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Quasi-Periodic Particle Acceleration in a Solar Flare

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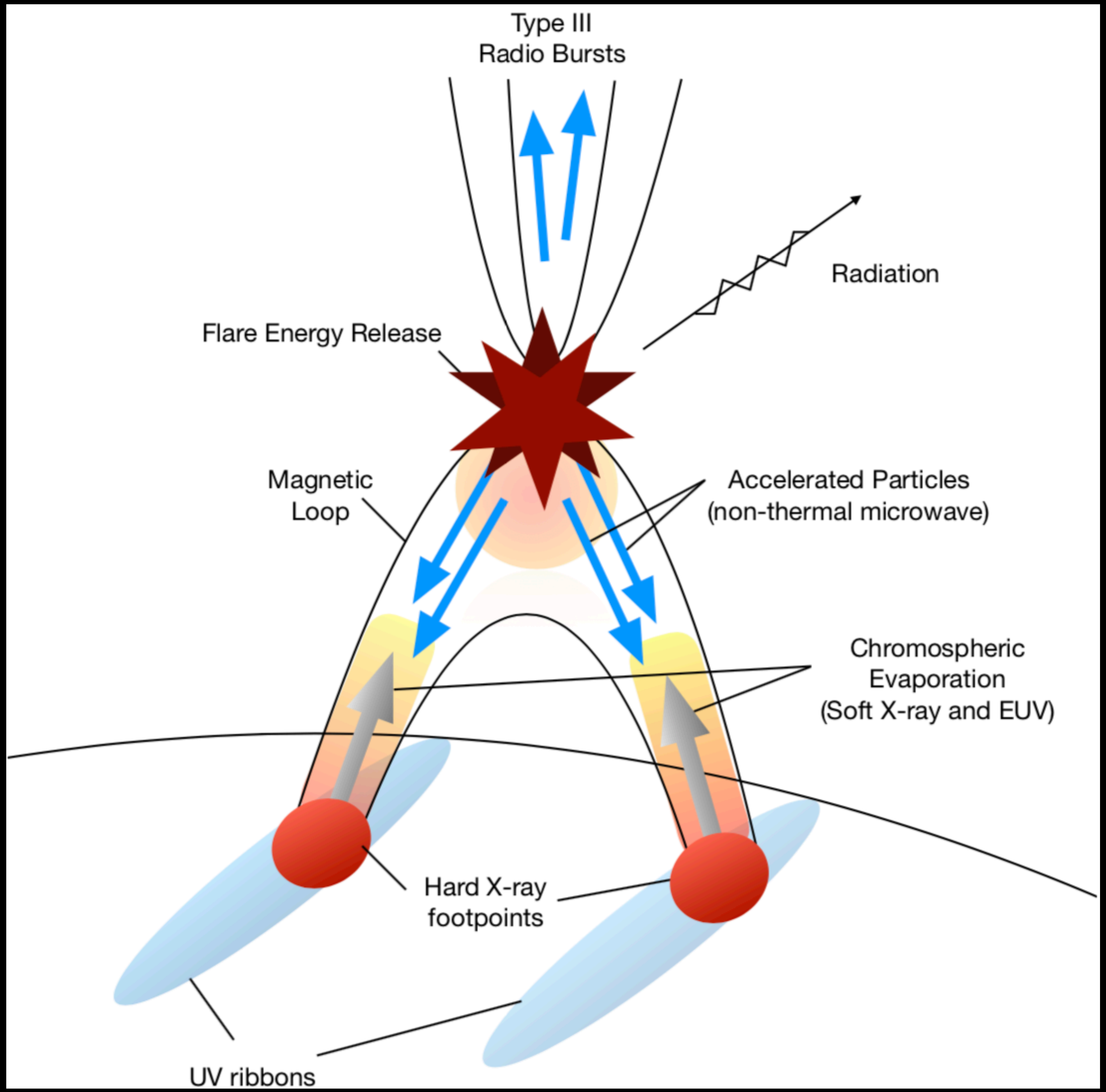
RHESSI Meeting 2021

SOLAR FLARE STANDARD MODEL

Multiple emission mechanisms produce radiation across EM spectrum

- Cyclotron emission
- Plasma emission
- Electron cyclotron maser (ECM) emission
- Bremsstrahlung
- Turbulence
- Shocks



Credit: Laura Hayes

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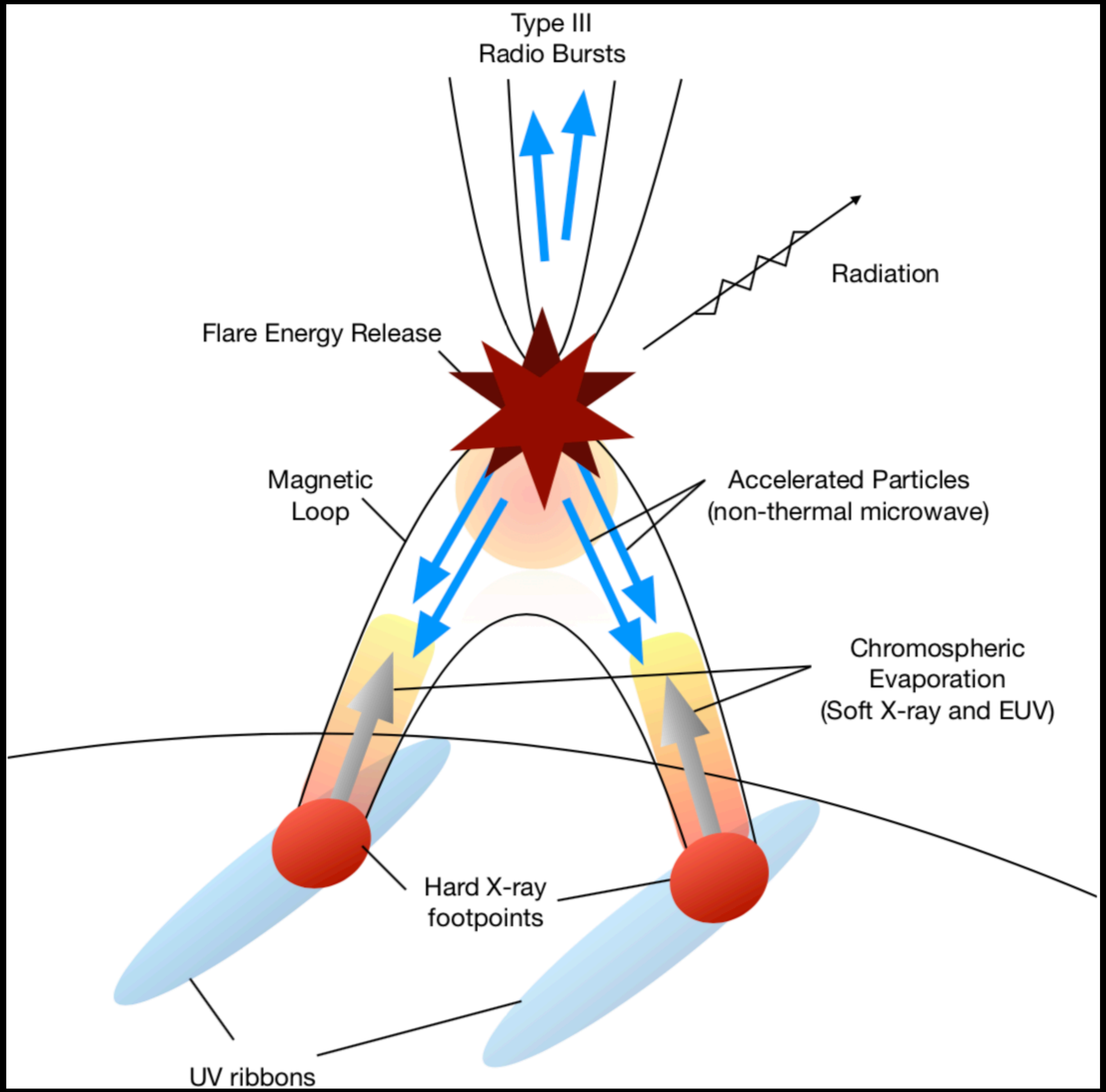
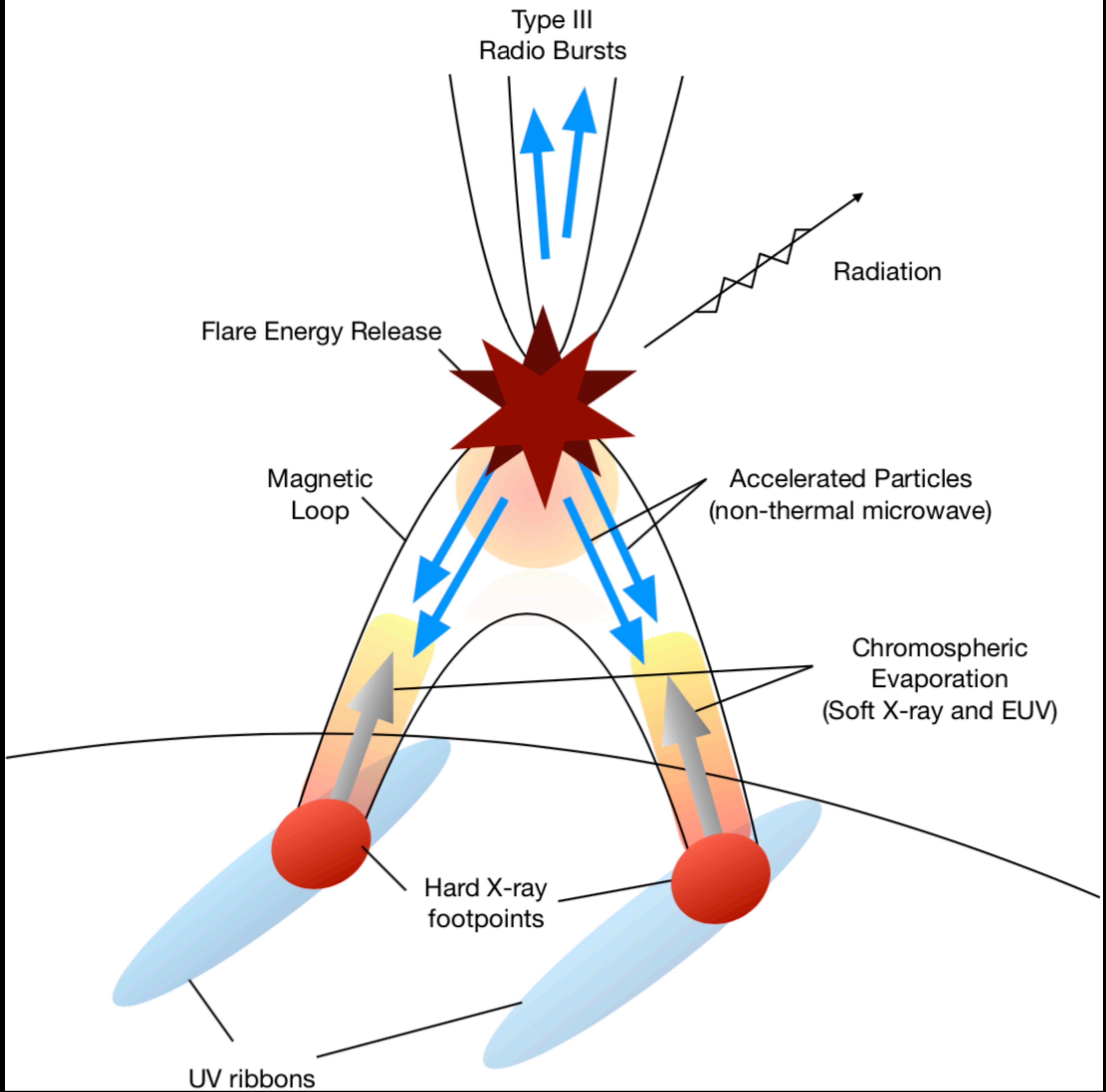
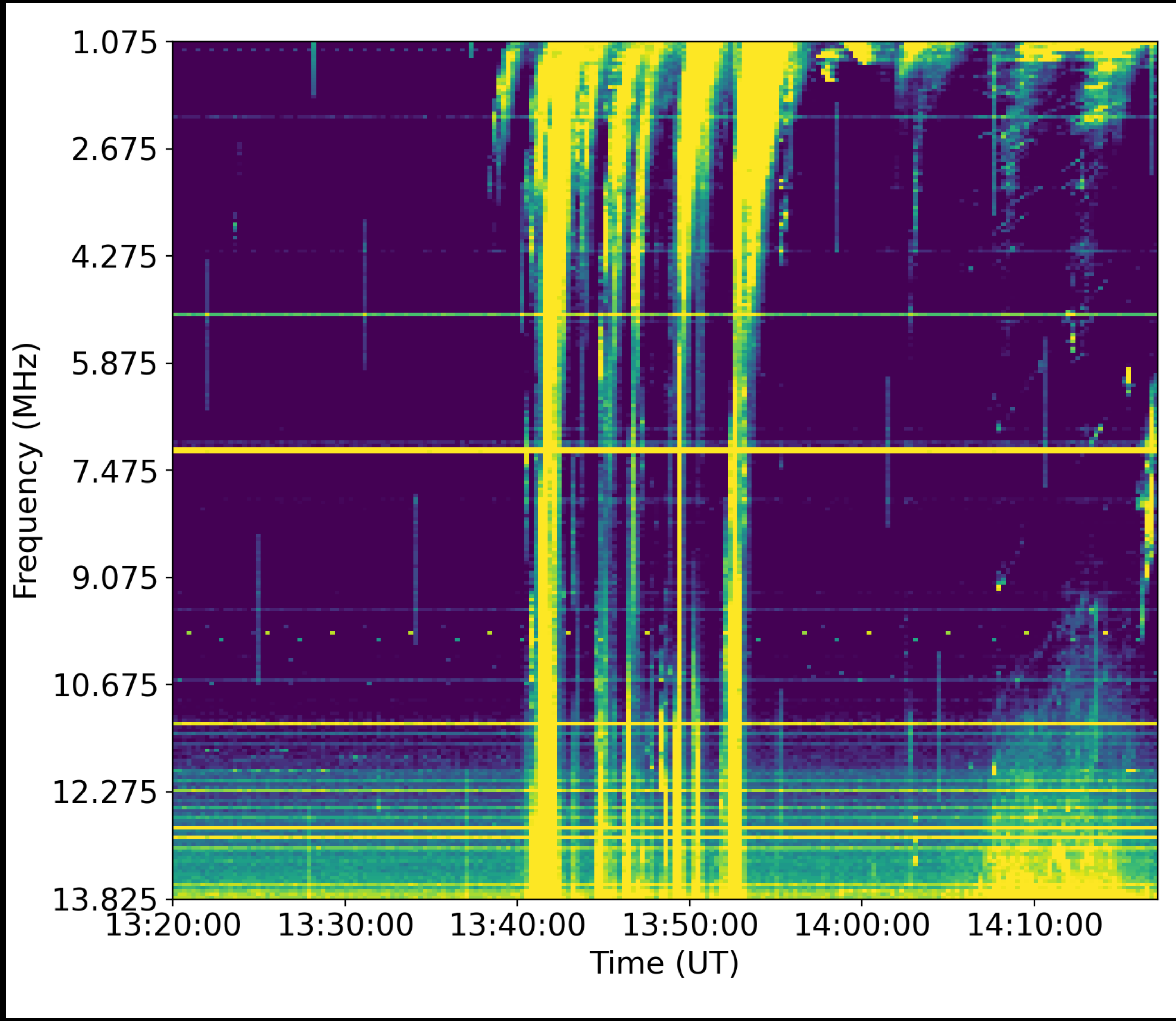


