Exoplanet Discoveries and Lessons from the Suitcase-Sized Space Telescope

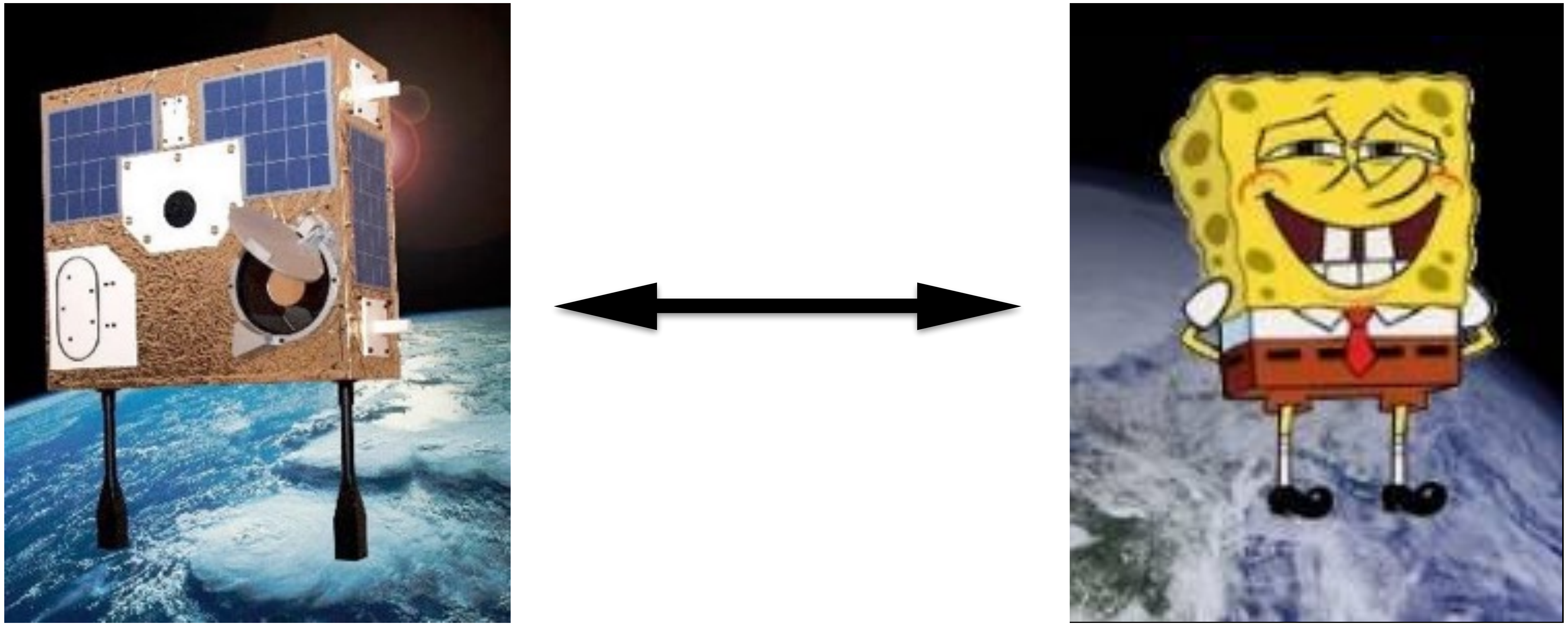
Diana Dragomir[1],
Jaymie Matthews (PI),Chris Cameron,
David B. Guenther, Anthony F. J. Moffat,
Jason F. Rowe, Slavek M. Rucinski,
Dimitar Sasselov, Werner W. Weiss

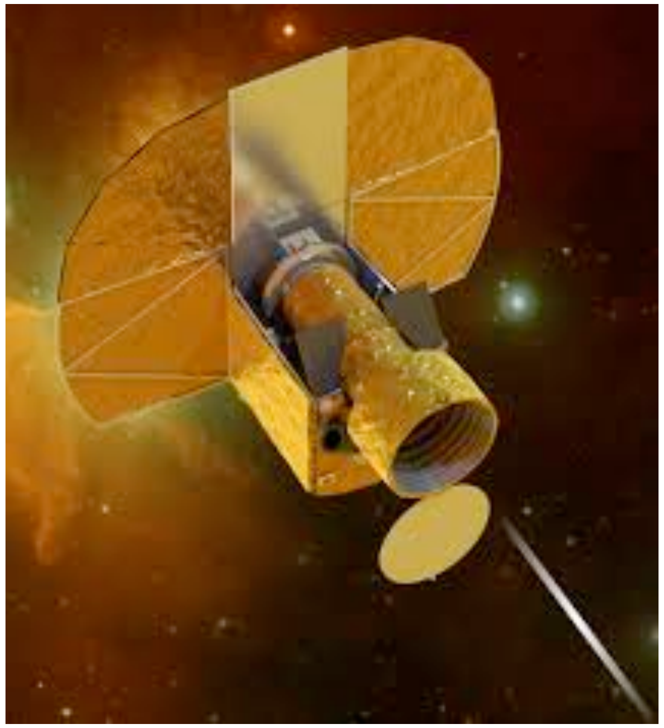
[1]UCSB/Las Cumbres Observatory Global Telescope (LCOGT)

CHEOPS Workshop #3

Madrid, Spain

June 18, 2015





?

MOST = Microvariability and Oscillations in STars

Microvariabilité et Oscillations STellaires

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First space telescope dedicated to asteroseismology

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Designed with exceptional pointing stability for μmag precision photometry (in frequency space)

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Microvariabilité et Oscillations STellaires

First space telescope dedicated to asteroseismology

Designed with exceptional pointing stability for μmag precision photometry (in frequency space)

Intended mission lifetime: 1 year

Actual mission lifetime: 10+ years

MOST Space Telescope

Weight = 54 kg

Size = 60×60×30 cm

Power: solar panels (peak ~ 38 W)

Attitude Control System: reaction wheels (pointing accuracy ~ 1”)

Communication: three ground stations using S-band frequency (~ 2 GHz)

Cost: 6 million USD

MOST Space Telescope

- 15-cm optical telescope
- 101.4 minutes low-Earth Sun-Synchronous (polar) orbit
- Continuous Viewing Zone (CVZ) with a declination range of $-18^{o} \leq \delta \leq +36^{o}$

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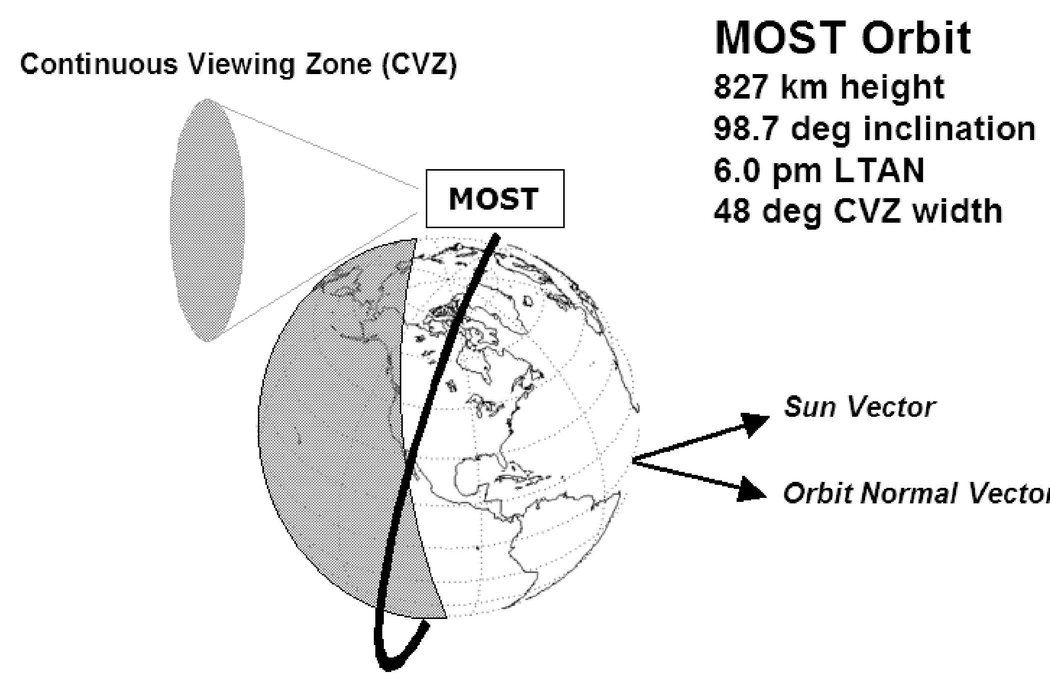
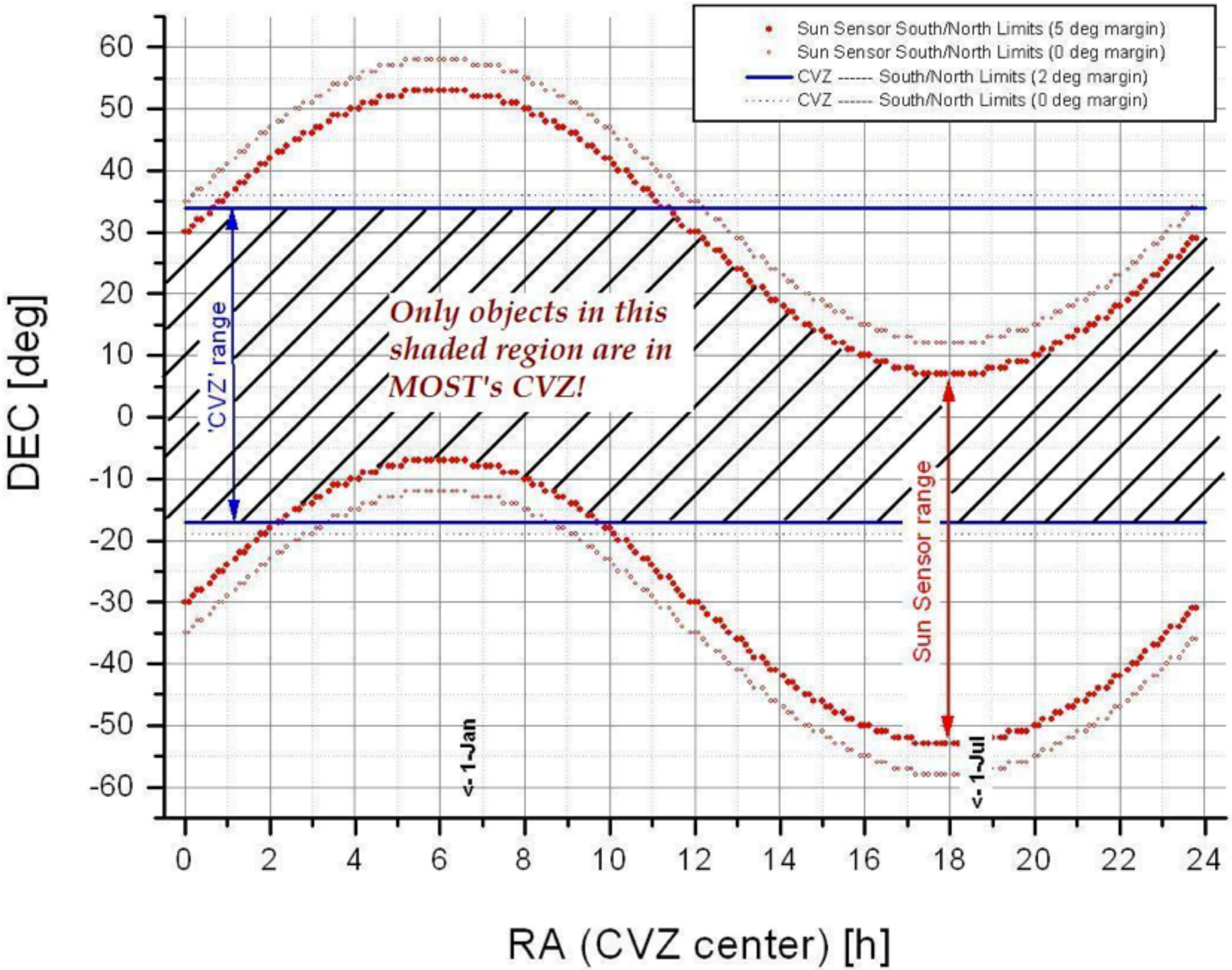
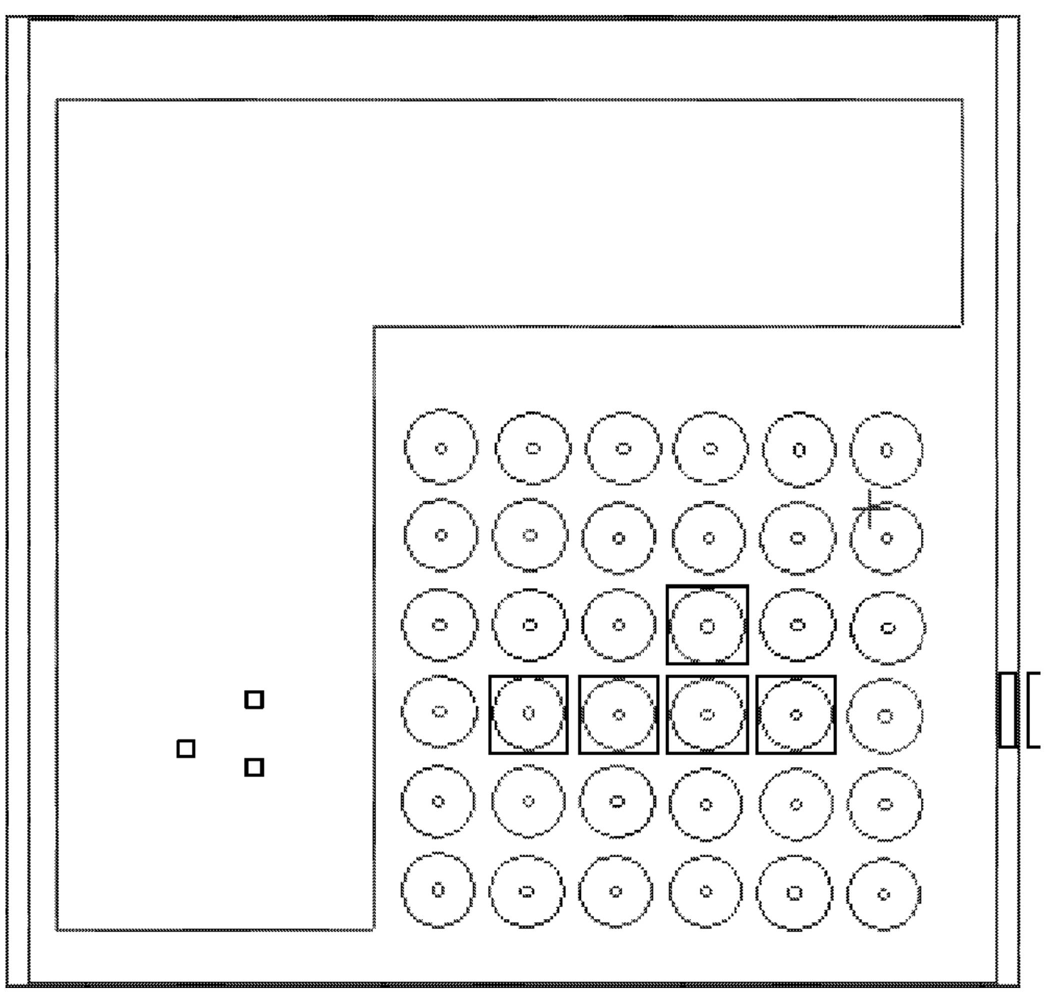


MOST Observing Limits and Continuous Viewing Zone



Observing modes:

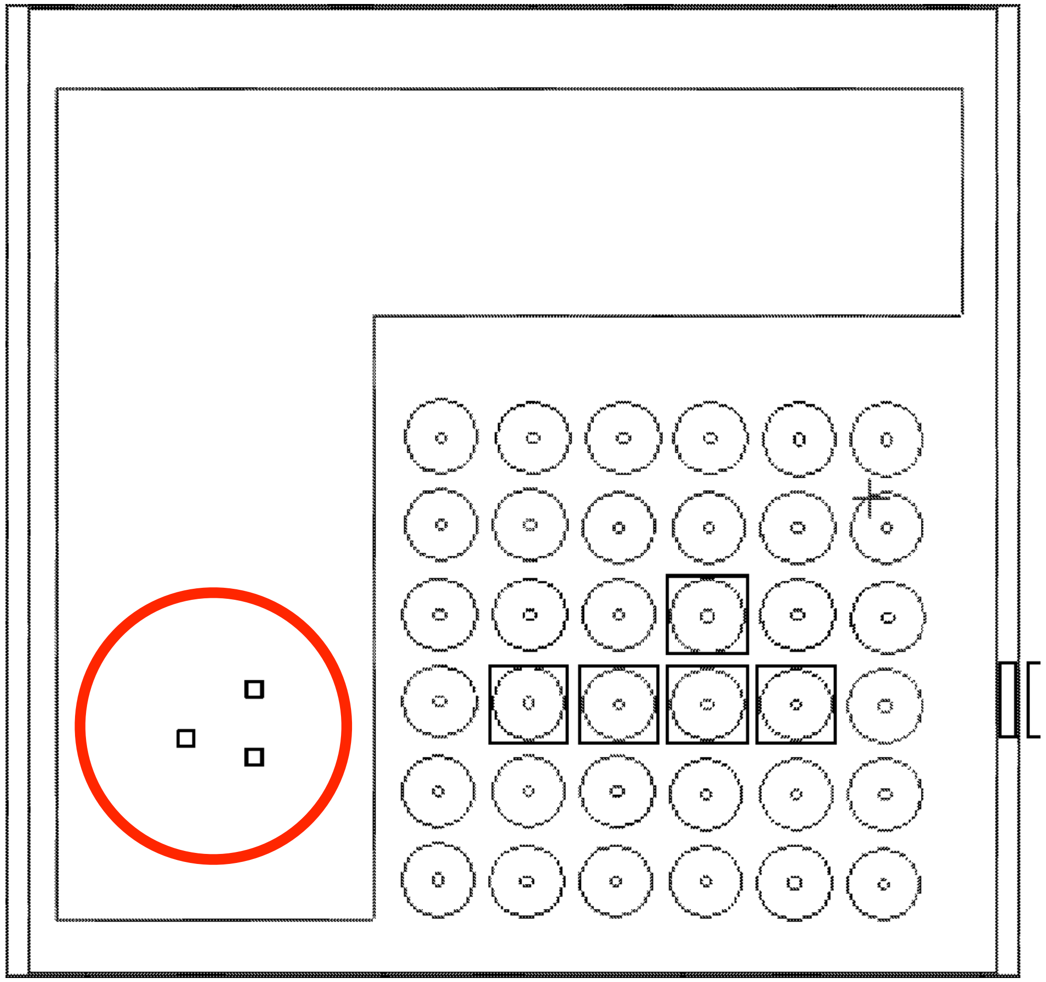
➡ Direct Imaging:
targets with magnitude
5 ≥ V ≥ 12



➡ Fabry Imaging:
targets brighter than V≈5

Observing modes:

➡ Direct Imaging:
targets with magnitude
5 ≥ V ≥ 12



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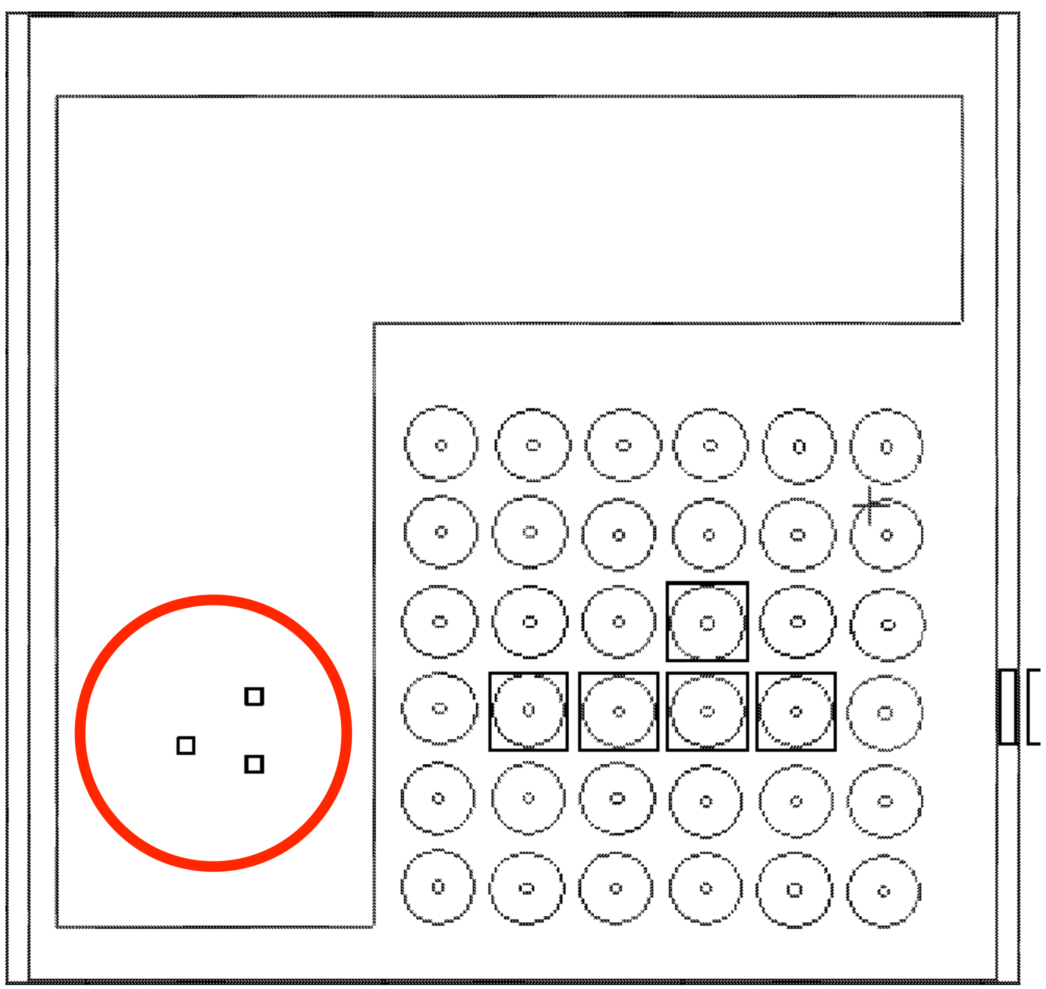

