Hard X-ray Imaging of Quasi-Periodic Pulsations at the Footpoints of a Solar Flare

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STIX Meeting

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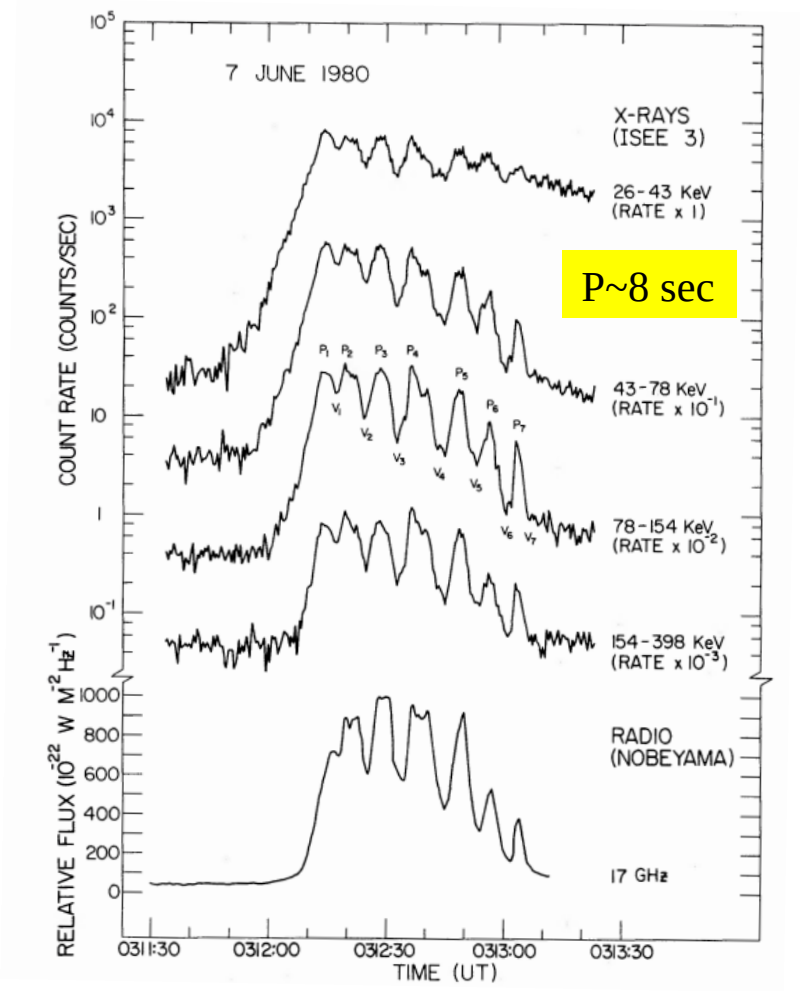
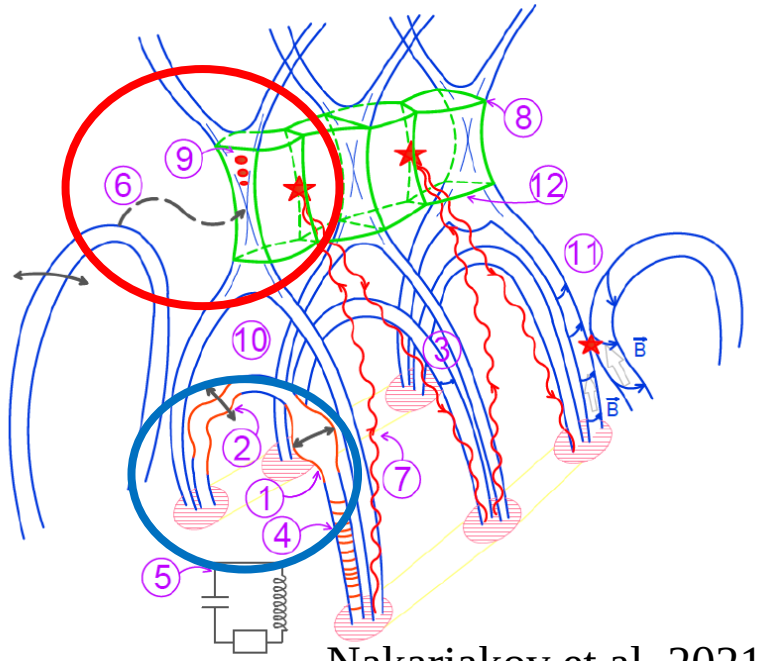
1.1 Quasi-Periodic Pulsations (QPPs)

- The quasi periodic variation of electromagnetic emissions in the solar (stellar) flares
- Period = seconds to minutes
- Visible in over 80% of flares



Kane, 1983



Nakariakov et al. 2021

MHD modulation

MHD waves modulate flare loop parameters (**B**, plasma density, …)
(Tian et al., 2016; Shi et al., 2022; Kupriyanova et al., 2019; Li et al., 2022; Nechaeva et al., 2019))

Oscillatory reconnection

Quasi periodic acceleration of electrons
(Kou et al., 2022; Lu et al., 2021)

1.2 HXR Emission and QPPs

HXR emissions often appear in the footpoints of the solar flares, in some case can also see the loop top source

1. QPPs in HXR light curves
2. Imaging of HXR sources

position, morphology, flux, spectrum, …

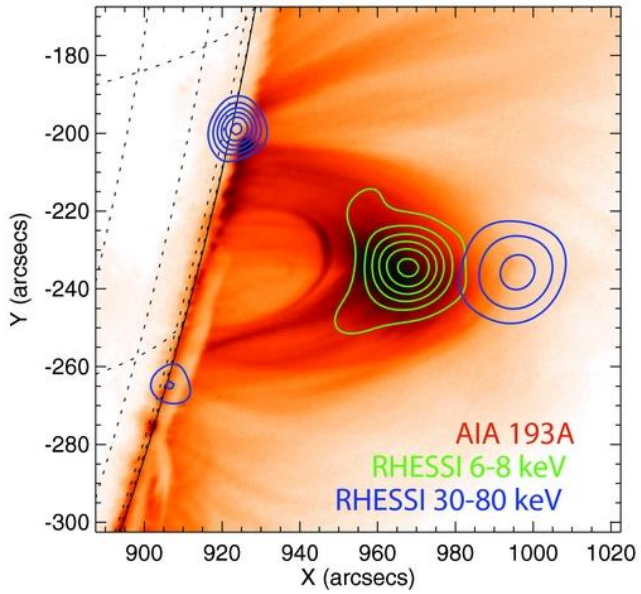
Key question

If these properties also exhibit similar quasi periodic variations?

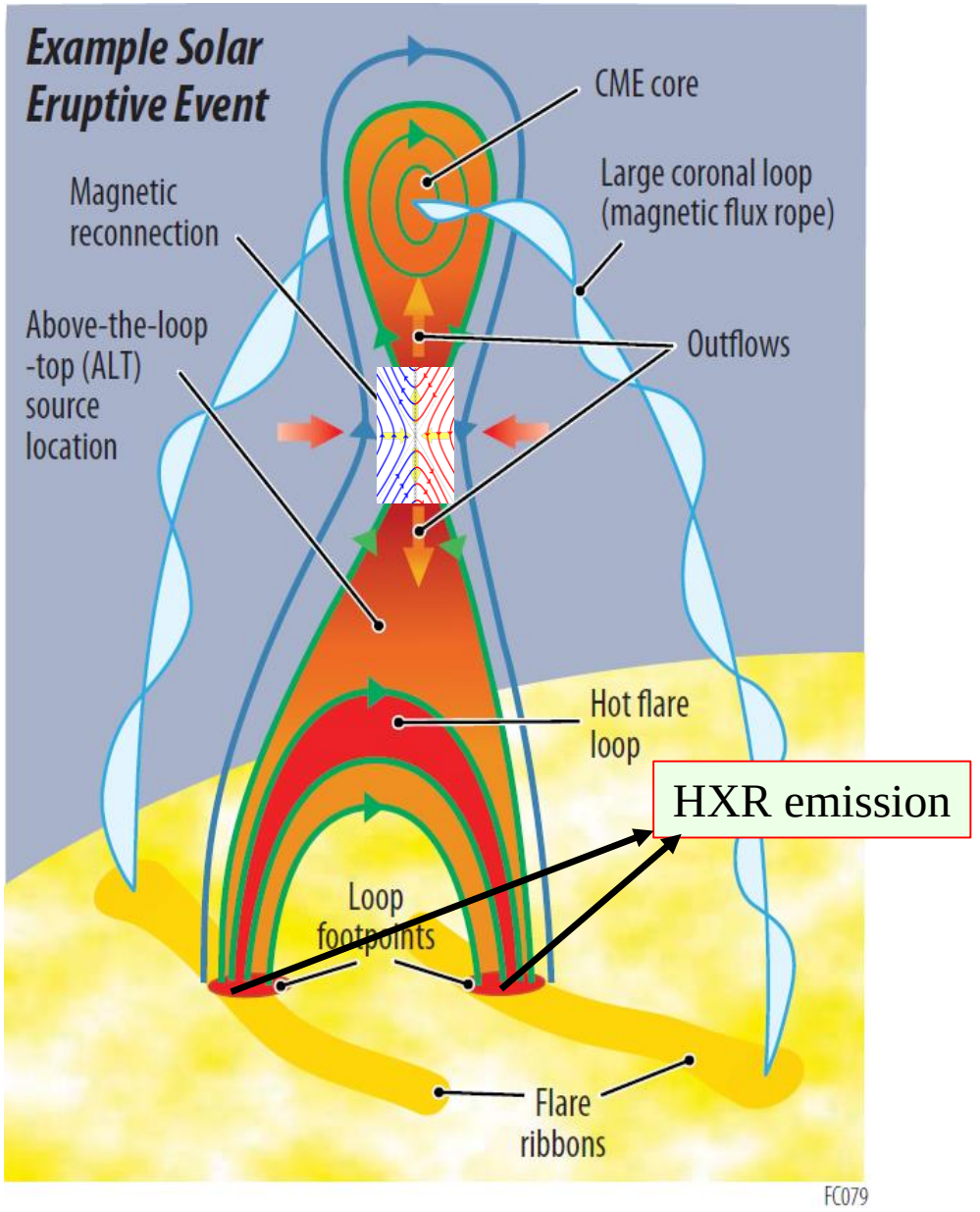
Lack HXR imaging of QPP

What do we need?

