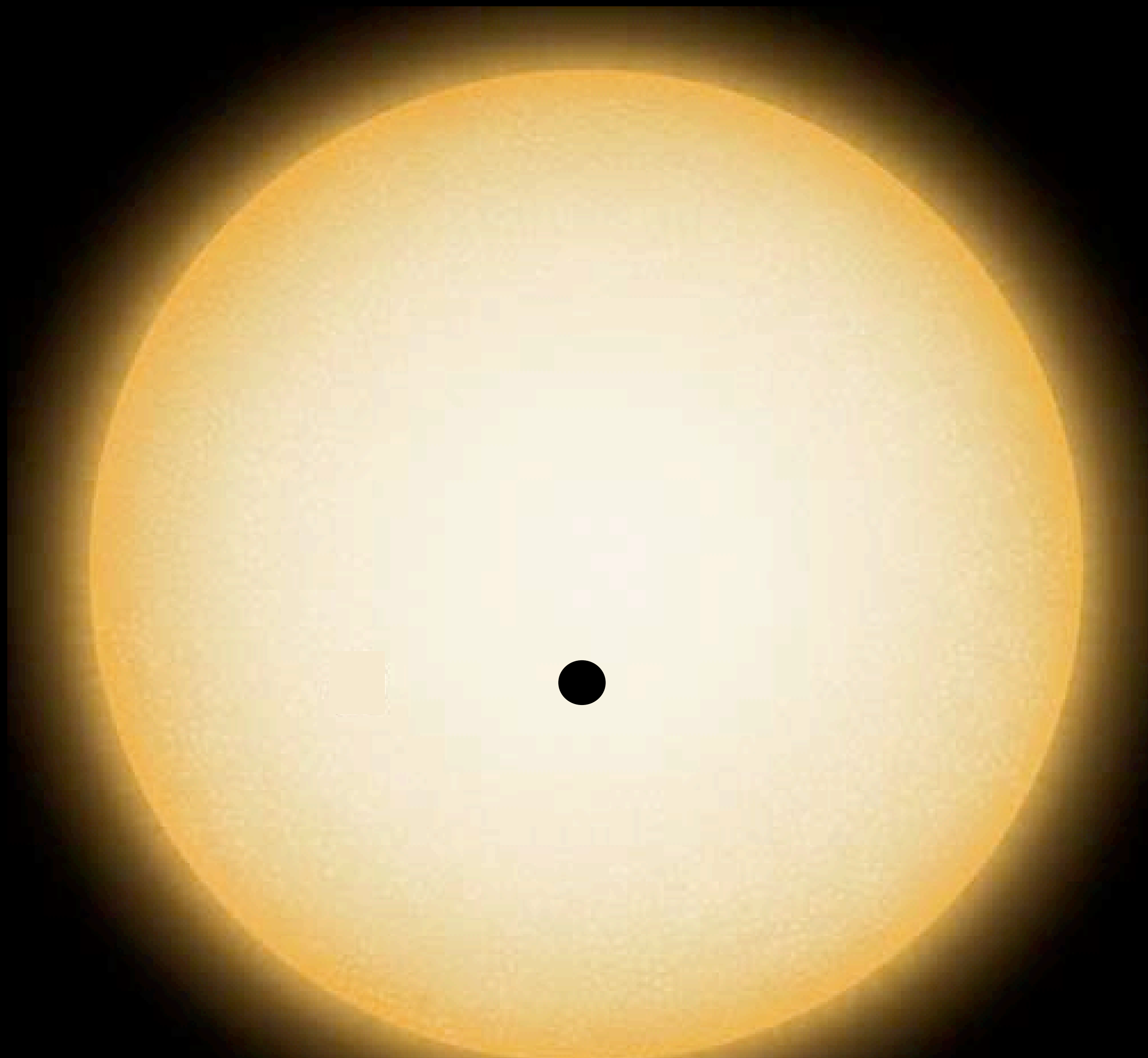


Agol & Steffen (2007)

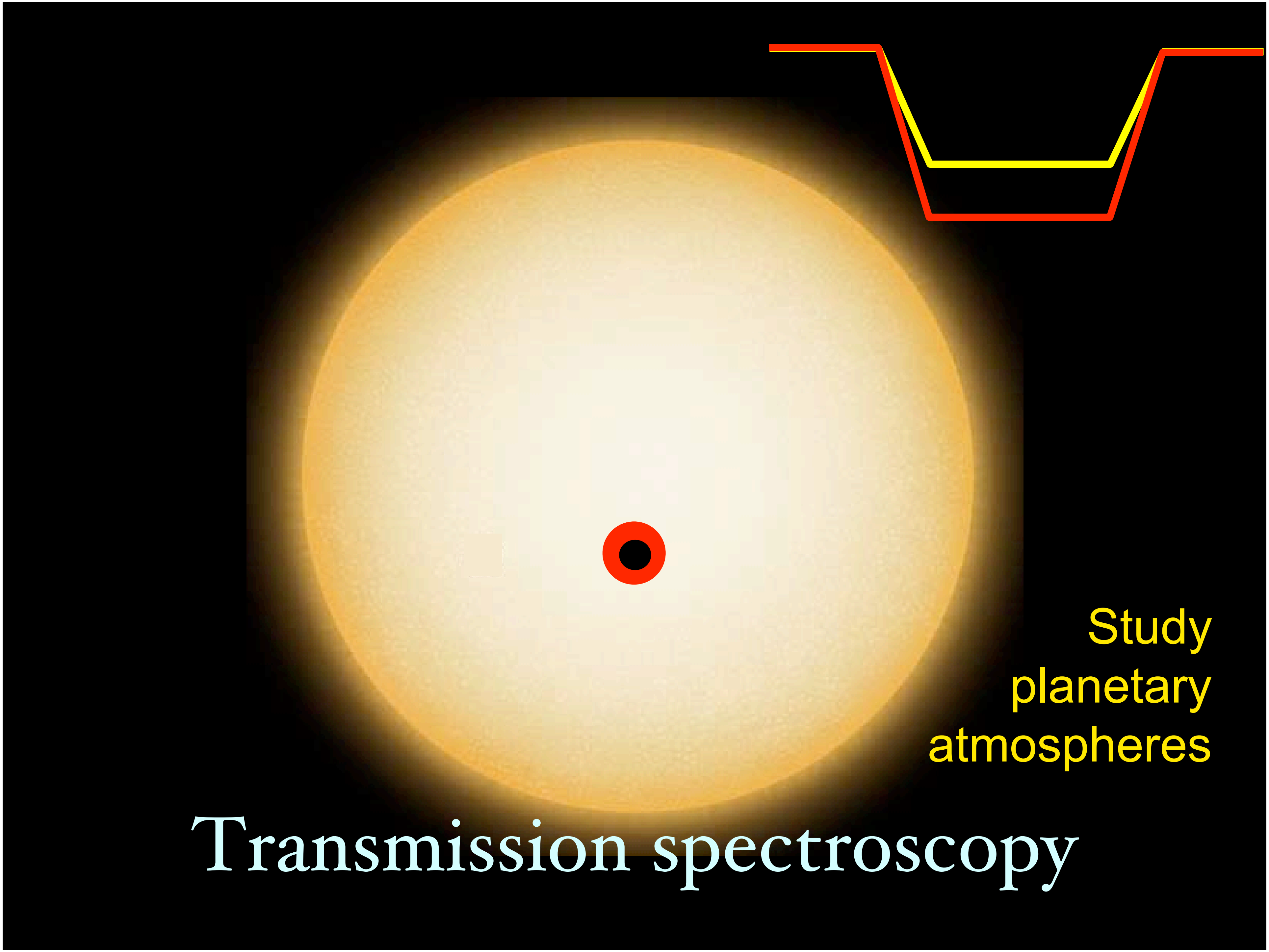


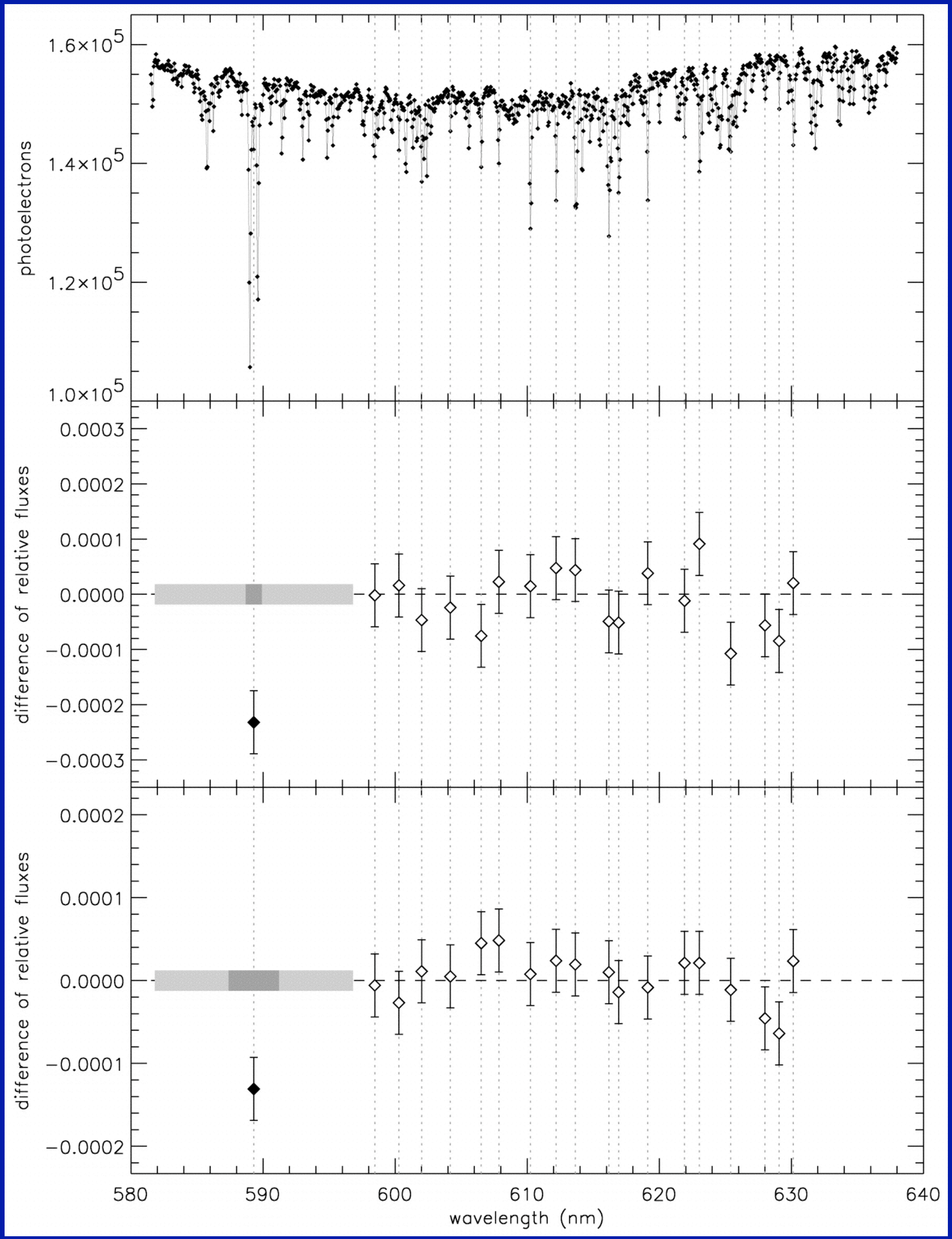
Finding Trojan planets

Ford & Gaudi (2006)