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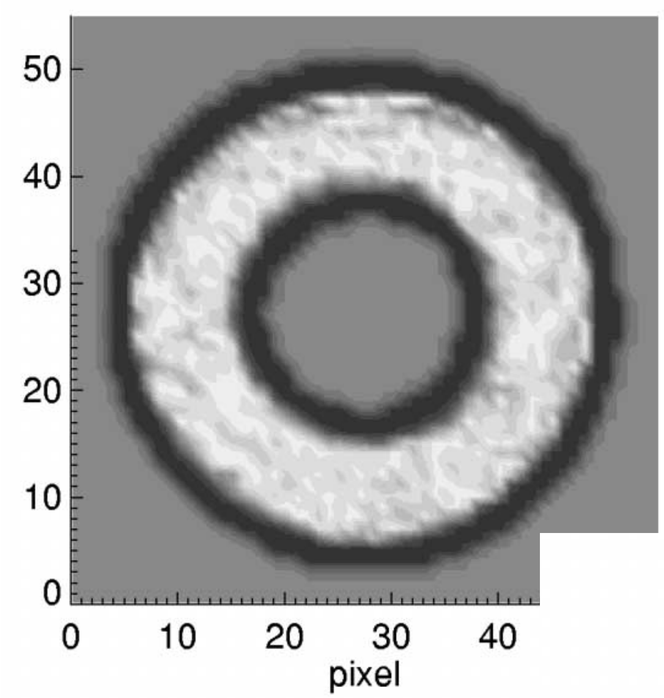
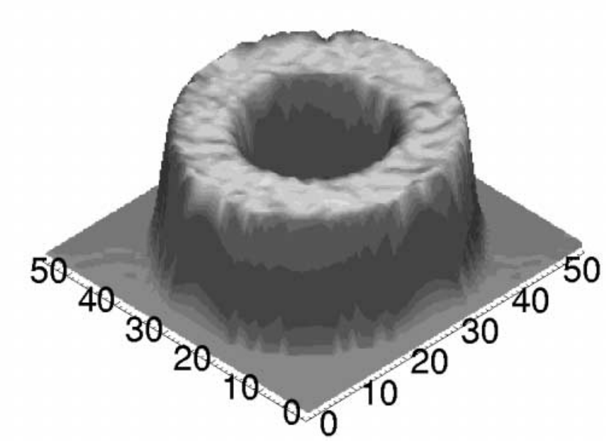
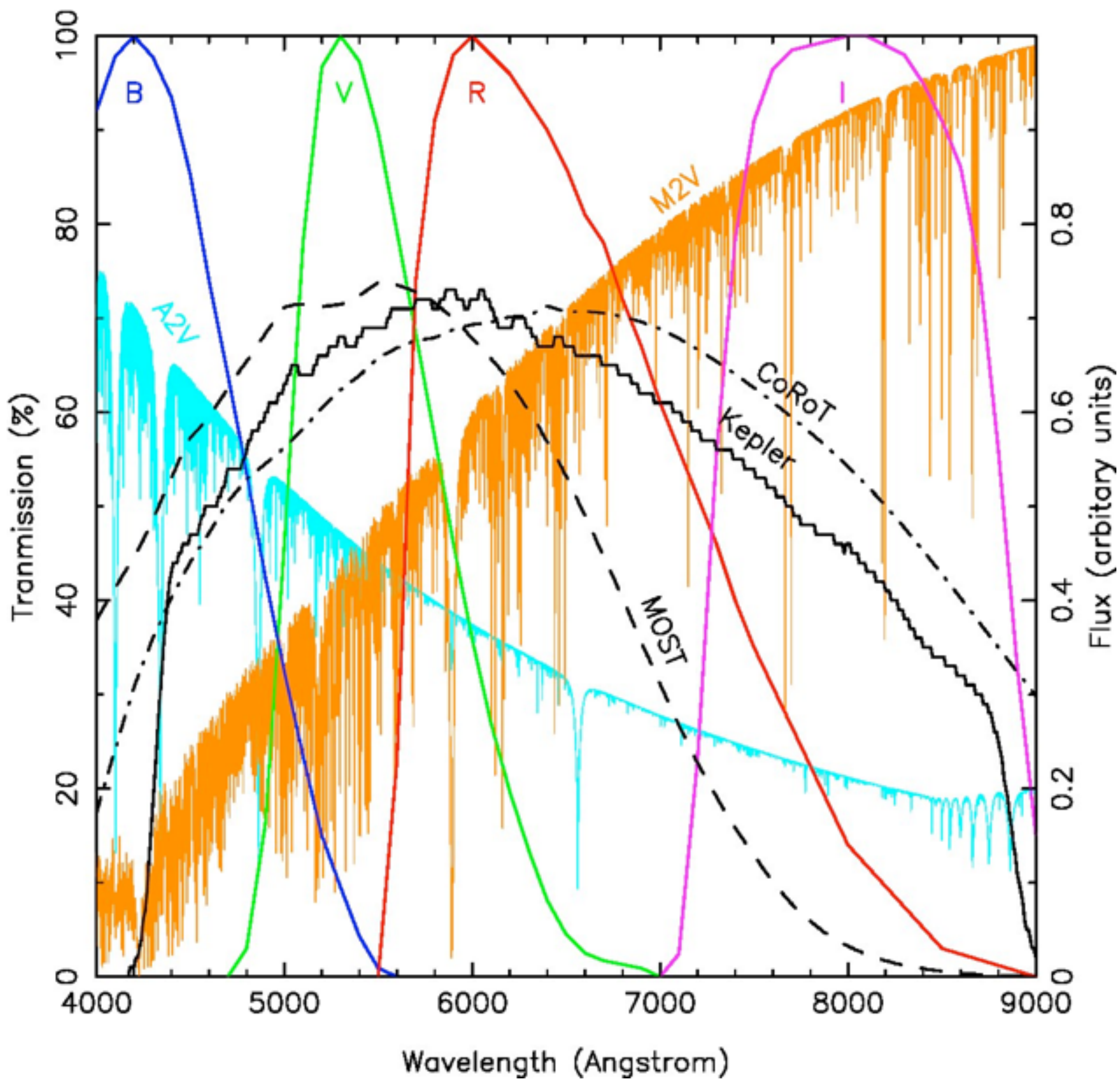
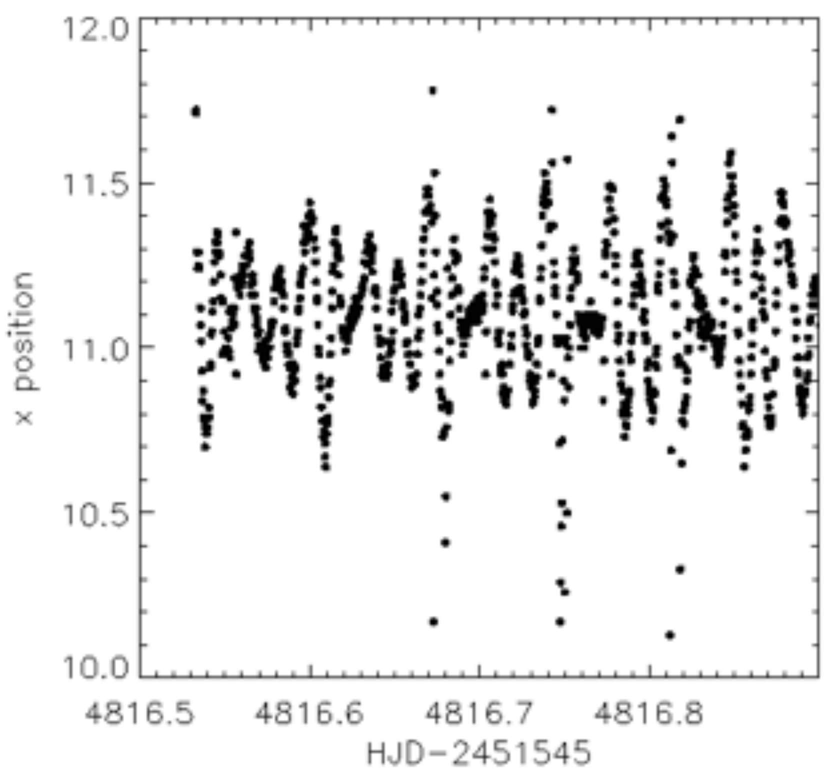


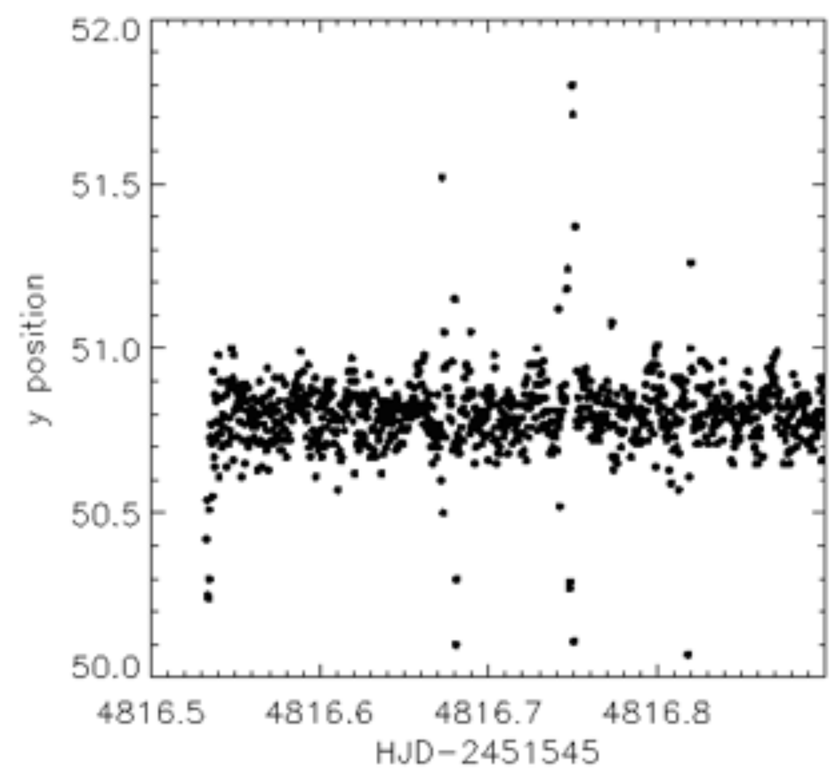


MOST Space Telescope



Correlated Noise Sources





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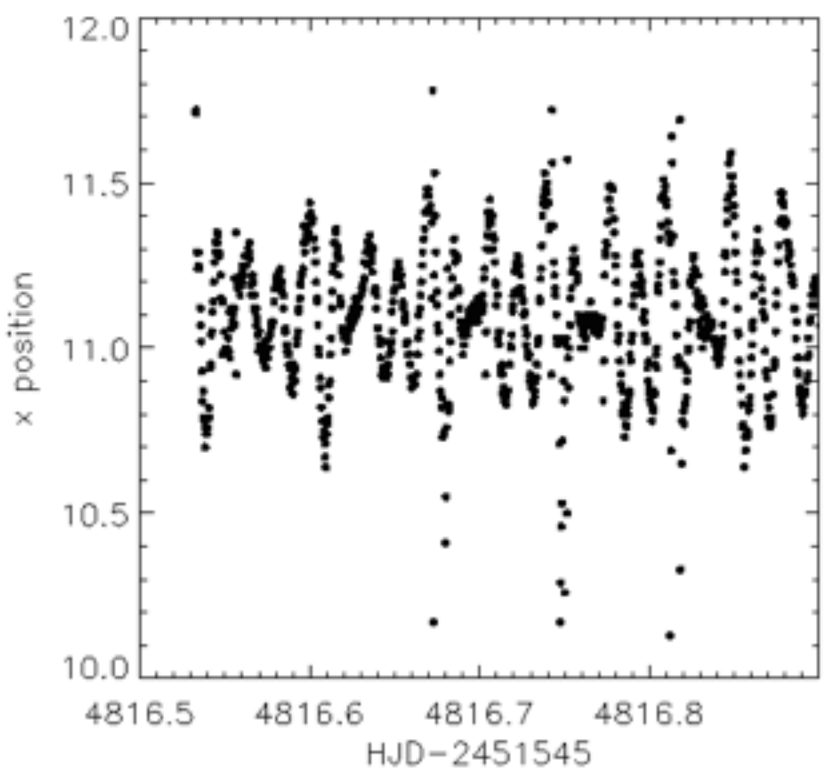
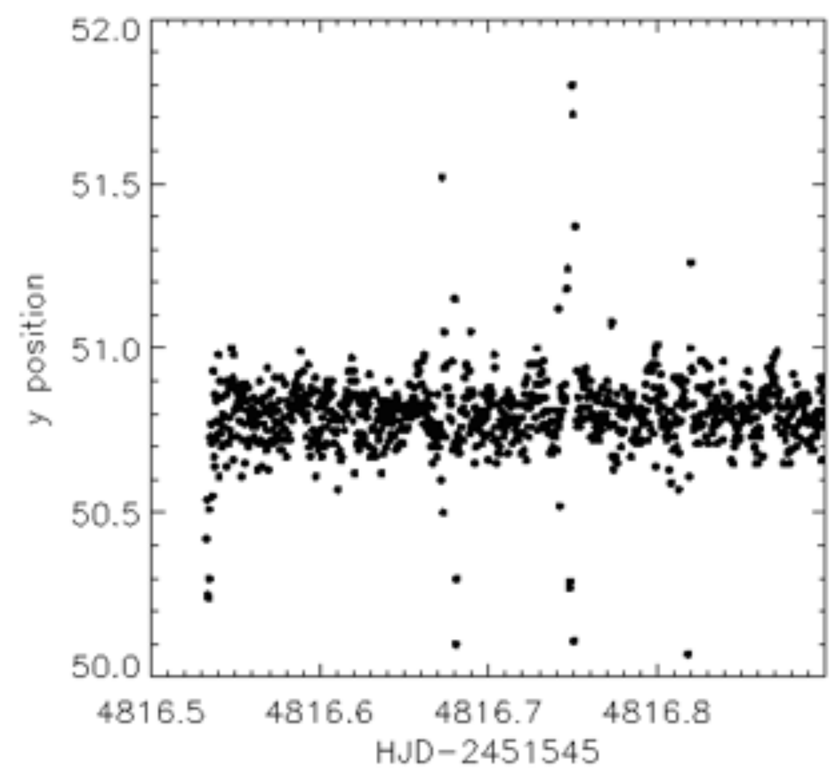
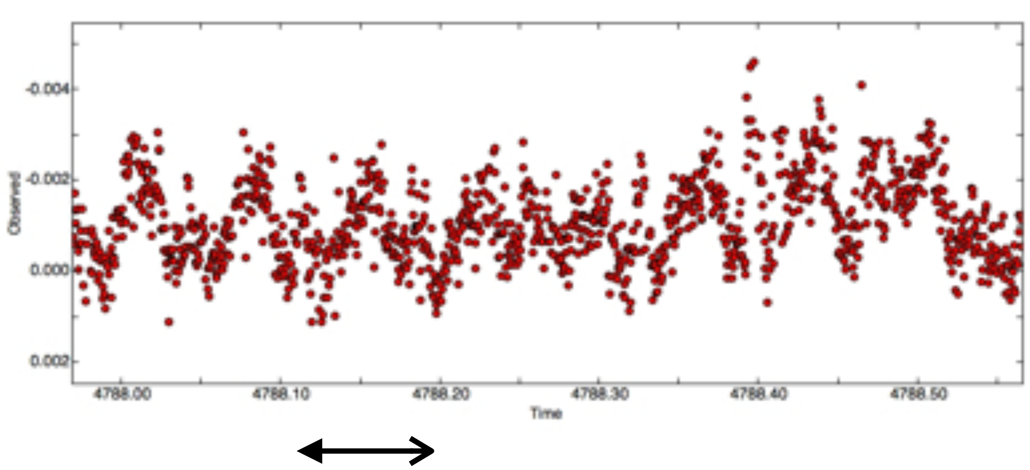
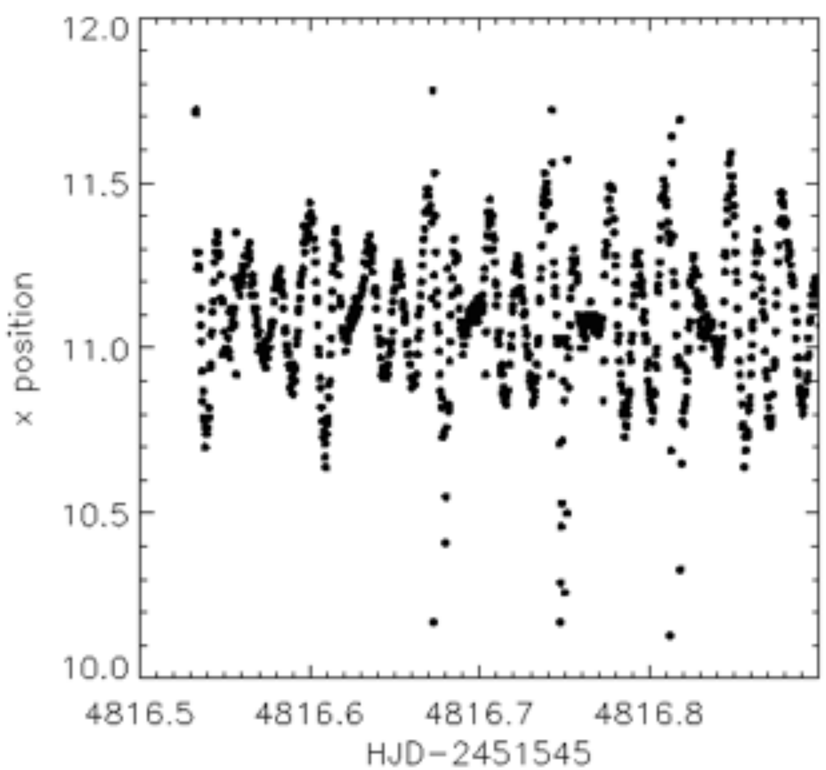


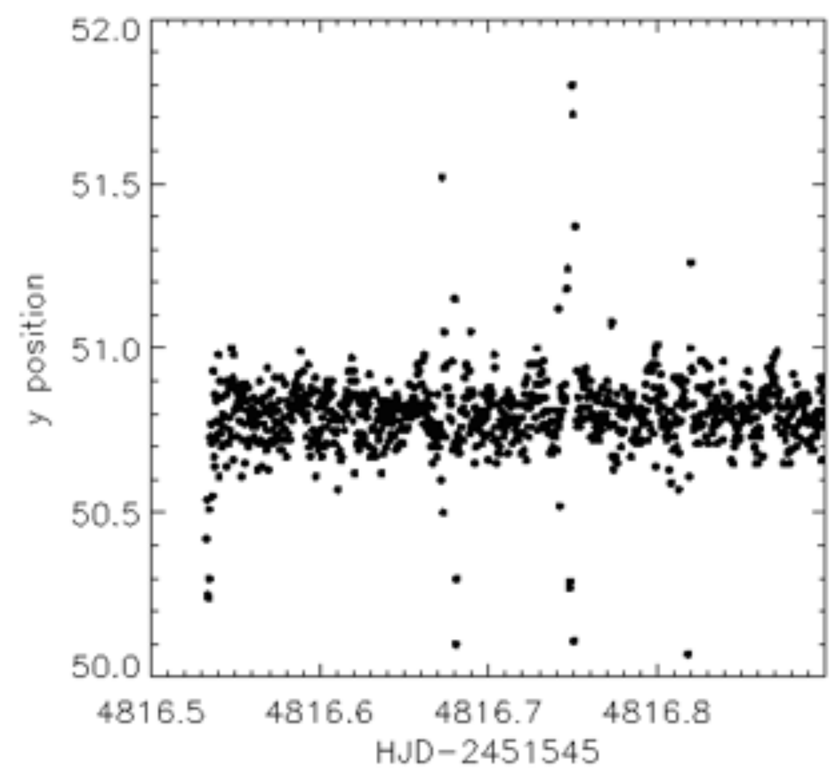


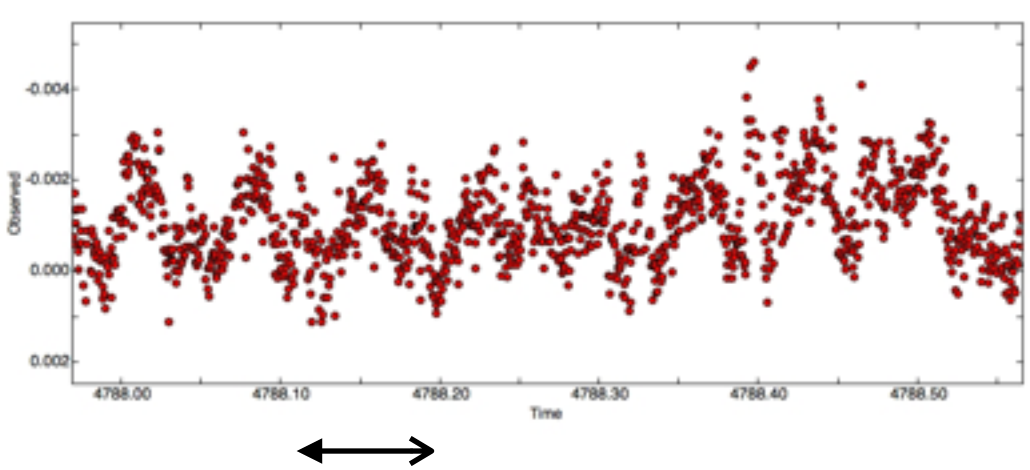


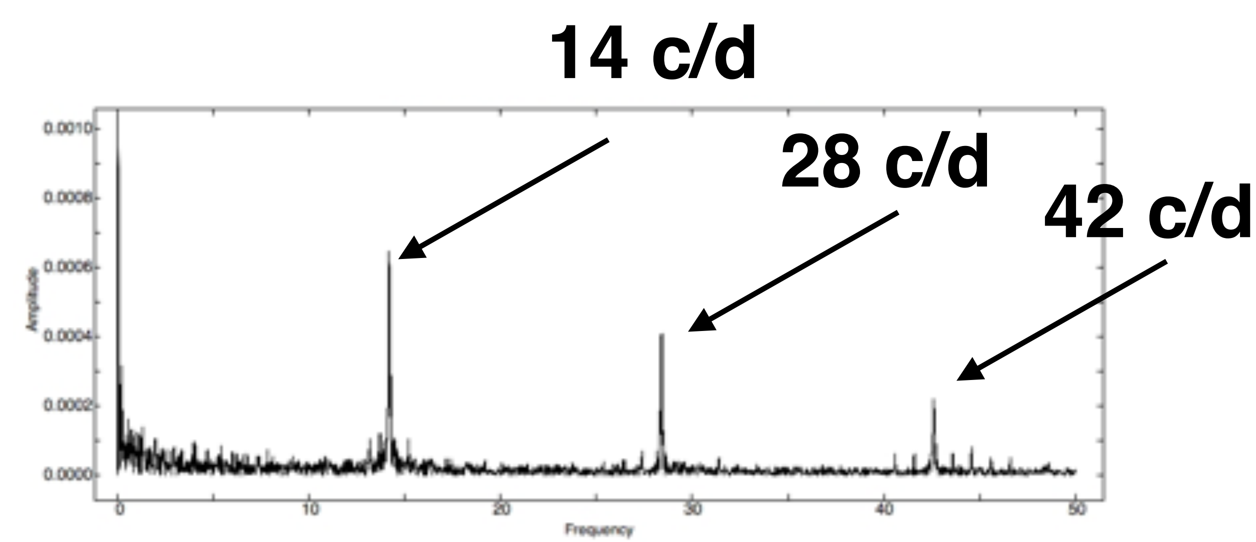
101 minutes (→ 14 cycles/day)

