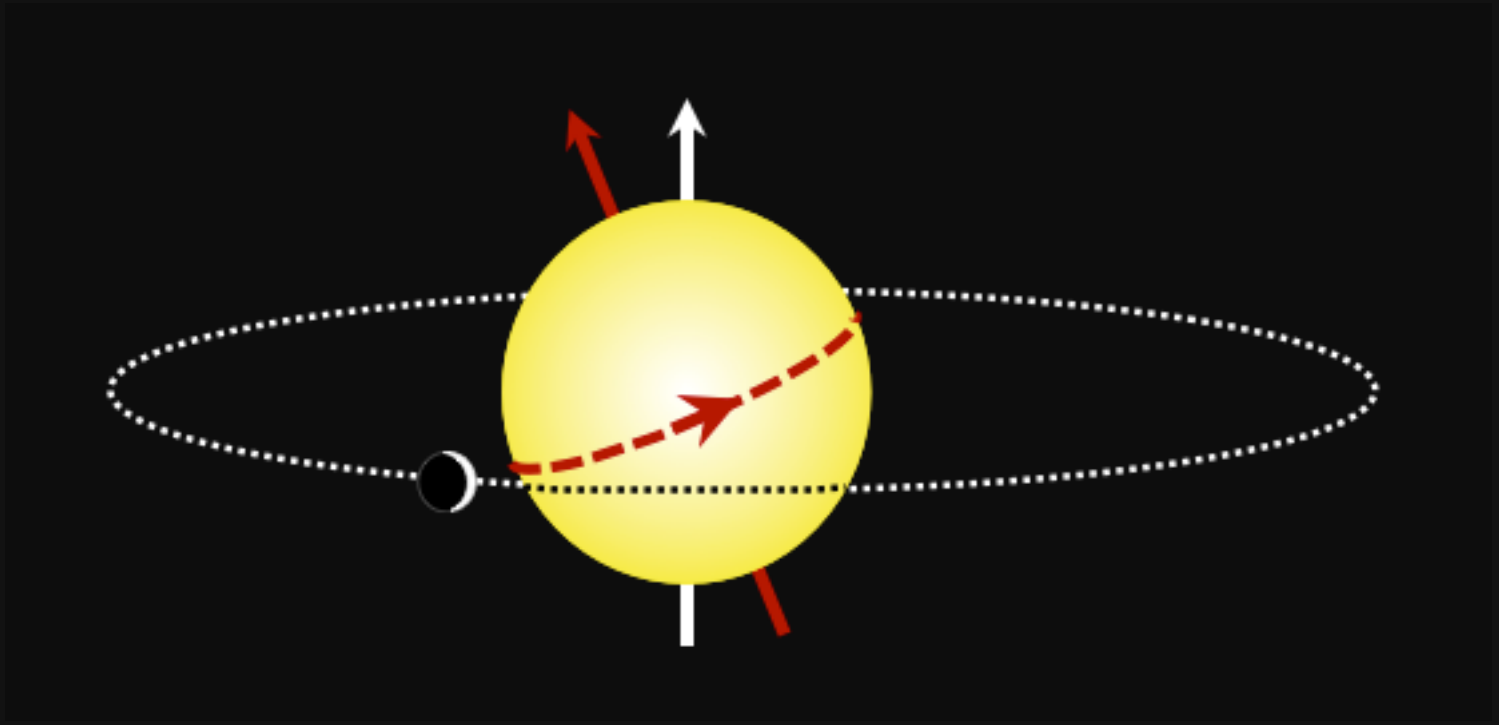
Spot-crossing models for Spin-Orbit alignment

Sagan Workshop 2012
Caltech, Pasadena

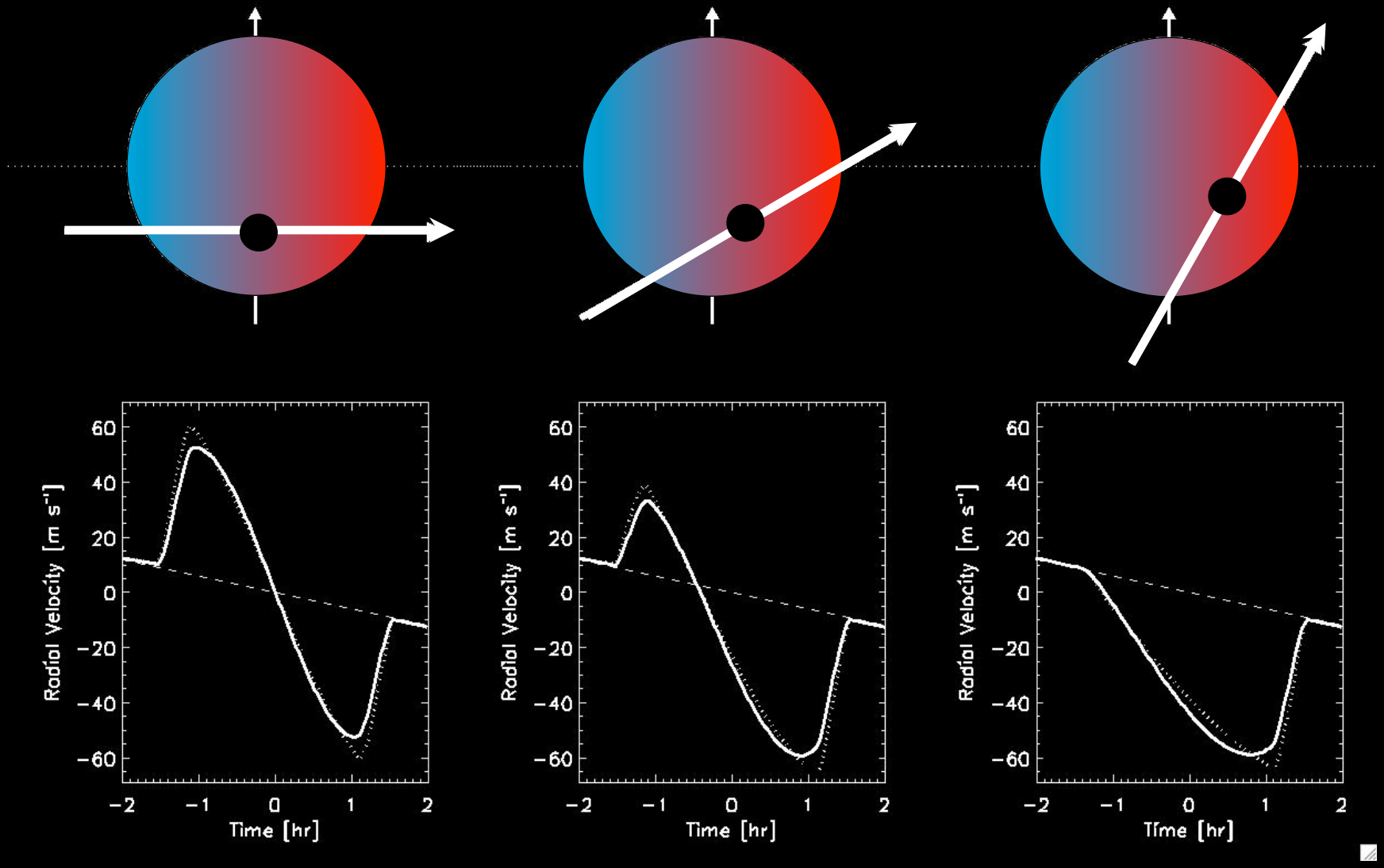
Roberto Sanchis Ojeda

Ph.D. candidate, MIT



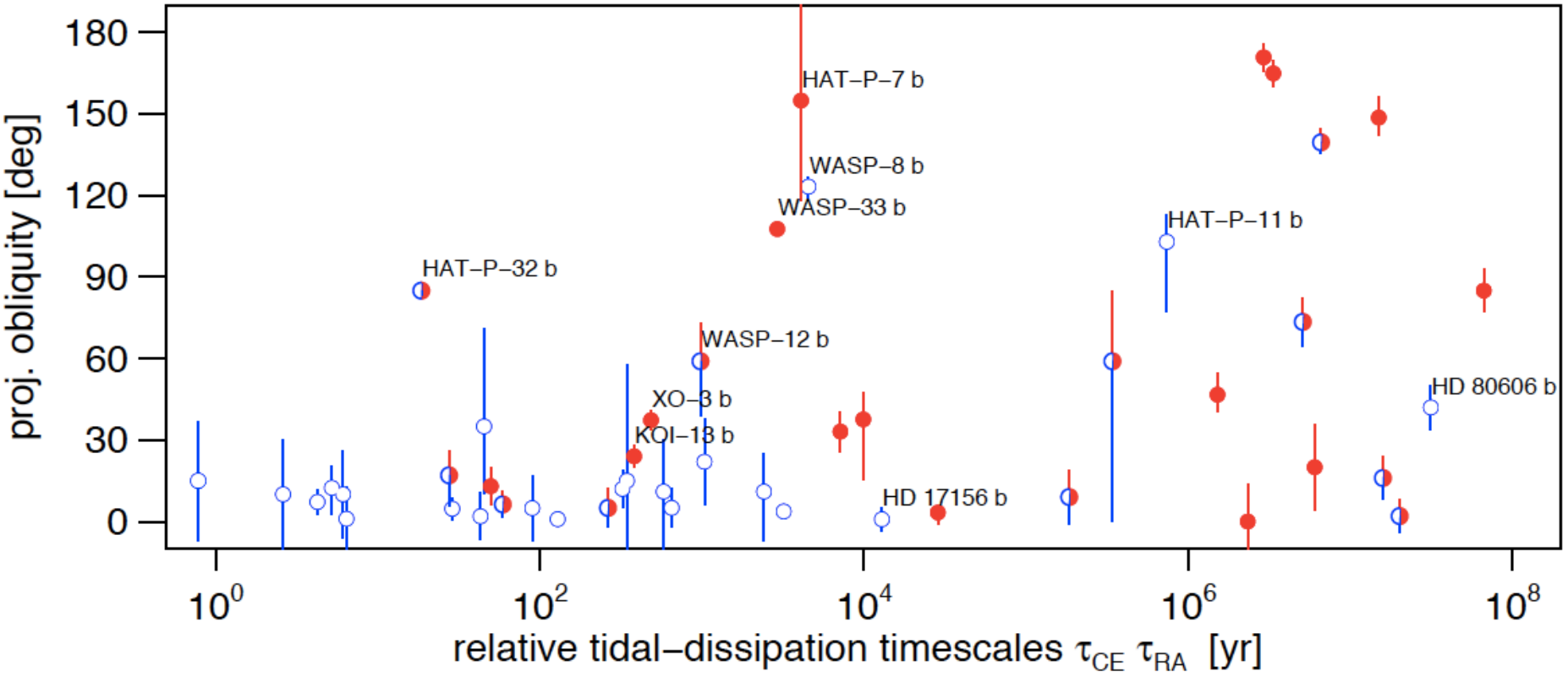
The obliquity (Ψ) or spin-orbit angle, is the angle between the spin axis of the host star and the orbital plane of the planet. Its projection on the sky plane is λ.

Measuring spin-orbit alignment



Ohta, Taruya, & Suto (2005); Gaudi & Winn (2007)

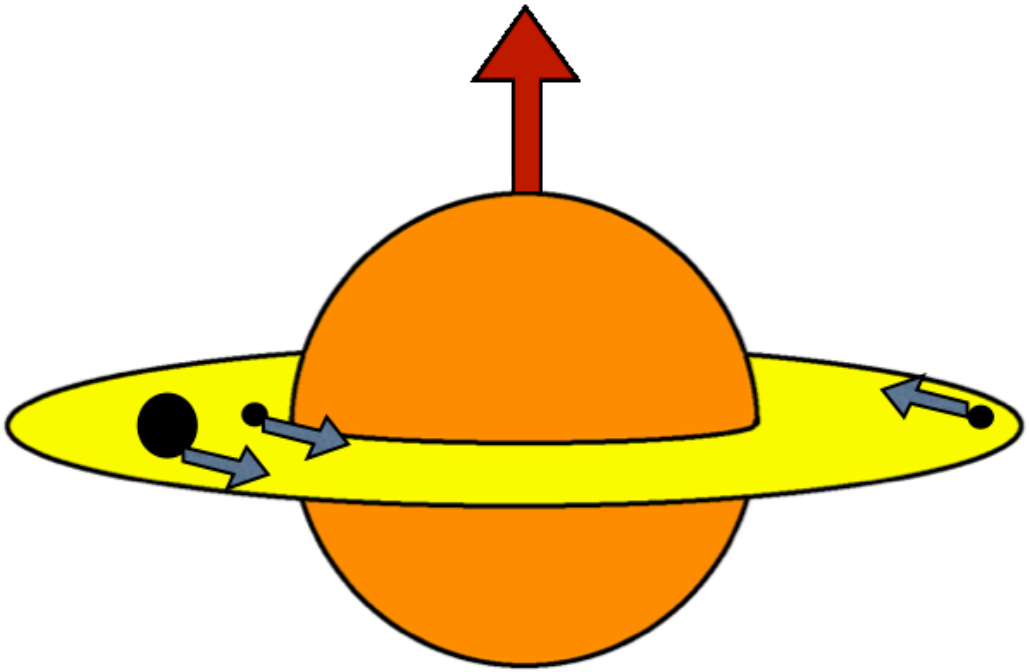
High obliquities among the Hot Jupiters



Albrecht et al. 2012 (see also Winn et al. 2010, Triaud et al. 2010)

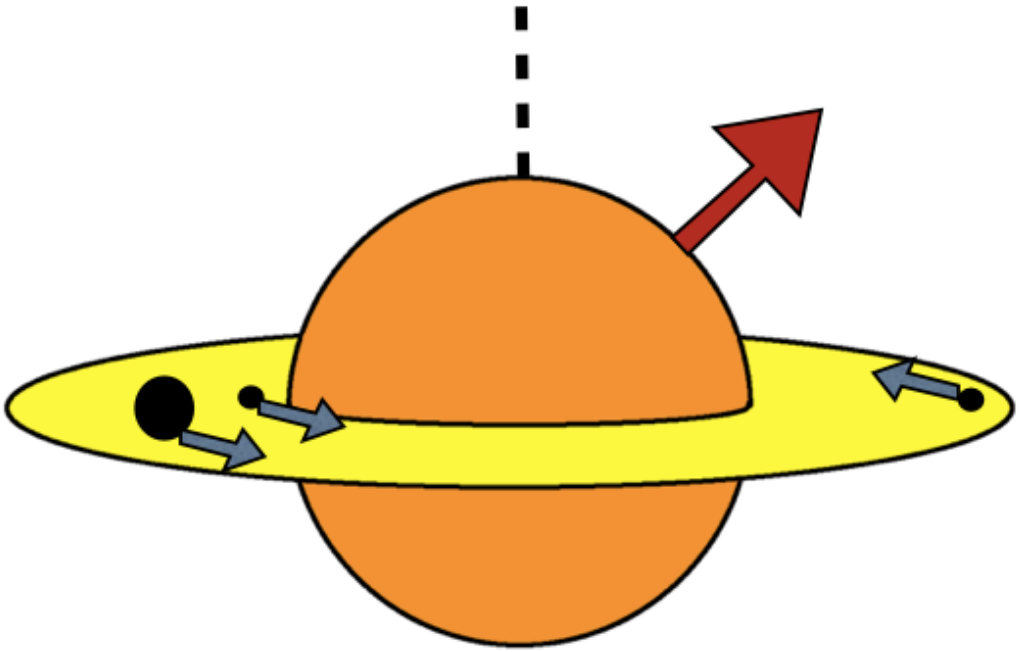
How did they get misaligned?

Formation on a spinning disk would suggest that all systems should have a small obliquity.



How did they get misaligned?

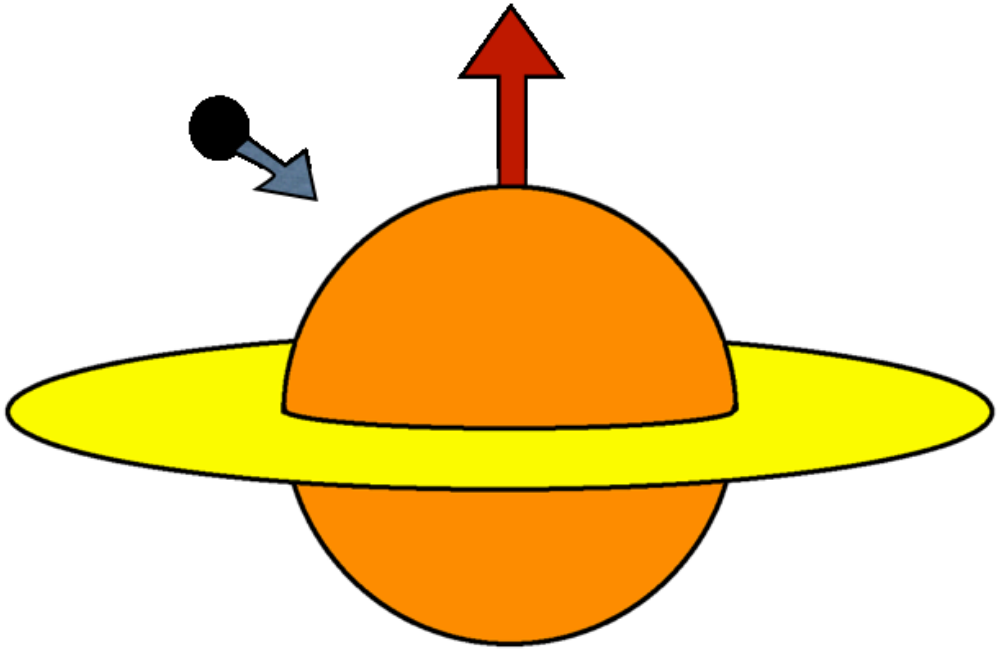
Star-disk misalignments: Chaotic accretion, magnetic interactions or torques from neighbor stars.



Bate et al. 2010, Lai et al. 2011

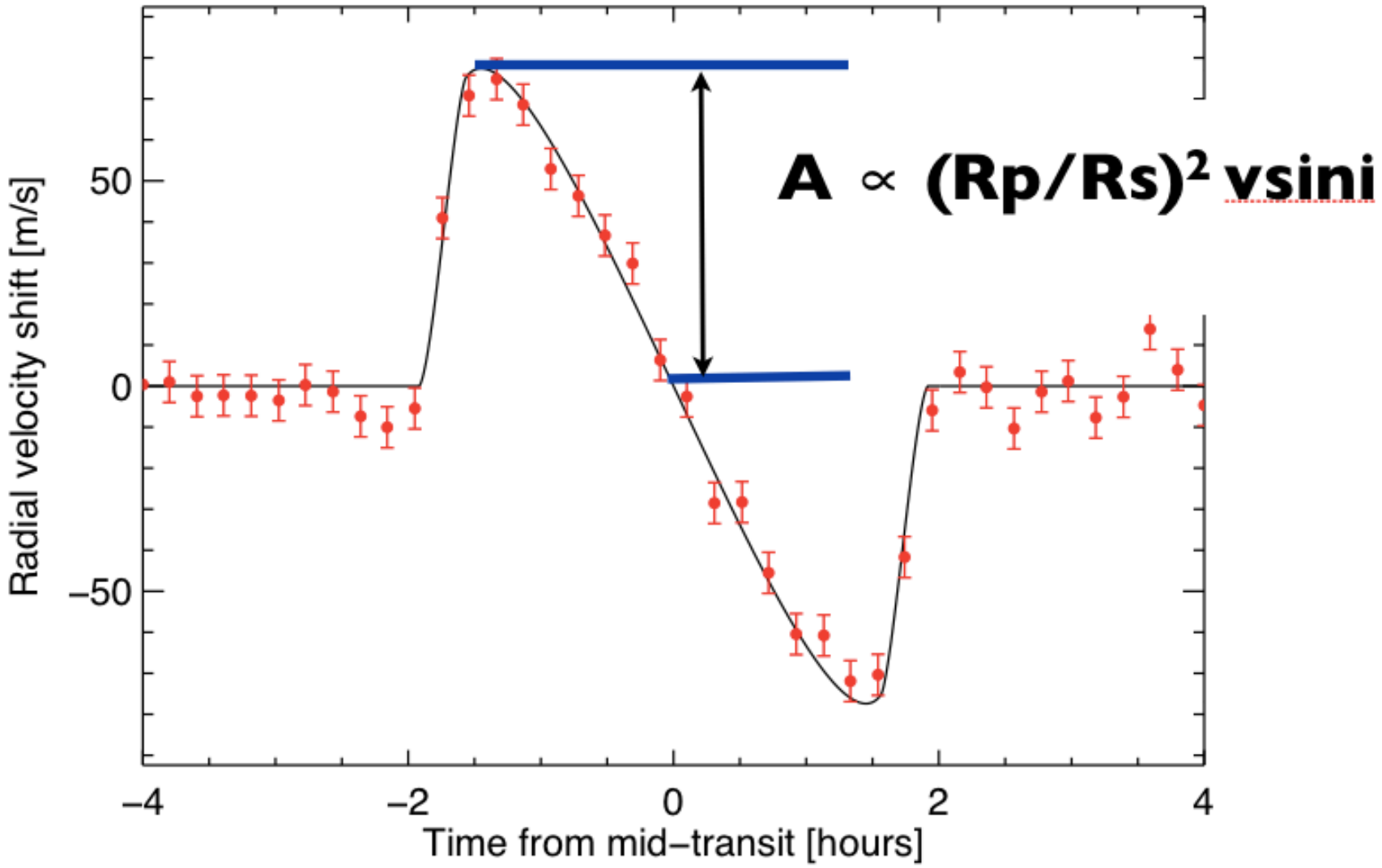
How did they get misaligned?

Planet-disk misalignments: Planet-planet scattering or Kozai cycles.

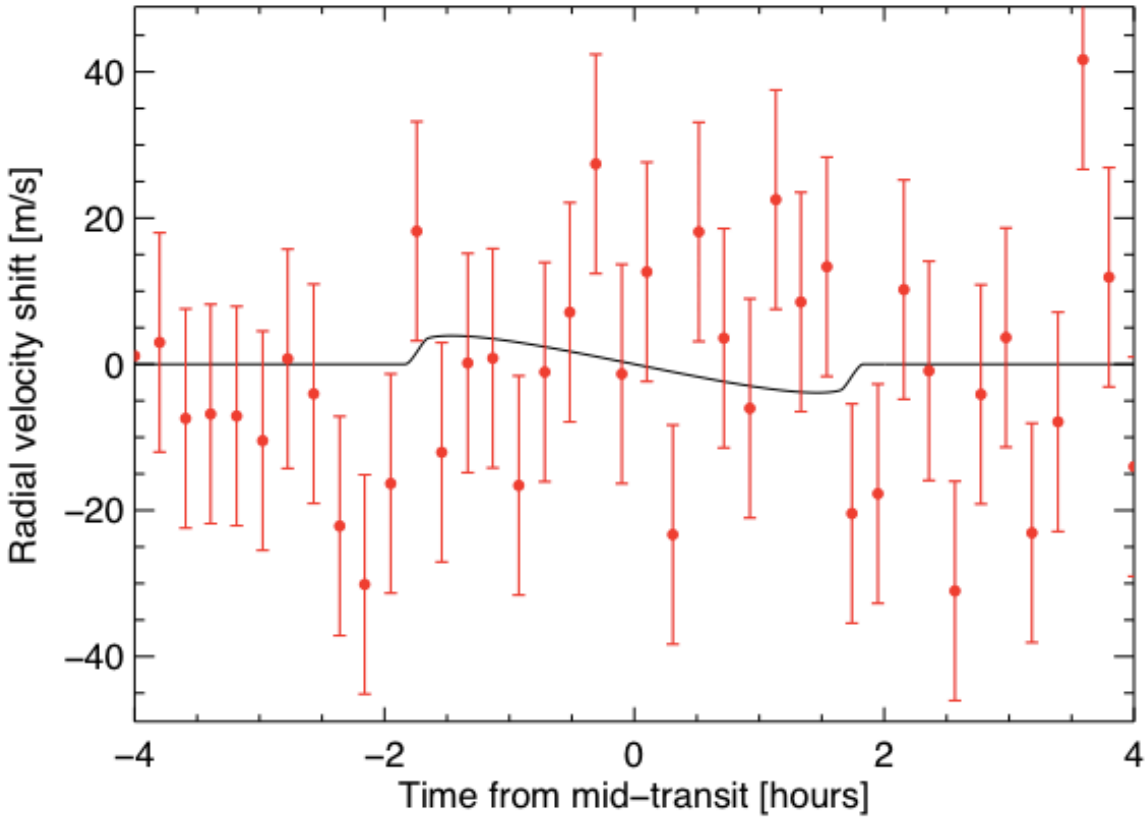


Fabrycky and Tremaine, 2007. Nagasawa et al. 2008.

