The Search for Exomoons

David M. Kipping[1,2]

[1] Harvard-Smithsonian Center for Astrophysics; [2] Carl Sagan Fellow

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- "For moons the effects are likely to be not just small, but minute—right on the hairy edge of what *Kepler* can do" Greg Laughlin, The Economist
- But, the potential for new understanding is extraordinary.

Motivations

- Intrinsic habitability
- Extrinsic habitability
- Planet formation theory

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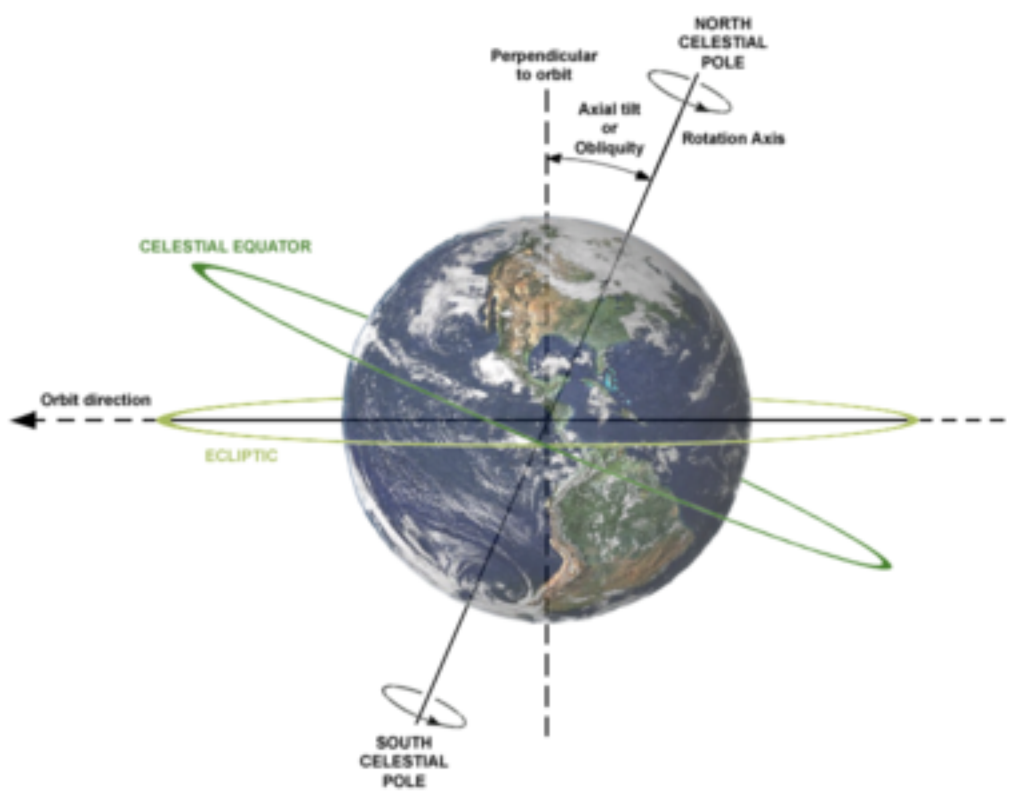

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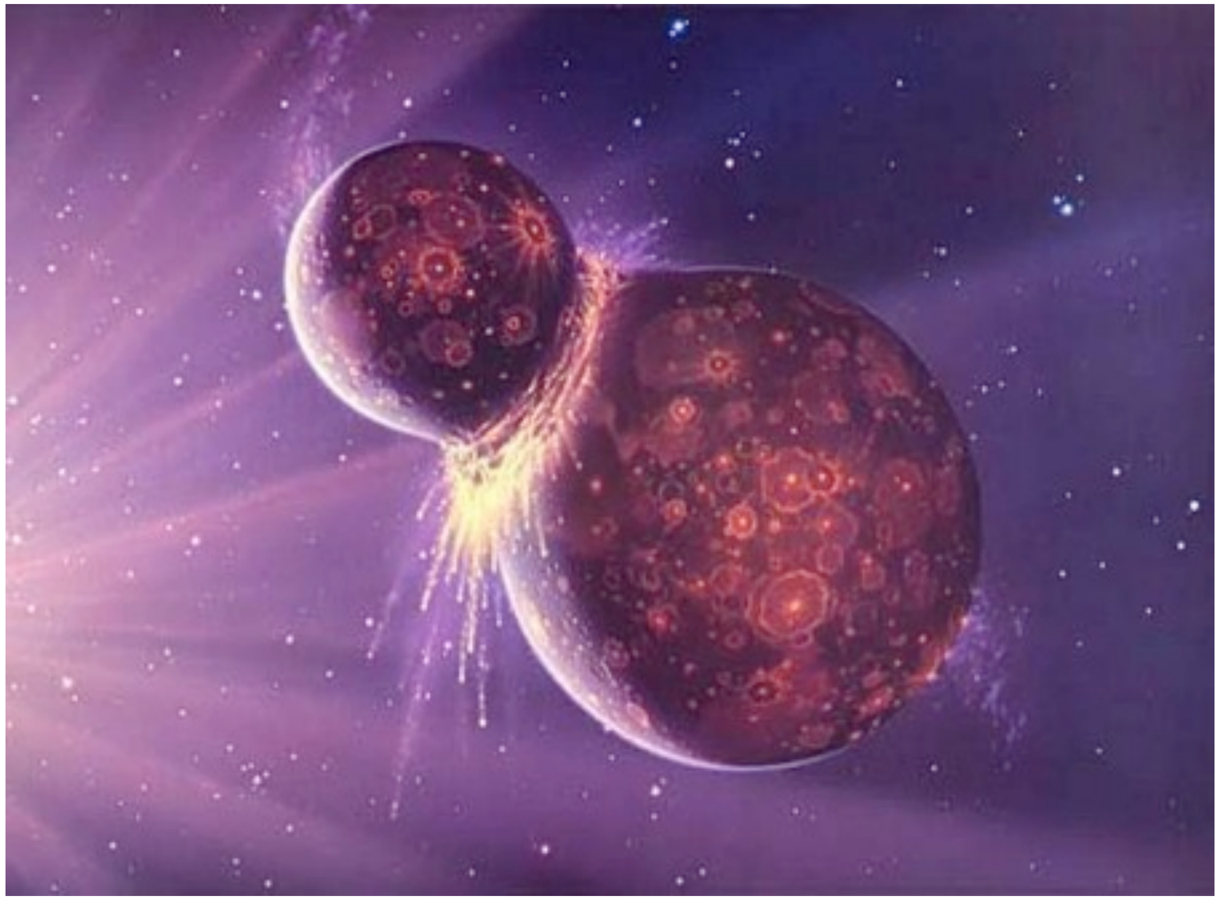

Order-of-Magnitude Feasibility

- Roughly, Kepler is sensitive to ~$1R_\oplus$ planets
- ⇒Kepler is sensitive to ~$1R_\oplus$ moons
- We may be able to detect Earth-sized/mass moons

Order-of-Magnitude Feasibility

No such moons in the Solar System, so we are searching for an alien class of object

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2. Eclipse effects (gives R_S)
   - (i) Auxiliary transits
   - (ii) Mutual events

LUNA

- *LUNA: An algorithm to generate dynamic planet-moon transits* (Kipping 2011)
- LUNA accounts for TTV/TDV-V/TDV-TIP as well as auxiliary transits/mutual events
- Fully dynamic and analytic => very fast
- Accounts for limb darkening too
- Even models previously unconsidered effects, such as ingress/egress asymmetry

