Leibniz-Institut für Astrophysik Potsdam

X-ray data analysis in the framework of the SOLER project

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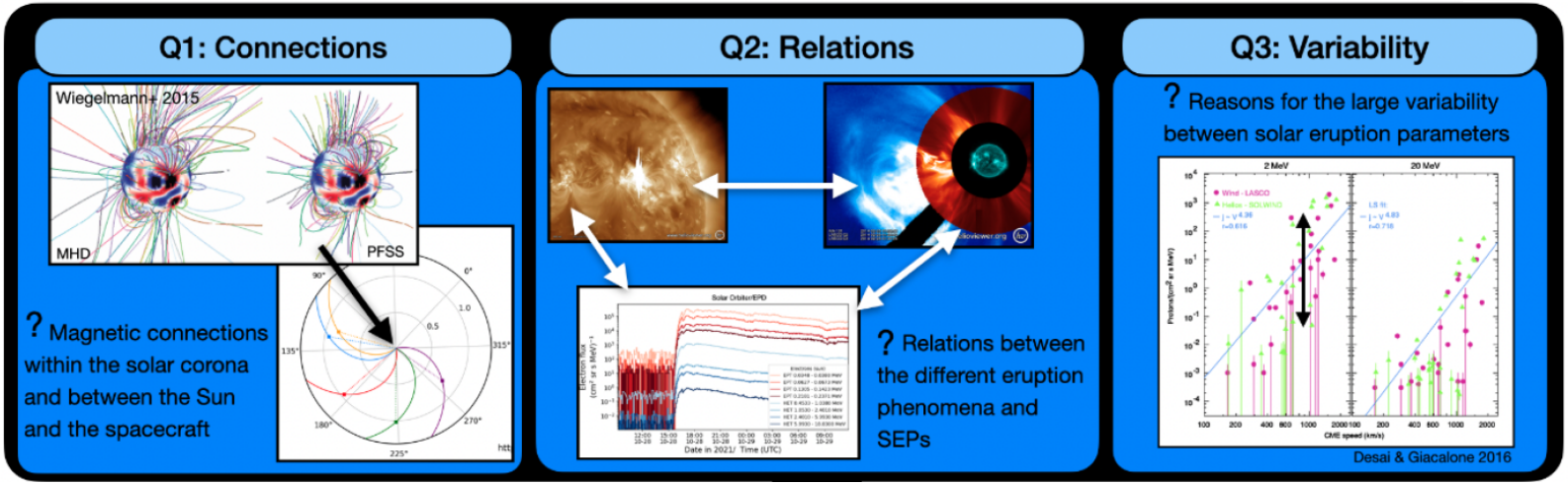
Overview

1. The SOLER project: tools and science
2. The SOLER flare sample
3. X-ray timeseries analysis
4. Summary and outlook

The SOLER project: tools and science

Energetic Solar Eruptions: Data and Analysis Tools (SOLER)



- Horizon Europe project (Turku, Helsinki, Graz, Paris-Meudon, AIP)
- investigate energetic solar eruptions from three perspectives: fast (>1000 km/s) CMEs, strong (>M5) X-ray flares, and large (>25 MeV) solar energetic particle (SEP) events
- tool development and scientific analysis

SOLER

Energetic Solar Eruptions: Data and Analysis Tools

SOLER tools

This organisation brings together the tools developed and delivered by the Energetic Solar Eruptions: Data and Analysis Tools (SOLER) Project.

For full project details, see our website at: https://soler-horizon.eu

- CIDER: Coronal magnetIc fieLD ExtRapolation tools: https://github.com/jpomoell/cider
- CREST: Coronal and Heliospheric Reconstruction and Visualisation: https://github.com/jpomoell/crest
- EASI: Electron Acceleration Simulation: https://github.com/SeveNyberg/easi
- ELECTRICIT: Electric Field Inversion Toolkit: https://github.com/jpomoell/electricit
- NenuFAR SUN: Solar Imaging Workflow: https://github.com/JingeZhang94/NenuFAR_SUN_Imaging_workflow
- NenuSunPy: Solar Radio Processing: https://gitlab.obspm.fr/soler/nenusunpy
- SEP Tools: Solar Energetic Particle (SEP) Analysis Tools https://github.com/soler-he/sep_tools
- SHELVIS: Solar and Heliospheric Visualisation tool: https://github.com/jpomoell/shelvis
- SJET: Solar Jet Extraction Tool: https://github.com/songsolarphysics/SJET
- SOLERsources: https://github.com/soler-he/SOLERsources
- SOLERWave: https://github.com/soler-he/SOLERwave_tool

SOLER has also contributed to:

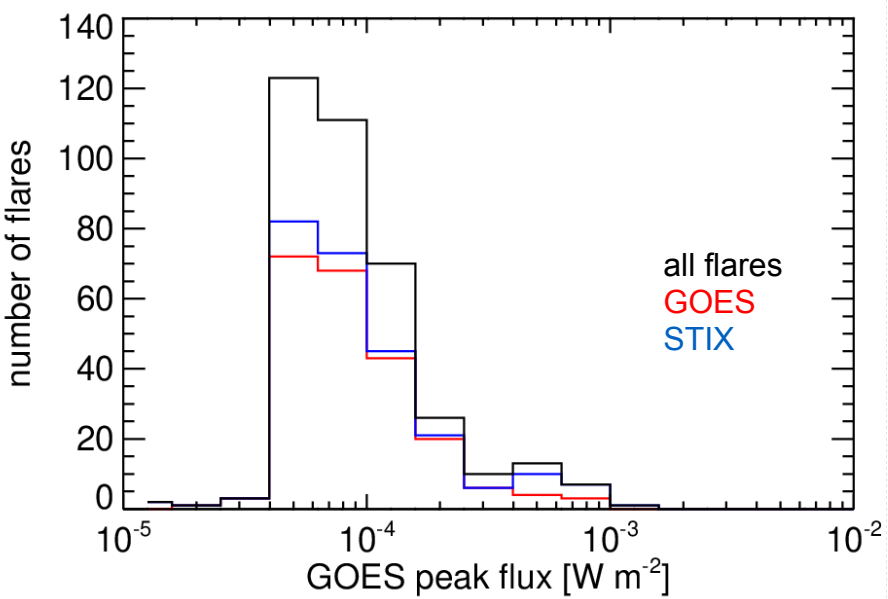
- STIXpy: https://github.com/TCDSolar/stixpy
- Sunkit-spex: https://github.com/sunpy/sunkit-spex

Flare-related SOLER tasks

- develop software tools for solar flare analysis:
  - X-ray timeseries analysis (this talk)
  - X-ray spectral analysis: *Sunkit-spex* (see Jake's talk)
  - X-ray imaging: *STIXpy* (see Jake's talk)
  - EUV jet analysis: *SJET* (see Song's talk)
- perform analysis for all M5 and larger flares of current solar cycle
- case studies and statistical studies
- deliver high-level datasets

SOLER flare sample

- all M5 and larger flares (GOES or GOES estimate from STIX) from 2020 to 2024
- derived from GOES SWPC and STIX science flare lists
- manual clean-up of merged list was necessary
- final list:
  - 367 unique flares (240 M, 127 X)
  - 220 GOES flares
  - 251 STIX flares
  - 104 flares with GOES and STIX coverage



X-ray timeseries analysis

Aims and Methodology

Aims

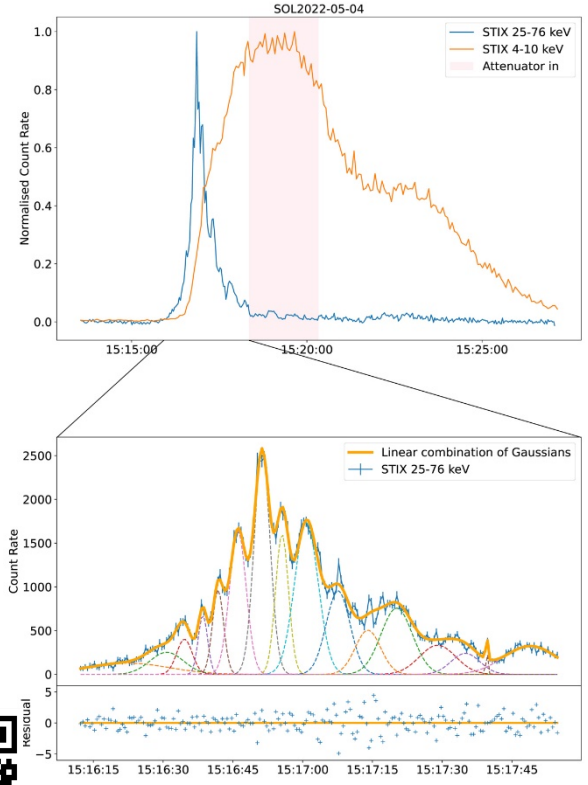
- Characterise the temporal behaviour of STIX flare lightcurves
- Identify statistical trends across multiple flare lightcurves
- Explore variations in frequency, number of peaks, and amplitudes
- Find potential links between parameters and GOES class of flares
- Cross validate fit statistics with existing tools and find potential QPPs

Methodology

- Use set of suitable STIX lightcurves that show significant temporal structures in HXR
- Use curve decomposition tool to extract period, amplitudes and durations for each component
- Compare parameters over entire dataset
- Compare results with *AFINO* (frequency domain) and Wavelet Analysis Tool

