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Inferring Fundamental Properties of the Flare Current Sheet Using Flare Ribbons:

Oscillations in the reconnection flux rates

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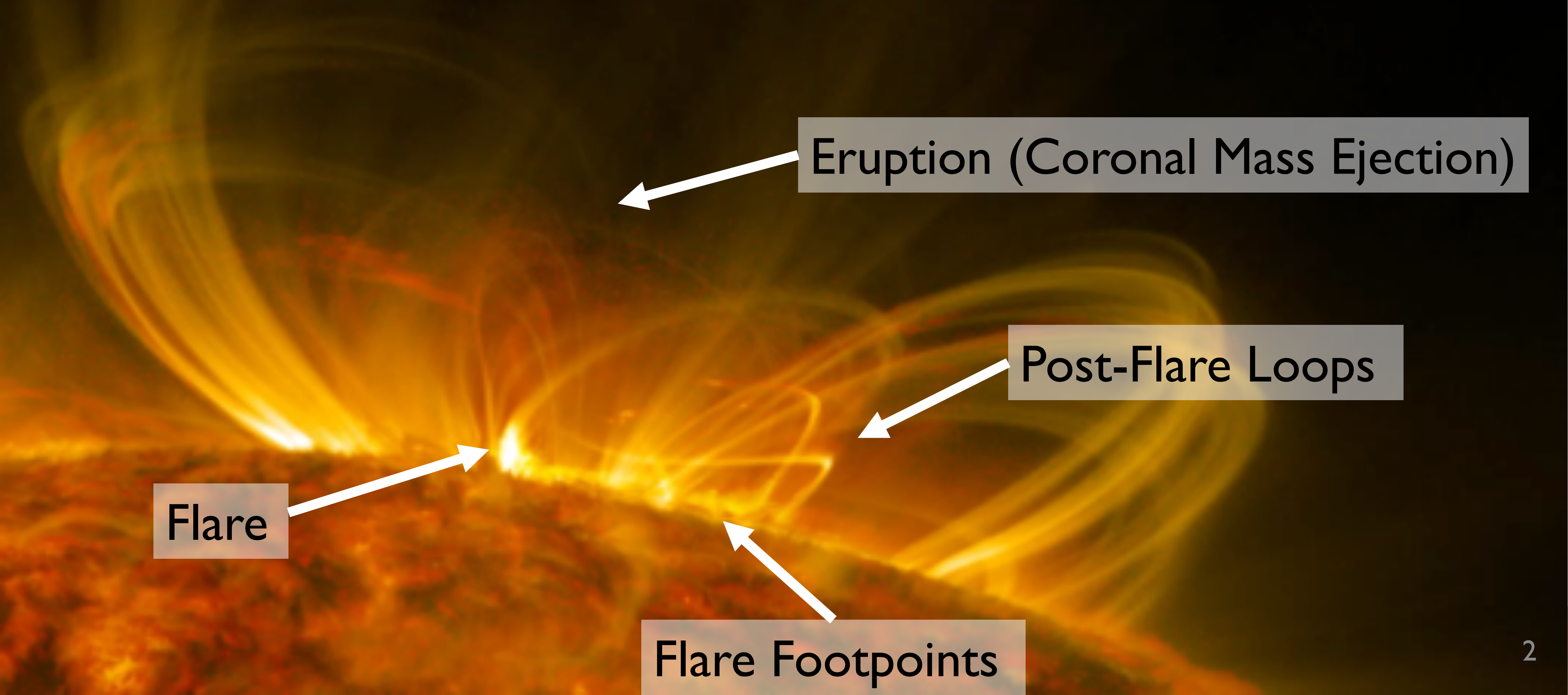
How can we unravel this?



Main Science Question

Is there observational evidence that magnetic reconnection occurs as a bursty oscillatory process? Are these bursts associated with dynamical processes in the current sheet?

Presentation Outline

I. Introduction:

Flare Ribbons

Standard Flare Model

Magnetic Reconnection

II. Data and Methods

Magnetic Reconnection Flux Proxies with SDO.

Flare Ribbon Fine-Structure with IRIS SJI.

Particle Acceleration Proxies with GOES and Fermi.

Detecting Quasi Periodic Pulsations with AFINO.

III. Results and Discussion:

Comparison of Flare Ribbon Evolution and Reconnection Rates.

Comparison of Reconnection Rates and X-ray Emission.

Summary of analysis of 73 flares.

IV. Conclusions

Introduction

Flare Ribbons

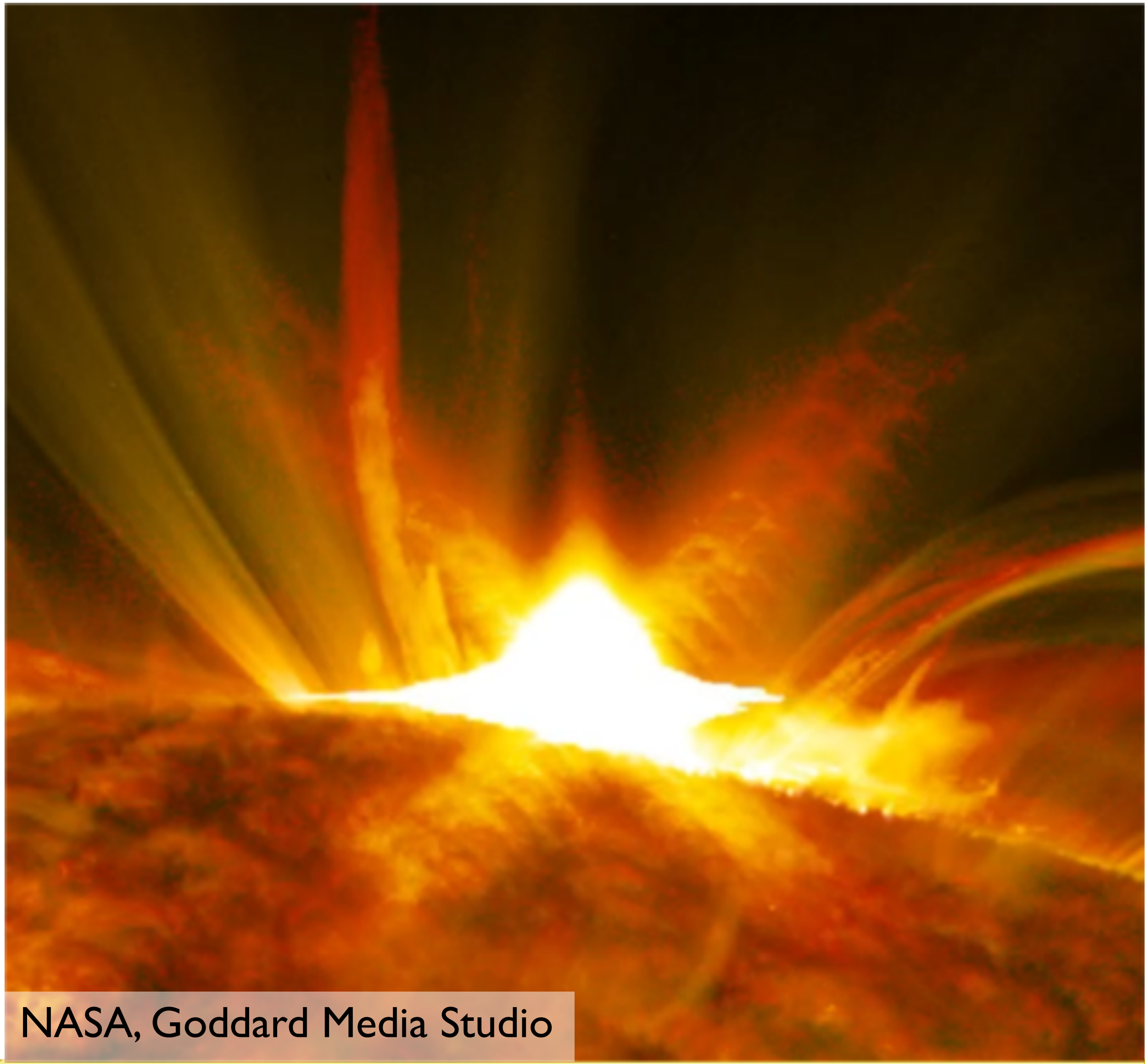
Standard Flare Model

Magnetic Reconnection

X8.2 Eruptive flare observed by SDO AIA 171- and 304- Å on 09/10/2017

Solar Flares are:

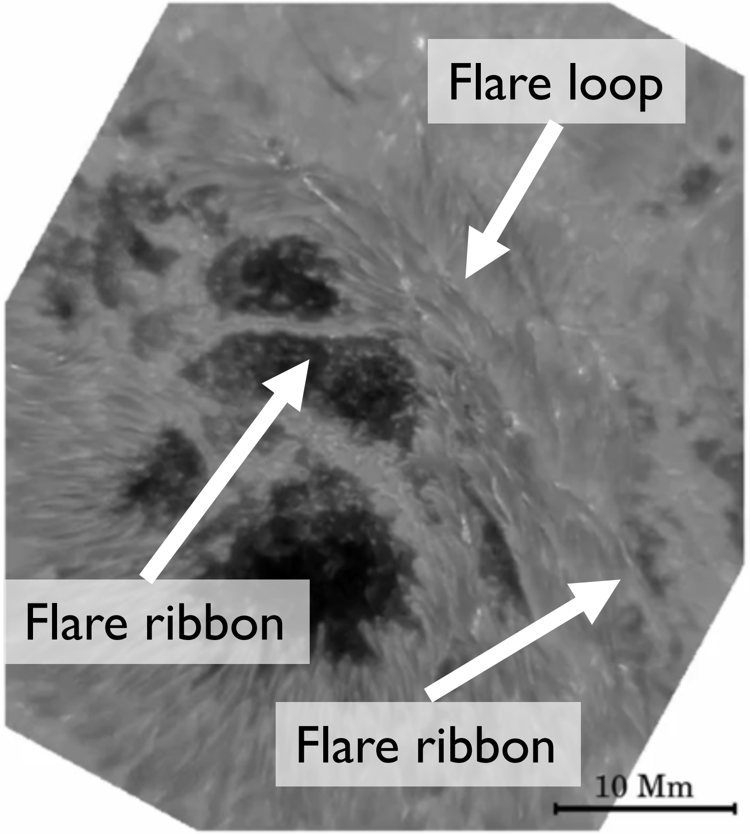
- Observed as sudden intense and localized emission of light (Radio waves to ɣ-rays).
  - Emission in such a broad-band requires many physical process.
- The process follows magnetic energy being transferred into particle acceleration, heat, and bulk motions coronal plasma.


