Fragile detection of solar g-modes

Hannah Schunker

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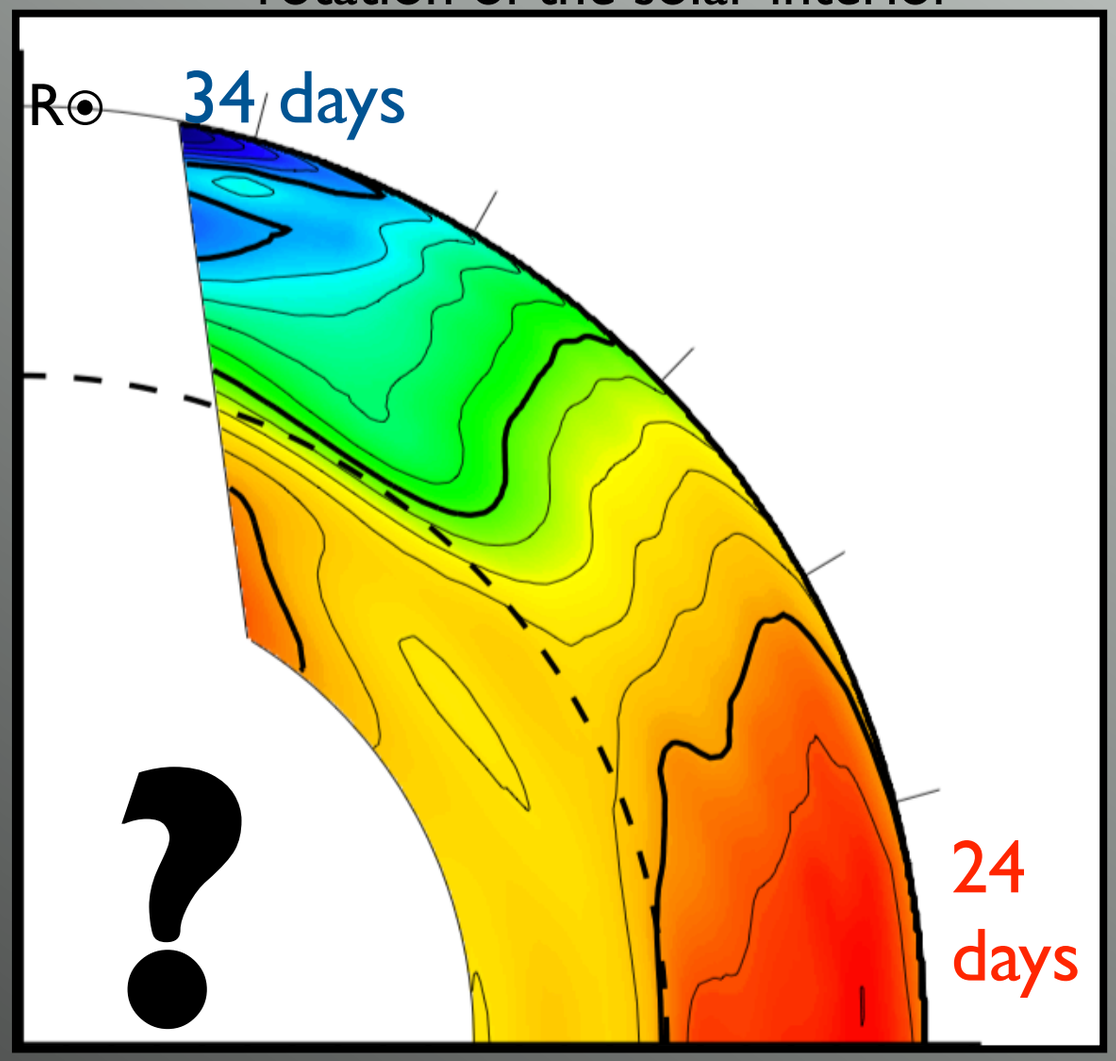
Fossat+2017: super exciting result

I am interested in understanding the solar dynamo

Rotation - in particular radial differential rotation - is important

Apply this method to other Sun-like stars

My goal was to understand the method and determine what is critical in order to apply the same principles to other stars



Schou+ 1998

Overview

1. Reproducing Fossat et al. 2017

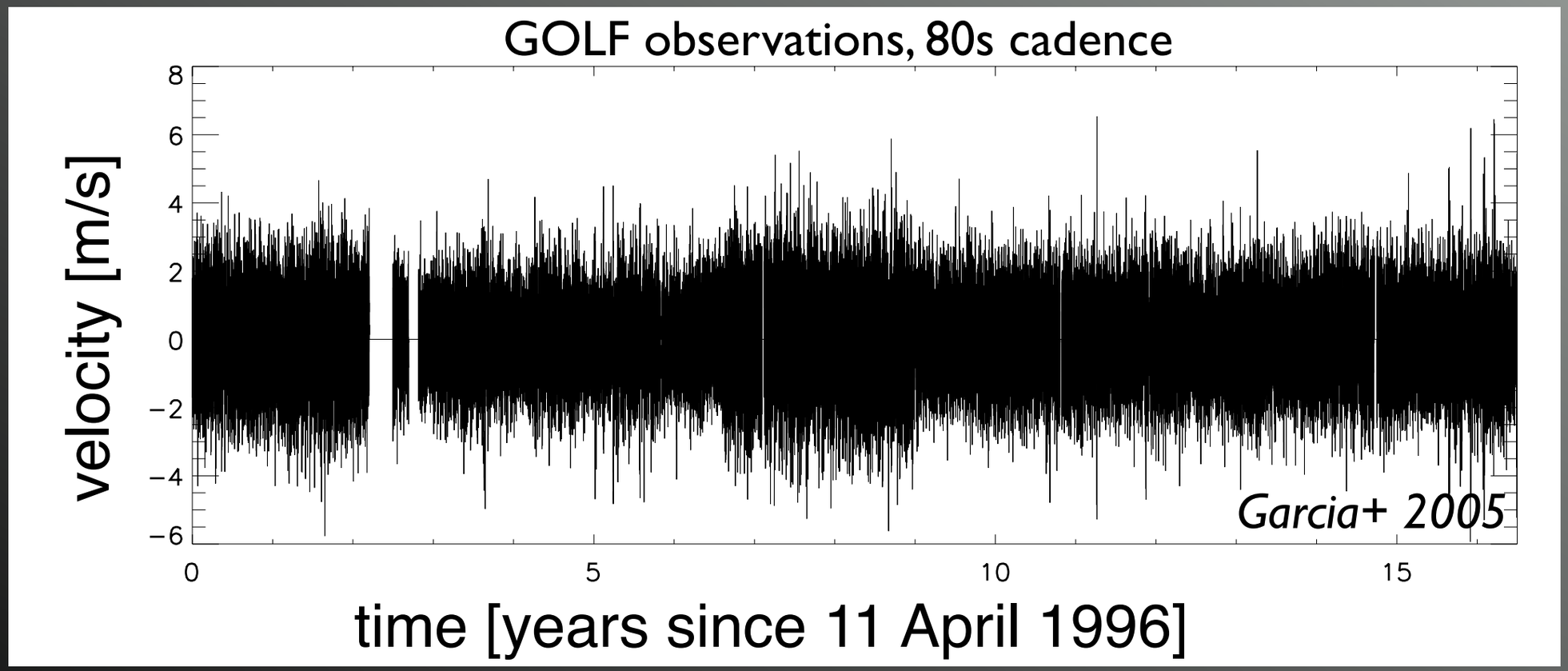
2. Sensitivity to parameters
   i. Fitting function to measure RTTT
   ii. Smoothing of AC
   iii. Start time of data series
   iv. Cadence of RTTT measurements
   v. Overlap of data segments

3. MC parameter study

Observations

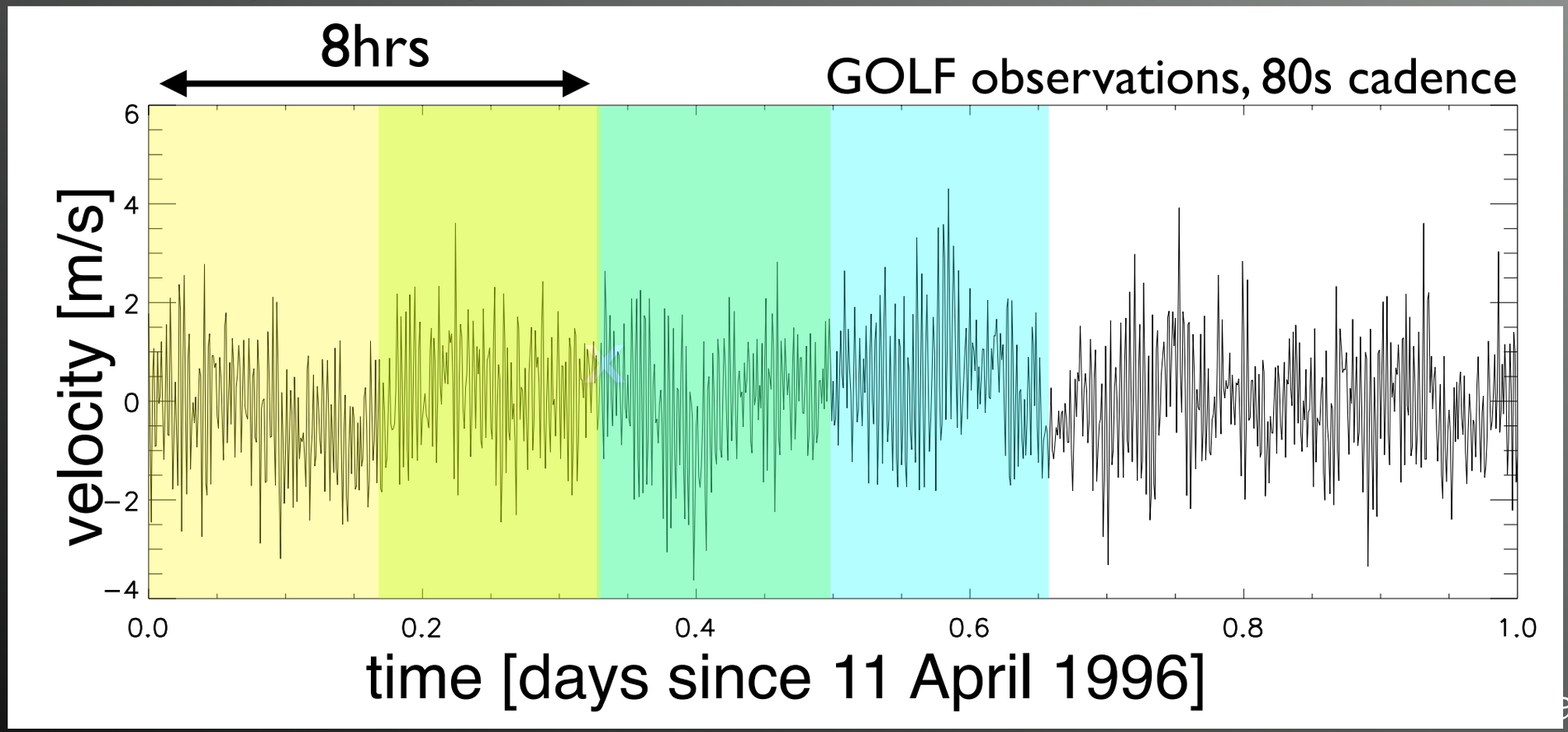
Global Oscillations at Low Frequencies (GOLF) onboard ESA/NASA's Solar and Heliospheric Observatory (SOHO)

16.5 years, 80 second cadence *Garcia et al. 2005*



Reproducing Fossat

- Measure changes to the round-trip travel-time (RTTT) of the *p*-modes over this 16 years of observations
- Divide the data series into segments 8 hours long, with a 4 hour cadence (36130)
- Zero-pad up to 10^6 seconds (278 hours)



Reproducing Fossat

Compute the FT of each 8-hour padded segment
Compute the mean 8-hour PS
Fit a Gaussian between 1.5 - 5 mHz

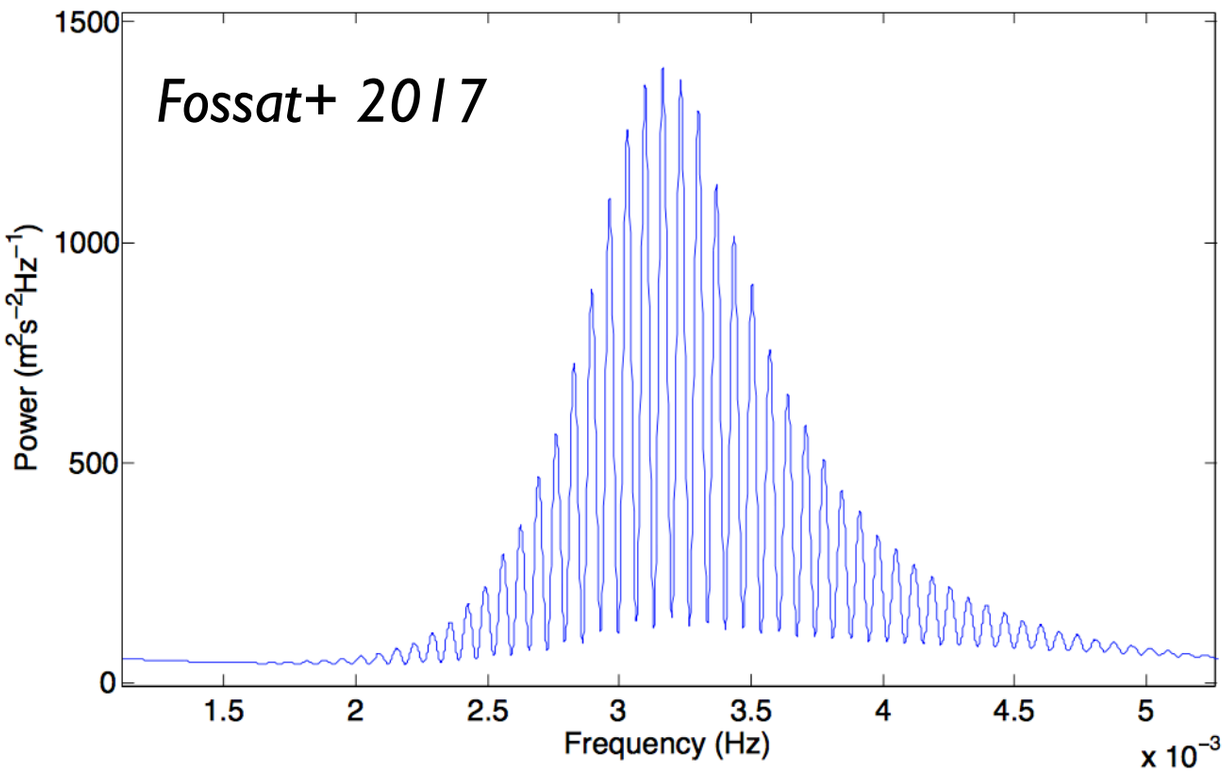
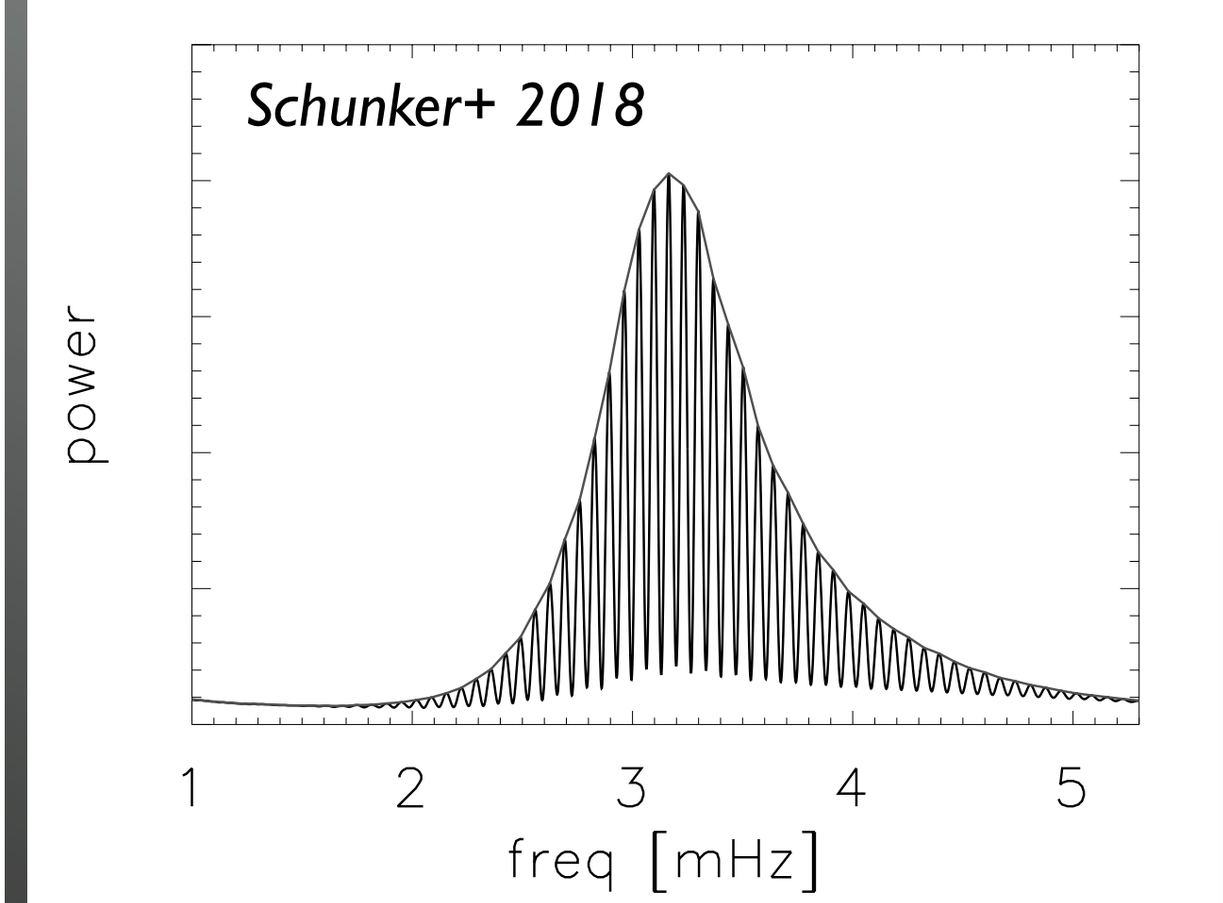


Fig. 2. From the same 16.5-year data set as Fig. 1, this is an average of 34 612 spectra computed from 8-h selections taken at intervals of 4 h.



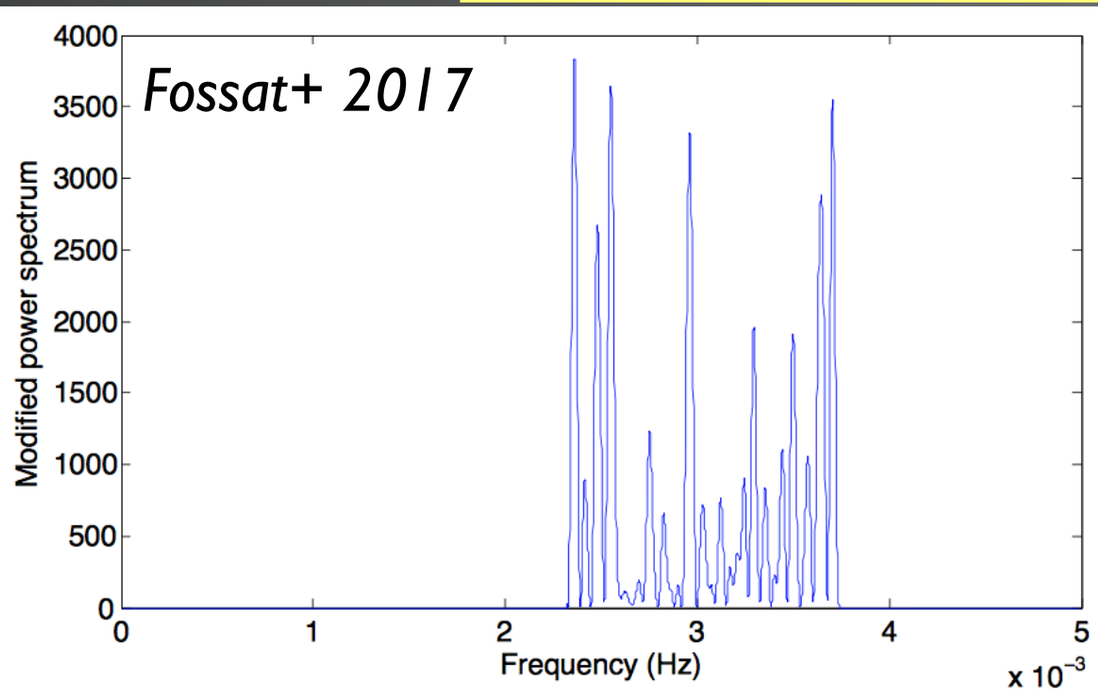
Reproducing Fossat

For each 8 hour segment, FT and filter for low-frequency *p*-modes

Normalise by the Gaussian fit

Shift to zero frequency, zero pad 125 mHz, FT

regular spacing of the *p*-modes with same harmonic degree



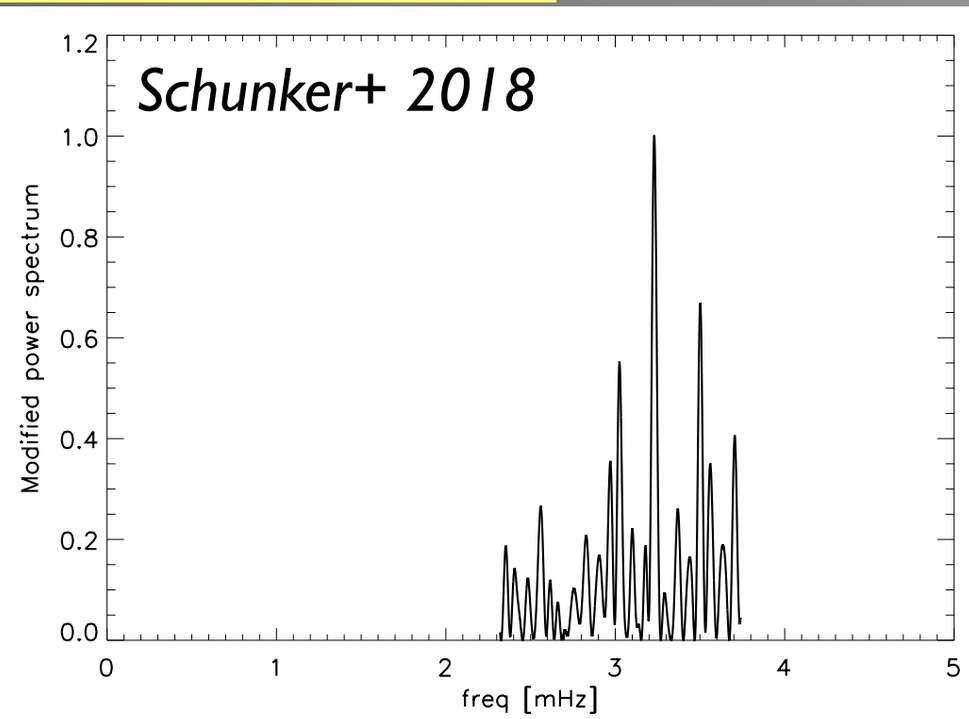
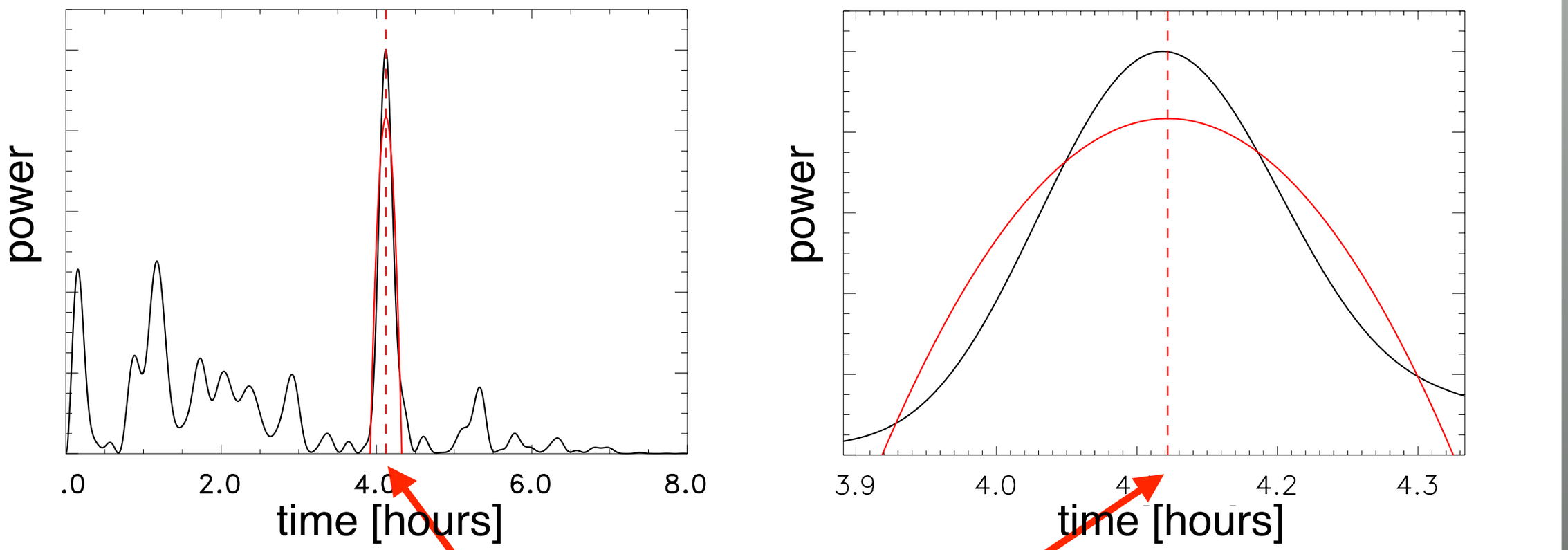


Fig. 3. Example of one of the 34612 GOLF power spectra, limited to the range 2.32–3.74 mHz and divided by the envelope of the mean spectrum of Fig. 2.

