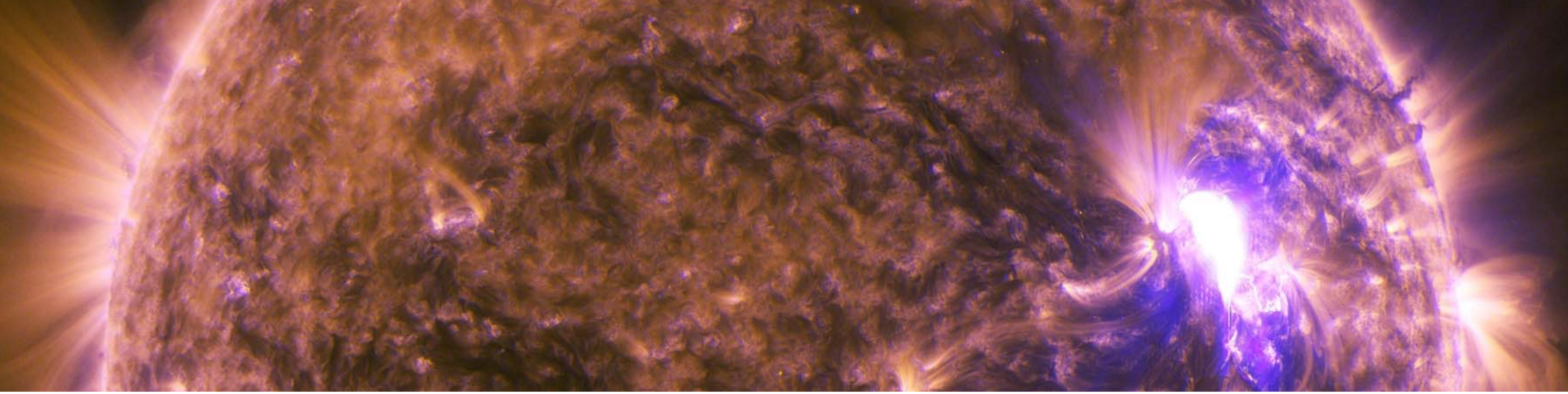

The Detection and Properties of Quasi-Periodic Pulsations in Solar Flares From a Single Active Region