Aims and Methodology: Decomposition Tool

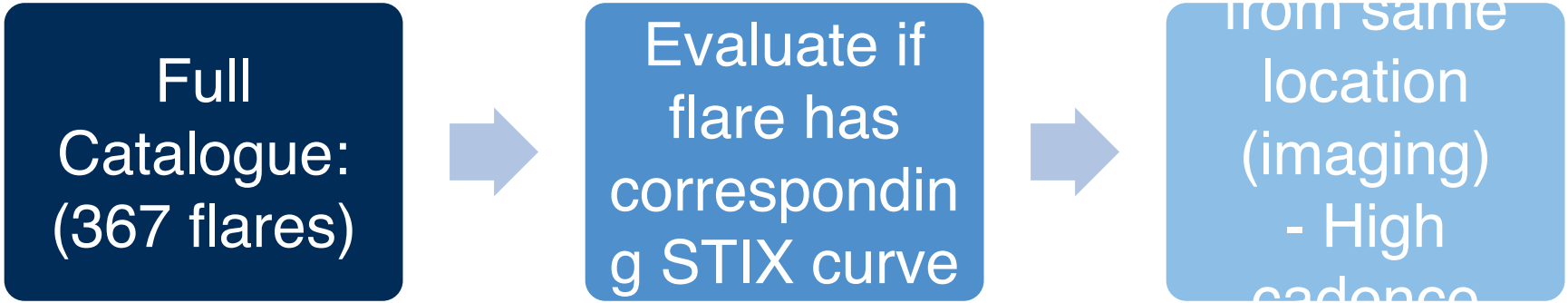
- Based on Collier et al. (2023)
- Curve decomposition
  - Preprocessing: normalisation and smoothing using Gaussian Process regression
  - Peak detection: use peaks of smoothed profile to estimate initial parameters for curves
  - Decompose signal into curve profiles (Gaussian, Lorentzian, and asymmetric Gaussian)
  - Extract fit data to determine number of peaks, frequency/periods, amplitude etc.



(Collier et al. 2023)

Data selection

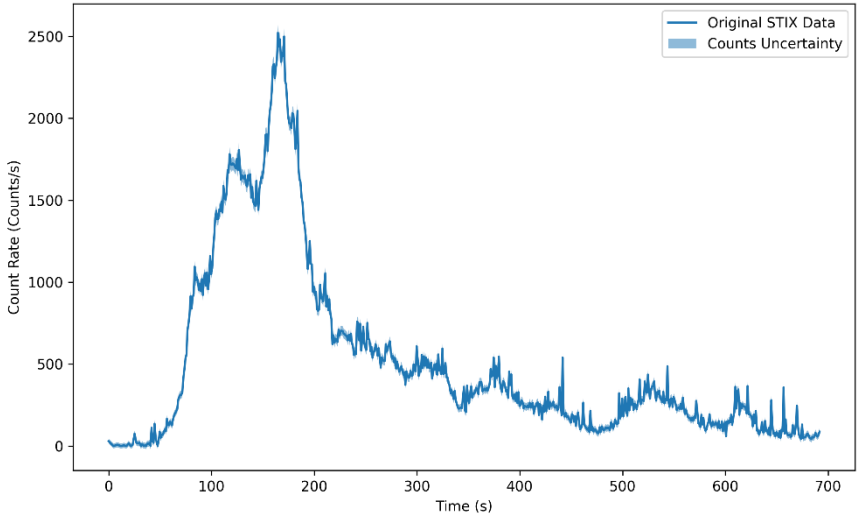
Data catalogue (SOLER project): all flares larger than M5 GOES class of current solar cycle



Decomposition tool I

Preprocessing:

- Time selection and background subtraction

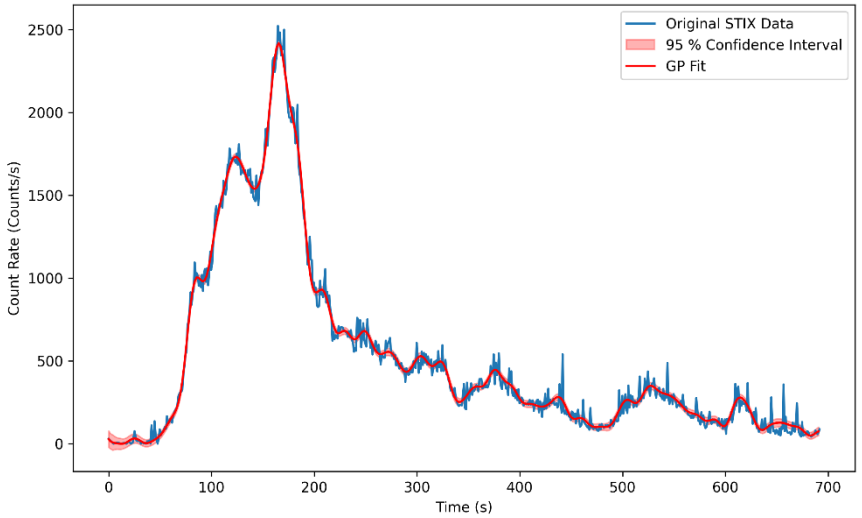


HXR lightcurve after background subtraction

Decomposition tool II

Preprocessing:

- Time selection and background subtraction
- Normalisation and smoothing using Gaussian Process regression