NASA, Goddard Media Studio

Flare Ribbons are:

- Local enhancement of chromospheric emission due to non-thermal particle precipitation from the corona, following magnetic reconnection.
- Flare Ribbons are the footpoints of the flare loops.

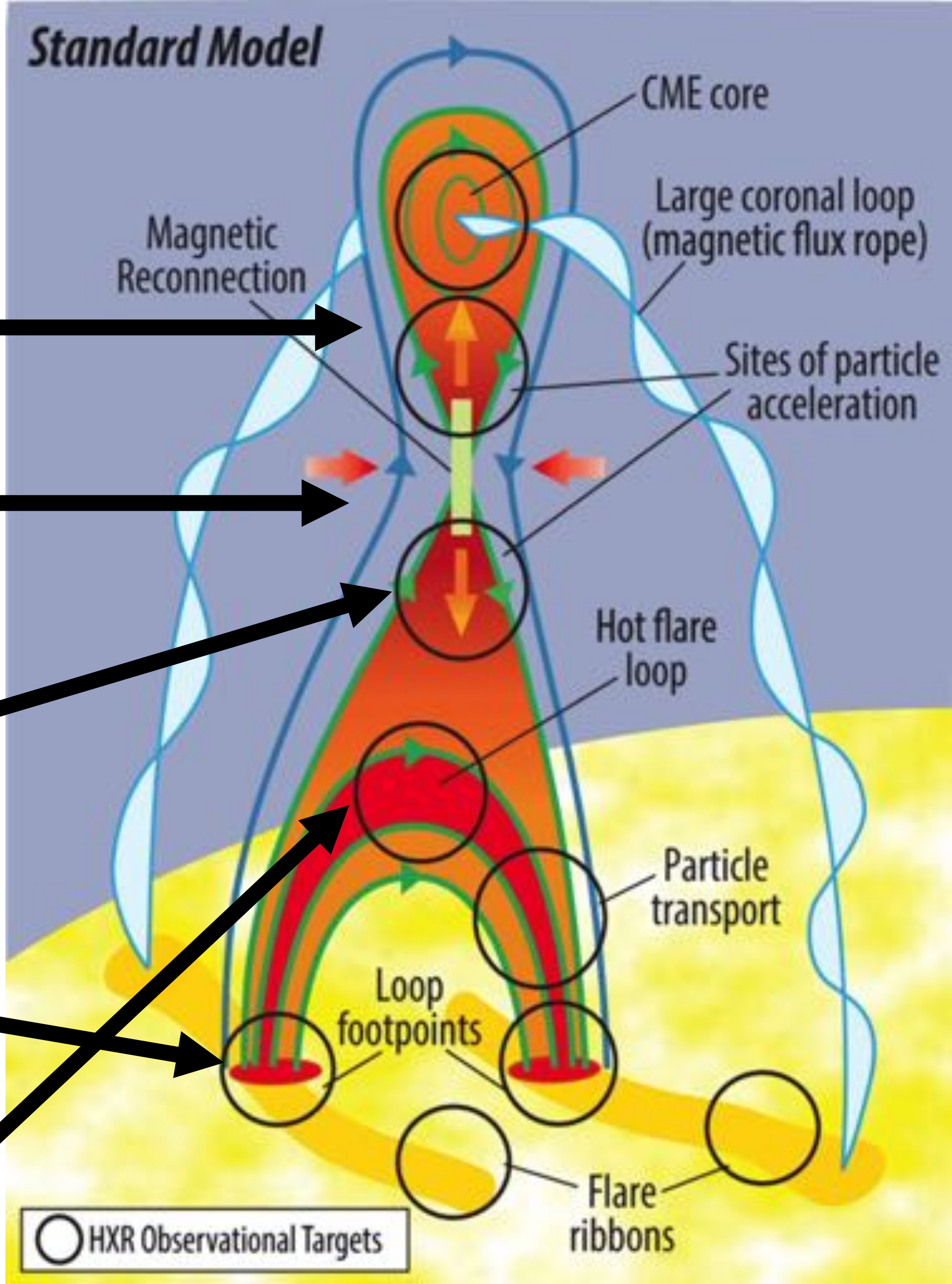
NST/VIS H_{α} line wing during M-class flare on 06/22/2015



Jing et al. (2016)

The 2D Standard Flare (CSHKP)

- Magnetic flux rope (FR) expands and is ejected (CME).
- Magnetic reconnection forms coronal/flare loops increasing.
- Particles are accelerated, and then propagate through the coronal loops.
- Non-thermal particles propagate downwards into the chromosphere were they deposit their energy (UV, HXR, γ-rays).
- Heated chromospheric material rises through the flare/loops emitting in SXR and UV.



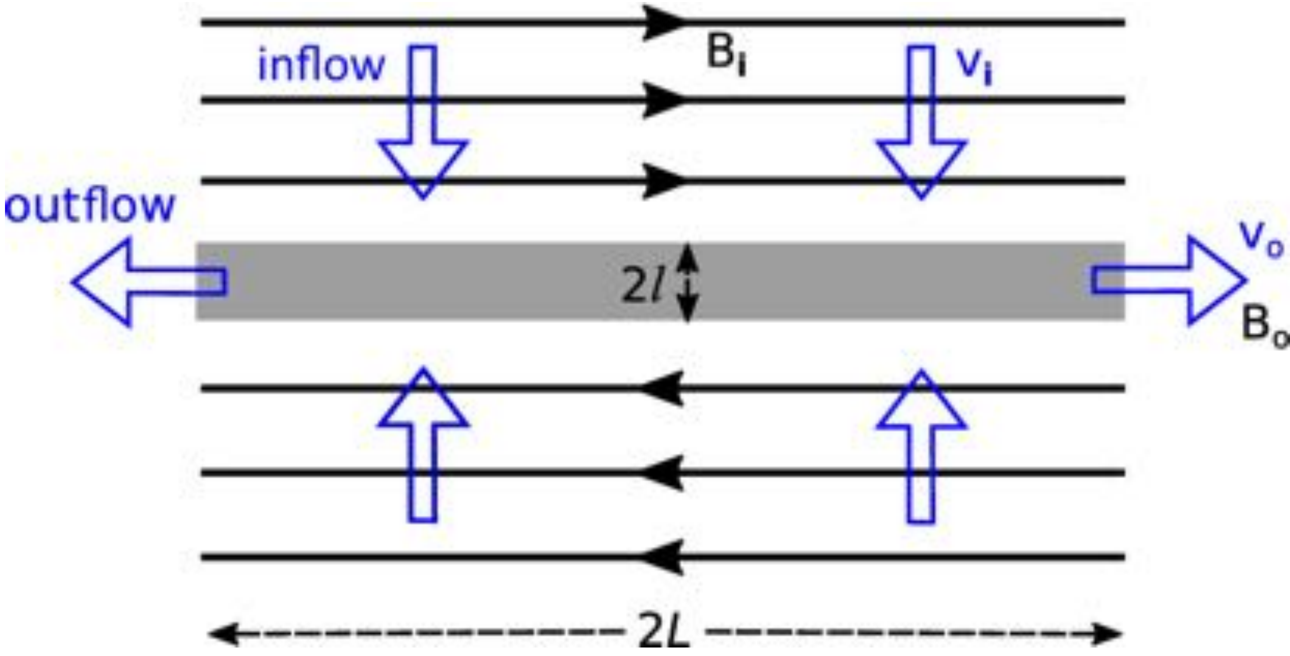
Christe et al. (2017)

Simplest Scenario of 2D Magnetic Reconnection

- Magnetic reconnection refers to the breaking and reconnecting of oppositely directed field lines.
- Sweet-Parker (SP) model, explains steady reconnection in large current sheet.