Test: Measuring RTTT

- Measure the RTTT by least-squares fitting a quadratic function (4 hours 3 minutes) for each 8 hour segment



Schunker+ 2018

Round Trip Travel Time

Reproducing Fossat

- Compare average temporal power spectrum

Average temporal power spectrum

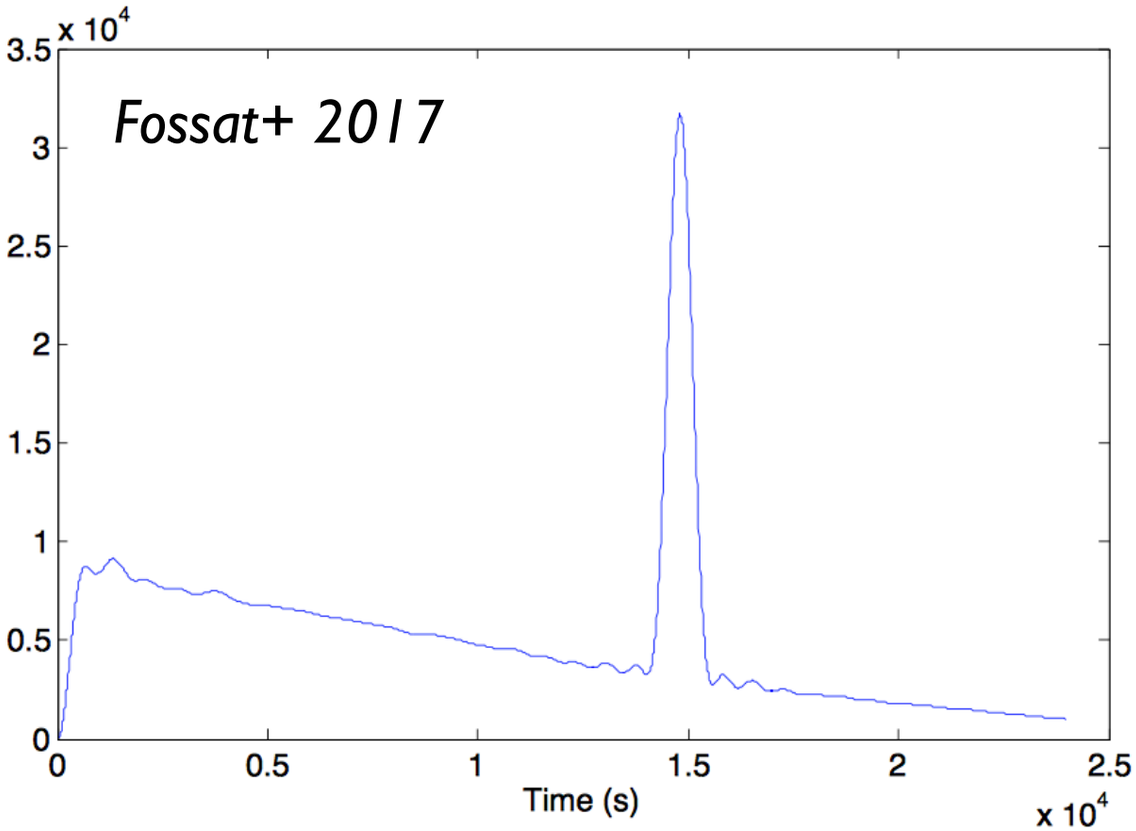
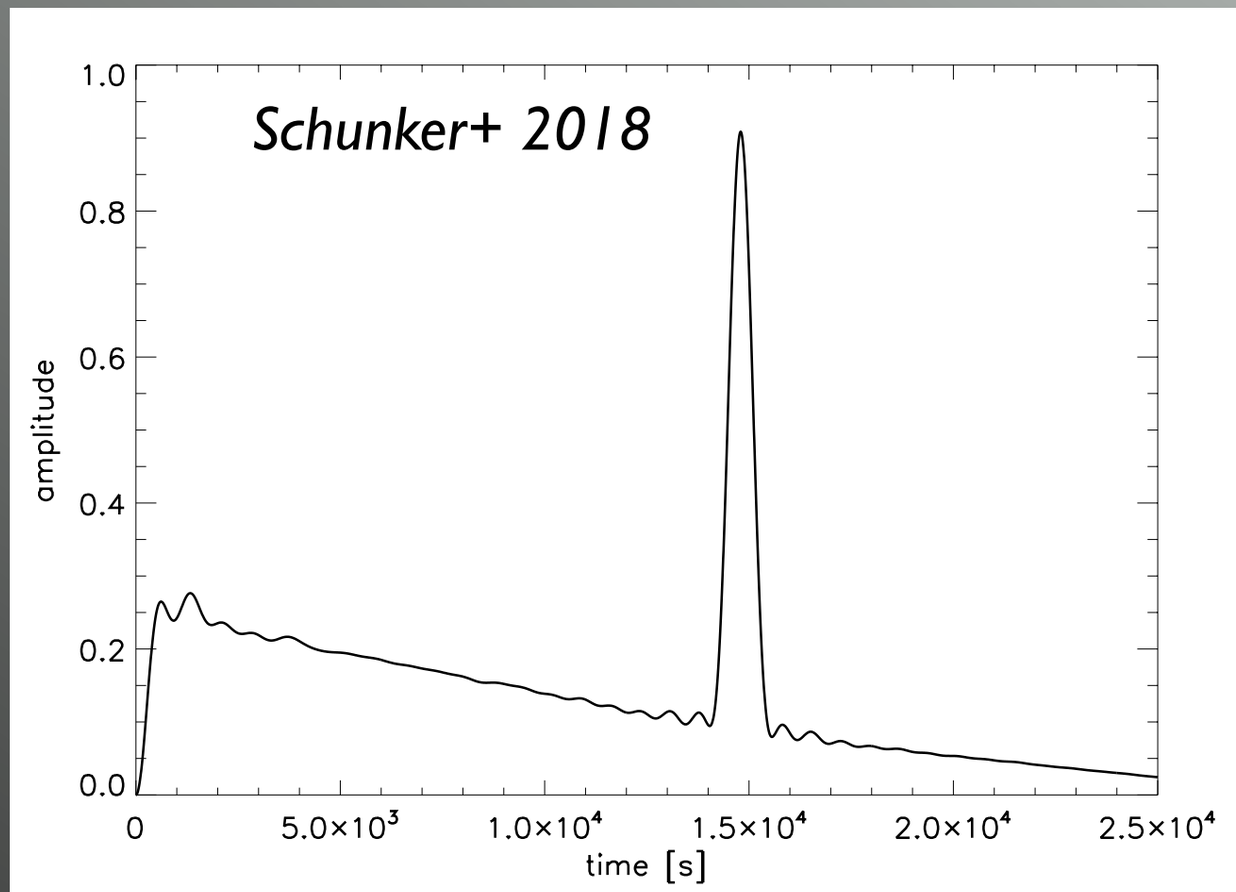


Fig. 5. Sum of 34 612 power spectra similar to the spectrum shown in Fig. 4.



4 hours 3 minutes

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Reproducing Fossat

- 16.5 year long series of the RTTT at a 4 hour cadence (clipped at +/- 240s)

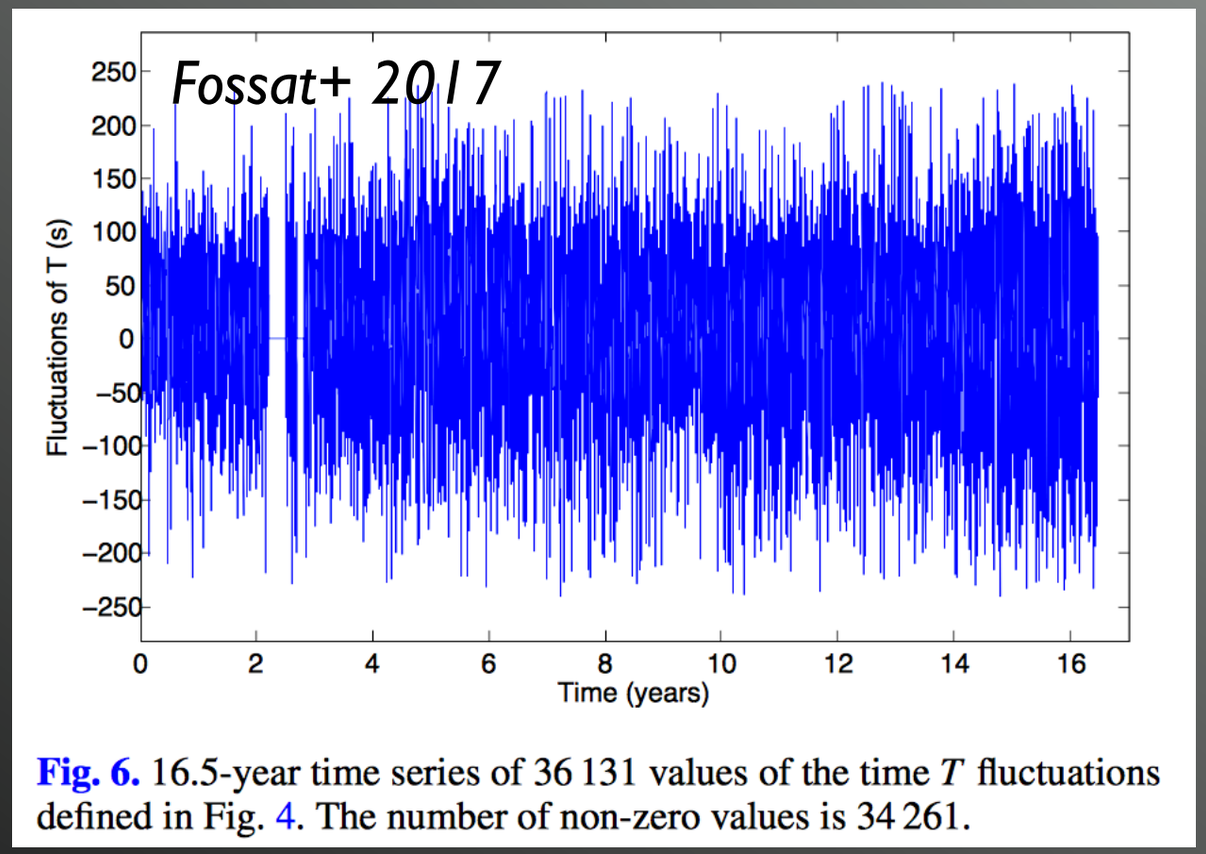
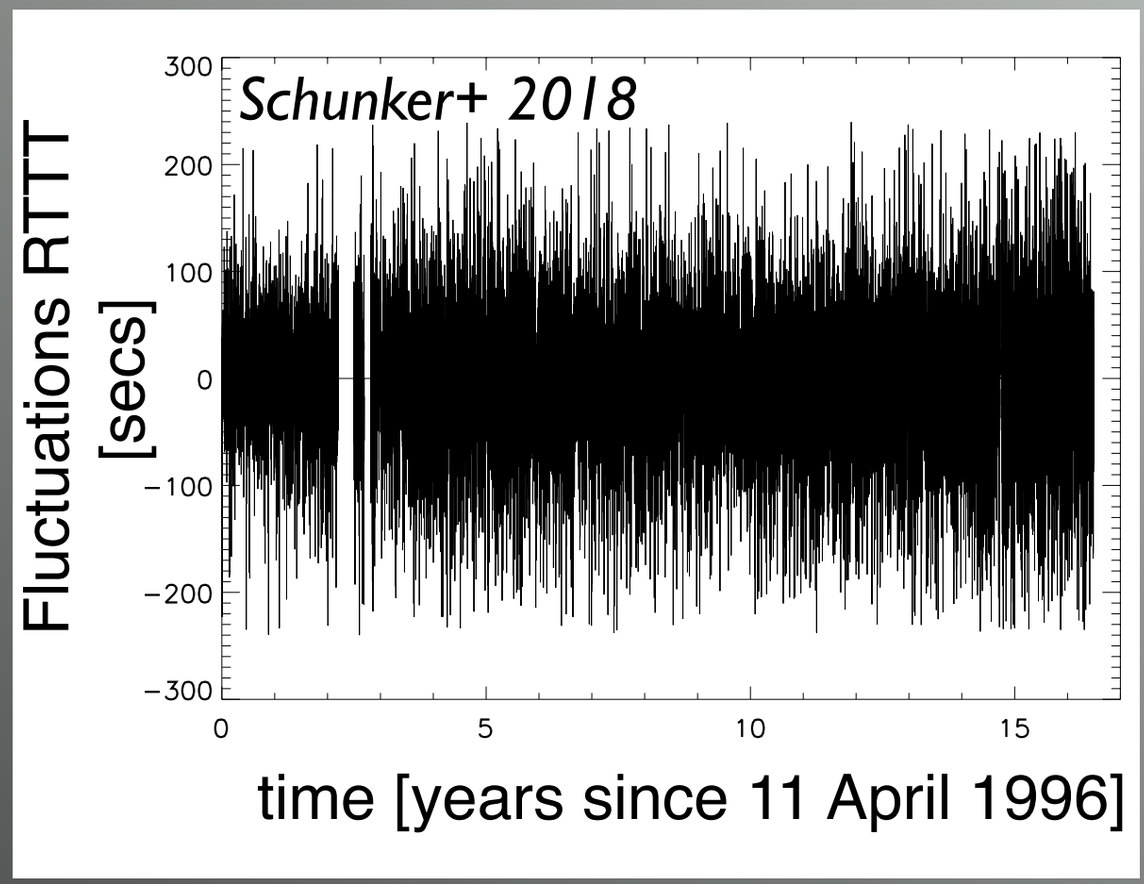


Fig. 6. 16.5-year time series of 36 131 values of the time T fluctuations defined in Fig. 4. The number of non-zero values is 34 261.



- Perturbations should vary at the frequency of the density perturbations to the core caused by the g-modes

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Reproducing Fossat

- Power spectrum should show the frequency at which the RTTT changes due to density perturbations of the core caused by g-modes

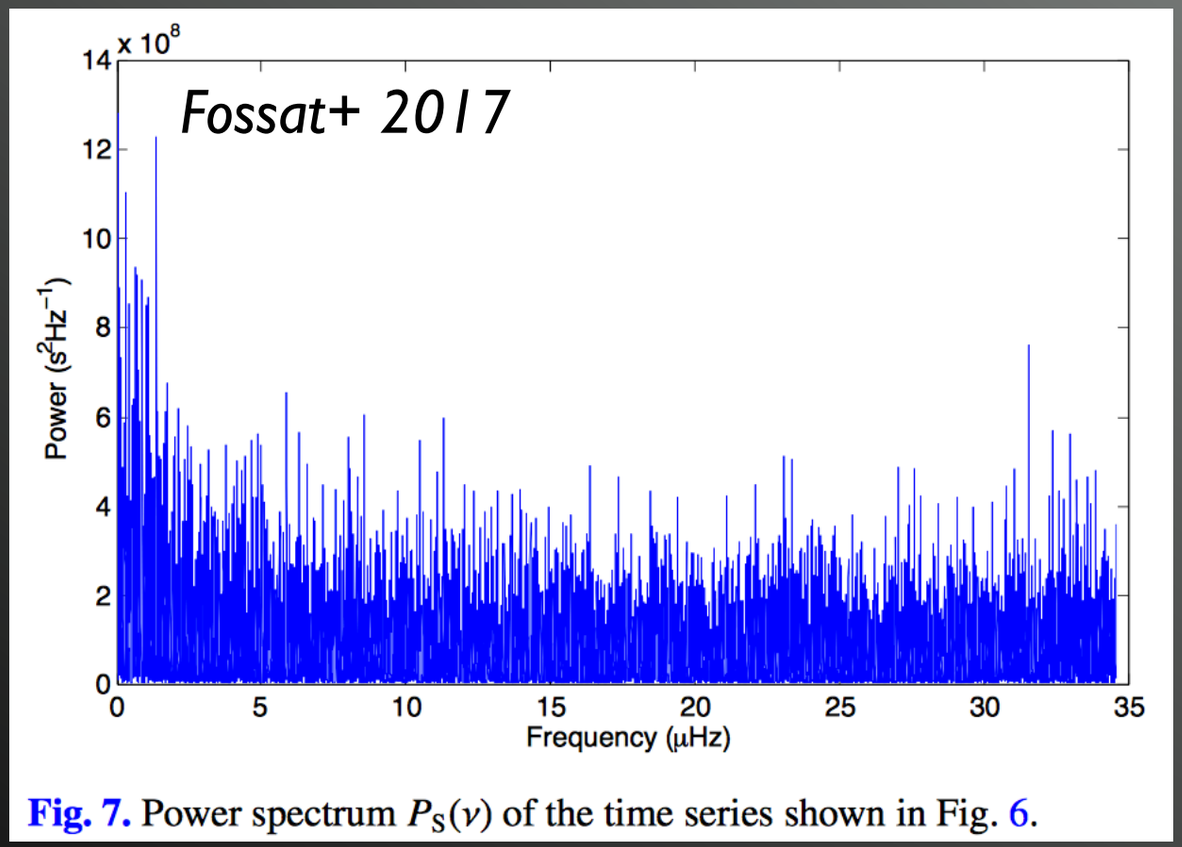
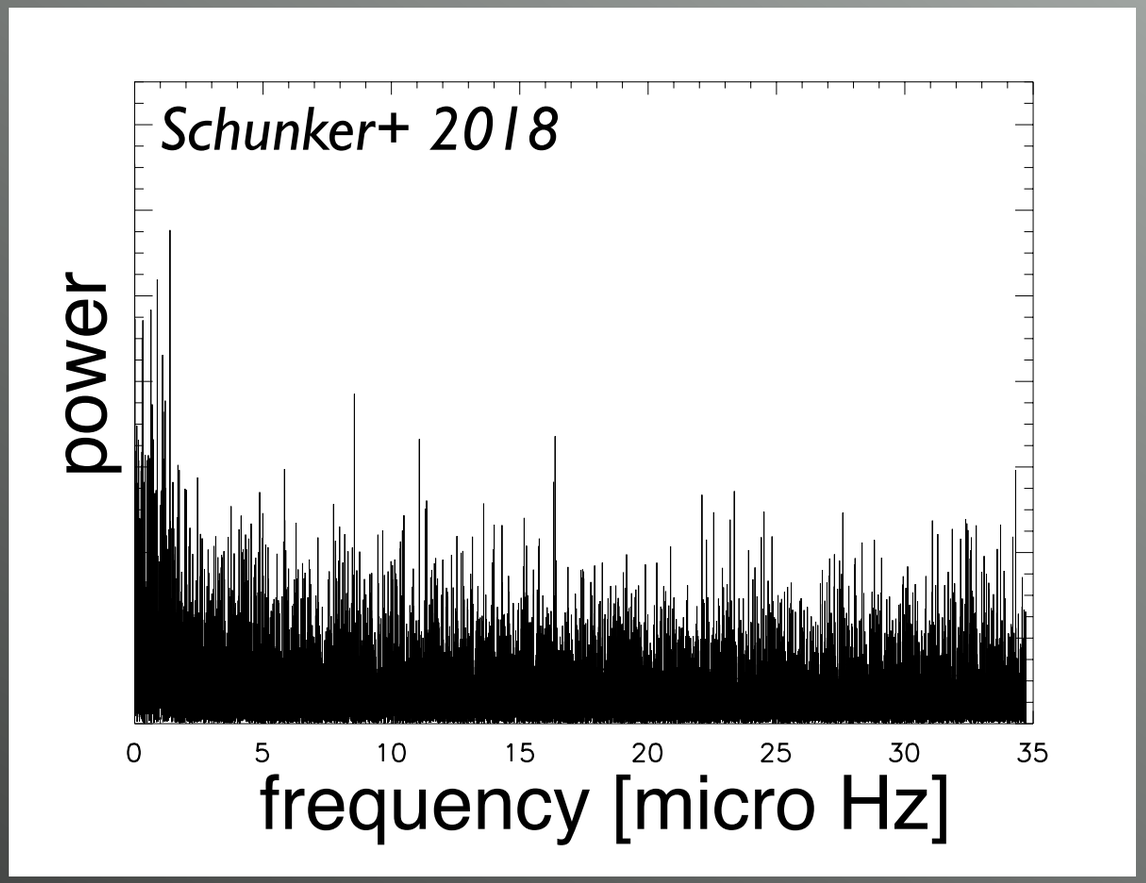


Fig. 7. Power spectrum $P_S(\nu)$ of the time series shown in Fig. 6.



