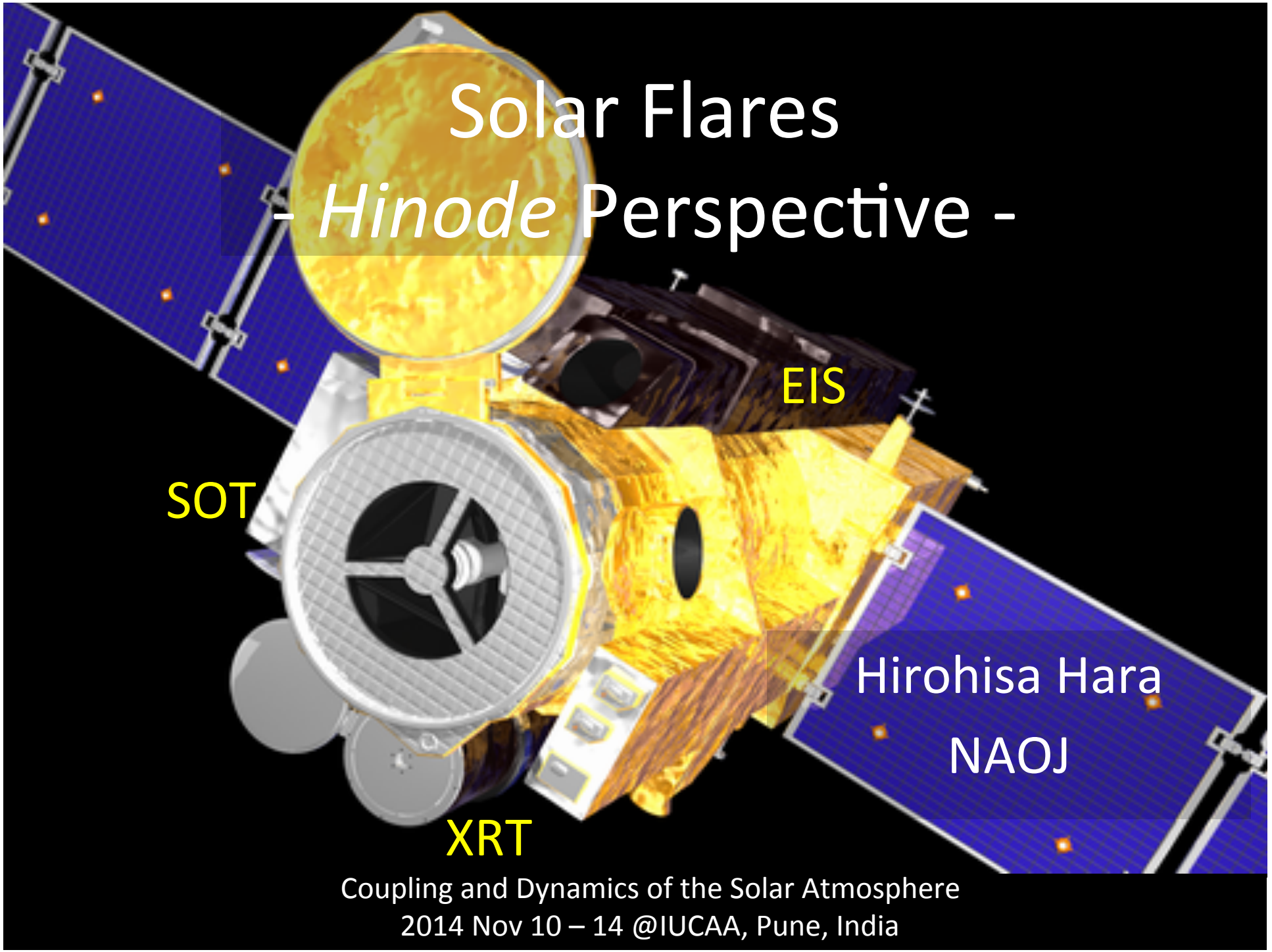
Solar Flares
- *Hinode* Perspective -



Hirohisa Hara
NAOJ

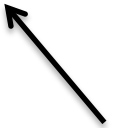
Coupling and Dynamics of the Solar Atmosphere
2014 Nov 10 – 14 @IUCAA, Pune, India

Solar Flare Research by *Hinode*

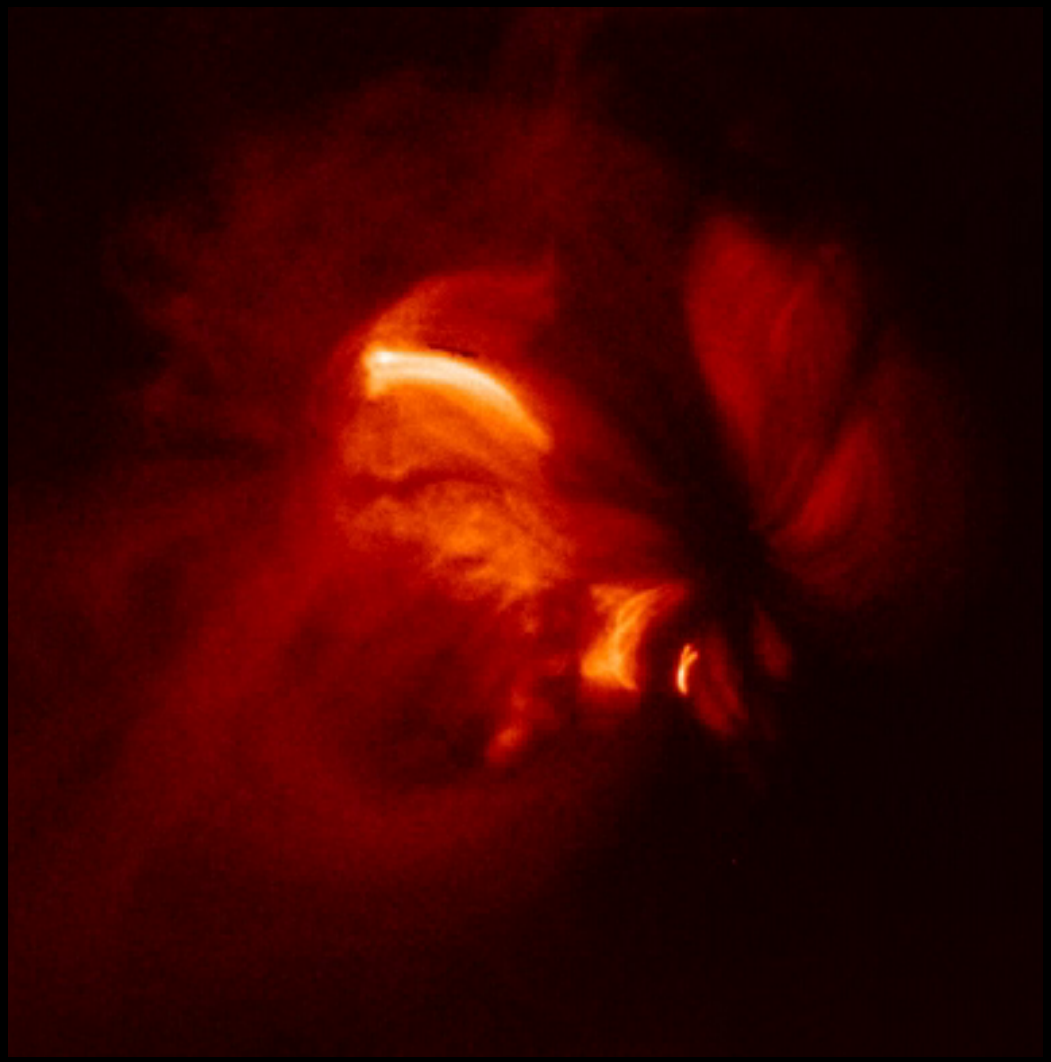
- Solar flares:

  explosive events on the Sun that produce >10MK plasmas and high-energy particles by heating and particle-acceleration processes.

- Research Topics
  - Energy storage and trigger processes
  - Particle acceleration and chromospheric evaporation
  - Magnetic reconnection
- Unique Approach by *Hinode* (SOT + XRT +EIS)
  - High-resolution; especially SOT sub-arcsec imaging
  - Photo. vector B field (imaging & spectro-polarimetry)
  - High-cadence X-ray imaging
  - EUV scanning spectroscopy



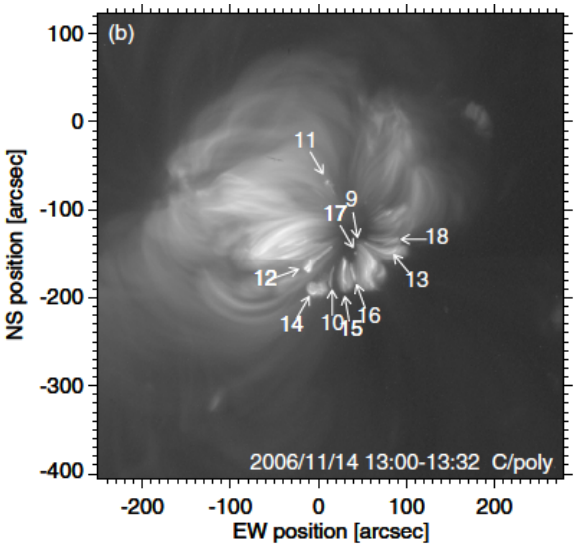
Limited capability

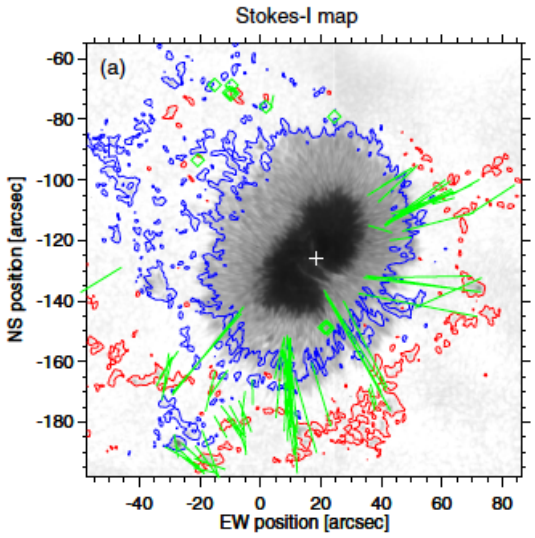


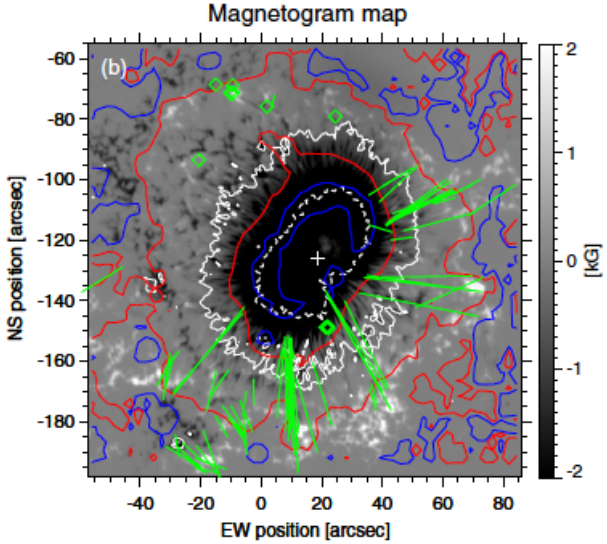
Microflares

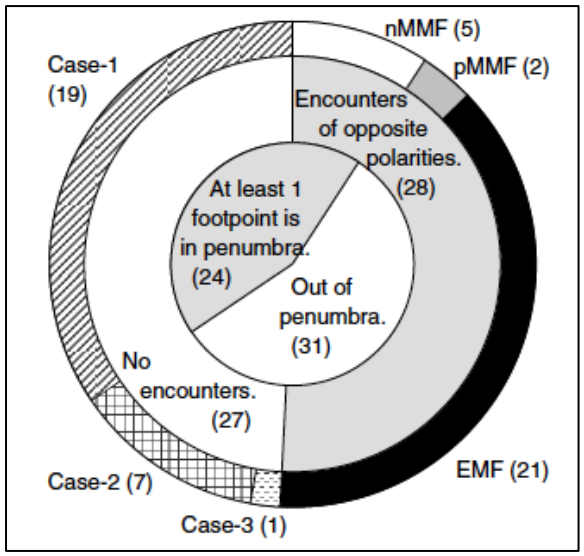
Magnetic Connectivity & Morphology

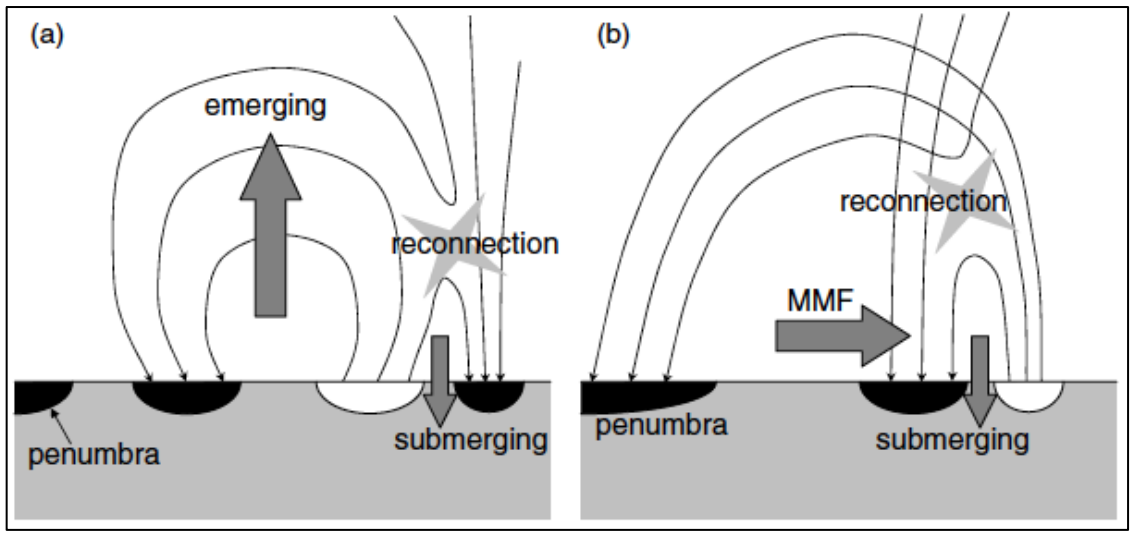
XRT + SOT Kano et al. (2010)





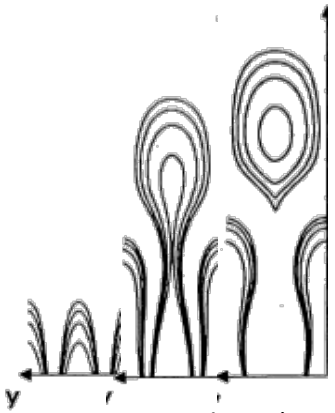




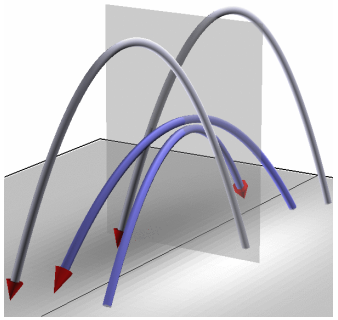


Onset Problem of Solar Eruptions

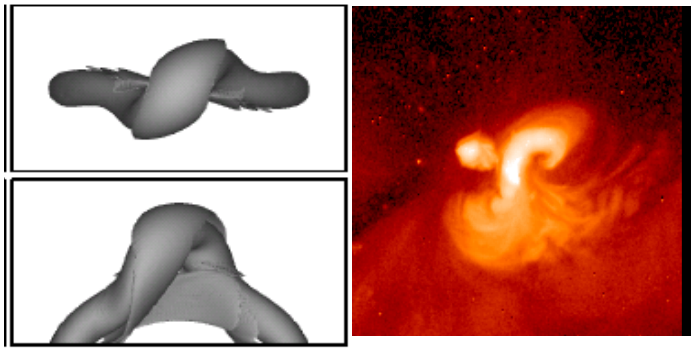
- Various models have been proposed to explain the onset of solar eruptions.



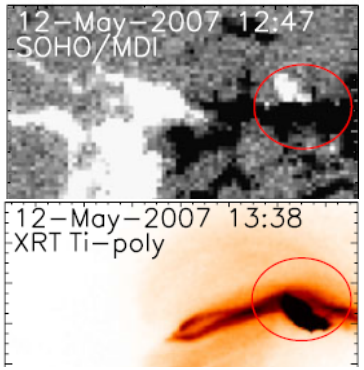
strong magnetic shear (Low 1977, Mikic & Linker 1994)



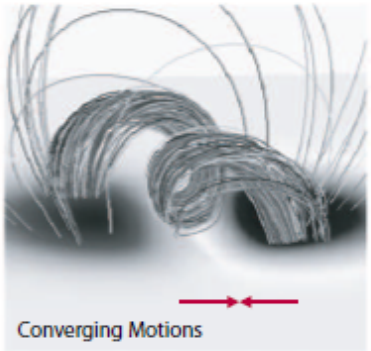
reversed shear (Kusano et al. 2004)



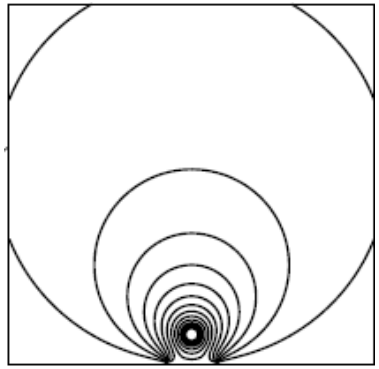
sigmoid & kinking (Rust & Kumar 1996, Canfield et al. 1999, Moore et al. 2001, Kliem et al. 2004)



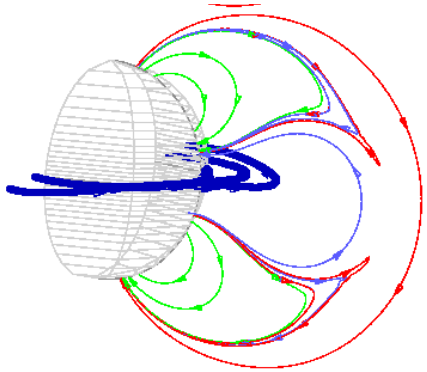
emerging fluxes (Heyvaerts et al. 1977; Wallace et al. 2010)



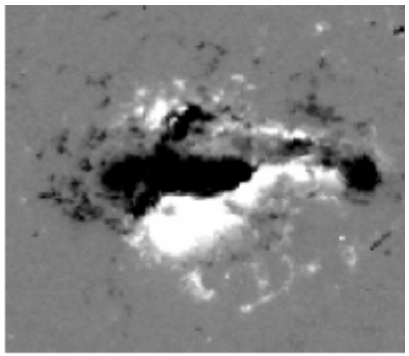
flux cancellation (van Ballegooijen & Martens 1989, Amari 1999, 2000, Green et al. 2011)



Loss-of-equilibrium model (Priest & Forbes 2002)

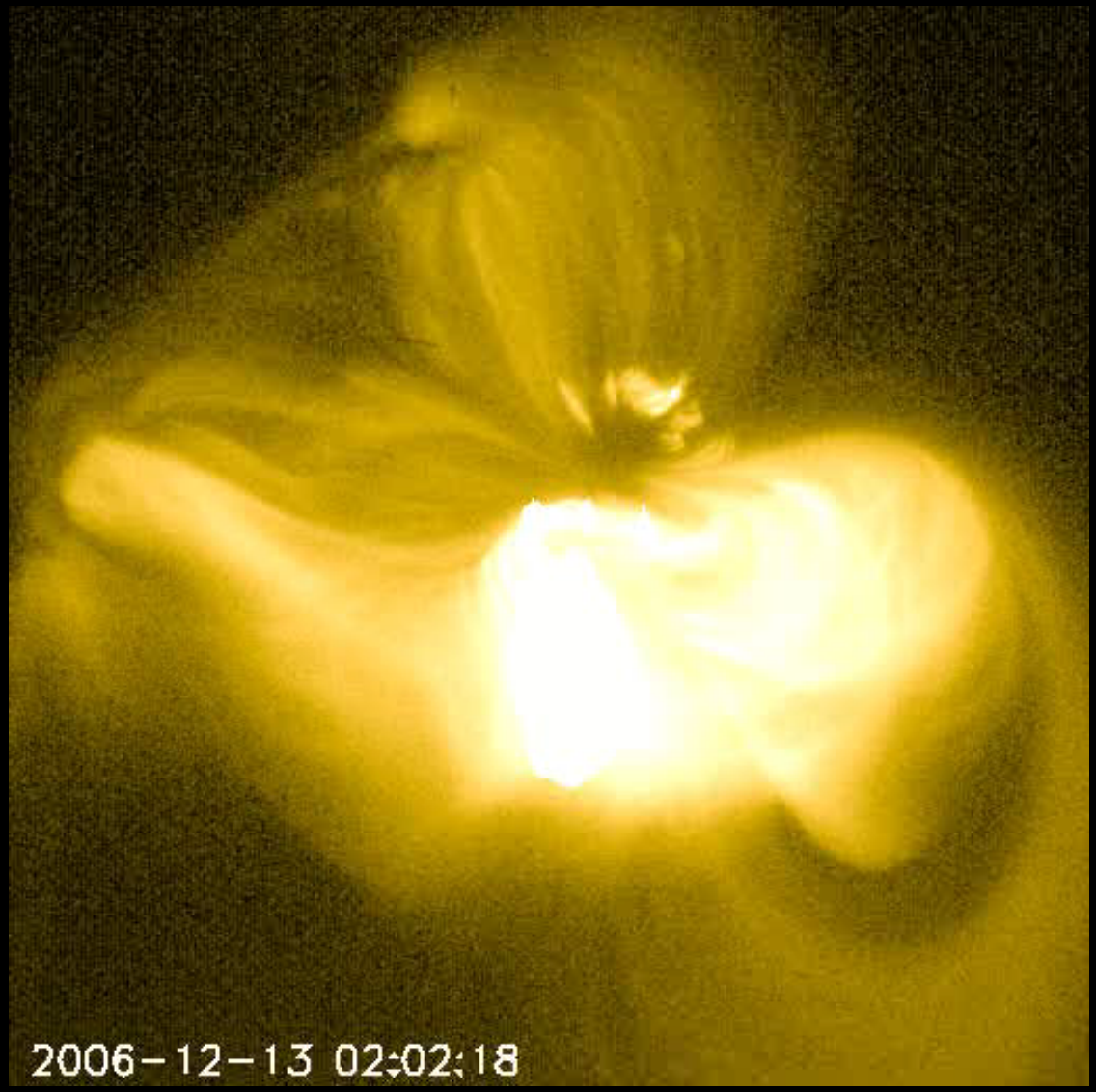


Breaqkout in multipolar topologies (Antiochos et al. 1999, Sterling & Moore 2004)



