Gaps in our understanding of flare energy release

and prospects with MUSE

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Long-standing open questions

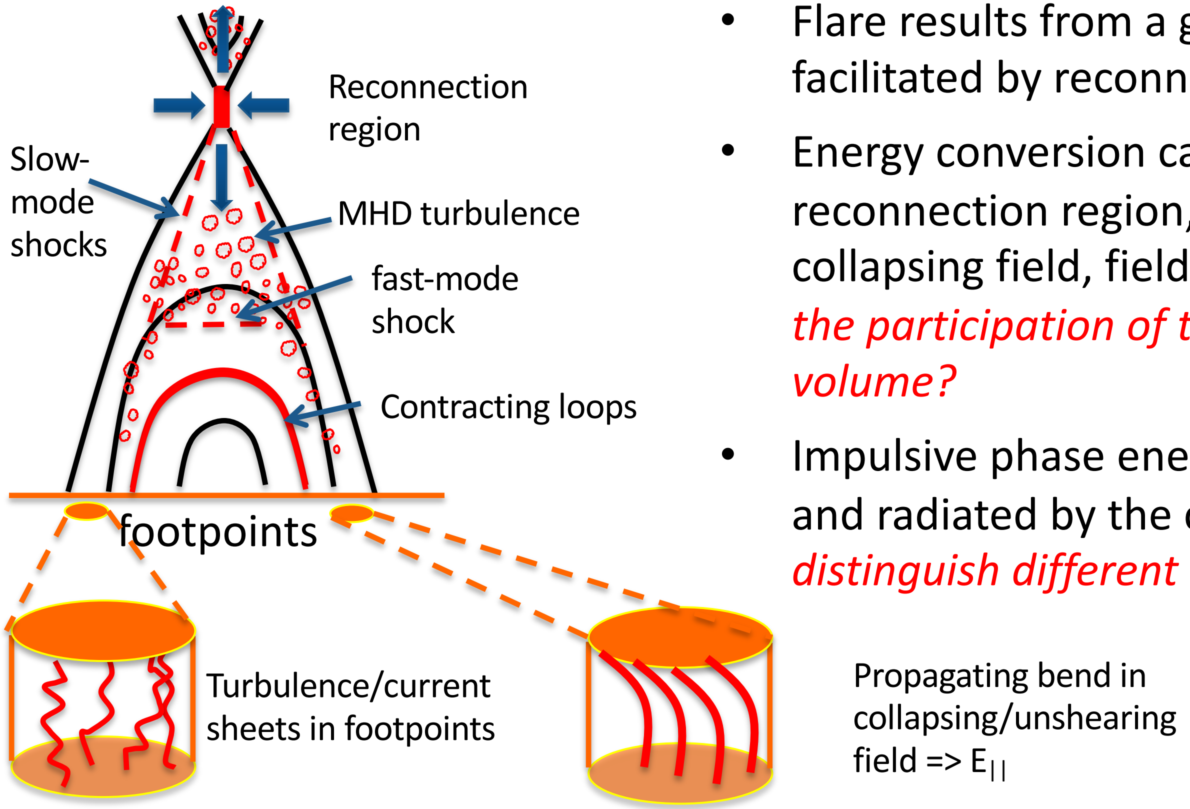
University of Glasgow

- why does flare energy release start? What does the onset look like?
- How and where is stored magnetic energy converted into other forms?
- how is that energy transported and dissipated in the atmosphere?

Answering these questions requires multi-wavelength observations and modelling, of the kind we have already seen discussed.

This is a selective discussion, focussing on flare early & impulsive phase, and biased towards problems that could be tackled by MUSE.