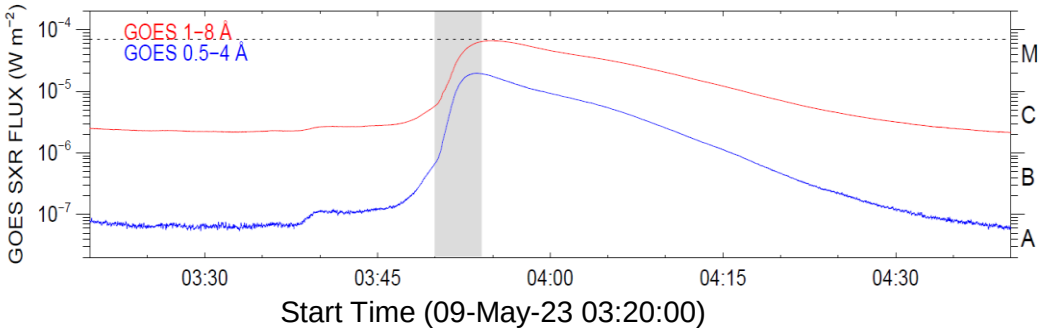
High temporal and spatial resolution hard X-ray imaging telescope



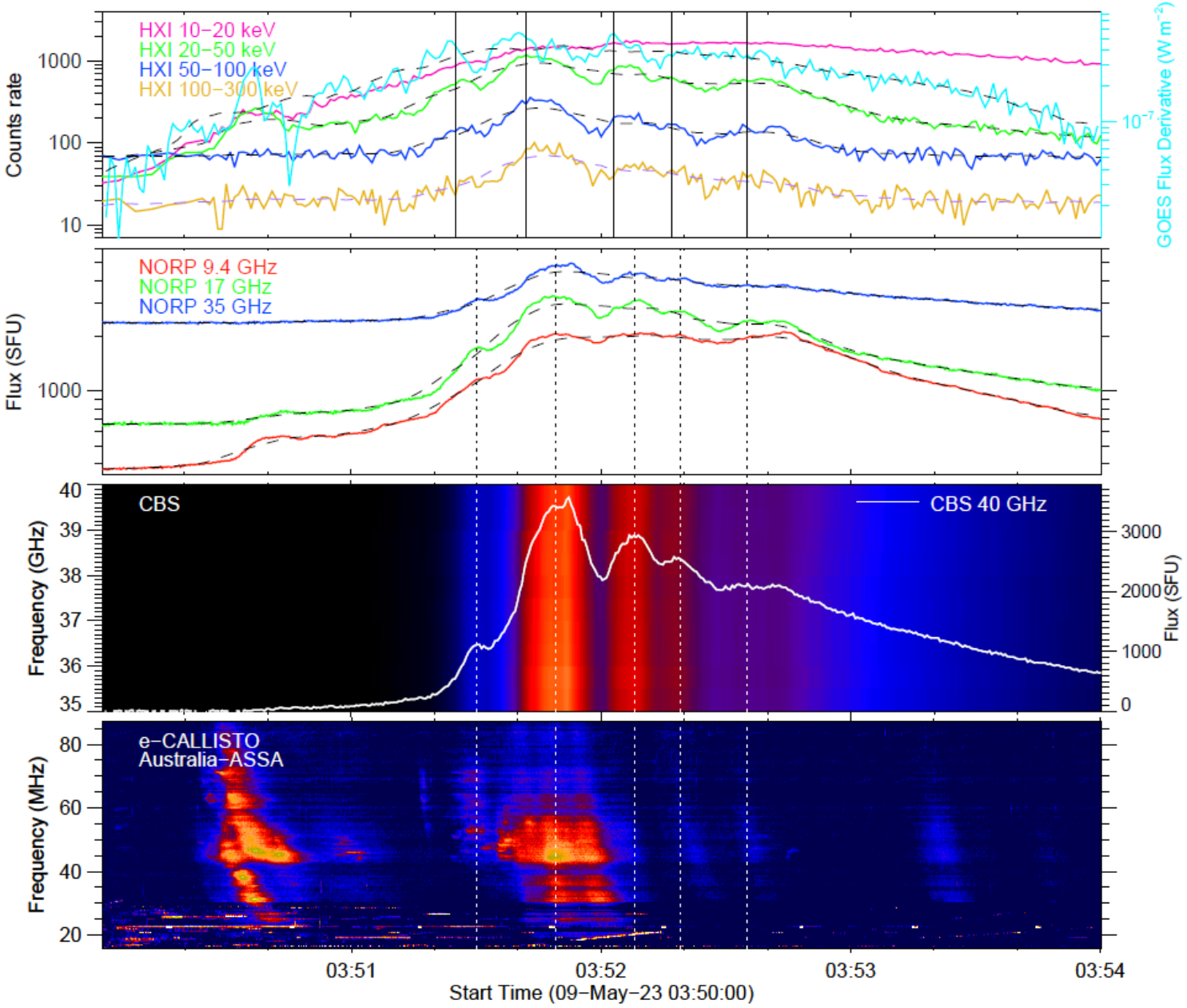
(Krucker and Battaglia, 2014)



2.1 QPP Event on 9 May 2023

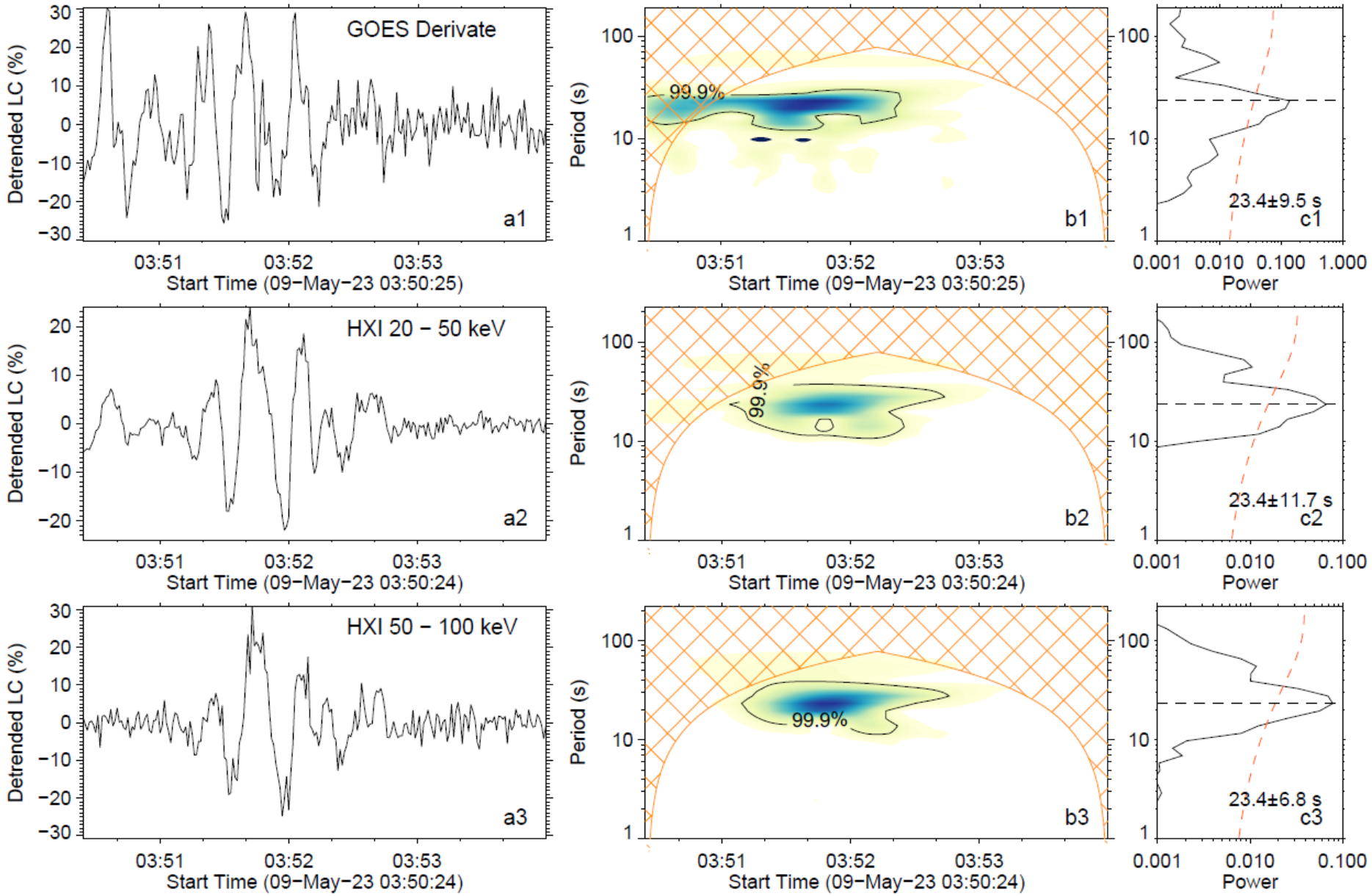


- AR13296 M6.5 class flare
- During impulsive phase (03:50–03:54UT), emission from HXR (observed by HXI instrument) and Microwave (NORP, CBS) both revealed QPPs.
- Accompanied by quasi periodic Type III burst in interplanetary space



