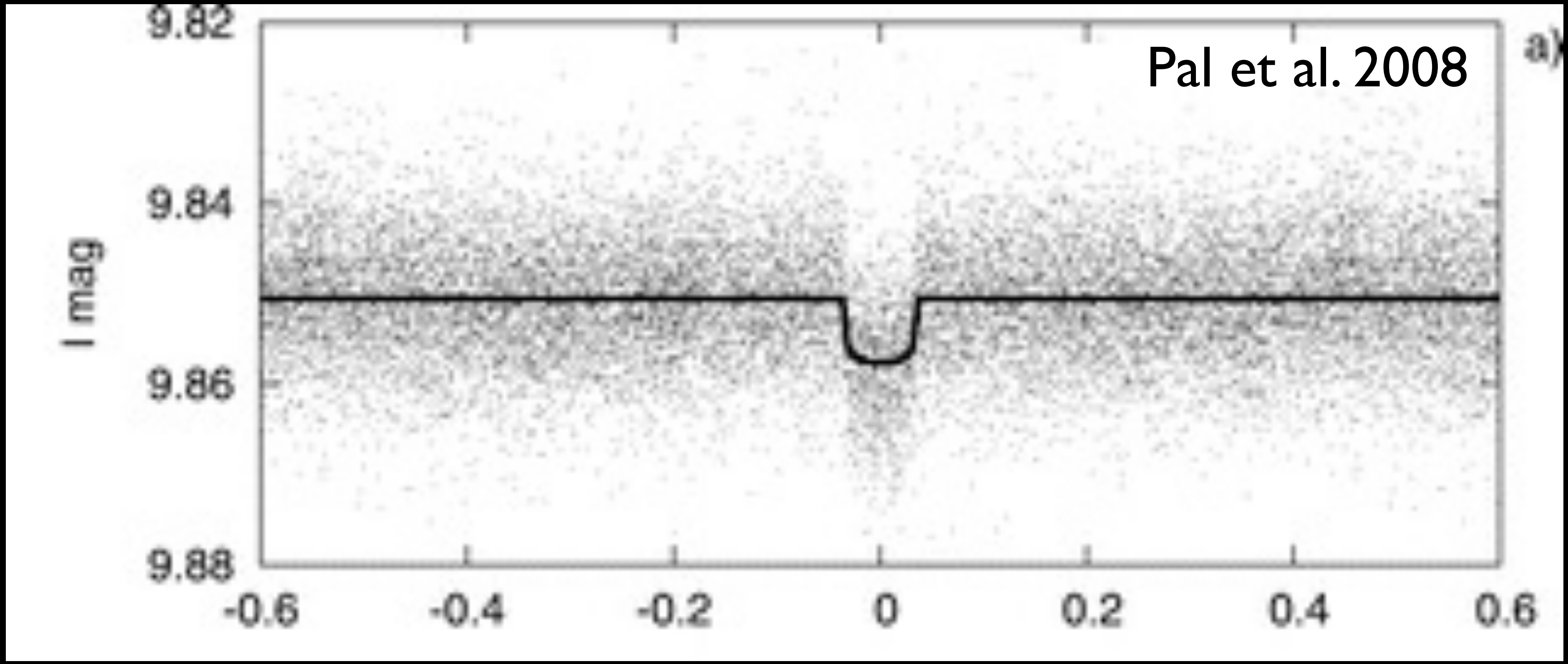
Doing *More* with Photometry

Studying binary companions with **photometric orbital modulations**

Avi Shporer
UCSB, LCOGT

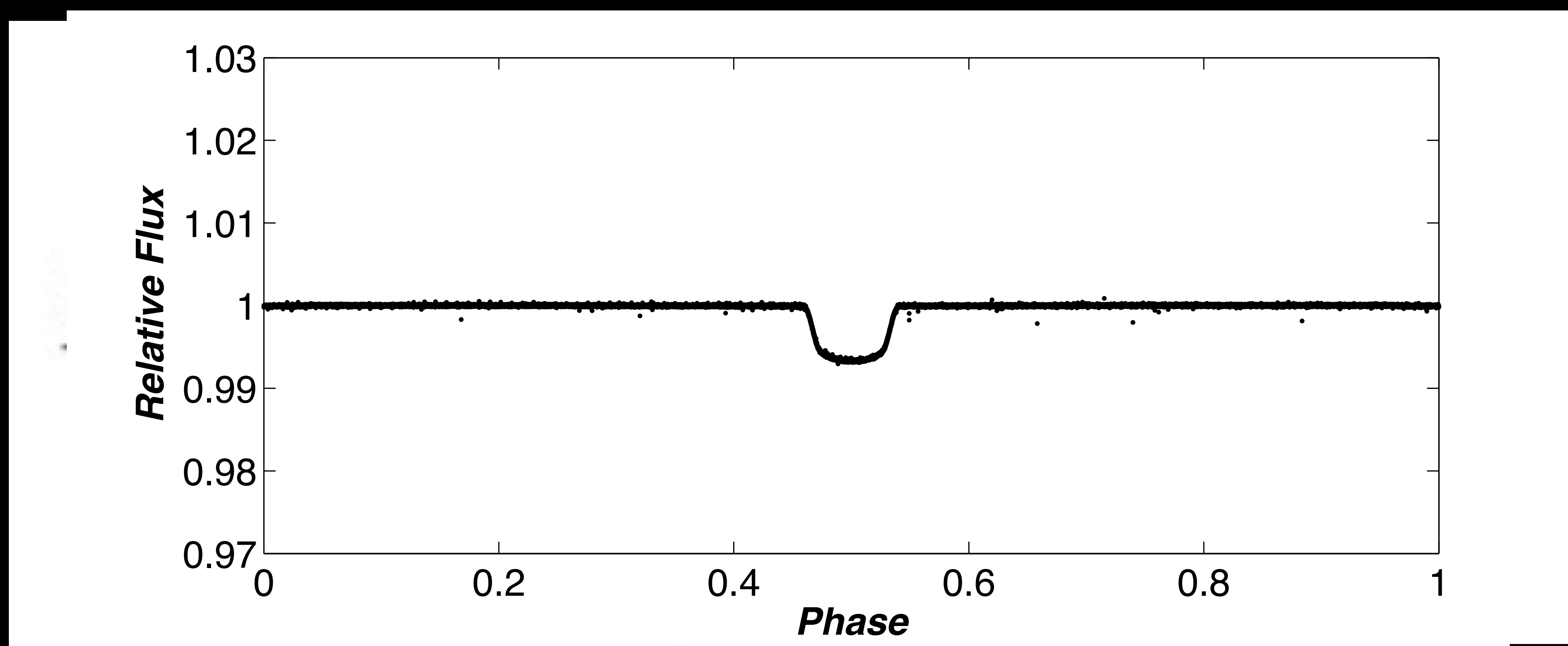
Sagan Summer Workshop
July 24 2012

Ground-based survey data

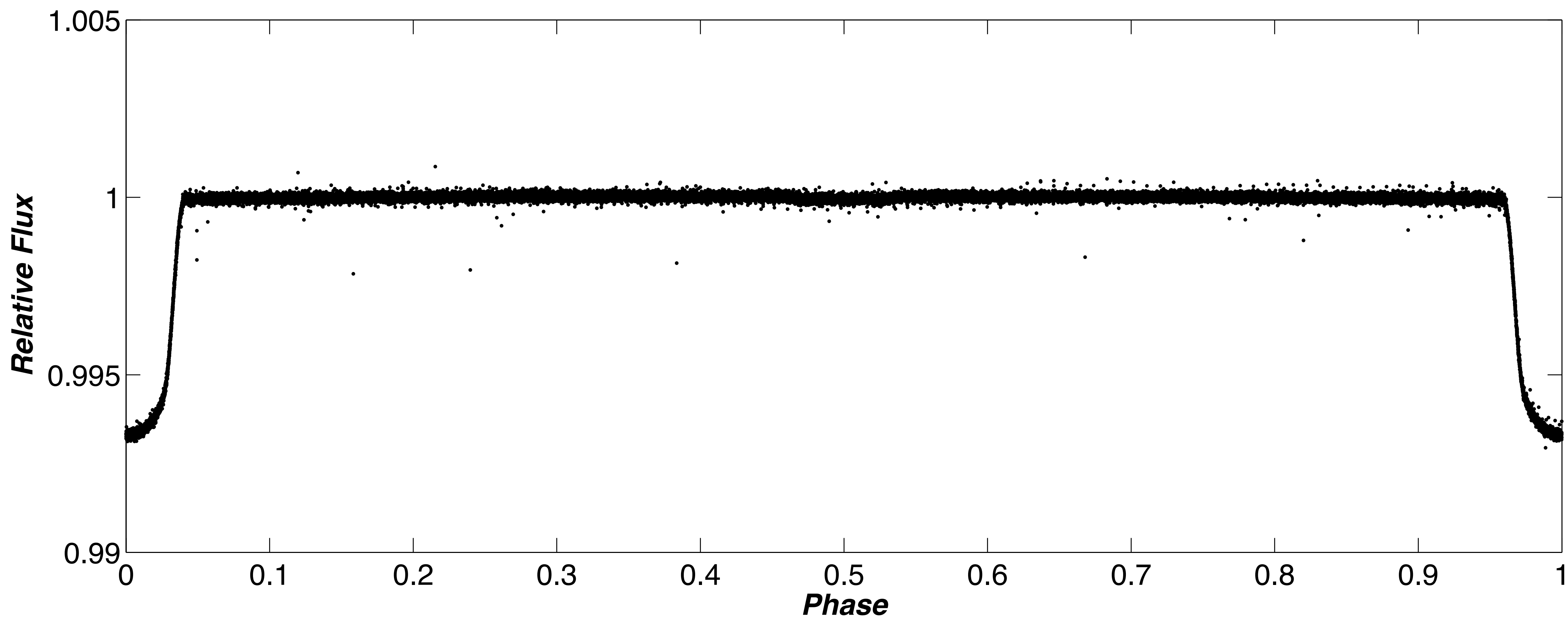


HAT-P-7b

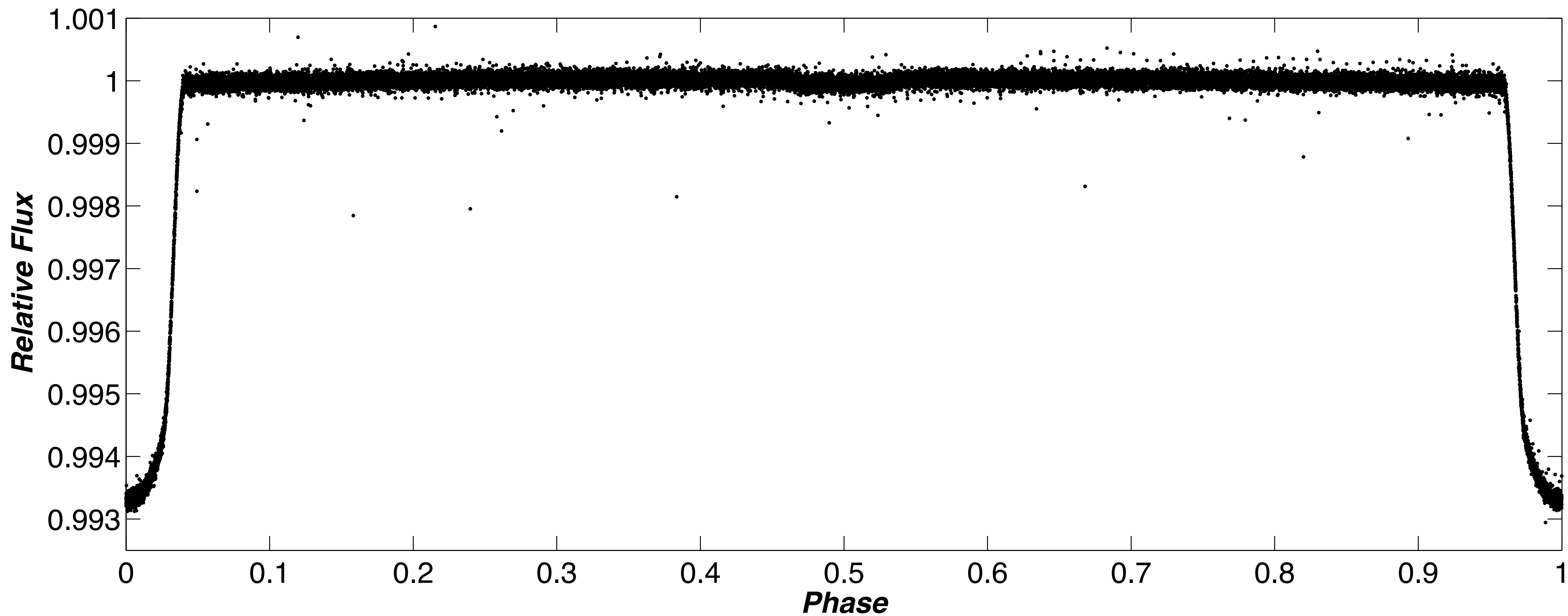
Space-based survey data

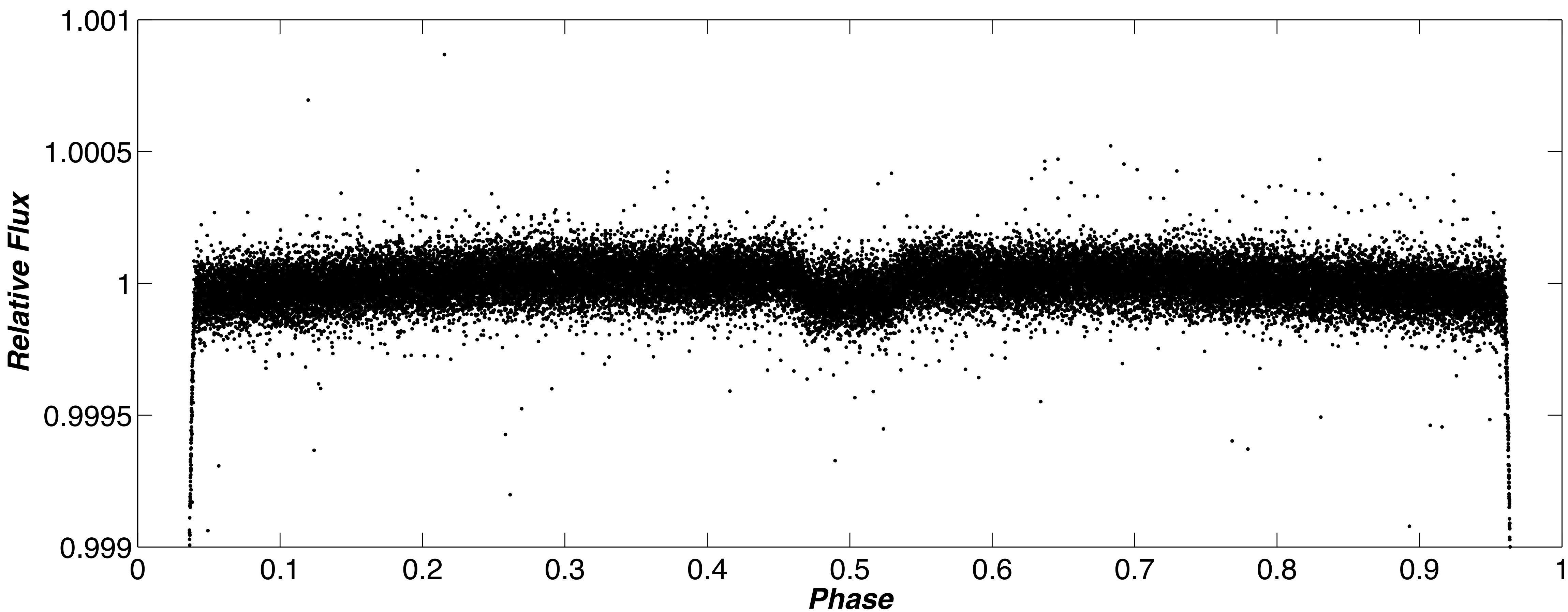


HAT-P-7b

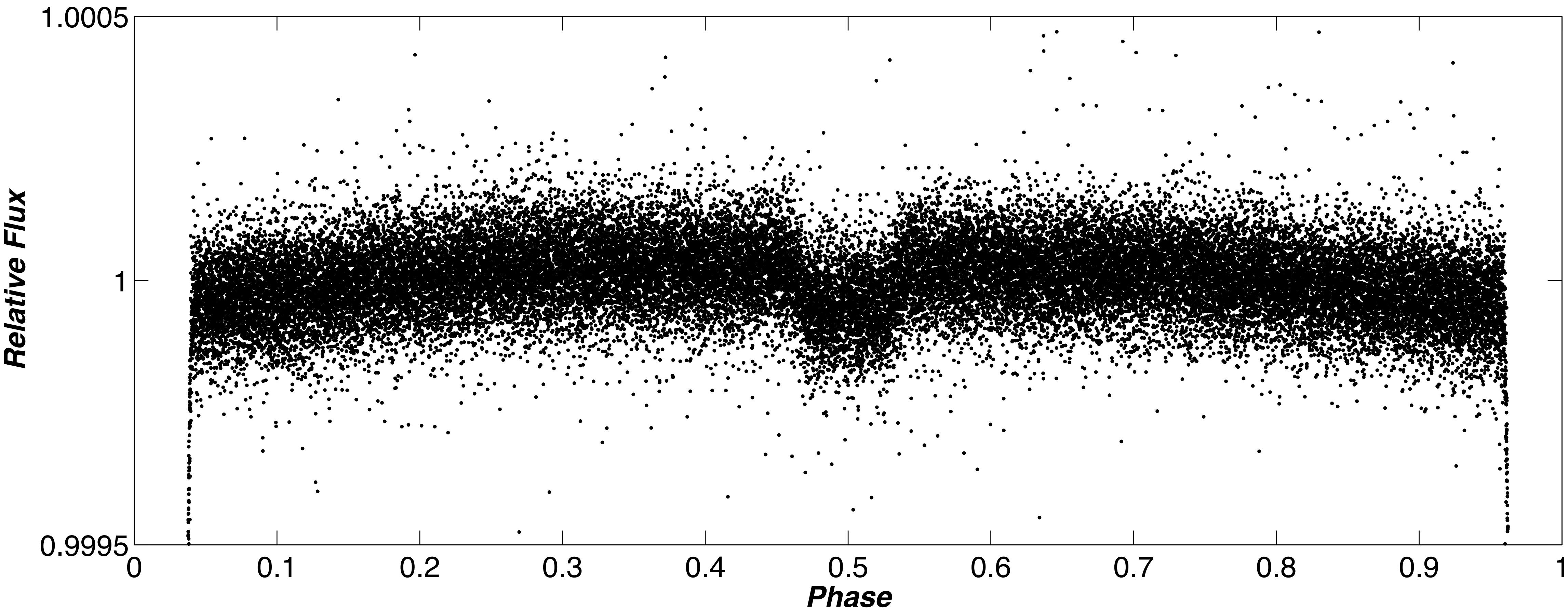


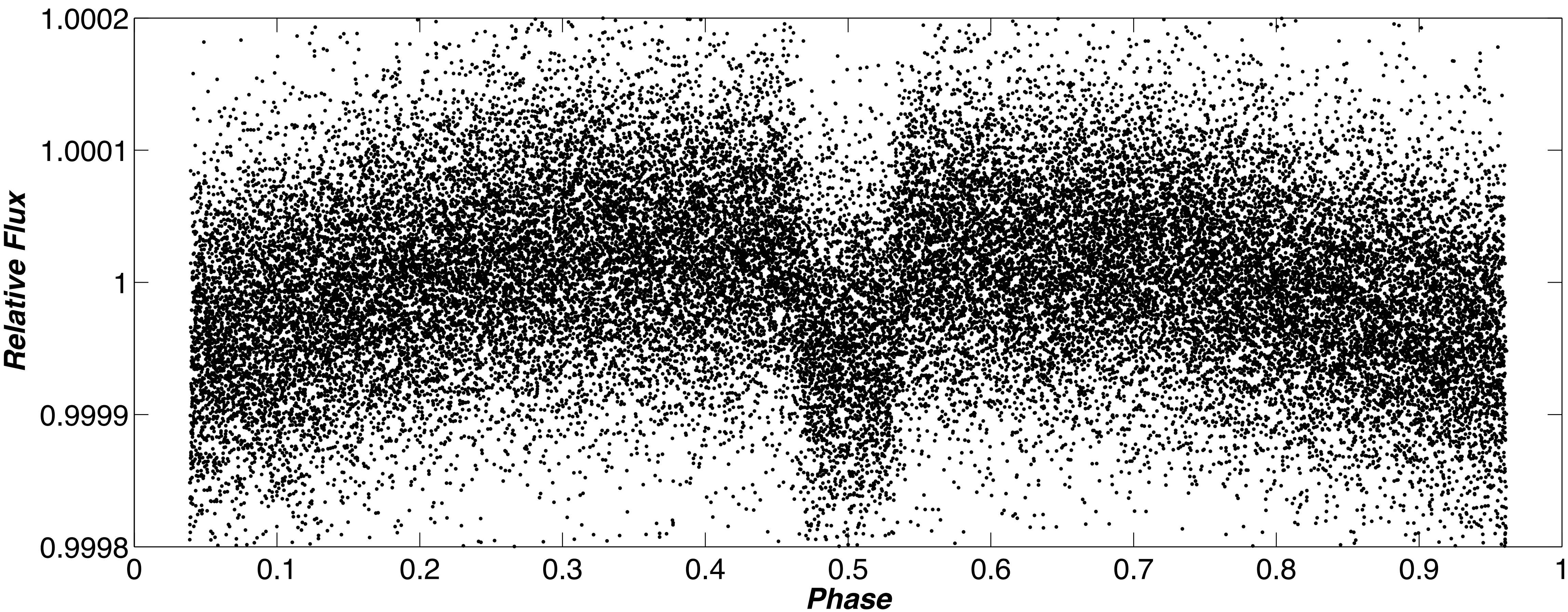
1.005
1
0.995
0.99
Relative Flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Phase

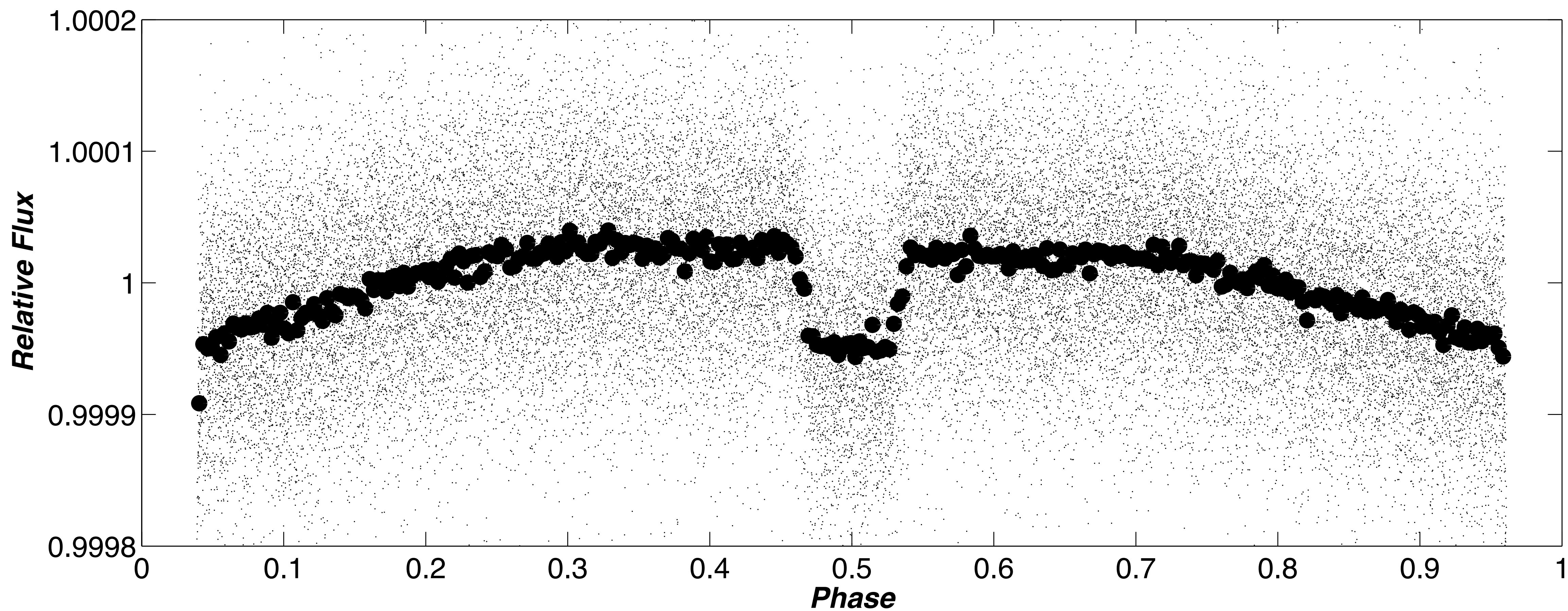

1.001
1
0.999
0.998
0.997
0.996
0.995
0.994
0.993
Relative Flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Phase



1.001
1.0005
1
0.9995
0.999
Relative Flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Phase


1.0005
1
0.9995
Relative Flux
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Phase

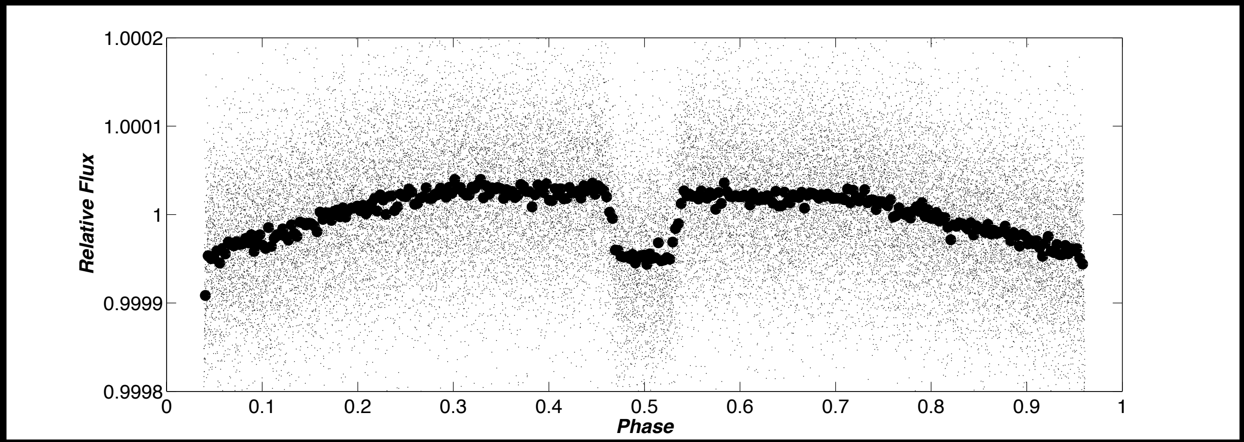

1.0002
1.0001
1
0.9999
0.9998
Relative Flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Phase



1.0002
1.0001
1
0.9999
0.9998
Relative Flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Phase

Photometric variability correlated with the orbit:

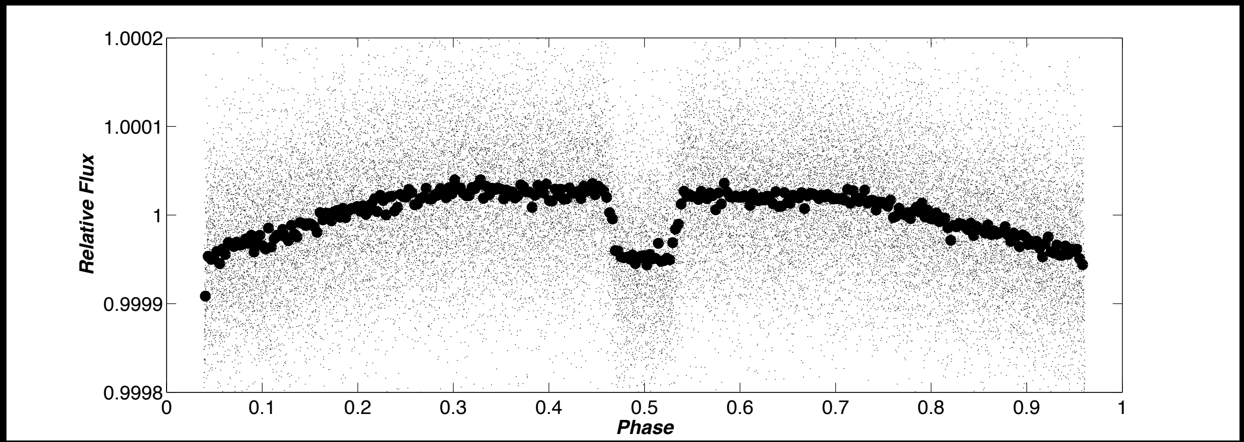
Loeb & Gaudi 2003, Jenkins & Doyle 2003, Zucker et al. 2007, Pfahl et al. 2008



Photometric variability correlated with the orbit:

Loeb & Gaudi 2003, Jenkins & Doyle 2003, Zucker et al. 2007, Pfahl et al. 2008

- **Beaming**
- **Tidal ellipsoidal deformation**
- **Reflection/heating**



The Beaming Effect
aka Doppler Boosting

The Beaming Effect
aka Doppler Boosting

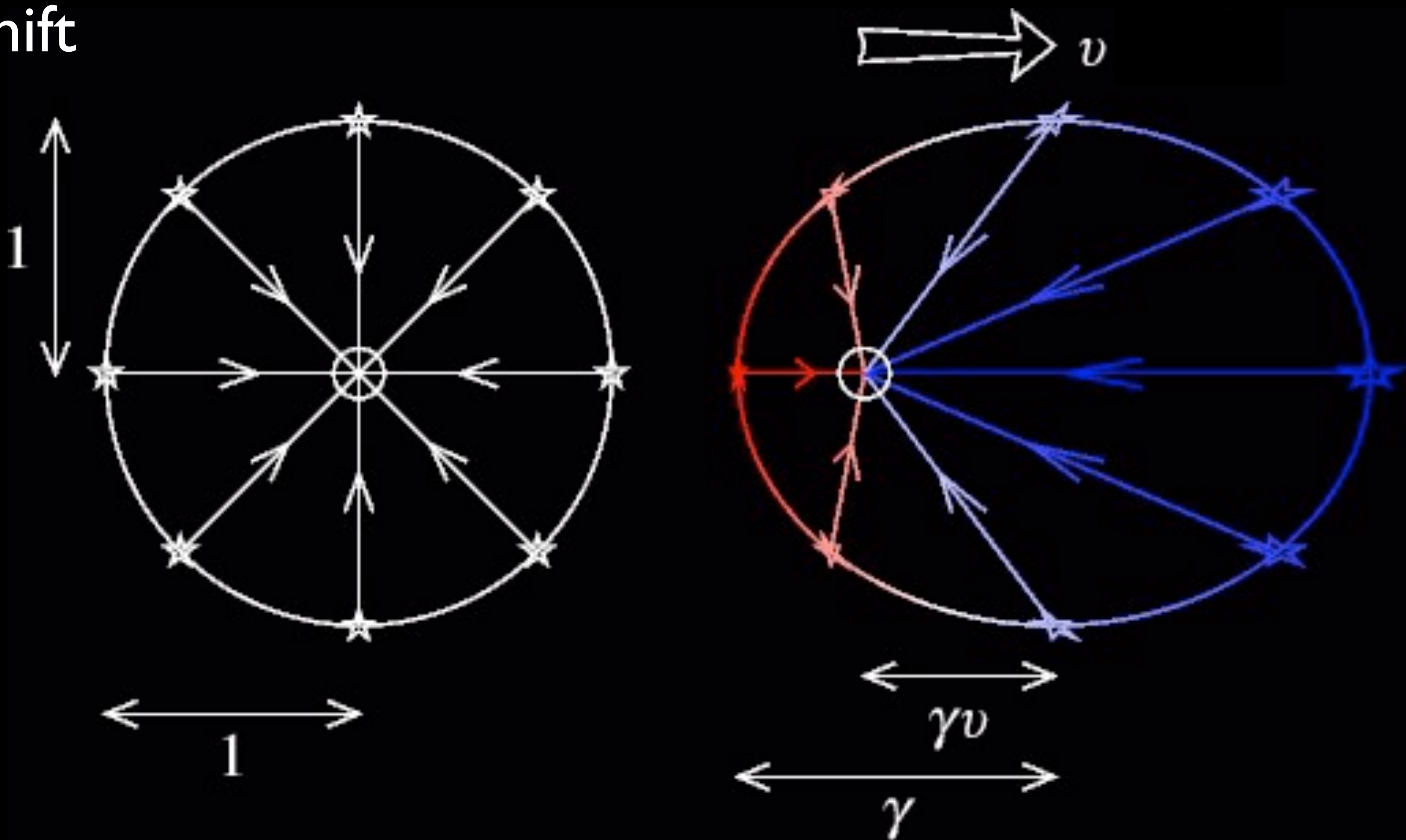
- Aberration
- Arrival rate

The Beaming Effect
aka Doppler Boosting

- Aberration
- Arrival rate
- Doppler shift

The Beaming Effect
aka Doppler Boosting

- Aberration
- Arrival rate
- Doppler shift



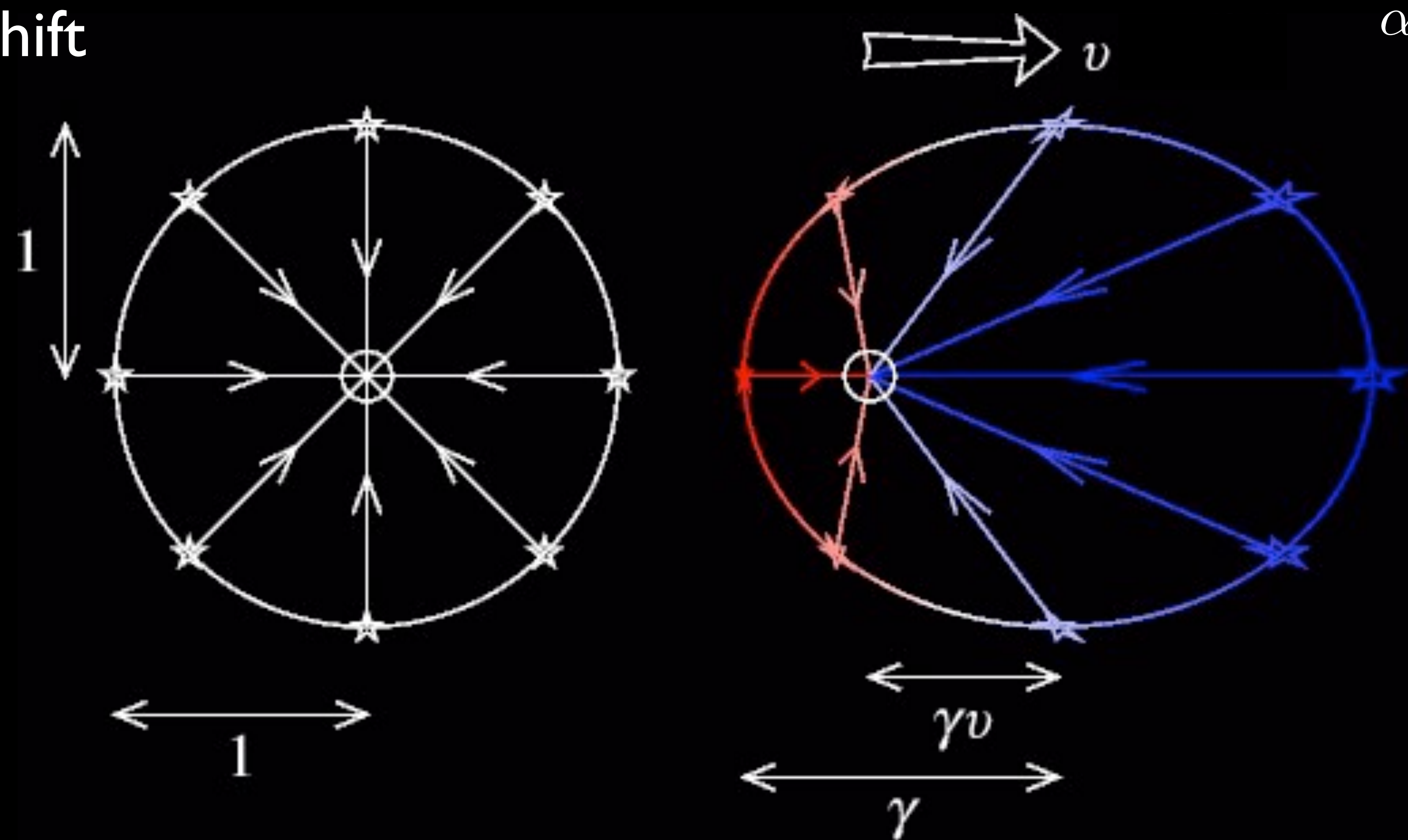
The Beaming Effect
aka Doppler Boosting

- Aberration
- Arrival rate
- Doppler shift

$$F_\nu = F_{\nu 0}[1 + (3-\alpha)\frac{v_r}{c}]$$

$$v_r \ll c$$

$$\alpha \equiv \frac{d \log F_\nu}{d \log \nu}$$



The Beaming Effect
aka Doppler Boosting

The Beaming Effect
aka Doppler Boosting

radial velocity
variation

The Beaming Effect
aka Doppler Boosting

radial velocity variation → variation in observed flux

The Beaming Effect
aka Doppler Boosting

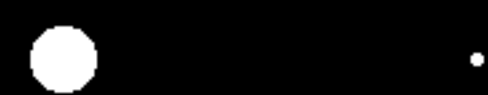
radial velocity variation ⇨ variation in observed flux

Photometric variation following orbital motion

The Beaming Effect
aka Doppler Boosting

radial velocity variation $\Rightarrow$ variation in observed flux

Photometric variation following orbital motion



The Beaming Effect
aka Doppler Boosting

radial velocity variation $\Rightarrow$ variation in observed flux

Photometric variation following orbital motion

$$A_{\mathrm{beam}} = \alpha_{\mathrm{beam}} 4 \frac{K_{RV}}{c}$$

The Beaming Effect

aka Doppler Boosting

radial velocity variation

variation in observed flux

Photometric variation following orbital motion

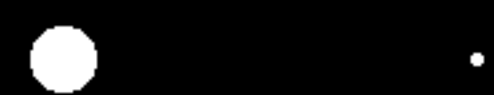
$$A_{\rm beam} = \alpha_{\rm beam} 4 \frac{K_{RV}}{c}$$

bolometric $\alpha_{\rm beam} = 1$

The Beaming Effect
aka Doppler Boosting

radial velocity variation $\Rightarrow$ variation in observed flux

Photometric variation following orbital motion



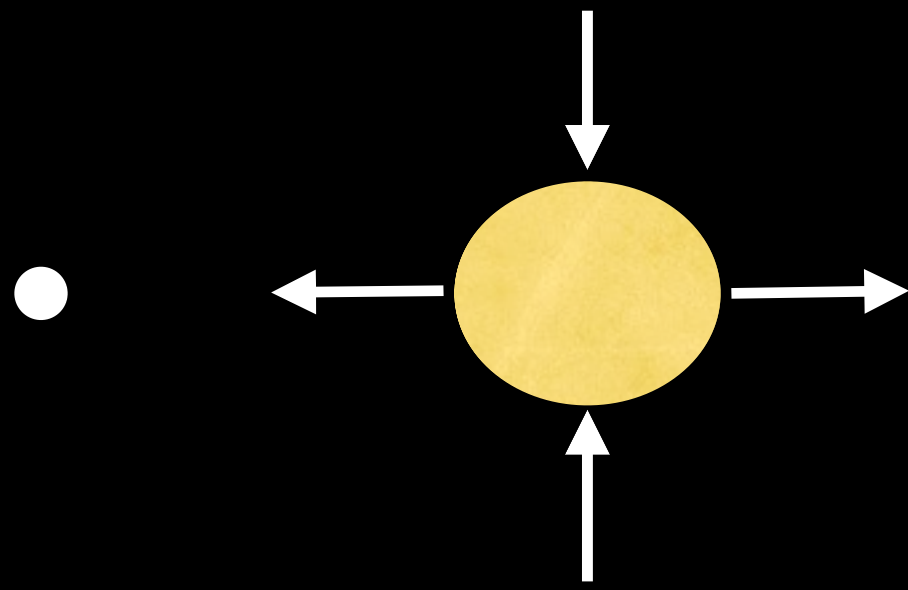
$$A_{\mathrm{beam}} = \alpha_{\mathrm{beam}} 4 \frac{K_{RV}}{c}$$

bolometric $\alpha_{\mathrm{beam}} = 1$

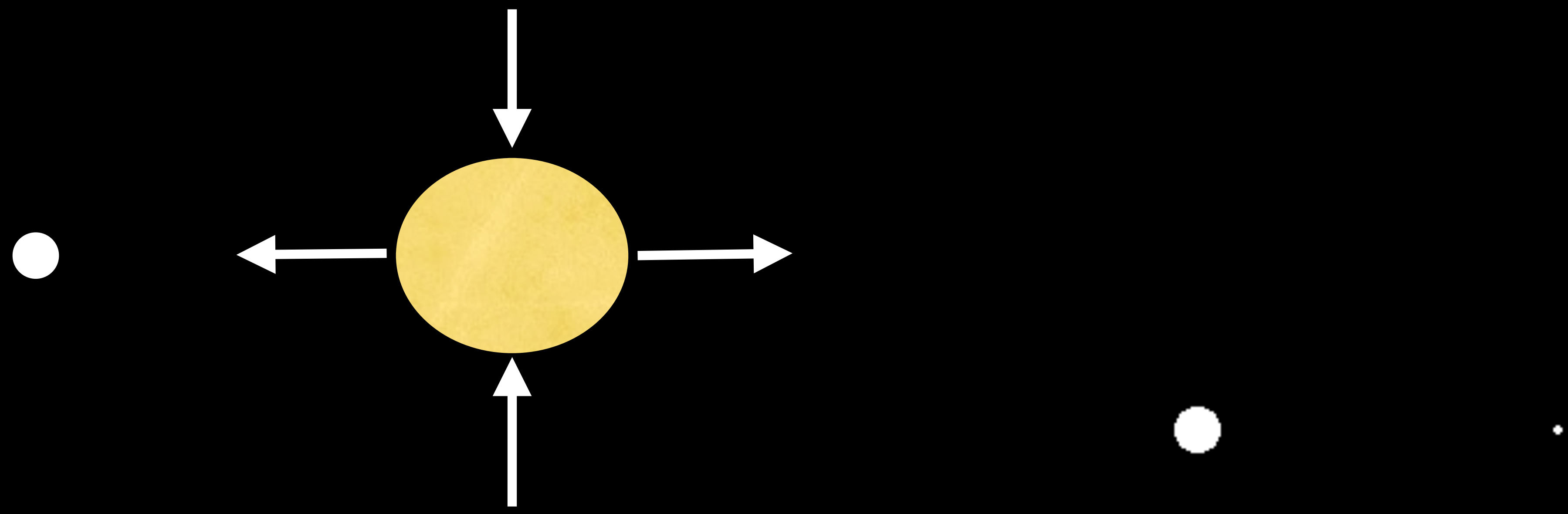
$$A_{\mathrm{beam}} = 2.7\ \alpha_{\mathrm{beam}} \left(\frac{M_s}{M_{sun}}\right)^{-2/3} \left(\frac{P_{orb}}{\mathrm{day}}\right)^{-1/3} \left(\frac{M_2 \sin i}{M_J}\right)\ \mathrm{ppm}$$

