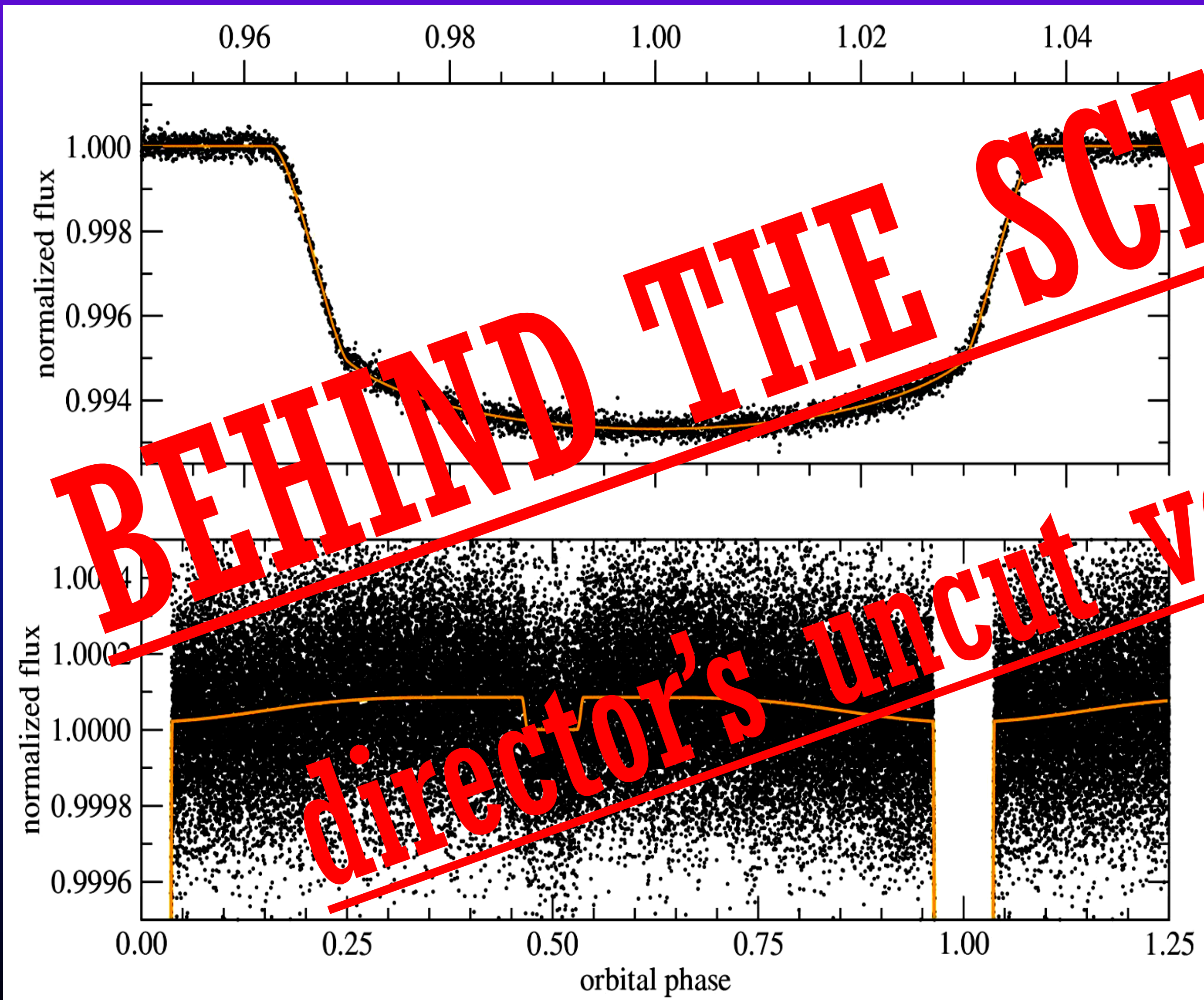
The *Kepler* Light Curve of HAT-P-7

BEHIND THE SCENES

director's uncut version



Bill Welsh

San Diego State University

with

J.A. Orosz,

S. Seager,

J.J. Fortney,

J.F. Rowe,

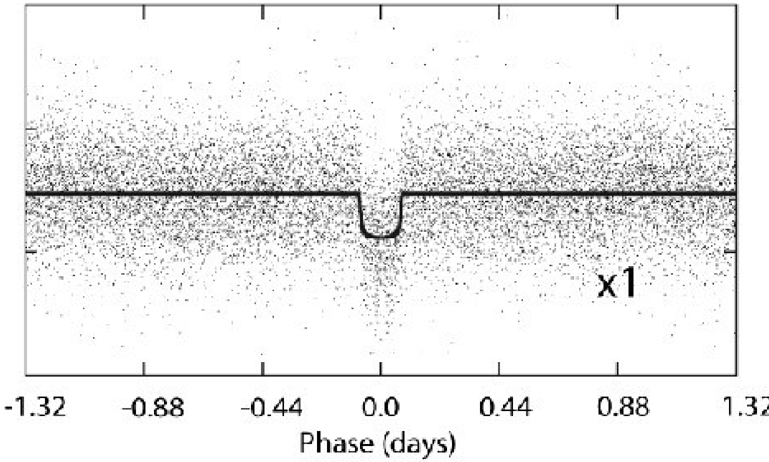
J. Jenkins,

D. Koch,

W.J. Borucki,

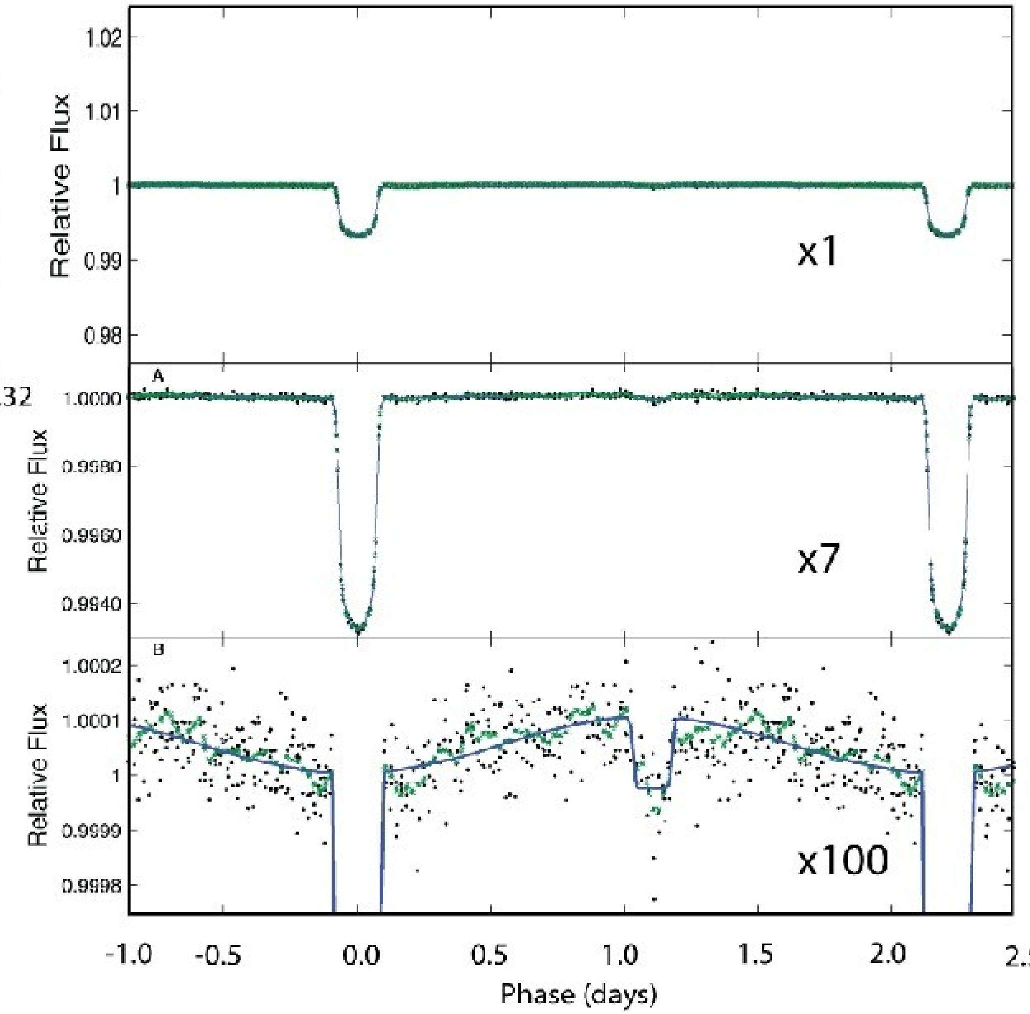
and the

***Kepler* Team**

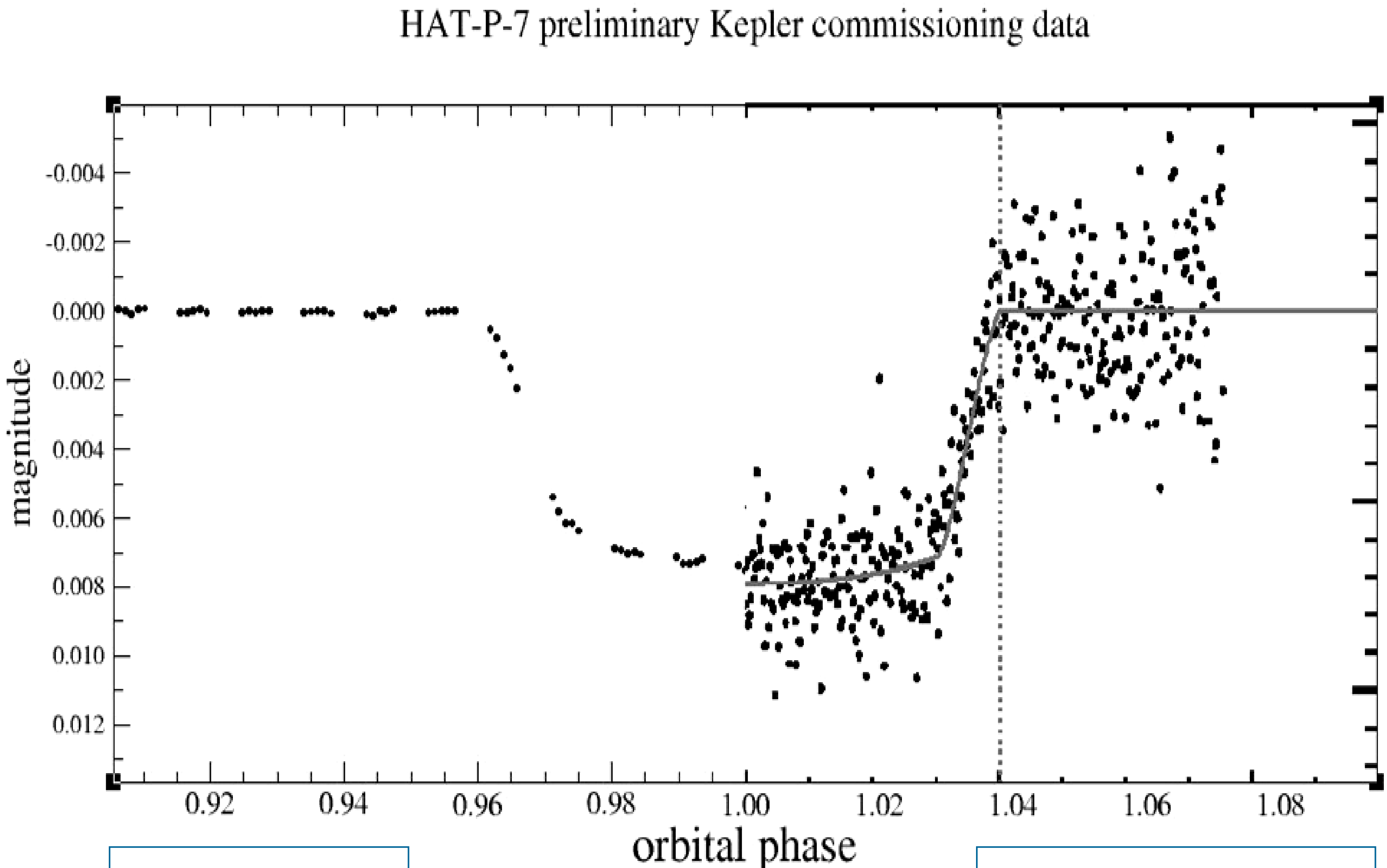


16,620 HATNet data points (57.7 days of data)

