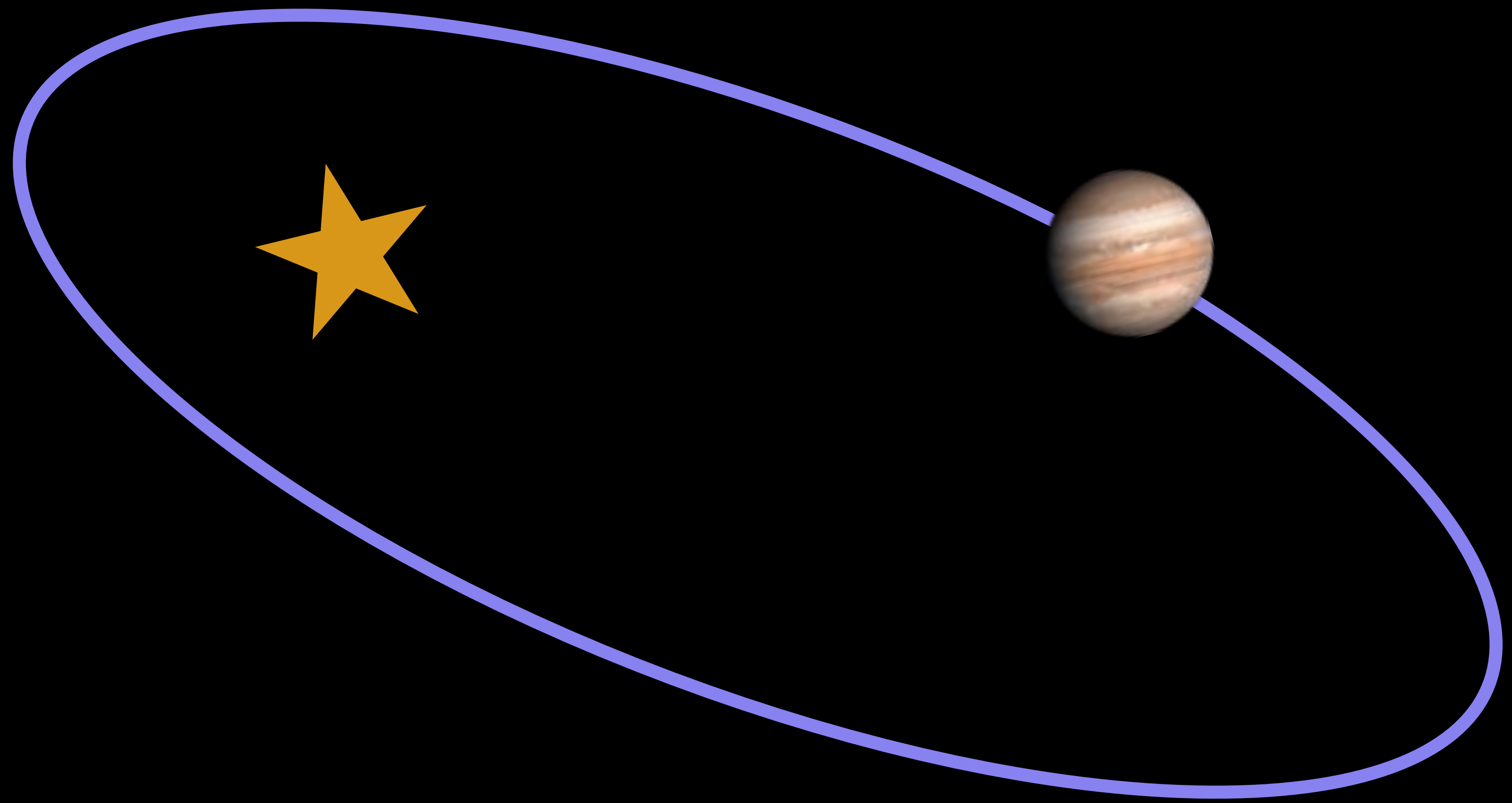
Characterizing *Kepler*'s Transiting Planets in the Presence of Correlated Noise



Rebekah (Bekki) Dawson
Penn State, Center for Exoplanets and Habitable Worlds

Acknowledgments: SAMSI Noise and Detrending Working Group (incl. Daniel Foreman-Mackey, Eric Ford, Ben Montet, Tom Loredo, Ruth Angus, Billy Quarles, Ian Czekala, Robert Wolpert, Jogesh Babu, Tom Barclay, David Hogg); Patricio Cubillos, Josh Carter

Kepler space telescope monitored the brightness of hundreds of thousands of stars

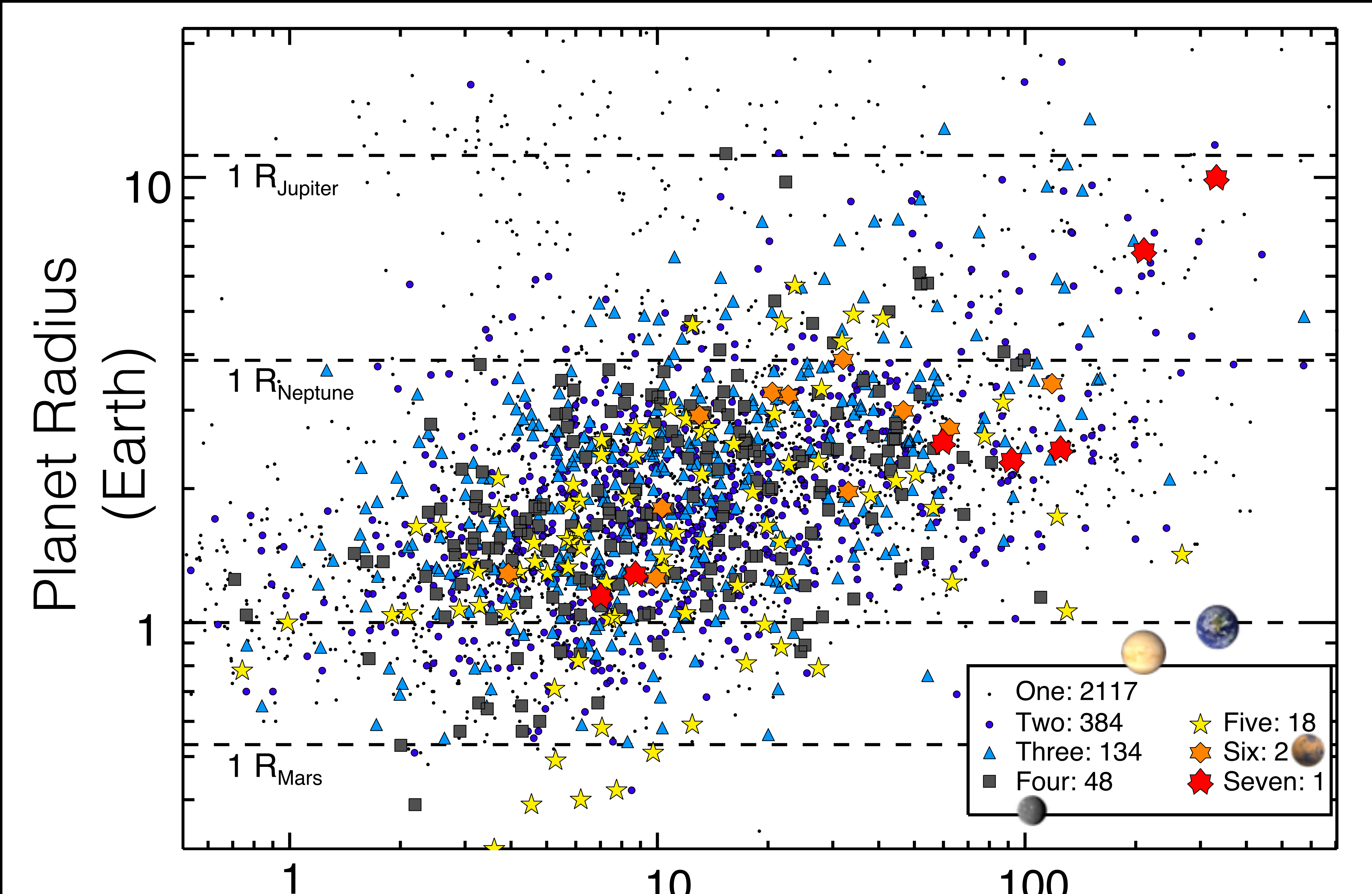
Star dims during planetary transit

Earth-sized: 80 ppm

Image Credit: NASA

Kepler discovered thousands of close-in planets

Kepler candidate discoveries: Borucki+11ab, Batalha+ 12, Burke+ 14, Mullaly+15



Lissauer, **RID**, & Tremaine 2014, *Nature* review

R. Dawson, SCMA, 06/09/16

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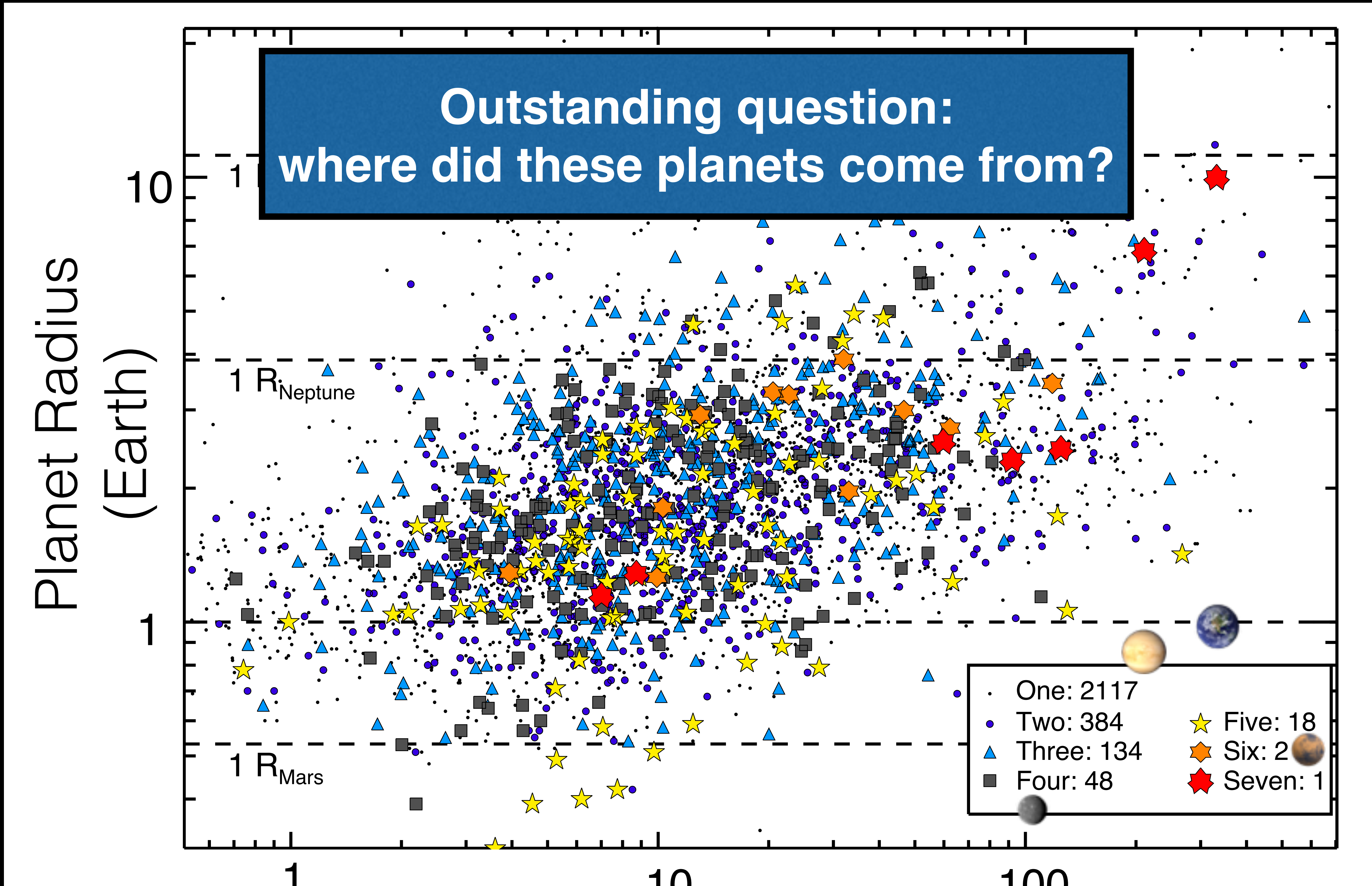


Lissauer, **RID**, & Tremaine 2014, *Nature* review

Gravitational interactions between planets cause transit timing variations

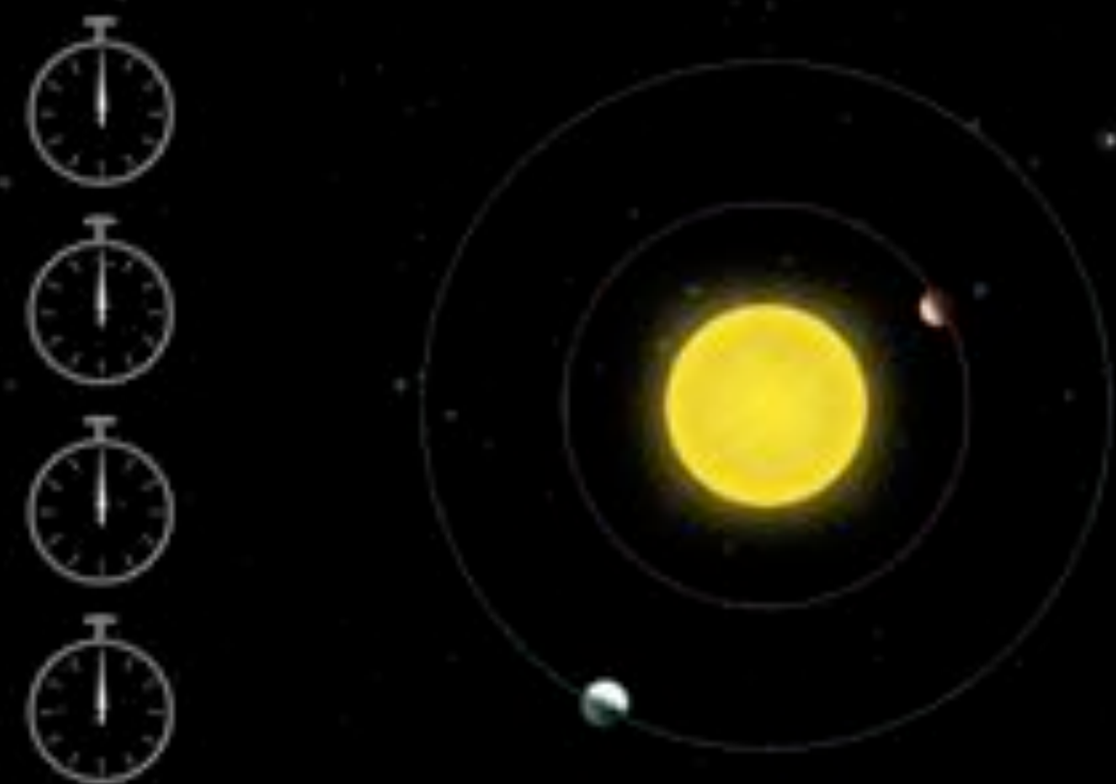
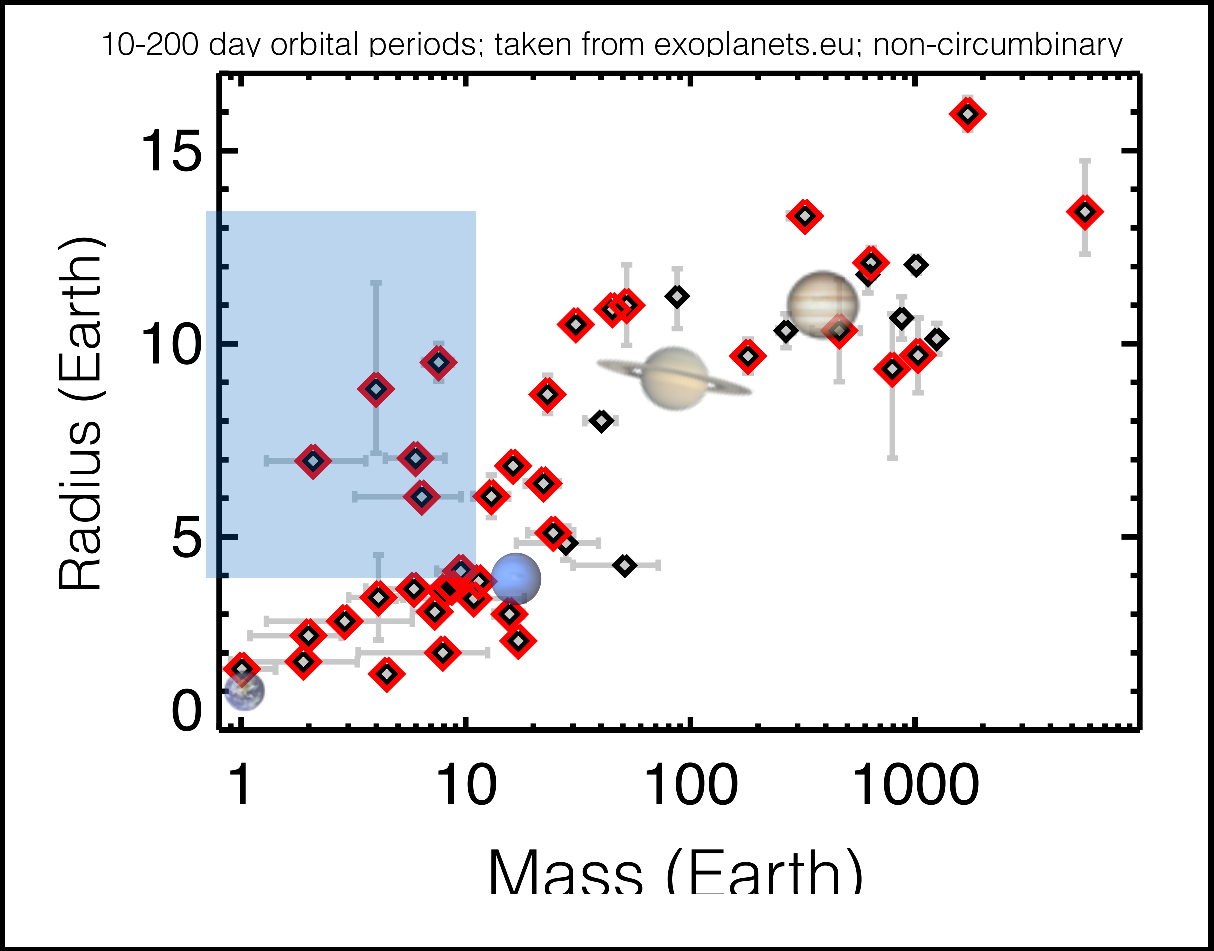


Image Credit: NASA Ames Research Center/Kepler Mission

Transit timing variations essential to understanding where close-in planets come from

e.g., Ultra-puffies



e.g. Jontof-Hutter et al. 2014,
formation: Lee & Chiang 2016

Resonant orbits
[with low libration amplitudes]

Kepler-223, Mills et al. 2016 *Nature*

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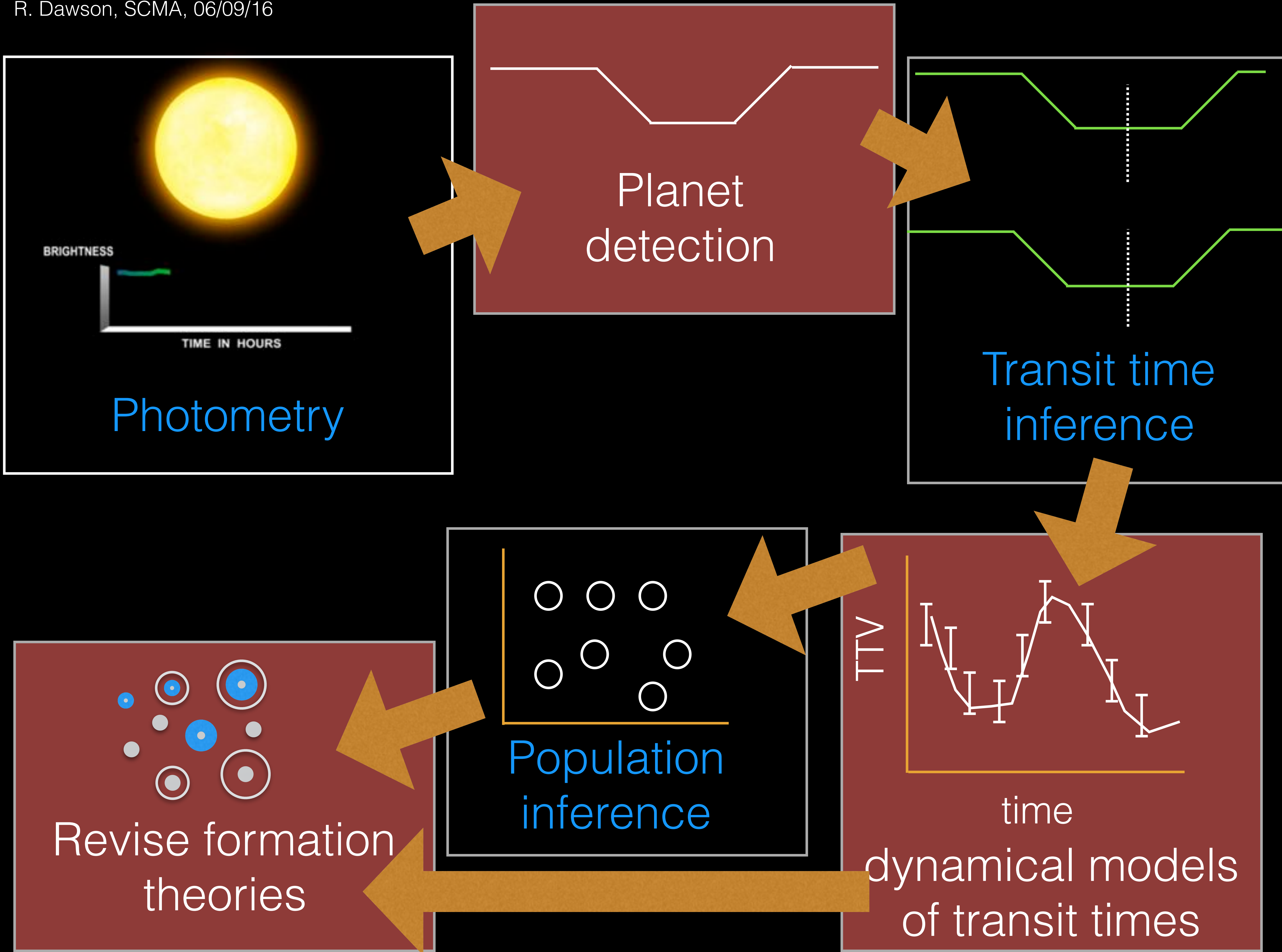
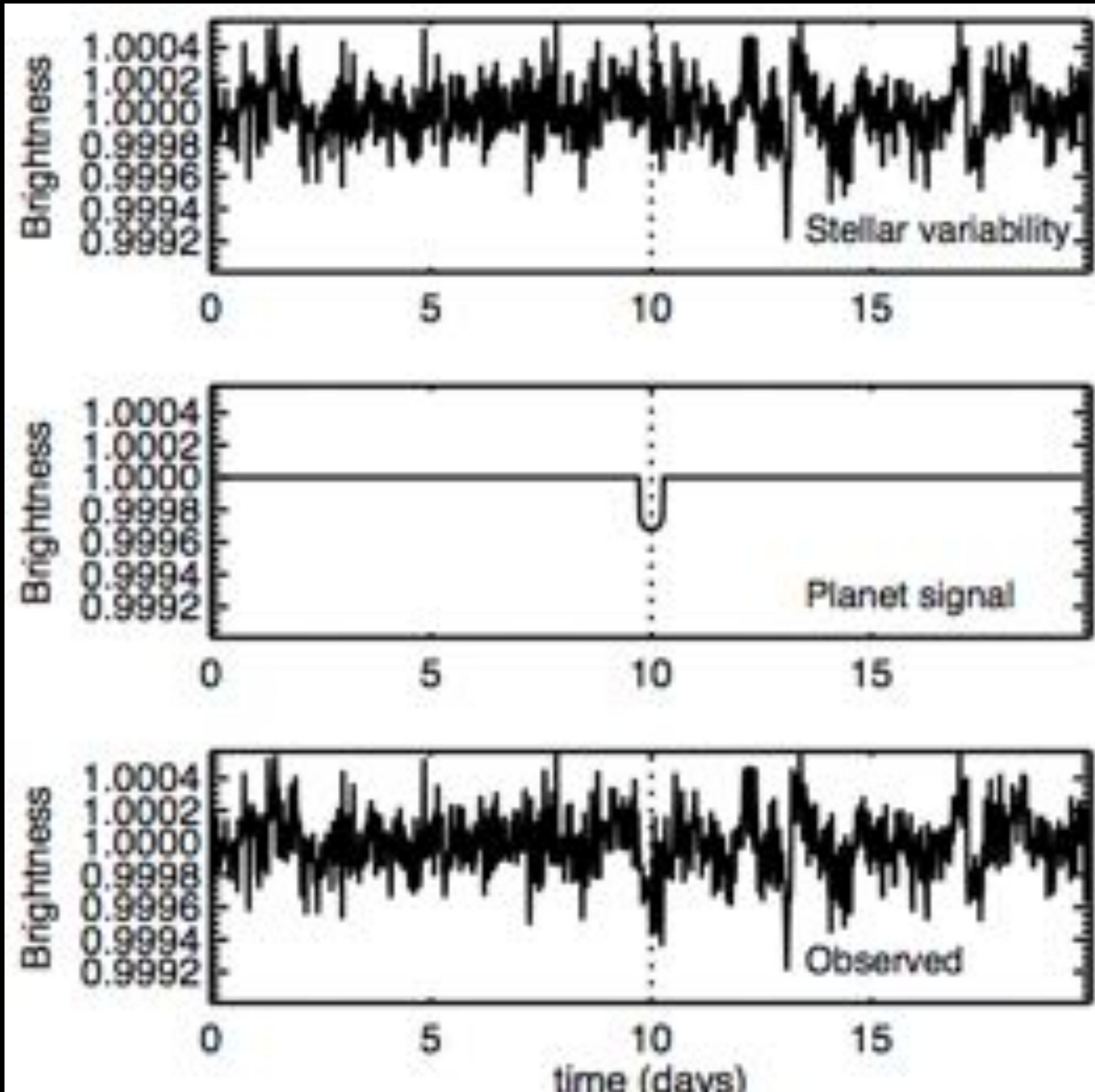


Kepler data key characteristics



Time span: 4 years
Cadence: 30 minutes (1 minute), evenly spaced
Noise floor: 15 ppm

Earth-like transit signal: 80 ppm, 12 hour duration, 1 year period

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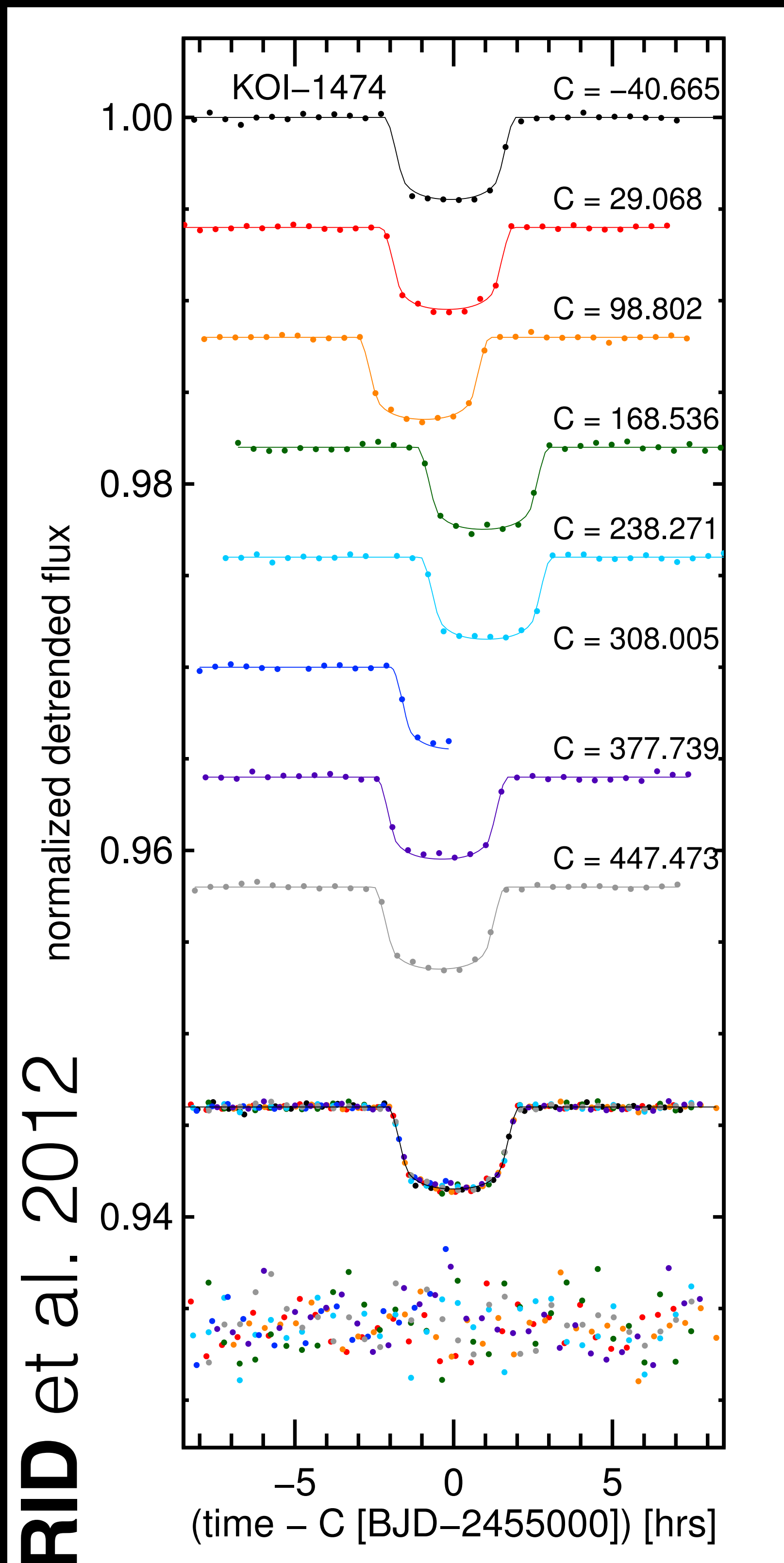
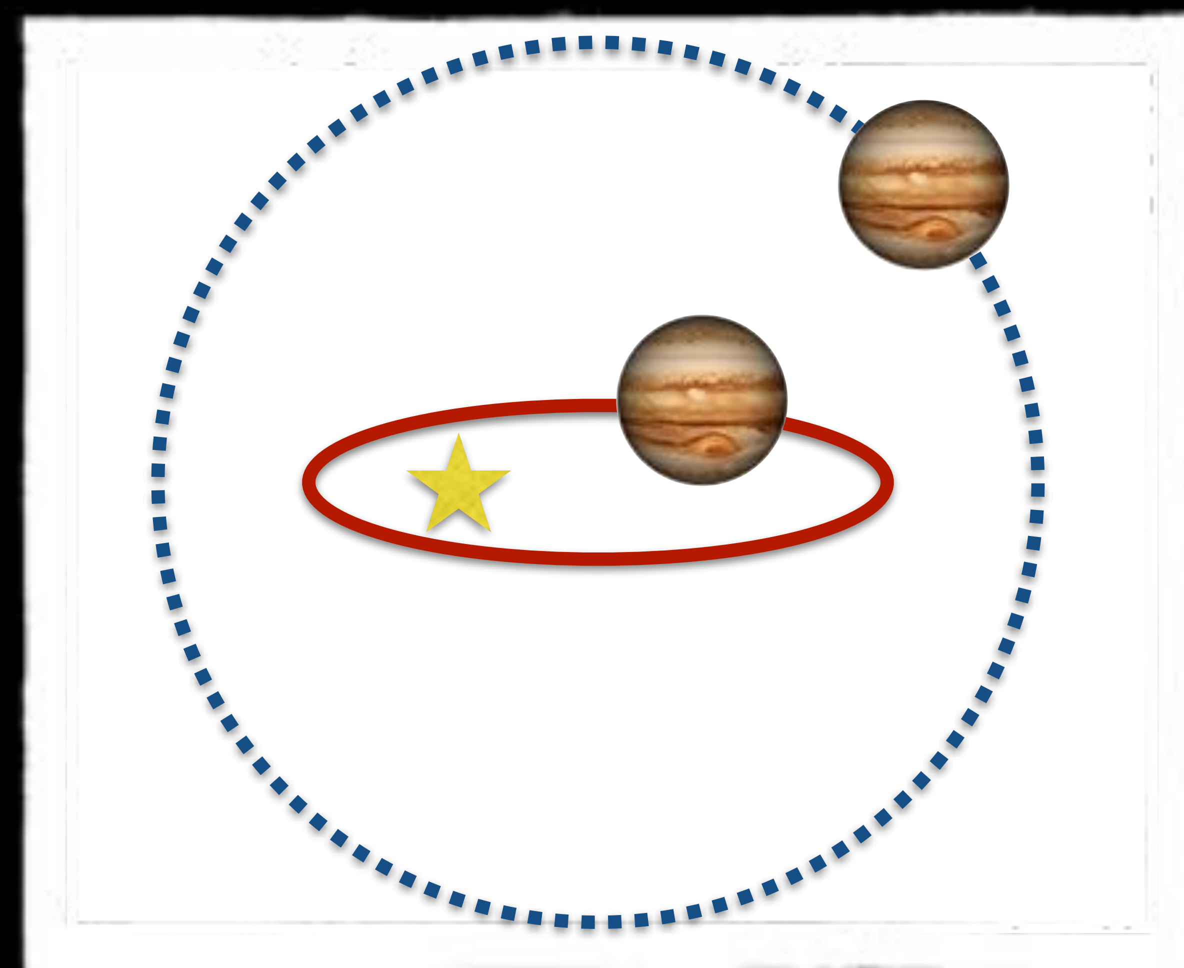
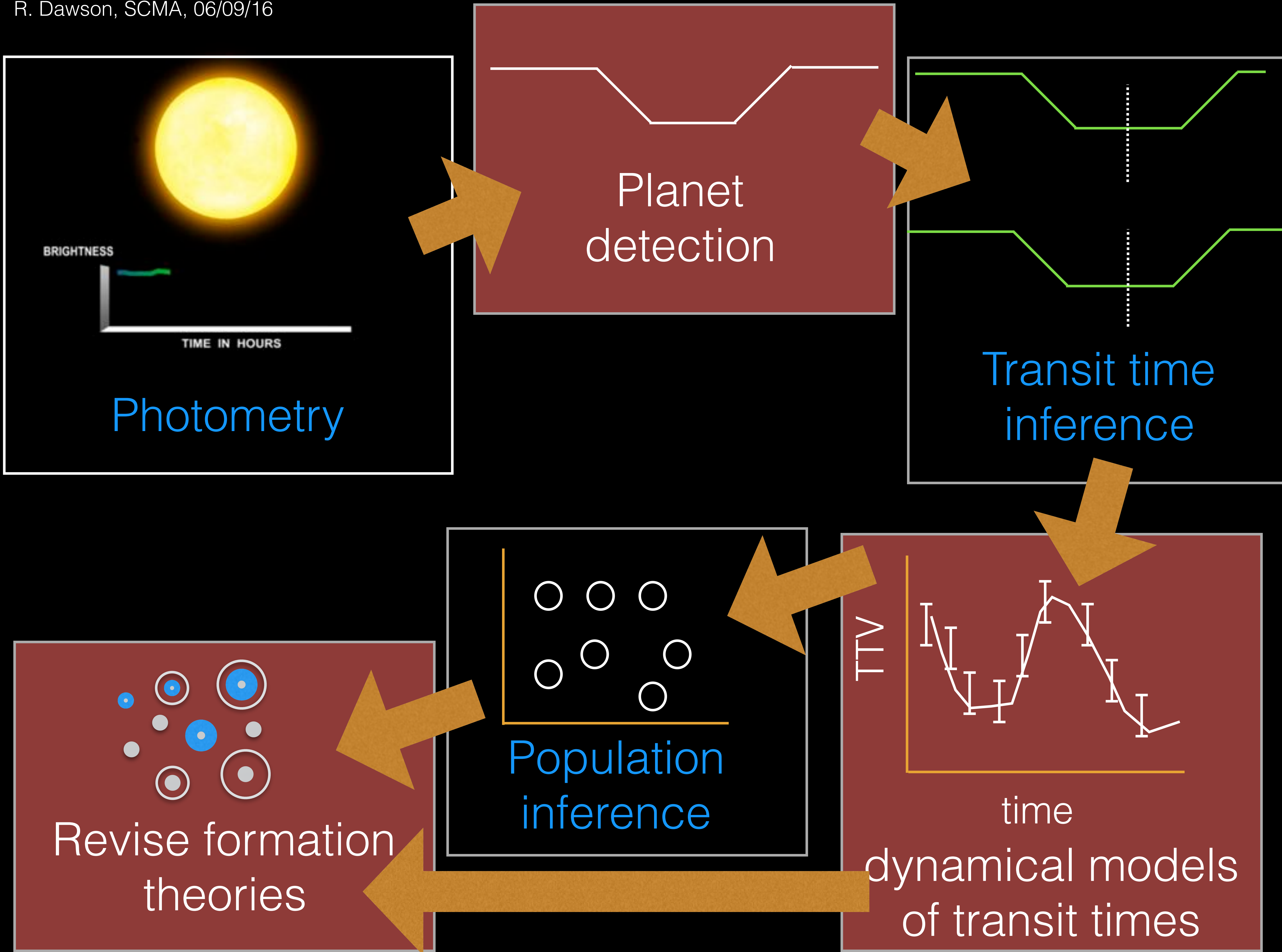
Case study: how did Kepler-419b achieve its close-in, highly elliptical orbit?