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Reproducing Fossat

- Low frequency range looks similar.
No sign of SOHO orbit or solar cycle

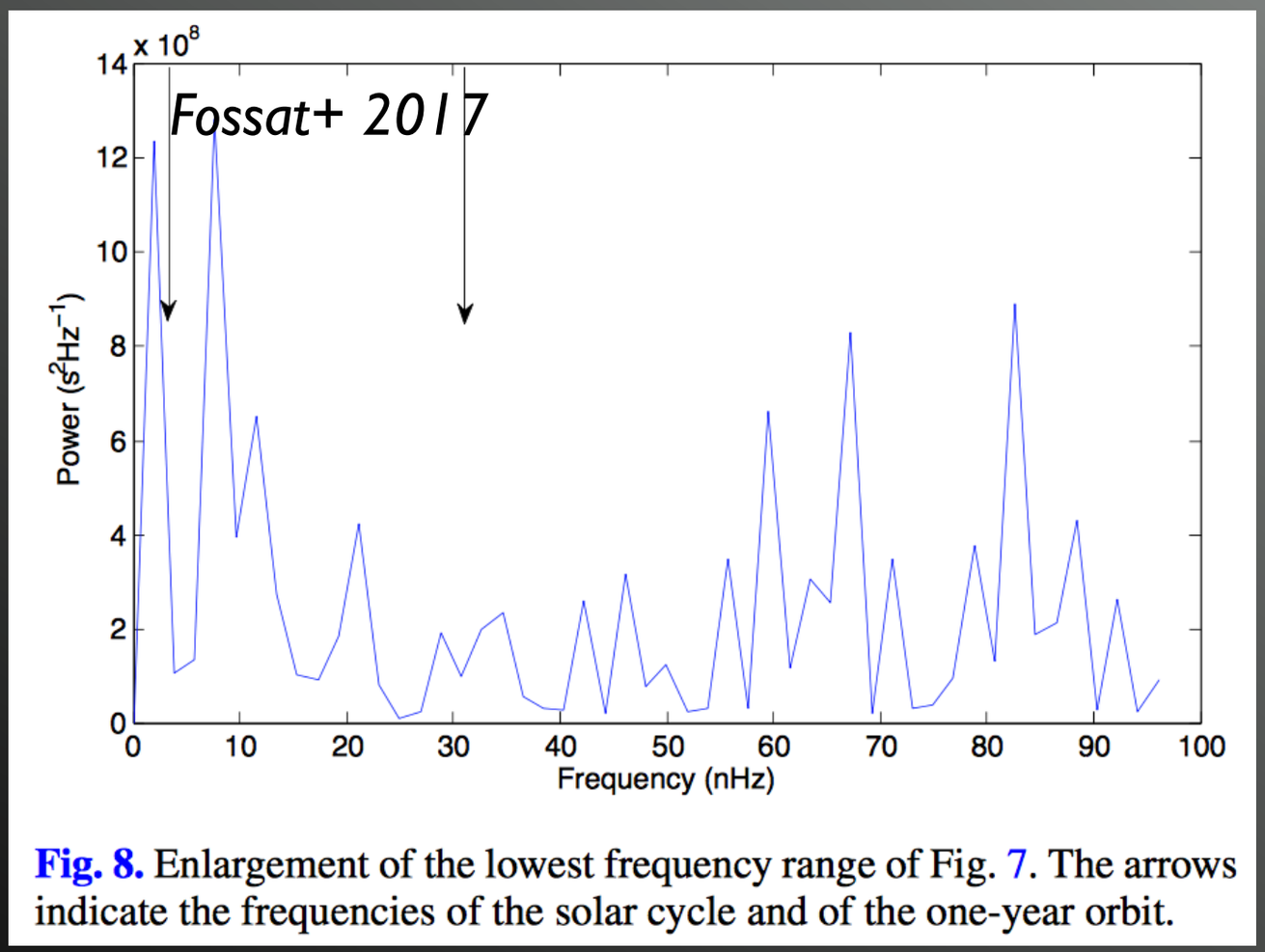
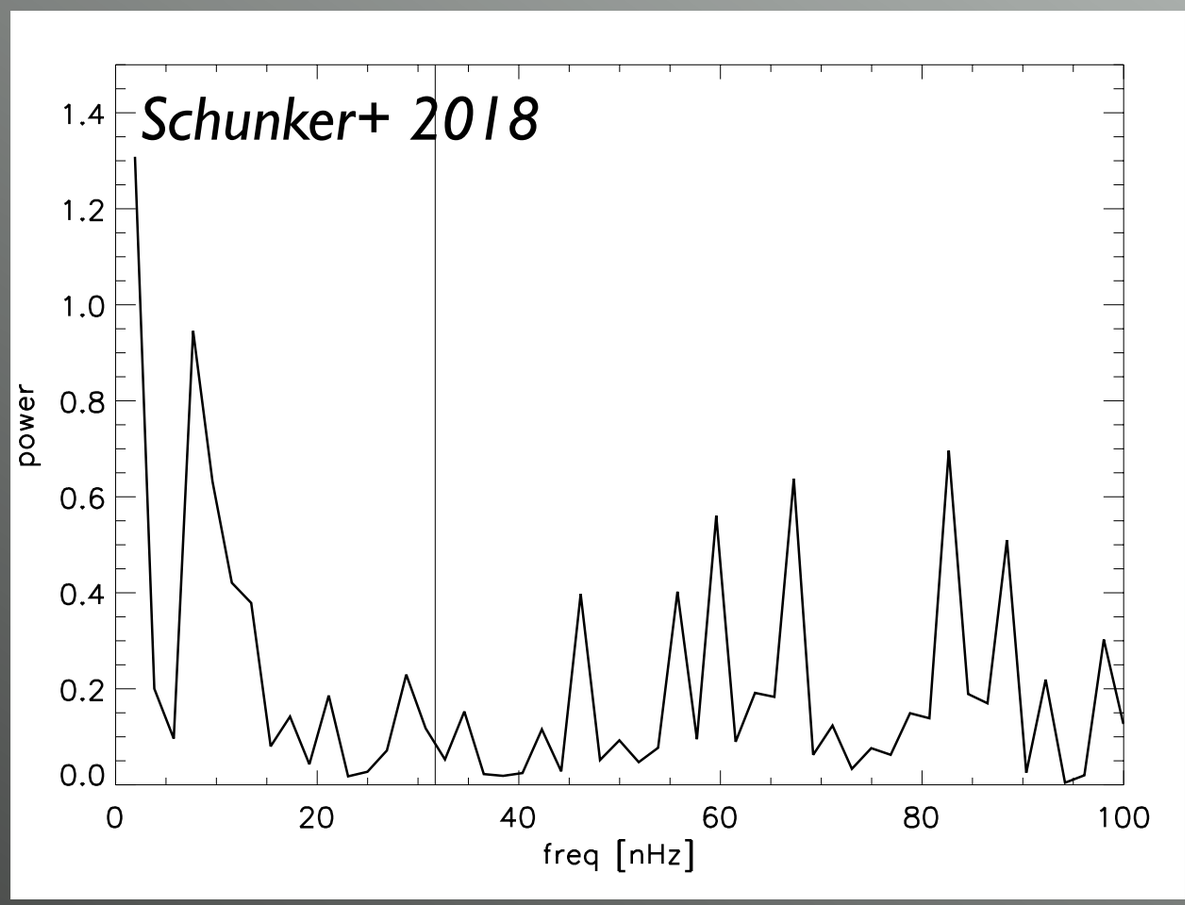


Fig. 8. Enlargement of the lowest frequency range of Fig. 7. The arrows indicate the frequencies of the solar cycle and of the one-year orbit.



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Reproducing Fossat

- Autocorrelate the power spectrum
- Peaks should correspond to rotational splittings; $\Omega_g = 1286\ \mathrm{nHz}$, 2.9 x Ω_p

Qualitative reproduction

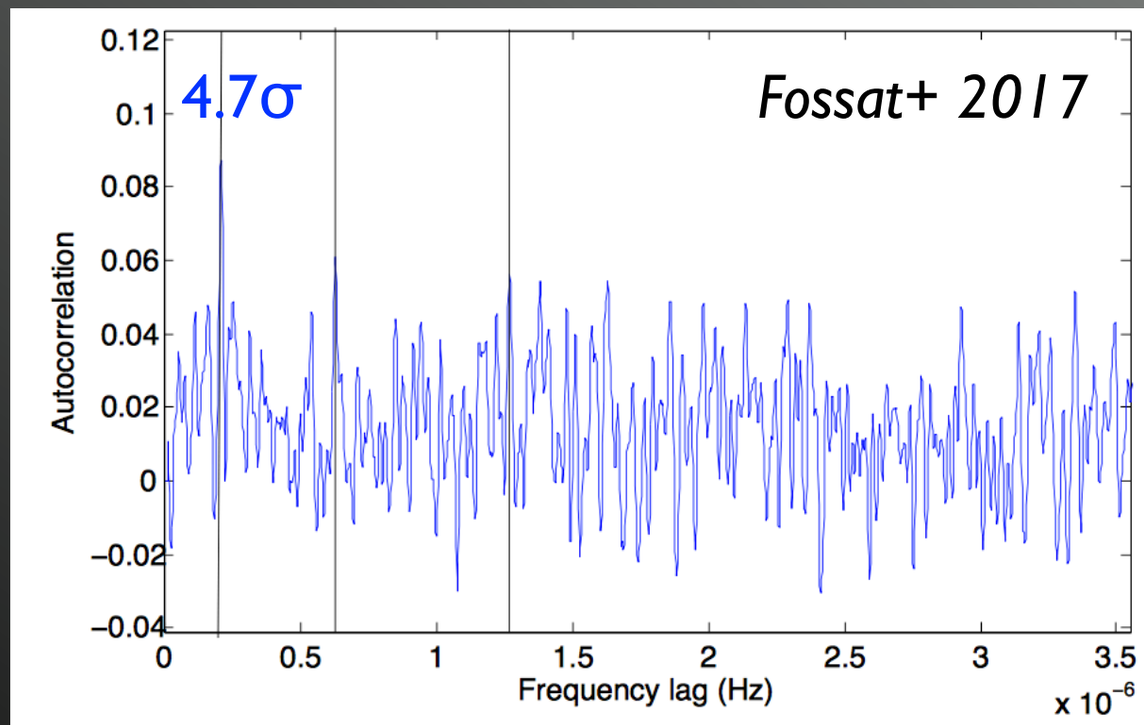
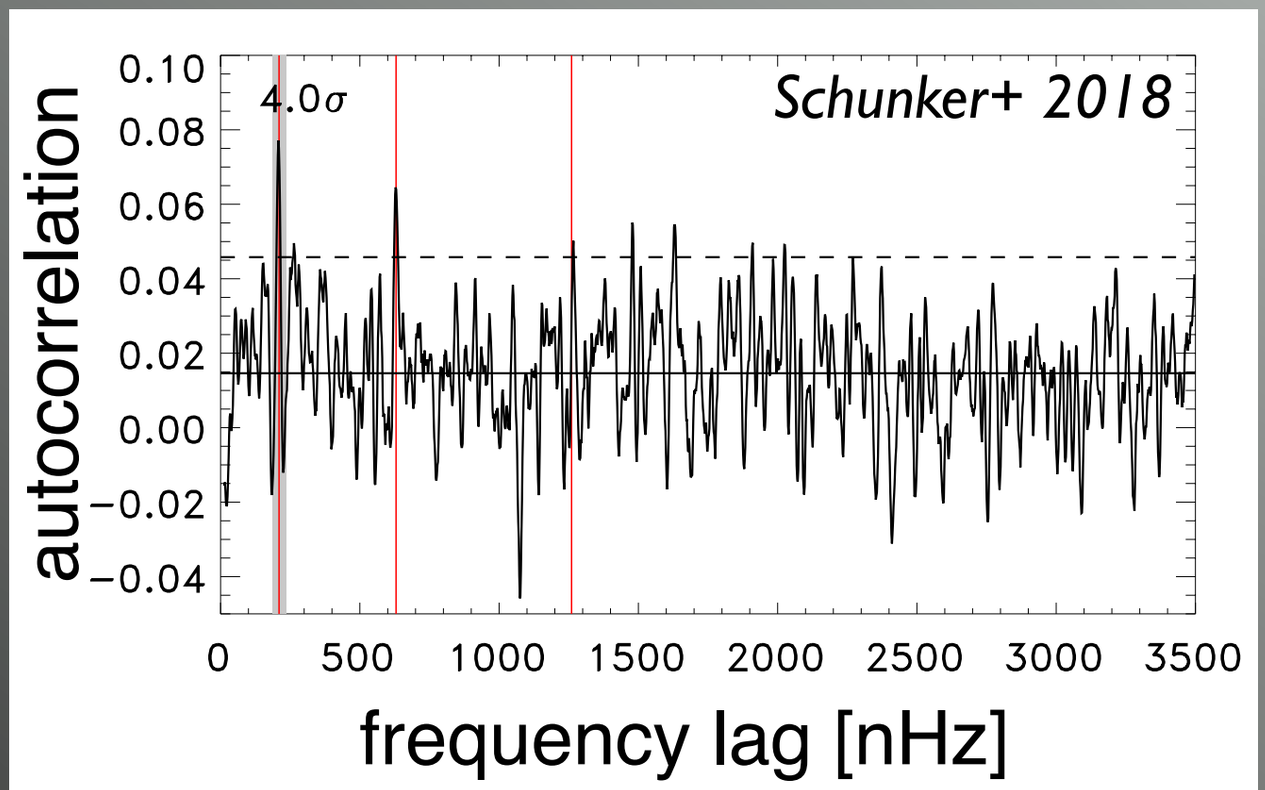


Fig. 10. Autocorrelation function $A(\nu)$ of the frequency range 5.5–34.7 μHz of the power spectrum shown in Fig. 7. The first value displayed is bin number 7, i.e., 0.013 μHz. The vertical lines are at 210, 630, and 1260 nHz.



Testing the Sensitivity

- Numerous subjectively chosen parameters
  - amount of data used (full 16.5 years)
  - cadence of the RTTT (4 hrs)
  - length of the segments (8 hrs)
  - amount of zero-padding (lots)
  - normalisation (Gaussian)
  - frequency band (2.32-3.74 mHz)
  - width to fit (800 seconds)
  - fitting function to measure RTTT (quadratic)
  - smoothing (6 pixels ~ 11 micro Hz)
  - …

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   iii. Start time of data series
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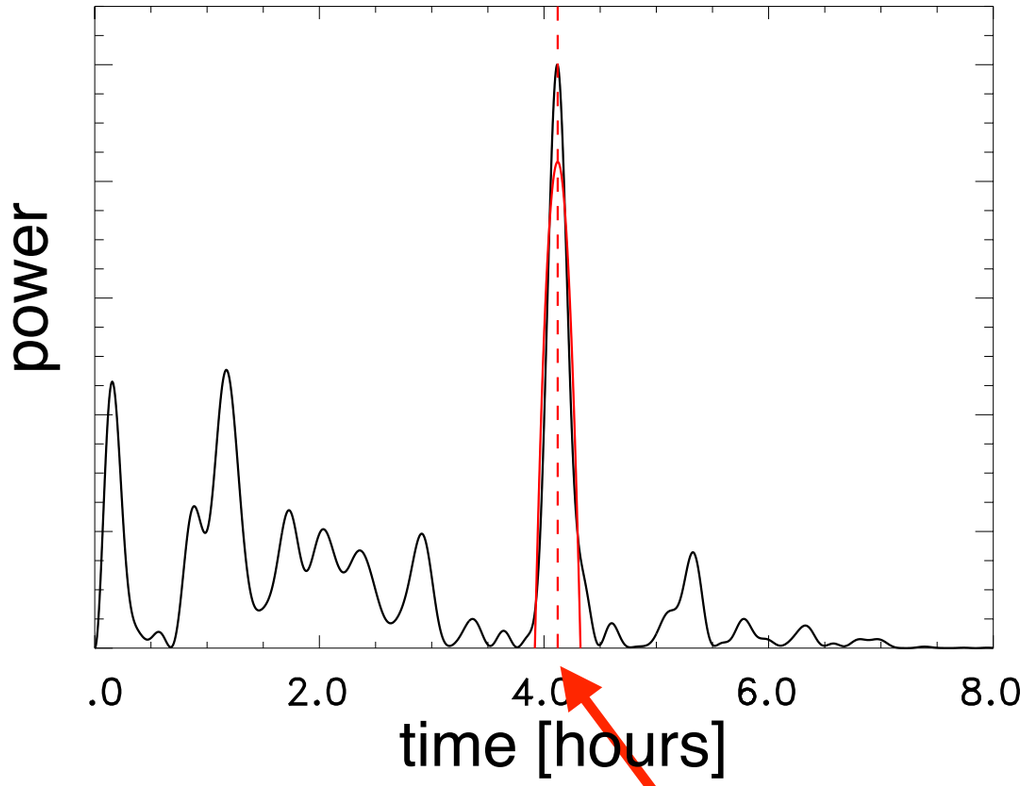
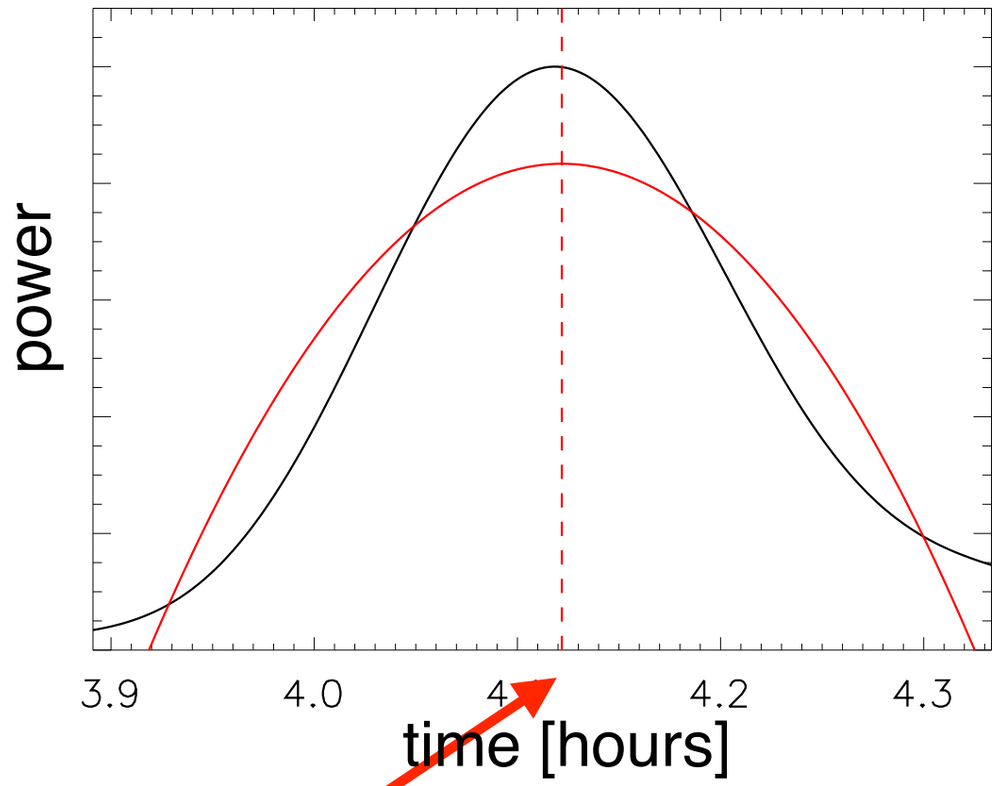
3. MC parameter study

Test: Measuring RTTT

- Measure the RTTT by fitting a quadratic function (4 hours 3 minutes)