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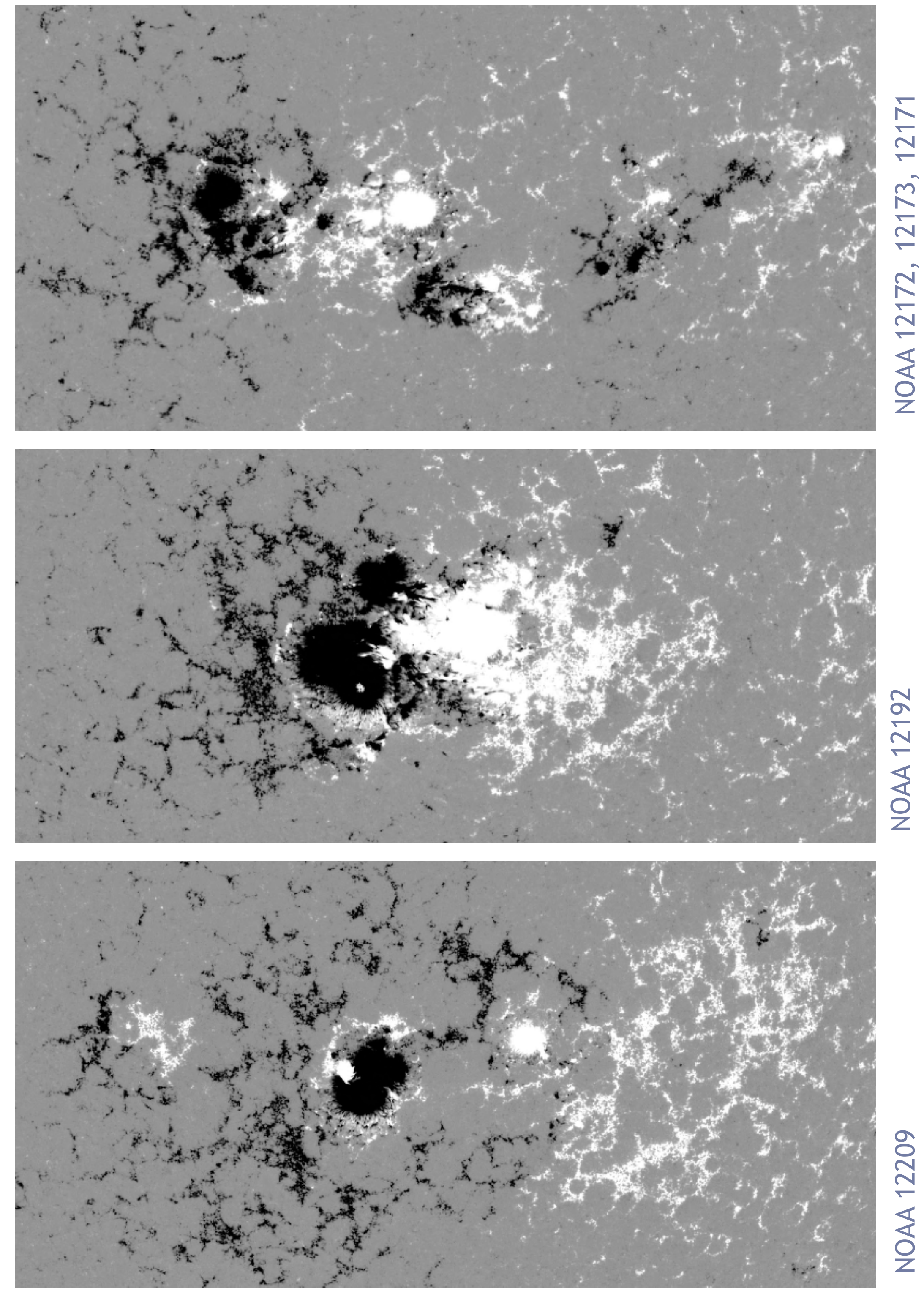
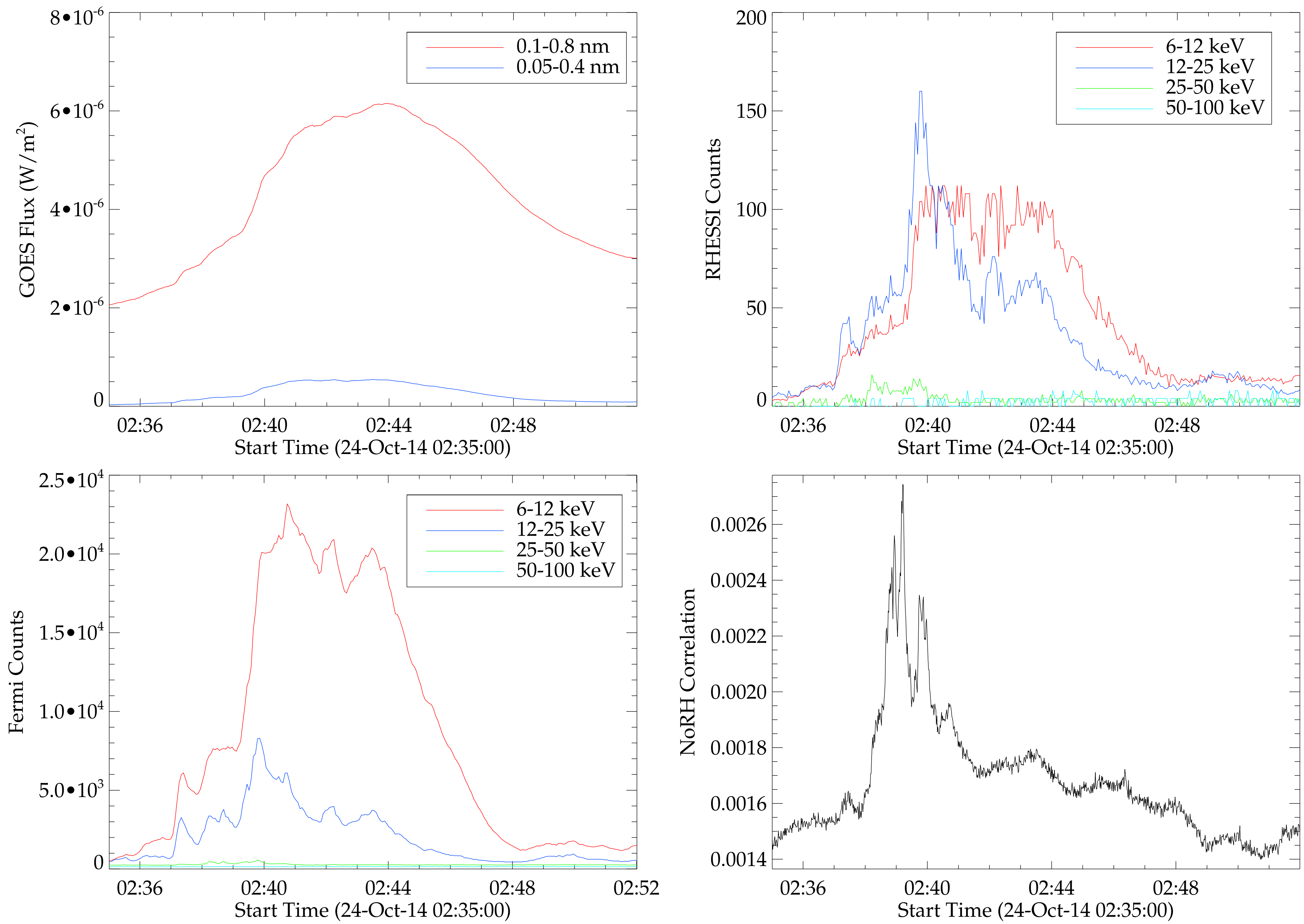
Solar flare QPP study

