

From Pixels to Planets

The process of validating transiting exoplanets

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Sagan Summer Workshop
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Images: NASA

The Process of Validating Transiting Exoplanets

K2 Pixel Data

Light Curves

Transit Search

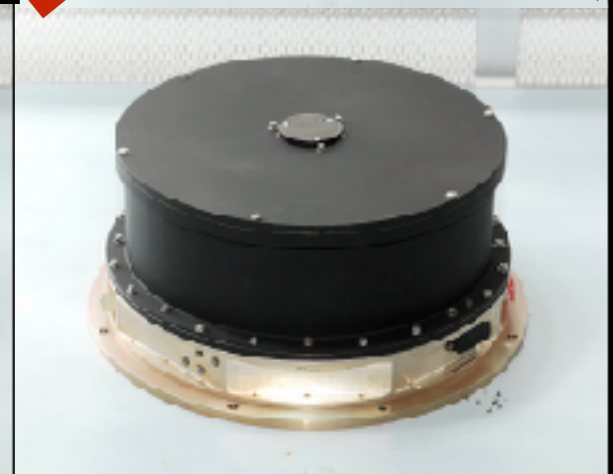
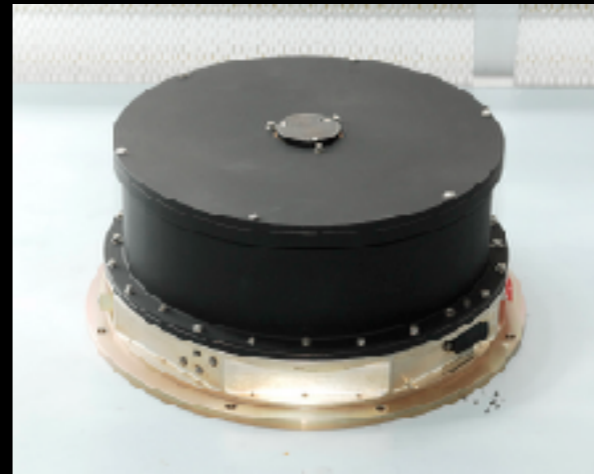
Threshold Crossing Events

Planet Candidates

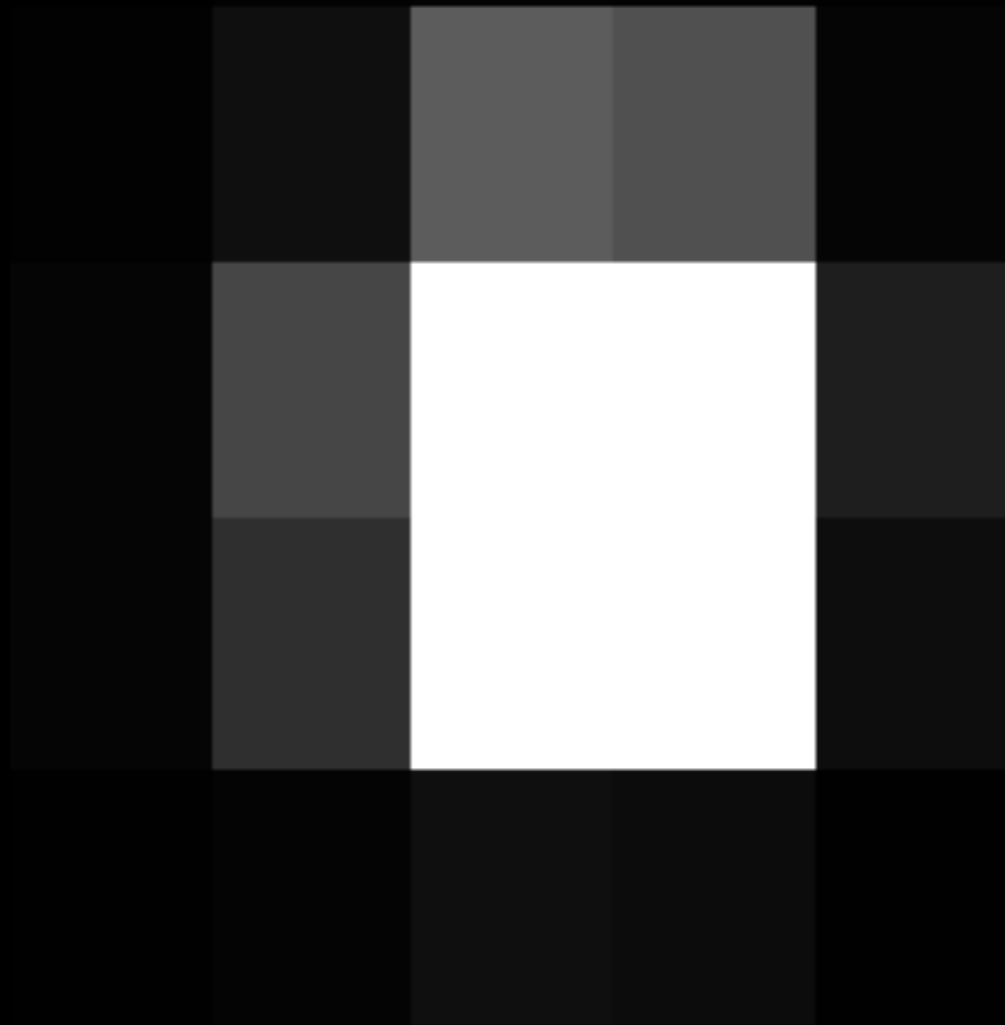
Validated Planets

Confirmed Planets

The K2 Mission



K2 Pixel Data

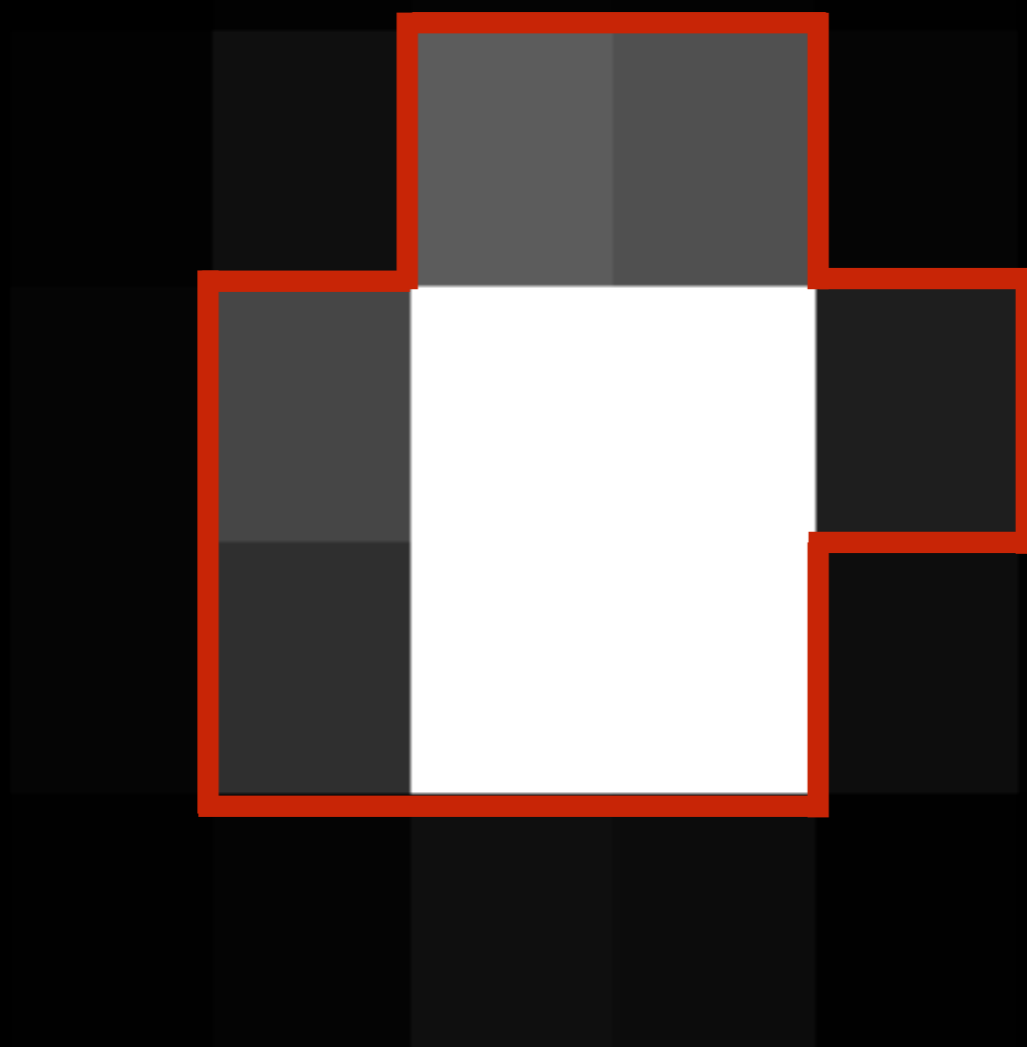


EPIC 212521166

2015-07-25 02:16:06

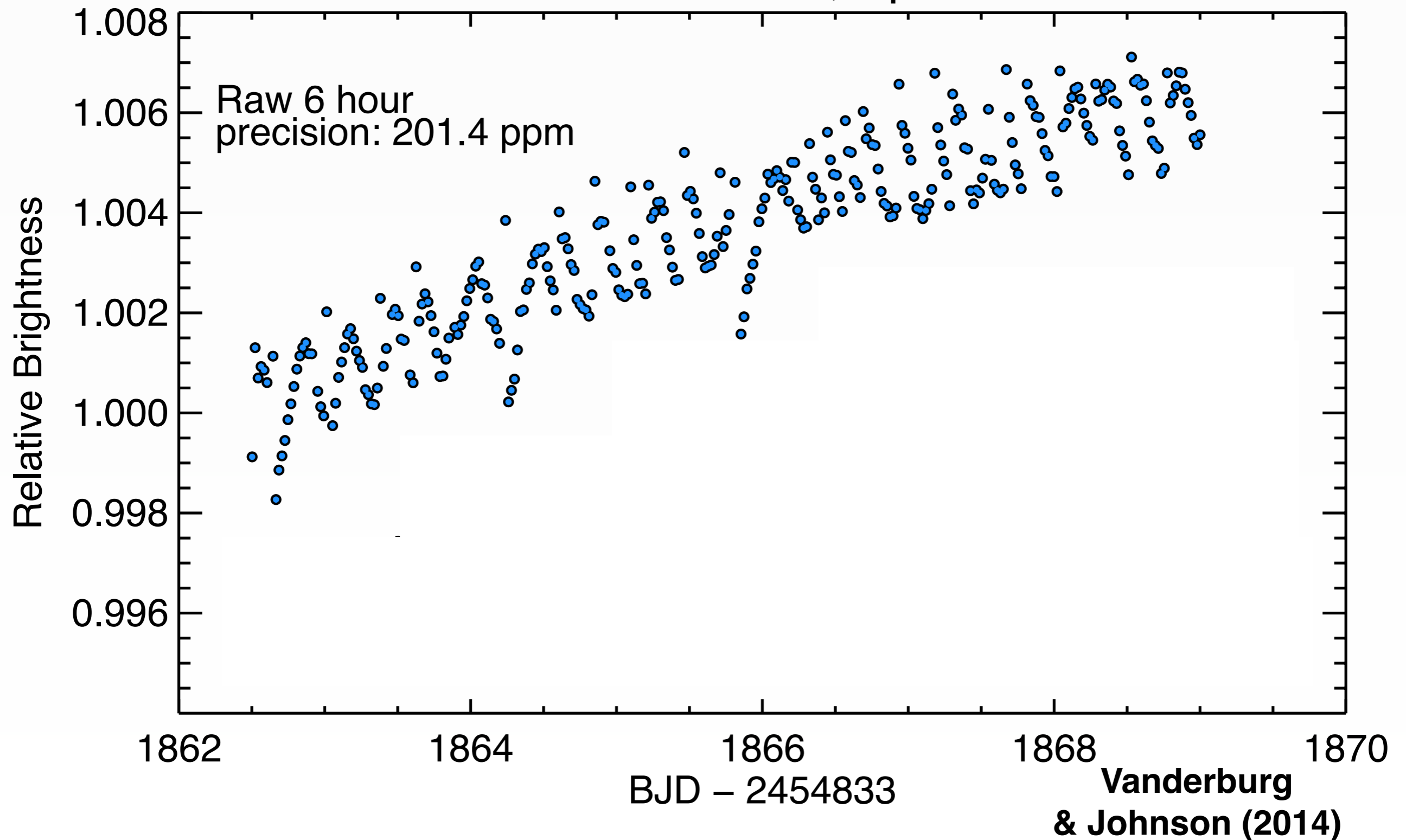
Animation: k2flix (Geert Barentsen)