HAT-P-7b data from the ground
A. Pal et al., 2008

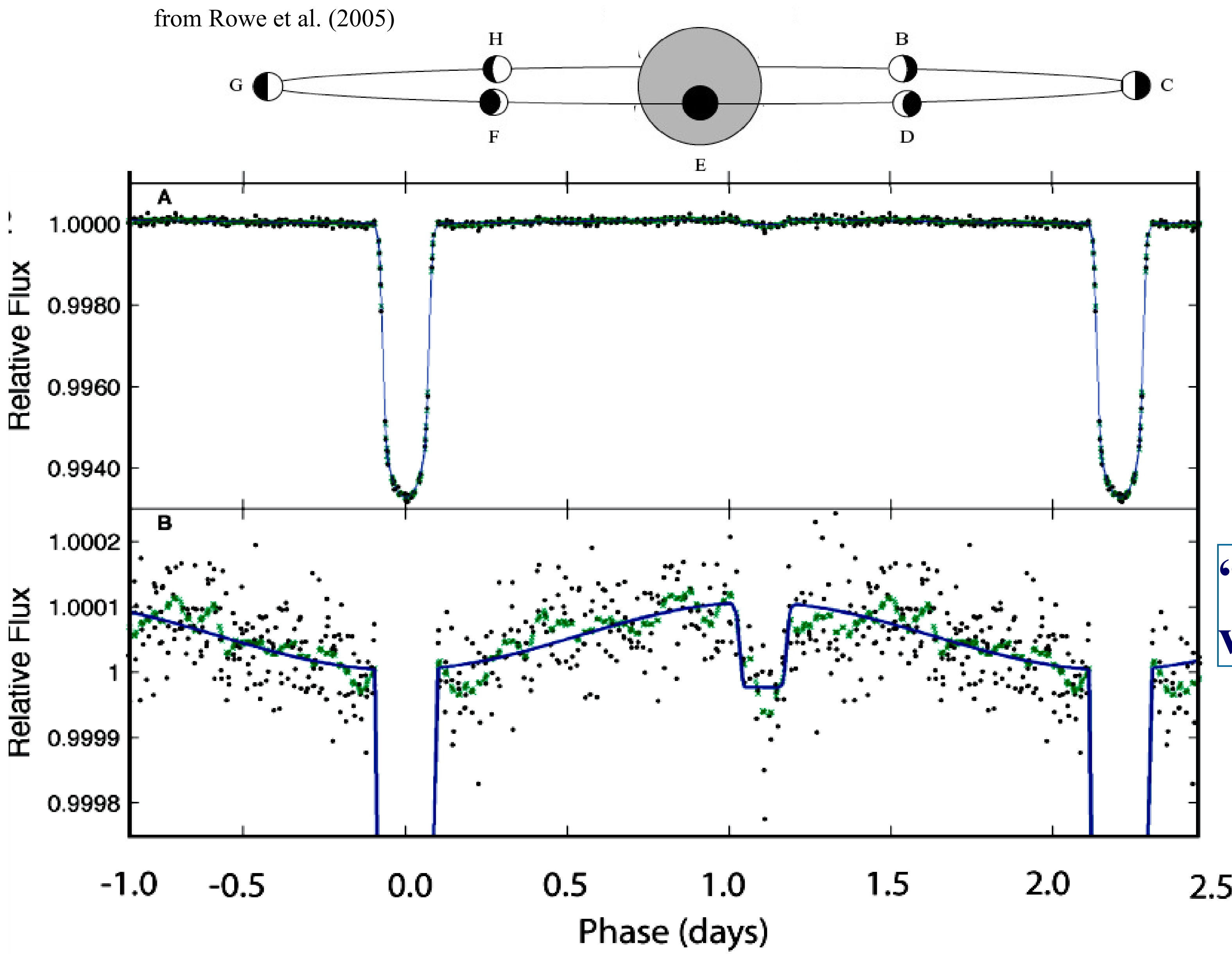


Kepler Commissioning data (10 days)
W. Borucki et al., 2009



Kepler observations

ground-based observations from Winn et al. (2009)