- 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 relate to the evolution of the active region properties?
- Do the QPP properties depend on the type of flare?



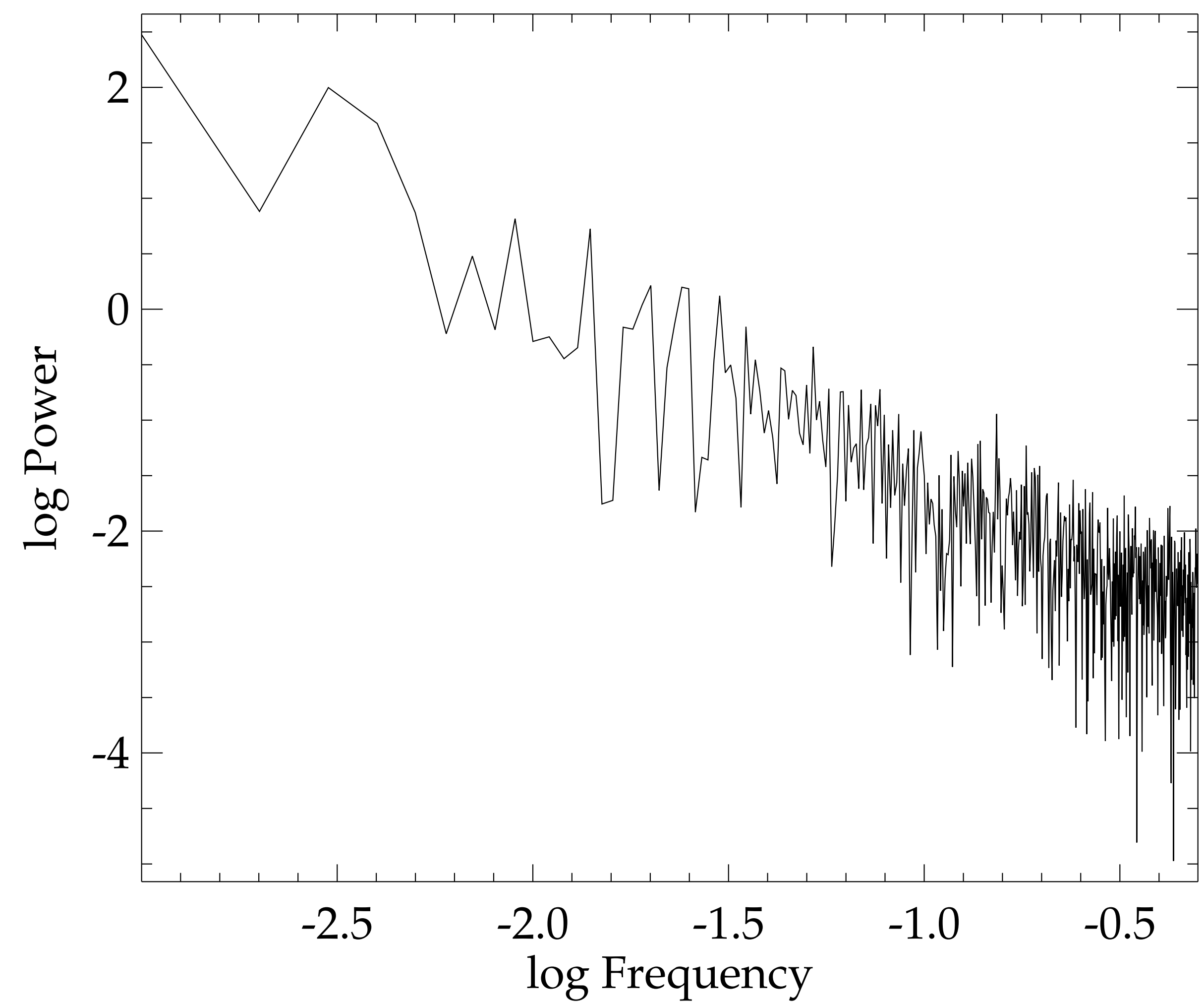
Solar flare QPP study

- Data from GOES, SDO/EVE, RHESSI, Fermi, Vernov (Myagkova et al. 2016), Nobeyama Radioheliograph (NoRH)



How to detect the QPPs?

- How to quantify a detection? → spectral analysis → periodogram or wavelet power spectrum→ confidence levels
- Flare time series have power law power spectra (due to trends and correlated noise)
- Some detrending methods can lead to false detections in the power spectrum (e.g. Gruber et al. 2011, Auchère et al. 2016)

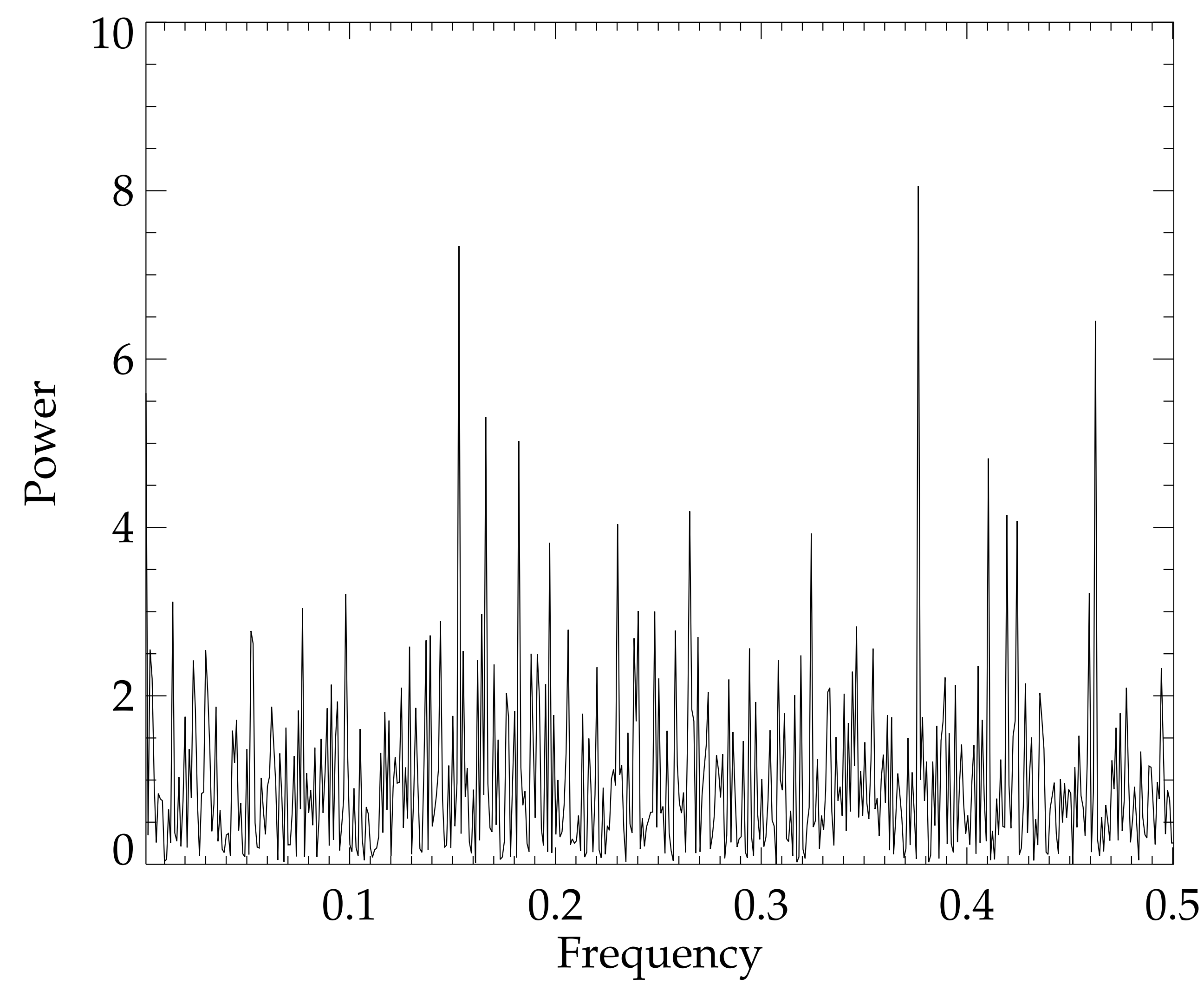


Confidence levels: white noise case

- For χ^2 distribution with 2 degrees of freedom (d.o.f), probability is:

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

- (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: power law case

- 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: power law case

- A confidence level can be found by solving this equation (see Vaughan 2005 or Pugh et al. 2017a 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:

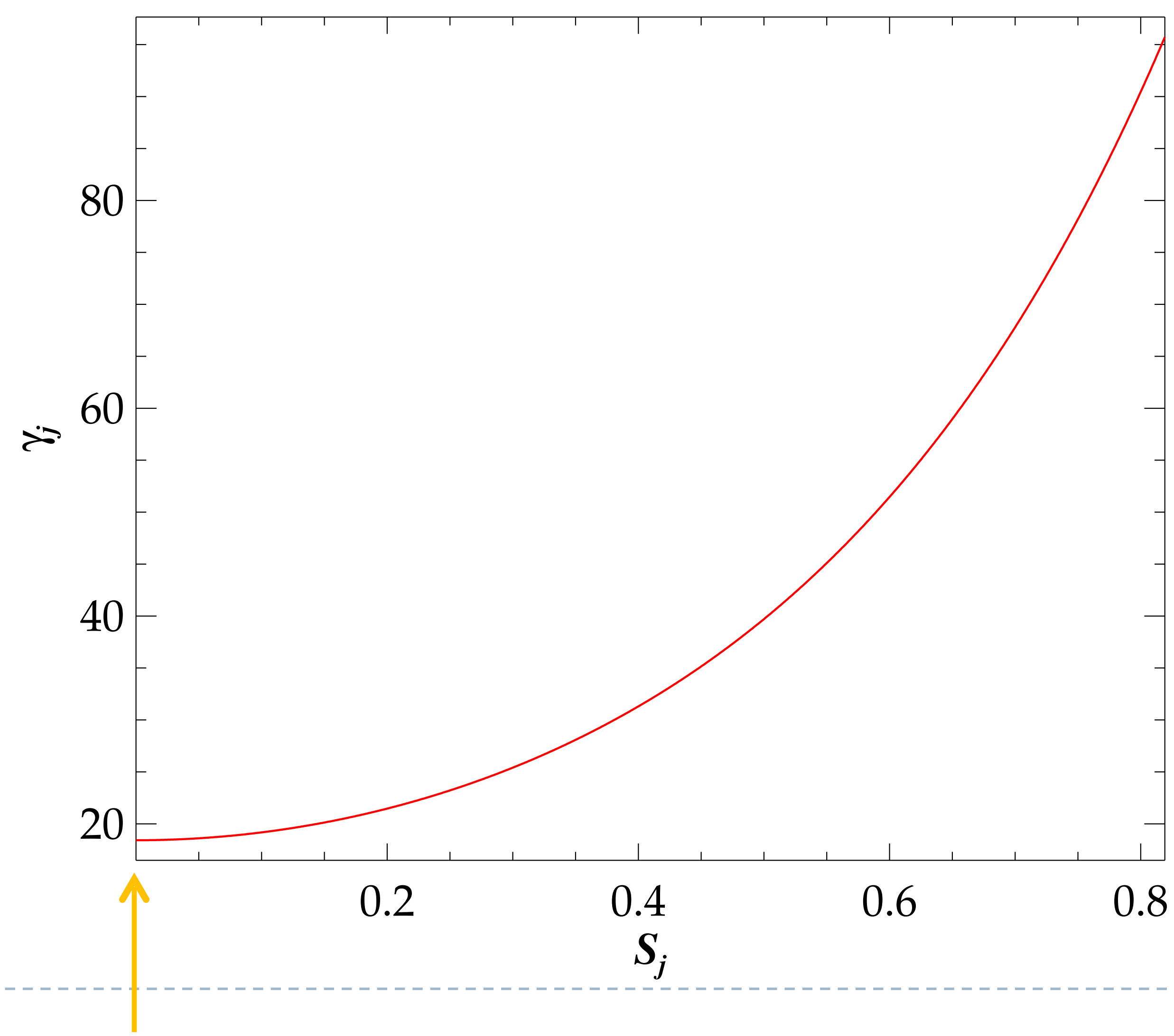
$$\Pr\left\{x_j > \gamma_j\right\} = \int_0^{\infty} \frac{1}{\sqrt{2\pi}S_j w} \exp\left\{\frac{-(\ln w)^2}{2S_j^2} - \frac{\gamma_j w}{2}\right\} dw$$

Confidence levels: power law case

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

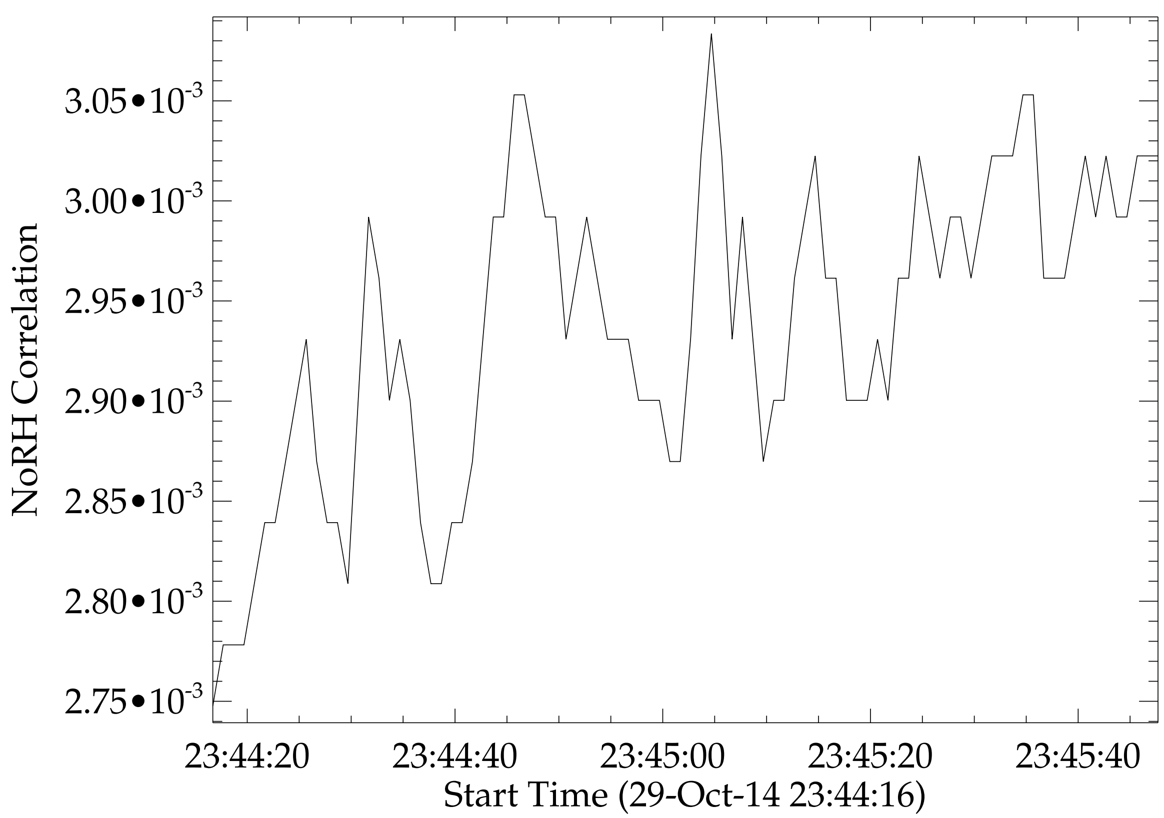
$$\Pr\left\{x_j > \gamma_j\right\} = \frac{0.01}{N} = \int_0^\infty \frac{1}{\sqrt{2\pi}S_j w} \exp\left\{\frac{-(\ln w)^2}{2S_j^2} - \frac{\gamma_j w}{2}\right\} dw$$

