Finding Young Transiting Planets

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Major contributions from the Zodiacal Exoplanets in Time (ZEIT) and TESS Hunt for Young and Maturing Exoplanets (THYME) teams.

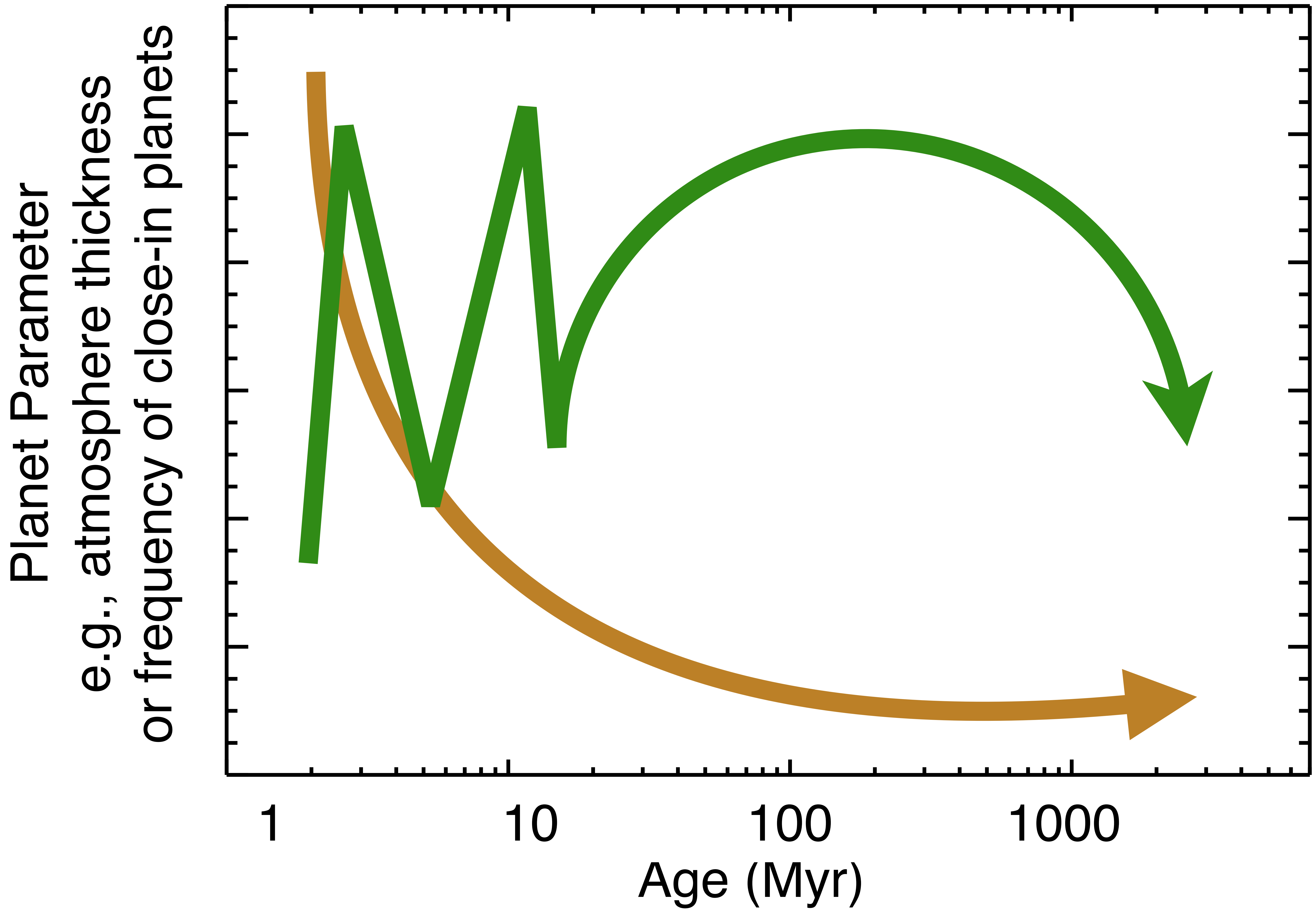
Sagan Workshop
July 2021

Why are we looking for young (transiting) planets?

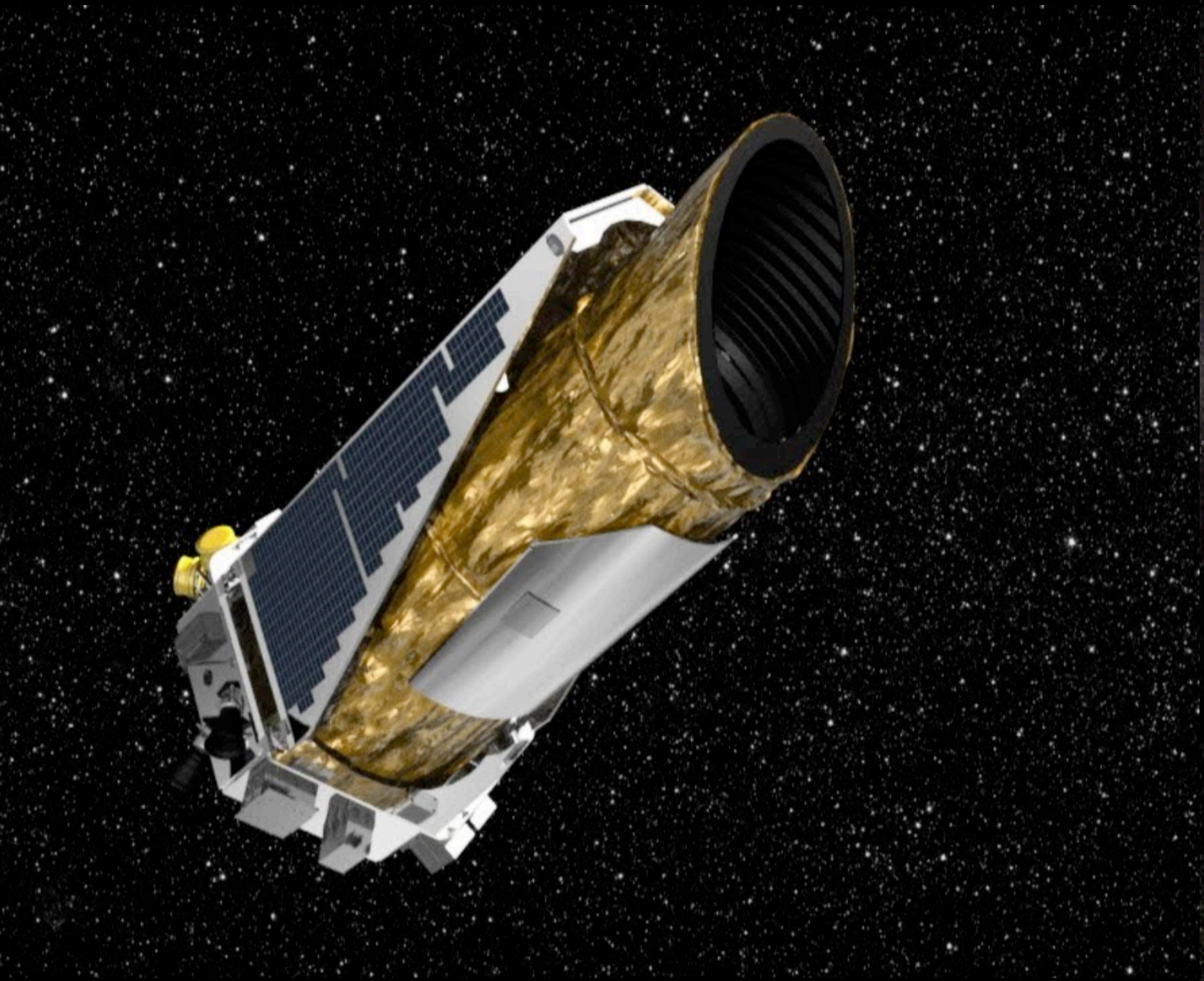
The answer sets the requirements for *how* we search.

Credit: NASA/FUSE/Lynette Cook

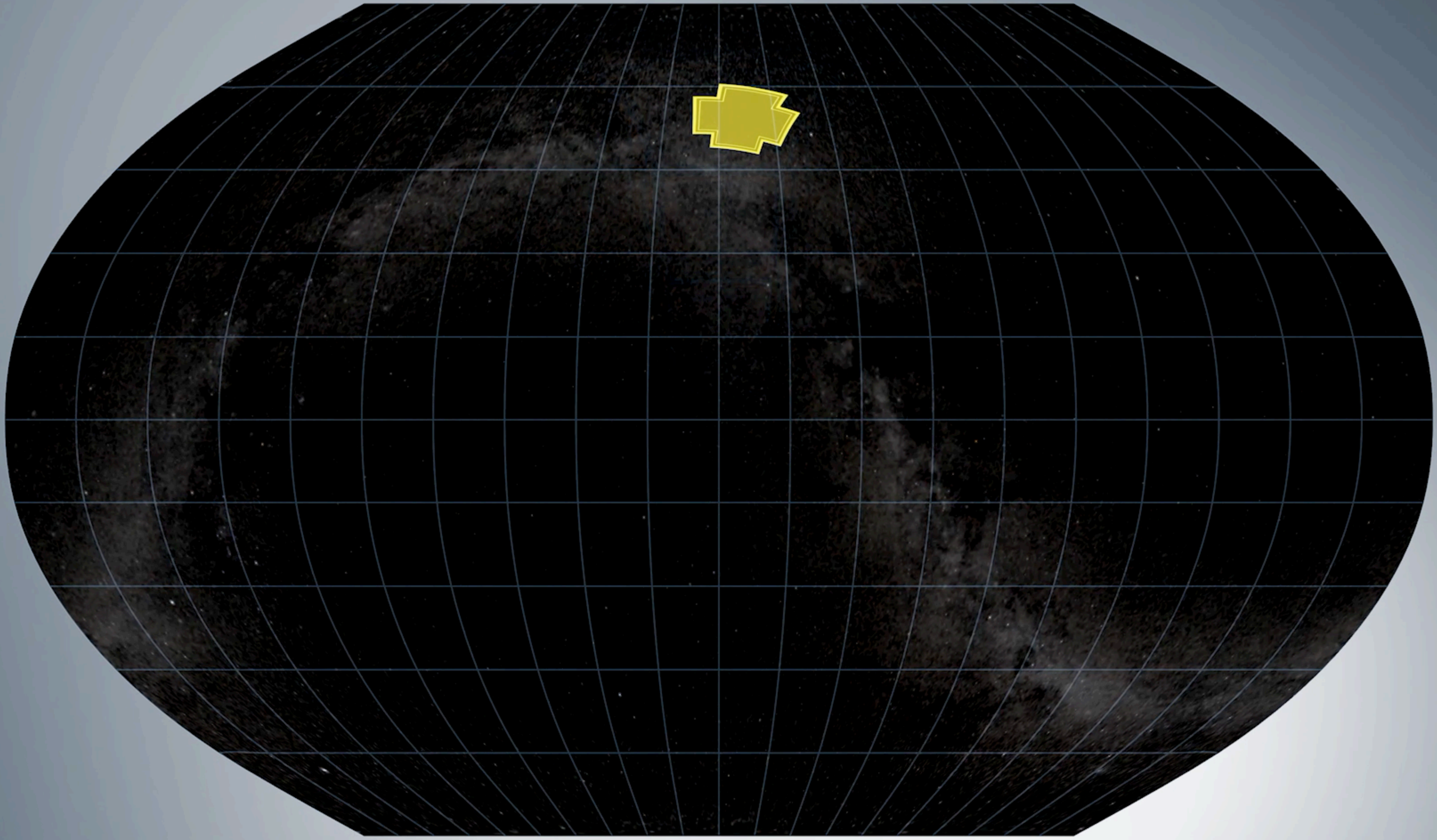
Statistical changes in planet properties with time



Kepler (and K2)

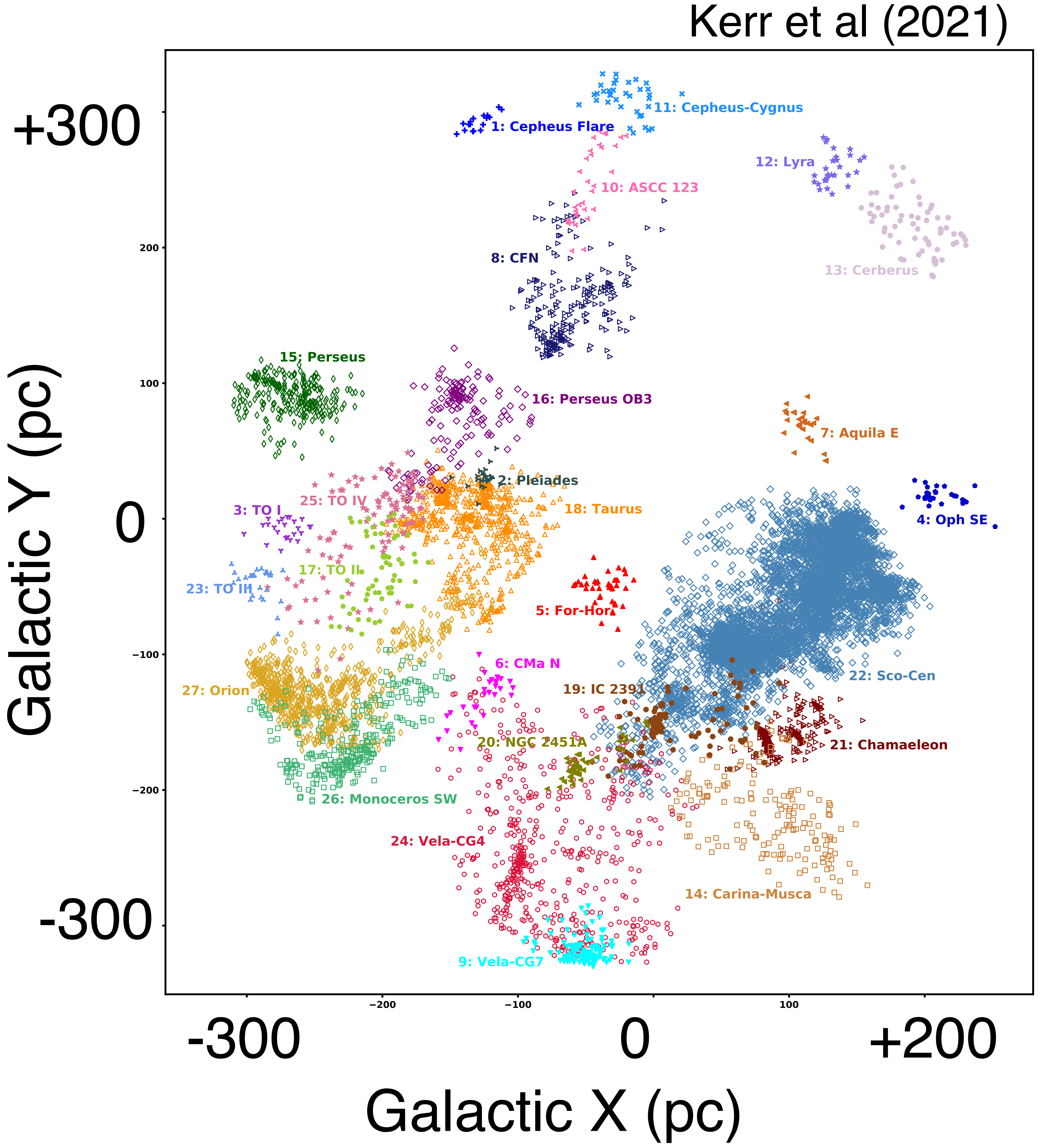


TESS



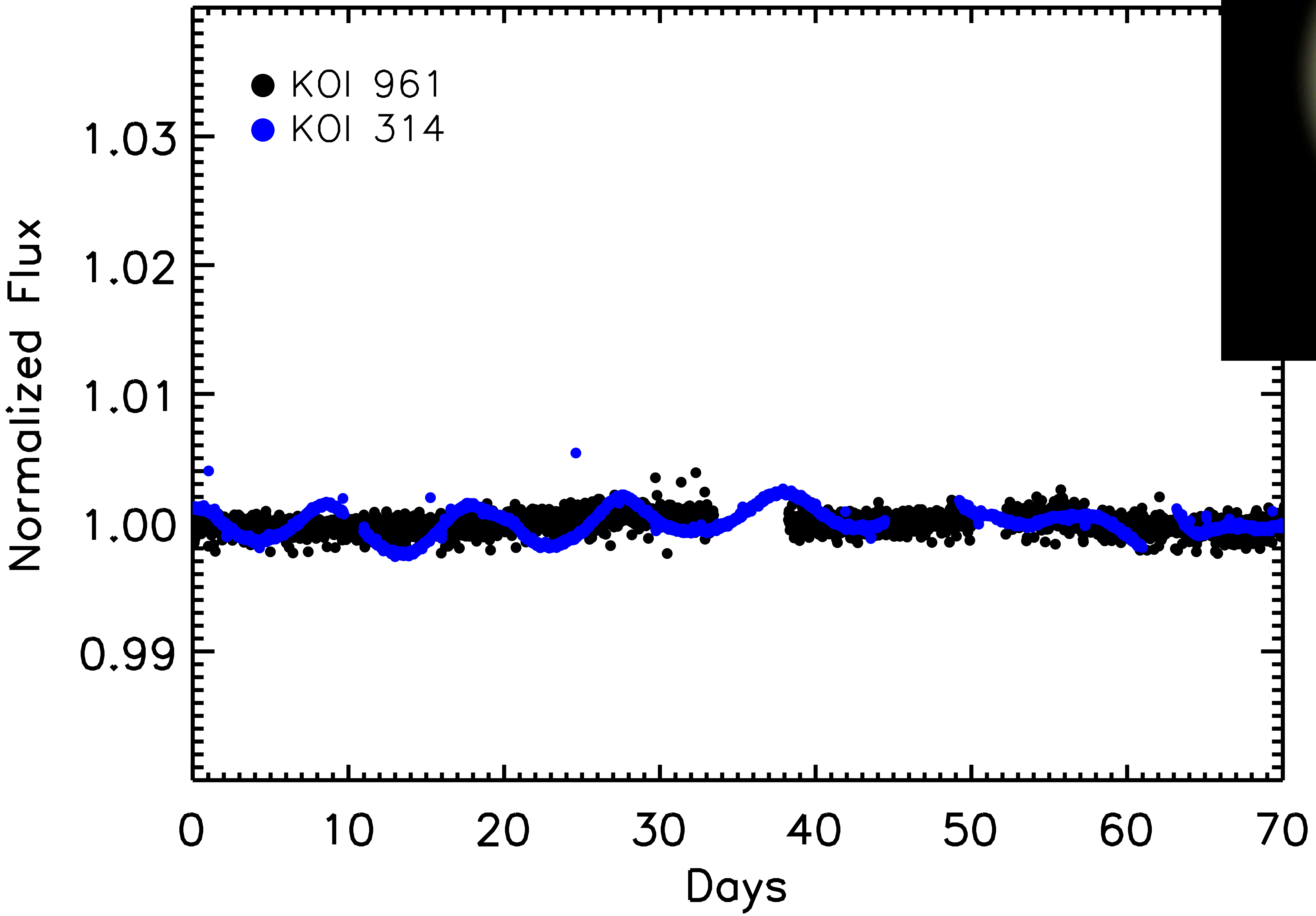
Credit: NASA/JPL-Caltech/T. Pyle, J. Vargas (IPAC)

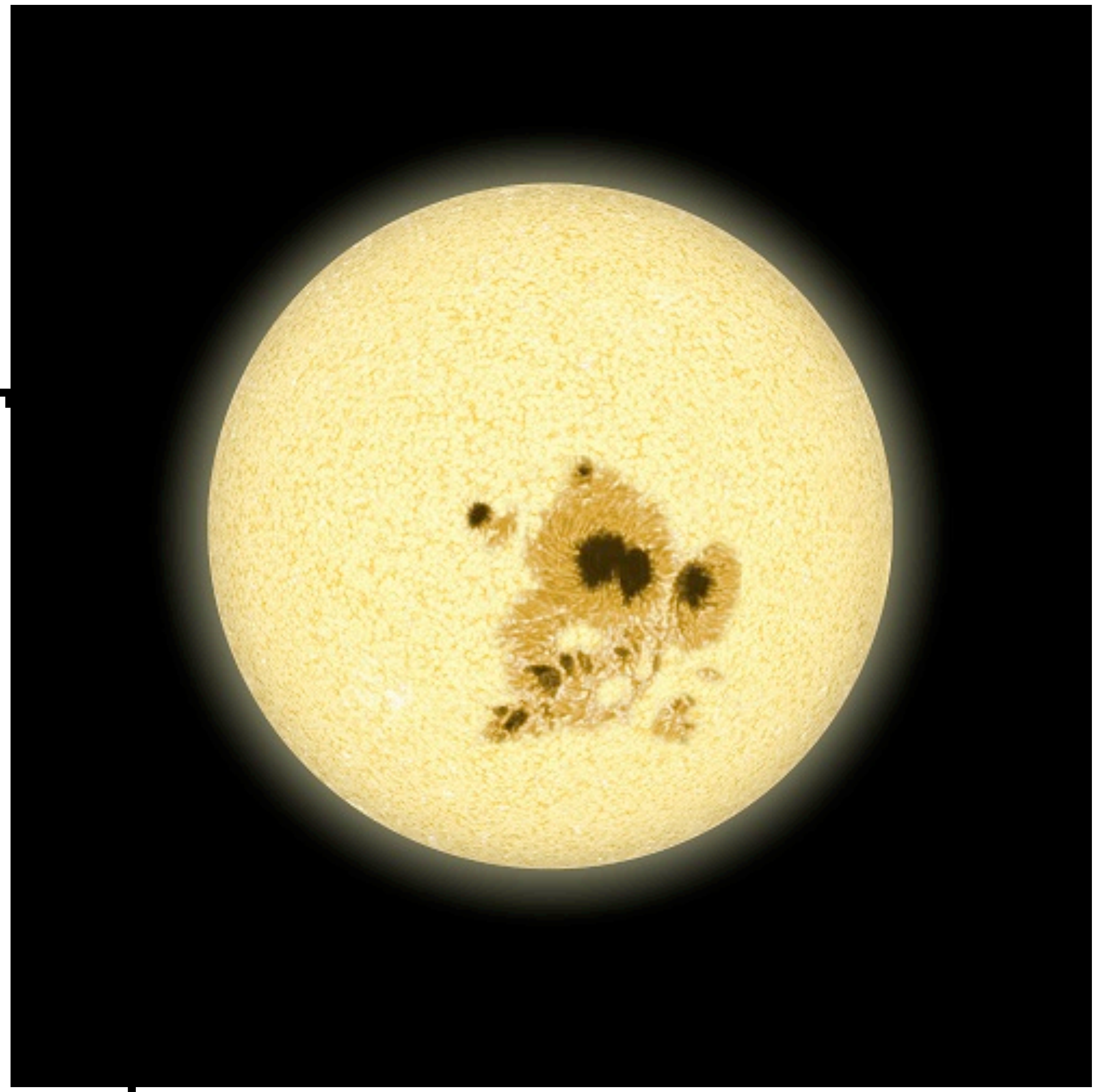
Coverage from *TESS* and *K2* is such that most of the nearby young stellar associations have light curves.



