



# PROBING TRAPPIST-1

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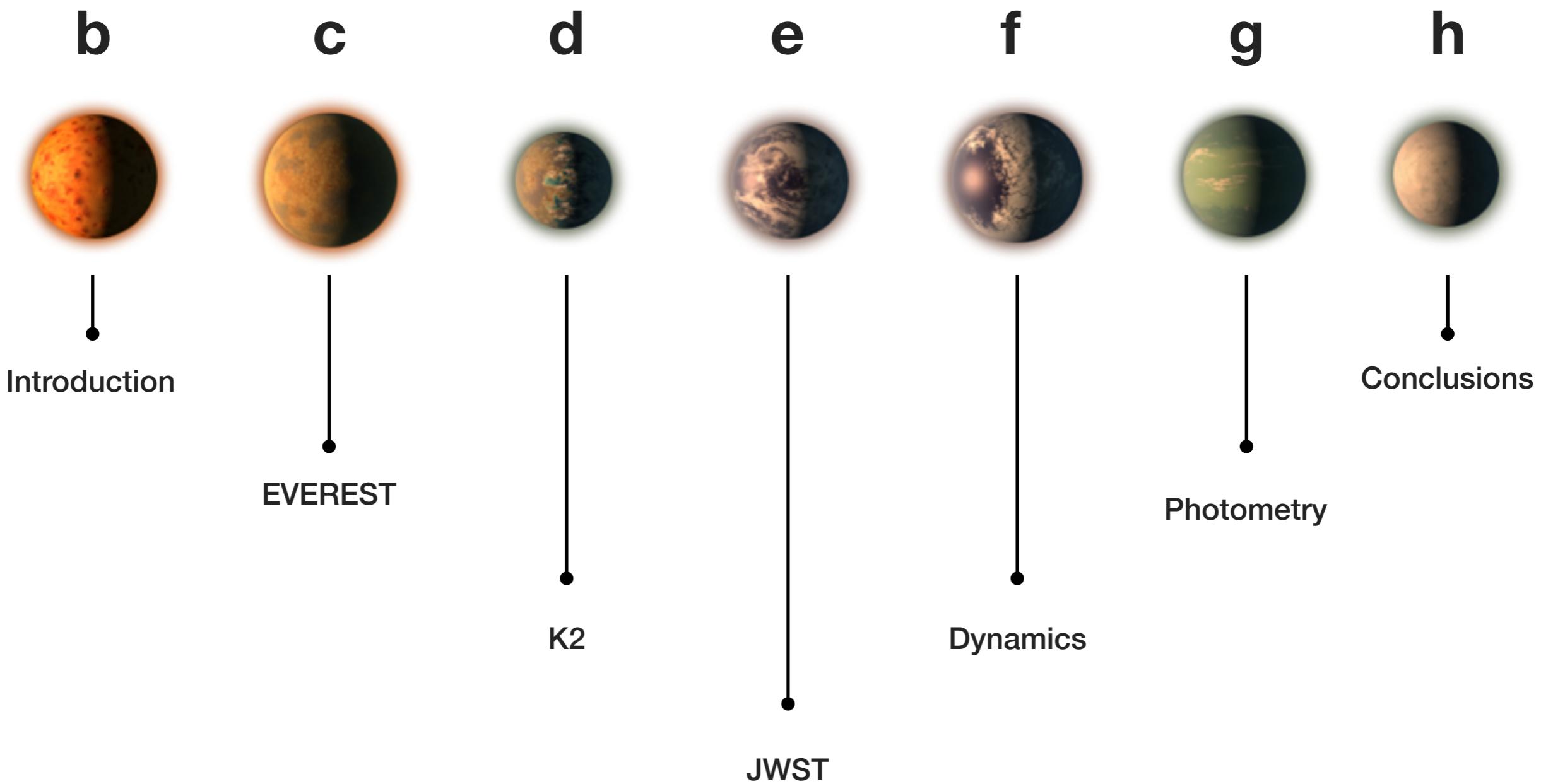
WITH K2, JWST, AND BEYOND

## RODRIGO LUGER

WITH

JACOB LUSTIG-YAEGER, ERIC AGOL

MARKO SESTOVIC, ETHAN KRUSE, SIMON L. GRIMM, BRICE-OLIVIER DEMORY, EMELINE BOLMONT, DANIEL FABRYCKY, CATARINA S. FERNANDES, VALÉRIE VAN GROOTEL, ADAM BURGASSER, MICHAËL GILLON, JAMES G. INGALLS, EMMANUËL JEHIN, SEAN N. RAYMOND, FRANCK SELSIS, AMAURY H.M.J. TRIAUD, THOMAS BARCLAY, GEERT BARENTSEN, STEVE B. HOWELL, LAETITIA DELREZ, JULIEN DE WIT, DANIEL FOREMAN-MACKEY, DANIEL L. HOLDSWORTH, JÉRÉMY LECONTE, SUSAN LEDERER, MARTIN TURBET, YASEEN ALMLEAKY, ZOUHAIR BENKHALDOUN, PIERRE MAGAIN, BRETT MORRIS, KEVIN HENG, AND DIDIER QUELOZ

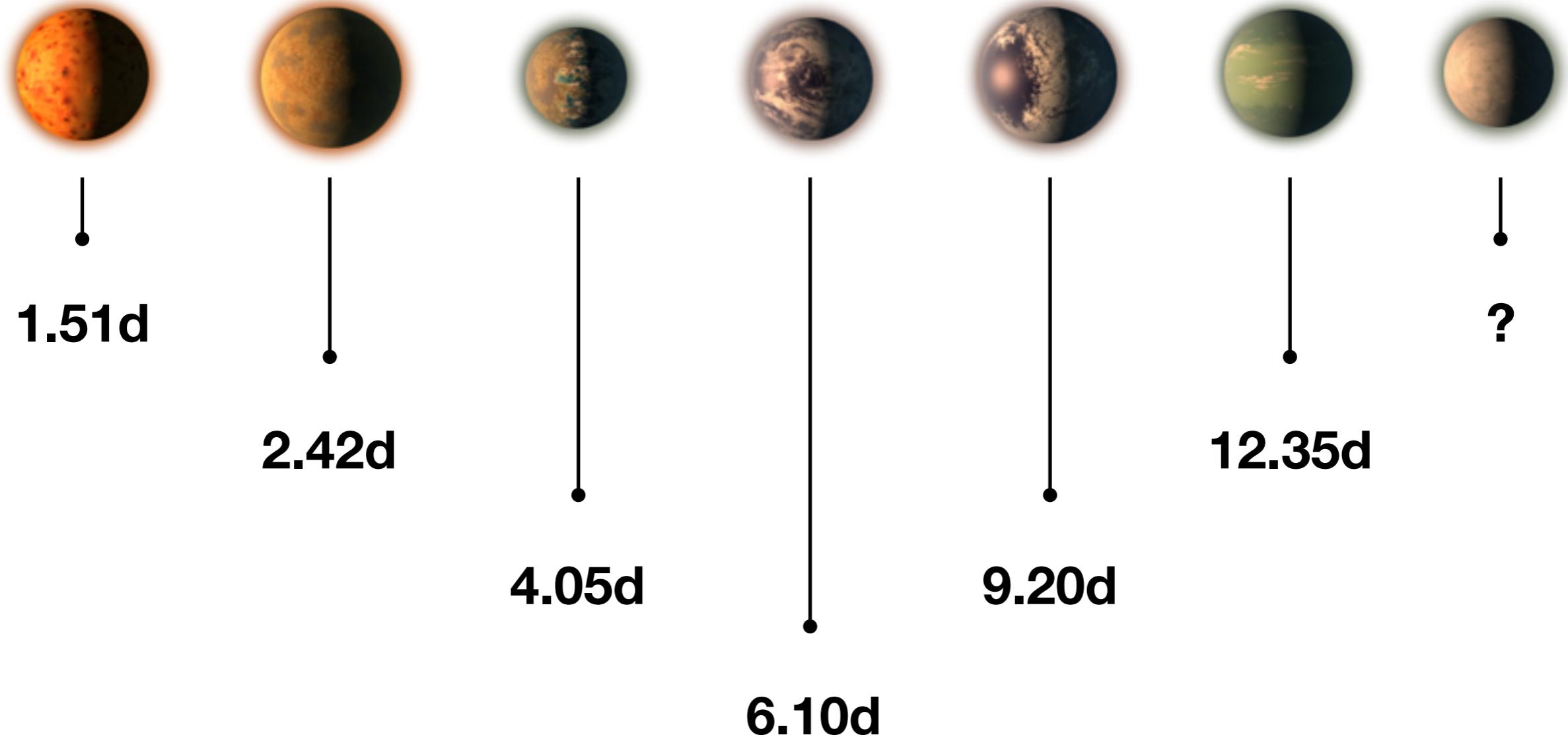


## PART b



*INTRODUCTION*

# TRAPPIST-1

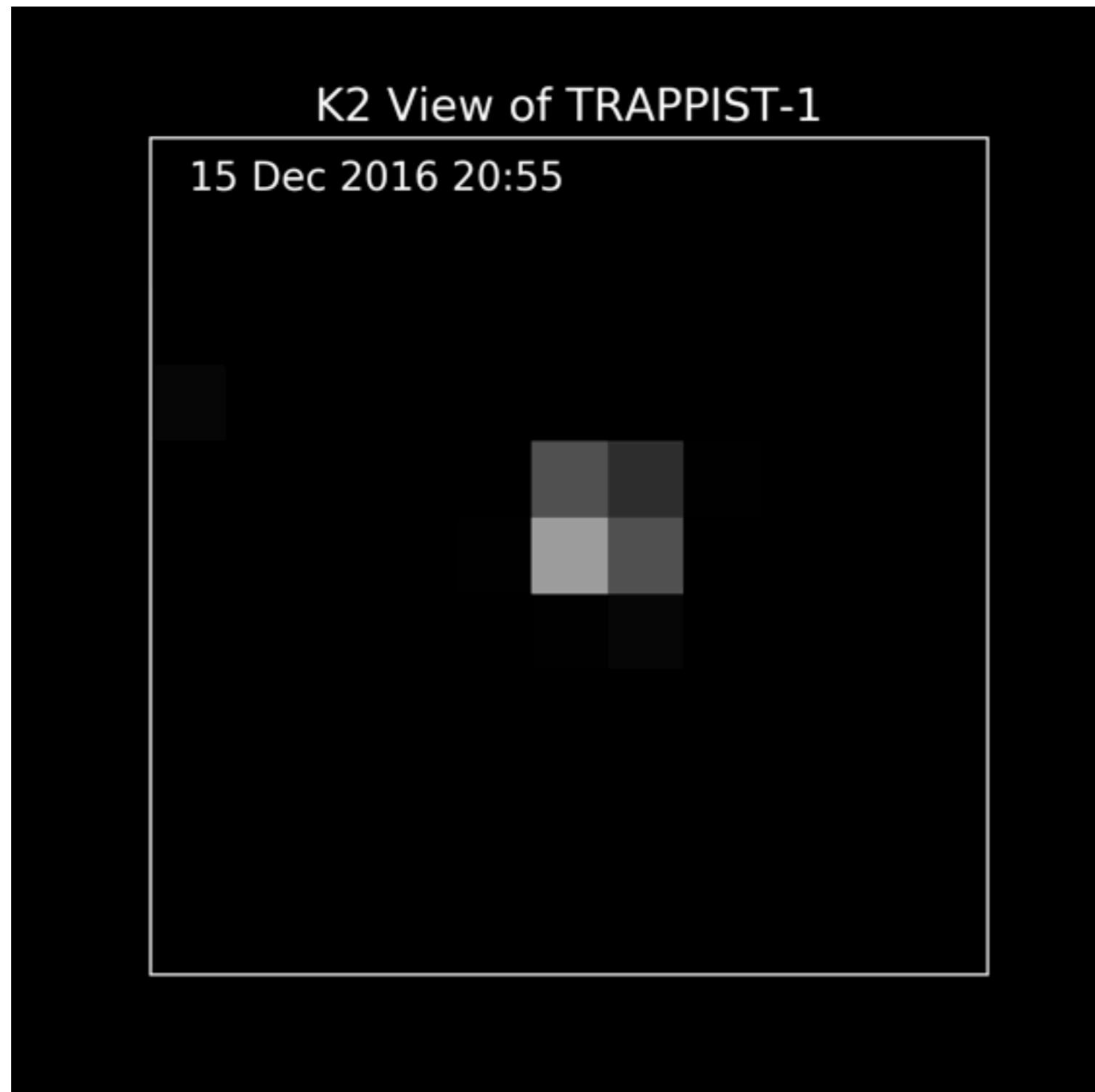


Gillon et al. (2016, 2017)



# TRAPPIST-1 with K2

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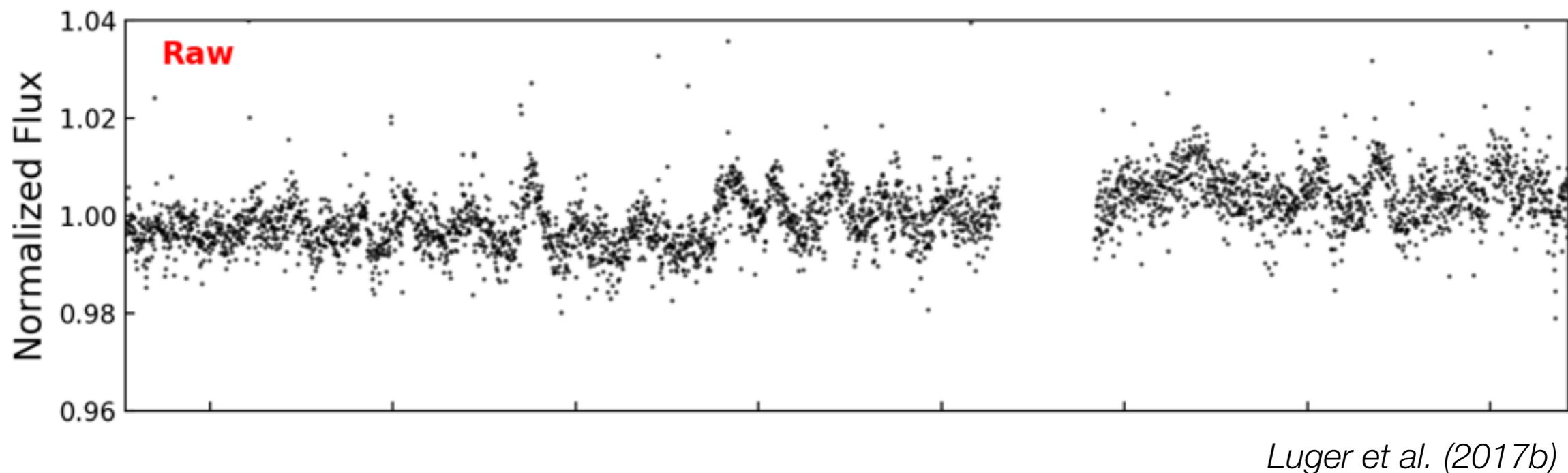


*Ethan Kruse*



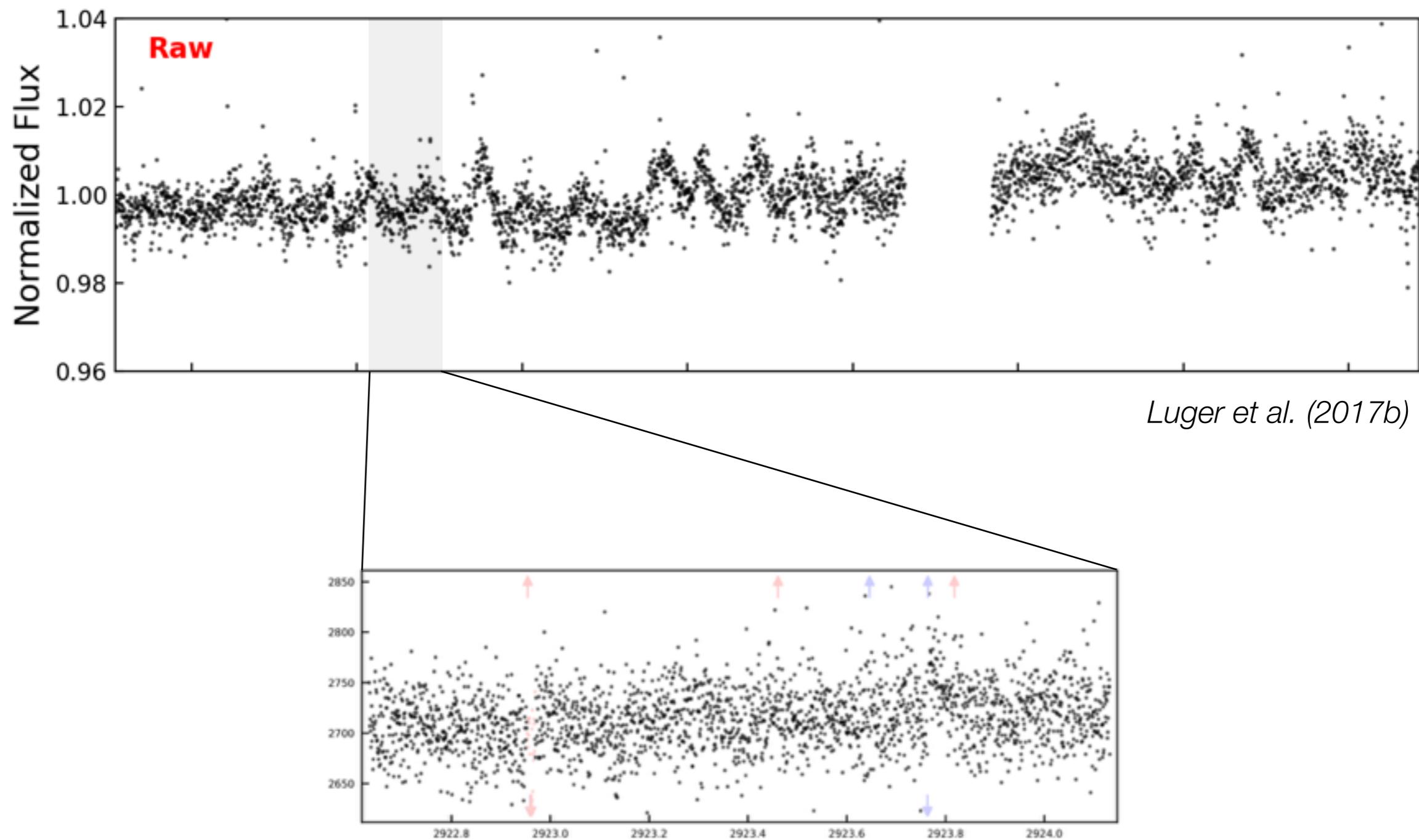
# TRAPPIST-1 with K2

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# TRAPPIST-1 with K2



## PART c

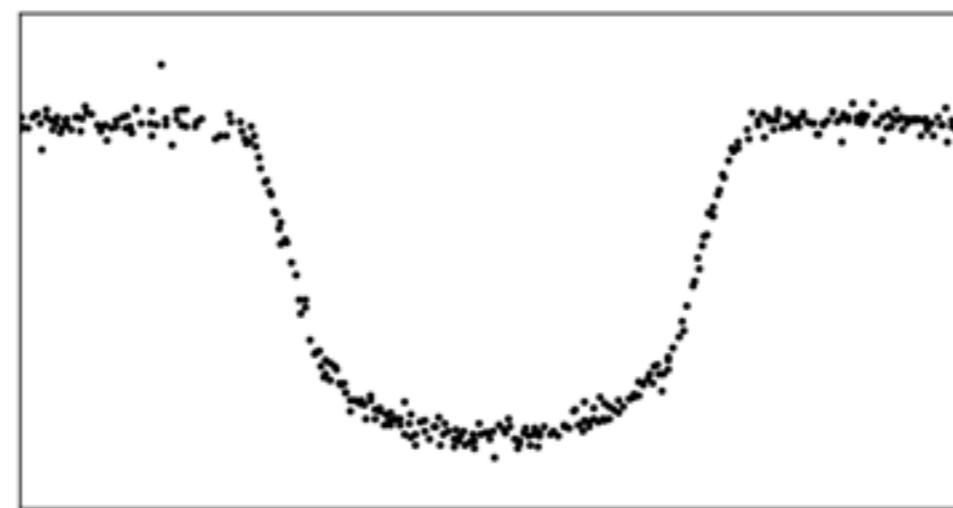
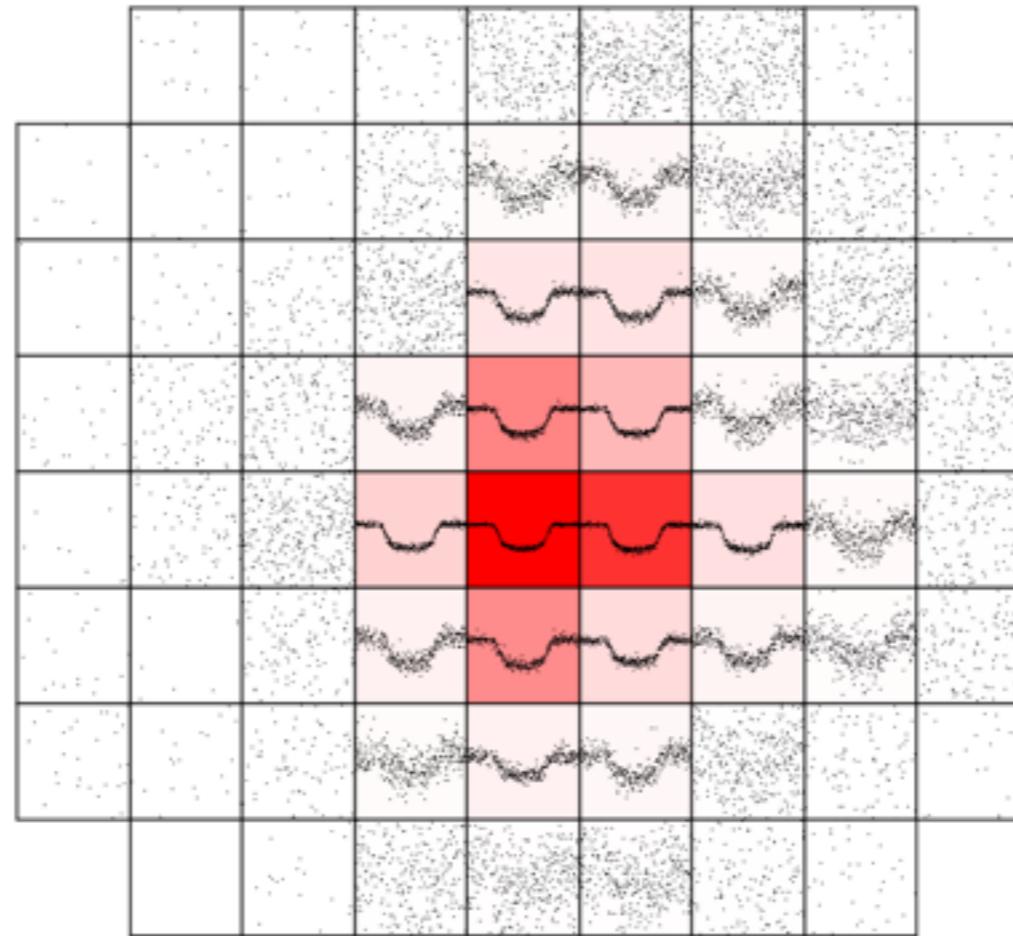


*EVEREST*

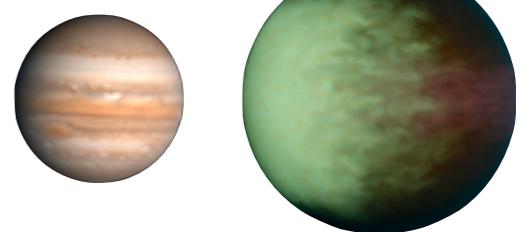


A typical postage stamp

$\Sigma$

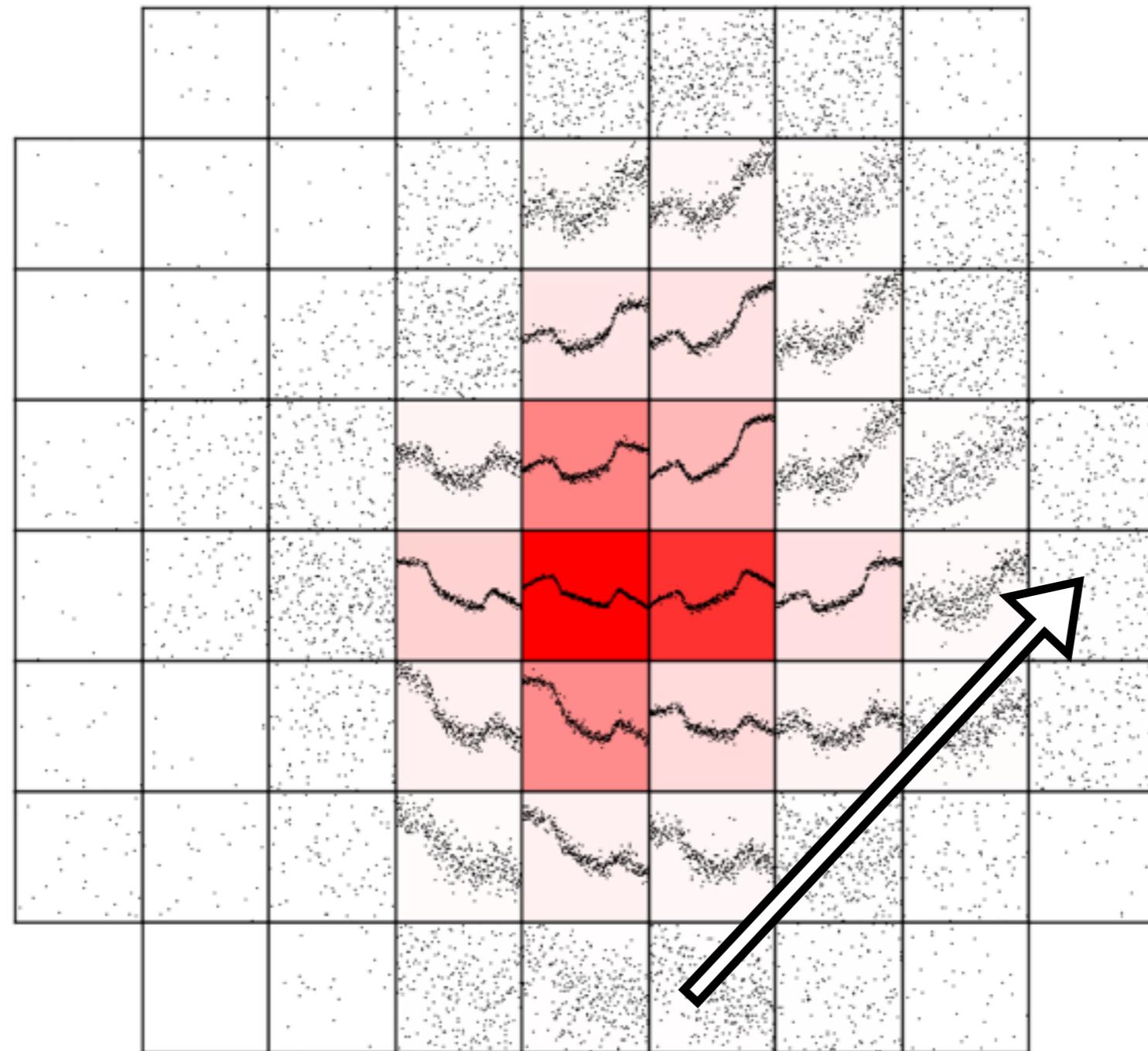


*Kepler-6b*





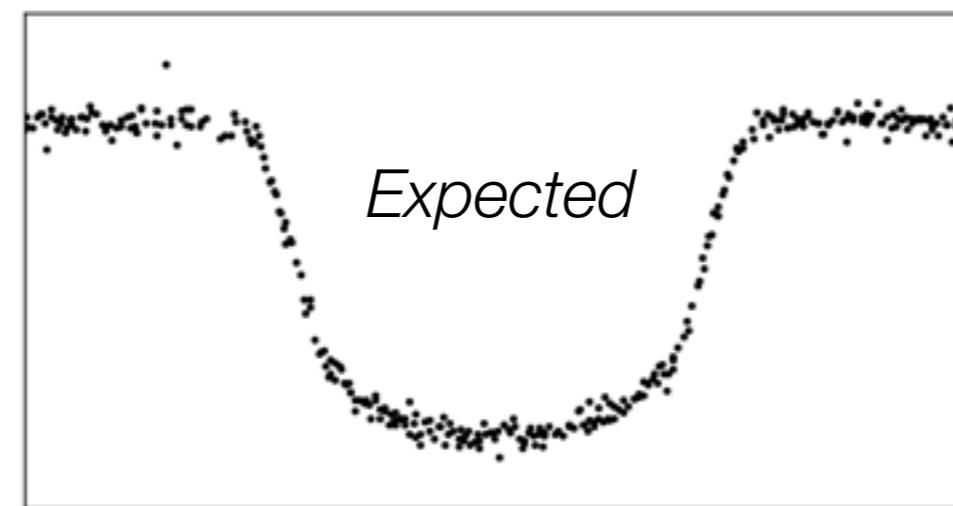
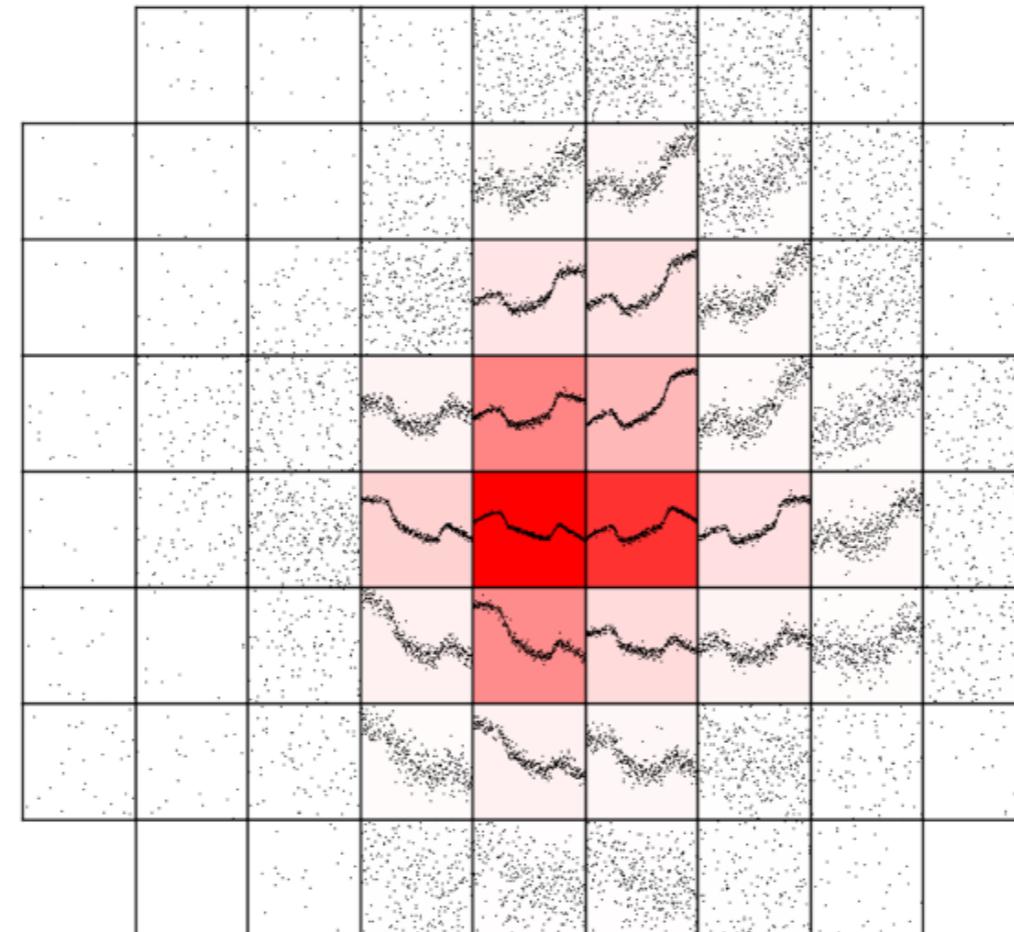
A typical postage stamp





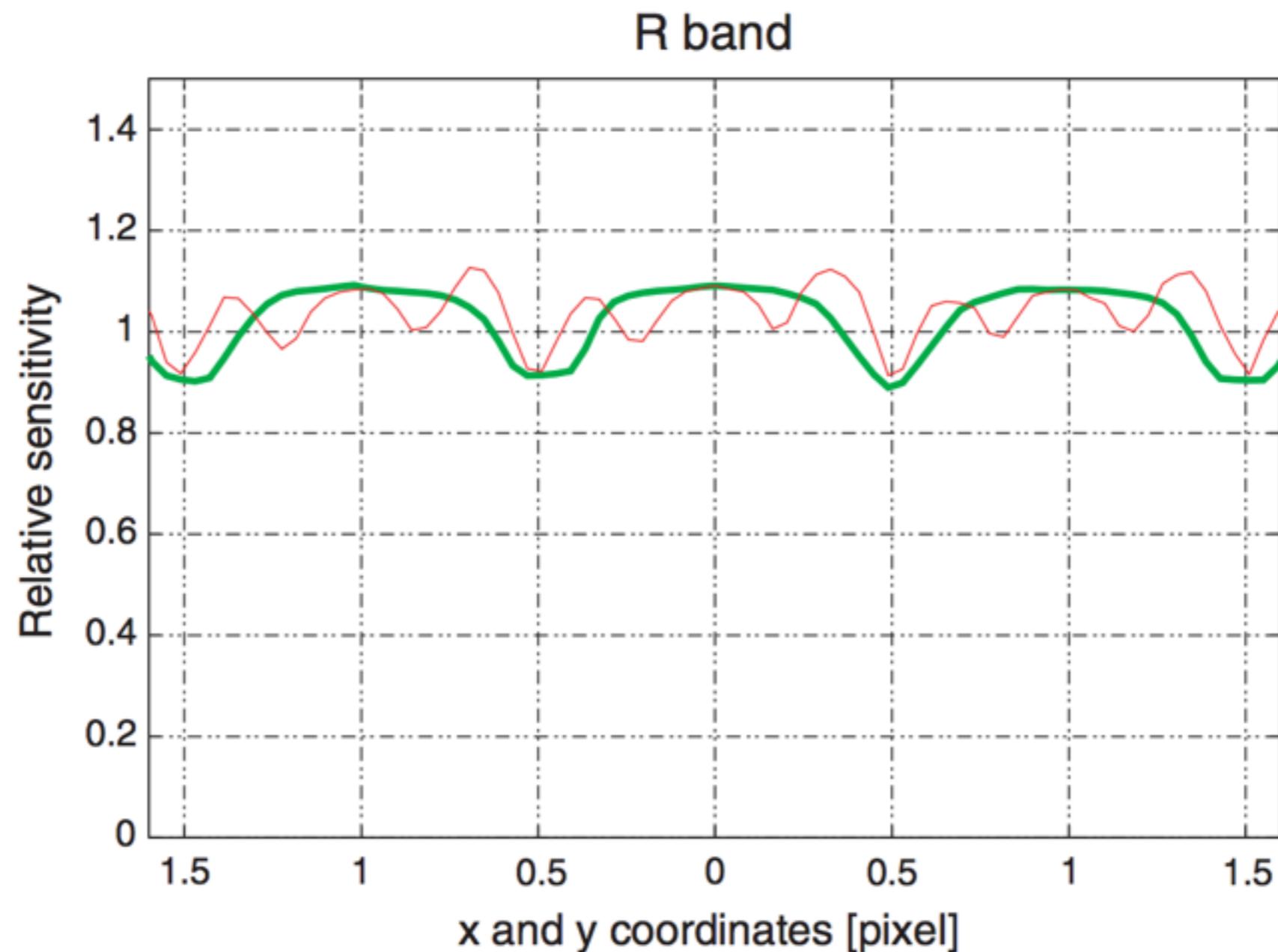
A typical postage stamp

$\Sigma$





Intrapixel sensitivity

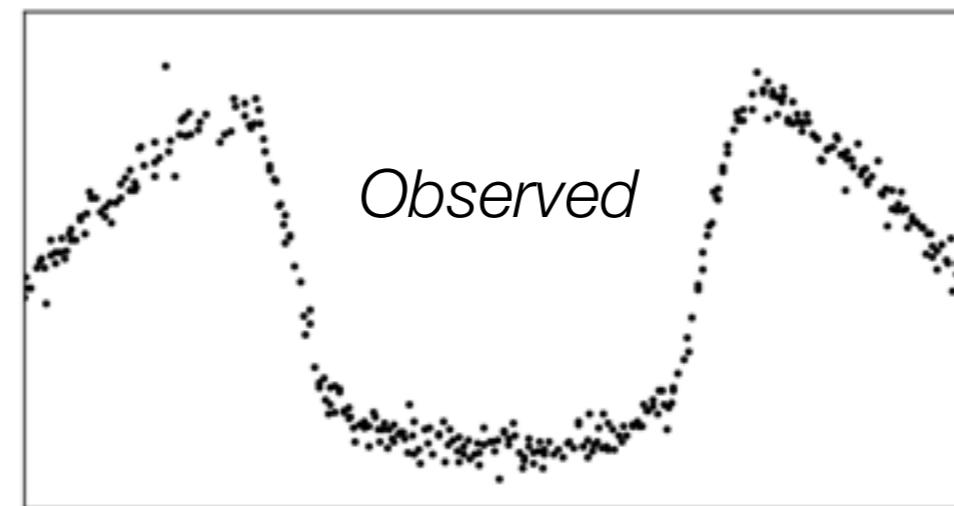
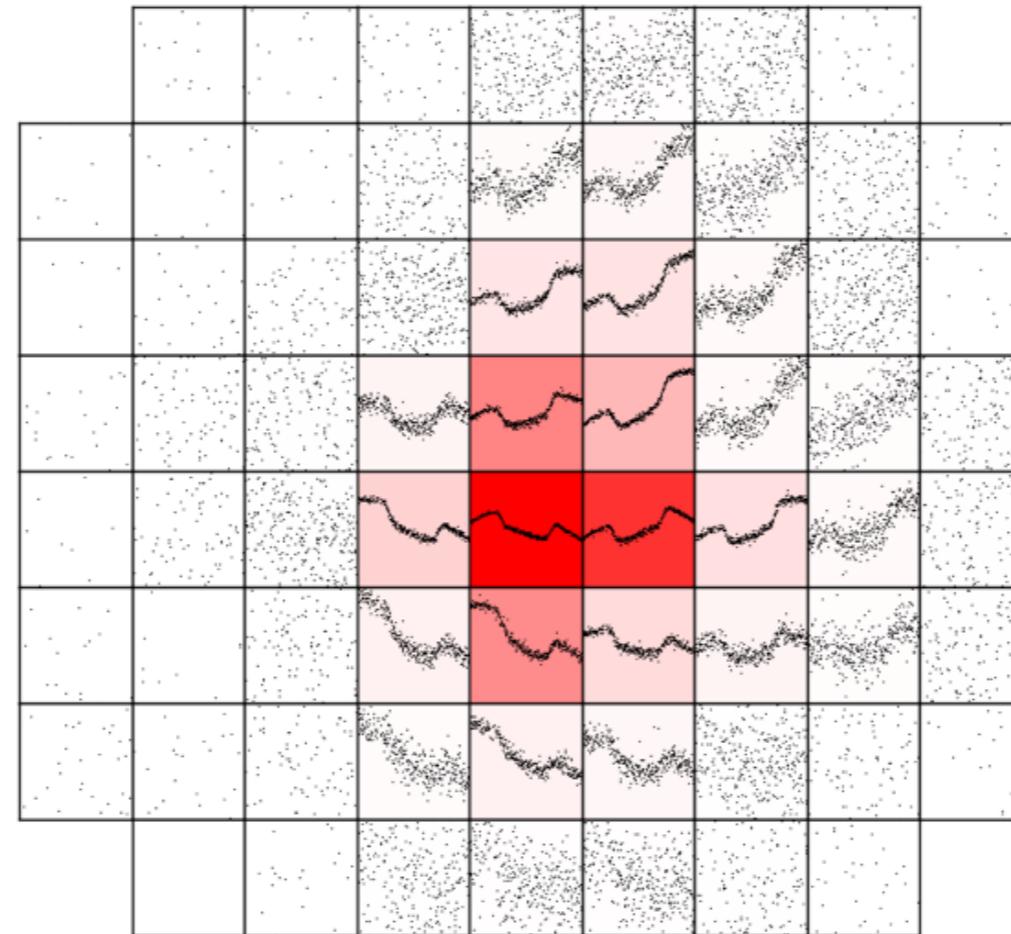


