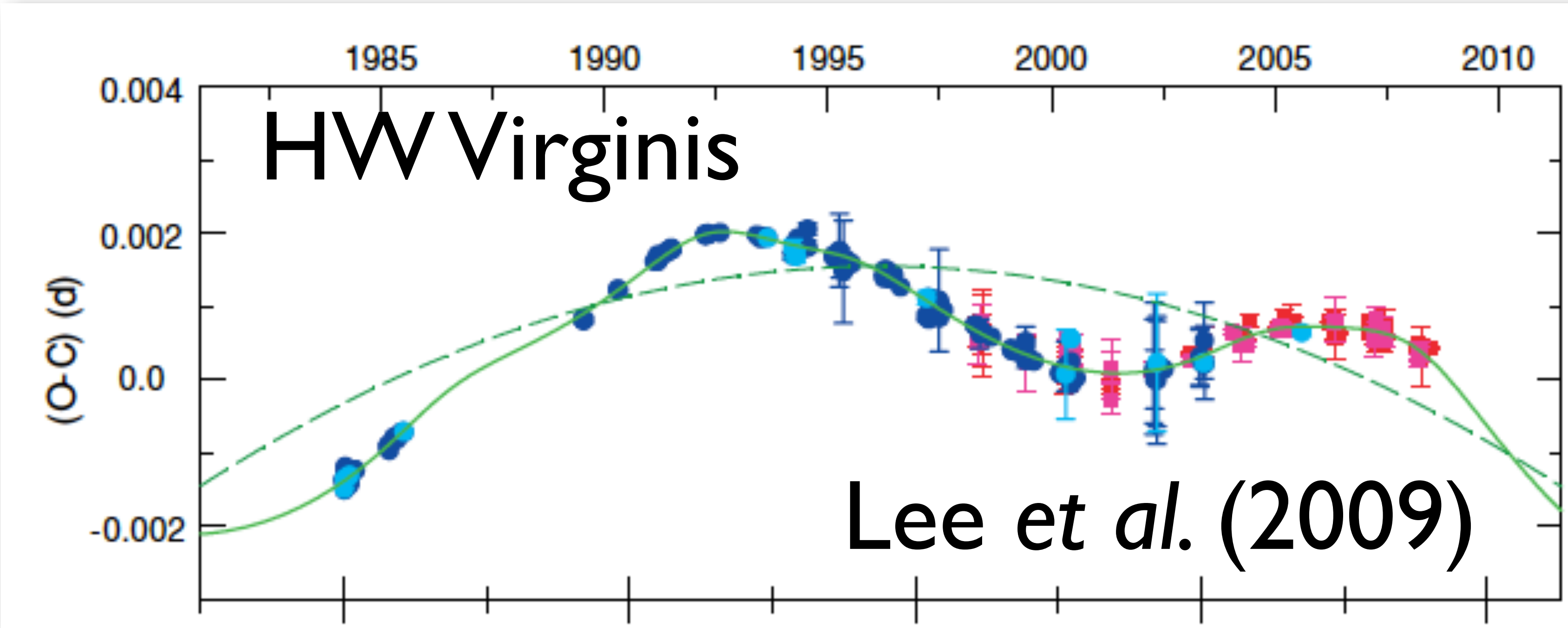
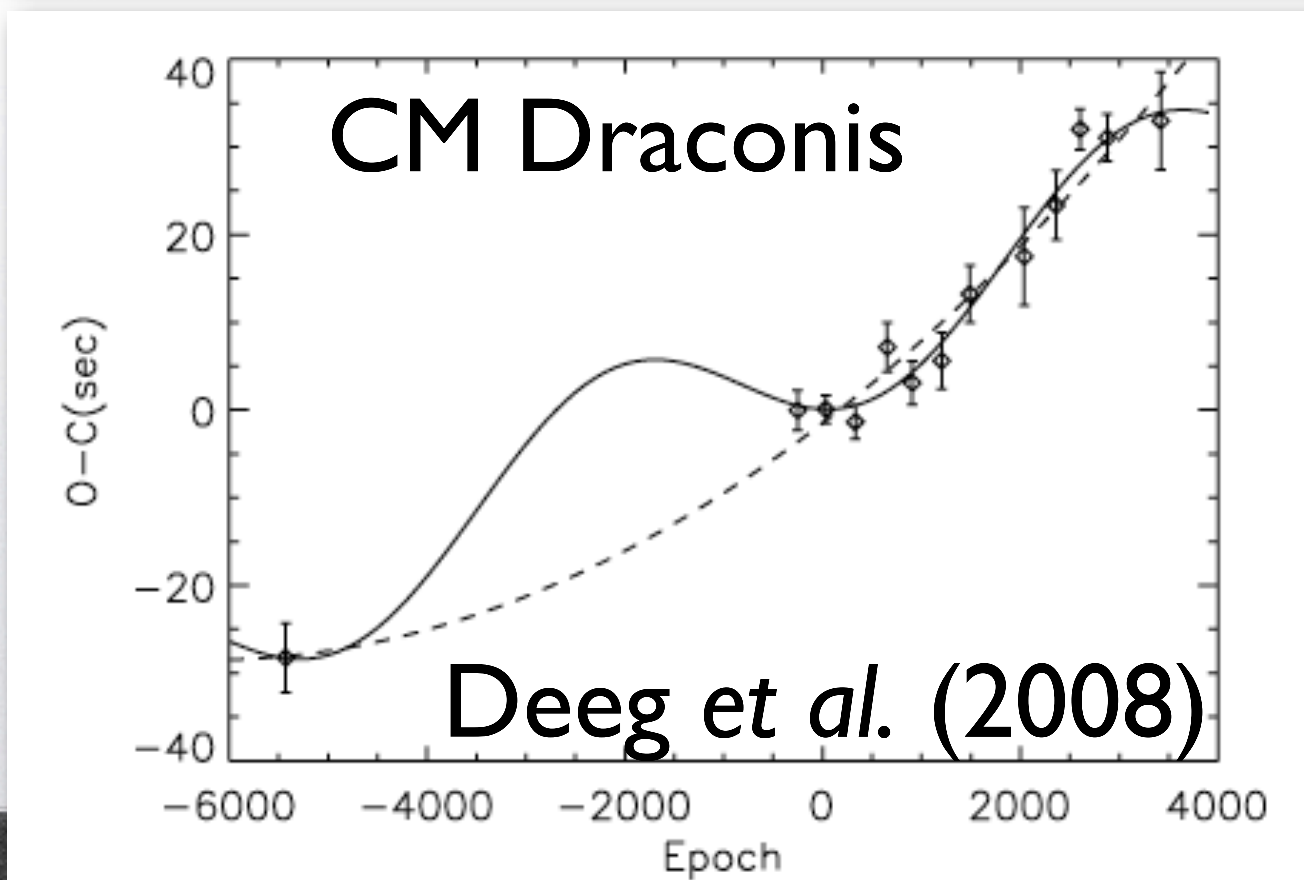
The Search for *Transiting* Circumbinary Planets

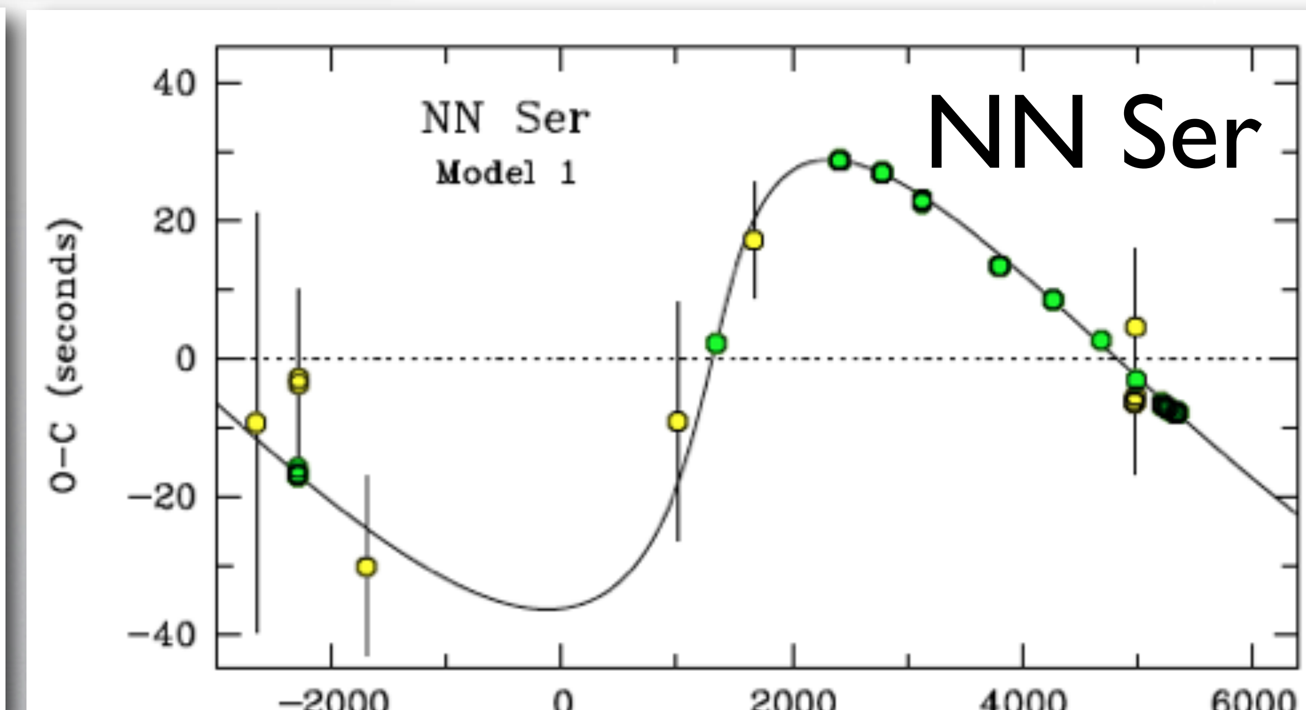
Josh Carter
Hubble Fellow
(Smithsonian Astrophysical Observatory)

The Search for Circumbinary Planets



Eclipse Timing Variations (ETVs) due to geometric effect ("Light-Time Effect")





Beuermann *et al.* (2010)

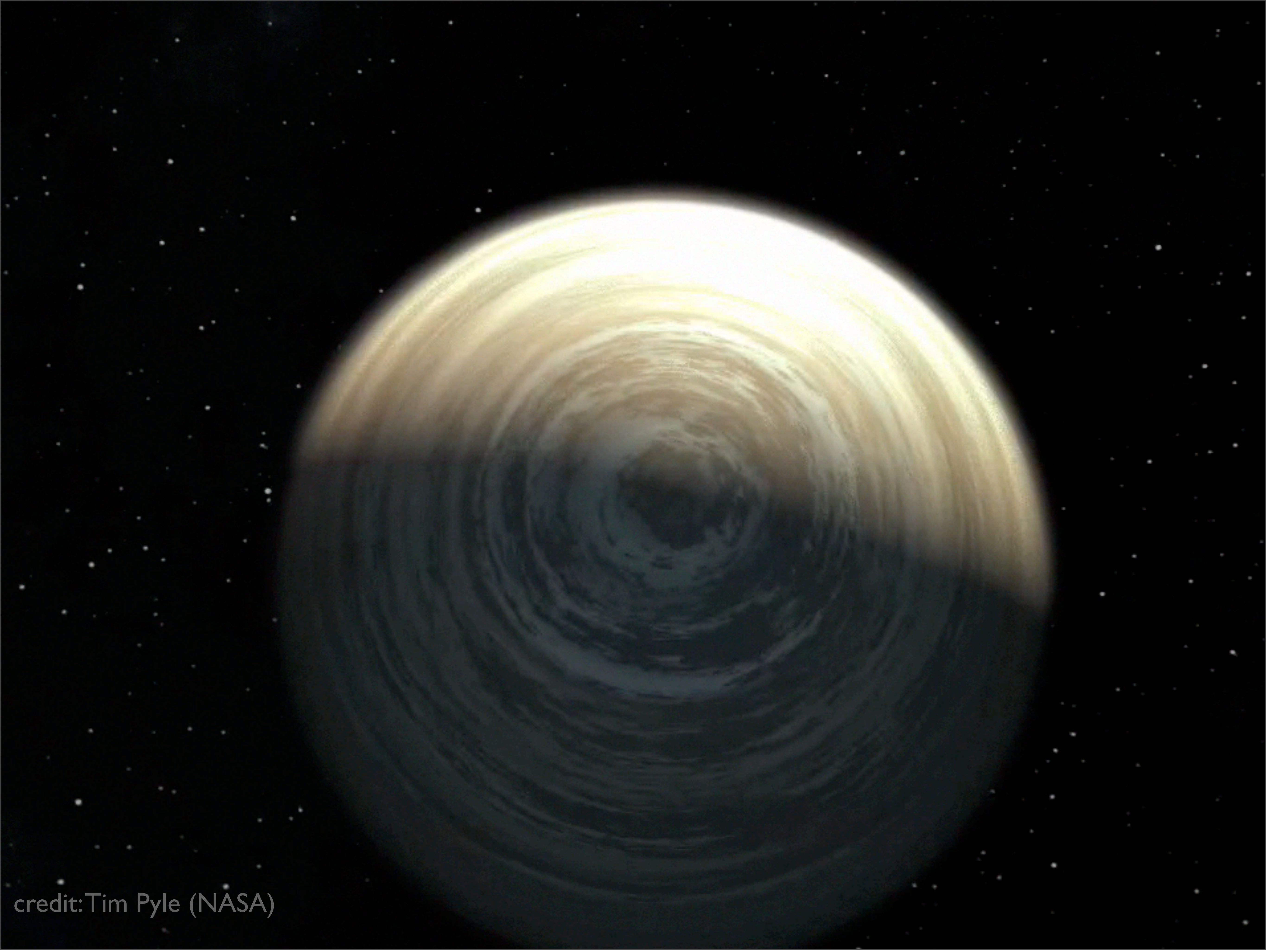
The Search for *Transiting* Circumbinary Planets

- A *transiting* system would bolster our detection confidence and precisely constrain the planetary properties

(e.g., Schneider & Chevreton 1990; Schneider 1994, Schneider & Doyle 1995; Deeg, Doyle et al. 1998; Ofir 2008)

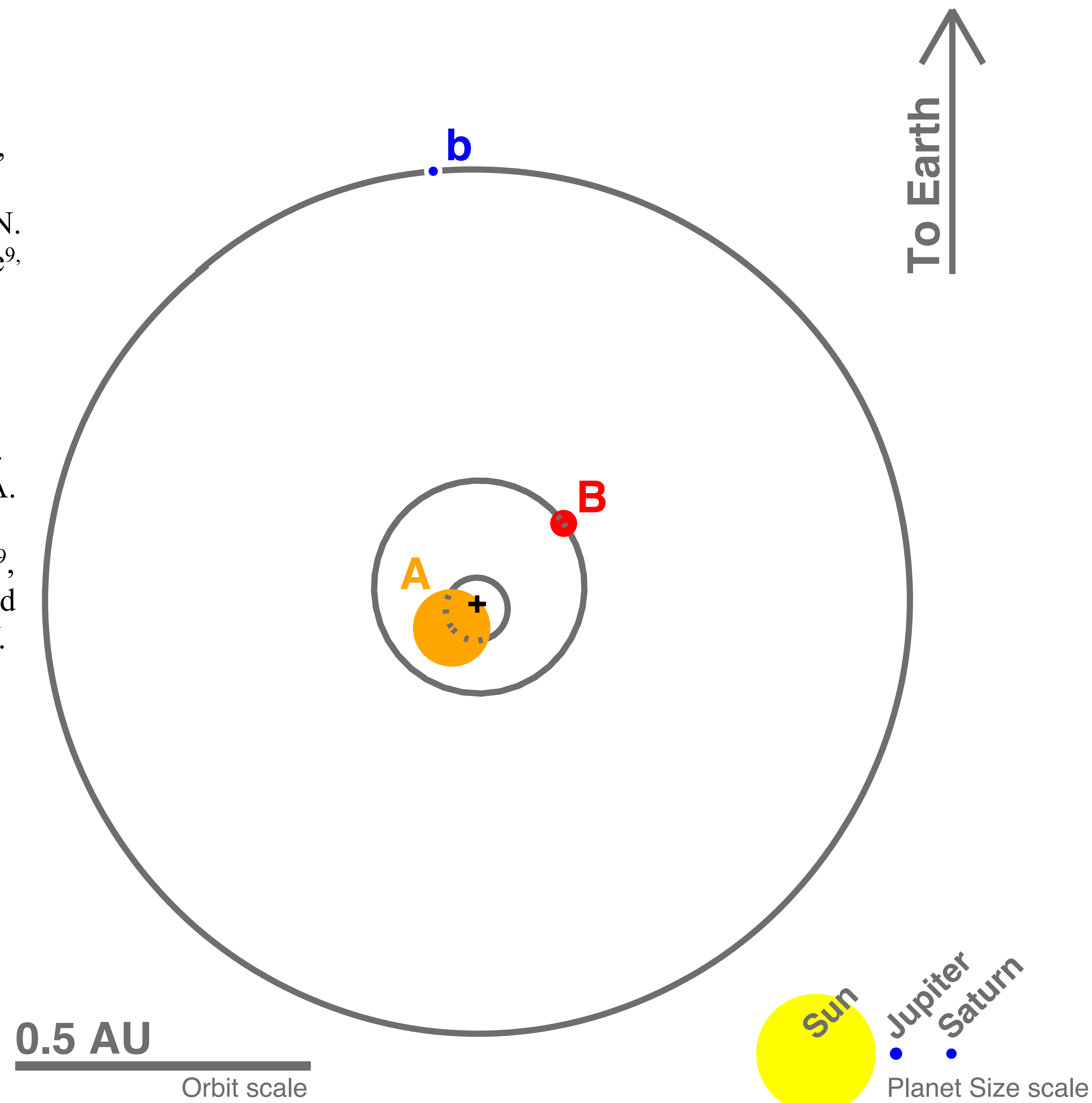
The Search for *Transiting* Circumbinary Planets

Josh Carter, ESS-II (September 15, 2011)

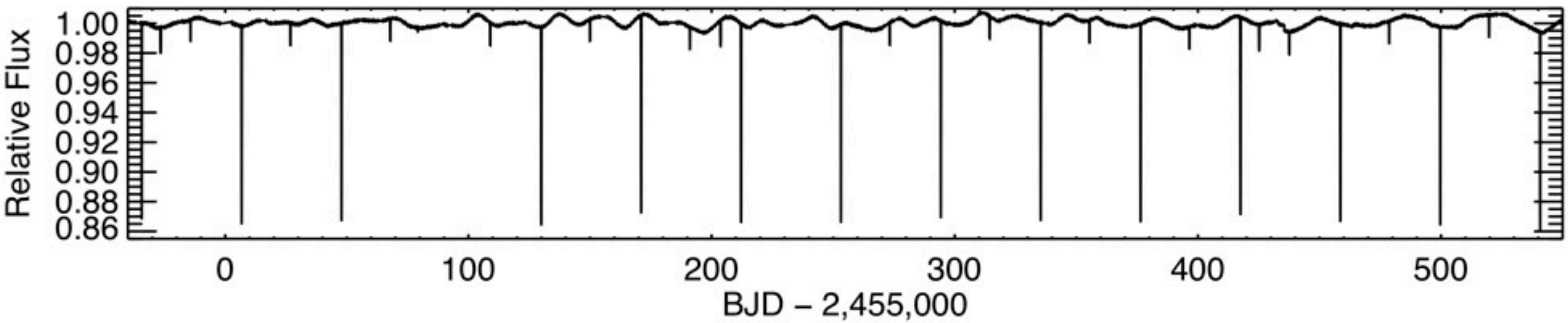

credit: Tim Pyle (NASA)

Kepler-16: A Transiting Circumbinary Planet

Laurance R. Doyle[1], Joshua A. Carter[2], Daniel C. Fabrycky[3], Robert W. Slawson[1], Steve B. Howell[4], Joshua N. Winn[5], Jerome A. Orosz[6], Andrej Prˇsa[7], William F. Welsh[6], Samuel N. Quinn[8], David Latham[8], Guillermo Torres[8], Lars A. Buchhave[9,10], Geoffrey W. Marcy[11], Jonathan J. Fortney[12], Avi Shporer[13,14], Eric B. Ford[15], Jack J. Lissauer[4], Darin Ragozzine[2], Michael Rucker[16], Natalie Batalha[16], Jon M. Jenkins[1], William J. Borucki[4], David Koch[4], Christopher K. Middour[17], Jennifer R. Hall[17], Sean McCauliff[17], Michael N. Fanelli[18], Elisa V. Quintana[1], Matthew J. Holman[8], Douglas A. Caldwell[1], Martin Still[18], Robert P. Stefanik[8], Warren R. Brown[8], Gilbert A. Esquerdo[8], Sumin Tang[8], Gabor Furesz[8,19], John C. Geary[8], Perry Berlind[20], Michael L. Calkins[20], Donald R. Short[21], Jason H. Steffen[22], Dimitar Sasselov[8], Edward W. Dunham[23], William D. Cochran[24], Alan Boss[25], Michael R. Haas[4], Derek Buzasi[26], Debra Fischer[27]

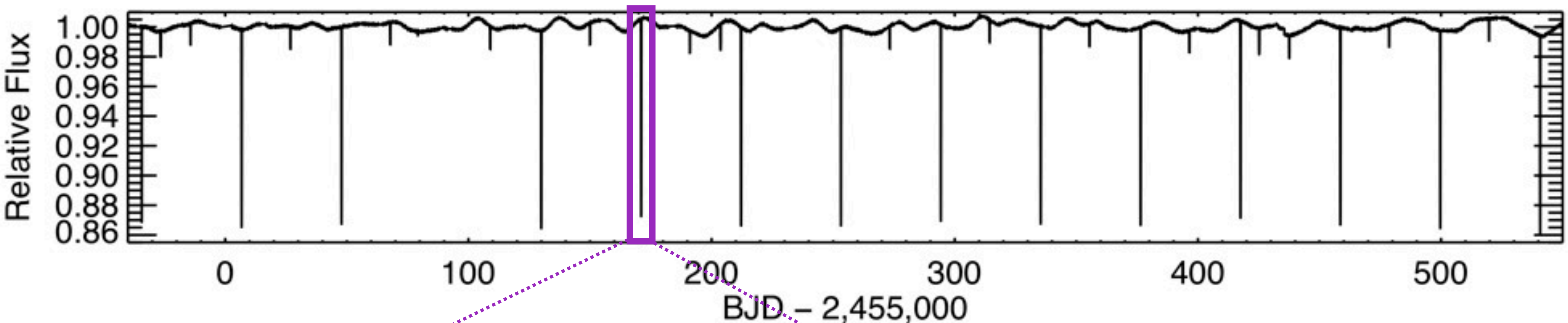


Kepler-16

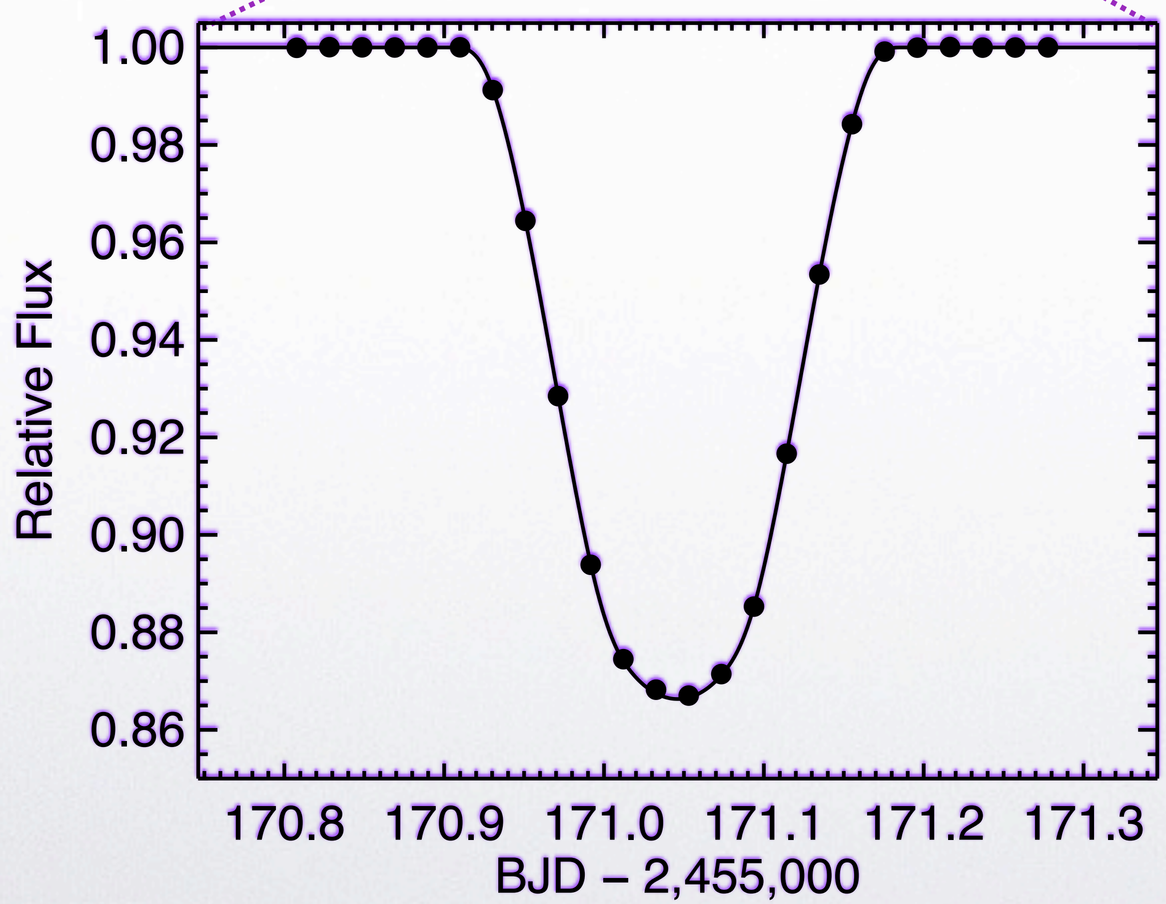


Relative Flux
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0
100
200
300
400
500
BJD – 2,455,000