Correlated Noise Sources



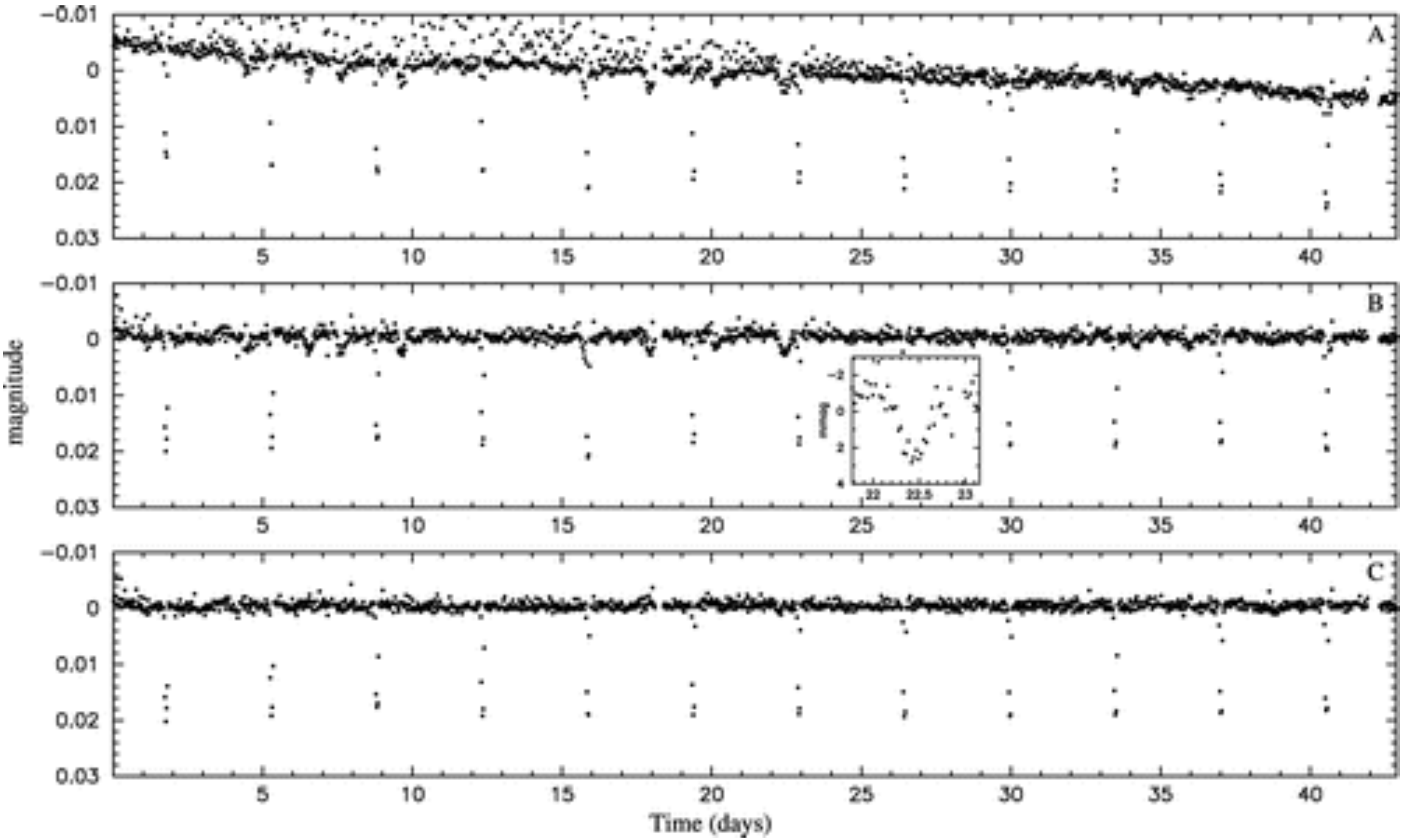






101 minutes (→ 14 cycles/day)

The First Measurement of the Albedo of an Exoplanet



Rowe et al. (2008)

V = 7.7

HD 189733b

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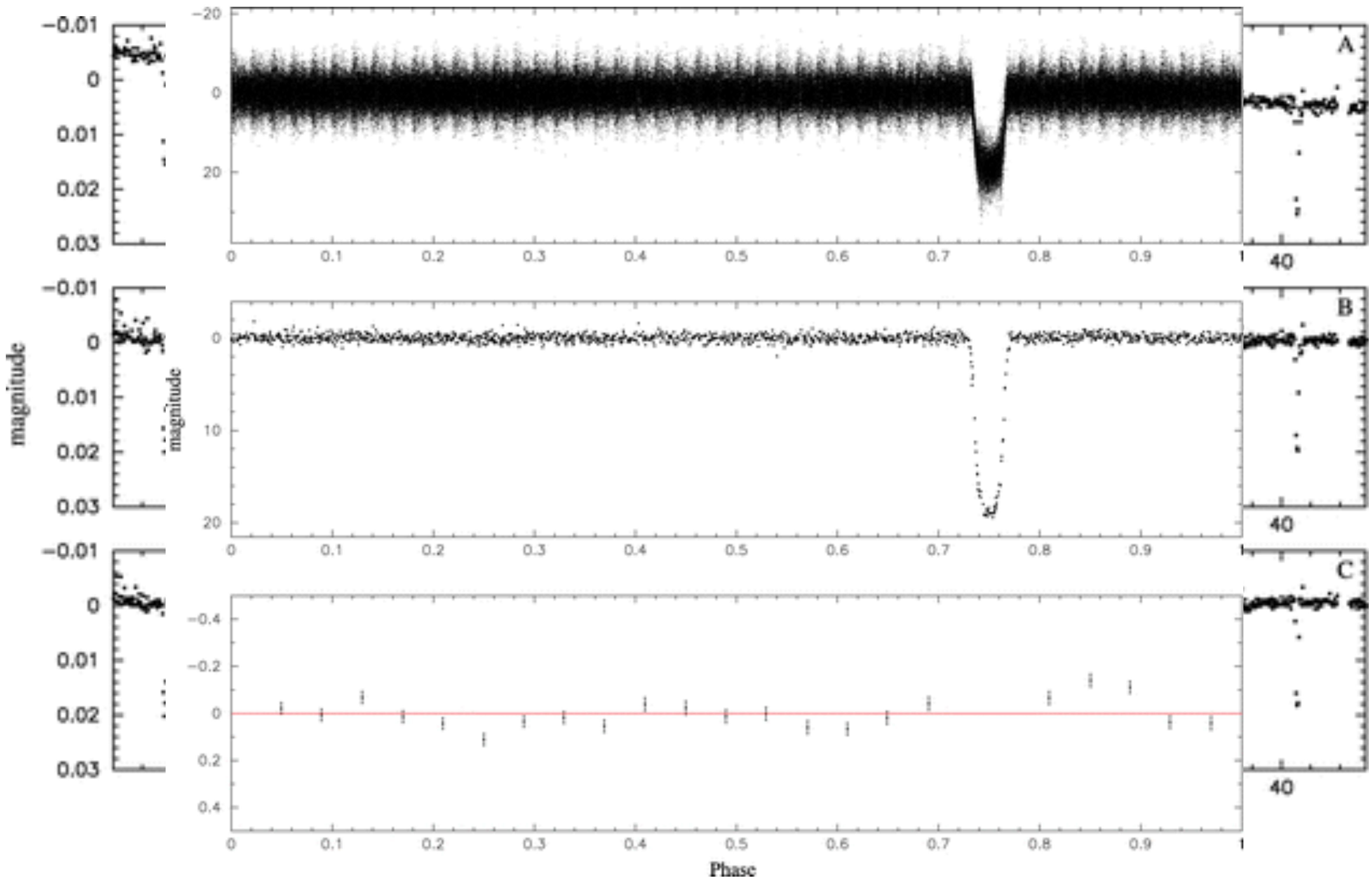

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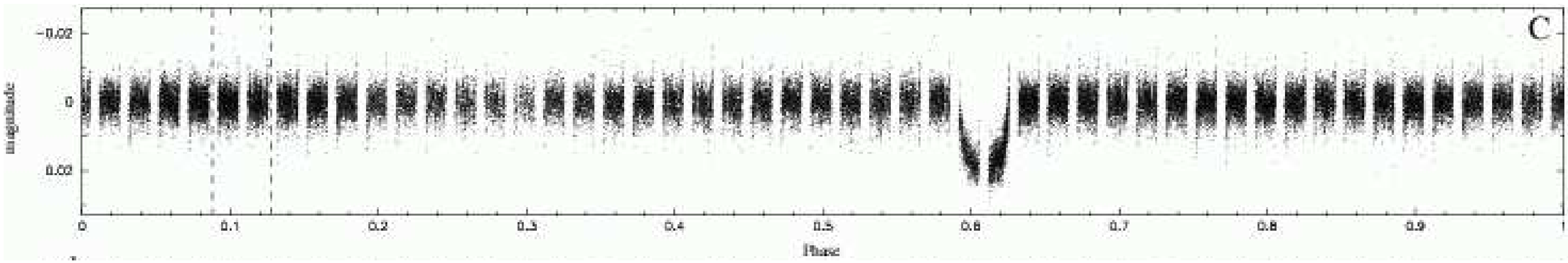


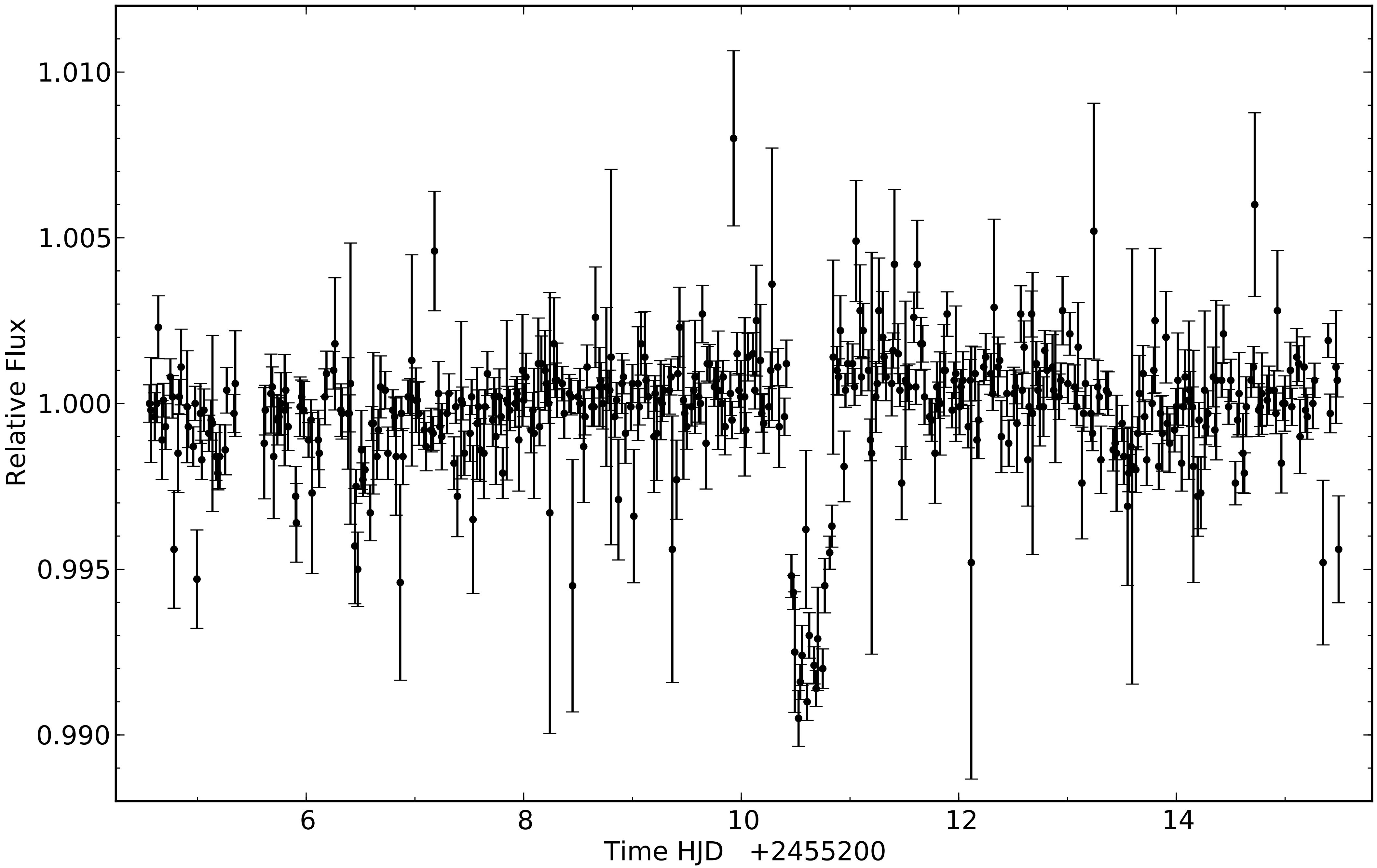
The First Measurement of the Albedo of an Exoplanet

The First Measurement of the Albedo of an Exoplanet

$A_g = 0.038 \pm 0.045$

2σ upper limit of 0.13

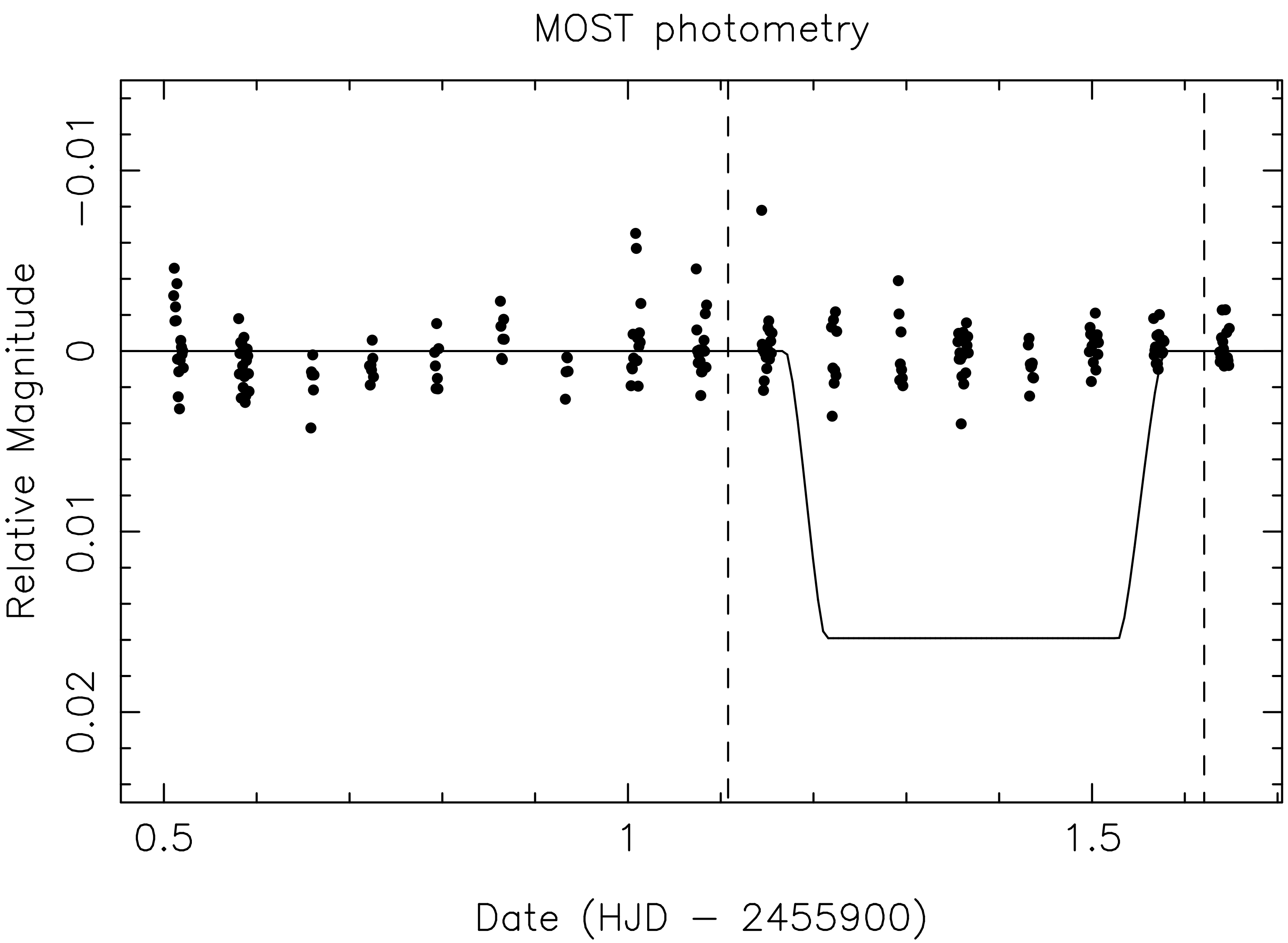
HD 80606b



V = 8.9

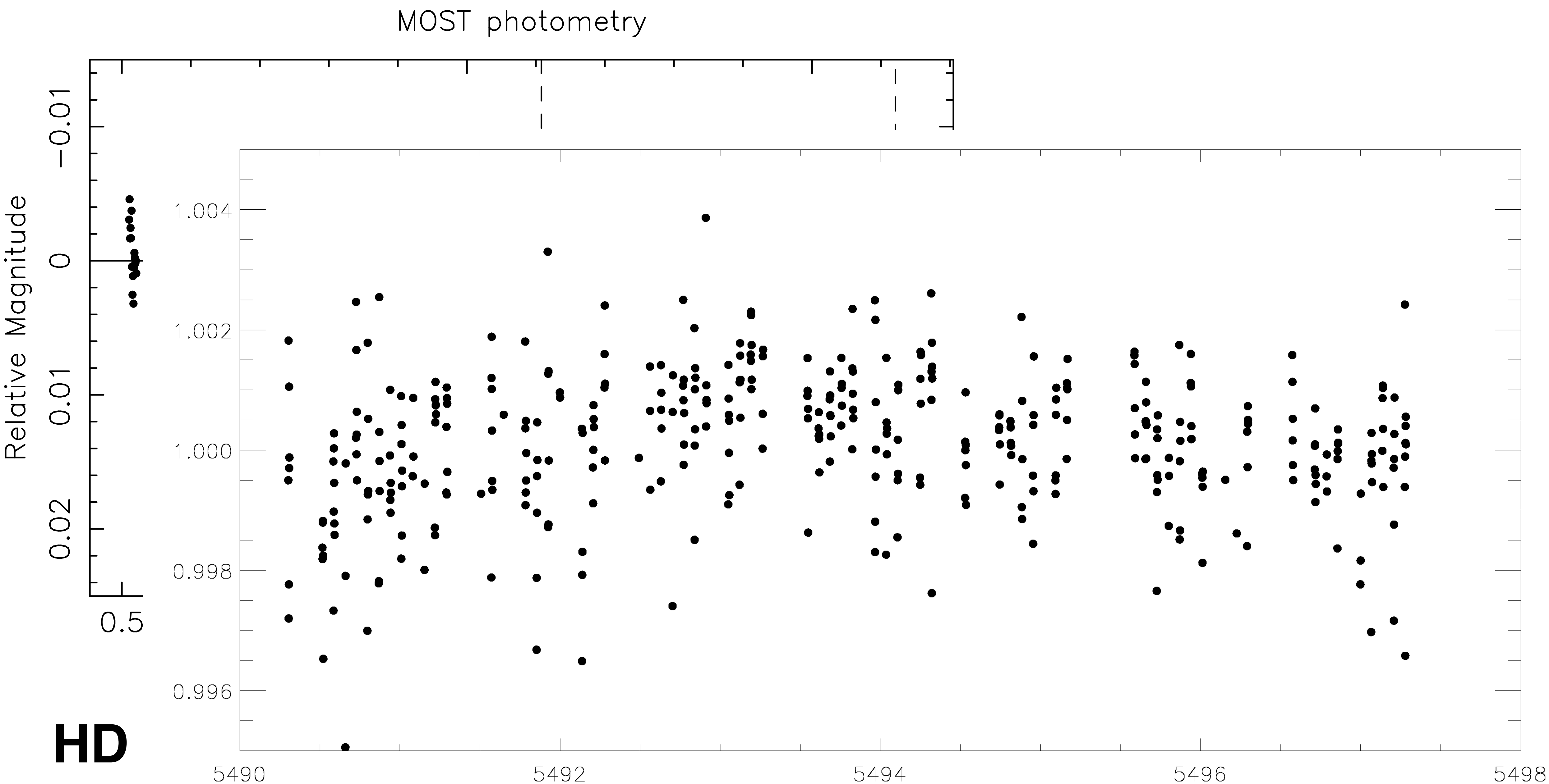
Roberts et al. (2013)

MOST Photometry for TERMS



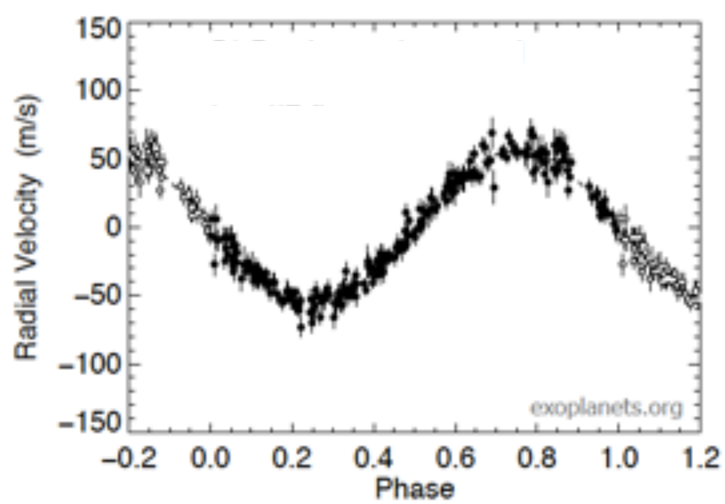
HD 37605b **V = 8.7** Wang et al. 2012

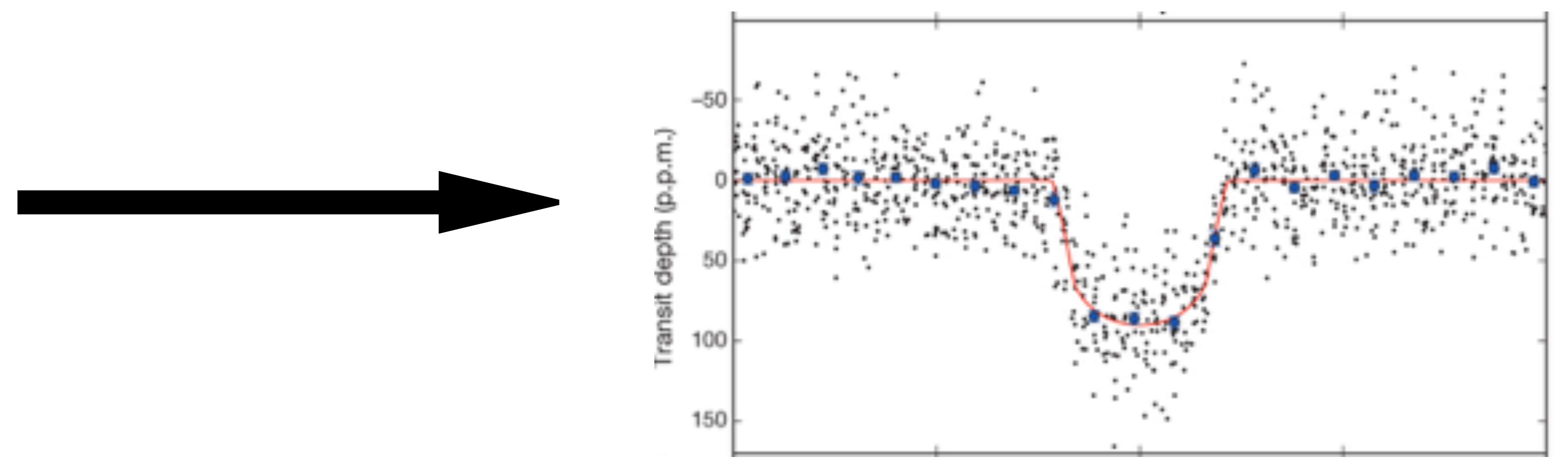
MOST Photometry for TERMS



HD 20782b **V = 7.4** Kane et al. (in prep.)