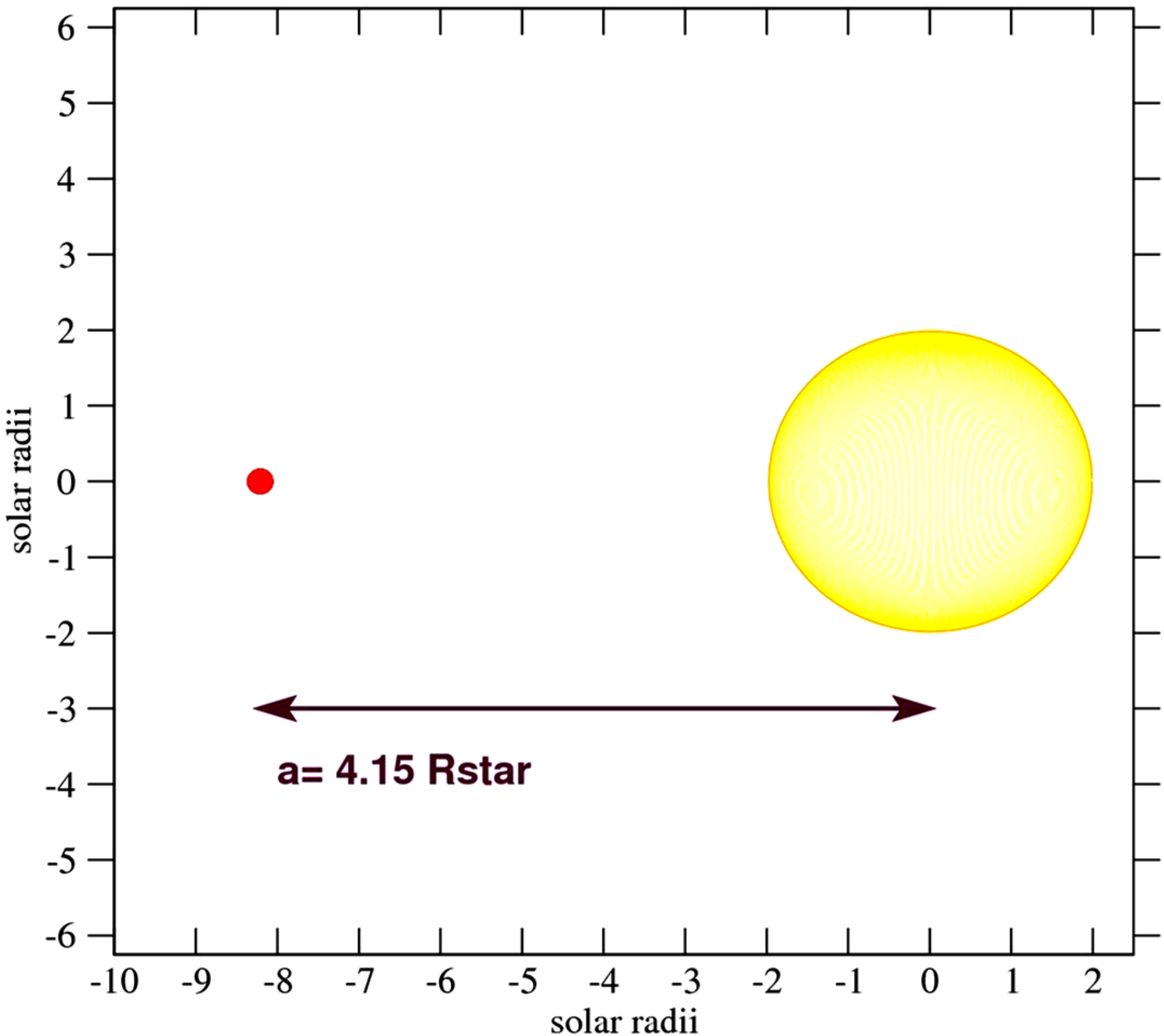
HAT-P-7

"phase" variation

Kepler Commissioning data (10 days)
W. Borucki et al., 2009

HAT-P-7

P=2.20 d; a=8.22 Rsun; Mstar=1.53; Mp=1.50 Rjup; Q=883



Main Point: Should not assume a spherical star

Star must be tidally distorted

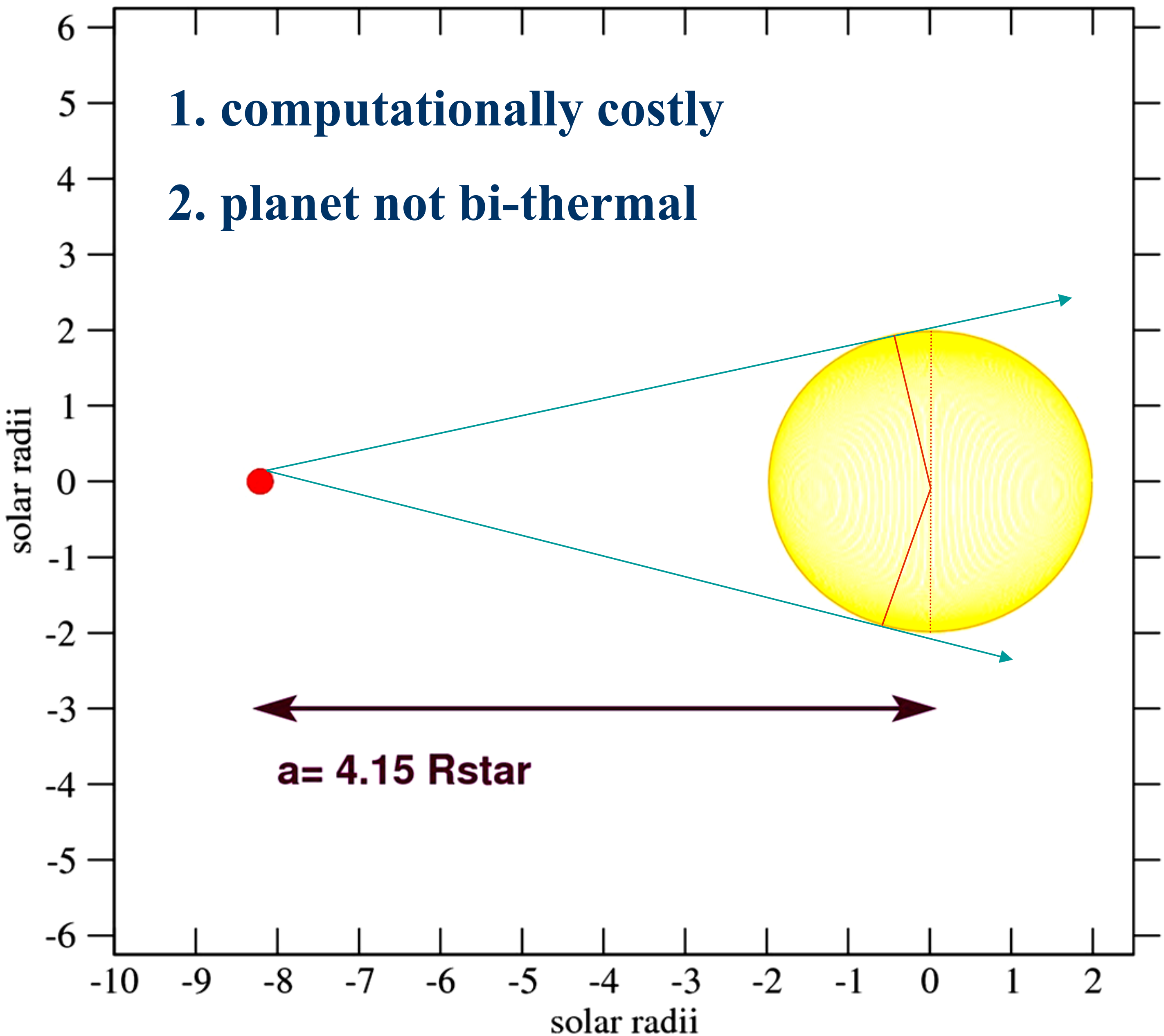
→ *"Ellipsoidal variations"*

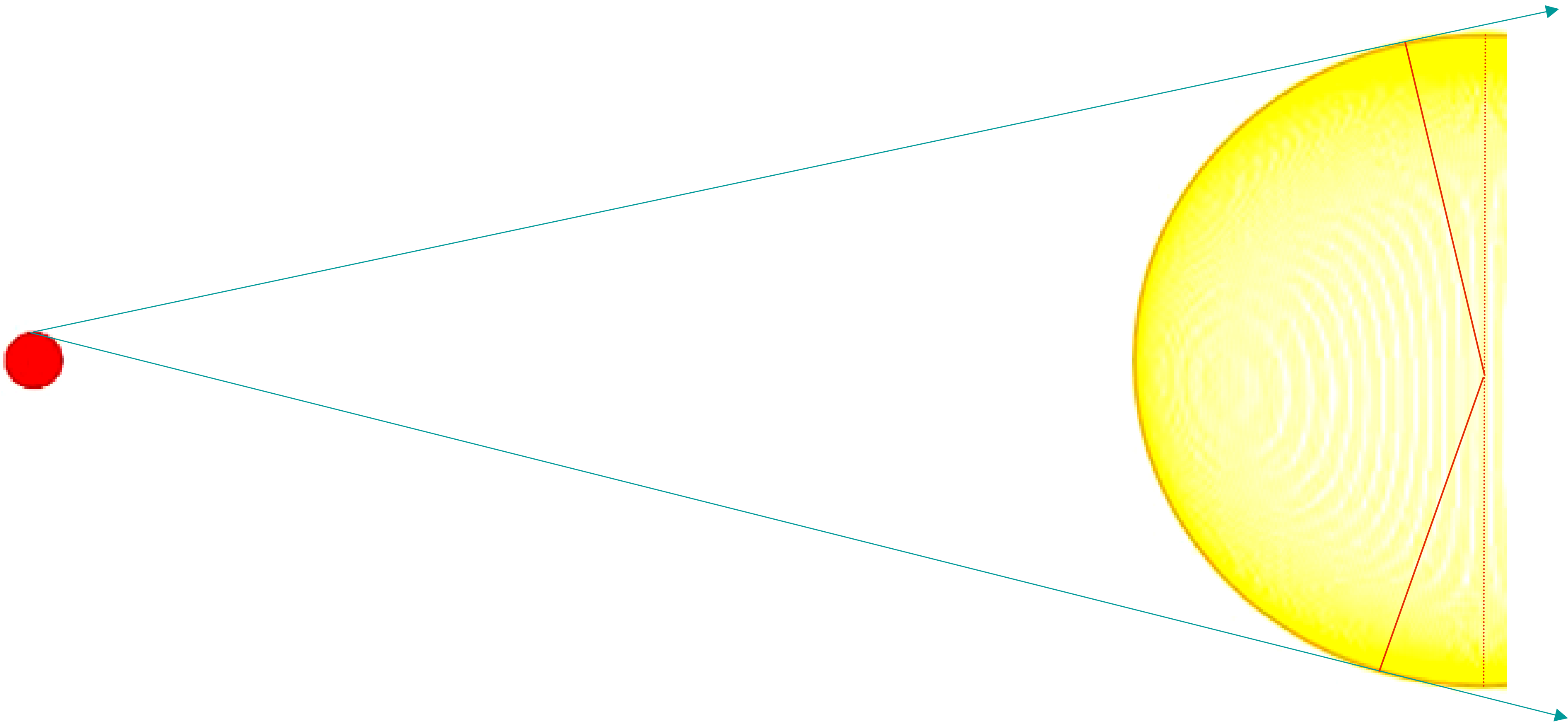
Need to combine ellipsoidal variations with thermal+scattered light from planet

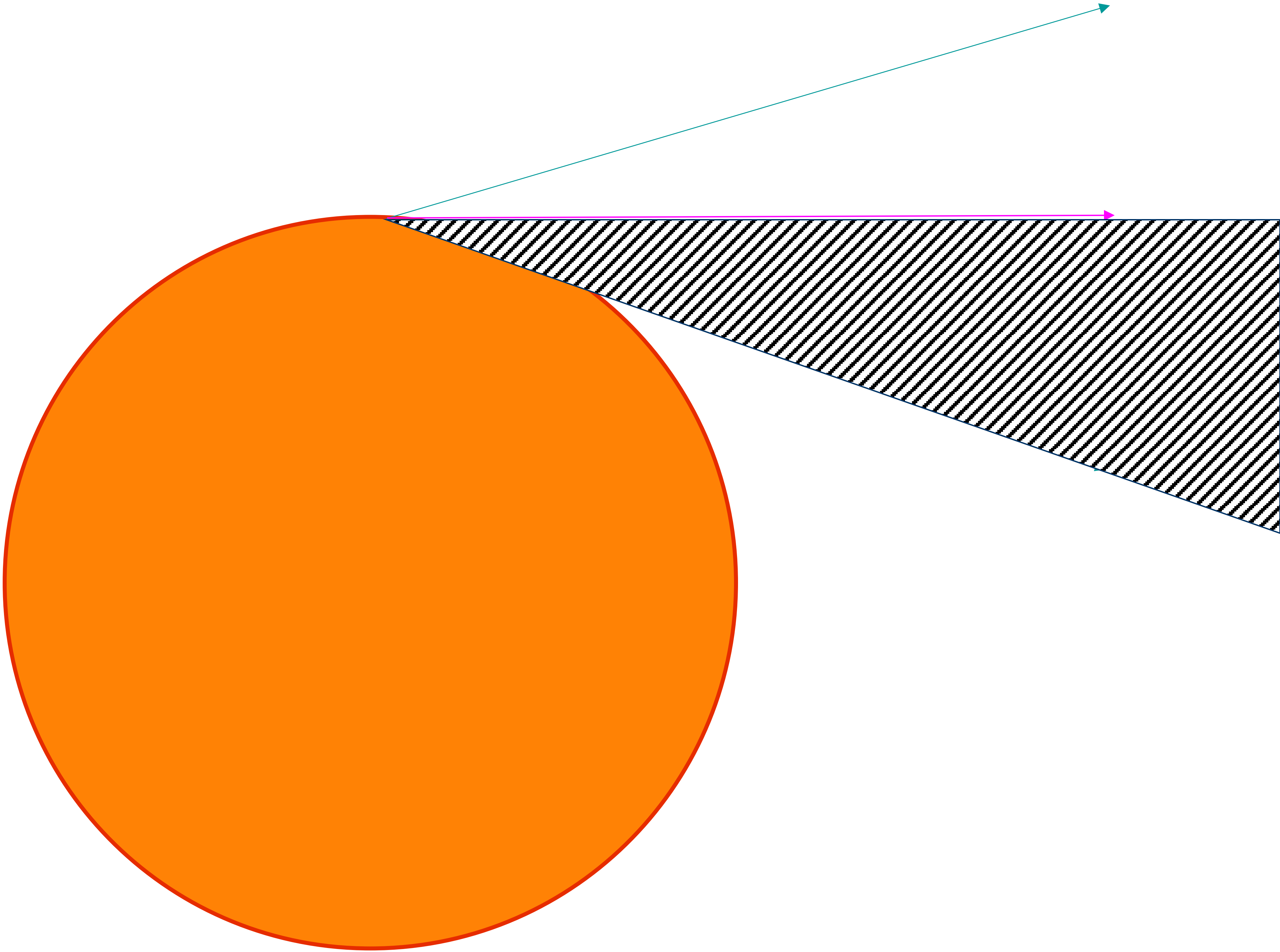
But is it really observable??