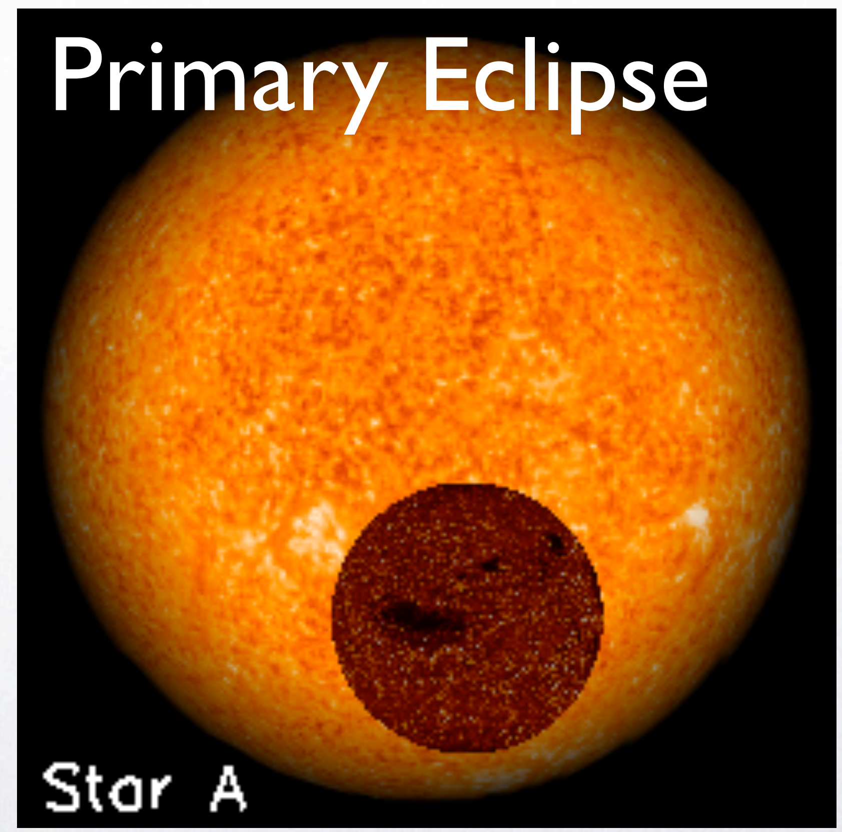
Kepler-16



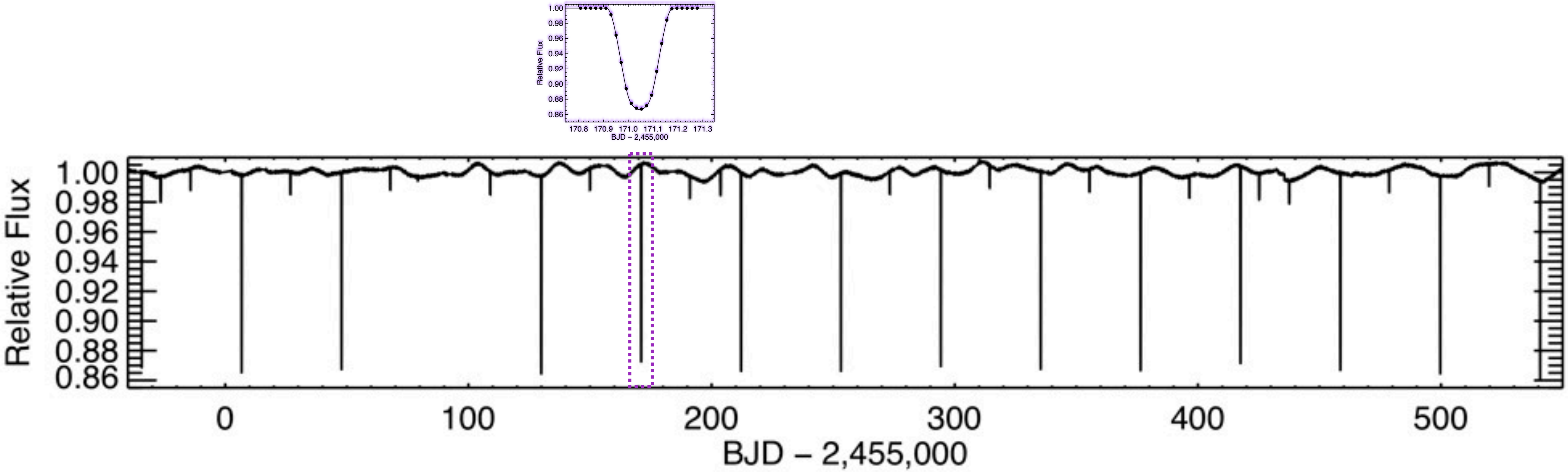
Relative Flux
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0
100
200
300
400
500
BJD – 2,455,000



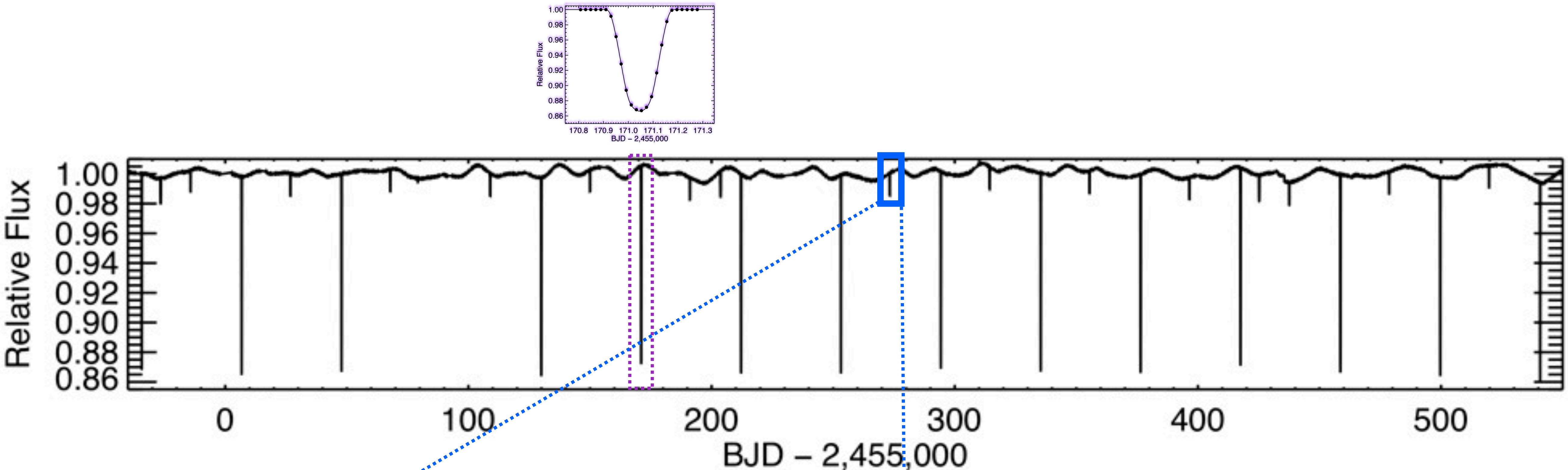
Relative Flux
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
170.8
170.9
171.0
171.1
171.2
171.3
BJD – 2,455,000

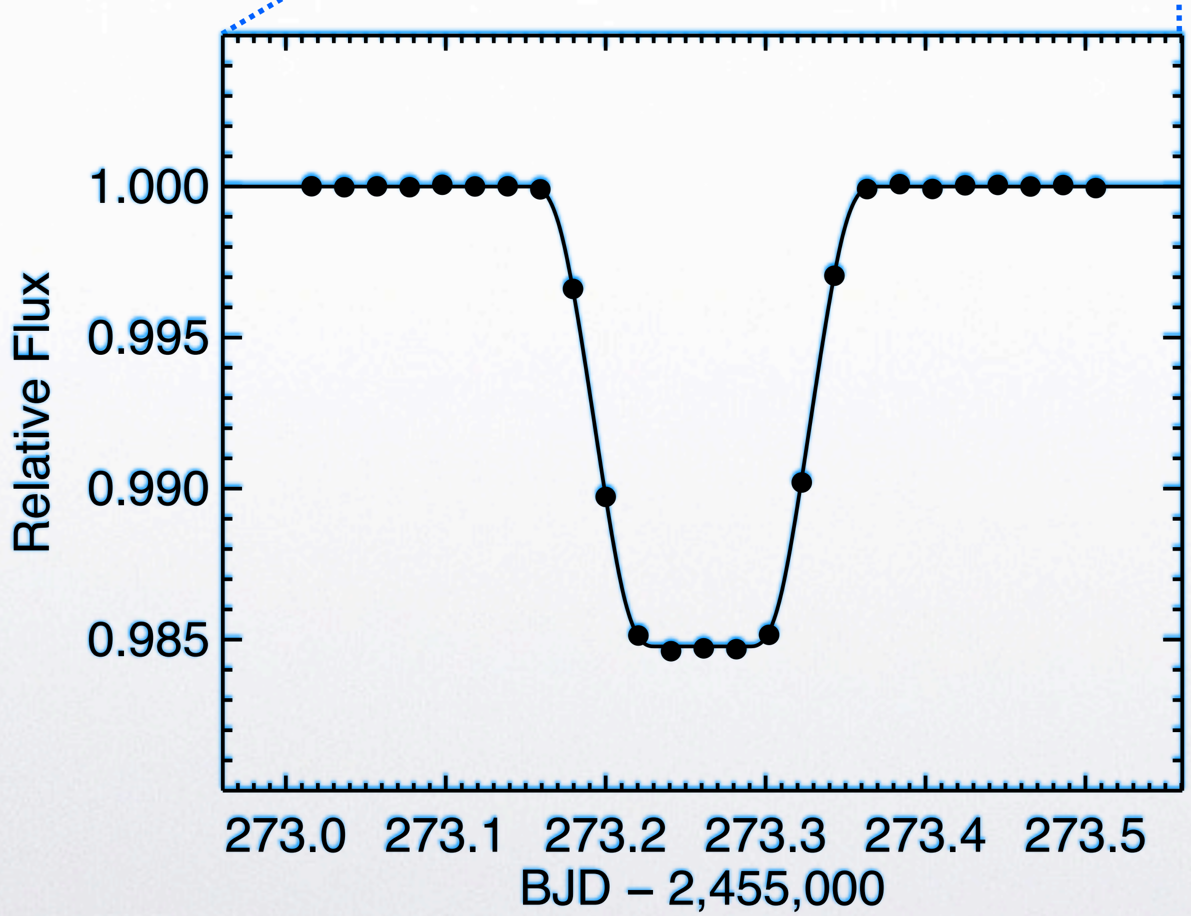


Primary Eclipse
Star A

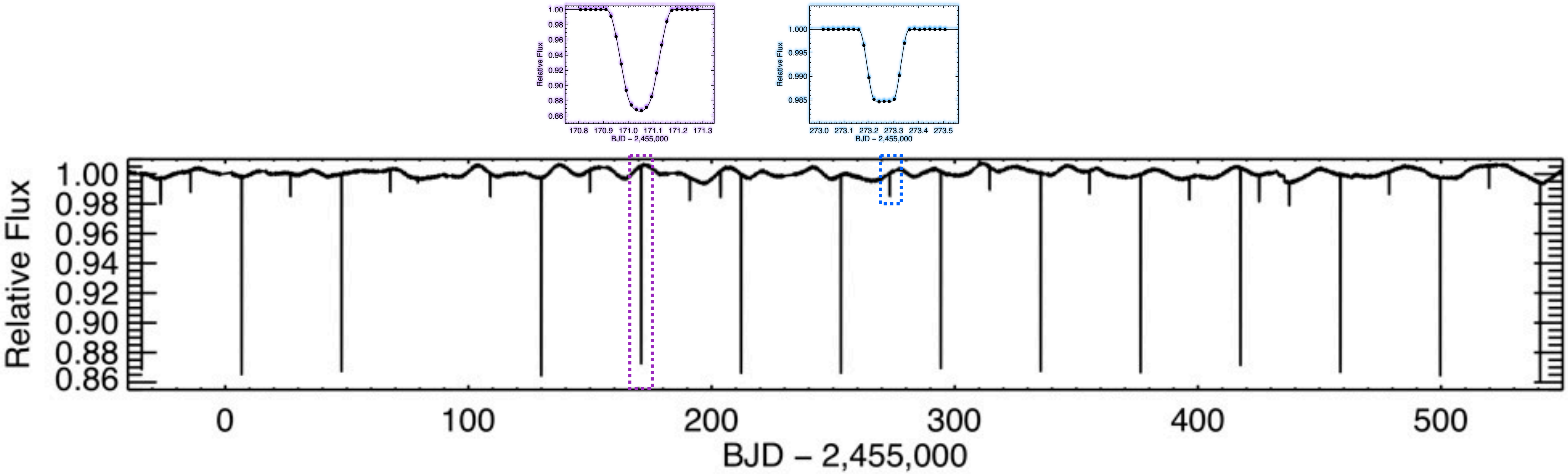


Relative Flux
BJD – 2,455,000
170.8 170.9 171.0 171.1 171.2 171.3
1.00 0.98 0.96 0.94 0.92 0.90 0.88 0.86
0 100 200 300 400 500

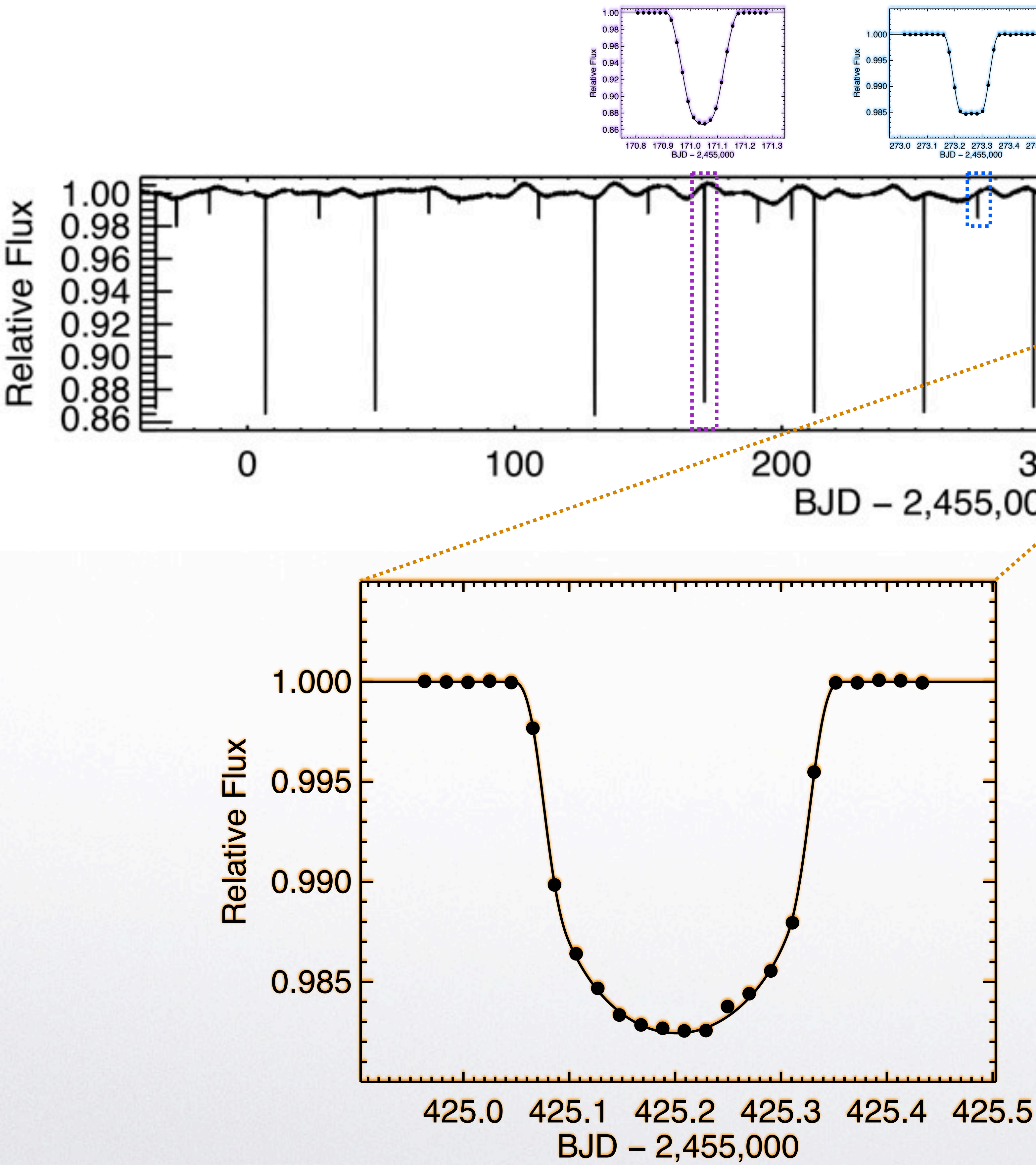

Relative Flux
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
170.8 170.9 171.0 171.1 171.2 171.3
BJD – 2,455,000
0
100
200
300
400
500
BJD – 2,455,000


Relative Flux
1.000
0.995
0.990
0.985
273.0 273.1 273.2 273.3 273.4 273.5
BJD – 2,455,000

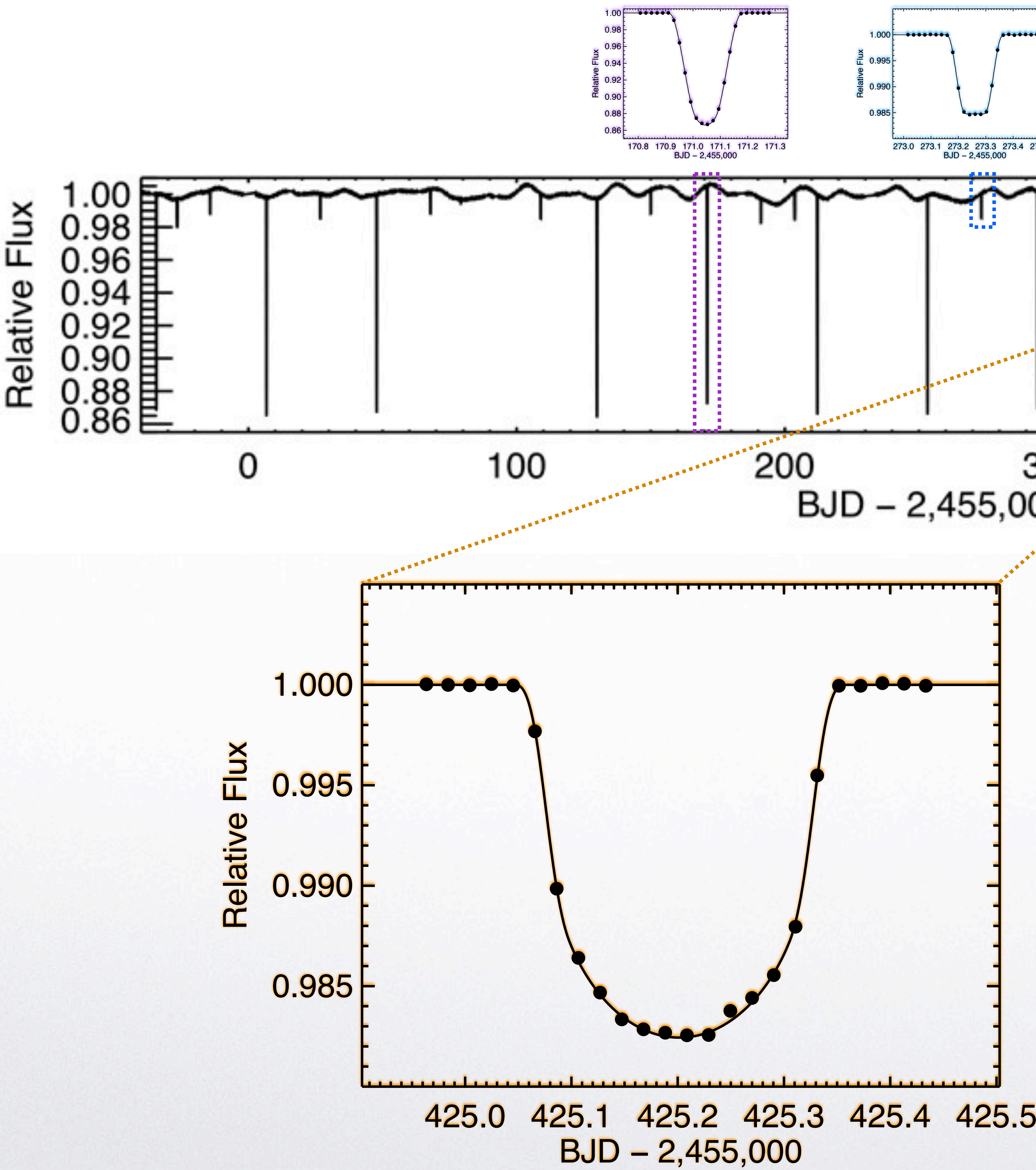

Secondary Eclipse
Star B



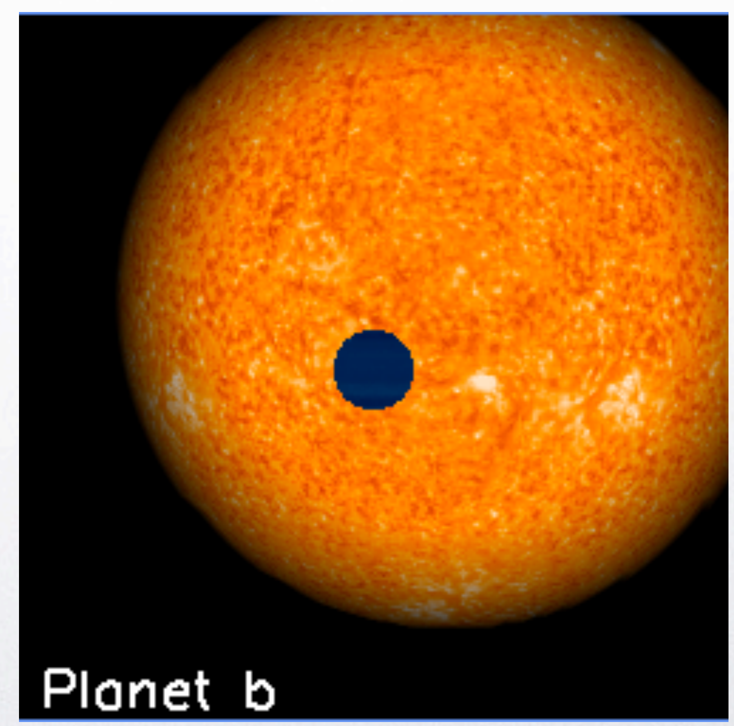
Relative Flux
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0
100
200
300
400
500
BJD – 2,455,000
170.8 170.9 171.0 171.1 171.2 171.3
BJD – 2,455,000
1.000
0.995
0.990
0.985
273.0 273.1 273.2 273.3 273.4 273.5
BJD – 2,455,000



Tertiary Eclipse!

