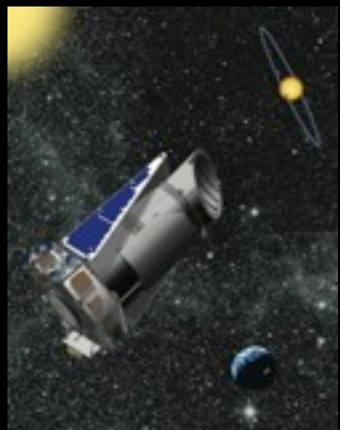
Doing *More* with Photometry

Detecting KOI-13.01 Using The **Photometric Orbit**

Avi Shporer
UCSB, LCOGT

KITP
Oct 27, 2011

KOI-13.01

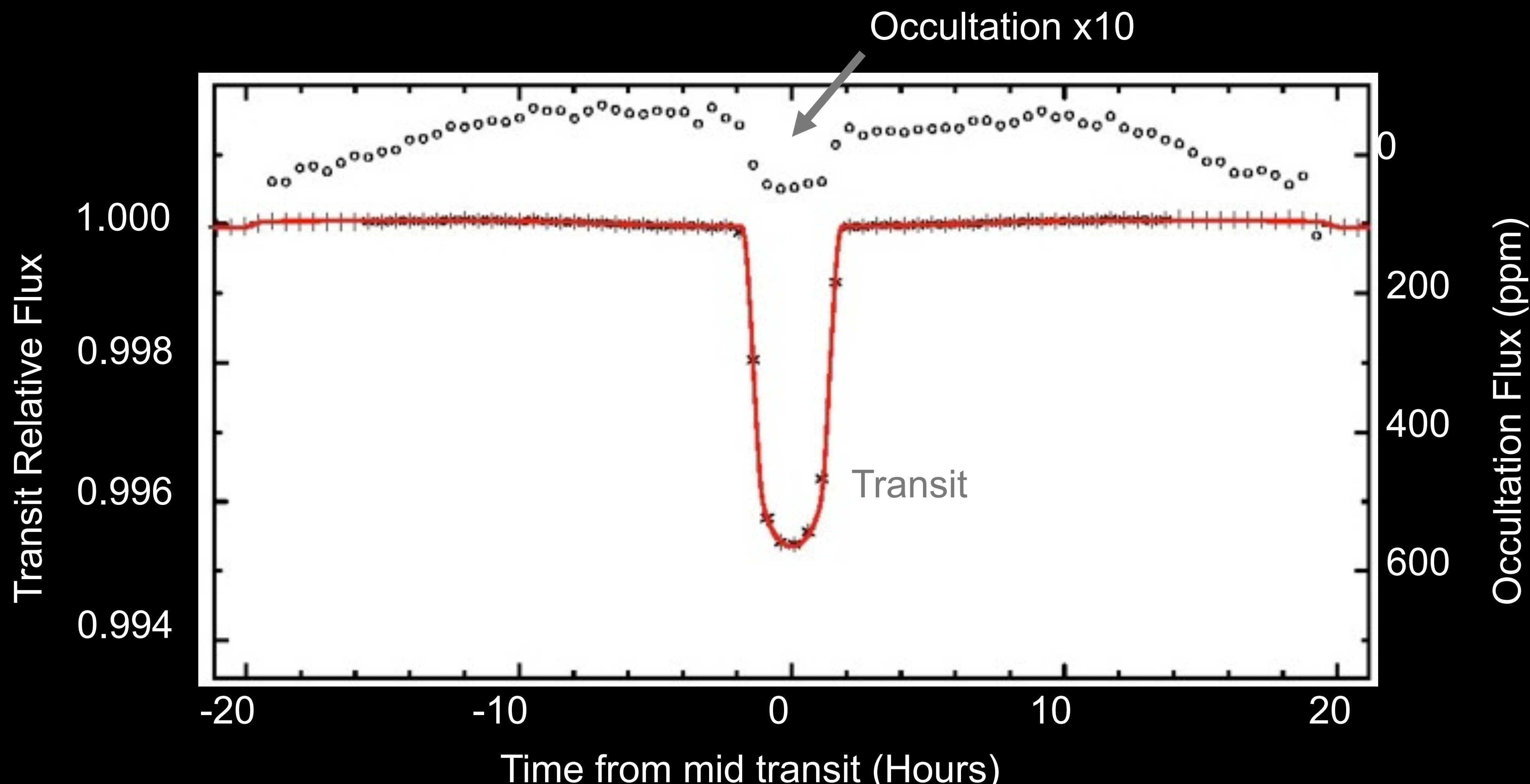


Announced at Jan 2011 AAS (Rowe et al. 2011, in prep)

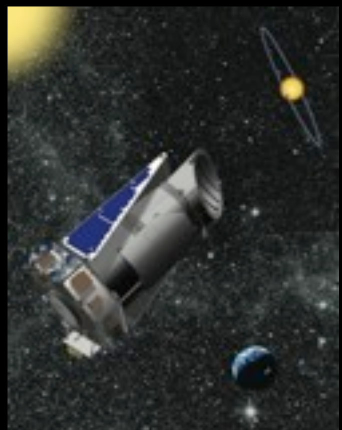
P_{orb} = 1.76 days

K_p = 10 mag

A-type star



KOI-13.01



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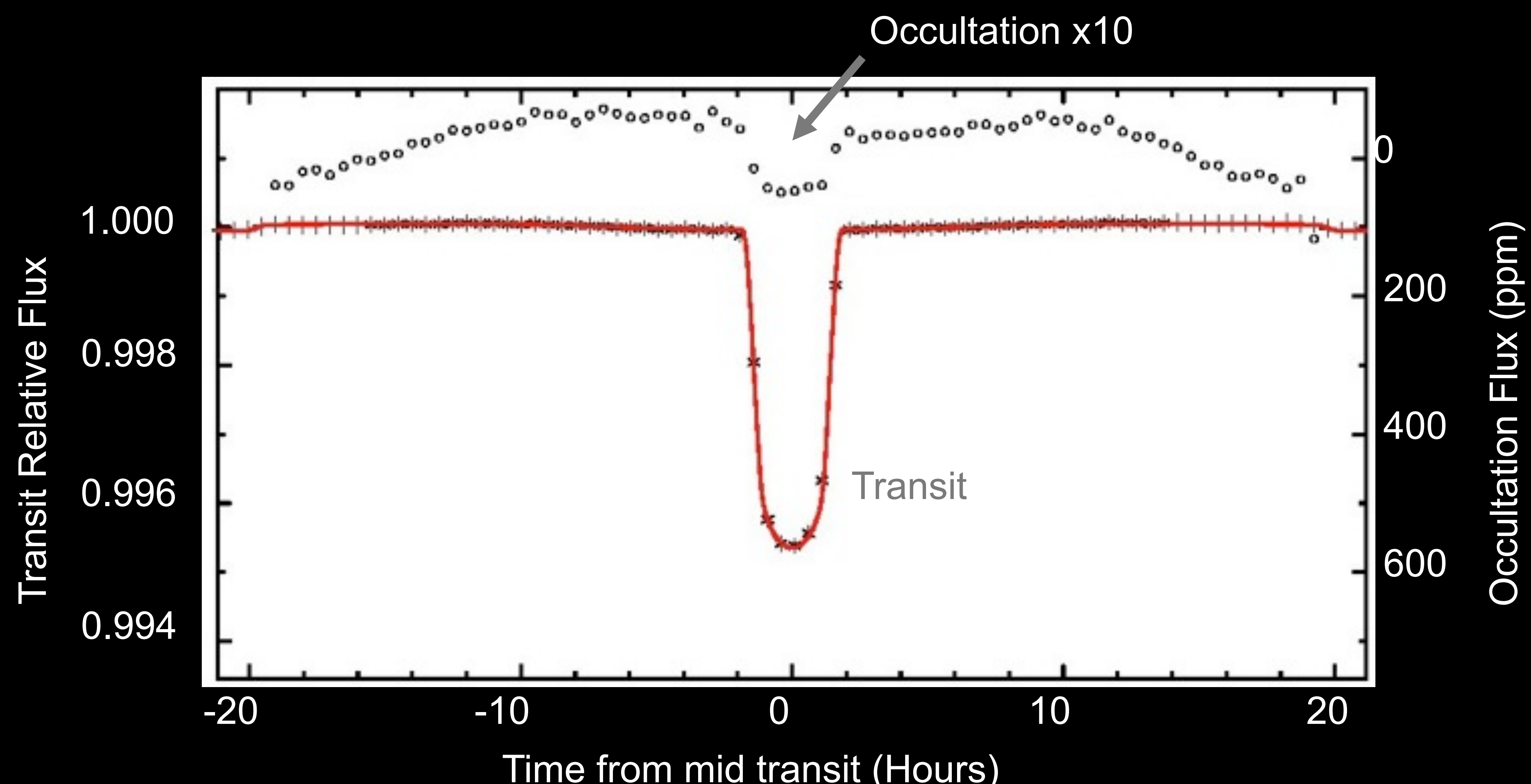
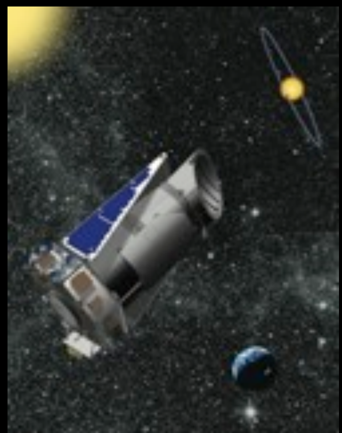


Can we use the out-of-eclipses light curve to detect the planet ?

Kepler

KOI-13.01



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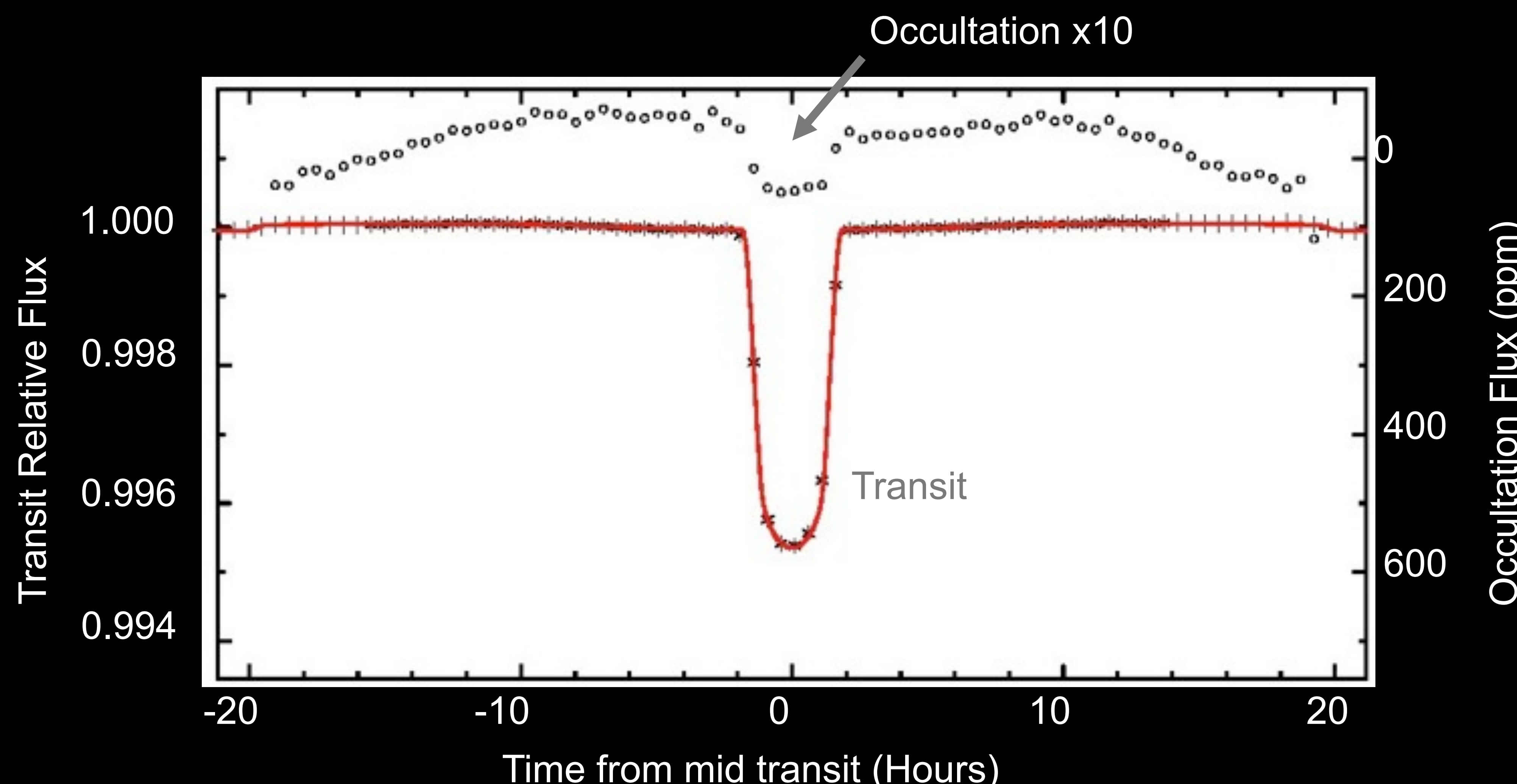

Can we use the out-of-eclipses light curve to detect the planet ?
or,
Can we detect non-transiting KOI-13.01-like planets ?

Photometric variability correlated with the orbit

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- **Beaming**

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Photometric variability correlated with the orbit

- **Beaming** $$4\frac{K_{RV}}{c}$$
- **Tidal ellipsoidal deformation** $$\frac{m_2}{m_s}\left(\frac{r_s}{a}\right)^3 \sin^2 i$$
- **Reflection/heating** $$\left(\frac{r_s}{a}\right)^2 \sin i$$

The (Relativistic) Beaming Effect

aka Doppler boosting

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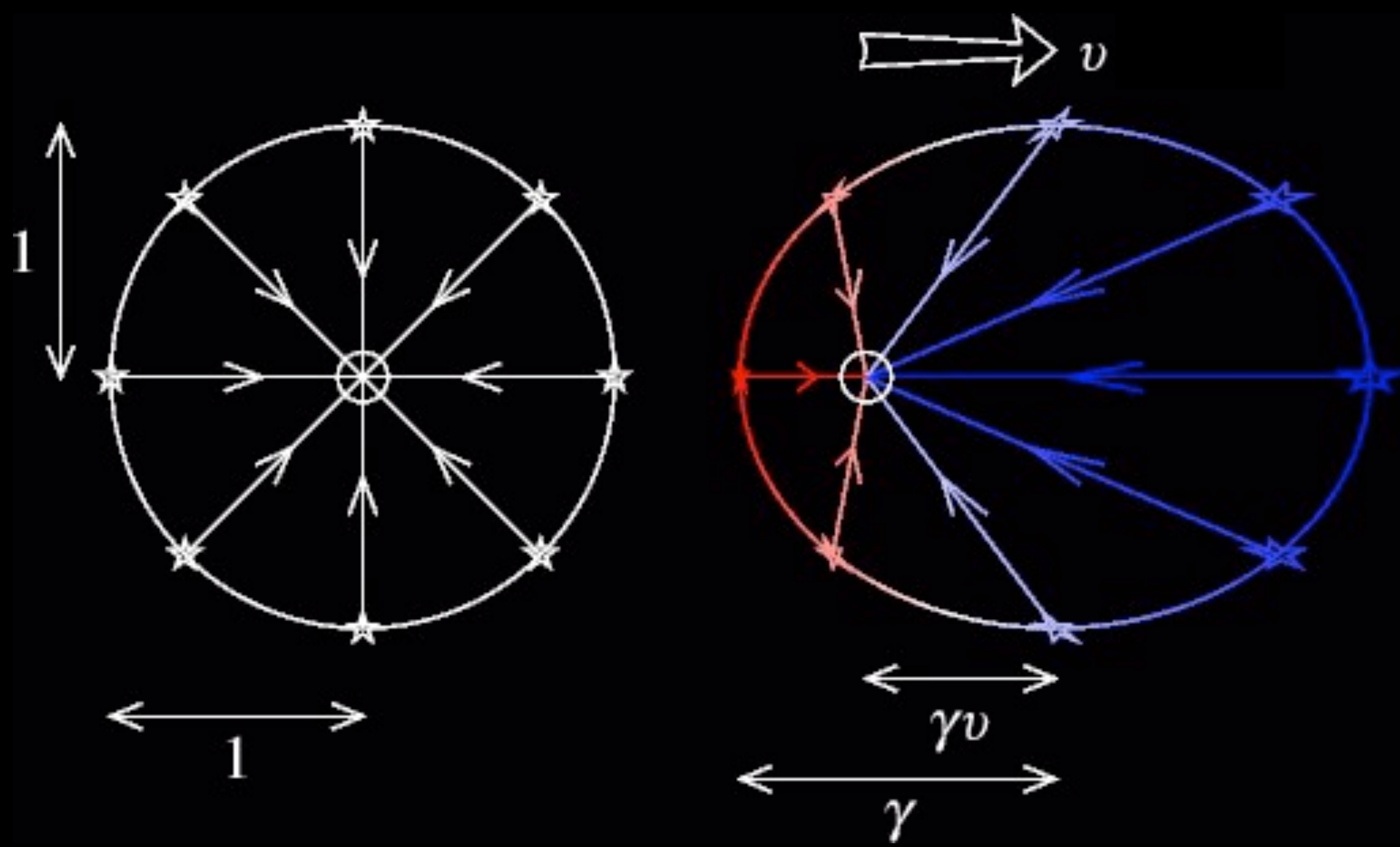