Tidal Ellipsoidal Deformation

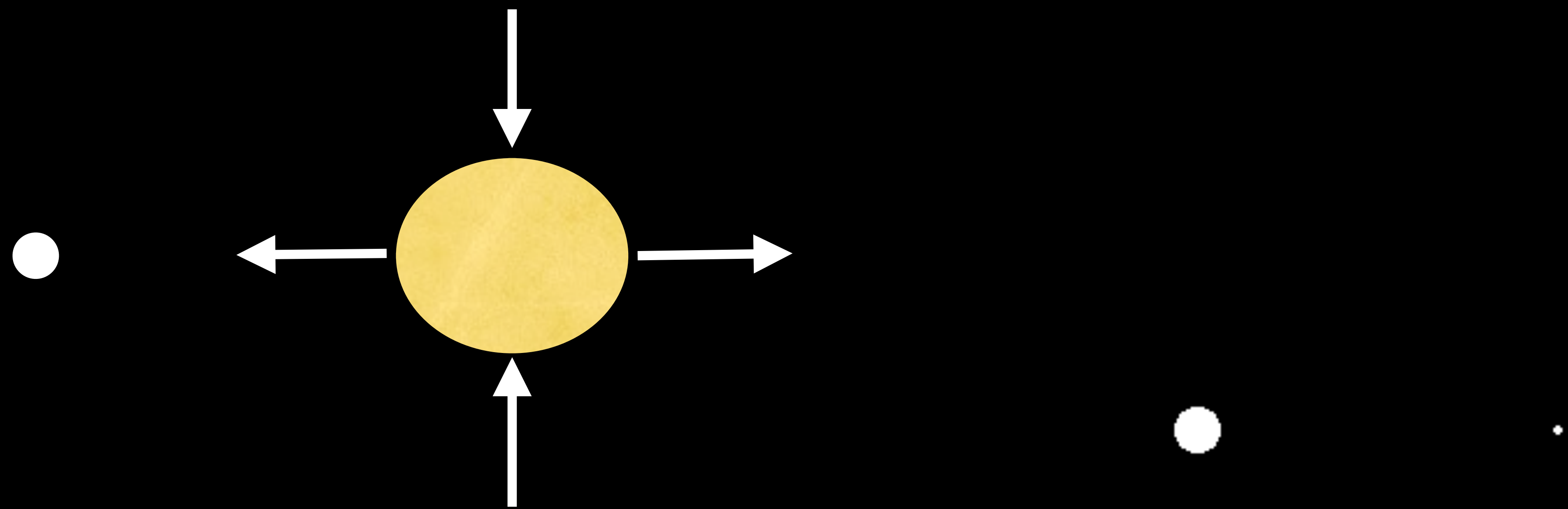
Tidal Ellipsoidal Deformation



Tidal Ellipsoidal Deformation

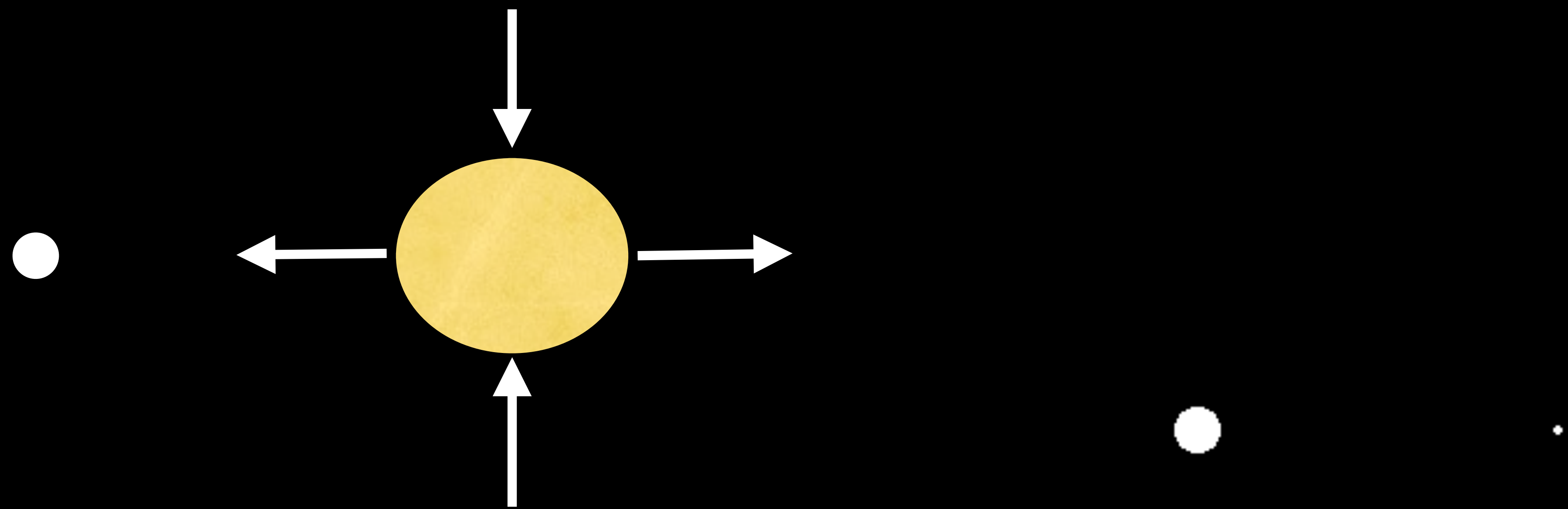


Tidal Ellipsoidal Deformation



$$A_{\rm ellip} = \alpha_{\rm ellip} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a} \right)^3 \sin i$$

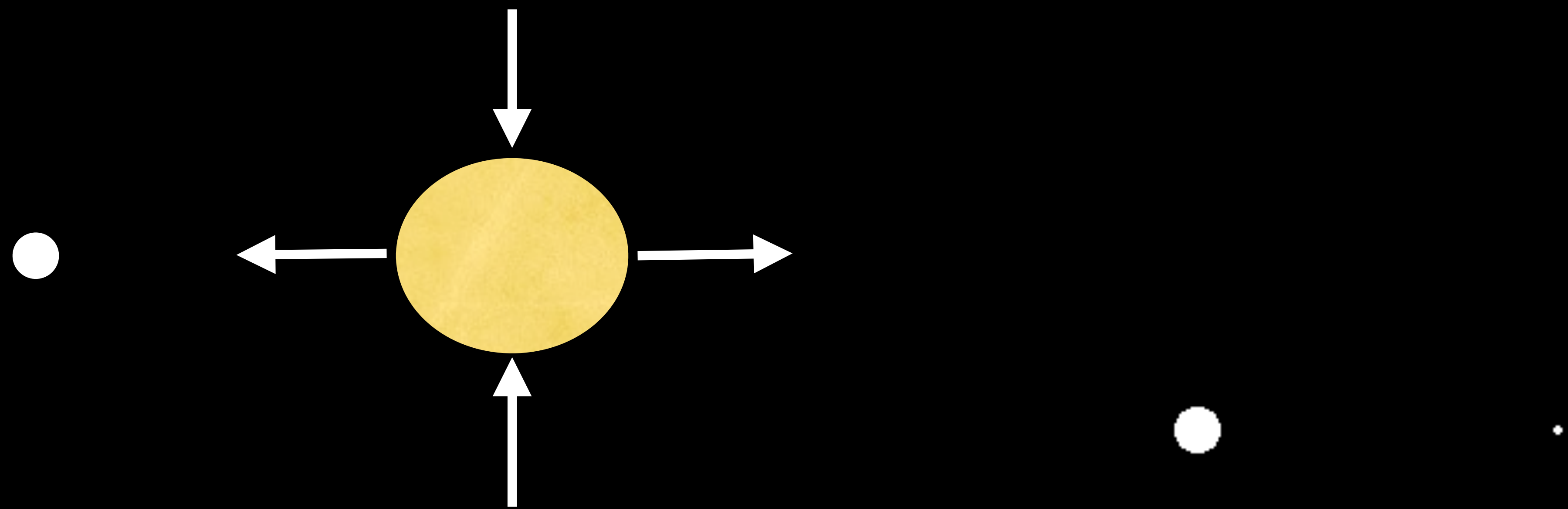
Tidal Ellipsoidal Deformation



$$A_{\rm ellip} = \alpha_{\rm ellip} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

$$A_{\rm ellip} = 13\ \alpha_{\rm ellip} \sin i \left(\frac{R_s}{R_{sun}}\right)^3 \left(\frac{M_s}{M_{sun}}\right)^{-2} \left(\frac{P_{orb}}{\rm day}\right)^{-2} \left(\frac{M_2 \sin i}{M_J}\right)\ {\rm ppm}$$

Tidal Ellipsoidal Deformation

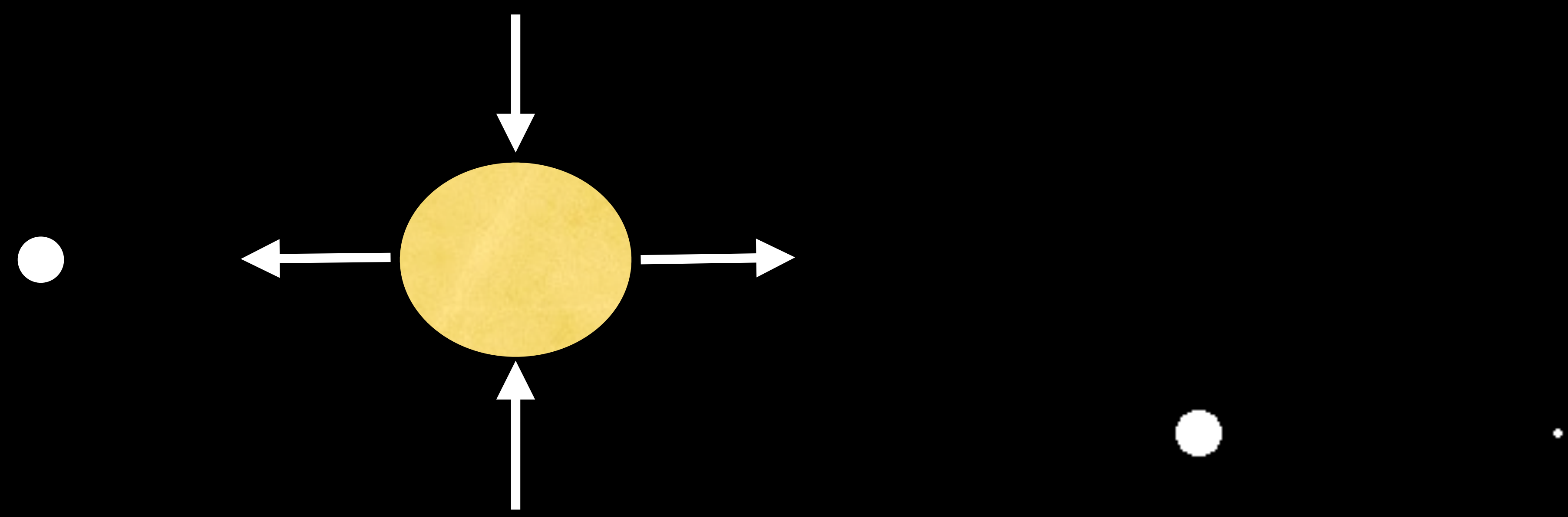


$$A_{\rm ellip} = \alpha_{\rm ellip} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

$$A_{\rm ellip} = 13\ \alpha_{\rm ellip} \sin i \left(\frac{R_s}{R_{sun}}\right)^3 \left(\frac{M_s}{M_{sun}}\right)^{-2} \left(\frac{P_{orb}}{\rm day}\right)^{-2} \left(\frac{M_2 \sin i}{M_J}\right) \ {\rm ppm}$$

$$\alpha_{\rm ellip} = 0.15 \frac{(15+u)(1+g)}{3-u}$$

Tidal Ellipsoidal Deformation



$$A_{\rm ellip} = \alpha_{\rm ellip} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

$$A_{\rm ellip} = 13\ \alpha_{\rm ellip} \sin i \left(\frac{R_s}{R_{sun}}\right)^3 \left(\frac{M_s}{M_{sun}}\right)^{-2} \left(\frac{P_{orb}}{\rm day}\right)^{-2} \left(\frac{M_2 \sin i}{M_J}\right) \ {\rm ppm}$$

$$\alpha_{\rm ellip} = 0.15 \frac{(15+u)(1+g)}{3-u}$$

gravity darkening

limb darkening

Reflection/Heating

Reflection/Heating

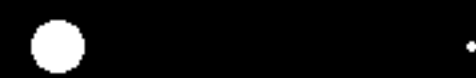
- Reflected light

Reflection/Heating

- Reflected light
- Thermal emission

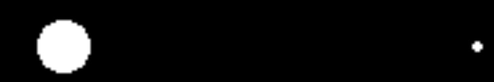
Reflection/Heating

- Reflected light
- Thermal emission



Reflection/Heating

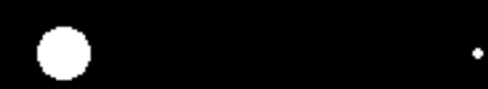
- Reflected light
- Thermal emission



$$A_{\text{refl}} = \alpha_{\text{refl}} 0.1 \left(\frac{R_2}{a} \right)^2 \sin i$$

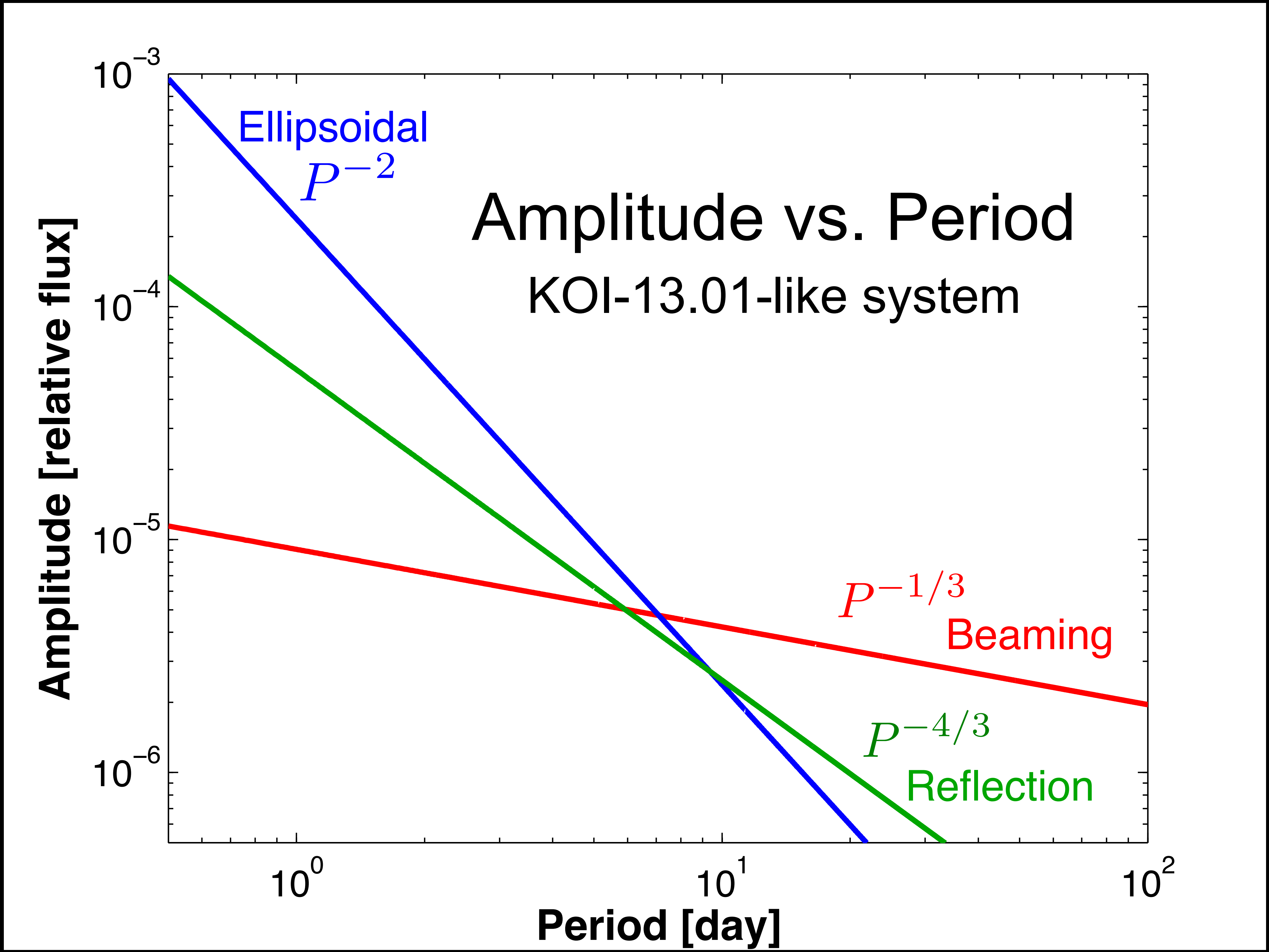
Reflection/Heating

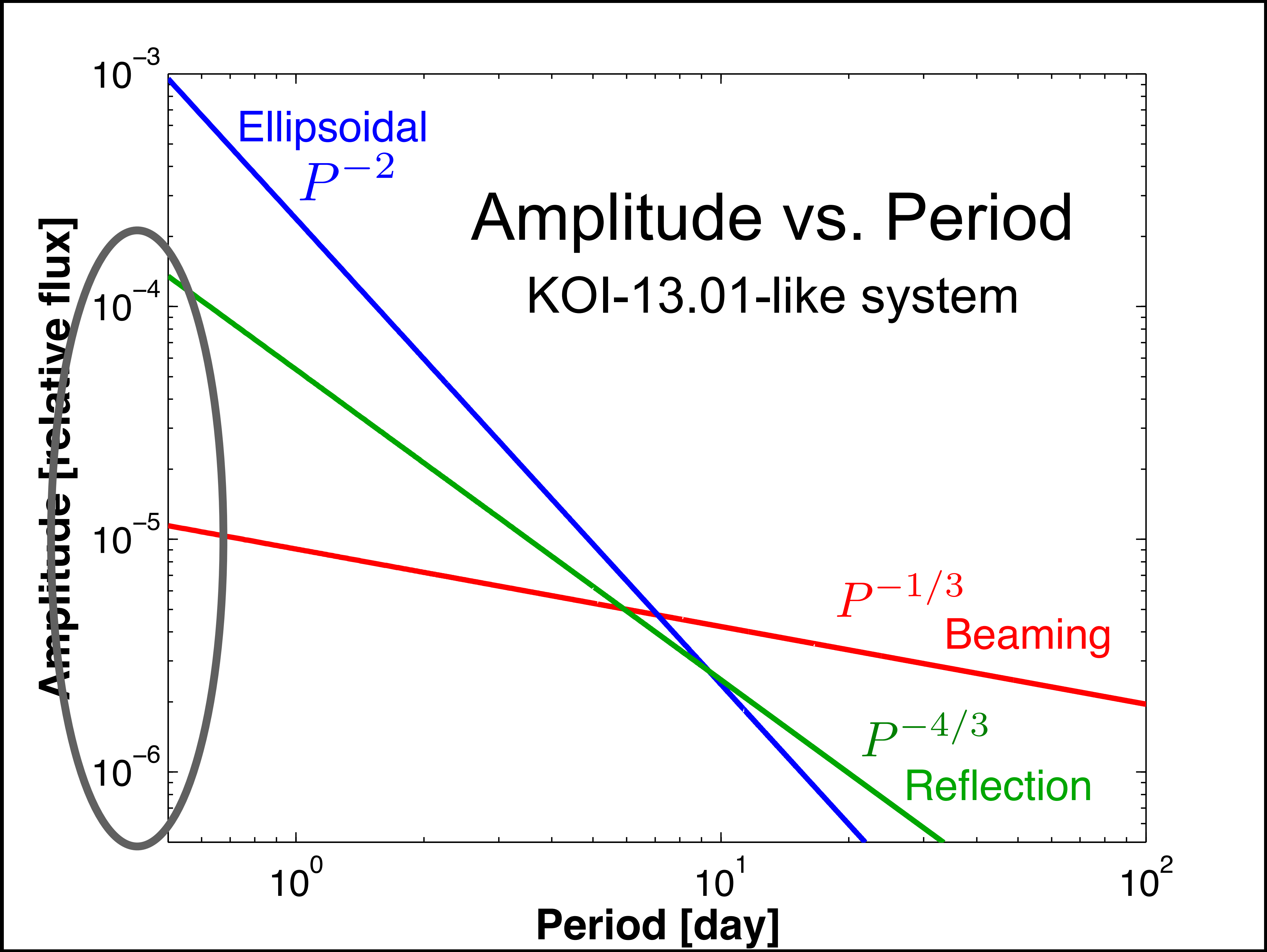
- Reflected light
- Thermal emission

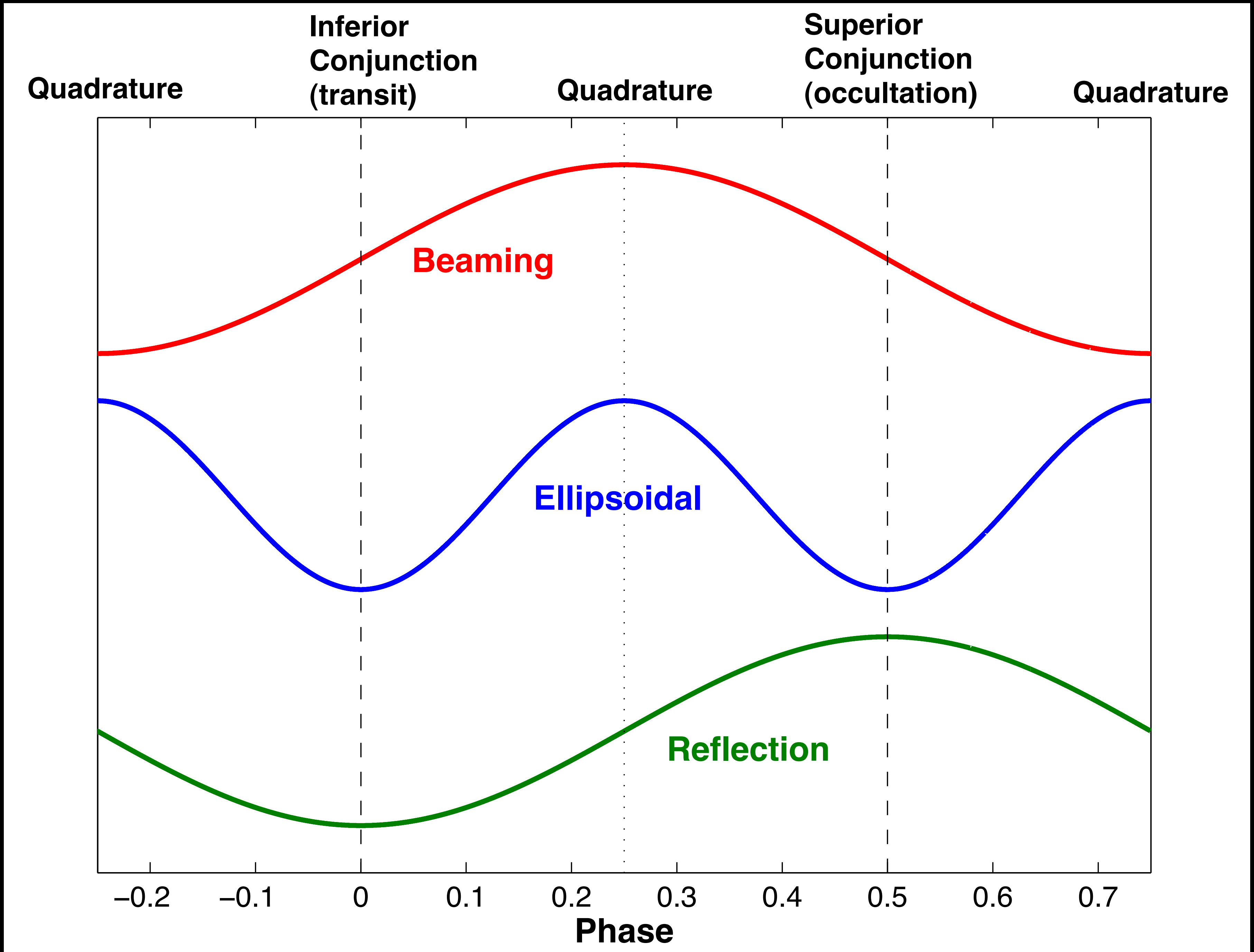


$$A_{\rm refl} = \alpha_{\rm refl} 0.1 \left(\frac{R_2}{a}\right)^2 \sin i$$

$$A_{\rm refl} = 57\ \alpha_{\rm refl} \sin i \left(\frac{M_s}{M_{sun}}\right)^{-2/3} \left(\frac{P_{orb}}{\rm day}\right)^{-4/3} \left(\frac{R_2}{R_J}\right)^2\ \rm ppm$$

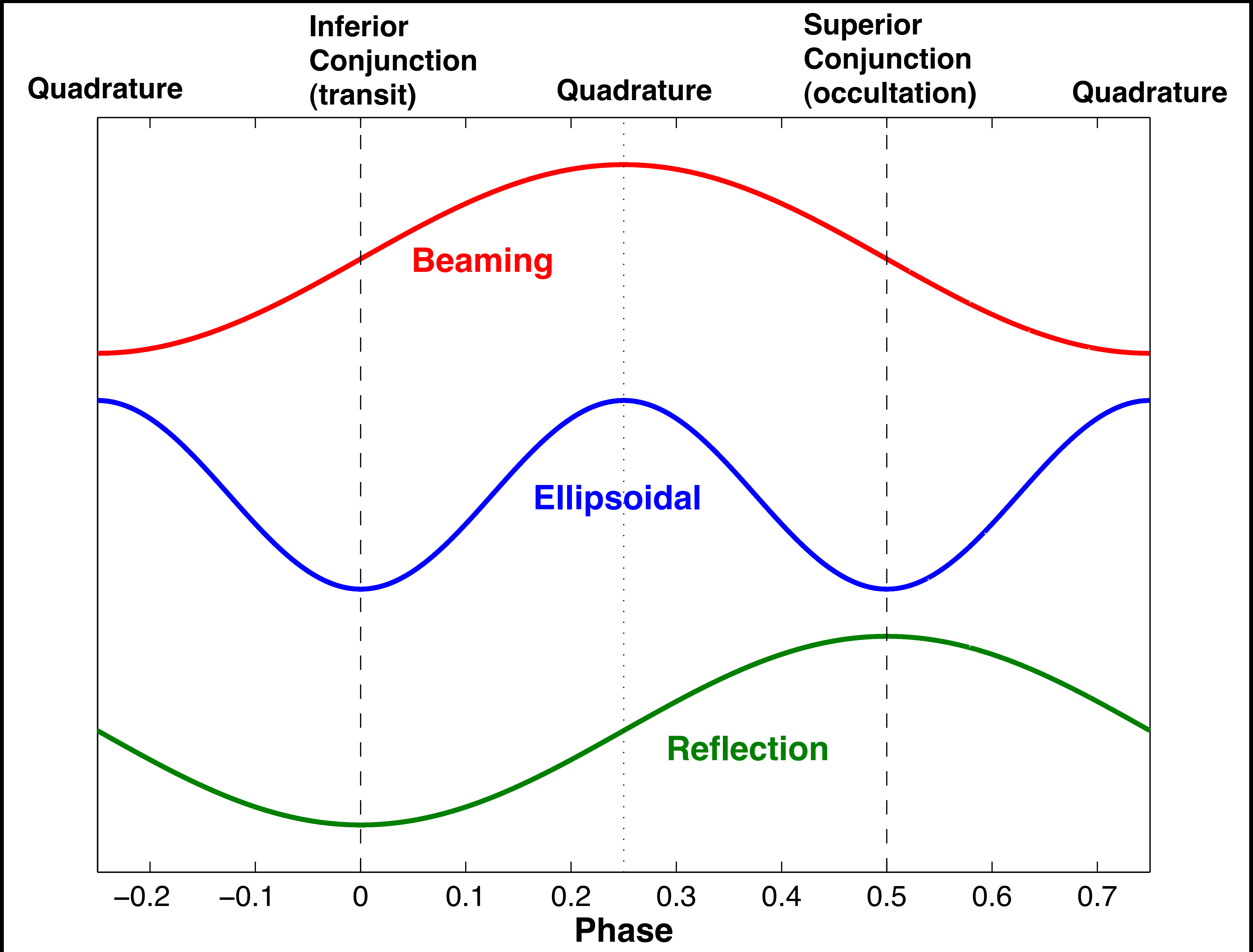

Amplitude vs. Period
KOI-13.01-like system
Ellipsoidal
P^{-2}
$P^{-1/3}$
Beaming
$P^{-4/3}$
Reflection
Amplitude [relative flux]
Period [day]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{0}
10^{1}
10^{2}


Amplitude vs. Period
KOI-13.01-like system
Ellipsoidal
P^{-2}
$P^{-1/3}$
Beaming
$P^{-4/3}$
Reflection
Amplitude [relative flux]
Period [day]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{0}
10^{1}
10^{2}


Quadrature
Inferior
Conjunction
(transit)
Quadrature
Superior
Conjunction
(occultation)
Quadrature
Beaming
Ellipsoidal
Reflection
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Phase

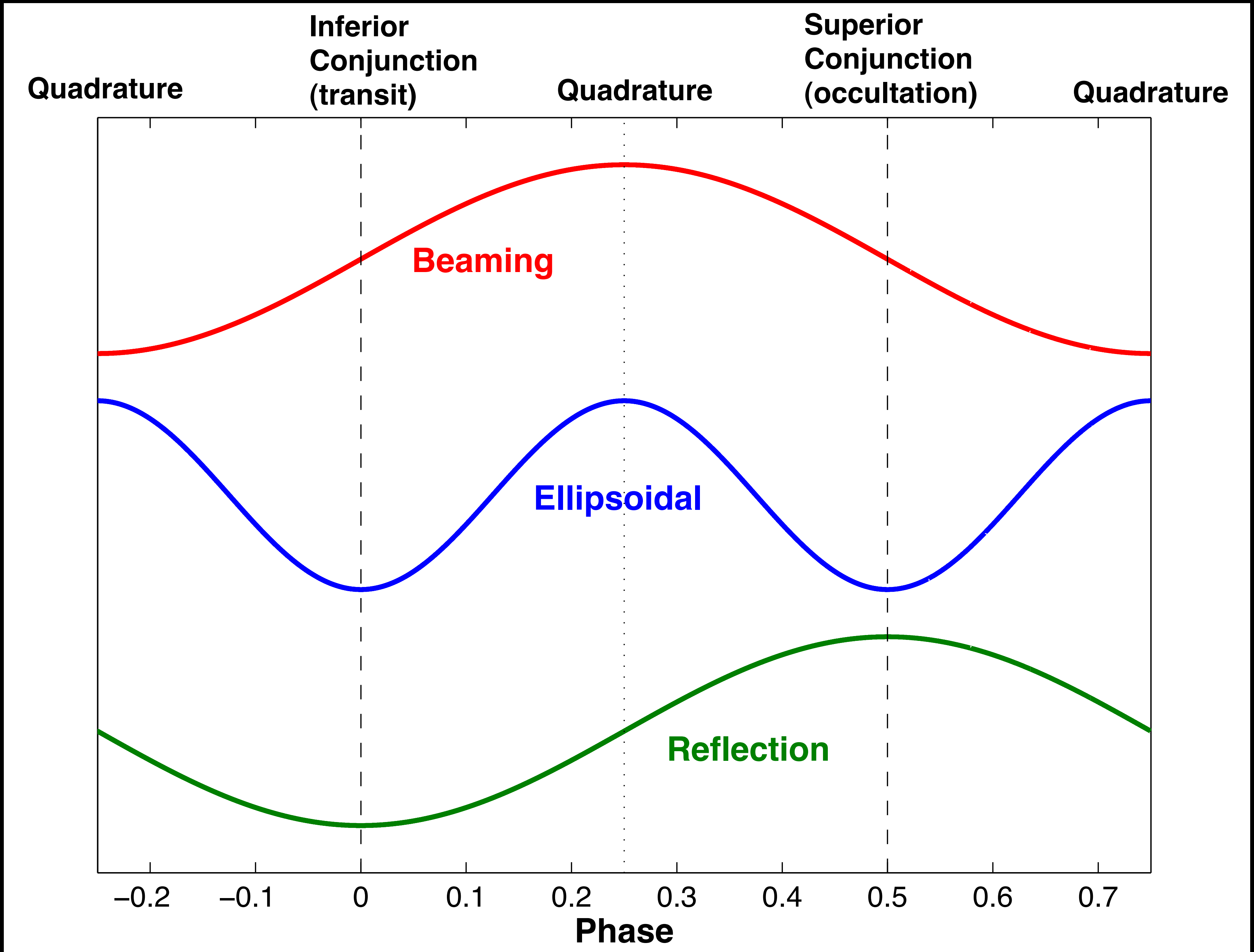
$$f(t) = a_0 + a_{1c}\cos\left(\frac{2\pi}{P}t\right) + a_{1s}\sin\left(\frac{2\pi}{P}t\right) + a_{2c}\cos\left(\frac{2\pi}{P/2}t\right) + a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)$$

double harmonic model



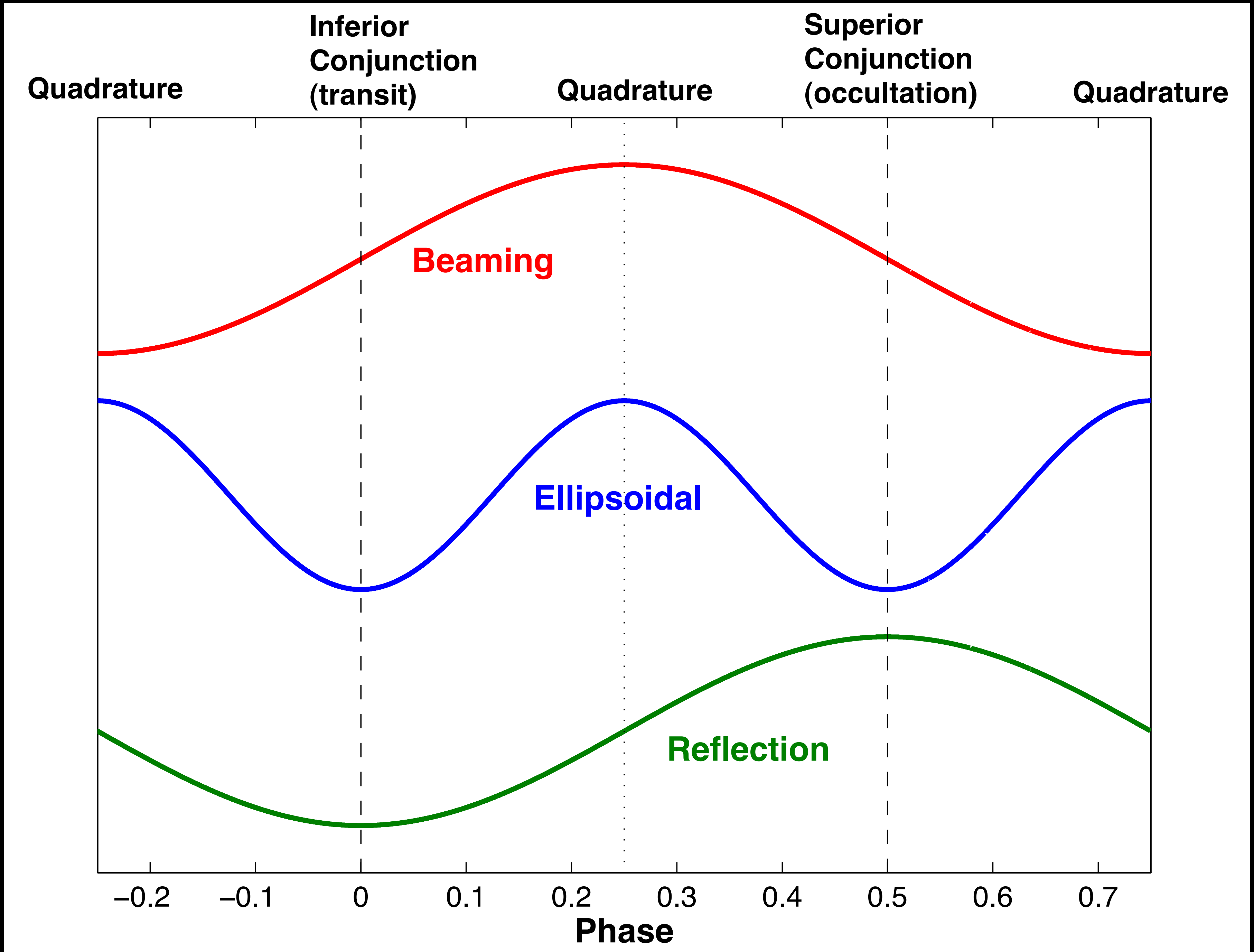
$$f(t) = a_0 + \boxed{a_{1c}\cos(\frac{2\pi}{P}t)} + a_{1s}\sin(\frac{2\pi}{P}t) + a_{2c}\cos(\frac{2\pi}{P/2}t) + a_{2s}\sin(\frac{2\pi}{P/2}t)$$

double harmonic model



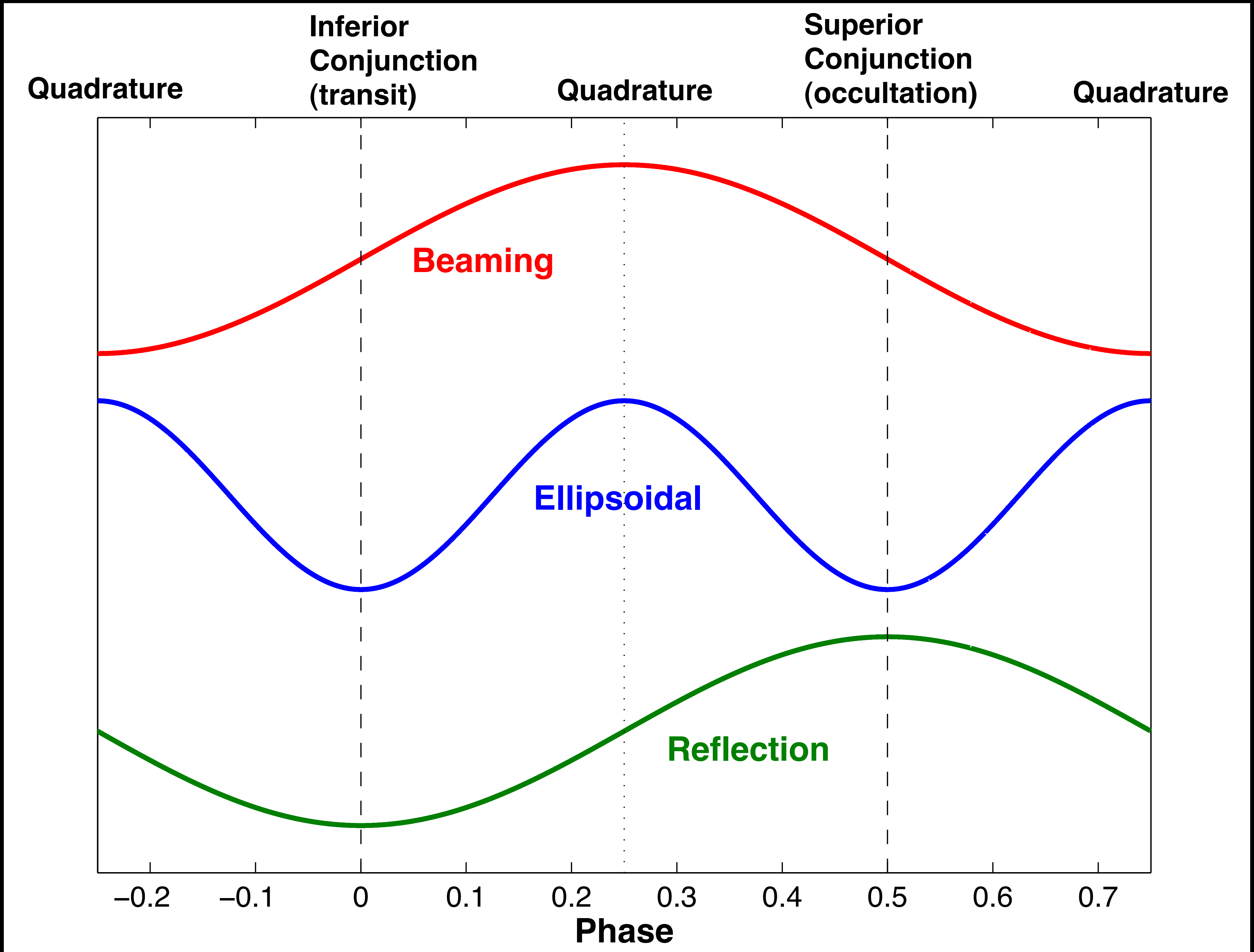
$$f(t) = a_0 + \boxed{a_{1c}\cos\left(\frac{2\pi}{P}t\right)} + \boxed{a_{1s}\sin\left(\frac{2\pi}{P}t\right)} + a_{2c}\cos\left(\frac{2\pi}{P/2}t\right) + a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)$$

double harmonic model



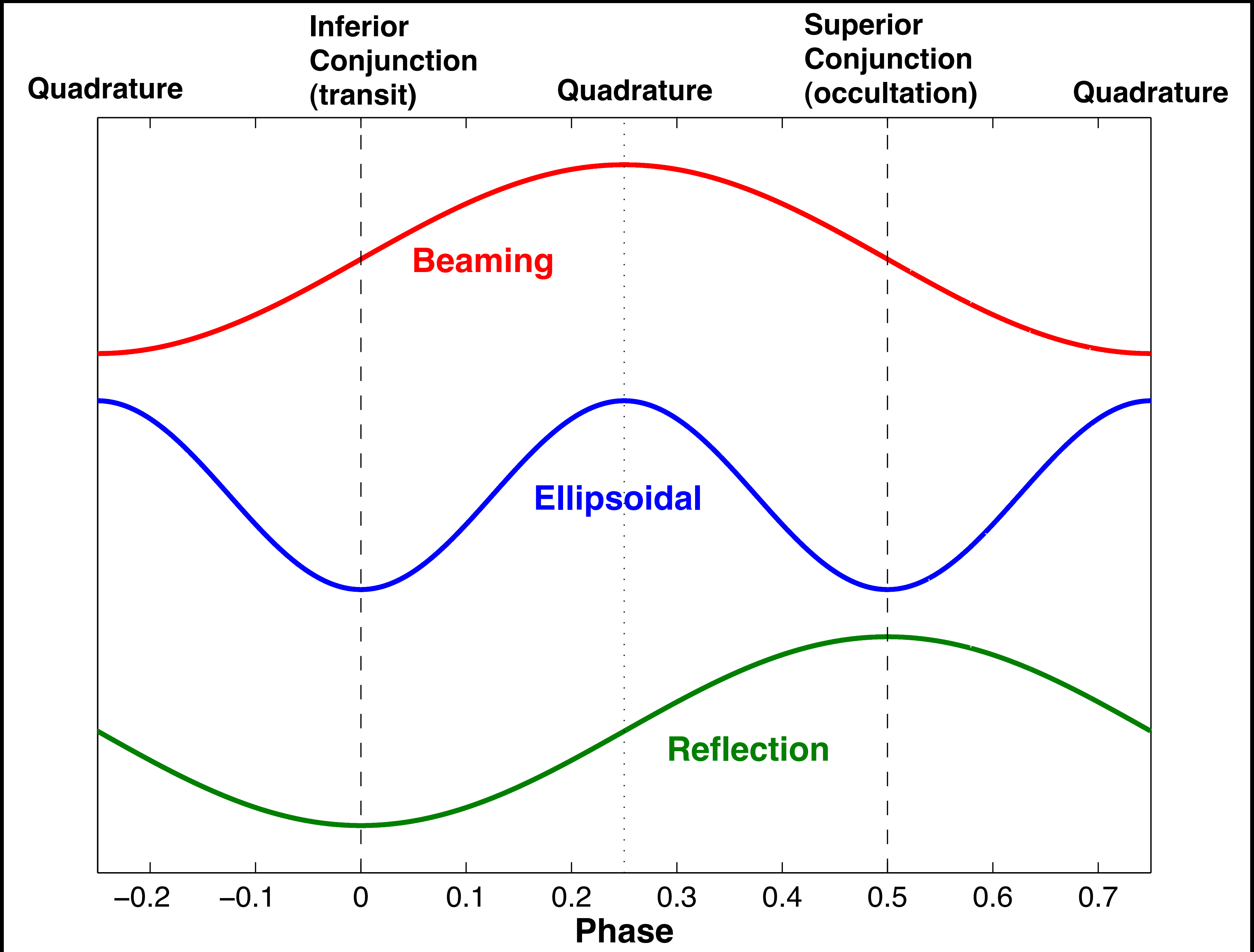
$$f(t) = a_0 + \boxed{a_{1c}\cos\left(\frac{2\pi}{P}t\right)} + \boxed{a_{1s}\sin\left(\frac{2\pi}{P}t\right)} + \boxed{a_{2c}\cos\left(\frac{2\pi}{P/2}t\right)} + a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)$$

double harmonic model



$$f(t) = a_0 + \boxed{a_{1c}\cos\left(\frac{2\pi}{P}t\right)} + \boxed{a_{1s}\sin\left(\frac{2\pi}{P}t\right)} + \boxed{a_{2c}\cos\left(\frac{2\pi}{P/2}t\right)} + \boxed{a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)}$$

double harmonic model



Orbital Modulations and White Dwarfs

Orbital Modulations and White Dwarfs

The observed radiation flux from ultra-short period binaries must be modulated due to Doppler effect.

Shakura & Postnov 1987

Orbital Modulations and White Dwarfs

The observed radiation flux from ultra-short period binaries must be modulated due to Doppler effect.