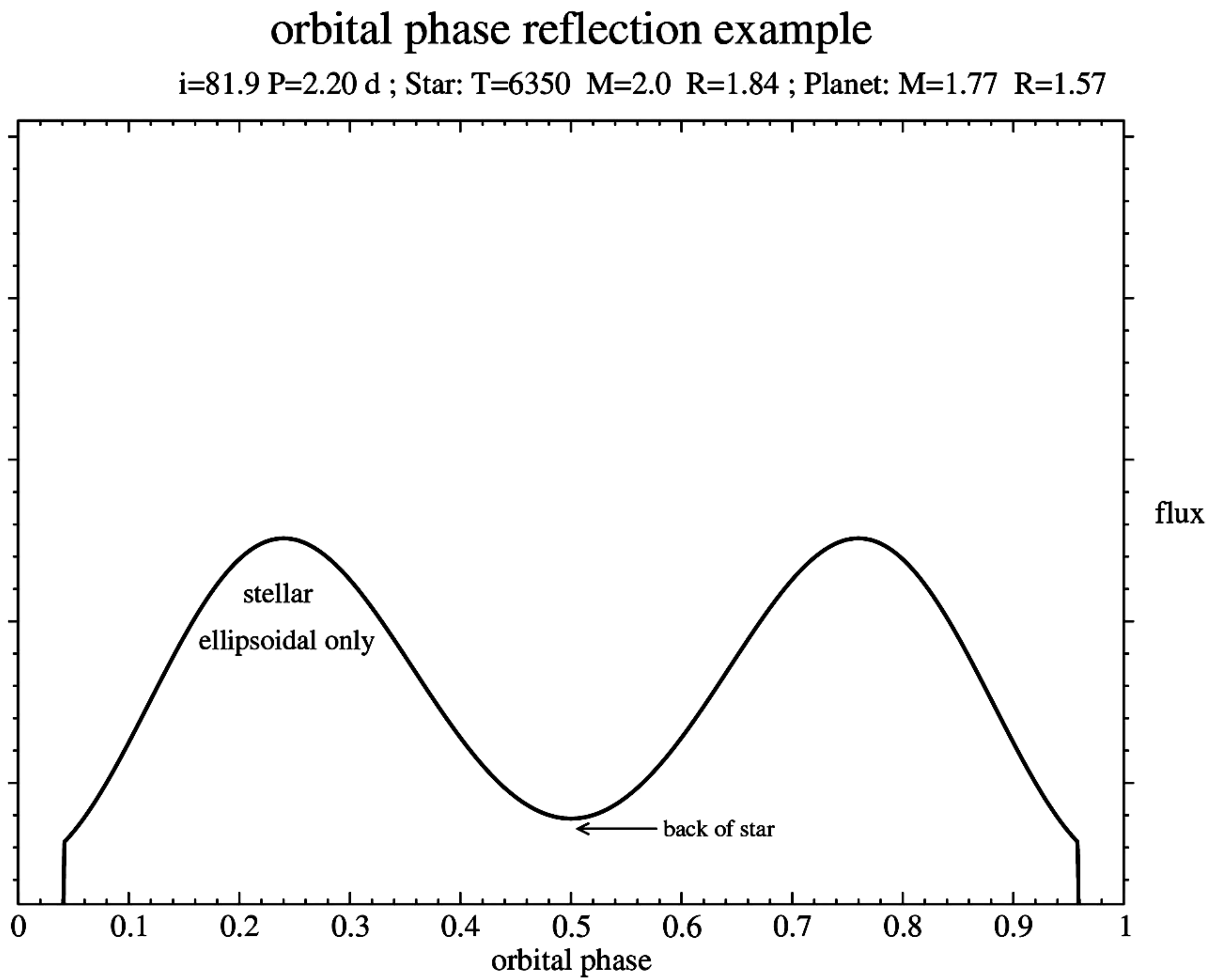
HAT-P-7

P=2.20 d; a=8.22 Rsun; Mstar=1.53; Mp=1.50 Rjup; Q=883



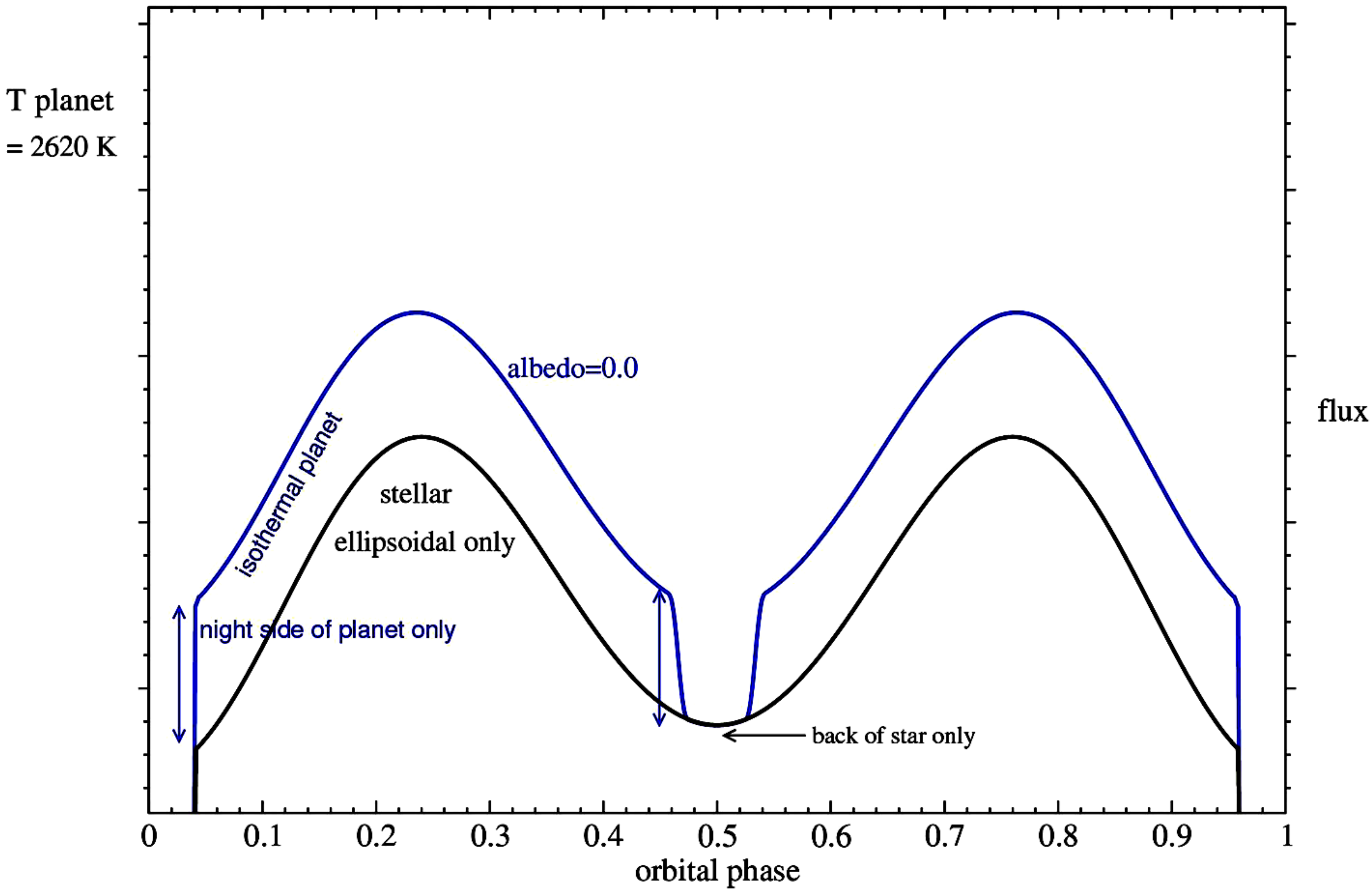


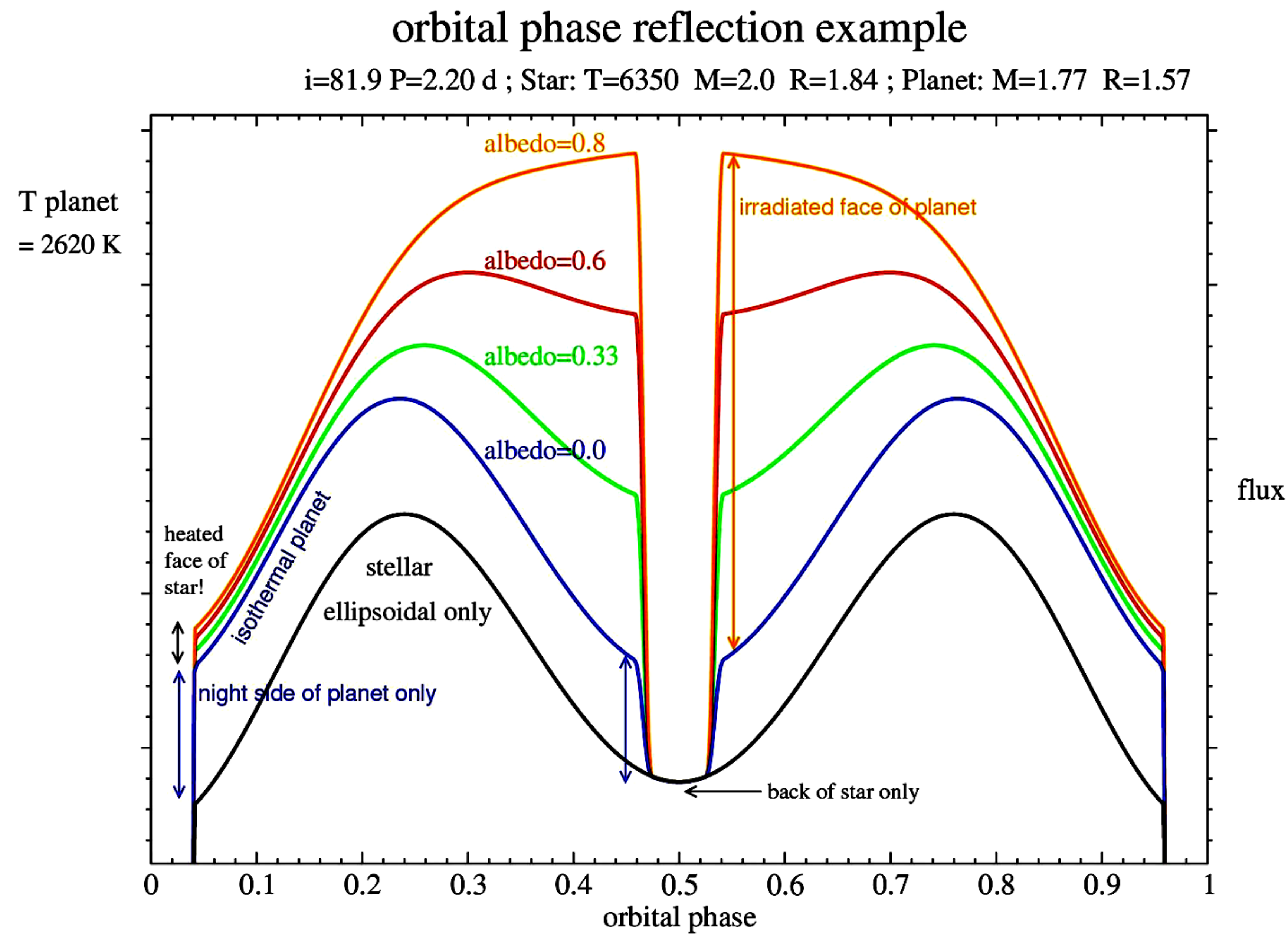



orbital phase reflection example
i=81.9 P=2.20 d ; Star: T=6350 M=2.0 R=1.84 ; Planet: M=1.77 R=1.57
stellar
ellipsoidal only
back of star
flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
orbital phase