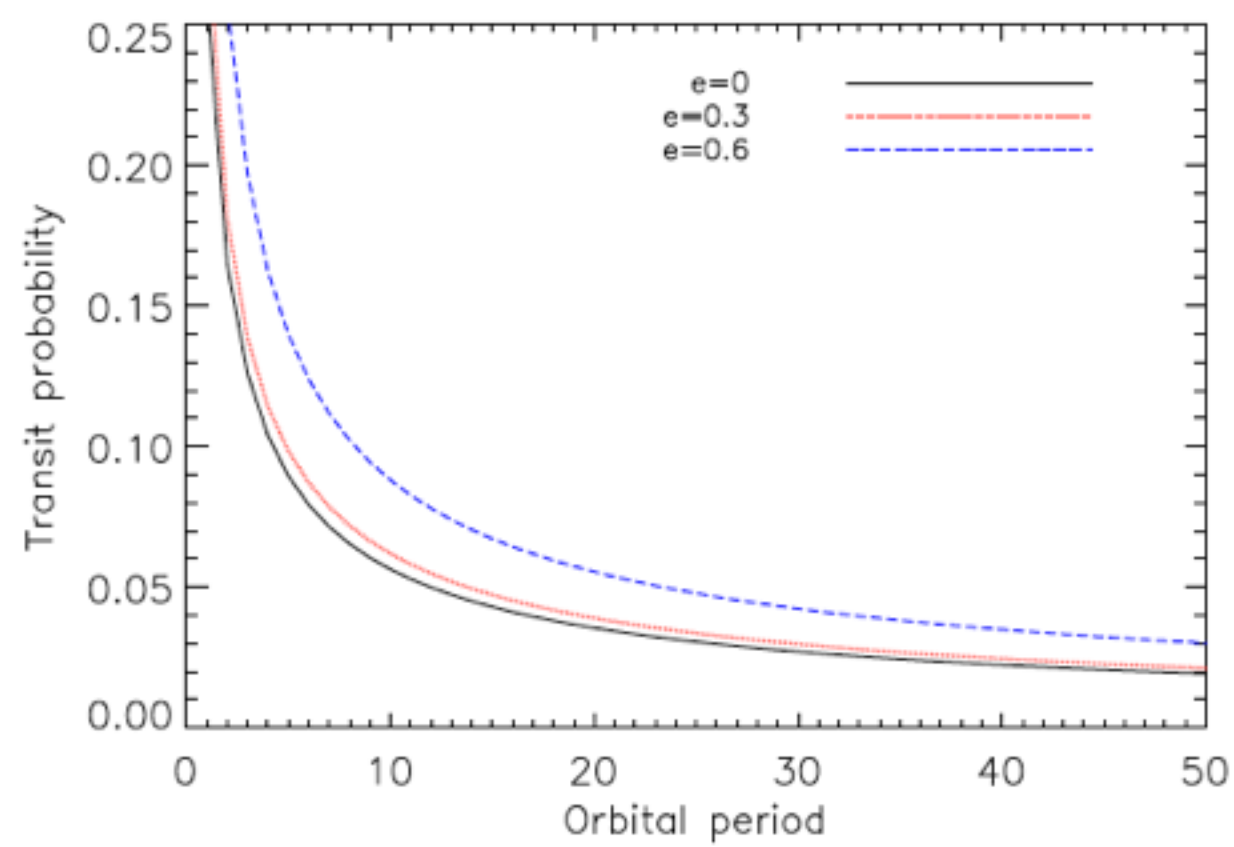
MOST Transit Search





Barclay et al. (2013)

- Exoplanets detected via radial velocity by the HARPS and HIRES surveys;
- Host stars with **V < 12** and accessible to MOST;
- Planets with **minimum mass in the super-Earth regime** (between 1 and 10 $M_\oplus$);
- Orbital **period ≤ 10 days**, leading to transit probability **≥ 5 %**;
- A total of 12 super-Earth candidates were observed.



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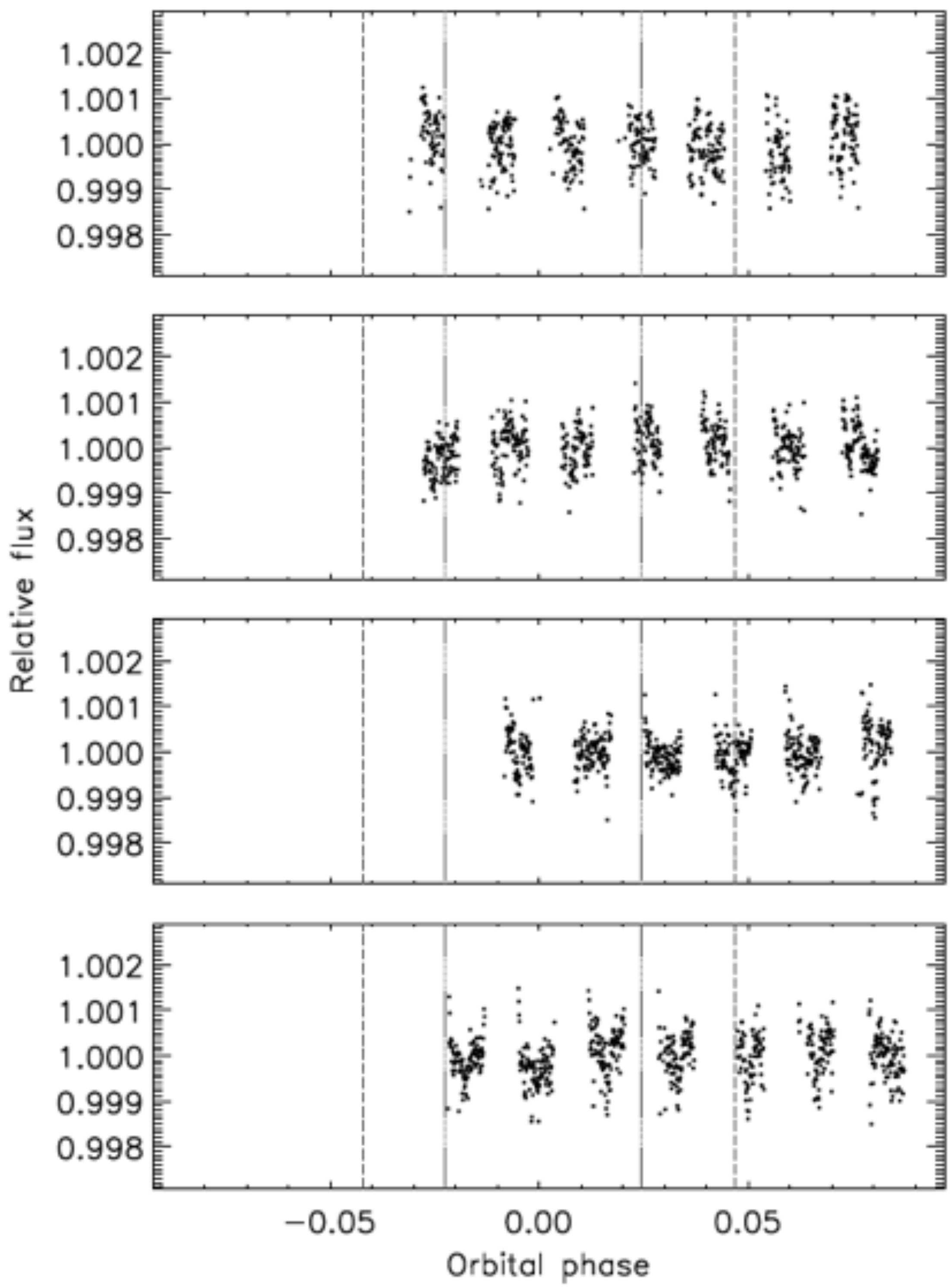

HD 115617b (61 Vir b)

$P = 4.21429 \pm 0.00046$ days

Determine predicted **transit times** and **transit window size** within the period of observability with MOST from the RV-derived ephemeris (the time of inferior conjunction ***T0*** and the orbital period ***P***):

$$T0_{new} = T0 + nP$$

$$T_{beg} = (T0 - \delta_- T0) + n(P - \delta_- P)$$
$$T_{end} = (T0 + \delta_+ T0) + n(P + \delta_+ P)$$

Observe during at least 2 predicted transit windows.

HD 156668b

RA: 17h 17m 40s   Dec: +29° 13′ 38″ → Not in the CVZ!

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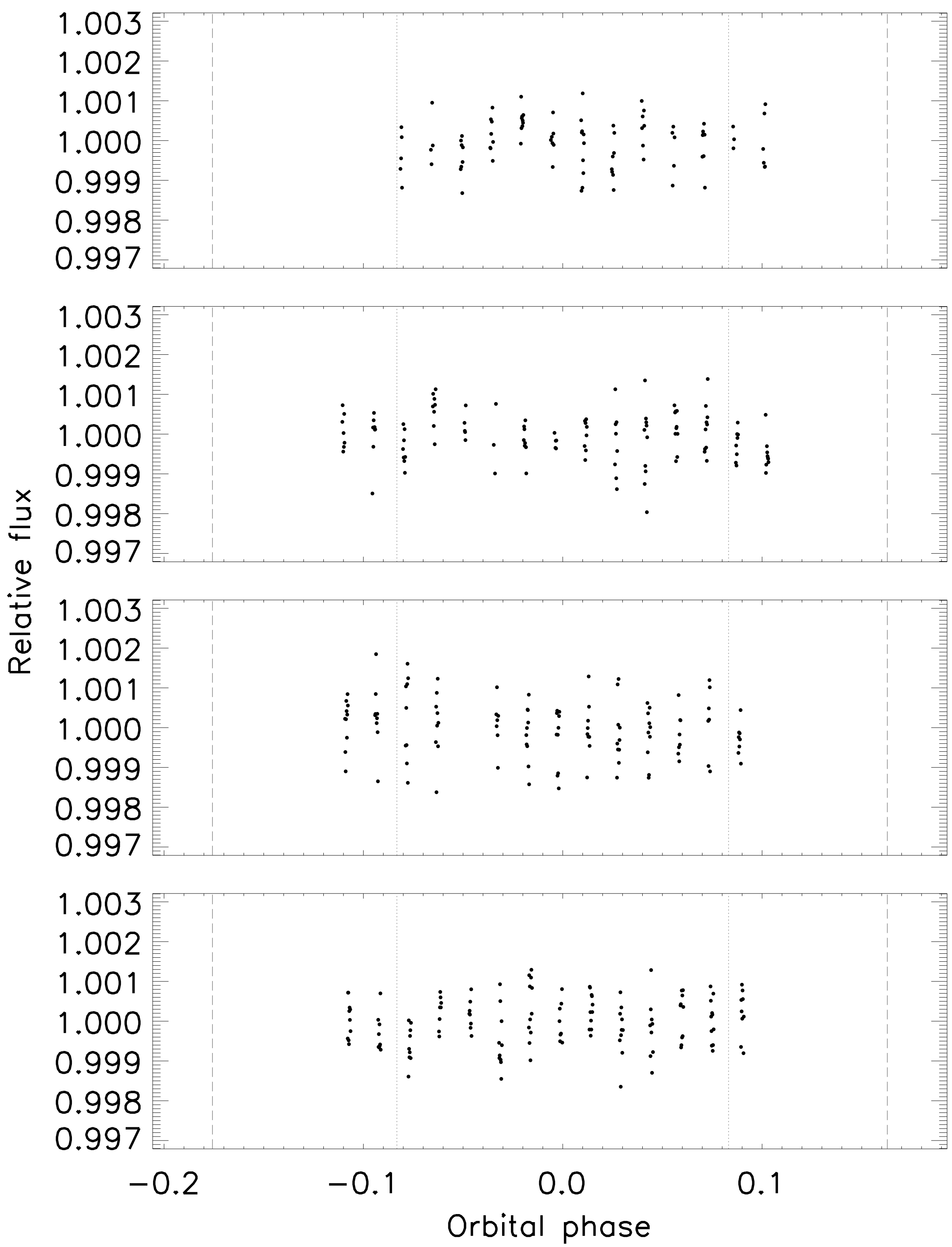
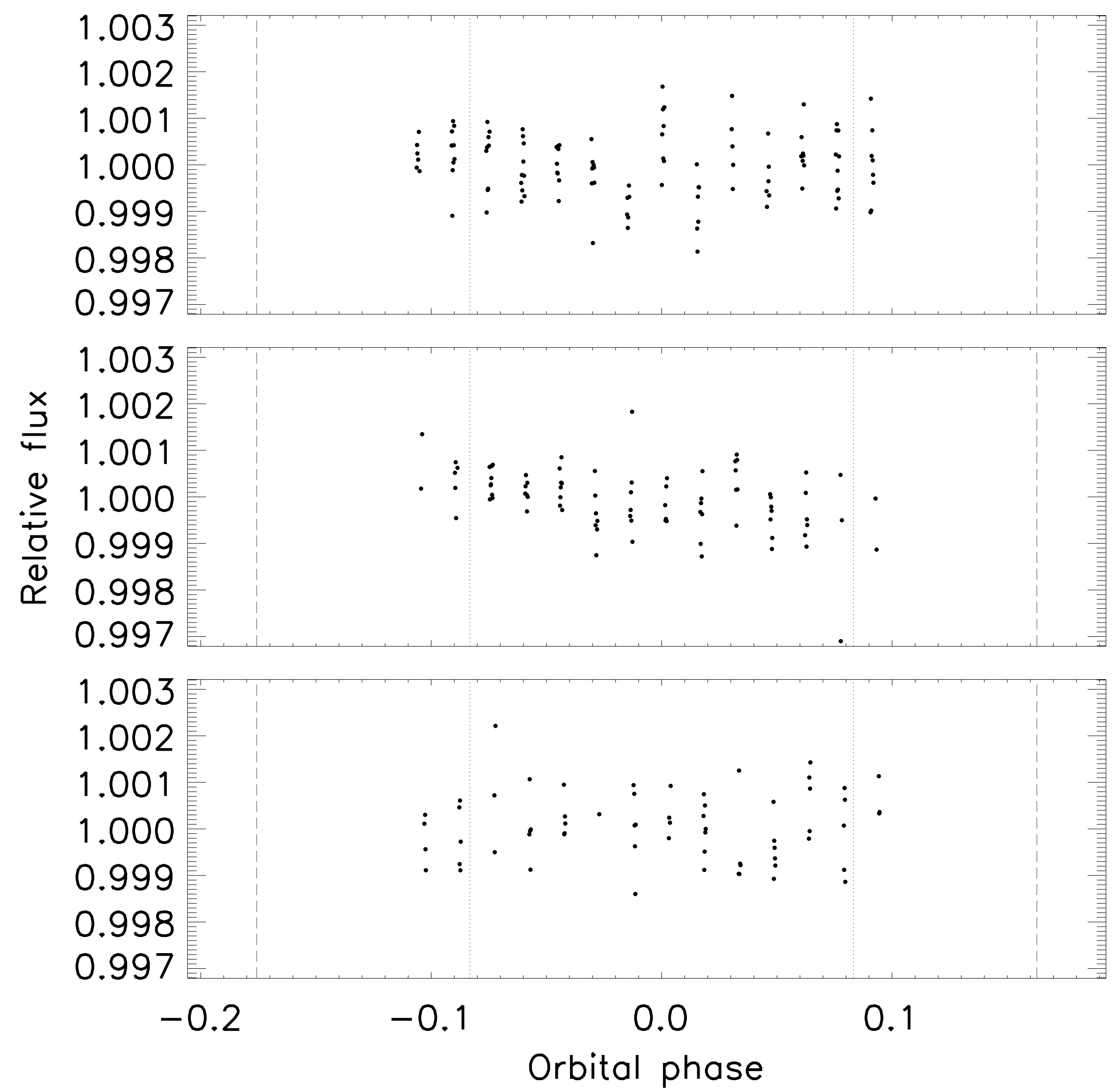
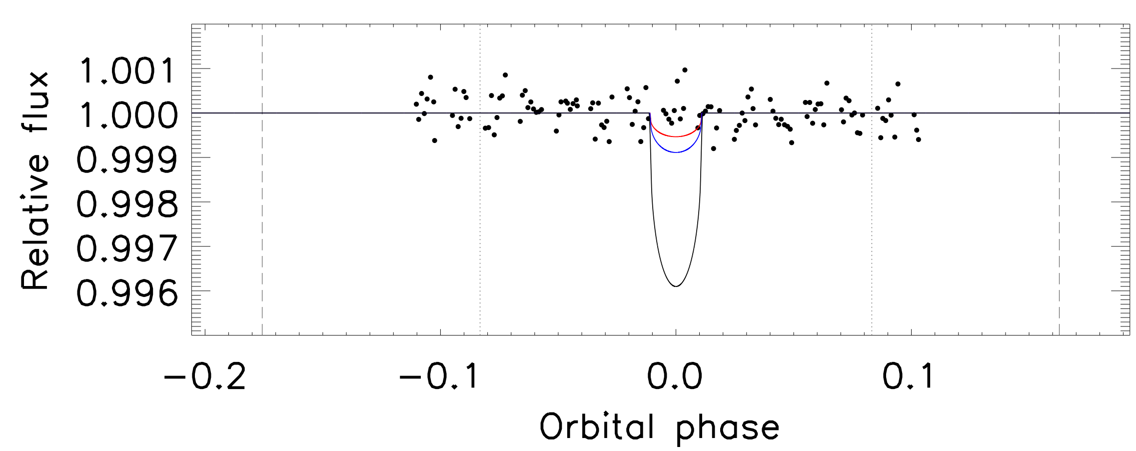




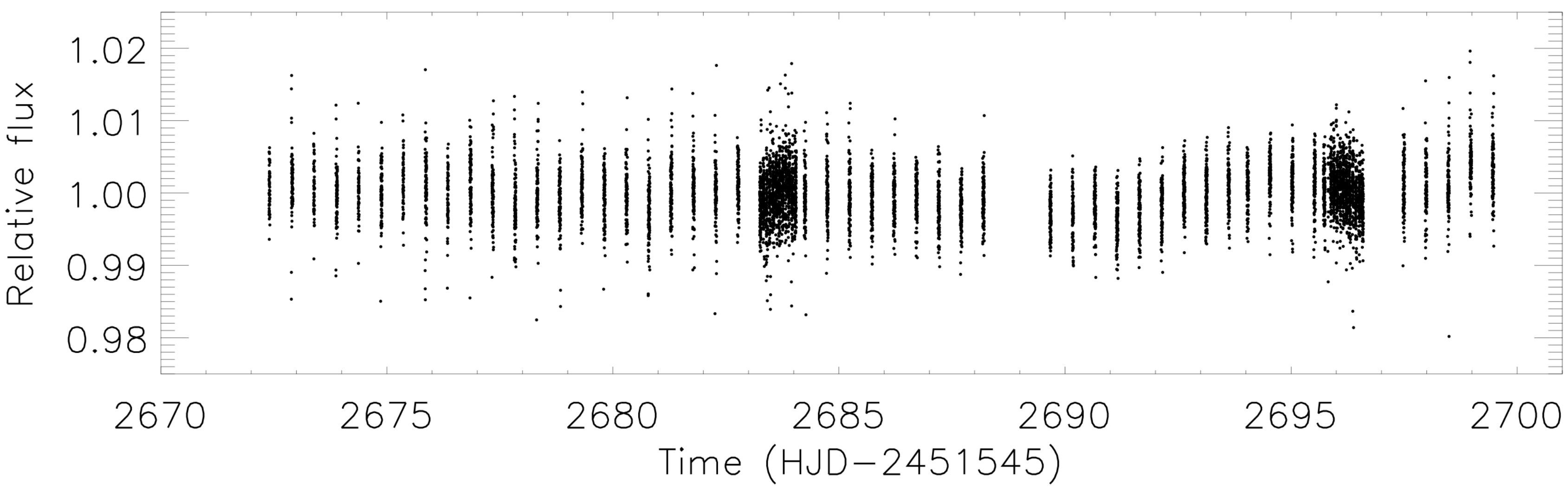


MOST Survey Results

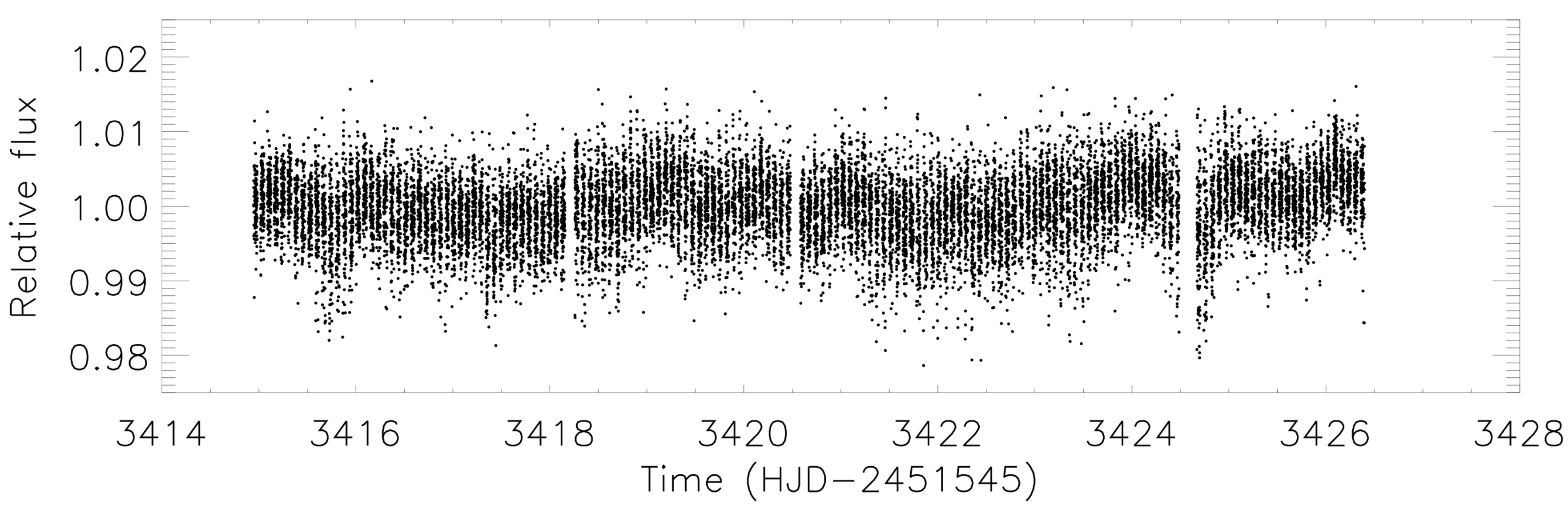
Planet	Period (d)	Transit probability (%)	Transit window coverage	Radius upper limits ($R_\oplus$) and composition constraints
GJ 581e	3.15	5	full	1.6 (water ice)
BD 082823b	5.59	6.7	1σ	2.13 (silicate)
HD 1461b	5.77	8	full	-
HD 69830b	8.67	5.2	< 1σ	5.4 (H/He)
HD 96700b	8.13	6.6	marginal	5.0 (H/He)
HD 115617b	4.21	9.8	most of 2σ	1.74 (silicate)
HD 125595b	9.67	4.5	most of 1σ	2.75 (water ice/silicate)
HD 125612c	4.16	13	2σ; contains gaps	3.02 (water ice)
HD 156668b	4.64	7	1σ	2.05 (water ice/silicate)
HD 160691c	9.64	5.6	< 1σ	5.5 (H/He)
55 Cnc e	**0.74**	**30**	**full**	**transit detected**
HD 97658b	**9.49**	**4**	**3σ**	**transit detected**

