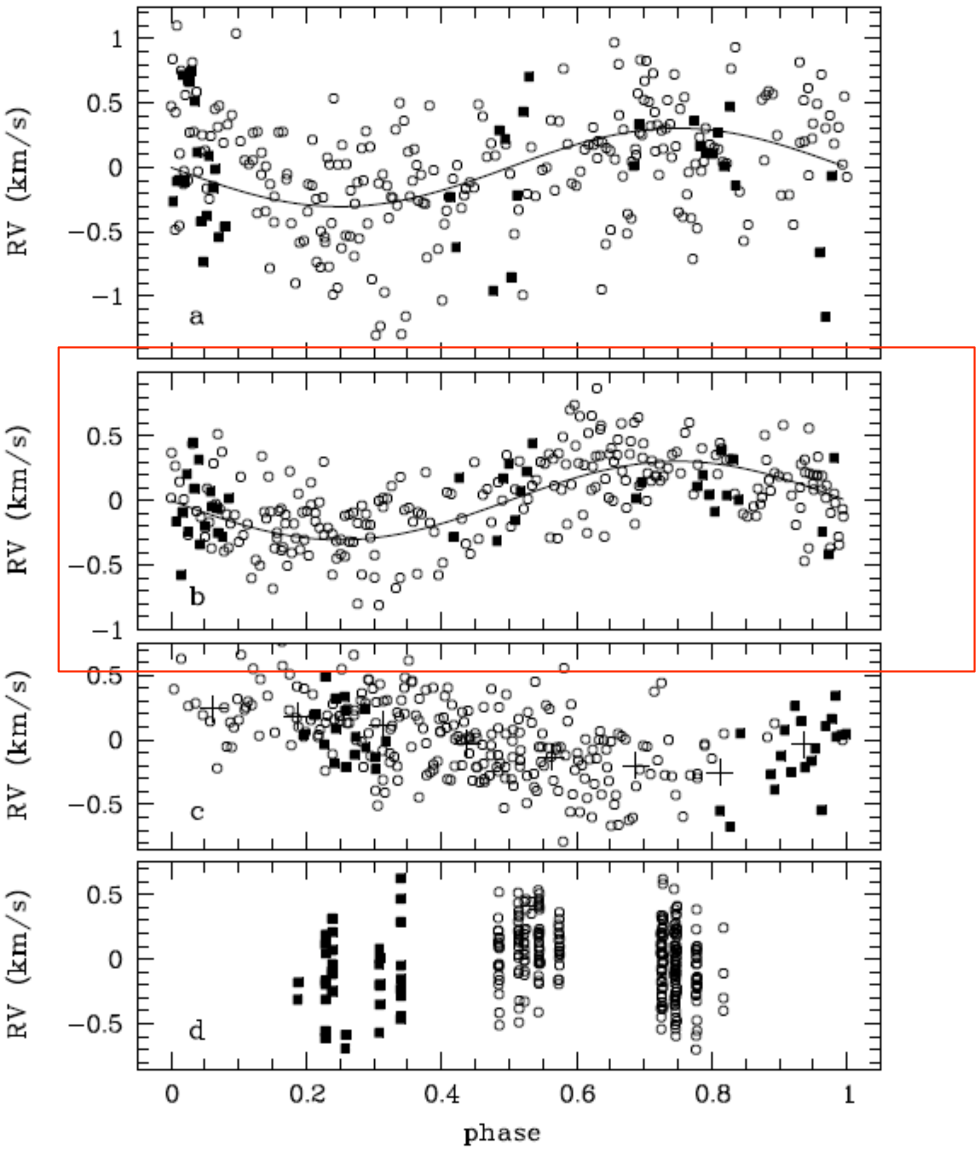
Dealing with the activity signal

1. Pre-whitening
2. Trend fitting
3. Floating chunk offset

The Mass of WASP-33b

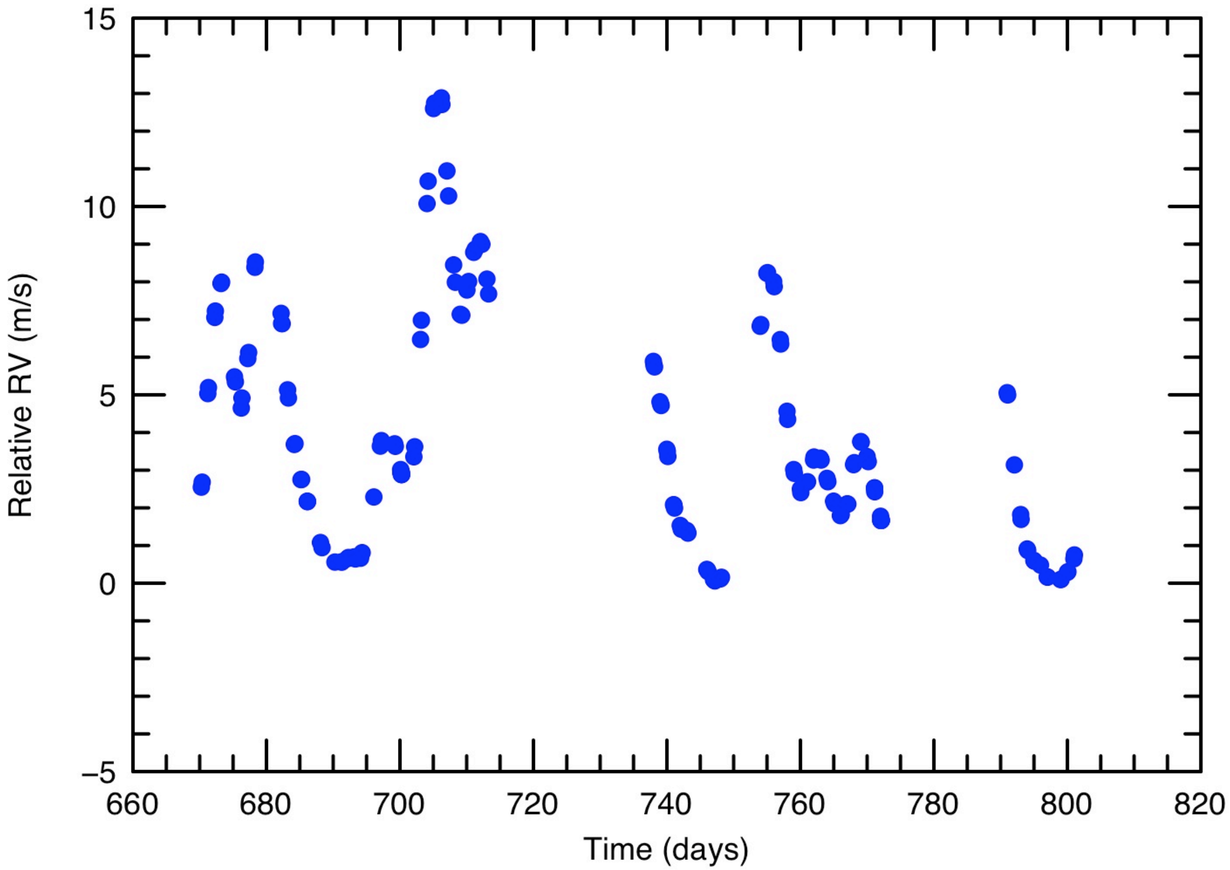


$M = 2.1 \pm 0.1\ M_J$

Cleaned with Period04

Lehmann et al. 2015

A simulated activity signal from SOAP:

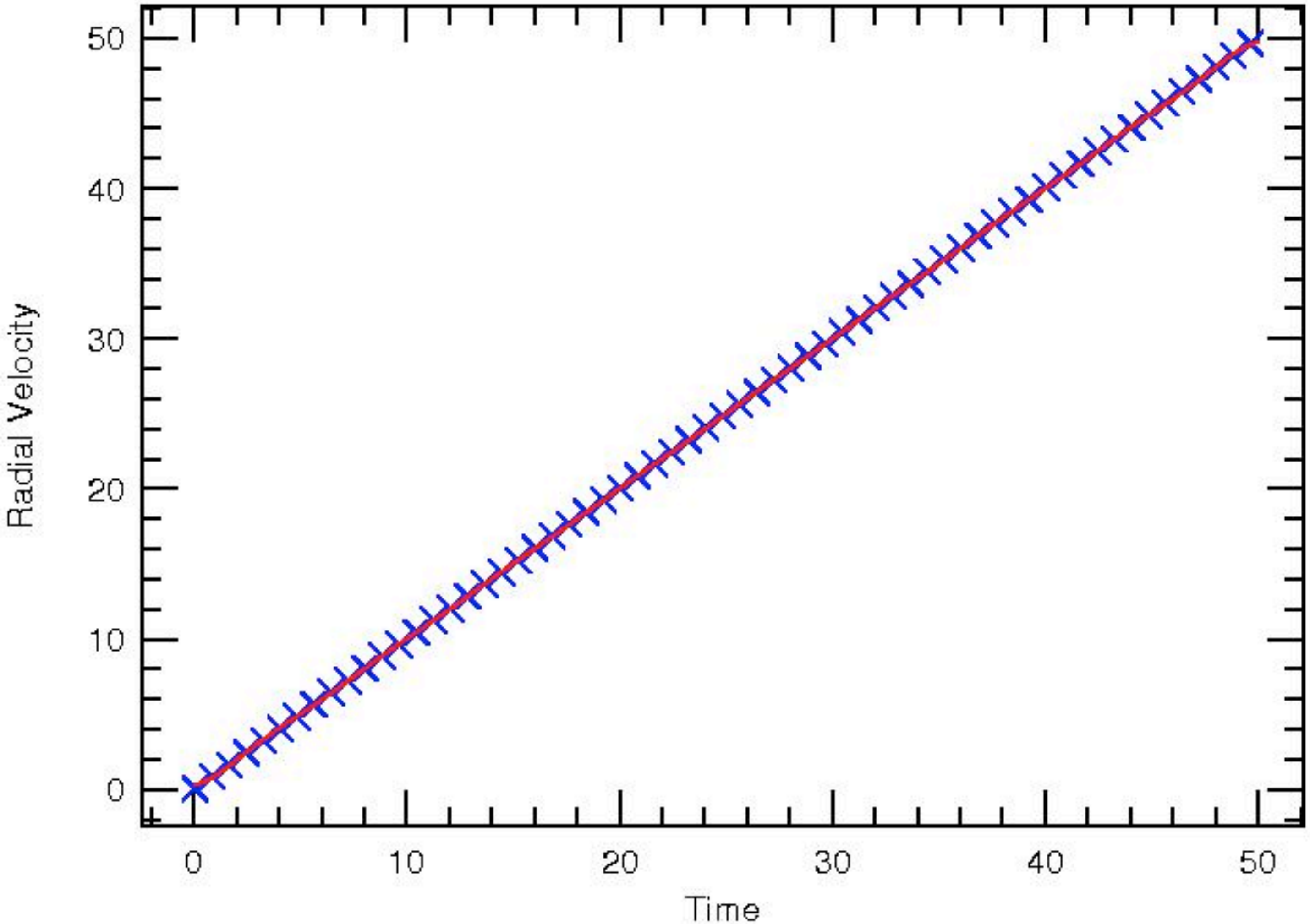


Can we Pre-whitening an activity signal?

“I question the validity of using a multi-sine component to fit the underlying activity signal.”

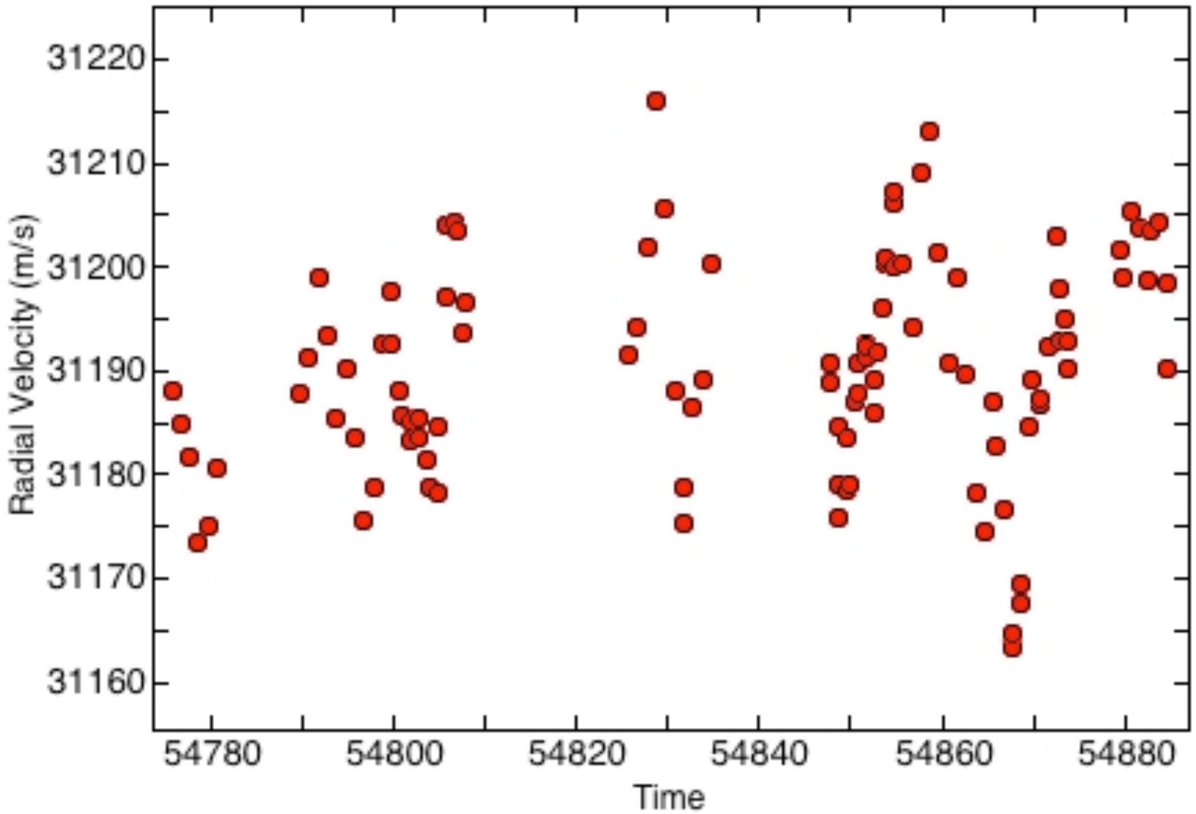
A continuous function can be represented by a linear combination of basis functions. Sine functions form a basis.

Gaps in the data and noise complicates the process and makes pre-whitening (Fourier Component Analysis) tricky.

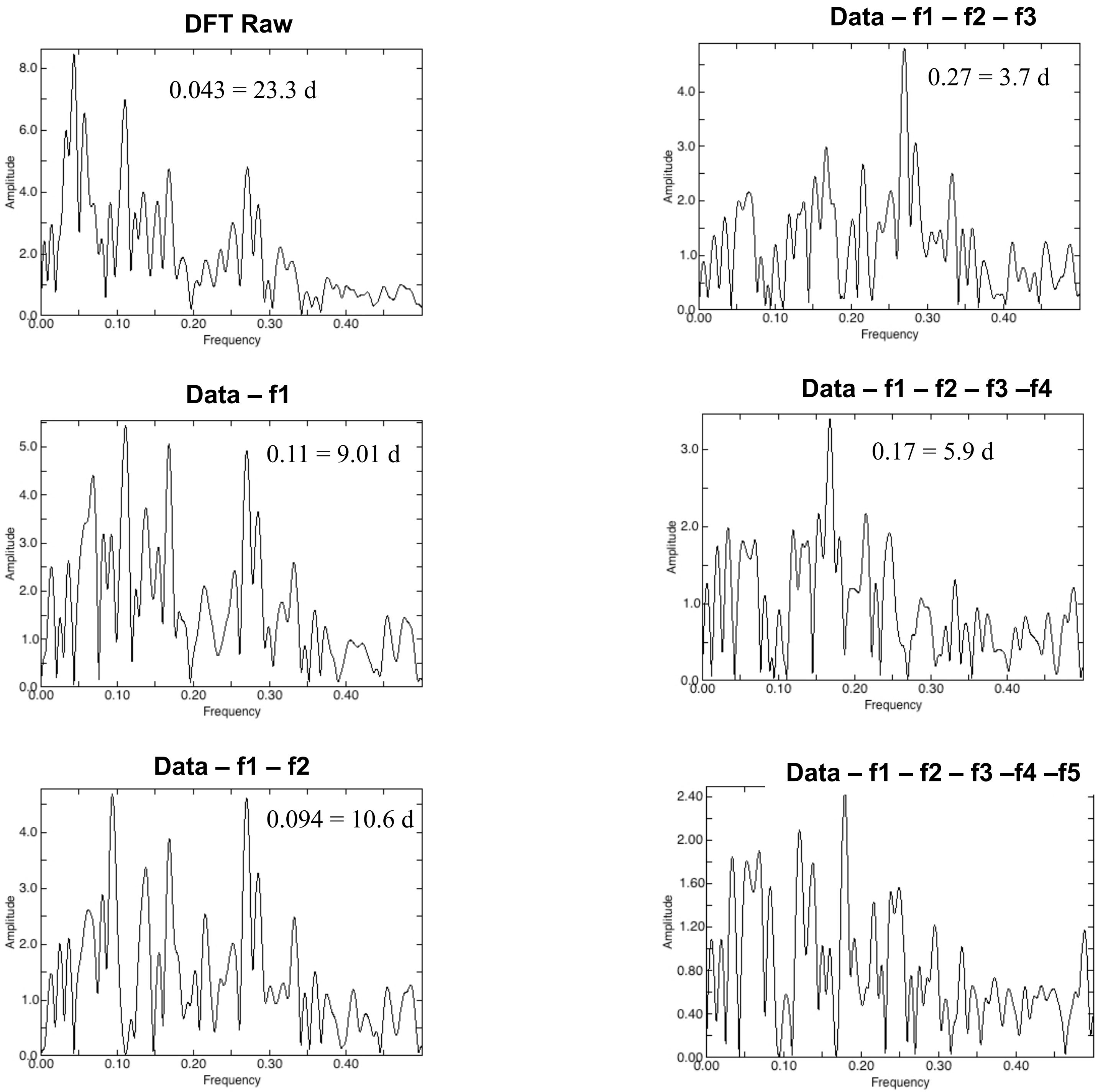


We will use Fourier pre-whitening to fit activity RV variations with multi-sine components

CoRoT-7 RVs



Transiting Superearth with a 0.85-d orbital period


DFT Raw
0.043 = 23.3 d
Amplitude
Frequency
Data – f1
0.11 = 9.01 d
Amplitude
Frequency
Data – f1 – f2
0.094 = 10.6 d
Amplitude
Frequency
Data – f1 – f2 – f3
0.27 = 3.7 d
Amplitude
Frequency
Data – f1 – f2 – f3 –f4
0.17 = 5.9 d
Amplitude
Frequency
Data – f1 – f2 – f3 –f4 –f5
Amplitude
Frequency

What are these frequencies?

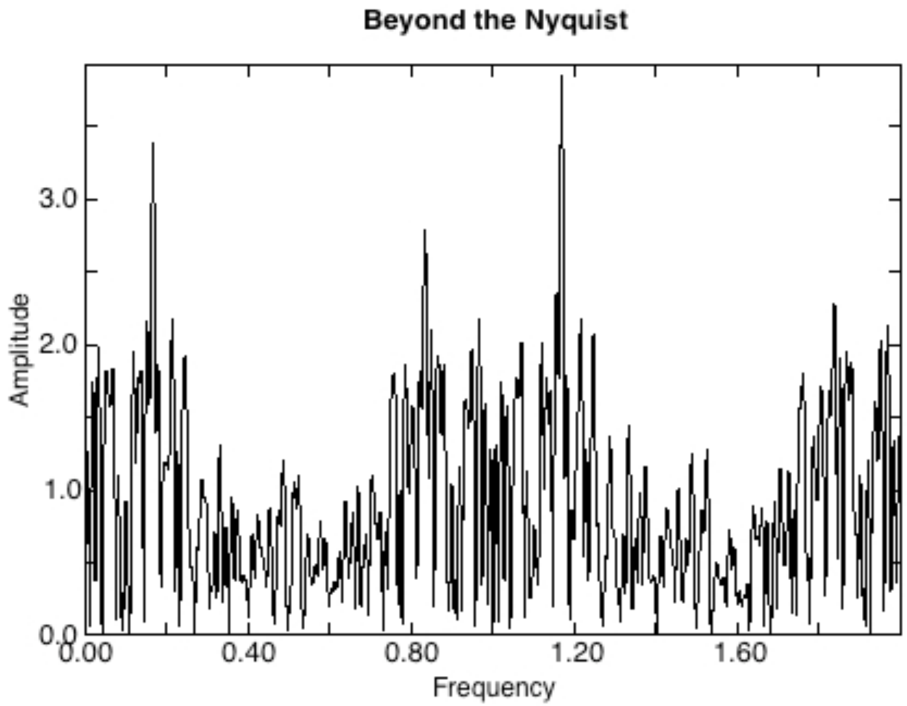
0.043 1/d = 23.2 d = stellar rotation period

0.094 1/d = 10.6 d = Prot/2

0.110 1/d = 9 d = Planet (?)

0.270 1/d = 3.7 d = Planet (?)

0.170 1/d = 5.9 d = Planet (???)