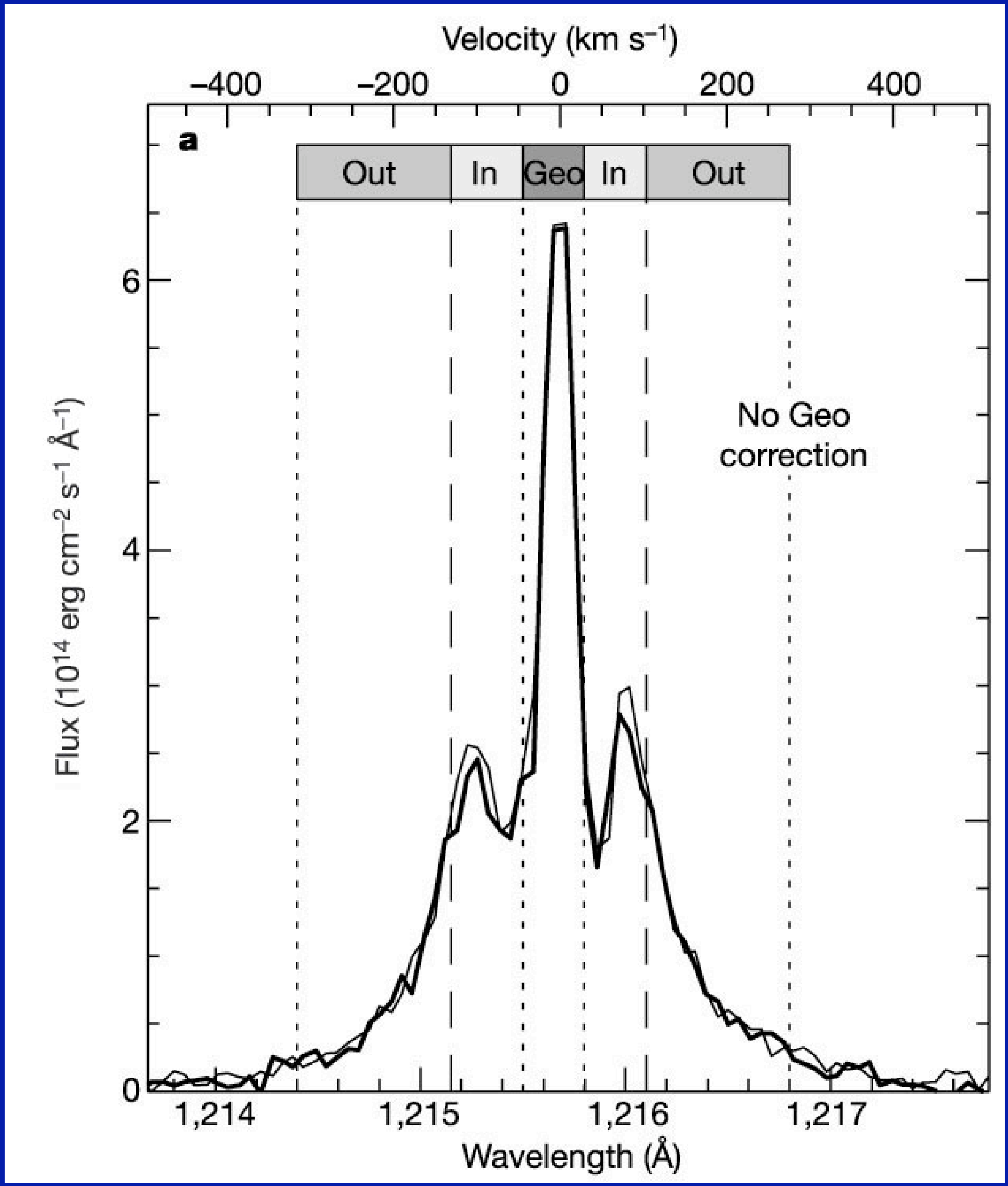
Spectroscopy of transits


Study
planetary
atmospheres
Transmission spectroscopy

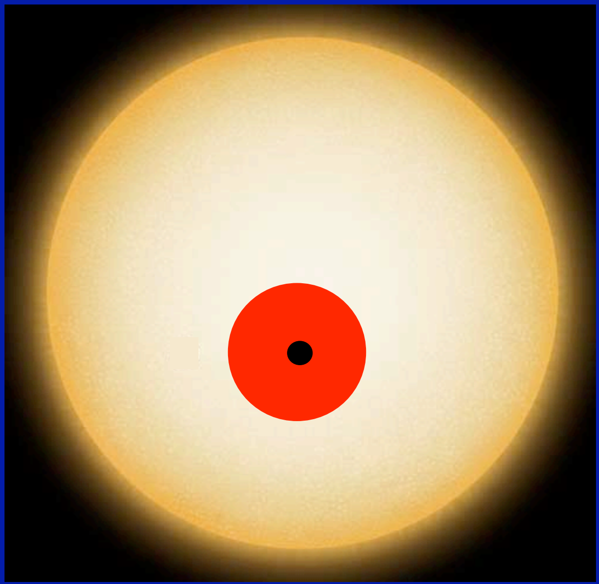


Detection of neutral sodium

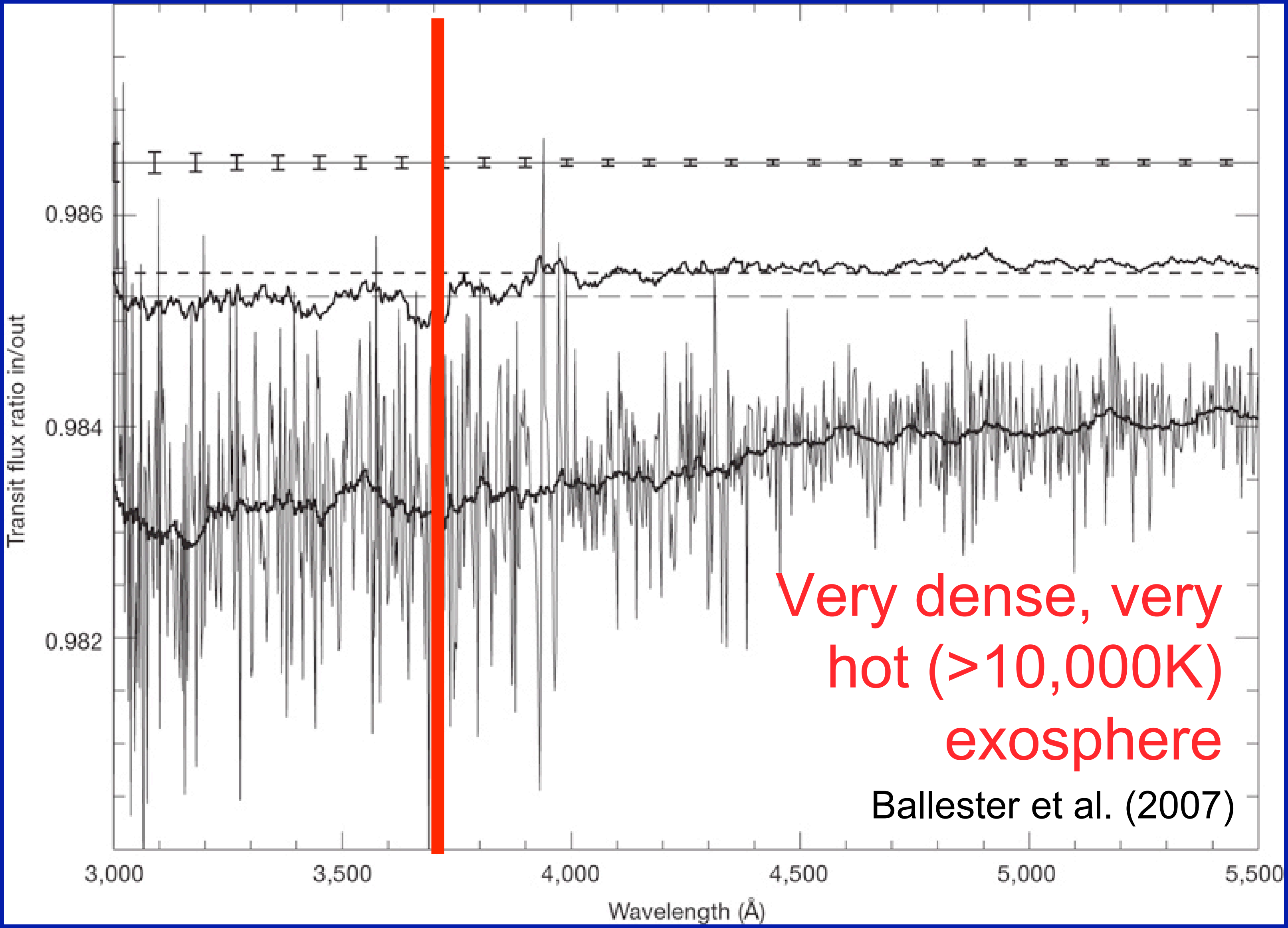
Charbonneau, Brown, Noyes & Gilliland (2002)