Sum the Pixels

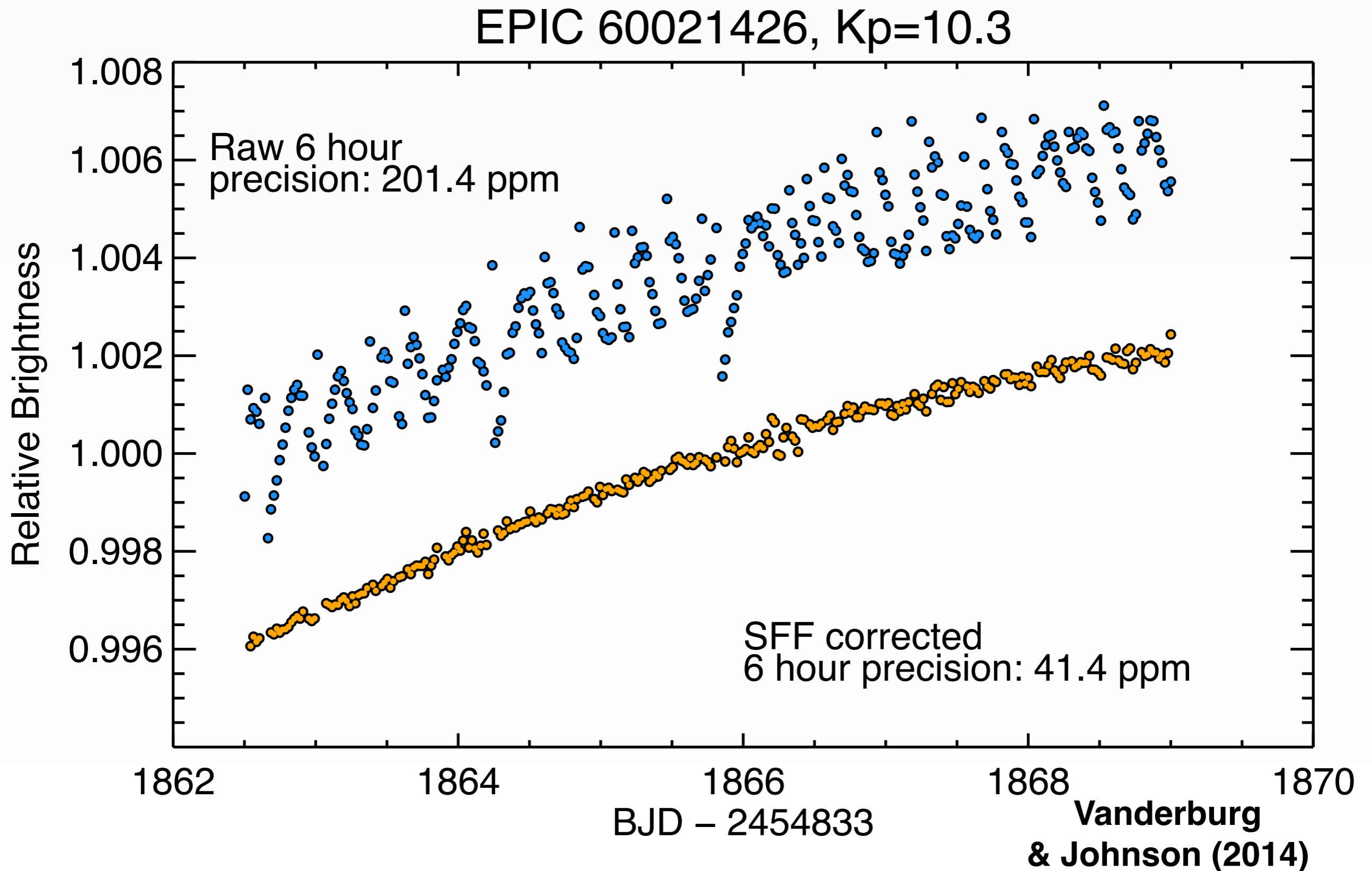


Light Curves

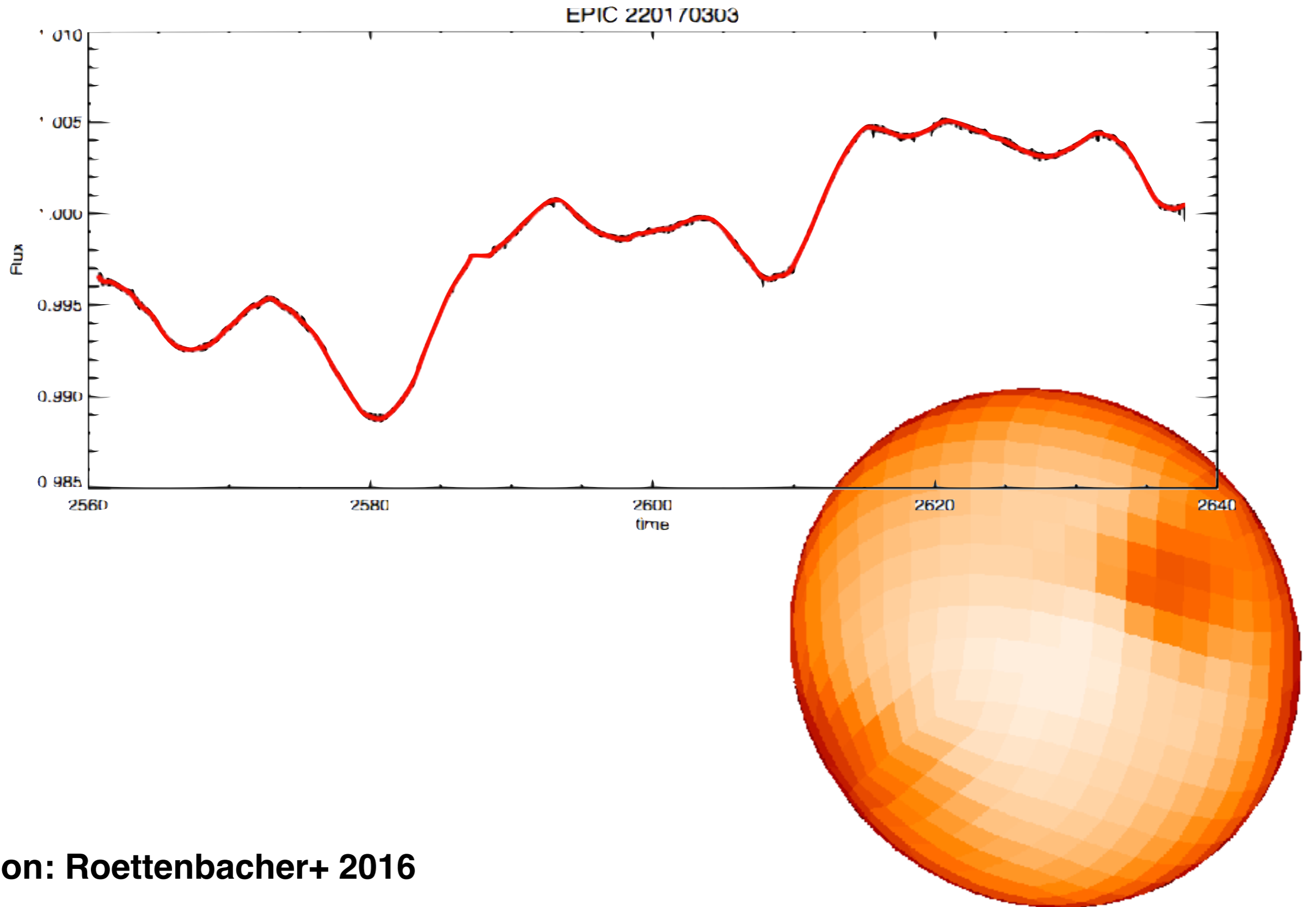
EPIC 60021426, $K_p=10.3$



Remove systematics

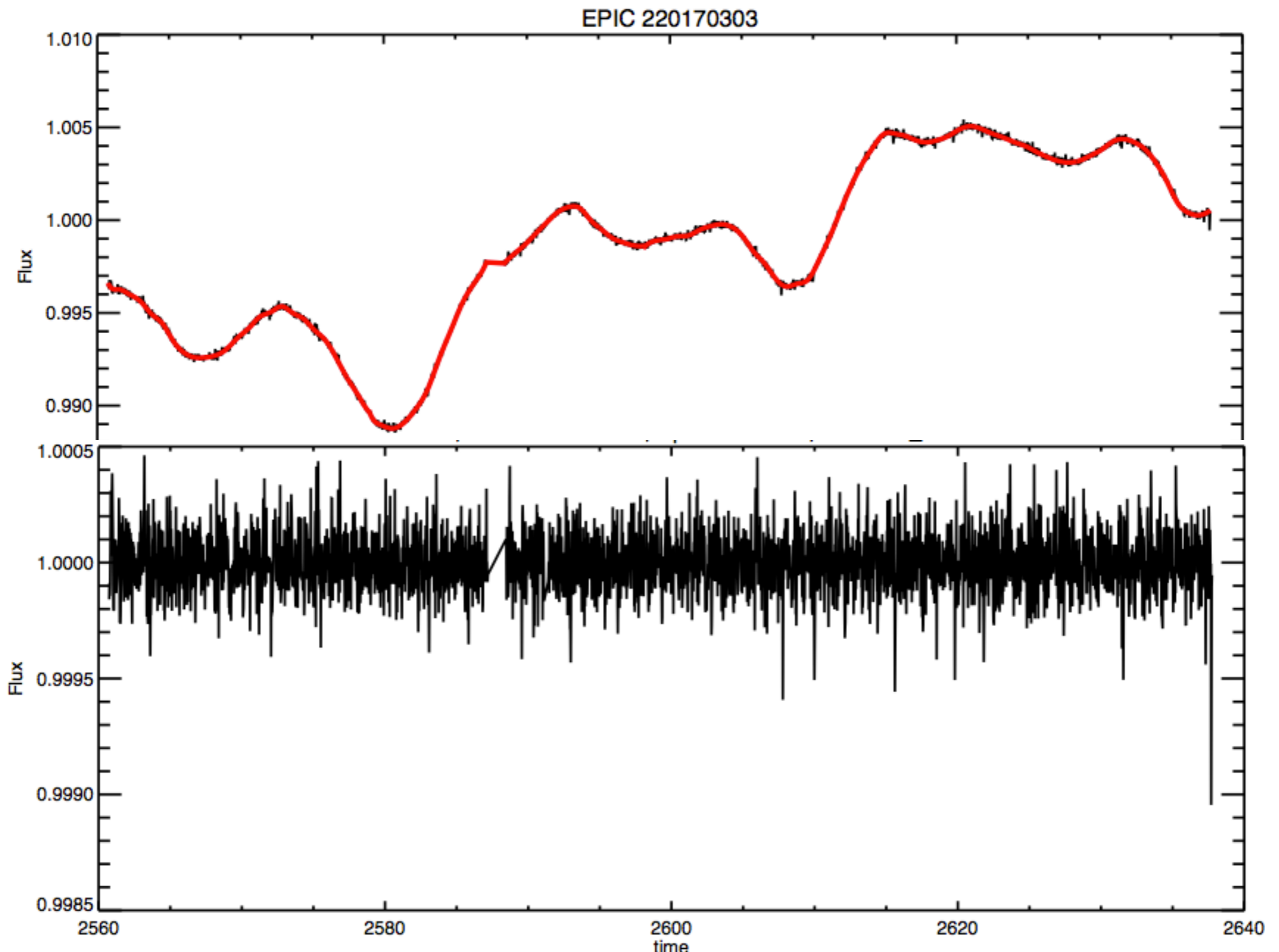


Remove low-frequency trends



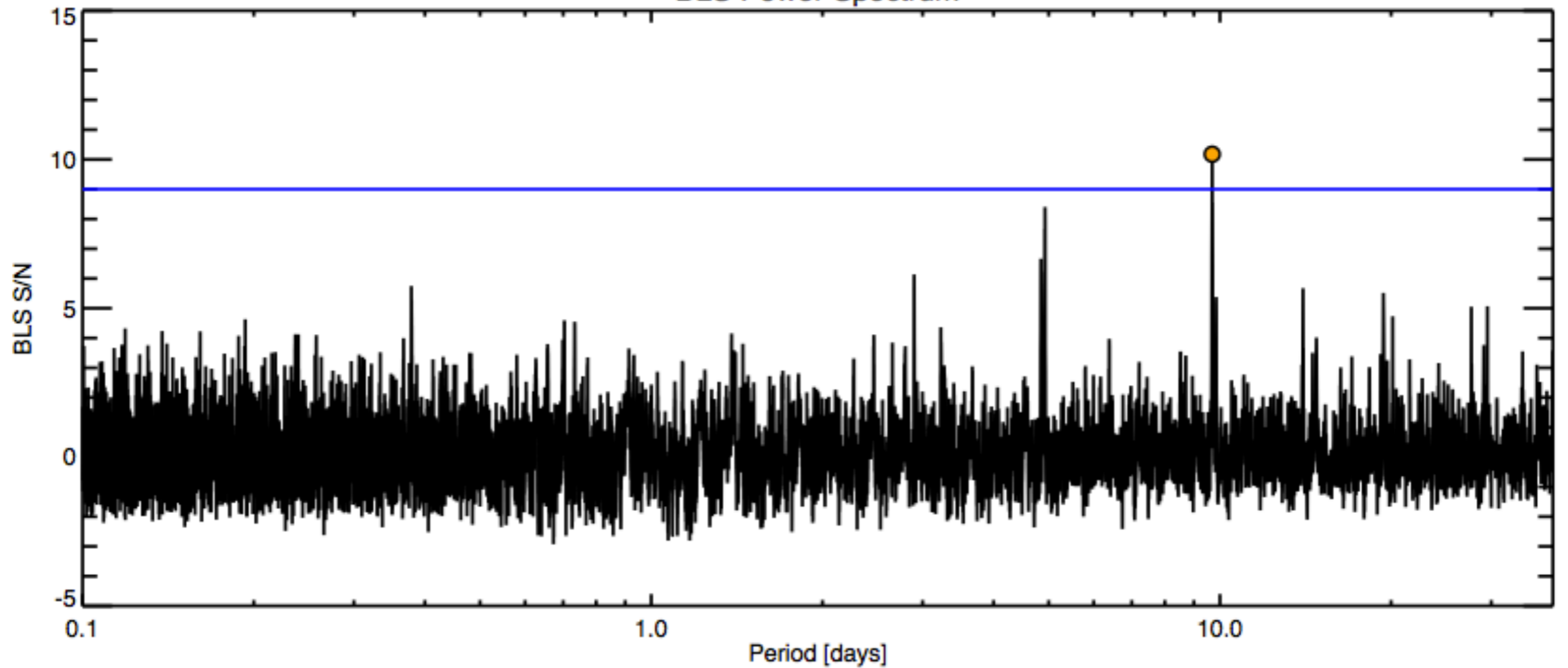
Animation: Roettenbacher+ 2016

Remove low-frequency trends

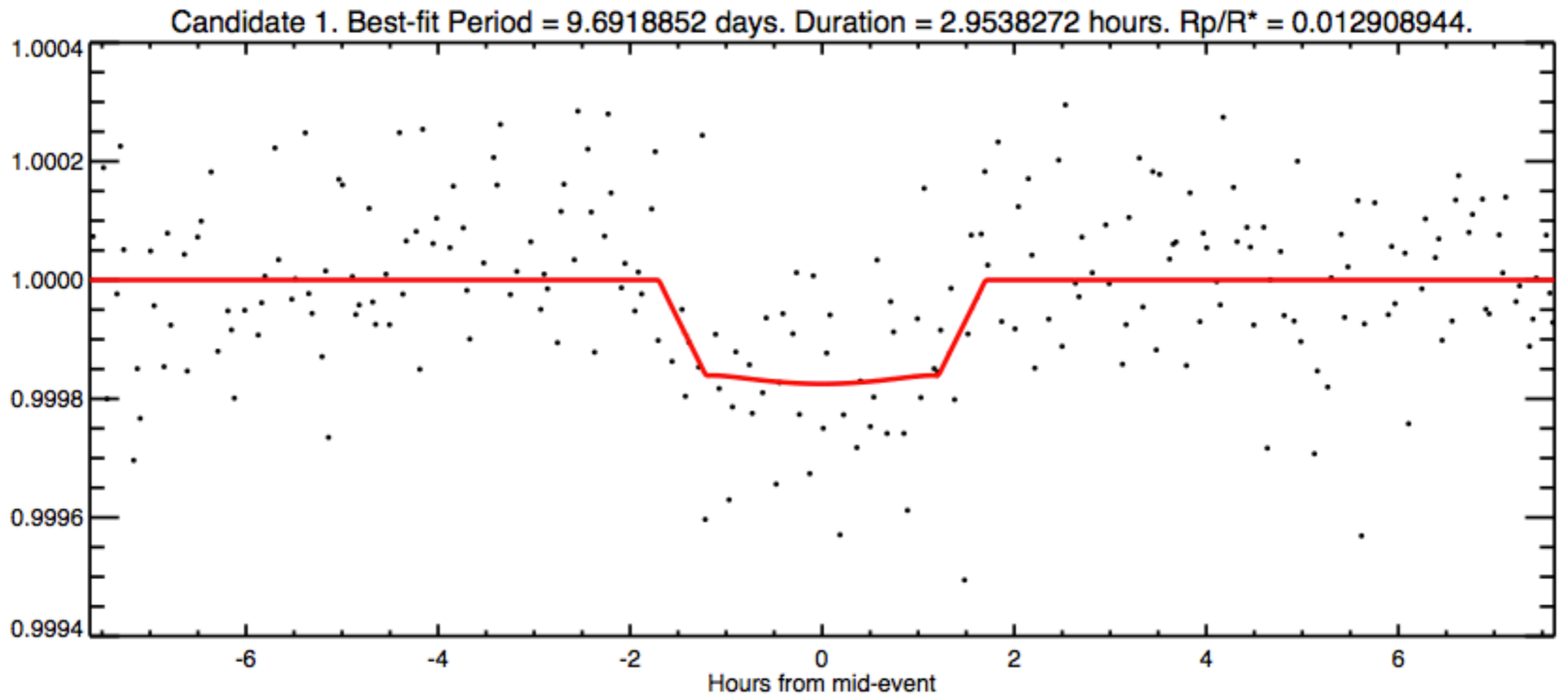


Transit Search (Box Least Squares Periodogram)

BLS Power Spectrum



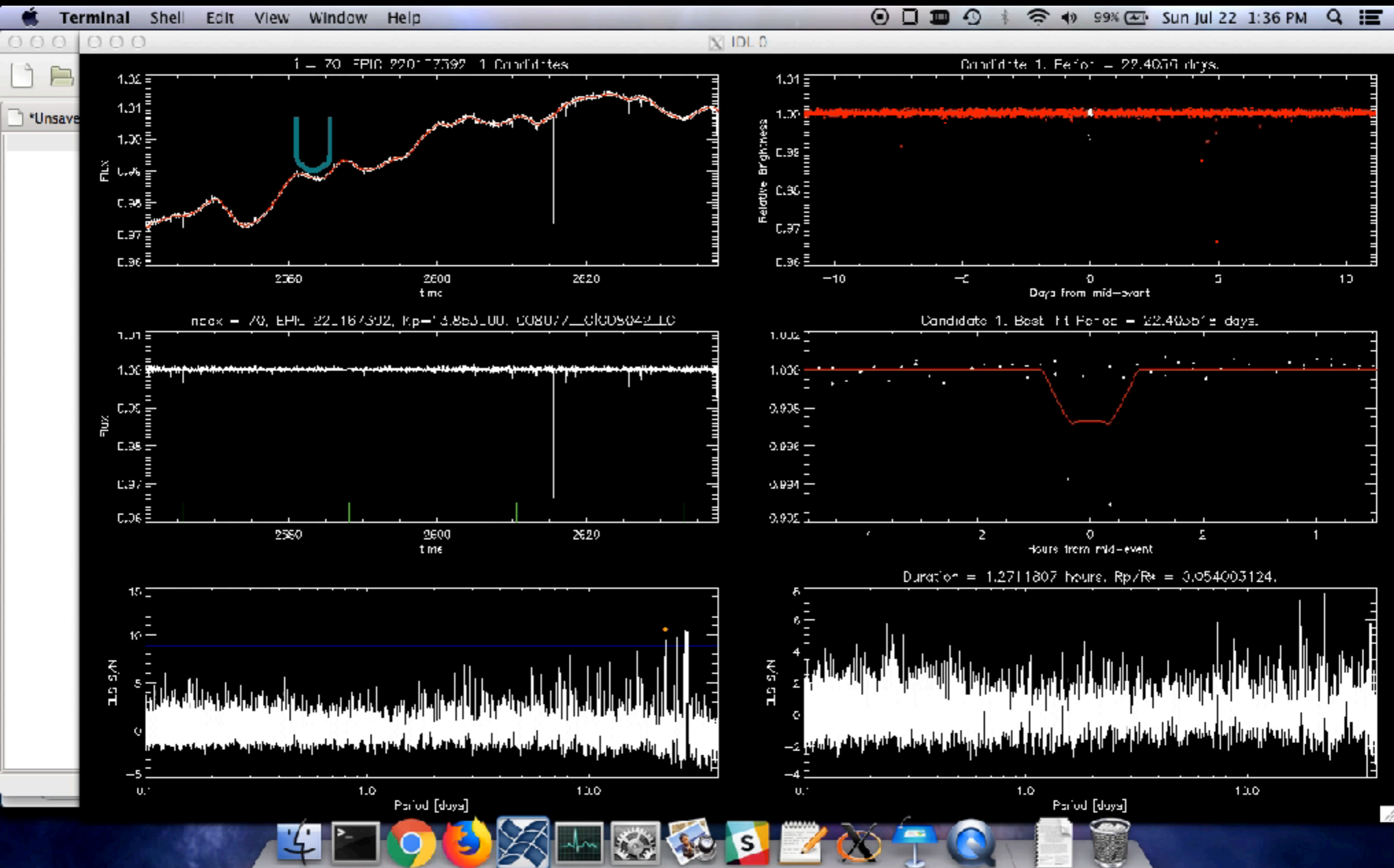
Transit Search (Box Least Squares Periodogram)



Threshold Crossing Event (TCE):

any possible transit signal
(period, t_0 , duration) in a
light curve strong enough
for a transit search
pipeline to identify.