The (Relativistic) Beaming Effect
aka Doppler boosting

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

$$v_r \ll c$$

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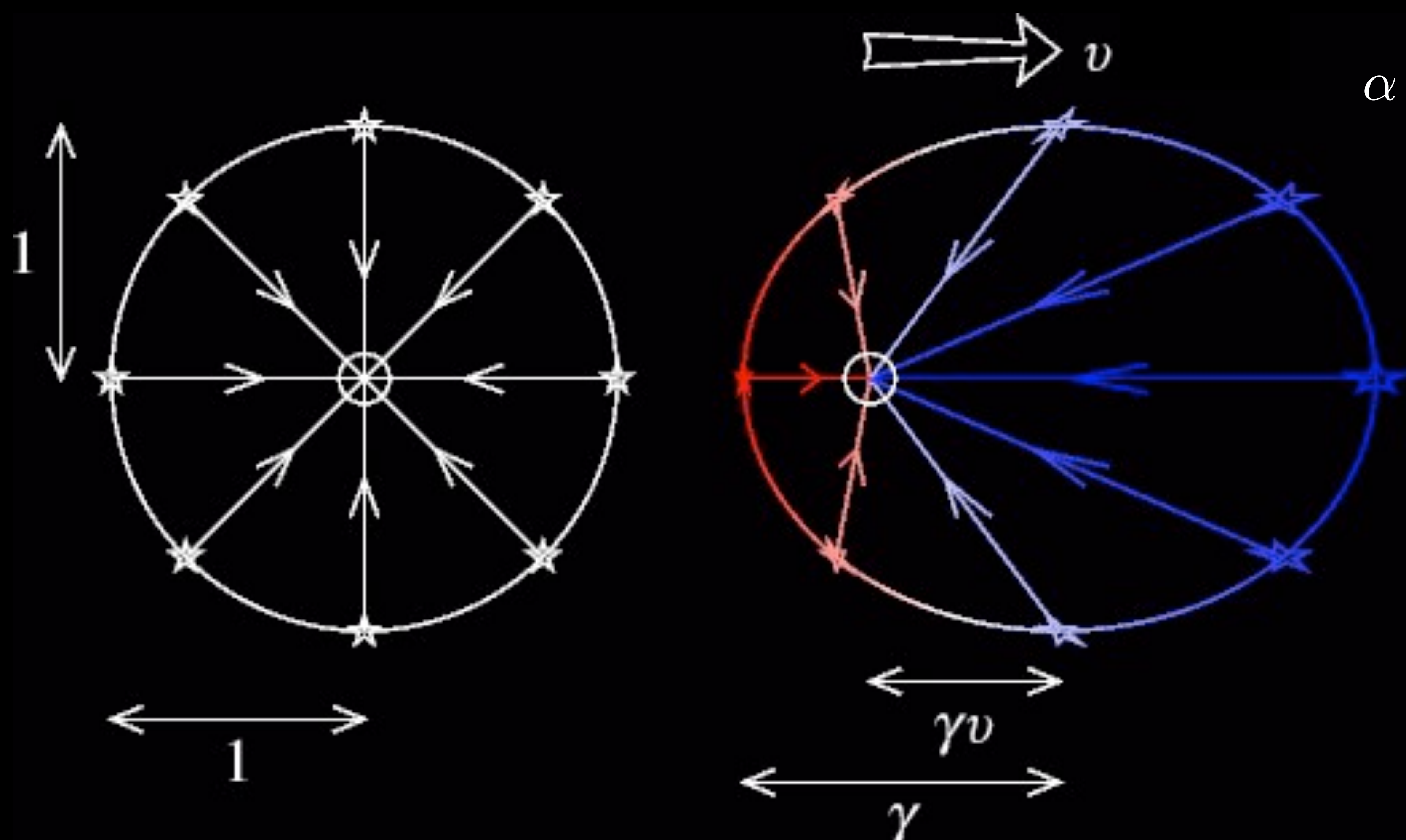

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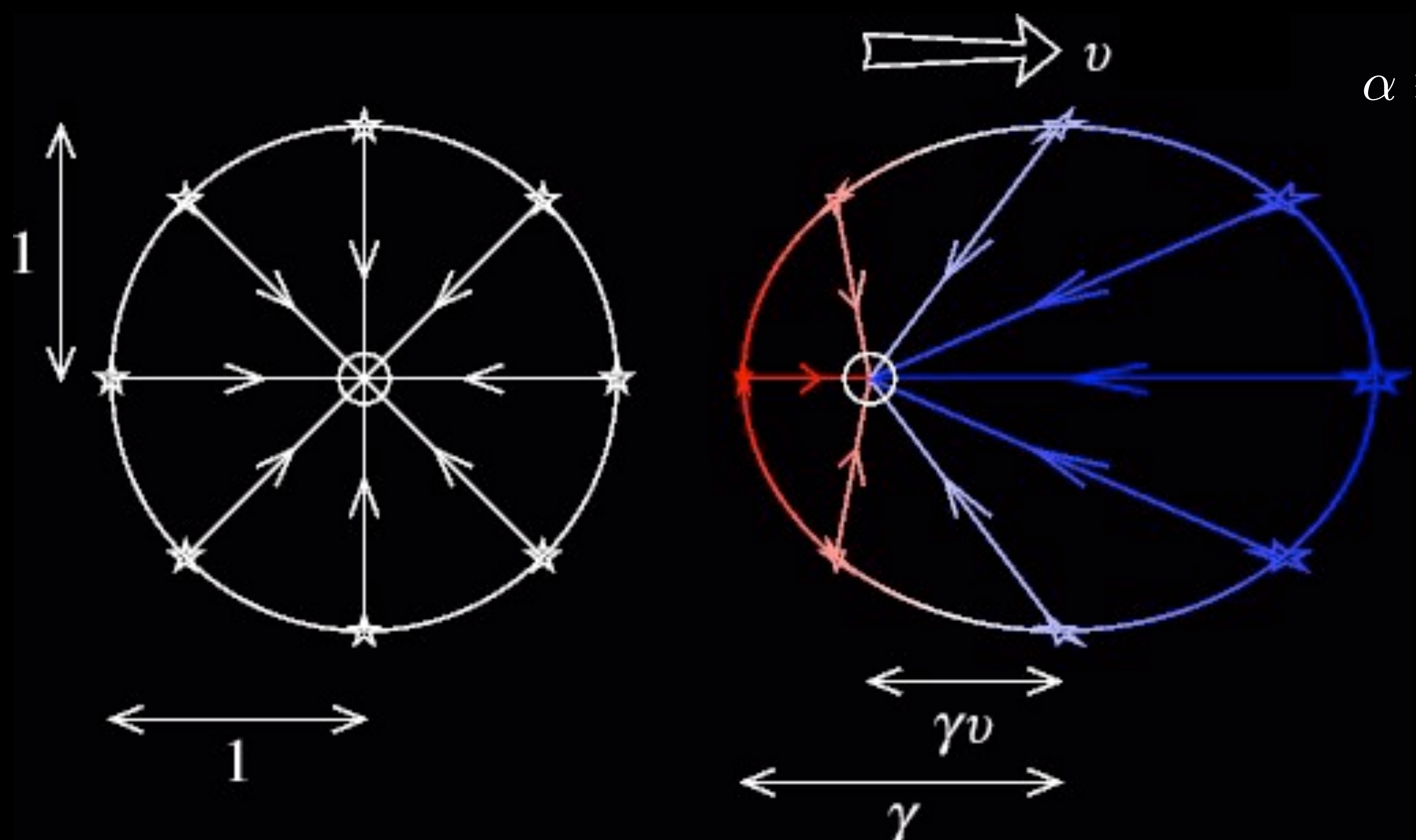
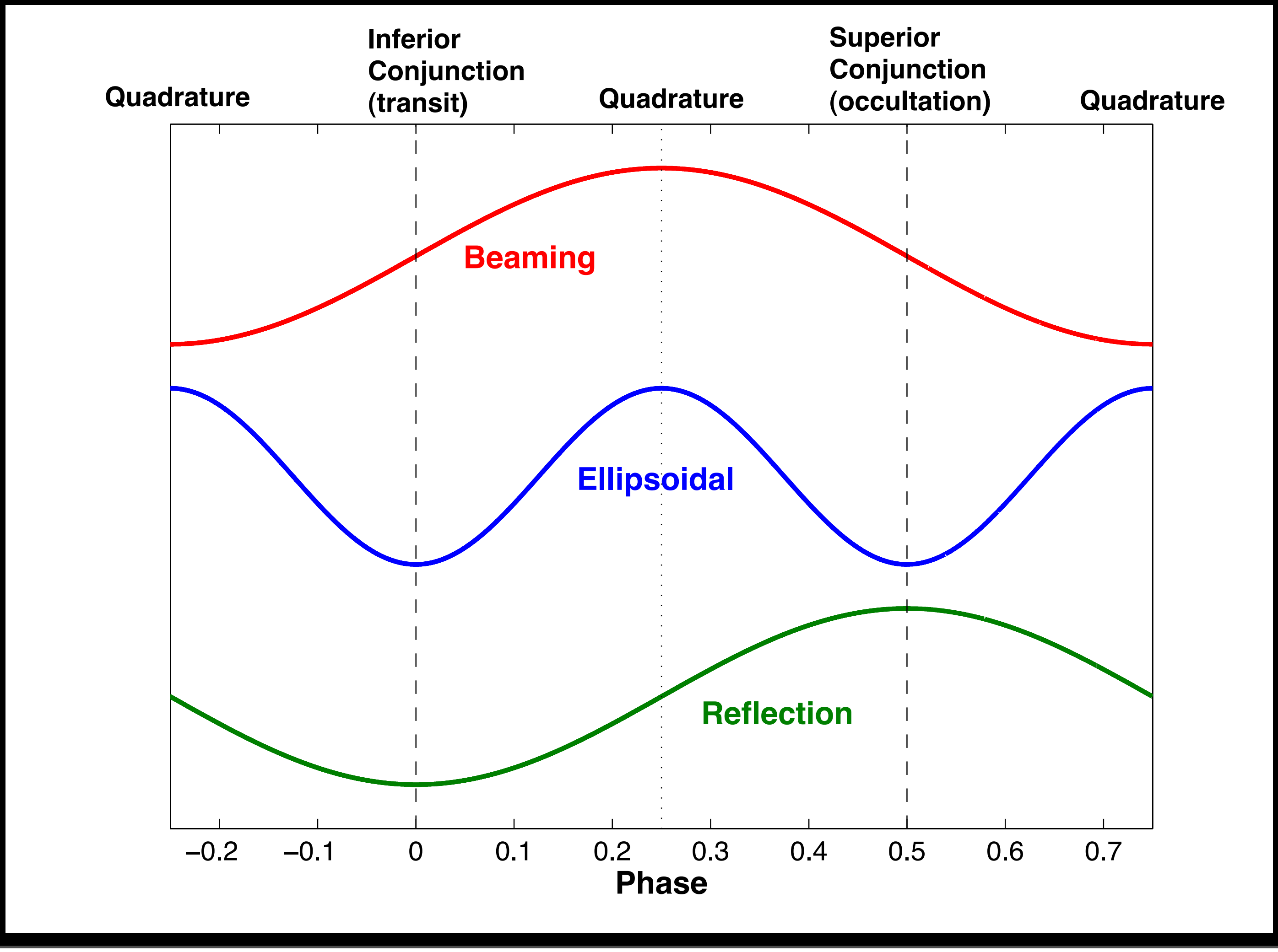


Photometric variation following ***orbital*** motion

Effect	Period	Max/Min	Function	Amplitude
Beaming	P_{orb}	quadrature	sin	$4\frac{K_{RV}}{c}$
Ellipsoidal	$P_{orb}/2$	Max: quadrature Min: conjunction	cos	$\frac{m_2}{m_s}\left(\frac{r_s}{a}\right)^3 \sin^2 i$
Reflection	P_{orb}	conjunction	cos	$\left(\frac{r_s}{a}\right)^2 \sin i$



Using Orbital Photometry for detection

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

reflection **beaming** **ellipsoidal**

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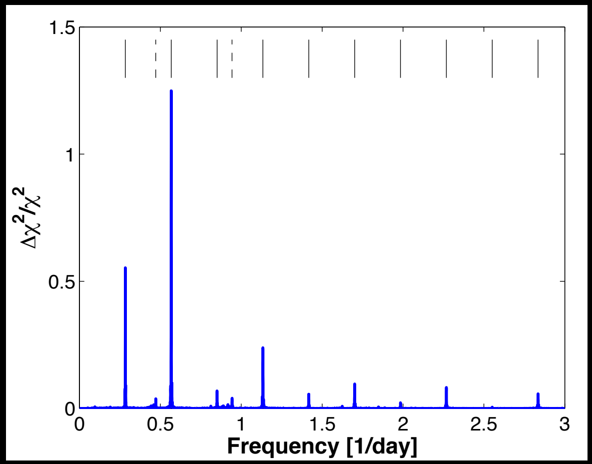

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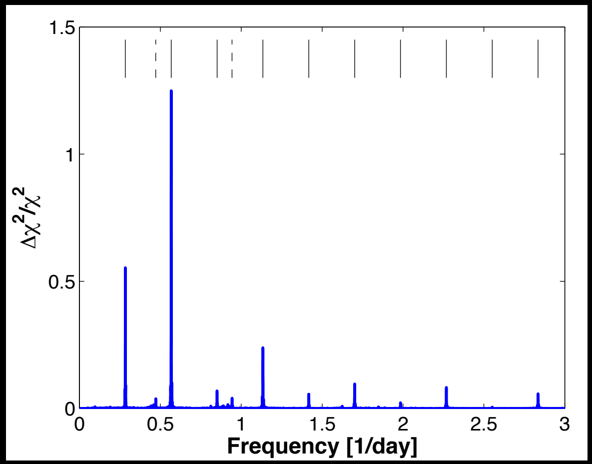
2. For best period, shift phase to zero out a_{2s}, and refit.



Detection of KOI-13.01 Using the Photometric Orbit

Shporer et al. 2011

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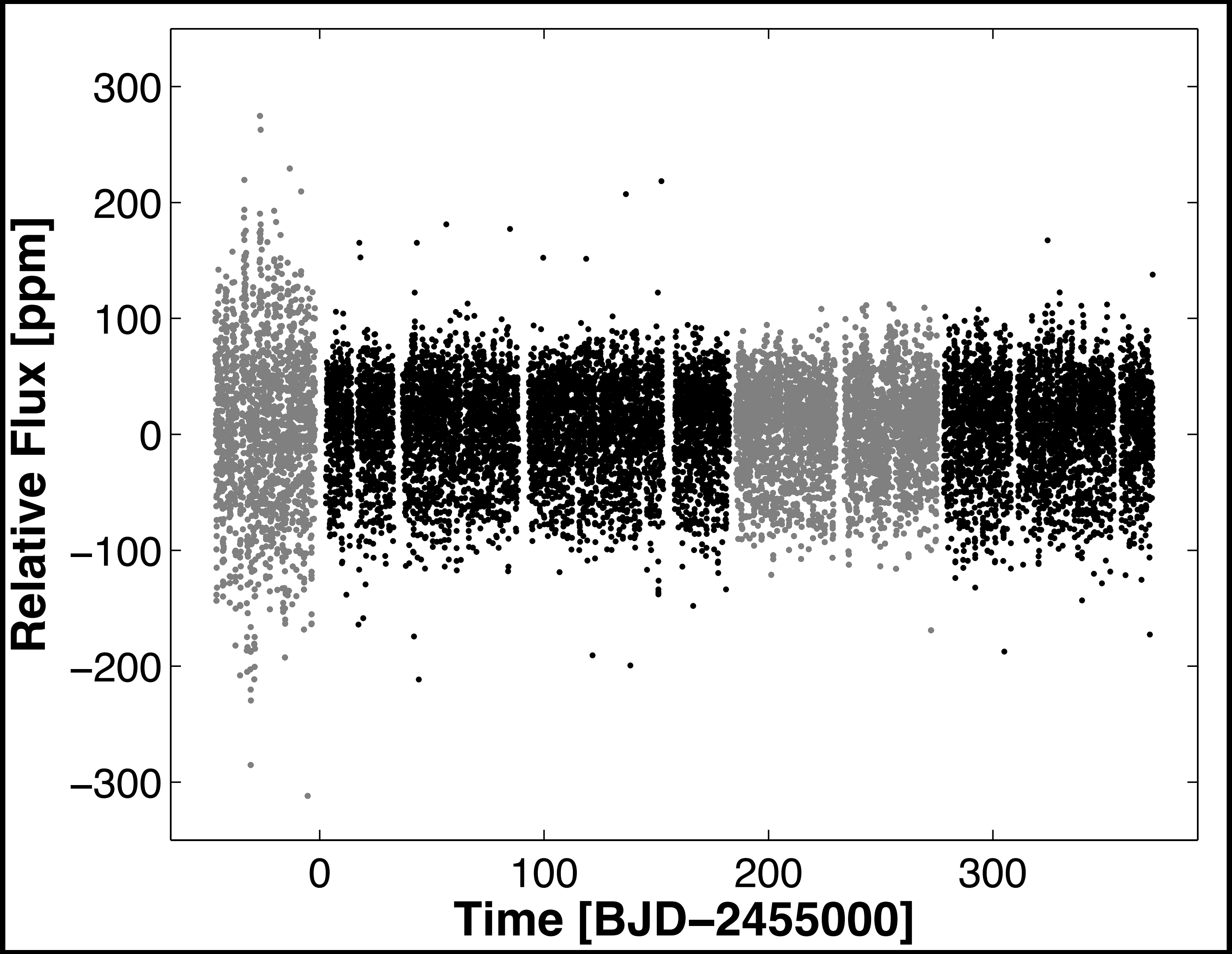
detrended light curve, Q0-Q5



Kepler

NASA

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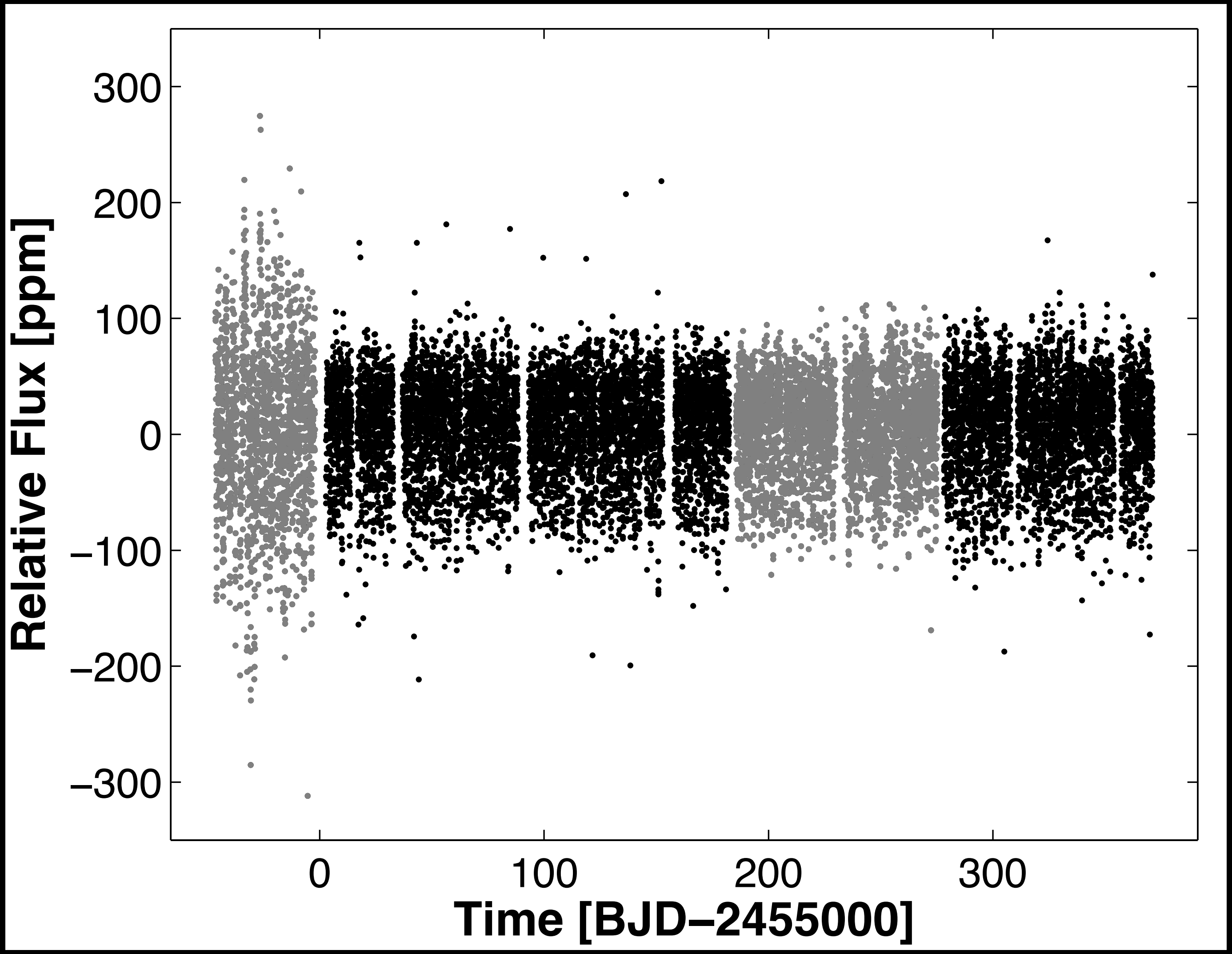