*Toyozumi (2005)*



A typical postage stamp

$\Sigma$

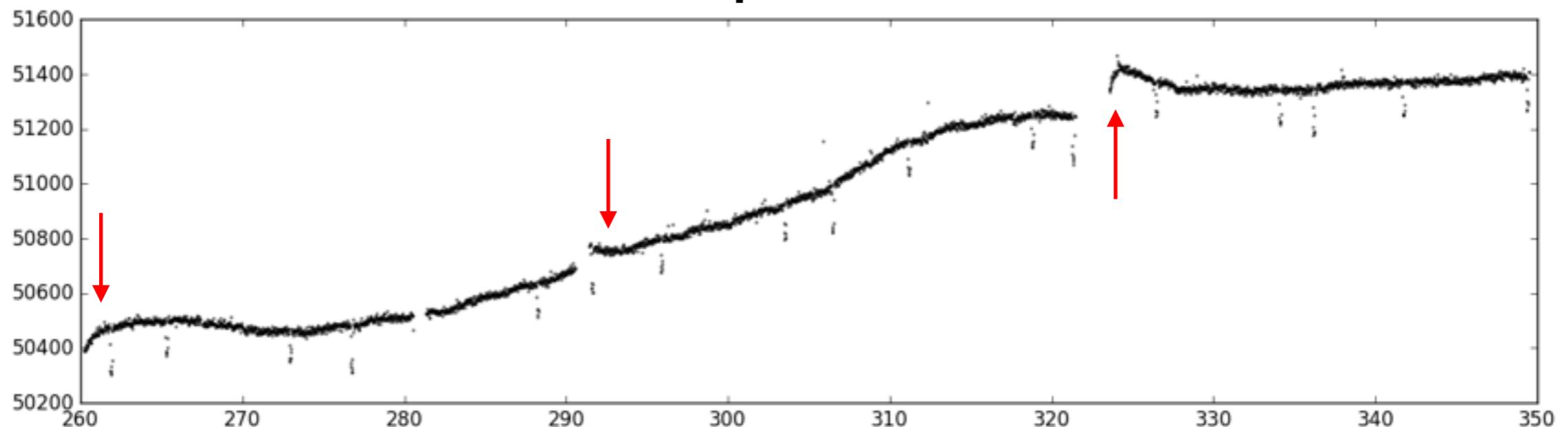




## Real Light Curves

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**Kepler 20**

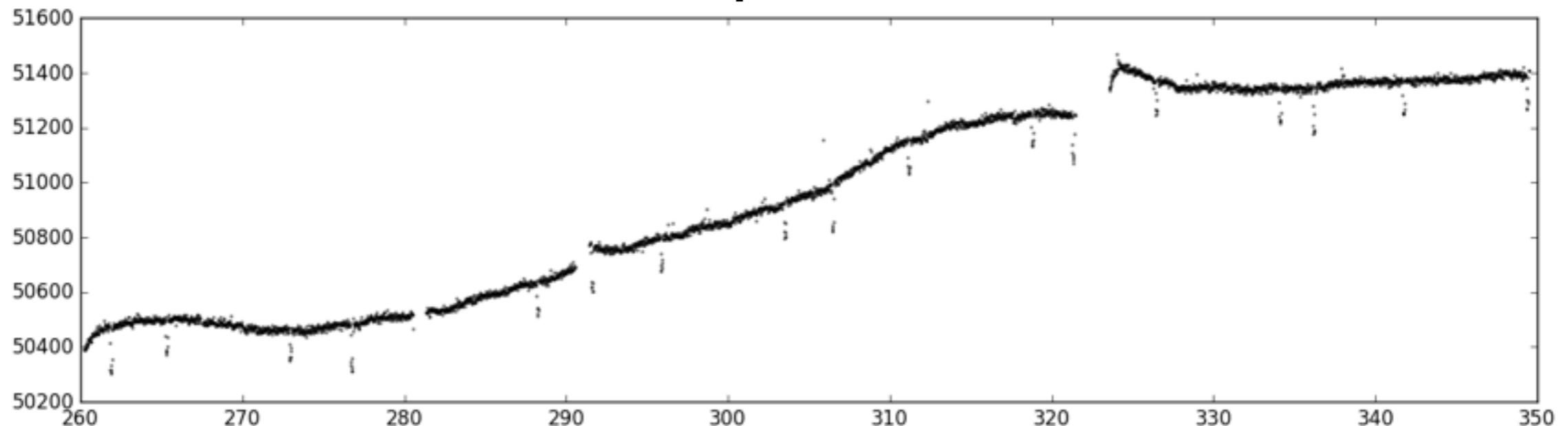




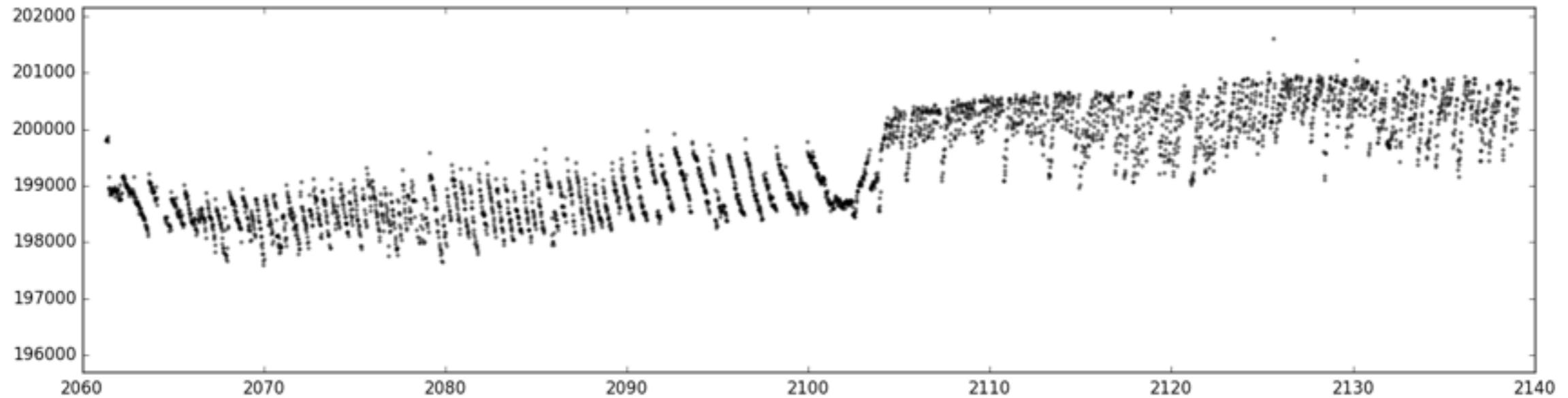
## Real Light Curves

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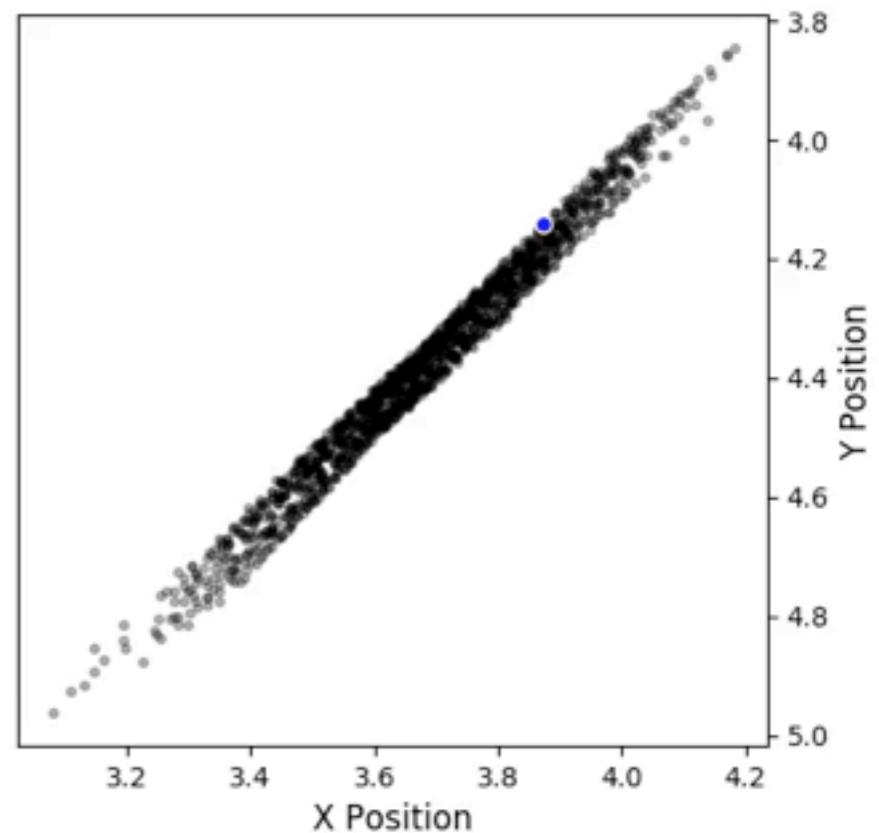
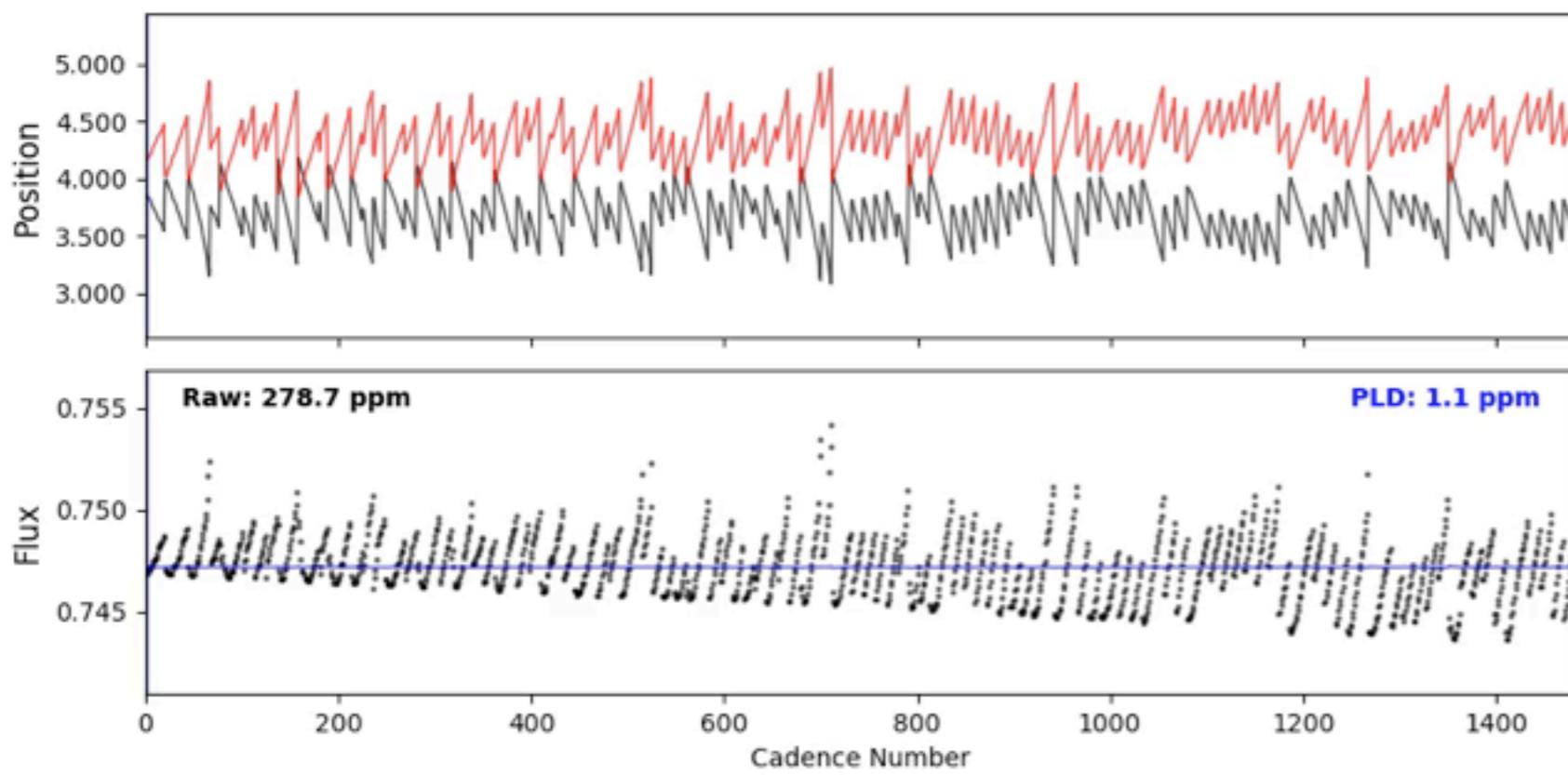
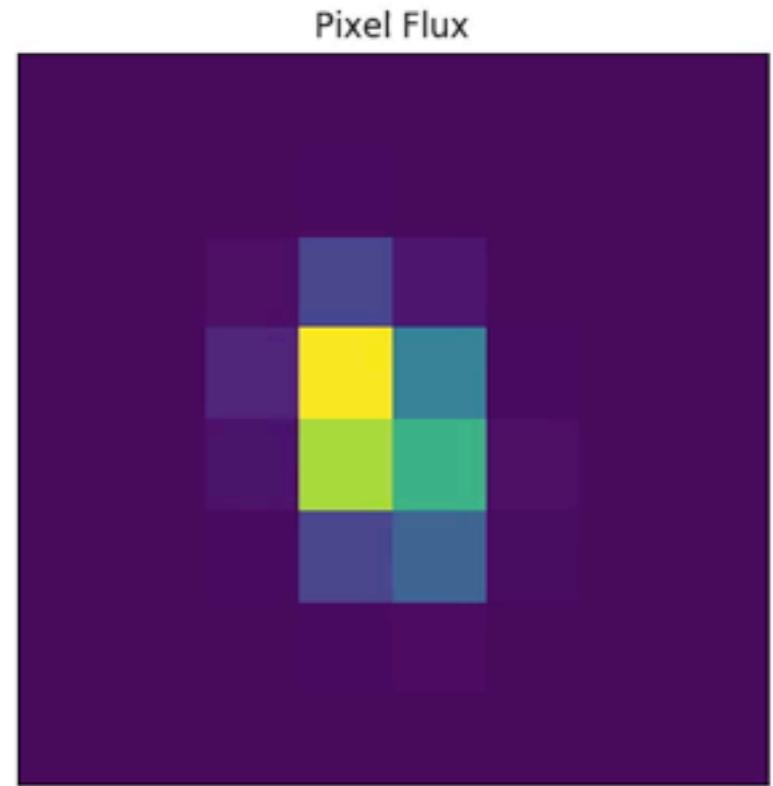
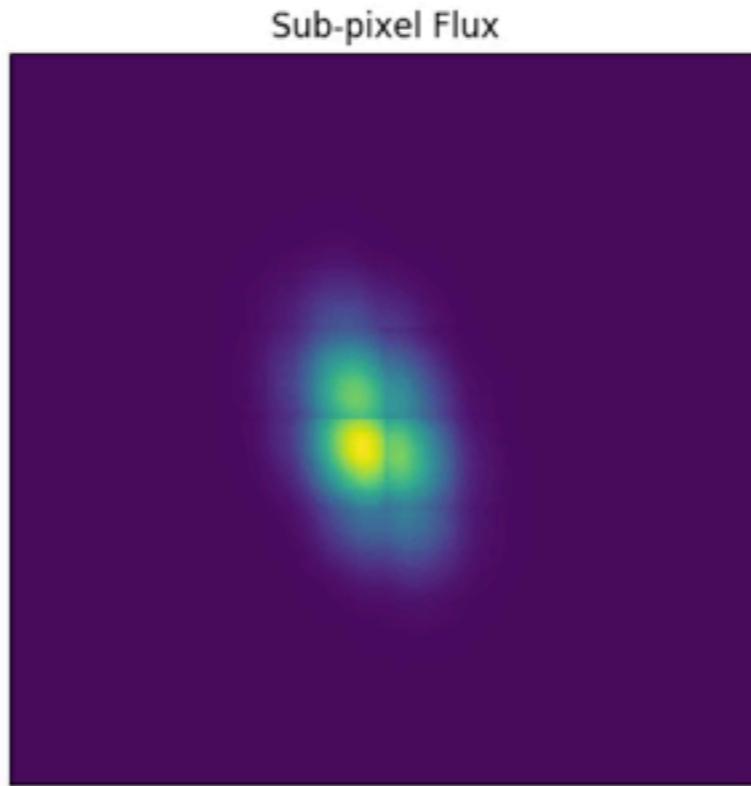
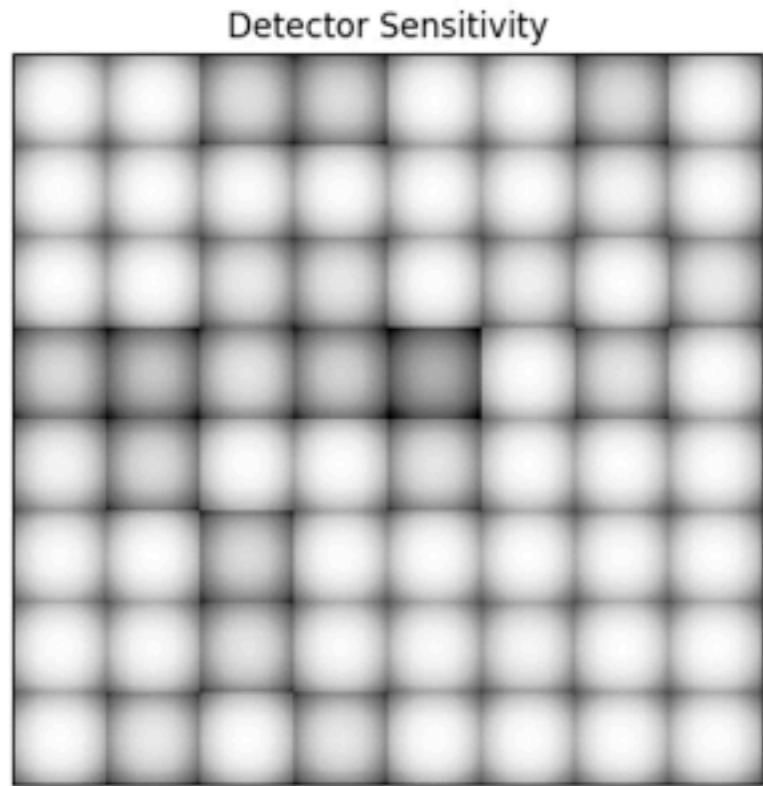
**Kepler 20**



**EPIC 205071984**



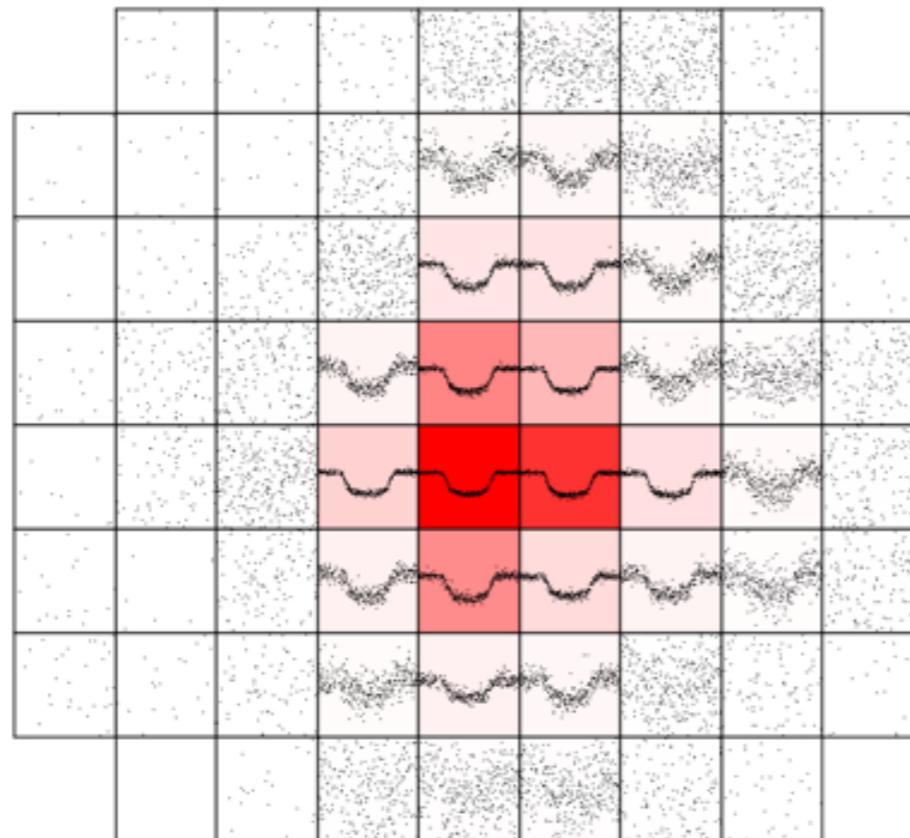
K2-32: Sinukoff et al. (2015)



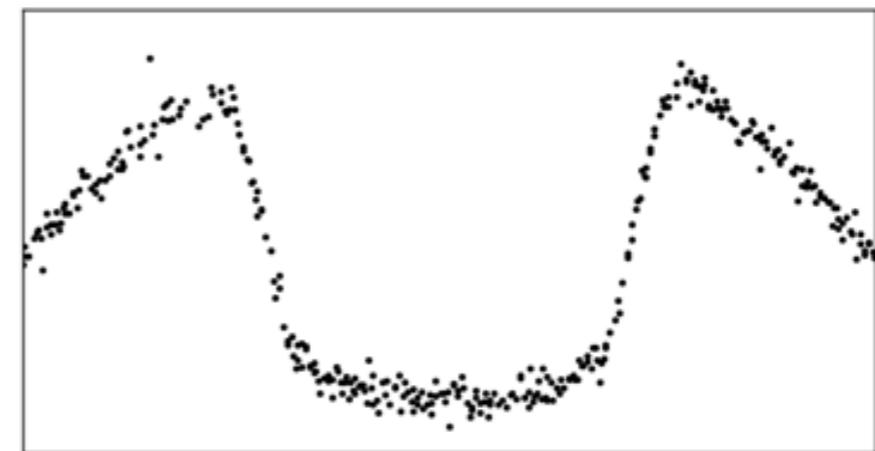
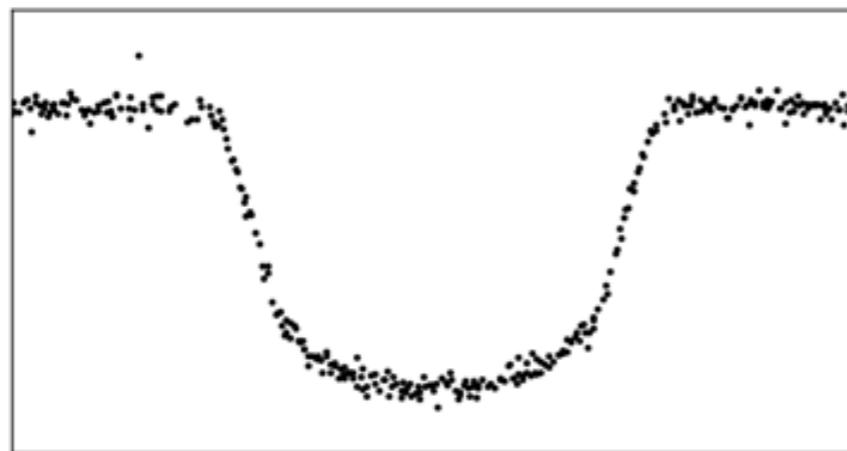
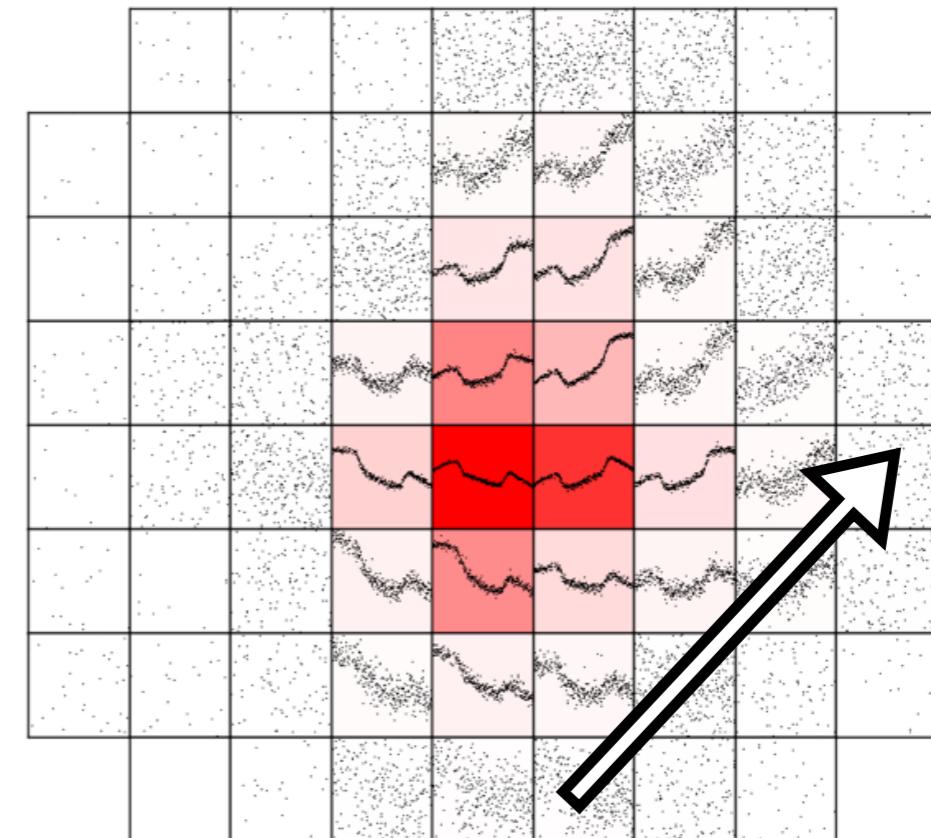


A typical postage stamp

*Ideal*

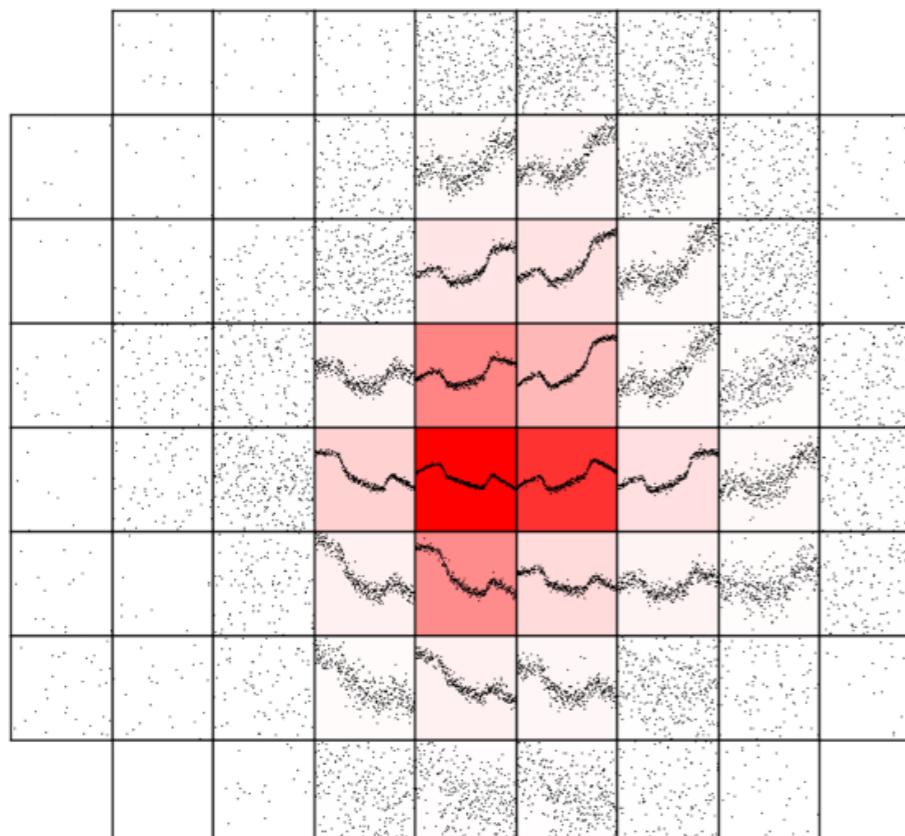


*Observed*

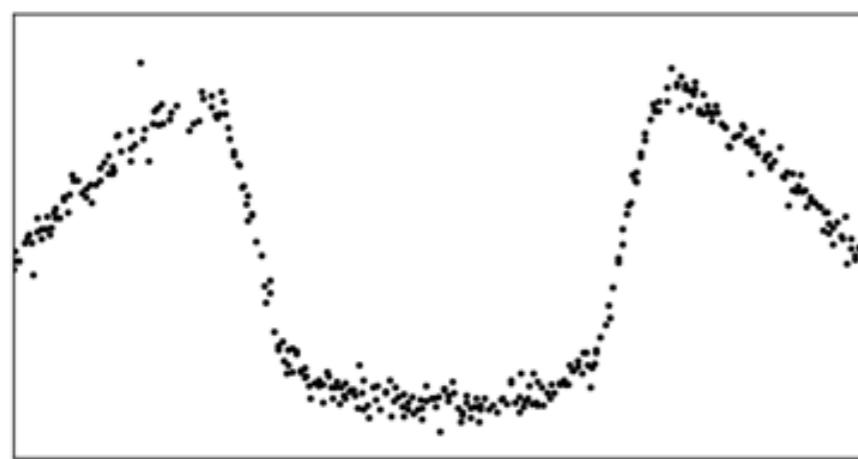
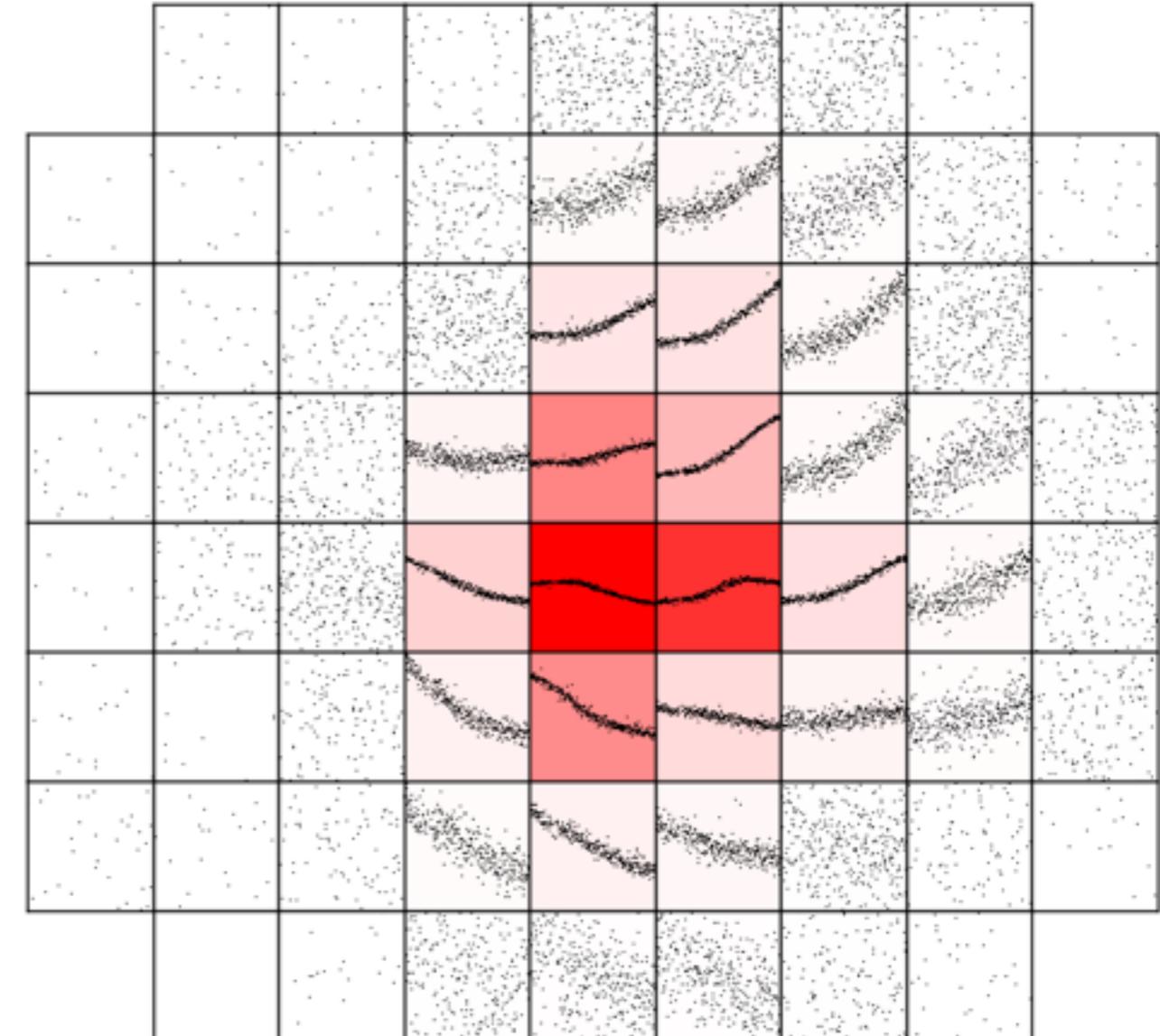




## Pixel Level Decorrelation



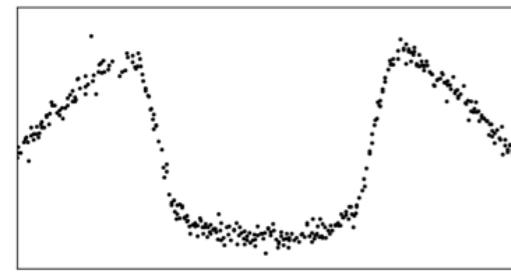
=



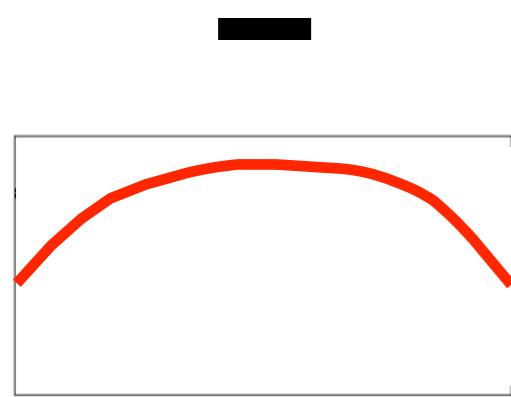
Deming et al. (2015)



## Pixel Level Decorrelation



*observed*



*instrumental*

$$= \Sigma$$

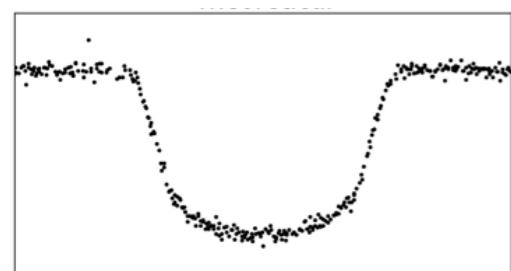
$$a_0 x \\ a_1 x \\ a_2 x$$

+

$$b_0 x \\ b_1 x \\ b_2 x$$

+

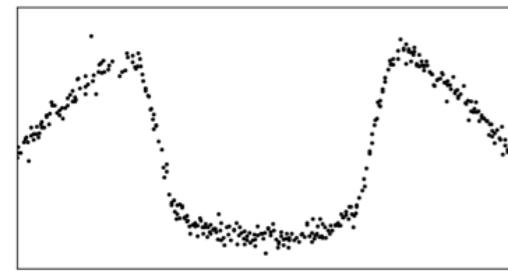
...



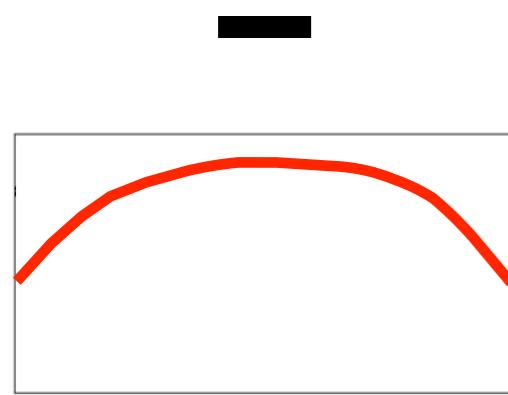
*de-trended*



## Pixel Level Decorrelation

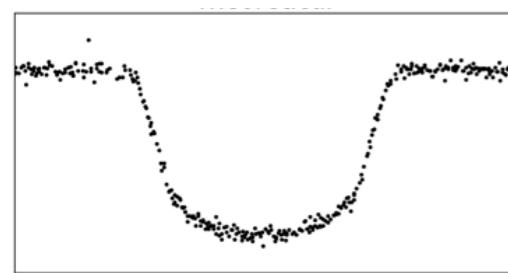


*observed*



*instrumental*

$$= \Sigma$$



*de-trended*

1st order PLD

2nd order PLD

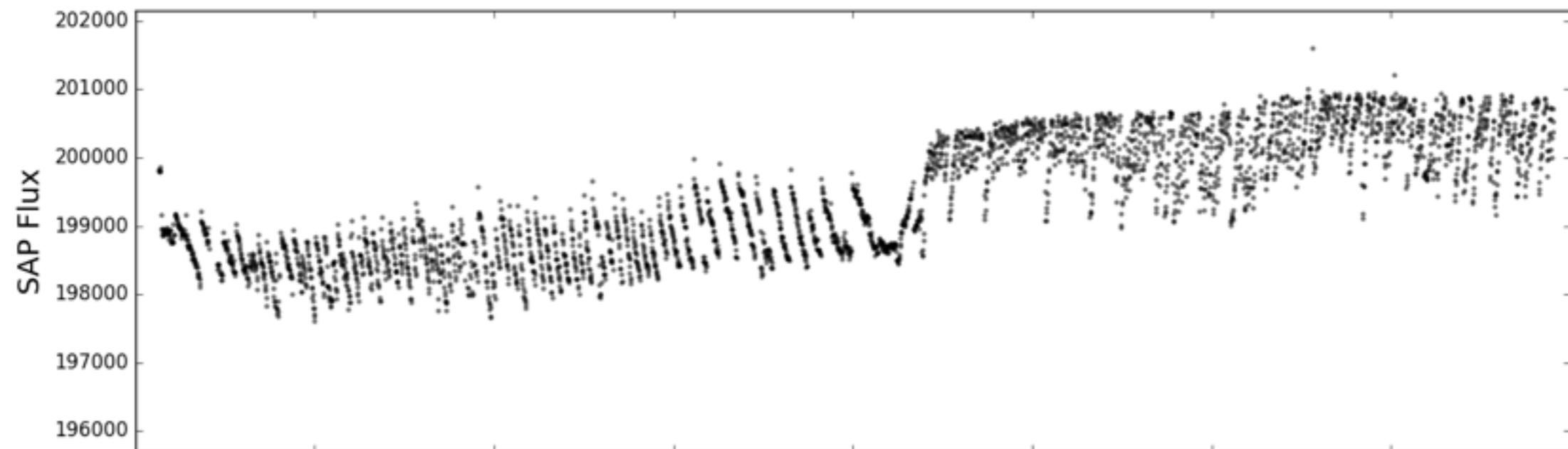
$$a_0 \times \begin{matrix} \textcolor{red}{\square} \\ \textcolor{red}{\square} \end{matrix} + a_1 \times \begin{matrix} \textcolor{pink}{\square} \\ \textcolor{pink}{\square} \end{matrix} + a_2 \times \begin{matrix} \textcolor{pink}{\square} \\ \vdots \\ \vdots \end{matrix} + b_0 \times \begin{matrix} \textcolor{red}{\square} \\ \textcolor{pink}{\square} \end{matrix} + b_1 \times \begin{matrix} \textcolor{red}{\square} \\ \textcolor{pink}{\square} \end{matrix} + b_2 \times \begin{matrix} \textcolor{red}{\square} \\ \vdots \\ \vdots \end{matrix} + \dots$$

The diagram illustrates the decomposition of the observed signal into a sum of basis functions. It shows a series of terms  $a_i \times$  followed by two square matrices. The first matrix has red squares at the top-left and bottom-right corners, and pink squares at the other four corners. The second matrix has pink squares at the top-left and bottom-right corners, and red squares at the other four corners. This pattern repeats for higher-order terms  $b_i$ . Ellipses indicate that the sequence continues.