Credit: exoplanets.nasa.gov

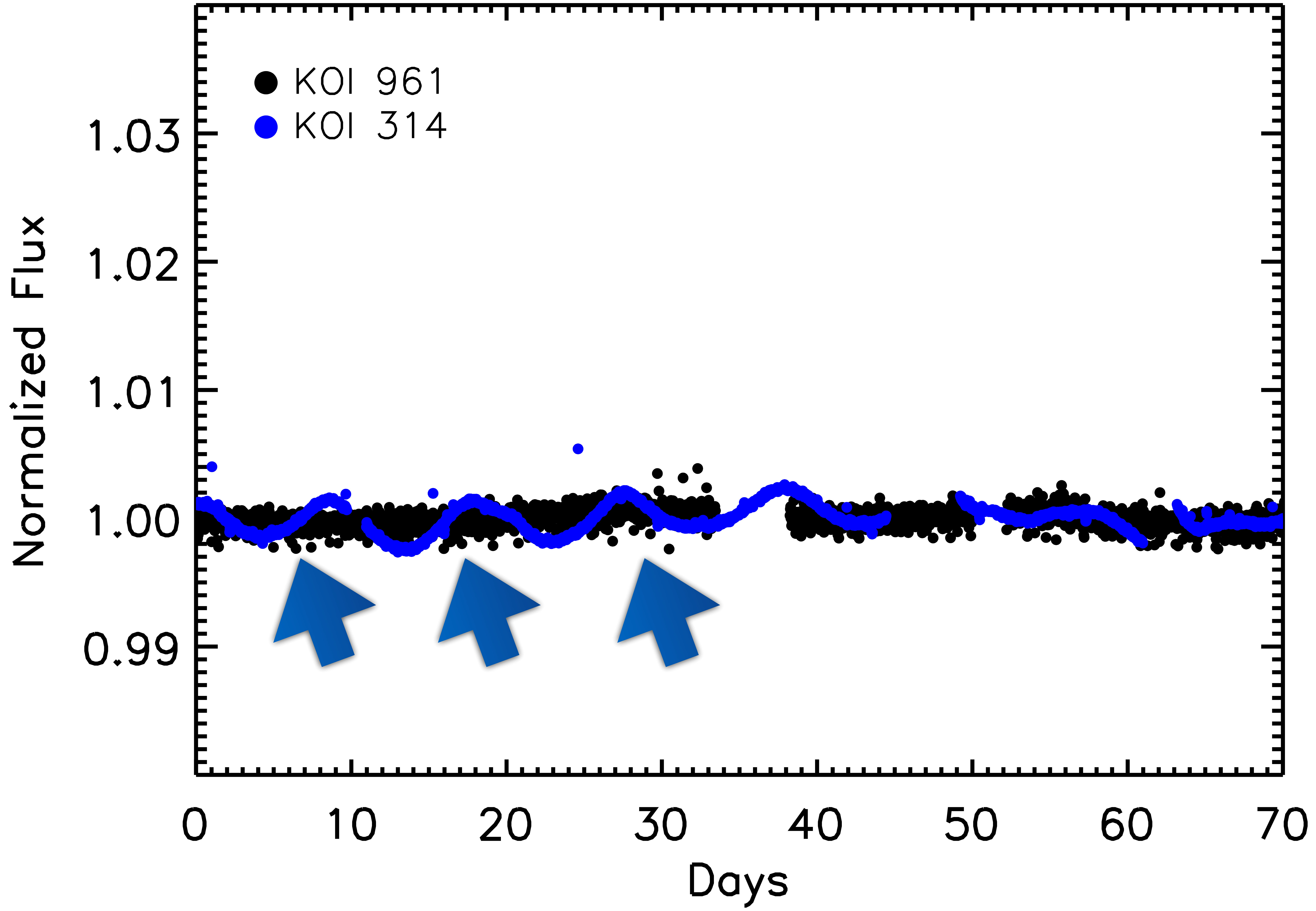
Stellar variability for old stars





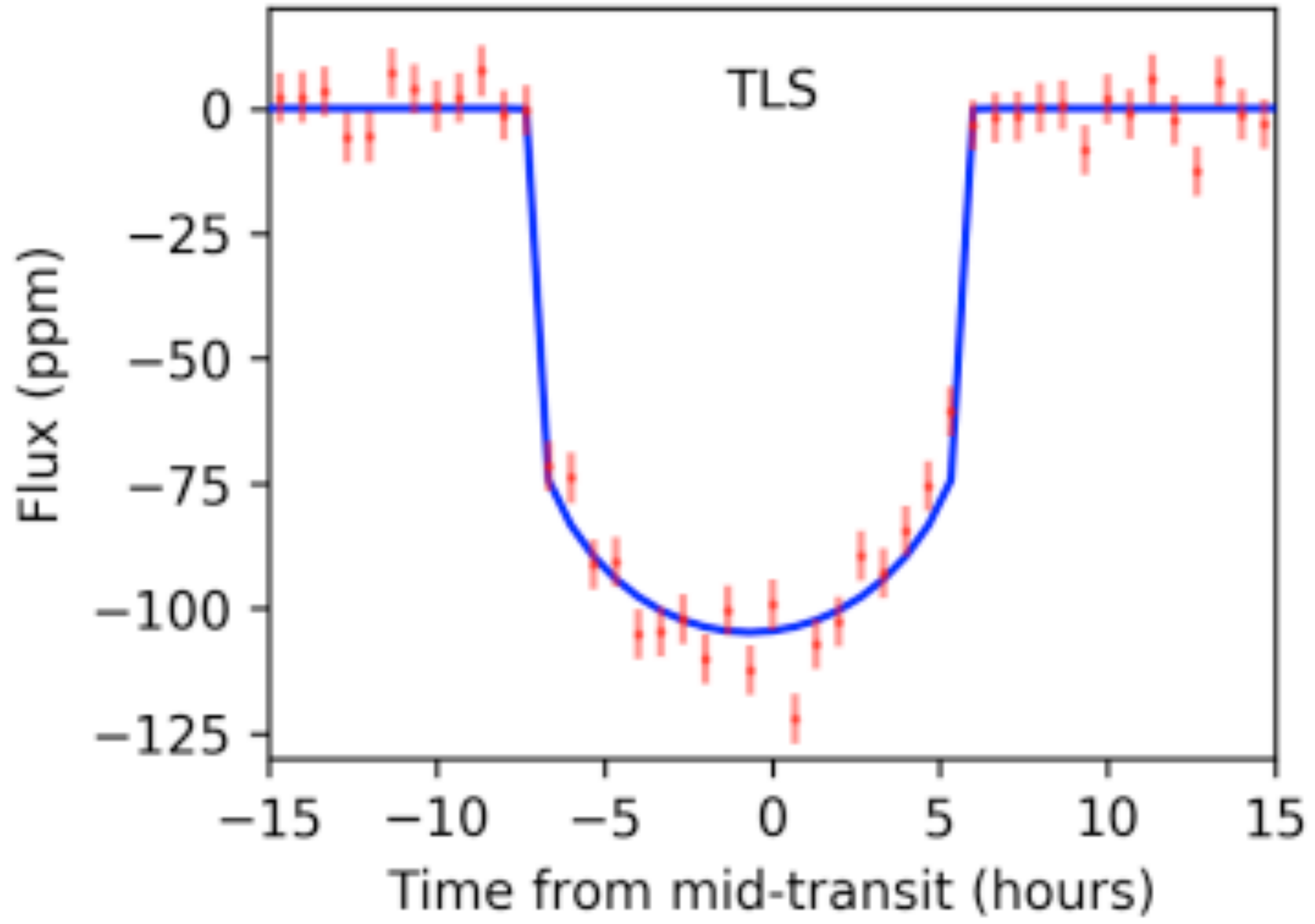
Credit: David A. Aguilar (CfA)

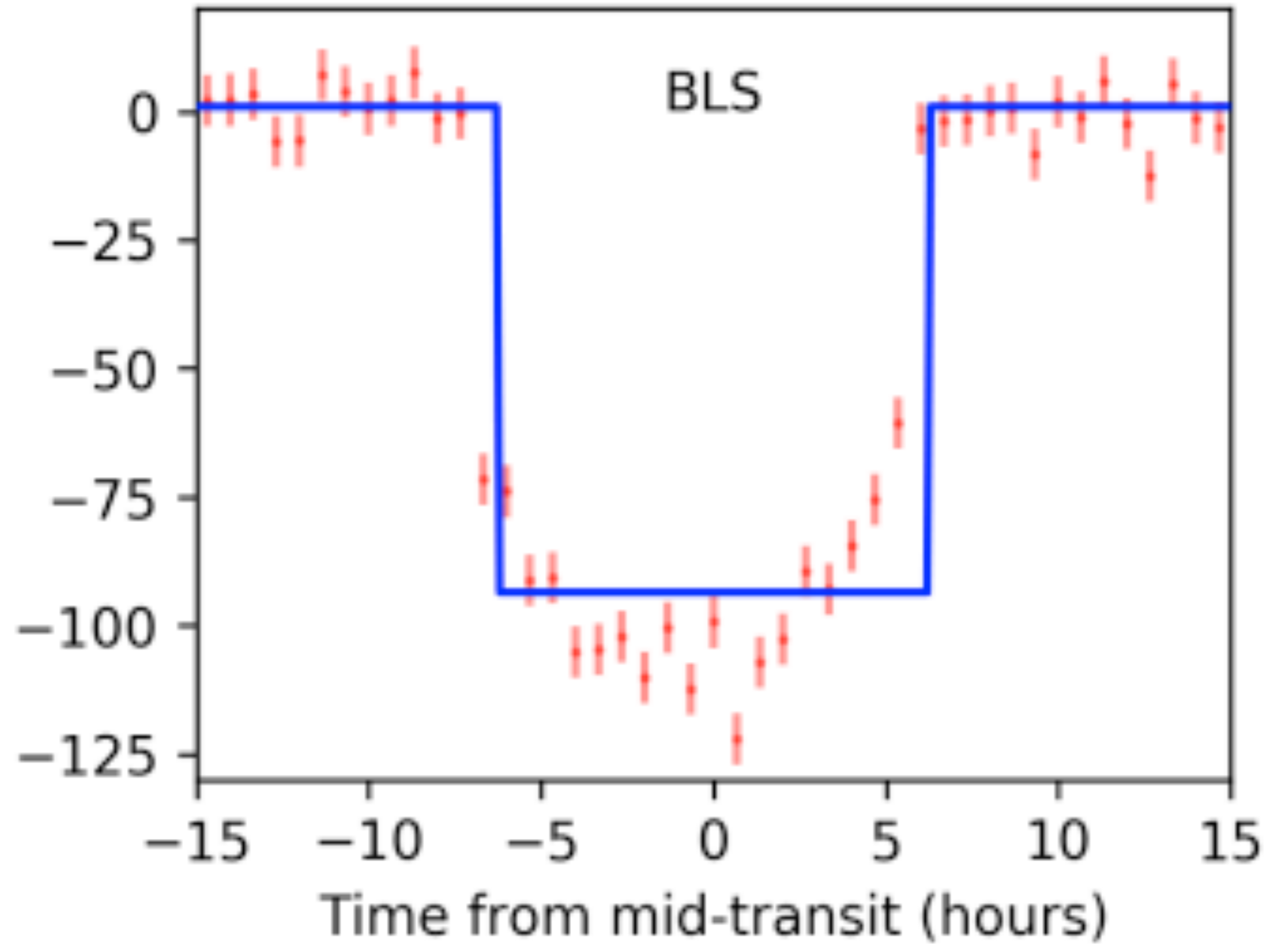
Stellar variability for old stars



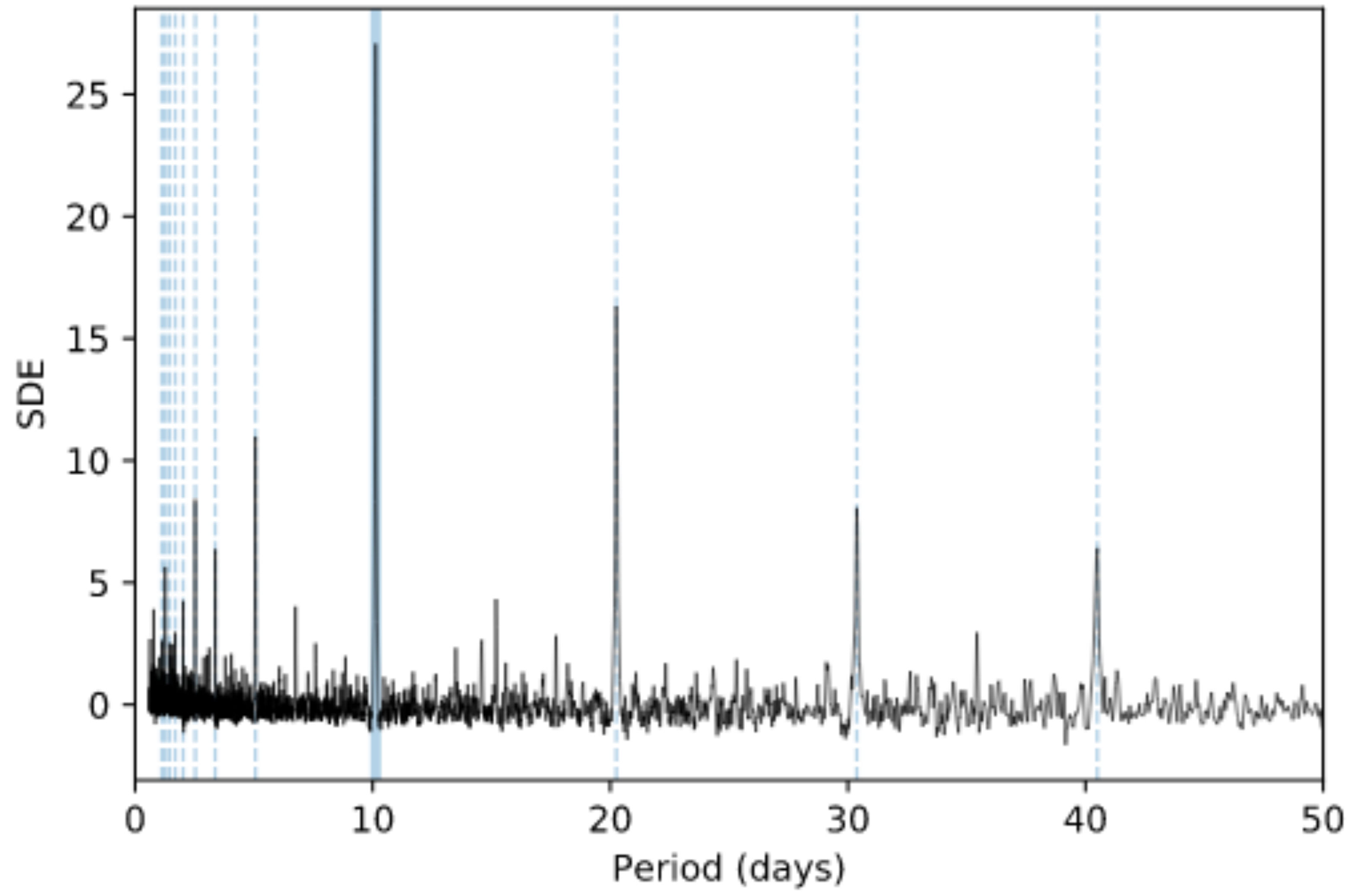
In the absence of stellar variation, finding planet(s) is (comparatively) easy

Transit least squares
(Hippie & Heller 2019)



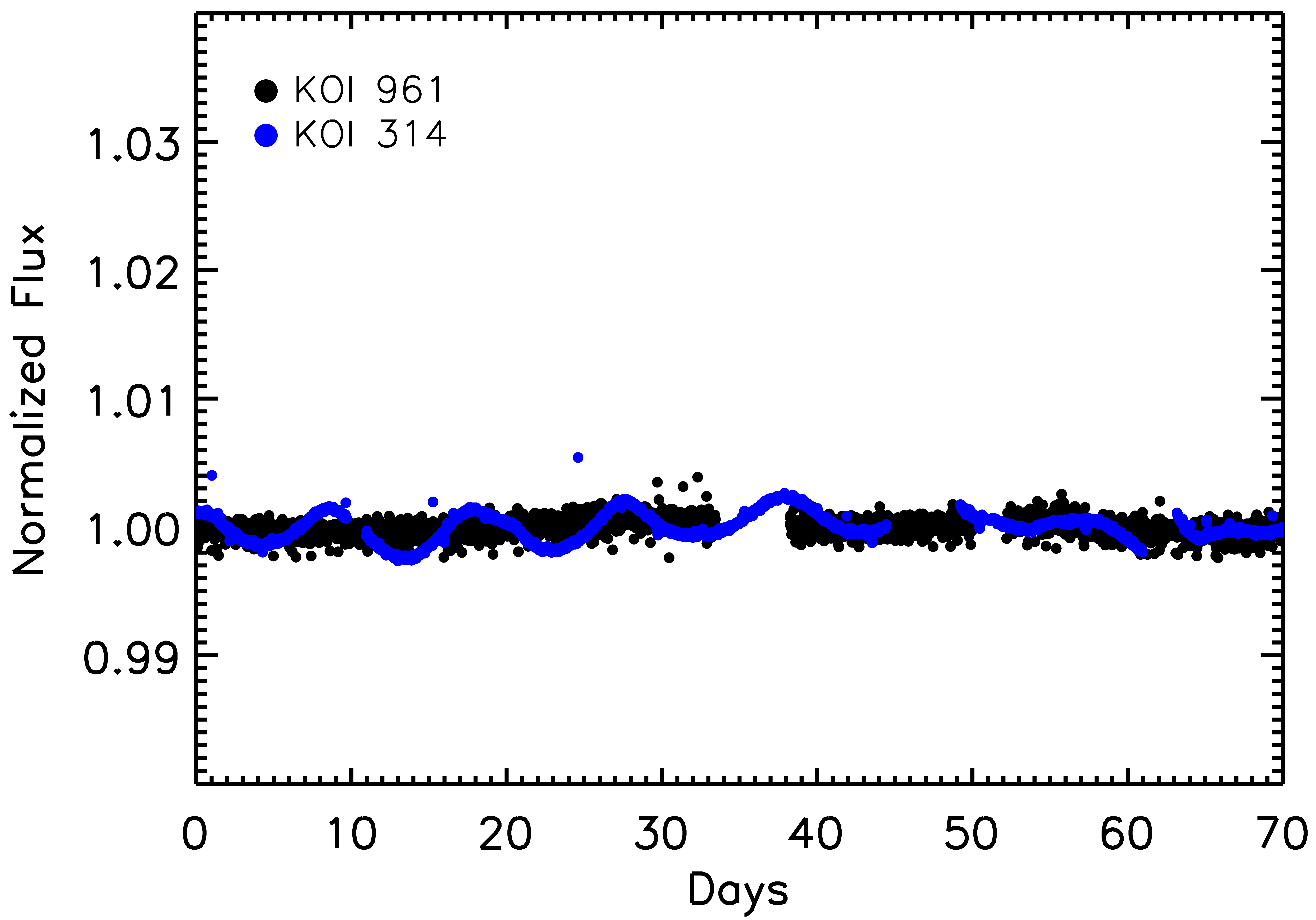


Box least squares
(Kovács et al. 2002)

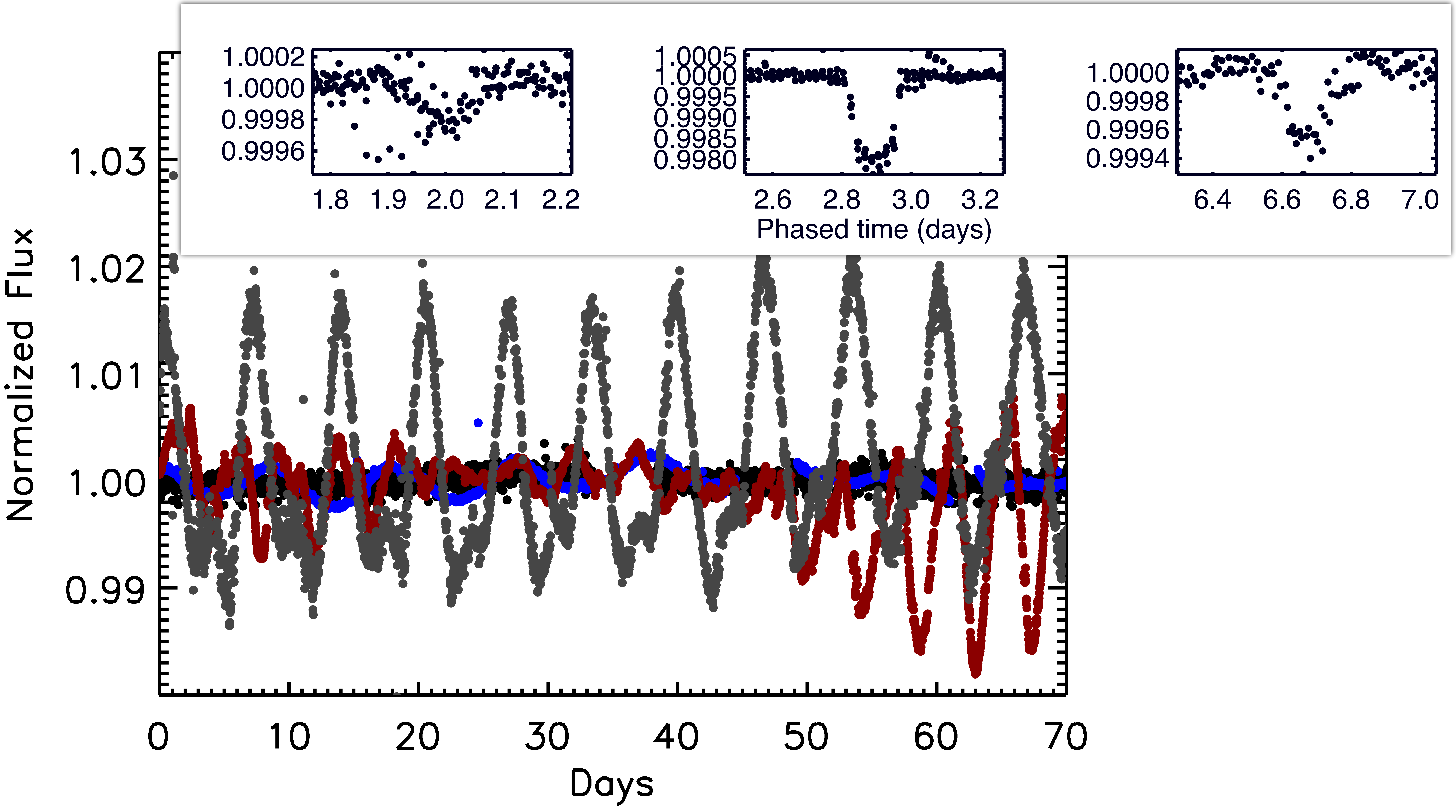



Spots
Disks
Flare

Stellar variability for old stars

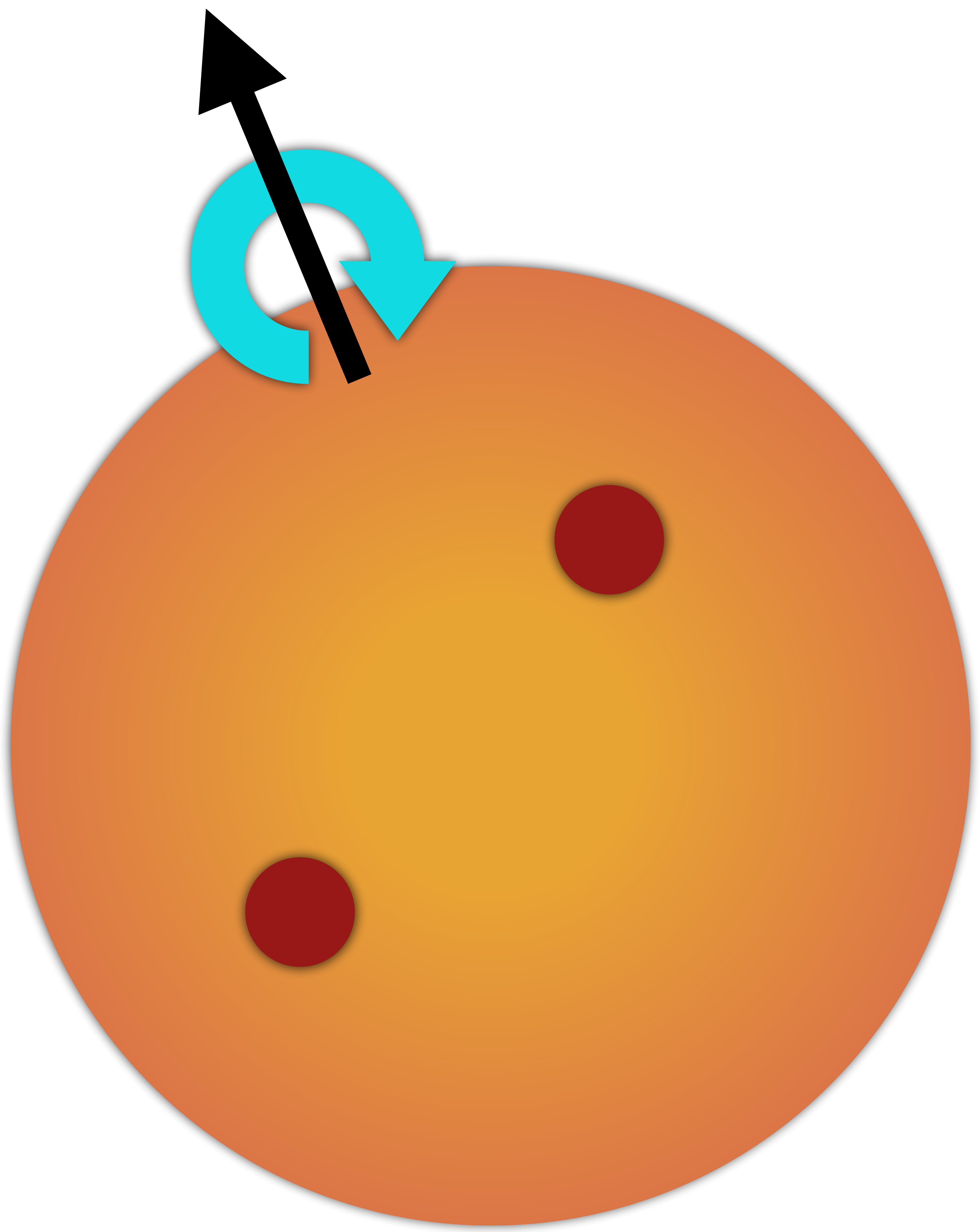


Compared to variability in young stars

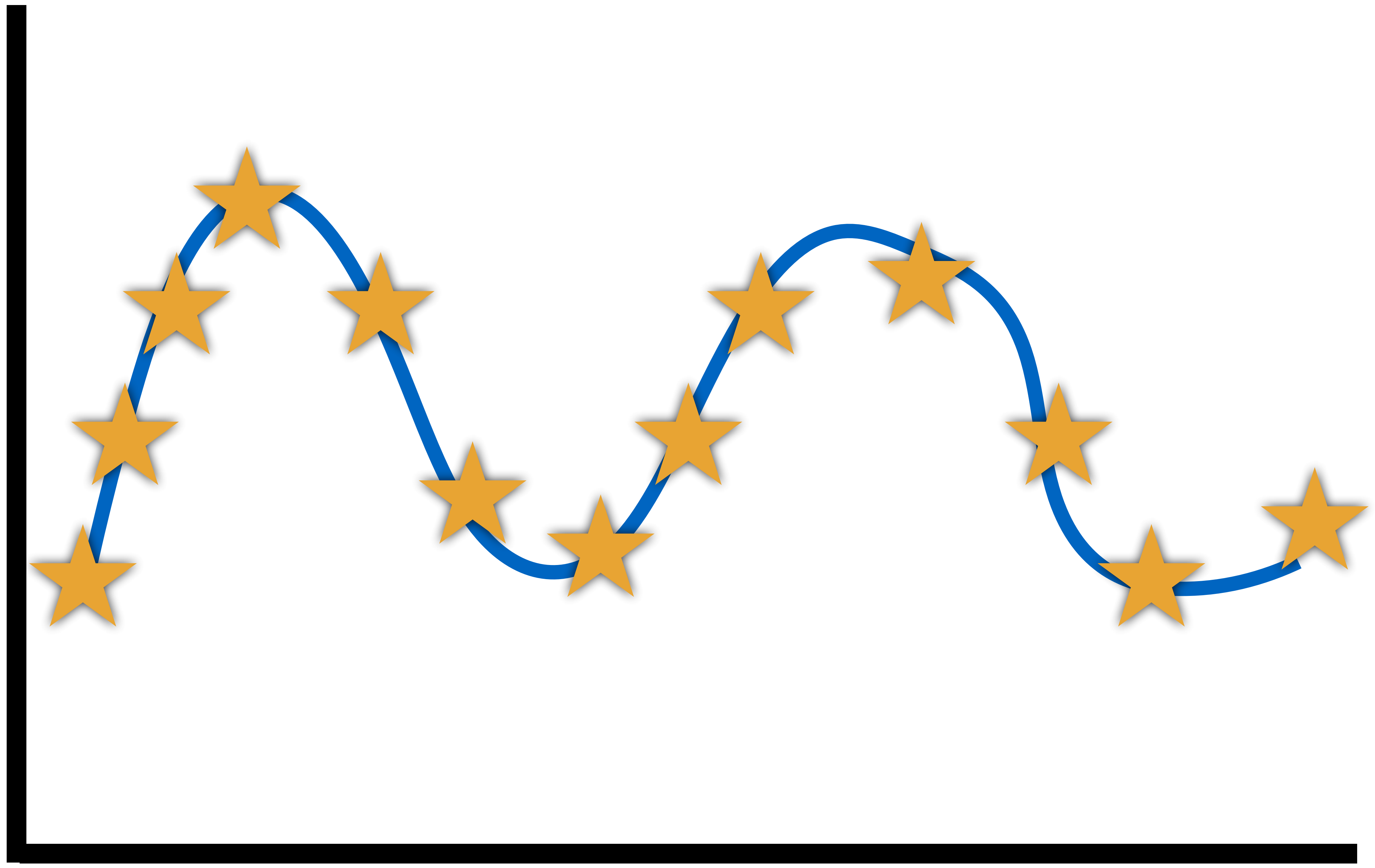


Removing stellar variability to search for transits

What about a physical model?