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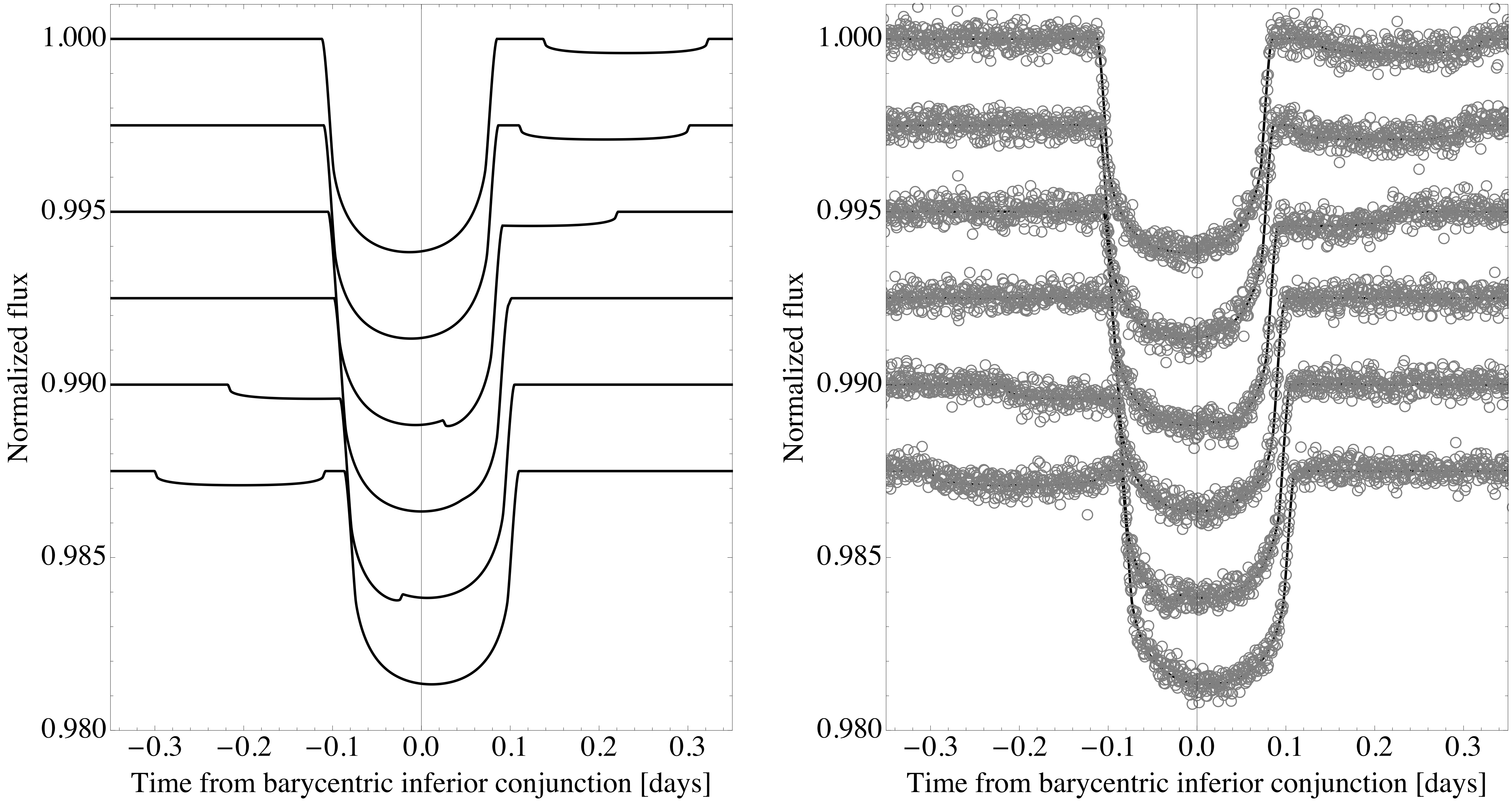

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50-sigma detection with Kepler.

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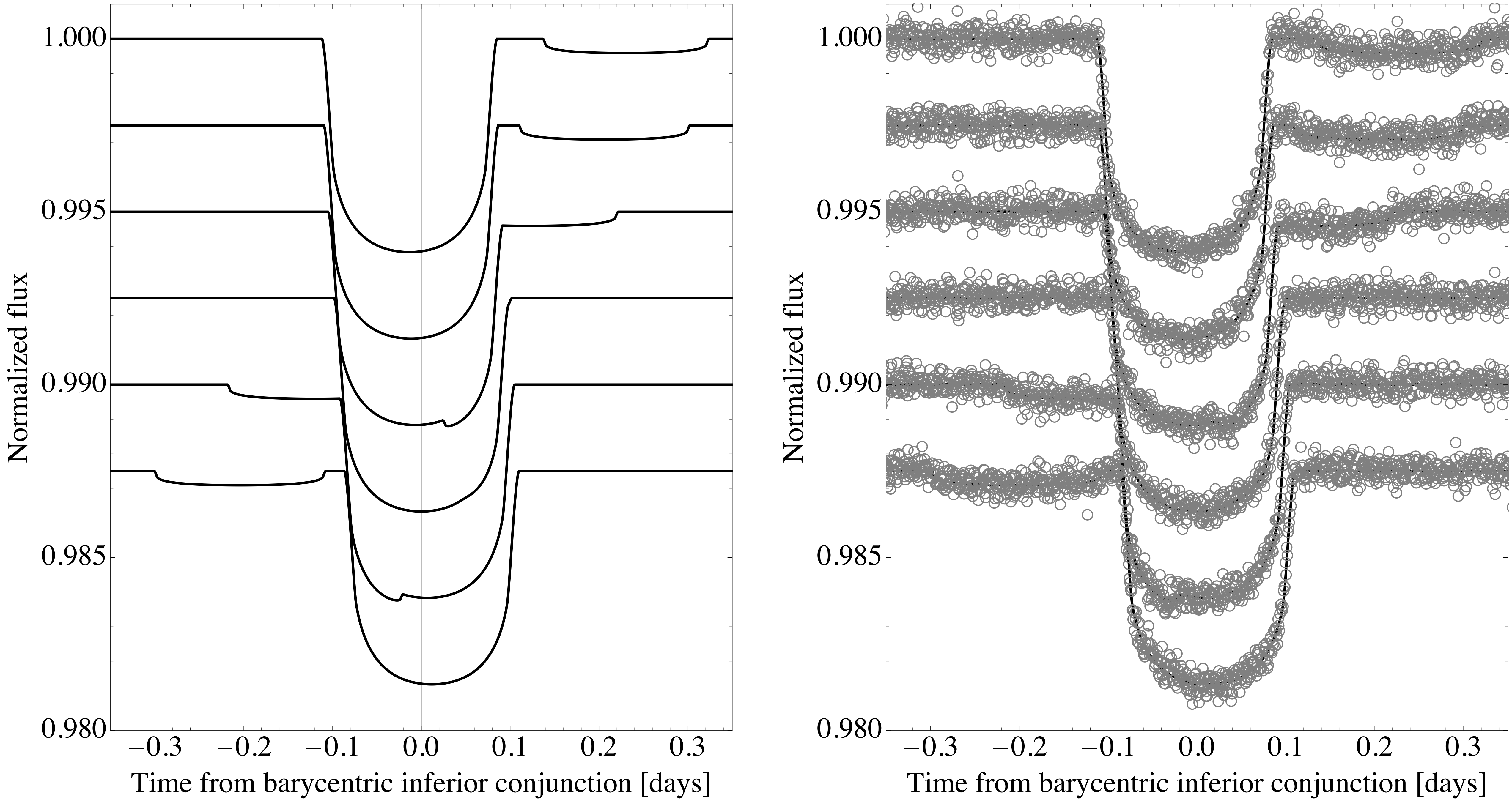