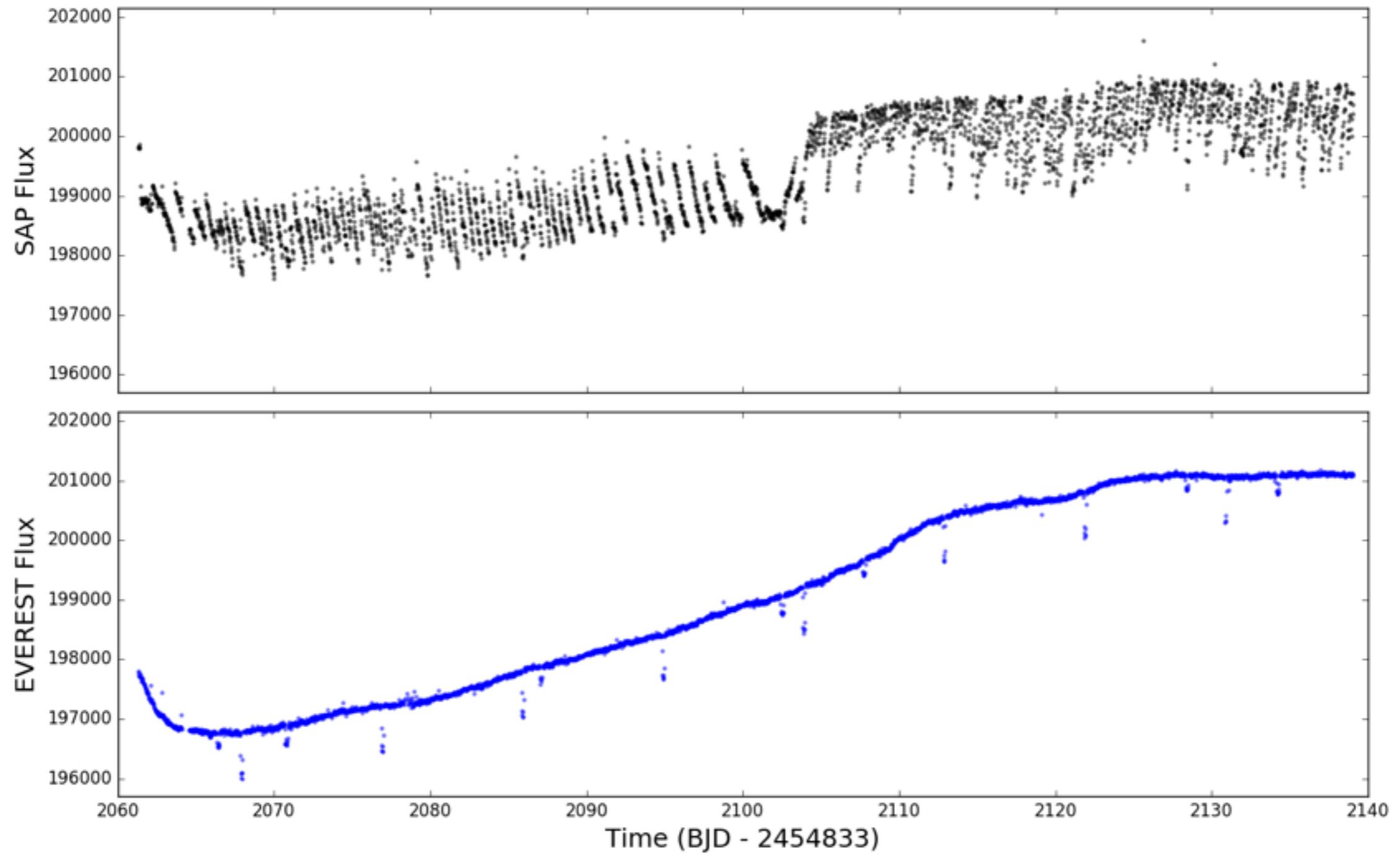
A typical K2 light curve

EPIC 205071984



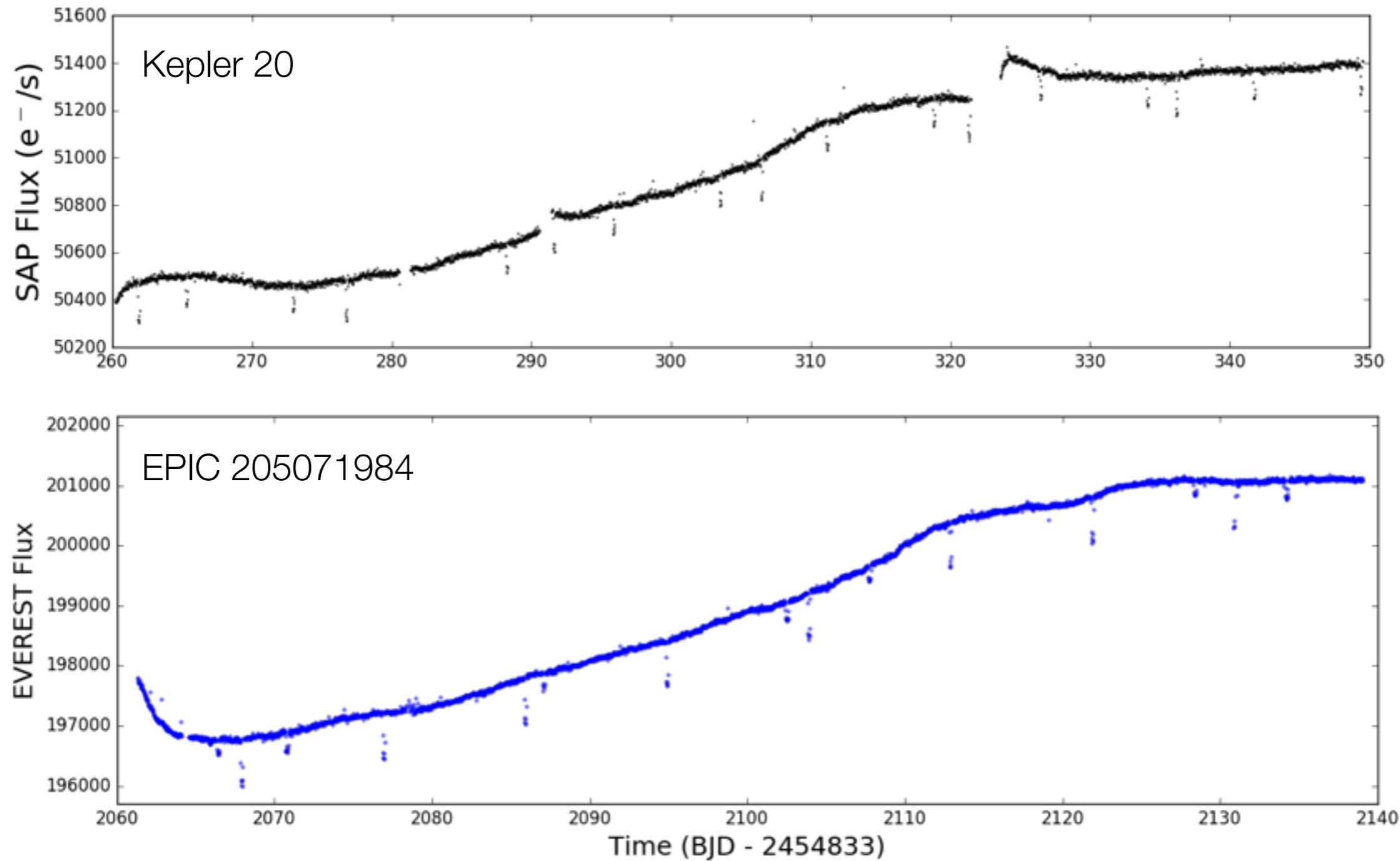


EPIC 205071984

*K2-32: Sinukoff et al. (2015)**Luger et al. (2016, 2017a)*



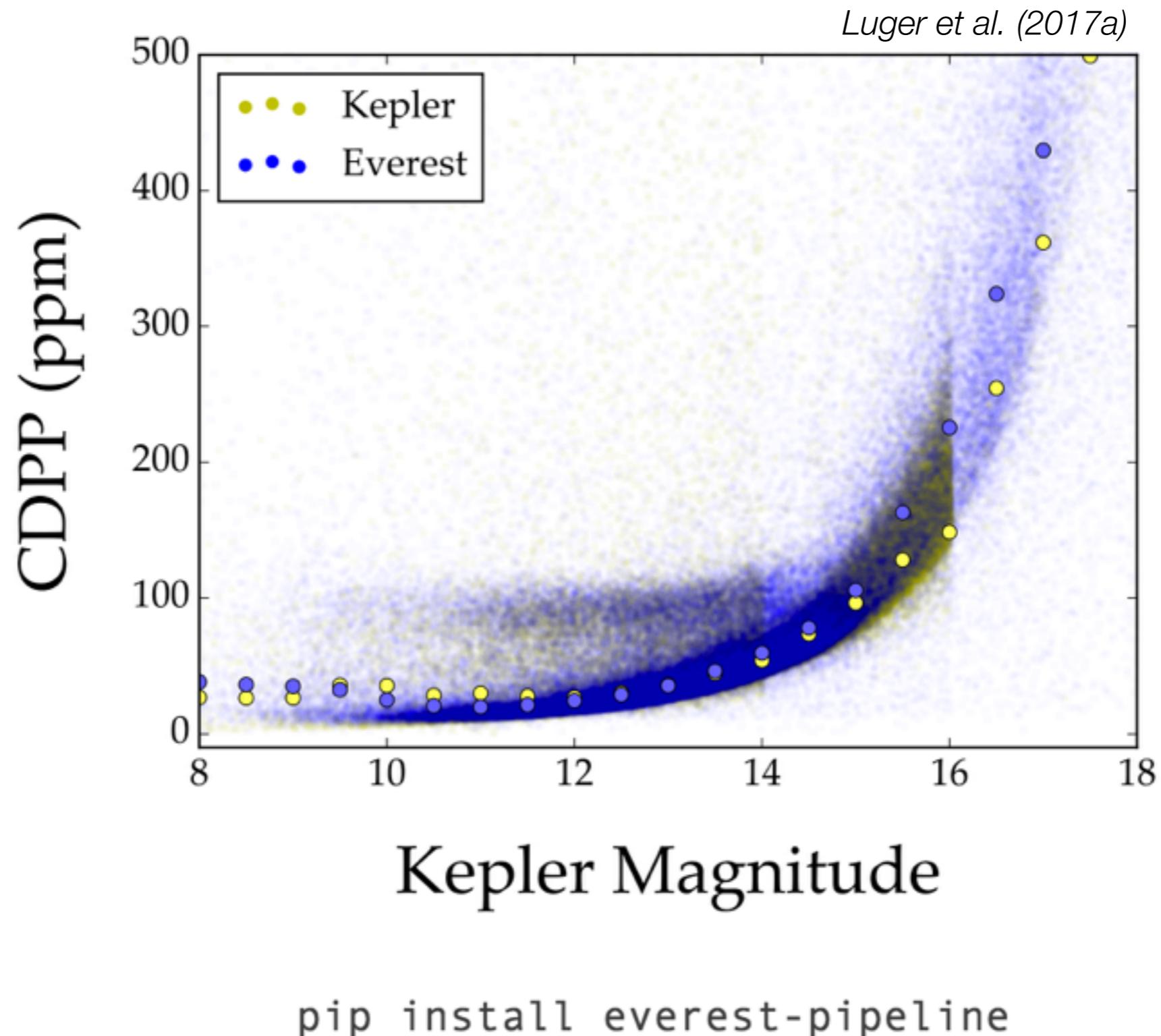
# Kepler precision for bright stars



Luger et al. (2016, 2017a)



## Kepler precision for bright stars



## PART d



*SCIENCE WITH K2*

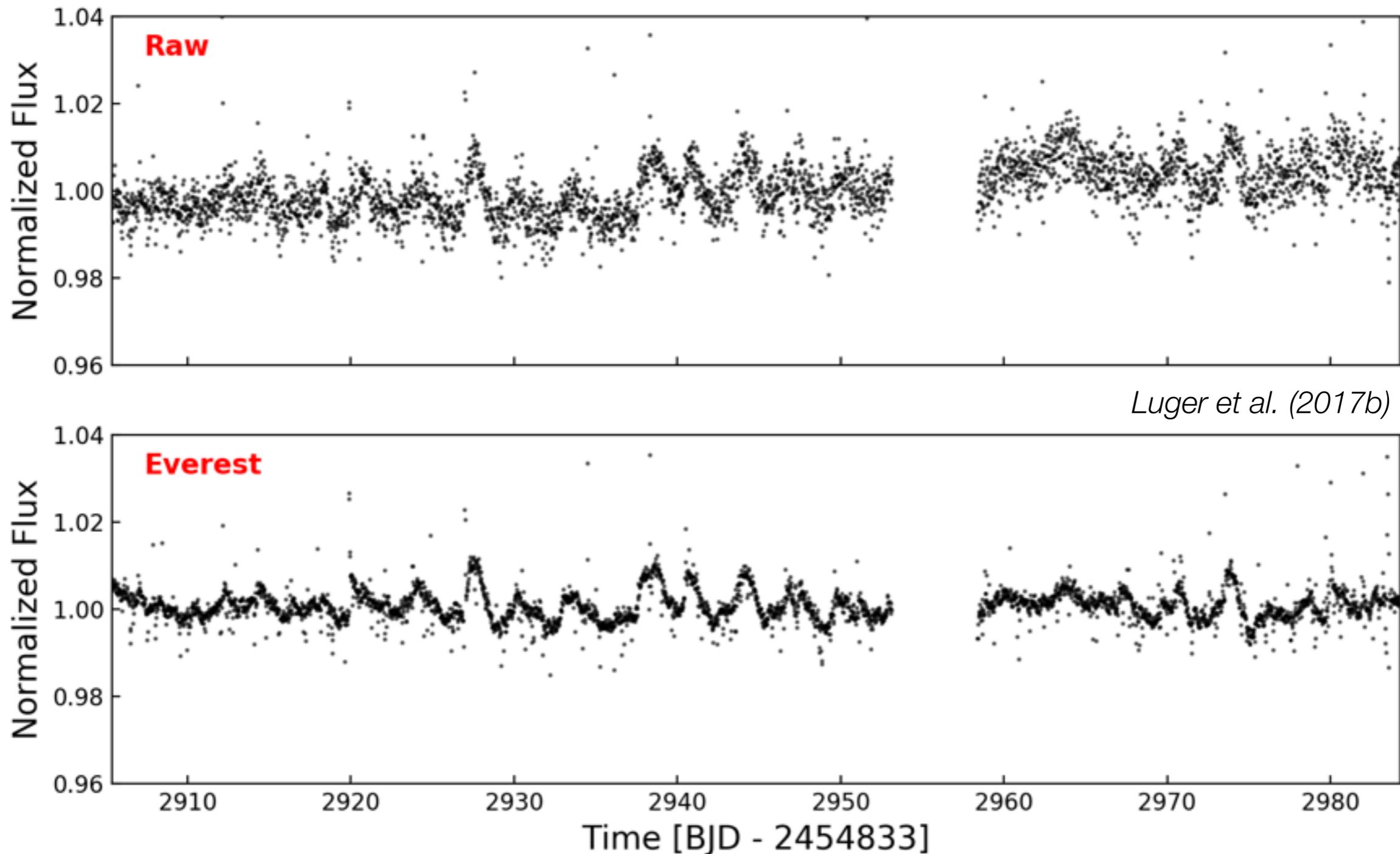


# TRAPPIST-1 + EVEREST

K2 C12: nPLDTrappist  
*manual, 12 neighbors*

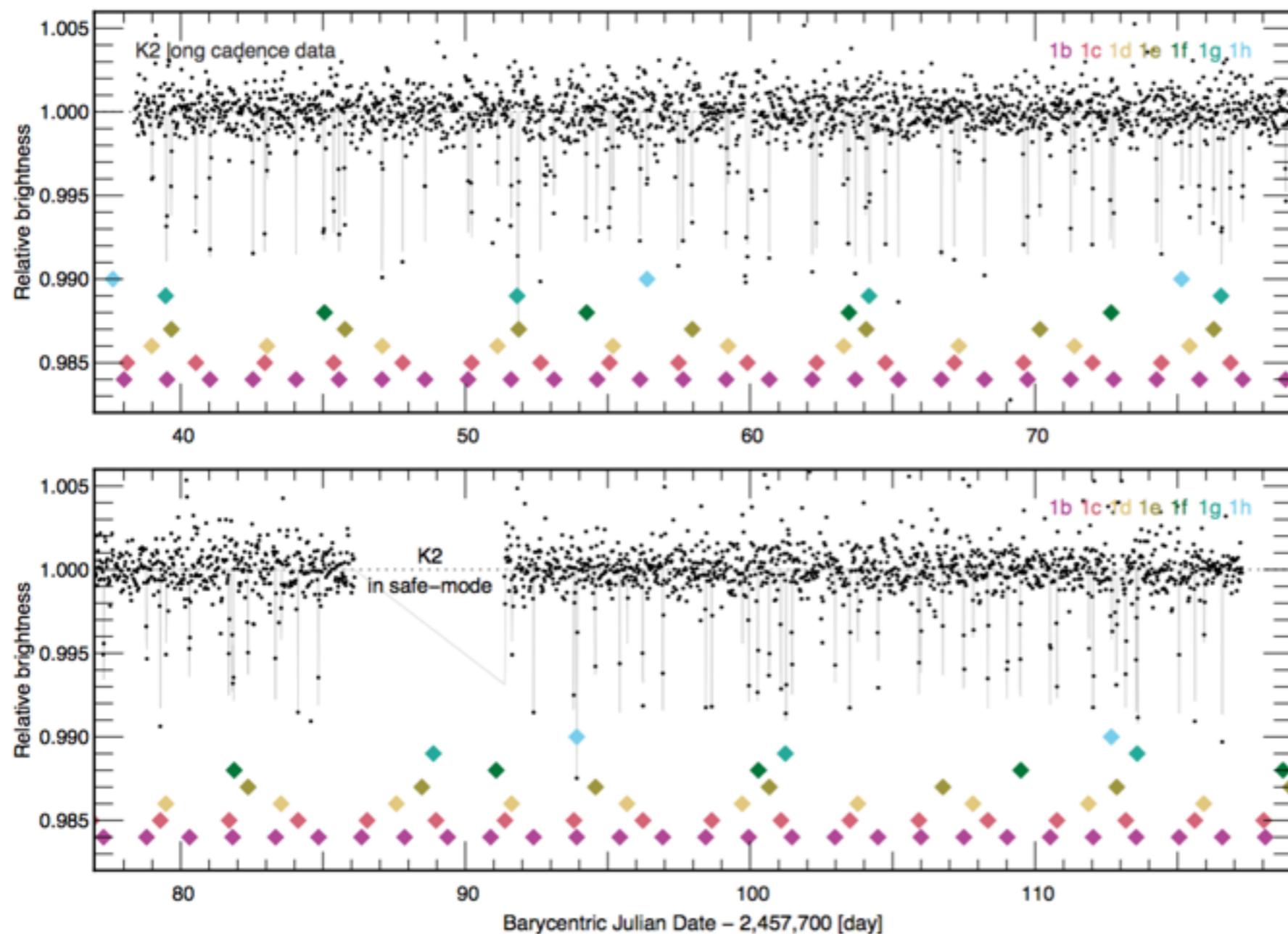
**EPIC 200164267**  
884.38 ppm  $\rightarrow$  281.30 ppm

$K_p$  17.000  
GP 279.879 ppm





# TRAPPIST-1 + EVEREST

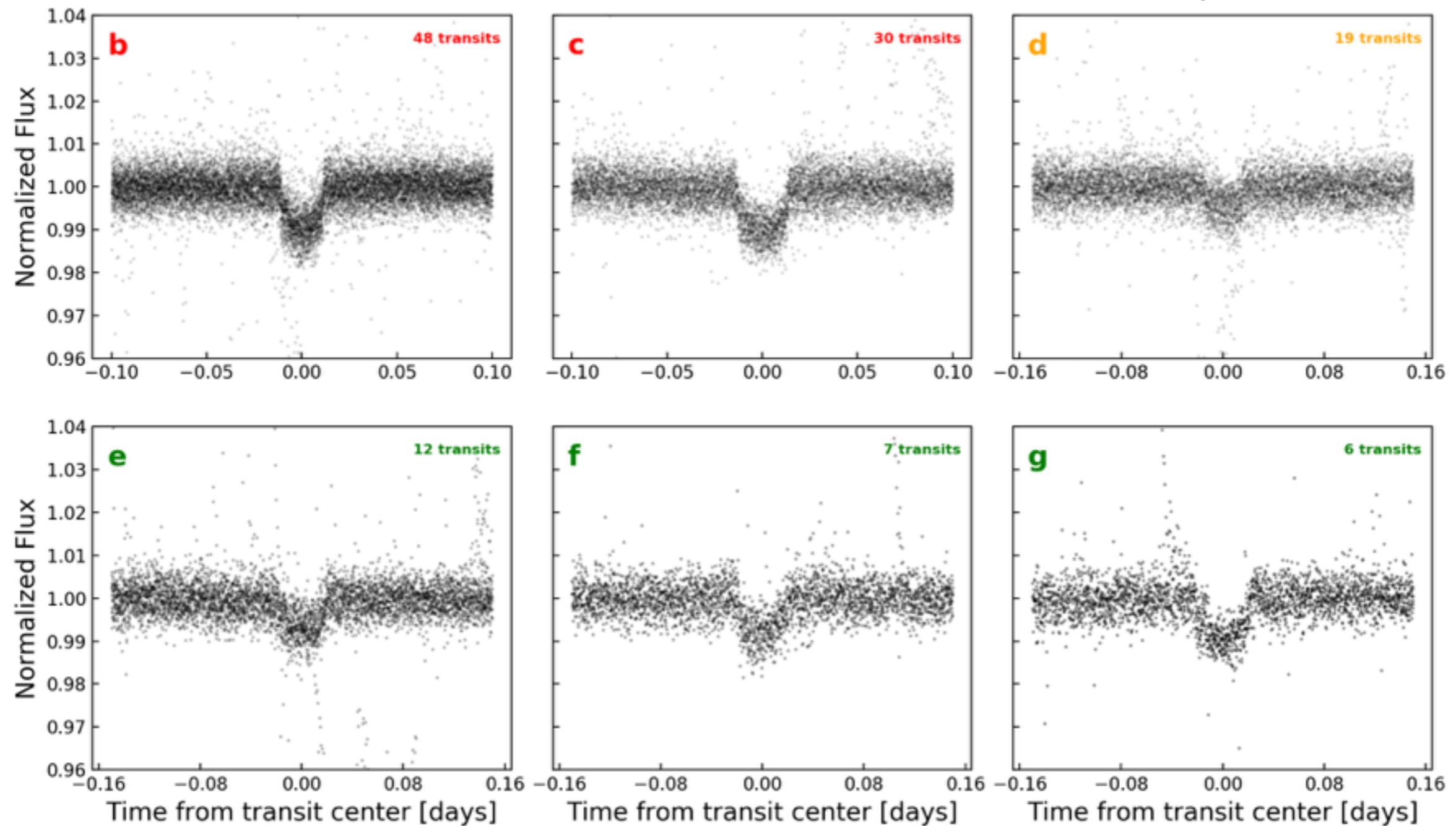


*Transits ~8% of the time!*

# TRAPPIST-1 + EVEREST



Luger et al. (2017b)





Where's h? \_\_\_\_\_





We knew where to look... 

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## Laplace resonances

$$\frac{2}{P_b} - \frac{(2+3)}{P_c} = -\frac{3}{P_d}$$

$$\frac{1}{P_c} - \frac{(1+2)}{P_d} = -\frac{2}{P_e}$$

$$\frac{2}{P_d} - \frac{(2+3)}{P_e} = -\frac{3}{P_f}$$

$$\frac{1}{P_e} - \frac{(1+2)}{P_f} = -\frac{2}{P_g}$$

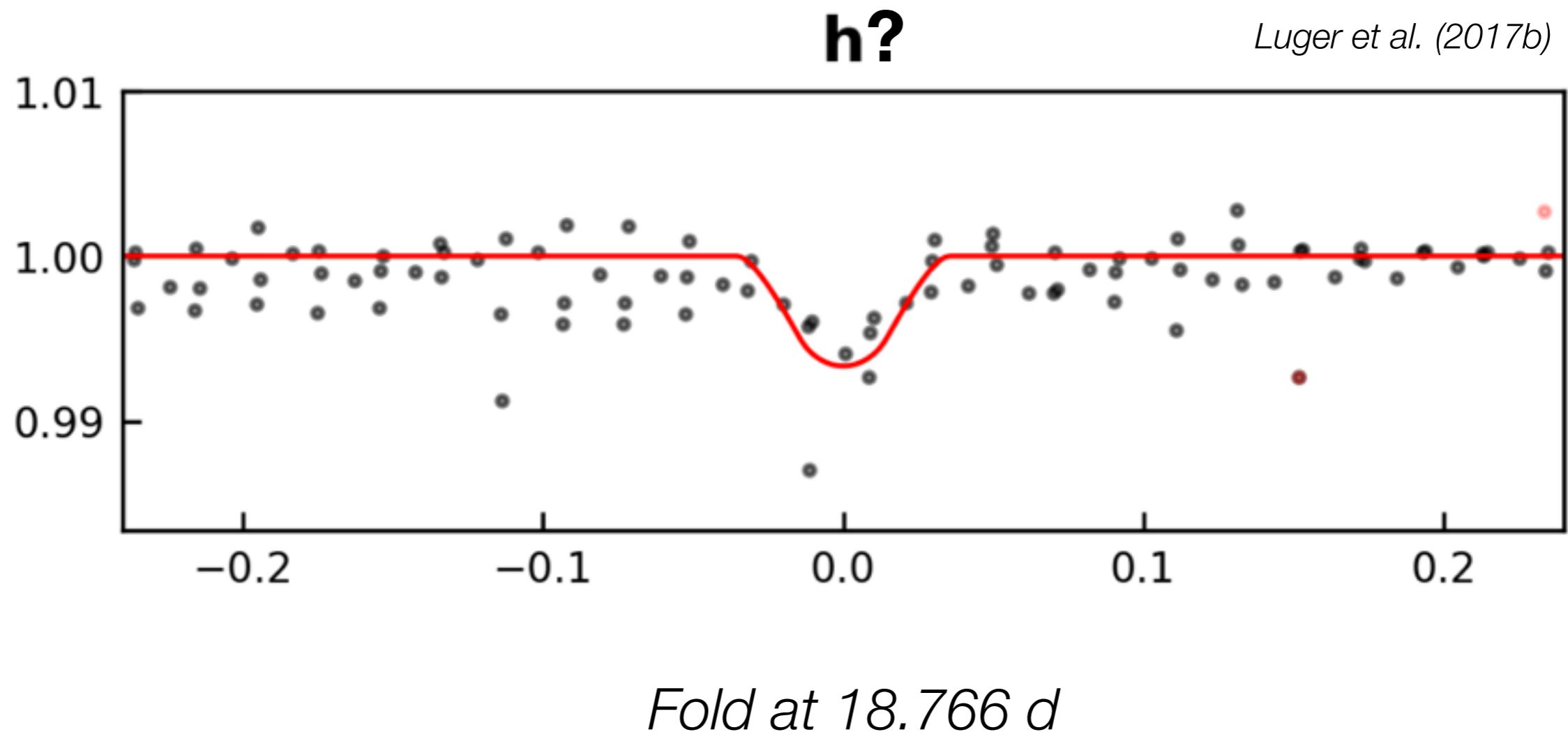
$$\frac{p}{P_f} - \frac{(p+q)}{P_g} = -\frac{q}{P_h}$$

<b><math>p</math></b>	<b><math>q</math></b>	<b><math>P_h</math> [d]</b>
1	1	18.766
1	2	14.899
2	1	39.026
2	3	15.998
1	3	13.941
3	2	25.345

*Luger et al. (2017b)*



## Search for TRAPPIST-1h





## We can do better: 1. Delta Chi Square

*Likelihood of data, no transit model*

$$\log \mathcal{L}_0 = -\frac{1}{2} \mathbf{y}^\top \boldsymbol{\Sigma}^{-1} \mathbf{y} + C$$

|  
raw data      \diagdown  
covariance

*Likelihood of data, transit model at  $t = t_0$*

$$\log \mathcal{L} = -\frac{1}{2} (\mathbf{y} - \mathbf{m}_{t_0})^\top \boldsymbol{\Sigma}^{-1} (\mathbf{y} - \mathbf{m}_{t_0}) + C$$

|  
transit model

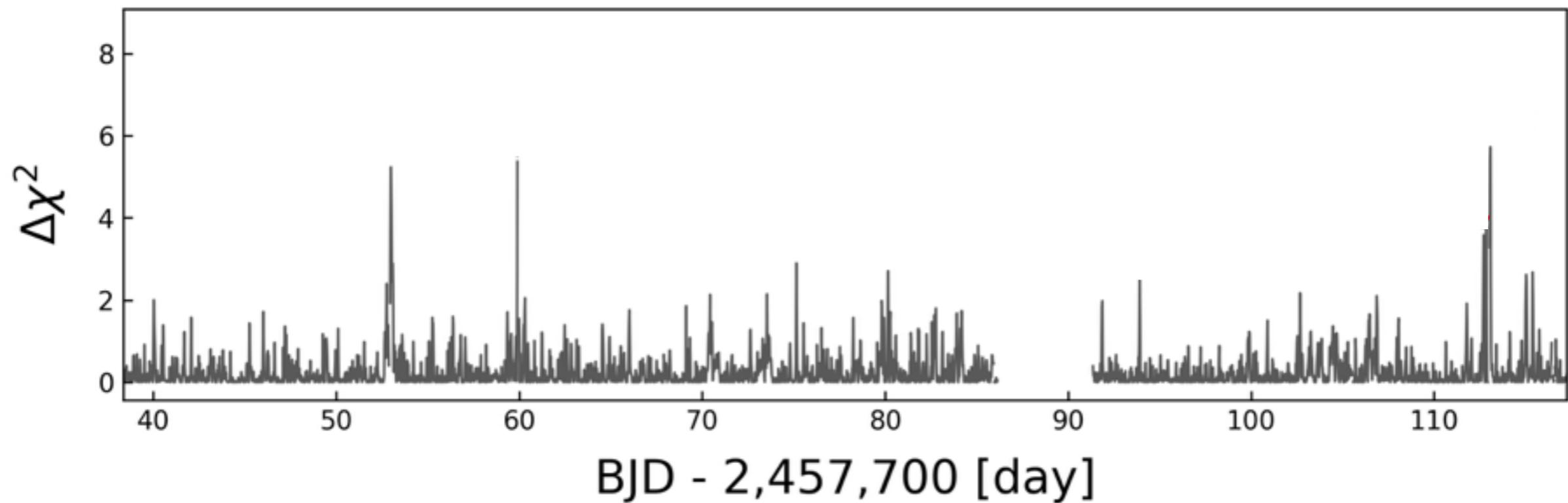
*Improvement in chi-squared metric*

$$\Delta\chi^2 = 2(\log \mathcal{L} - \log \mathcal{L}_0)$$



## We can do better: 1. Delta Chi Square

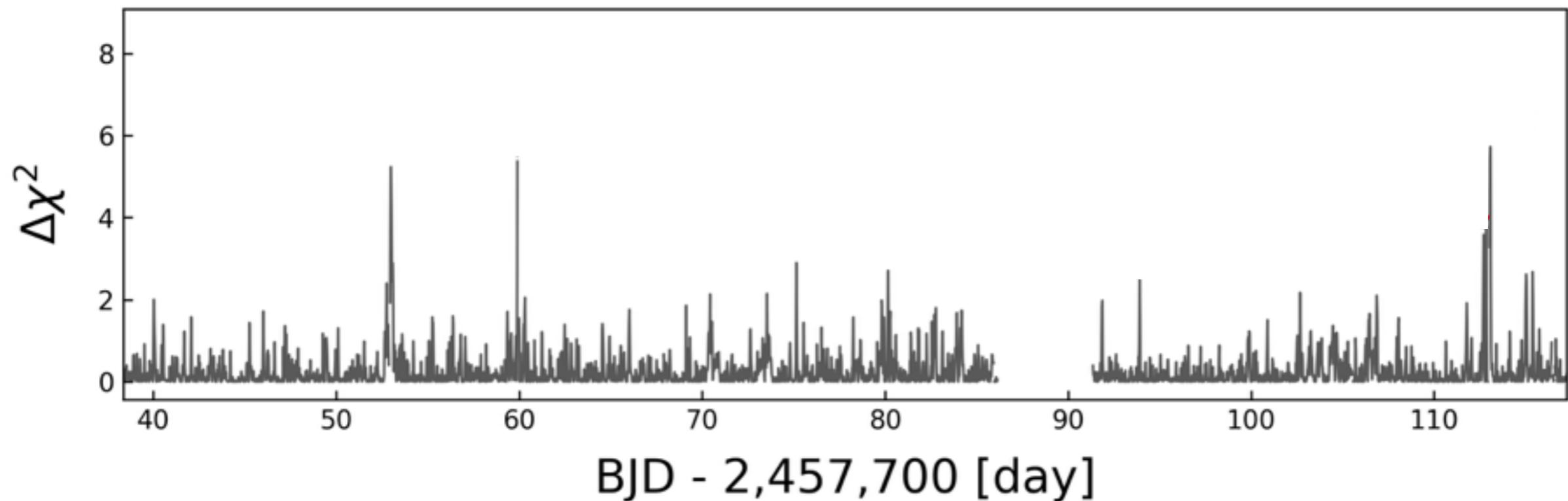
Luger et al. (2017b)





## We can do better: 1. Delta Chi Square

*Luger et al. (2017b)*

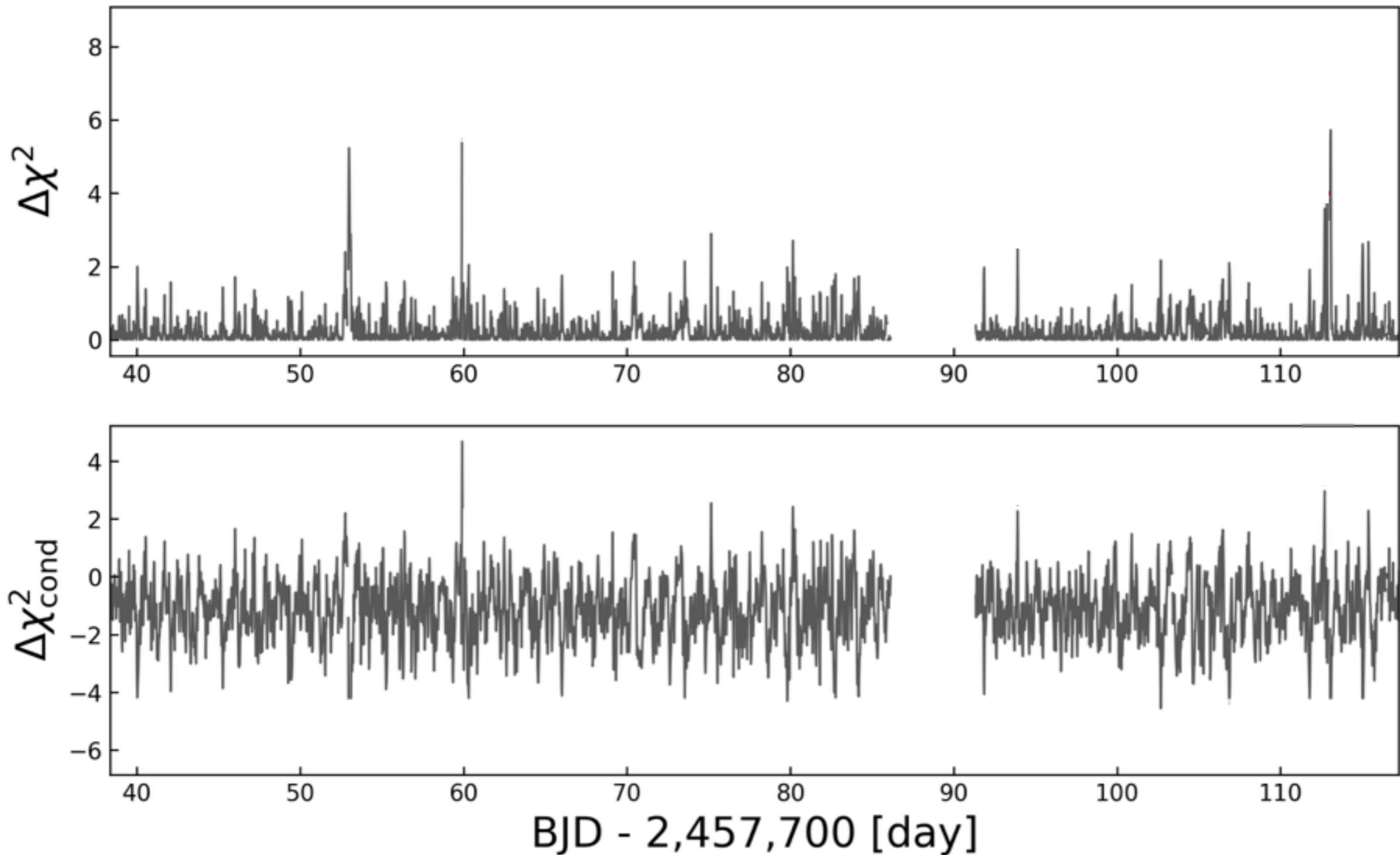


*Meh.*



## We can do better: 2. Condition on depth

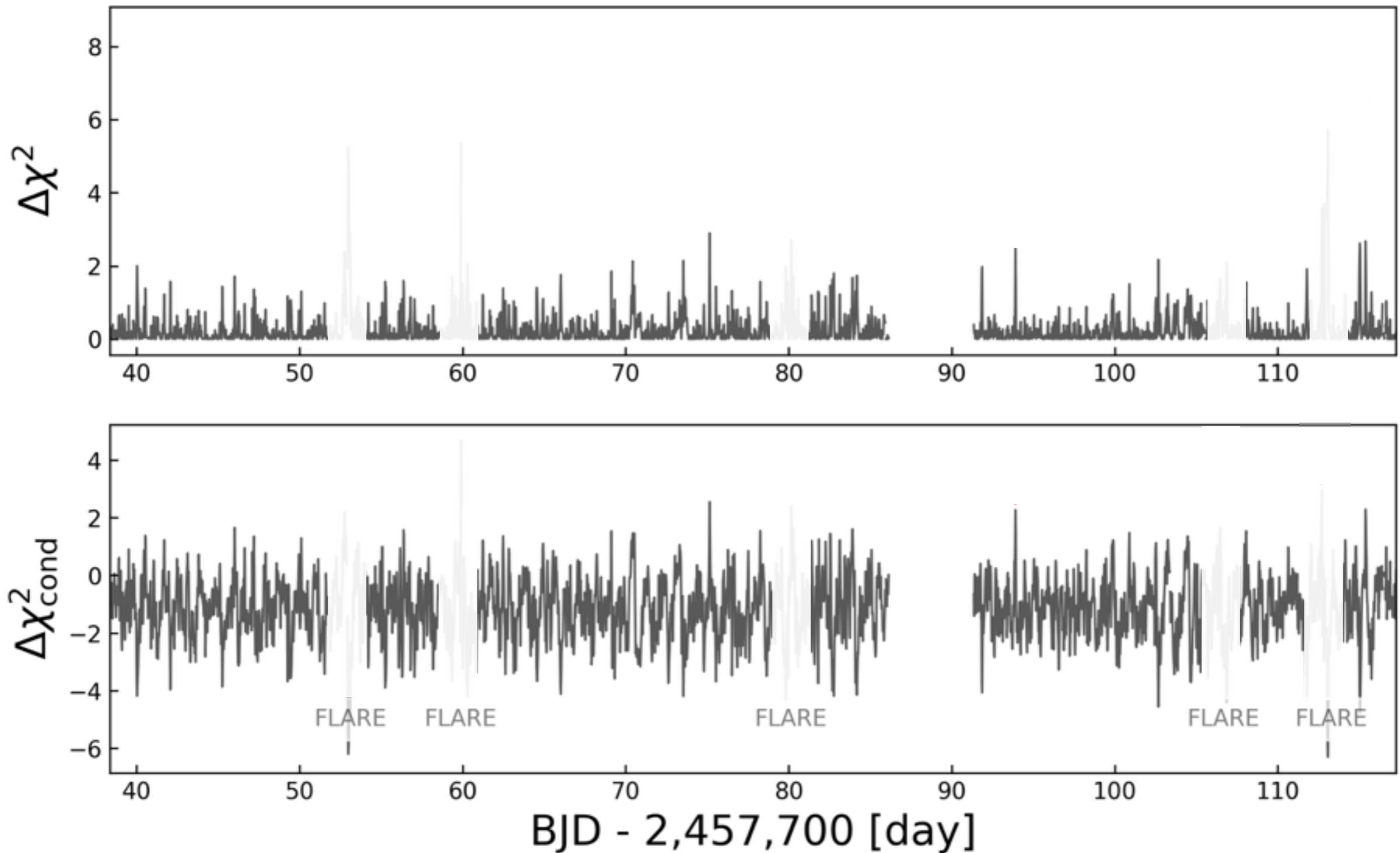
Luger et al. (2017b)