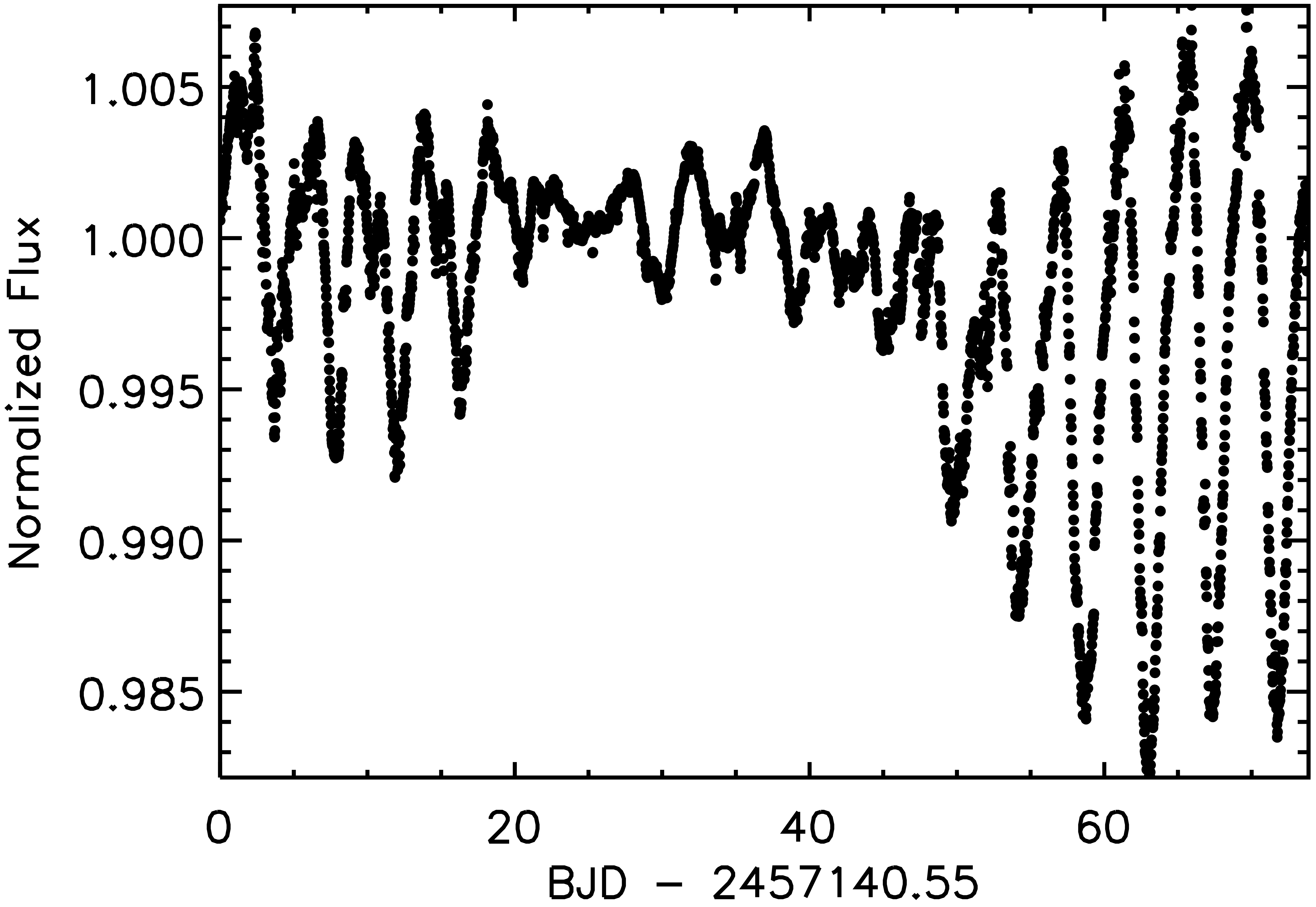
Number of spots
Spot size
Spot contrast
Spot position



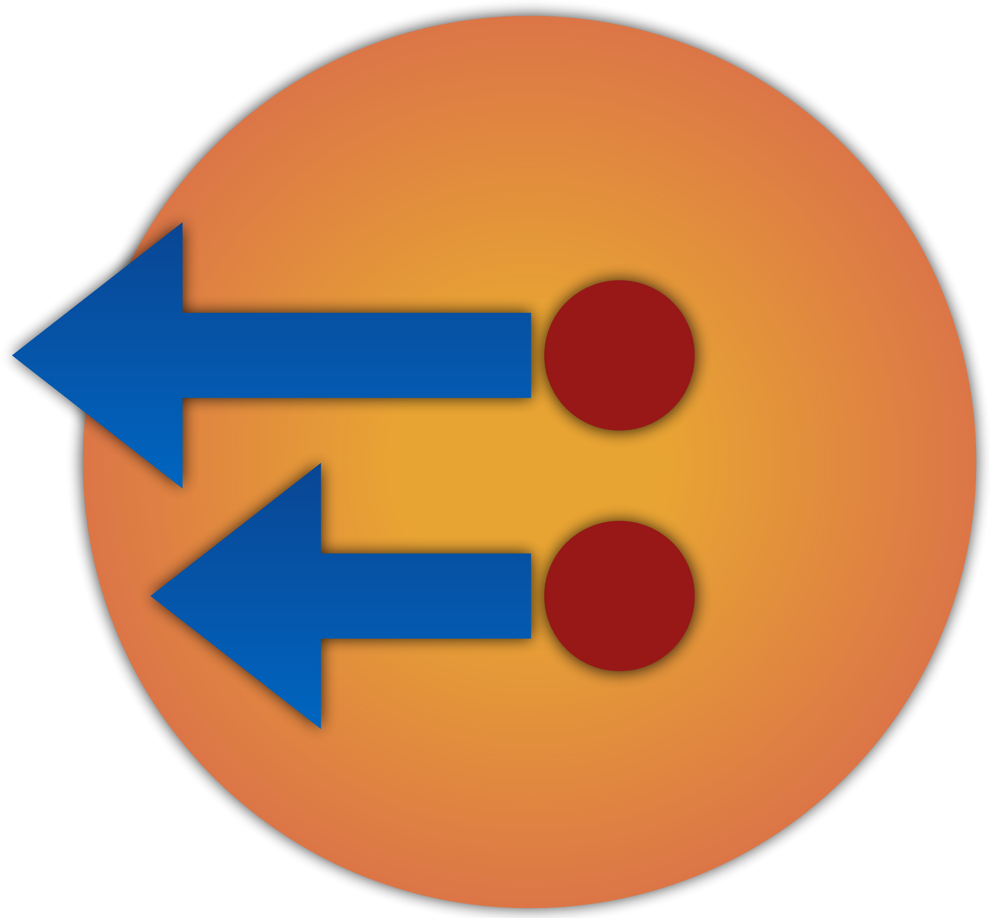
Fleck (Morris 2020):
https://github.com/bmorris3/fleck

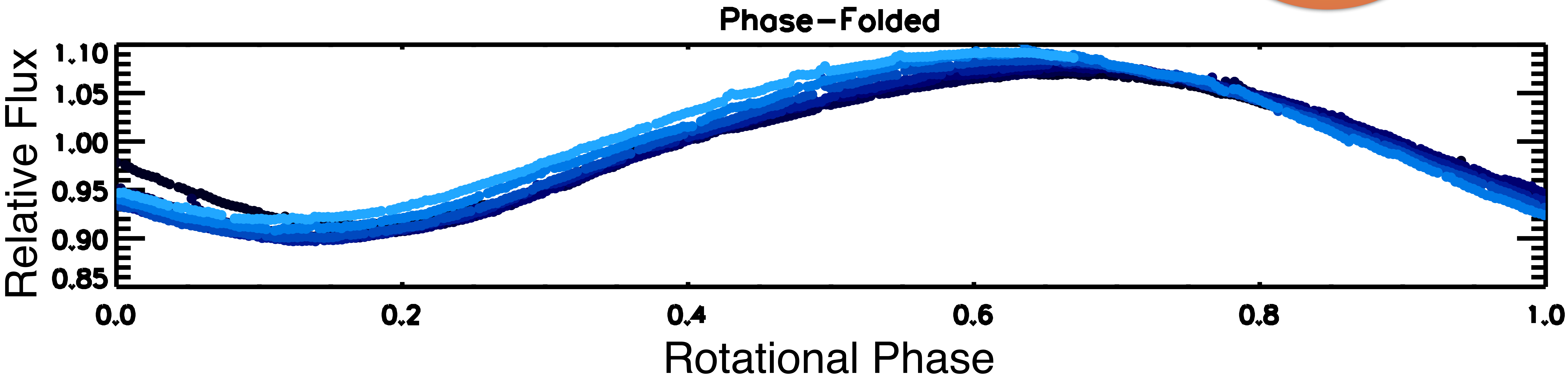
Starry-process (Luger et al. 2021):
https://github.com/rodluger/starry_process

Spots Appear and Disappear

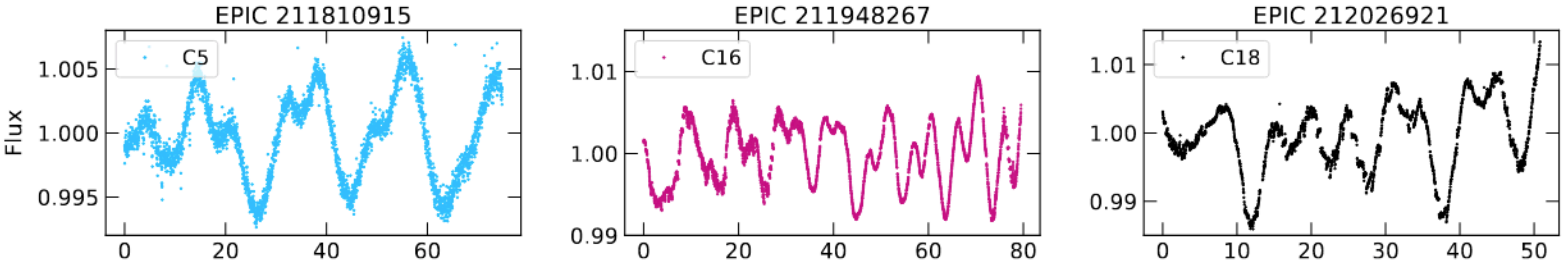


Differential Rotation

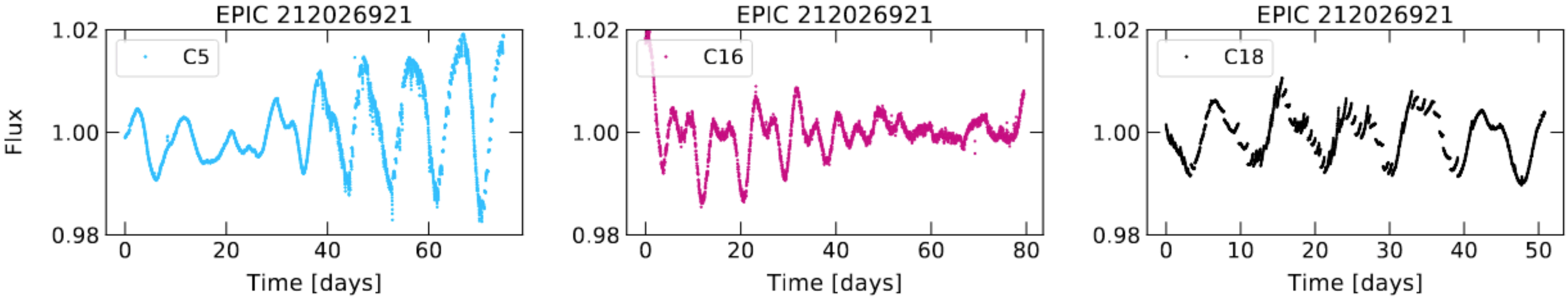




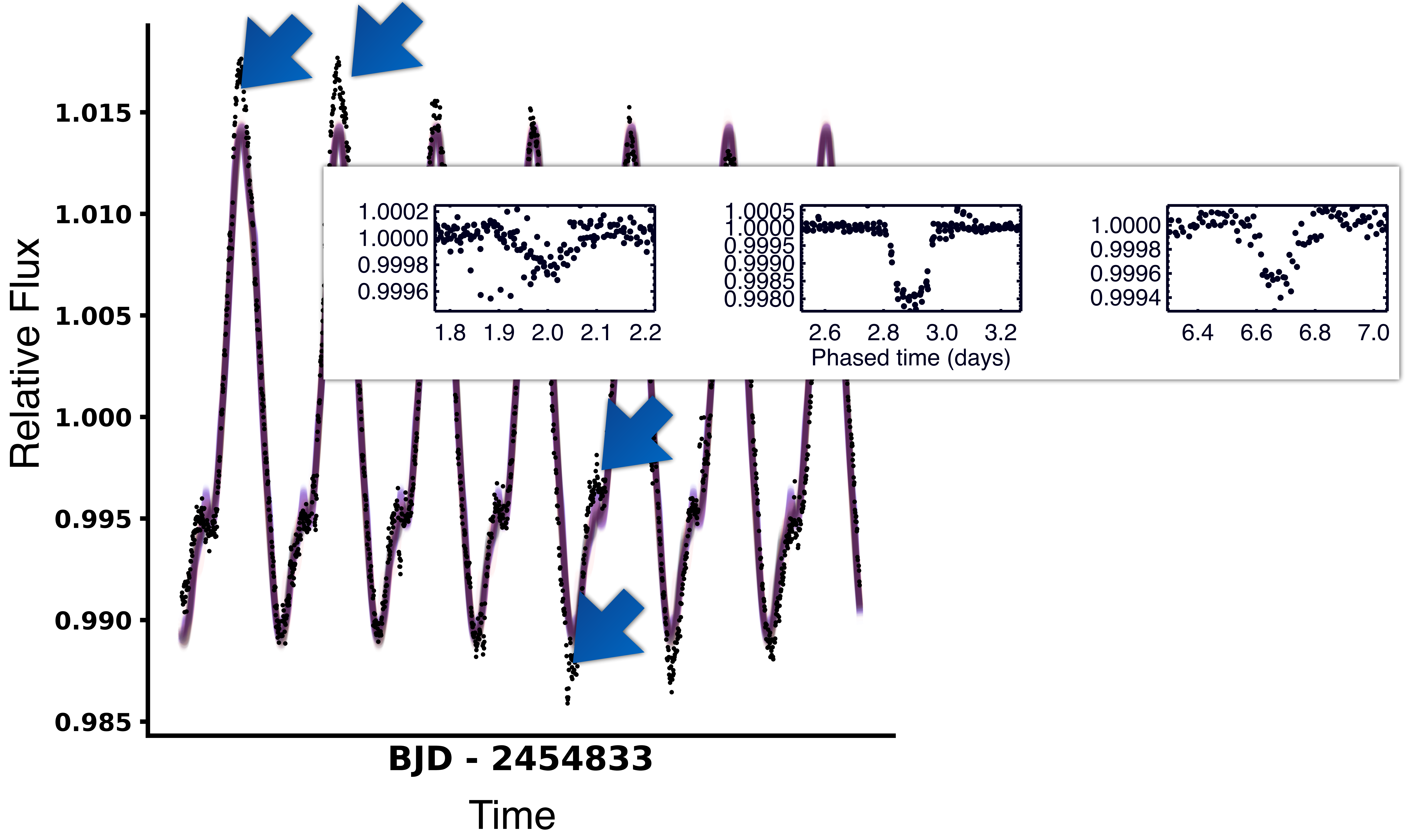
Variation over <100 days



Variation over years



Rampalli et al. (2021)

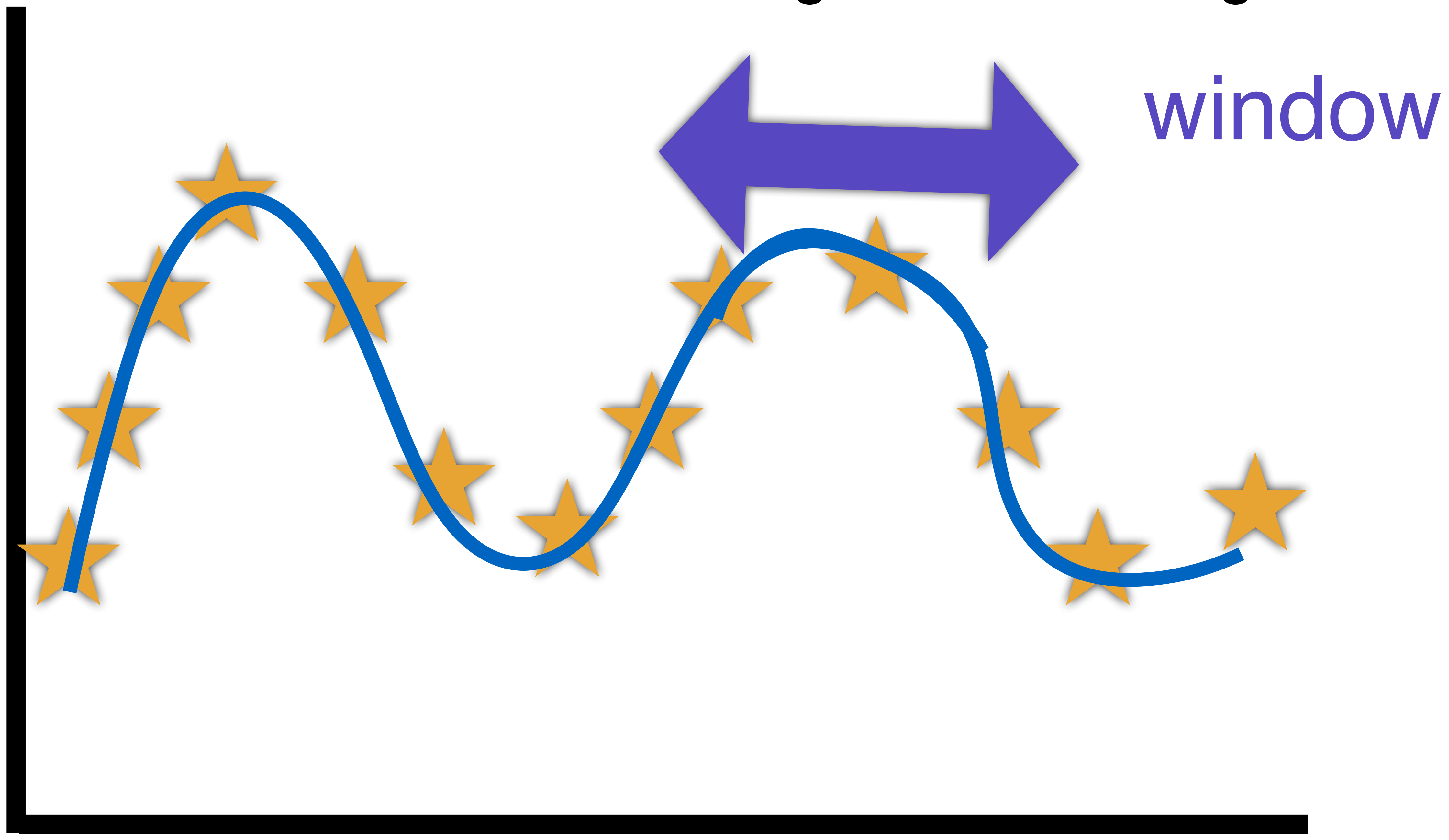


Relative Flux
1.015
1.010
1.005
1.000
0.995
0.990
0.985
BJD - 2454833
Time
1.0002
1.0000
0.9998
0.9996
1.8
1.9
2.0
2.1
2.2
1.0005
1.0000
0.9995
0.9990
0.9985
0.9980
2.6
2.8
3.0
3.2
Phased time (days)
1.0000
0.9998
0.9996
0.9994
6.4
6.6
6.8
7.0

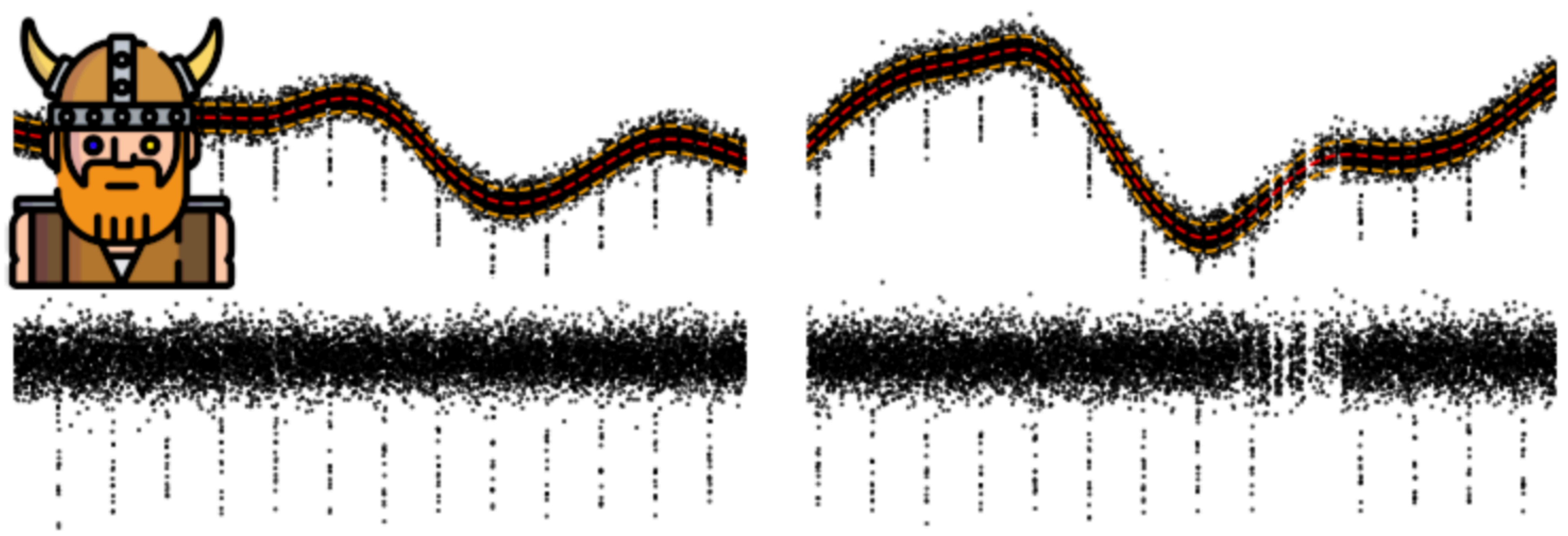
Removing stellar variability to search for transits