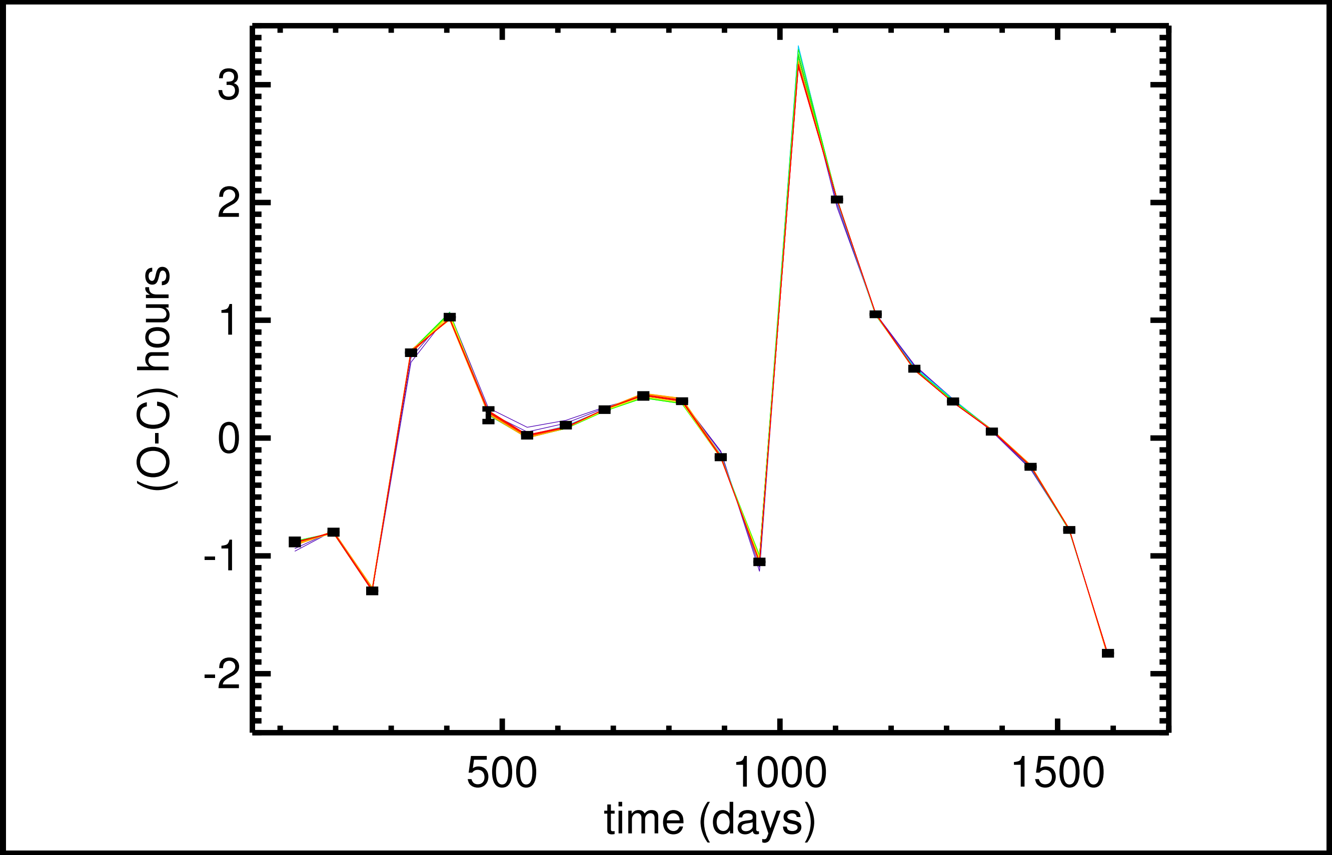


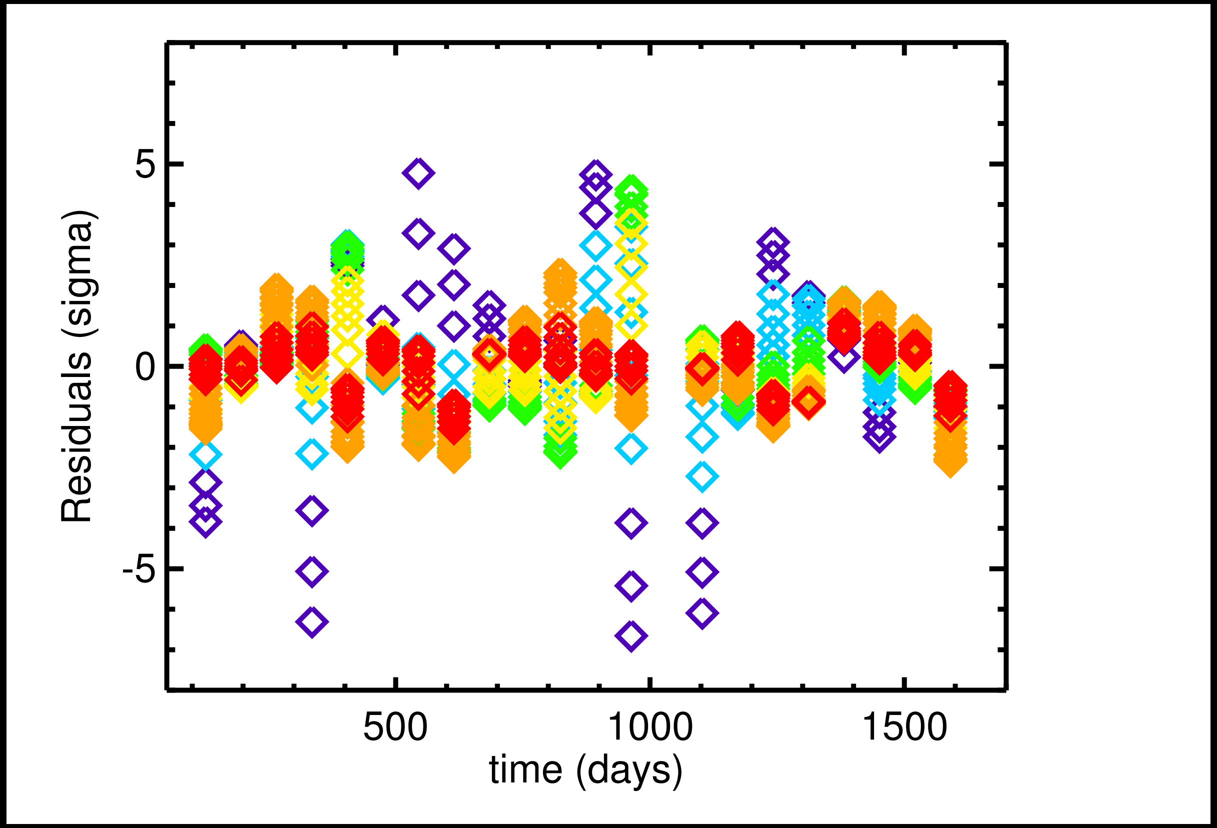


Is its non-transiting companion orbiting in the same plane?

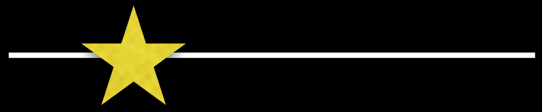

BRIGHTNESS
TIME IN HOURS
Photometry
Planet detection
Transit time inference
TTV
time
dynamical models of transit times
Population inference
Revise formation theories

The companion's inclination has a subtle effect on the signal





RID et al. 2014



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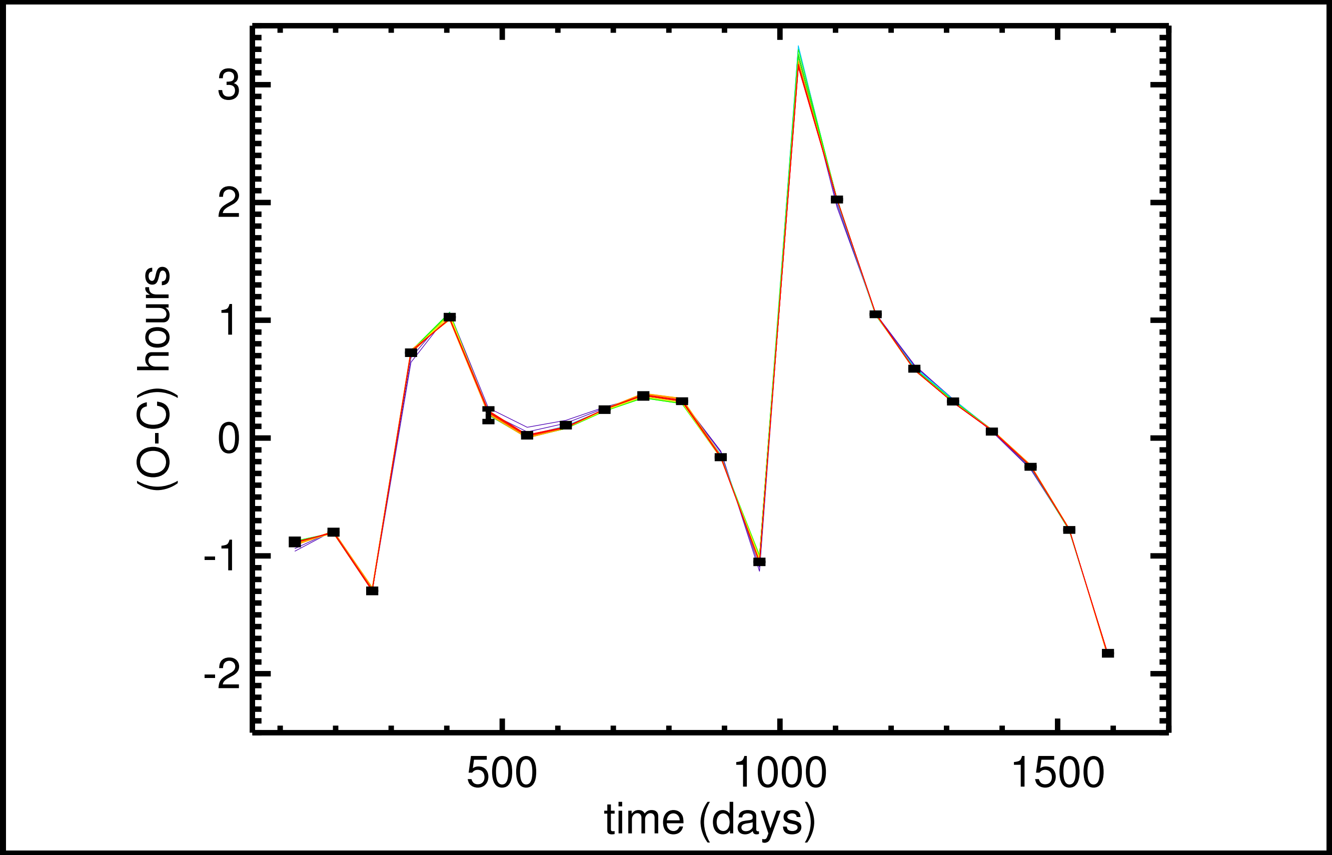
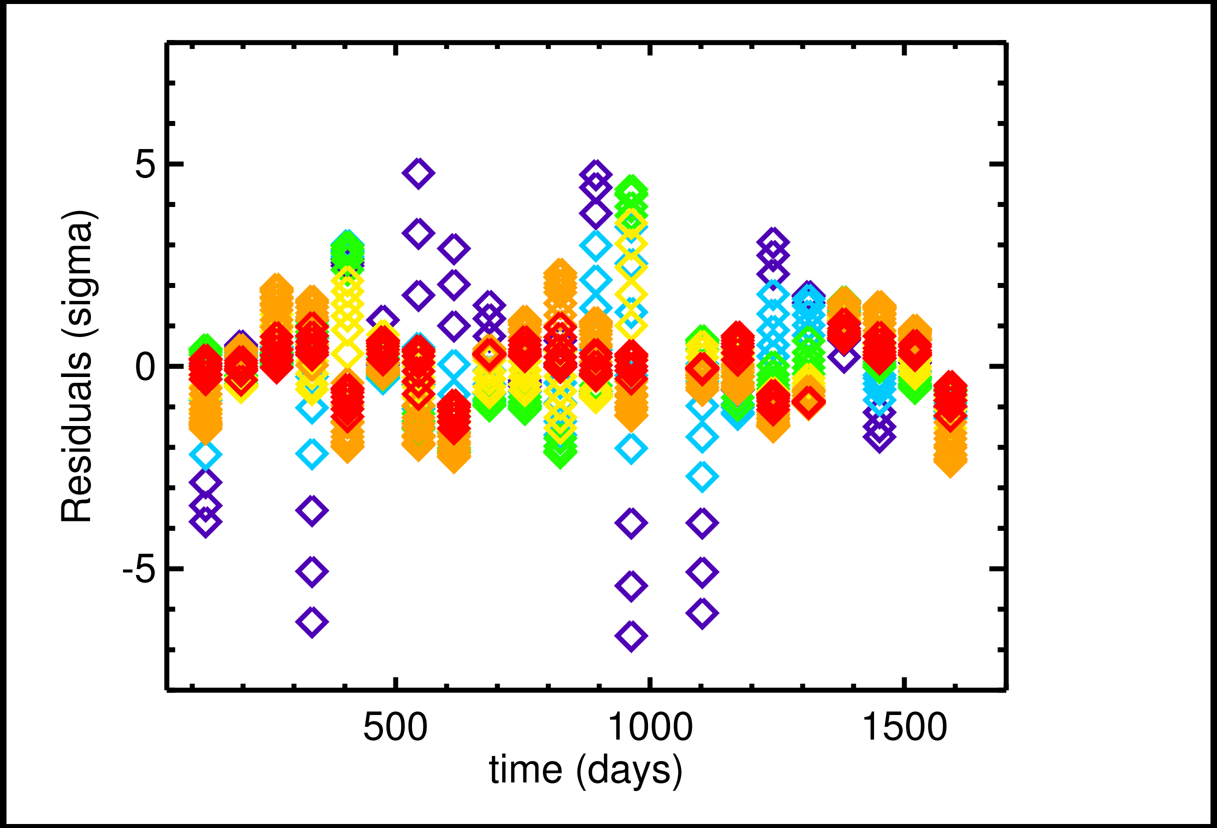
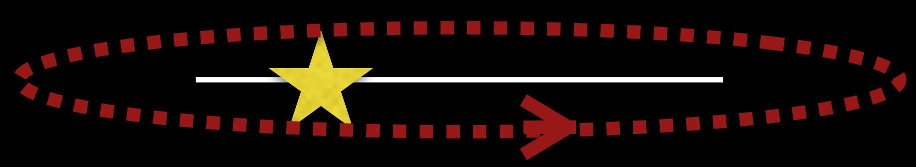




RID et al. 2014



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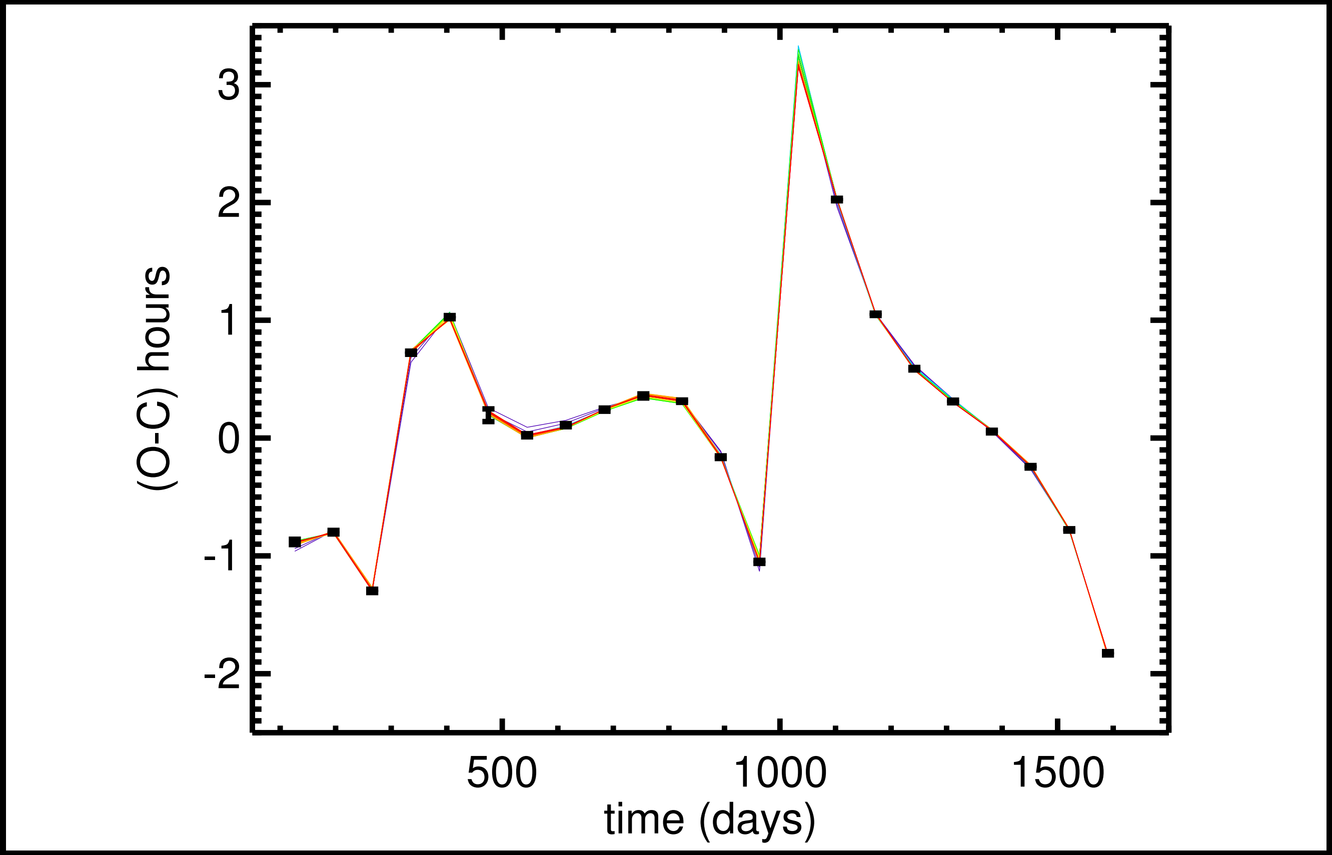
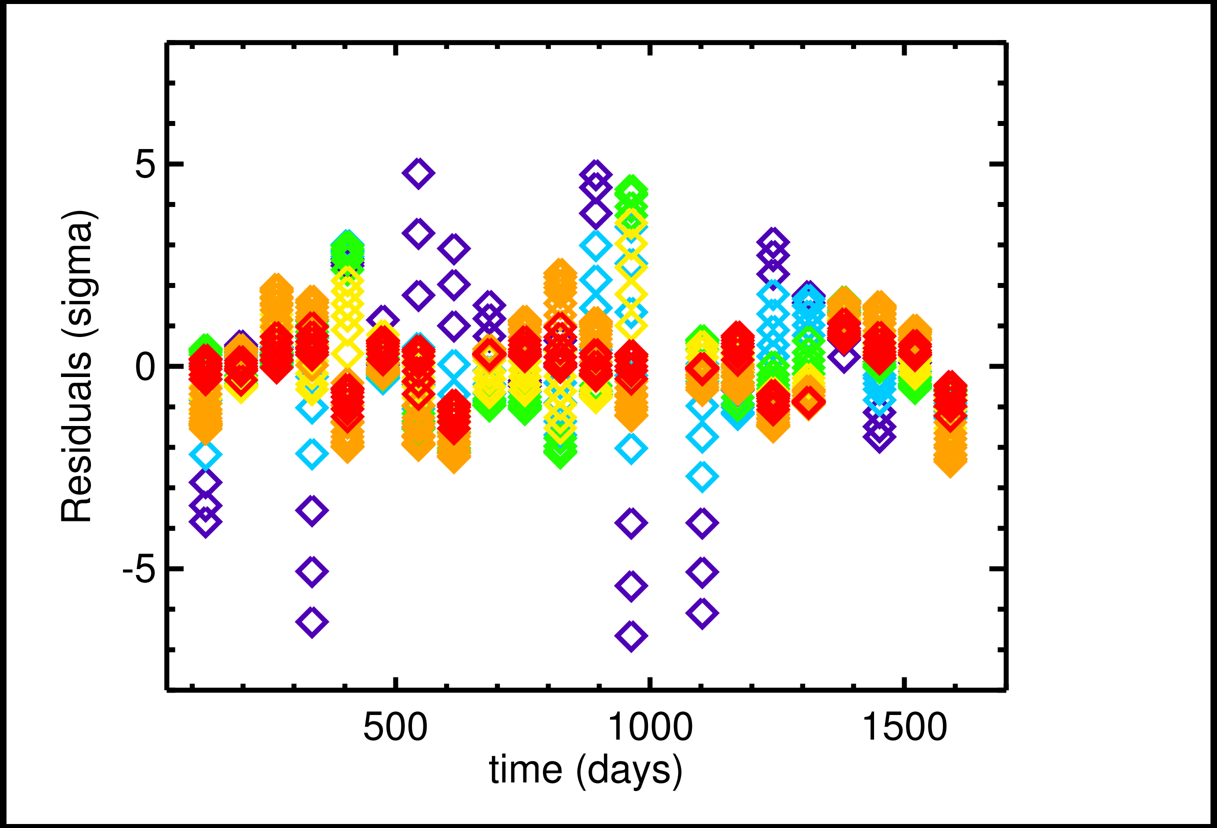
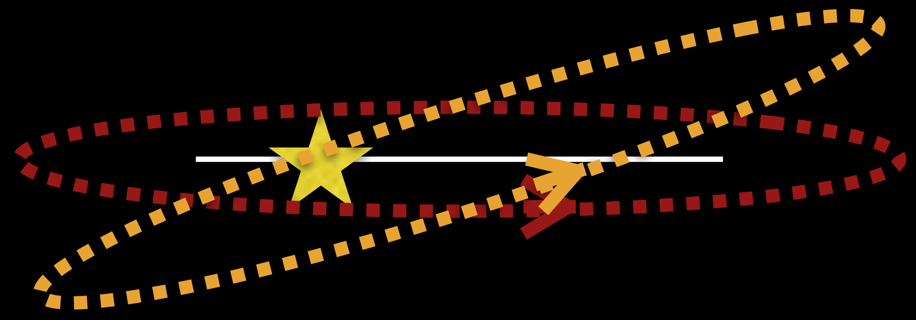




RID et al. 2014



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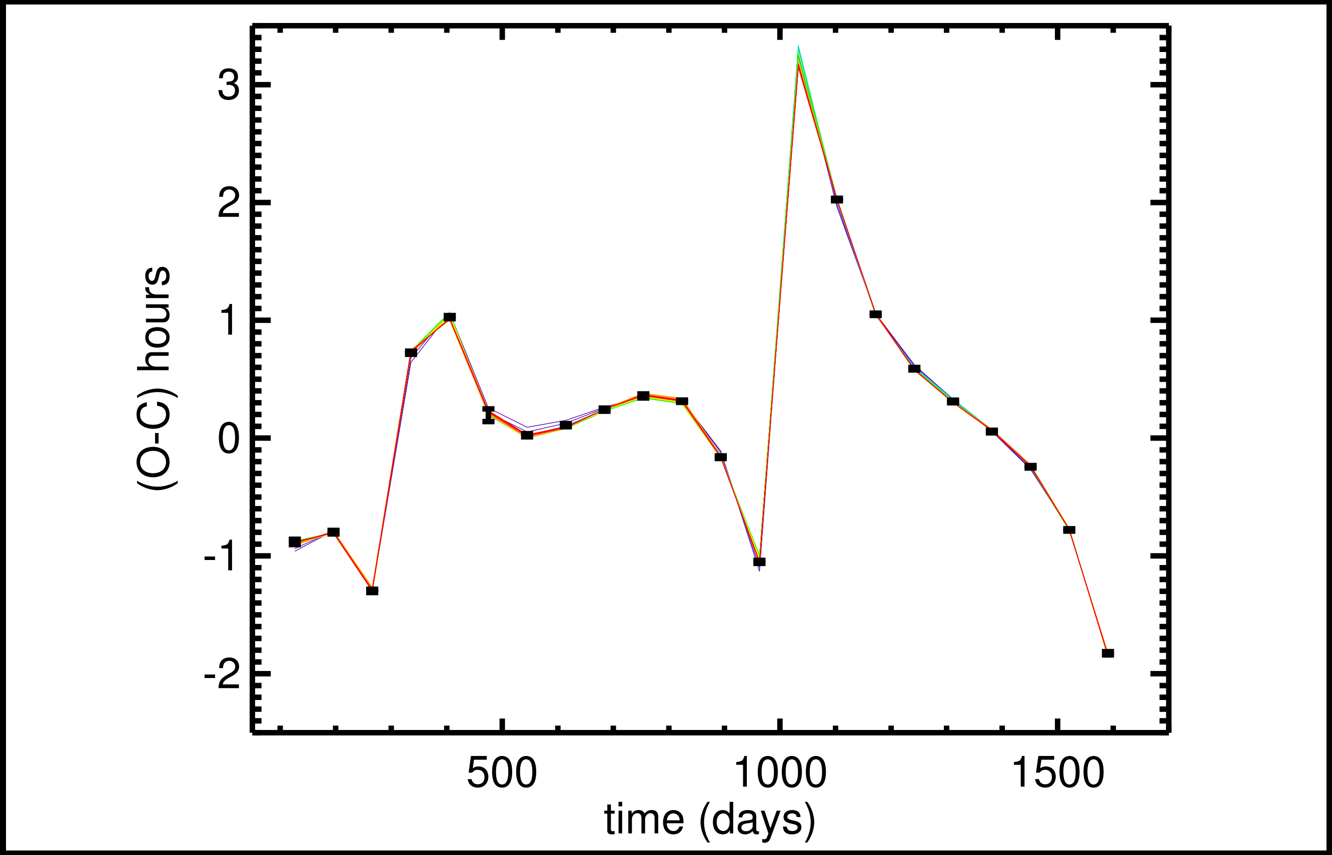
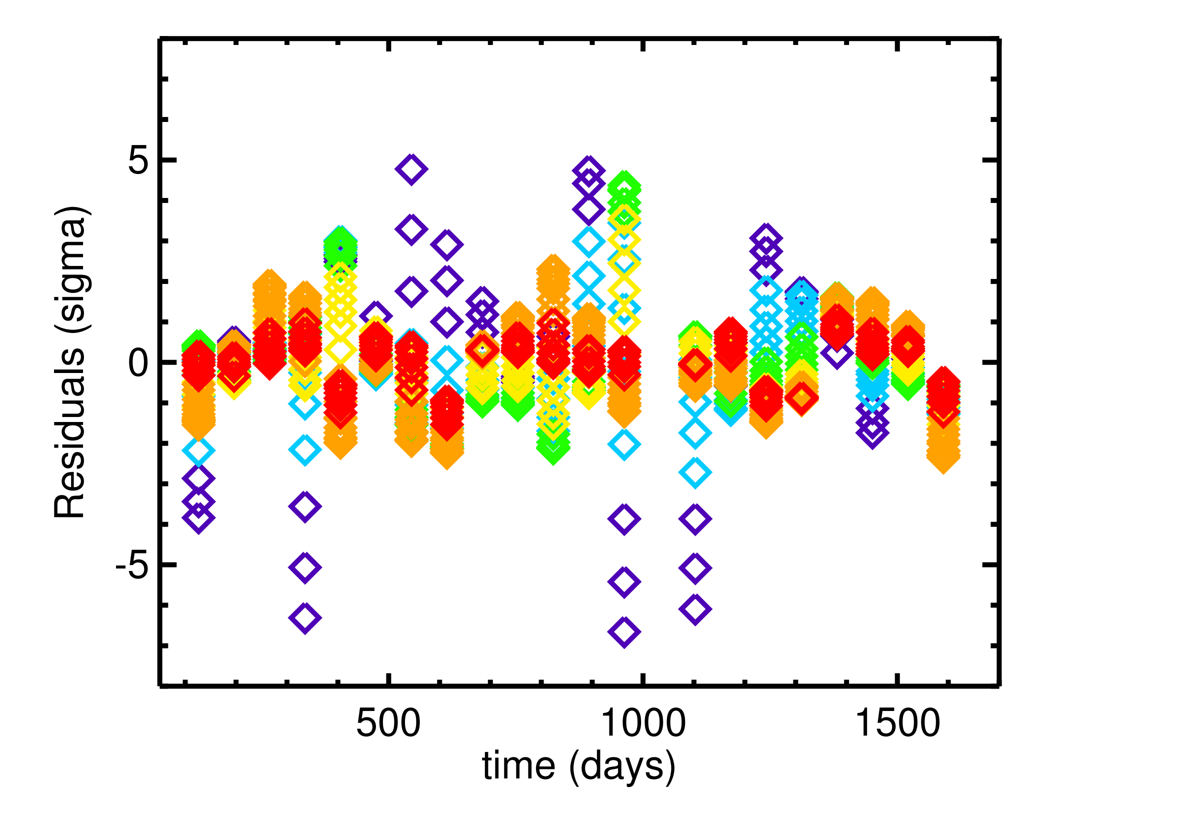
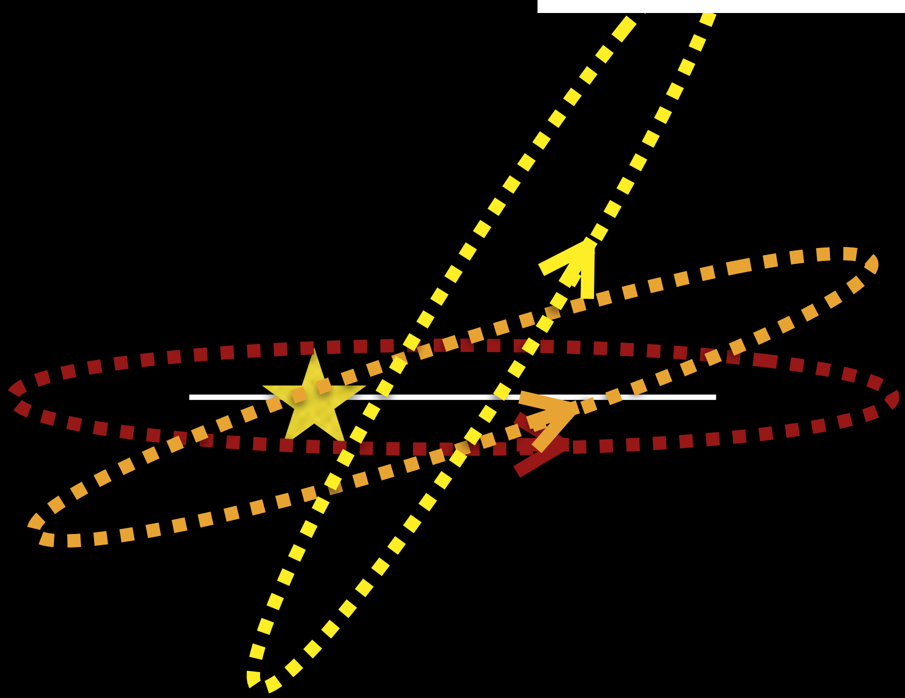