HXR lightcurve and smoothed profile

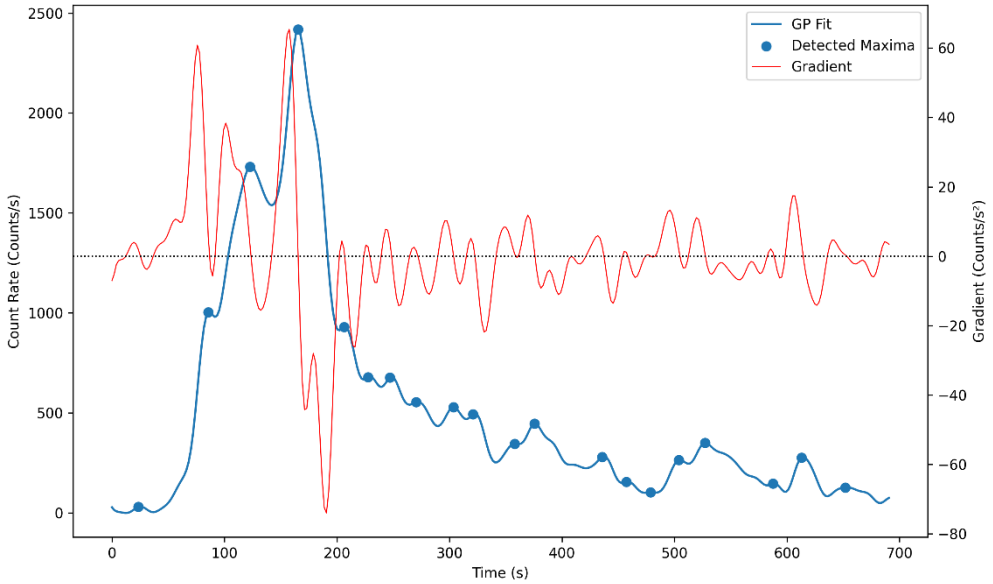
Decomposition tool III

Preprocessing:

- Time selection and background subtraction
- Normalisation and smoothing using Gaussian Process regression

Peak detection:

- Numerical gradient of smoothed signal is computed and peaks are extracted



Smoothed profile and numerical gradient

Decomposition tool IV

Preprocessing:

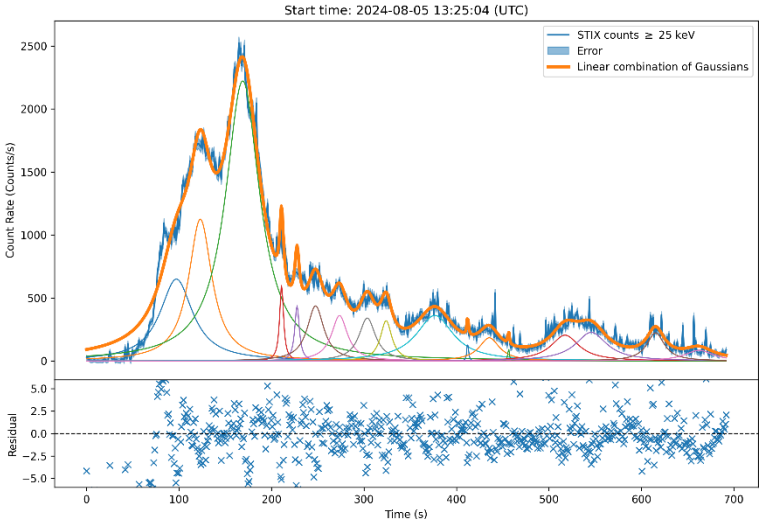
- Time selection and background subtraction
- Normalisation and smoothing using Gaussian Process regression

Peak detection:

- Numerical gradient of smoothed signal is computed and peaks are extracted

Decomposition:

- Peaks are used to fit curve profiles
  - Lorentzian
  - Gaussian
  - Asymmetric Gaussian



Combination of Lorentzian curve profiles

Decomposition tool V

Preprocessing:

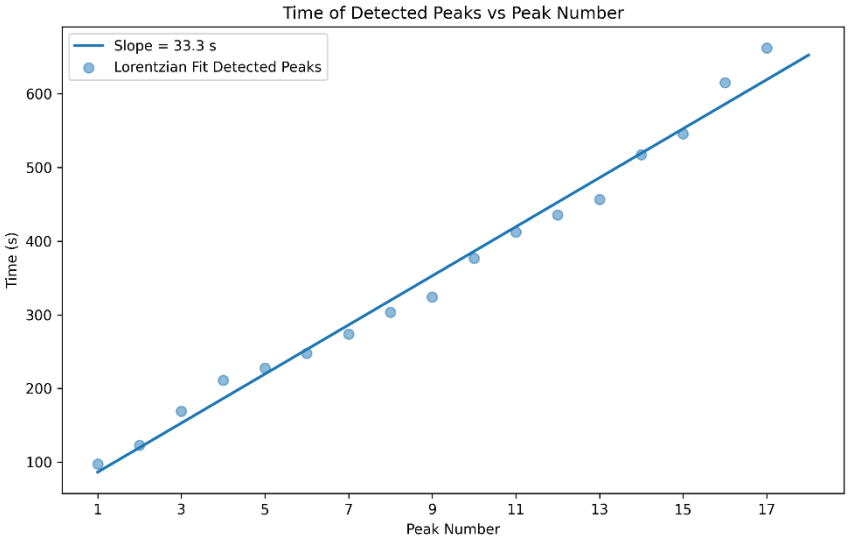
- Background subtraction
- Normalisation and smoothing using Gaussian Process regression

