The AFINO approach to finding oscillations in solar and stellar flares

latest results and updates

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The AFINO method: motivation

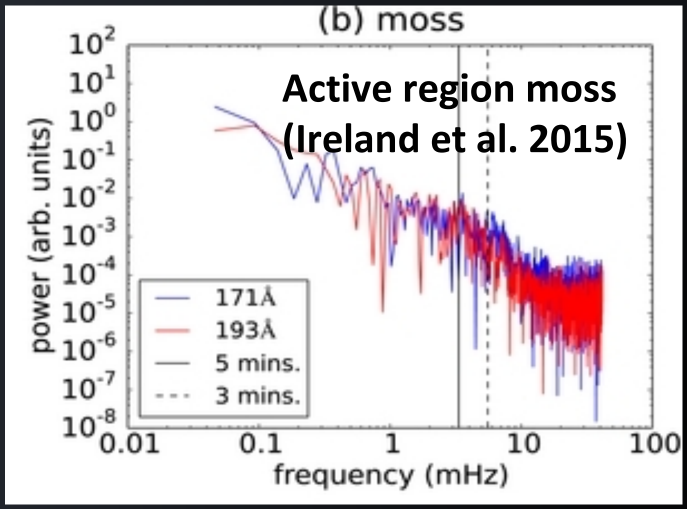
AFINO is an automated but customizable technique for analyzing lightcurves in search of oscillatory behavior. The development of AFINO was motivated by three main factors:

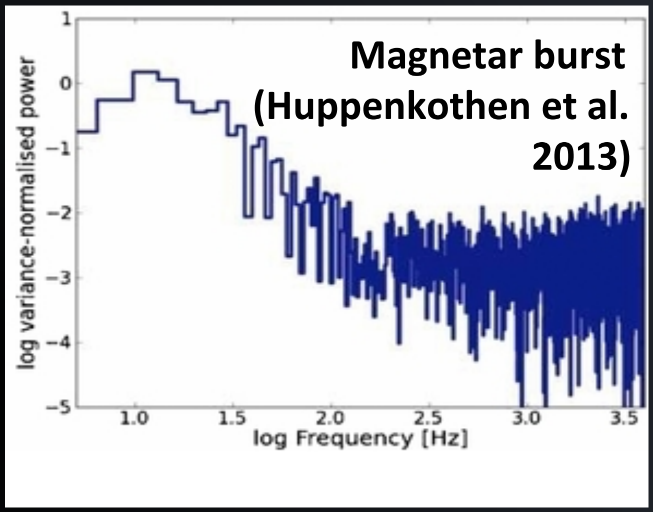
1. **Scalability**: needed the ability to analyse large numbers of solar and stellar flares in a consistent way. This is needed to understand QPPs in a statistical sense.

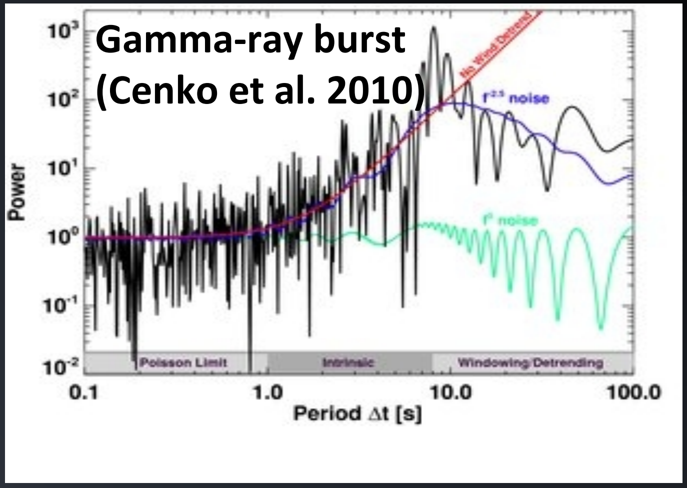
2. **Reproducibility:** wanted to minimize the number of user decisions and avoid use of ad-hoc techniques, e.g. background subtraction, filtering. Should be able to reproduce again the analysis of any flare without special work.

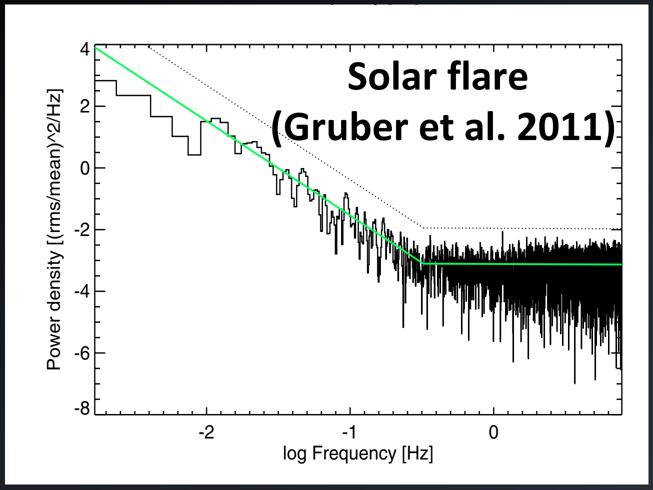
3. **Power laws**: Power laws in frequency space are ubiquitous in astrophysics. Searches for QPPs need to account for this possibility.