RID et al. 2014



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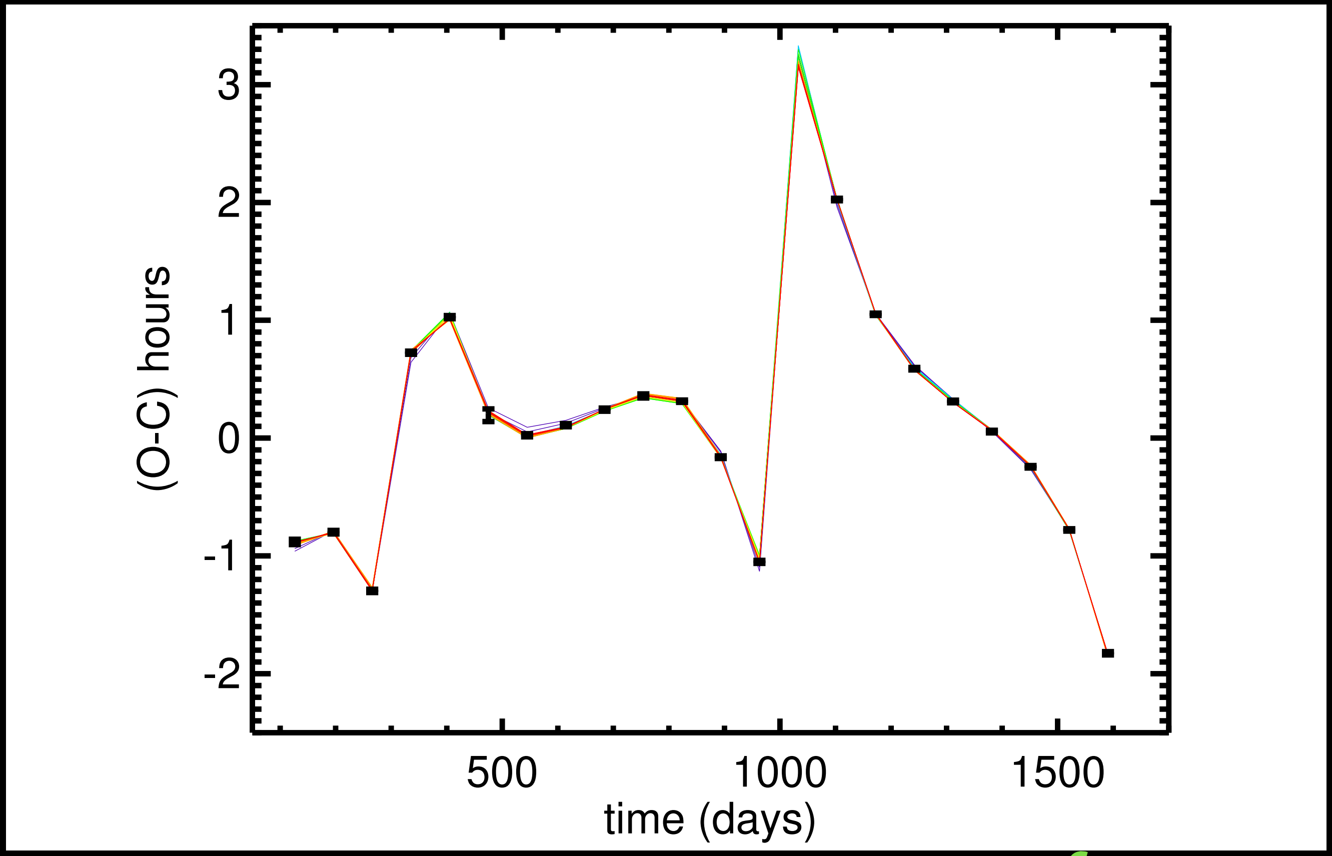
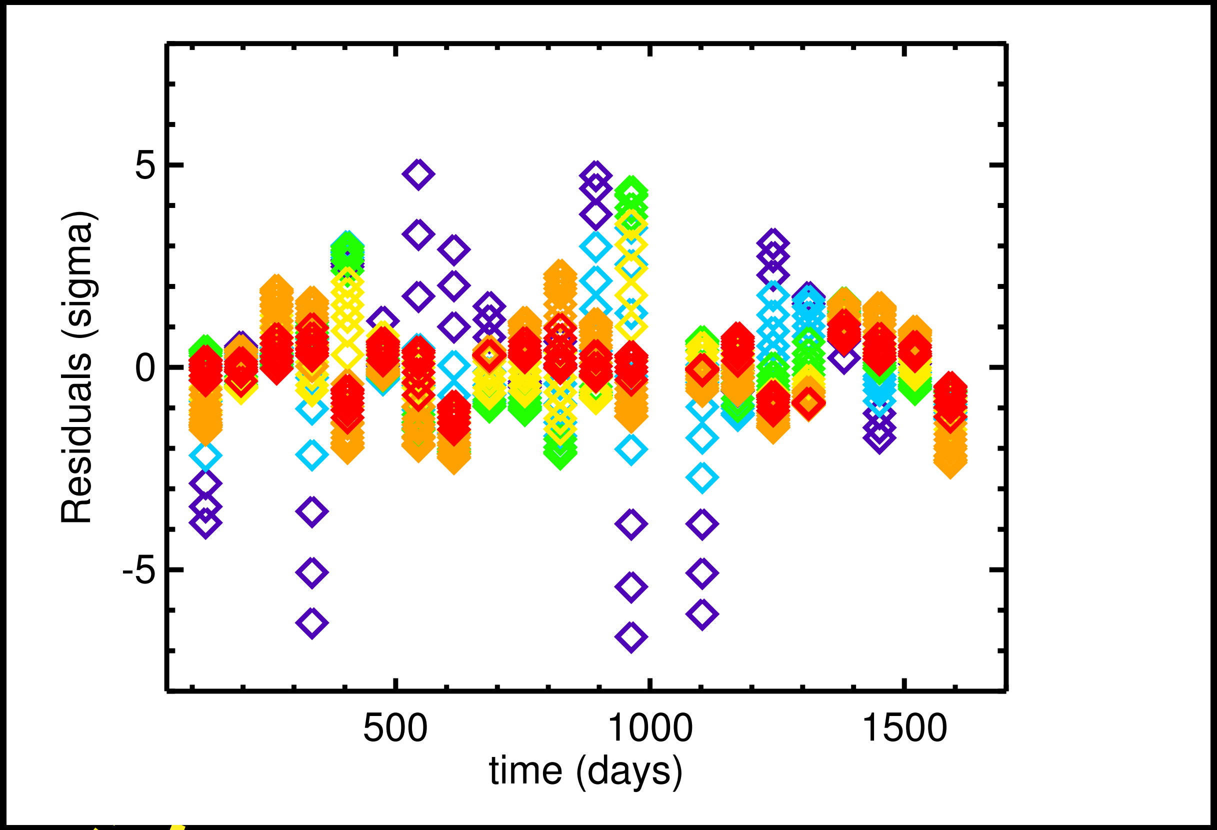
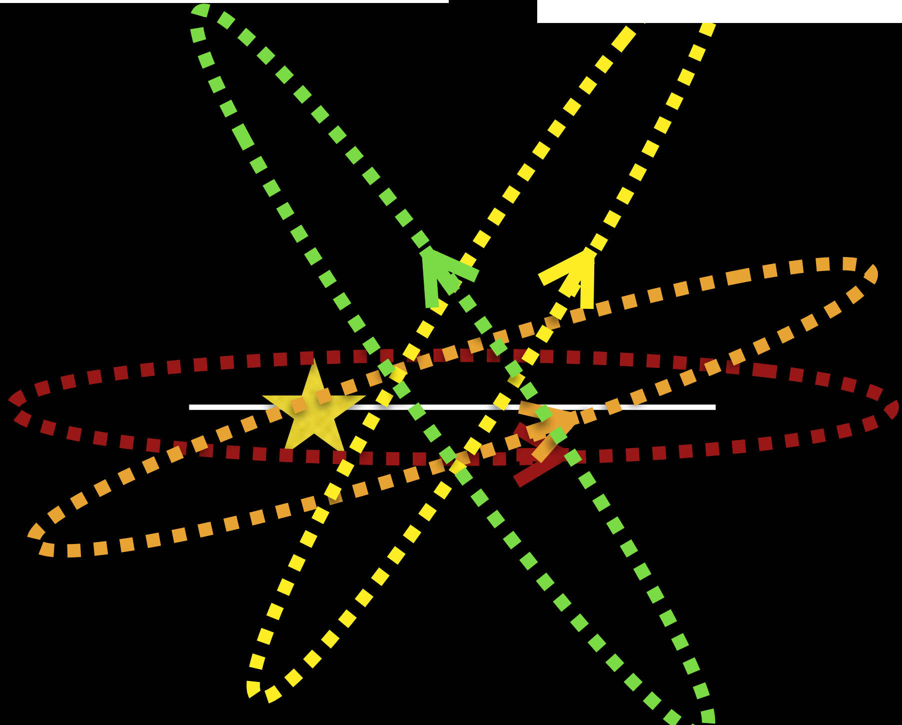




RID et al. 2014



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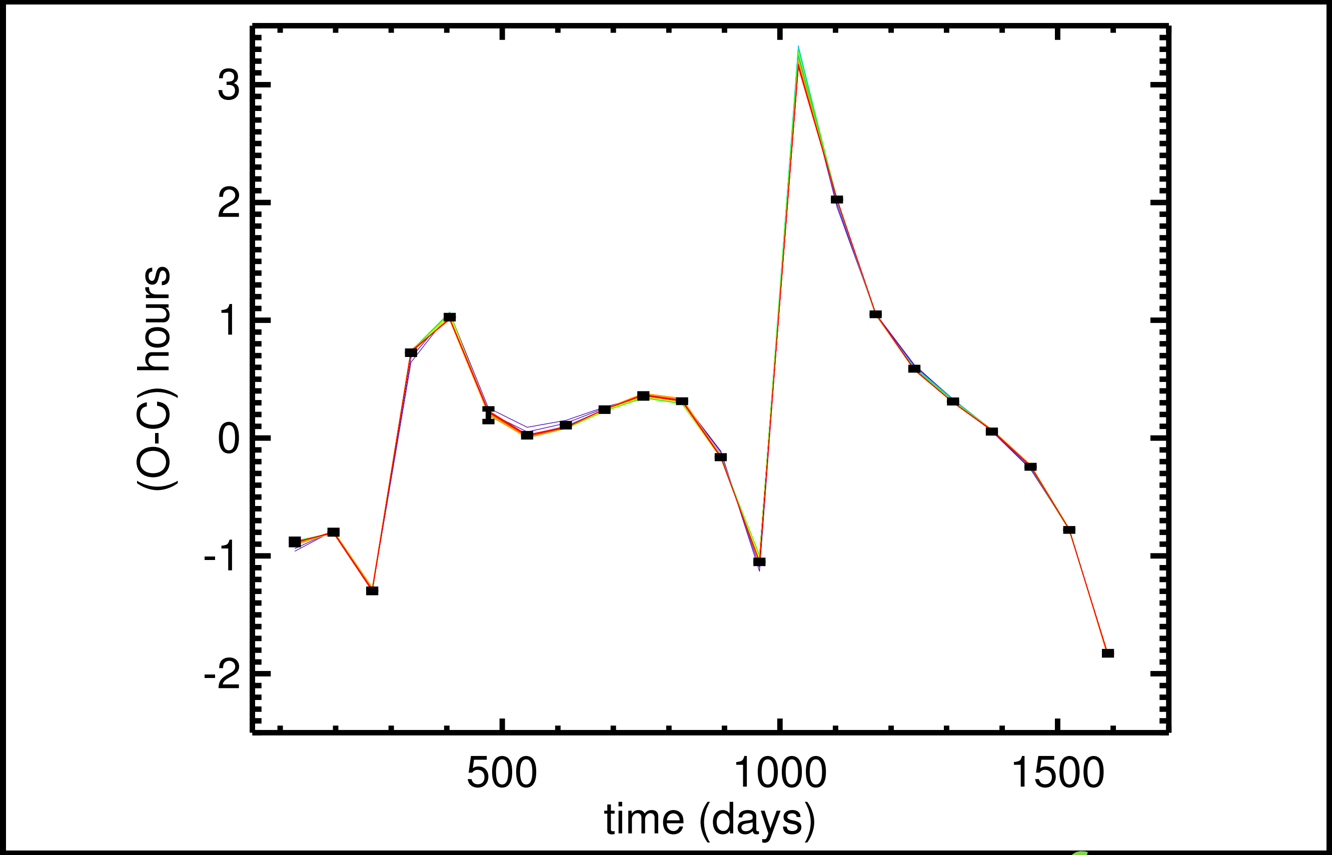
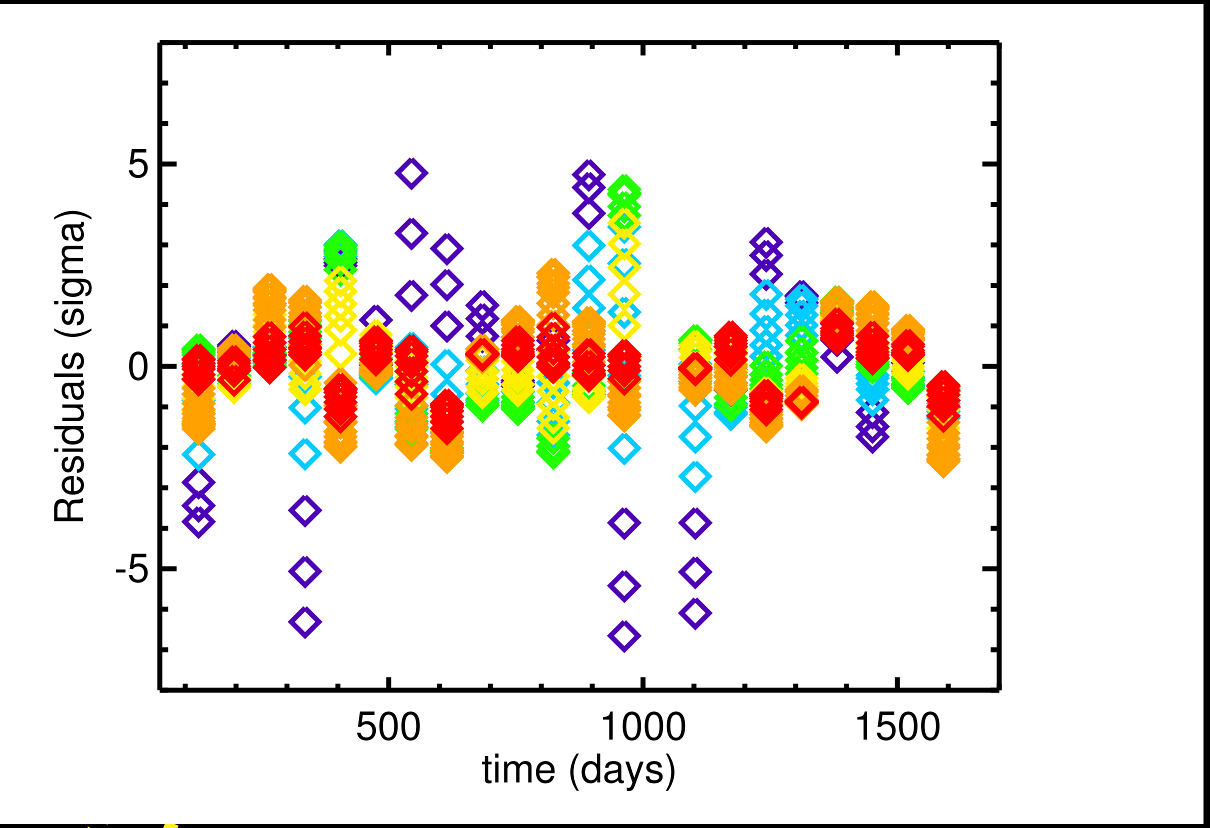
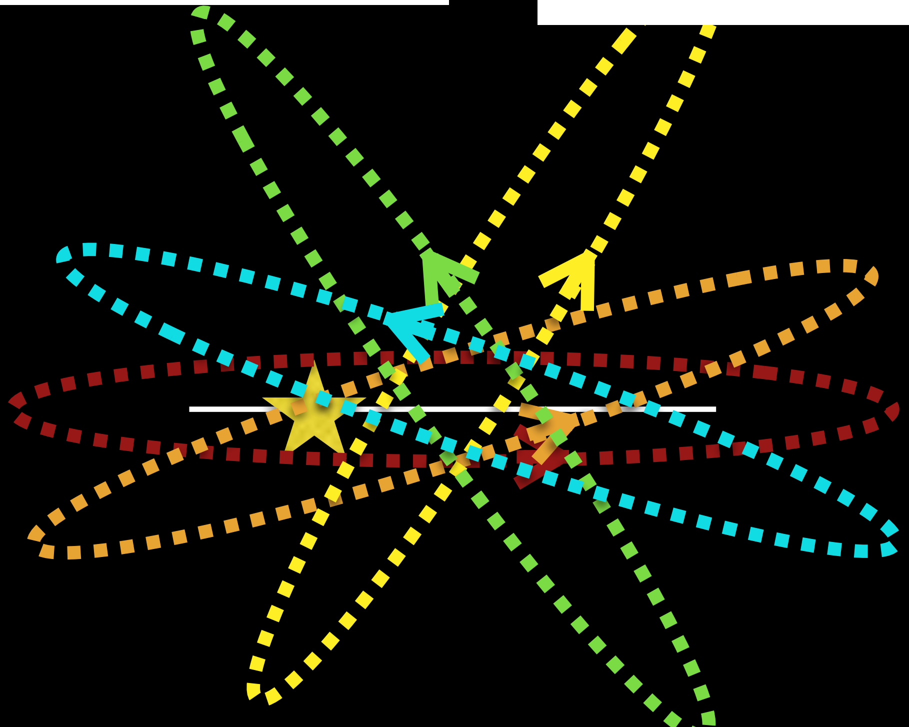




RID et al. 2014



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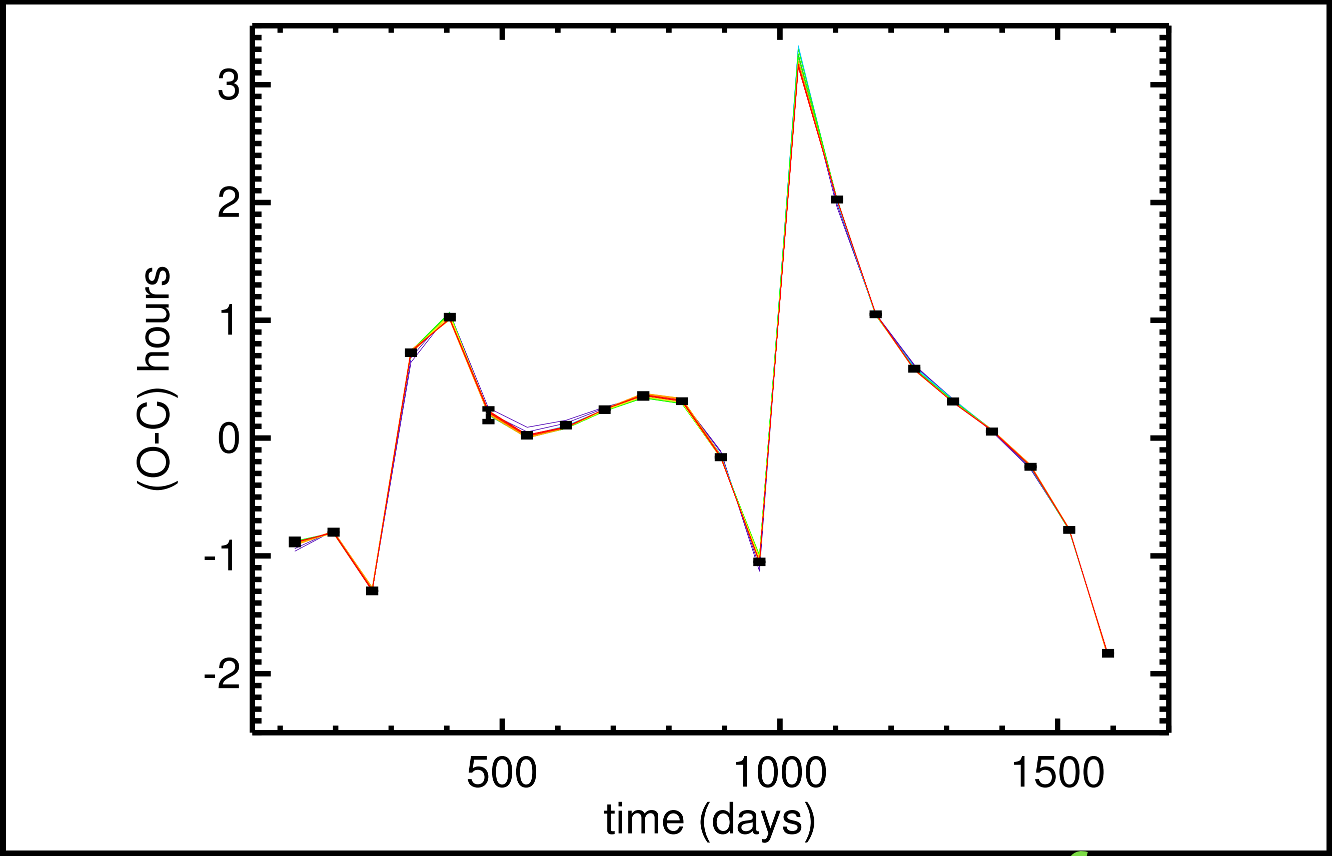

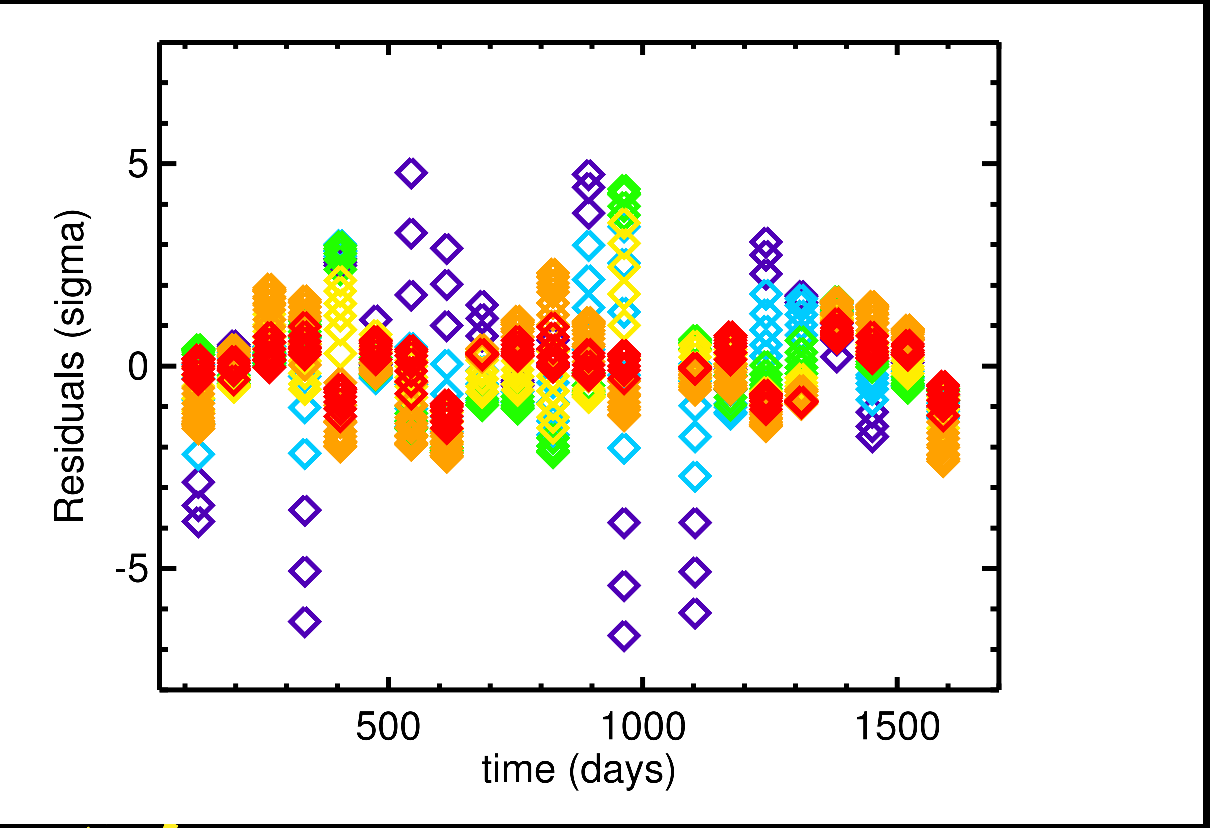

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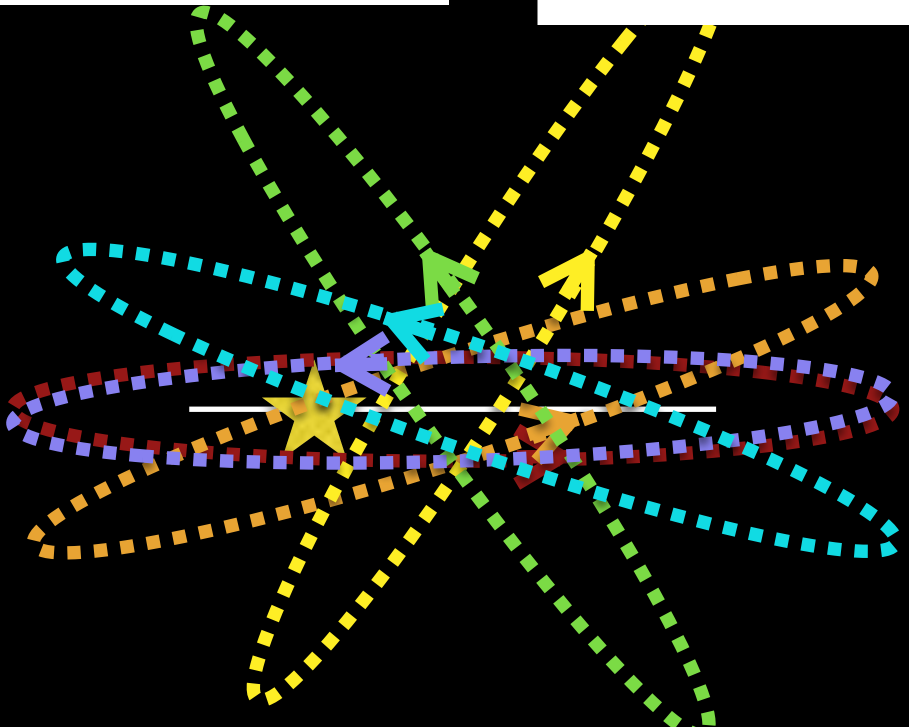
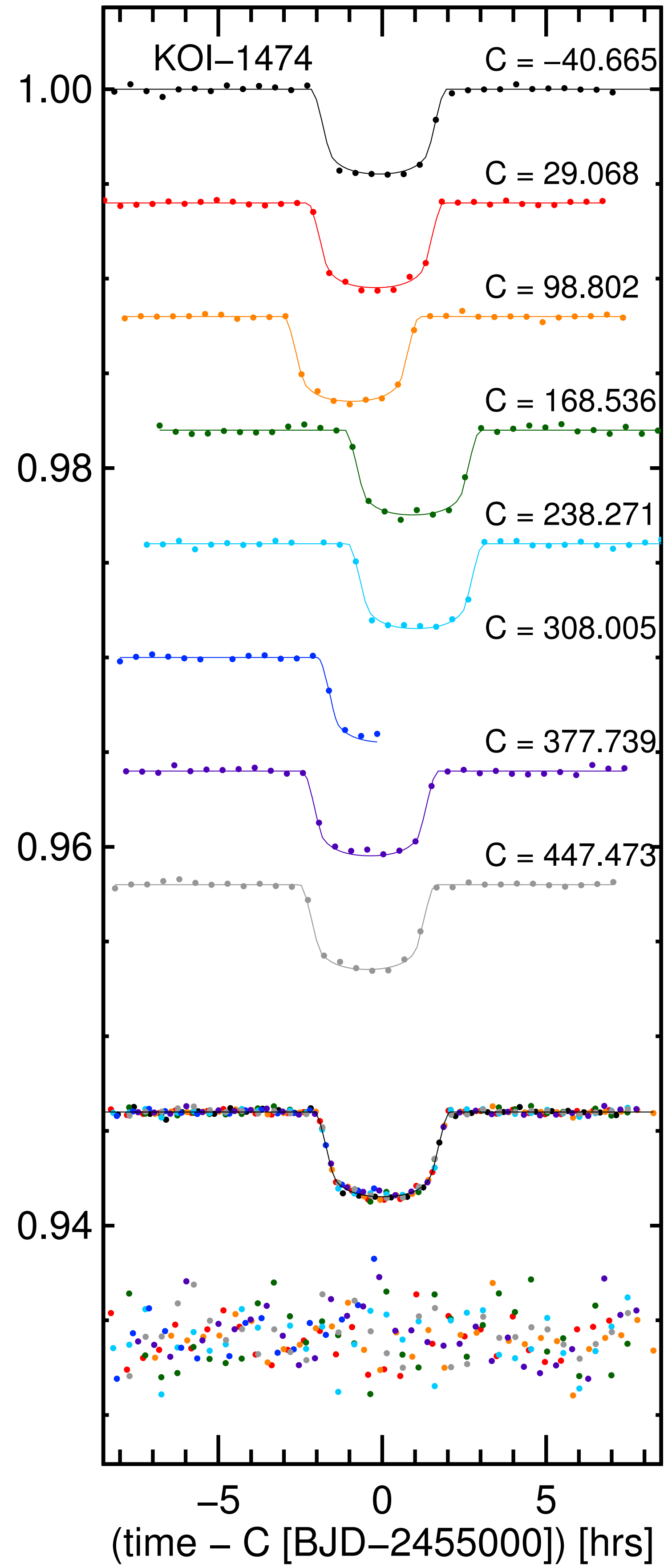
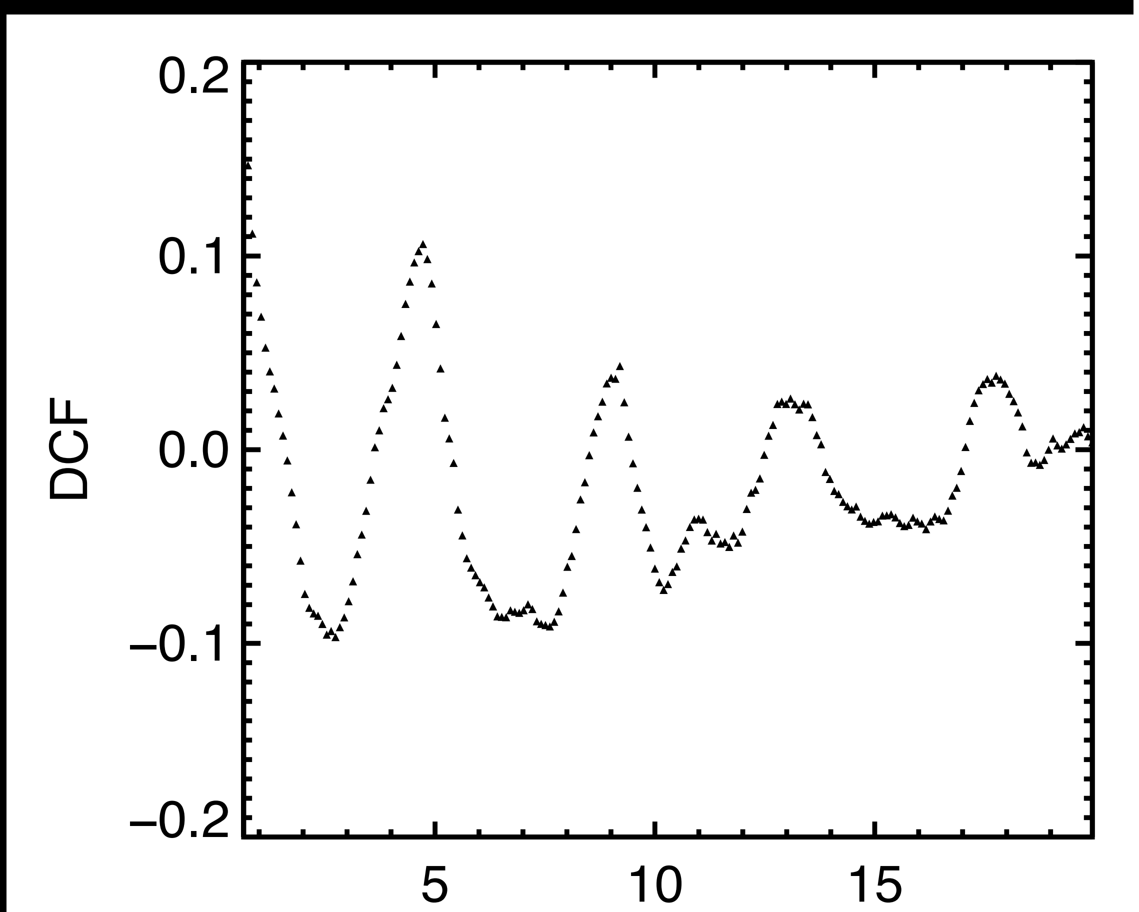