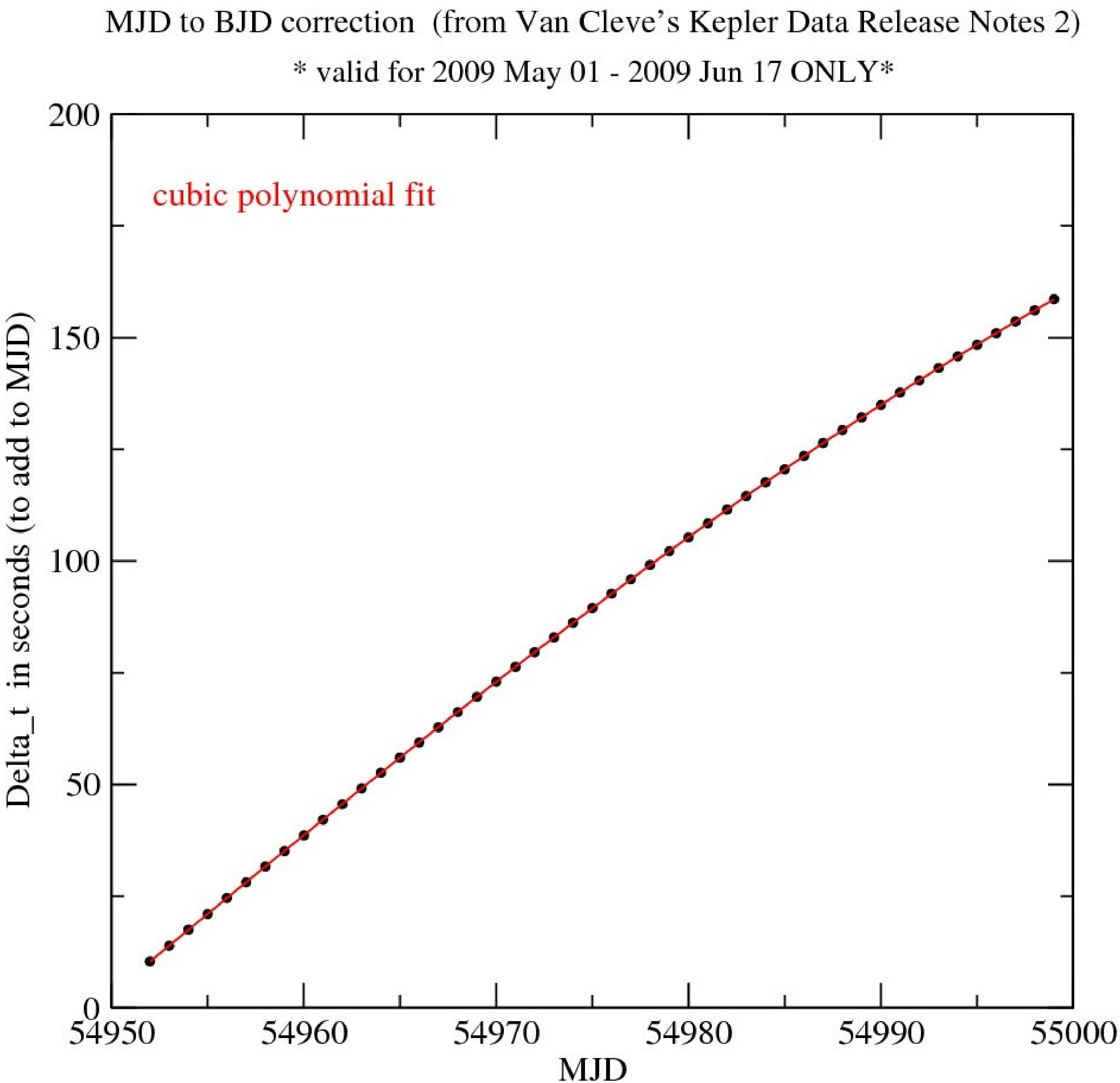
orbital phase reflection example

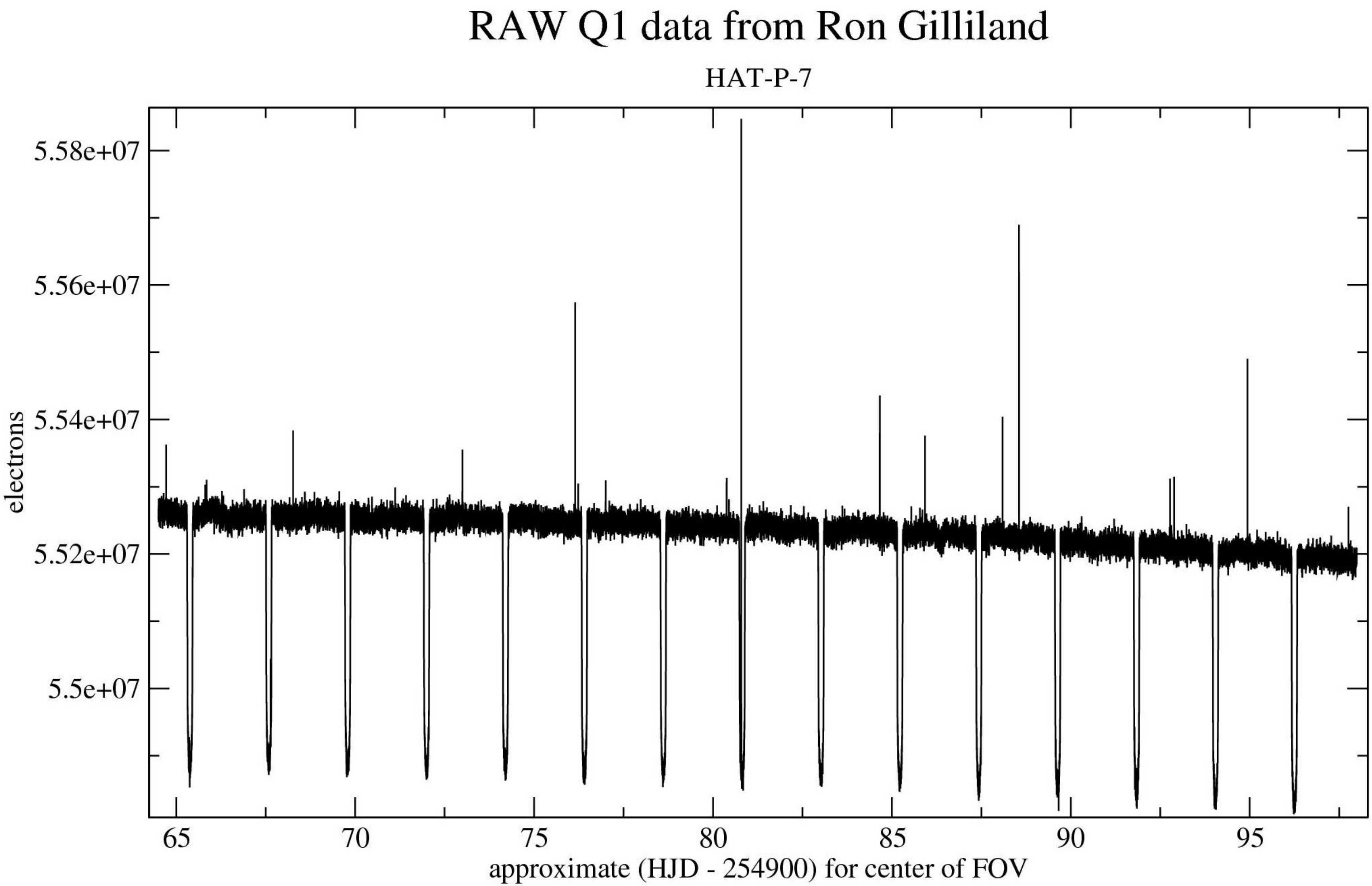
i=81.9 P=2.20 d ; Star: T=6350 M=2.0 R=1.84 ; Planet: M=1.77 R=1.57



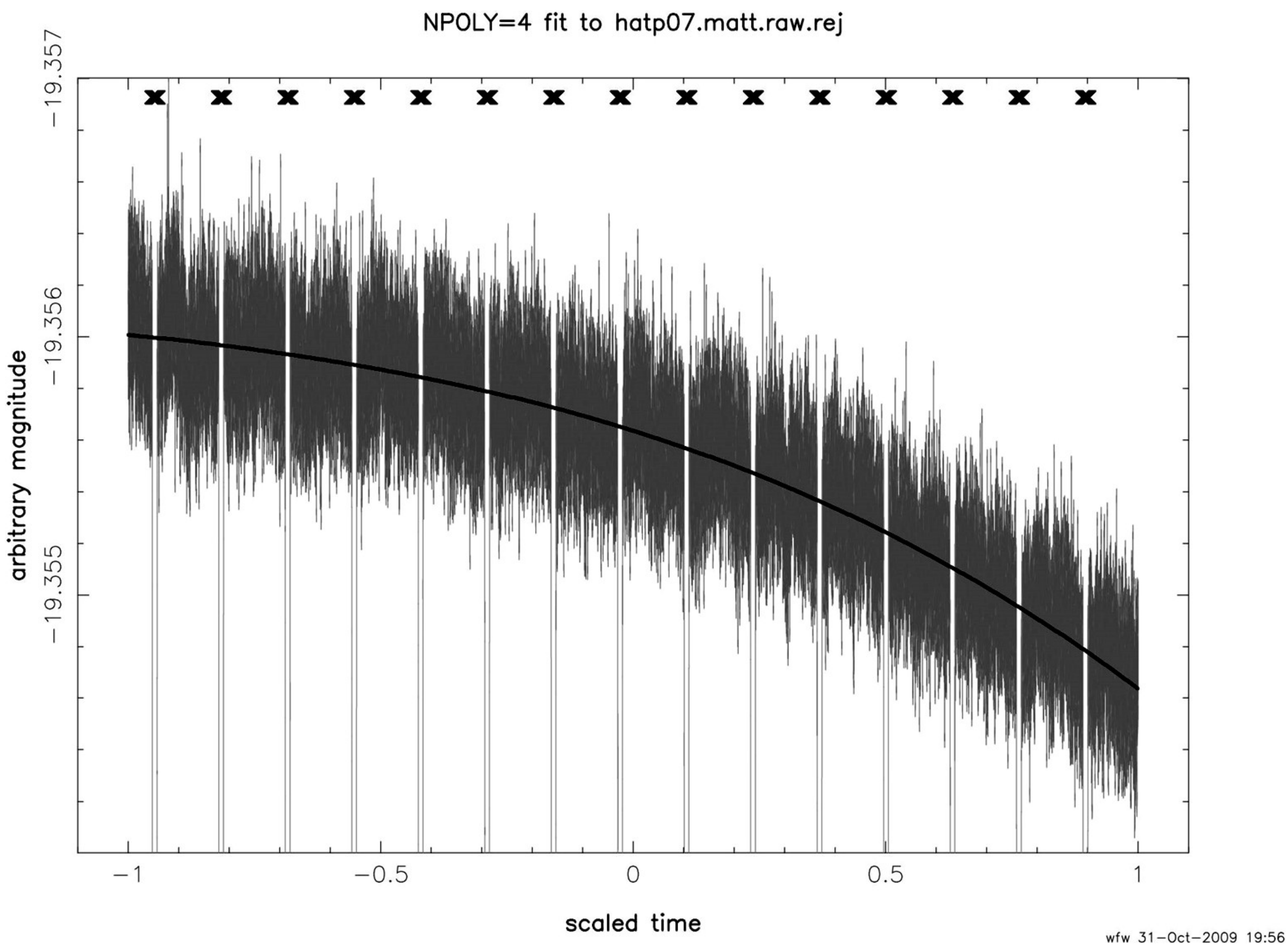


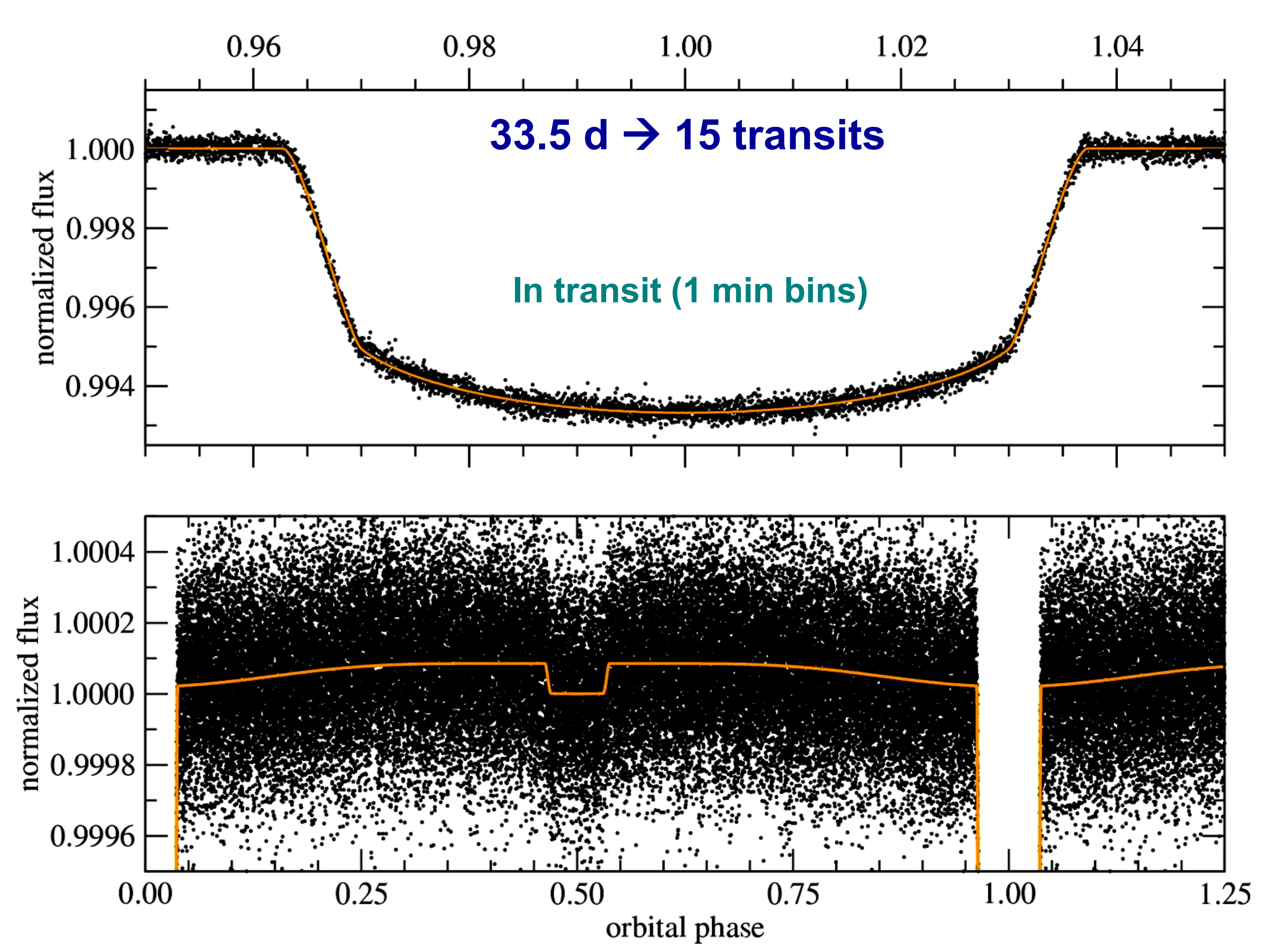
orbital phase reflection example
i=81.9 P=2.20 d ; Star: T=6350 M=2.0 R=1.84 ; Planet: M=1.77 R=1.57
T planet
= 2620 K
albedo=0.8
albedo=0.6
albedo=0.33
albedo=0.0
irradiated face of planet
isothermal planet
heated face of star!
stellar ellipsoidal only
night side of planet only
back of star only
flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
orbital phase