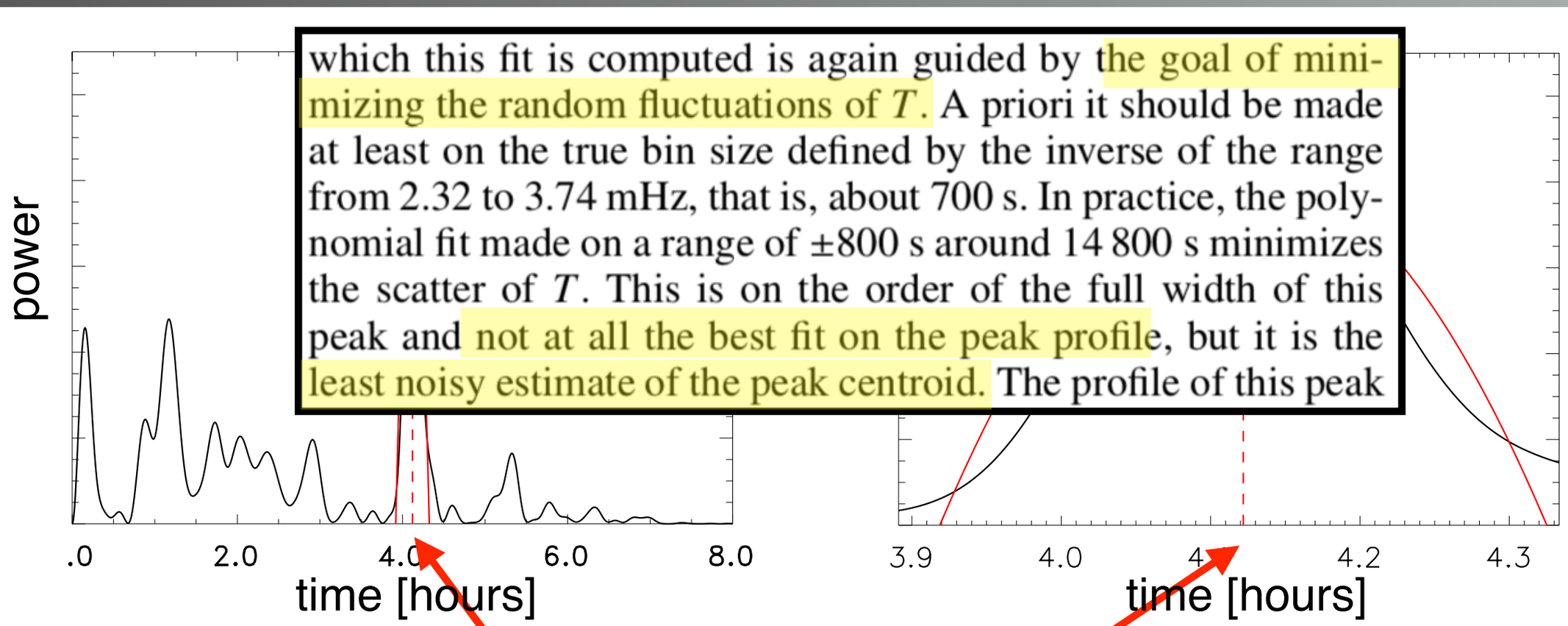




Round Trip Travel Time

Test: Measuring RTTT

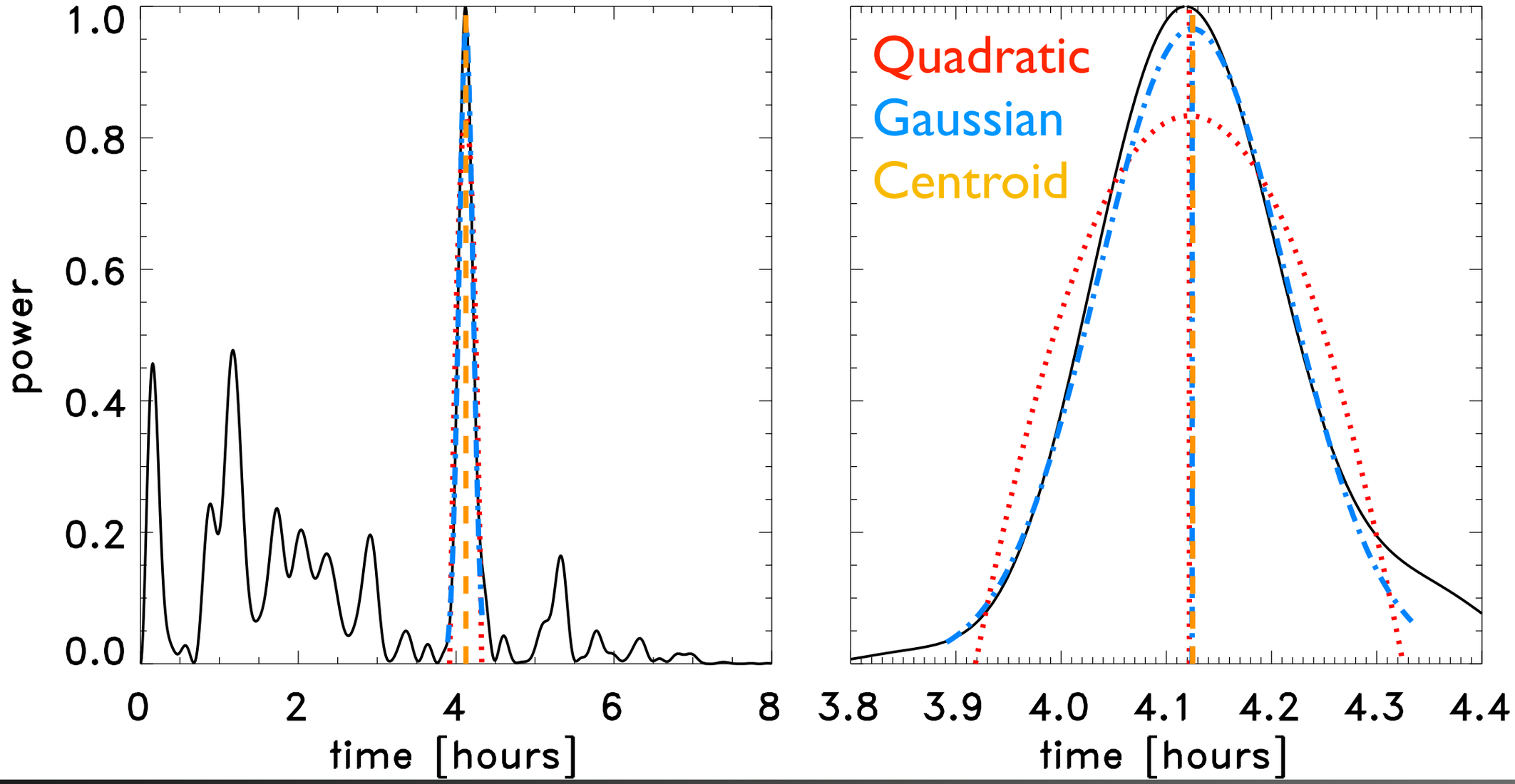
- Measure the RTTT by fitting a quadratic function (4 hours 3 minutes)



Round Trip Travel Time

Test: Measuring RTTT

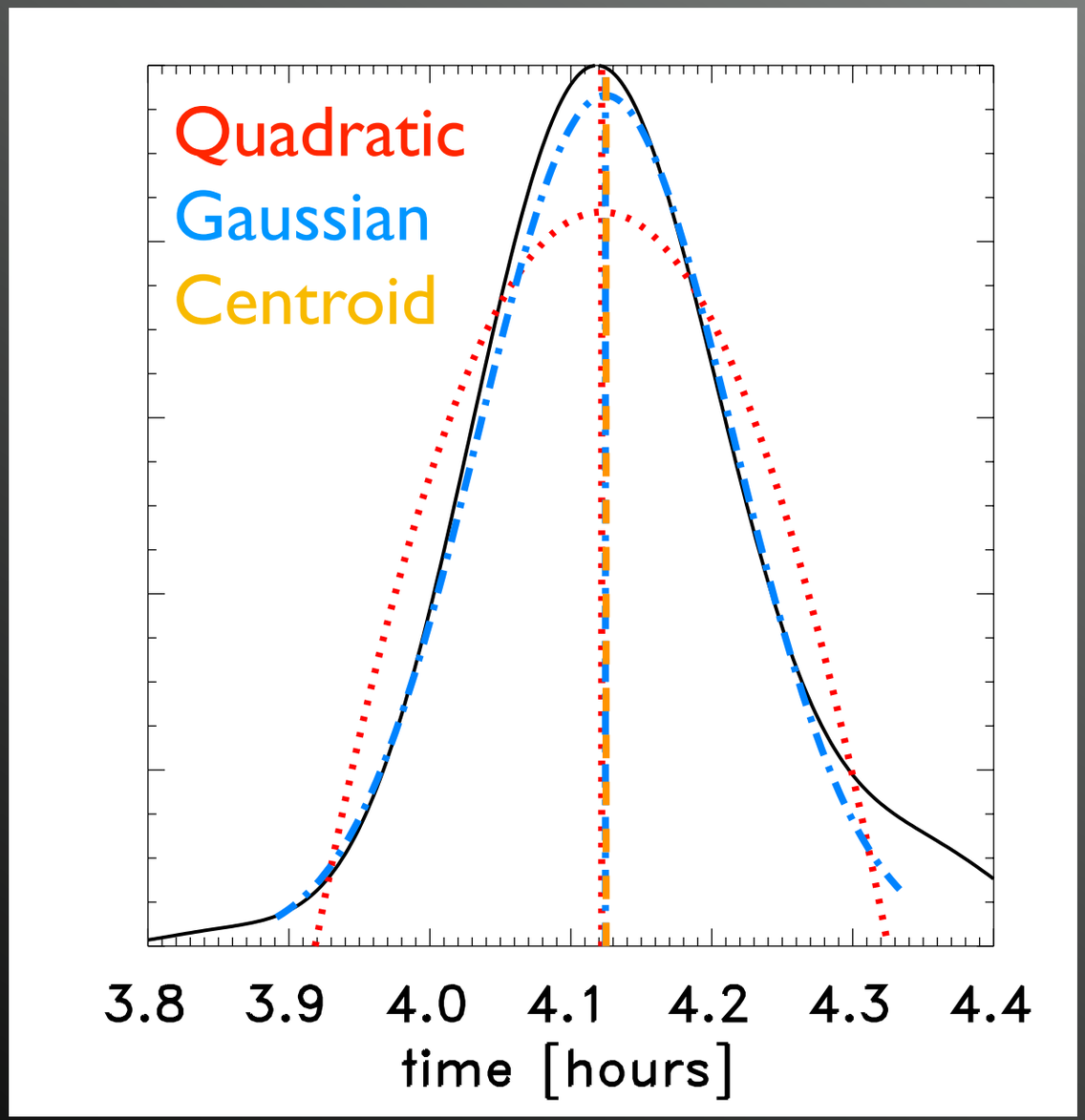
- Try other fitting functions

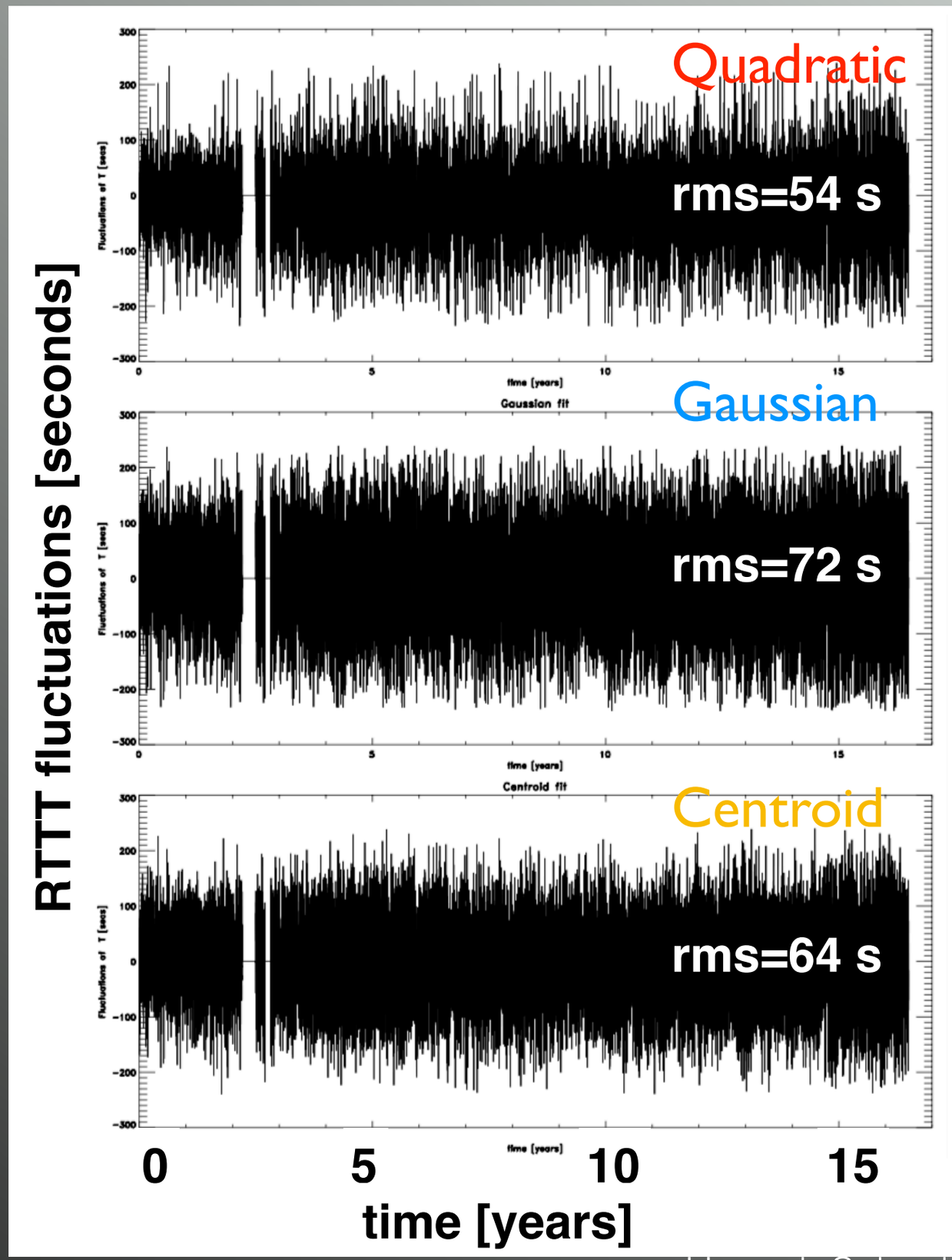


Example of one 8 hour segment

Test: Measuring RTTT

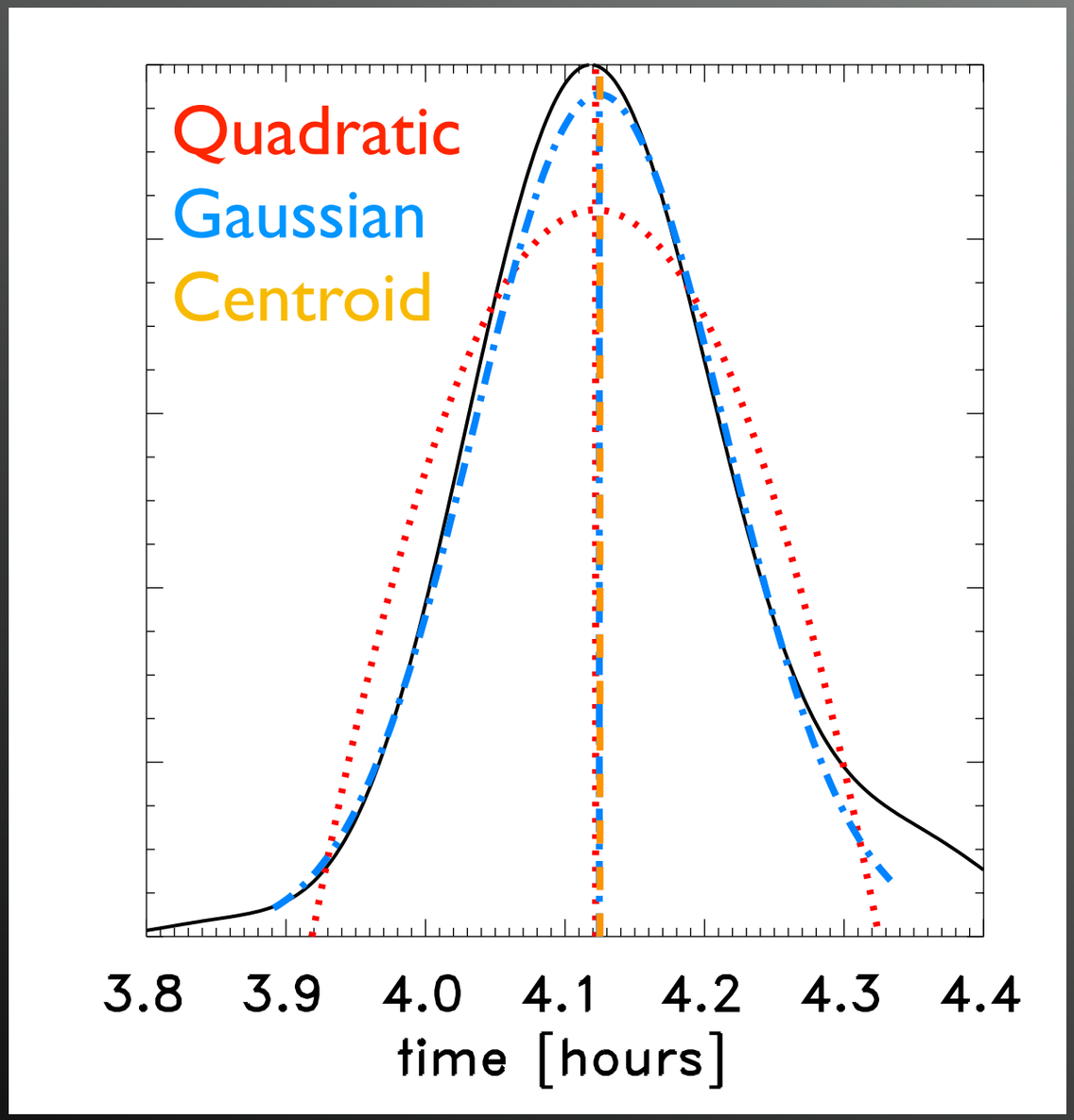
- Try fitting other functions
- Clip at +/- 240s