## We can do better: 2. Condition on depth

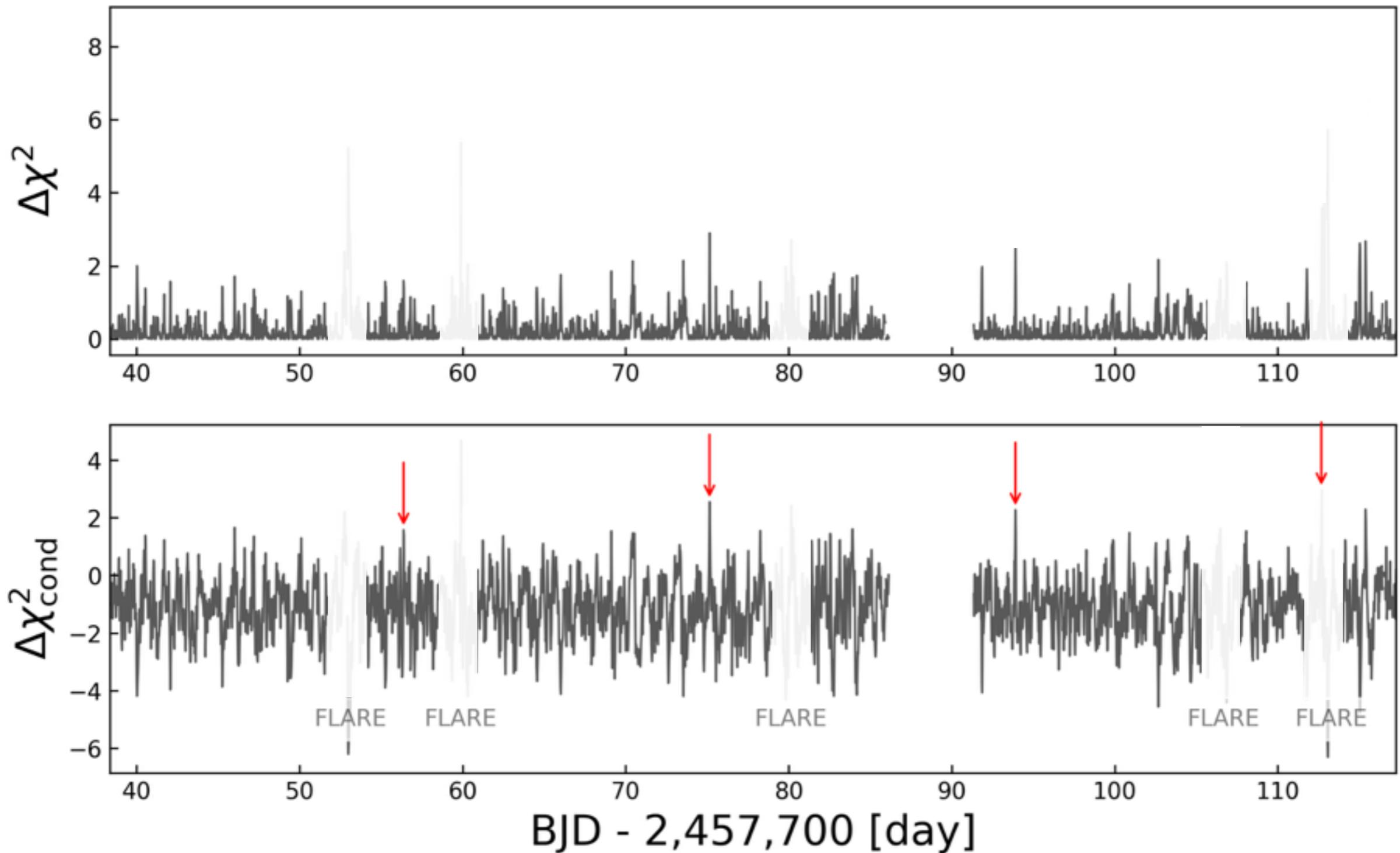
Luger et al. (2017b)





## We can do better: 2. Condition on depth

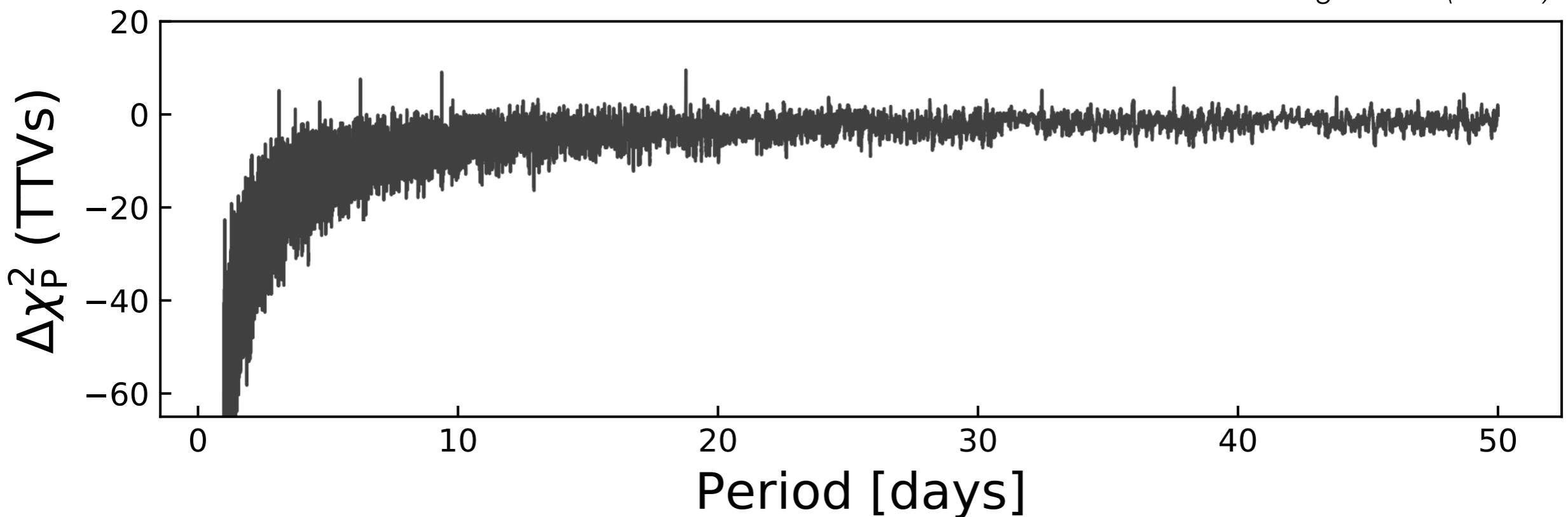
Luger et al. (2017b)





We can do better: 3. Condition on to

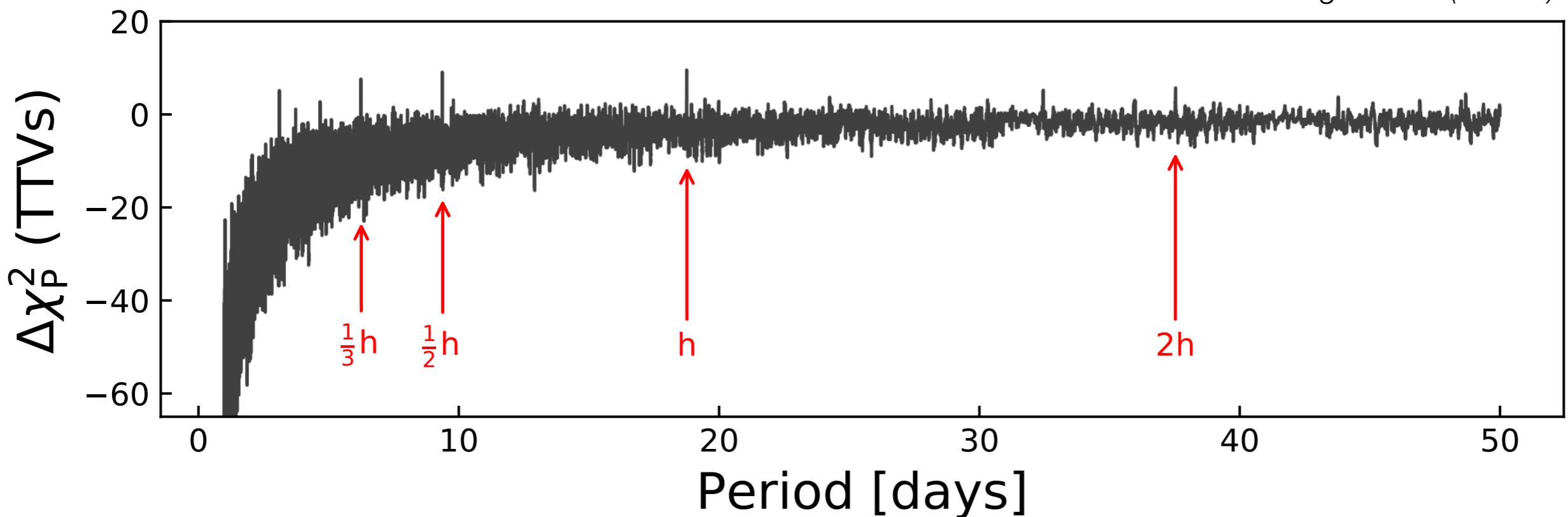
Luger et al. (2017b)





We can do better: 3. Condition on to

Luger et al. (2017b)

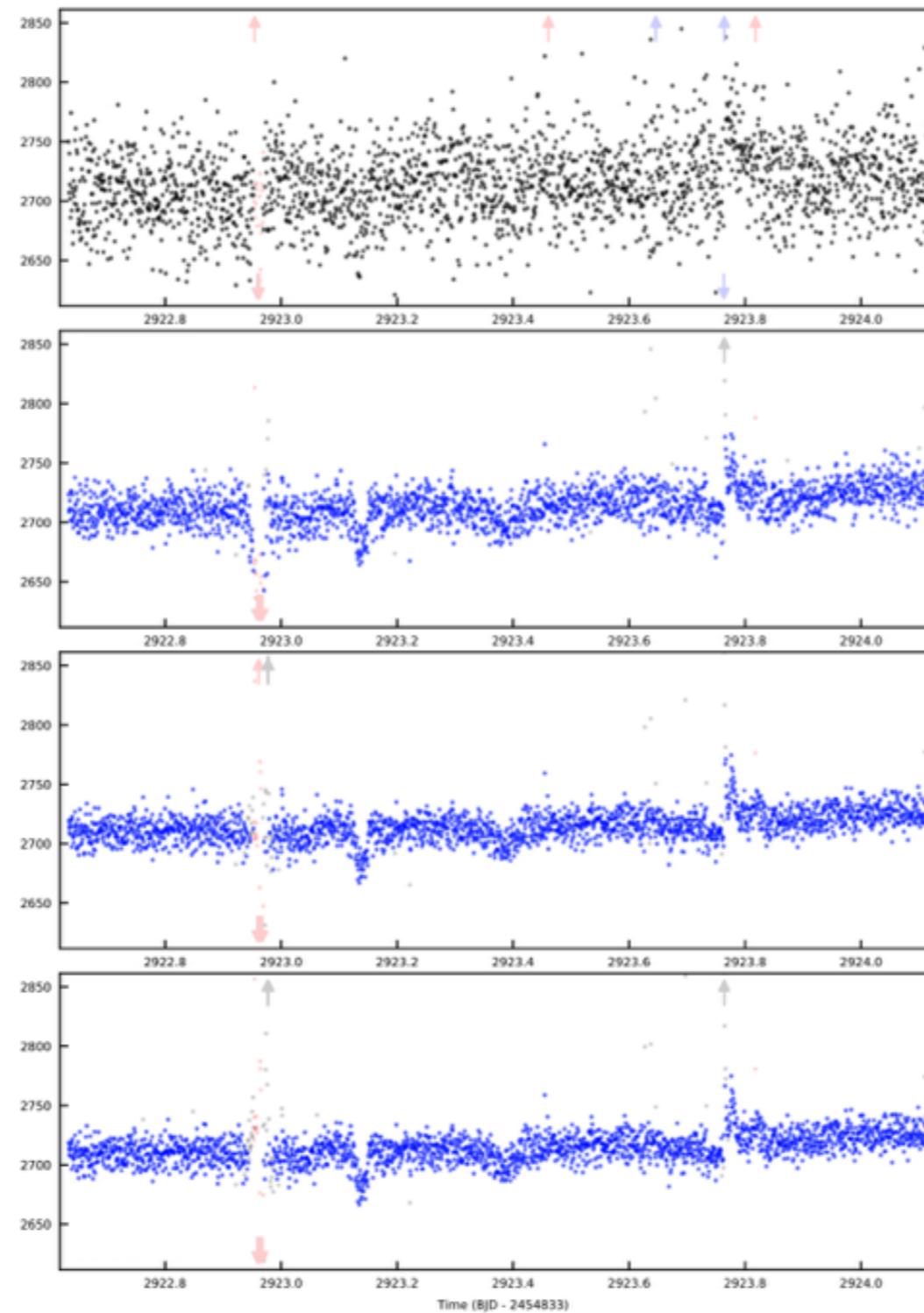




## We can do better: 4. Go to short cadence

Raw

*Luger et al. (2017b)*



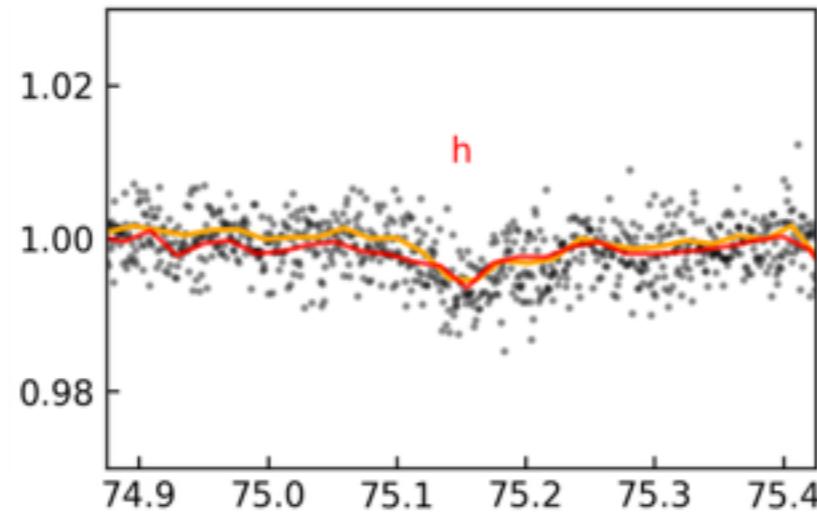
2nd order

3rd order

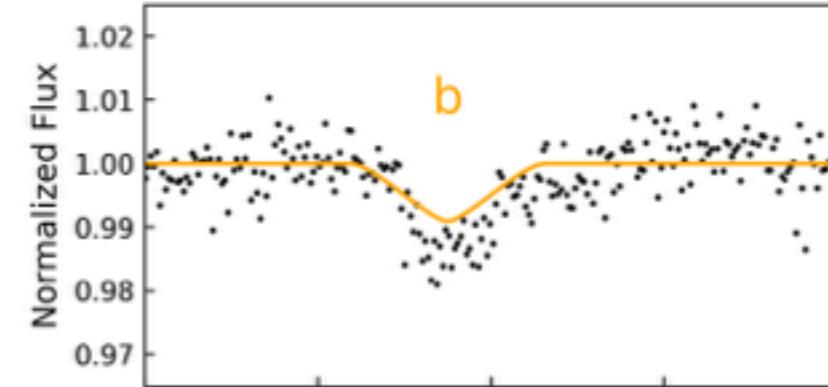


We were somewhat unlucky...

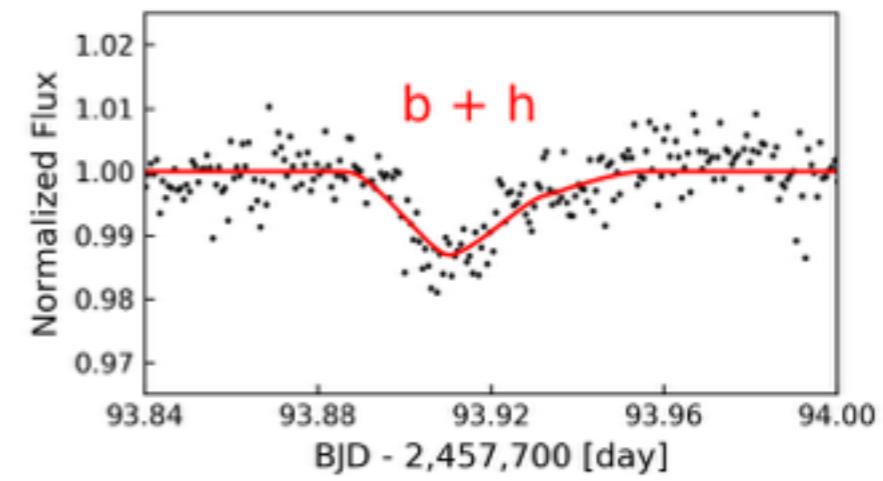
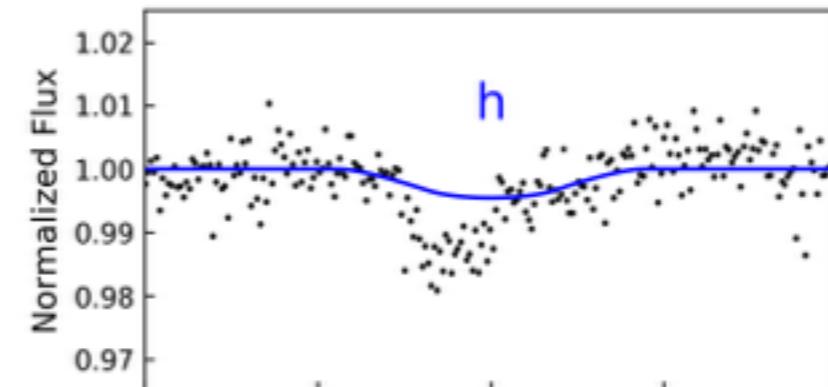
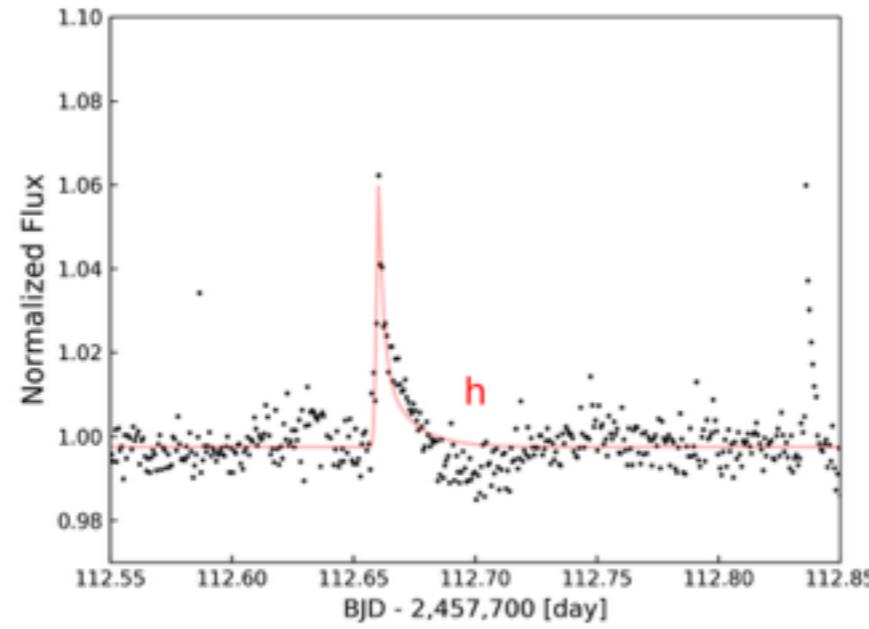
Transit #2



Transit #3



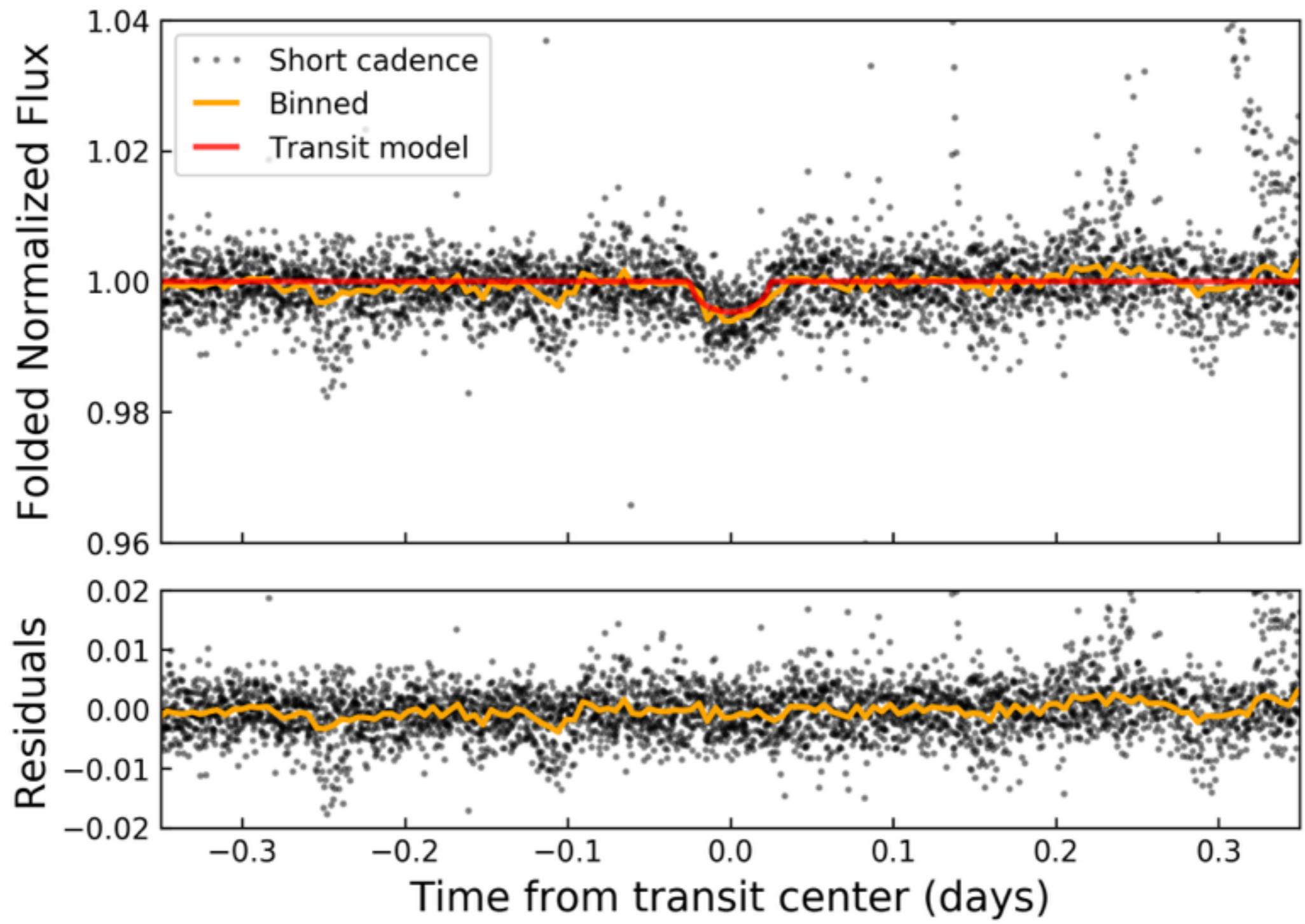
Transit #4



Luger et al. (2017b)



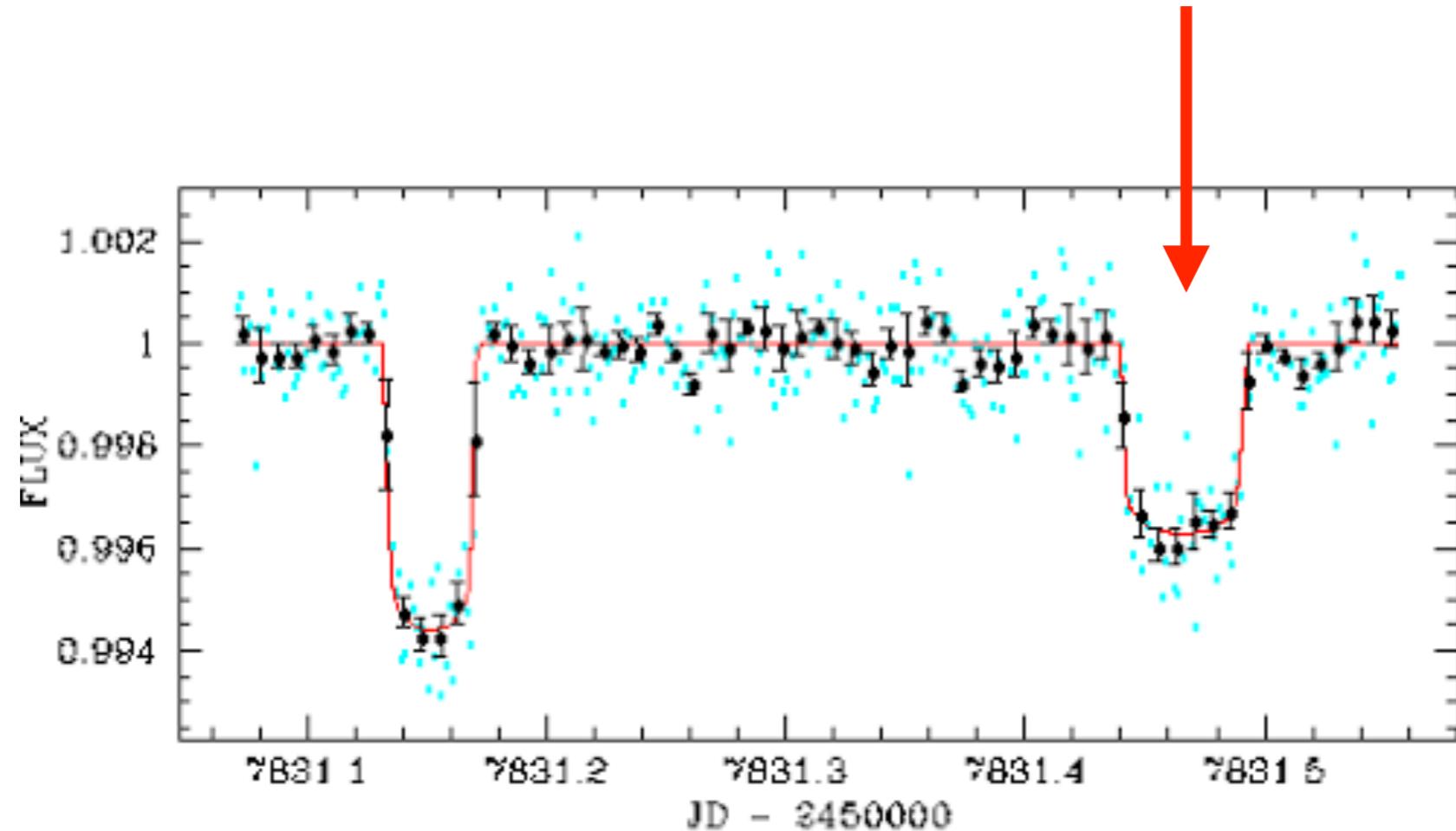
# Introducing TRAPPIST-1h



Luger et al. (2017b)



Phew...!



Michaël Gillon

## PART e

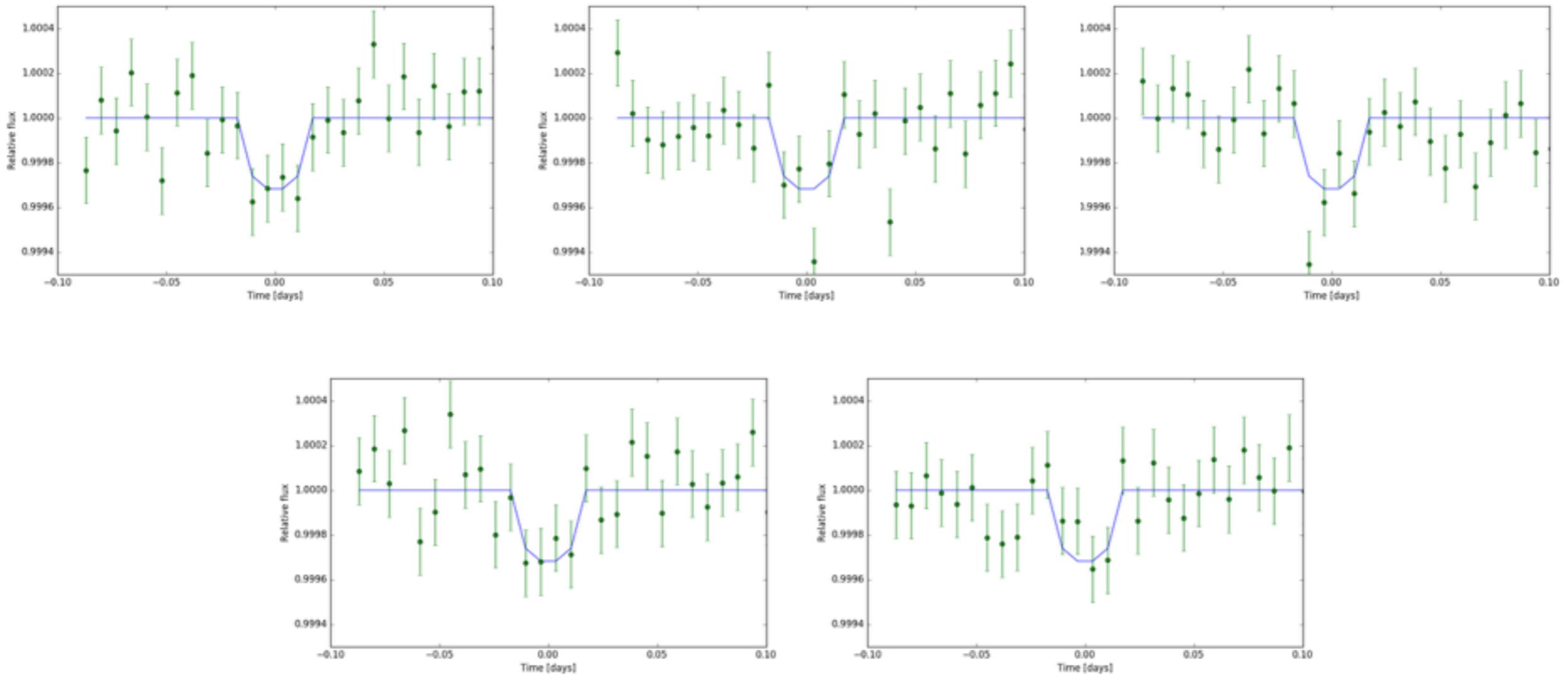


*JWST*



Secondary eclipse: **b**

*MIRI 15 $\mu$ m @ 10 min cadence  
400 K blackbody*

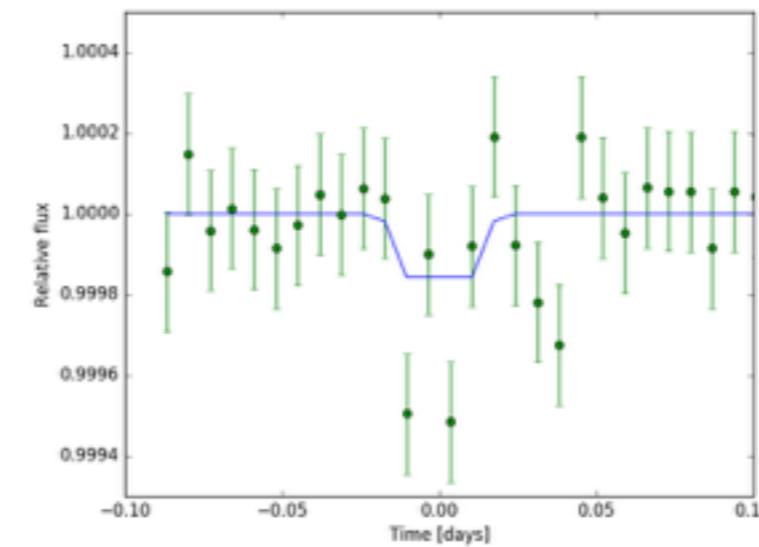
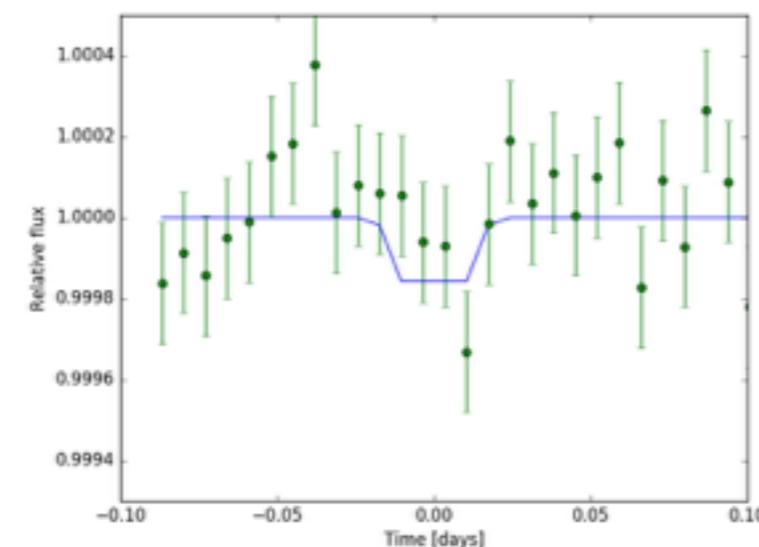
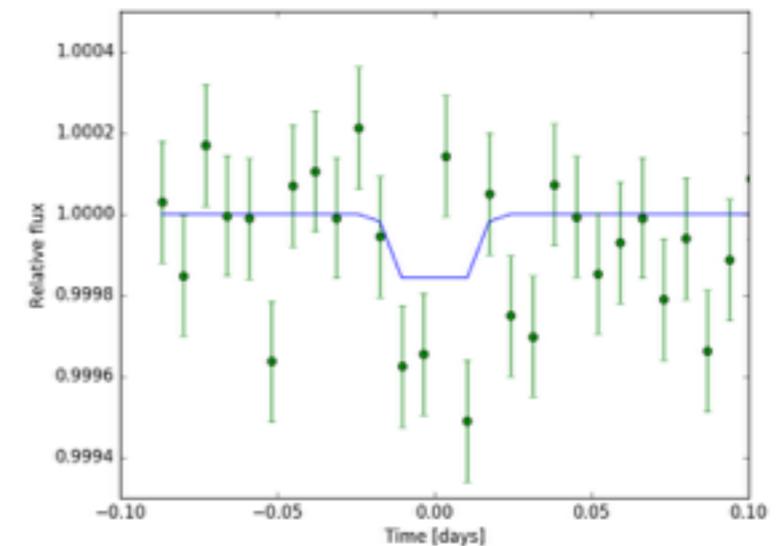
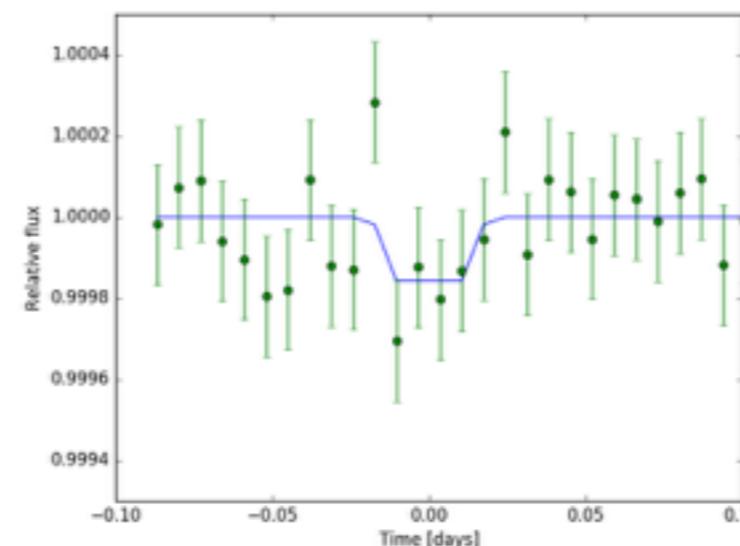
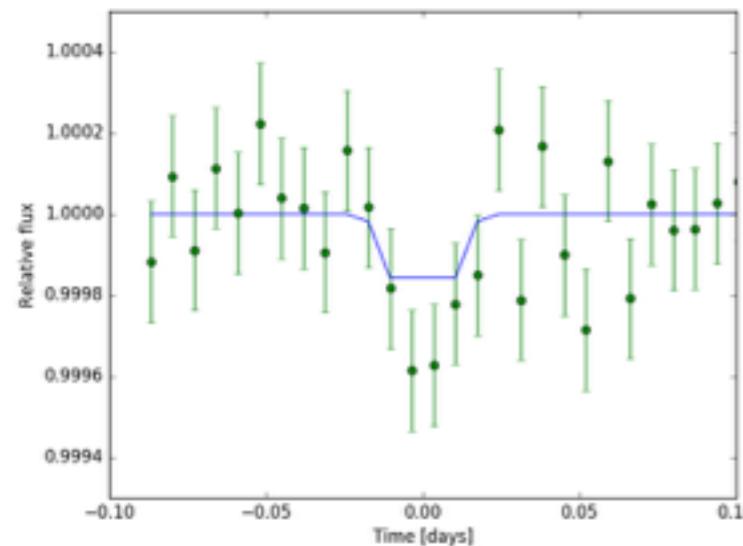