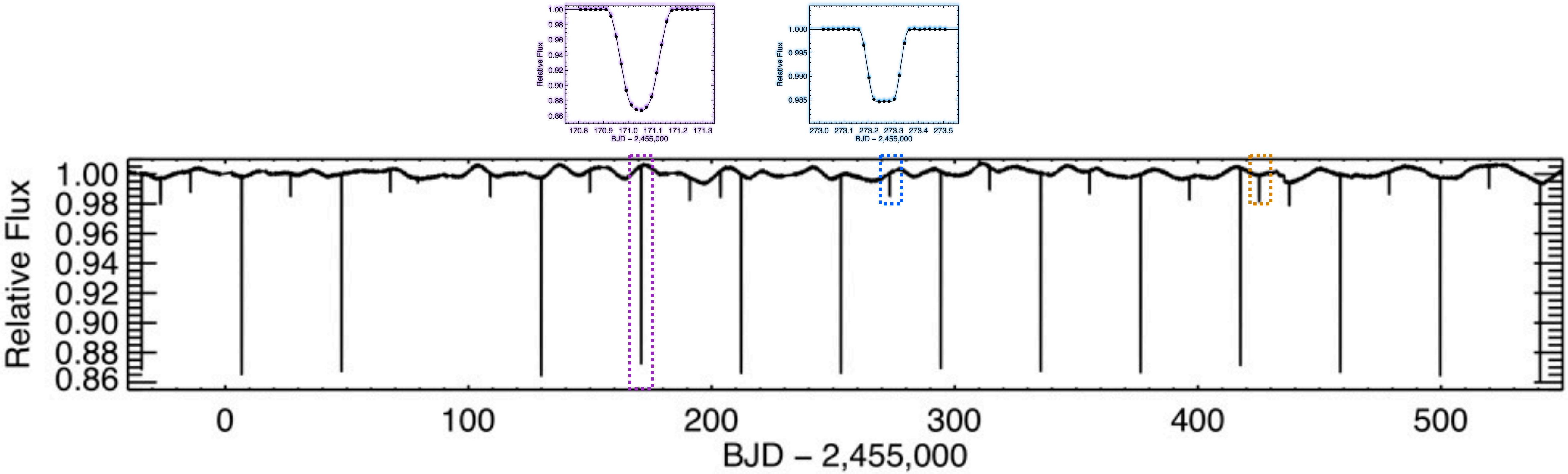


Tertiary Eclipse!

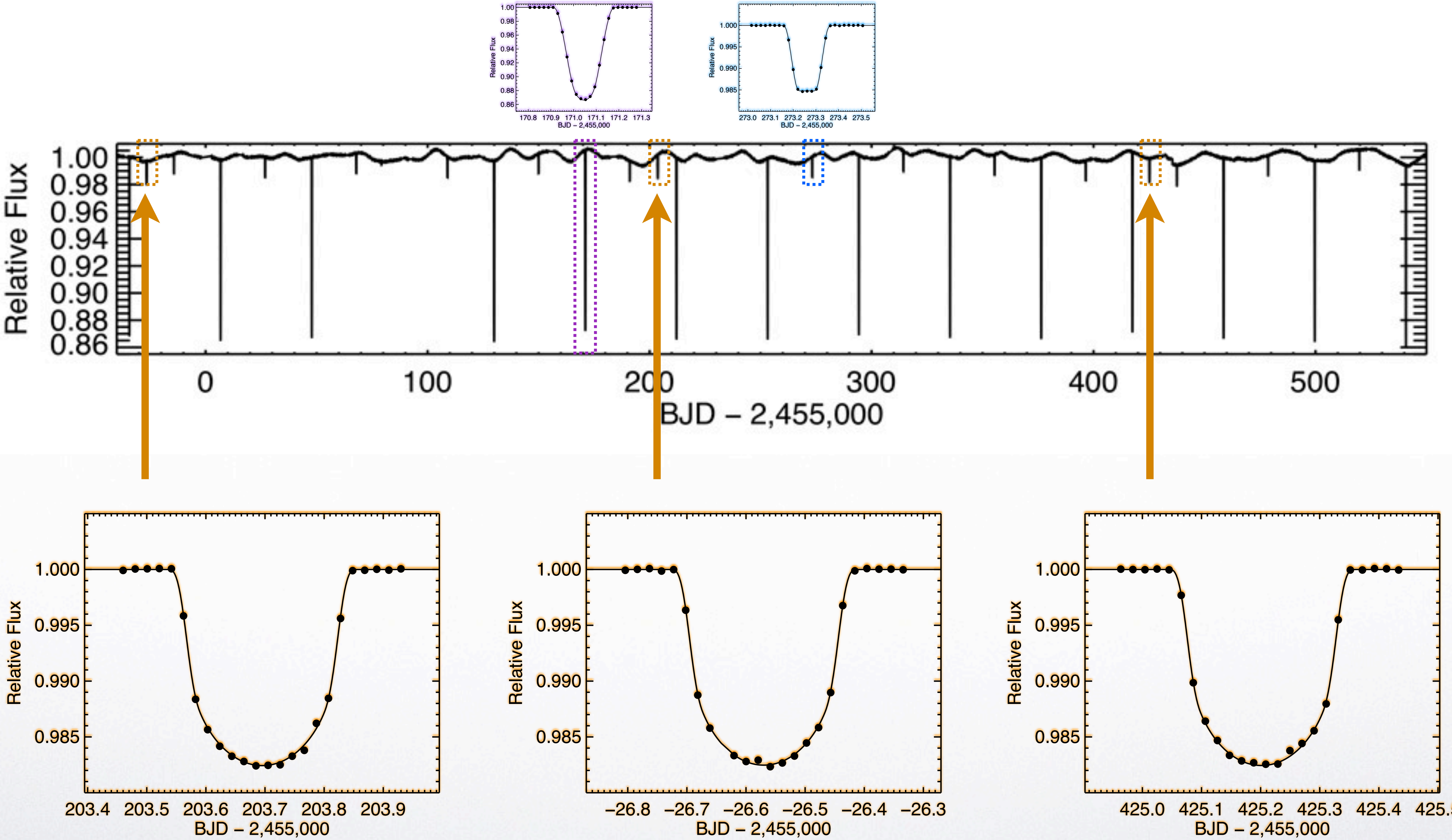


??

Josh Carter, ESS-II (September 15, 2011)

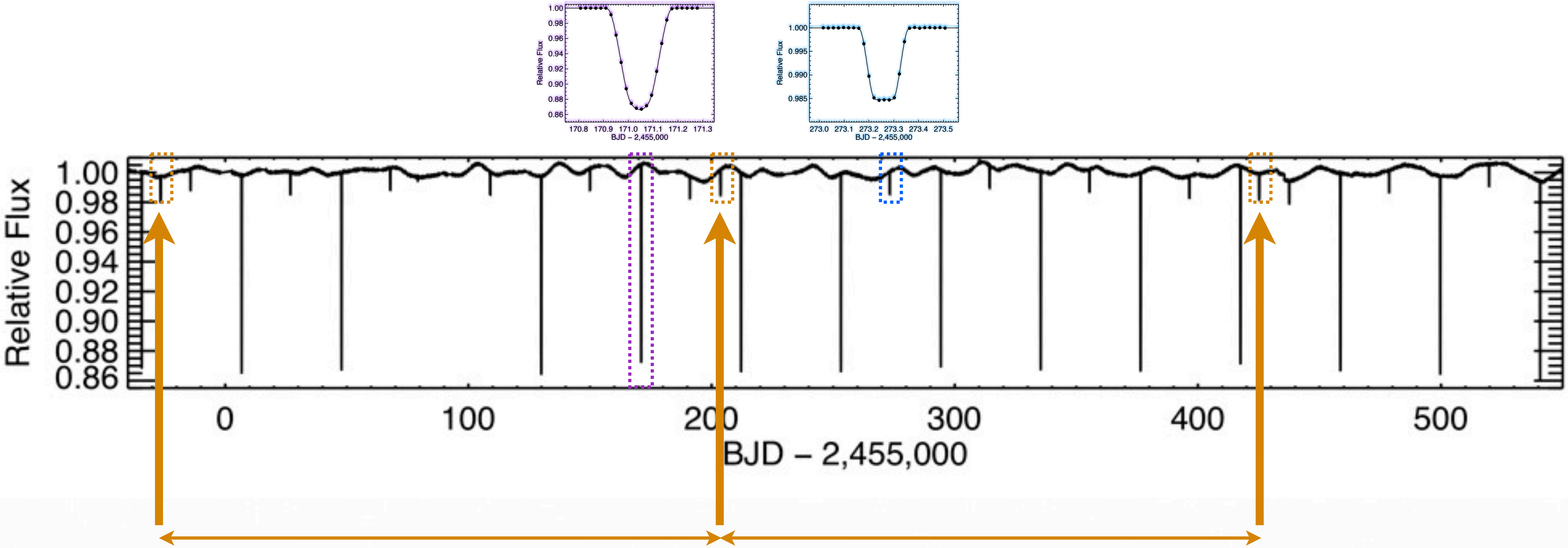


Josh Carter, ESS-II (September 15, 2011)

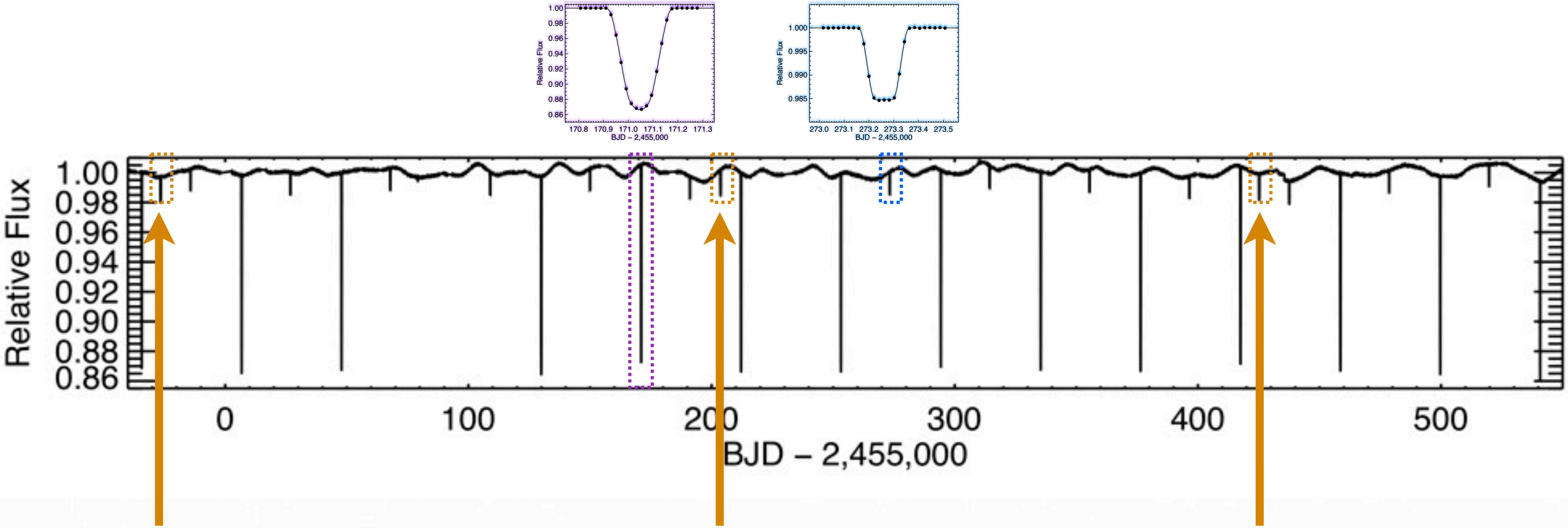


Josh Carter, ESS-II (September 15, 2011)

Tuesday, February 7, 2012



Josh Carter, ESS-II (September 15, 2011)



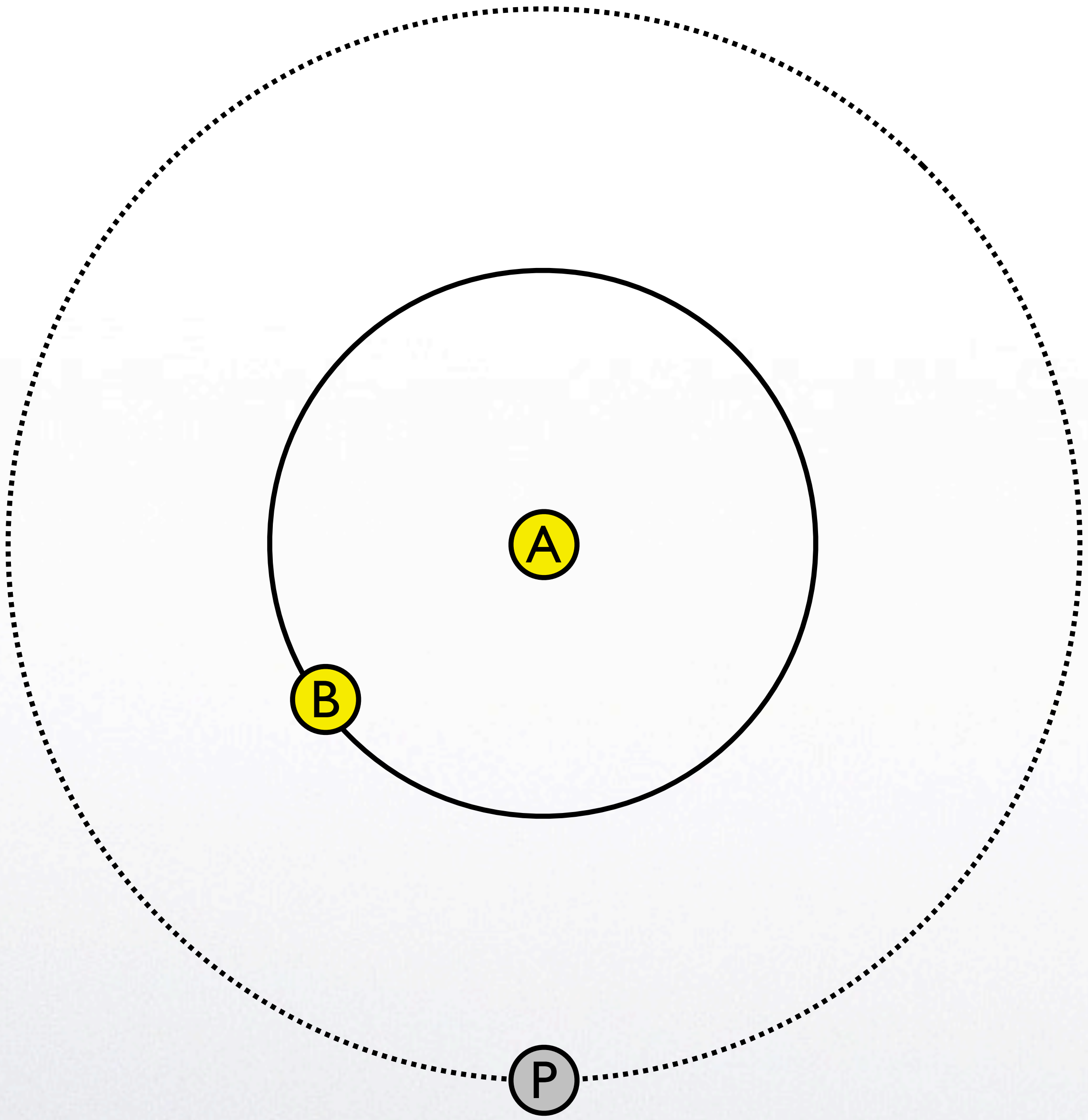
230.3 days

221.5 days

Josh Carter, ESS-II (September 15, 2011)

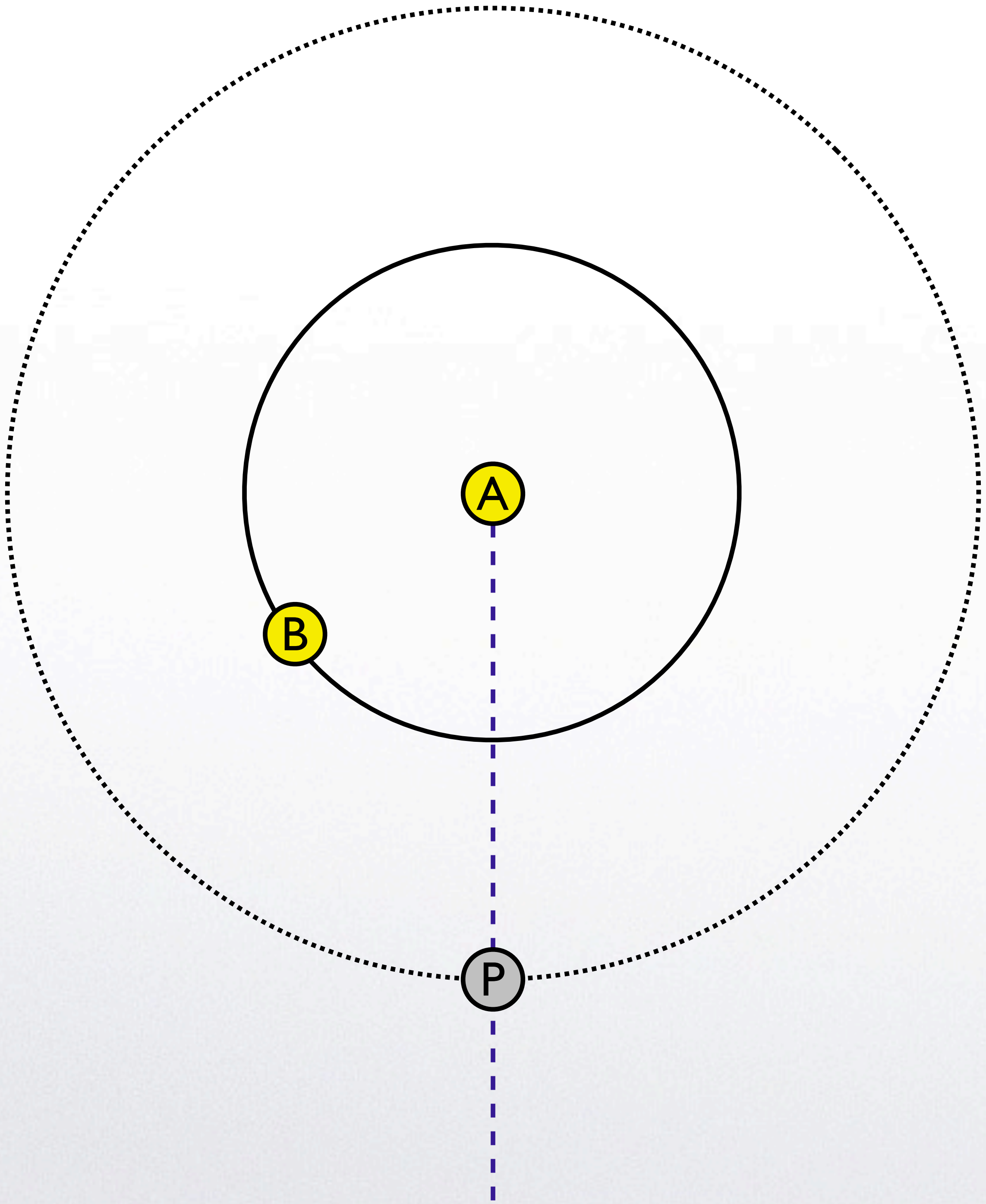
Planetary Transit Timing Variation (Tertiary Transits)

$M_B << M_A$

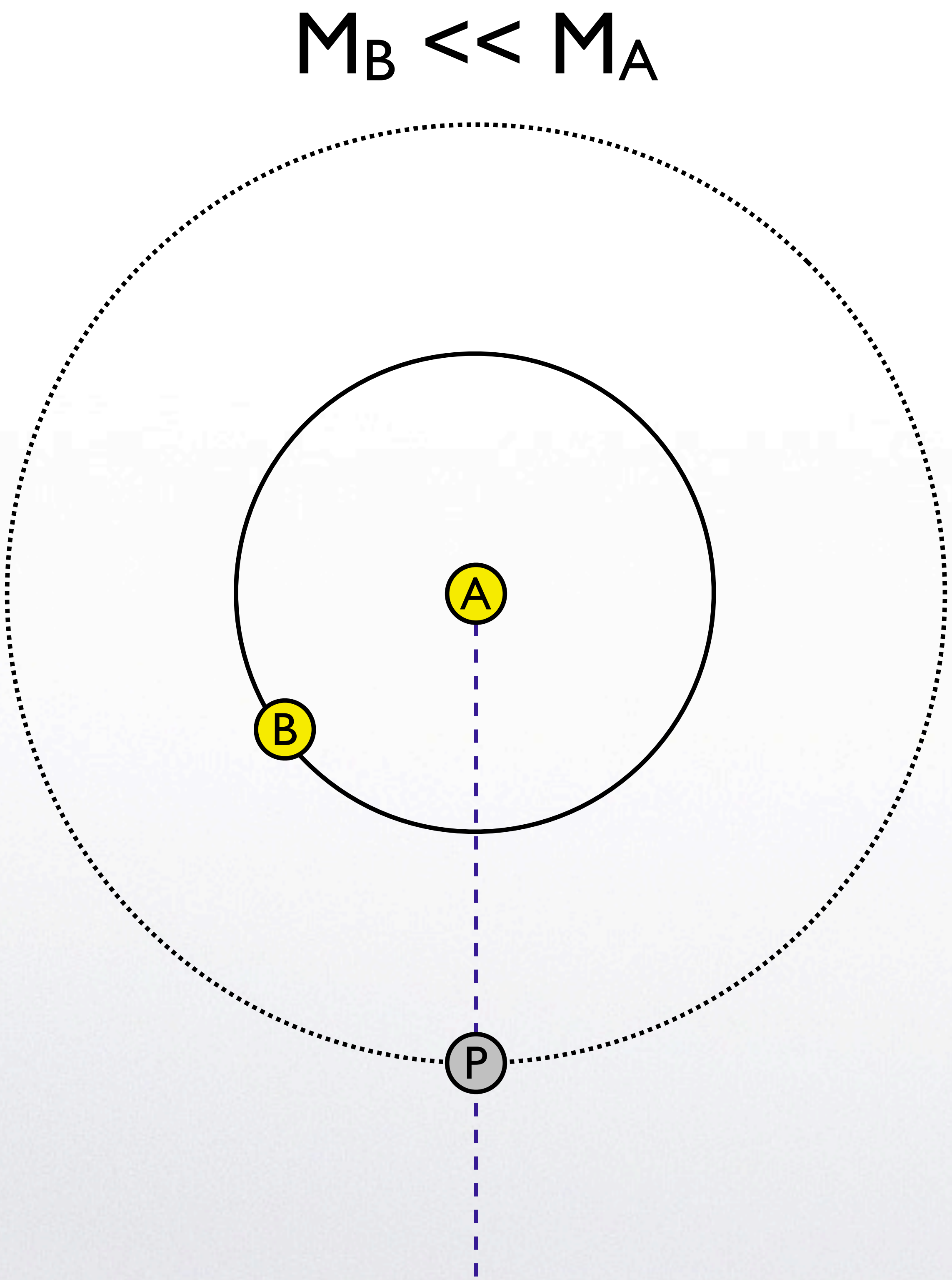


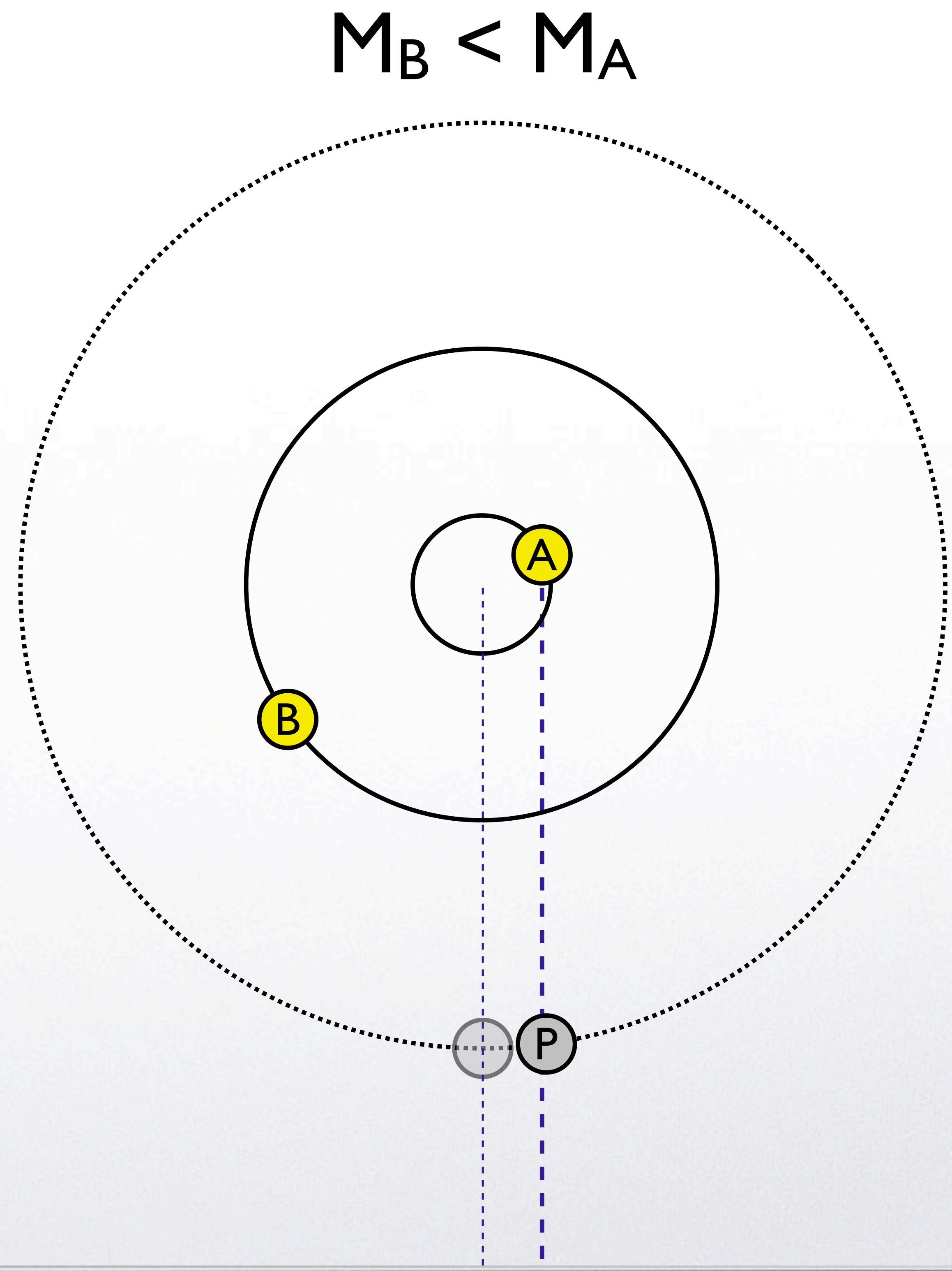
Planetary Transit Timing Variation (Tertiary Transits)