Flexible (non-physical) methods

Time-variable filtering or local fitting

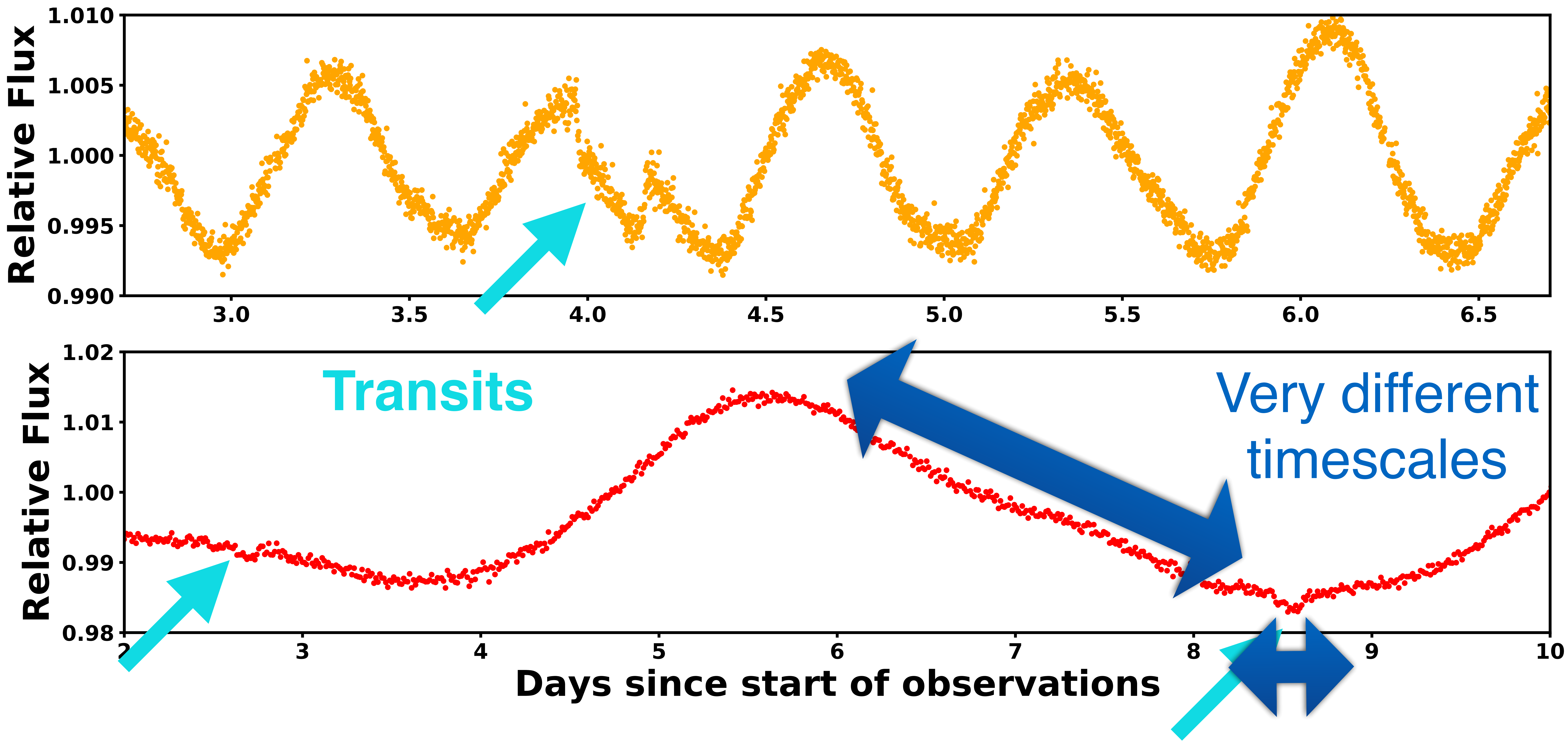


https://github.com/hippke/wotan

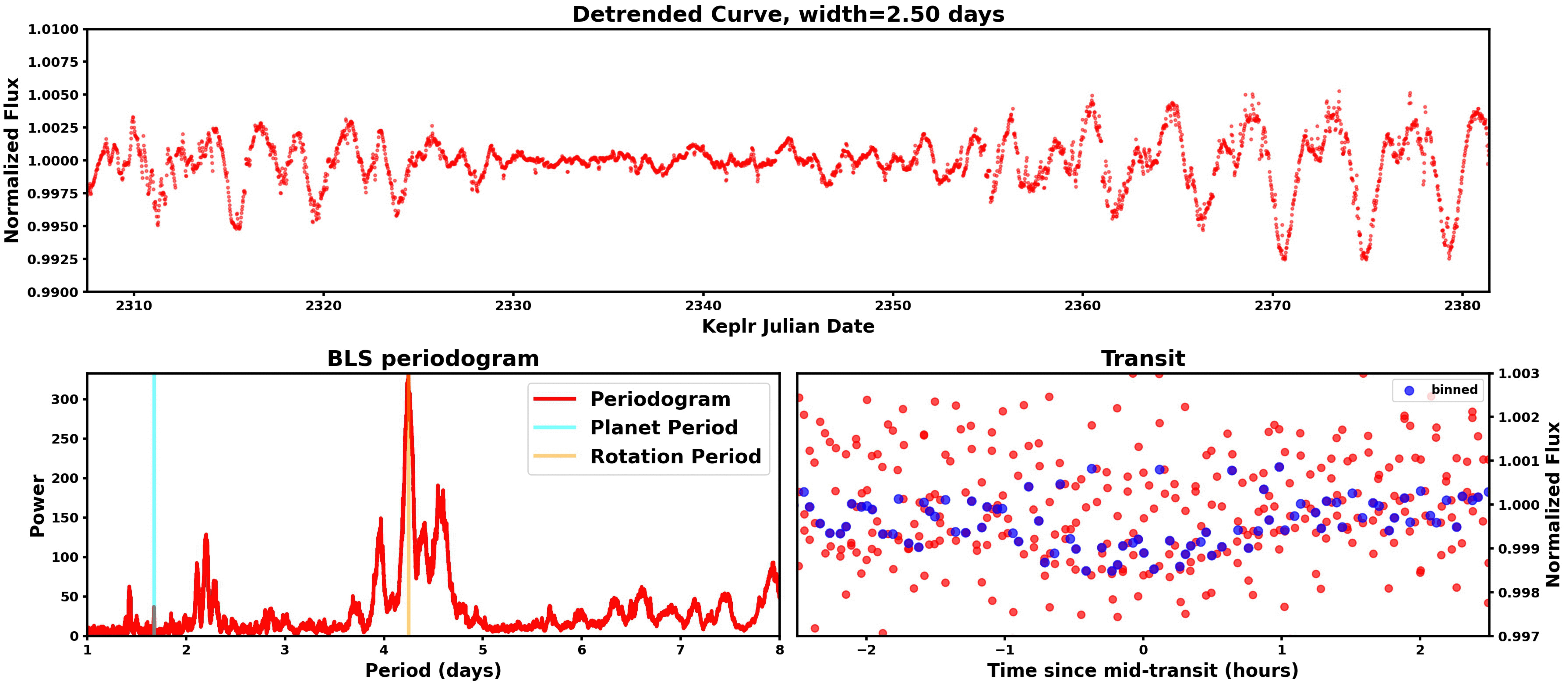


Hippke et al. (2019)

Removing stellar variability to search for transits

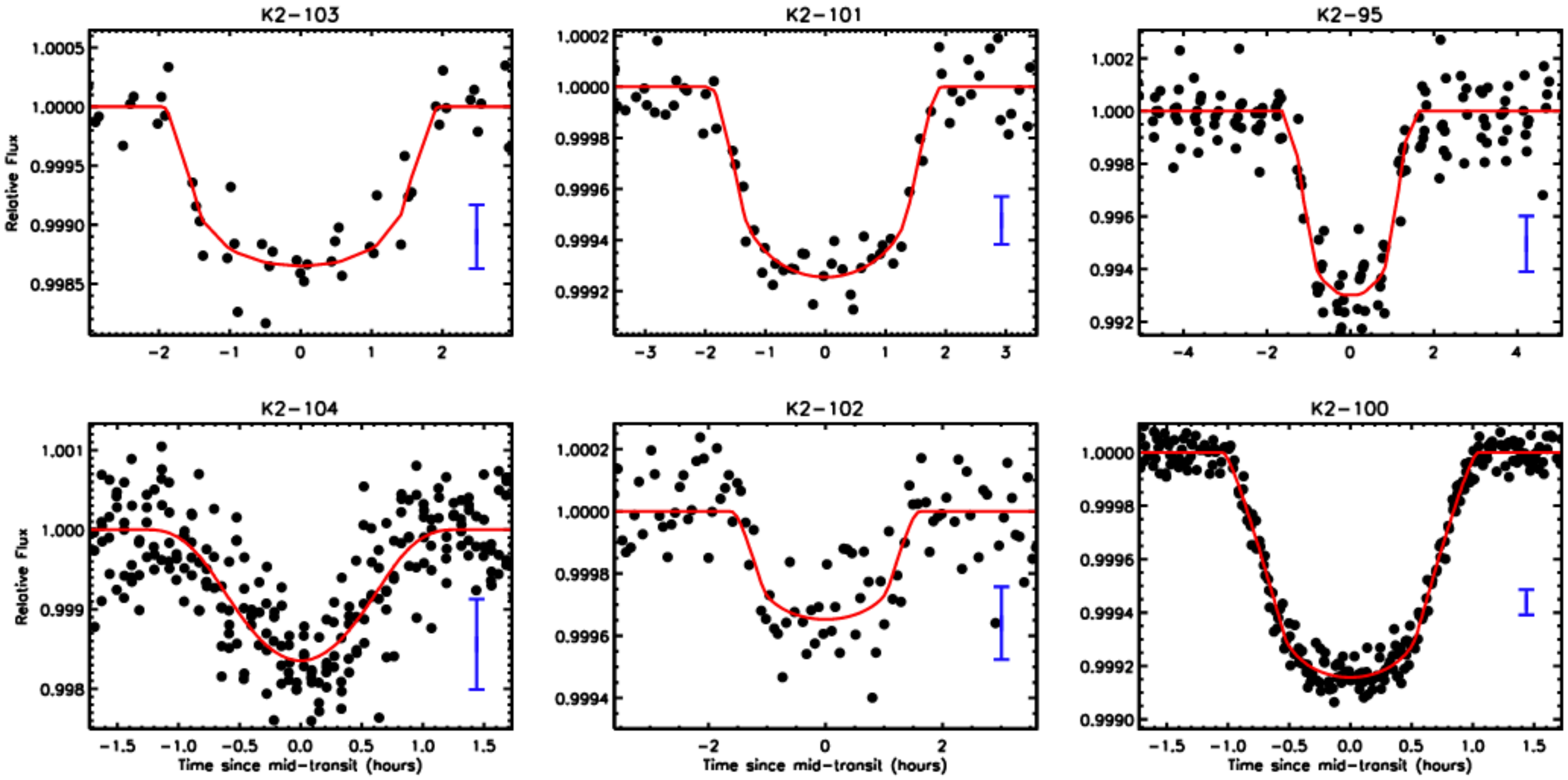


Variability removal with a (local) filter



Variability removal with a (median) filter

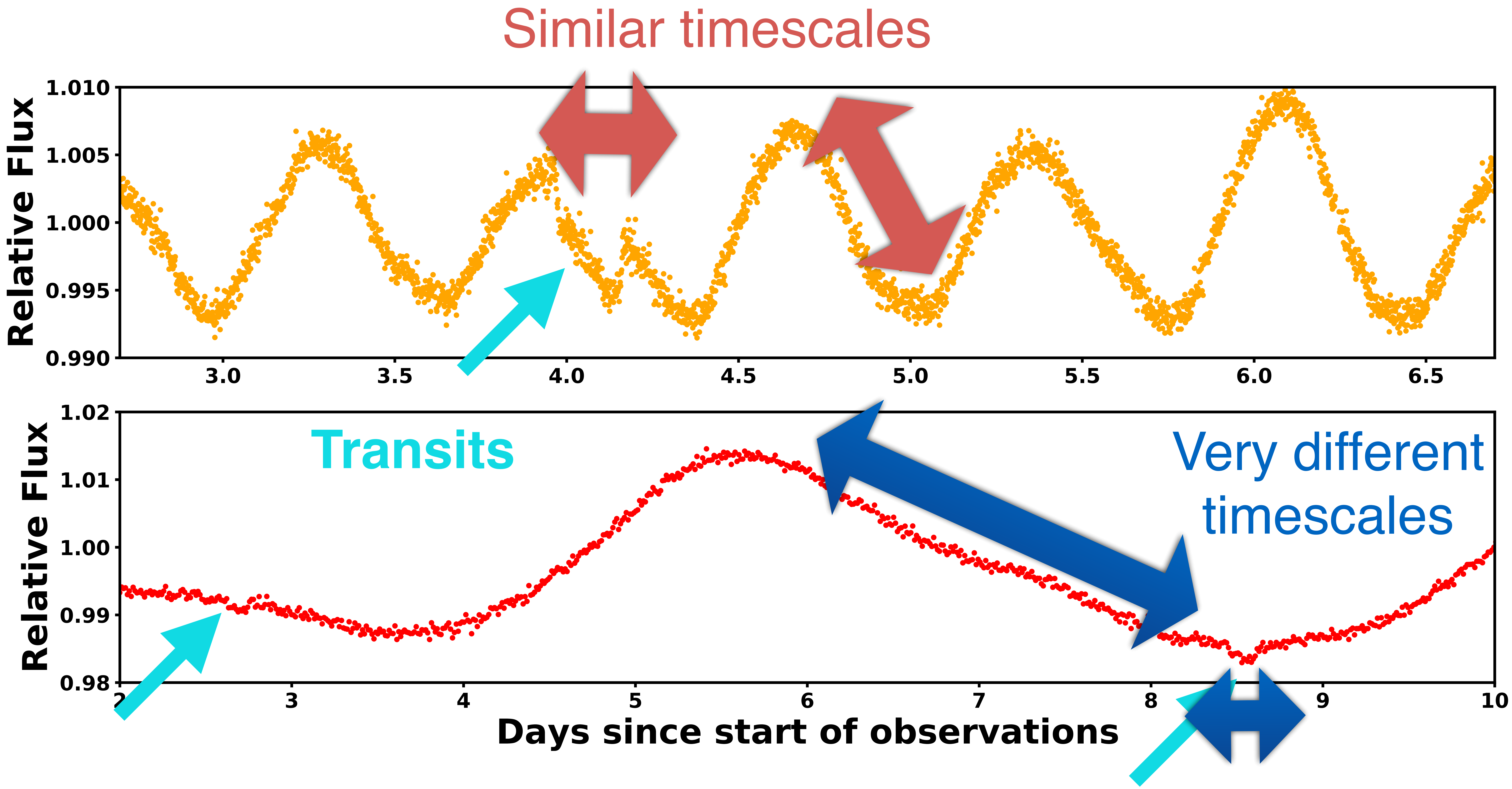
Most (but not all) of the planets from the
Zodiacal Exoplanets in Time (ZEIT) survey were found this way



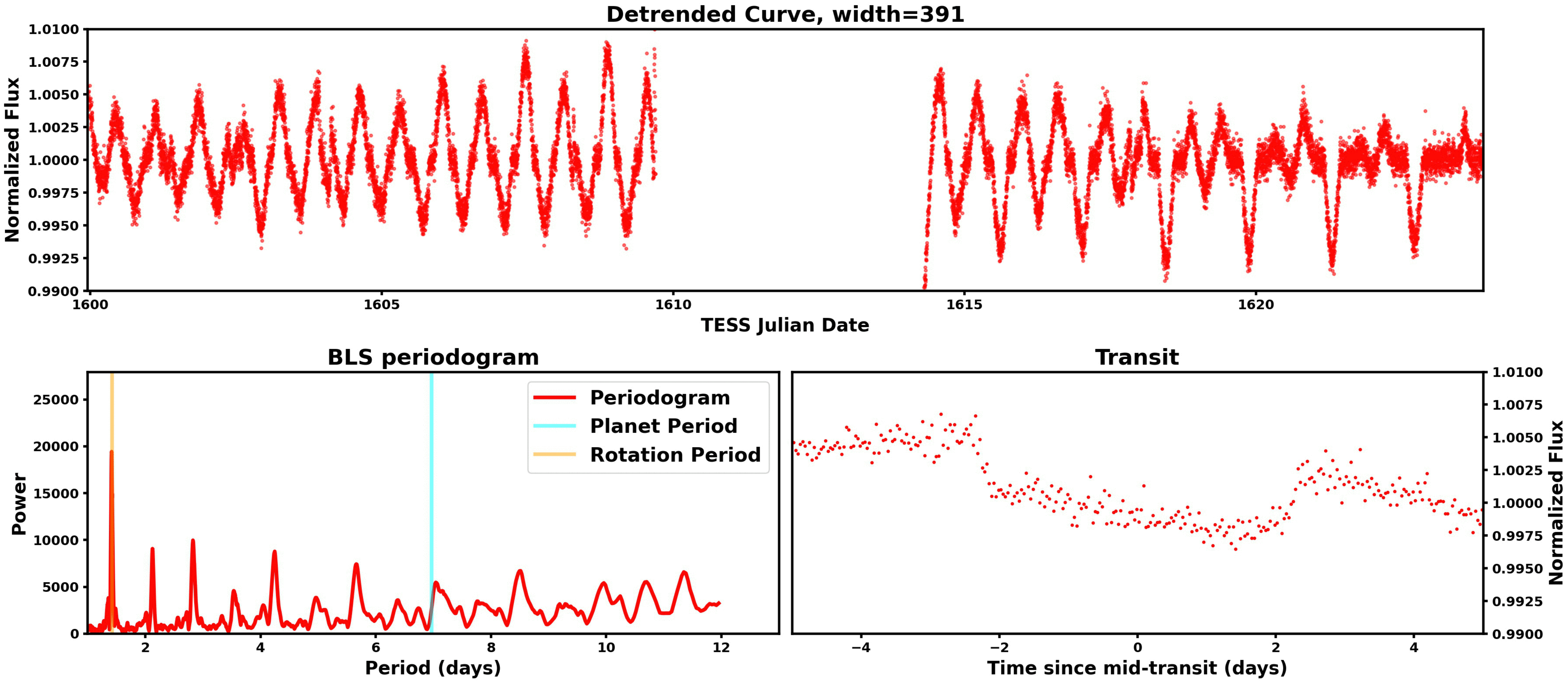
Mann et al. (2016, 2017, 2018)

Gaidos et al. (2017); Vanderburg et al. (2018)

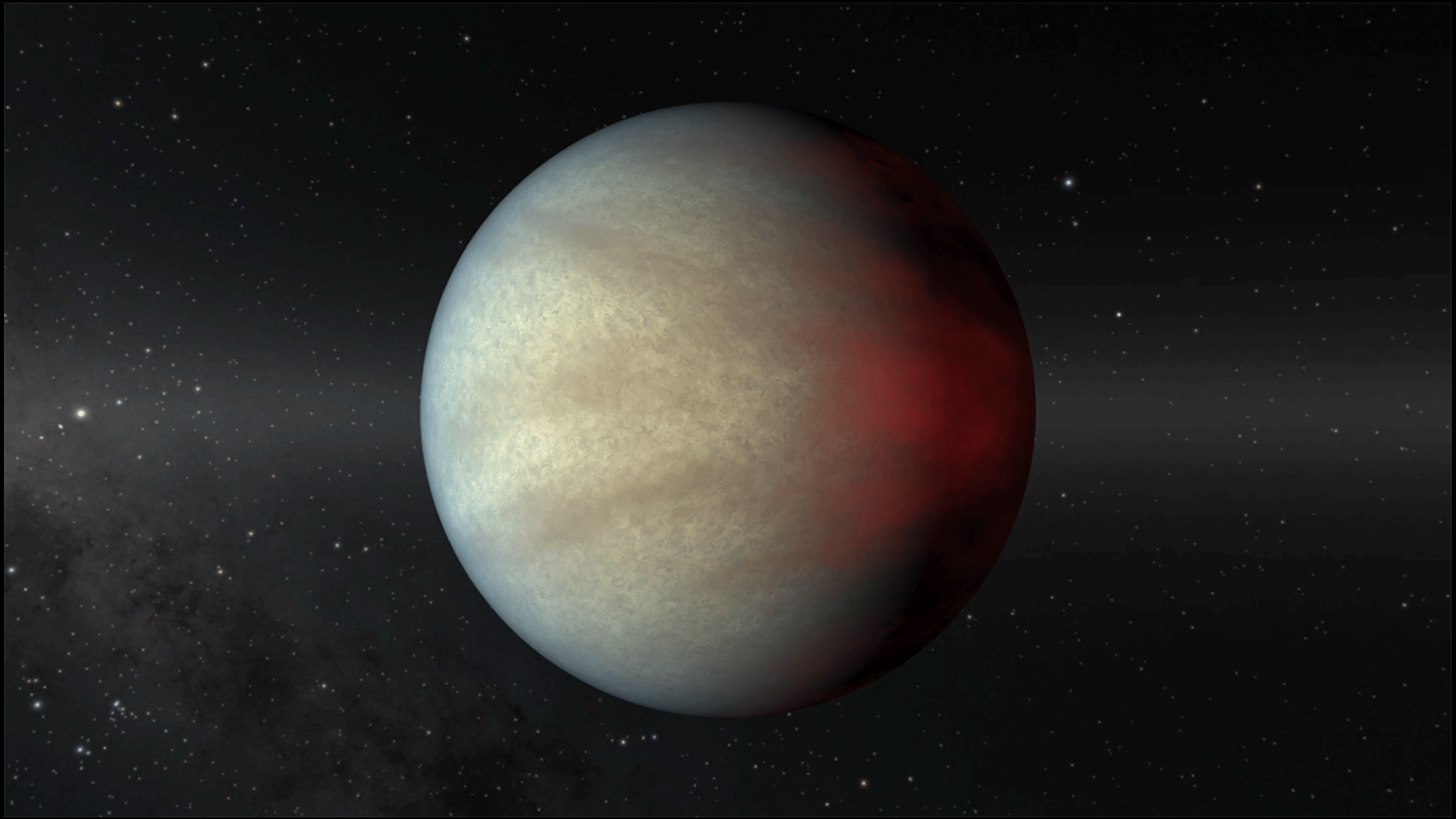
Removing stellar variability to search for transits



Variability removal with a (median) filter



HIP 67522 b
~20 Myr Hot Jupiter (JWST atmosphere target)



Gaussian Process Regression

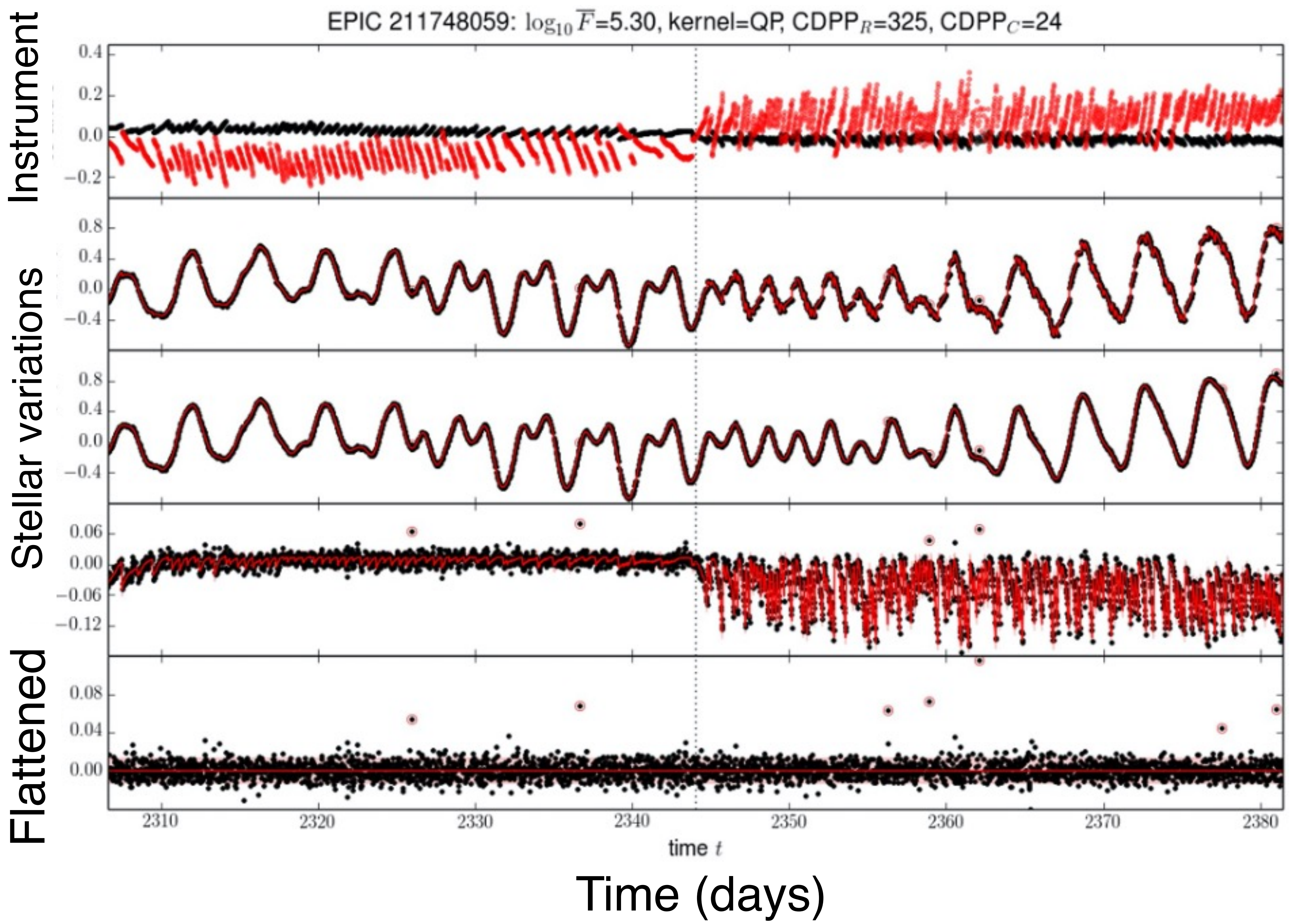
GPs offer a flexible method to model correlated noise in time series

Advantages:

-Can fit a wide variety of stellar variations.