Credit: Laura Hayes

ELECTRON BEAMS & TYPE III RADIO BURSTS

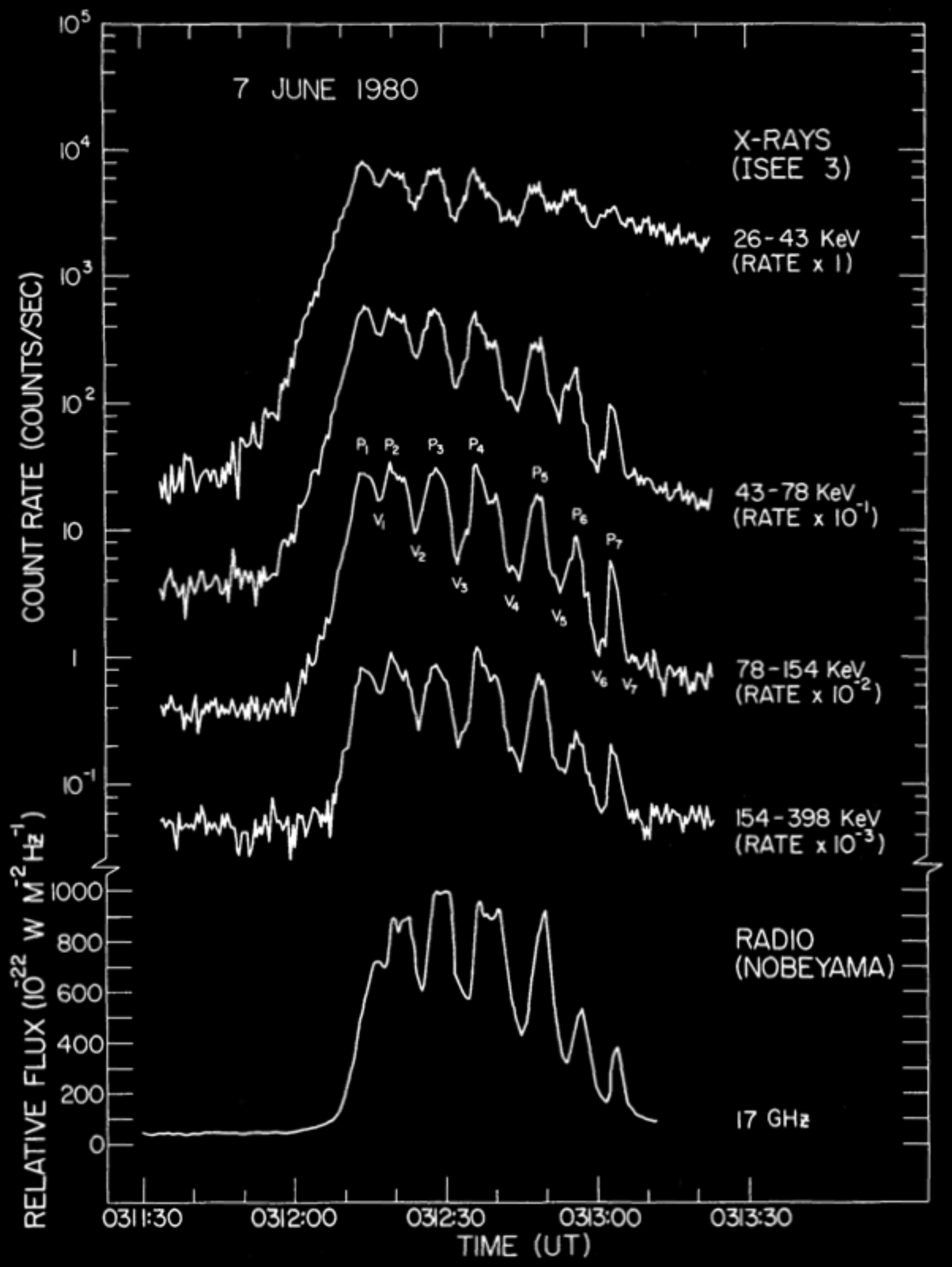




QUASI-PERIODIC PULSATIONS IN FLARES

The presence of intensity modulations in solar flare EM radiation

- Periods of < 1 s to minutes
- Common feature of EM emission in flares
- Underlying mechanism remains unknown
- QPPs are crucial aspect of fully understanding energy release in flares
    - Result of MHD waves/oscillations?
    - Result of intermittent/bursty energy release?

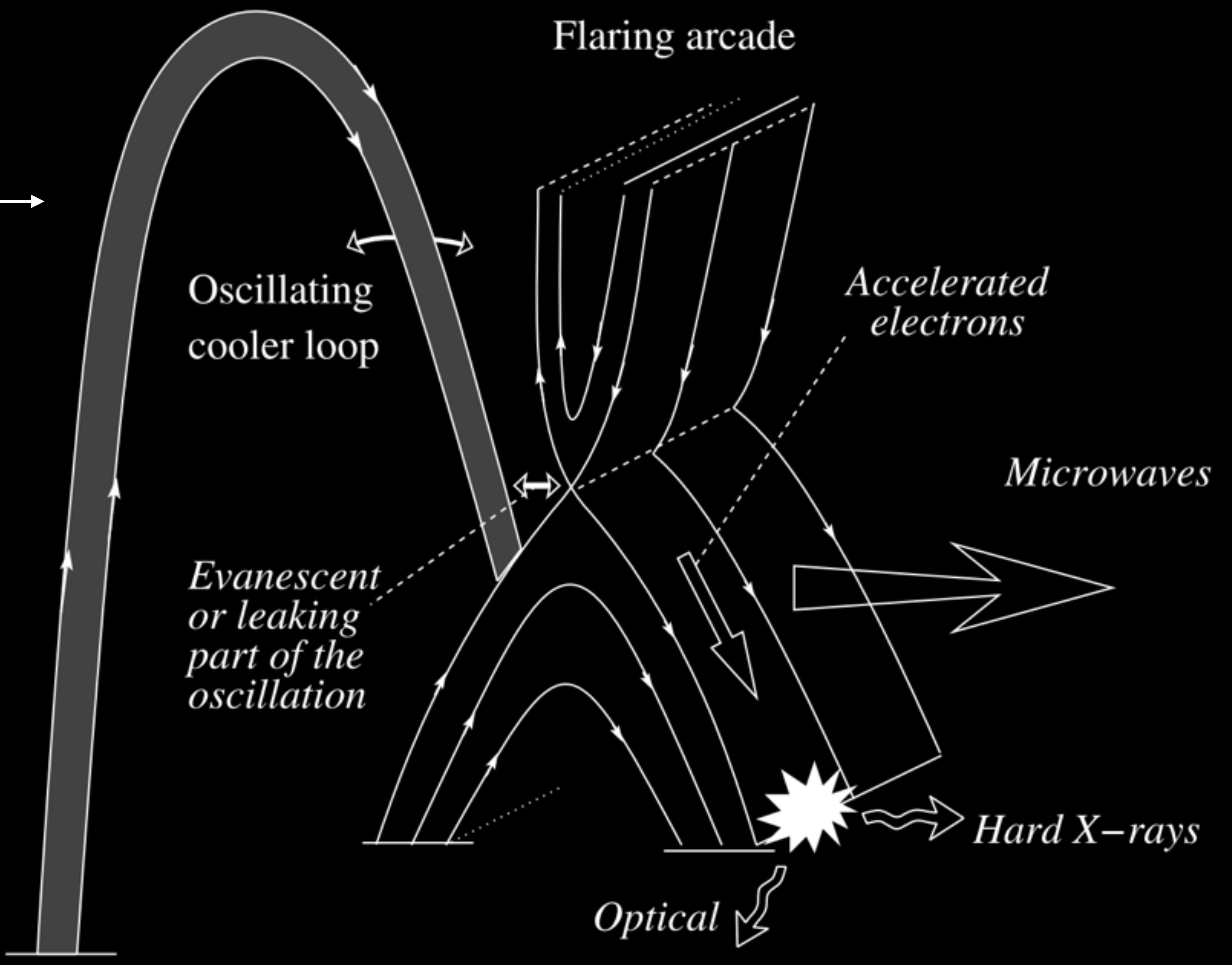


Kane et. al (1983)

WHAT THEORIES ARE THERE?

