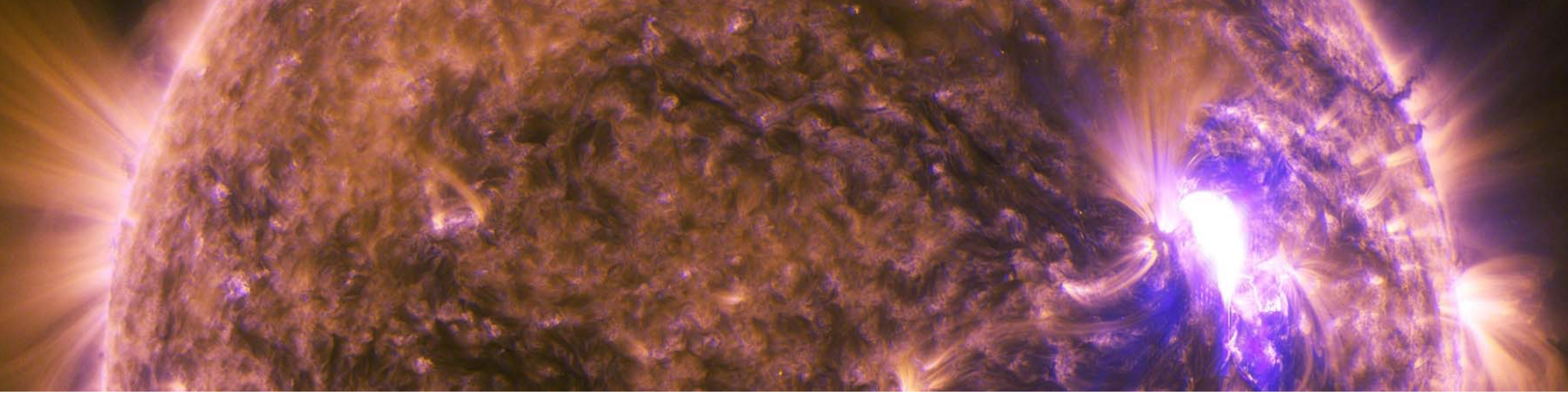

The Detection of Quasi-Periodic Pulsations in Solar Flares From a Single Active Region

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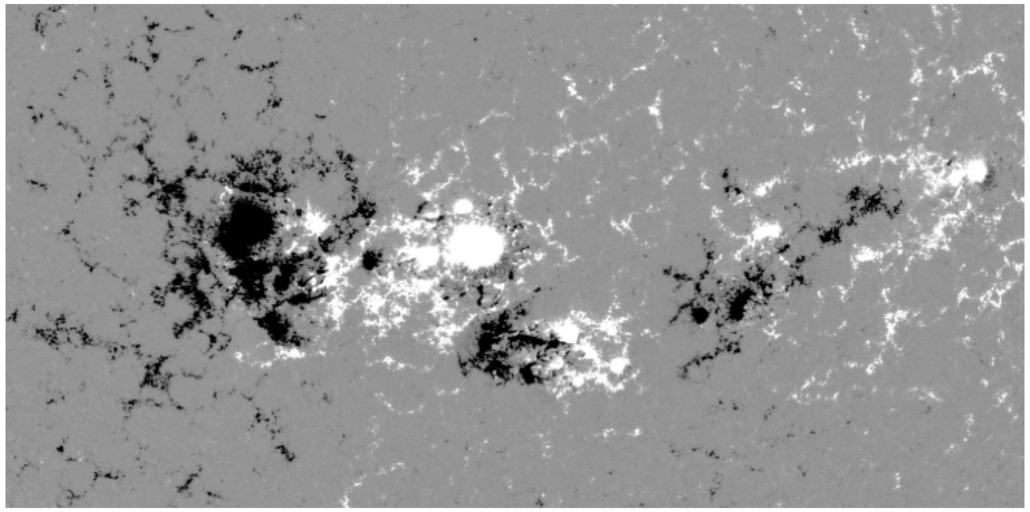
Overview

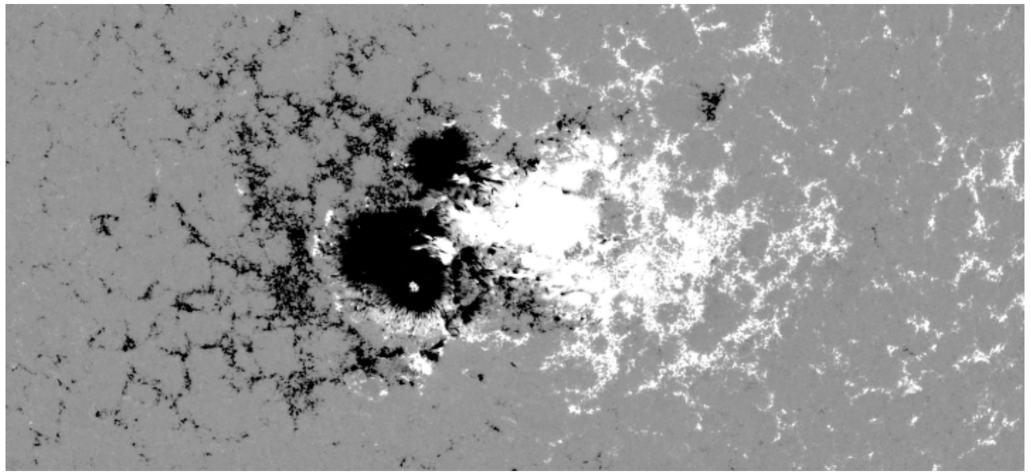
- Study of quasi-periodic pulsations (QPPs) in solar flares from a single long-lived active region
- Detection methods - accounting for red noise and data uncertainties
- Examples of solar flares with candidate QPPs
- Outline of sample of flares with QPPs from the same active region