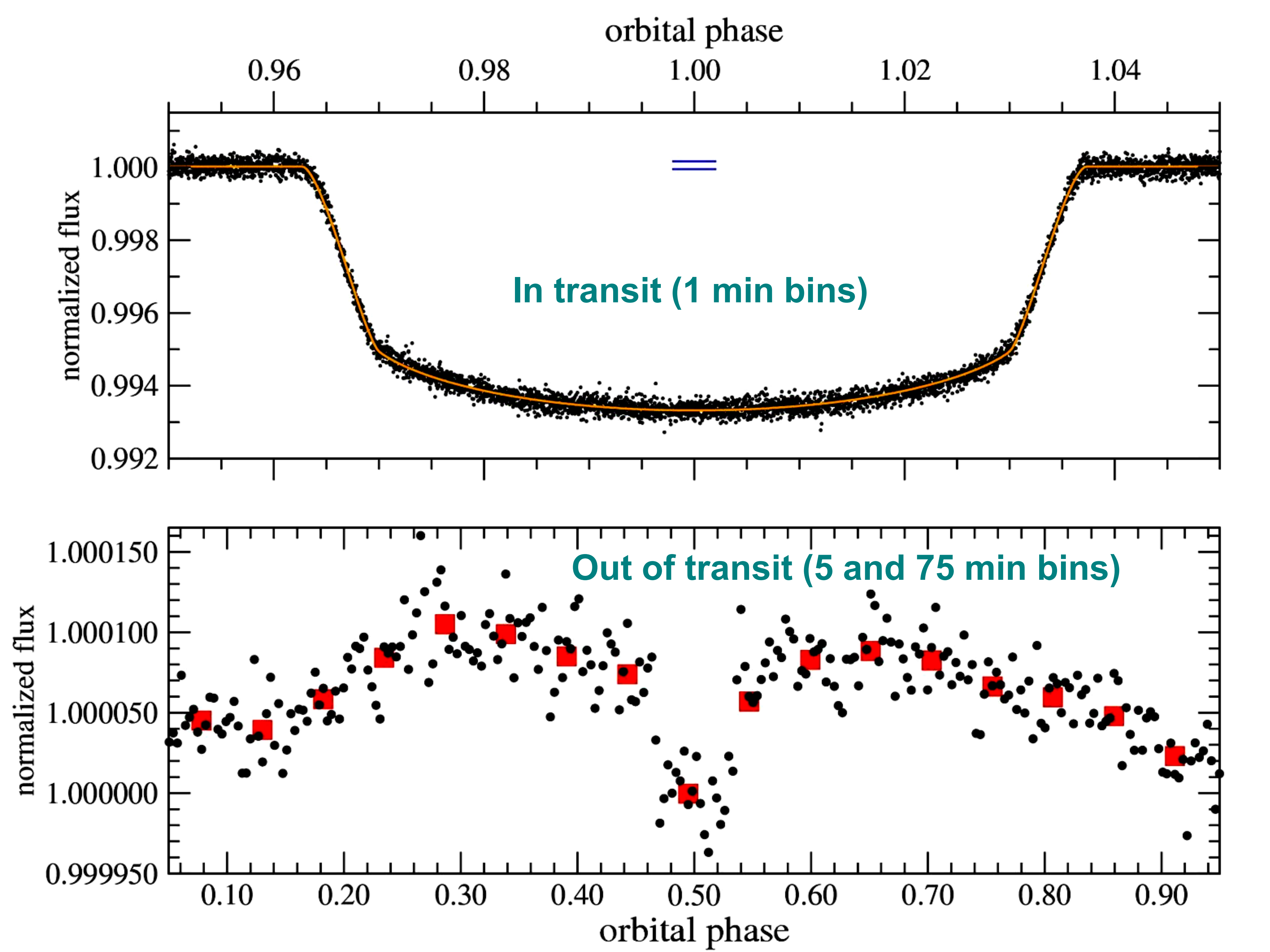

MJD to BJD correction (from Van Cleve's Kepler Data Release Notes 2)
* valid for 2009 May 01 - 2009 Jun 17 ONLY*
cubic polynomial fit
Delta_t in seconds (to add to MJD)
0
50
100
150
200
54950
54960
54970
54980
54990
55000
MJD



RAW Q1 data from Ron Gilliland
HAT-P-7
electrons
5.58e+07
5.56e+07
5.54e+07
5.52e+07
5.5e+07
65
70
75
80
85
90
95
approximate (HJD - 254900) for center of FOV

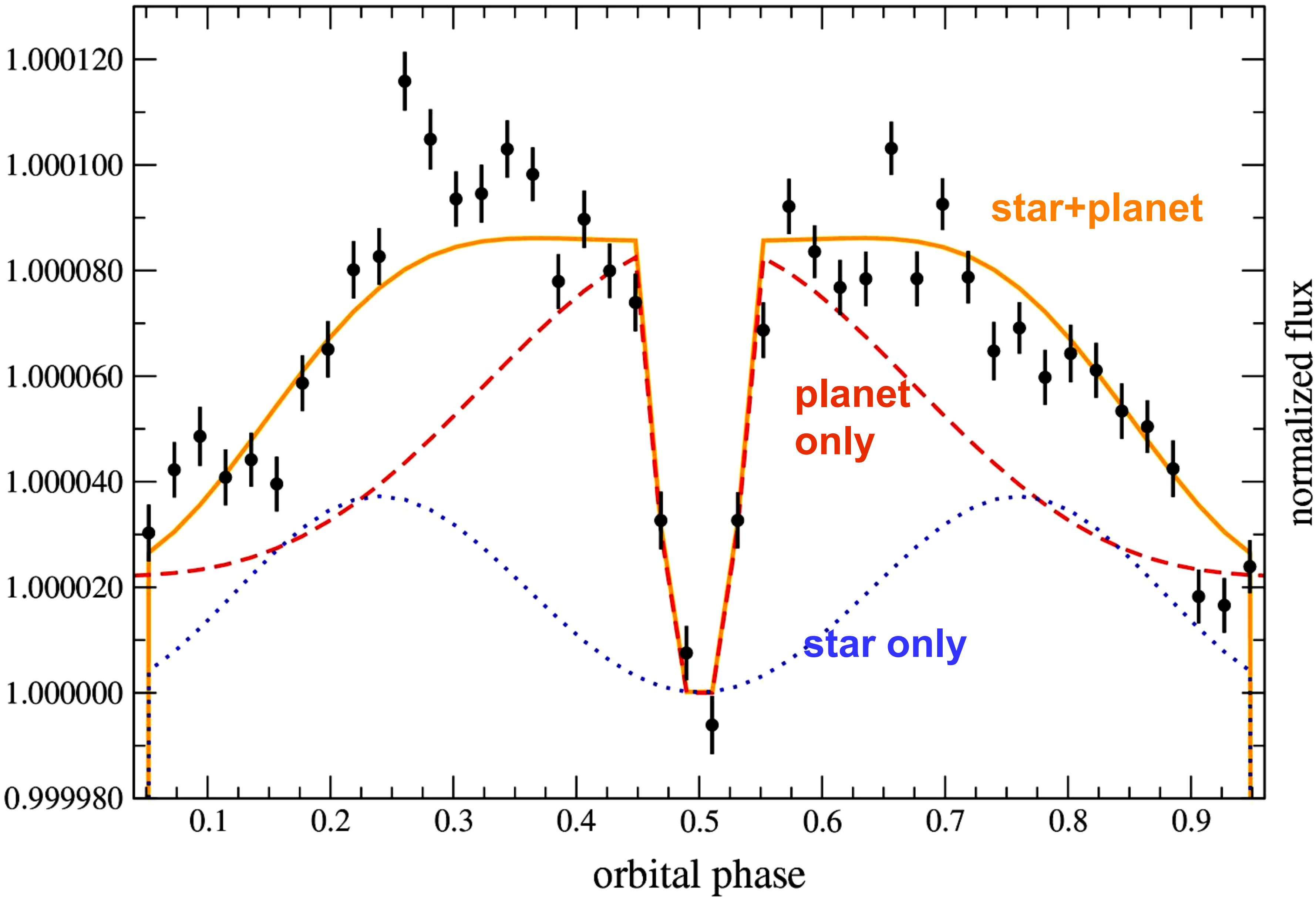

NPOLY=4 fit to hatp07.matt.raw.rej
−19.357
−19.356
−19.355
arbitrary magnitude
−1
−0.5
0
0.5
1
scaled time
wfw 31−Oct−2009 19:56


33.5 d → 15 transits
In transit (1 min bins)
normalized flux
1.000
0.998
0.996
0.994
0.96
0.98
1.00
1.02
1.04
normalized flux
1.0004
1.0002
1.0000
0.9998
0.9996
0.00
0.25
0.50
0.75
1.00
1.25
orbital phase