-Don't need a physical model, just pick a kernel (use a periodic one).

-Easy-to-use implementations (see Celerite https://celerite.readthedocs.io/en/stable/).



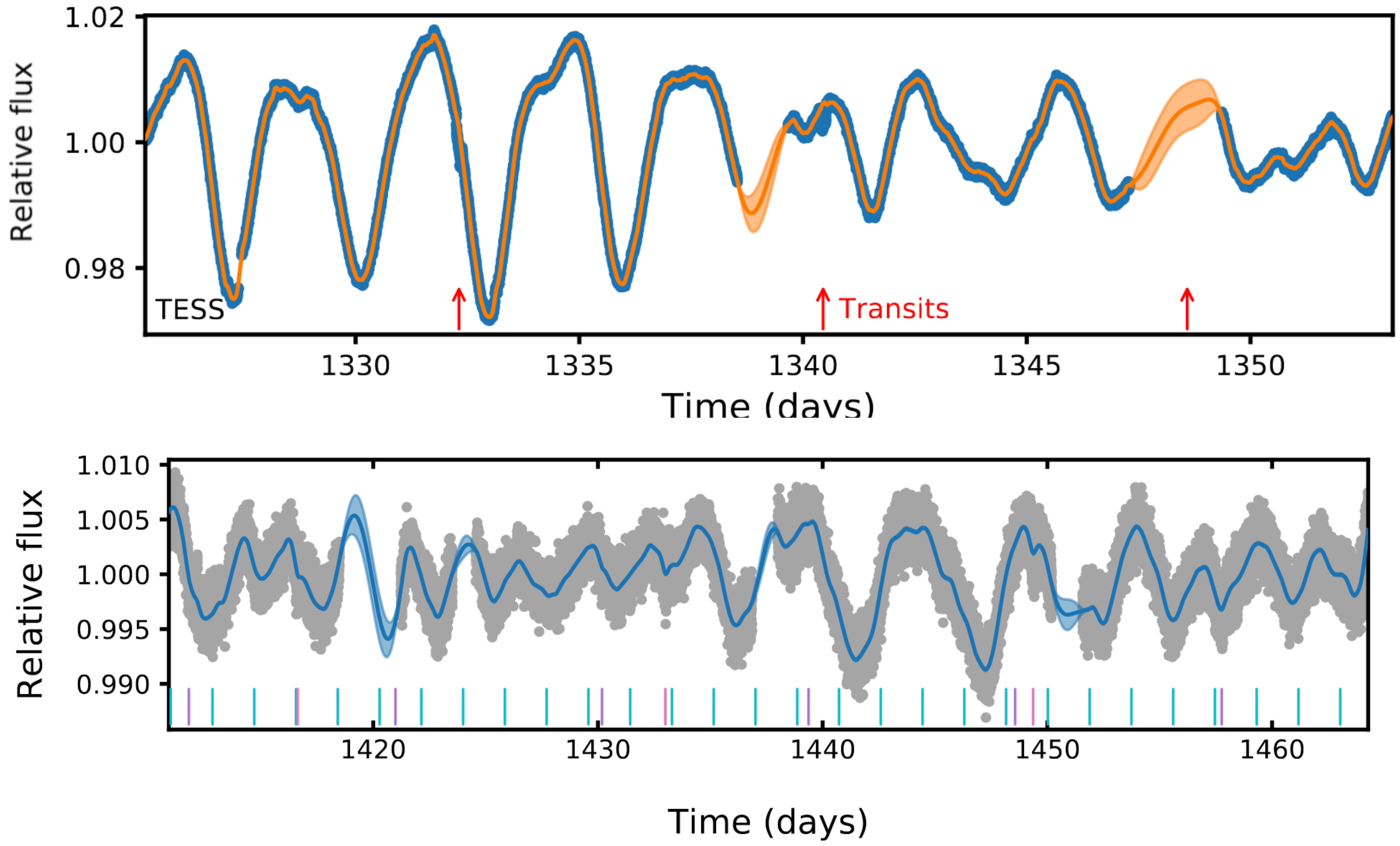
K2SC Aigrain et al. (2016)

Gaussian Process Regression

GPs offer a flexible method to model correlated noise in time series

Disadvantages:

-Computationally expensive (impractical for large datasets).



Newton et al. (2019, 2021)
Mann et al. (in prep)

Gaussian Process Regression

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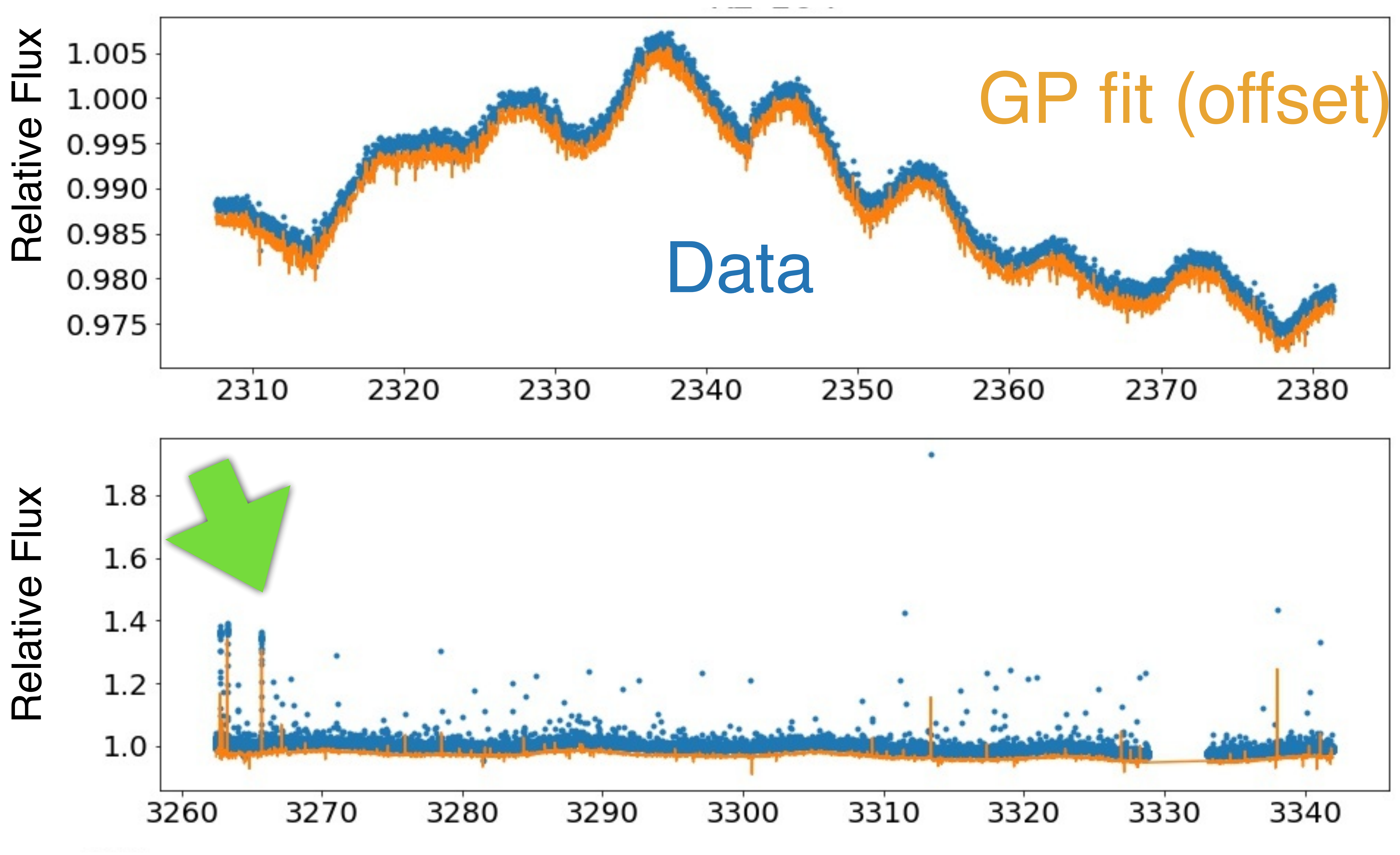
Disadvantages:

-Computationally expensive (impractical for large datasets).

-Highly sensitive to outliers.



Gaussian Process Regression

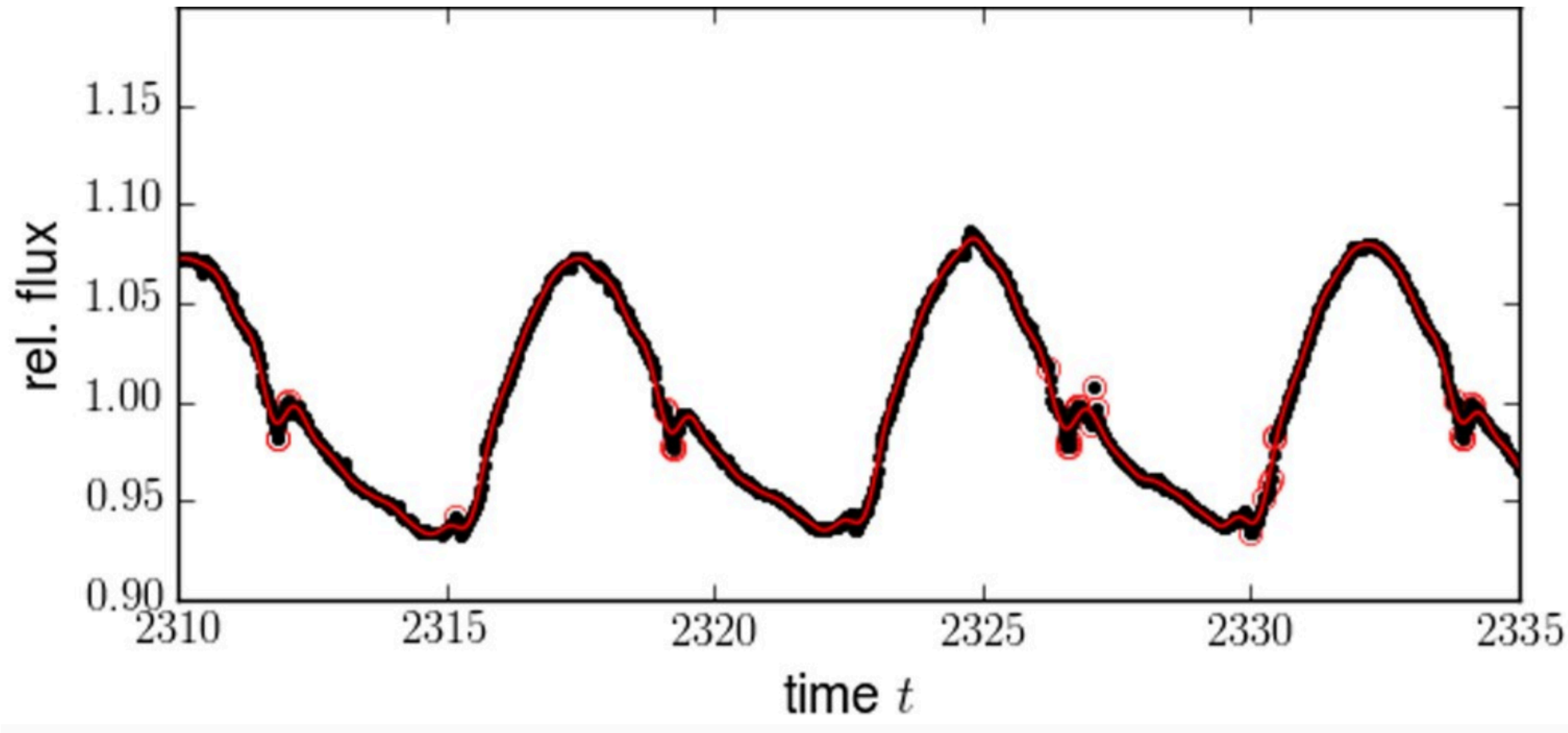
GPs offer a flexible method to model correlated noise in time series

Disadvantages:

-Computationally expensive (impractical for large datasets).

-Highly sensitive to outliers.

-Can impact or remove planets (GP does not know what a transit looks like).



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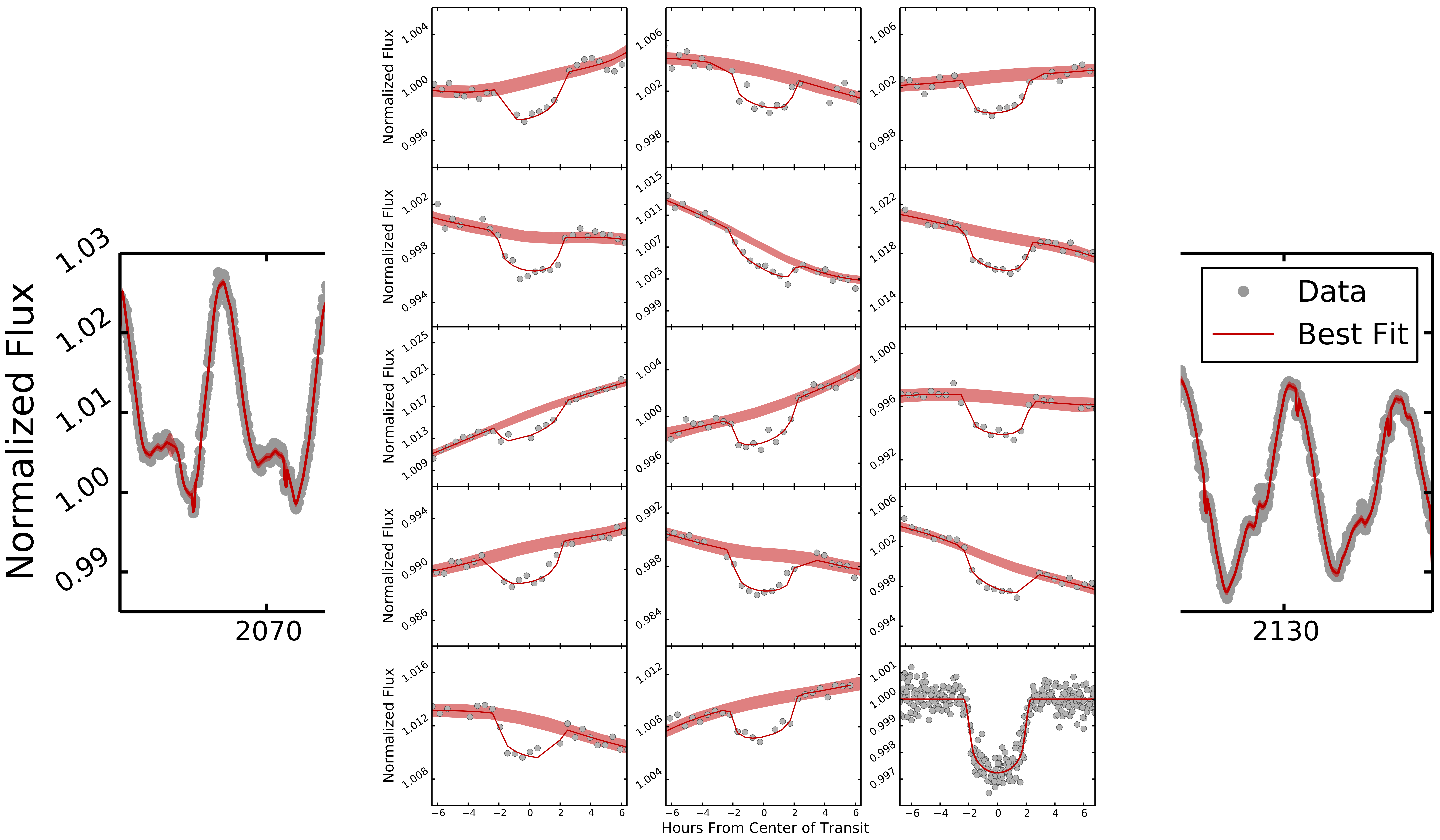


Normalized Flux
1.03
1.02
1.01
1.00
0.99
2070
Hours From Center of Transit
2130
Data
Best Fit

More aggressive methods remove stellar variability, but impact (or remove) the transit.

Less aggressive methods leave the stellar variability intact, making it challenging to detect a weak transit.

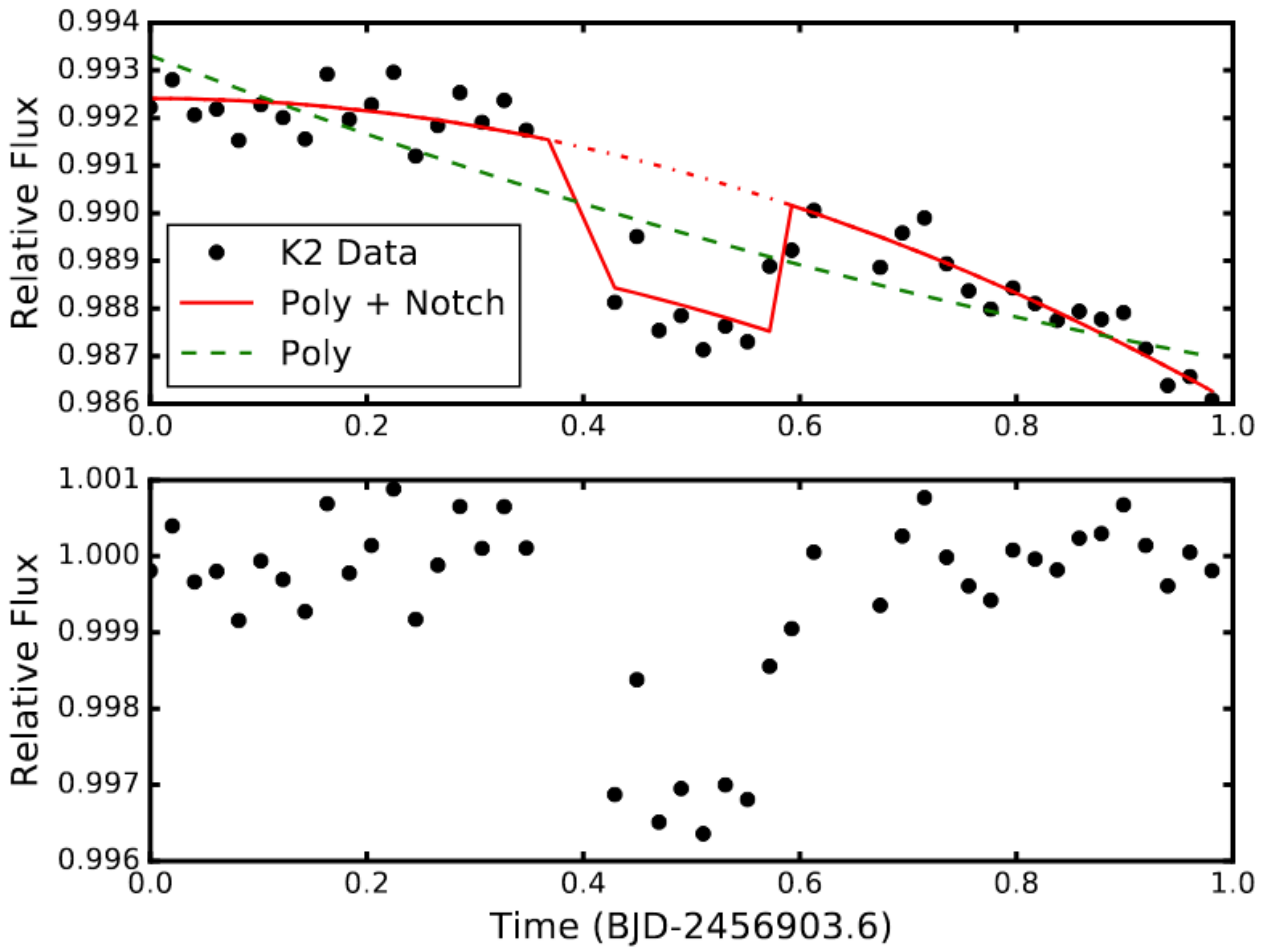
Mitigation methods will almost always incur a computational cost.

Notch Filter

A hybrid method:

-Assume there's a transit in the data, force a transit-like model.

-Use flexible (polynomial or spline) detrending.



https://github.com/arizzuto/Notch_and_LOCoR
Rizzuto, Mann, Vanderburg et al. (2017)

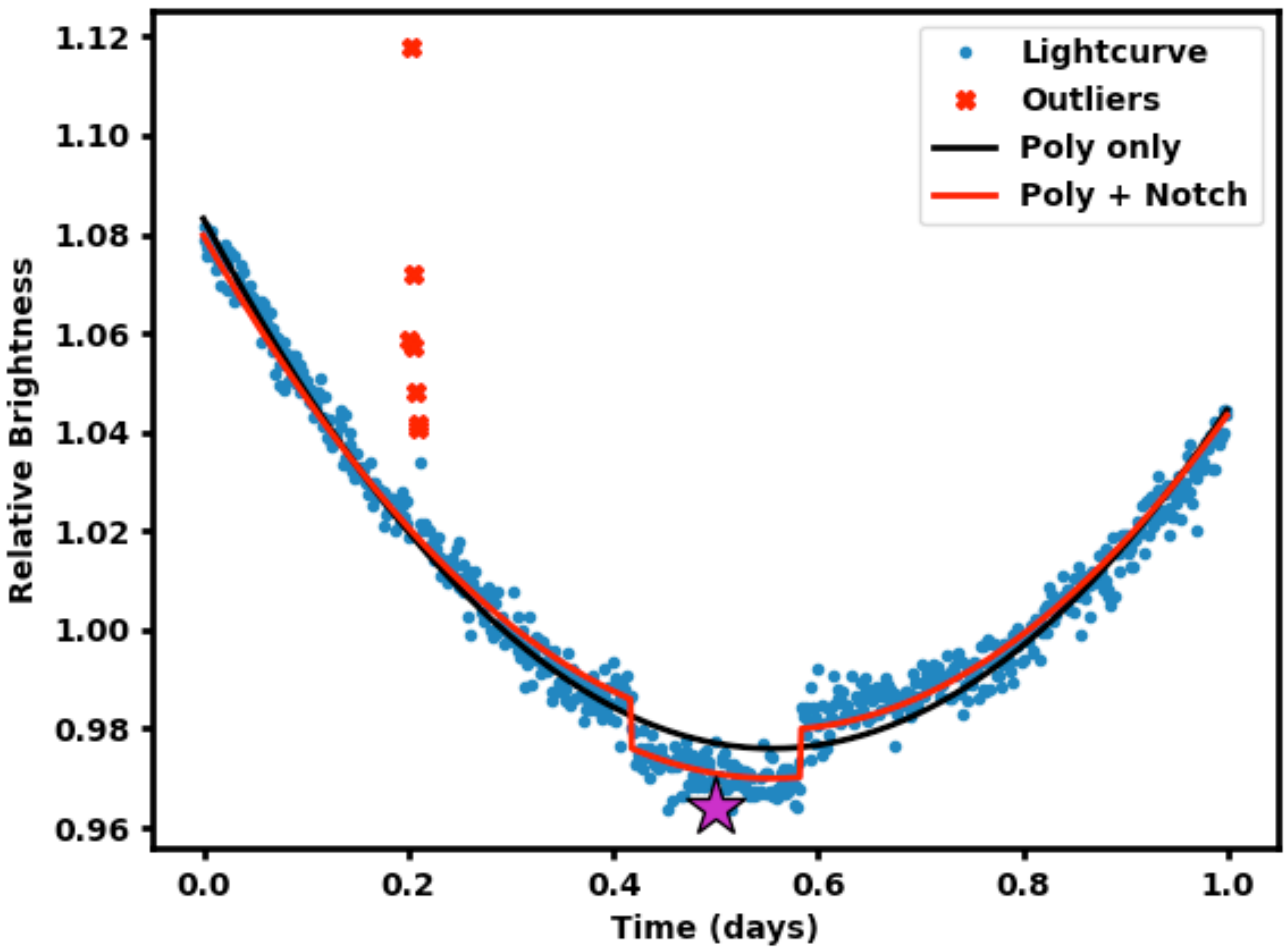
Notch Filter

A hybrid method:

-Assume there's a transit in the data, force a transit-like model.

-Use flexible (polynomial or spline) detrending.