SP Reconnection

Ideal MHD



Ideal MHD

Pontin & Priest (2022)

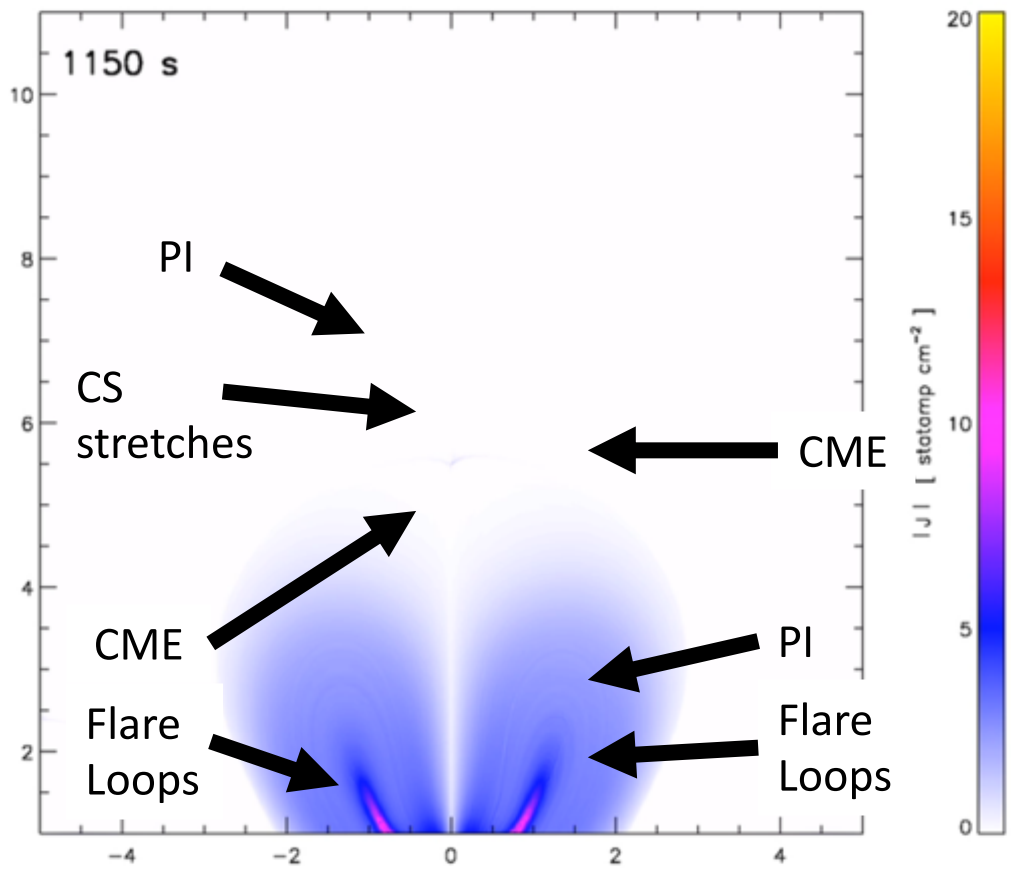
The SP model is too slow

- It describes flares duration in the order of months (inflow is < 10^{-4} of the coronal Alfvén speed) which is not supported by observation:
  - A flare's lifetime ranges from seconds to hours.
- Typically the reconnection inflow speed needs to be 0.1 – 0.01 of the Alfvén speed in the corona to explain flares.
- Reconnection needs to happen faster!

Fast Reconnection: Bursty Reconnection

- Reconnection is modulates as plasmoids exit the current sheet, enhancing the efficiency of reconnection.
- Right: 2 CME model with Plasmoid Instability (PI) in the current sheet (CS).
- Plasmoids (of different scales) are formed as the current sheet thins out, and are ejected in opposite direction in the current sheet.

Current Density in 2D Double CME model



Lynch et al. 2016

Connecting Reconnection to Particle Acceleration

Is reconnection steady?

- CME models show PI forming in their current sheet (Lynch et al. 2016) and bursty reconnection.

How are particles accelerated?

- Numerical (Drake et al. 2006; Guidoni et al. 2016) and analytical (Guidoni et al. 2022) results suggest that plasmoids can accelerate particles trapped within them to non-thermal energies.

Are there 3D effects in play?

- The presence of a magnetic field component parallel to the PIL (guide field) can suppress the efficiency of plasmoids to accelerate particles (Arnold et al. 2021), leading to periods of bursty reconnection with little particle acceleration.

Can flare ribbon morphology inform us about the current sheet:

- Fine-structures in flare ribbons fronts (swirls and wave-breaks; Wyper & Pontin 2021) associated with plasmoids.
- Bursty modulations of flare ribbon fronts (Naus et al. 2022) suggests bursty reconnection.

Bursty Magnetic Reconnection driven by the PI captures this scenario.

Remainder: In this talk we address,

Is there observational evidence that magnetic reconnection occurs as a bursty oscillatory process? Are these bursts associated with dynamical processes in the current sheet?

Data and Methods

Magnetic Reconnection Flux Proxies with SDO.

Flare Ribbon Fine-Structure with IRIS SJI.

Particle Acceleration Proxies with GOES and Fermi.

Detecting Quasi Periodic Pulsations with AFINO.

Data & Methods: SDO, IRIS, GOES & FERMI

SDO – AIA1600 Å

IRIS – SJI 1330 & 1400 Å

Estimating Cumulative Flare Ribbon Evolution

(Kazachenko et al. 2017)

$$\mathcal{M}^{(I_c)}(x_i, y_j, t_k) = \mathcal{M}^{(I_c)}(x_i, y_j, t_{k-1}) \bigcup \mathcal{N}^{(I_c)}(x_i, y_j, t_k).$$

Where M and N are the cumulative and instantaneous ribbons masks, respectively.

SDO – AIA 1600 Å

SDO – HMI

Calculating the Reconnection Flux Proxy

(Forbes & Priest 1984 & Forbes & Lin 2000)

$$\Phi^{(I_c)}(t_k) \approx \sum_{i}^{N_i} \sum_{j}^{N_j} \mathcal{M}^{(I_c)}(x_i, y_j, t_k) B_r(x_i, y_j, t_k) \Delta A.$$

GOES – XRS

FERMI – GBM

Particle Acceleration: X-ray emission in 0.5 – 4 Å and 1 – 8 Å, and 0 – 300 keV.

Methods: Describing periodicity with the Automated Flare Inference of Oscillations (AFINO)

Inglis et al. 2015, 2016 introduced AFINO. Main idea:

$$S^*(t_k) = \frac{S(t_k) - mean(S)}{mean(S)}$$

Normalize and center the signal distribution at 0.

$$\hat{S}^*(f)$$

Calculate the FFT

$$M_0(f) = A_0 f^{\alpha_0} + C_0,$$

$$M_1(f) = A_1 f^{\alpha_1} + B \exp\left(\frac{-(\ln f - \ln f_p)^2}{2\sigma^2}\right) + C_1$$

$$M_2(f) = \begin{cases} A_2 f^{-\alpha_a} + C_2 & f < f_{break} \\ A_2 f_{break}^{-(\alpha_a+\alpha_b)} f^{-\alpha_b} + C_2 & f > f_{break} \end{cases}$$

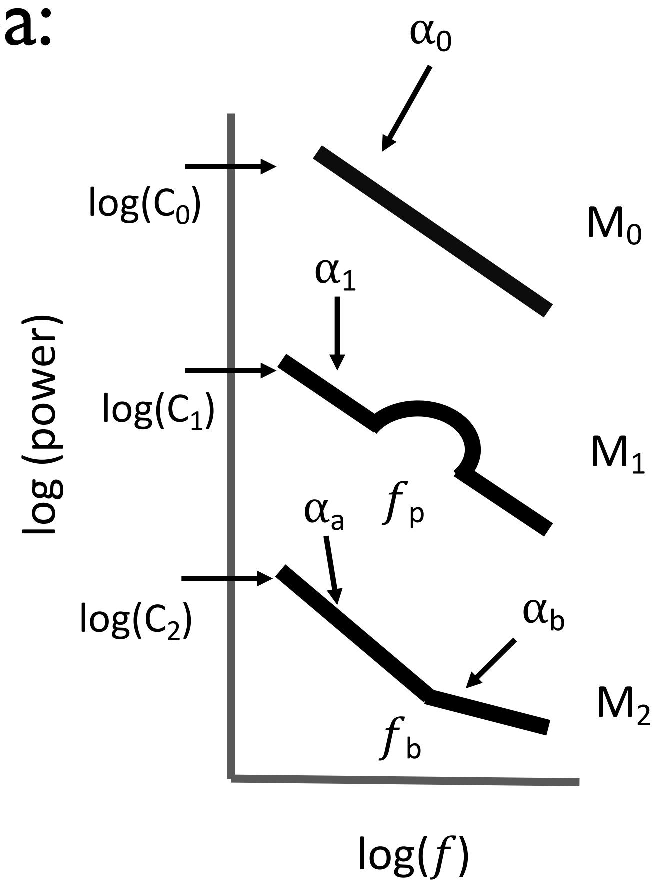
Get the best fit out of 20 trials of possible scenarios:
0 – Noise with 1 background
1 – Quasi Periodic Pulsation (QPP)
2 - Noise with 2 background distributions.

$$BIC_i - BIC_j < -10$$

Determine which model is strongly favored.