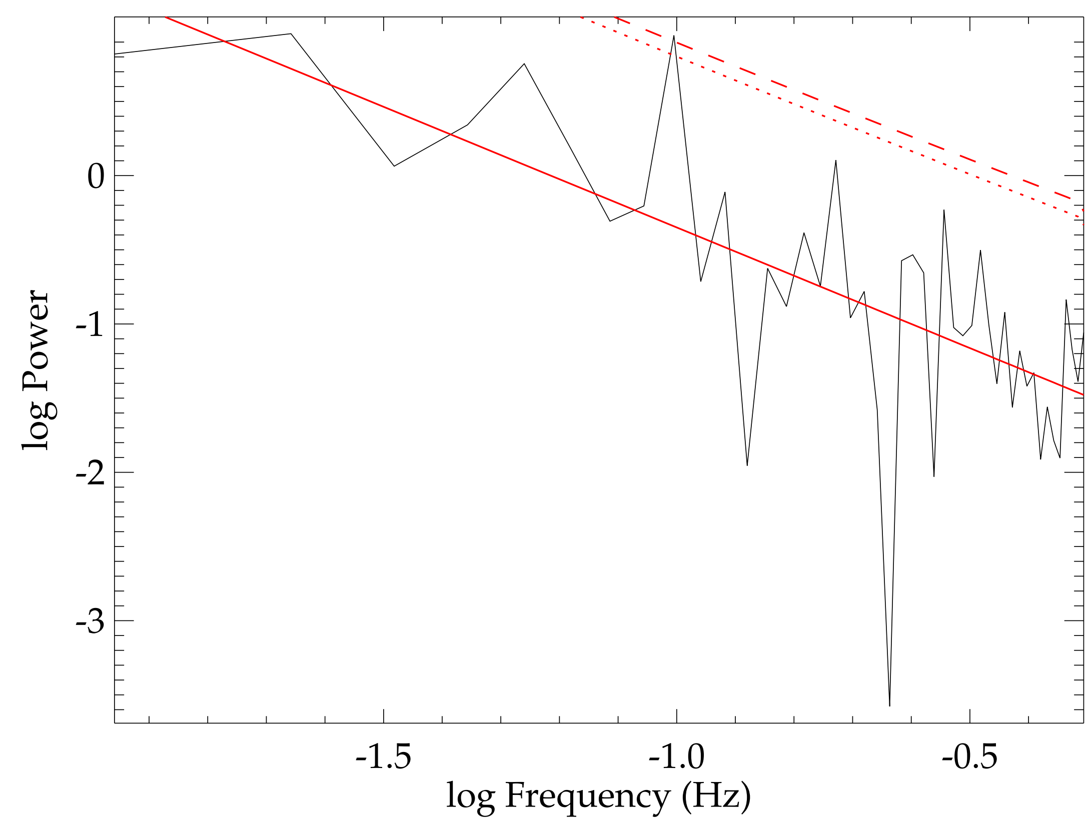
Number of values in the power spectrum (set to 100 here)



Examples

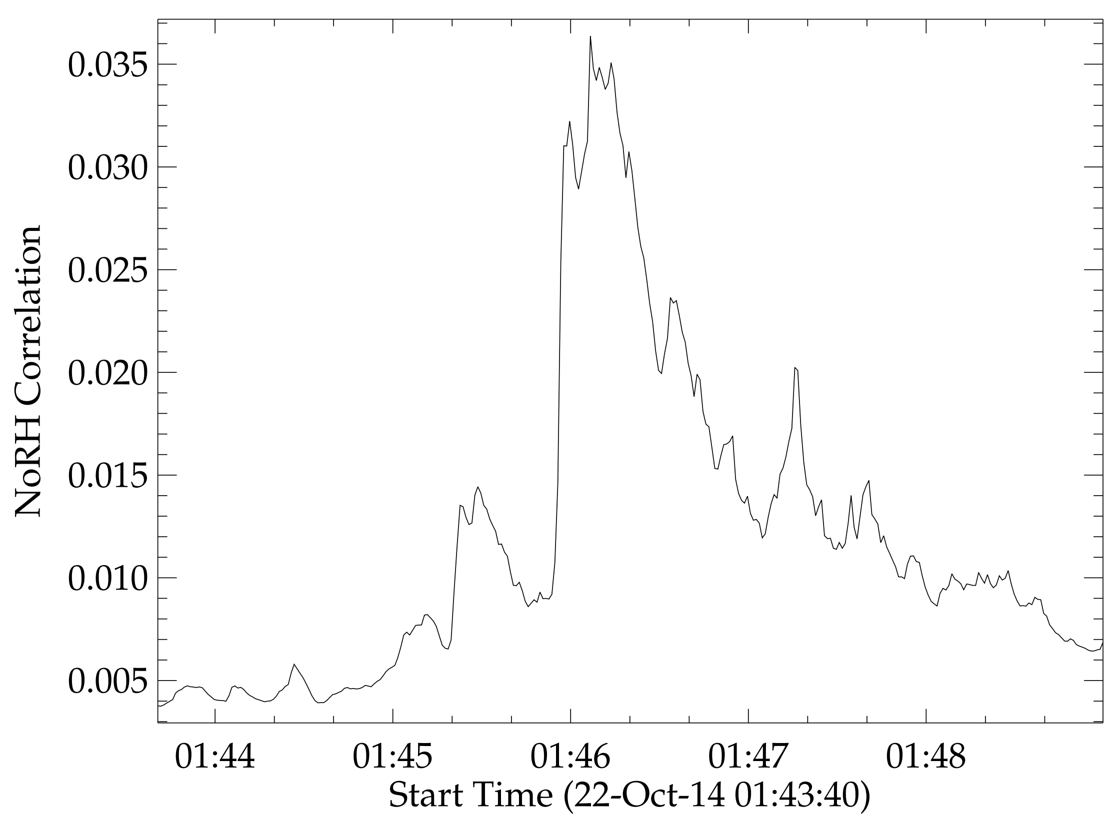
- Solar flare observed by Nobeyama Radioheliograph
- *Left*: Correlation time series of part of a flare
- *Right*: Periodogram with a peak above 99% confidence level, at a period of ~10 seconds