Solar flare QPP study

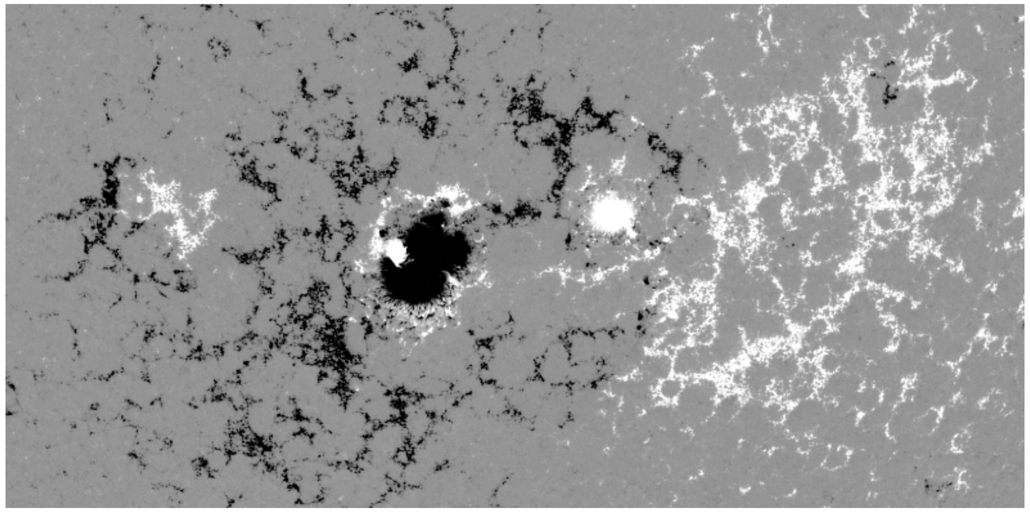
- 181 GOES class flares from a single (very) active region
- 137 C class, 38 M class, 6 X class
- How many have QPPs?
- Do QPP properties evolve with time?
- Do QPP properties depend on the type of flare?



NOAA 12172, 12173, 12171



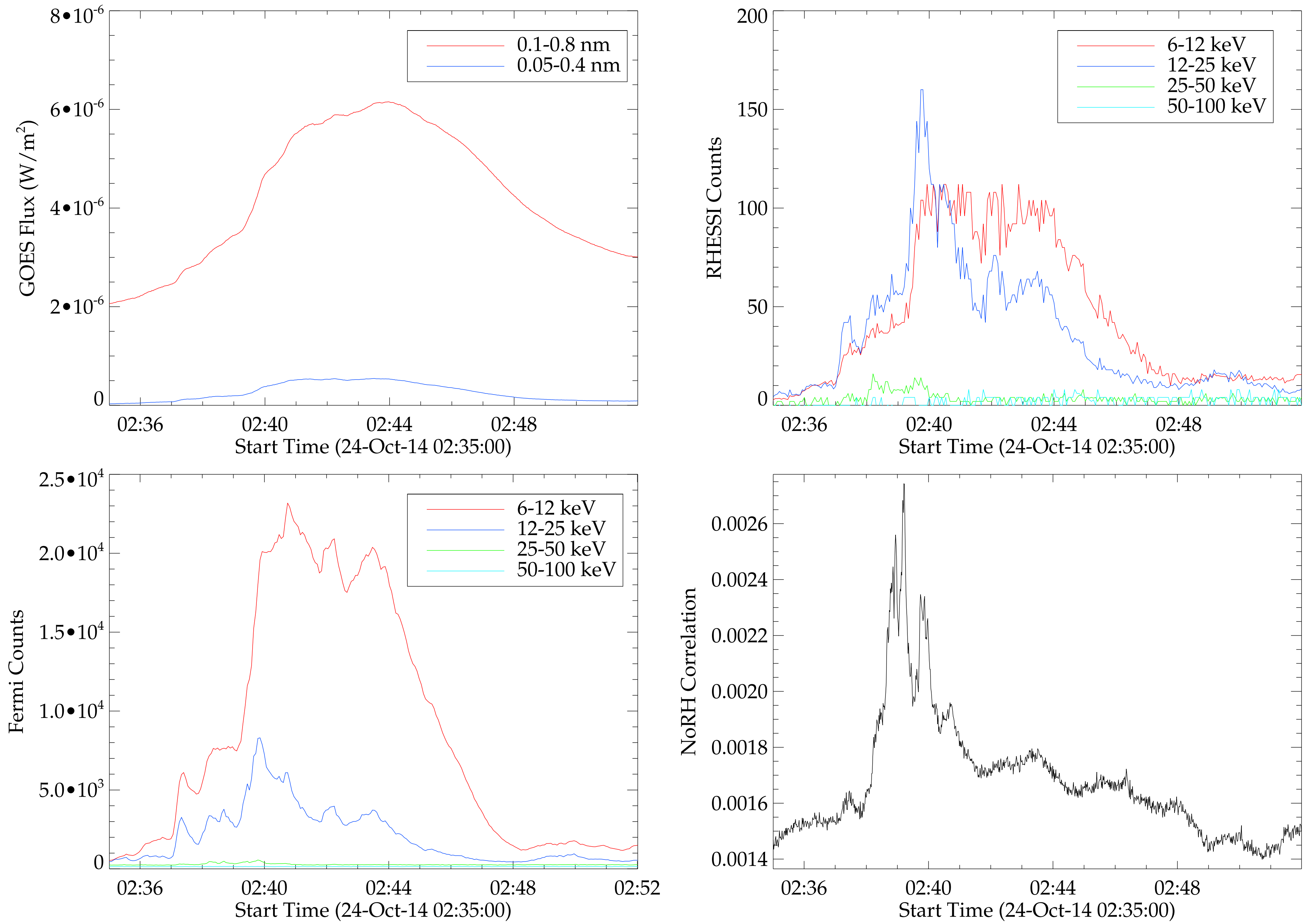
NOAA 12192



NOAA 12209

Solar flare QPP study

- GOES, RHESSI, Fermi, Vernov (Myagkova et al. 2016), Nobeyama Radioheliograph (NoRH)



How to detect the QPPs?