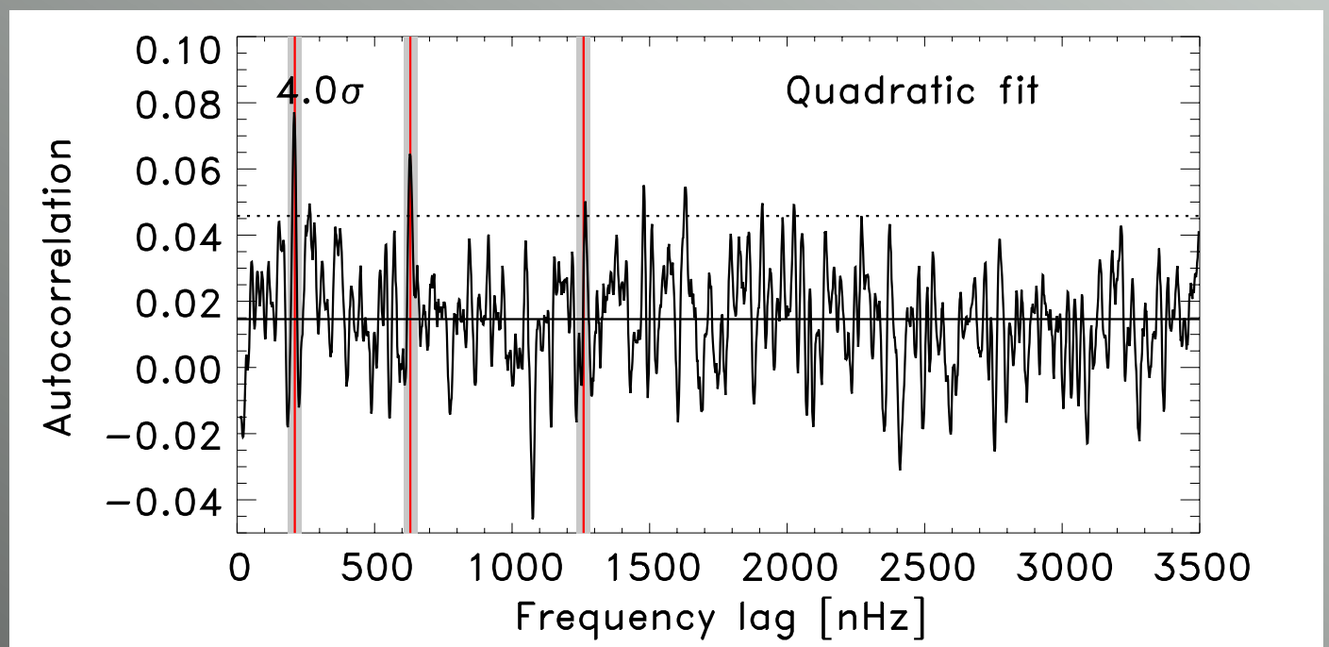




Test: Measuring RTTT

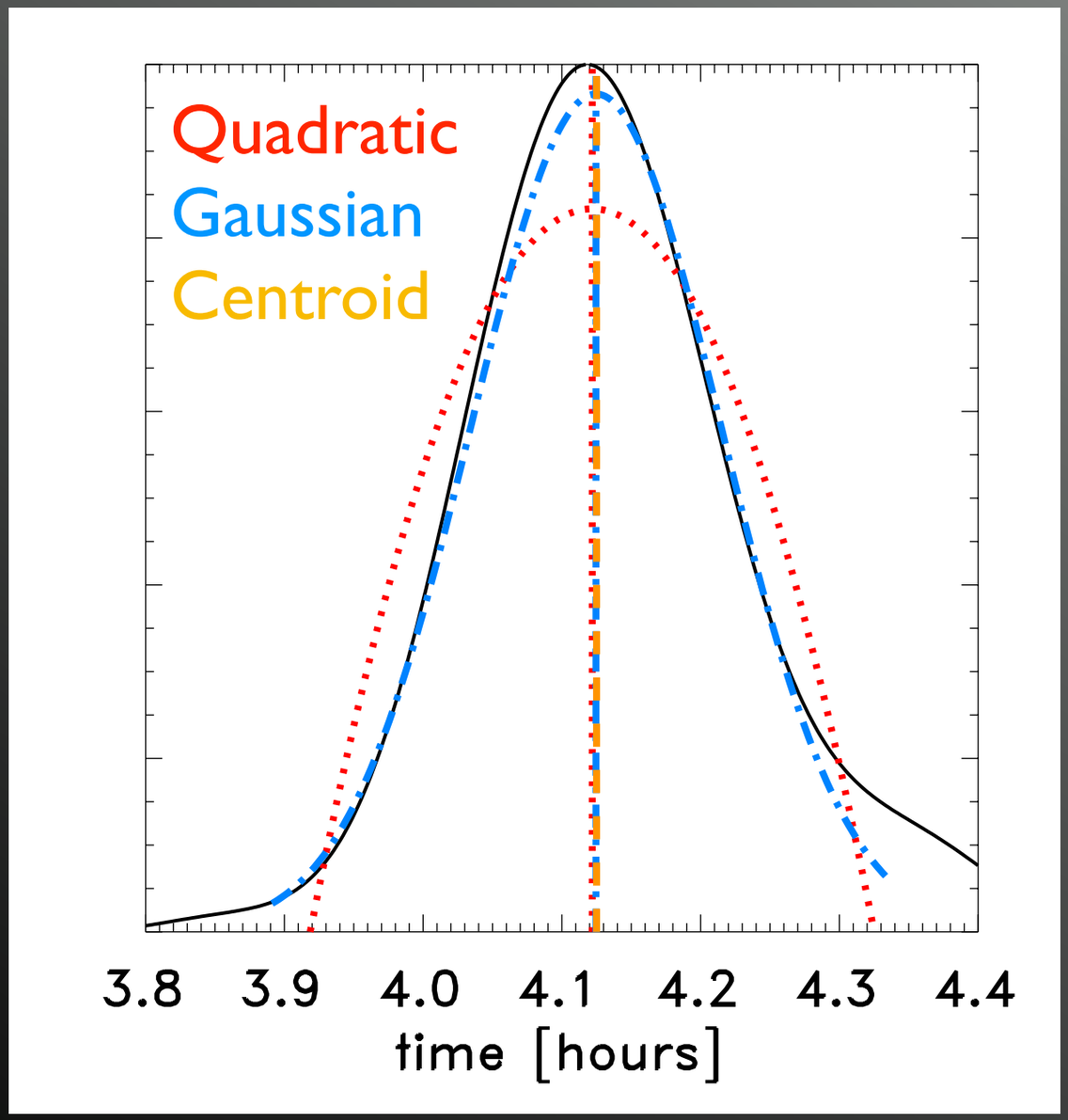
- Try fitting other functions

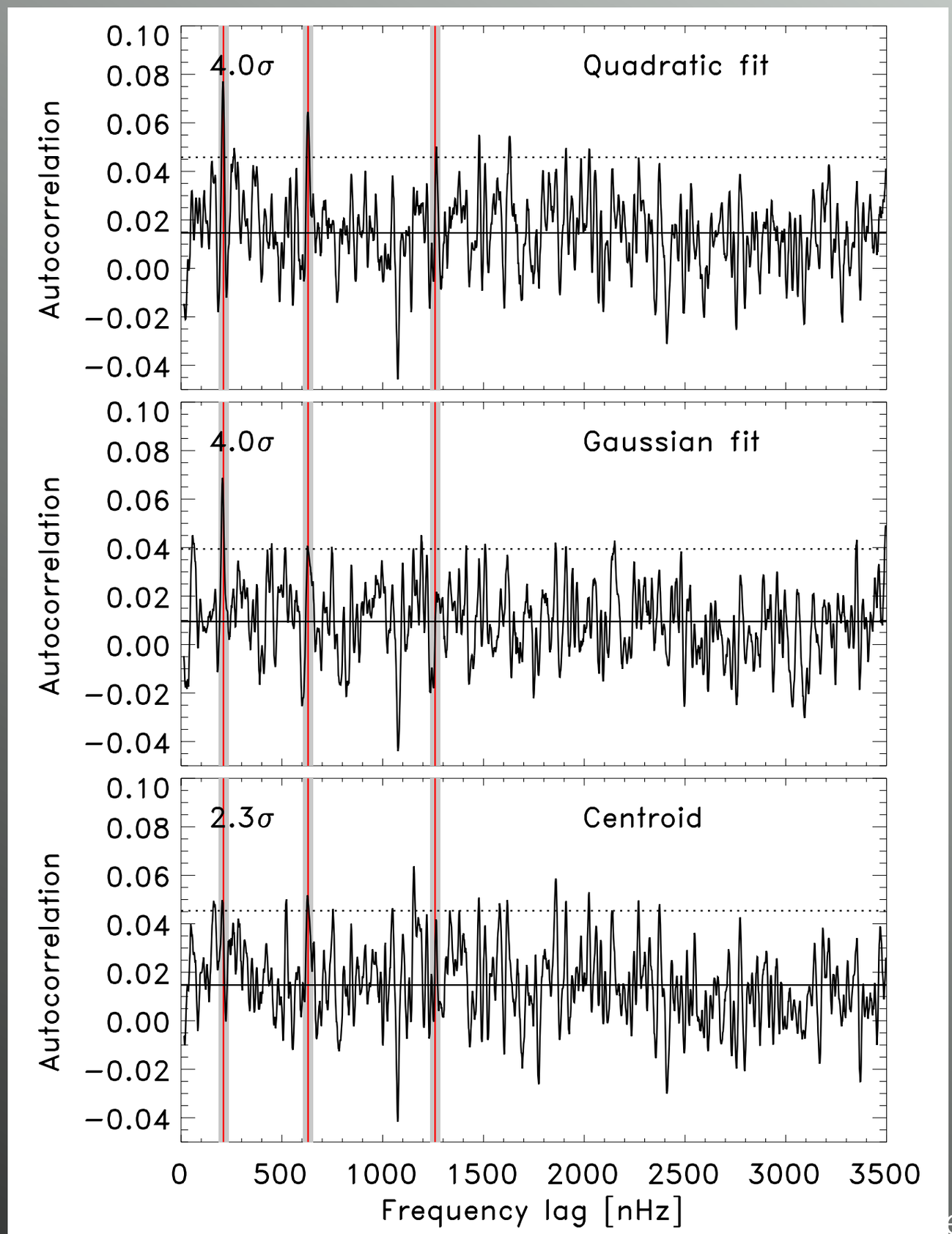




Test: Measuring RTTT

- Try fitting other functions





Overview

1. Reproducing Fossat et al. 2017

2. Sensitivity to parameters
   i. Fitting function to measure RTTT
   ii. Smoothing of power spectrum
   iii. Start time of data series
   iv. Cadence of RTTT measurements
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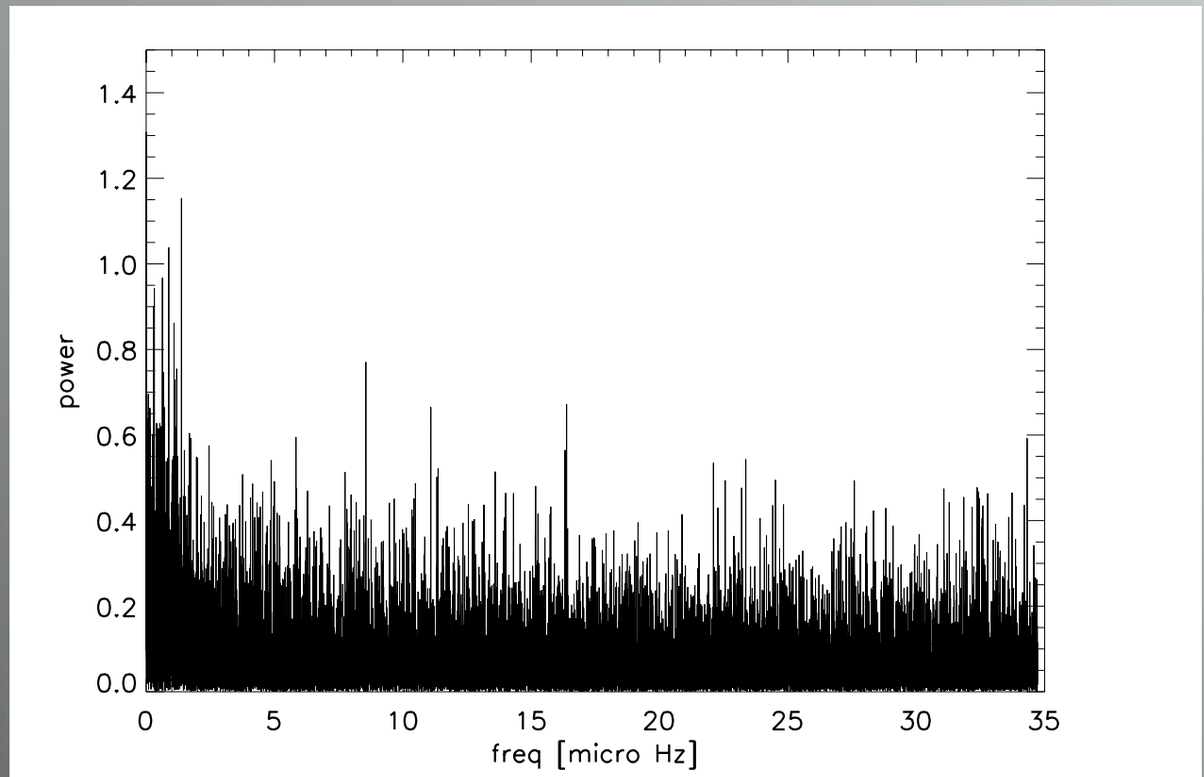
3. MC parameter study

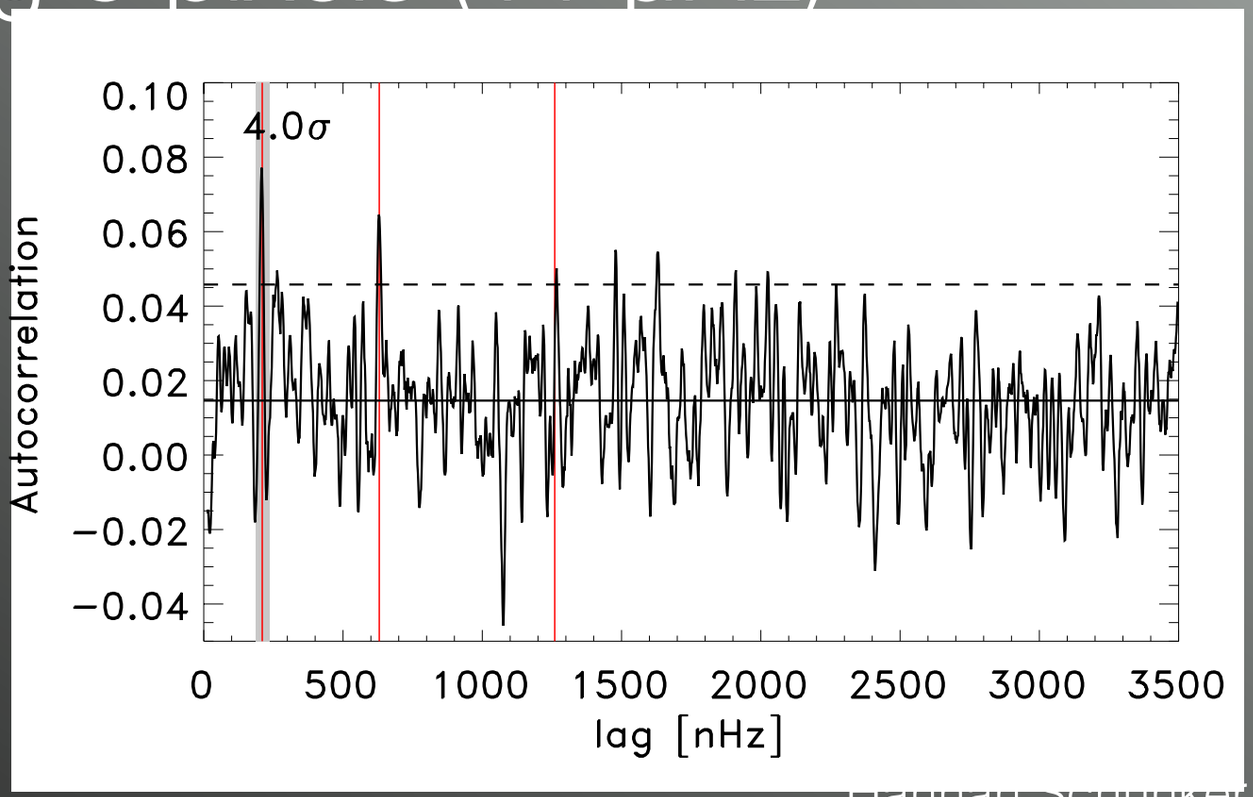
Test: Smoothing

Power spectrum

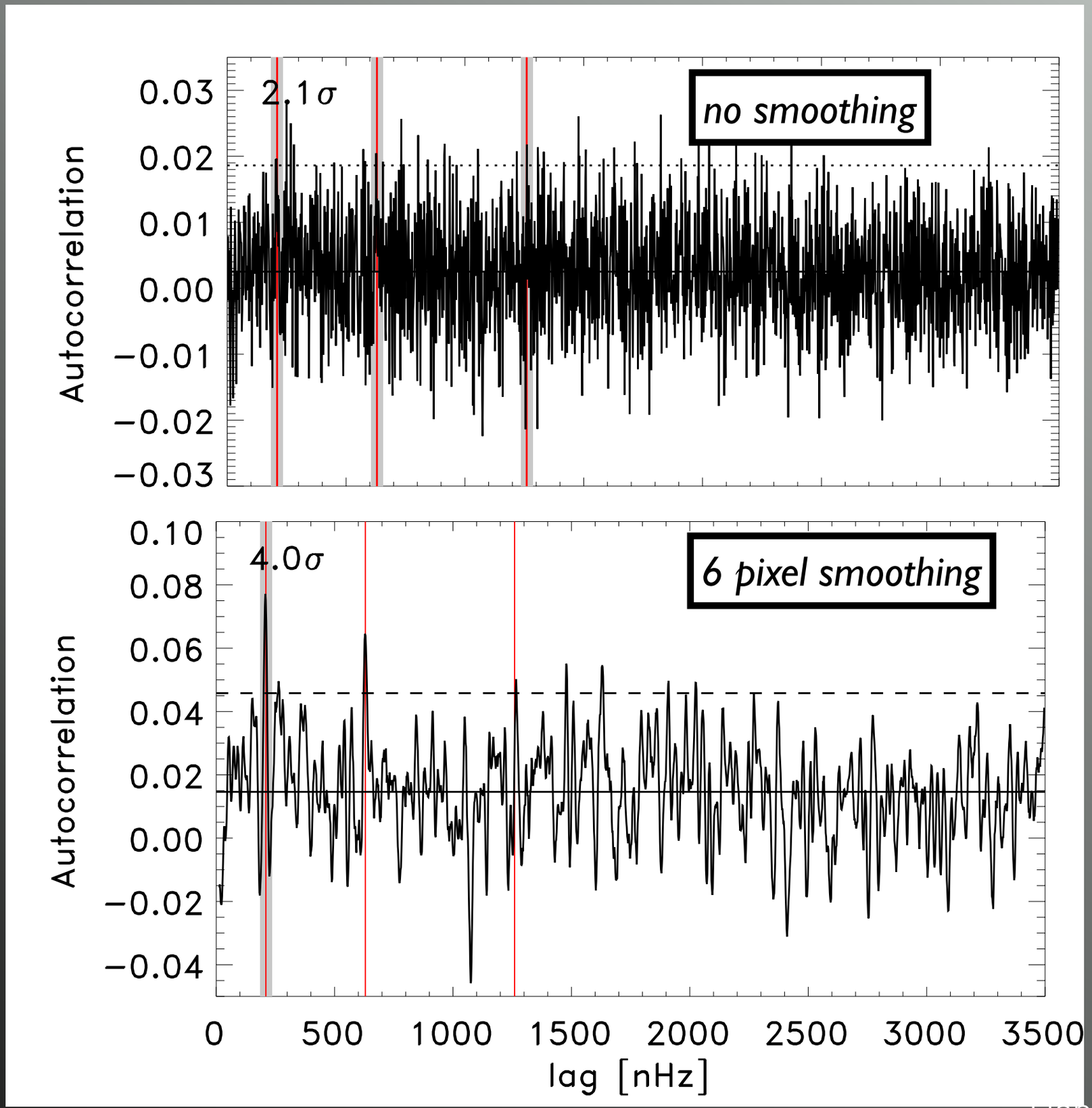


Box-car smoothing 6 pixels (11 μHz)

Auto-correlation

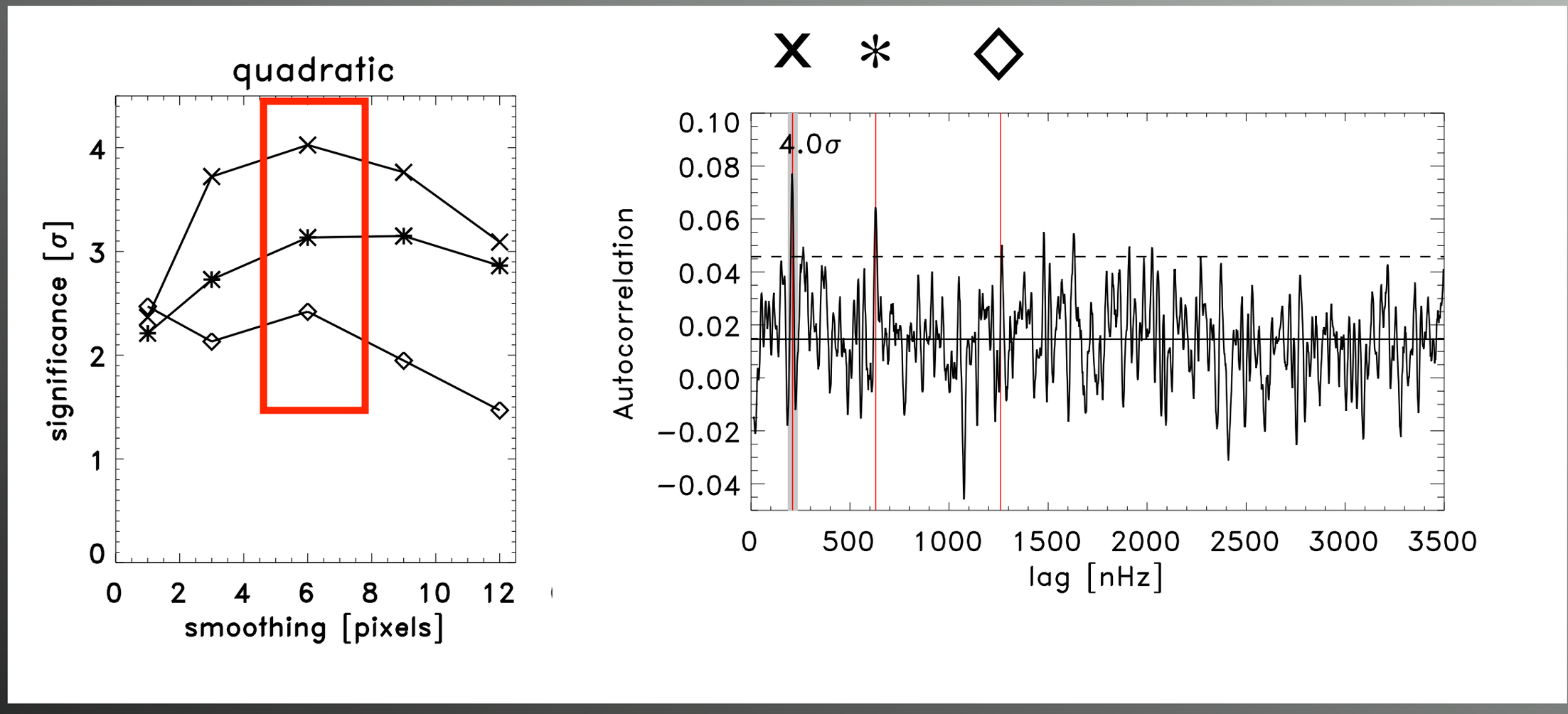


Test: Smoothing



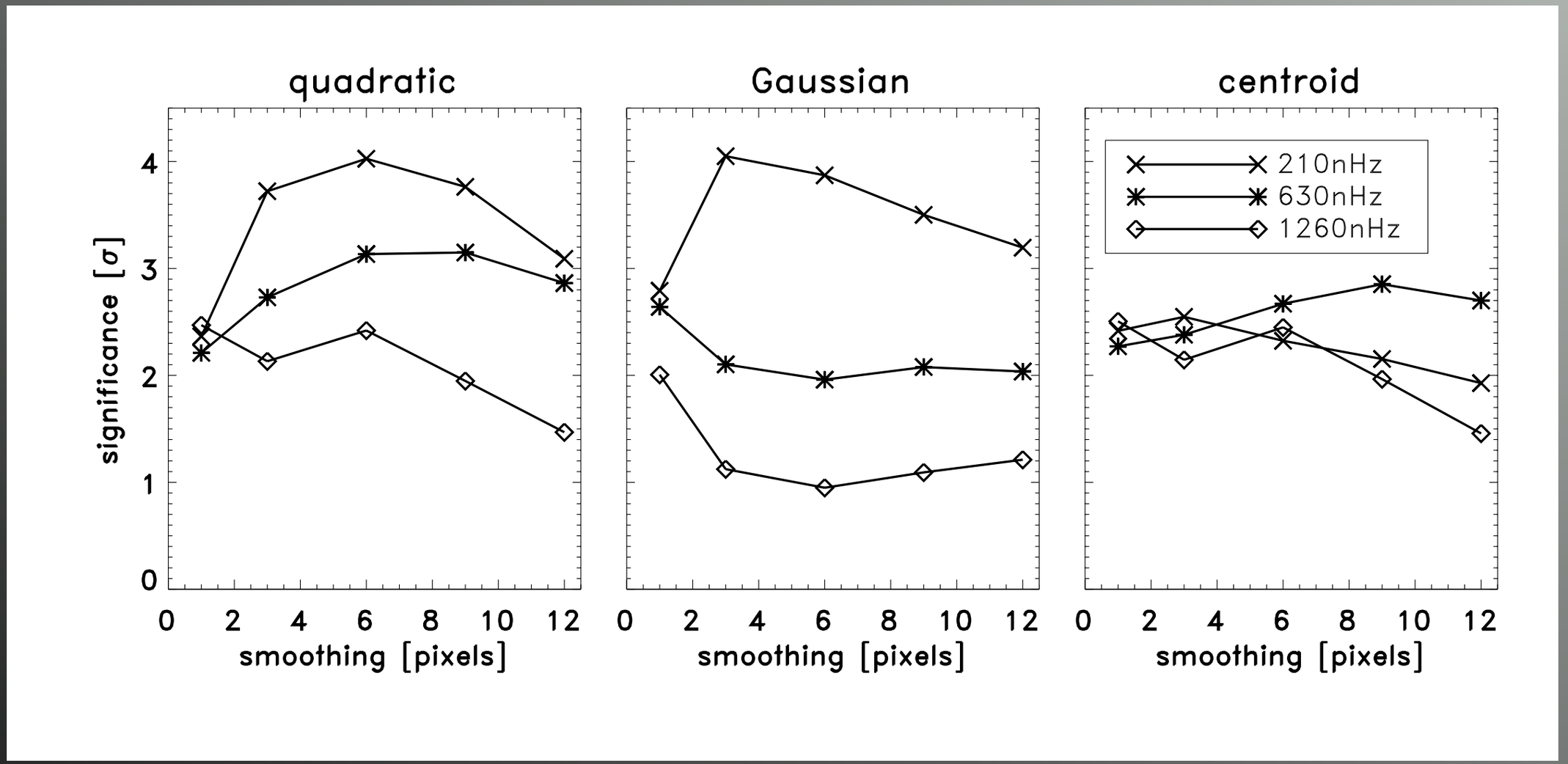
Test: Smoothing

- Smoothing is key to obtaining the significance



- Required because the modes are not strictly equally spaced (asymptotic)

