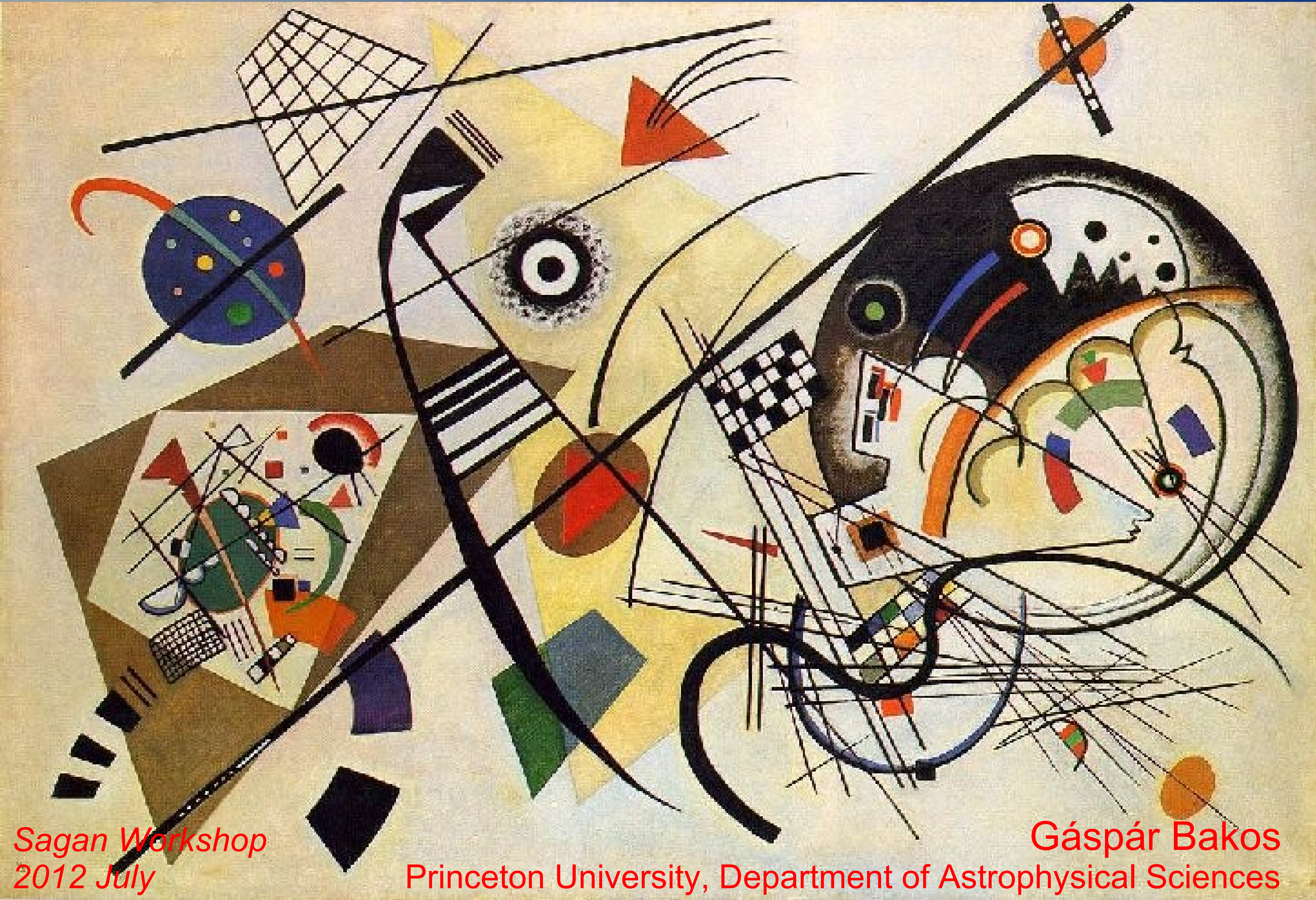
Confirmation and validation of transit signals



Sagan Workshop
2012 July

Gáspár Bakos
Princeton University, Department of Astrophysical Sciences

KH 15D

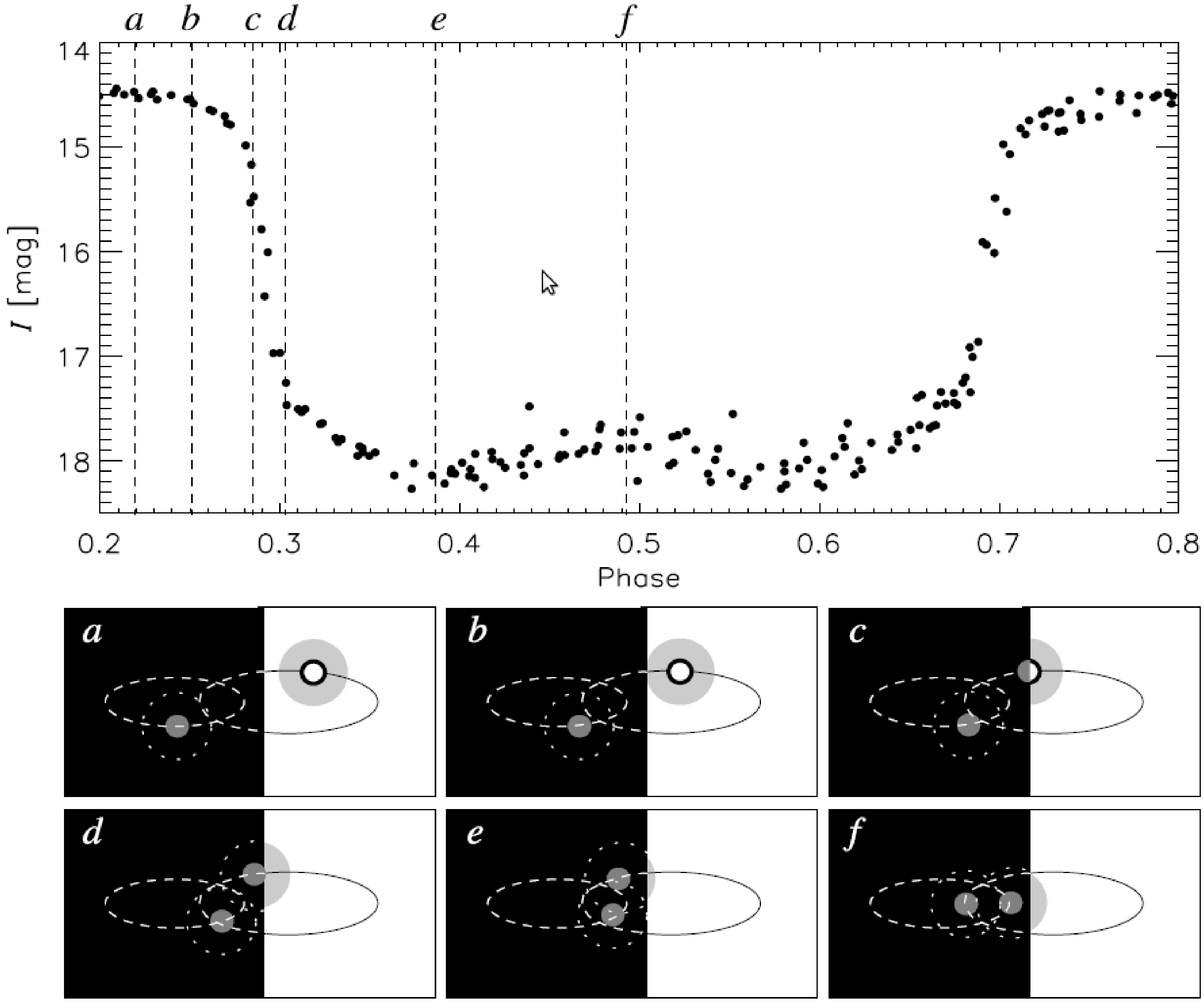


FIG. 9.—Illustration of the model for the occultation light curve. *Top:* Phased light curve from the 2001–2002 season, with six particular phases marked with vertical dashed lines. *Bottom:* Corresponding configurations of the stars, halos, and the occulting edge. These are cartoons only, and do not represent optimized model parameters. In particular, the best-fitting model halos are *asymmetric* unlike the circular halos drawn here.

Winn 2006

What do we call a(n) (exo)planet?

- Definition from the IAU: Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are "planets" (no matter how they formed).

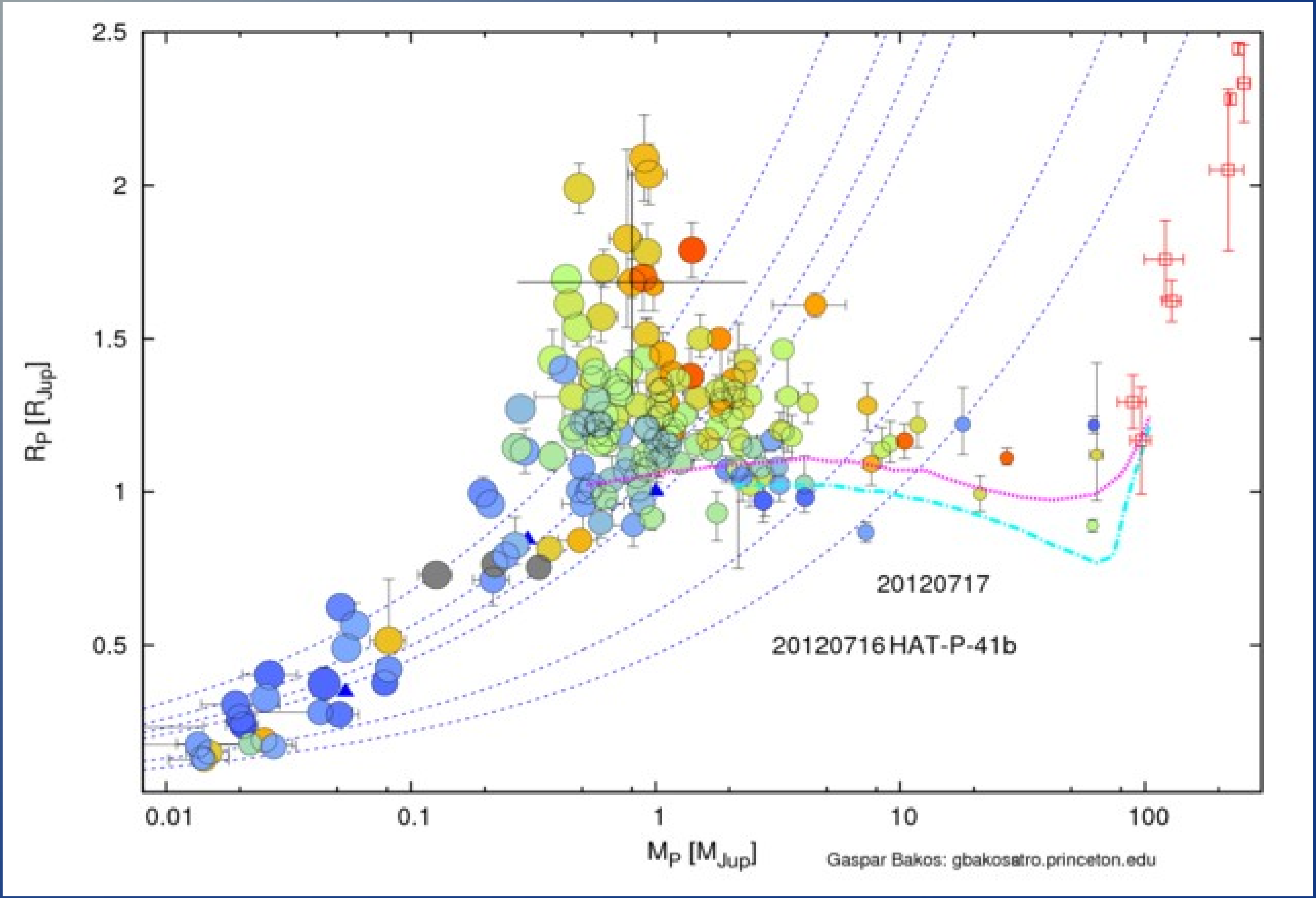
- The 13 Jupiter-mass cutoff does not have precise physical significance.

- The Extrasolar Planets Encyclopaedia includes objects up to 25 Jupiter masses.

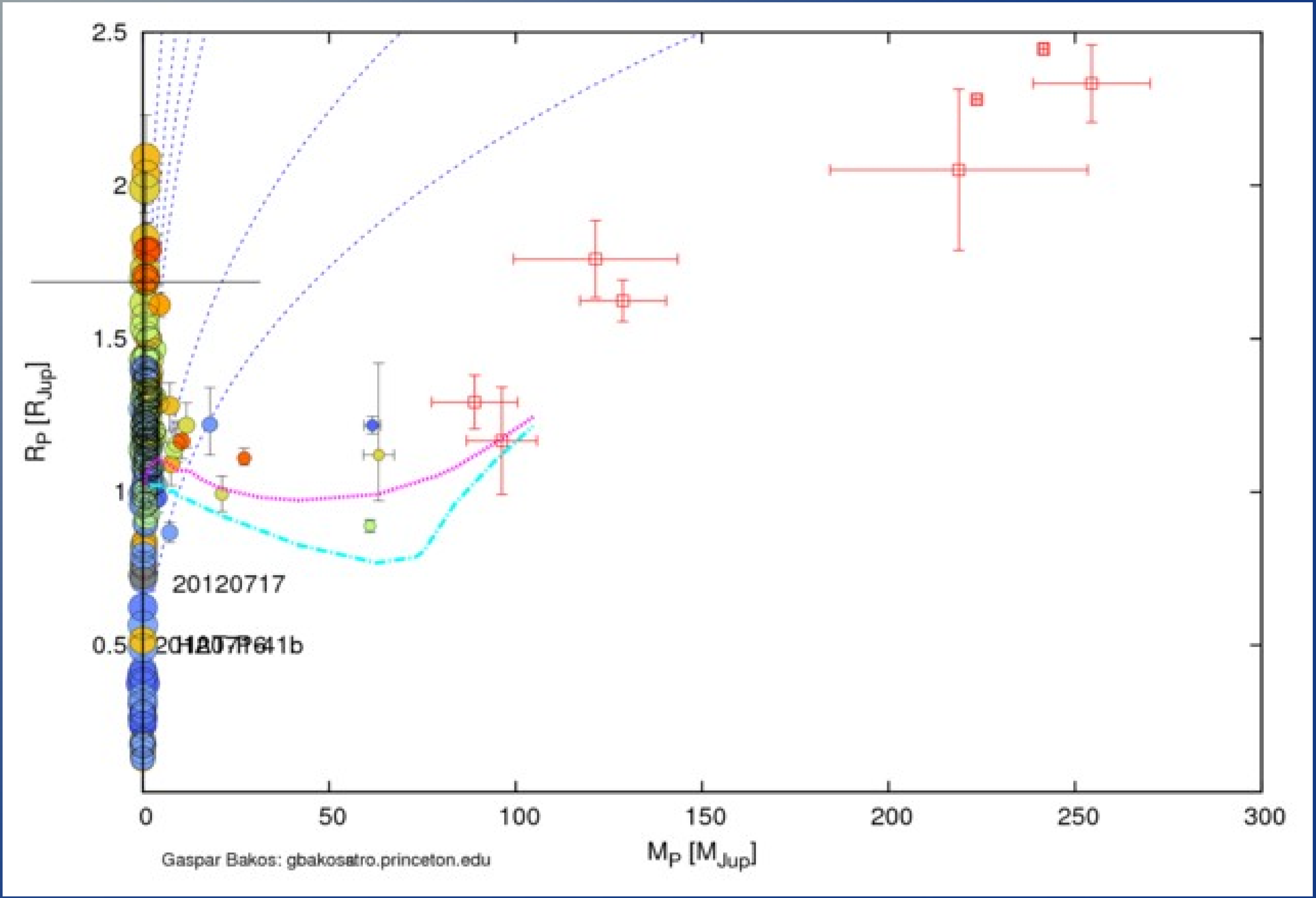
- Why is the mass so special in this game? Why is it not trivial to confirm the planetary nature of an object?