Power-law power spectrum: examples







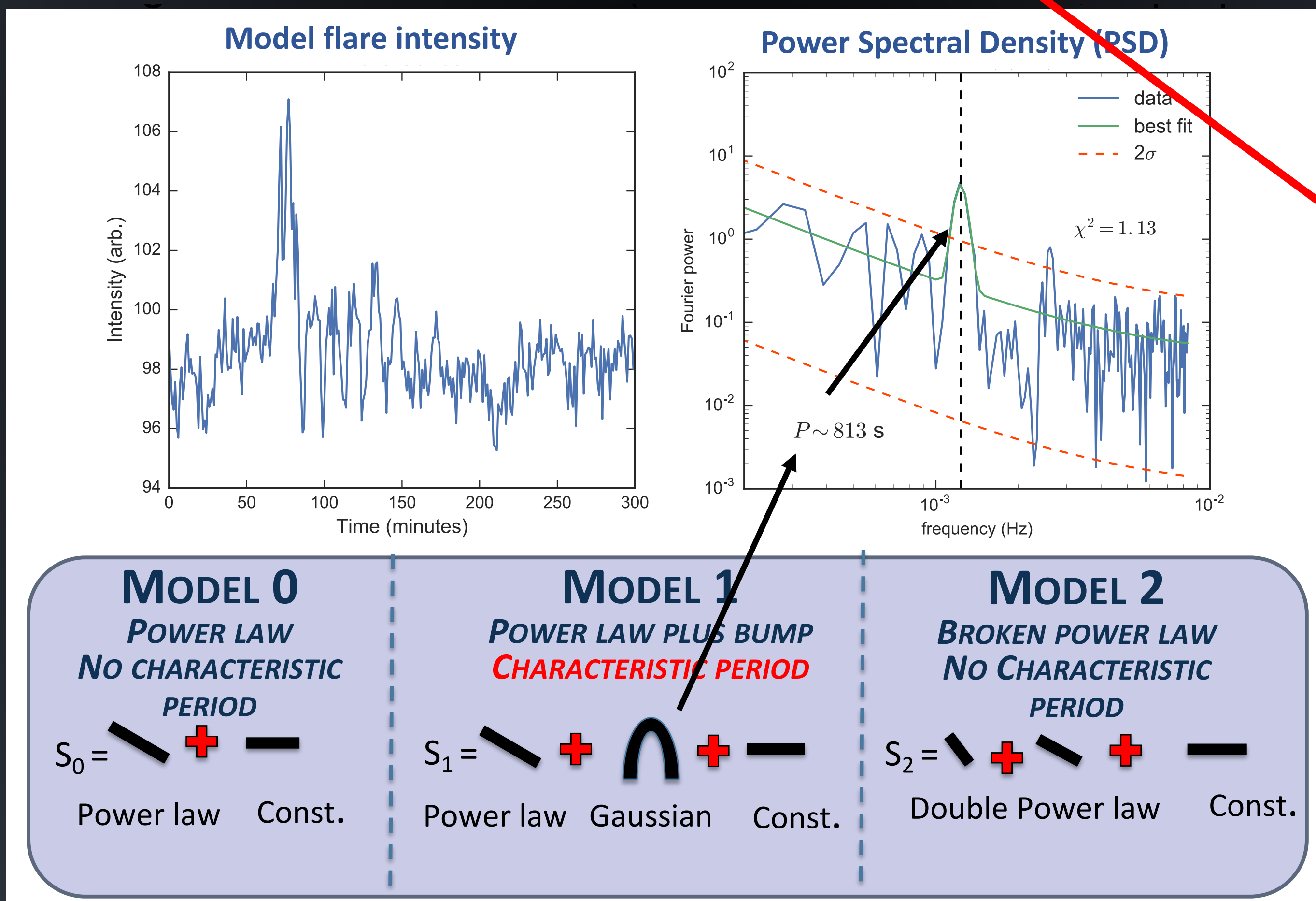


The AFINO method

AFINO fits different models to the Fourier Power Spectral Density (PSD) of solar flares. **Model 1** includes a ‘bump’ that represents a QPP signature. The Bayesian Information Criterion (BIC) can be used to test which model is most appropriate given the data.

$$\mathbf{BIC = -2\ ln(\mathit{L}) + \mathit{k}\ ln(\mathit{n})}$$

Extra parameter penalty term



Blind testing of QPP detection methods
Broomhall et al., ApJS, 2019

Recently, a number of QPP detection methods were assessed using a **blind test**. Synthetic flare-like signals were provided to be analysed using different methods. Some contained oscillatory signatures while others did not.

Crucially, the scientists applying the various techniques did not know the properties of these signals.

For AFINO, there were two main findings:

- AFINO had a low false alarm probability, the lowest among the methods tested. In general, when AFINO claimed the presence of an oscillation, the result was correct.

- However, AFINO is also conservative, it missed a number of oscillatory signals in the data.

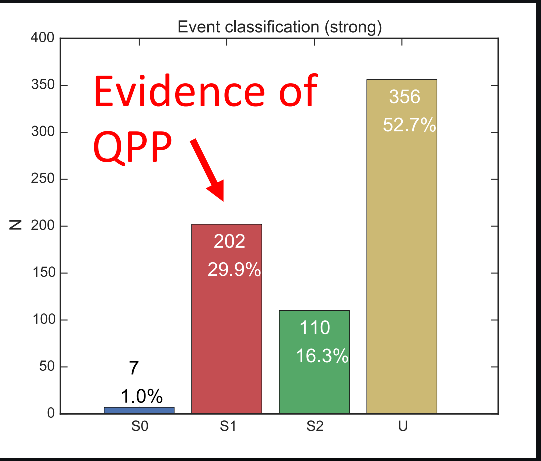
This performance is consistent with our original motivation.