*Luger, Lustig-Yaeger, and Agol (2017, in prep)*



Secondary eclipse: **C**

*MIRI 15 $\mu$ m @ 10 min cadence  
320 K blackbody*



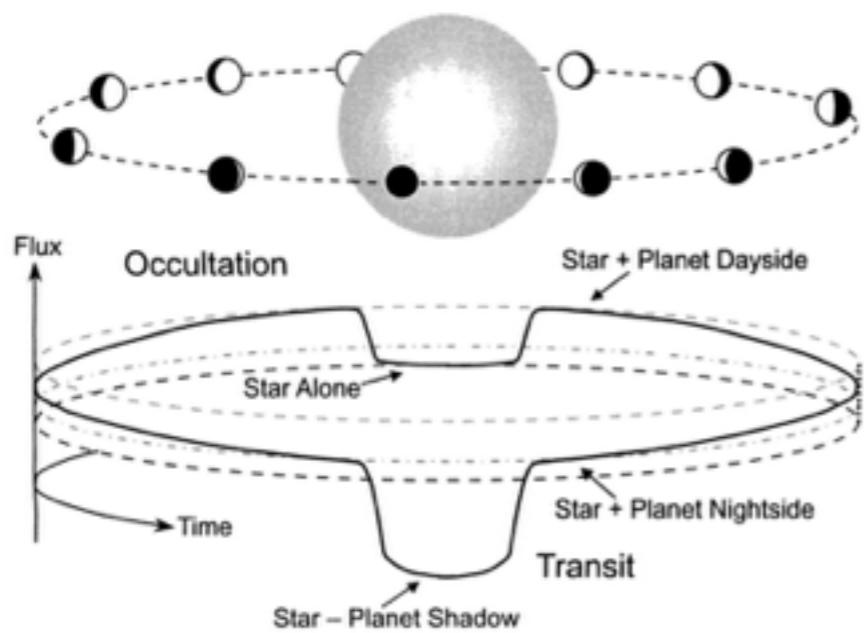
*Luger, Lustig-Yaeger, and Agol (2017, in prep)*



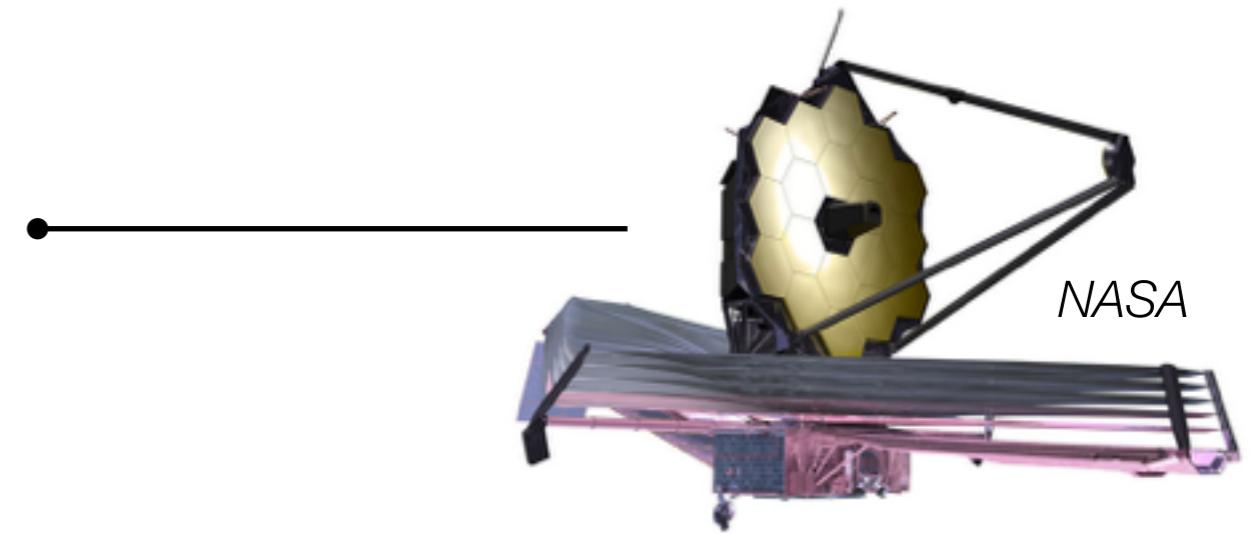
## Secondary eclipses

*Should be detectable with JWST*

*Josh Winn*

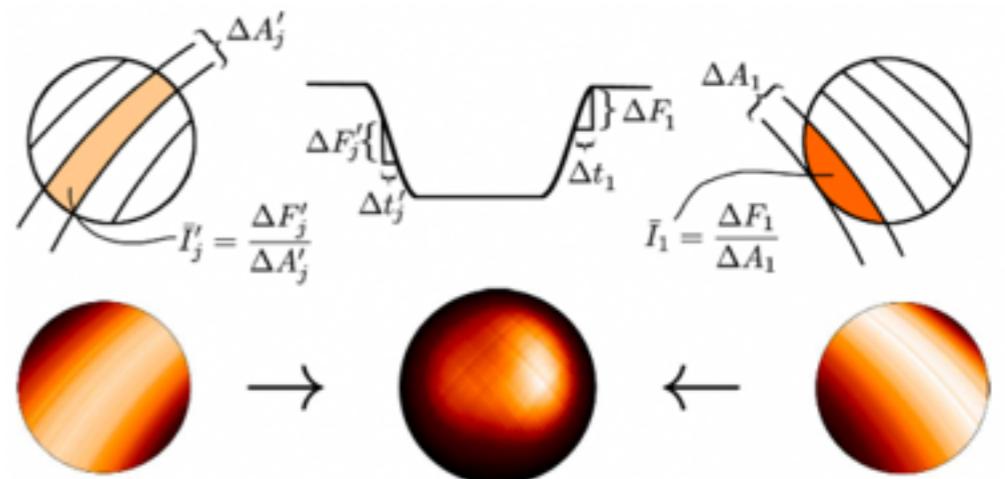


*Surface mapping\*\**



*Timing constrains eccentricity\**  
*Depth constrains albedo*

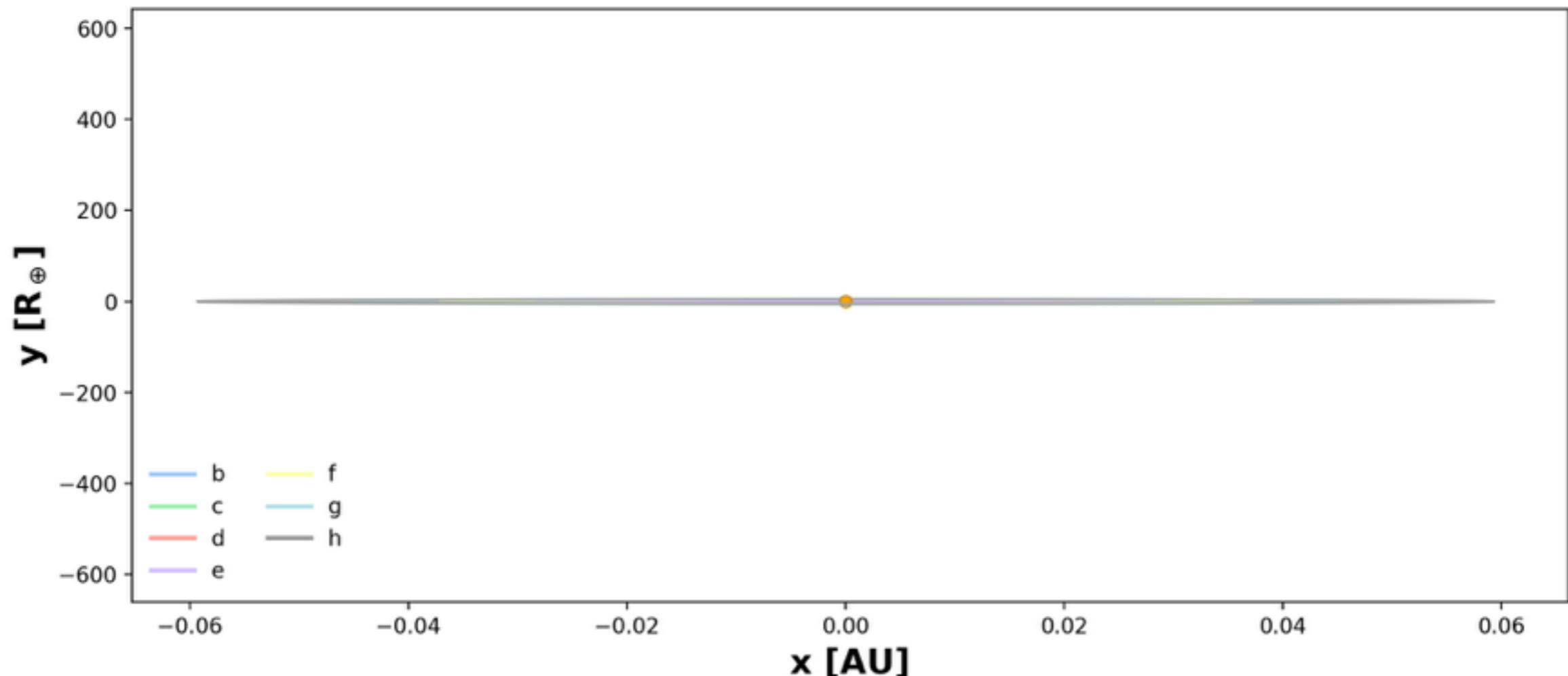
*Majeau, Agol & Cowan (2012)*





# The TRAPPIST-1 system

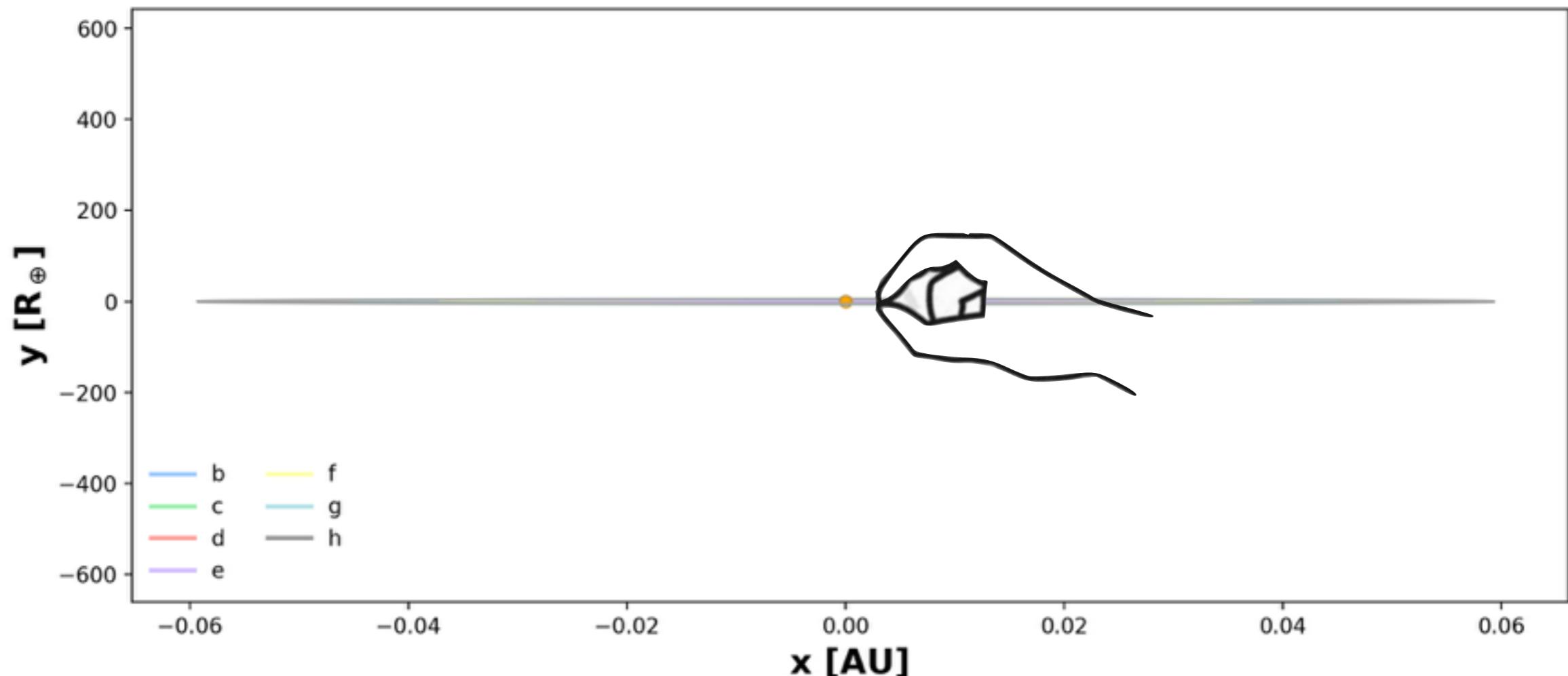
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# The TRAPPIST-1 system

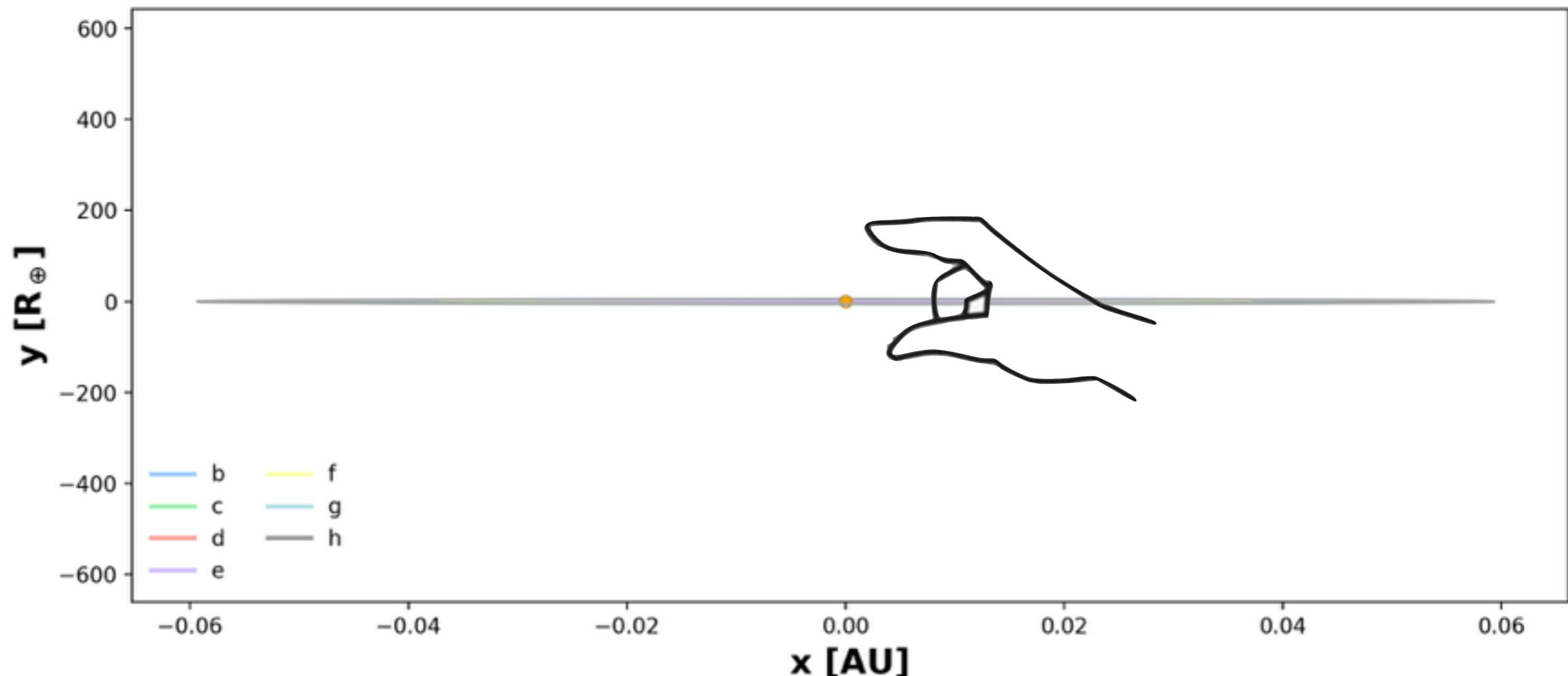
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# The TRAPPIST-1 system

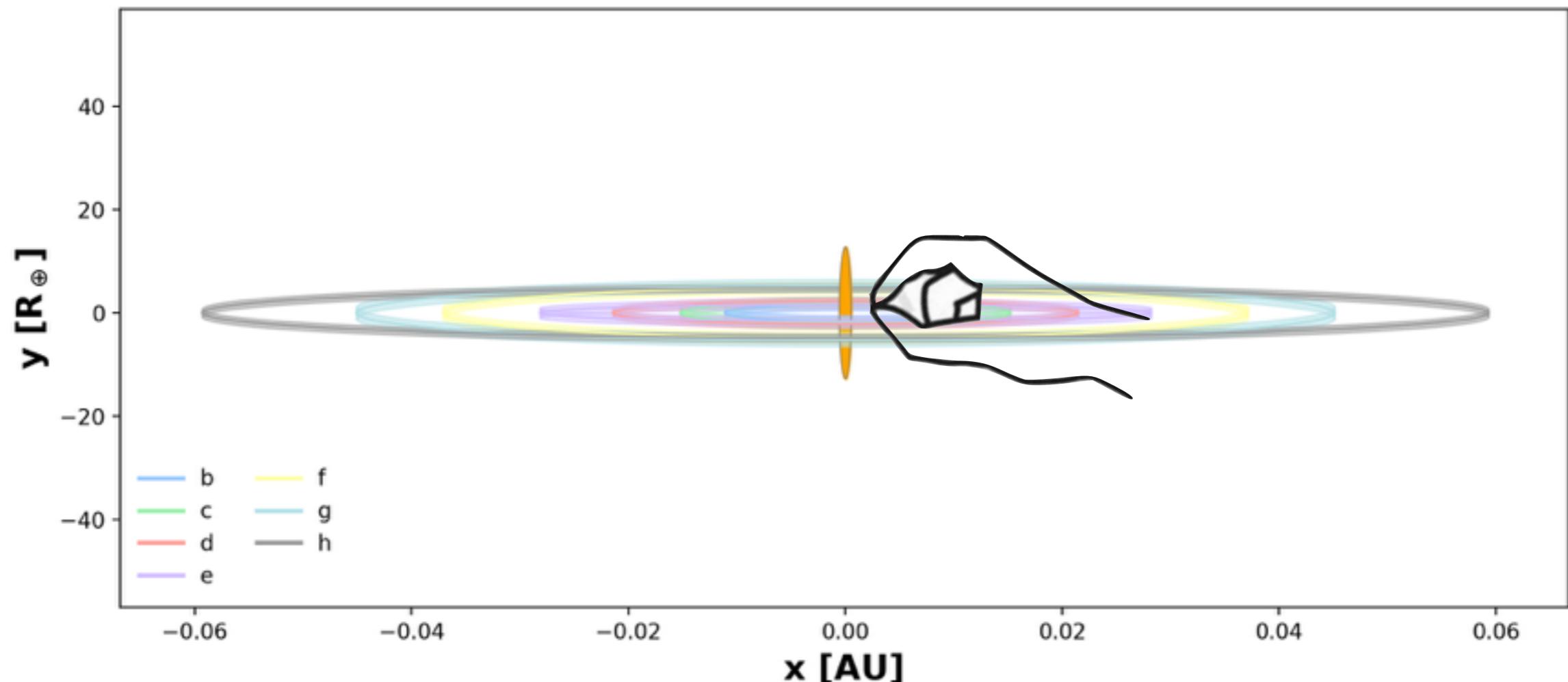
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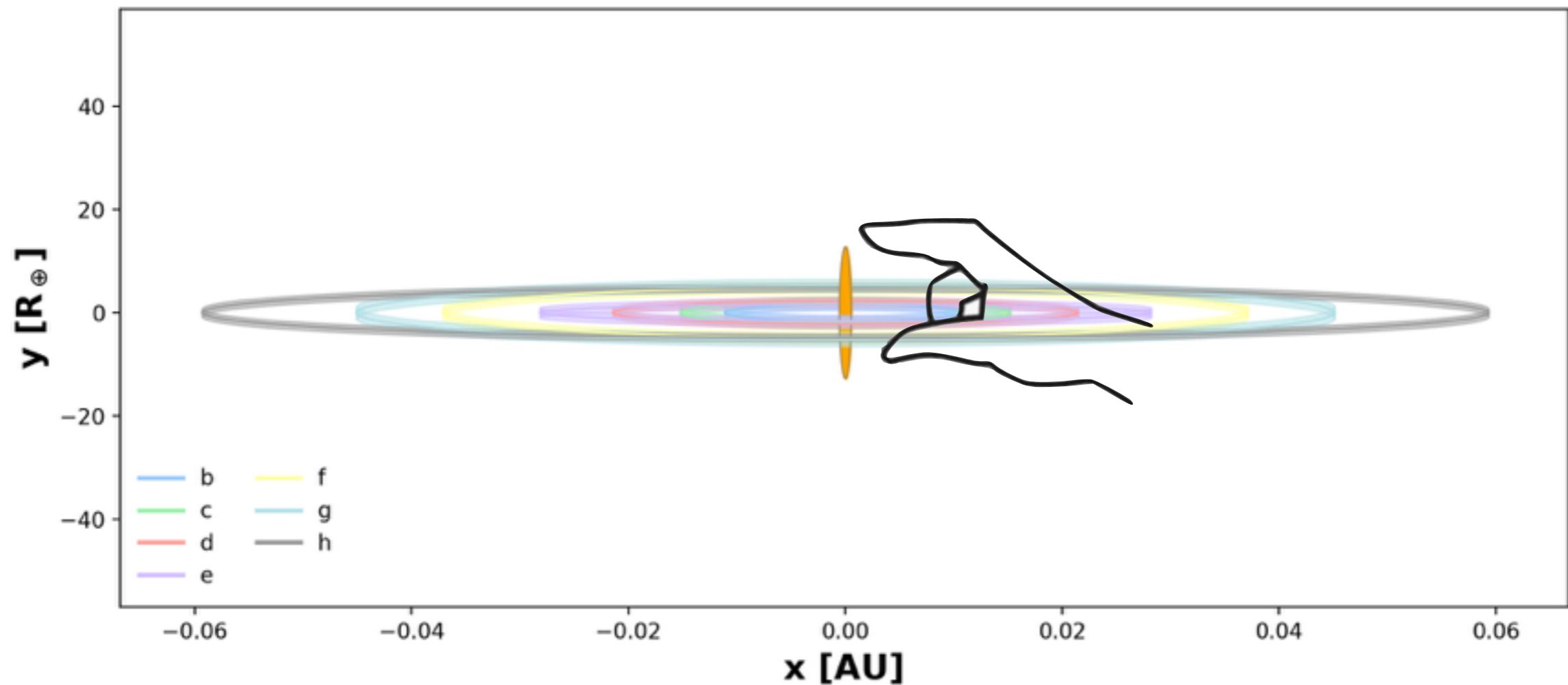
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# The TRAPPIST-1 system

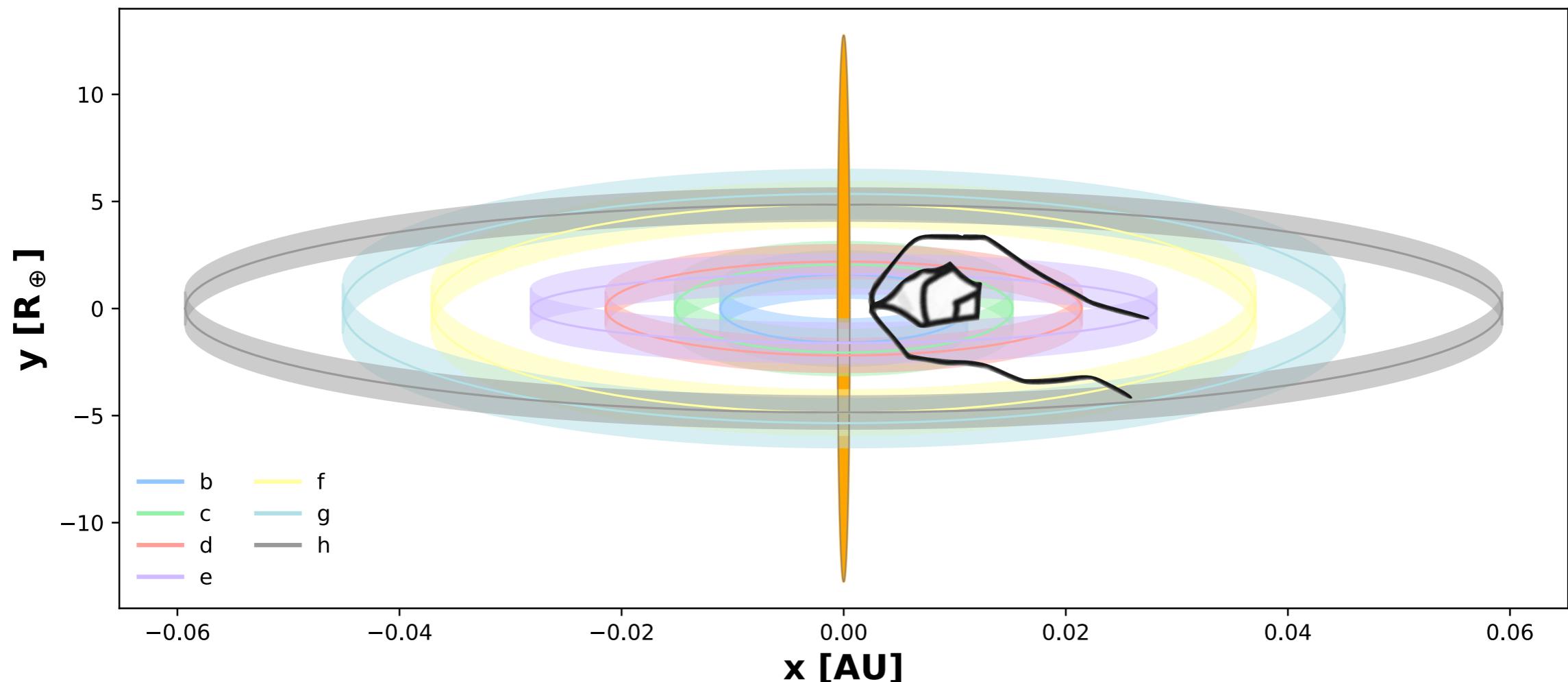
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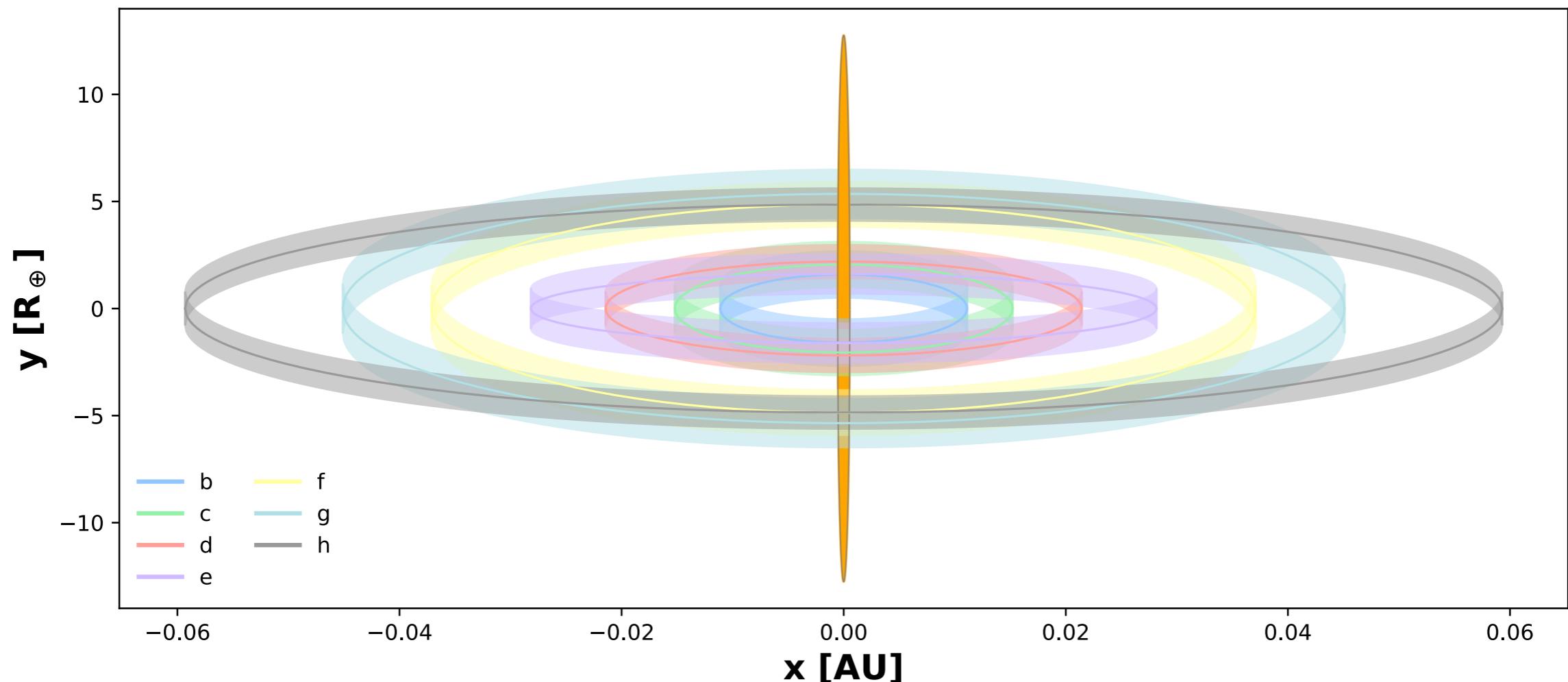
# The TRAPPIST-1 system

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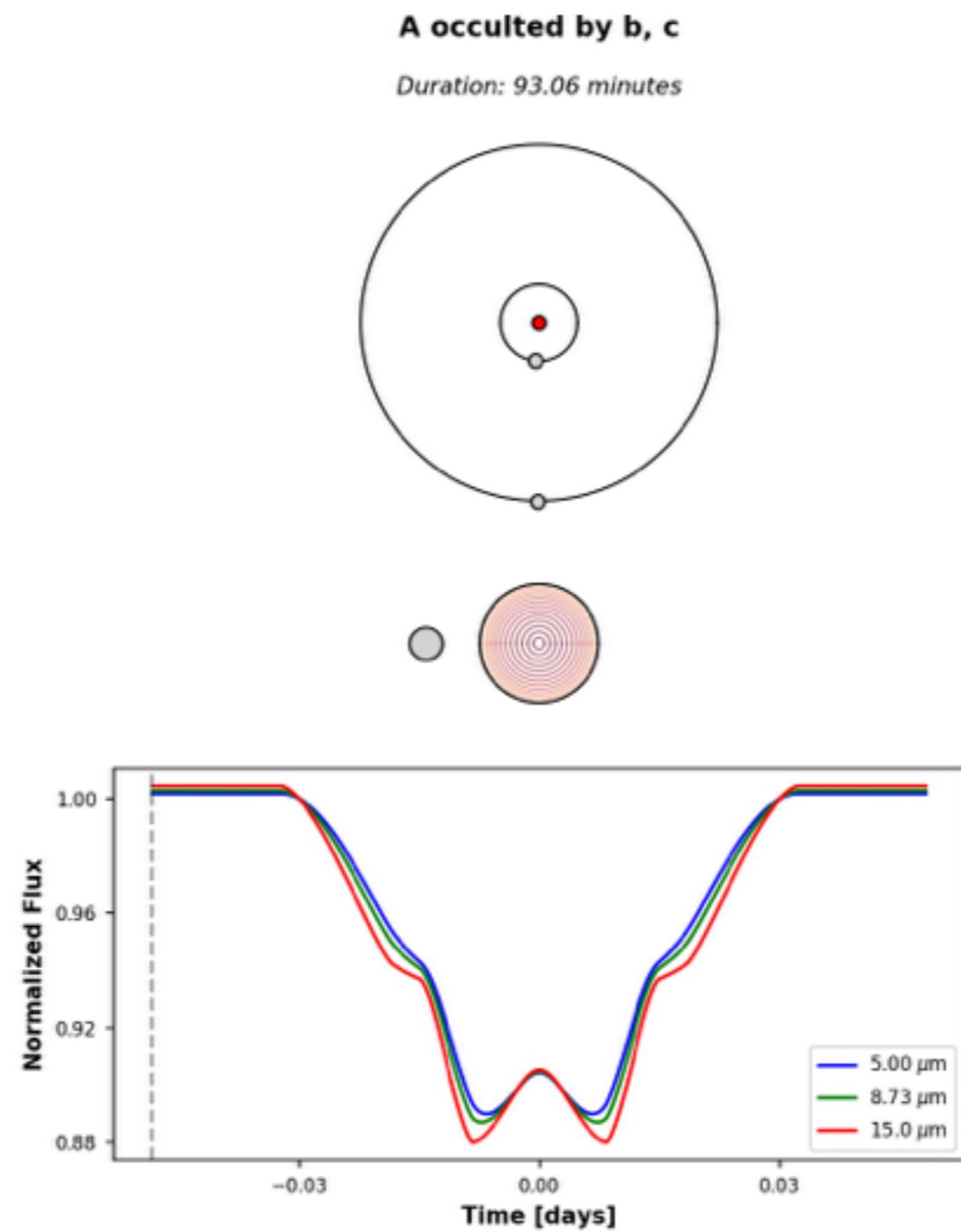


# The TRAPPIST-1 system



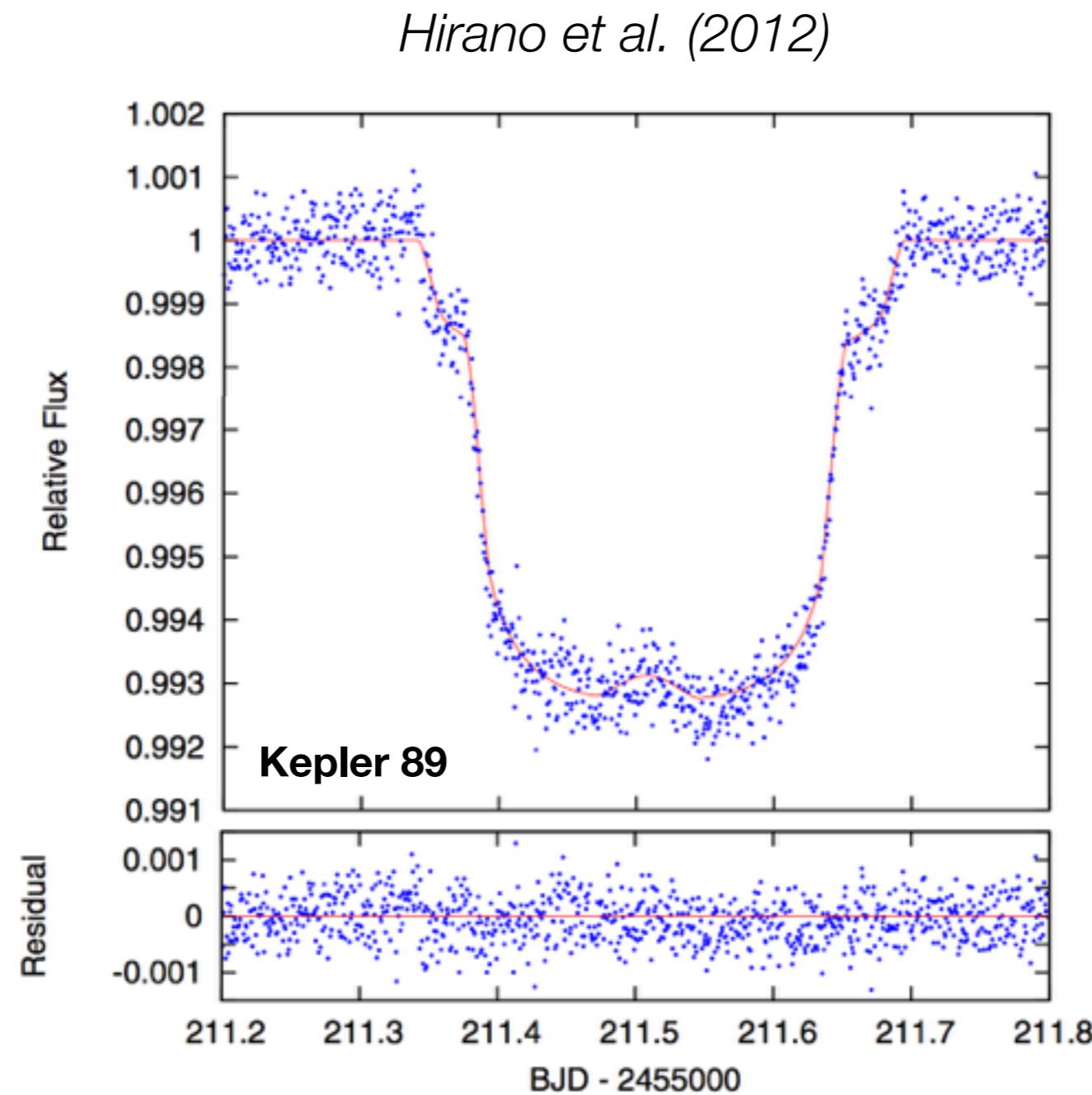


## Mutual transits





## Mutual transits



**See also**

*Pál (2011)*

*Kipping (2011)*

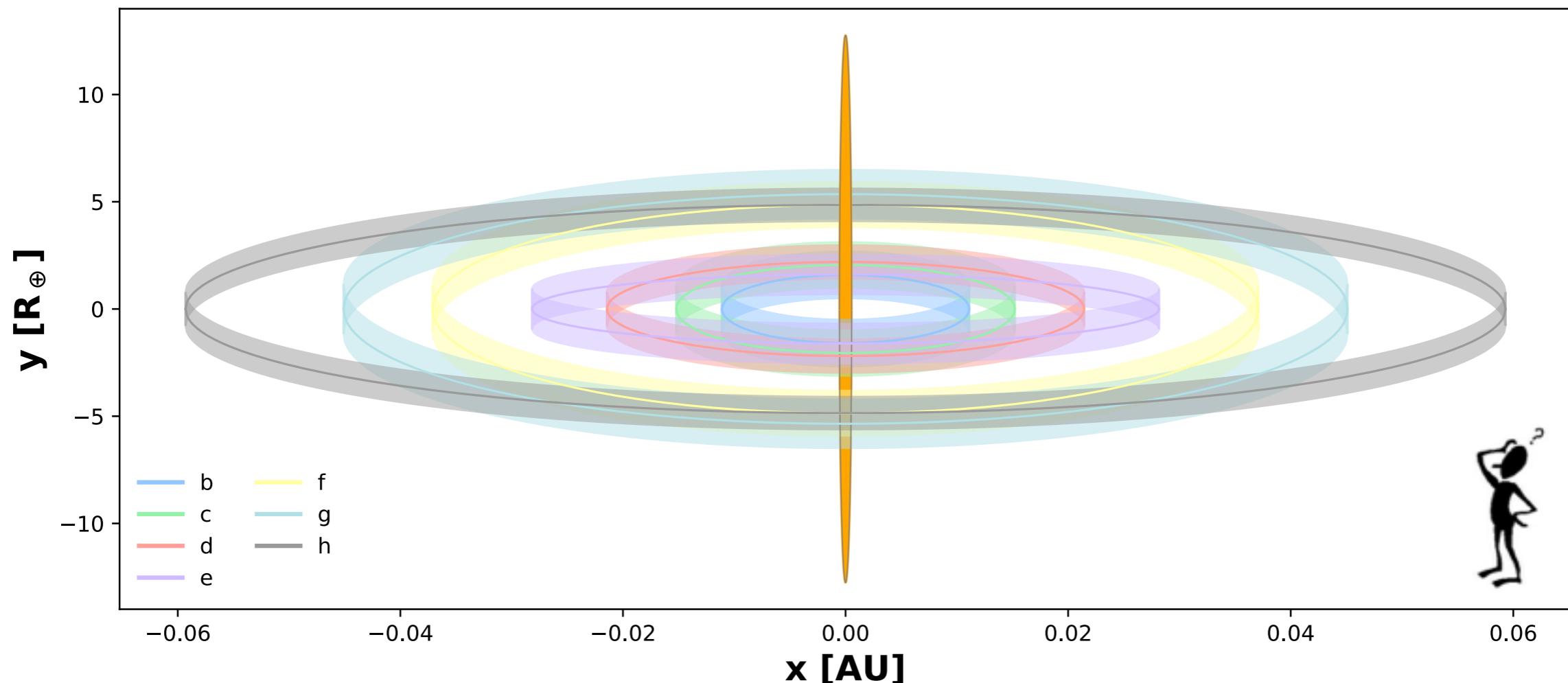
*Masuda et al. (2014)*

*& others*



# The TRAPPIST-1 system

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## Planet-planet occultations