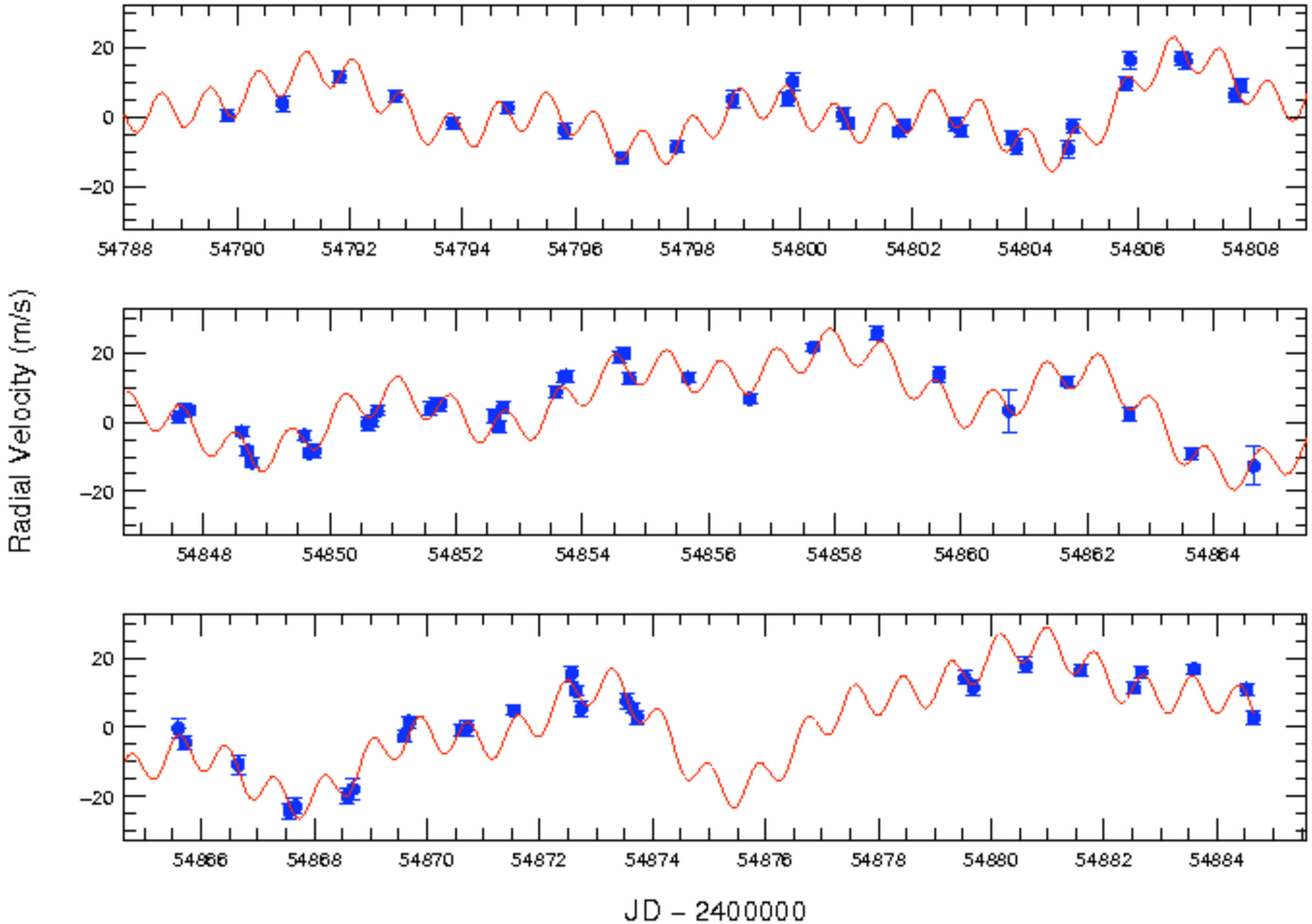


$0.17 + 1.0 = 1.17$ c/d

➔ 0.85 d = orbital period of CoRoT-7b

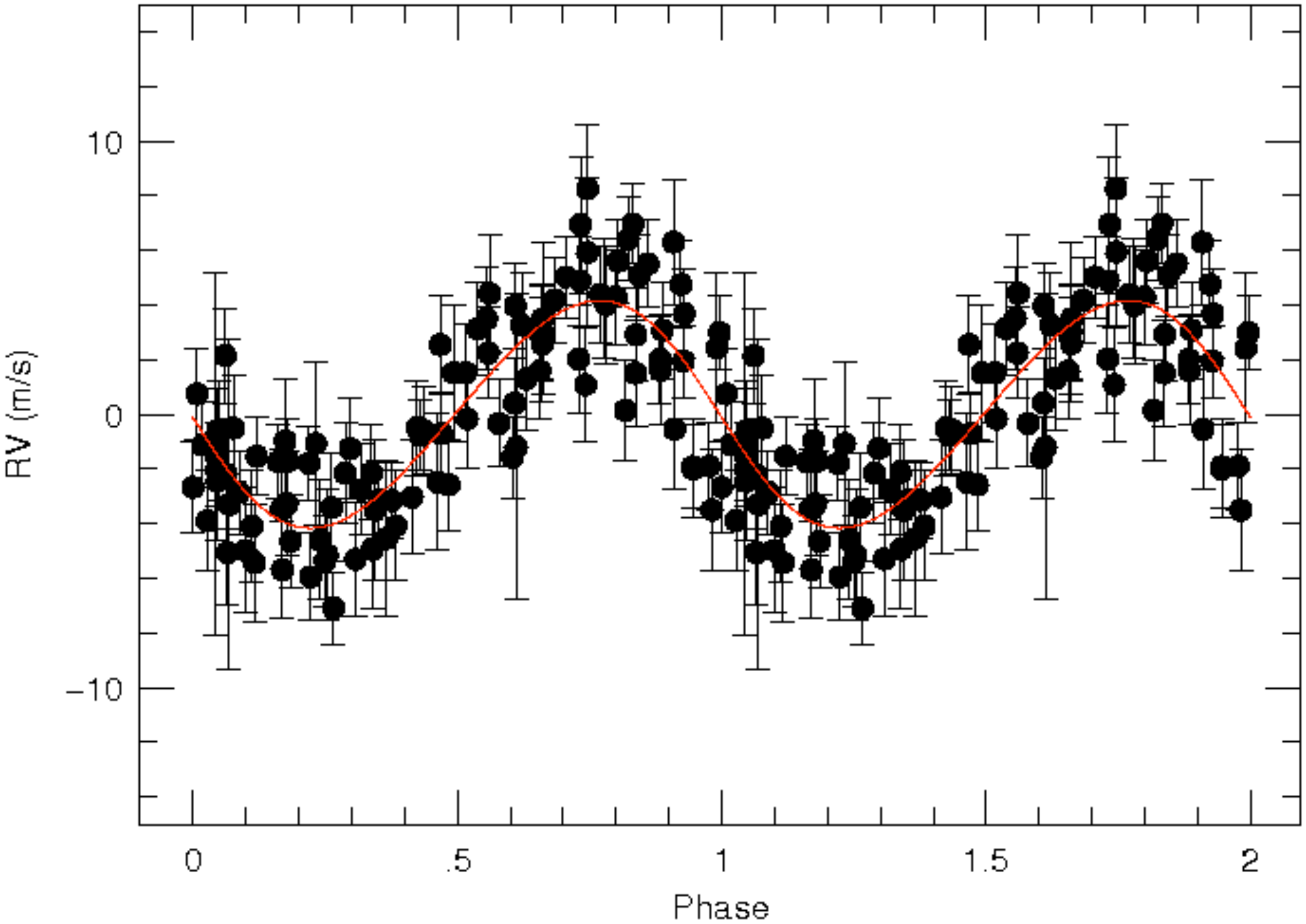
This is the one day alias

If you want to detect a period at 0.85 d **do not** make only one measurement per night!



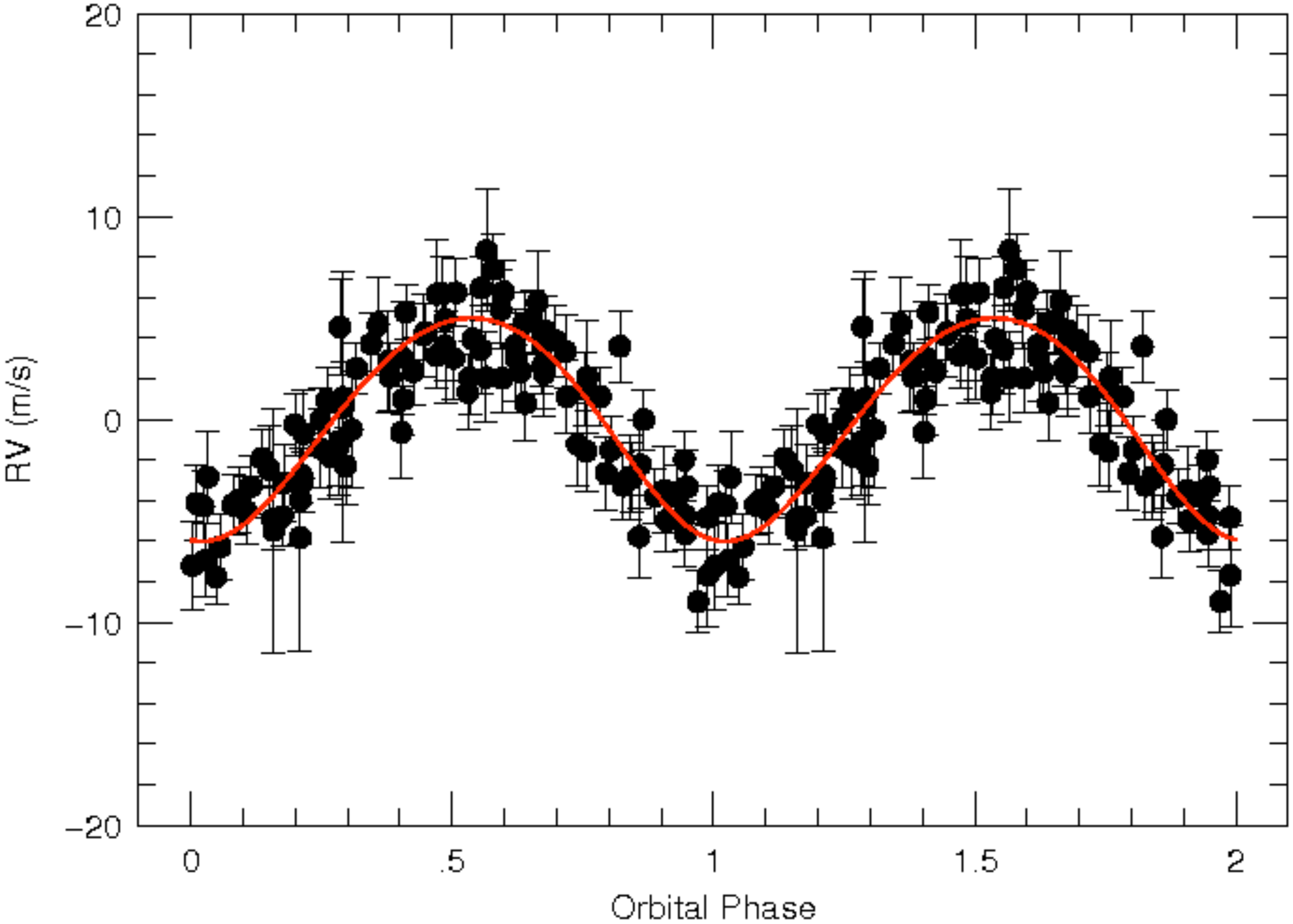
Radial Velocity (m/s)
JD – 2400000
20
0
–20
54788
54790
54792
54794
54796
54798
54800
54802
54804
54806
54808
54848
54850
54852
54854
54856
54858
54860
54862
54864
54866
54868
54870
54872
54874
54876
54878
54880
54882
54884

P = 0.853538 d K = 4.16 ± 0.27 m/s e = 0.07 ± 0.07

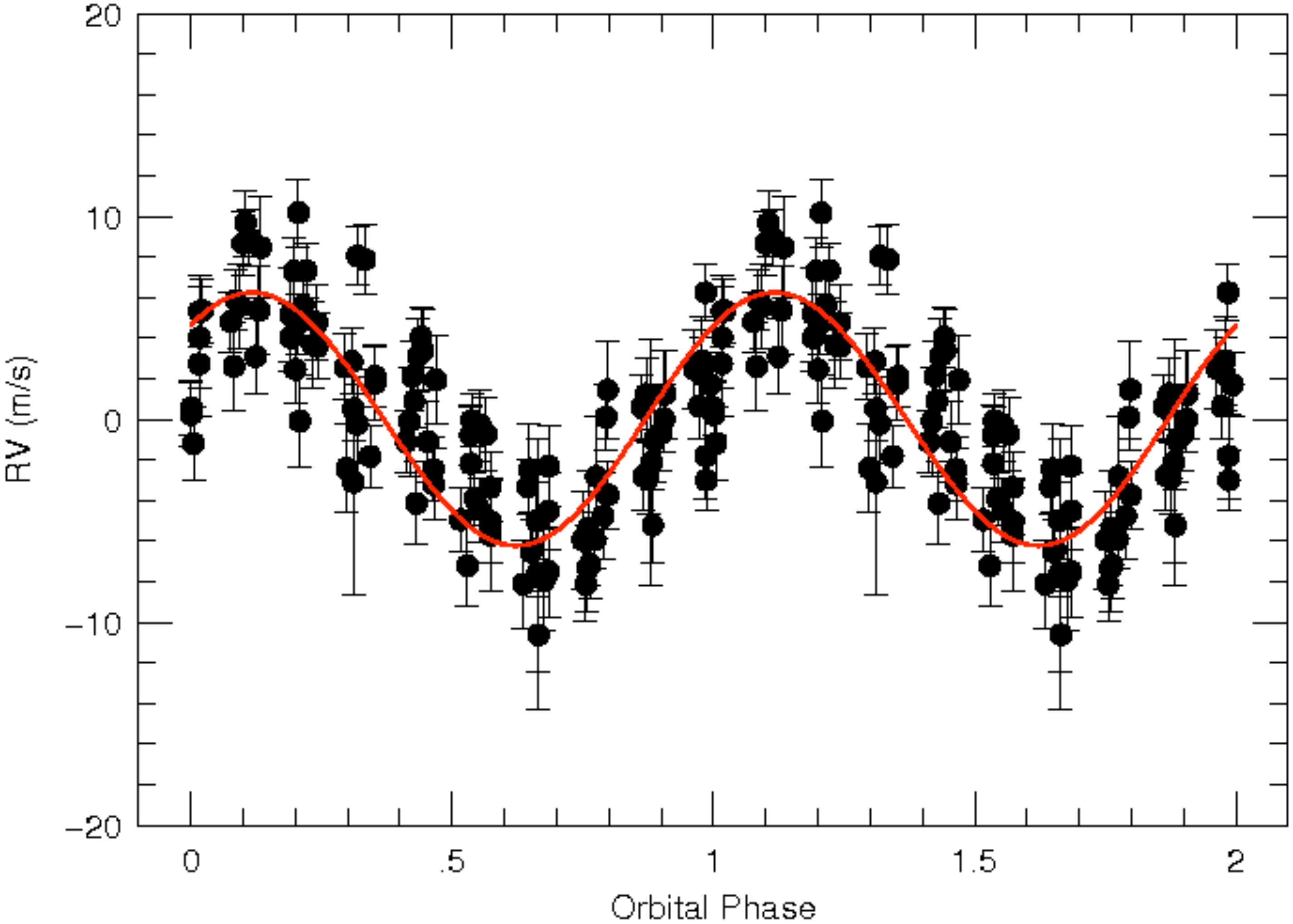


Best fit solution (#3)

P = 3.7 d K = 5.03 m/s



P = 9.03 d K = 6.23 m/s



THE LICK–CARNEGIE EXOPLANET SURVEY: A 3.1 $M_\oplus$ PLANET IN THE HABITABLE ZONE OF THE NEARBY M3V STAR GLIESE 581

Steven S. Vogt[1], R. Paul Butler[2], E. J. Rivera[1], N. Haghighipour[3], Gregory W. Henry[4], and Michael H. Williamson[4]
[1] UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA

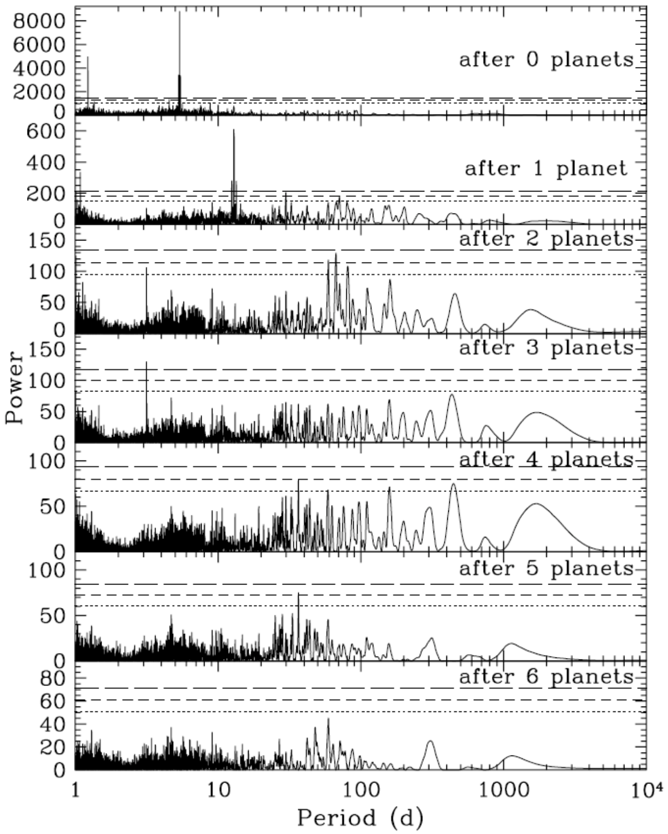


Figure 3. From top to bottom, power spectra of the residuals to the 0-, 1-, 2-, 3-, 4-, 5-, and 6-planet solutions, respectively. The horizontal lines in each periodogram roughly indicate the 0.1%, 1.0%, and 10.0% false-alarm probability (FAP) levels from top to bottom.

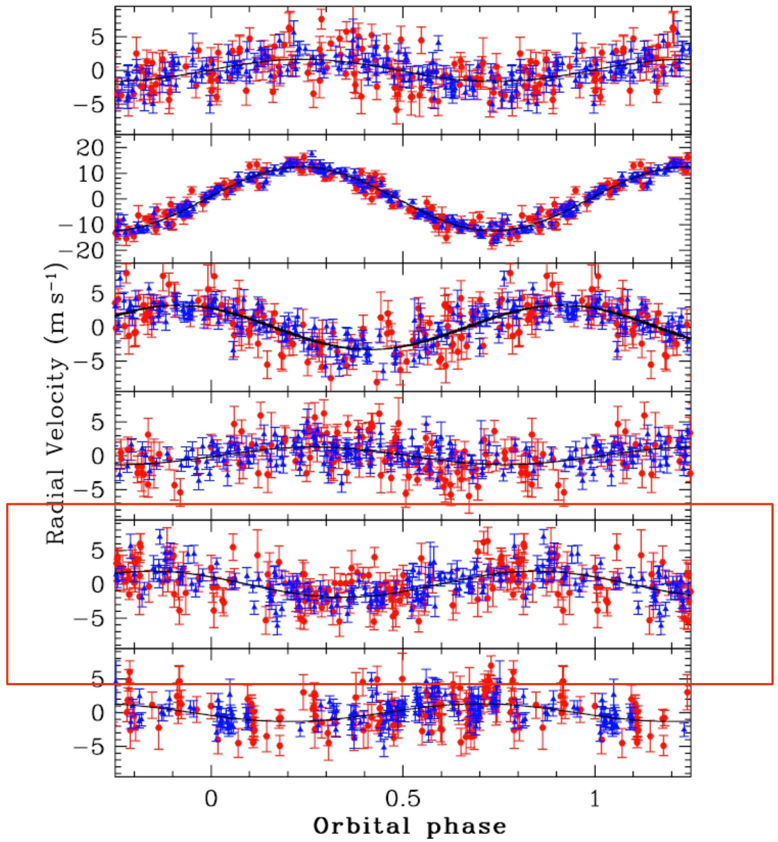
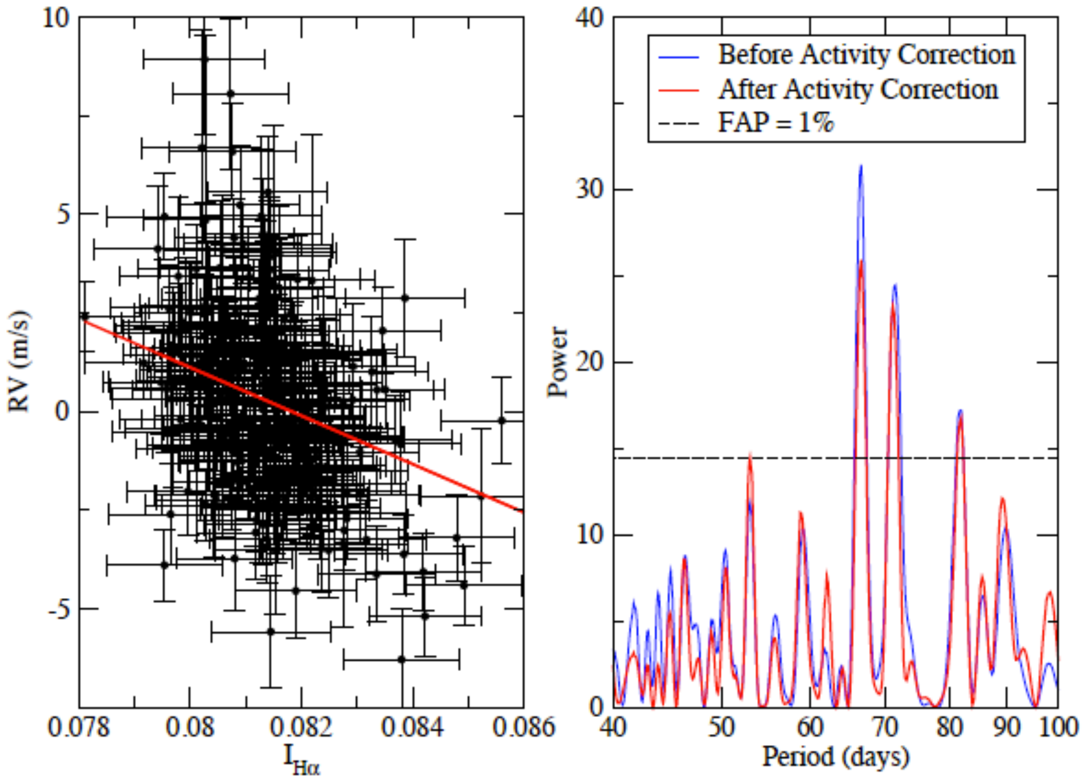


Figure 5. Phased reflex barycentric velocities of the host star due individually to the planets at 3.15 days, 5.37 days, 12.9 days, 37 days, 67 days, and 433 days from the all-circular fit of Table 2. Filled (red) hexagon points are from Keck while filled (blue) triangles are from HARPS.