2.2 Pulsation Period of HXR

"Morlet" wavelet analysis method

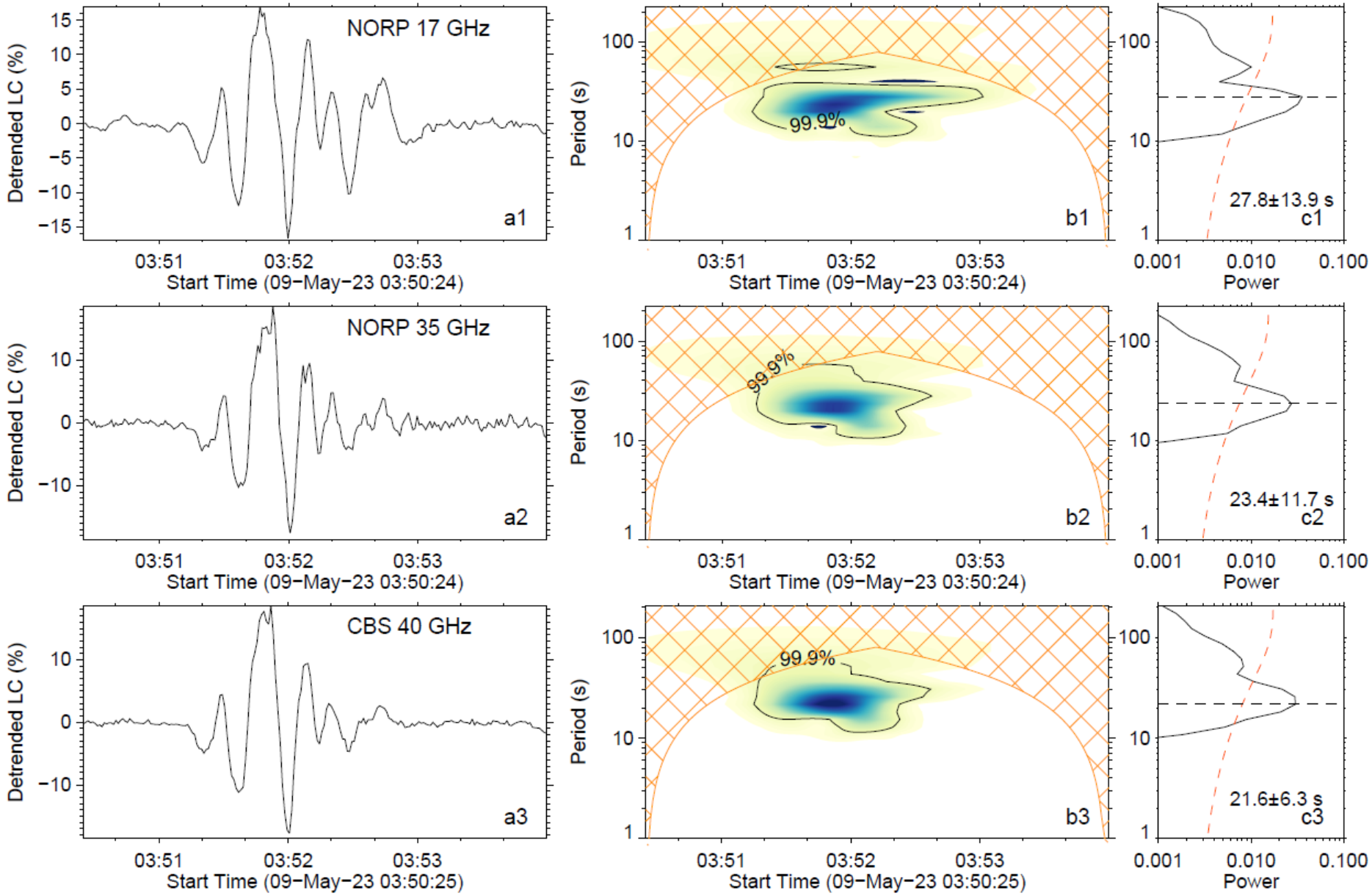


P ~ 23.4 sec

P ~ 23.4 sec

P ~ 23.4 sec

2.2 Pulsation Period of Microwave

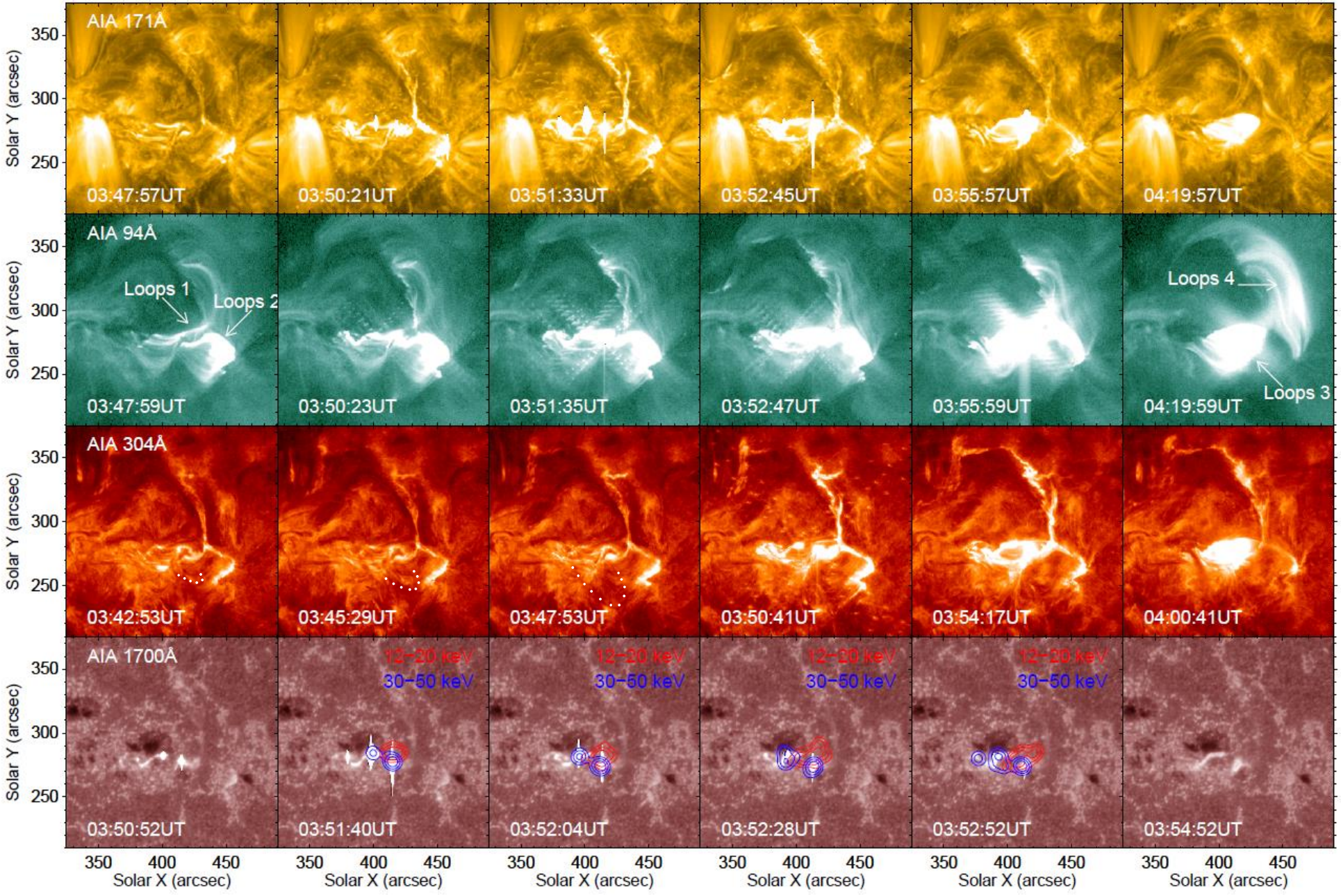


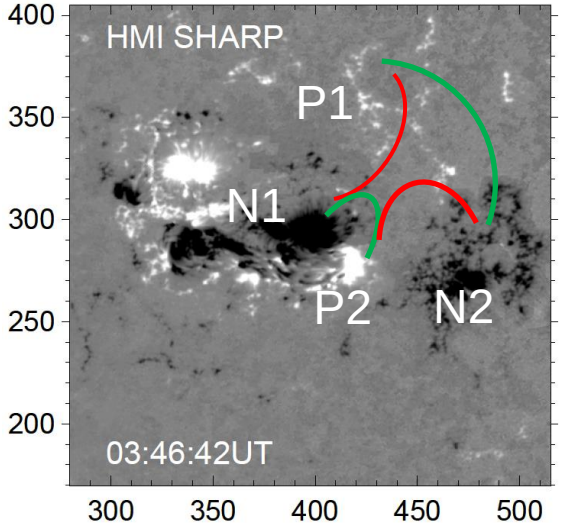
P ~ 27.8 sec

P ~ 23.4 sec

P ~ 21.6 sec

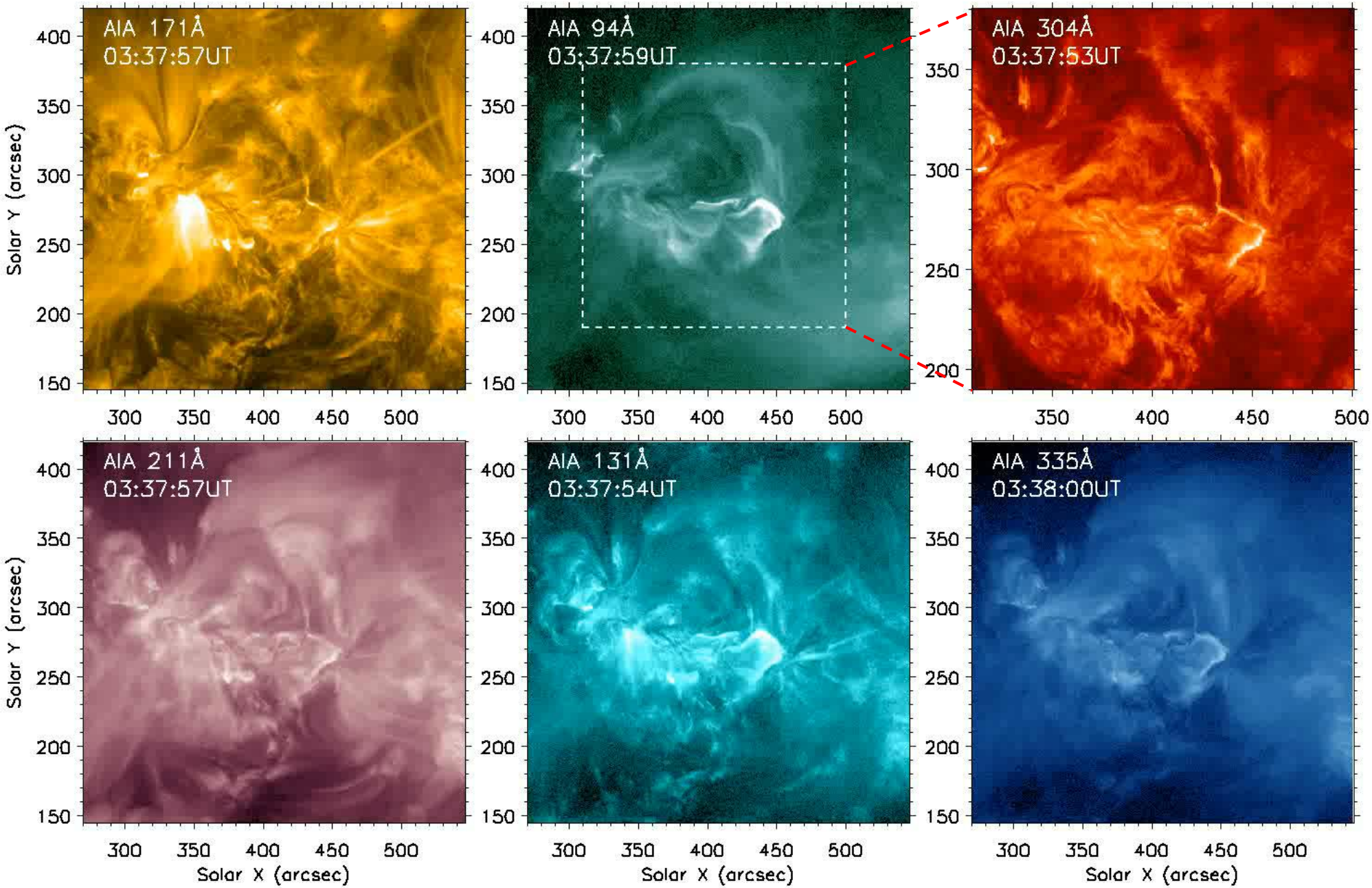
2.3 EUV and HXR Imaging





- pre-flare :
  - A micro-filament (doted lines in 304 panel) erupted
  - Loops 1 & Loops 2
  - N1-P1 & N2-P2
- post-flare :
  - Loops 3 & Loops 4
  - N1-P2 & N2-P1
- 30-50keV sources are co-spatial with the flare ribbons