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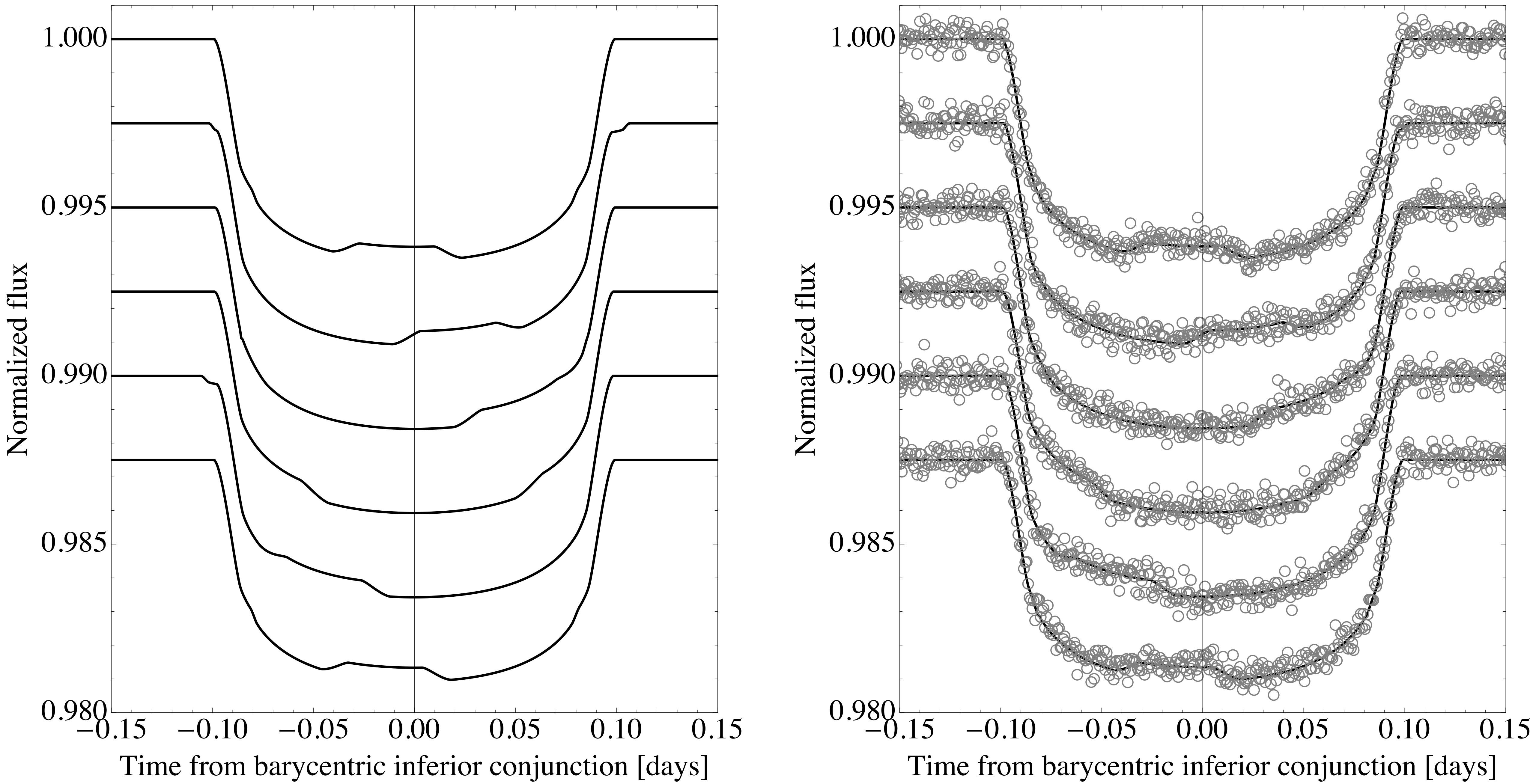

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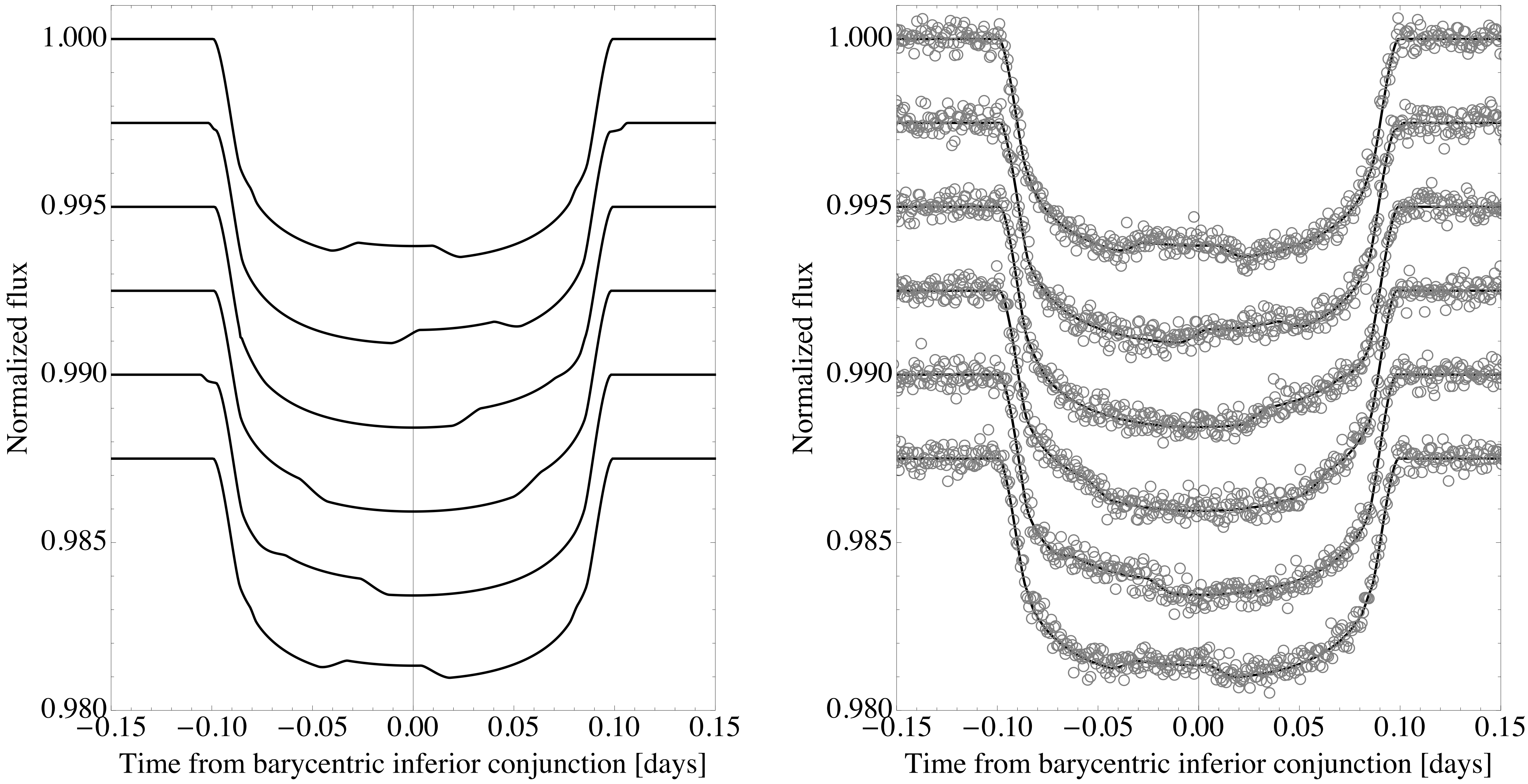

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hek

The Hunt for Exomoons with Kepler

David M. Kipping[1,2], Gáspár Á. Bakos[3], Lars Buchhave[4], David Nesvorný[5], Joel Hartman[3], Allan Schmitt[6]

[1] Harvard-Smithsonian Center for Astrophysics; [2] Carl Sagan Fellow; [3] Princeton University; [4] Neils Bohr Institute; [5] Southwest Research Institute; [6] Citizen Scientist

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- The first systematic search for transiting exomoons.
- Using public Kepler data
- Utilizing LUNA to identify exomoons
- Primary goal: detect a transiting exomoon(s)
- Secondary goal: obtain upper limits
- Tertiary goal: determine the frequency of large moons around viable planet hosts, $\eta_{☾}$