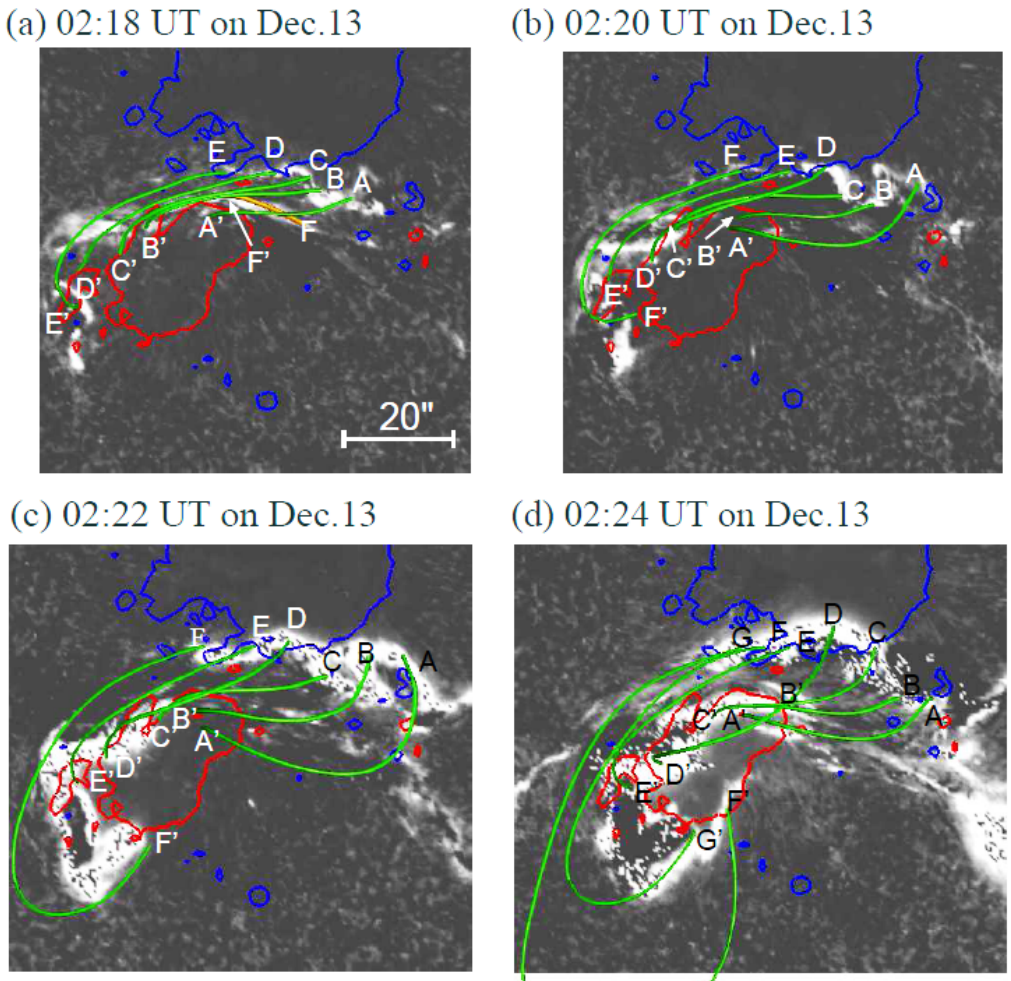
sharp gradient of B (Schrijver 2007)

Hinode Flare



Stability of Active Region

Inoue, Kusano et al. ApJ 2011



Magnetic field at 20:30UT on Dec.12, 2006
Flare onset at 02:12UT on Dec.13, 2006

Hinode/SOT

↓

Vector Magnetogram

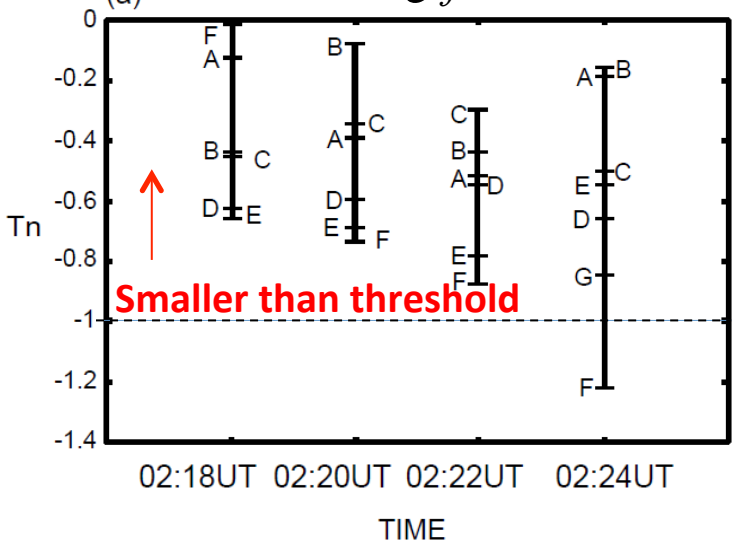
↓

NLFFF

↓

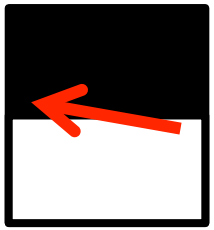
Magnetic Twist

$$T_n = (4\pi)^{-1} \int_{field\ line} \alpha\ dl$$

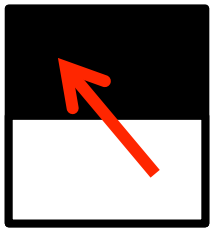


Ensemble Simulation Study

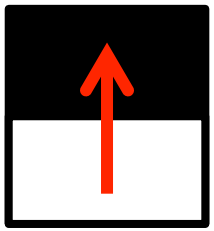
Kusano+2012



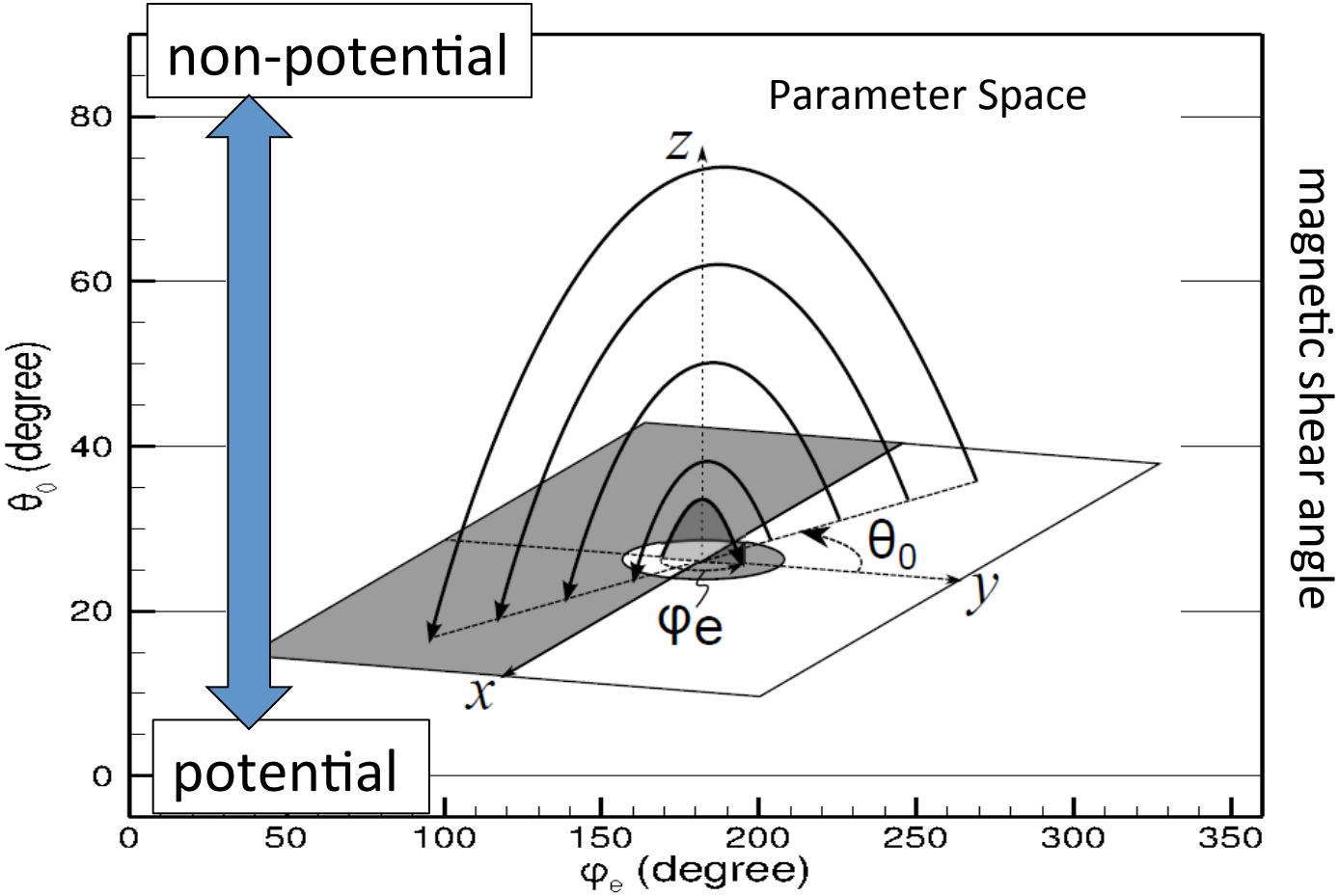
strong shear



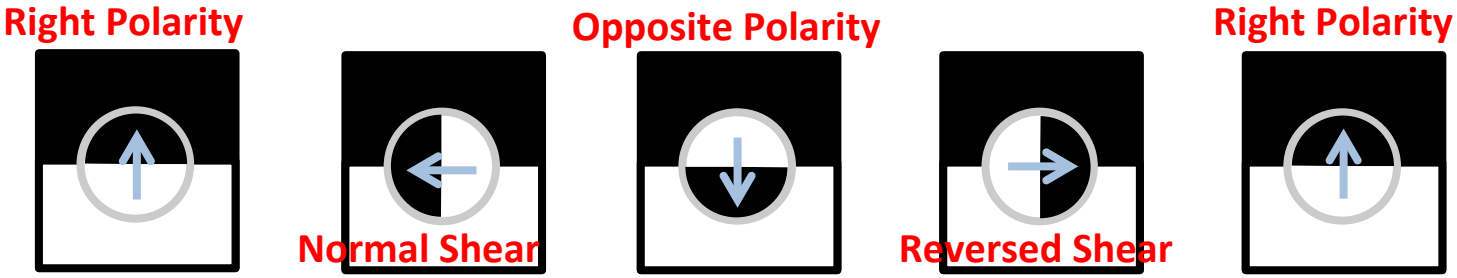
weak shear



potential field

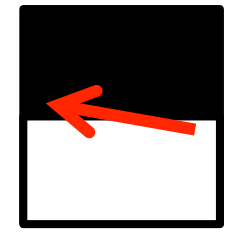


azimuth angle of small magnetic disturbance

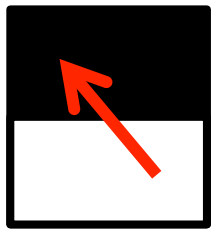


Simulation Results

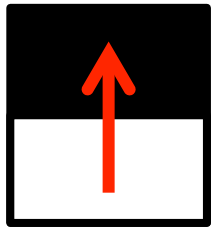
Flare phase diagram (Kusano et al. 2012)



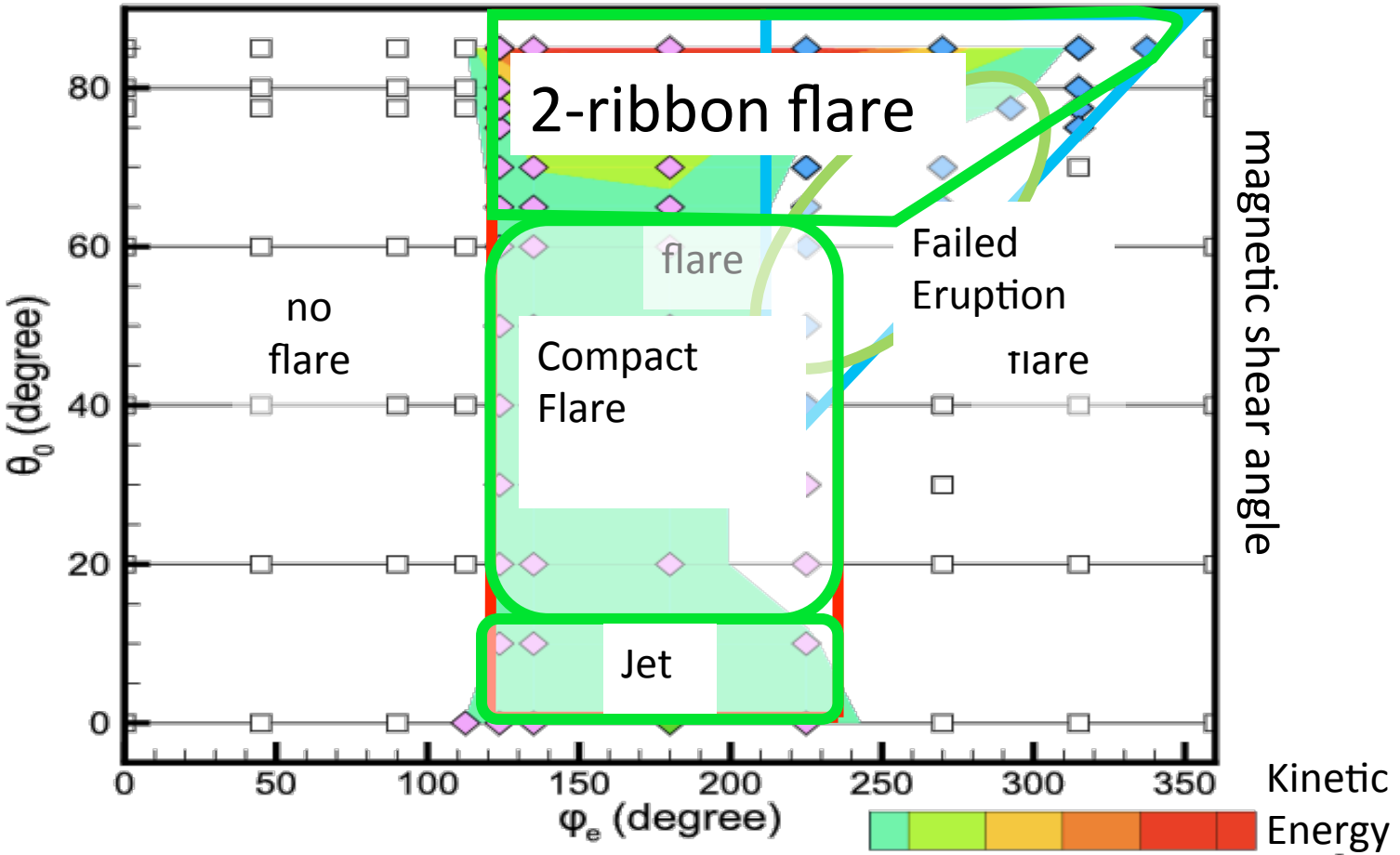
strong shear



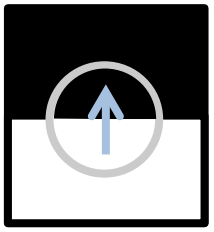
weak shear



potential field

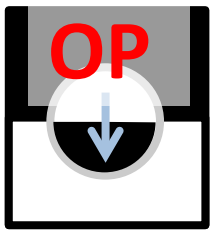


Right Polarity

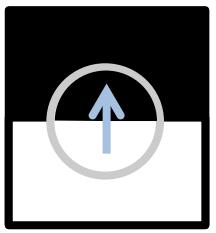


Normal Shear

Opposite Polarity



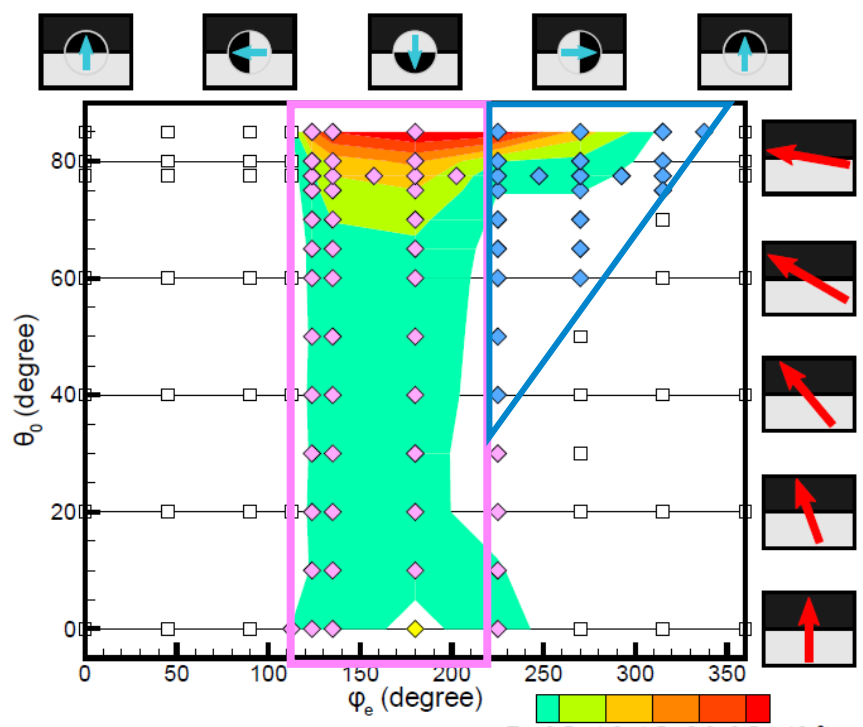
Reversed Shear

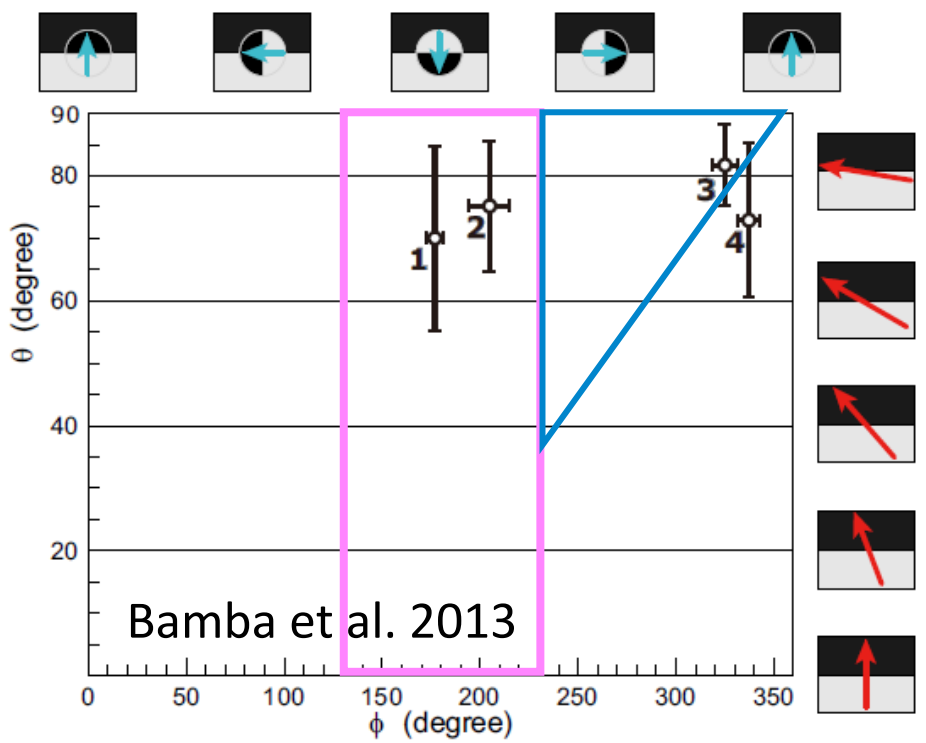


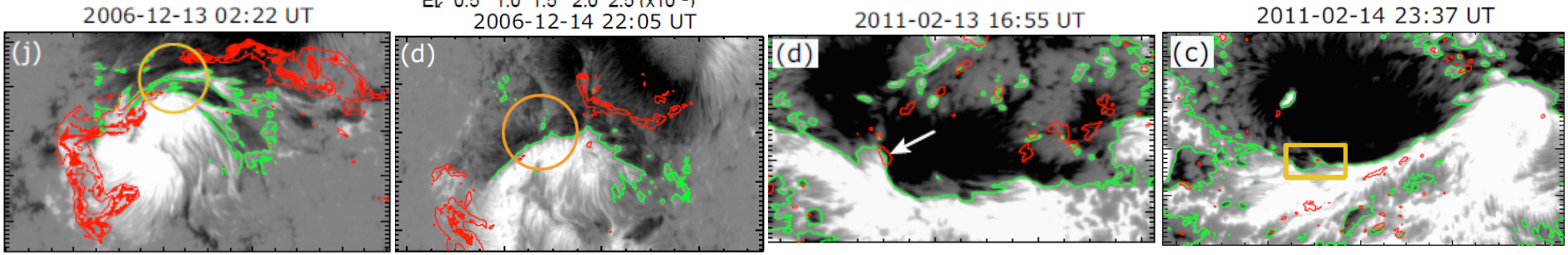
Observational Evidence

Simulation (flare phase diagram)

Observation (Hinode)