$M_B << M_A$

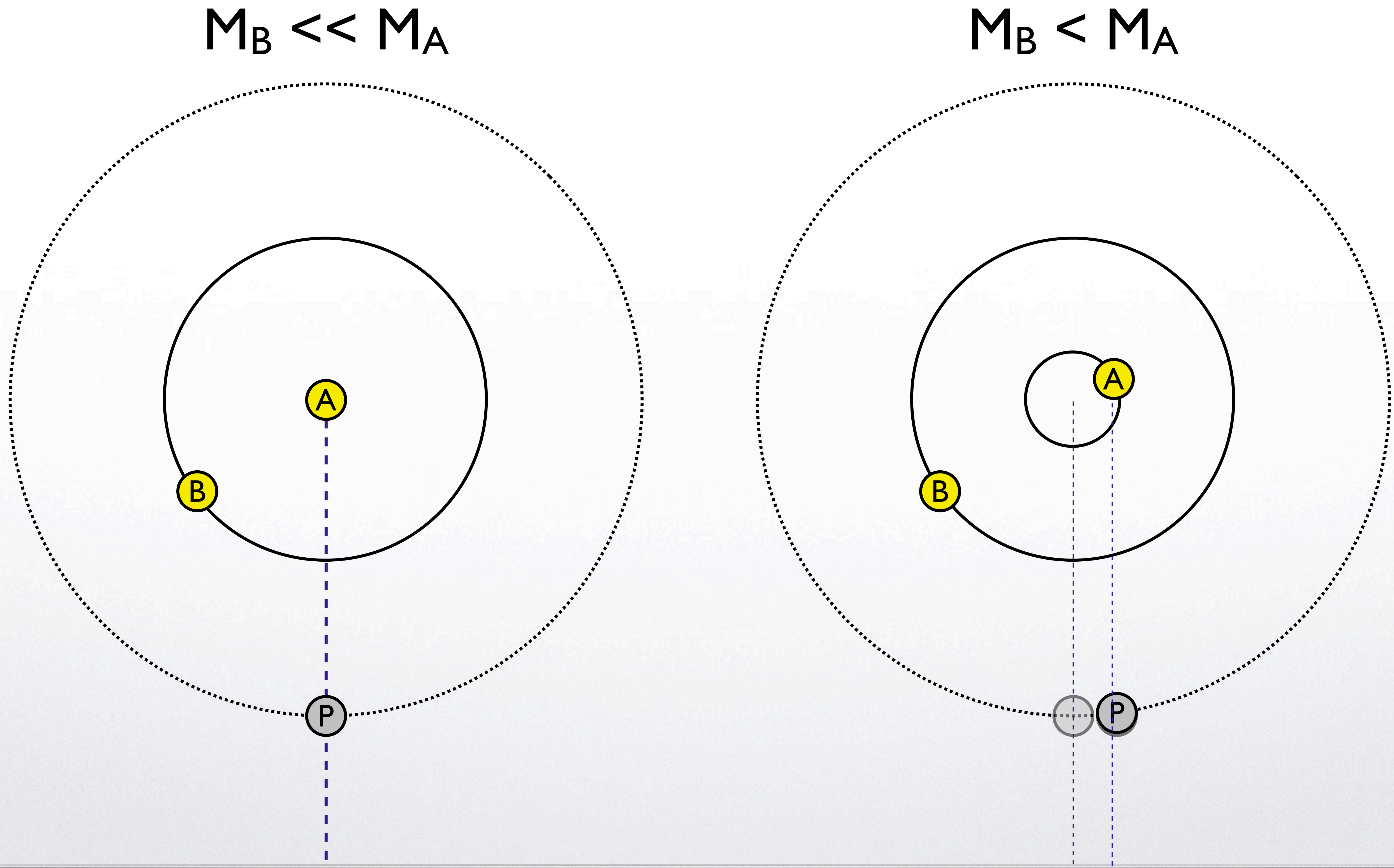


Planetary Transit Timing Variation (Tertiary Transits)

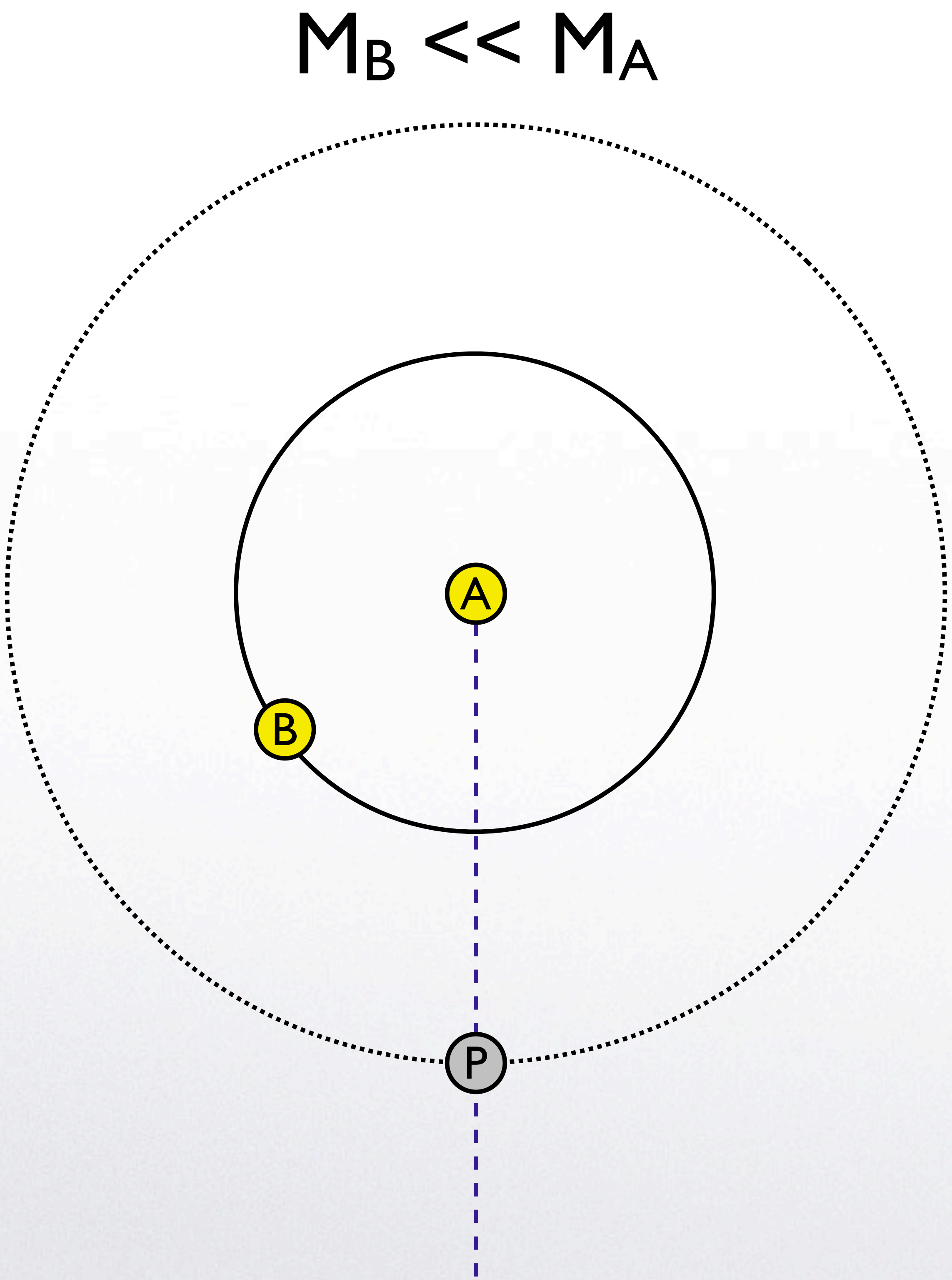


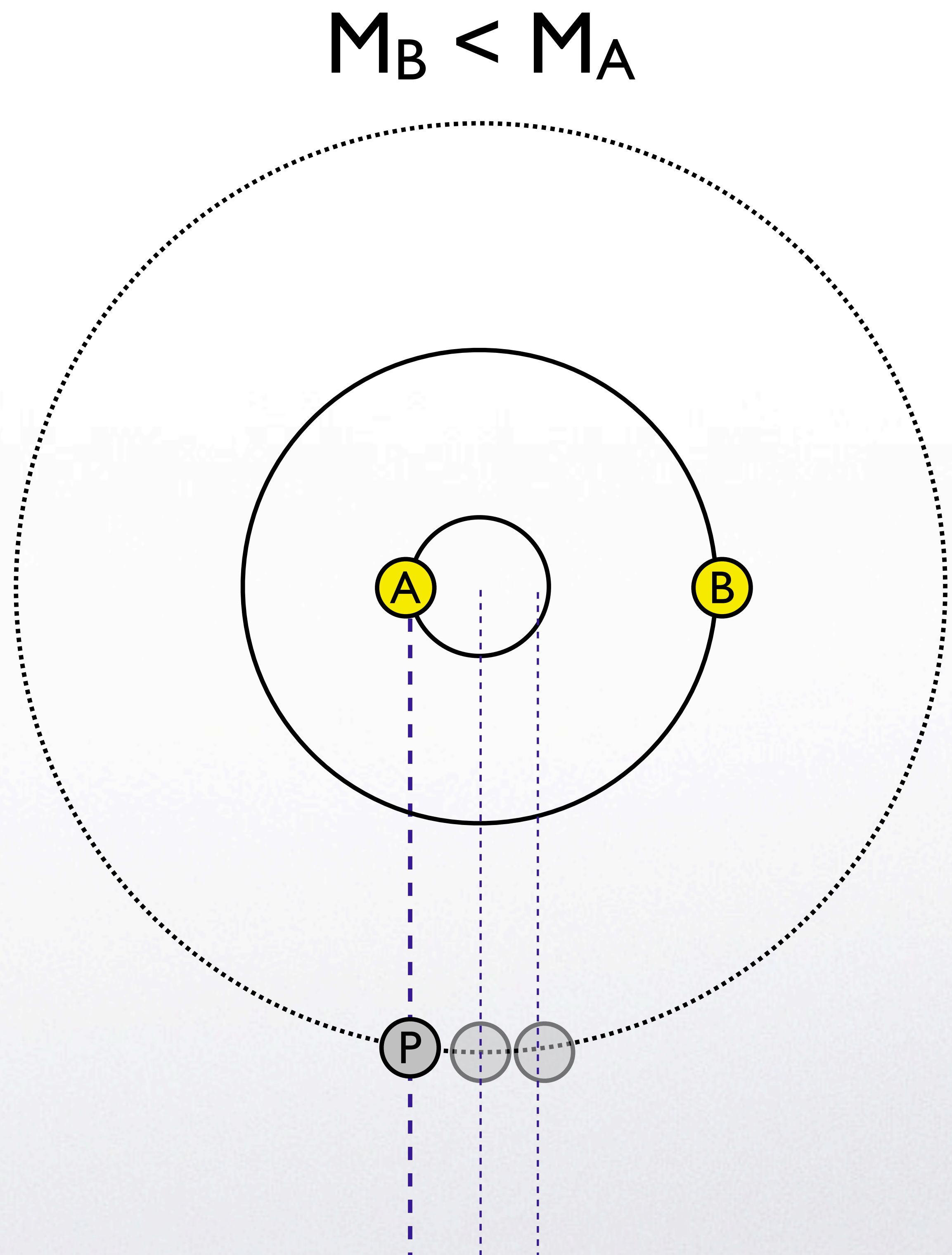


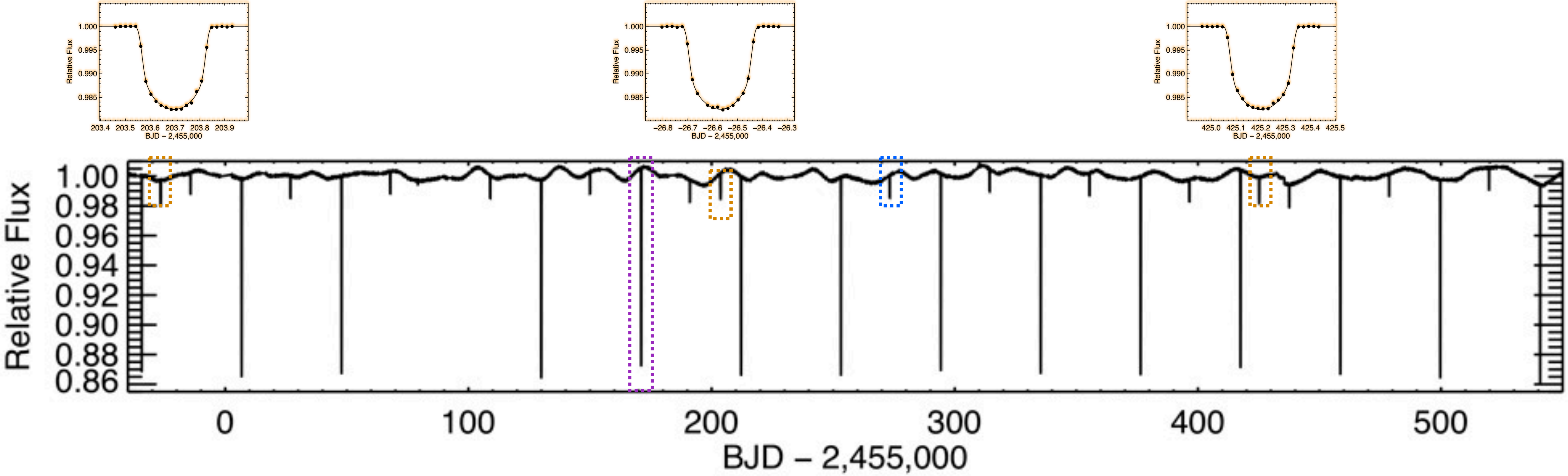
Planetary Transit Timing Variation (Tertiary Transits)



Planetary Transit Timing Variation (Tertiary Transits)

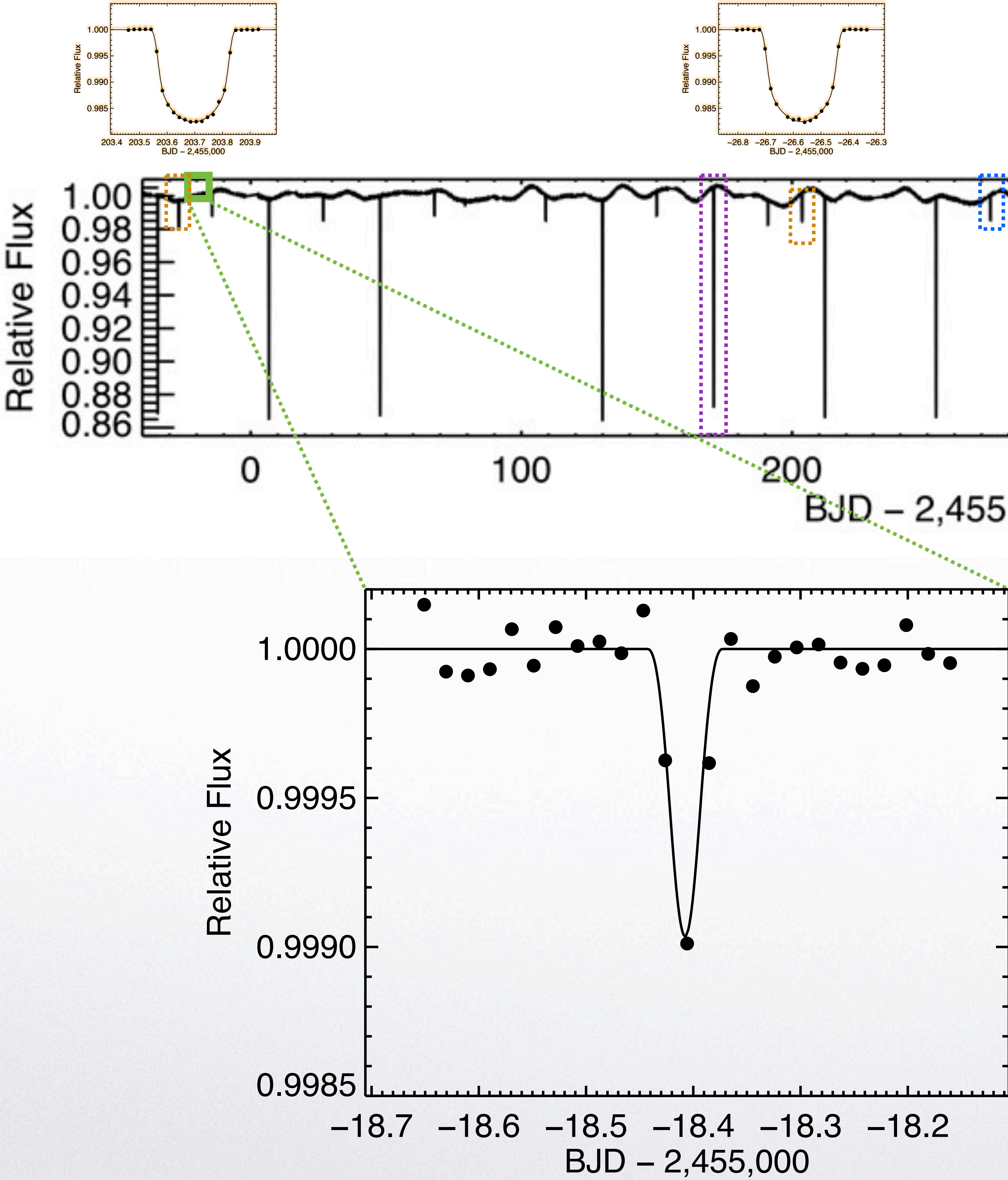




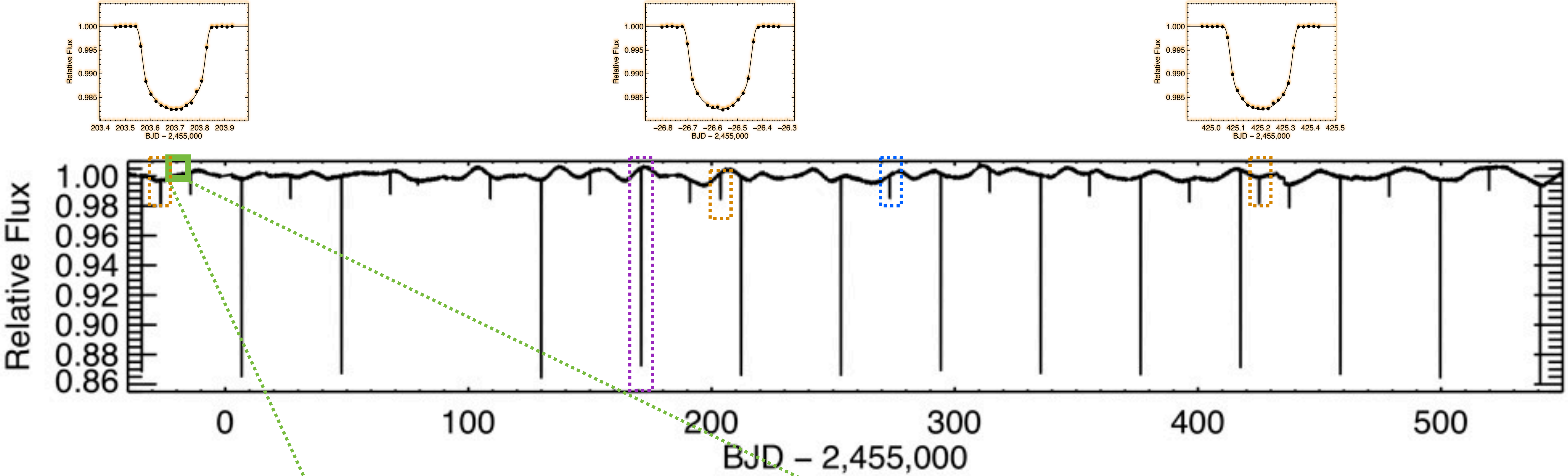


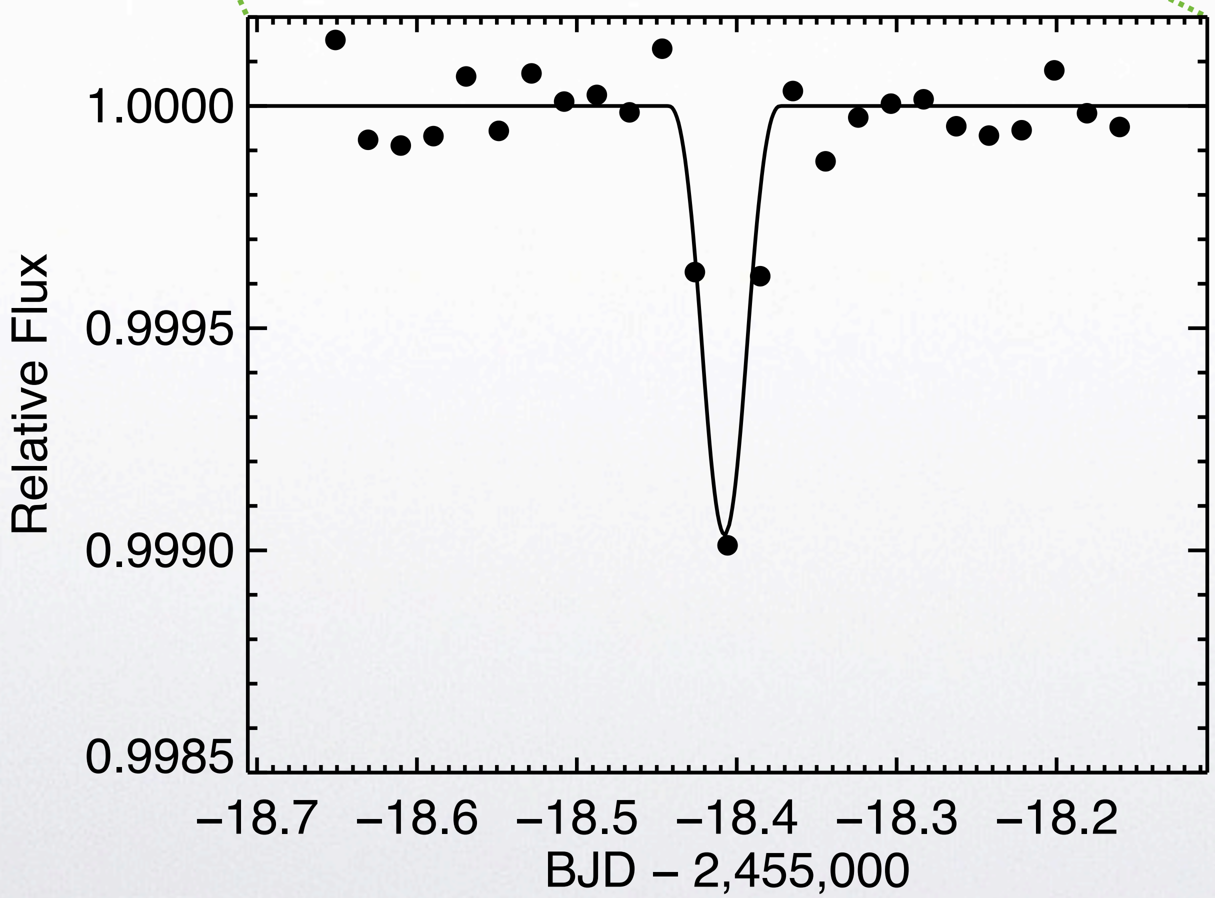
Josh Carter, ESS-II (September 15, 2011)

Tuesday, February 7, 2012

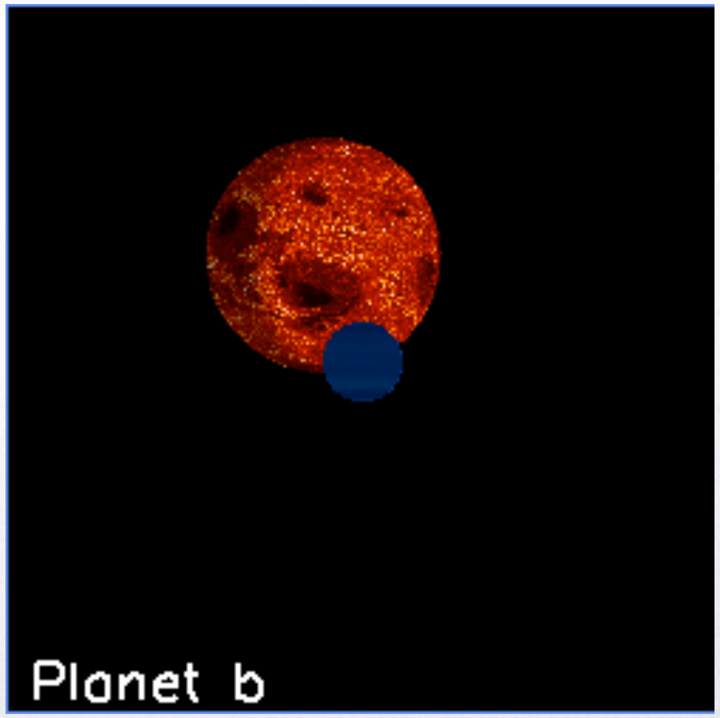


Quaternary Eclipse!