1. → MASS degeneracy
2. → Other scenarios mimicking planetary transits

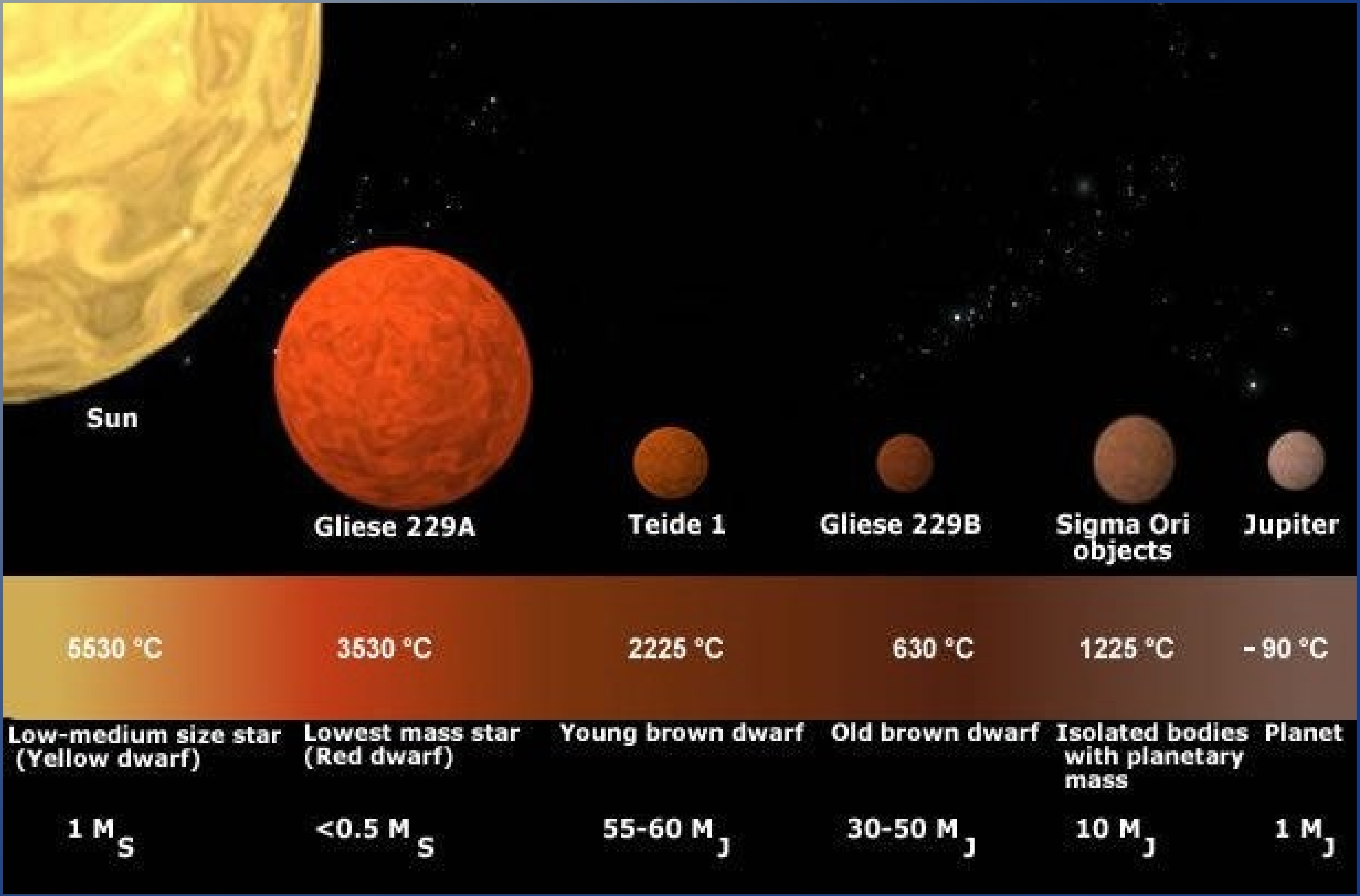
The M_P – R_P degeneracy



The M_P – R_P degeneracy

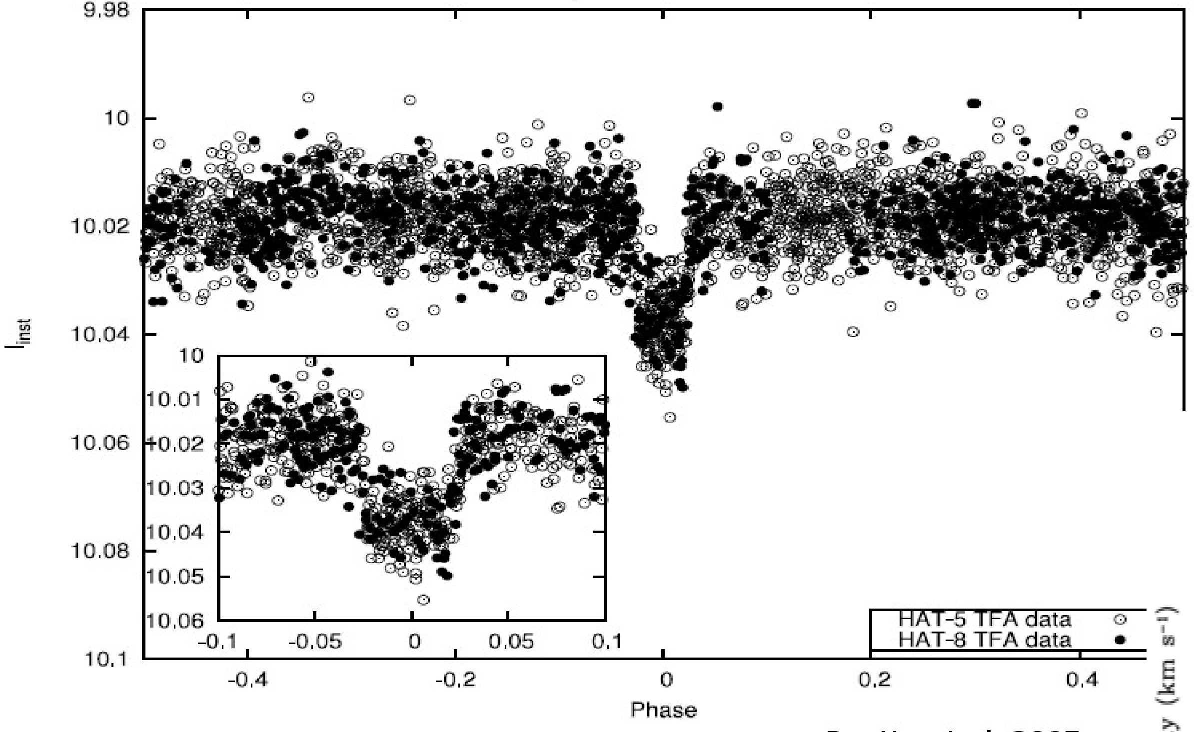


Sub-stellar mass objects

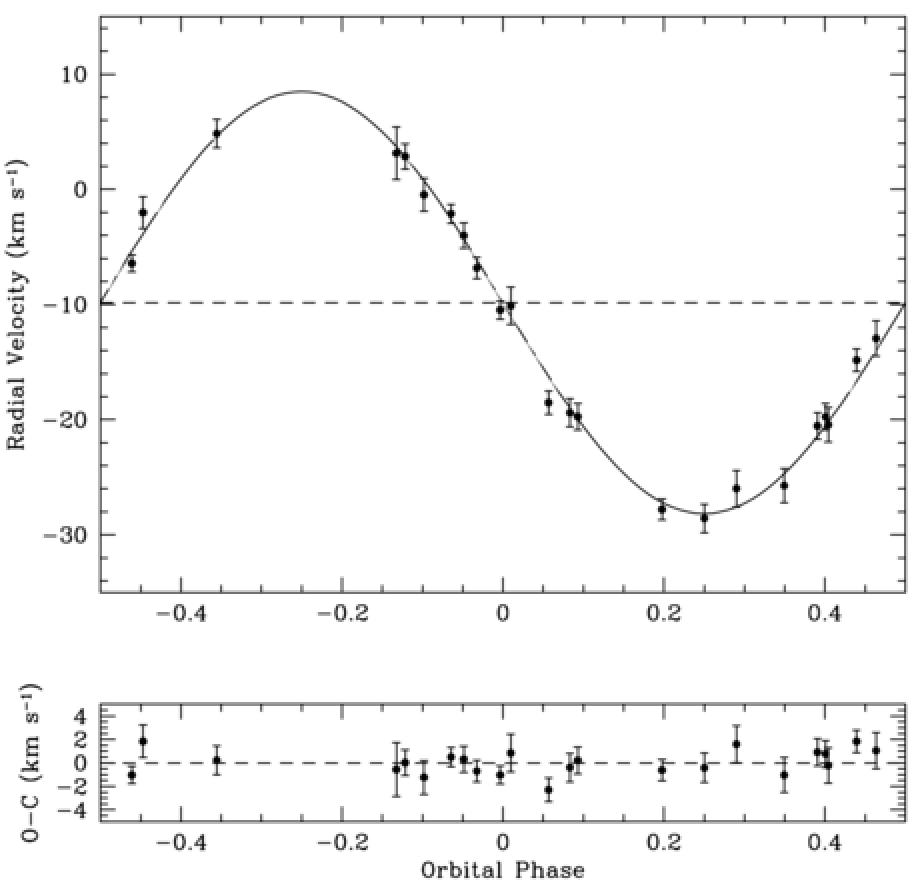


Sun	Gliese 229A	Teide 1	Gliese 229B	Sigma Ori objects	Jupiter
5530 °C	3530 °C	2225 °C	630 °C	1225 °C	- 90 °C
Low-medium size star (Yellow dwarf)	Lowest mass star (Red dwarf)	Young brown dwarf	Old brown dwarf	Isolated bodies with planetary mass	Planet
$1\ M_S$	$<0.5\ M_S$	$55\text{-}60\ M_J$	$30\text{-}50\ M_J$	$10\ M_J$	$1\ M_J$

HAT-TR-205-013



Beatty et al. 2007



List of impostors (scenarios that may mimick planetary transits)

Tim Brown's scheme (2003):

- Is the primary of the eclipsing system a main-sequence star (M) or a giant (G)?
- Is the secondary a main-sequence star (S) or a Jovian planet (P)?
- Is the light from the binary undiluted by a third star (U) or diluted (D)?
- If diluted, is the third star a foreground object (F), or is the system a bound triple (T)?

→ This scheme yields a number of possibilities. Tough ones are MSD(F|T), MPD(F|T).

Another classification (in order of increasing complexity in differentiating from a pure planetary transit:

- Giant + Star [long duration, low stellar mean density, etc]

- Grazing Eclipsing Binary (GEB) [light curve shape, RV variations]

- GEB + S (diluted) [light curve shape, RV variations, centroids]

- Star + M dwarf or Brown dwarf (S+S or S+B) [high RV variations, LC effects]

- S+S or S+B and other S (diluted) [bisector variations, LC effects, centroids]

- S+Planet + S [spectrum composite, color anomalous, RV trend]

Validation, confirmation, physical parameters

GOALS:

1. Understand which scenario we are dealing with, and prove that this is indeed the case, if needed, in a quantitative way.

2. Accurately measure the physical properties of the system, along with reliable error-bars.

VALIDATION:

In case of a suspected planetary transit, prove that it is indeed the most likely hypothesis. Provide the probability of this hypothesis. Eliminate other blend scenarios. For example, prove that the transit is not due to a blend (or, if it is a blend, measure the level of blending). Validation uses archival data, discovery data, and may use various follow-up data. Validation measures certain physical properties of the system.

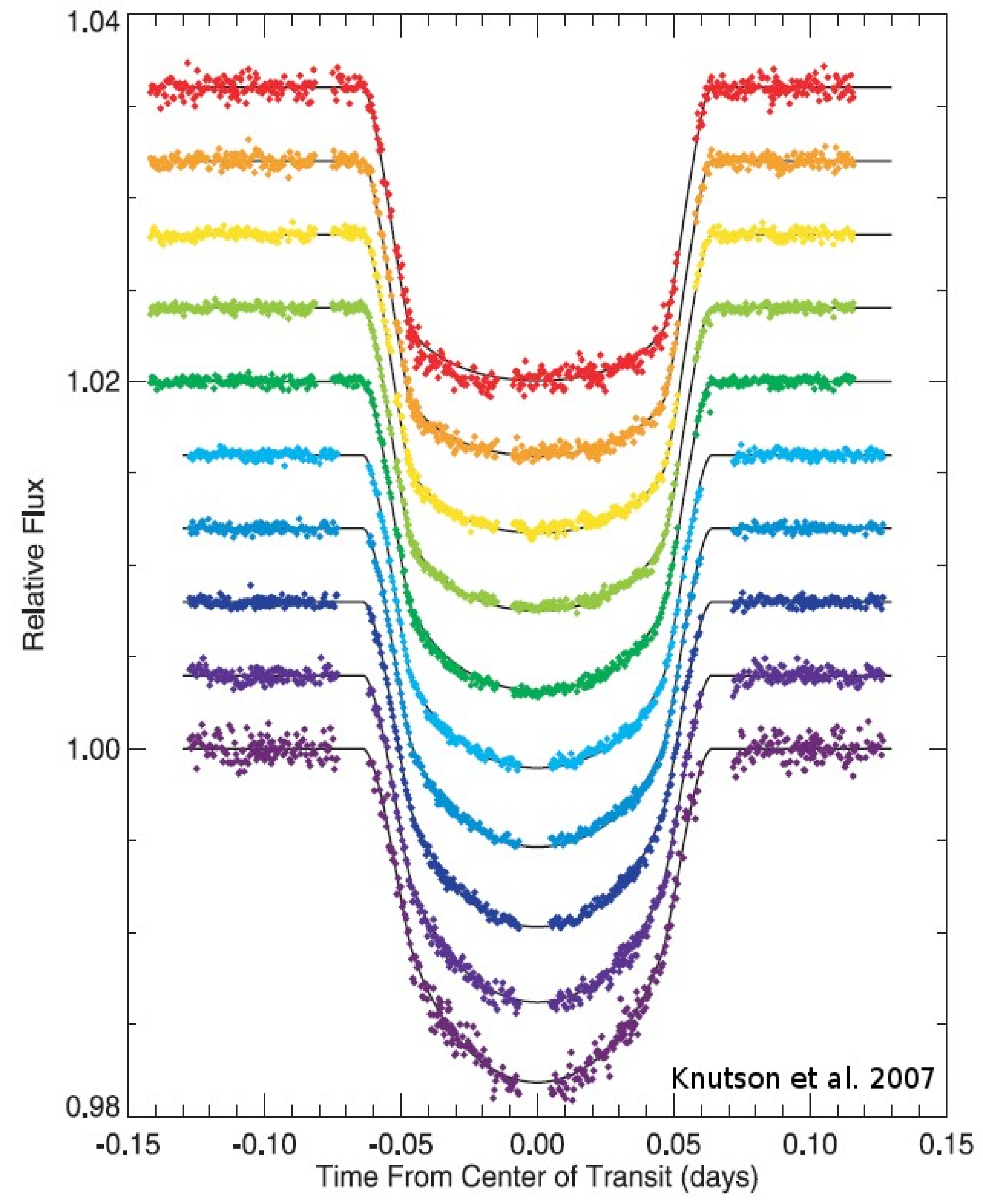
CONFIRMATION: this is VALIDATION plus:

Measure the physical properties, notably the mass. Due to the mass--radius degeneracy, this is the ultimate confirmation of the planetary nature of an object. Typically (but not necessarily, see beaming, ellipsoidal variations, etc) done by spectroscopy, i.e. high precision radial velocities (RVs).

Understanding the planetary transit signal

Planetary transits have a characteristic shape. Simplest case: full transit of a circular shaped planet on a circular orbit around a circular star with small limb darkening (e.g IR).

The often heard statement "planetary transits are achromatic" is an approximation.



Nuances

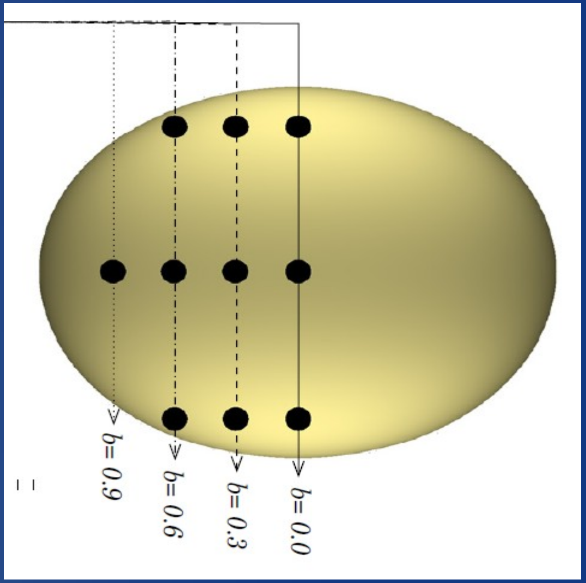
These are important for proper interpretation of the system, and in certain cases for correct measurement of the system parameters.

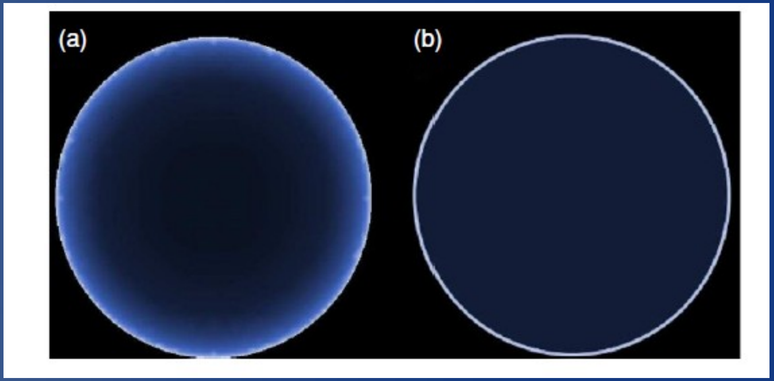
Planet:

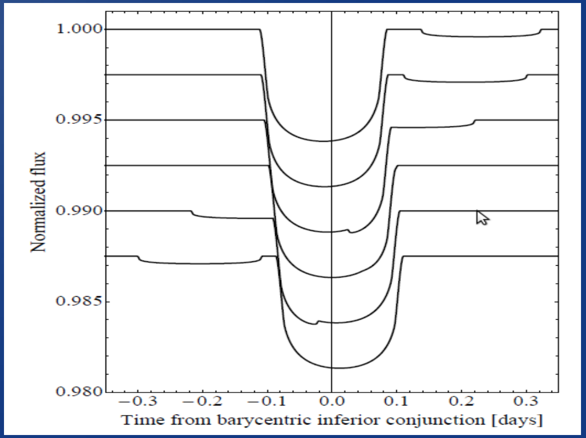
Ringed (Barnes 2004), oblate (Carter 2010), with/out moon (Kipping 2010), multiple planets: multiple transits, TTVs, single transit events (see e.g. Yee & Gaudi, 2008), microlensing the star (Sahu 2003).

Star:

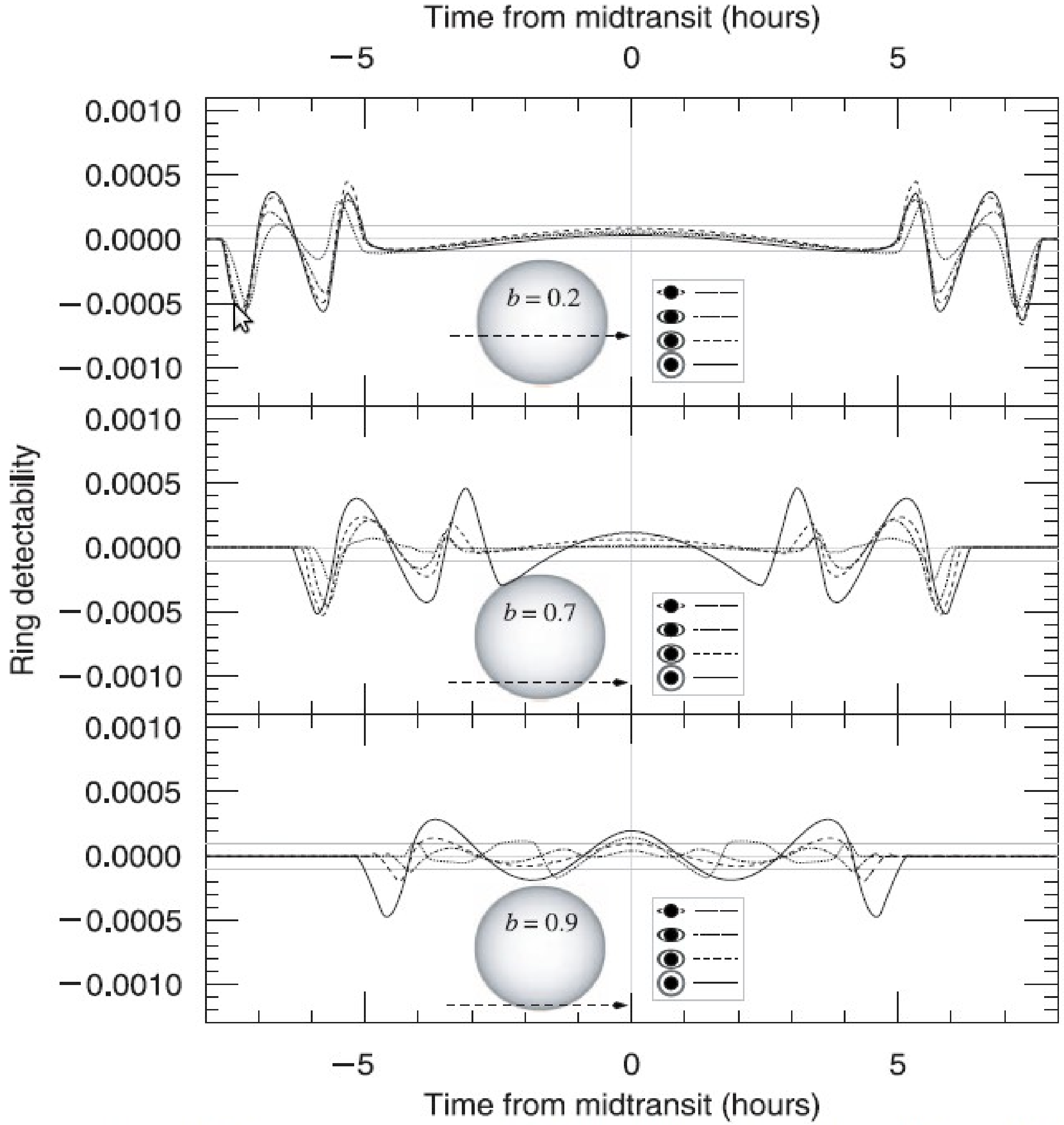
Oblate, spotted, variable, limb-darkened or brightened (Schlawin 2010), gravity darkened (Barnes 2009), multiple stellar systems (e.g. Kepler-16).