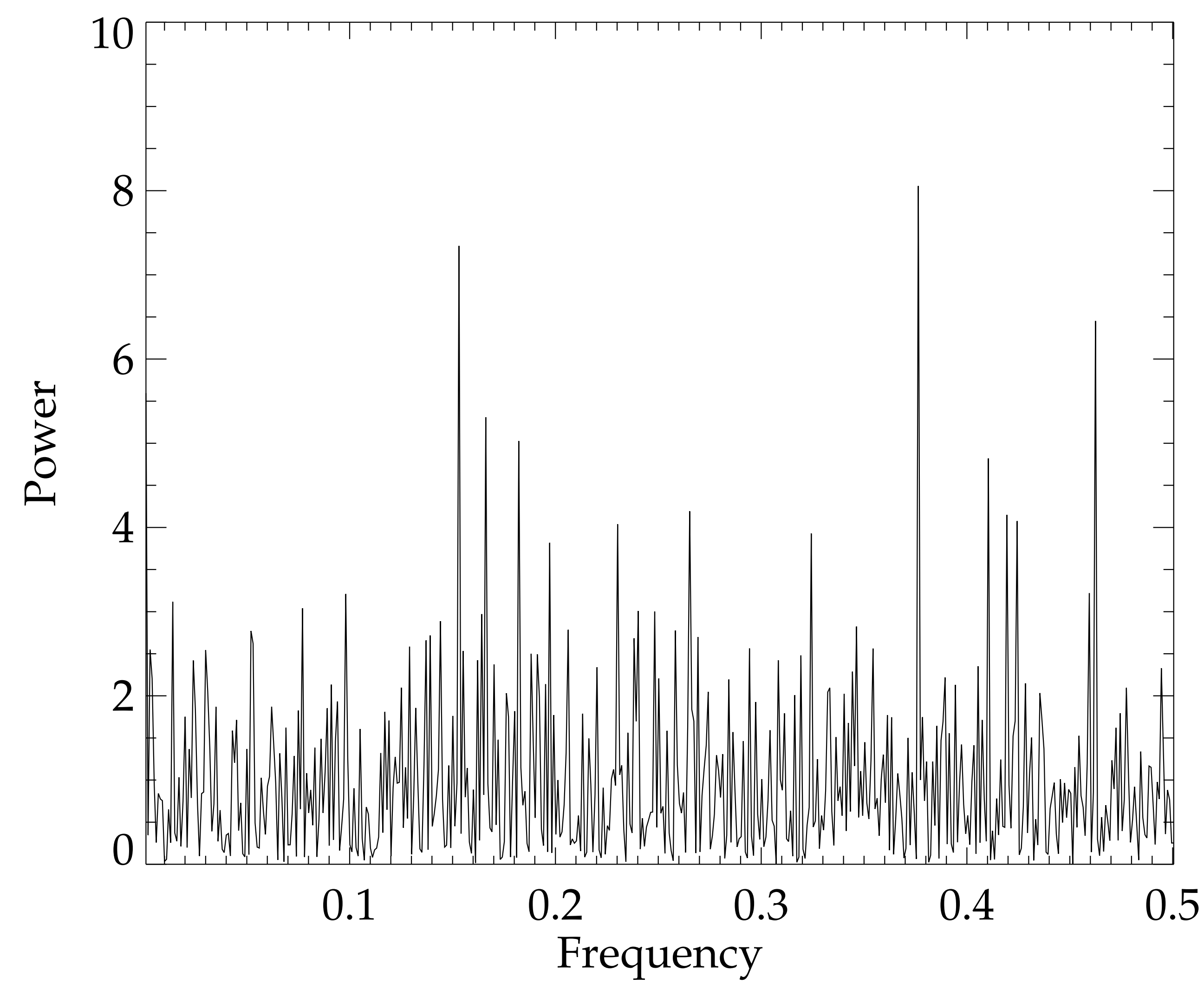
- Definition of QPP signal:
  - At least 3 cycles of oscillation (or 3 pulses with ~equal time spacing)
  - Can be in rise and/or decay phase of flare
  - Can have modulated amplitude
  - Stationary or non-stationary (focus on stationary here)
- How to quantify a detection? —> Fourier analysis —> periodogram or wavelet —> confidence levels
- Flare time series data has trends/intrinsic red noise —> to detrend or not to detrend?

Confidence levels: white noise case

- For χ^2 distribution with 2 degrees of freedom, probability is:

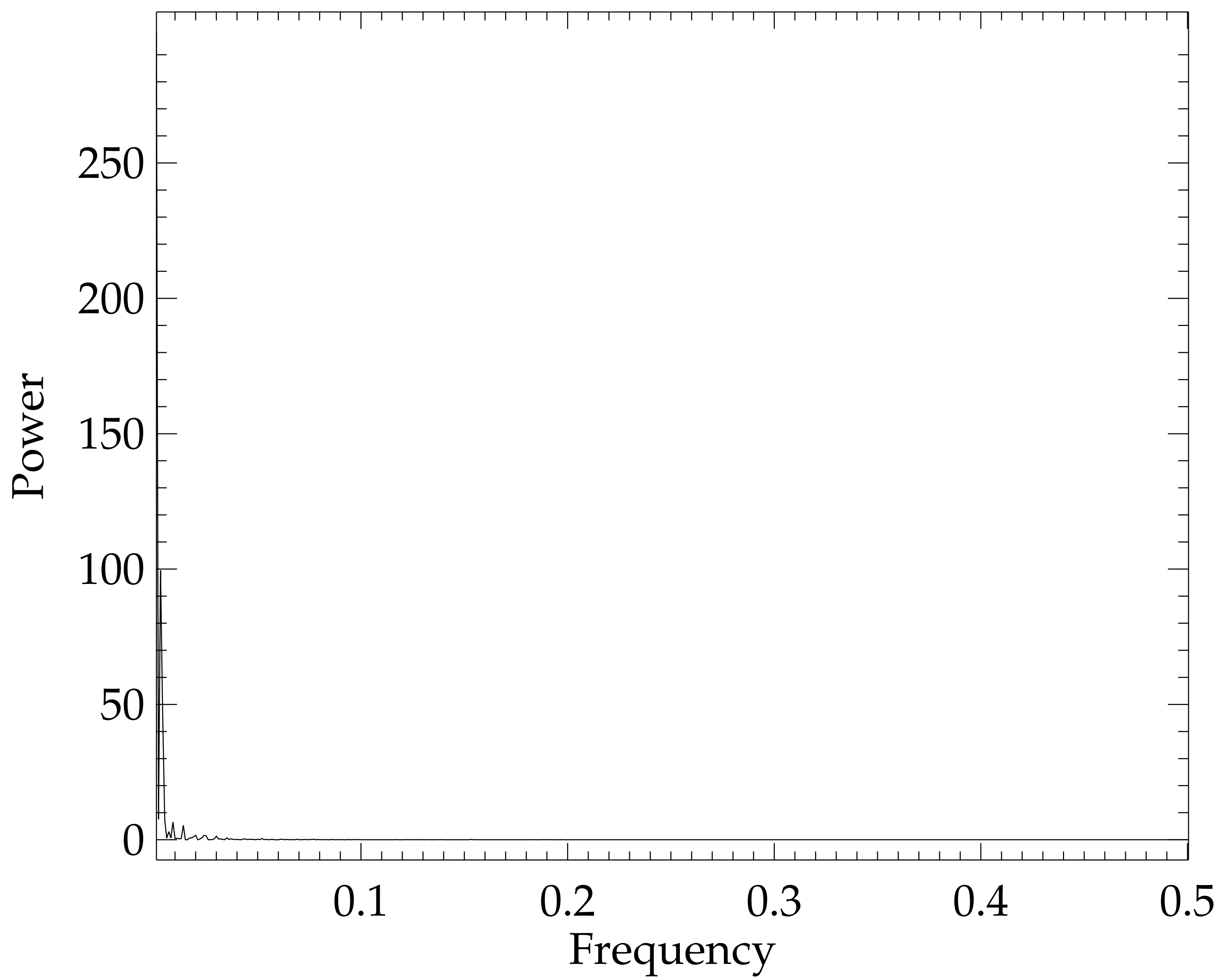
$$\Pr\left\{\chi^2 > \gamma\right\} = \frac{1}{2}\int_{\gamma}^{\infty} e^{-x/2}\, dx = e^{-\frac{\gamma}{2}}$$