R. Dawson, SCMA, 06/09/16

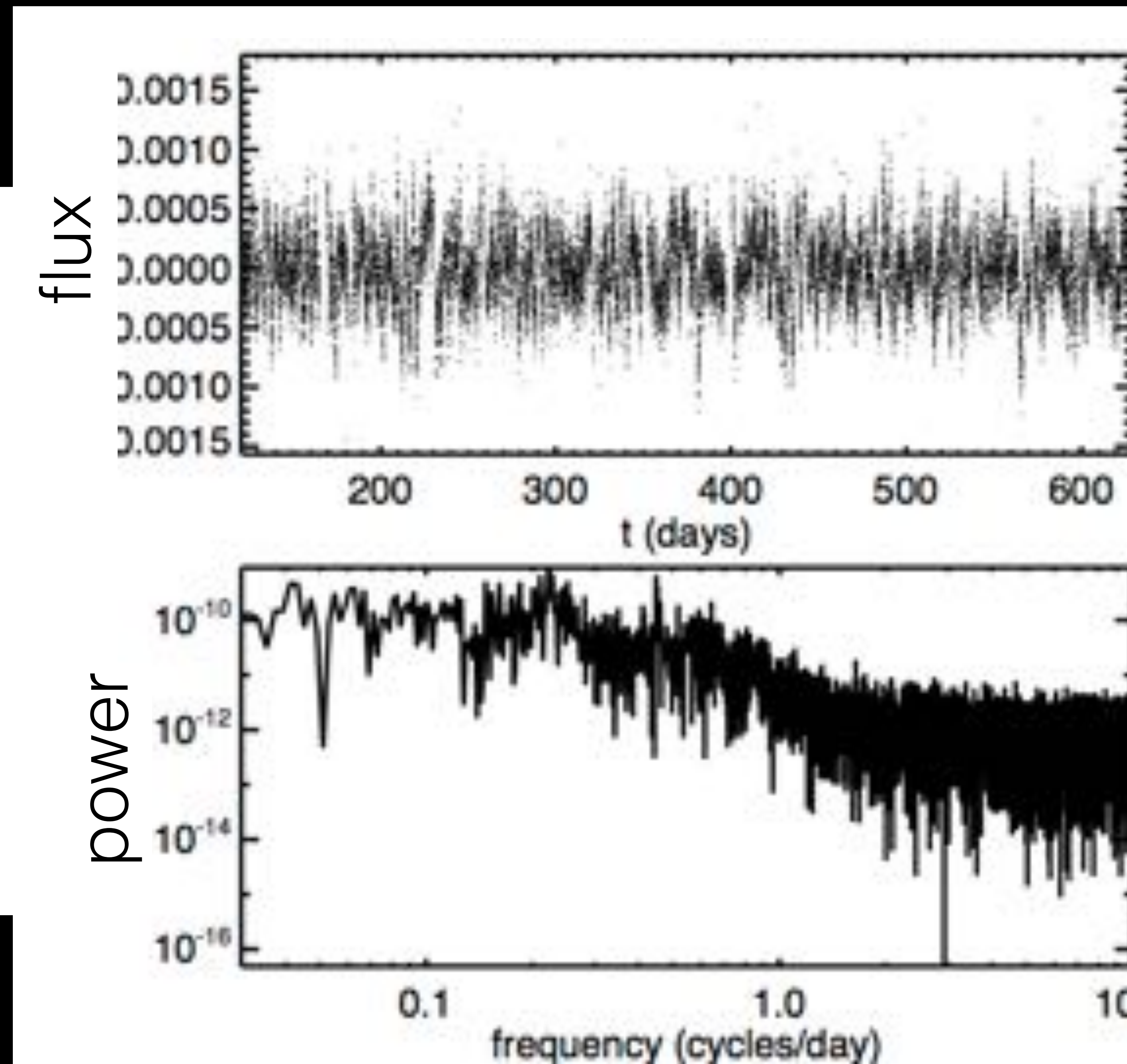


RID et al. 2012

We know the Kepler-419 dataset contains correlated noise

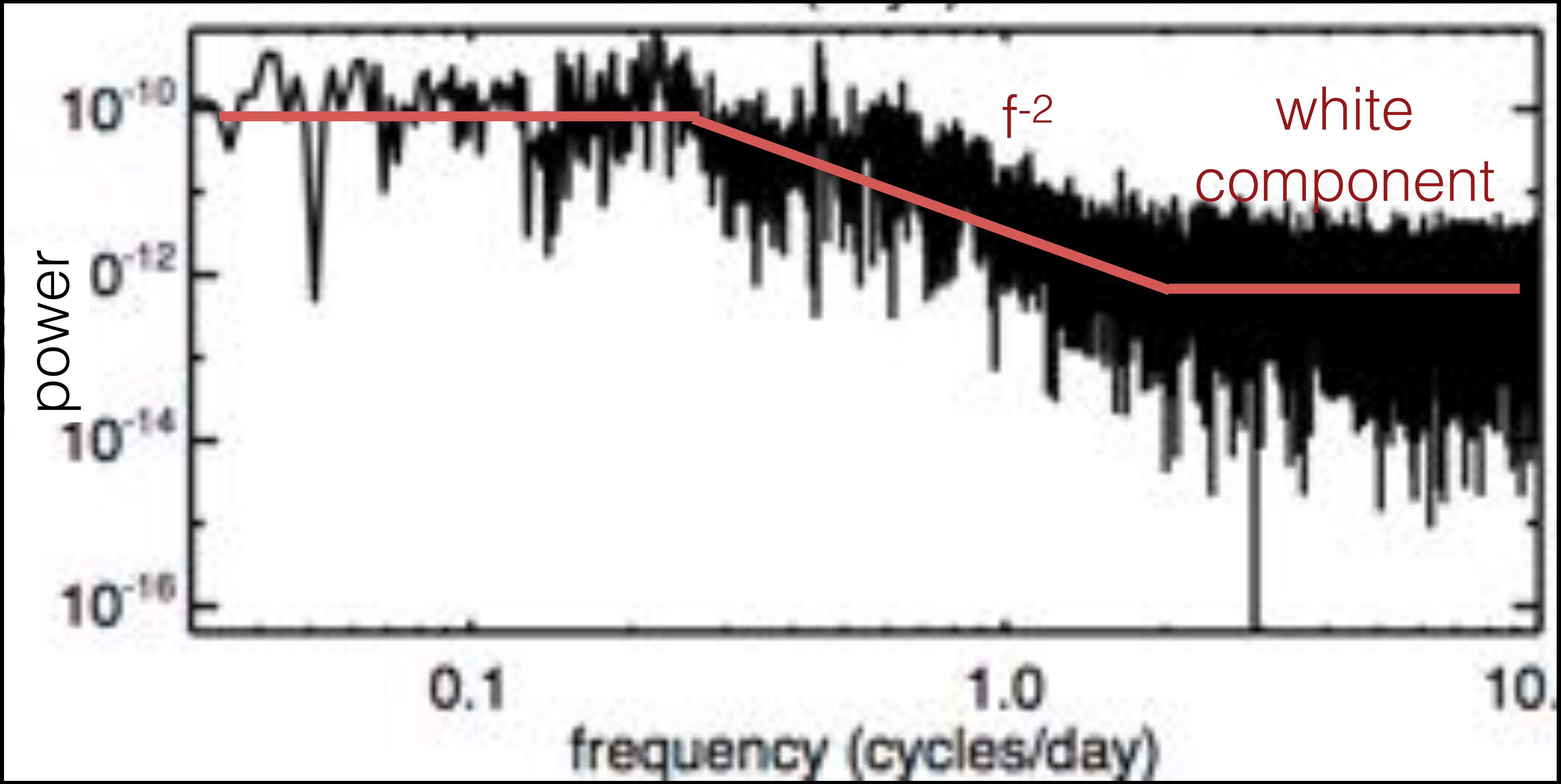


RID et al. 2012



R. Dawson, SCMA, 06/09/16

Common behavior: three segment spectrum



R. Dawson, SCMA, 06/09/16

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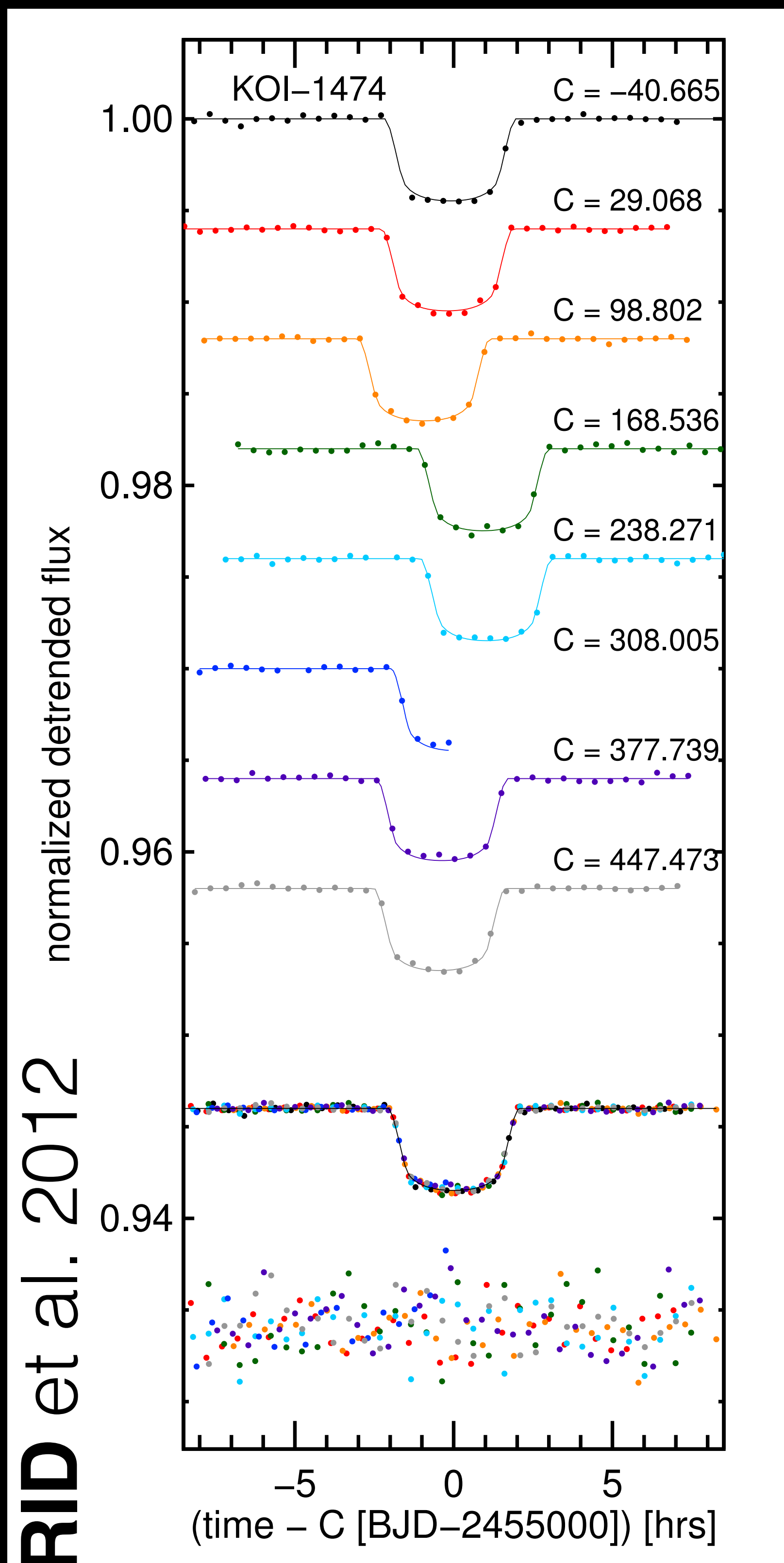

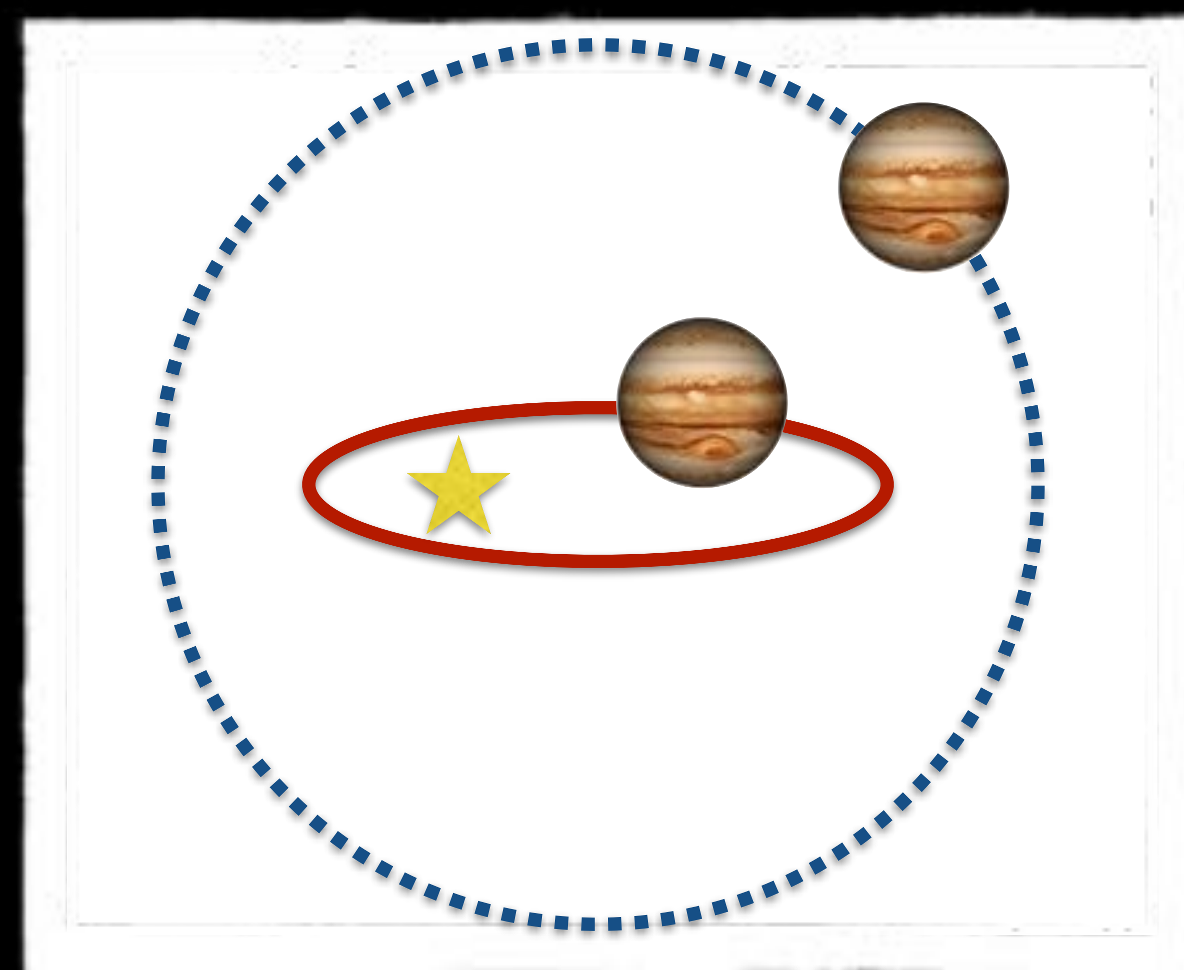

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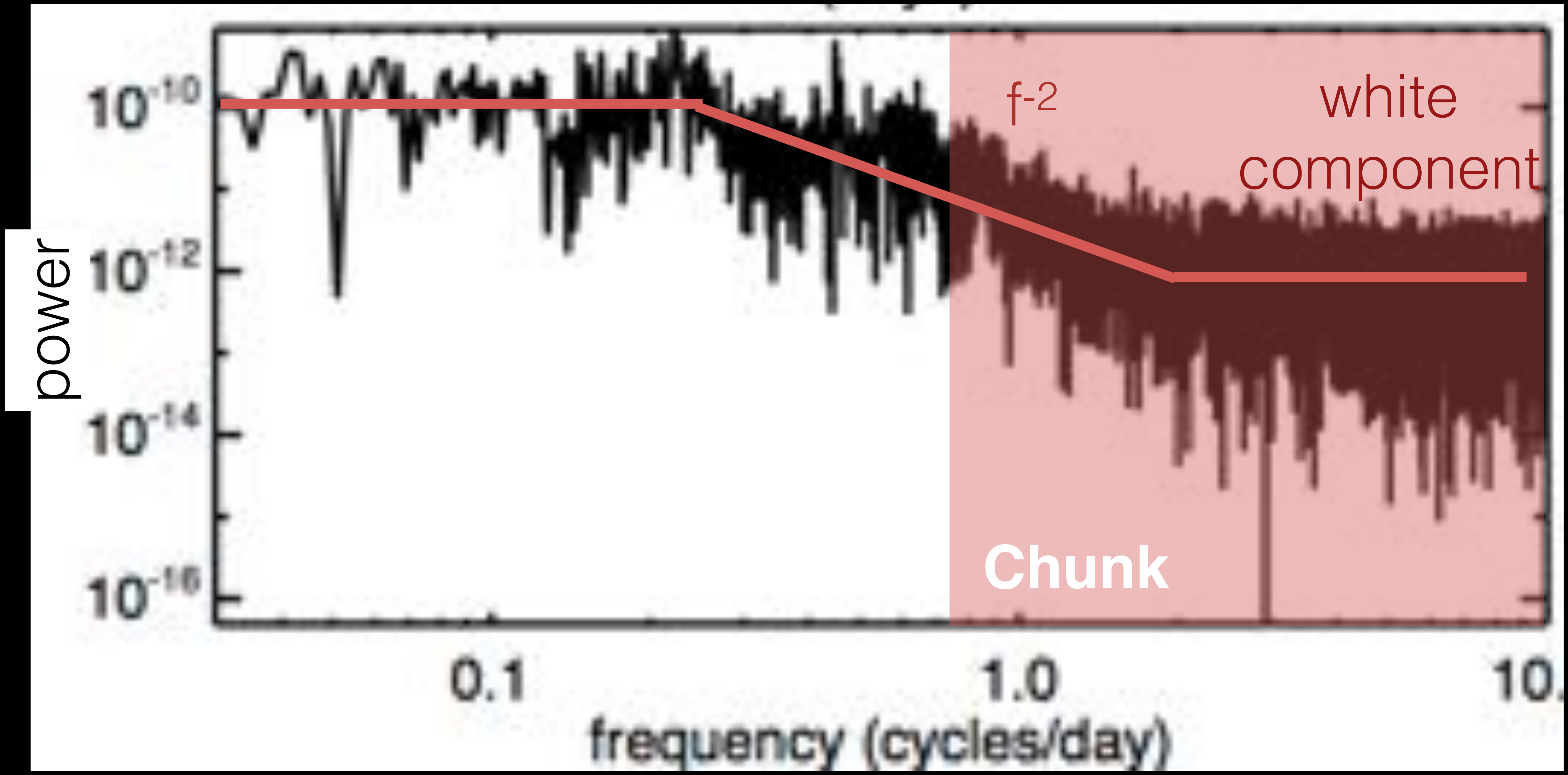
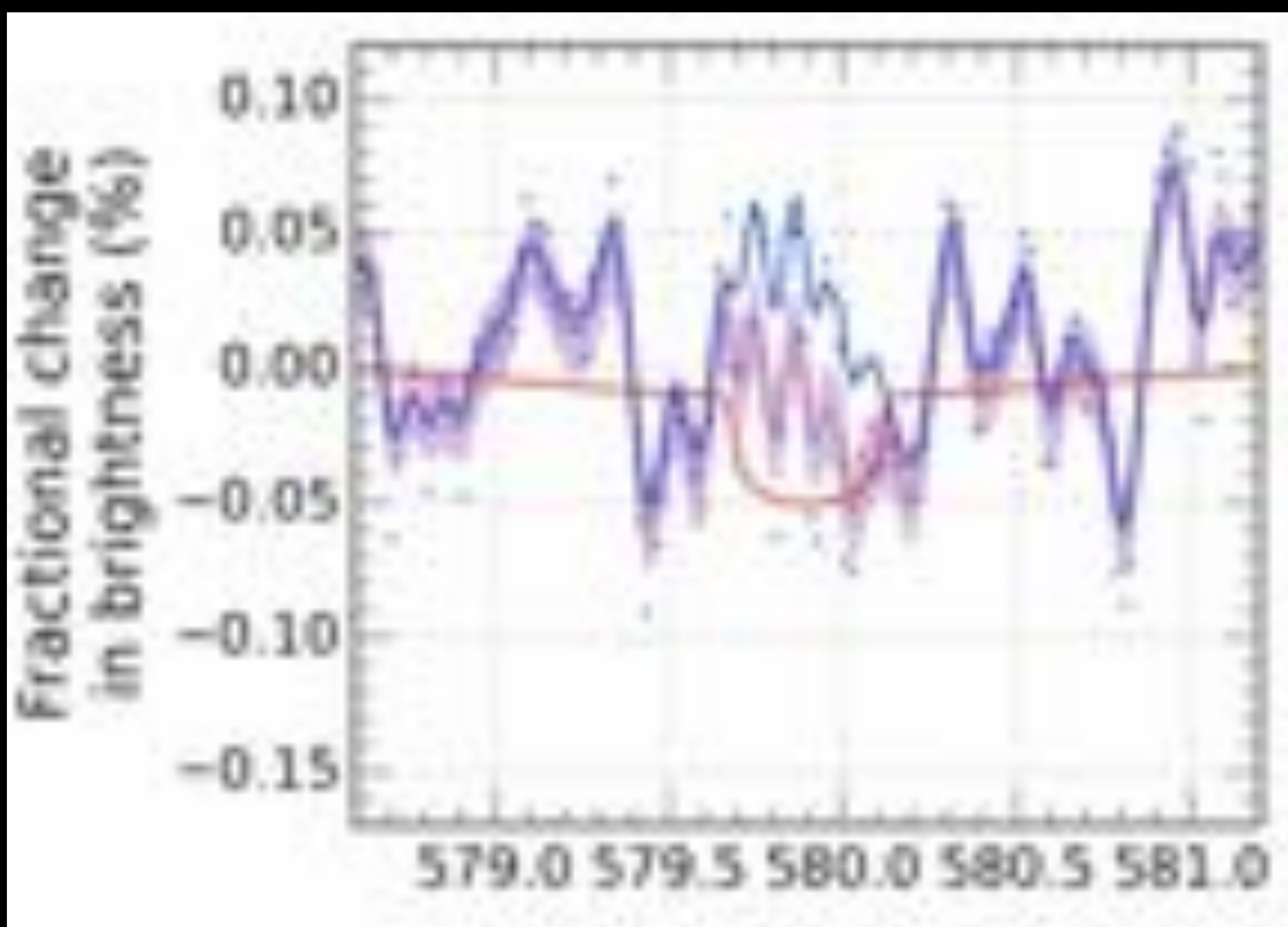
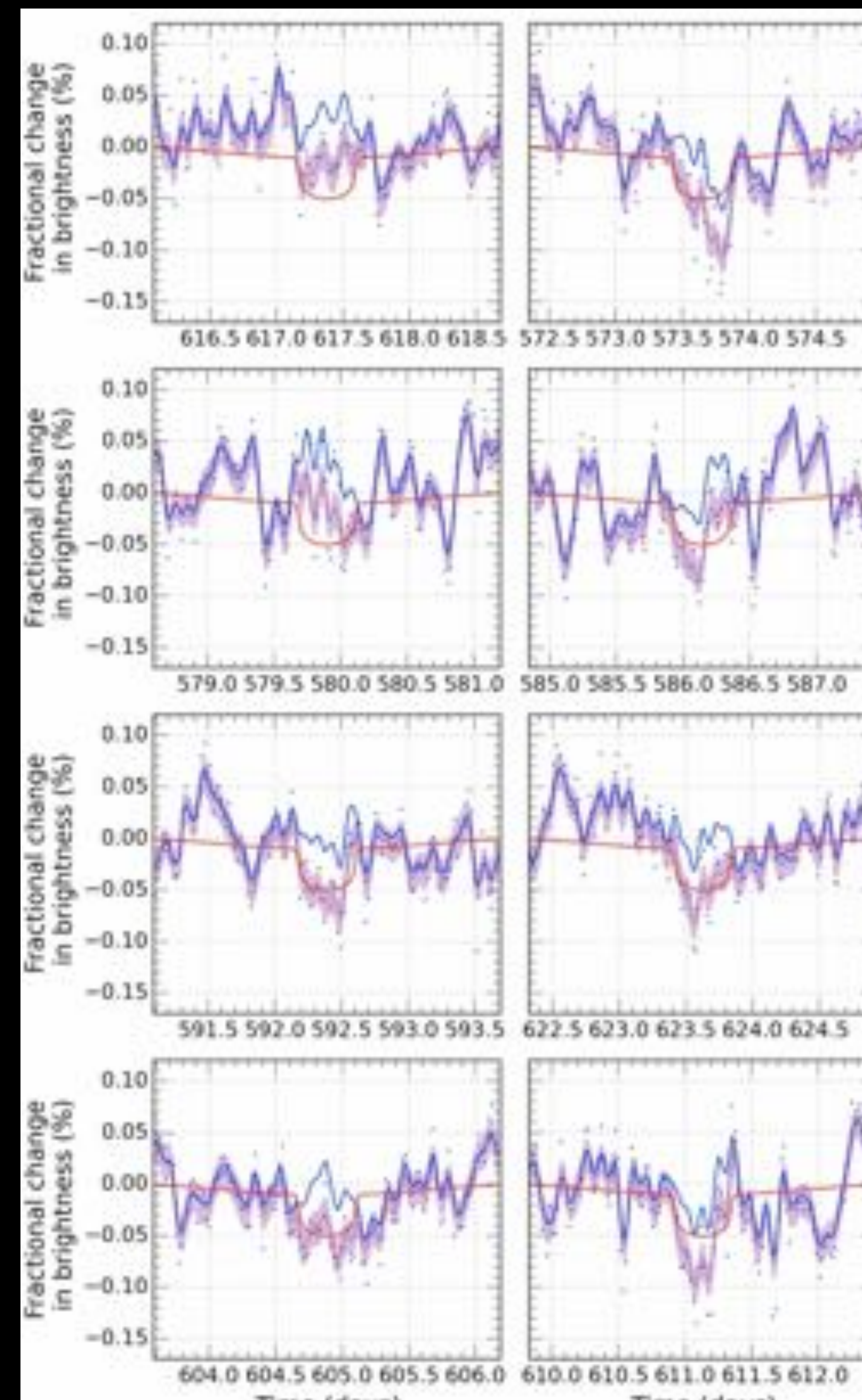


Pre-detrending the data can lead to errors in the inferred planet properties

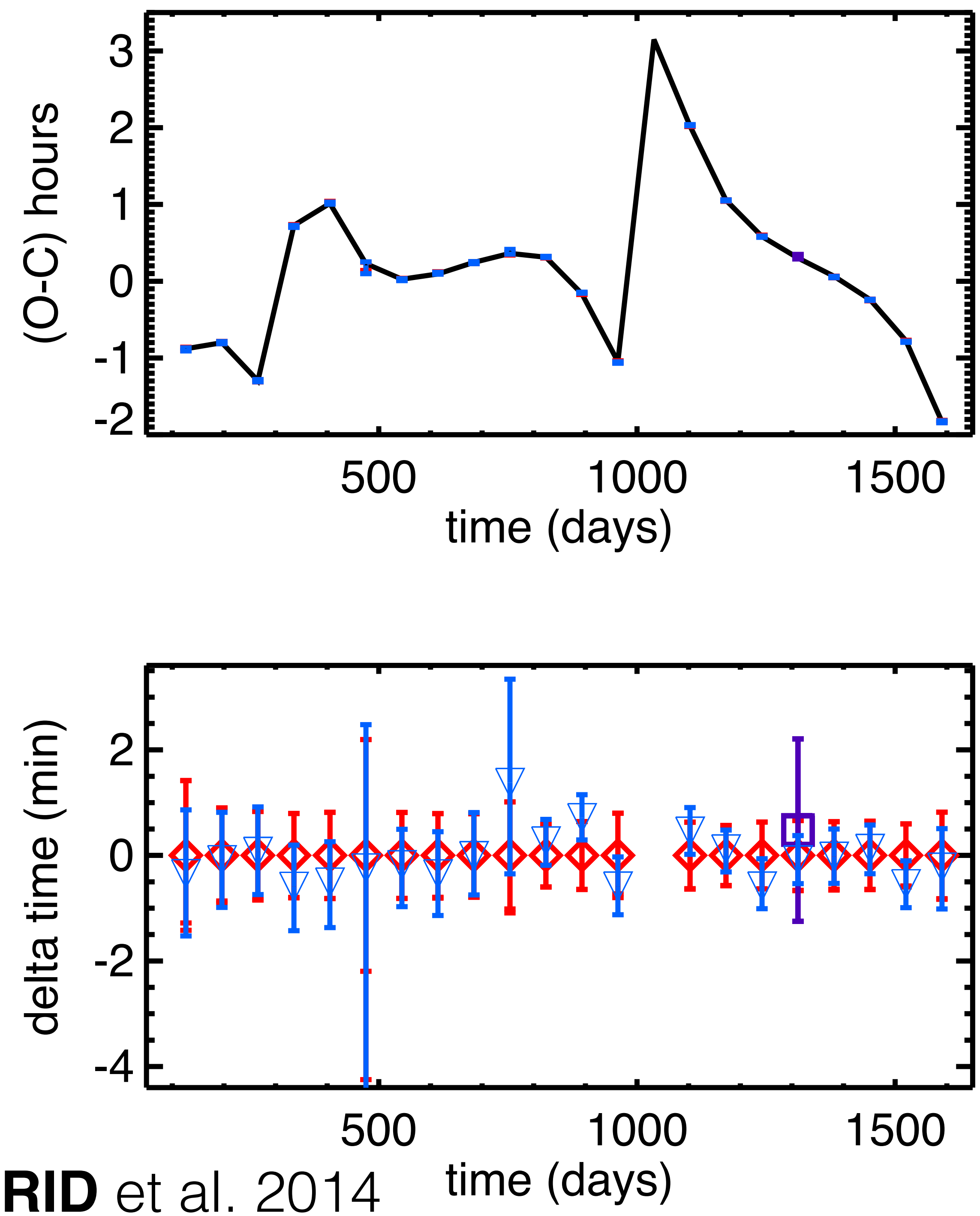
Barclay et al. 15, Kepler-91b
Gaussian process regression correlated noise using george (Foreman-Mackey et al. in prep)





Previous pre-whitening treatment caused this planet to be misdiagnosed as an astrophysical false positive (Sliski & Kipping 14)

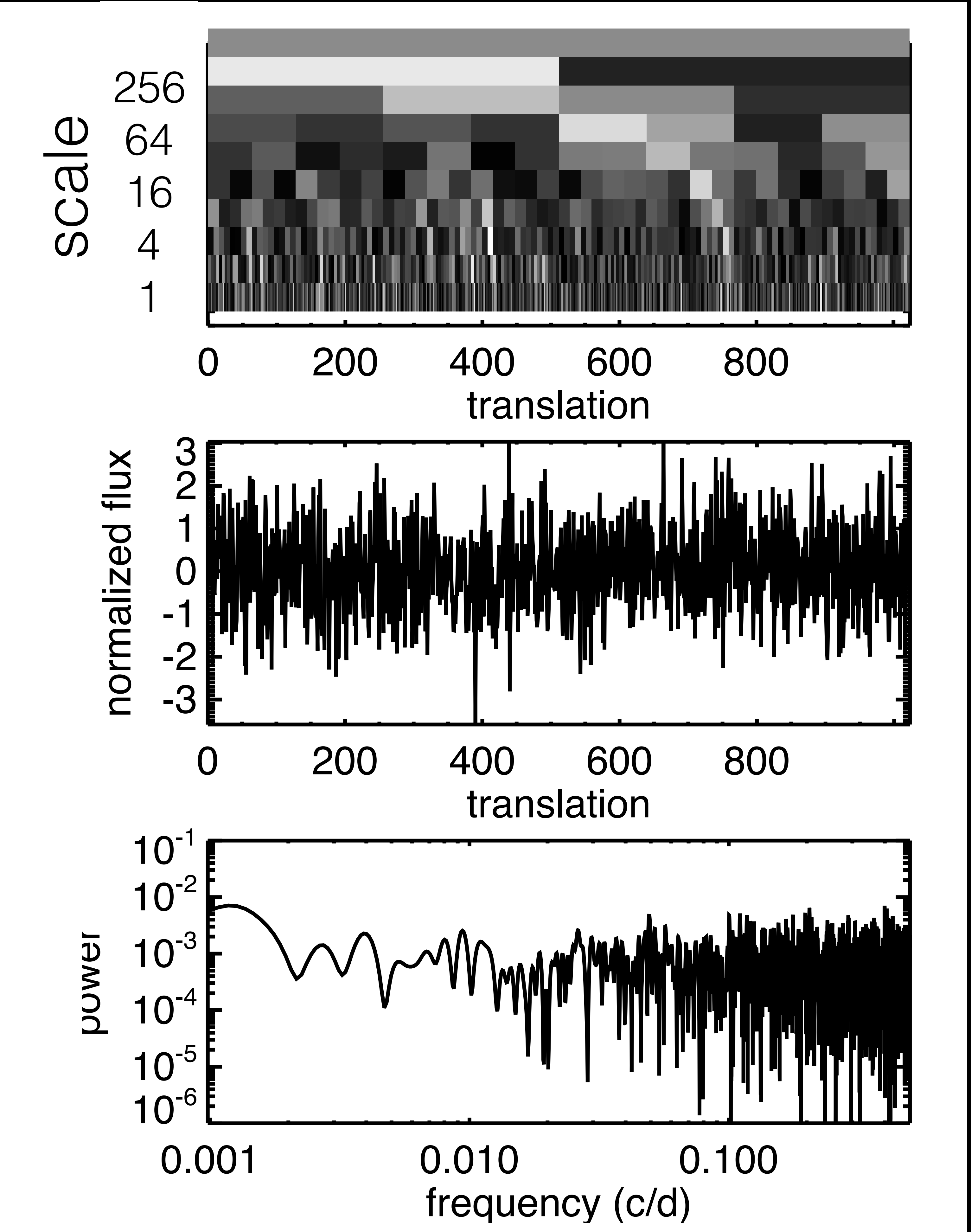
Two different correlated noise treatments yield consistent transit times