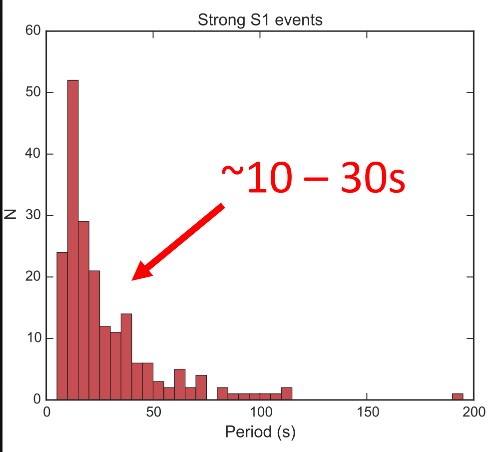
Original survey results (Inglis et al. 2016)

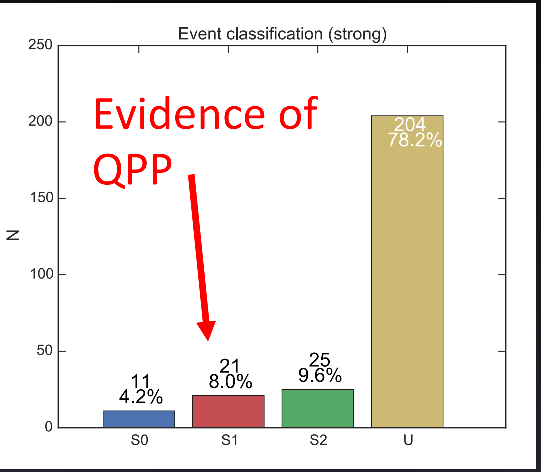
We used AFINO to search for evidence of QPP signatures in 600+ flares observed in soft X-rays by GOES and 15-25 keV X-rays by Fermi/GBM (Inglis et al. 2016). The time period was 2011 – 2015.

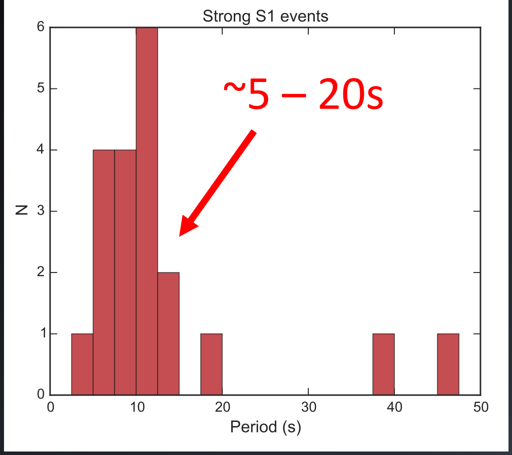
~30% of events show strong evidence for the 'QPP-like' model in GOES thermal X-rays.
Characteristic timescales of these events were preferentially in **the 10-30s range**.

Only **~8%** of GBM events showed strong evidence for QPP signatures. However, the observed period range was consistent with the GOES observations.



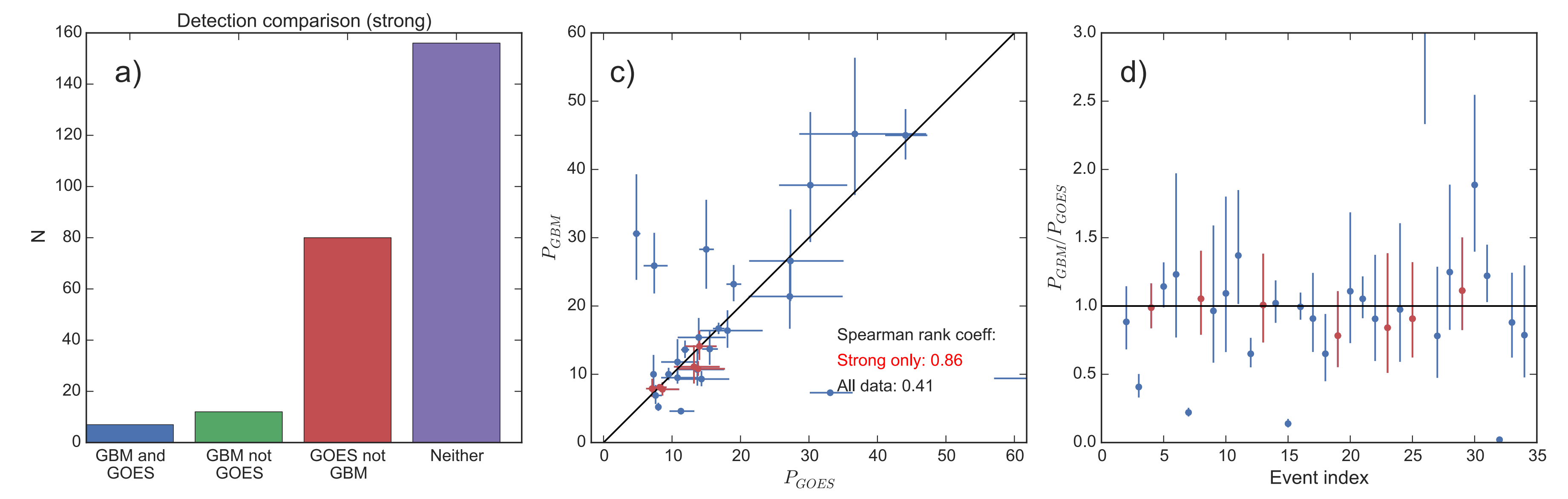






Comparison between soft and hard X-rays

There were 7 events that showed strong evidence for QPP-like signatures in both the GOES and GBM datasets.
There were 34 events that both show some evidence for QPP in both datasets.