Shakura & Postnov 1987

NLTT11748

Steinfadt et al. 2010

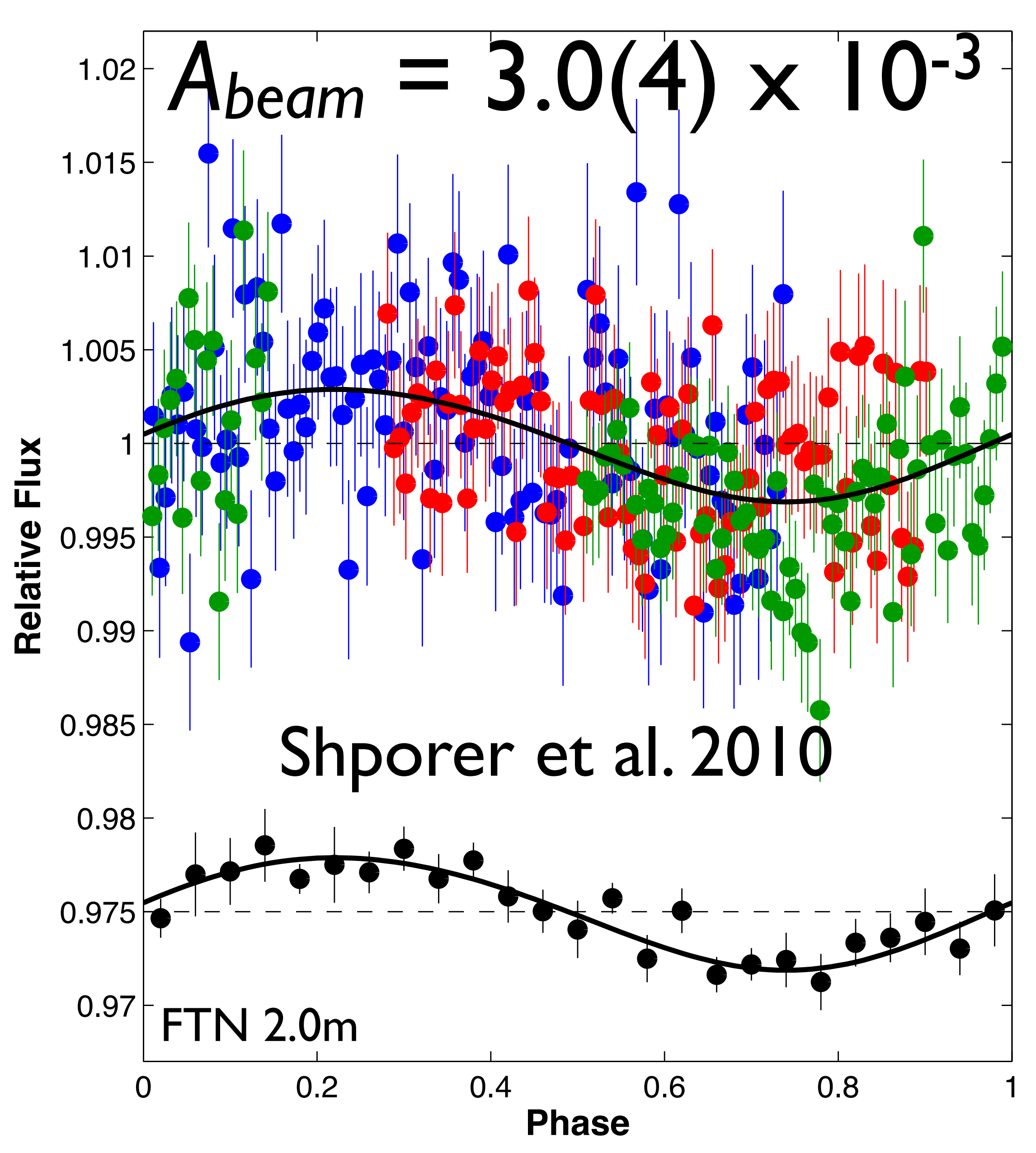
Orbital Modulations and White Dwarfs

The observed radiation flux from ultra-short period binaries must be modulated due to Doppler effect.

Shakura & Postnov 1987

NLTT11748

Steinfadt et al. 2010



Orbital Modulations and White Dwarfs

> The observed radiation flux from ultra-short period binaries must be modulated due to Doppler effect.

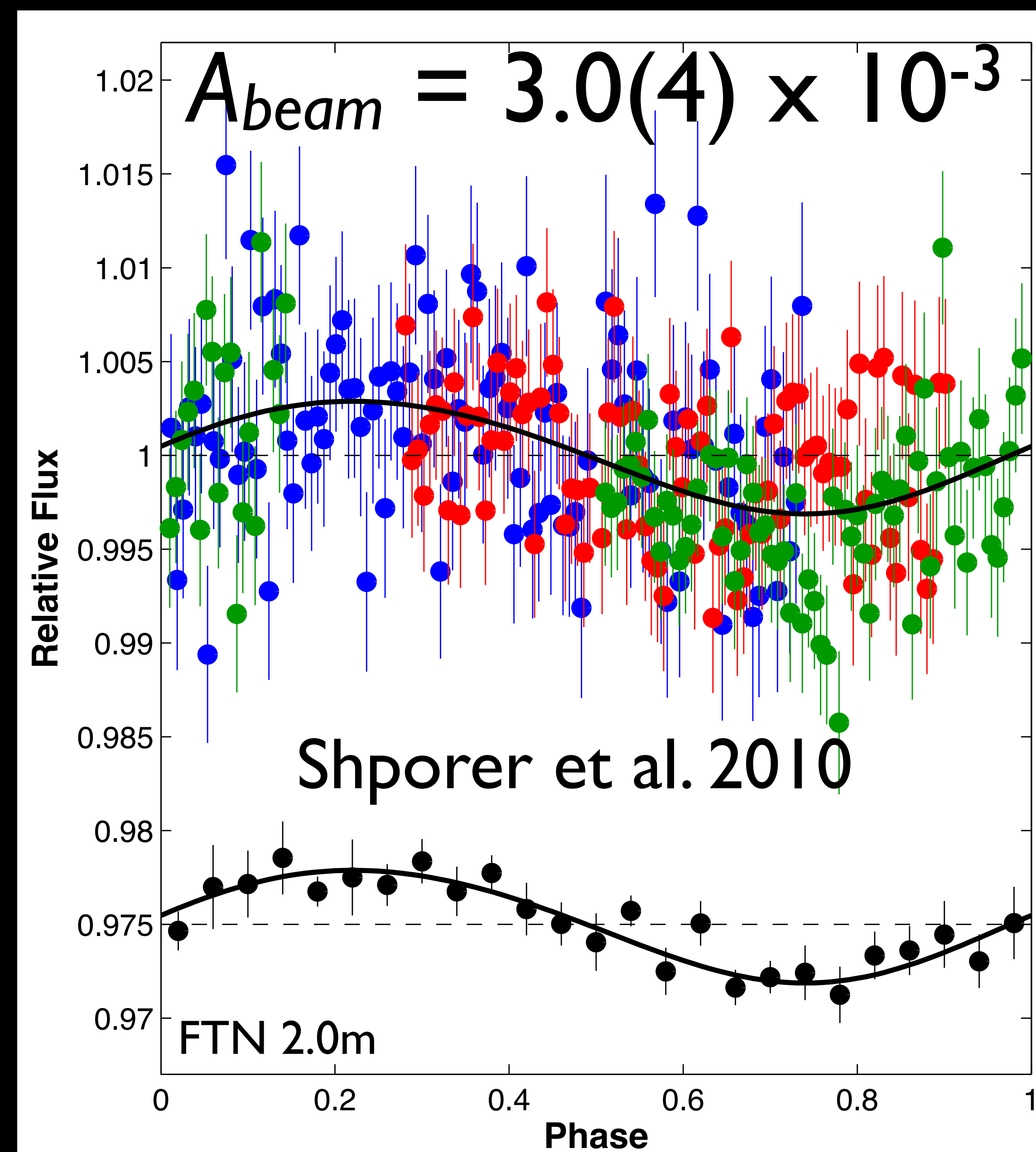
Shakura & Postnov 1987

NLTT11748

Steinfadt et al. 2010

<u>WD + WD, ground-based:</u>

Shporer et al. 2010
Vennes et al. 2011
Brown et al. 2011
Kilic et al. 2011
Hermes et al. 2012



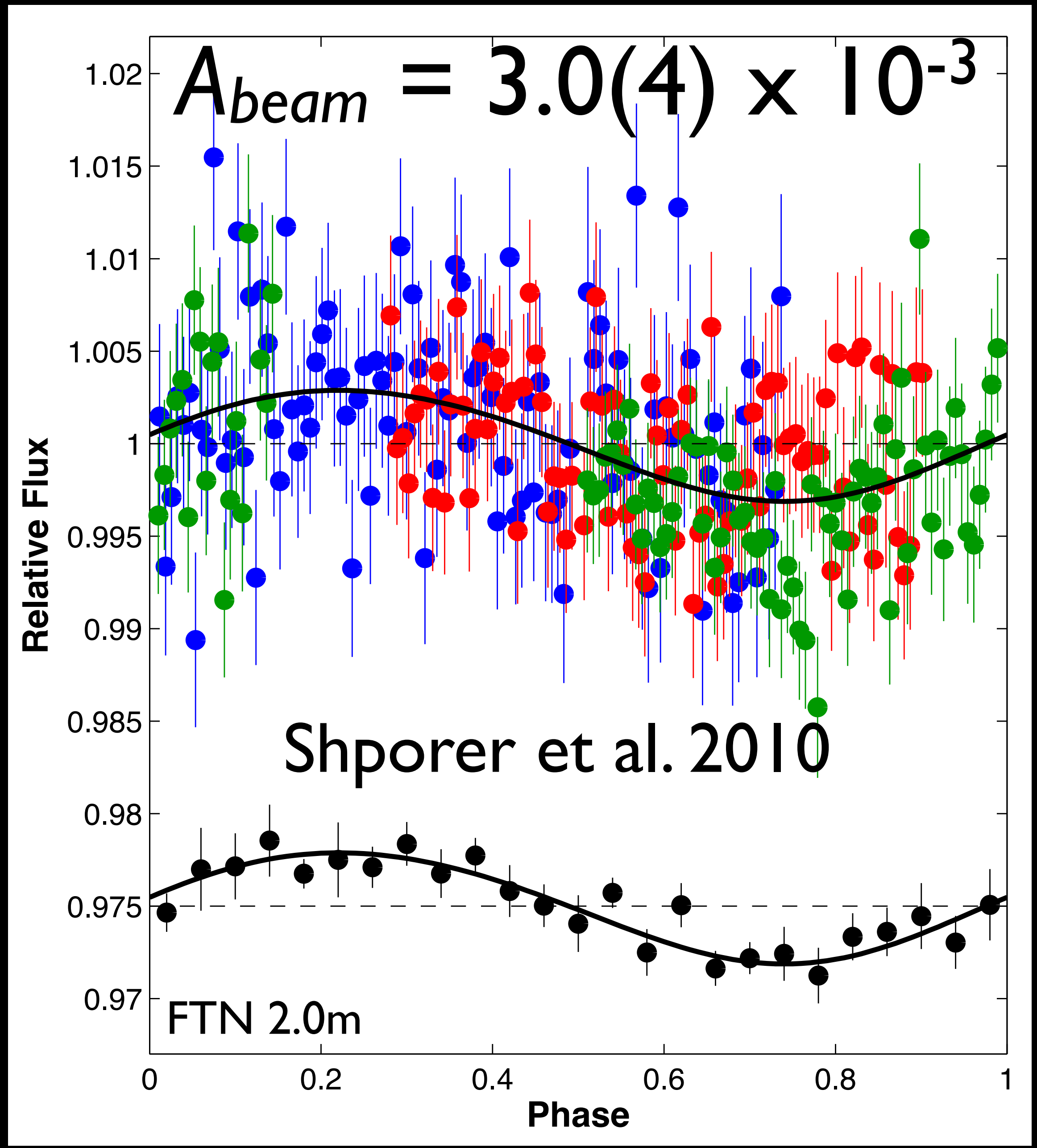
Orbital Modulations and White Dwarfs

> The observed radiation flux from ultra-short period binaries must be modulated due to Doppler effect.

Shakura & Postnov 1987

NLTT11748

Steinfadt et al. 2010



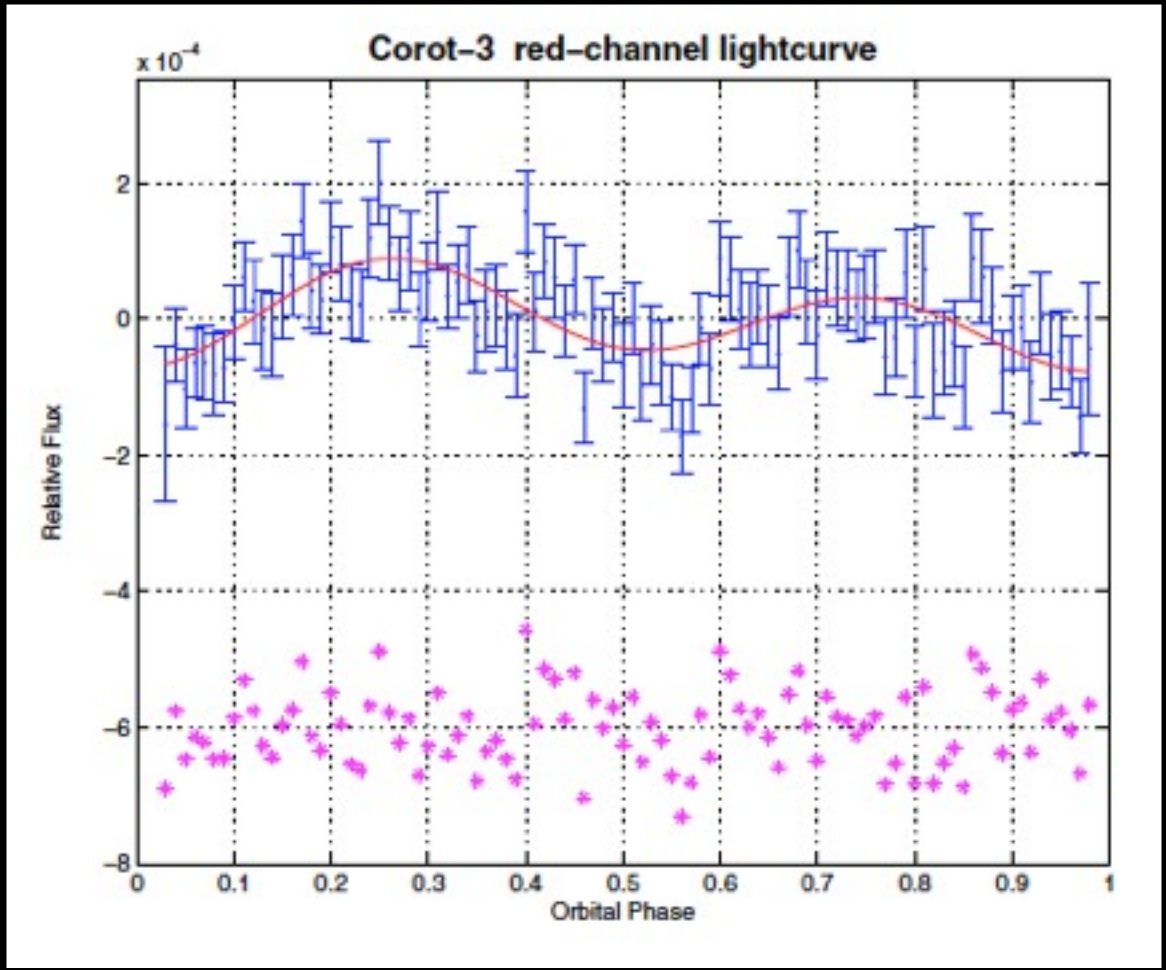
WD + WD, ground-based:

Shporer et al. 2010
Vennes et al. 2011
Brown et al. 2011
Kilic et al. 2011
Hermes et al. 2012

	Maxted et al. 2000	sdB + WD
Kepler	van Kerkwijk et al. 2010	A + WD
Kepler	Bloemen et al. 2011	sdB + WD
Kepler	Carter et al. 2011	A + WD
Kepler	Breton et al. 2012	F + WD
Kepler	Silvotti et al. 2012	sdB + WD

Orbital Modulations and Exoplanets

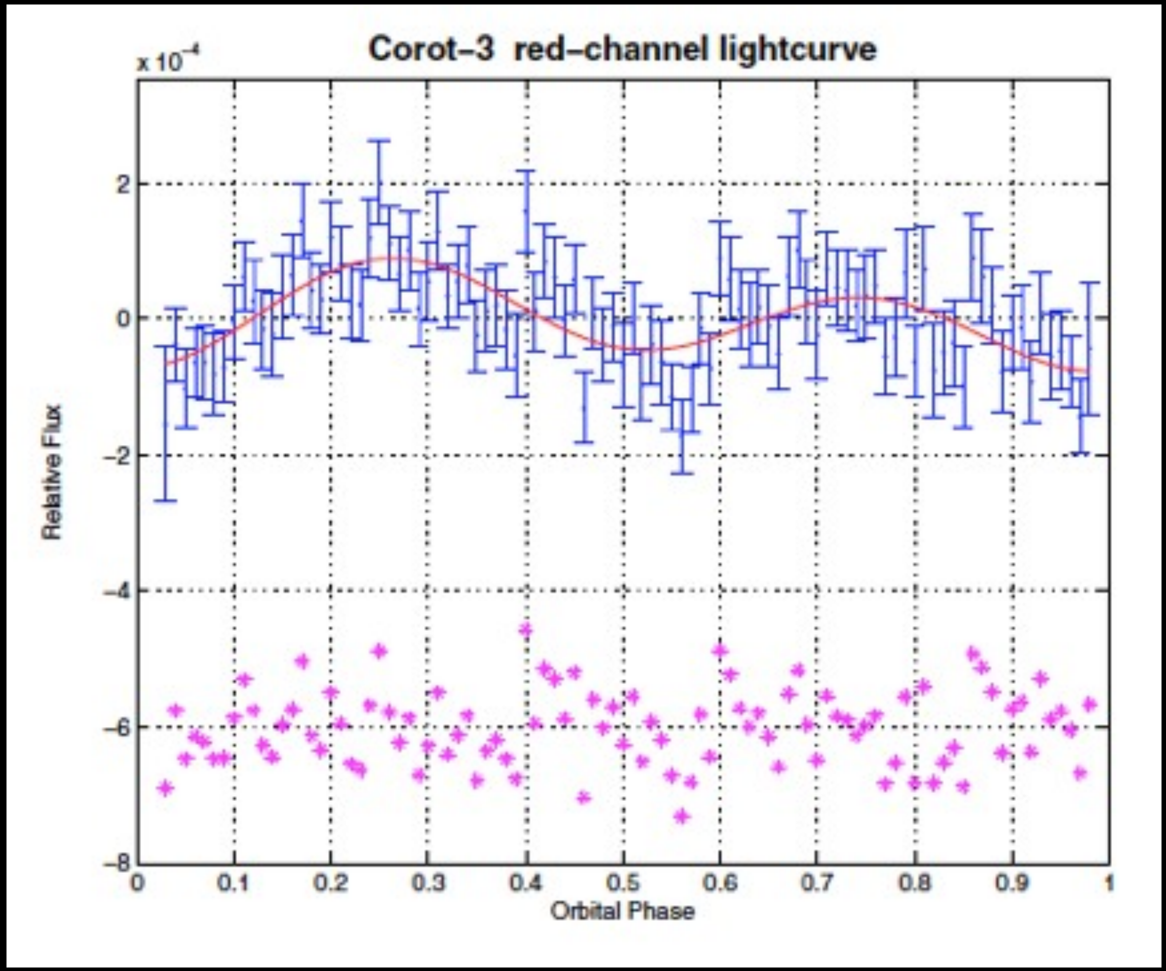
Orbital Modulations and Exoplanets



Mazeh & Faigler 2010

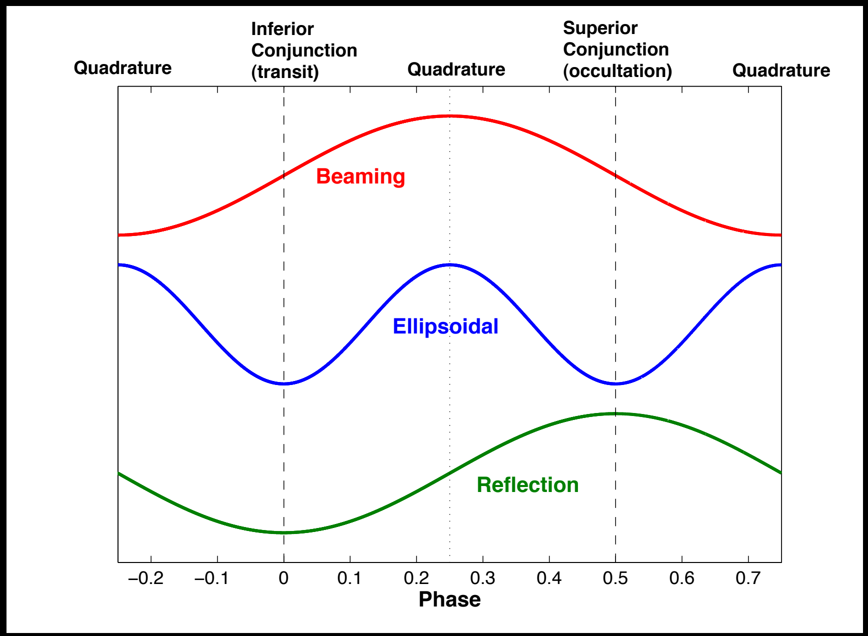
Orbital Modulations and Exoplanets

Mazeh & Faigler 2010
Welsh et al. 2010
Faigler & Mazeh 2011
Shporer et al. 2011
Kipping & Spiegel 2011
Faigler et al. 2012
Mislis et al. 2012
Jackson et al. 2012
Mazeh et al. 2012
Mislis & Hodgkin 2012
Barclay et al. 2012, in prep.
Quintana et al. 2012, in prep.



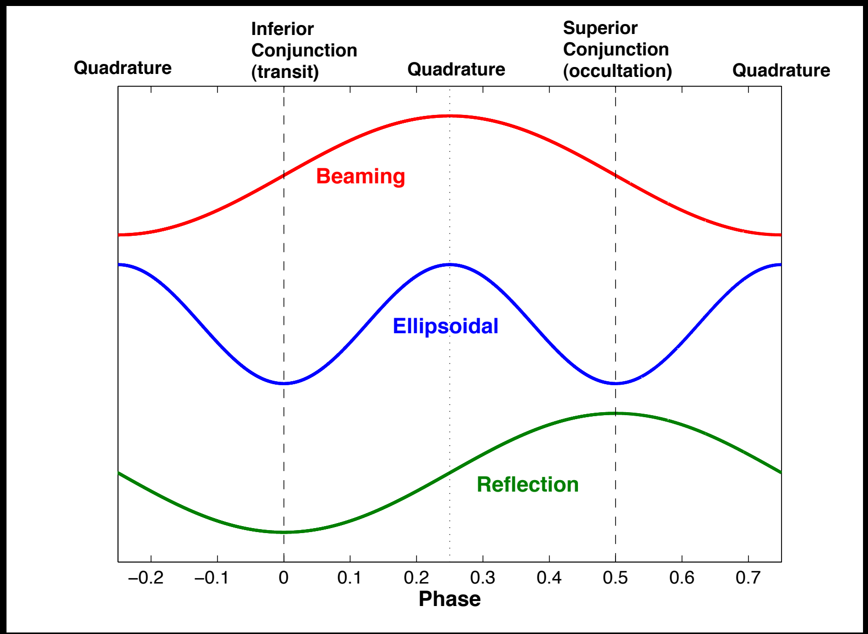
Mazeh & Faigler 2010

“Orbital Photometry” as a tool



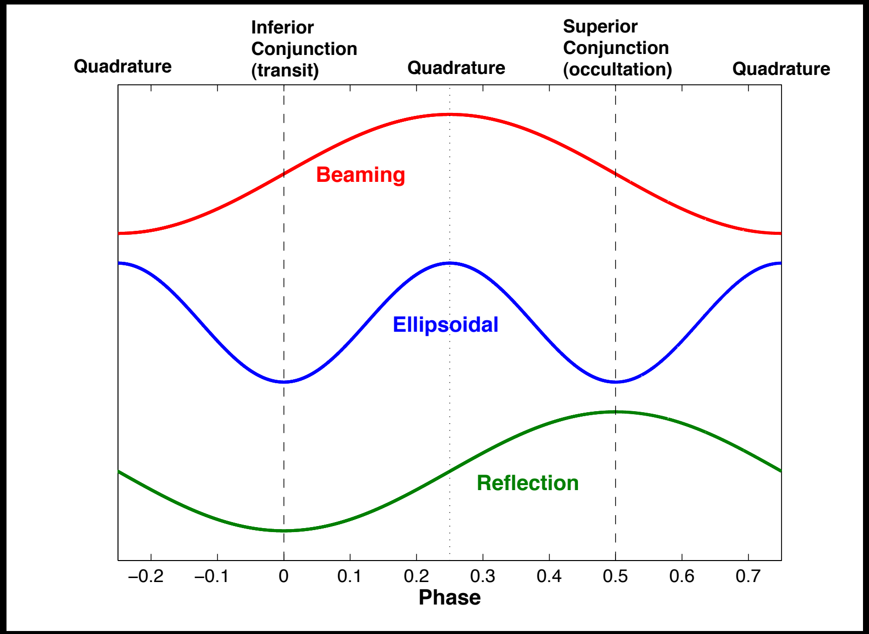
“Orbital Photometry” as a tool

- Look for non-transiting companions



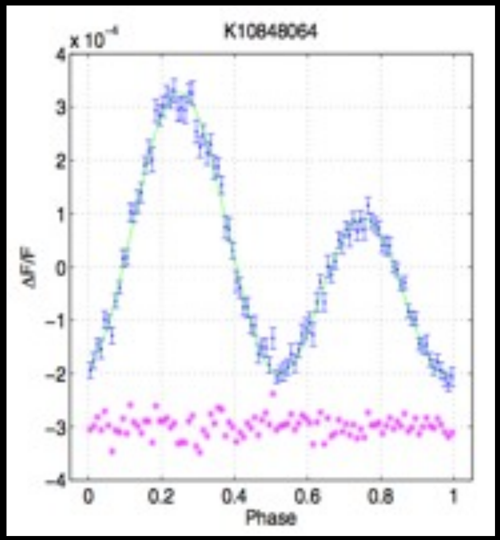
“Orbital Photometry” as a tool

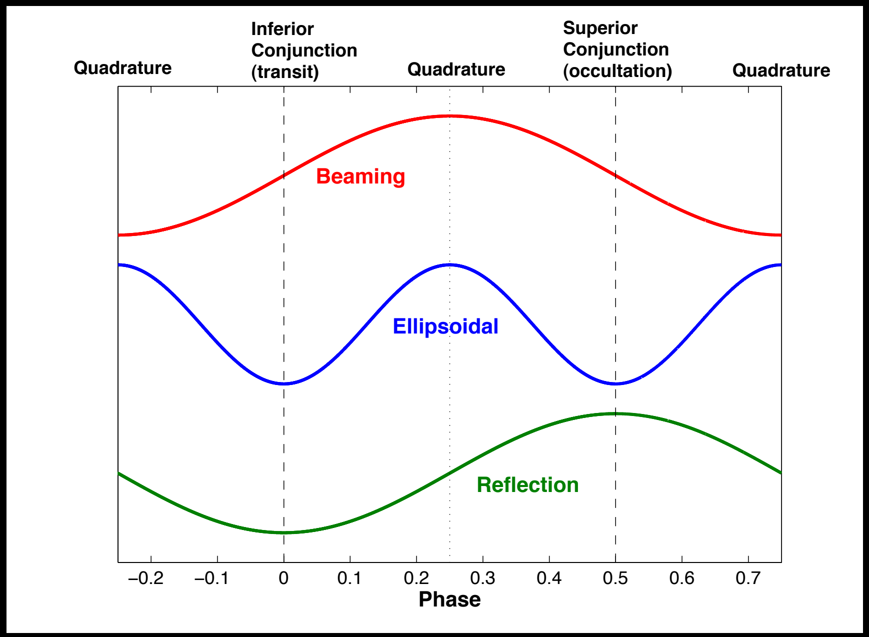
- Look for non-transiting companions
  - ➡BEER, Faigler & Mazeh 2011, Faigler et al. 2012



“Orbital Photometry” as a tool

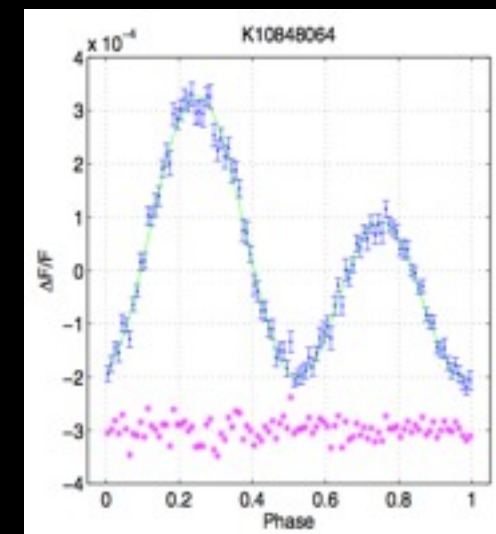
- Look for non-transiting companions
  - ➡BEER, Faigler & Mazeh 2011, Faigler et al. 2012

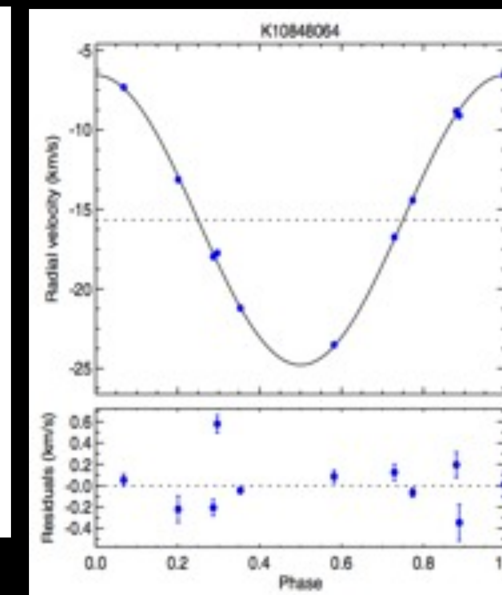


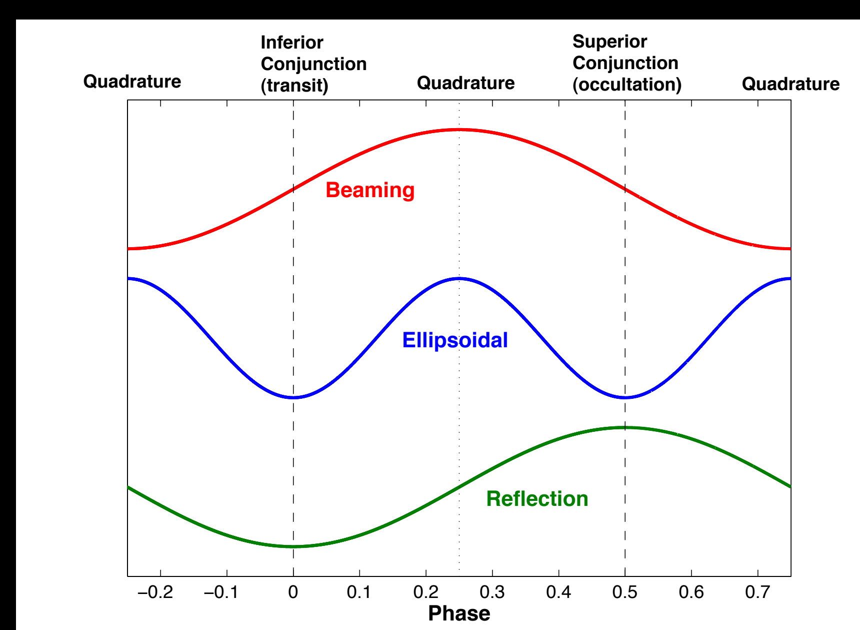


“Orbital Photometry” as a tool

- Look for non-transiting companions
  - ➡BEER, Faigler & Mazeh 2011, Faigler et al. 2012

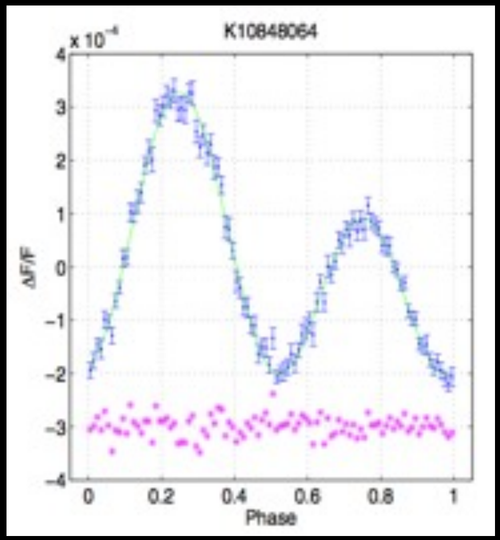


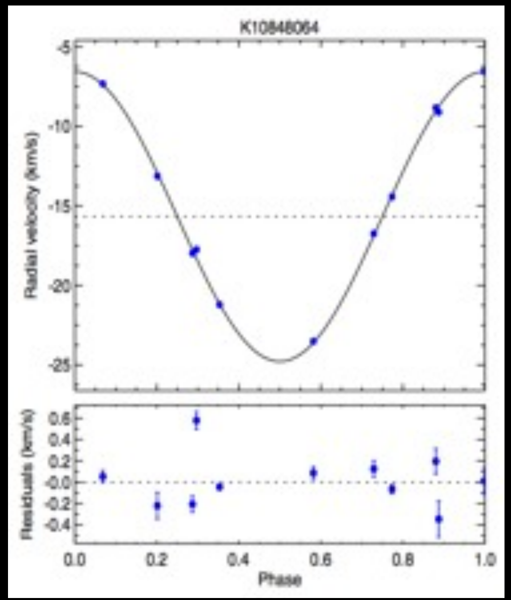


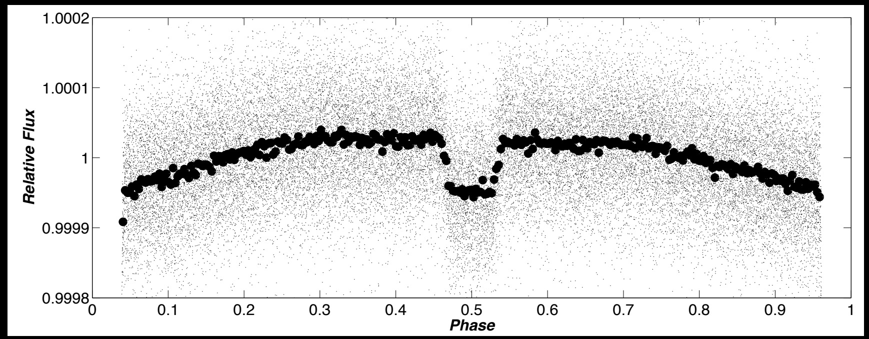


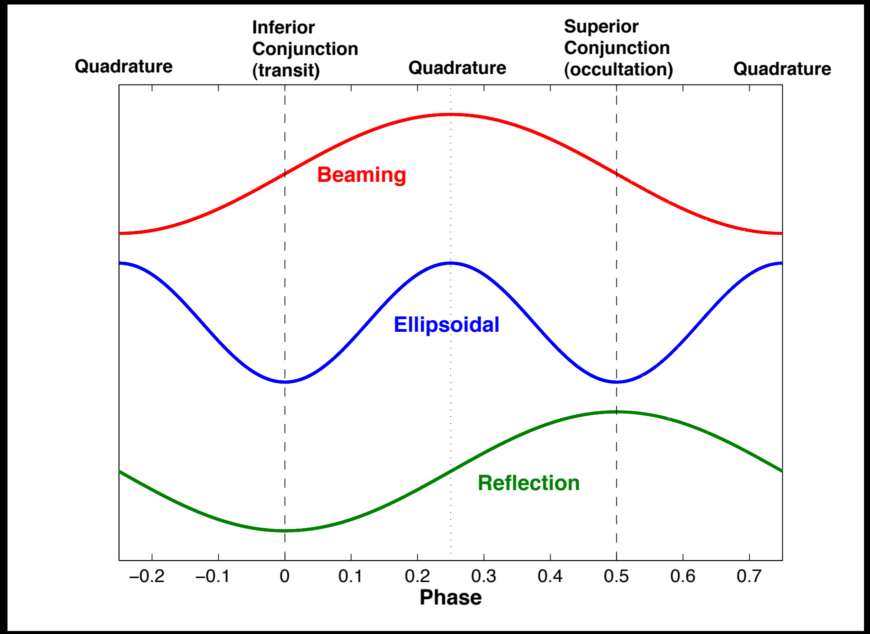
“Orbital Photometry” as a tool

- Look for non-transiting companions
  - ➡BEER, Faigler & Mazeh 2011, Faigler et al. 2012
- Detailed study of transiting objects:



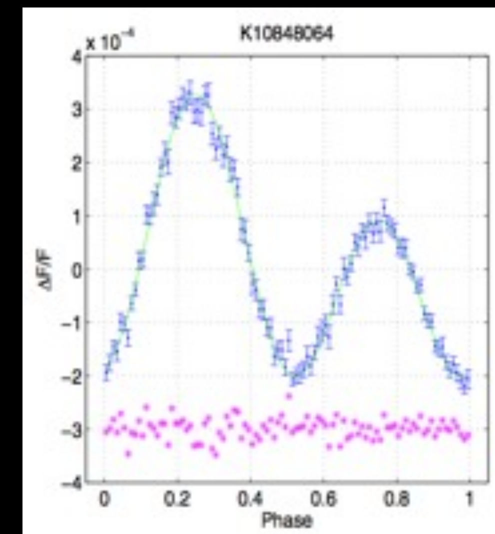


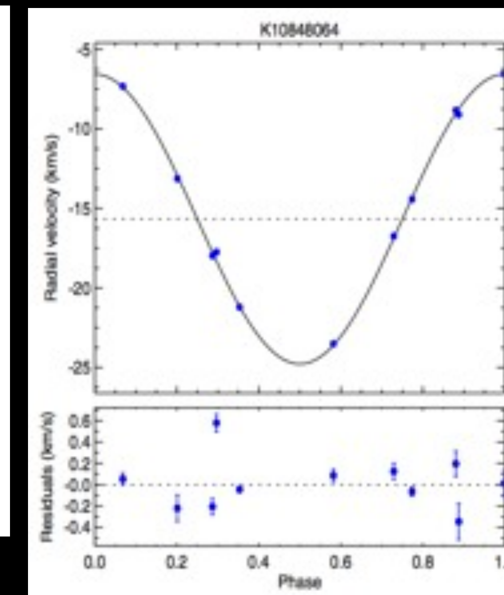




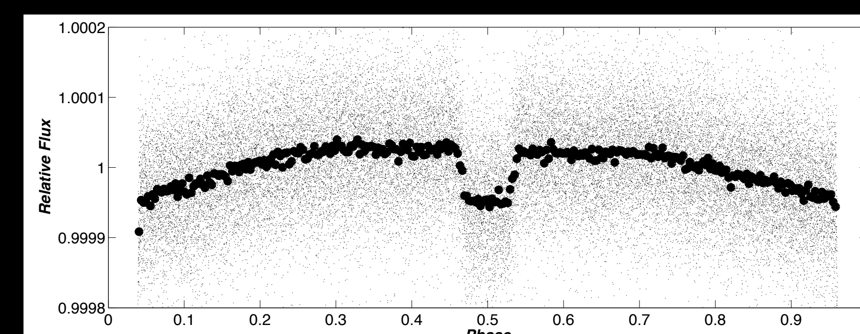
“Orbital Photometry” as a tool

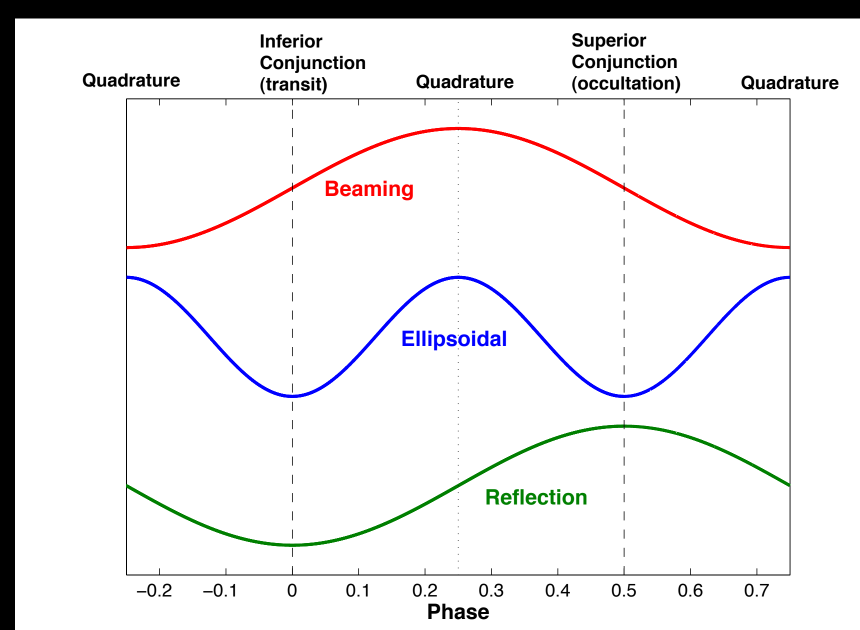
- Look for non-transiting companions
  - ➡BEER, Faigler & Mazeh 2011, Faigler et al. 2012





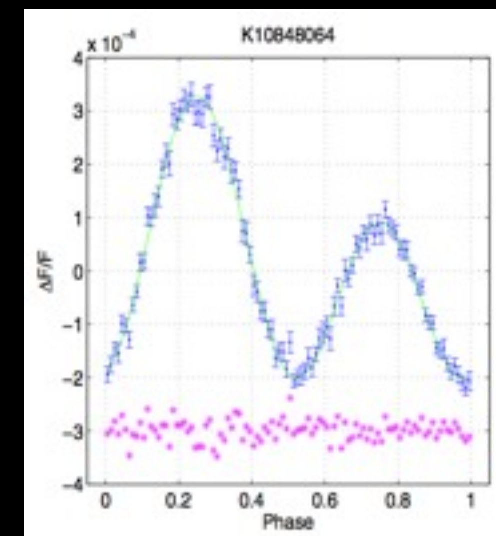
- Detailed study of transiting objects:
  - -Beaming (and ellipsoidal): photometric mass measurement

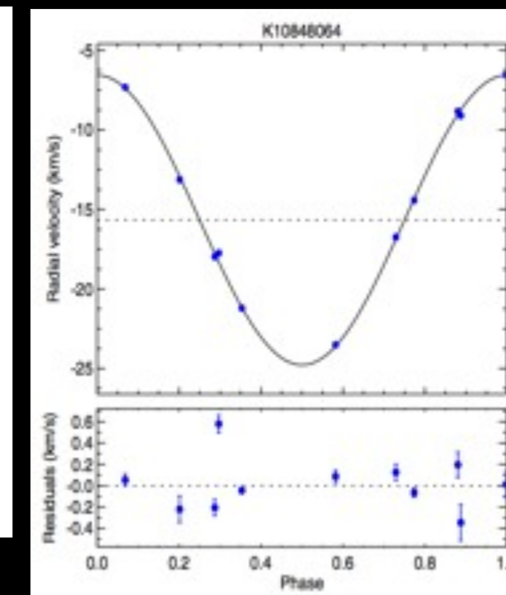




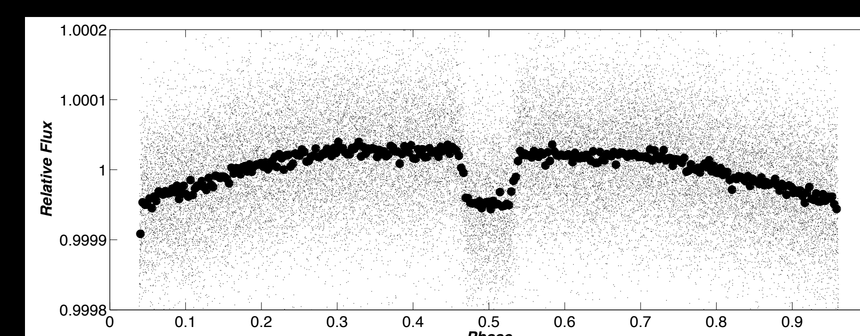
“Orbital Photometry” as a tool

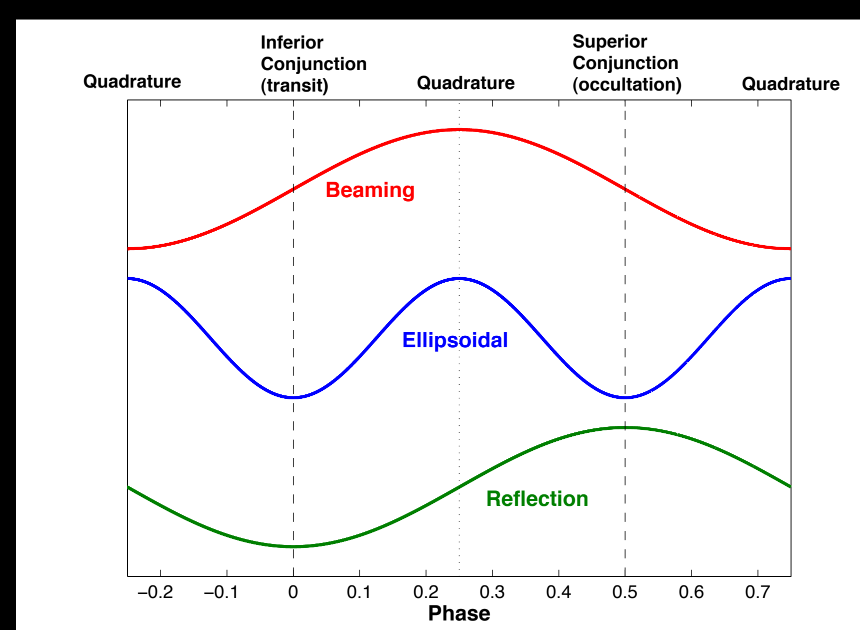
- Look for non-transiting companions
  ➡BEER, Faigler & Mazeh 2011, Faigler et al. 2012



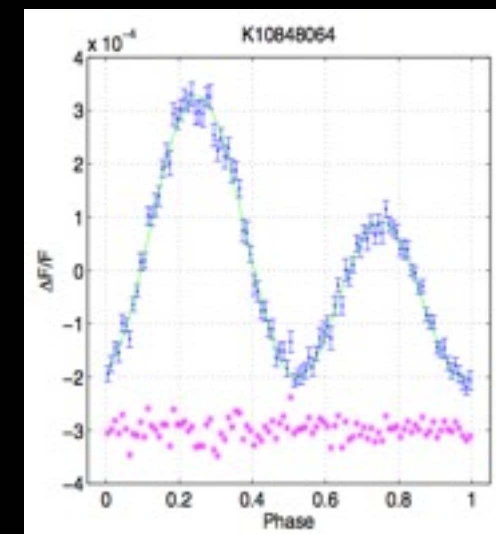


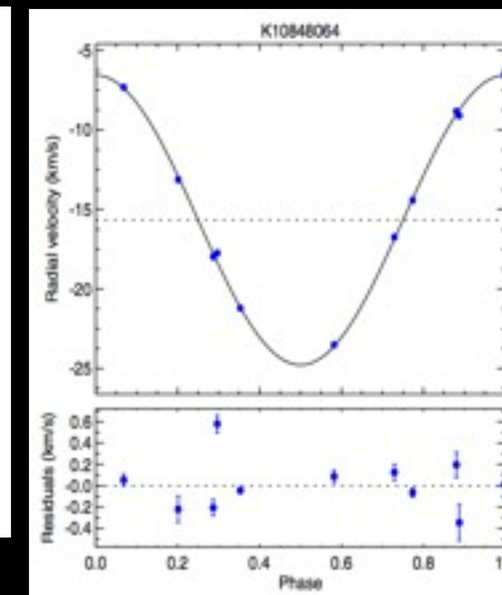
- Detailed study of transiting objects:
  - Beaming (and ellipsoidal): photometric mass measurement
    - stars with no high-precision RV