Cumulative: 68%

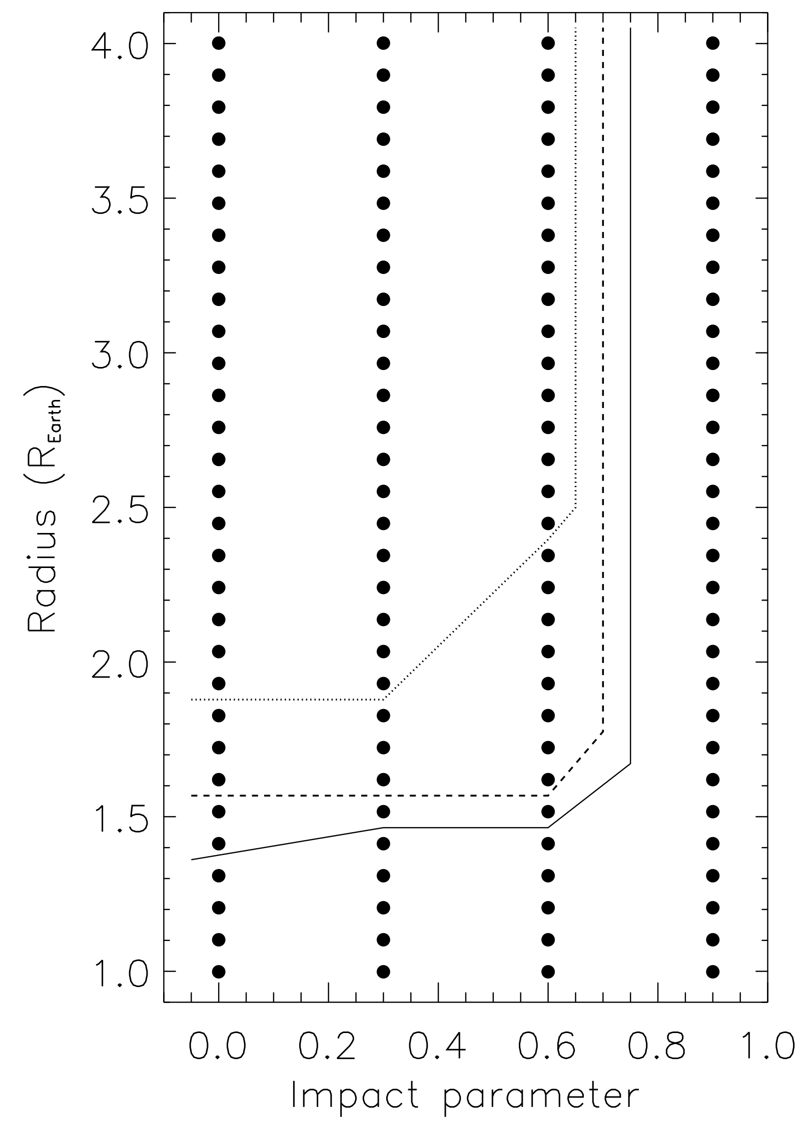
A Search for Transits of GJ 581e



2007 photometry



2009 photometry



55 Cnc e
Background and Discovery

55 Cancri A (G8 dwarf, V=5.95) has 5 known planets.

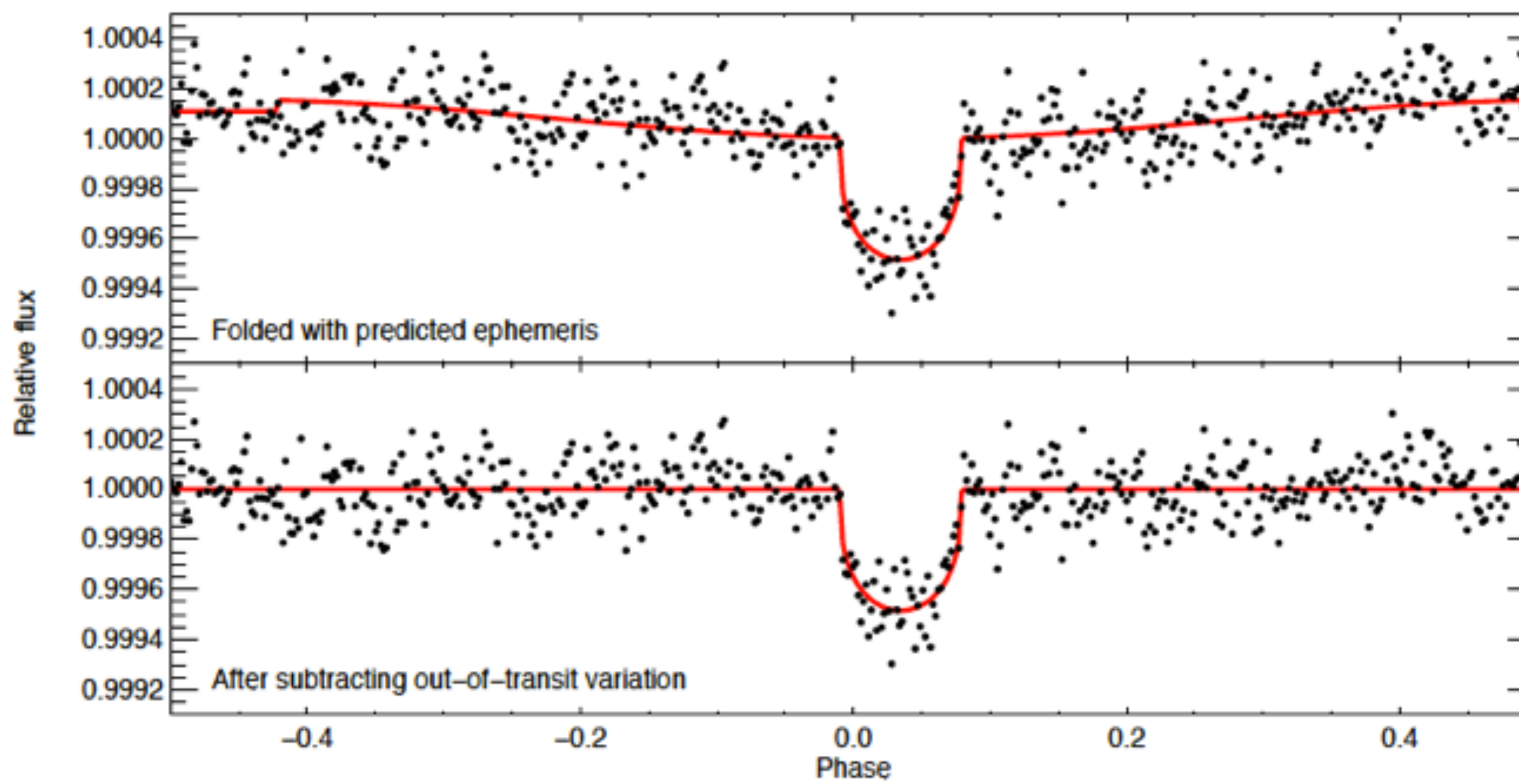
Dawson & Fabrycky (2010) reanalyzed the discovery RV data (McArthur et al. 2004, Fischer et al. 2008) and predicted it could have a much shorter orbital period:

P =0.74 days = 17h 41m,

leading to a *a priori* transit probability of **~30%**.

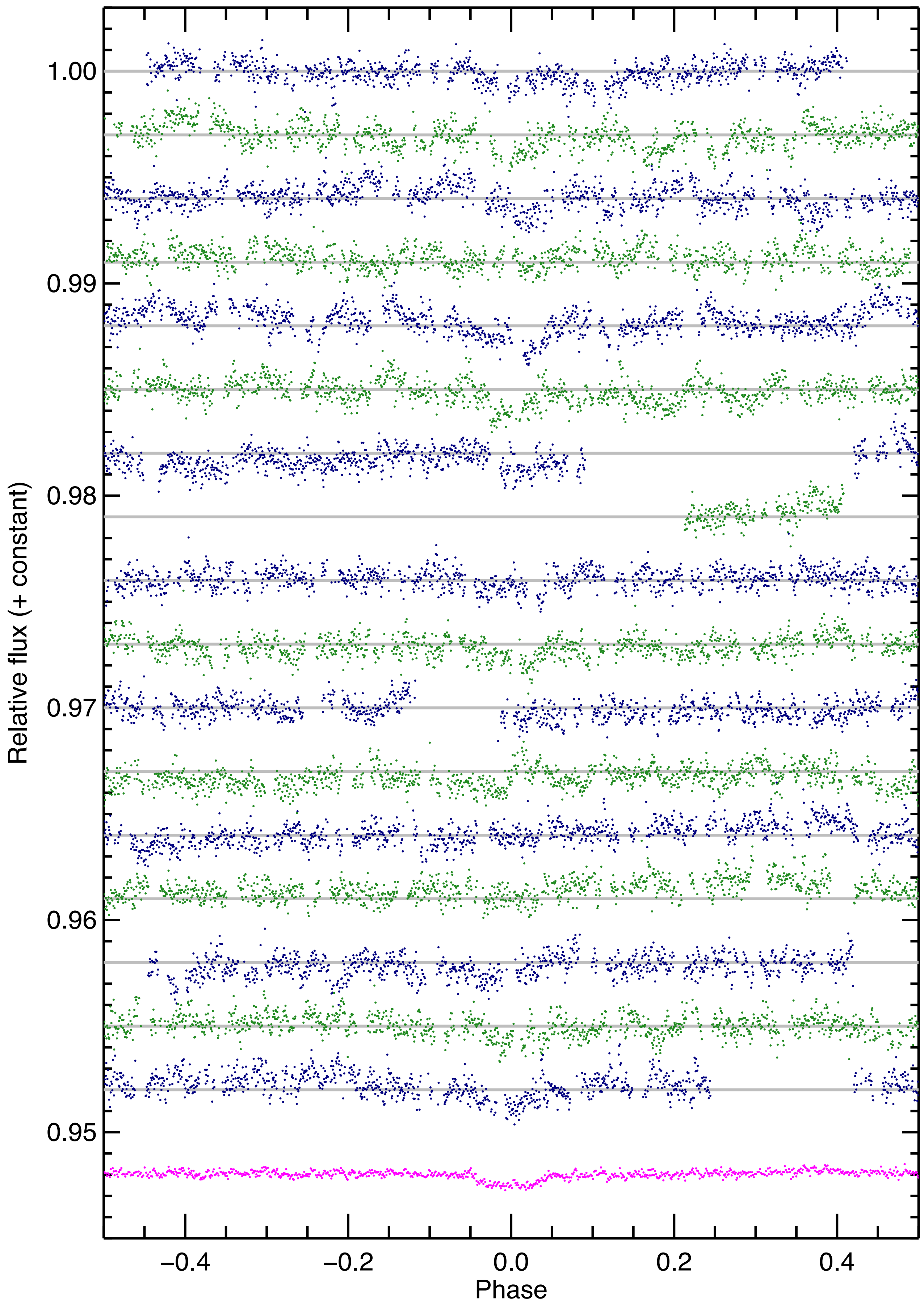
Transit discovery:

Winn, Matthews et al. (2011) used the MOST space telescope to confirm the prediction with a transit detection.



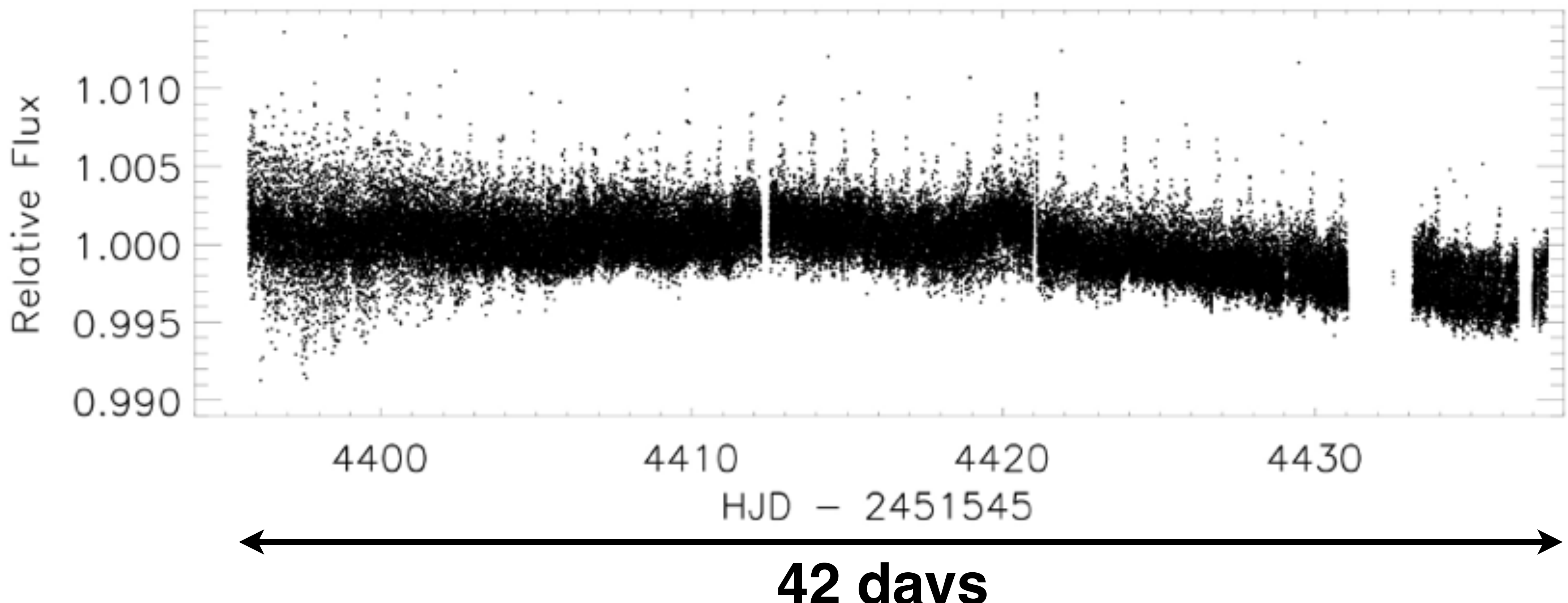
Winn et al. (2011)

Cnc e
al Transits

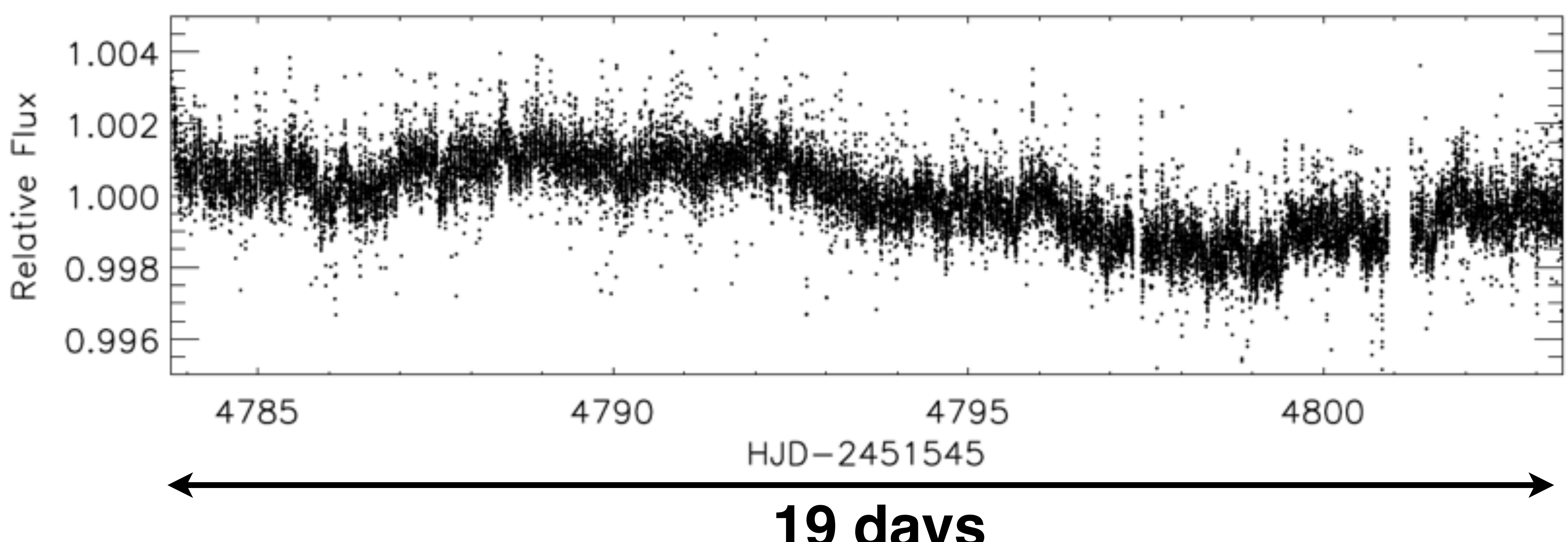


55 Cnc e
Follow-up MOST photometry

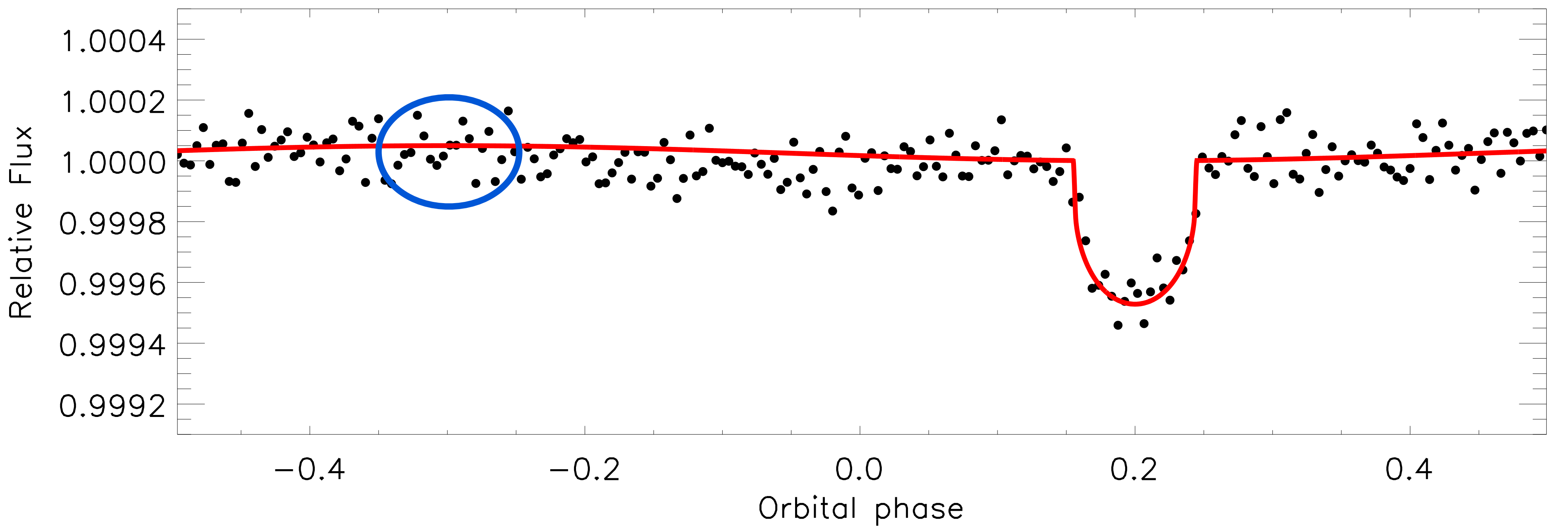
2012



2013



55 Cnc e
Optical secondary eclipse (*MOST*)



Eclipse depth = -1 $^{+12}_{-18}$ ppm

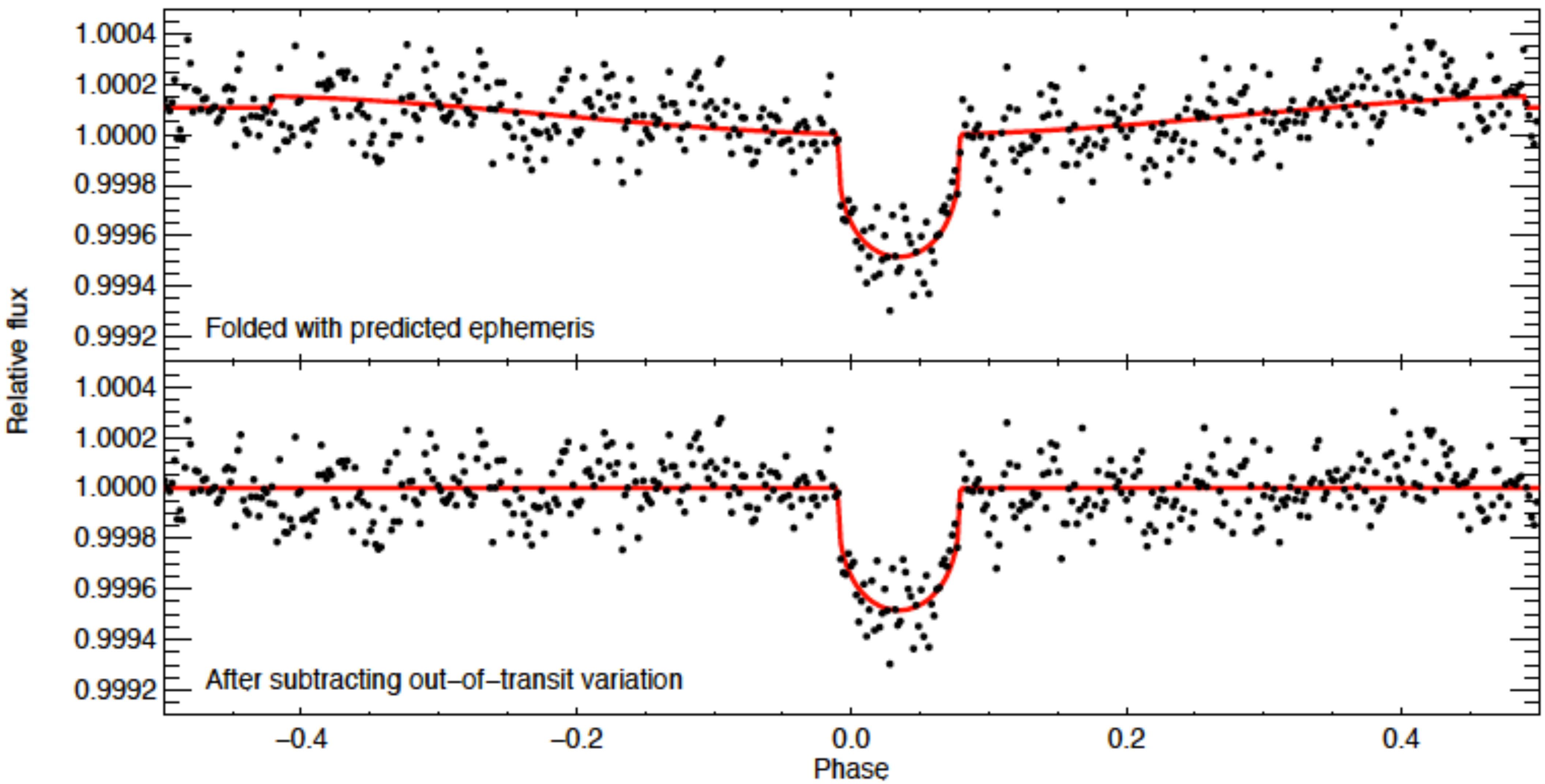
≤ 13 ppm

Geometric albedo ≤ 0.45 (at 1σ)

=> Bond albedo ≤ 0.68

55 Cnc e: 2011 run

Star-planet interaction?