2.3 EUV Time Series

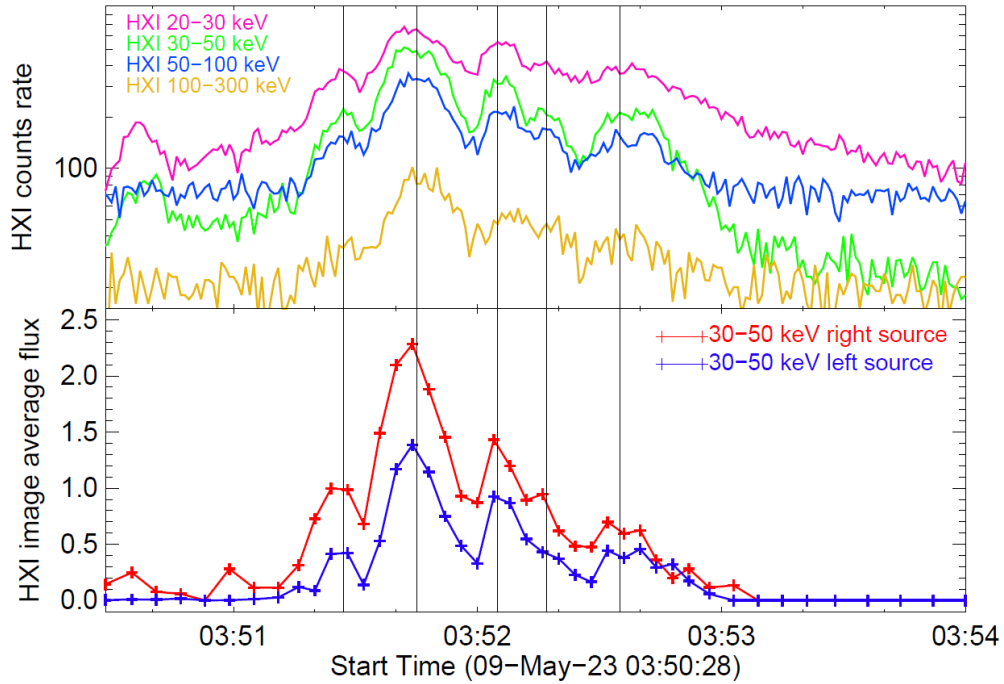


1700 Å brightening along the flare ribbons

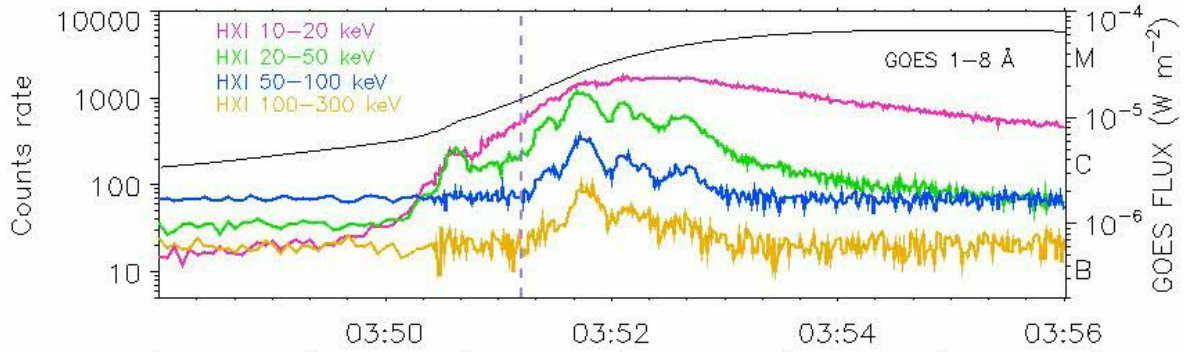
2.4 HXR Imaging of Footpoints

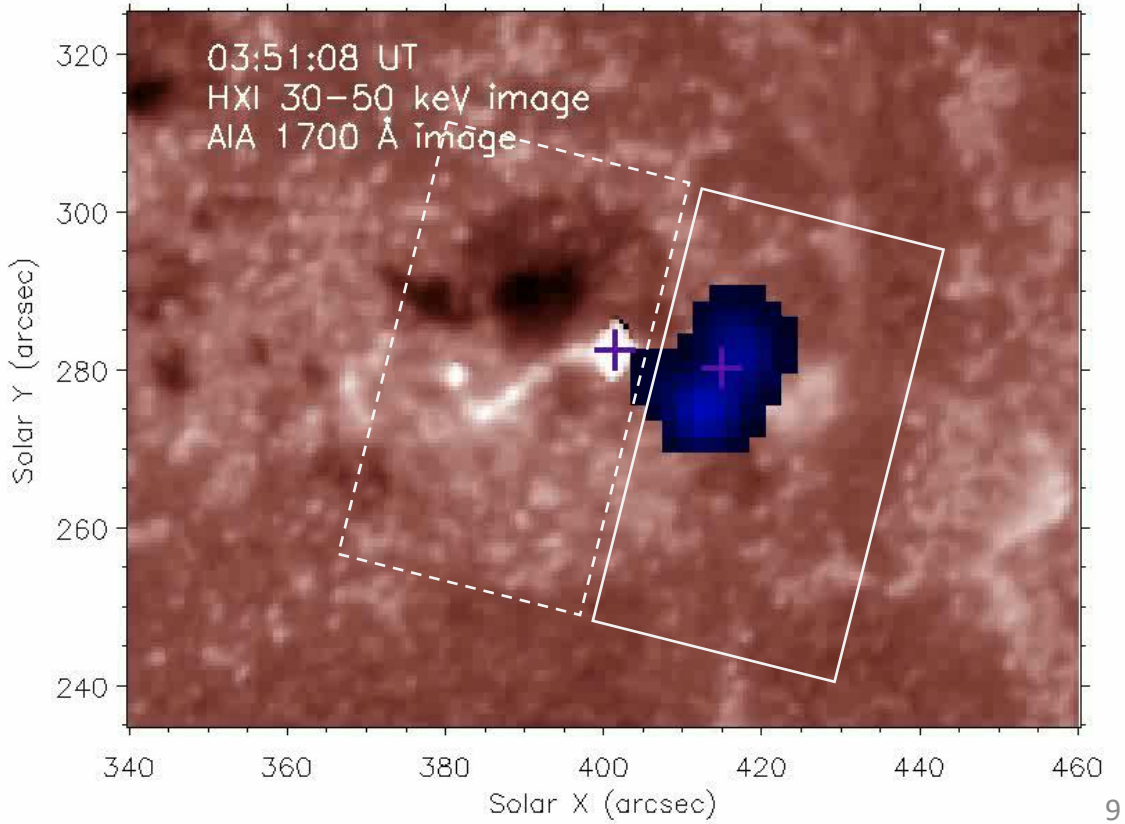
- Integration time：6s ~ 4s （ensure enough photons）
- Energy range：30 ~ 50 keV
- Detectors：HXI G2-G10 (Det.9-91)
- Algorithm：CLEAN

1. The centroid (plus sign) motion of HXR sources is consistent with AIA 1700 Å brightening
2. The flux of each source exhibits quasi-periodic pulsations