Triage

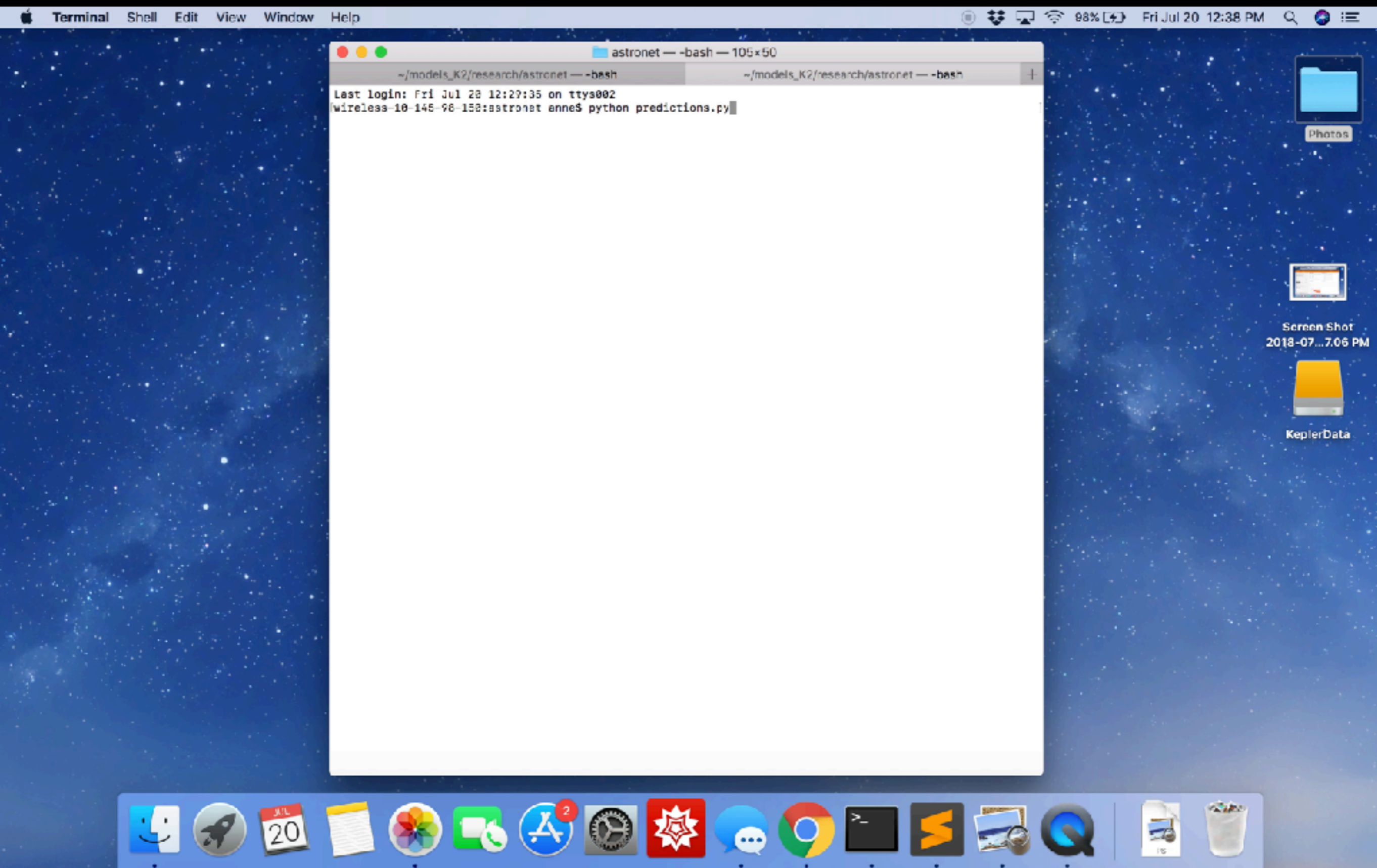


Speeding up triage for K2 with deep neural networks

Anne Dattilo, UT Austin rising senior undergraduate



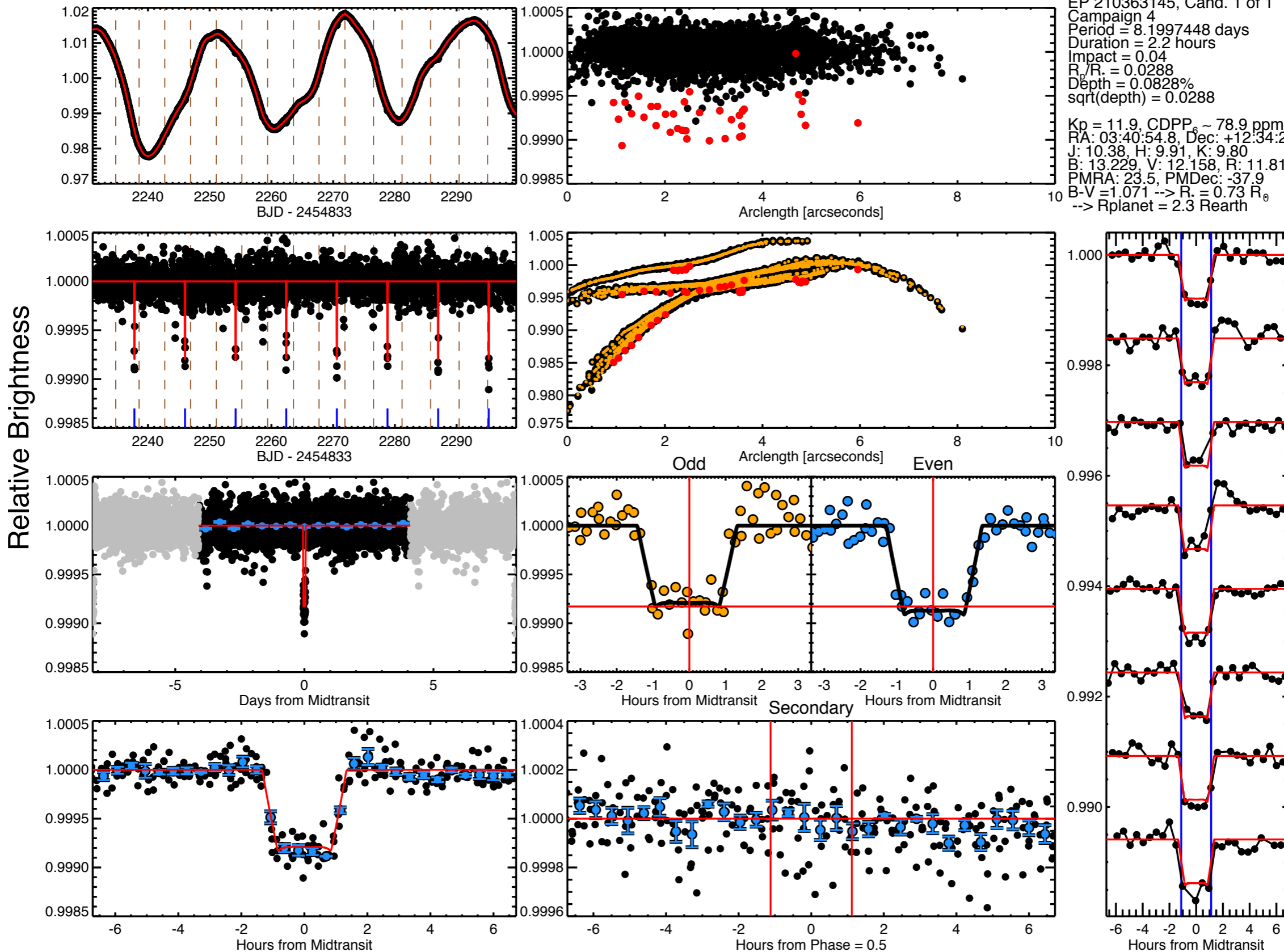
3000 signals, 98% accuracy, 20 seconds



Post-triage vetting

EPIC 210363145, Candidate 1 of 1

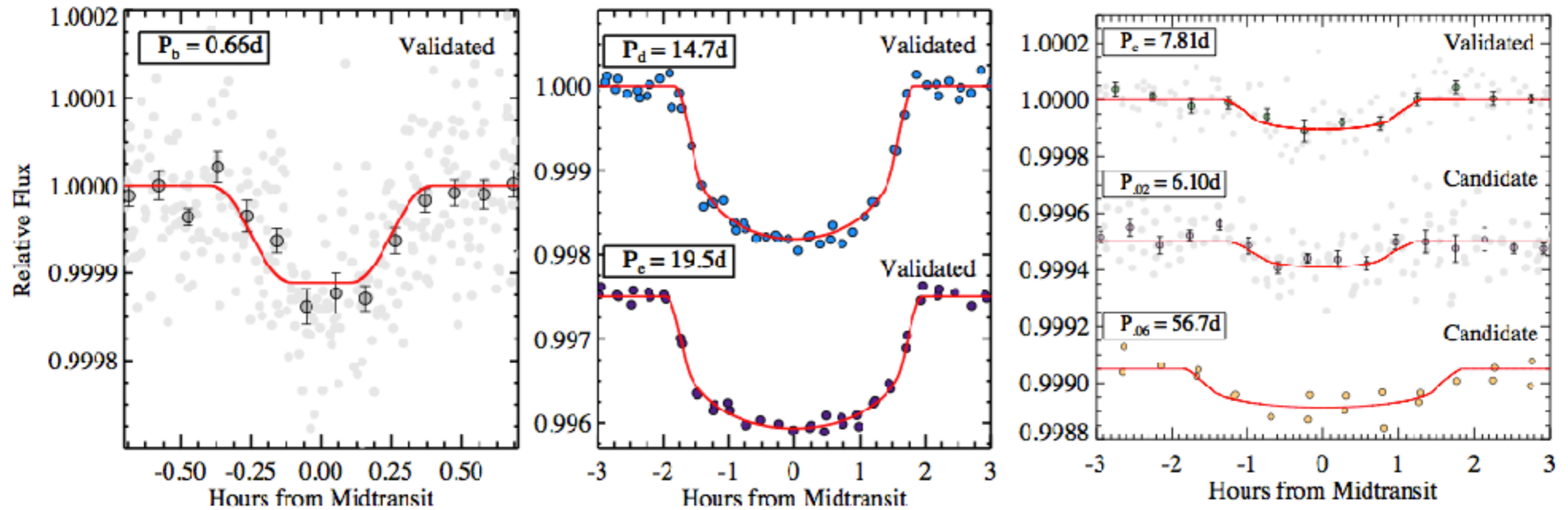
EP 210363145, Cand. 1 of 1
Campaign 4
Period = 8.1997448 days
Duration = 2.2 hours
Impact = 0.04
 $R_p/R_s = 0.0288$
Depth = 0.0828%
 $\text{sqrt}(\text{depth}) = 0.0288$
 $K_p = 11.9$, $\text{CDPP}_6 \sim 78.9$ ppm
RA: 03:40:54.8, Dec: +12:34:21
J: 10.38, H: 9.91, K: 9.80
B: 13.229, V: 12.158, R: 11.816
PMRA: 23.5, PMDec: -37.9
 $B-V = 1.071 \rightarrow R_s = 0.73 R_\odot$
 $\rightarrow R_{\text{planet}} = 2.3 R_{\text{Earth}}$