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*Planet-planet occultations are a powerful tool  
to characterize the TRAPPIST-1 planets*



## Ragazzine & Holman (2010)

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“ place very tight constraints on the orientation of the planetary system, since there would be information on the relative astrometric position along a line of sight different than that connecting the Earth the star ”

“ can even characterize the reflected/emitted light spatially on the occulted planet, possibly leading to surface maps ”

“ It might be possible, in well-characterized systems, to predict such events and observe them in the infrared, where the signal is likely to be higher. The *James Webb Space Telescope* may be able to detect some of these short but highly interesting events. ”

### See also

Cabrera & Schneider (2007)

Sato & Assada (2009, 2010)

Pál (2011)

Veras & Beredt (2017)



# Planet-planet occultations

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**N-body code**  
**rebound** + **Occultation code**  
**planetplanet**

*Rein & Liu (2012)*  
*Rein & Tamayo (2015, 2016)*

*Luger, Lustig-Yaeger,  
and Agol (2017, in prep)*

## PART f

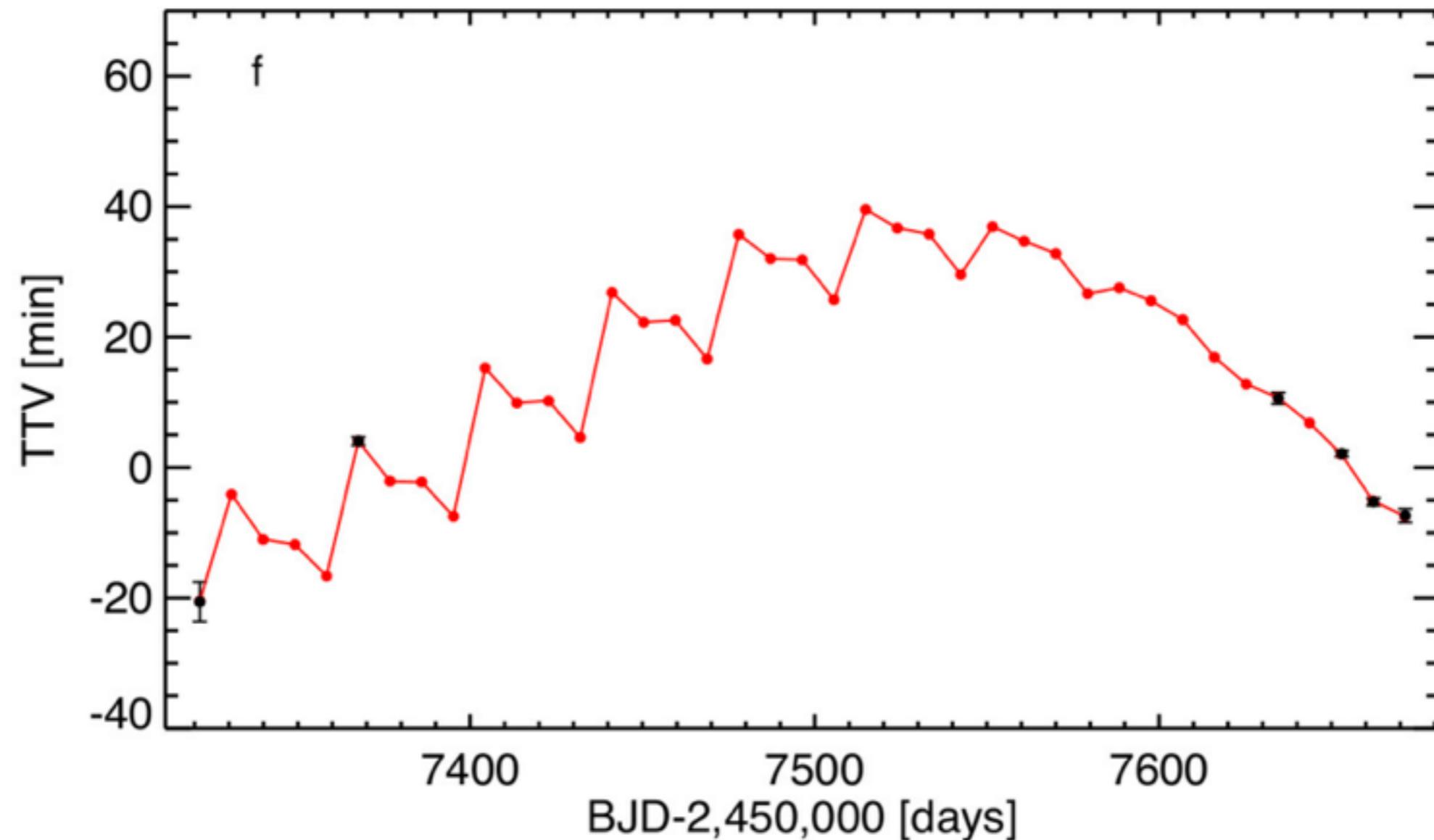


*DYNAMICS OF PLANET-PLANET OCCULTATIONS*



# Transit Timing Variations

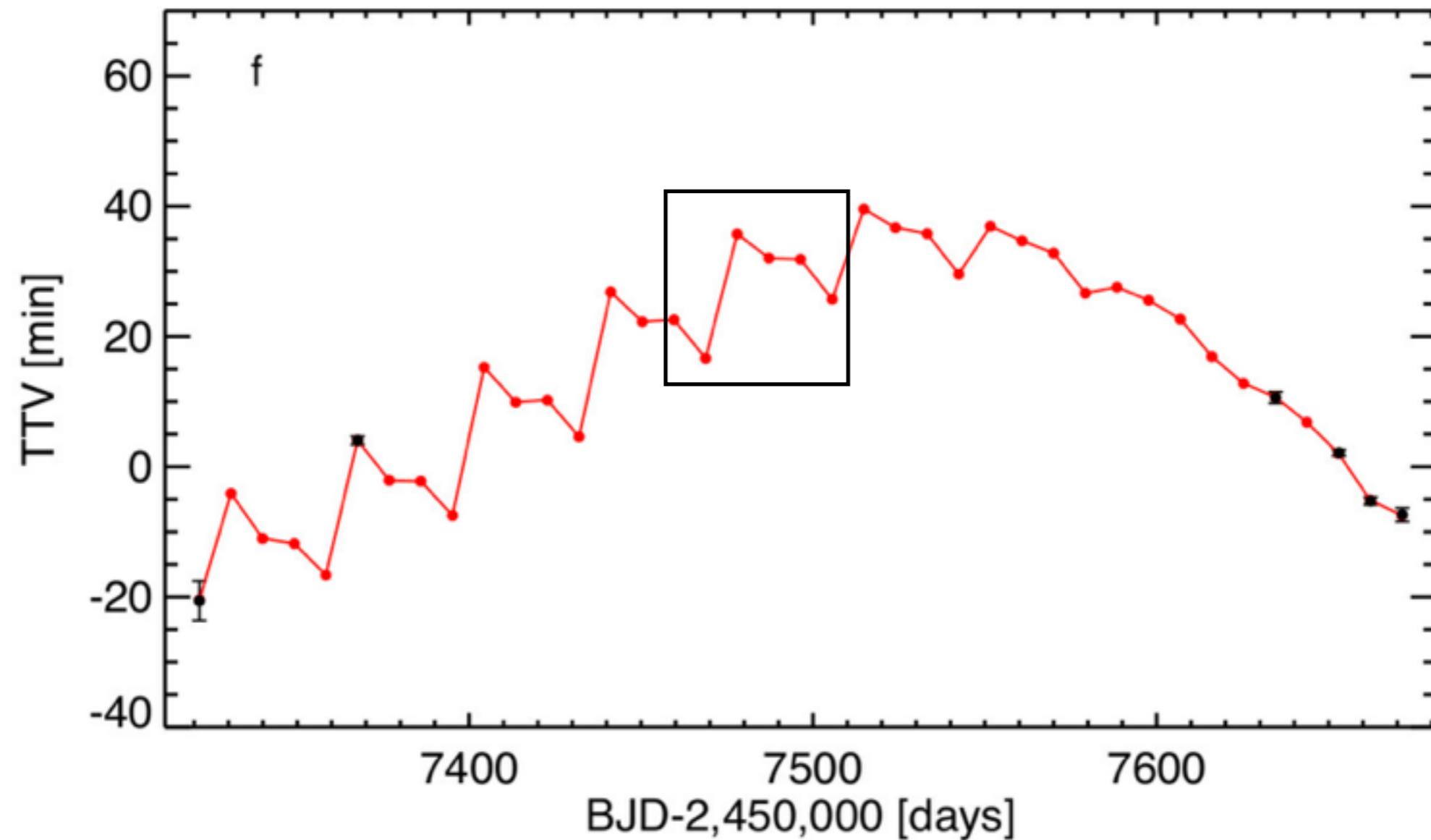
Gillon et al. (2017)





# Transit Timing Variations

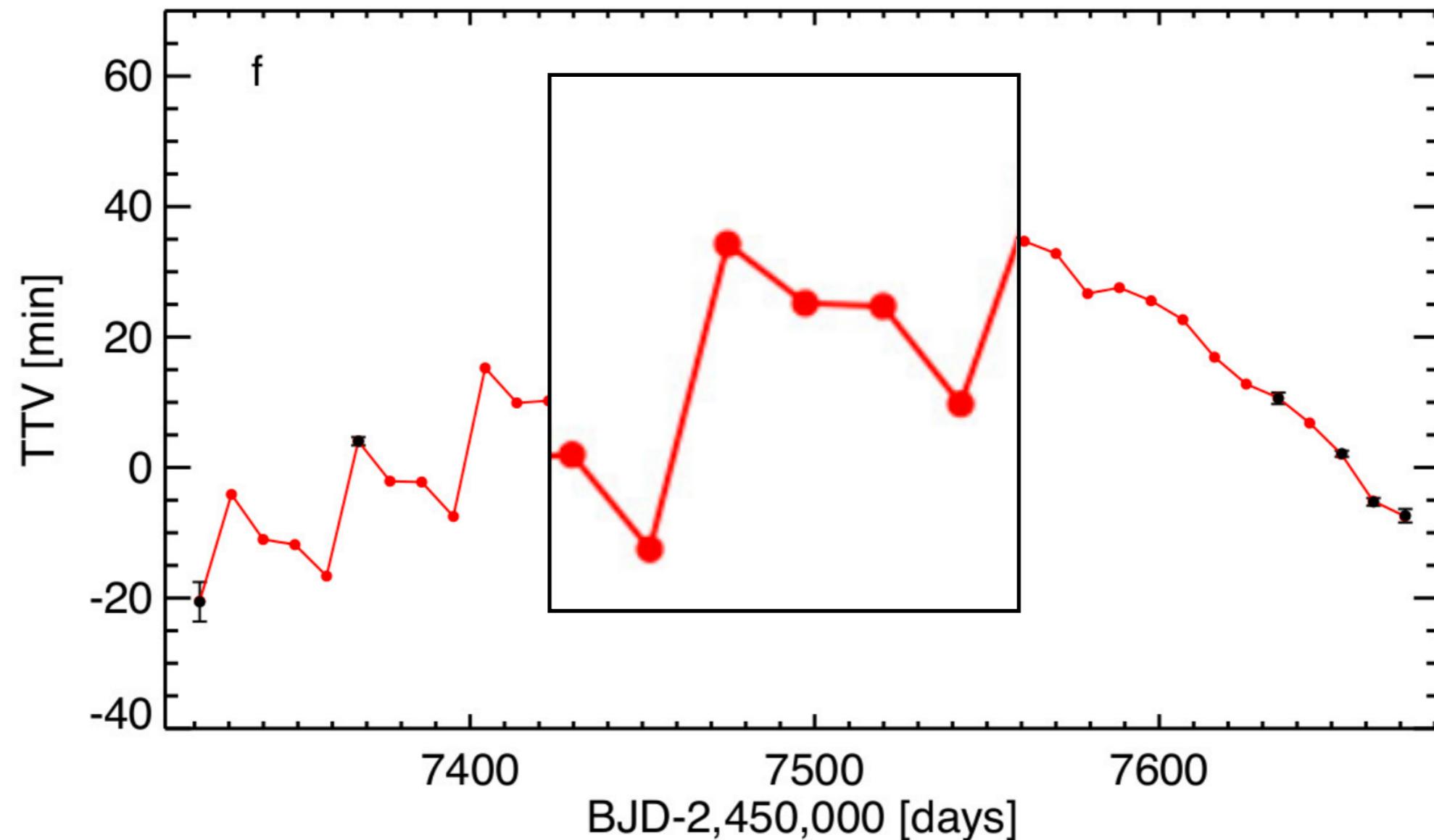
Gillon et al. (2017)





# Transit Timing Variations

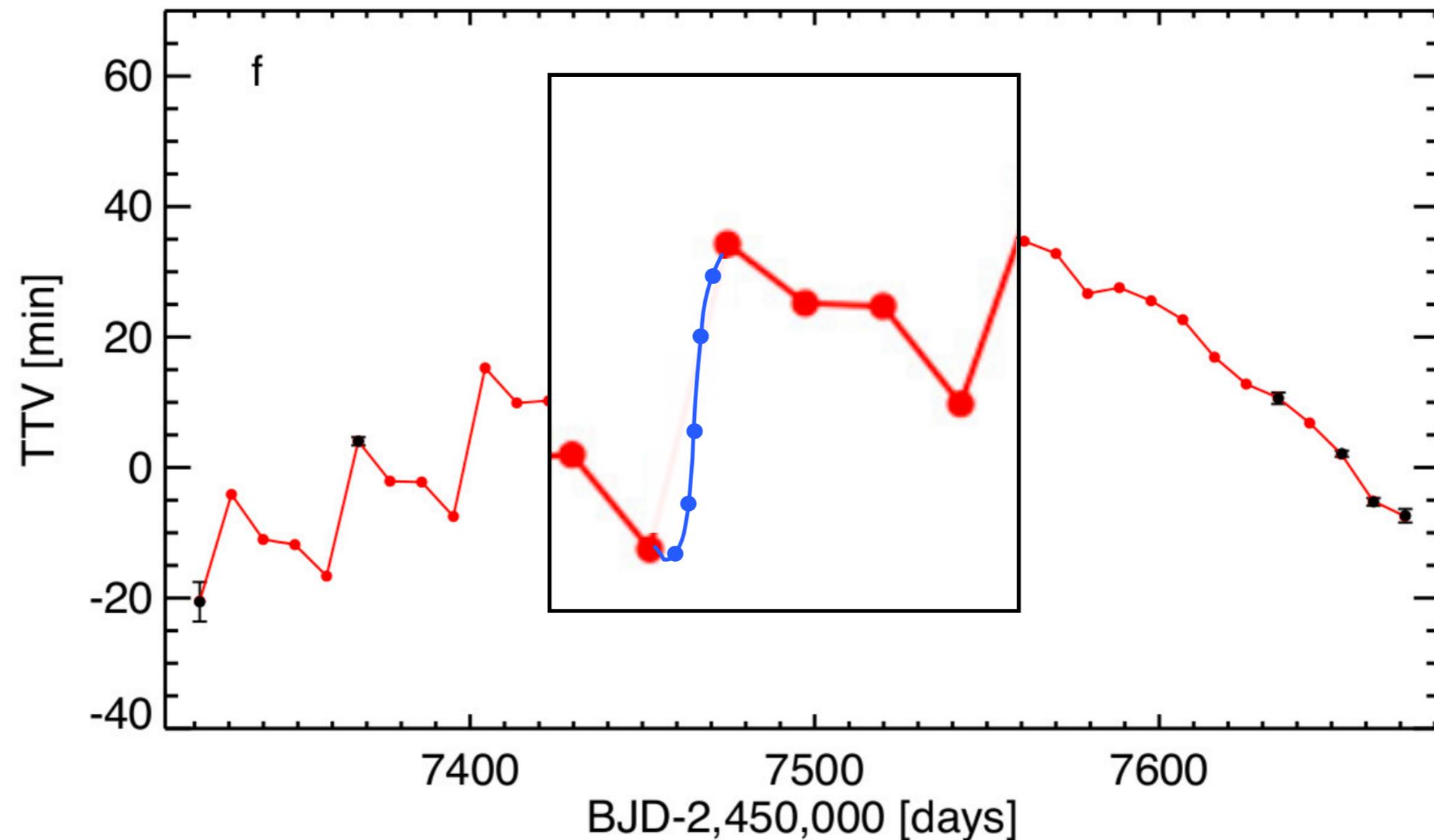
Gillon et al. (2017)





# Transit Timing Variations

Gillon et al. (2017)





## Planet-planet occultations

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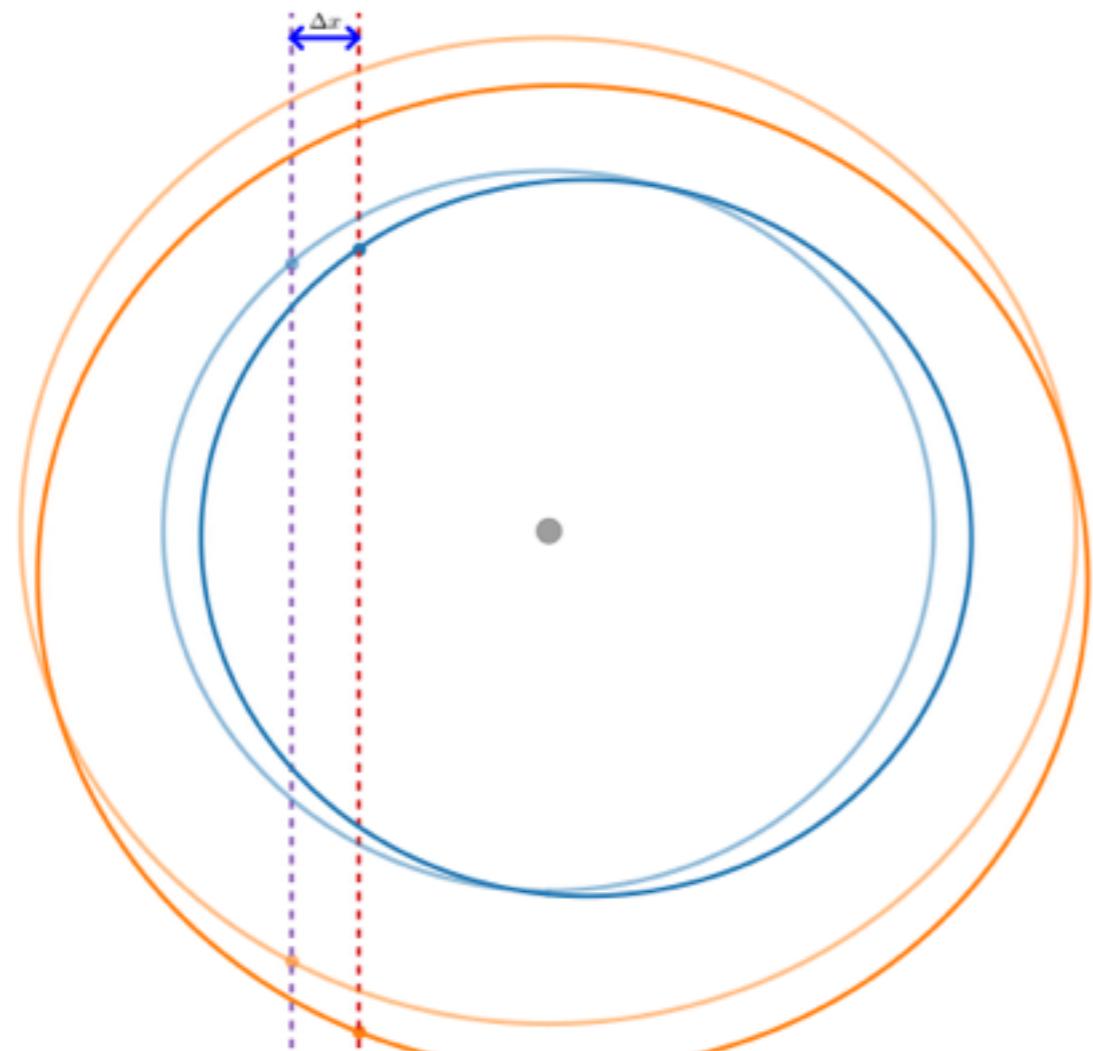
*Planet-planet occultations break TTV degeneracies*



# Planet-Planet Timing Variations

*Occultation condition (circular, coplanar orbits)*

$$(P_i/P_j)^{2/3} \cos\left(\frac{2\pi(t_k^0 - t_{0i})}{P_i}\right) = \cos\left(\frac{2\pi(t_k^0 - t_{0j})}{P_j}\right)$$



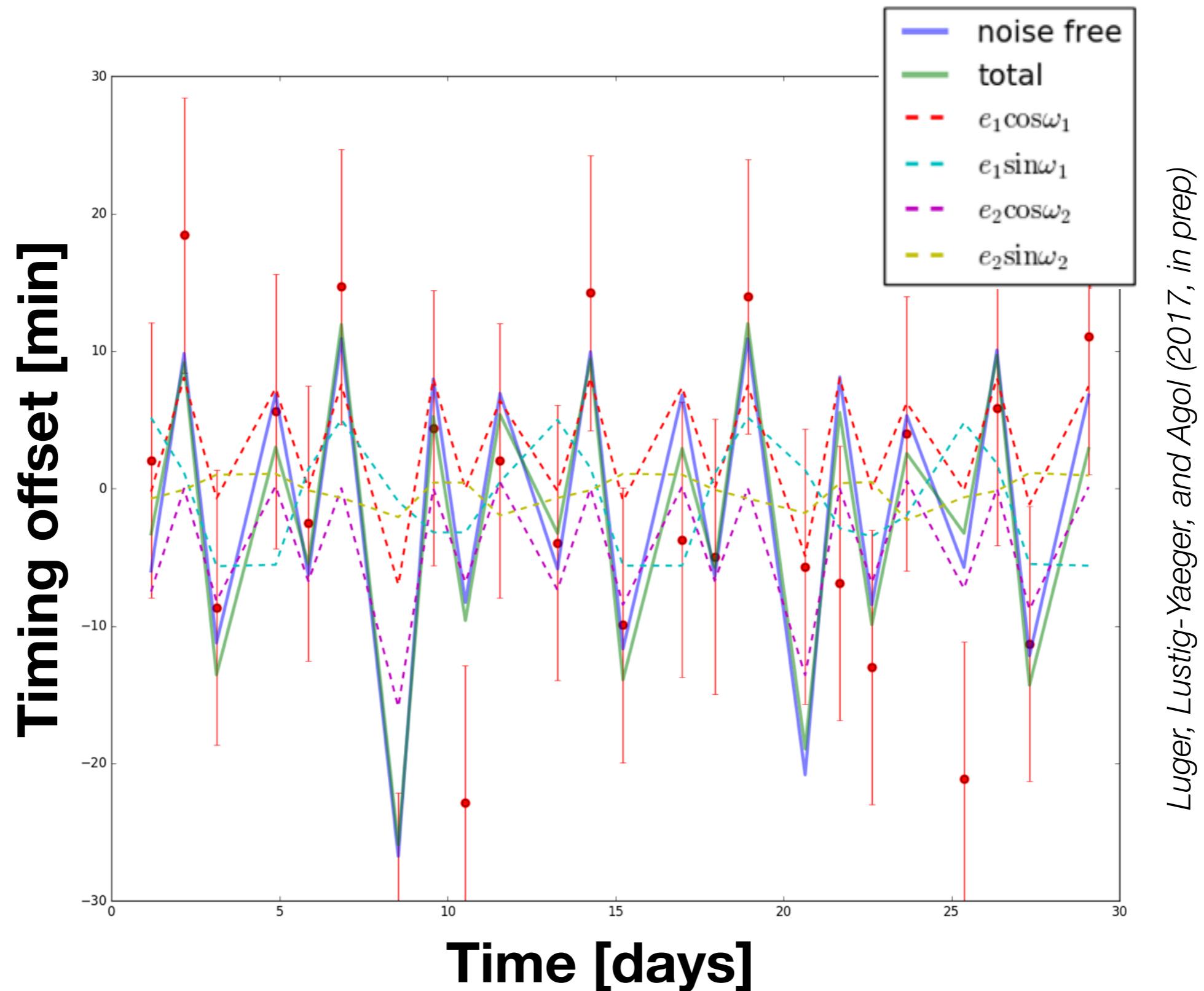
**Epicyclic approximation**

Solve for  $\delta t_k = t_k - t_k^0$

Luger, Lustig-Yaeger, and Agol (2017, *in prep*)



# Planet-Planet Timing Variations



Luger, Lustig-Yaeger, and Agol (2017, in prep)

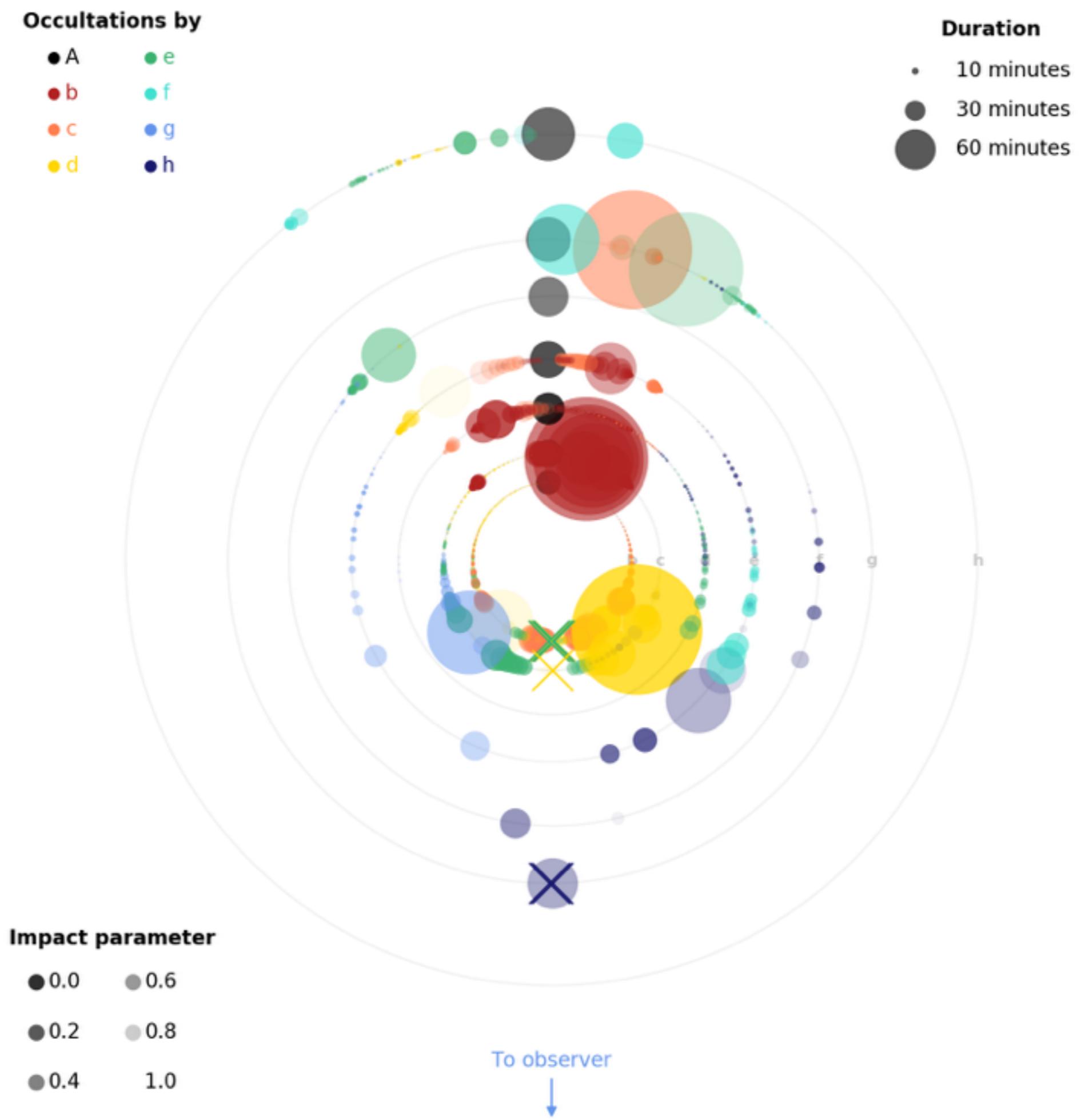


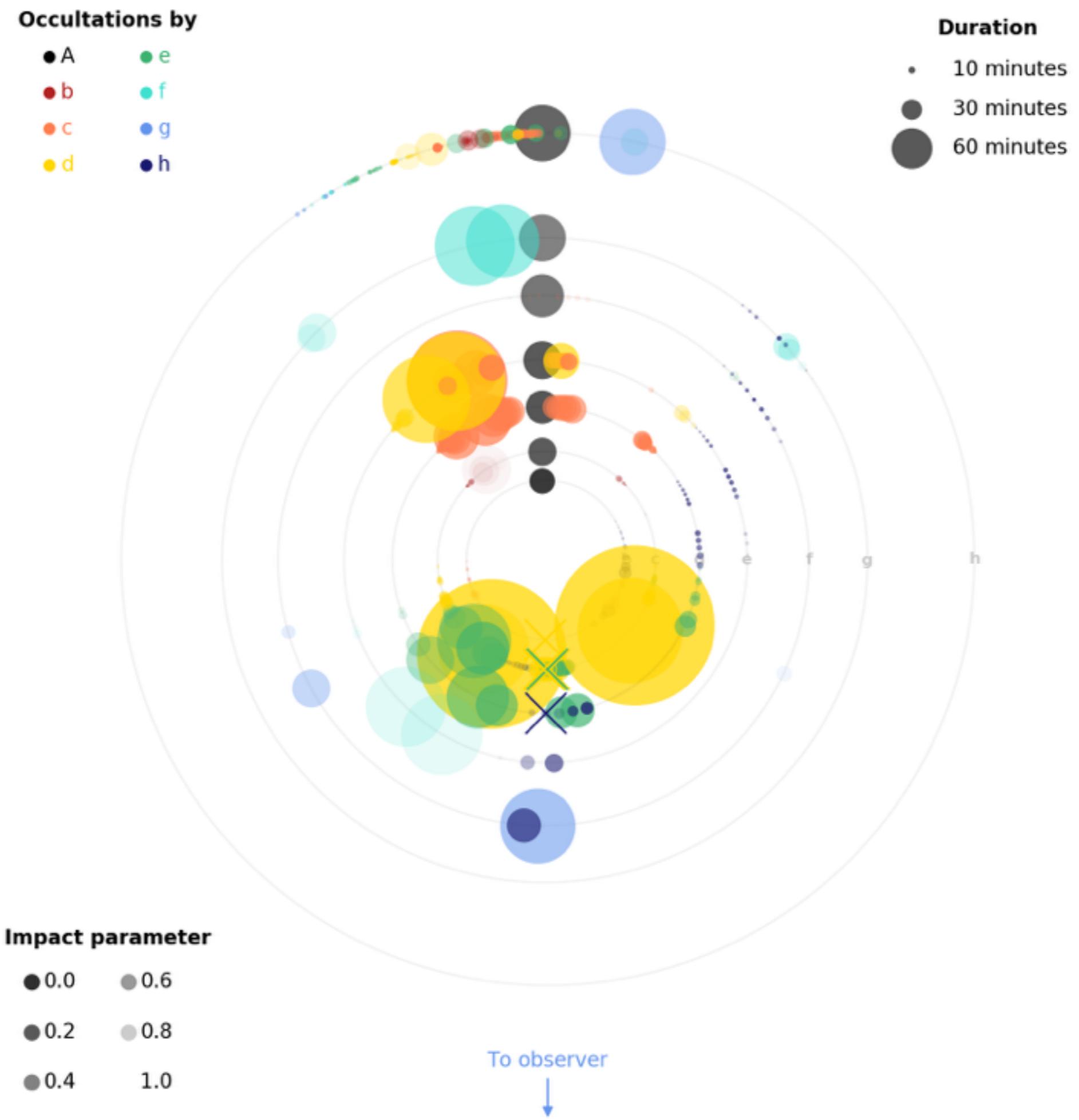
## Planet-planet occultations

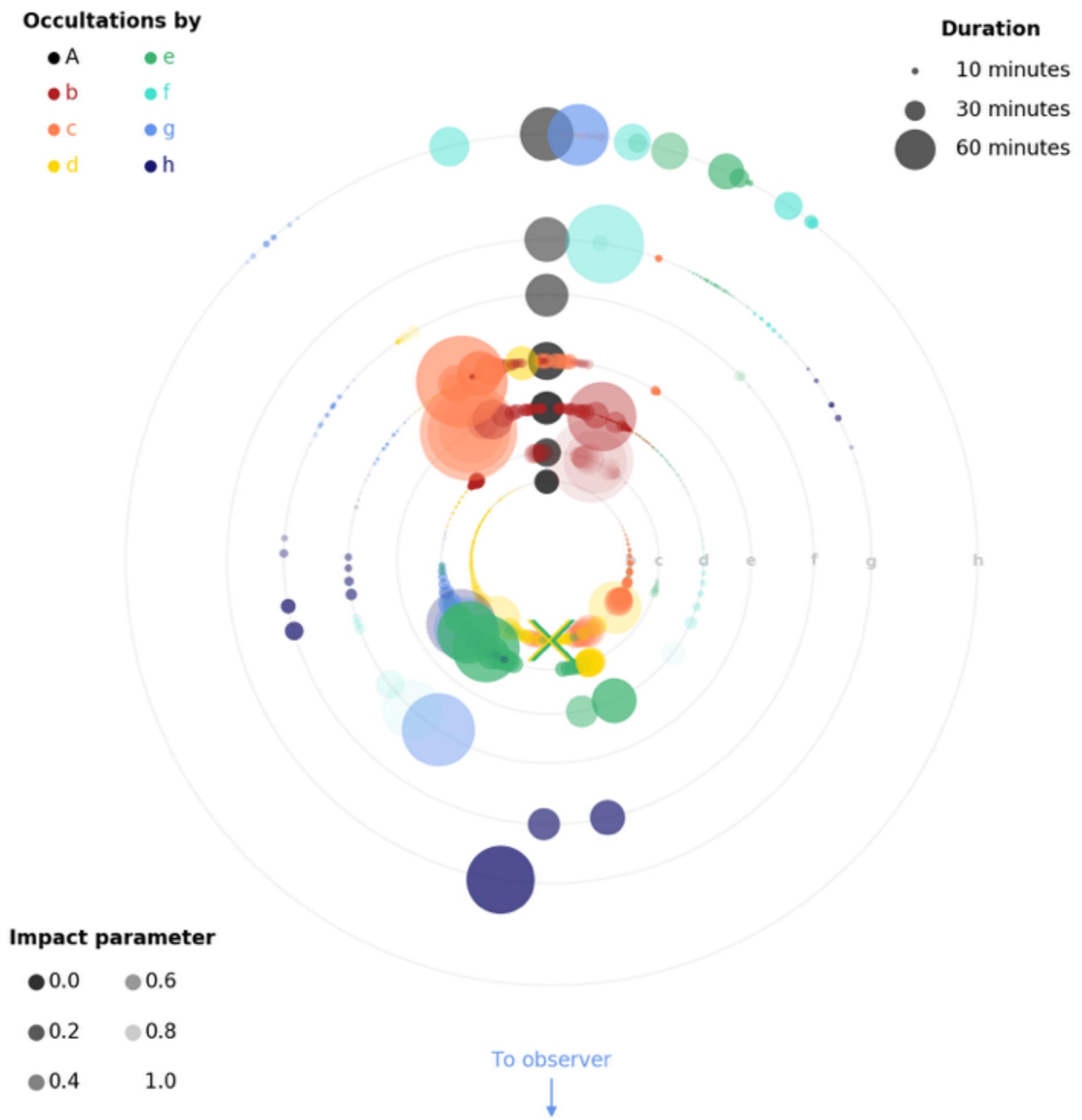
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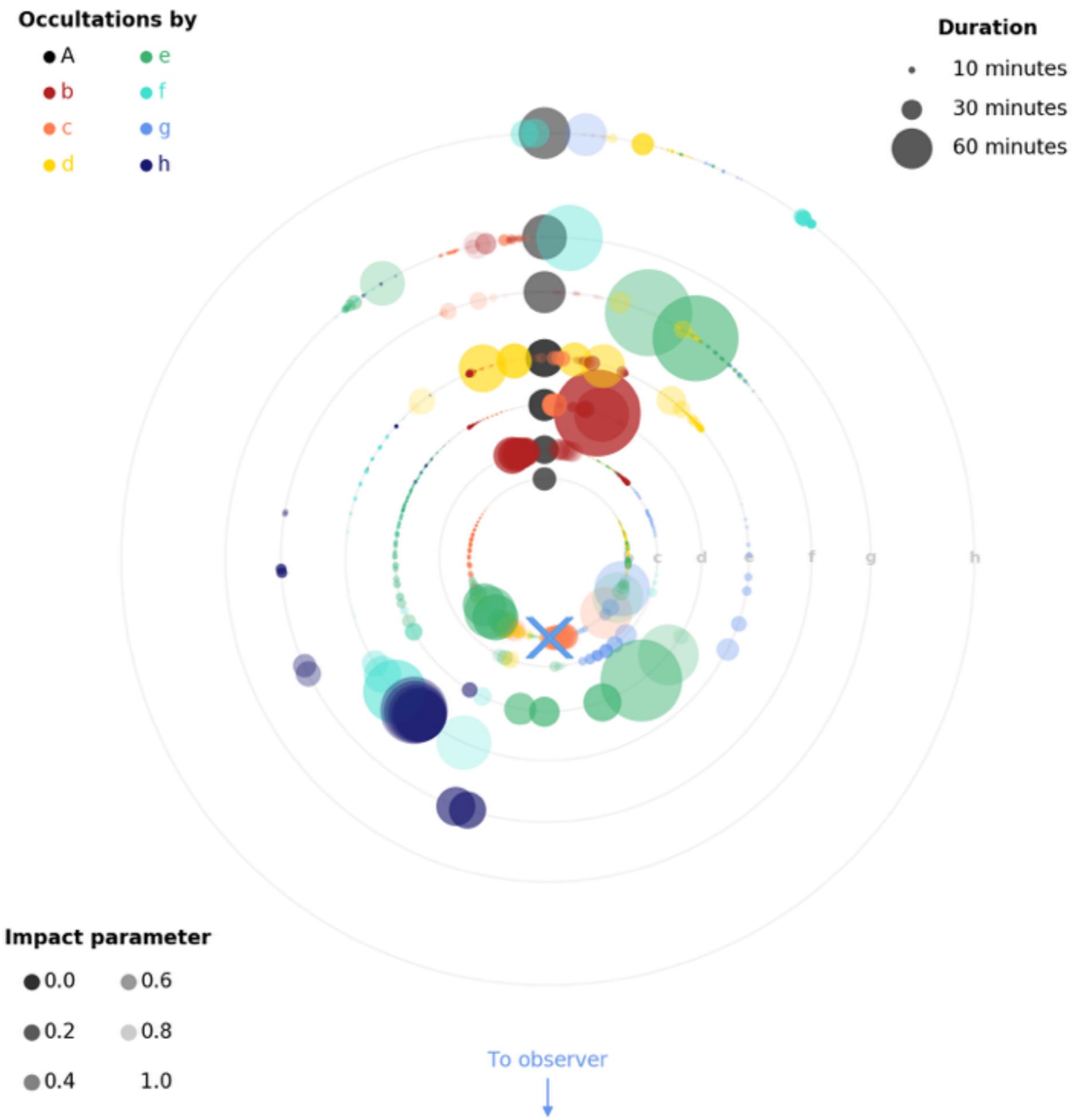