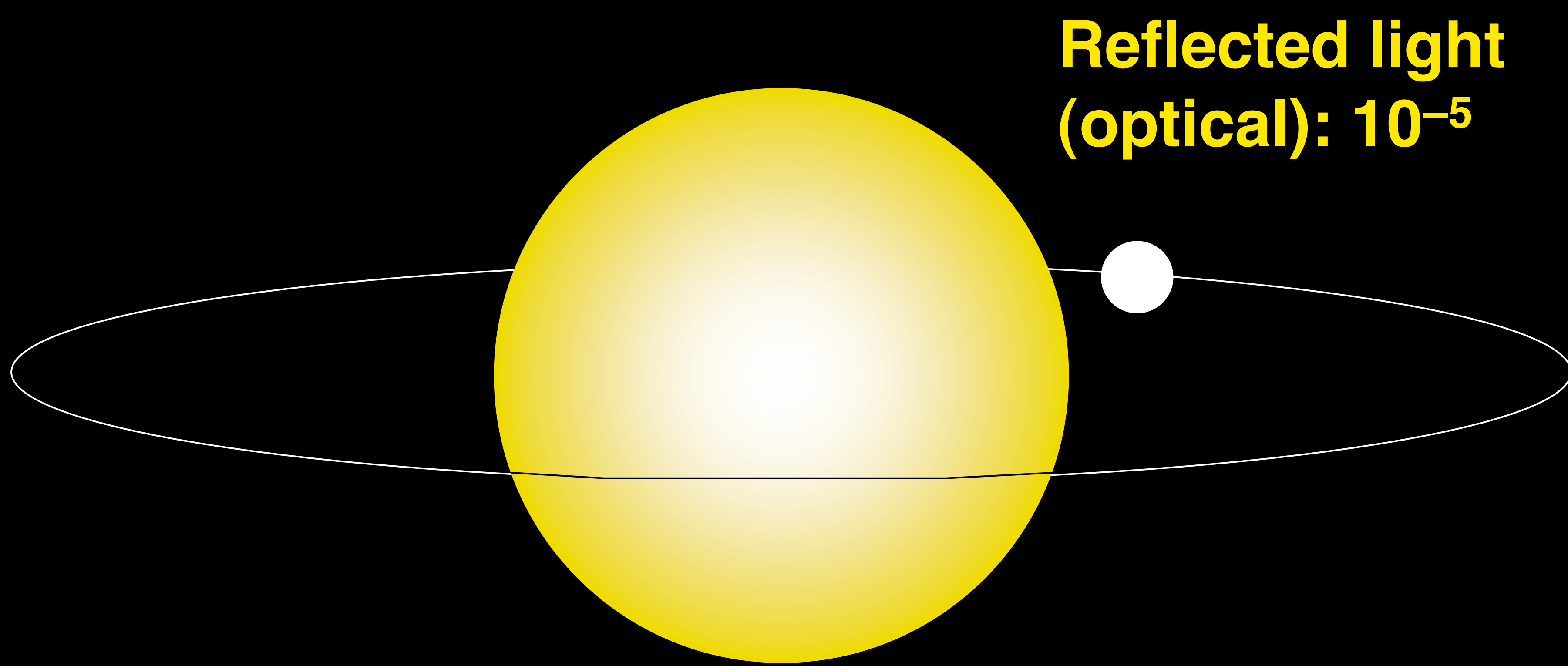
Detection of cold (n = 1) neutral hydrogen



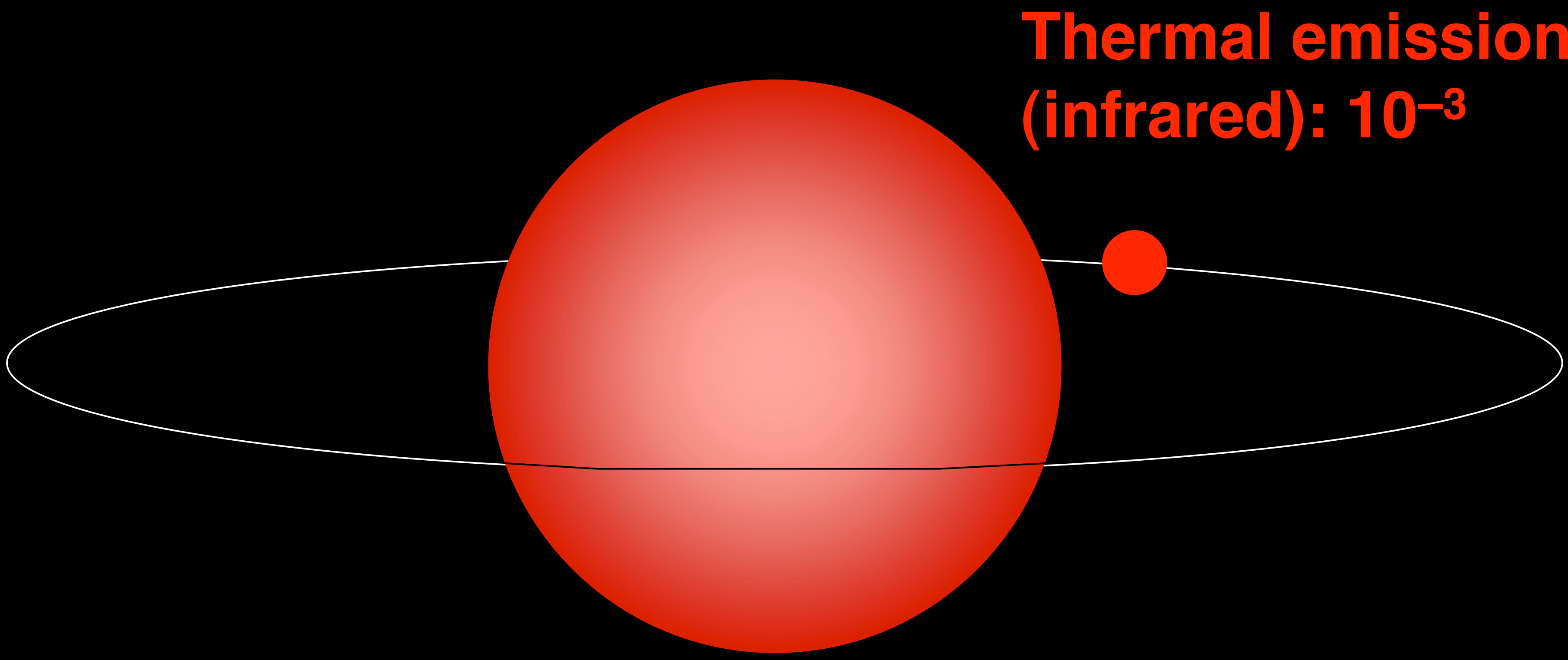
Detection of hot (*n*=2) neutral hydrogen