1. MHD oscillations triggering magnetic reconnection

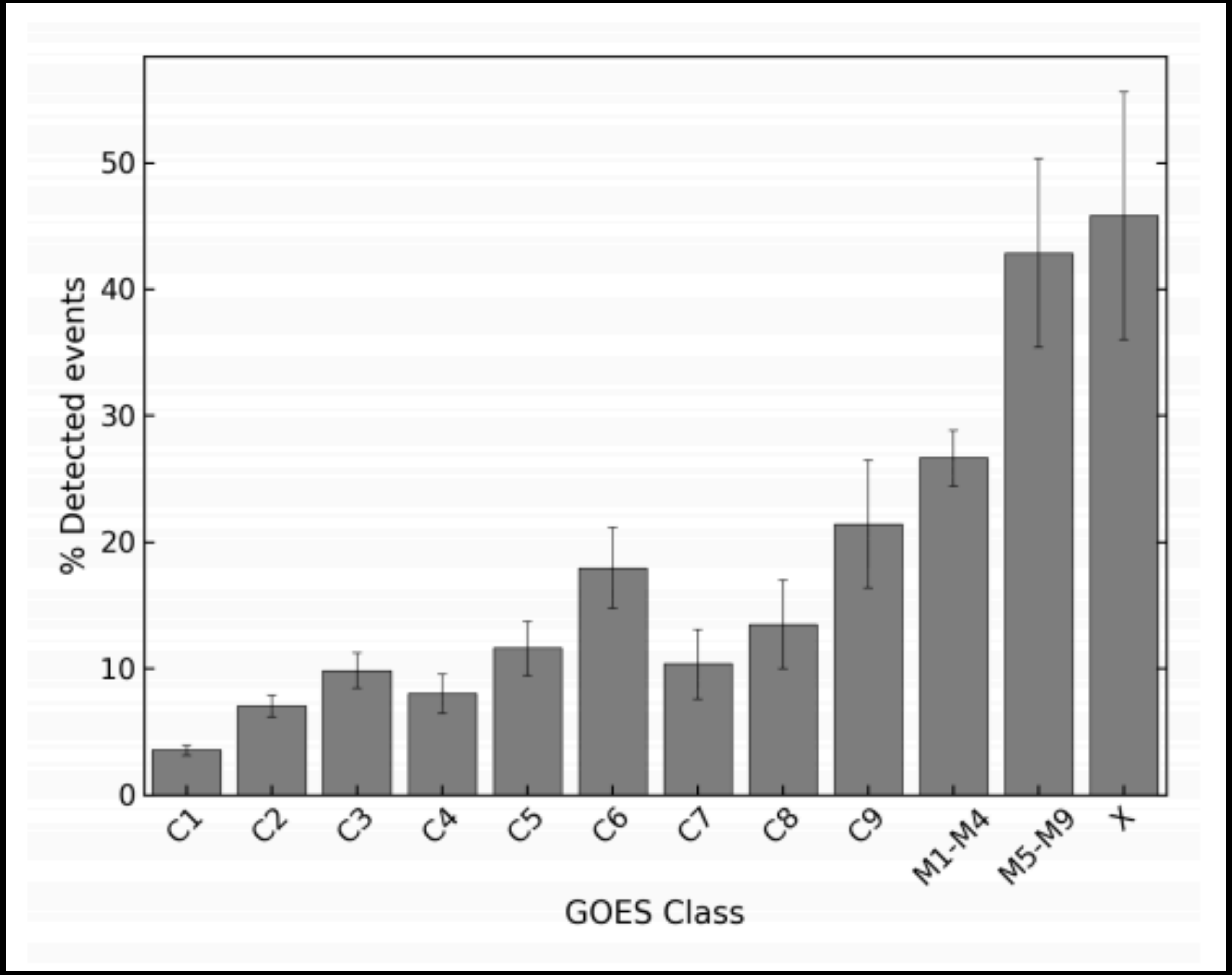
2. Bursty self oscillatory magnetic reconnection



Magnetic reconnection is inherently time-dependent: new insight into this phenomenon

HOW COMMON ARE QPPs?

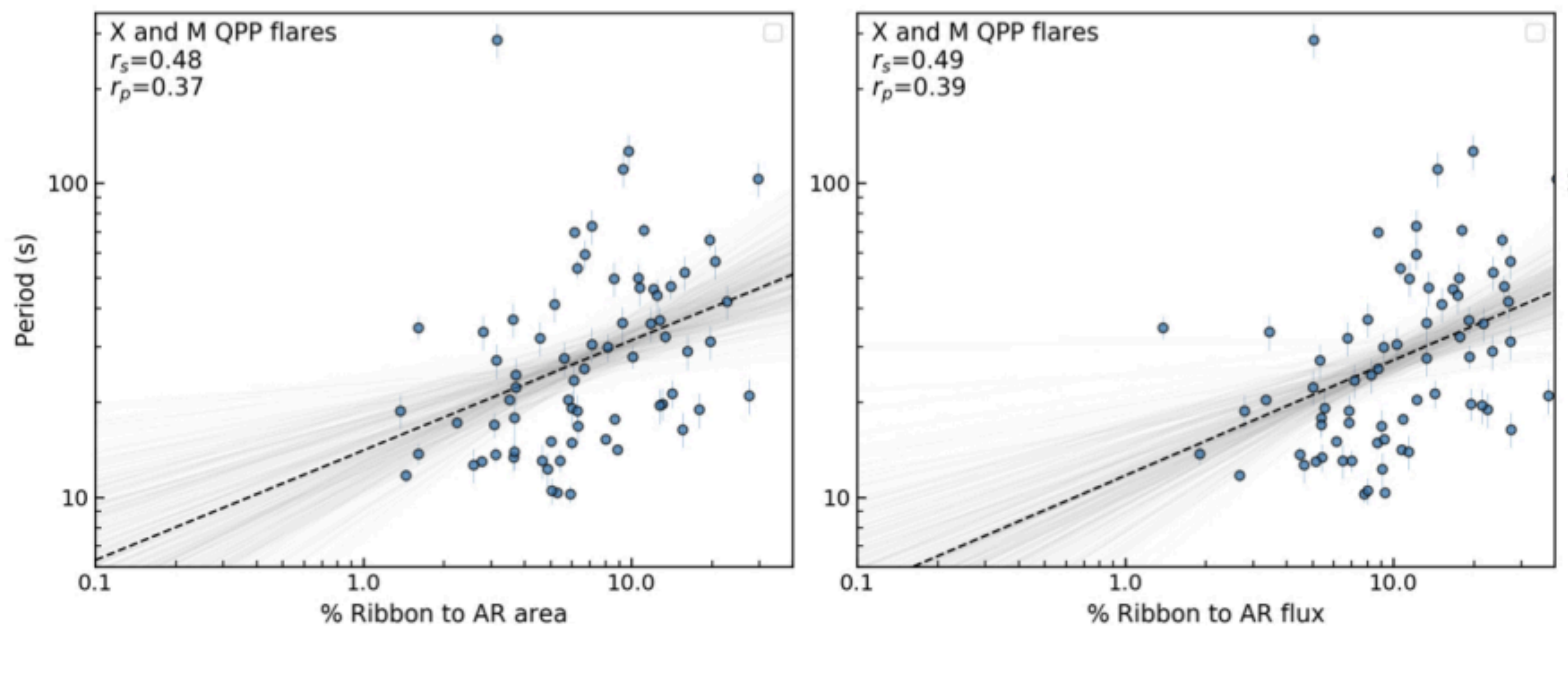
- Typically observed as non thermal HXR/radio pulses
- More recently we see a thermal component
    - ~46% of X-class flares in last solar cycle contained QPPs



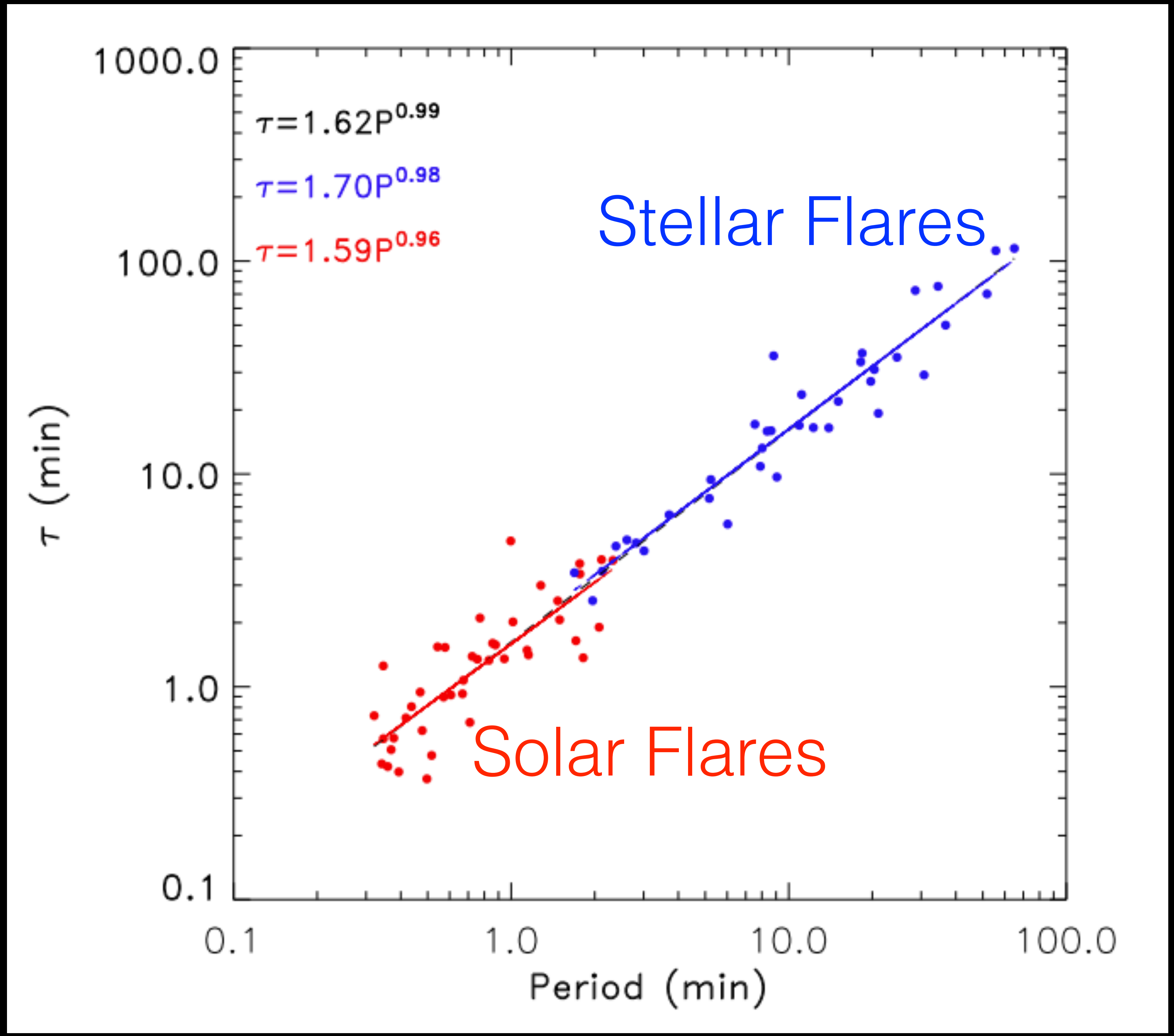
Hayes et al. (2020)