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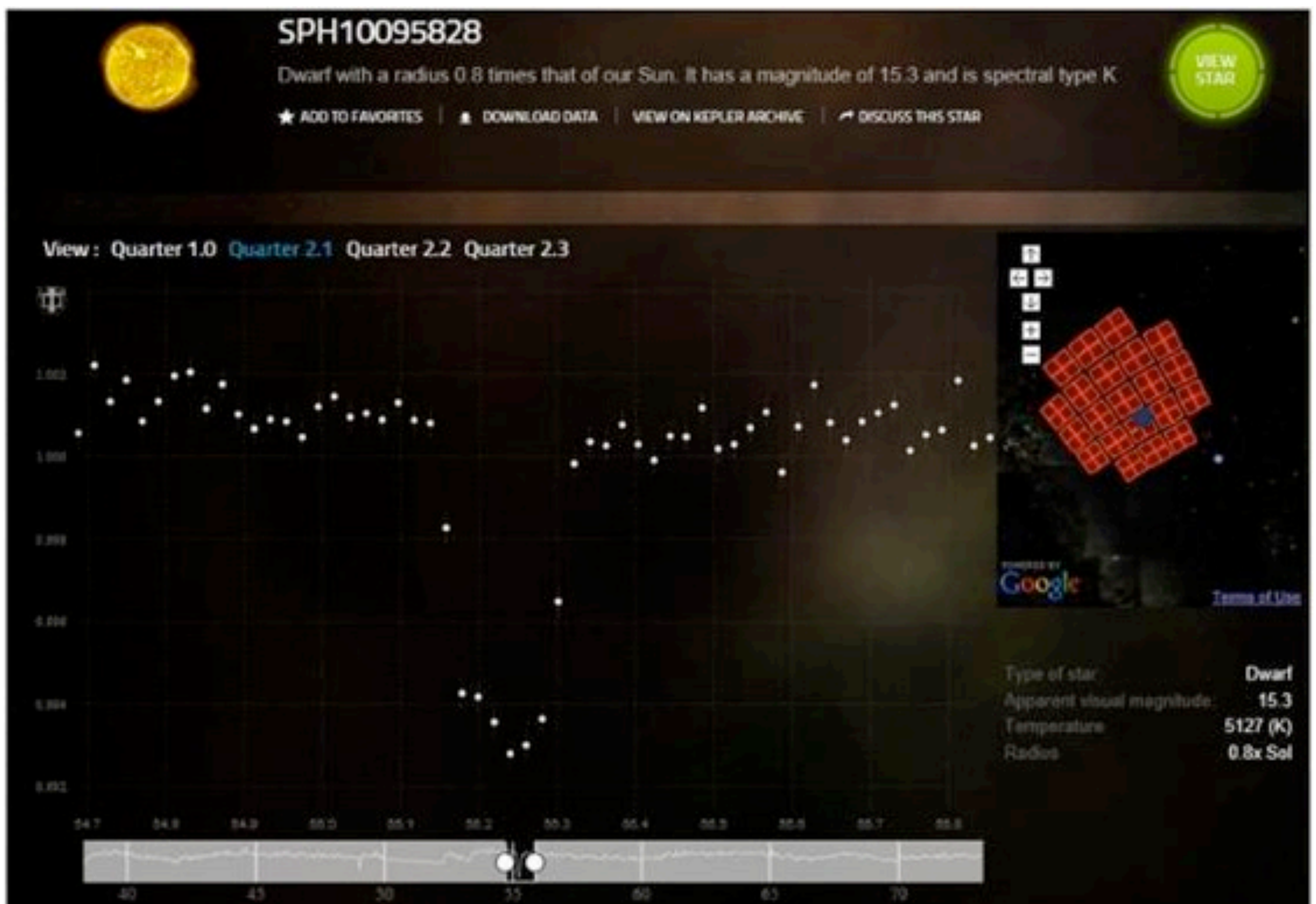
- Starspots, correlated noise and perturbing planets are challenging sources of false positive
- Bayesian model selection and inference is a must
- No-one has ever done this anything like this before - we are forced to invent everything as we go

KOI-872.01

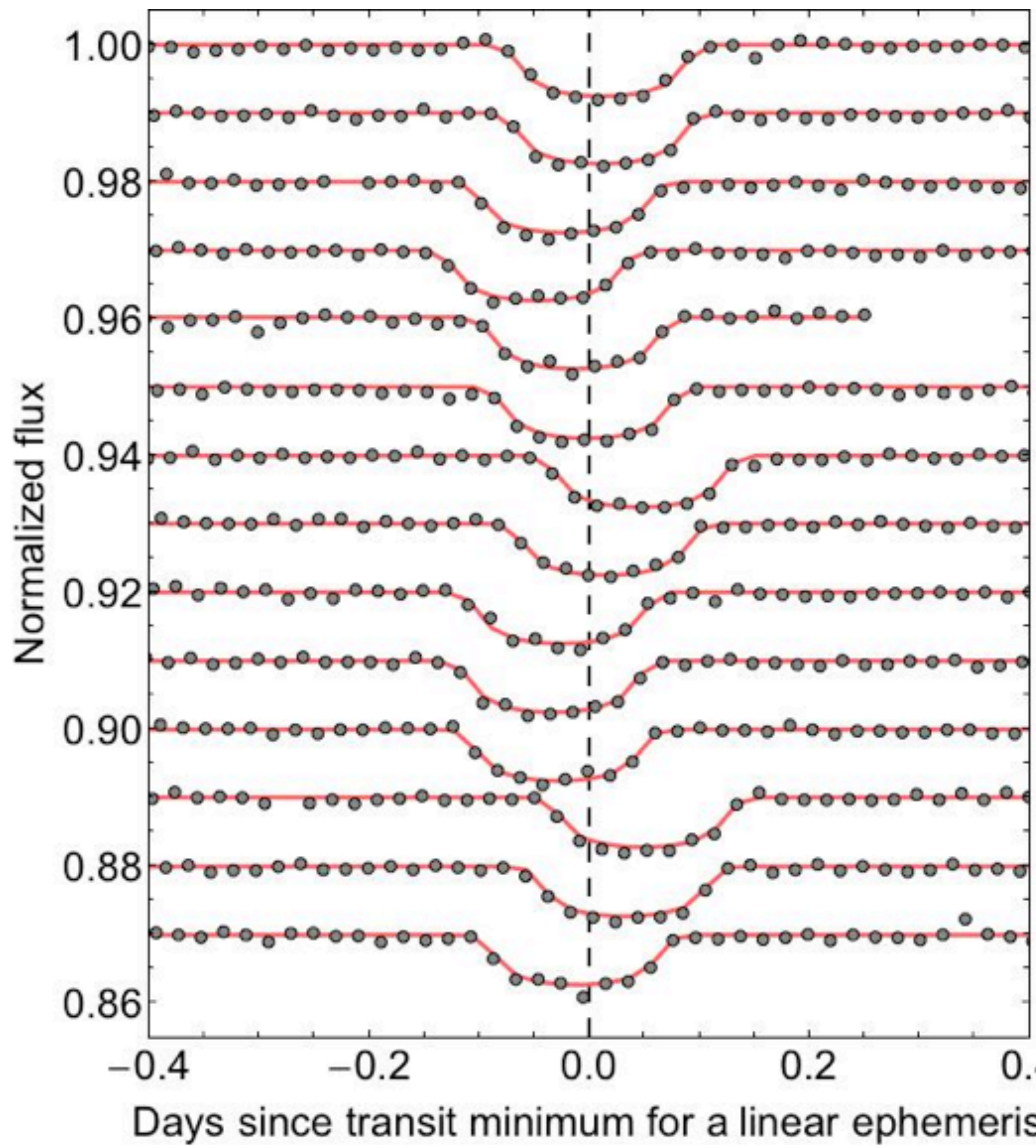
- One of our first TSVs (target selection visual), identified as showing in-transit anomalies:



Identified by Kepler (Borucki et al. 2010) as a candidate planet with P=33.6 d, Saturn-sized transit dip. Only one candidate in the system.