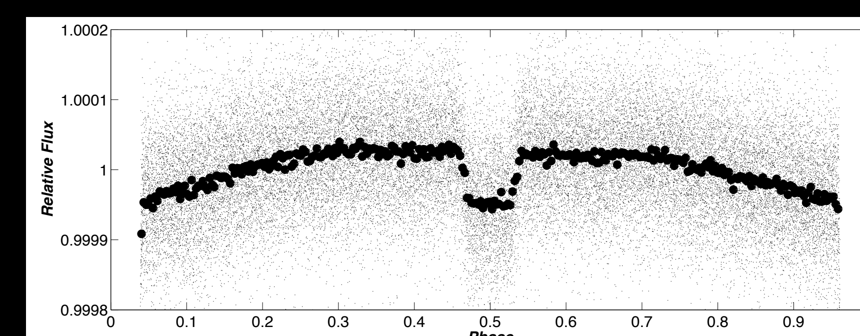
“Orbital Photometry” as a tool

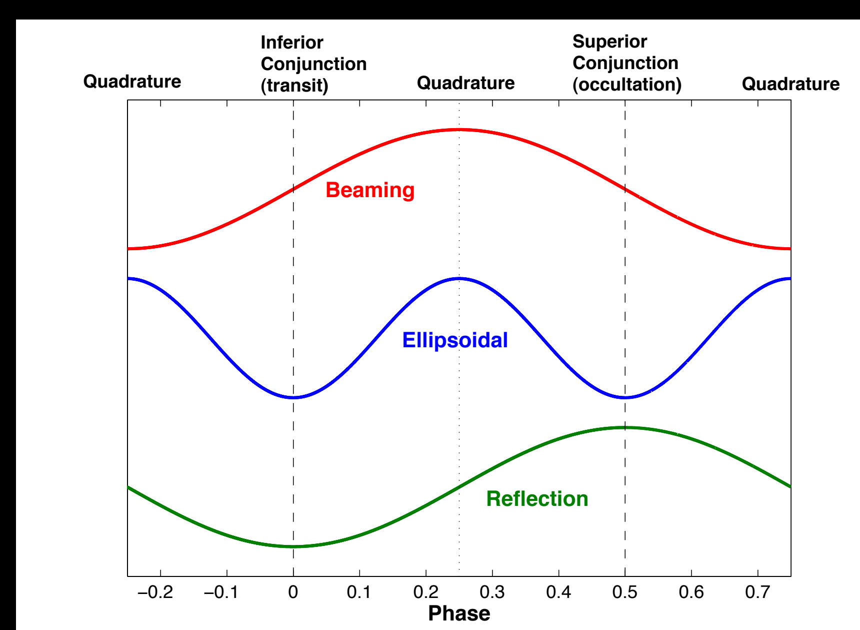




- Look for non-transiting companions
  - ➡BEER, Faigler & Mazeh 2011, Faigler et al. 2012

- Detailed study of transiting objects:
  - -Beaming (and ellipsoidal): photometric mass measurement
    - stars with no high-precision RV
  - -Reflection/heating: Albedo and day-night difference





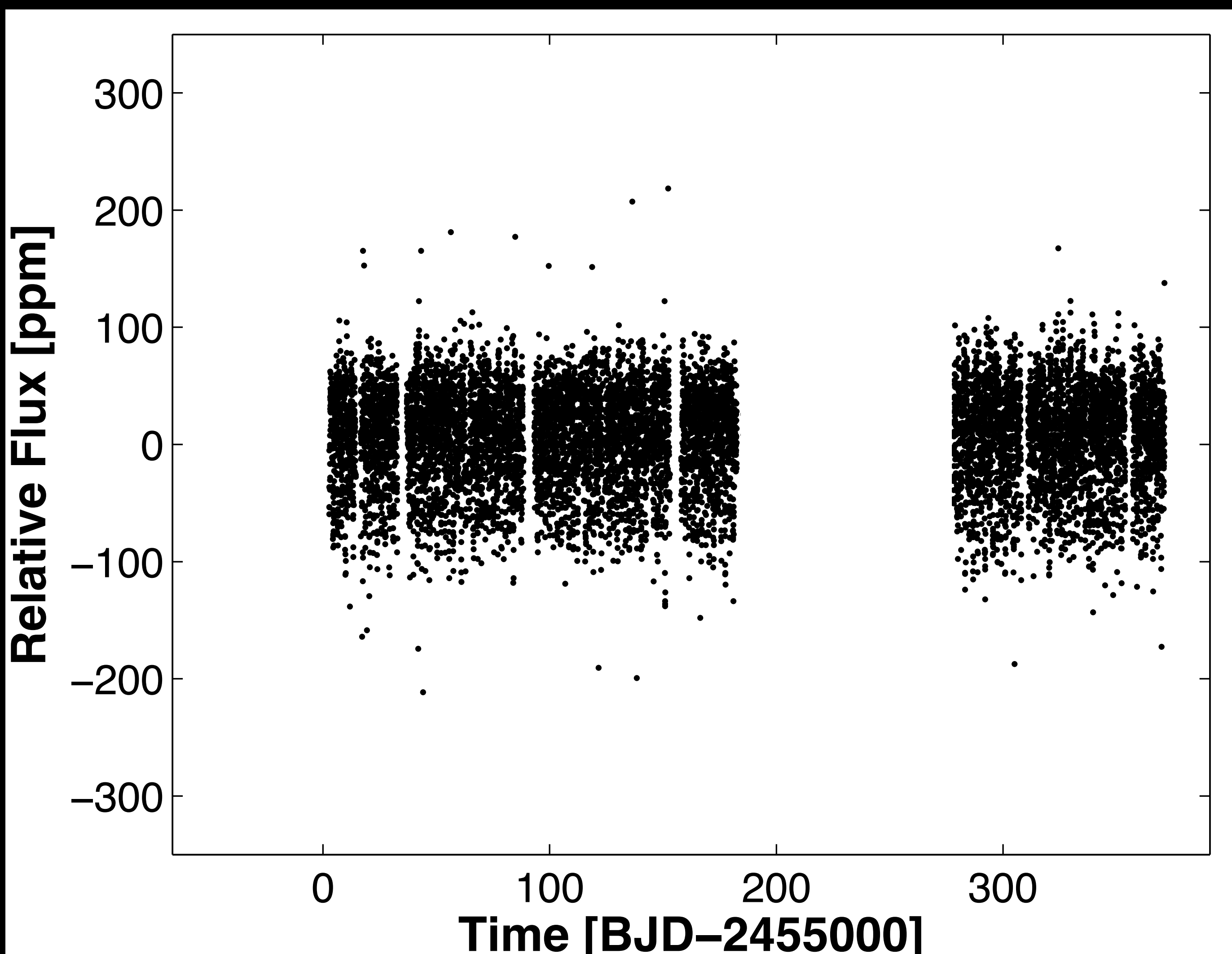
Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

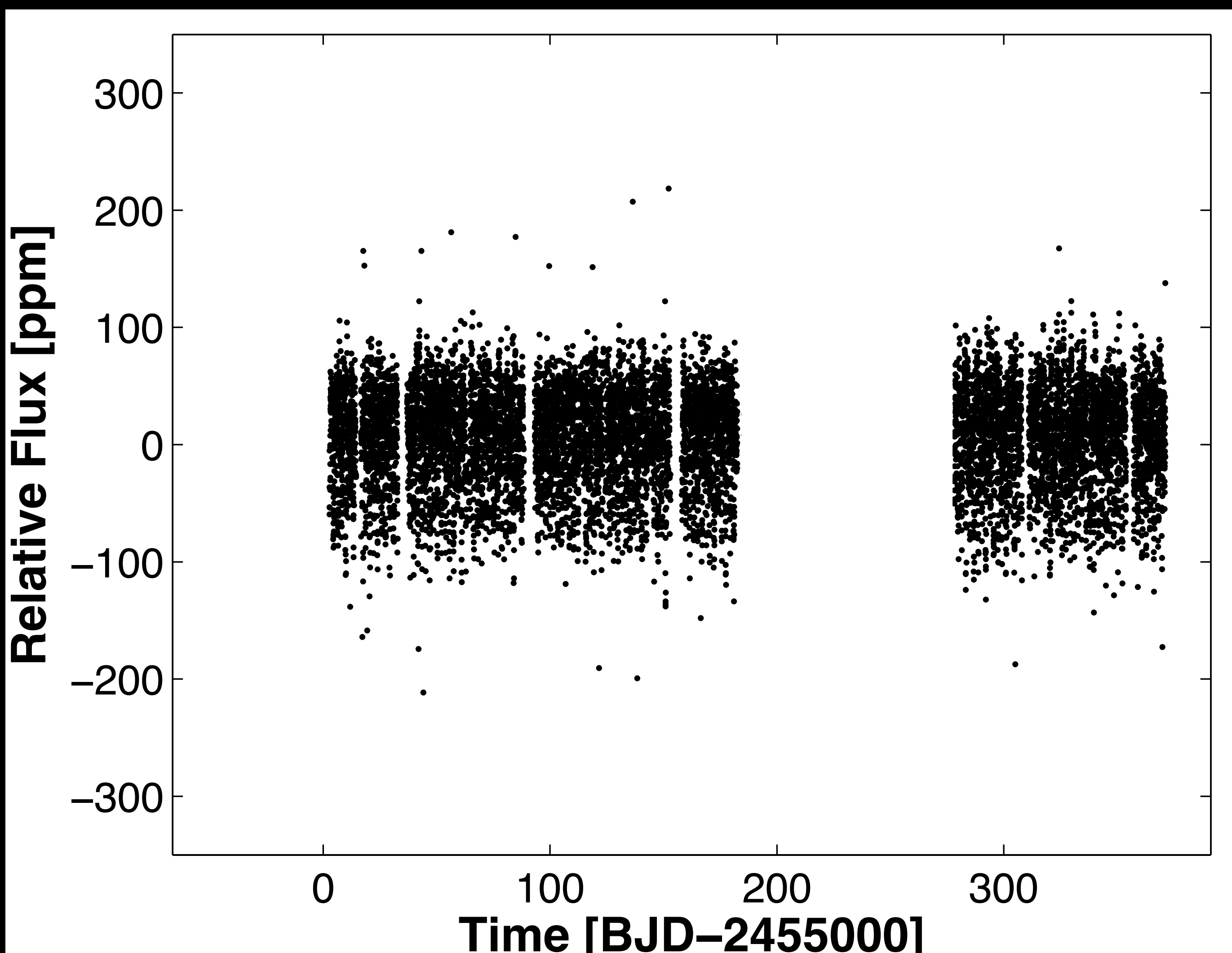
detrended light curve, Q0-Q5



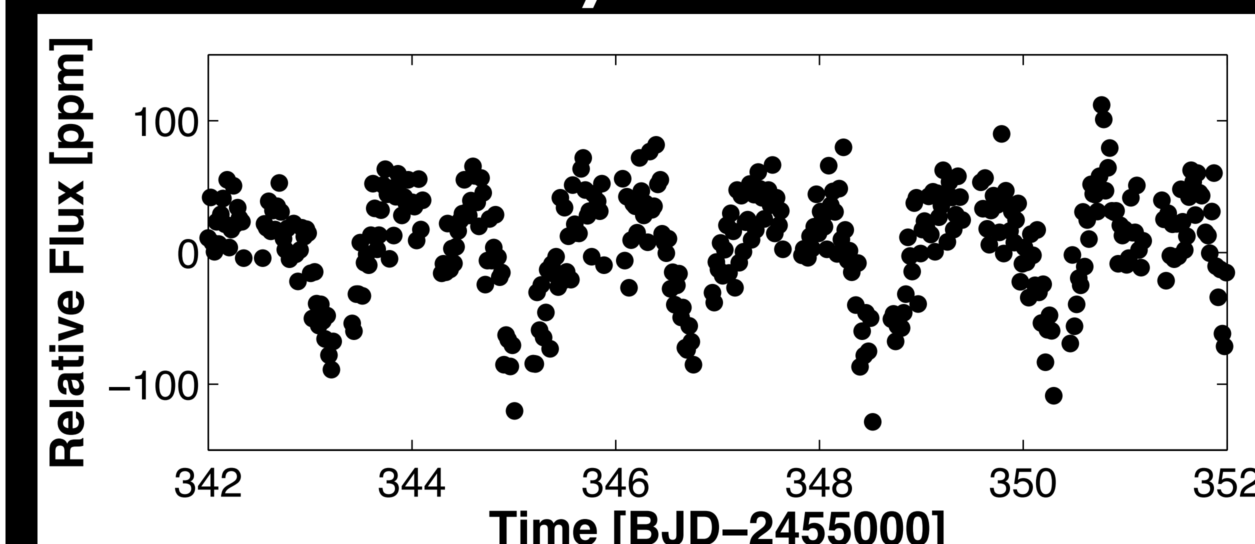
Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

detrended light curve, Q0-Q5



10 days of data



Transit+occultation data removed

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

Double harmonic period analysis

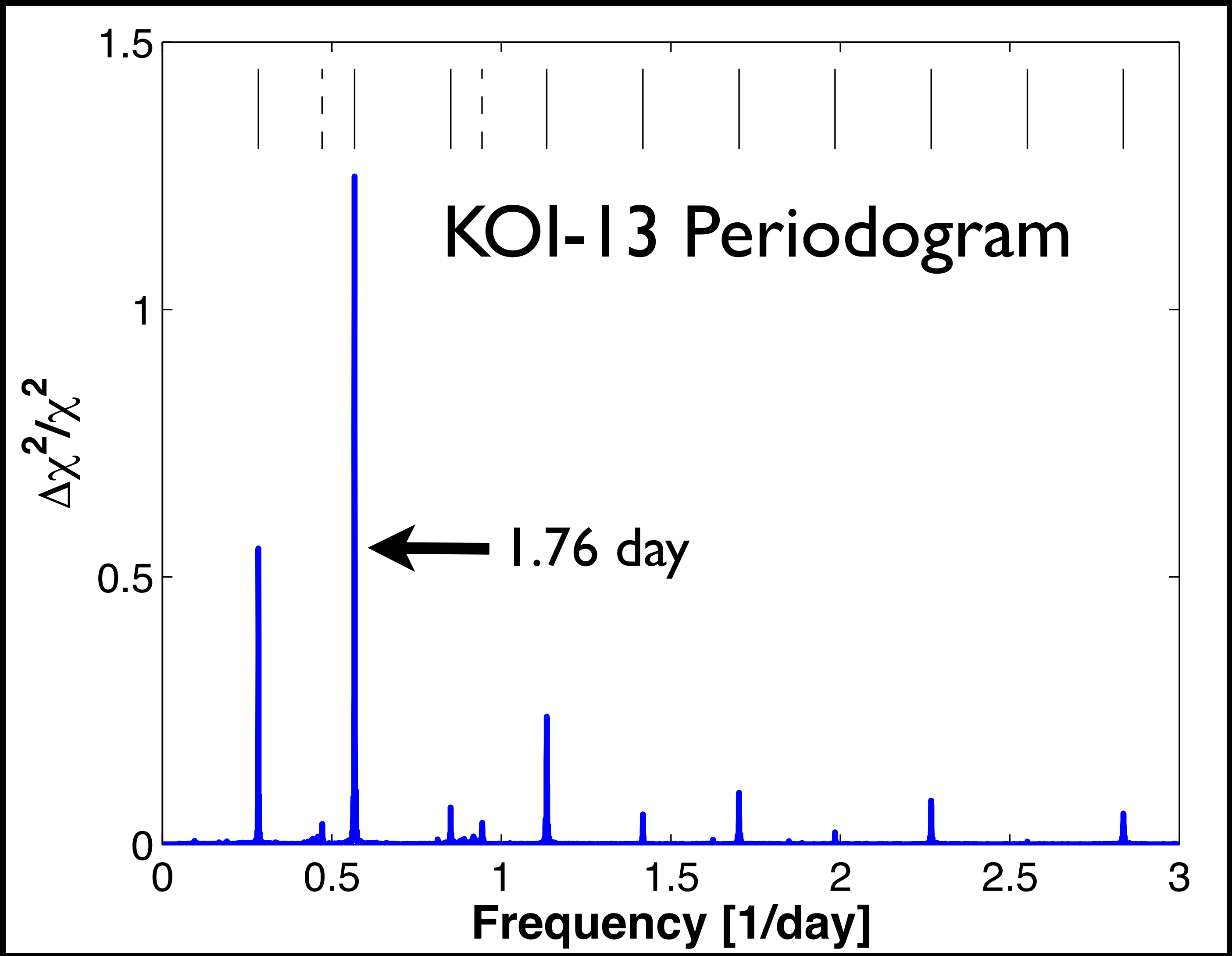
$$f(t) = a_0 + a_{1c}\cos(\frac{2\pi}{P}t) + a_{1s}\sin(\frac{2\pi}{P}t) + a_{2c}\cos(\frac{2\pi}{P/2}t) + a_{2s}\sin(\frac{2\pi}{P/2}t)$$

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

Double harmonic period analysis

$$f(t) = a_0 + a_{1c}\cos\left(\frac{2\pi}{P}t\right) + a_{1s}\sin\left(\frac{2\pi}{P}t\right) + a_{2c}\cos\left(\frac{2\pi}{P/2}t\right) + a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)$$



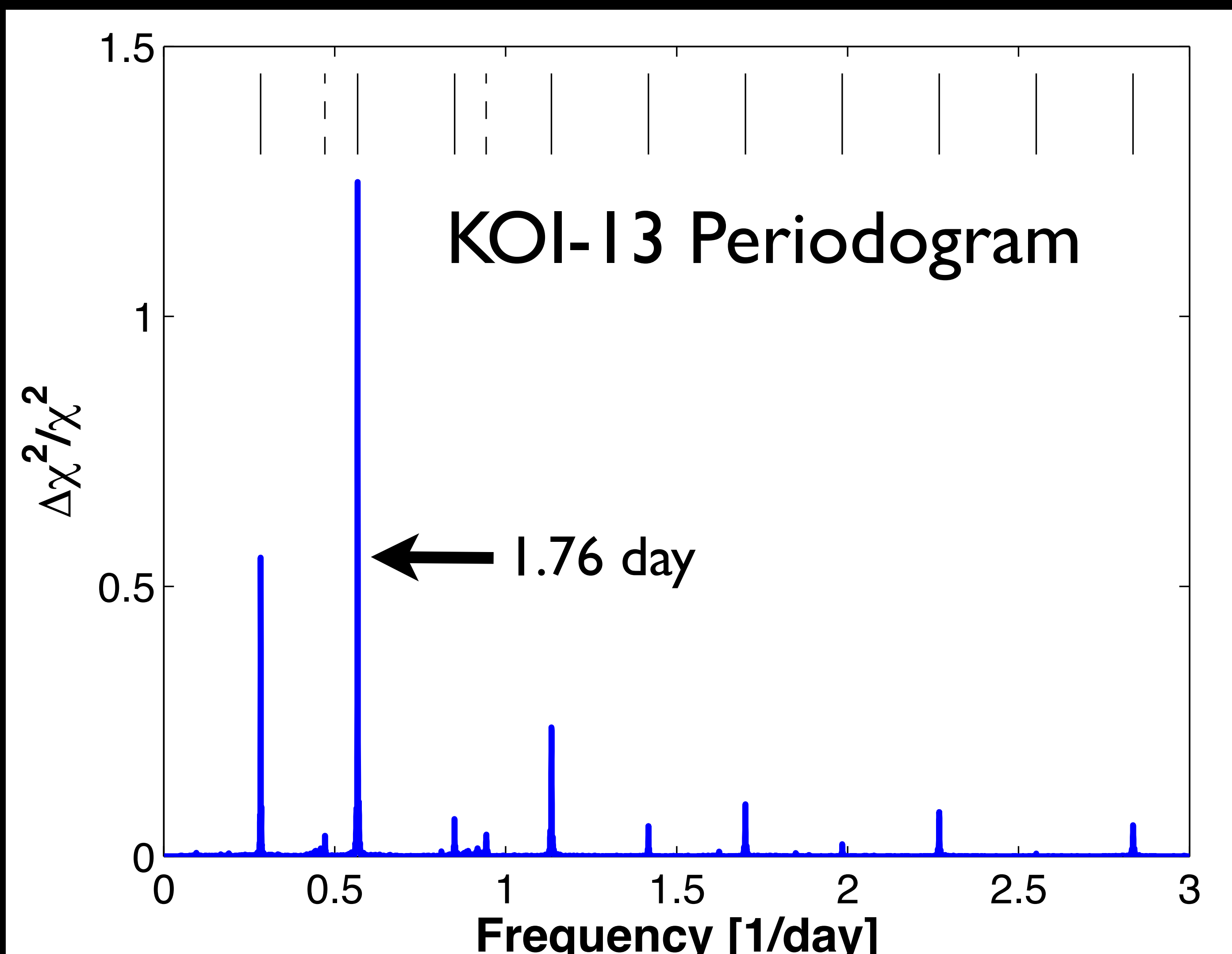
$$\frac{\Delta\chi^2}{\chi^2} = \frac{\chi^2_{mean} - \chi^2}{\chi^2}$$

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

Double harmonic period analysis

$$f(t) = a_0 + a_{1c}\cos\left(\frac{2\pi}{P}t\right) + a_{1s}\sin\left(\frac{2\pi}{P}t\right) + a_{2c}\cos\left(\frac{2\pi}{P/2}t\right) + a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)$$



$$\frac{\Delta\chi^2}{\chi^2} = \frac{\chi^2_{mean} - \chi^2}{\chi^2}$$

Parameter	Value
Orbital period, P_{orb} (days)	1.7637 ± 0.0013
Inferior conjunction time, T_0 (BJD)	2455138.7439 ± 0.0013

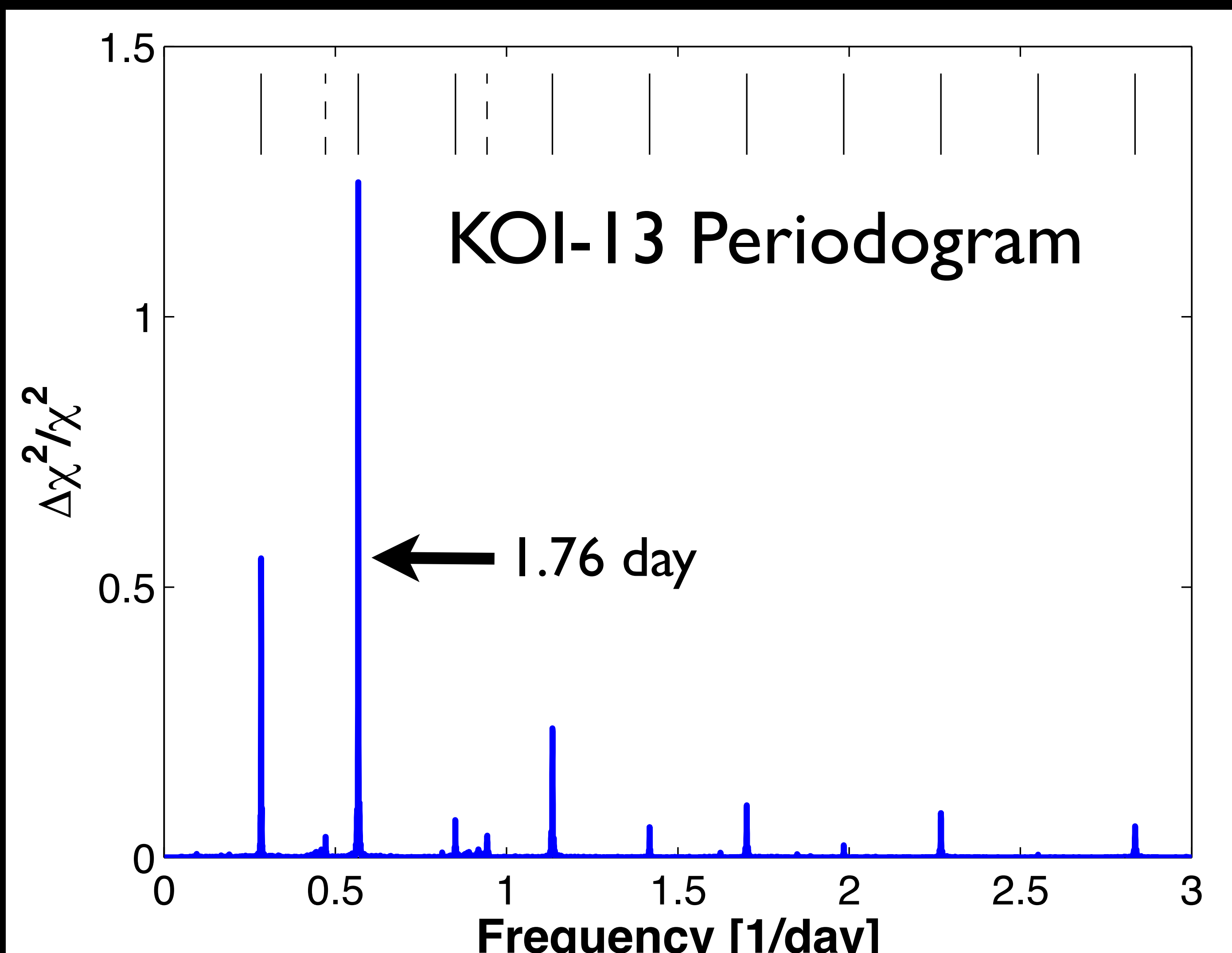
Consistent with transit ephemeris

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

Double harmonic period analysis

$$f(t) = a_0 + a_{1c}\cos\left(\frac{2\pi}{P}t\right) + a_{1s}\sin\left(\frac{2\pi}{P}t\right) + a_{2c}\cos\left(\frac{2\pi}{P/2}t\right) + a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)$$



$$\frac{\Delta\chi^2}{\chi^2} = \frac{\chi^2_{mean} - \chi^2}{\chi^2}$$

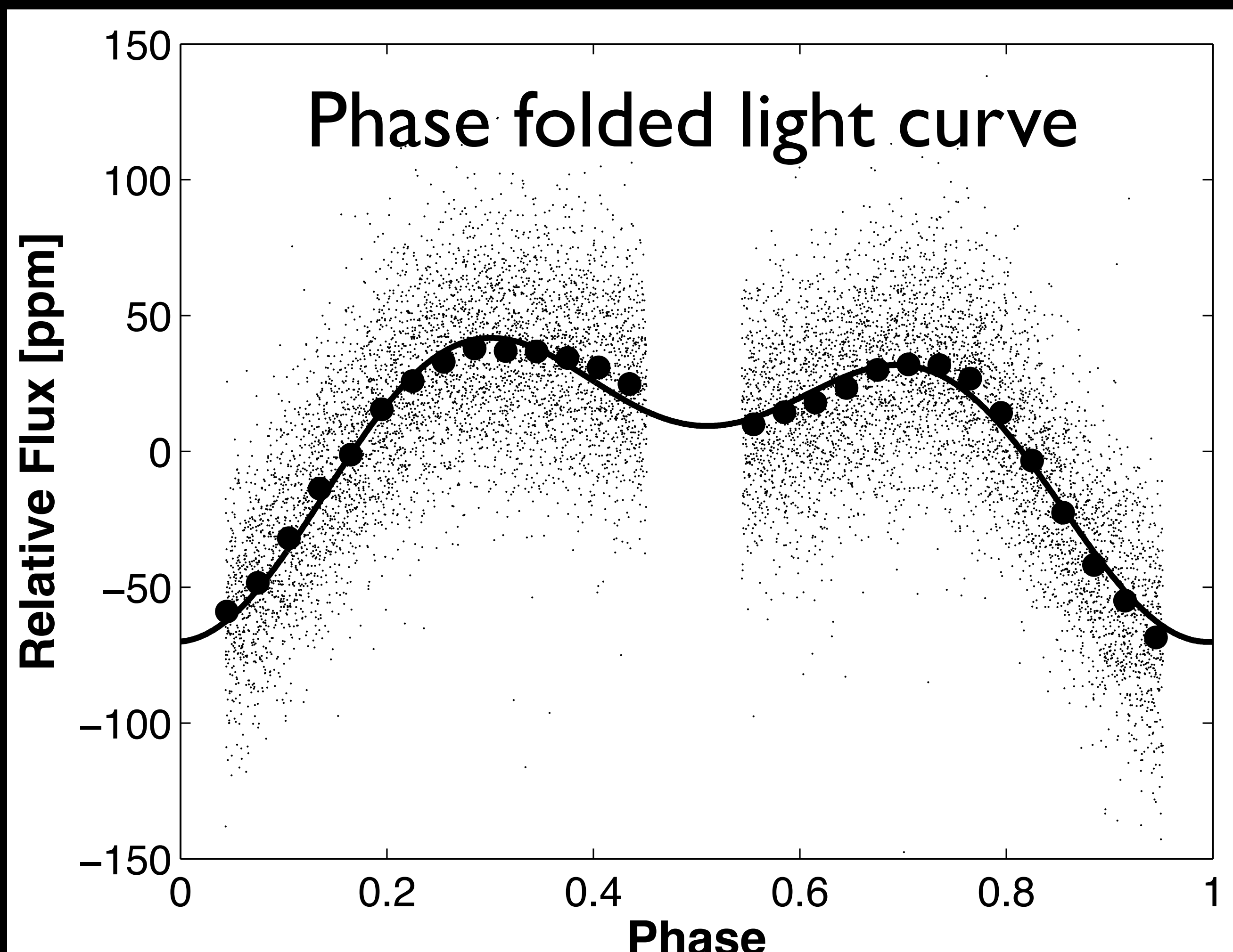
Parameter	Value
Orbital period, P_{orb} (days)	1.7637 ± 0.0013
Inferior conjunction time, T_0 (BJD)	2455138.7439 ± 0.0013

Consistent with transit ephemeris

Non-transiting KOI-13.01-like planets can be detected

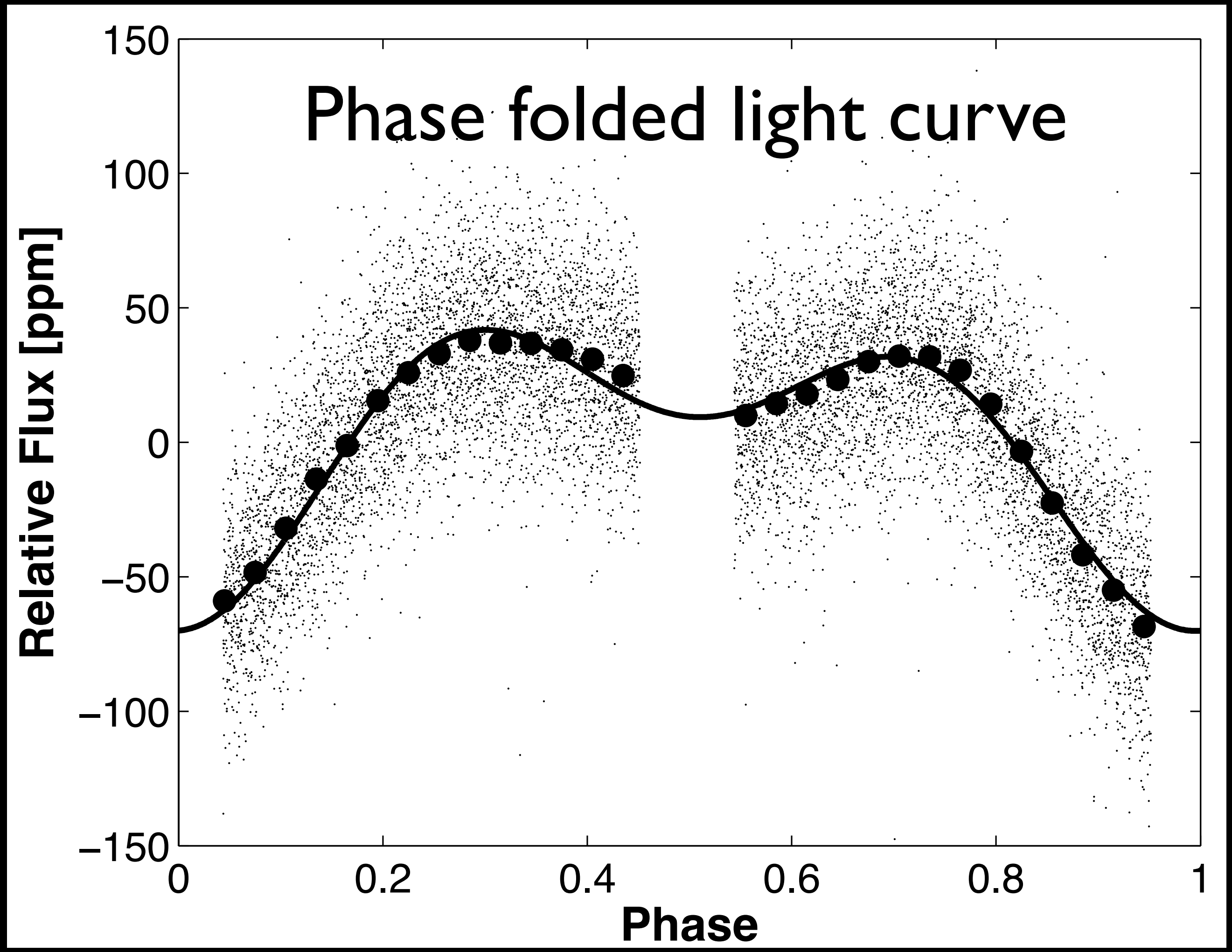
Detection of KOI-13.01 with the photometric orbit

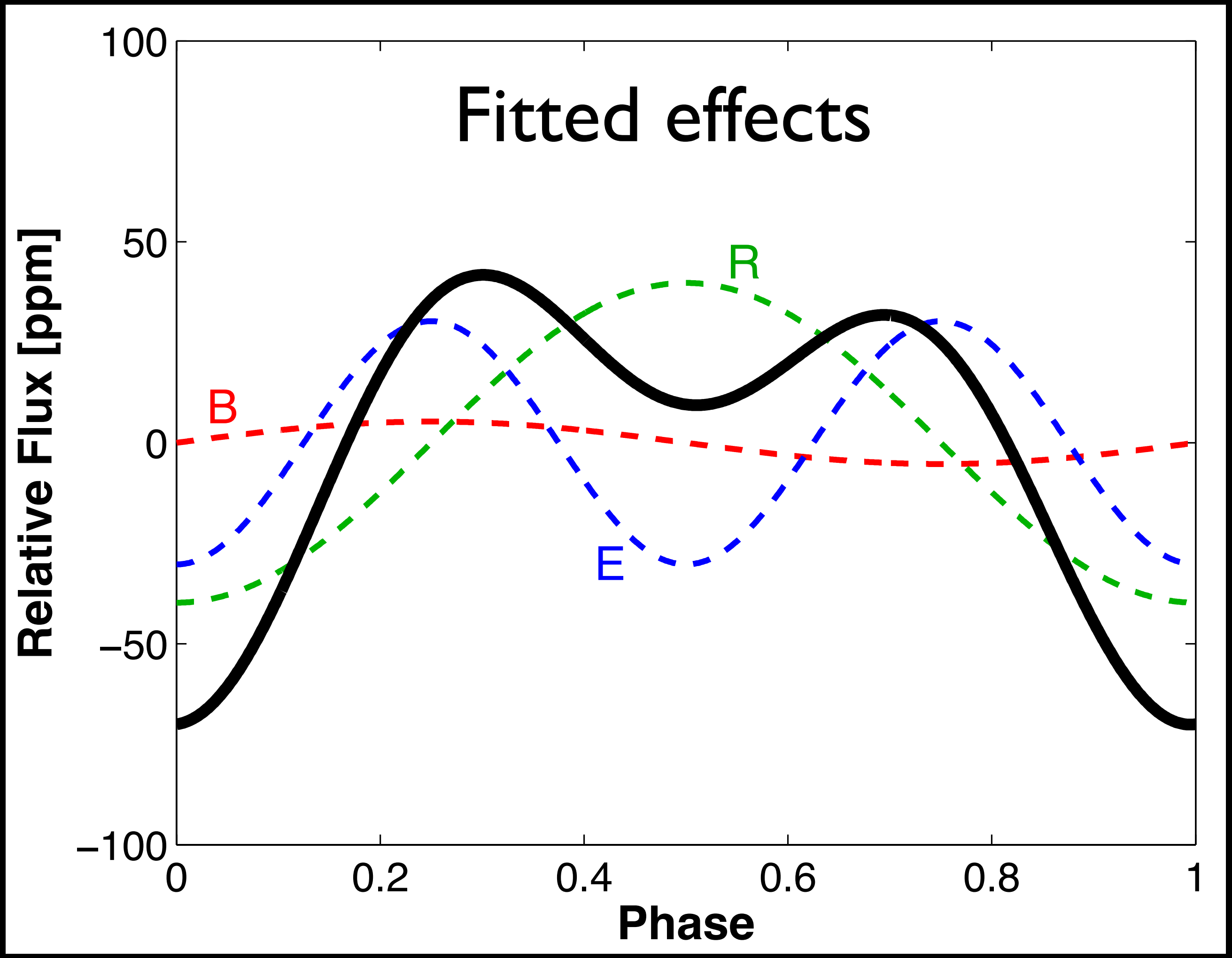
Shporer et al. 2011



Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011





Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

$$f(t) = a_0 + a_{1c}\cos\left(\frac{2\pi}{P}t\right) + a_{1s}\sin\left(\frac{2\pi}{P}t\right) + a_{2c}\cos\left(\frac{2\pi}{P/2}t\right) + a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)$$

Fitted coefficients

a_{1c}	Reflection	-39.8 ± 0.5
a_{1s}	Beaming	5.3 ± 0.4
a_{2c}	Ellipsoidal	-30.3 ± 0.5
a_{2s}	---------	0.0 ± 0.5

Realistic error estimate:
Cyclic residuals permutations.
2 x "formal" estimate.

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

$$f(t) = a_0 + a_{1c}\cos\left(\frac{2\pi}{P}t\right) + a_{1s}\sin\left(\frac{2\pi}{P}t\right) + a_{2c}\cos\left(\frac{2\pi}{P/2}t\right) + a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)$$

Fitted coefficients

a_{1c}	Reflection	-39.8 ± 0.5
a_{1s}	Beaming	5.3 ± 0.4
a_{2c}	Ellipsoidal	-30.3 ± 0.5
a_{2s}	---------	0.0 ± 0.5

Photometric mass measurement:

Realistic error estimate:
Cyclic residuals permutations.
2 x "formal" estimate.

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

$$f(t) = a_0 + a_{1c}\cos\left(\frac{2\pi}{P}t\right) + a_{1s}\sin\left(\frac{2\pi}{P}t\right) + a_{2c}\cos\left(\frac{2\pi}{P/2}t\right) + \boxed{a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)}$$

Fitted coefficients

a_{1c}	Reflection	-39.8 ± 0.5
a_{1s}	Beaming	5.3 ± 0.4
a_{2c}	Ellipsoidal	-30.3 ± 0.5
a_{2s}	---------	0.0 ± 0.5

Photometric mass measurement:

$$\boxed{M_2 \sin i = 9.2 \pm 1.1\ \mathrm{M_J}}$$

see also: Mazeh et al. 2012
Mislis et al. 2012

Realistic error estimate:
Cyclic residuals permutations.
2 x "formal" estimate.

Detection of KOI-13.01 with the photometric orbit

Shporer et al. 2011

$$f(t) = a_0 + a_{1c}\cos\left(\frac{2\pi}{P}t\right) + a_{1s}\sin\left(\frac{2\pi}{P}t\right) + a_{2c}\cos\left(\frac{2\pi}{P/2}t\right) + a_{2s}\sin\left(\frac{2\pi}{P/2}t\right)$$

Fitted coefficients

a_{1c}	Reflection	-39.8 ± 0.5
a_{1s}	Beaming	5.3 ± 0.4
a_{2c}	Ellipsoidal	-30.3 ± 0.5
a_{2s}	---------	0.0 ± 0.5

Realistic error estimate:
Cyclic residuals permutations.
2 x "formal" estimate.

Photometric mass measurement:

$M_2 \sin i = 9.2 \pm 1.1\ M_J$

see also: Mazeh et al. 2012
Mislis et al. 2012

Massive planet orbiting A-type star

Beaming planets

ongoing work...

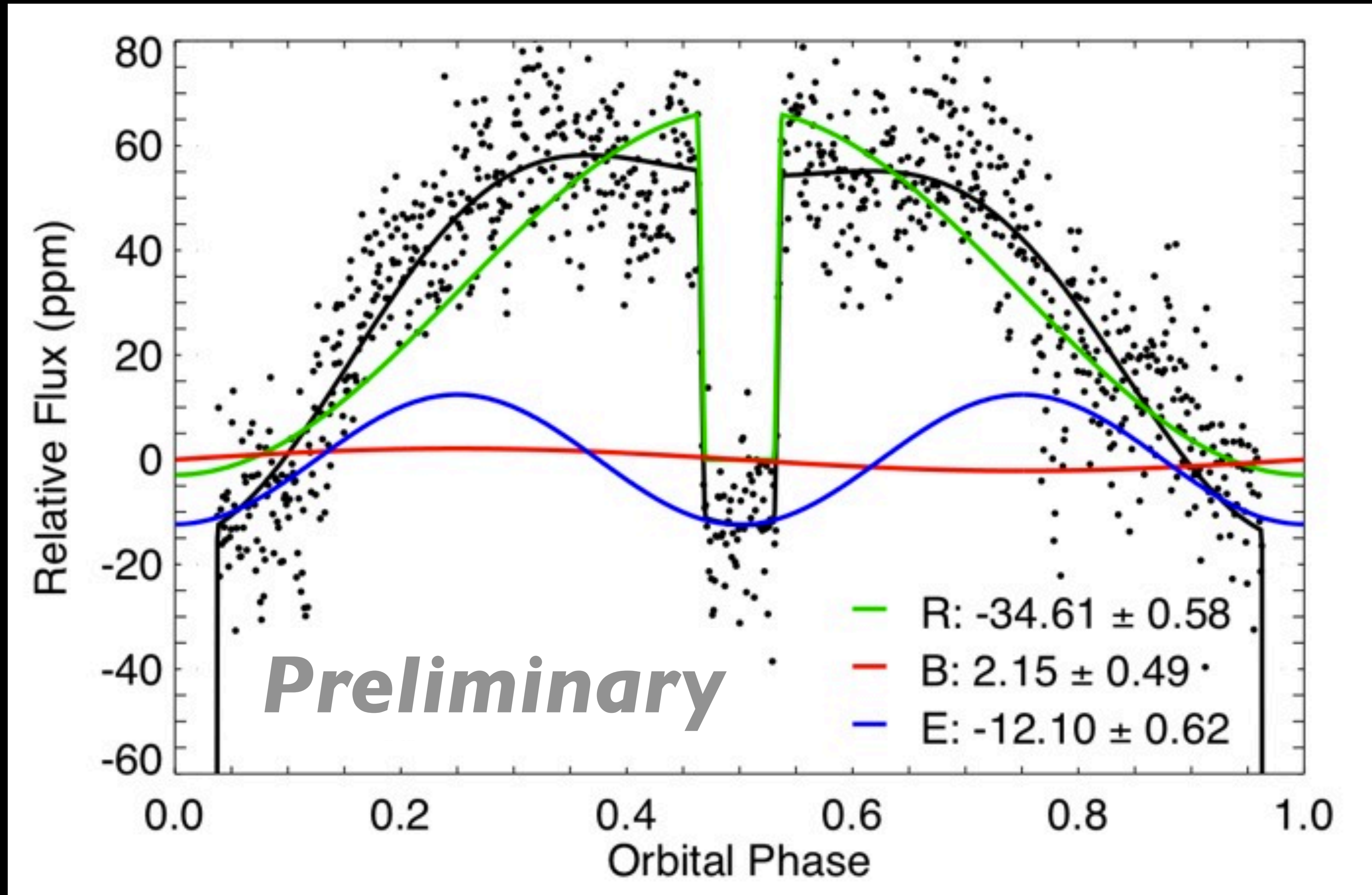
Beaming planets

ongoing work...