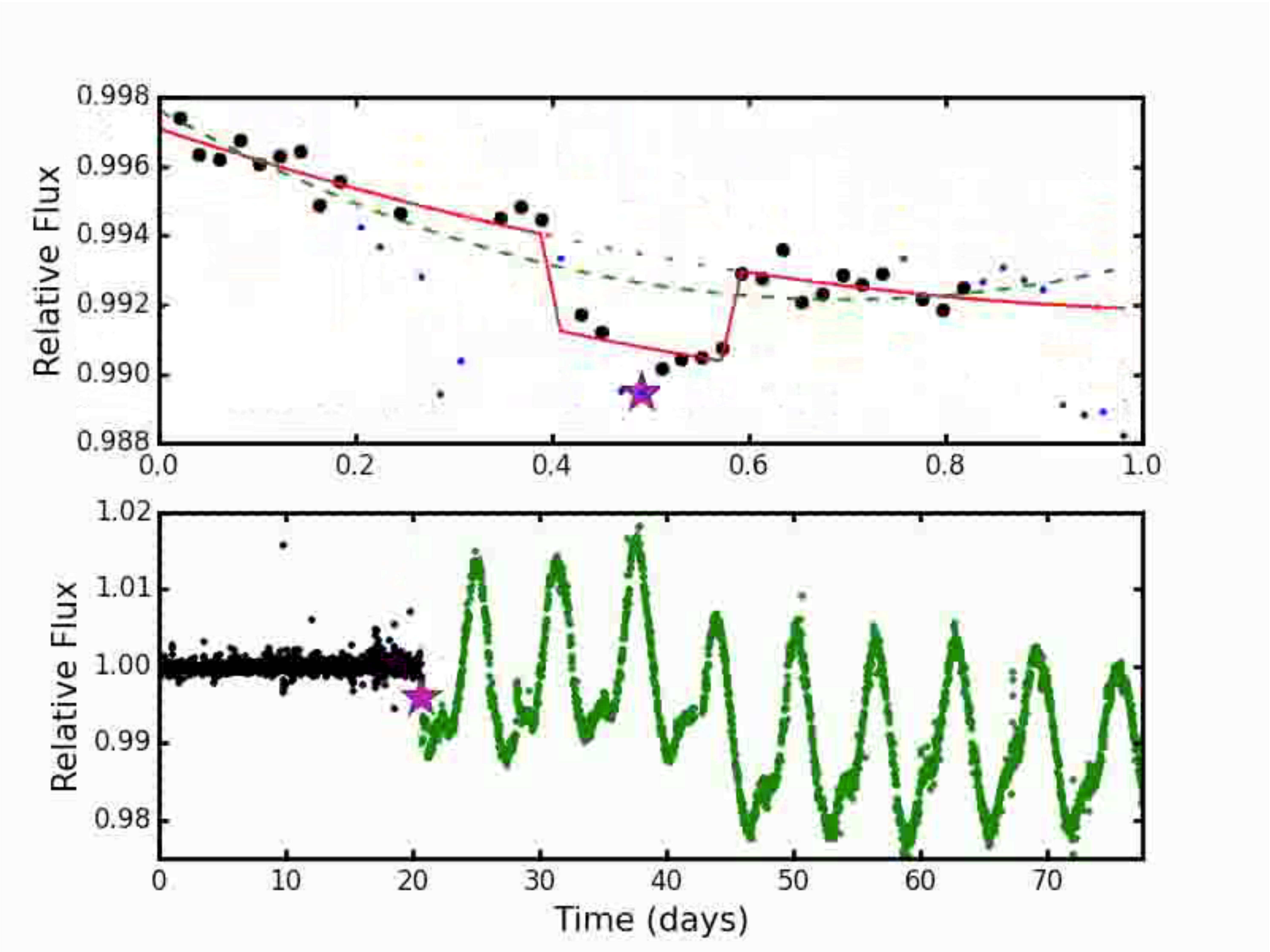
-Iterate to remove outliers (e.g., flares).



https://github.com/arizzuto/Notch_and_LOCoR
Rizzuto, Mann, Vanderburg et al. (2017)

Works like a matched filter
e.g., Berta et al. 2012 and Foreman-Mackey et al. 2015

Notch Filter



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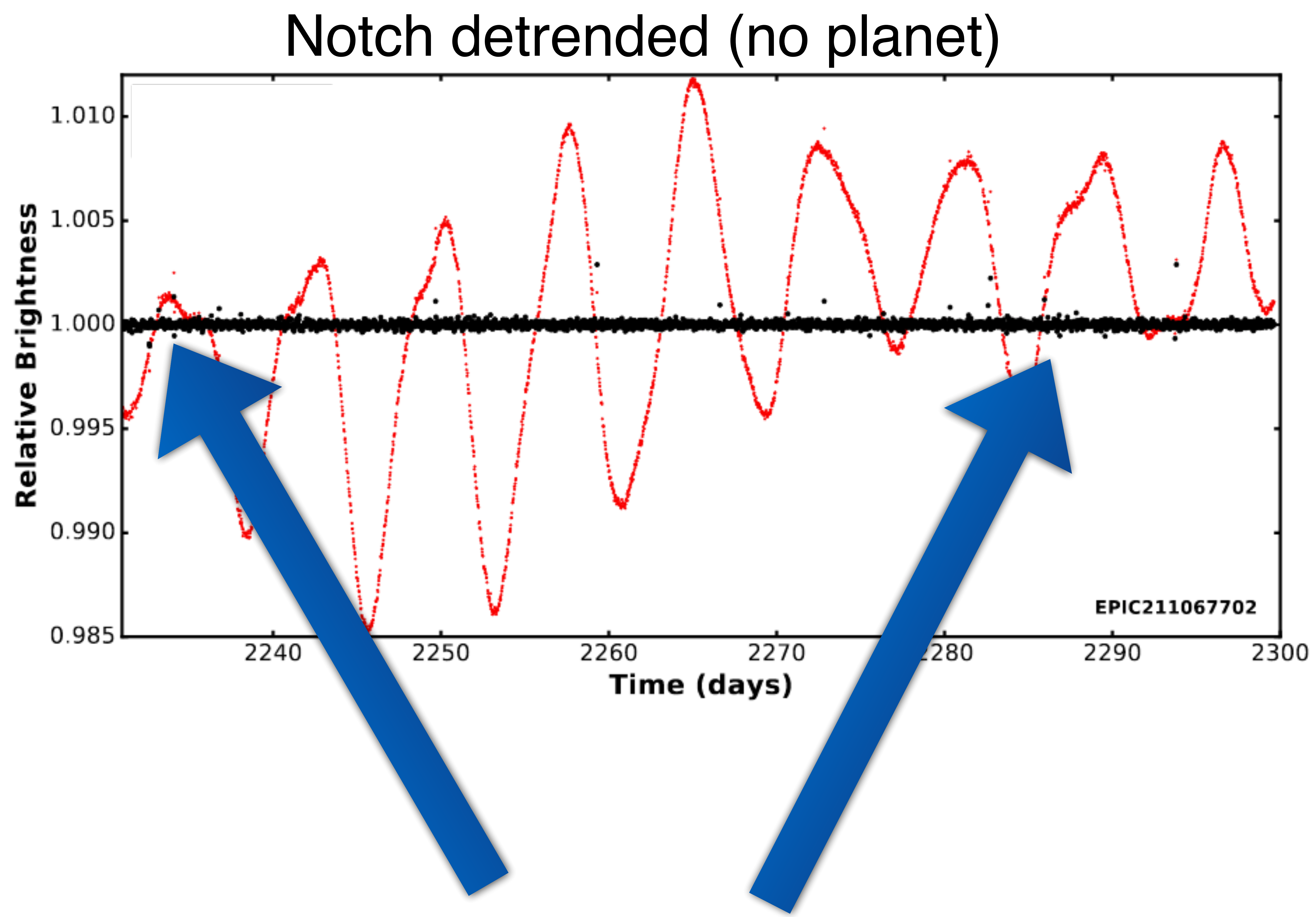
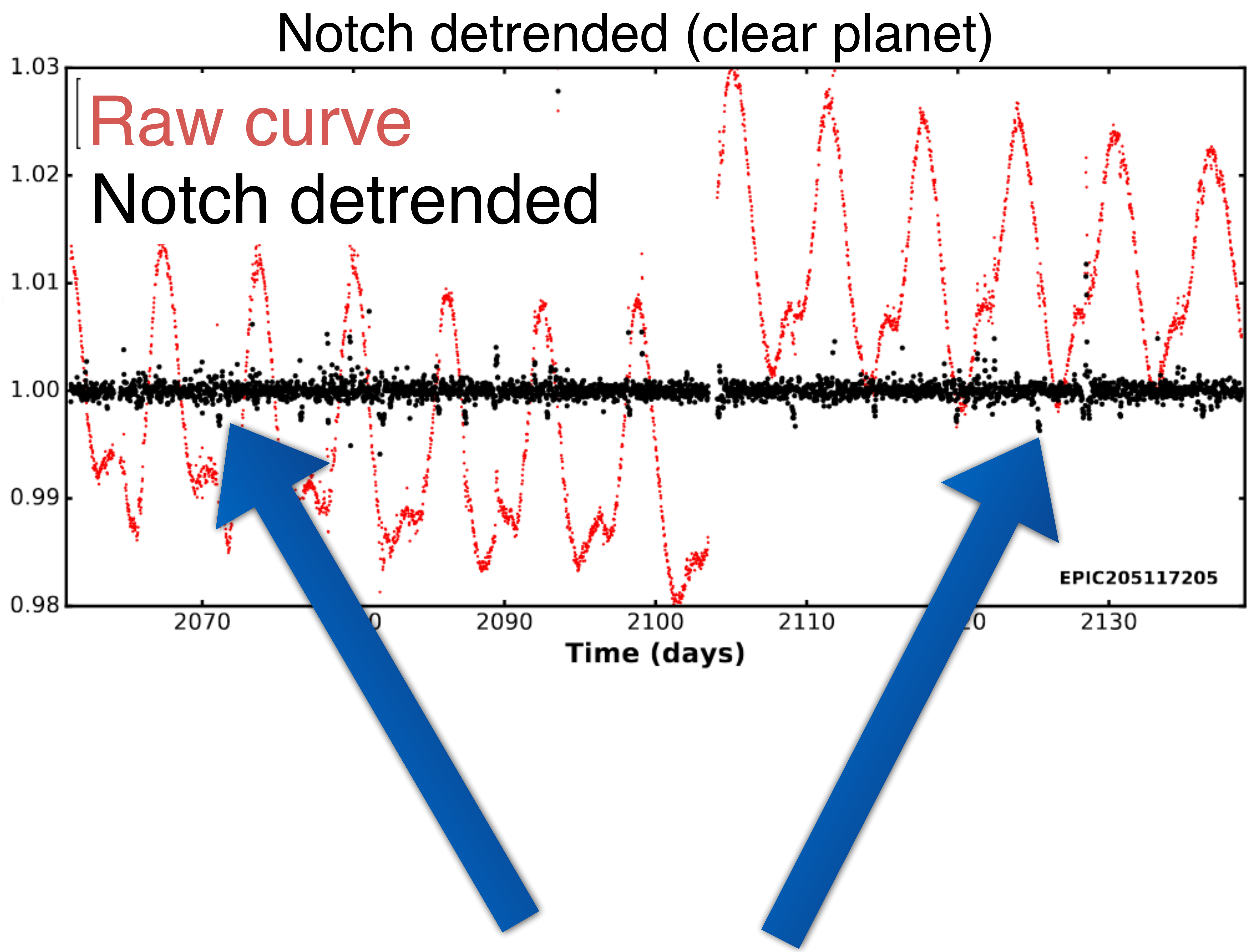
Notch Filter

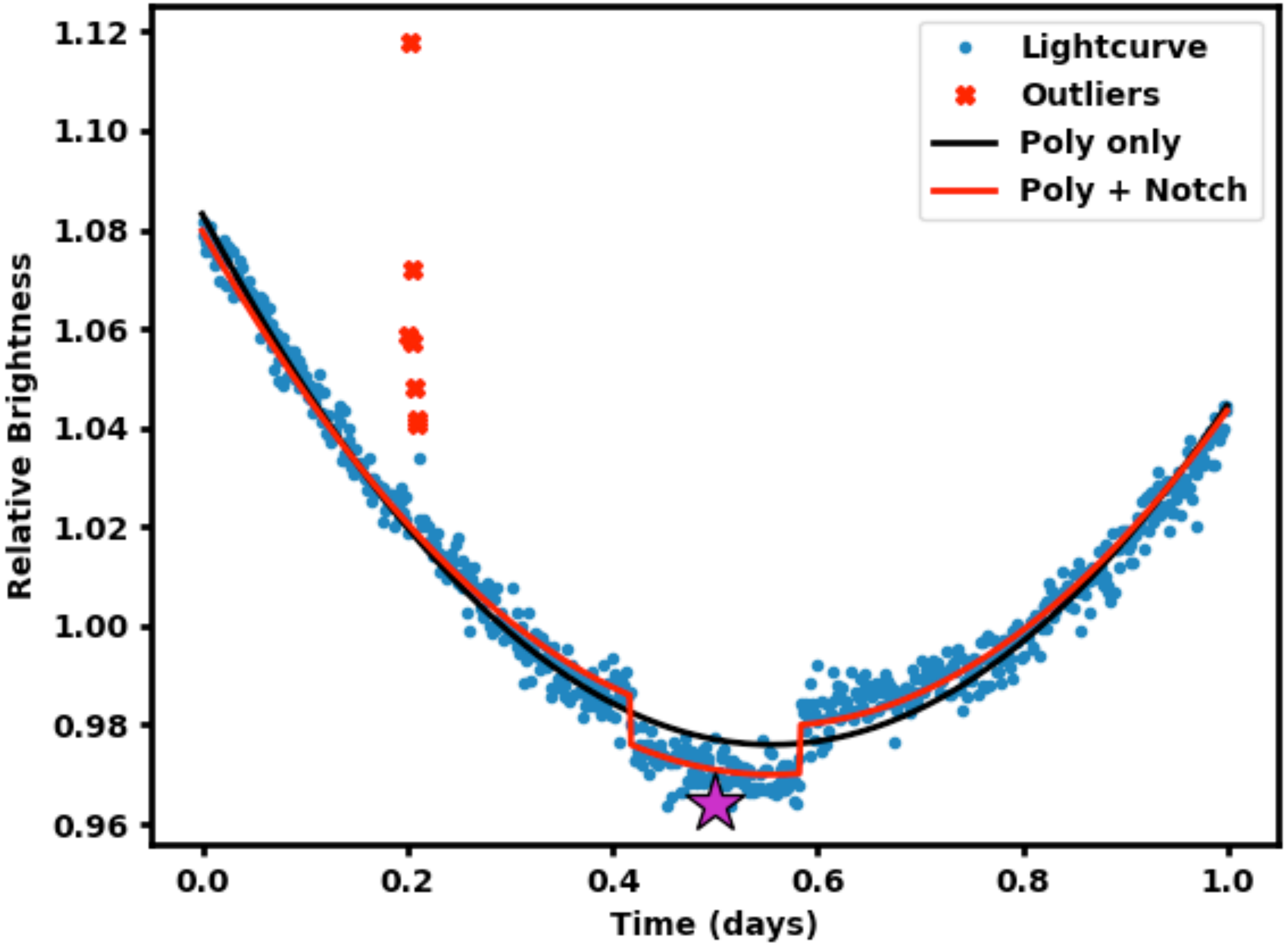




Some low points survive,
but they don't phase to a constant period

Many surviving low points are both transit shaped
And phase to a constant period.

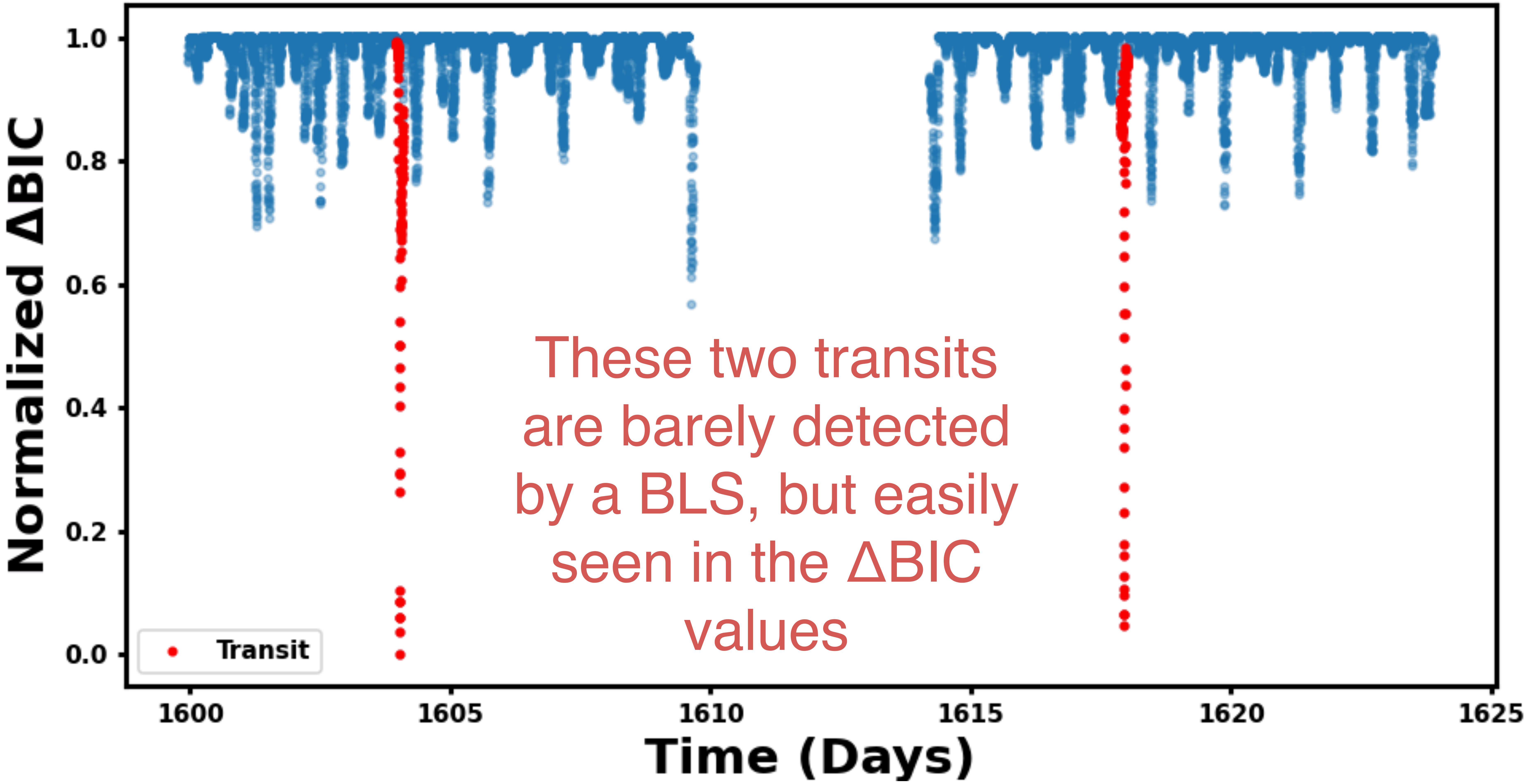
Notches are included only if they improve the fit.



Improvement based on Bayesian information criterion (BIC) test. The BIC values are recorded.

Notch Filter

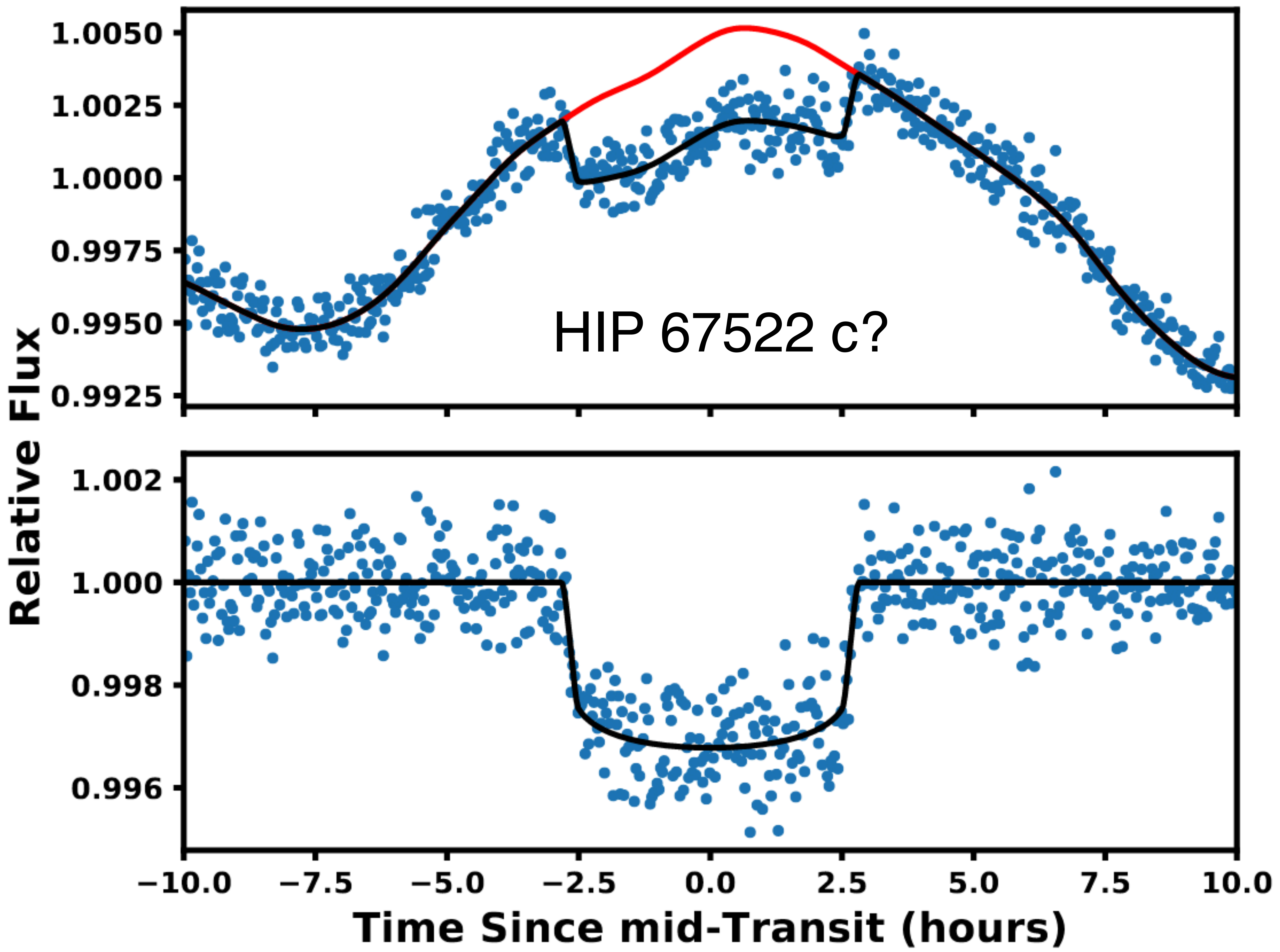
Individual "notches" contain useful information.



This is largely independent of running Box-least-squares (BLS) search.

We often run a periodogram on the ΔBIC values.

Notch Filter

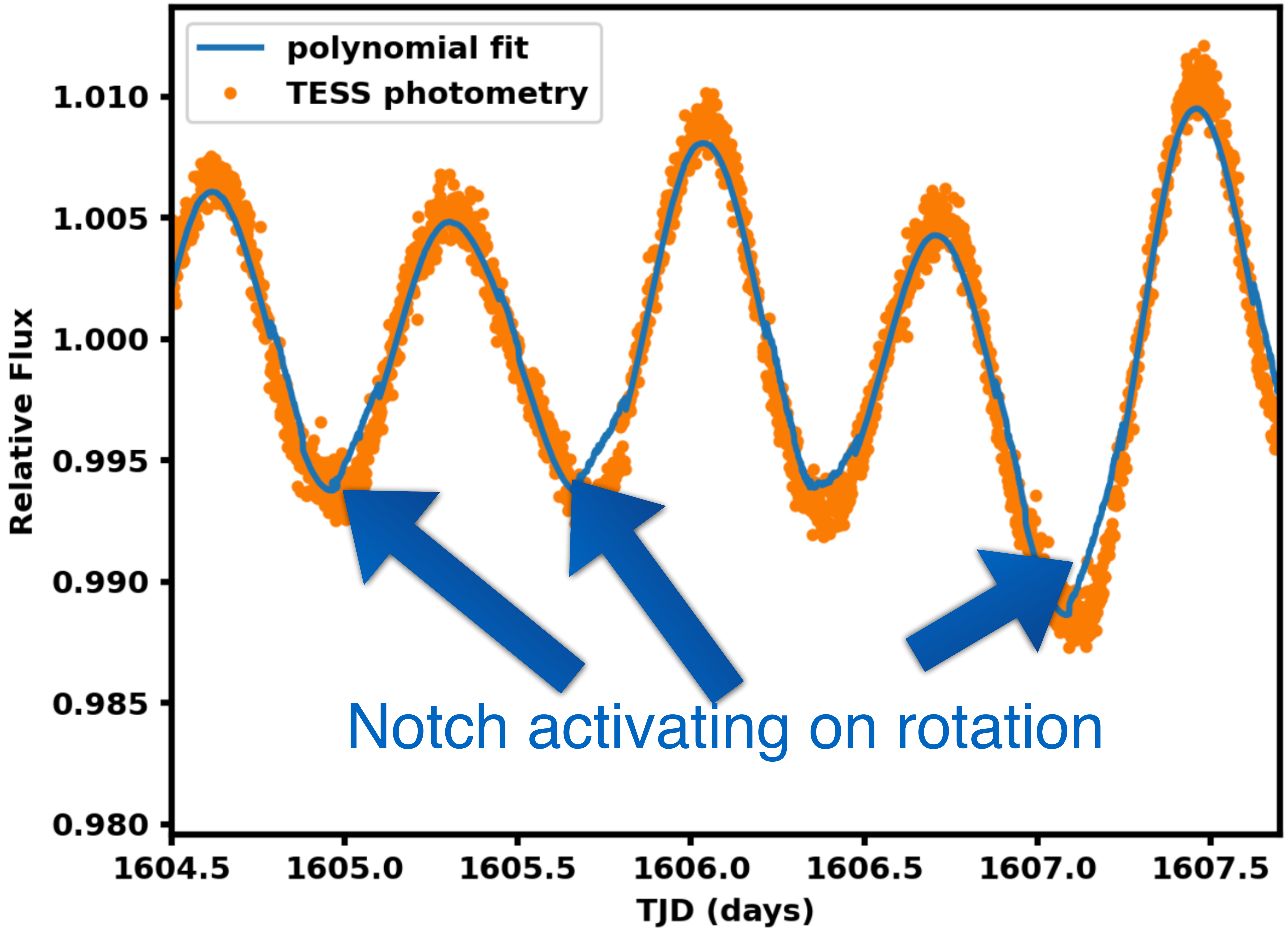


This is largely independent of running Box-least-squares (BLS) search.