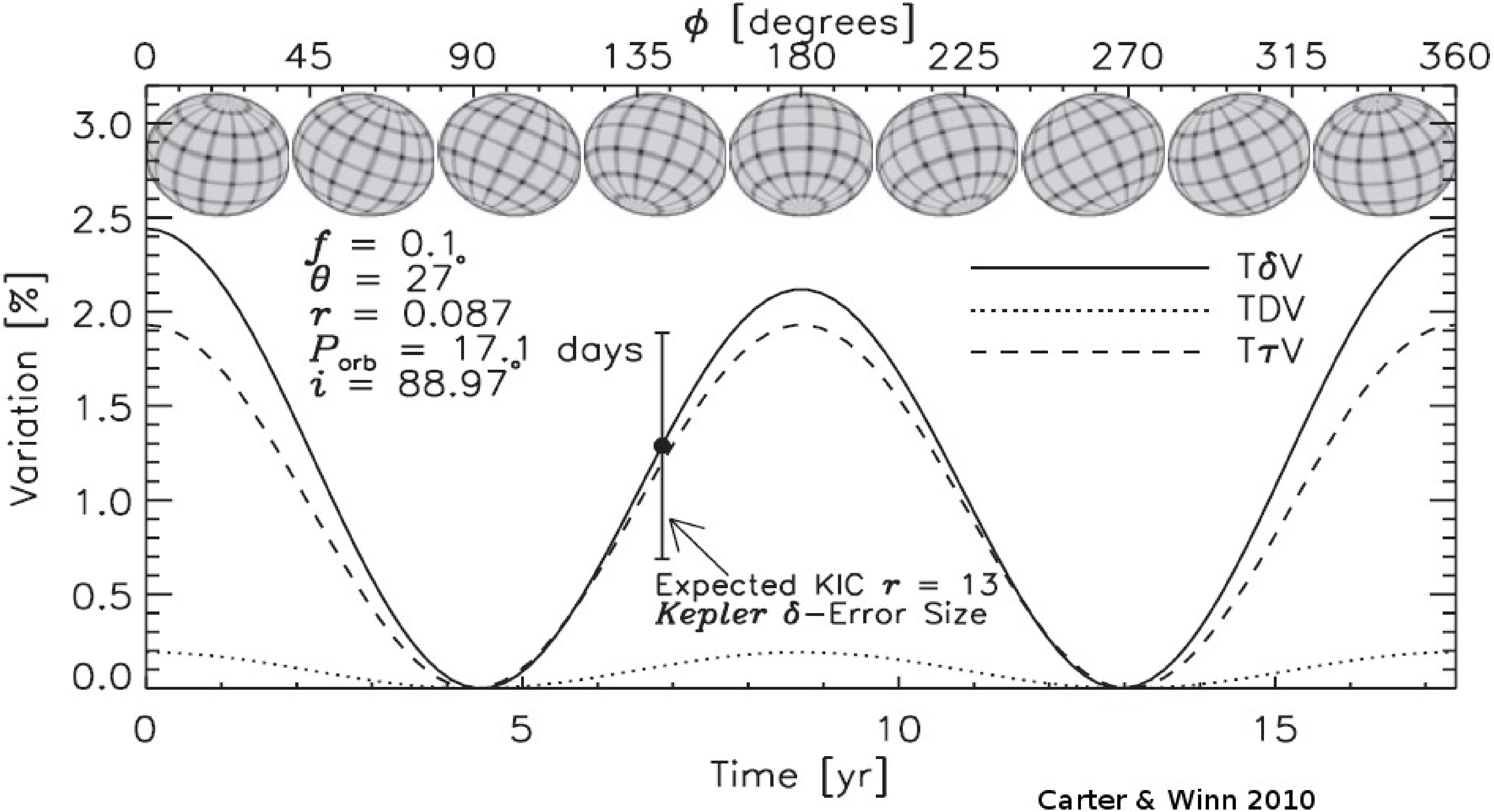
Rings



Barnes & Fortney 2004

Fig. 1.—Detectability of extinction through symmetric planetary rings in transit, defined as the difference between the transit light curve of the given ringed planet and its best-fit spherical planet model. These graphs show the detectabilities for rings tilted directly toward the observer; those in Fig. 2 show the detectability for asymmetric geometries. Each graph shows the detectability for planets of four different obliquities, 10° (*dotted line*), 30° (*dash-dotted line*), 45° (*dashed line*), and 90° (*solid line*; face-on) for simulated transits with impact parameter 0.2 (*top*), 0.7 (*middle*), and 0.9 (*bottom*). The signal is greater than the typical noise limit for both *Kepler* and the *HST* HD 209458b observations, 1×10^{-4} (*gray lines*), but is very localized in time to the regions surrounding ingress and egress. Both high photometric precision and high temporal resolution would be necessary to detect the ring signal.

Oblate and precessing planet



Carter & Winn 2010

Figure 4. Variations in the transit light curve due to an oblate, oblique, precessing exoplanet. Plotted are the transit depth (δ), total duration ($T_{\rm full}$), and ingress duration (τ) fractional variations (TδV's, TDVs, and TτV's, respectively) that are expected for a uniformly precessing Saturn-like planet around a Sun-like star. The timescale is based on the assumption $P_{\rm orb} = 17.1$ days.

Moons

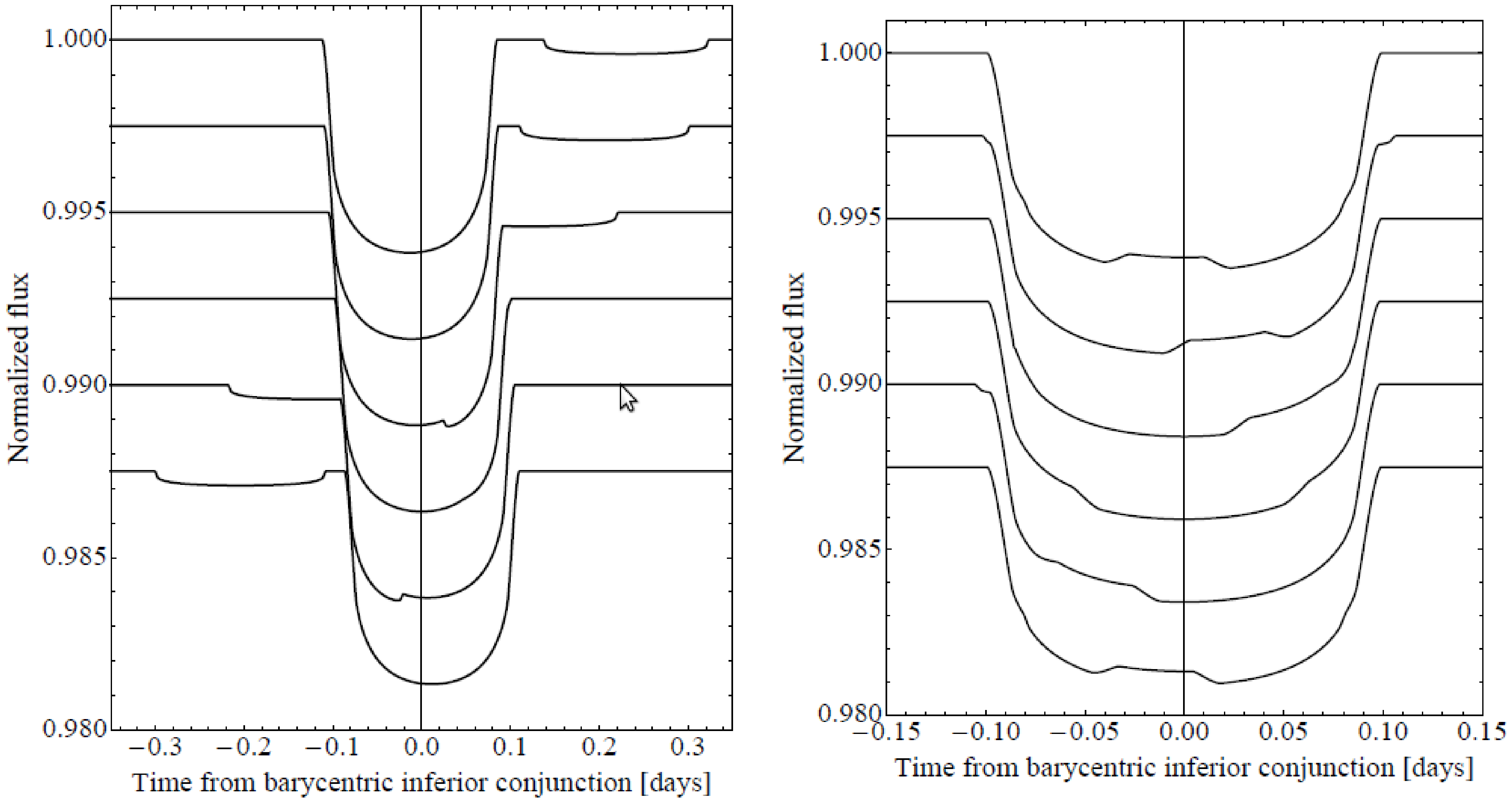


FIG. 2.— *Left panel: transit light curves of a planet with a moon on a wide separation, demonstrating auxiliary transits. Right panel: transit light curves of a planet with a close-in moon, demonstrating mutual events. See Kipping (2011a) for details of the parameters used in these simulations (Figures 7&6 respectively).*

Transit Timing Variations (TTVs)

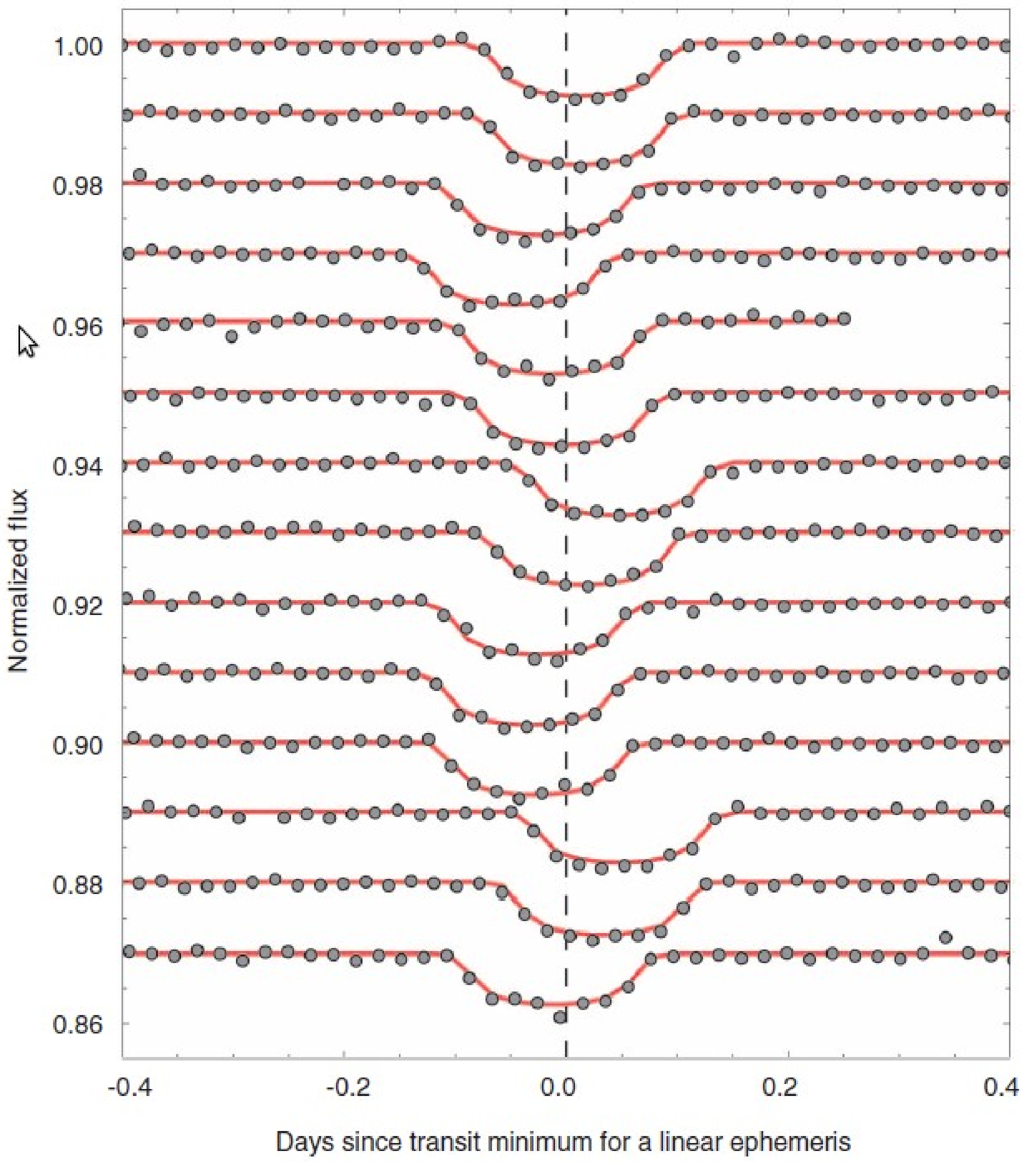


Fig. 1. Maximum-likelihood transit model (red line) overlaid with the long-cadence Kepler offsetted data for KOI-872b. The large TTVs are evident visually from the light curve. The ramp-affected transit is excluded here (see fig. S2).

Nesvorny et al 2012

Limb darkening plus gravity darkening

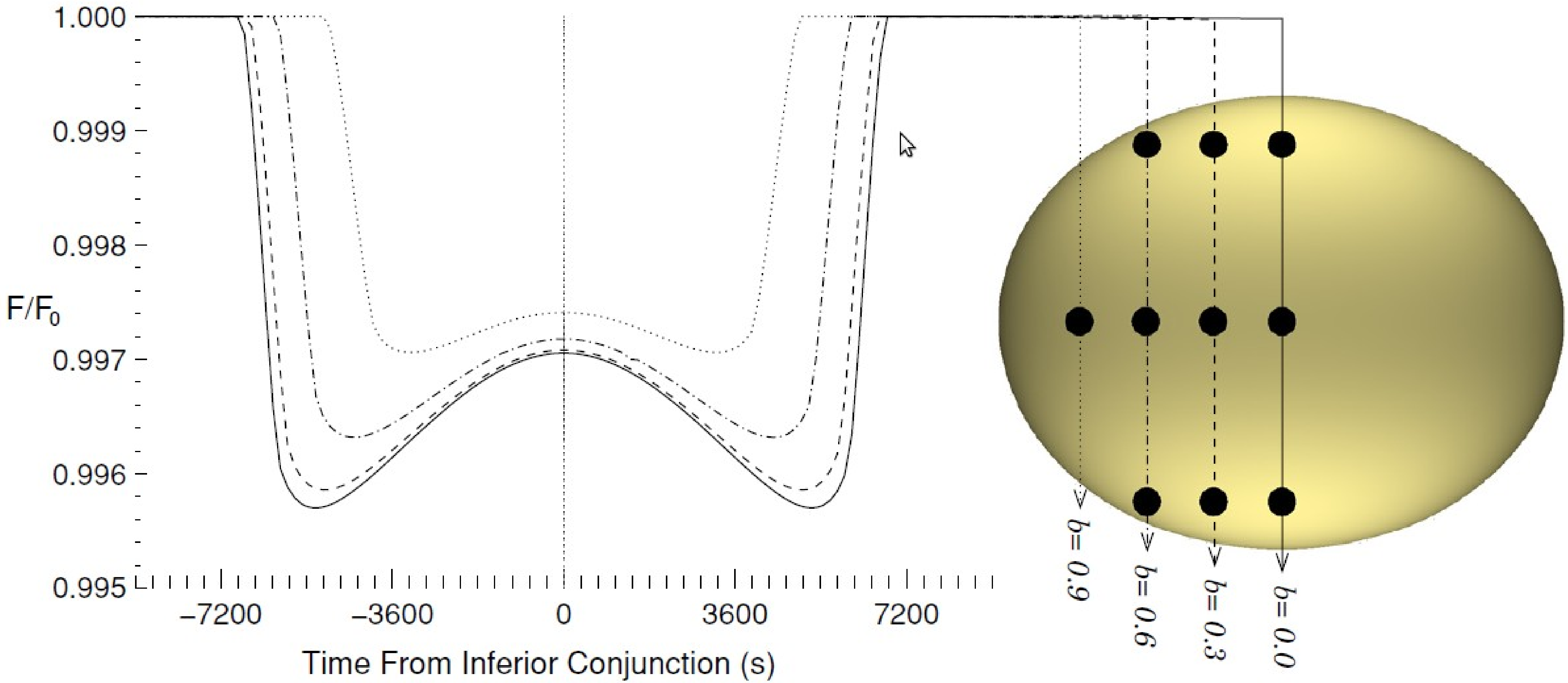


Figure 5. Synthetic lightcurves for transiting 1 R_{Jup} in a 0.05 AU orbit around an Altair-like star with obliquity 0° (equator-on) are plotted, similar to Figure 2, but this time with an azimuthal angle of $\alpha = 90°$. The four curves correspond to planets with transit impact parameters of $b = 0.0\ R_{\mathrm{pole}}$ (solid), $b = 0.3\ R_{\mathrm{pole}}$ (dashed), $b = 0.6\ R_{\mathrm{pole}}$ (dot-dashed), and $b = 0.9\ R_{\mathrm{pole}}$ (dotted). This unlikely 90° transit geometry also produces symmetric transit lightcurves, albeit highly unusual ones. These curves are deepest near second and third contacts, and shallow at mid-transit. If assuming a spherical-star model, then the interpretation of this "double-horned" structure might be a negative limb-darkening coefficient possibly associated with a temperature inversion in the stellar atmosphere; however, such a model fits these data very poorly (see the text).