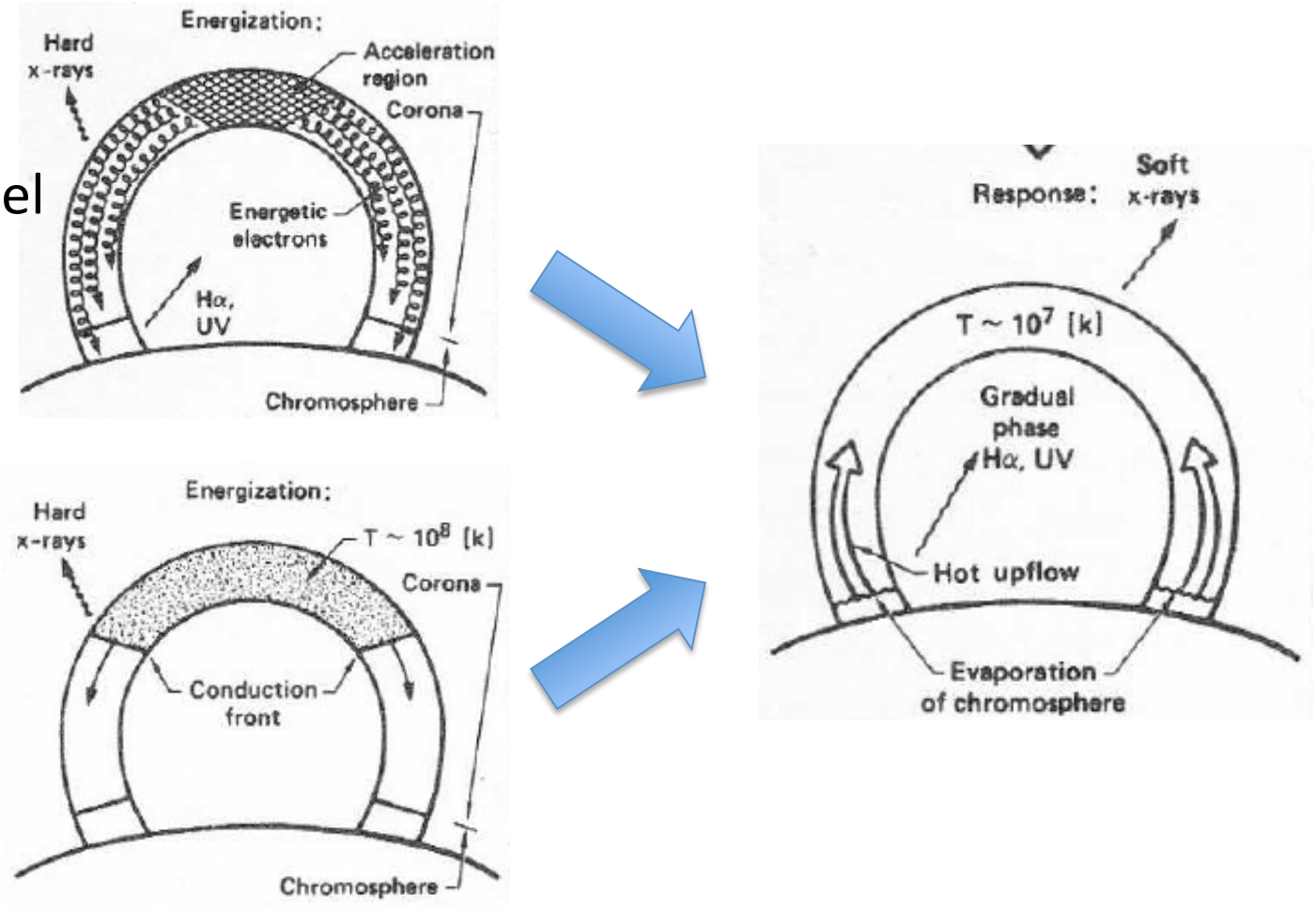


AR10930 X3.4 AR10930 X1.5 AR11158 M6.6 AR11158 X2.2

Chromospheric evaporation

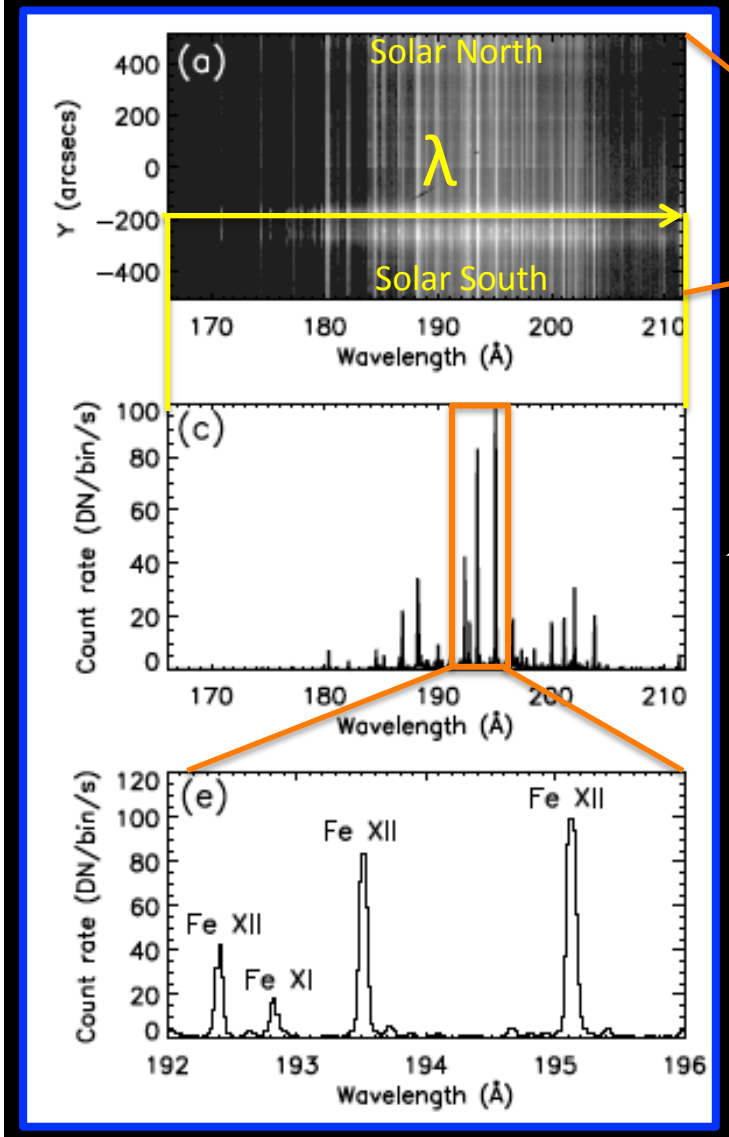
Non-thermal
thick-target model

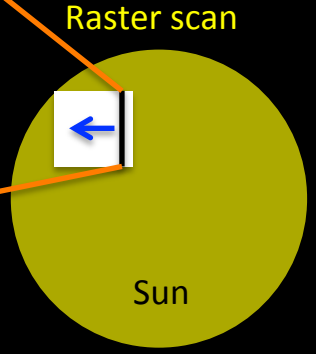
Thermal model

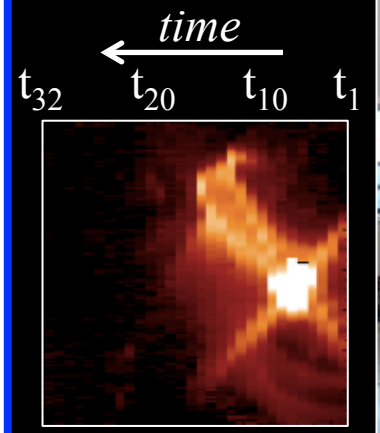


From Fisher (1986)

EUV imaging spectrograph







Example of
Raster scan image

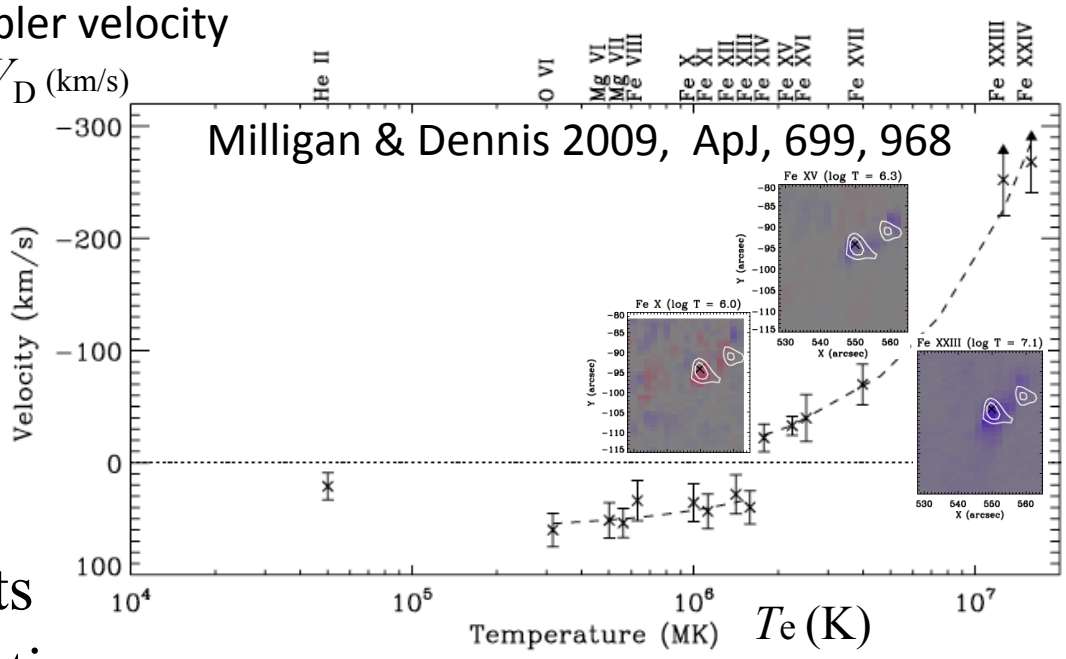
2006 -

Slit of both spectrographs is oriented in the north-south direction.

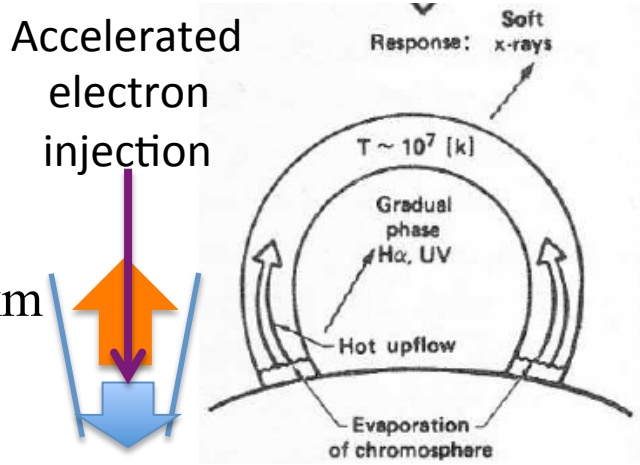
Chromospheric Evaporation studied by plenty of EUV spectral lines

Mostly studied from EIS data.

- T_e dependent flow speed
  - Milligan & Dennis (2009)
  - Watanabe et al. (2010)
  - Chen & Ding (2010)
  - Li & Ding (2010)

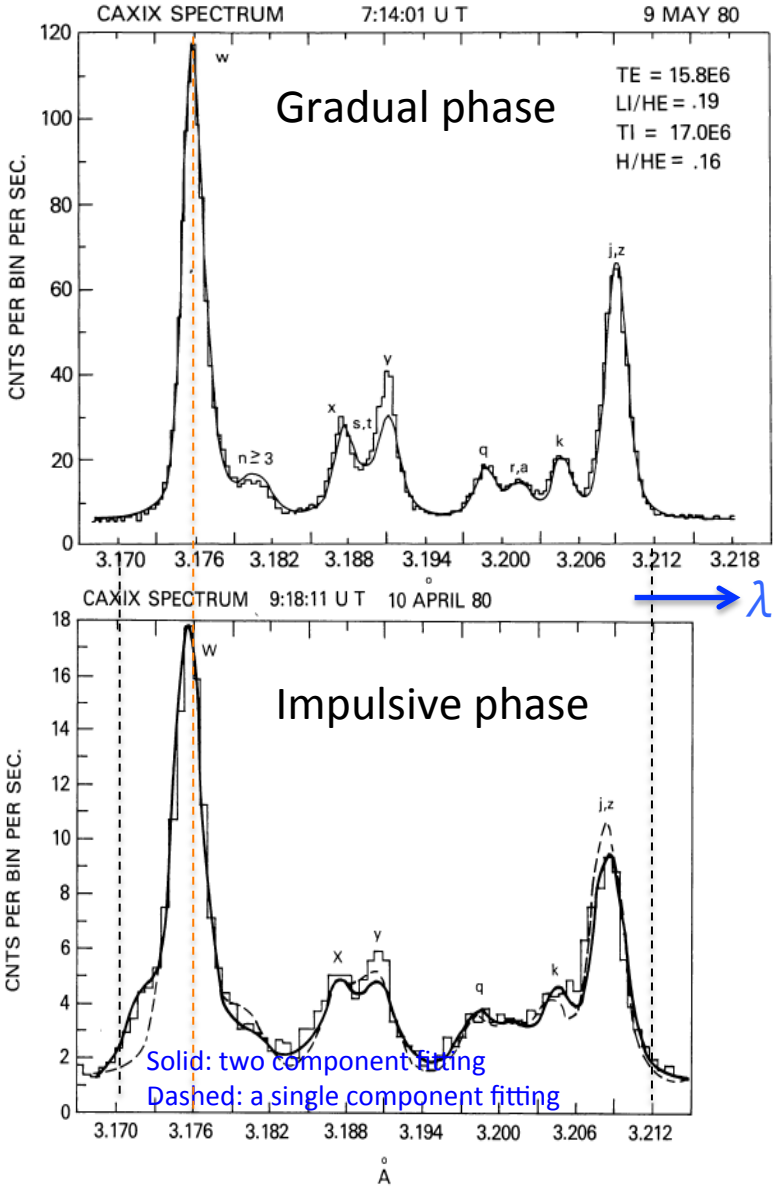


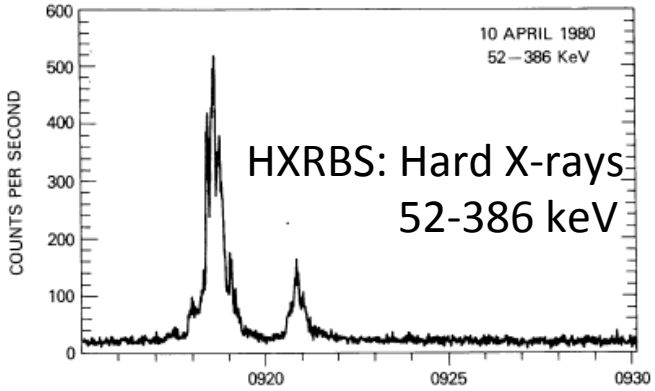
- High density at the footpoints from density sensitive line ratio
  - Fe XIII-XIV: $10^{10.5}$ cm^{-3} (Watanabe et al. 2010)
  - Fe XII-XIV: $10^{11.5}$ cm^{-3} (Milligan 2011)
  - Fe XIV : 10^{11} cm^{-3} (Del Zanna et al. 2011)
    - High-density kernels are in a narrow layer ≤200km
  - Fe XIII : $10^{10.3}$ cm^{-3} (Graham et al. 2011)

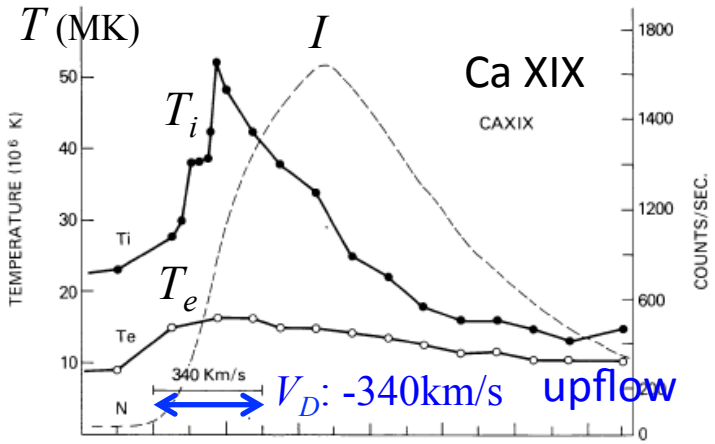


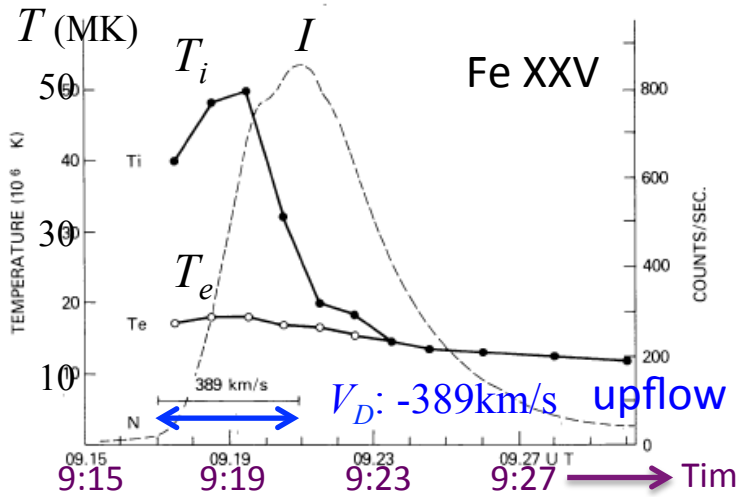
Non-thermal broadening

SMM/BCS: Antonucci et al. (1982)









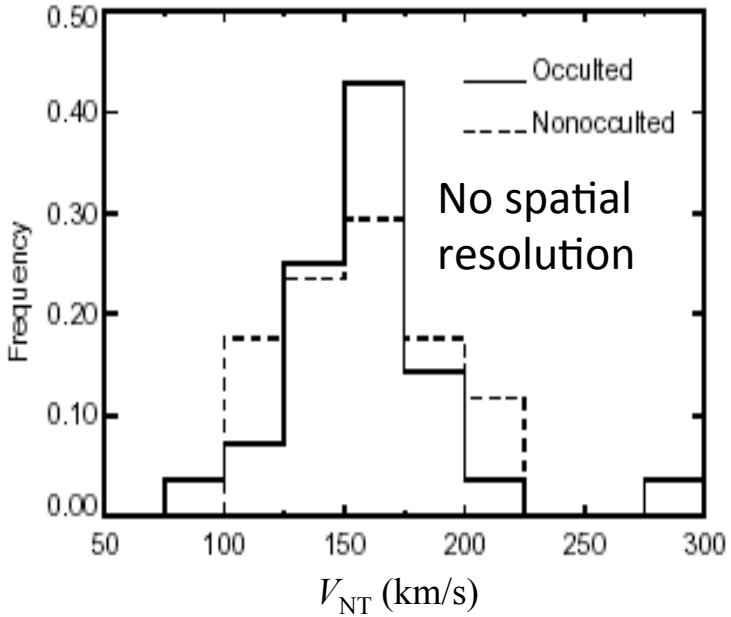
Non-thermal Velocity in Flares

- Site of non-thermal velocity observed in flaring loops and its size has not been understood.

$$W_{\rm obs} = \sqrt{W_{\rm I}^2 + 4\ln 2\left(\frac{2kT_i}{M_i} + V_{\rm NT}^2\right)} \equiv \sqrt{W_{\rm I}^2 + W^2}$$

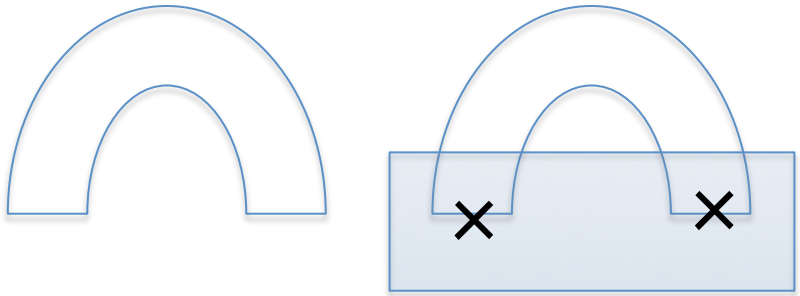
$W_{\rm obs}$: observed FWHM of an emission line

Yohkoh BCS observations



From Mariska and McTiernan 1999, ApJ, 514, 484-492

FIG. 5.—Normalized histograms of the peak nonthermal broadening velocity measured in the BCS Ca XIX channel for each flare listed in Tables 1 and 2.

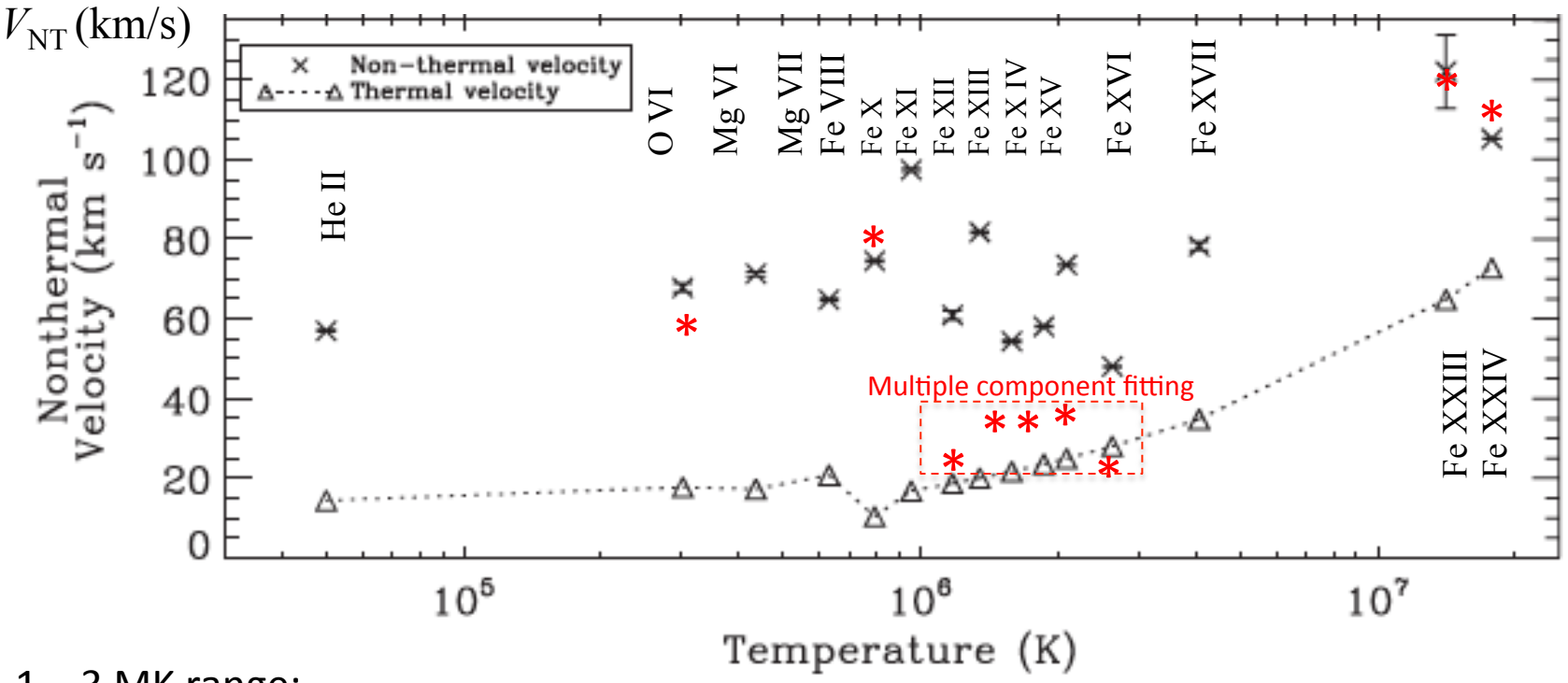


Occulted flare by the disk at the limb

$V_{\rm NT}$ at the footpoints

from Non-thermal broadening of emission lines at Flare Kernel

Milligan (2011), Young et al. (2013)



1 – 3 MK range:

Milligan (2011): unresolved flow structures, turbulence (?)