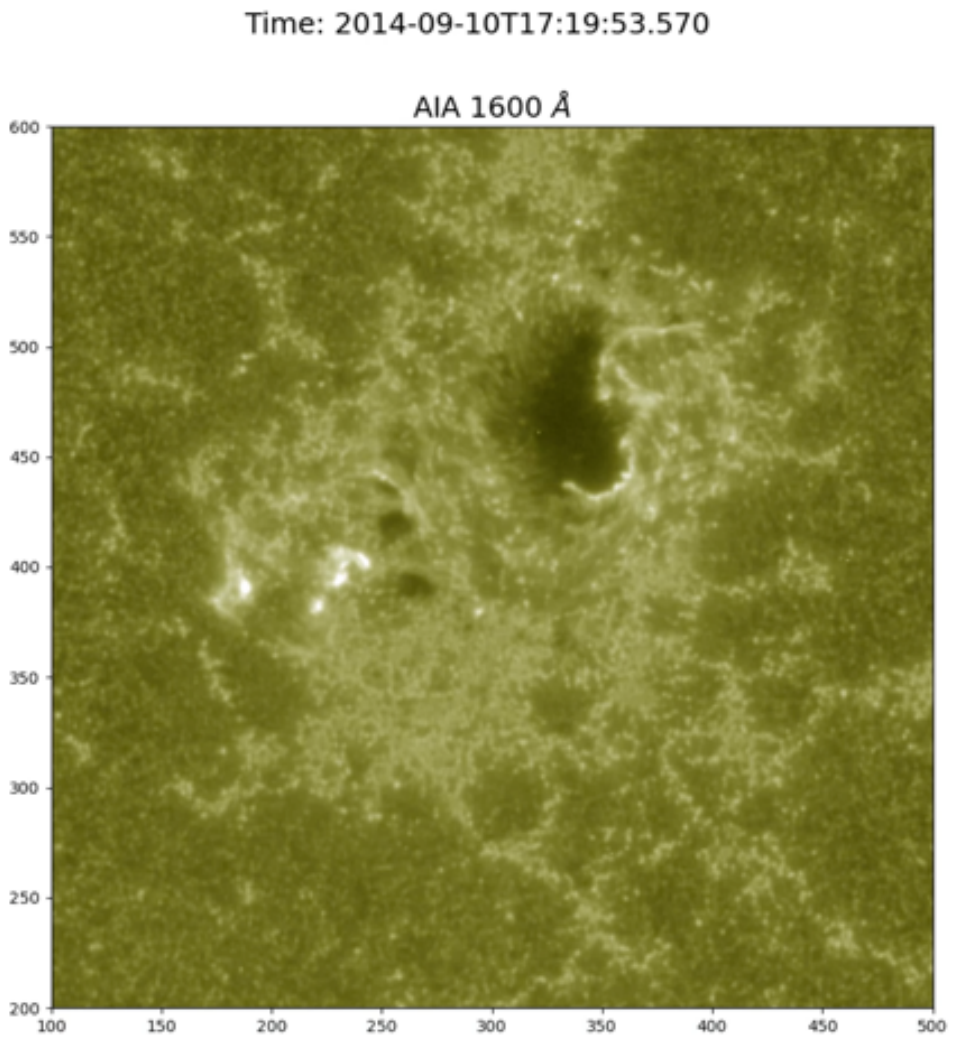
$$\chi_\nu^2 = \frac{1}{\nu} \sum_{j=1}^{N/2} \left(1 - \frac{s_j}{m_j}\right)^2$$

Evaluate the goodness of the fit.



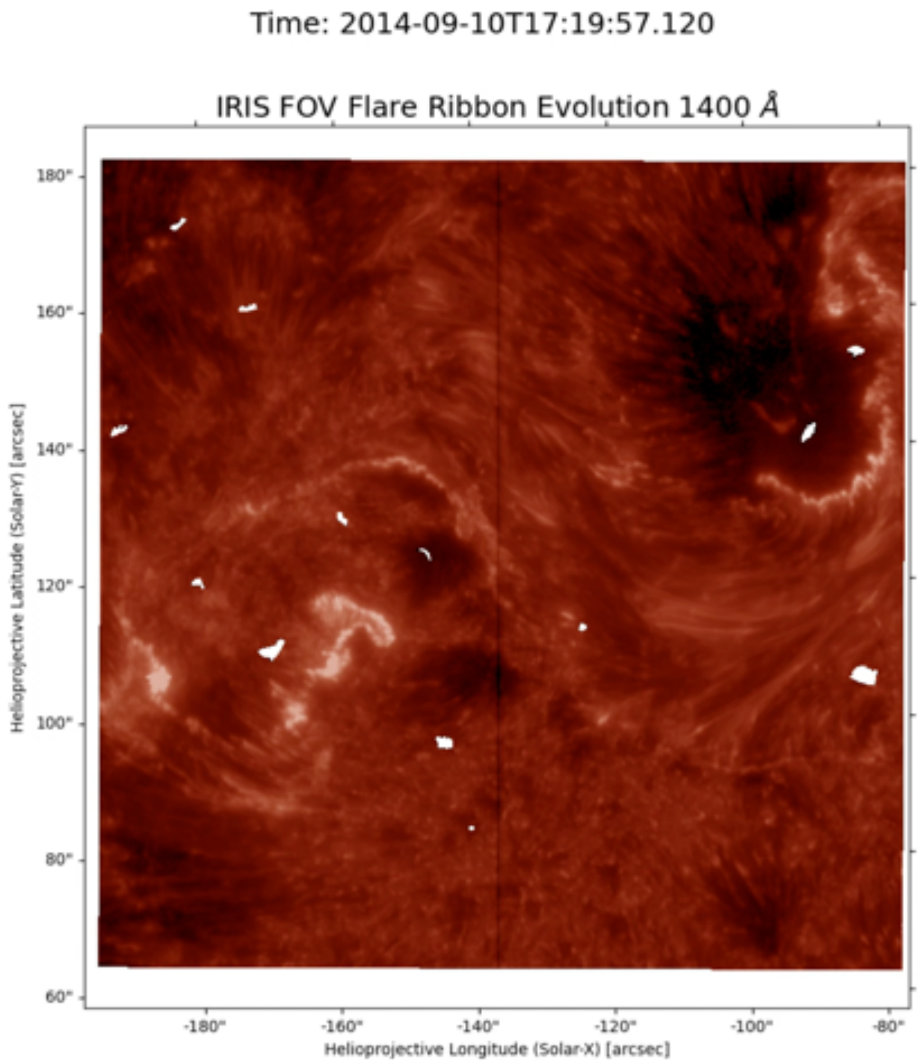
Data: Tracking Evolution of Flare Ribbons with SDO/AIA 1600 Å

- Right: example of flare ribbons in an X1.6 flare.
- Problem: low spatial resolution and saturation make it difficult to describe fine details in the ribbon fronts.



Data: Tracking Evolution of Flare Ribbons with IRIS SJI 1400 Å

- IRIS SJIs provide comparable observations with higher resolution and smaller FOV.
- Right: same flare observed by IRIS
- Note the fine structure, swirls.



Data & Methods (4/4)

Result & Discussion

Comparison of Flare Ribbon Evolution and Reconnection Rates.

Comparison of Reconnection Rates and X-ray Emission.

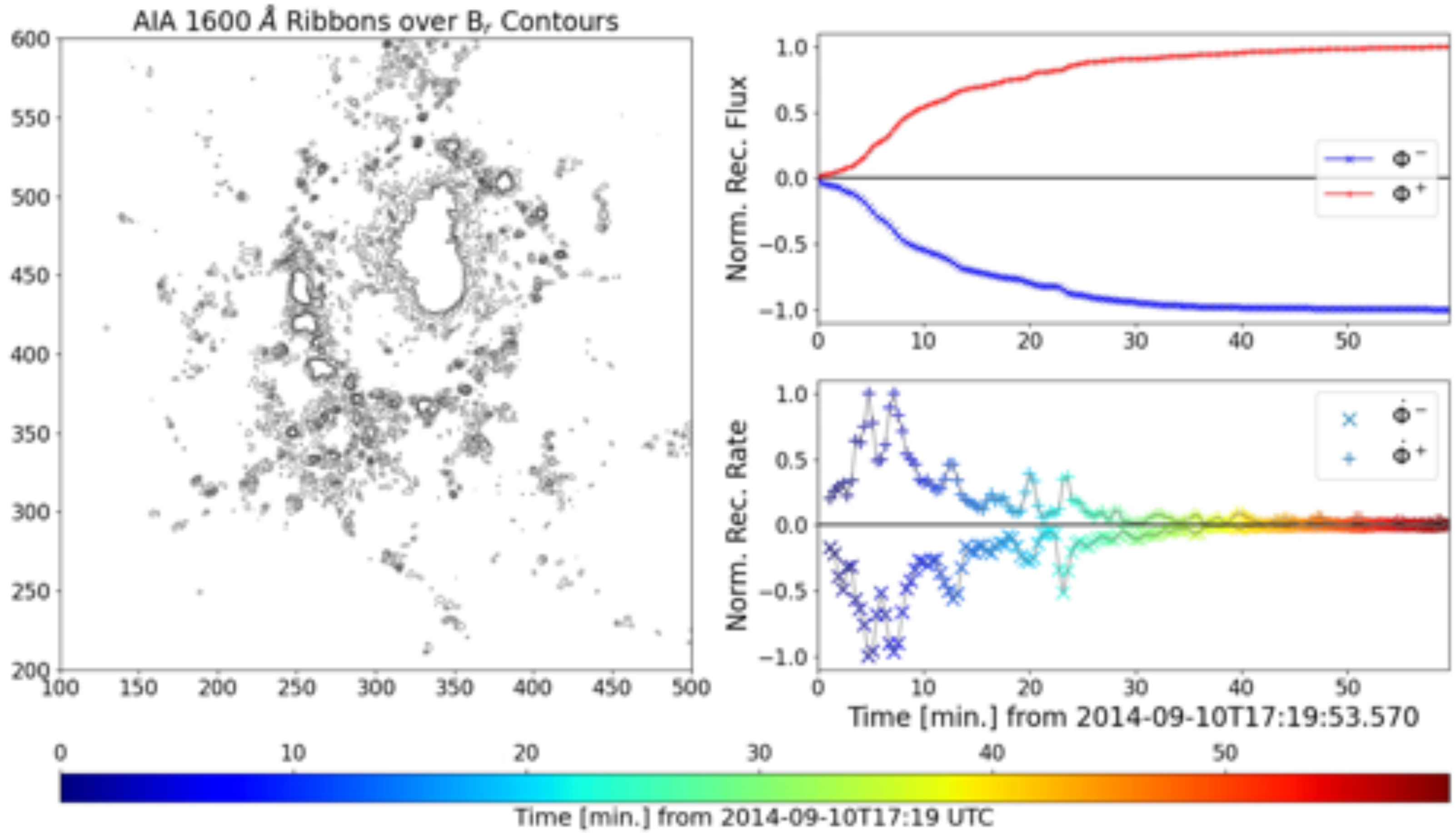
Summary of analysis of 73 flares.