Barnes 2009

(von Zeipel effect (1924) for rotating stars. See KOI-13)

Limb brightening

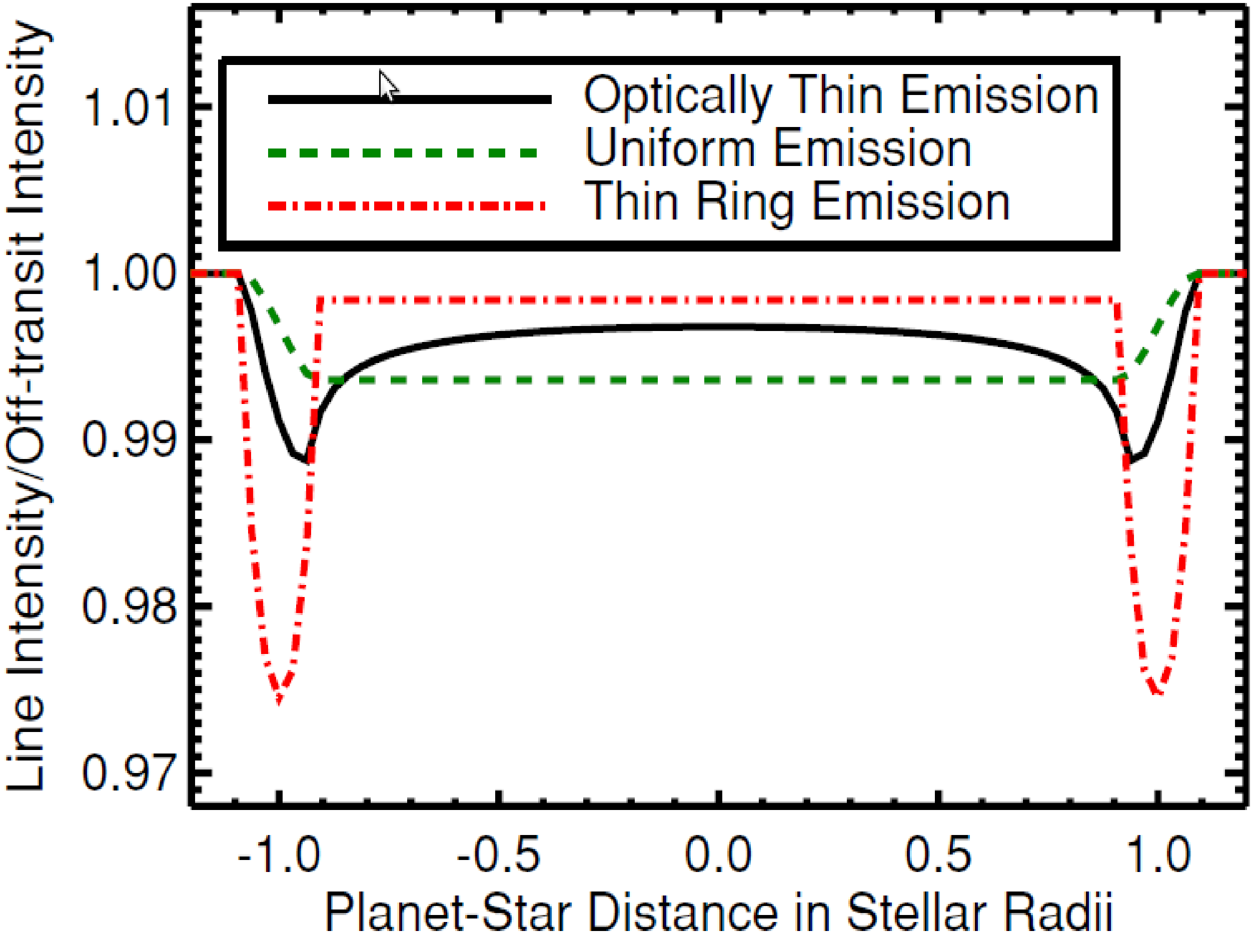


Figure 2. Transit light curve for $R_p/R_* = 0.08$, using a family of three different models. The solid line is for a transit of an optically thin shell using Equation (1)

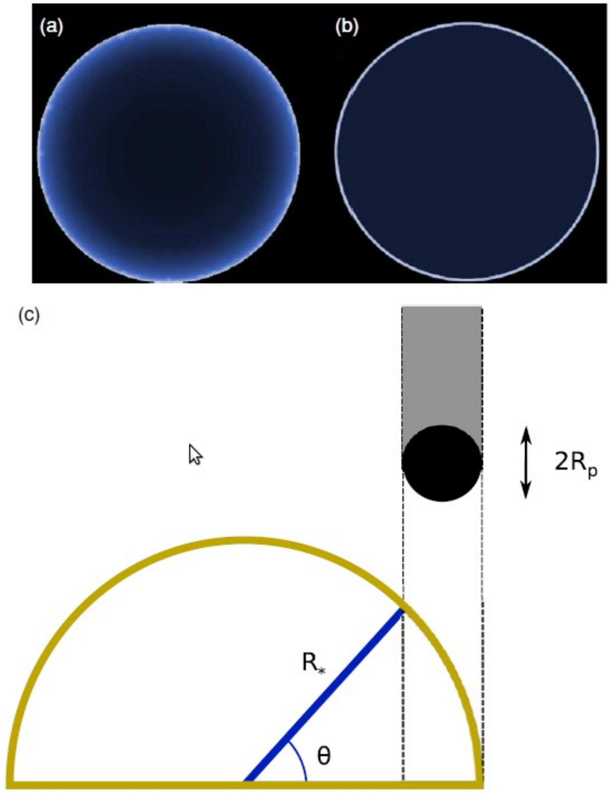


Figure 1. Model limb brightening. (a) A model of spherically symmetric optically thin emission varies continuously from limb to center. (b) An approximate model where most of the emission is from the stellar limb surrounding a uniformly emitting circle. We employ the model shown in (a) for Si IV emission, whose transit light curve is given by Equation (1). (c) Edge-on view of area of stellar emission and the amount blocked by a planet. This blocked surface area is the same as the area of a shadow cast by a sphere on a

Schlawin et al 2010

Microlensing during transit

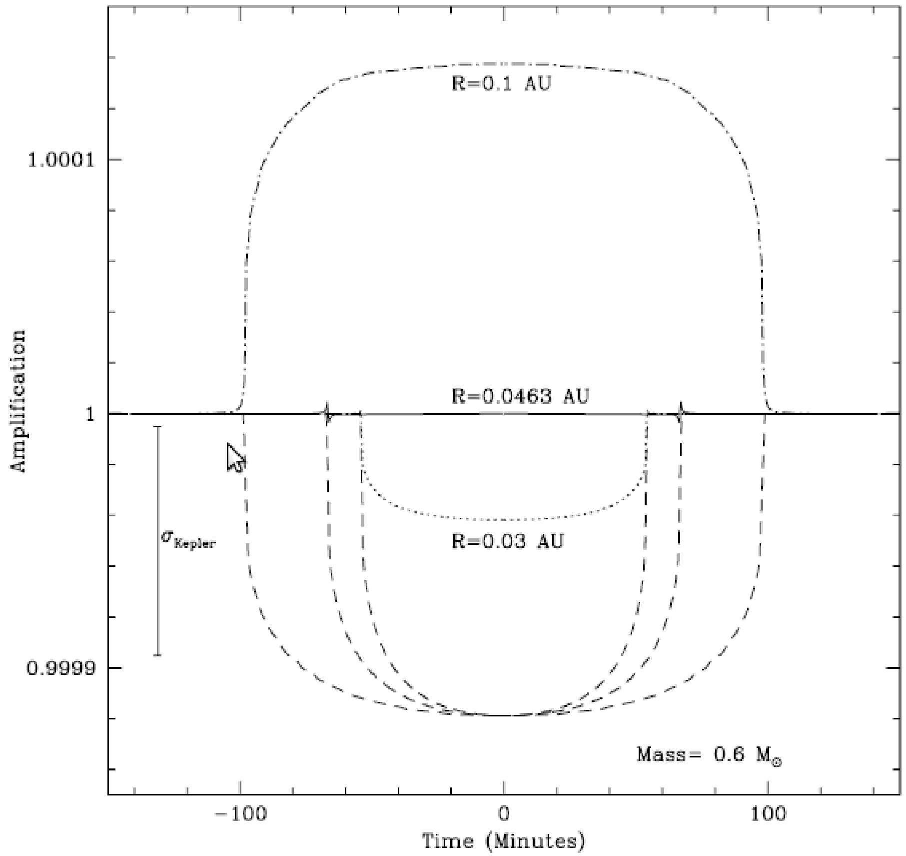


FIG. 14.—Light curves caused by a 0.6 $M_\odot$ white dwarf at 0.03, 0.0463, and 0.1 AU from a solar-type star. The dashed curves show what one would expect purely from transit. The corresponding upper curves (*dotted, solid, and dot-dashed curves, respectively*) take both the transit and the microlensing contributions into account and hence correspond to the actual light curves that one would observe. Note that, even at a small orbital radius of 0.03 AU (where the white dwarf is likely to produce tidal distortions on the companion), the microlensing contribution is significant. At an orbital radius of 0.0463 AU, the microlensing contribution almost exactly cancels out the transit contribution. At an orbital radius of 0.1 AU, the net effect is a positive amplification that is easily detectable by *Kepler*.

Sahu et al. 2003

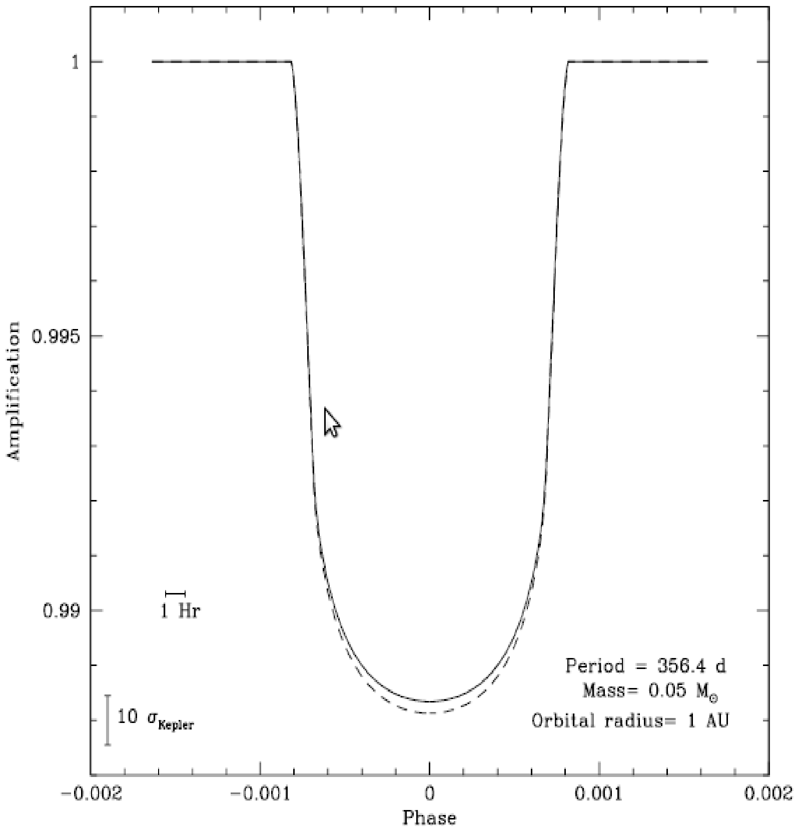
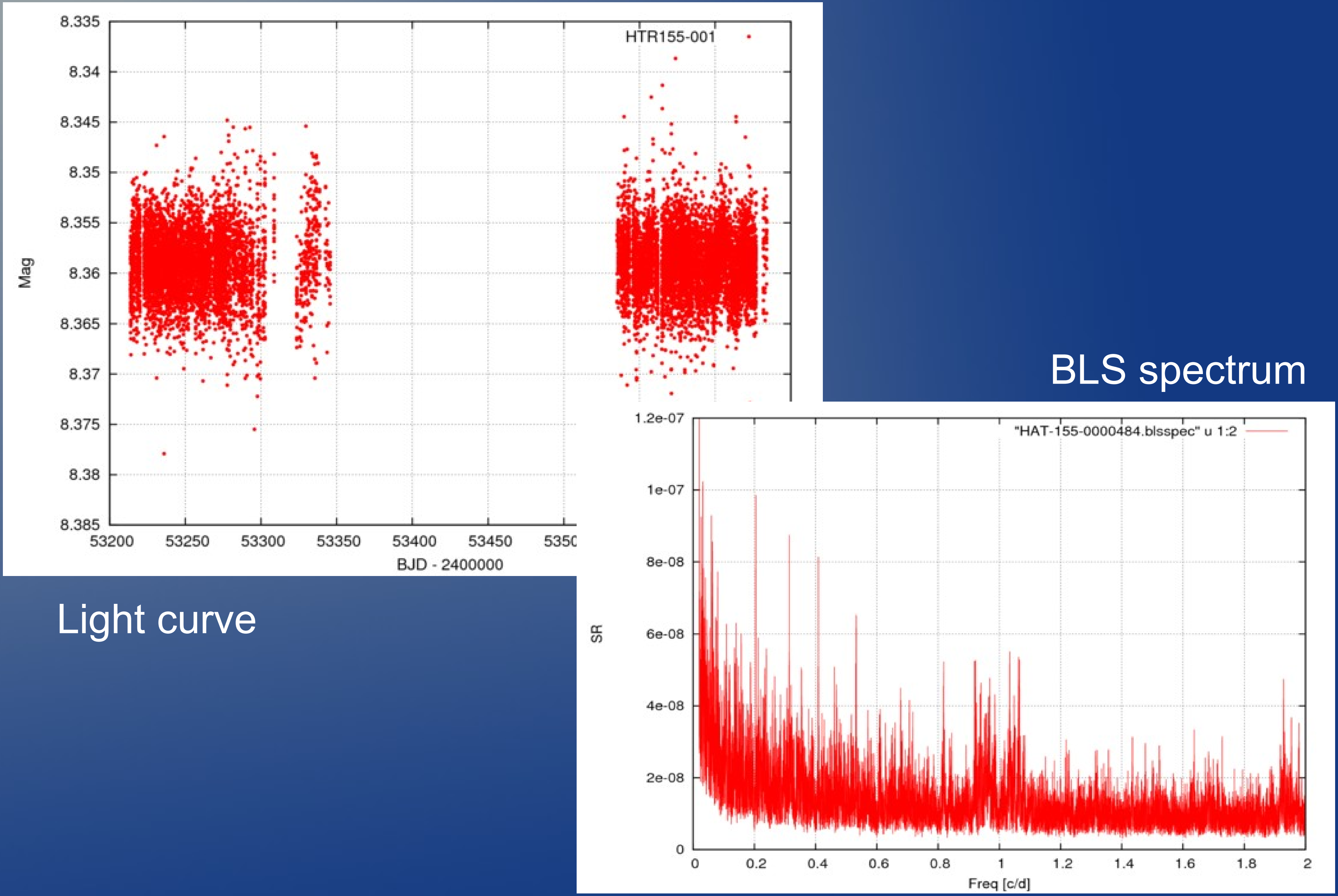


FIG. 12.—Light curves caused by a 0.05 $M_\odot$ brown dwarf and a Jupiter at 1 AU from a solar-type star. The dashed curve shows what one would expect purely from transit. The solid curve shows the combined effect of the transit and microlensing for a brown dwarf. The combined effect of transit and microlensing is indistinguishable from a pure transit curve for a Jupiter, since the shapes of the combined and the transit light curves are very similar. The depth of the observed light curve would be smaller for a brown dwarf than for a Jupiter.