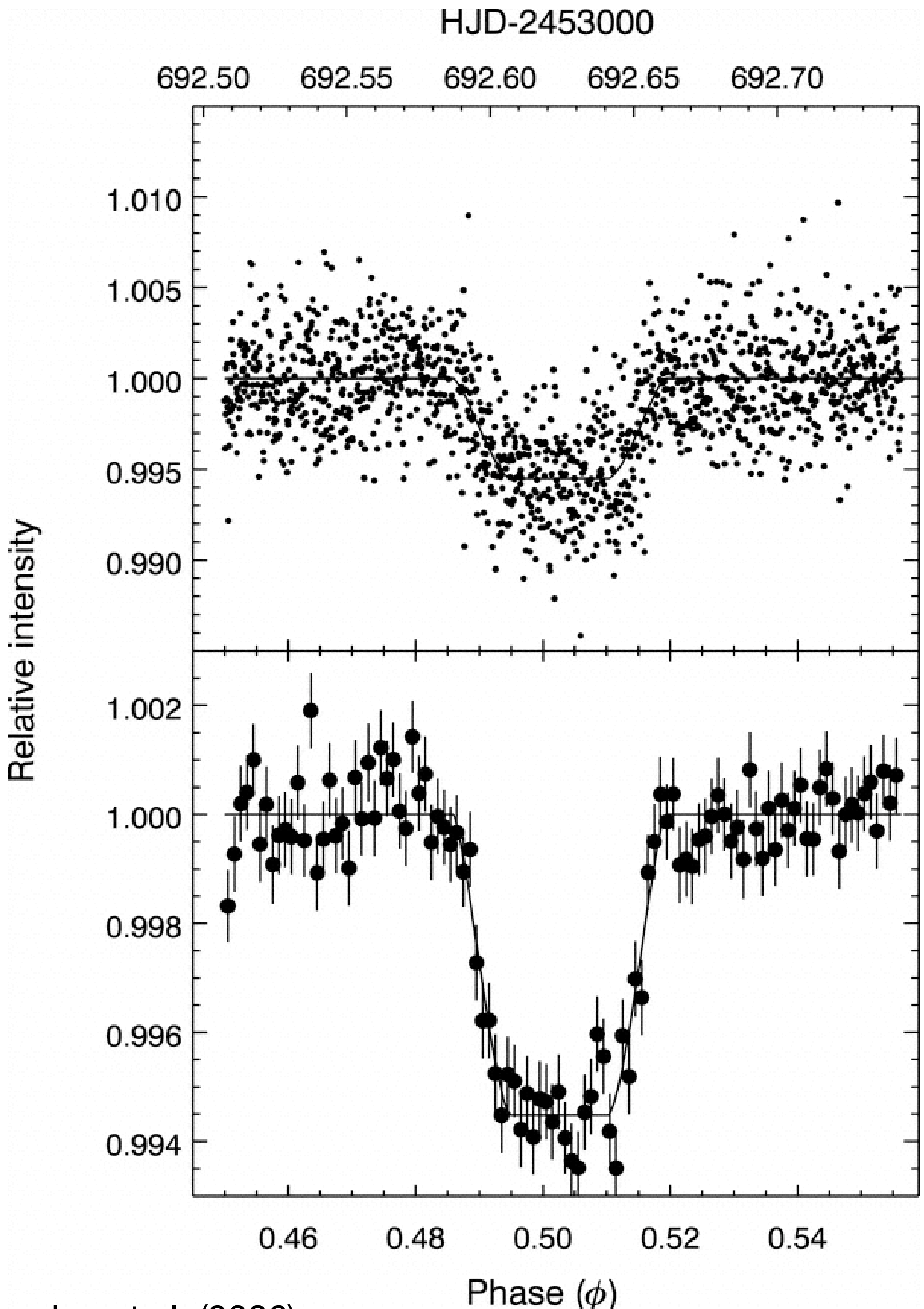


Secondary eclipses



Secondary eclipses

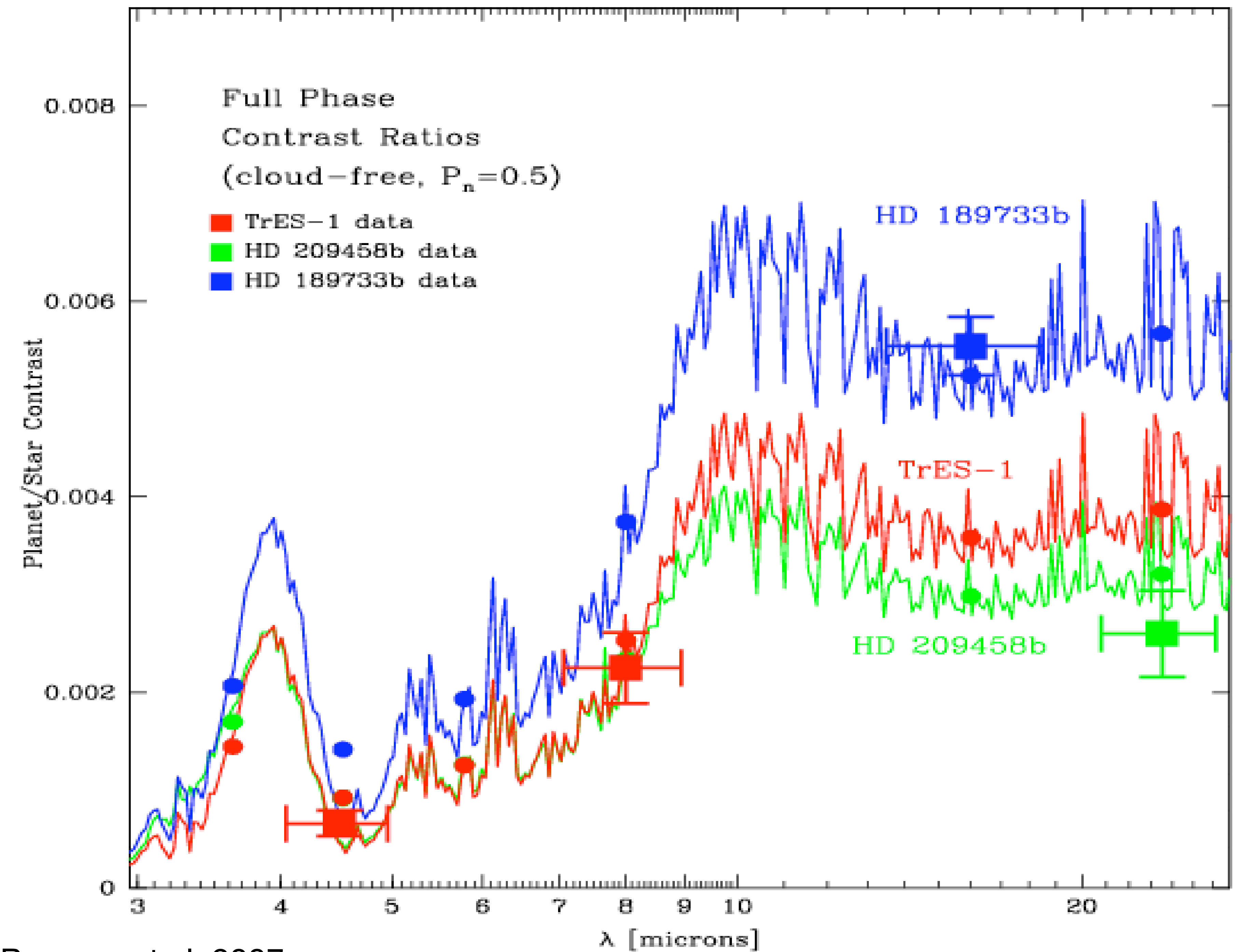




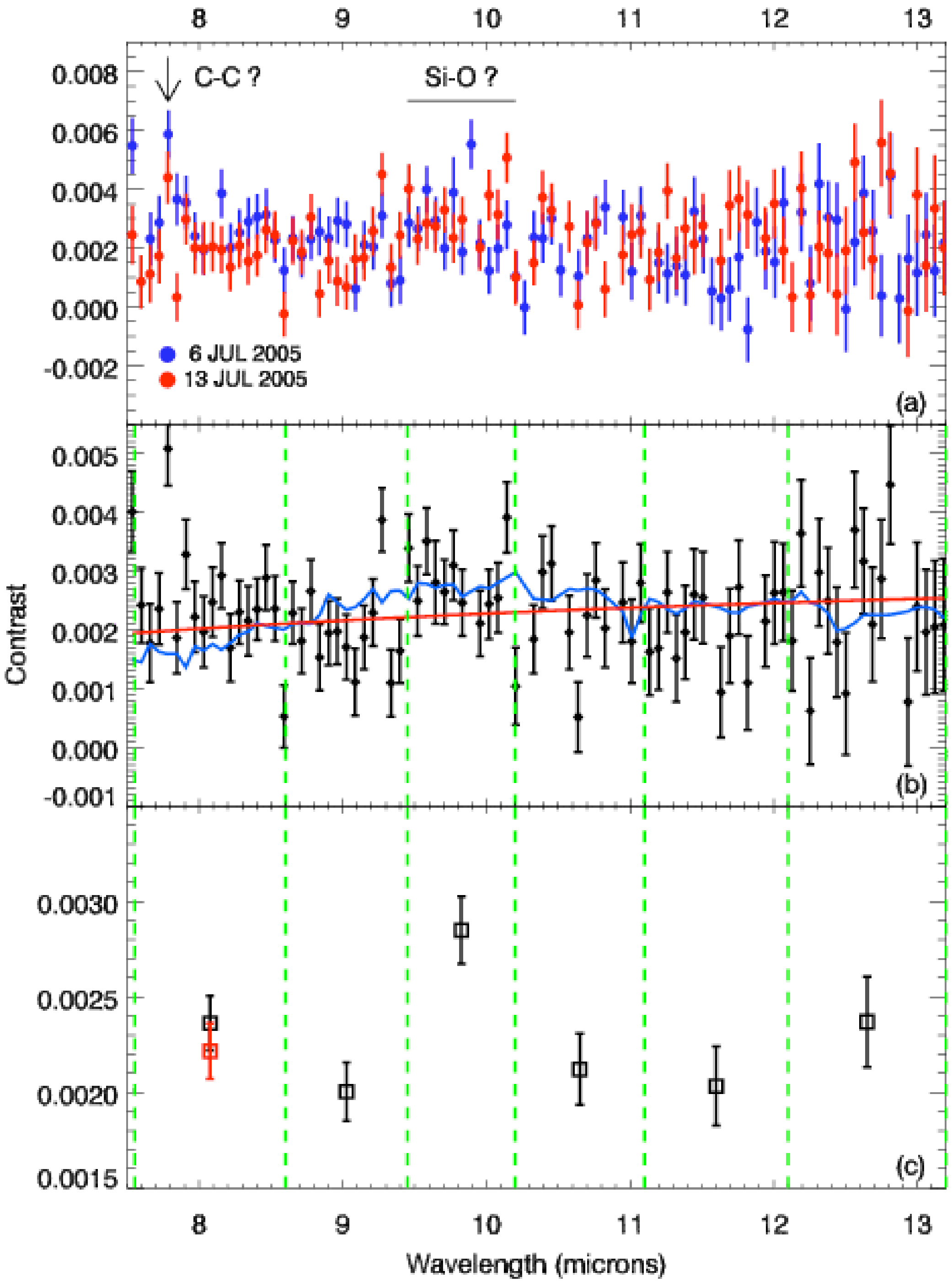
Deming et al. (2006)