For these events, there is a substantial correlation between the periods observed in GOES soft X-rays and GBM 15-25 keV X-rays.

On at least some occasions, two instruments seem to be **observing the same signature**. But, the majority of the time only one instrument (or neither) detects a signature.

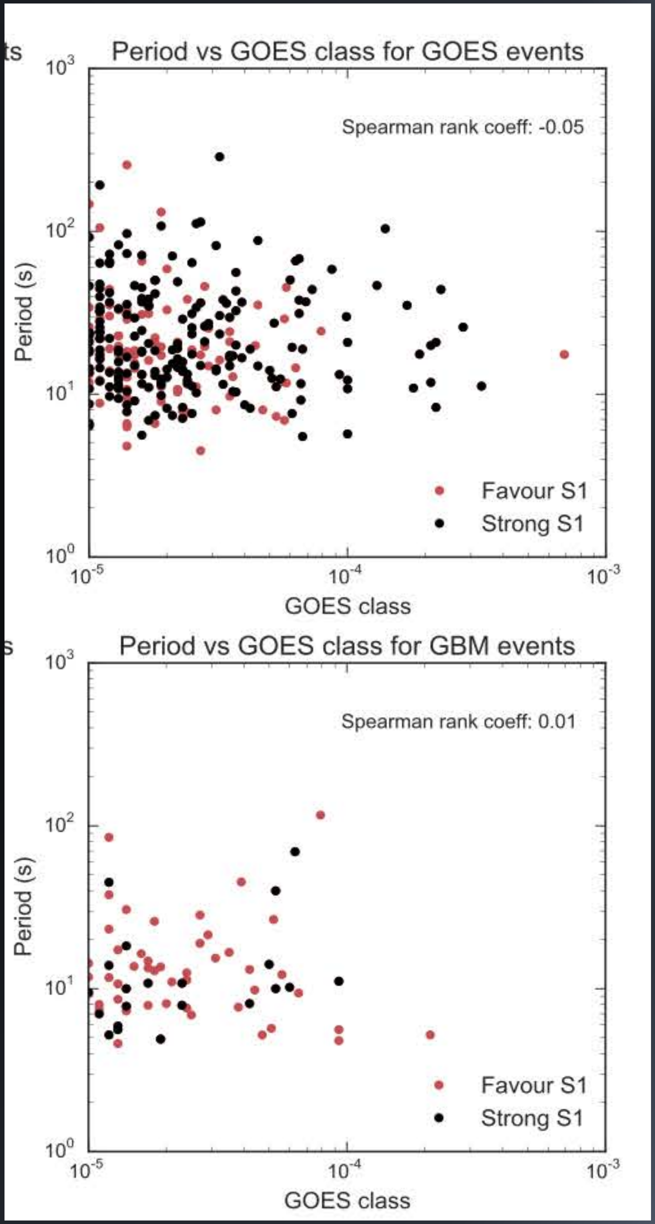
Period vs flare magnitude

An important finding is that the observed periods of QPP flares has **no dependence** on flare magnitude, i.e. GOES class.

This is important because:

- Whatever mechanism generates QPPs it is broadly independent of the amount of energy released.
- If this is also true for stellar flare oscillations, it suggests a common origin. Does this hold in the stellar domain?

We can compare this finding with the QPP mechanisms described by McLaughlin et al. 2018.



Period vs flare duration

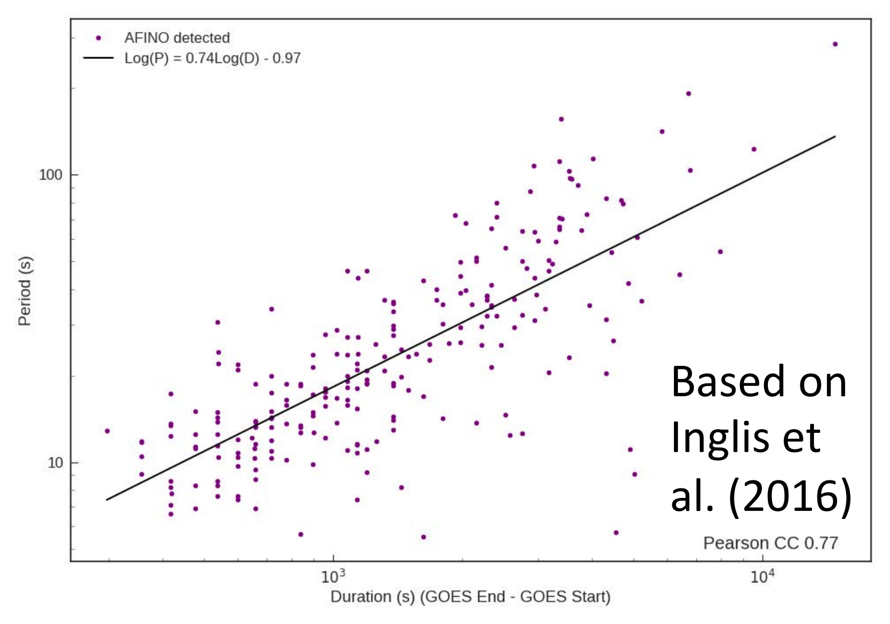
However, a clear output from the survey was that longer periods were associated with long duration events.