The RM effect works well for Hot Jupiters orbiting bright fast rotators



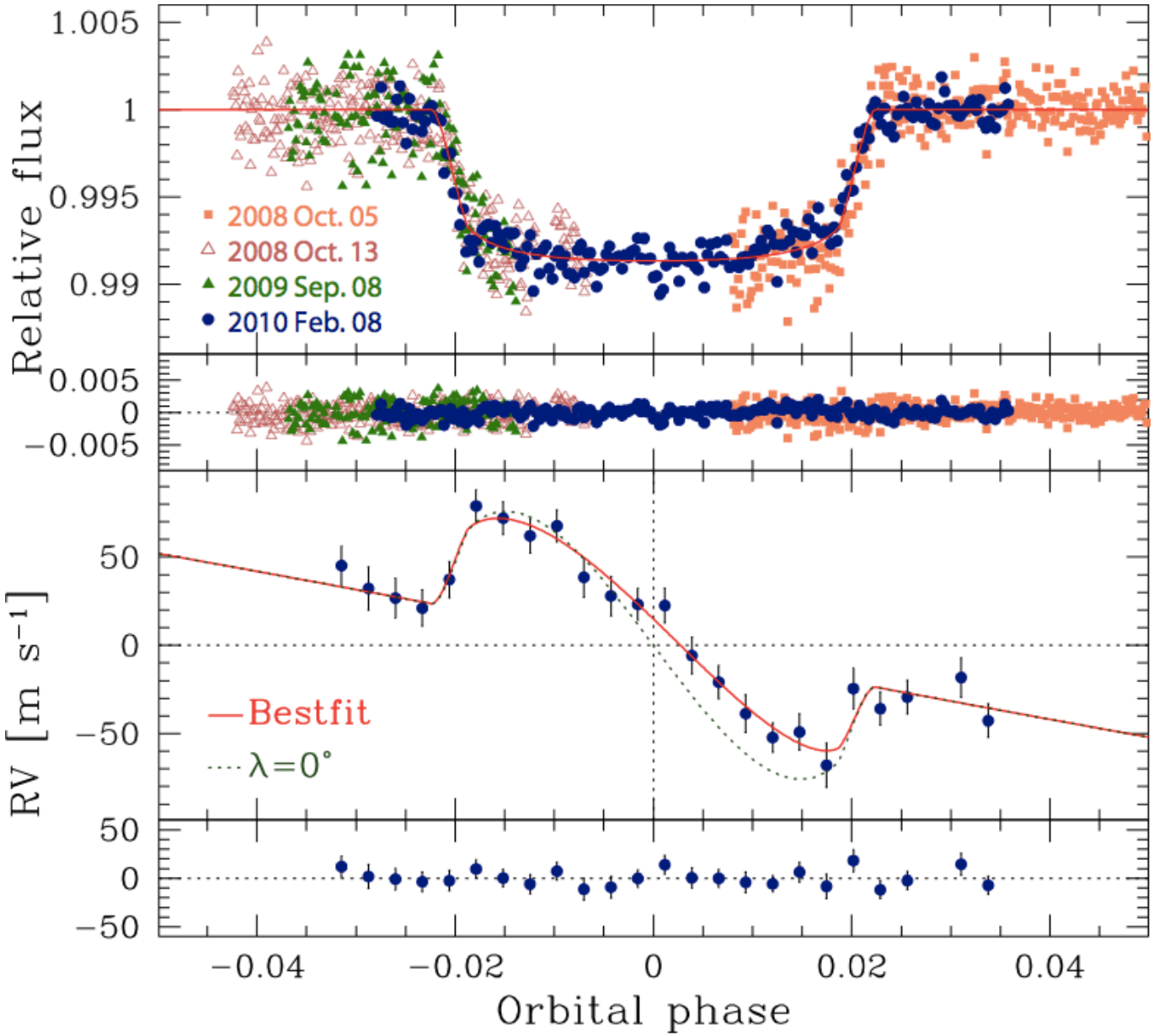
The RM effect is hard to use for Kepler multiple systems



Kepler faint apparent magnitudes and the long orbital periods of the large multiple planet systems, make it hard to do follow up, but Kepler data can provide a lot of information.

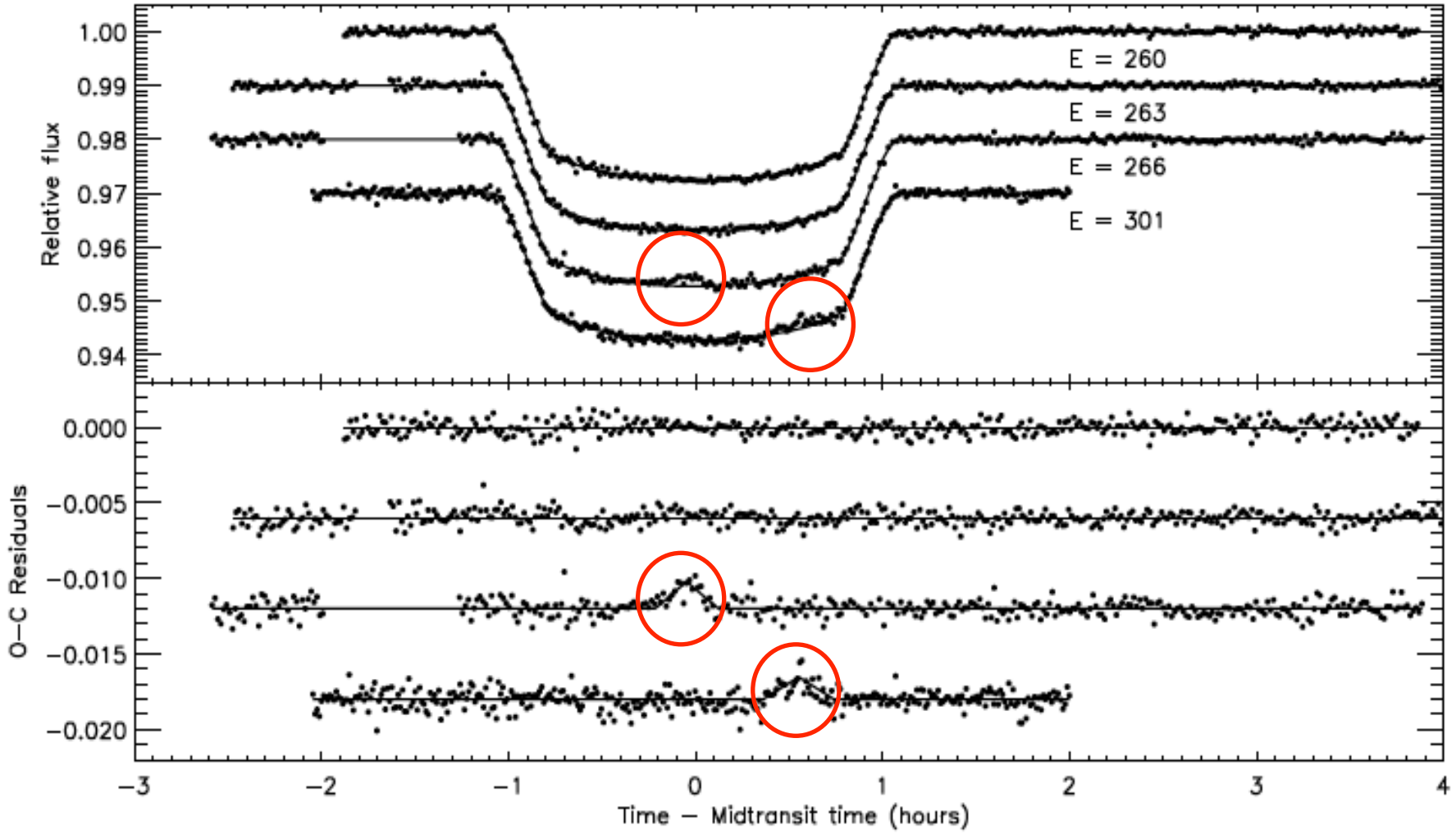

MASSACHVSETTS INSTITVTE OF TECHNOLOGY


δ_{obs}



Narita et al. 2010

My new transits of WASP-4b



Sanchis-Ojeda et al. 2011

AT&T 3G 1:25 AM 100%

Messages

Astrochat

Edit

What are these strange bumps in the light curves, some strange systematic artifact?

Have you checked if the residuals correlate with anything you can ever imagine?

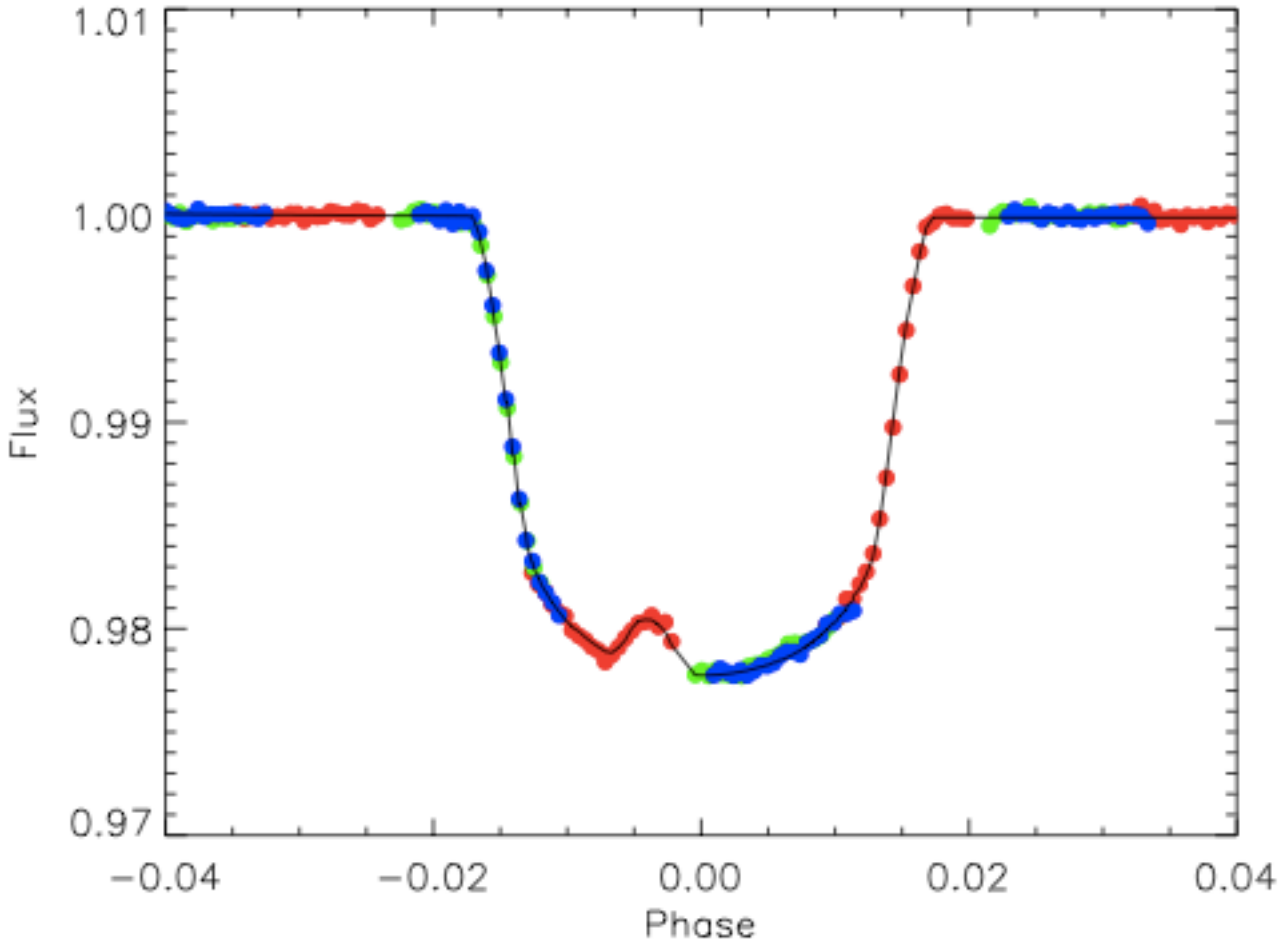
Yes.

Then it is astrophysical, probably due to spots. If it is the same spot, we might be able to get the obliquity of the system. Can you come up with a nice way of doing this?

Challenge accepted!

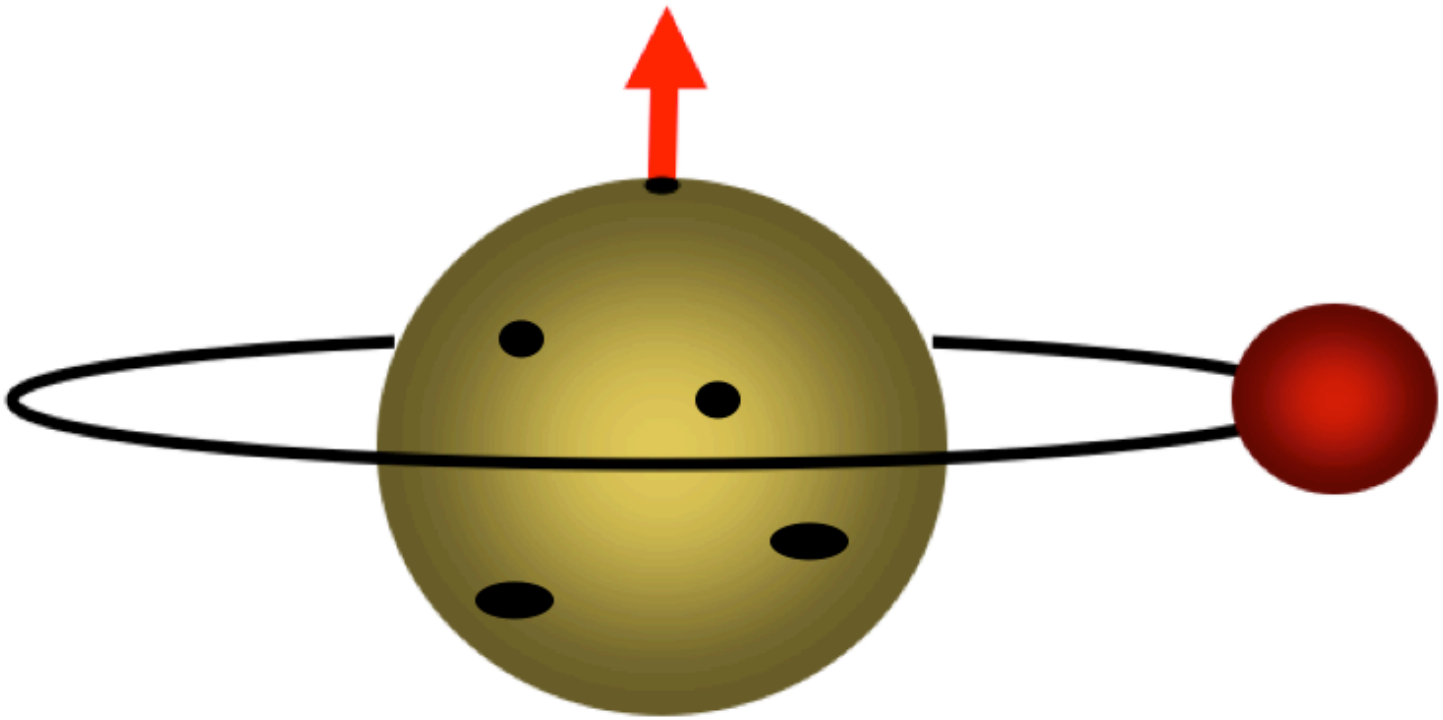
Send

Starspots, and old enemy

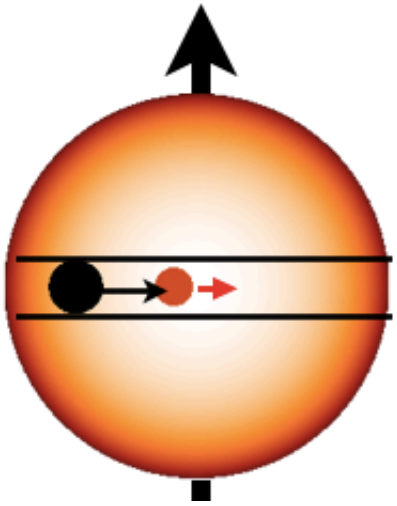


Like the Sun, slow rotators have spots in their surfaces. They have been a nuisance (Rabus et al. 2008)

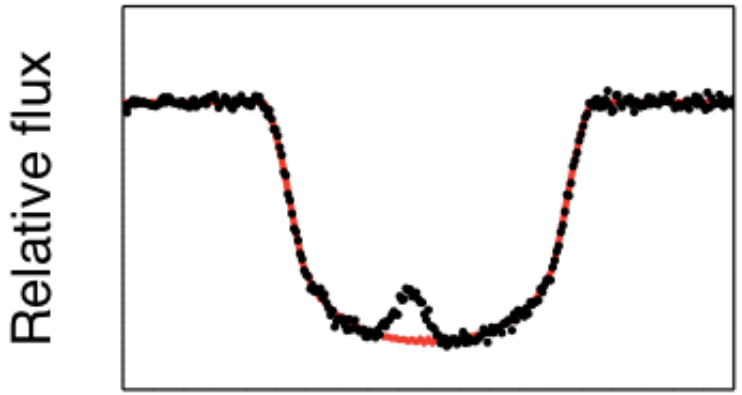
Aligned system: Follow spots

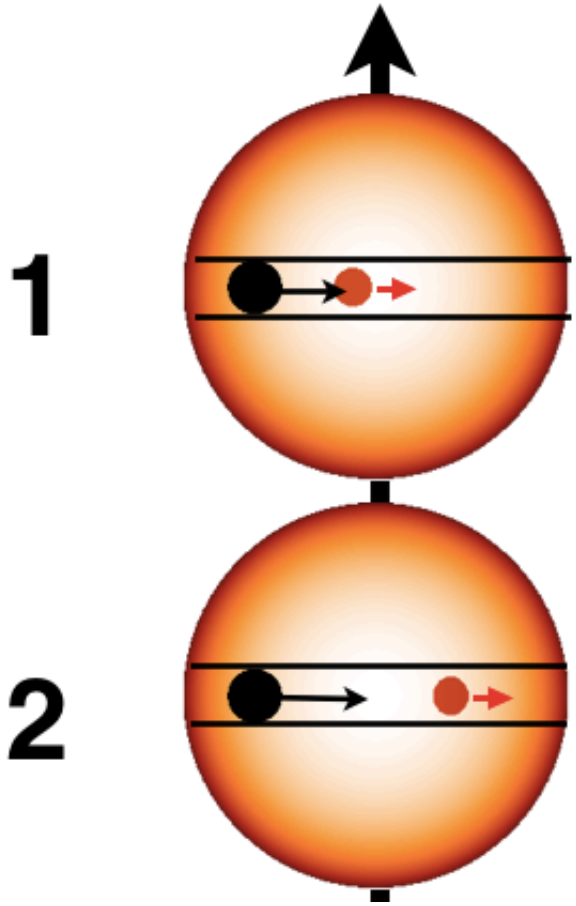


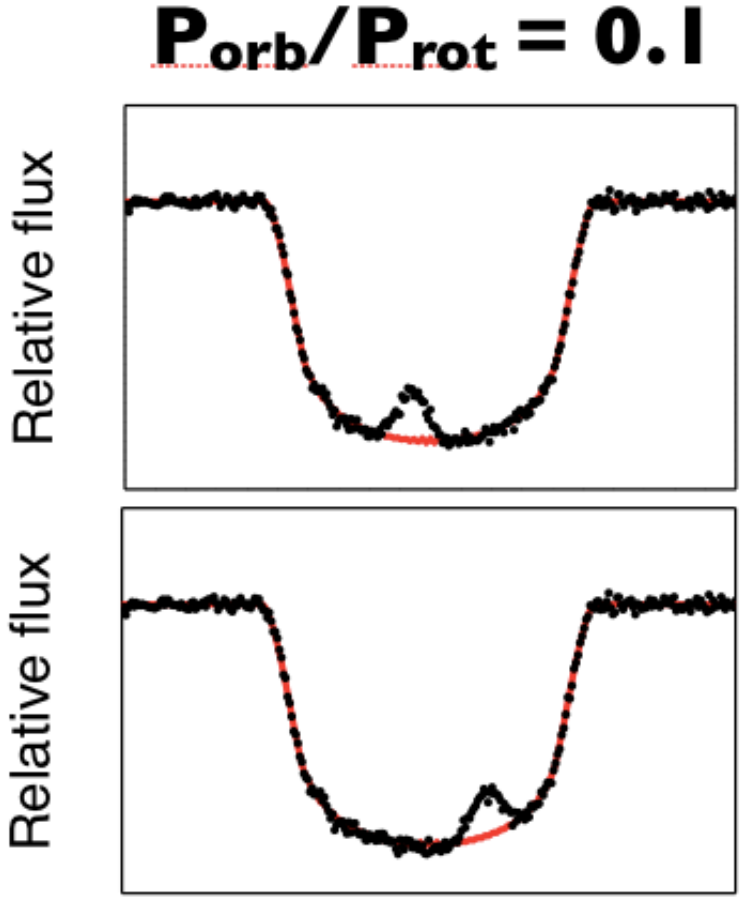
1

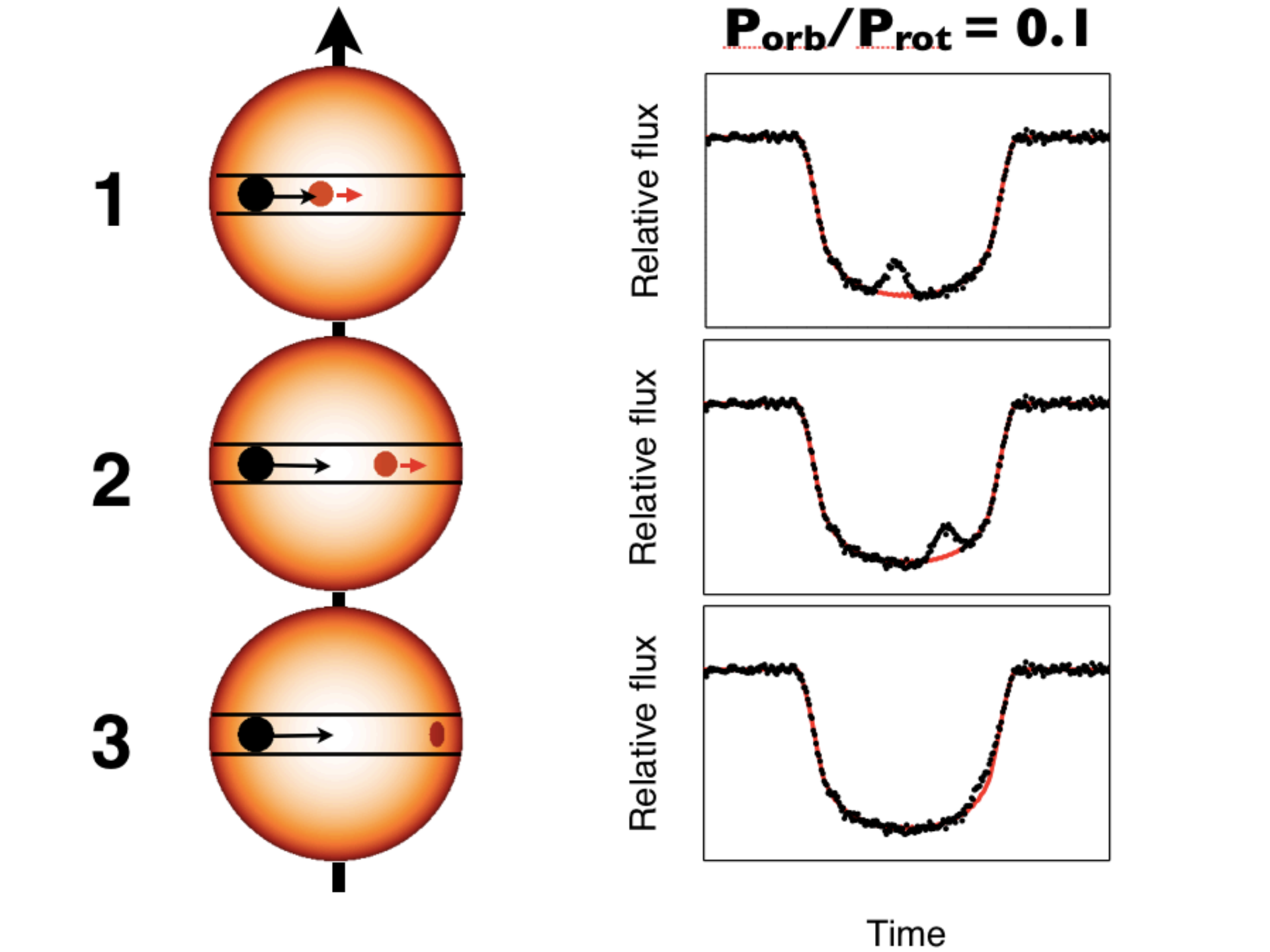


$P_{orb}/P_{rot} = 0.1$

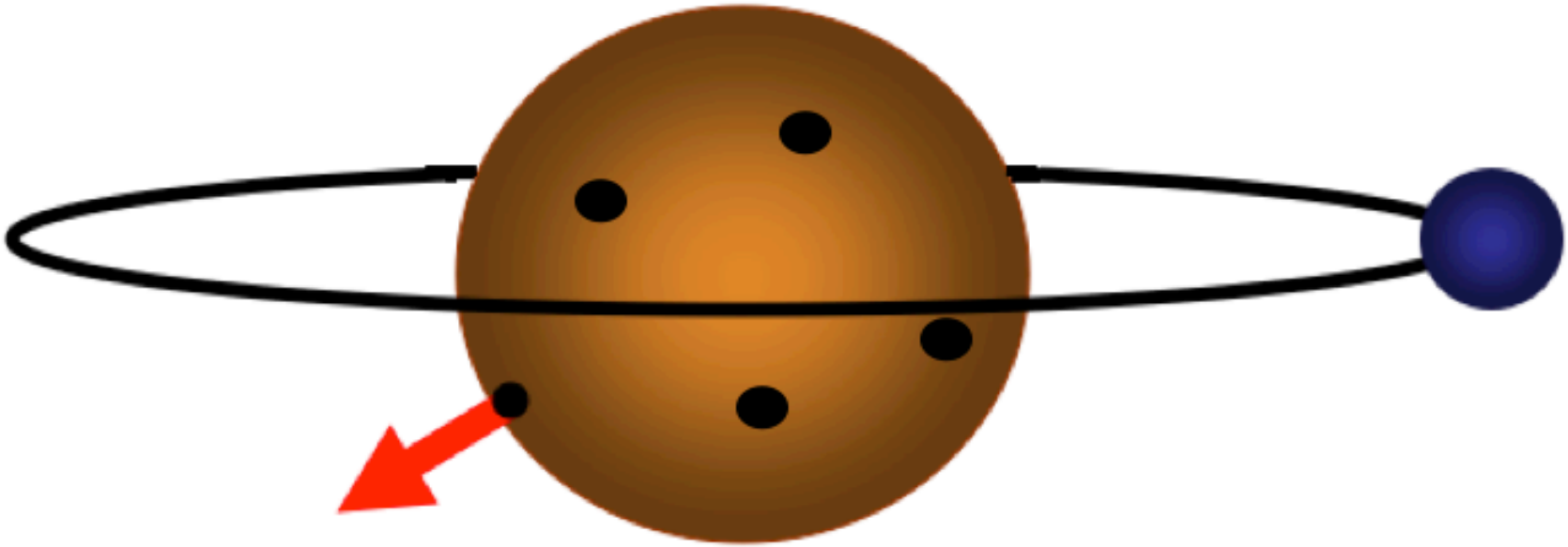



1
2


P_{orb}/P_{rot} = 0.1
Relative flux
Relative flux

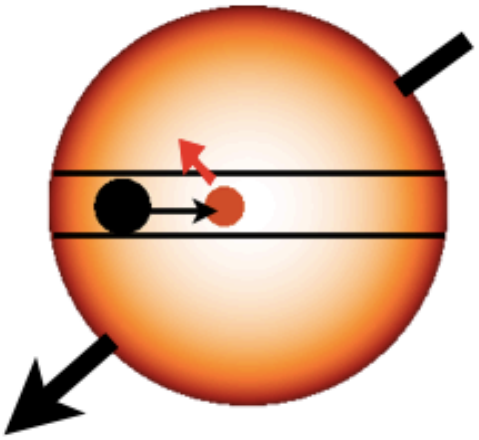

P_{orb}/P_{rot} = 0.1
1
2
3
Relative flux
Relative flux
Relative flux
Time

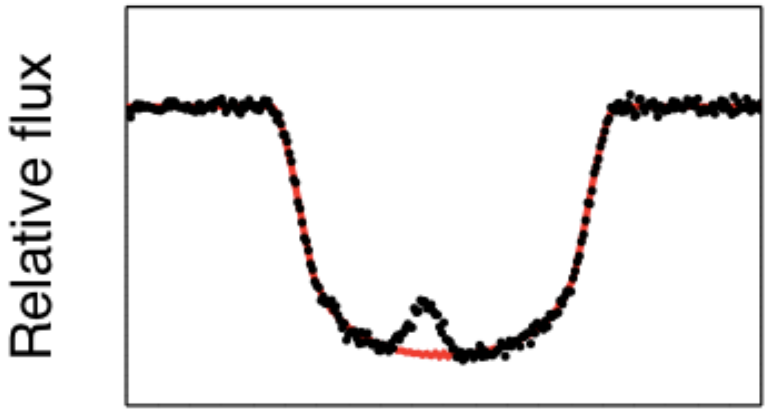
Misaligned system: Spots are not seen in consecutive transits