Transit+occultation data removed (18%)

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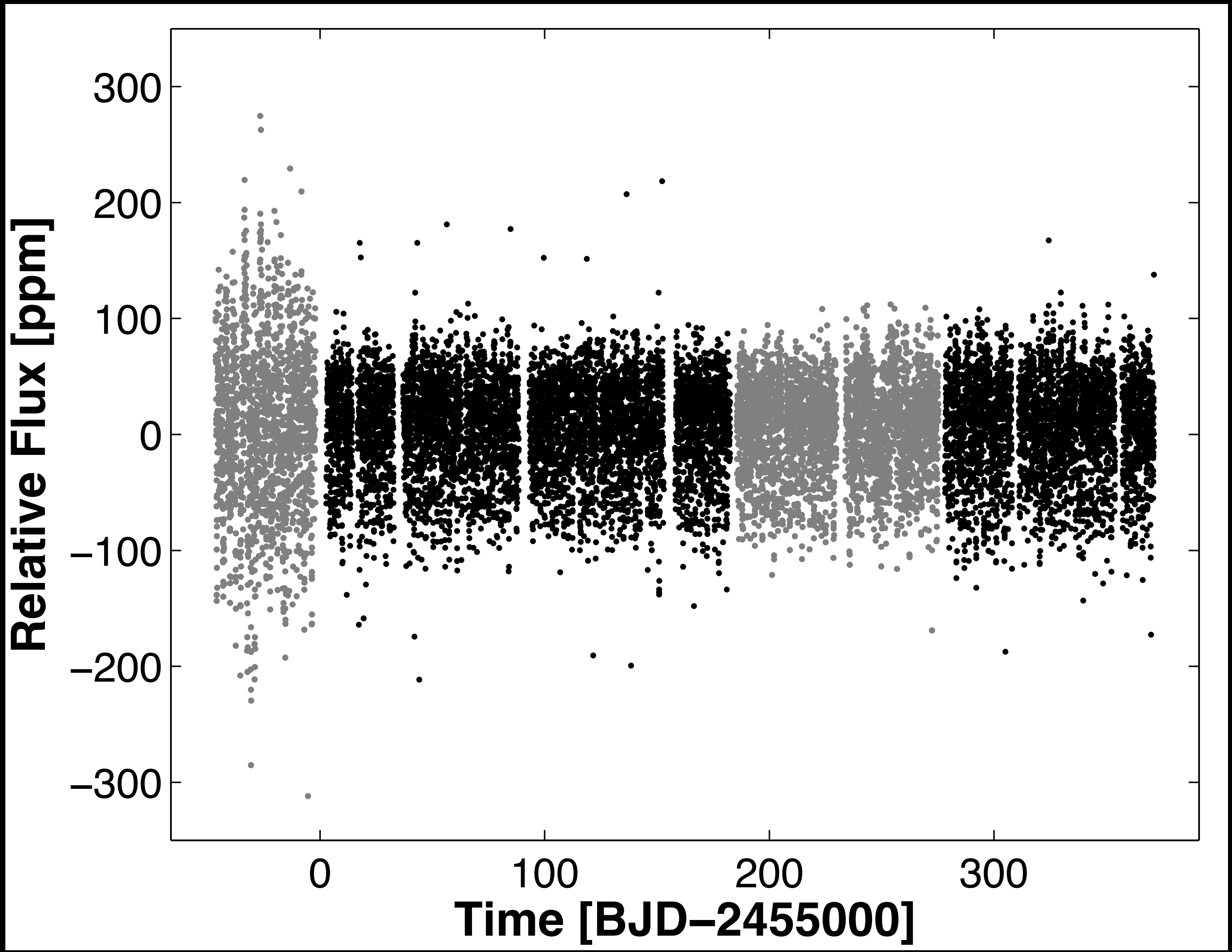
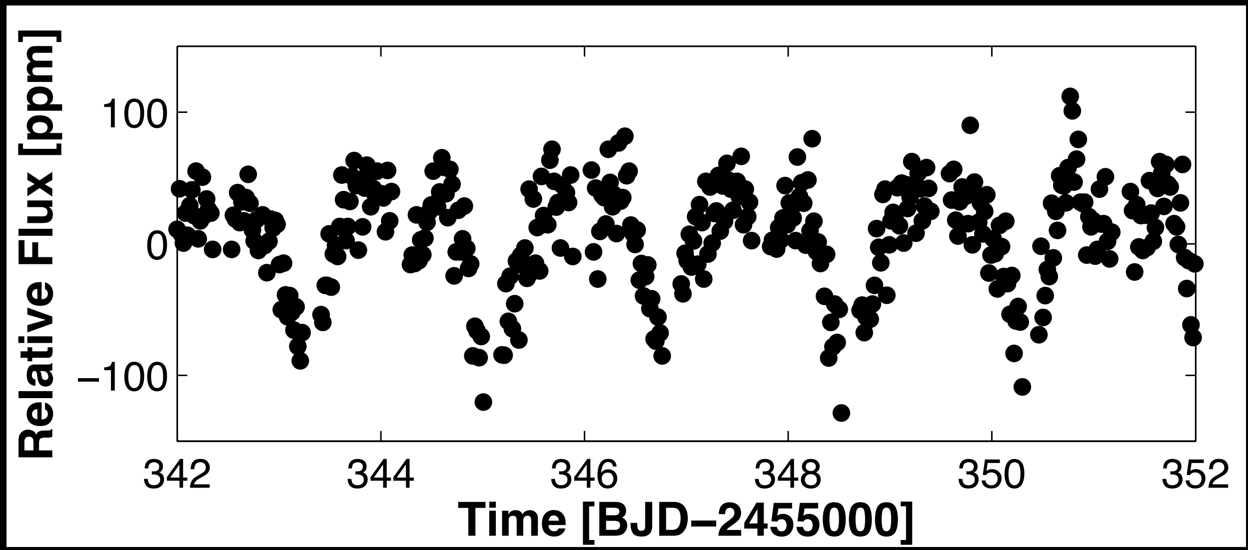


10 days of data



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Double harmonic period analysis

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

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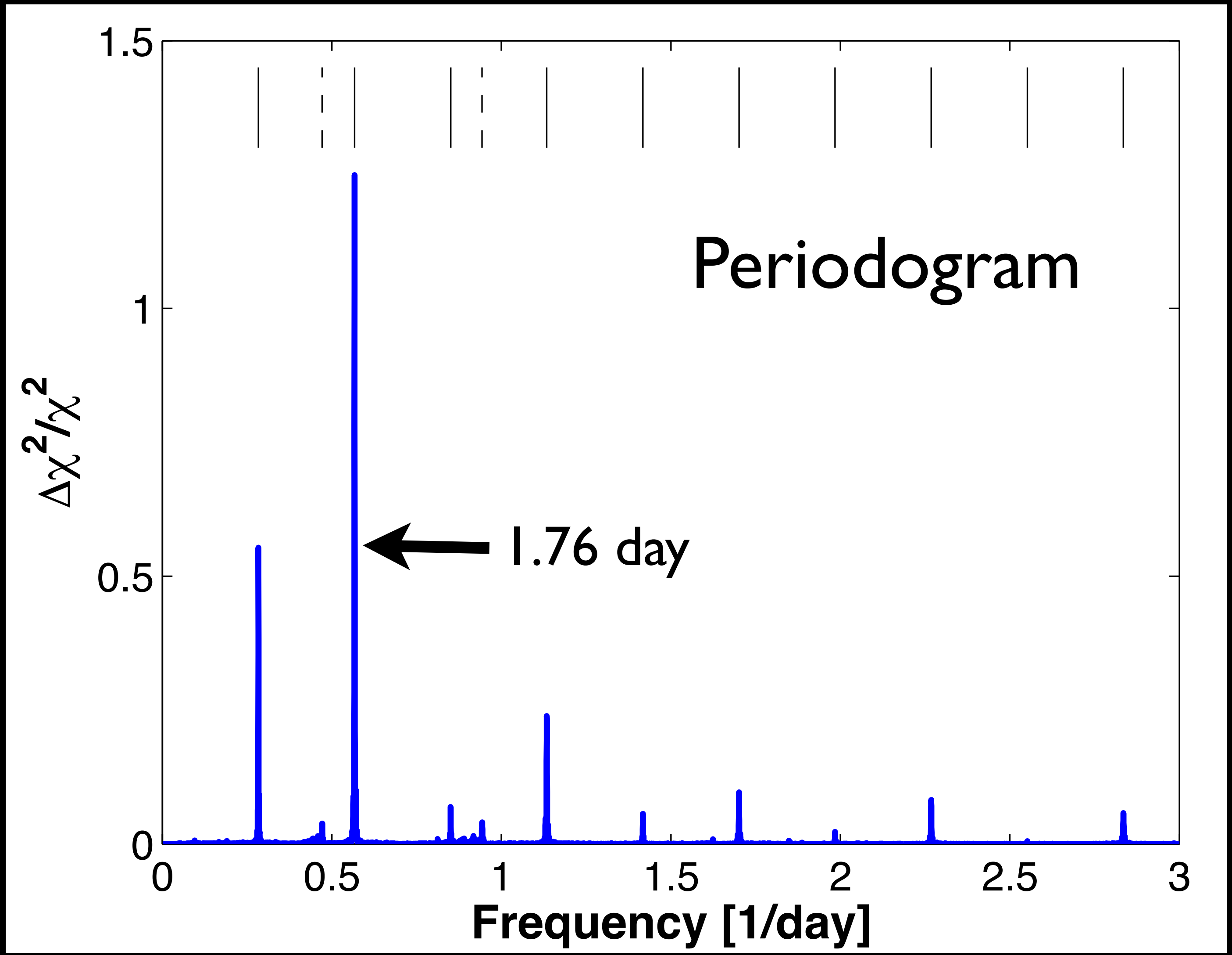

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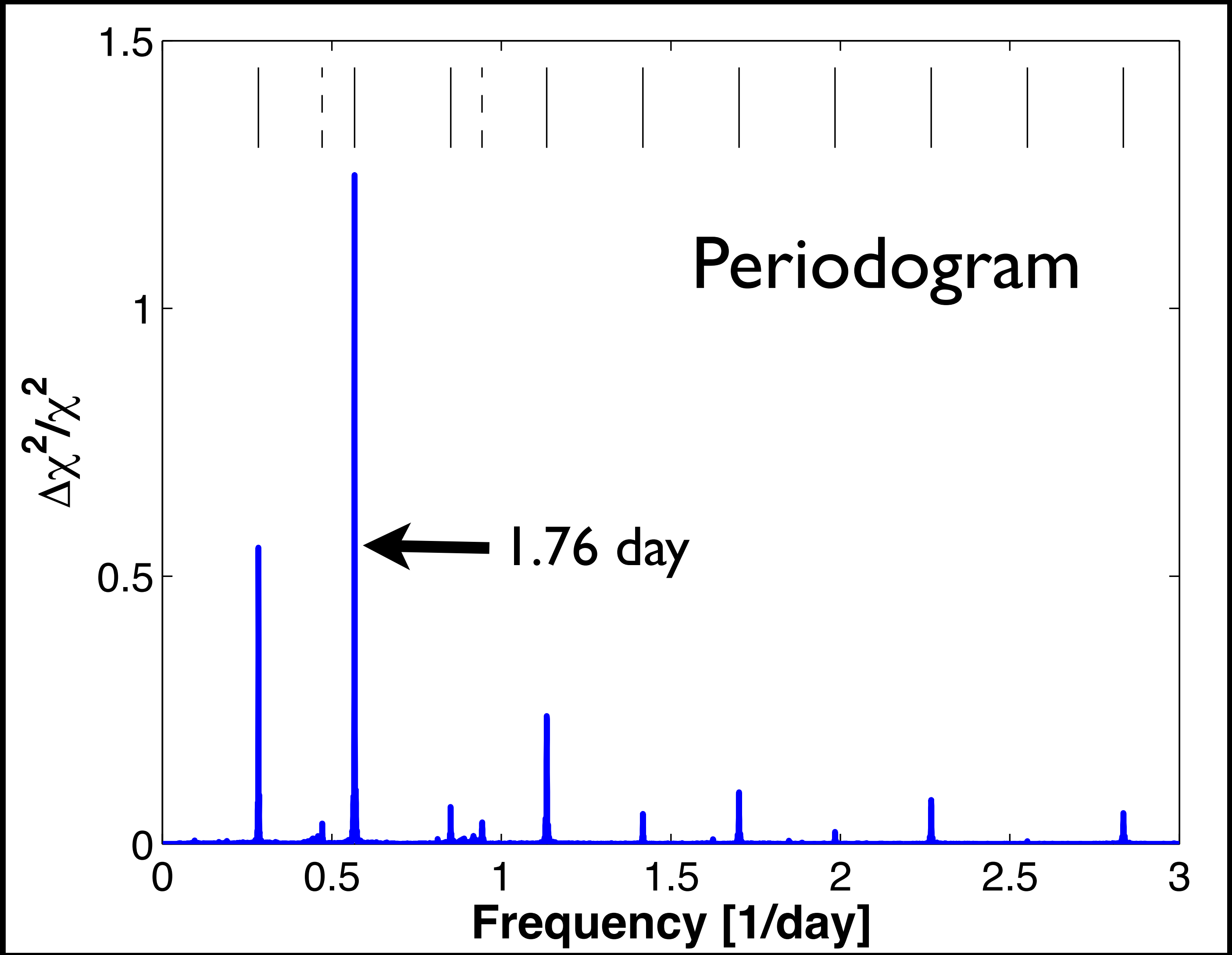

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Parameter	Value
Orbital period, P_{orb} (days)	1.7637 ± 0.0013
Inferior conjunction time, T_0 (BJD)	2455138.7439 ± 0.0013

Consistent with Borucki et al. (2011)

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Companion
mass estimate:

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

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Based on stellar parameters of Szabo et al. (2011)

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Photometric mass measurement

Based on stellar parameters of Szabo et al. (2011)

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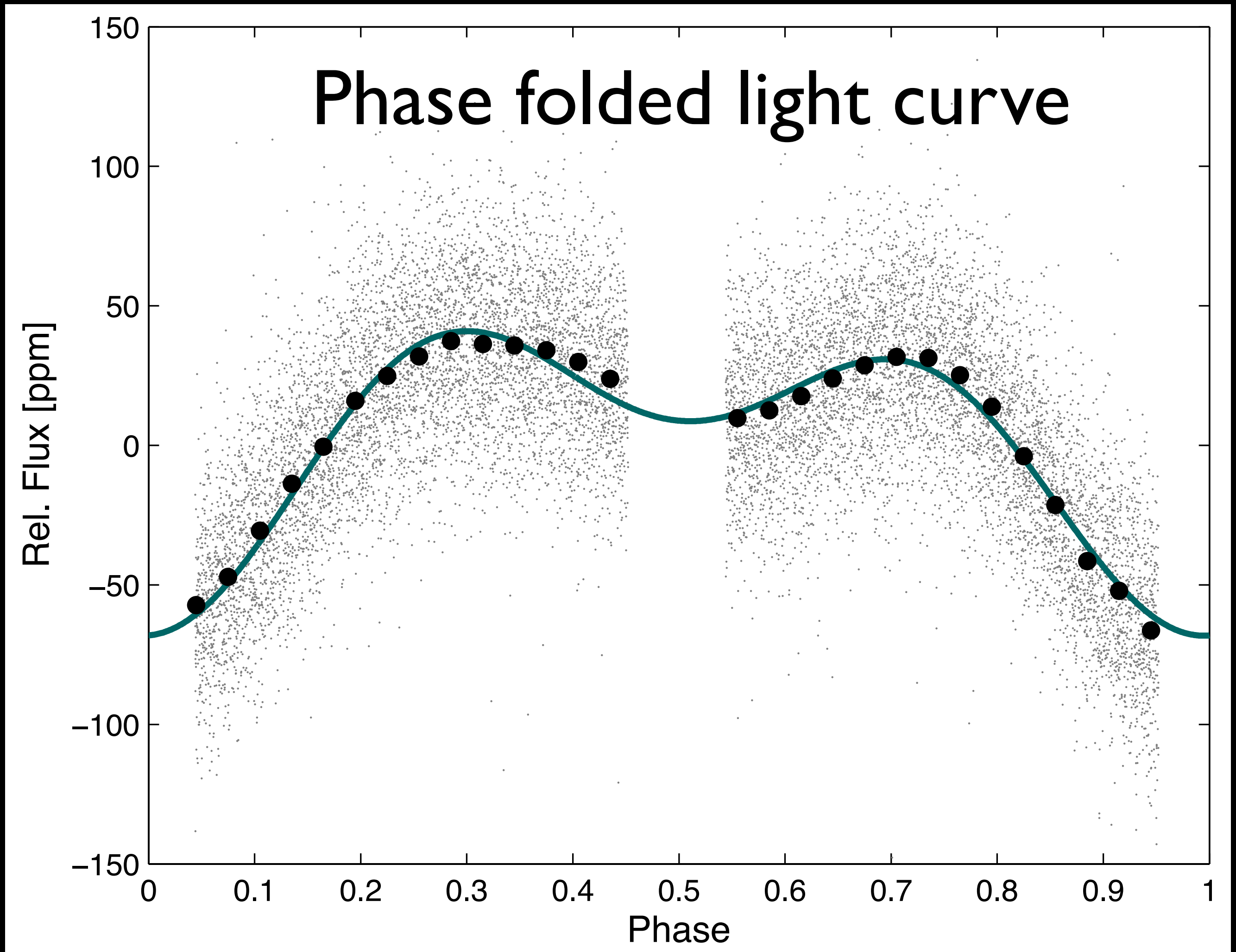