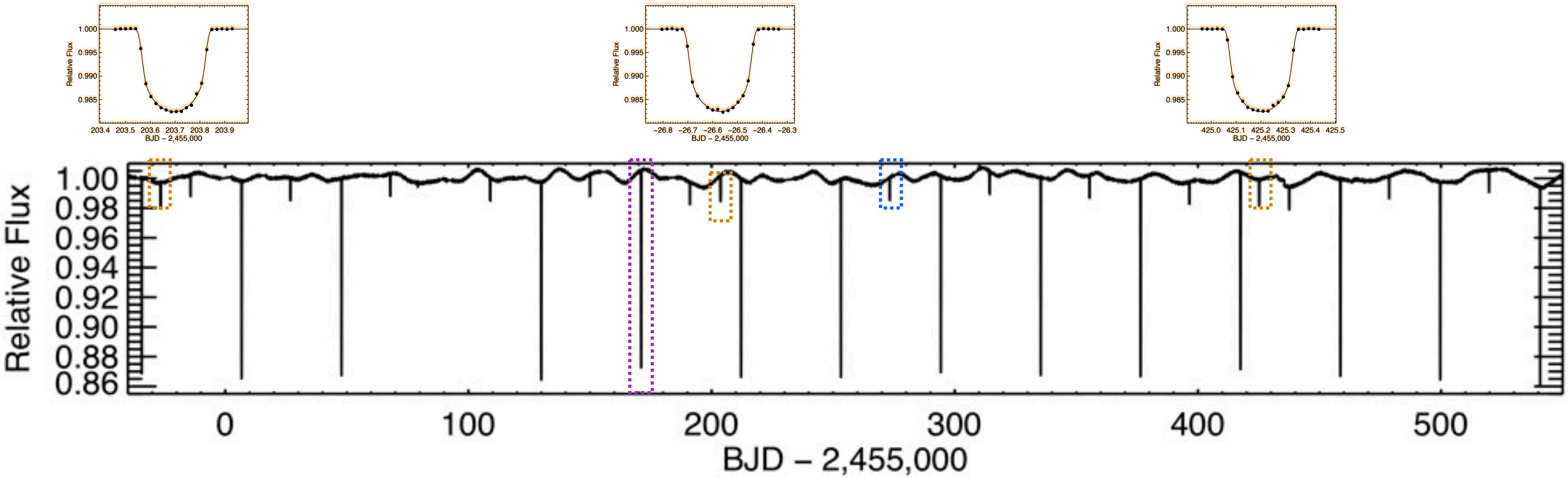


Quaternary Eclipse!

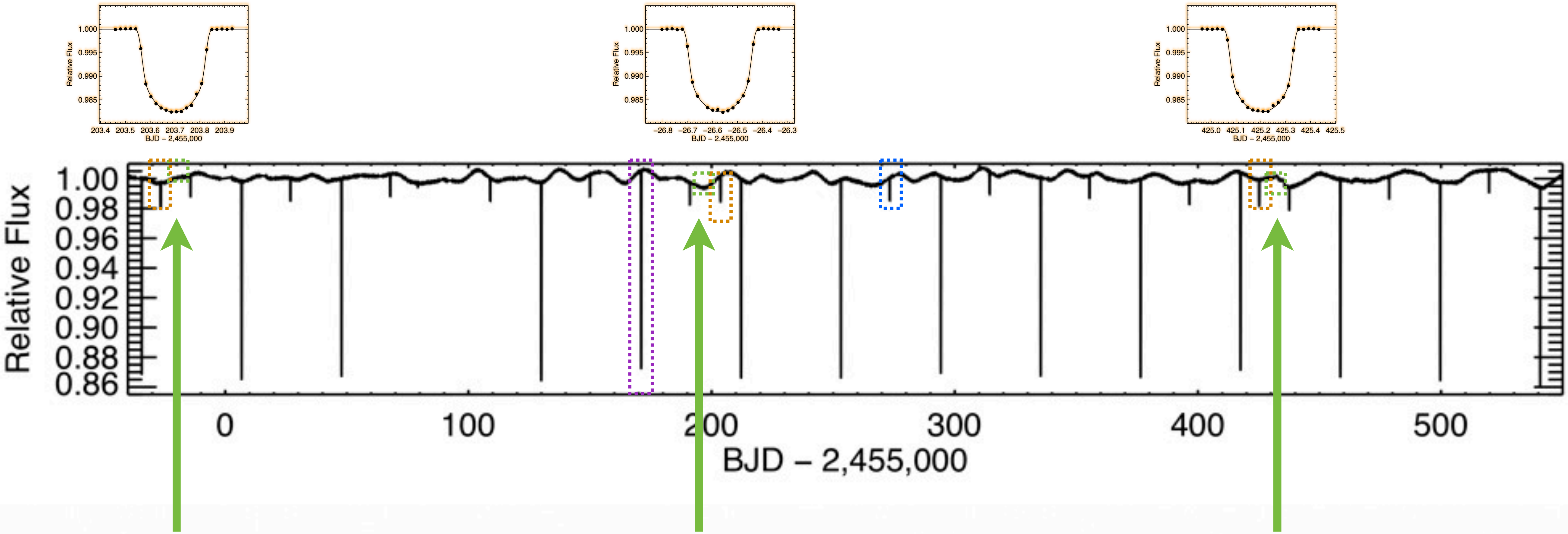


??

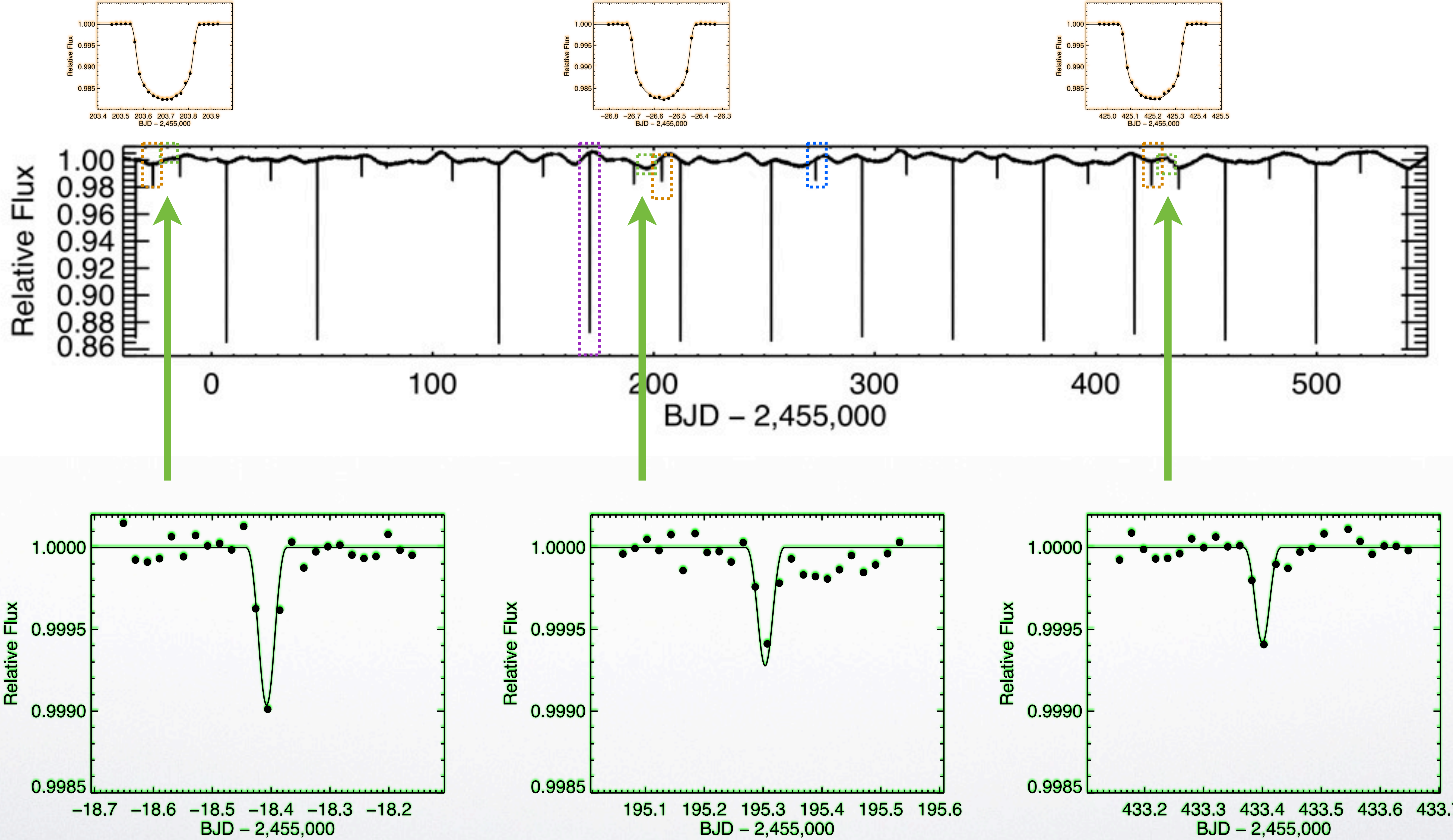
Josh Carter, ESS-II (September 15, 2011)



Relative Flux
BJD – 2,455,000
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0
100
200
300
400
500

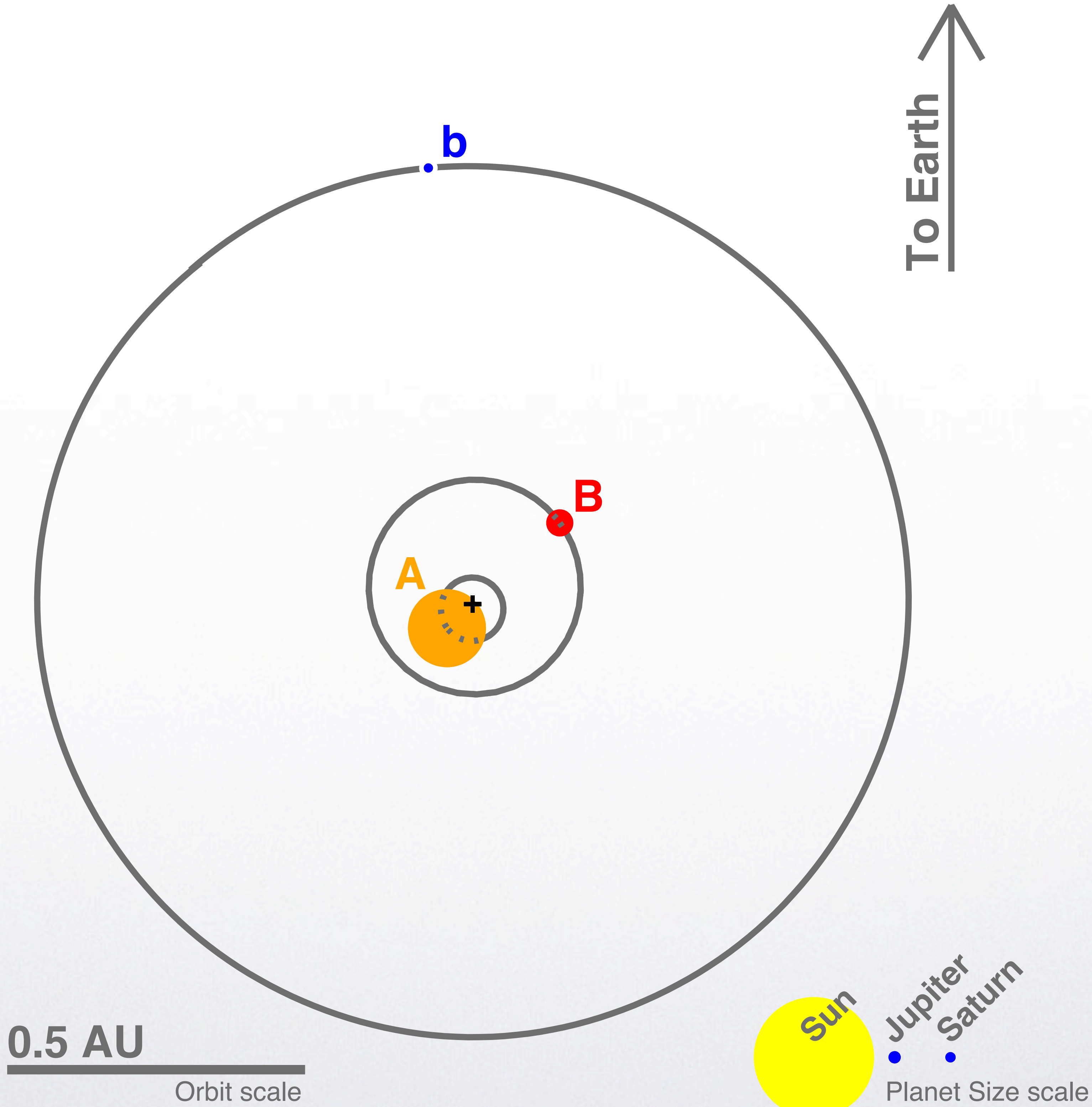


1.000
0.995
0.990
0.985
Relative Flux
203.4 203.5 203.6 203.7 203.8 203.9
BJD – 2,455,000
−26.8 −26.7 −26.6 −26.5 −26.4 −26.3
425.0 425.1 425.2 425.3 425.4 425.5
Relative Flux
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0
100
200
300
400
500
BJD – 2,455,000



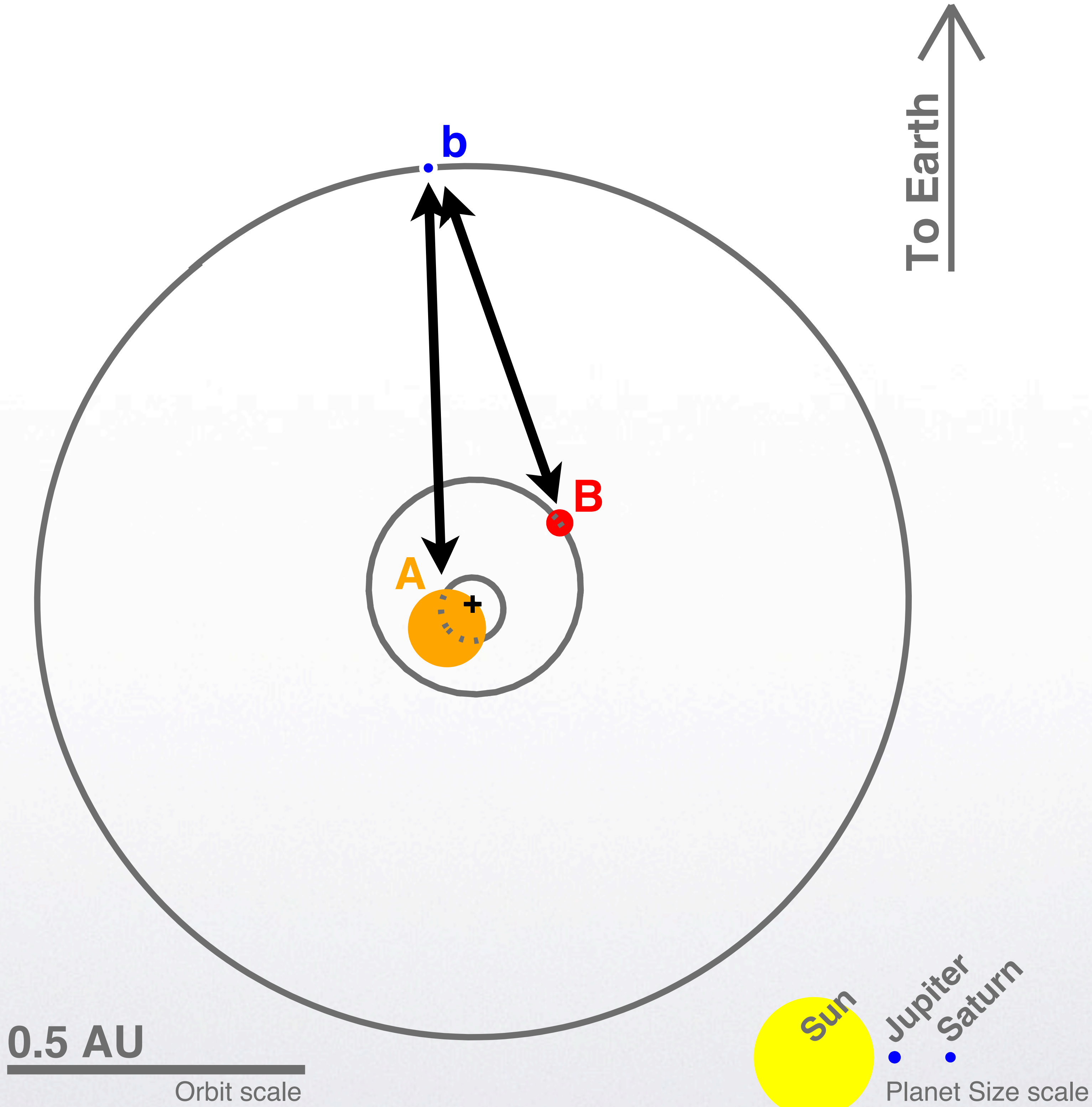
Josh Carter, ESS-II (September 15, 2011)

Kepler-16: The Mass of b



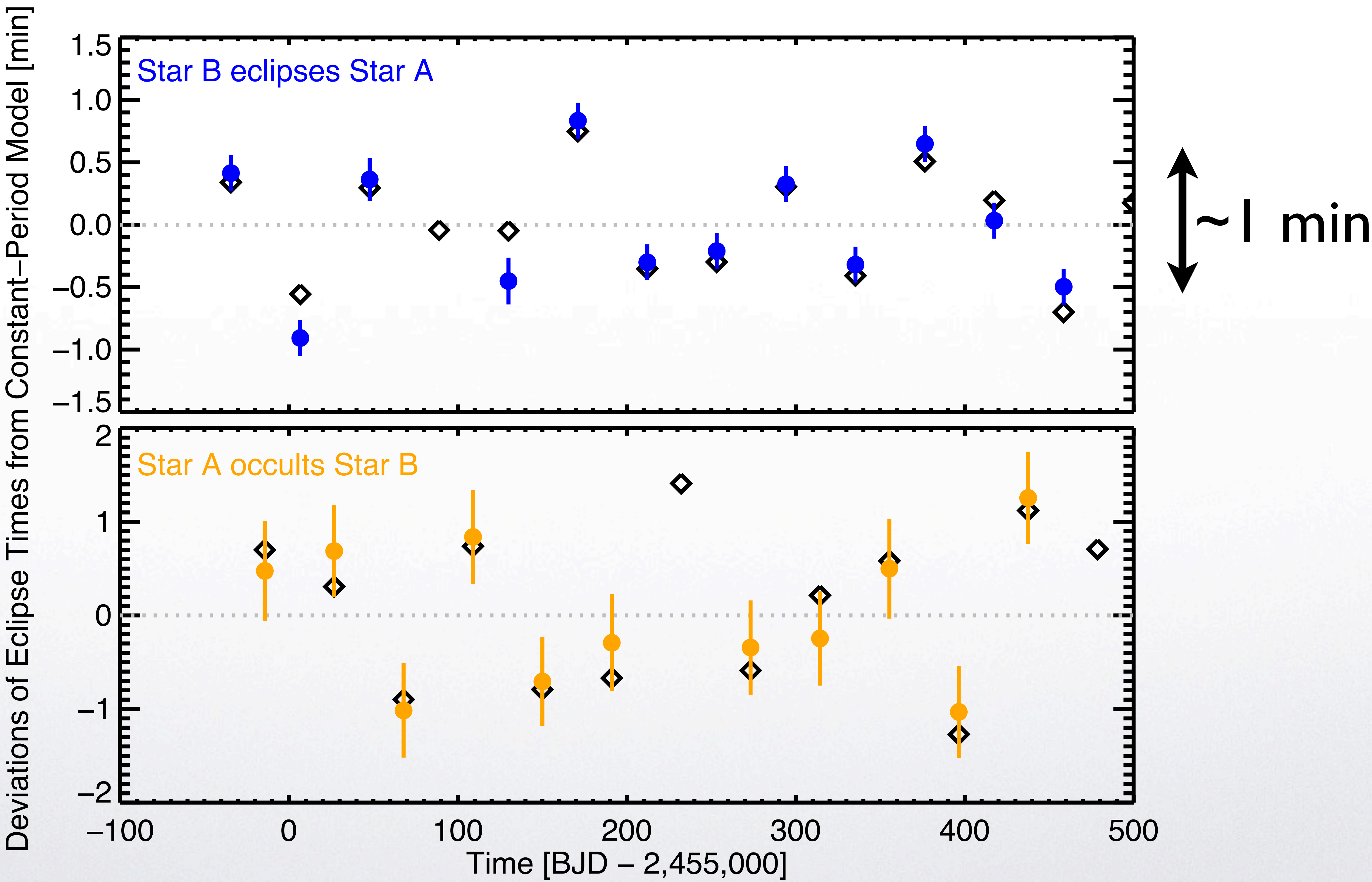
Josh Carter, ESS-II (September 15, 2011)

Kepler-16: The Mass of b



Josh Carter, ESS-II (September 15, 2011)

Kepler-16: The Mass of b



Josh Carter, ESS-II (September 15, 2011)

Eclipse Timing Variations (ETVs) due to planet

Eclipse Timing Variations (ETVs) due to planet

$$A_{\mathrm{primary}} \equiv \frac{\Delta P_{\mathrm{primary}}}{P_{\mathrm{primary}}}$$