RID et al. 2014

- Median filter detrending, Carter & Winn 2009 wavelet likelihood
- Foreman-Mackey et al. in prep. Gaussian process regression likelihood with squared exponential covariance kernel, dan.iel.fm/george

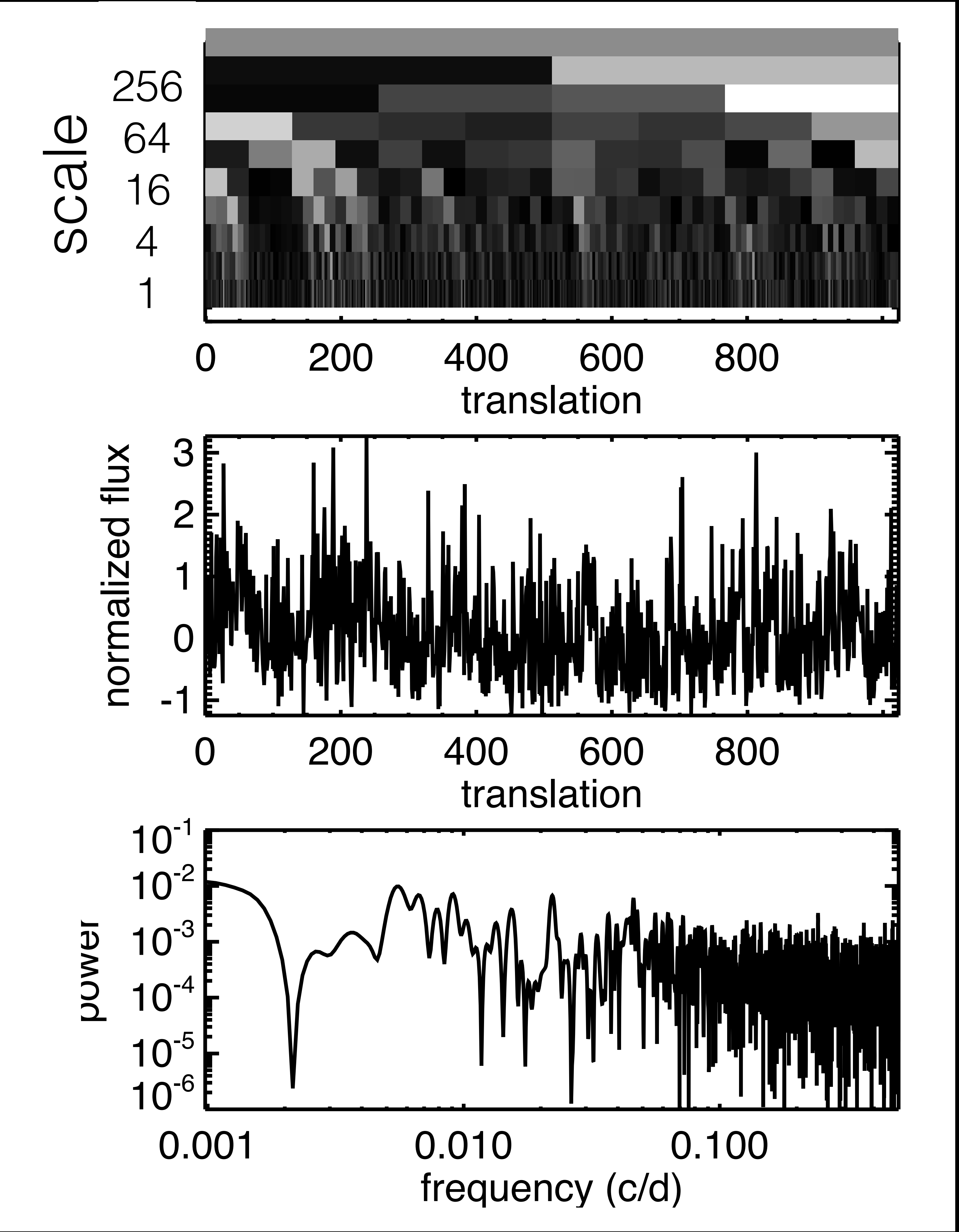
R.



White noise

Wavelet transform computes power for different translations and scales

R.



Pink (1/f) noise

Wavelet transform computes power for different translations and scales

Wavelet likelihood method parametrizes noise into red σ_r and white σ_w component

Carter & Winn 2009 (144 citations)

based on Wornell 1996:

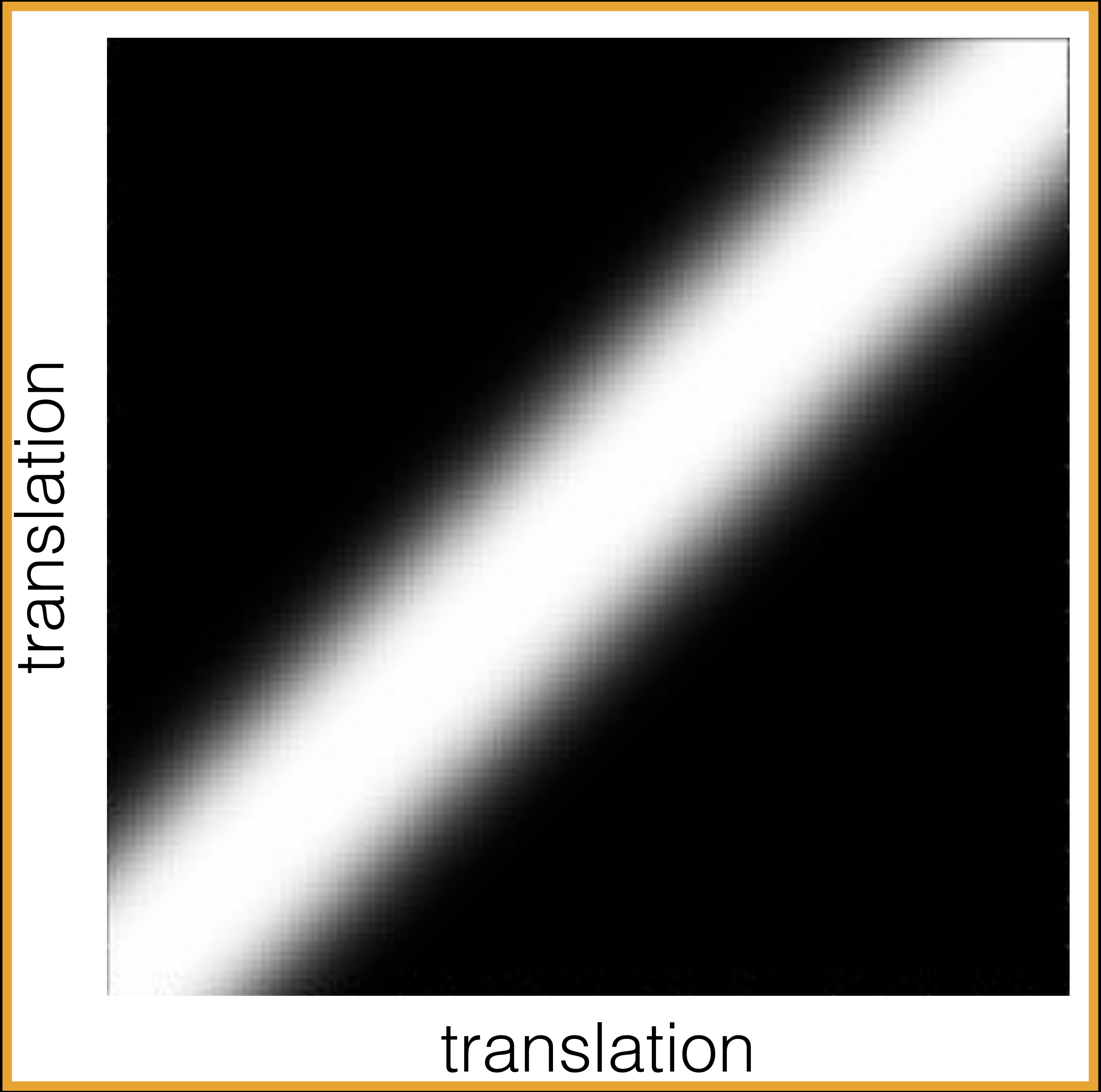
Signal Processing with Fractals: A Wavelet-Based Approach

$$\mathcal{L} = \left\{ \prod_{m=2}^{M} \prod_{n=1}^{n_0 2^{m-1}} \frac{1}{\sqrt{2\pi\sigma_W^2}} \exp\left[-\frac{(r_n^m)^2}{2\sigma_W^2} \right] \right\} \times \left\{ \prod_{n=1}^{n_0} \frac{1}{\sqrt{2\pi\sigma_S^2}} \exp\left[-\frac{(\bar{r}_n^1)^2}{2\sigma_S^2} \right] \right\},$$

$$\sigma_S^2 = \sigma_r^2 2^{-\gamma} g(\gamma) + \sigma_w^2,$$

$$\sigma_W^2 = \sigma_r^2 2^{-\gamma m} + \sigma_w^2,$$

Dictated relationship between scale coefficients for $1/f^\gamma$ noise



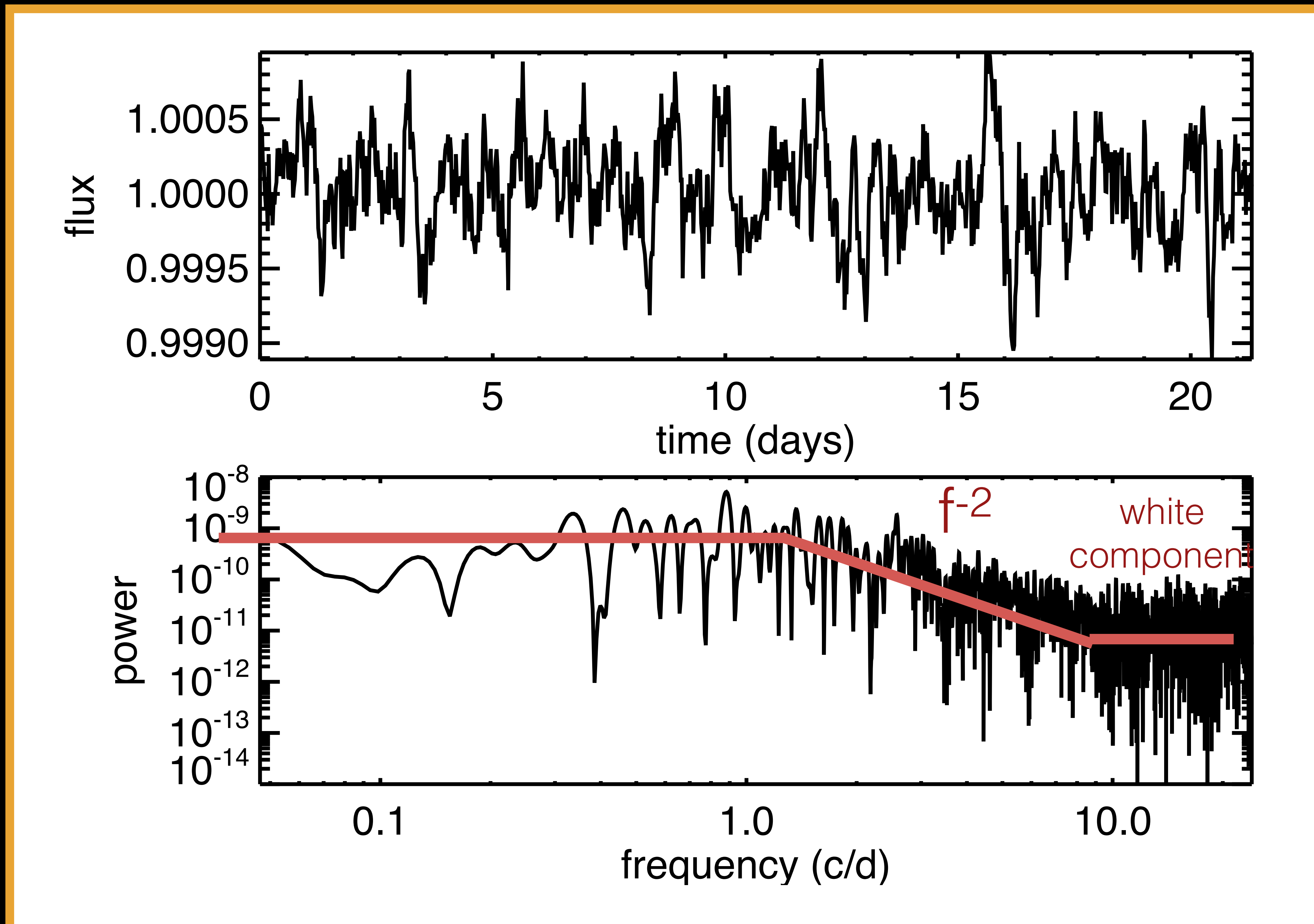
Gaussian process regression likelihood: prescription for covariance matrix

implemented using
dan.iel.fm/george

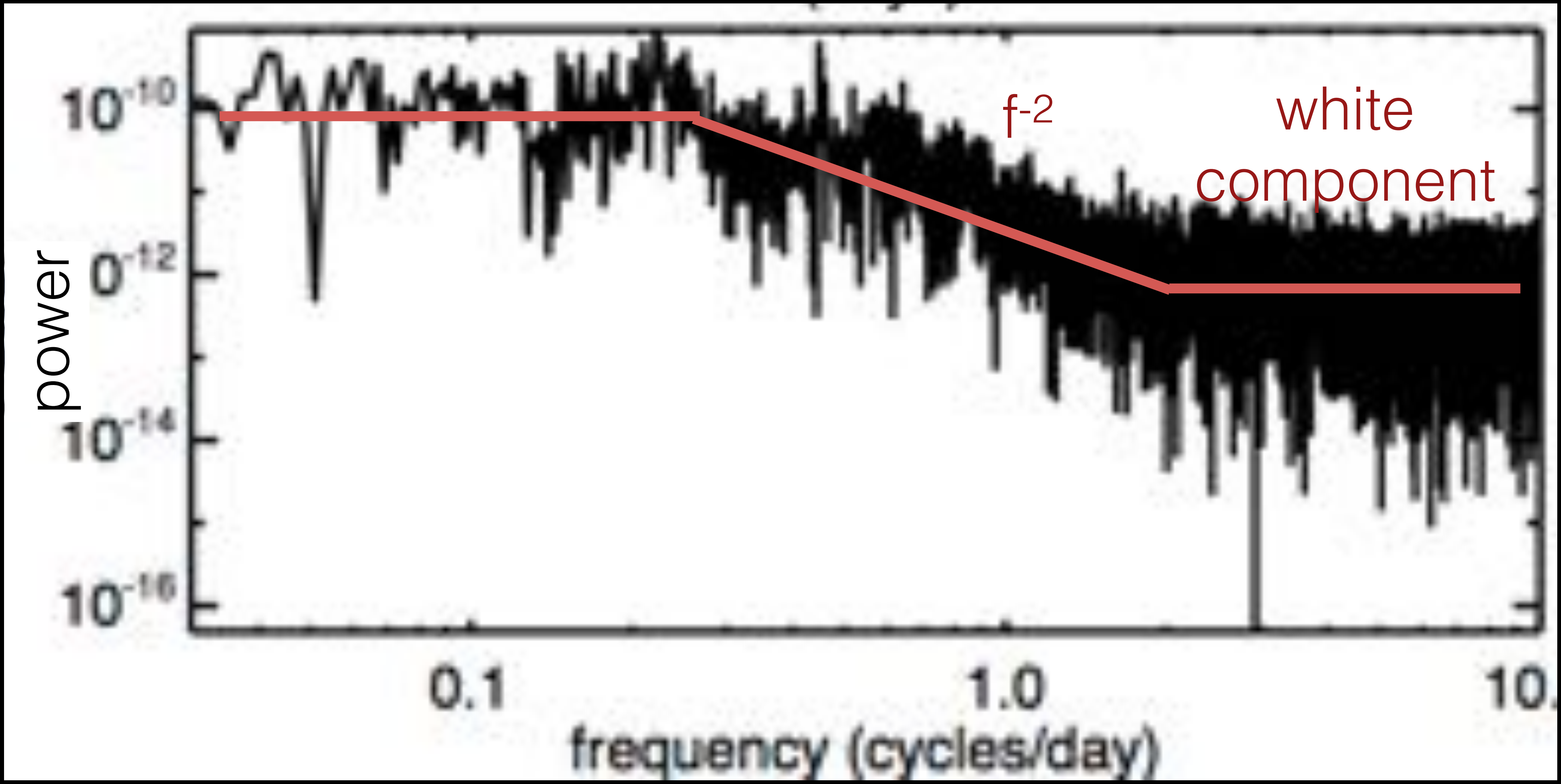
$$k(r^2) = \left(1 + \sqrt{5\,r^2} + \frac{5\,r^2}{3}\right)\,\exp\left(-\sqrt{5\,r^2}\right)$$

Radial Matern
5/2 kernel

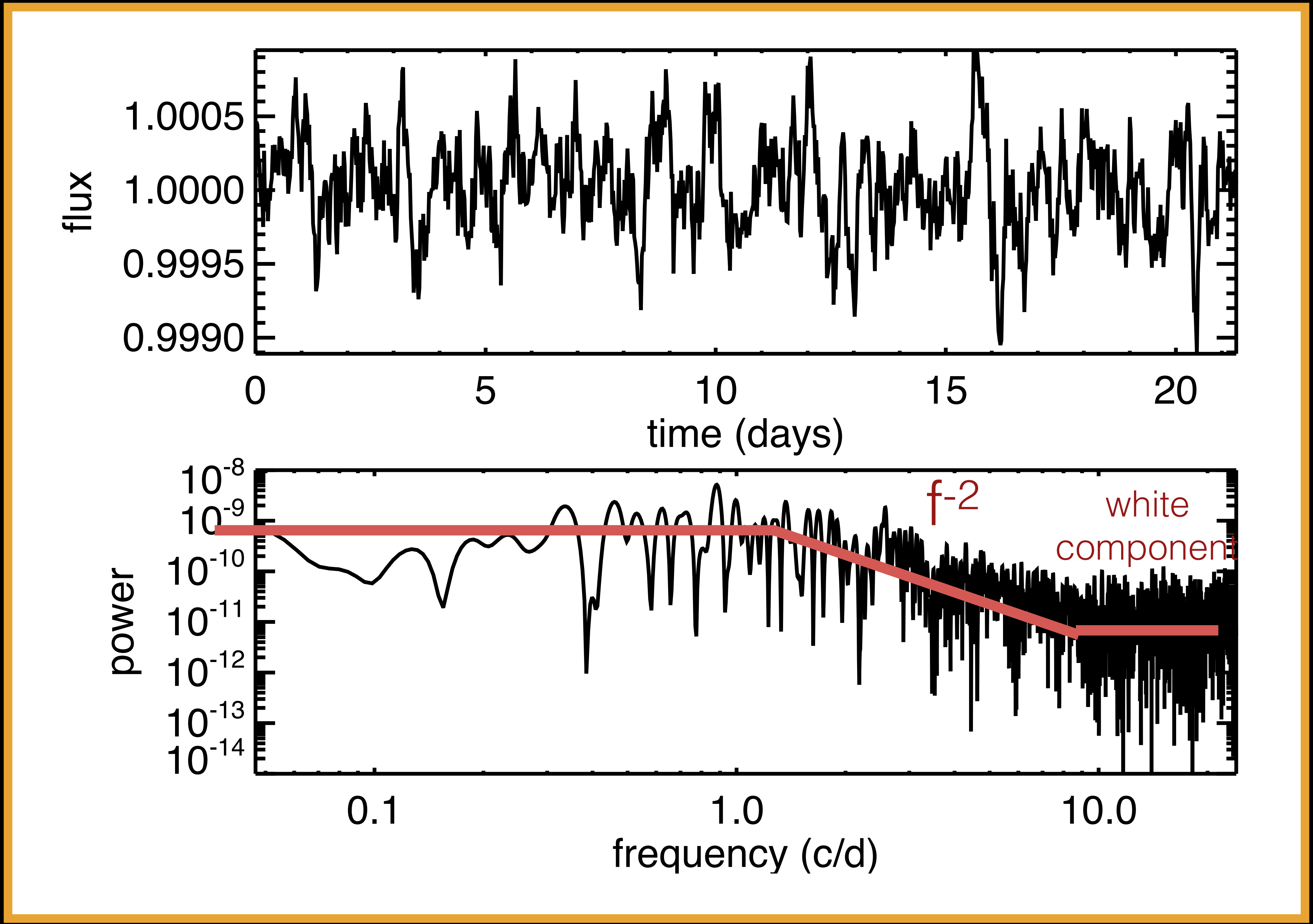
Gaussian process generated with Matern kernel in frequency space



Common behavior: three segment spectrum



Gaussian process generated with Matern kernel in frequency space



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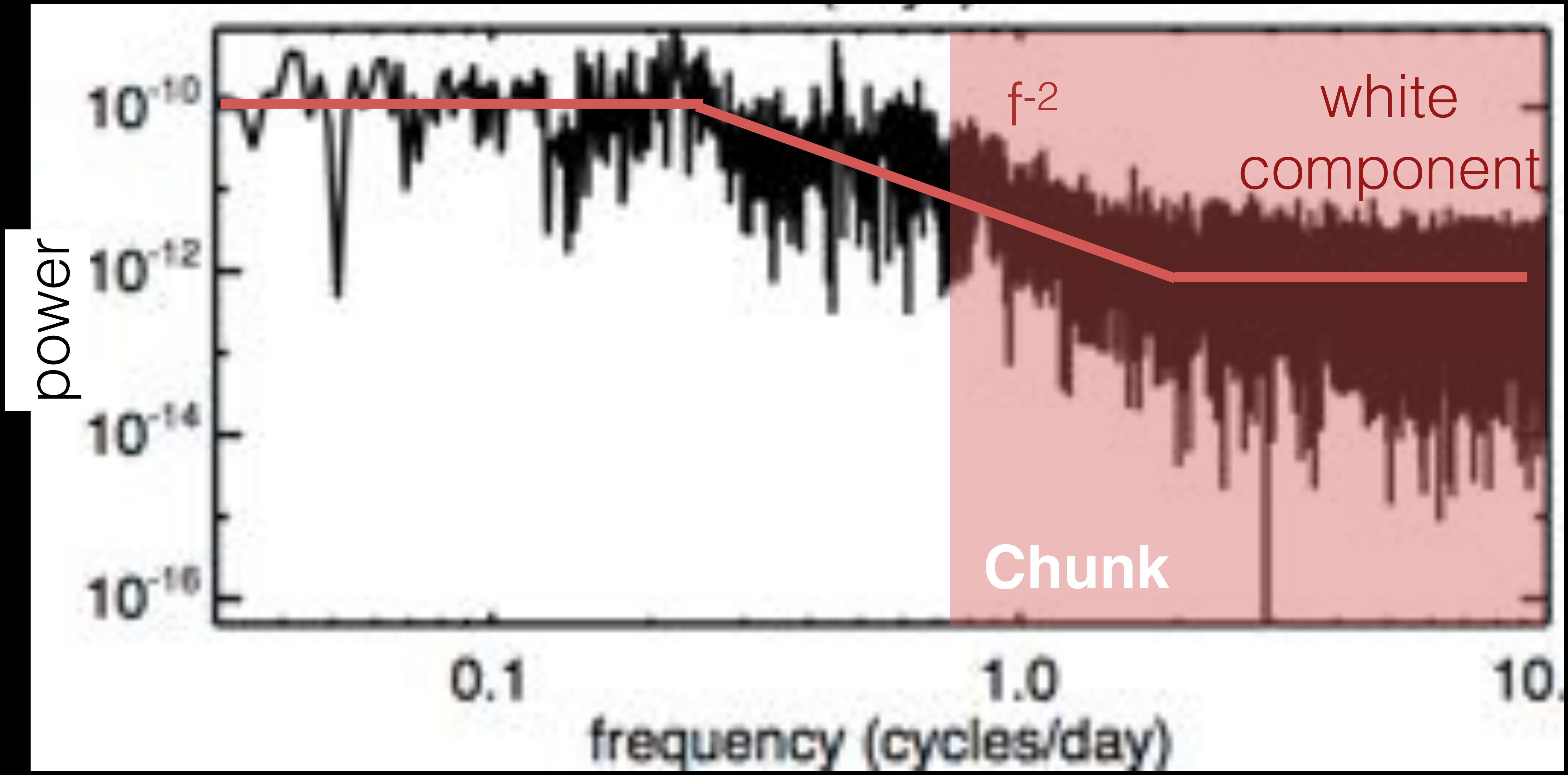
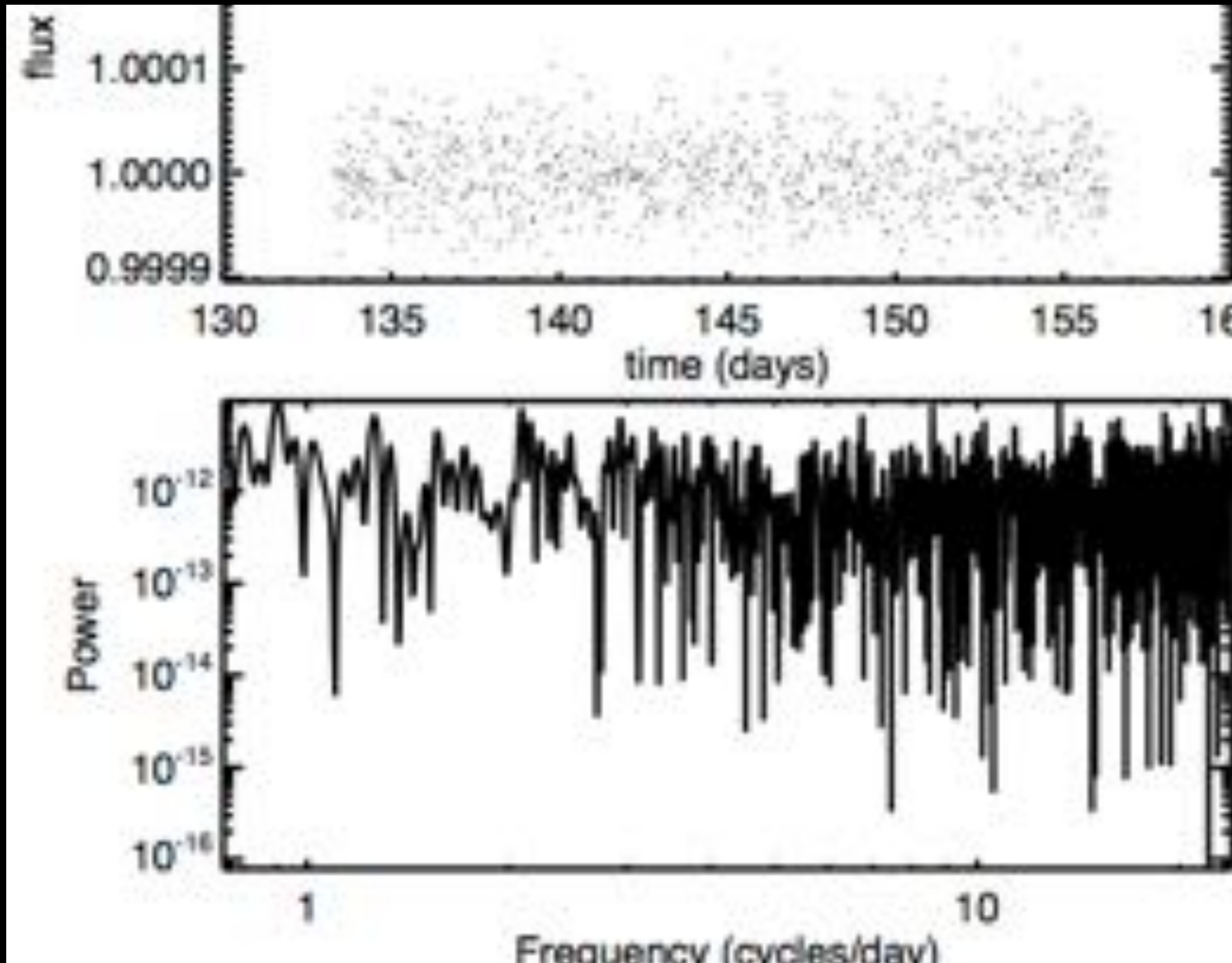