Sahu et al. 2003

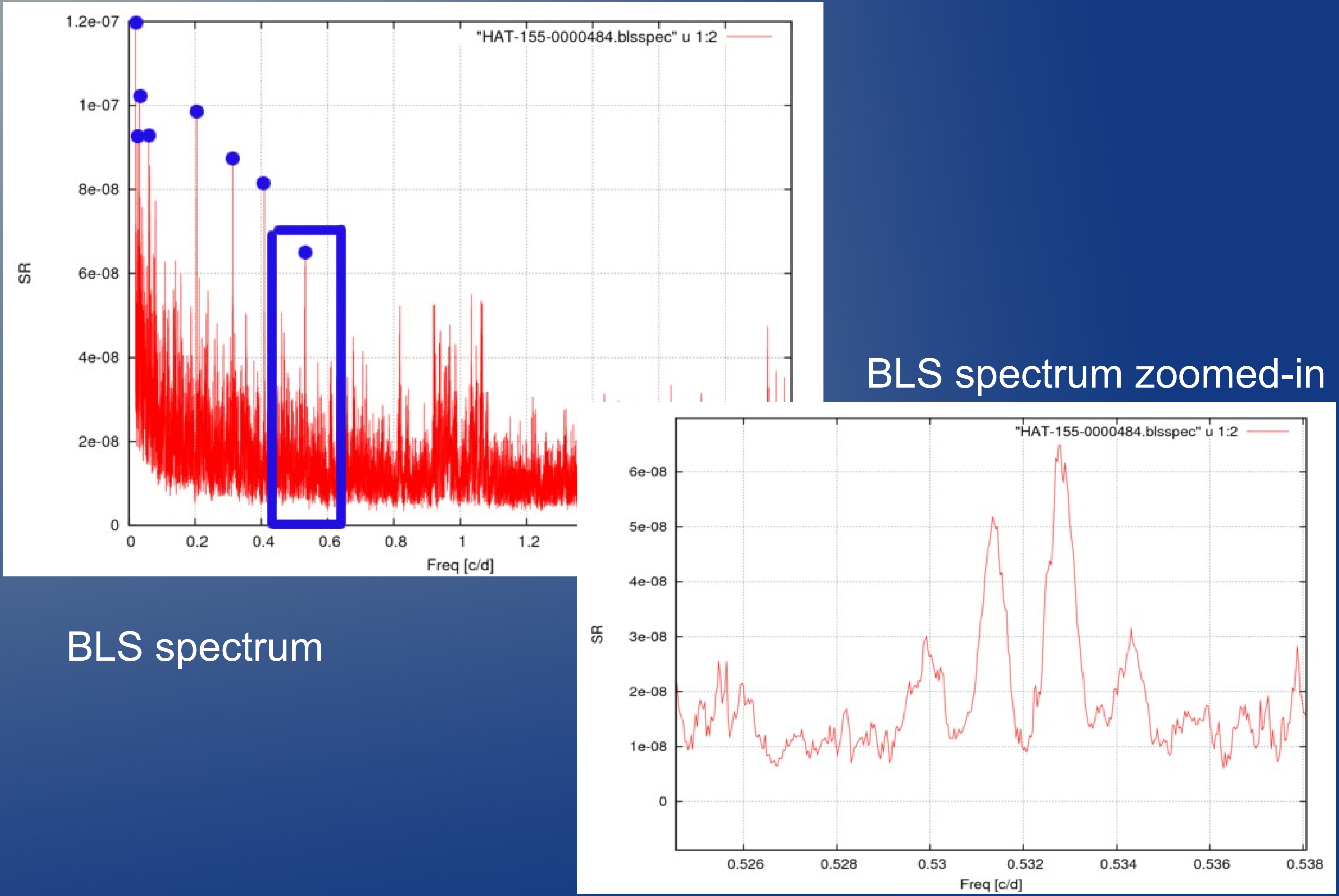
Finding and confirming a transiting planet in practice



BLS spectrum

Light curve

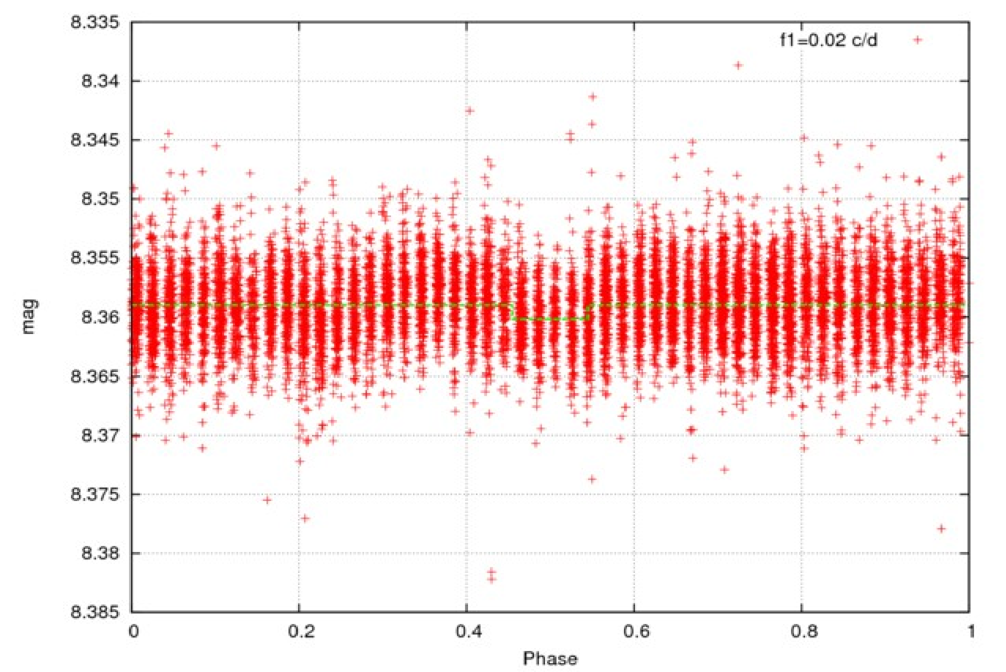
Finding and confirming a transiting planet in practice



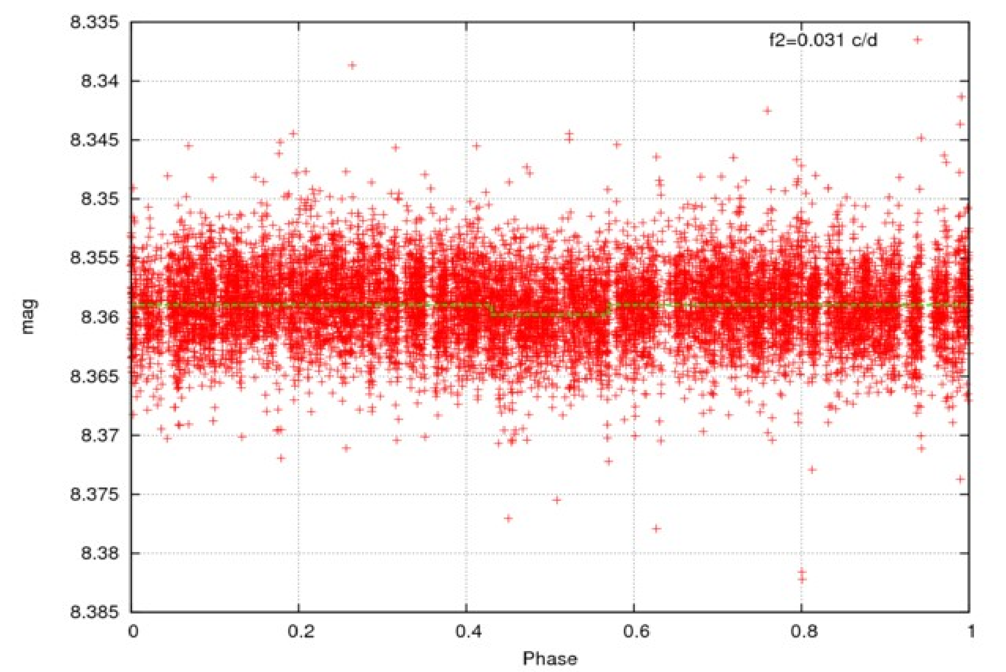
BLS spectrum zoomed-in

BLS spectrum

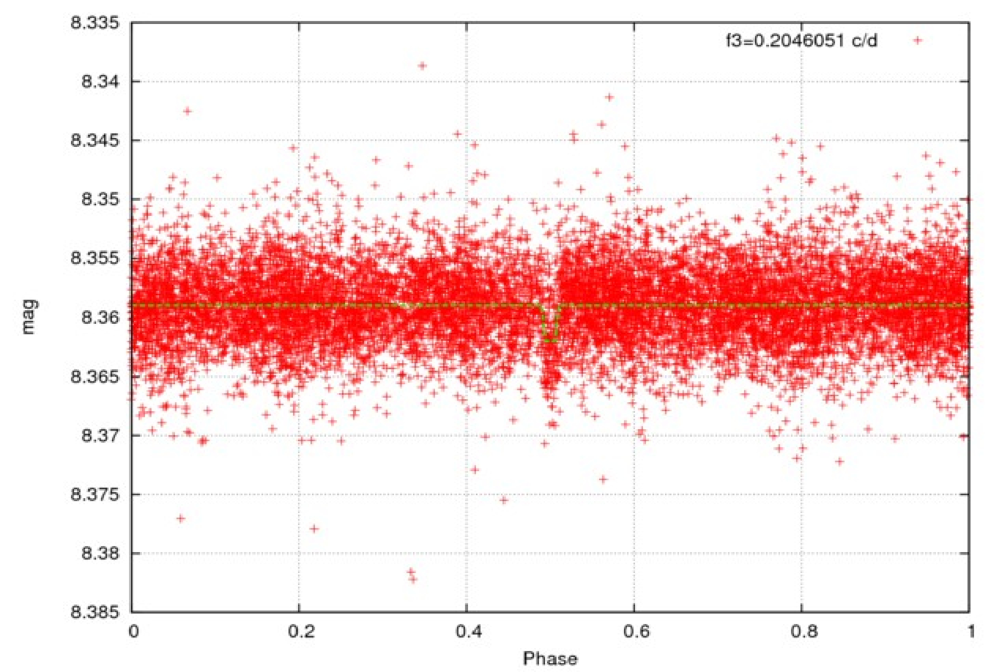
Various phase foldings for HTR155-001



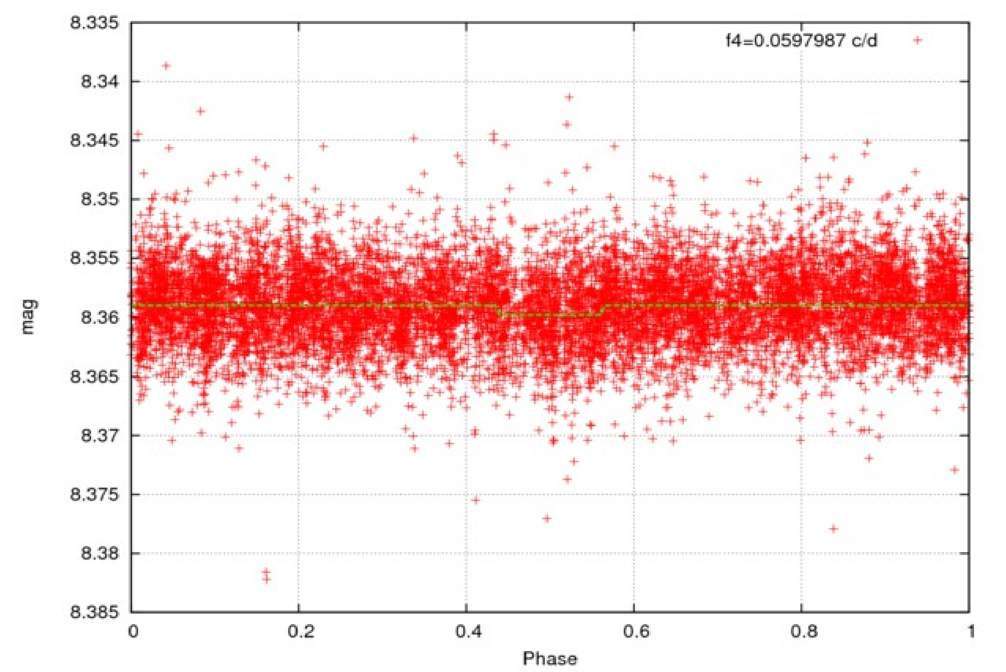
Peak #1



Peak #2

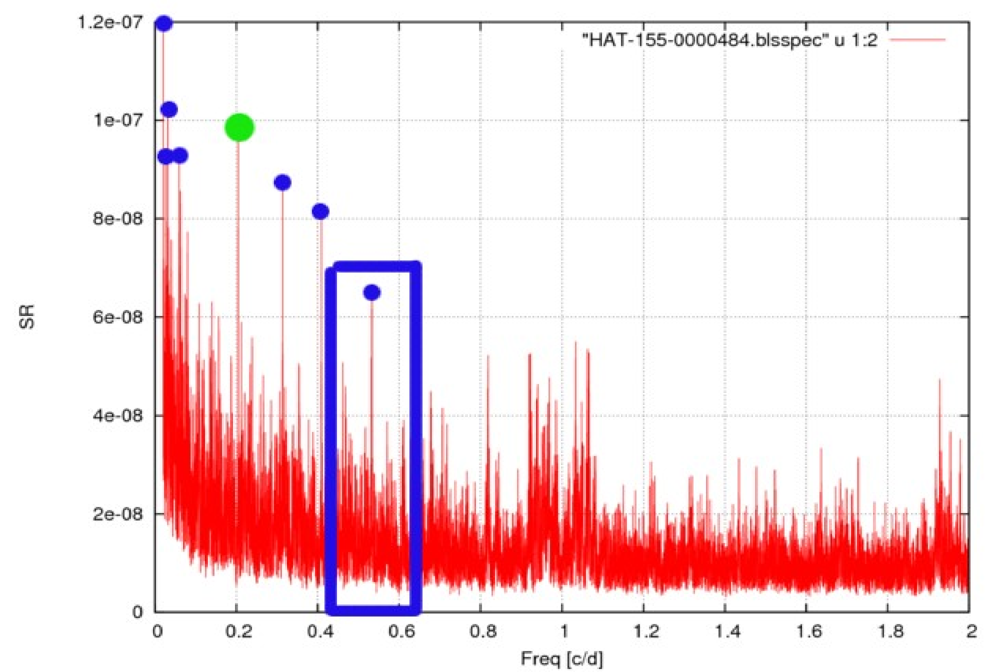


Peak #3

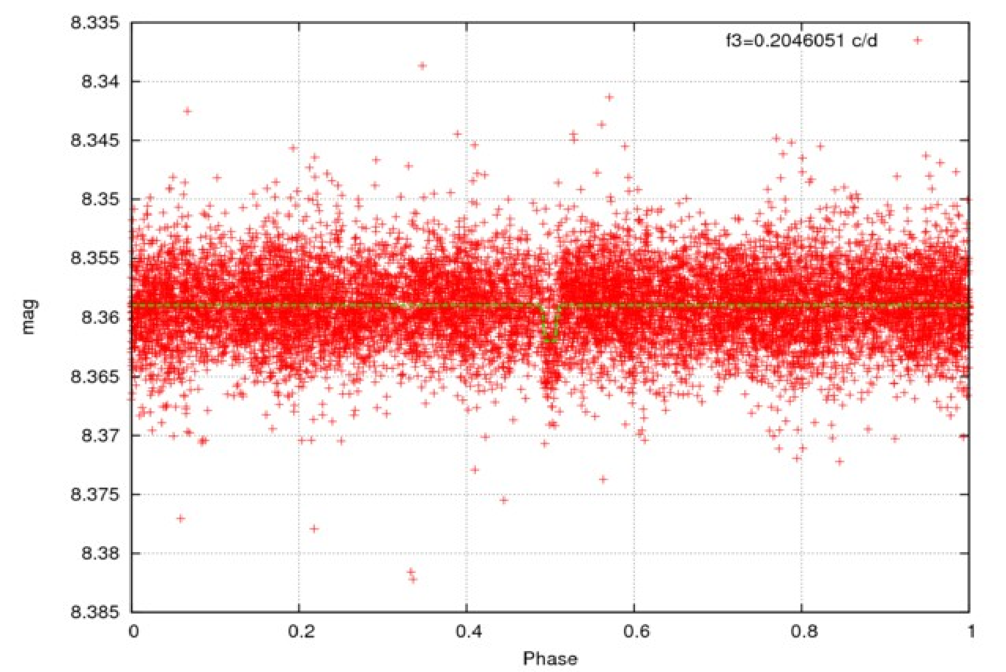


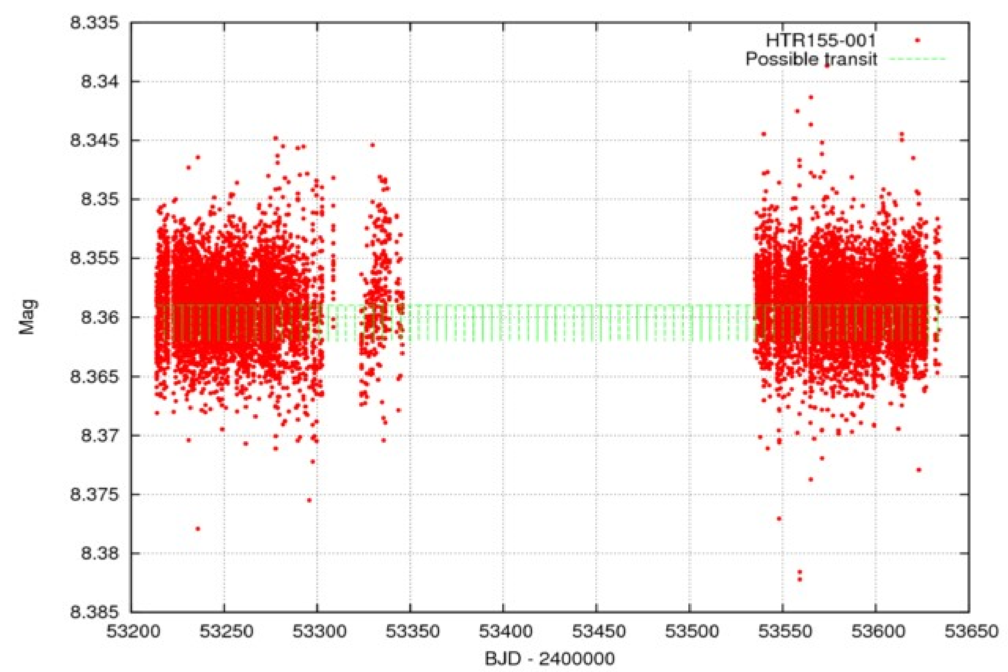
Peak #4

A promising folding at P=4.88d



Peak #3





Peak #3

Selection and filtering criteria

The first step in confirmation/validation of the signal
… as based on the discovery data:

- Limit the minimum and maximum depth of the transit.
- Confidence: e.g. at least two transit events with altogether at least 50 data-points in transit.
- Limit the maximum radius of the transiting object to be e.g. < 2 Rjup.
- Limit the ratio of the transit duration to the predicted transit duration.
- Limit OOT variations, e.g. through lomb-scargle false alarm probability (V).
- Limit the maximum gap in the phased lc (e.g. 0.2).
- Impose threshold on signal to pink noise ratio.
- Limit the ratio of the RMS of points in transit to out-of-transit
- Existence of secondary? Check for the difference in chi^2 between the best fit transit model, and the best fit model where even and odd transits are allowed to have different depths (V).