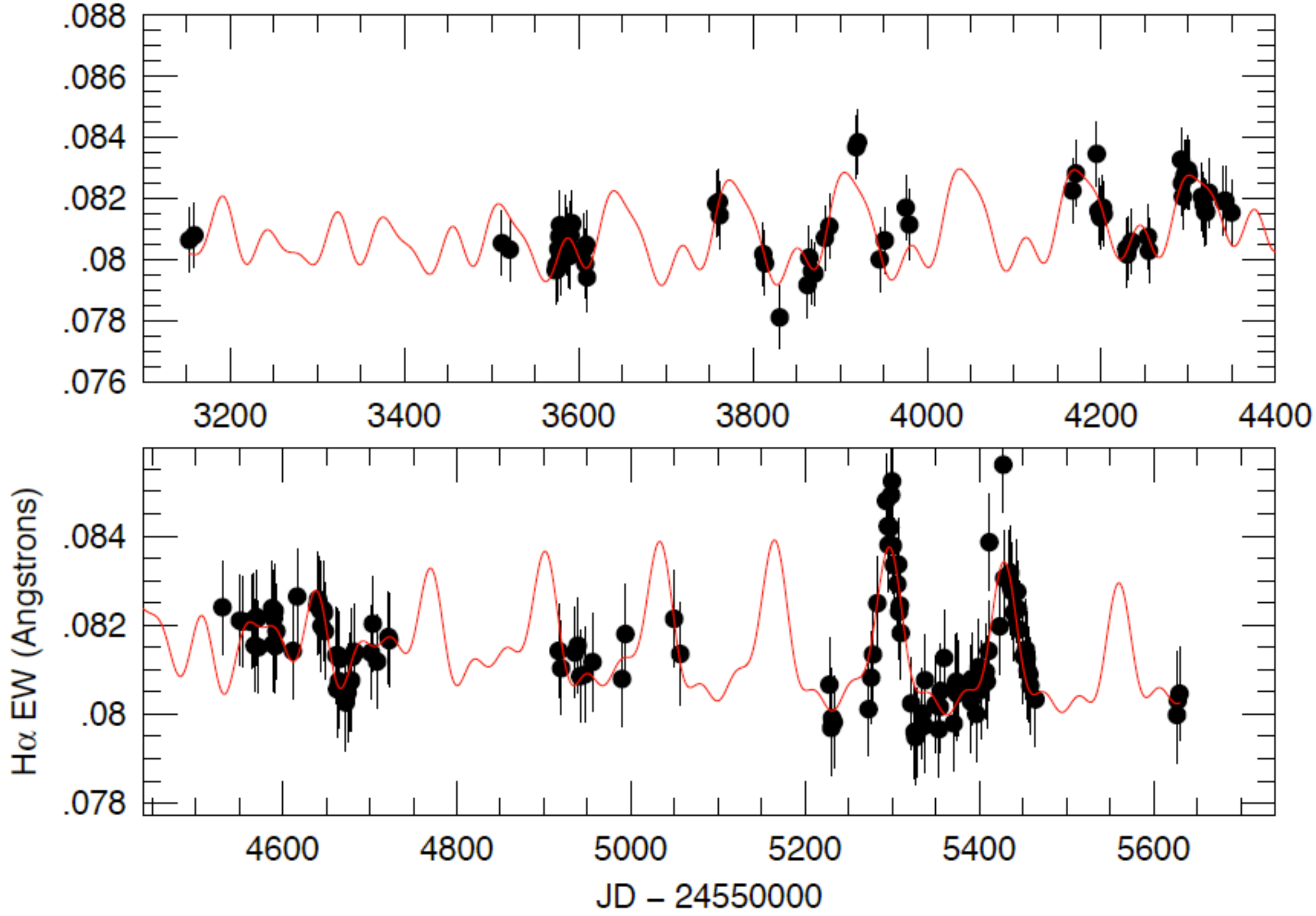
Stellar Activity Masquerading as Planets in the Habitable Zone of the M dwarf Gliese 581

Paul Robertson[1,2], Suvrath Mahadevan[1,2,3], Michael Endl[4], Arpita Roy[1,2,3]

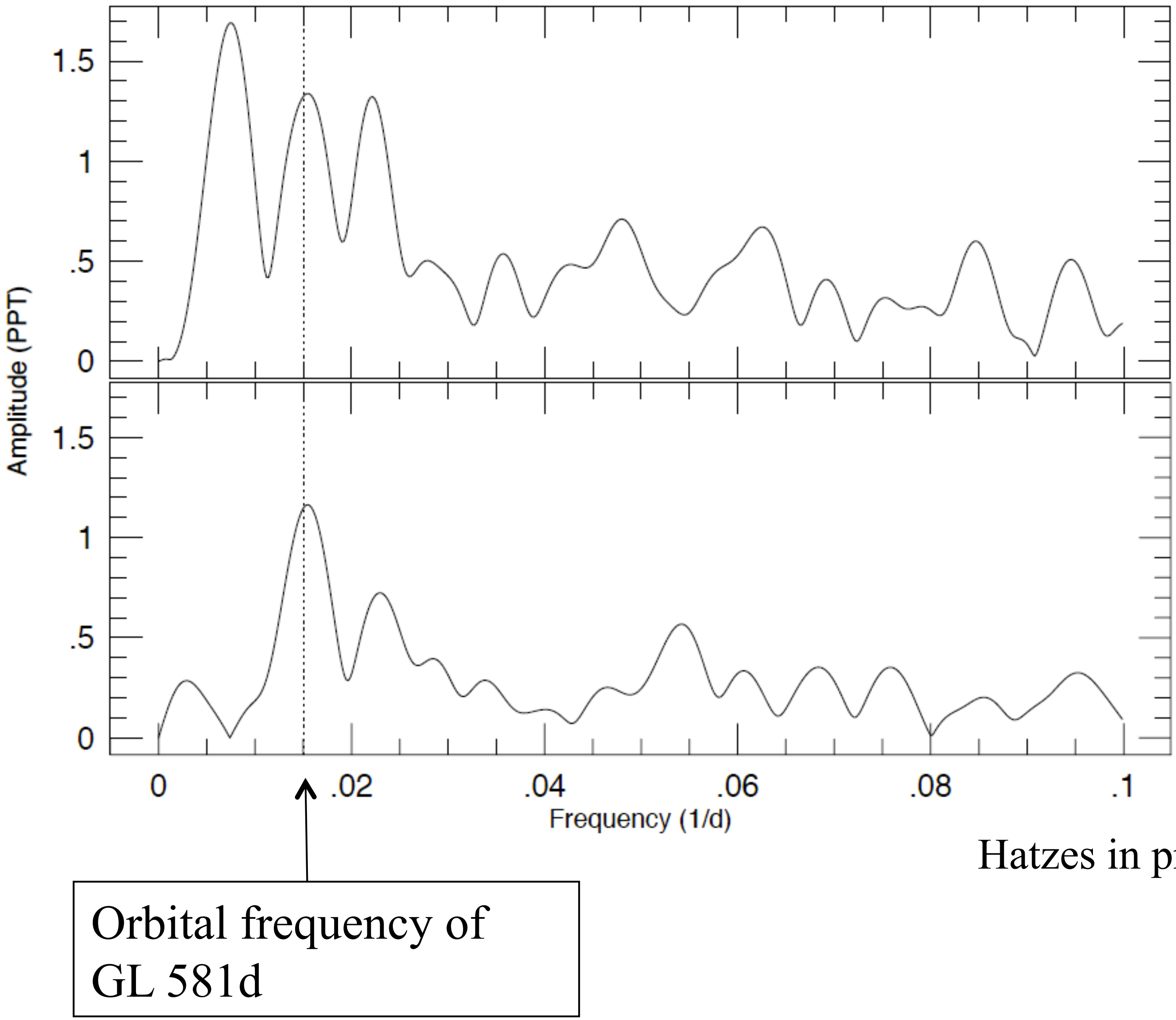


A 67-d RV period was attributed to a planet in the "habitable zone". This is probably the signature of stellar activity

Hα variations from Robertson et al.

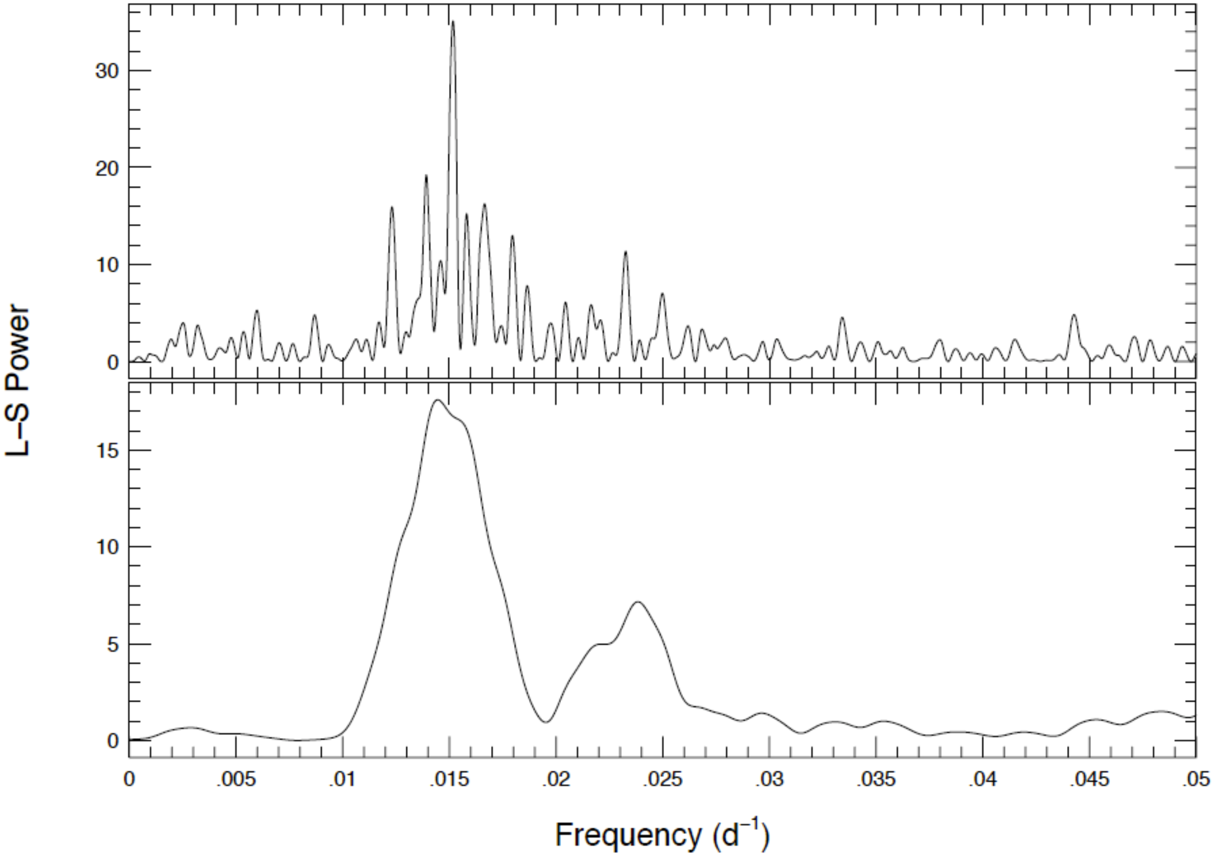


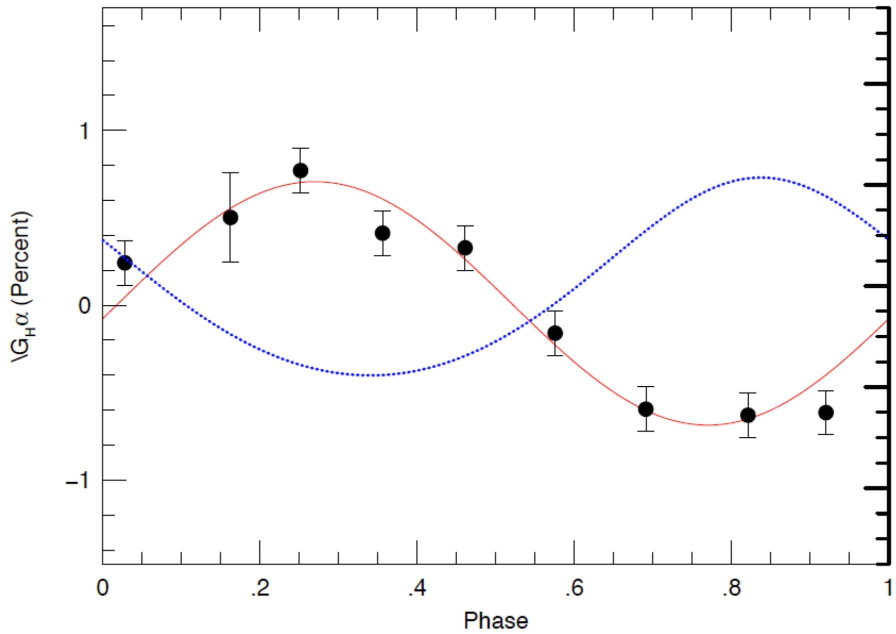
Hα variations from Robertson et al.

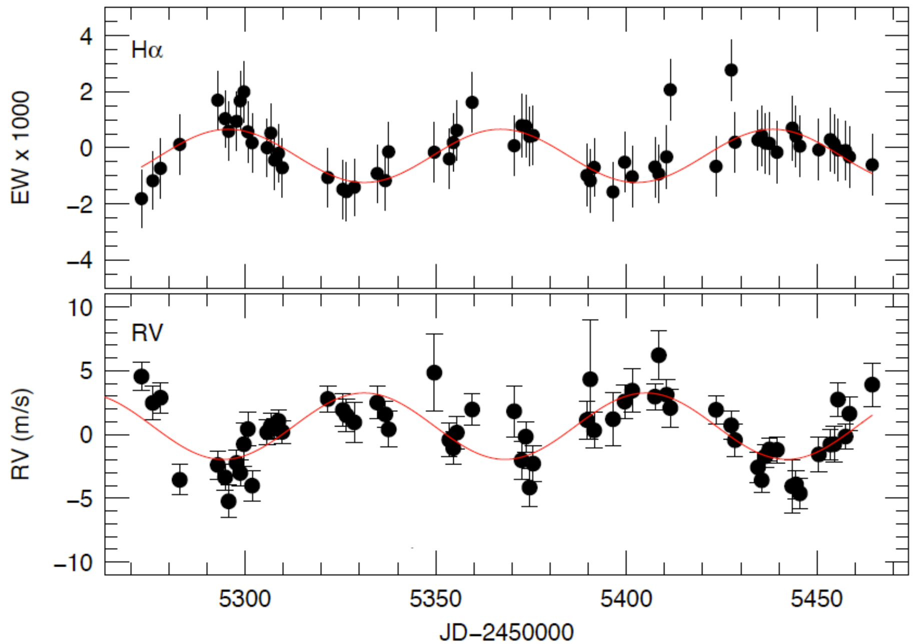


Hatzes in prep.

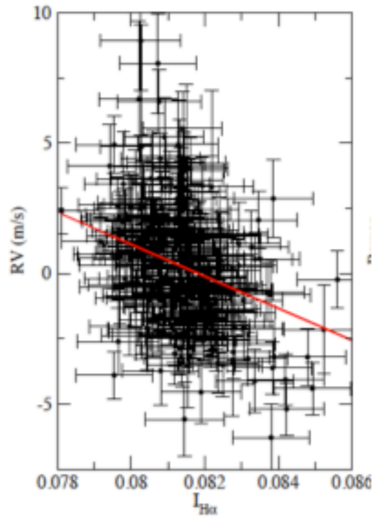
Scarge Periodogram of the Hα residual variations







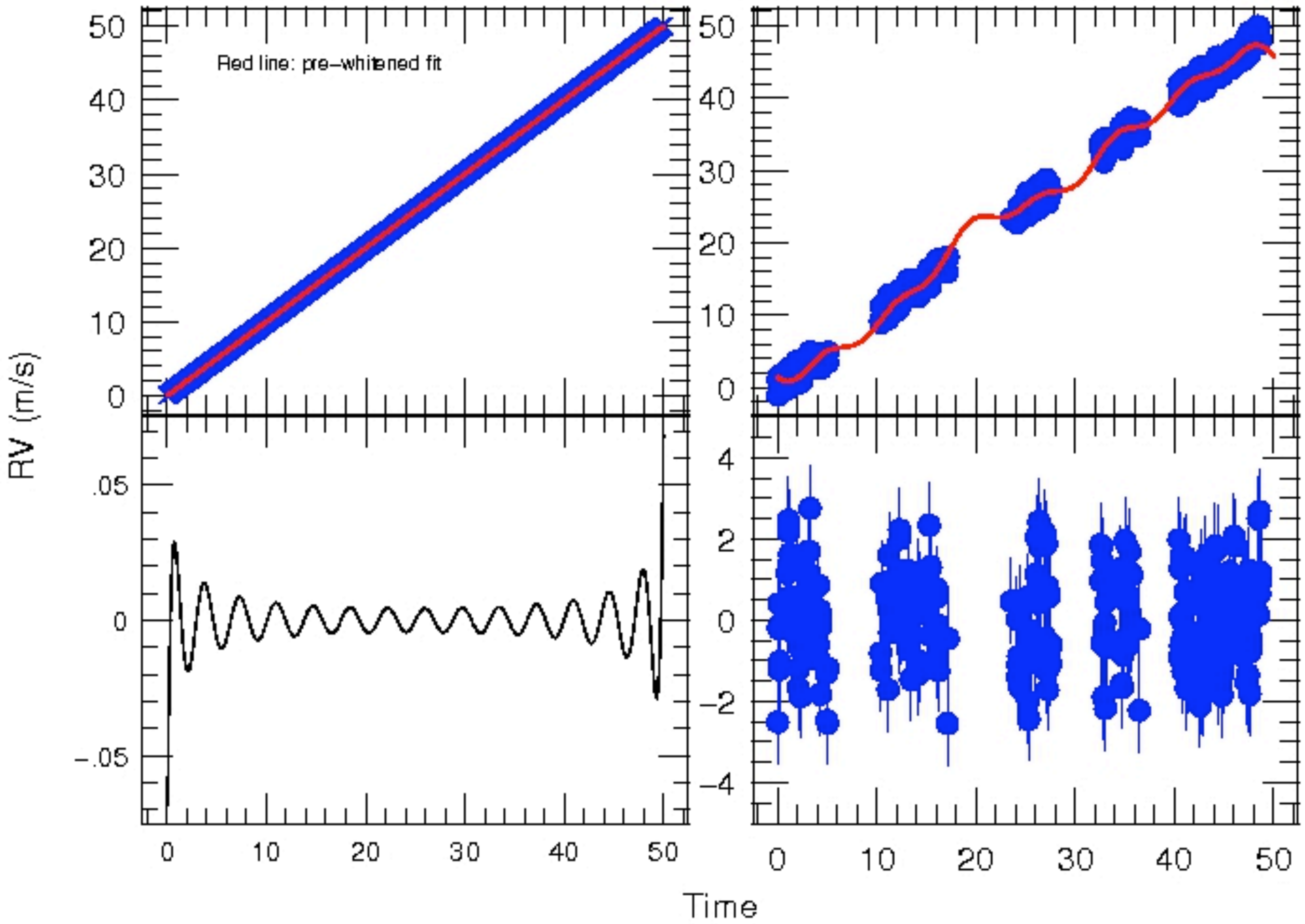
All data binned
red: Halpha
blue: RV



Subset data

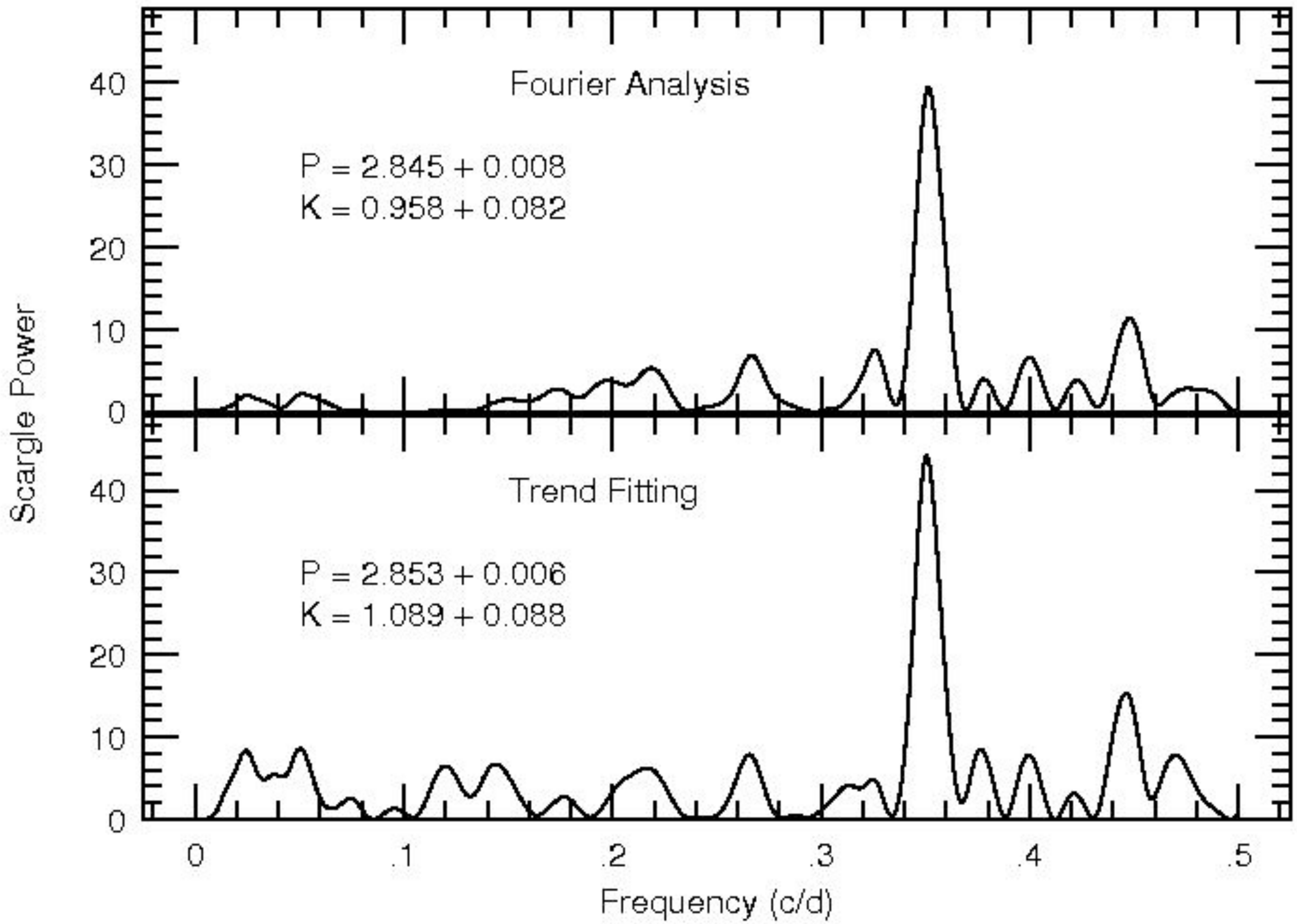
Local trend filtering

Two approaches: Pre-whitening and local trend filtering…



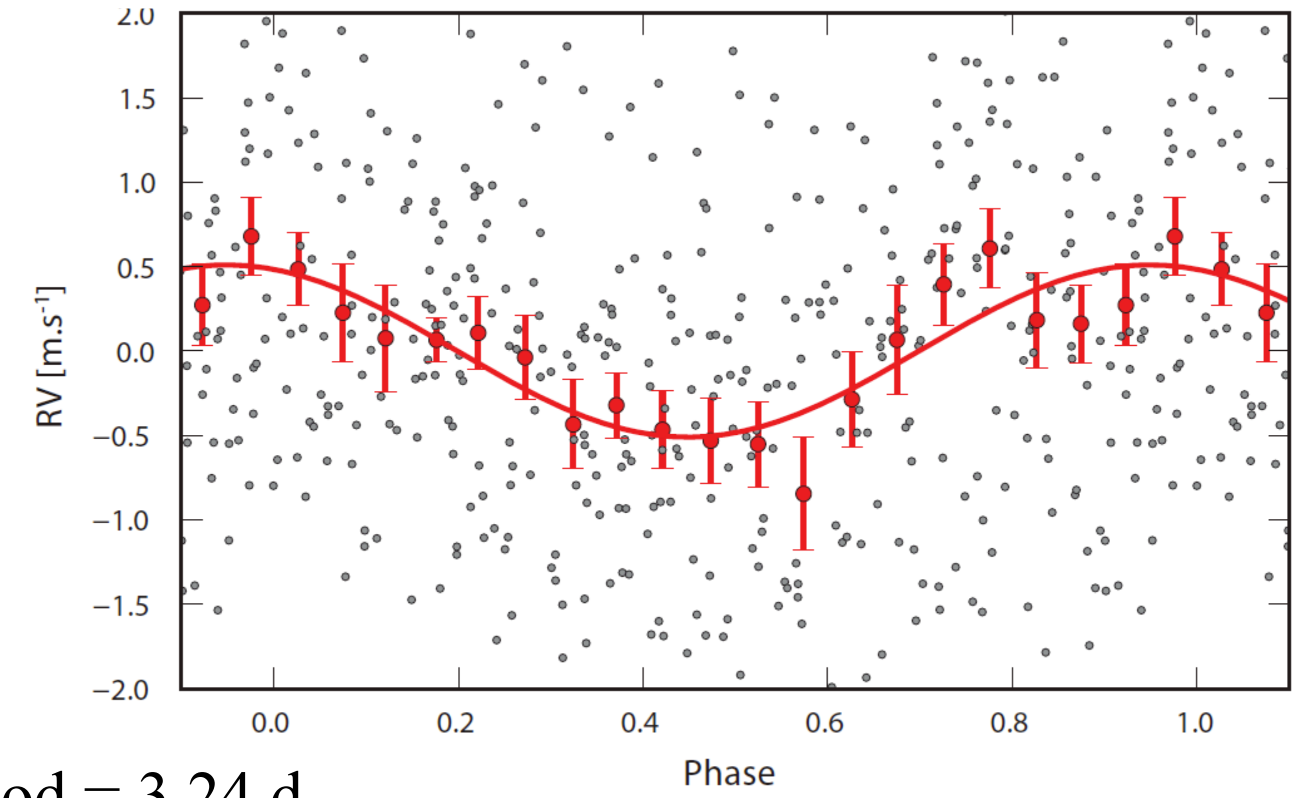
Gaps in the data and noise complicates the process and makes pre-whitening (Fourier Component Analysis) tricky.