We often run a periodogram on the ΔBIC values.

Let's us find single-transiting systems!

Notch Filter

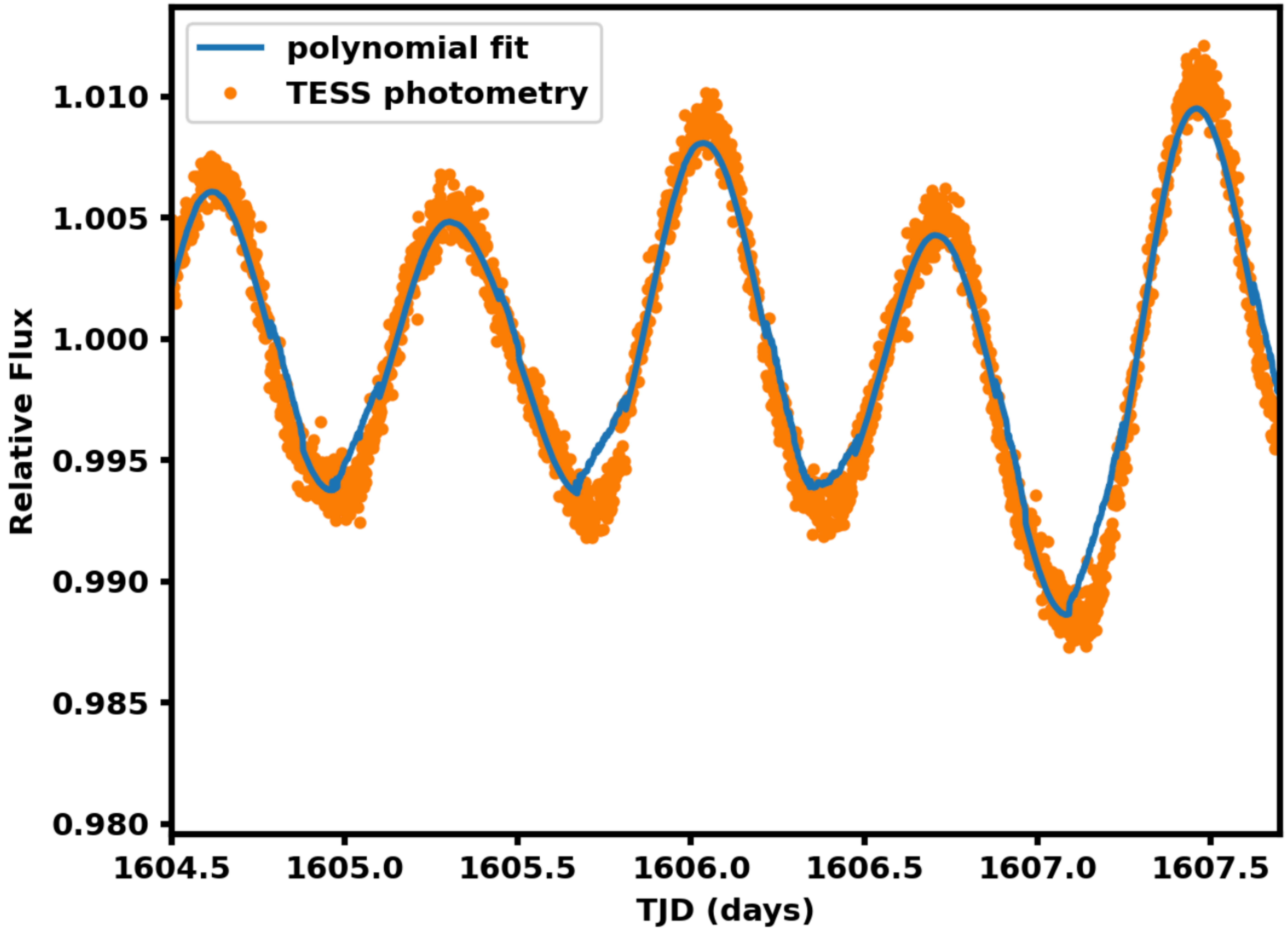


Cons:

-More computationally expensive than most filtering options.

-Notch can be tricked by rotation.

Notch Filter



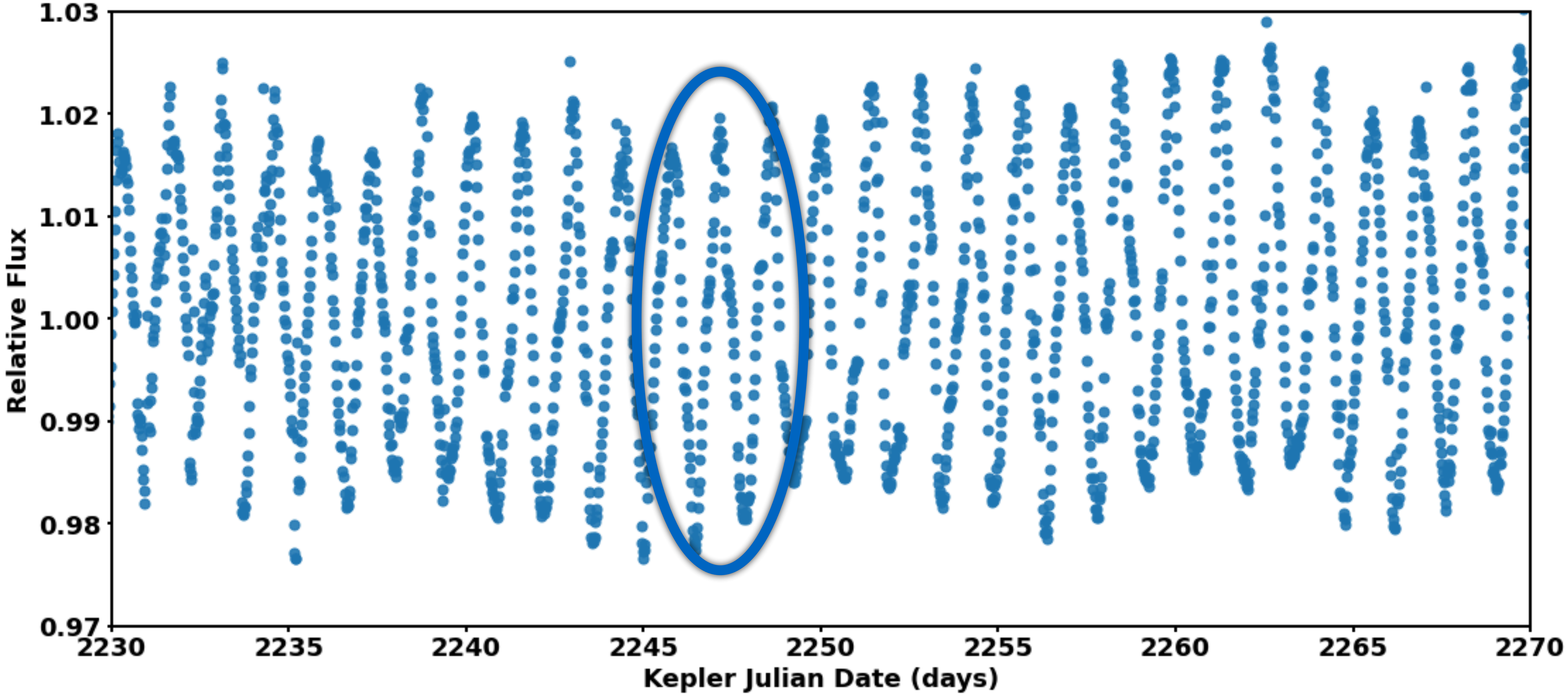
Cons:

-More computationally expensive than most filtering options.

-Notch can be tricked by rotation.

-Performs poorly for the fastest rotators and planets near the rotation period.

Problem: what do we do about the fastest rotators?

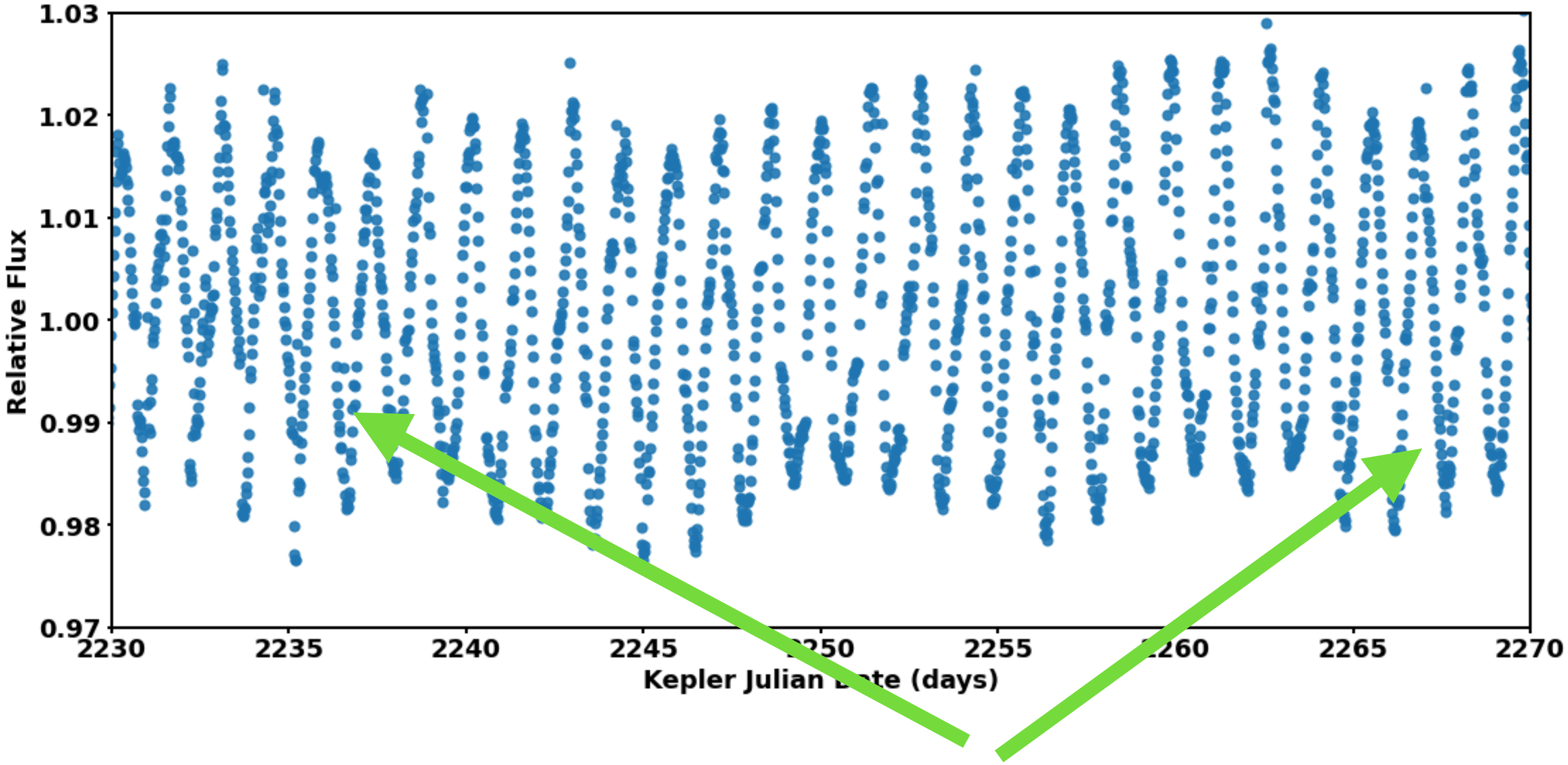


Notch and similar filters use 'local' information.

This is a challenge for fast rotators because there are only a handful of 'local' measurements for a given rotation.

Our Second Approach: LoCoR

Problem: what do we do about the fastest rotators?



Notch and similar filters use 'local' information.

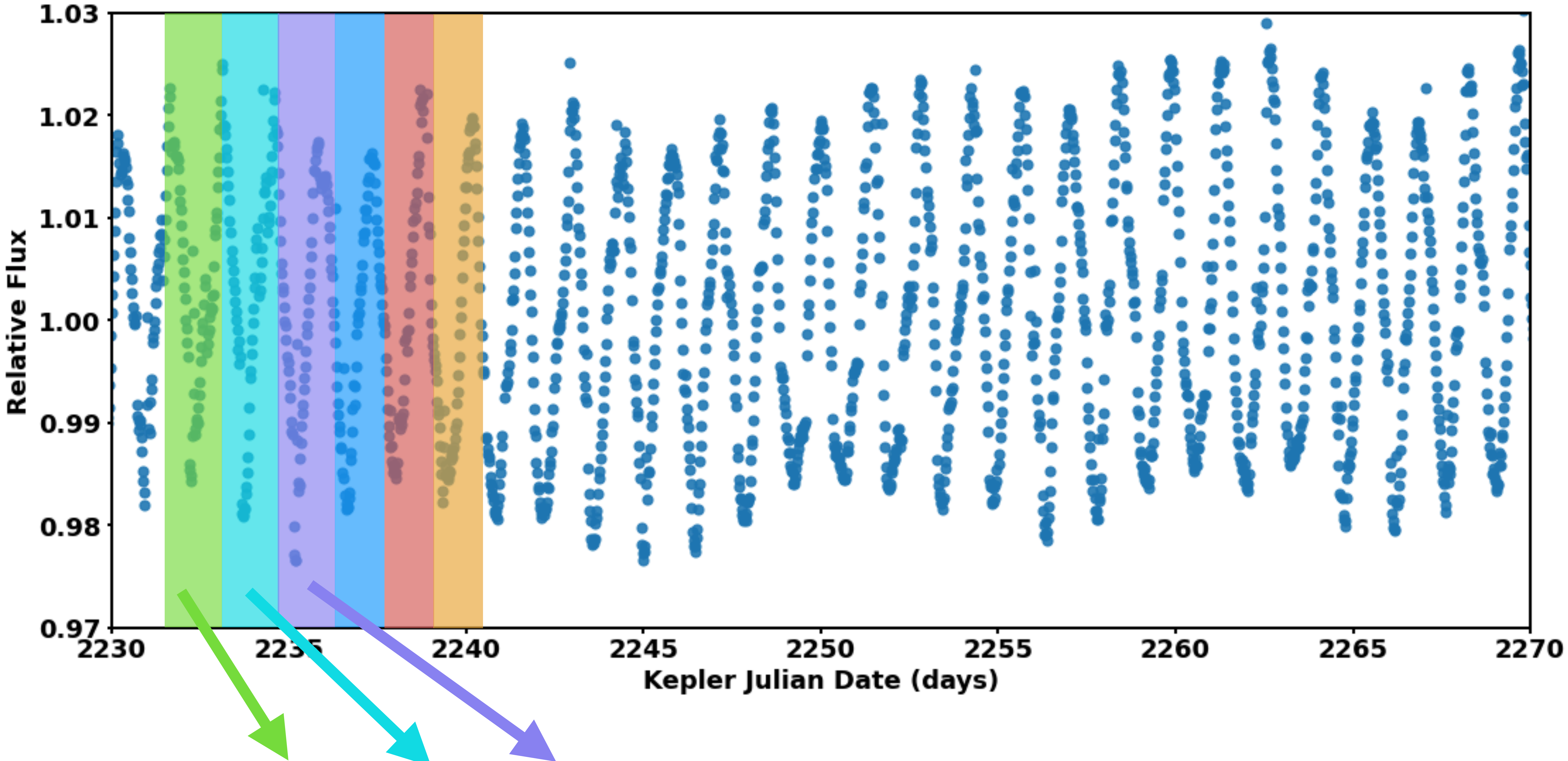
This is a challenge for fast rotators because there are only a handful of 'local' measurements for a given rotation.

The solution is to use 'global' information.

Rotation modulation changes,
but there are similarities over the whole curve

Our Second Approach: LoCoR

Problem: what do we do about the fastest rotators?



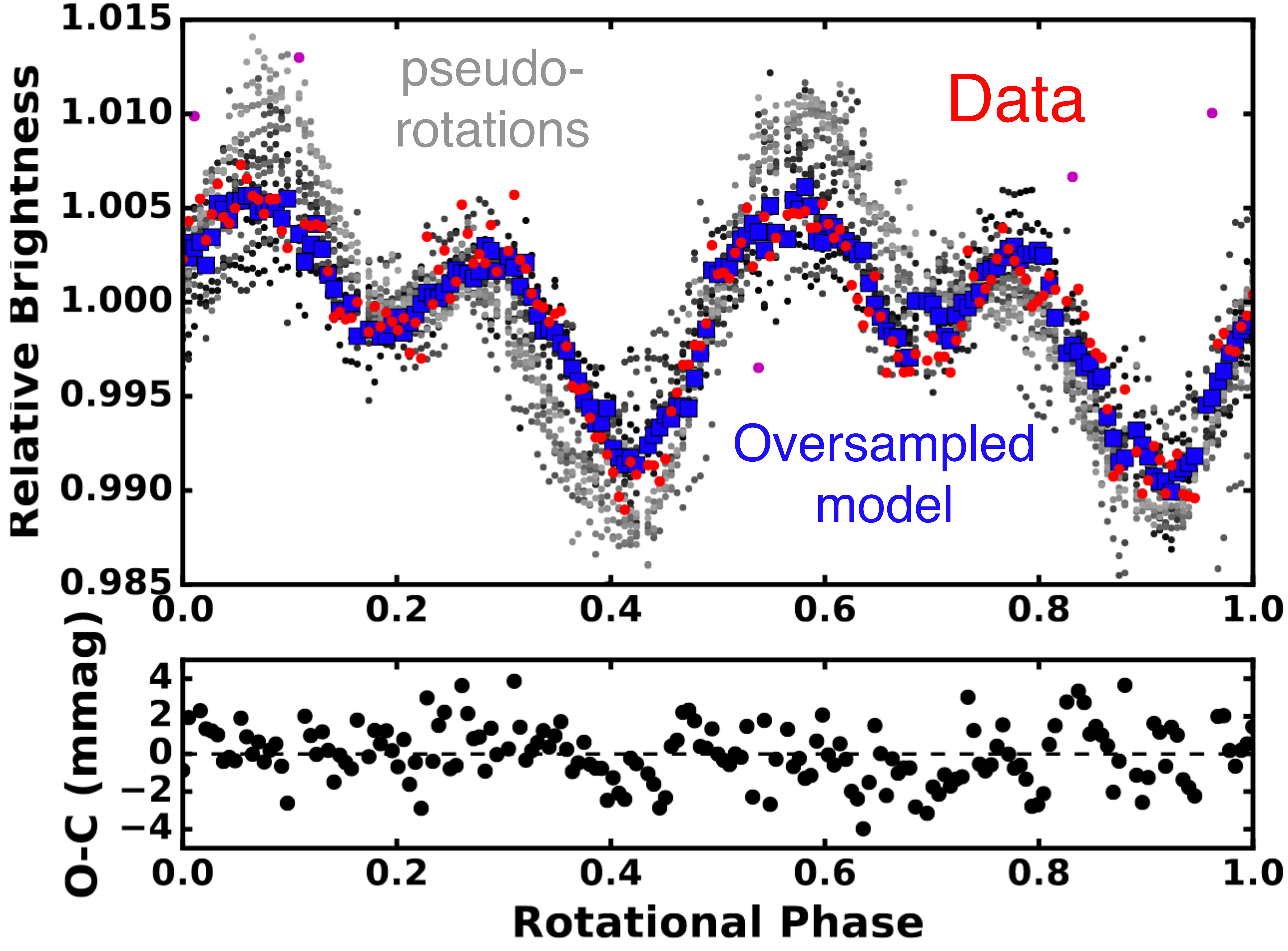
Take each individual ‘pseudo-rotation’.

Build a light curve from linear combinations of pseudo-rotation curves.

Effectively, fit the light curve using other parts of the curve.

Model = aP1+ bP2 + cP3 + …

LoCoR



Residual suggests we can take 1-2% remove rotational modulation to better than 0.1%.

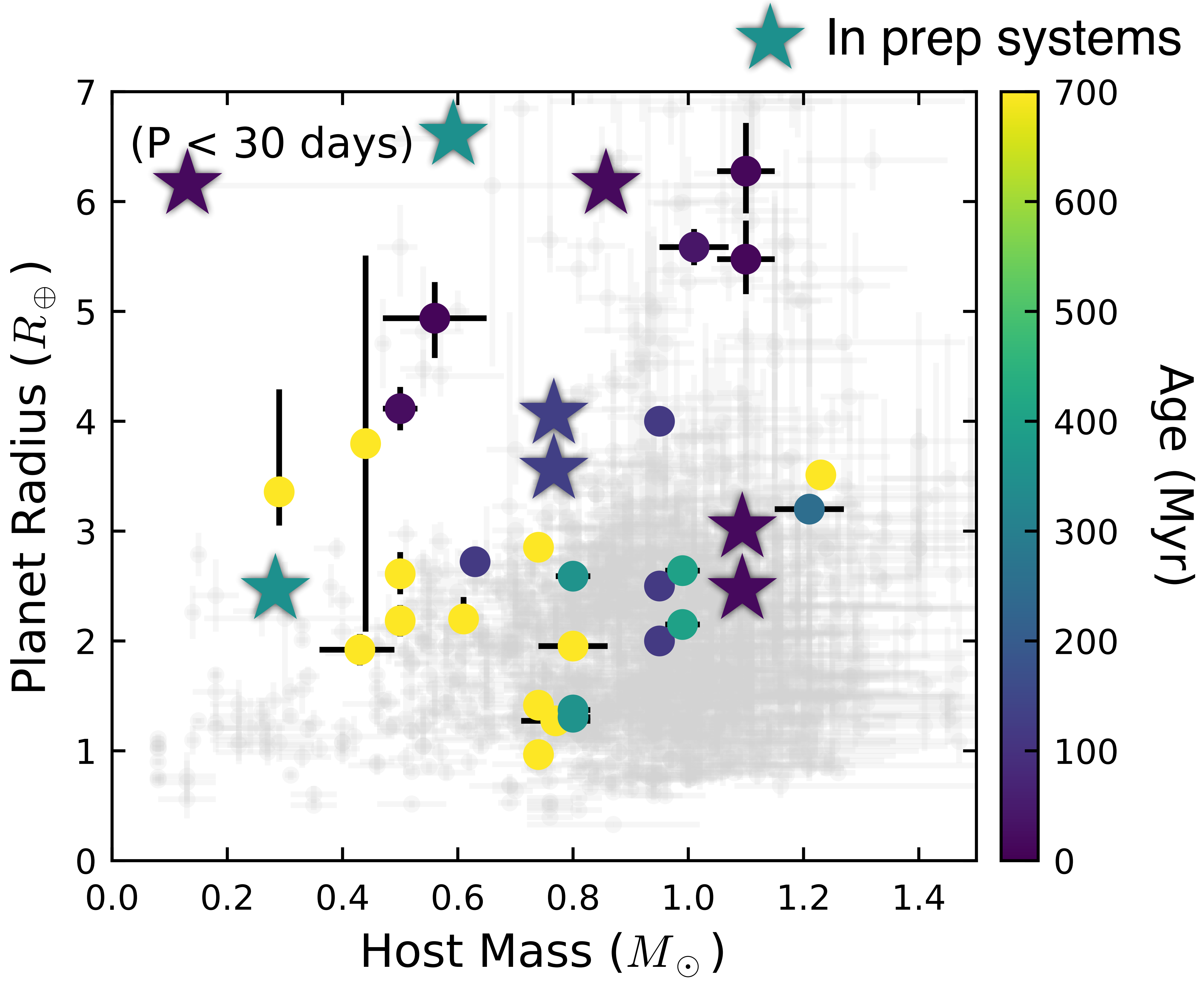
Better data and better methods have greatly expanded the sample of young transiting planets

~40 young transiting planets so far.