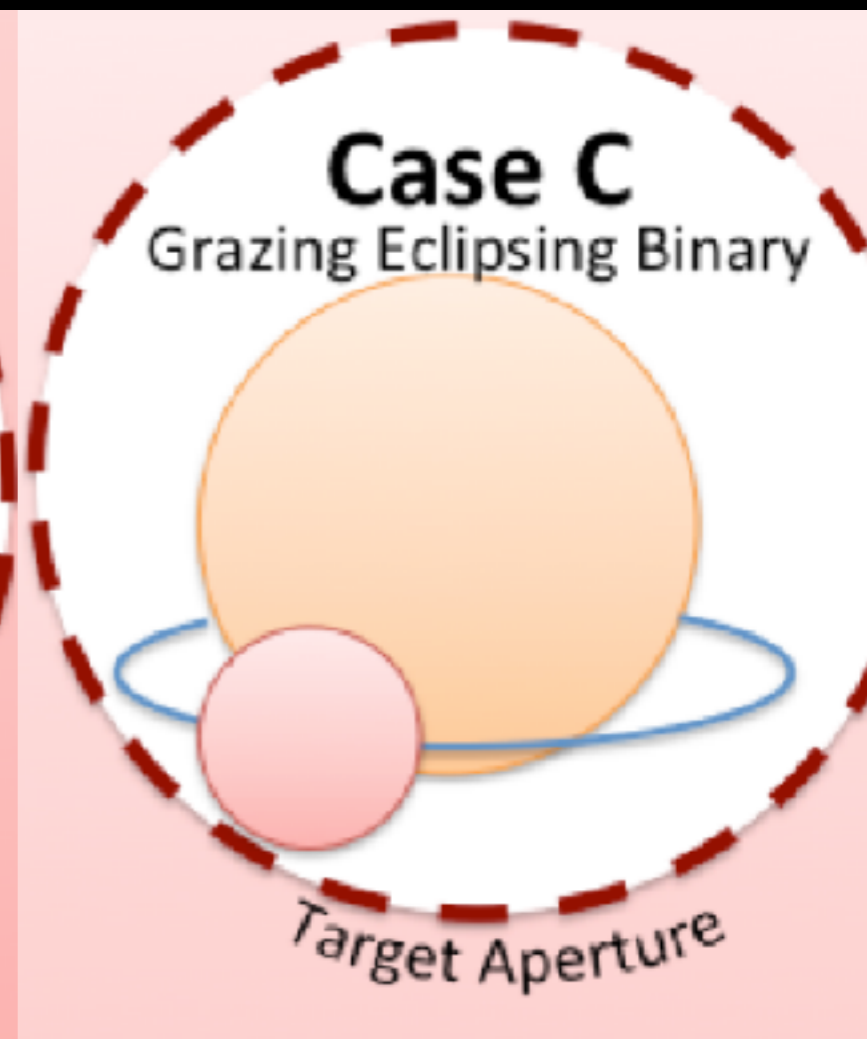
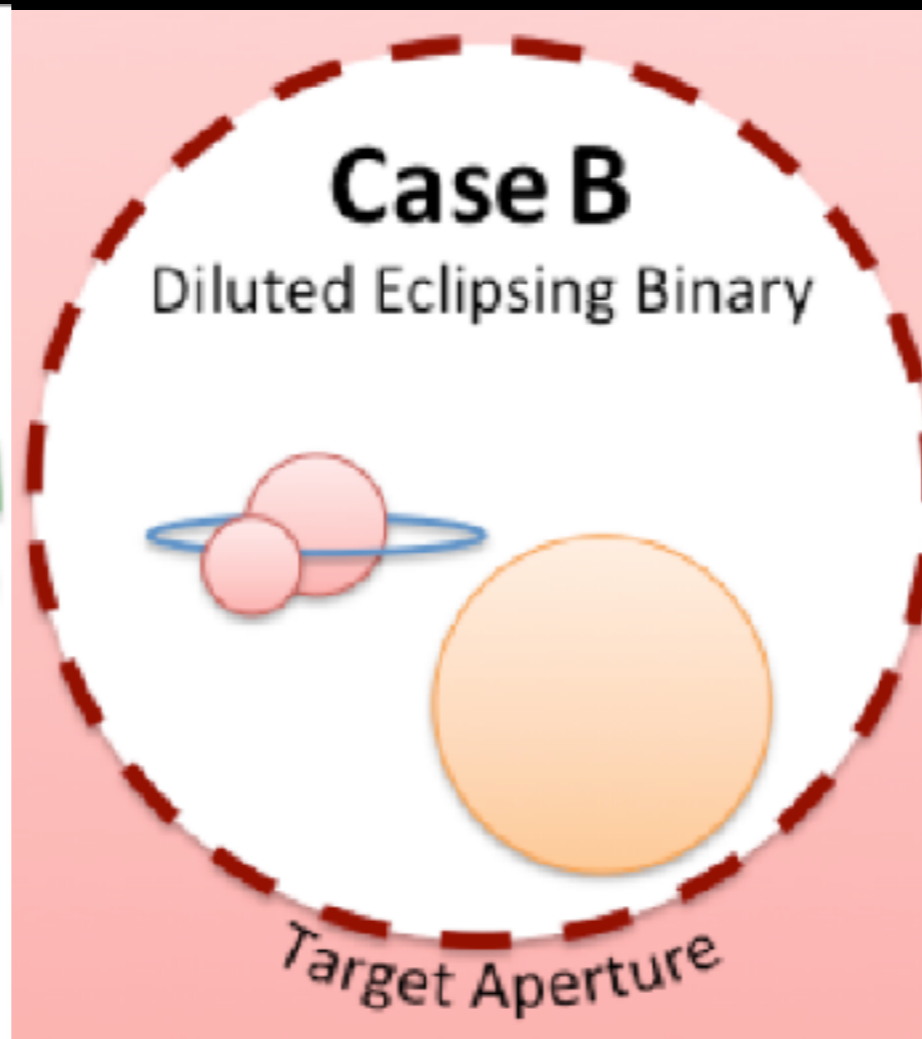
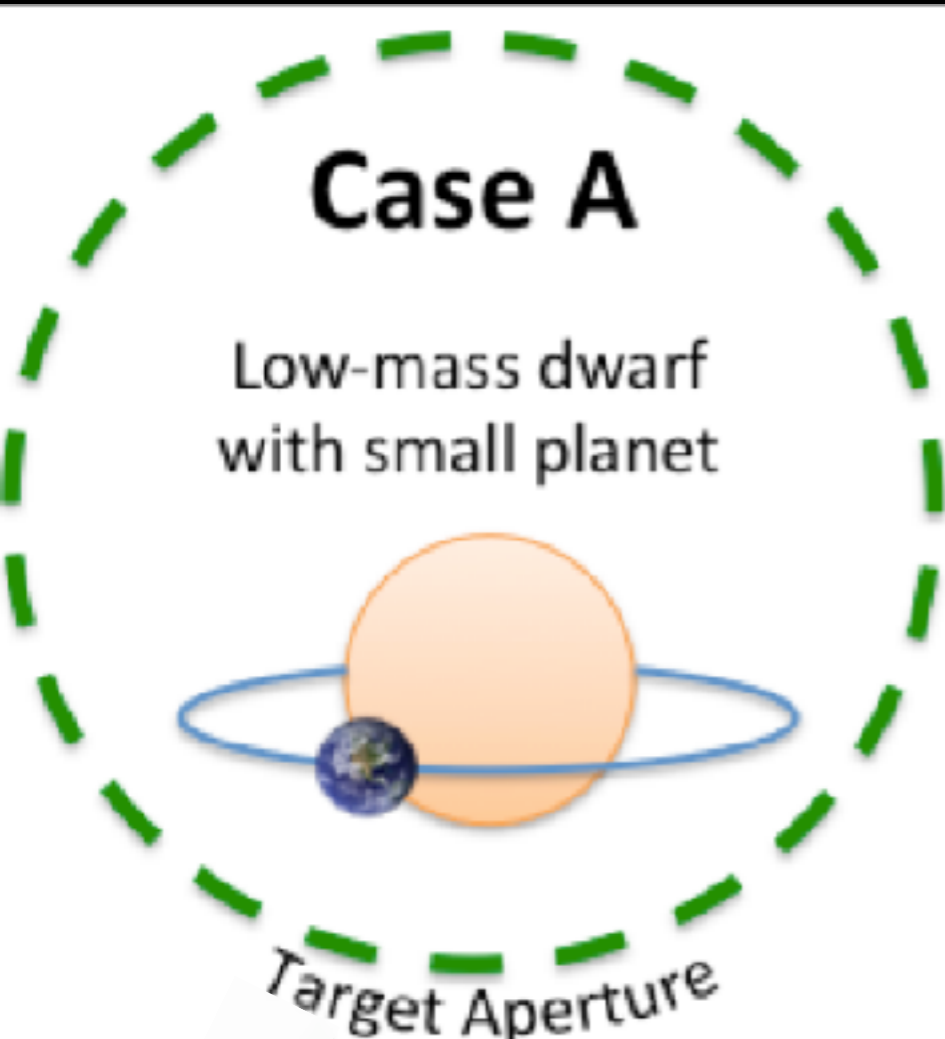
Planet Candidate:

A TCE which has passed initial triage inspection and additional vetting to identify false positives.

Example: EPIC 248435473

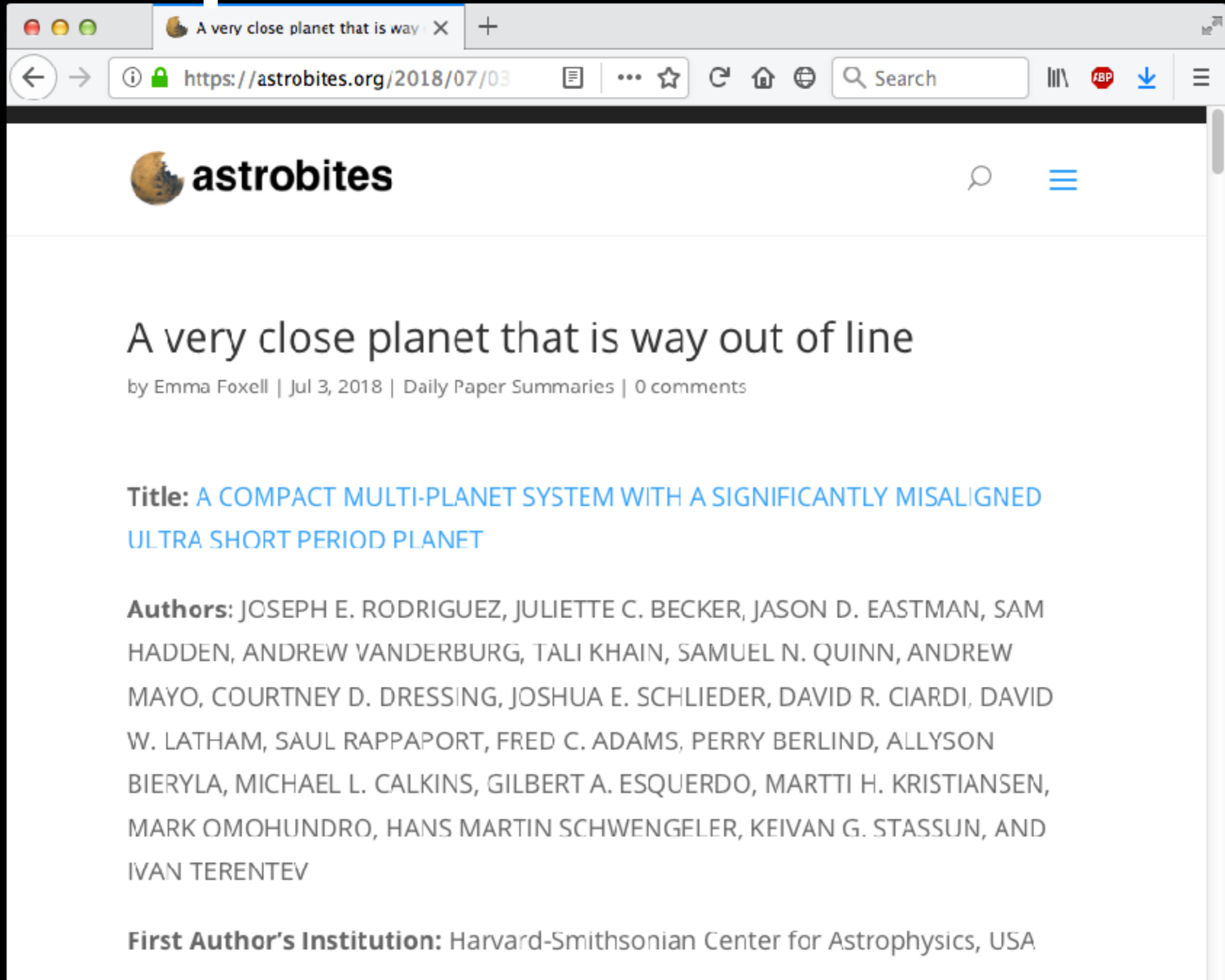


Ruling out False Positives



Case D
Instrumental Glitch

Example: EPIC 248435473



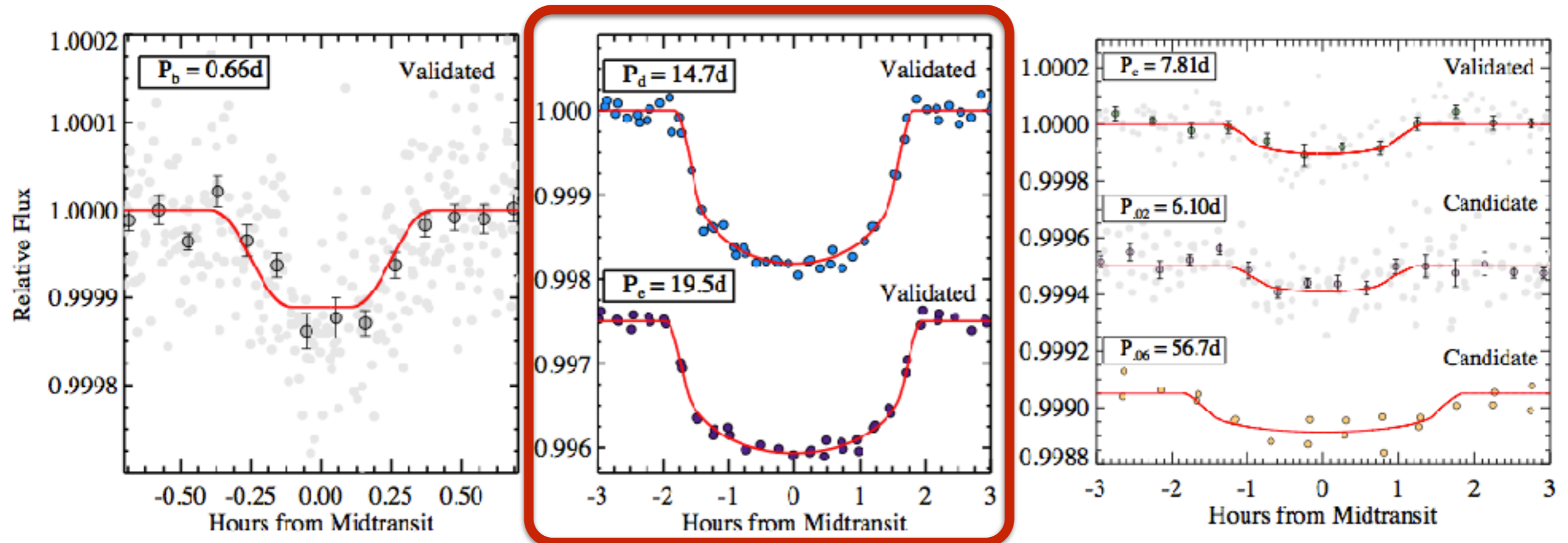
A screenshot of a web browser displaying an article on the website astrobites.org. The browser's address bar shows the URL <https://astrobites.org/2018/07/03>. The article title is "A very close planet that is way out of line" by Emma Foxell, dated July 3, 2018. The article title is followed by a blue link to the full paper: "A COMPACT MULTI-PLANET SYSTEM WITH A SIGNIFICANTLY MISALIGNED ULTRA SHORT PERIOD PLANET". The authors listed are JOSEPH E. RODRIGUEZ, JULIETTE C. BECKER, JASON D. EASTMAN, SAM HADDEN, ANDREW VANDERBURG, TALI KHAIN, SAMUEL N. QUINN, ANDREW MAYO, COURTNEY D. DRESSING, JOSHUA E. SCHLIEDER, DAVID R. CIARDI, DAVID W. LATHAM, SAUL RAPPAPORT, FRED C. ADAMS, PERRY BERLIND, ALLYSON BIERYLA, MICHAEL L. CALKINS, GILBERT A. ESQUERDO, MARTTI H. KRISTIANSEN, MARK OMOHUNDRO, HANS MARTIN SCHWENGELER, KEIVAN G. STASSUN, AND IVAN TERENCEV. The first author's institution is listed as Harvard-Smithsonian Center for Astrophysics, USA.

Title: [A COMPACT MULTI-PLANET SYSTEM WITH A SIGNIFICANTLY MISALIGNED ULTRA SHORT PERIOD PLANET](#)

Authors: JOSEPH E. RODRIGUEZ, JULIETTE C. BECKER, JASON D. EASTMAN, SAM HADDEN, ANDREW VANDERBURG, TALI KHAIN, SAMUEL N. QUINN, ANDREW MAYO, COURTNEY D. DRESSING, JOSHUA E. SCHLIEDER, DAVID R. CIARDI, DAVID W. LATHAM, SAUL RAPPAPORT, FRED C. ADAMS, PERRY BERLIND, ALLYSON BIERYLA, MICHAEL L. CALKINS, GILBERT A. ESQUERDO, MARTTI H. KRISTIANSEN, MARK OMOHUNDRO, HANS MARTIN SCHWENGELER, KEIVAN G. STASSUN, AND IVAN TERENCEV

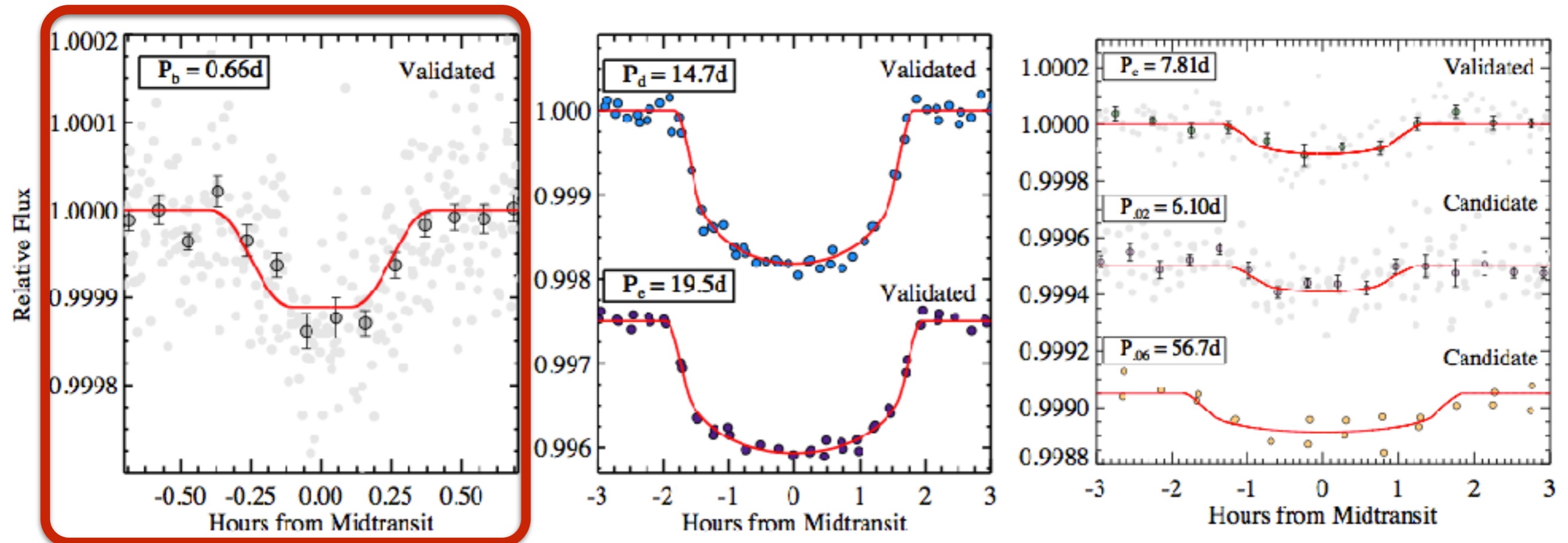
First Author's Institution: Harvard-Smithsonian Center for Astrophysics, USA

