Spectroscopy at the site of Magnetic Reconnection in the X-class Flare on 2013 May 15

- inward reconnection outflow -

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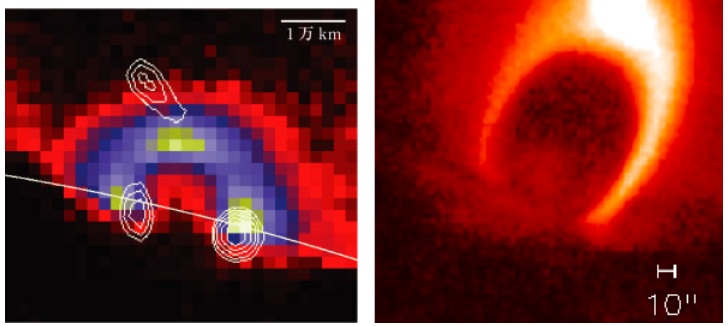
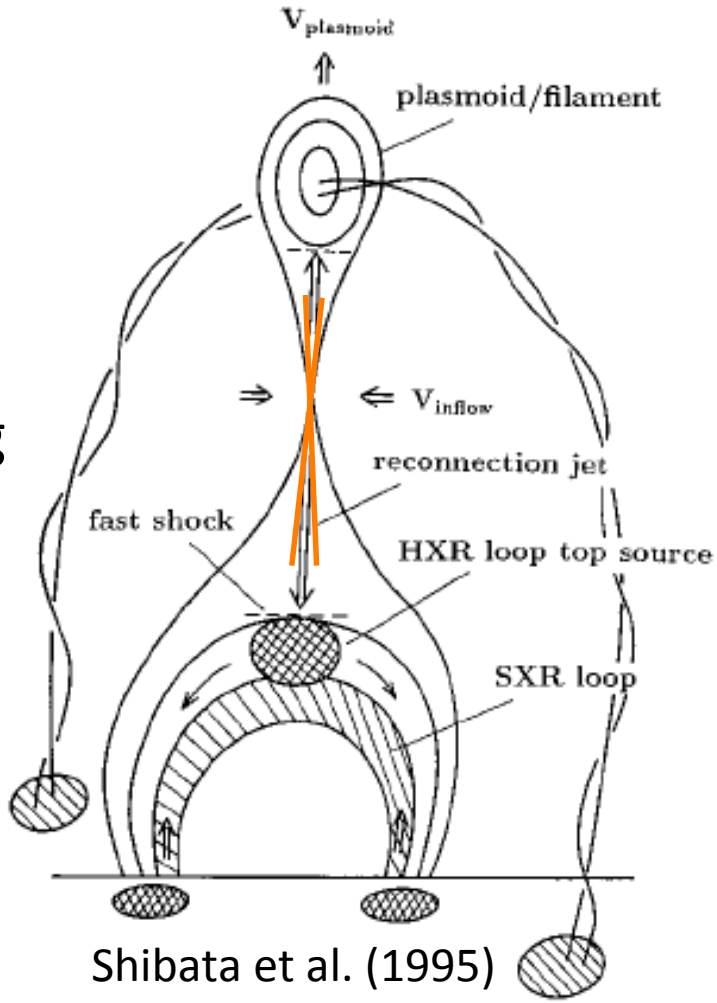
Magnetic Reconnection: a model based on *Yohkoh* imaging observations

The following should be investigated by spectroscopy to understand magnetic reconnection process working in the solar atmosphere.

- Reconnection inflow
- Reconnection outflow
- Position of enhanced hot line broadening found in 1970s
- MHD Shock





Shibata et al. (1995)

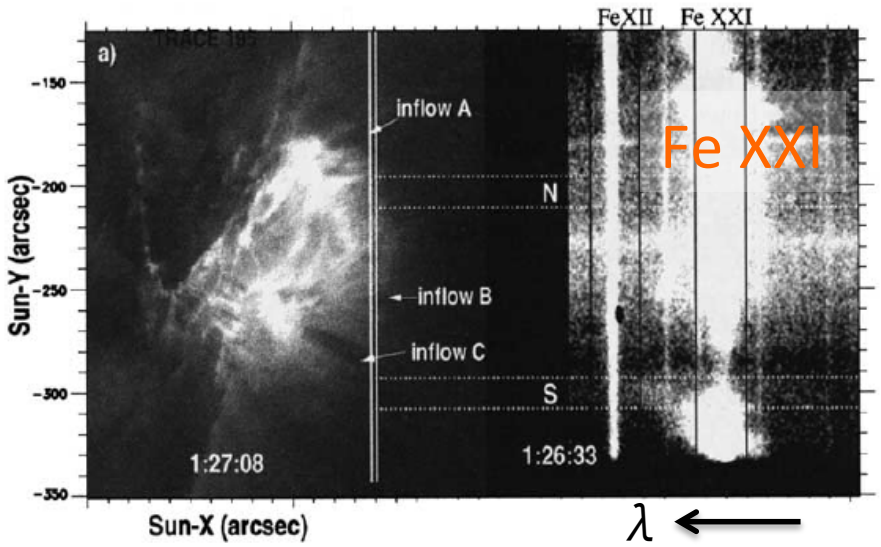
Spectroscopic observations

- In addition to imaging observations, imaging spectroscopy has been expected for observing solar flares
  - to prove plasma motions of reconnection inflow/outflow
  - to identify the source of enhanced line broadening that appears in the impulsive phase
  - to measure plasma parameters (N_e, T_e) from line spectroscopy
- Scanning imaging spectroscopy
  - Pros:
    - Shapes and locations of an object are identified when observed.
  - Cons:
    - Low probability to detect flare-like events due to small field of view.
    - Cadence of observations is slow for short duration events.

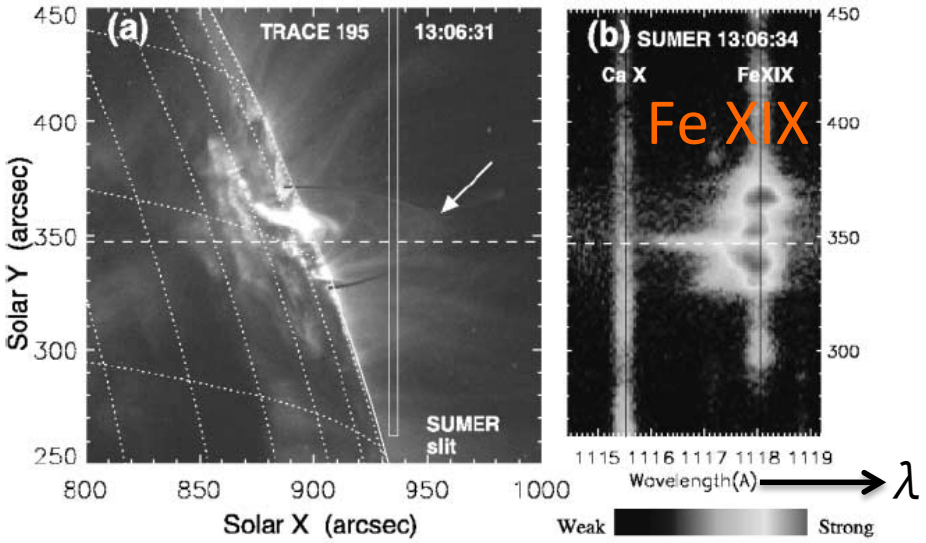
Previous studies

- A few cases have only been reported on the spectrum of reconnection outflow.
  - SOHO/SUMER: Innes+2003(X1.5) Fe XXI
    Wang+2007(M2.5) Fe XIX
  - Hinode/EIS: Hara+2011(B9.5) Fe XXIV, Fe XXIII, Ca XVII

Innes+2003 (GOES X1.5)



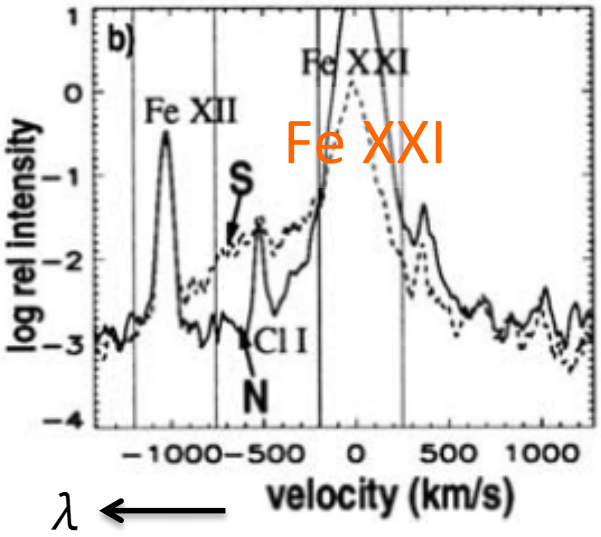
Wang+2007 (GOES M2.5)



Previous studies

- A few cases have only been reported on the spectrum of reconnection outflow. A dark structure in general.
  - SOHO/SUMER: Innes+2003(X1.5) Fe XXI
    Wang+2007(M2.5) Fe XIX
  - Hinode/EIS: Hara+2011(B9.5) Fe XXIV, Fe XXIII, Ca XVII

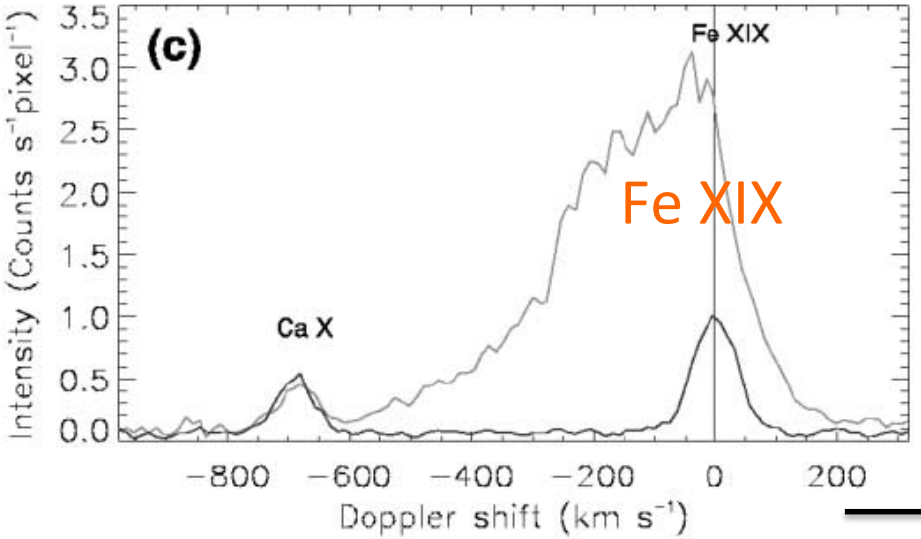
Innes+2003 (GOES X1.5)



red

λ ←

Wang+2007 (GOES M2.5)