Results: SDO Flare Ribbons and Reconnection Flux/Rate for X1.6 flare

Positive and negative reconnection fluxes are approximately balanced:

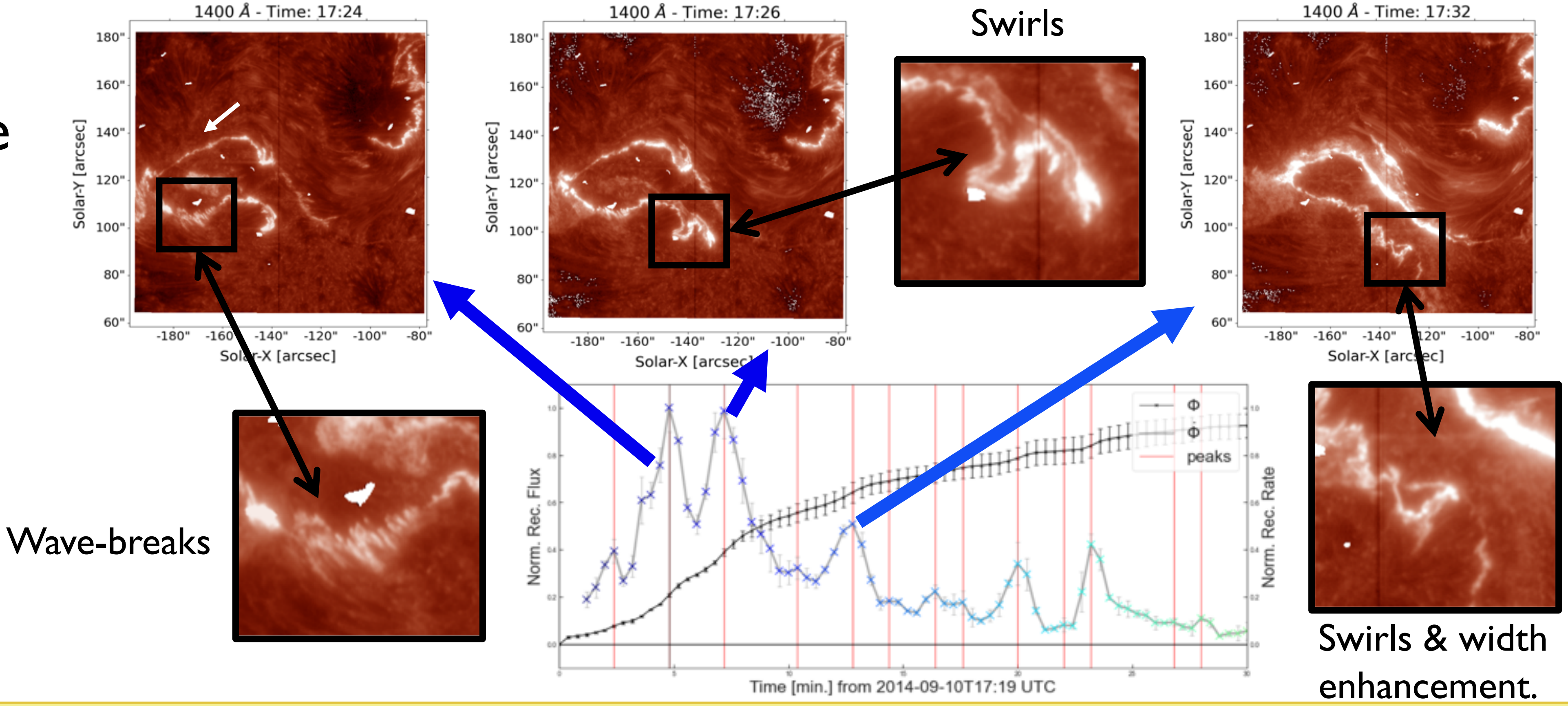
- $\Phi_{pos} = 6.5 \times 10^{21}$ Mx,
- $\Phi_{neg} = -5.6 \times 10^{21}$ Mx.

Reconnection rates derived from flare ribbon evolution show bursts.



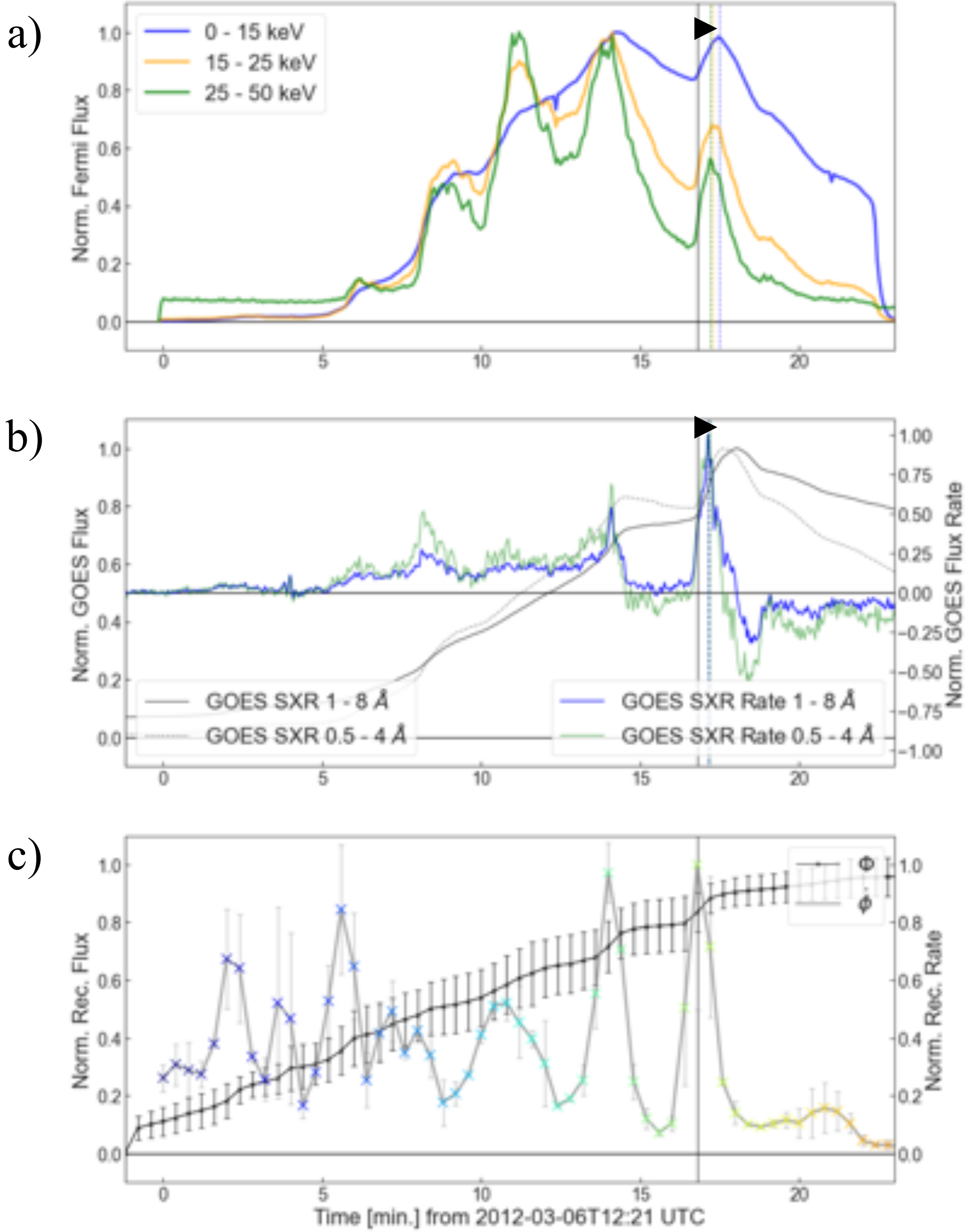
Results: Fine-Structures in Flare Ribbons and Reconnection Flux/Rate: X1.6 flare

Reconnection rate burts are co-temporal with development of fine-structures in the flare ribbon fronts.



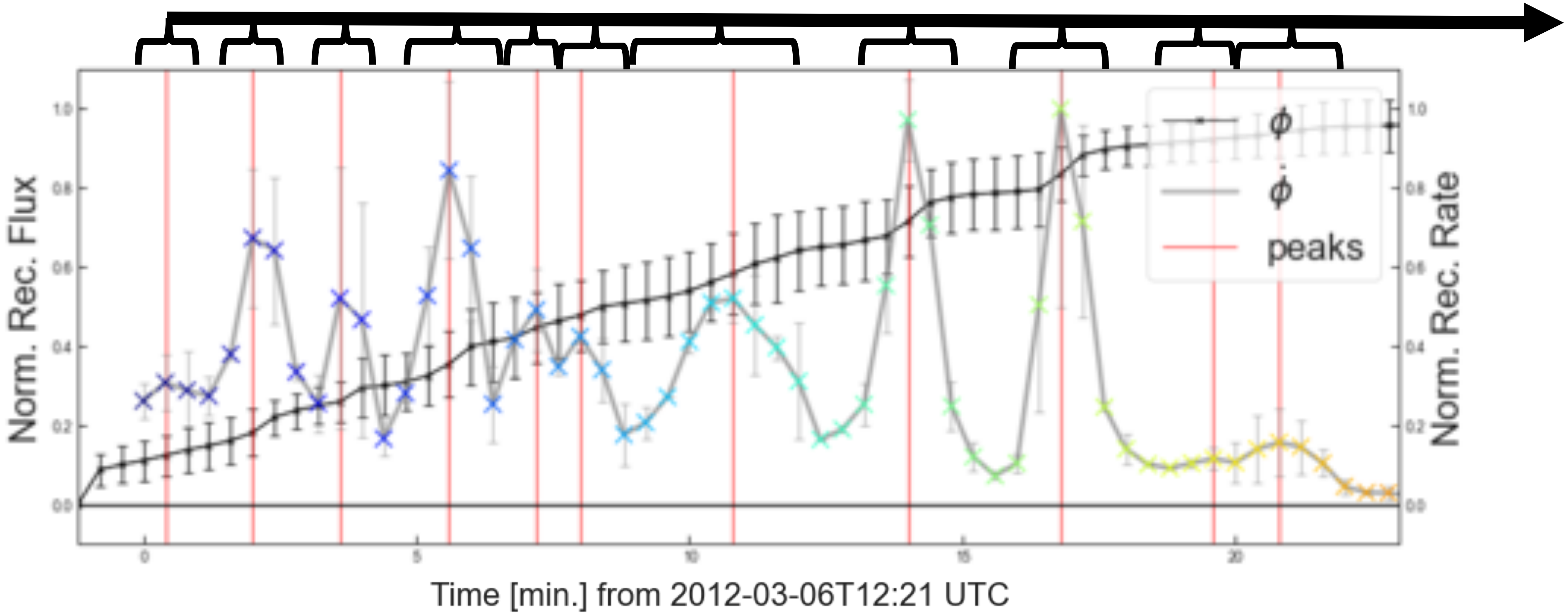
Results: Reconnection Rate Burst vs. HXR emission: M2.1 Flare

- *Top*: Fermi emission in 3 channels
- *Middle*: SXR emission in 2 channels; note similarities with Fermi (15 - 50 keV).
- *Bottom*: Reconnection rates display quasi-periodicity (≈3 min).
- *Note*: Bursts in X-ray emission occur with little delay (≈42 s, arrow heads) from the rec. rate bursts.