Young+ (2013): multiple flow component (upflow and downflow simultaneously detected)

V_{NT} at/above the loop tops

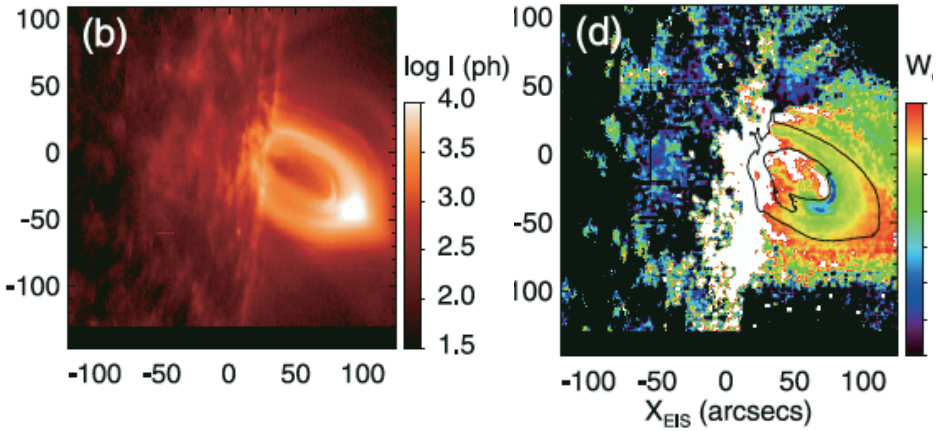
- Impulsive phase:
  - $V_{NT} = 100 - 230$ km/s

    Hara et al. (2011, 2014)

    Kawate & Imada (2013)
- Peak to late phase:
  - $V_{NT} = 40 - 70$ km/s

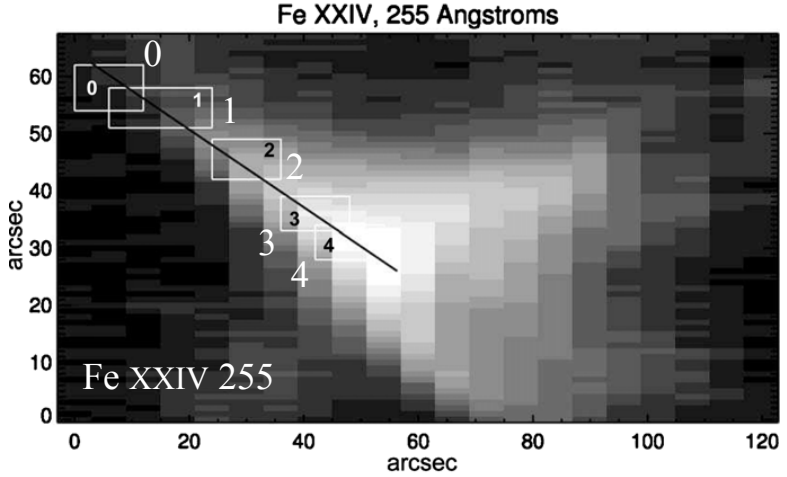
    Hara et al. (2008)

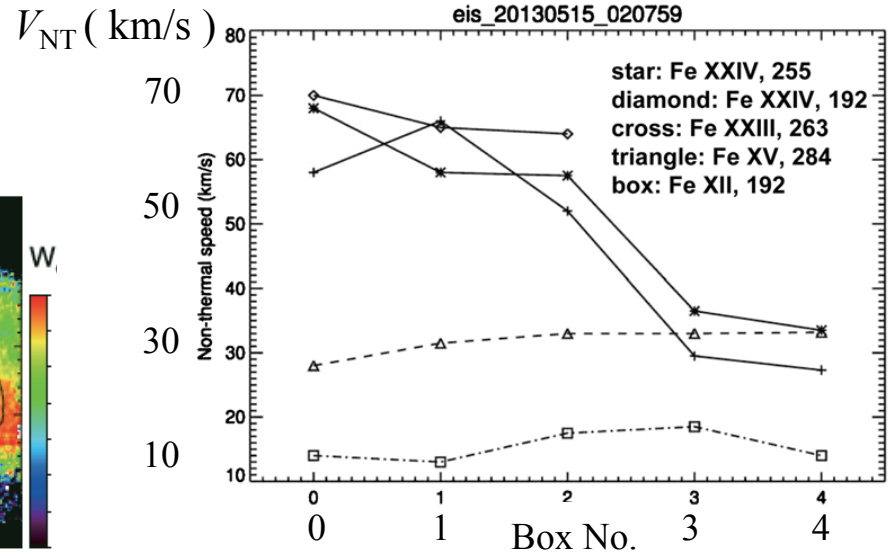
    Doschek et al. (2014)



Hara et al. (2008)

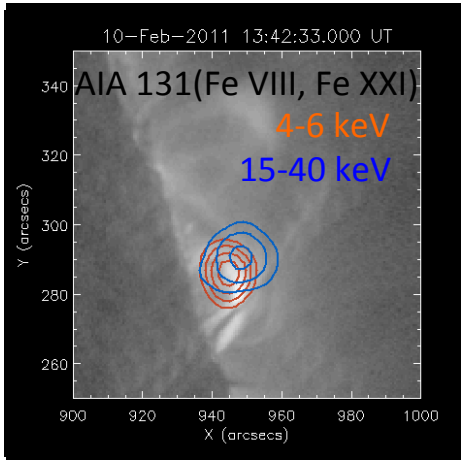
Late Phase of an X-class Flare



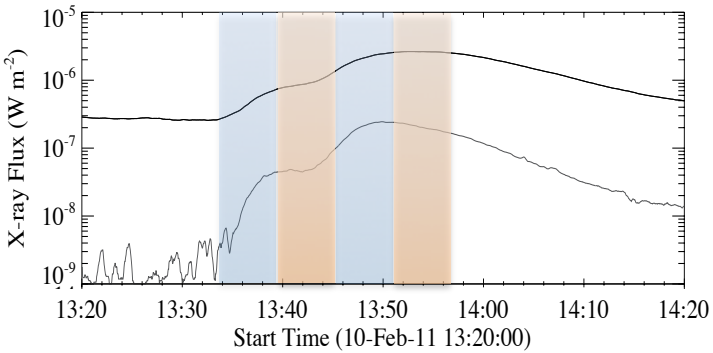


Doschek et al. (2014)

Line broadening at the loop top
- a side view -

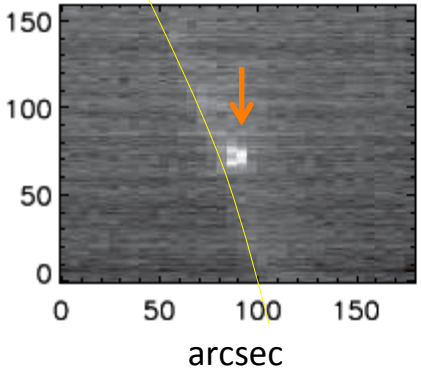


- Symmetric line profile with enhanced line broadening



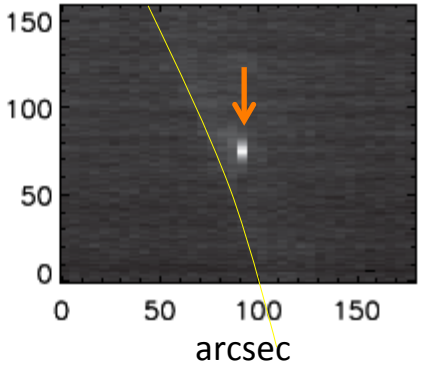
EIS: Fe XXIII 263.76 line intensity

13:33:50 - 13:39:36



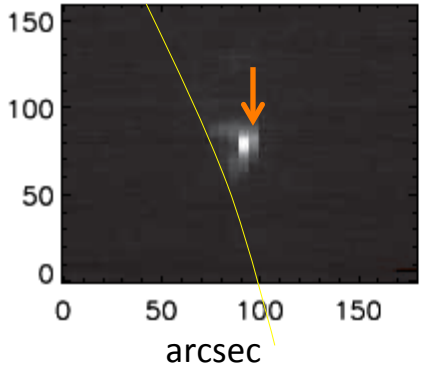
$T_e \sim 11$MK
$T_i \sim 50$ MK
(or $V_{NT} \sim 110$ km/s)

13:39:39 - 13:45:25



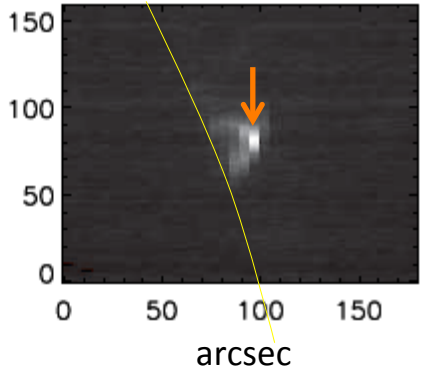
$T_e \sim 11$ MK
$T_i \sim 20$ MK
(or $V_{NT} \sim 40$ km/s)

13:45:28 - 13:51:15



$T_e \sim 14$MK
$T_i \sim 45$ MK
(or $V_{NT} \sim 100$ km/s)

13:51:18 - 13:57:04



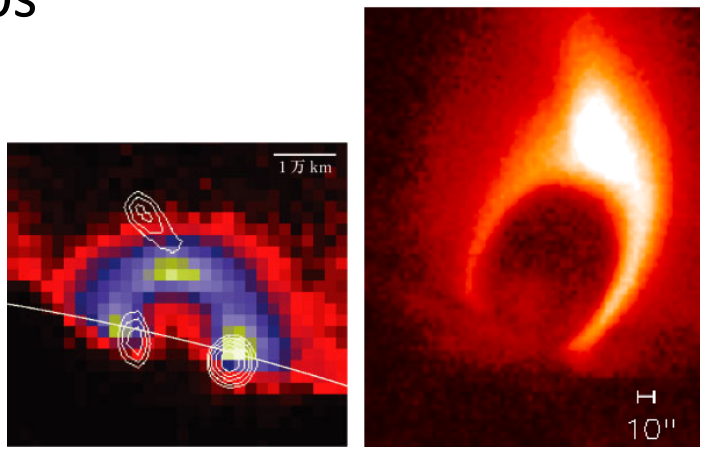
$T_e \sim 12$ MK
$T_i \sim 20$ MK
(or $V_{NT} \sim 40$ km/s)

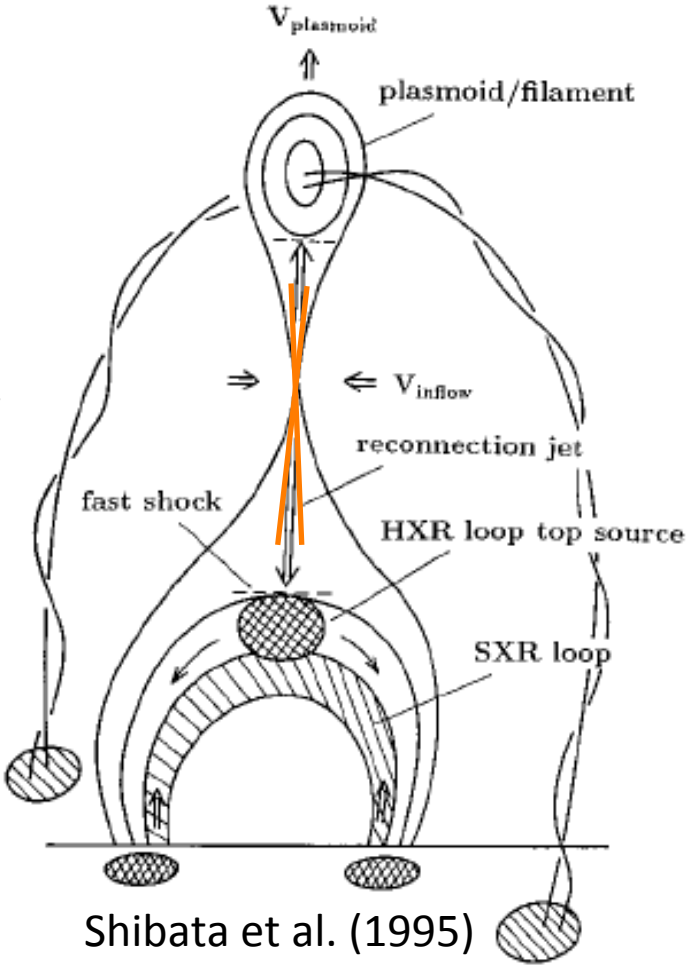
Hara+ (2014)

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

Topics investigated by spectroscopy to understand magnetic reconnection processes in the solar atmosphere.

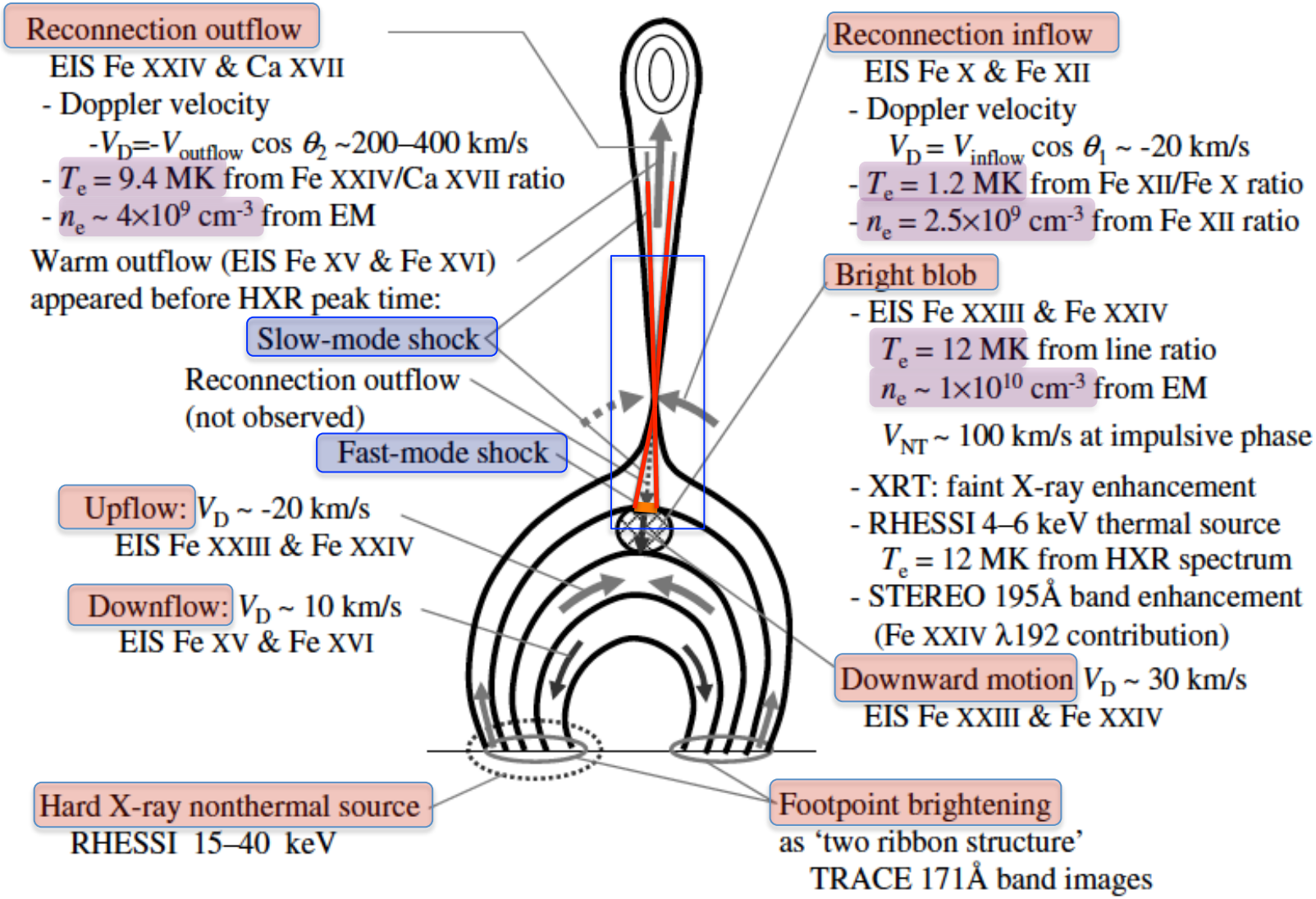
- Reconnection inflow
- Reconnection outflow/plasmoid
- Position of enhanced hot line broadening found in 1970s
- MHD Shock





Shibata et al. (1995)

Observed & Suggested Structures in 2007 May 19 Flare (GOES B9.5)

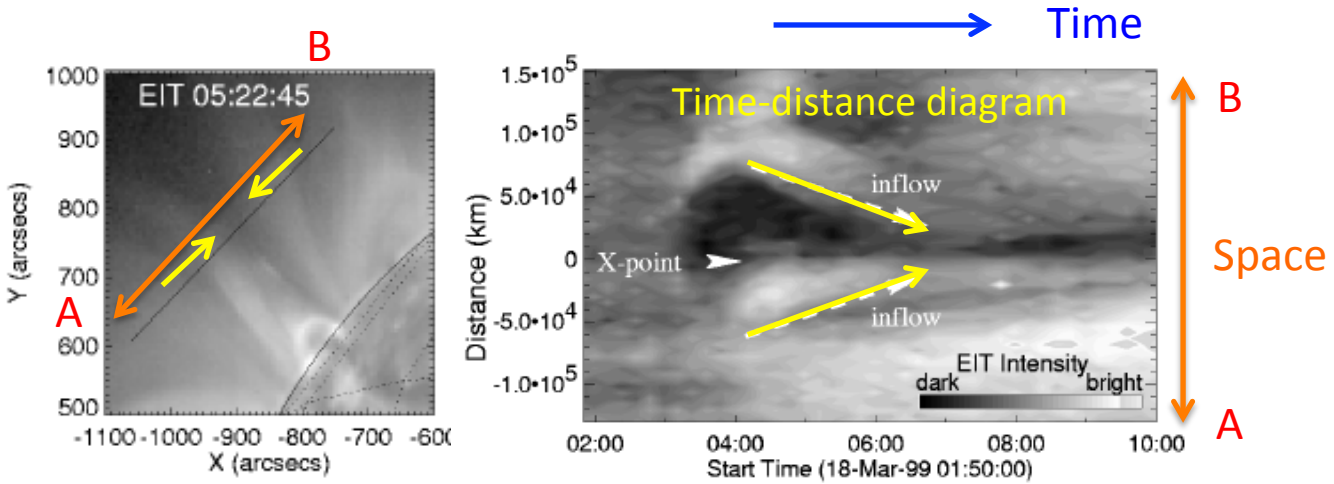


$$V_{inflow} / V_{outflow} = (V_{D,\,inflow} / V_{D,\,outflow}) (\cos\theta_2 / \cos\theta_1) = 0.067 (\cos\theta_2 / \cos\theta_1)$$

Hara+2011, ApJ, 741, 107

Reconnection Inflow

EUV Imaging Observations: Reconnection Inflow

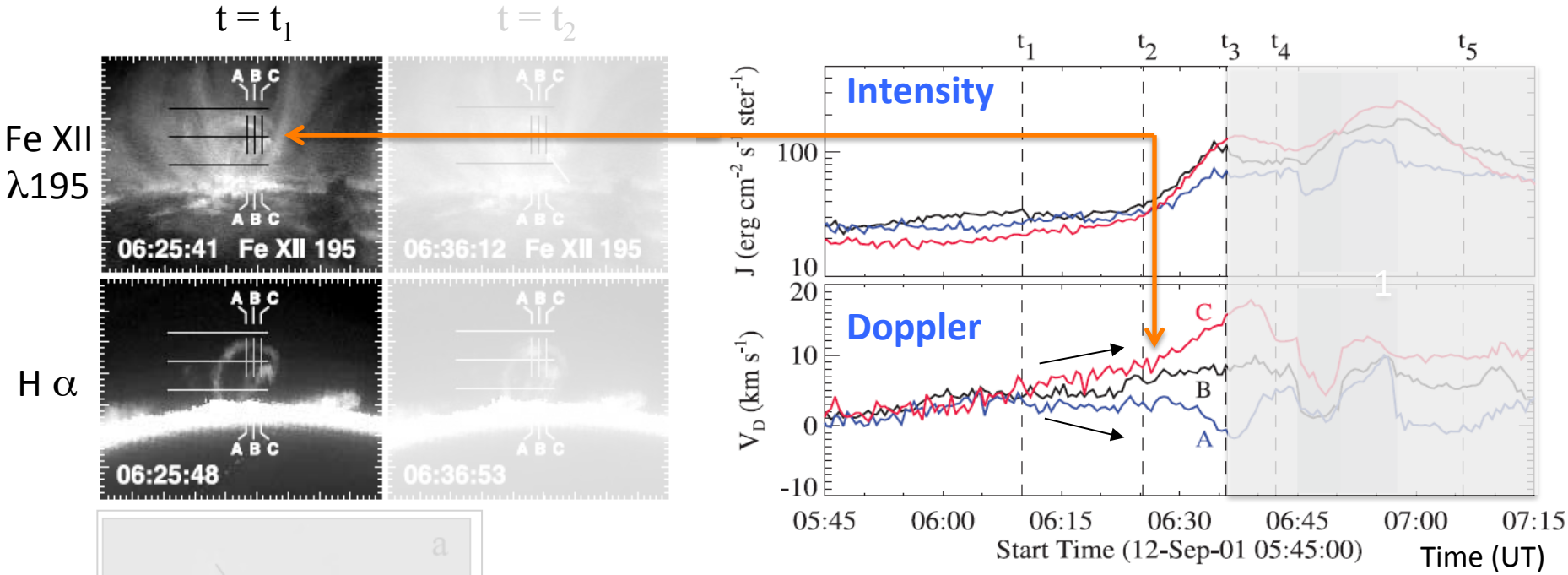


SOHO/EIT Observation

Yokoyama et al. (2001)

- Yokoyama et al. (2001)
  - Estimation of inflow speed from apparent motion of coronal structures around a flare
  - $V_{\rm inflow} \sim 5$ km/s, $M_{\rm A}=V_{\rm inflow}/V_{\rm A}=0.001$–$0.03$ (uncertainty in $V_{\rm A}$)
- Narukage & Shibata (2006); 6 events
  - $V_{\rm inflow}= 2$–14 km/s, $M_{\rm A}=V_{\rm inflow}/V_{\rm A}=0.001$–$0.07$