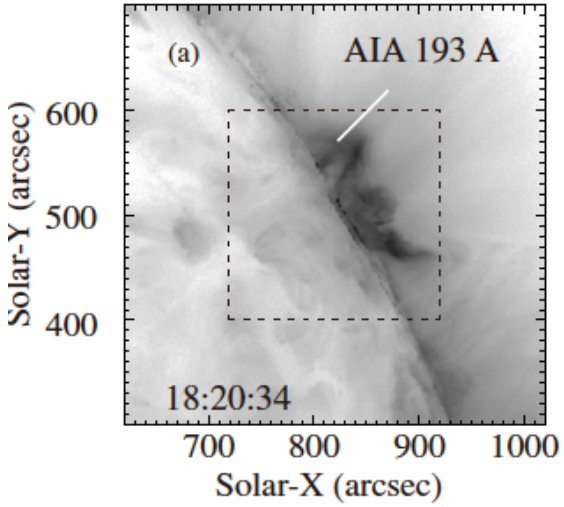


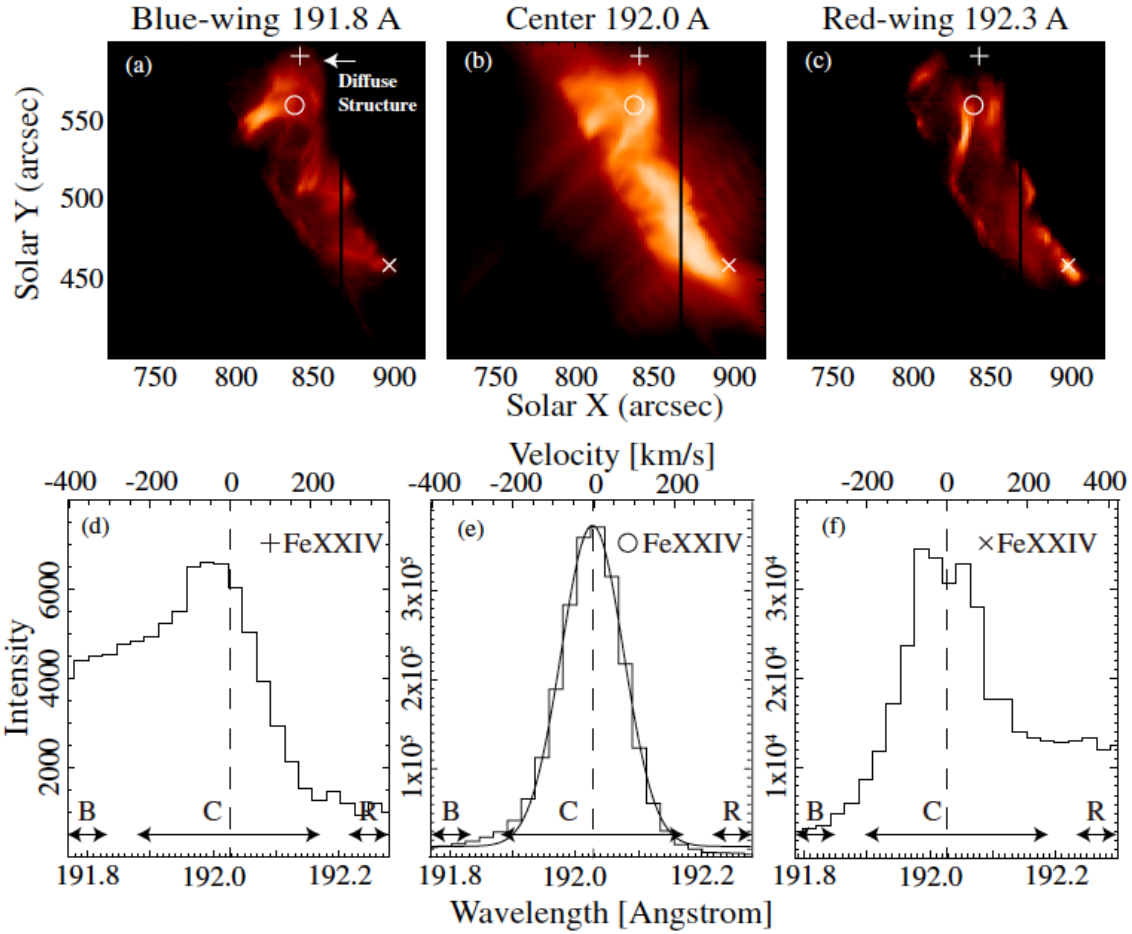
red

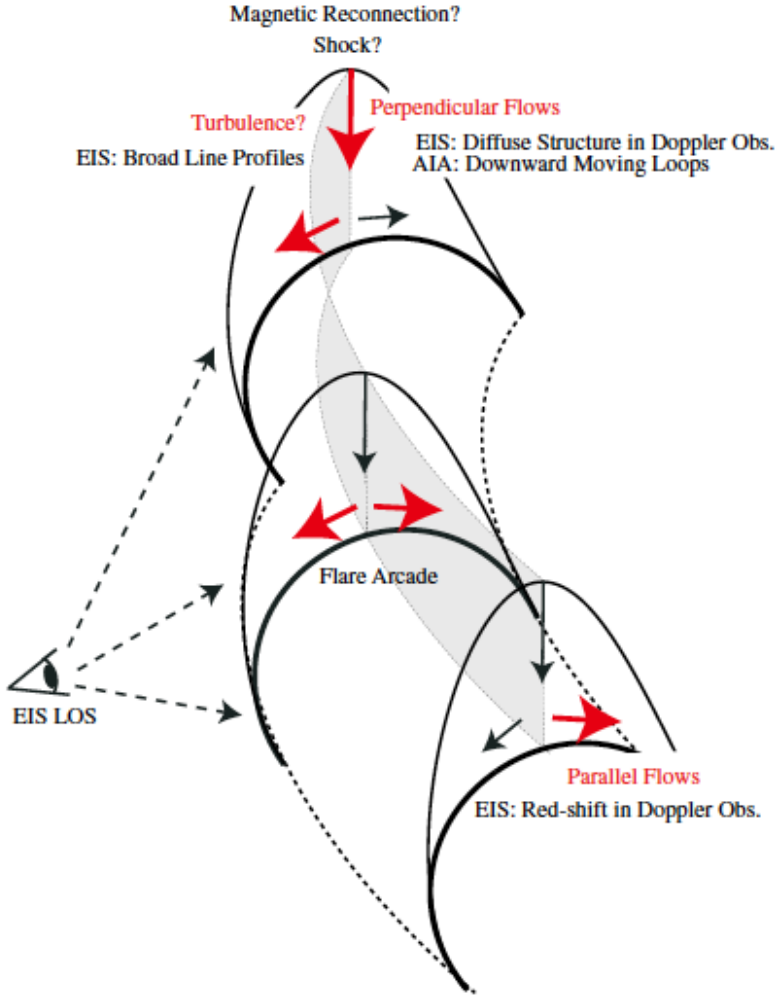
→ λ

Hot fast outflow near the peak phase

Imada et al. ApJ, 776, L11 (2013)

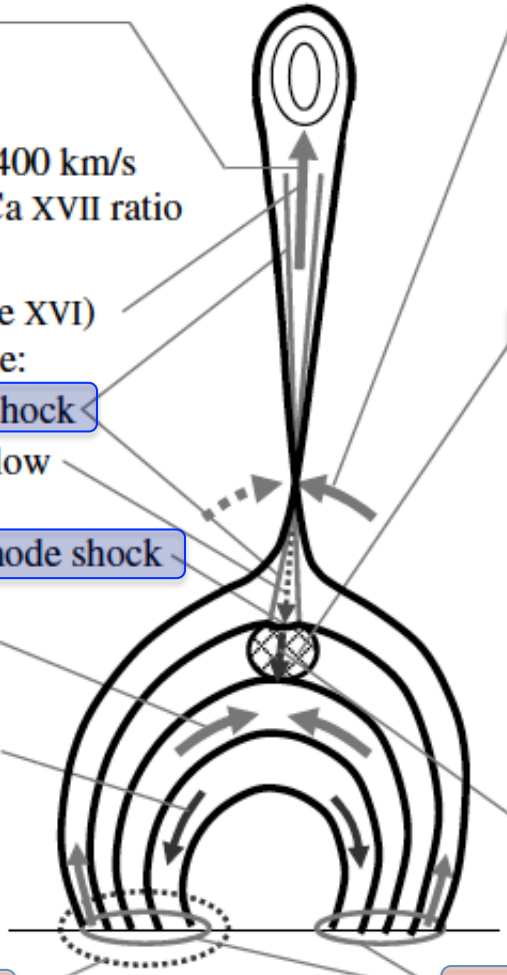






Observed & Suggested Structures in 2007 May 19 event from EIS Obs.

Hara et al. (2011)



Reconnection outflow
EIS Fe XXIV & Ca XVII
- Doppler velocity
  $-V_D = -V_{outflow} \cos \theta_2$ ~200–400 km/s
- T_e = 9.4 MK from Fe XXIV/Ca XVII ratio
- $n_e \sim 4\times10^9$ cm^{-3} from EM

Warm outflow (EIS Fe XV & Fe XVI) appeared before HXR peak time:

Slow-mode shock

Reconnection outflow (not observed)

Fast-mode shock

Upflow: V_D ~ -20 km/s
EIS Fe XXIII & Fe XXIV

Downflow: V_D ~ 10 km/s
EIS Fe XV & Fe XVI

Hard X-ray nonthermal source
RHESSI 15–40 keV

Reconnection inflow
EIS Fe X & Fe XII
- Doppler velocity
  $V_D = V_{inflow} \cos \theta_1$ ~ -20 km/s
- T_e = 1.2 MK from Fe XII/Fe X ratio
- $n_e = 2.5\times10^9$ cm^{-3} from Fe XII ratio

Bright blob
- EIS Fe XXIII & Fe XXIV
  T_e = 12 MK from line ratio
  $n_e \sim 1\times10^{10}$ cm^{-3} from EM
  V_{NT} ~ 100 km/s at impulsive phase
- XRT: faint X-ray enhancement
- RHESSI 4–6 keV thermal source
  T_e = 12 MK from HXR spectrum
- STEREO 195Å band enhancement
  (Fe XXIV λ192 contribution)

Downward motion V_D ~ 30 km/s
EIS Fe XXIII & Fe XXIV

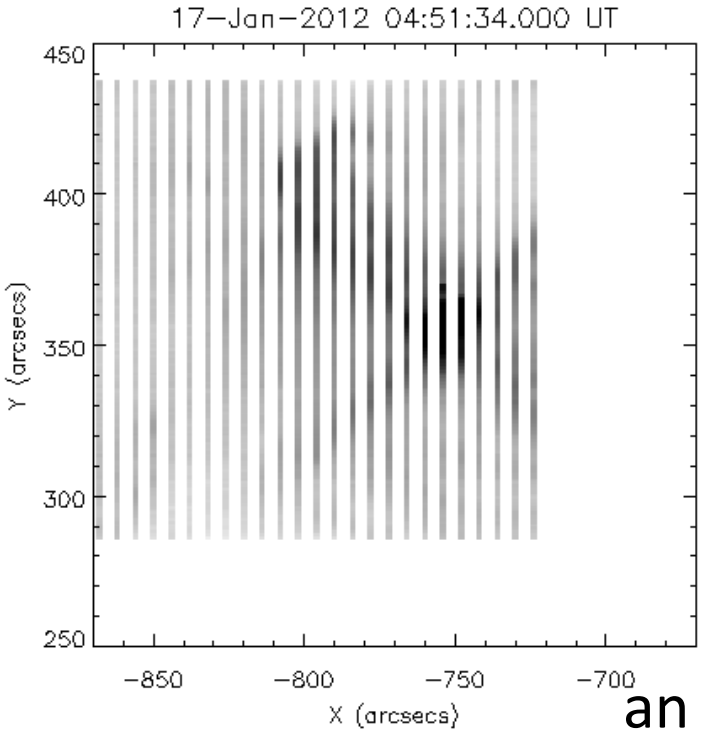
Footpoint brightening
as 'two ribbon structure'
TRACE 171Å band images

$$V_{inflow} / V_{outflow} = (V_{D,\,inflow} / V_{D,\,outflow}) (\cos \theta_2 / \cos \theta_1) = 0.067 (\cos \theta_2 / \cos \theta_1)$$

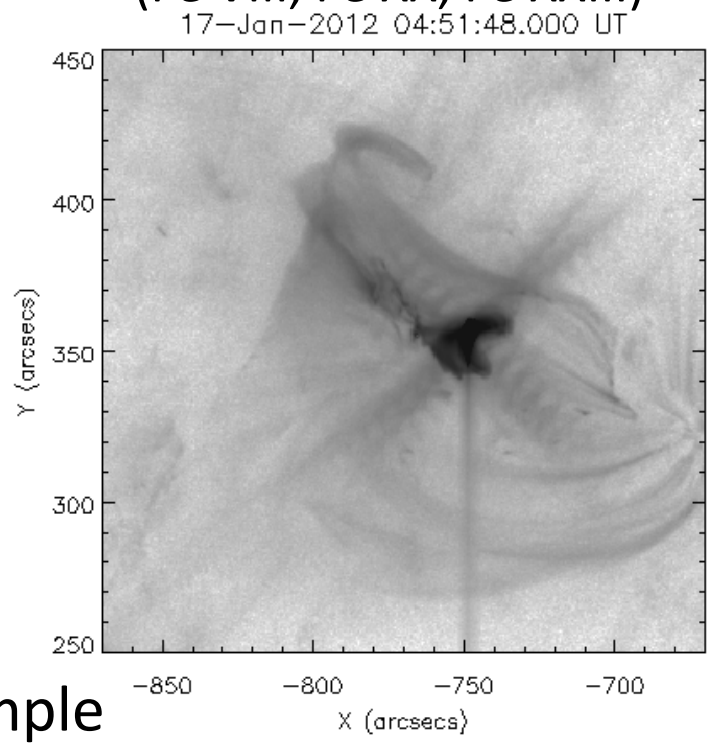
Sparse Raster Observations

- Satisfy both a modest cadence observation and a wide field of view for a high probability of flare detection.
- Detection of various signatures for magnetic reconnection

EIS Fe XXIV 192



AIA 131
(Fe VIII, Fe XX, Fe XXIII)