HAT-P-7b:

M_p = 1.8 M_J
P = 2.20 d

See also:
Borucki et al. 2009
Welsh et al. 2010
Mislis et al. 2012
Jackson et al. 2012

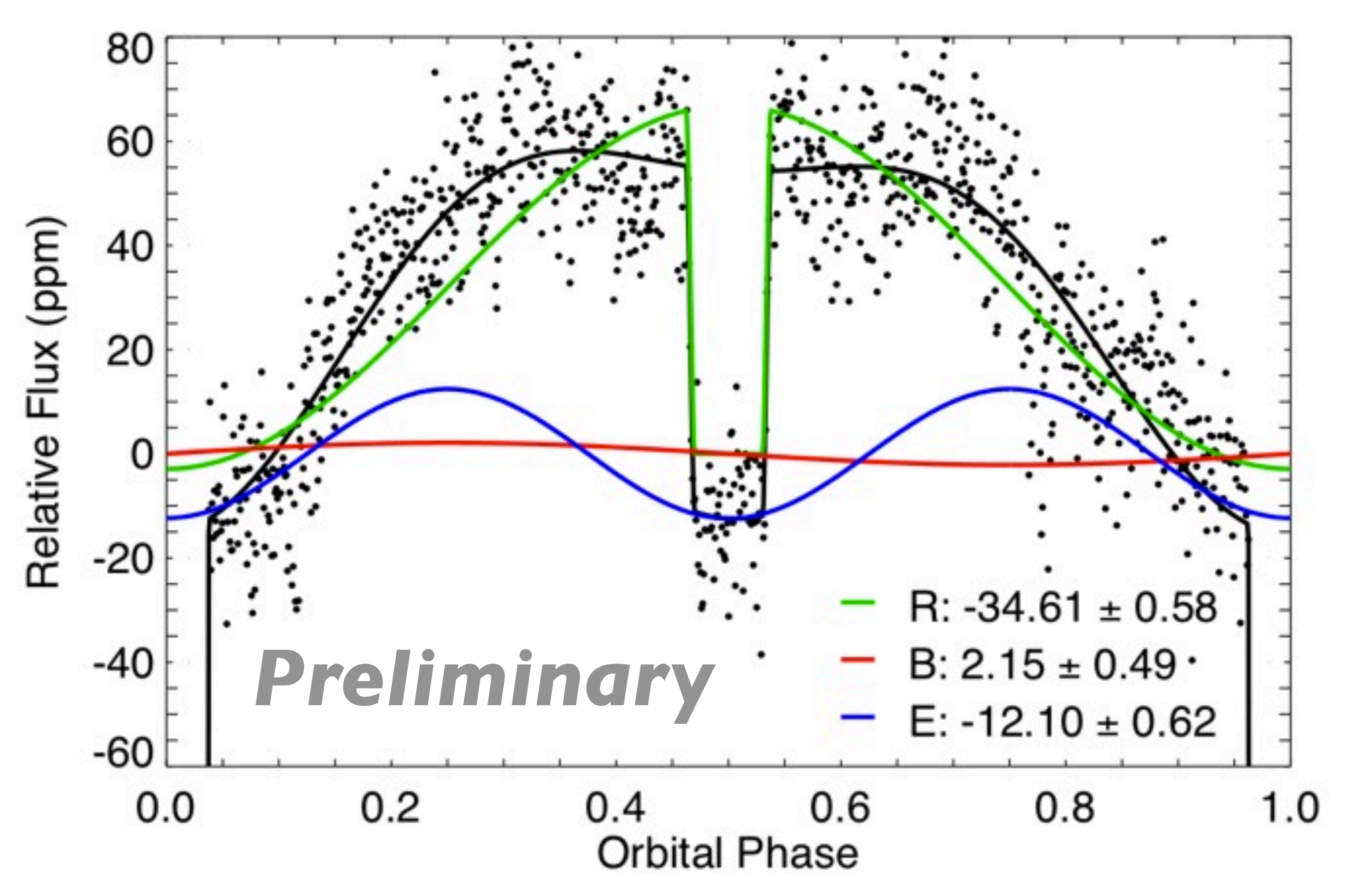


Beaming planets

ongoing work...

HAT-P-7b:

M_p = 1.8 M_J
P = 2.20 d



See also:
Borucki et al. 2009
Welsh et al. 2010
Mislis et al. 2012
Jackson et al. 2012

Full light curve analysis
Extended EXOFAST (Eastman et al. 2012)

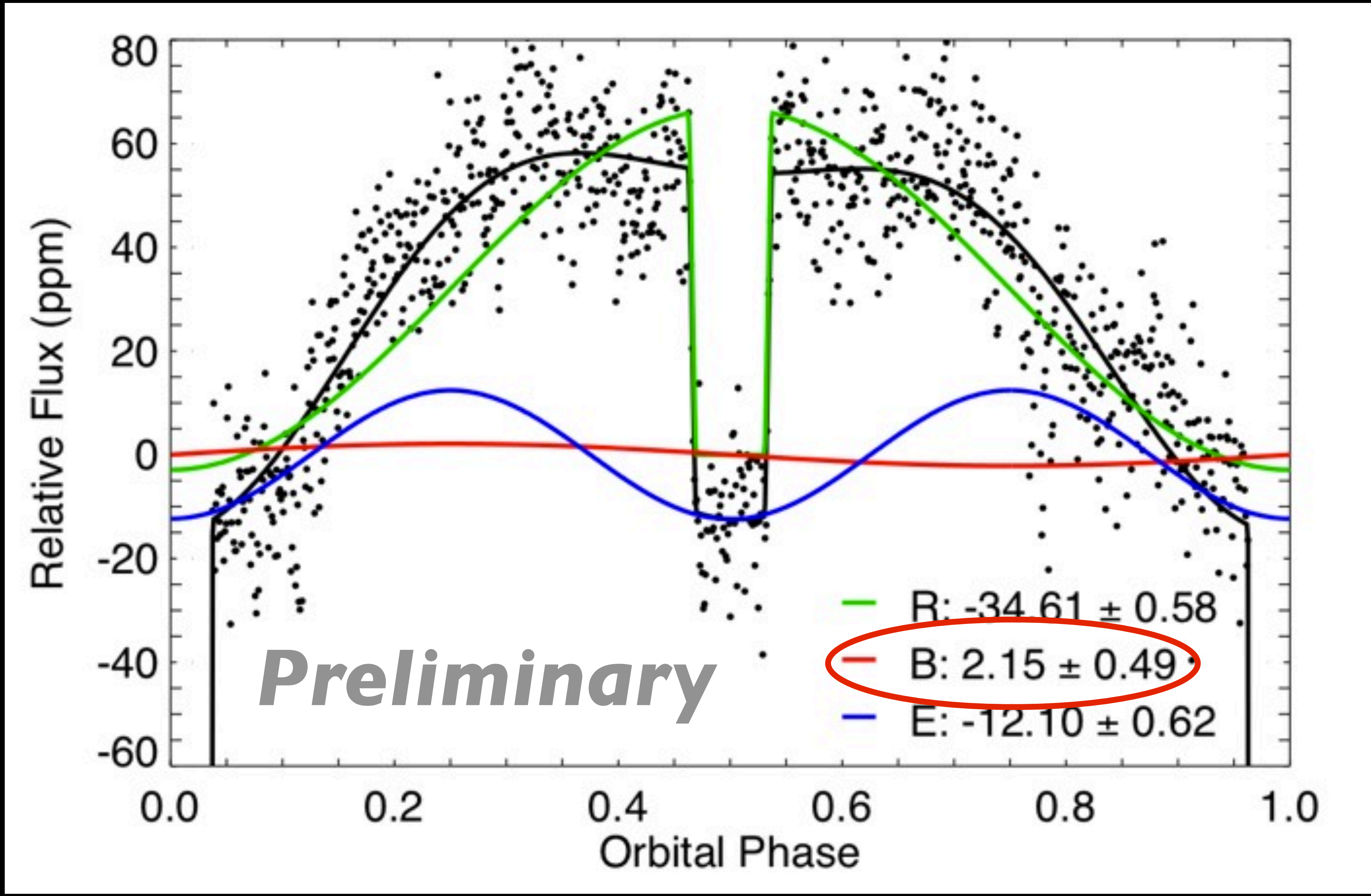
Beaming planets

ongoing work...

HAT-P-7b:

M_p = 1.8 M_J
P = 2.20 d

See also:
Borucki et al. 2009
Welsh et al. 2010
Mislis et al. 2012
Jackson et al. 2012



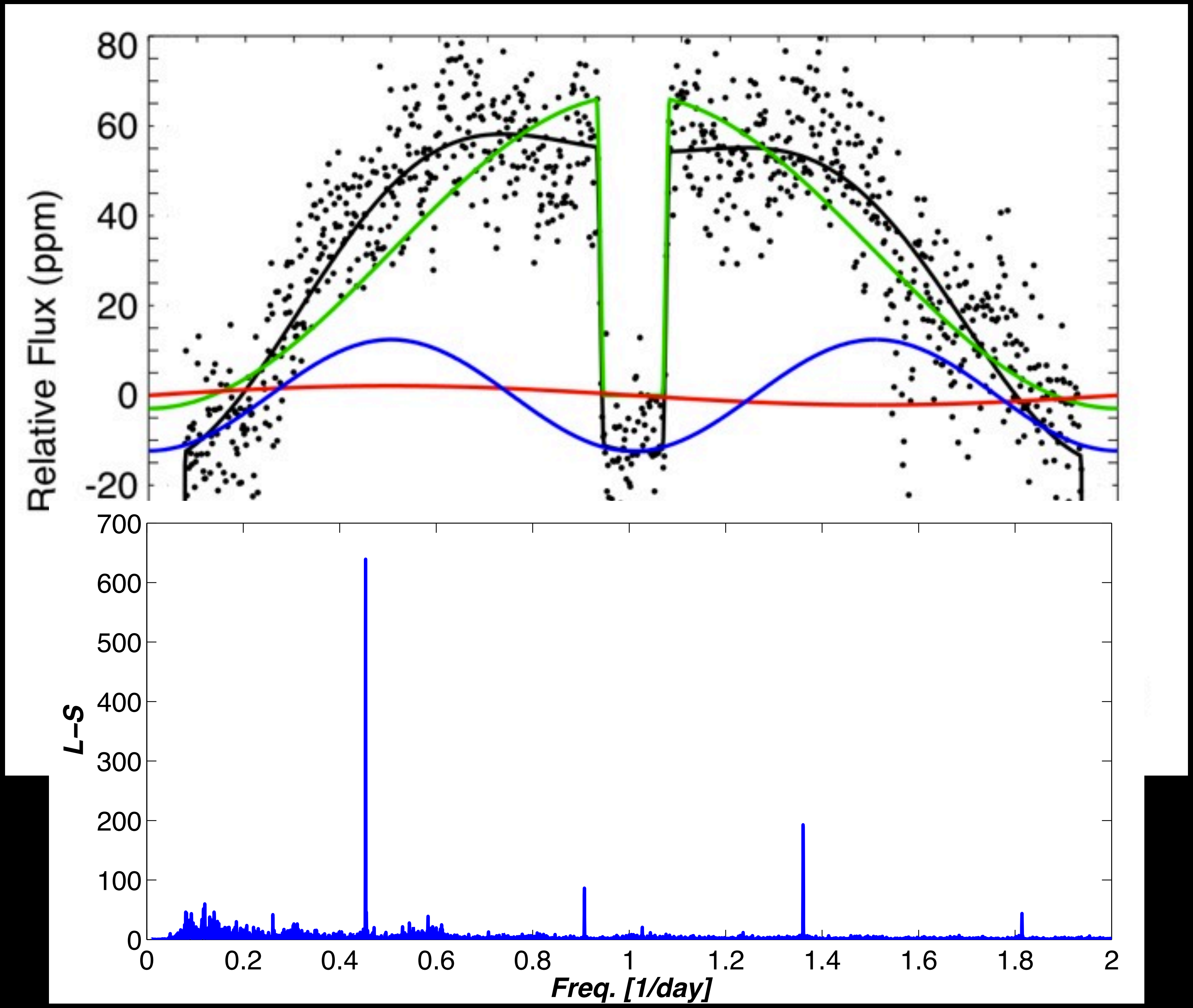
Full light curve analysis
Extended EXOFAST (Eastman et al. 2012)

Beaming planets

ongoing work...

HAT-P-7b:

M_p = 1.8 M_J
P = 2.20 d



See also:
Borucki et al. 2009
Welsh et al. 2010
Mislis et al. 2012
Jackson et al. 2012

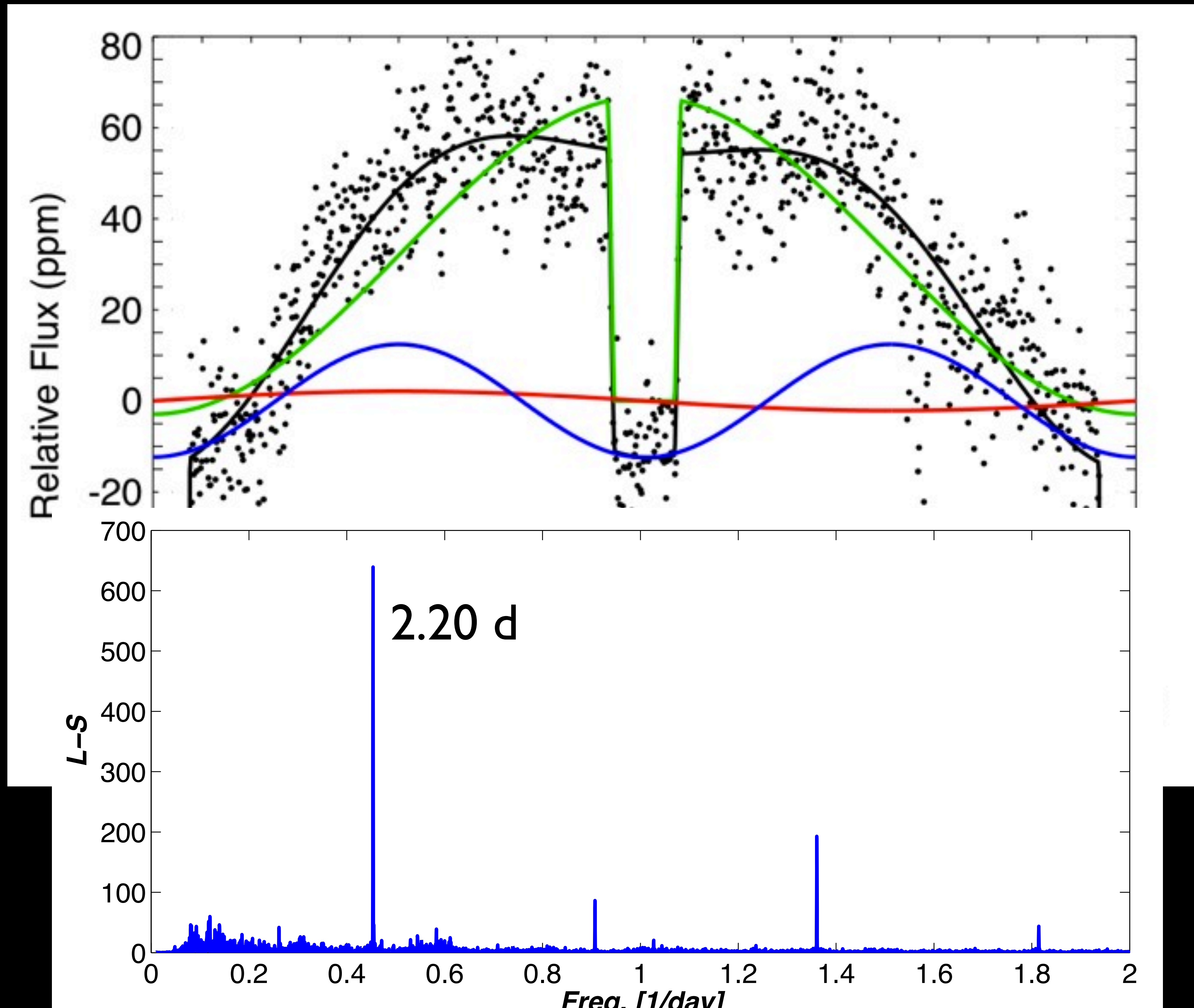
Beaming planets

ongoing work...

HAT-P-7b:

M_p = 1.8 M_J
P = 2.20 d

See also:
Borucki et al. 2009
Welsh et al. 2010
Mislis et al. 2012
Jackson et al. 2012



Mass-ratio inconsistency for early-type primaries

Mass-ratio inconsistency for early-type primaries

$$A_{\rm beam} = \alpha_{\rm beam} 4 \frac{K_{RV}}{c}$$

$$A_{\rm ellip} = \alpha_{\rm ellip} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

Mass-ratio inconsistency for early-type primaries

$$A_{\mathrm{beam}} = \alpha_{\mathrm{beam}} 4 \frac{K_{RV}}{c}$$

$$A_{\mathrm{ellip}} = \alpha_{\mathrm{ellip}} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

A-star-primary systems:

van Kerkwijk et al. 2010	KOI 74
Carter et al. 2011	KIC 10657664
Mazeh et al. 2012	KOI 13

Mass-ratio inconsistency for early-type primaries

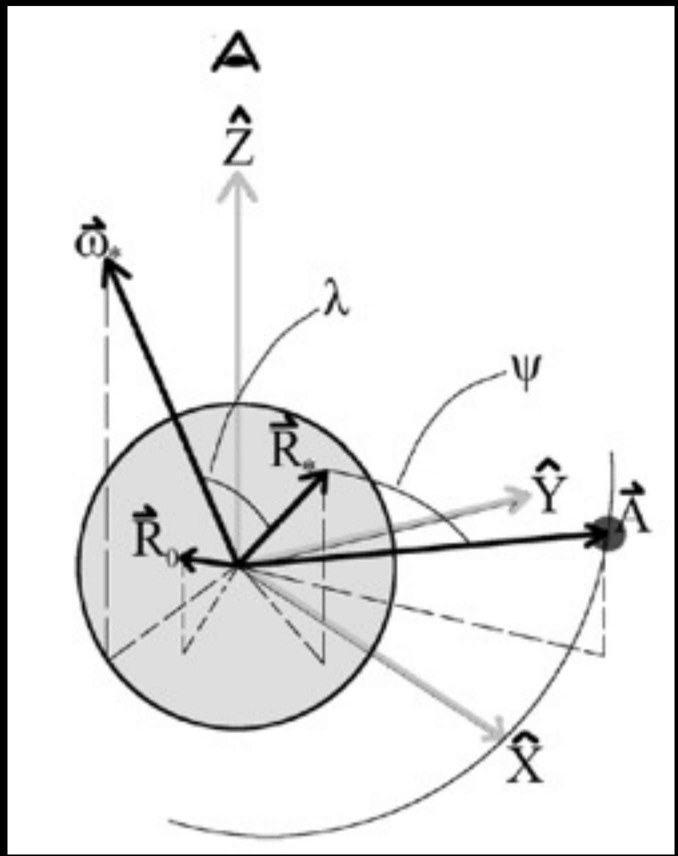
$$A_{\rm beam} = \alpha_{\rm beam} 4 \frac{K_{RV}}{c}$$

$$A_{\rm ellip} = \alpha_{\rm ellip} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

A-star-primary systems:

van Kerkwijk et al. 2010	KOI 74
Carter et al. 2011	KIC 10657664
Mazeh et al. 2012	KOI 13

$$U = \frac{GM_\star}{R_\star} + \frac{GM_p}{(A^2 - 2R_\star A \cos\psi + R_\star^2)^{1/2}}$$



Mass-ratio inconsistency for early-type primaries

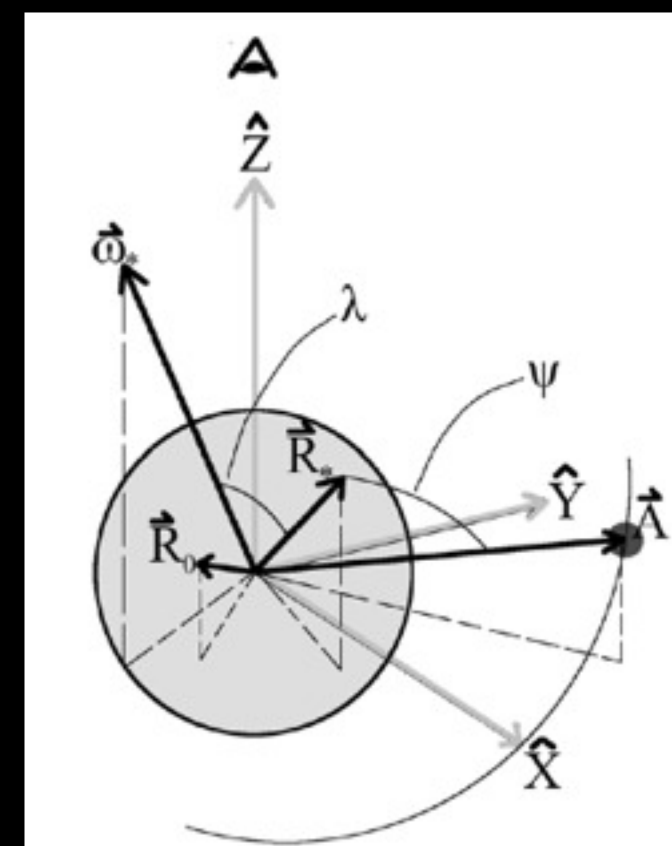
$$A_{\mathrm{beam}} = \alpha_{\mathrm{beam}} 4 \frac{K_{RV}}{c}$$

$$A_{\mathrm{ellip}} = \alpha_{\mathrm{ellip}} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

A-star-primary systems:

van Kerkwijk et al. 2010	KOI 74
Carter et al. 2011	KIC 10657664
Mazeh et al. 2012	KOI 13

$$U = \frac{GM_\star}{R_\star} + \frac{GM_p}{(A^2 - 2R_\star A \cos\psi + R_\star^2)^{1/2}}$$



Approximations assume:

Mass-ratio inconsistency for early-type primaries

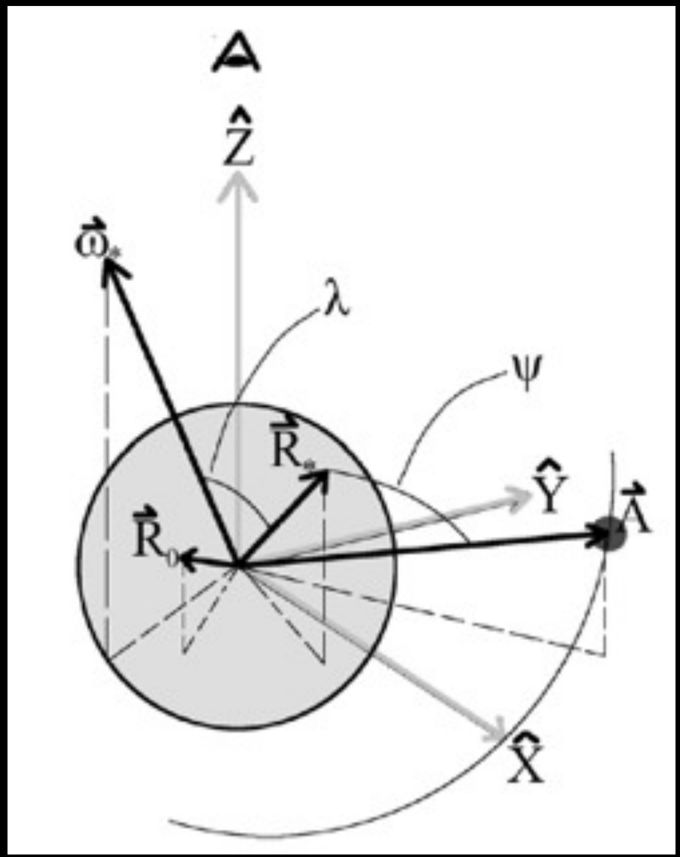
$$A_{\rm beam} = \alpha_{\rm beam} 4 \frac{K_{RV}}{c}$$

$$A_{\rm ellip} = \alpha_{\rm ellip} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

A-star-primary systems:

van Kerkwijk et al. 2010	KOI 74
Carter et al. 2011	KIC 10657664
Mazeh et al. 2012	KOI 13

$$U = \frac{GM_\star}{R_\star} + \frac{GM_p}{(A^2 - 2R_\star A\cos\psi + R_\star^2)^{1/2}}$$



Approximations assume:

- Synchronization

Mass-ratio inconsistency for early-type primaries

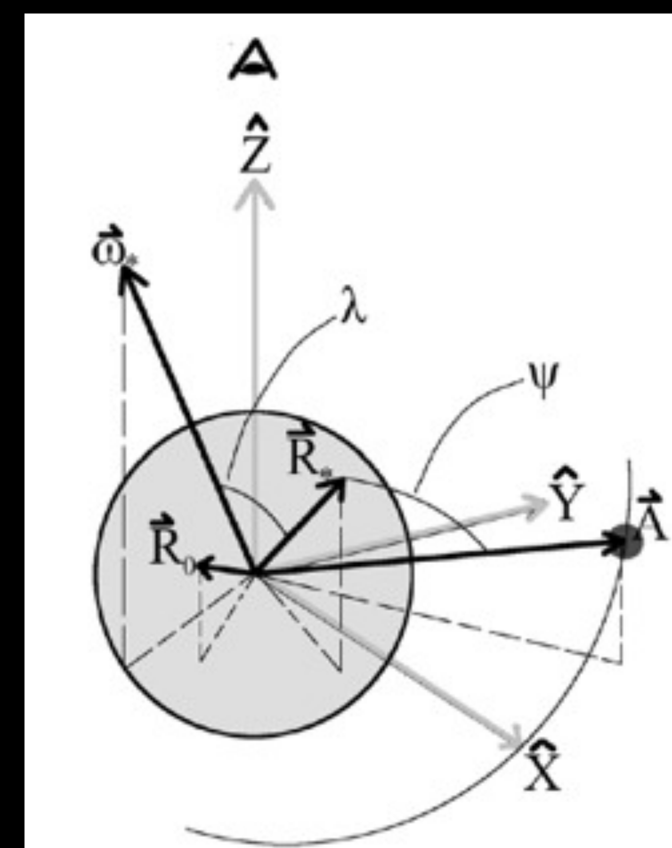
$$A_{\rm beam} = \alpha_{\rm beam} 4 \frac{K_{RV}}{c}$$

$$A_{\rm ellip} = \alpha_{\rm ellip} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

A-star-primary systems:

van Kerkwijk et al. 2010	KOI 74
Carter et al. 2011	KIC 10657664
Mazeh et al. 2012	KOI 13

$$U = \frac{GM_\star}{R_\star} + \frac{GM_p}{(A^2 - 2R_\star A \cos\psi + R_\star^2)^{1/2}}$$



Approximations assume:

- Synchronization
- Alignment

Mass-ratio inconsistency for early-type primaries

$$A_{\rm beam} = \alpha_{\rm beam} 4 \frac{K_{RV}}{c}$$

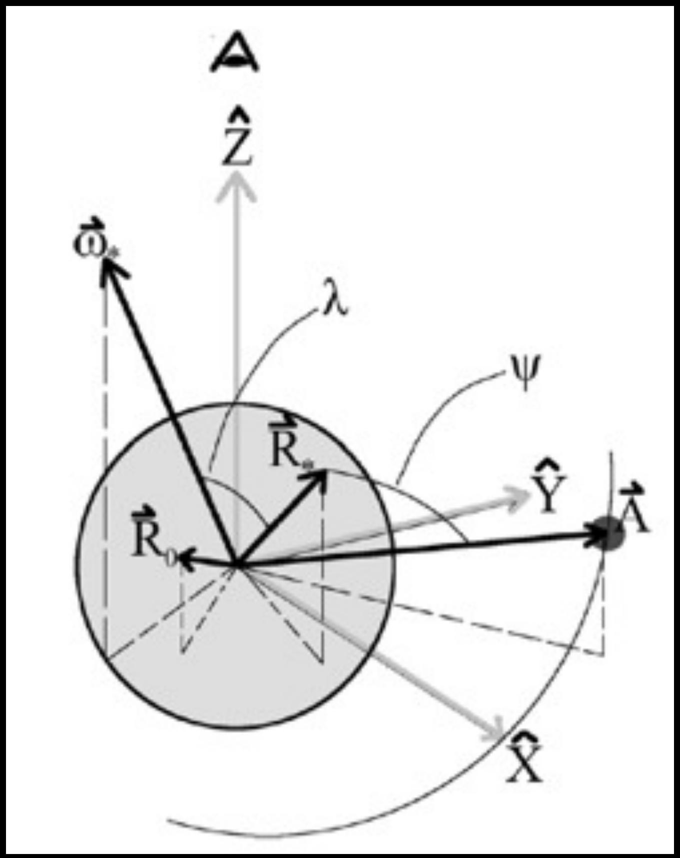
$$A_{\rm ellip} = \alpha_{\rm ellip} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a}\right)^3 \sin i$$

A-star-primary systems:

van Kerkwijk et al. 2010	KOI 74
Carter et al. 2011	KIC 10657664
Mazeh et al. 2012	KOI 13

$$U = \frac{GM_\star}{R_\star} + \frac{GM_p}{(A^2 - 2R_\star A \cos\psi + R_\star^2)^{1/2}} + \frac{1}{2}\omega_\star^2 R_\star^2 (1 - \cos^2\lambda)$$

Adopted from Jackson et al. 2012



Approximations assume:

- Synchronization
- Alignment

Mass-ratio inconsistency for early-type primaries

$$A_{\mathrm{beam}} = \alpha_{\mathrm{beam}} 4 \frac{K_{RV}}{c}$$

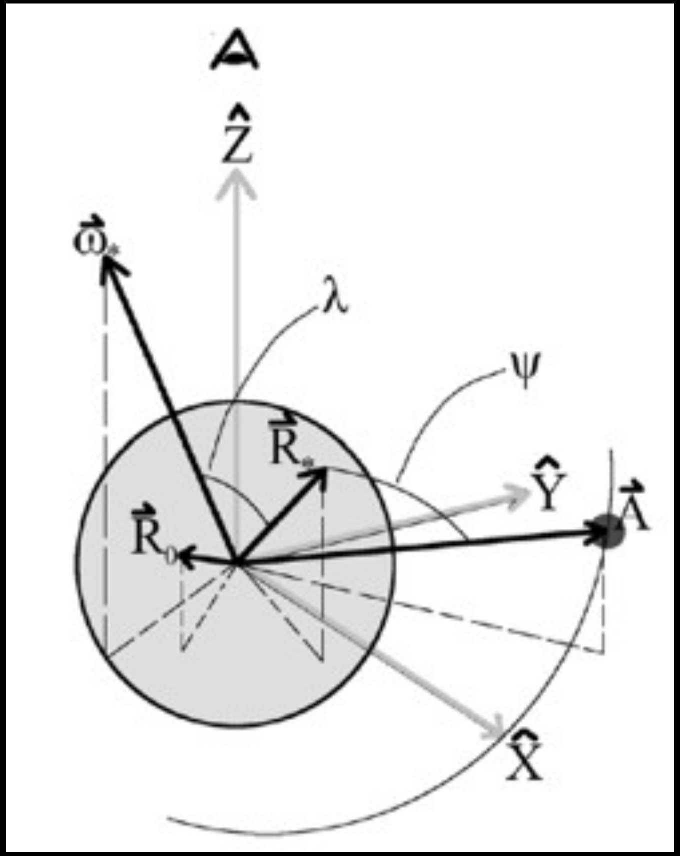
$$A_{\mathrm{ellip}} = \alpha_{\mathrm{ellip}} \frac{M_2 \sin i}{M_s} \left(\frac{R_s}{a} \right)^3 \sin i$$

A-star-primary systems:

van Kerkwijk et al. 2010	KOI 74
Carter et al. 2011	KIC 10657664
Mazeh et al. 2012	KOI 13

$$U = \frac{GM_\star}{R_\star} + \frac{GM_p}{(A^2 - 2R_\star A \cos\psi + R_\star^2)^{1/2}} + \frac{1}{2}\omega_\star^2 R_\star^2 (1 - \cos^2\lambda)$$

Adopted from Jackson et al. 2012



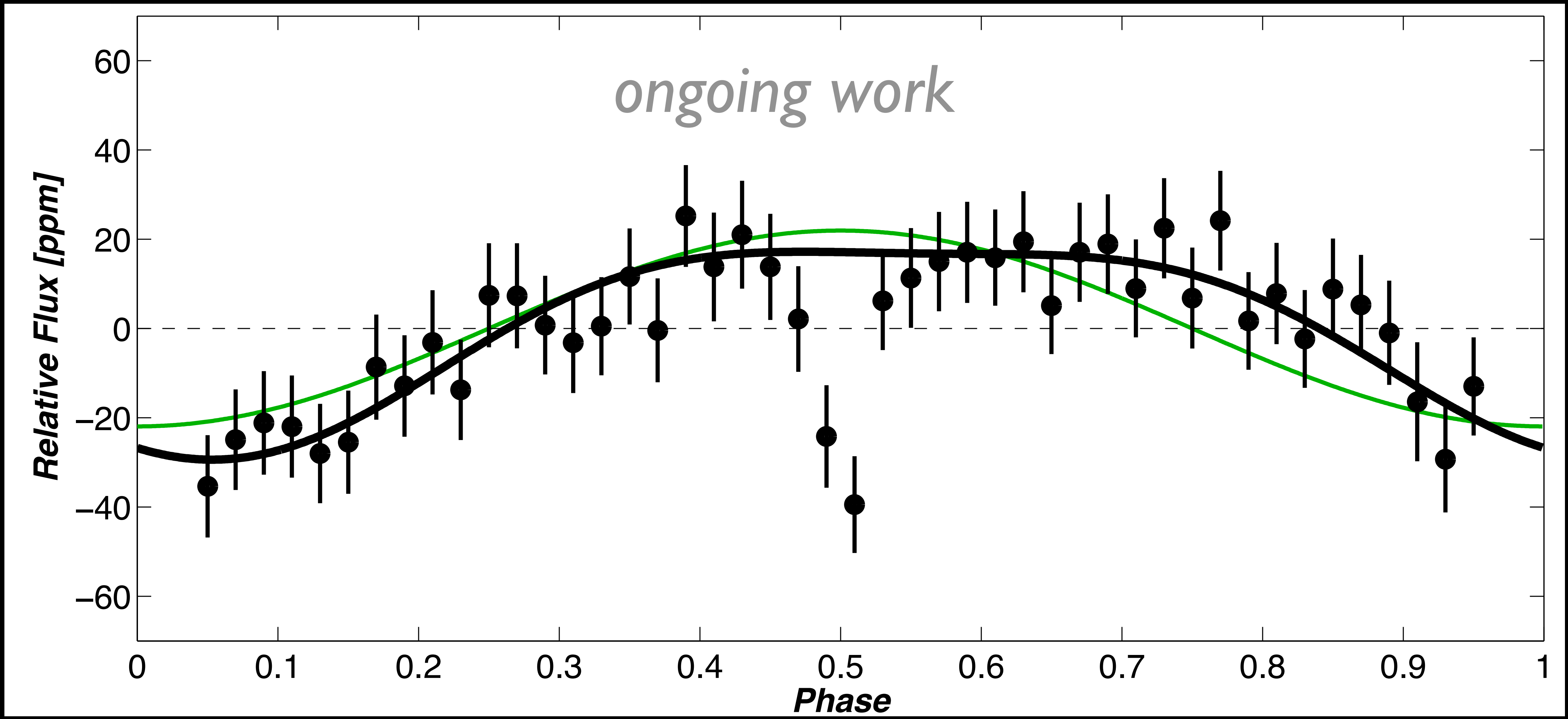
Approximations assume:

- Synchronization
- Alignment

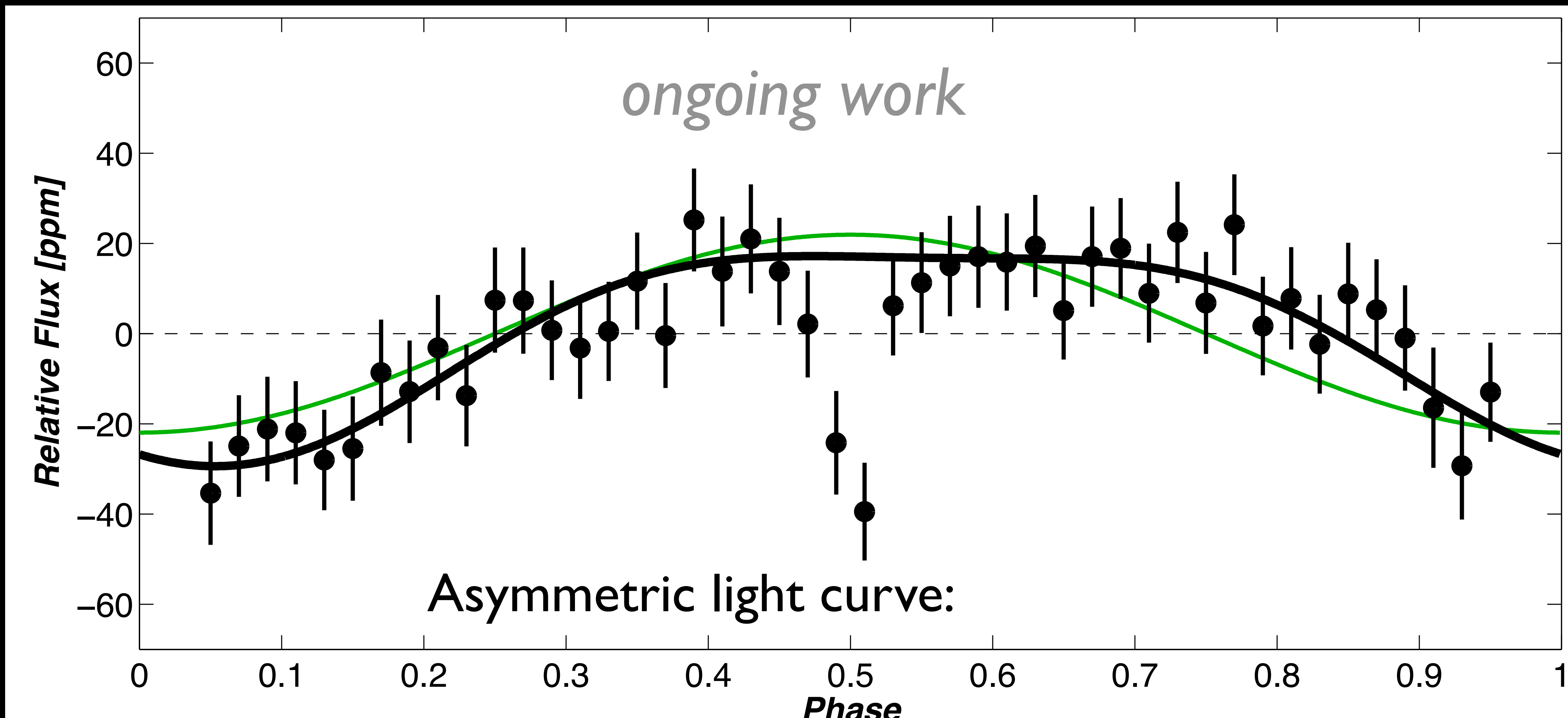
Jackson et al. 2012: Allowing non-synchronization and misalignment (see also Pfahl et al. 2008)

Asymmetric reflection/heating ?

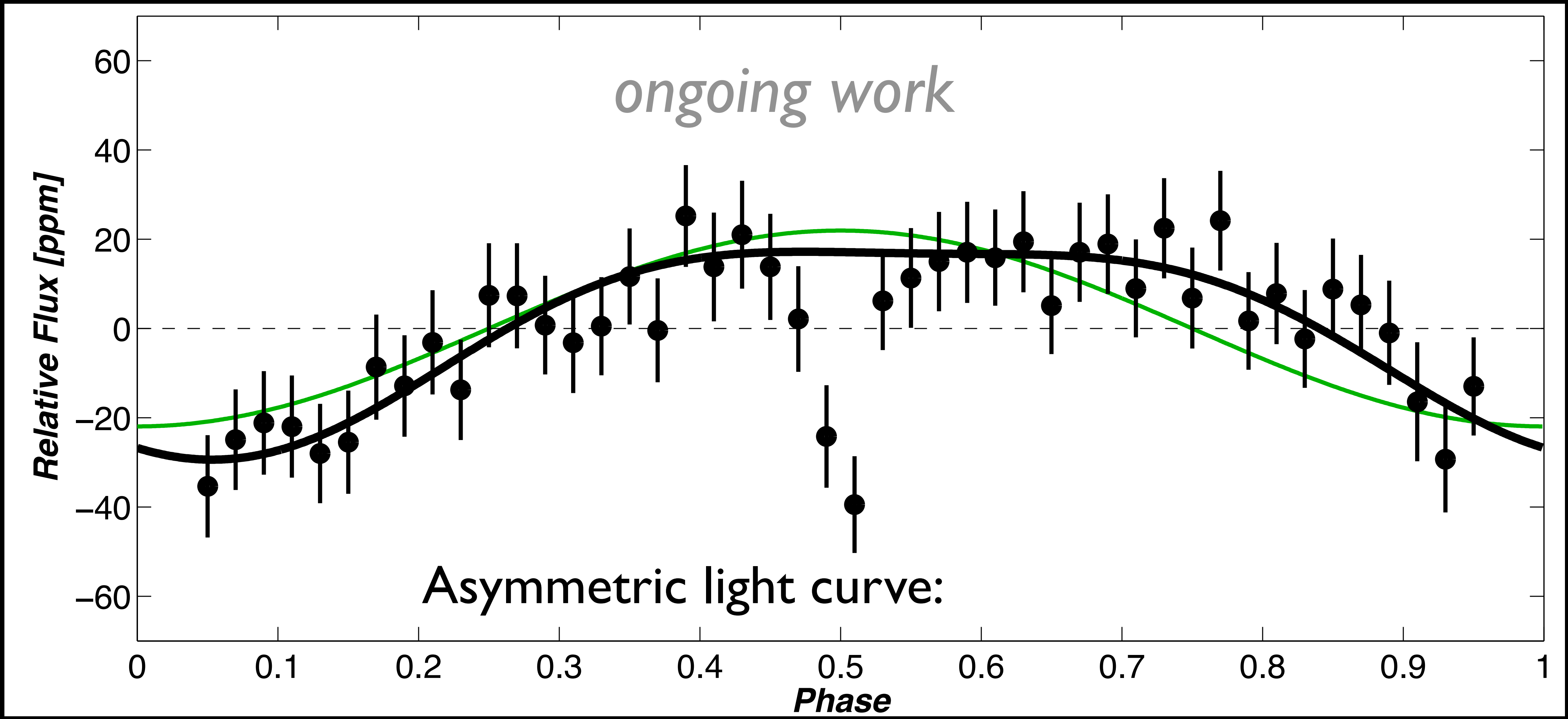
Asymmetric reflection/heating ?



Asymmetric reflection/heating ?

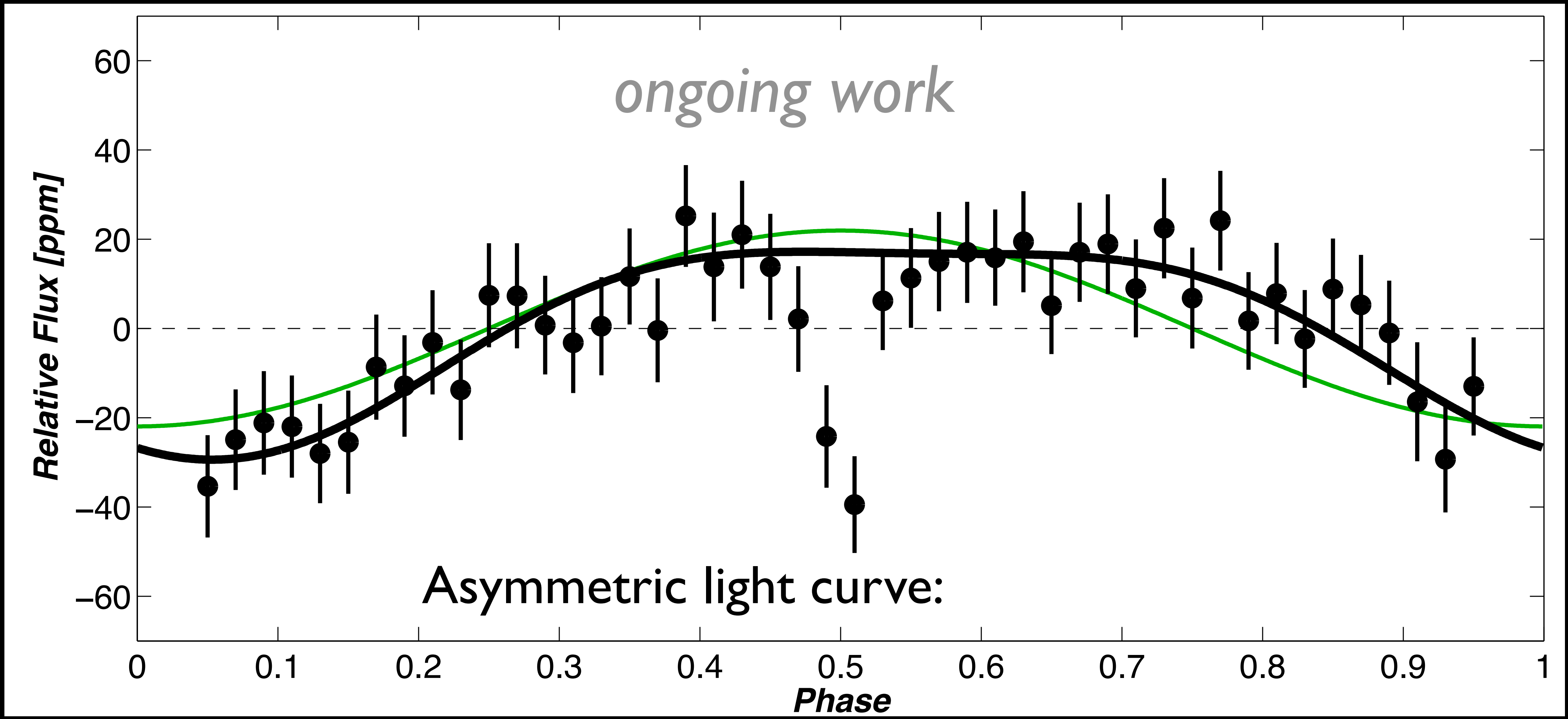


Asymmetric reflection/heating ?