Secondary eclipse

HD 189733:
T = 1117 +/– 42 K



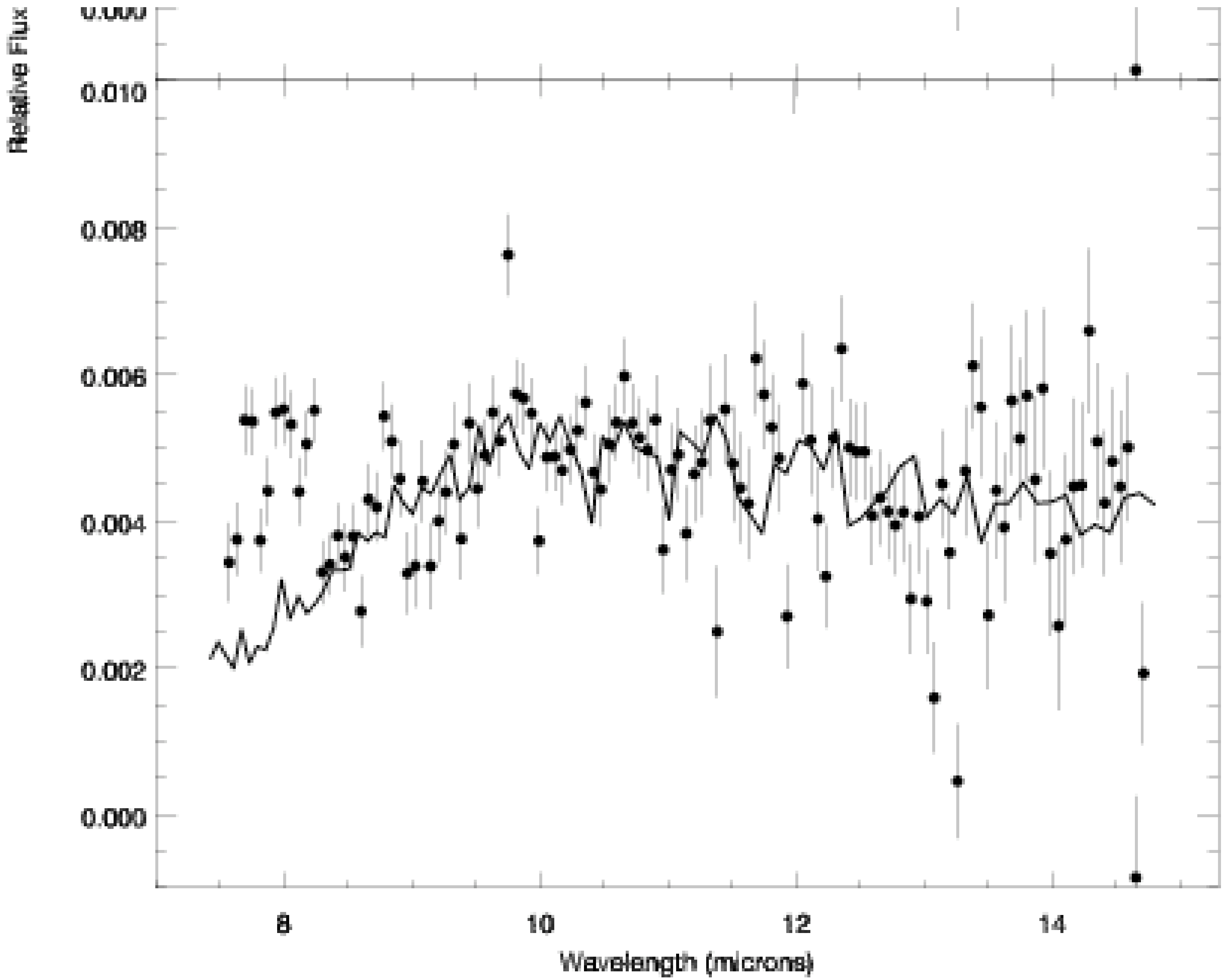
Burrows et al. 2007



R=80 spectra of hot Jupiters

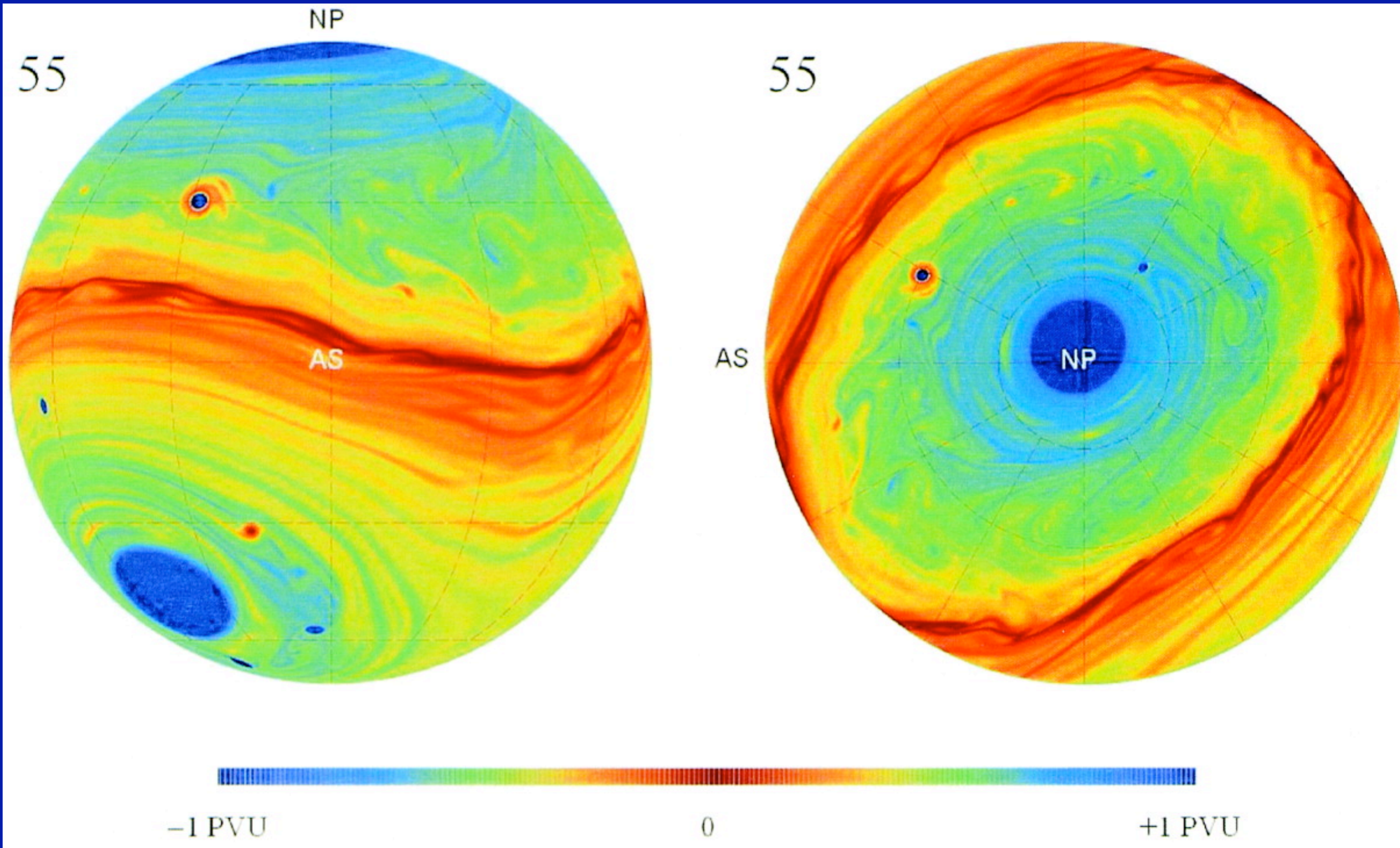
Featureless continuum; no water absorption