MOTIVATION

- Build complete model of flares
- Understand nature of energy release in solar/stellar flares
- Probe properties of distant stellar coronae and solar corona



Kazachenko et al. (2017)

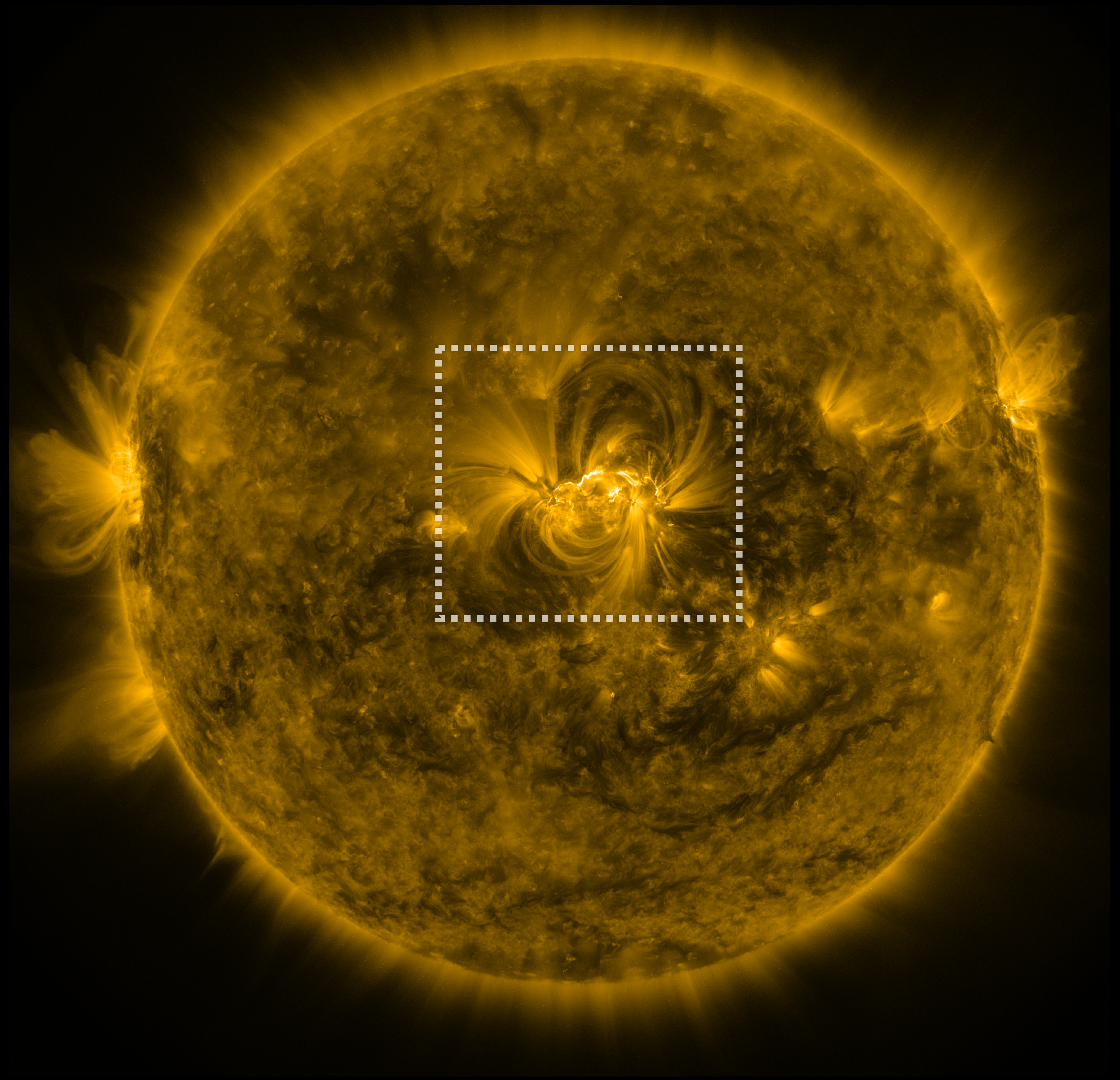


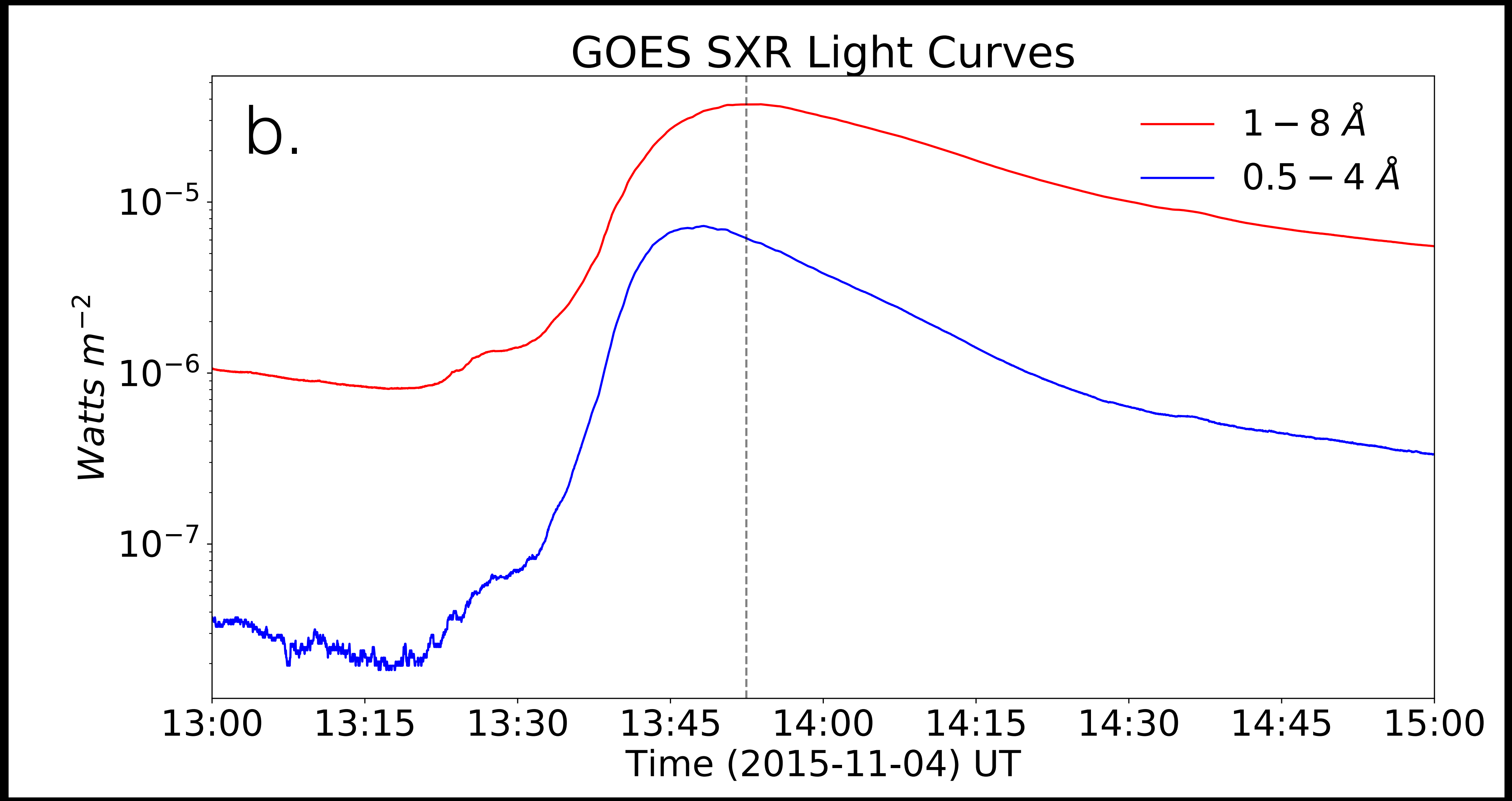
Cho et al. (2016)

Seismological Possibilities

EVENT UNDER INVESTIGATION

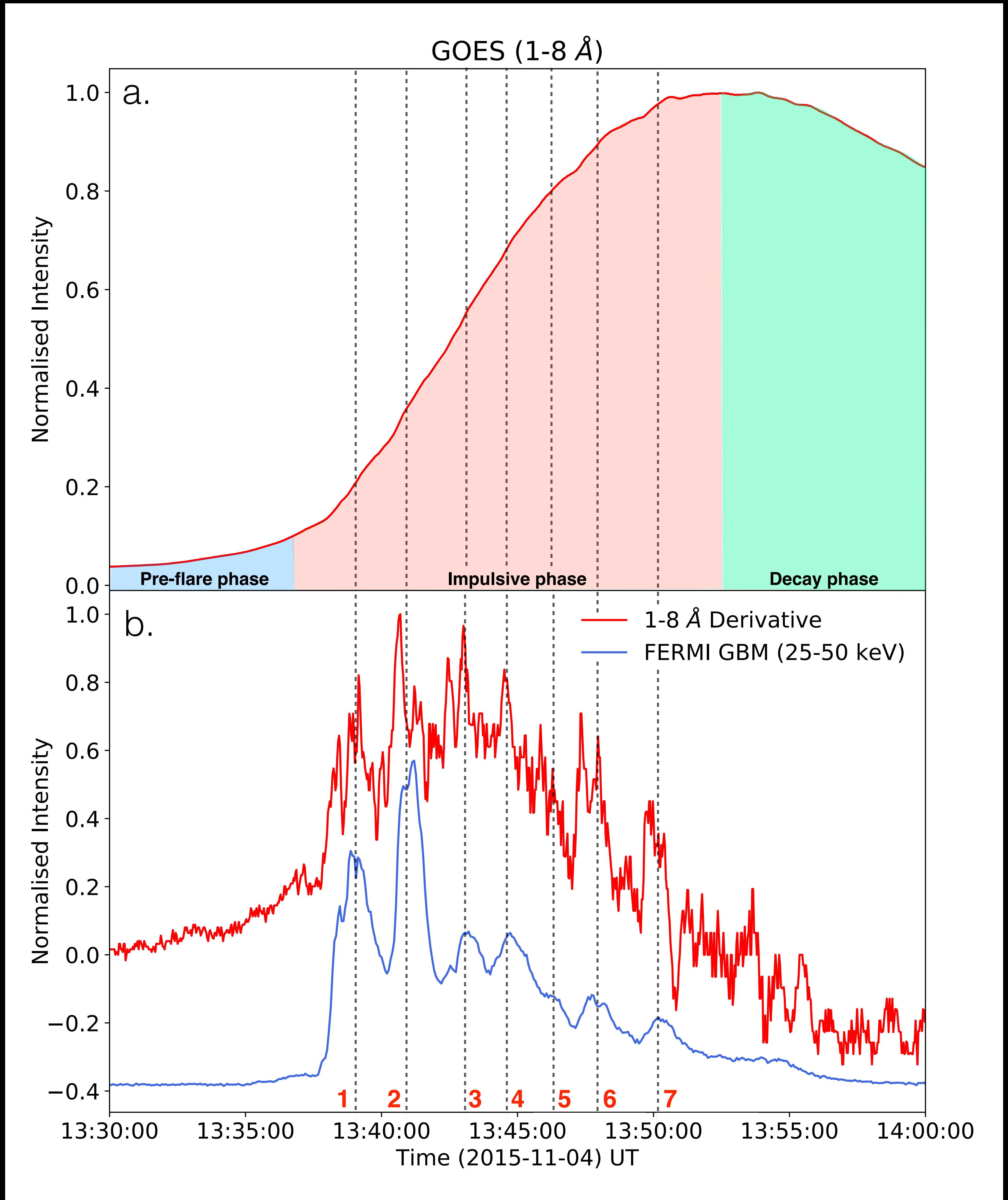
Case studies of specific flares are often studied to understand various phenomena