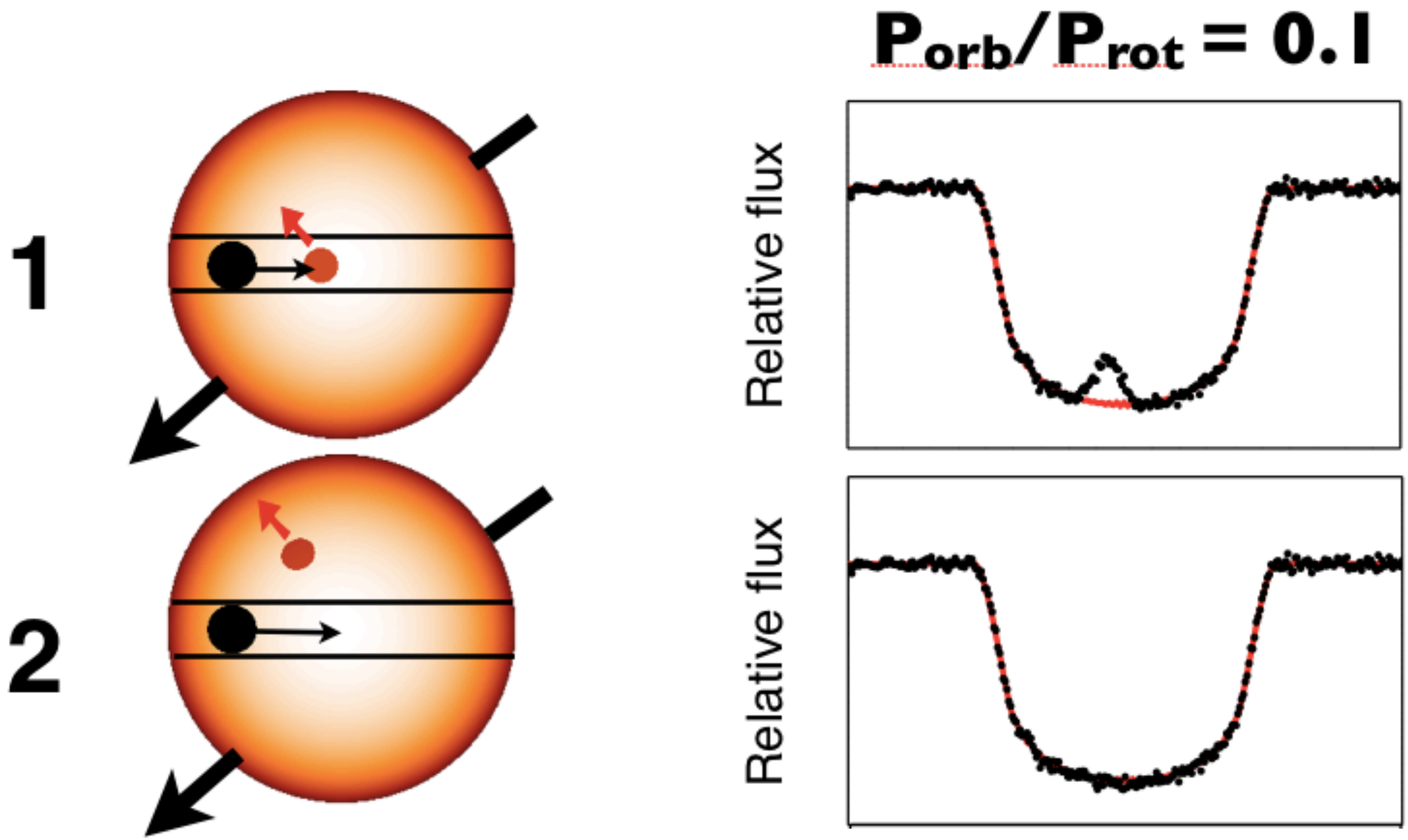


$P_{orb}/P_{rot} = 0.1$

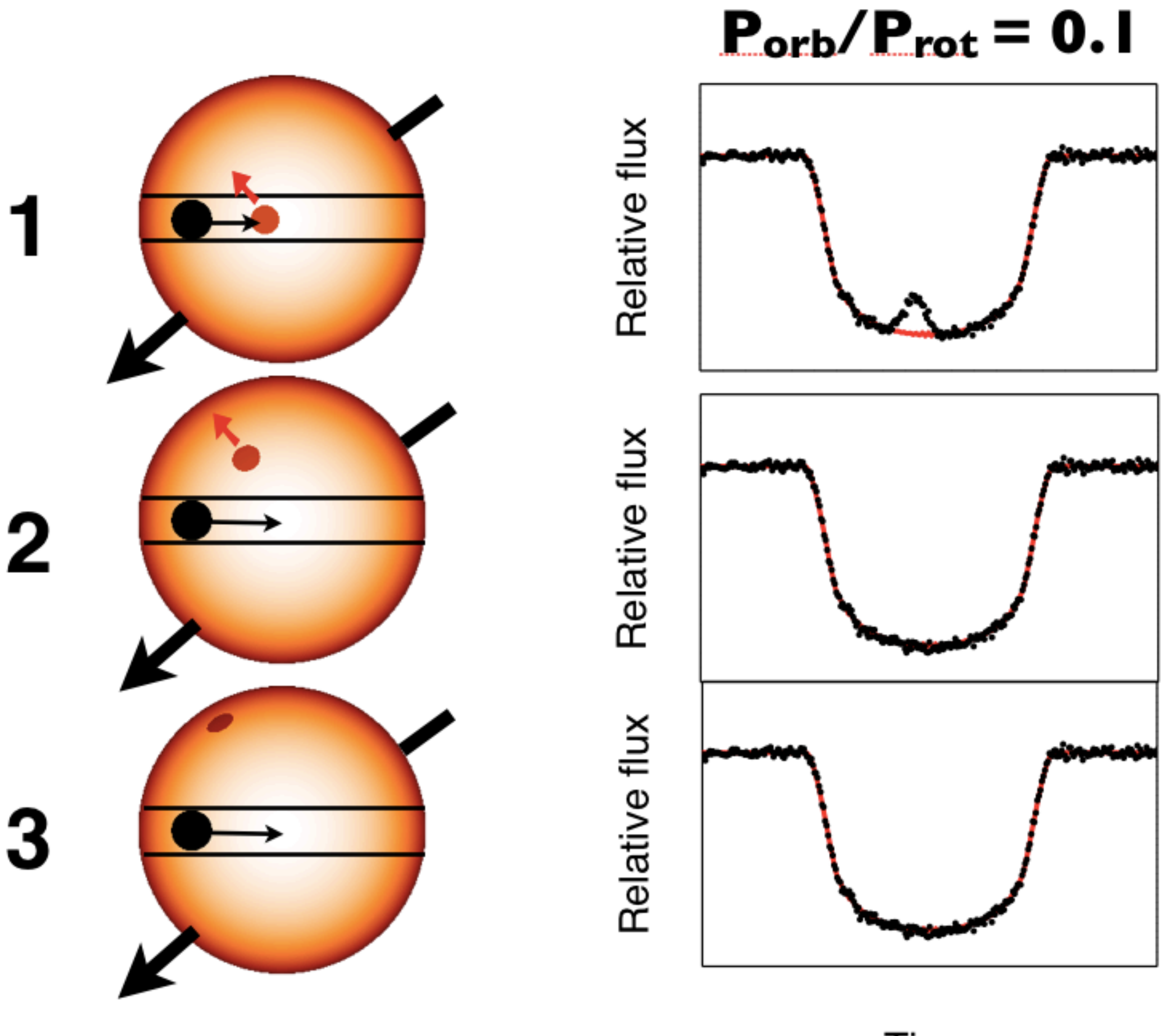
1





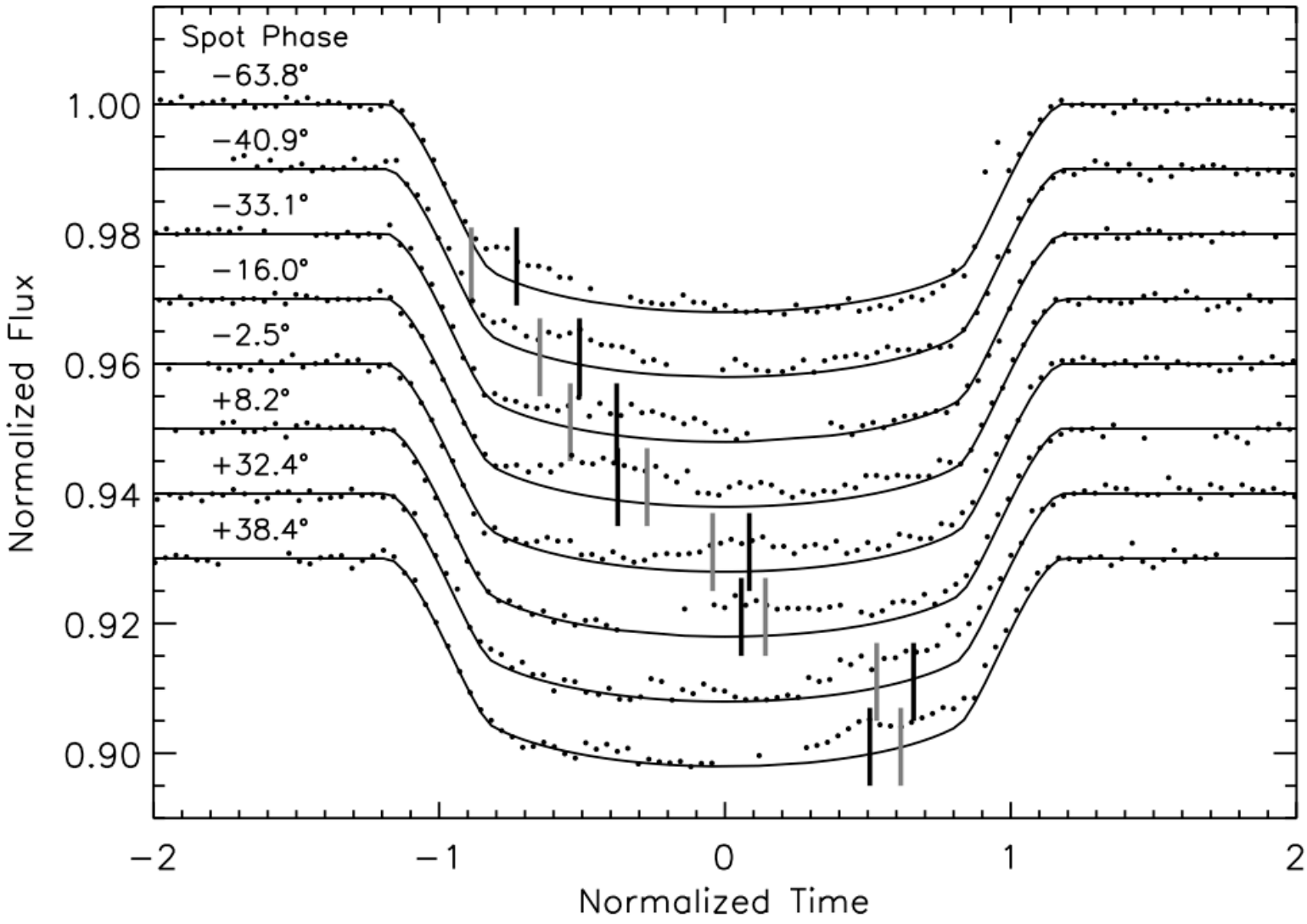


$P_{orb}/P_{rot} = 0.1$
1
2
Relative flux
Relative flux



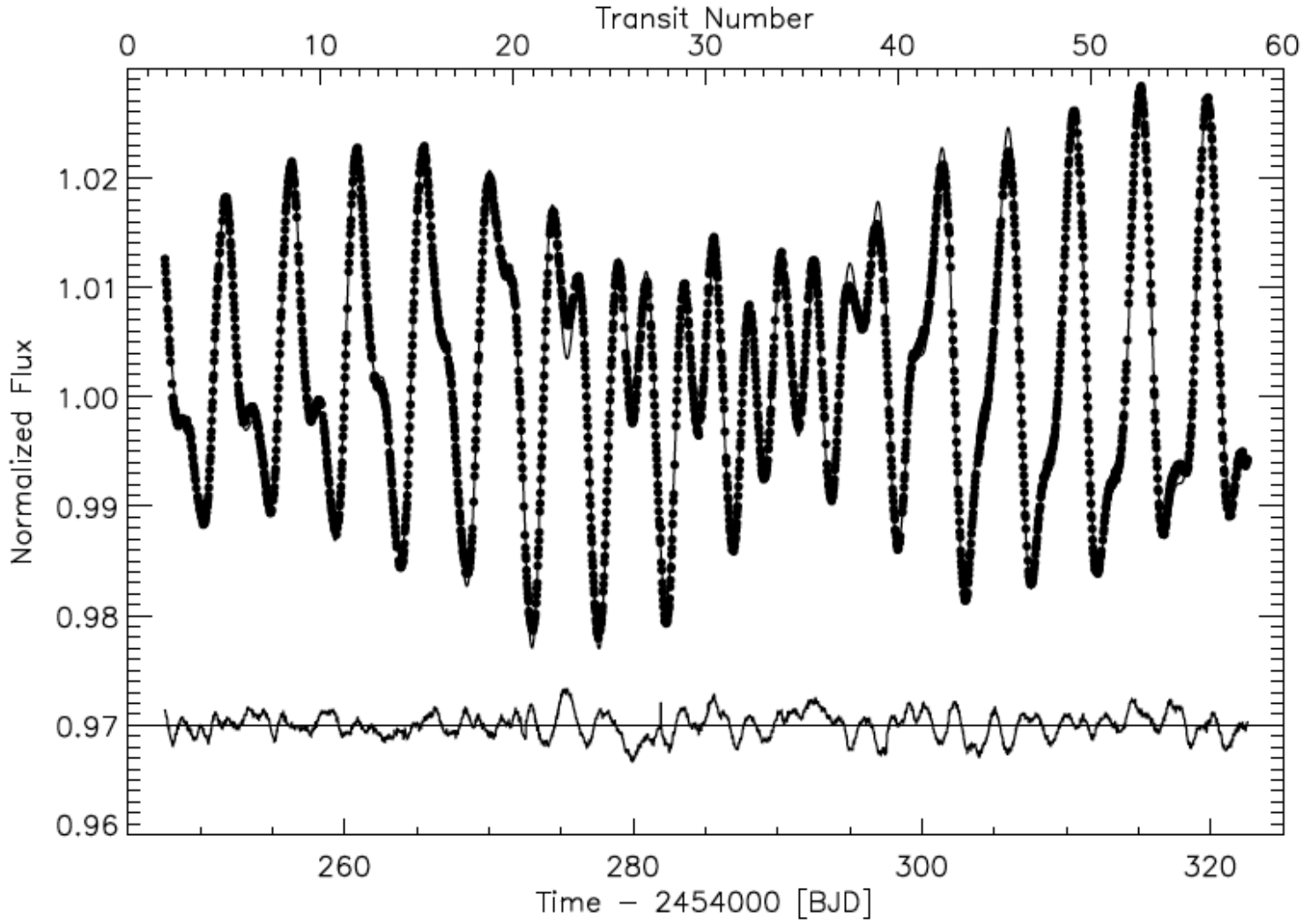
$P_{orb}/P_{rot} = 0.1$
1
2
3
Relative flux
Relative flux
Relative flux