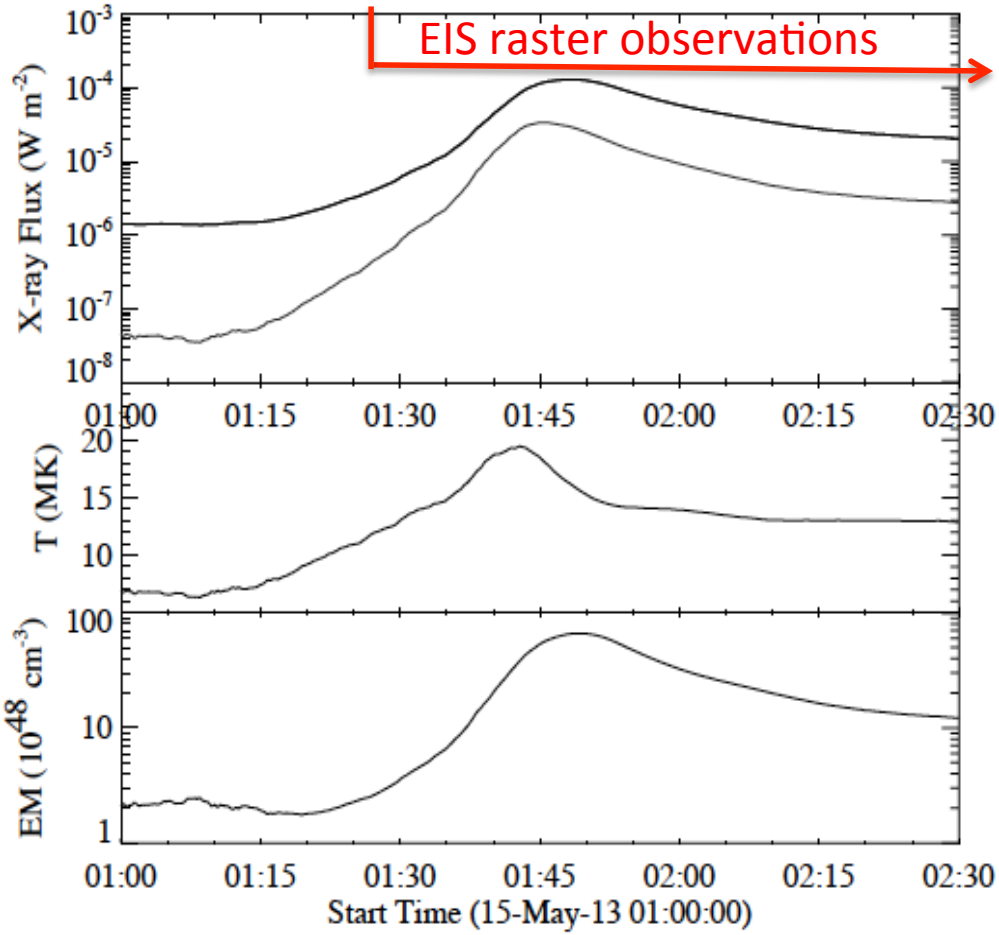


an example

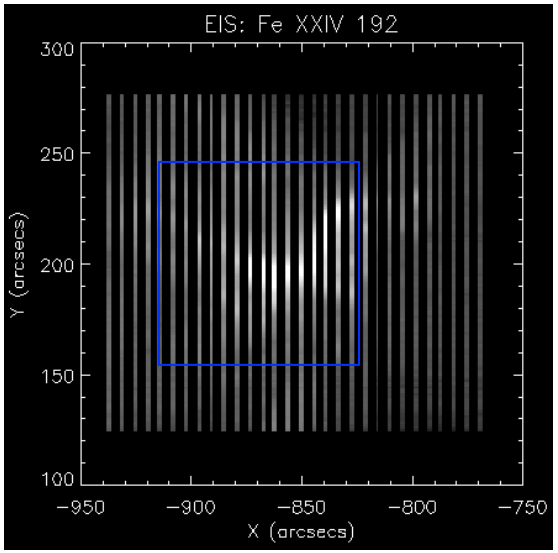
2013 May 15 Flare

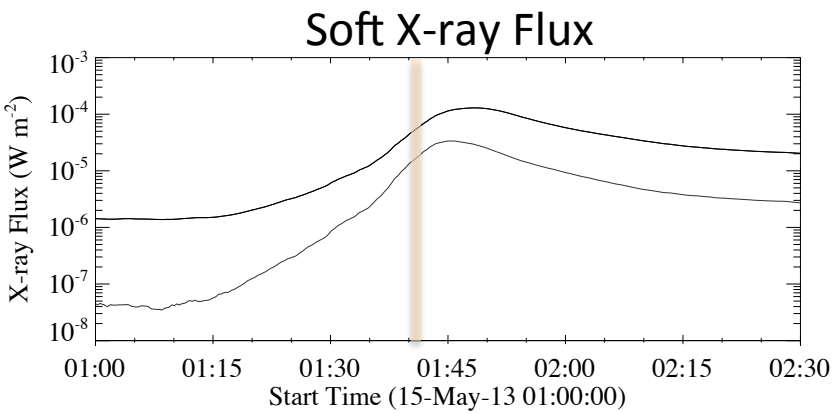
- GOES X1.2 flare (N12, E68)
- EIS sparse raster obs. from the start to end
  - ~5 min cadence raster
  - 6” raster step by 2” wide slit
- RHESSI and NoRH data are also available.
- Events in the data
  - Evaporation
  - Inward/outward fast flows

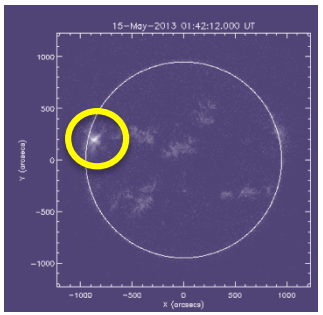
    including supra-archade downflows
  - Inflows
  - HXR above-the-loop-top source



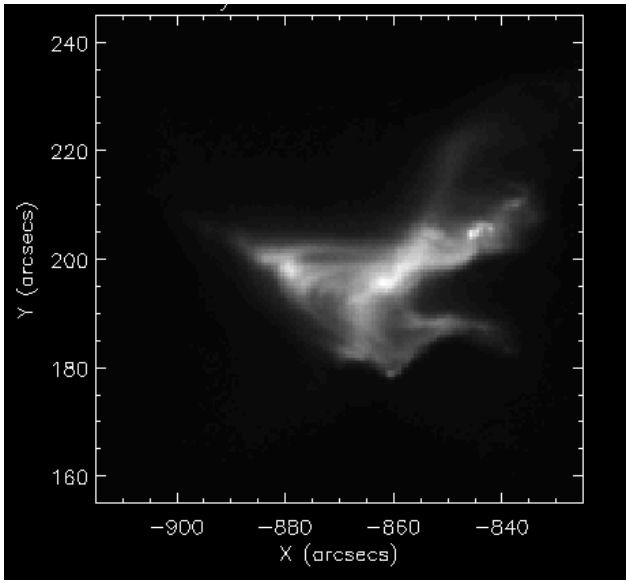
Hard X-ray Sources

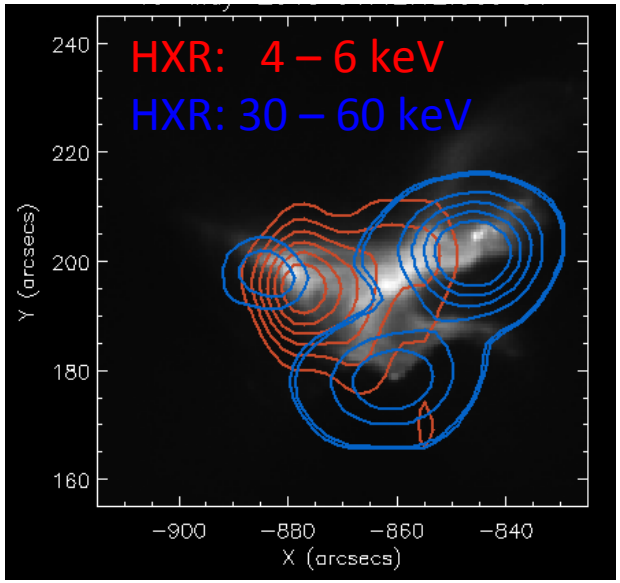




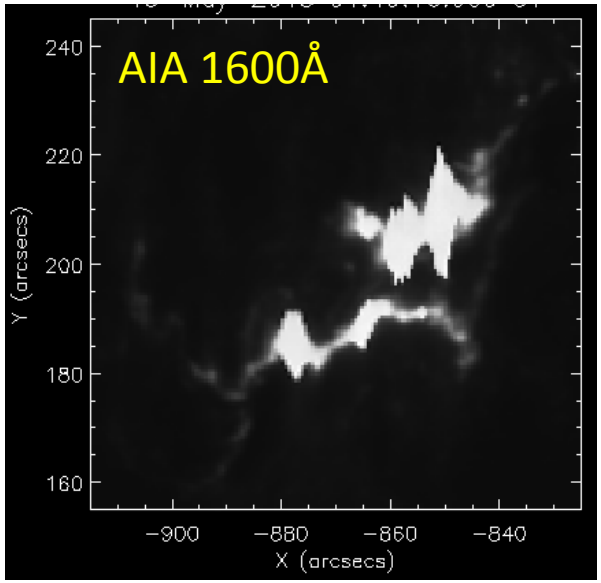


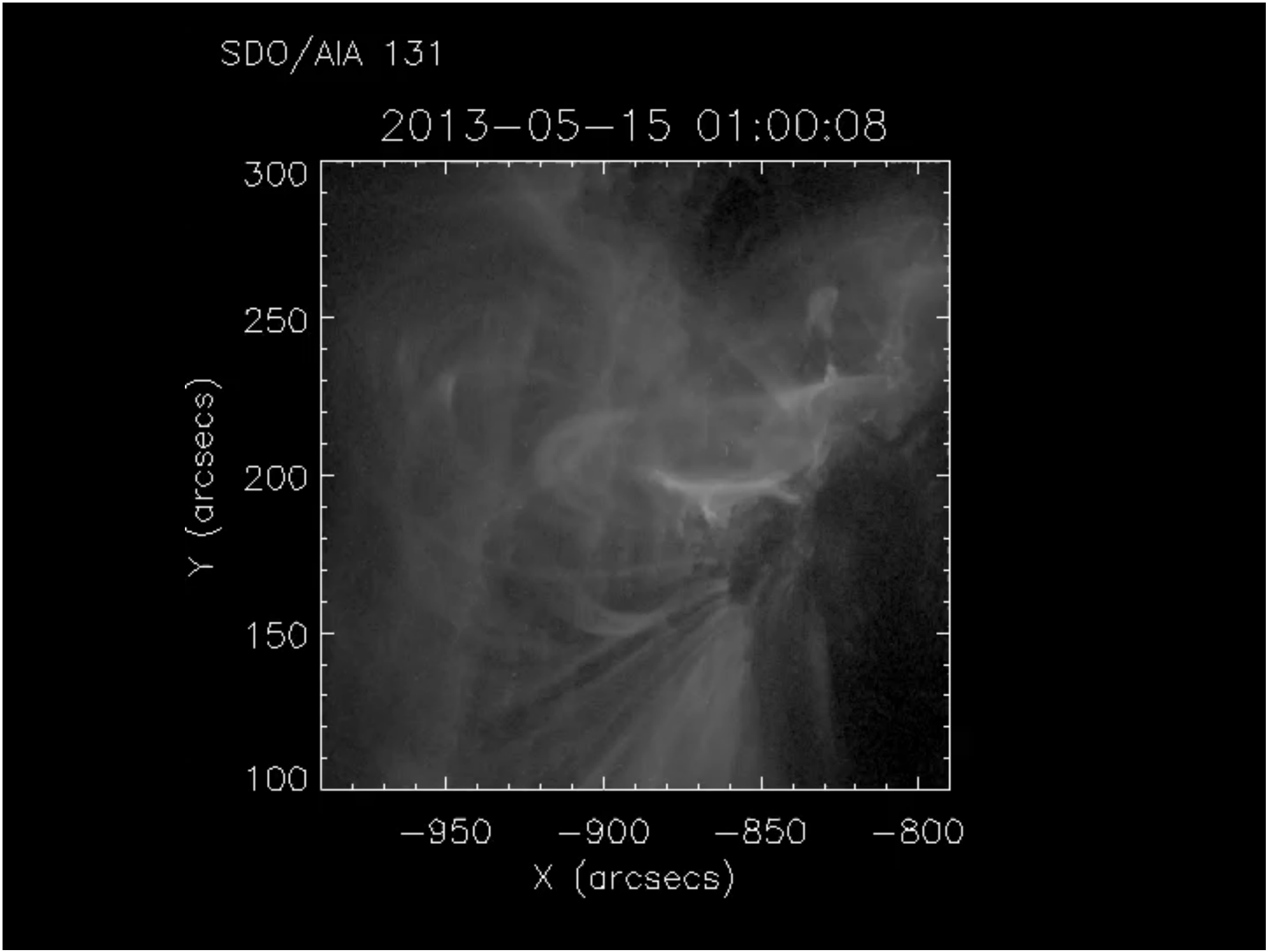
AIA 131Å (Fe XXI ~10^7 K)





Response of TR (~10^5 K)