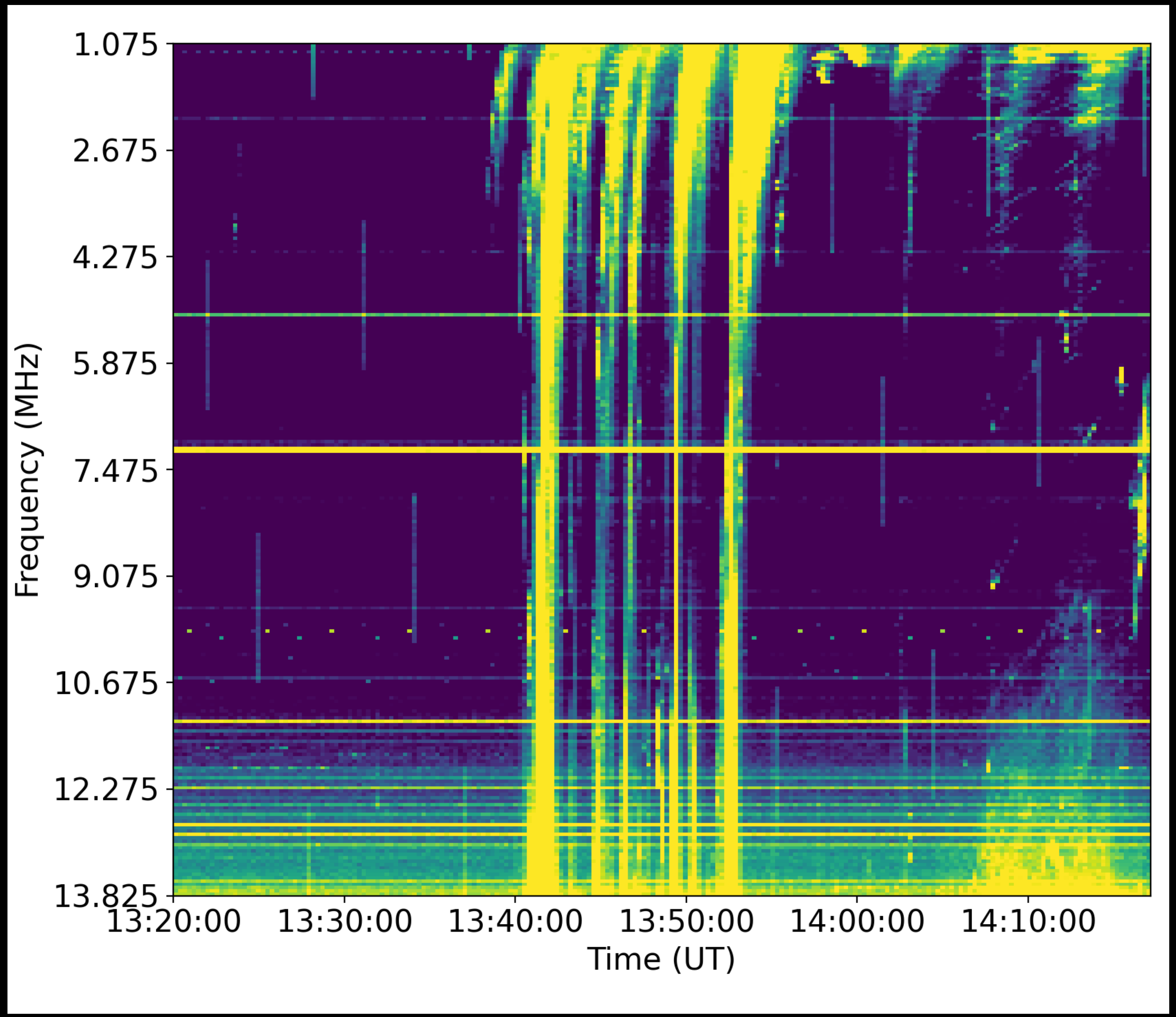


- M class flare on disk center with pronounced broadband QPPs
- Observed by GOES, RHESSI, GBM, AIA, ORFEES, NDA, WIND

EVENT UNDER INVESTIGATION



- 7 distinct pulsations occurring in the impulsive phase of the flare
- This is signature of intermittent electron acceleration during the flare
- Bremsstrahlung and heating/cooling occurring at the flare site (surface)

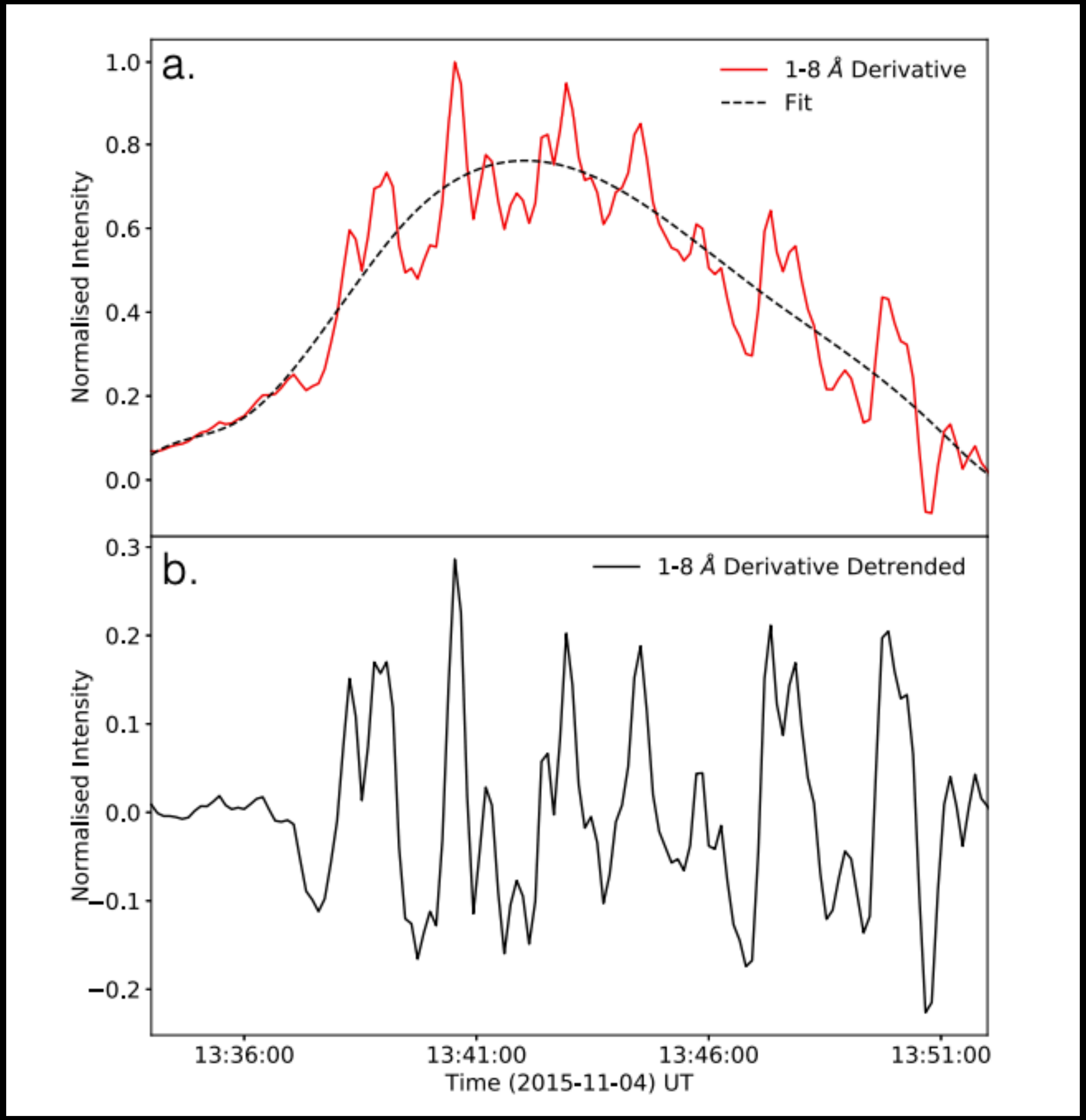


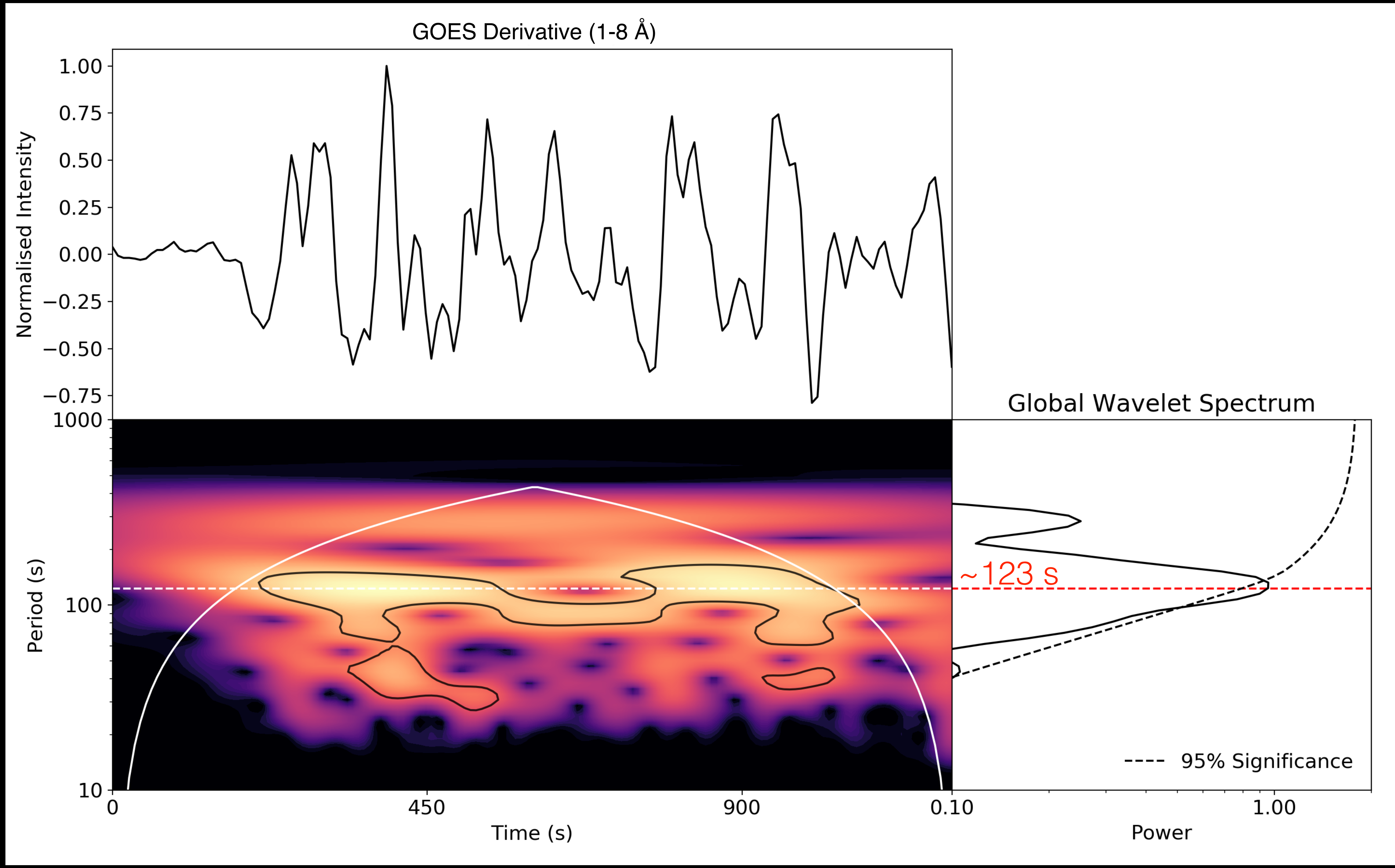
Sequence of type III radio bursts observed at same time

Are they related?