CoRoT-2b has also low λ

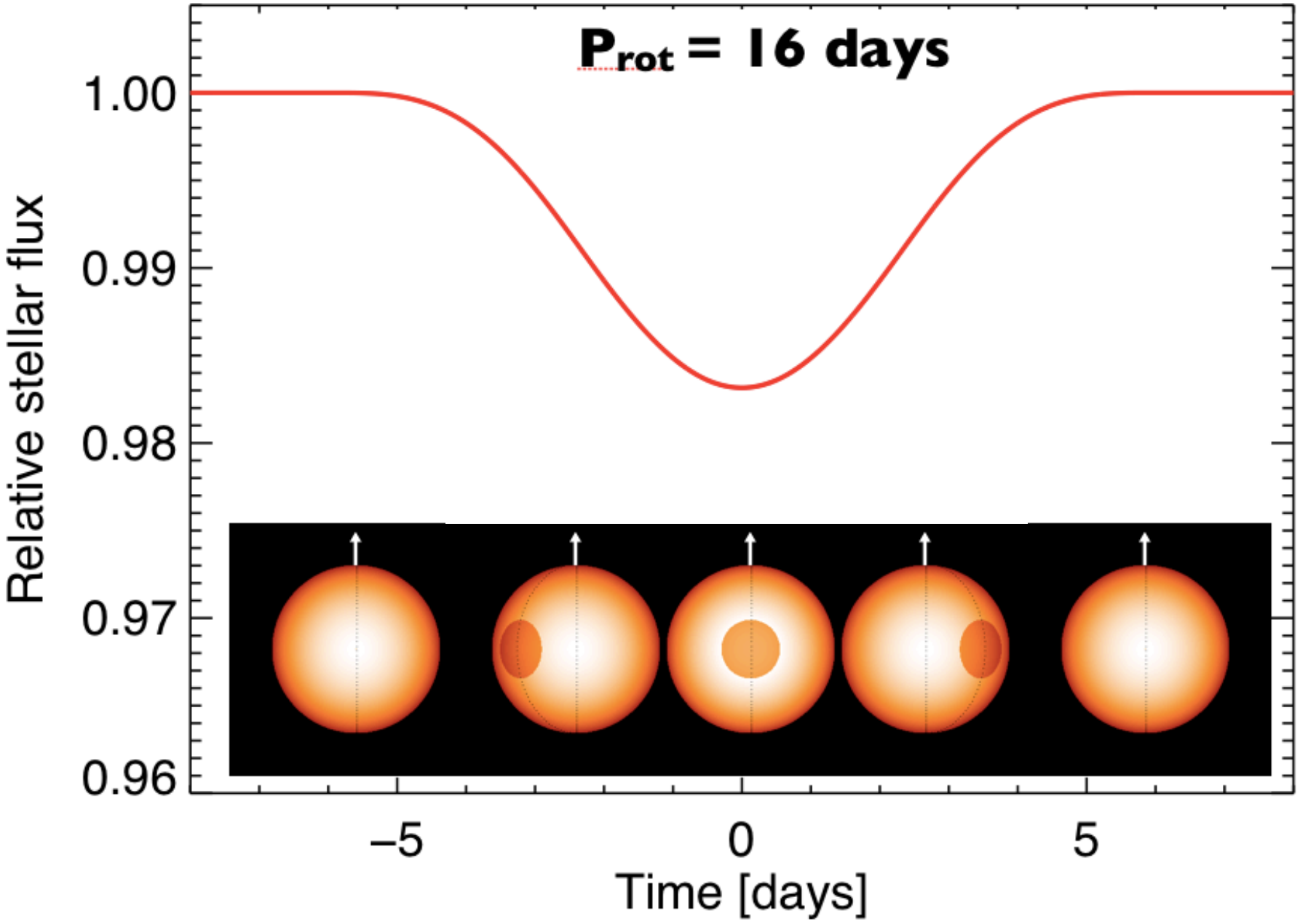


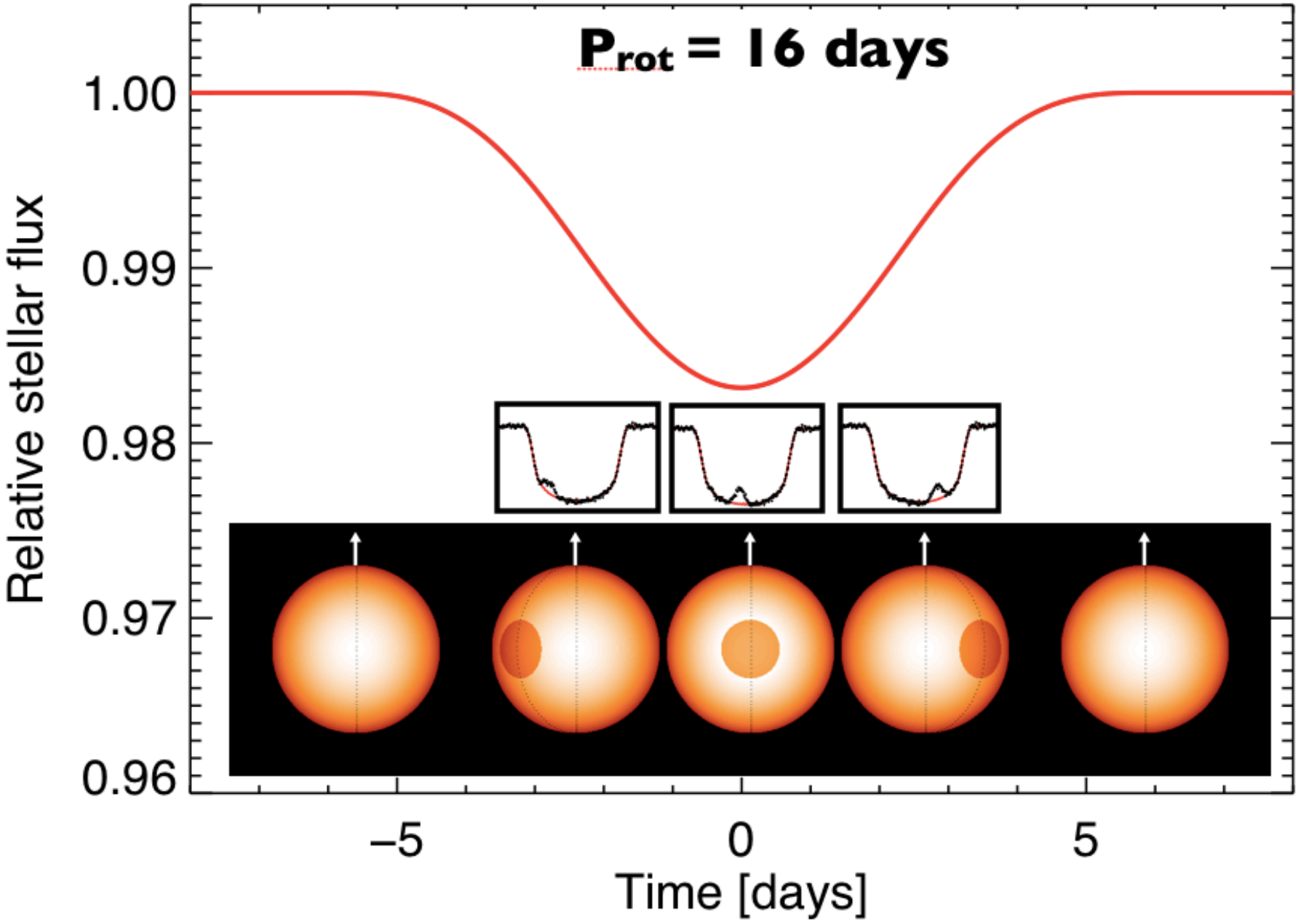
Nutzman et al. 2011

Stellar flux variations, good source of information

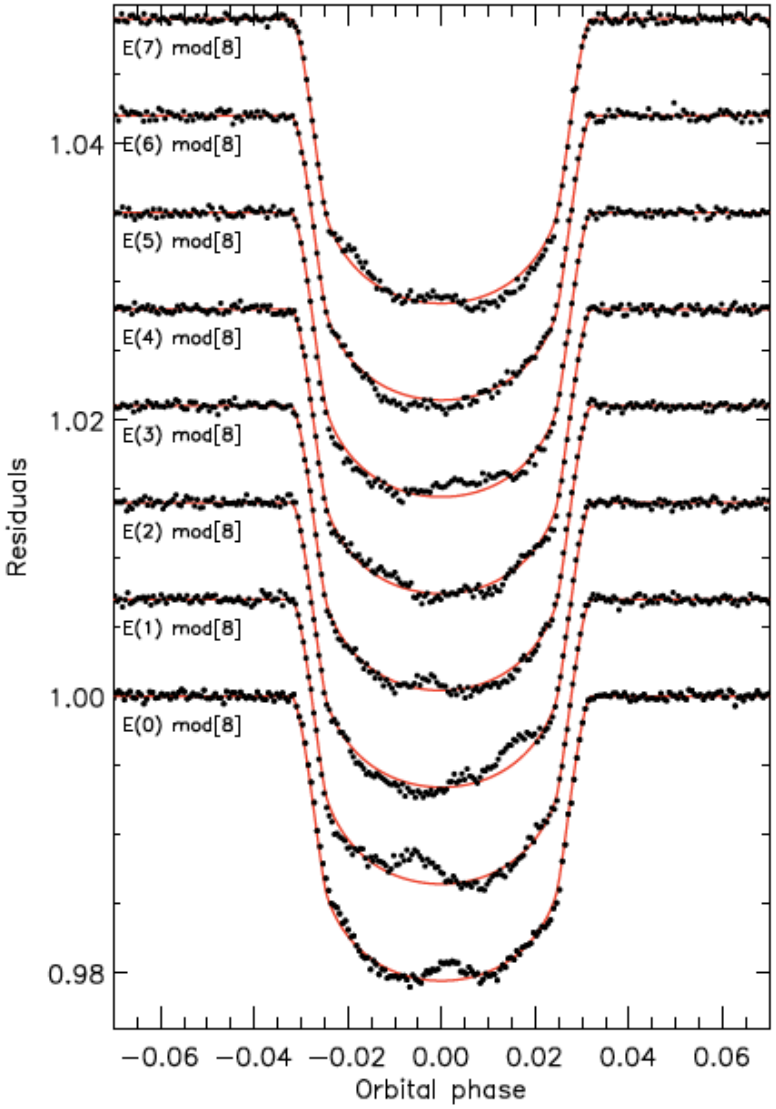


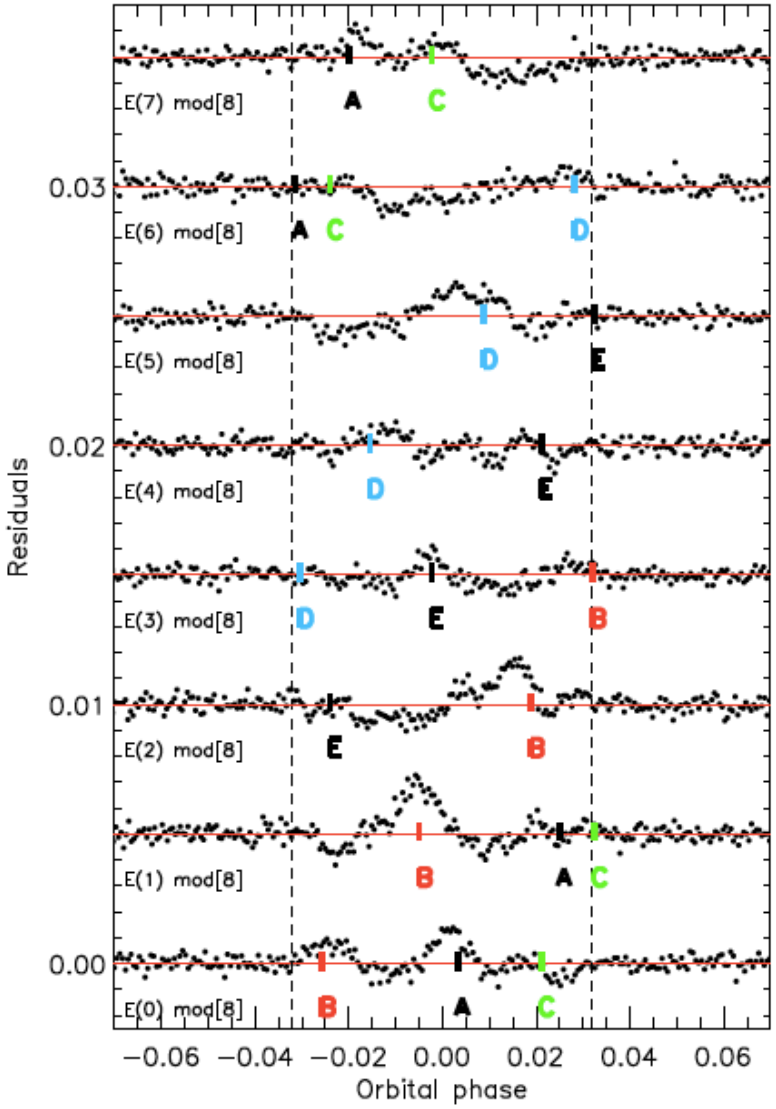
Nutzman et al. 2011


P_{rot} = 16 days
1.00
0.99
0.98
0.97
0.96
Relative stellar flux
–5
0
5
Time [days]


P_{rot} = 16 days
1.00
0.99
0.98
0.97
0.96
Relative stellar flux
–5
0
5
Time [days]

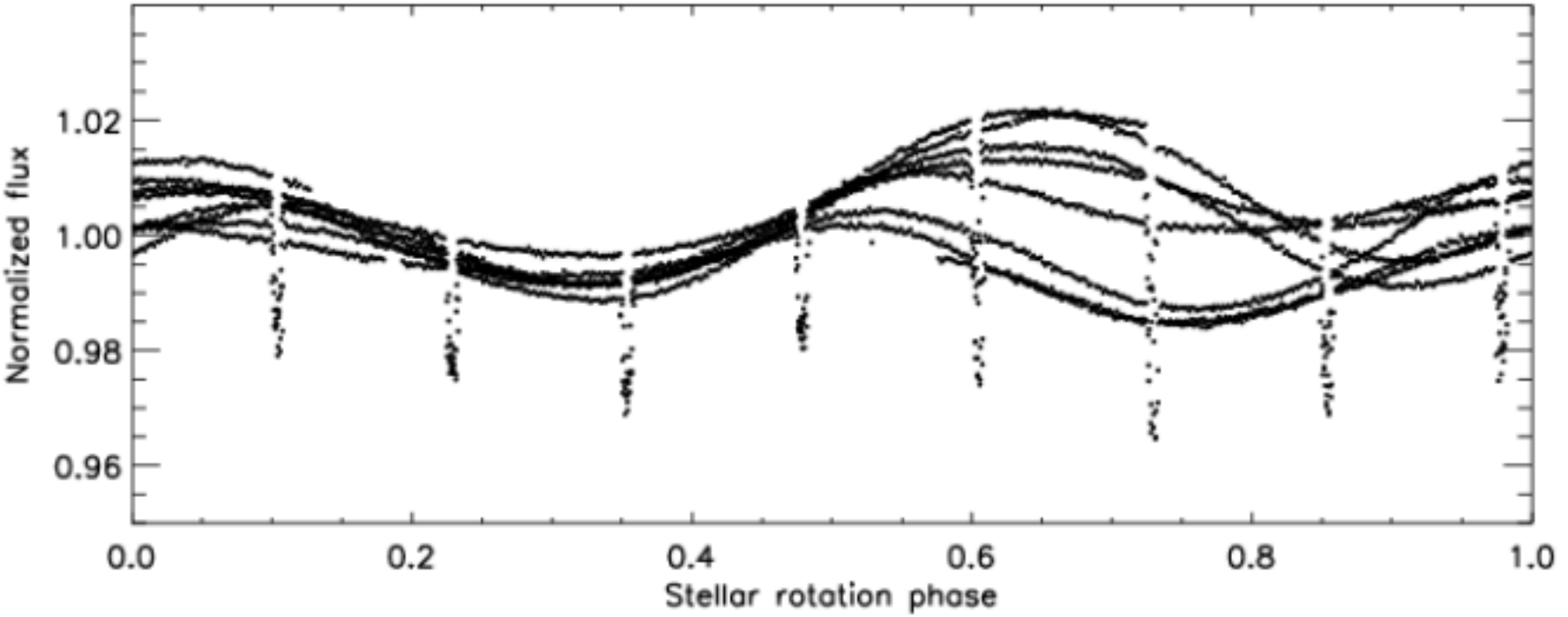
Kepler-17b has also a low obliquity





Désert et al. 2011

The stroboscopic effect

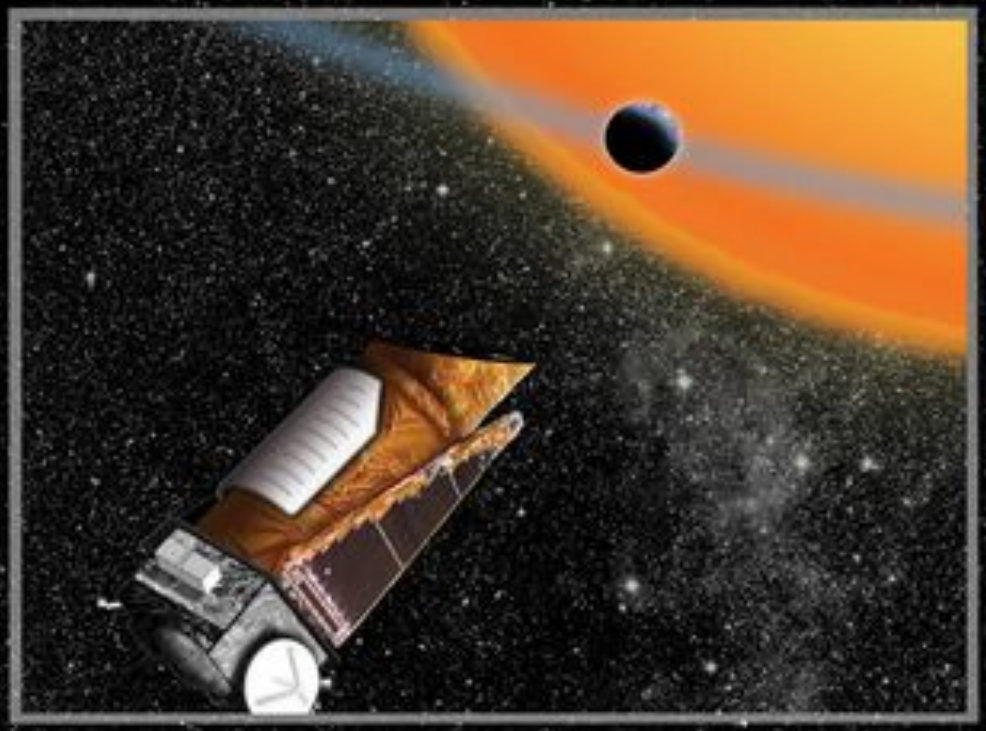


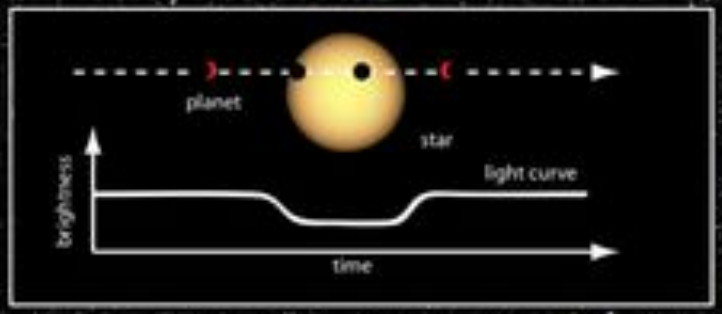
$$P_{rot} = 8\ P_{orb}$$

Désert et al. 2011

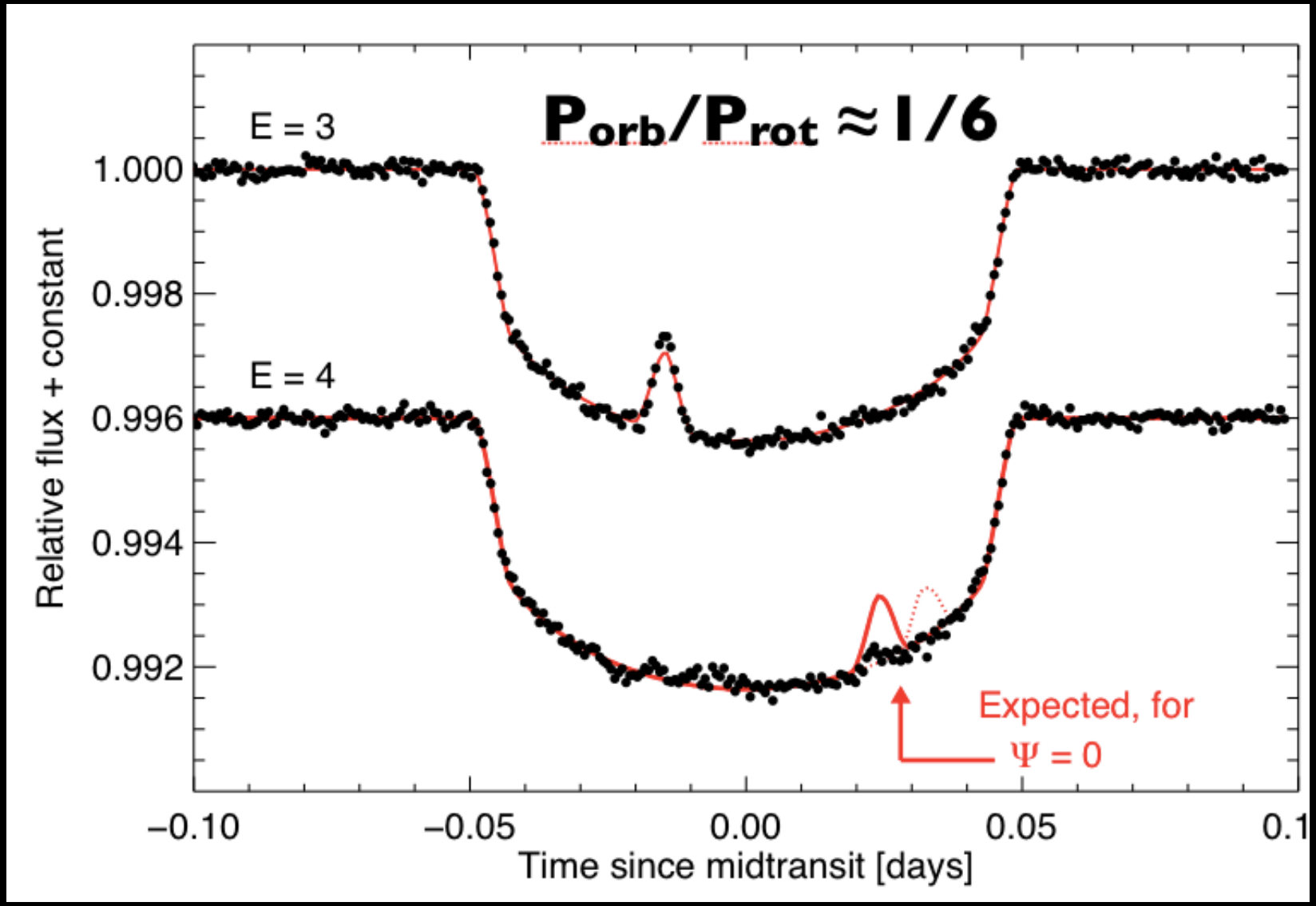
Kepler Mission

The determination of the frequency of Earth-size & larger planets in and near the habitable zone of solar-like stars



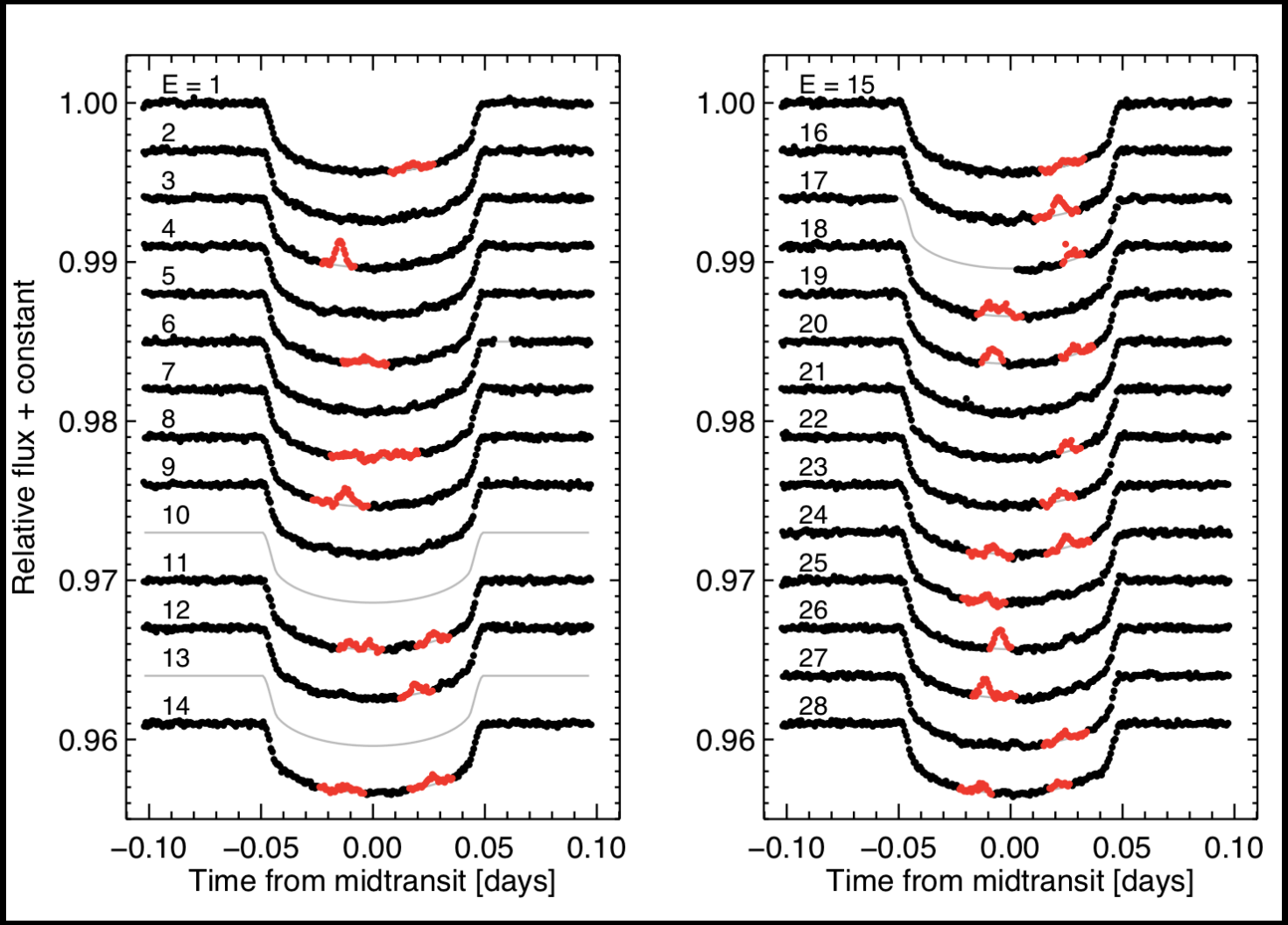


HAT-P-11b is misaligned



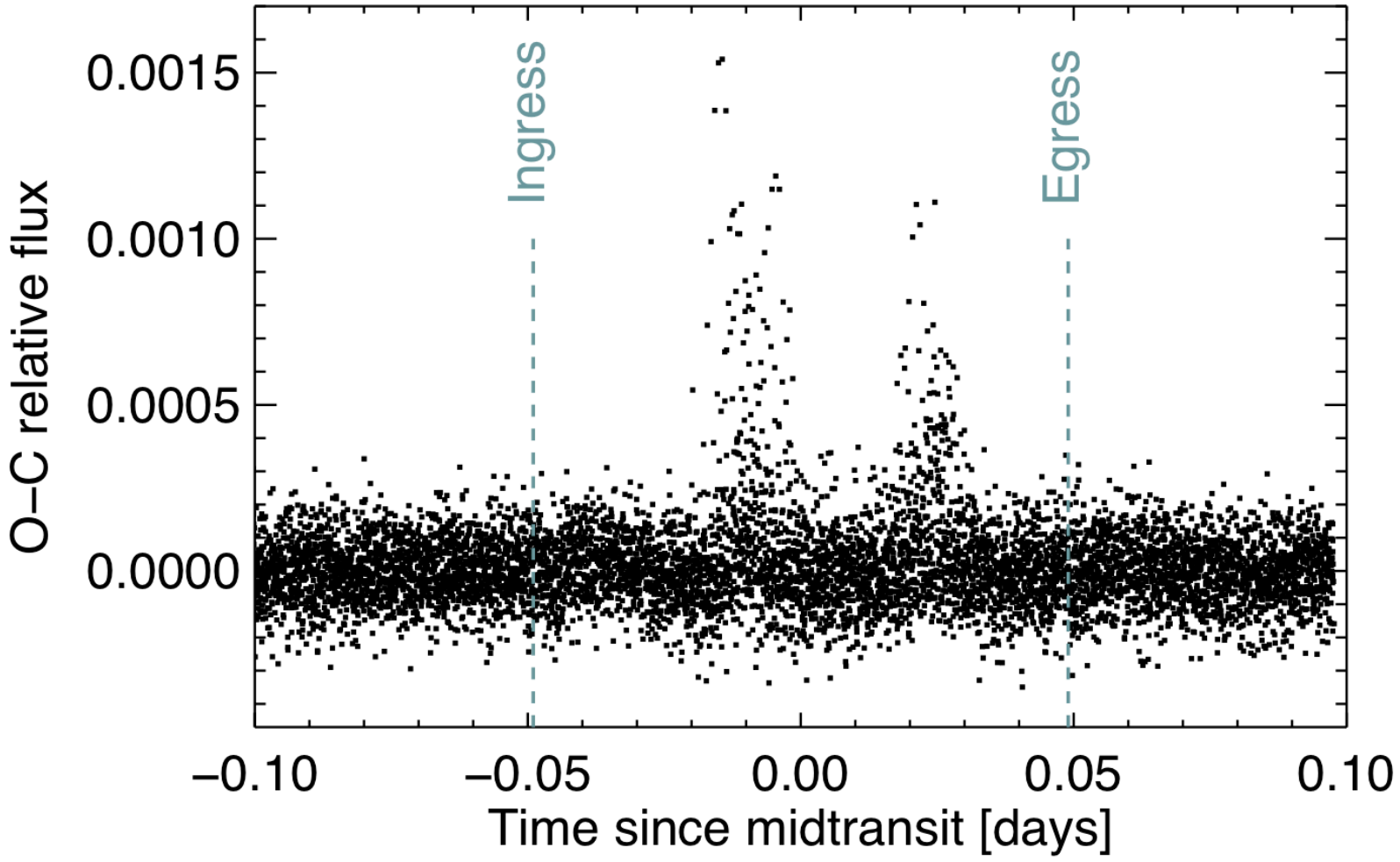
Sanchis-Ojeda and Winn 2011

HAT-P-11b, a strange pattern?



High stellar activity makes the pairing process subjective. But wait…

HAT-P-11b, active latitudes



Spot anomalies only appear at two particular phases of the transit.

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Messages

Astrochat

Edit

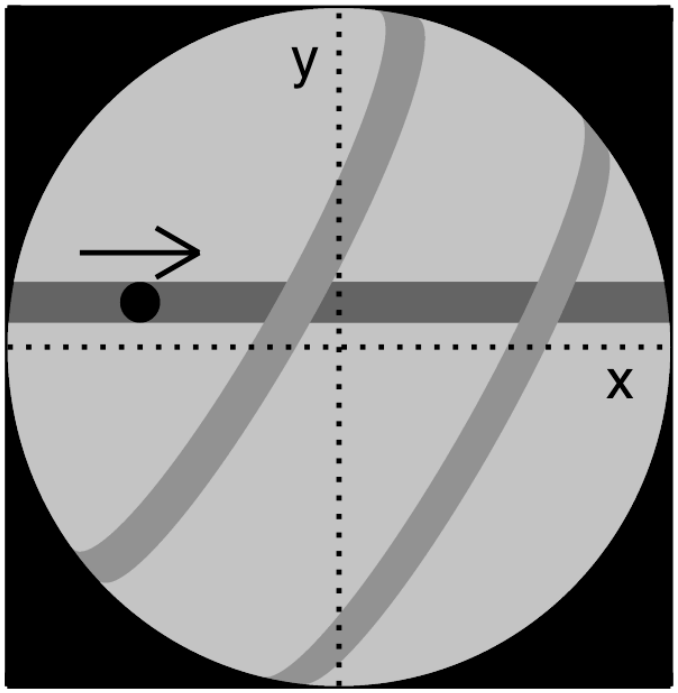
HAT-P-11 is so active that the only thing I can say is that it is misaligned. The star seems to have active latitudes like the Sun that produce a strange spot anomaly pattern.

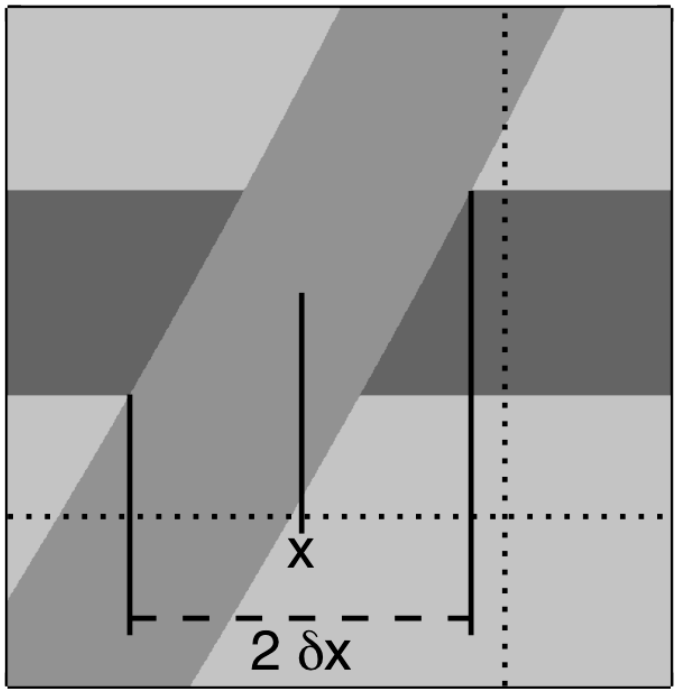
This is very interesting stuff. Can we generalize these findings and find a way to calculate the obliquity of the system from the spot pattern?

Challenge accepted!