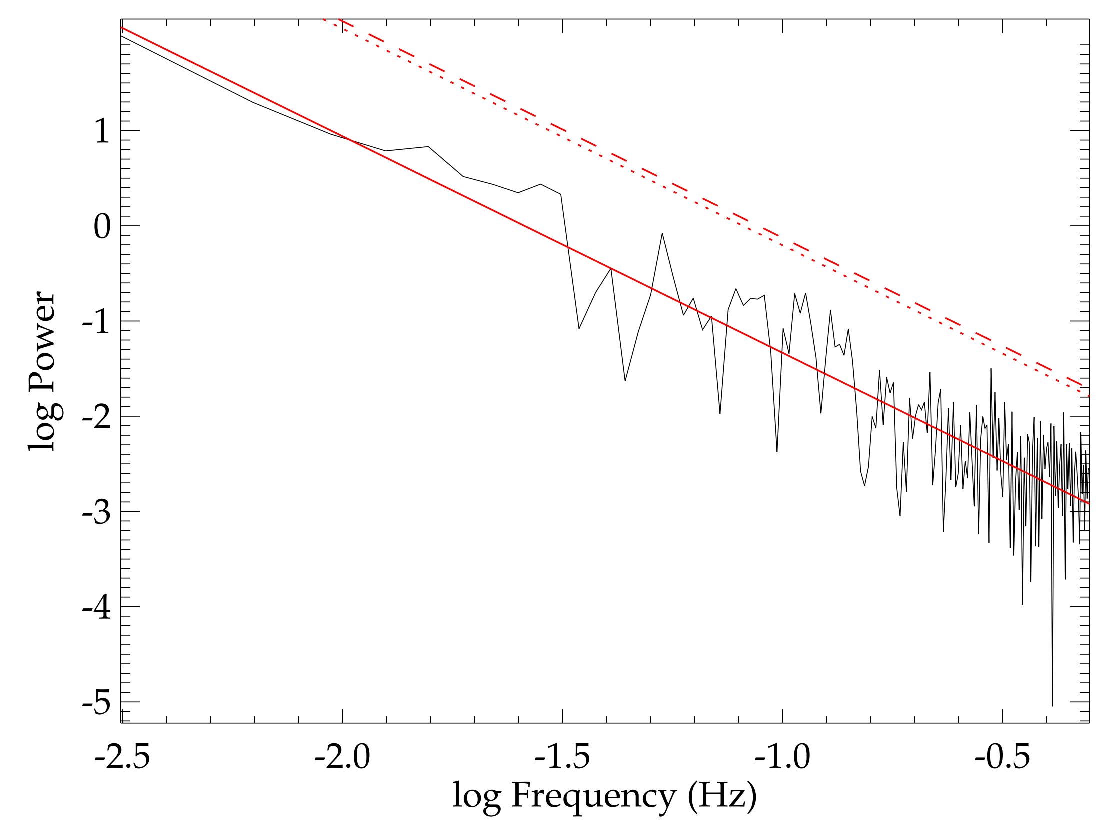




Examples

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





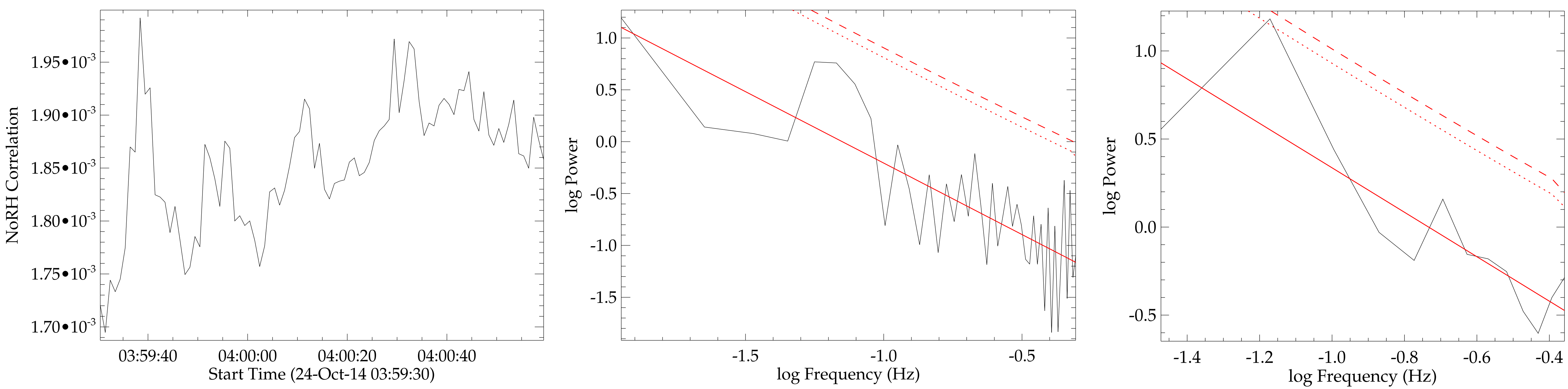
Confidence levels: power law case

- Additional trick: rebinning the power spectra
- Helpful for broad peaks in the power spectrum
- 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. 2017a):