First Spectroscopic Observation of Reconnection Inflow

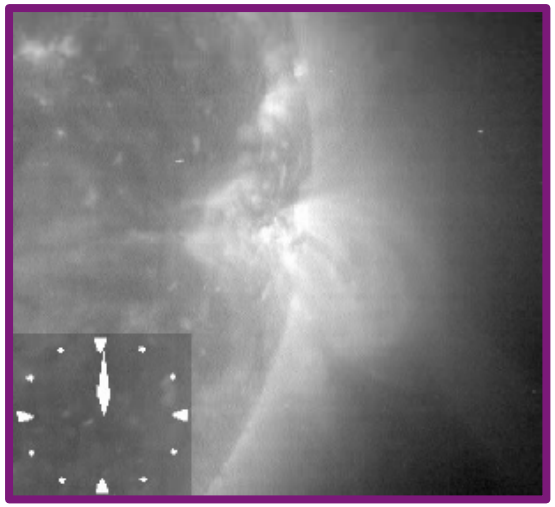


Difference of EUV images

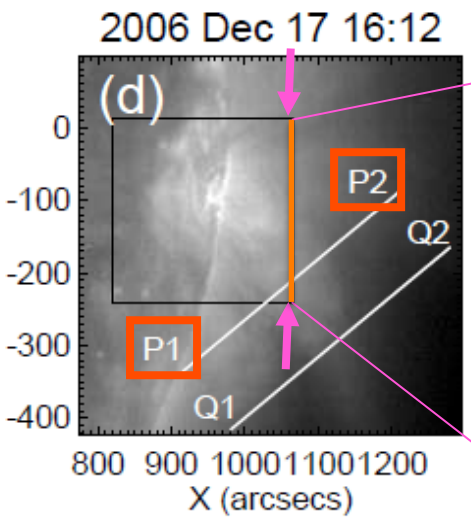
- Fe X 6374 observation
  at Norikura Solar Observatory of NAOJ ($\lambda/\Delta\lambda$=1E5)
  [Hara et al. 2006, ApJ, 648, 728]
- $V_{D,\,inflow} \sim 3$ km/s [observation]
- $M_A \sim 0.003$ when $V_A \sim 1000$ km/s in the corona
  [assumption in B]

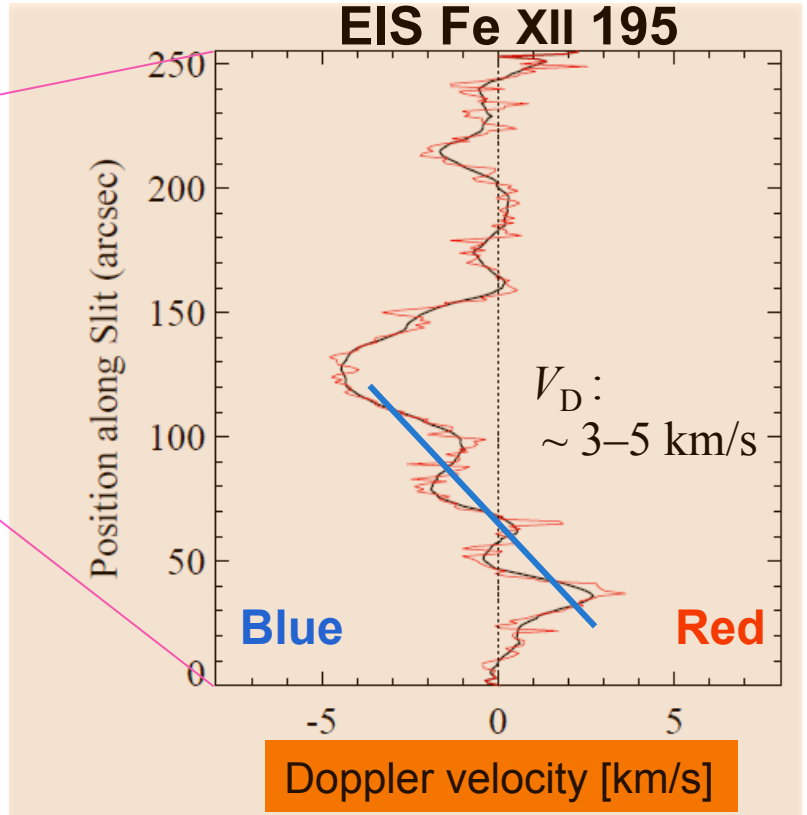
EIS Spectroscopic Observations:

- Reconnection Inflow in an eruptive event -

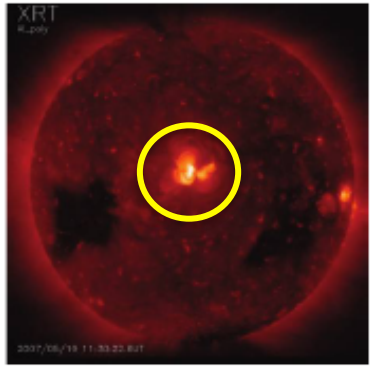


GOES C2.1



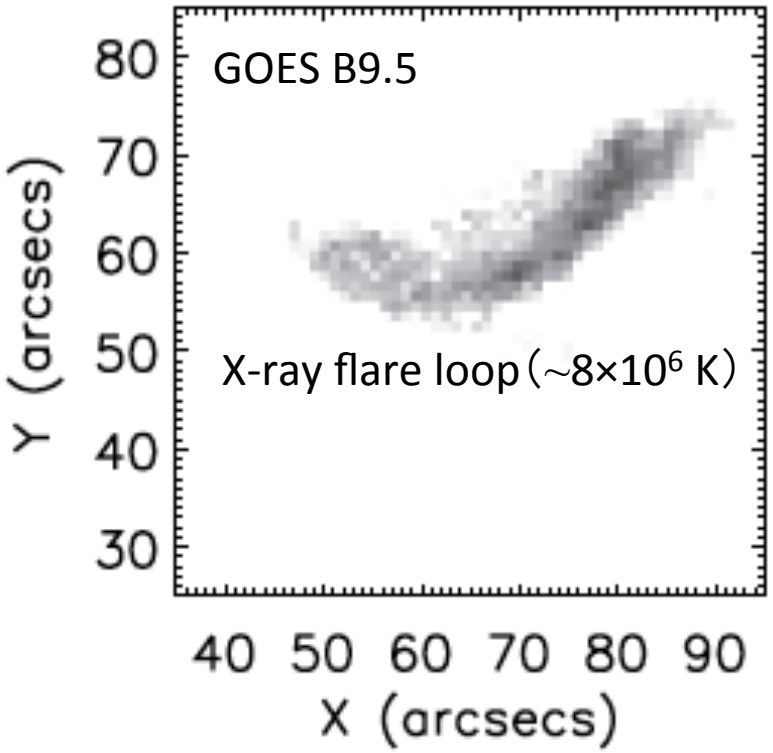


- Weak Doppler signature of inflow
- No multiple observations to prove
- No 10^7 K line observations



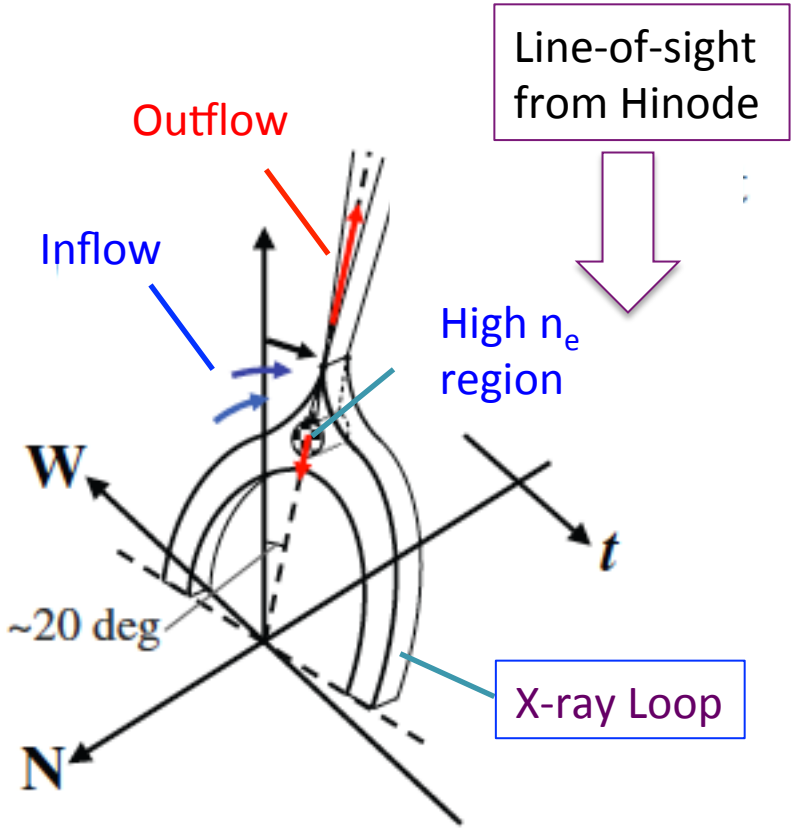
Magnetic Reconnection in an eruptive event

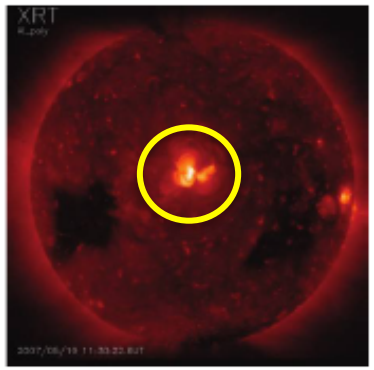
N



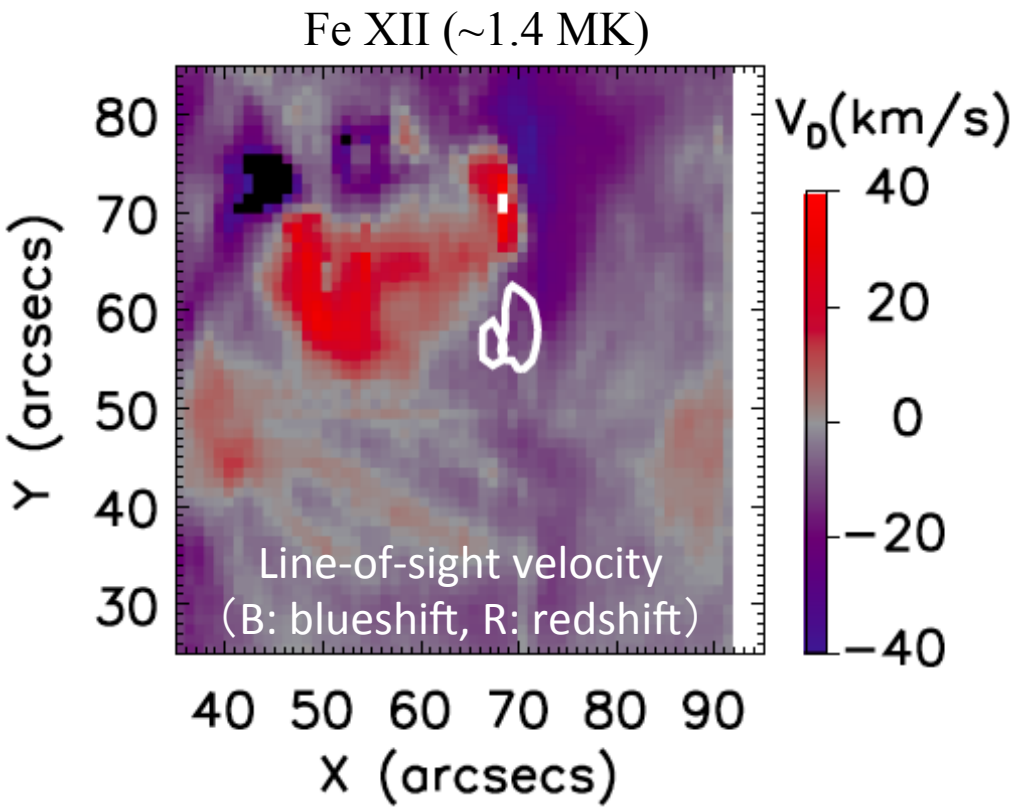
W

1 arcsec = ~700 km on the Sun

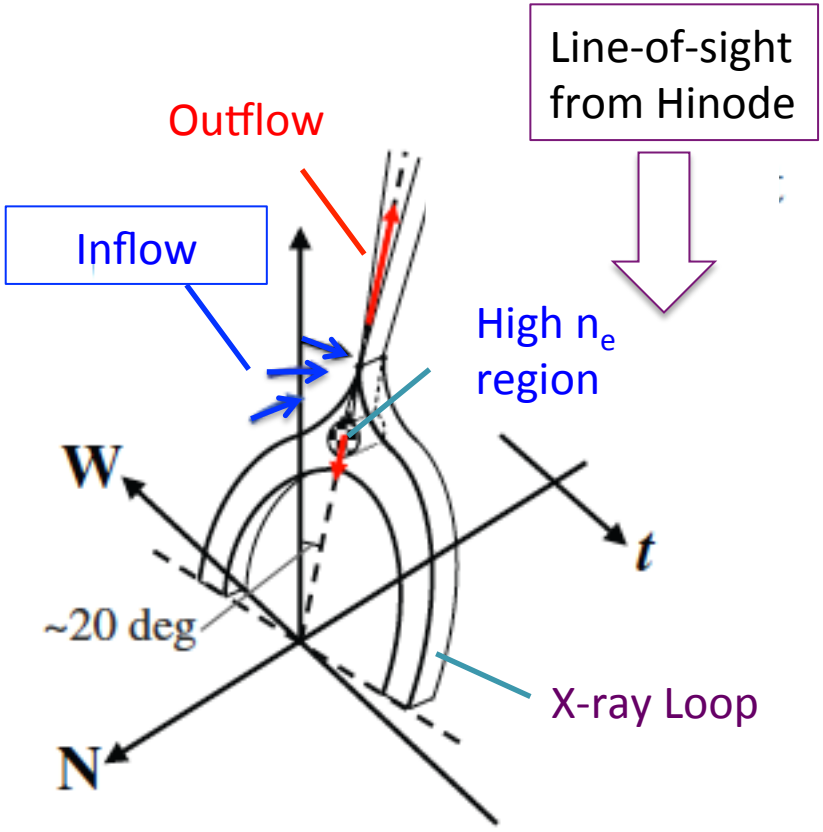




Magnetic Reconnection in an eruptive event

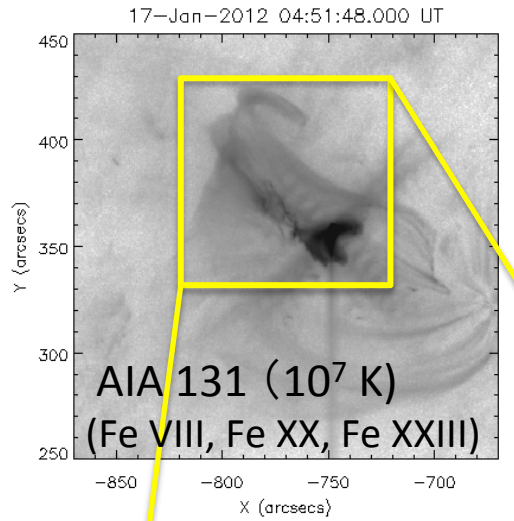


1 arcsec = ~700 km on the Sun

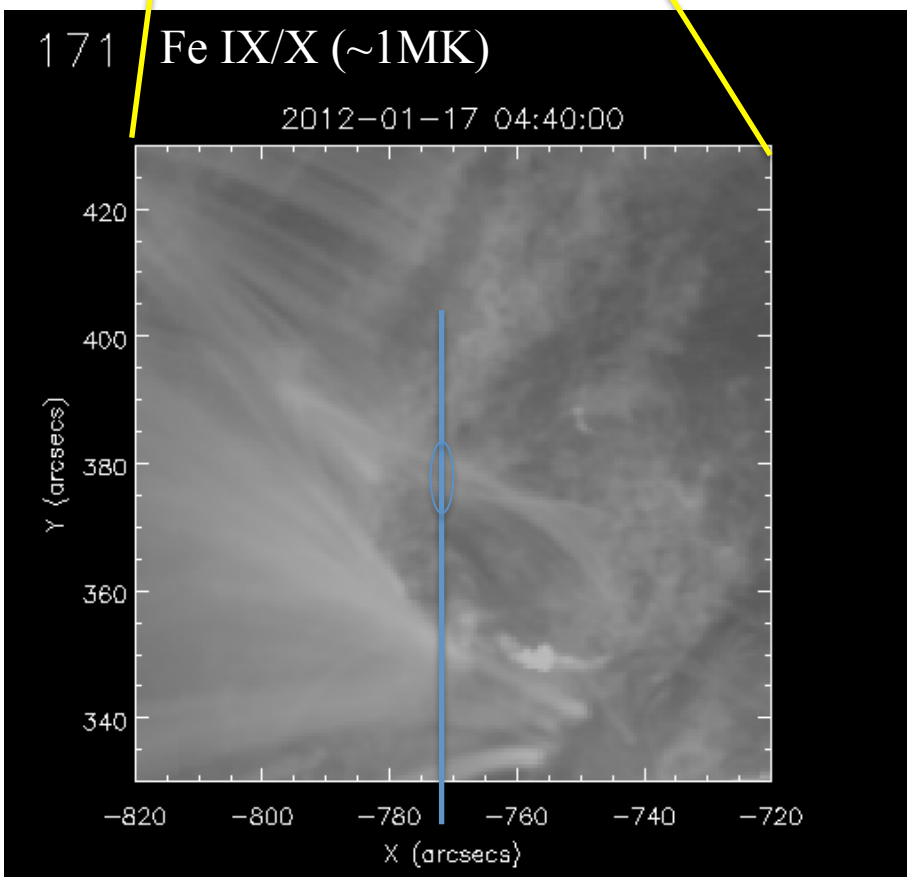


Inflow speed: $V_D \sim -20$ km/s

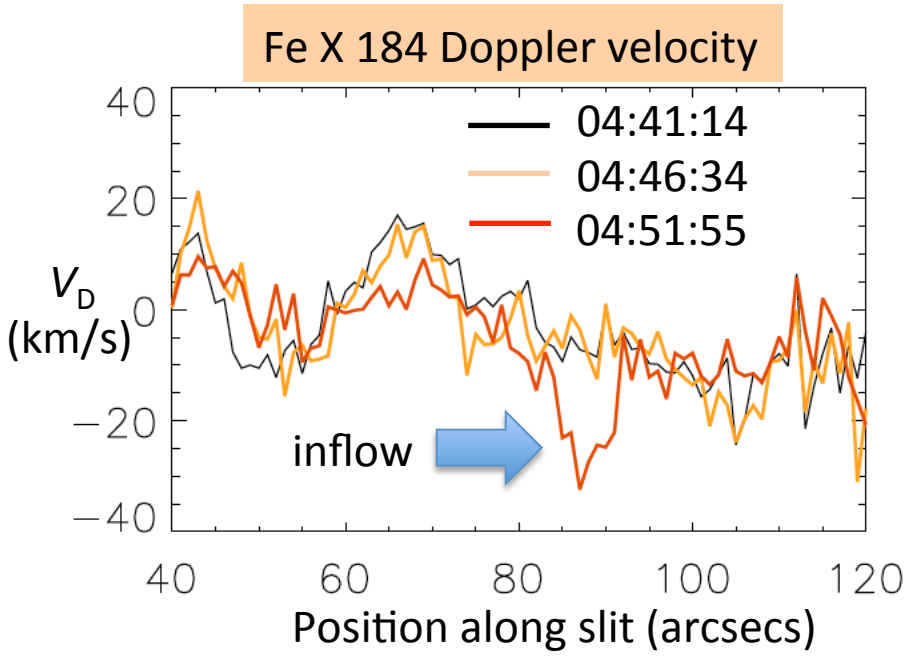
Reconnection Inflow



GOES M1.0



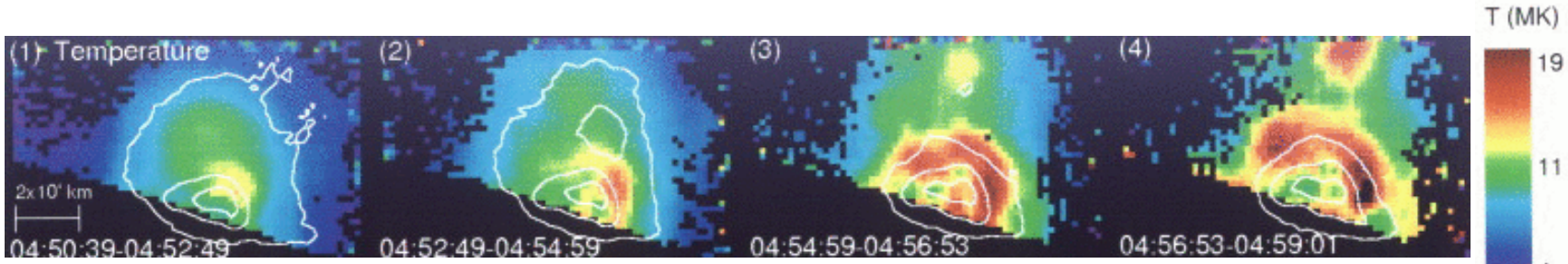
- Signature of reconnection inflow structure was observed in AIA171 as a disappearing loop: apparent speed ~50 km/s
- EIS observed blueshift of -25 km/s and intensity decrease in Fe X 184.
- $M_A \sim V_{inflow}/V_{outflow} \sim 0.1$



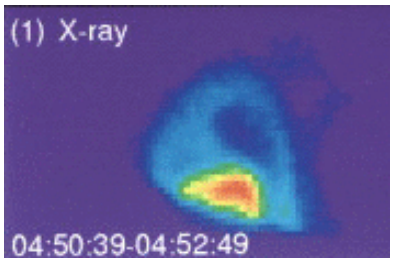
Reconnection Outflow/Plasmoids

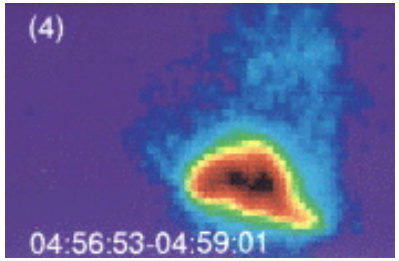
Yohkoh Imaging Observations: Plasma Ejections