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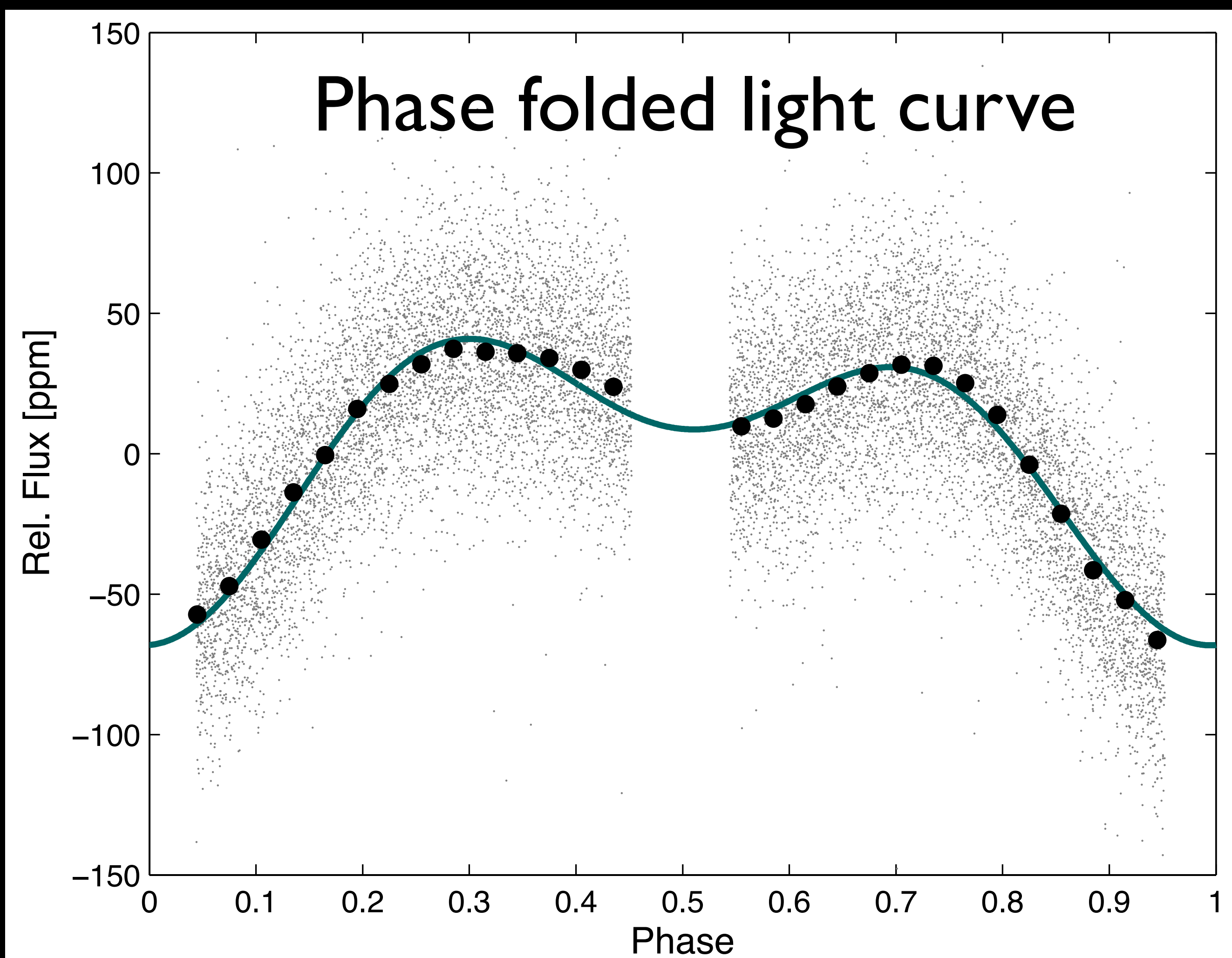

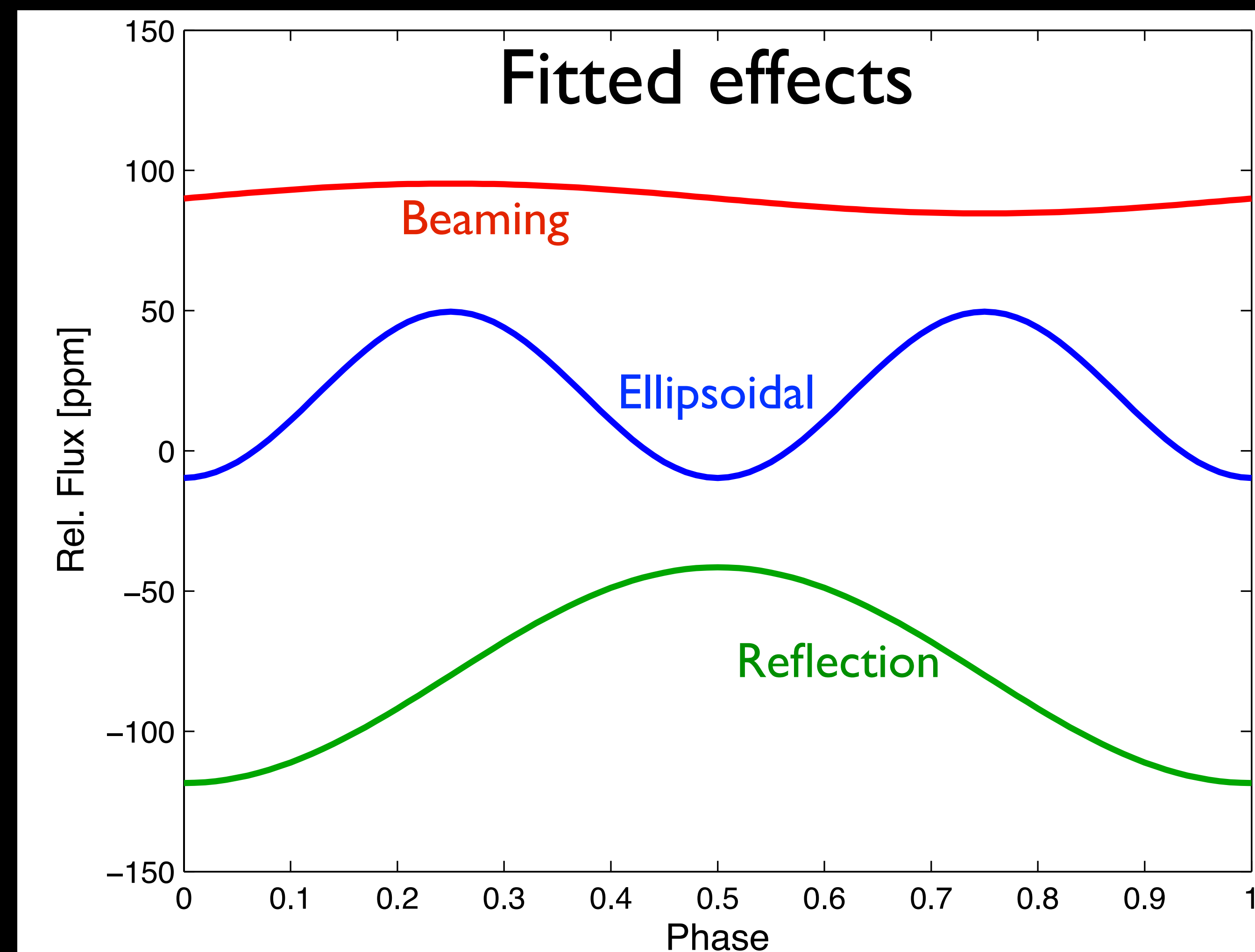

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Fitted coefficients

Coefficient	Effect	Value [ppm]
a_{1c}	Reflection	-39.78 ± 0.52
a_{1s}	Beaming	5.28 ± 0.44
a_{2c}	Ellipsoidal	-30.25 ± 0.62
a_{2s}	—	0.0 ± 0.48

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Sensitivity diagrams - M_2 vs. Period

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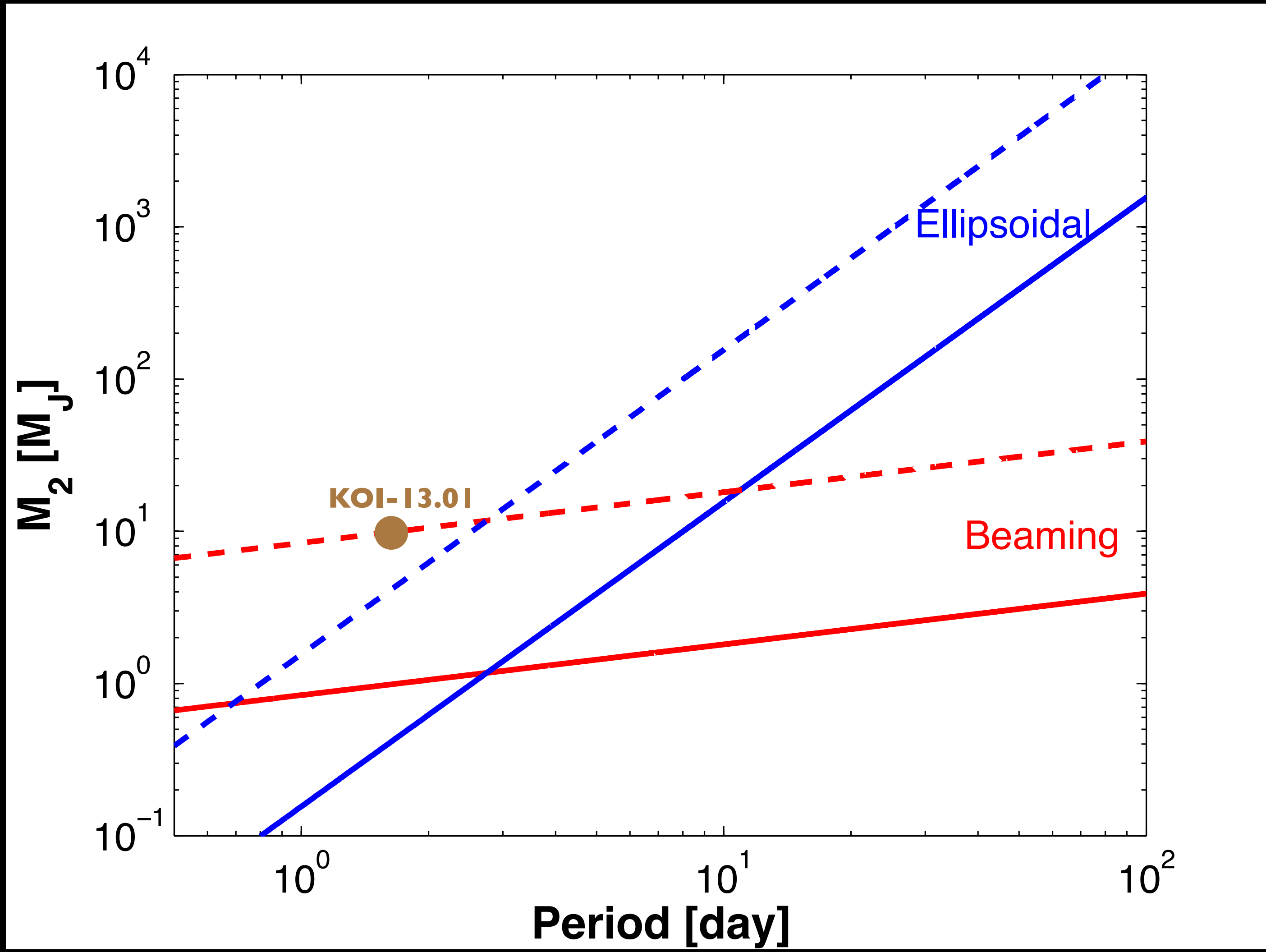
Sensitivity diagrams - M_2 vs. Period

—— 2 ppm, 10 mag
- - - 20 ppm, 15 mag

Assuming:

- 7σ detection
- 3.5 yr mission
- i = 60 deg



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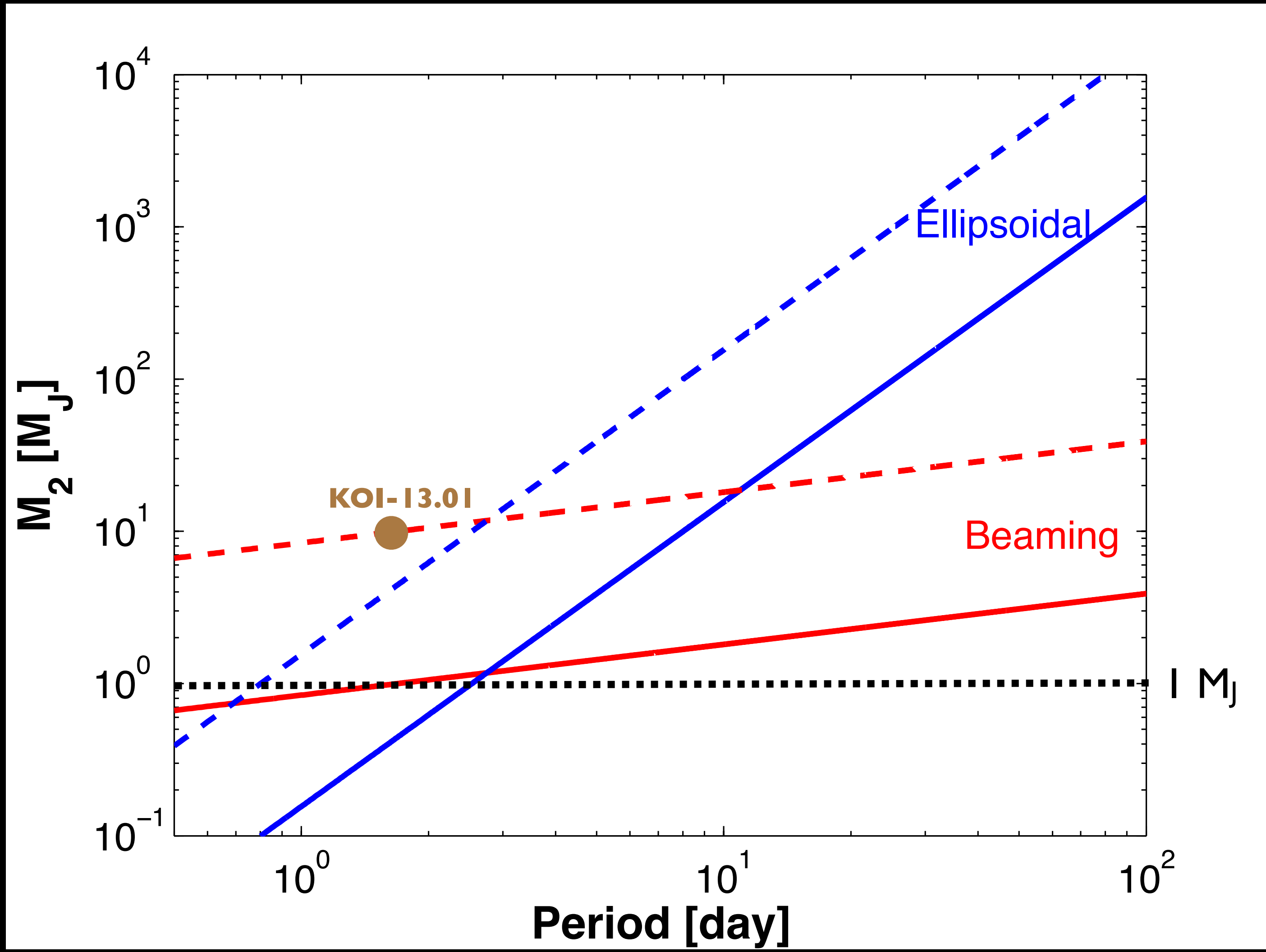

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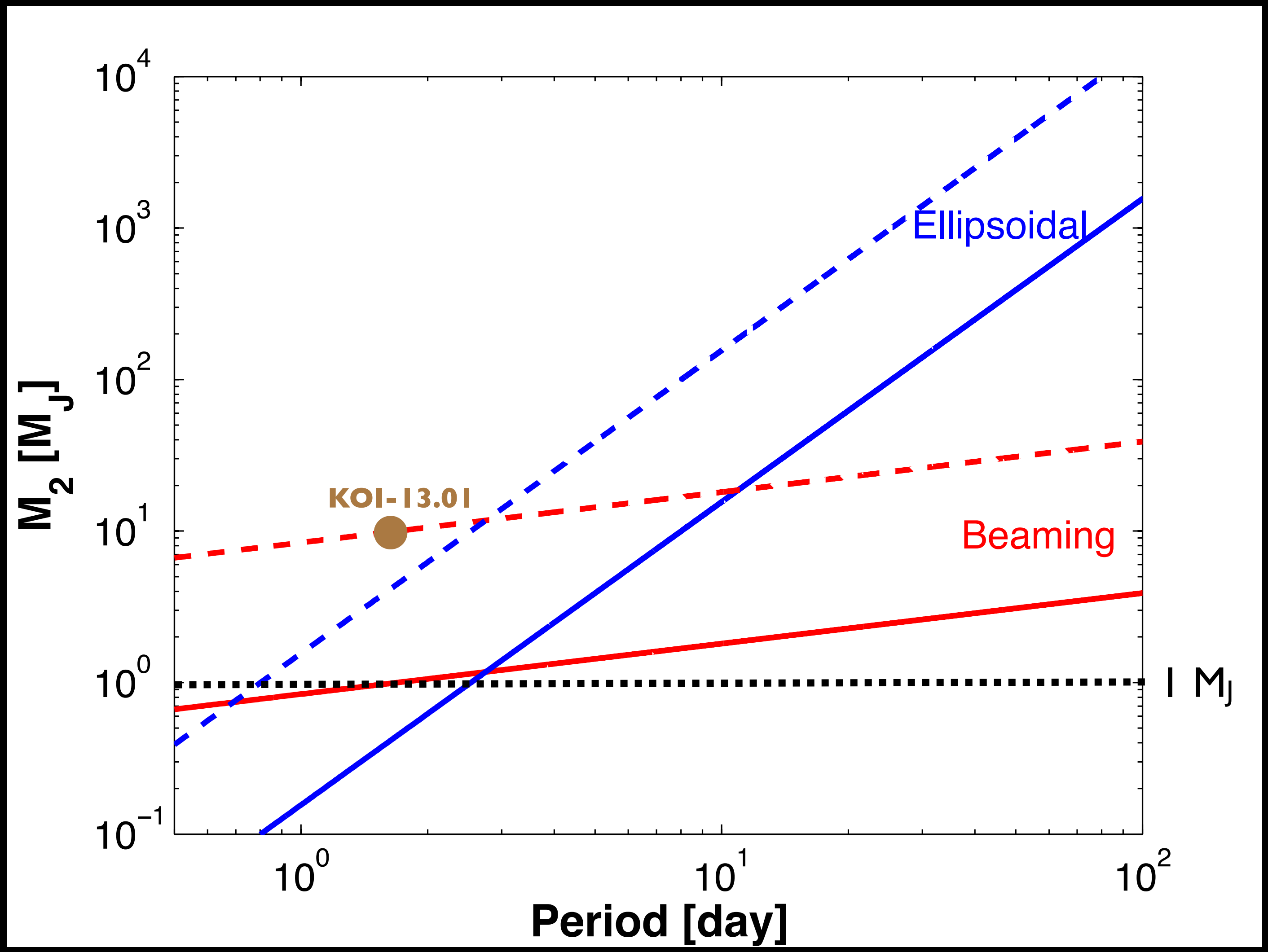