Test: Smoothing



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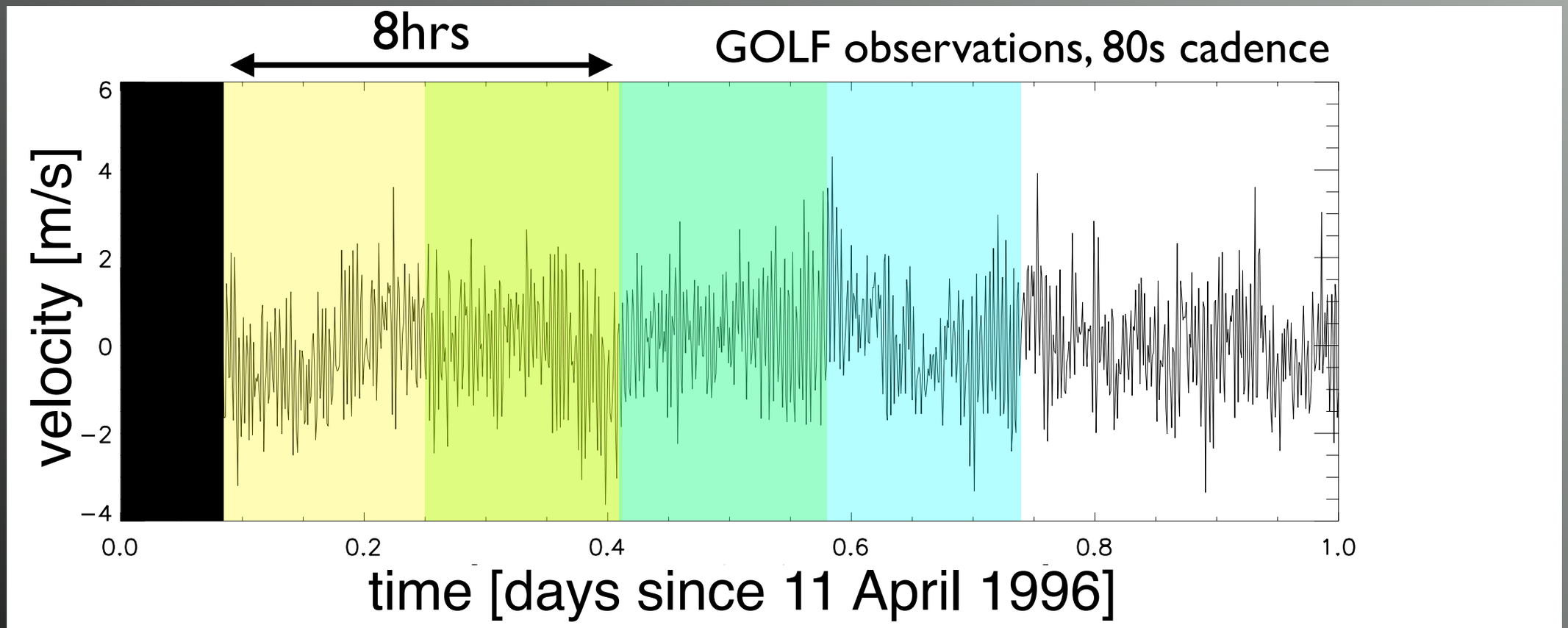
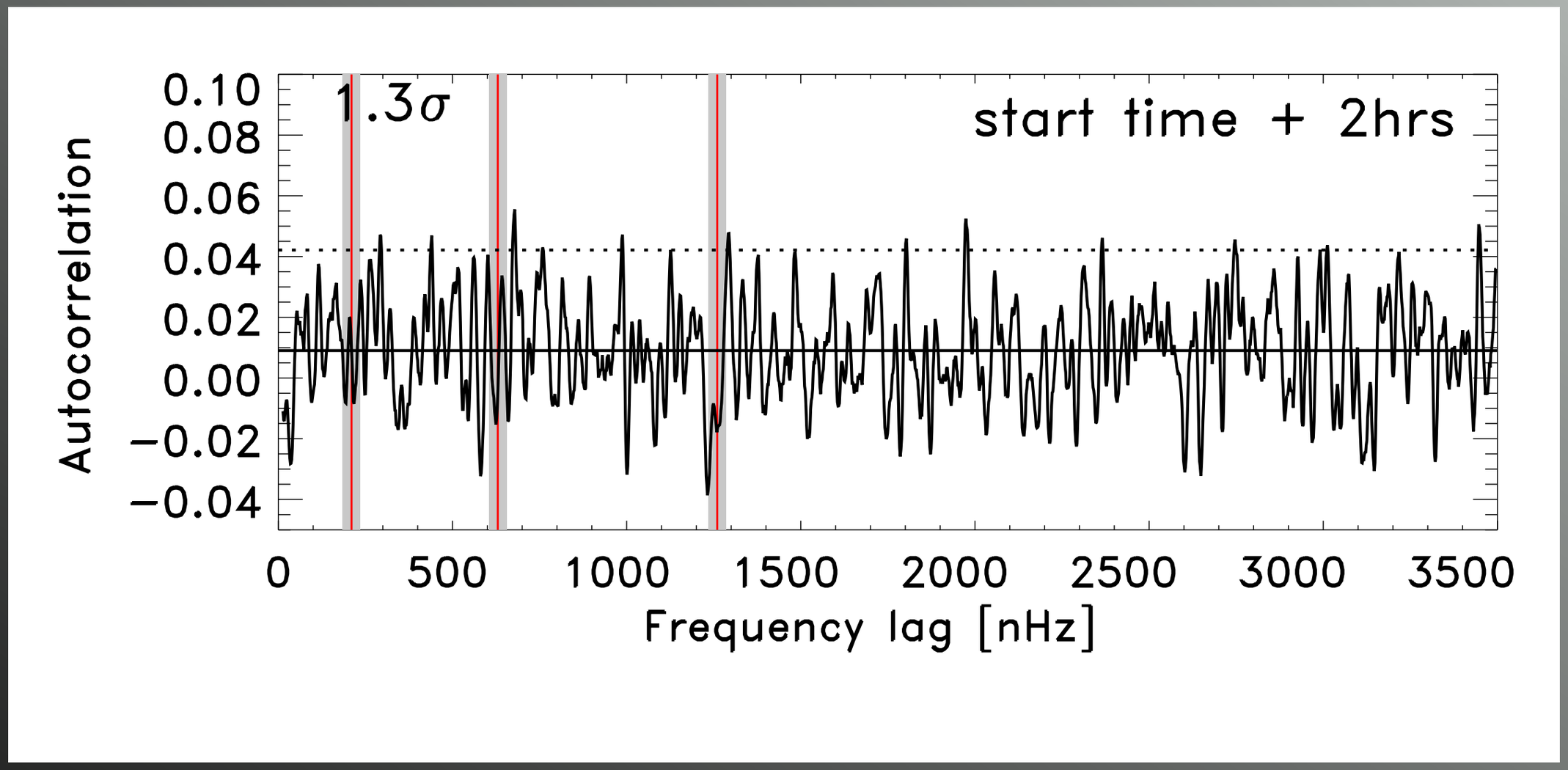
Test: offset data segments

- Removed 2 hours from beginning of 16.5 year data series

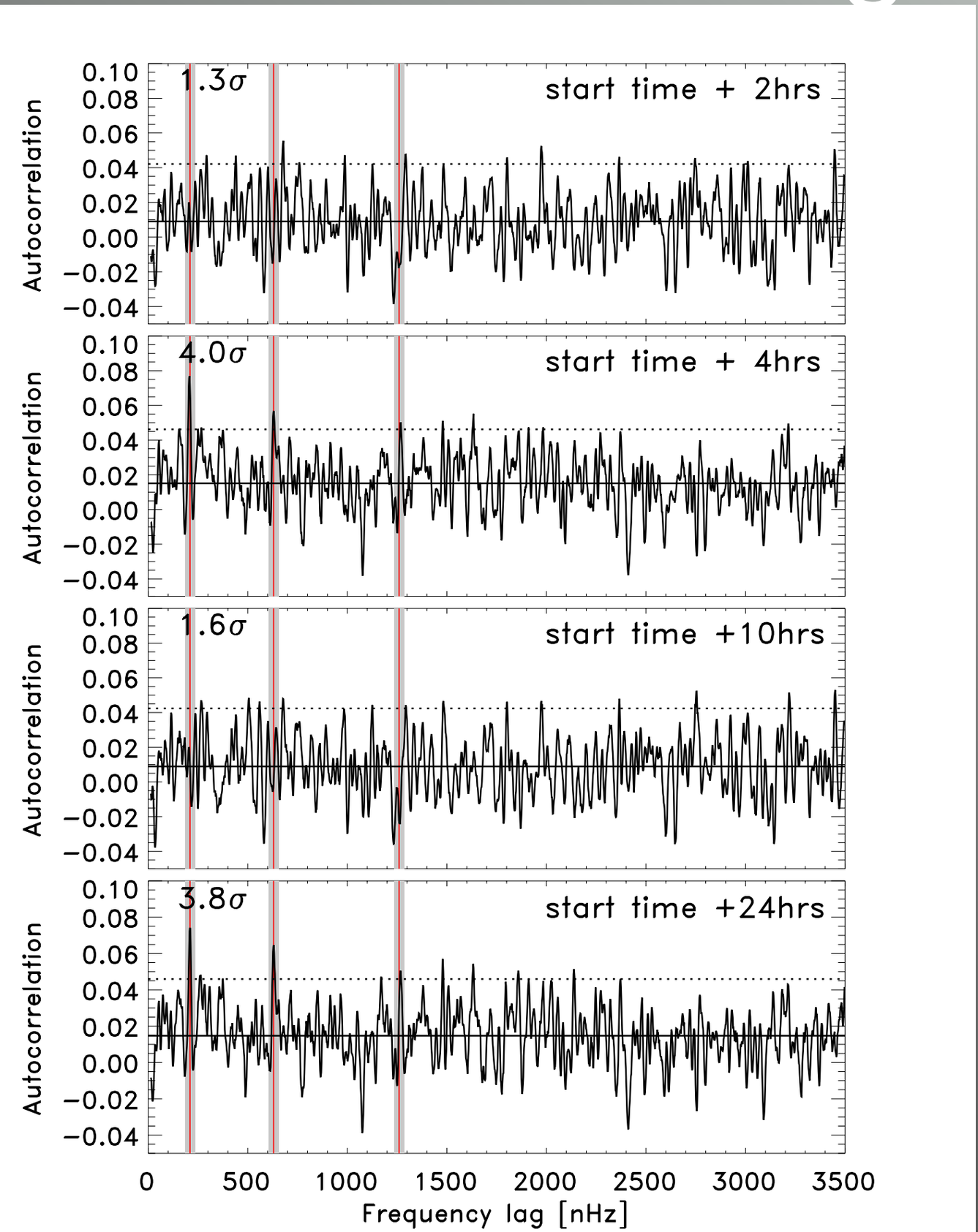


- Repeated exactly the same original analysis

Test: offset data segments



Test: offset data segments



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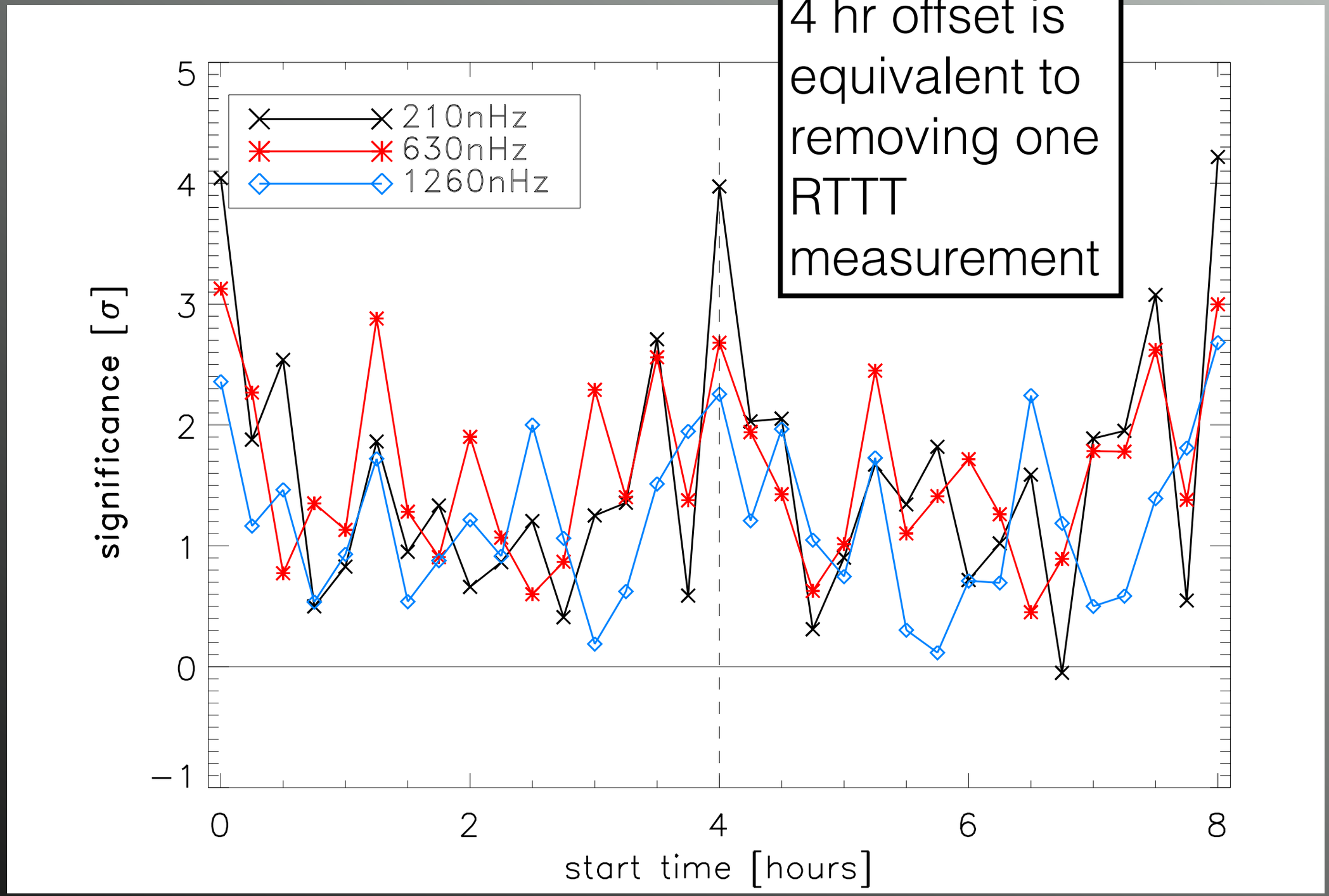

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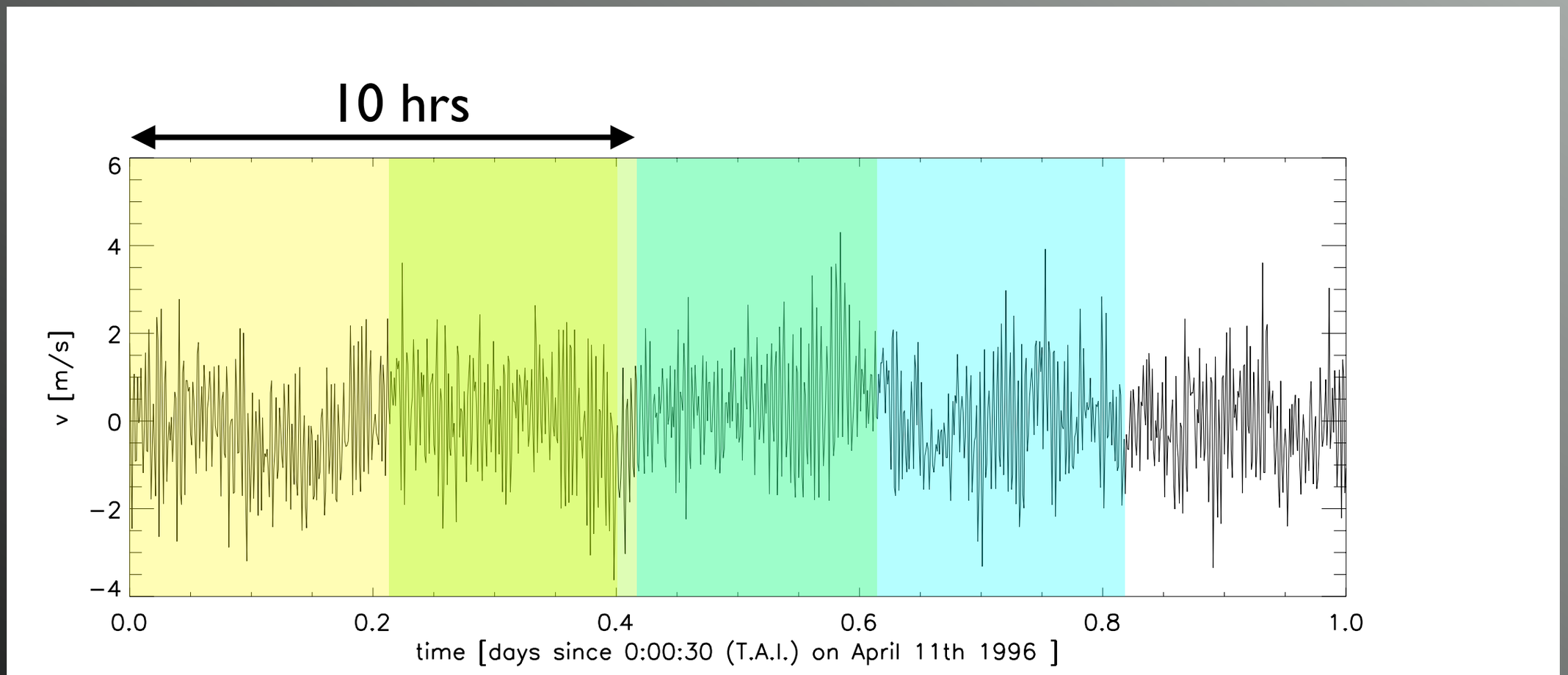
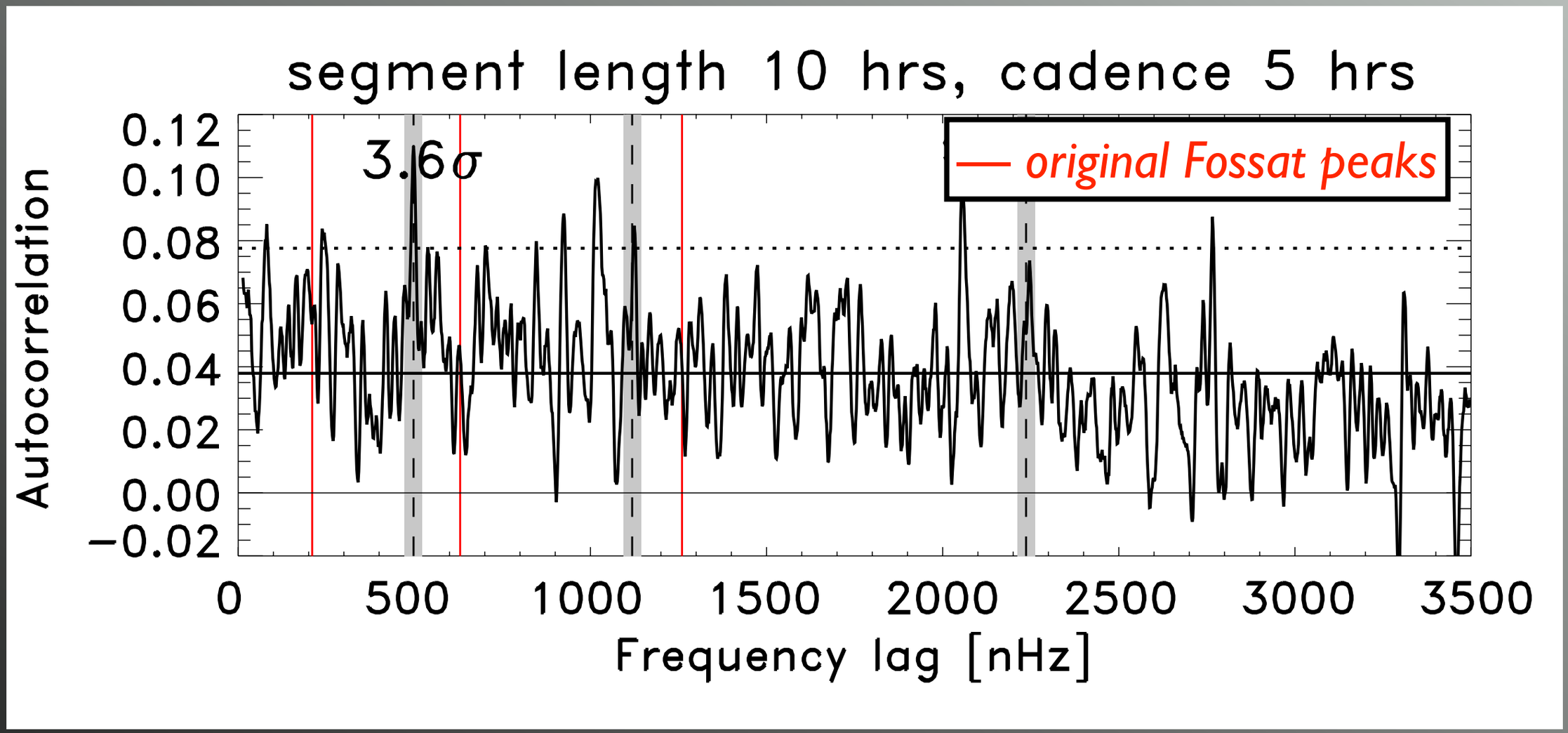
Test: cadence of RTTT measurements

Original segments 8 hrs long with a 4 hr cadence
Now we try 10 hrs long with a 5 hr cadence

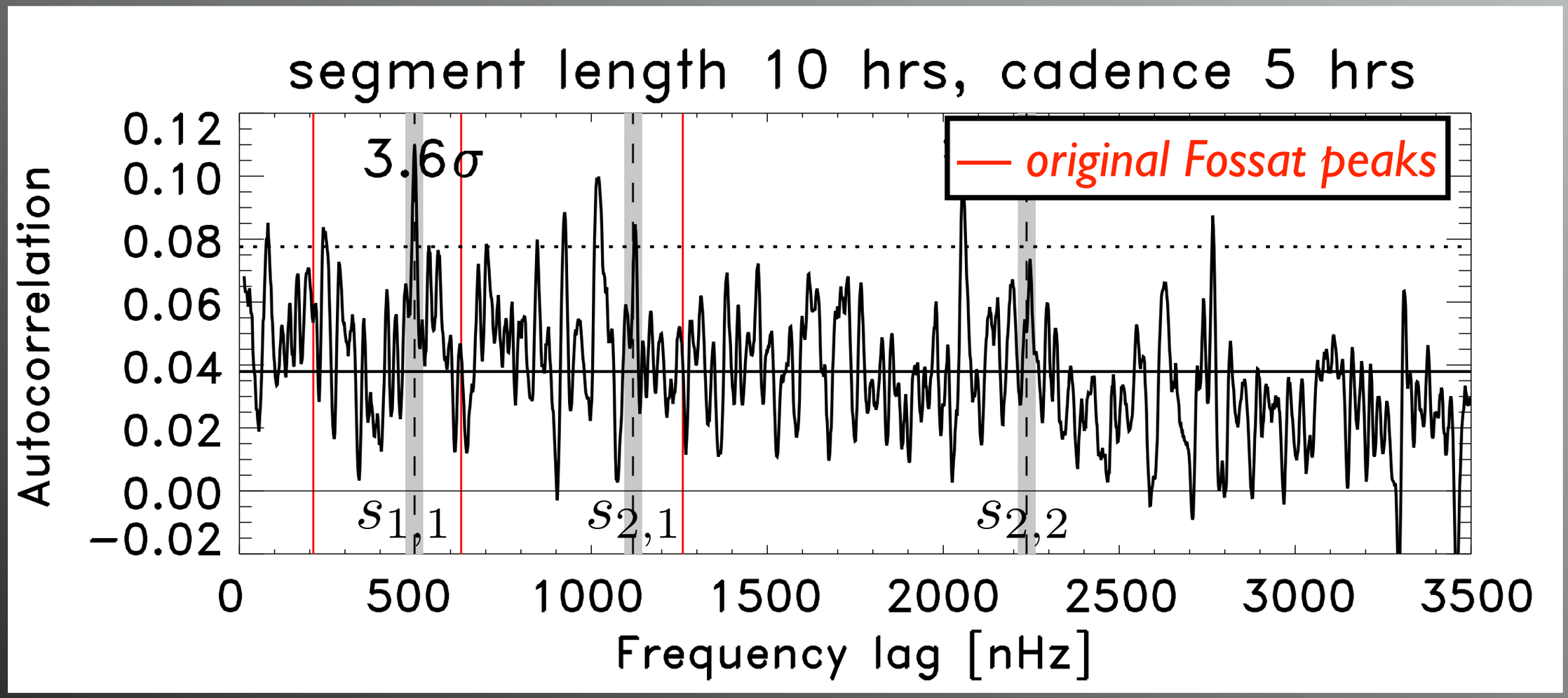


Test: cadence of RTTT measurements



- Scaled the clipping of RTTT fluctuations by the ratio to the rms of the nominal case