- (See Horne and Baliunas 1986 for more detail)
- Right: periodogram of white noise, which follows a χ^2, 2 d.o.f distribution



Confidence levels: red noise

- Red noise means a power-law power spectrum — power depends on frequency



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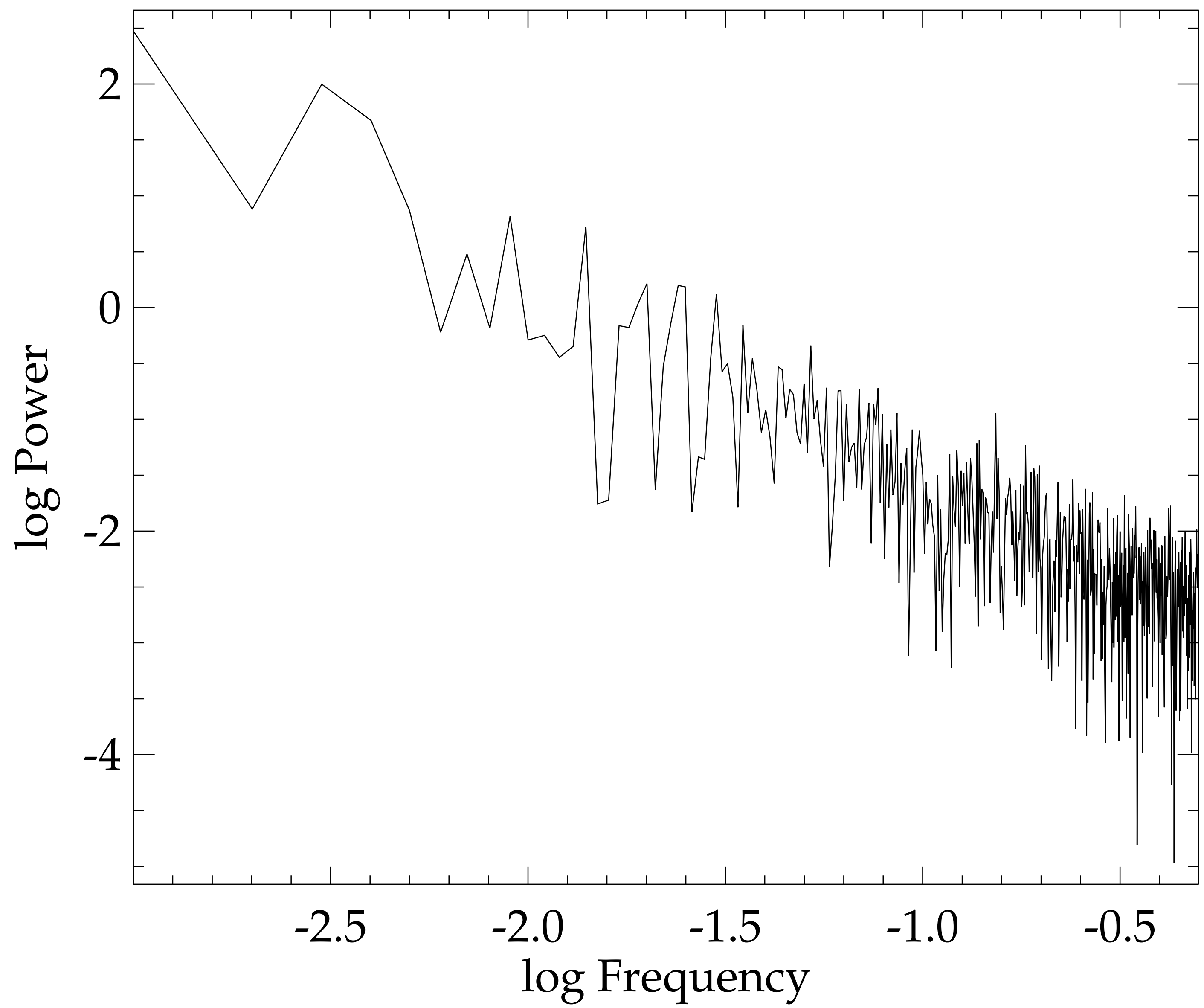


Confidence levels: red noise

- We can fit a (broken) power law model to the spectrum:

$$\log(\hat{P}(f)) = \begin{cases} \log(A) - \alpha \log(f) & f < f_{break} \\ \log(A) - \beta \log(f) - (\alpha - \beta)\log(f_{break}) & f > f_{break} \end{cases}$$