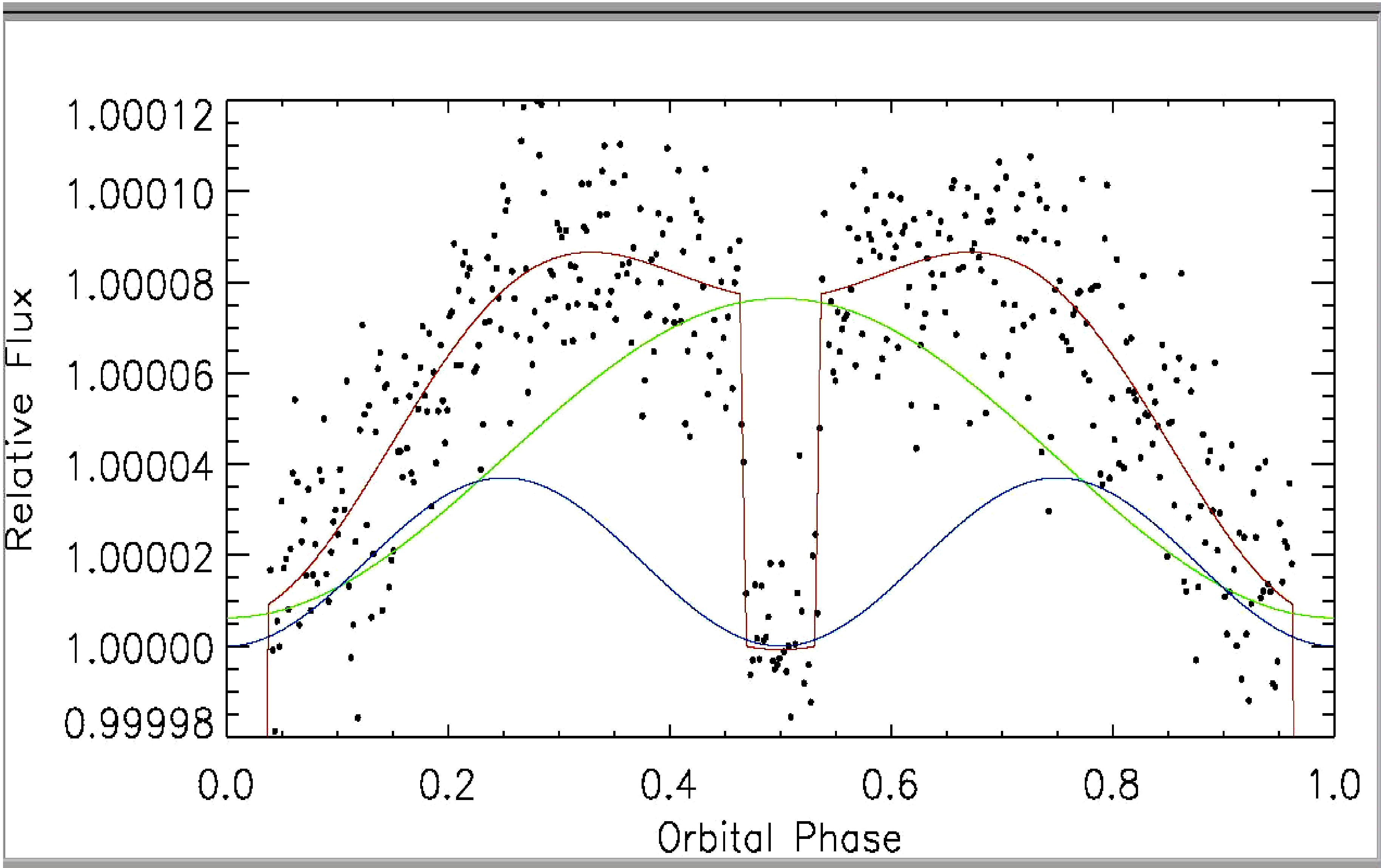


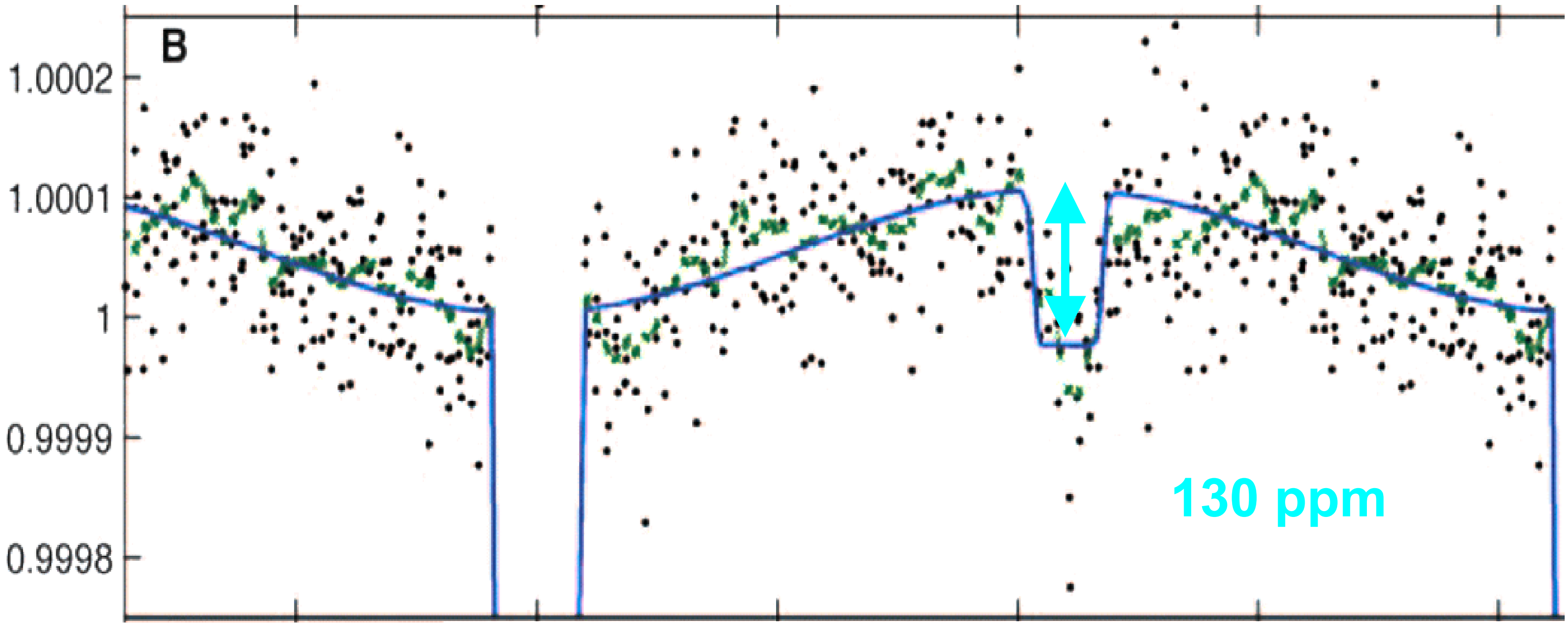
orbital phase
0.96
0.98
1.00
1.02
1.04
1.000
0.998
0.996
0.994
0.992
normalized flux
In transit (1 min bins)
1.000150
1.000100
1.000050
1.000000
0.999950
normalized flux
Out of transit (5 and 75 min bins)
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
orbital phase

Model fit (30 min bins)

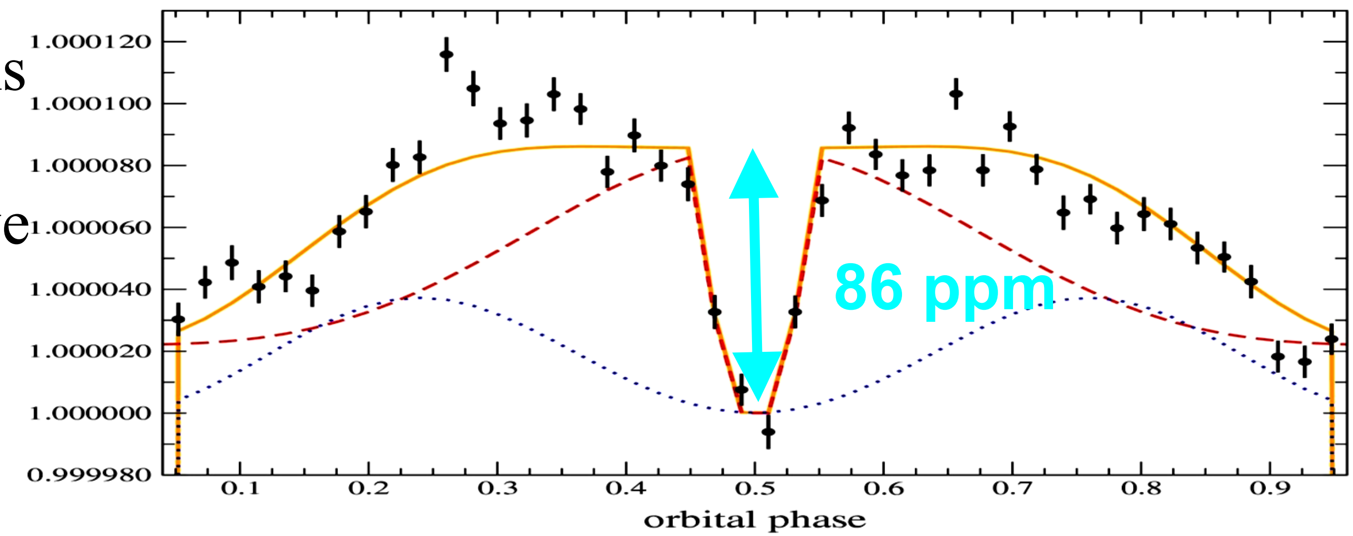


Joshua Carter: sanity check *par excellence* – wavelet 1/f de-noised LC, OOT fit with $\sin\varphi + \sin^2\varphi$





Ellipsoidal variations do not affect peak height of phase curve



T_{day} =

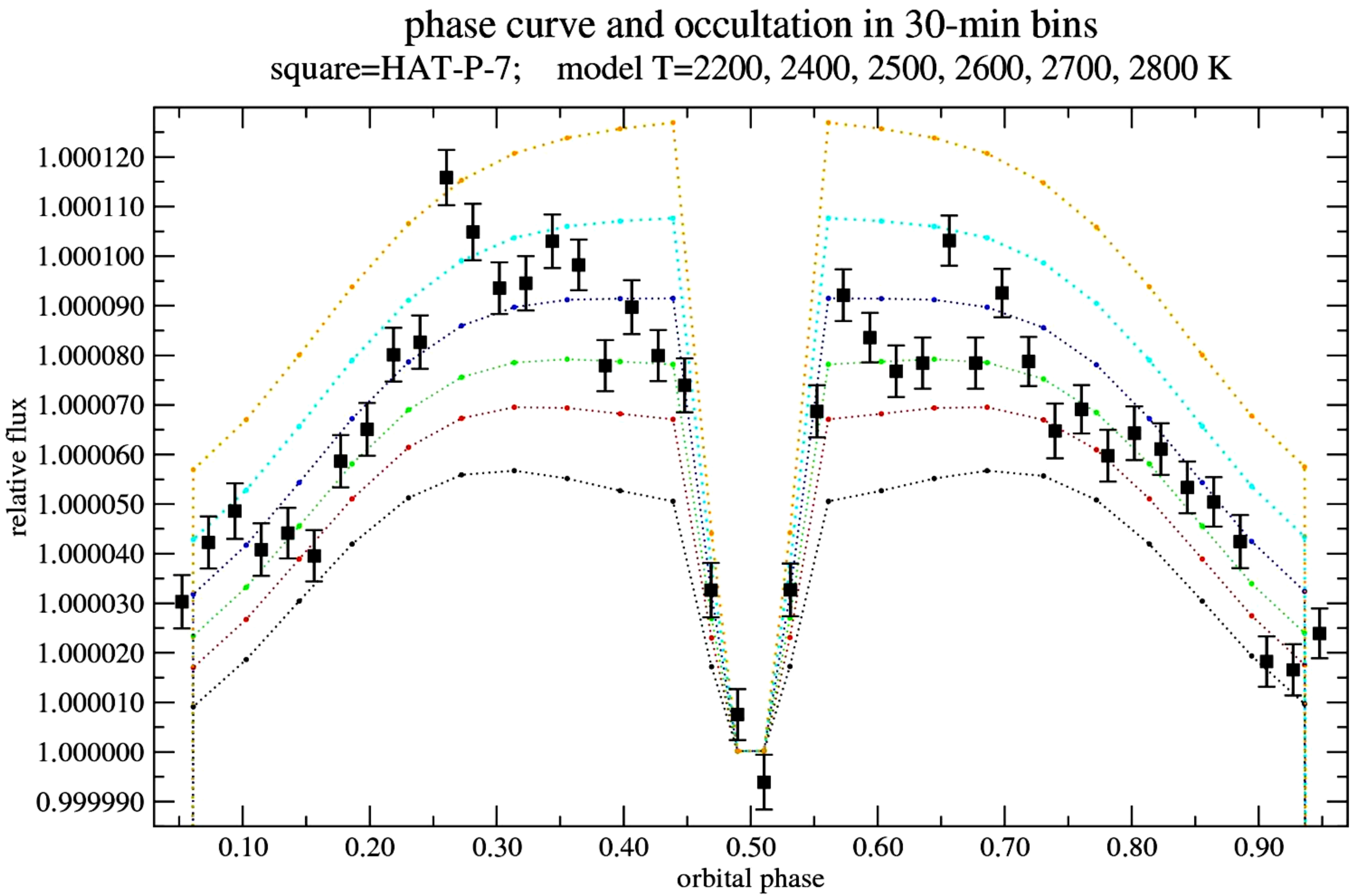
2560 +/- 100 K

vs.