T_e

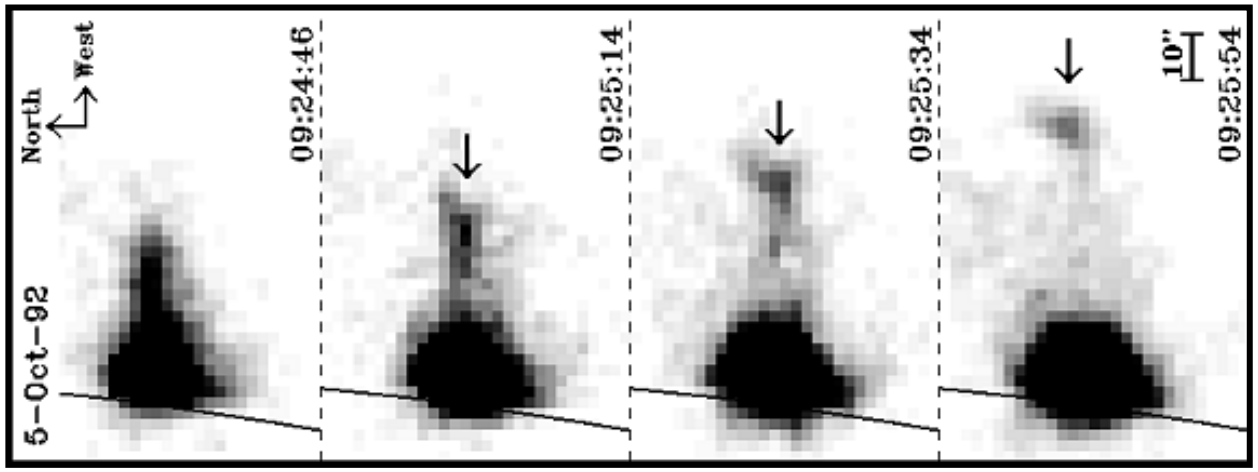


I

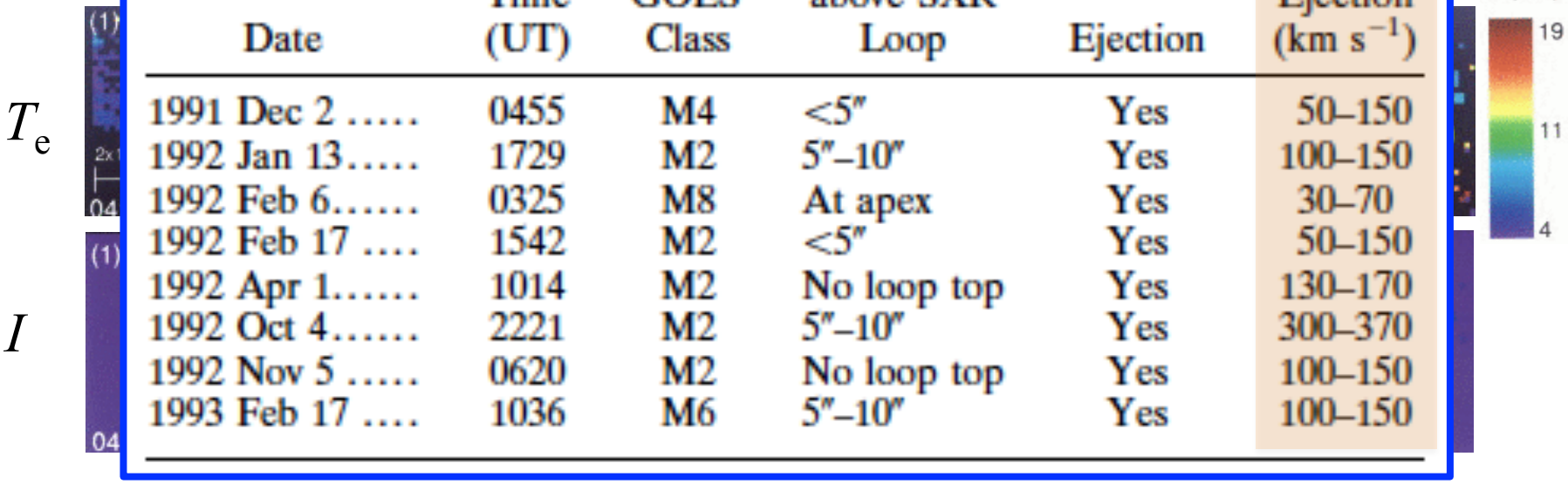




Tsuneta (1997)

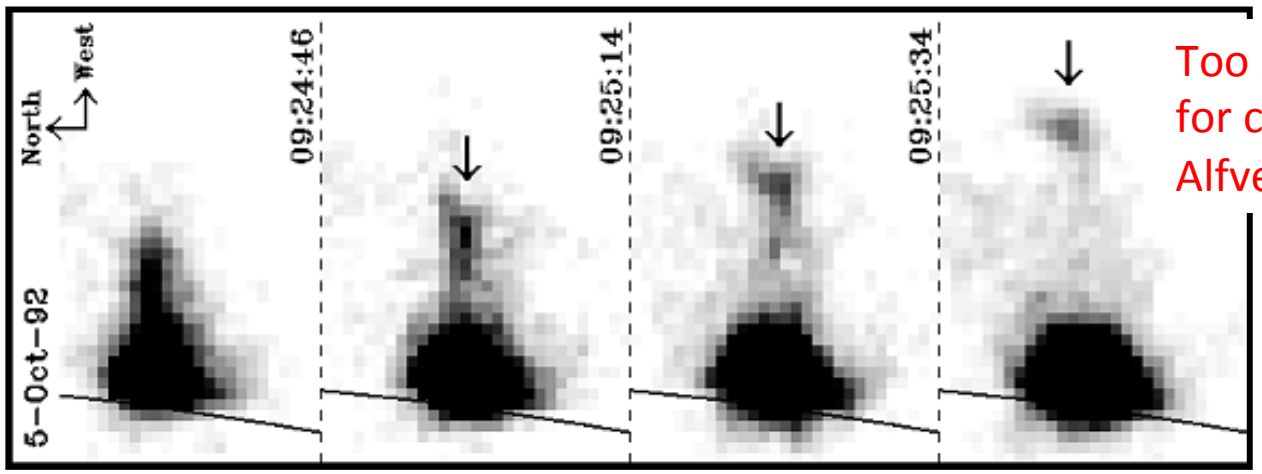


Ohyama & Shibata (1998)



SUMMARY OF EIGHT COMPACT-LOOP LIMB FLARES

Date	Peak Time (UT)	GOES Class	Height of HXR Source above SXR Loop	Ejection	Apparent Velocity of Ejection (km s^{-1})
1991 Dec 2	0455	M4	<5″	Yes	50–150
1992 Jan 13.....	1729	M2	5″–10″	Yes	100–150
1992 Feb 6.....	0325	M8	At apex	Yes	30–70
1992 Feb 17	1542	M2	<5″	Yes	50–150
1992 Apr 1.....	1014	M2	No loop top	Yes	130–170
1992 Oct 4.....	2221	M2	5″–10″	Yes	300–370
1992 Nov 5	0620	M2	No loop top	Yes	100–150
1993 Feb 17	1036	M6	5″–10″	Yes	100–150



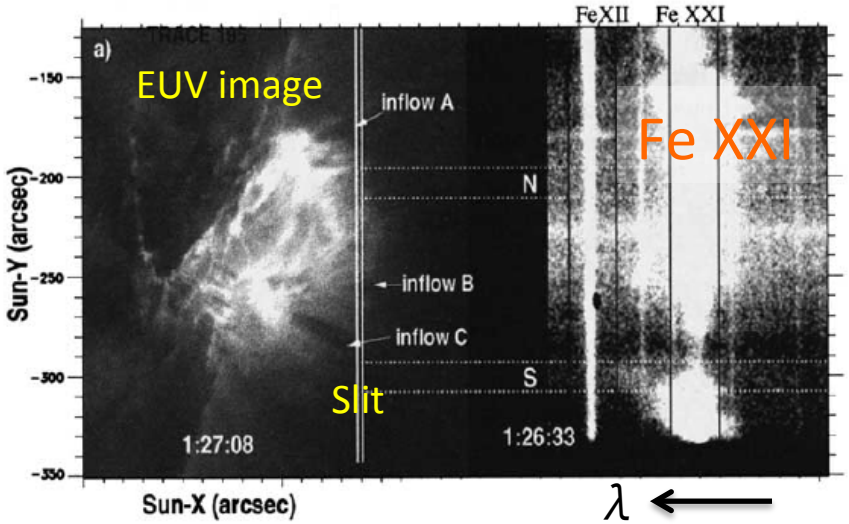
Too slow for coronal Alfven speed

Ohyama & Shibata (1998)

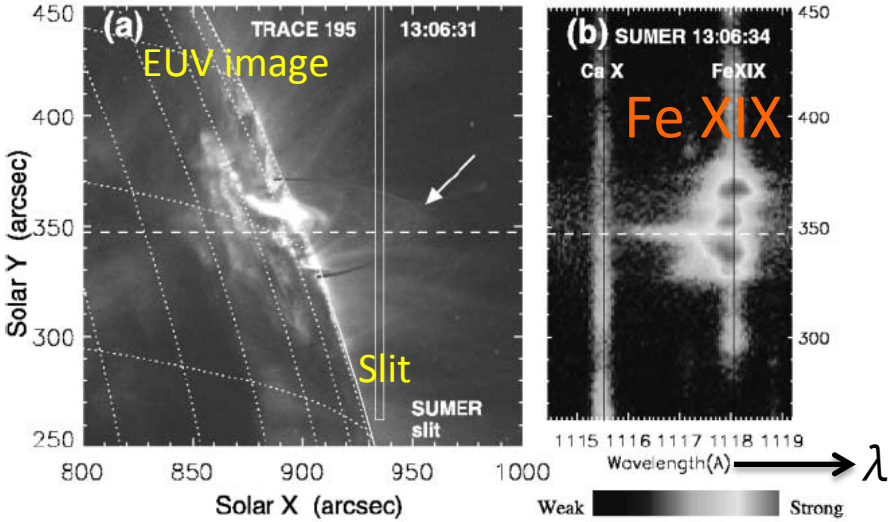
Reported EUV Observations of Reconnection Outflows

- 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
    } No scanning observations
  - Hinode/EIS: Hara+2011 (B9.5) Fe XXIV, Fe XXIII, Ca XVII
    Imada+2013 (X1.7) Fe XXIV

Innes+2003 (GOES X1.5)



Wang+2007 (GOES M2.5)



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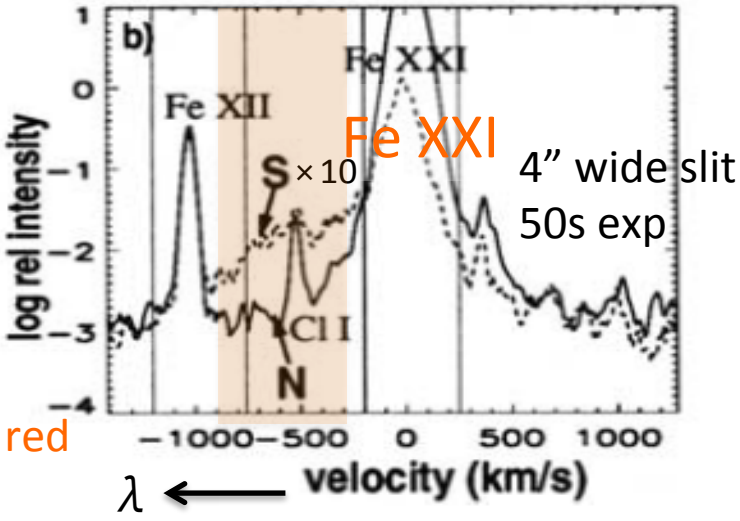

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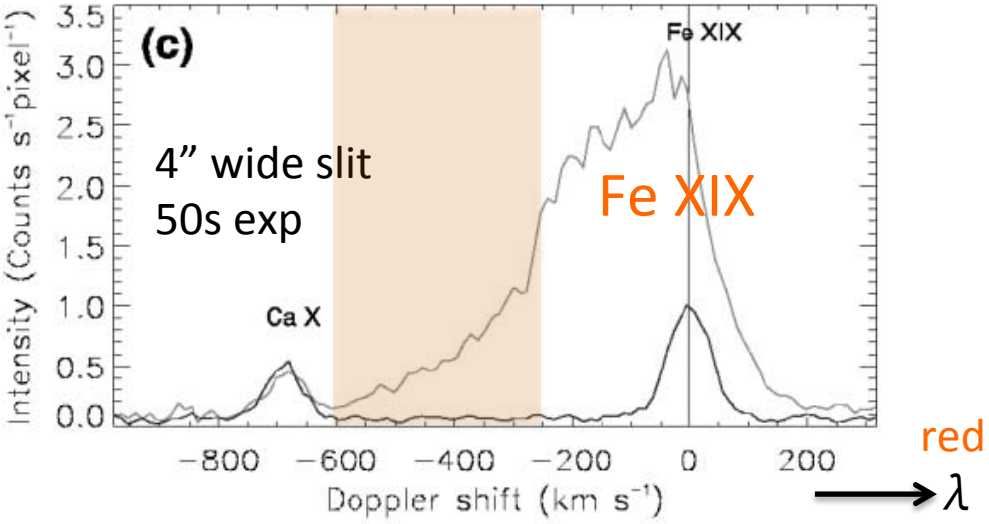

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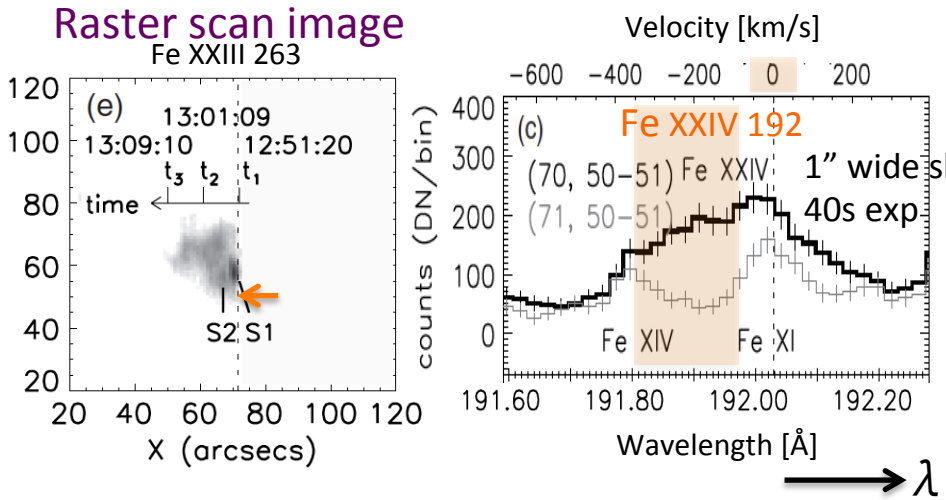
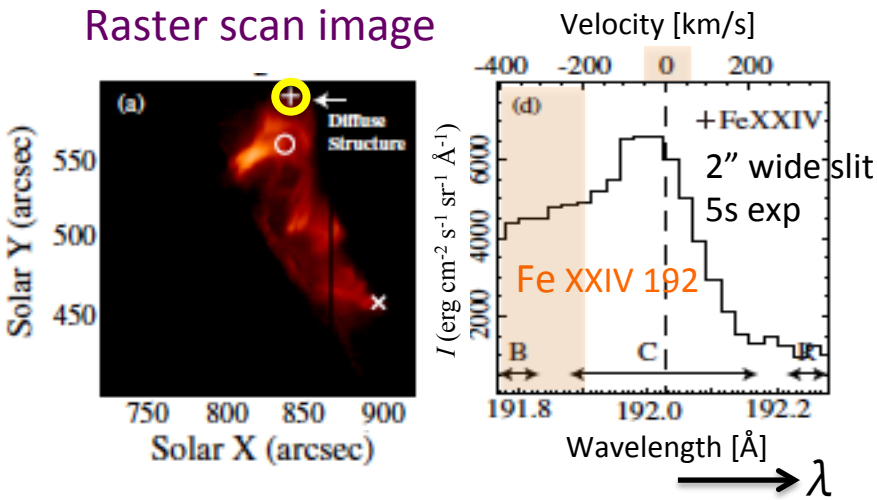
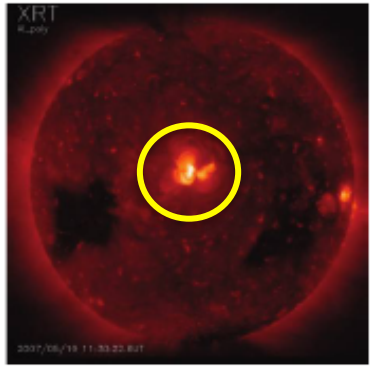
    with scanning observations
    Imada+2013 (X1.7) Fe XXIV

Hara+2011 (GOES B9.5)

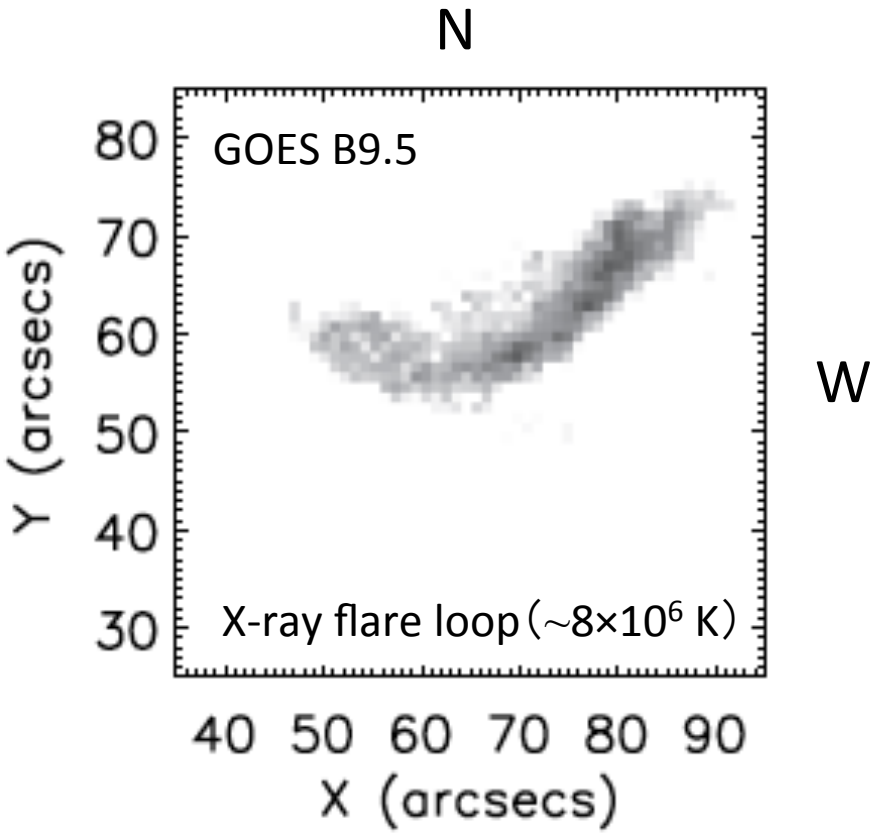


Imada+2013 (GOES X1.7)