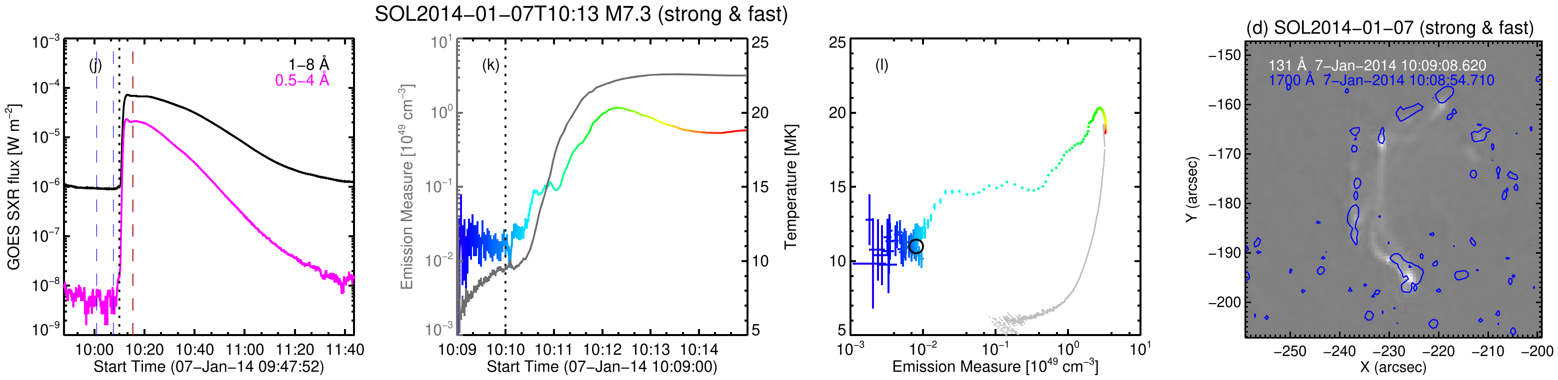
Flare cartoon



- Flare results from a global convulsion of the field, facilitated by reconnection – *how is this initiated?*
- Energy conversion can happen not just in the reconnection region, but also in turbulence, collapsing field, field-aligned currents – *what is the participation of the whole magnetised volume?*
- Impulsive phase energy mostly transported to and radiated by the chromosphere – *how can we distinguish different transport mechanisms?*

Onset: Hot early onsets

- `Hot Early Onsets' (Hudson+21) are an apparently ubiquitous flare pre-cursor
- Heating before the impulsive phase (i.e. before particle acceleration)
- 131 Å images suggest heating in both loops and footpoints

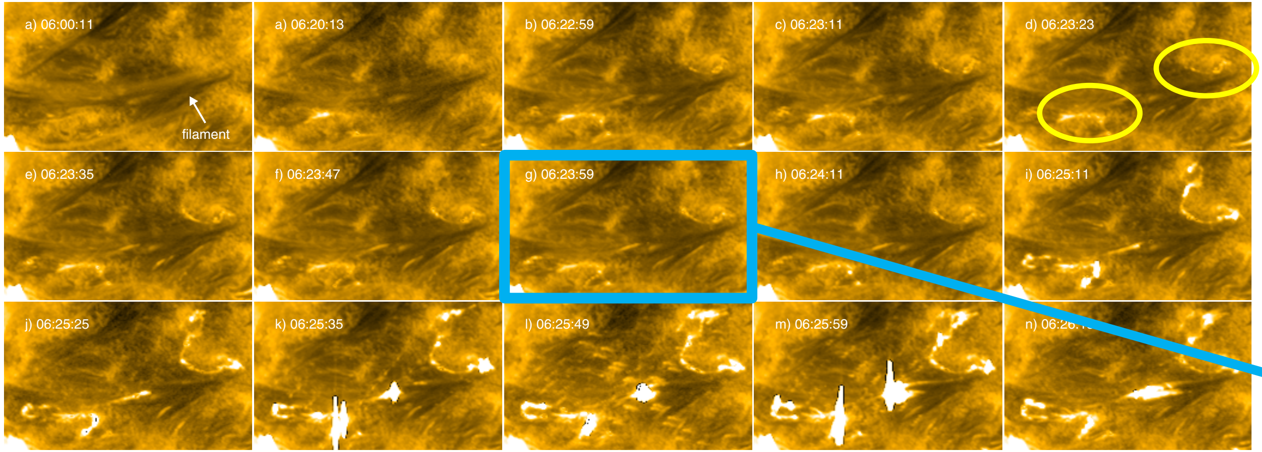


1-2 minutes before the impulsive phase, temperature obtained from GOES and RHESSI jumps to 10-15MK and EM increases.

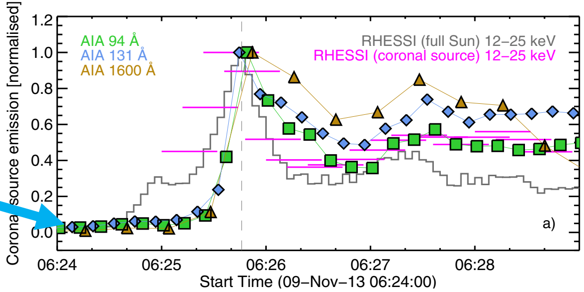
Also Awasthi & Jain 11, Silva+23 in prep

Onset: Pre-flare ribbons

Faint ribbons can appear in UV/EUV 1-5 minutes before hard X-rays (i.e. electron acceleration) at/very close to impulsive-phase ribbon locations.