Noise properties of Sun-like *Kepler* stars

Sometimes white-noise dominates

e.g., sun-like star KIC 12011630

σ_W=35±1 ppm

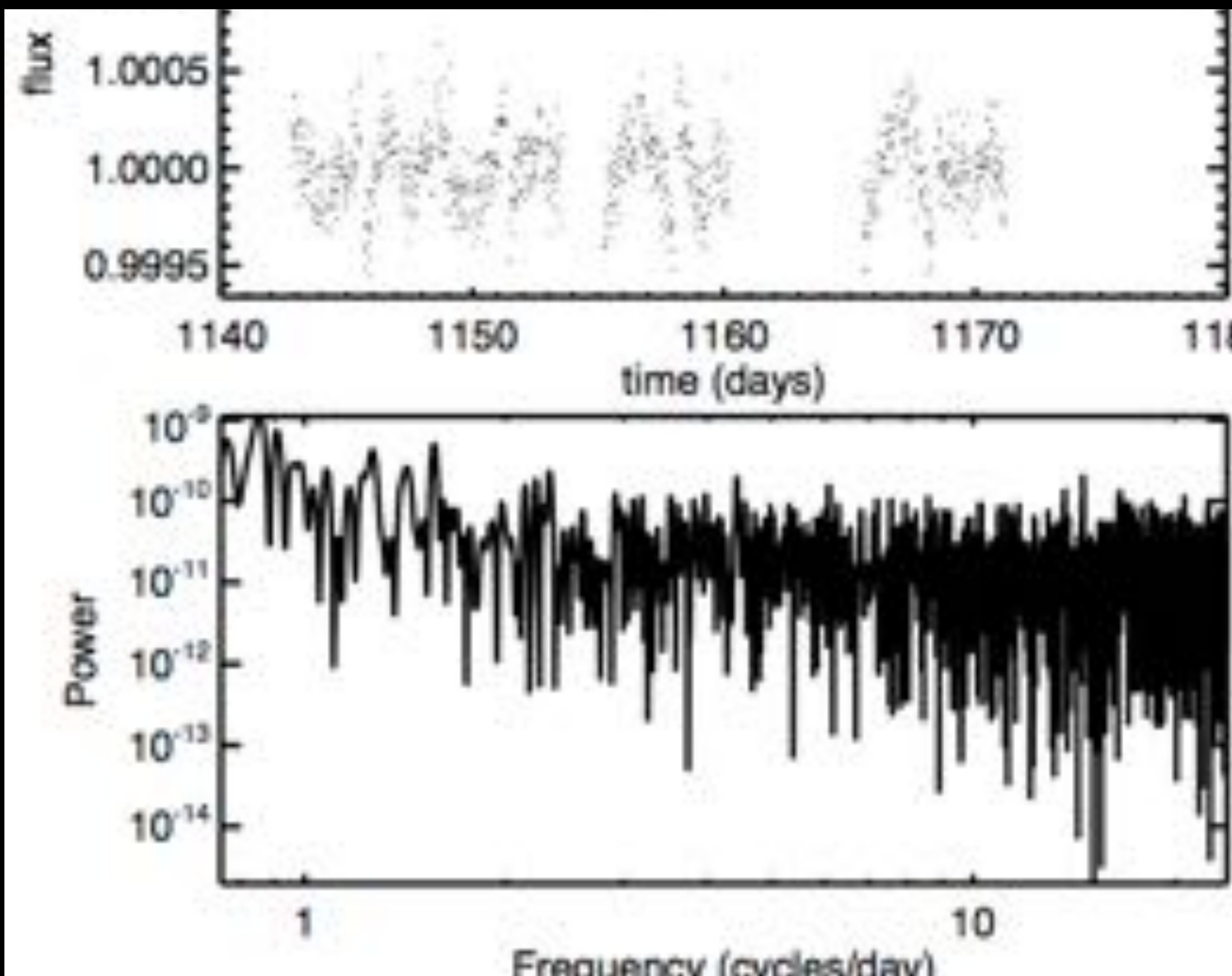


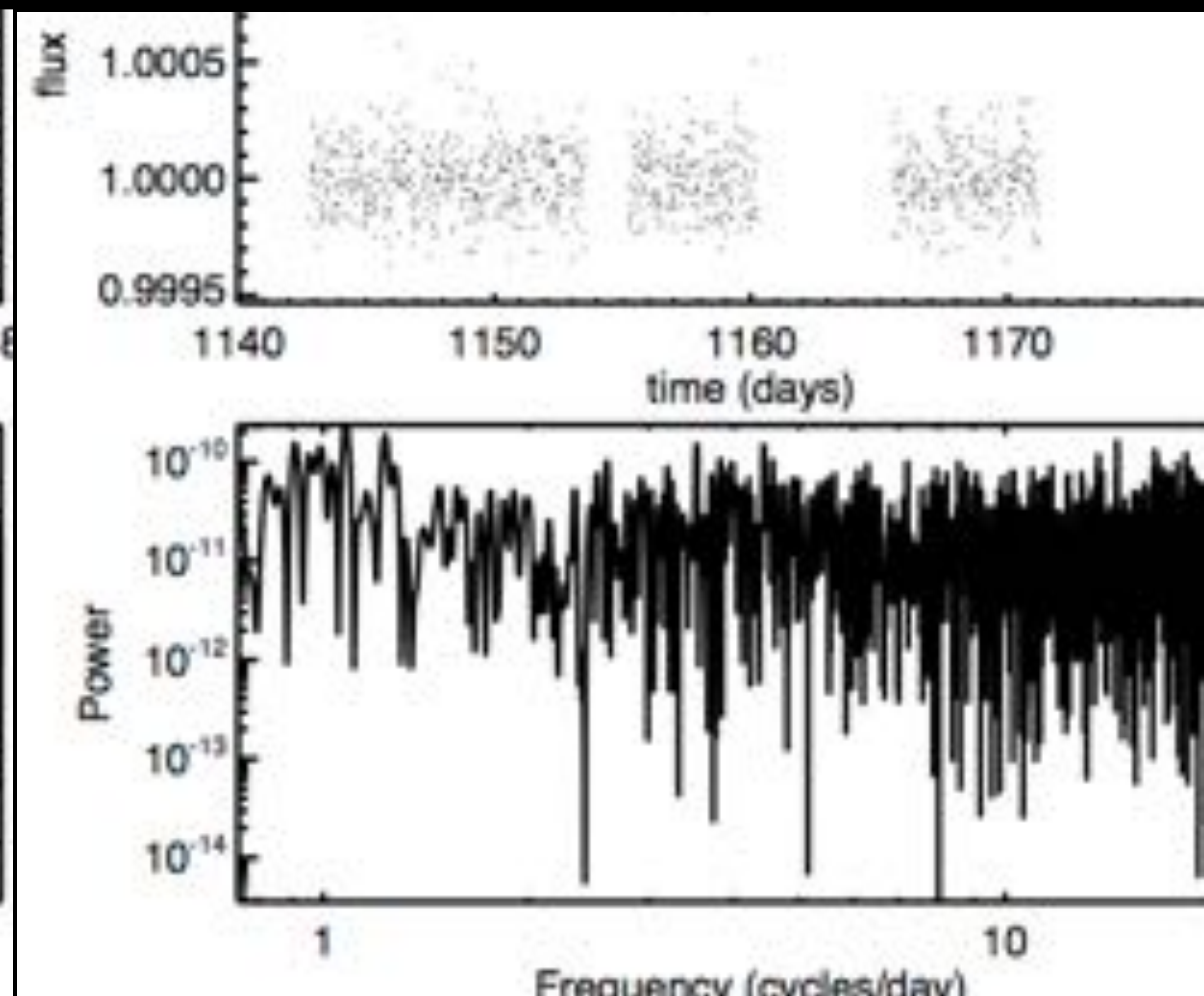
Simultaneous linear fitting: sometimes sufficient

e.g., sun-like star KIC 8374139

σ_W=106±8 ppm,
σ_r=700±40 ppm

σ_W=150±5 ppm



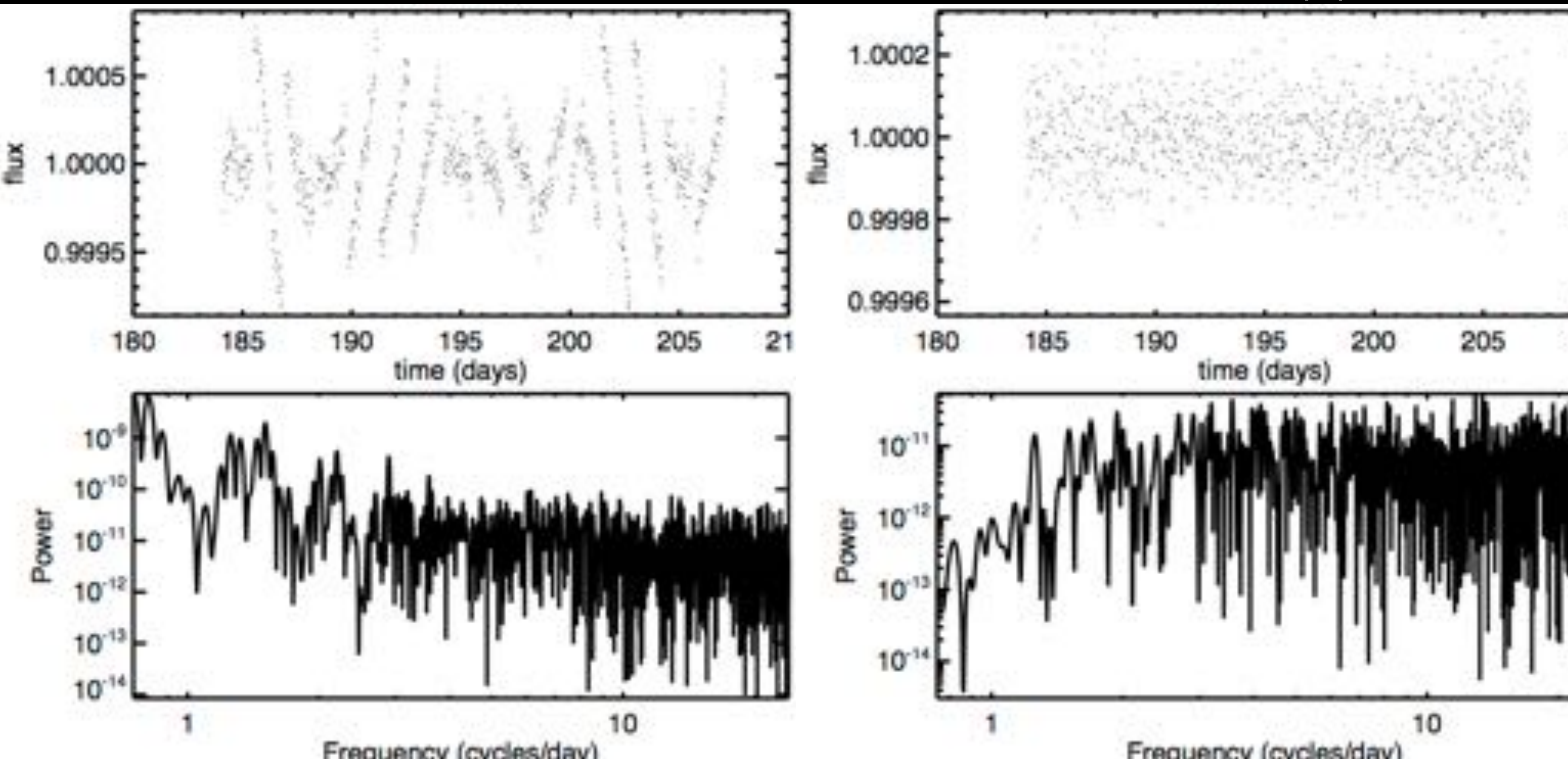


Simultaneous polynomial fitting: sometimes sufficient

e.g., sun-like star KIC 3970397

σ_W=88±2 ppm, σ_r=53±5 ppm

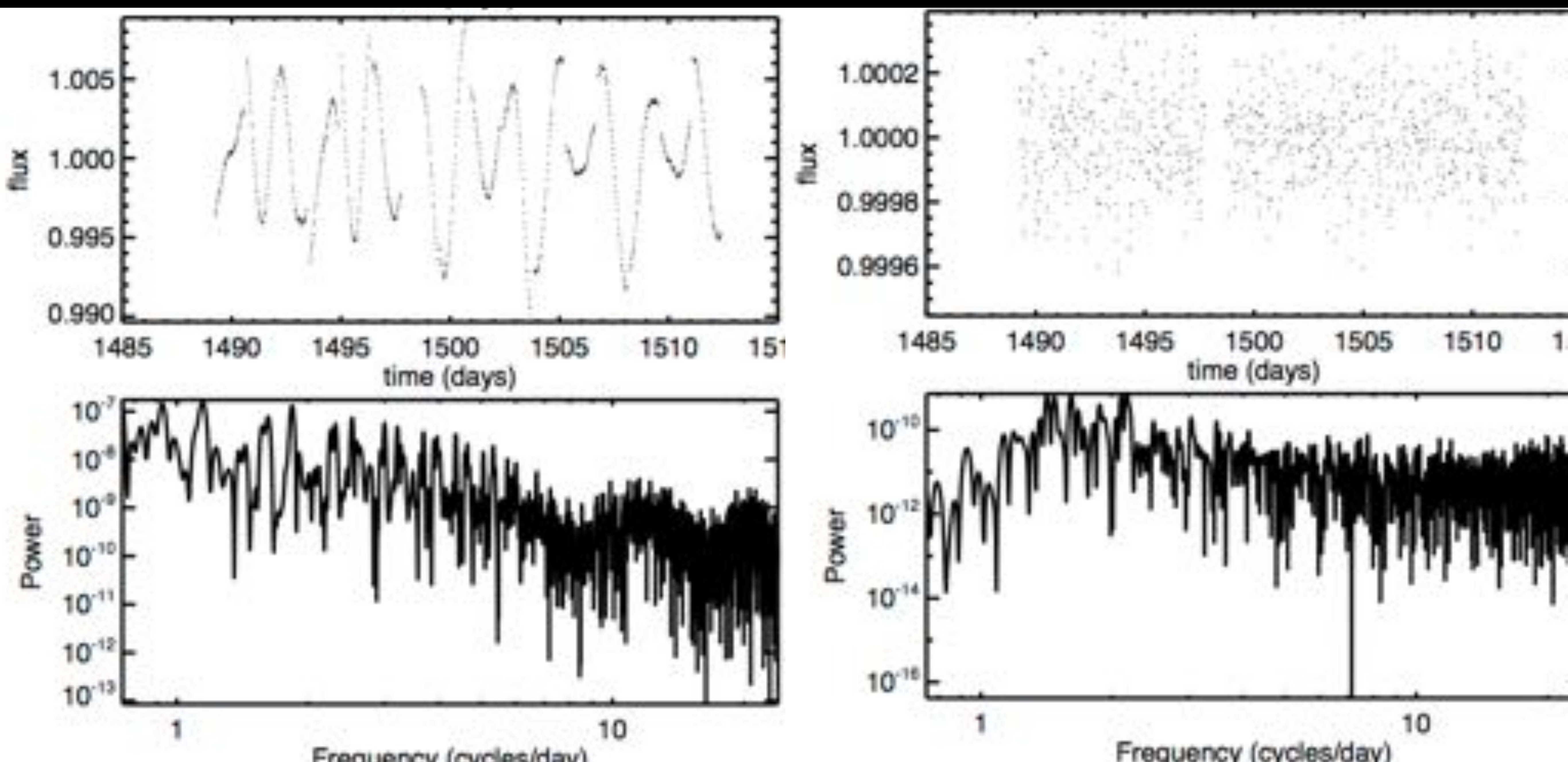
σ_W=86±3 ppm



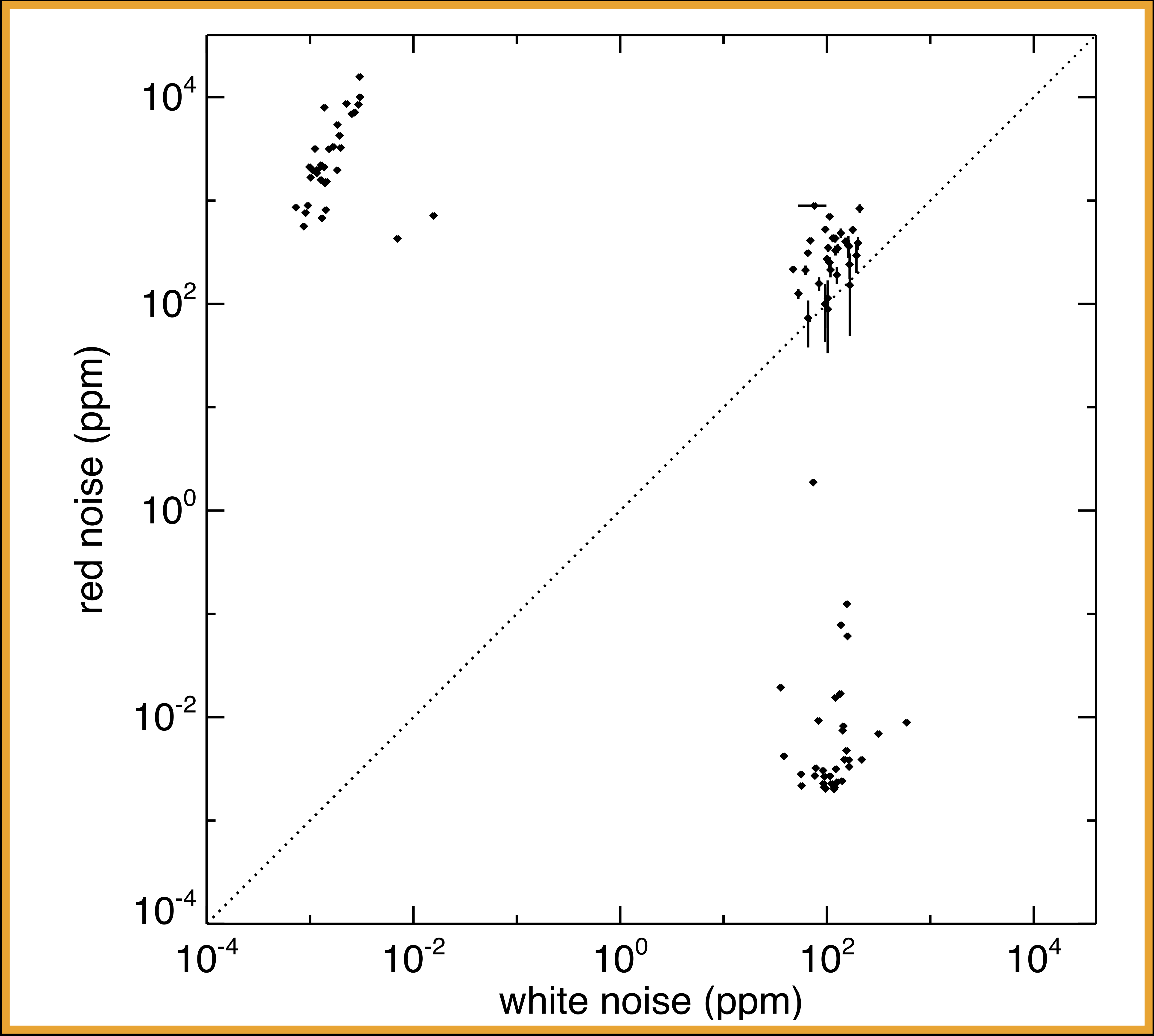
Simultaneous polynomial fitting: sometimes insufficient