Peak detection:

- Numerical gradient of smoothed signal is computed and peaks are extracted

Decomposition:

- Peaks are used to fit curve profiles
  - Lorentzian
  - Gaussian
  - Asymmetric Gaussian
- Periods, amplitudes, and widths extracted from curve parameters

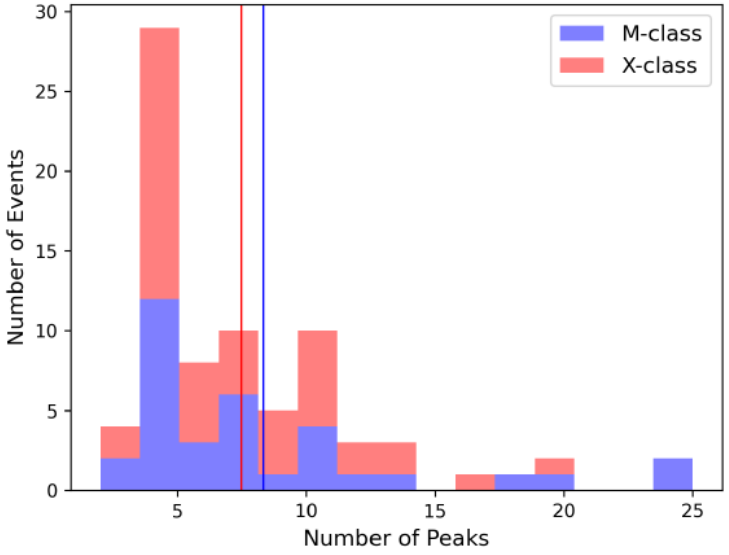


Linear fit of peak times vs. number of peaks (average period)

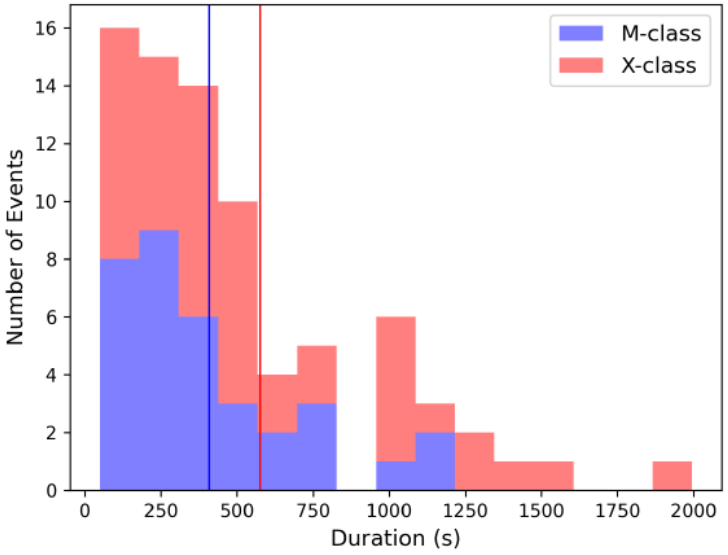
Decomposition tool: Overall Performance

- 80 flares successfully analysed
- Analysis failed for 15 flares
  - Structure of lightcurves
  - Insufficient temporal resolution
  - Insufficient S/N ratio
- Best fit through reduced χ^2:
  - 77 Lorentzians
  - 3 Gaussians
- Lorentzian is best suited to reproduce more extended wings of HXR emission pulses