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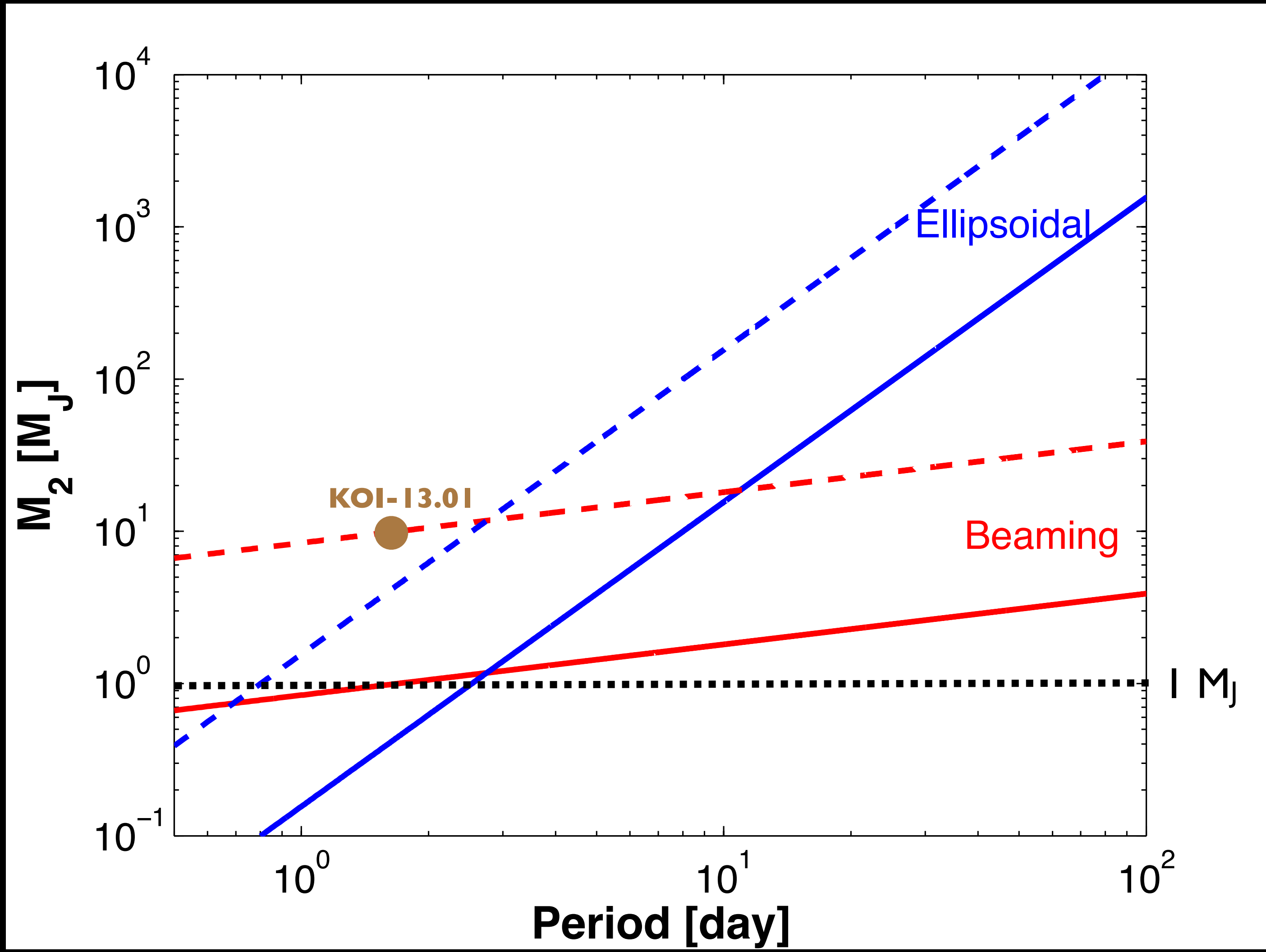

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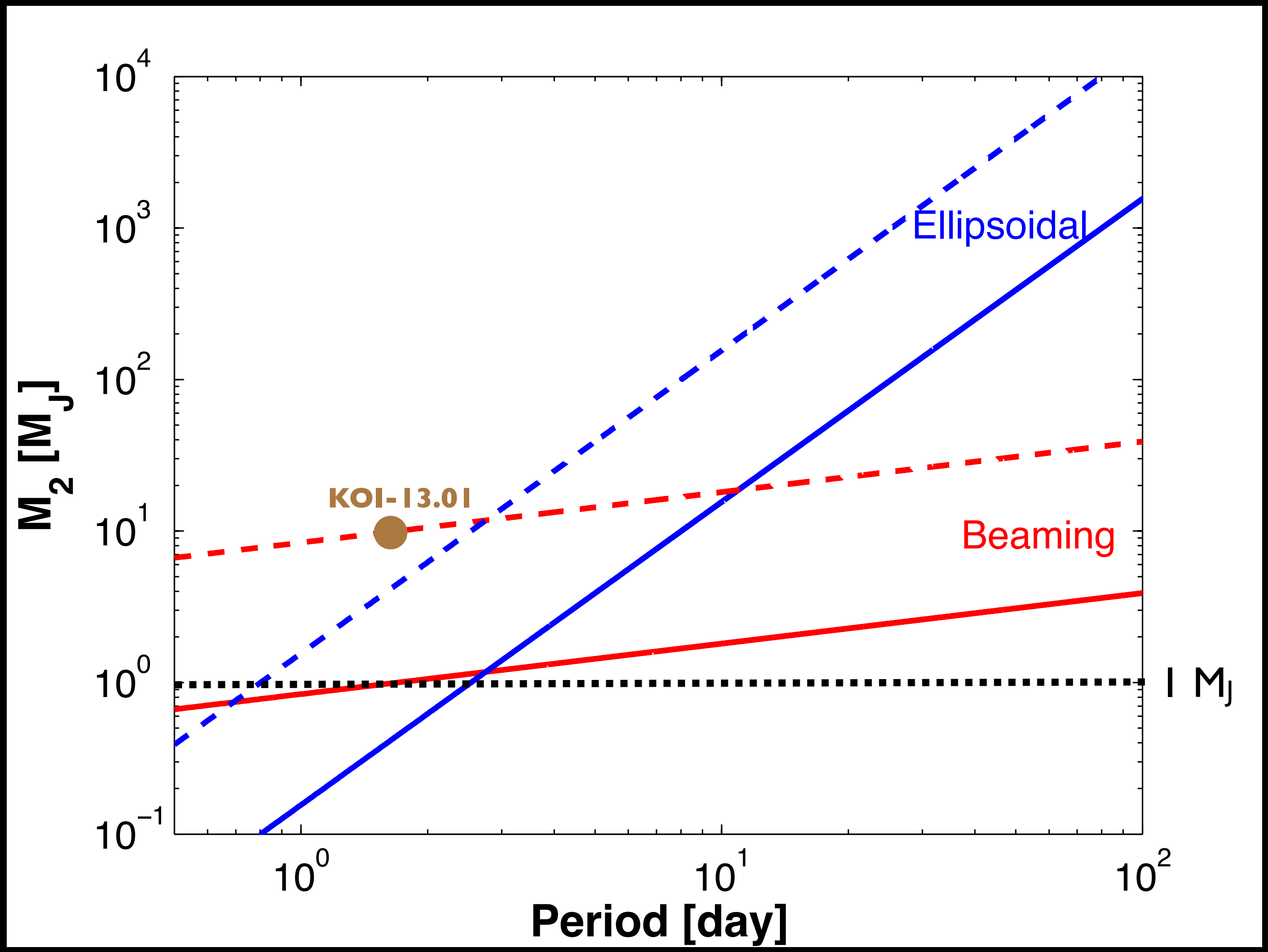

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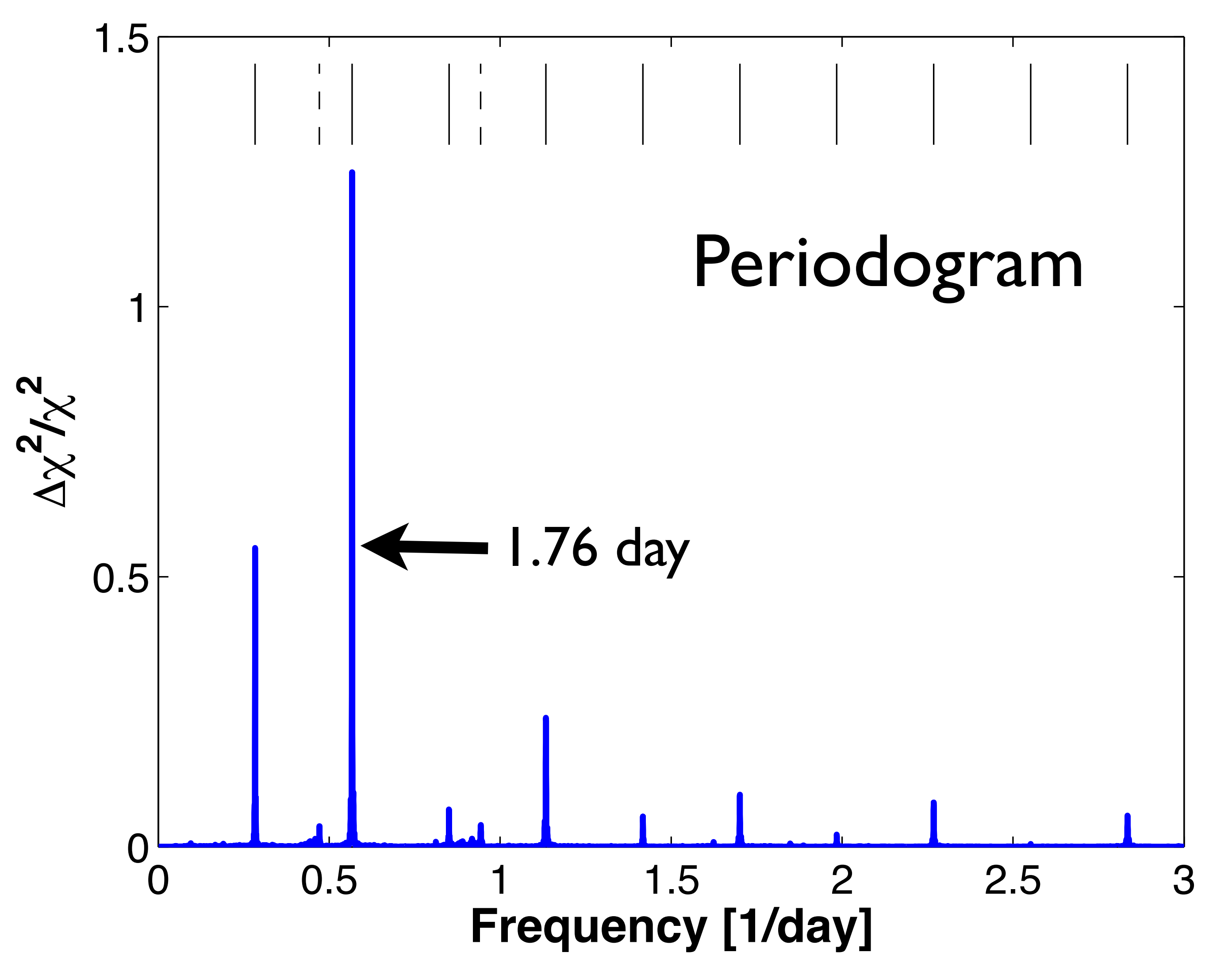
- Non-transiting companions down to ~1 M_J

KOI-13 secondary periodicity



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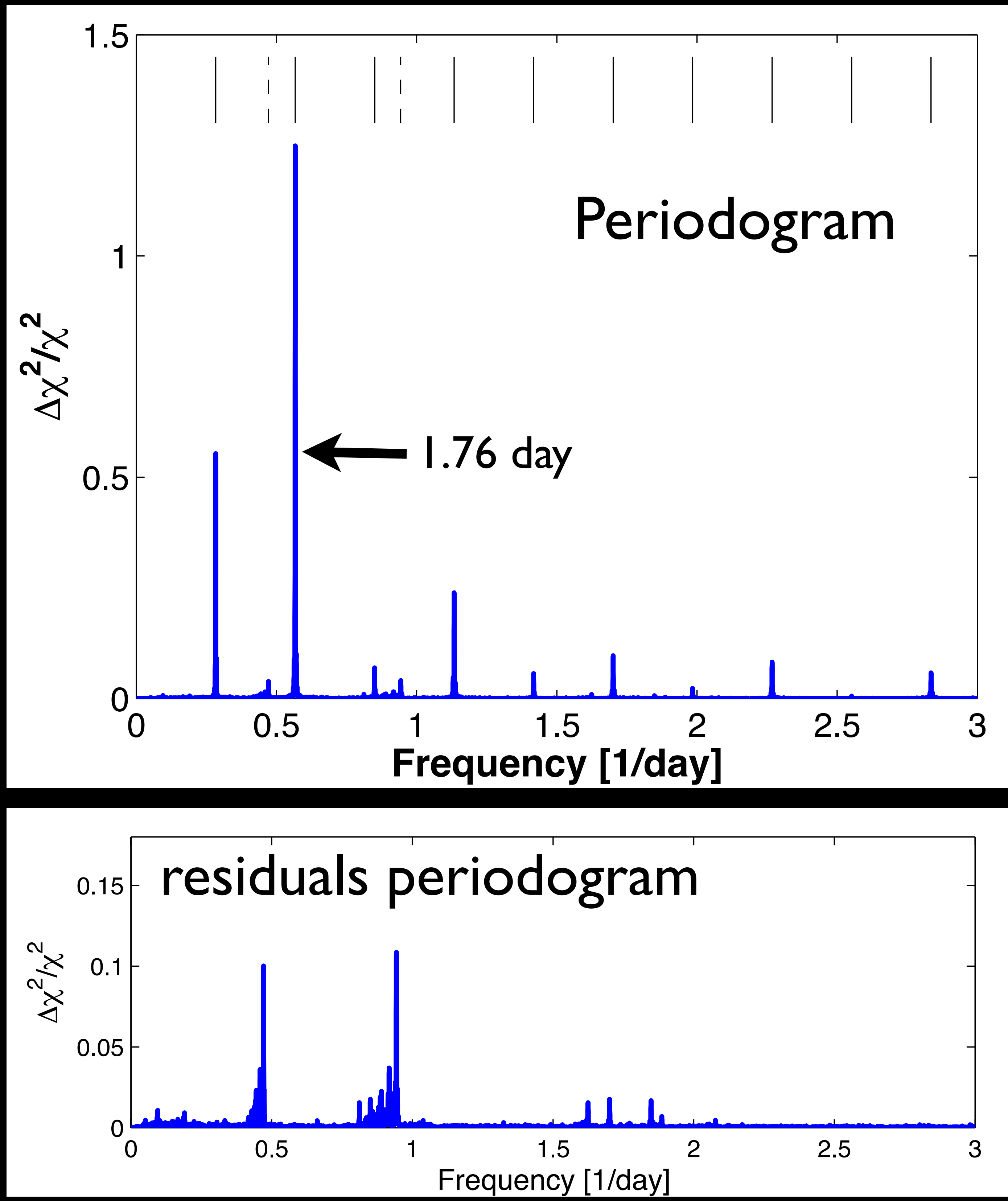

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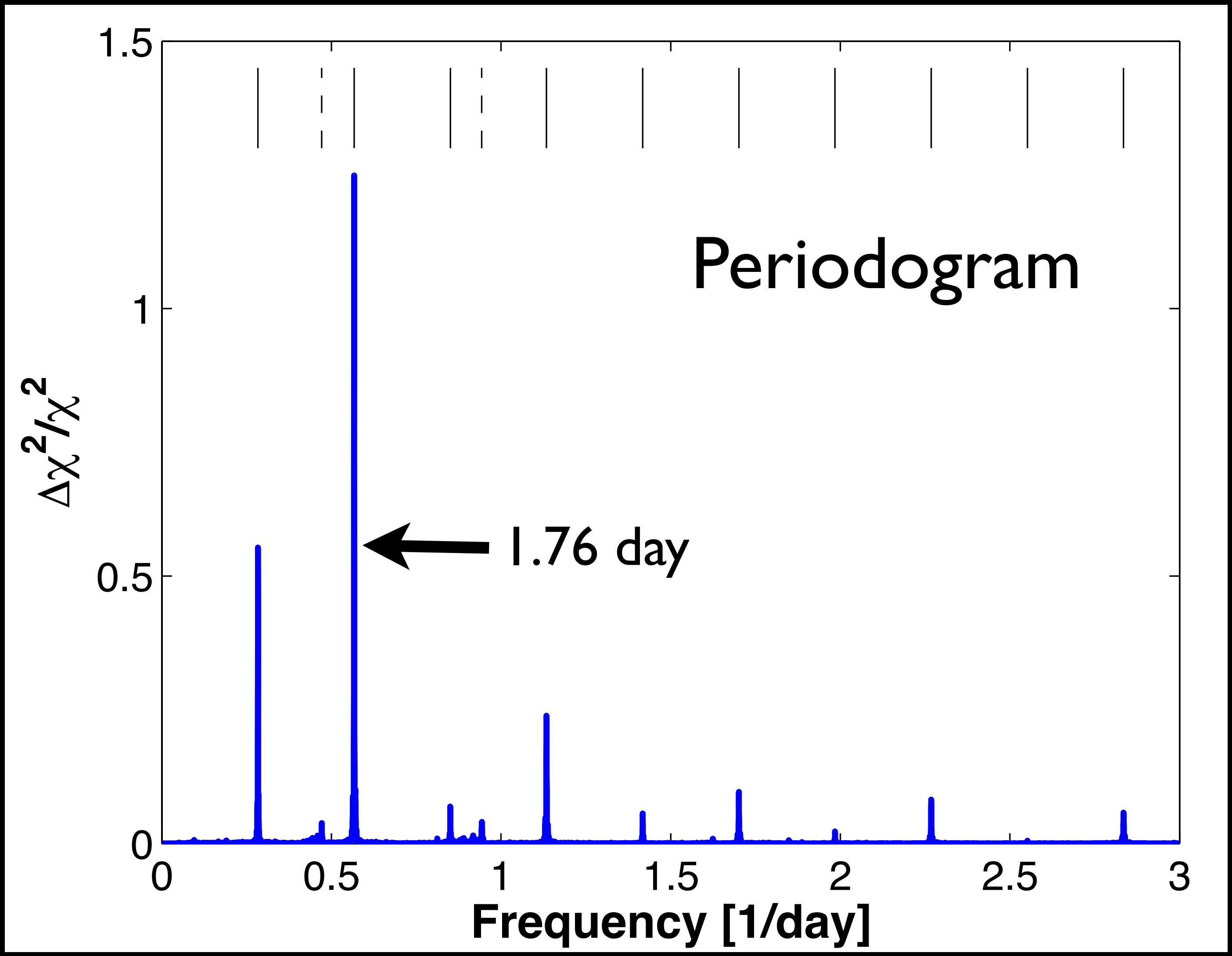