…with consistent results



Our closest neighbor: an Earth mass planet around Alpha Centauri B (?)

Xavier Dumusque[1,4], Francesco Pepe[1], Christophe Lovis[1], Damien Ségransan[1], Johannes Sahlmann[1], Willy Benz[2], François Bouchy[1,3], Michel Mayor[1], Didier Queloz[1], Nuno Santos[4,5] and Stéphane Udry[1]

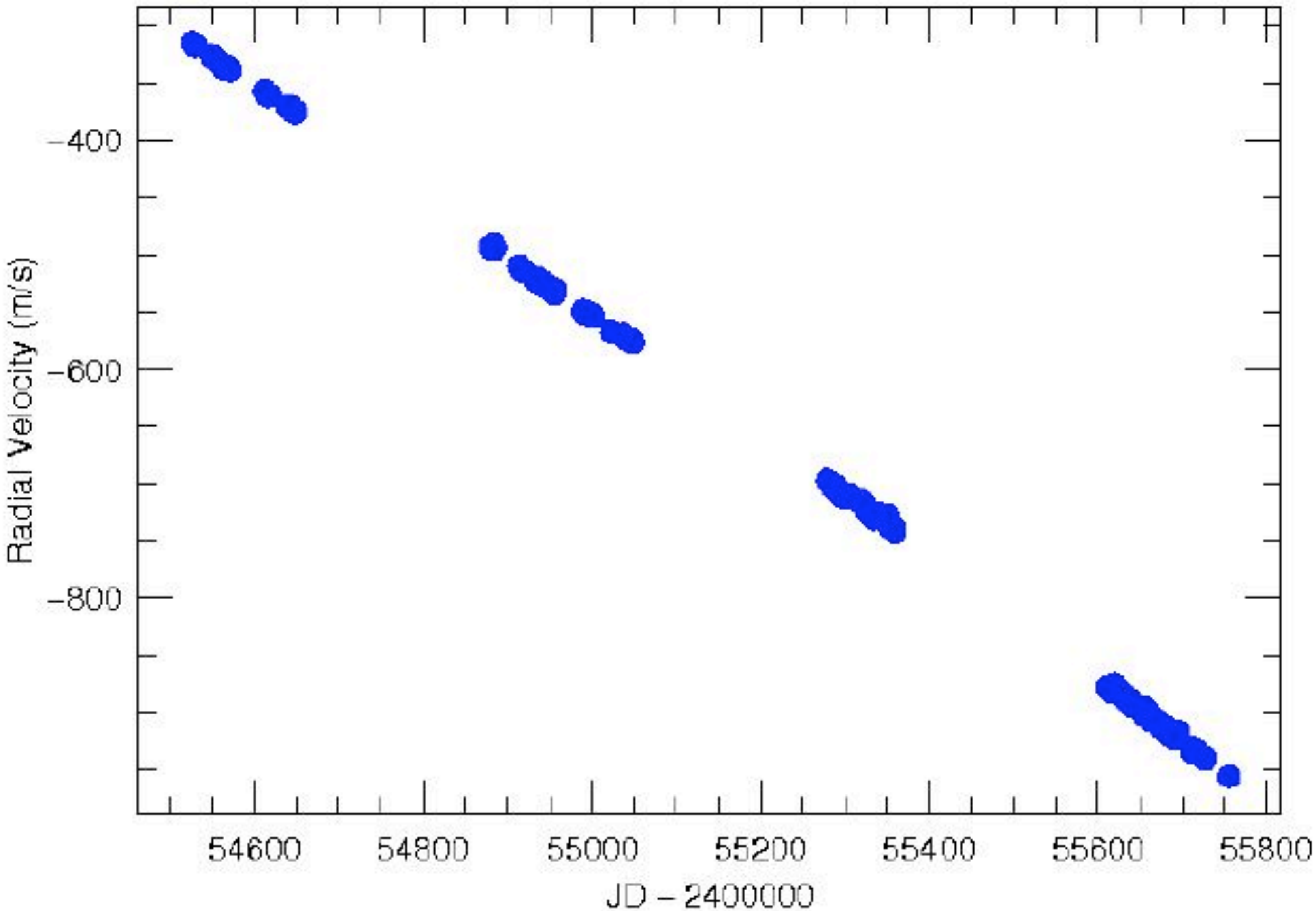


Period = 3.24 d

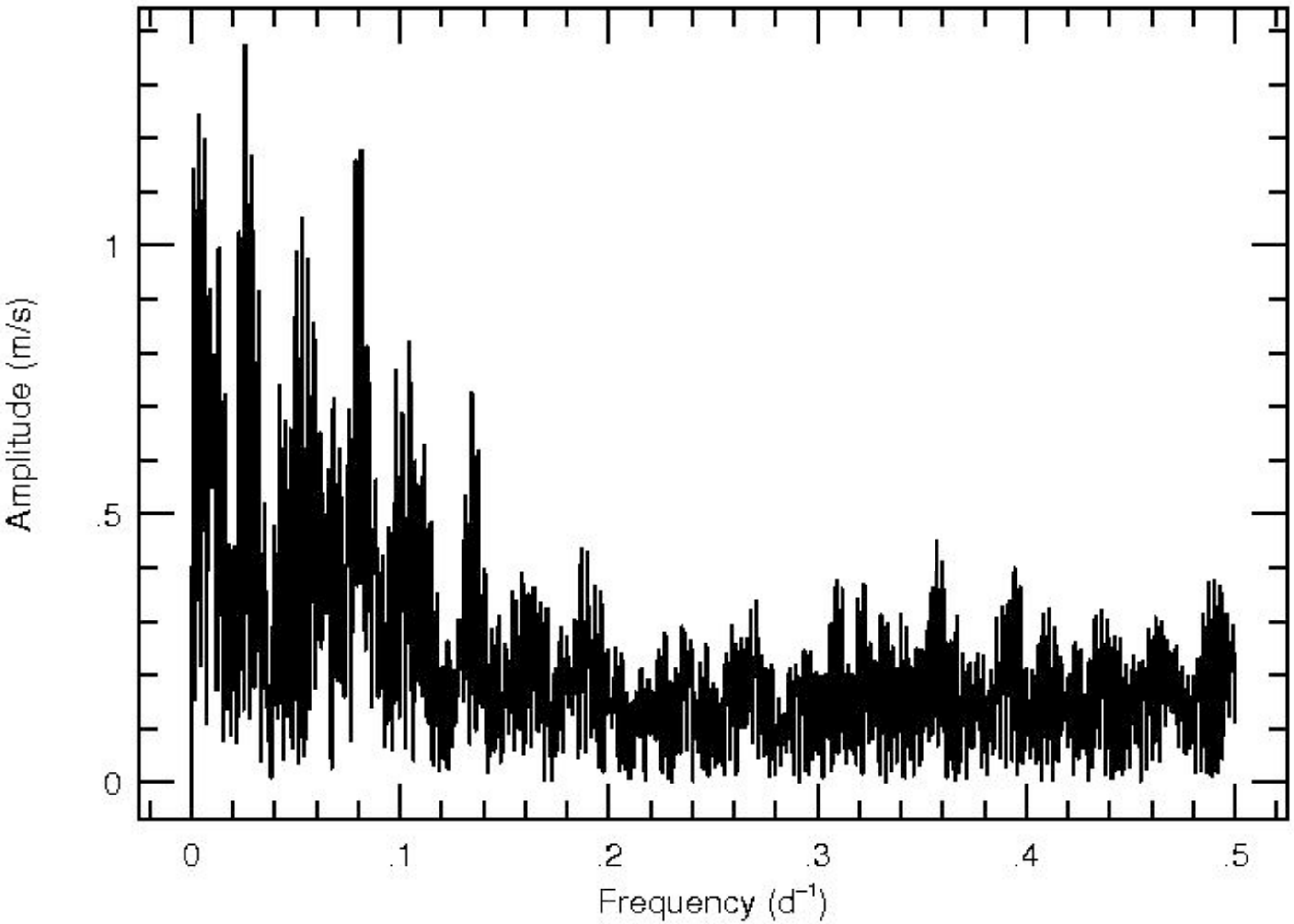
Msini = 1.13 M_{Earth}

Is Alpha Cen Bb really there?

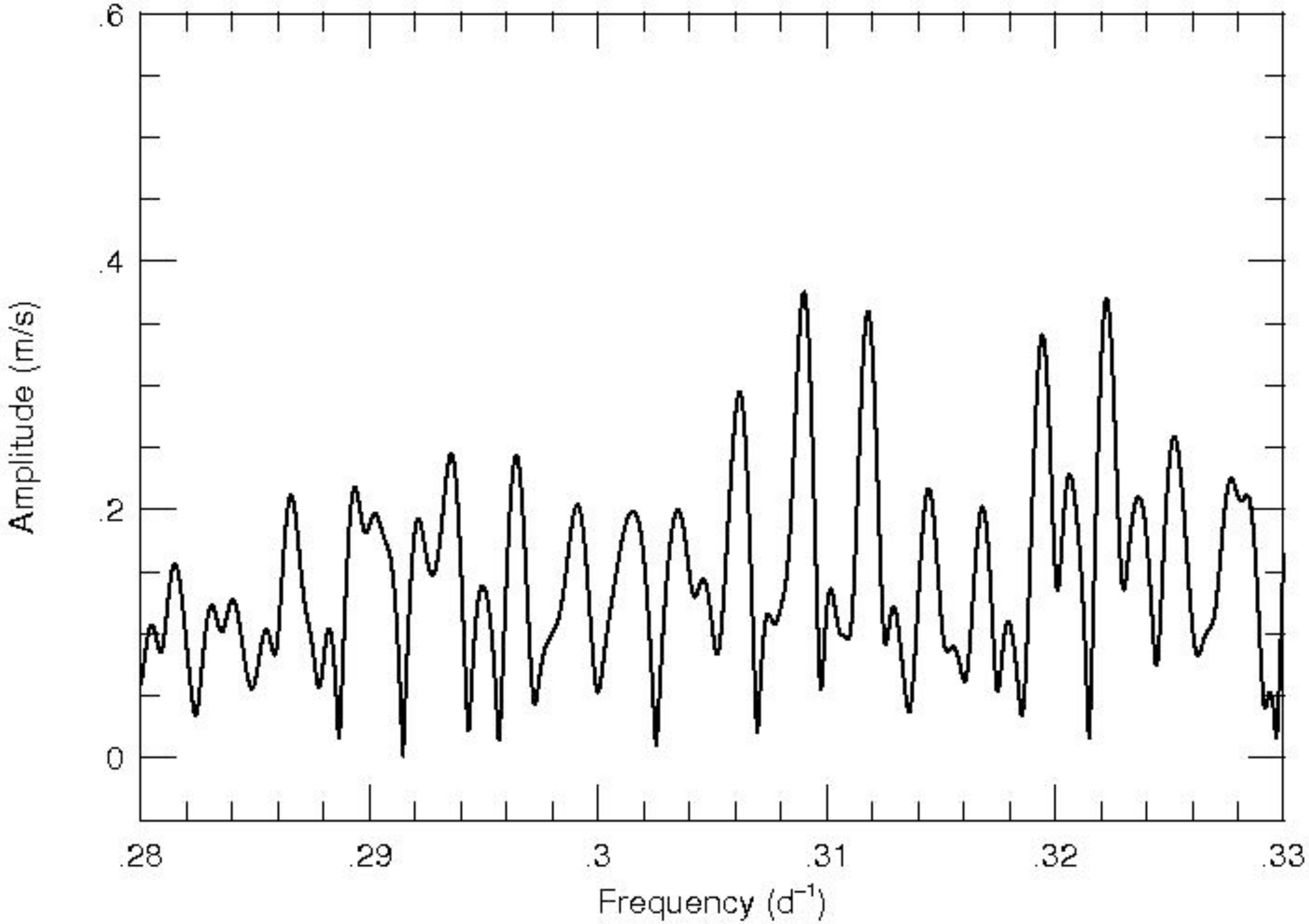
Orbital Motion of Binary



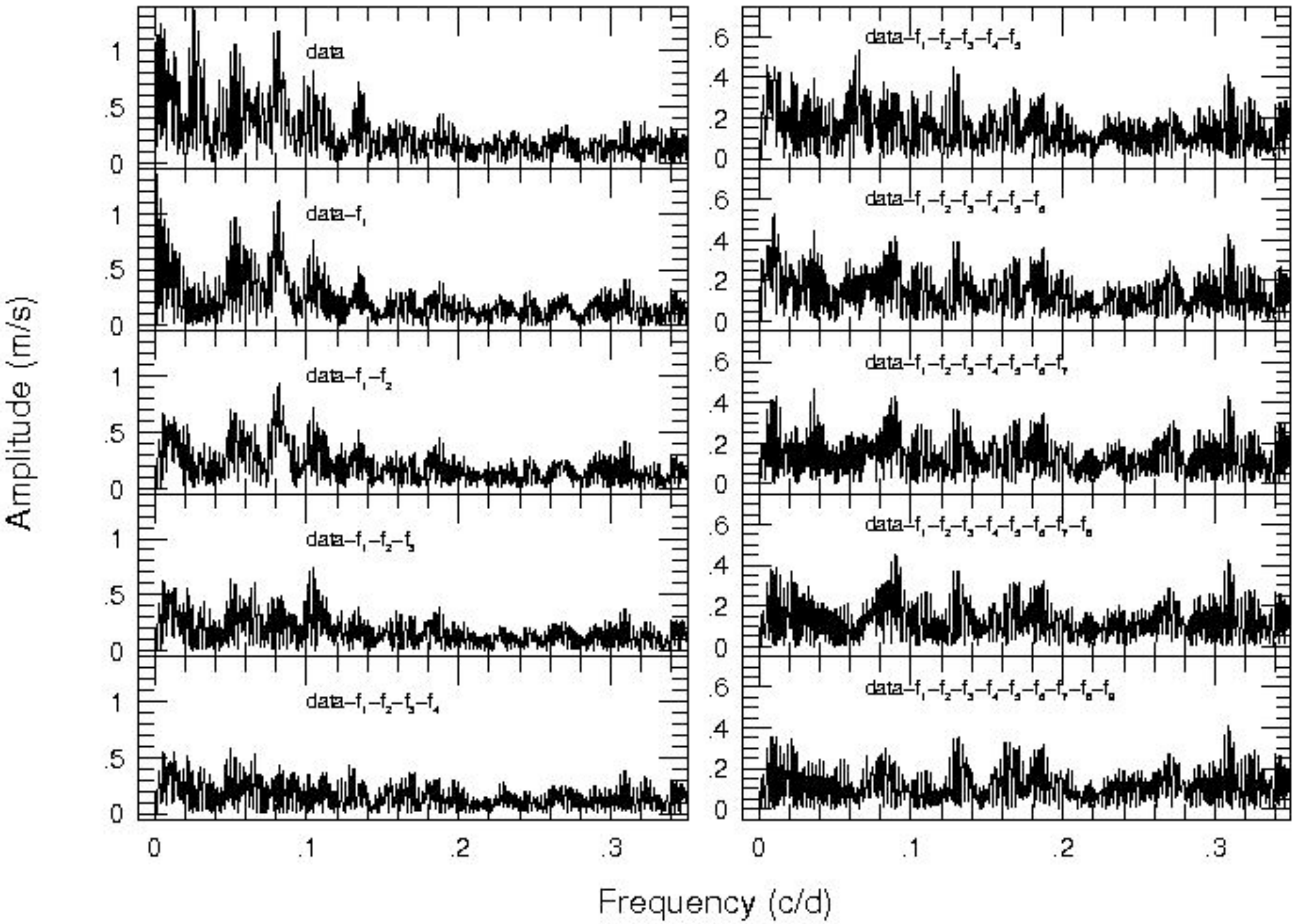
The Fourier Amplitude Spectrum of α Cen B



Binary motion removed


.6
.4
.2
0
Amplitude (m/s)
.28
.29
.3
.31
.32
.33
Frequency (d^{-1})