Test: cadence of RTTT measurements



$$s_{\ell,m} = m[\beta_\ell \Omega_{\rm g} - \Omega_{\rm p}] \qquad \Omega_{\rm p} = 433 \text{ nHz}$$

Assume largest peak is $\ell = 1, m = 1$,

$\Omega_g = 1862$ nHz 4.3x Ω_p

(1277 ±10 nHz, 2.9x Ω_p)

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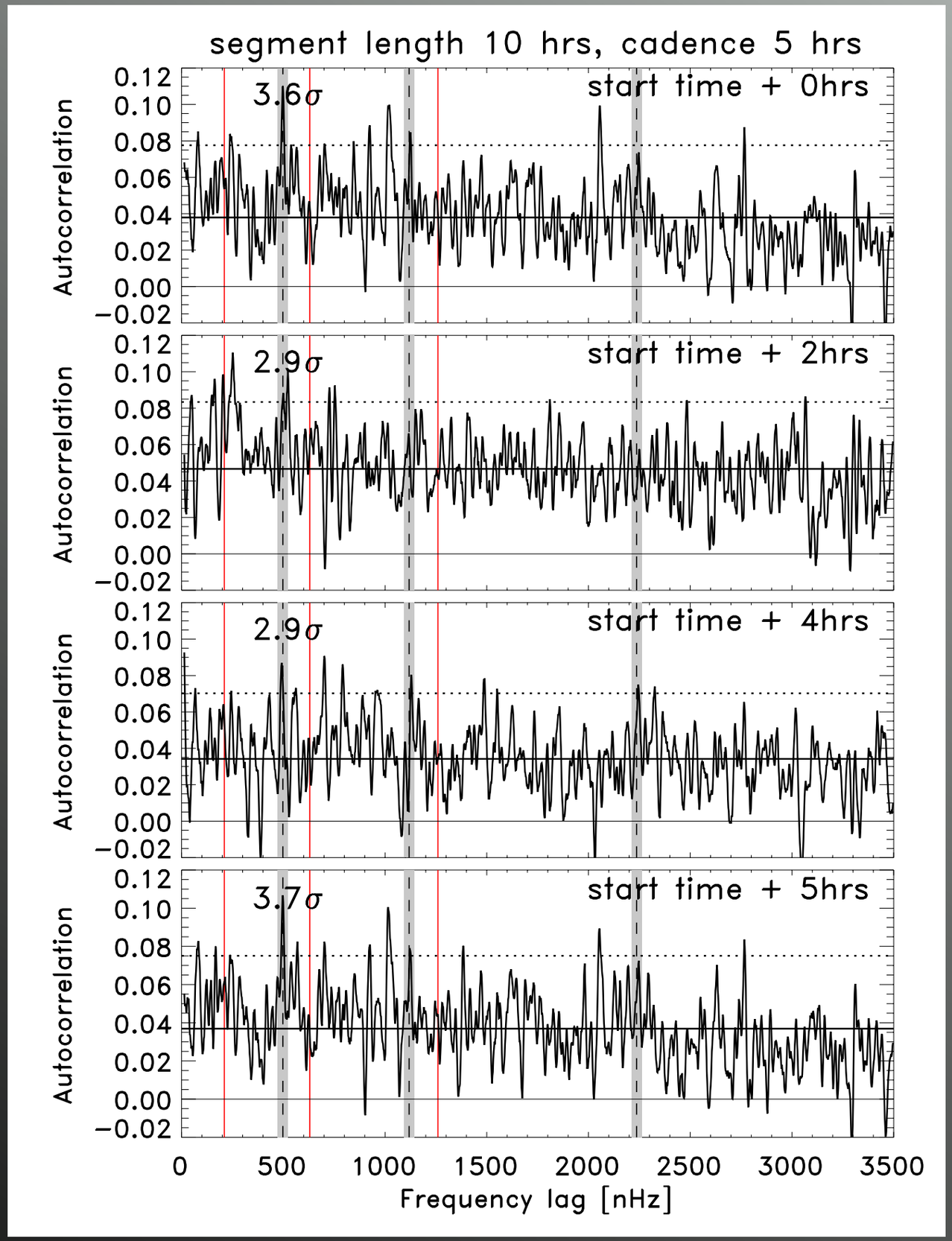
Test: offset and cadence



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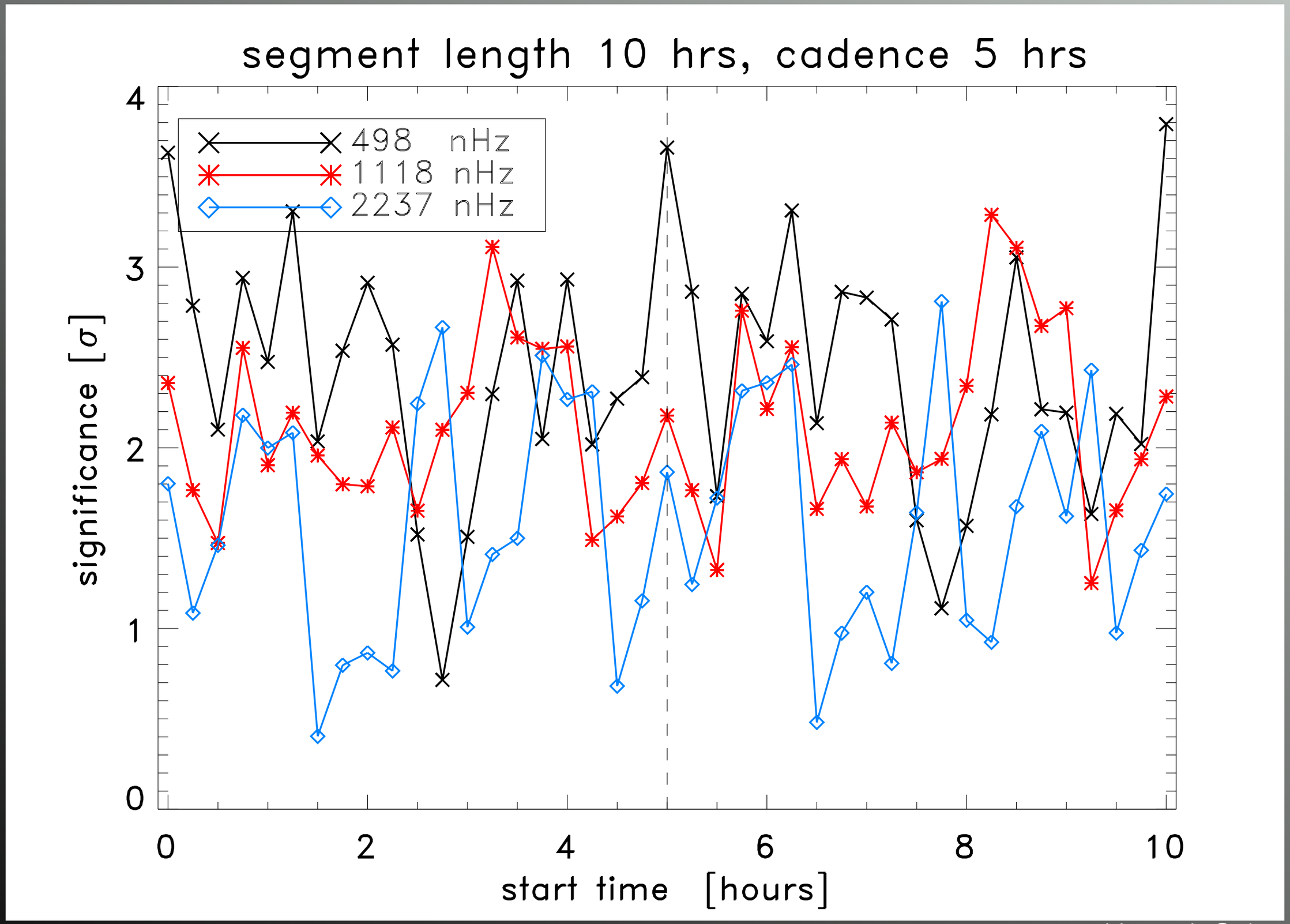
Test: offset and cadence



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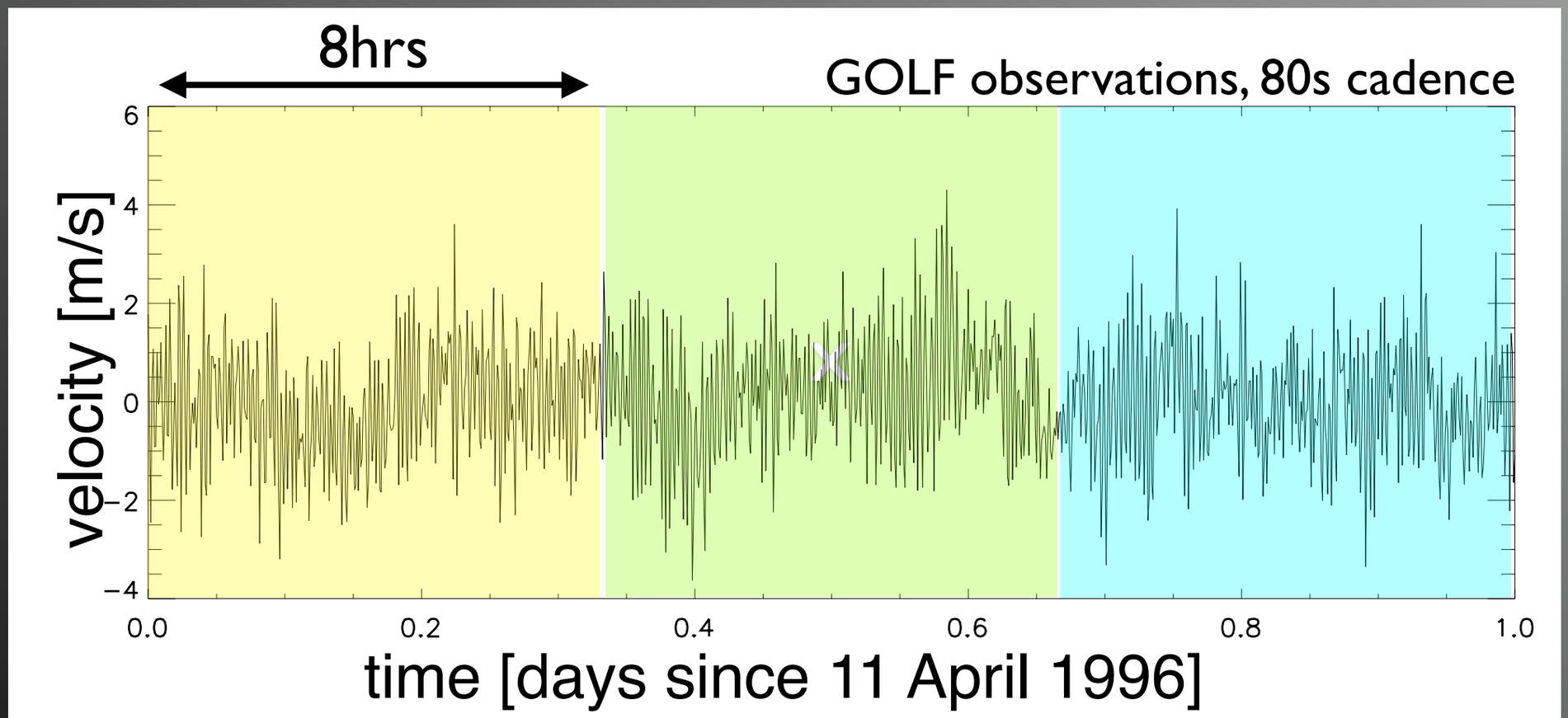
Test: overlap

- No overlapping segments
  - 8 hr segment lengths and an 8 hr cadence
- No offset

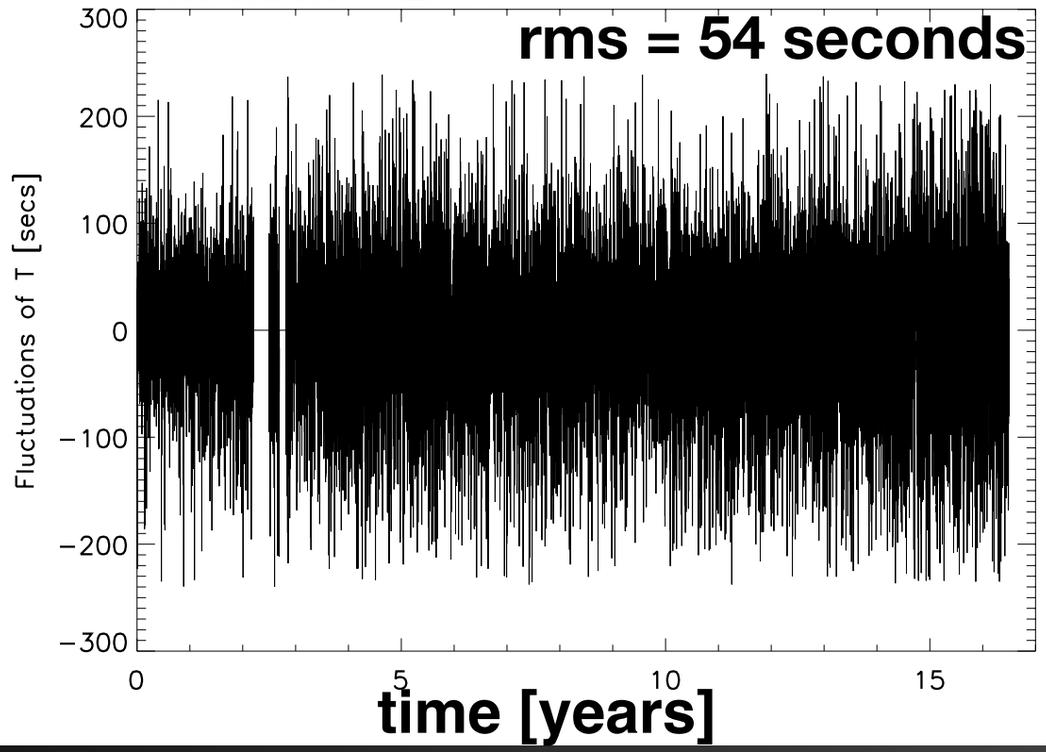


Test: overlap

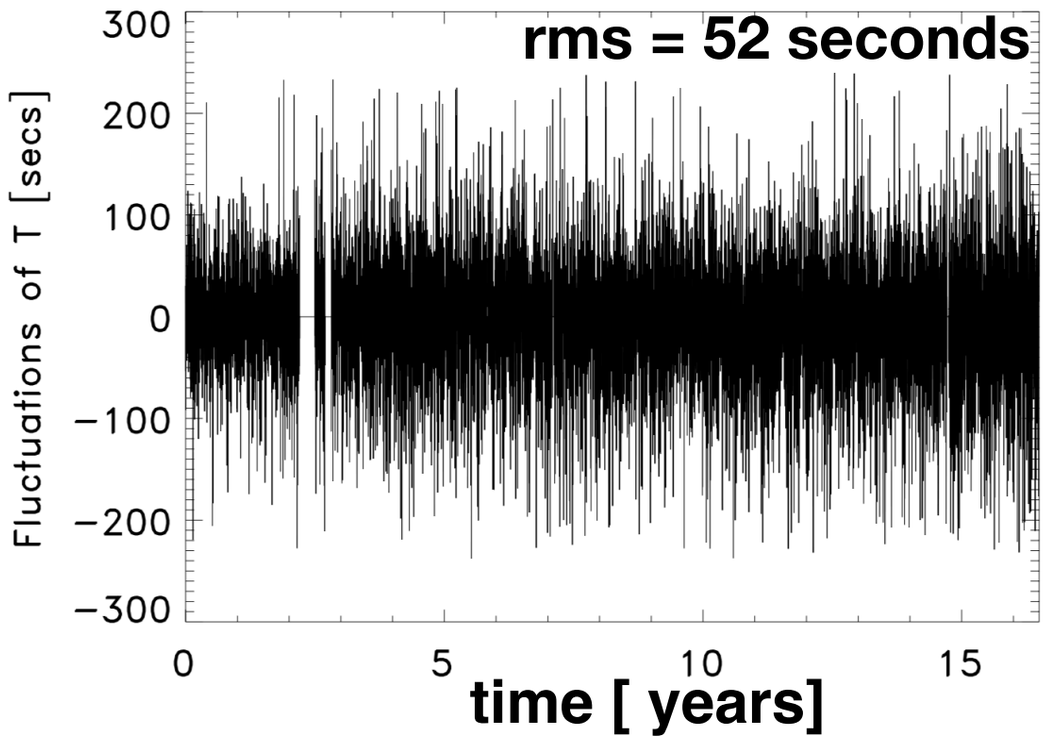
- No overlapping segments
  —> different noise properties
- No offset

Qualitative reproduction of *Fossat+ 2017*
4 hour cadence, 8 hour segment length

Schunker+ 2018



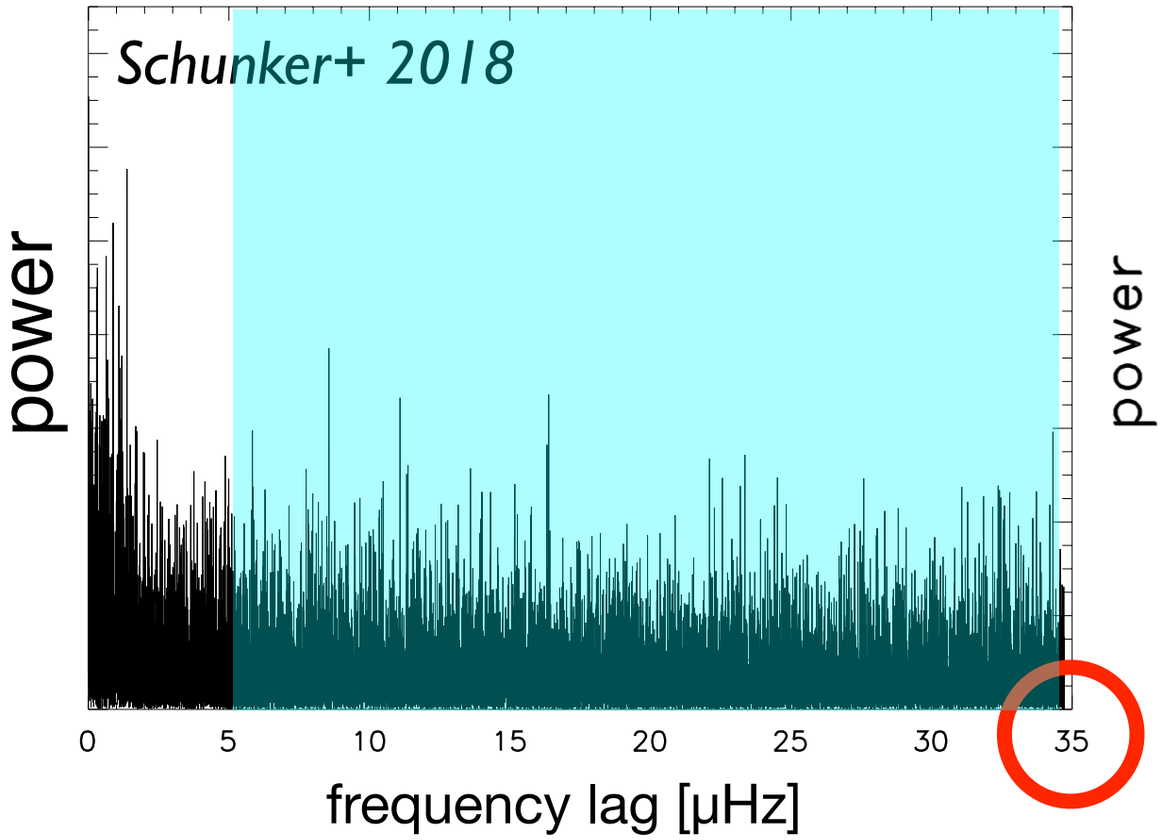
8 hour cadence, 8 hour segment length,
NO OVERLAP