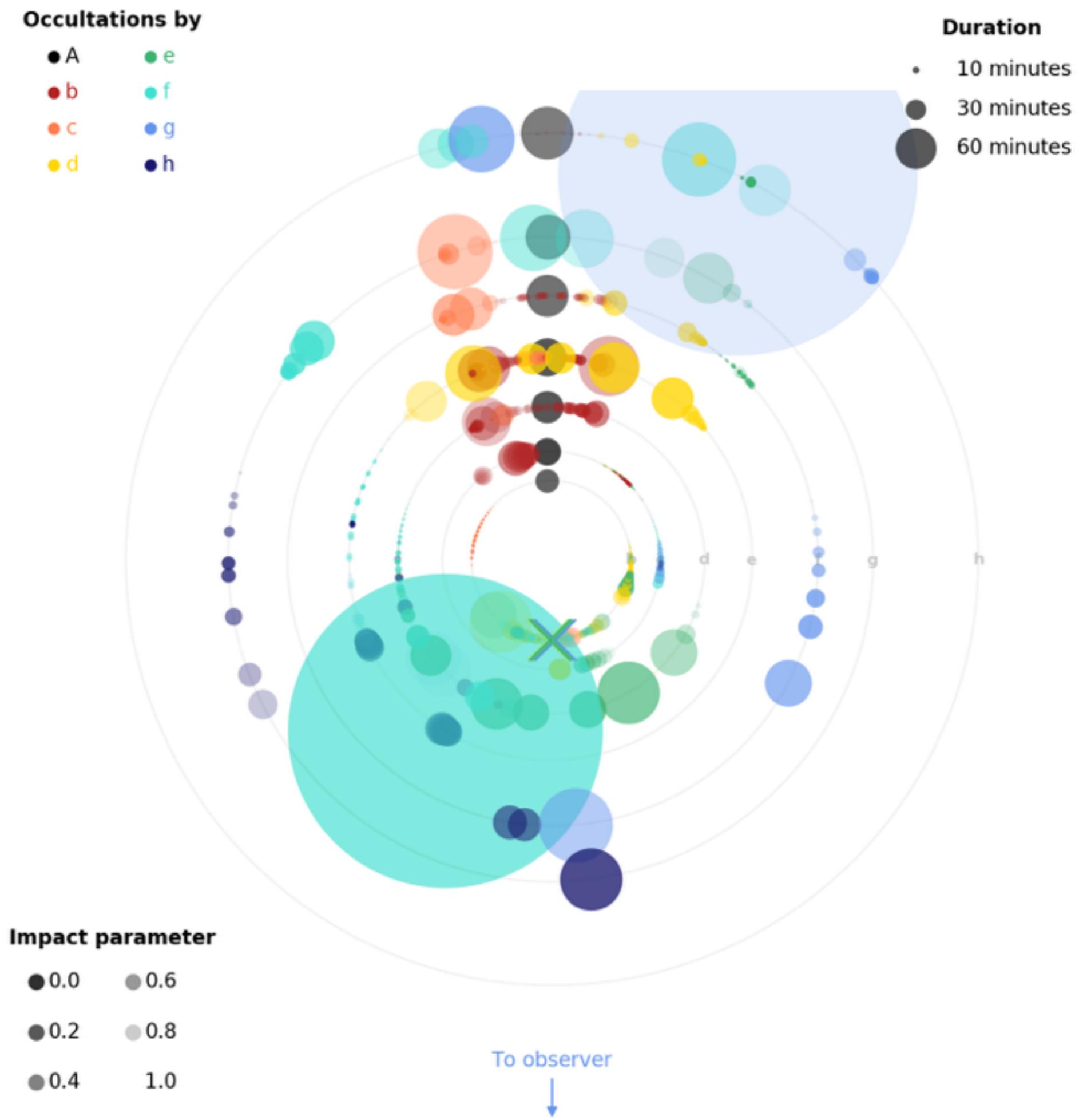
*Planet-planet occultations yield eccentricities*





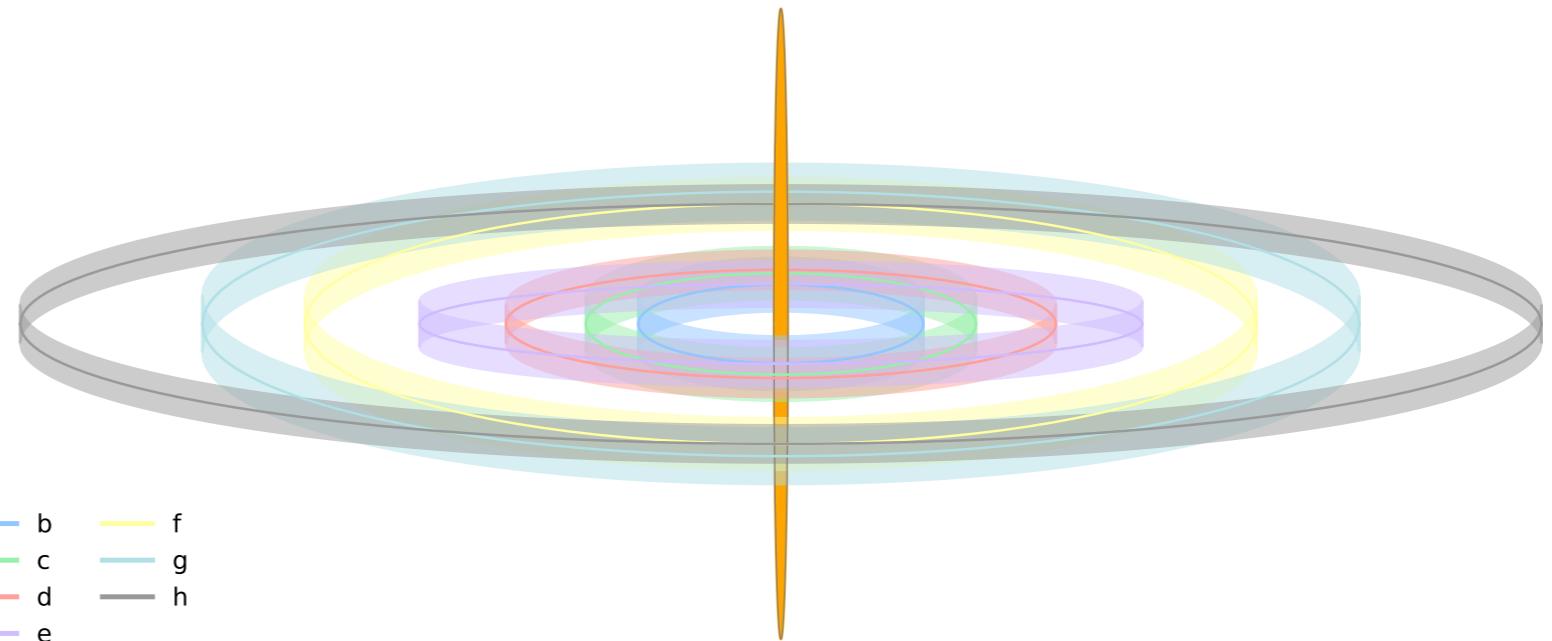
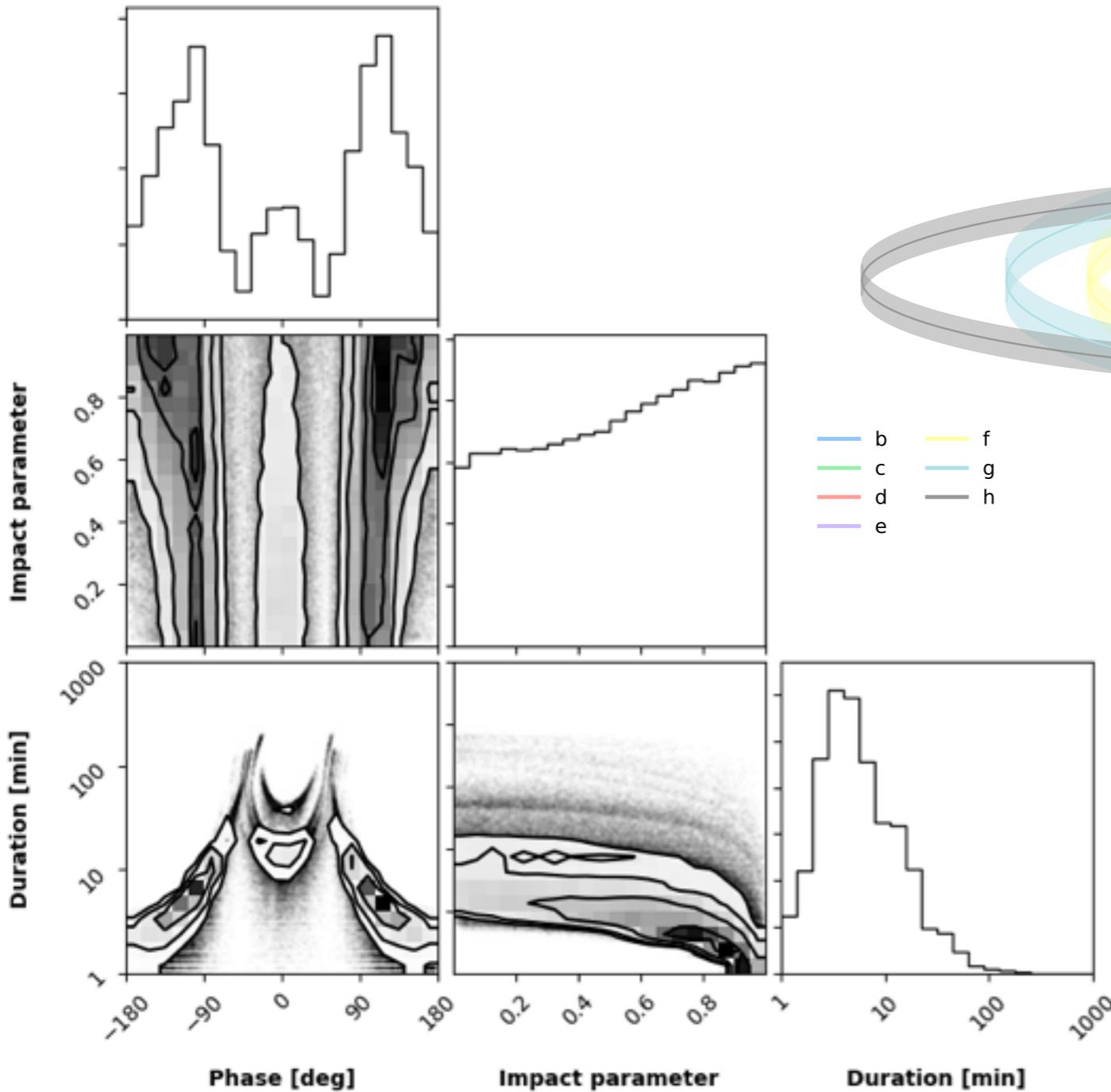








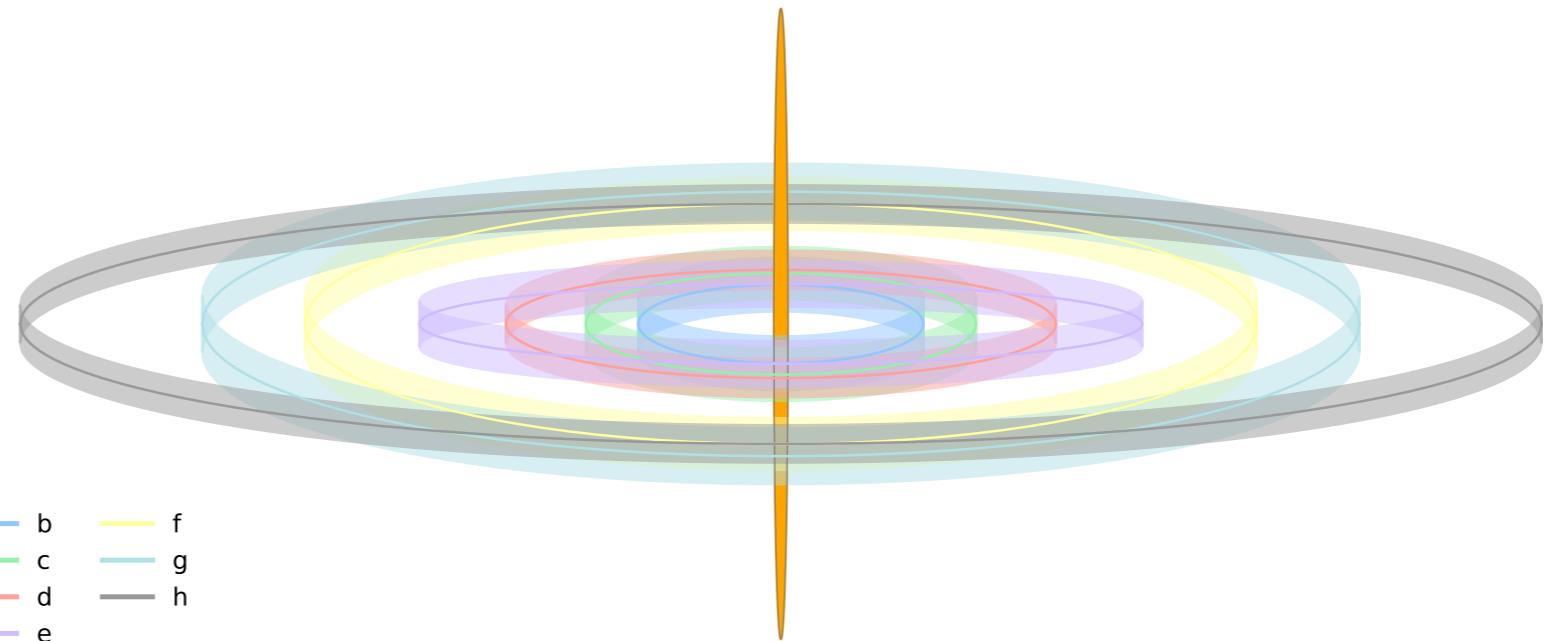
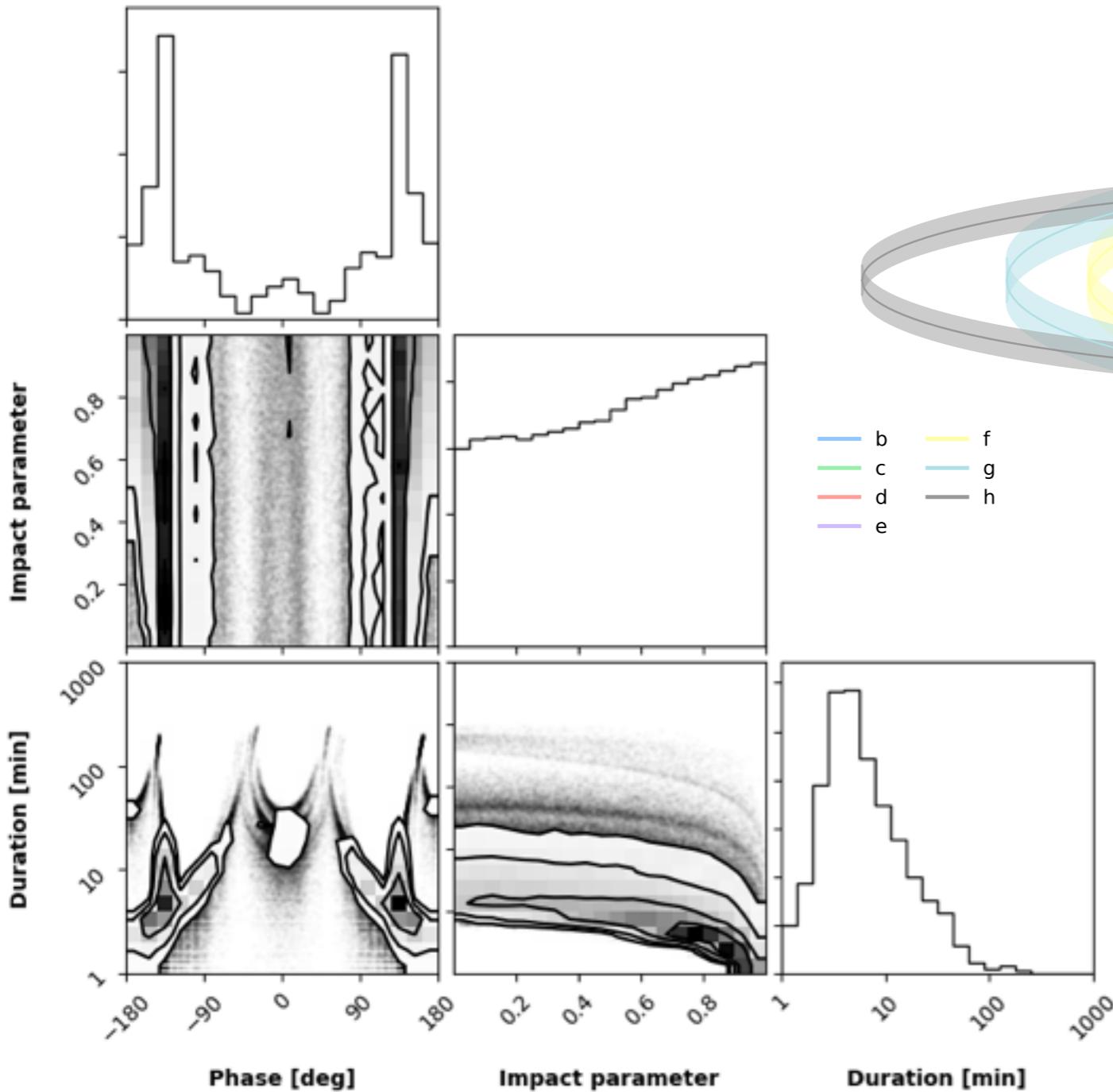
# Occultations of **b**



Luger, Lustig-Yaeger, and Agol (2017, *in prep*)



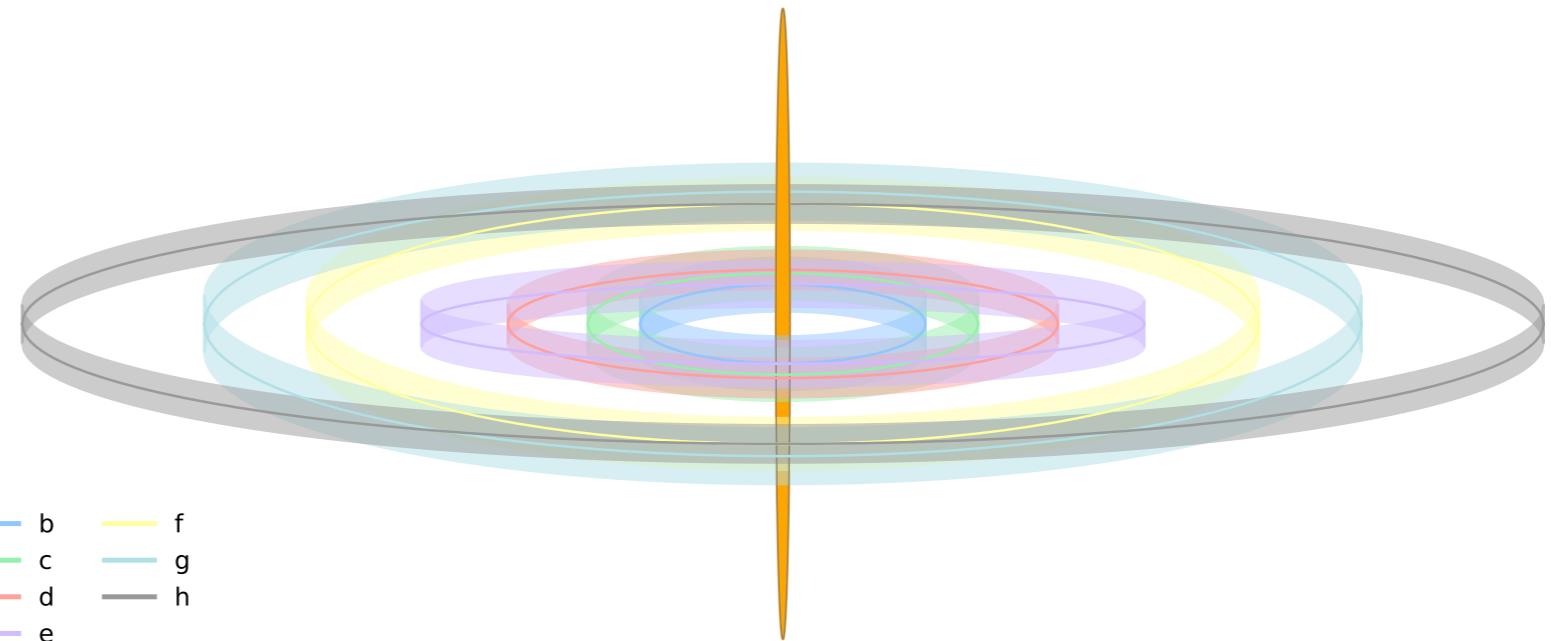
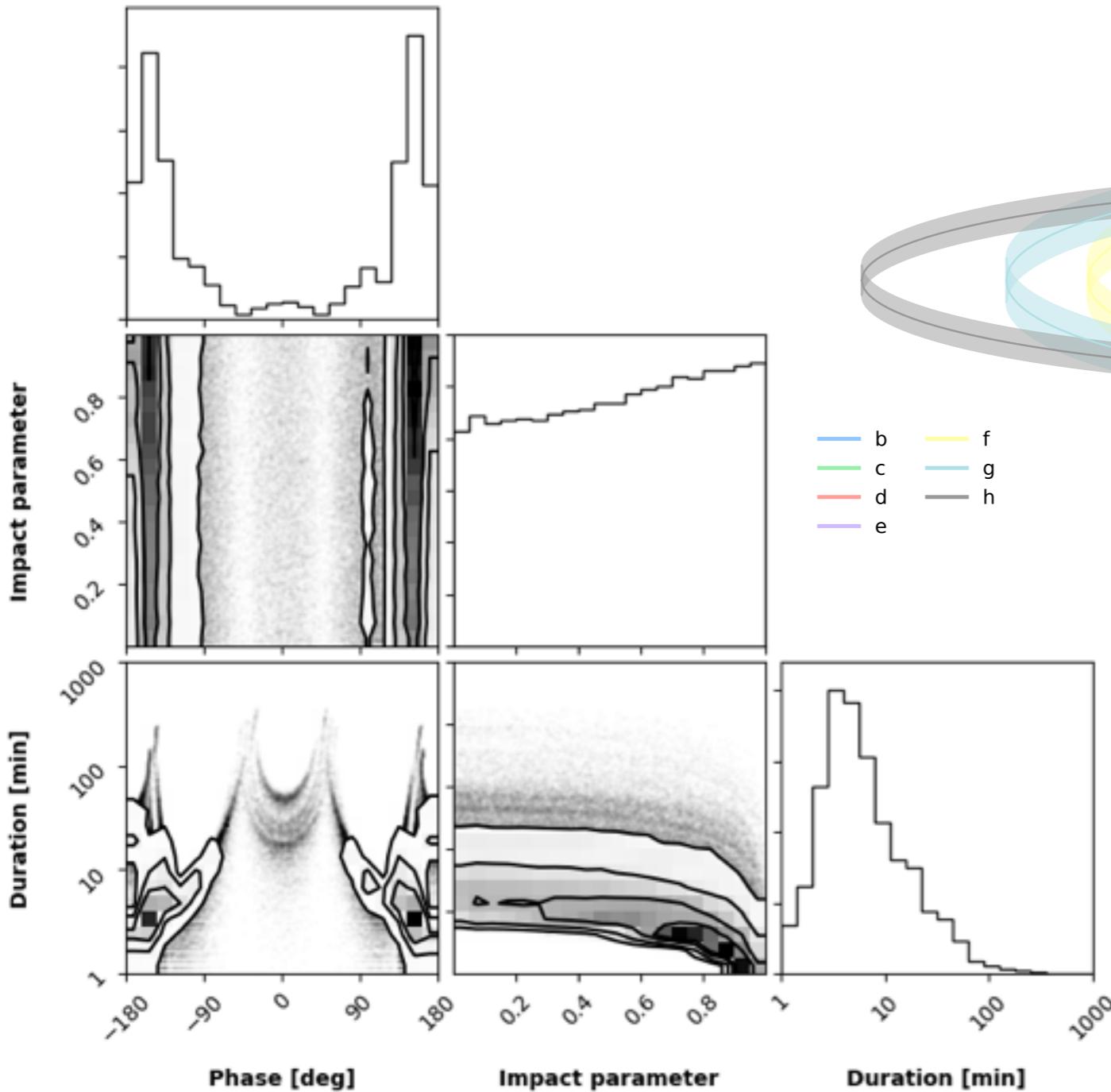
# Occultations of **C**



Luger, Lustig-Yaeger, and Agol (2017, *in prep*)



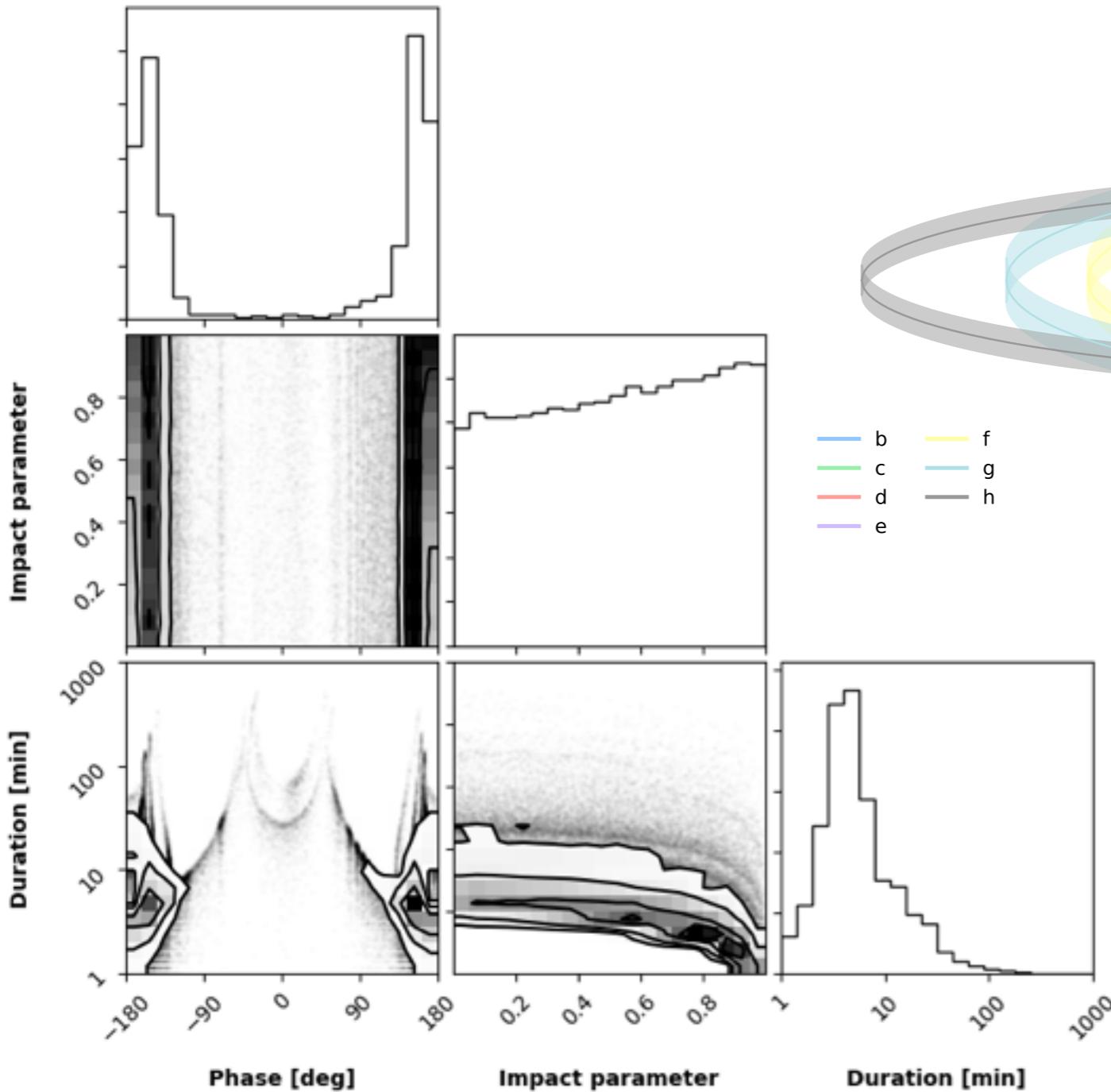
# Occultations of **d**



Luger, Lustig-Yaeger, and Agol (2017, *in prep*)



# Occultations of e



Luger, Lustig-Yaeger, and Agol (2017, *in prep*)



## Planet-planet occultations

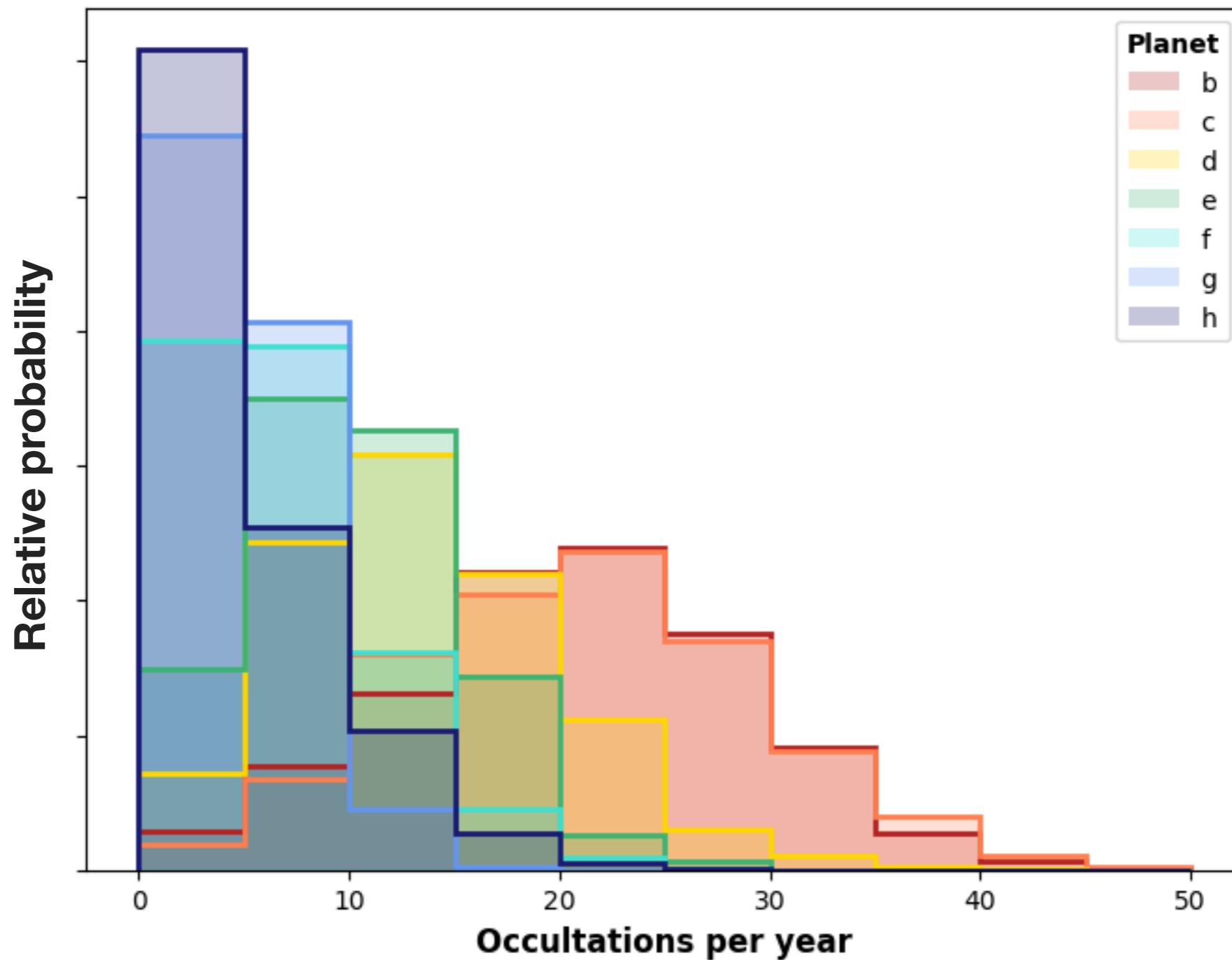
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*Planet-planet occultations constrain the full three-dimensional structure of the system*



Occultations are frequent



Luger, Lustig-Yaeger, and Agol (2017, *in prep*)



## Planet-planet occultations

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*Planet-planet occultations are common in  
TRAPPIST-1*

## PART g

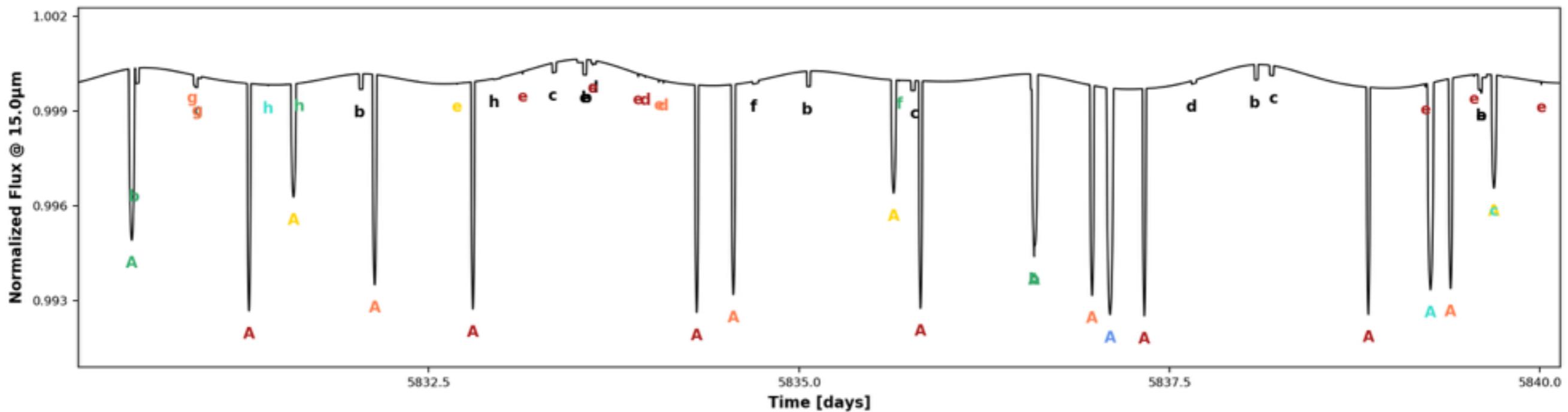


*PLANET-PLANET OCCULTATION PHOTOMETRY*



# Occultation light curves

Occultations by ● A ● b ● c ● d ● e ● f ● g ● h



rebound

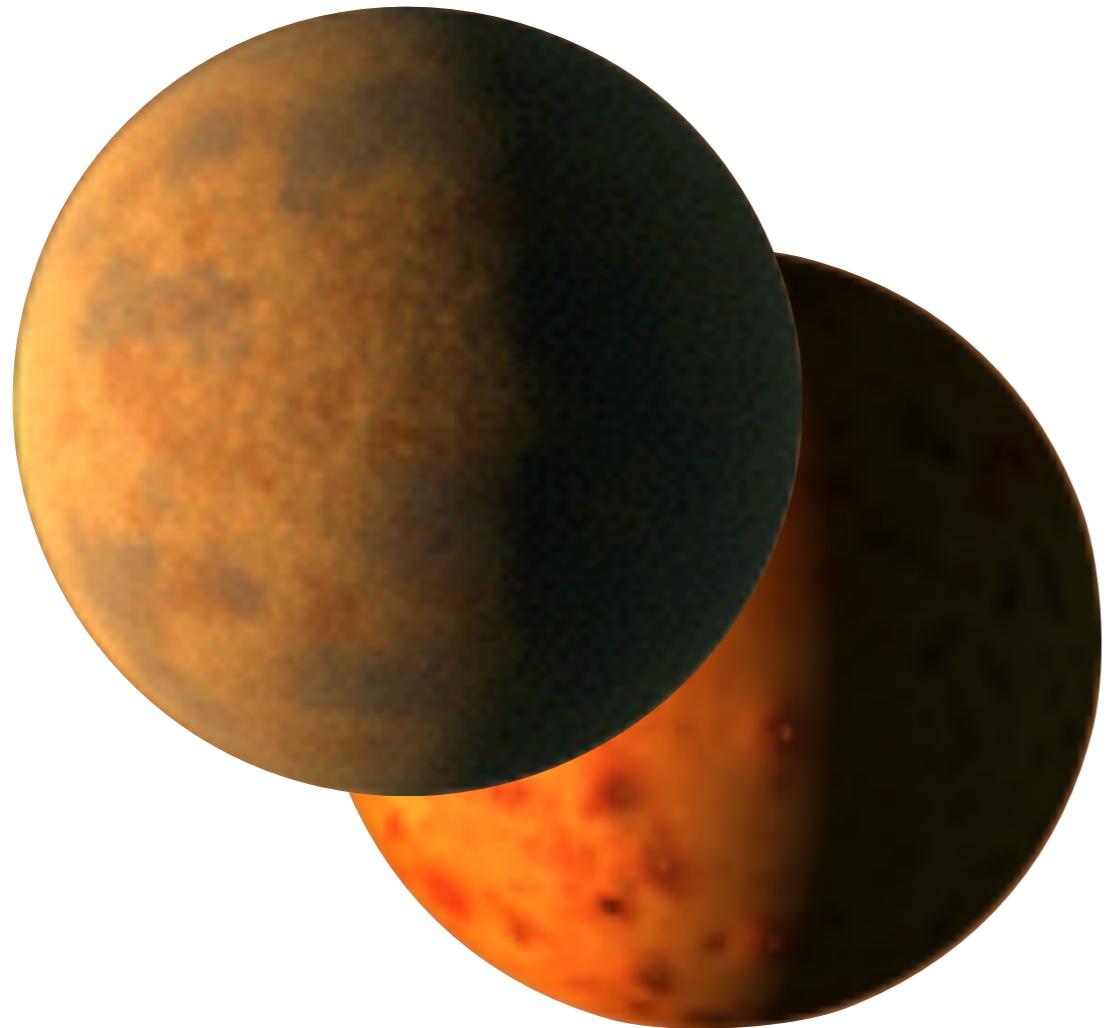
+

planetplanet



## Occultation light curves

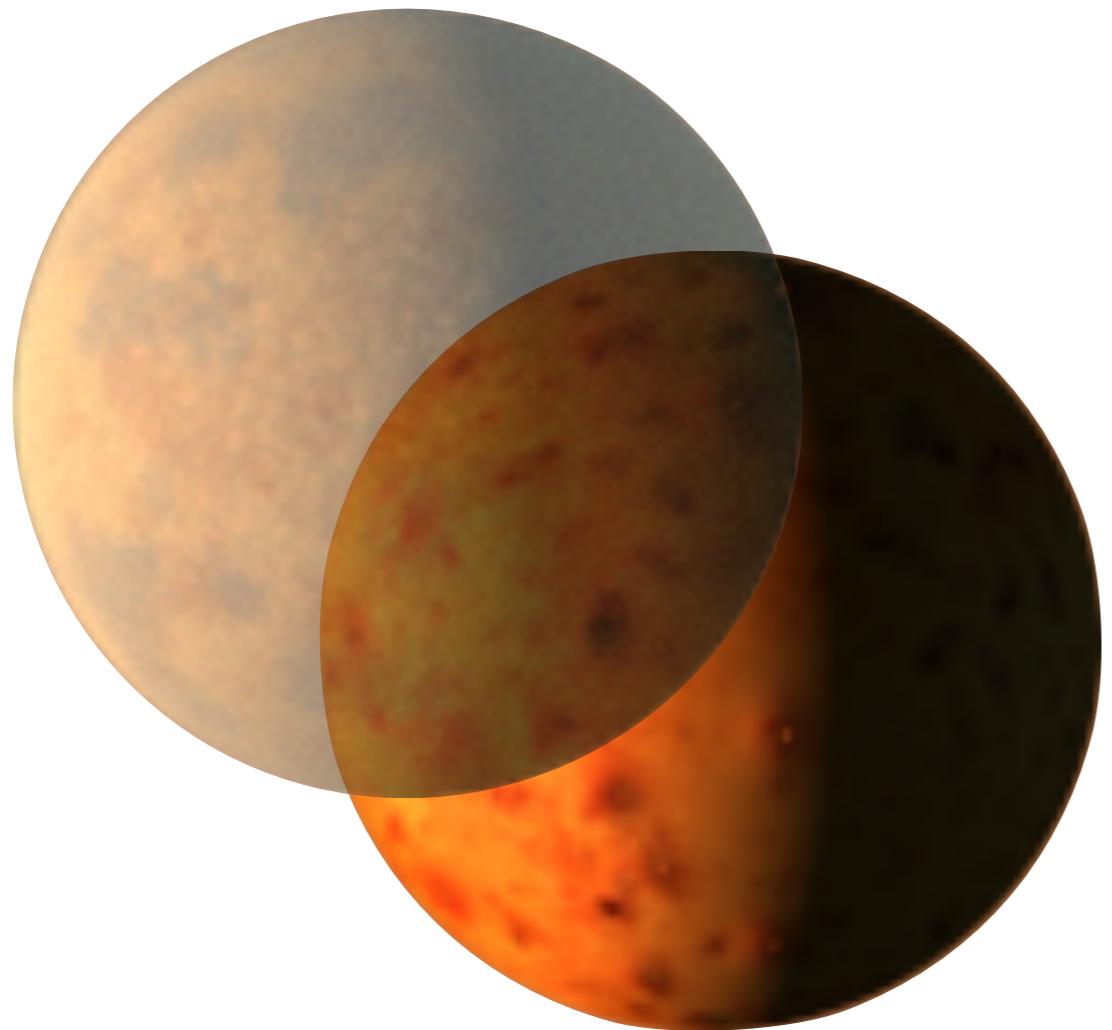
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## Occultation light curves