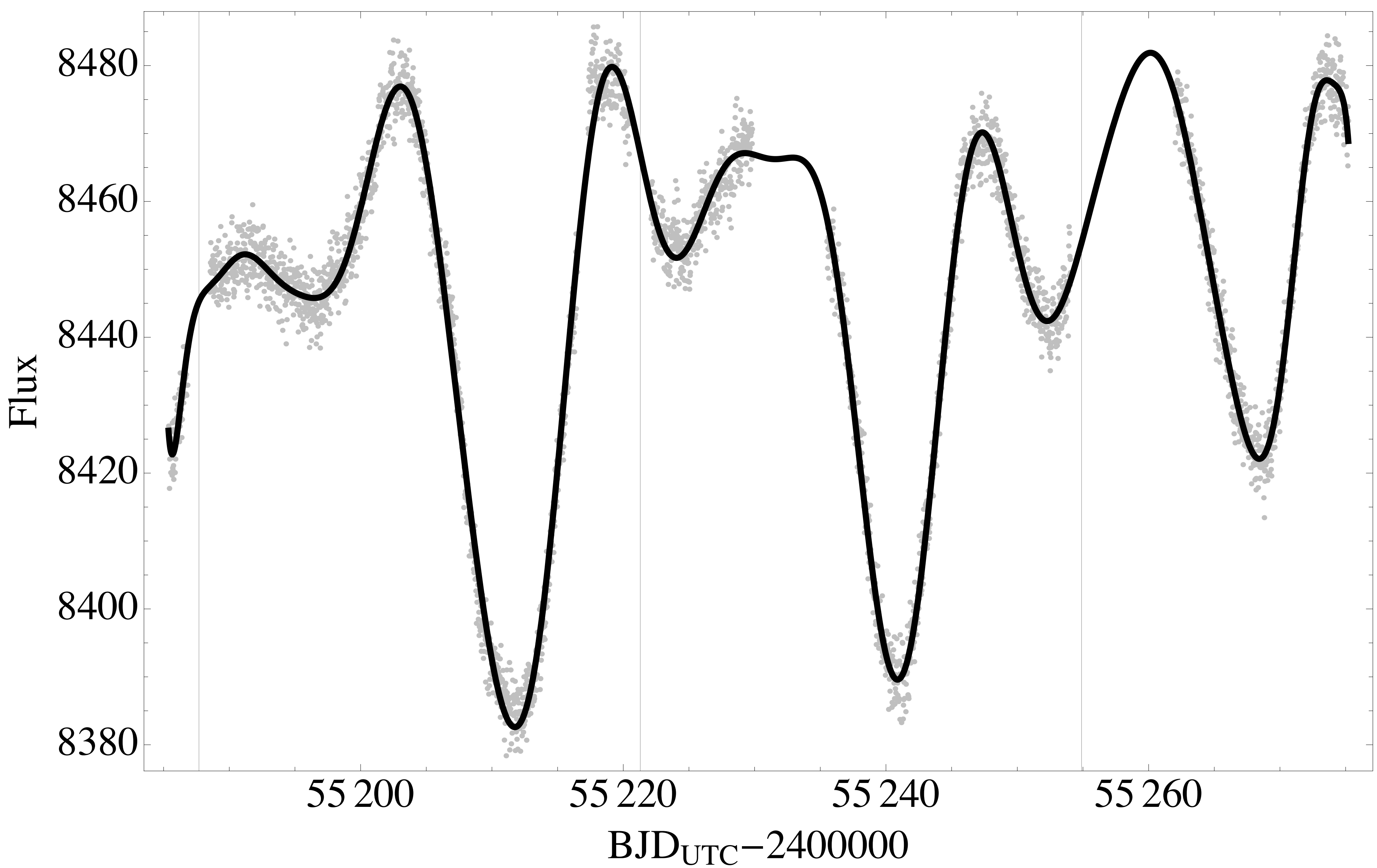
KOI-872.01

- More detailed study showed huge TTVs...



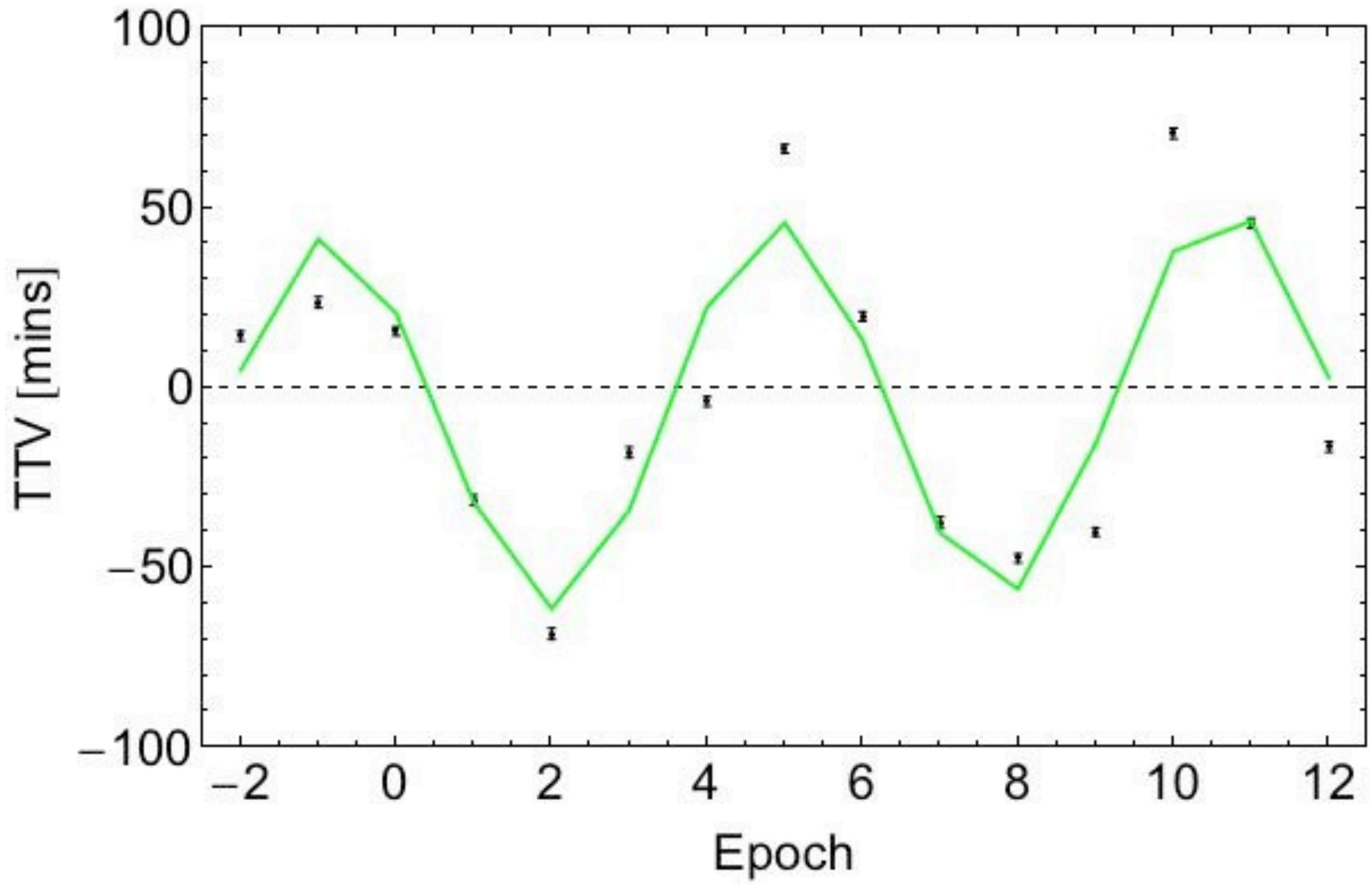
KOI-872.01

- And also stellar activity (like rotating spots)...