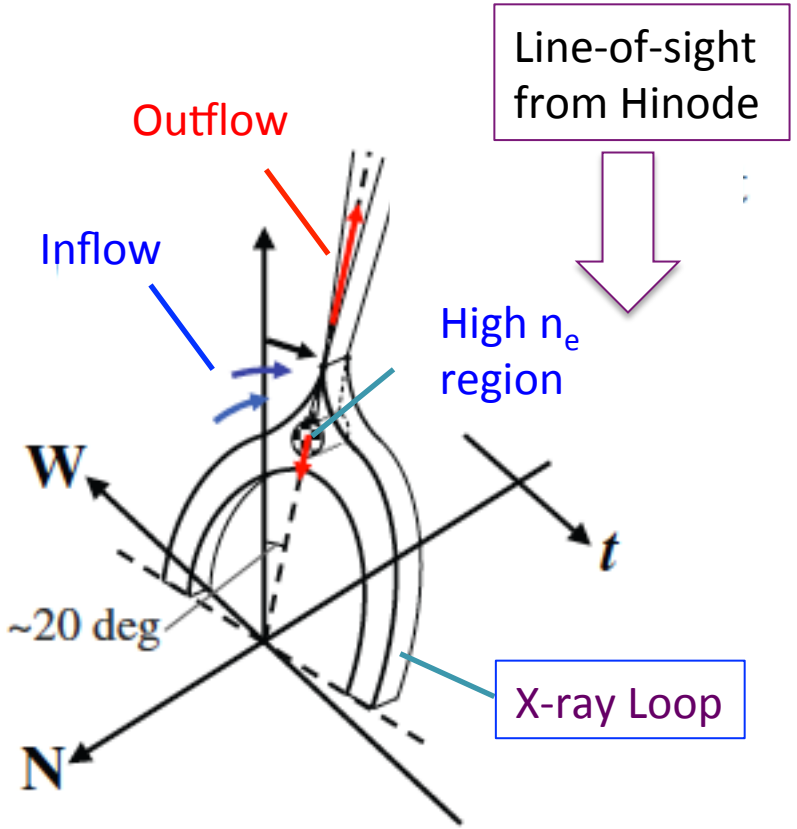


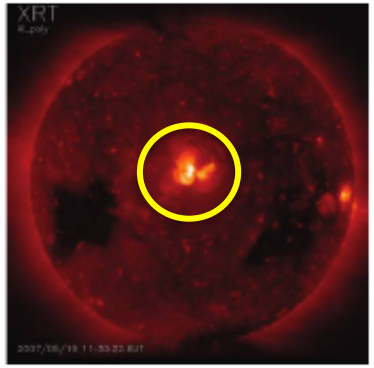


Magnetic Reconnection in an eruptive event



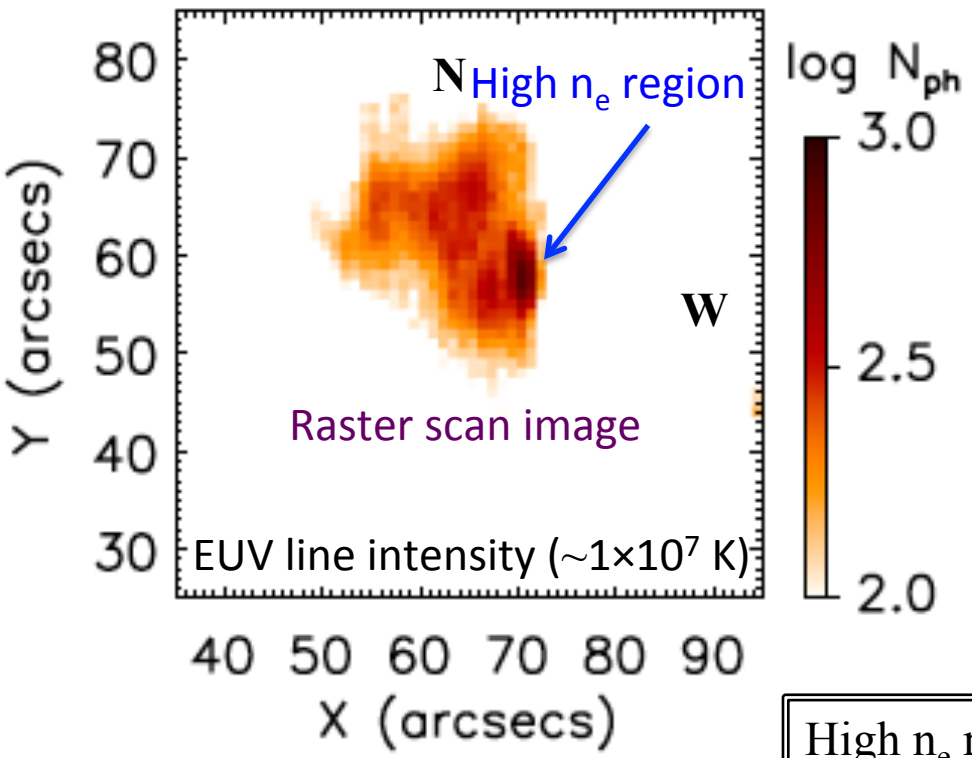
1 arcsec = ~700 km on the Sun





Magnetic Reconnection in an eruptive event

Duration of impulsive phase



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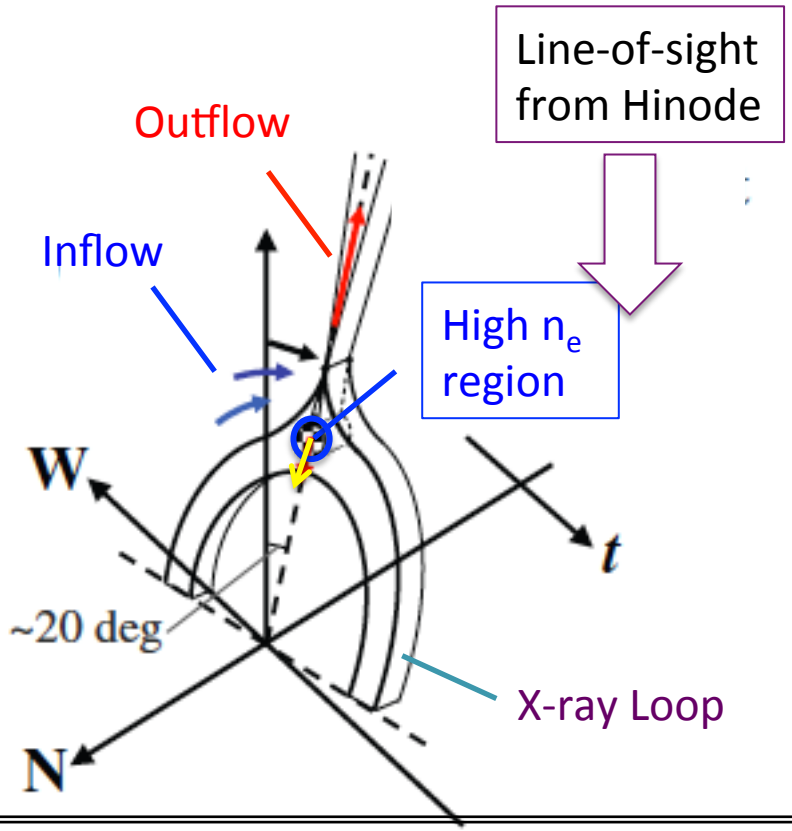
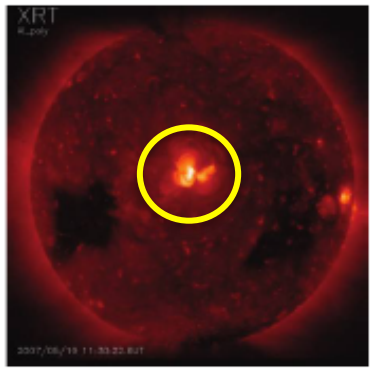
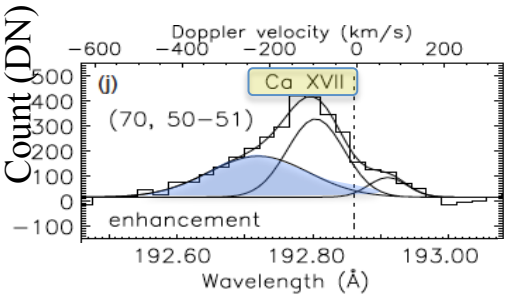
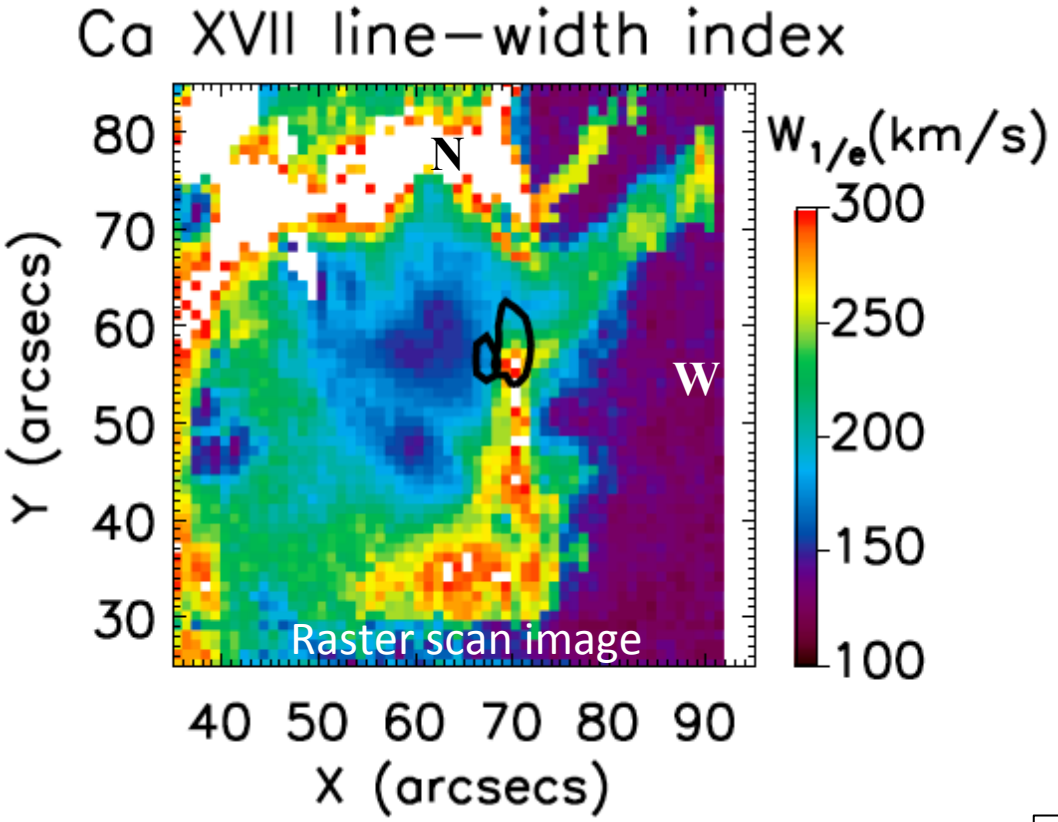


High n_e region:
T_e = 12 MK [Fe XXIV/Fe XXIII, RHESSI continuum]
T_i = 50 MK (or V_{NT} =100 km/s) [Fe XXIII line width]
V_D = 30 km/s (downward)

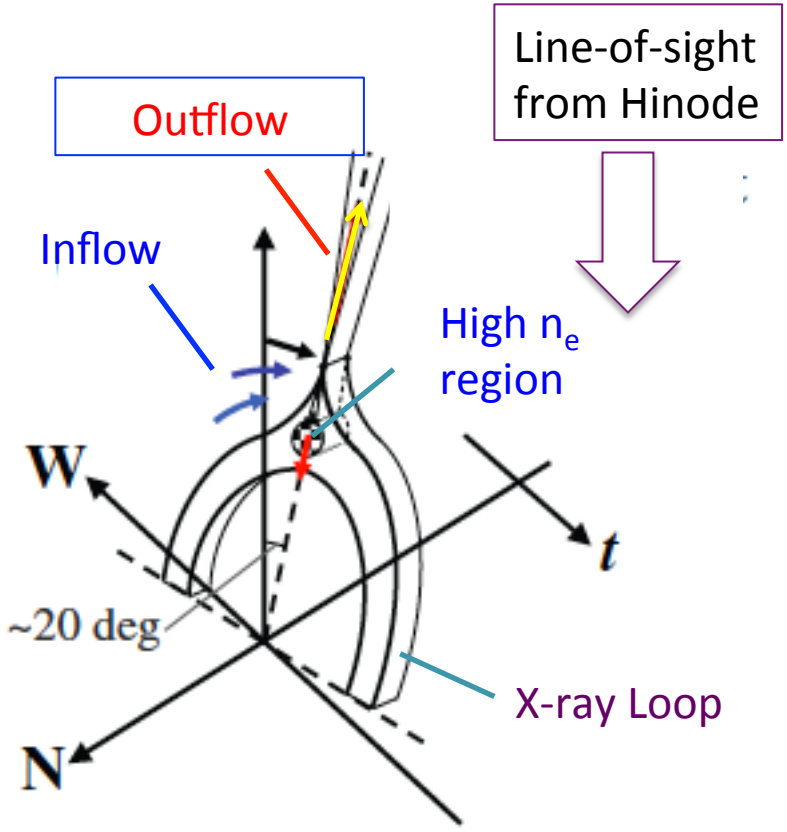


Magnetic Reconnection in an eruptive event





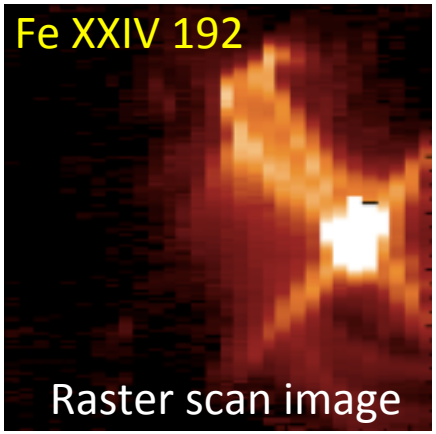
1 arcsec = ~700 km on the Sun



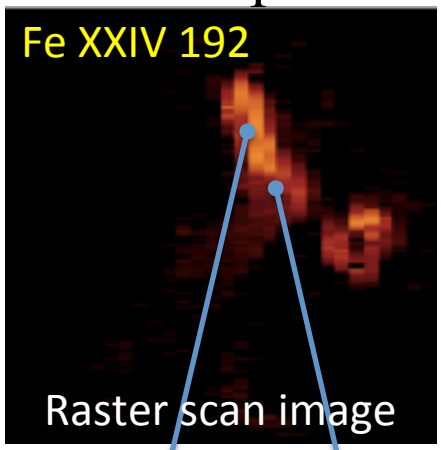
Outflow speed: $V_D = 200 - 400$ km/s

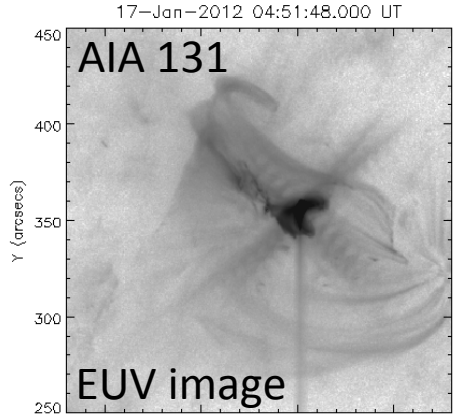
Slow component

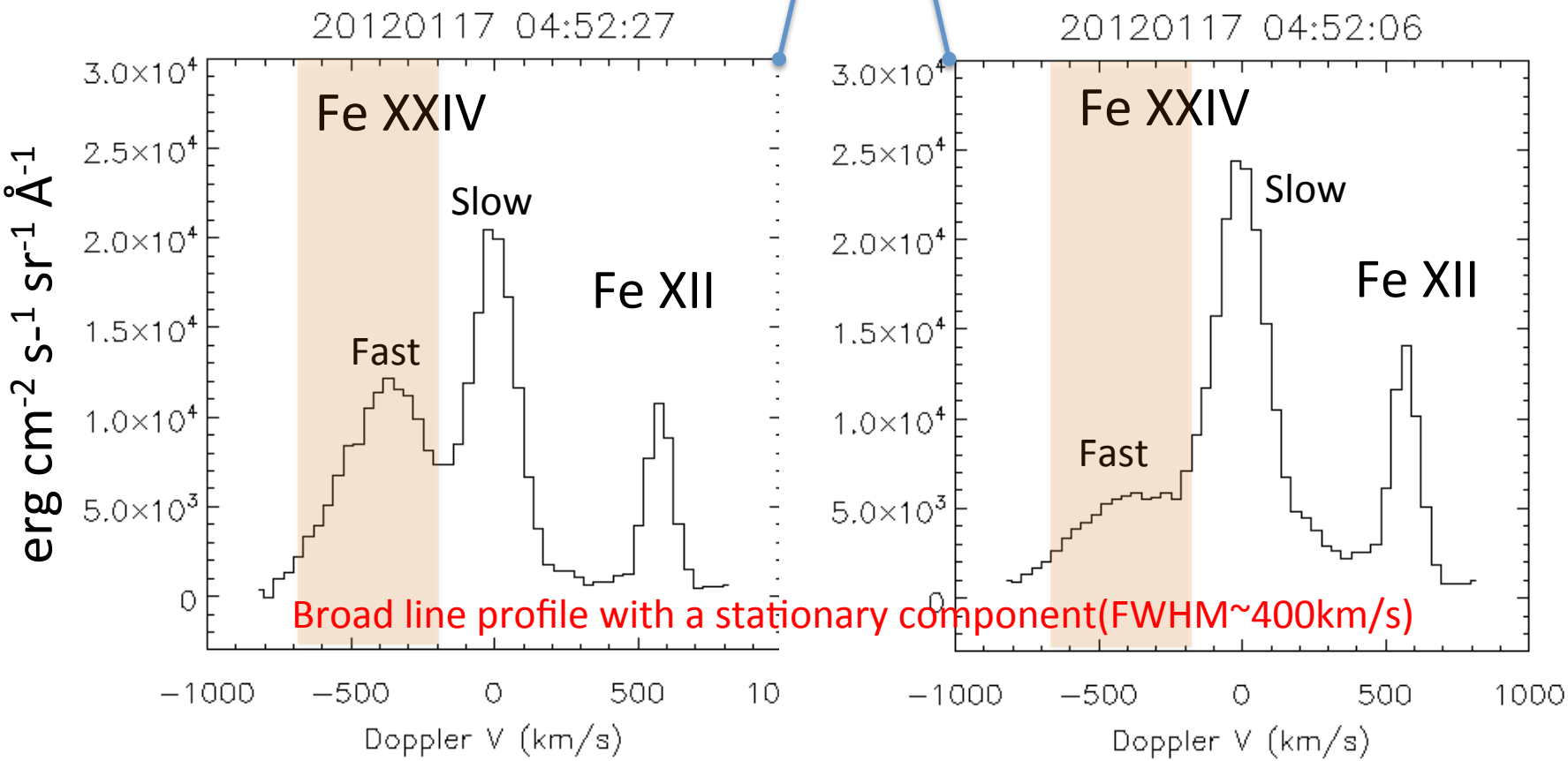
Fast component ($|V| > 200$ km/s)



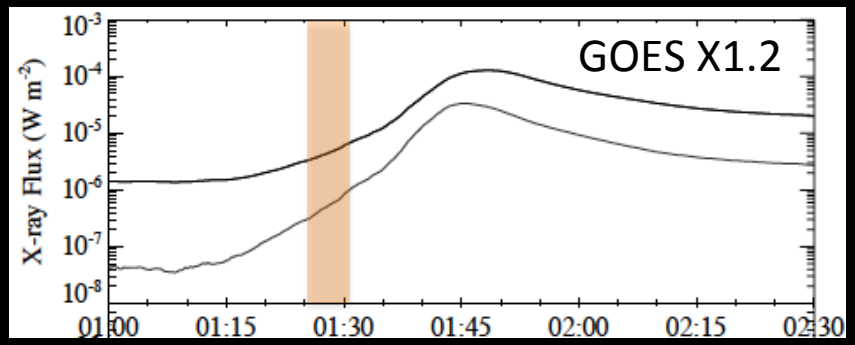
GOES M1.0



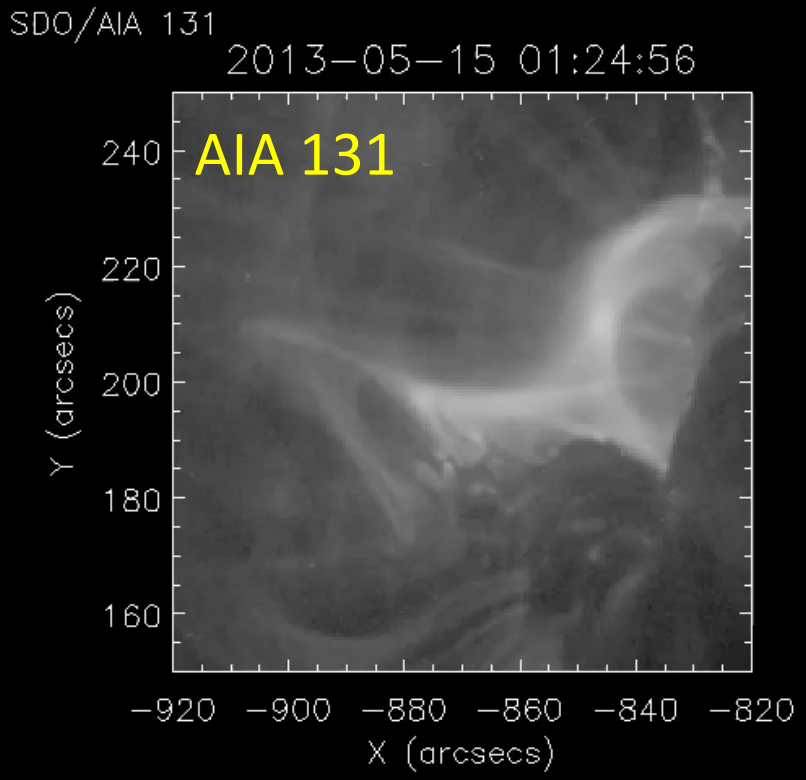


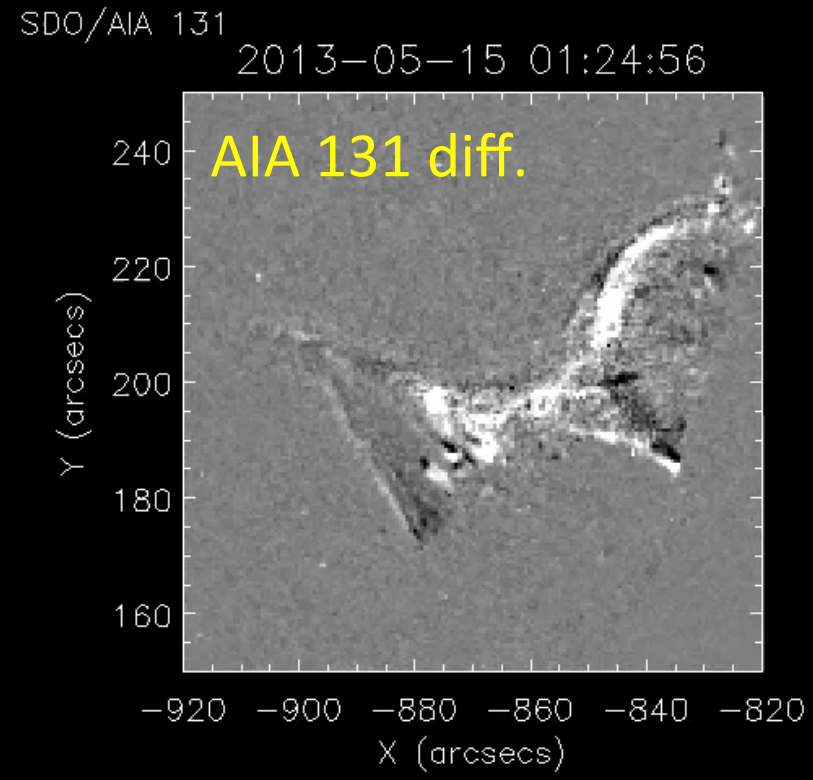


Dynamics in an EIS sparse raster

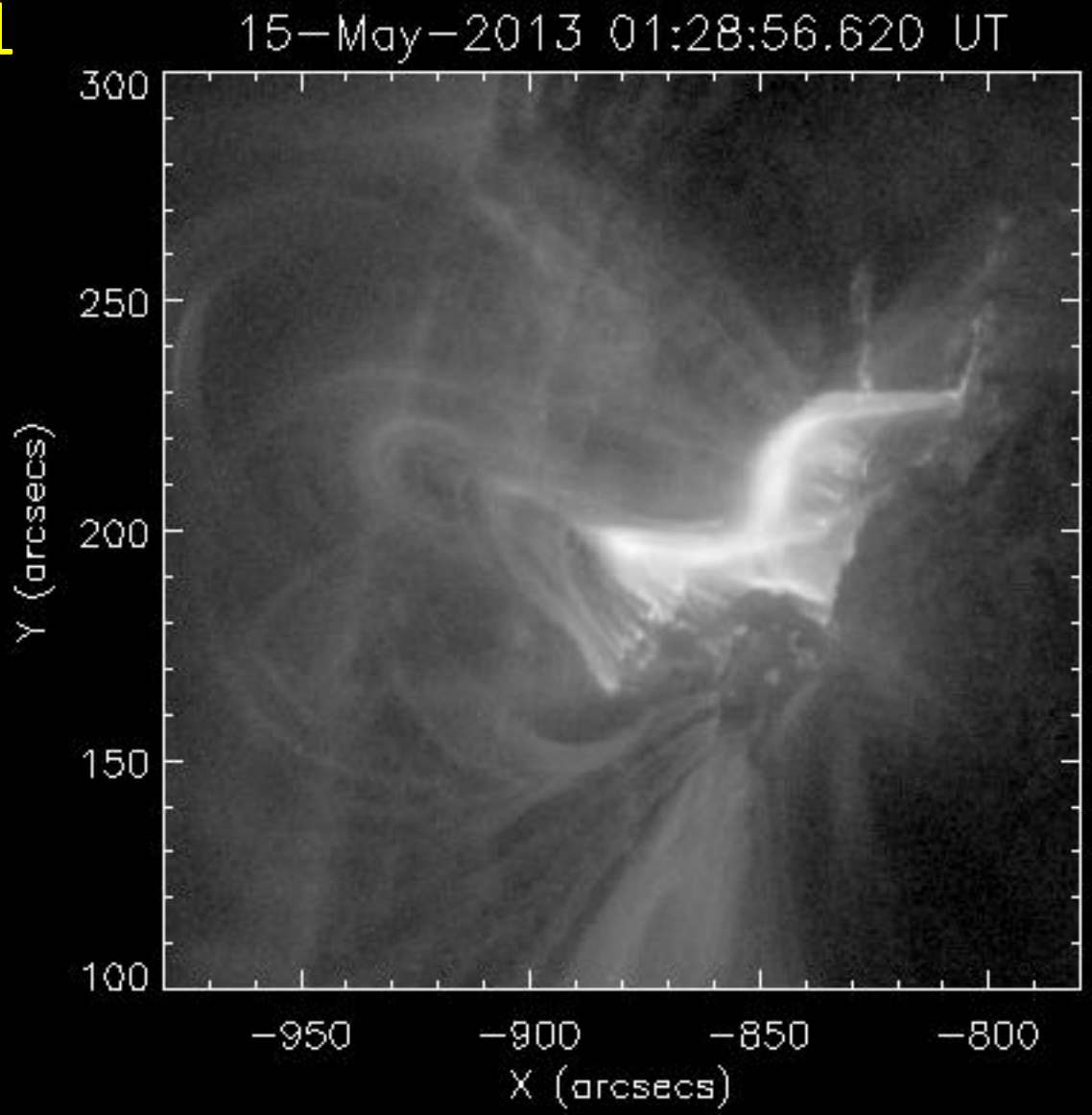


- Many changes are going on during a single EIS raster observation.