- Data have associated uncertainties —> periodogram powers will have uncertainties —> fitted power law model will have uncertainties
- Can estimate uncertainties on power law model by performing monte carlo simulations with original time series data uncertainties
- Additional source of uncertainty from model will affect probability distribution

Confidence levels: red noise

- A confidence level can be found by solving this equation (see Vaughan 2005 or Pugh et al. 2017 (in prep) for more detail):

Probability of a value x_j being greater than some threshold γ_j

Log-normal distribution of model uncertainties

w and z are dummy variables representing power

$$\Pr\left\{x_j > \gamma_j\right\} = \int_{\gamma_j}^{\infty}\int_0^{\infty} \frac{1}{\sqrt{8\pi S_j}} \exp\left\{\frac{-(\ln w)^2}{2S_j^2} - \frac{wz}{2}\right\} dw\, dz$$

Uncertainty on the model

Exponential χ^2 2 d.o.f distribution

- which reduces to:

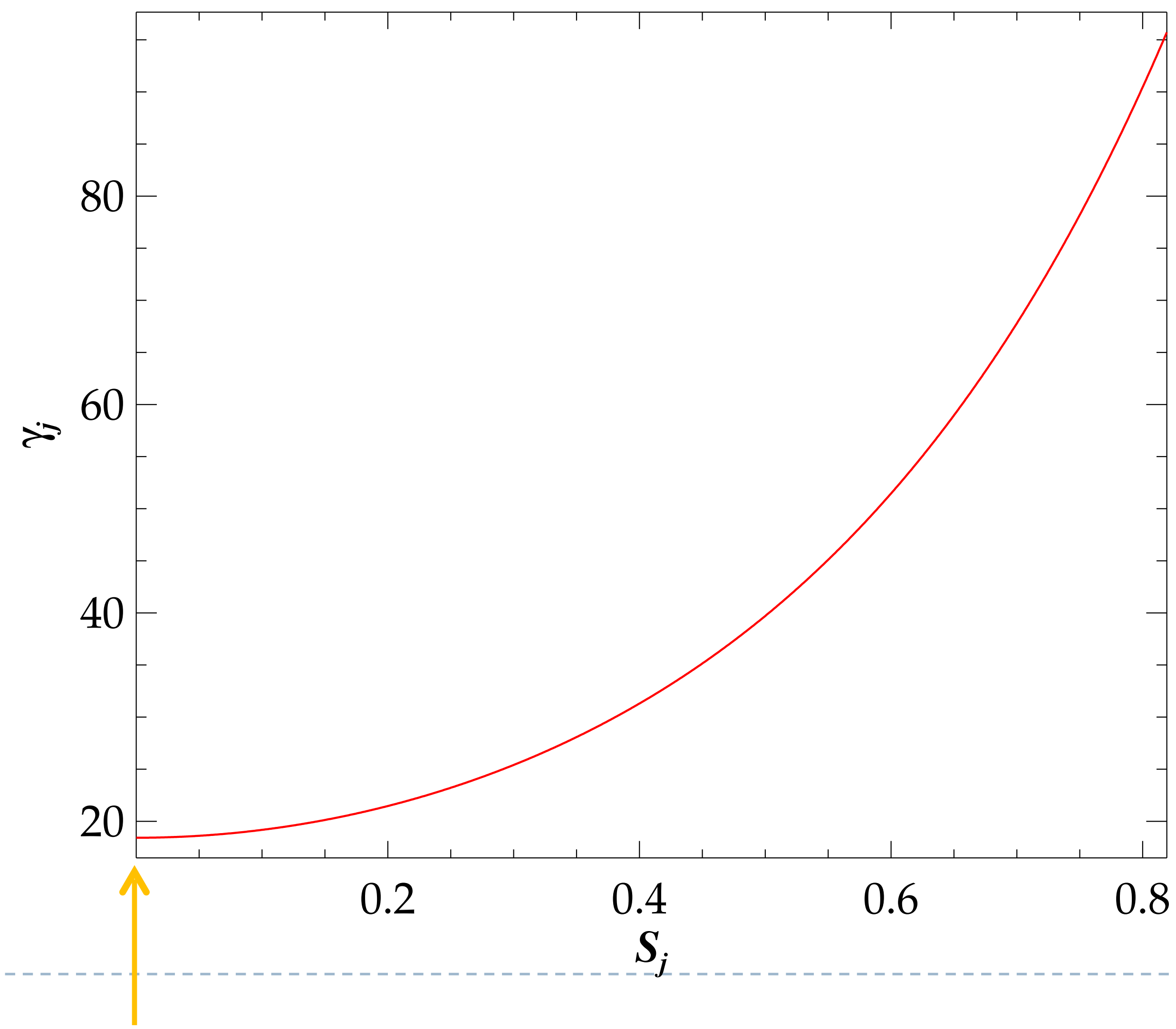
$$\Pr\left\{x_j > \gamma_j\right\} = \int_0^{\infty} \frac{1}{\sqrt{2\pi S_j w}} \exp\left\{\frac{-(\ln w)^2}{2S_j^2} - \frac{\gamma_j w}{2}\right\} dw$$