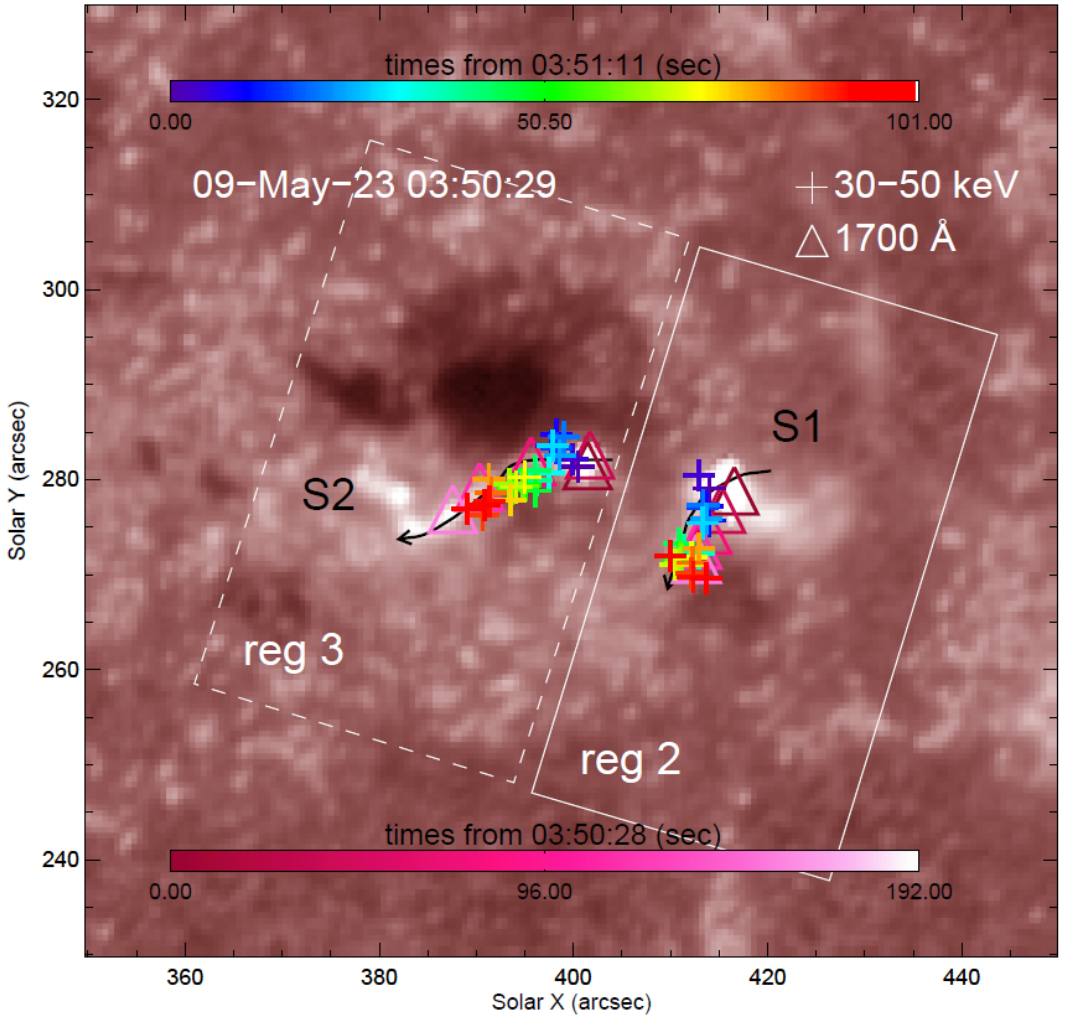


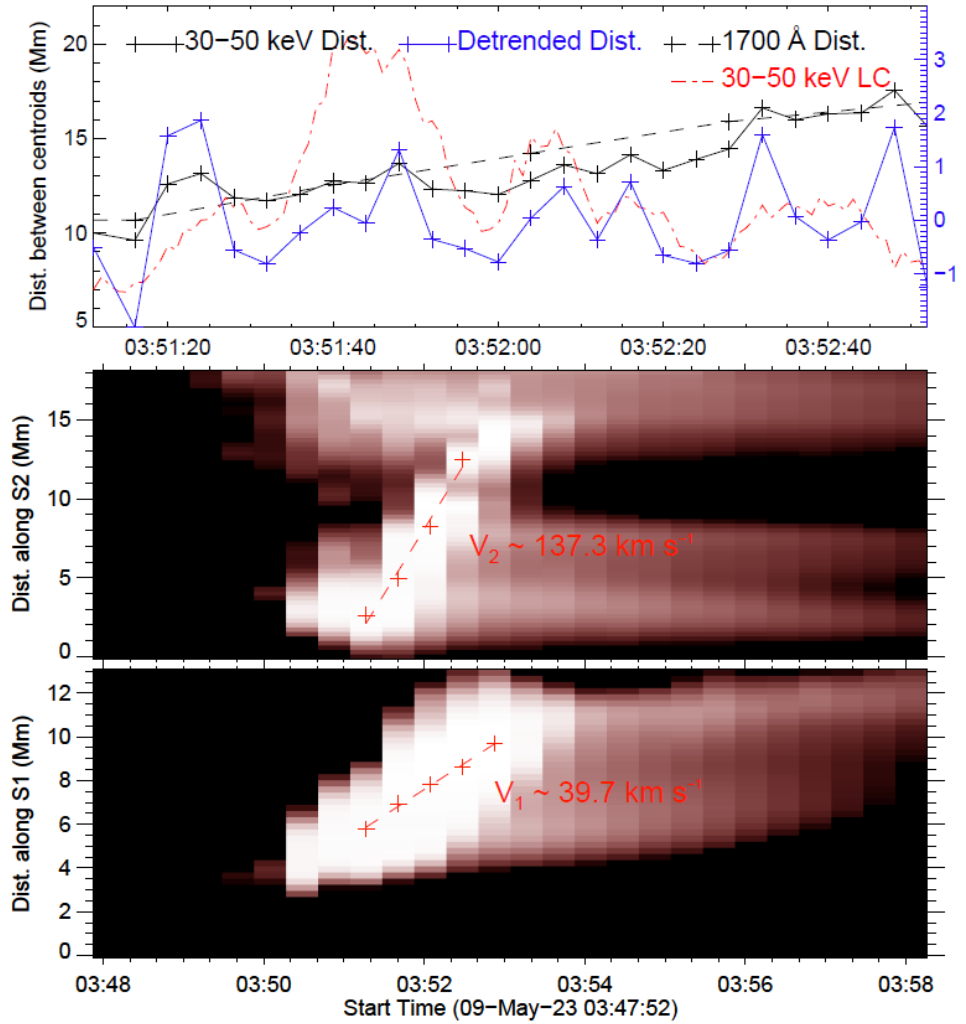
Detailed parameters of HXI refer to tomorrow's talk





2.4 HXR Imaging of Footpoints

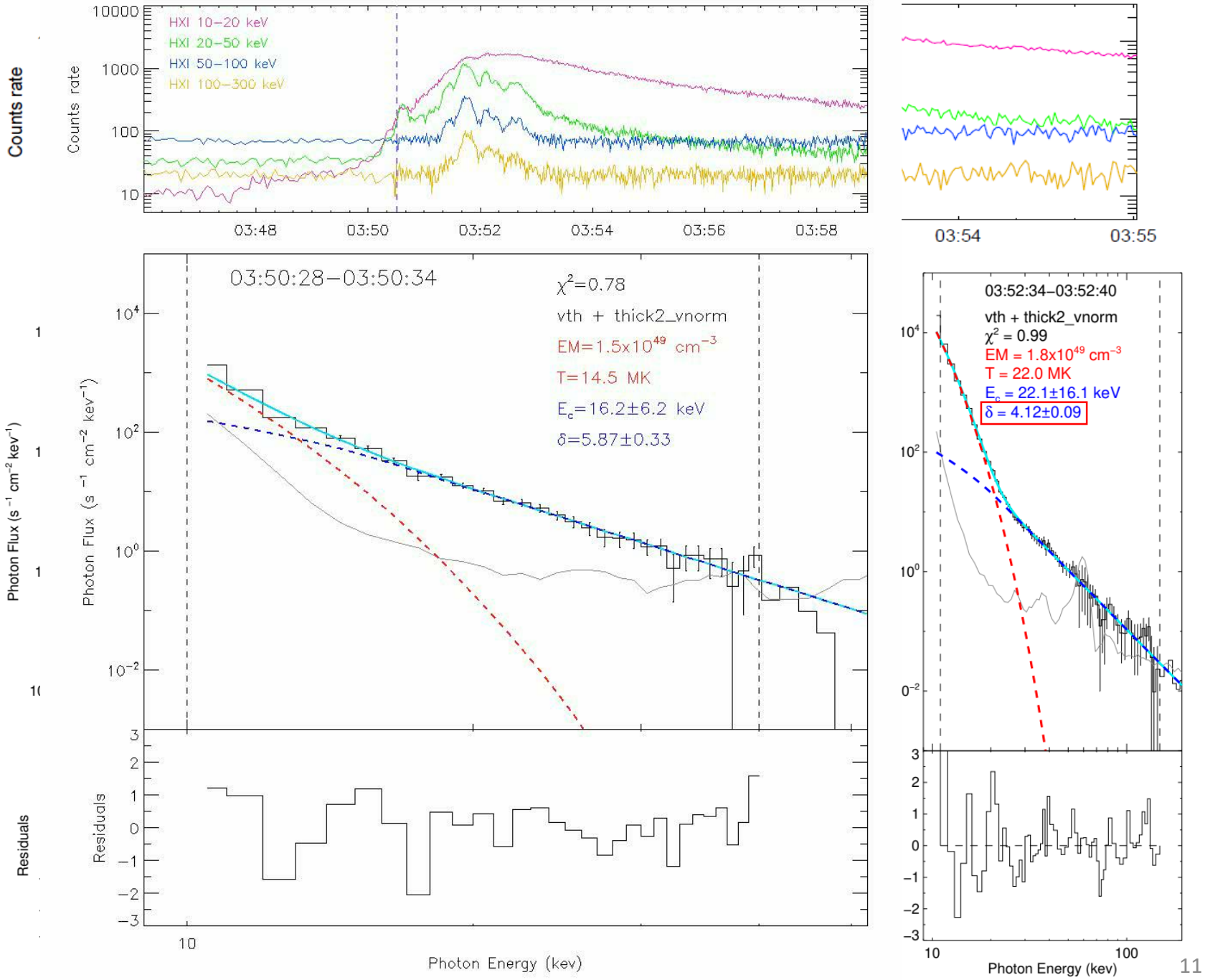




- The distance between HXR sources (plus sign) and the distance between 1700Å brightening (triangle) have good consistency (see upper right panel))
- The distance between HXR sources also varies quasi-periodically similar to HXR light curves.
- The velocities of 1700Å brightening along the flare ribbons are 137km/s (left-S2) and 40km/s (right-S1) respectively