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

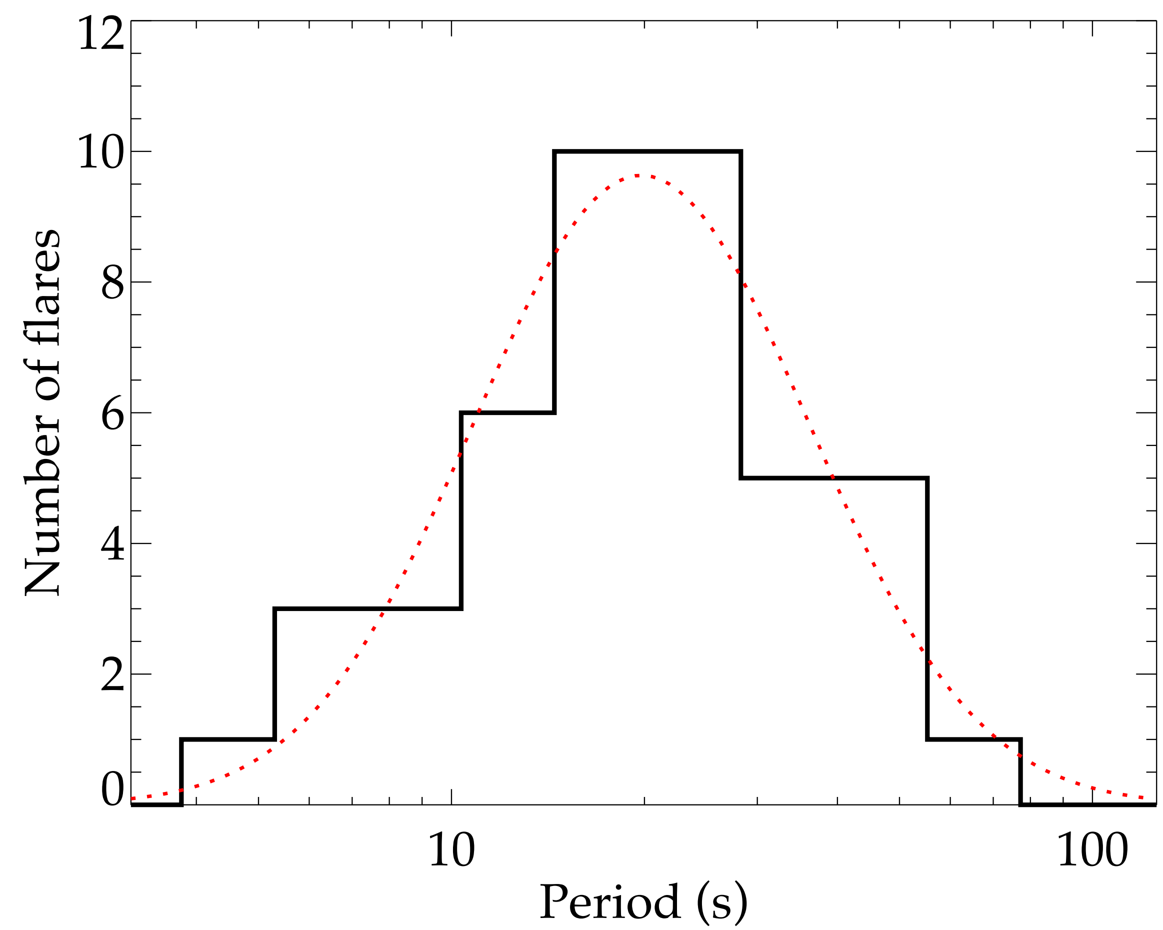
Examples

- Solar flare observed by Nobeyama Radioheliograph
- *Left*: Correlation time series of part of the 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