- Centroid offsets/motion, rain diagrams, as 'invented' by the XO project. (V)
- …

Expected characteristics of the transiting planet light curve

Combined light, due to the planet:

- Primary transit (Mandel & Agol)
- Phase function
- Occultation (depending on e, ω)

Out-of-transit (OOT) variations:

- Ellipsoidal (Morris 1985, Welsh 2010 for HATP7. Also, Sirko & Paczynski 2003). P/2.
- Reflection/heating (e.g. Maxted 2002). P. (light reflected from the component)
- relativistic beaming (Rybicki & Lightman 1979, Maxted 2000). P.

$$\frac{\Delta F_{\rm ellip}(\hat{t})}{\bar{F}} = -A_{\rm ellip} \cos\left(\frac{2\pi}{P_{\rm orb}/2}\hat{t}\right),$$

$$\frac{\Delta F_{\rm beam}(\hat{t})}{\bar{F}} = A_{\rm beam} \sin\left(\frac{2\pi}{P_{\rm orb}}\hat{t}\right),$$

$$\frac{\Delta F_{\rm refl}(\hat{t})}{\bar{F}} = -A_{\rm refl} \cos\left(\frac{2\pi}{P_{\rm orb}}\hat{t}\right),$$

Faigler & Mazeh 2011

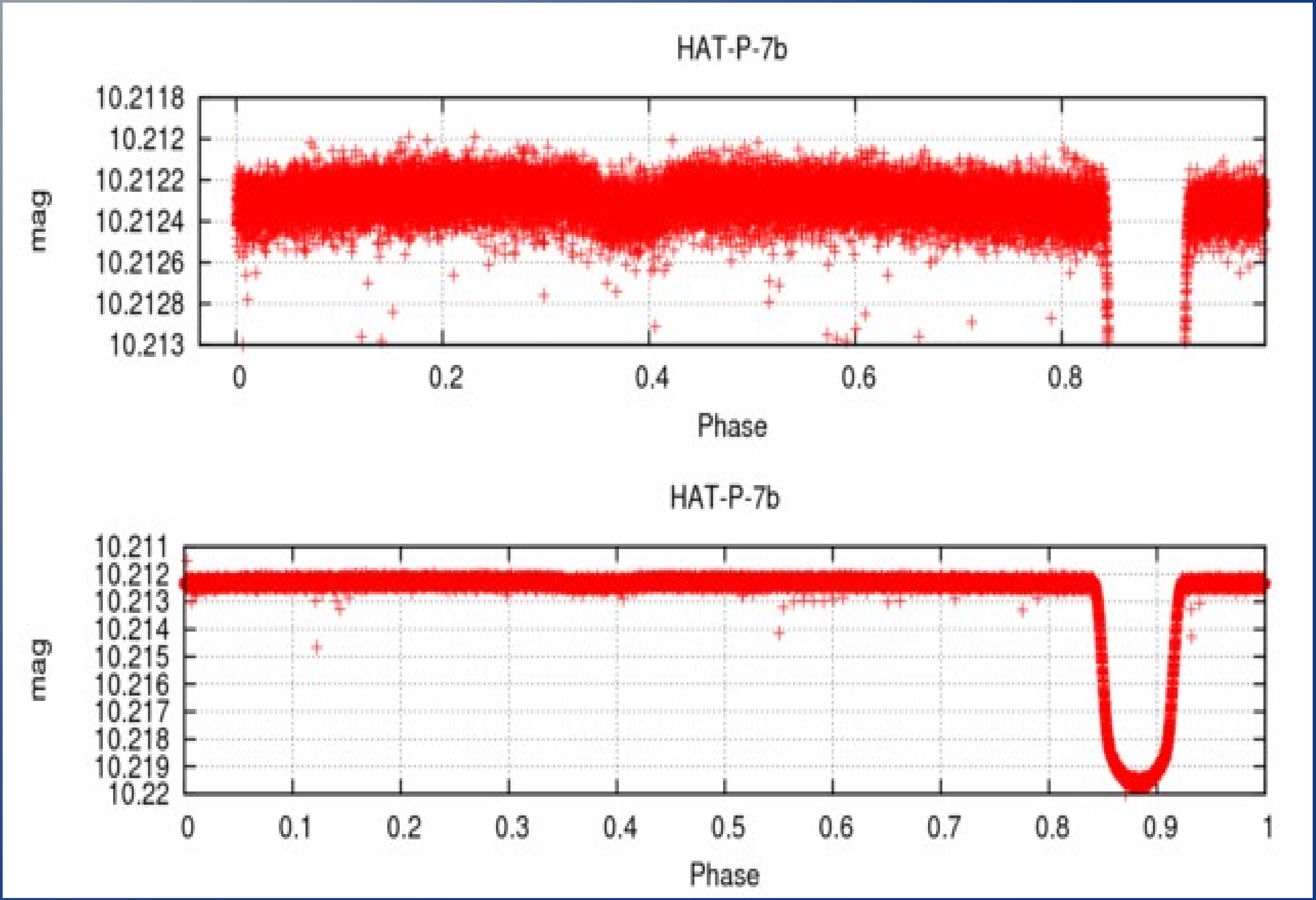
$$A_{\rm beam} = \alpha_{\rm beam}\, 4\frac{K_{\rm RV}}{c} = 27\ \alpha_{\rm beam}\left(\frac{M_*}{M_\odot}\right)^{-2/3}\left(\frac{P_{\rm orb}}{1\ {\rm day}}\right)^{-1/3}\left(\frac{m_2 \sin i}{10\ M_{\rm Jup}}\right)\ {\rm ppm}, \qquad (1)$$

$$A_{\rm ellip} = \alpha_{\rm ellip}\frac{m_2 \sin i}{M_*}\left(\frac{R_*}{a}\right)^3 \sin i = 128\ \alpha_{\rm ellip} \sin i\left(\frac{R_*}{R_\odot}\right)^3\left(\frac{M_*}{M_\odot}\right)^{-2}\left(\frac{P_{\rm orb}}{1\ {\rm day}}\right)^{-2}\left(\frac{m_2 \sin i}{10\ M_{\rm Jup}}\right)\ {\rm ppm}, \qquad (2)$$

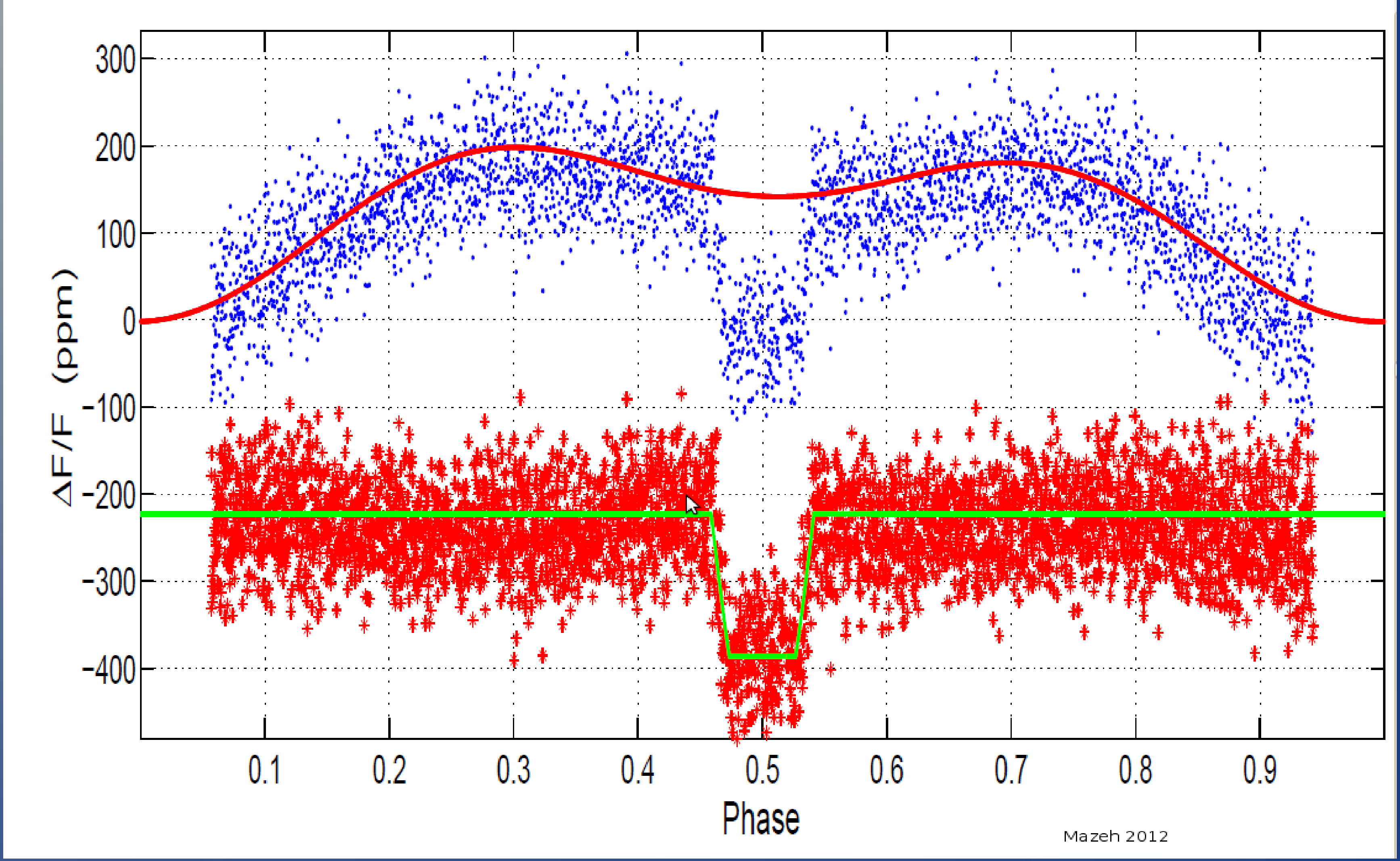
$$A_{\rm refl} = \alpha_{\rm refl}\, 0.1\left(\frac{r_2}{a}\right)^2 \sin i = 57\ \alpha_{\rm refl} \sin i\left(\frac{M_*}{M_\odot}\right)^{-2/3}\left(\frac{P_{\rm orb}}{1\ {\rm day}}\right)^{-4/3}\left(\frac{r_2}{R_{\rm Jup}}\right)^2\ {\rm ppm}. \qquad (3)$$

Faigler & Mazeh 2011

OOT variation of HAT-P-7b (Kepler)

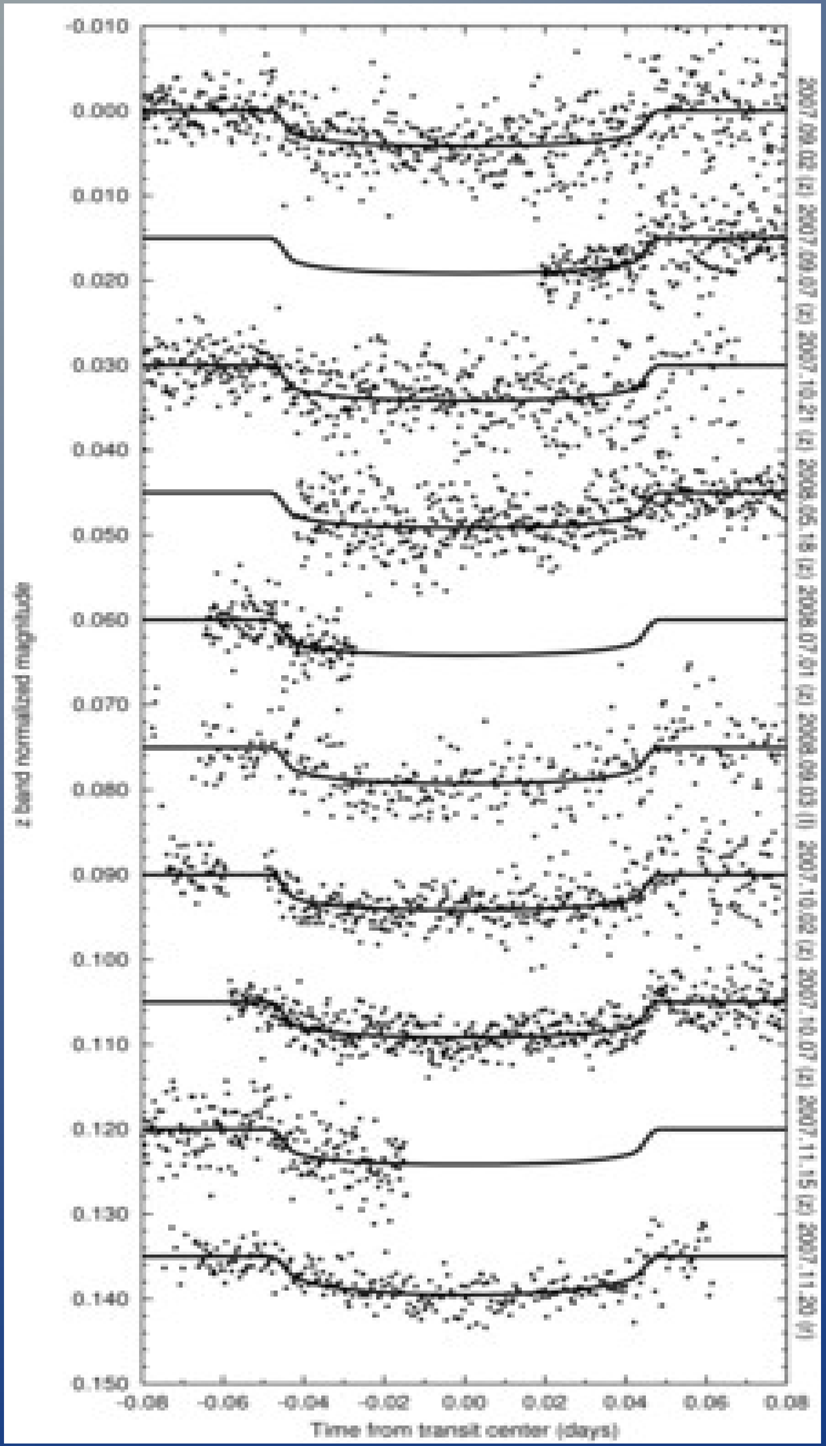


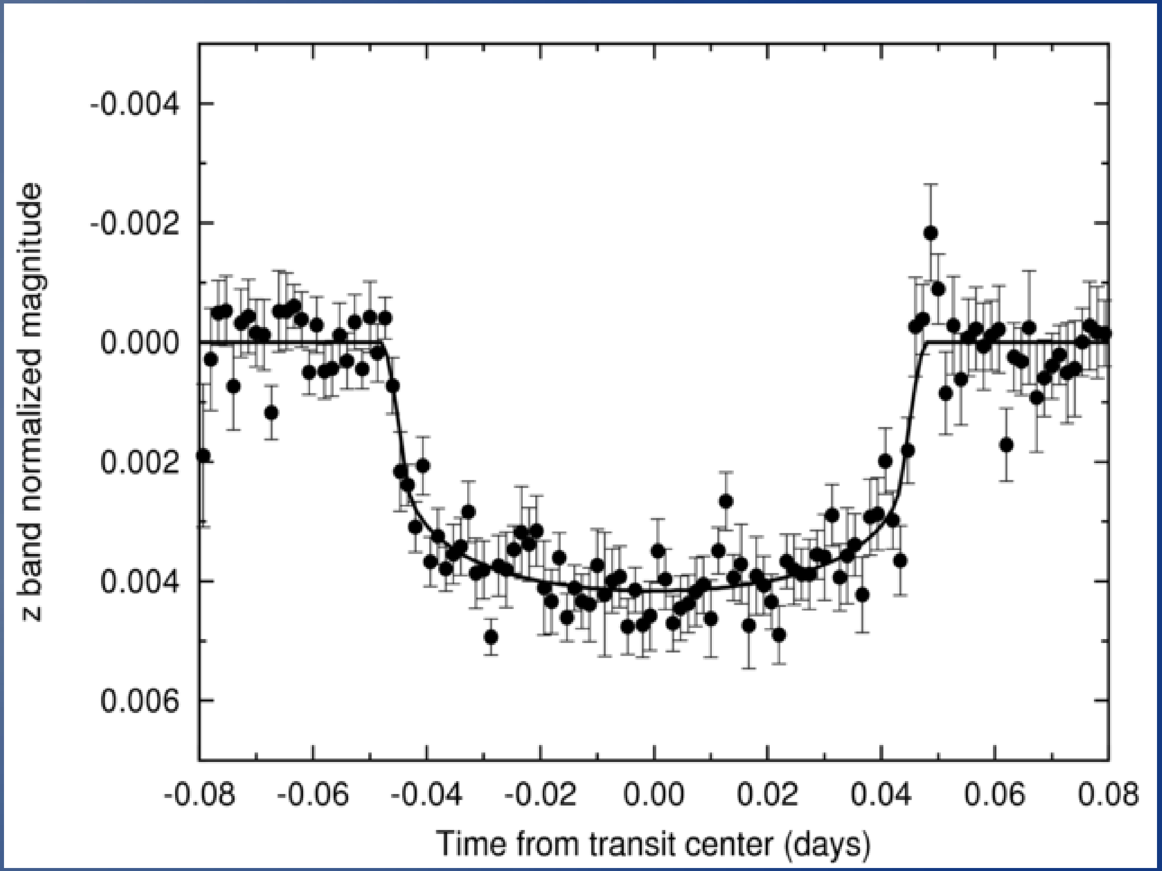
Occultation and phase function of KOI-13



Amplitudes of the
beaming: 8.6 +/- 1.1 ppm
ellipsoidal: 66.8 +/- 1.6 ppm
reflection modulations: 72.0 +/- 1.5 ppm (parts per million).
Estimated 10 +/- 2 Mj mass. (Mazeh et al 2012)

Catching the transit – constraining the ephemeris





HTR155-001 (again...)

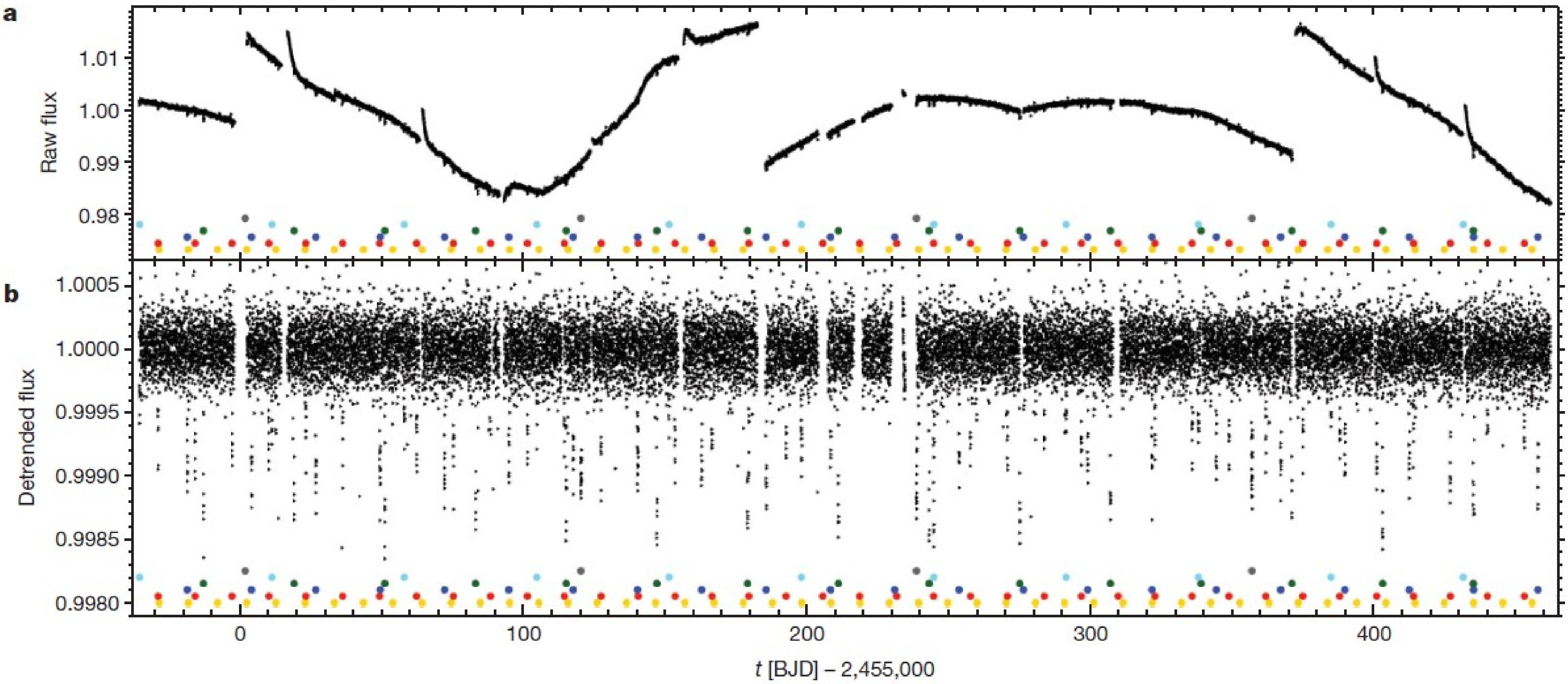
Follow-up (or archival) observations can help confirming the existence of the transit, and refining the ephemeris.