SDO/AIA 131
2013-05-15 01:00:08
300
250
200
150
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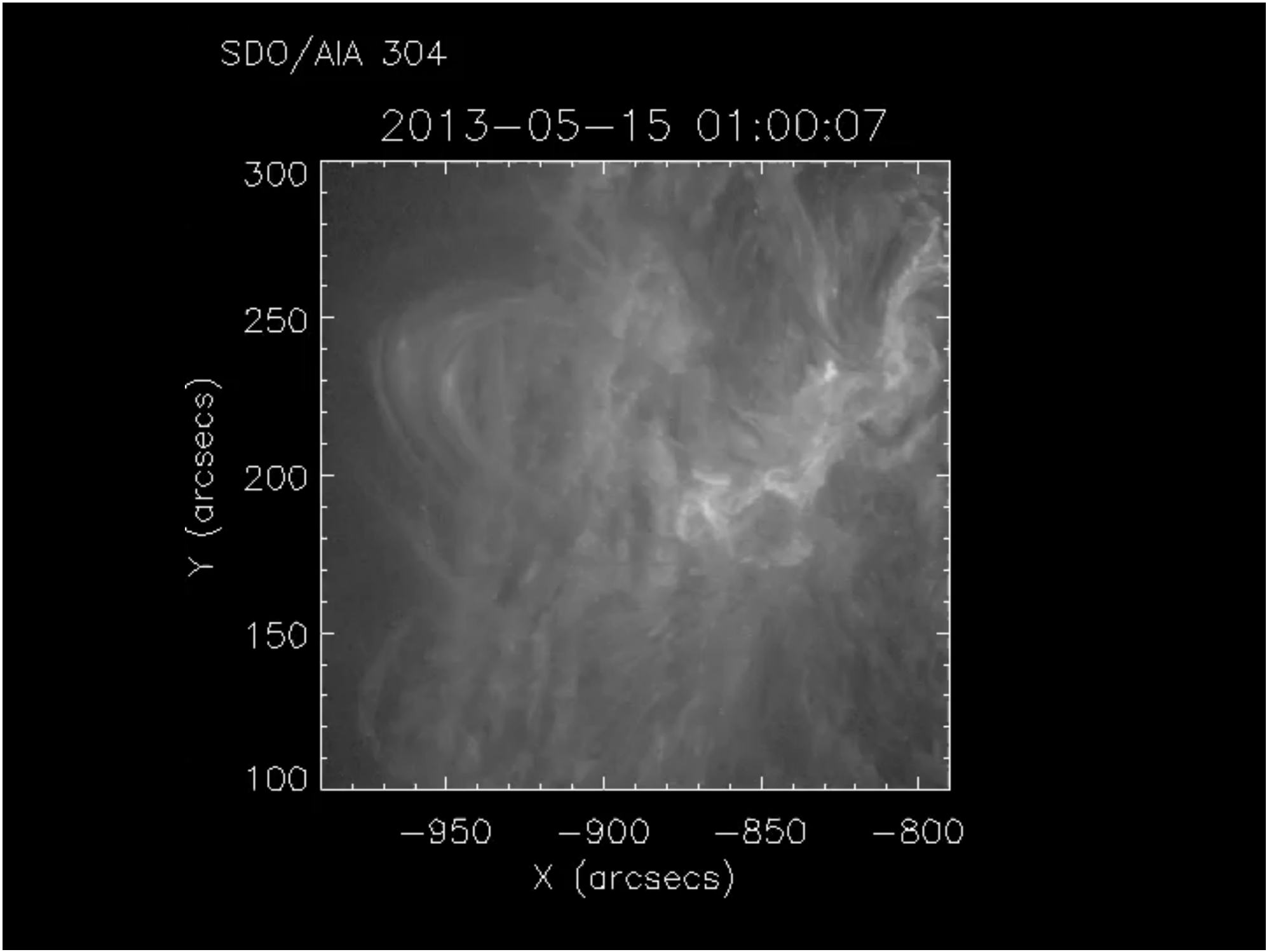
Y (arcsecs)
-950
-900
-850
-800
X (arcsecs)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Y (arcsecs)
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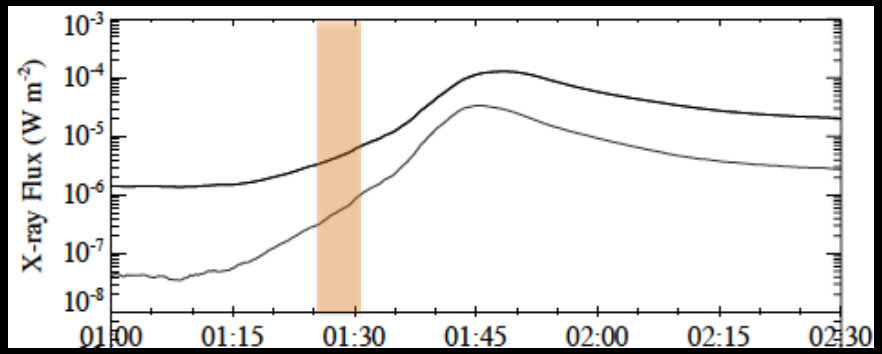
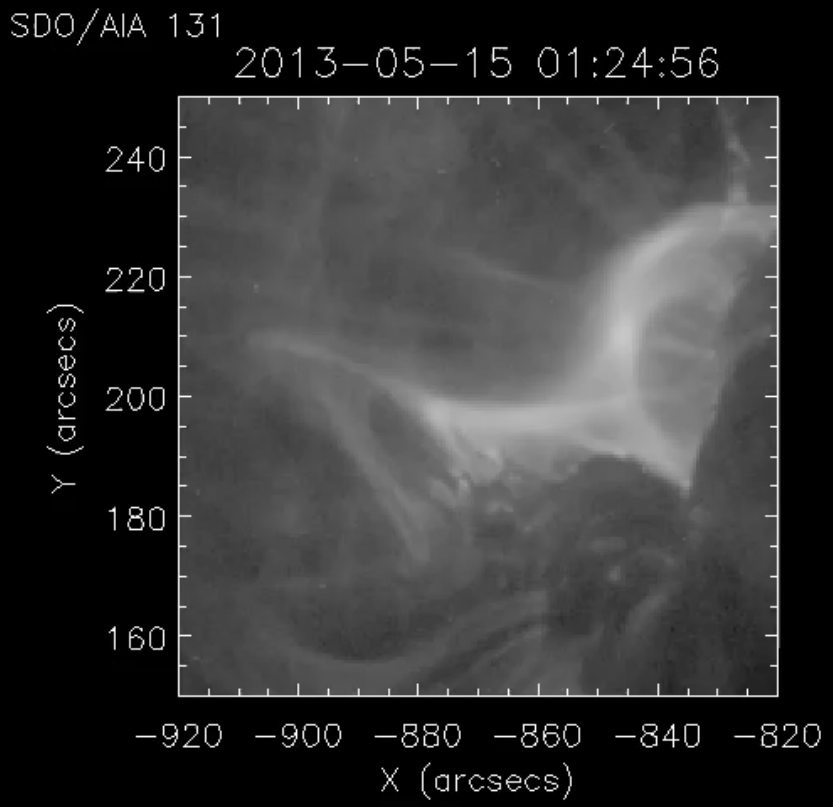
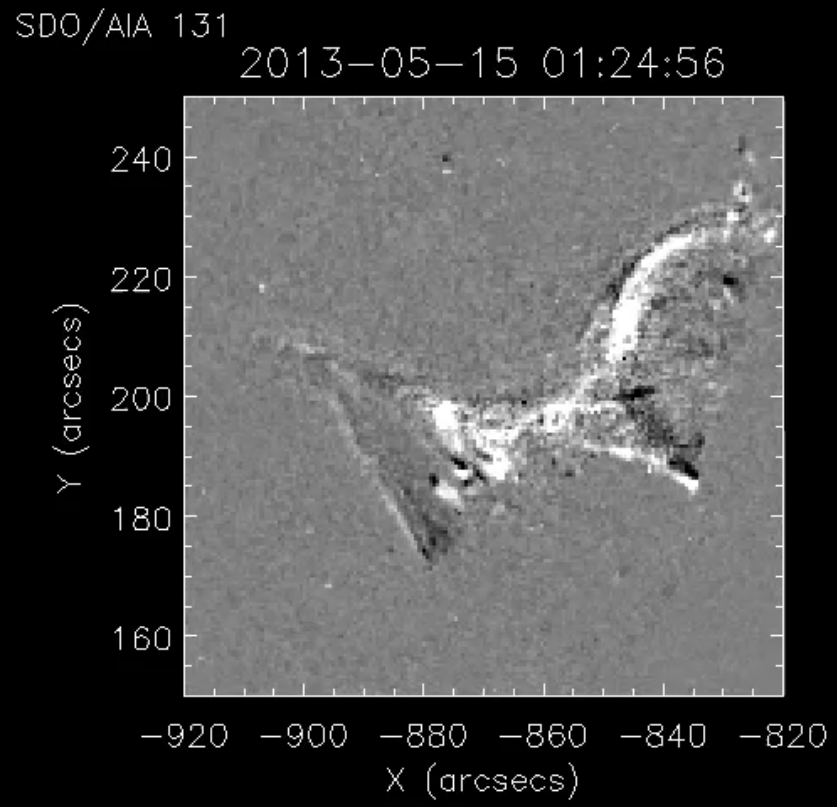
-800
X (arcsecs)

Dynamics in an EIS sparse raster

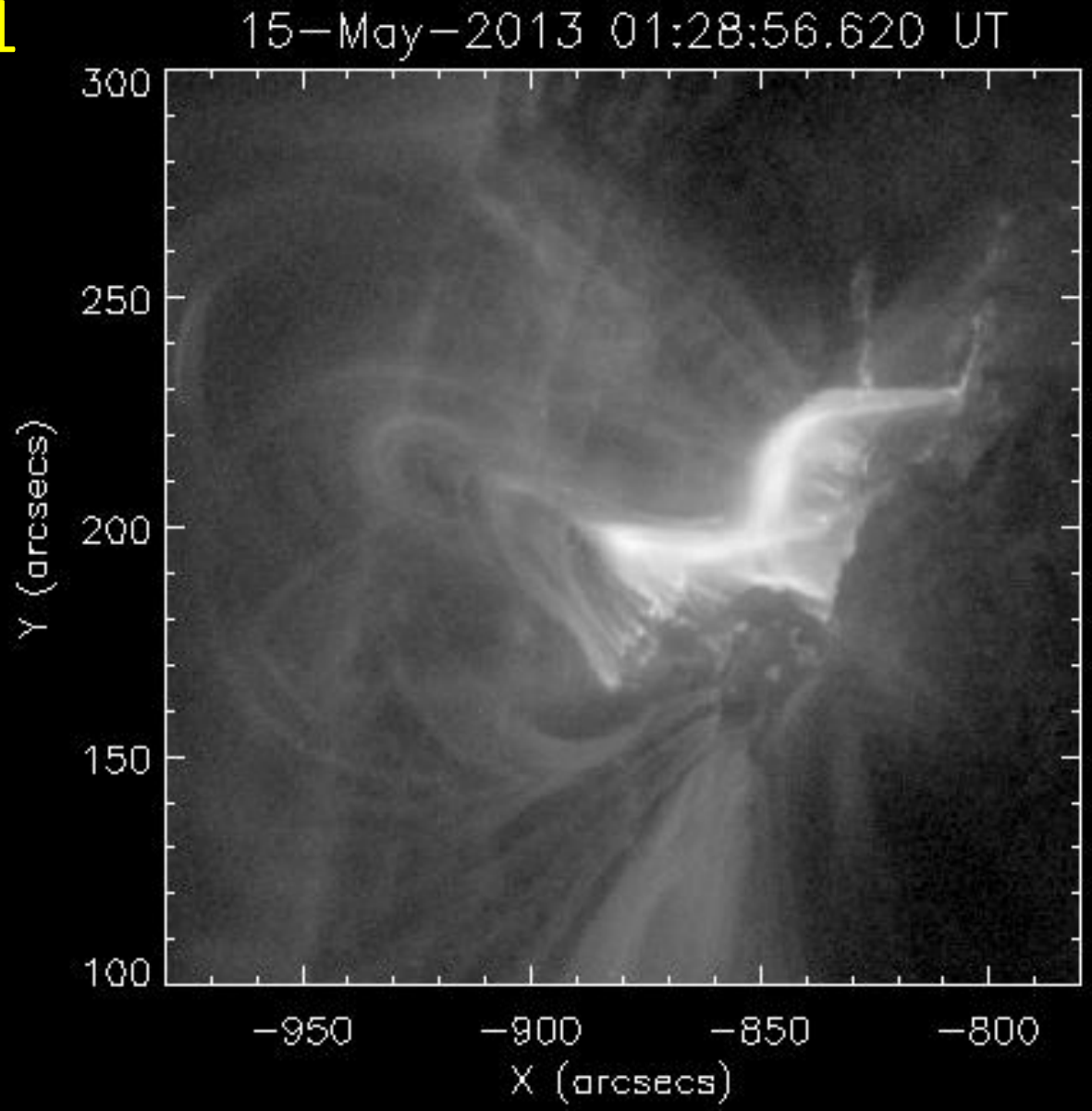


- Many changes are going on during a single EIS raster observation.





AIA 131


15-May-2013 01:28:56.620 UT
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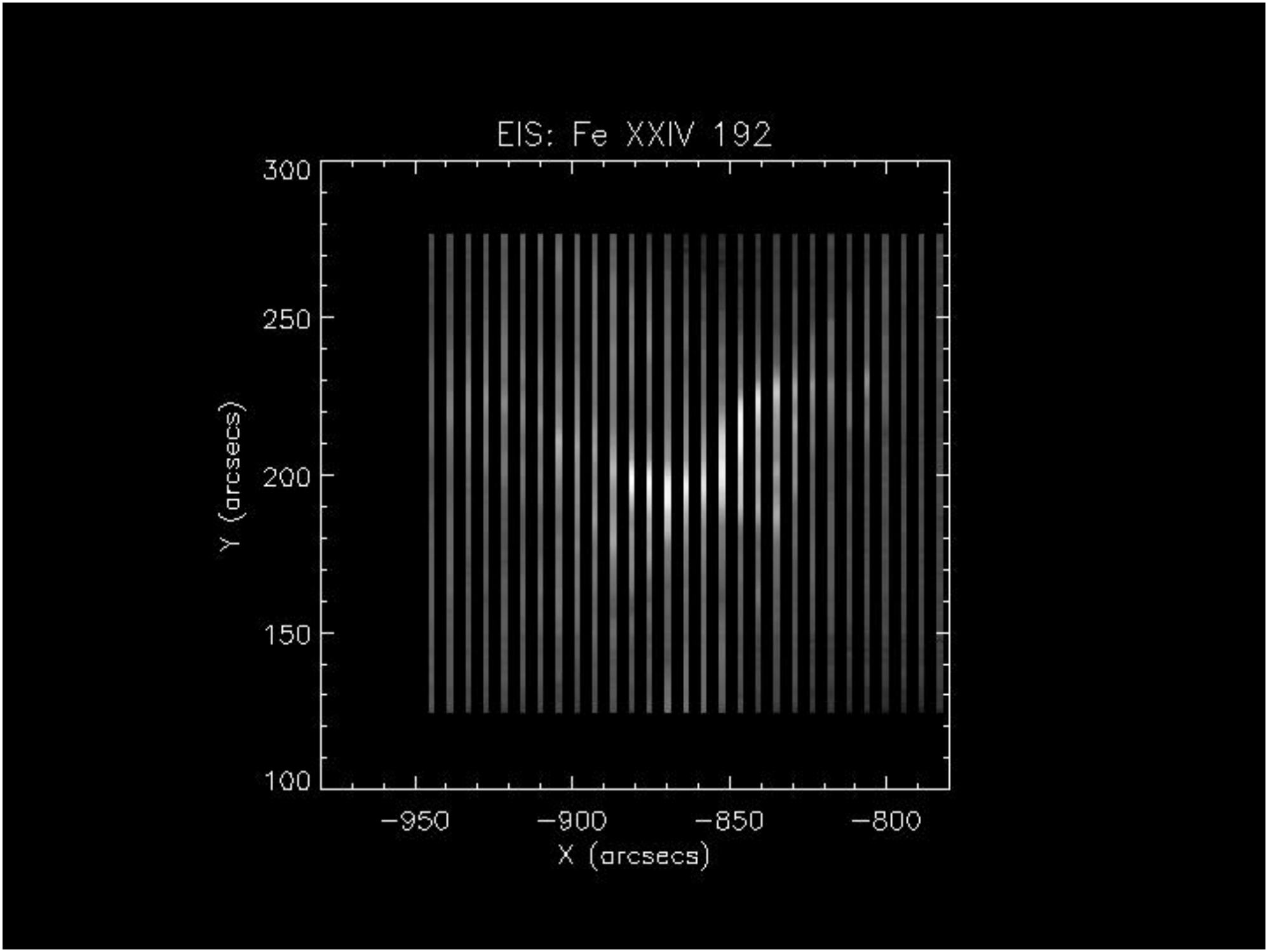
X (arcsecs)