Example: EPIC 248435473



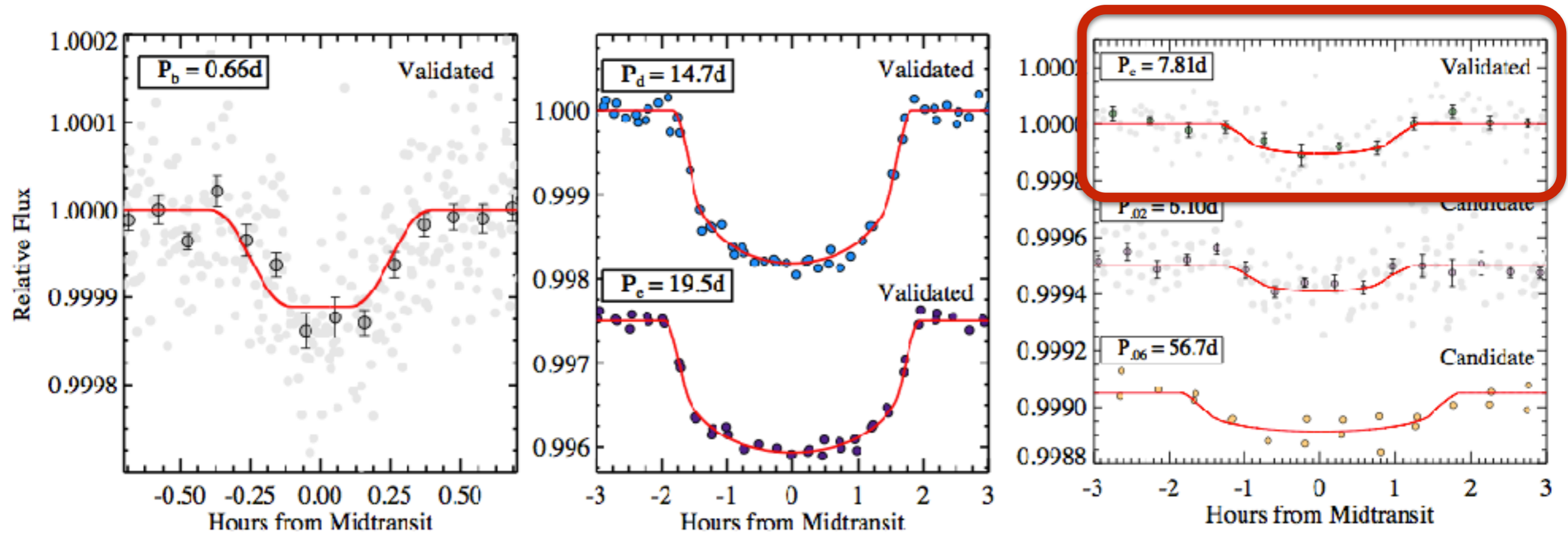
Two sub-Neptune candidates detected at $\sim 110\sigma$ near resonance.

Example: EPIC 248435473



**One ultra-short-period
super-Earth candidate
detected at ~ 13 sigma**

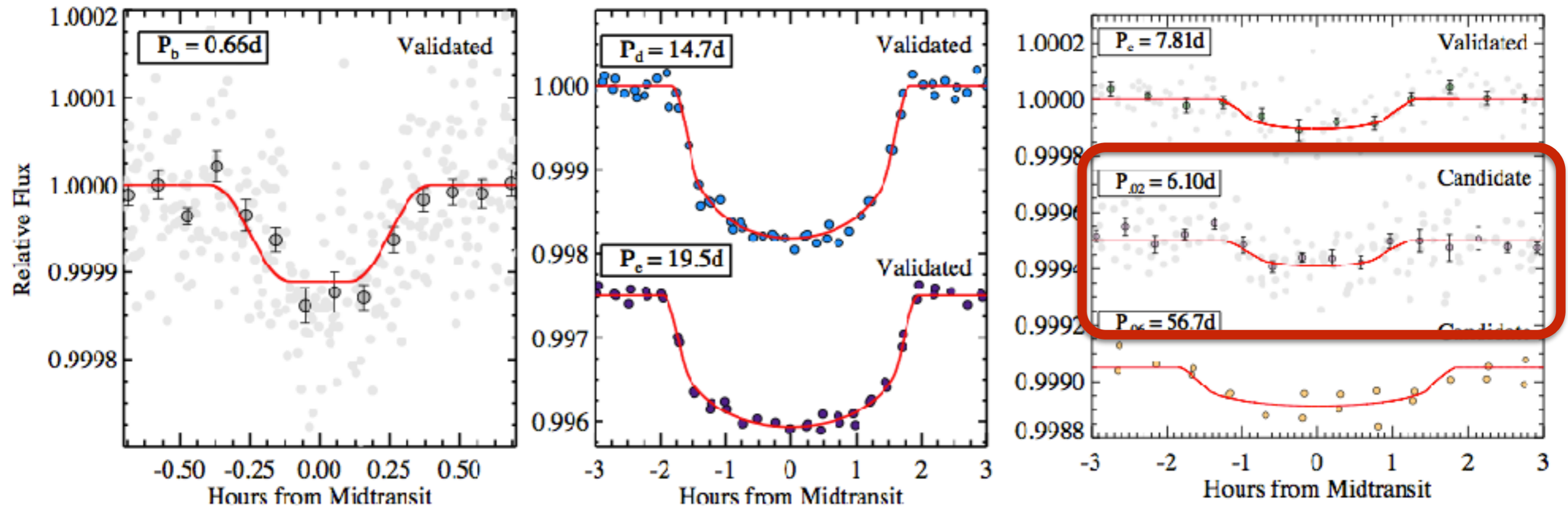
Example: EPIC 248435473



One Mars-sized planet candidate detected at ~ 10 sigma

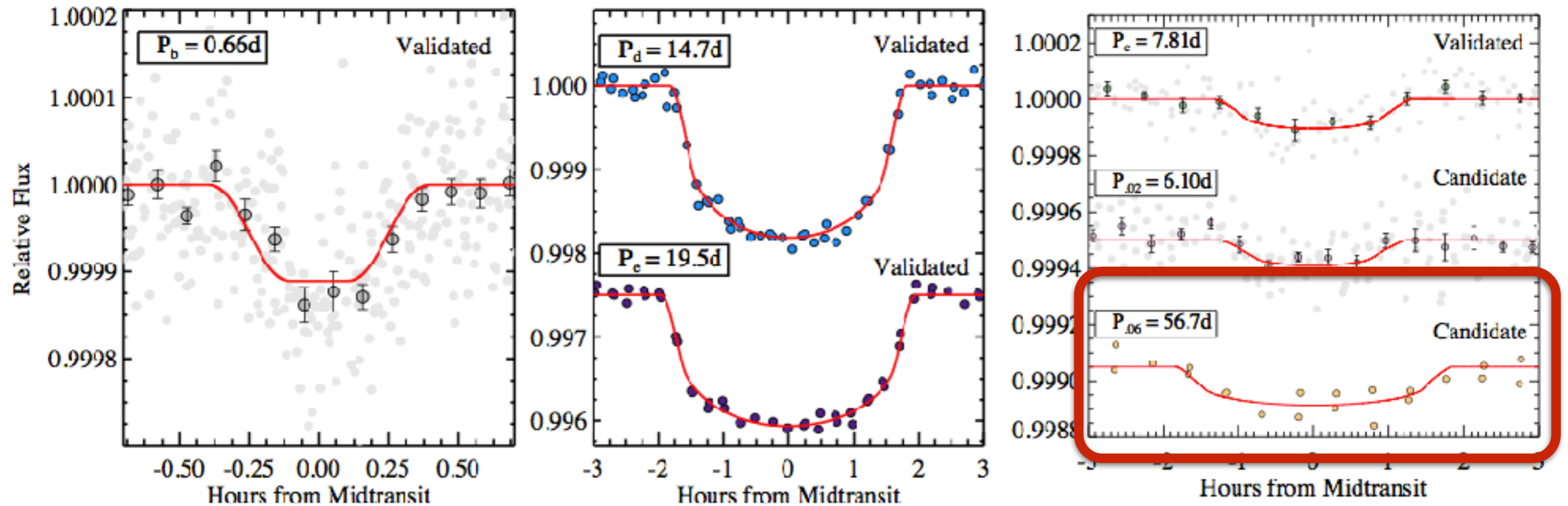
Rodriguez+ 2018

Example: EPIC 248435473



One Mars-sized planet candidate tentatively detected at ~ 8 sigma
Rodriguez+ 2018