Decomposition tool results: number of peaks and flare durations



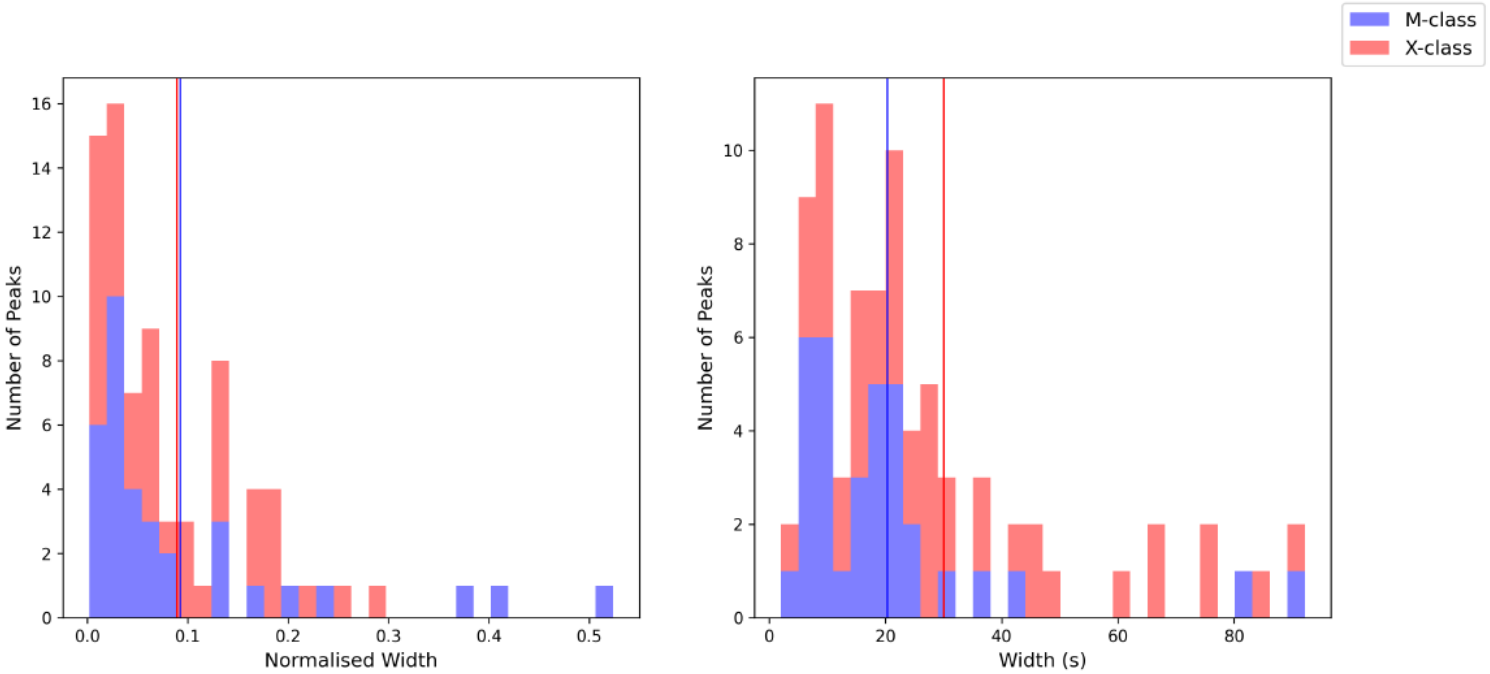
(a) Number of peaks



(b) Duration

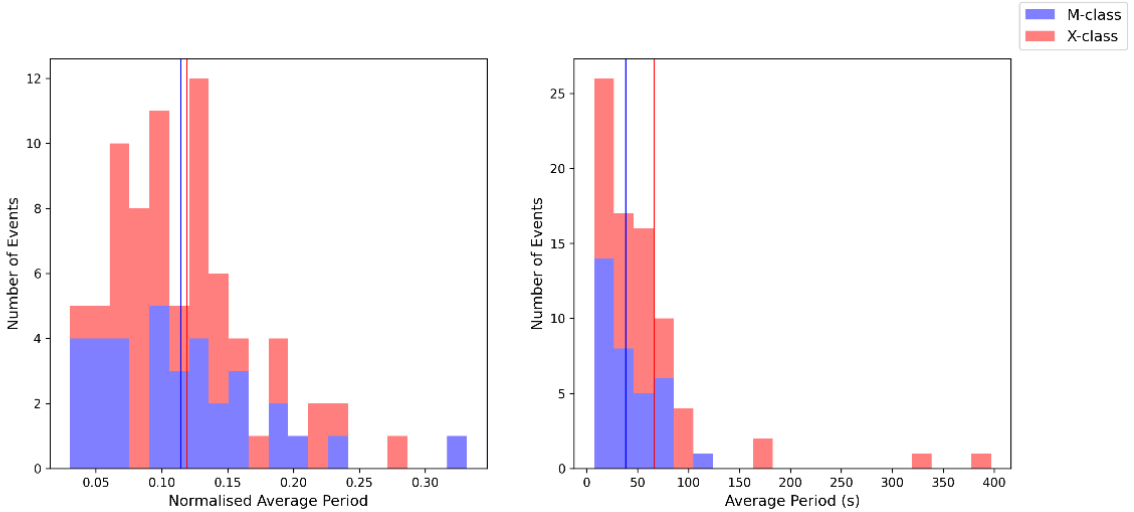
- 612 pulses in 80 flares
- most events show small number of pulses

Decomposition tool results: distribution of all pulse widths



Decomposition tool results: Periods

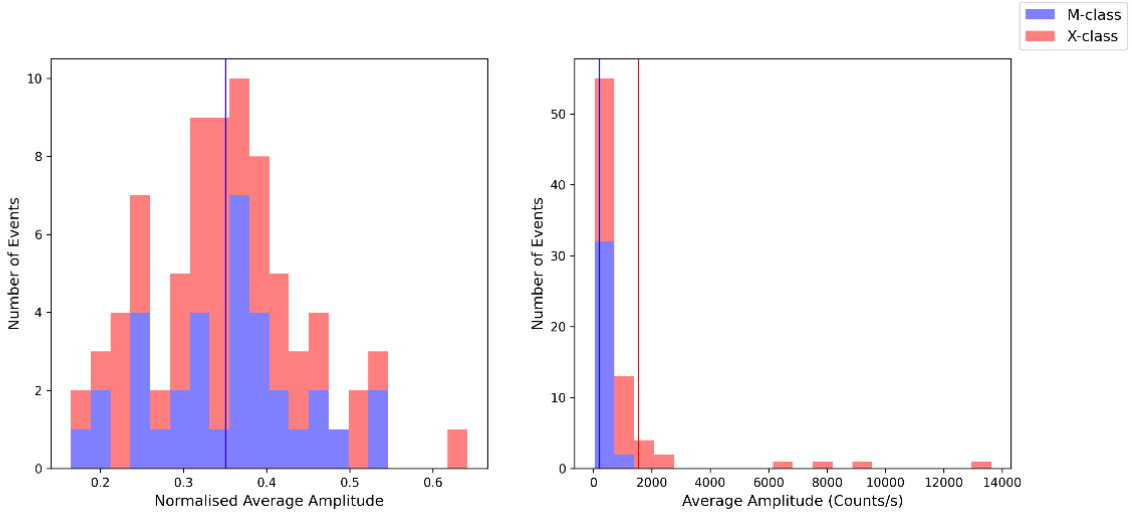
- Extracted parameters show wide range among both M- and X-class flares
  - Periods: similar especially when normalised against flare duration