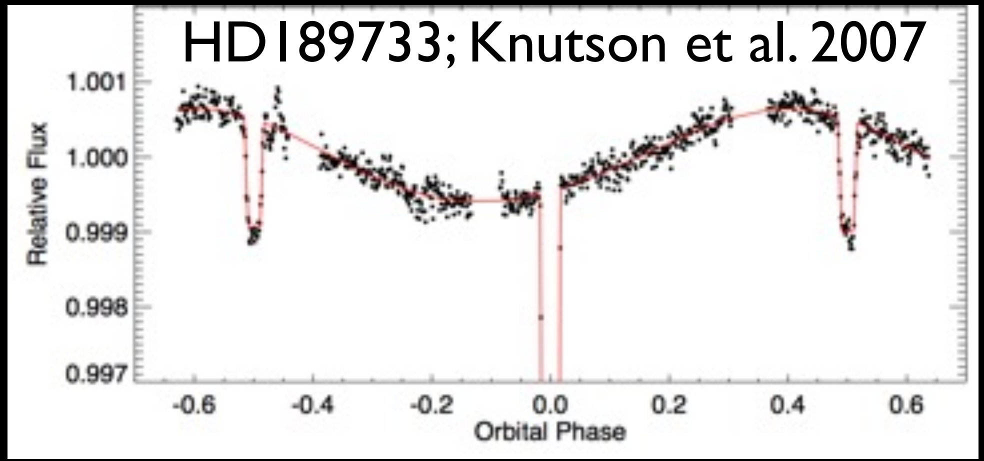


Assuming tidal locking and no “hotspot”

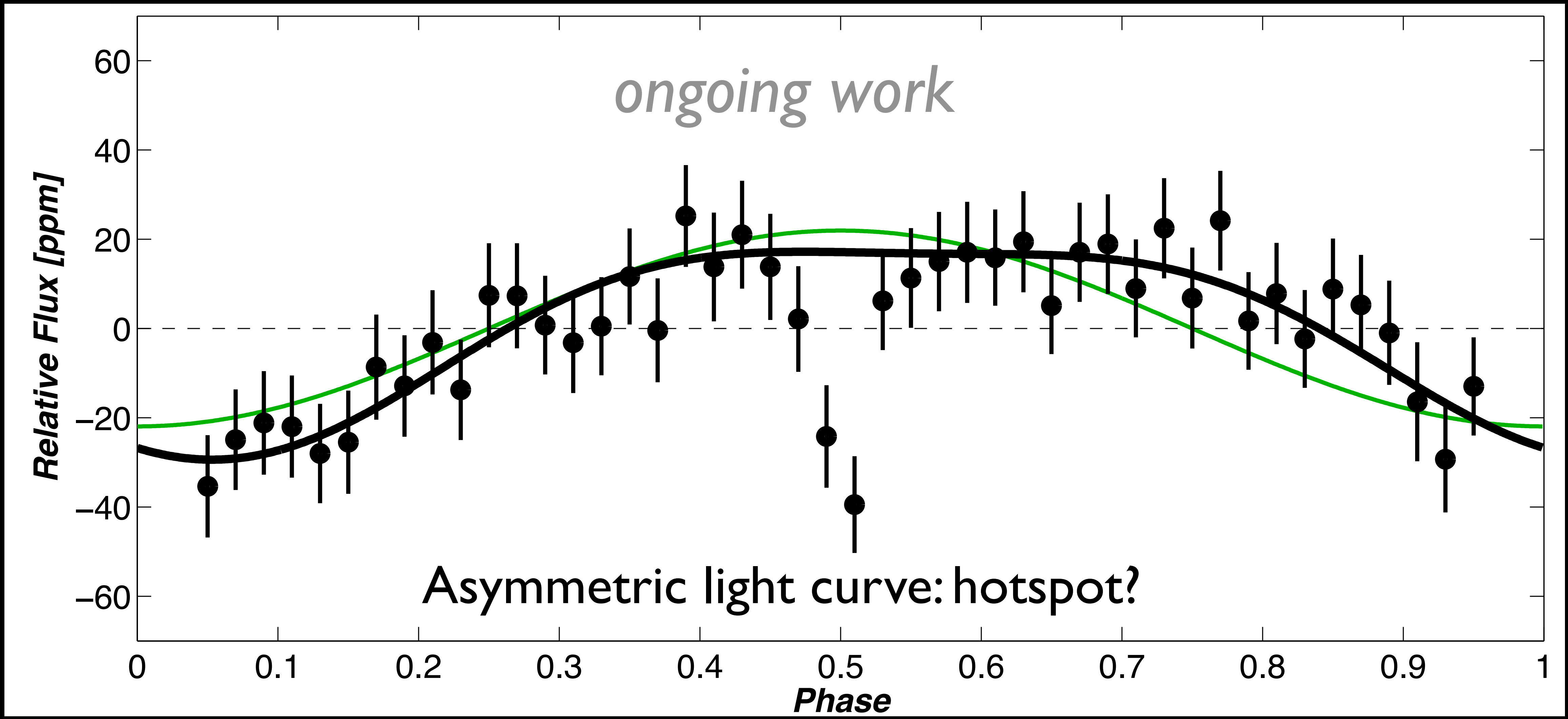
Asymmetric reflection/heating ?



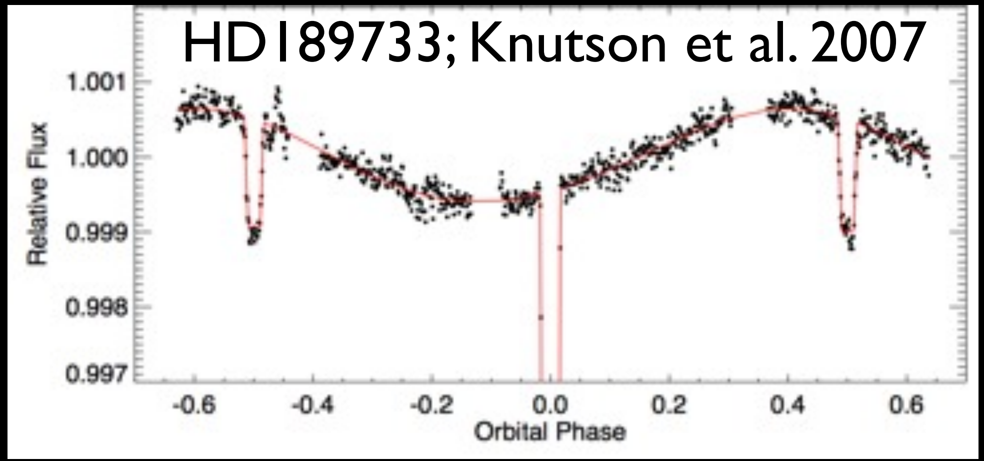
Assuming tidal locking and no "hotspot"



Asymmetric reflection/heating ?



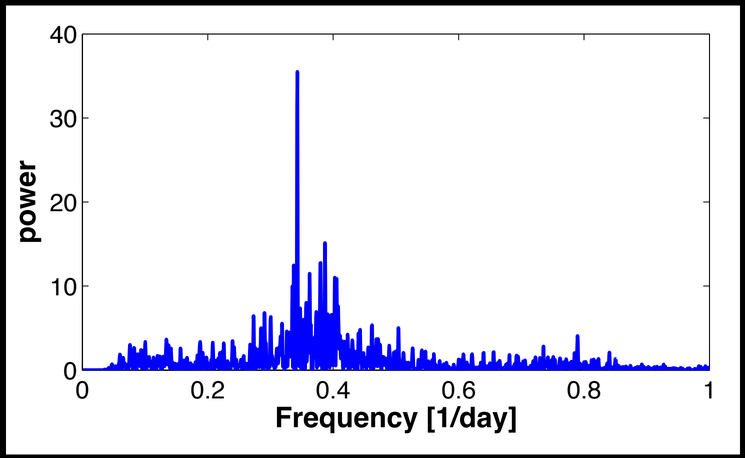
Assuming tidal locking and no "hotspot"

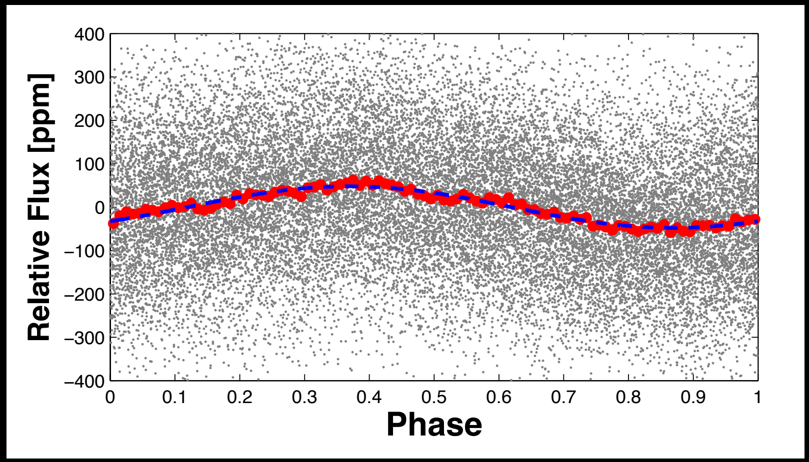


Stellar activity

Stellar activity

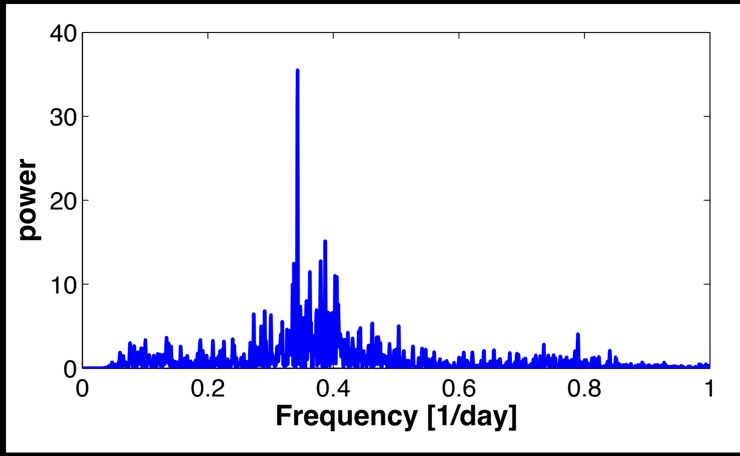
Kepler-14 (KOI-98)
Buchhave et al. 2011

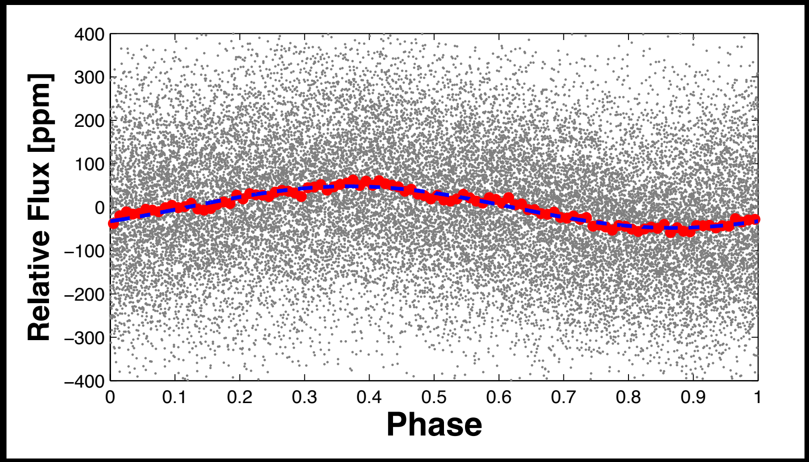




Stellar activity

Kepler-14 (KOI-98)
Buchhave et al. 2011

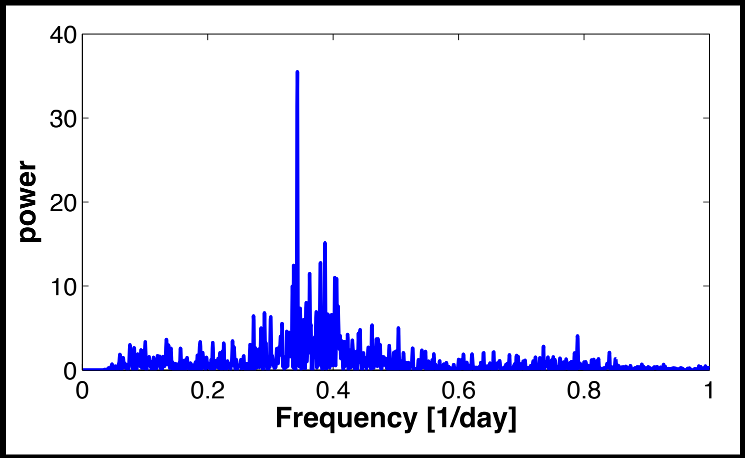


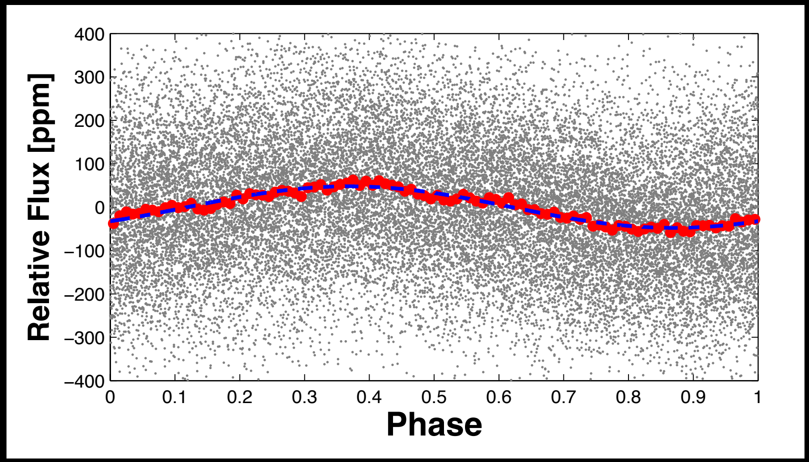


P_{orb} = 6.79 d
P_{phot} = 2.92 d
activity?

Stellar activity

Kepler-14 (KOI-98)
Buchhave et al. 2011



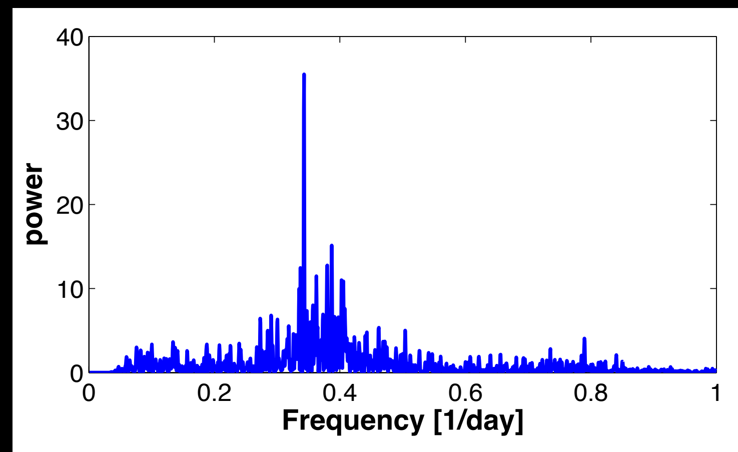


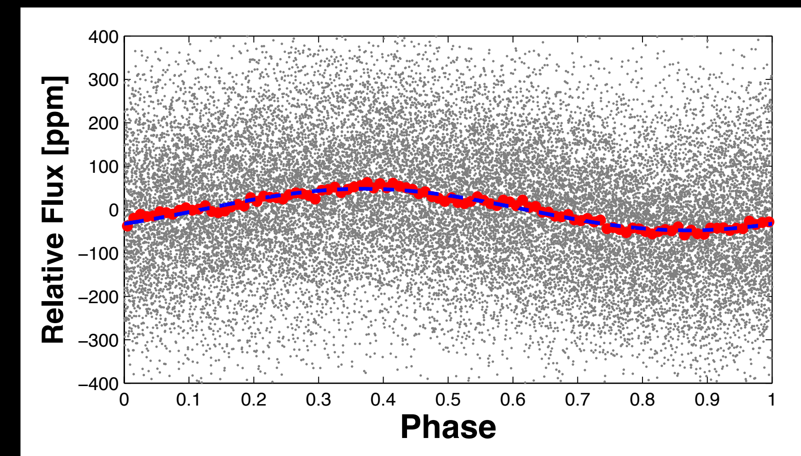
P_{orb} = 6.79 d
P_{phot} = 2.92 d
activity?

Scalogram - time evolving periodogram

Stellar activity

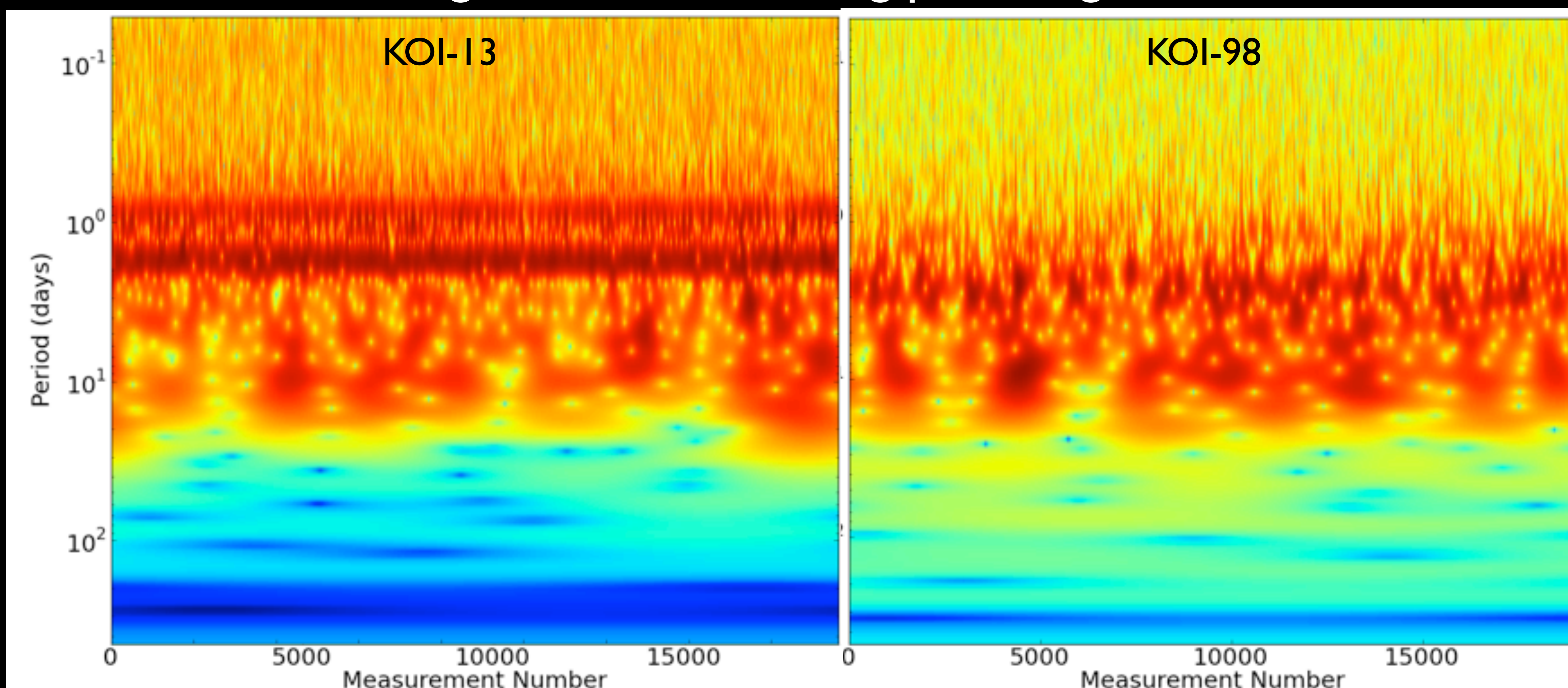
Kepler-14 (KOI-98)
Buchhave et al. 2011





P_{orb} = 6.79 d
P_{phot} = 2.92 d
activity?

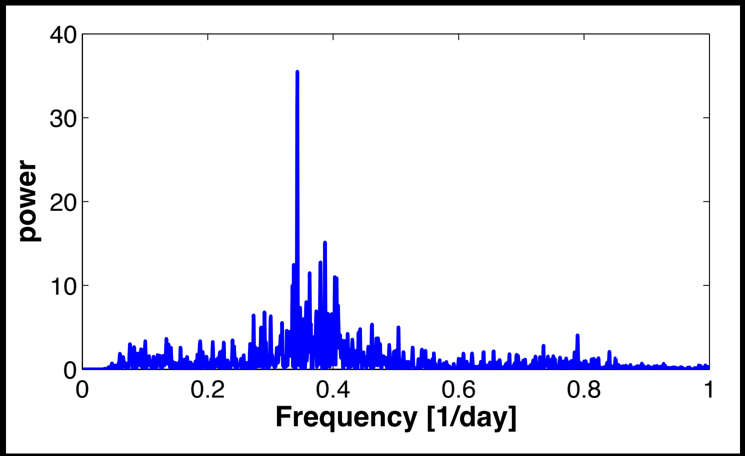
Scalogram - time evolving periodogram

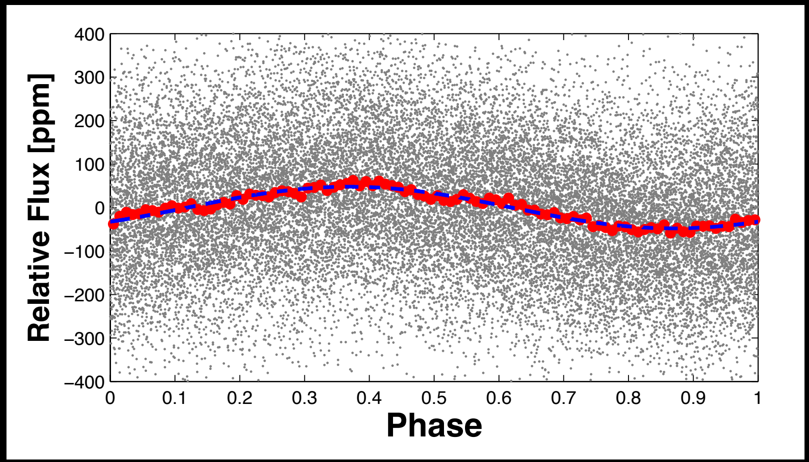


Benjamin Fulton (LCOGT)

Stellar activity

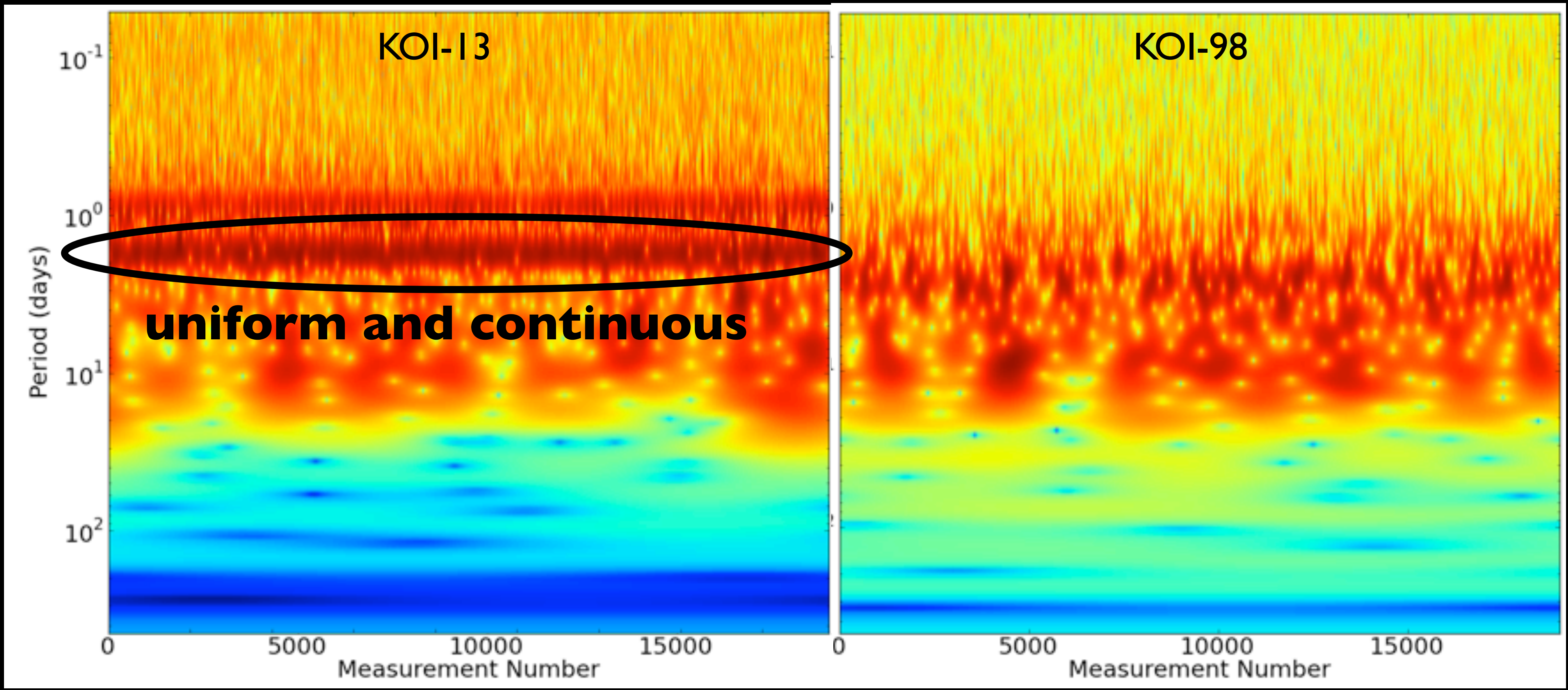
Kepler-14 (KOI-98)
Buchhave et al. 2011





P_{orb} = 6.79 d
P_{phot} = 2.92 d
activity?

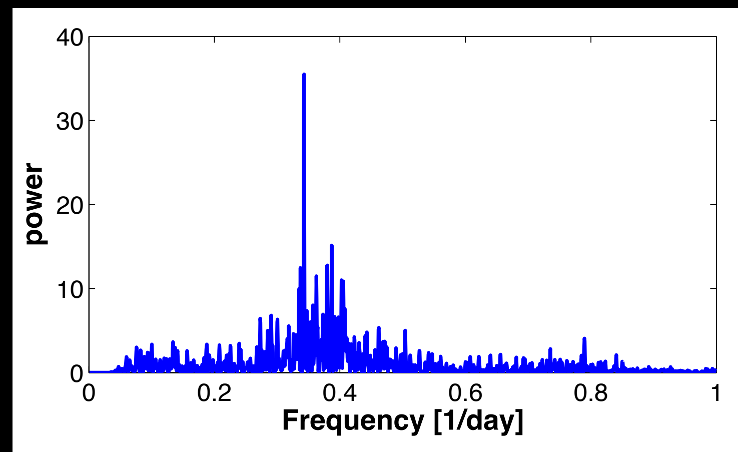
Scalogram - time evolving periodogram

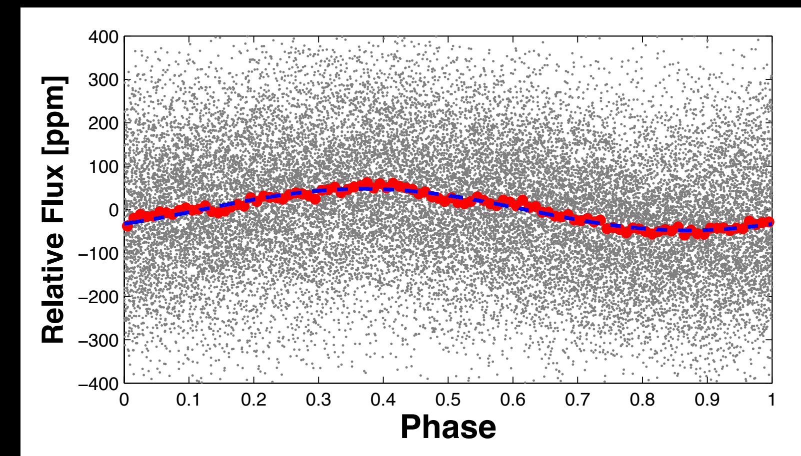


Benjamin Fulton (LCOGT)

Stellar activity

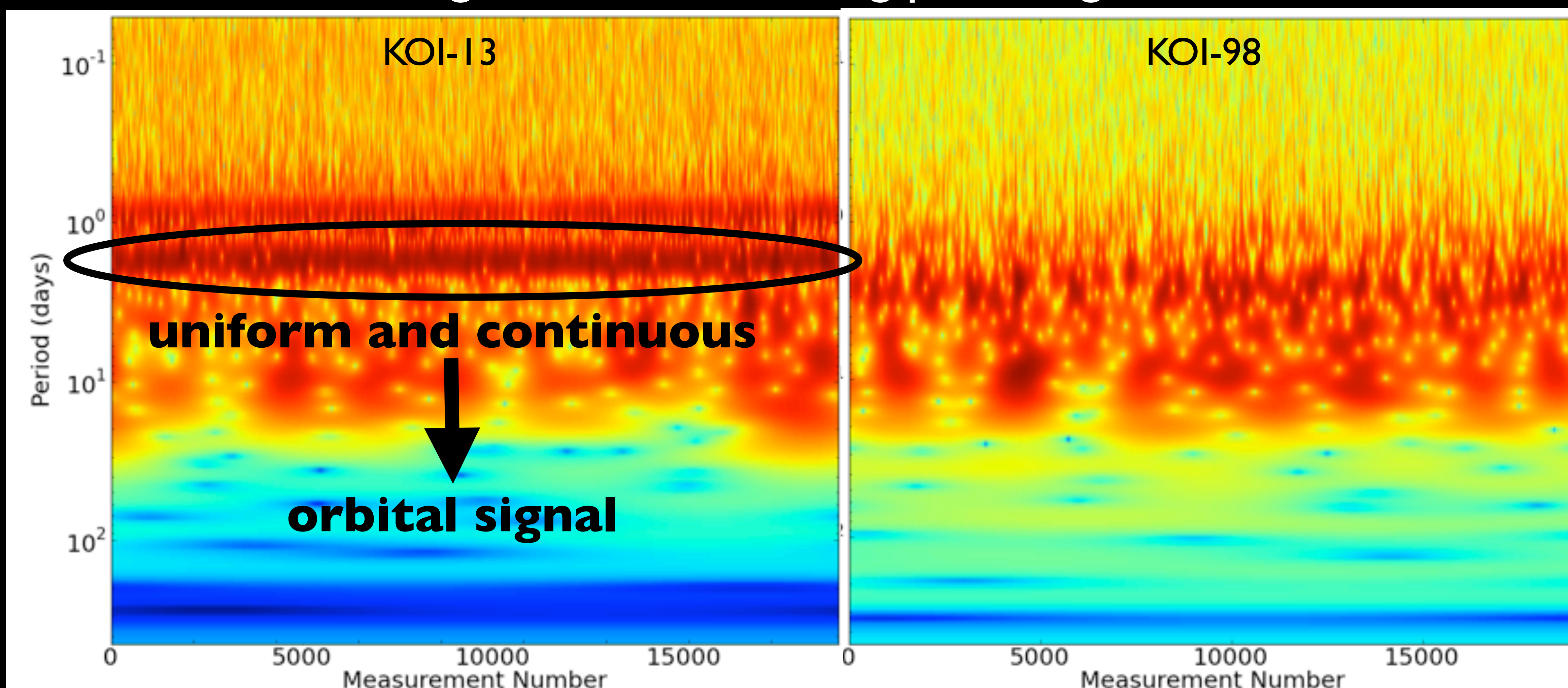
Kepler-14 (KOI-98)
Buchhave et al. 2011





P_{orb} = 6.79 d
P_{phot} = 2.92 d
activity?

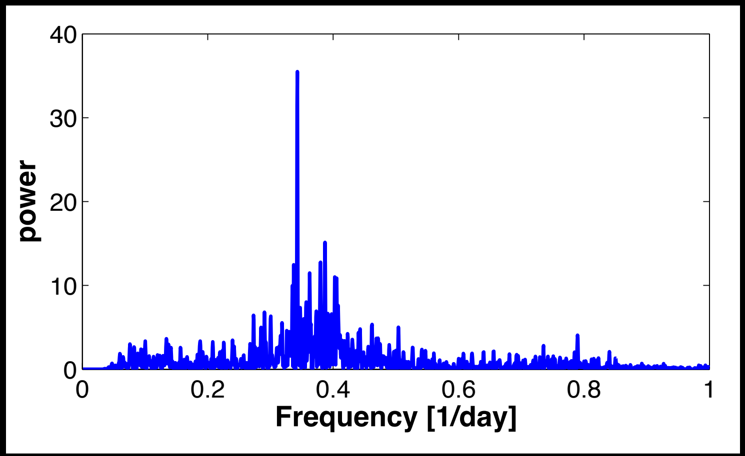
Scalogram - time evolving periodogram

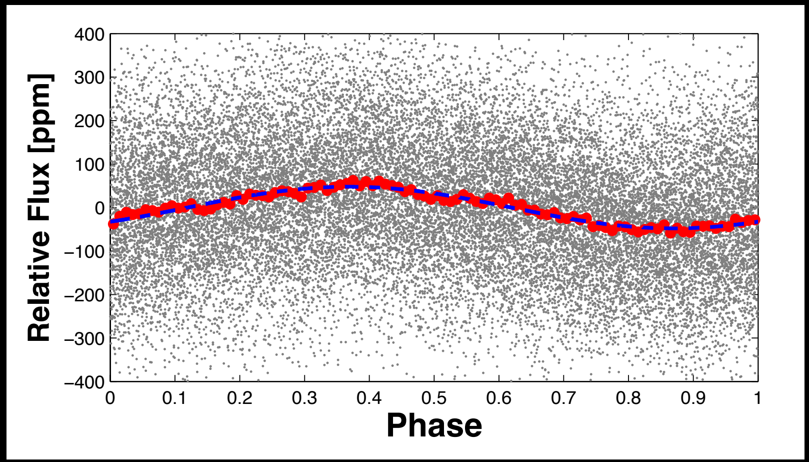


Benjamin Fulton (LCOGT)

Stellar activity

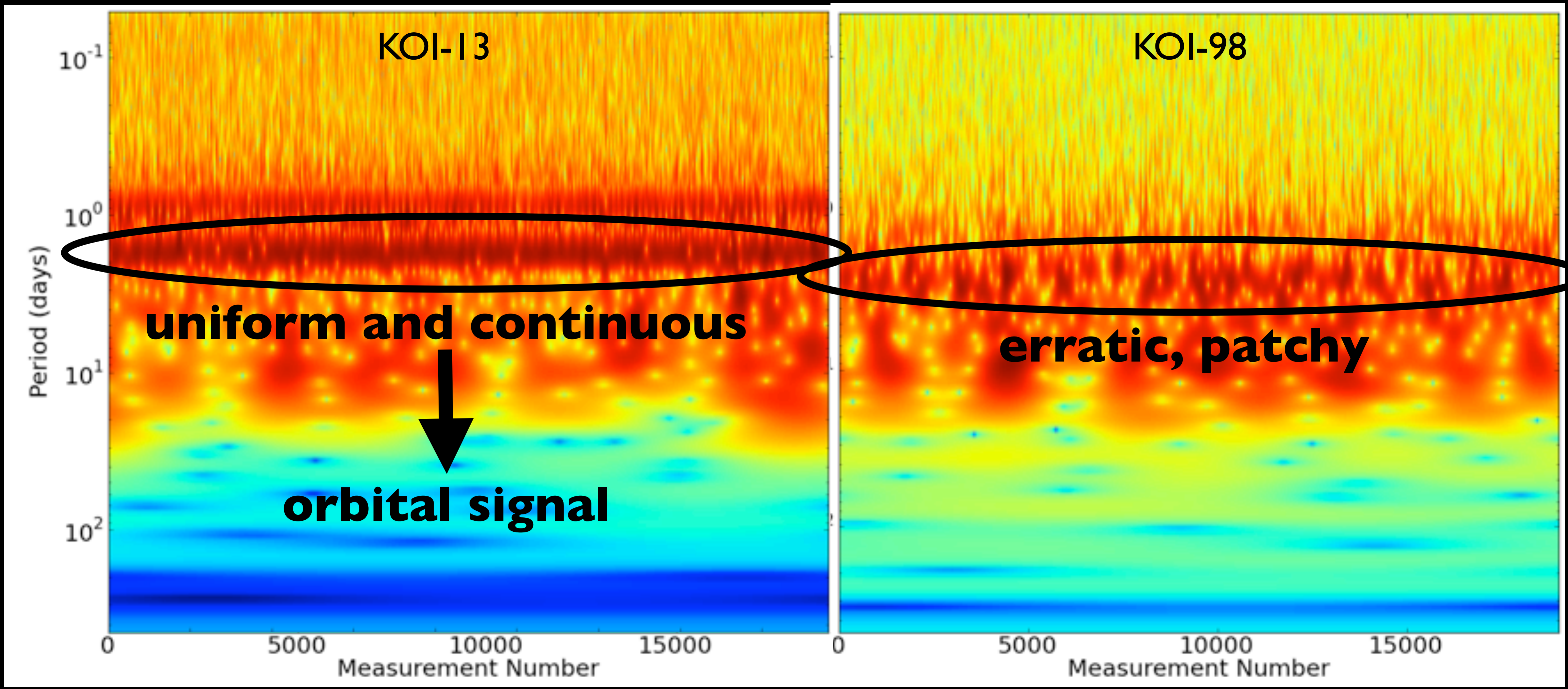
Kepler-14 (KOI-98)
Buchhave et al. 2011





P_{orb} = 6.79 d
P_{phot} = 2.92 d
activity?

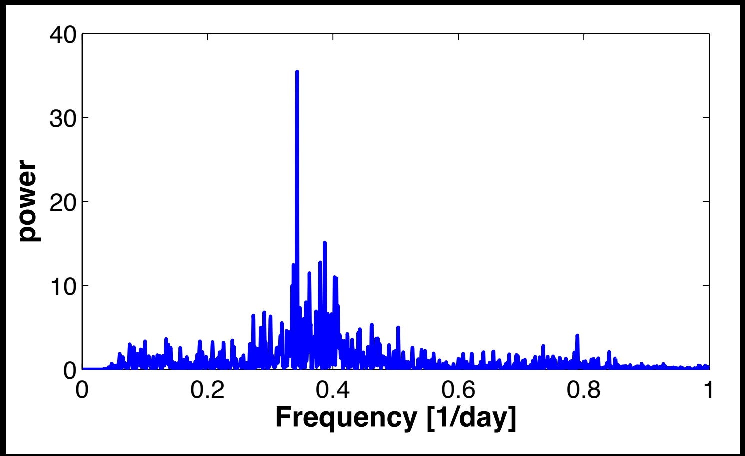
Scalogram - time evolving periodogram

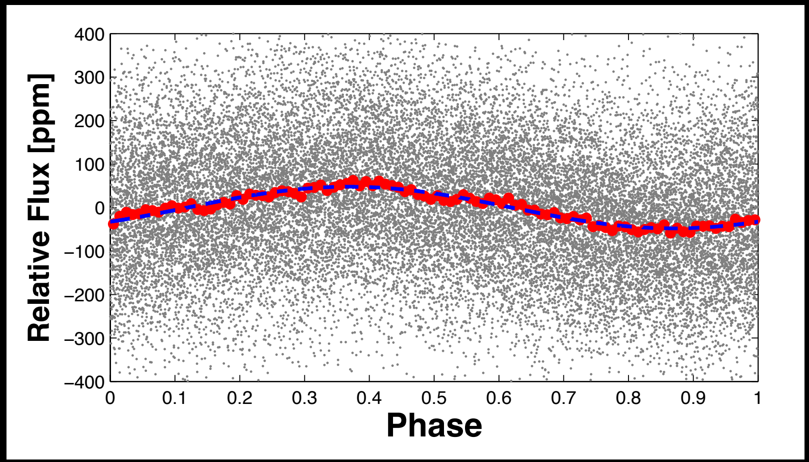


Benjamin Fulton (LCOGT)

Stellar activity

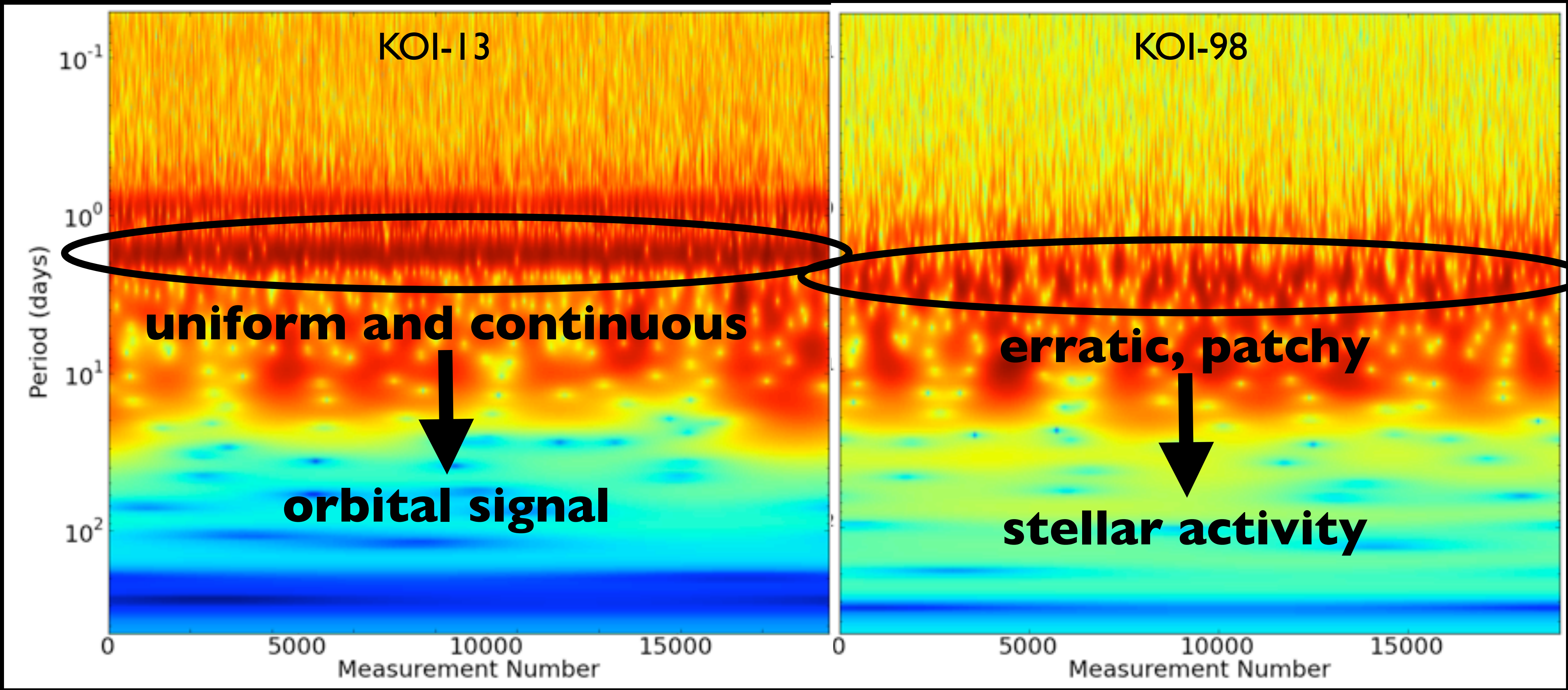
Kepler-14 (KOI-98)
Buchhave et al. 2011





P_{orb} = 6.79 d
P_{phot} = 2.92 d
activity?