Harrington et al. 2007



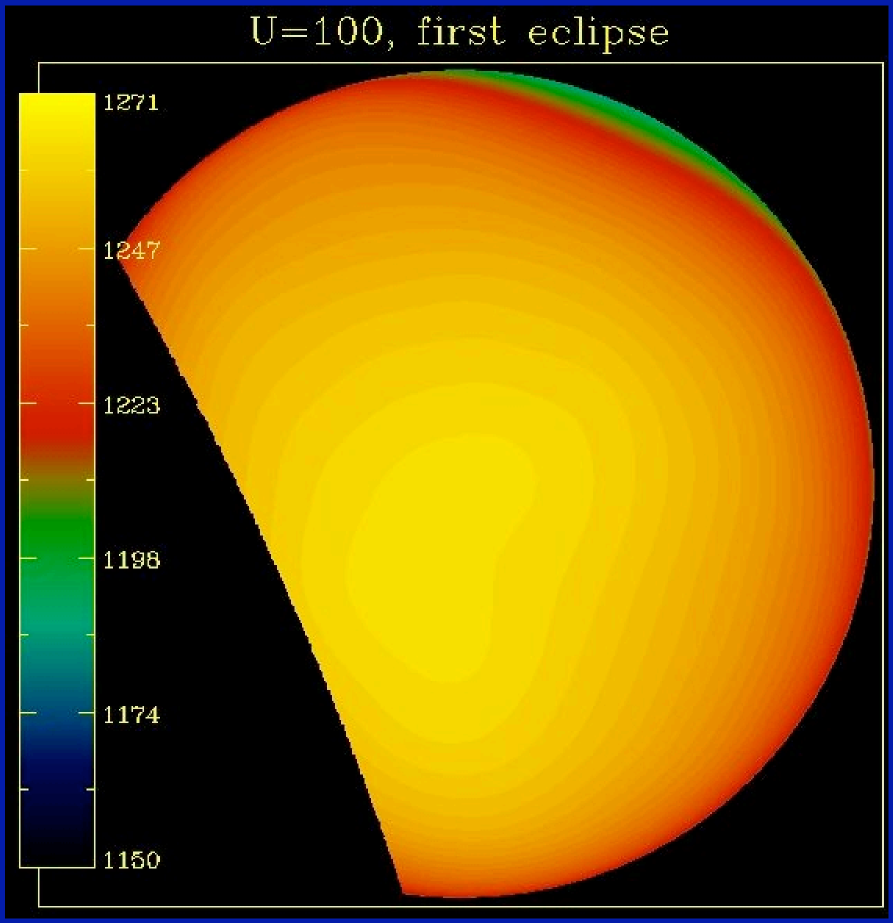
Grillmair et al. 2007

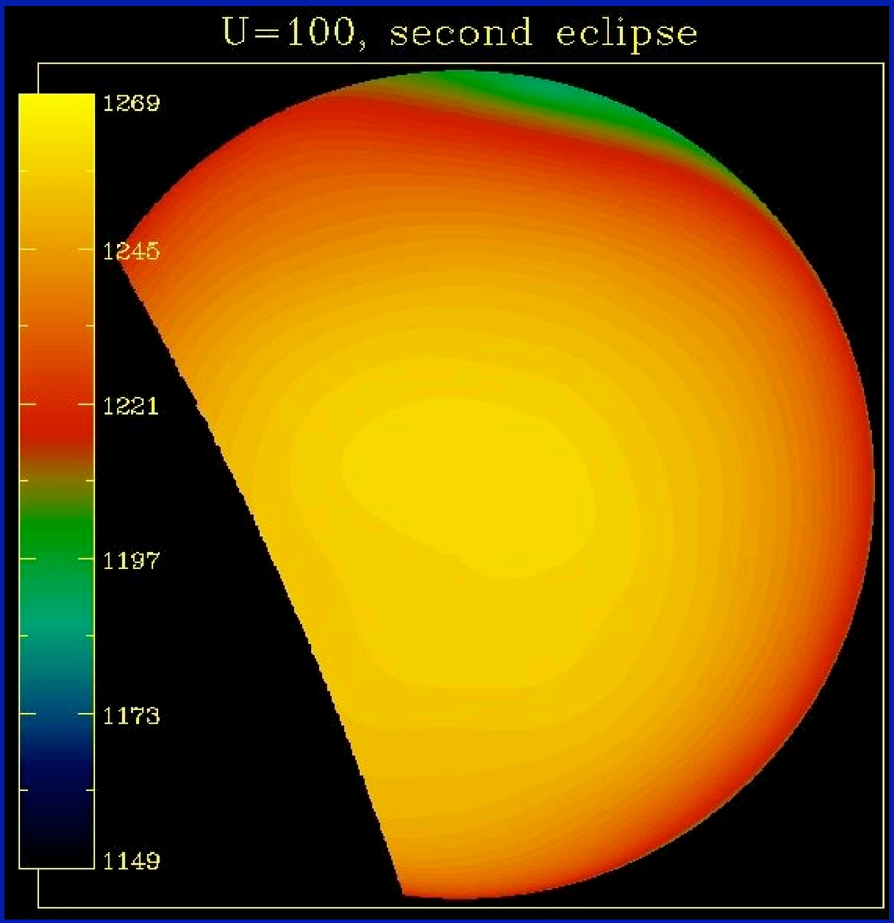
Atmospheric circulation models



Cho, Menou, Hansen, & Seager 2003

Secondary eclipse mapping





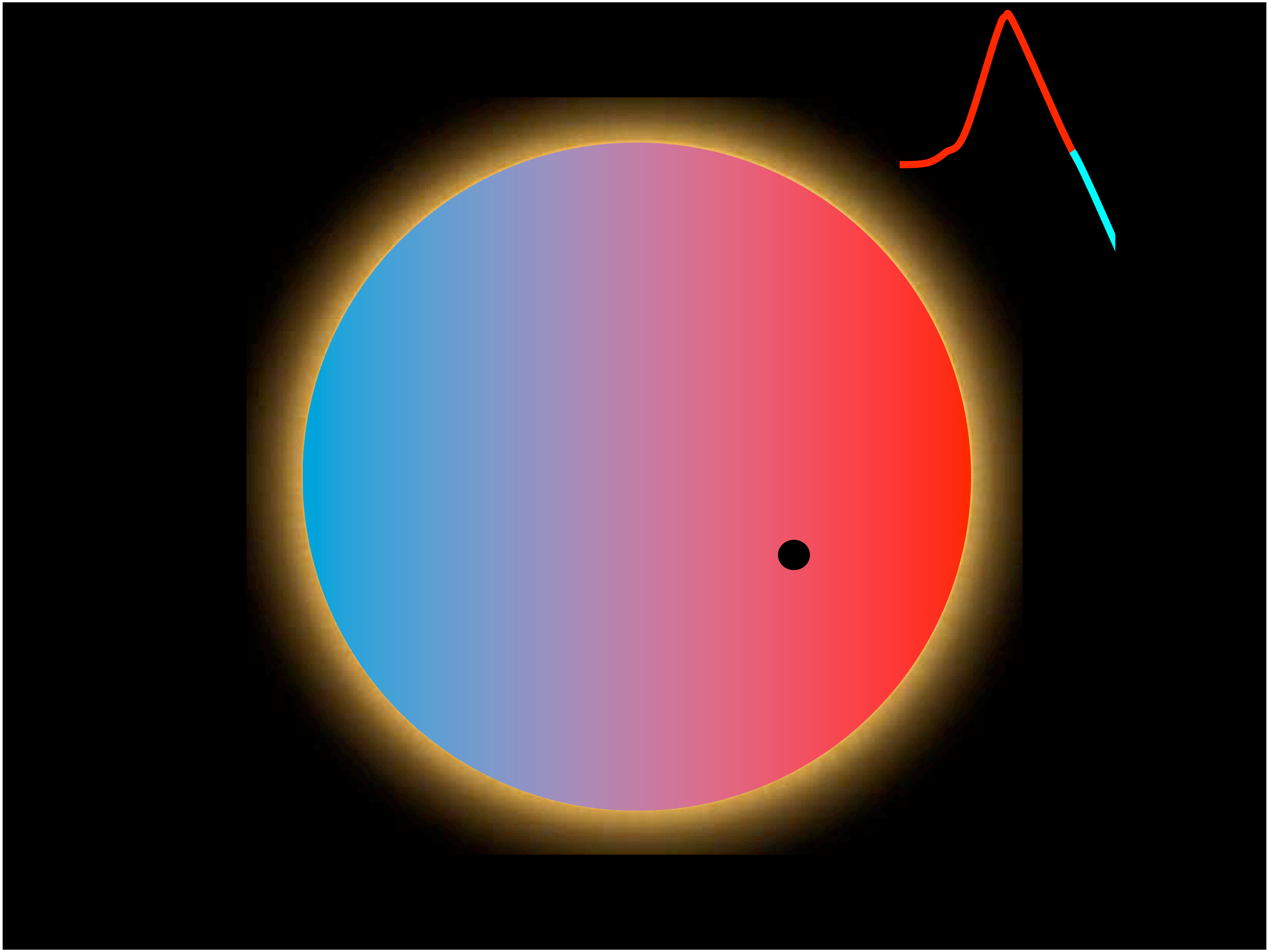
Rauscher, Menou, Seager, et al. 2007

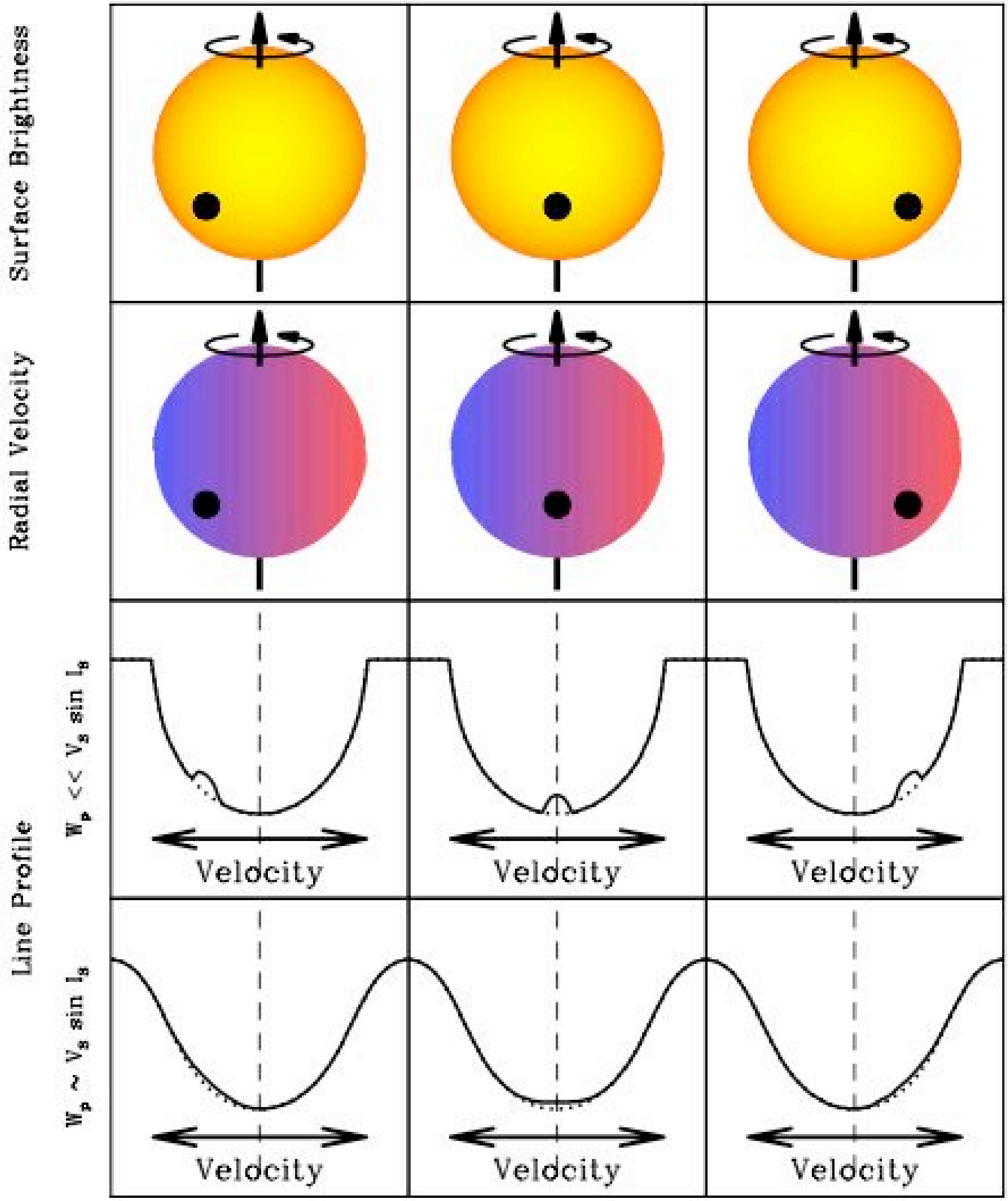
What can we learn from transits?

- Orbital period
- Planetary mass
- Planetary radius
- Moons, additional planets (*via* timing)
- Effective temperature
- Crude infrared spectrum and surface map
- Alignment between orbit, stellar spin

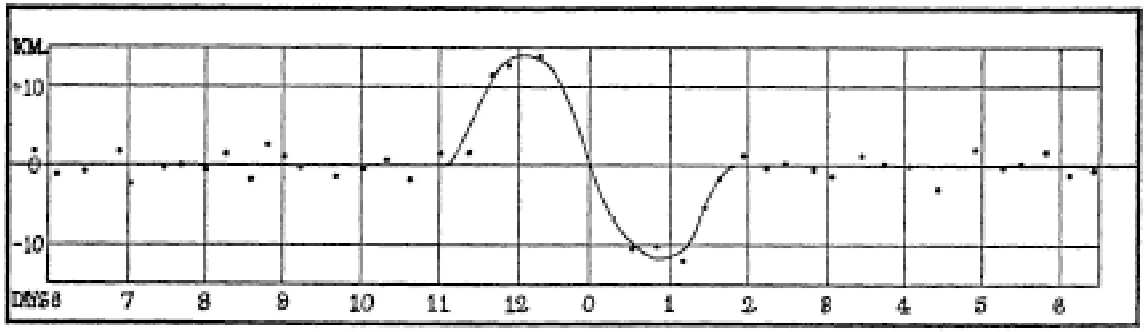
Spin-orbit alignment for exoplanets

- 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

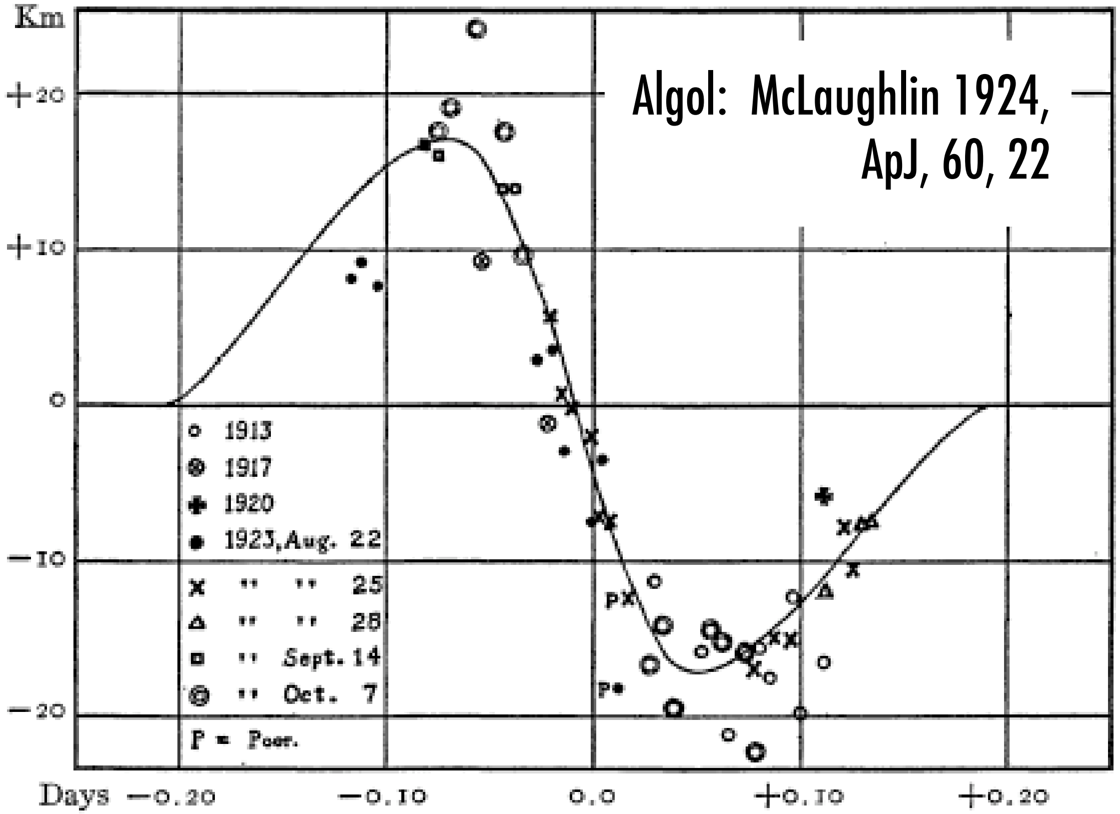




Gaudi & Winn
(2007)