Histograms of extracted periods for M- and X-class flares

Decomposition tool results: Amplitudes

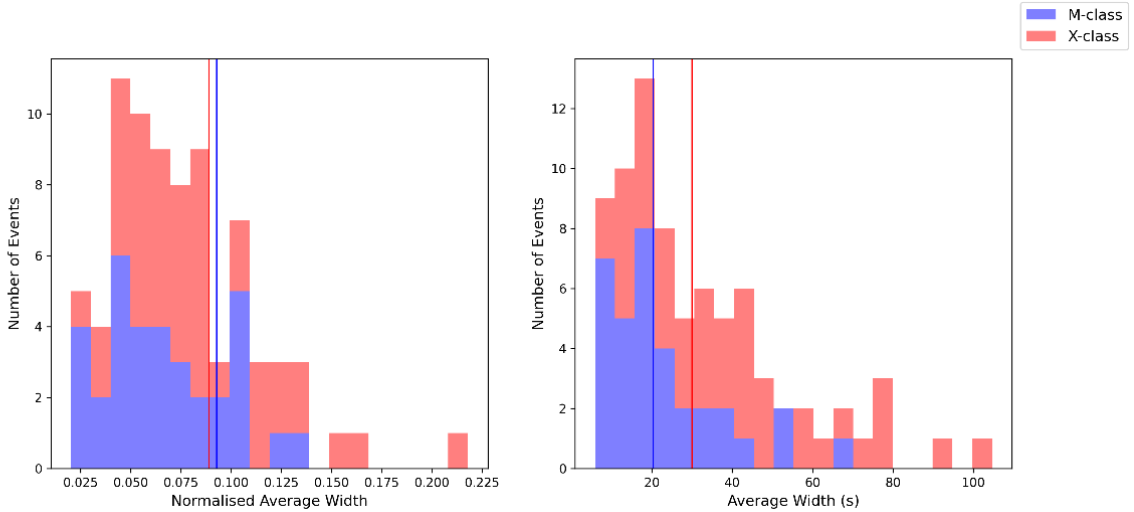
- Extracted parameters show wide range among both M- and X-class flares
  - Periods: similar especially when normalised against flare duration
  - Amplitudes: mean nearly identical between classes



Histograms of extracted amplitudes for M- and X-class flares

Decomposition tool results: Pulse widths

- Extracted parameters show wide range among both M- and X-class flares
  - Periods: similar especially when normalised against flare duration
  - Amplitudes: mean nearly identical between classes
  - Temporal widths: similar especially when normalised against flare duration