Pre-whitening of the RVs of α Cen B



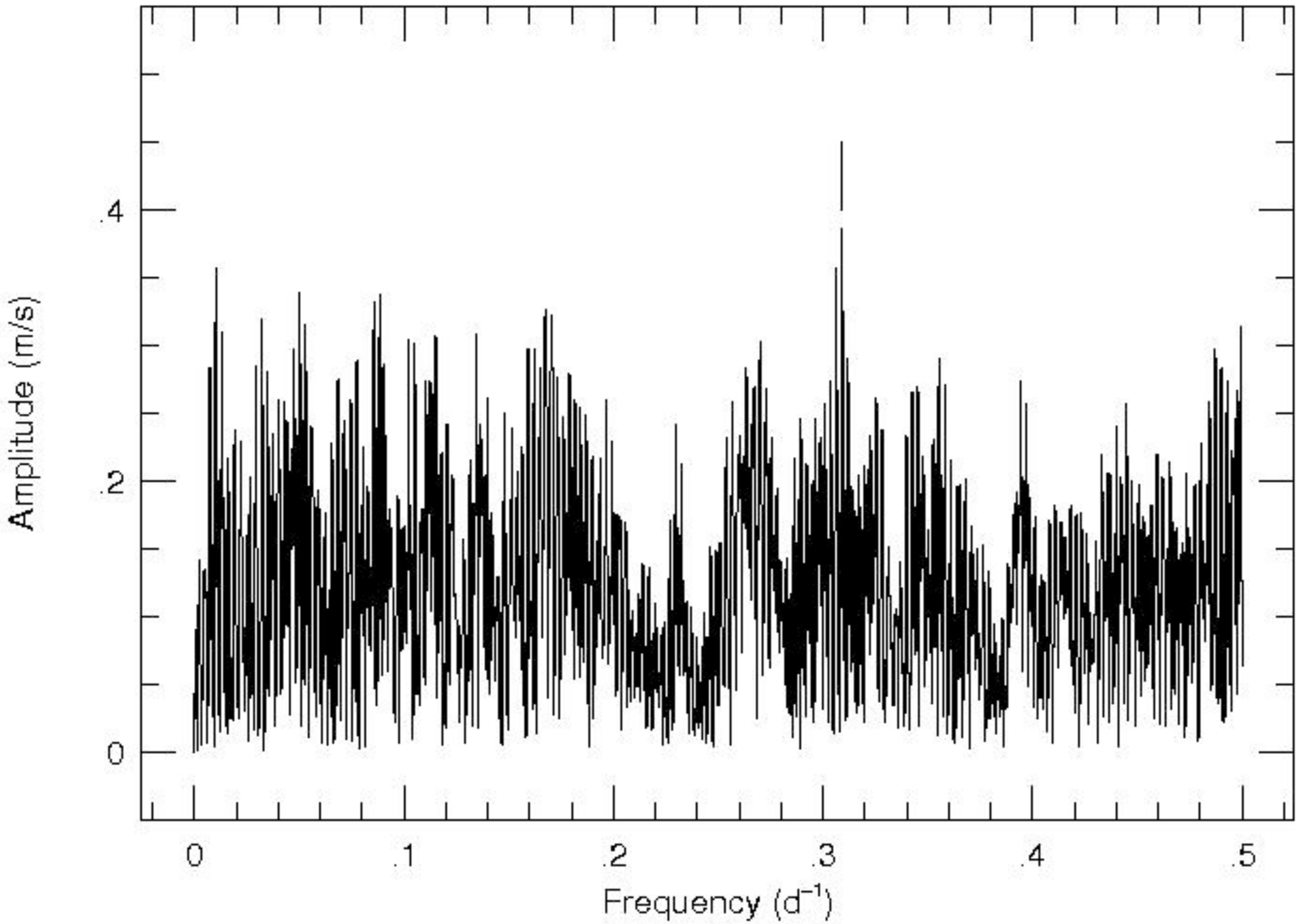
Pre-whitening α Cen B

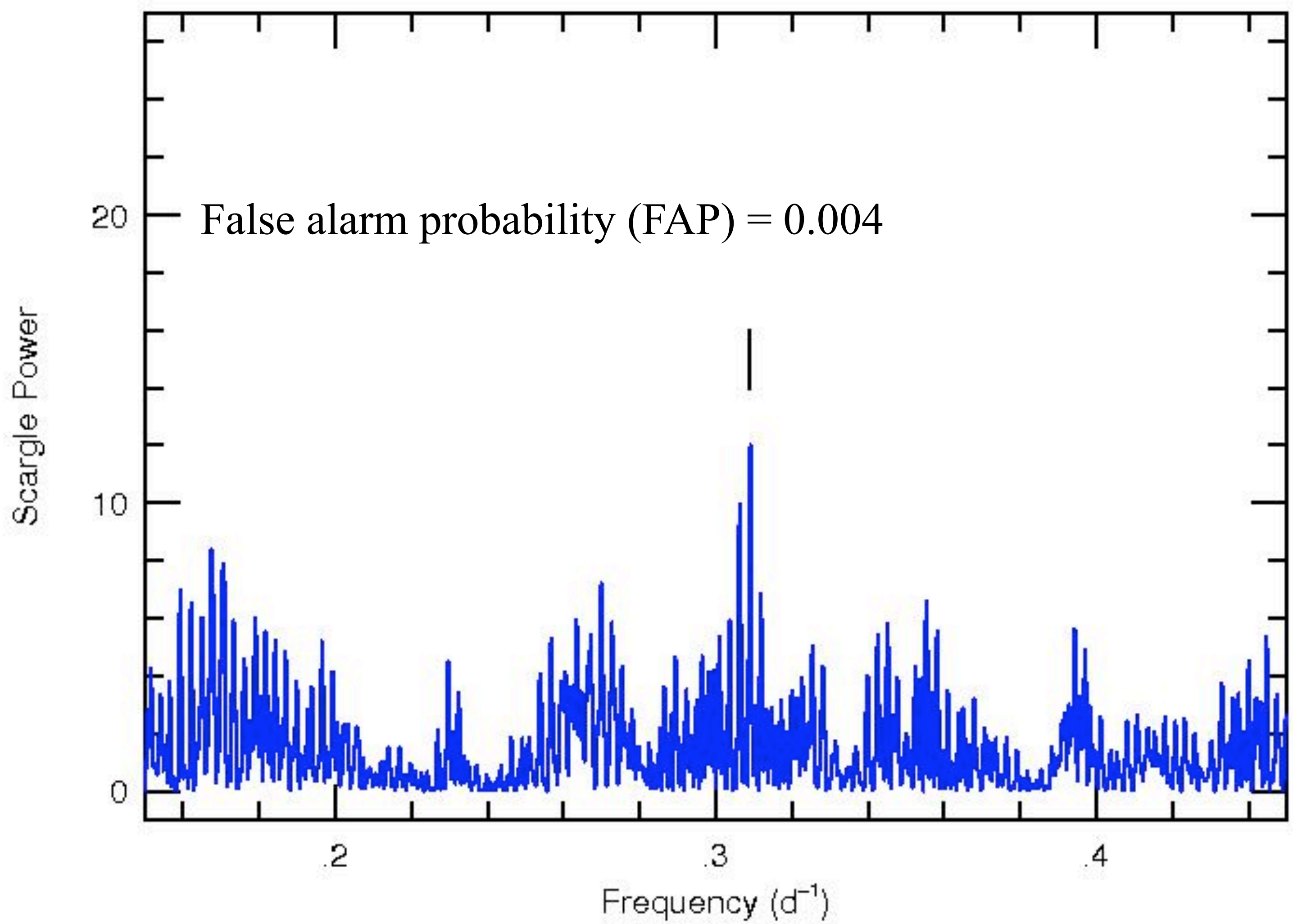
ν (1/d)	P (days)	K (m/s)	Comment
0.0259	38.6	1.69	f_{rot}
0.0013	763.4	1.15	f_2
0.0816	12.25	1.05	$2f_{rot}$
0.1045	9.57	0.84	f_3
0.0060	165.8	0.97	
0.0663	15.8	0.71	
0.033	101.11	0.67	
0.0784	12.75	0.77	
0.3090	3.24	0.41	α Cen Bb?

$\sigma = 1.19$ m/s

The sum of the first 8 frequencies is our "activity signal"

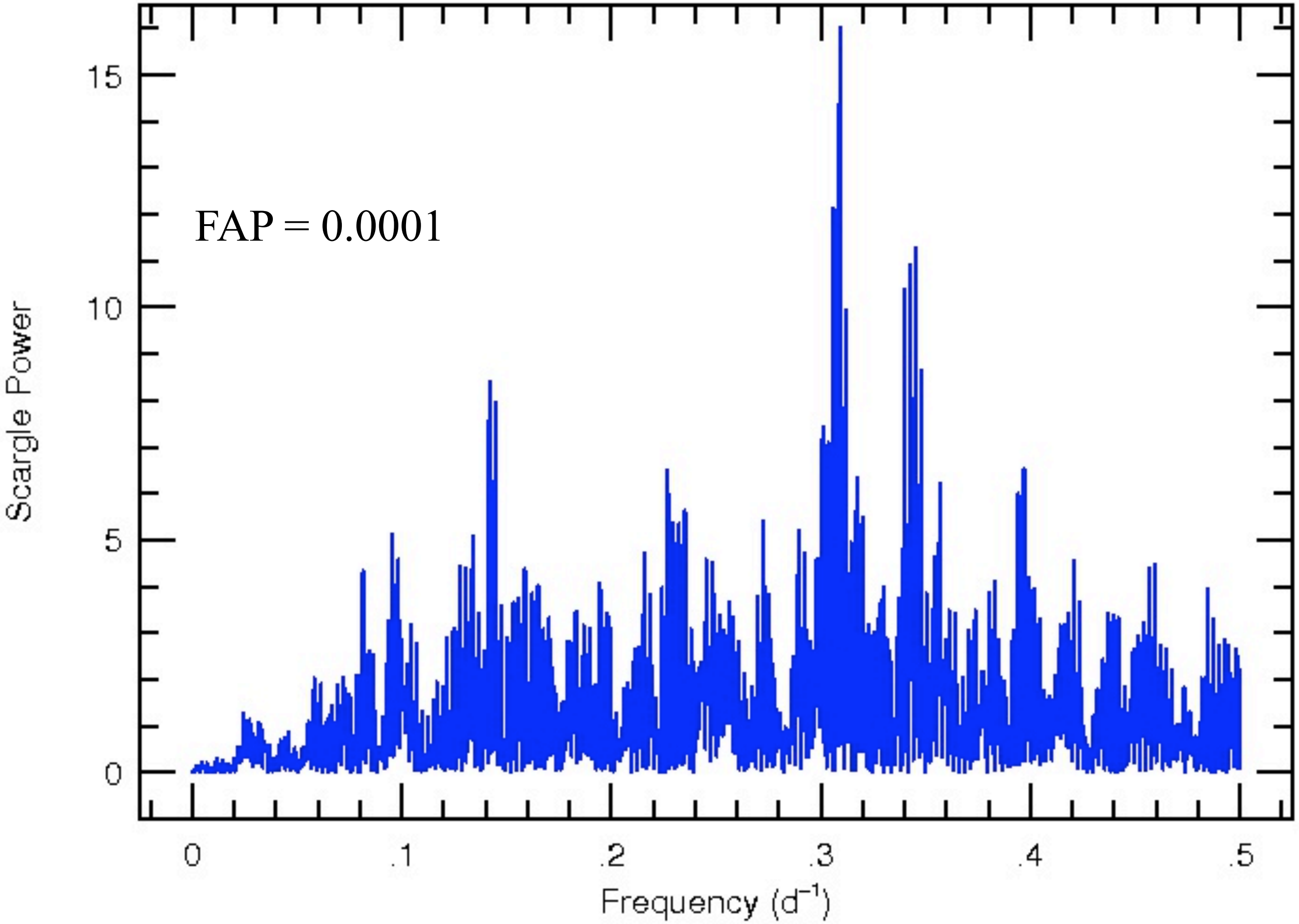
Pre-whitened result



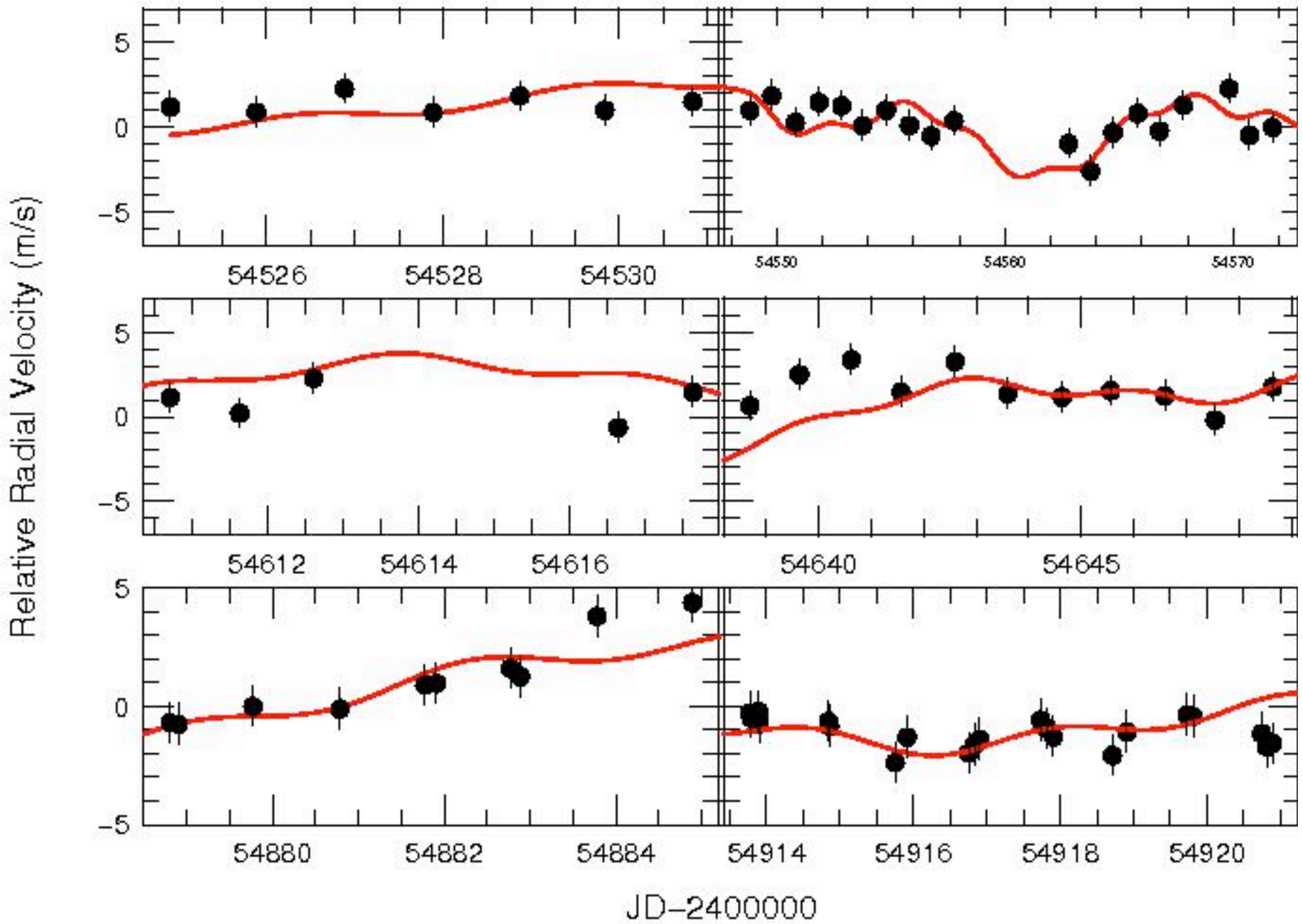

False alarm probability (FAP) = 0.004
Scargle Power
20
10
0
.2
.3
.4
Frequency (d^{-1})

Fourier	Dumusque et al.
P = 3.2356 ± 0.0001 d	P = 3.2357 ± 0.008 d
K = 0.42 ± 0.08 m/s	K = 0.51 ± 0.04 m/s
FAP = 0.4 %	FAP = 0.02 %

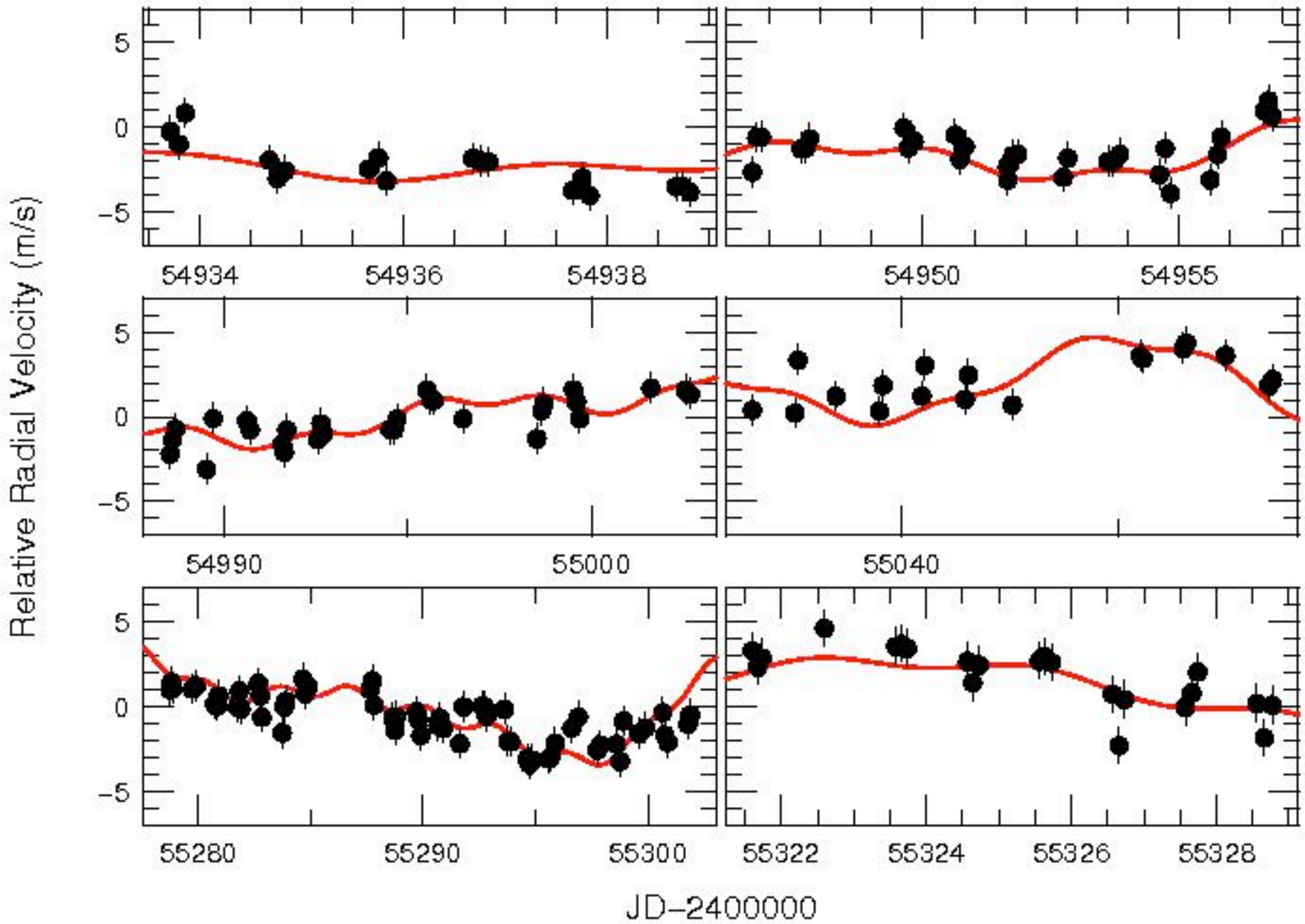
Result is consistent with Dumusque et al. result



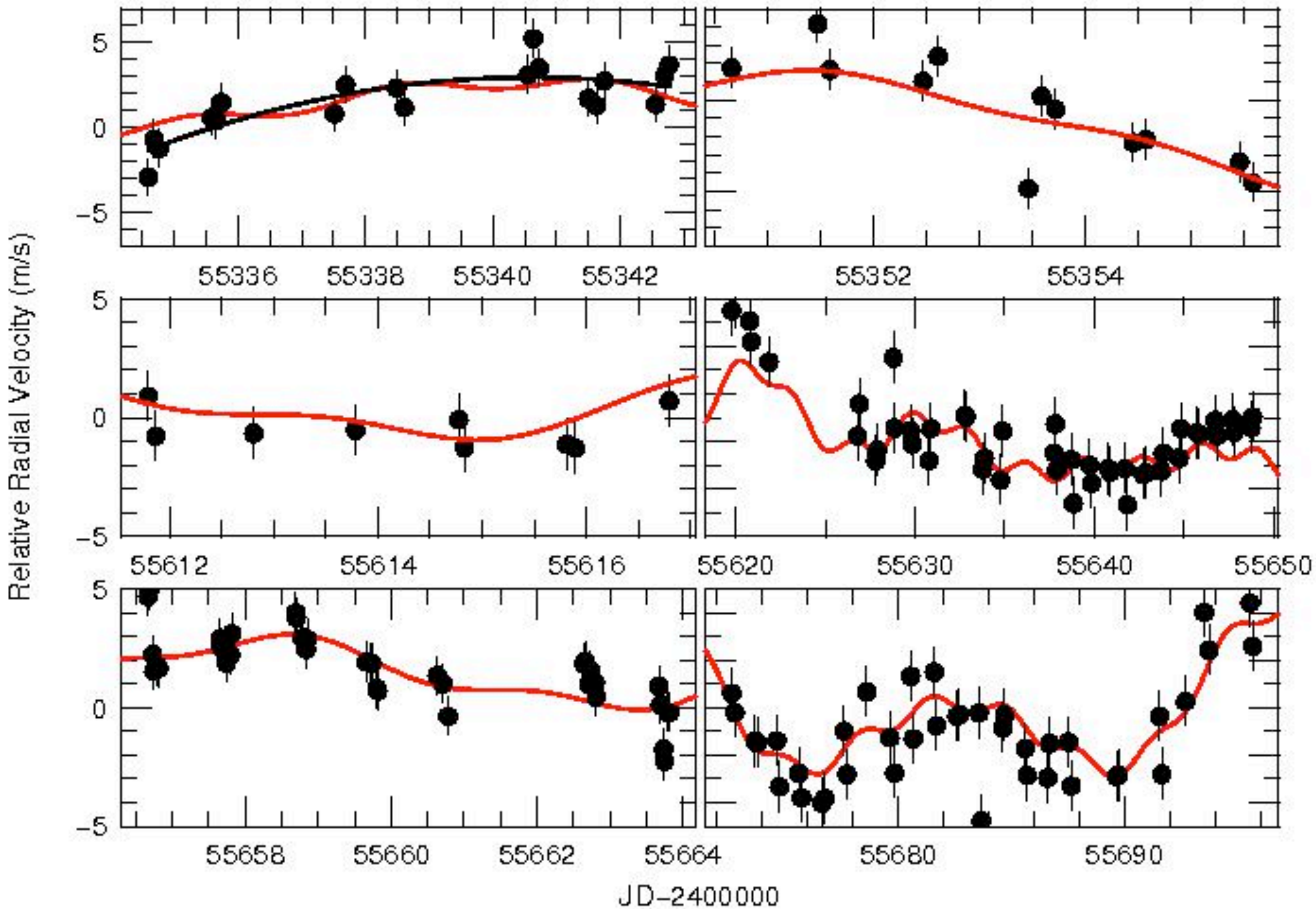
Simulations show that α Cen Bb should have been detected with much higher significance



Relative Radial Velocity (m/s)
JD−2400000
5
0
−5
54526
54528
54530
54550
54560
54570
54612
54614
54616
54640
54645
54880
54882
54884
54914
54916
54918
54920



Relative Radial Velocity (m/s)
JD–2400000
5
0
–5
54934
54936
54938
54950
54955
54990
55000
55040
55280
55290
55300
55322
55324
55326
55328


Relative Radial Velocity (m/s)
JD−2400000
55336
55338
55340
55342
55352
55354
55612
55614
55616
55620
55630
55640
55650
55658
55660
55662
55664
55680
55690
5
0
−5

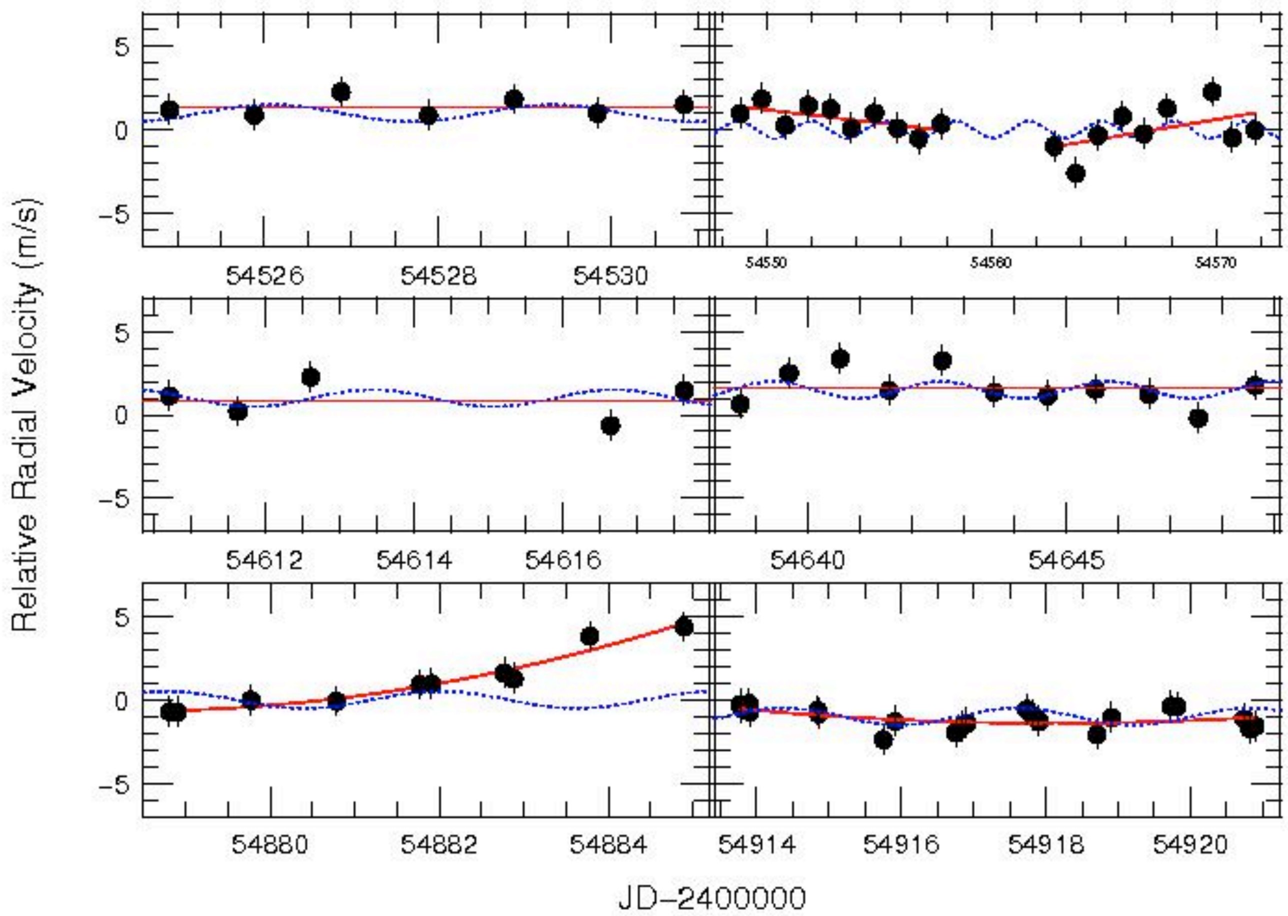
Local Trend Fitting

Exploit the fact that you know two time scales: the rotation period (38 d) and the orbital period of the planet (3.2 d). Assume that the spot distribution does not change in one rotation. Fit the the „local“ variations of the activity over a short time span Δt:

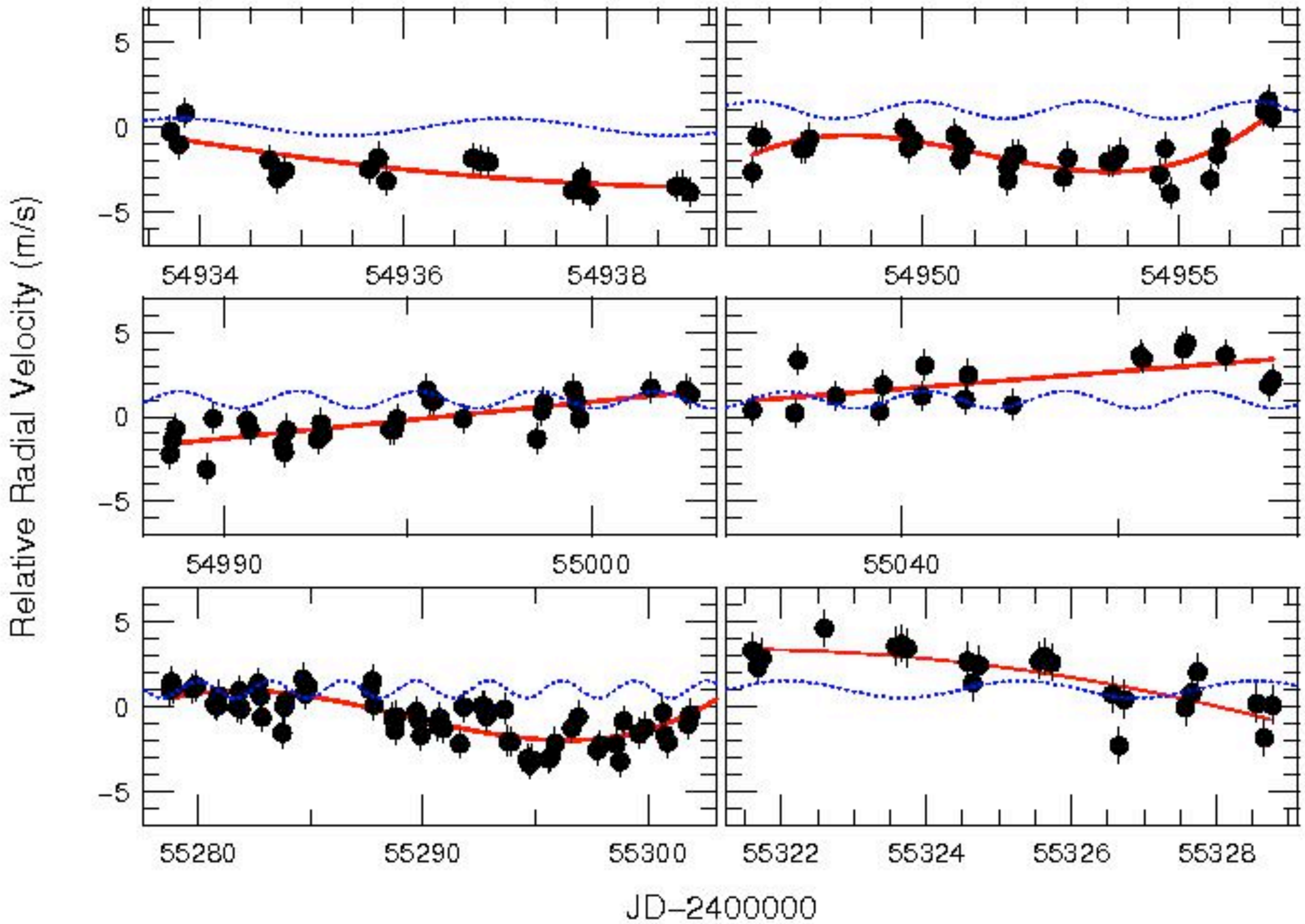
$$P_{planet} < \Delta t < P_{rotation}$$

Try to avoid large data gaps, use data on consecutive nights when possible

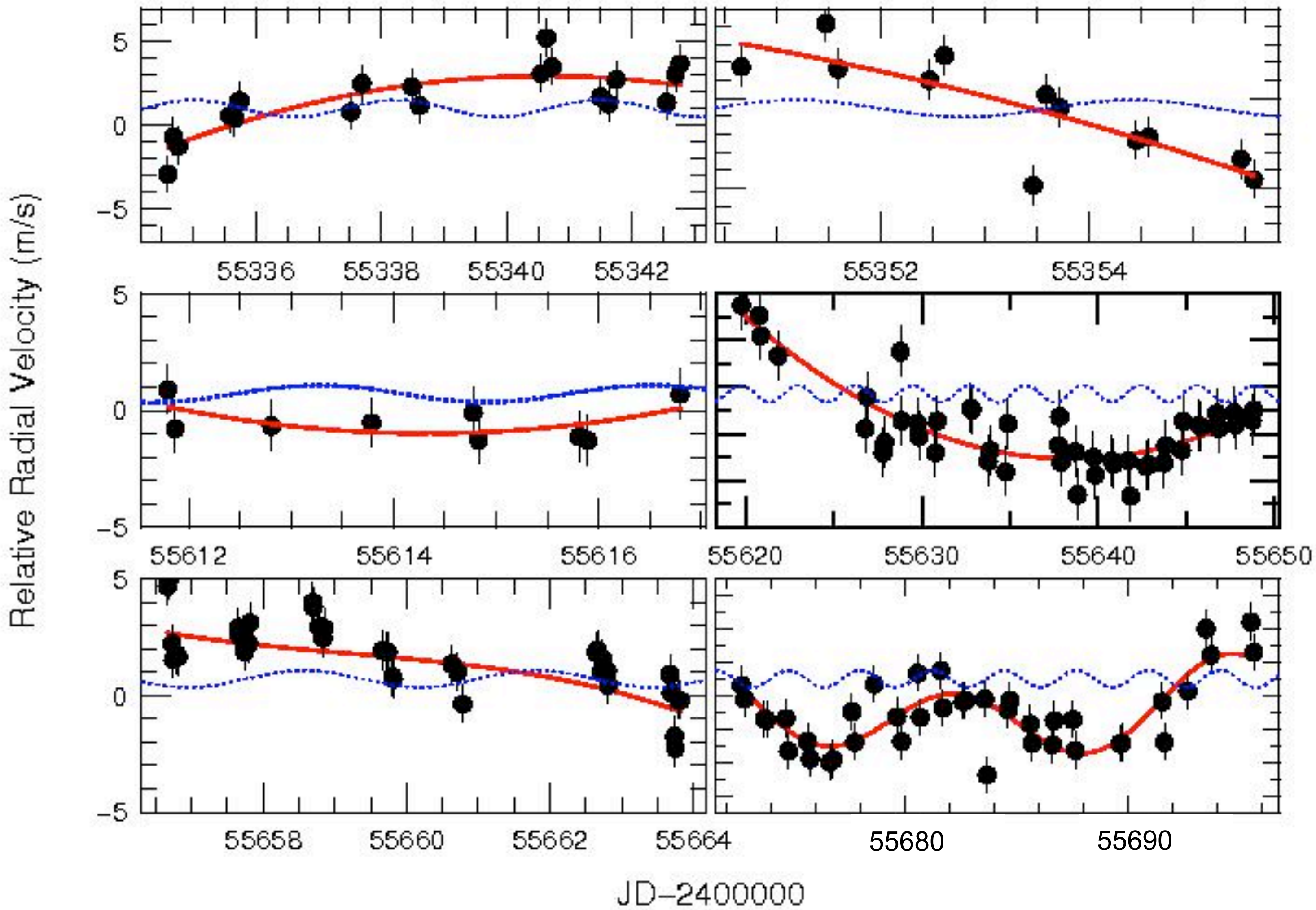
Local Trend Fitting



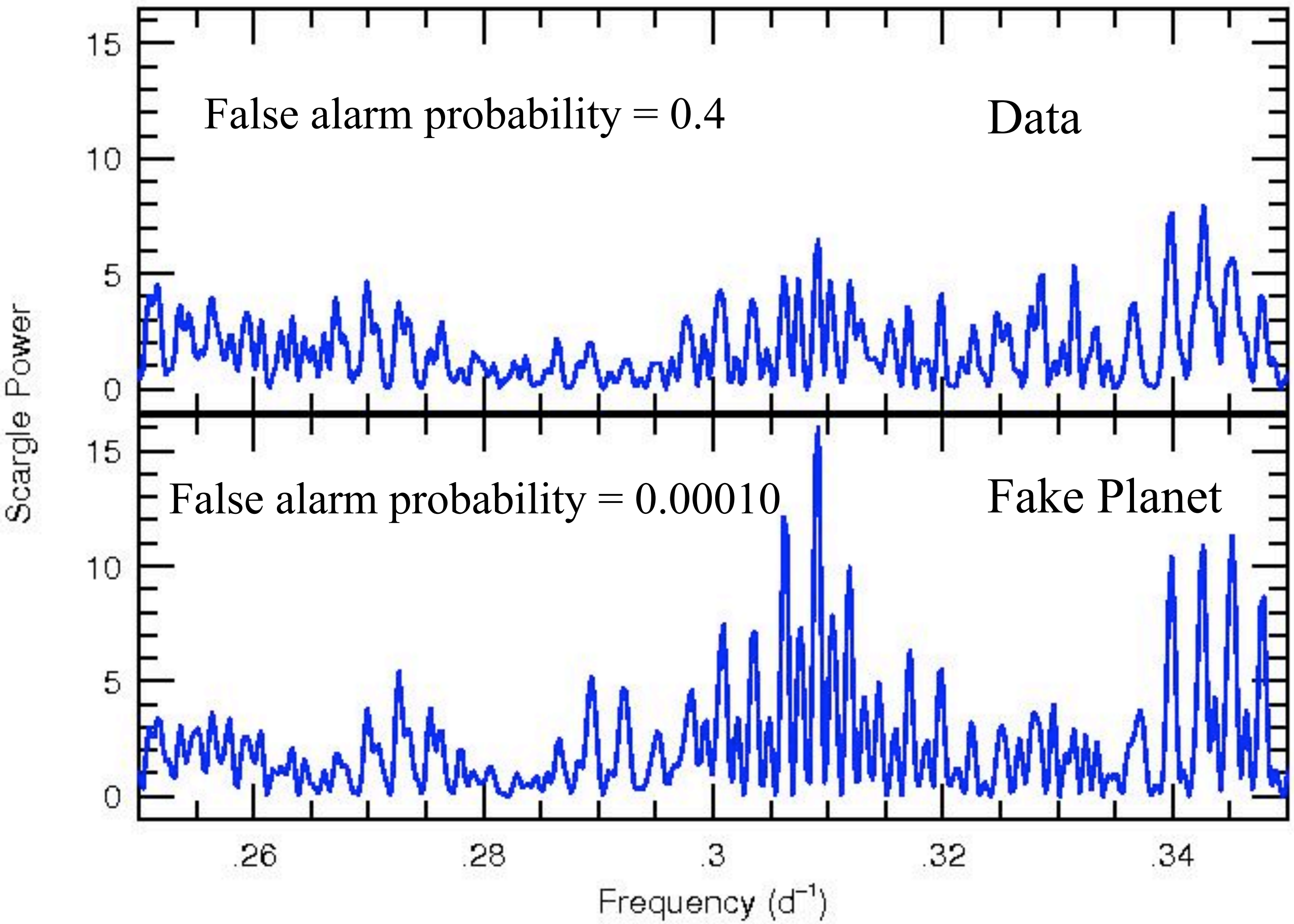
red line: trend fit, blue: planet orbit



Relative Radial Velocity (m/s)
JD−2400000
5
0
−5
54934
54936
54938
54950
54955
54990
55000
55040
55280
55290
55300
55322
55324
55326
55328

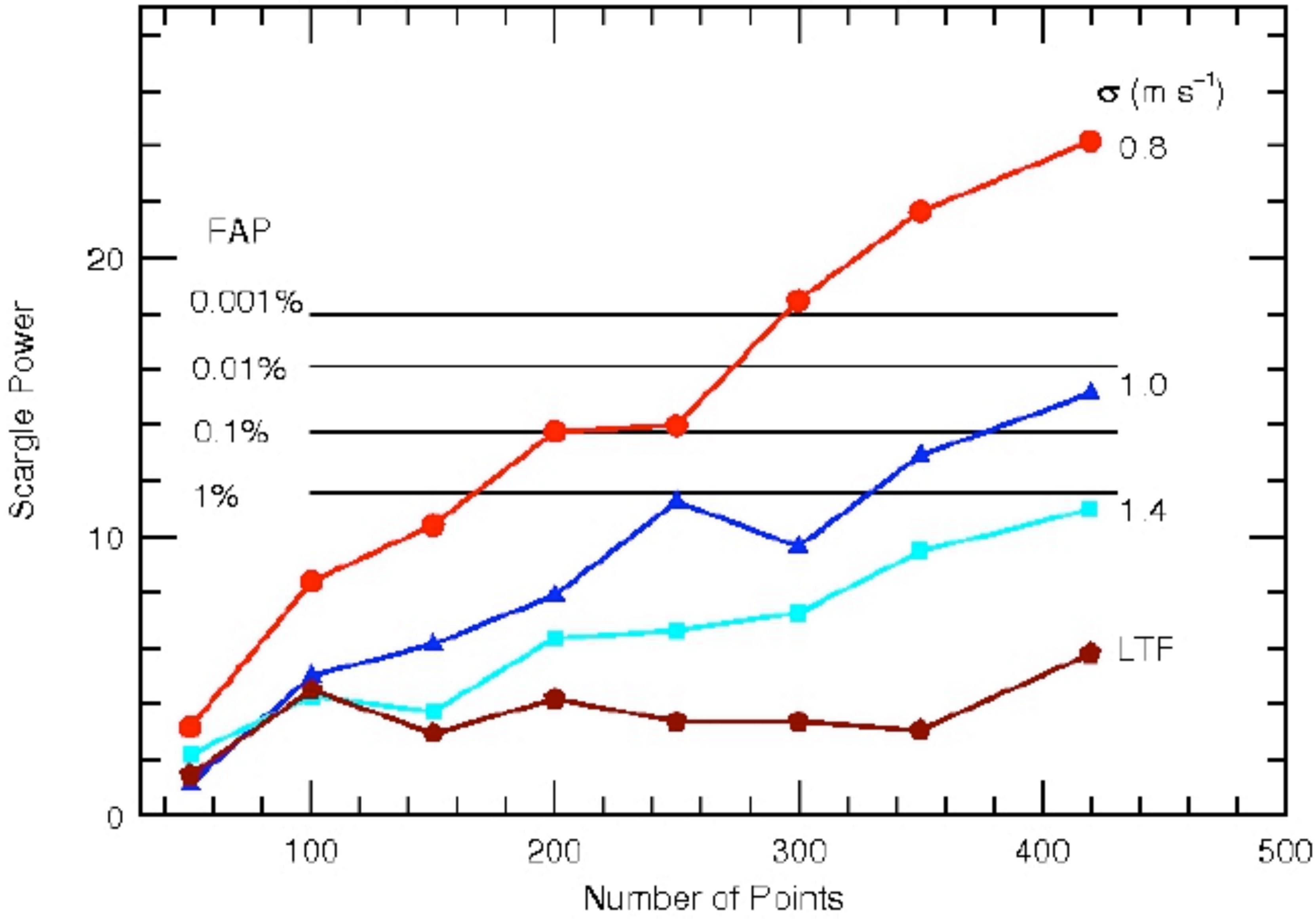


Relative Radial Velocity (m/s)
5
0
−5
55336
55338
55340
55342
55352
55354
55612
55614
55616
55620
55630
55640
55650
55658
55660
55662
55664
55680
55690
JD−2400000

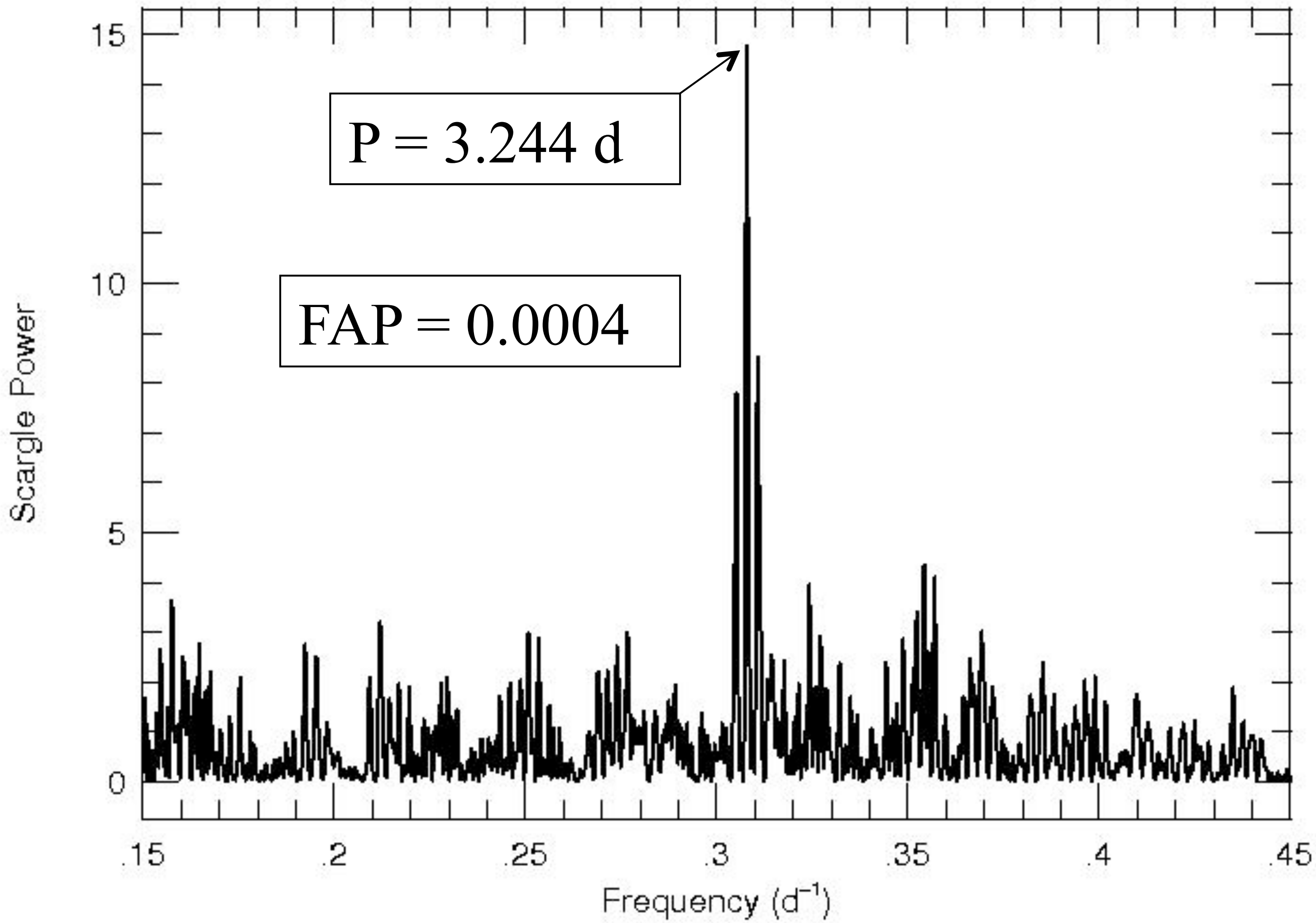


Planet signal is not present! It should have been found with high significance

The Power Behavior of the Real and Simulated Data

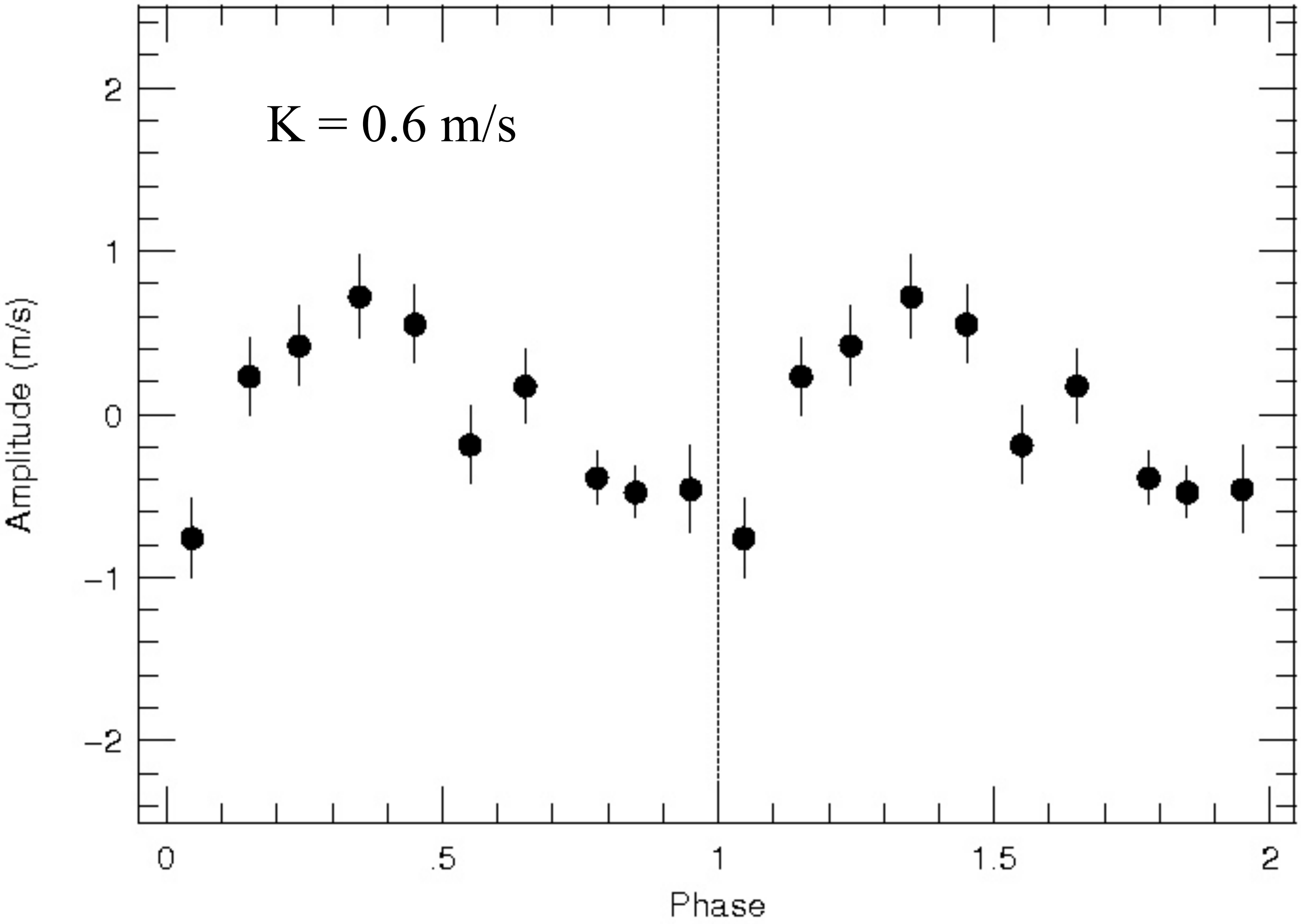


A Simulated Data Set



Scargle periodogram of residuals after removing activity signal.