β Lyrae: Rossiter 1924, ApJ, 60, 15

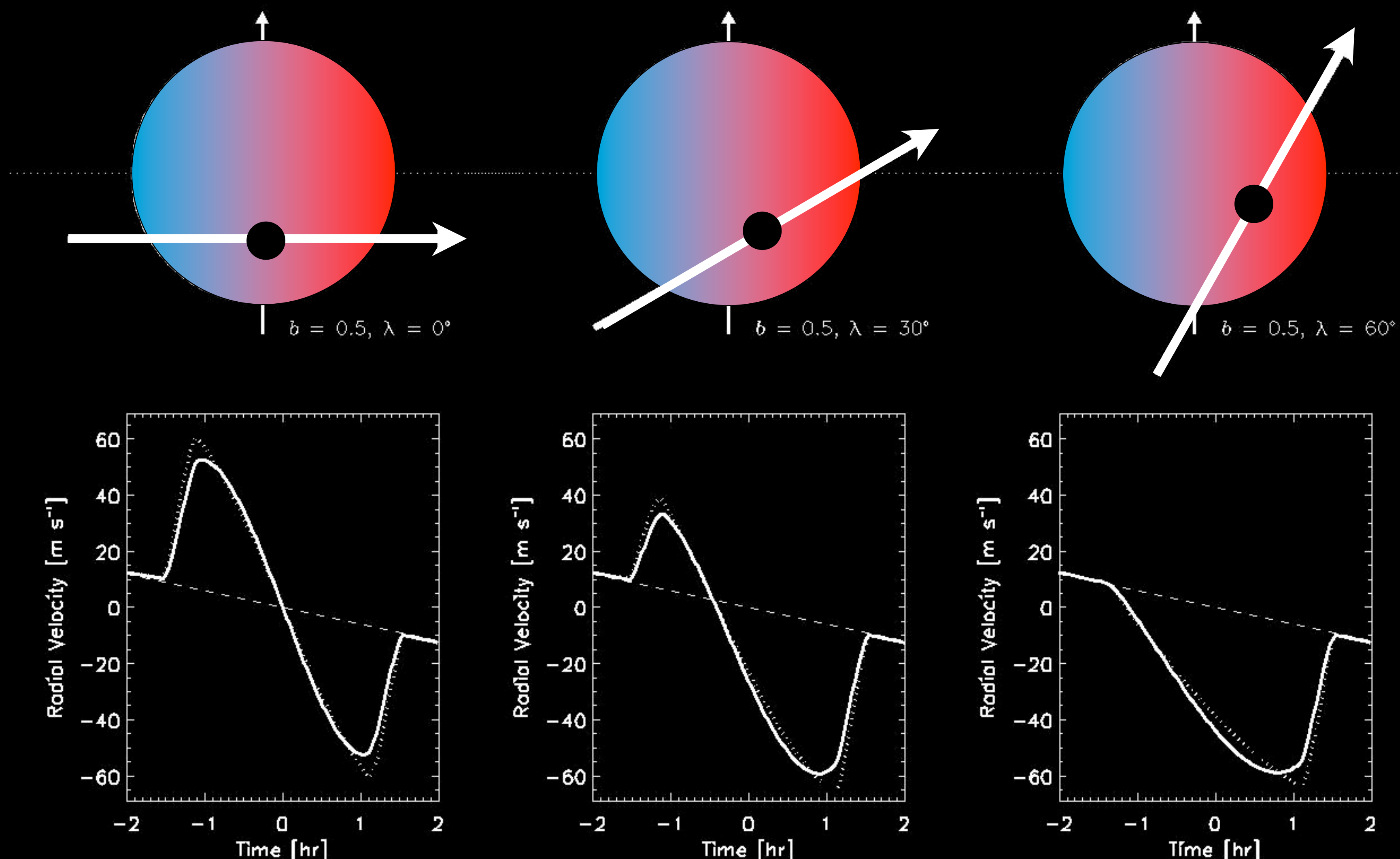


Algol: McLaughlin 1924, ApJ, 60, 22

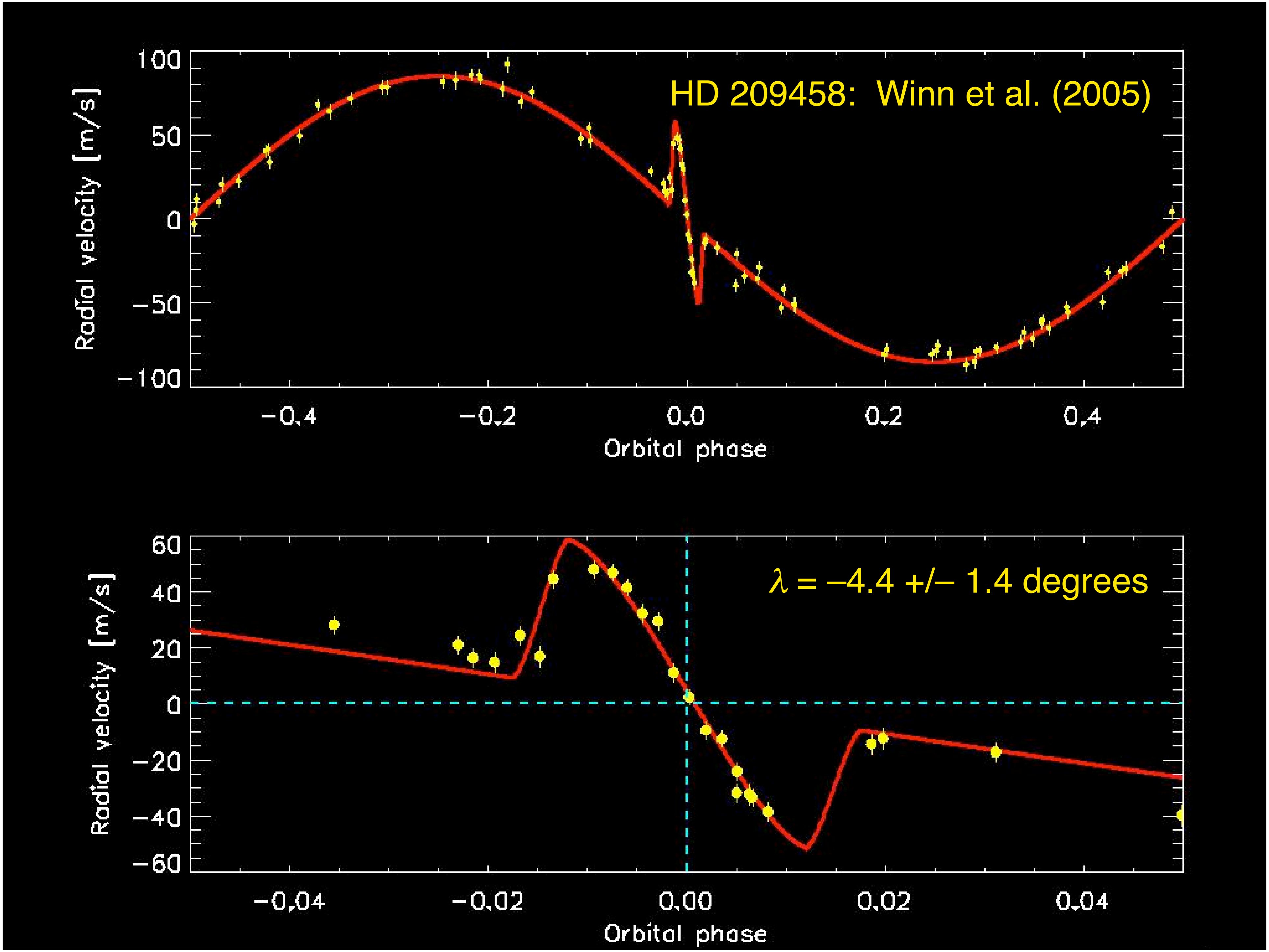
FIG. 1.—Curve of the rotational effect in Algol

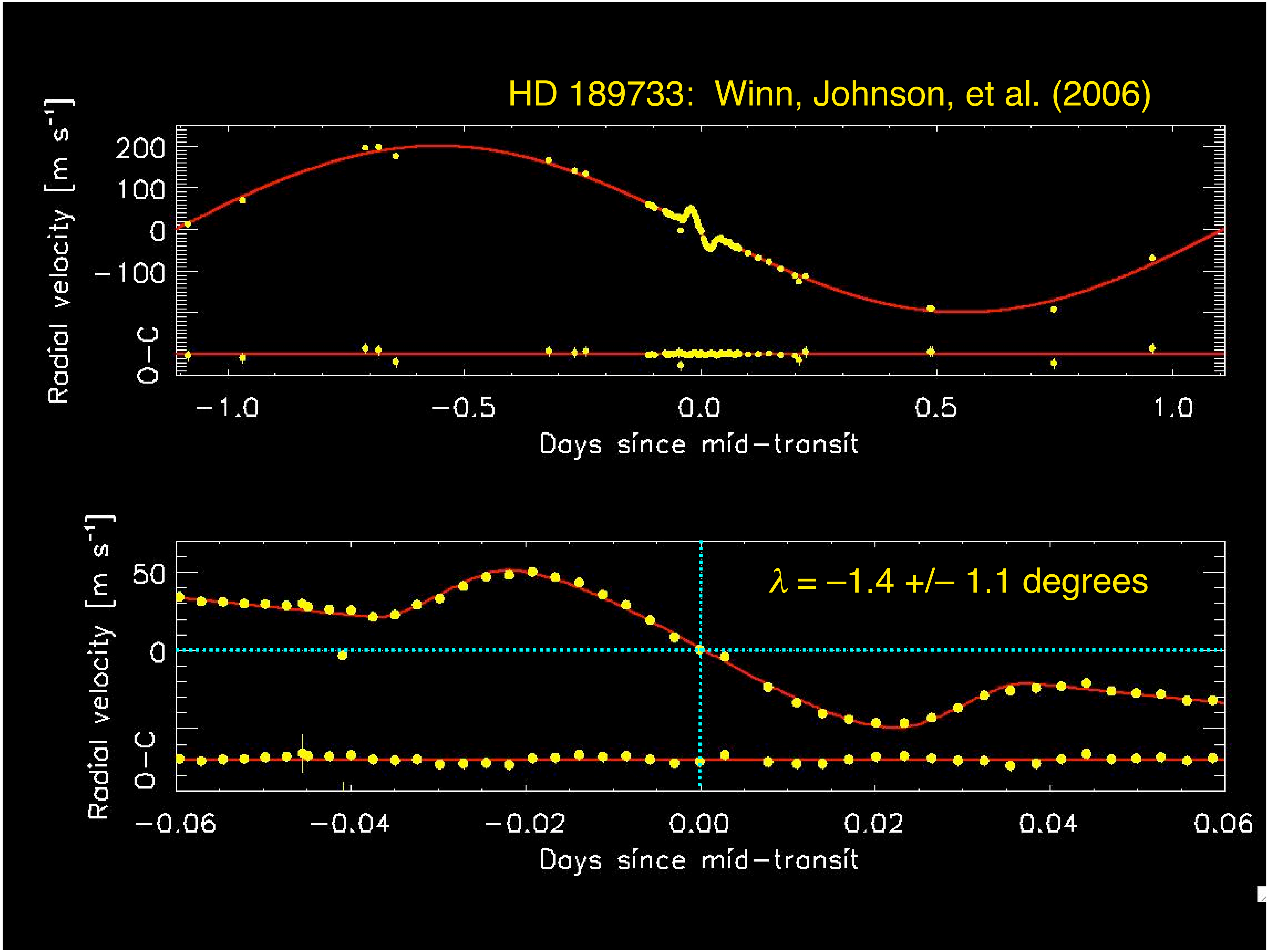
R. A. Rossiter
(1896-1977)