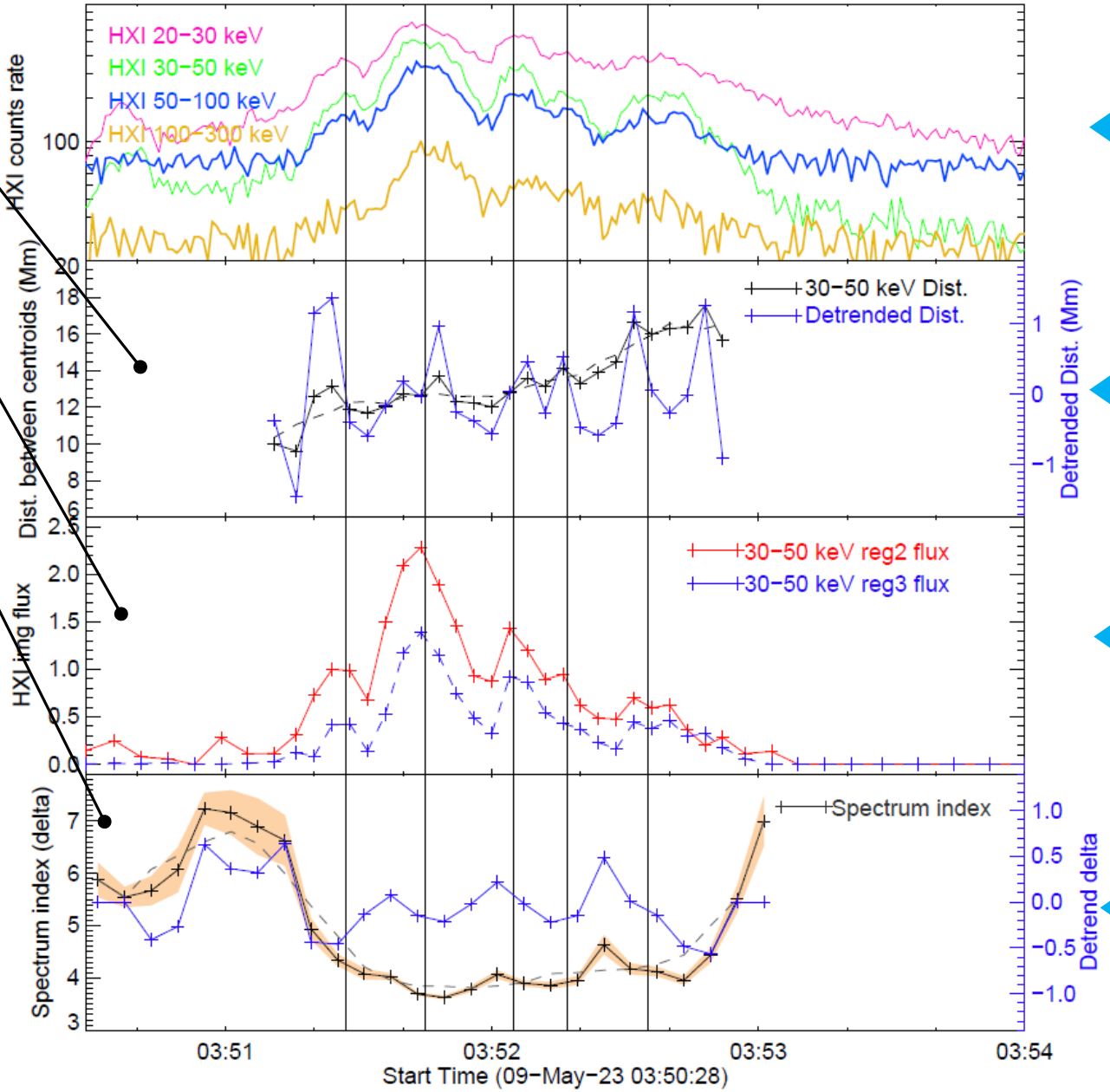
2.5 HXR Spectrum

- During the entire flare impulsive phase, the non-thermal electron spectrum exhibits the well-known soft-hard-soft variation
- From the movie, the spectral index also varies quasi periodically (soft-hard-soft-hard-soft…) between several peaks of the HXR light curve



2.6 Observation Summary

- The distance between HXR sources varies quasi periodically
- The fluxes of two sources are inconsistent but have the same pulsation period
- Non thermal electron spectral index has quasi periodicity
- The above periodicities are all consistent with the 23.4 second period of light curve
- Suggest that QPPs mainly come from quasi periodic accelerating electrons (associated with magnetic reconnection)