A Nice planet detection…



The Simulated Data:

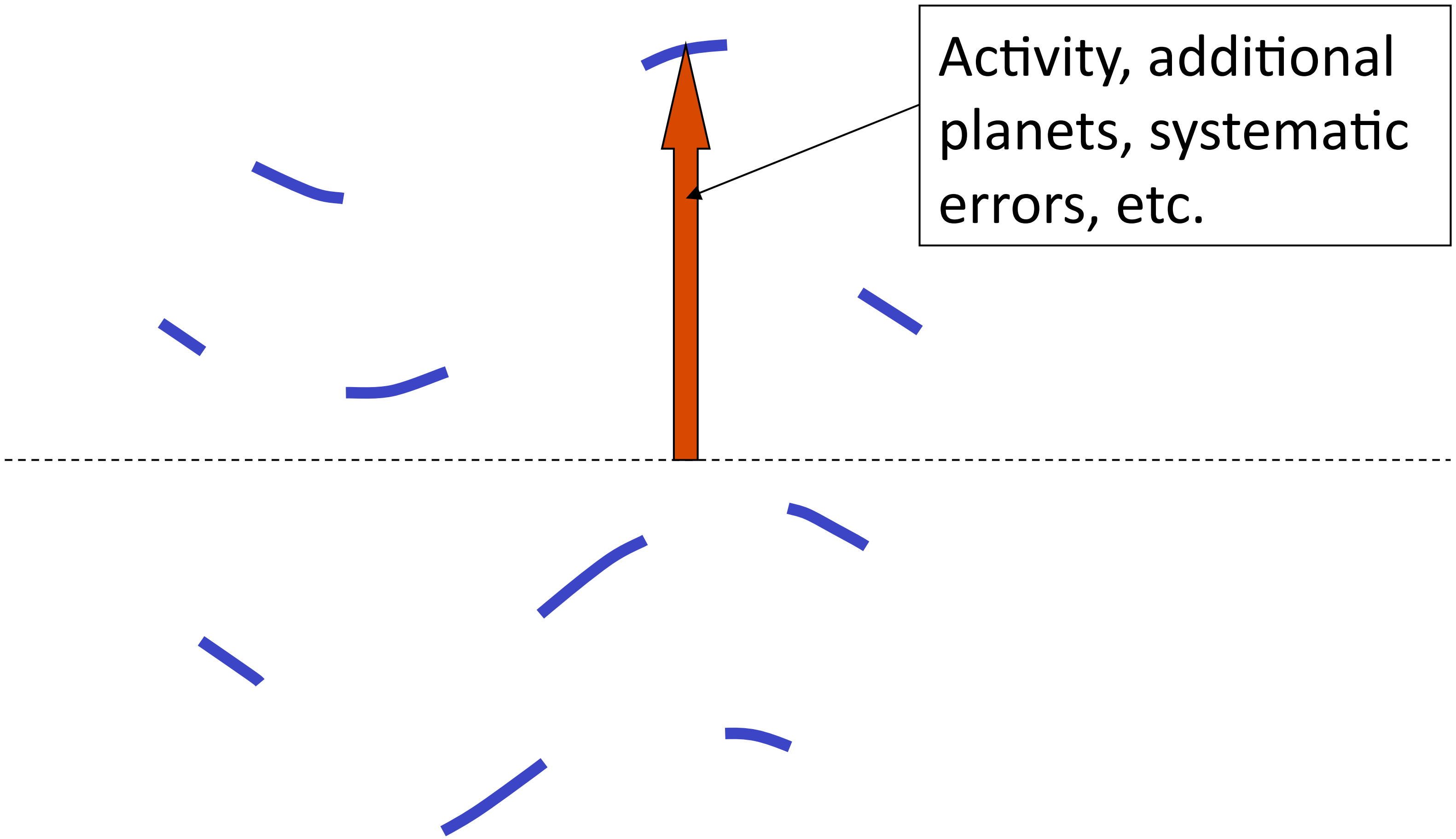
1. Took activity signal: multi-sine fit without the planet signal
2. Sampled this the same way as the data
3. Added random noise (σ = 2 m/s)
4. Filtered the data using pre-whitening

“Science is a way of trying not to fool yourself. The first principle is that you must not fool yourself, and you are the easiest person to fool.”

– Richard Feynman

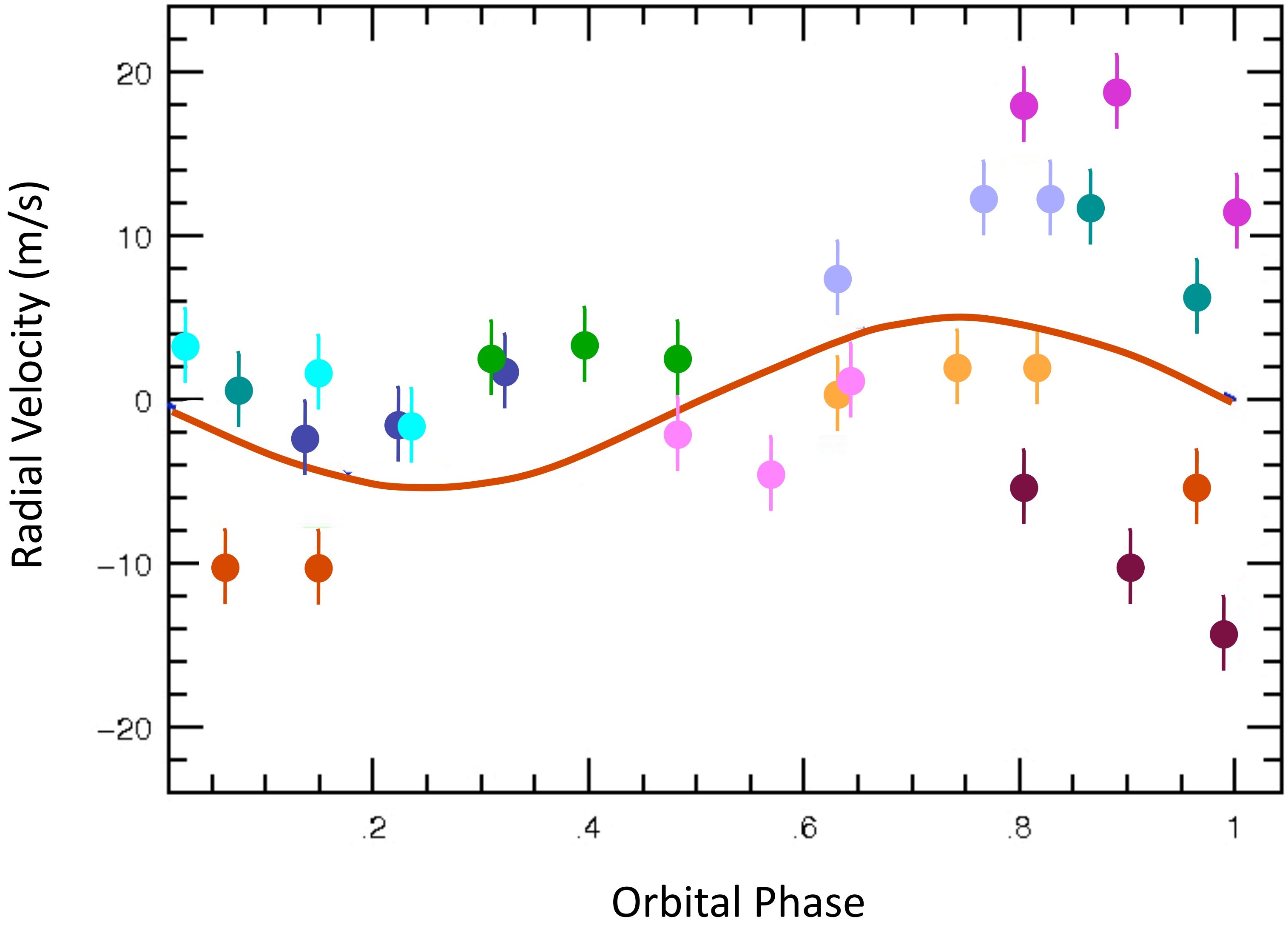
Floating Chunk Offset Periodogram

For short period planets we can use a trick

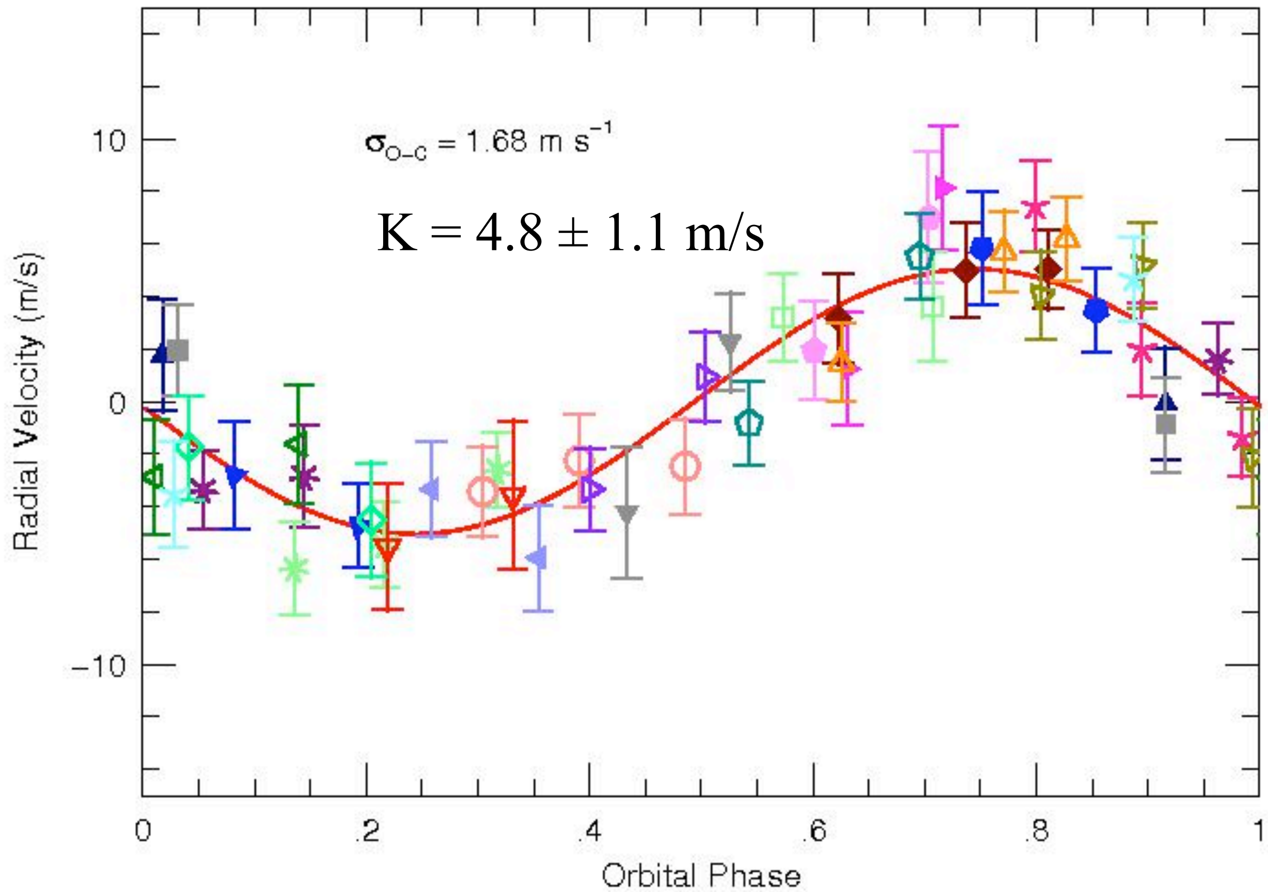


Each night the orbital motion of the planet is part of a sine-curve. We just have to stich the segments together as long as the rotation period is much longer than the orbital period

Let's try this on CoRoT-7b (known orbital period)



A least squares solution with period fixed to transit period



Zero point offset and phase are the only free parameters. The period is kept fixed ➔ transit phase recovered!

The Floating Chunk Offset Periodogram

1) Search for periods much shorter than the stellar rotational period

2) For periods less than about a day most of the variations on a given night are due to the planet and represent a segment of the orbit (sine curve)

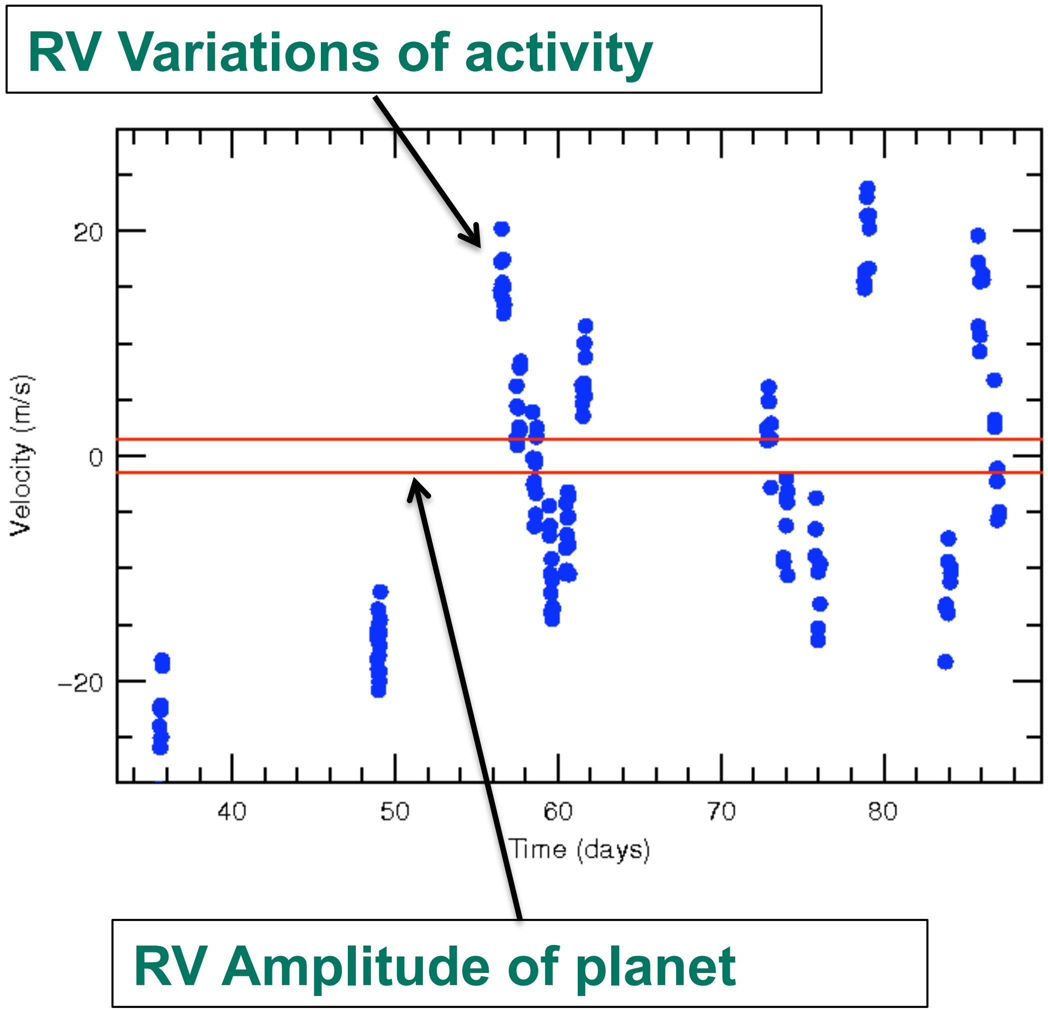
3) RV contribution from activity, long-period planets, systematic errors (long term) is constant

4) For a given trial period, vary the nightly offset until you have a good fit to the sine function. Look at χ^2

5) Vary period and minimize χ^2

6) Only works if you have good sampling (N>2) on a given night

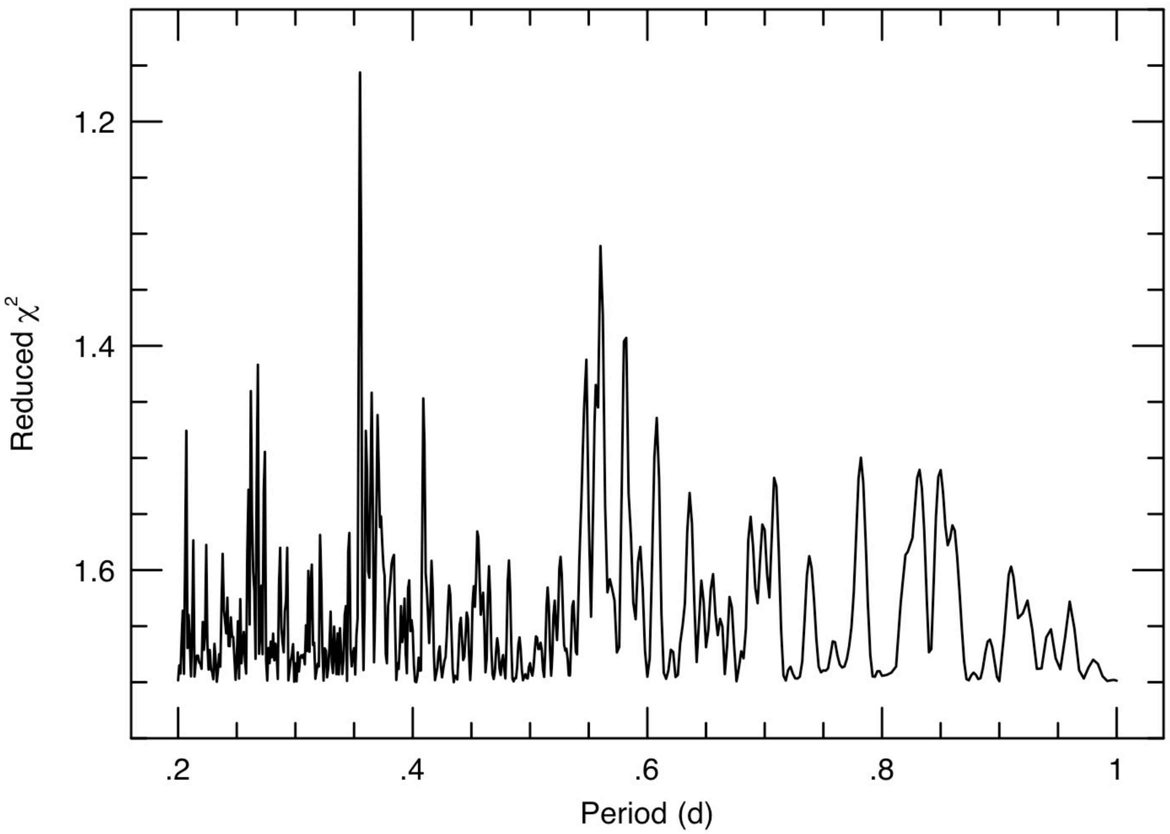
RV variations from a simulated activity signal