Can QPPs at solar surface result in related radio pulsations at > 16 solar radii

MEASURING THE PERIOD

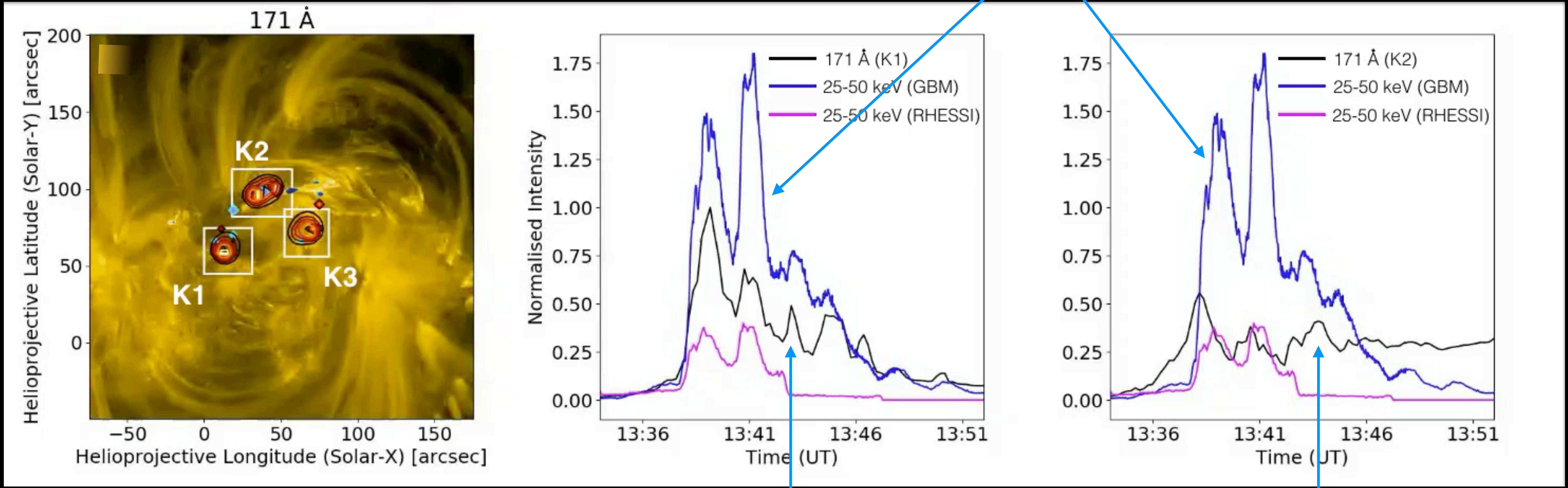




- Measure with and without detrending
- Measured manually and via wavelet analysis

CAN WE LOCATE THE QPP SOURCE?

HXR emission

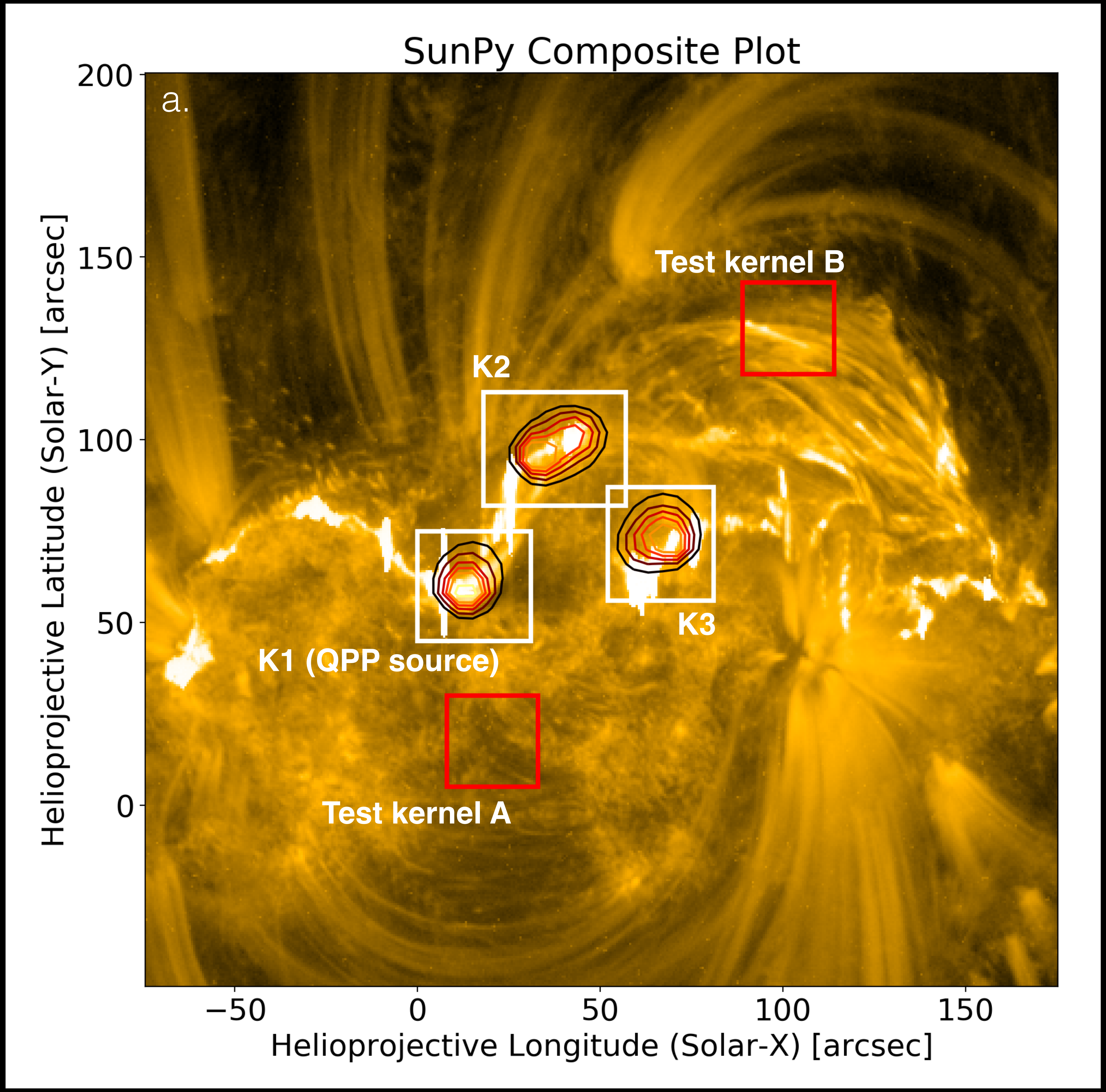


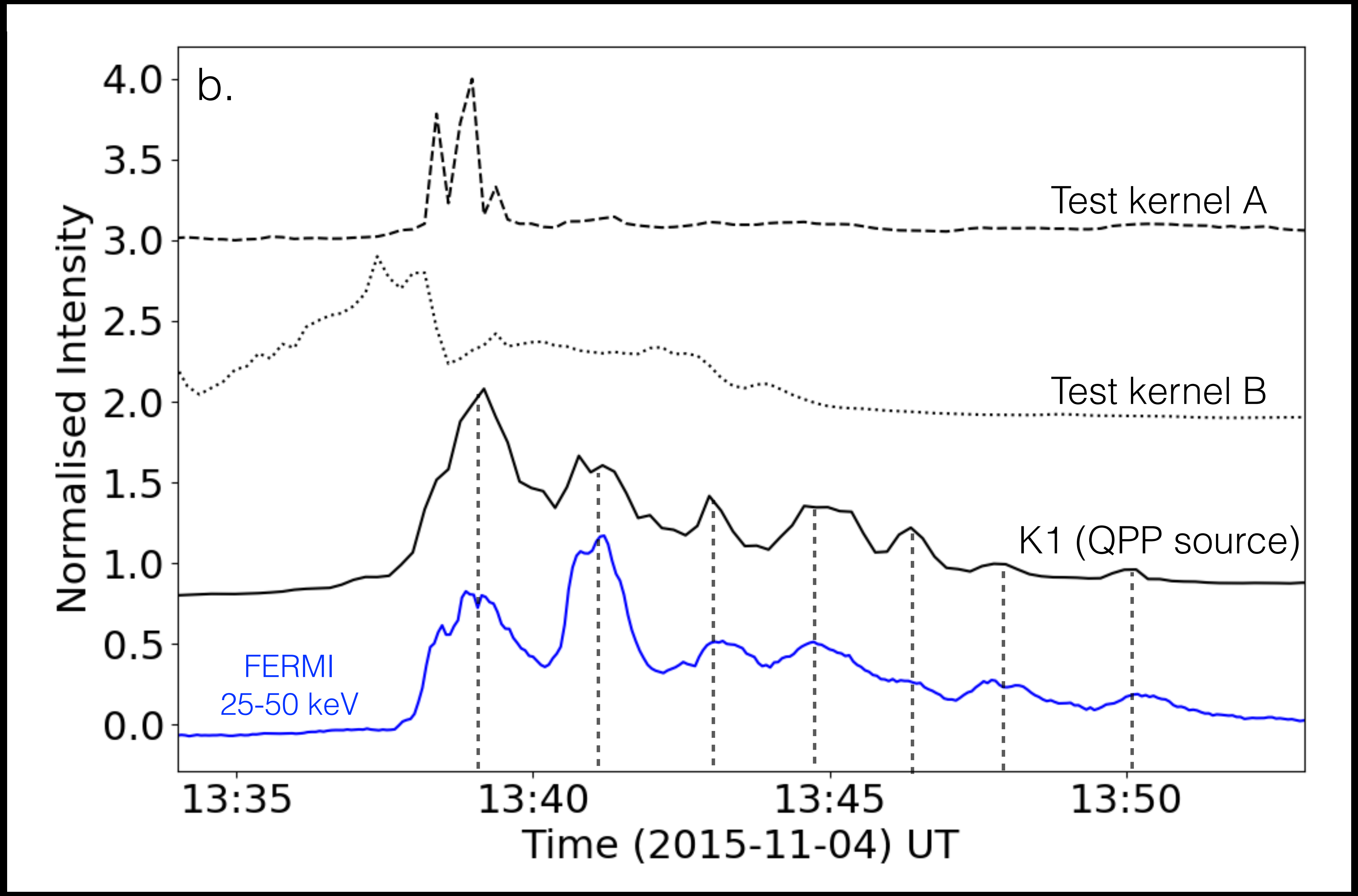
EUV Emission from flare site
HXRs sources overplotted