- Geometrical Effect

- Dynamical Effect

Eclipse Timing Variations (ETVs) due to planet

$$A_{\mathrm{primary}} \equiv \frac{\Delta P_{\mathrm{primary}}}{P_{\mathrm{primary}}}$$

- Geometrical Effect

$$A_{\mathrm{LITE,primary}} \approx \frac{M_p}{(M_p+M_A+M_B)^{2/3}} \left(\frac{P_{\mathrm{planet}}}{P_{\mathrm{binary}}}\right)^{2/3} \left(\frac{G M_A}{2\pi P_{\mathrm{binary}} c^3}\right)^{1/3}$$

- Dynamical Effect

e.g., Borkovits et al. 2003, 2010; Kopal 1978, Ch.V

Eclipse Timing Variations (ETVs) due to planet

$$A_{\rm primary} \equiv \frac{\Delta P_{\rm primary}}{P_{\rm primary}}$$

- Geometrical Effect

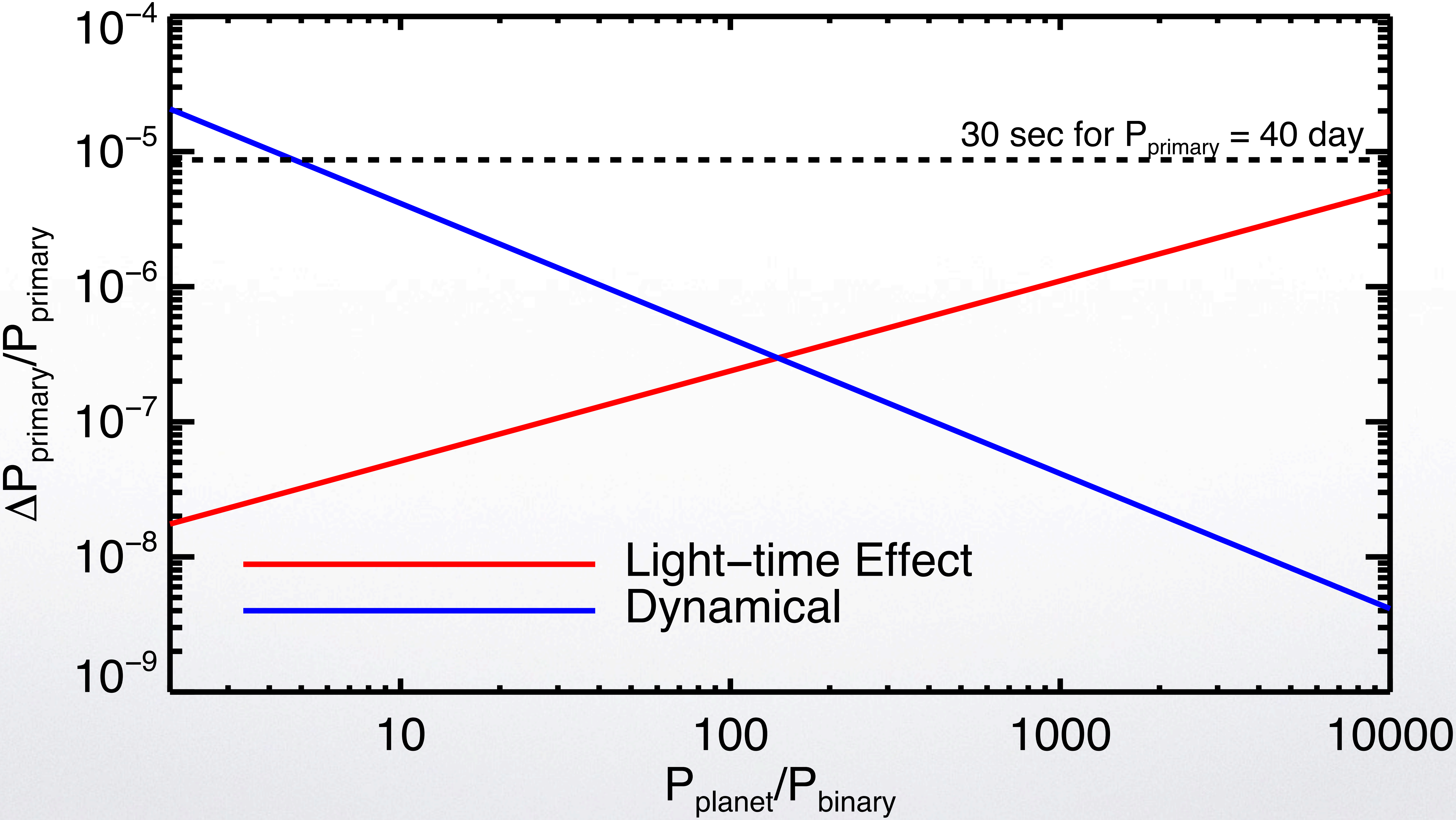
$$A_{\rm LITE,primary} \approx \frac{M_p}{(M_p+M_A+M_B)^{2/3}} \left(\frac{P_{\rm planet}}{P_{\rm binary}}\right)^{2/3} \left(\frac{GM_A}{2\pi P_{\rm binary} c^3}\right)^{1/3}$$

- Dynamical Effect

$$A_{\rm dyn.,primary} \approx \frac{3}{8\pi} \frac{M_p}{M_p+M_A+M_B} \left(\frac{P_{\rm binary}}{P_{\rm planet}}\right)$$

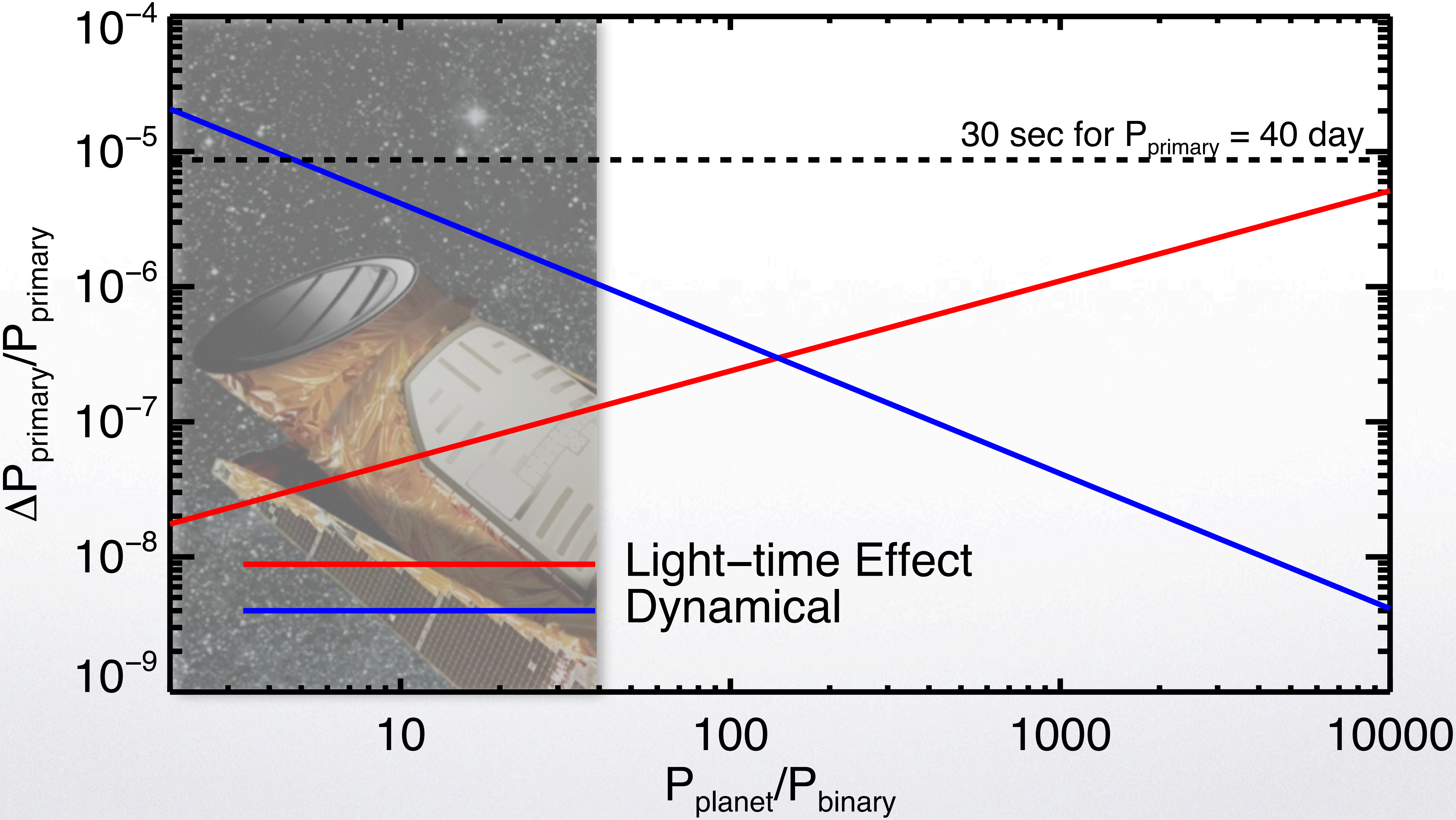
e.g., Borkovits et al. 2003, 2010; Kopal 1978, Ch.V

Stellar Eclipse Timing Variations (ETVs) due to planet

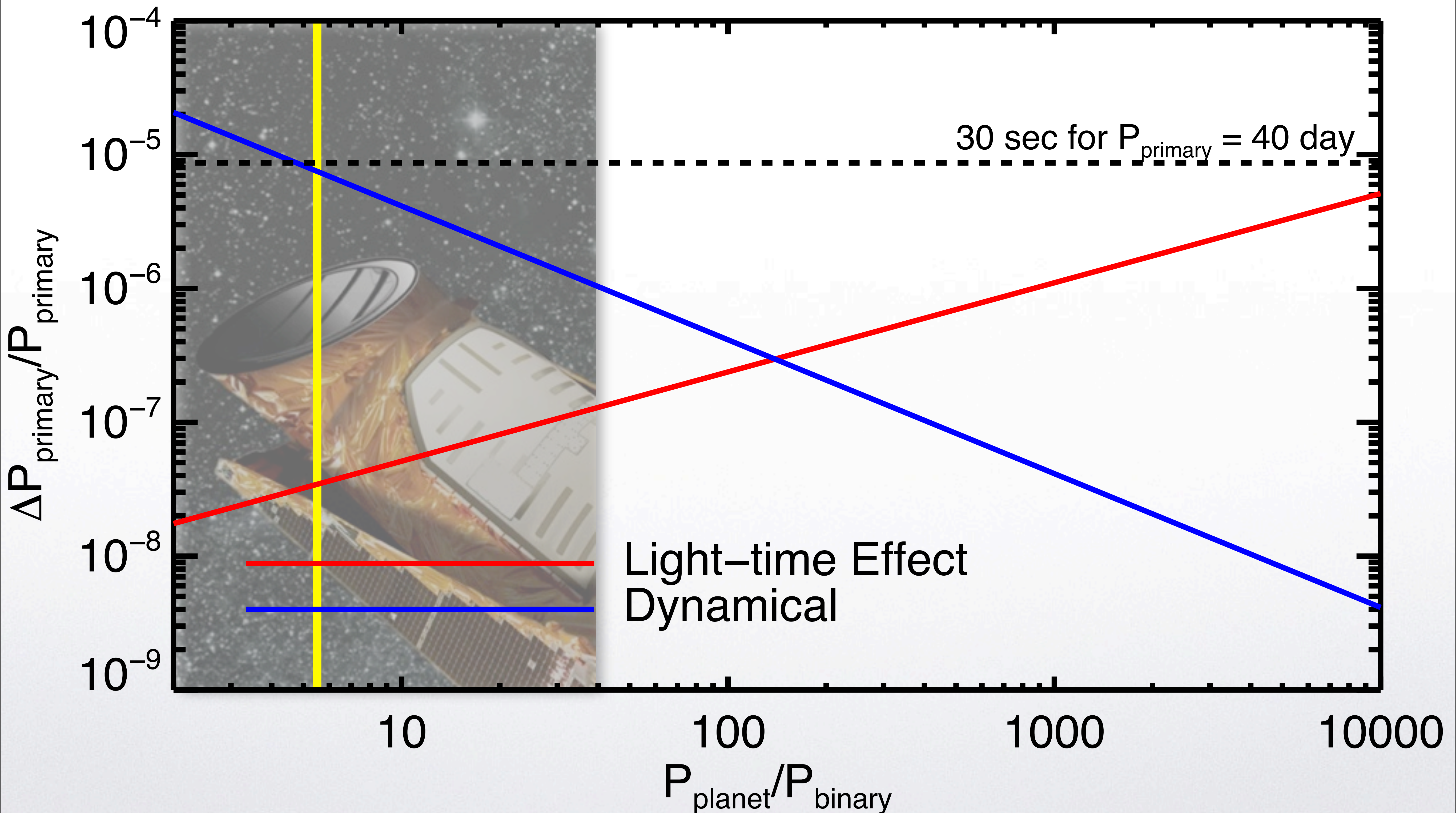


Josh Carter, ESS-II (September 15, 2011)

Stellar Eclipse Timing Variations (ETVs) due to planet



Stellar Eclipse Timing Variations (ETVs) due to planet



Kepler-16: The Mass of b

Kepler-16: The Mass of b

- From the light curve fit (with dynamics)

Kepler-16: The Mass of b

- From the light curve fit (with dynamics)
    - All Mass ratios (to ~0.1% stars, 5% planet)

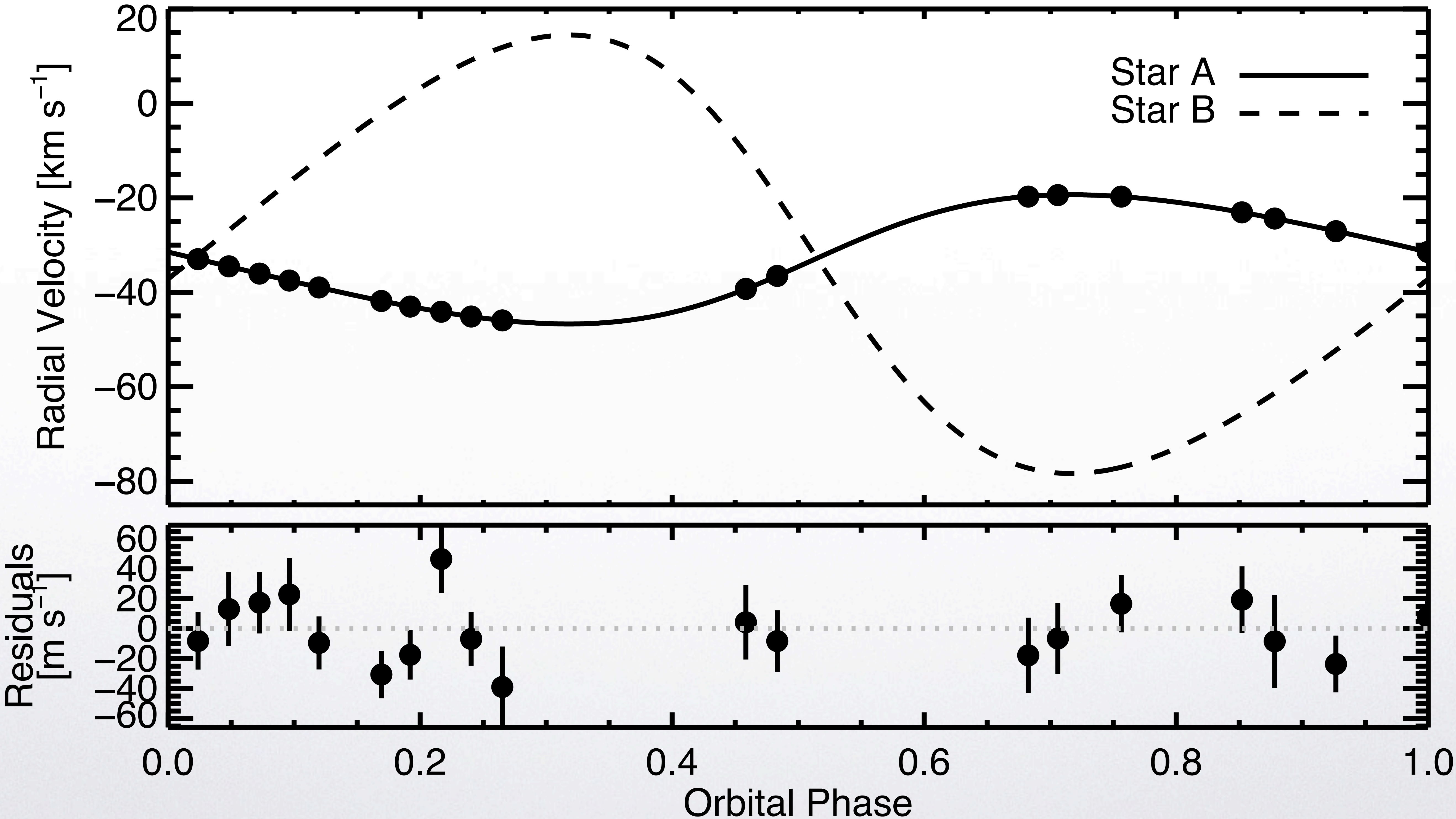
Kepler-16: The Mass of b

- From the light curve fit (with dynamics)
  - All Mass ratios (to ~0.1% stars, 5% planet)
  - All Radii Ratios (to <1%)

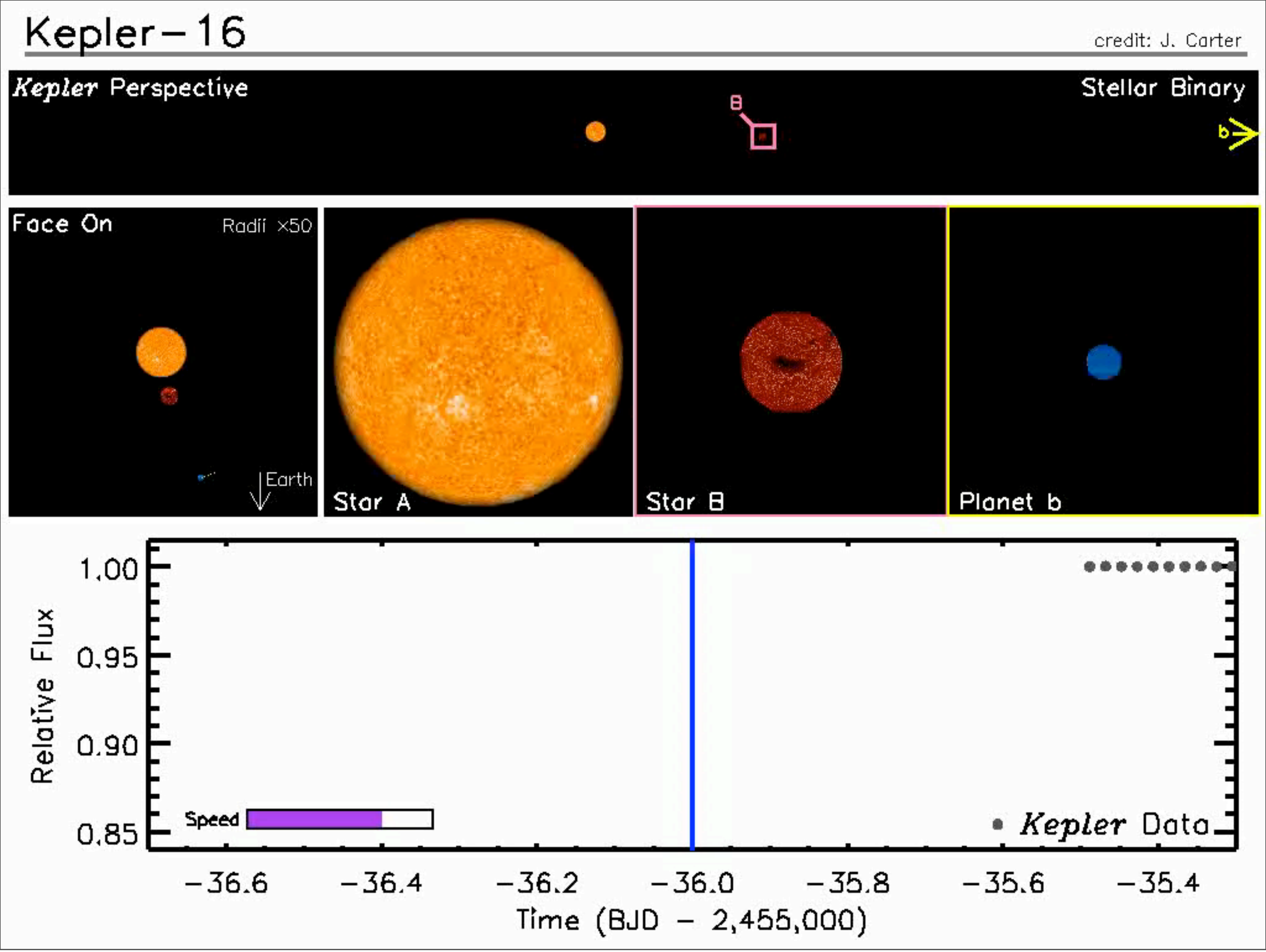
Kepler-16: The Mass of b

- From the light curve fit (with dynamics)
  - All Mass ratios (to ~0.1% stars, 5% planet)
  - All Radii Ratios (to <1%)
  - Mean Stellar Density of Primary (to ~1%)

Kepler-16: The Mass of b



Josh Carter, ESS-II (September 15, 2011)


Kepler−16
credit: J. Carter
Kepler Perspective
Stellar Binary
B
b
Face On
Radii ×50
Earth
Star A
Star B
Planet b
1.00
0.95
0.90
0.85
Relative Flux
Speed
Kepler Data
−36.6
−36.4
−36.2
−36.0
−35.8
−35.6
−35.4
Time (BJD − 2,455,000)

Kepler-16: Accurate Masses and Radii

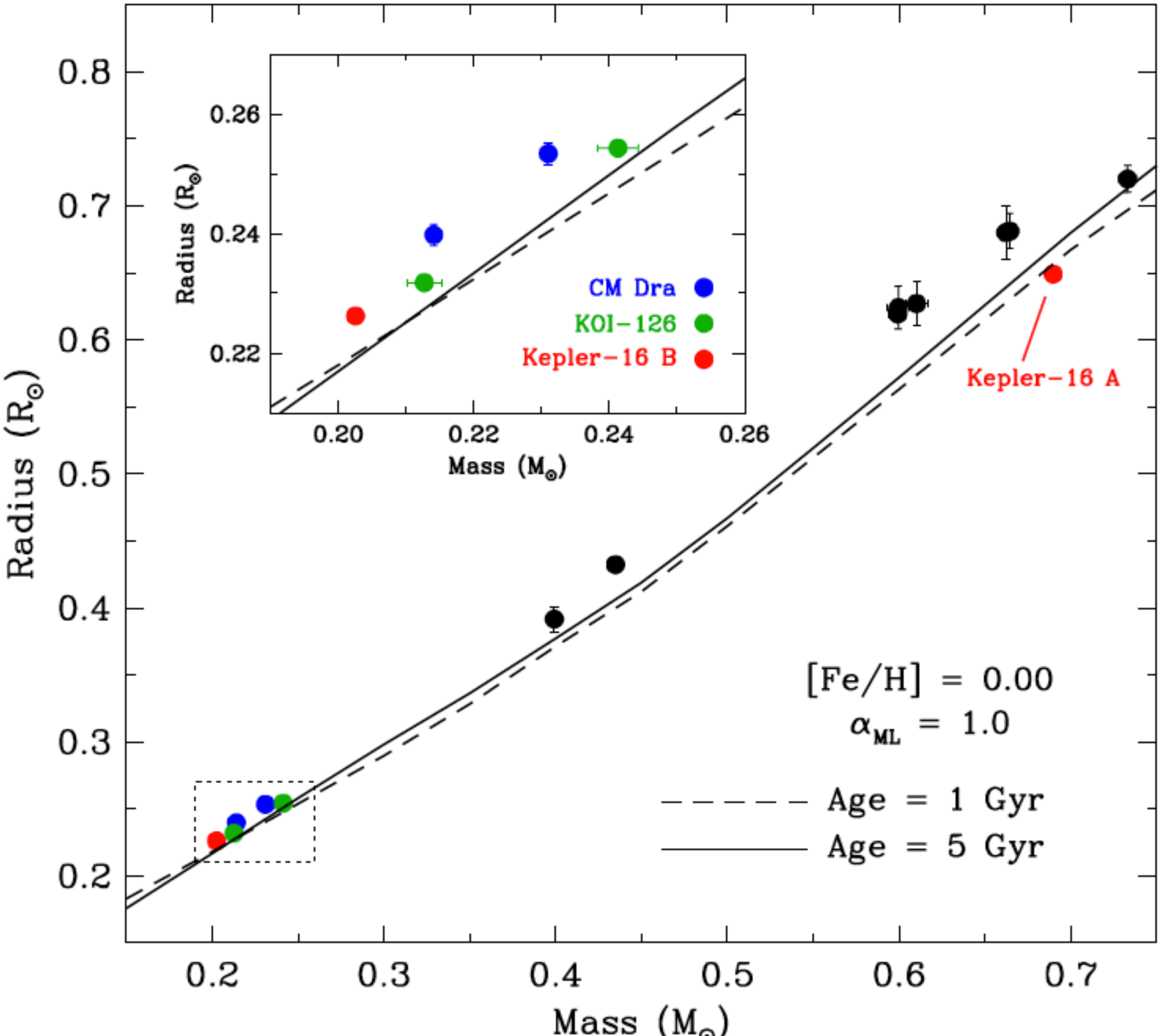
Parameter	Value and Uncertainty
Star A	
Mass, M_A ($M_\odot$)	$0.6897^{+0.0035}_{-0.0034}$
Radius, R_A ($R_\odot$)	$0.6489^{+0.0013}_{-0.0013}$
Mean Density, ρ_A (g cm^{-3})	$3.563^{+0.017}_{-0.016}$
Surface Gravity, $\log g_A$ (cgs)	$4.6527^{+0.0017}_{-0.0016}$
Effective Temperature, $T_{\rm eff}$ (K)	4450 ± 150
Metallicity, [m/H]	-0.3 ± 0.2
Star B	
Mass, M_B ($M_\odot$)	$0.20255^{+0.00066}_{-0.00065}$
Radius, R_B ($R_\odot$)	$0.22623^{+0.00059}_{-0.00053}$
Mean Density, ρ_B (g cm^{-3})	$24.69^{+0.13}_{-0.15}$
Surface Gravity, $\log g_B$ (cgs)	$5.0358^{+0.0014}_{-0.0017}$
Planet b	
Mass, M_b ($M_{\rm Jupiter}$)	$0.333^{+0.016}_{-0.016}$
Radius, R_b ($R_{\rm Jupiter}$)	$0.7538^{+0.0026}_{-0.0023}$
Mean Density, ρ_b (g cm^{-3})	$0.964^{+0.047}_{-0.046}$
Surface Gravity, g_b (m s^{-2})	$14.52^{+0.70}_{-0.69}$