2885 +/- 100 K

Parameter	Value	Uncertainty	Unit
T_*[a]	6350	—	K
M_*[b]	1.53	0.04	$M_\odot$
R_*[b]	1.98	0.02	$R_\odot$
K_*[c]	212	5	m s^{-1}
Orbital inclination, i	83.1	0.5	degrees
Orbital period, P	2.204733	0.000010	days
Star-to-planet radius, R_*/Rp	12.85	0.05	
limb dark coefficient x	0.58	0.08	
limb dark coefficient y	0.21	0.13	
Mass of planet, Mp	1.82	0.03	M_{Jup}
Radius of planet, Rp	1.50	0.02	R_{Jup}
Semimajor axis, a	8.22	0.02	$R_\odot$
Bolometric (heat) albedo, A_{bol}	0.57	0.05	
Tp (night side)	2570	95	K
Tp (average day side)	2885	100	K

geometric A_g =0.18



phase curve and occultation in 30-min bins
square=HAT-P-7; model T=2200, 2400, 2500, 2600, 2700, 2800 K
relative flux
1.000120
1.000110
1.000100
1.000090
1.000080
1.000070
1.000060
1.000050
1.000040
1.000030
1.000020
1.000010
1.000000
0.999990
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
orbital phase

Conclusions:

First detection of exoplanet-induced ellipsoidal variation

amplitude = 37 ppm (= 34 micromag)

→ illustrates precision of Kepler (Earth-Sun transit = 84 ppm)

Modeling ellipsoidal variations:

→ more accurate planet phase-emission measurements (therefore T, albedo, etc)

→ constrains mass ratio + inclination

→ properties of stellar envelope (radiative/convective)

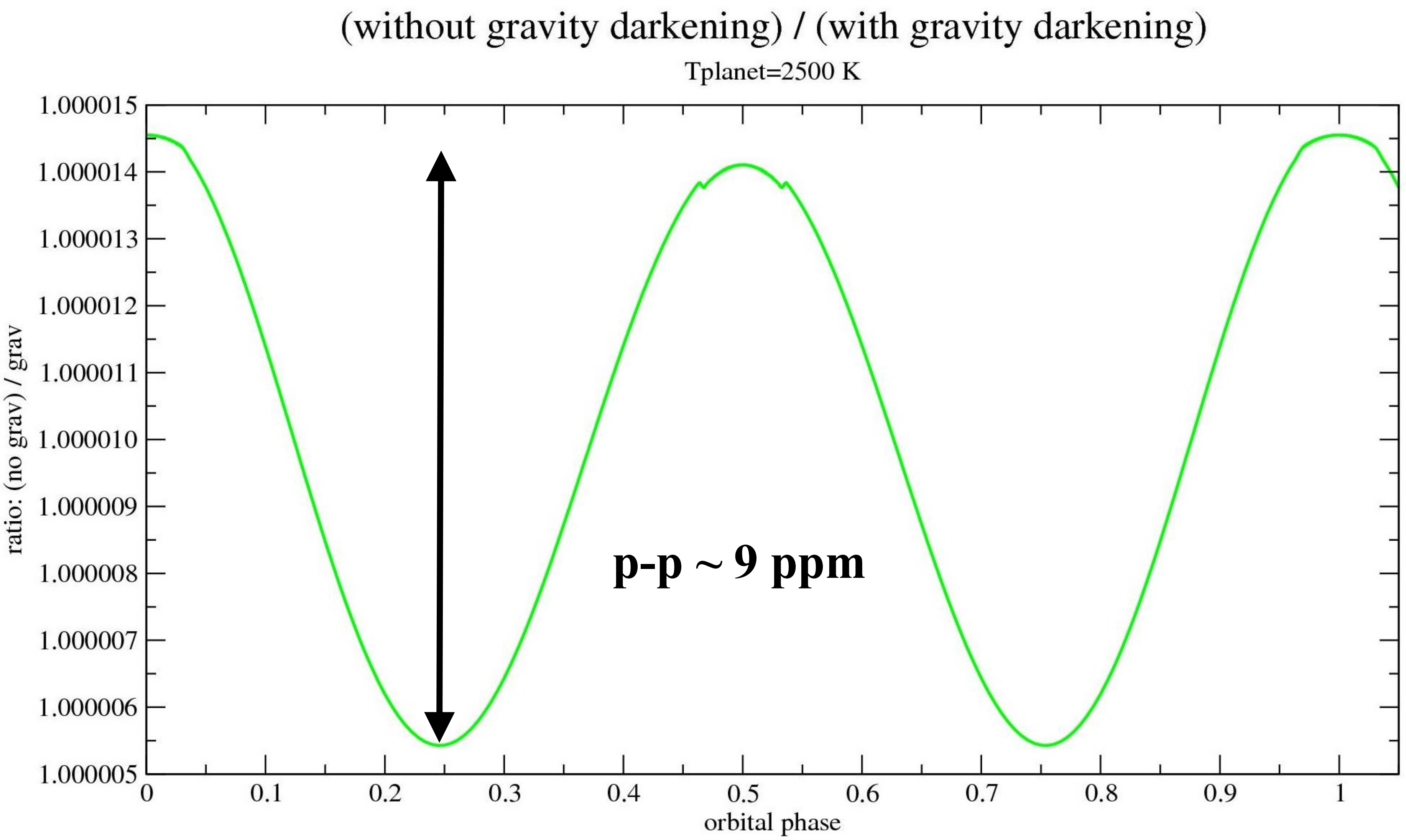
→ lag might lead to info on tidal energy dissipation [Q]

Caveats:

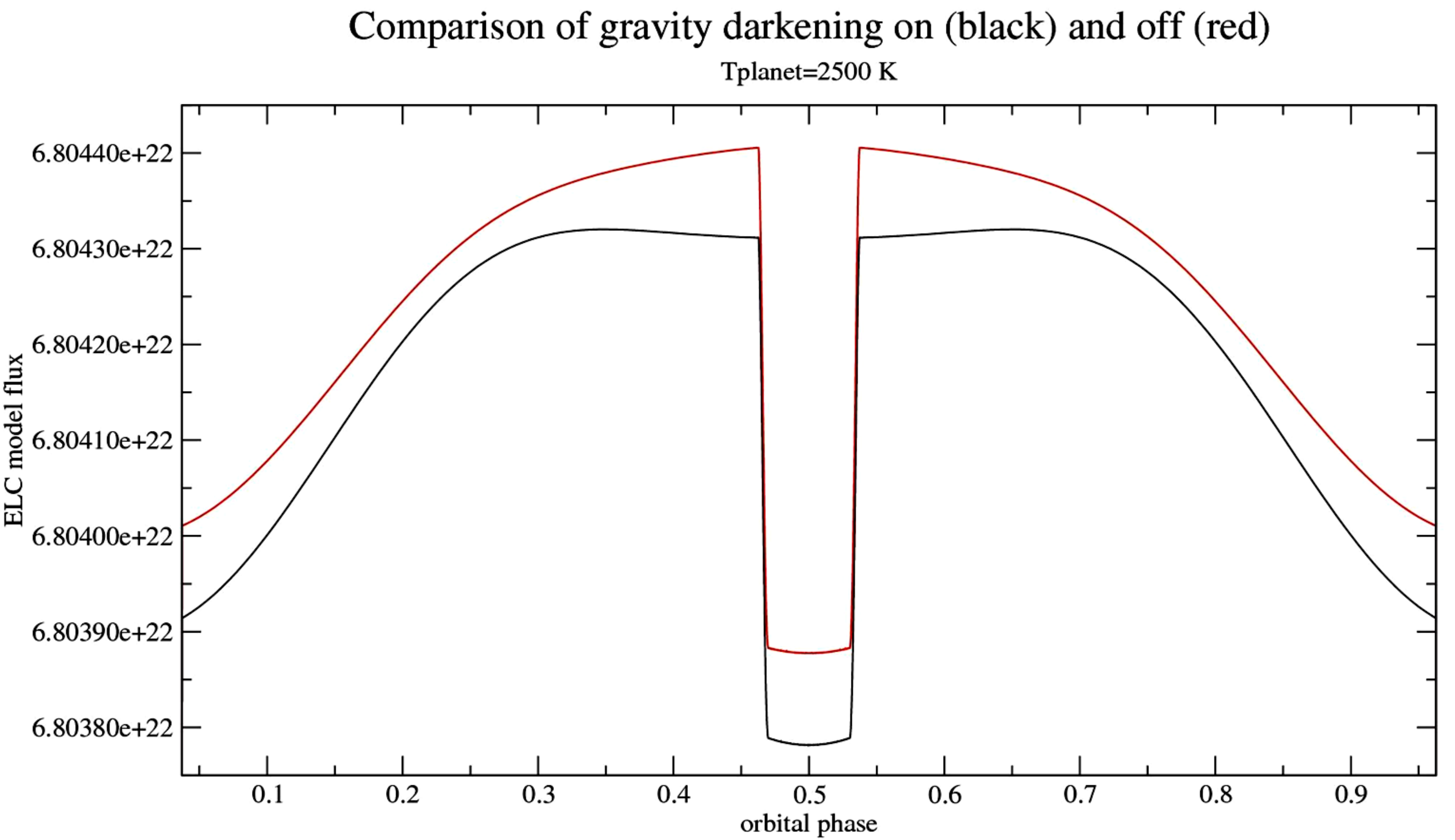
→ in general: star not tidally locked – not quite Roche potential

→ HAT-P-7: star spin and planet orbit axes not aligned (R-M effect) [Winn et al. 2009, Narita et al. 2009]

Importance of Gravity Darkening



Importance of Gravity Darkening



→ sensitivity to gravity darkening; and strong change in gravity darkening exponent at slightly higher temperature (β~0.08 → 0.25)

→ equilibrium tide model (Pfhal et al.) ==> sensitivity to stellar envelope (convective vs. radiative) changes ellipsoidal amplitude

→ overestimate T_{day}, since scattering could be present

→ T_{night} = 2570 K is too hot! T_{night} > Teq= 2213 K.

→ Why isn't stellar better than BB model??

→ monochromatic evaluation of BB at 6000 A instead of integration over bandpass

→ planet atmospheric phenomena

Note: ELC uses bolometric or *heat albedo*, not Bond albedo