Scalogram - time evolving periodogram



Benjamin Fulton (LCOGT)

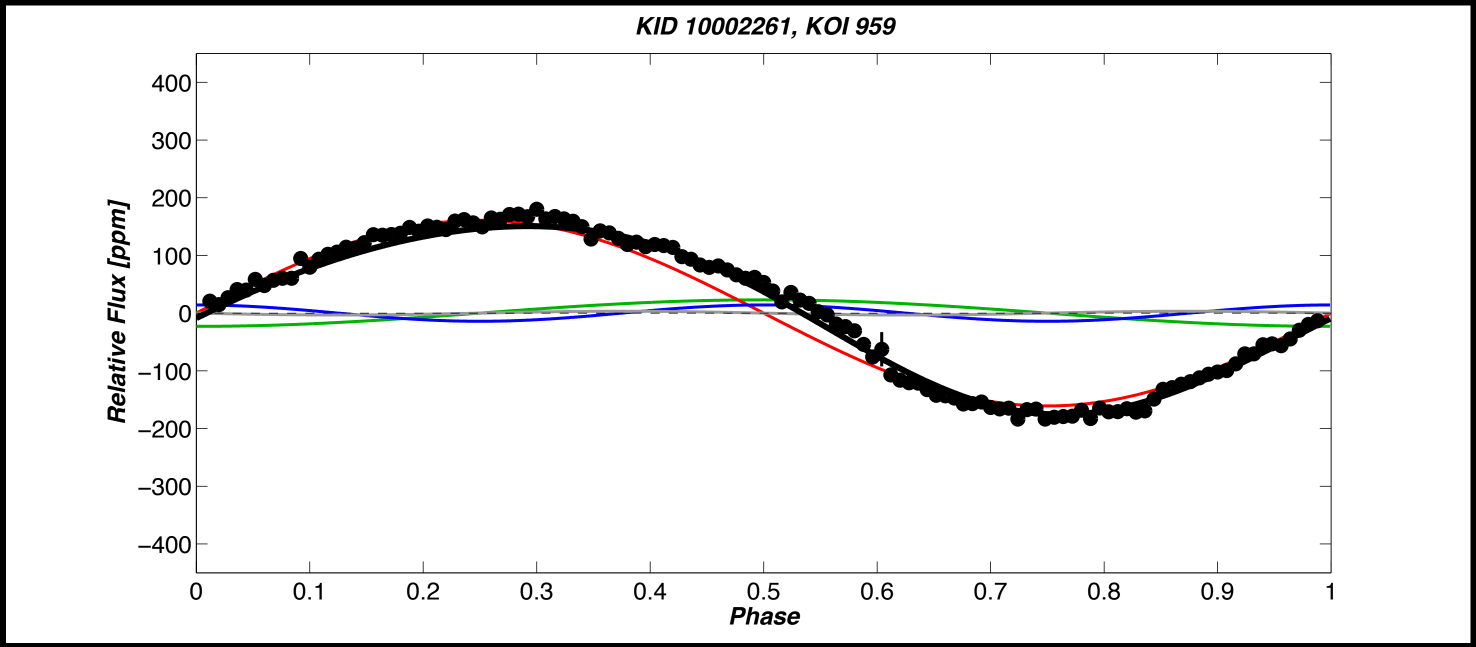
The cold star opportunity

The cold star opportunity

LHS 6343 (Johnson et al. 2012)
Brown dwarf + M-star, P = 12.7 d

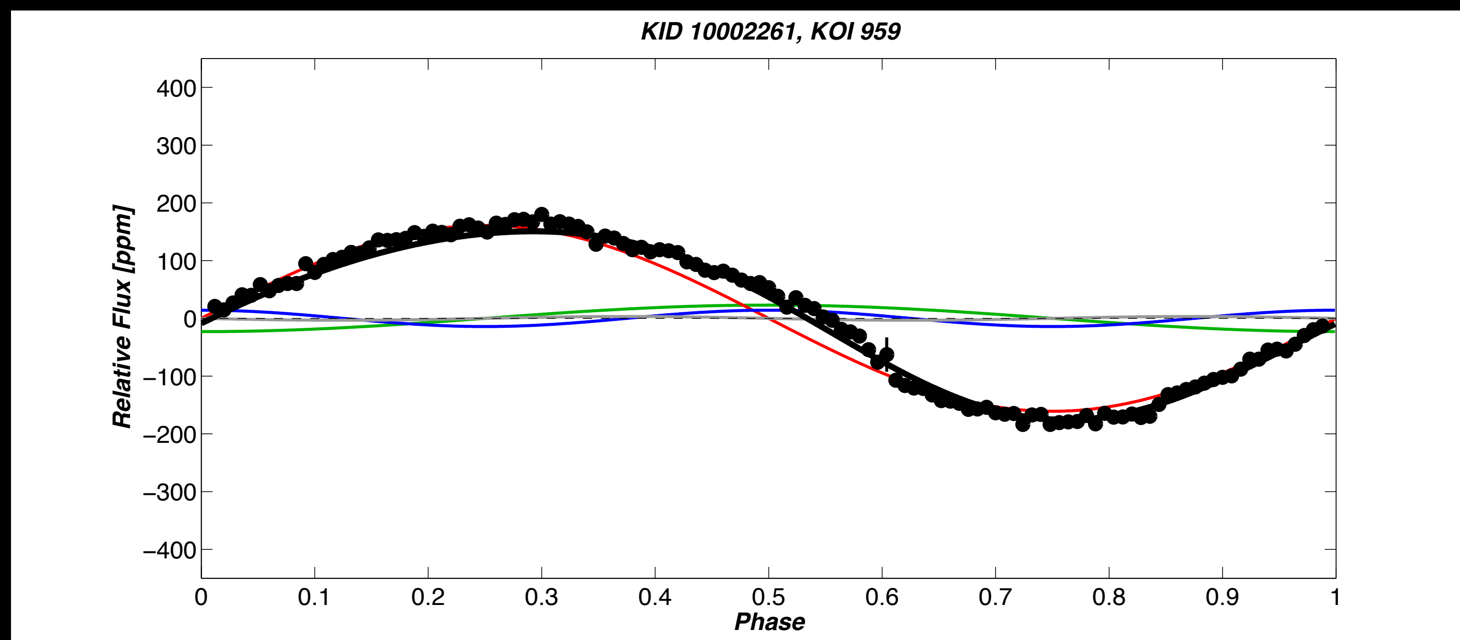
The cold star opportunity

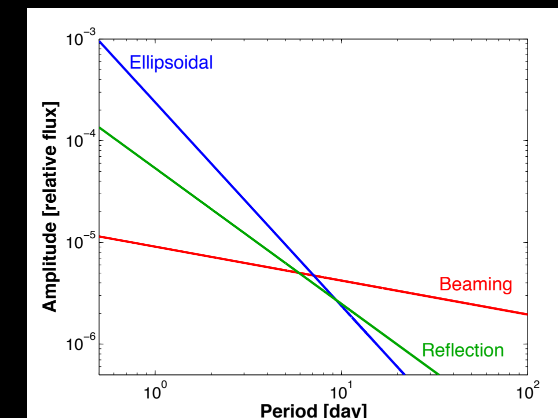
LHS 6343 (Johnson et al. 2012)
Brown dwarf + M-star, P = 12.7 d



The cold star opportunity

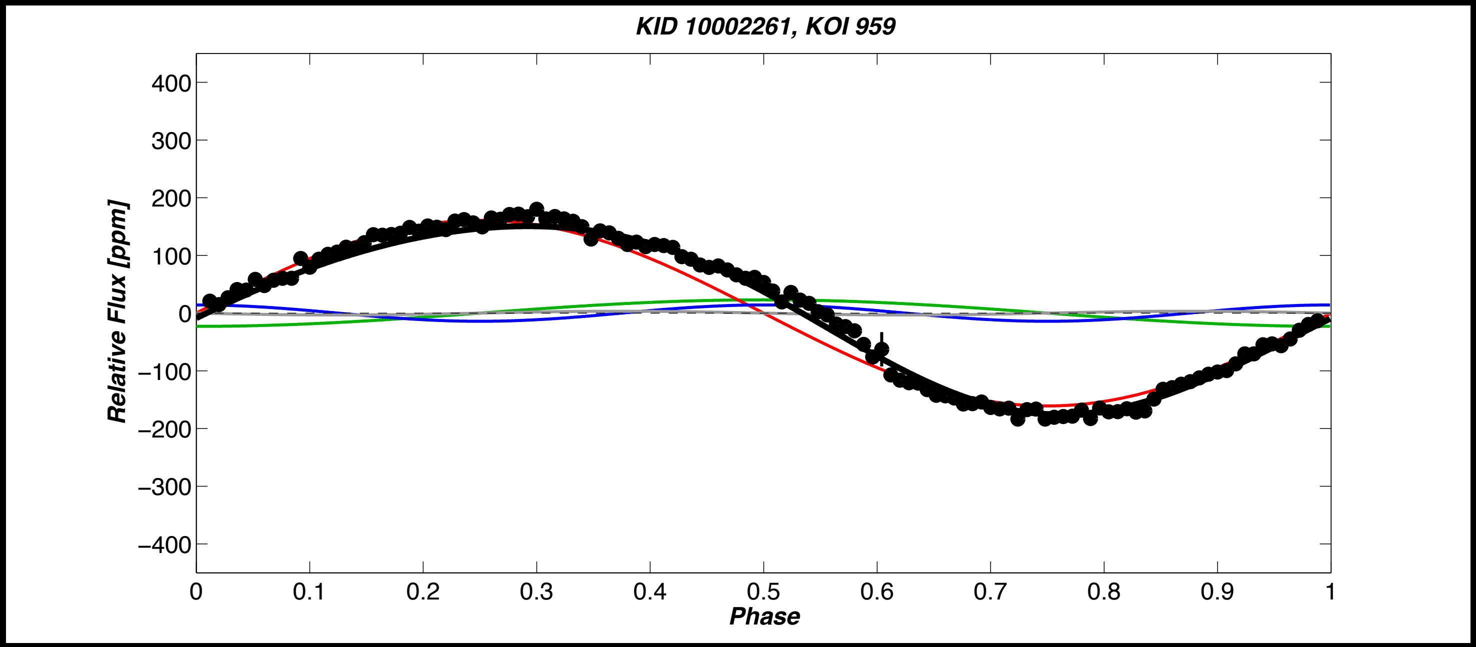
LHS 6343 (Johnson et al. 2012)
Brown dwarf + M-star, P = 12.7 d

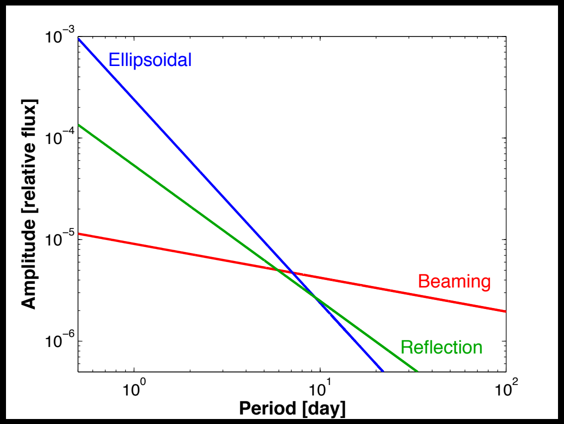




The cold star opportunity

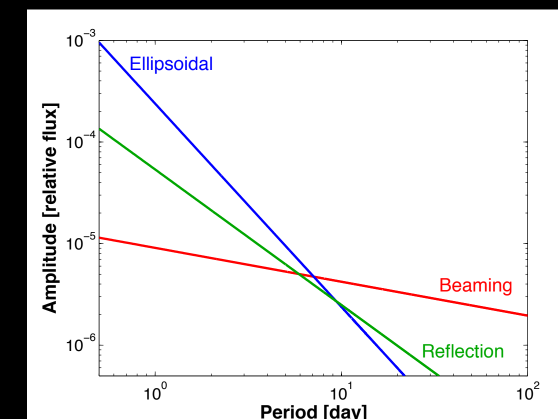
LHS 6343 (Johnson et al. 2012)
Brown dwarf + M-star, P = 12.7 d



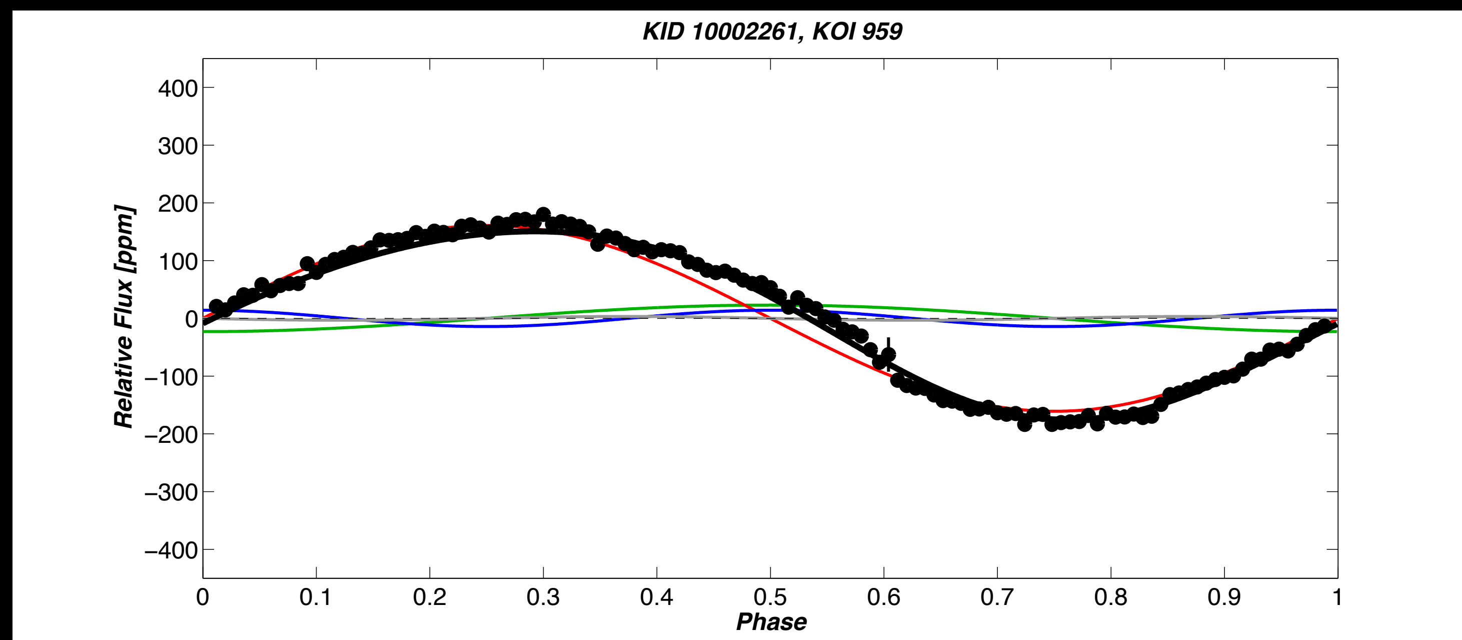


$$\alpha_{\mathrm{beam}} = 5 + \frac{d\log F_\lambda}{d\log\lambda}$$

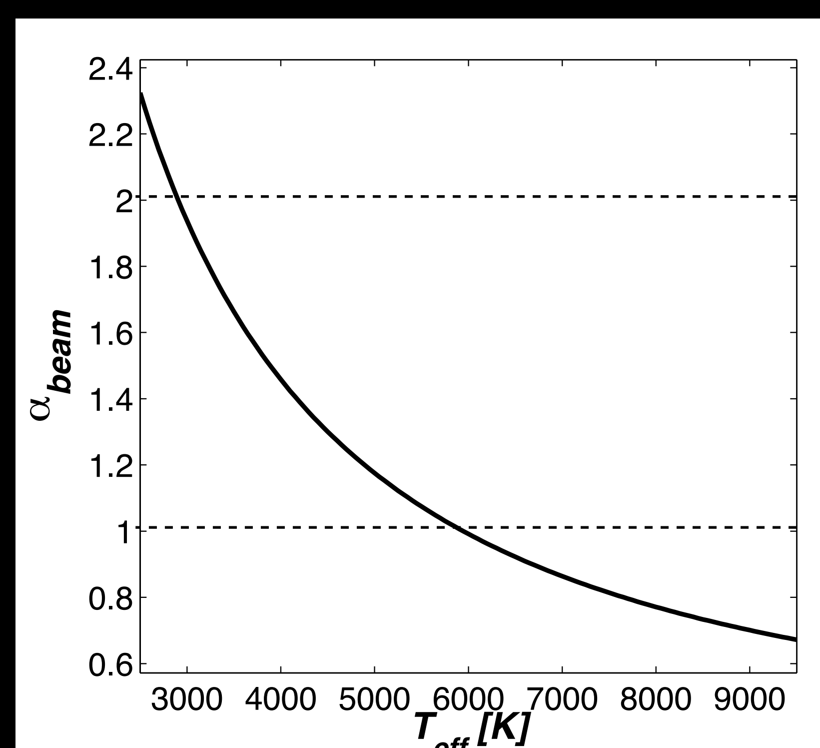
The cold star opportunity



LHS 6343 (Johnson et al. 2012)
Brown dwarf + M-star, P = 12.7 d

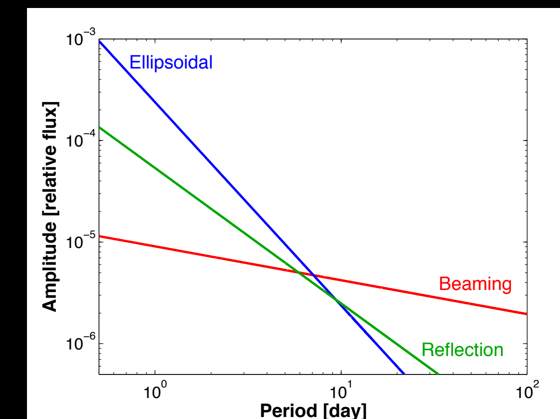


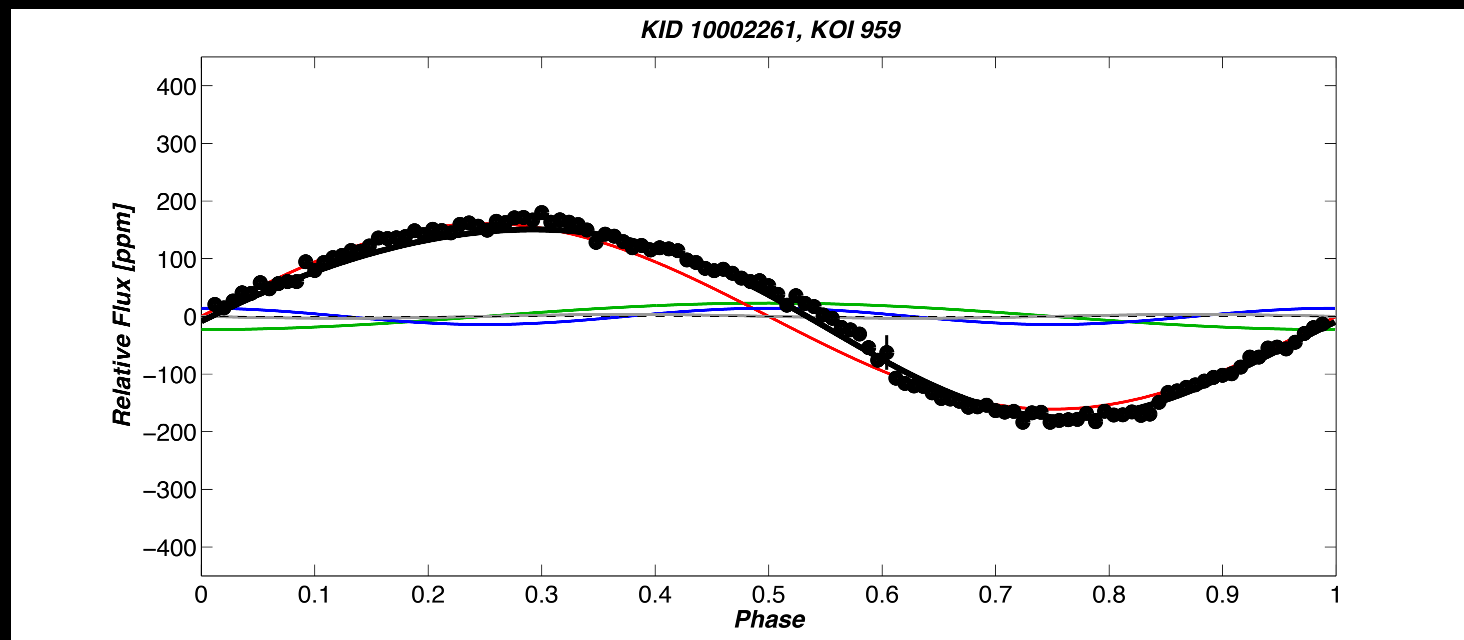
$$\alpha_{\mathrm{beam}} = 5 + \frac{d\log F_\lambda}{d\log \lambda}$$



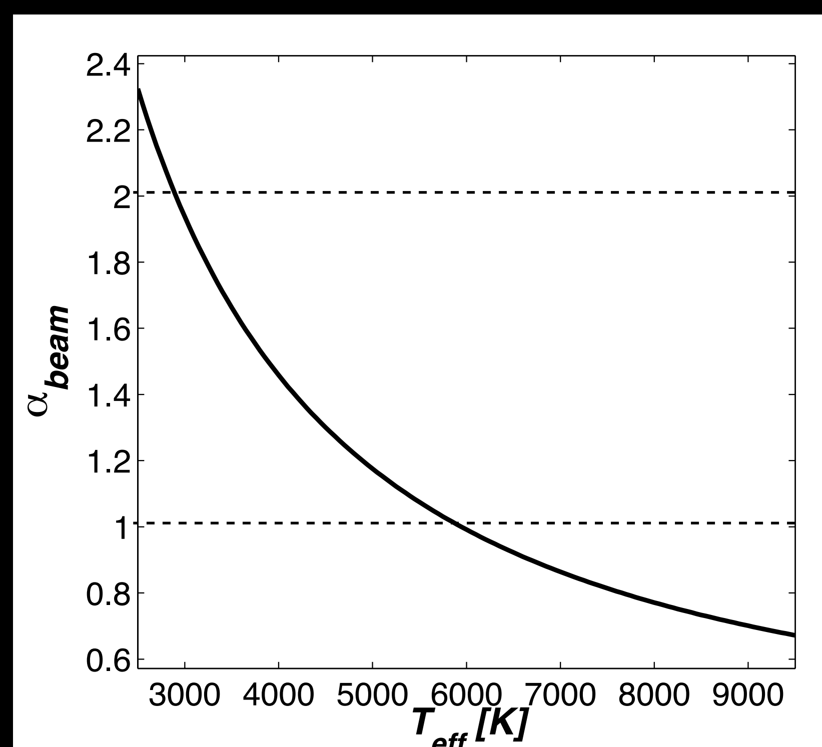
The cold star opportunity

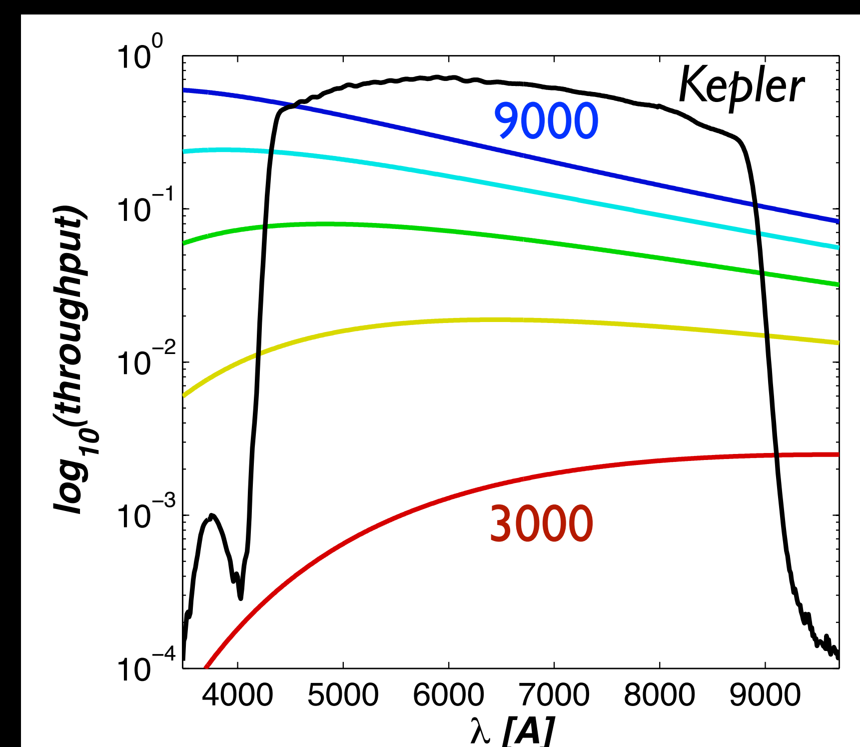
LHS 6343 (Johnson et al. 2012)
Brown dwarf + M-star, P = 12.7 d





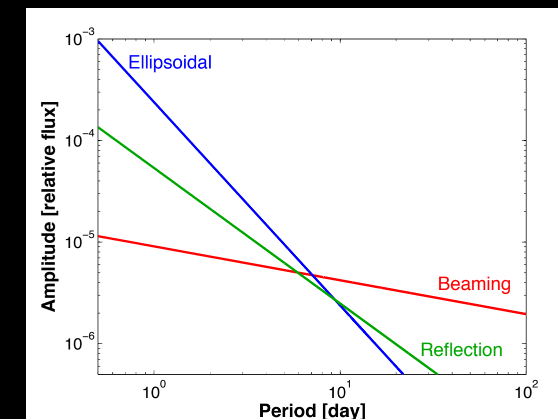
$$\alpha_{\rm beam} = 5 + \frac{d\log F_\lambda}{d\log\lambda}$$

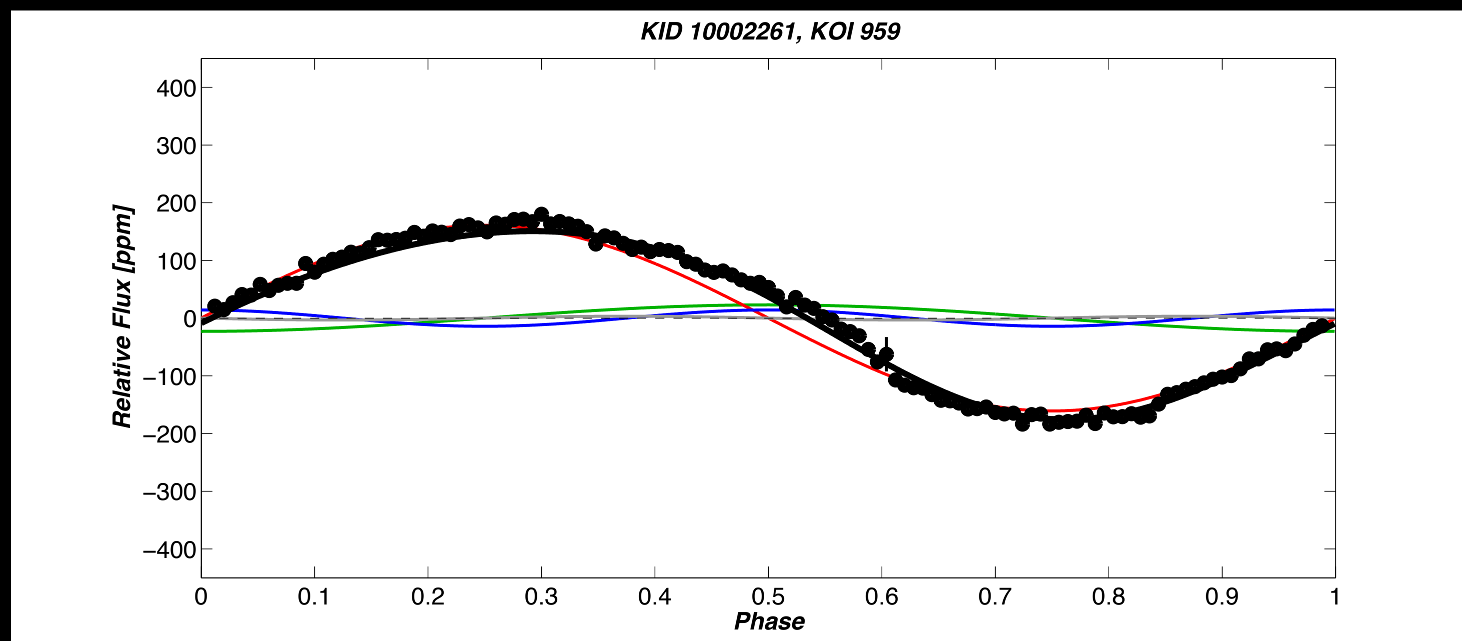




The cold star opportunity

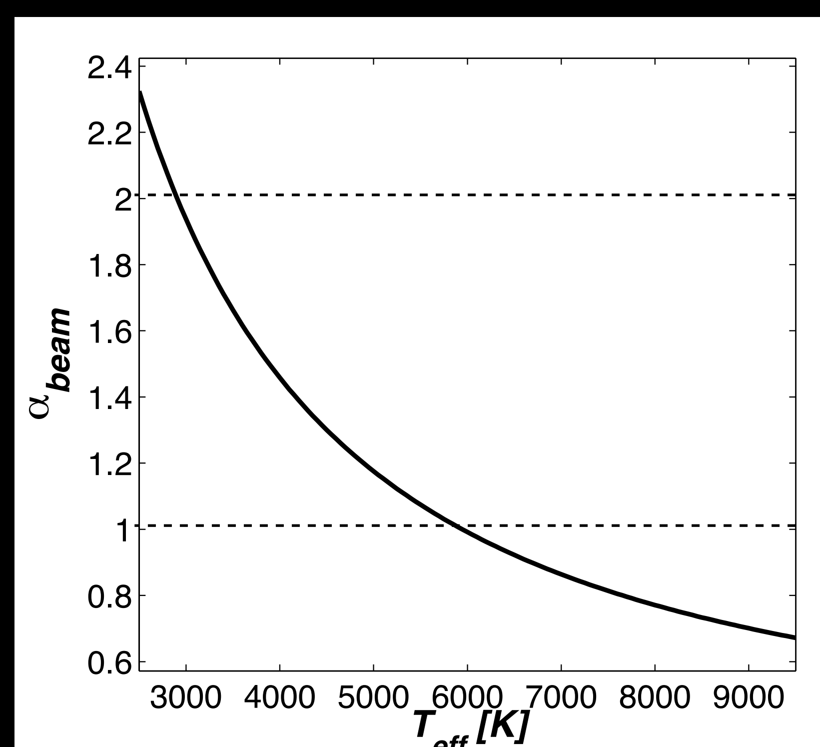
LHS 6343 (Johnson et al. 2012)
Brown dwarf + M-star, P = 12.7 d

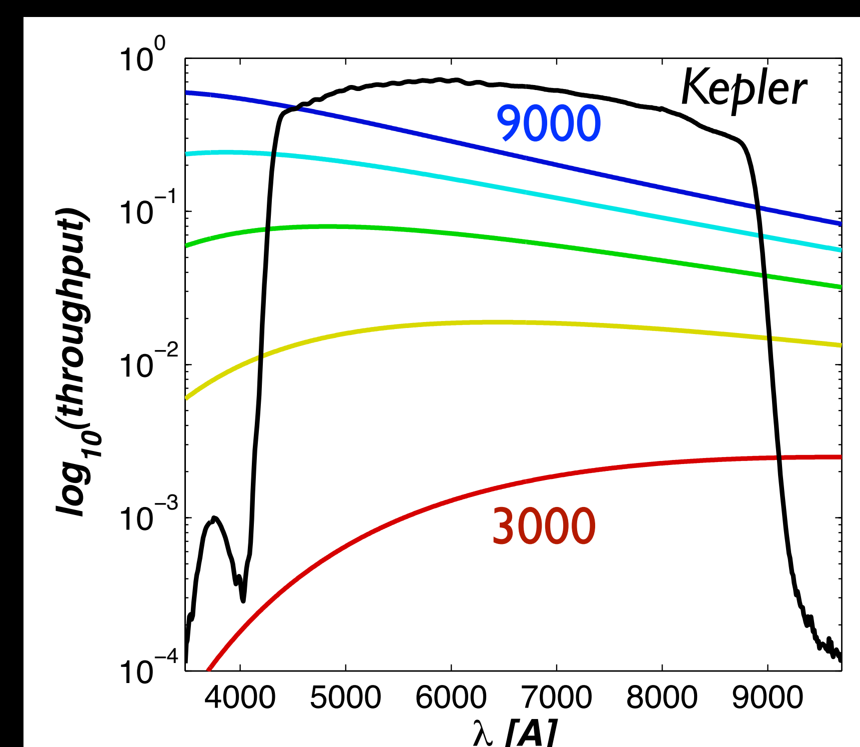




$$\alpha_{\mathrm{beam}} = 5 + \frac{d \log F_\lambda}{d \log \lambda}$$

Beaming in binaries: flux-weighted difference (Zucker et al. 2007, Shporer et al. 2010)





Doing *Even More* with Photometry

Photometric spin-orbit alignment measurement

Doing *Even More* with Photometry

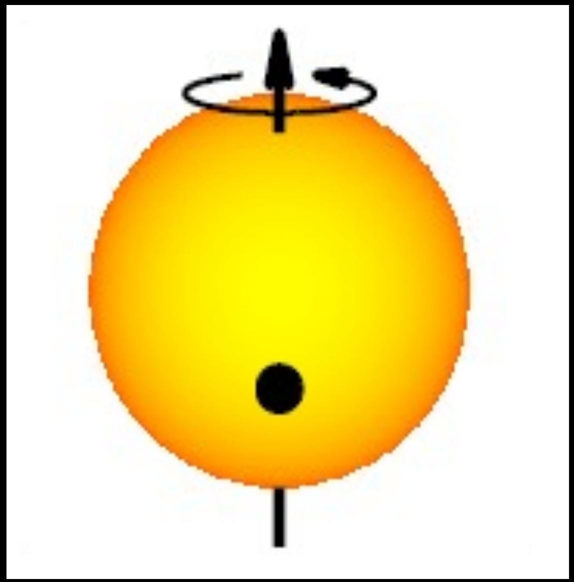
Photometric spin-orbit alignment measurement

The Rossiter-McLaughlin (RM) effect:

Doing *Even More* with Photometry

Photometric spin-orbit alignment measurement

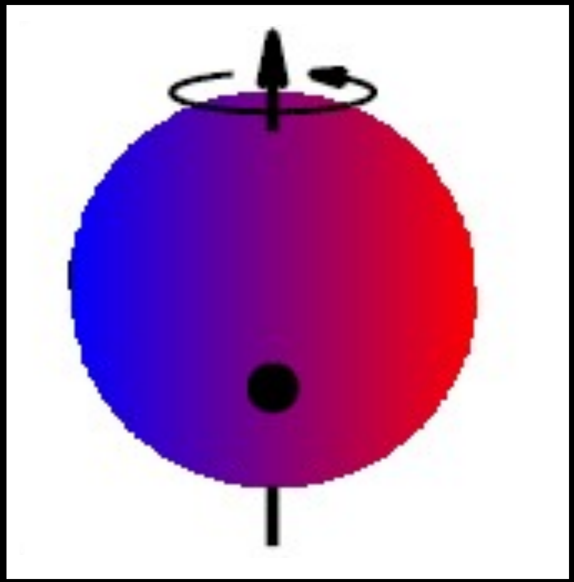
The Rossiter-McLaughlin (RM) effect:



Doing *Even More* with Photometry

Photometric spin-orbit alignment measurement

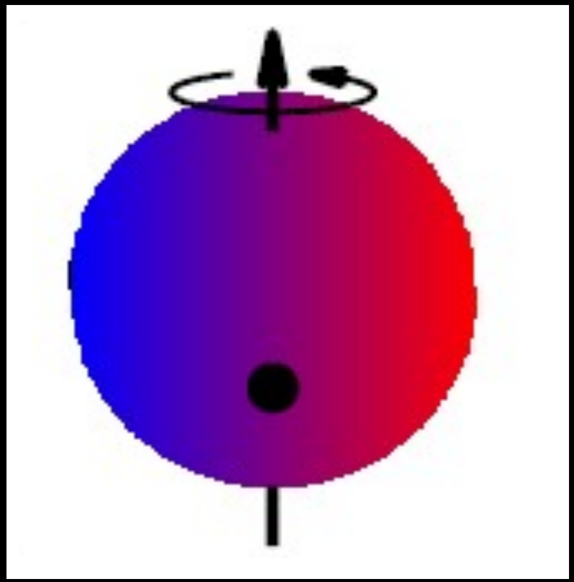
The Rossiter-McLaughlin (RM) effect:

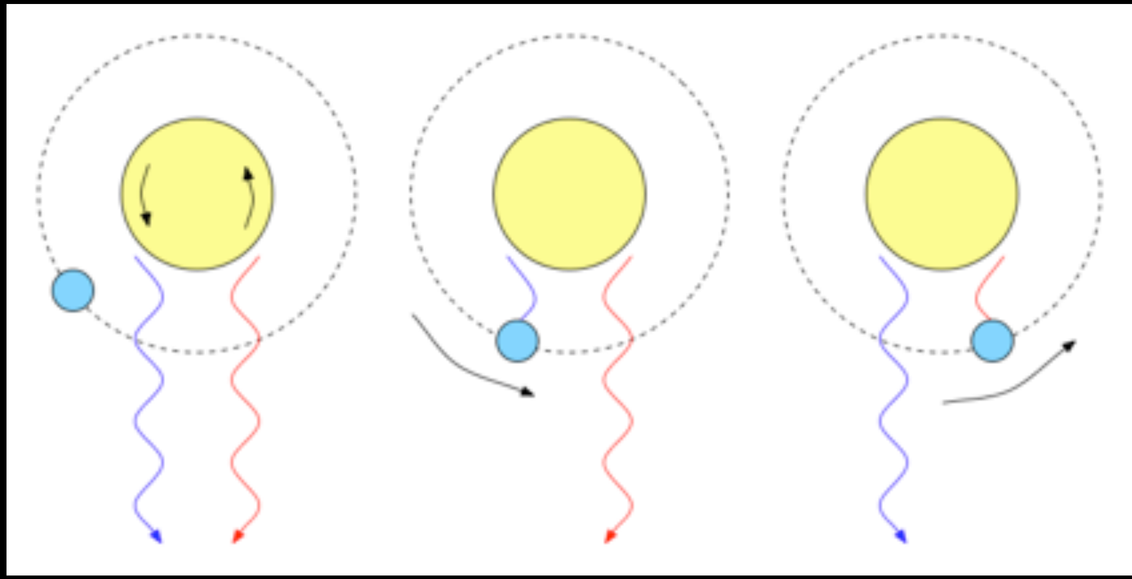


Doing *Even More* with Photometry

Photometric spin-orbit alignment measurement

The Rossiter-McLaughlin (RM) effect:

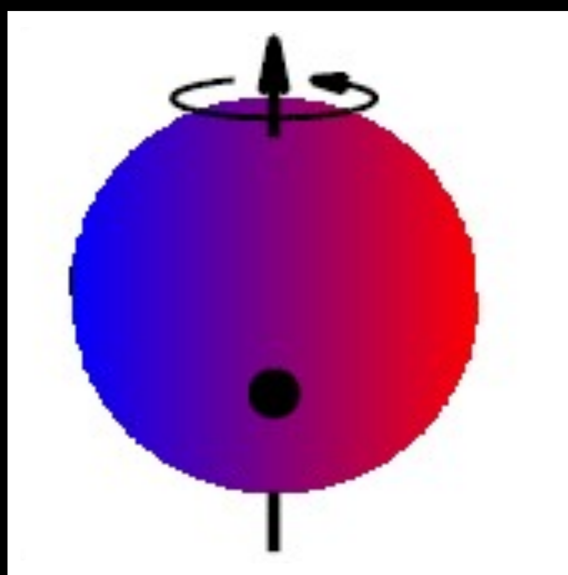


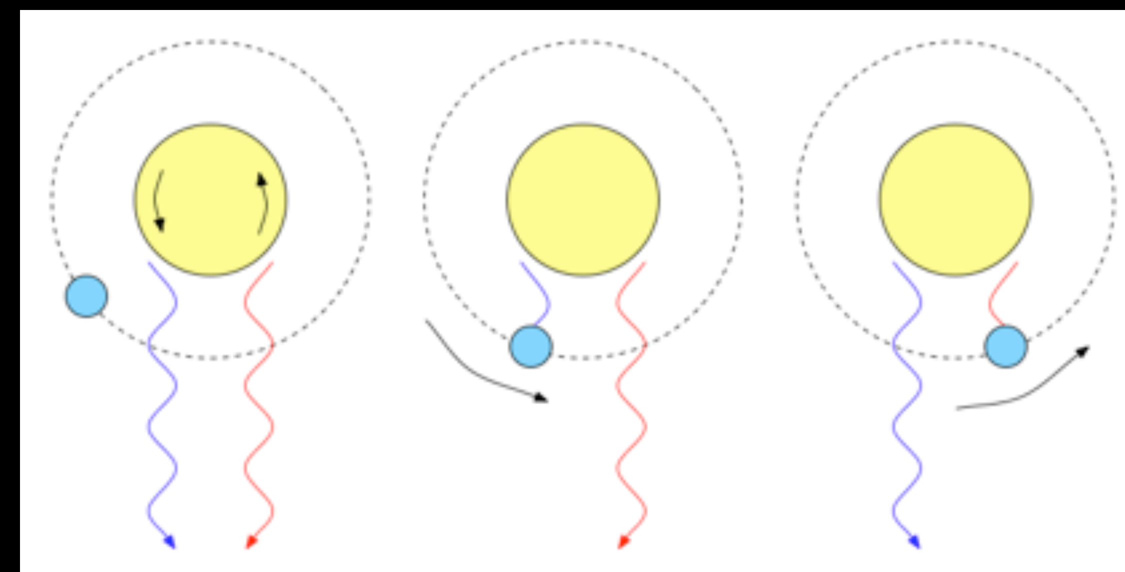


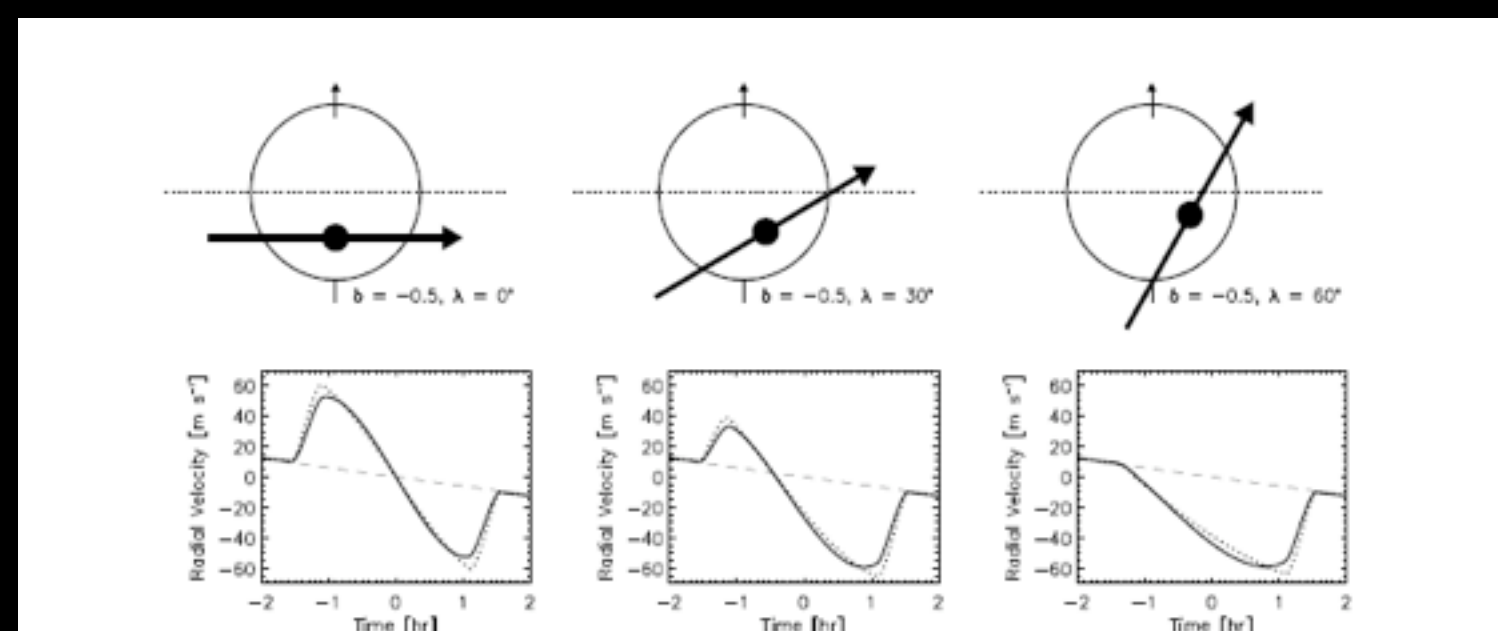
Doing *Even More* with Photometry

Photometric spin-orbit alignment measurement

The Rossiter-McLaughlin (RM) effect:





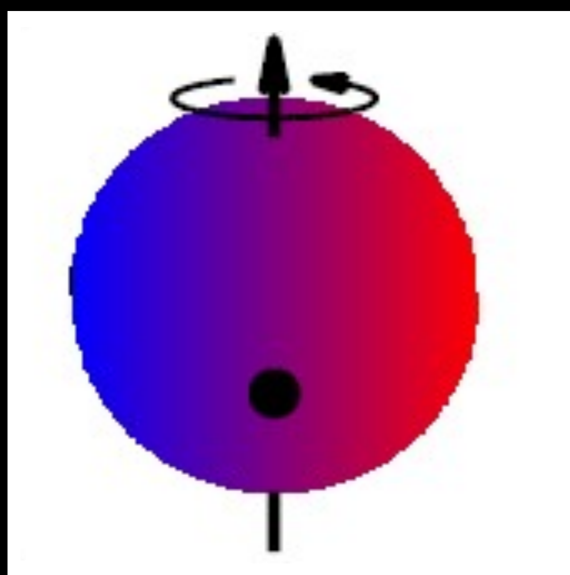


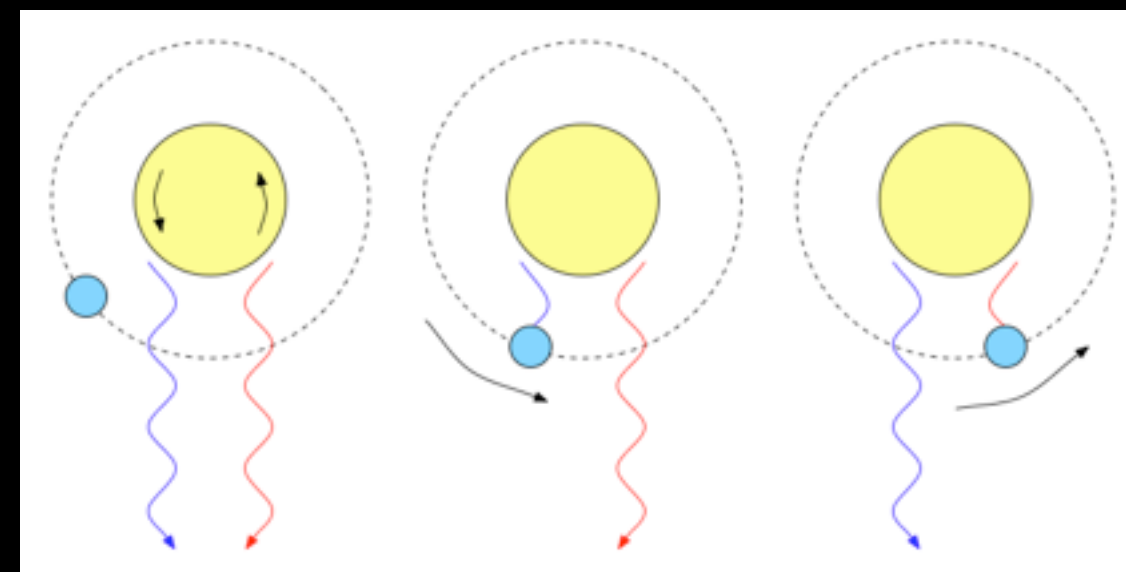
Gaudi & Winn (2006)