Confidence levels: red noise

Set false alarm probability to 1% for 99% confidence level

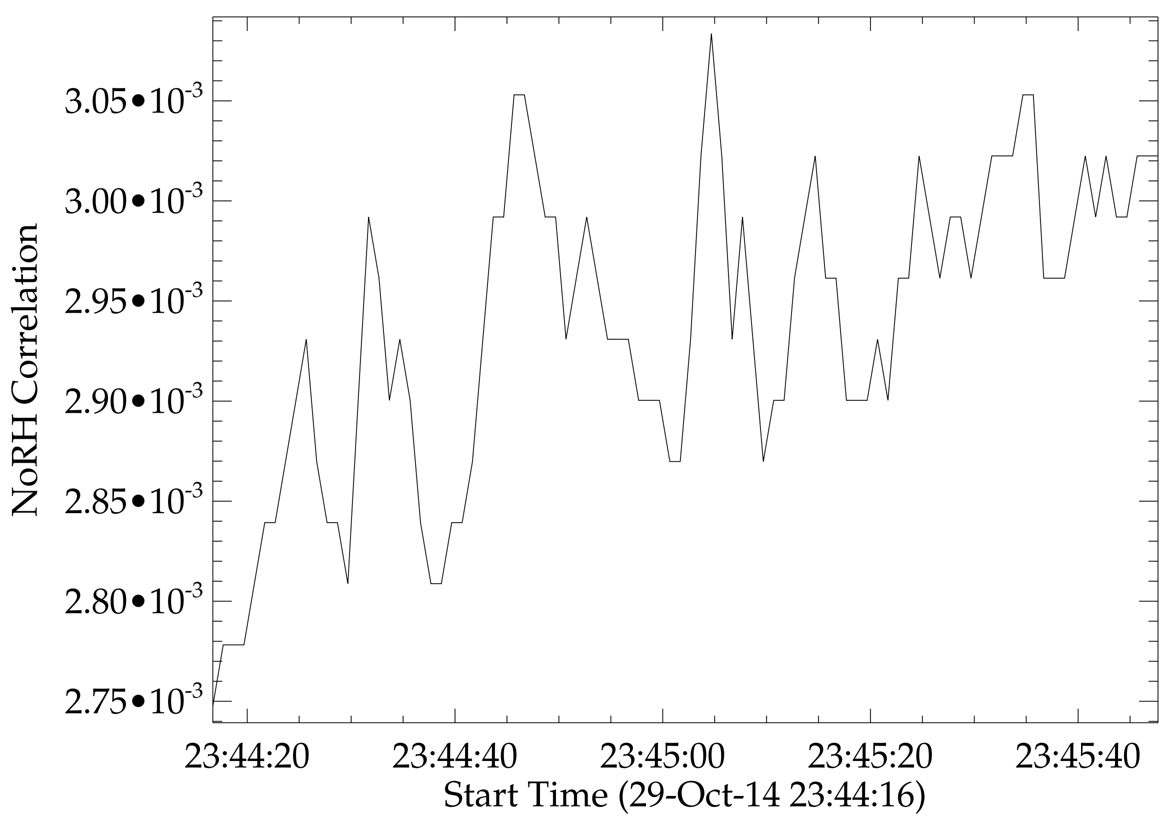
$$\Pr\{x_j > \gamma_j\} = \frac{0.01}{N} = \int_0^\infty \frac{1}{\sqrt{2\pi}S_j w} \exp\left\{\frac{-(\ln w)^2}{2S_j^2} - \frac{\gamma_j w}{2}\right\} dw$$

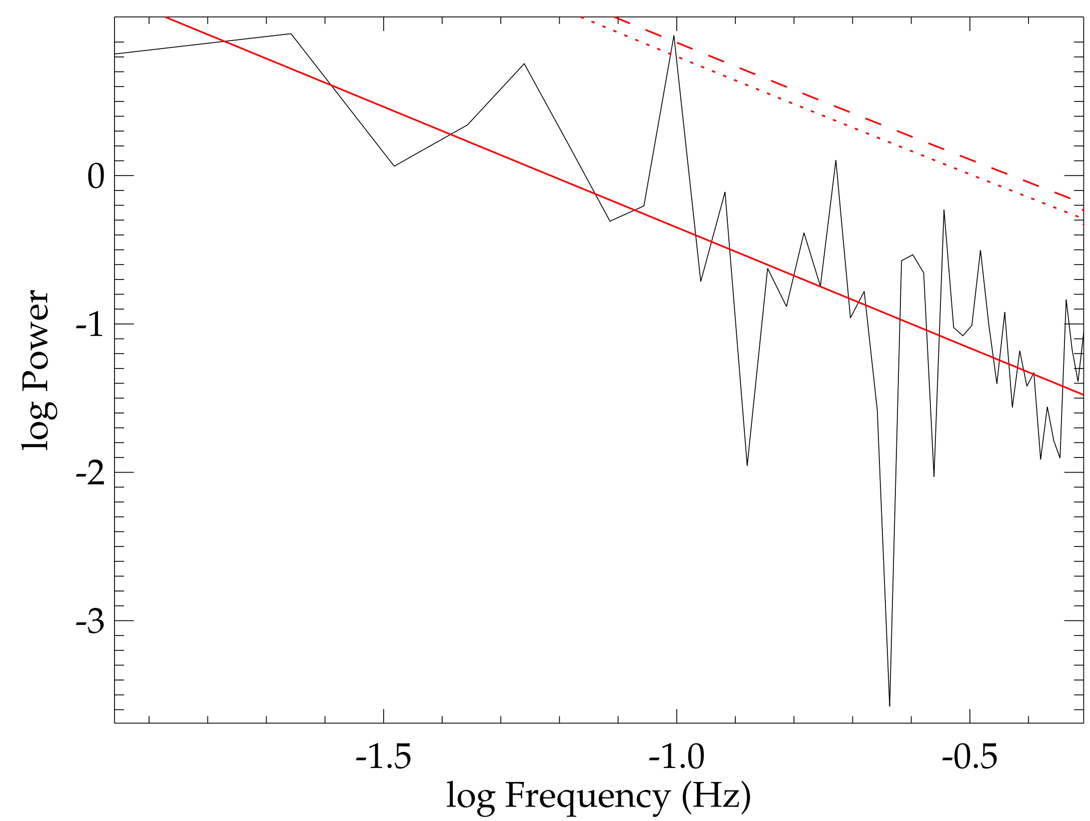
Number of values in the power spectrum (set to 100 here)