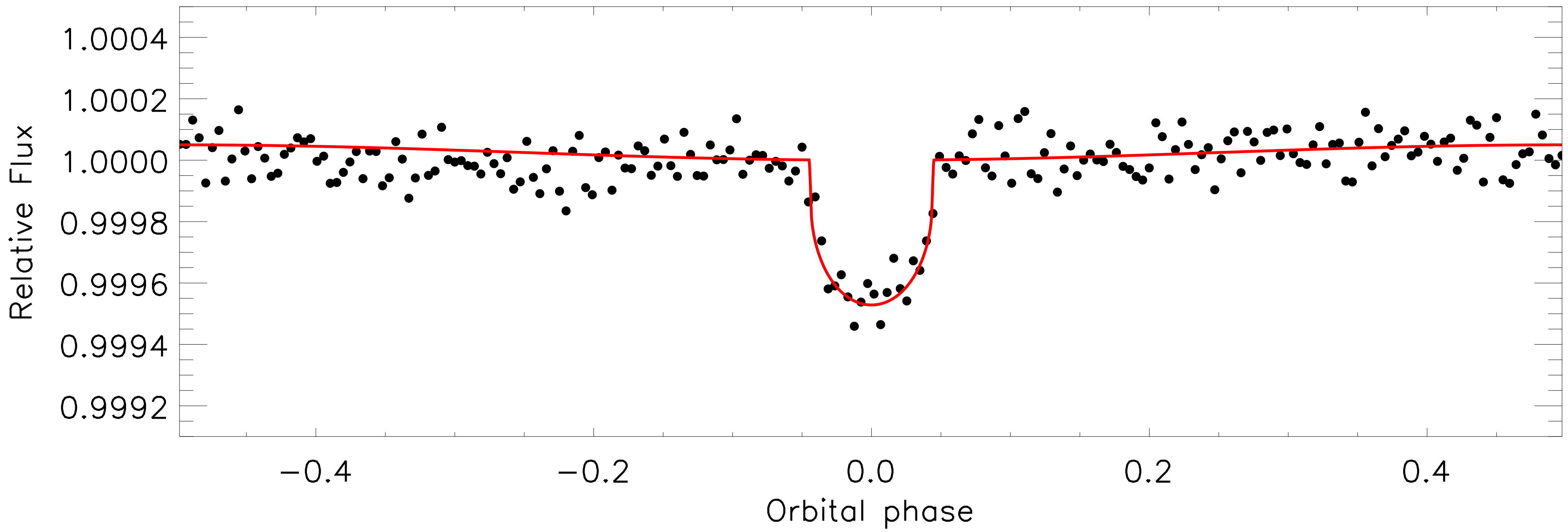


amplitude:
168 ± 70 ppm

Winn et al. (2011)

Winn et al. (2011) detected modulation of light in phase with orbit of planet e:
→ interaction of planet magnetosphere with stellar magnetic field?

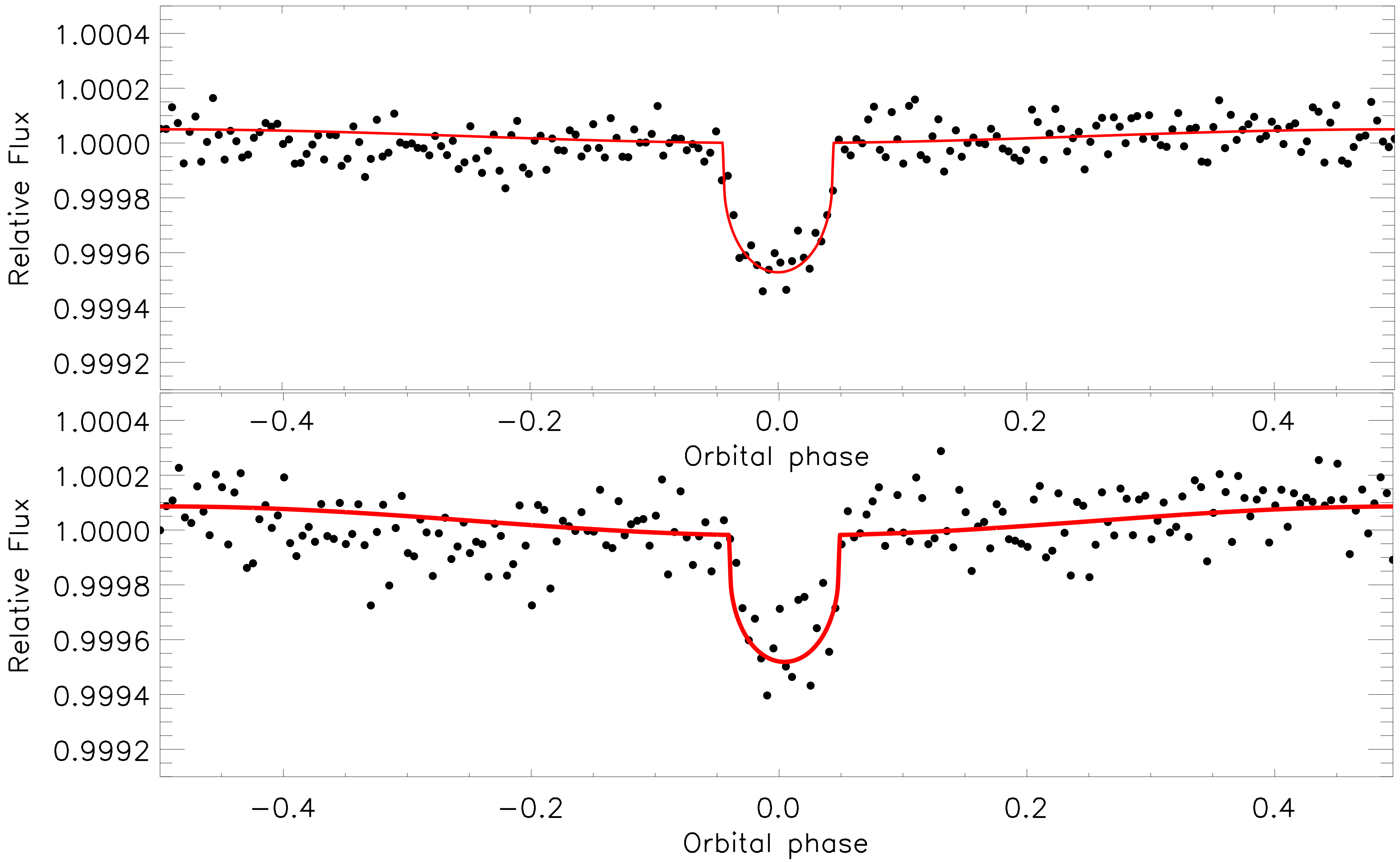
55 Cnc e: 2012 run
Star-planet interaction?



All 2012 photometry

Amplitude of the modulation changes from epoch to epoch and even within 2012 observing run.

55 Cnc e: 2012 run
Star-planet interaction?



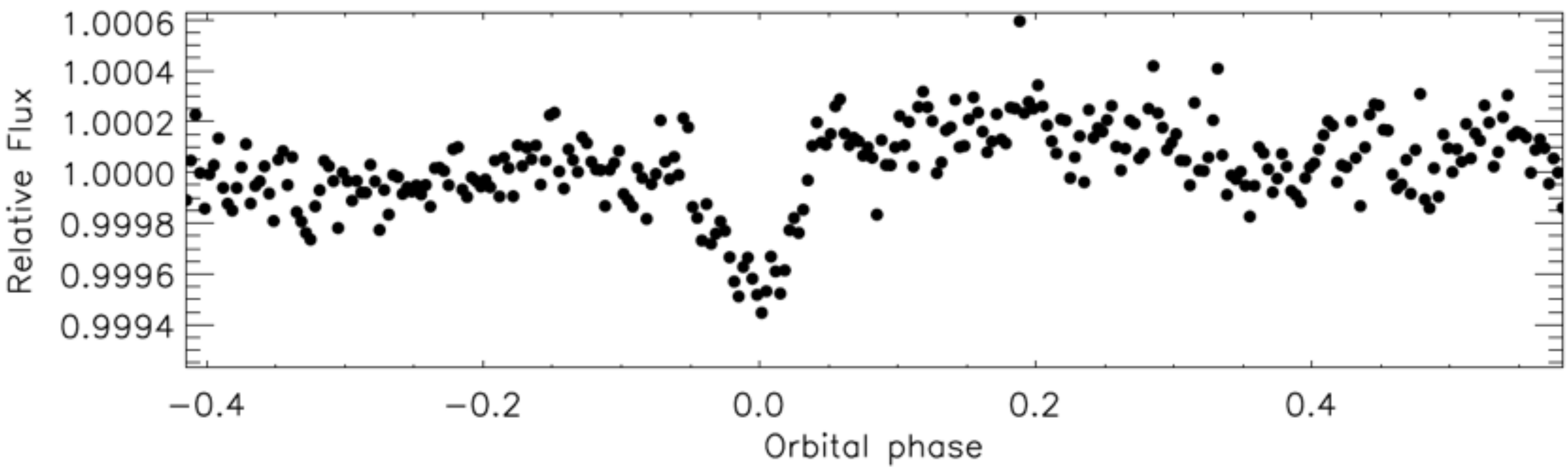
All 2012 photometry

Middle 2/3 of 2012 light curve

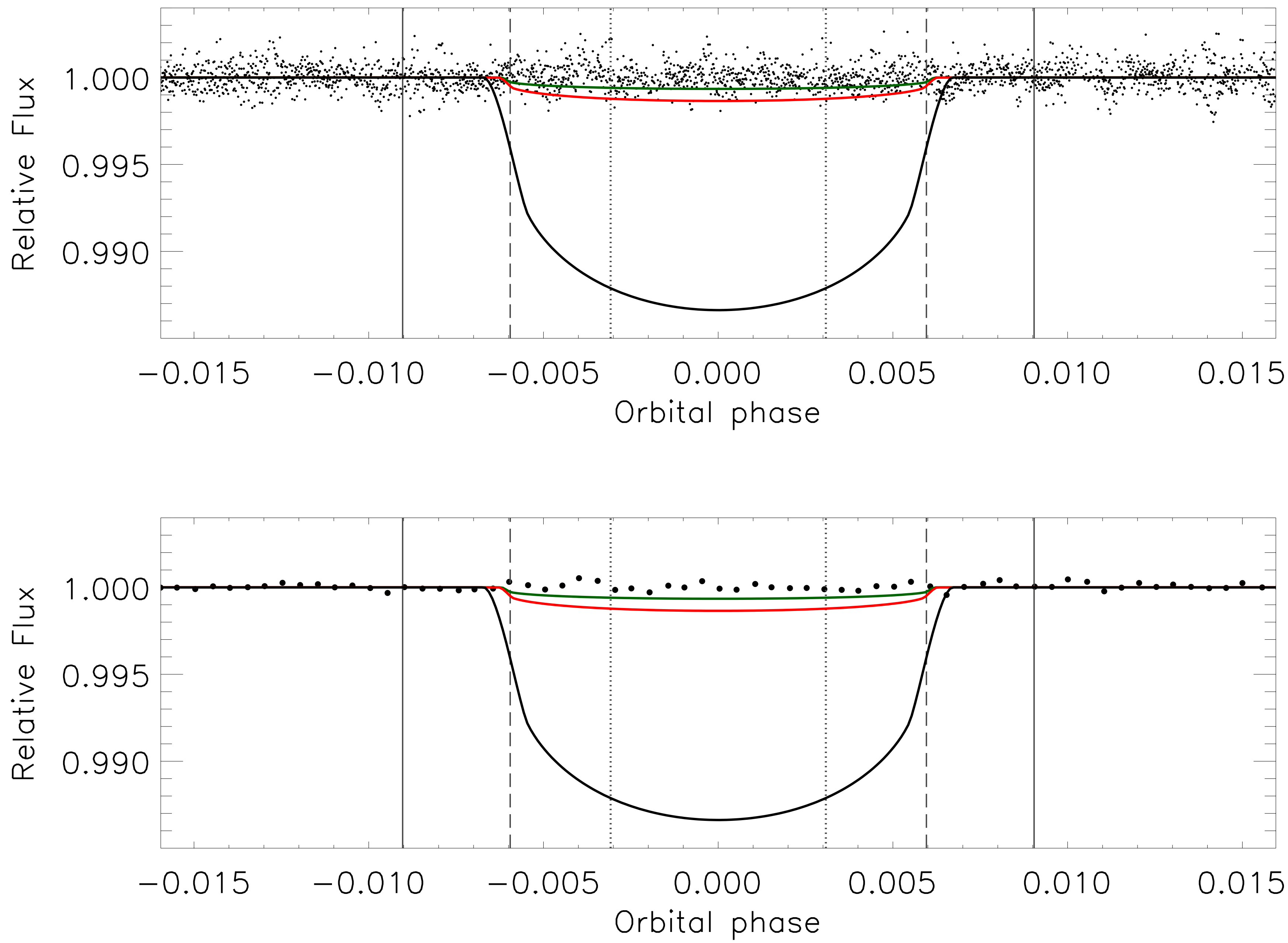
Amplitude:
84 ± 36 ppm

Amplitude of the modulation changes from epoch to epoch and even within 2012 observing run.

55 Cnc e: 2013 run
Star-planet interaction?



55 Cnc b

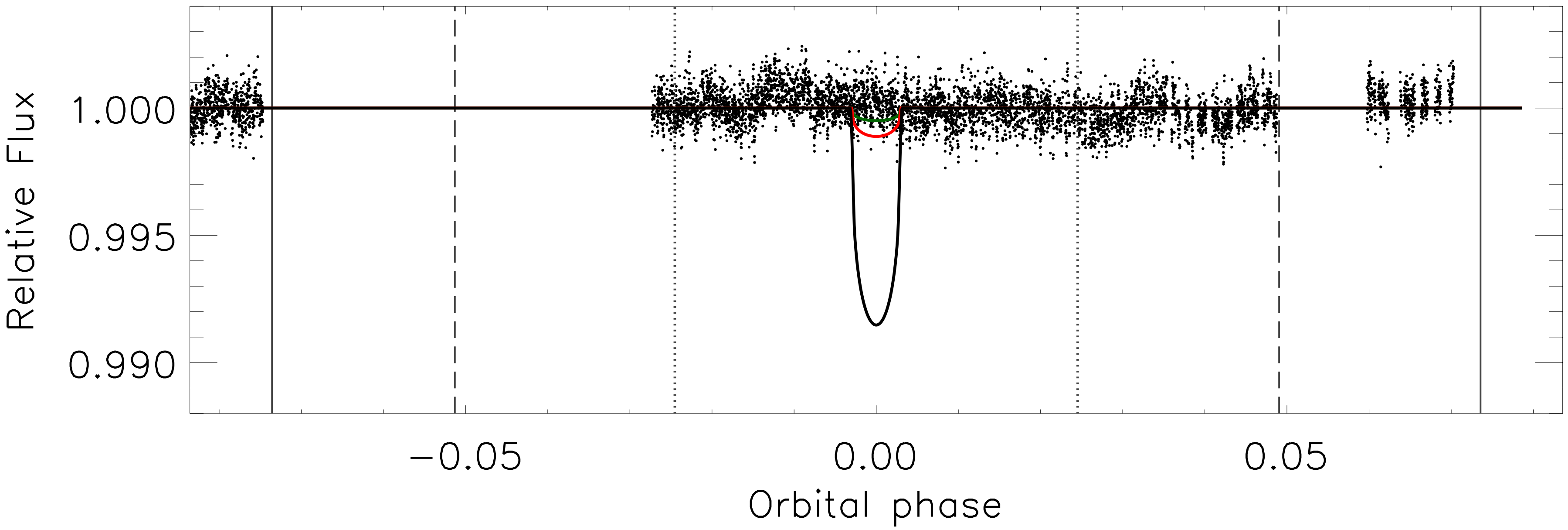


Period = 14. 65 days

$M_p \sin i = 0.826\ M_{Jup}$

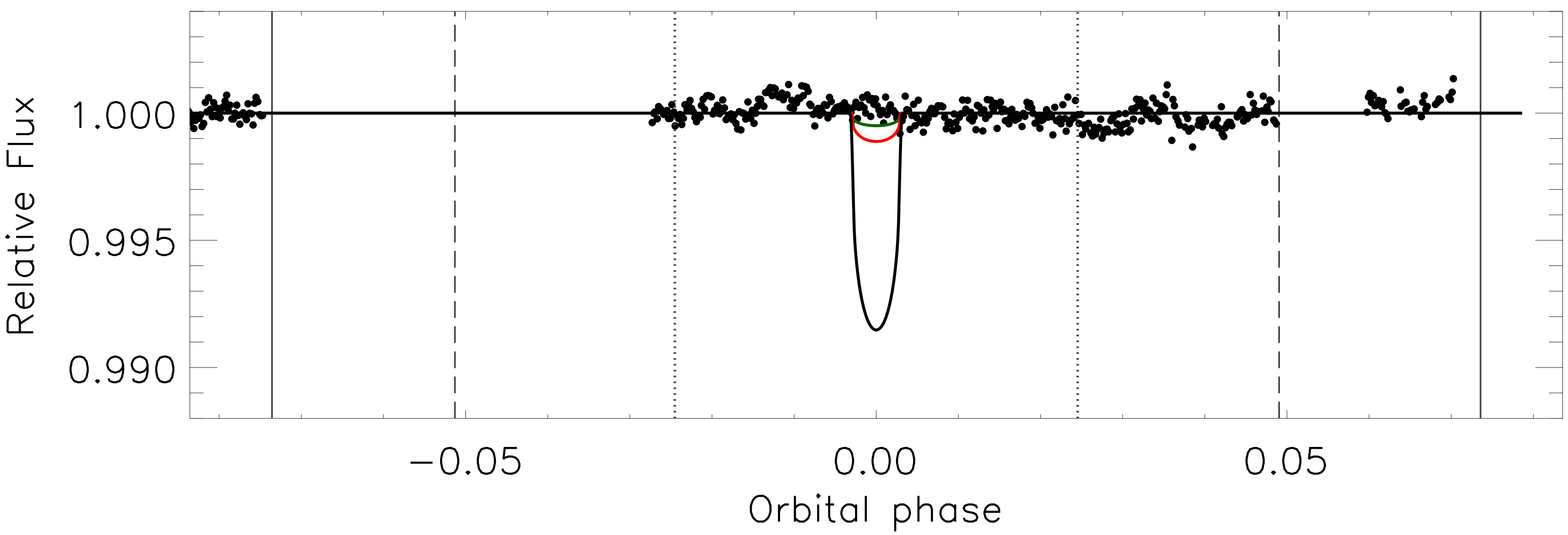
No transits with impact parameter < 1.02

55 Cnc c



Period = 44.37 days

$M_p \sin i = 0.171\ M_{Jup}$



For partial transit window coverage,
no transits for a gas giant 55 Cnc c for impact parameter < 1.

HD 97658b - Background
Radial velocities

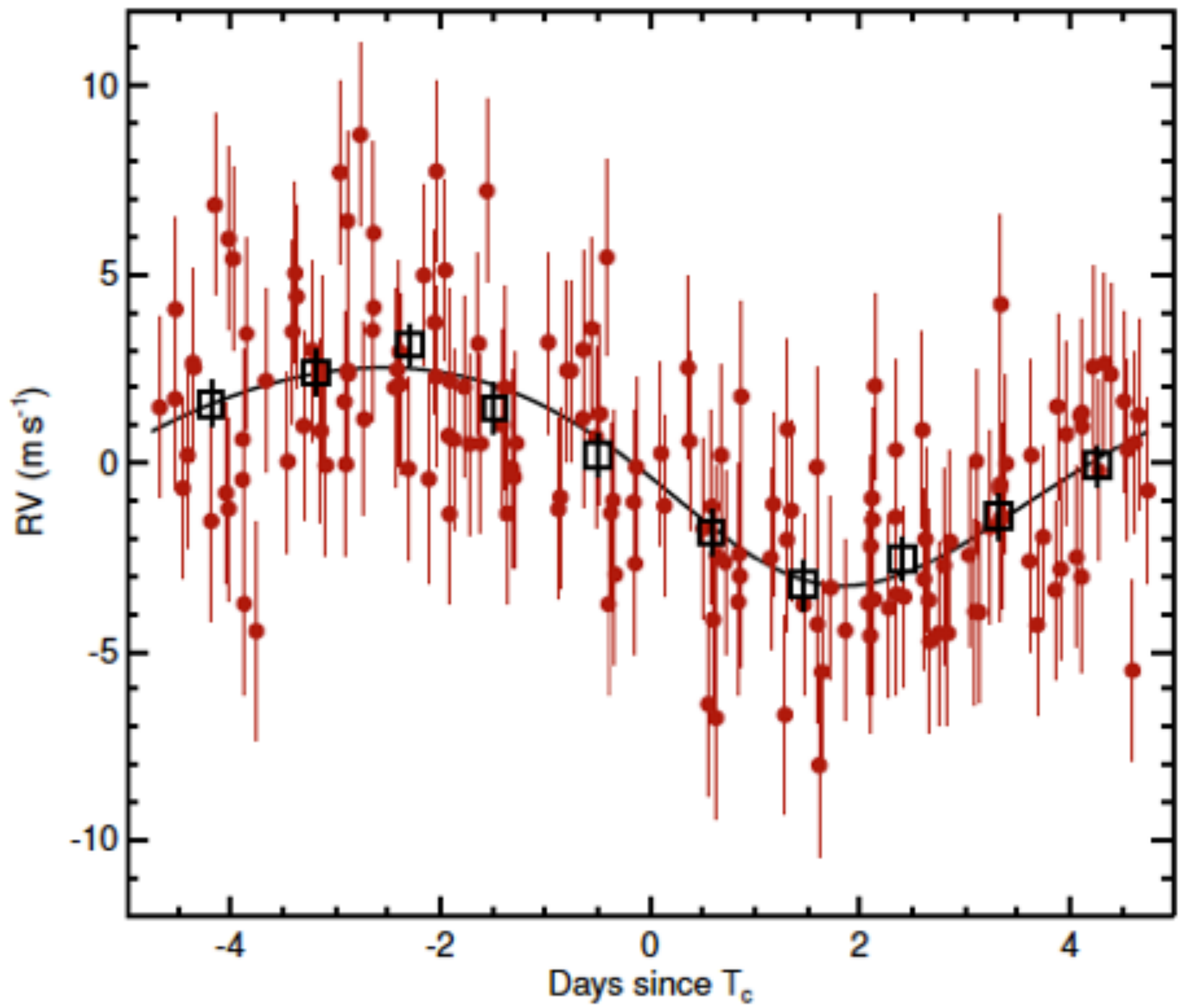
Discovery by Howard et al. (2011)