Measuring spin-orbit alignment



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


HD 209458: Winn et al. (2005)
Radial velocity [m/s]
Orbital phase
λ = –4.4 +/– 1.4 degrees
Radial velocity [m/s]
Orbital phase



HD 189733: Winn, Johnson, et al. (2006)
Radial velocity [m s⁻¹]
200
100
0
−100
O−C
−1.0
−0.5
0.0
0.5
1.0
Days since mid−transit
Radial velocity [m s⁻¹]
50
0
O−C
λ = –1.4 +/– 1.1 degrees
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06
Days since mid−transit

Spin-orbit alignment for exoplanets

- Random alignments ruled out (>99.9% CL)
- Tidal coplanarization takes too long

$$\tau \sim \frac{4\pi r_g^2 Q_S}{3k} \frac{R_S^3}{G M_S P} \left(\frac{M_S}{M_P}\right)^2 \left(\frac{a}{R_S}\right)^6 \sim 5 \times 10^{12} \text{ yr}$$

Hut 1981; Queloz et al. 2000; Winn et al. 2005

- Migration generally preserves spin-orbit alignment

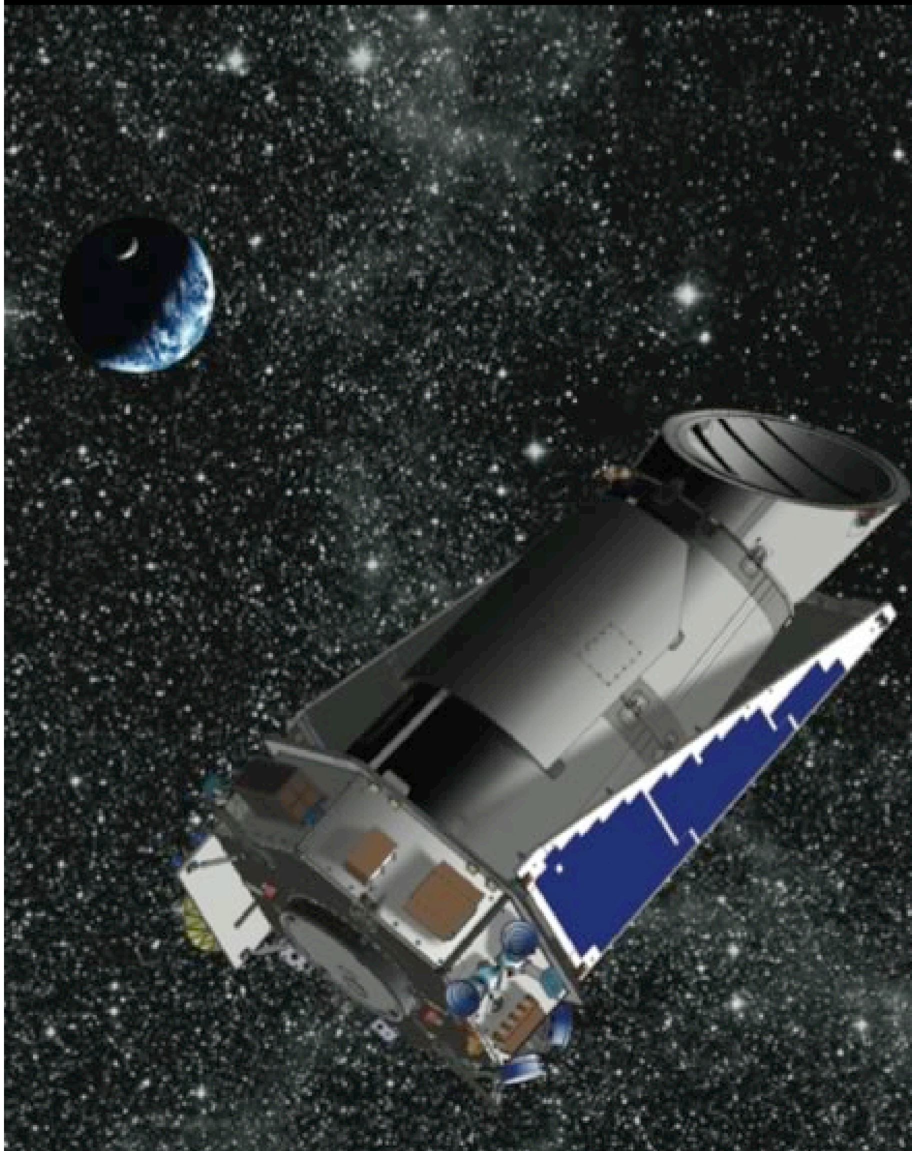
What *might* we learn from transits?

- Optical albedo (Rowe et al. 2006)
- Star spots (Brown et al., in preparation)
- Differential rotation (Gaudi & Winn 2007)
- Planetary rings (Ohta, Taruya, & Suto 2007)
- Planetary spin (Seager & Hui; Hui & Seager 2002; Spiegel et al.)
- Artificial planet-sized objects (Arnold 2005)
- **SMALL PLANETS**: abundance, structure

Corot

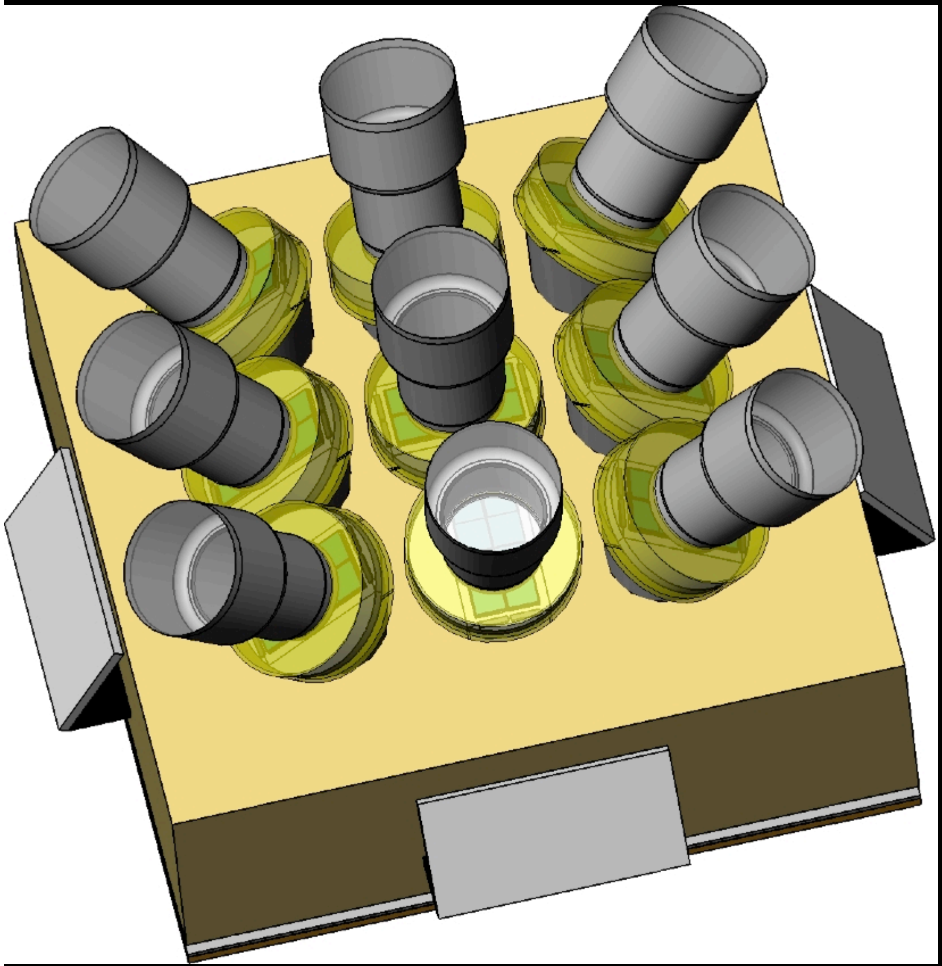
- French, German, and other partners
- Launched Dec. 2006
- Monitor 10 fields of 12,000 stars each, for 150 days
- Lots of hot Jupiters
- A handful of “rocky” planets ($<10\ M_{earth}$)

Kepler



- NASA Discovery (Ames/ Ball Aerospace)
- Launch Oct. 2008
- Earth-trailing orbit
- Monitor one field of 100,000 stars for 4 yr
- > 200 giant planets
- ~50*f* Earth-like planets in the "habitable zone"

Transiting Exoplanet Survey Satellite



- MIT–Harvard–Ames
- HETE legacy
- Survey the **brightest** stars on the sky
- 1,000 giant planets
- **Nearby** stars with Earth-like planets in the “habitable zone”

Mikhail Lomonosov (1711-1765)