Send

Two symmetric active bands

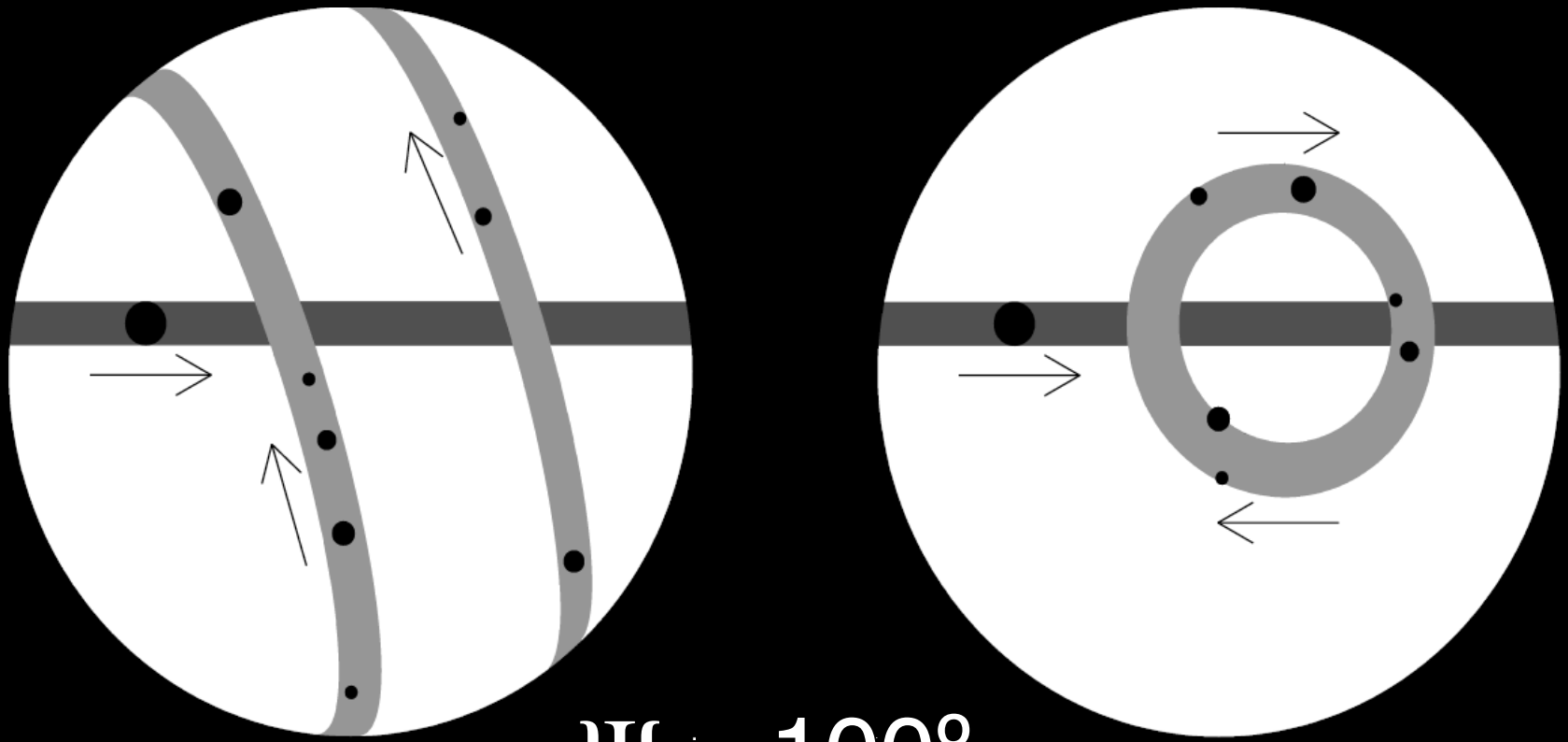




- We interpret the preferred phases as intersections of the trajectory of the planet with active spot bands.

- The intersection and the effective width of the band can be directly measured from the residuals.

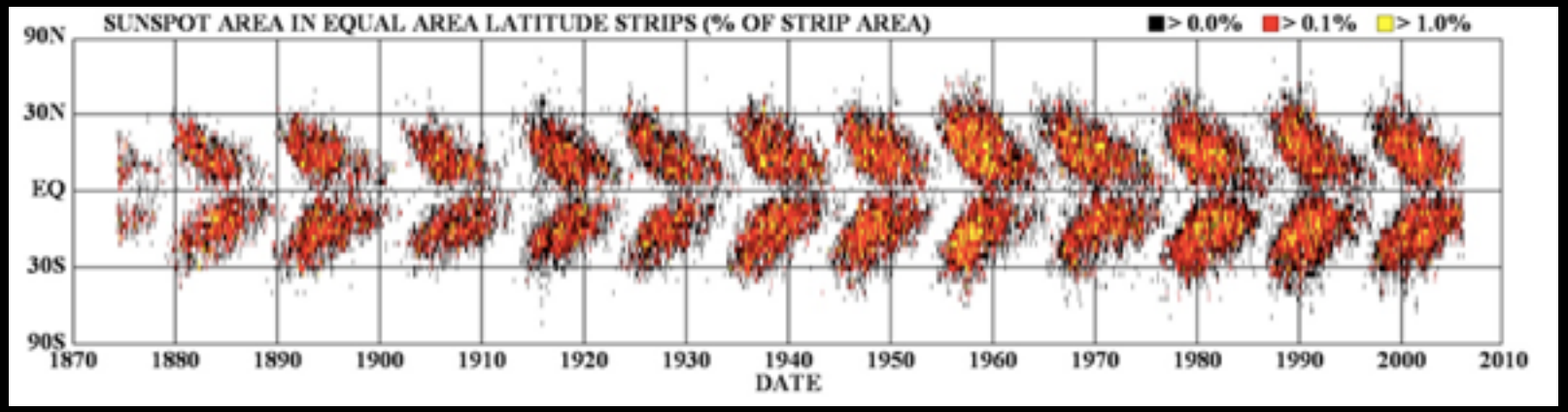
Detection of active bands gives $\Psi \neq 0°$ with photometry

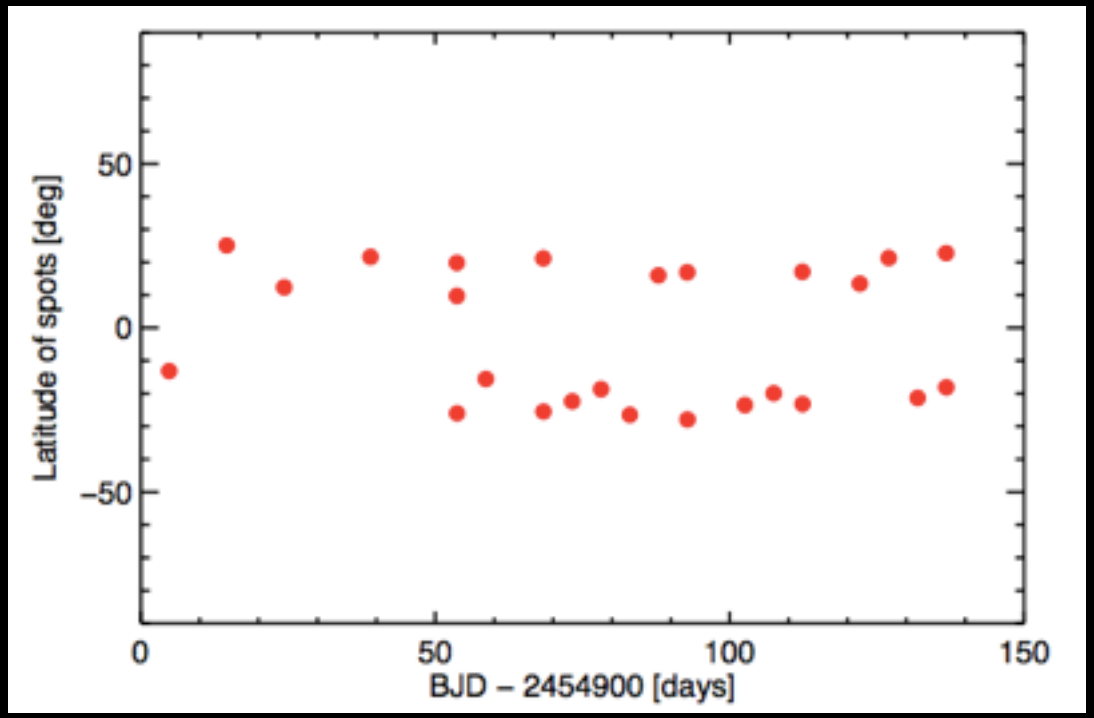


$\Psi \approx 100°$

Sanchis-Ojeda and Winn 2011

The butterfly diagram of HAT-P-11b





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Messages Astrochat Edit

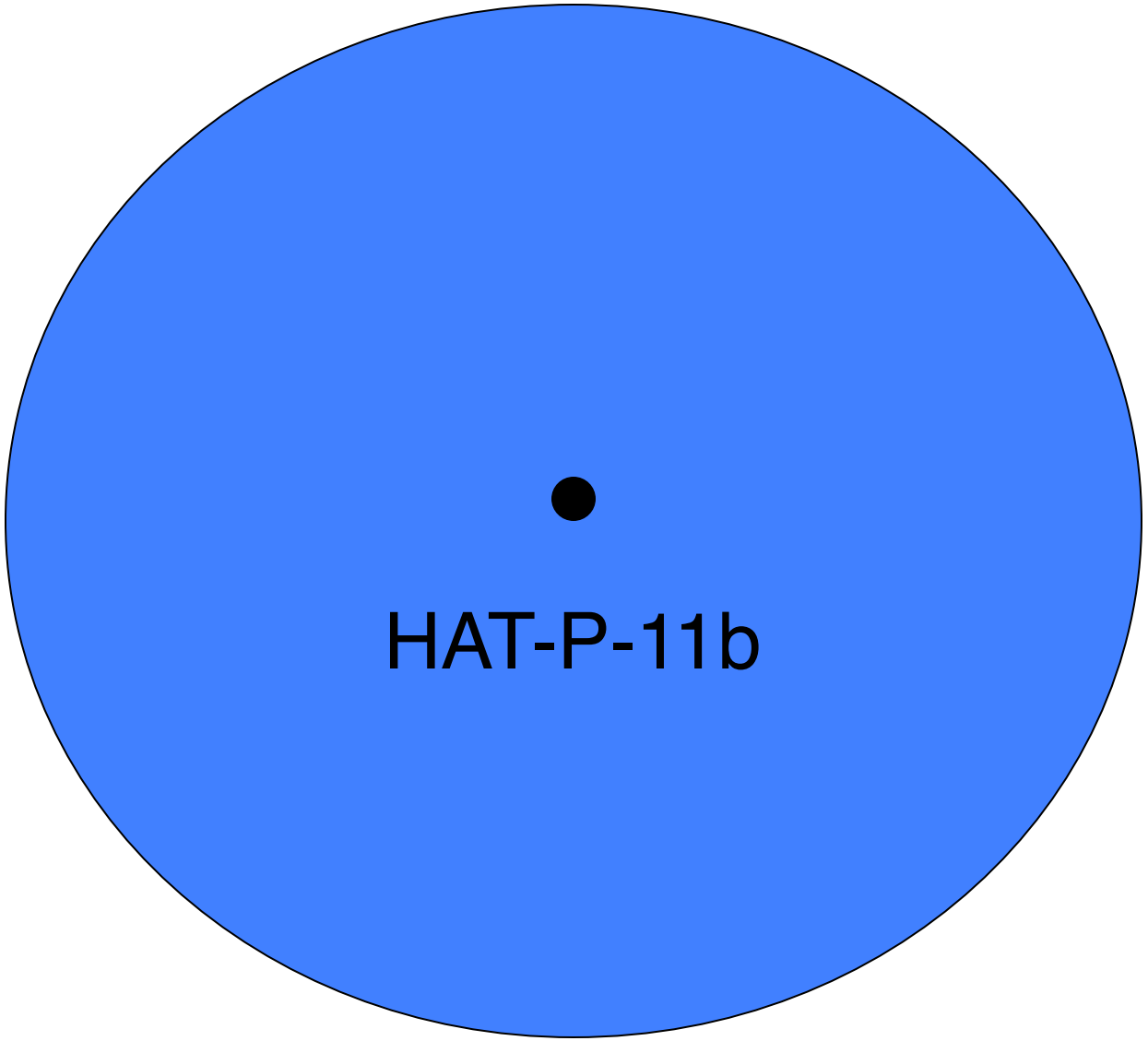
I have passed my quals! One less thing to worry about. Should we write the paper about HAT-P-11b?

Great news! It was a good idea for you to take one month off to study for them, but on the meantime one of my collaborators has sent me a draft of a very similar paper. The papers are different enough to publish both, and they agreed to put them on the arxiv on the same day.

Great, let's do it.