EIS: Fe XXIV 192
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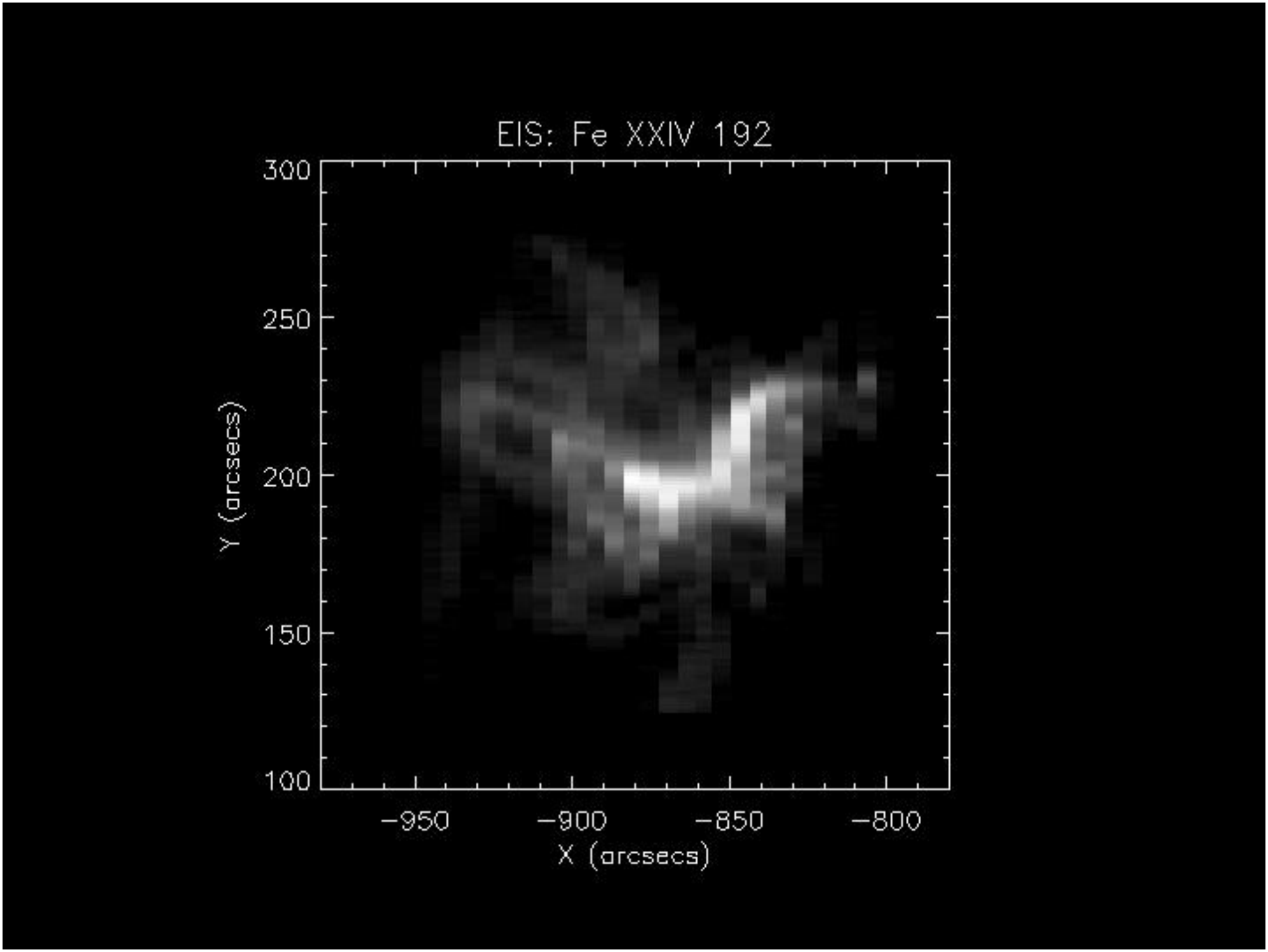
Y (arcsecs)
−950
−900
−850
−800
X (arcsecs)


EIS: Fe XXIV 192
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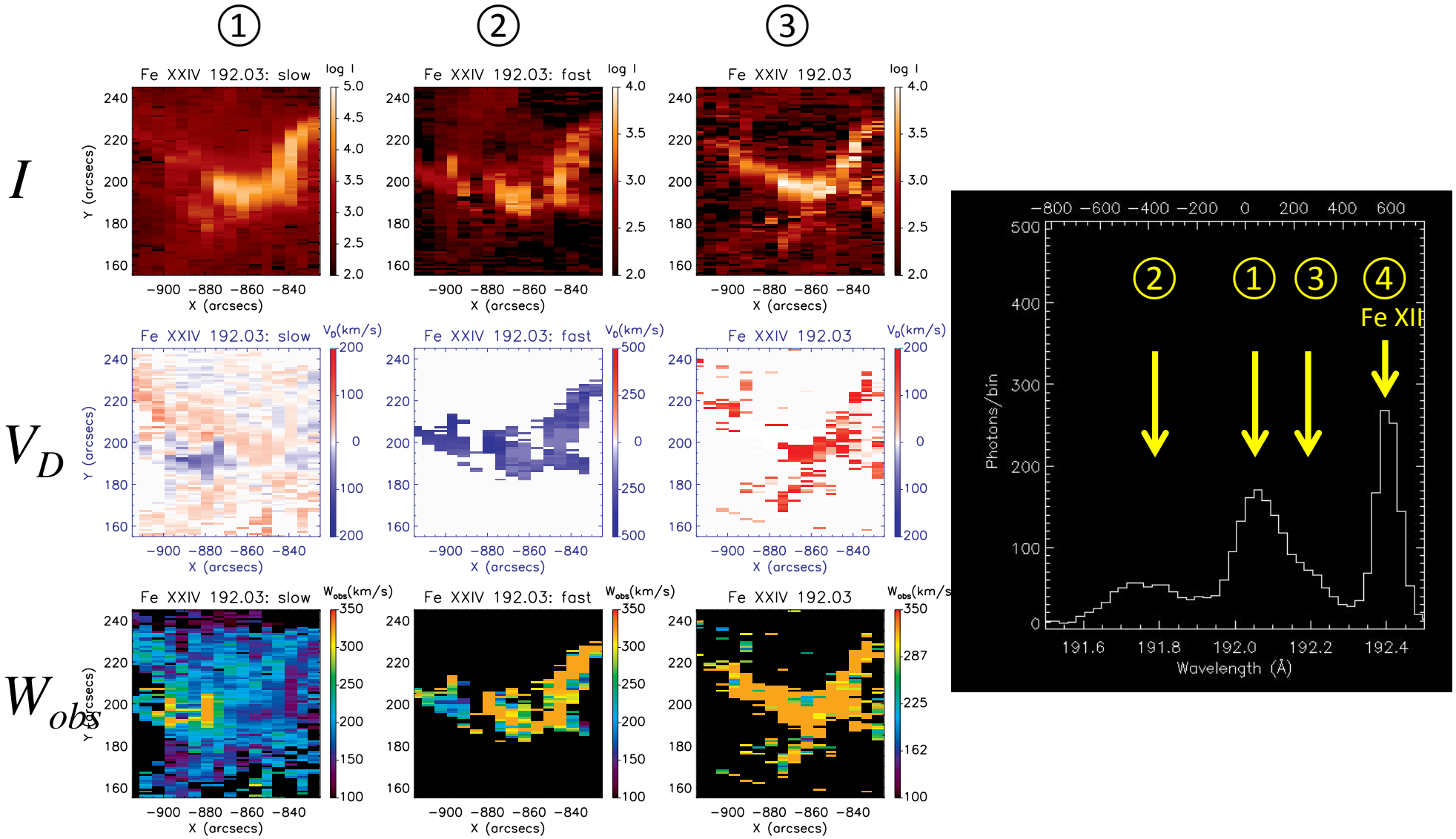
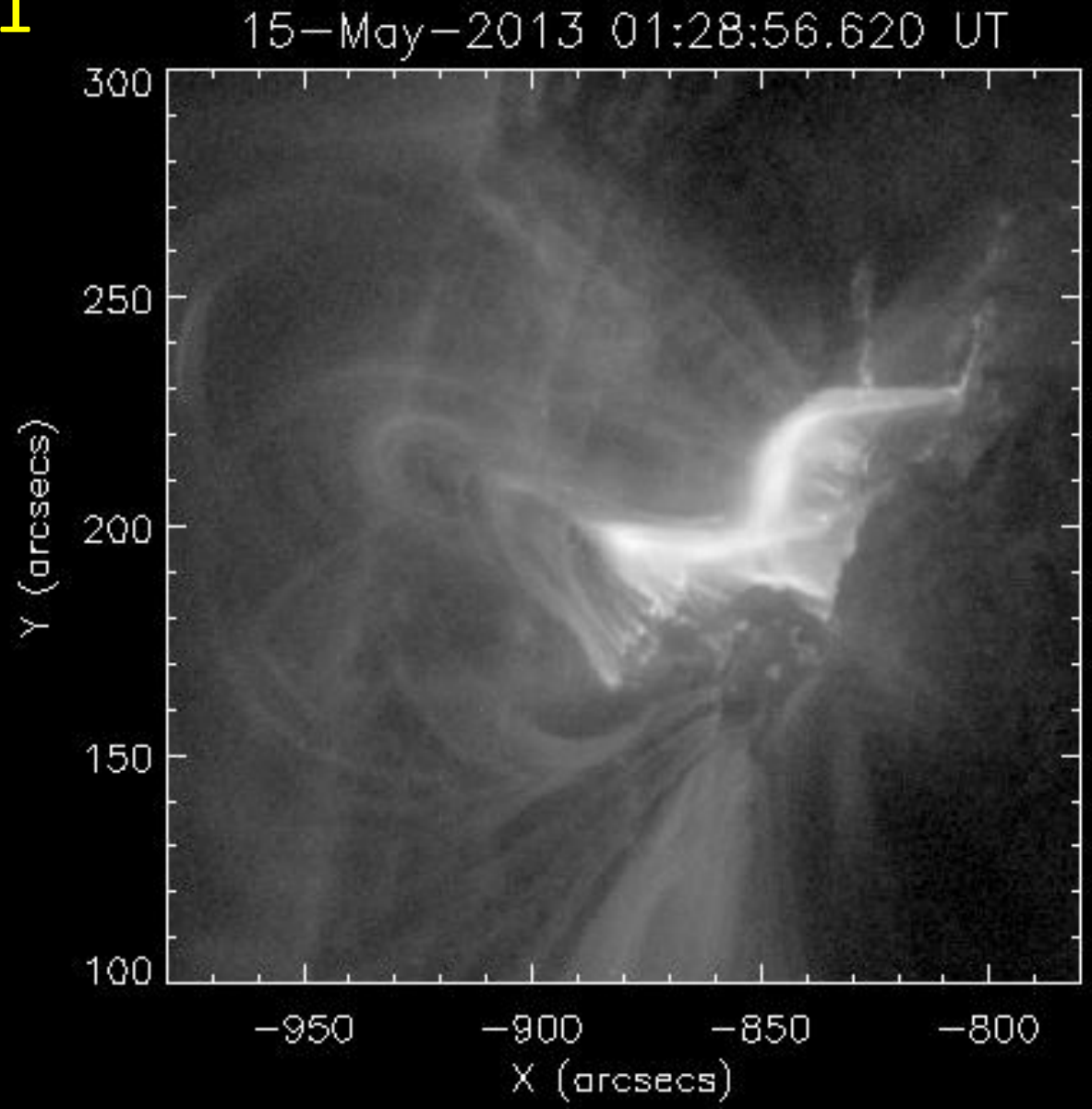
X (arcsecs)