Footpoints gradually brighten, seen here in AIA 171

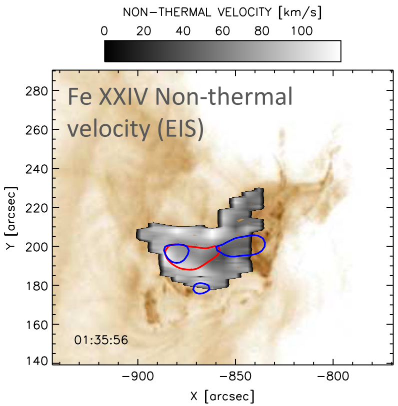


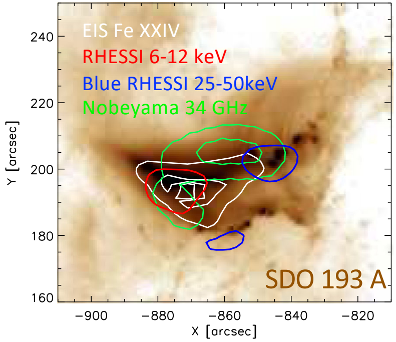
Simões+15, see also Warren & Warshall 01, Battaglia+09, Fletcher+13

What causes these pre-flare ribbons? How are they related to development of the instability? How do they compare to their flare equivalents in space, time and spectrum?

Onset: Pre-flare line broadening

Kontar+17



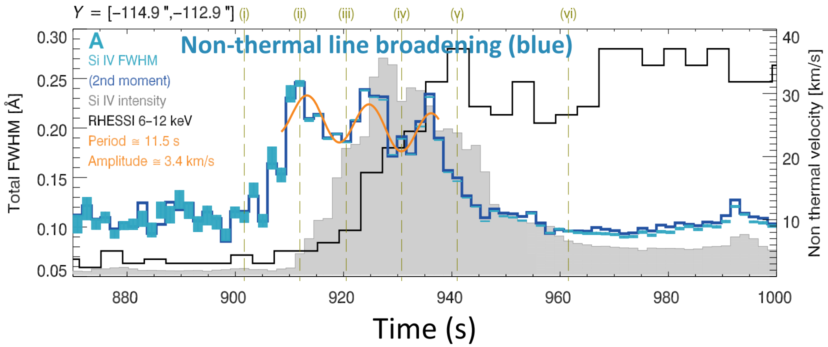


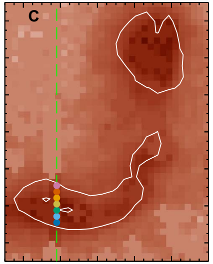
Also Harra+09,13

Non-thermal line broadening is observed in the corona and in chromosphere prior to the impulsive phase.

Decays as particles accelerated – interpreted as turbulence feeding acceleration

Implies turbulence loading/dissipation timescale 1-10s





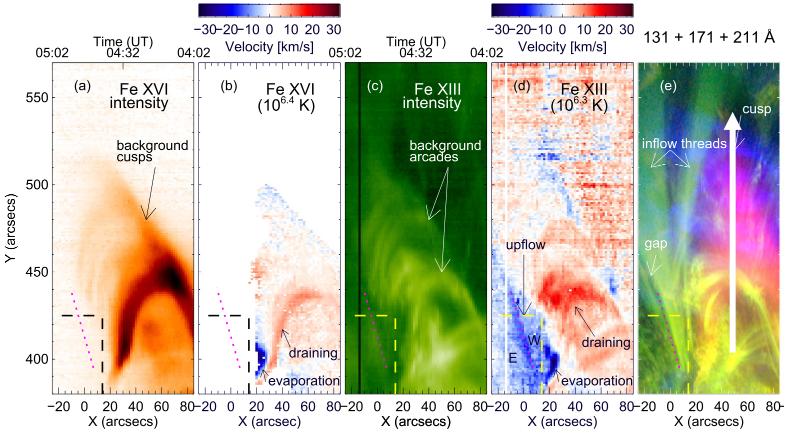
Jeffrey+18

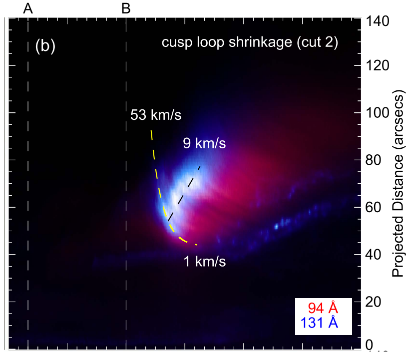
Conversion: Global reconnection dynamics