EUV Emission from K1

EUV Emission from K2

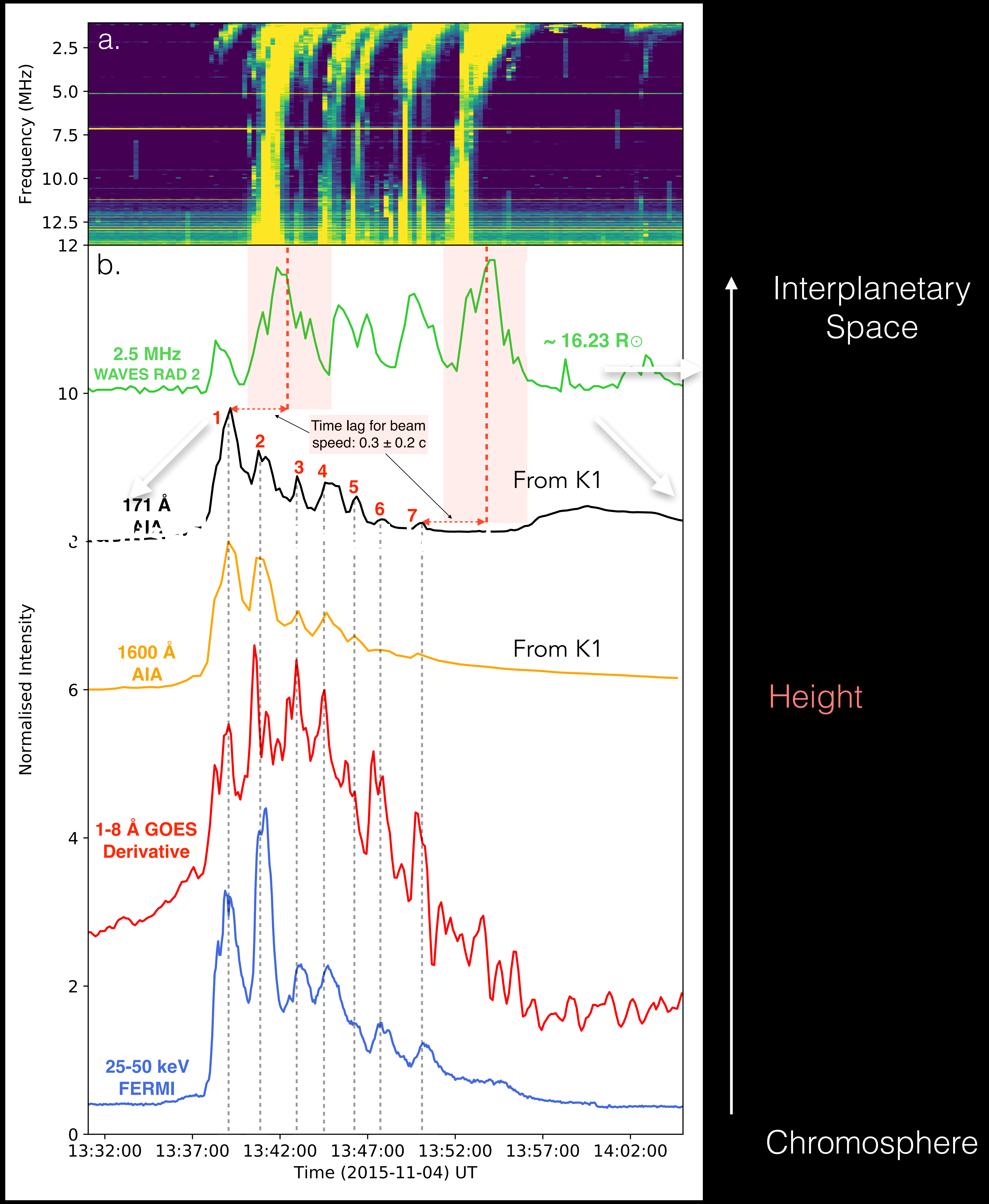
CAN WE LOCATE THE QPP SOURCE?





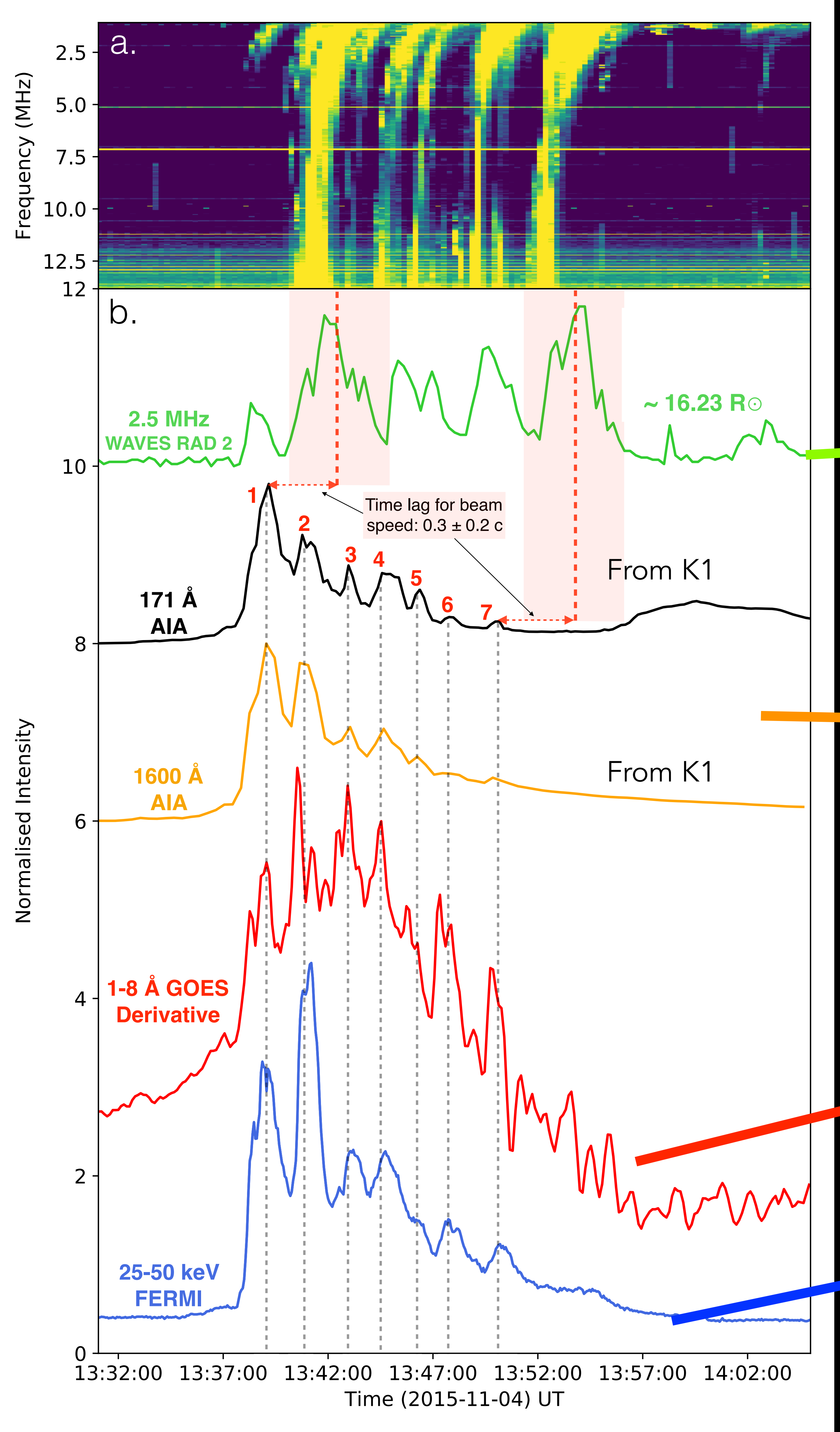
- X-ray imaging reveals three sources on the flare ribbons
- The EUV emission is origination from the source at K1
- We have localised the QPP source to a specific region of the flare