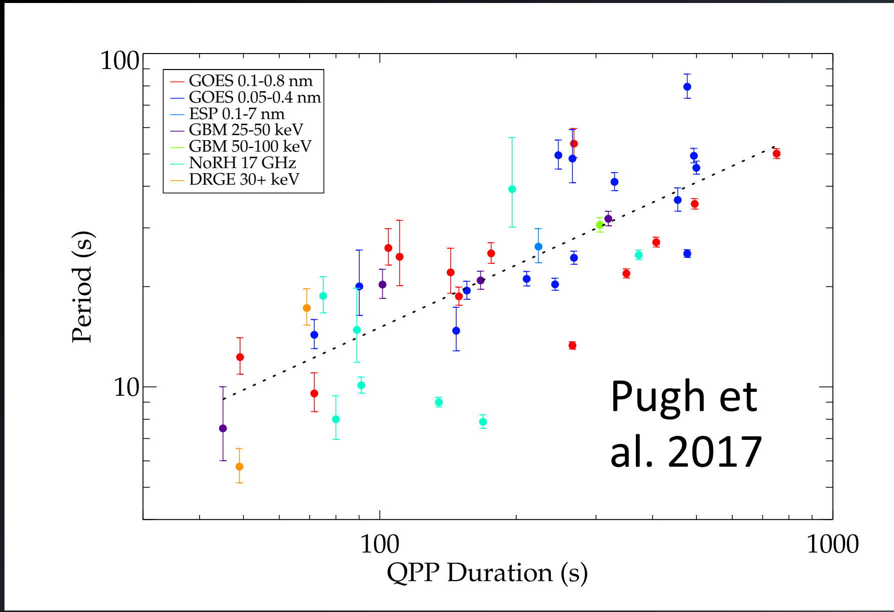
This is not fully explained by observational bias, e.g. longer periods can only be seen in long flares.

Pugh et al. (2017, 2019) reported a very similar result in stellar flare observations.

This suggests that in many flares either:

1. The period of an excited oscillation grows over time, or
2. Different processes may be excited as the flare evolves and transitions between impulsive and gradual phases.

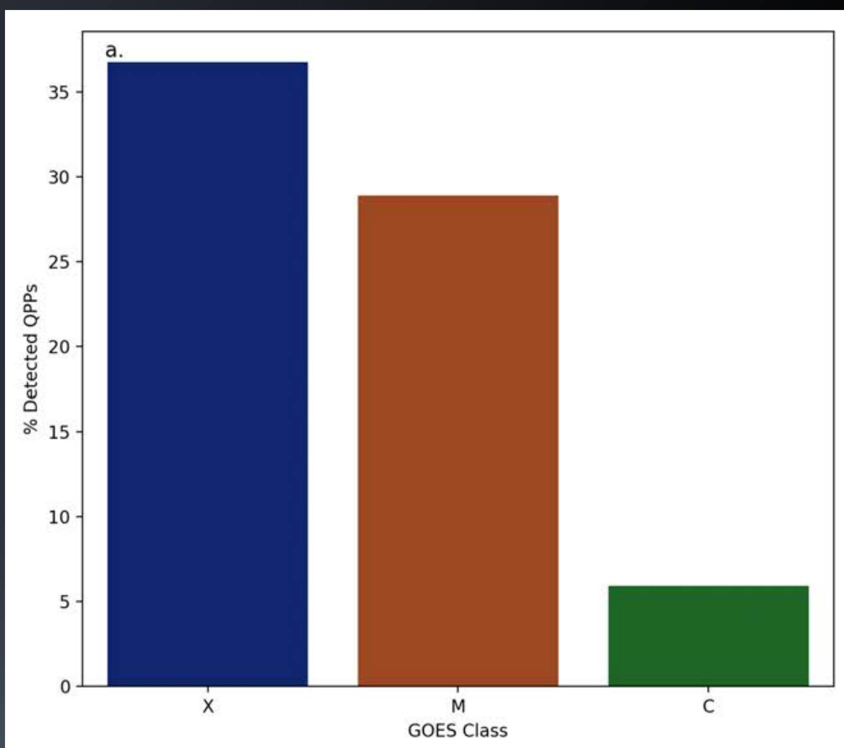


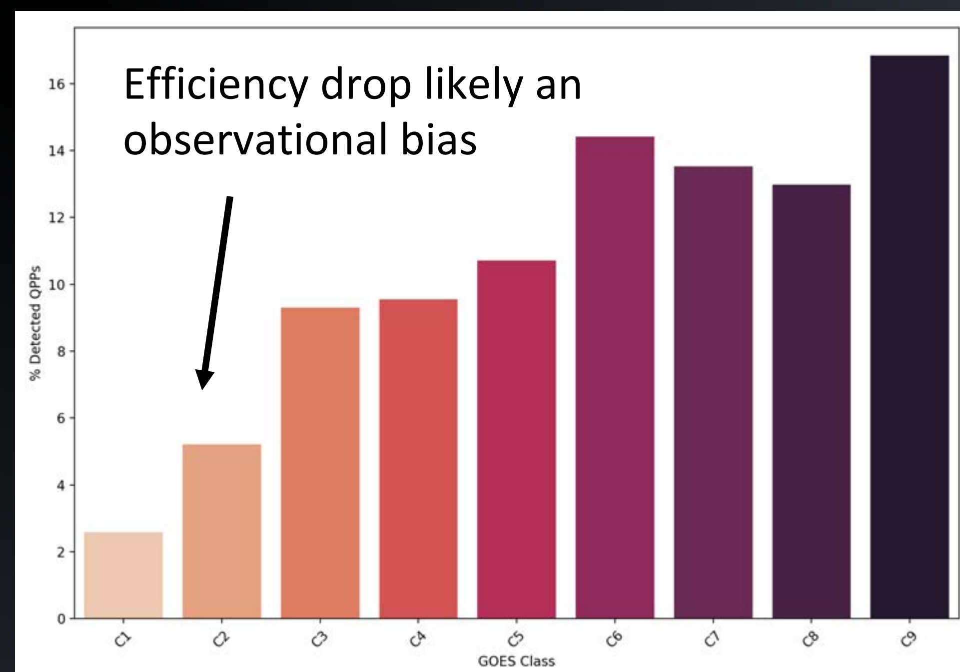


Expanding on the original survey (Hayes et al. 2020)