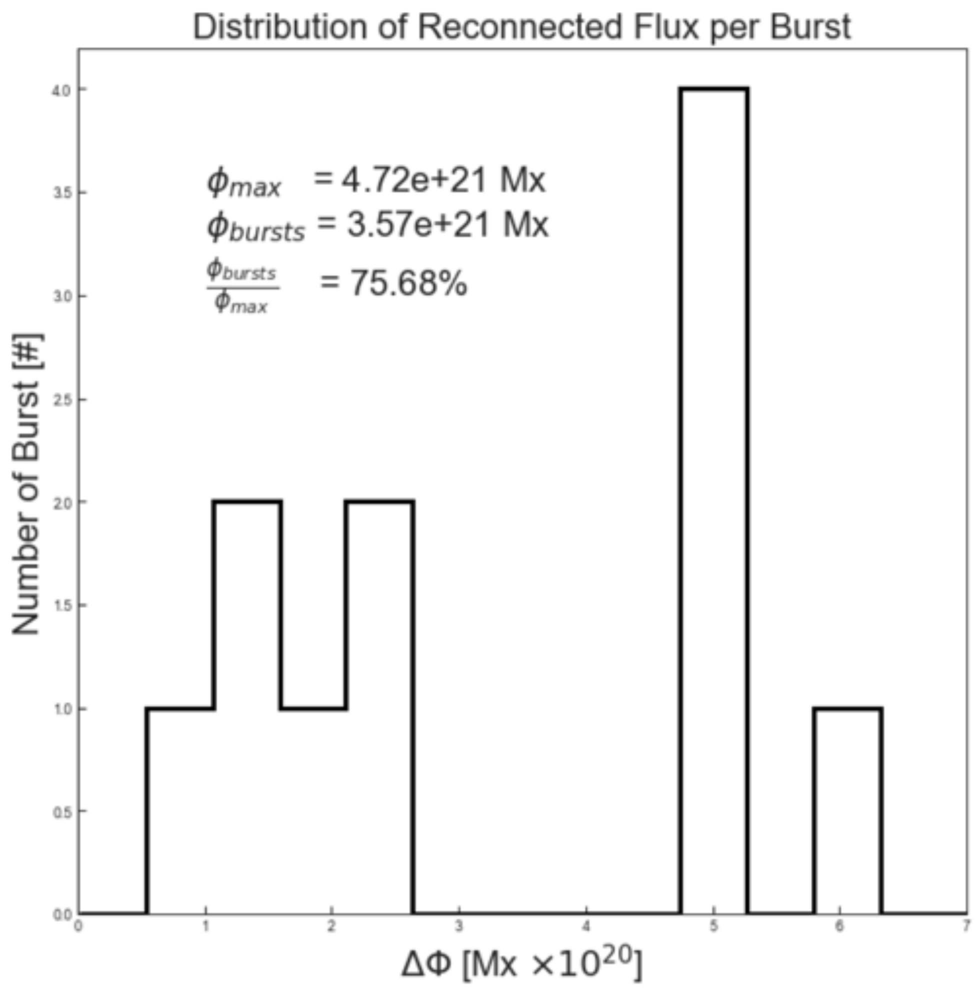
Results: How much flux gets reconnected in each burst? Let's look at the same M2.1 flare

- The flare exhibits 11 bursts:



Results: Plotting magnetic-flux distribution of separate bursts we find that:

- 11 individual bursts in this event have magnetic fluxes from: $(0.1 - 7) \times 10^{20}$ Mx.
- The bursty-part of reconnected flux accounts for approximately 75% percent of the total reconnection budget (3.6 from 4.7×10^{21} Mx).
- Does each of 11 bursts correspond to reconnection of separate island?

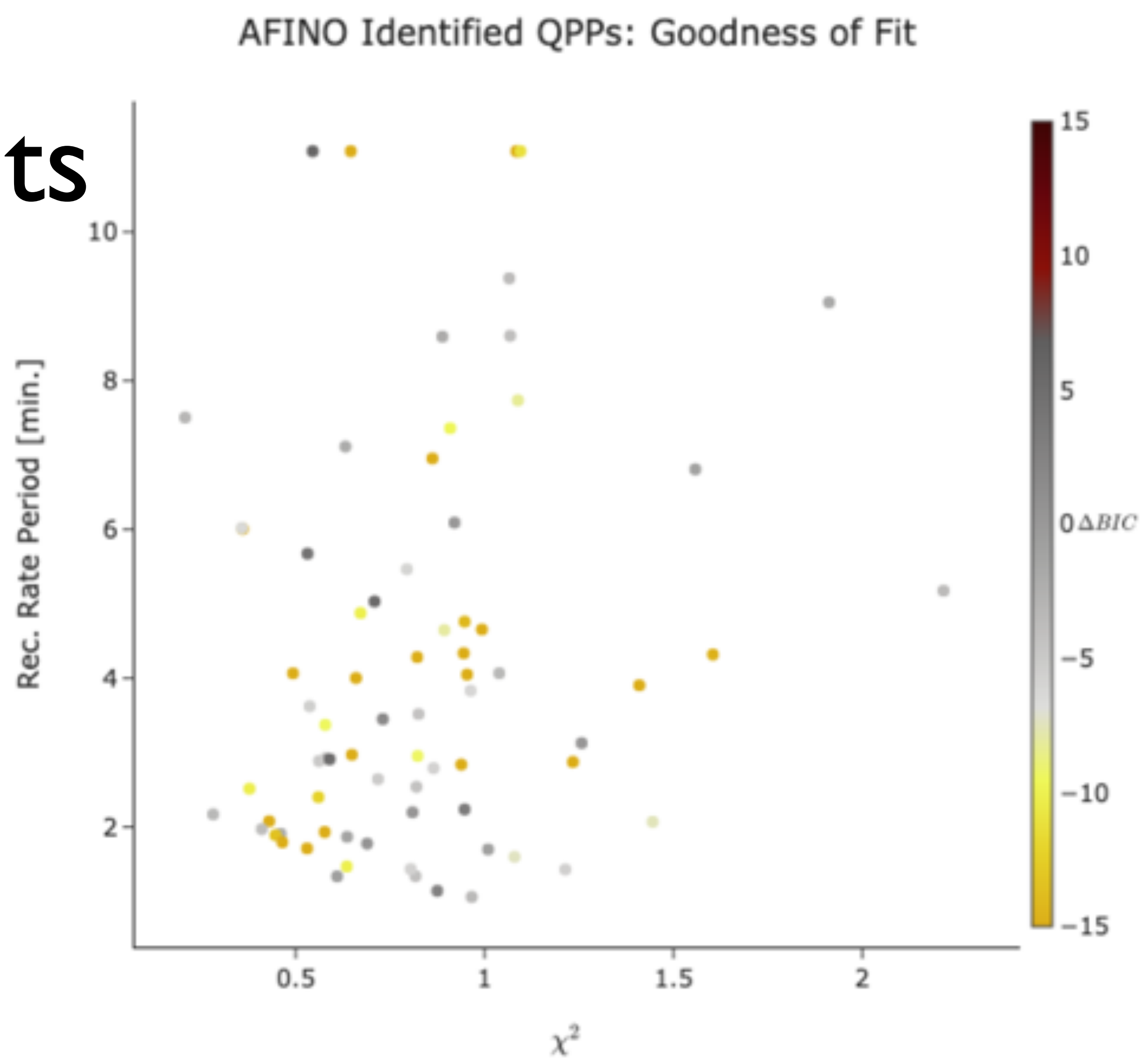


Discussion: Interpreting the Analysis of Flare Ribbons and Reconnection Rates

- The fine-structure and the modulation of the flare ribbon-front widths contribute to the larger bursty evolution of flare ribbons area.
- We emphasize that these swirls and wave-breaks (Wyper et al. 2021) have been associated to plasmoid structures in the current sheet.
- Modulations of the flare ribbon front have been associated to bursty reconnection and co- spatial and temporal HXR emission (Naus et al. 2022).