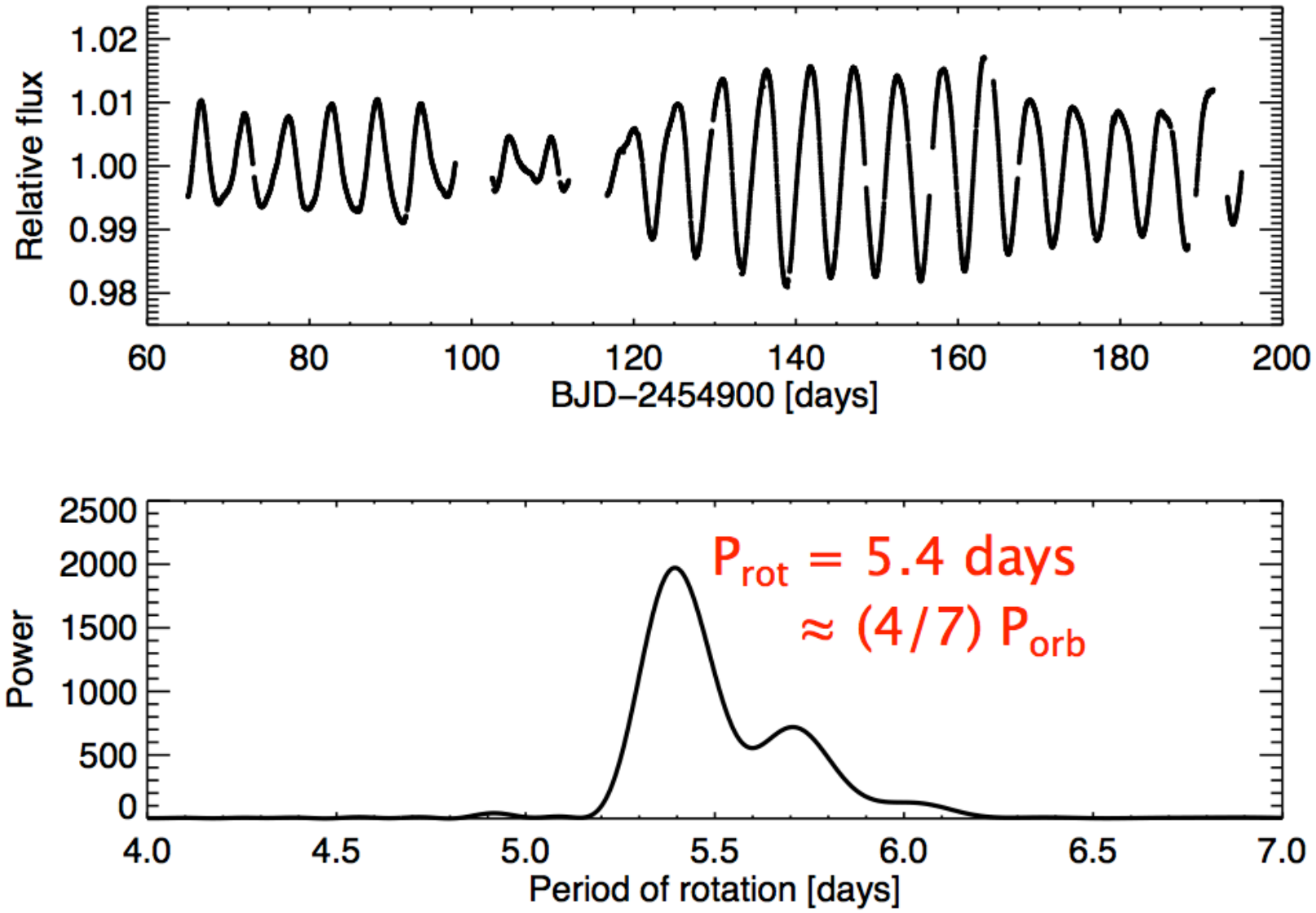
Aquamacs

First search of Kepler data: June 2011

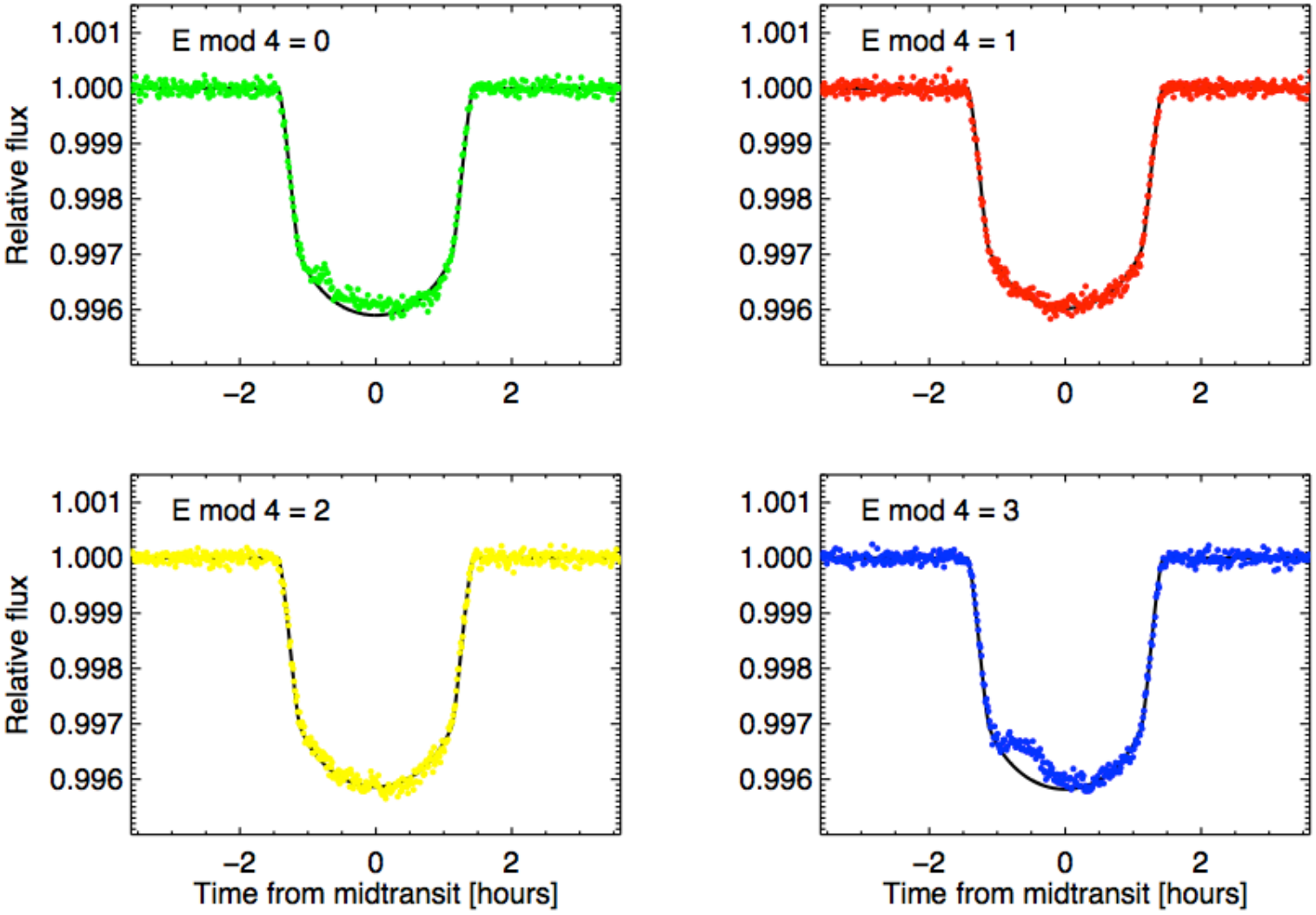


Public SC Q0-3 Kepler data for planet candidates

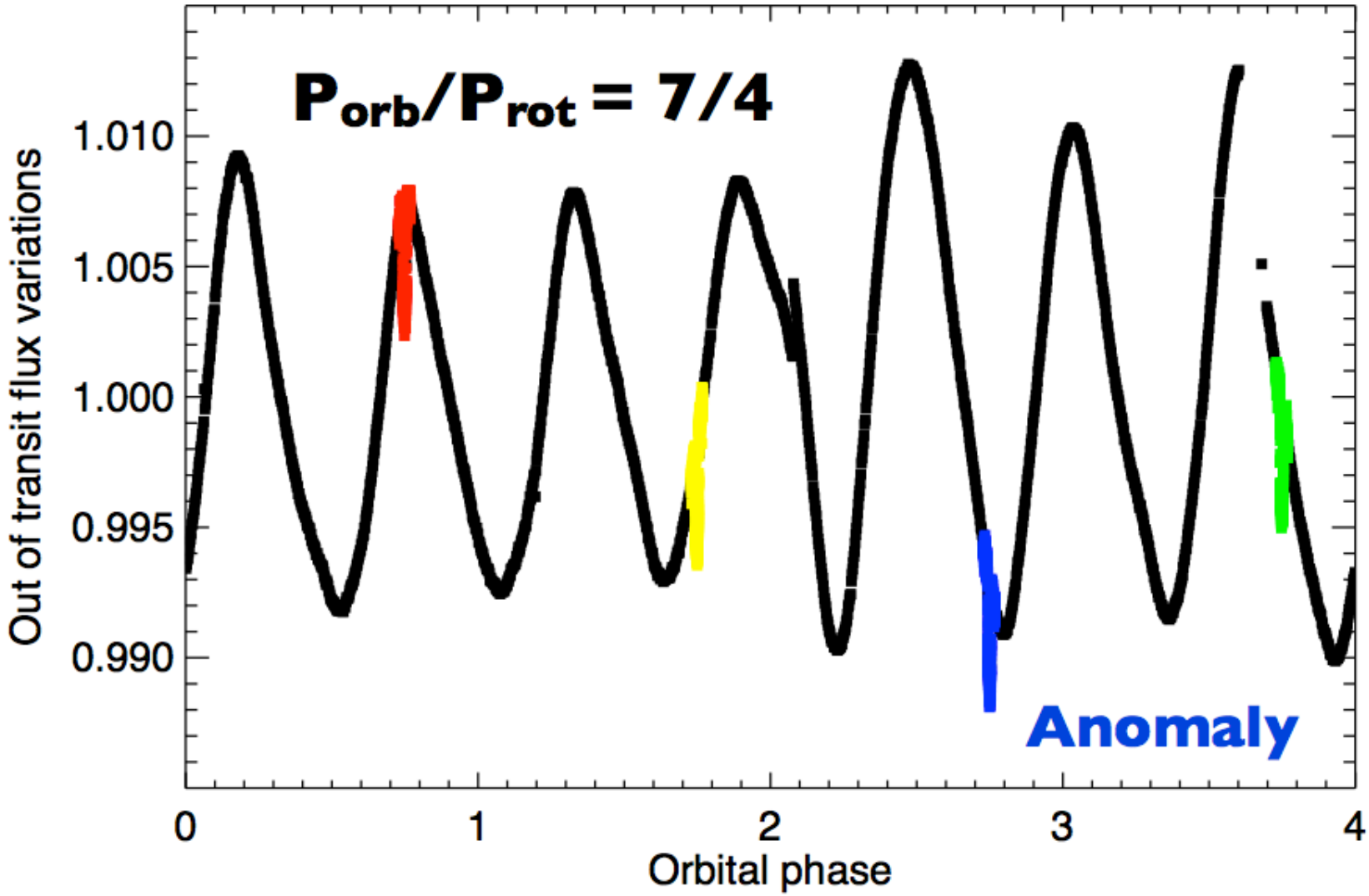
KOI 63, a very active star

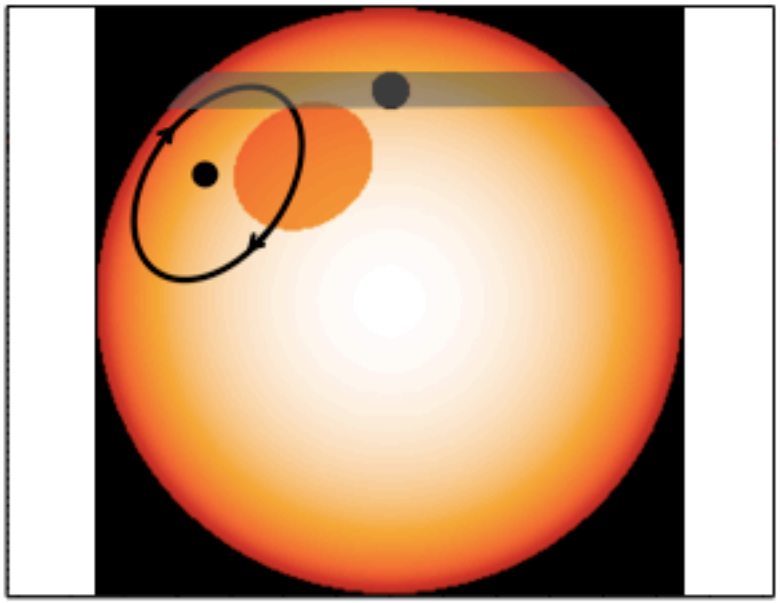


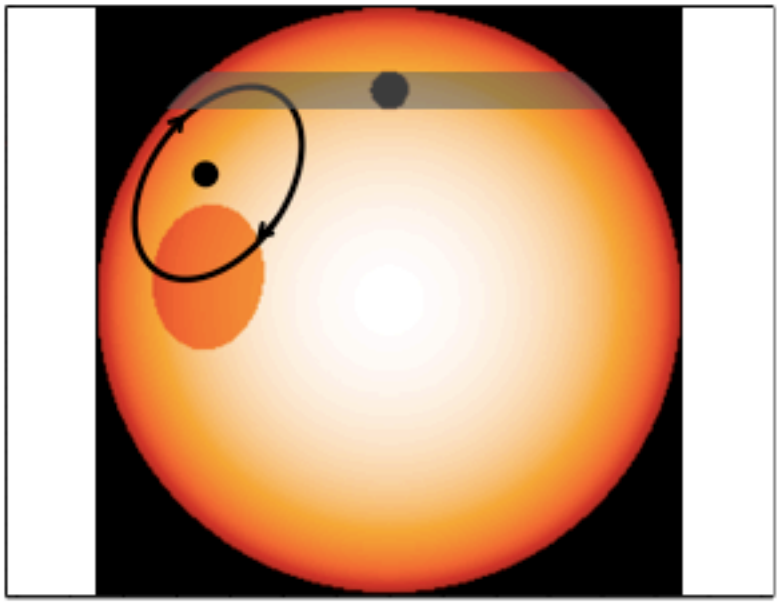
Huge anomaly every 4th transit

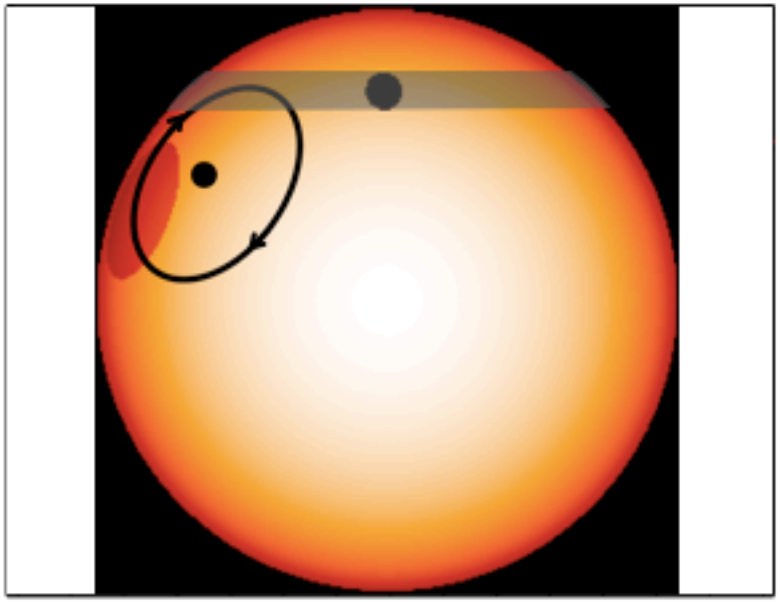


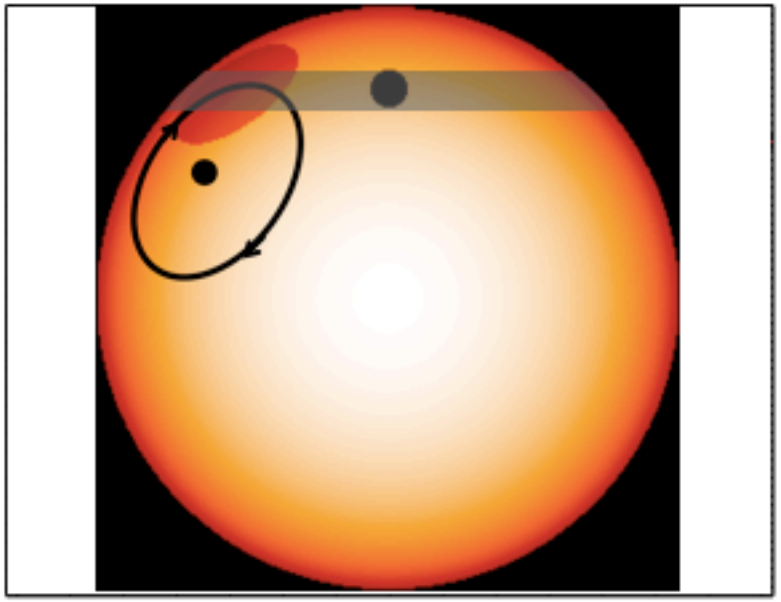
A powerful piece of information











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Messages

Astrochat

Edit

I have a nice model for the spot anomalies of KOI 63, I think the system is misaligned!

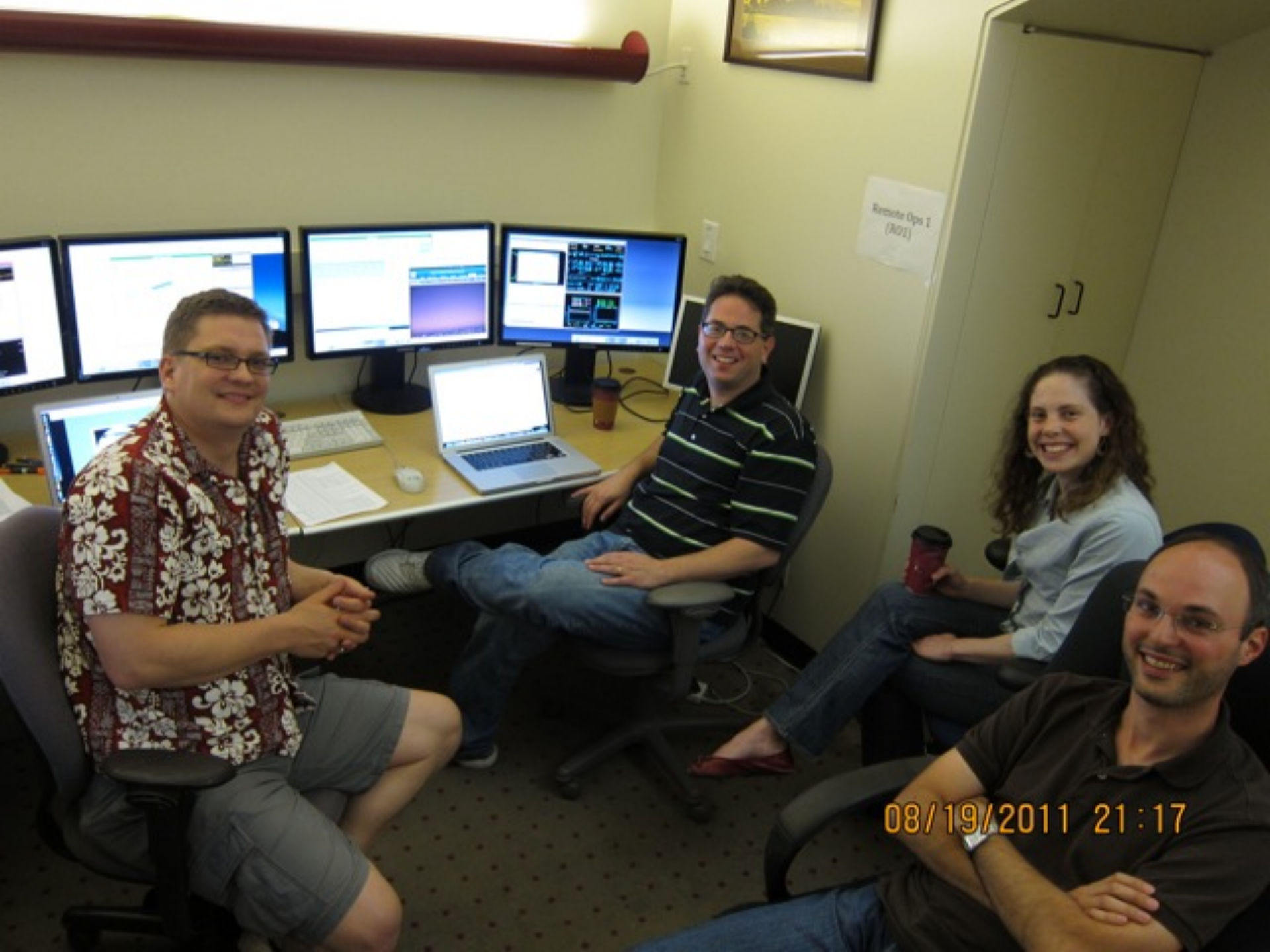
Great, I am going to observe the RM effect in a few days, let's see if you are right. Can you give me a prediction?

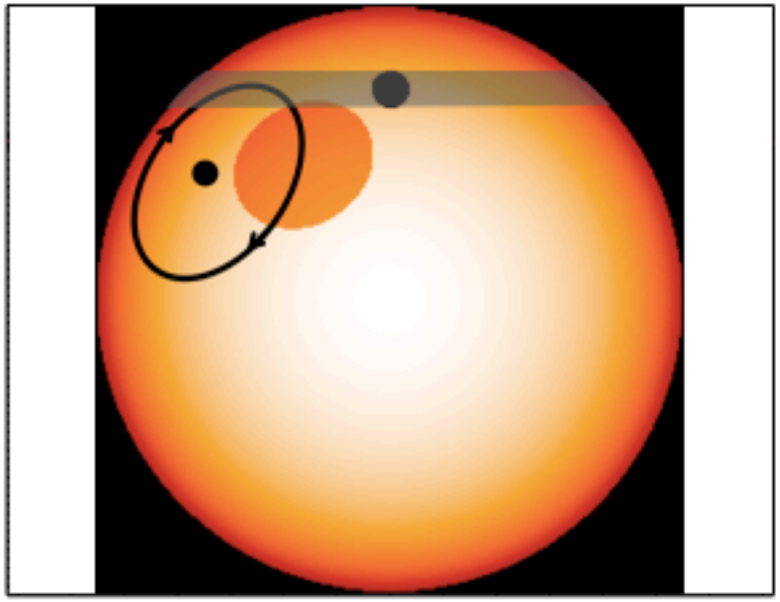
Yes, I think that lambda is -130 degrees.

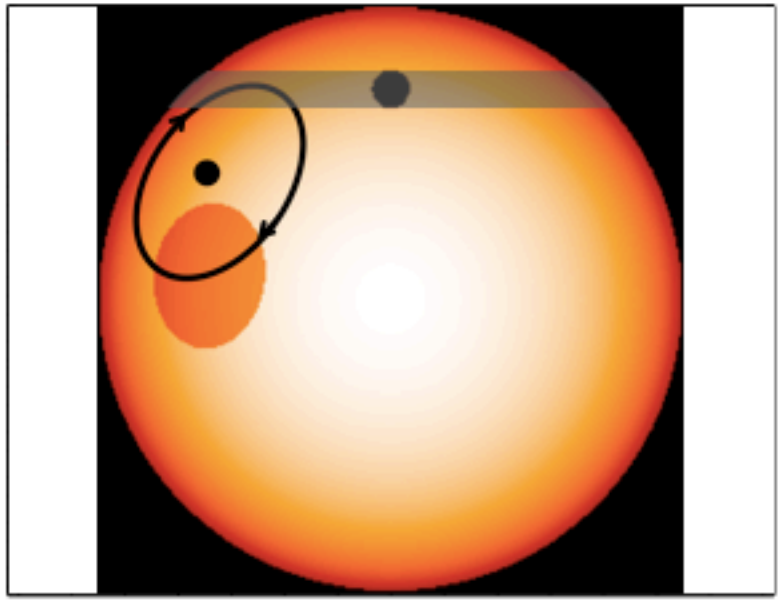
No, I meant, can you plot a predicted RM effect? We are going to observe in a few hours!

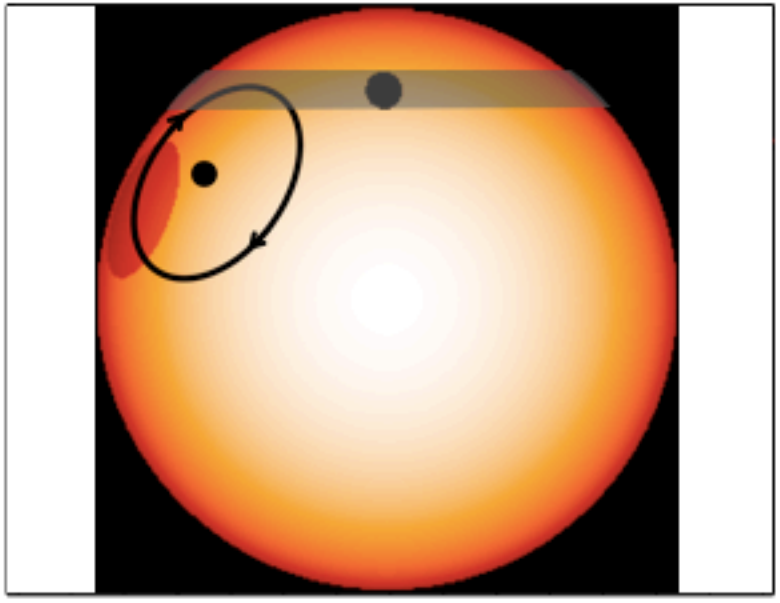
Challenge accepted!