Recently, we extended the Inglis et al. 2016 survey to include C class flares. QPPs are also regularly detected for these smaller flares. Detection efficiency drop is very likely due to observational bias.

Similar periods are found for C-class flares.

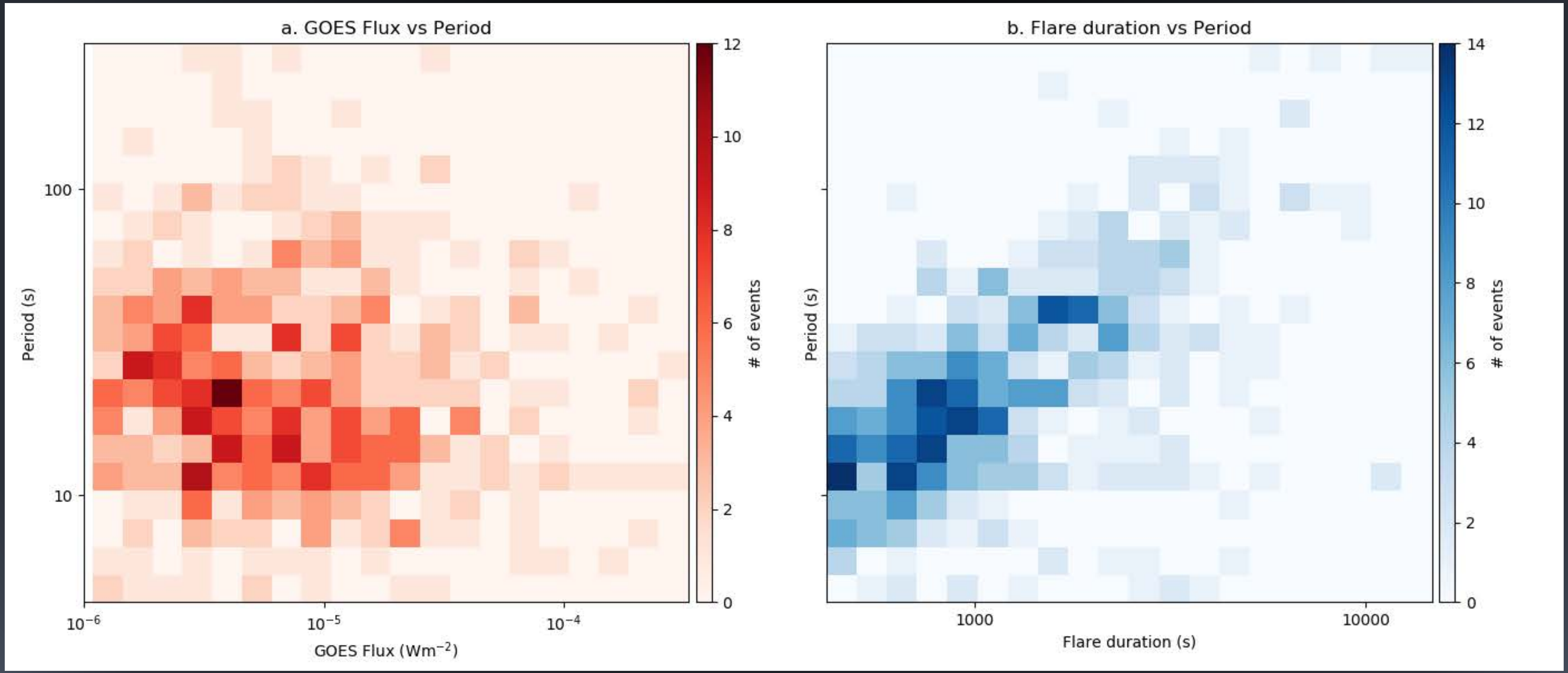




Expanding on the original survey (Hayes et al. 2020)