KOI-872.01

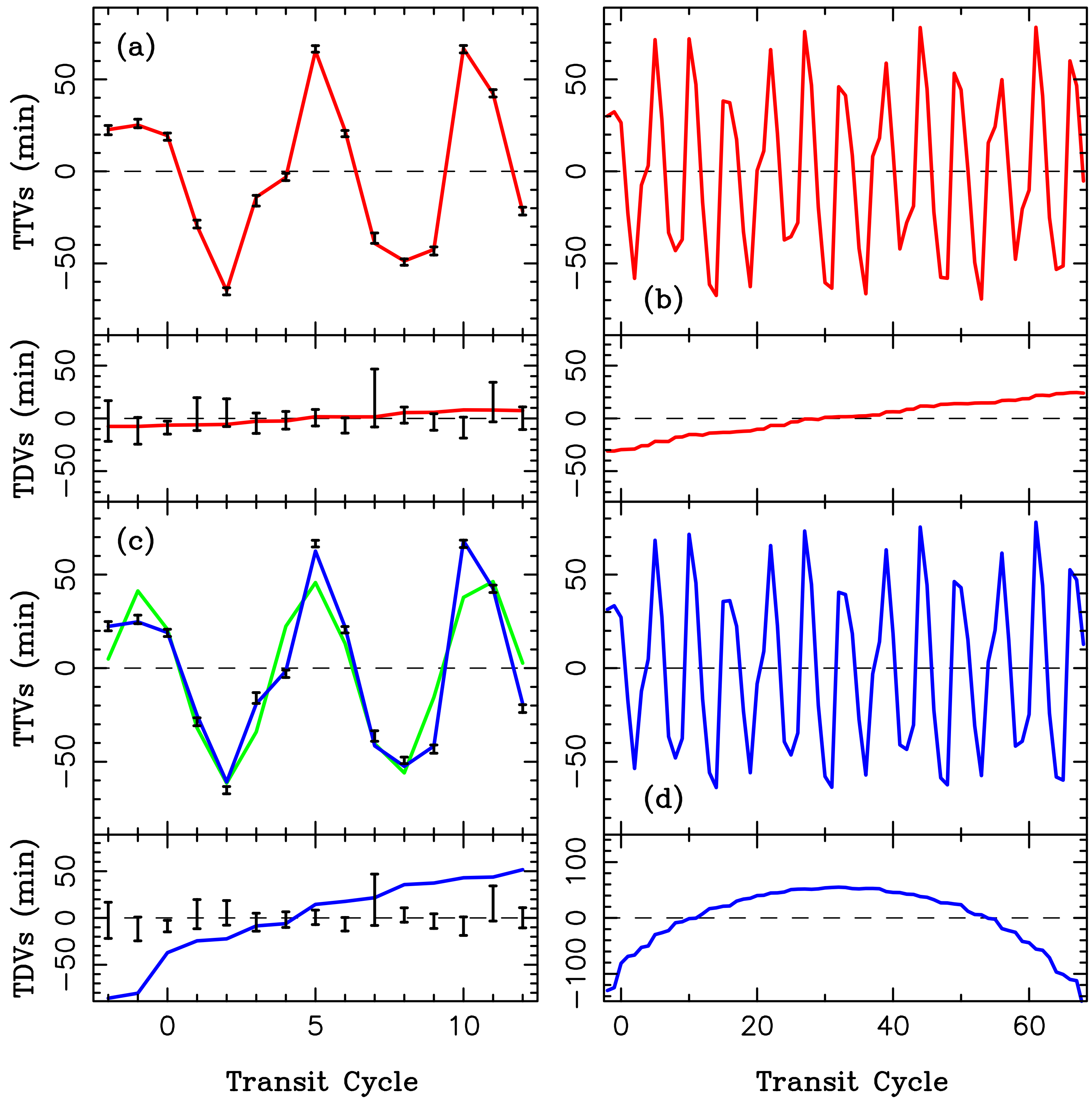
- But the TTVs are not poorly fit by a moon model...



- + lack of TDVs + spots = moon unlikely

KOI-872.01

- So we tried a second planet instead.
- 5:3 resonance (red) works very well.
- 5:2 does OK (blue) but requires an inclined planet => TDVs, which we do not see.



KOI-872.02 = KOI 872c

- The 2nd planet is very precisely pinned down.
- Dynamically measured mass ratio confirms the candidate is a real planet of Saturn-mass.

	KOI-872b	**KOI-872c**
τ_0 (BJD_{UTC})	$2455053.2826^{+0.0013}_{-0.0014}$	–
P_P (days)	$33.60134^{+0.00021}_{-0.00020}$	$57.004^{+0.091}_{-0.100}$
R_P/R_*	$0.0887^{+0.0011}_{-0.0012}$	–
b_P	$0.759^{+0.022}_{-0.027}$	$3.1^{+1.1}_{-1.9}$
a_P/R_*	$44.9^{+2.1}_{-1.8}$	$63.9^{+2.9}_{-2.5}$
i_P (°)	$89.033^{+0.076}_{-0.069}$	$87.25^{+1.70}_{-0.95}$
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e_P	$0.01^{+0.01}_{-0.01}$	$0.0145^{+0.0035}_{-0.0039}$
Ω_P (°)	270	303^{+20}_{-34}
ϖ_P (°)	–	$329.4^{+11}_{-9.2}$
λ_P (°)	0	$338.3^{+1.3}_{-1.4}$
M_P/M_*	$<6.4 \times 10^{-3}$	$3.97^{+0.17}_{-0.14} \times 10^{-4}$
M_P (M_J)	<6	$0.376^{+0.023}_{-0.020}$
R_P (R_J)	$0.812^{+0.043}_{-0.043}$	–
ρ_P (kg m^{-3})	<14000	–
T_{eq} (K)	544^{+16}_{-16}	456^{+13}_{-13}

KOI-872.01 = KOI 872b

- TTVs do not allow us to measure mass of inner object (yet).
- However, dynamical stability requires mass is less than 6 Jupiter masses => a real planet