Period = 9.4930 ± 0.0021 days

T_C = 2,455,982.59 ± 0.31

$M_P \sin i$ = 7.7 ± 0.7 M_{Earth}

K1V type host star
V mag = 7.7

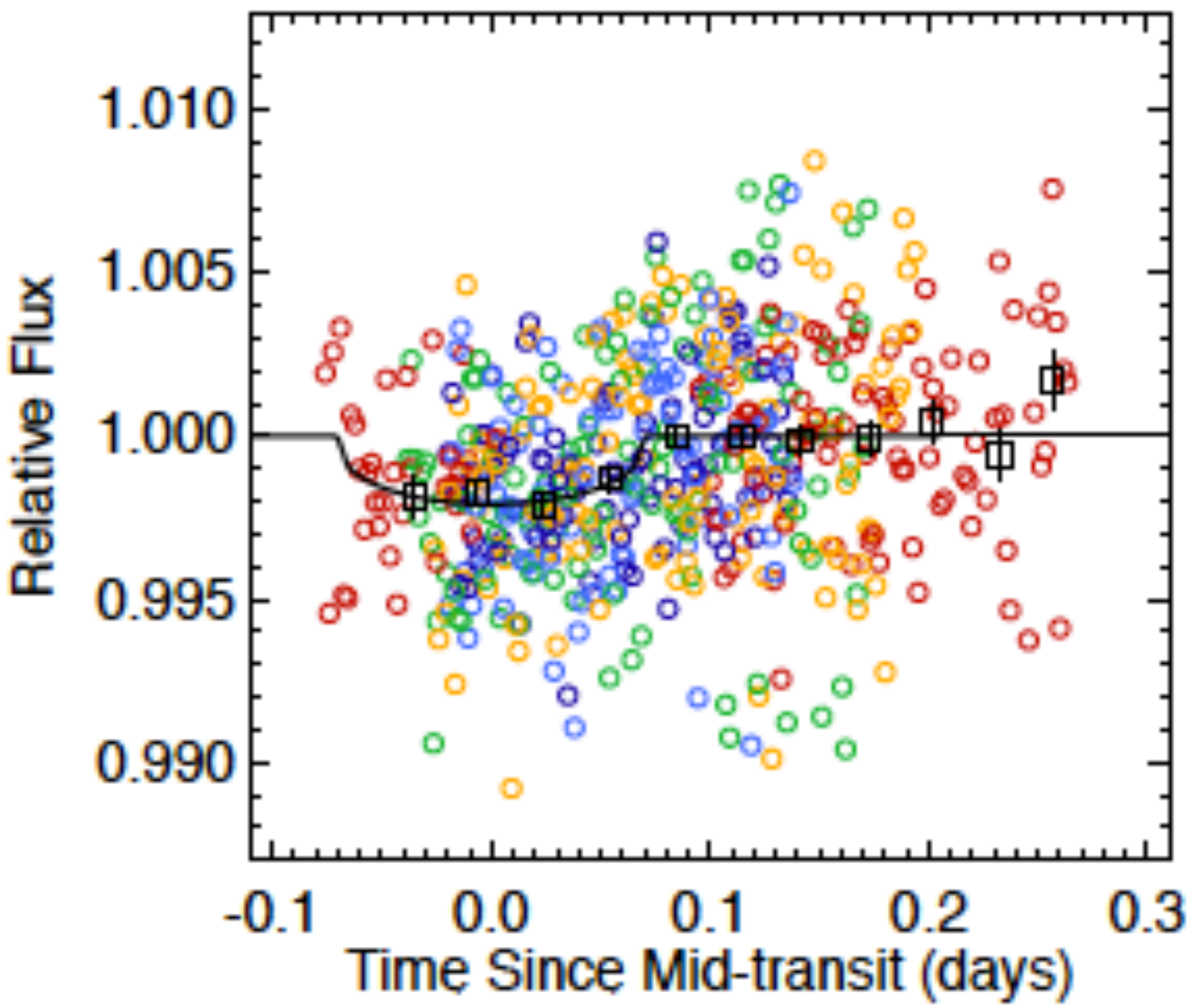


4% *a priori* geometric transit probability

Dragomir et al. (2012)

3σ transit window size in spring 2012: **1.9 days**

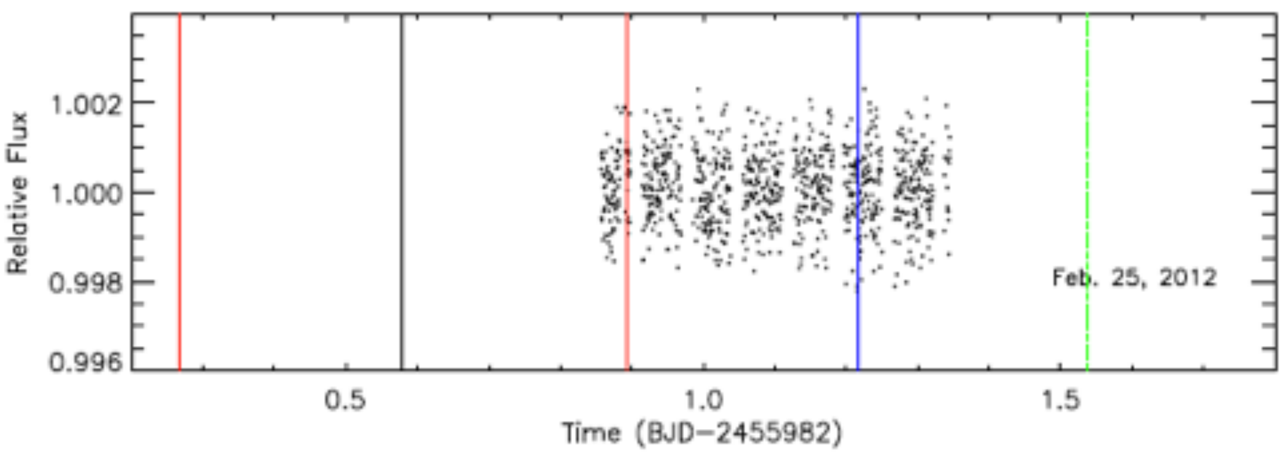
Announcement of transit-like signals for HD 97658b with APT data (2011)



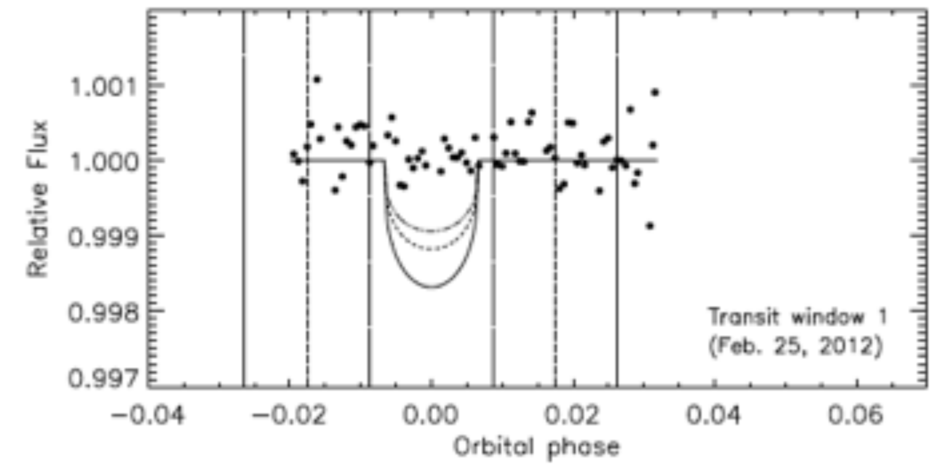
Henry et al. (withdrawn)

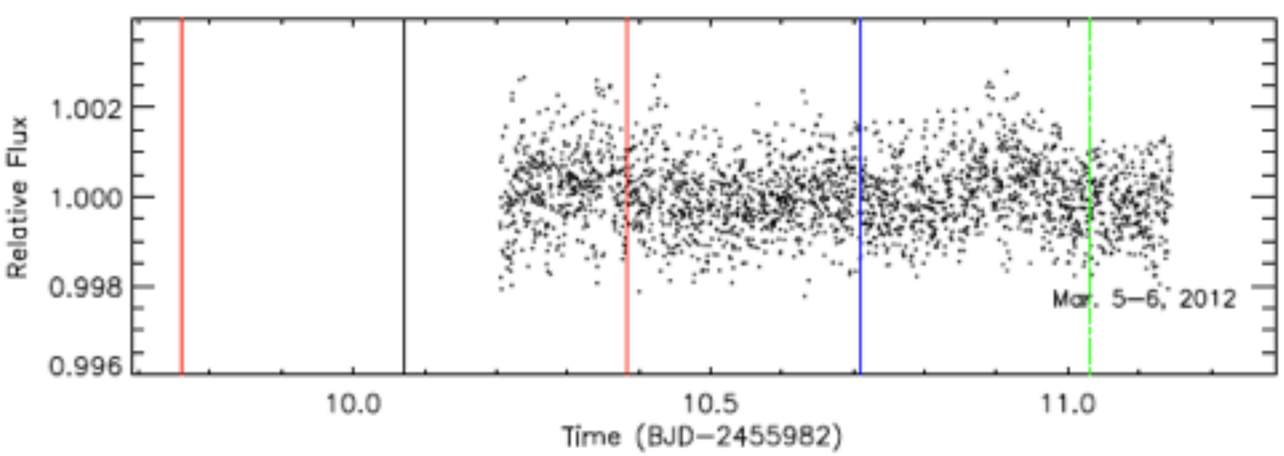
Transit candidate depth suggested a low-density super-Earth with 2.9 ± 0.3 R_{Earth} radius

MOST Photometry (2012)

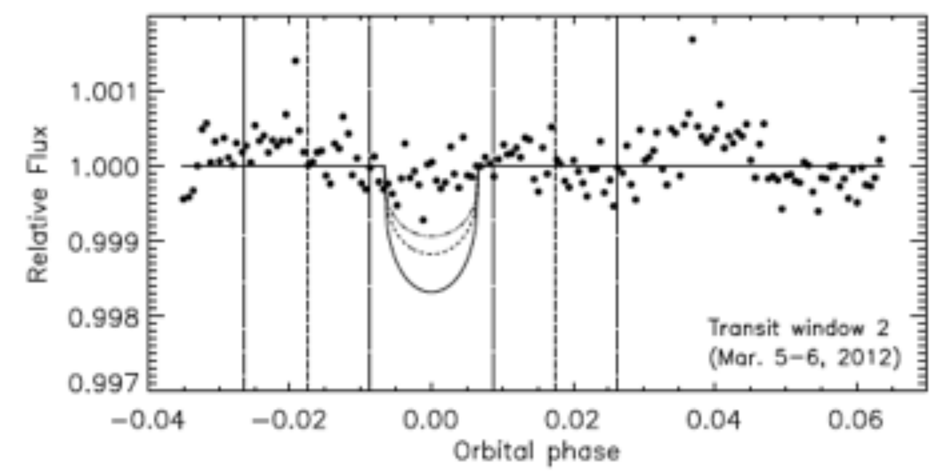


binning

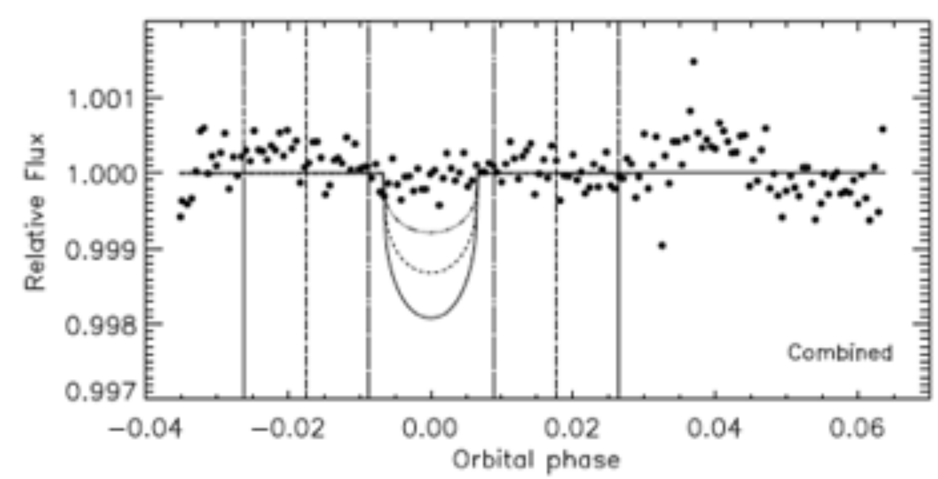




binning



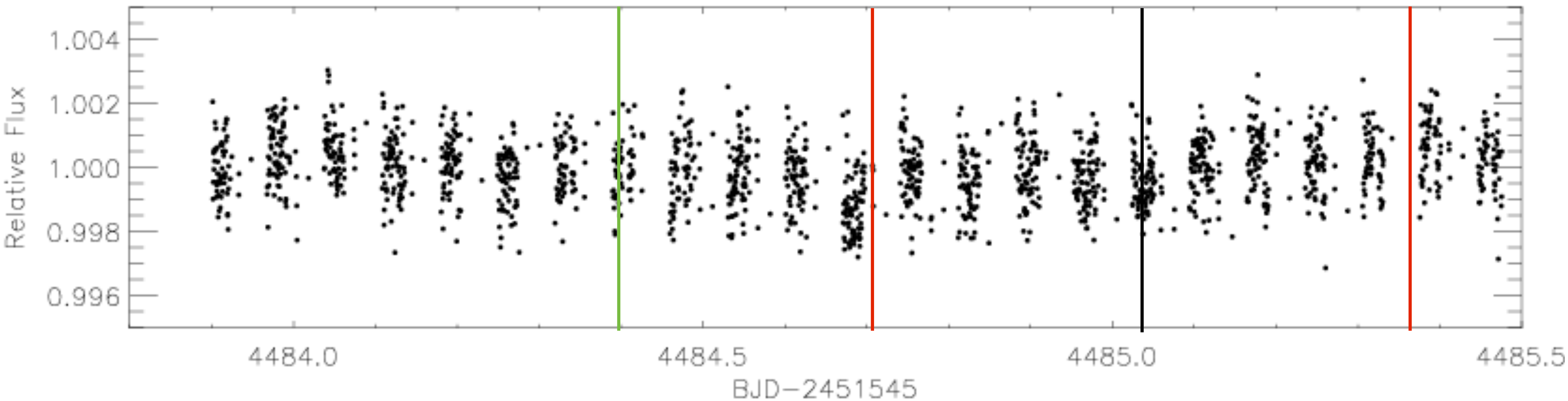
both light curves phased and binned



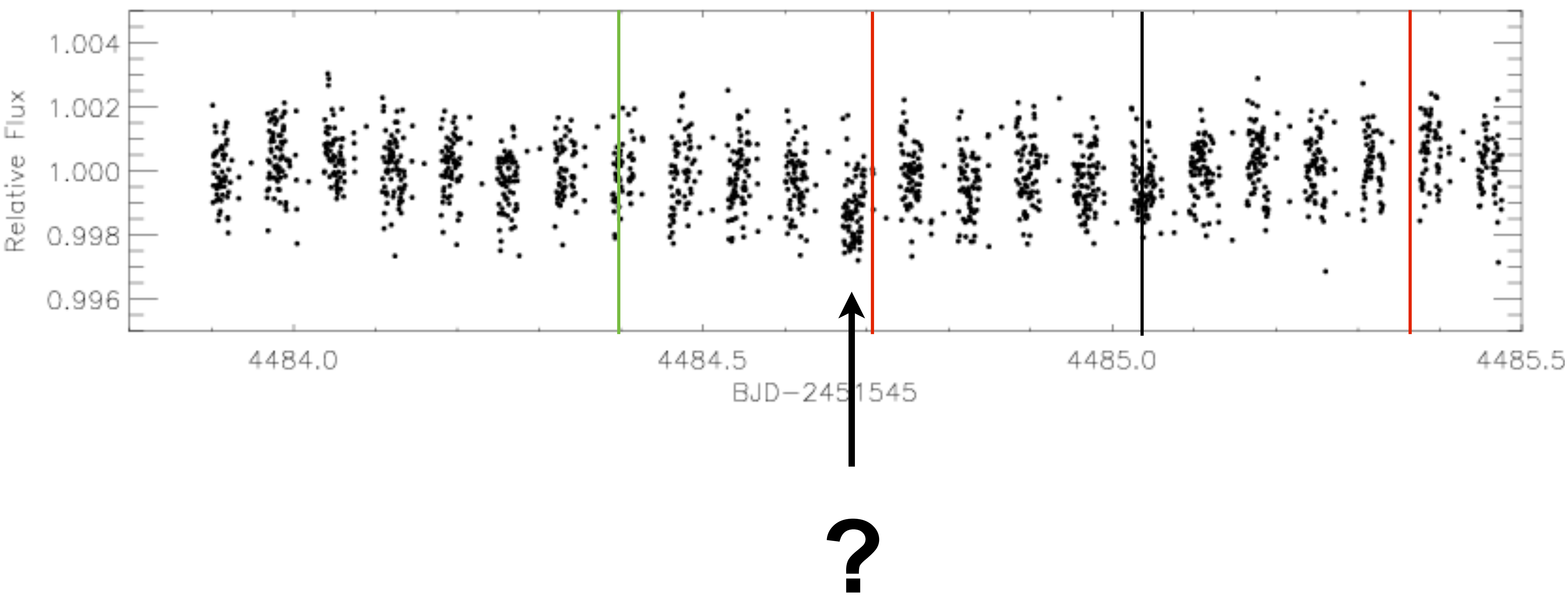
No transit at expected time

Dragomir et al. (2012)

MOST Photometry (2012)
Completing the 3σ transit window coverage

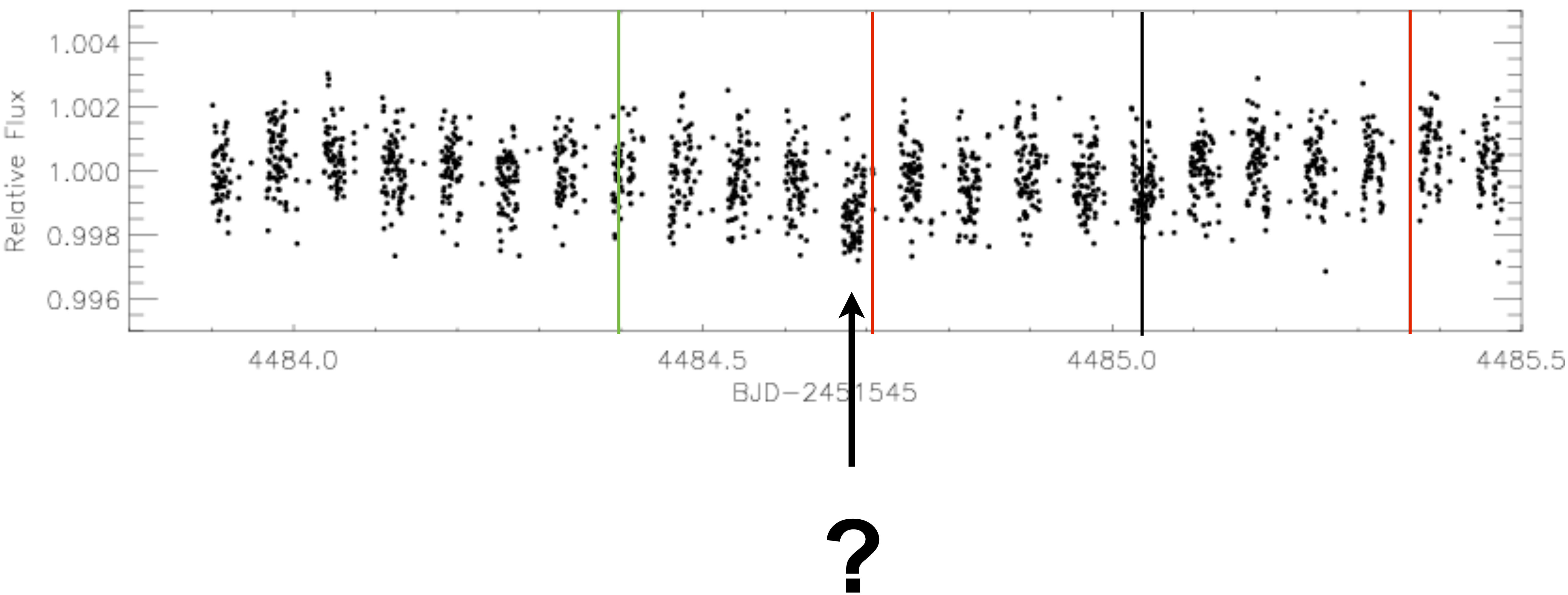


MOST Photometry (2012)
Completing the 3σ transit window coverage



MOST Photometry (2012)

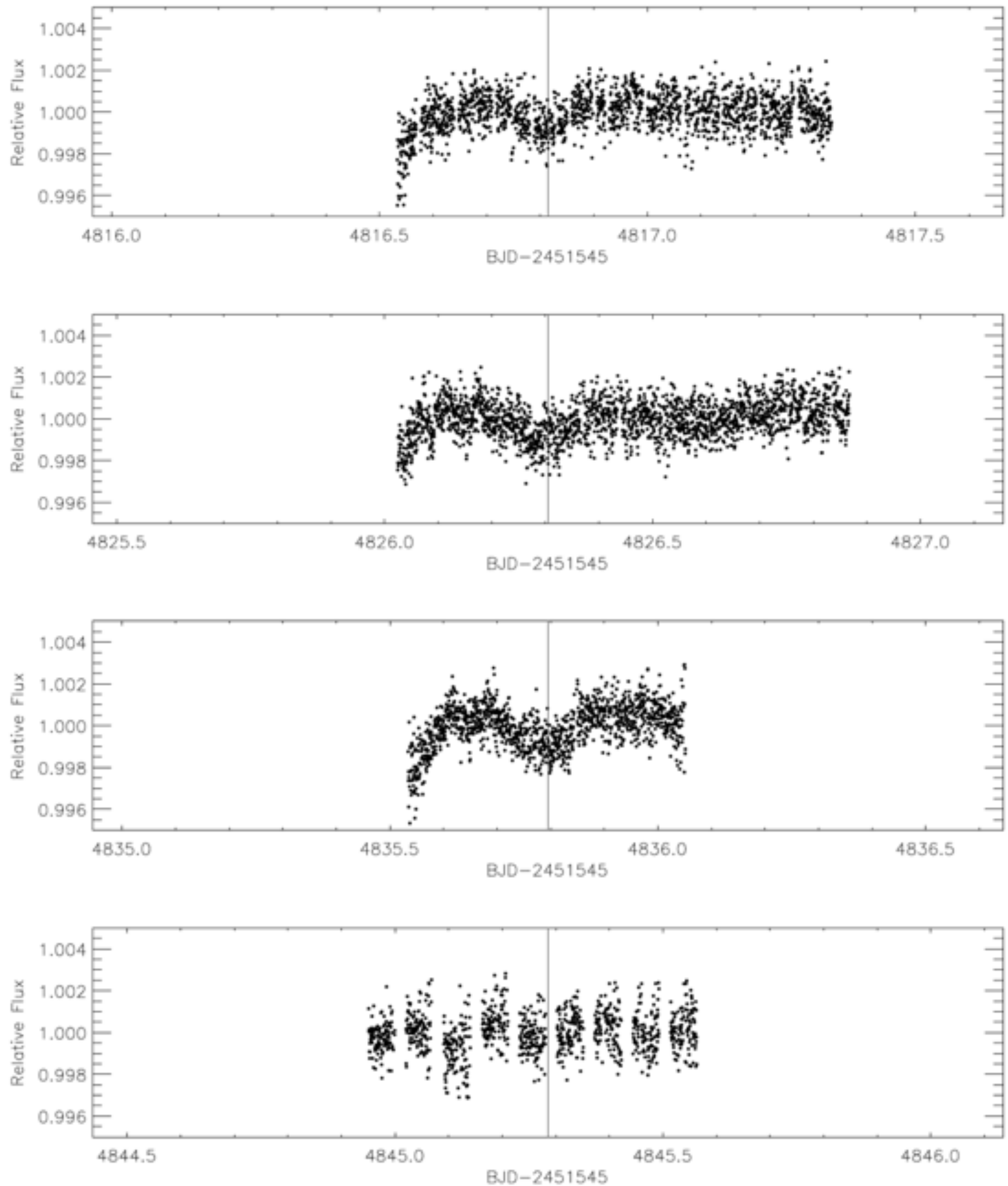
Completing the 3σ transit window coverage



HD 97658 leaving the MOST Continuous Viewing Zone.