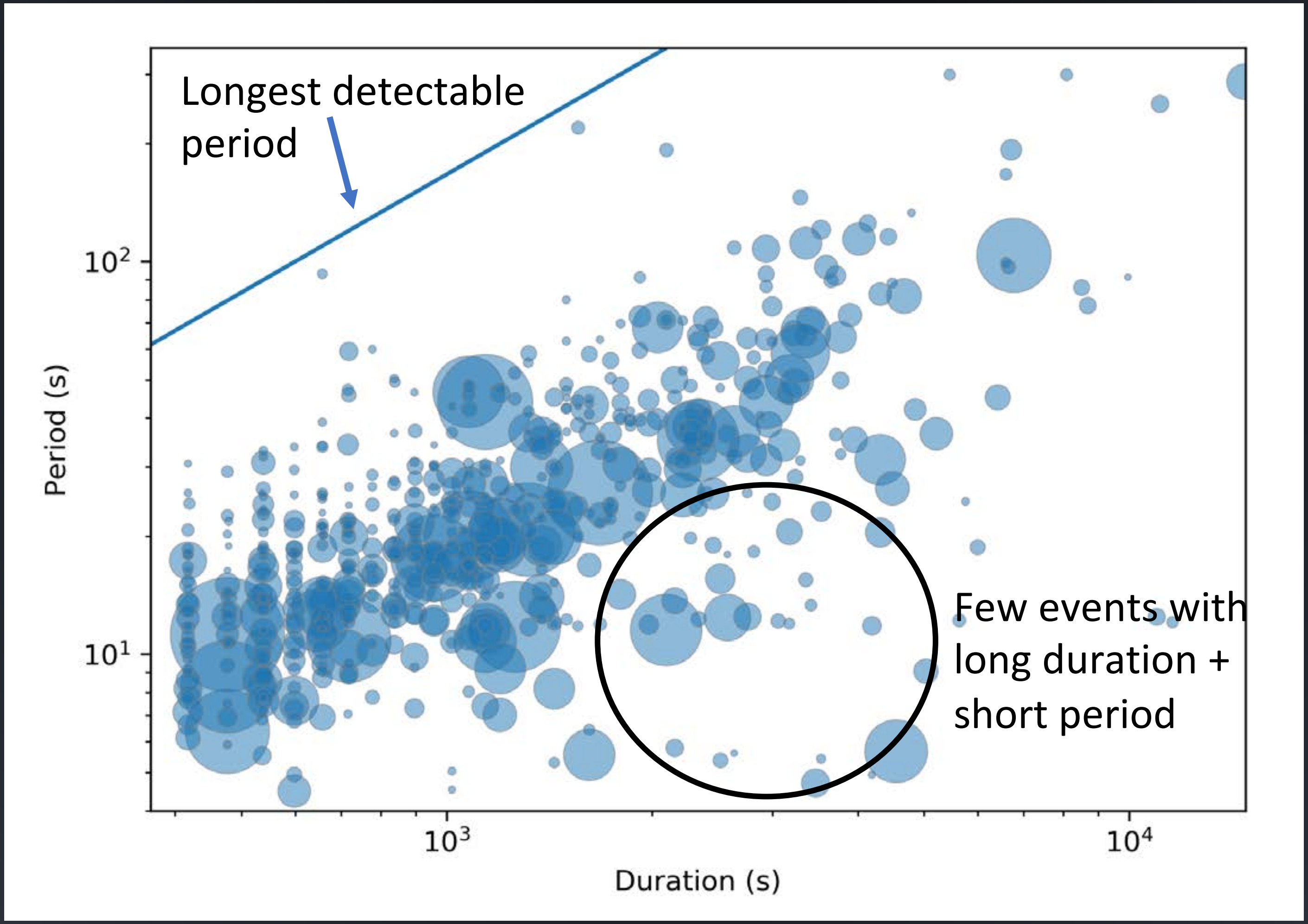
For this much larger sample, two main conclusions still hold:

1. The observed period is mostly independent of flare magnitude (i.e. GOES class)
2. The observed period scales with flare duration
   - does this imply a 'growth' mechanism over time?



Expanding on the original survey (Hayes et al. 2020)

This finding is not easily explained simply by bias or selection effects. See also Pugh et al. (2019). Need to understand flare and QPP evolution.



TESS flare observations

AFINO can also be easily applied to other datasets, including TESS stellar observations. TESS was launched in Spring 2018.

TESS surveys patches of the sky at optical wavelengths on a monthly timescale using four widefield 24x24 degree cameras.

A selection of targets within the field of view are observed at 2-minute cadence. This is promising for observing oscillations in transient events such as stellar flares.

- We proposed (Co-I: Josh Schlieder) a TESS Guest Investigation to study ~50 bright, nearby M-dwarf stars in search of flare oscillations, with the goal of linking solar and stellar QPP properties.

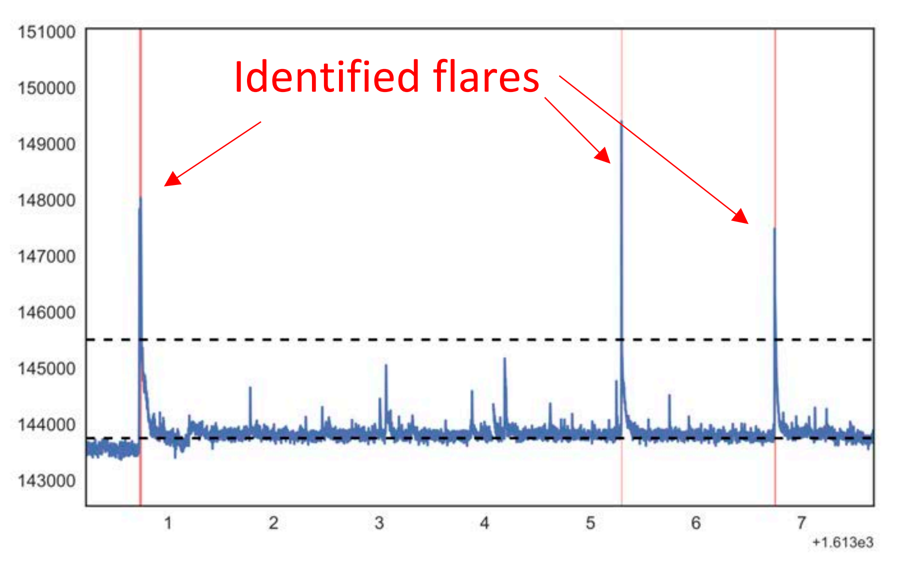
- The proposal was not funded, but many of the proposed targets were selected for 2-minute cadence observations.