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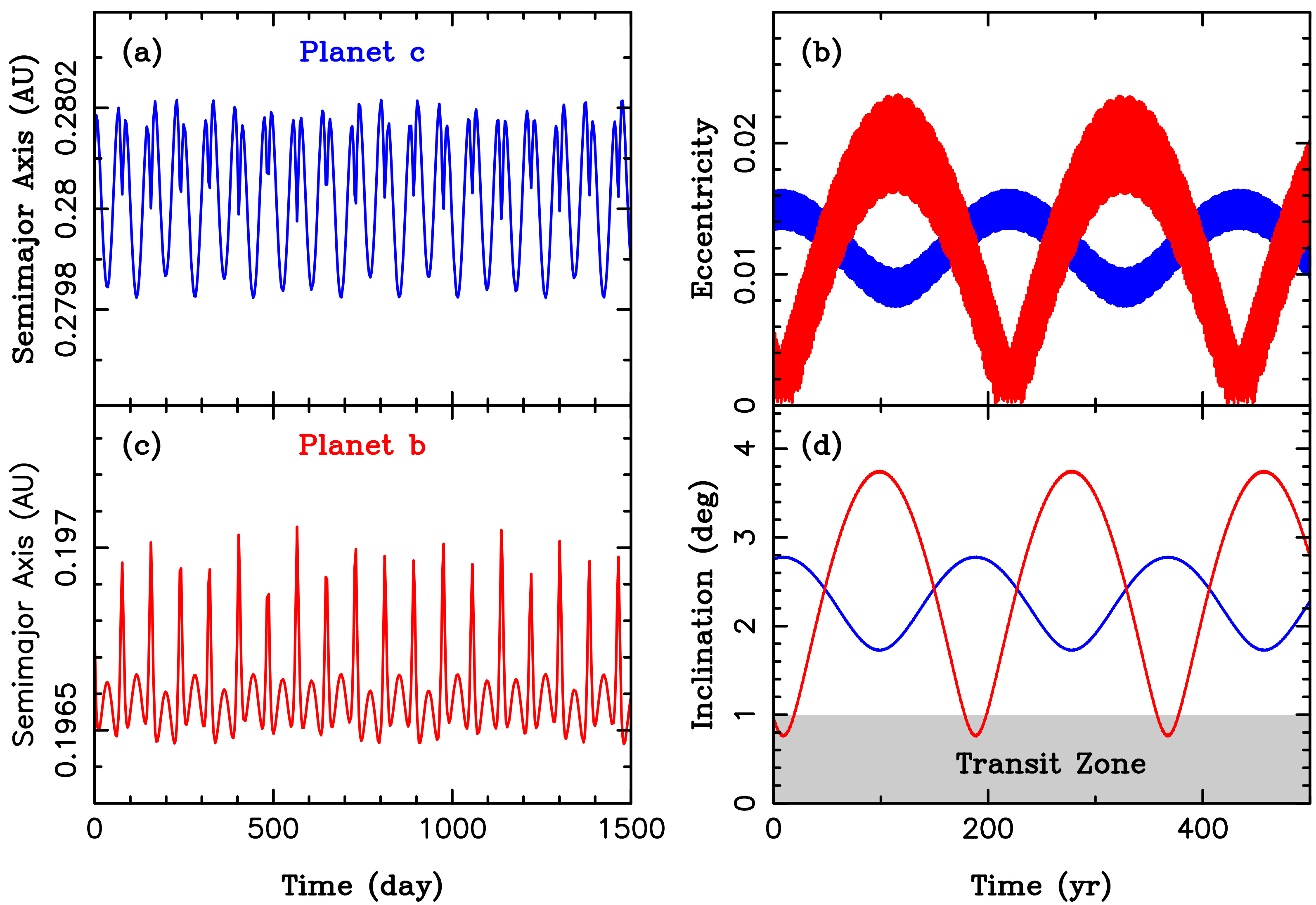
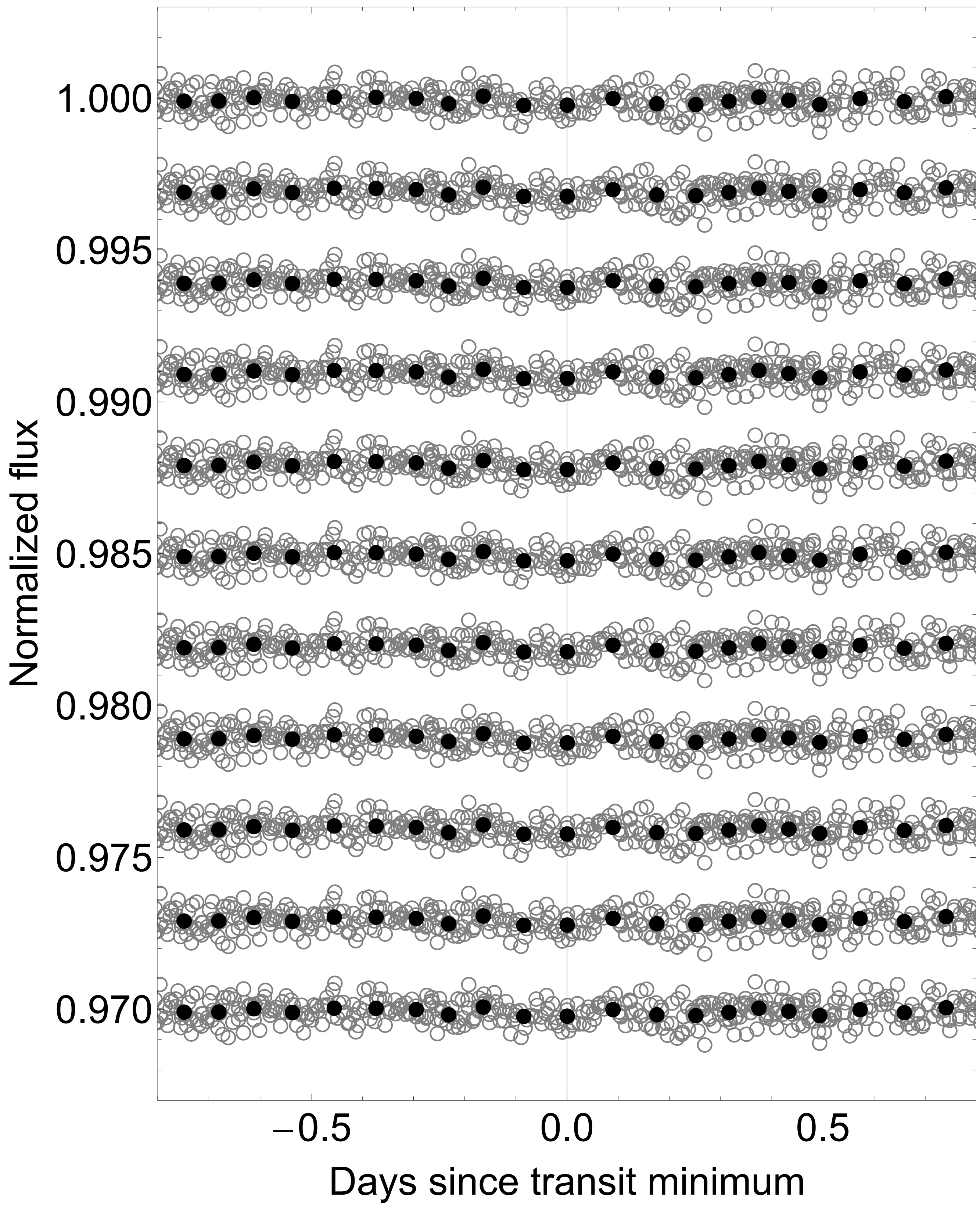
Does KOI 872c transit?

- TTVs imply c does not transit, now or ever.



KOI-872c does not transit



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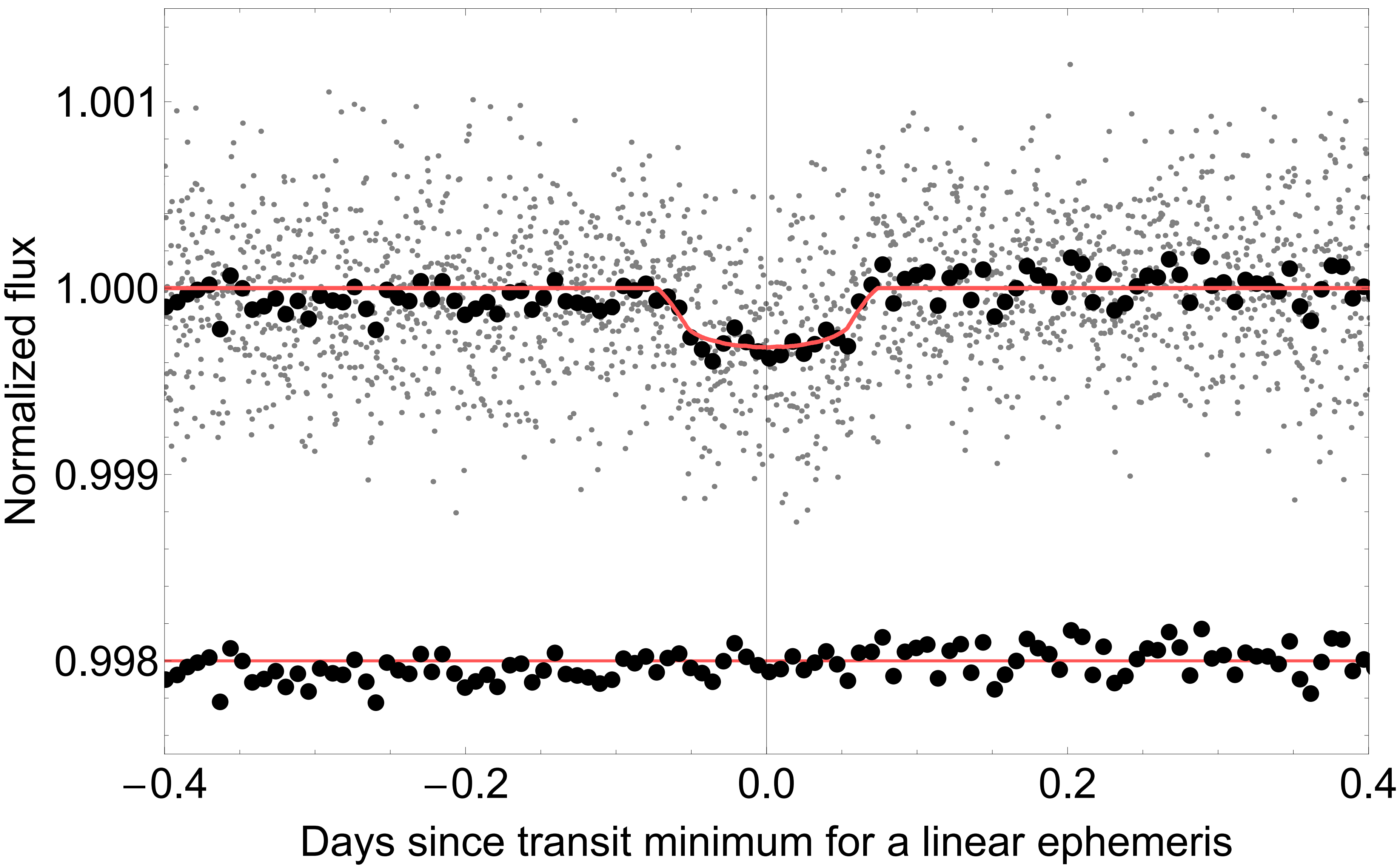