Kepler-16: Accurate Masses and Radii

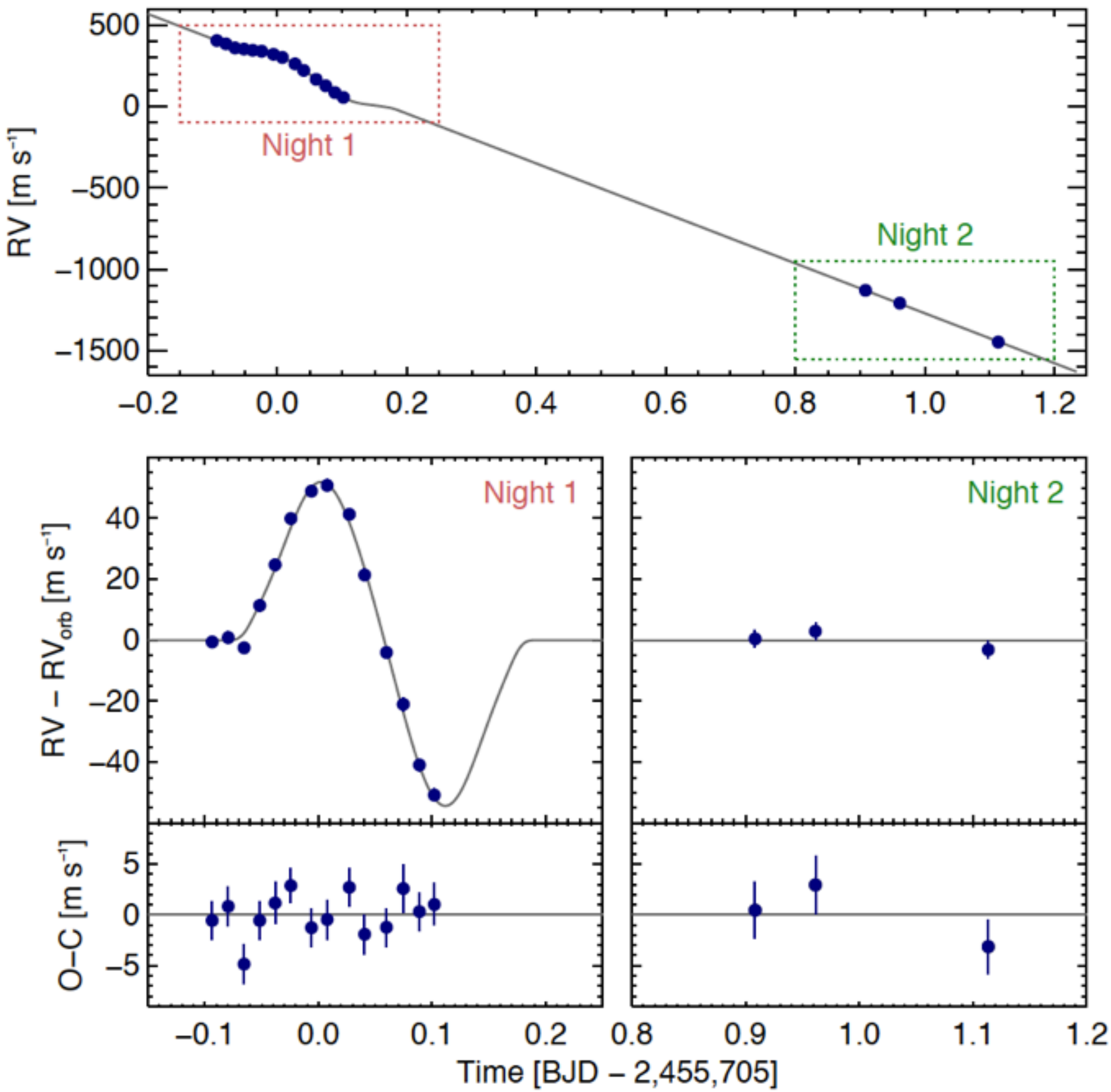
	Parameter	Value and Uncertainty
	Star A	
0.50%	Mass, M_A ($M_\odot$)	$0.6897^{+0.0035}_{-0.0034}$
0.20%	Radius, R_A ($R_\odot$)	$0.6489^{+0.0013}_{-0.0013}$
	Mean Density, ρ_A (g cm^{-3})	$3.563^{+0.017}_{-0.016}$
	Surface Gravity, $\log g_A$ (cgs)	$4.6527^{+0.0017}_{-0.0016}$
	Effective Temperature, $T_{\rm eff}$ (K)	4450 ± 150
	Metallicity, [m/H]	-0.3 ± 0.2
	Star B	
0.33%	Mass, M_B ($M_\odot$)	$0.20255^{+0.00066}_{-0.00065}$
0.26%	Radius, R_B ($R_\odot$)	$0.22623^{+0.00059}_{-0.00053}$
	Mean Density, ρ_B (g cm^{-3})	$24.69^{+0.13}_{-0.15}$
	Surface Gravity, $\log g_B$ (cgs)	$5.0358^{+0.0014}_{-0.0017}$
	Planet b	
	Mass, M_b ($M_{\rm Jupiter}$)	$0.333^{+0.016}_{-0.016}$
	Radius, R_b ($R_{\rm Jupiter}$)	$0.7538^{+0.0026}_{-0.0023}$
	Mean Density, ρ_b (g cm^{-3})	$0.964^{+0.047}_{-0.046}$
	Surface Gravity, g_b (m s^{-2})	$14.52^{+0.70}_{-0.69}$

Kepler-16: Accurate Masses and Radii

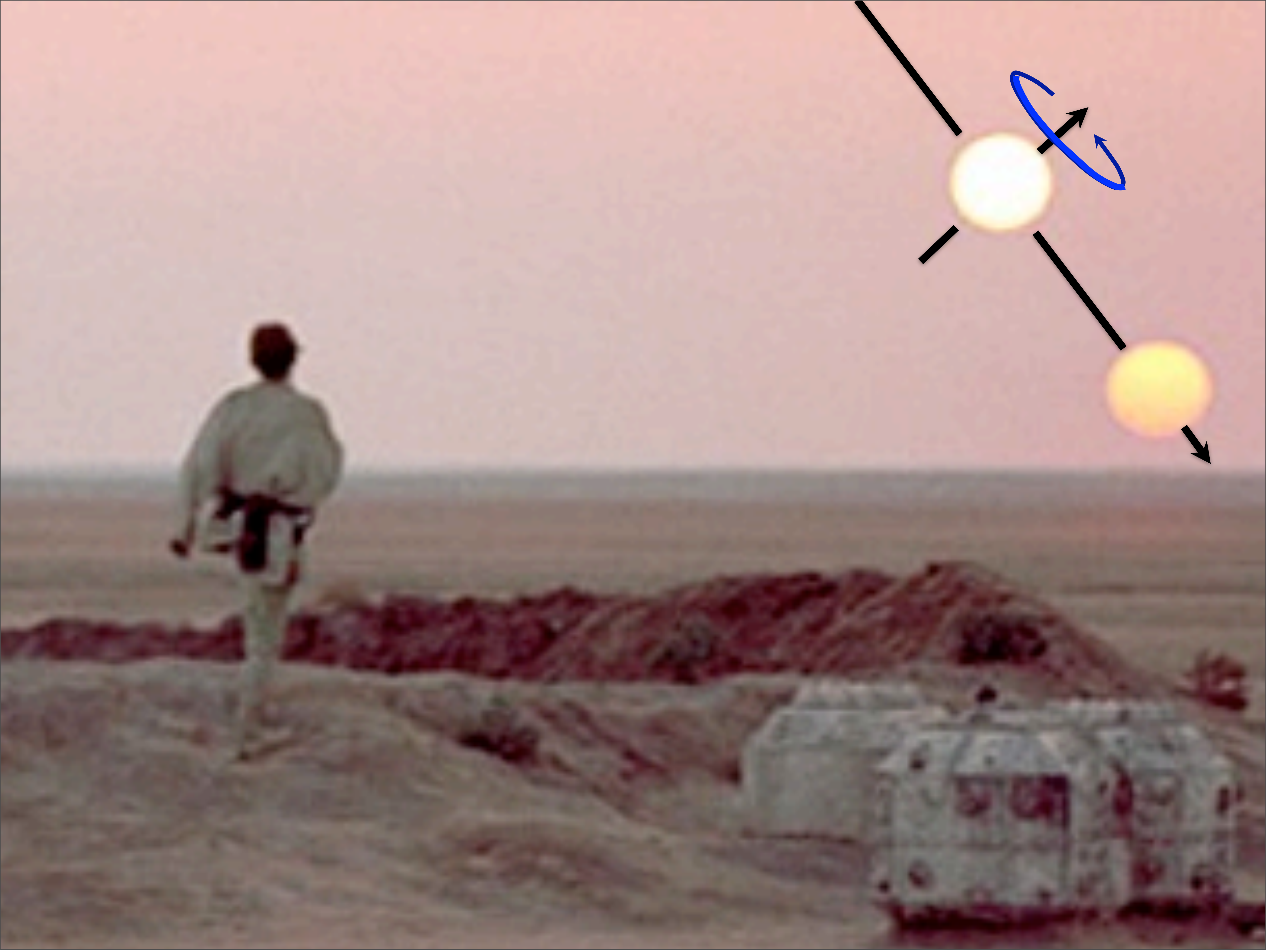
	Parameter	Value and Uncertainty
	Star A	
0.50%	Mass, M_A ($M_\odot$)	$0.6897^{+0.0035}_{-0.0034}$
0.20%	Radius, R_A ($R_\odot$)	$0.6489^{+0.0013}_{-0.0013}$
	Mean Density, ρ_A (g cm^{-3})	$3.563^{+0.017}_{-0.016}$
	Surface Gravity, $\log g_A$ (cgs)	$4.6527^{+0.0017}_{-0.0016}$
	Effective Temperature, $T_{\rm eff}$ (K)	4450 ± 150
	Metallicity, [m/H]	-0.3 ± 0.2
	Star B	
0.33%	Mass, M_B ($M_\odot$)	$0.20255^{+0.00066}_{-0.00065}$
0.26%	Radius, R_B ($R_\odot$)	$0.22623^{+0.00059}_{-0.00053}$
	Mean Density, ρ_B (g cm^{-3})	$24.69^{+0.13}_{-0.15}$
	Surface Gravity, $\log g_B$ (cgs)	$5.0358^{+0.0014}_{-0.0017}$
	Planet b	
4.8%	Mass, M_b ($M_{\rm Jupiter}$)	$0.333^{+0.016}_{-0.016}$
0.34%	Radius, R_b ($R_{\rm Jupiter}$)	$0.7538^{+0.0026}_{-0.0023}$
	Mean Density, ρ_b (g cm^{-3})	$0.964^{+0.047}_{-0.046}$
	Surface Gravity, g_b (m s^{-2})	$14.52^{+0.70}_{-0.69}$



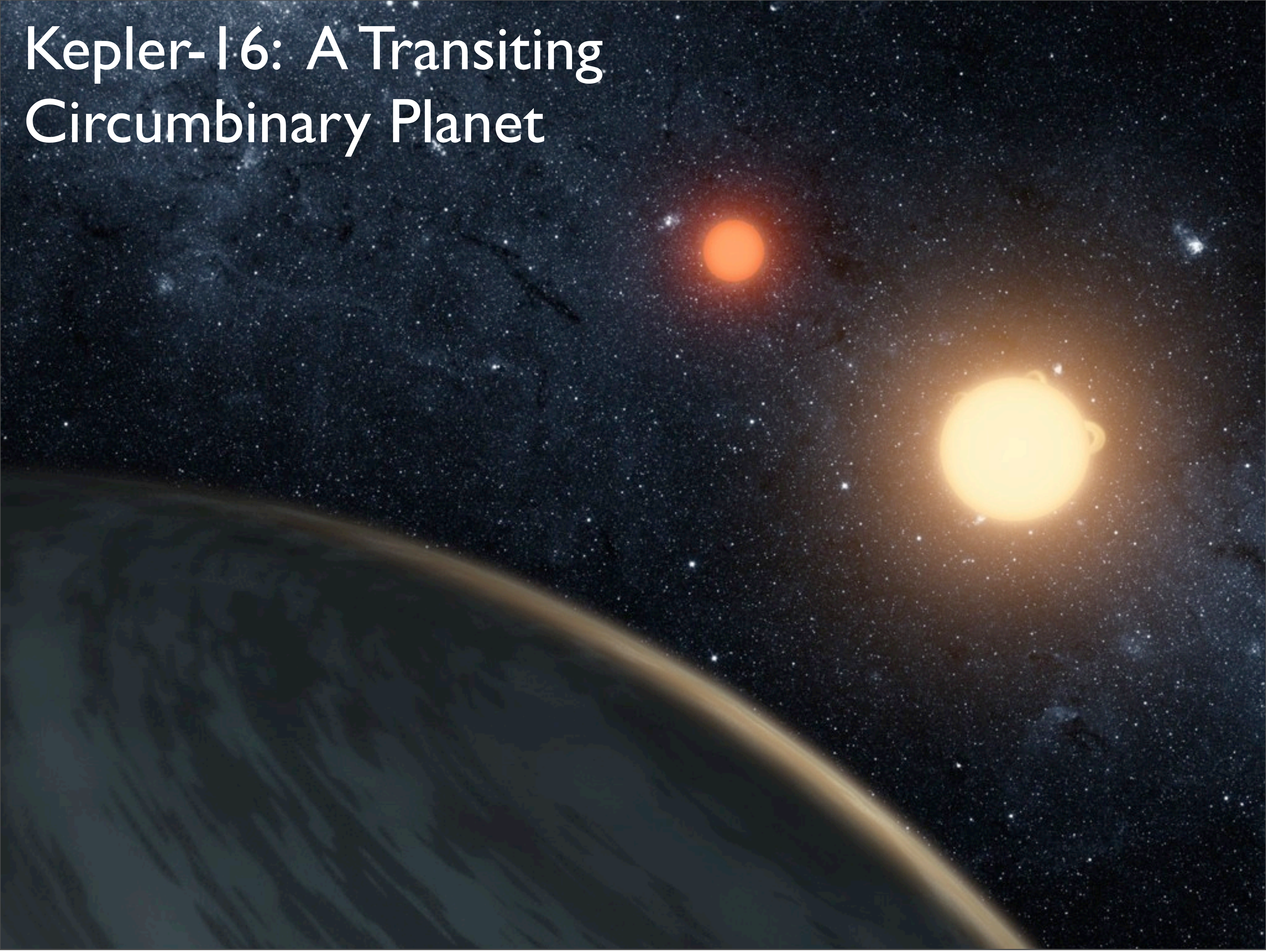
Winn, Albrecht, Johnson et al. (2011)

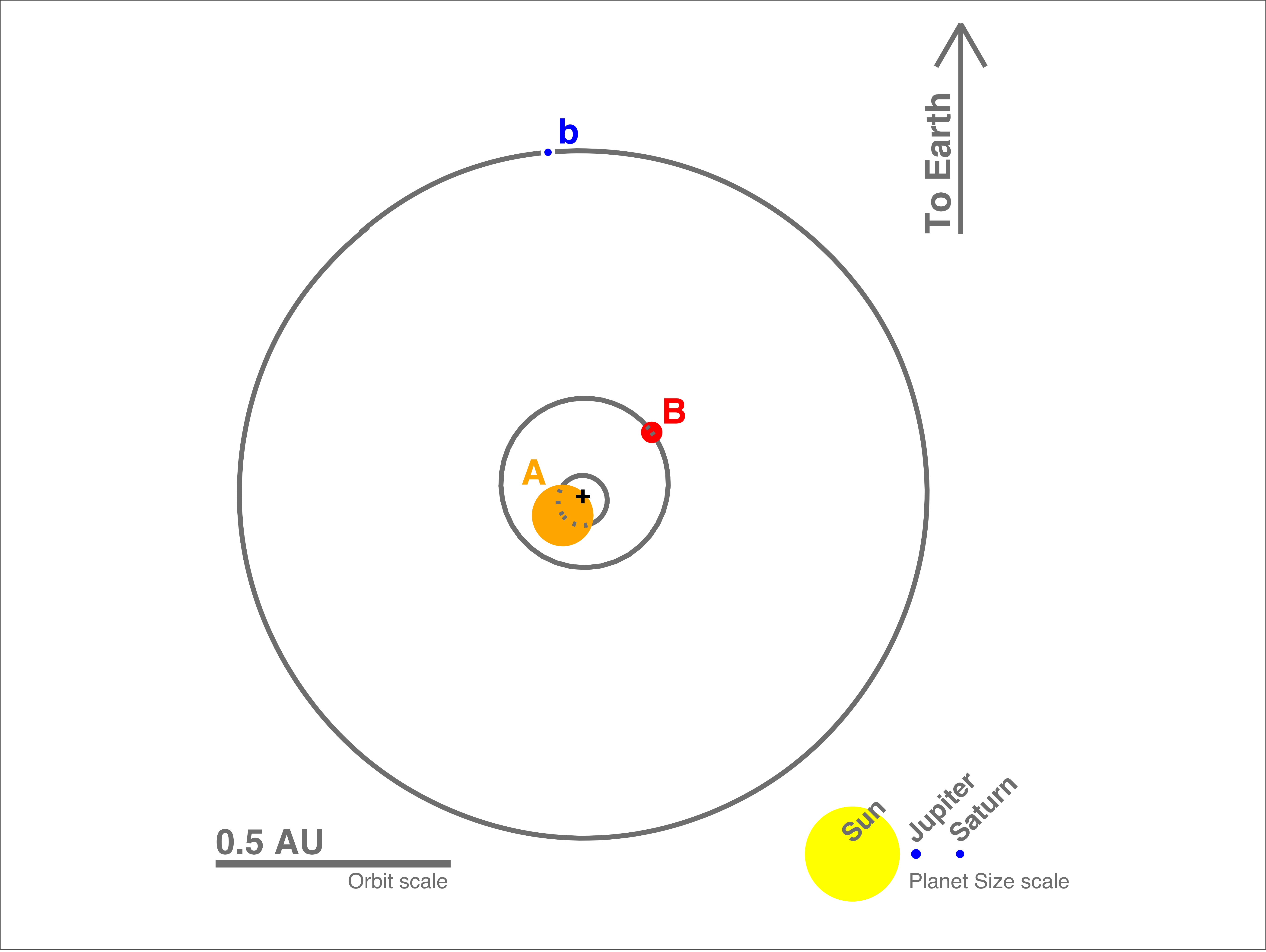


Winn, Albrecht, Johnson et al. (2011)