Example: EPIC 248435473



One sub-Earth-sized planet candidate tentatively detected at ~ 7 sigma

Follow-up Observations: Spectroscopy

**Palomar 200" NIR
low resolution spectrum**

**Mt. Hopkins 60" optical
high resolution spectra**

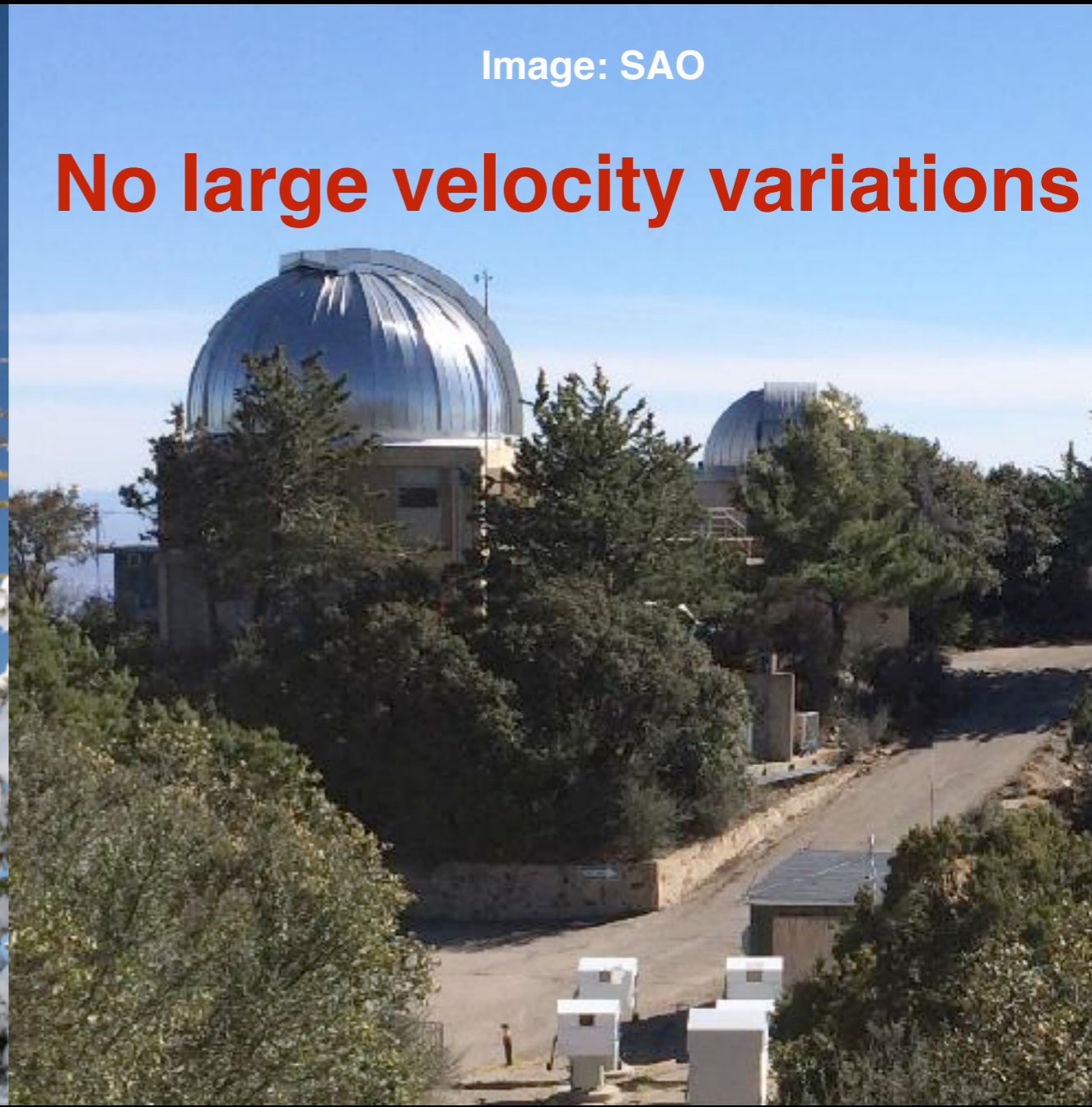
Image: Caltech

Determine stellar parameters



Image: SAO

No large velocity variations



Follow-up Observations: Spectroscopy

Palomar 200
low resolution

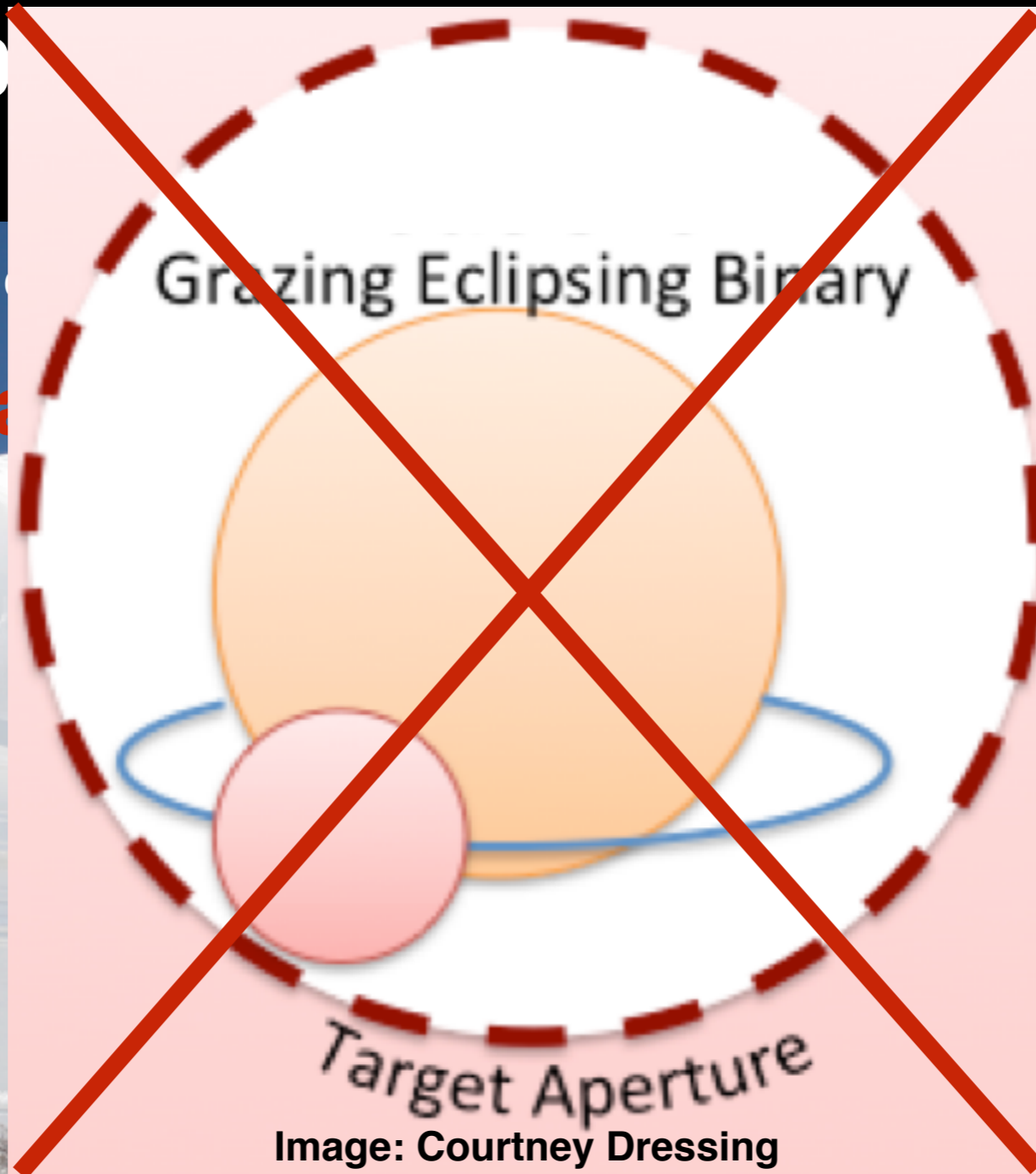
60" optical
resolution spectra

Image: SAO

Image: SAO

Determine stellar

velocity variations

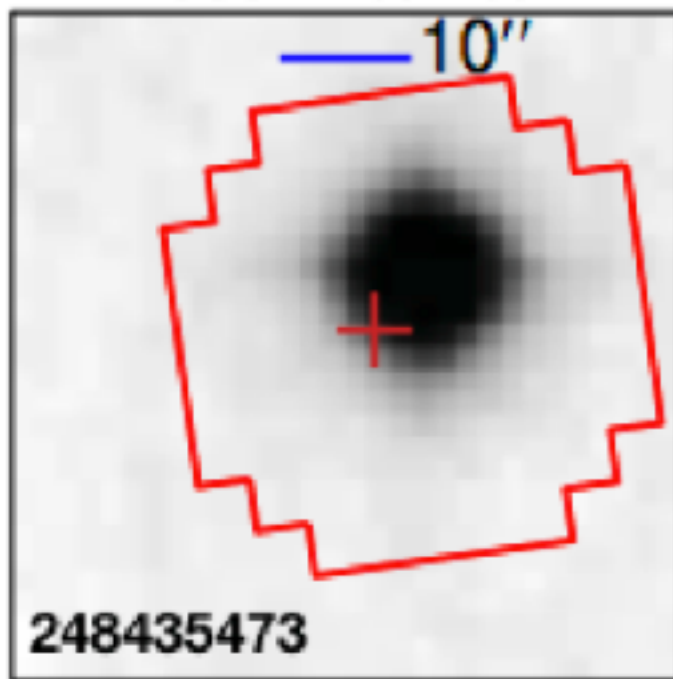


Follow-up Observations: Archival Imaging

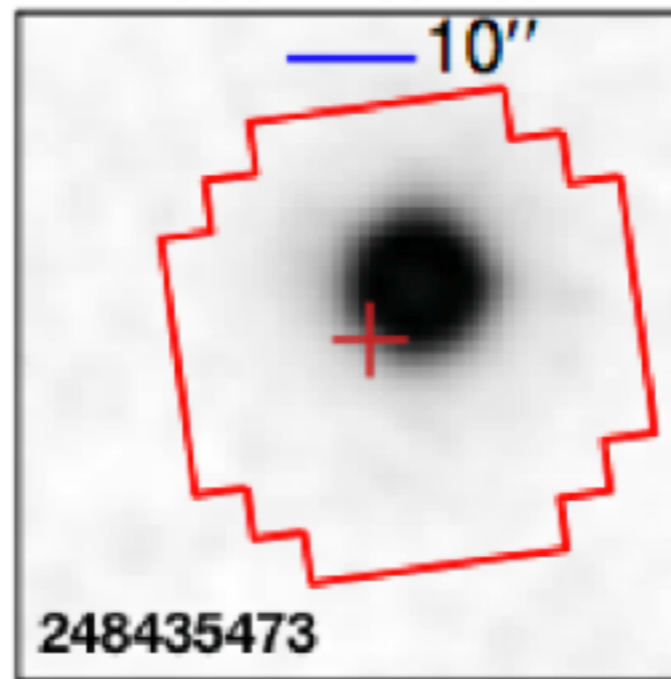
Palomar Observatory
Sky Survey

Pan-STARRS Data
Release 1

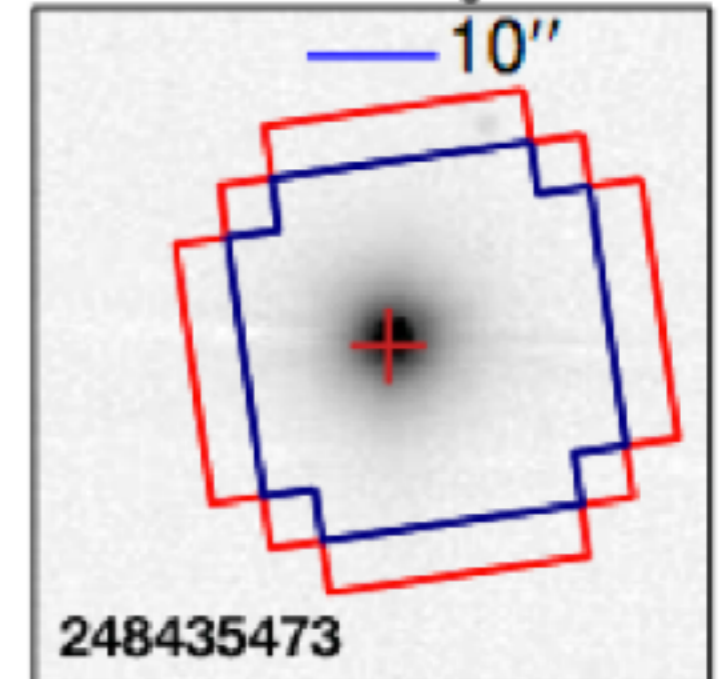
POSS-I Red: 1952



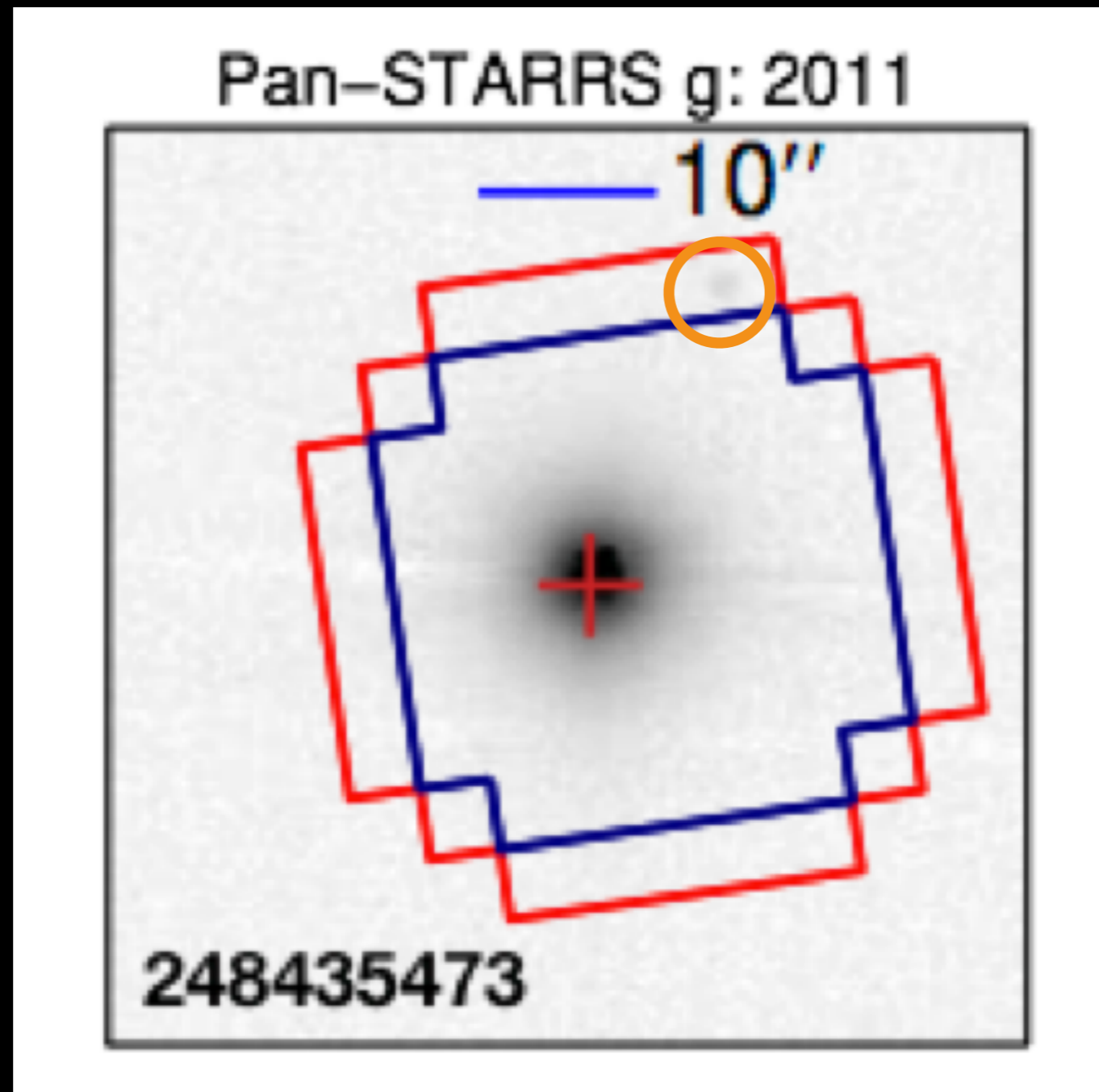
POSS-I Blue: 1952



Pan-STARRS g: 2011



Follow-up Observations: Archival Imaging



Pan-STARRS Data
Release 1

Follow-up Observations: Adaptive Optics Imaging

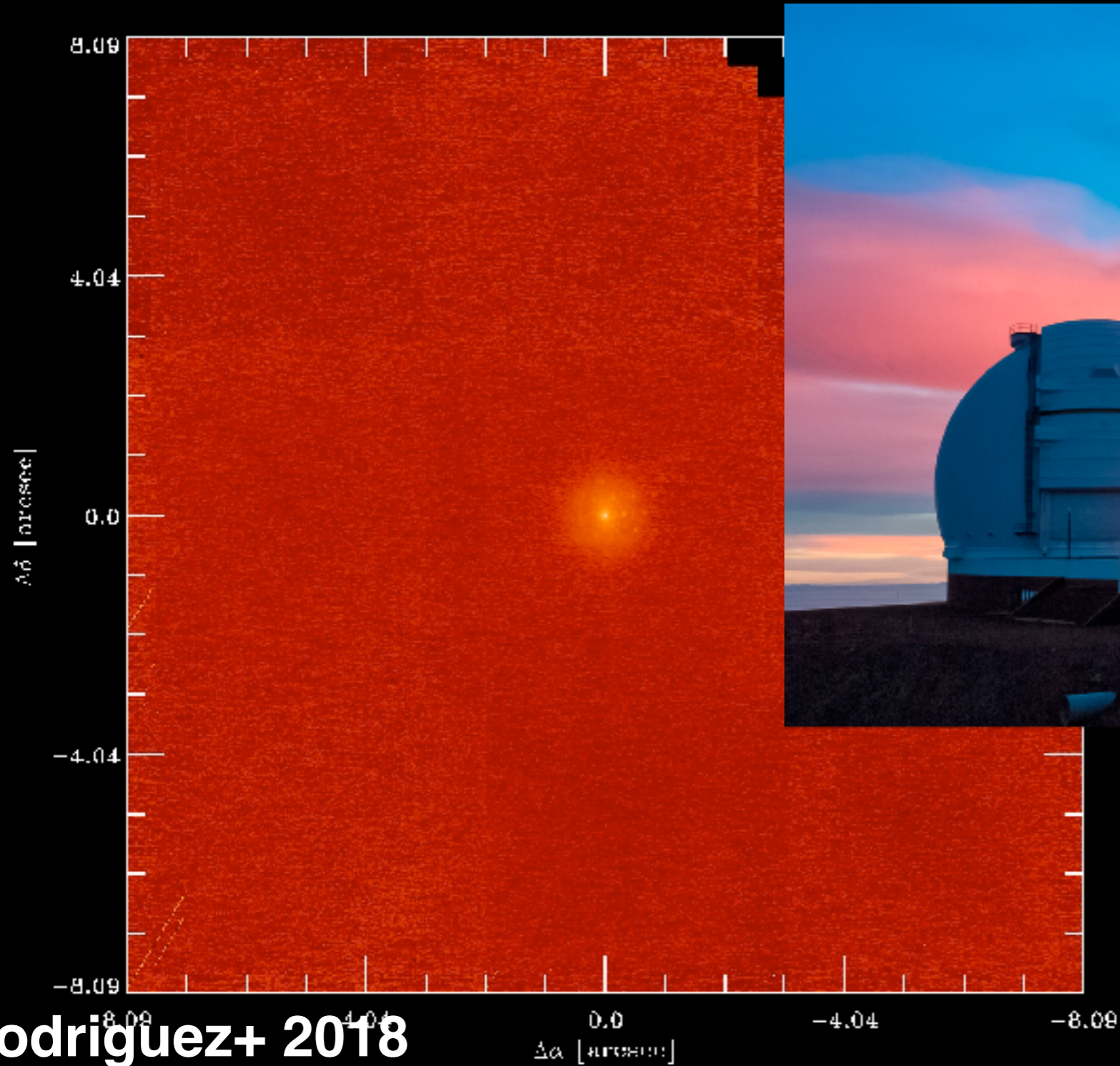


Image: Big Island Now

Rodriguez+ 2018

Follow-up Observations:

Adaptive

Optimizing

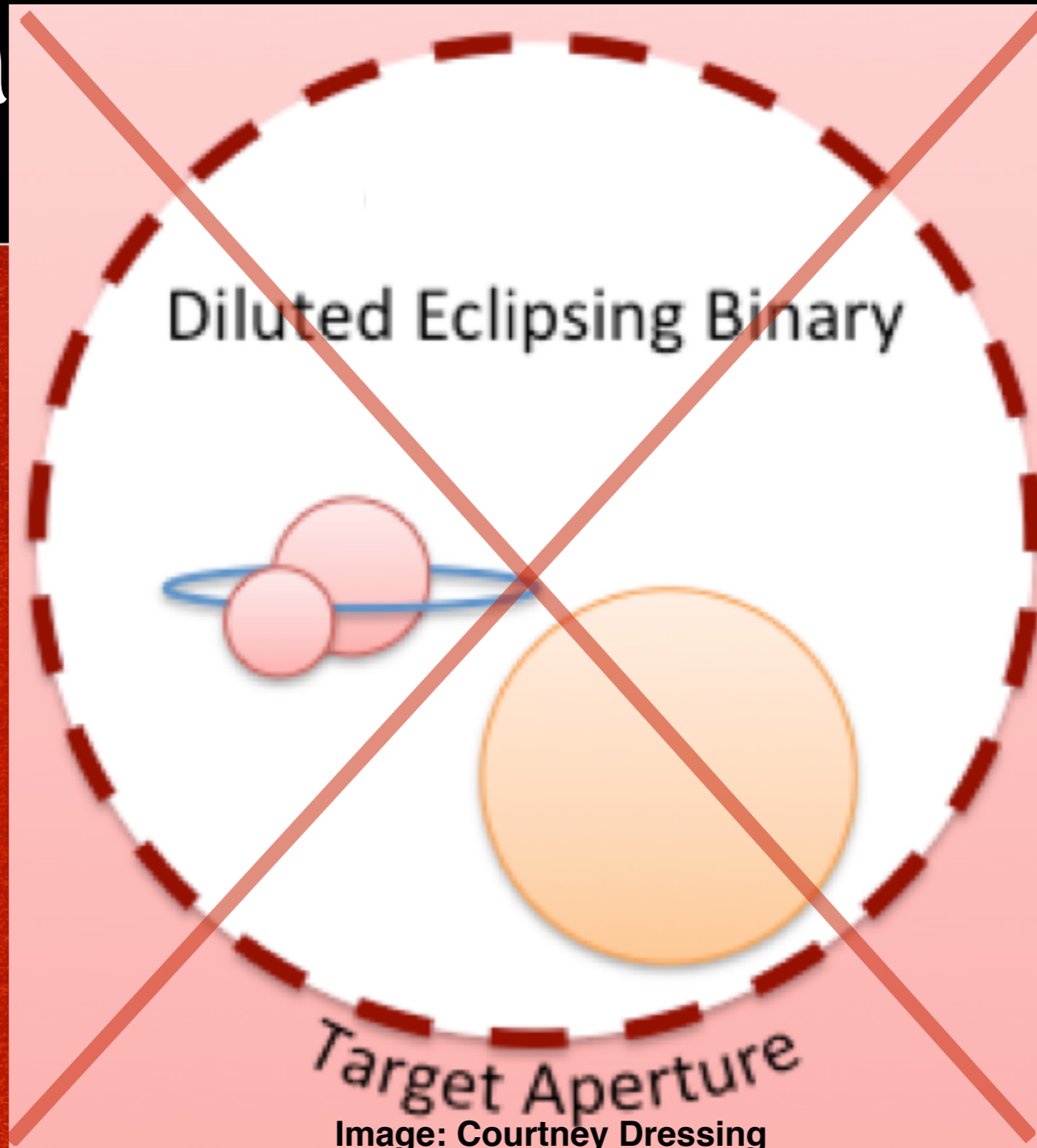
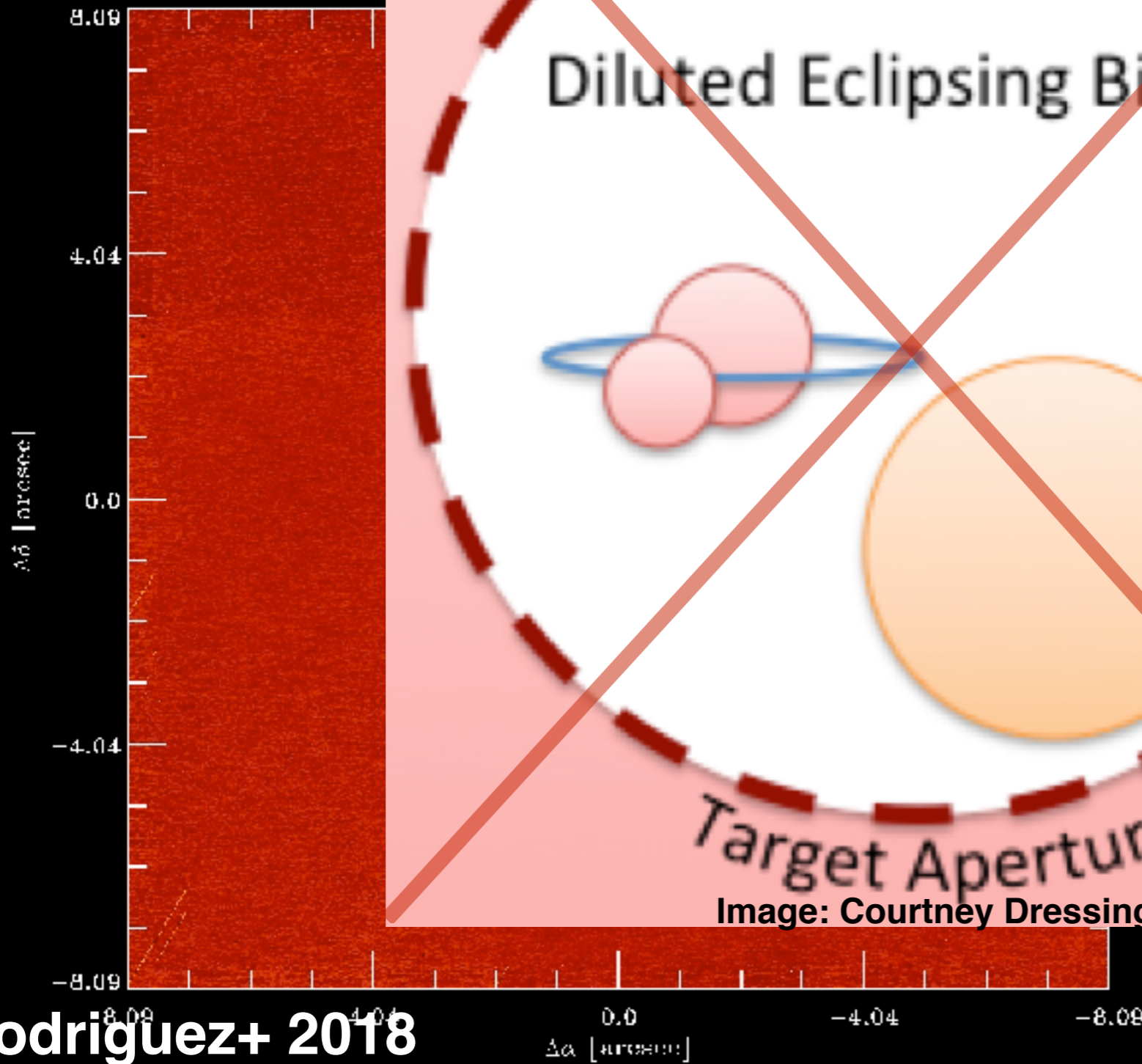


Image: Courtney Dressing



Image: Big Island Now

Rodriguez+ 2018

Ruling out Instrumental False Positives

EPIC 248435473.01: 114.6 sigma

EPIC 248435473.02: 111.5 sigma

EPIC 248435473.03: 13.0 sigma

EPIC 248435473.05: 10.6 sigma

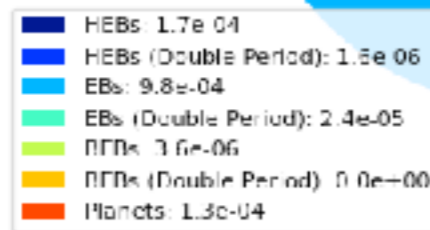
EPIC 248435473.04: 8.3 sigma

EPIC 248435473.06: 6.6 sigma

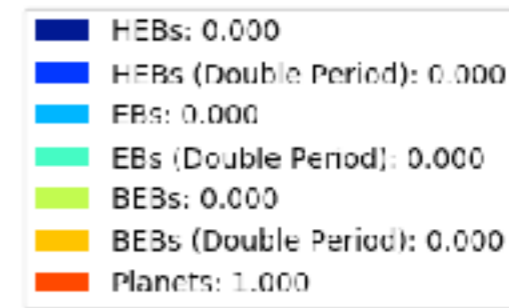
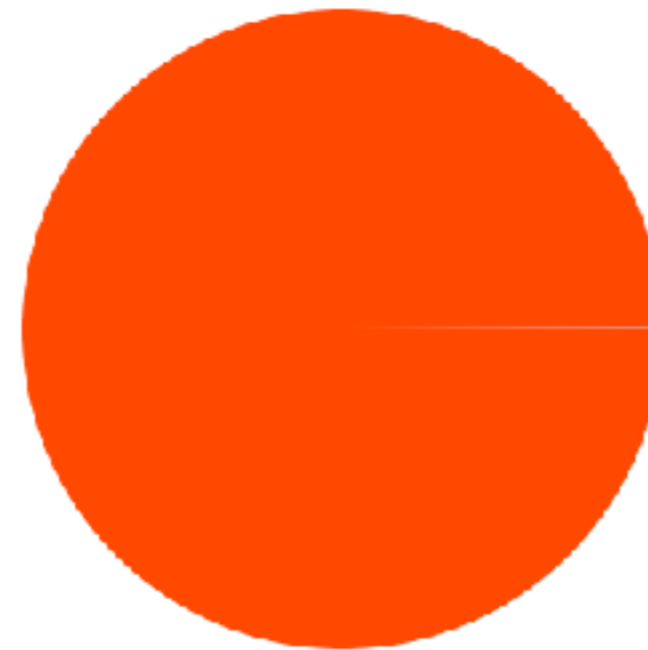
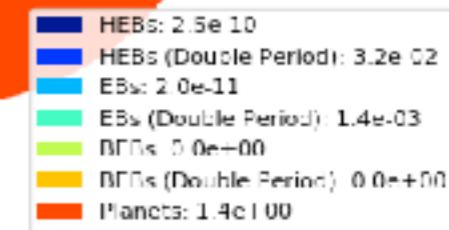
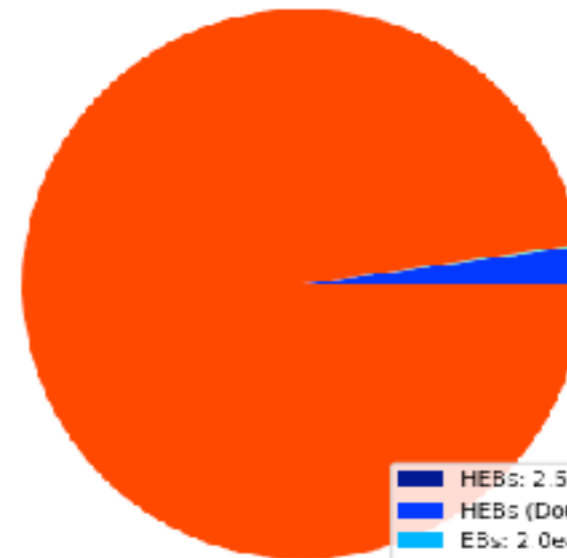
False Positive Probability Calculation with vespa

ep248435473d

Priors



Likelihoods

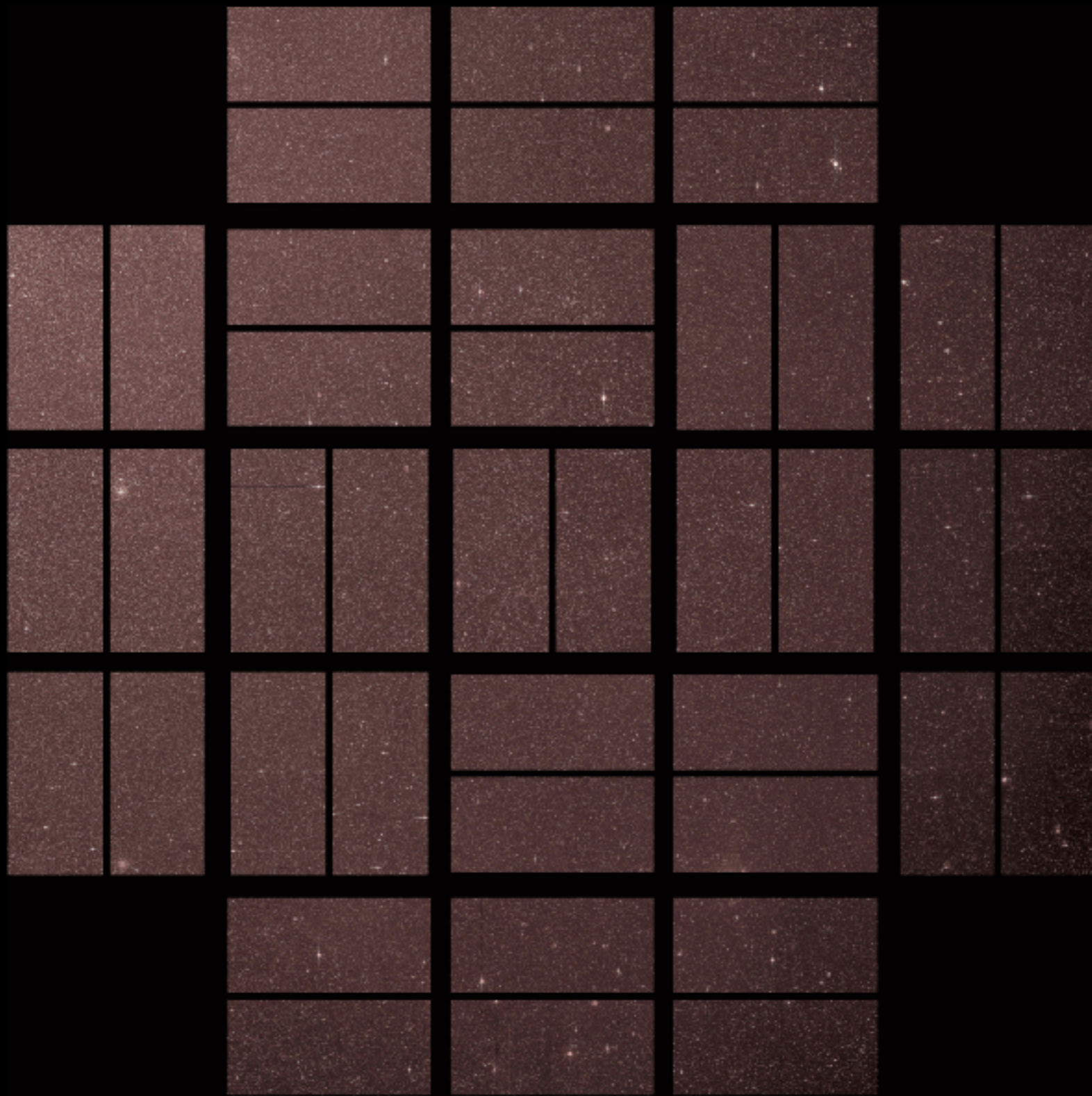


Constraints:
 dc20171227 J band contrast curve
 secondary depth < 3.84e-05
 odd-even < 0.000108
 dc20171227 K-band contrast curve

Final Probability

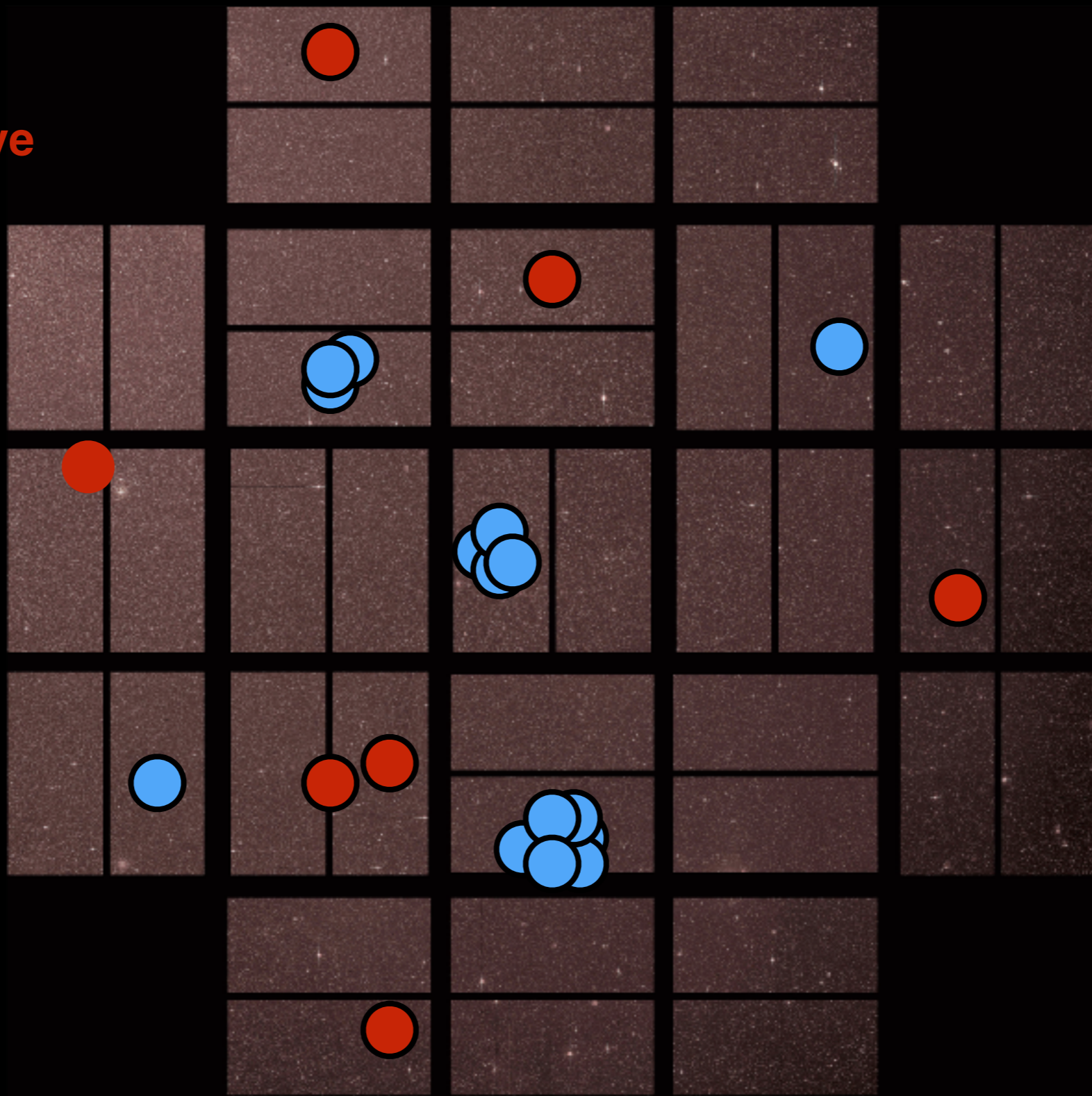
$f_{pl,v} = 0.000$
 FPP: 1 in 2128

**Multiple candidates around one
star are more likely planets**



Multiple candidates around one star are more likely planets

- Candidate
- False Positive

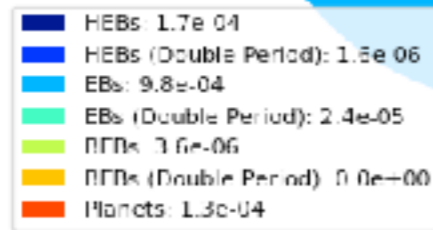


Candidates in multi systems are 20-50 times more likely to be planets than candidates in single systems.