Reconnection in a current sheet (volume!) facilitates release of stored energy, but energy is stored (e.g. Longcope & Tarr 2012) and may be converted throughout the corona

e.g. shocks in retracting flux tubes (Longcope+09), betatron (Giuliani+05), turbulent outflows (LaRosa & Moore 96)

So we need the global picture of the reconfiguring field - inflows, dipolarisation, implosion



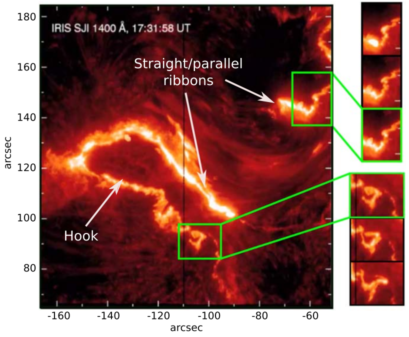


Example: EIS raster of a slow flare, taking ~ 1 hour (Wang+17)

Conversion: tracking coronal scales in the chromosphere

Flare ribbons map the ends of energised (presumed "just reconnected") field, and probe coronal reconnection – Jiong's talk.

IRIS SJI & SG used to examine ribbon sub-structure suggesting, variously, plasmoids (Wyper & Pontin 21); tearing mode (French+19); turbulence (Chitta & Lazarian 20)



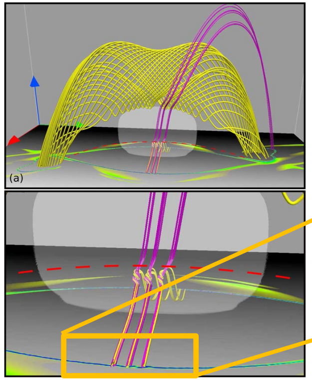
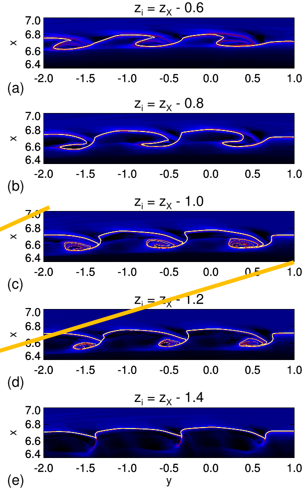
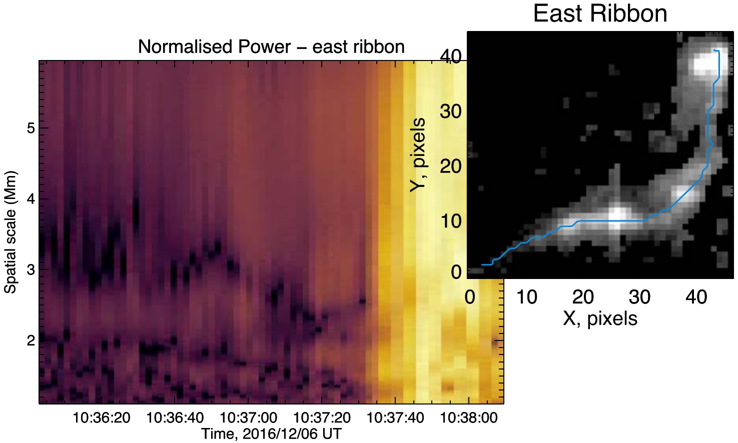


Figure 8. Field lines within three oblique flux ropes formed within the current layer below the HFT. The dashed red line shows the approximate position of the HFT.



Wyper & Pontin 21
Waves/spirals in ribbons predicted by current sheet tearing/plasmoid formation