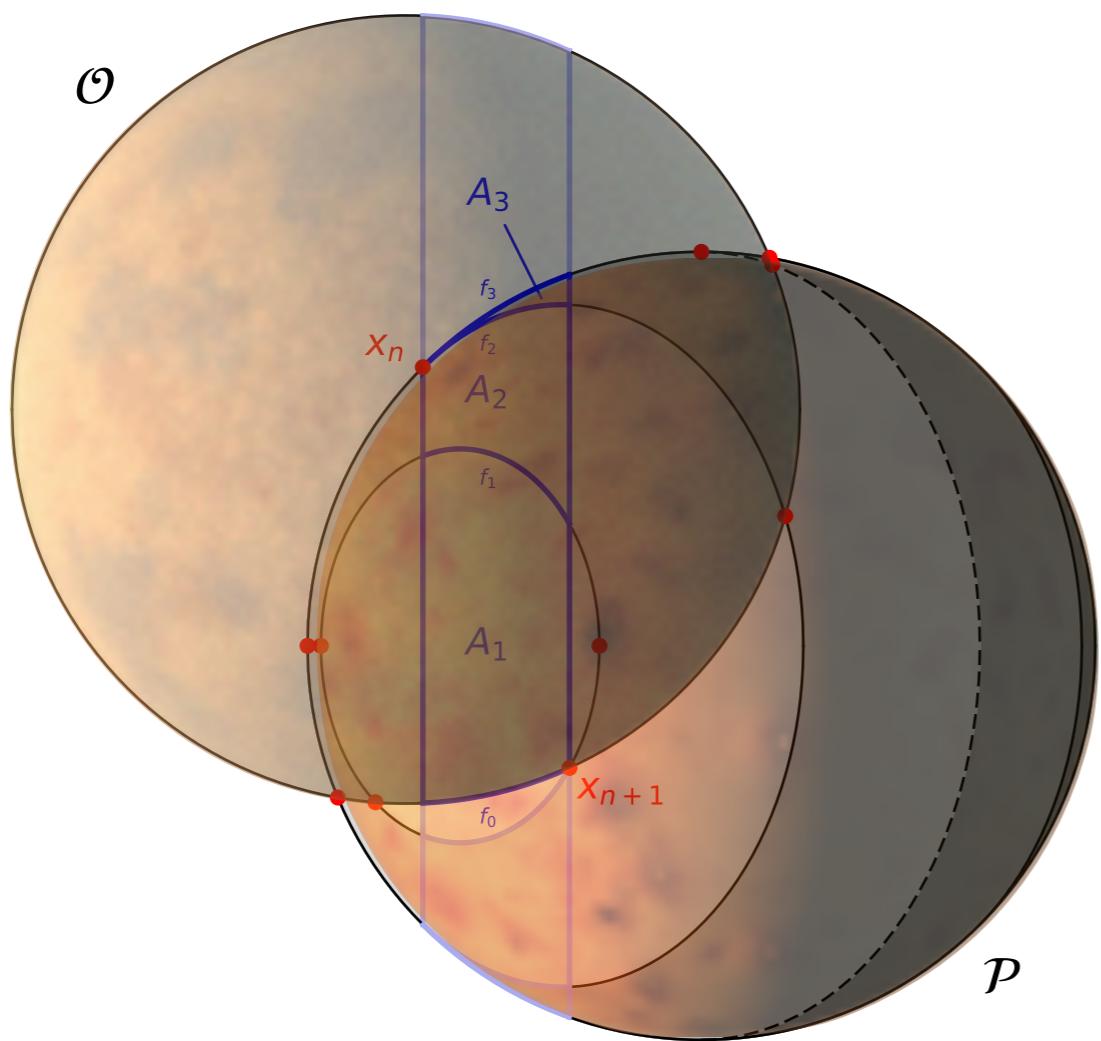
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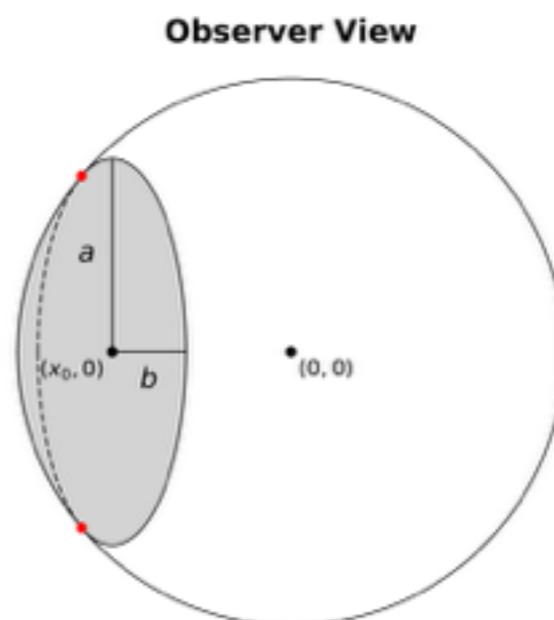
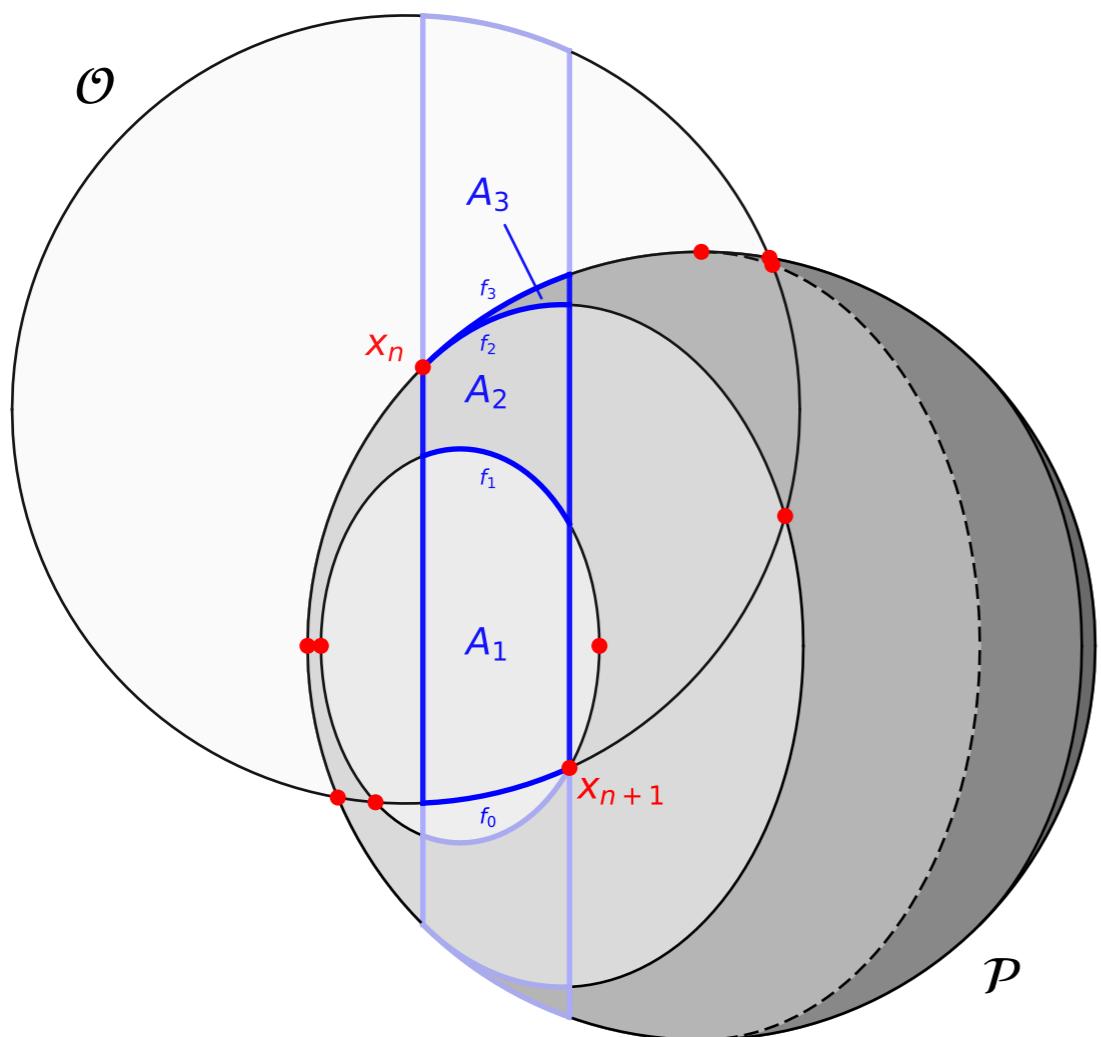
# Occultation light curves

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# Occultation light curves

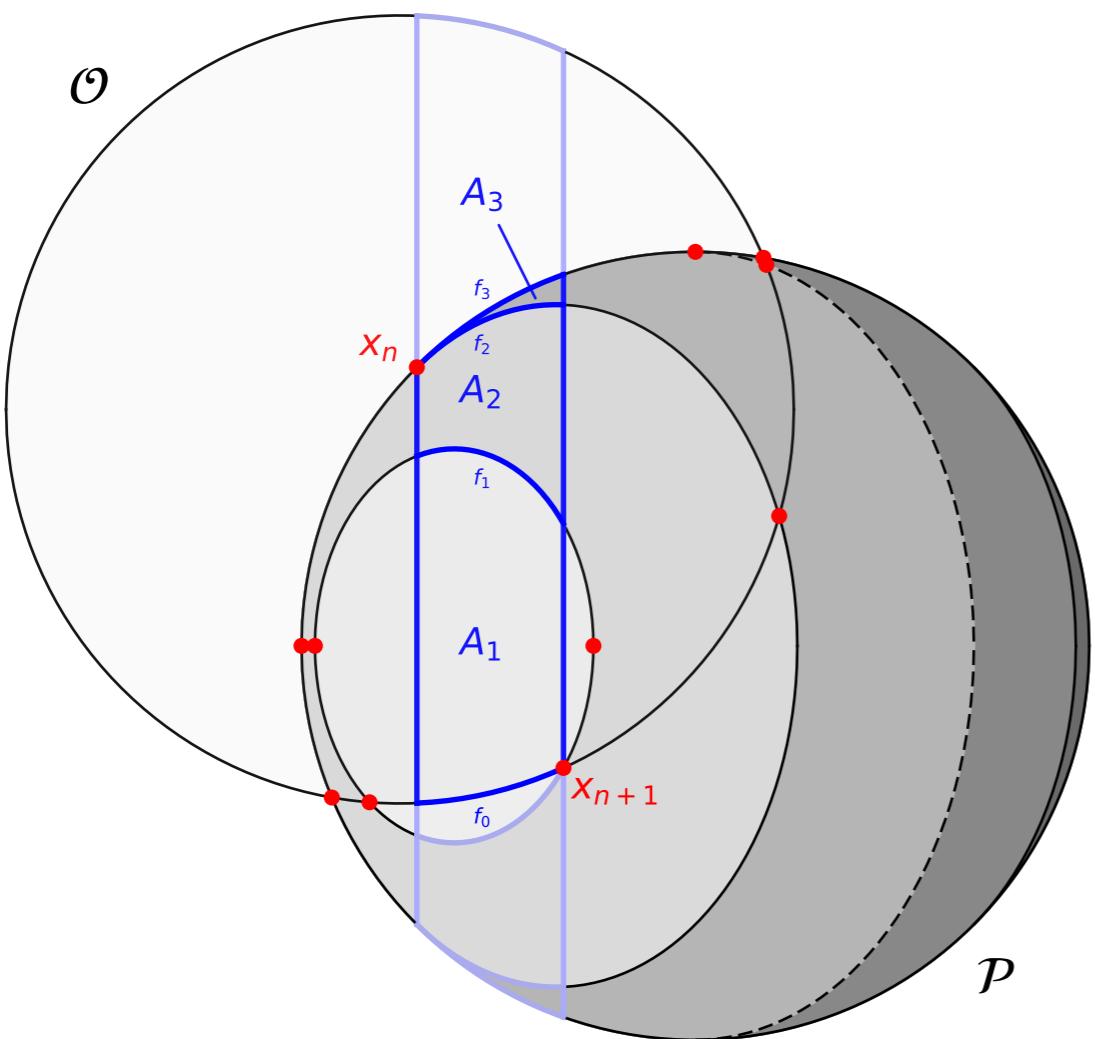


Luger, Lustig-Yaeger, and Agol (2017, *in prep*)

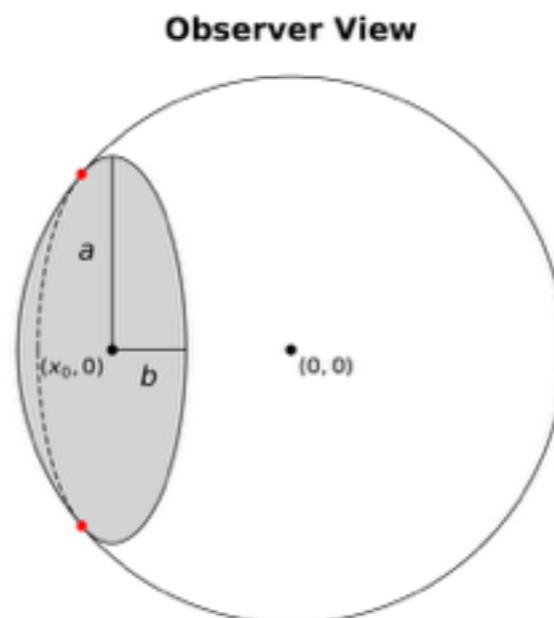


The integral of an ellipse is analytic

$$\int y(x)dx = y_0x \pm \frac{a}{2b} \left[ z(x - x_0) + b^2 \arctan \left( \frac{x - x_0}{z} \right) \right] + C$$



$$z = \sqrt{(b + x - x_0)(b - x + x_0)}$$

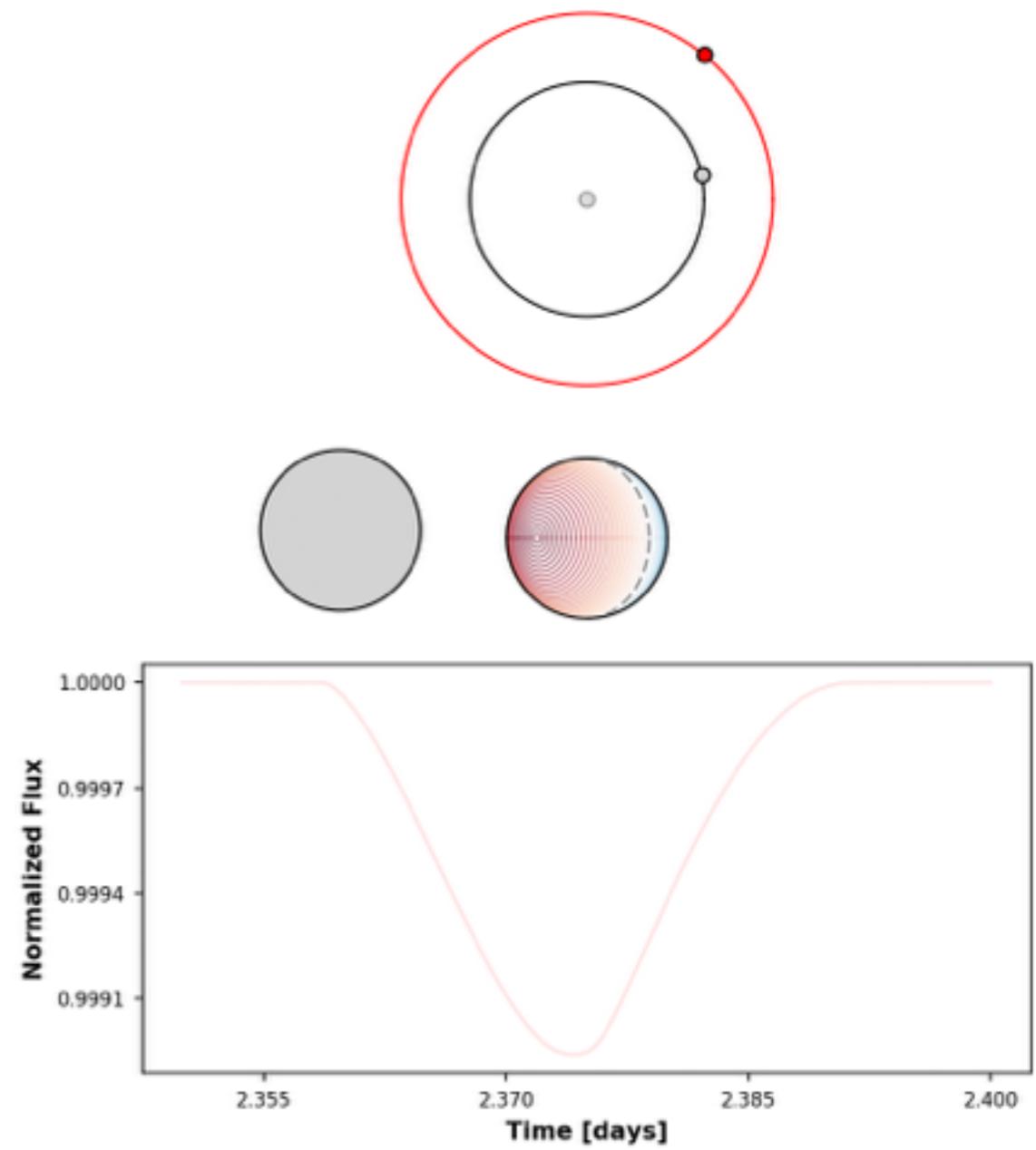
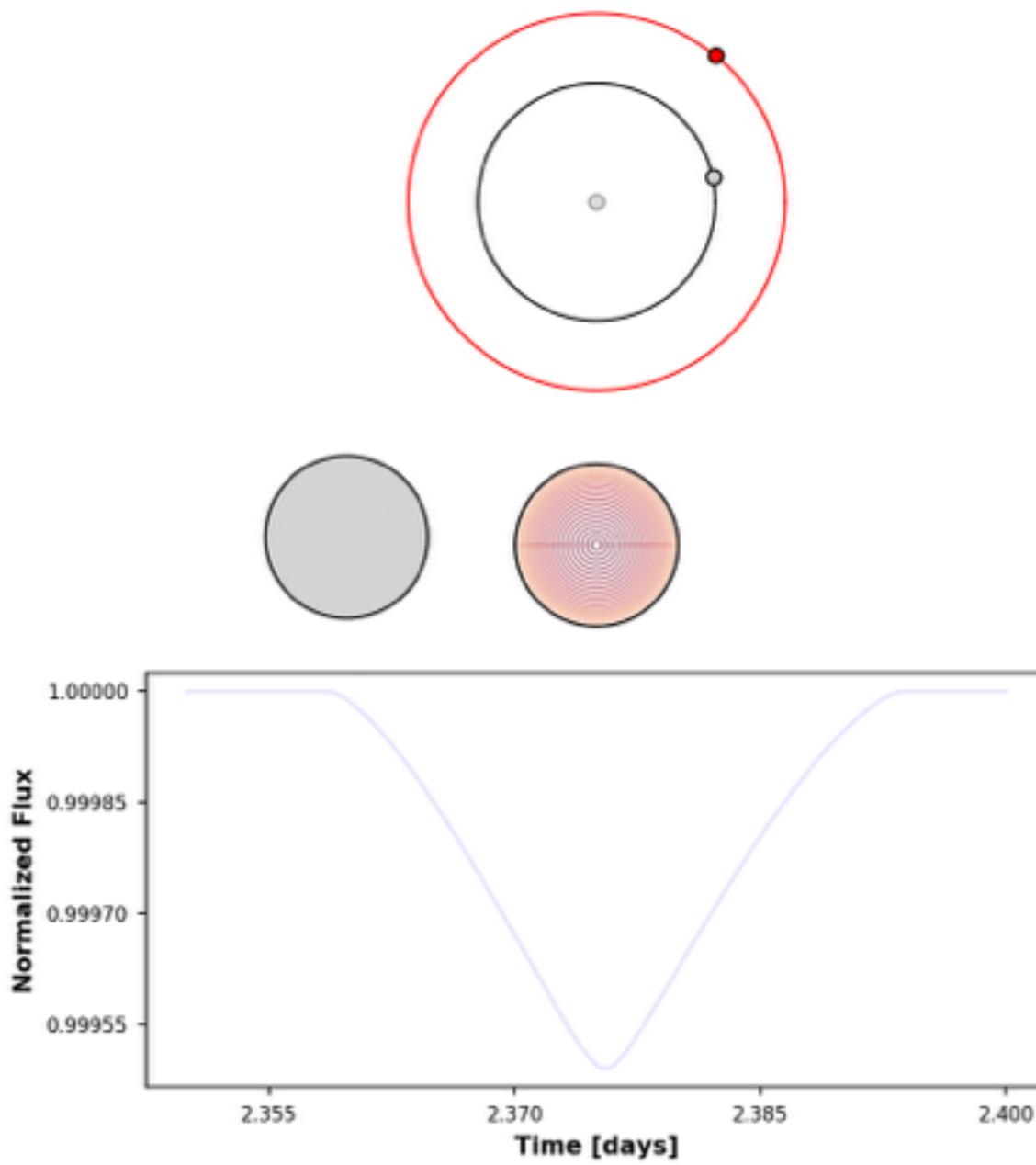


Luger, Lustig-Yaeger, and Agol (2017, in prep)



planetplanet

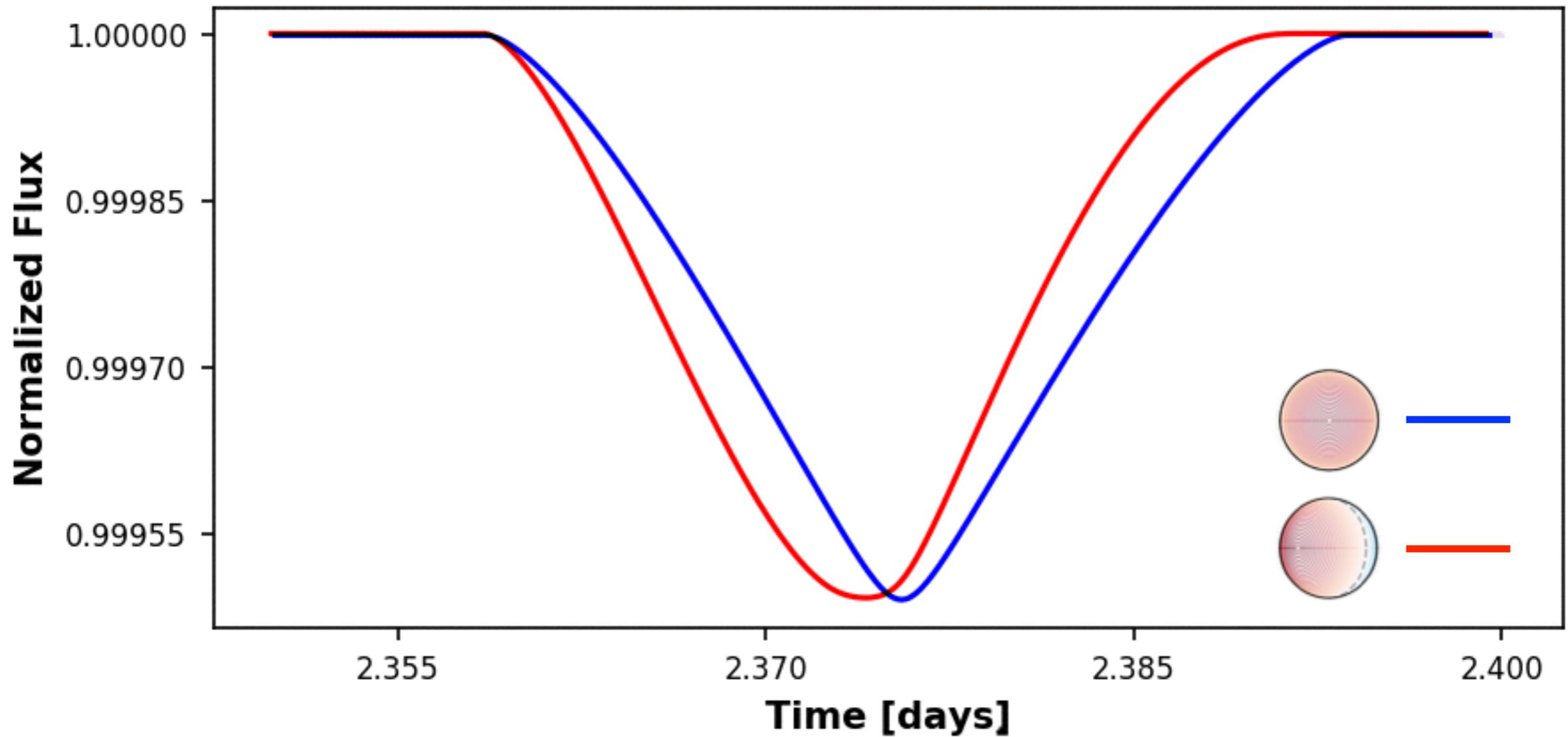
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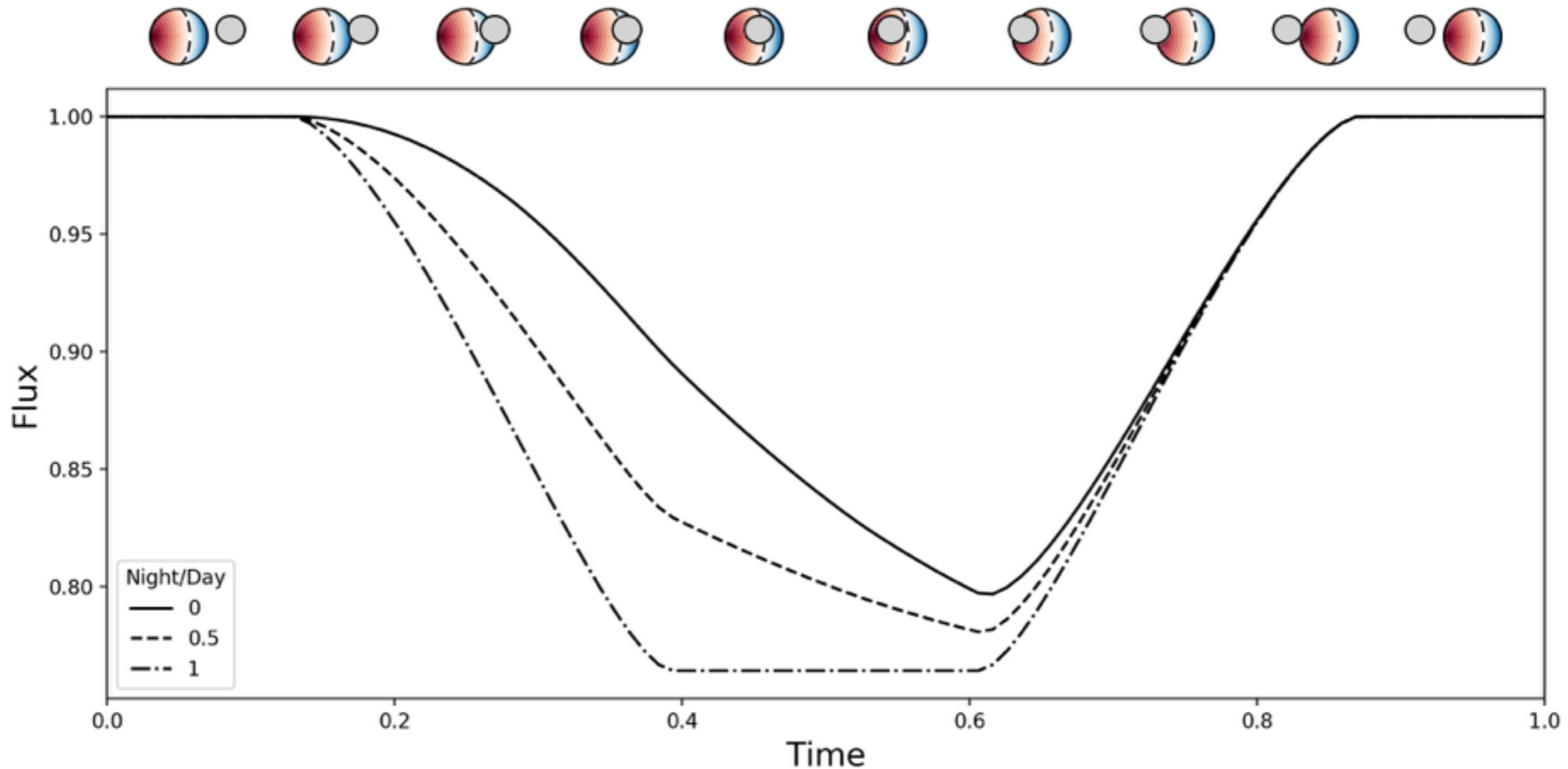
planetplanet

Luger, Lustig-Yaeger, and Agol (2017, *in prep*)





planetplanet





## Planet-planet occultations



*Planet-planet occultations are a direct probe of the day-night temperature contrast*



## Planet-planet occultations

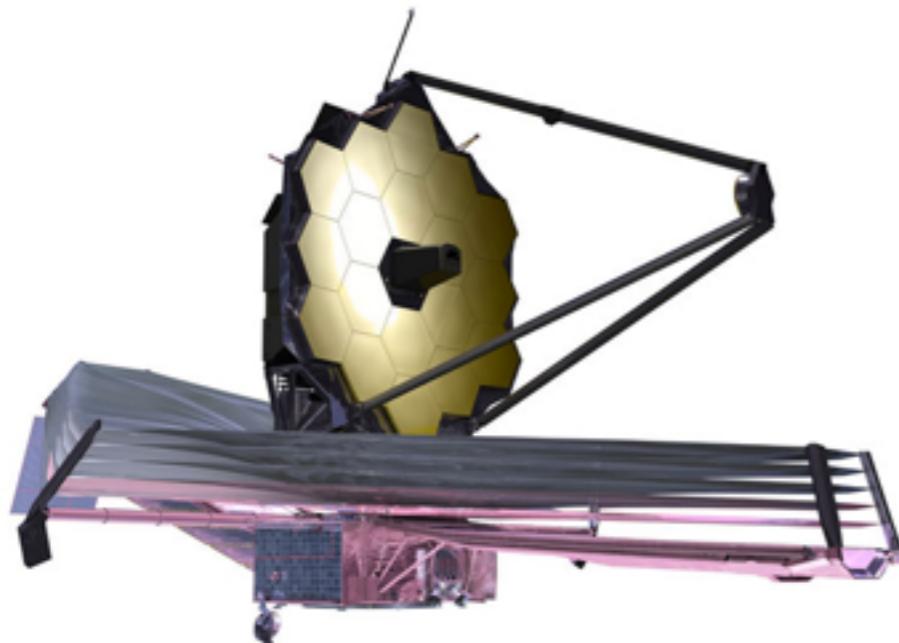


*Occultations between **b** and **c** are  
~200 ppm events at 15 $\mu$ m*

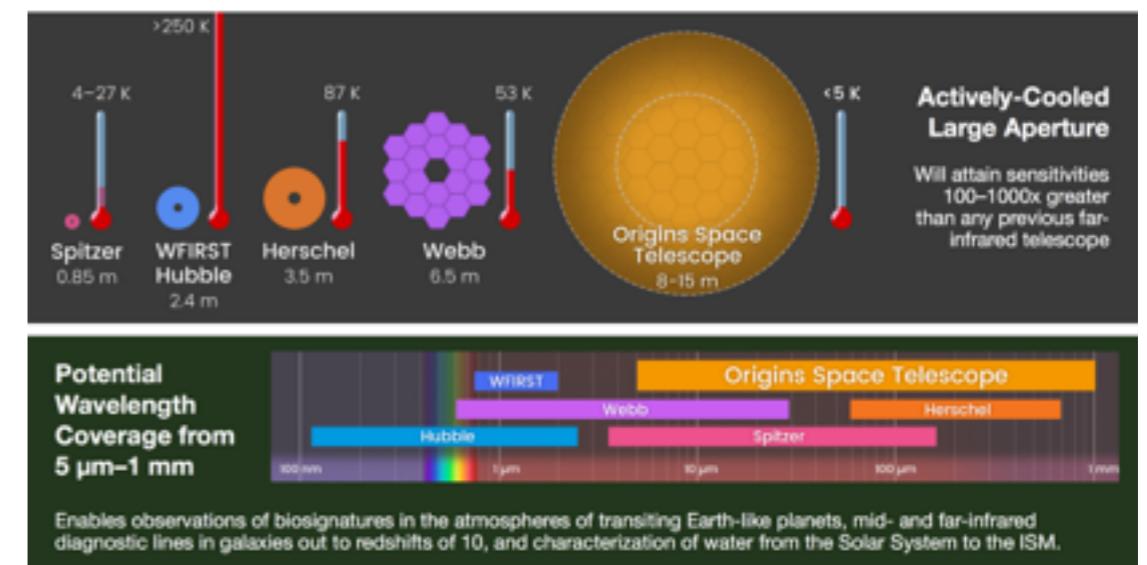


Planet-planet occultations

## JAMES WEBB SPACE TELESCOPE



*3D structure; day-night contrast*



*HZ planets; surface mapping*

## PART h



CONCLUSIONS



## Conclusions

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TRAPPIST-1 hosts seven small planets in a complex chain of 3-body resonances



Planet-planet occultations constrain the 3D architecture of multi-planet systems



Planet-planet occultations are **common** in TRAPPIST-1



Planet-planet occultations probe the day-night temperature contrast



Planet-planet occultations will soon be **detectable**



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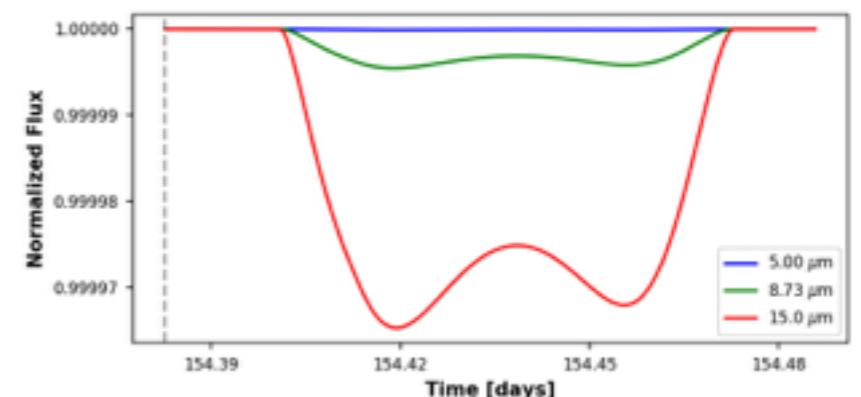
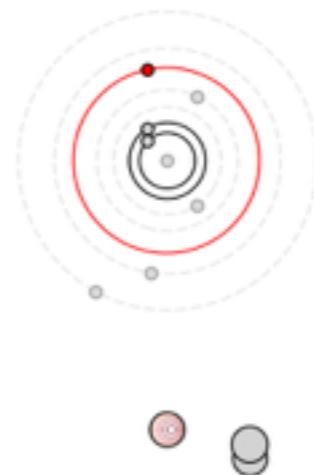


Planet-planet occultations probe the day-night temperature contrast



Planet-planet occultations will soon be **detectable**

**f occulted by c, b**  
Duration: 104.07 minutes



*Luger, Lustig-Yaeger, and Agol (2017, in prep)*