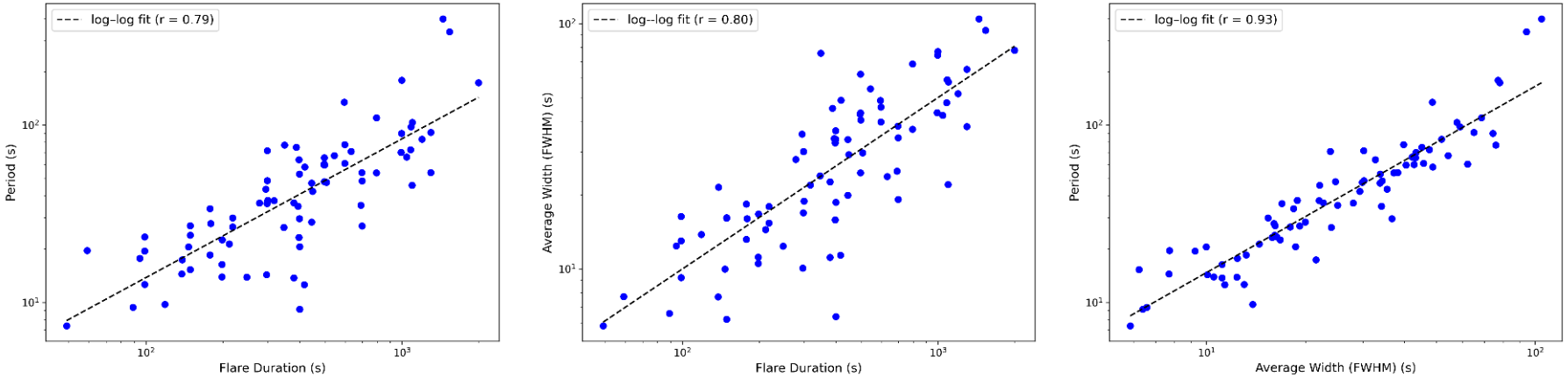


Histograms of extracted temporal widths for M- and X-class flares

Decomposition tool results: Discussion

- Extracted parameters show wide range among both M- and X-class flares
  - Periods: similar especially when normalised against flare duration
  - Amplitudes: mean nearly identical between classes
  - Temporal widths: similar especially when normalised against flare duration
- Mean period (ca. 55 s) is longer than in literature (below ~30 s, cf. Pugh et al. 2017, Simoes et al. 2015)
  - Other studies only consider events marked as having a QPP
- No strong indication for link between GOES class (flare strength) and periodicities or other fitting parameters
  - Flare strength not a strong indicator for temporal characteristics of emission
  - Consistent with literature (e.g. Hayes et al. 2020)

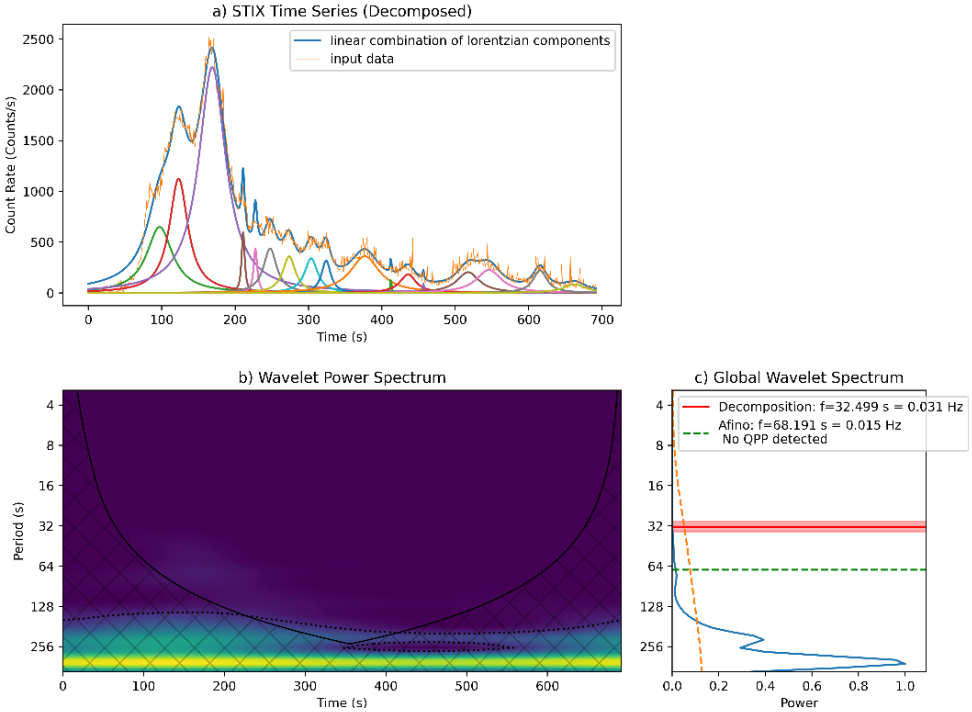
Decomposition tool: Correlations



Strongest correlations. Left: period vs flare duration, centre: Temporal with vs duration, right: period vs temporal width

- Correlation between characteristic period and flare duration consistent with Hayes et al. 2020
- Longer lasting flares exhibit broader HXR emission features likely caused by longer periods of particle acceleration

- Generally low agreement between all three methods ($r = 0.04 - 0.30$)
- Particularly low between AFINO and Wavelet Analysis tools
- Discrepancies might arise from:
  - Methodological differences (detrending/smoothing, frequency/ time domain)
  - Differing sensitivity to fast-time variability → tools may recover different aspects of complex HXR lightcurves
  - Inadequate choice of input parameters for Wavelet tool



Comparison plot of periodicities from all three tools

Conclusion and outlook on HXR timeseries analysis

- Analysis of HXR lightcurves from STIX of current solar cycle
- Curve decomposition to analyse oscillations in lightcurves
- 80 lightcurves were analysed: Lorentzian most common best fit
- Periods, temporal widths, and flare durations correlate
- No correlations found between flare strength and parameters
- Low agreement between methods

➢Find out why analysis failed for some lightcurves

➢Reevaluate input parameters for Wavelet Analysis tool to investigate discrep

➢Investigate differences between eruptive and confined flares

➢**Timeseries analysis workflow available on github and SOLER Jupyter h**

Summary and outlook

Summary and outlook

- have developed analysis tools for X-ray lightcurves, spectra, and images, as well as for EUV jets
- tools have been used for case studies, statistical studies are underway

- Outlook:
  - finalize tools (e.g. joint spectral fitting)
  - perform HXR spectroscopy and imaging for full sample of flares
  - statistical study of energetic electron characteristics and flare energetics
  - joint study considering CME and SEP parameters
  - provide spectral fits to community