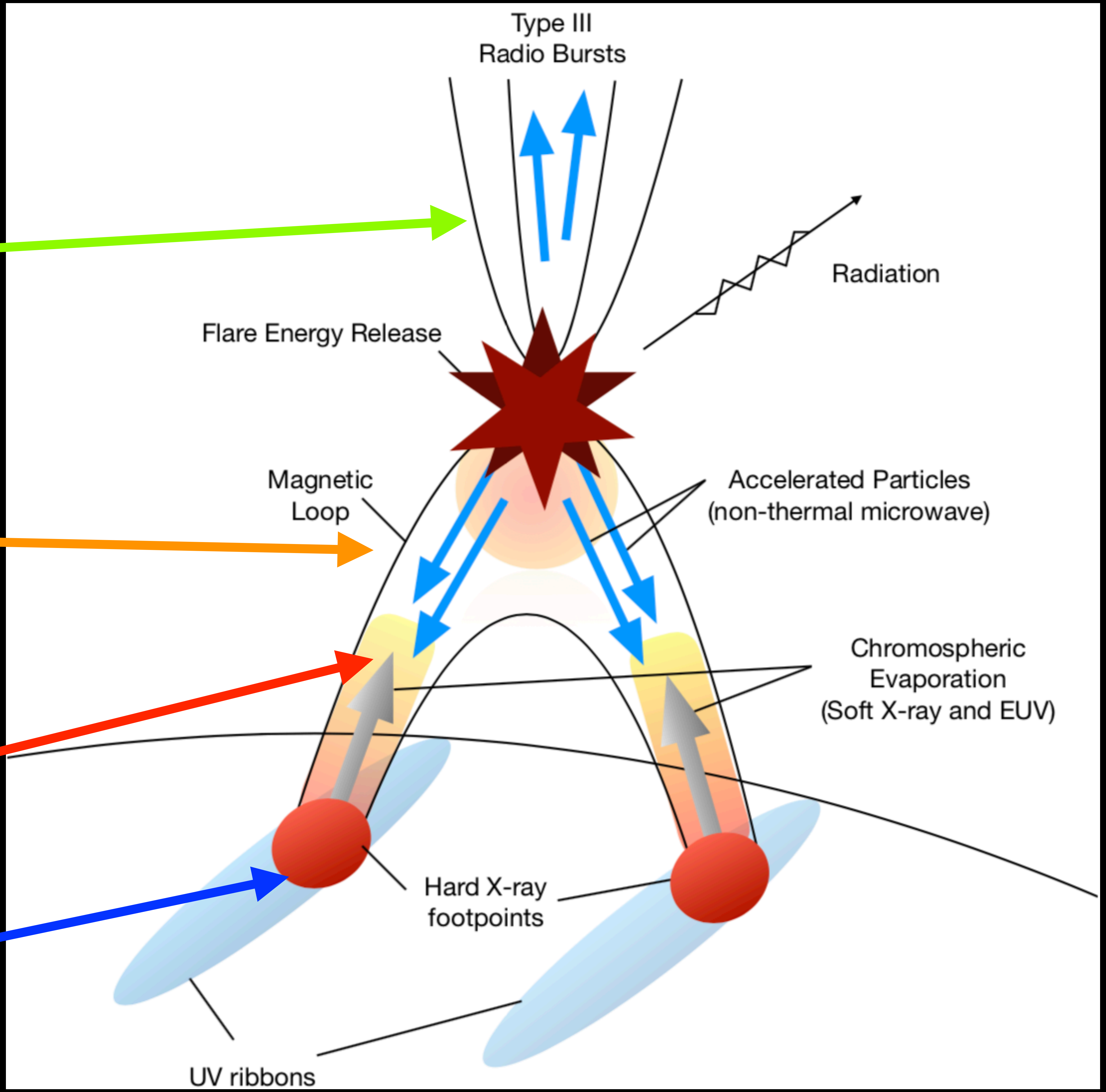
QPPs ACROSS THE EM SPECTRUM



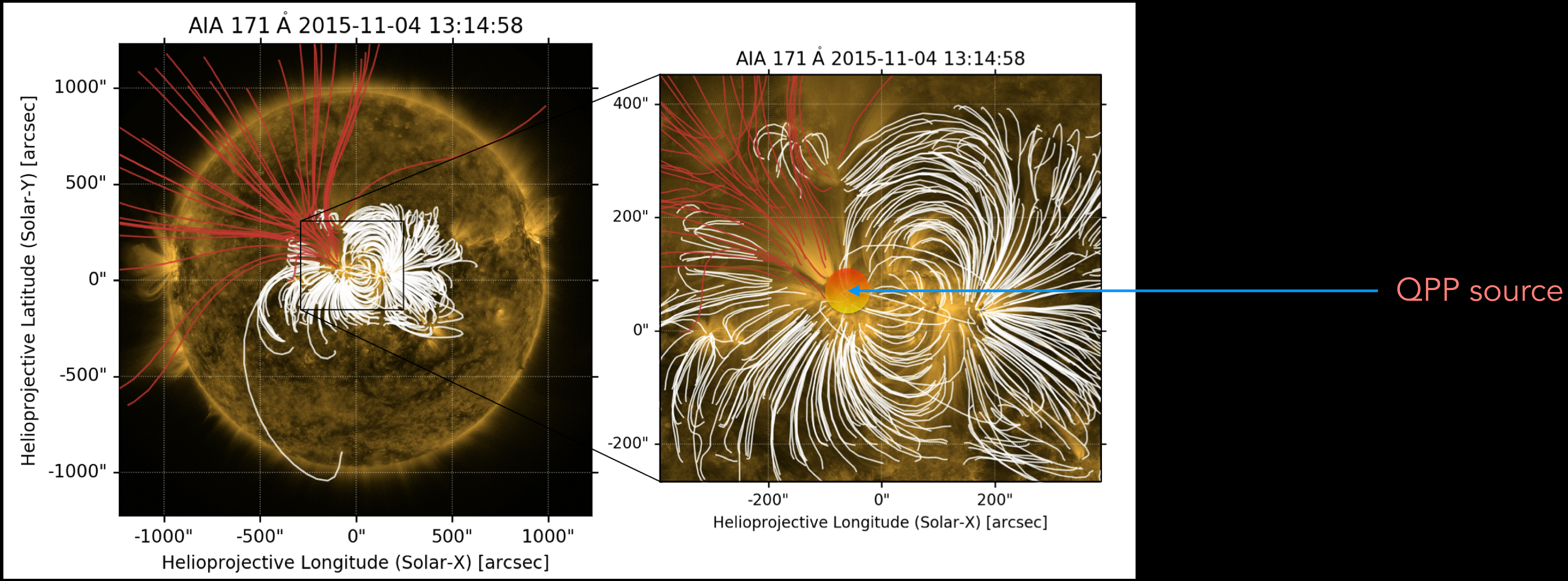
- Pronounced pulsations across EM spectrum
- Delay between X-ray and radio and consistent
- QPPs manifesting via common progenitor at the base of the solar surface through to interplanetary space

QPPs ACROSS THE EM SPECTRUM



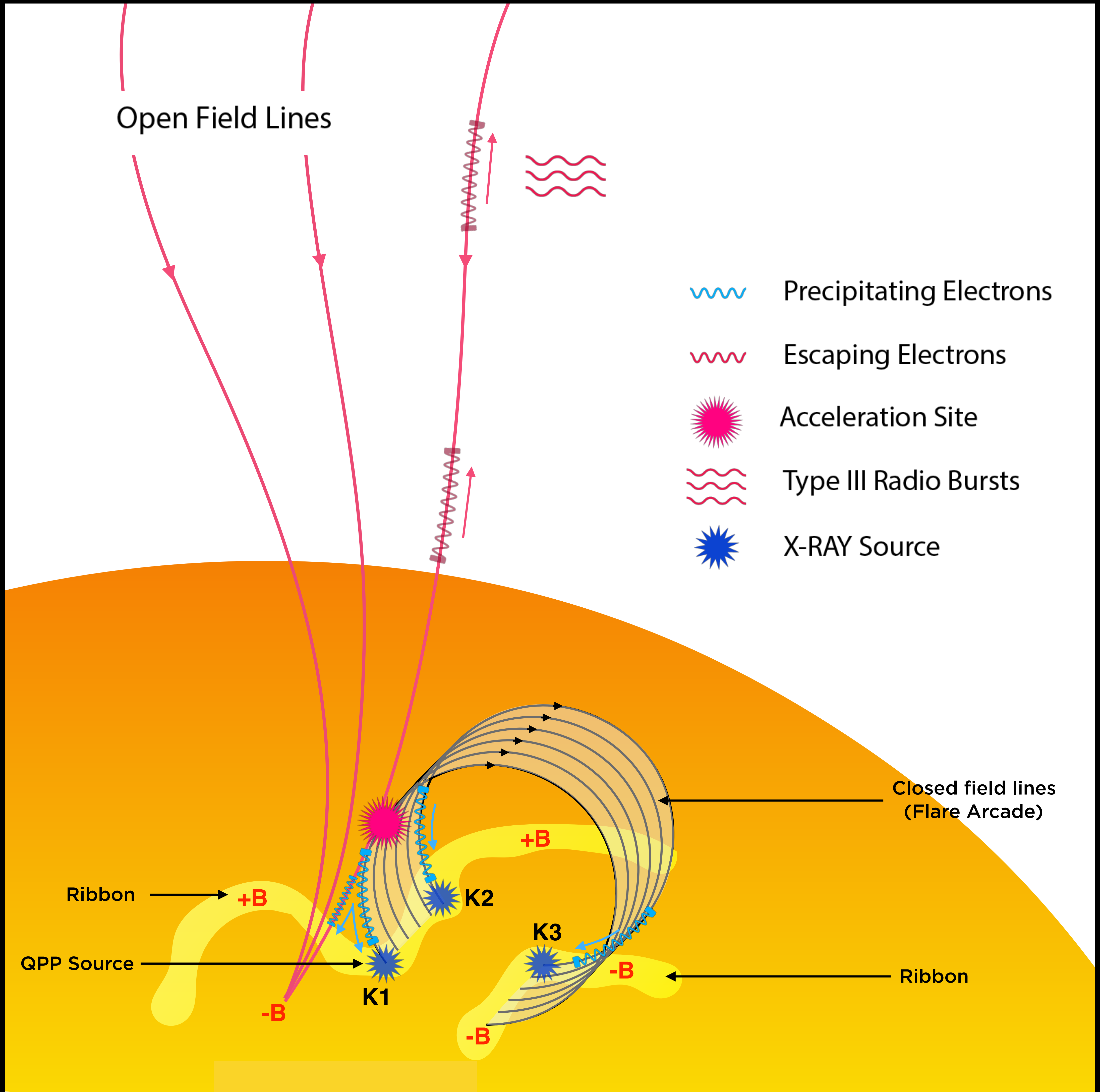


MAGNETIC FIELD GEOMETRY



- Magnetic field modelling shows QPP source is associated with region near open field lines
- Allows for the escape of the radio producing electron beams

INTERPRETATION



- Bursty magnetic (self-oscillatory) reconnection is intermittently accelerating electron beams
- Upward travelling beams produce radio bursts in interplanetary space
- Downward travelling beams produce x-ray and EUV emission

SUMMARY

1. Unusually broad band QPPs produced via **bursty magnetic reconnection**
2. **Localised** to specific regions of flare site
3. Manifest over **vast distances** via several emission mechanisms
4. New insight into energy release in flares

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Quasi-periodic Particle Acceleration in a Solar Flare

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Abstract

A common feature of electromagnetic emission from solar flares is the presence of intensity pulsations that vary as a function of time. Known as quasi-periodic pulsations (QPPs), these variations in flux appear to include periodic components and characteristic timescales. Here, we analyze a GOES M3.7 class flare exhibiting pronounced QPPs across a broad band of wavelengths using imaging and time series analysis. We identify QPPs in the time series of X-ray, low-frequency radio, and extreme ultraviolet (EUV) wavelengths using wavelet analysis, and localize the region of the flare site from which the QPPs originate via X-ray and EUV imaging. It was found that the pulsations within the 171 Å, 1600 Å, soft X-ray, and hard X-ray light curves yielded similar periods of 122^{+26}_{-22} s, 131^{+36}_{-27} s, 123^{+11}_{-26} s, and 137^{+49}_{-56} s, respectively, indicating a common progenitor. The low-frequency radio emission at 2.5 MHz contained a longer period of ~231 s. Imaging analysis indicates that the location of the X-ray and EUV pulsations originates from a hard X-ray footpoint linked to a system of nearby open magnetic field lines. Our results suggest that intermittent particle acceleration, likely due to "bursty" magnetic reconnection, is responsible for the QPPs. The precipitating electrons accelerated toward the chromosphere produce the X-ray and EUV pulsations, while the escaping electrons result in low-frequency radio pulses in the form of type III radio bursts. The modulation of the reconnection process, resulting in episodic particle acceleration, explains the presence of these QPPs across the entire spatial range of flaring emission.

Unified Astronomy Thesaurus concepts: Solar flares (1496); Solar activity (1475); Solar radio flares (1342); Solar x-ray flares (1816); Solar extreme ultraviolet emission (1493); Solar oscillations (1515)

Supporting material: animation

1. Introduction

Quasi-periodic pulsations (QPPs) are an important feature observed in solar and stellar flare emission (Nakariakov & Melnikov 2009; Van Doorsselaere et al. 2016; Kupriyanova et al. 2020). This puzzling phenomenon lacks a concrete definition; however, they are typically described by variations in the flux from a flare as a function of time that appear to include periodic components and timescales that typically range from 1 s up to 1 min, and in extreme cases from $\leqslant$1 s up to several minutes (Karlický et al. 2005; Tan et al. 2010; Li et al. 2015; Hayes et al. 2019). QPPs are typically observed during the impulsive phase of solar flares; however, in recent years it has become clear that they can persist through to the decay phase, after the impulsive energy release (Hayes et al. 2016, 2019; Dennis et al. 2017).

QPPs have been reported in a broad range of wavelengths from decametric radio (Li et al. 2015; Carley et al. 2019), through to extreme ultraviolet (EUV) and X-rays, (Dolla et al. 2012; Dominique et al. 2018), and even γ-rays (Nakariakov et al. 2009; Li et al. 2020). Statistical studies suggest that QPPs are a common feature, especially in larger flaring events (Simões et al. 2015; Inglis et al. 2016; Hayes et al. 2020). Within the decametric wave band, QPPs can manifest as a sequence of type III radio bursts emanating from the corona as a consequence of accelerated beams of electrons escaping along open magnetic field lines away from the flare site (Aschwanden et al. 1994; Ning et al. 2005; Kupriyanova et al. 2016). In contrast, QPPs in the EUV are typically observed to originate from the hot plasma in the coronal loops of a flaring region (Van Doorsselaere et al. 2016). In addition to studies of QPPs analyzed within specific spectral domains, some research has been done focusing on events containing QPPs across a wide band of wavelengths. For example, Aschwanden et al. (1993) investigated the timing of hard X-ray (HXR) pulsations with respect to pulsations seen in radio wavelengths (100–300 MHz) and found evidence for a strong causal connection. Additionally, Tajima et al. (1987) found that current loop coalescence can lead to quasi-periodic amplitude oscillations in the microwave, X-ray, and γ-ray wave bands. More recently, Kumar et al. (2016) presented a multi-wavelength analysis of QPPs found to be occurring in HXR, radio (25180, 245, 610 MHz), and EUV wavelengths.

Several models have been proposed as explanations for the presence of QPPs in solar and stellar flares (McLaughlin et al. 2018), which are typically categorized as oscillatory or self-oscillatory processes. In the regime of oscillatory processes, QPPs are interpreted as a signature of magnetohydrodynamic (MHD) oscillations inducing periodic motions about an equilibrium in the flaring region. This explanation has been promising for some events, as some observed periodicities of QPPs are in good agreement with those of the timescales of MHD waves in the corona (Nakariakov & Melnikov 2009). There is widespread observational evidence for MHD waves existing in the corona and it is possible that kink, toroidal, longitudinal, or sausage modes could cause some of the thermal and non-thermal intensity variations that we observe.

For example, kink mode oscillations have been reported that have an overlapping timescale (~1.5–10 min) with observed QPP periodicities (Anfinogentov et al. 2015). Such waves could periodically modulate emission or influence particle dynamics (Nakariakov & Melnikov 2009). It is also possible