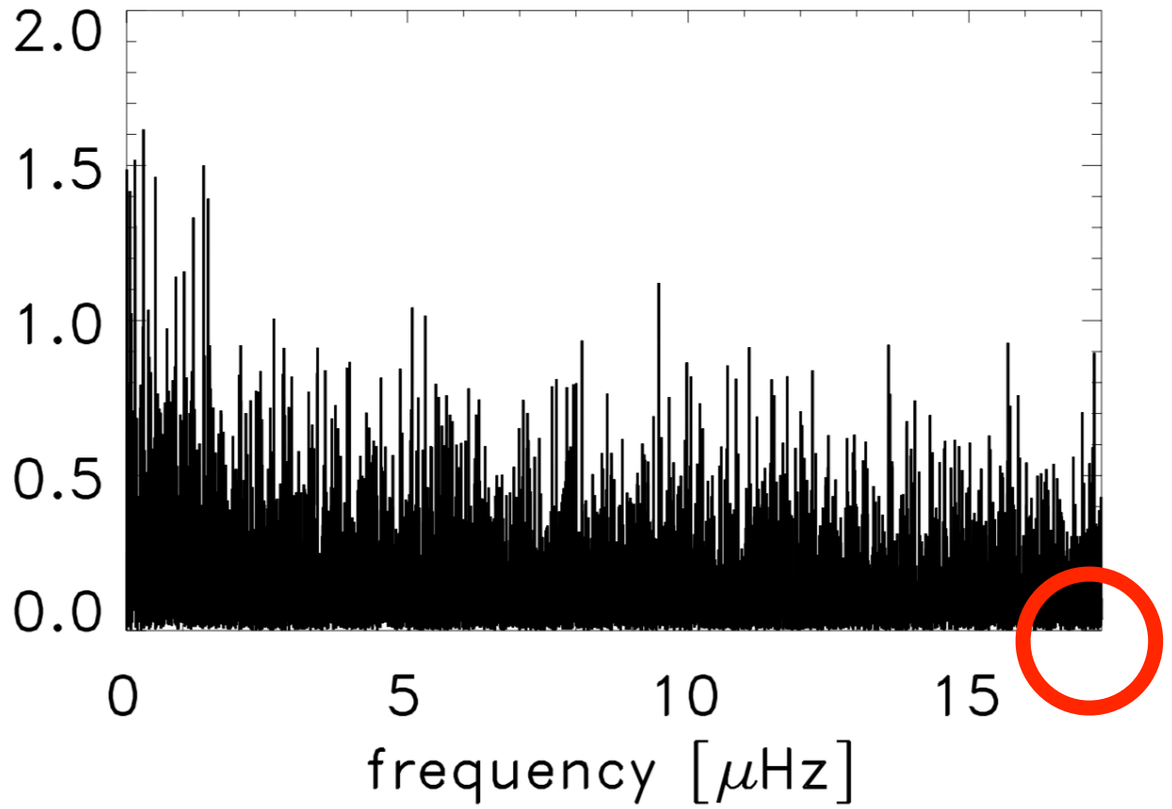
Test: overlap

- Power spectrum looks similar

Qualitative reproduction of *Fossat+ 2017*
4 hour cadence, 8 hour segment length



8 hour cadence, 8 hour segment length,
NO OVERLAP



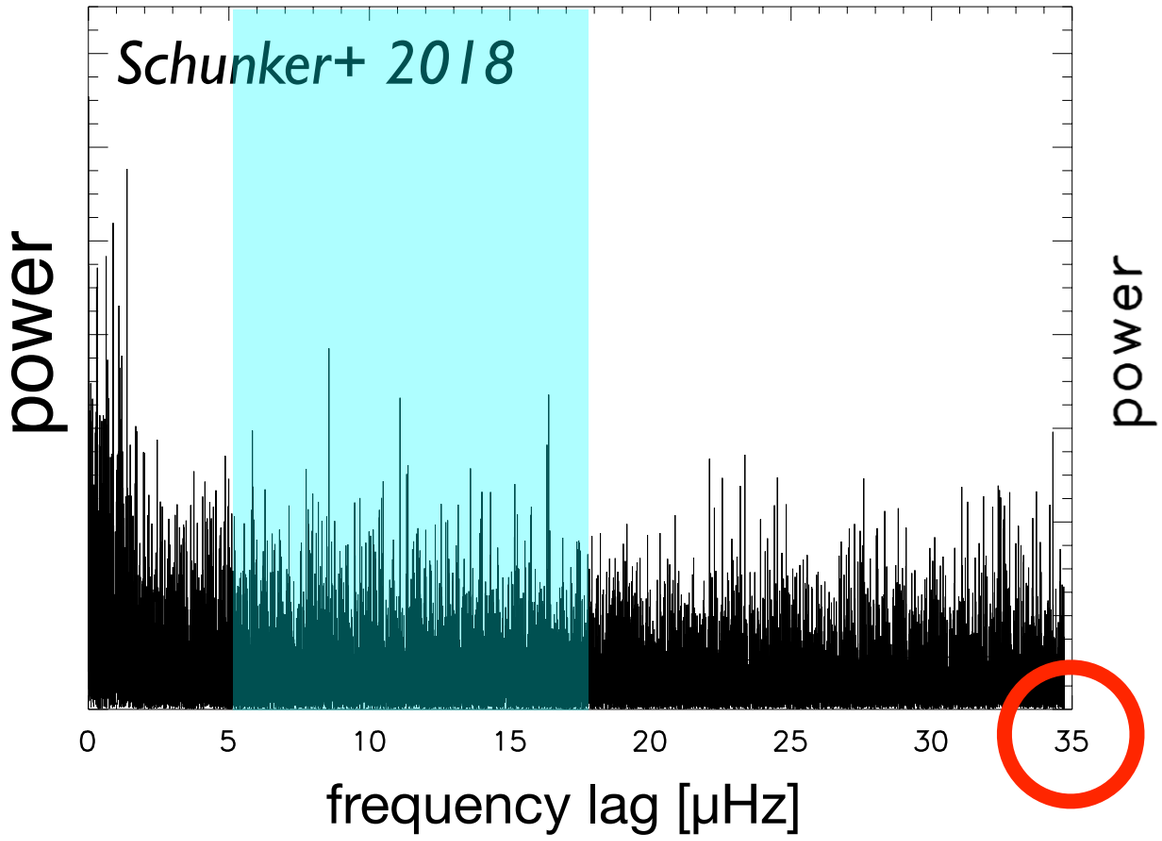
Note: Nyquist is now halved

Hannah Schunker

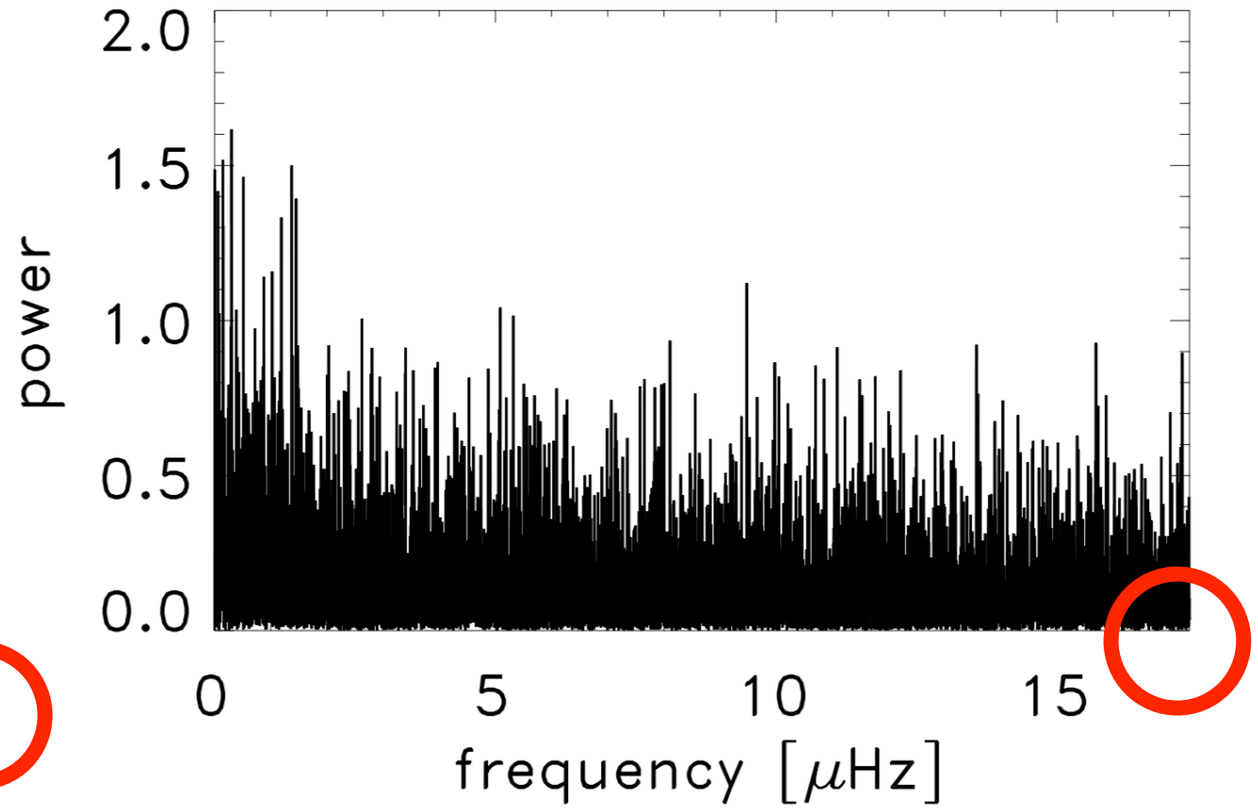
Test: overlap

- Power spectrum looks similar

Qualitative reproduction of *Fossat+ 2017*
4 hour cadence, 8 hour segment length



8 hour cadence, 8 hour segment length,
NO OVERLAP

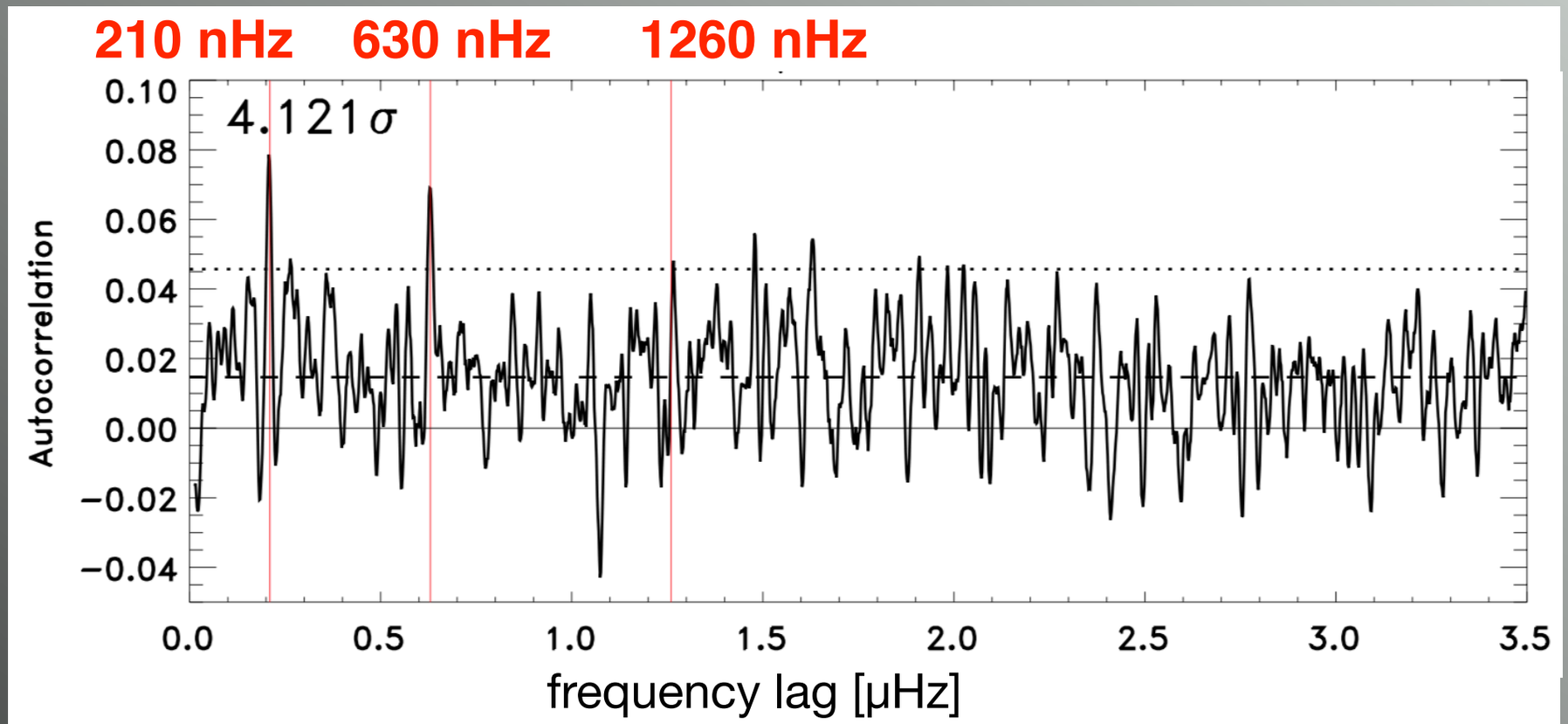


Note: Nyquist is now halved

Hannah Schunker

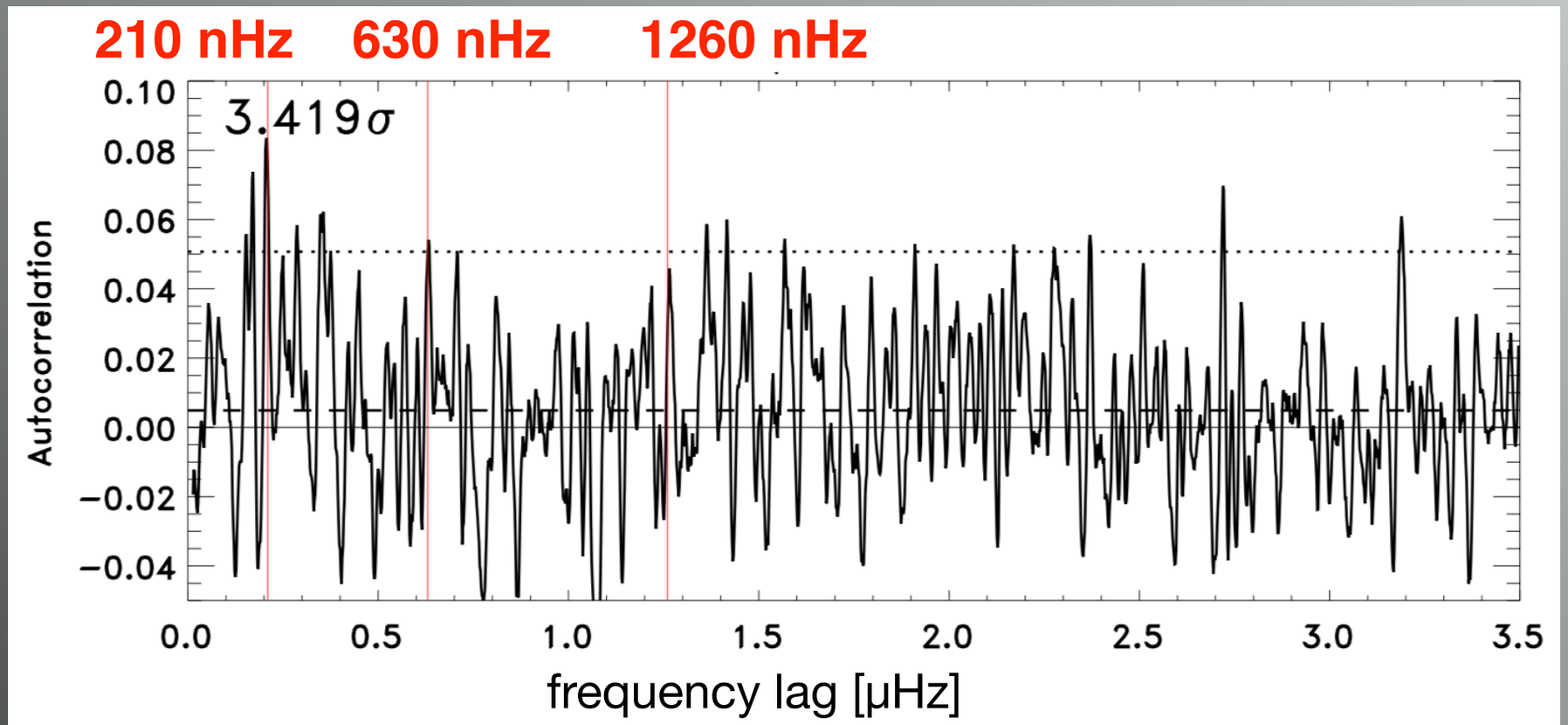
Test: overlap

- ‘Original’
  8 hr segment length,
  4 hr cadence,
  AC
  5.5-35μHz



Test: overlap

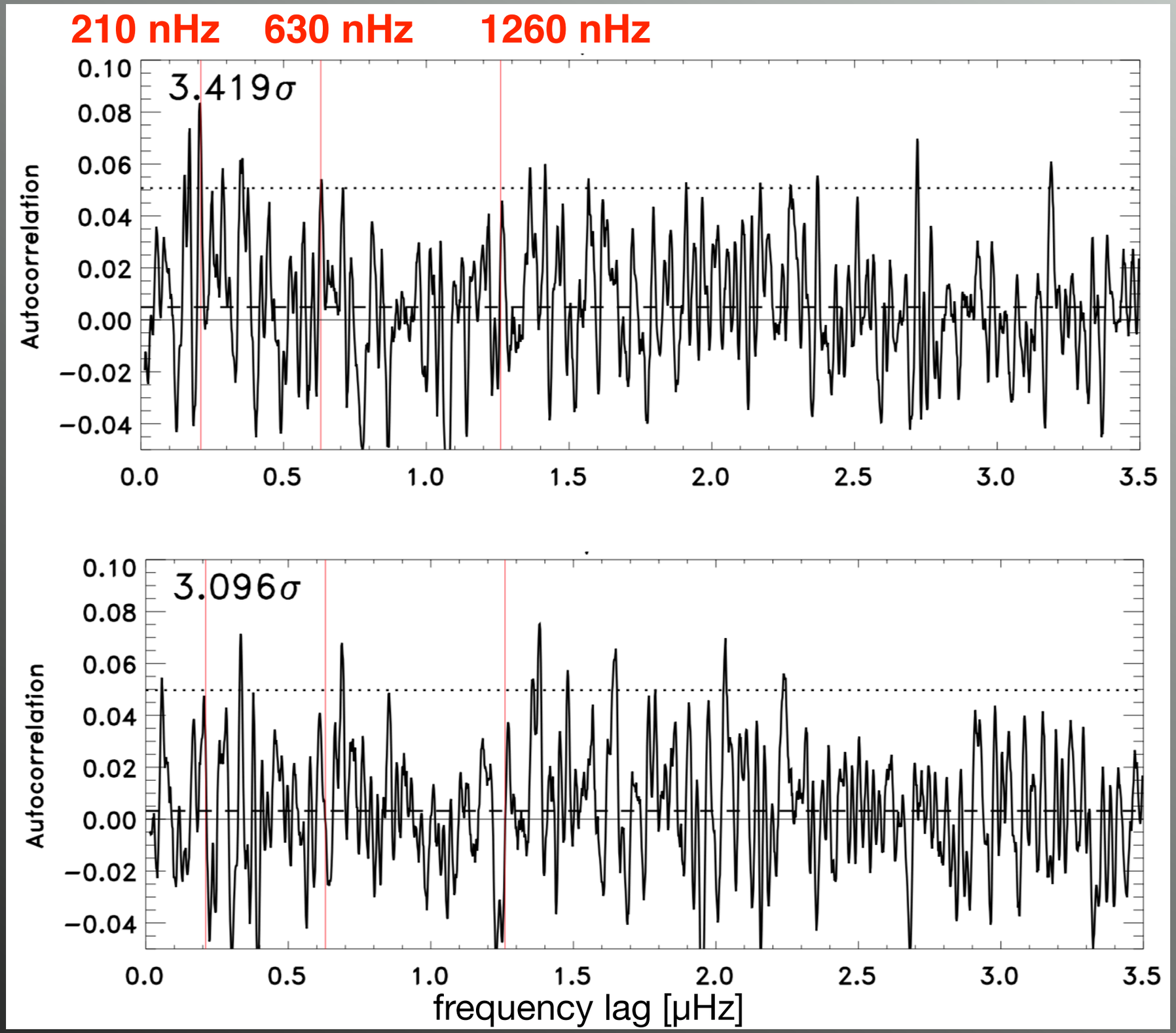
- ‘Original’
  8 hr segment length,
  4 hr cadence,
  AC
  5.5-17μHz



Test: overlap

- ‘Original’
  8 hr segment length,
  4 hr cadence,
  AC
  5.5-17μHz

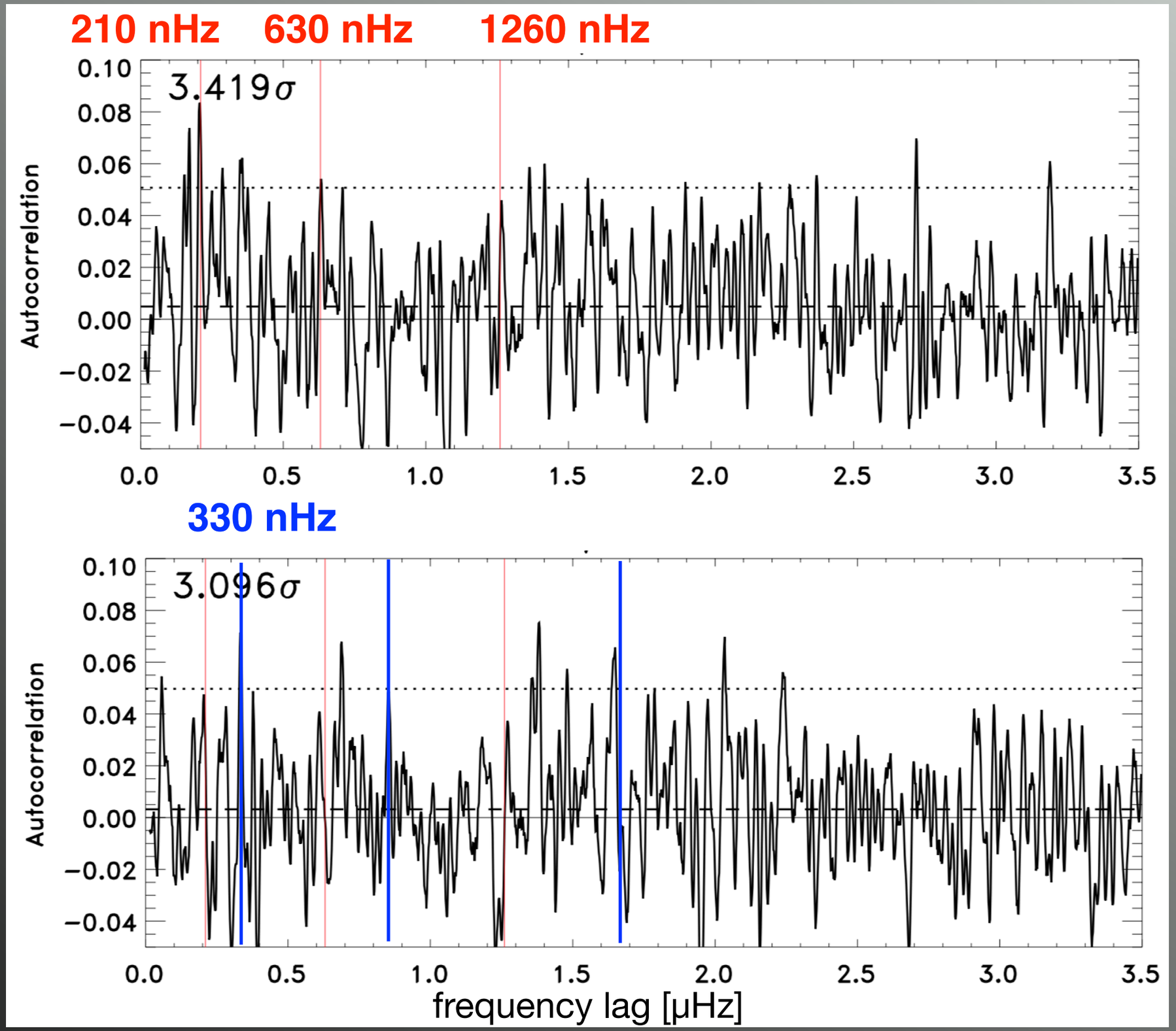
- ‘No overlap’
  8 hr segment length,
  8 hr cadence,
  AC
  5.5-17μHz



Test: overlap

- ‘Original’
  8 hr segment length,
  4 hr cadence,
  AC
  5.5-17μHz

- ‘No overlap’
  8 hr segment length,
  8 hr cadence,
  AC
  5.5-17μHz



Summary

1. Qualitatively reproduce Fig. 10 *Fossat et al. 2017*

2. Detection is sensitive to a number of parameters in the analysis method
   i. Fitting function to measure RTTT
   ii. Smoothing of AC
   iii. Start time of data series
   iv. Cadence of RTTT measurements (5 hrs; $4.3\Omega_p$)
   v. Overlap of the segments to measure RTTT

Conclusion:

- easily broken fragile detection
- start time dependence extremely worrying

→

Further Tests of Robustness

1. Independent instrument confirmation
   MDI, HMI, BiSON, GONG

2. Explore physical assumptions
   Assume: $\ell = 2 \quad \Omega_{\rm g} = 458\ {\rm nHz}$

3. Other stars with *g*-, *p*-, and mixed modes
   Kepler