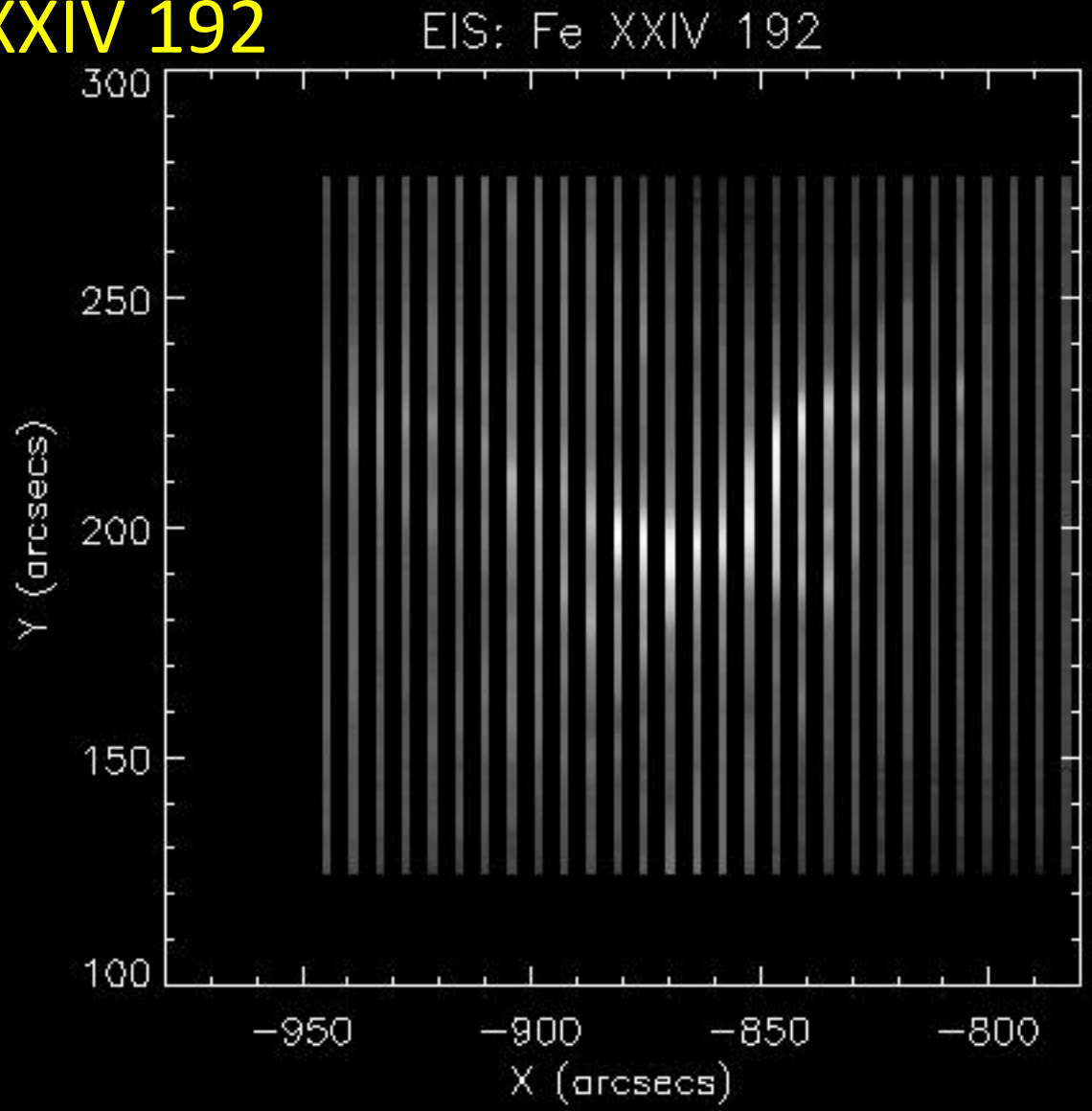




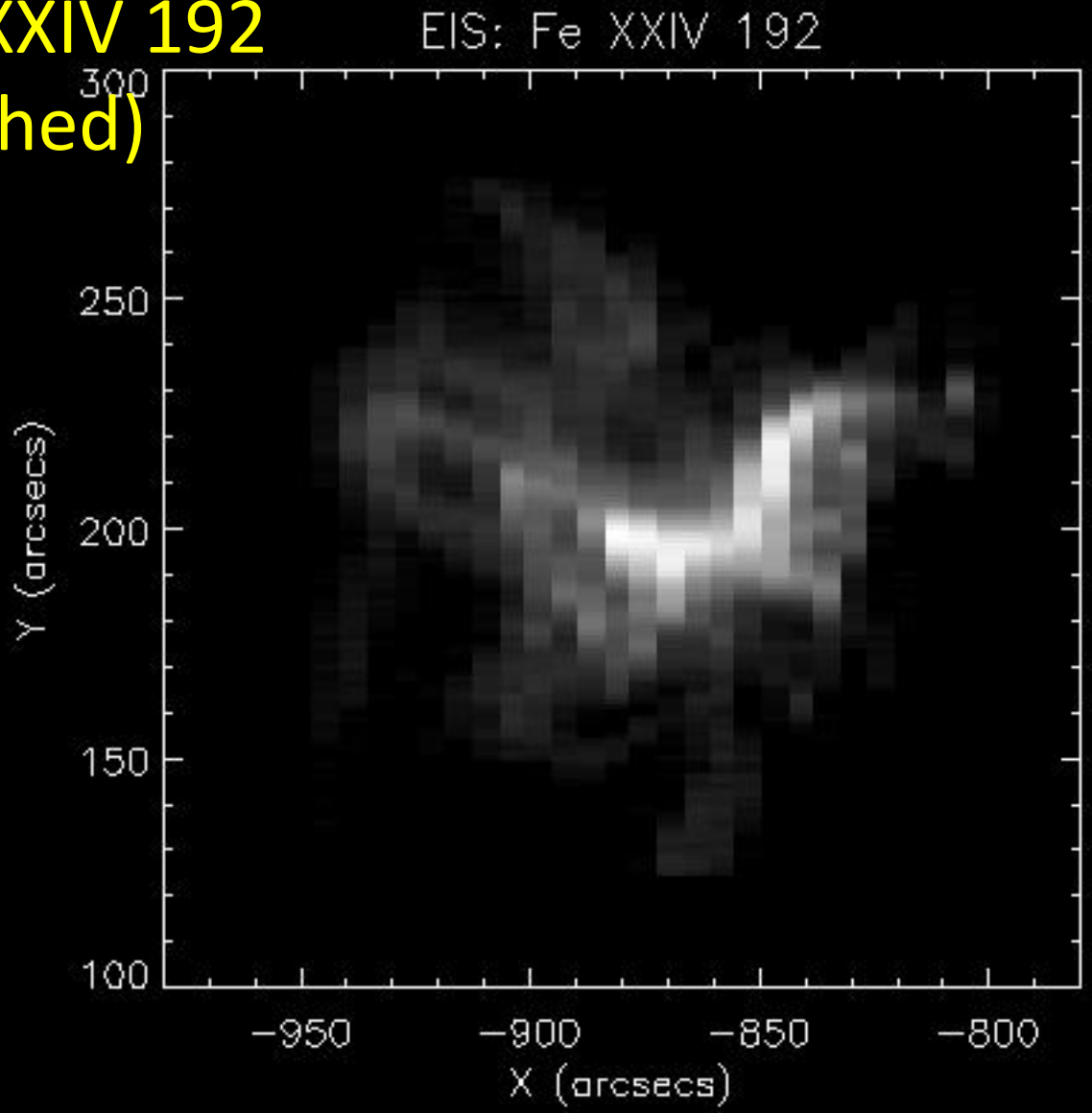
AIA 131


15-May-2013 01:28:56.620 UT
300
250
200
150
100
Y (arcsecs)
-950
-900
-850
-800
X (arcsecs)

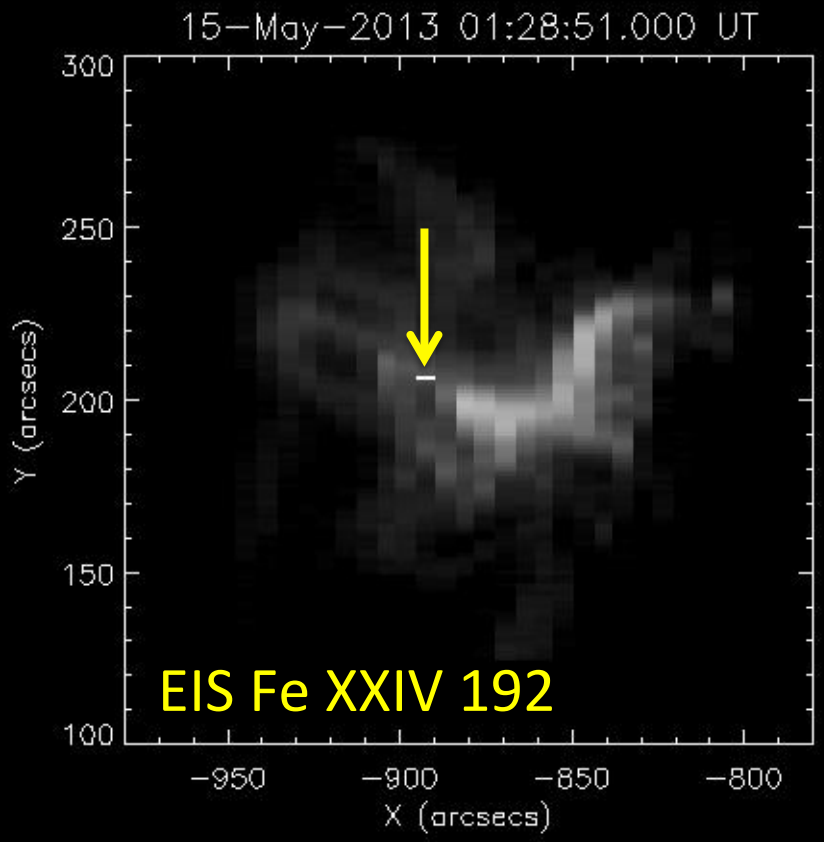
EIS Fe XXIV 192



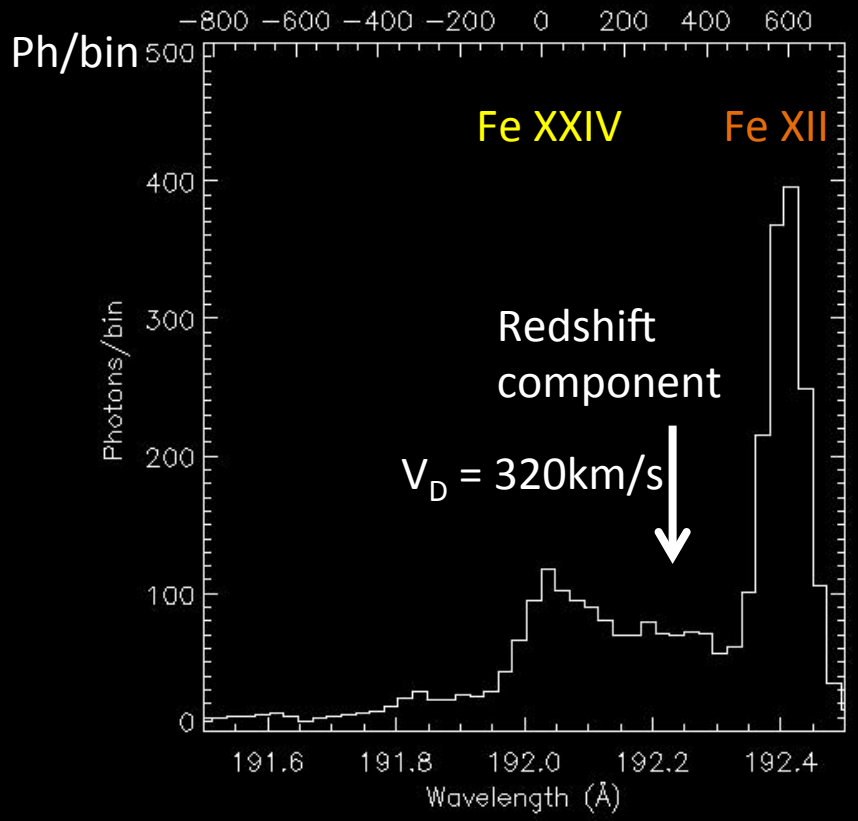
EIS Fe XXIV 192 (smoothed)



Spectrum in the thin structure above the cusp



Doppler Velocity V_D (km/s)

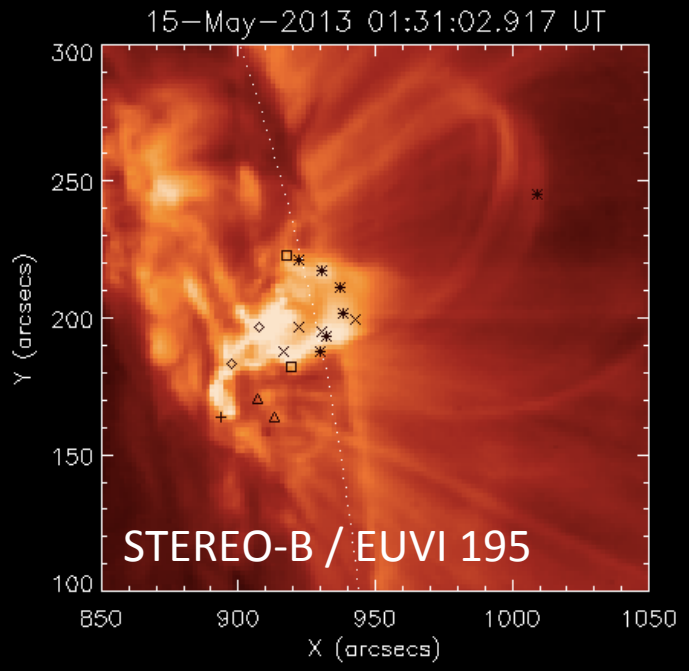


Broad profile with a stationary component

Shifted component: FWHM=400km/s

V_{NT} = 230 km/s (T_i=1.0E7 K) or T_i = 2.0E8 K

$$W_{obs} = \sqrt{W_I^2 + 4 \ln 2 \left(\frac{2kT_i}{M_i} + V_{NT}^2\right)} \equiv \sqrt{W_I^2 + W^2}$$



Geometry & V_{outflow}

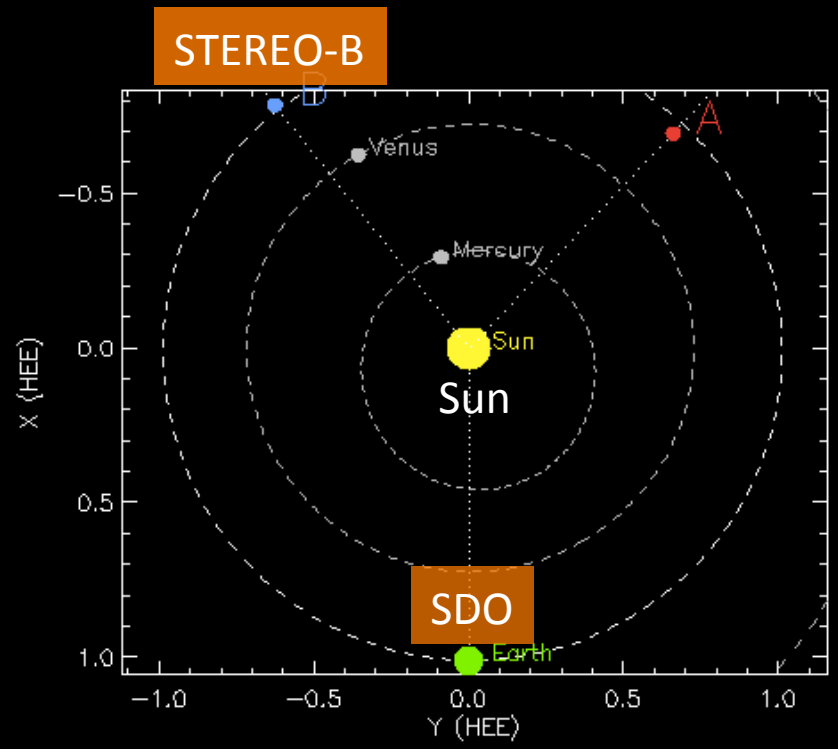
AIA & EUVI images:

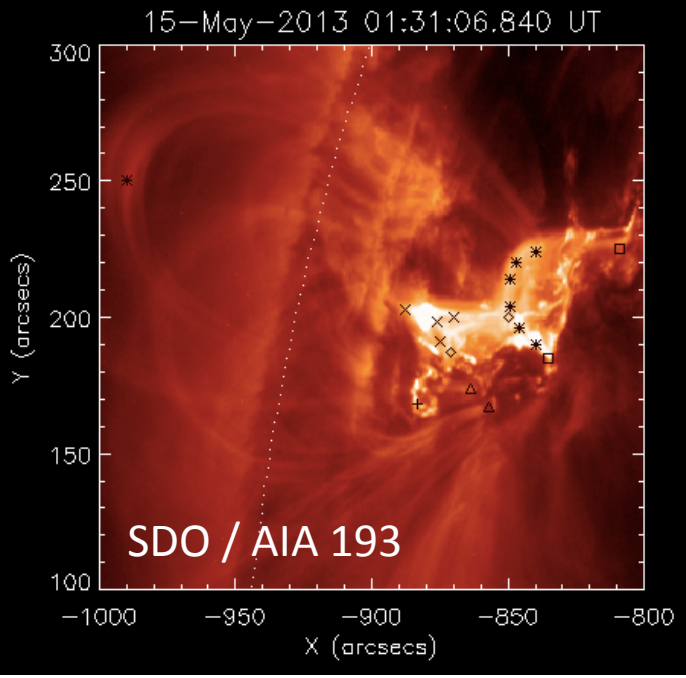
$1 / \cos\theta = 2.1 – 3.6$

$V_{\text{outflow}} = V_D\ (320\ \text{km/s}) / \cos\theta$

$= 650 – 1200\ [\ \text{km/s}\ ]$

$M_{\text{outflow}} = V_{\text{outflow}} / V_{\text{Fast}} > 1.18$ at least





MR: gain from *Hinode*

Recent EUV spectrograph observations have revealed:

Reconnection Inflow:

Speed: V_D = 3 – 20 km/s

❖Disappear after entering reconnection region due to heating

$M_{A,\,inflow} \sim 0.01$ - 0.1

Slow & Fast Shock:

❖Presence suggested from thermal parameters

$T_{e,\,outflow}/T_{e,inflow}$, $n_{e,\,outflow}/n_{e,\,inflow}$

$T_{e,\,blob}/T_{e,outflow}$, $n_{e,\,blob}/n_{e,\,outflow}$

❖An example: $V_{outflow}/V_{fast} > \sim 1.2$

Reconnection outflow/plasmoid:

Speed: V_D = 200 – 500 km/s

some $V \sim V_A$

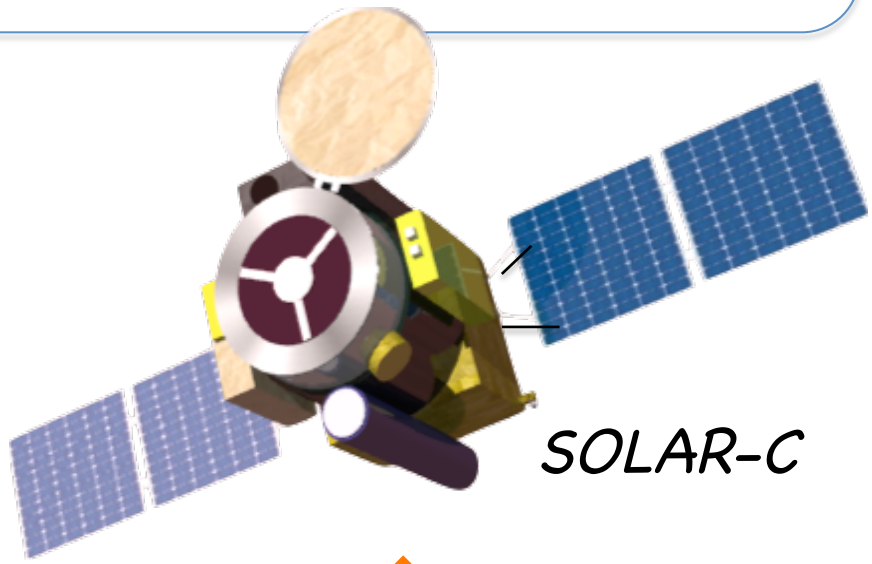
❖Dark structure in general

❖Broad line profile (turbulence)

❖with stationary component

❖Blobby structure, 3D geometry

❖An example: $V_{outflow}/V_{fast} > \sim 1.2$



Improved observations:

~30sec integration is required for pixel-by-pixel investigation using the current instrumentation in *Hinode*.

Further sensitivity for more rapid and pixel-by-pixel analysis

Summary

- From vector *B* measurements by Hinode and MHD simulations, some promising models for solar flare are appearing. Observations of chromospheric structures and *B* are crucial.
- Atmospheric response to the accelerated electrons in solar flares has been investigated from high-resolution imaging and TR-corona spectroscopy.
- Flow structures near the site of magnetic reconnection have been mapped in the EUV spectroscopy, and the presence of temperature structure in the current sheet may be becoming visible.