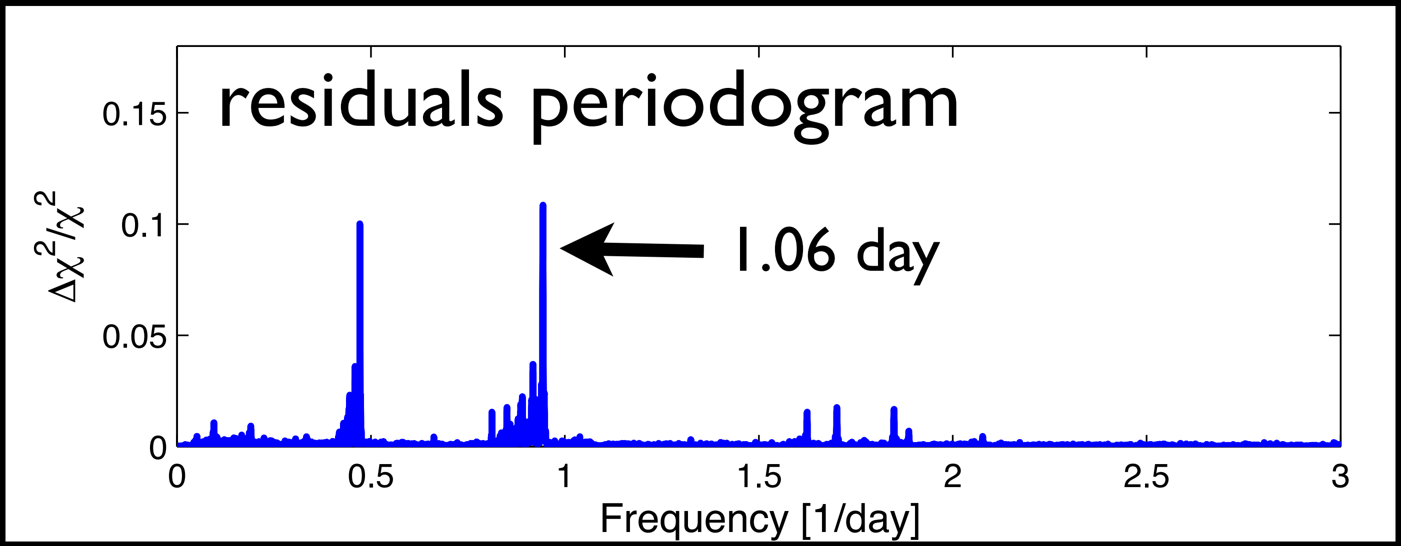

independently detected by Mazeh et al. 2011

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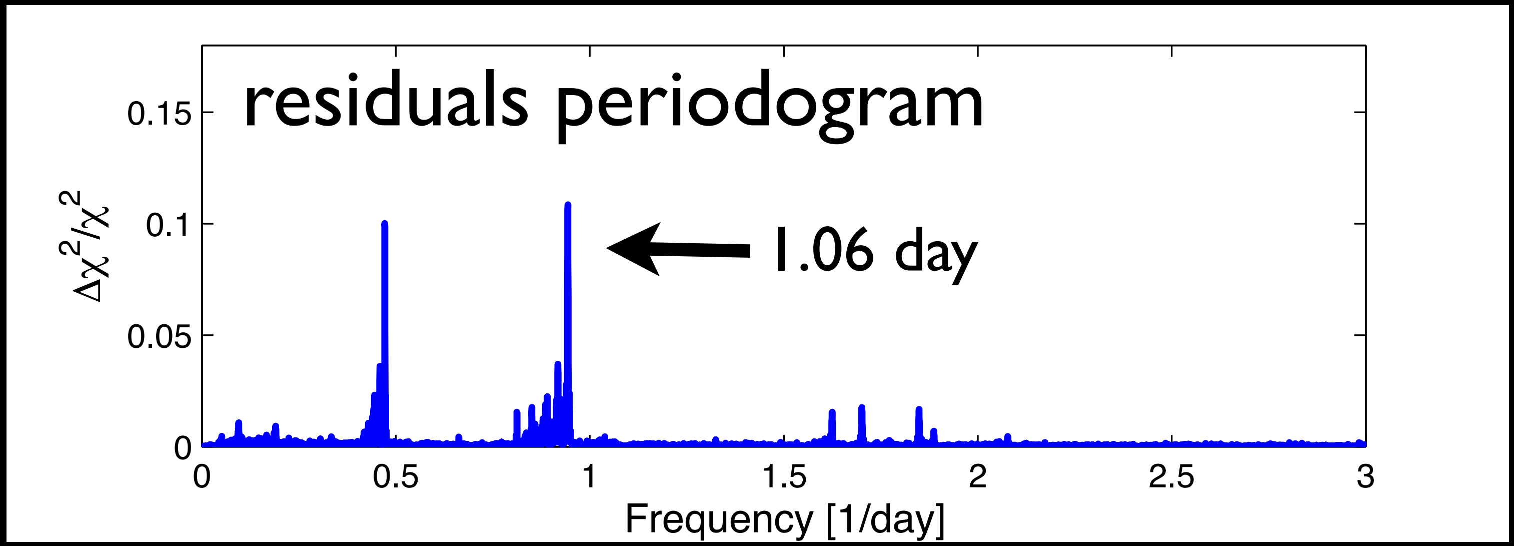
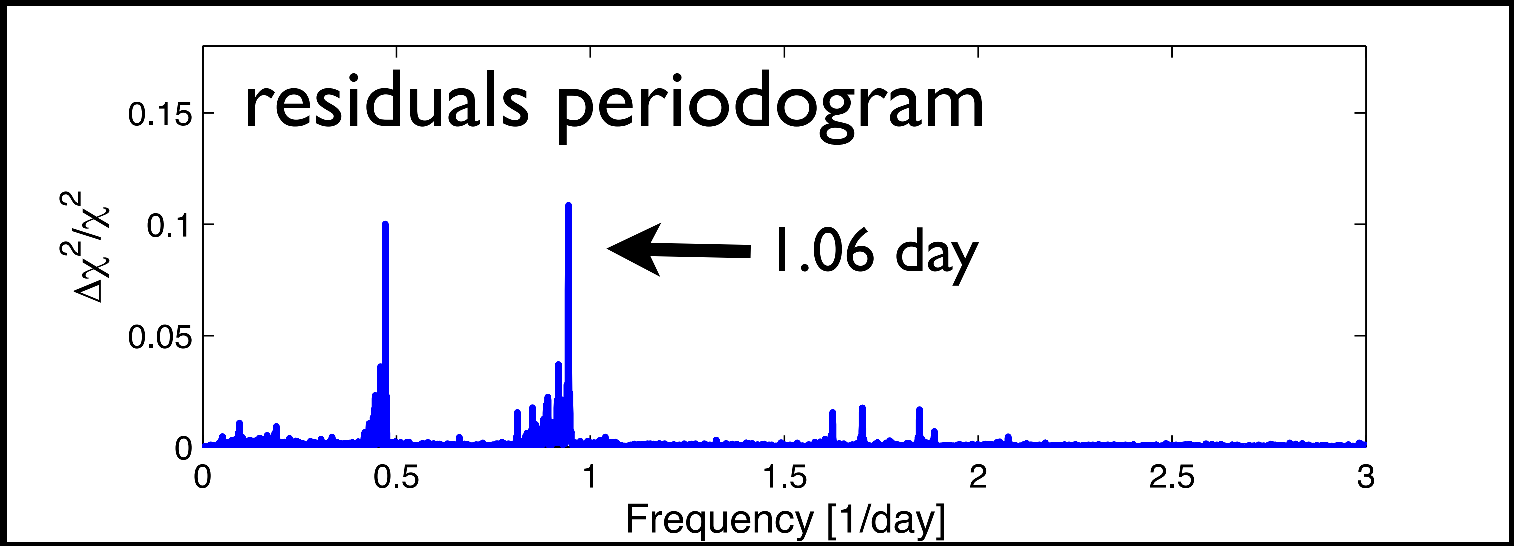
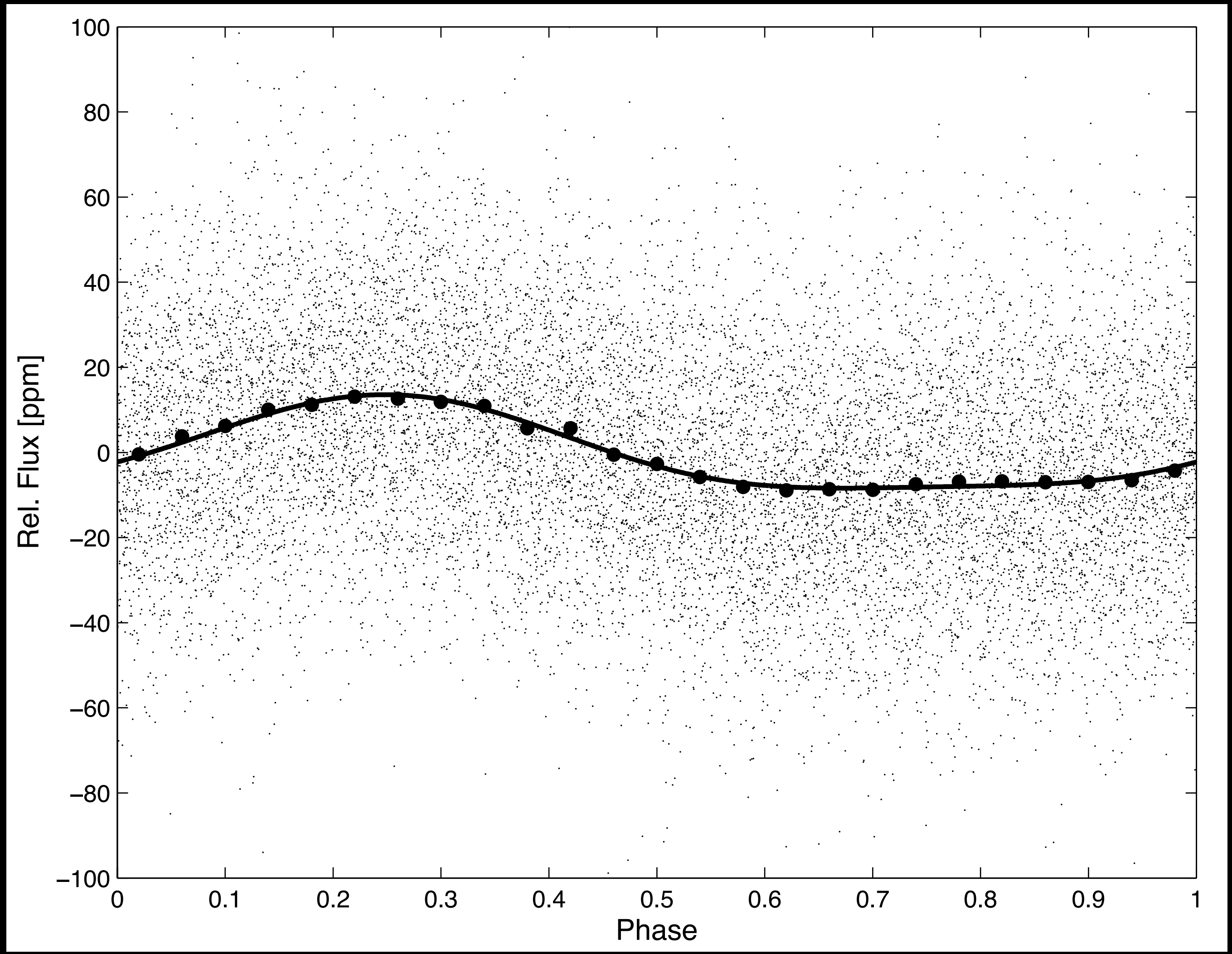
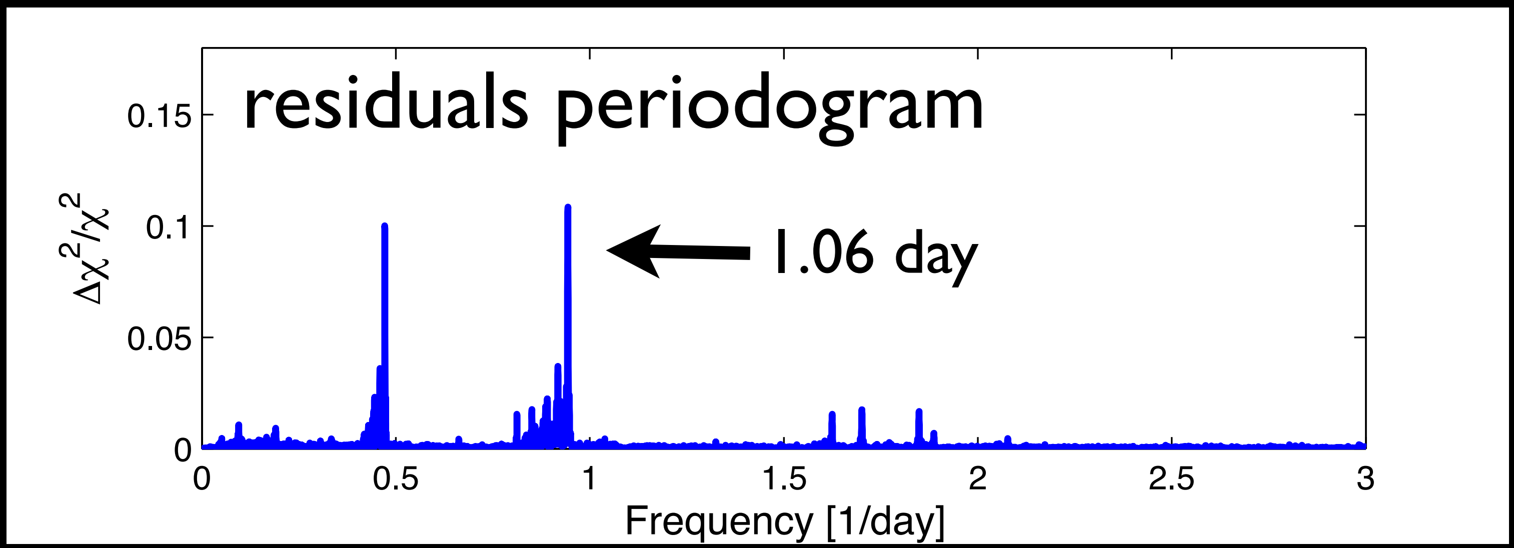


KOI-13 secondary periodicity

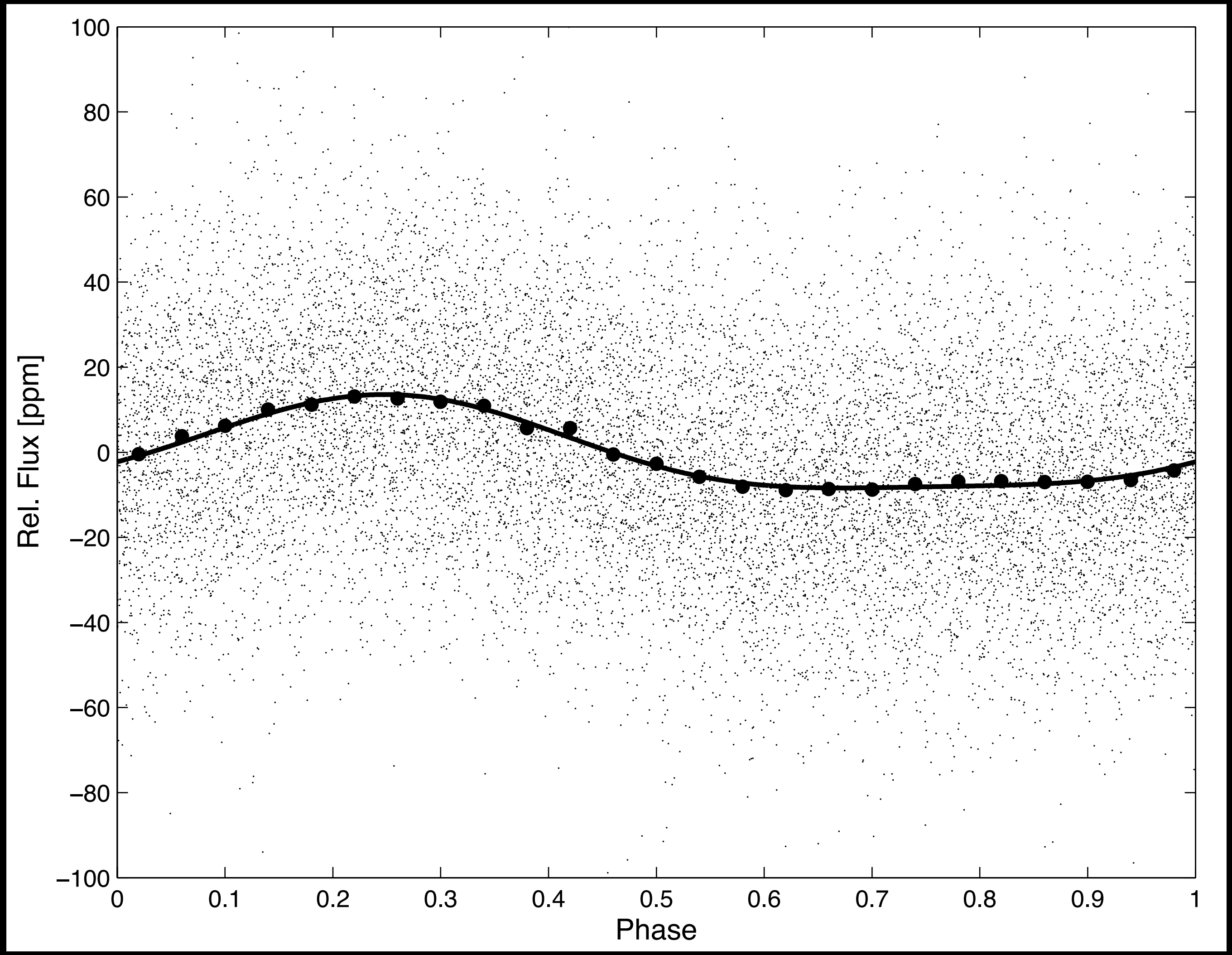




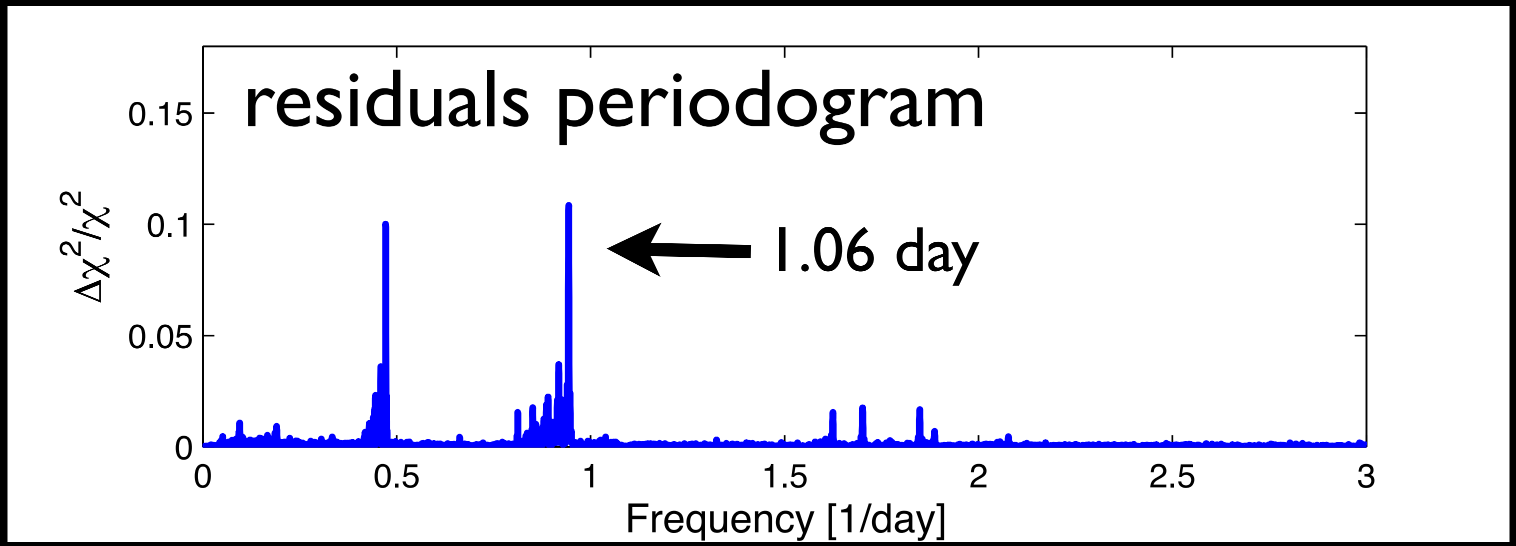
KOI-13 secondary periodicity



Unlikely to be a 2nd planet...