Flatline observations do contain information!

Photometry FU vs. RV FU.

Multiple transiting planets

RESEARCH ARTICLE

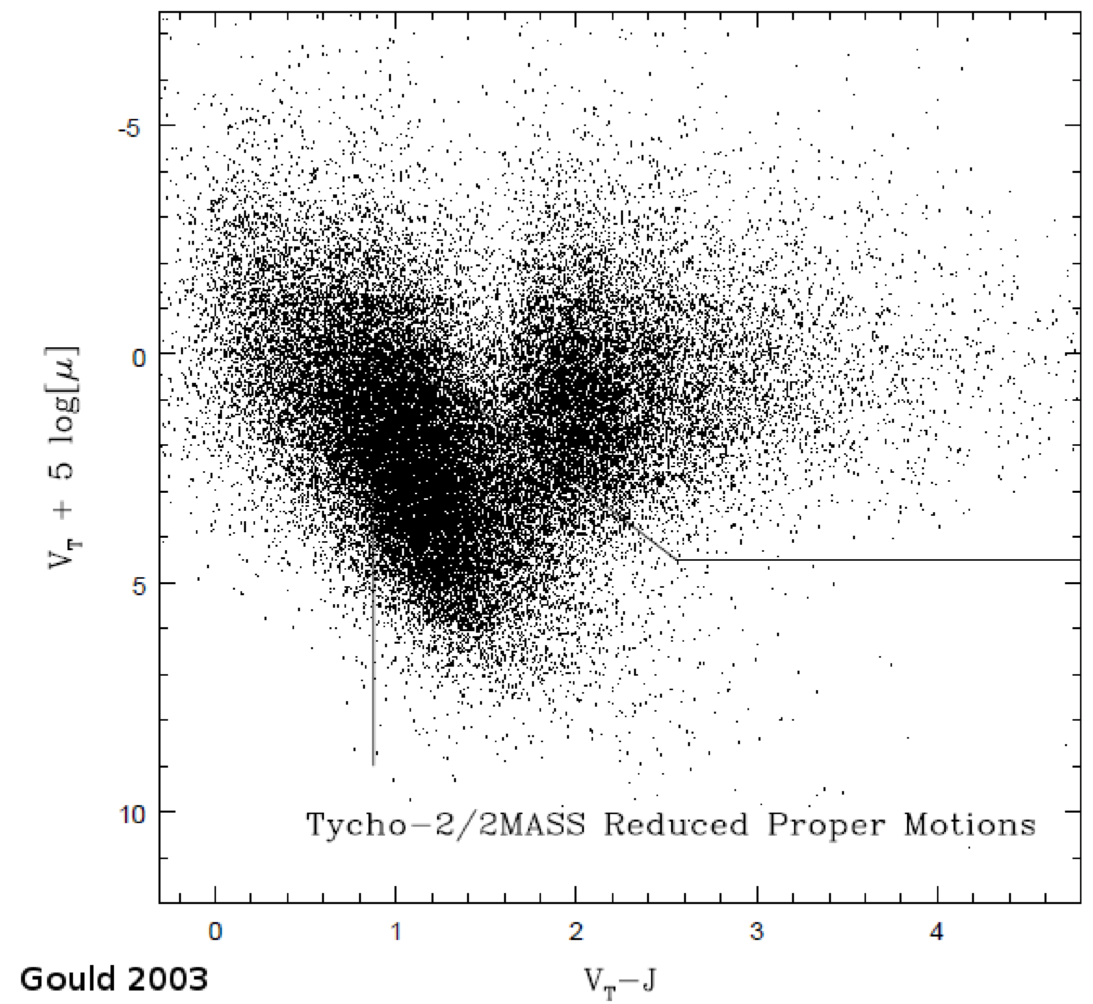


Transit identification and determination of the ephemeris may be tricky!

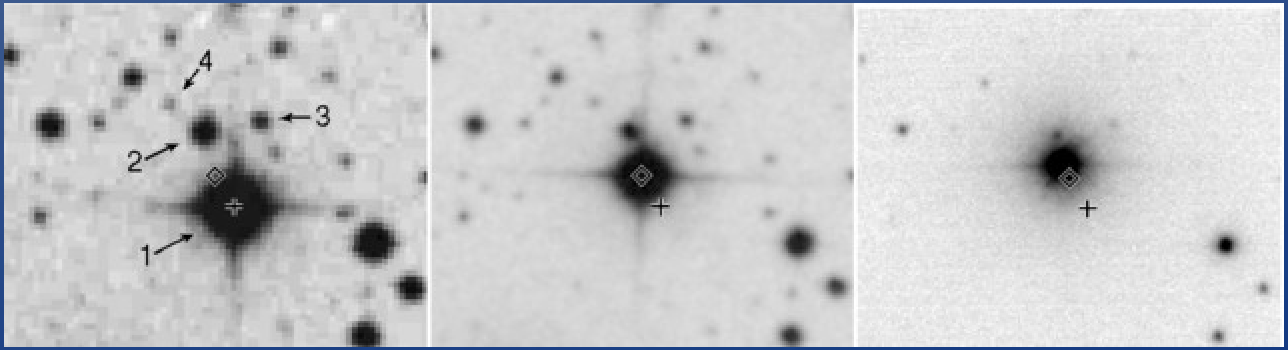
Use of archival data for confirmation & validation

- Proper motion: if large enough, using archival images, check what is in the place of the object.
- Reduced proper motion: how likely is that the star is a dwarf?
- Multi-color observations
- Archival photometry (ASAS Hipparcos, etc).
- X-ray variability (indicative of M dwarfs)

$$V_{\rm RPM} \equiv V + 5\log\mu = M_V + 5\log\frac{v_\perp}{47.4\ {\rm km\ s^{-1}}}$$



Gould 2003



HTR155-001

Statistics from HATNet

- HATNet observes 30K dwarfs per yr at 1% light curve rms ($r \in [9.5,12]$), and 90K dwarfs per yr at 2% lc rms ($r \in [7.5,13]$).

- HATNet has found ~1500 transiting planet *candidates.*

- Intensive and coordinated follow-up effort to weed out false alarms: F+M binaries, grazing EBs, triples (52%), giants (18%), resolved blends (11%), false photometry (10%), rapid rotators (15%). False alarm rate > Kepler

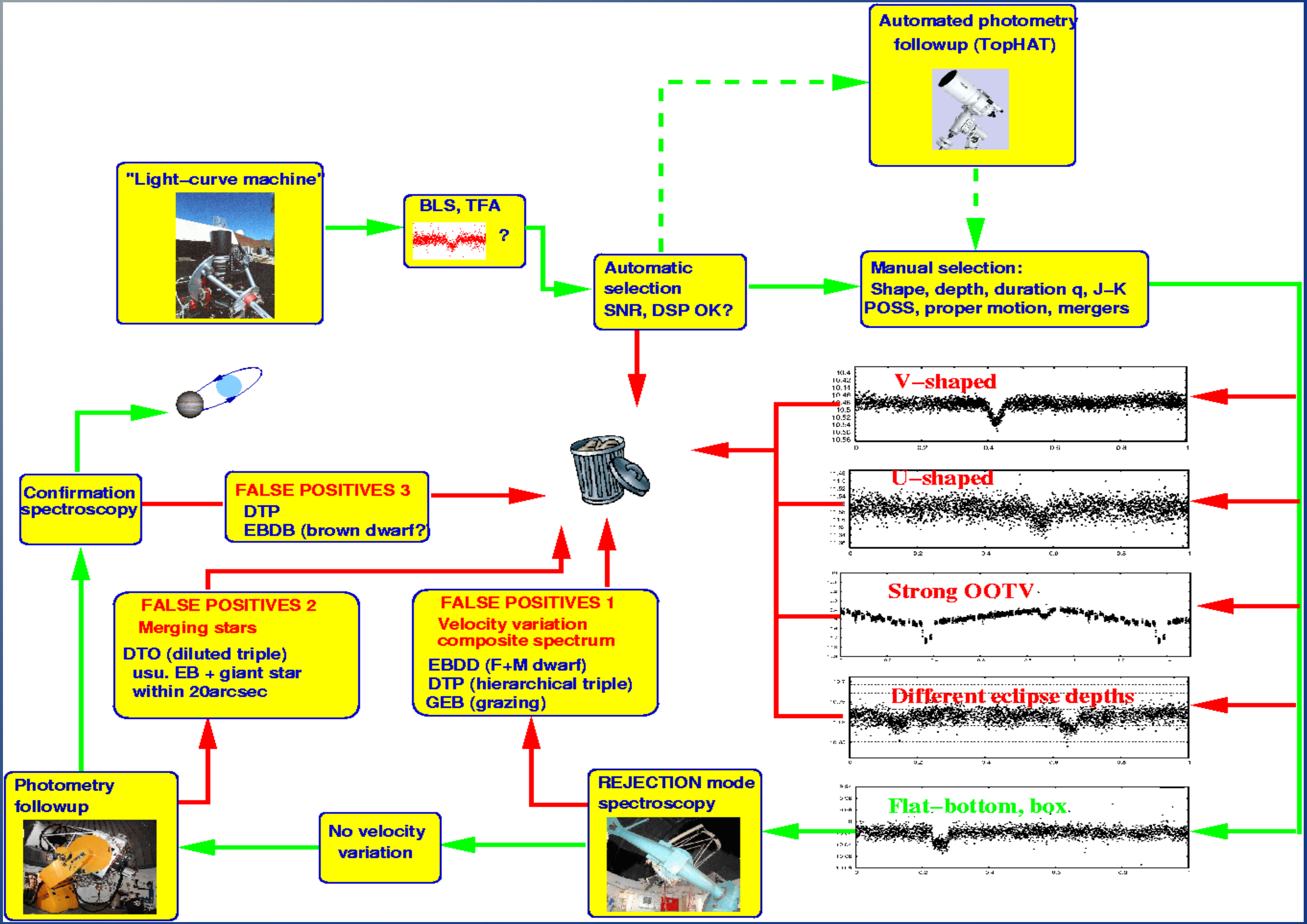
- Photometry follow-up with 0.25m TopHAT, 1.2m FLWO, LCOGT (2m Faulkes, 0.8m BOS) and other telescopes.

- High resolution low S/N “reconnaissance” spectroscopy with the 1.5m FLWO reflector + TRES.

- Additional low S/N spectroscopy: ANU 2.3m, DuPont 2.5m, NOT/FIES 2.3m.

- About 1 in 20 candidates survives. These survivors reach Keck/HIRES (NASA, NOAO), NOT/FIES, Subaru/HDS, OHP1.93/SOPHIE. Outcome: stellar atmospheric parameters (SME), bisector spans (BS),activity (S), high resolution snapshots (imaging), RVs, planetary mass.

Follow-up scheme



"Light–curve machine"

BLS, TFA ?

Automatic selection
SNR, DSP OK?

Automated photometry followup (TopHAT)

Manual selection:
Shape, depth, duration q, J–K
POSS, proper motion, mergers

V–shaped

U–shaped

Strong OOTV

Different eclipse depths

Flat–bottom, box

Confirmation spectroscopy

FALSE POSITIVES 3
DTP
EBDB (brown dwarf?)

FALSE POSITIVES 2
Merging stars
DTO (diluted triple)
usu. EB + giant star
within 20arcsec

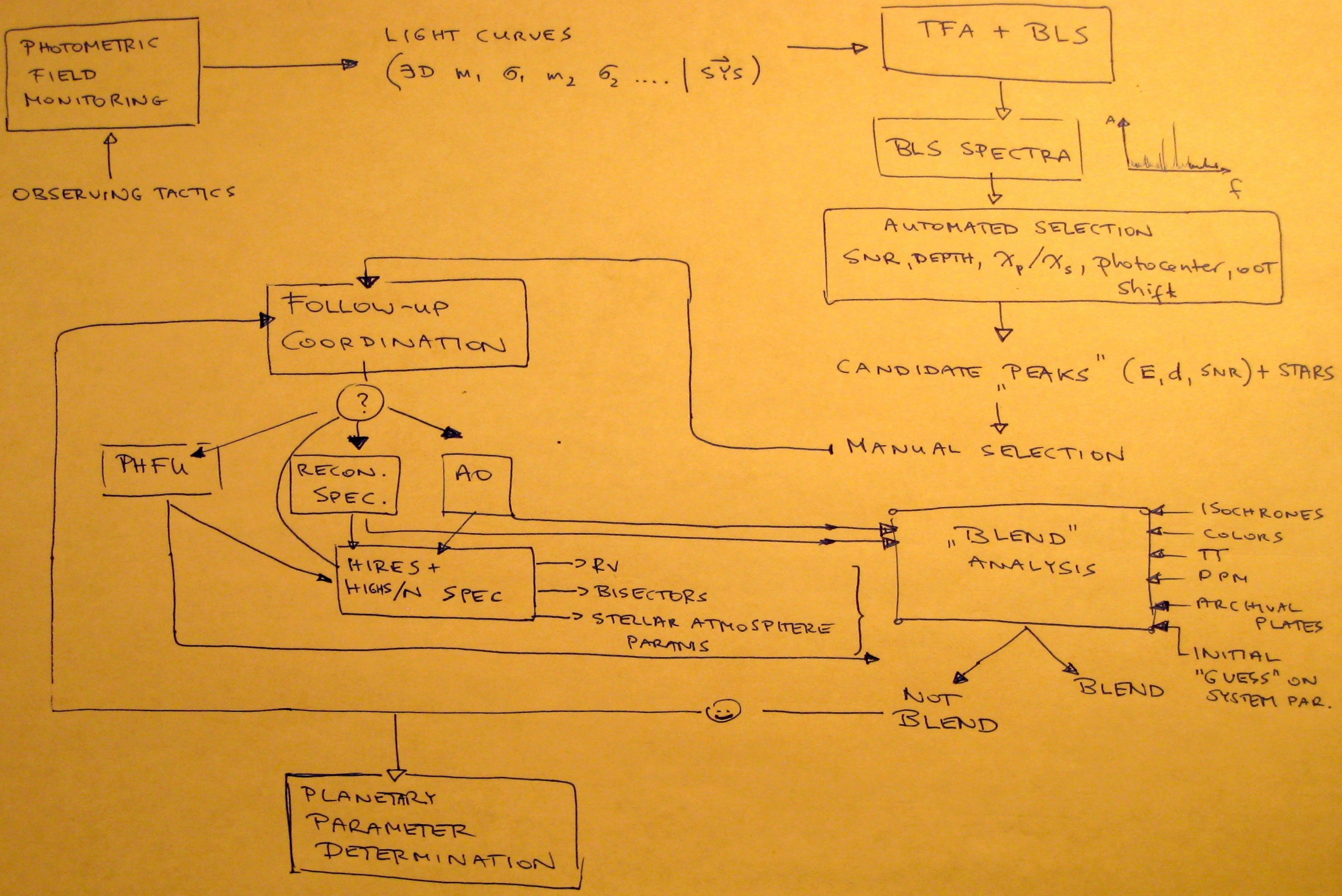
FALSE POSITIVES 1
Velocity variation
composite spectrum
EBDD (F+M dwarf)
DTP (hierarchical triple)
GEB (grazing)