- So far (up to TESS Sector 17), ~12 of these targets have been observed, some for more than one Sector.

TESS preliminary analysis

We adopt a simple technique to identify large, longer-duration flares in the TESS data. This is at the expense of shorter events. This approach is valid since only the longer flares have sufficient data to realistically search for oscillations.

- So far we have analysed 45 flares from 6 different M dwarfs observed by TESS
- Only study the flare flux from **after** the peak, to avoid problems.
- Five flares so far show moderate evidence of an oscillatory signature

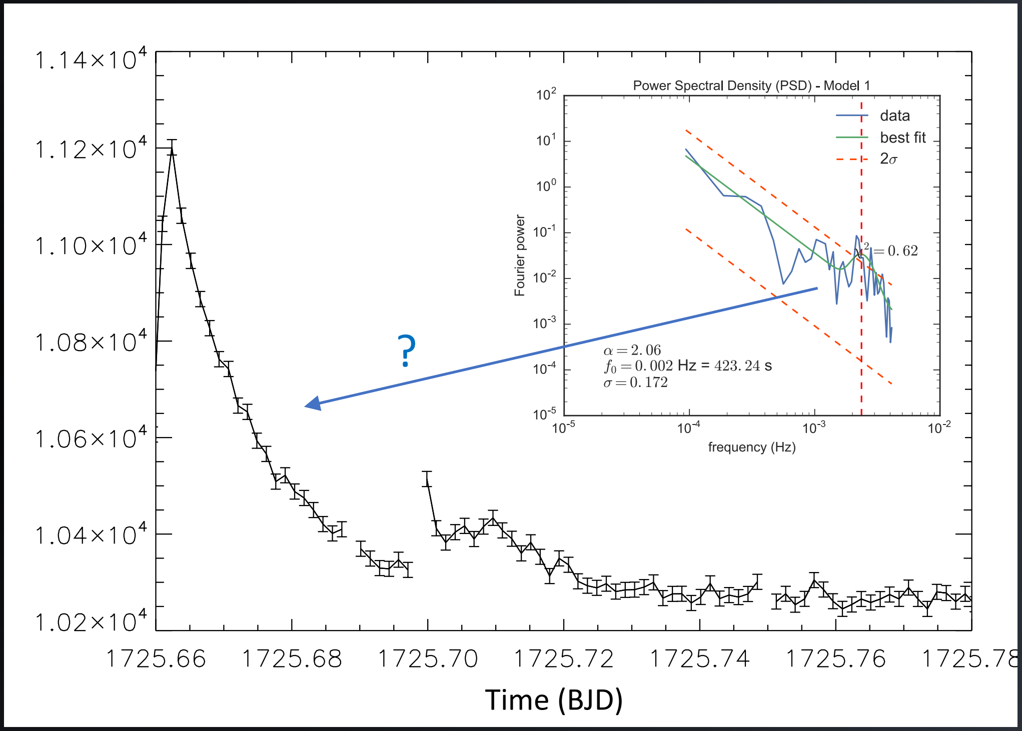


Caveat: The AFINO method is quite conservative when the number of data points is small. This poses a challenge for stellar flares.

TESS preliminary analysis: example flare

- Using AFINO, this flare presented mild evidence for periodic behavior on the ~ 400s timescale.
- Possible signs of this in the flare decay, but debatable.
- The uncertainties in the data illustrate the problem of searching for small-amplitude pulsations.

TIC 233068870



Future goal: Perform a model comparison to the timeseries itself: fit models with and without an oscillation to the data. Test if there is sufficient evidence for an oscillation component.

Future plans

- Upgrade the AFINO code and release for everyone to use. Updates include:
  - Convert existing code from Python 2.7 to Python 3.6
  - Add additional models to the fitting options (e.g. two-peak model)
  - Add unit tests for code integrity
  - Complete documentation and examples
  - Release as open source on Github

Applied for funding from the NASA Heliophysics Data Environment Emphasis (HDEE) proposal solicitation to help achieve this.

- Complete expanded study of GOES flares, including C-class events, and studying the **difference between impulsive and decay phases**. Look for Hayes et al. (2020).

- Continue investigating TESS M-dwarf flare data from targets as it becomes available. Explore solar-stellar links. **Note**: likely that **in the future 20s data will be available** from TESS for select targets.

Stingray
(Huppenkothen et al. 2019)

A new comprehensive time series analysis code is now available (Huppenkothen et al., ApJ, 2019). It is called Stingray.

Stingray is freely available online on Github: http://stingraysoftware.github.io/

Stingray: A Modern Python Library for Spectral Timing

Show affiliations

Huppenkothen, Daniela; Bachetti, Matteo; Stevens, Abigail L.; Migliari, Simone; Balm, Paul; Hammad, Omar; Khan, Usman Mahmood; Mishra, Himanshu; Rashid, Haroon; Sharma, Swapnil; Martinez Ribeiro, Evandro; Valles Blanco, Ricardo

This paper describes the design and implementation of stingray, a library in Python built to perform time series analysis and related tasks on astronomical light curves. Its core functionality comprises a range of Fourier analysis techniques commonly used in spectral-timing analysis, as well as extensions for analyzing pulsar data, simulating data sets, and statistical modeling. Its modular build allows for easy extensions and incorporation of its methods into data analysis workflows and pipelines. We aim for the library to be a platform for the implementation of future

An example of Stingray in action. The data shows a QPO in RXTE observations of black hole X-ray binary GX 339-4.