Multi-Gaussian fitting for Quick Look



AIA 131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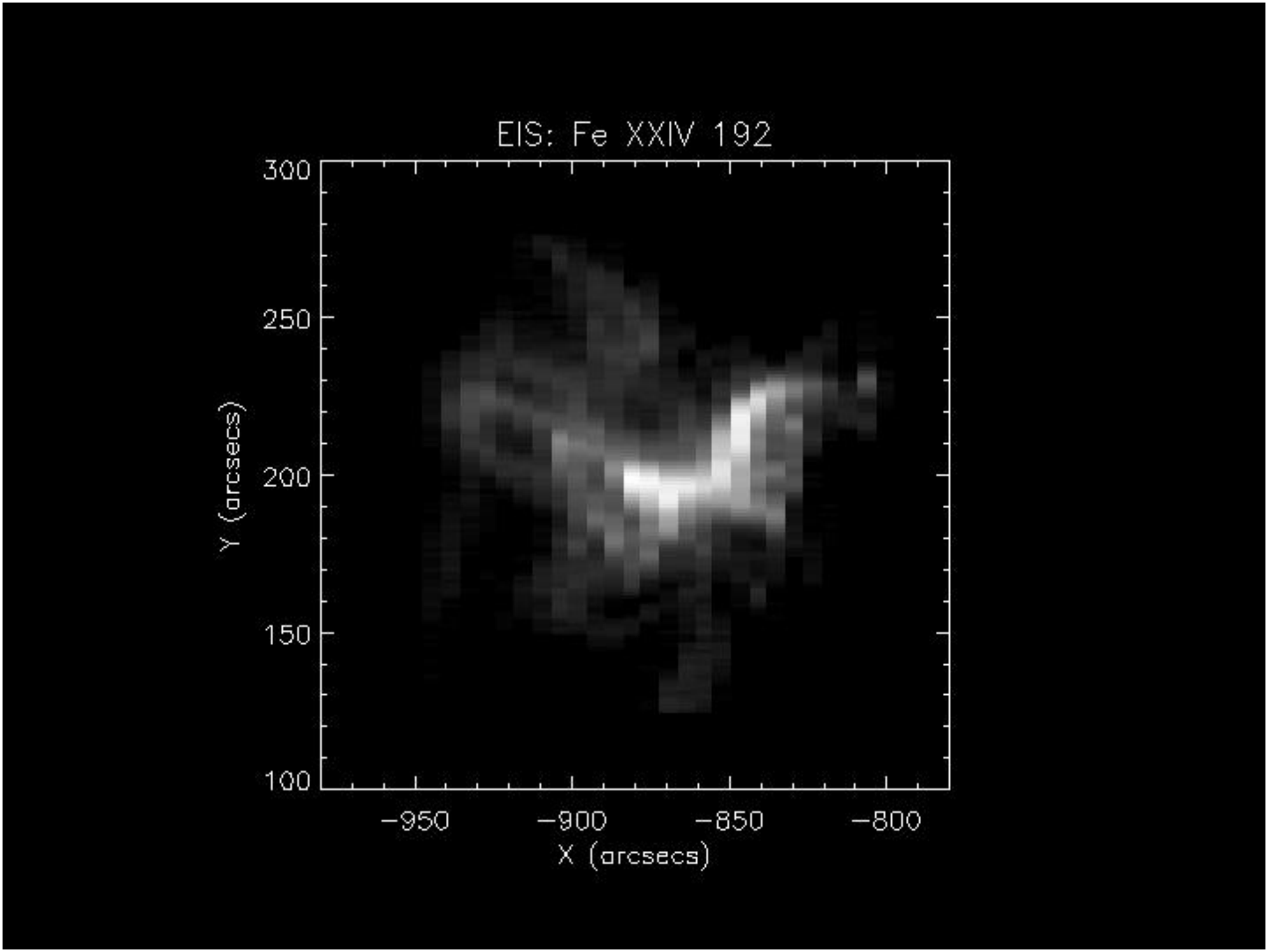
EIS: Fe XXIV 192
300
250
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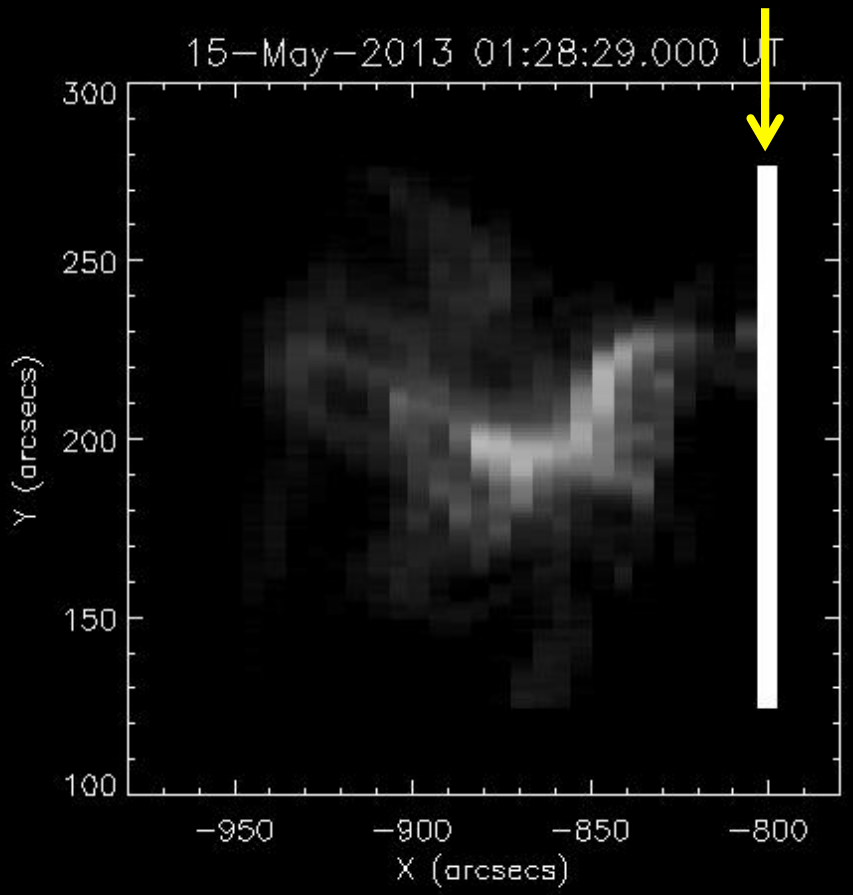
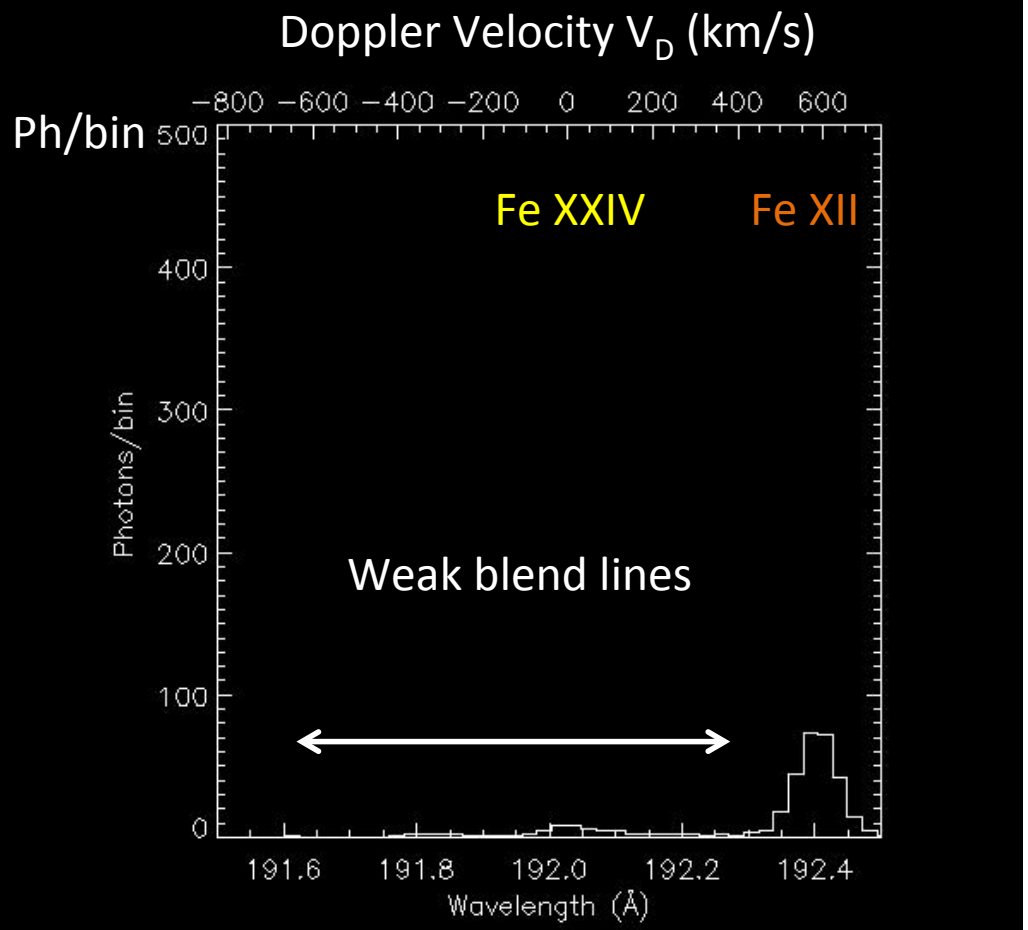
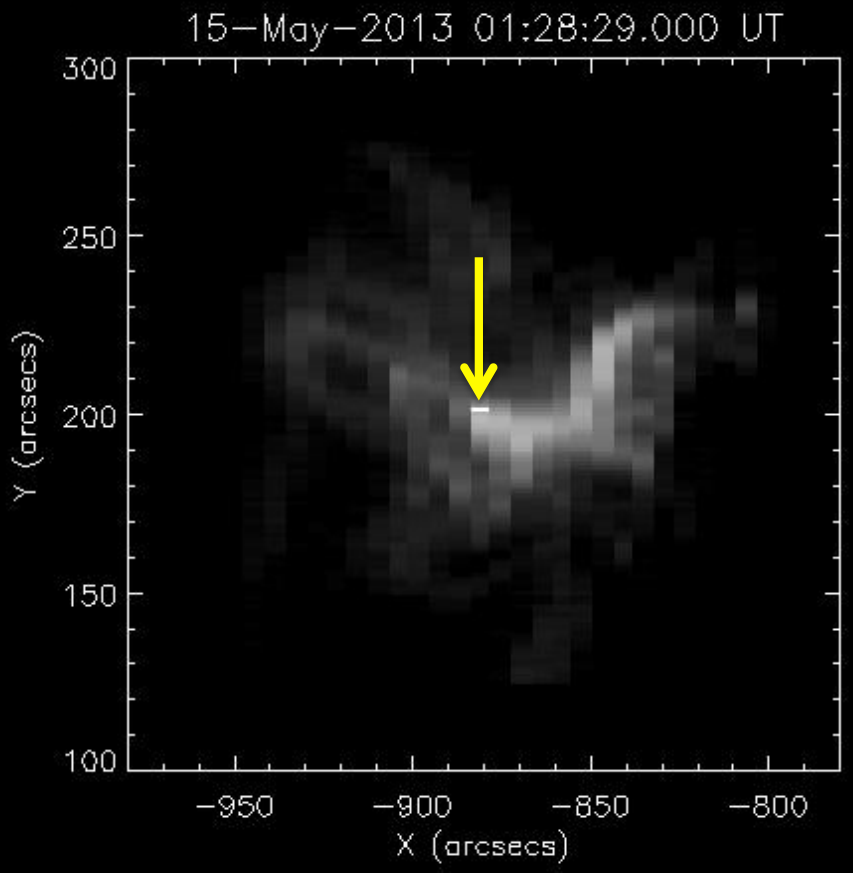
150
100
Y (arcsecs)
−950
−900
−850
−800
X (arcsecs)