KOI-13 secondary periodicity



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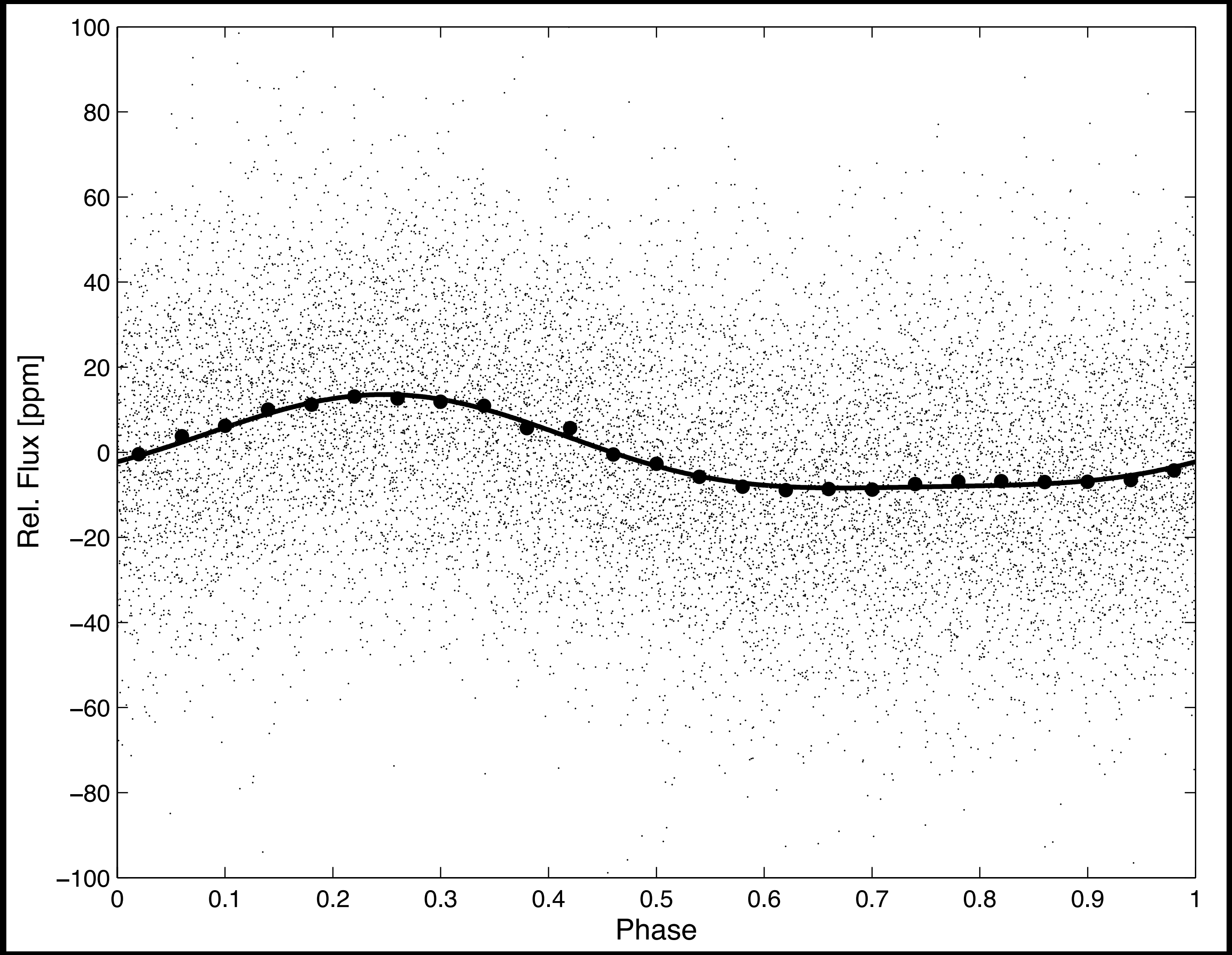
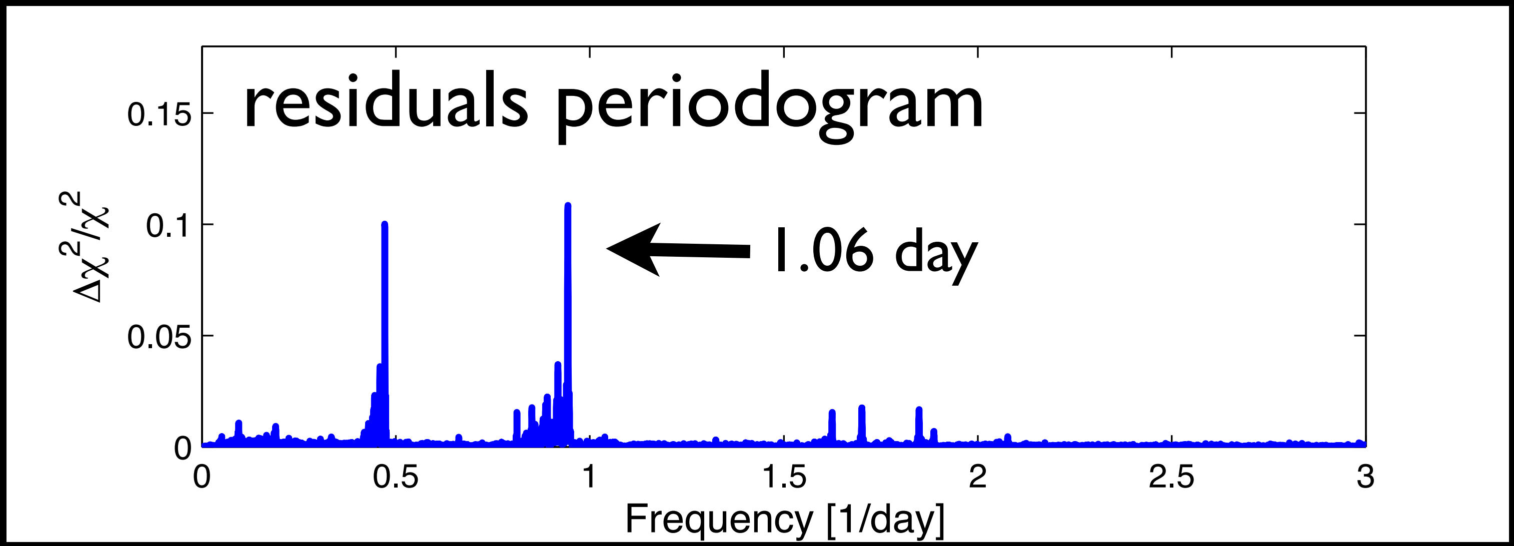
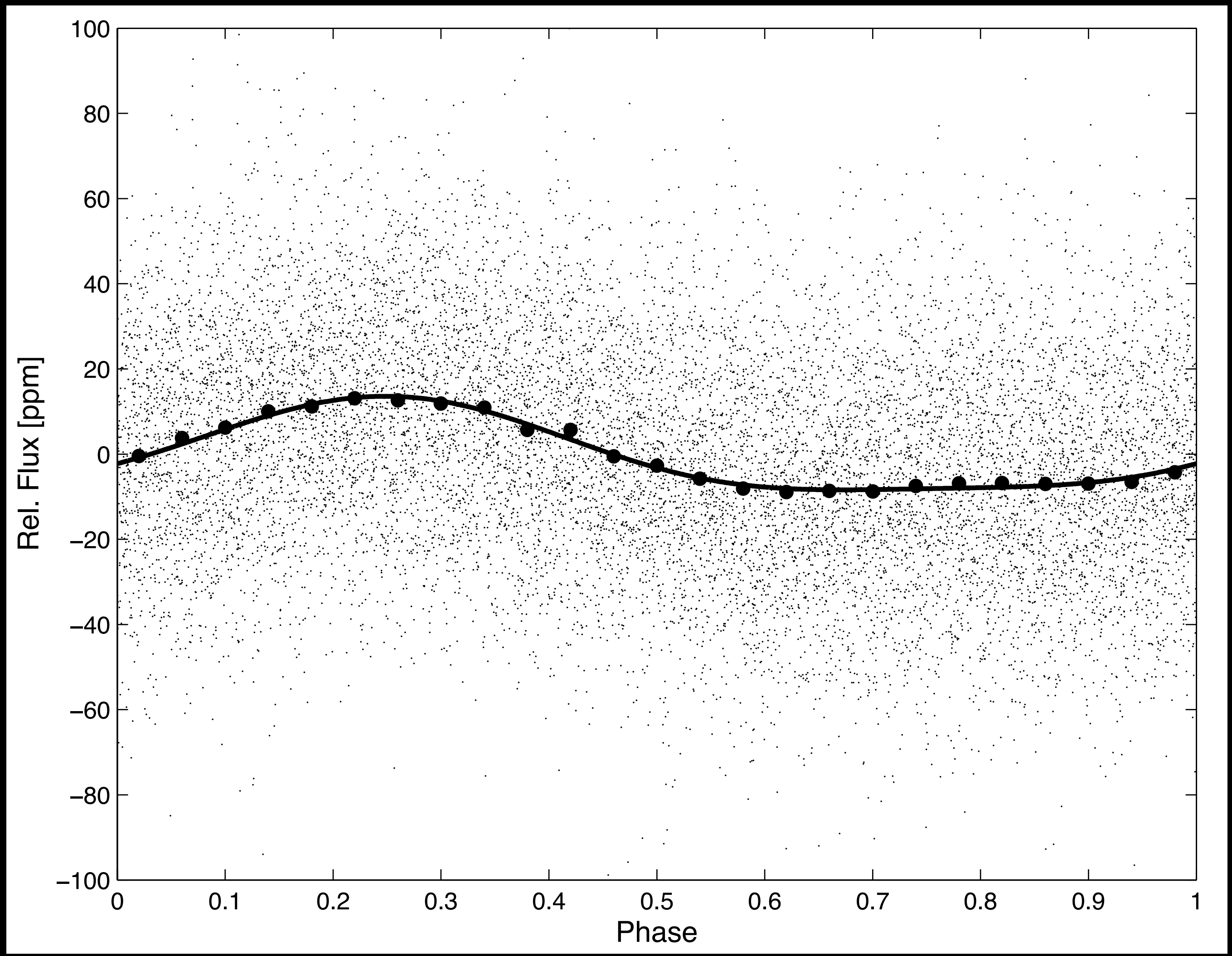


$$P_{2nd} : P_{orb} = 1.06 : 1.76 = 3{:}5$$

KOI-13 secondary periodicity



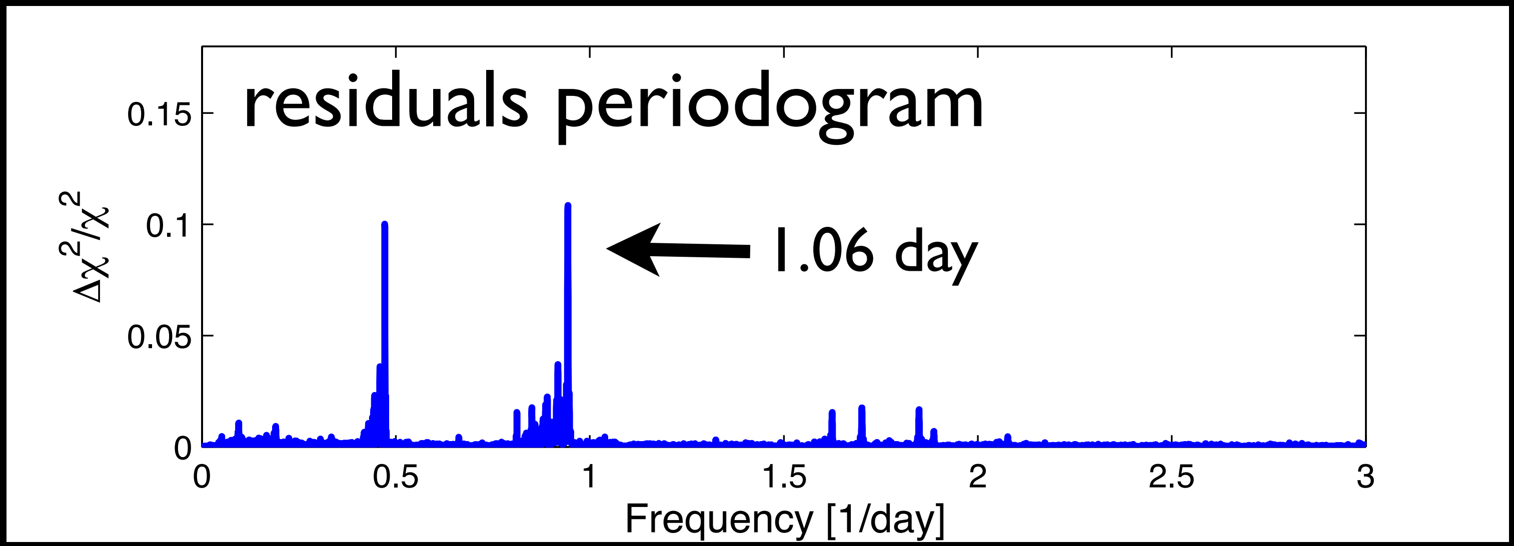


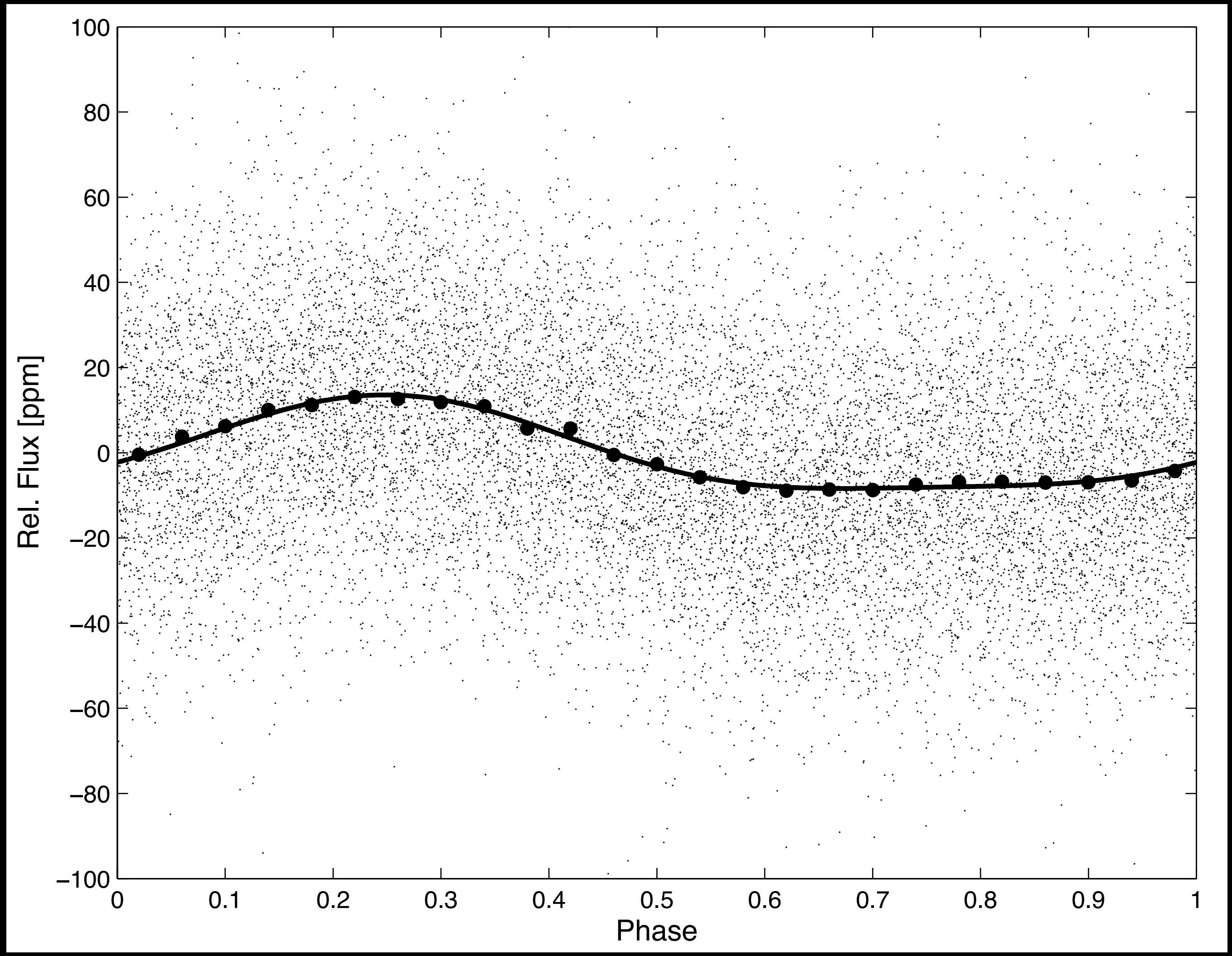
Unlikely to be a 2nd planet...

$P_{2nd} : P_{orb}$ = 1.06 : 1.76 = 3:5

Planet induced pulsation?

KOI-13 secondary periodicity





Unlikely to be a 2nd planet...