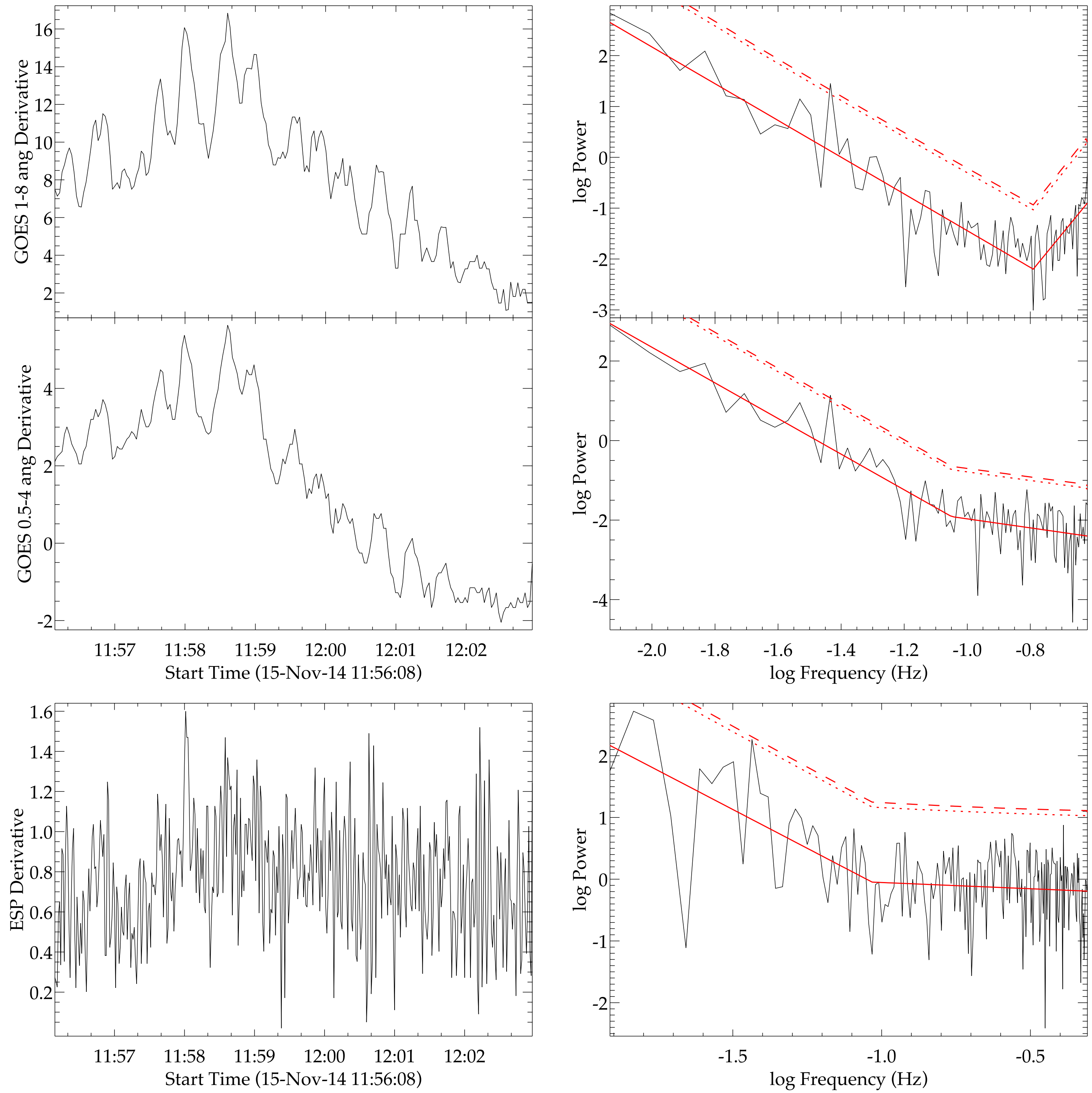
The set of flares with significant QPPs

- Out of 181 flares: 37 with periodic signal above 95% *global* confidence level (20% of sample)
- *Right*: histogram of periods, with mean period of 20^{+16}_{-9} seconds
- Most results consistent with Inglis et al. 2016, who used a different method
- Pugh et al. 2017b



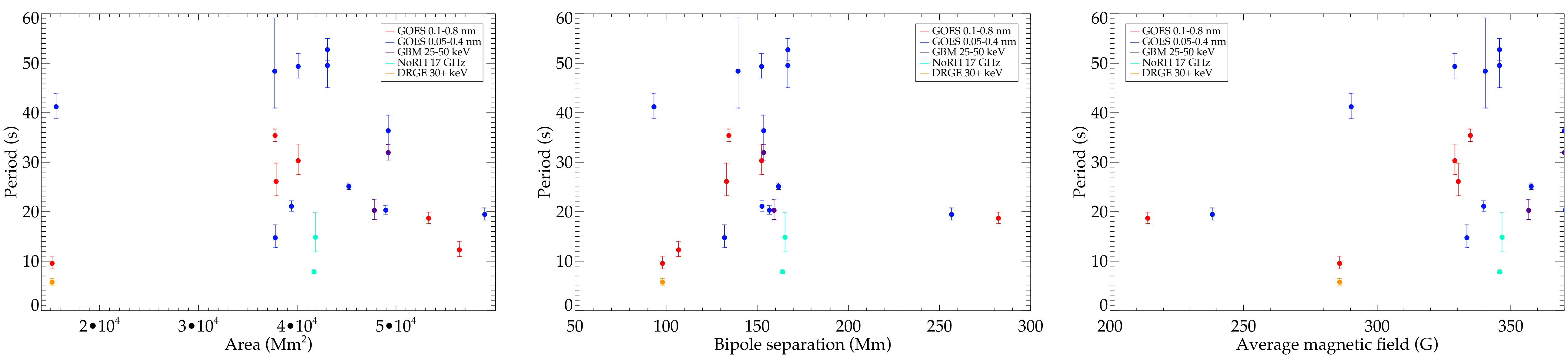
The set of flares with significant QPPs

- Seven of these flares have the same QPP signal detected above the 95% confidence level in data from two different instruments
- *Right*: 27 s period detected in both GOES/XRS and EVE/ESP light curves



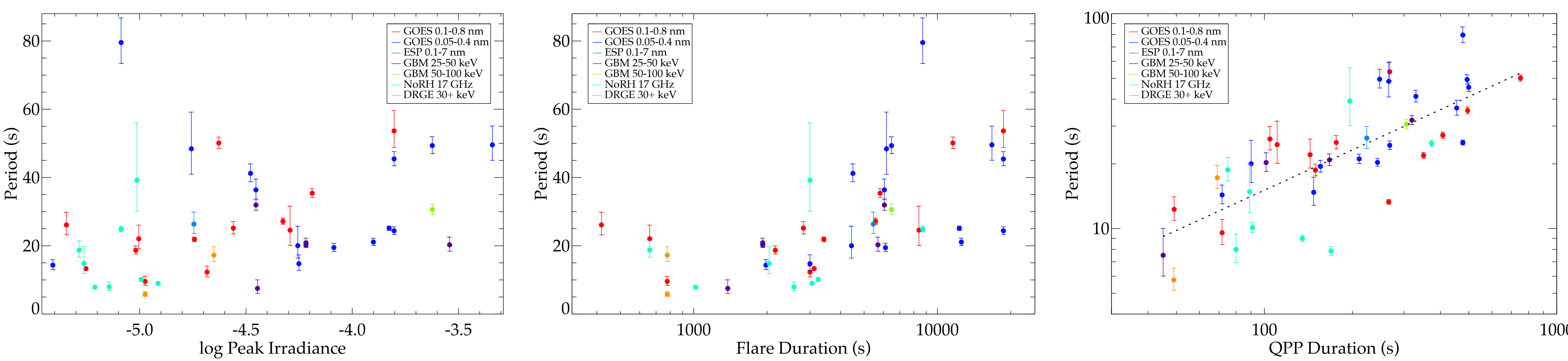
Relation to active region (AR) properties?

- AR properties as a function of time determined from SDO/HMI line-of-sight magnetograms (following similar method to Higgins et al. 2011, accounting for line-of-sight effects)
- No correlation between the QPP period and AR area *(left)*, bipole separation distance *(middle)*, or field strength *(right)*
- Probably because only part of the AR produces the flares!
- Next step: estimate size of flare sites from Hinode/XRT, RHESSI, etc data



Relation to flare properties?

- QPP periods plotted against flare amplitude, flare duration, and the duration of the QPP signal
- Period vs flare duration correlation: observational bias?
- Period vs QPP signal duration: can't detect long-period short-duration QPP signals, but should be able to detect short-period long-duration signals



Summary

- Adapted the method described by Vaughan 2005 to test for the presence of QPPs in flares, which accounts for data uncertainties and power-law power spectra, and avoids detrending
- Applied the method to a sample of solar flares from a single active region
- 20% of flares have a periodic signal above the 95% *global* confidence level in the power spectra
- No correlation of QPP periods with AR properties measured at the photosphere
- Need to try measuring sizes of flaring sites using spatially resolved X-ray/radio observations