e.g., sun-like star KIC 4819602

σ_W=0±10 ppm, σ_r=8799±200 ppm σ_W=64±8 ppm, σ_r=580±30 ppm

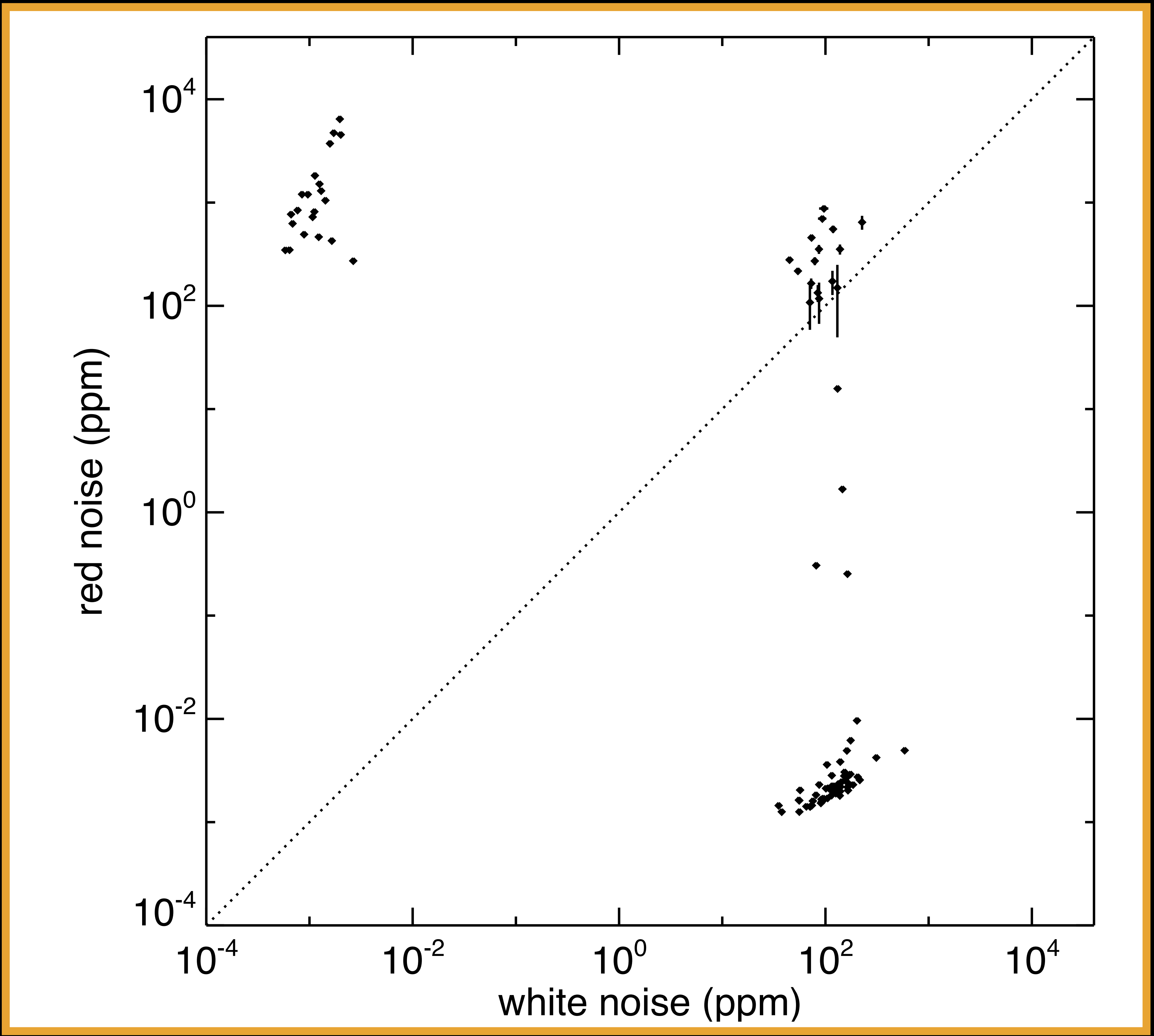


Kepler sun-like star properties: wavelet likelihood



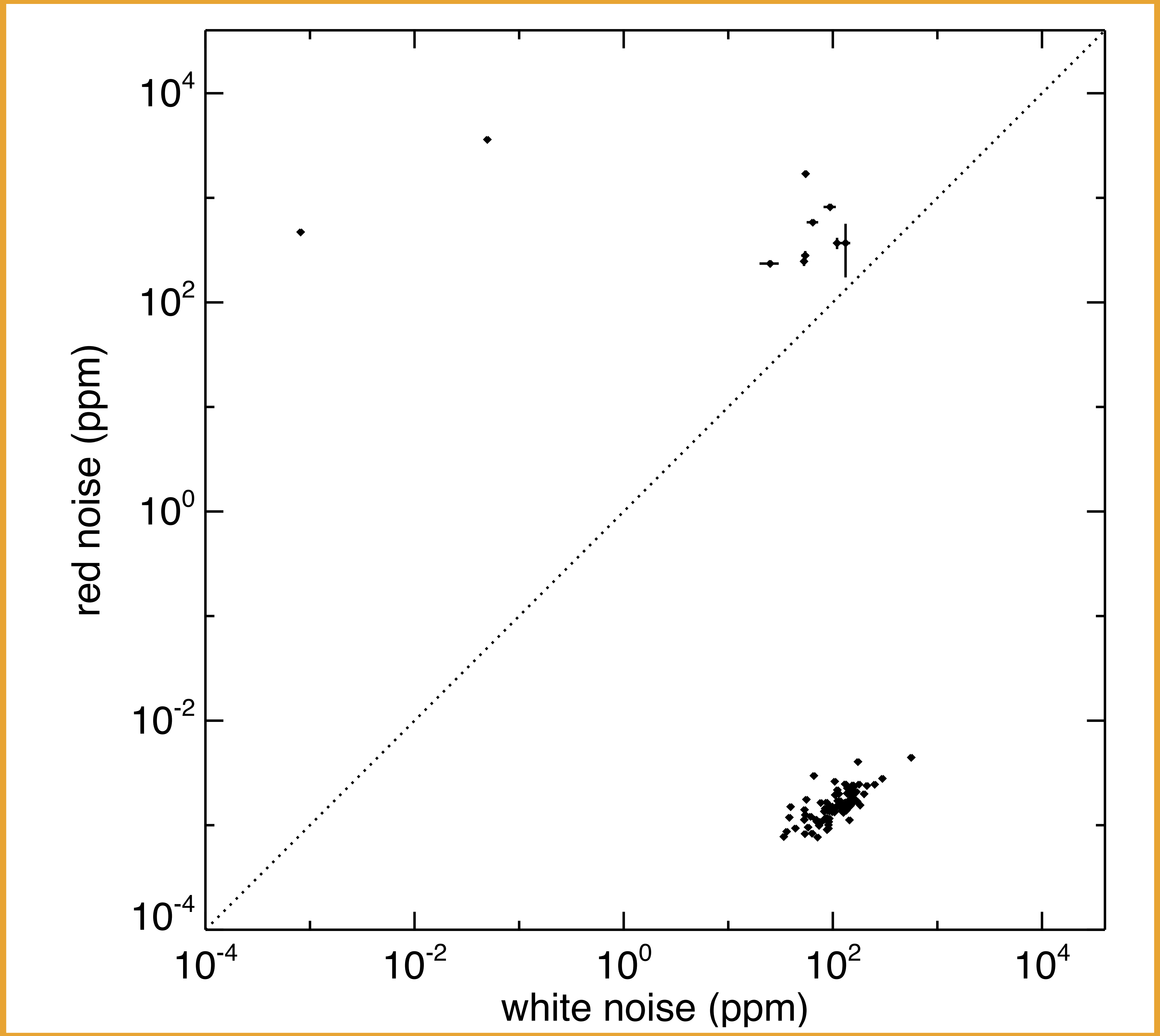
no polynomial

Kepler sun-like star properties: wavelet likelihood



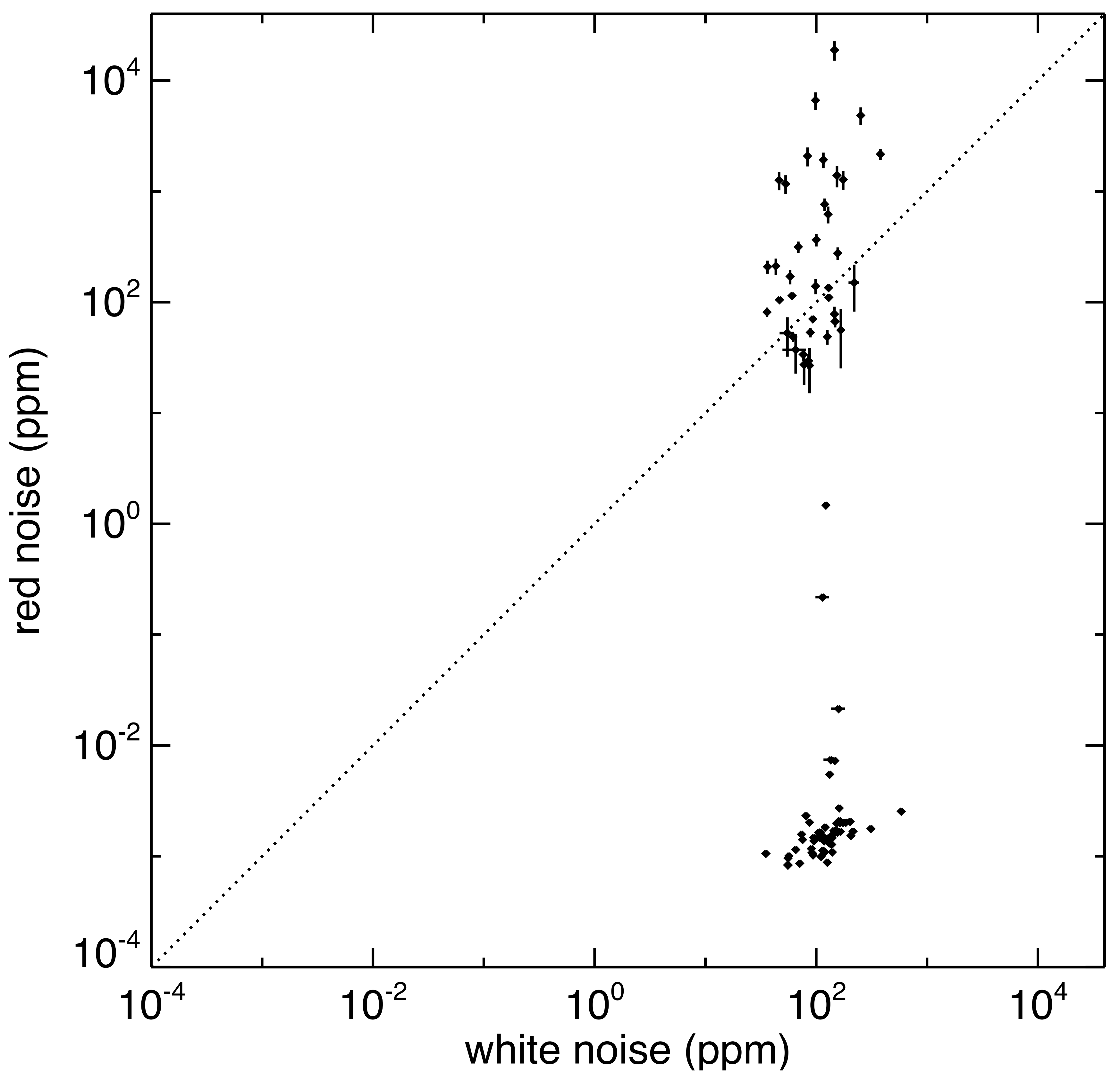
simultaneous line

Kepler sun-like star properties: wavelet likelihood



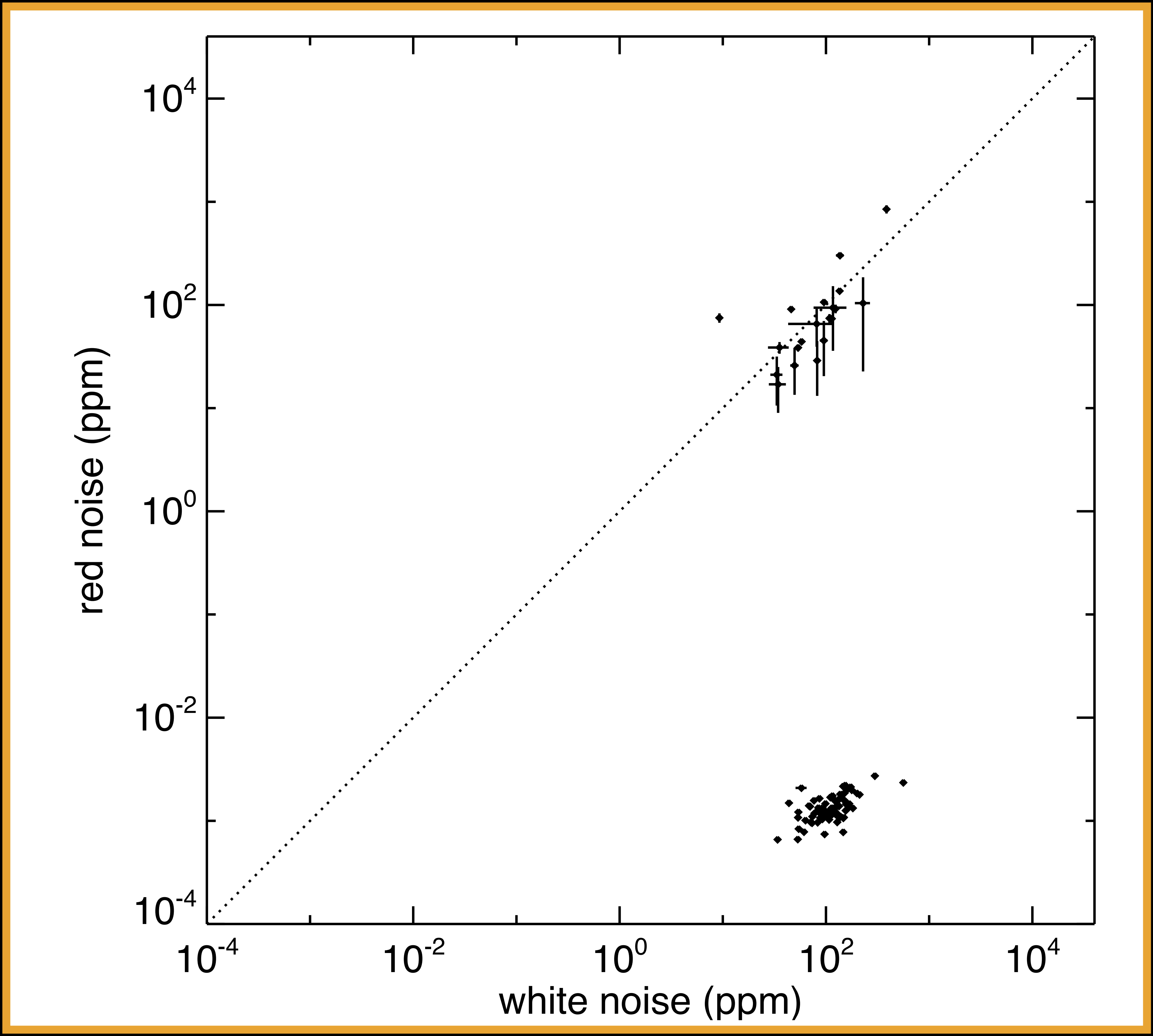
simultaneous polynomial

Kepler sun-like star properties: GPR likelihood



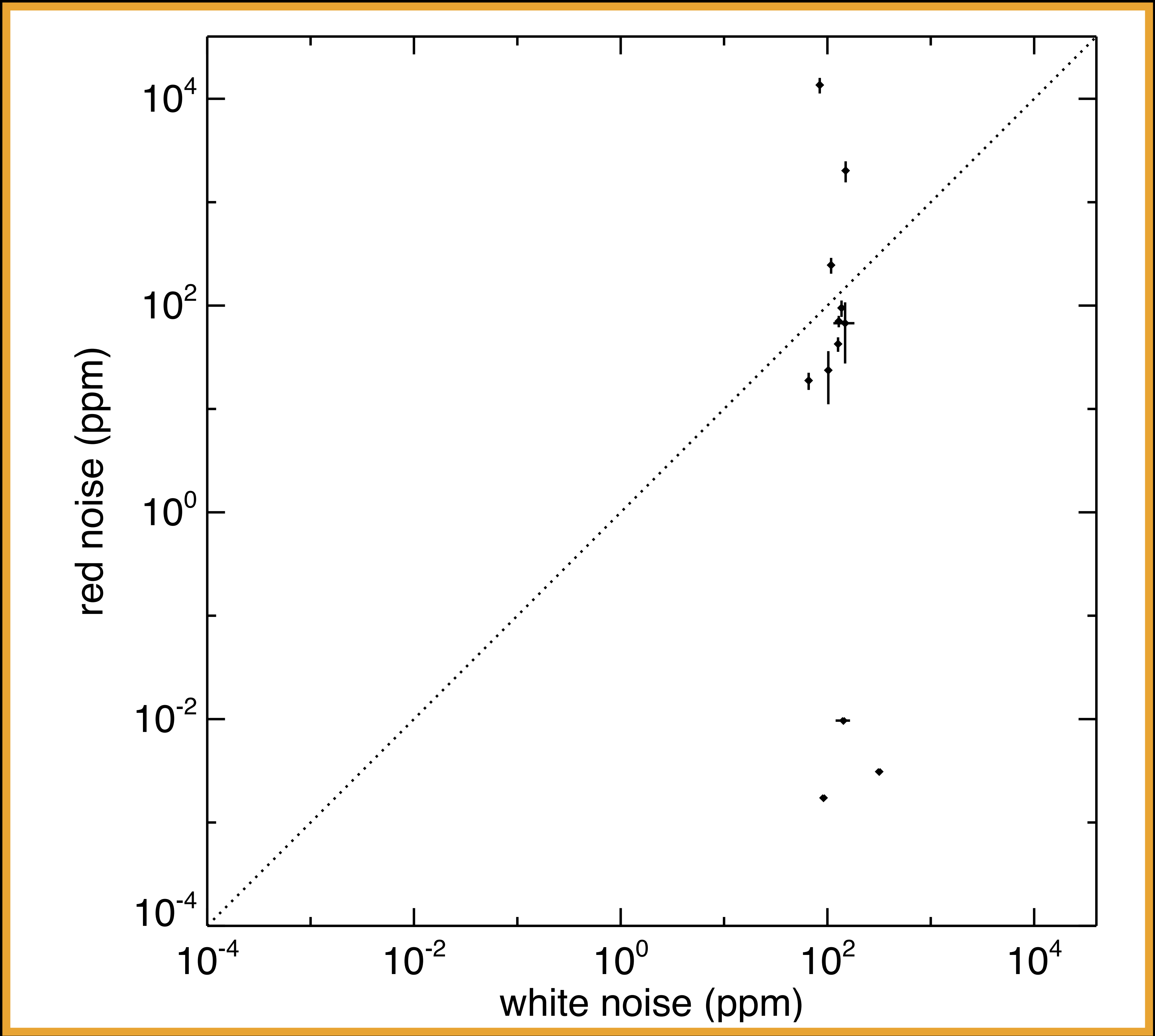
simultaneous line

Kepler sun-like star properties: GPR likelihood



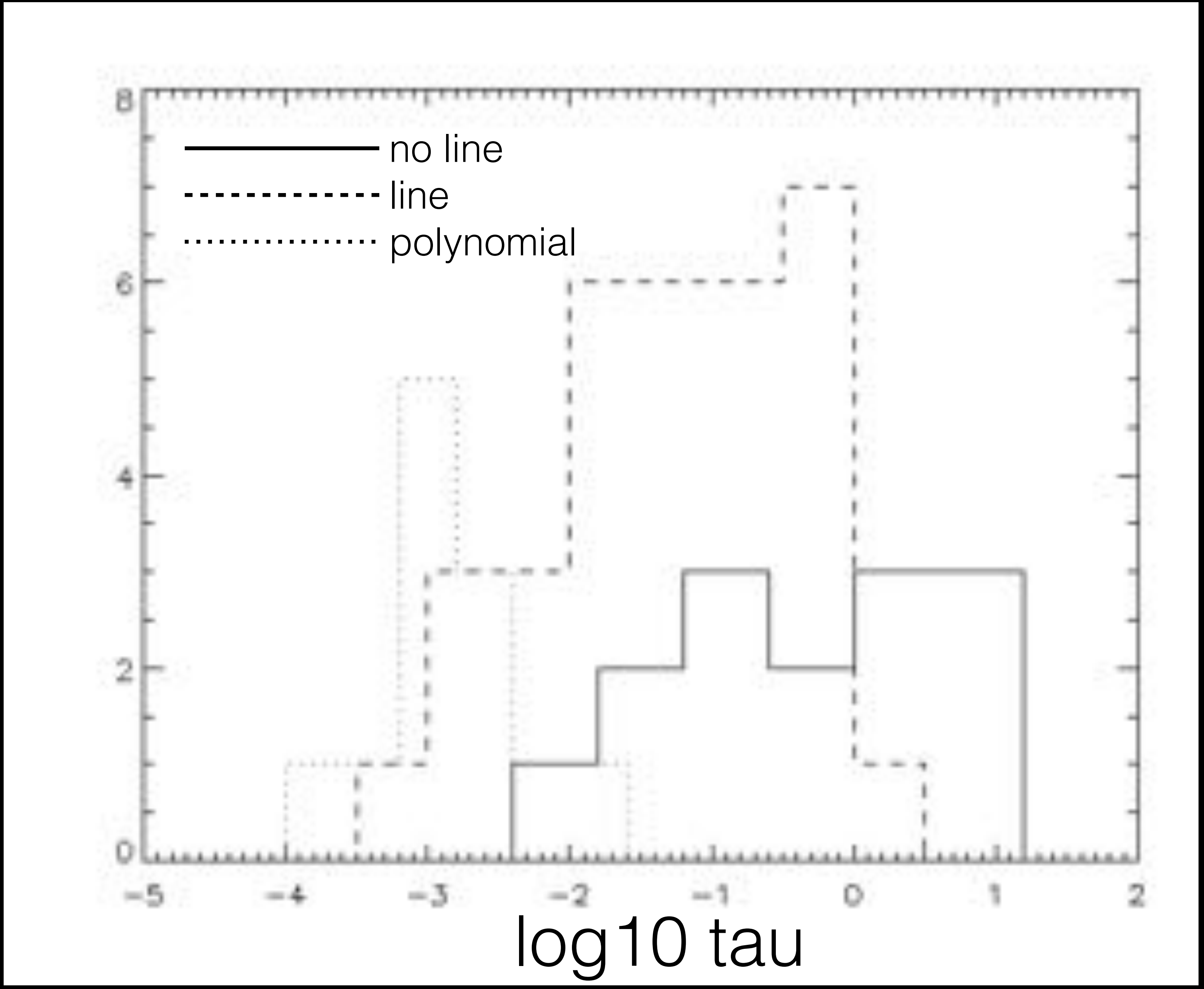
simultaneous polynomial

Kepler sun-like star properties: GPR likelihood



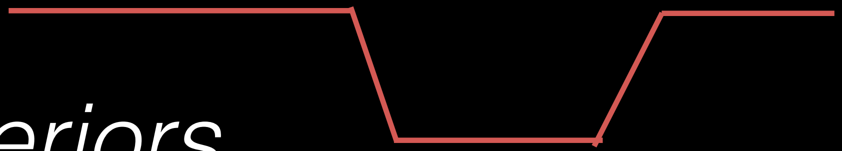
no polynomial

Kepler sun-like star properties: Gaussian process regression, timescale



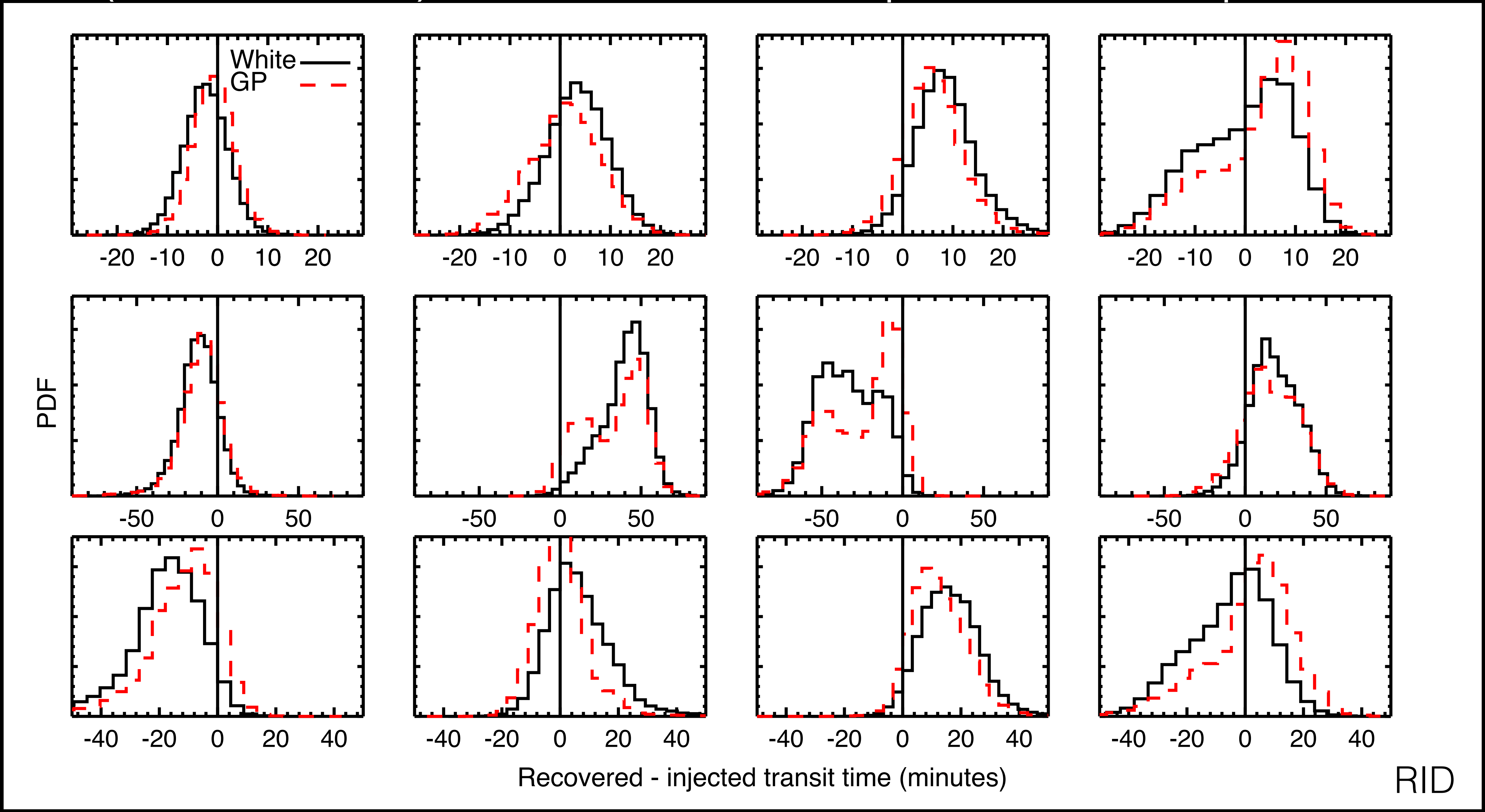
Correlated noise treatment: key questions

- Which stars merit a correlated noise treatment?
- How do we optimize the use of out-of-transit data to infer noise hyperparameters?
- Do wavelet likelihood functions or Gaussian process regression likelihood functions perform better? Which wavelet families and noise power law (wavelets) or kernels (GP regression) is best suited?
- What degree polynomial, if any, should be simultaneously fit to each data chunk?
- How do correlated noise treatments perform on short cadence data? (1 min vs. 30 min cadence)



Example transit time posteriors

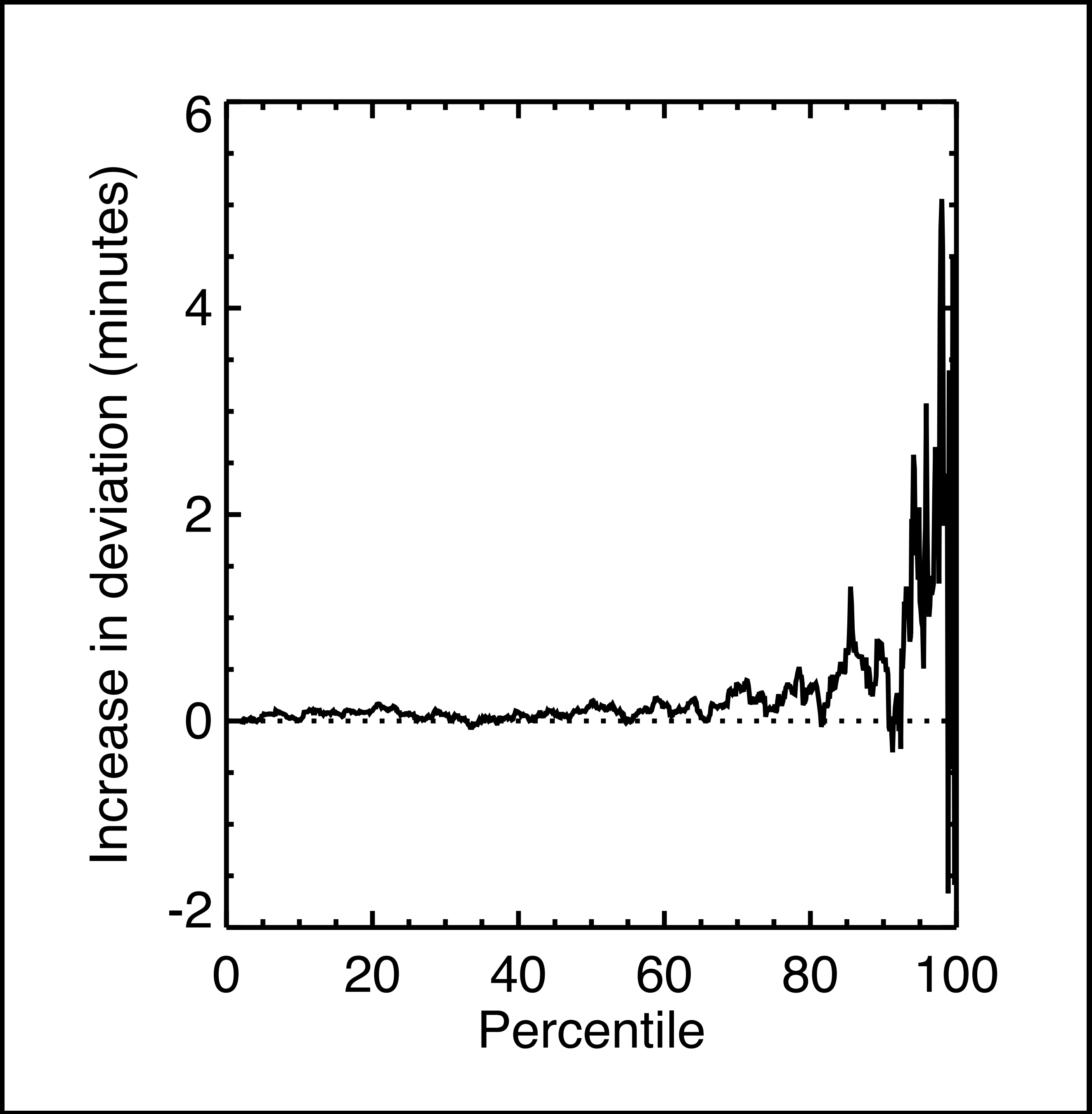
Better recovery when accounting for correlated noise (red dashed) and multi-modal posteriors captured



Model 1: Joint modeling of transits + line with white noise likelihood

Model 2: Joint modeling of transits + line with Gaussian process likelihood

Worse recovery when correlated noise is not accounted for in the likelihood

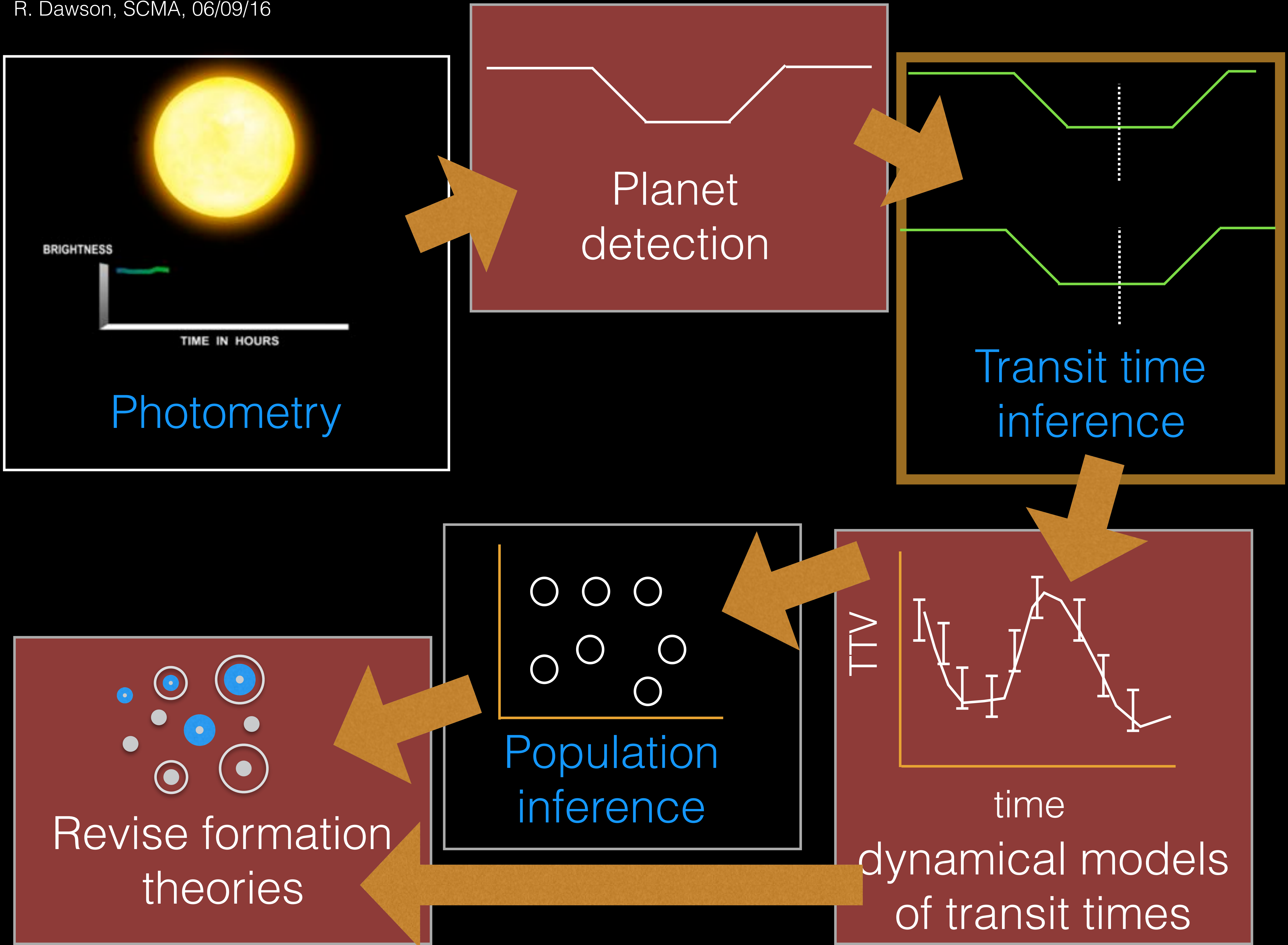


Based on fits to 50 sets of 16 injected transits for Sun-like star with significant correlated noise

Summary and future work

- Systematic study of correlated noise treatment for inferring transit times is underway; will only be relevant for subset of stars
- Correlated noise treatment needs to be assessed for its impact on other key transit observables, e.g., depth, duration
- Correlated noise is an even more severe problem for radial velocity method of planet detection and characterization, including interplay of noise and aliasing due to gaps in time sampling

R. Dawson, SCMA, 06/09/16



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Extra slides

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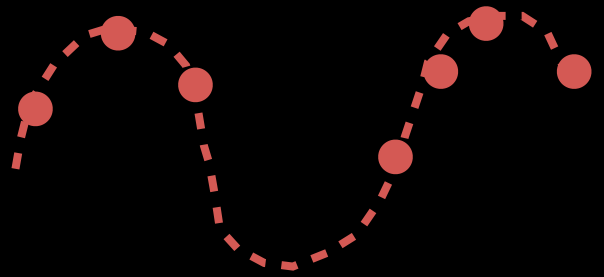
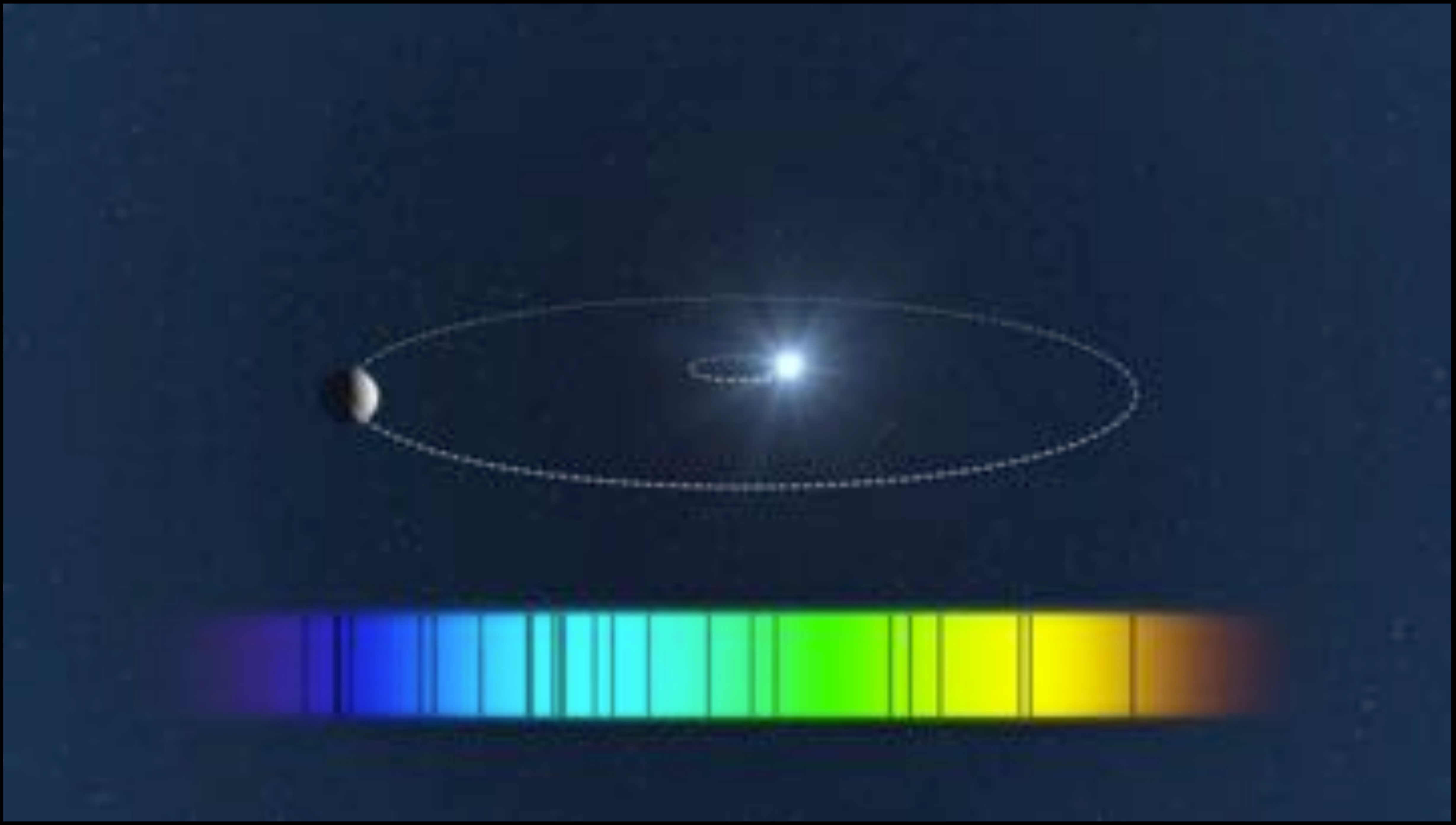
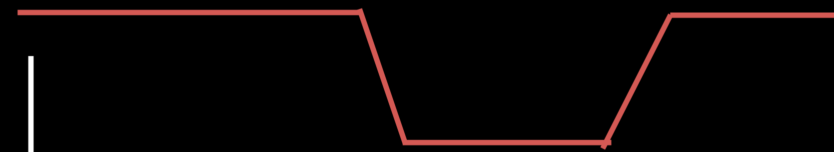
The radial-velocity technique

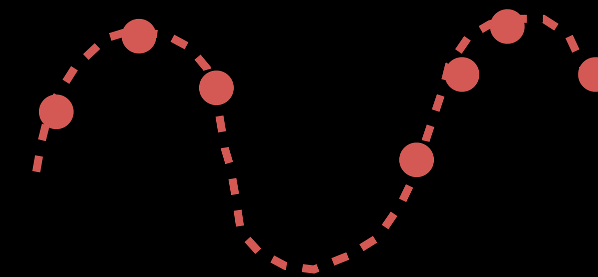




Earth twin: 10 cm/s

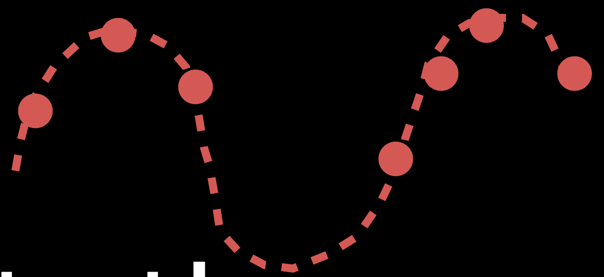
Image Credit: ESO/L. Calçada





Transit vs. radial-velocity challenges	**Transit (mostly space)**	**Radial-velocity (ground)**
Planet duty cycle	Low (0.3% for Earth twin)	100% (but 0% for other line diagnostics)
A priori planet probability	Low (~few percent)	High (≥~50%)
Datapoints	~100,000 or more	~100
Signal repetition	Detectable changes in period, duration	Undetectable for most planets
Time sampling	Even, continuous	Uneven, gaps

Time sampling complicates RV interpretation



55 Cnc e

One of first mini-Neptunes discovered

GJ 581d

Habitable zone super-Earth

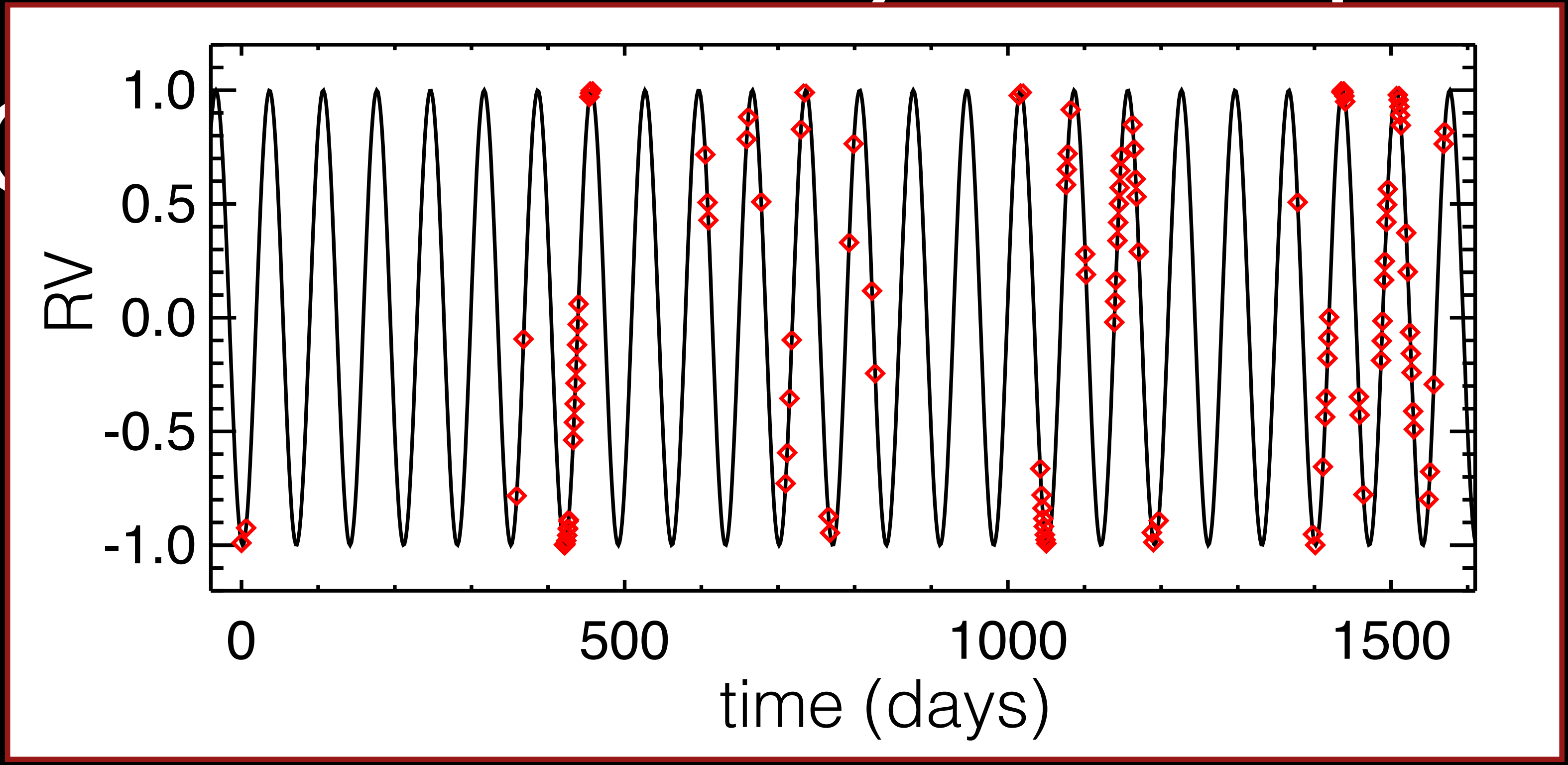
Alpha Cen b

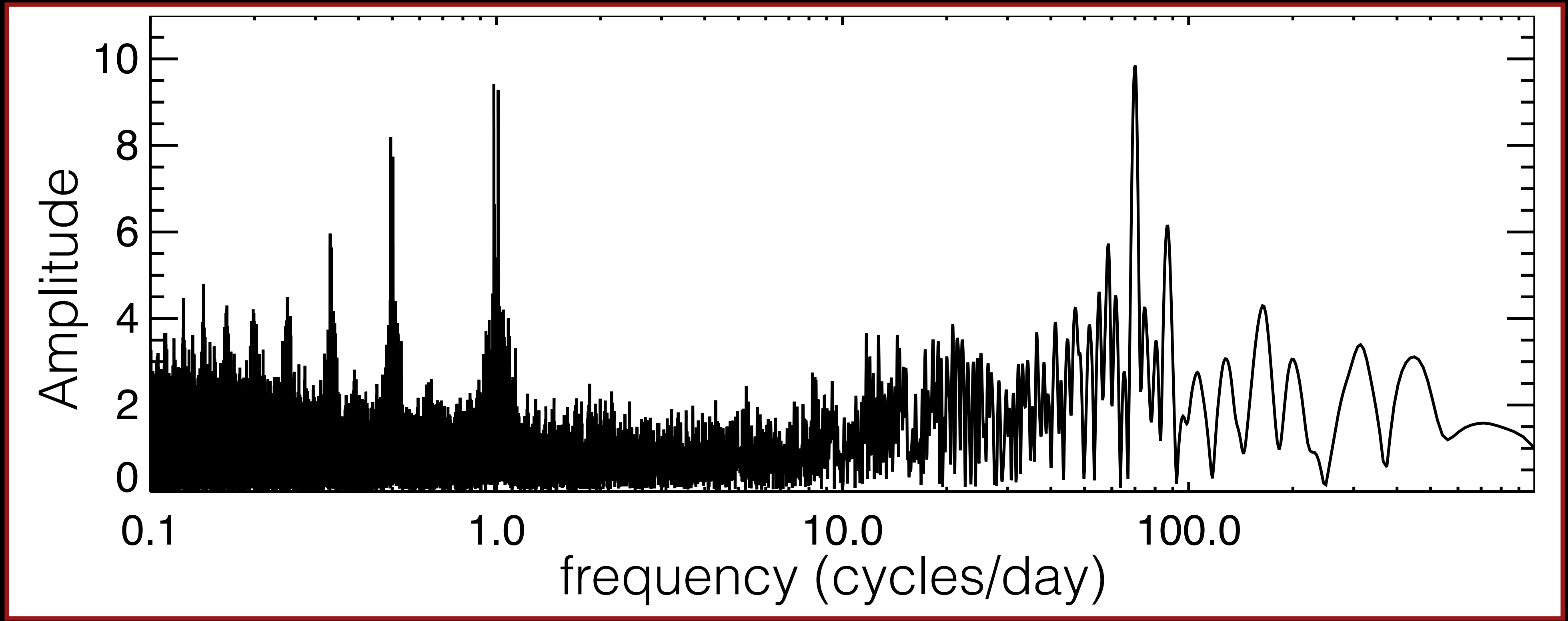
Orbits nearby star

R. Dawson, SCMA, 06/09/16

Radial velocity sampling

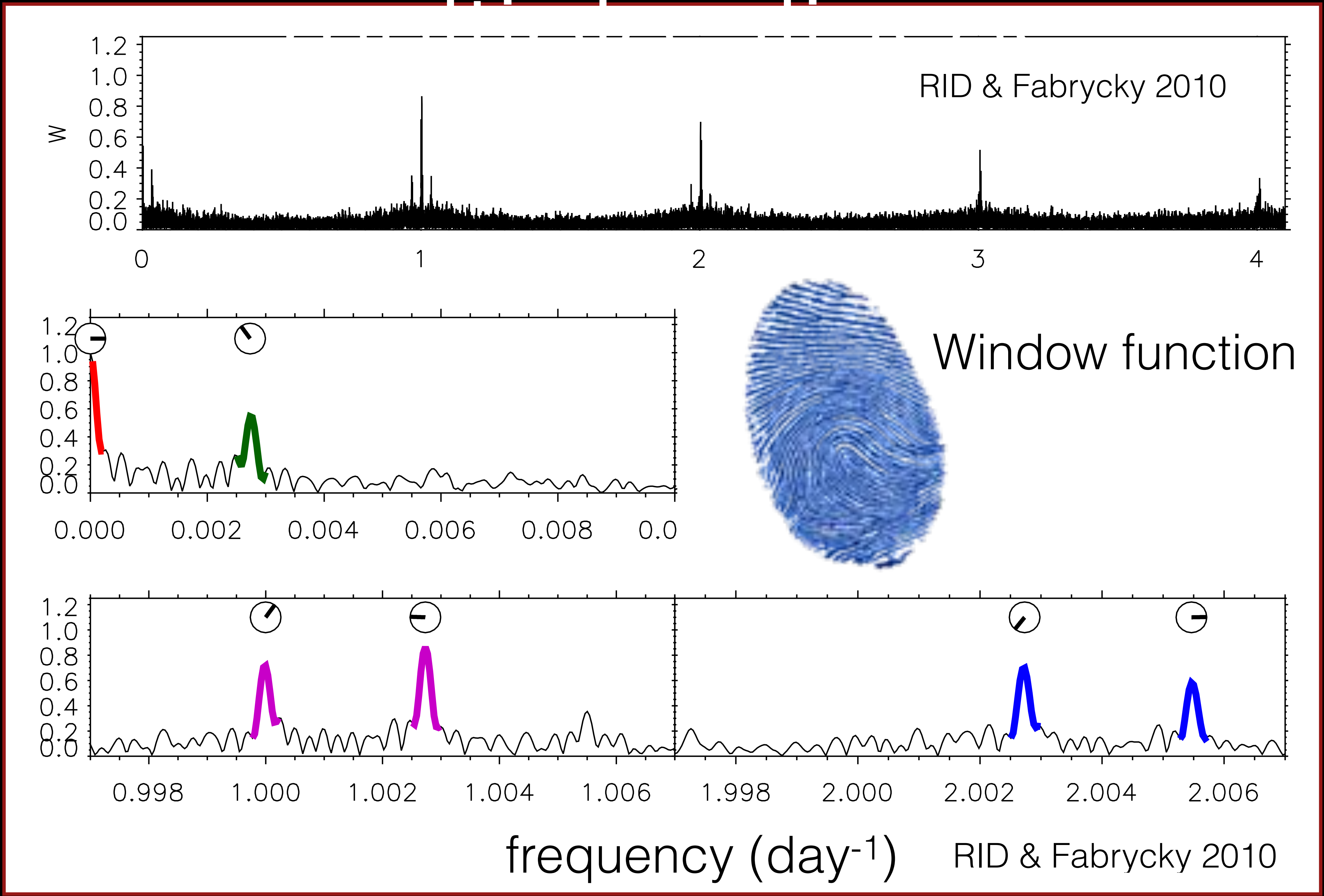
Noise-free sinusoid with Gl 581 HARPS sampling