Doing *Even More* with Photometry

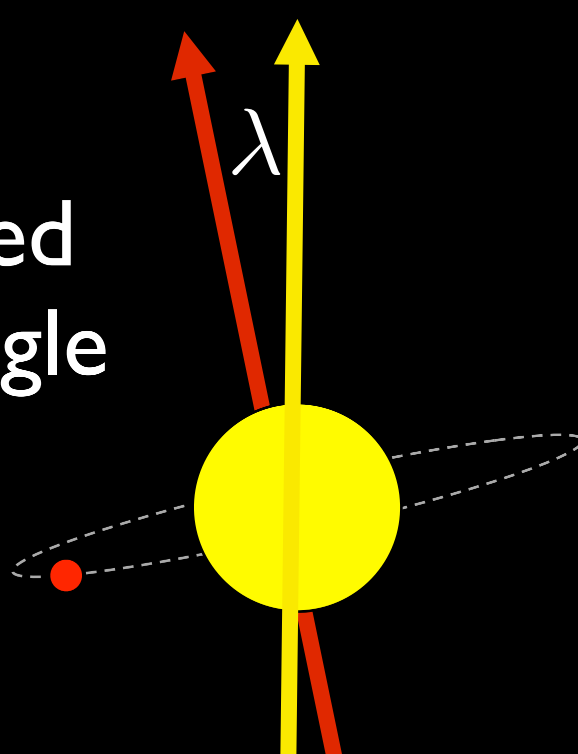
Photometric spin-orbit alignment measurement

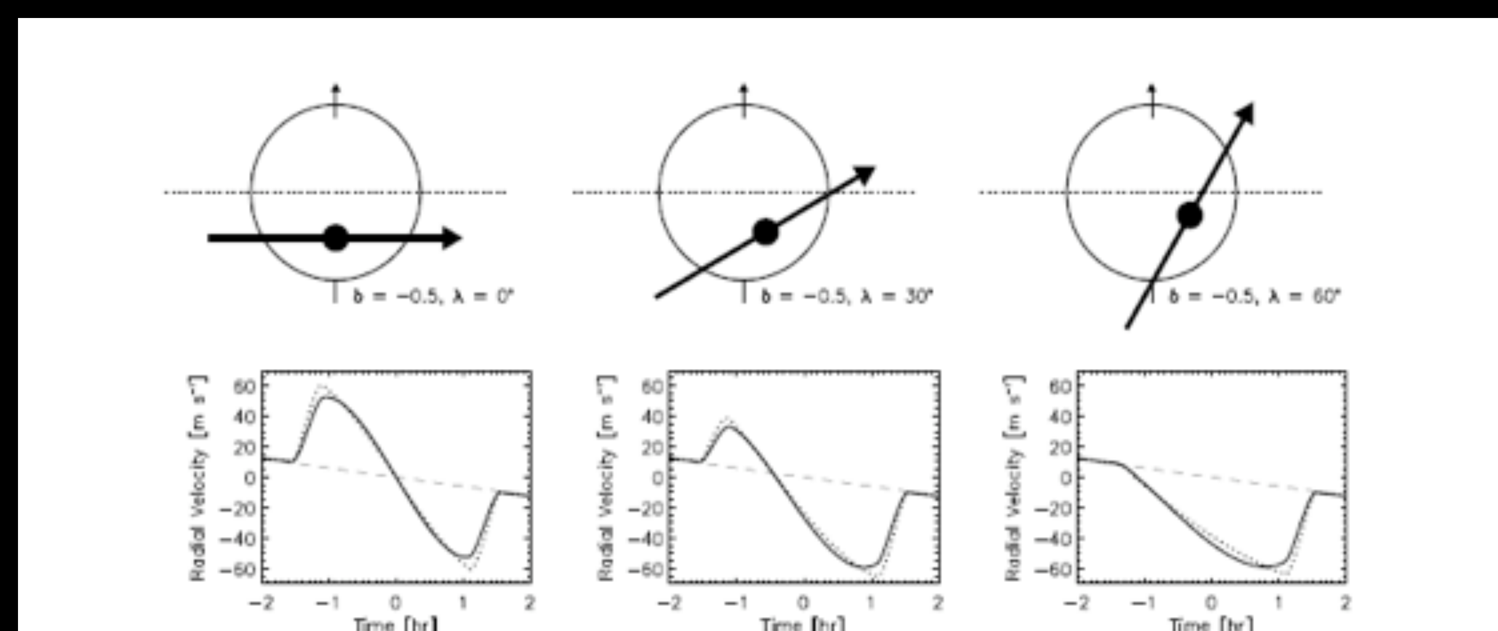
The Rossiter-McLaughlin (RM) effect:





Sky-projected spin-orbit angle



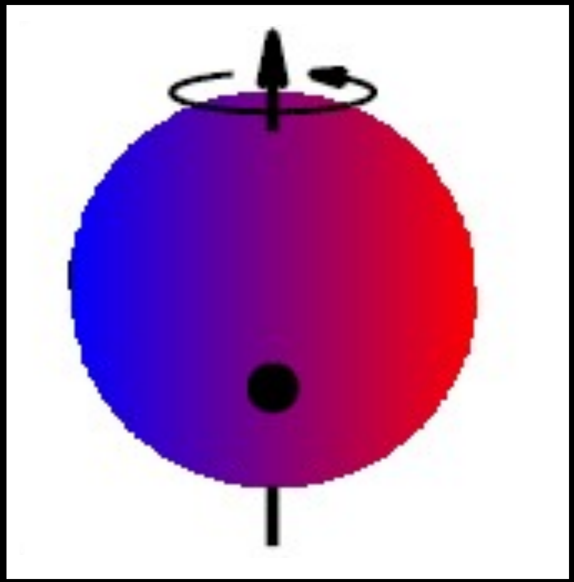


Gaudi & Winn (2006)

Doing *Even More* with Photometry

Photometric spin-orbit alignment measurement

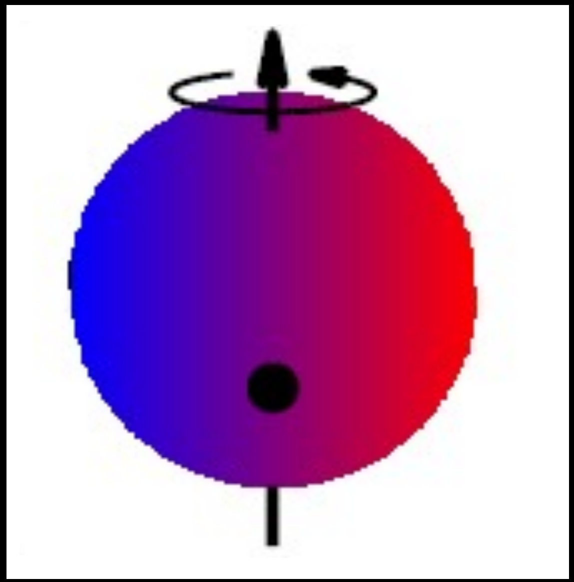
The RM effect



Doing *Even More* with Photometry

Photometric spin-orbit alignment measurement

The RM effect

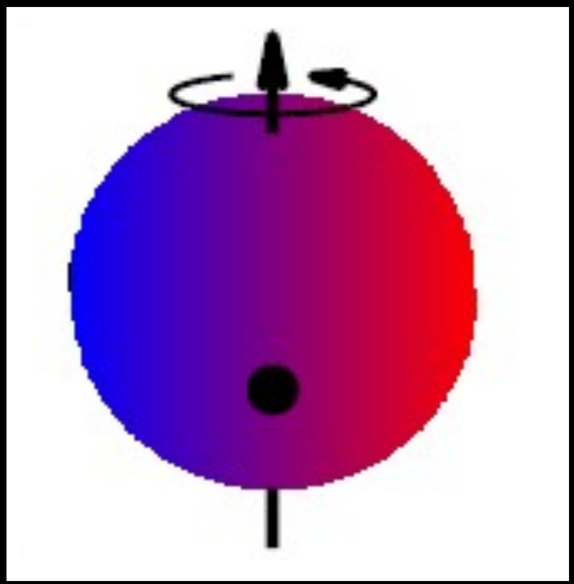


+

Doing *Even More* with Photometry

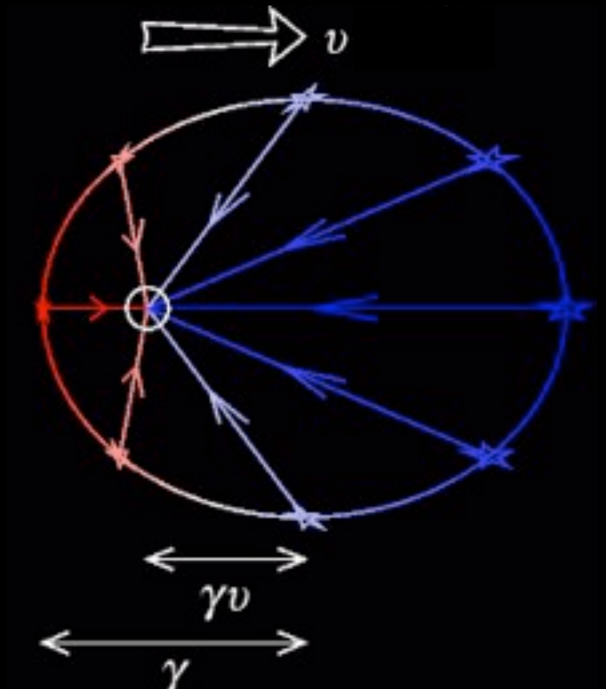
Photometric spin-orbit alignment measurement

The RM effect



+

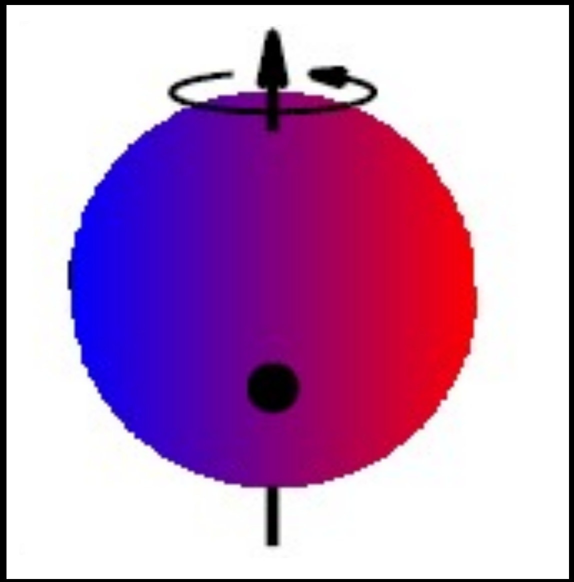
The beaming effect



Doing *Even More* with Photometry

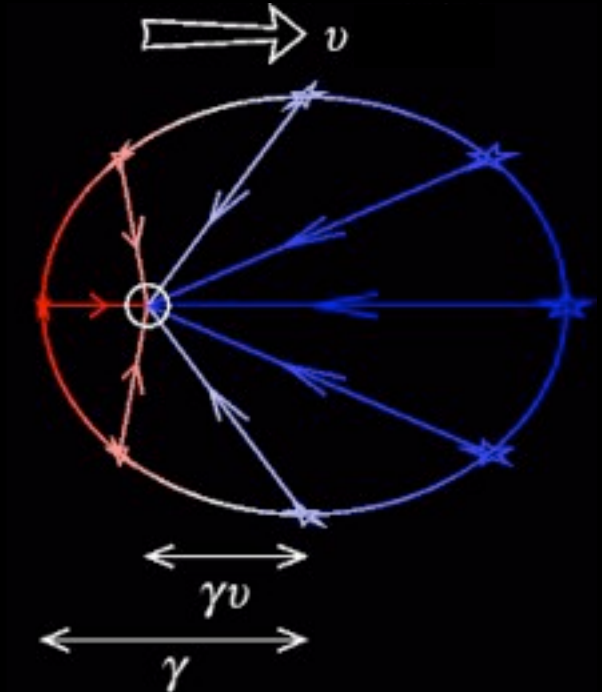
Photometric spin-orbit alignment measurement

The RM effect



+

The beaming effect



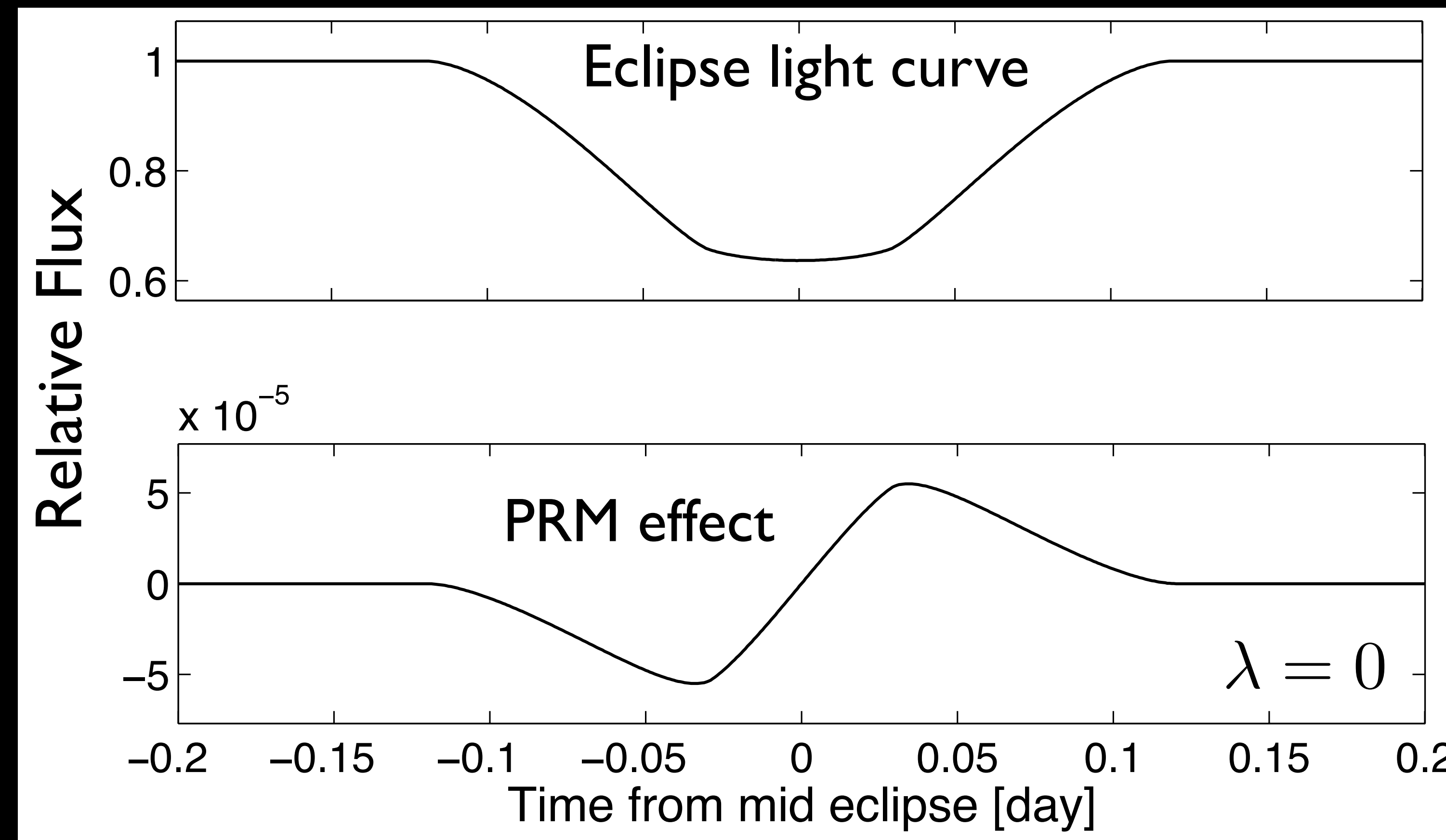
The Photometric RM (PRM) effect

Shporer et al. 2012

see also: Groot 2012, Hills & Dale 1974

The Photometric RM (PRM) Effect

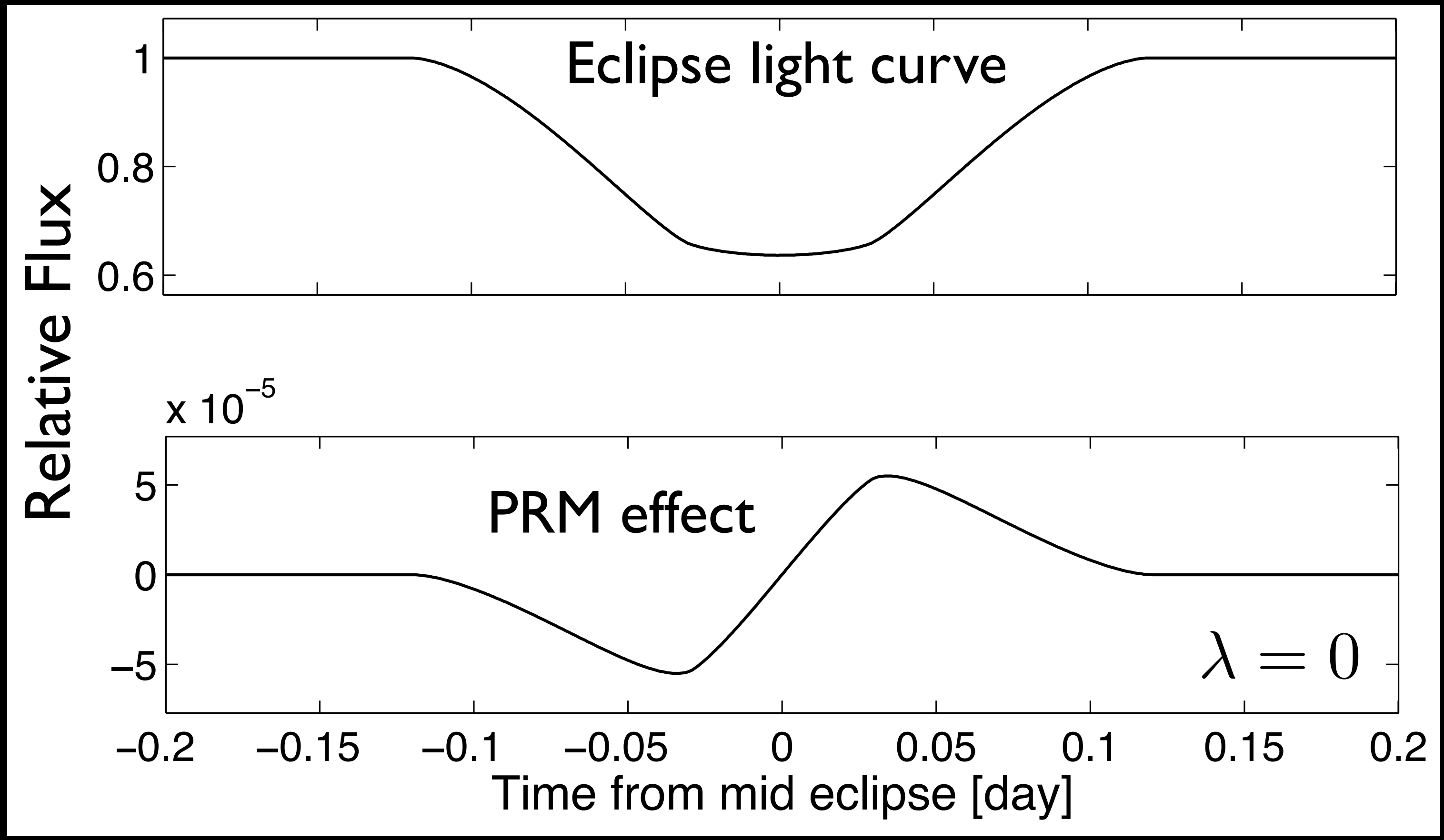
Shporer et al. 2012



The Photometric RM (PRM) Effect

Shporer et al. 2012

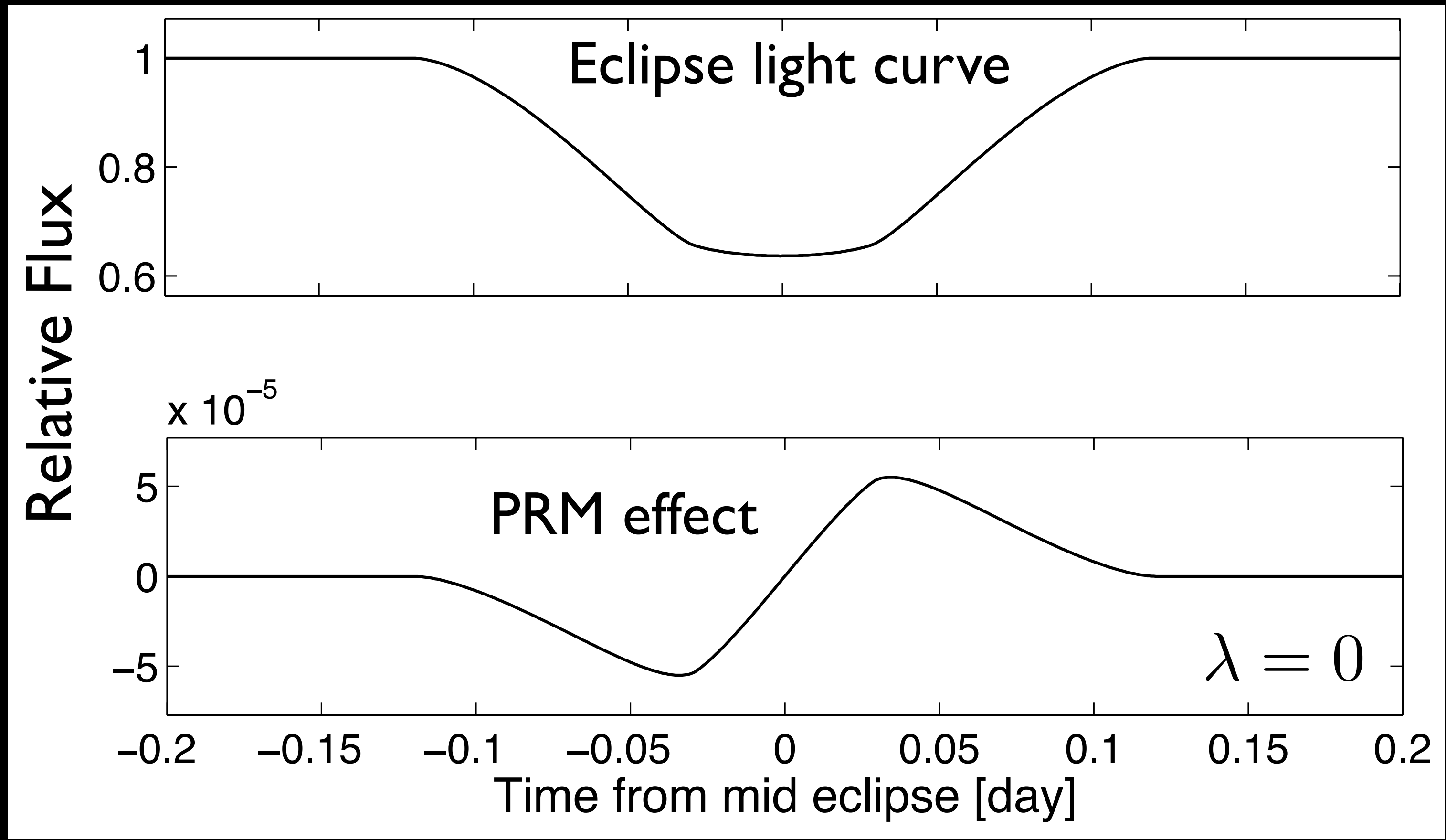
Primary eclipse



The Photometric RM (PRM) Effect

Shporer et al. 2012

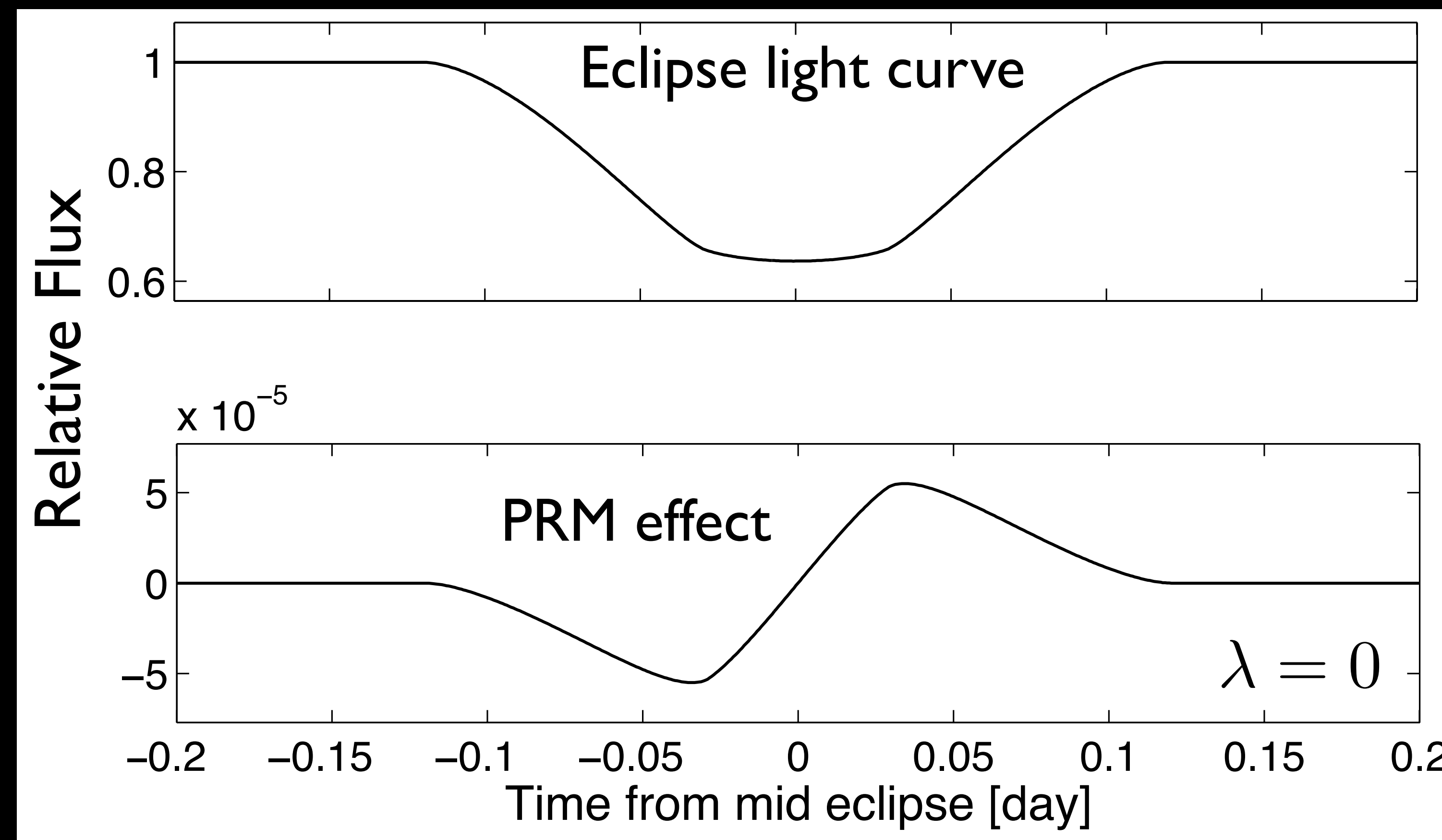
Primary eclipse
main sequence binaries



The Photometric RM (PRM) Effect

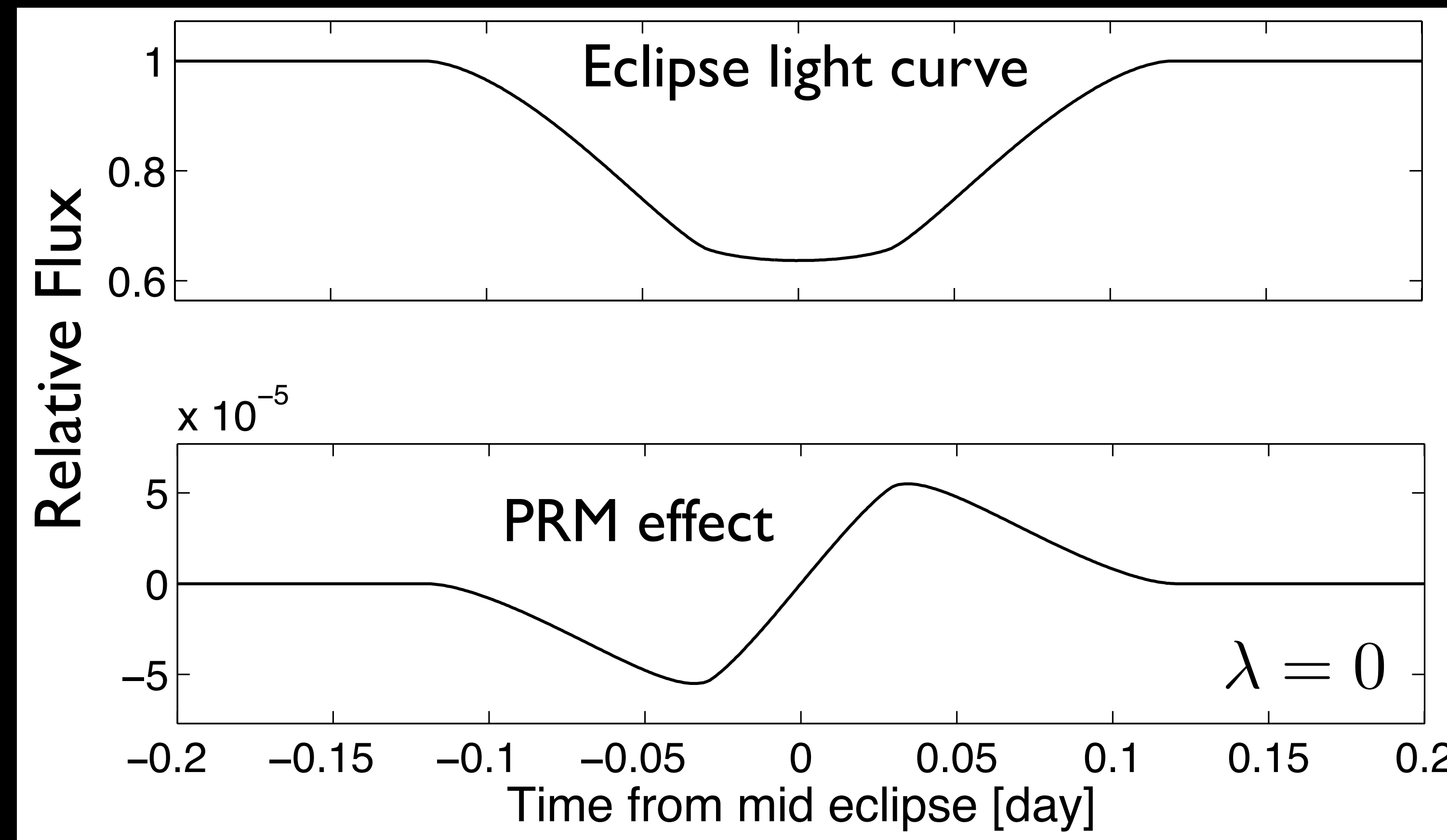
Shporer et al. 2012

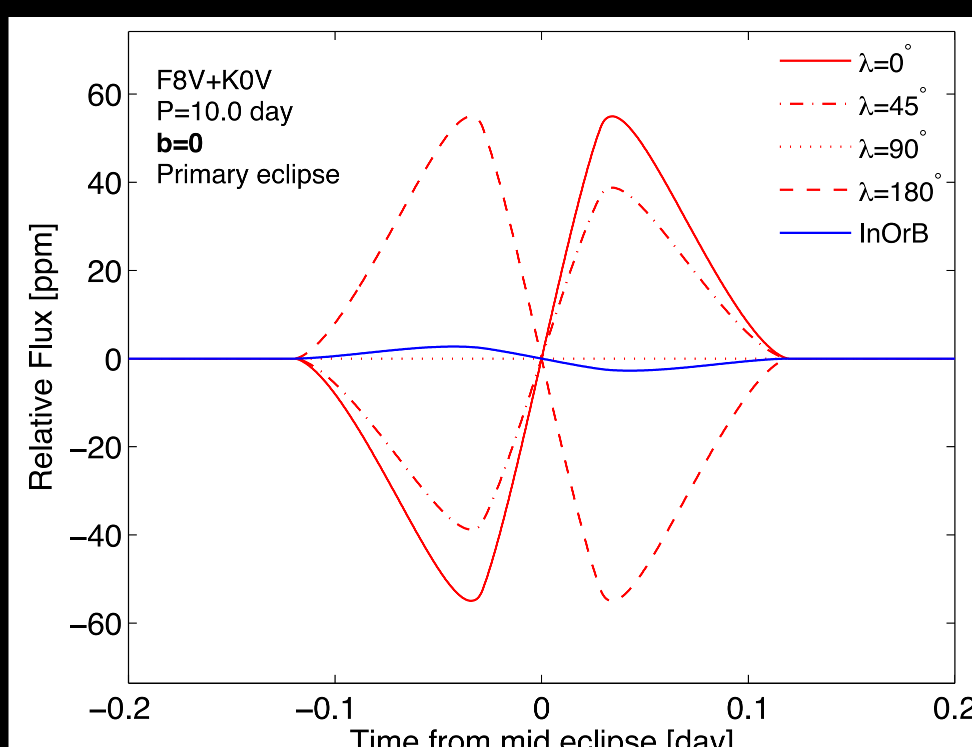
Primary eclipse
main sequence binaries
low mass ratio

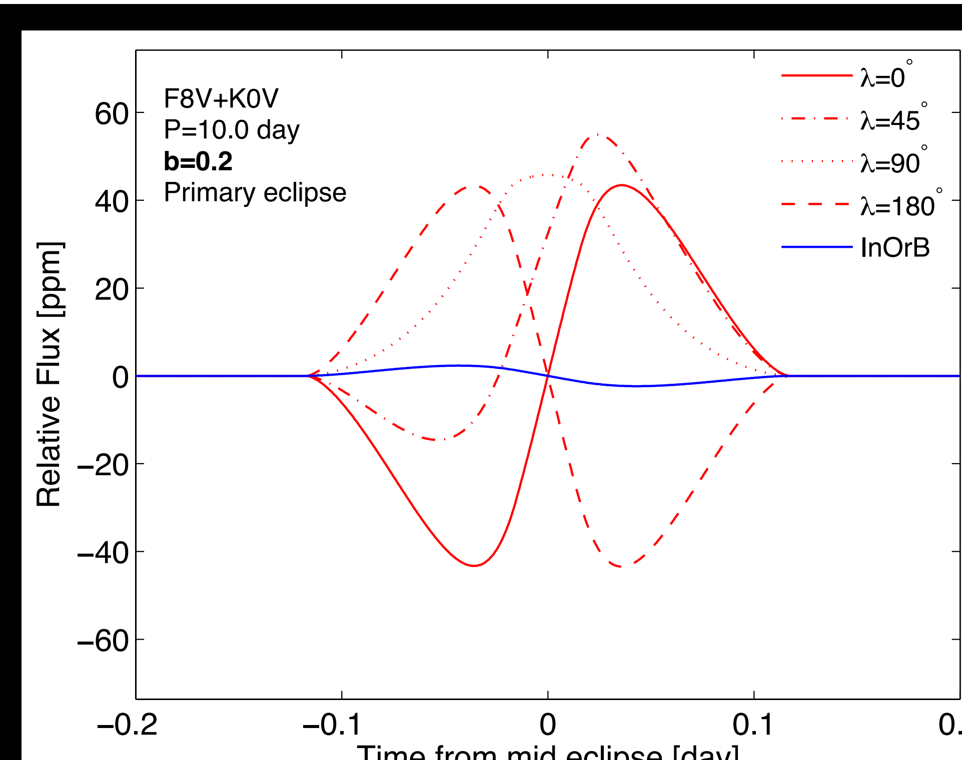


The Photometric RM (PRM) Effect
Shporer et al. 2012

Primary eclipse
main sequence binaries
low mass ratio

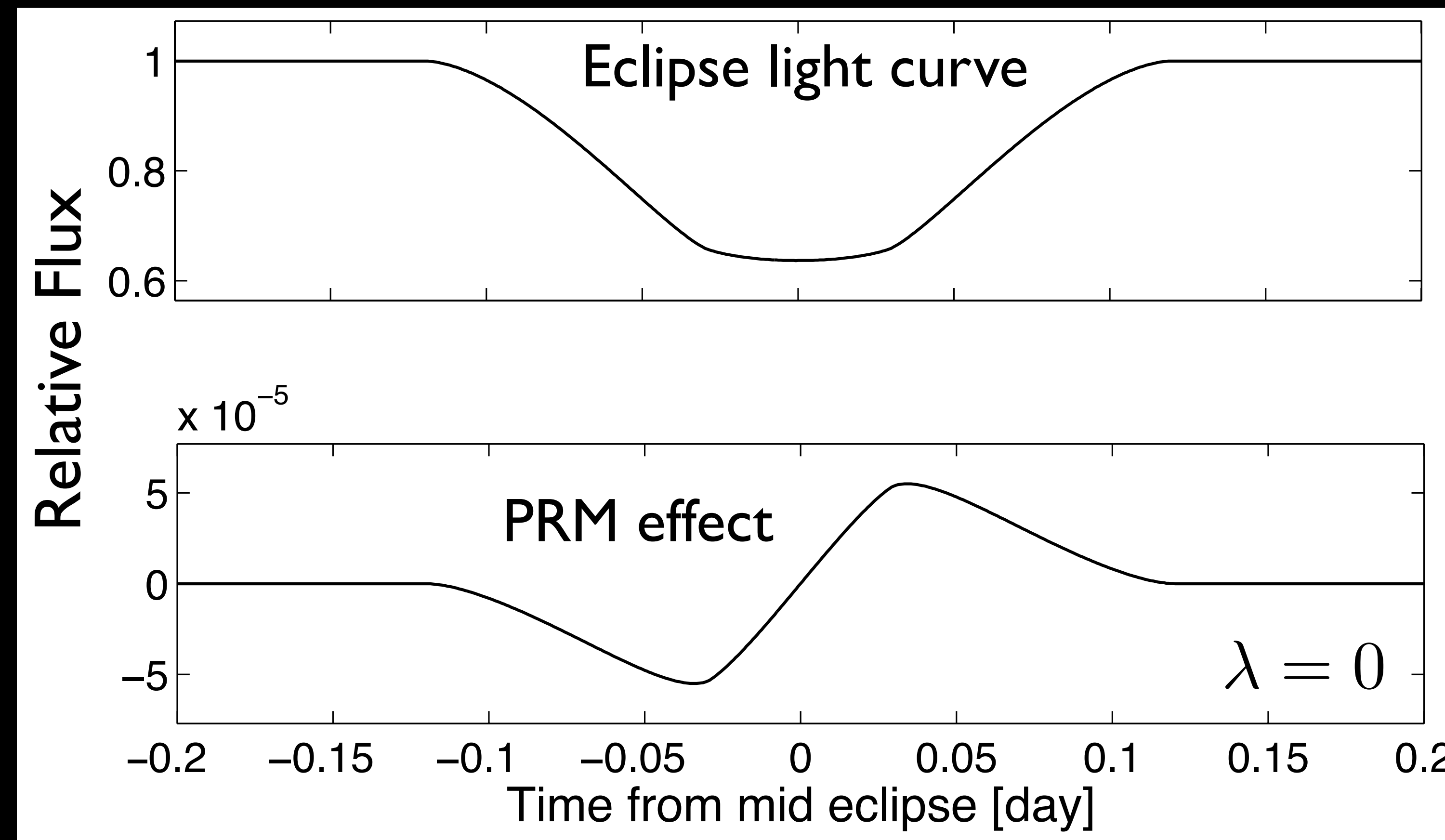






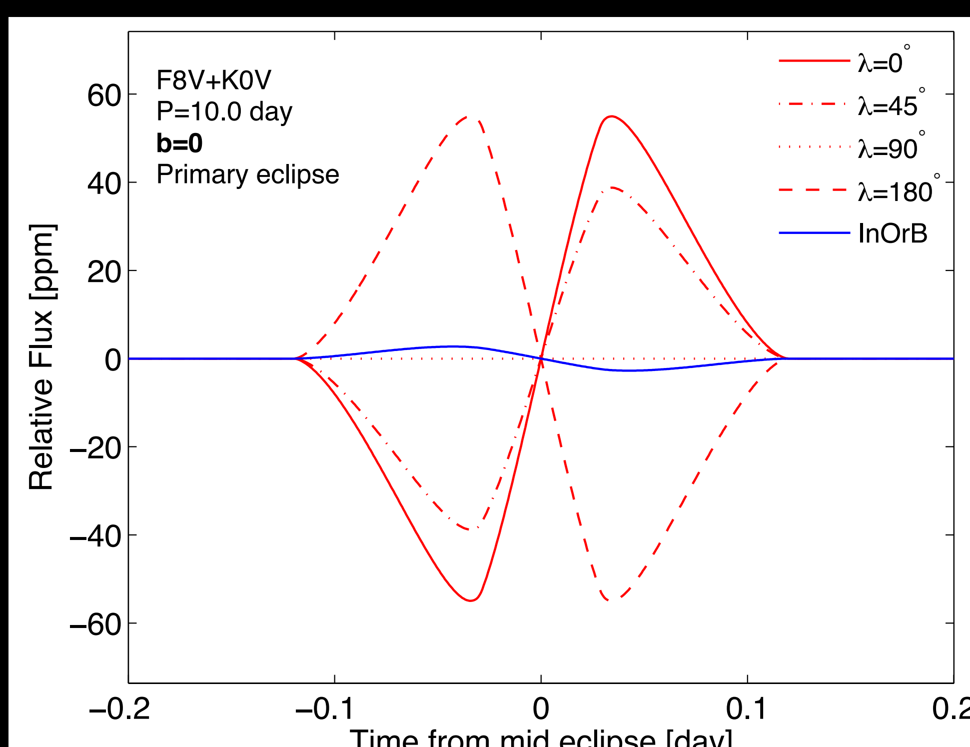
The Photometric RM (PRM) Effect

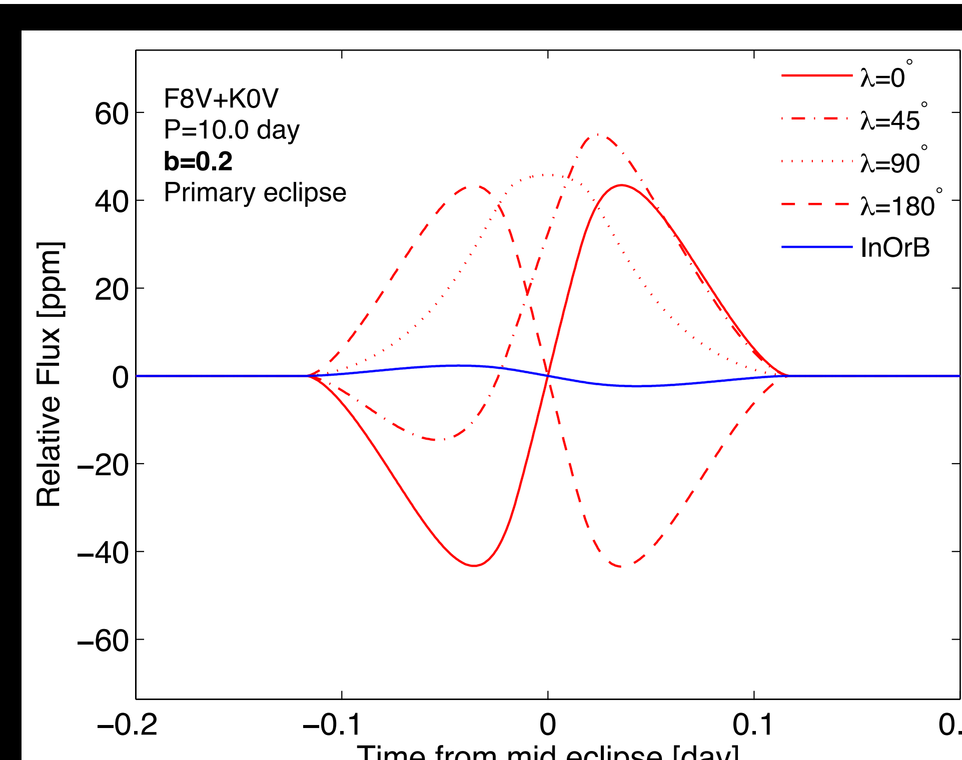
Shporer et al. 2012



Primary eclipse
main sequence binaries
low mass ratio

Kepler GO30029





Doing *More* with Photometry

Studying binary companions with **photometric orbital modulations**

Avi Shporer
UCSB, LCOGT

Sagan Summer Workshop
July 24 2012