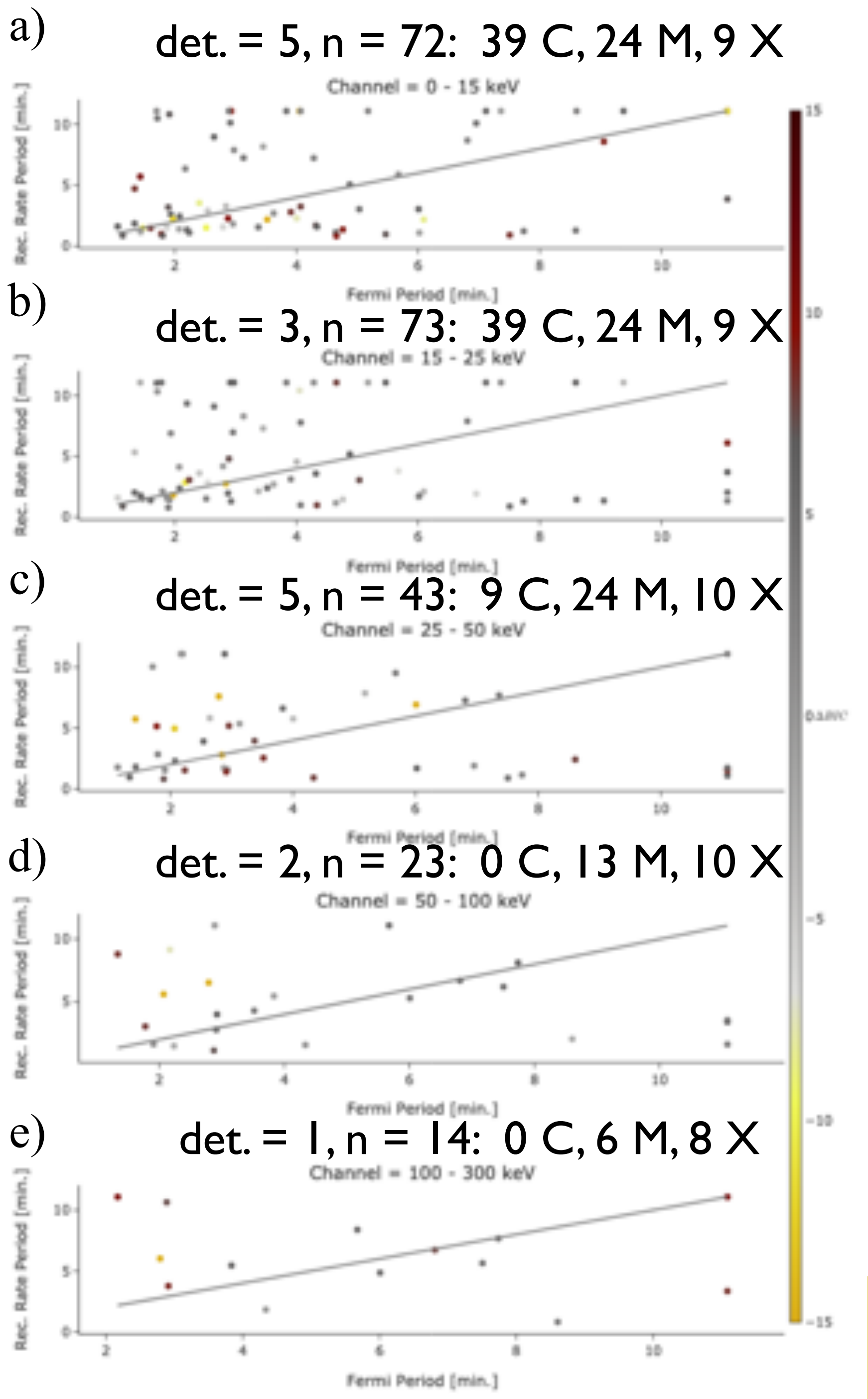
Results: QPP periods in Reconnection Rate Bursts

- Summary of 73 flares: 39 C-, 24 M-, and 10 X-class flares.
- QPP periods in the reconnection rate have periods between 1 – 11 minutes.
- Although overall good fits, only 26 events (yellow) show preference for the QPP model.



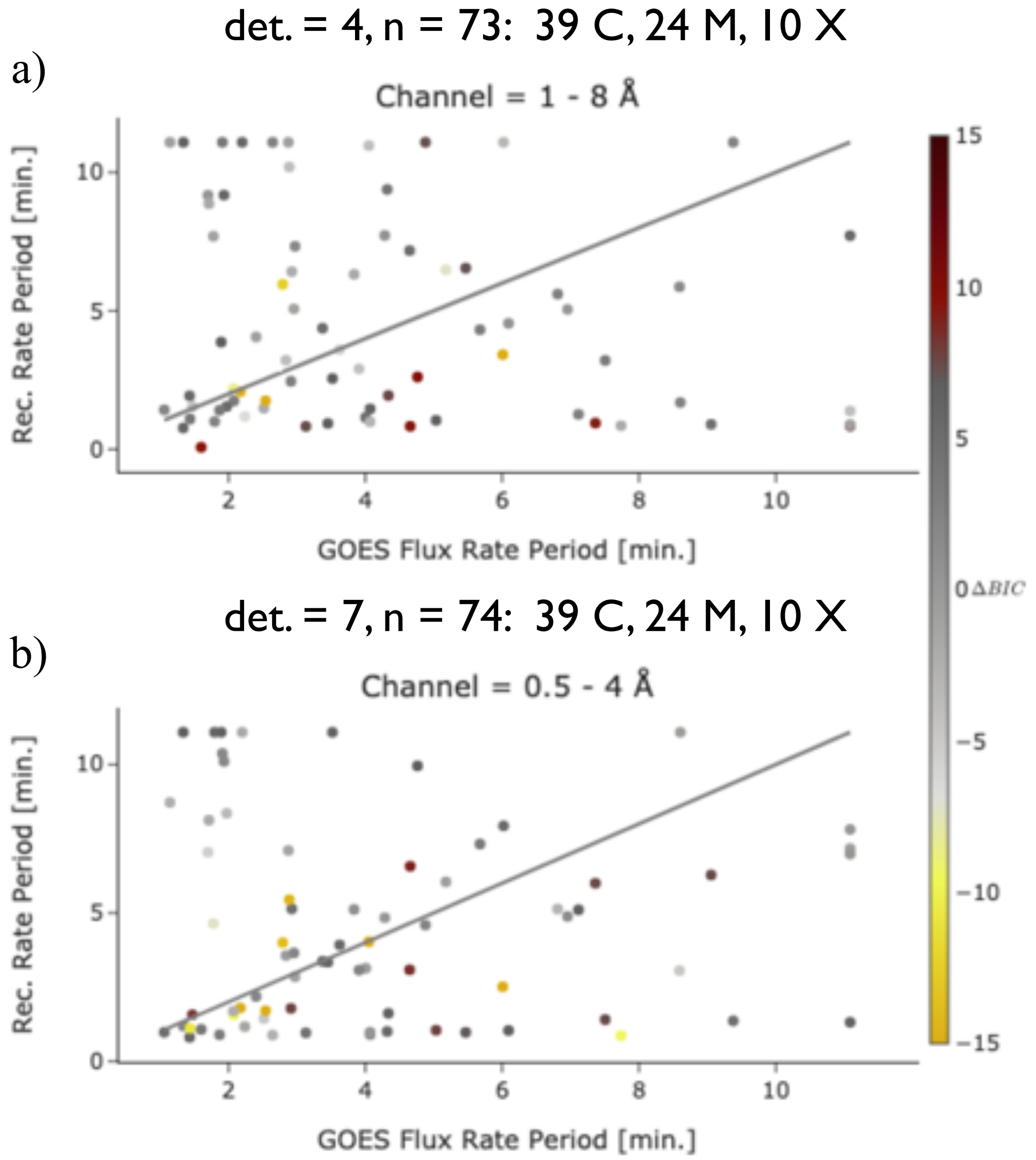
Results: Are the QPPs in Rec. Rates related to QPPs in HXR (Fermi)?

- Low detection of QPP using AFINO.
- Some correspondence between periods < 5 minutes in lower energy channels.
- Higher energy channels include less events (only a few M- and X-class flares).
- Inconsistent detection across energy channels.



<u>Results</u>: Are the QPPs in Rec. Rates related to QPPs in SXR Rate (GOES)?

- Low detection of QPP using AFINO.
- Both channels include the full sample of flares.
- More consistent periods across energy channels.