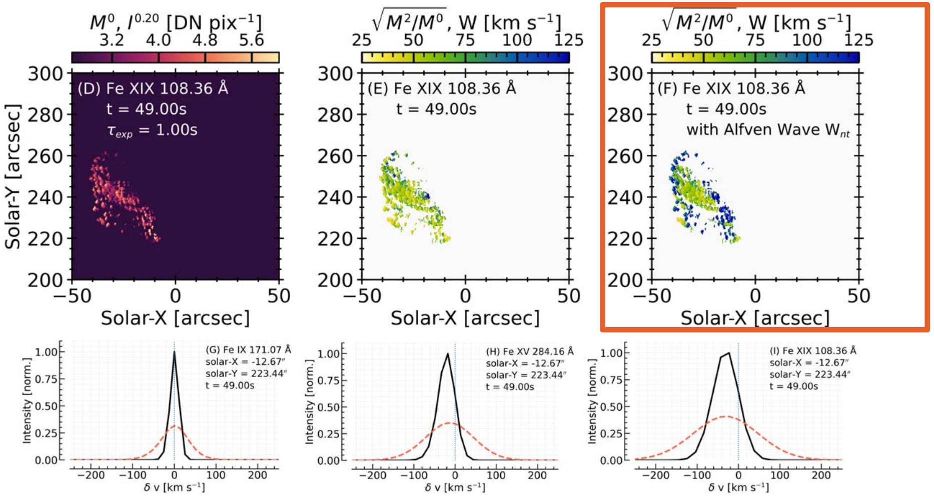
French+19: exponential growth at 1.75Mm spatial scale, possible forward/inverse cascade



Energy transport: spectra

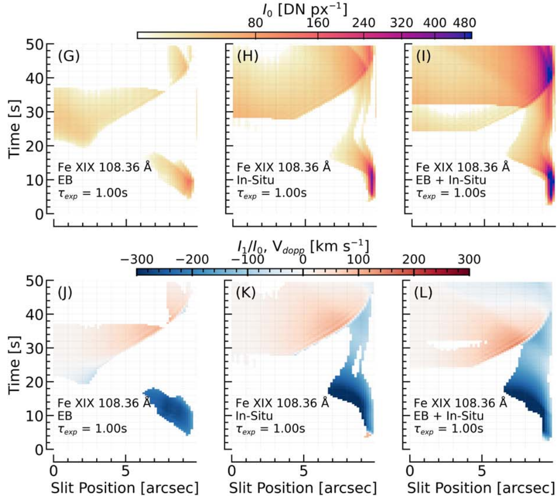
- Fast particles, conduction and waves probably all involved in energy transport.
- Might be distinguished spectroscopically from chromospheric and coronal signatures (Graham's talk).

Predicted line broadening for AW excitation



Predictions for MUSE, from Cheung+2022

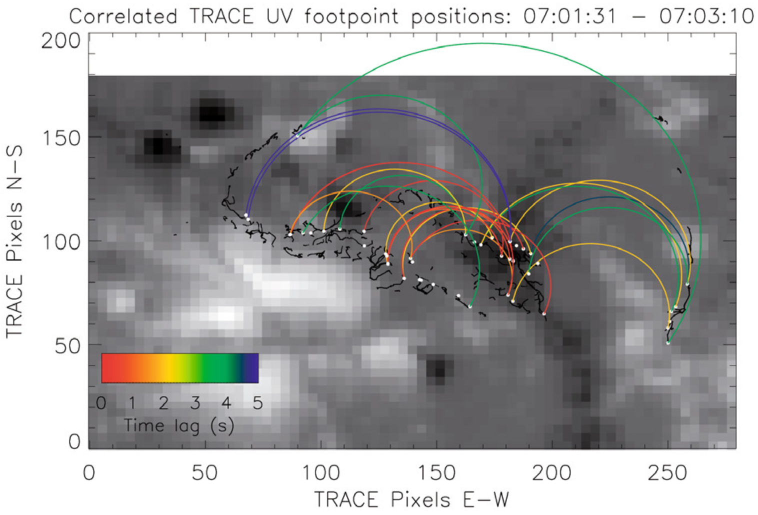
Time evolution of I, v_{DOPP}



Electron beam Heat flux Both

Energy transport: timing

- Electron-beam transport will lead to ~simultaneous footpoint pairs.
- Conduction/wave energy transport may introduce time-lags
- Very few observations have had the cadence and FOV to examine this



2s cadence TRACE UV observations sufficient to find correlated footpoint pairs, and lag between them (Fletcher 09)

Time lags measured during the impulsive phase - often too long for electron transport.

(Look out also for Simões et al. in prep, using observations at 5 and 8 μm)

Conclusions: Targets for MUSE

MUSE capabilities: imaging & spectroscopy at Fe IX/XV/XIX/XXI, large FOV, high cadence make it ideal to tackle some of these long-standing questions

Pre-flare evolution:

- Identify and characterise sources of 'hot onsets'
- Non-thermal broadening & flows in pre-flare ribbons and coronal sources

Conversion:

- quasi-3D flow (& turbulence?) maps in the region around current sheets, including dipolarising loops
- fine structure in space and time in flare ribbons

Energy transport:

- spectroscopic signatures at footpoints, comparison with predictions of RADYN-type modelling
- Timing analysis of footpoint pairs