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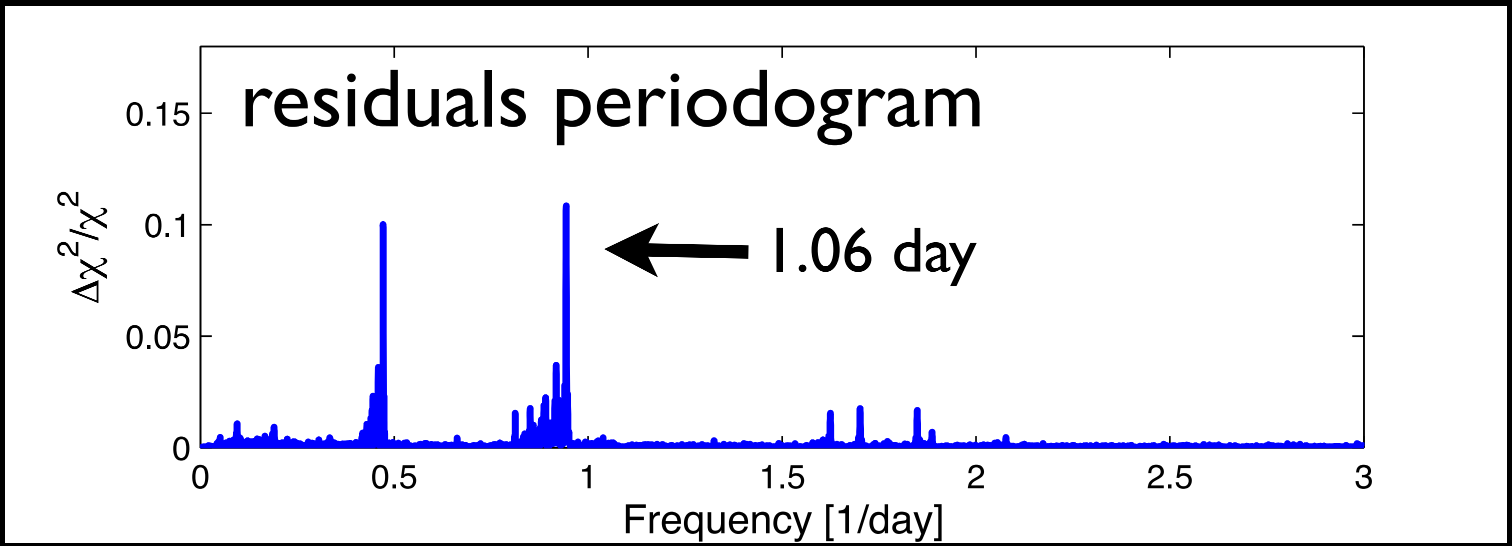
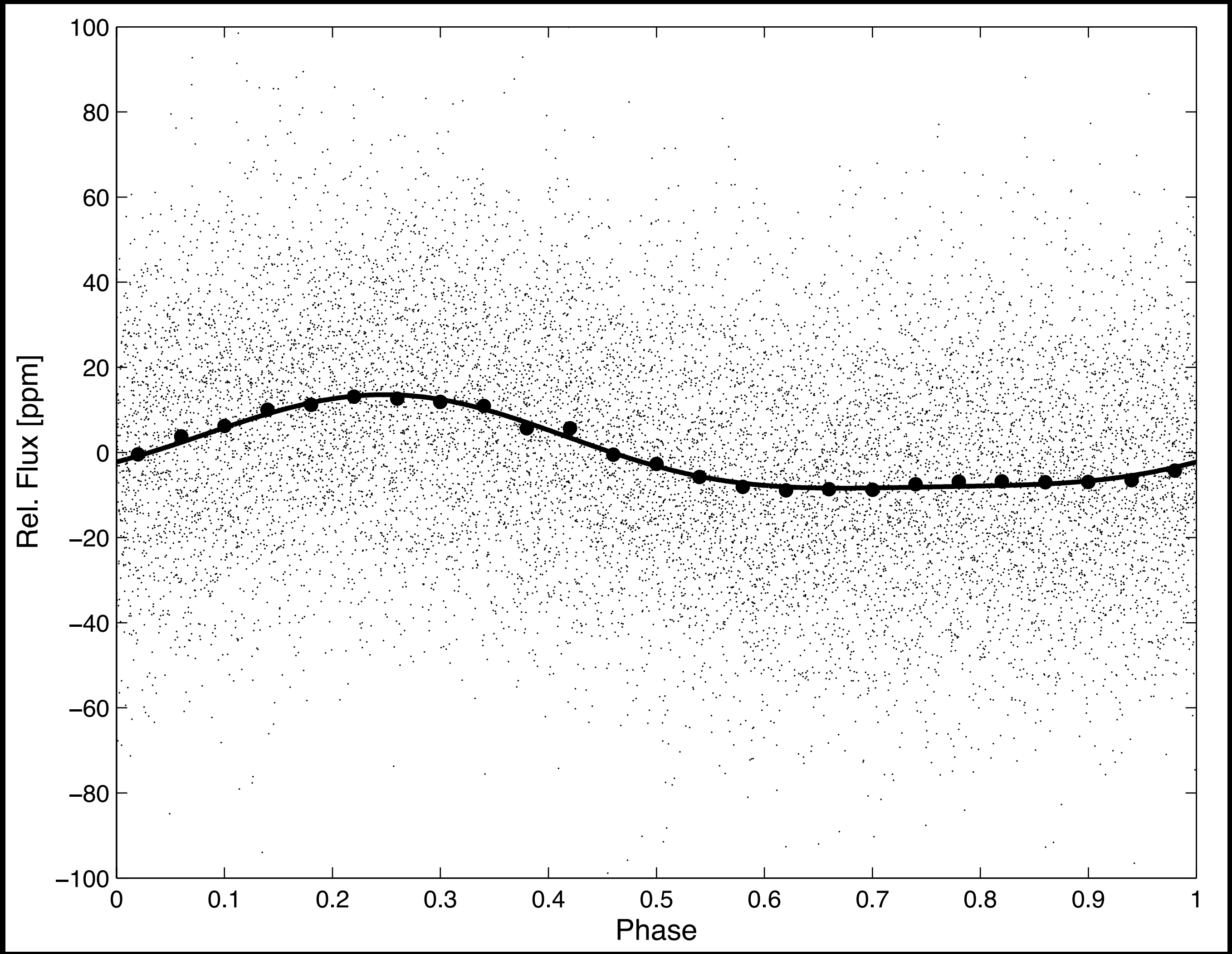
Planet induced pulsation?

Like WASP-33 pulsations ?

KOI-13 secondary periodicity





Unlikely to be a 2nd planet...

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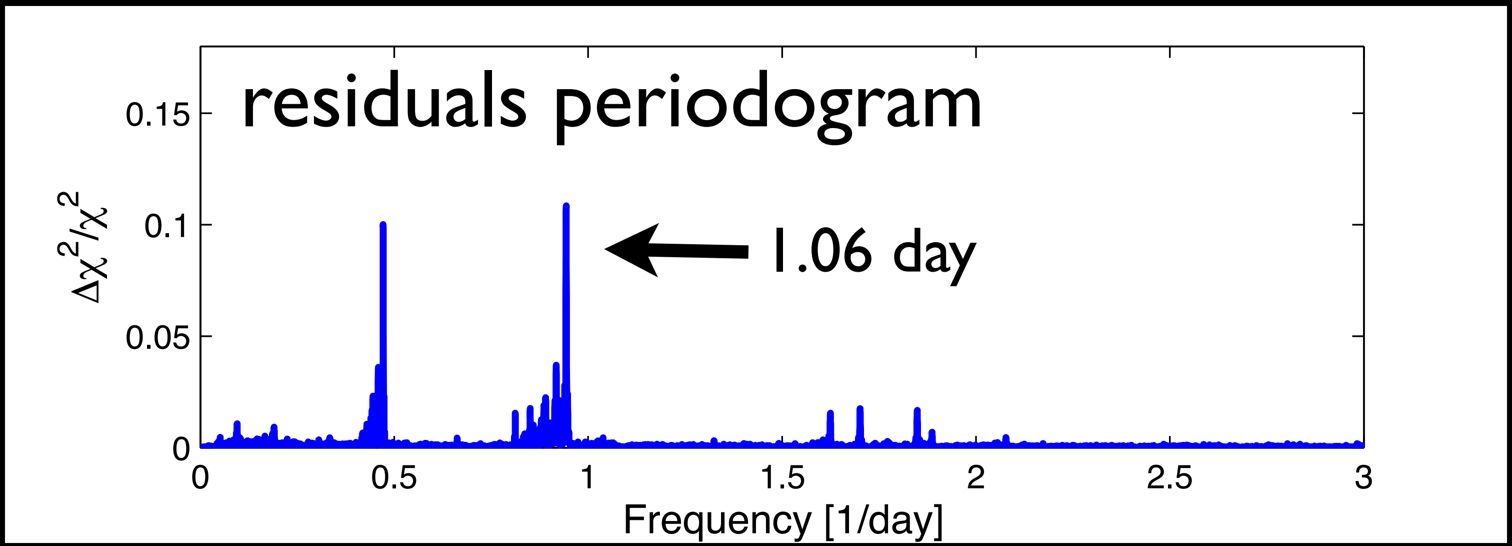
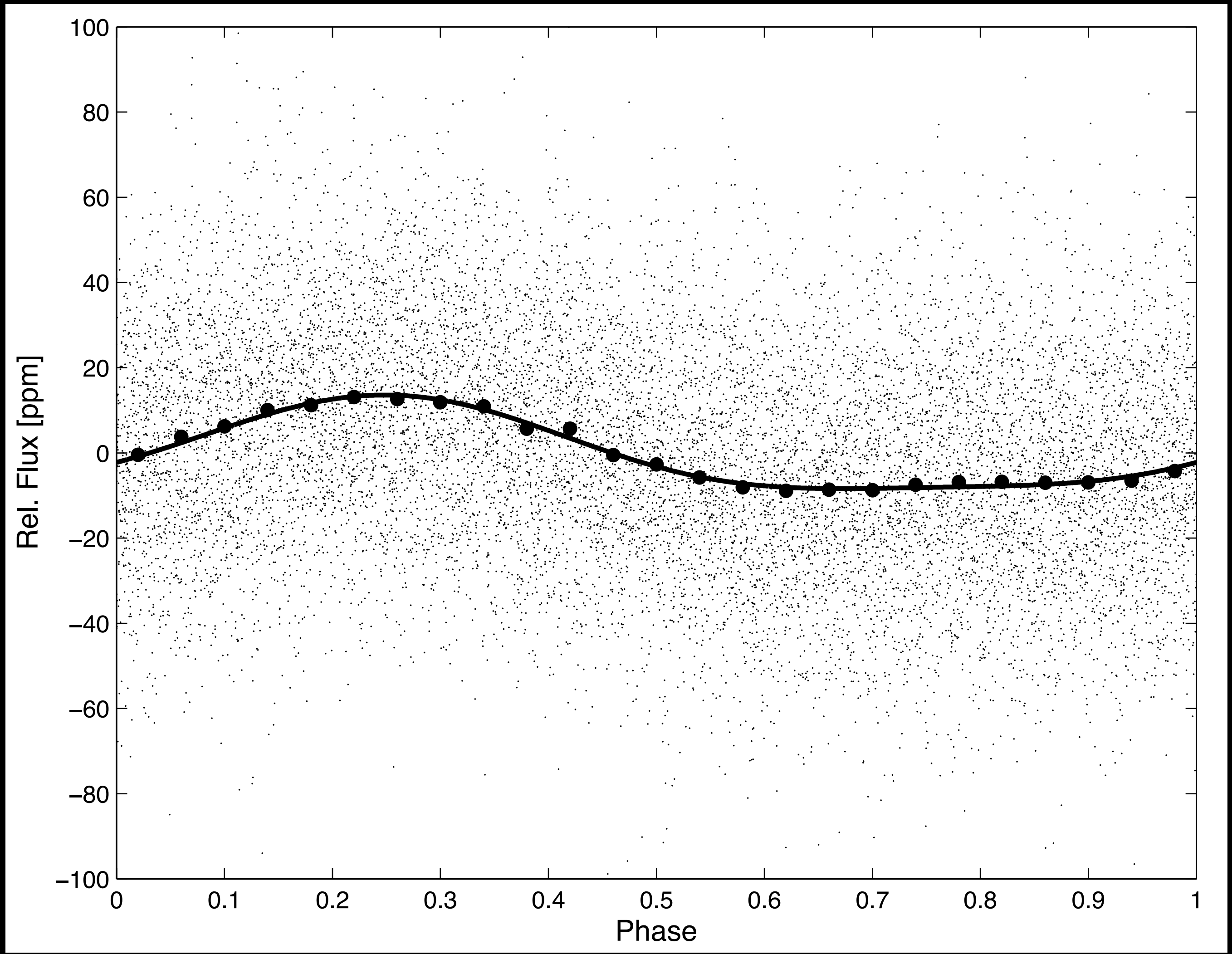
Planet induced pulsation?

Like WASP-33 pulsations ?

- A-type host

KOI-13 secondary periodicity





Unlikely to be a 2nd planet...

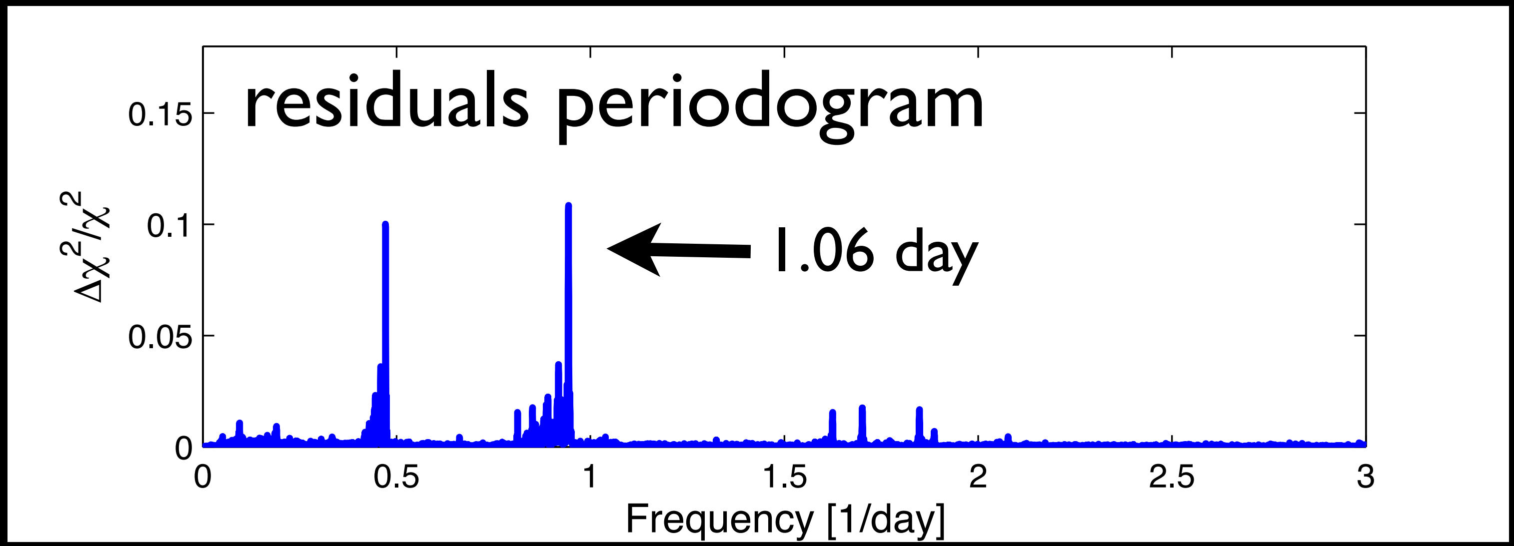
$P_{2nd} : P_{orb}$ = 1.06 : 1.76 = 3:5

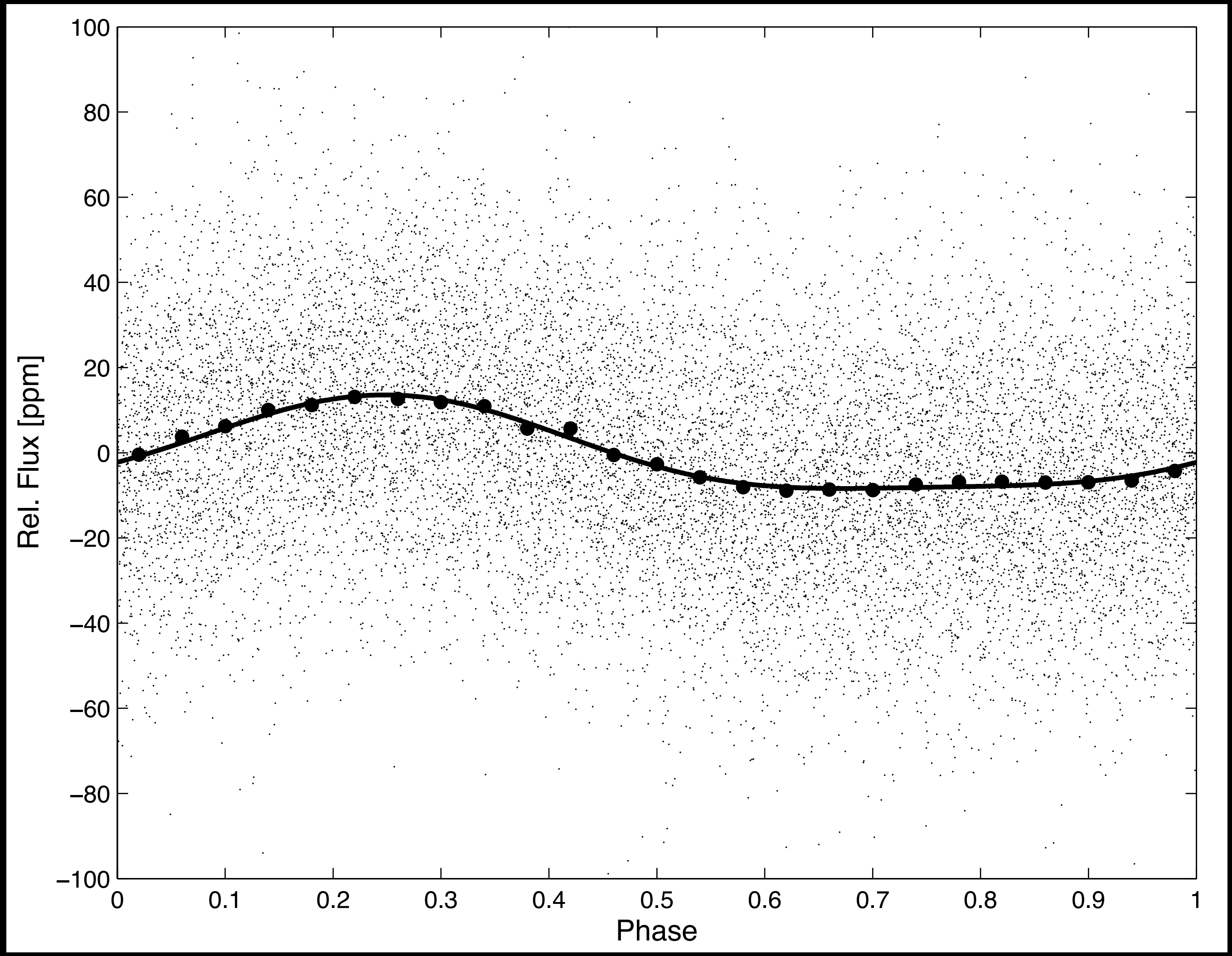
Planet induced pulsation?

Like WASP-33 pulsations ?

- A-type host
- P_{orb} =1.2 d

KOI-13 secondary periodicity





Unlikely to be a 2nd planet...

$P_{2nd} : P_{orb}$ = 1.06 : 1.76 = 3:5

Planet induced pulsation?

Like WASP-33 pulsations ?

- A-type host
- P_{orb} =1.2 d
- Spin-orbit misaligned

Szabo et al. 2011:
Spin-orbit resonance

...and we can do ***MUCH*** more with photometry with the Kepler ***Extended Mission***