HXR light curves

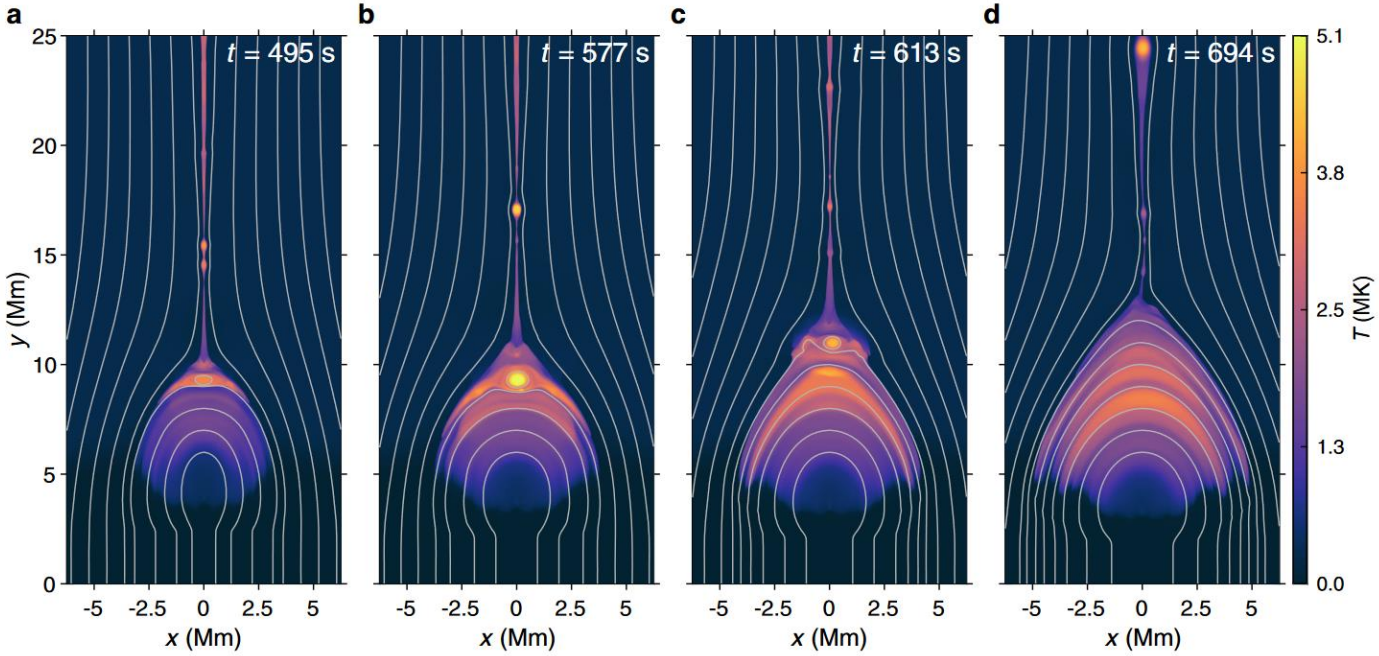
Distance between two footpoint sources

HXR flux of two footpoint sources

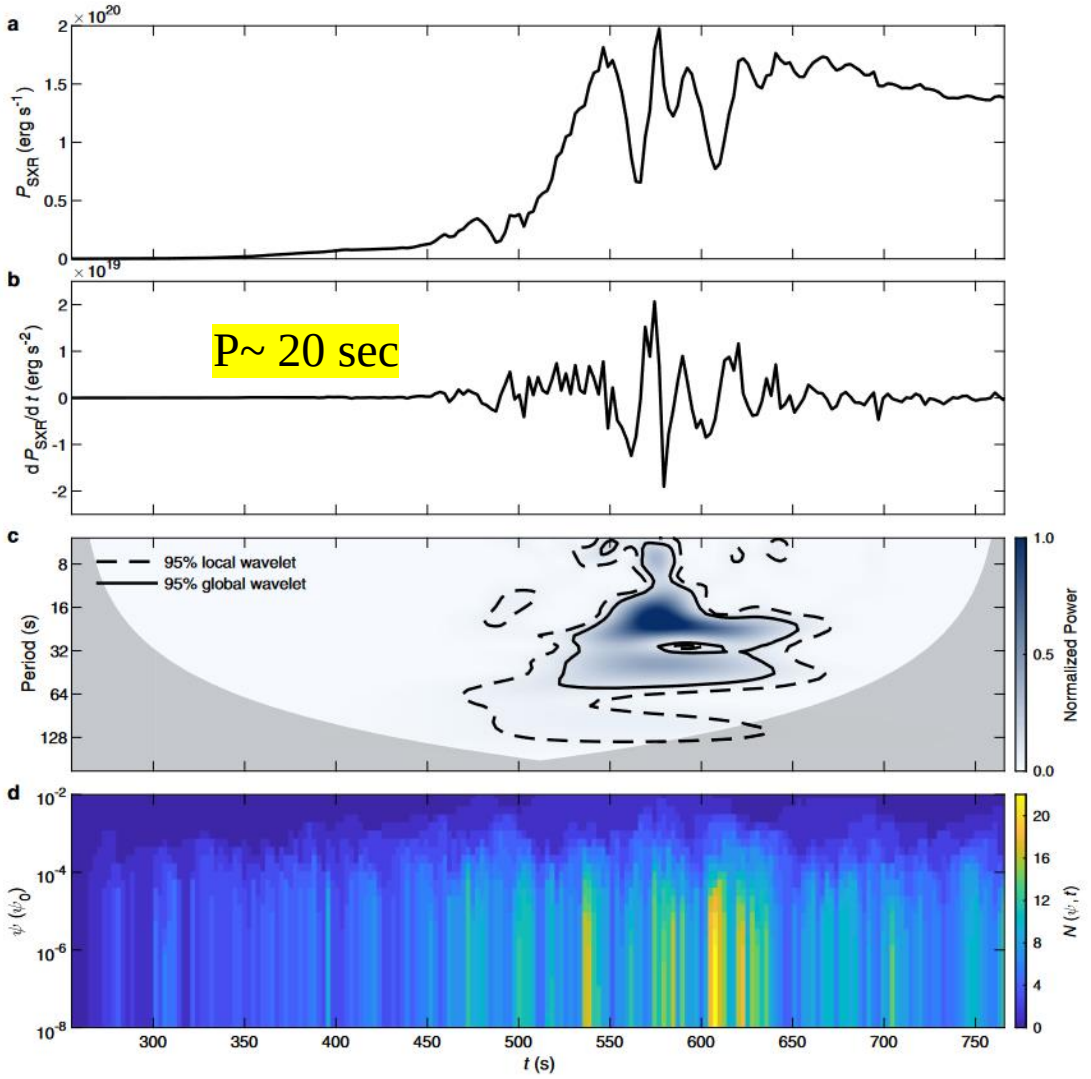
Spectral index

3.1 Discussion - How electrons are quasi periodically accelerated?

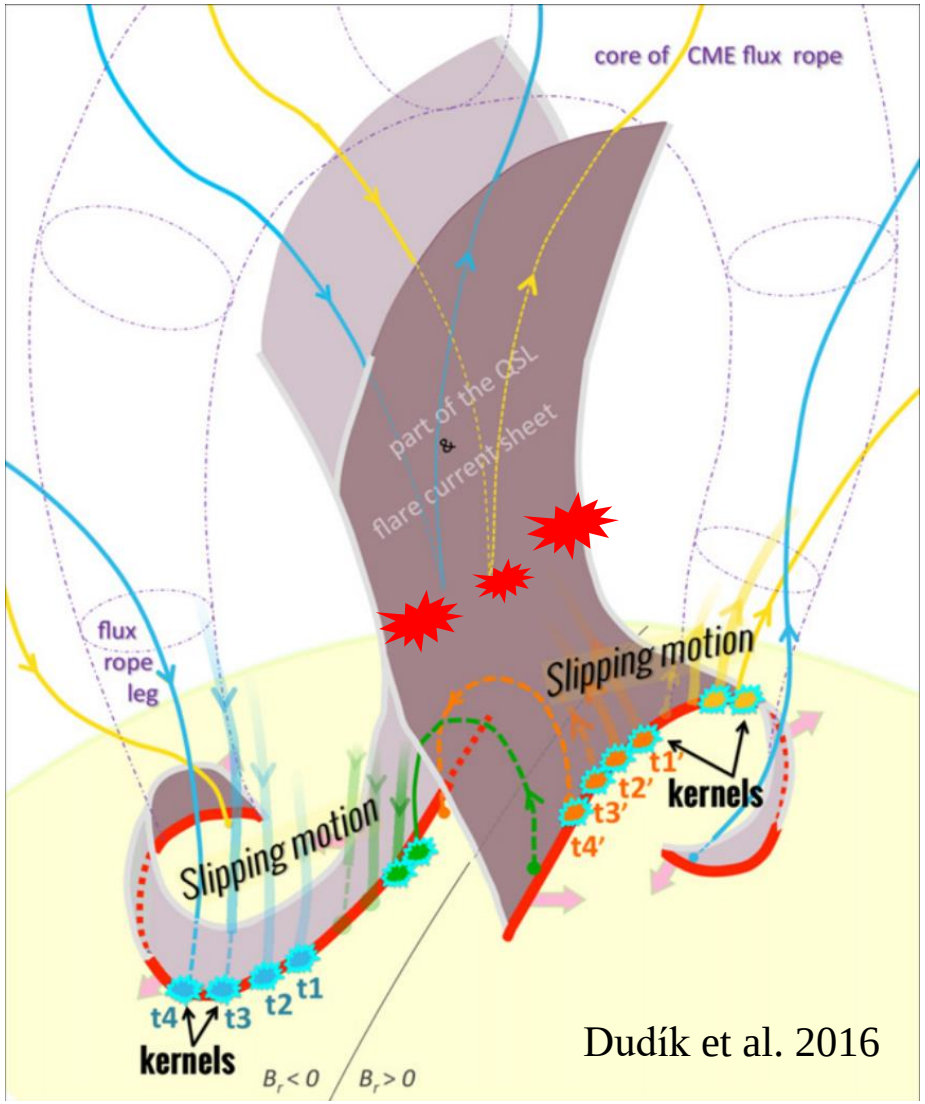
Quasi-periodic reconnection, modulation of magnetic island in the current sheet ?



Kou et al. 2022



3.2 Discussion – The distribution of magnetic flux is quasi periodic



Dudík et al. 2016

- In 3D flare model, magnetic reconnection preferentially takes place at the intersection of two quasi-separatrix layers (QSLs)
- The ribbons often coincide with the footprints of QSLs

A simpler and more straightforward process

Reconnection occurs and slips at the QSLs

+

The magnetic flux at the QSLs has spatial quasi periodicity

↓

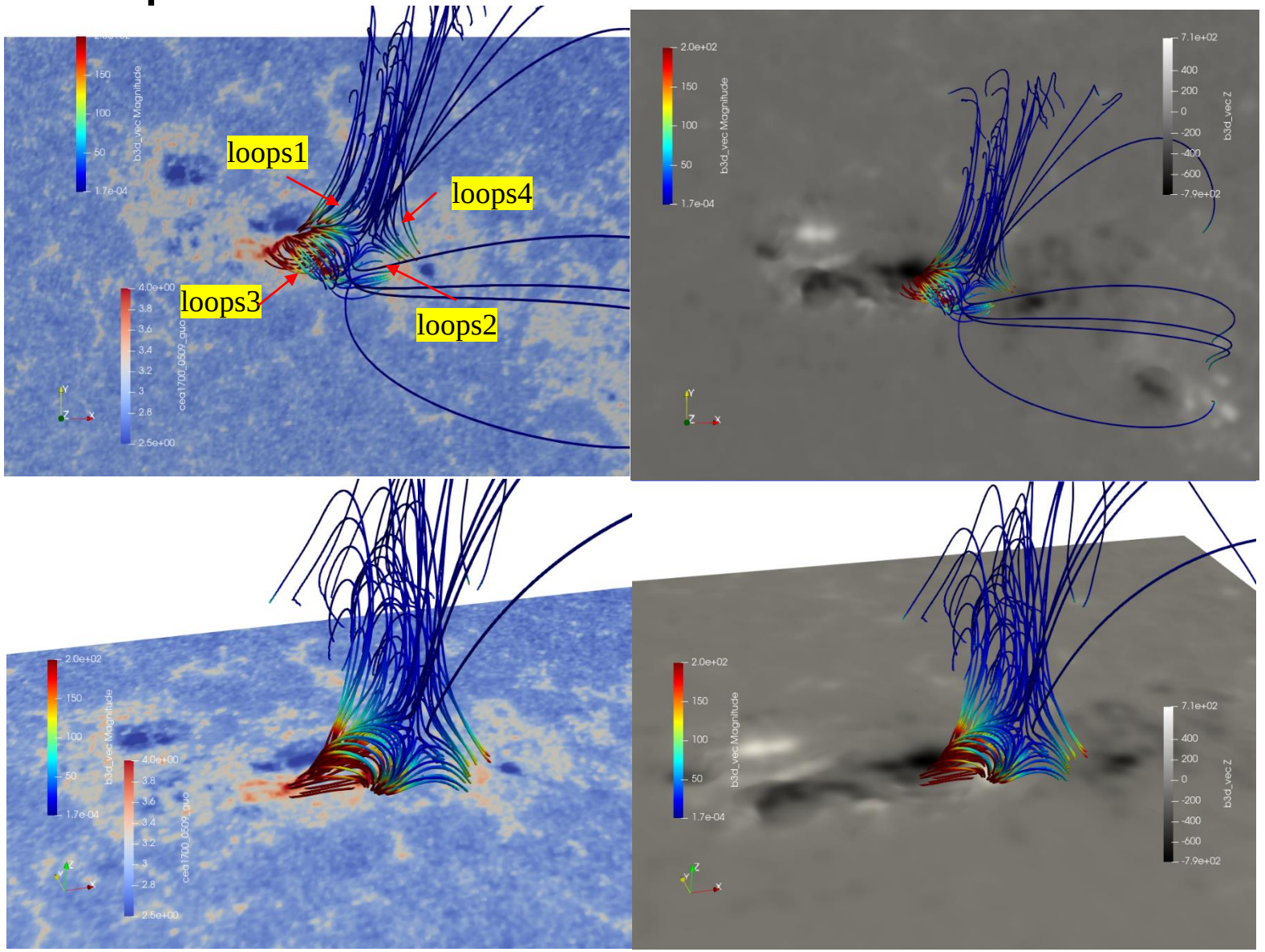
The energy released by the corresponding magnetic reconnection will also be quasi periodic

↓

Electrons are quasi periodically accelerated

3.2 Discussion – The distribution of magnetic flux is quasi periodic

Magnetic field extrapolation

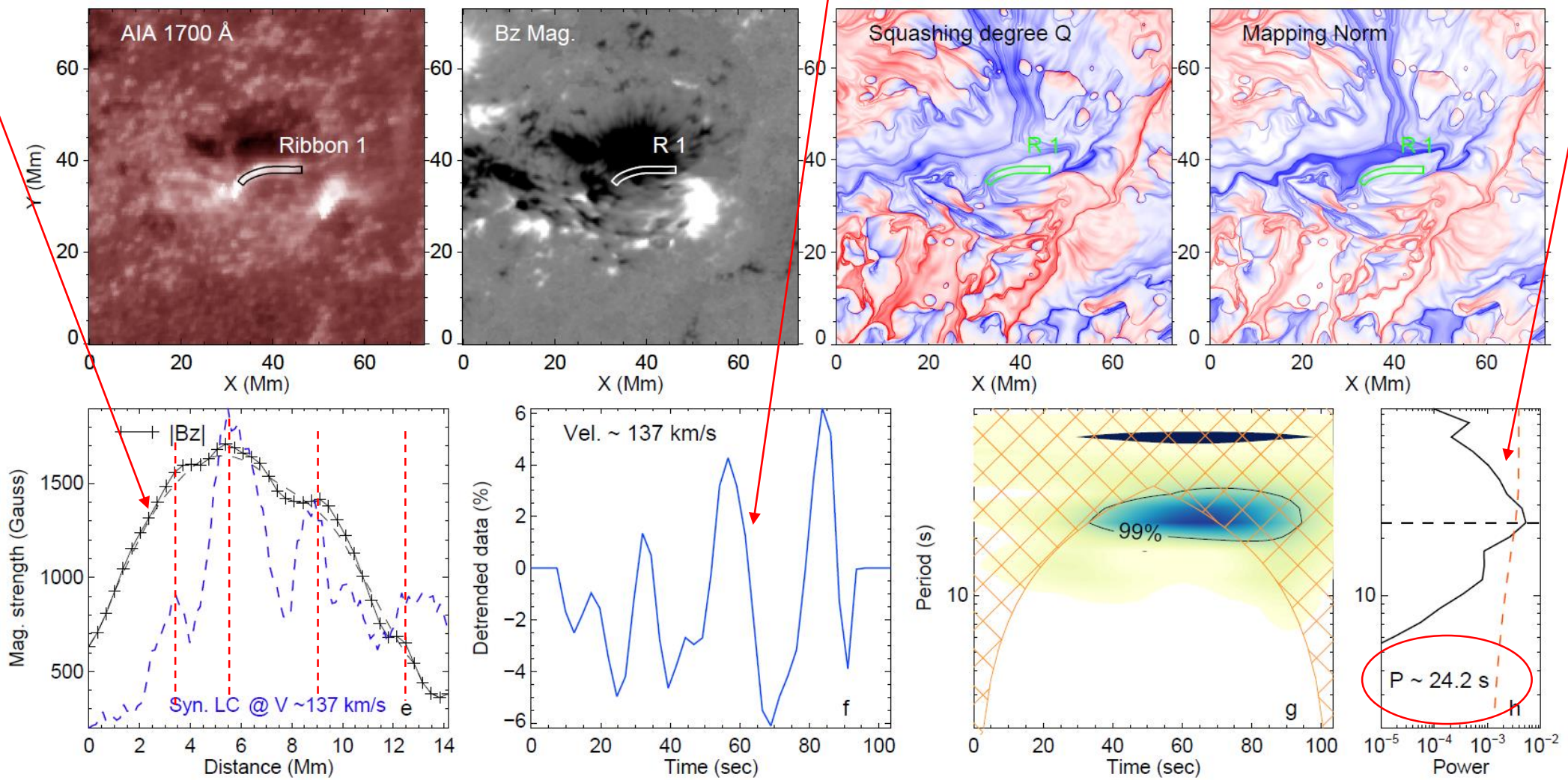


3.2 Discussion - The distribution of magnetic flux is quasi periodic

Extract vertical magnetic field along the ribbon (here horizontal field is "flat" and weak)