$$f_{alias} = | f_{true} \pm f_{sample} |$$

Use the fingerprint of

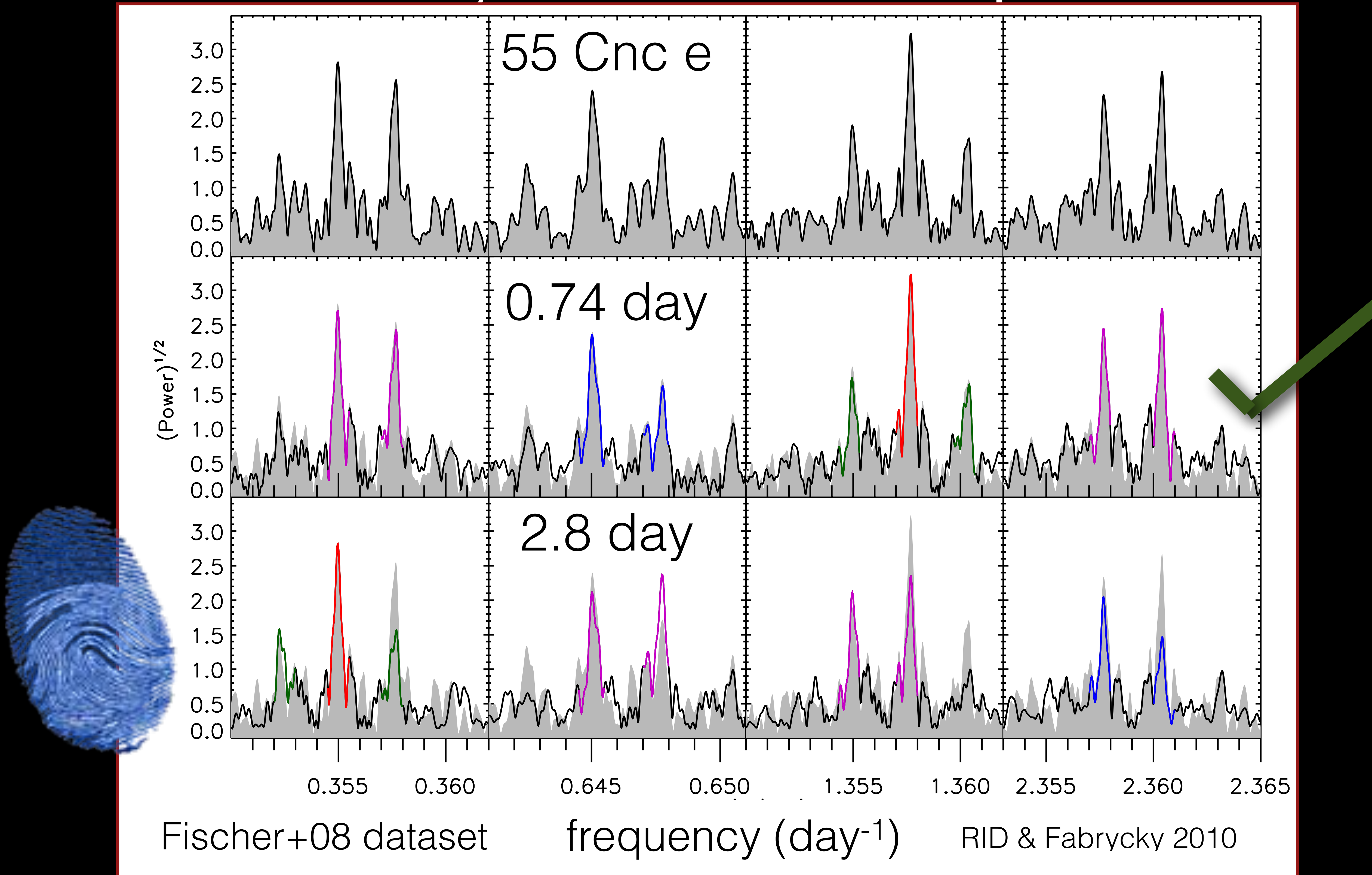


Fischer+08 dataset

$$f_{alias} = | f_{true} \pm f_{sample} |$$

55 Cnc

A revised, ultra-short period



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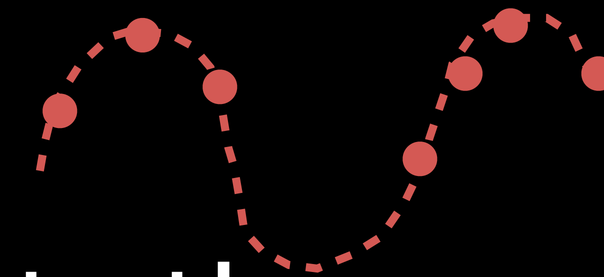
Time sampling complicates RV interpretation



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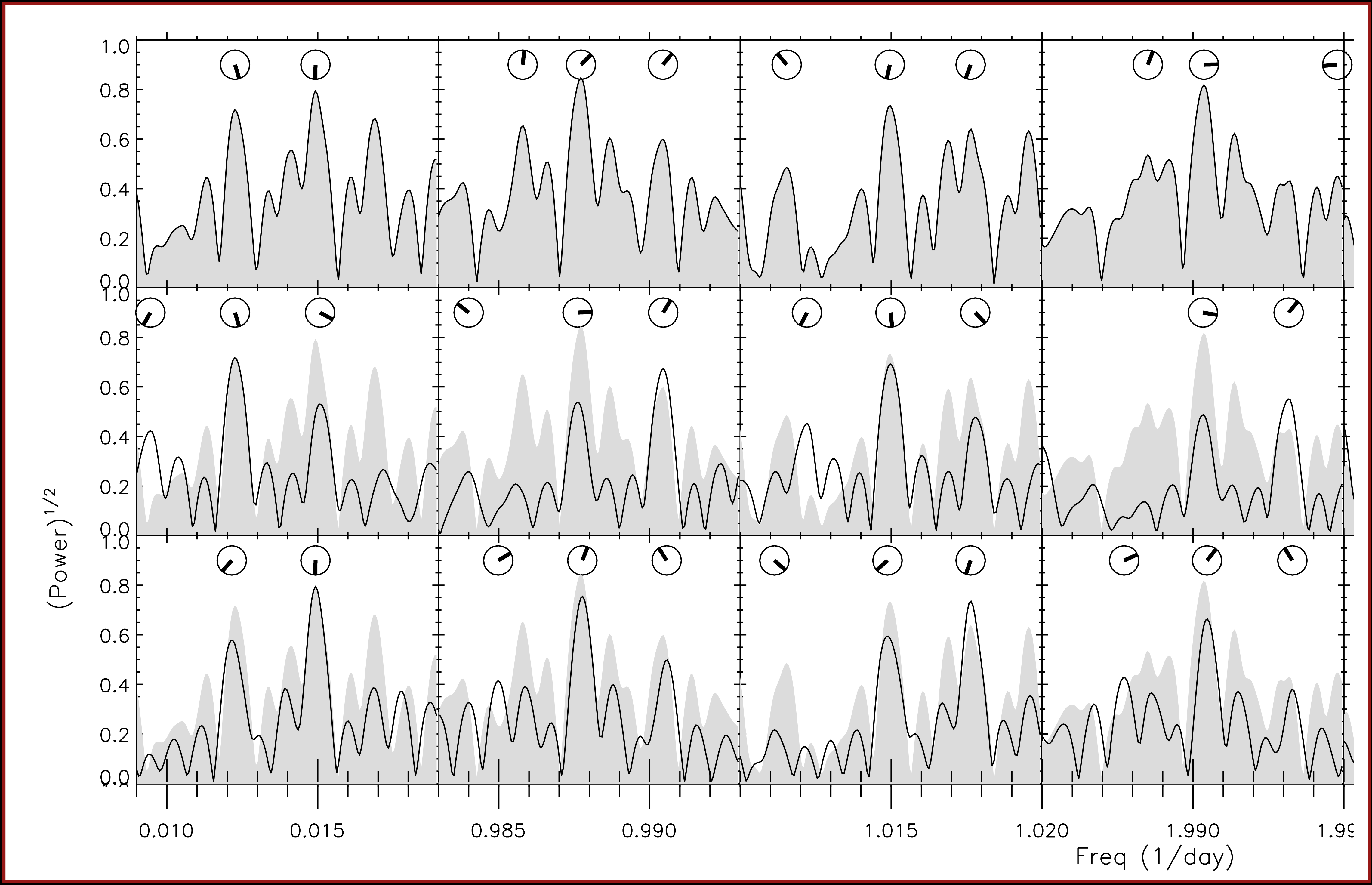
Gl 581 d: alias ambiguity

Udry: 07:
P = 84 days

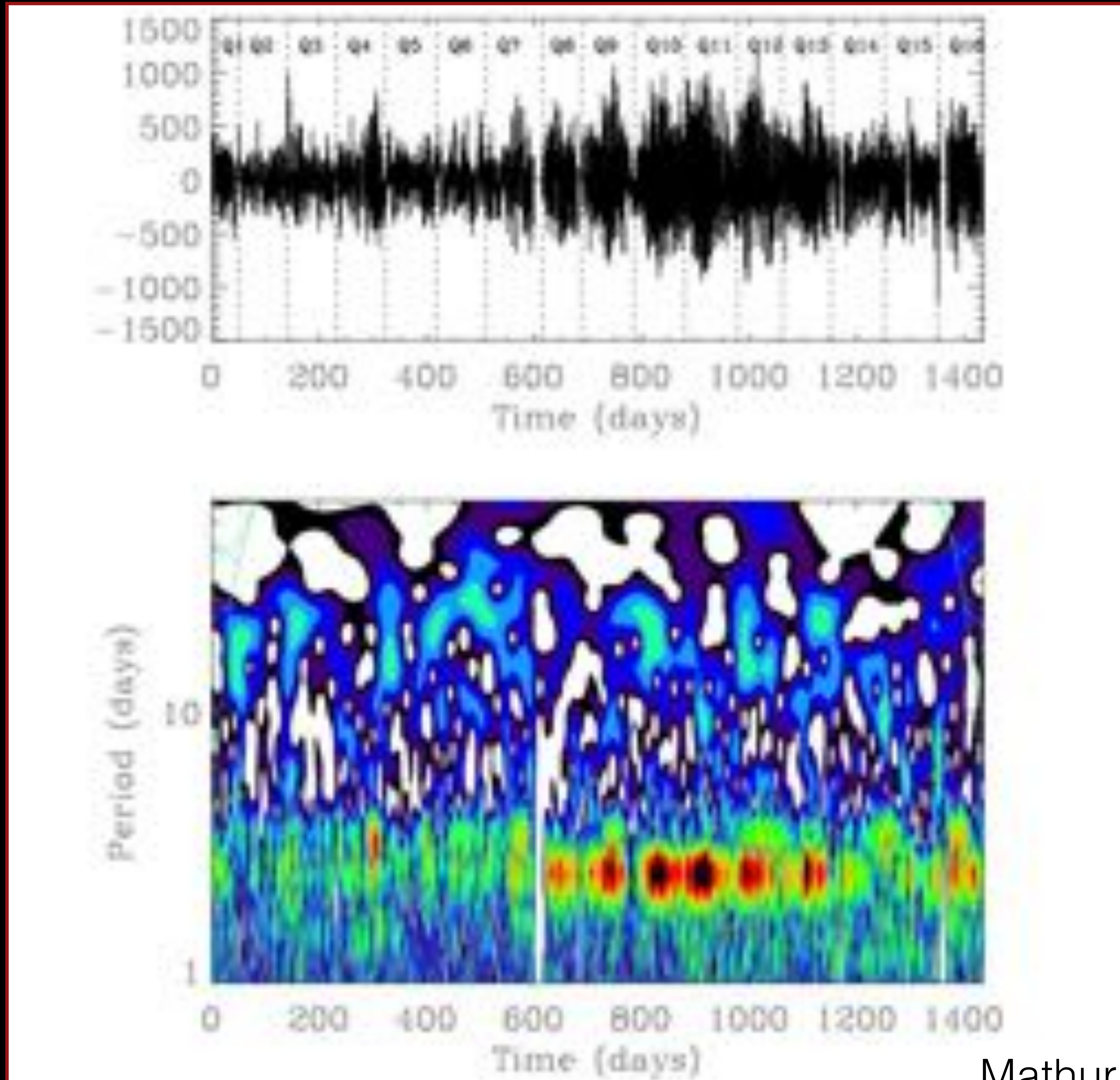
Mayor+ 09:
P = 67 days

RID & Fabrycky 10:
P = ?

Robertson+ 14:
Stellar activity



Stellar activity: a stochastic, quasi-periodic signal



Mathur+ 14

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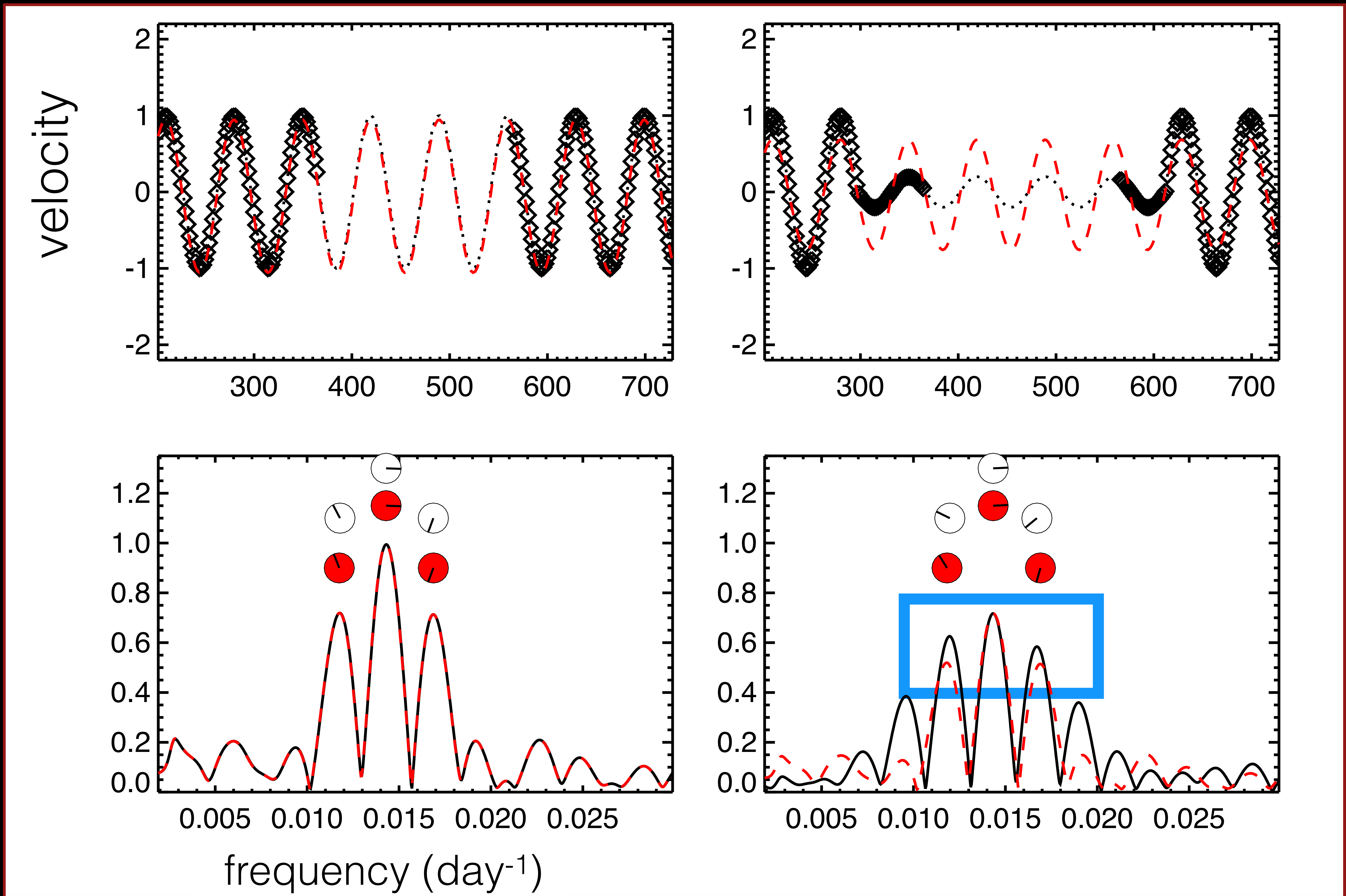
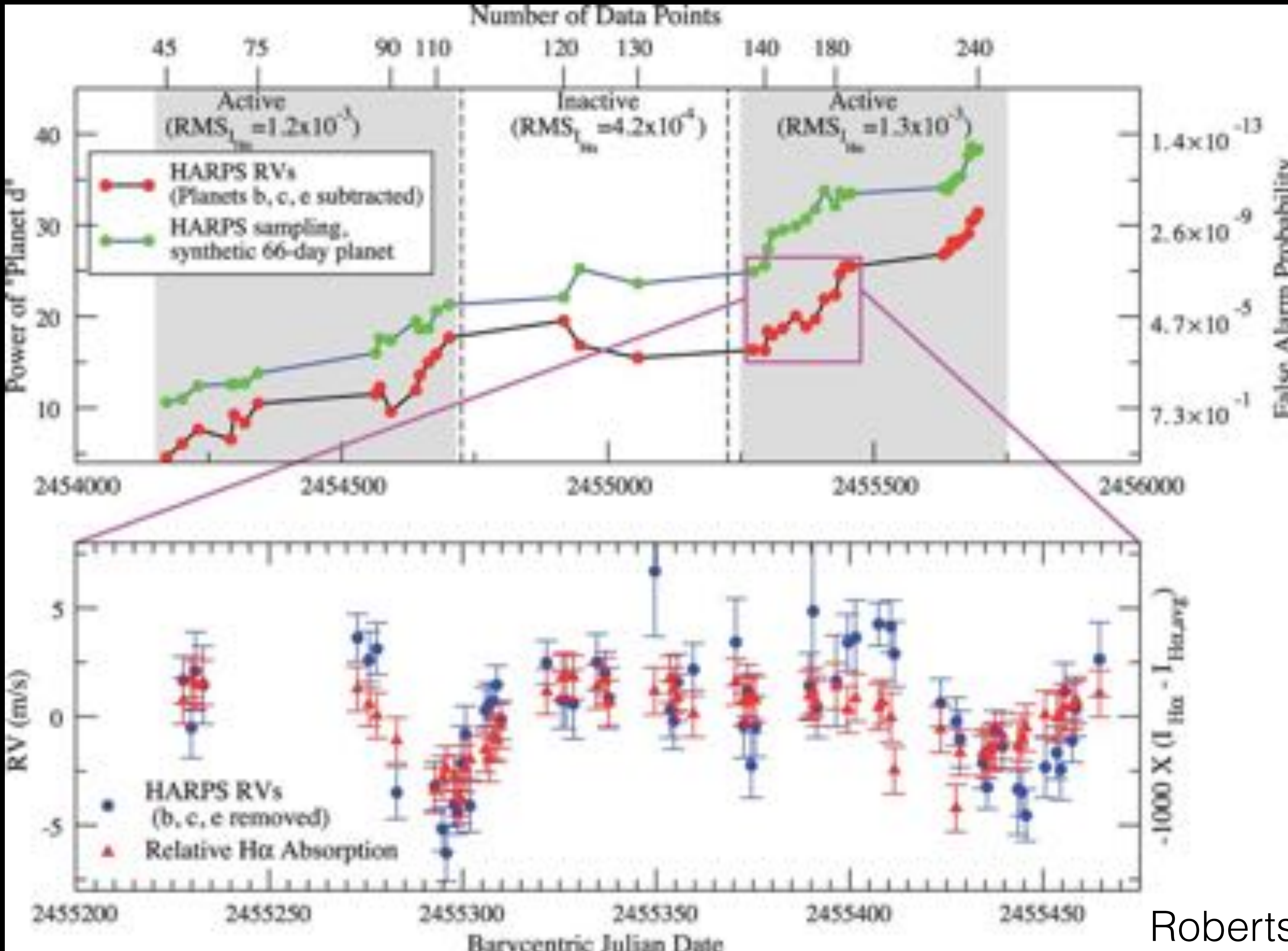
Aliasing and activity cycles



Less time sampling during inactive cycle

Gl 581



Robertson+ 14

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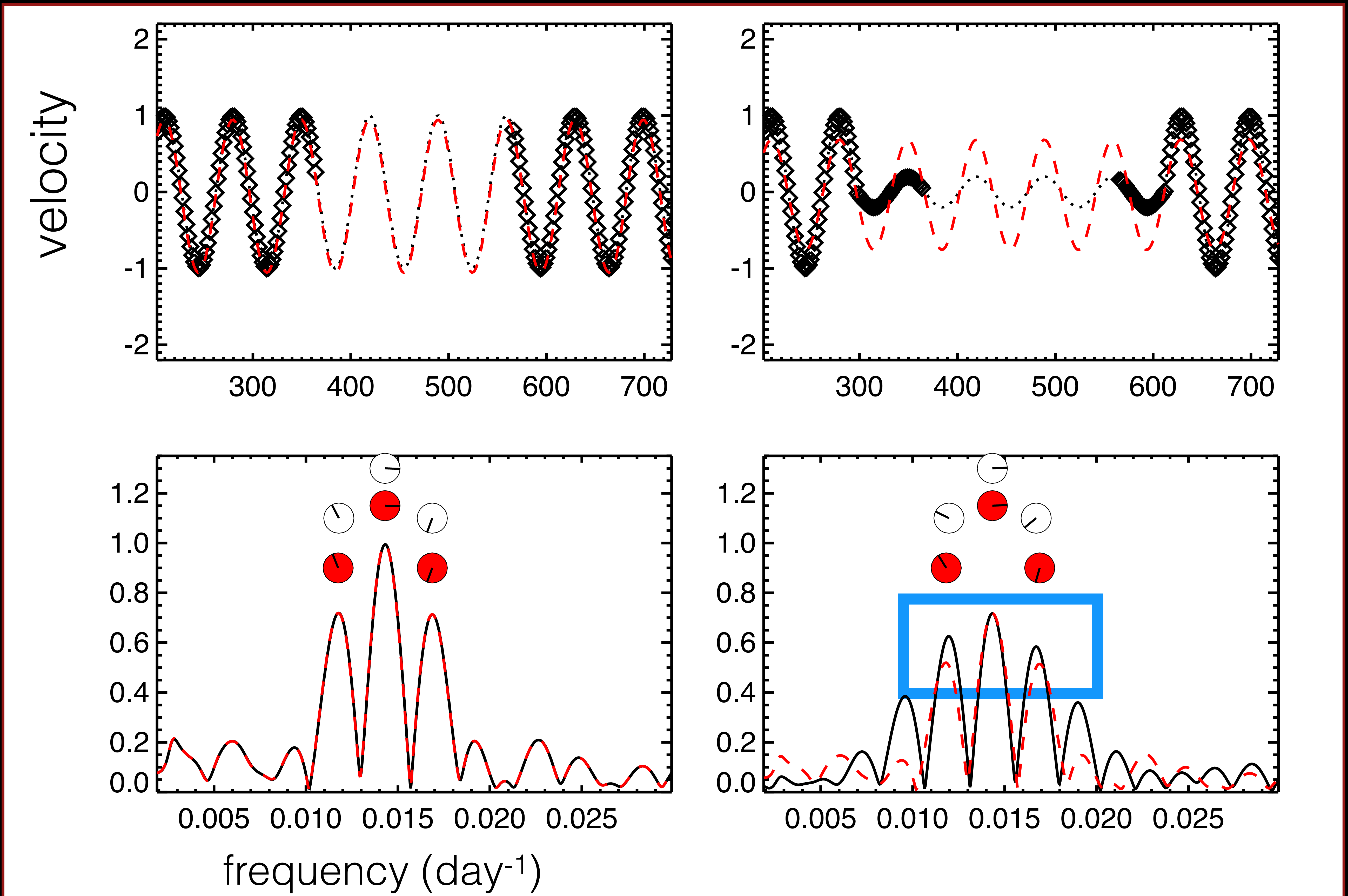
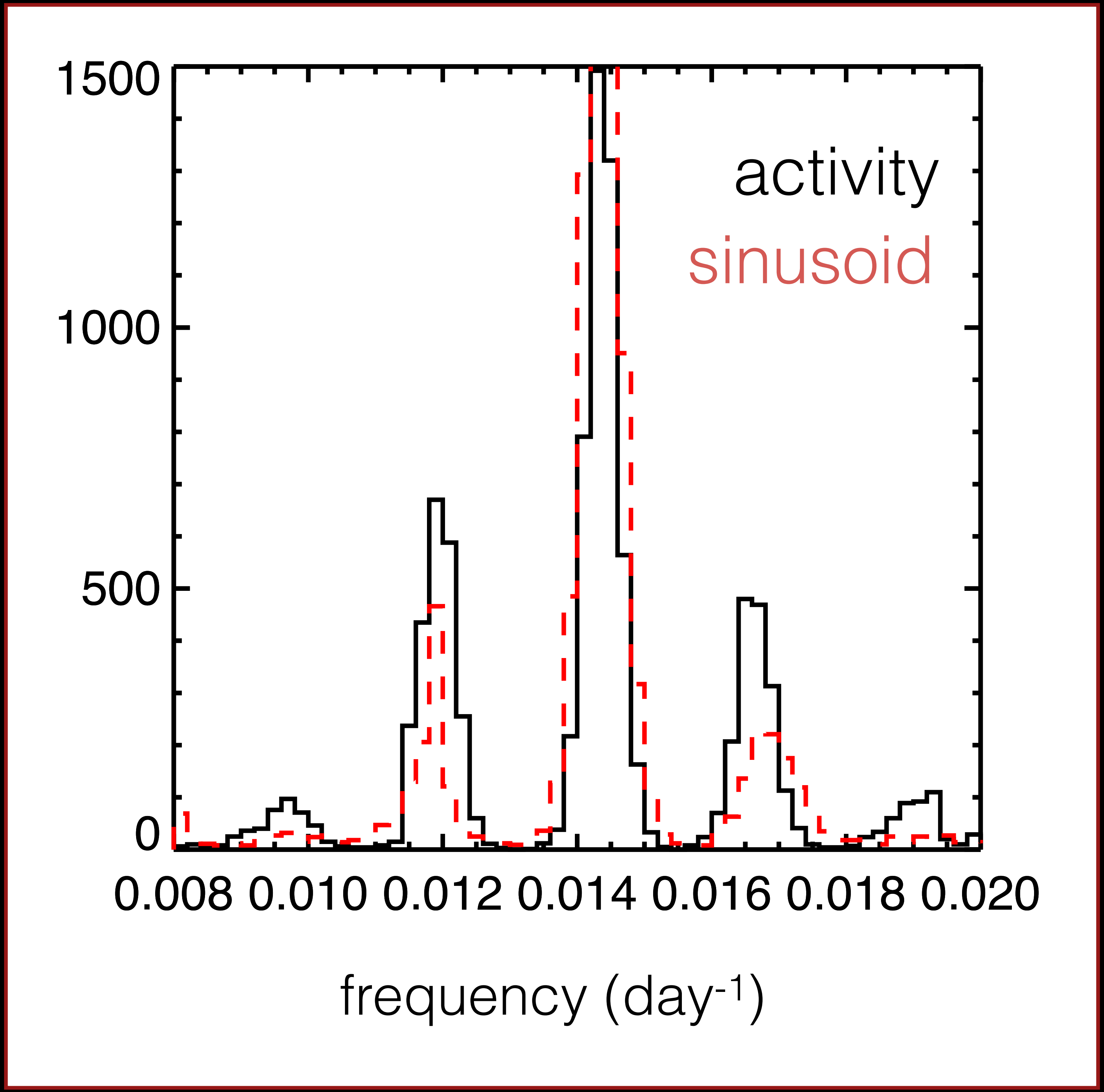


Stellar activity signal experiences extra aliasing when activity is low during sampling gap



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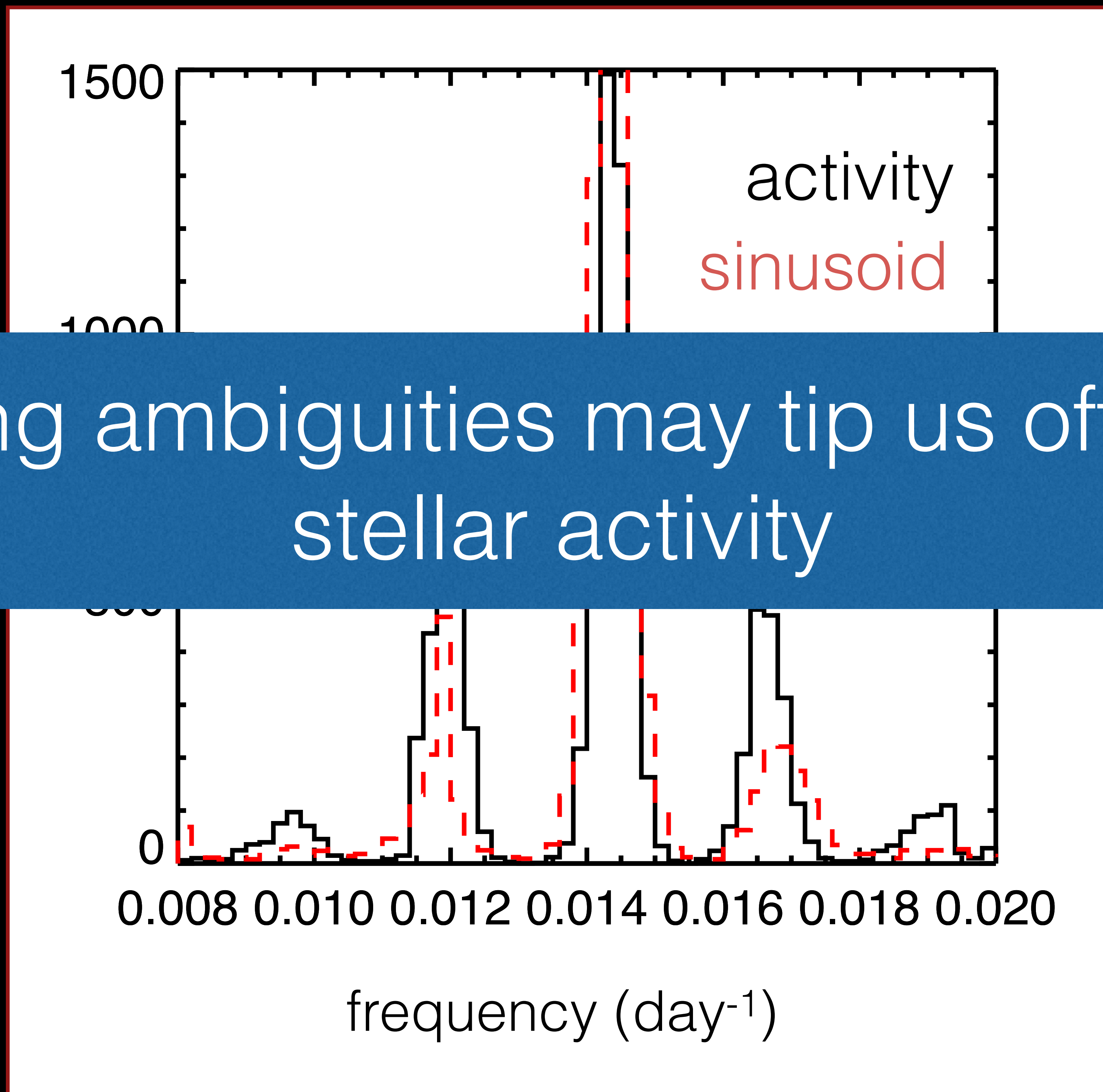
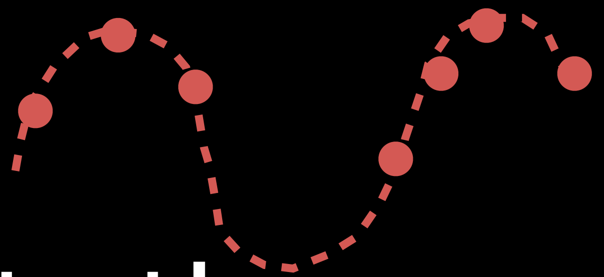


Aliasing ambiguities may tip us off about stellar activity

Time sampling complicates RV interpretation



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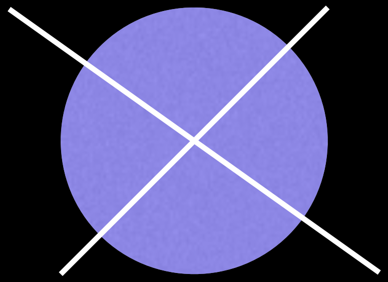
Alpha Cen b: the danger of pre-whitening

Dumusque+ 12:
1) detrend
2) fit planet parameters
3) check for aliasing



Rajpaul+15, 16
1) notice planet frequency in the window function
2) account for stellar activity simultaneous with orbit fitting with Gaussian processes

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long-term activity!