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- Depth implies a radius of 1.7 Earth radii.
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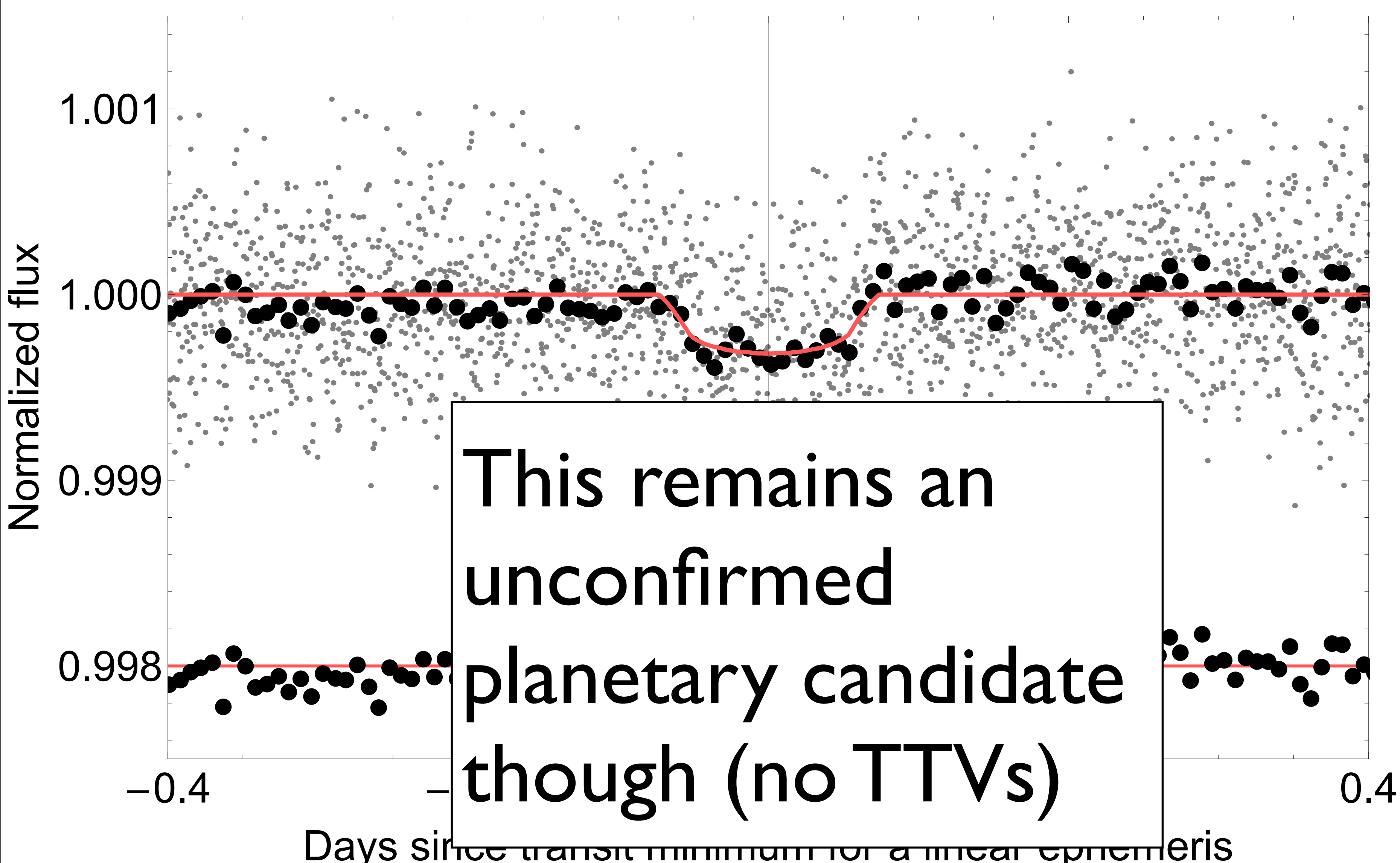

This remains an unconfirmed planetary candidate though (no TTVs)

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Final Parameters

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M_{moon}/M_P	<0.021	–	–

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M_* ($M_\odot$)	$0.902^{+0.040}_{-0.037}$
R_* ($R_\odot$)	$0.940^{+0.039}_{-0.040}$
log g_*	$4.445^{+0.041}_{-0.036}$
T_{eff} (K) (SPC)	5155 ± 105
L_* ($L_\odot$)	$0.559^{+0.0793}_{-0.0699}$
M_V	$5.60^{+0.17}_{-0.17}$
Age (Gyr)	$9.9^{+3.5}_{-3.1}$
Distance (pc)	857^{+69}_{-64}
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ϖ_P (°)	–	$329.4^{+11}_{-9.2}$	–
λ_P (°)	0	$338.3^{+1.3}_{-1.4}$	–
M_P/M_*	$<6.4 \times 10^{-3}$	$3.97^{+0.17}_{-0.14} \times 10^{-4}$	–
M_P (M_J)	<6	$0.376^{+0.023}_{-0.020}$	–
R_P (R_J)	$0.812^{+0.043}_{-0.043}$	–	$0.1513^{+0.0085}_{-0.0089}$
ρ_P (kg m^{-3})	<14000	–	–
T_{eq} (K)	544^{+16}_{-16}	456^{+13}_{-13}	924^{+37}_{-36}
M_{moon}/M_P	<0.021	–	–

	KOI-872
ρ_* (kg m^{-3})	1520^{+220}_{-170}
M_* ($M_\odot$)	$0.902^{+0.040}_{-0.037}$
R_* ($R_\odot$)	$0.940^{+0.039}_{-0.040}$
$\log g_*$	$4.445^{+0.041}_{-0.036}$
T_{eff} (K) (SPC)	5155 ± 105
L_* ($L_\odot$)	$0.559^{+0.0793}_{-0.0699}$
M_V	$5.60^{+0.17}_{-0.17}$
Age (Gyr)	$9.9^{+3.5}_{-3.1}$
Distance (pc)	857^{+69}_{-64}
(M/H) (SPC)	0.41 ± 0.10

Final Parameters

	KOI-872b	KOI-872c	KOI-872.03
τ_0 (BJD$_{UTC}$)	$2455053.2826^{+0.0013}_{-0.0014}$	–	$2455255.2603^{+0.0032}_{-0.0031}$
P_P (days)	$33.60134^{+0.00021}_{-0.00020}$	$57.004^{+0.091}_{-0.100}$	$6.76671^{+0.00013}_{-0.00012}$
R_P/R_*	$0.0887^{+0.0011}_{-0.0012}$	–	$0.01656^{+0.00079}_{-0.00082}$
b_P	$0.759^{+0.022}_{-0.027}$	$3.1^{+1.1}_{-1.9}$	$0.39^{+0.19}_{-0.12}$
a_P/R_*	$44.9^{+2.1}_{-1.8}$	$63.9^{+2.9}_{-2.5}$	$15.58^{+0.51}_{-0.49}$
i_P (°)	$89.033^{+0.076}_{-0.069}$	$87.25^{+1.70}_{-0.95}$	$88.56^{+0.48}_{-0.69}$
a_P (AU)	$0.1967^{+0.0029}_{-0.0028}$	$0.2799^{+0.0041}_{-0.0040}$	$0.0680^{+0.0030}_{-0.0030}$
e_P	$0.01^{+0.01}_{-0.01}$	$0.0145^{+0.0035}_{-0.0039}$	0 (assumed)
Ω_P (°)	270	303^{+20}_{-34}	–
ϖ_P (°)	–	$329.4^{+11}_{-9.2}$	–
λ_P (°)	0	$338.3^{+1.3}_{-1.4}$	–
M_P/M_*	$<6.4 \times 10^{-3}$	$3.97^{+0.17}_{-0.14} \times 10^{-4}$	–
M_P (M_J)	<6	$0.376^{+0.023}_{-0.020}$	–
R_P (R_J)	$0.812^{+0.043}_{-0.043}$	–	$0.1513^{+0.0085}_{-0.0089}$
ρ_P (kg m^{-3})	<14000	–	–
T_{eq} (K)	544^{+16}_{-16}	456^{+13}_{-13}	924^{+37}_{-36}
M_{moon}/M_P	<0.021	–	–
	KOI-872		
ρ_* (kg m^{-3})	1520^{+220}_{-170}		
M_* ($M_\odot$)	$0.902^{+0.040}_{-0.037}$		
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Age (Gyr)	$9.9^{+3.5}_{-3.1}$		
Distance (pc)	857^{+69}_{-64}		
(M/H) (SPC)	0.41 ± 0.10		

No moon, but when life gives you lemons, make lemonade!

hek

The Hunt for Exomoons with Kepler

Questions?