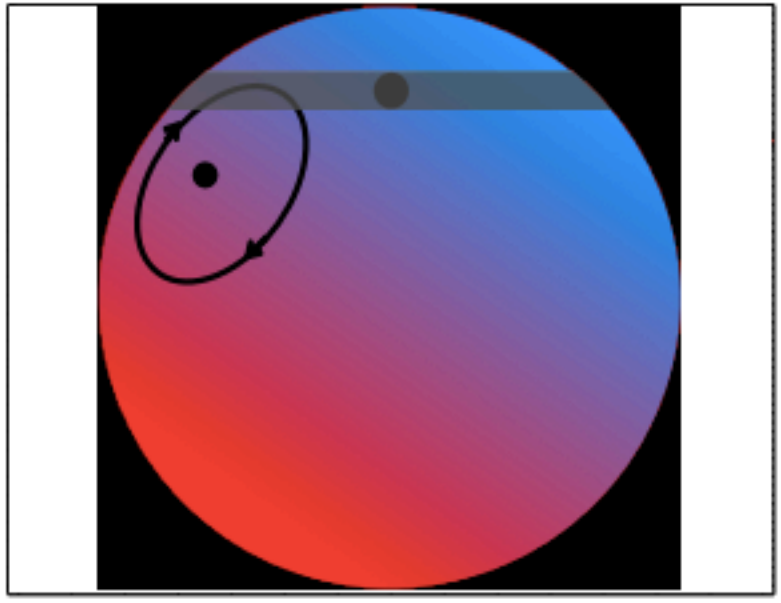
Send


08/19/2011 21:17

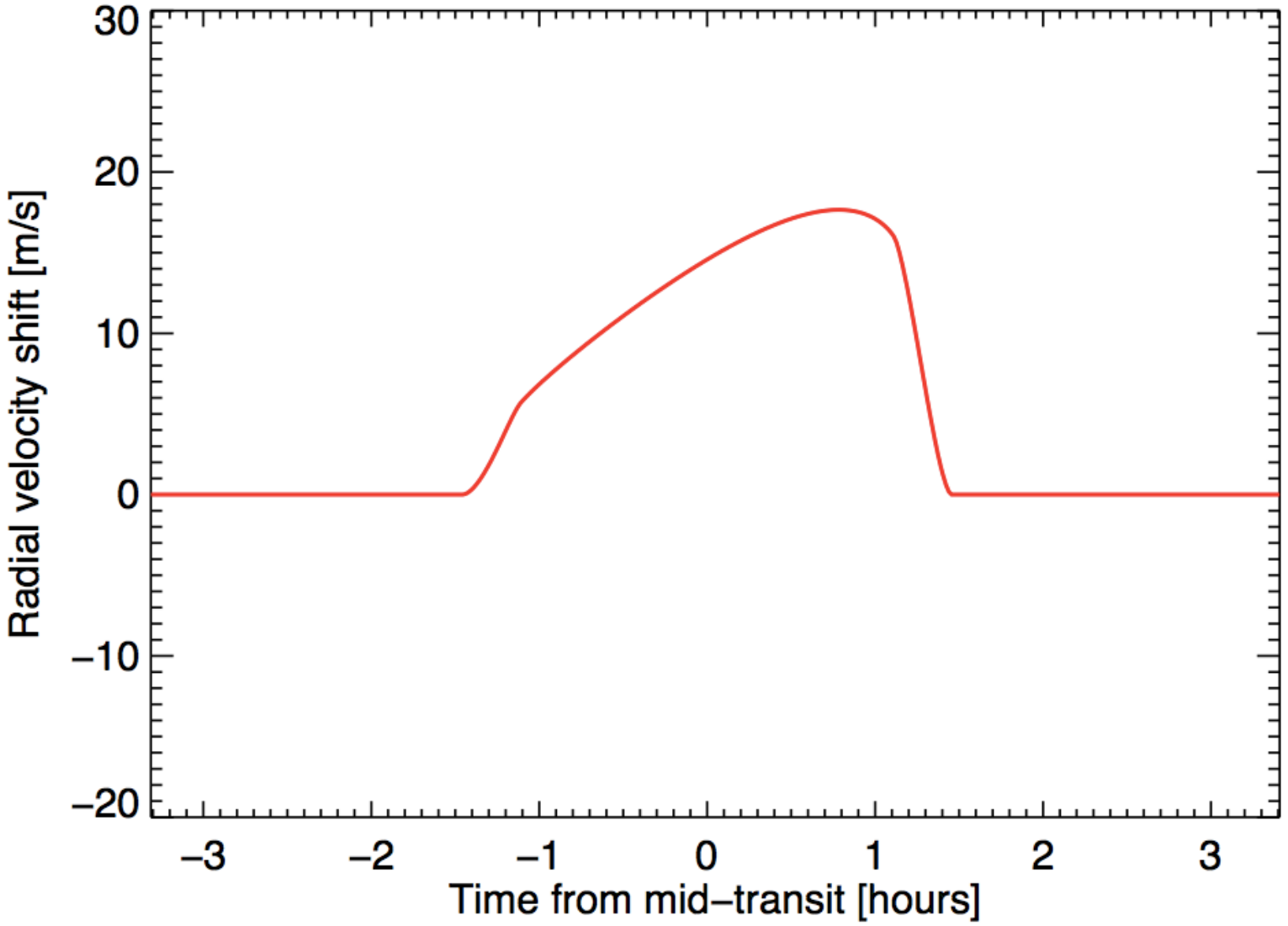




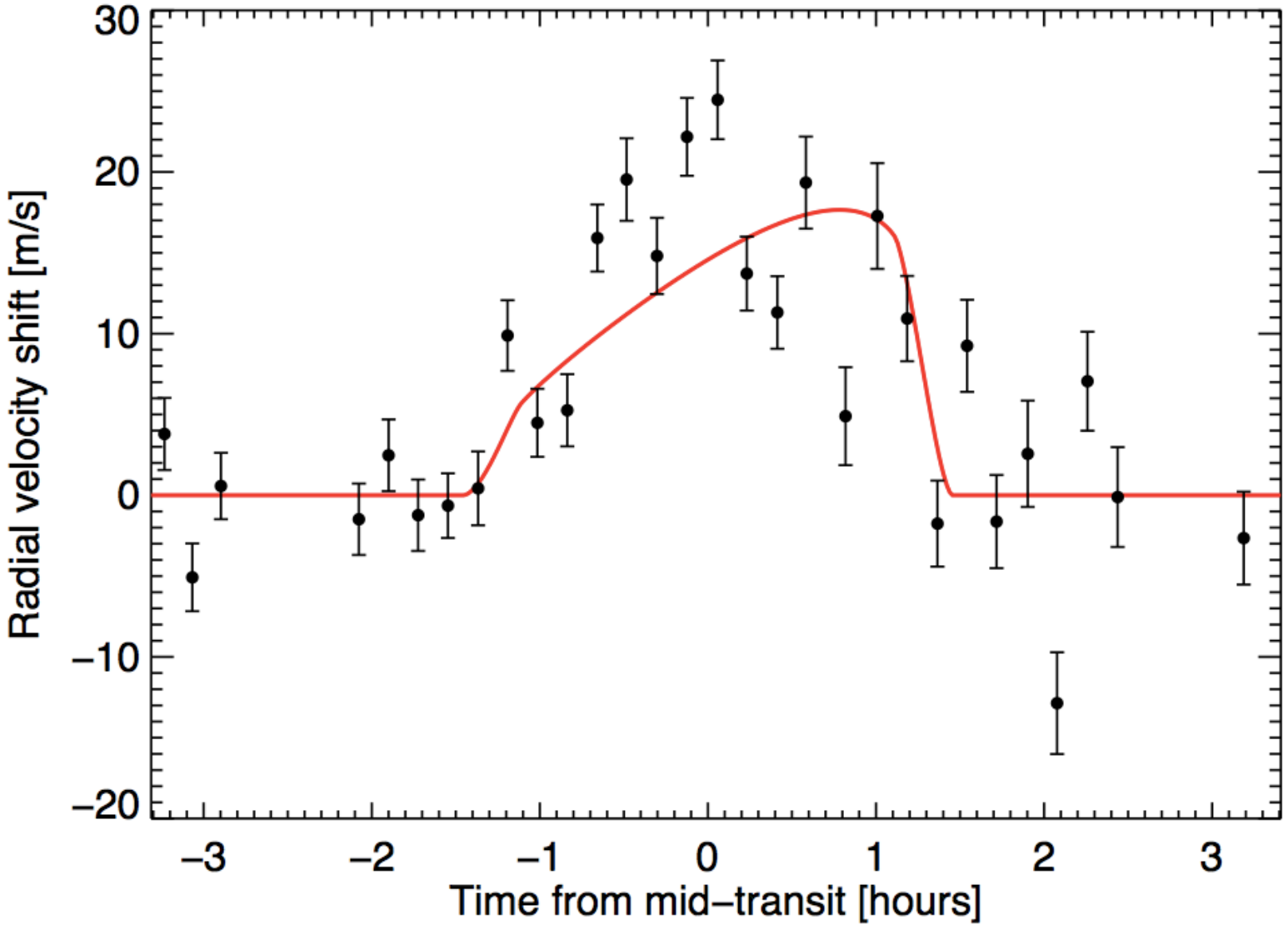




Specific 3 AM prediction of the RM

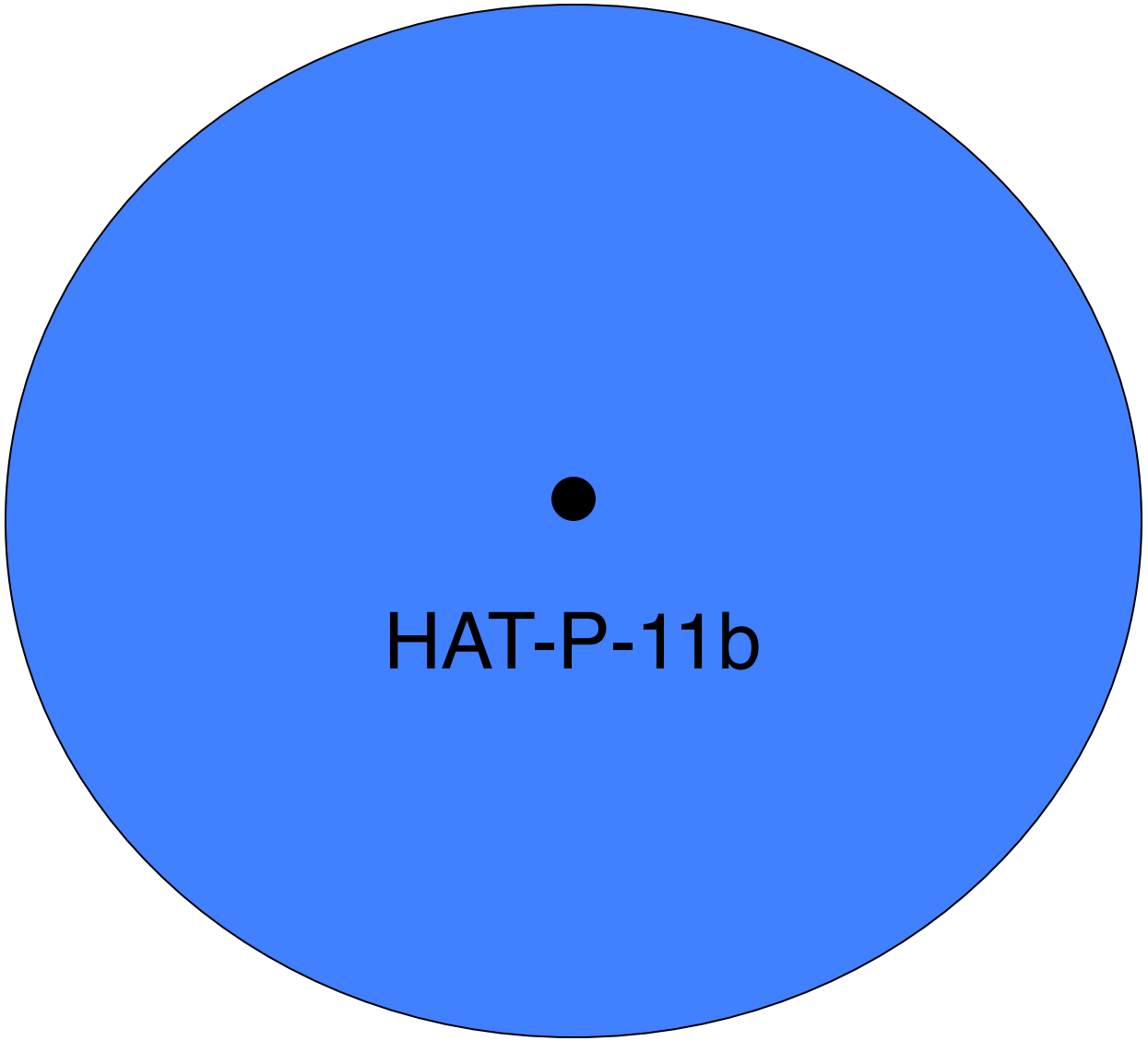


Confirmed prediction, the method works



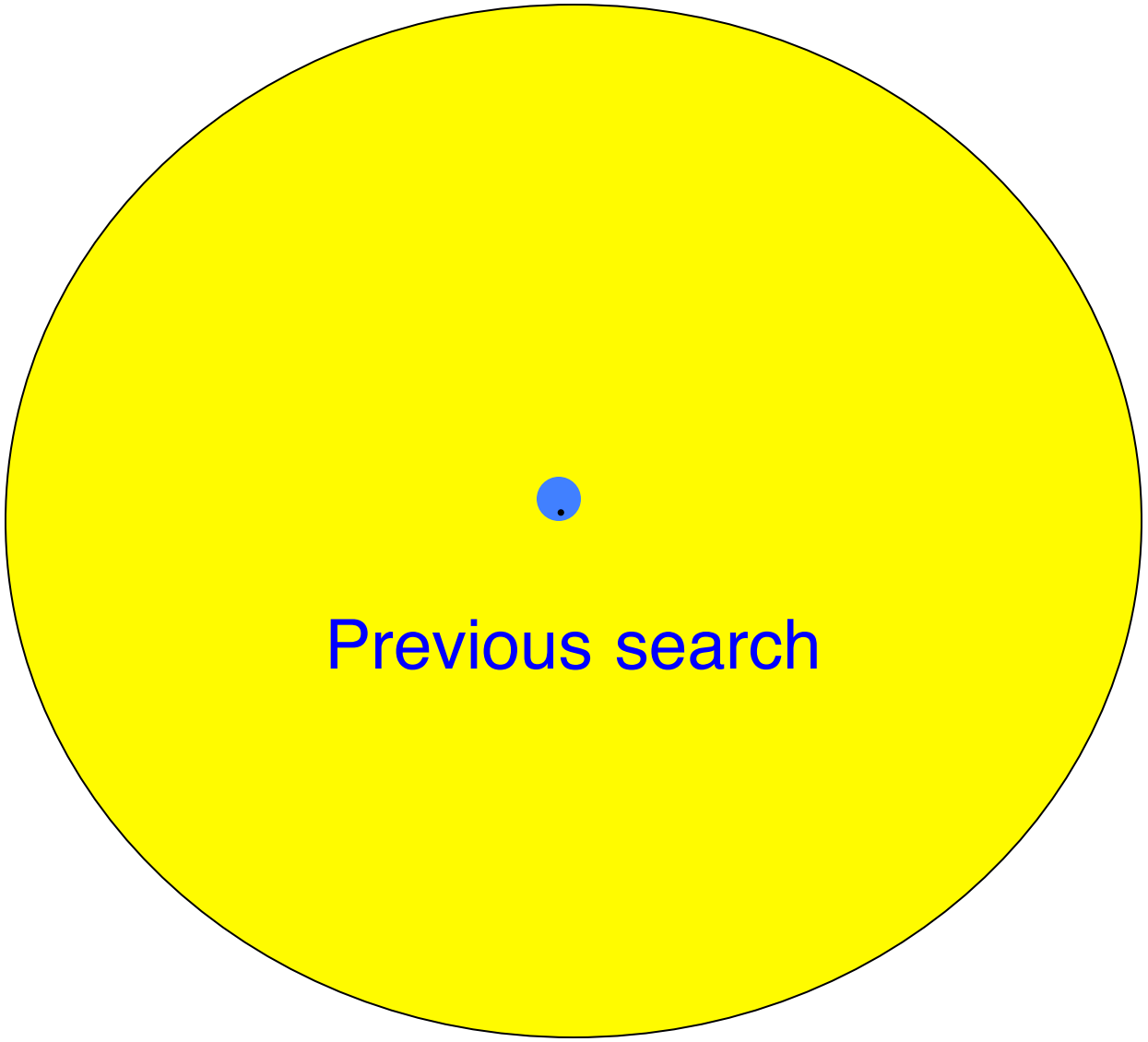
Sanchis-Ojeda et al. In prep since then

First search of Kepler data: June 2011



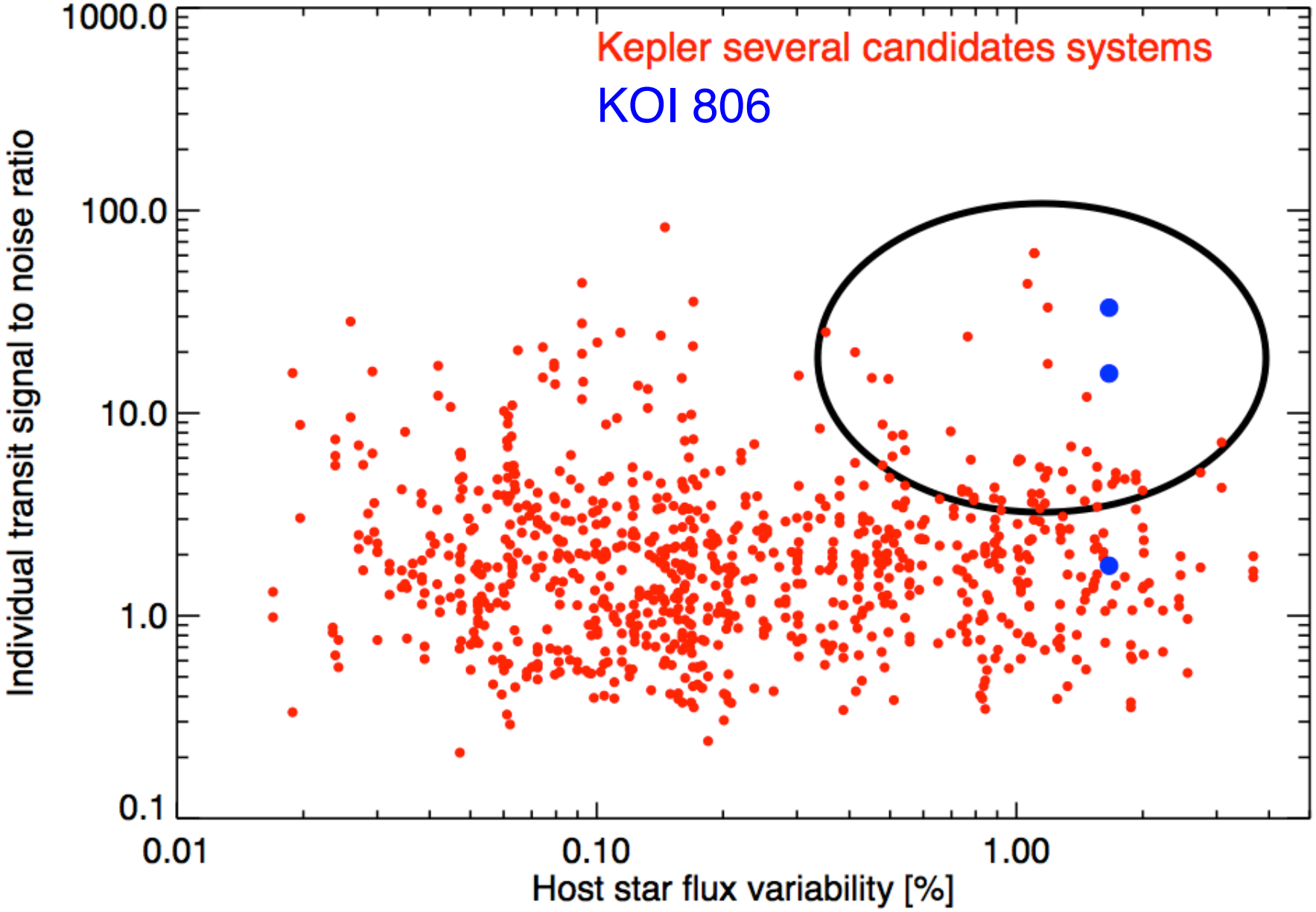
Public SC Q0-3 Kepler data for planet candidates

Second search of Kepler data: September 2011

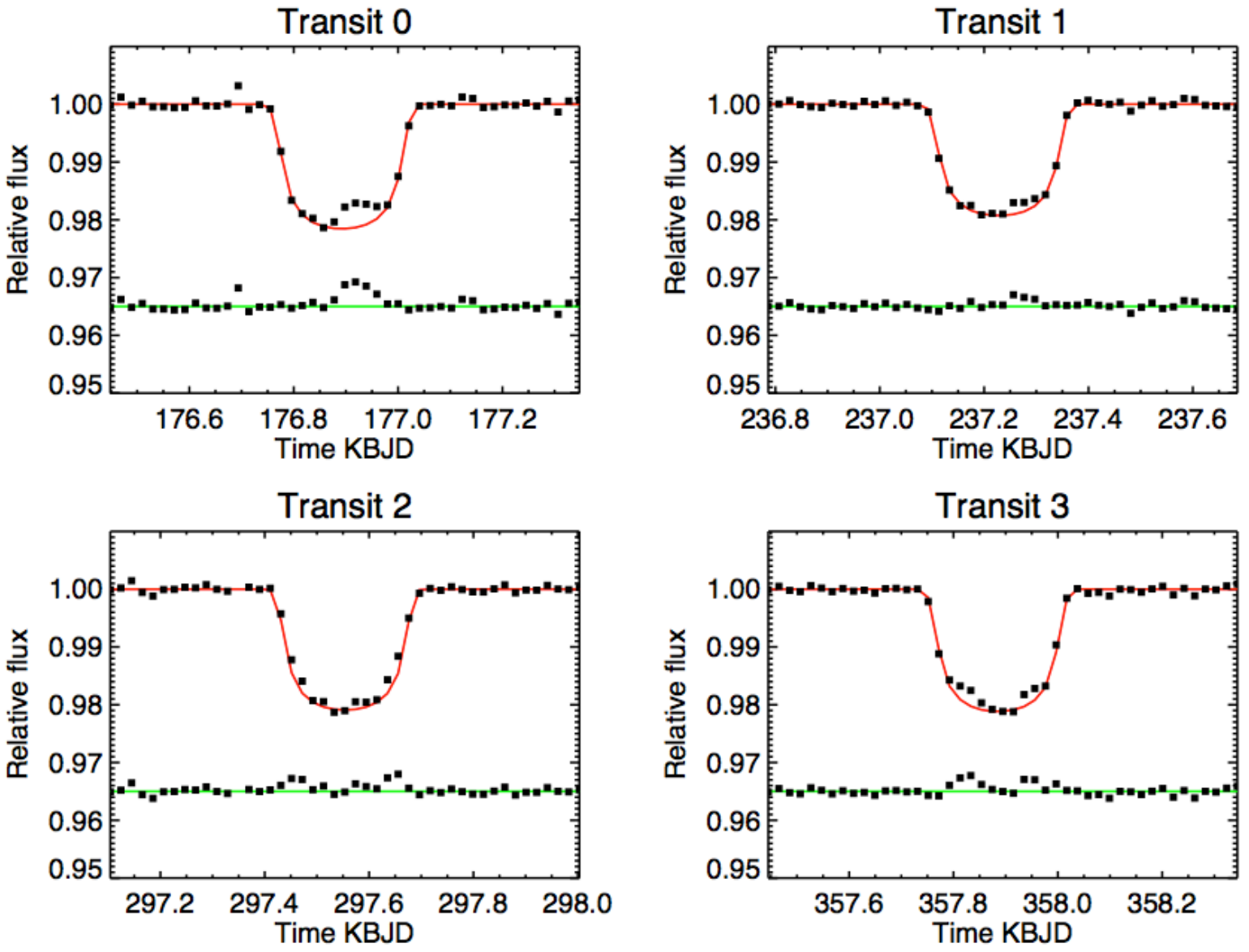


Private Q0-8 Kepler data for private planet candidates

Multiple candidate systems from Kepler



KOI 806, a three candidate system with long transits. Anomalies clear in LC data



AT&T 3G 1:01 PM 100%

Messages | Astrochat | Edit

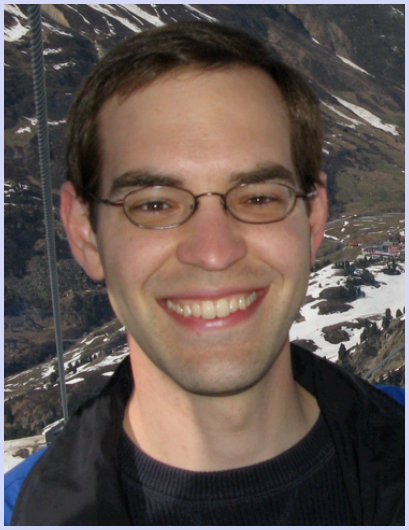
Here I present KOI 806 as Kepler 30, a system with an anticorrelated TTV signal on the transits of its three planets. The presence of spots could provide the obliquity of the system.

Dan, I think the system is aligned.

I am not as sure as you are, but we should work on it, this is very interesting.

Let me ask Josh to see what he thinks, I should finish my KOI 63 paper.

Send



AT&T 3G 10:26 AM 100%

Messages Astrochat Edit

Josh, Dan presented at the Kepler conference Kepler 30, a system with three planets. I think the obliquity is low because of the spot anomalies.

Really? That would be exciting! How sure are you?

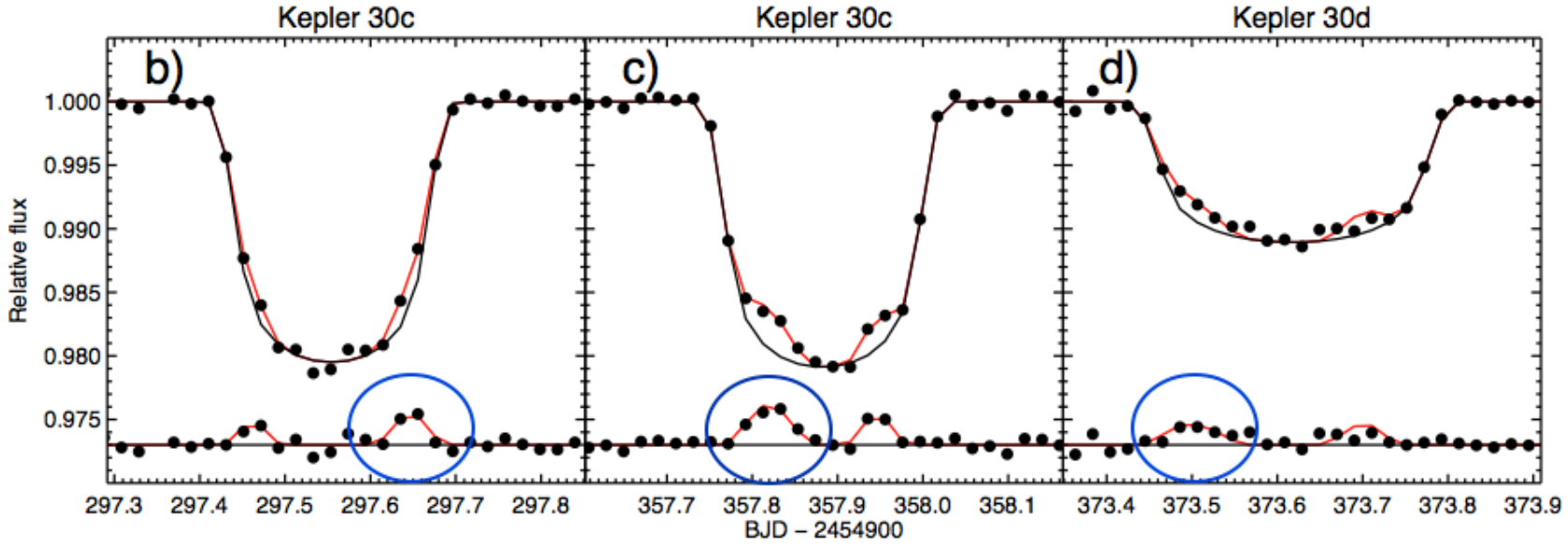
90%.

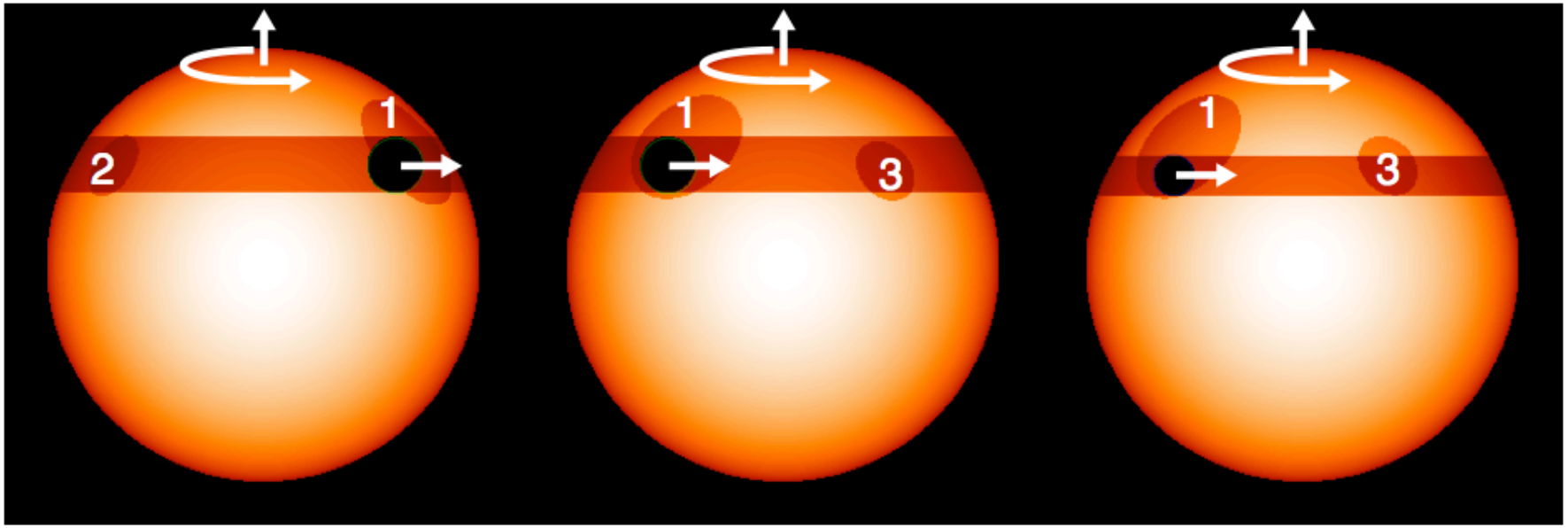
If you push it to 99% we publish right now.

Challenge accepted!

Send

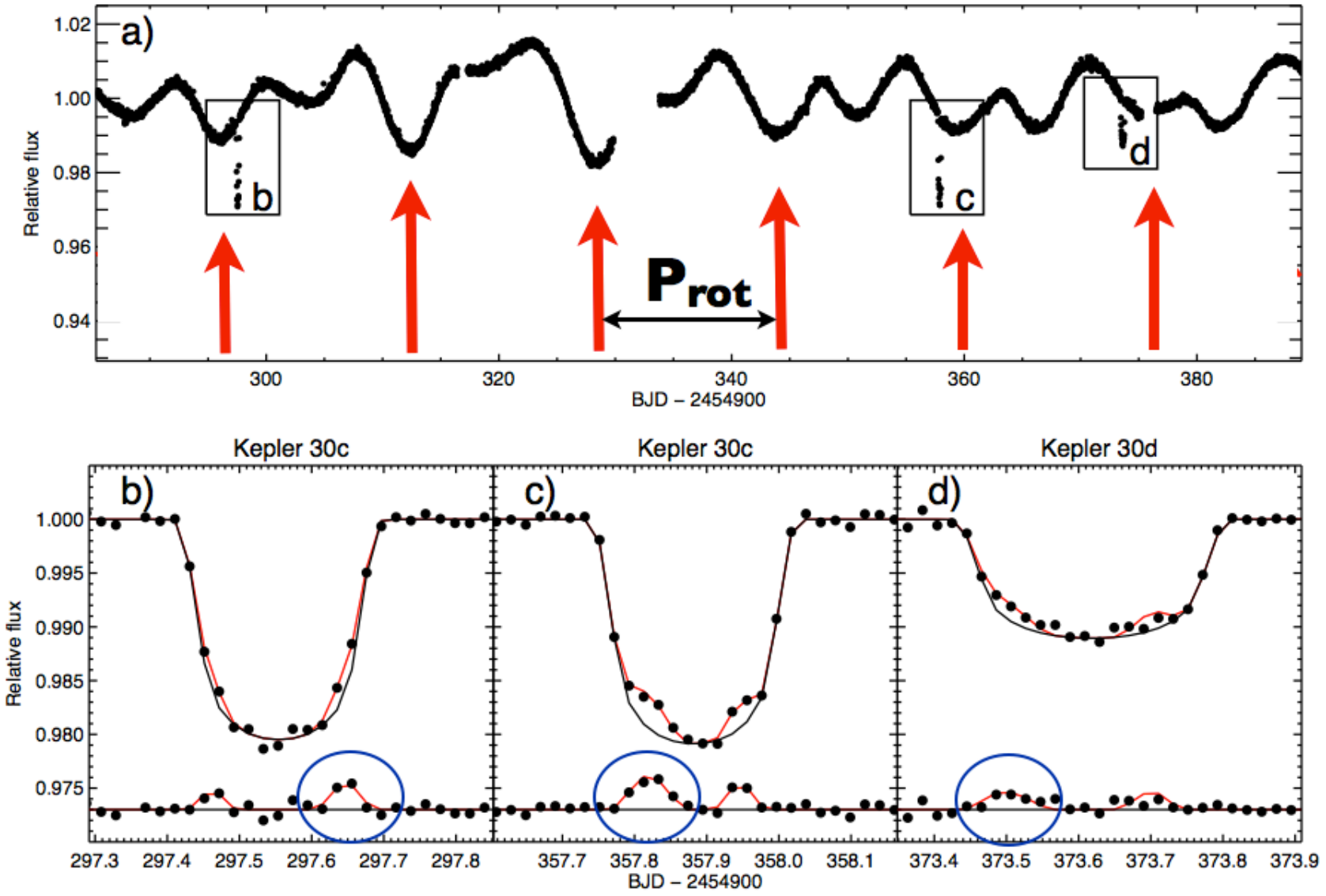
One recurrence observed

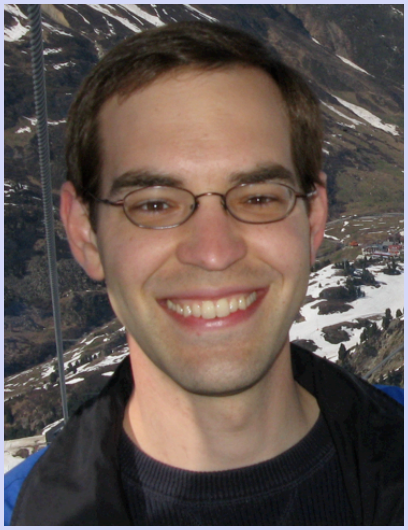




Sanchis-Ojeda, Fabrycky, Winn et al. 2012

Kepler 30c has a low obliquity





AT&T 3G 2:11 AM 100%

Messages Astrochat Edit

My analysis of the starspot-crossing events is done, the obliquity is low. Let's submit the paper.

Yes! My TTV/TDV analysis shows that the three planets are coplanar. Let's submit to Nature!

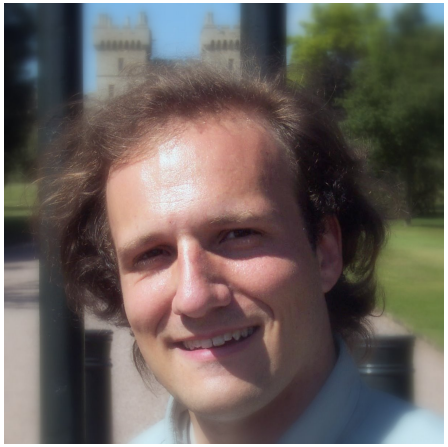
If you think we have a chance, let's do it.

Yes! Laplace and Kant are jumping up and down in their graves. Let's check with the Kepler team first.