Photometry followup

No velocity variation

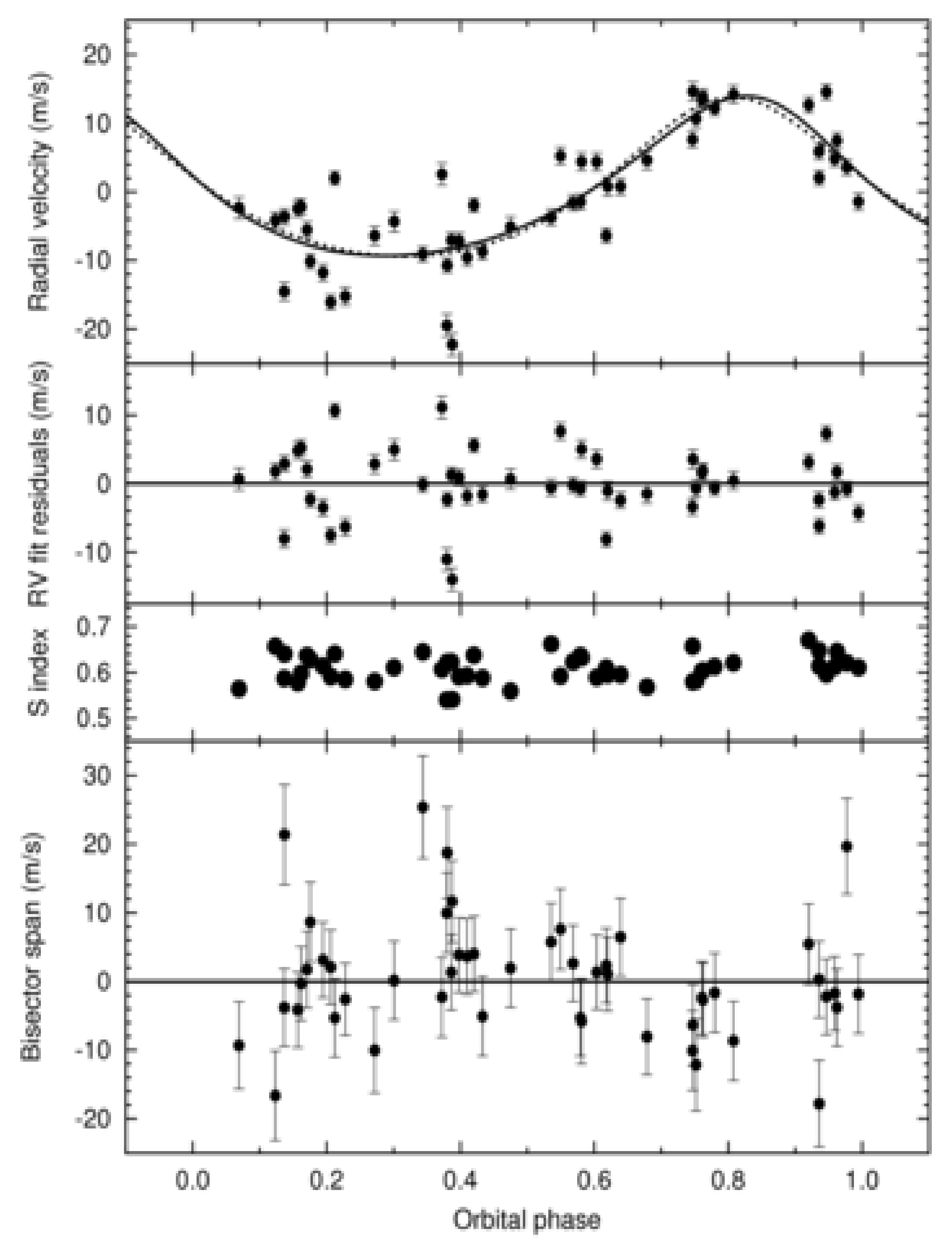
REJECTION mode spectroscopy

Follow-up scheme

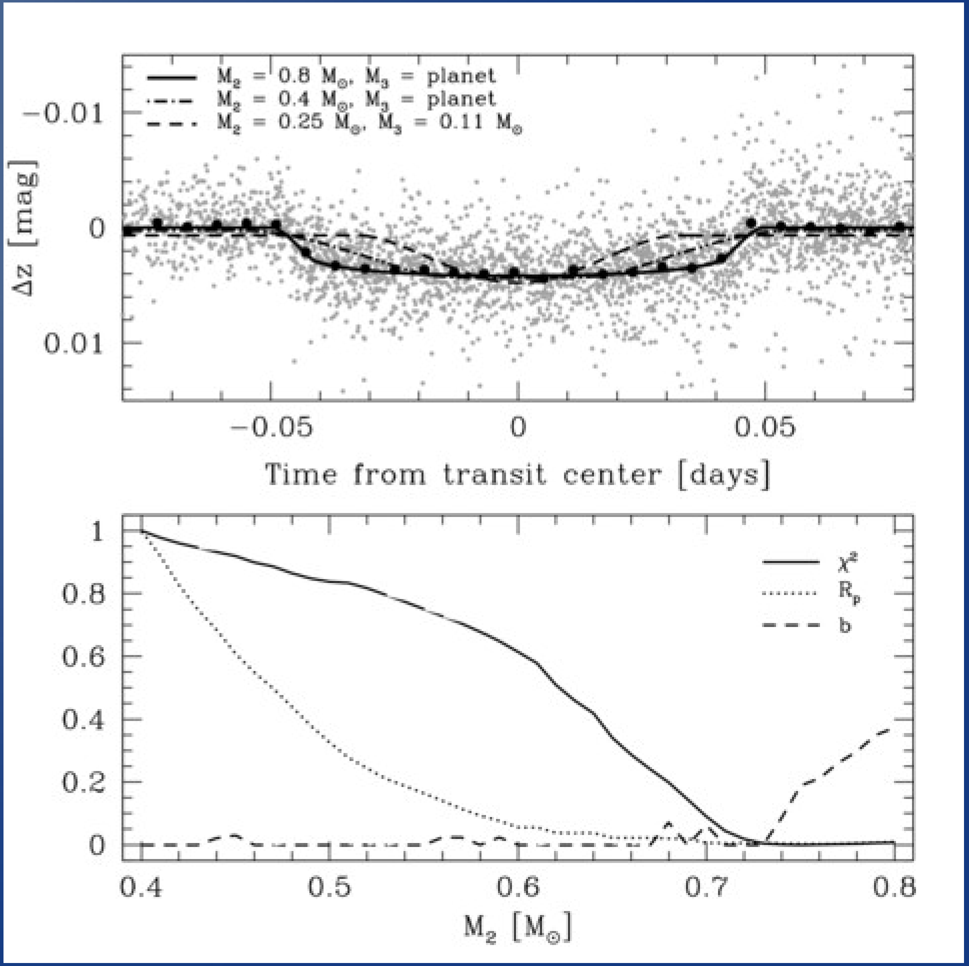


2010 July 26
BG

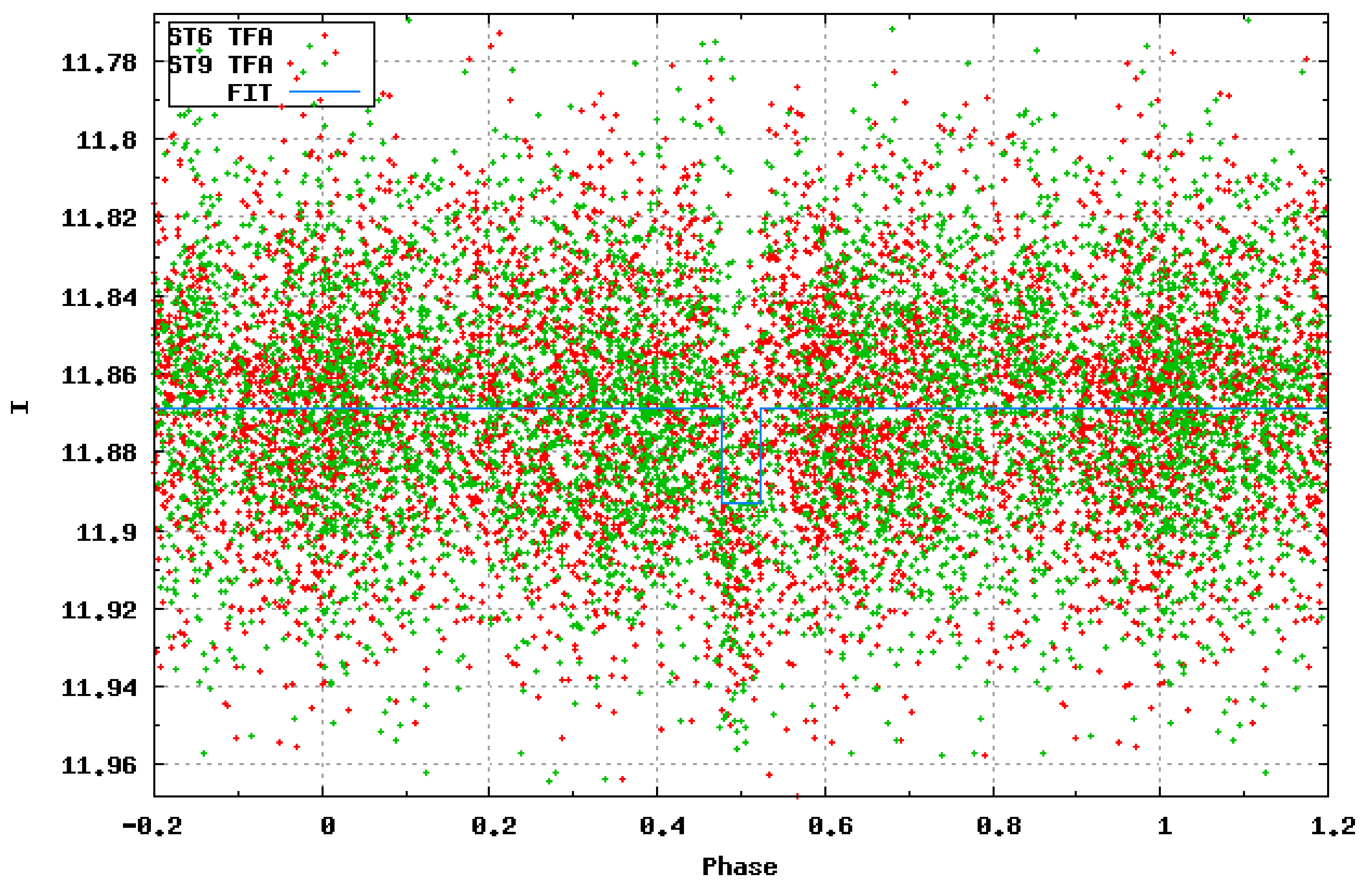
RV confirmation and blend modeling



HTR155-001 = HAT-P-11

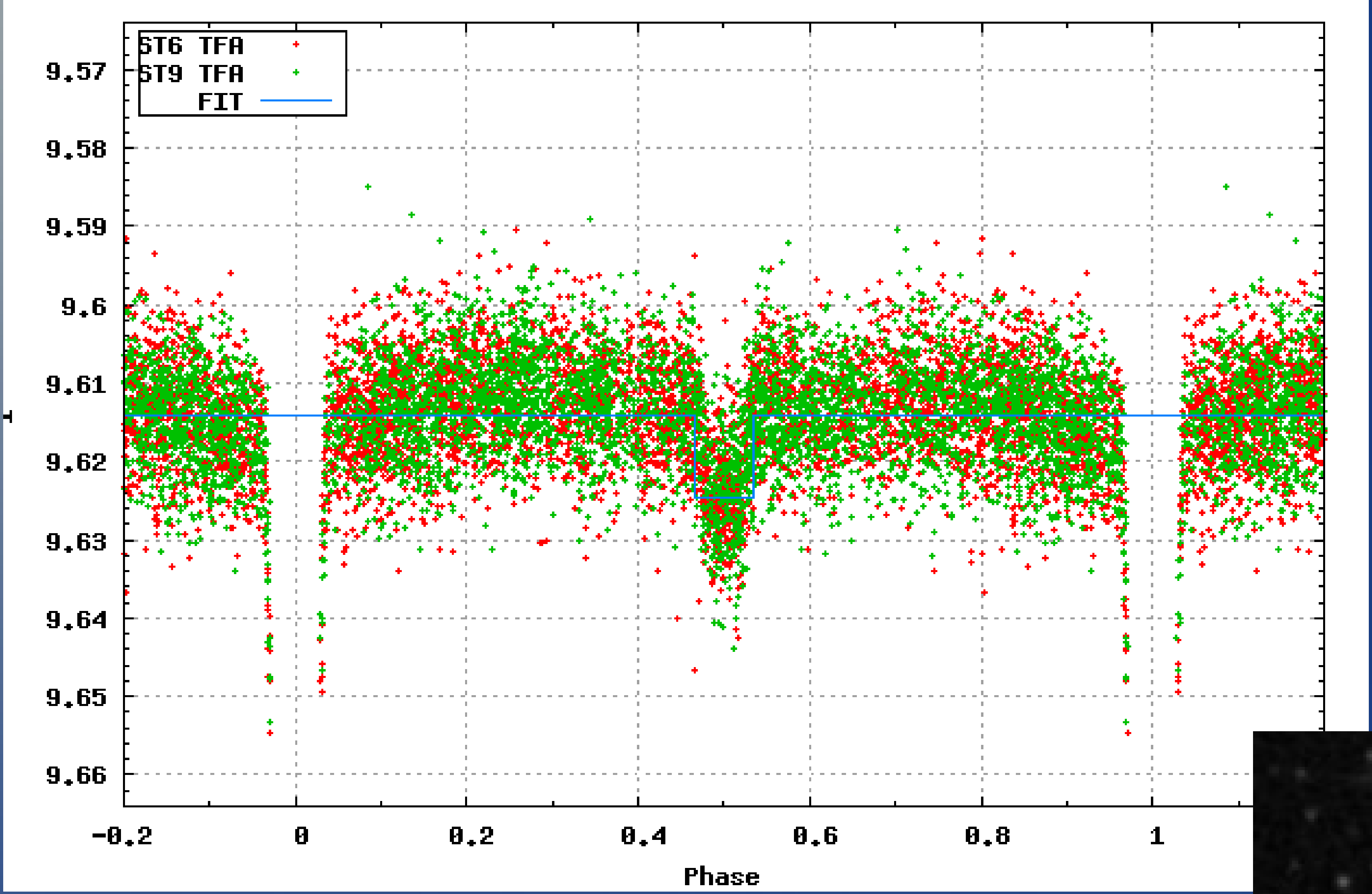


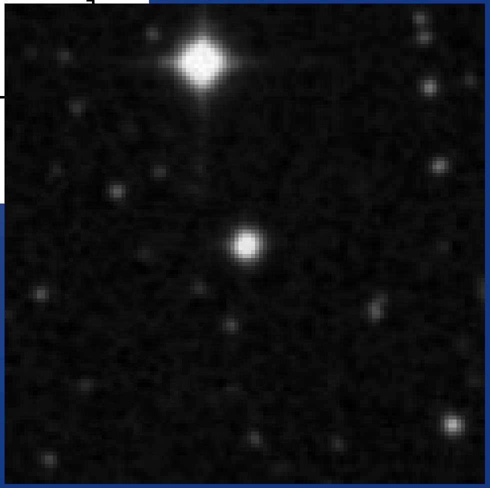
Example for a DTO (MSDF) : HAT-171-0008850



Transit candidate

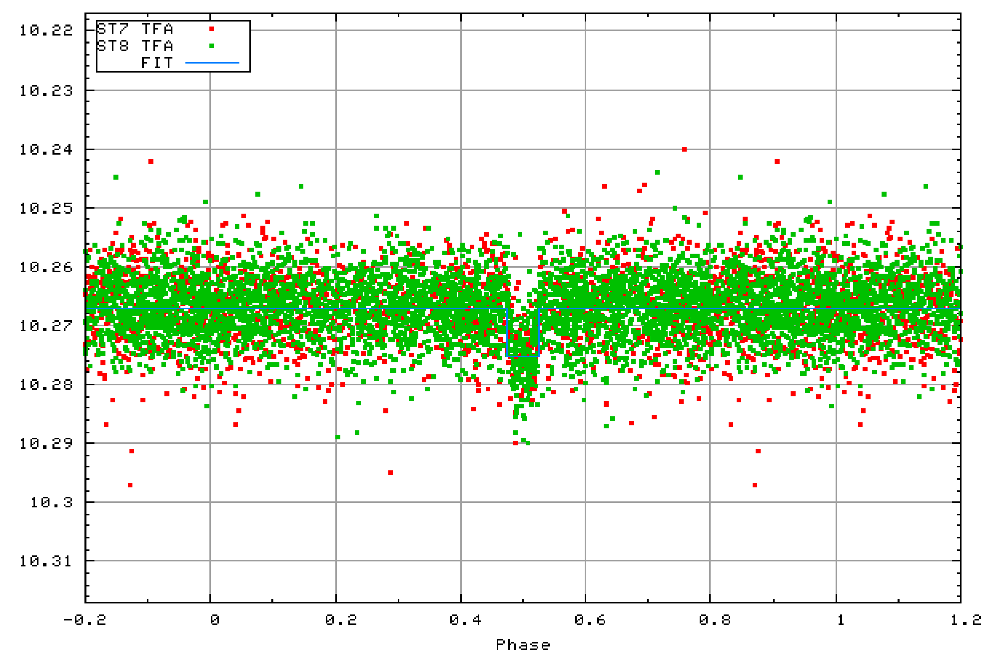
HAT-171-0008850 cont'd

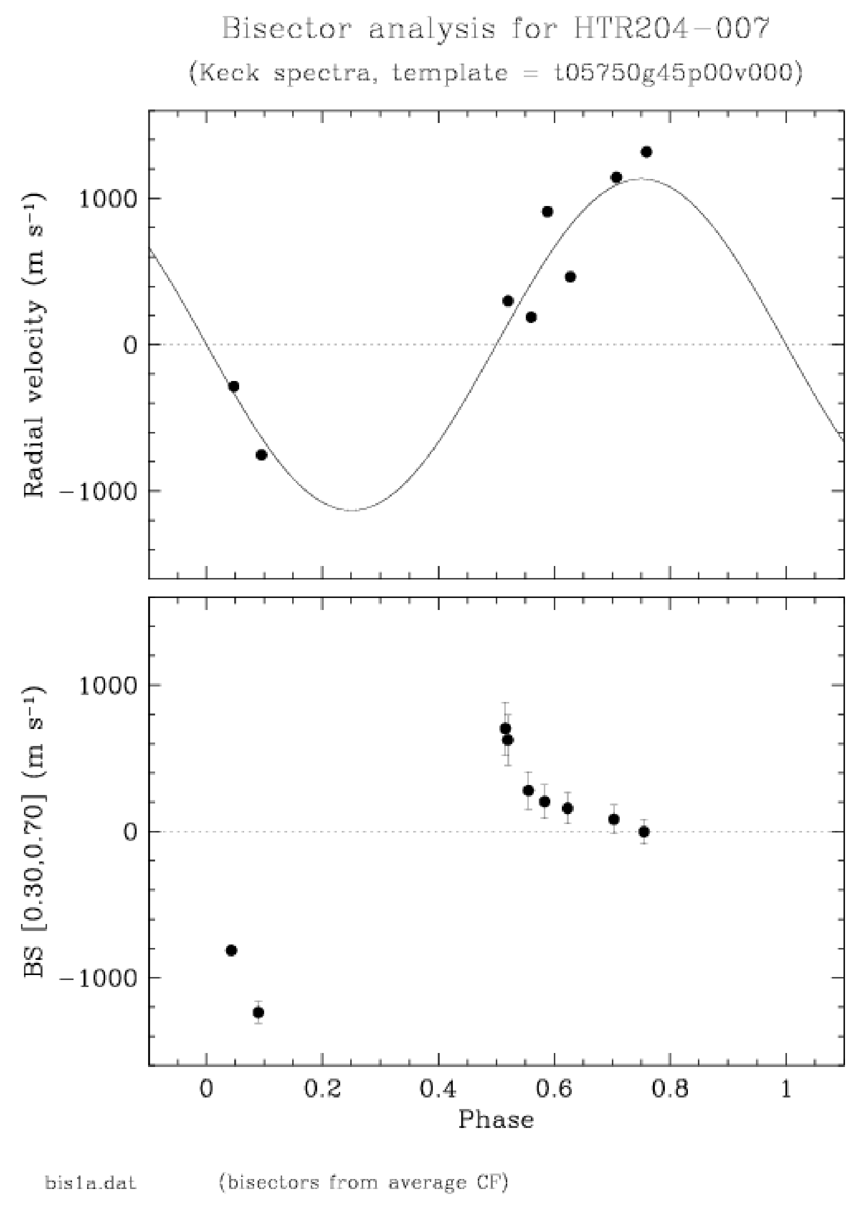




Near-by EB star

Example: HTR204-007





$5M_J$ transit candidate, Keck radial velocities show 1 km/s amplitude AND strong bisector variations in phase with the RV.

Will It Blend? - iPhone

10,860,554

Uploaded by Blendtec on Jul 10, 2007

25,585 likes, 2,937 dislikes

Everybody knows that the iPhone can make phone calls, play movies & music, surf the web, and a lot more. But, Will It Blend? That is the question. Tell us what to blend next here http://on.fb.me/blendstuff.