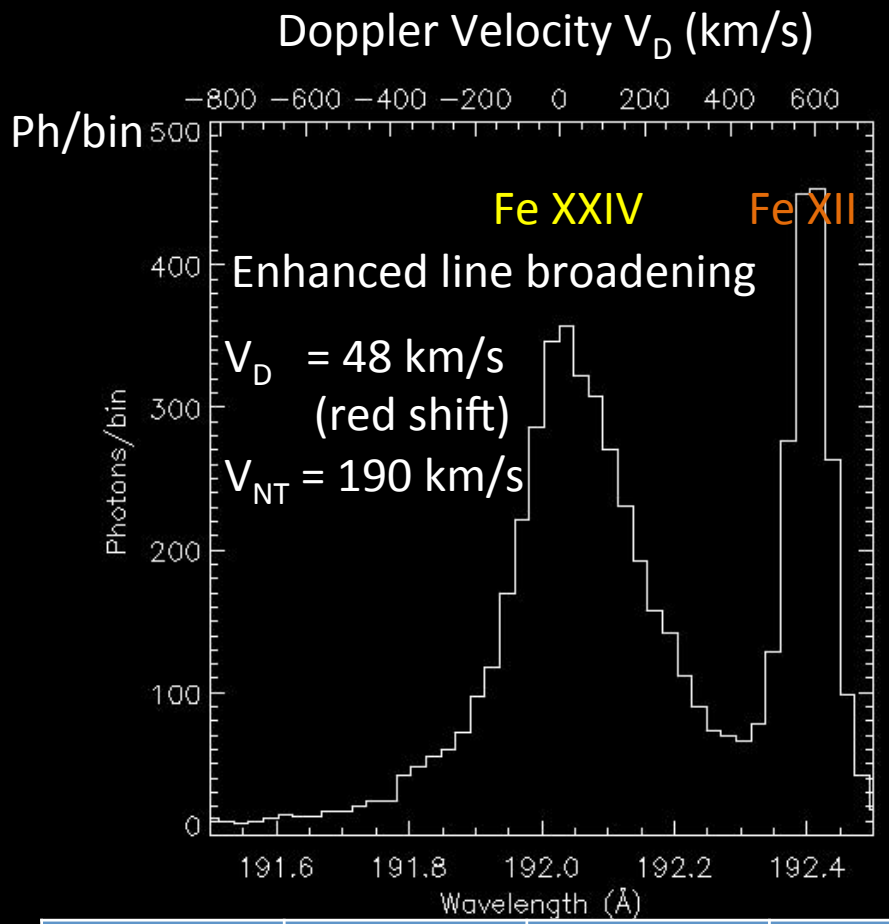
Average spectrum outside Flare Region





Spectrum in the thin structure at the loop top

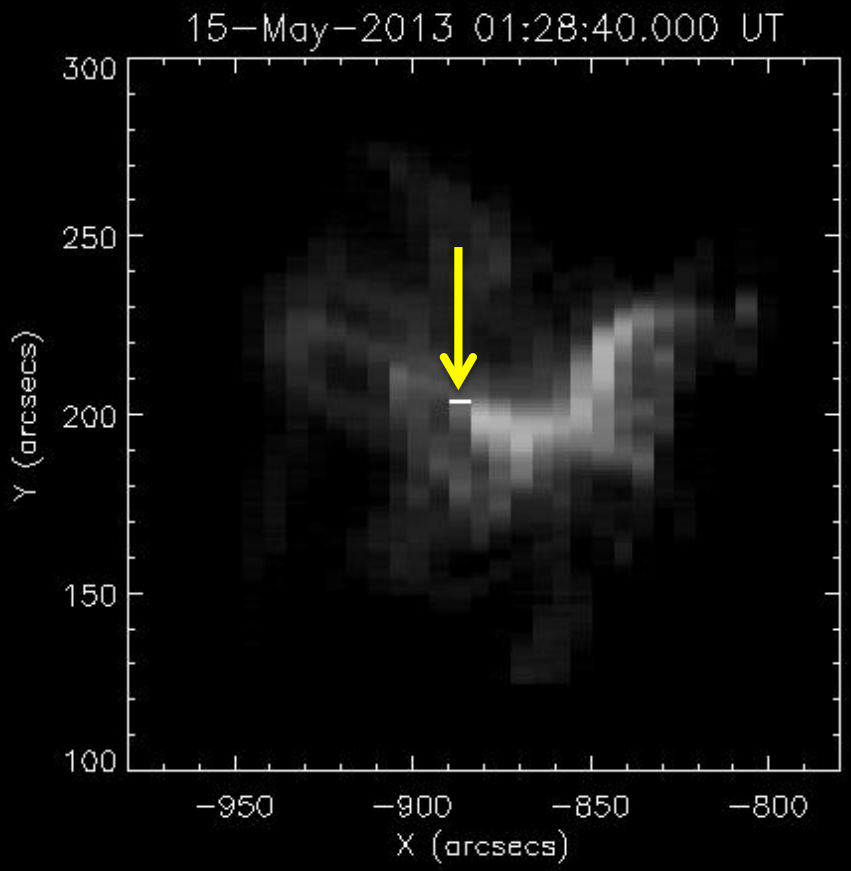


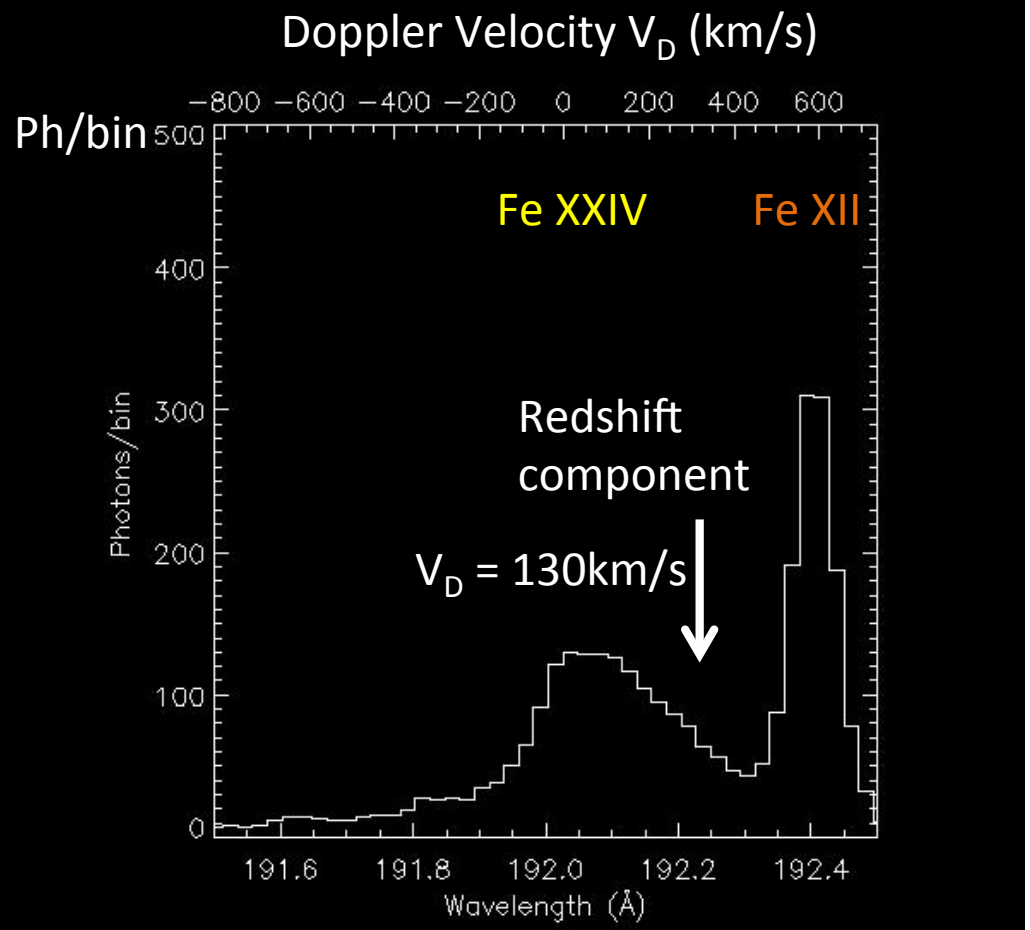


V_D and V_{NT} at the bright loop-top structure

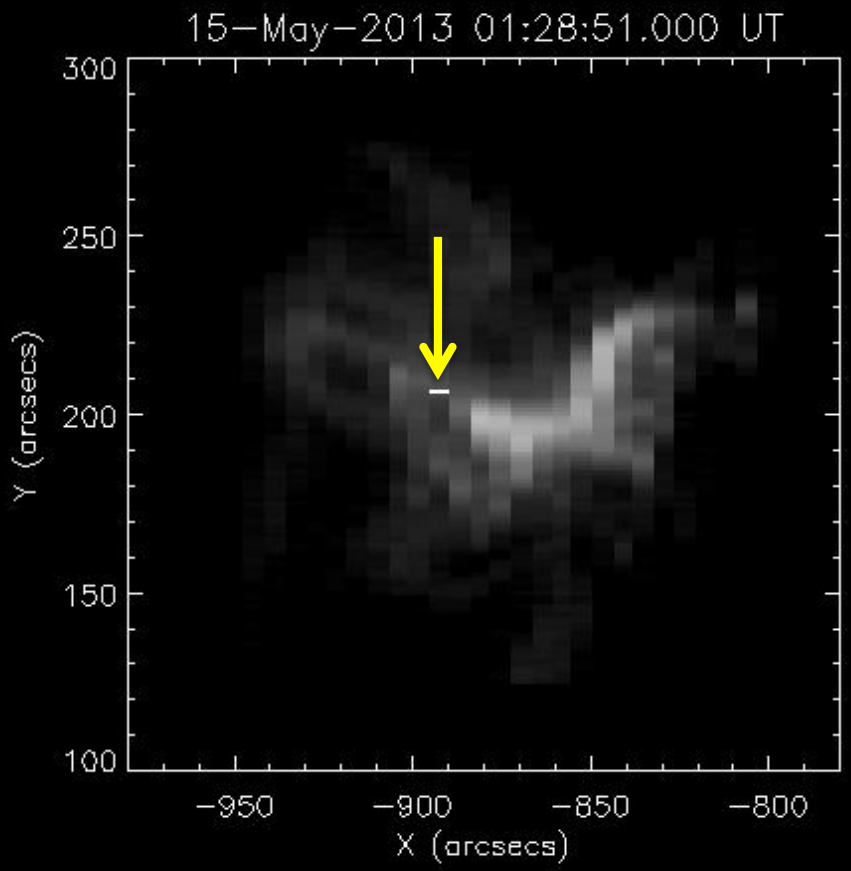
	2007 05 19	2012 01 17	2013 05 15
V_D (km/s)	+30	+16	+48
V_{NT} (km/s)	100	140	190

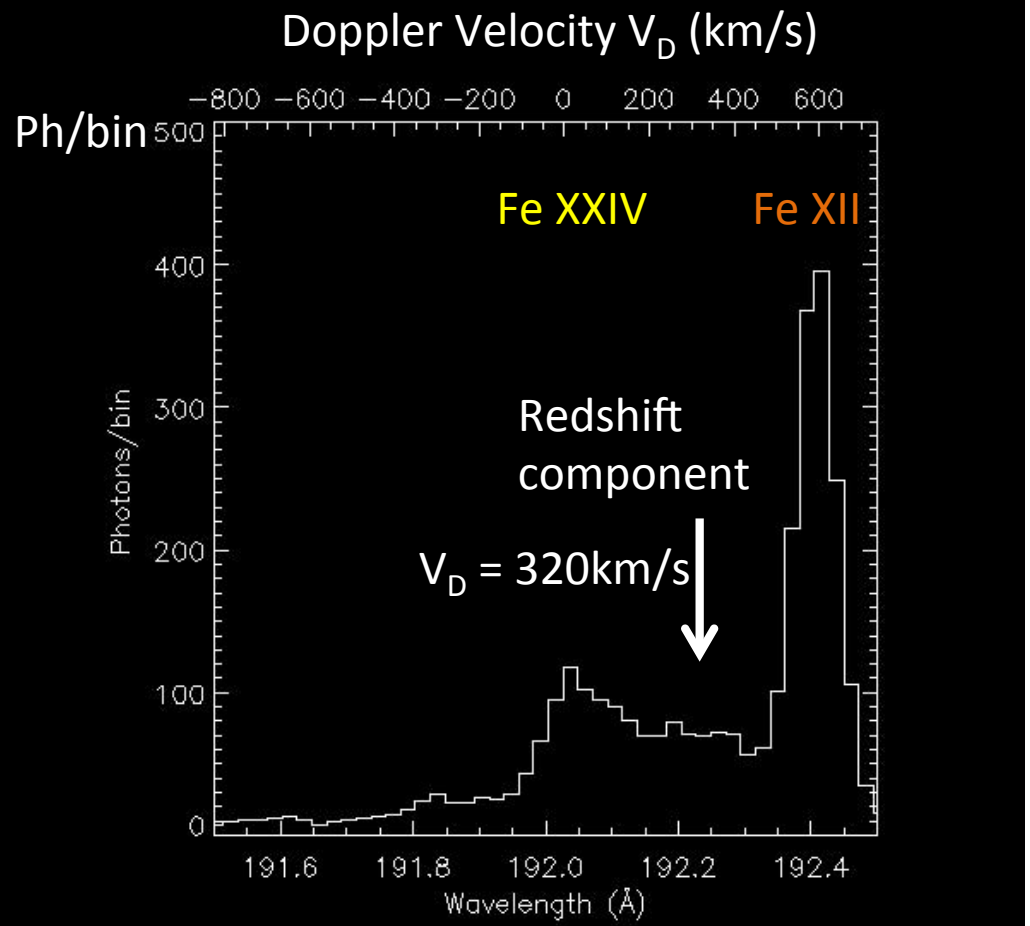
Spectrum in the thin structure above the cusp