Examples

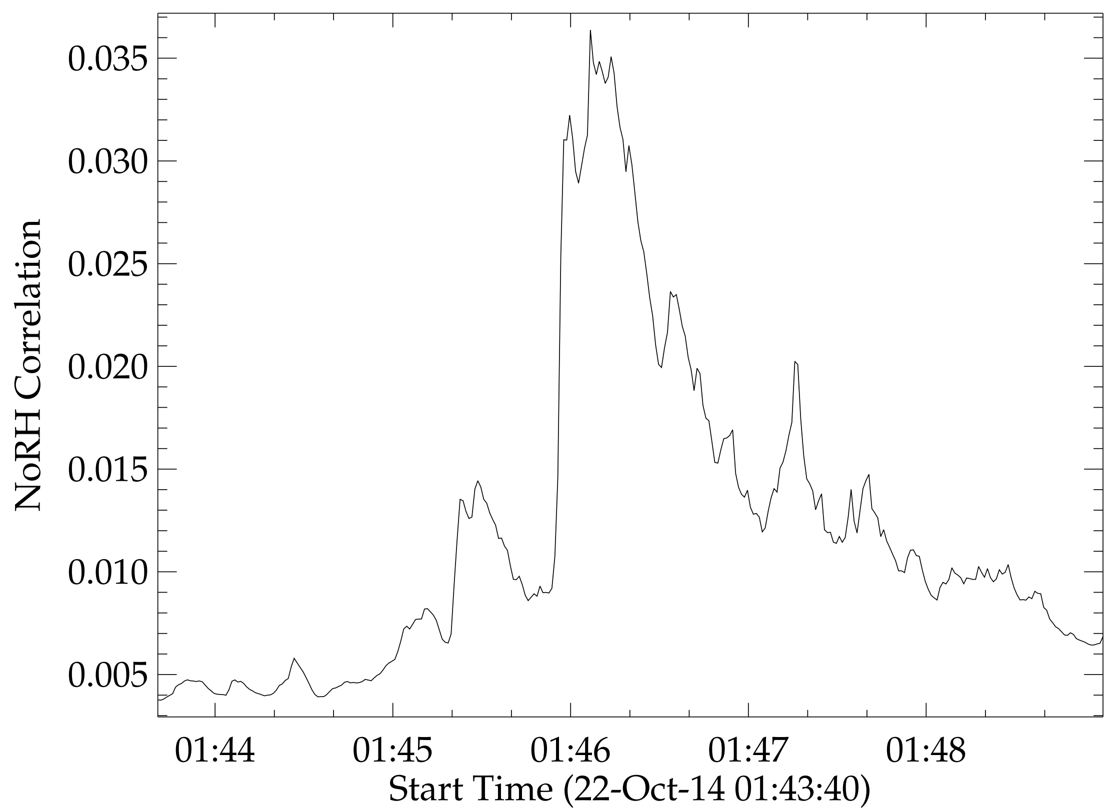
- Solar flares observed by Nobeyama Radioheliograph
- Left: Correlation time series of part of a flare
- Right: Periodogram with a peak above 99% confidence level, at a period of ~10 seconds

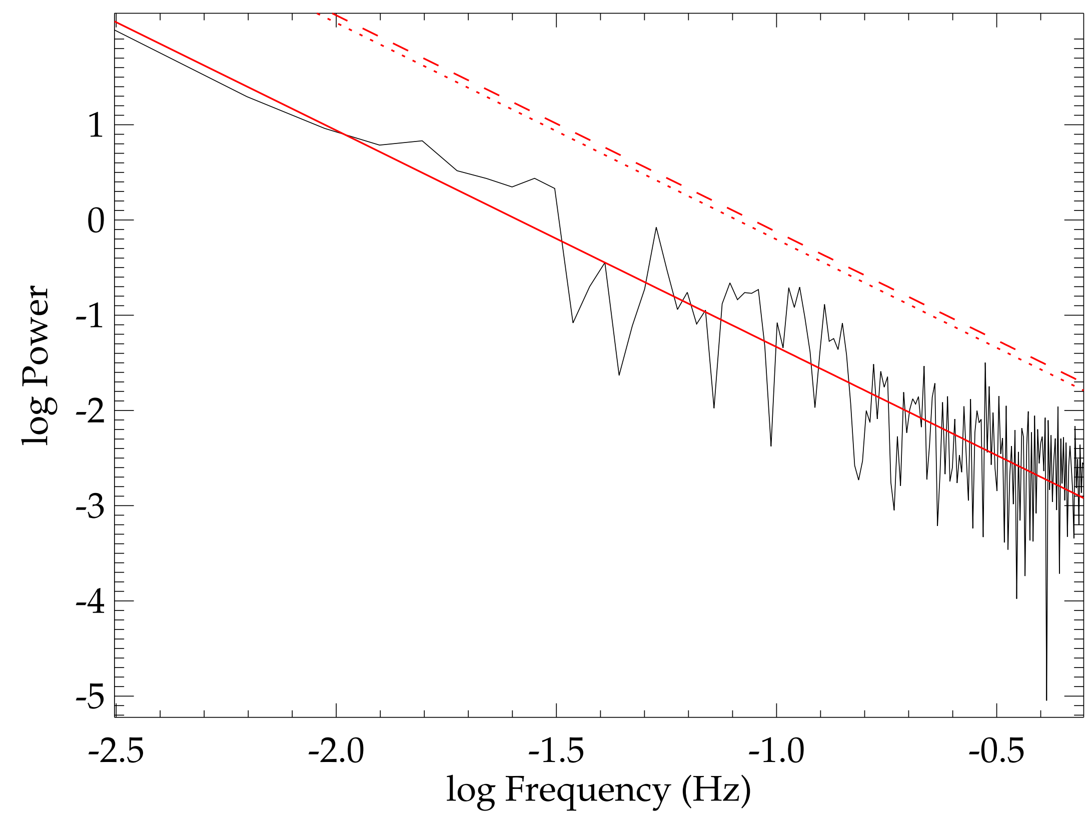




Examples

- Solar flares observed by Nobeyama Radioheliograph
- Left: Correlation time series of part of a different flare
- Right: Periodogram with no significant peak