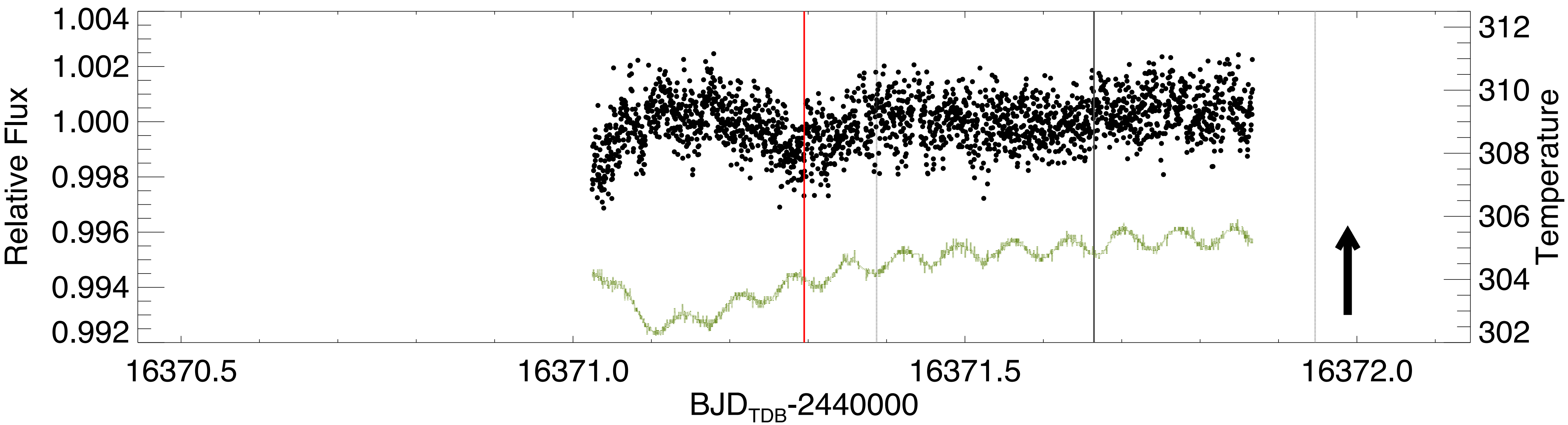
Must wait until next year (2013) to find out.

MOST photometry (2013)

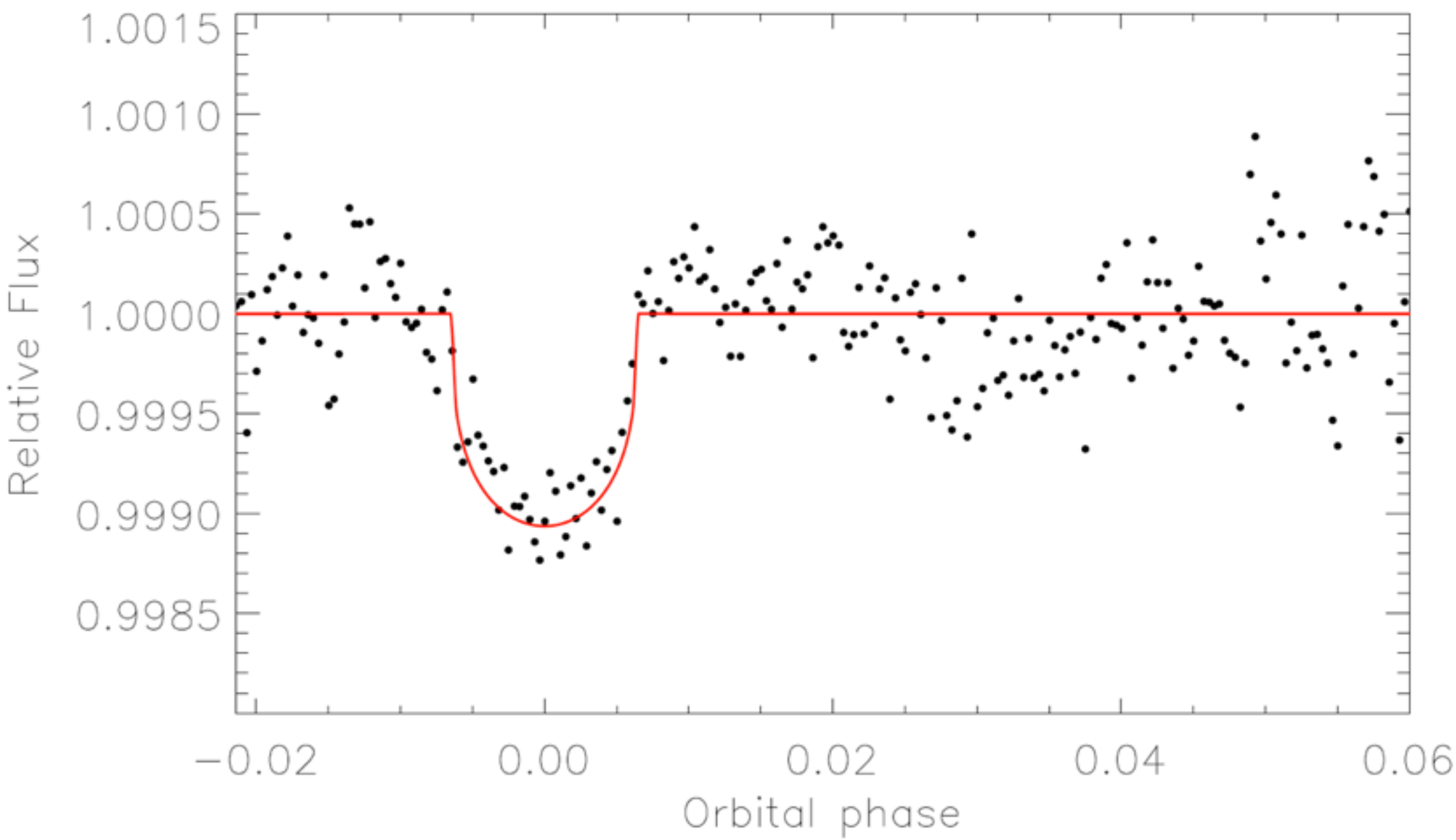


Dragomir et al. (2013)

Temperature Trend Artefacts

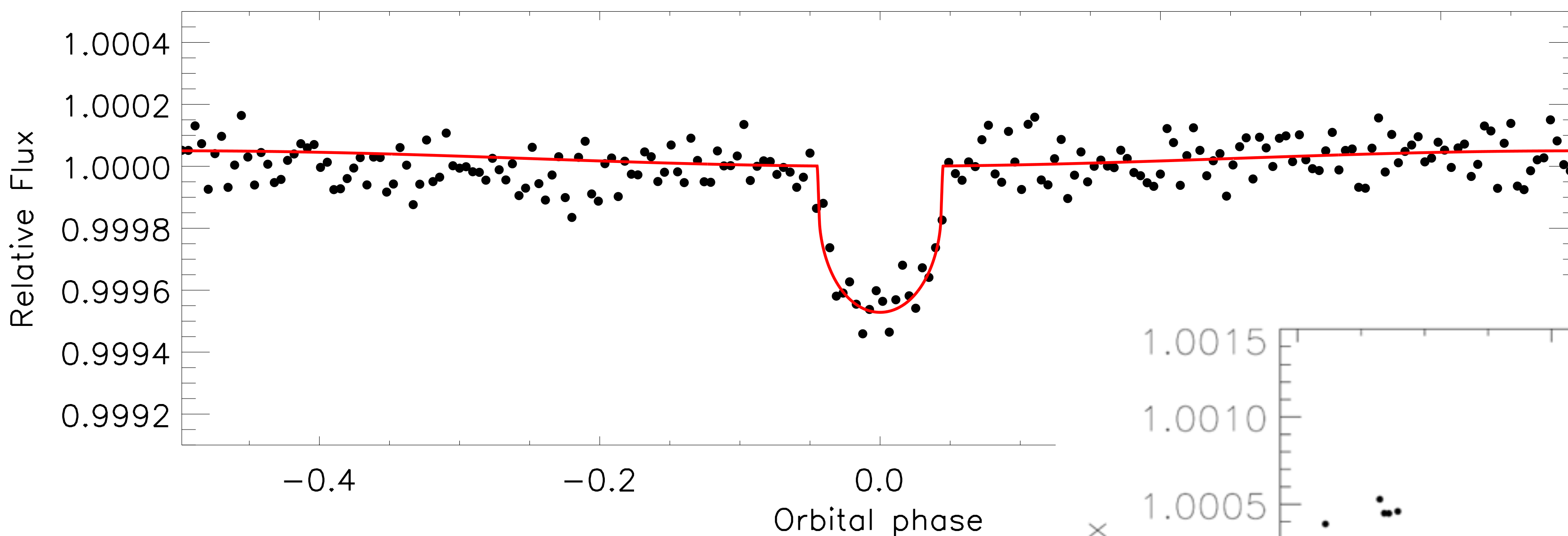


HD 97658b



Dragomir et al. (2013)

55 Cancri e

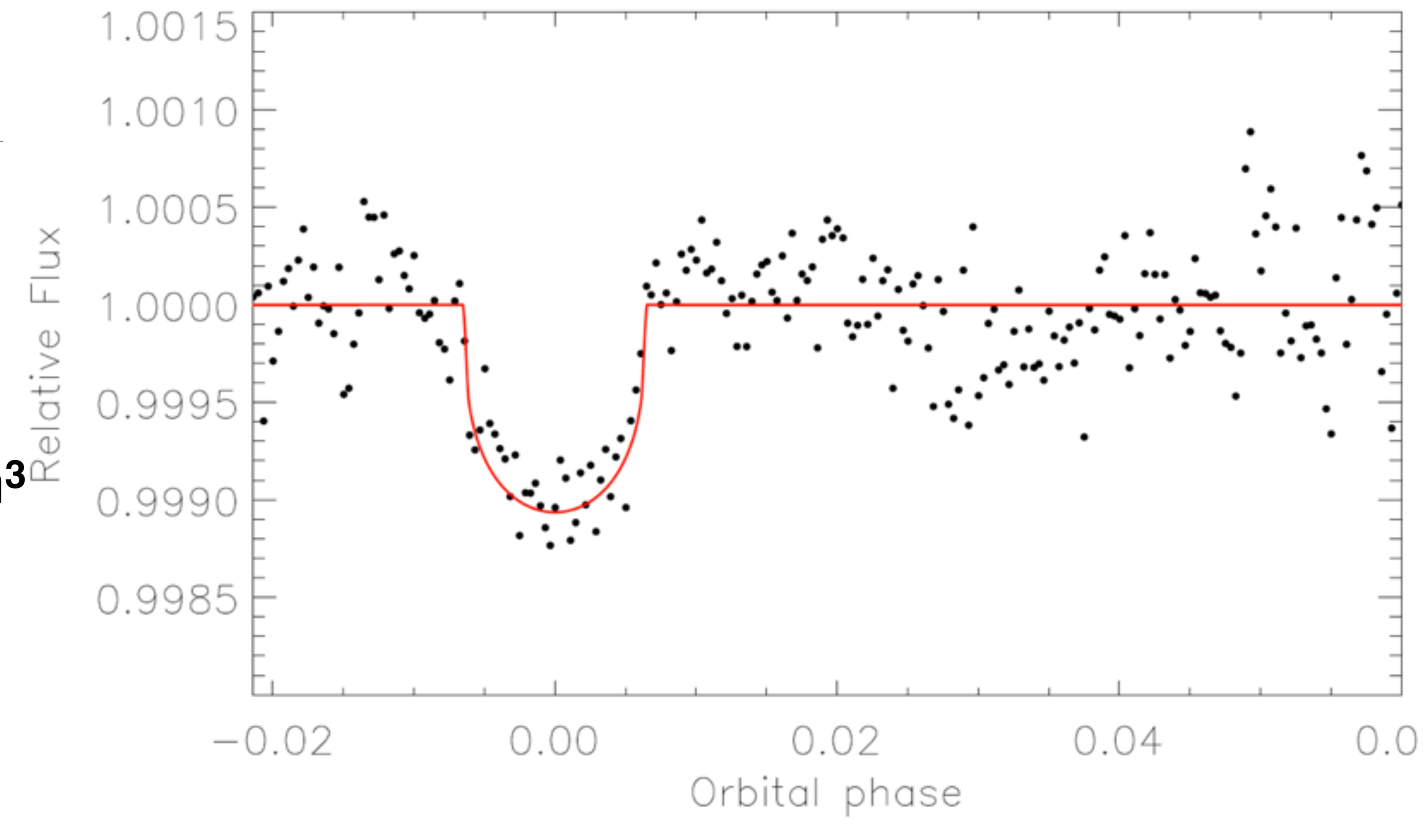


planetary radius = **1.990 ± 0.082 R_{Earth}**
planetary mass = **7.81 ± 0.56 M_{Earth}**
planetary mean density = **5.49 ± 0.79 g/cm^3**

stellar radius = **0.943 ± 0.010 R_{Sun}**
stellar mass = **0.905 ± 0.015 M_{Sun}**

orbital inclination = 85.4 ± 2.5 deg
period=0.7365417 ± 0.0000027 days

HD 97658b

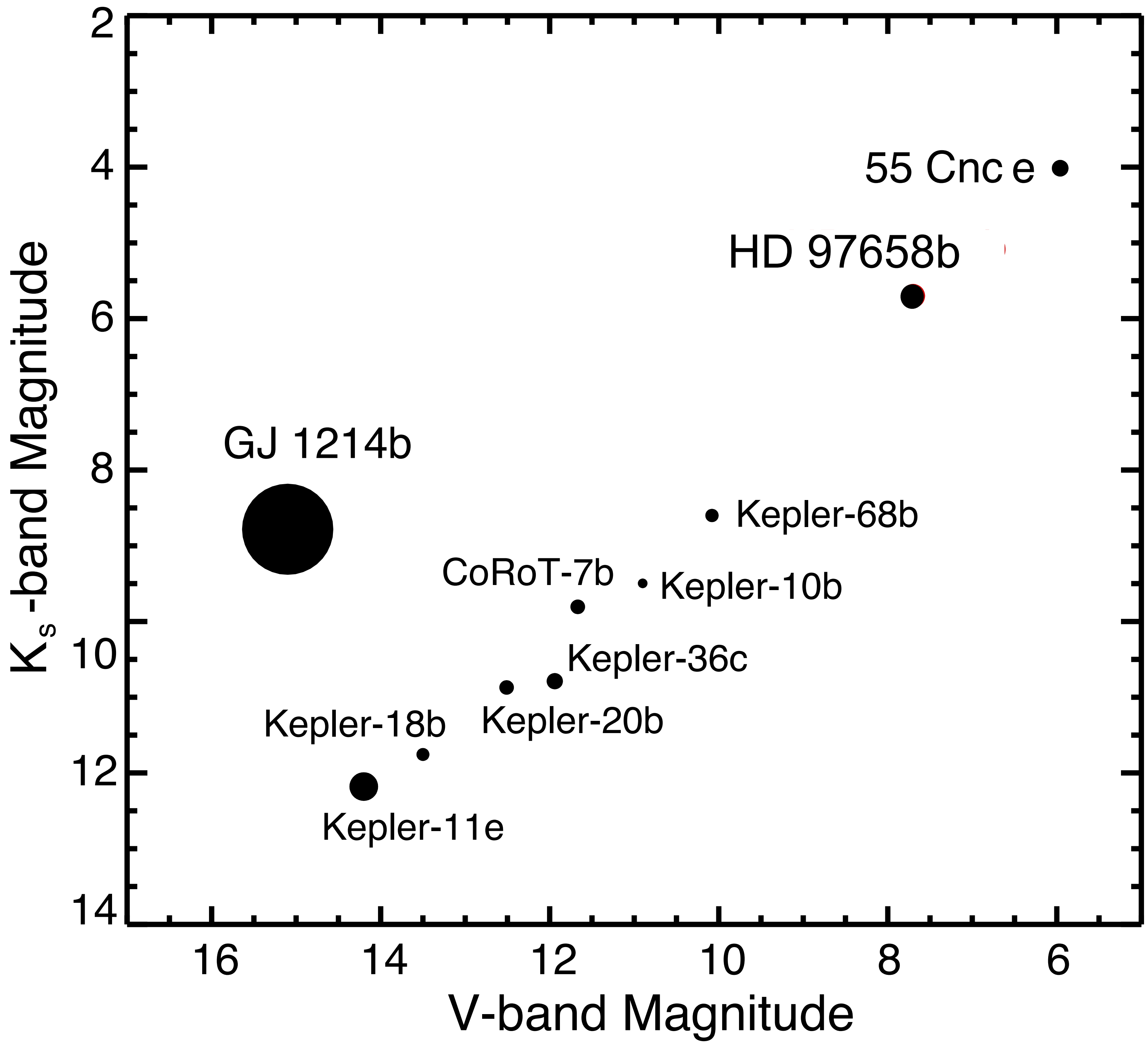


planetary radius = **2.34 ± 0.16 R_{Earth}**
planetary mass = **7.86 ± 0.73 M_{Earth}**
planetary mean density = **3.4 ± 0.7 g/cm^3**

stellar radius = **0.943 ± 0.010 R_{Sun}**
stellar mass = **0.905 ± 0.015 M_{Sun}**

orbital inclination = 89.45 ± 0.4 deg
period=9.4894 ± 0.0002 days

The super-Earths 55 Cnc e & HD 97658b



The super-Earths 55 Cnc e & HD 97658b

55 Cnc e

No Hydrogen...

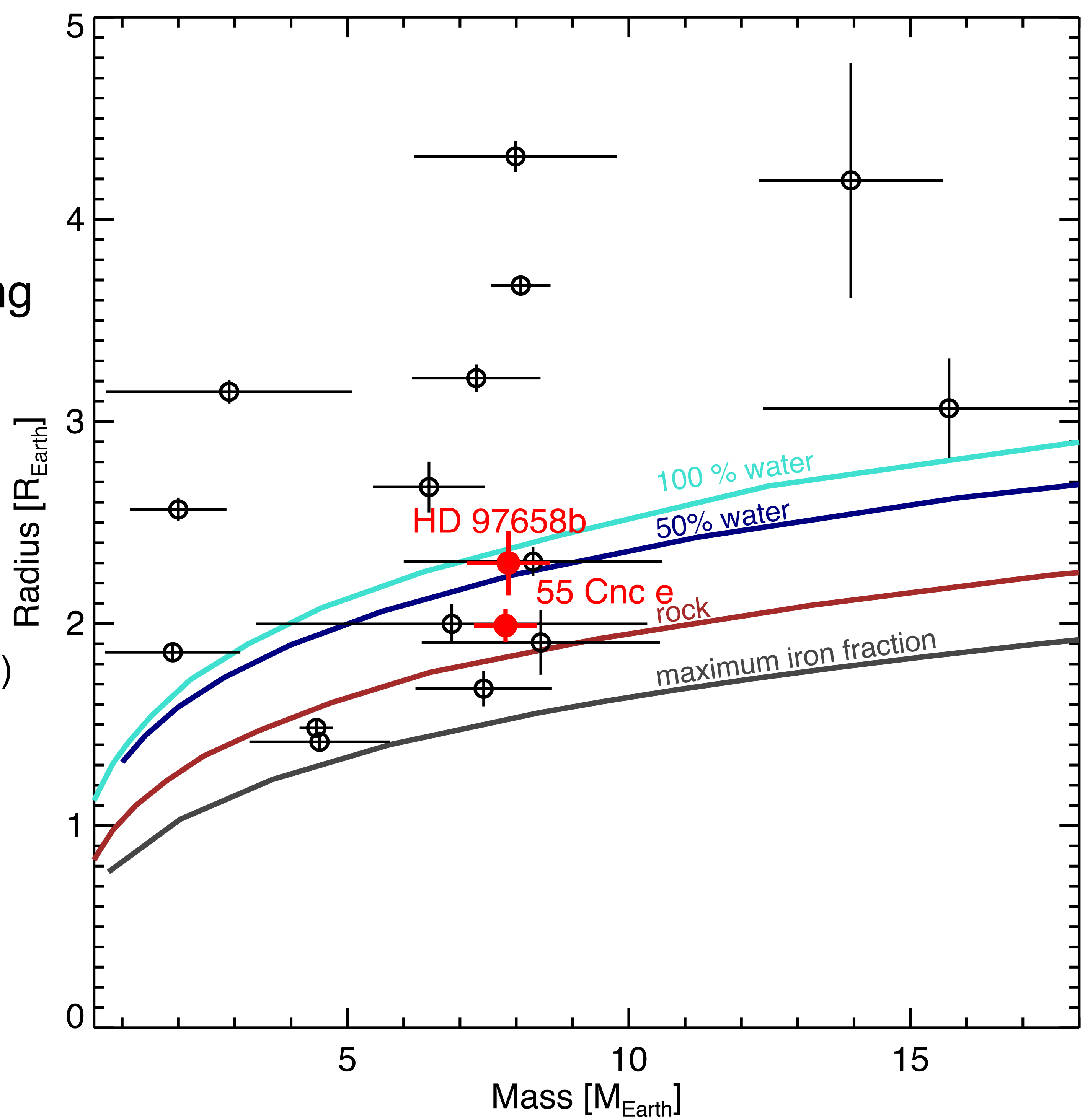
Ehrenreich (2012)

Atmosphere containing some water vapor?

(Gillon et al. 2012; Valencia et al. 2010)

Carbon planet?

(Madhusudhan et al. 2012)

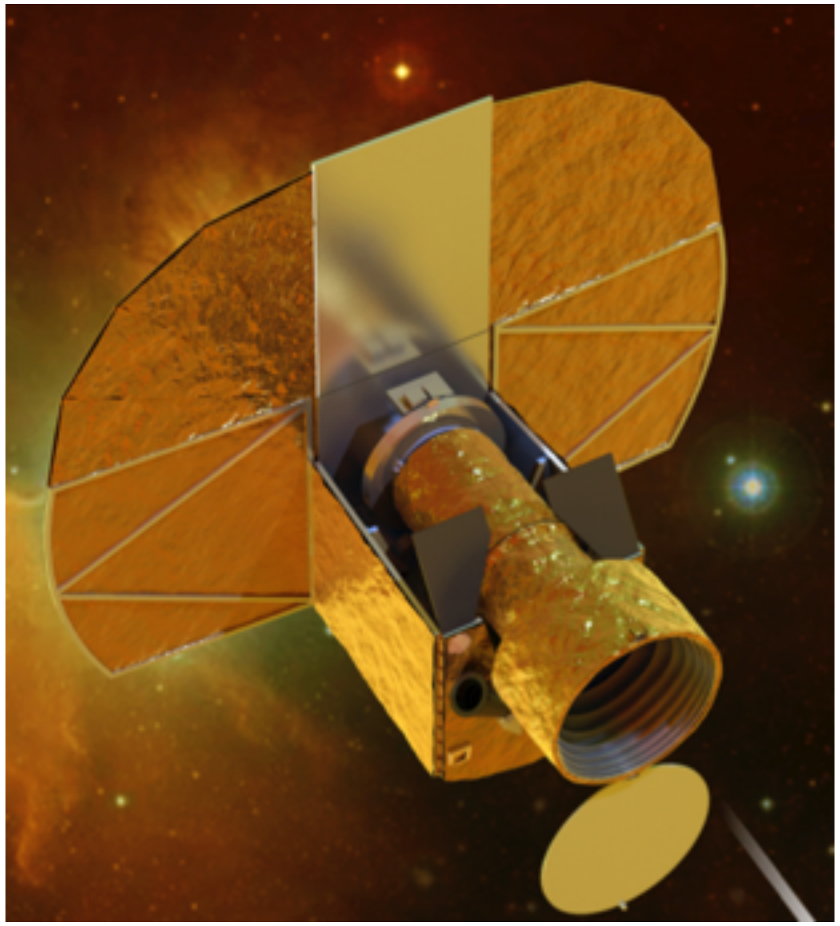


HD 97658b

A low mean molecular weight (hydrogen?) atmosphere fits the planetary density;

Though HST WFC3 observations show a flat spectrum (so far)

CHEOPS



CHEOPS - Credit: University of Bern

CHEOPS features many improvements over the design of MOST.

It will excel at transit searches of RV planets, follow-up of transit survey candidates, phase variation studies…

Its discoveries will also identify the most promising targets for further characterization by JWST and the ELTs.

Summary

Though it has a smaller aperture, MOST bears many similarities to CHEOPS.

MOST has demonstrated the power of low-cost microsatellites for exoplanet science.

It brought about the first significant constraints on the albedo of an exoplanet, and the discovery of transits for two super-Earths orbiting very bright stars.

It has led to the development of creative observing and data analysis strategies (and so far has survived them all).

It now looks forward to the discoveries of its successor.