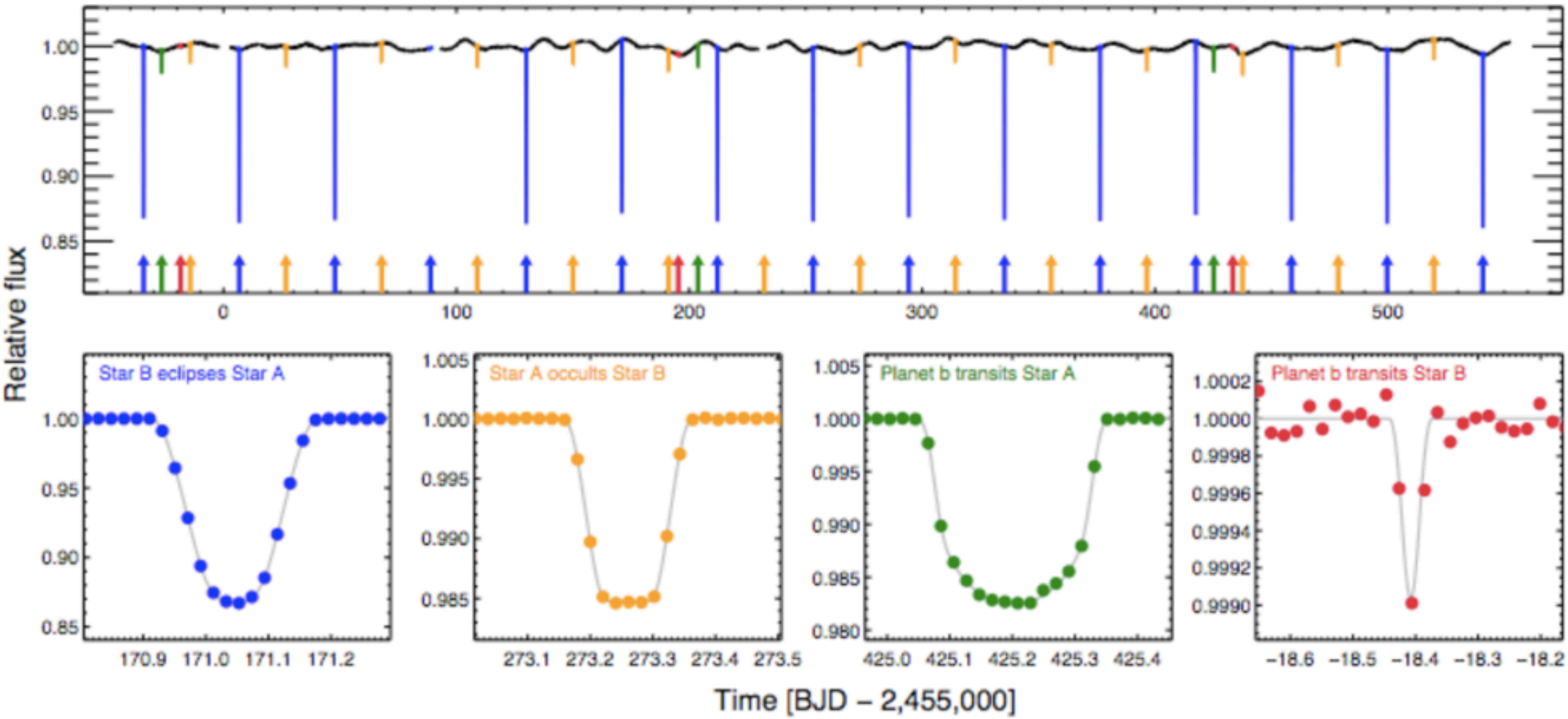


Kepler-16: A Transiting Circumbinary Planet

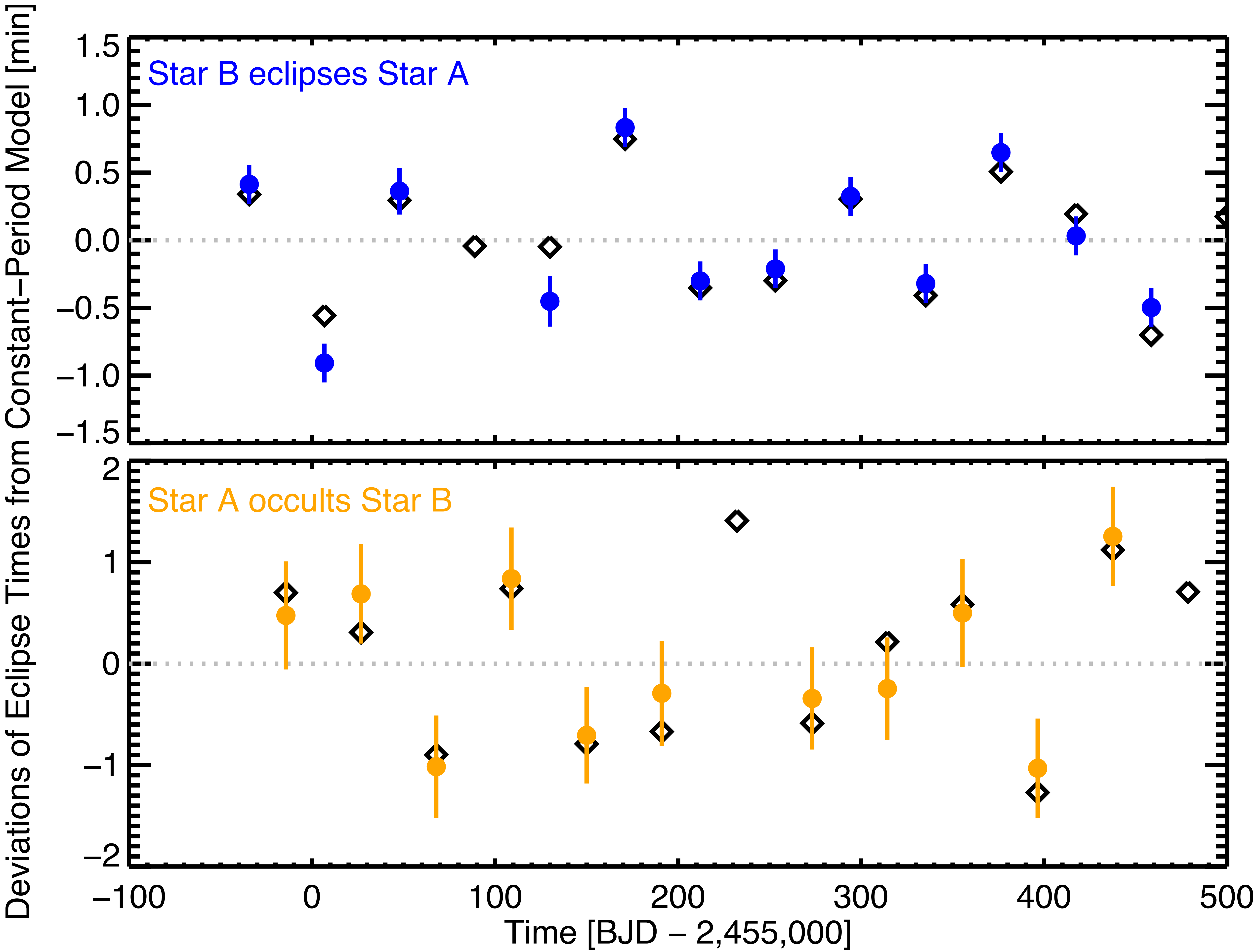




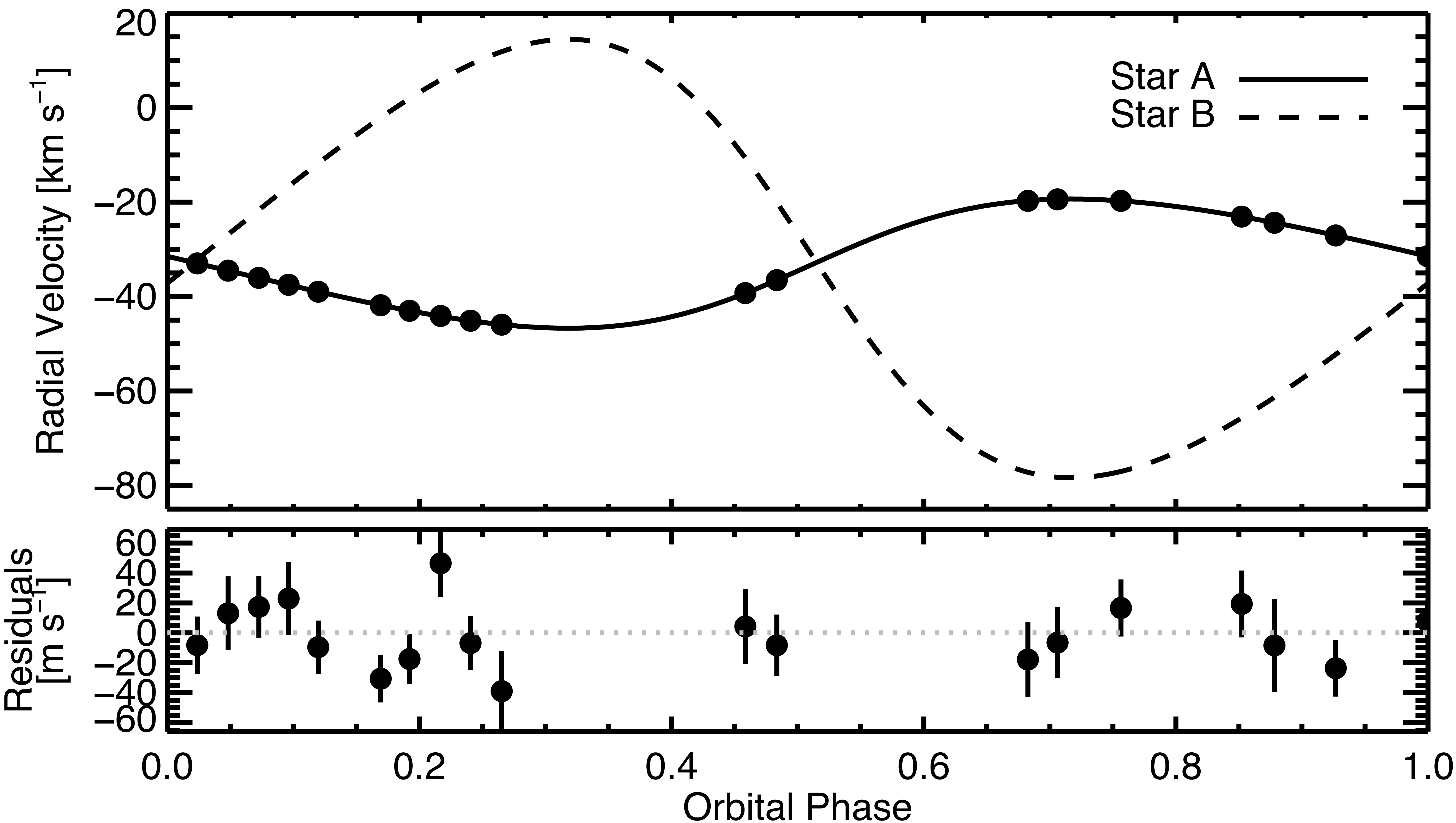
b
To Earth
B
A
0.5 AU
Orbit scale
Sun
Jupiter
Saturn
Planet Size scale

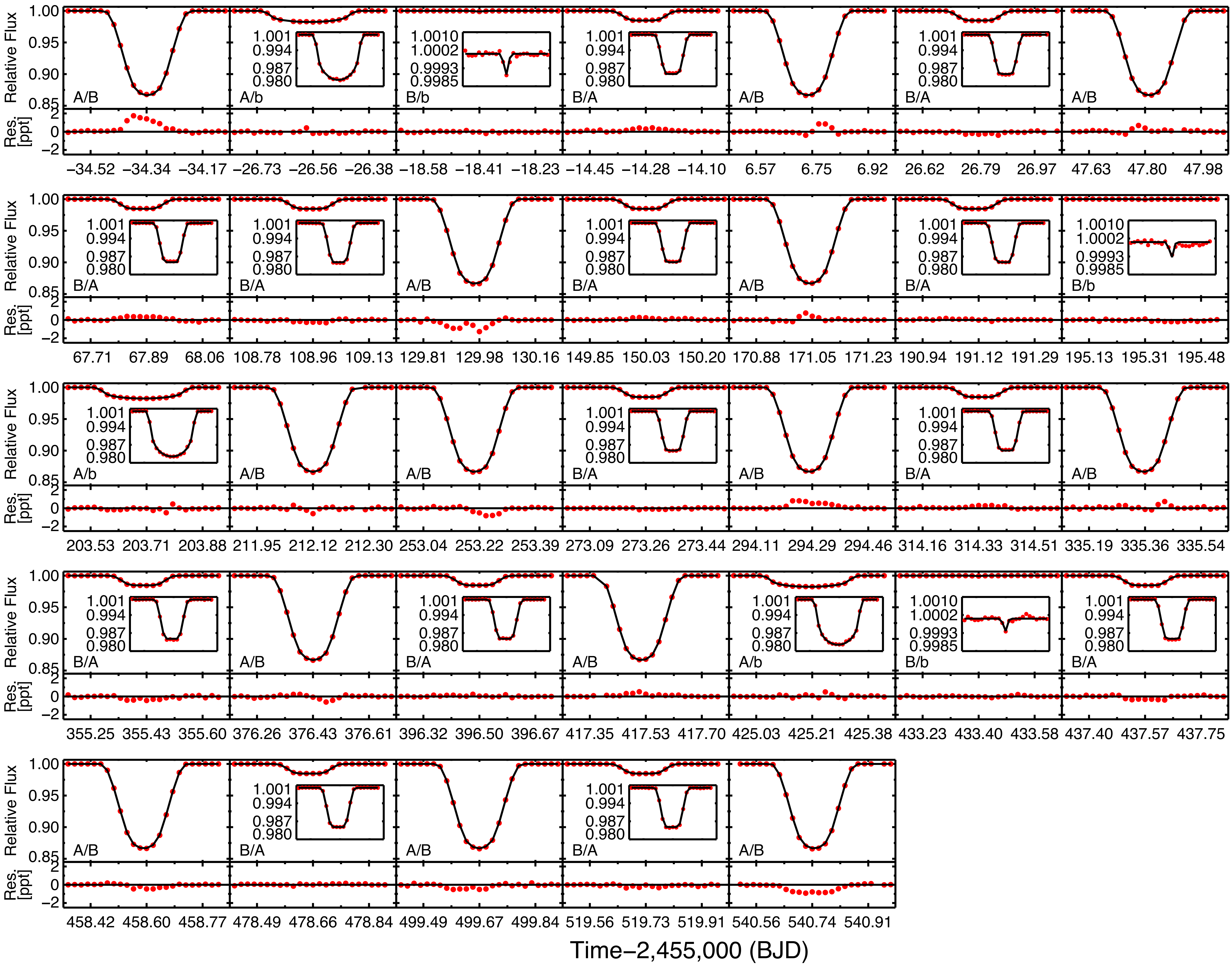


Relative flux
Star B eclipses Star A
Star A occults Star B
Planet b transits Star A
Planet b transits Star B
Time [BJD – 2,455,000]

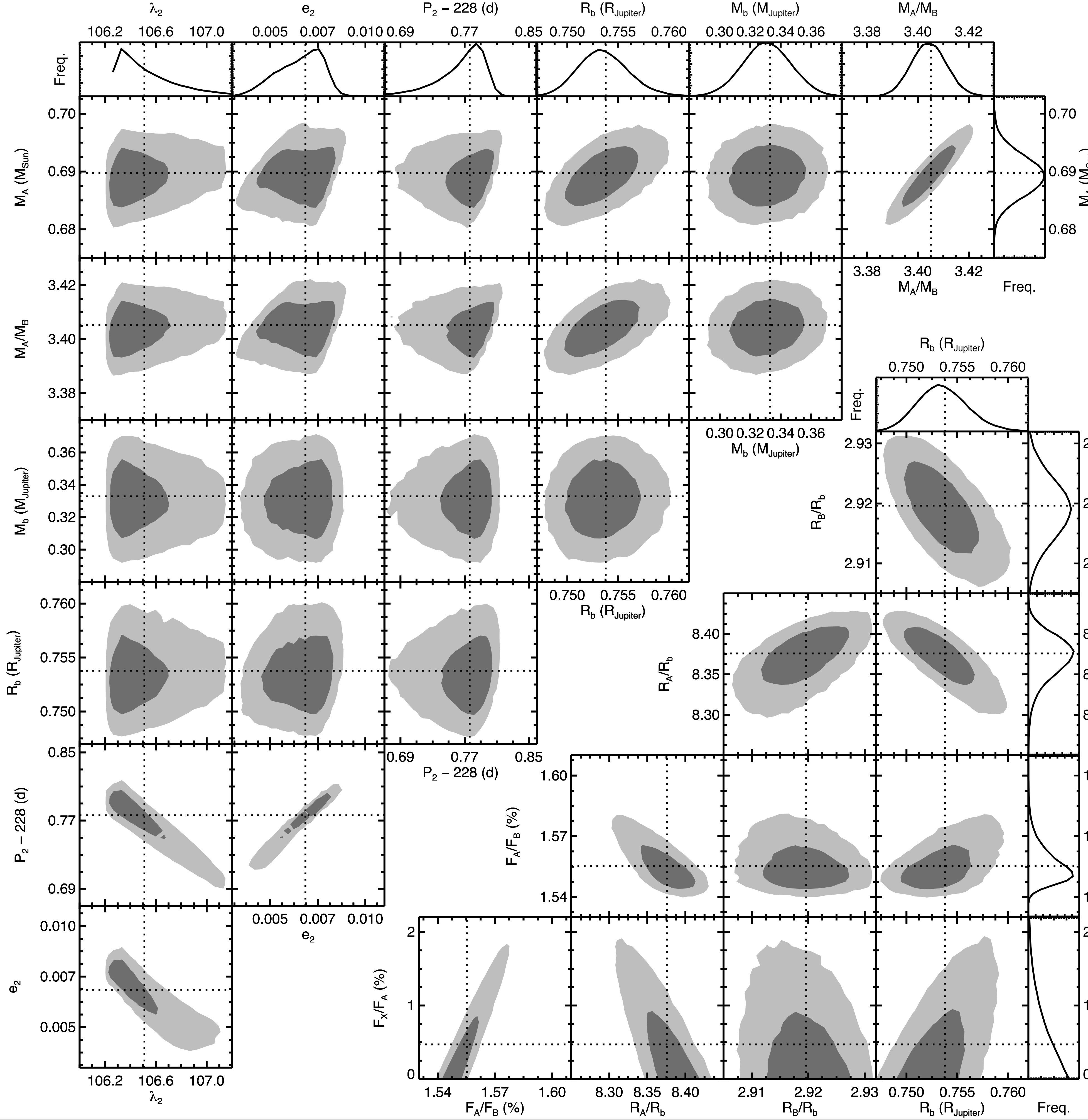


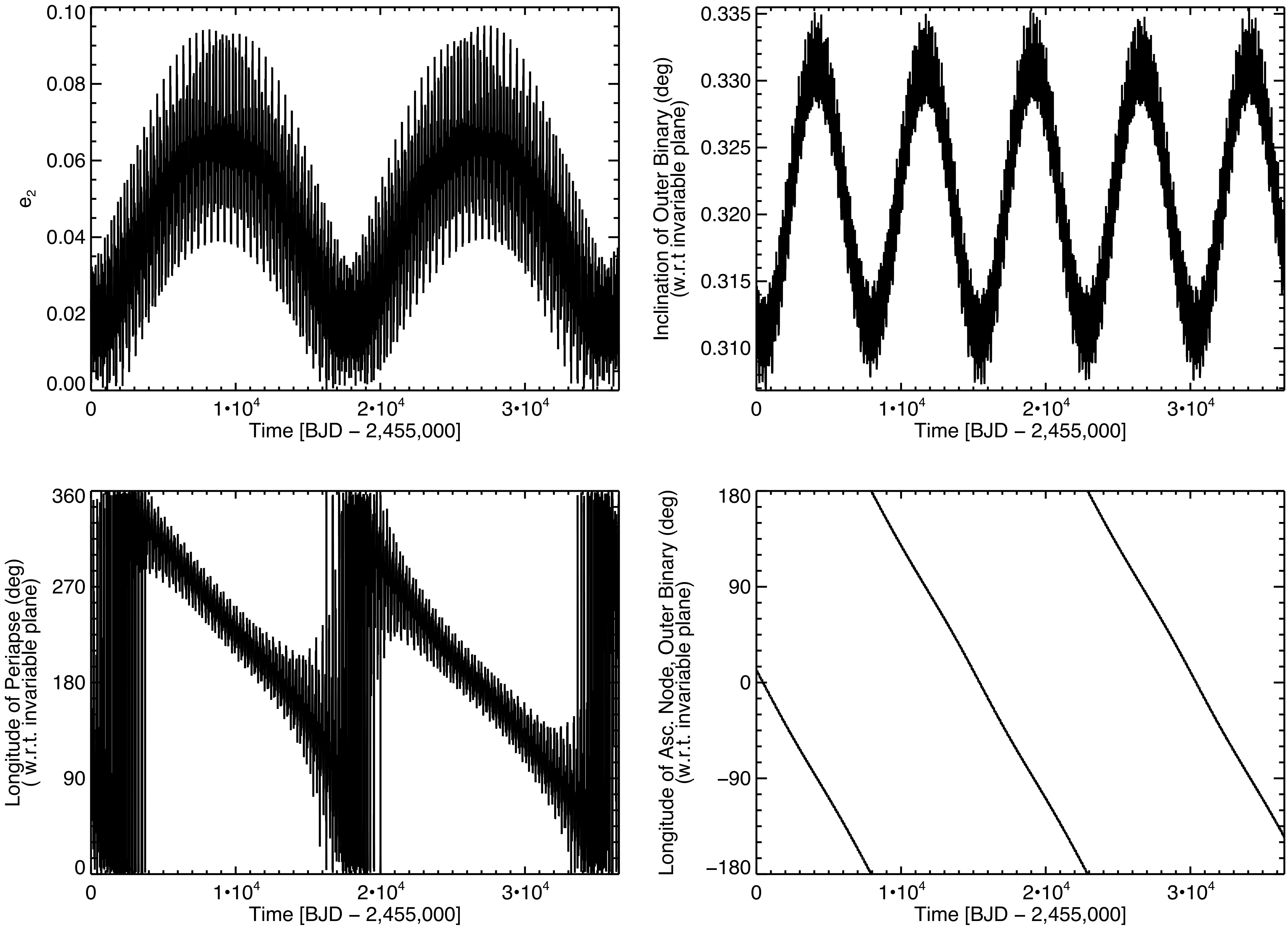
Star B eclipses Star A
Star A occults Star B
Deviations of Eclipse Times from Constant–Period Model [min]
Time [BJD – 2,455,000]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
2
1
0
−1
−2
−100
0
100
200
300
400
500


Star A
Star B
Radial Velocity [km s^{-1}]
20
0
−20
−40
−60
−80
Residuals [m s^{-1}]
60
40
20
0
−20
−40
−60
0.0
0.2
0.4
0.6
0.8
1.0
Orbital Phase

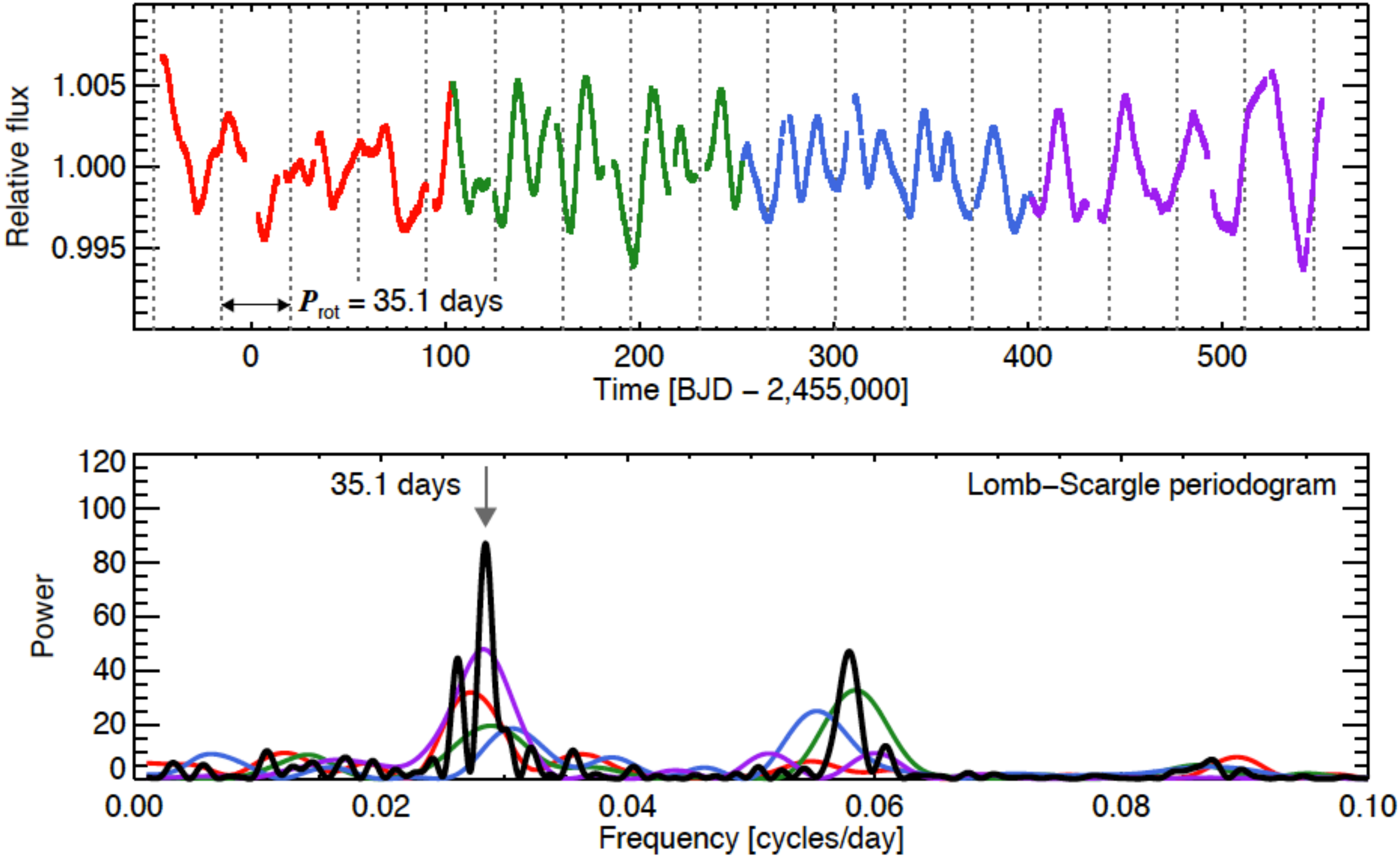


Tuesday, February 7, 2012


λ2
e2
P2 – 228 (d)
Rb (RJupiter)
Mb (MJupiter)
MA/MB
MA (MSun)
Freq.
RB/Rb
RA/Rb
FA/FB (%)
FX/FA (%)
λ2
106.2
106.6
107.0
0.005
0.007
0.010
0.69
0.77
0.85
0.750
0.755
0.760
0.30
0.32
0.34
0.36
3.38
3.40
3.42
0.68
0.69
0.70
2.91
2.92
2.93
8.30
8.35
8.40
1.54
1.57
1.60
0
1
2



0.10
0.08
0.06
0.04
0.02
0.00
e_2
0
1•10^4
2•10^4
3•10^4
Time [BJD – 2,455,000]
0.335
0.330
0.325
0.320
0.315
0.310
Inclination of Outer Binary (deg)
(w.r.t invariable plane)
0
1•10^4
2•10^4
3•10^4
Time [BJD – 2,455,000]
360
270
180
90
0
Longitude of Periapse (deg)
(w.r.t. invariable plane)
0
1•10^4
2•10^4
3•10^4
Time [BJD – 2,455,000]
180
90
0
–90
–180
Longitude of Asc. Node, Outer Binary (deg)
(w.r.t. invariable plane)
0
1•10^4
2•10^4
3•10^4
Time [BJD – 2,455,000]



$$\sin i = (v \sin i) / (2\pi R/P_{rot}) = 0.994$$

Winn et al. (2011)