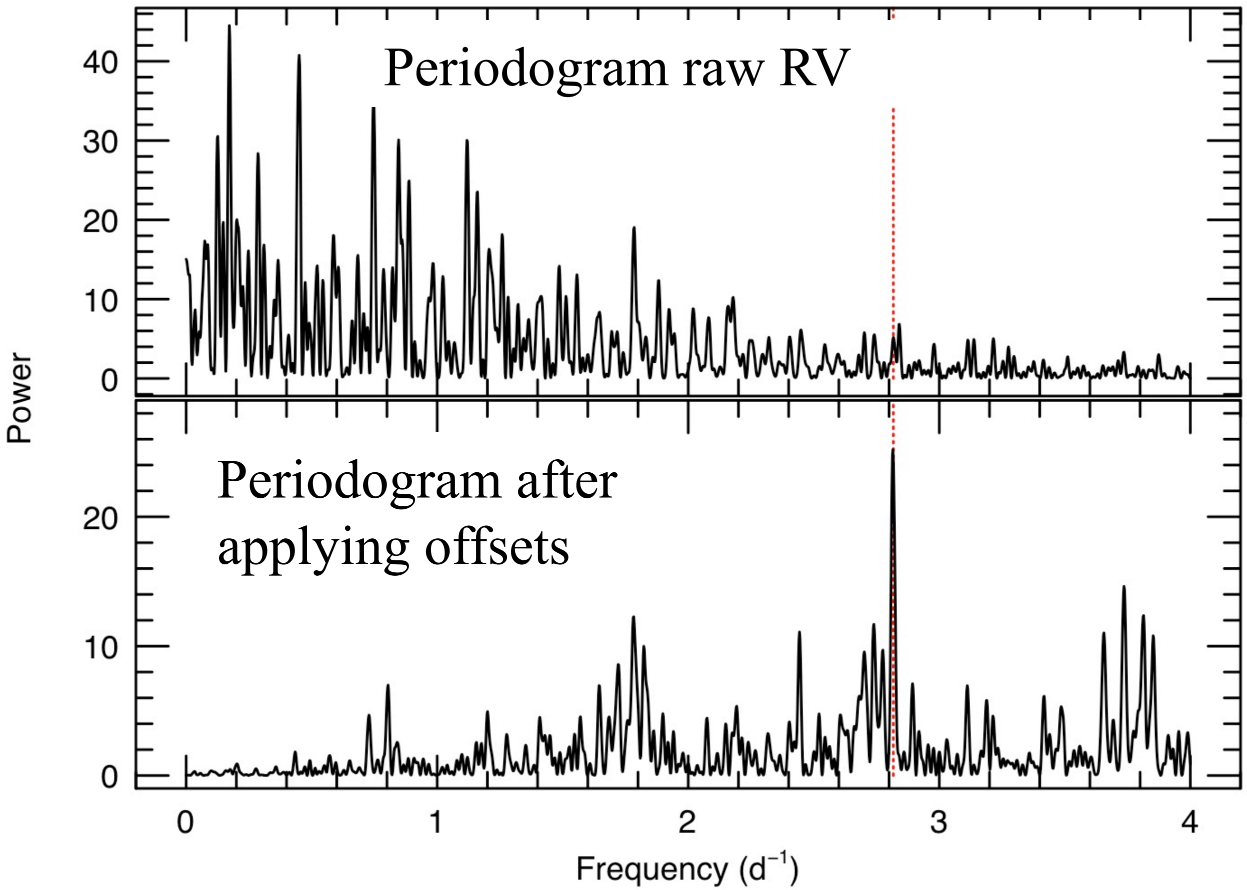
- Activity signal with P_{rot} = 12 d plus harmonics but different for each epoch
- Amplitude ~20 m/s, but varies from epoch to epoch

P_{Planet} = 0.35 d
K = 1.5 m/s
σ = 2.4 m/s

FCO of the simulated data

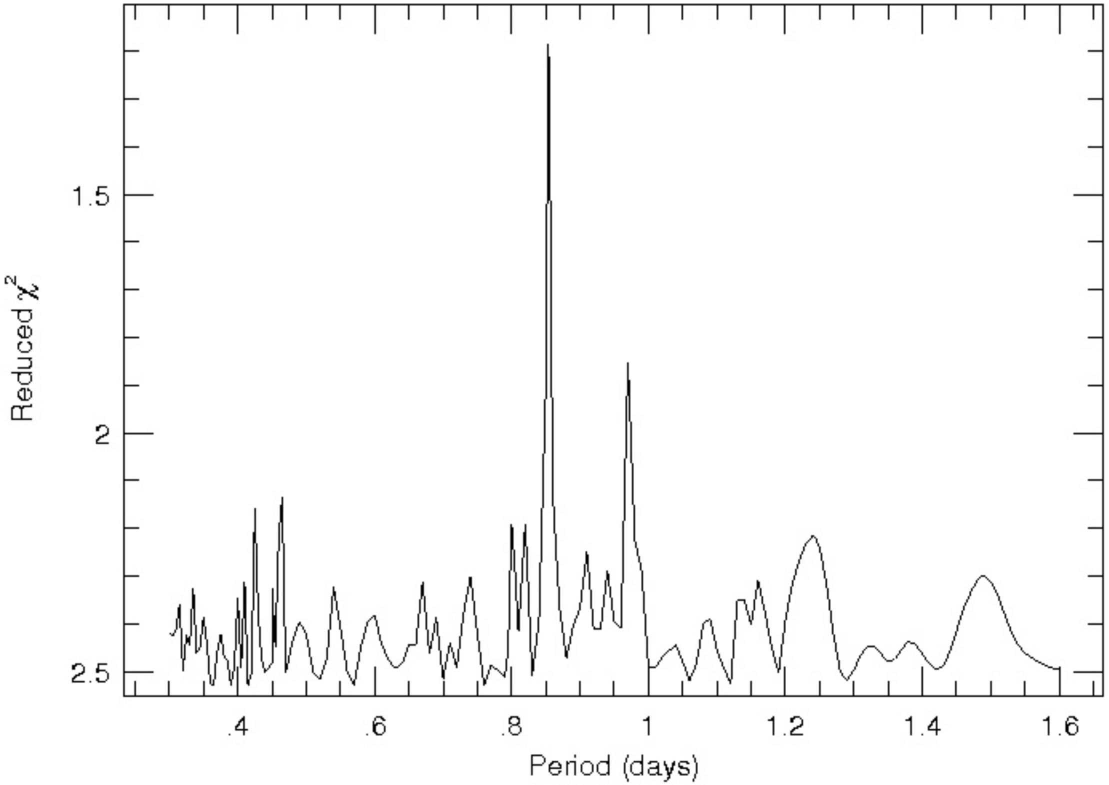


FCO acts as a high pass filter:



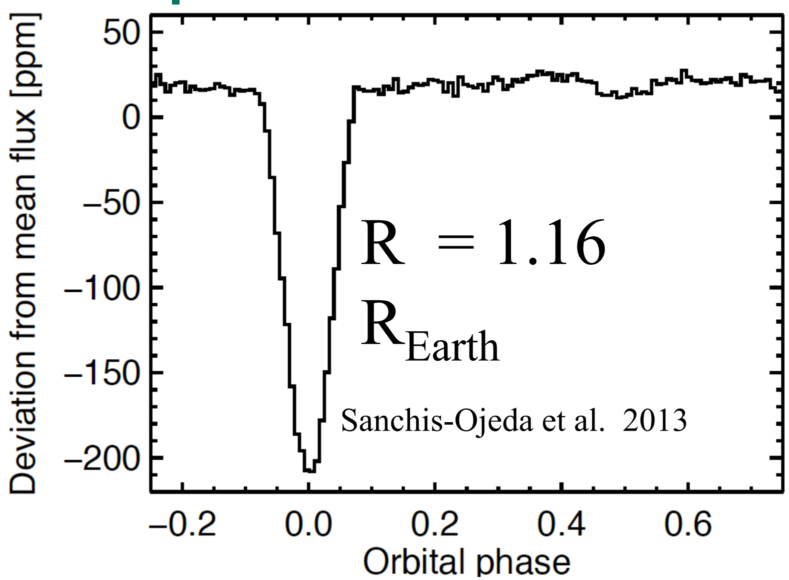
FCO Periodogram of CoRoT-7b Radial Velocities

P_{planet} = 0.85 d
$P_{rotation}$ = 23 d



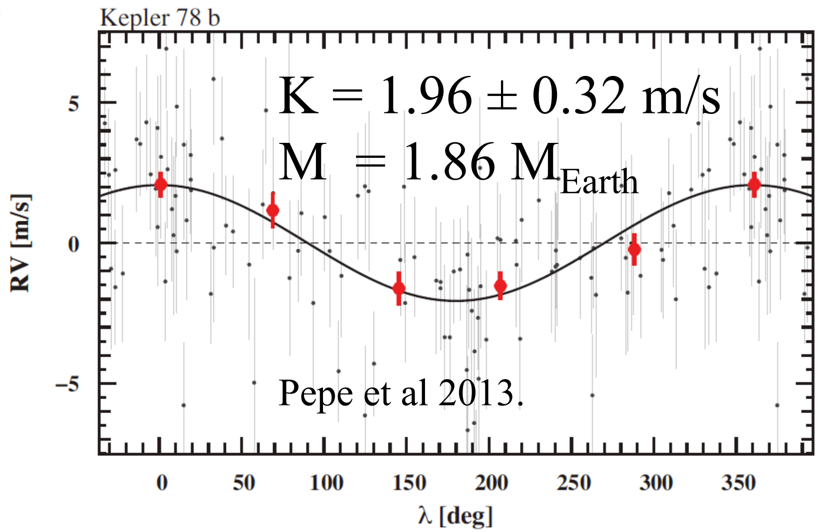
Application to Kepler-78b

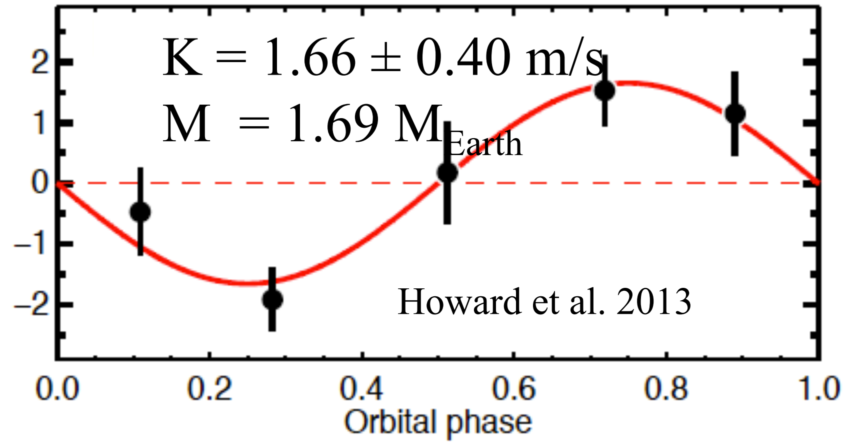
Kepler transit curve



Although we know the orbital period of Kepler-78b (0.355 d), let's assume that we do not.

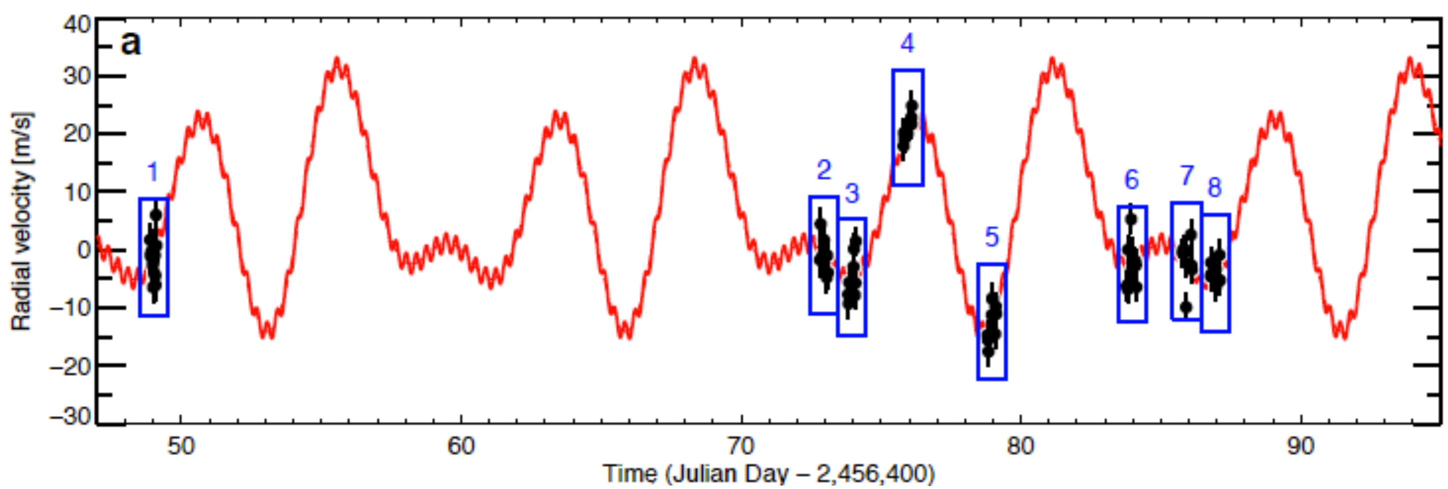
RV Confirmation



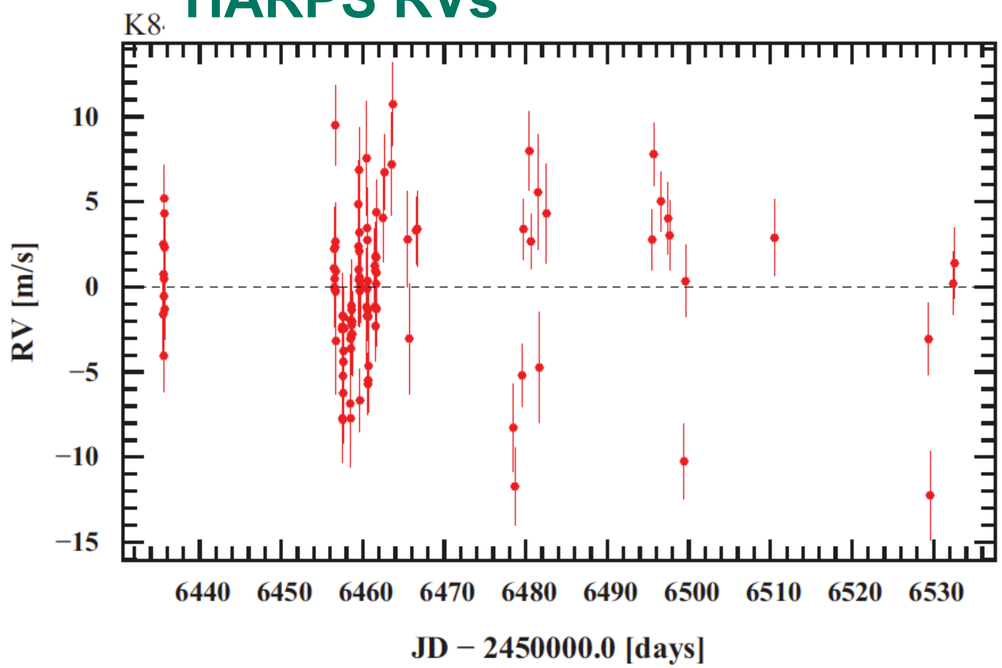


The RV variations are dominated by the activity

Keck RVs



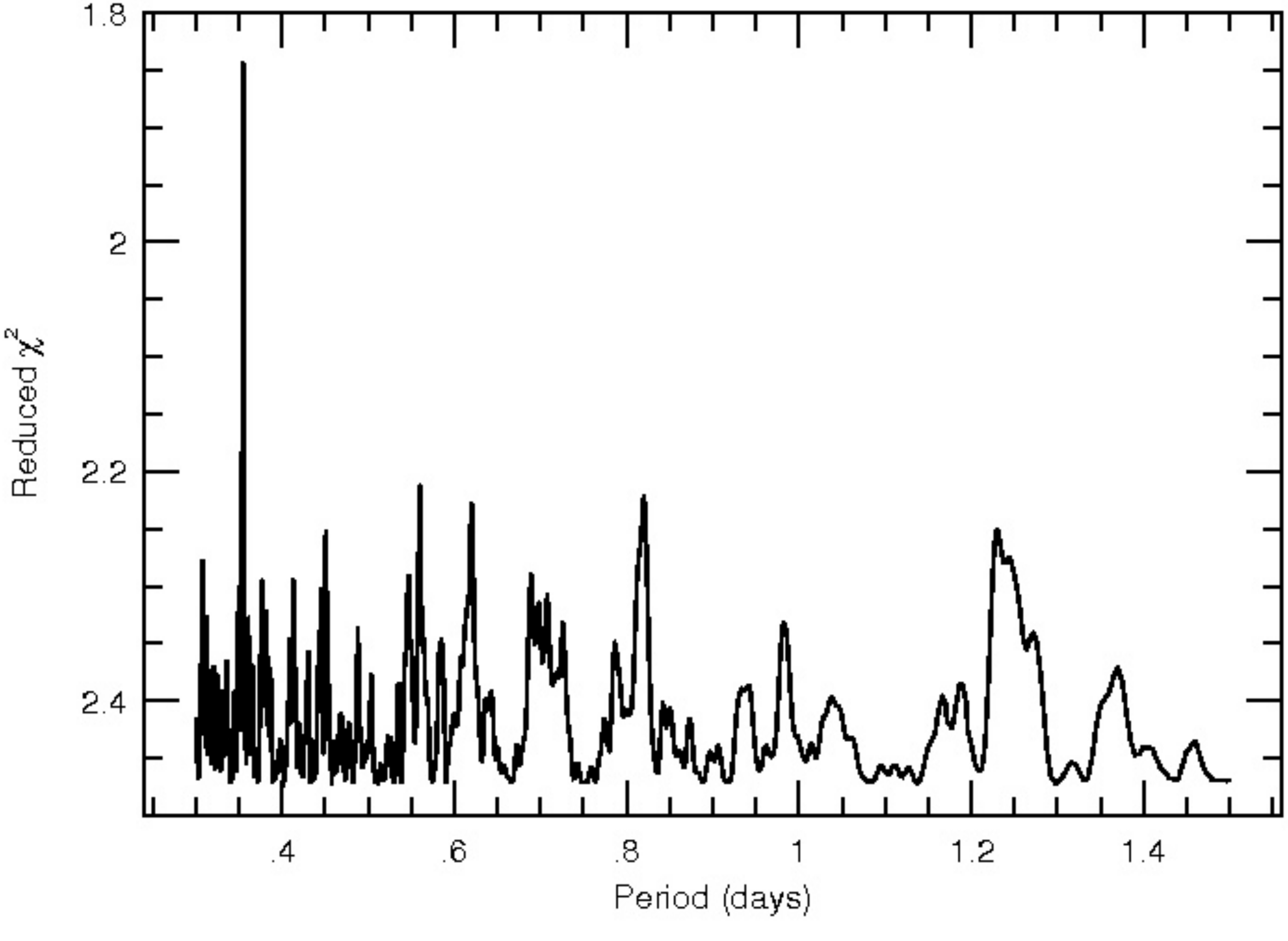
HARPS RVs



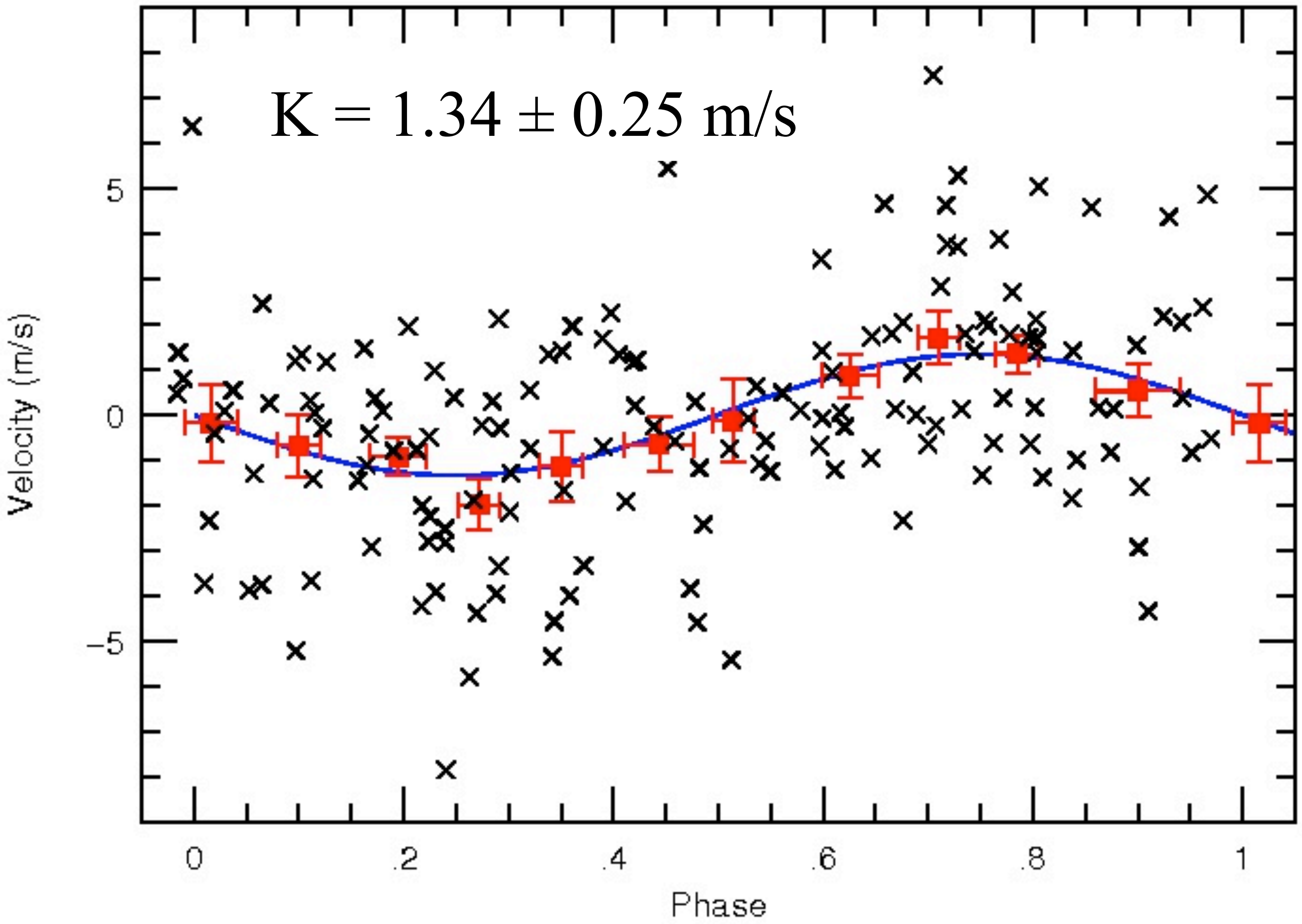
By combining both data sets you should get an improved measurement of the mass

FCO provides a natural way of combining the data

The FCO Periodogram of the Kepler-78 RVs (HARPS + Keck)



The orbital curve of Kepler-78b using only data with N ≥ 3 observations per night



$M = 1.31 \pm 0.24\ M_{Earth}$

Summary

- Pre-whitening can be an effective tool for filtering out the activity signal, BUT check your results with other methods.
- Local trend fitting can check pre-whitening results, but only for proper periods (Fourier speak: planet orbit has a high frequency and you are fitting low frequencies to the activity)
- The FCO periodogram/method is an effective high pass filter that can detect ultra-short period (< 1 d) planets with orbital periods less than the rotation period of the star (or harmonics) Need a phase change of ~ 0.1 in one night, and orbital period ~ 1/10 shortest period harmonic of rotation
- Good time sampling is important