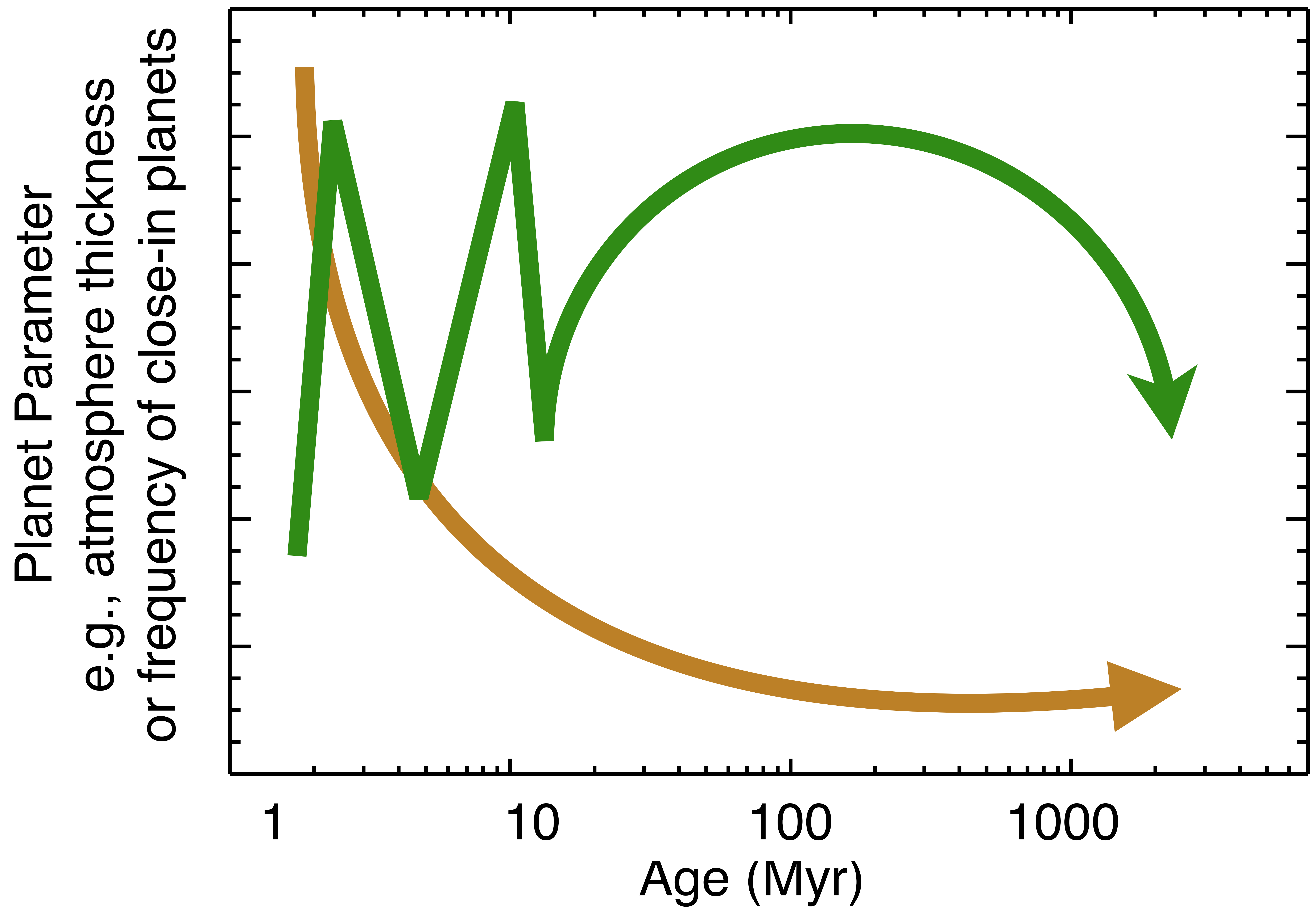
Most found with simple filtering methods.

But only Notch/LoCoR recovered all of them consistently.

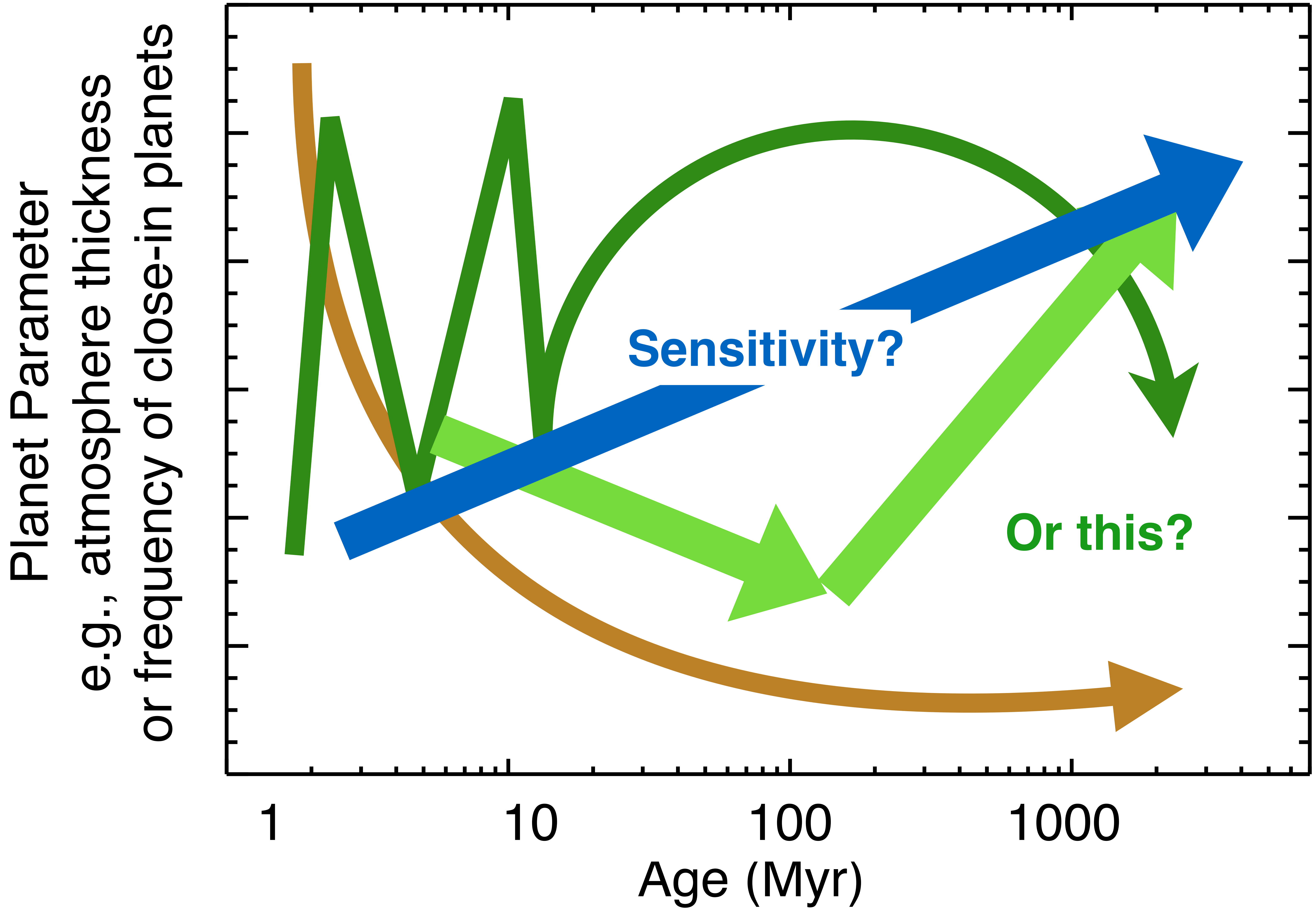
Discoveries across *TESS*, *K2*, and *Kepler* mission data.



Statistical changes in planet properties with time



Statistical changes in planet properties with time



Statistical changes in planet properties with time

How do you measure sensitivity?

Statistical changes in planet properties with time

Injection/Recovery

How do you measure sensitivity?

Statistical changes in planet properties with time

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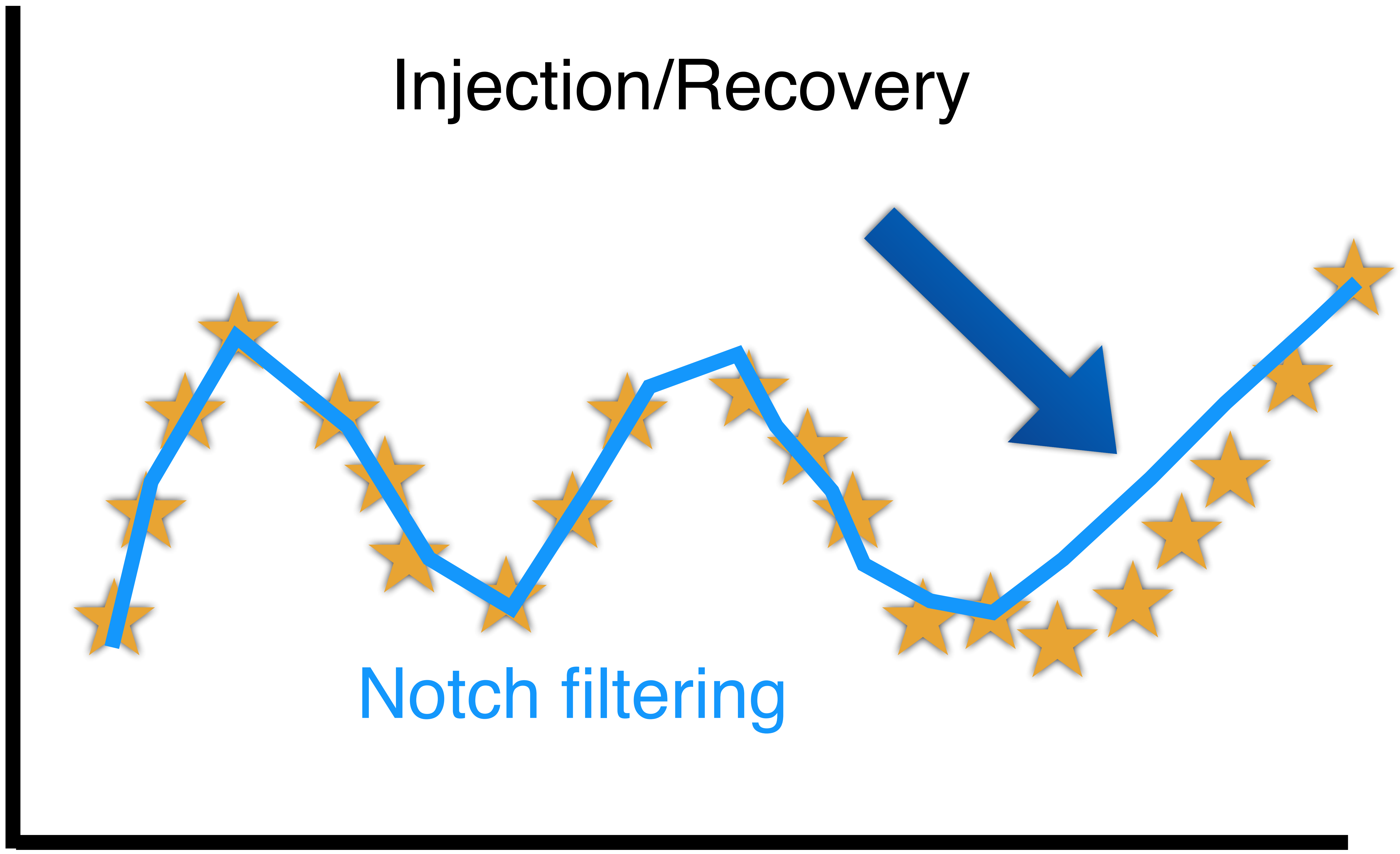
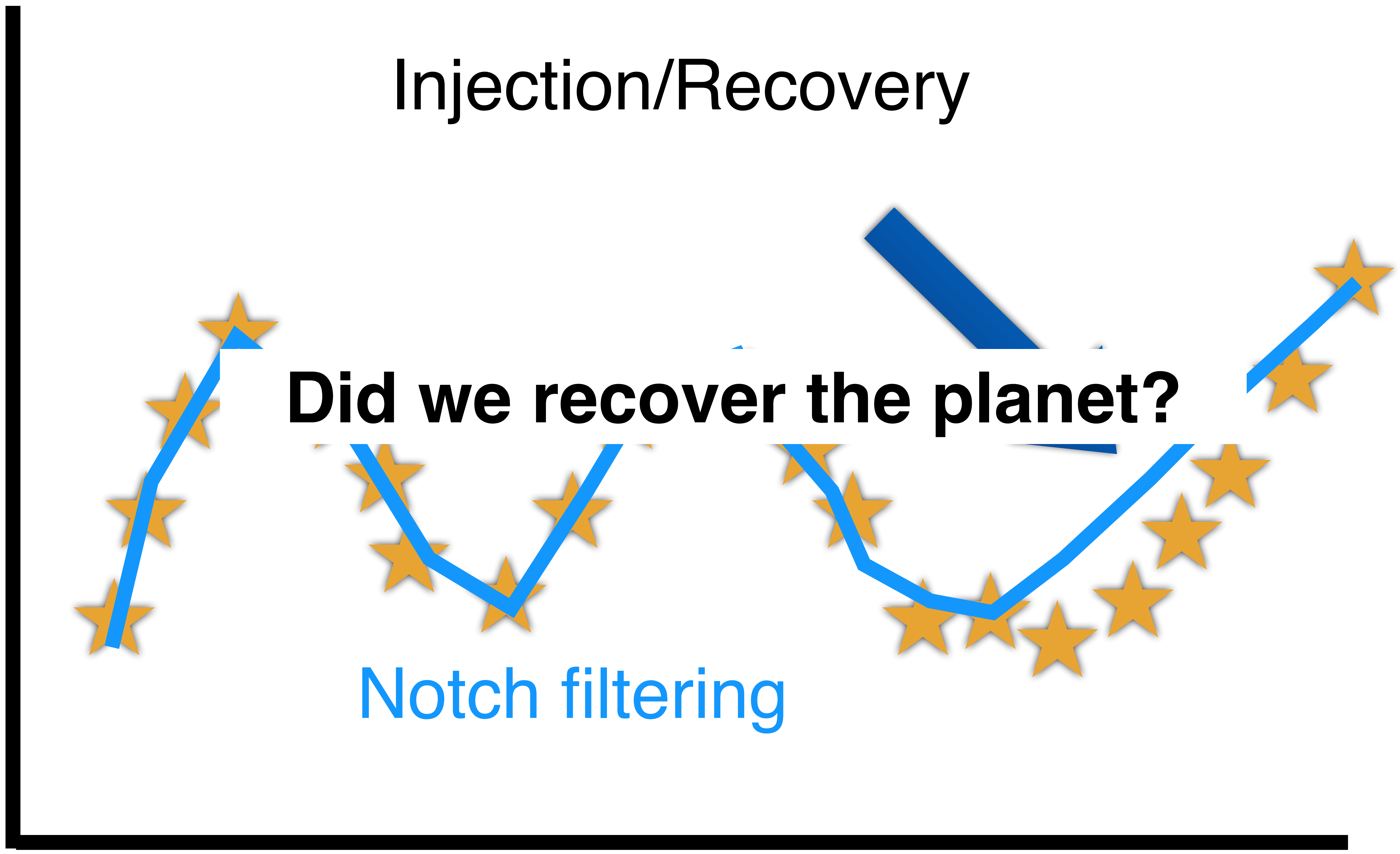
Statistical changes in planet properties with time



How do you measure sensitivity?

Statistical changes in planet properties with time

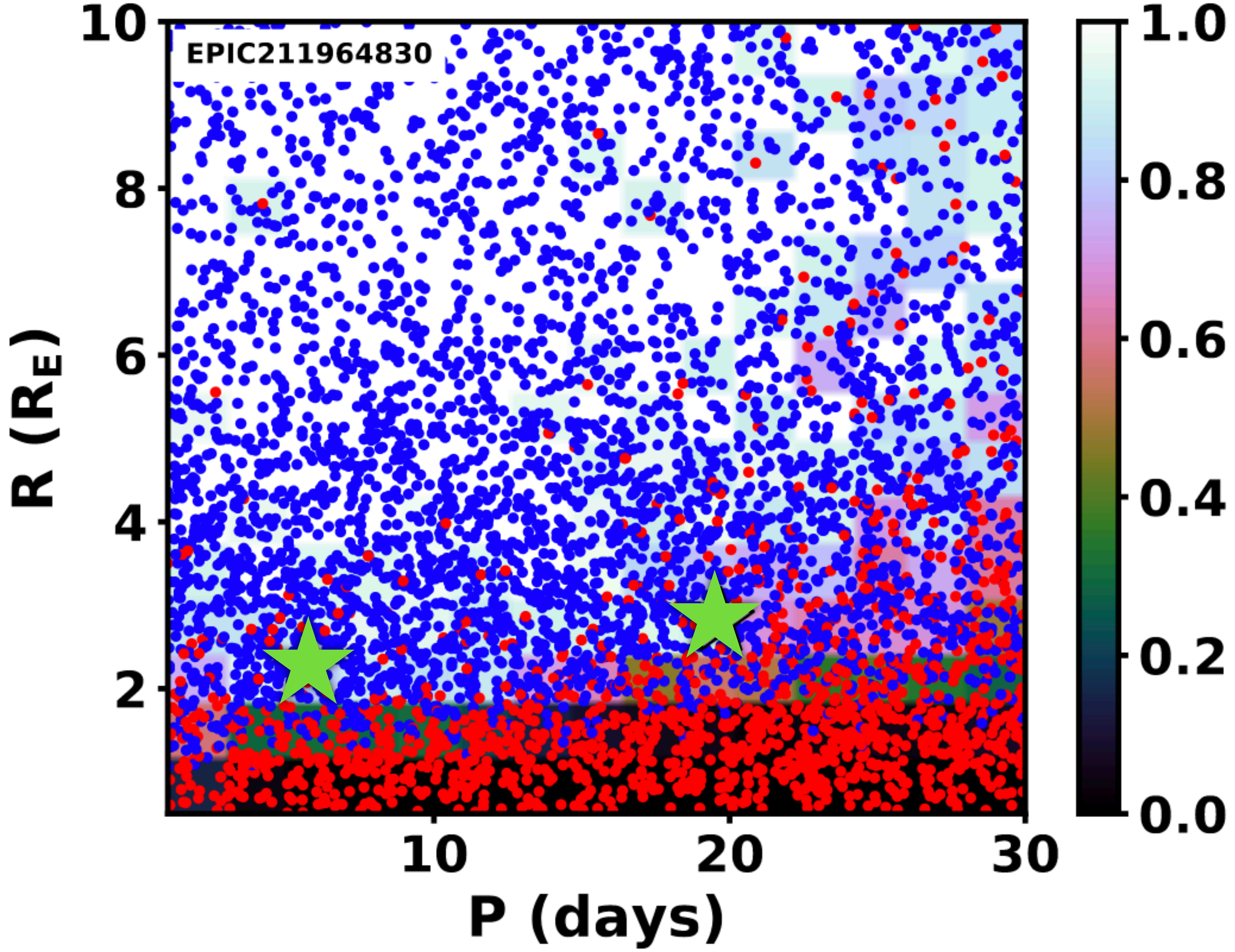


How do you measure sensitivity?

Statistical changes in planet properties with time

How do you measure sensitivity?

Injection/Recovery



Blue = recovered planet

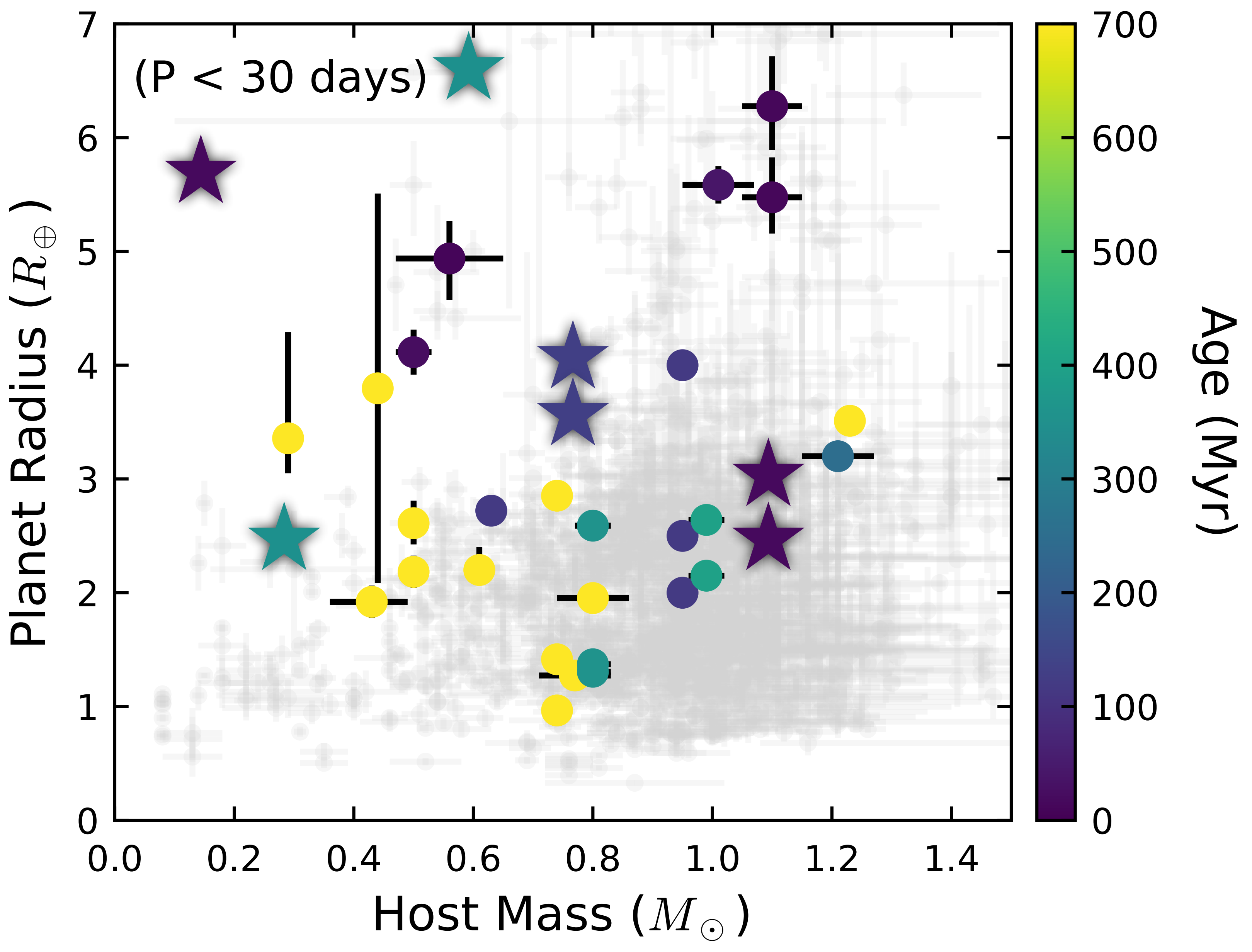
Red = not recovered planet

Green star = real planet

https://github.com/arizzuto/Notch_and_LOCoR
Rizzuto, Mann, Vanderburg et al. (2017)
Used in most ZEIT and THYME papers

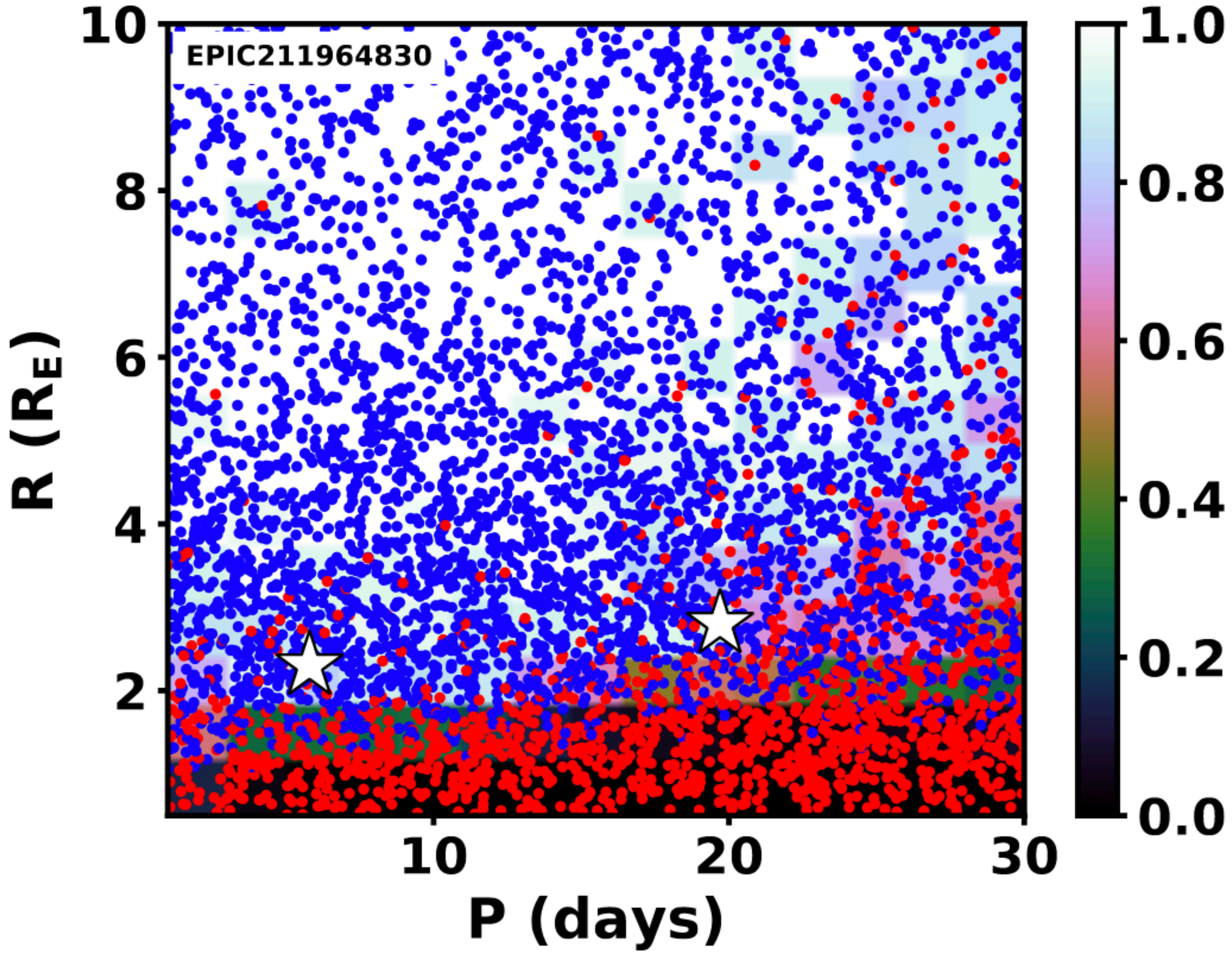
Statistical changes in planet properties with time

Detections



+

Completeness



= Statistics

-Exoplanet migration
-Density evolution
-Photoevporation
-Planet cooling
…

Questions?

Ask me during the live session
Or
One of the ‘meet the speakers’ sessions
Or
Email me: awmann@unc.edu