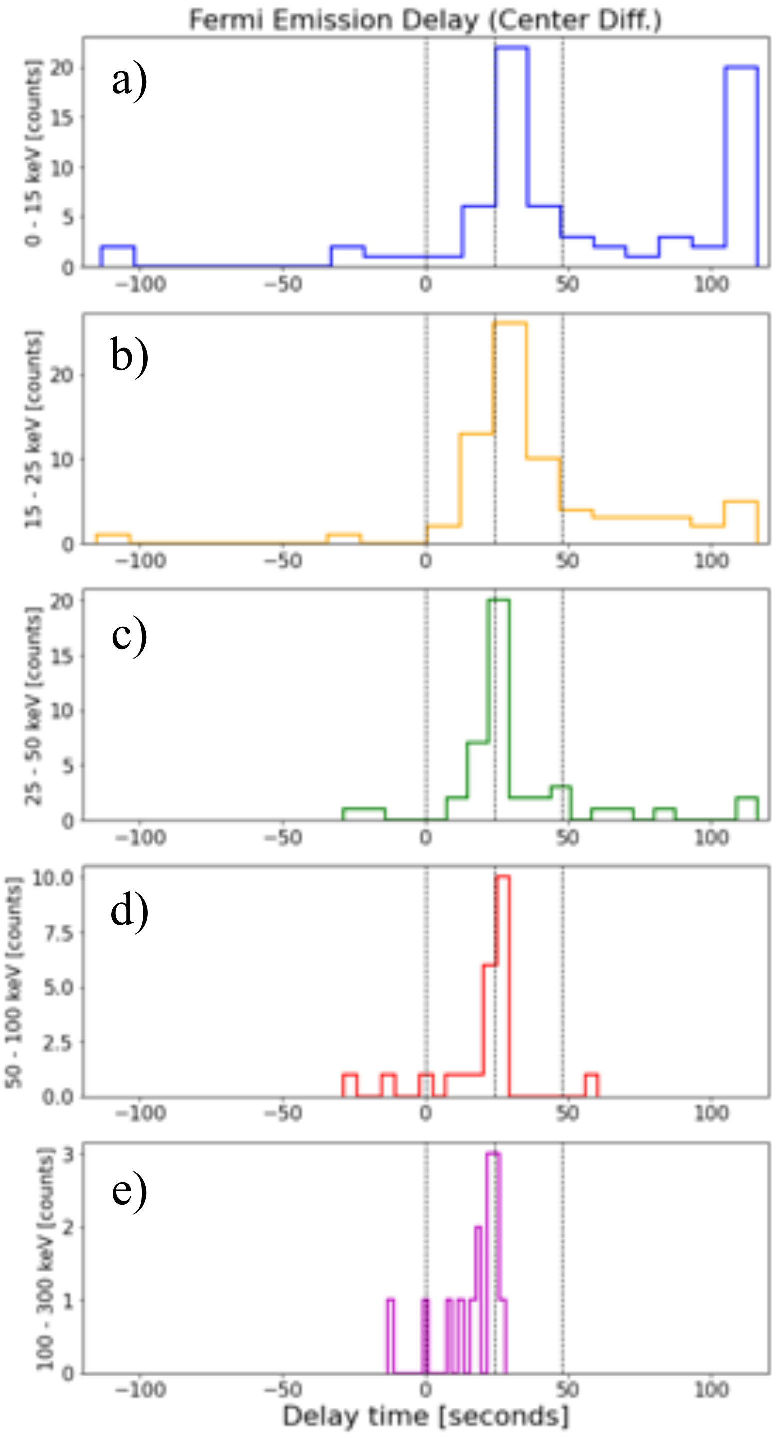


Discussion: Interpreting QPP Results

- Magnetic reconnection rates can be accurately represented by QPP model in some cases (26/73), suggesting quasi periodic burst in reconnection.
- The QPPs periods in the X-ray emission are only consistent with QPP periods in the reconnection rates for a few low periodicity events.
- AFINO methodology fails to characterize oscillations periods shown in X-ray data, and detects very few events.

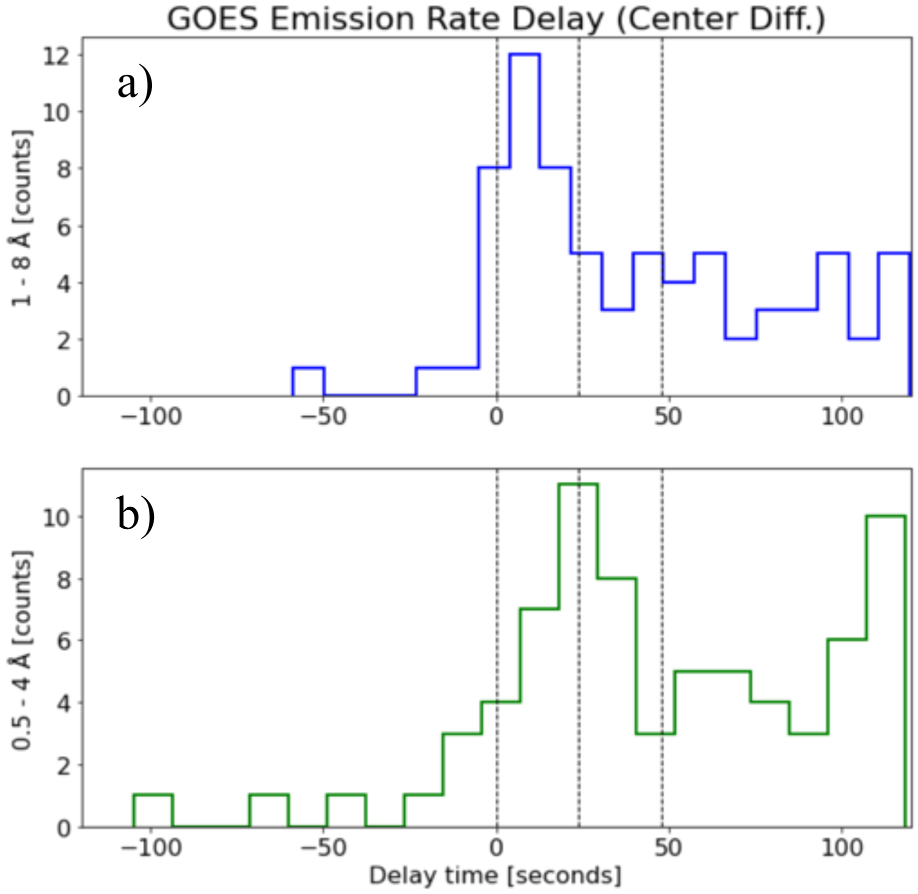
Results: What is the temporal Evolution of Rec. Rate Burst and HXR Excitation?

- Emission of HXR is delayed to the reconnection burst in the impulsive phase by ~24 s in all of the Fermi GBM channels.
- 24 s corresponds to the AIA cadence; yet, we find that it is not due to numerical approximation of the time derivatives.



Results: What is the temporal Evolution of Rec. Rate Burst and SXR Rate Excitation?

- Emission of SXR Rate is delayed to the reconnection burst in the impulsive phase by 0 – 48 s in all of the GOES SXR data.
- Shows agreement with Fermi HXR emission.



Discussion: Interpreting the Delays in HXR emission Compared to Reconnection Rates

- Miklenic et al. (2007) and Veronig & Polanec (2015) found similar delays (in the order of seconds to minutes) when comparing reconnection rates and HXR emission.
- They suggest that two populations of non-thermal particles accelerating at different sites of the current sheet could explain flaring HXR emission being delayed from the brightening of new flare ribbon kernels.
- No evidence suggesting such a mechanism.

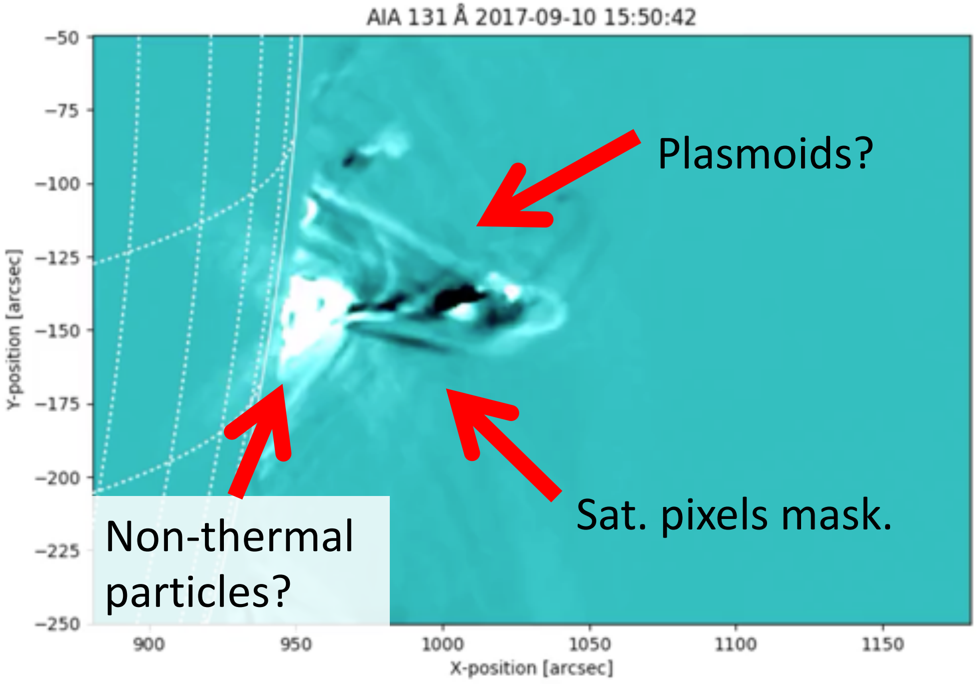
Conclusions

- We find that magnetic reconnection, as described by reconnection rates derived from flare ribbons, occurs in bursts:
  - Sometimes (26/73) these bursts could be fitted by a QPP model with periods ranging on scales of minutes (1 to 11 minutes):
  - The bursts account for a significant amount of the total reconnection budget (0.1- 20 x 10^{20} Mx).
- Fermi and GOES observations show X-ray bursts that are nearly co-temporal, delayed by up to a minute from bursts in the reconnection rates.
- 8 IRIS SJI observations show fine structure like bursty modulation of the ribbon front widths (Naus et al. 2022), and swirls and wave-breaks in the ribbon fronts (Wyper & Pontin 2021) which have been associated with tearing mode instability in the current sheet.
- We suggest that nearly co-temporal QPP bursts in the rec. rates and X-ray emission provide evidence of oscillatory process in the reconnection region and plasmoid dynamics (Kliem et al. 2000; Takahashi et al. 2017); this in turn leads to bursty particle acceleration (Takahashi et at. 2017; Drake et al. 2006; Guidoni et al. 2016, 2022).

Moving Forward

- Our analysis is incapable of distinguishing which mechanism could produce the clearly co-temporal QPPs in the reconnection rates and HXR emission.
- On-limb observations have shown QPPs in UV and SFX emission associated with downward motions (plasmoids?) that collide with flare loops (Hayes et al. 2019).
- Observations with Solar Orbiter (when its 90° from the Sun-Earth line) and other Sun-Earth line aligned instruments could provide opportunities for simultaneous limb and disk observations.

Running difference movie showing downwards motions interacting with flare loops during X8.2 flare on 09/10/2017.



Hayes et al. (2019)

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Thank You!
¡Gracias!