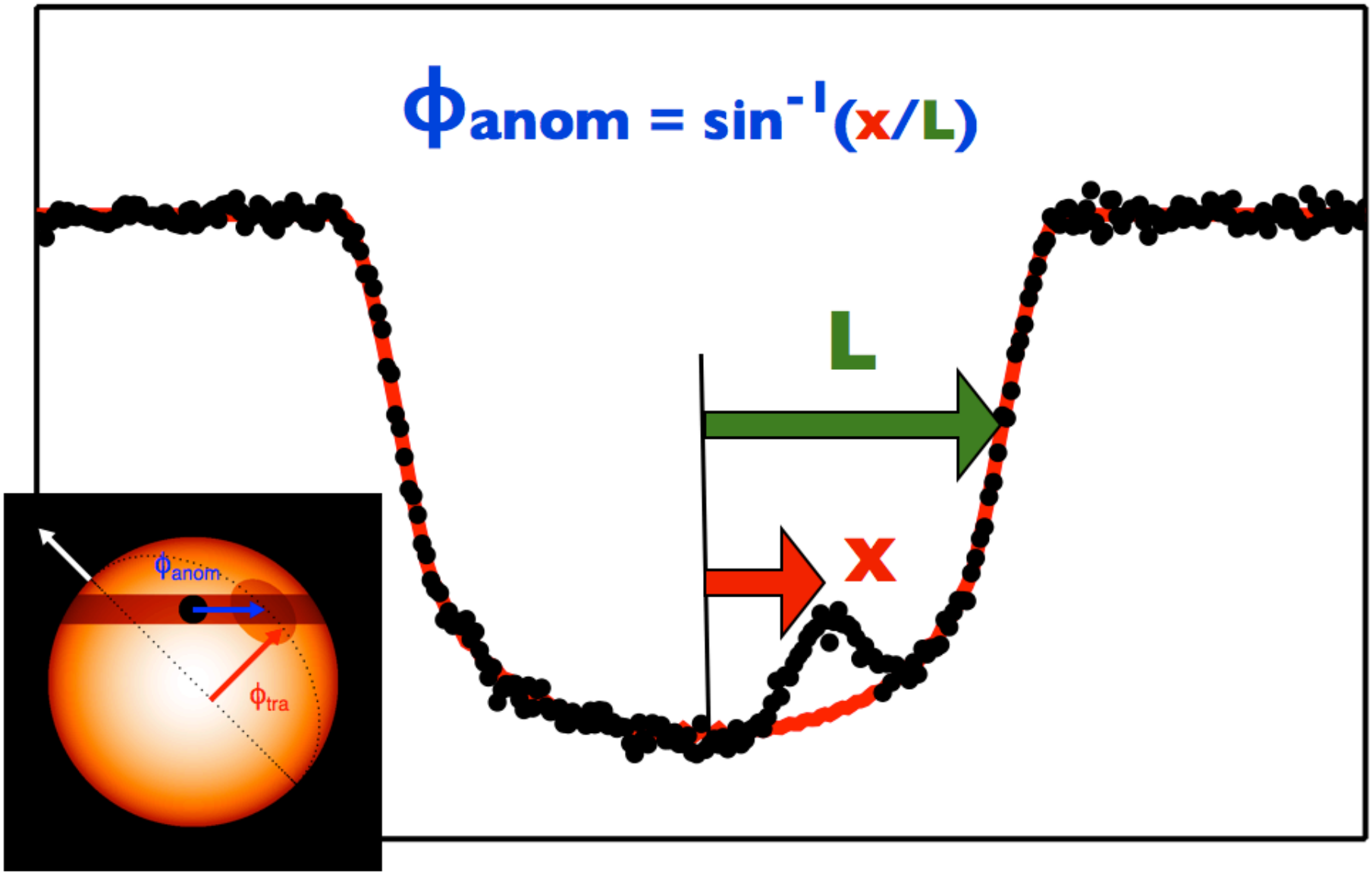
Send

Dear Kepler Team members: here is our paper about the alignment of Kepler-30. Let me know if you have any comments

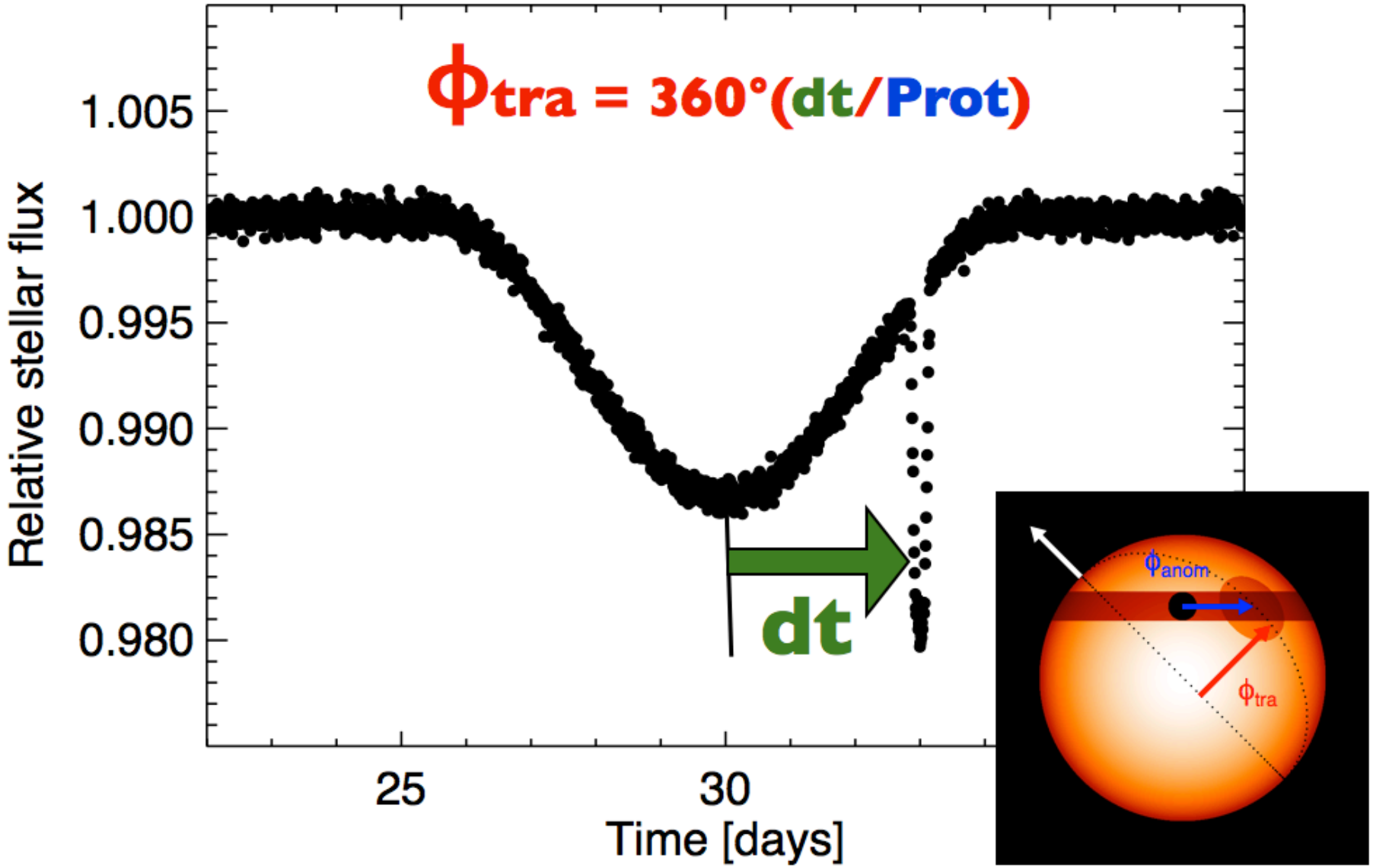
Great paper! But, spots suffer from DEGENERACY, DEGENERACY and DEGENERACY! + only one system



Measuring the anomaly phase from the transit



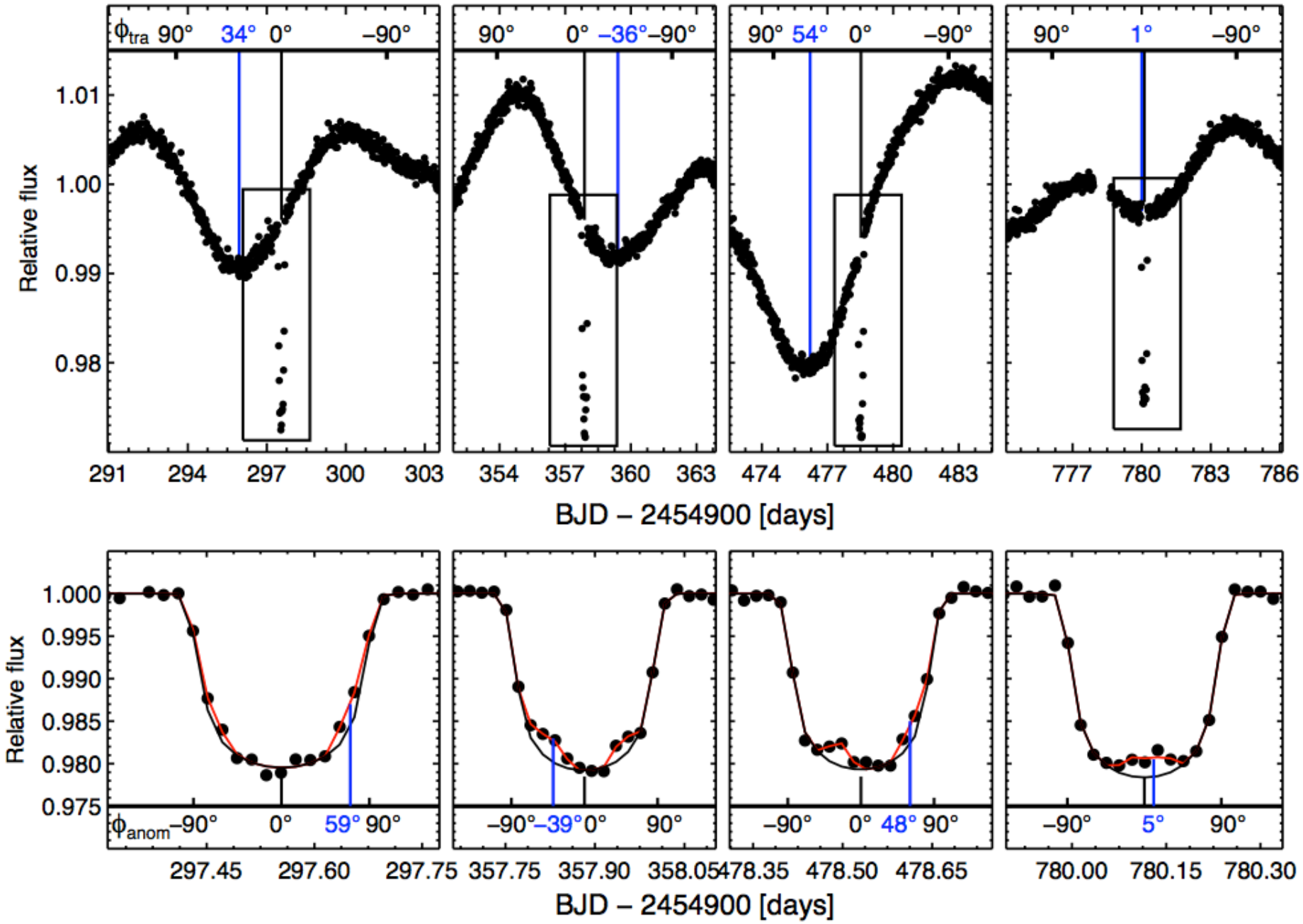
Measuring the transit phase from the stellar flux

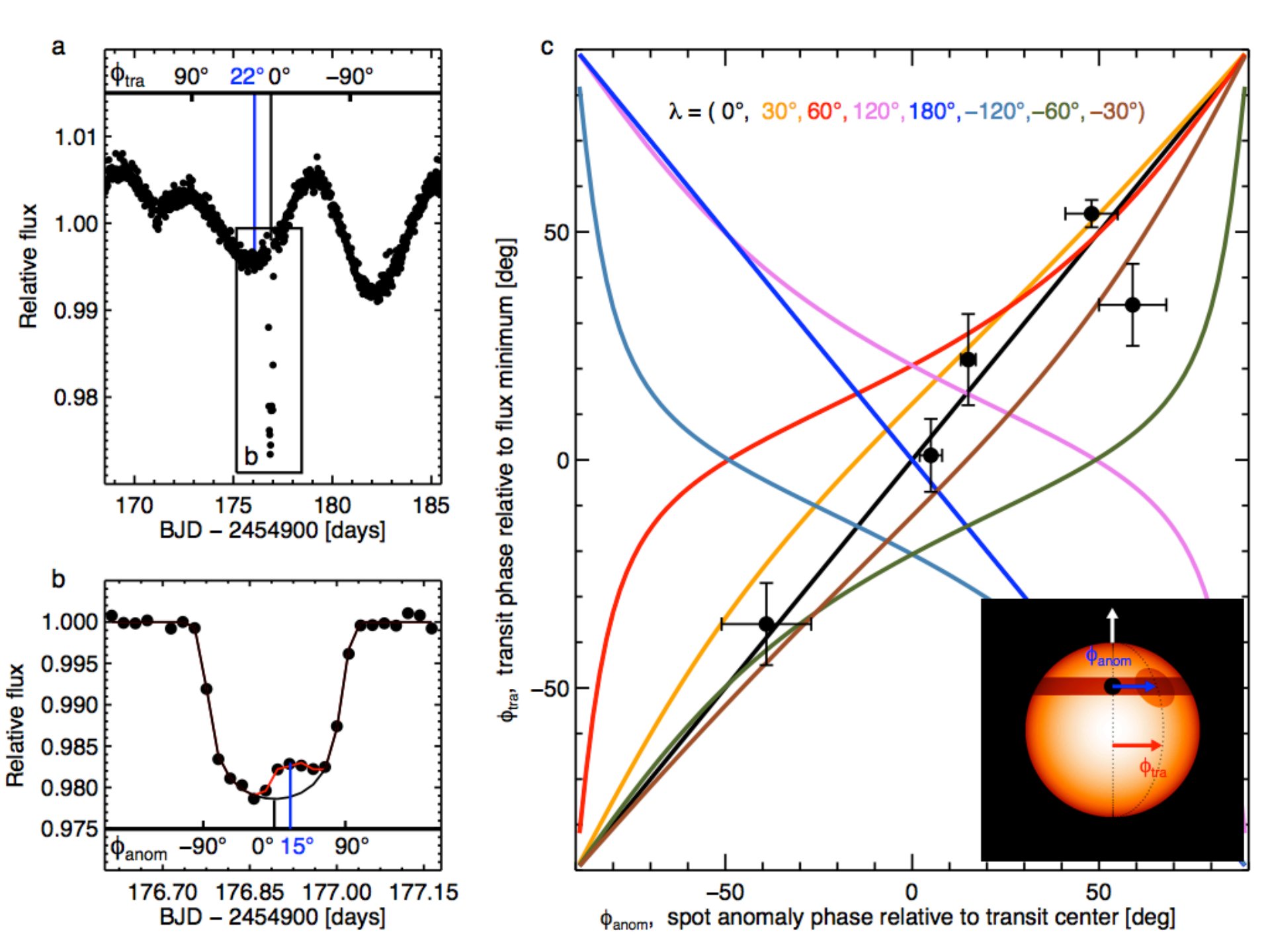


Careful selection is crucial

- We select spots that are large enough to be easily distinguishable in both transit and stellar flux.

- We omit transits close to large data gaps or strange systematic artifacts.

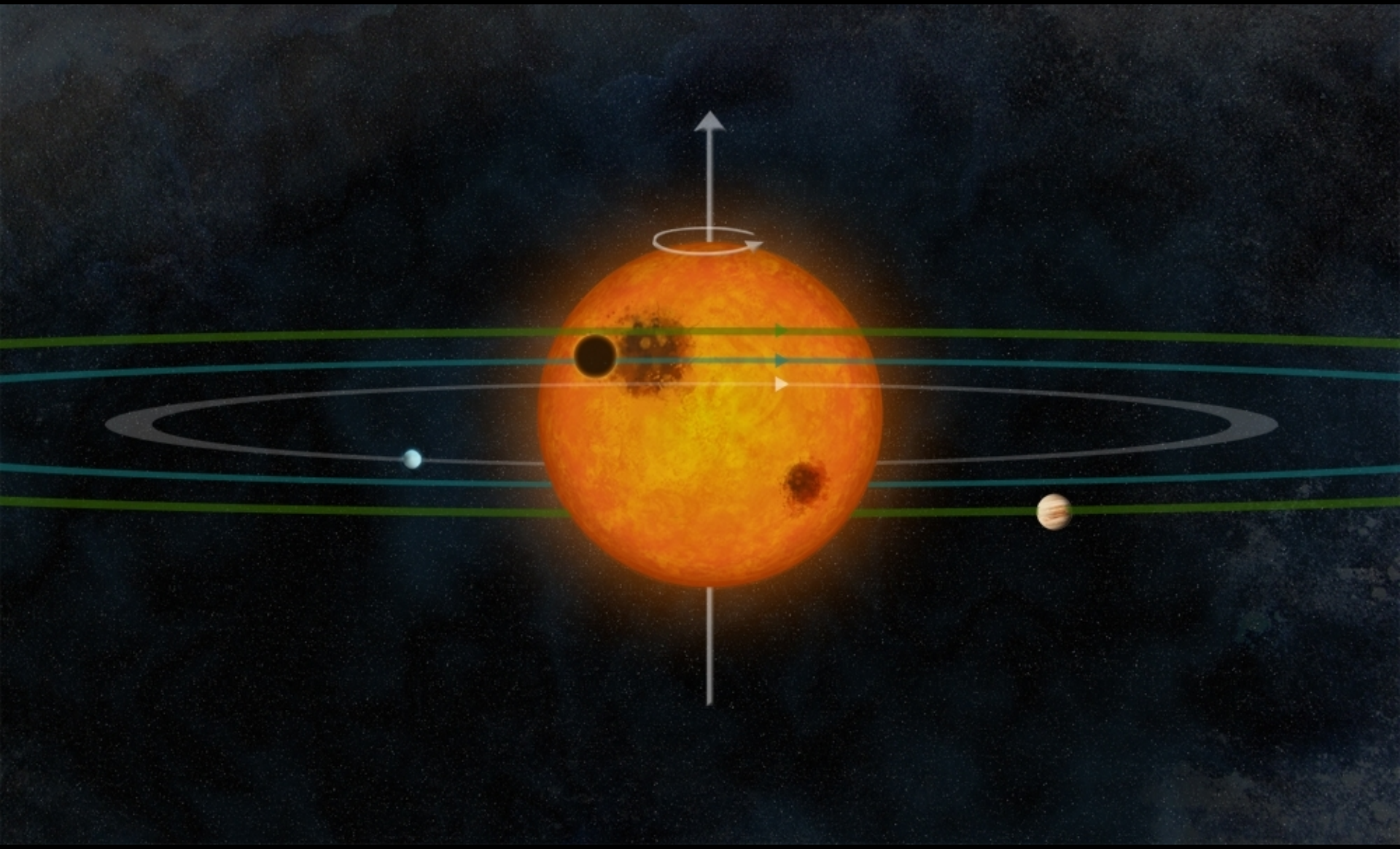

ϕ_{tra} 90° 34° 0° −90°
90° 0° −36° −90°
90° 54° 0° −90°
90° 1° −90°
Relative flux
1.01
1.00
0.99
0.98
291 294 297 300 303
354 357 360 363
474 477 480 483
777 780 783 786
BJD − 2454900 [days]
1.000
0.995
0.990
0.985
0.980
0.975
ϕ_{anom} −90° 0° 59° 90°
−90° −39° 0° 90°
−90° 0° 48° 90°
−90° 5° 90°
297.45 297.60 297.75
357.75 357.90 358.05
478.35 478.50 478.65
780.00 780.15 780.30
BJD − 2454900 [days]


a
ϕ_{tra} 90° 22° 0° −90°
1.01
1.00
0.99
0.98
Relative flux
b
170 175 180 185
BJD − 2454900 [days]
b
1.000
0.995
0.990
0.985
0.980
0.975
Relative flux
ϕ_{anom} −90° 0° 15° 90°
176.70 176.85 177.00 177.15
BJD − 2454900 [days]
c
λ = (0°, 30°, 60°, 120°, 180°, −120°, −60°, −30°)
50
0
−50
ϕ_{tra}, transit phase relative to flux minimum [deg]
−50 0 50
ϕ_{anom}, spot anomaly phase relative to transit center [deg]
ϕ_{anom}
ϕ_{tra}

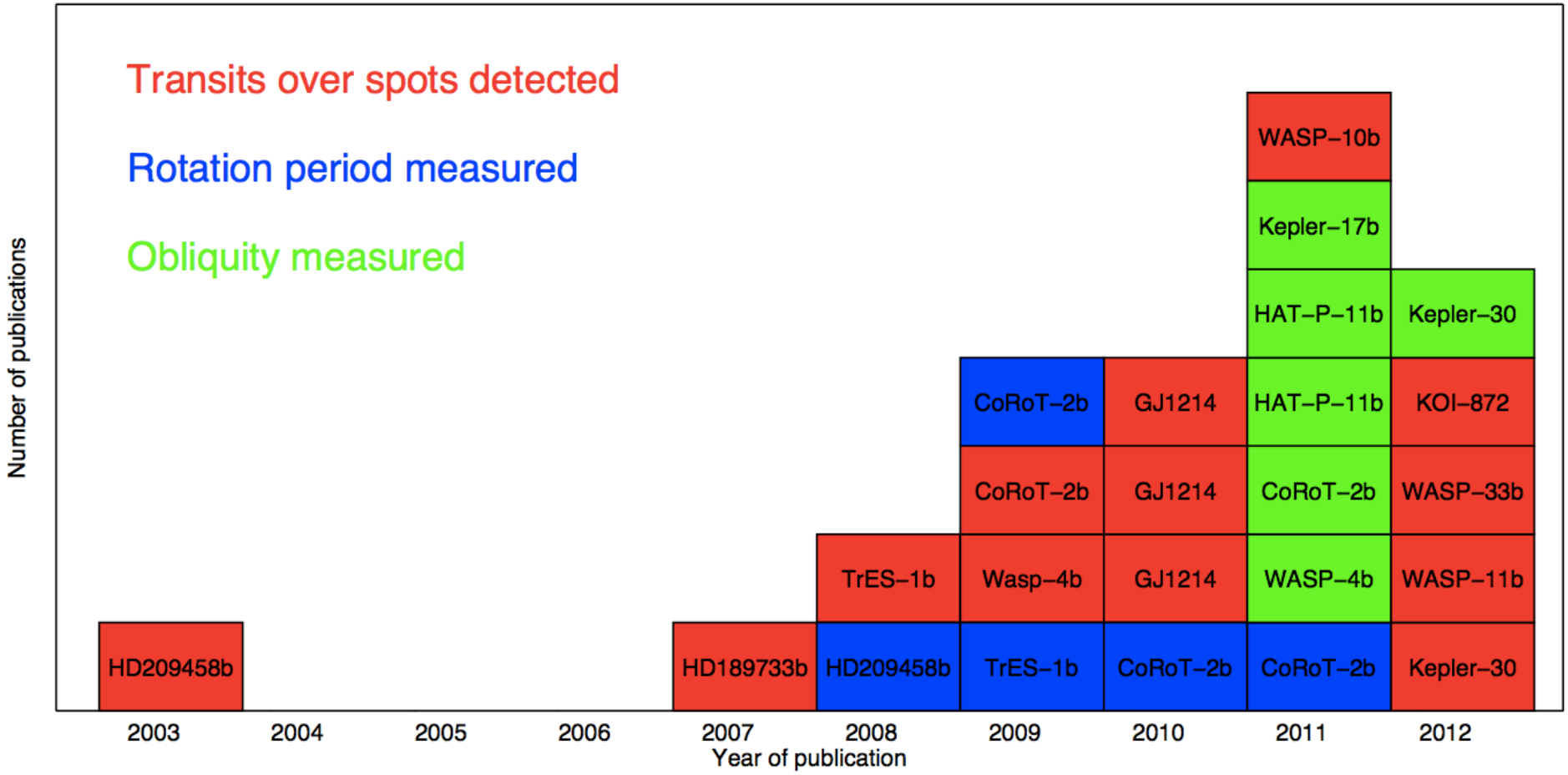
- Transits over starspots can be used to measure the obliquities of Kepler multiplanet systems.

- The low obliquity of Kepler-30 suggests that high obliquities are confined to HJ systems, and therefore that HJs arise from few-body dynamics.

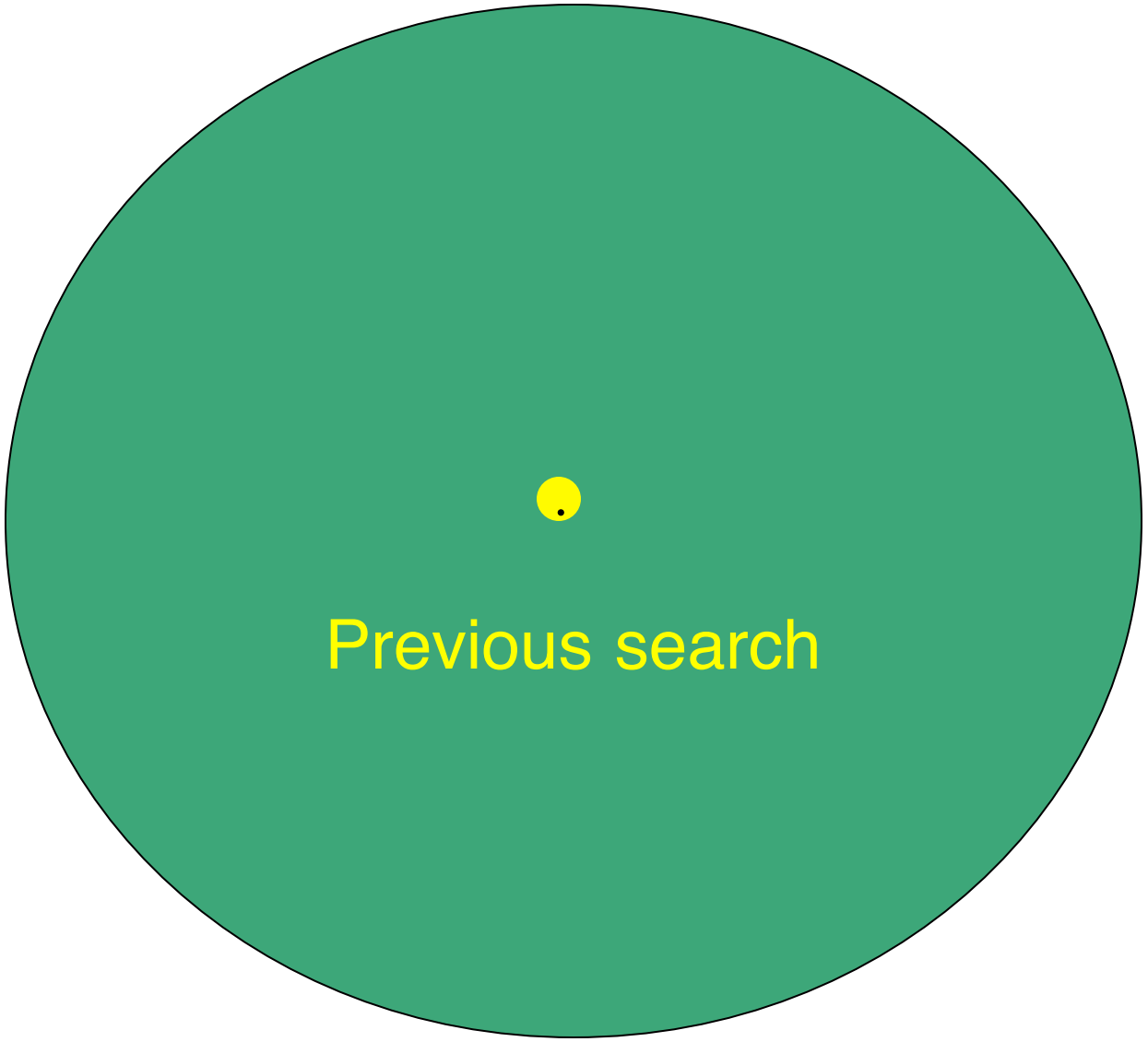
- Additional stars with coplanar multiplanet systems should be observed, and are predicted to have low obliquities.



The field is growing



Next search of Kepler data: xxx 2012



Public Q0-13 Kepler data for planet and binary systems

We will find…

- Misaligned single planet systems. Butterfly diagrams and more.
- A few more multiple planet systems. If coplanar, all probably aligned.
- A huge amount of binary stars. Most of them expected to be aligned.
- Special attention to Red Giant + Main sequence stars, huge spots!
- Circumbinary planets, binary star makes it easier!
- X, you tell me…