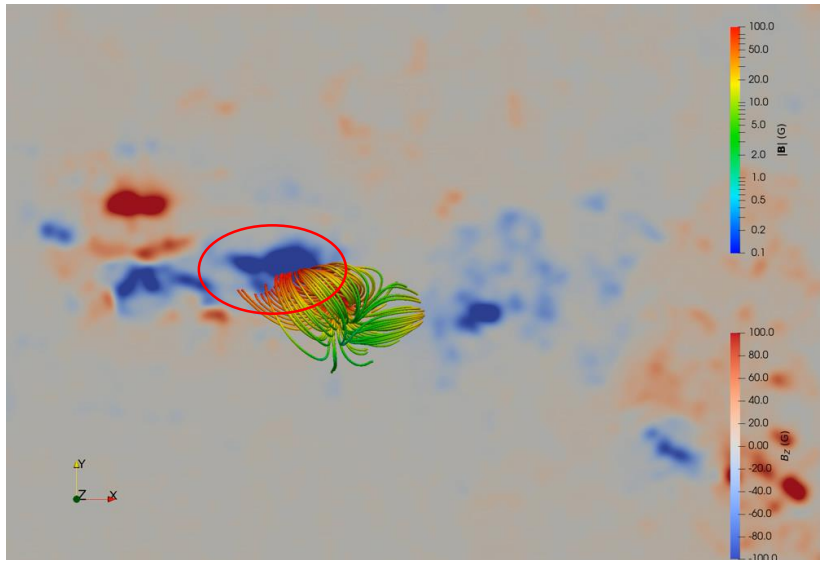
Transfer variations in space to that in time based on the aforesaid movement speed (and vice versa, such as synthetic HXR light curve)

Wavelet analysis
Period~24.2 sec !!!
Period of LC is 23.4 sec

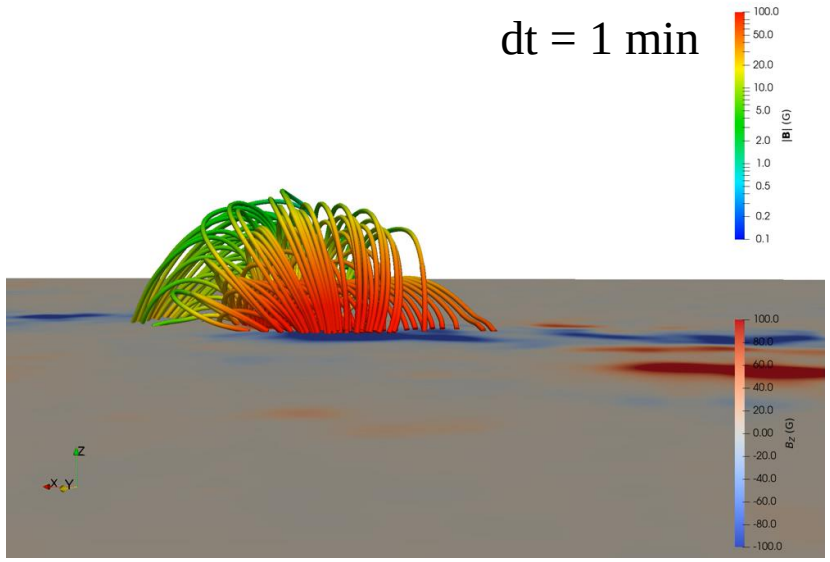


3.2 Discussion – The distribution of magnetic flux is quasi periodic

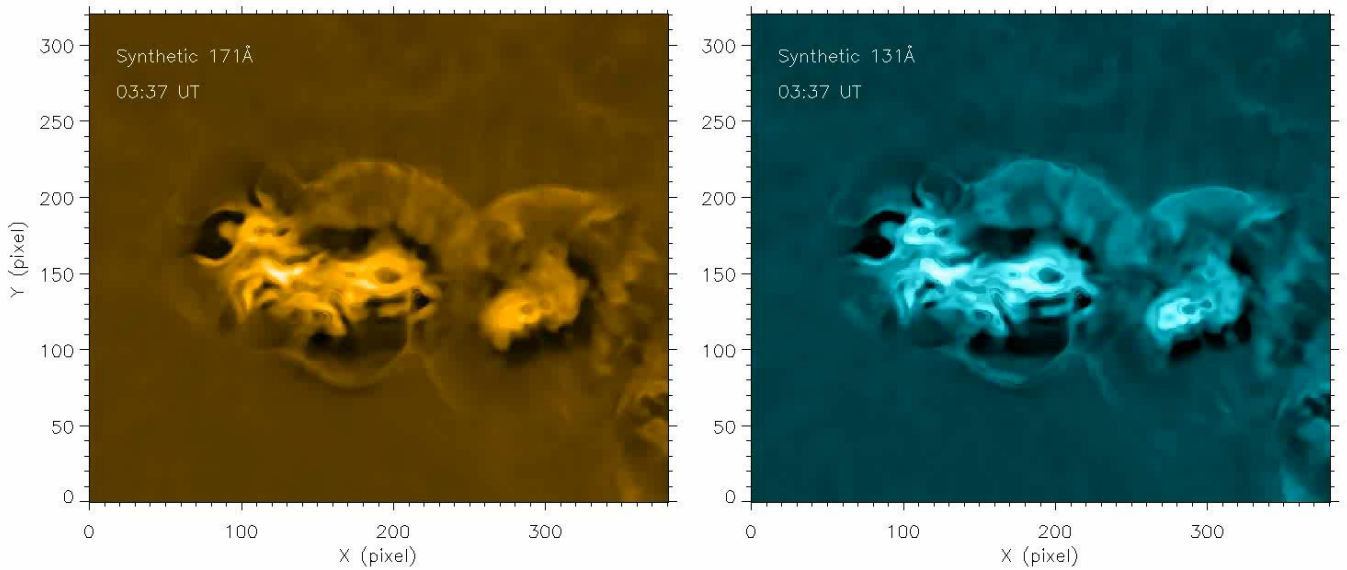
RMHD simulation (Preliminary result, detailed analysis in progress)

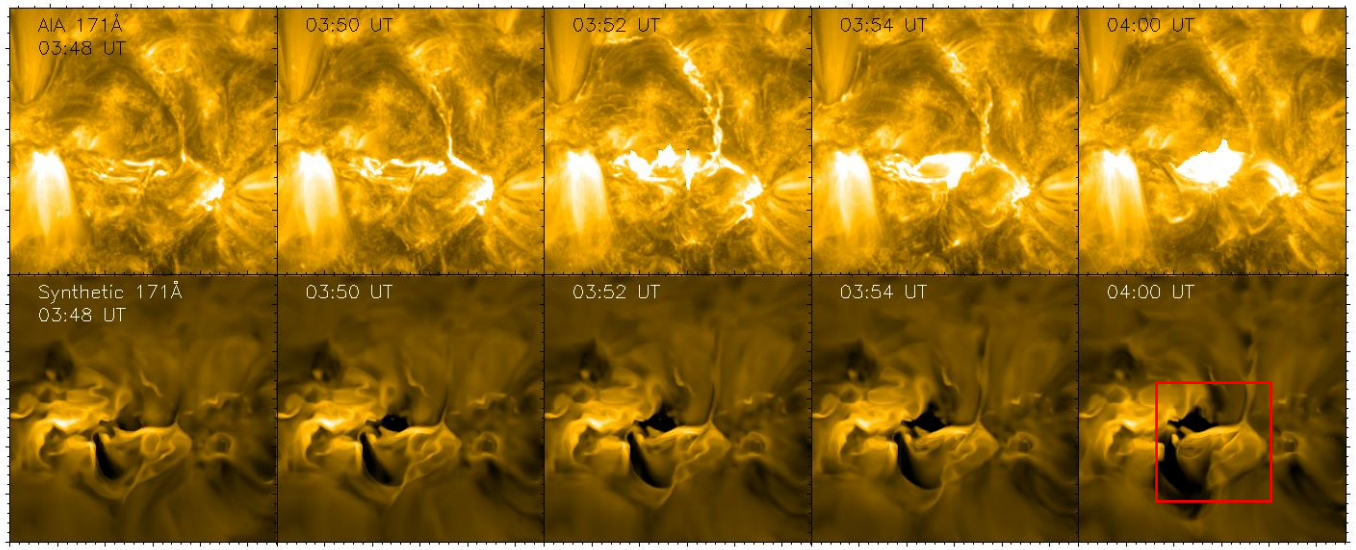


dt = 1 min



Synthetic EUV emission





4 Conclusion

- The flare QPP with a quasi-period of 23.4 seconds was observed in HXR and microwave emissions during the impulsive phase

- Reveal the characteristics of HXR QPPs from the perspective of HXR imaging for the first time:
  1. The distance between HXR sources varies quasi periodically
  2. The fluxes of two sources have the same pulsation period
  3. Non-thermal electron spectral index has quasi periodicity
  4. All of the above periods are close to 23.4 seconds

- This flare originated from the slipping reconnection process along QSLs.

- The magnetic field distribution along the flare ribbon has spatial periodicity, and combined with the motion speed, the equivalent time period is 24.2 seconds

- QPP mechanism: The periodically distributed non-uniform magnetic flux on QSLs causes quasi periodic energy release during the reconnection process, eventually accelerating electrons periodically

This work is in preparation

Thank you for attention !