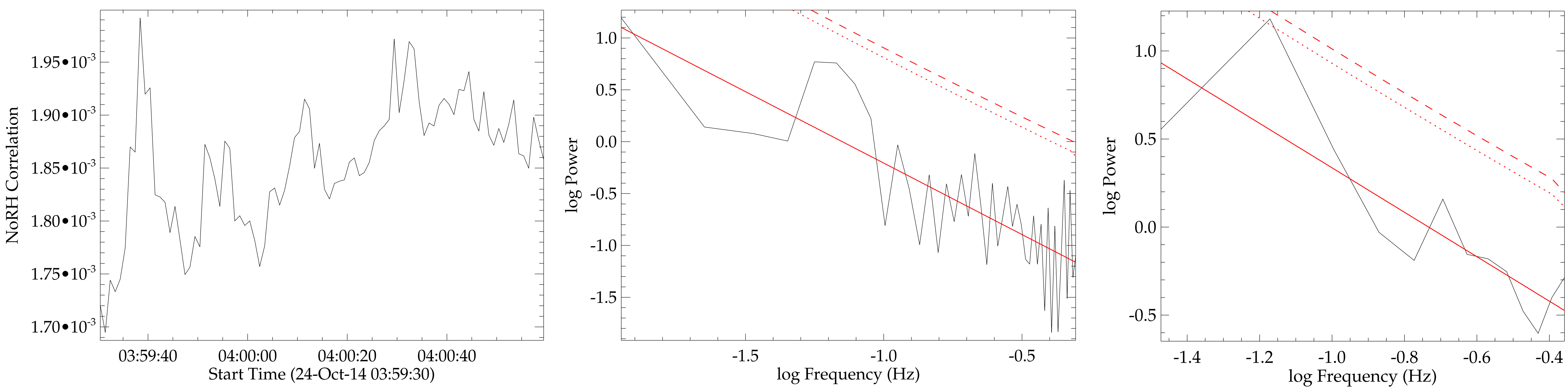
Confidence levels: red noise

- Additional trick: rebinning the power spectra
- Sum over every n frequency bins, so instead of χ^2 2 d.o.f statistics we have χ^2 2n d.o.f
- The new probability integral can be derived (Pugh et al. 2017, in prep):

$$\Pr\left\{x_j > \gamma_j\right\} = \int_{\gamma_j}^{\infty}\int_0^{\infty} \frac{(wz/2)^{n-1}}{\sqrt{8\pi}S_j\Gamma(n)} \exp\left\{\frac{-(\ln w)^2}{2S_j^2} - \frac{wz}{2}\right\} dw\, dz$$

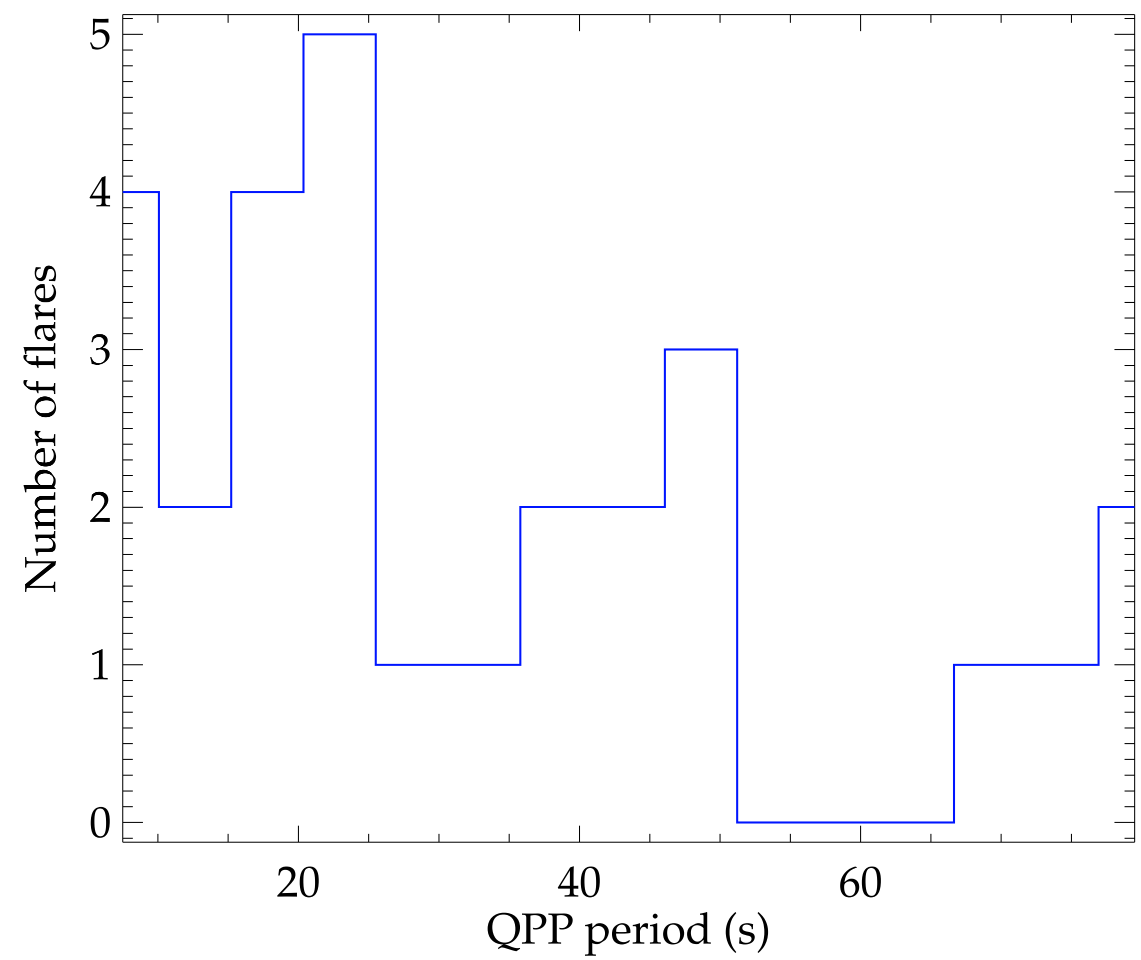
Examples

- Solar flares observed by Nobeyama Radioheliograph
- Left: Correlation time series of part of a flare
- Middle: Periodogram with a broad peak below the 95% confidence level
- Right: Rebinned periodogram (with n=3), where the peak is now above the 95% confidence level, at a period of ~15 seconds



QPPs in flares from a single AR

- Out of 181 flares: 16 with QPPs above 99% level, 23 above 95% level
- Periods ranging from 7.5 to 79.5 seconds
- Right: histogram of QPP periods
- Can also use method described by Inglis et al. 2015/2016 to test for presence of QPPs



Summary

- Solar flares have intrinsic red noise/trends — need to account for this in the statistics
- We have adapted the method described by Vaughan 2005 to test for the presence of QPPs in flares
- Applied the method to a sample of solar flares from a single active region
- Now we have a sample of flares with candidate QPPs, we can use these to investigate whether the QPP properties relate to the active region or flare properties