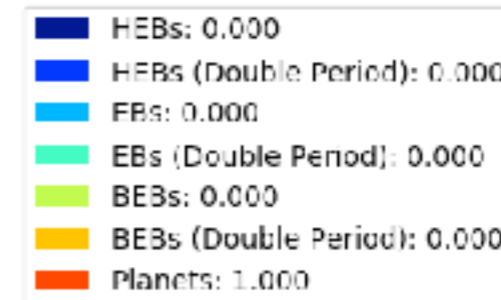
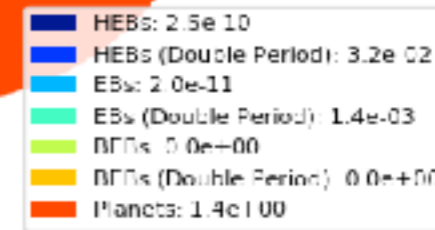
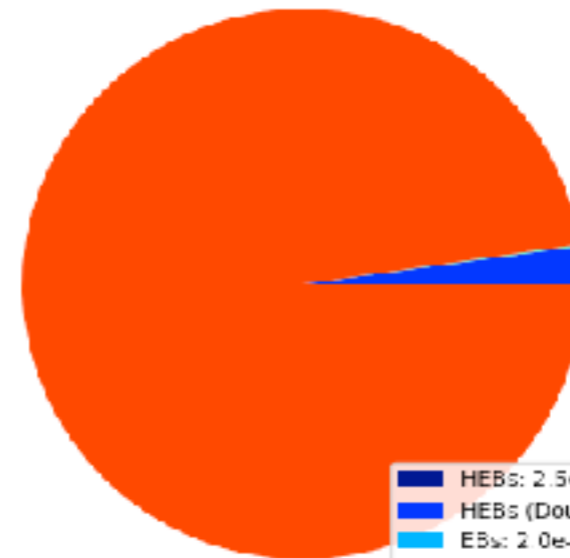
False Positive Probability Calculation with vespa

ep248435473d

Priors



Likelihoods



Constraints:
 dc20171227 J band contrast curve
 secondary depth < 3.84e-05
 odd-even < 0.000108
 dc20171227 K-band contrast curve

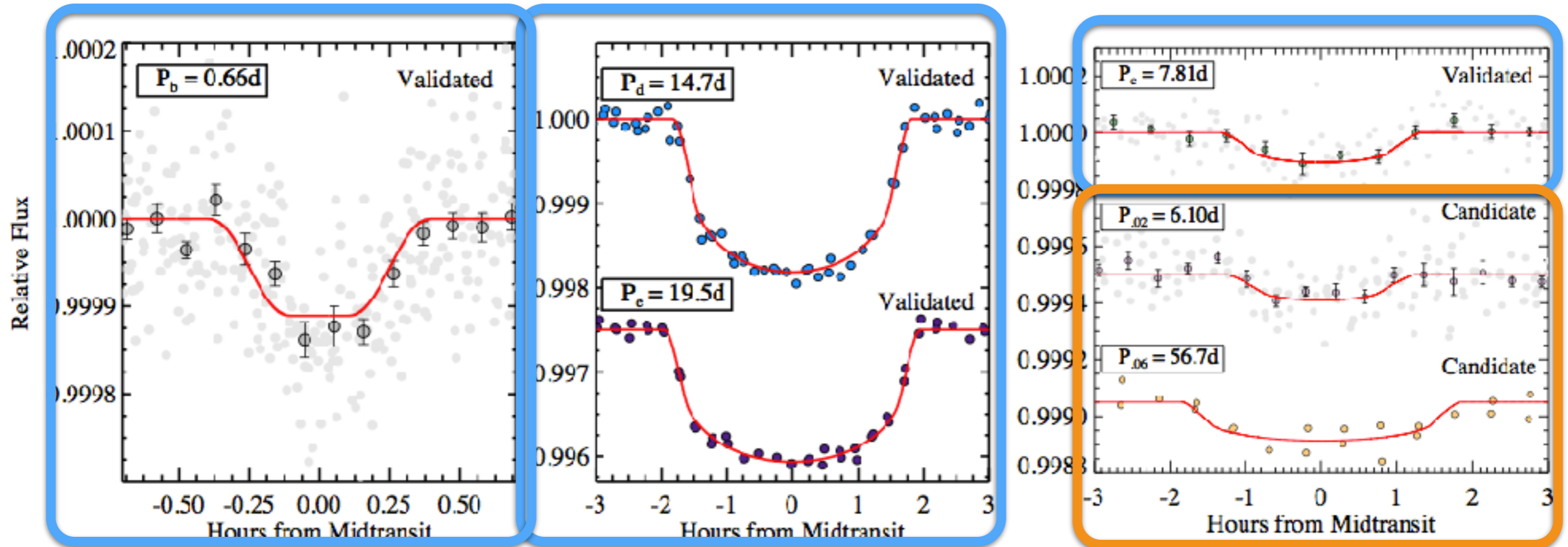
Final Probability

$f_{pl,v} = 0.000$
 FPP: 1 in 2128

Validated Planet:

A vetted planet candidate which has a calculated False Positive Probability (FPP) less than some threshold value (often 1% or 0.1%).

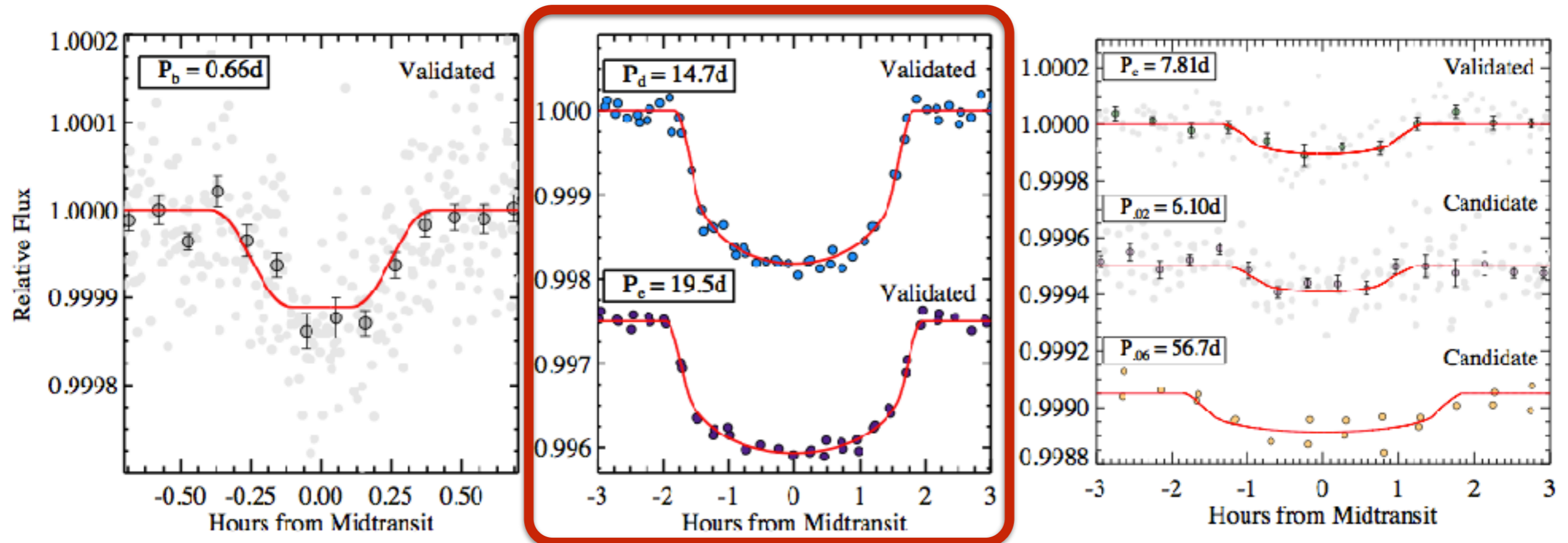
Example: EPIC 248435473



Confirmed Planet:

A planet candidate which either has a mass measurement (showing the companion is planetary mass) or has been detected by some other technique (e.g. Doppler Tomography).

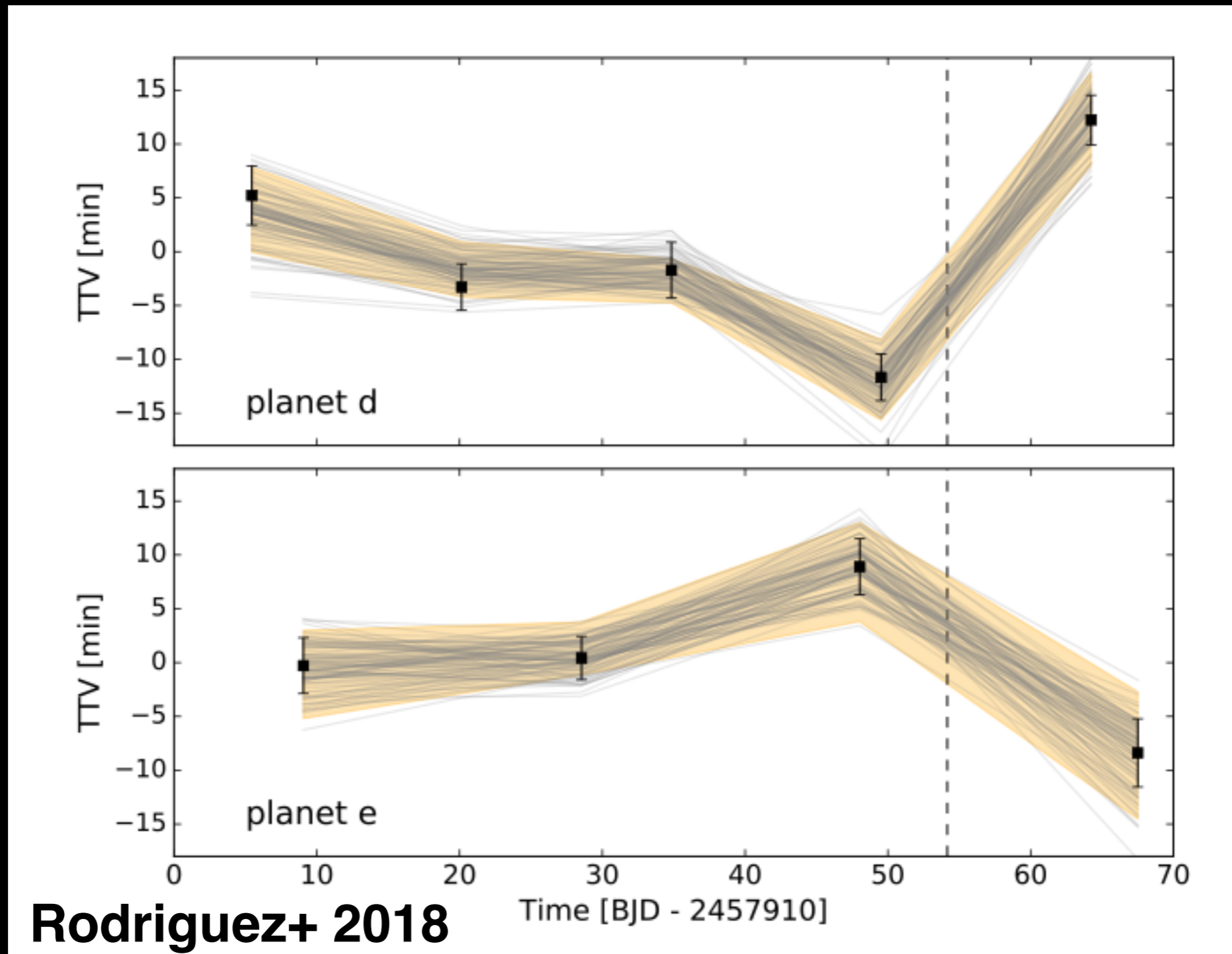
Example: EPIC 248435473



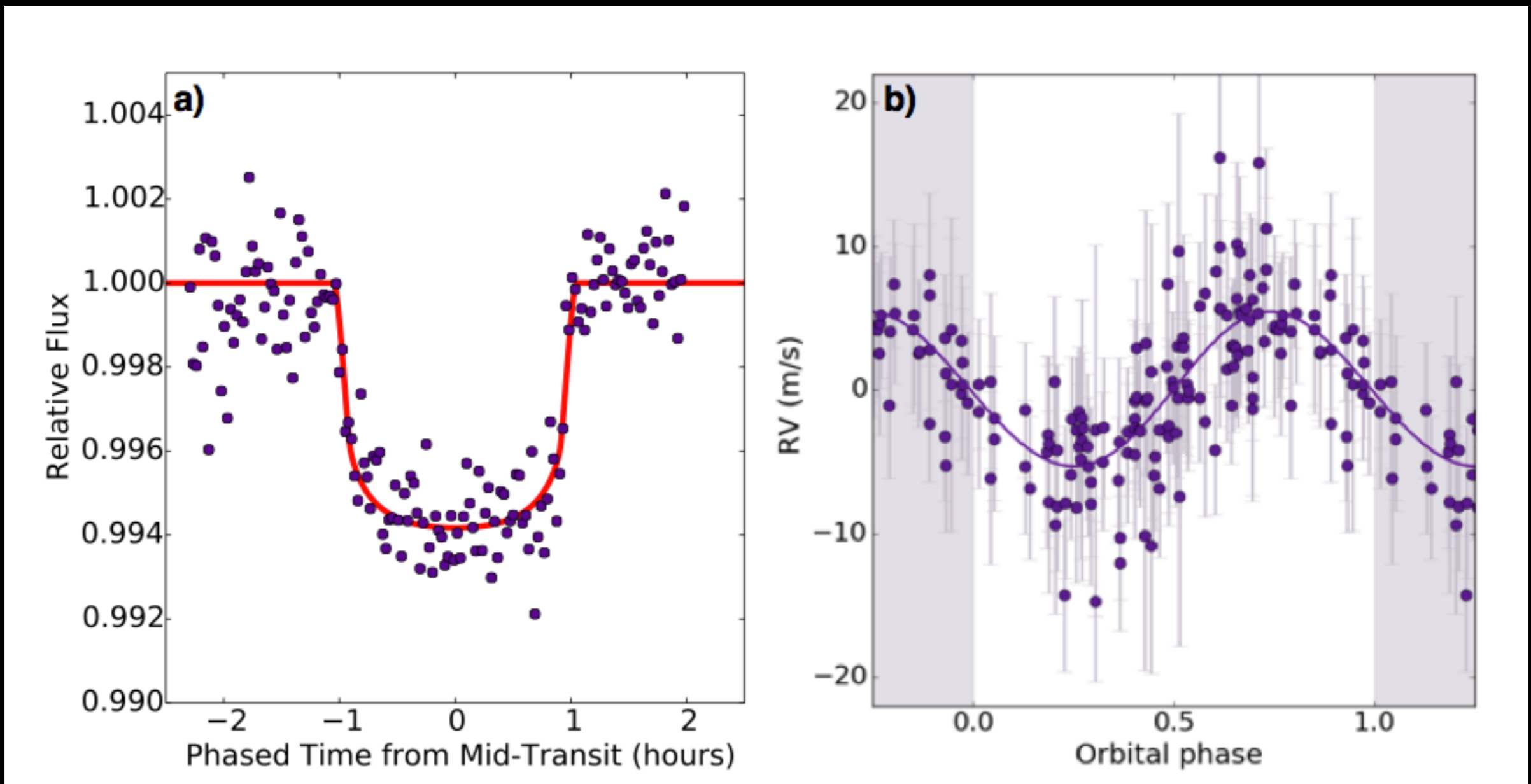
**Two sub-Neptune
validated planets detected
at $\sim 110\sigma$ near resonance.**

Example: EPIC 248435473

TTV confirmation



Another Example: LHS 1140b



The Process of Validating Transiting Exoplanets

K2 Pixel Data

Sum the pixels to get

Light Curves

Remove systematics and slow variability and perform a

Transit Search

to find signals where the brightness may be decreasing, or

Threshold Crossing Events

and identify which are astrophysical and not false positives, or

Planet Candidates

and obtain follow-up observations and calculate FPP to yield

Validated Planets

and in some cases, use other independent information to get

Confirmed Planets