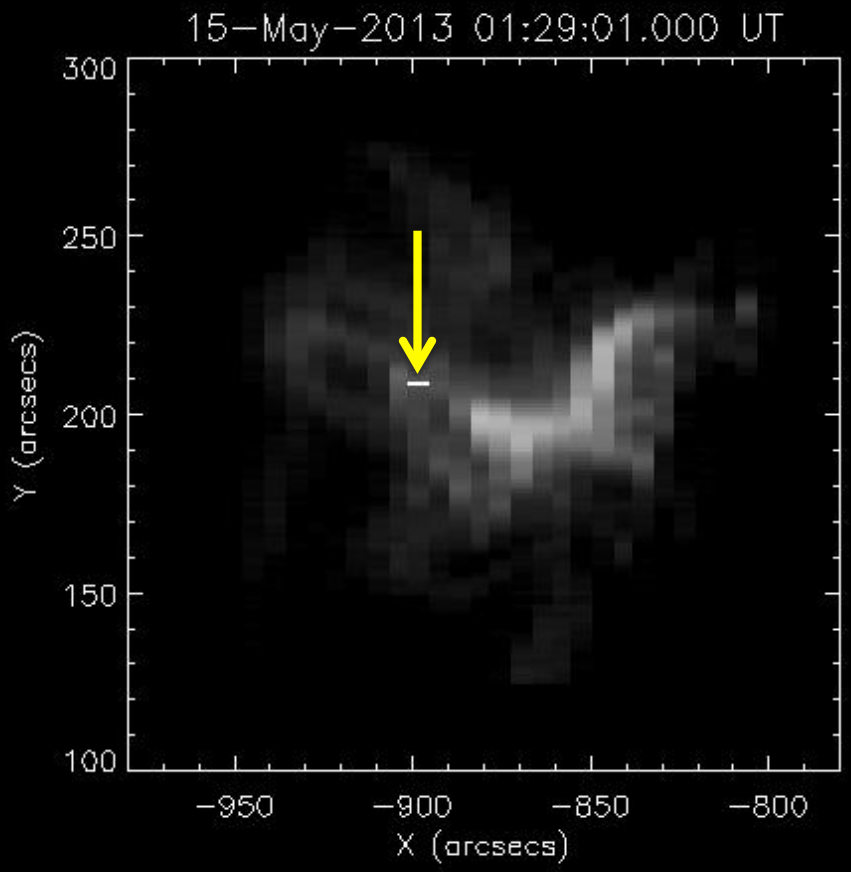


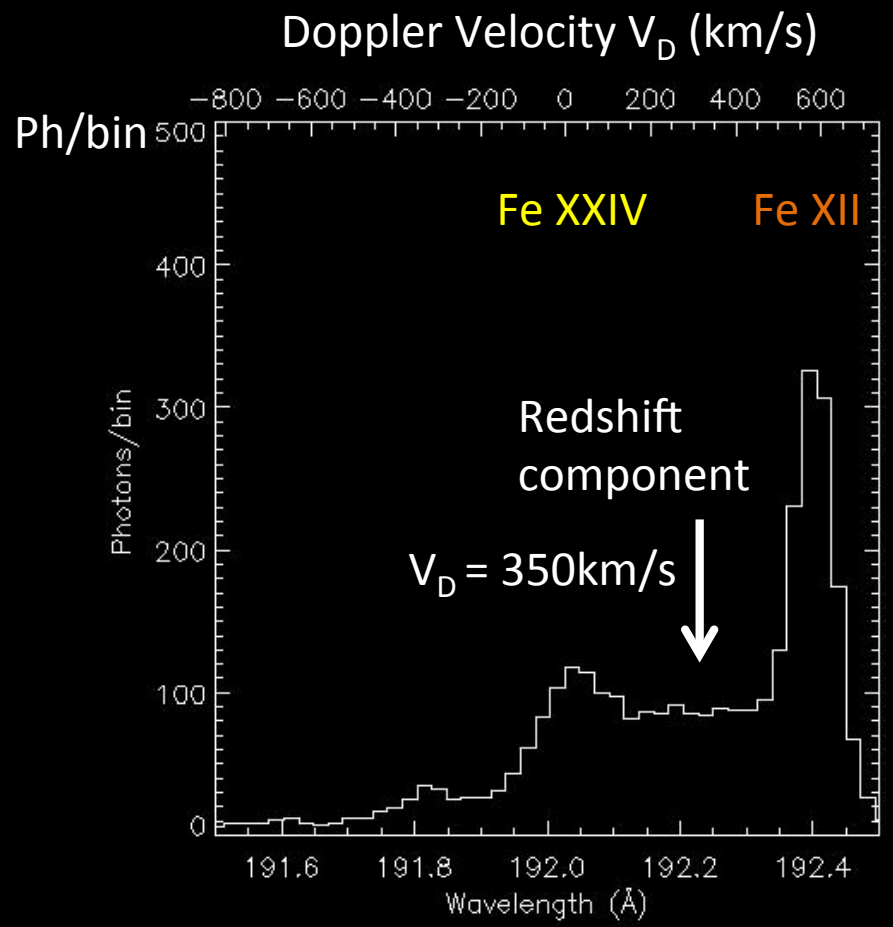
Spectrum in the thin structure above the cusp



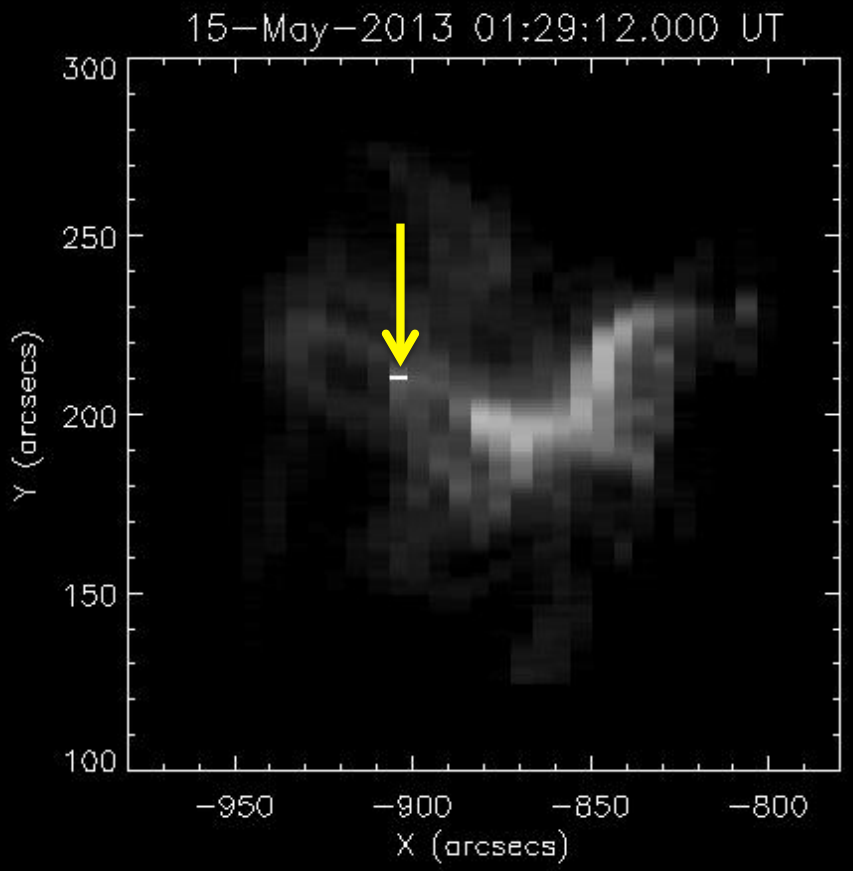


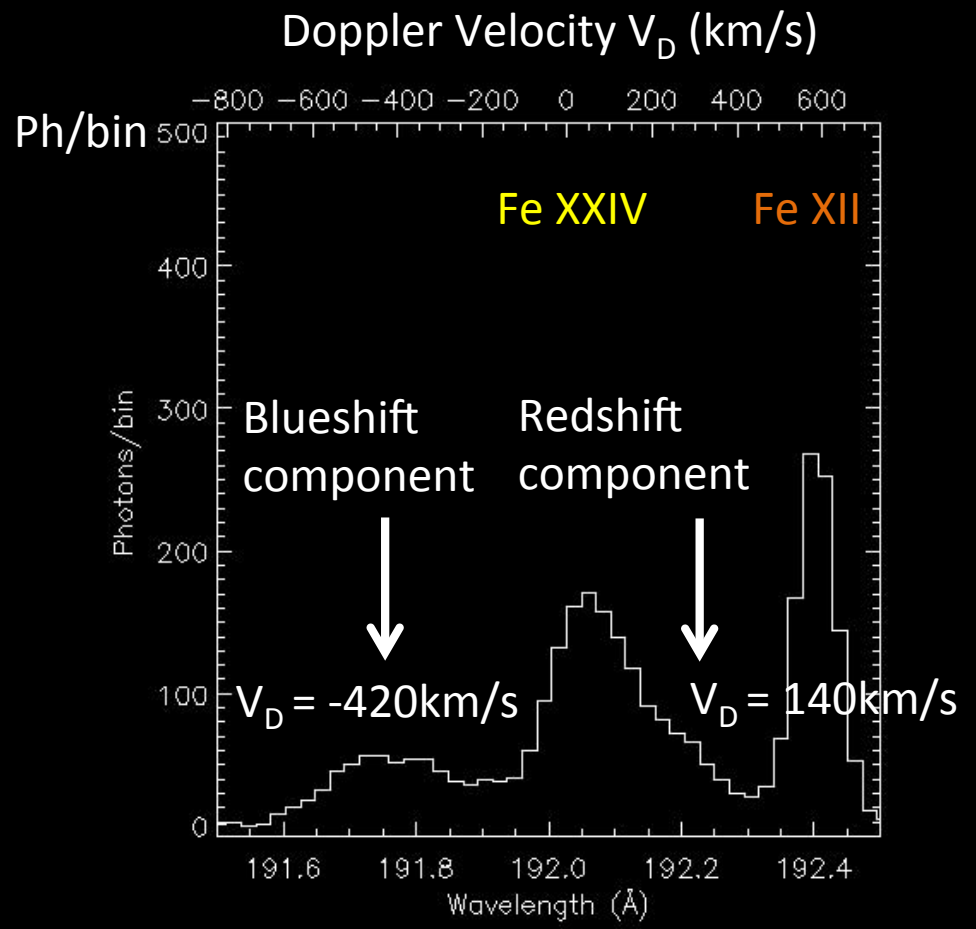
Spectrum in the thin structure above the cusp

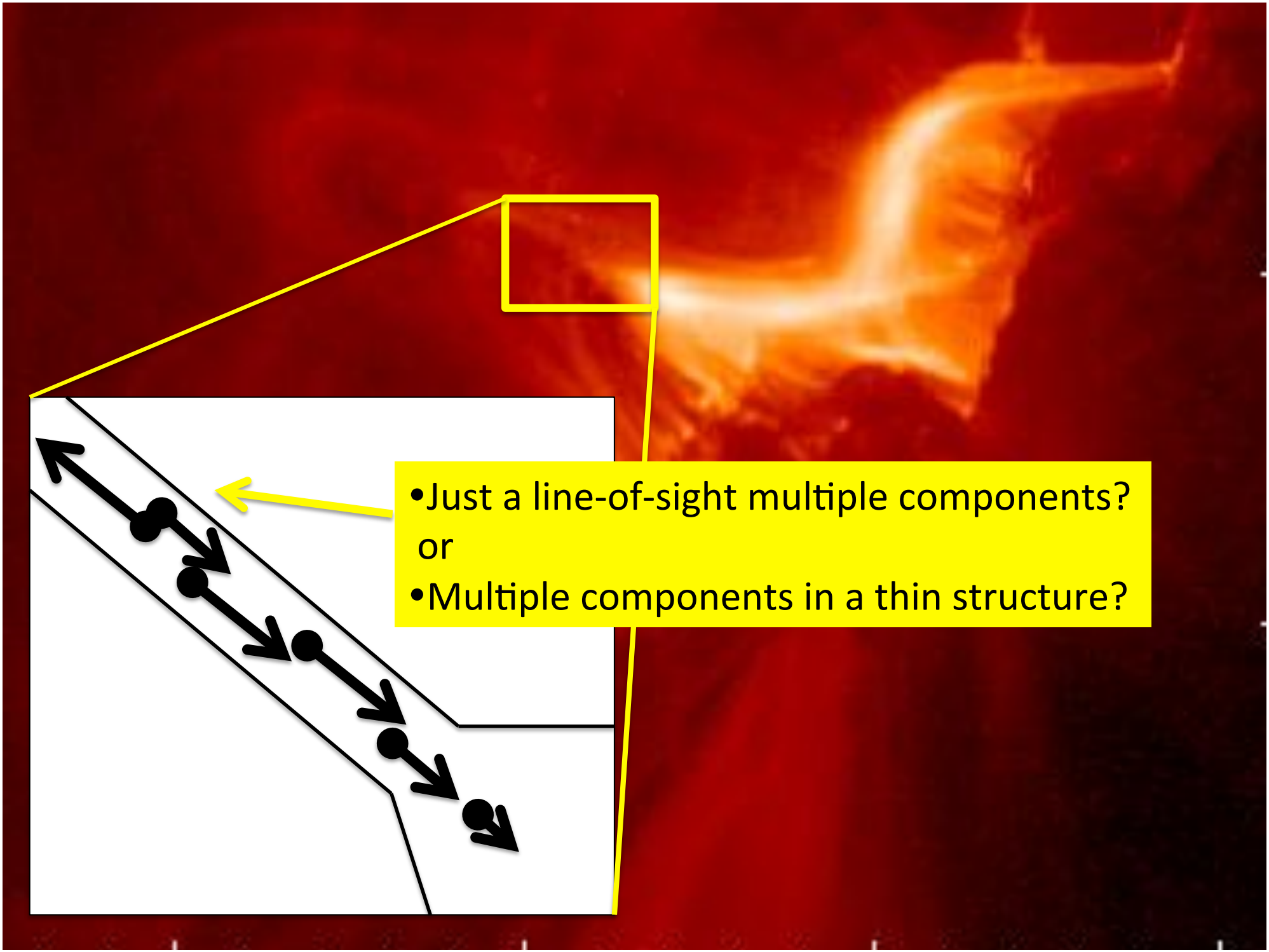




Spectrum in the thin structure above the cusp






•Just a line-of-sight multiple components?
or
•Multiple components in a thin structure?

Summary

- EIS sparse raster observations of the X1.2 flare on 2013 May 15 have caught bi-directional flows from EUV spectra in a thin structure above the flare loop that appeared later.
  - First clear detection of inward outflow signature in the EIS obs.
  - We interpret the flows as reconnection outflows from the site of magnetic reconnection (MR).
  - There appears to be multiple reconnection sites in the thin structure. Need more careful look for AIA images.
- Topological changes of magnetic fields in details near the reconnection site are recorded in AIA data, and to be investigated for understanding MR in 3D.
  - Magnetic topology and dynamics near the above-the-loop-top HXR source that appeared later are to be studied soon.