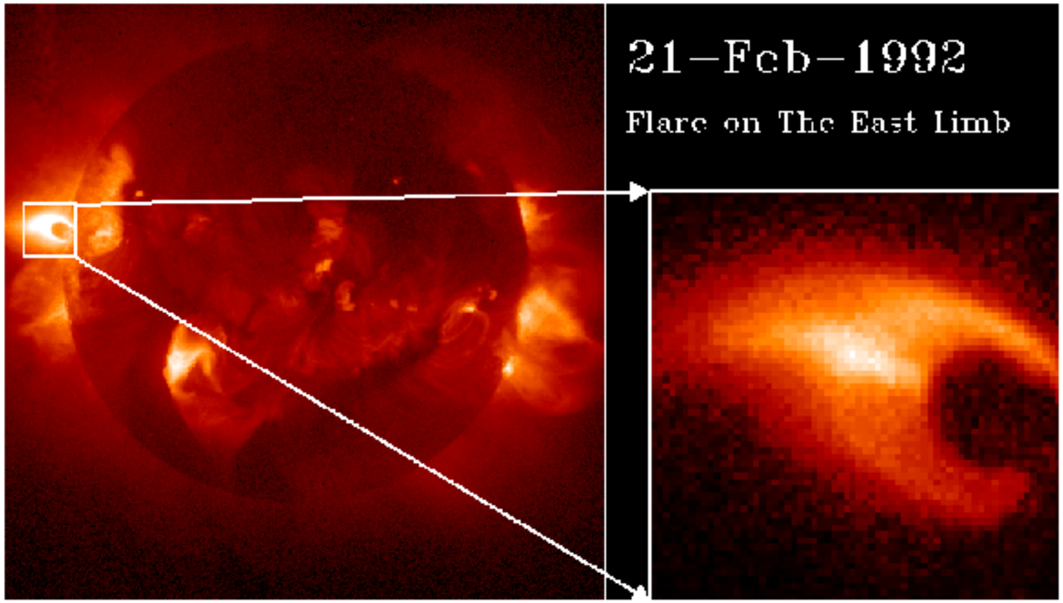
Magnetic reconnection in solar atmosphere

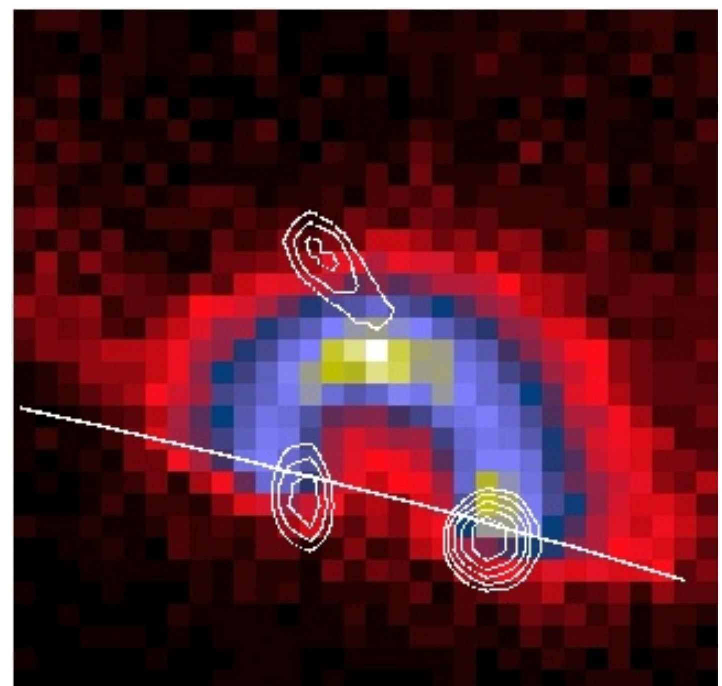
Hiroaki Isobe (Kyoto University)

- Reconnection in the corona
- Reconnection in the lower atmosphere

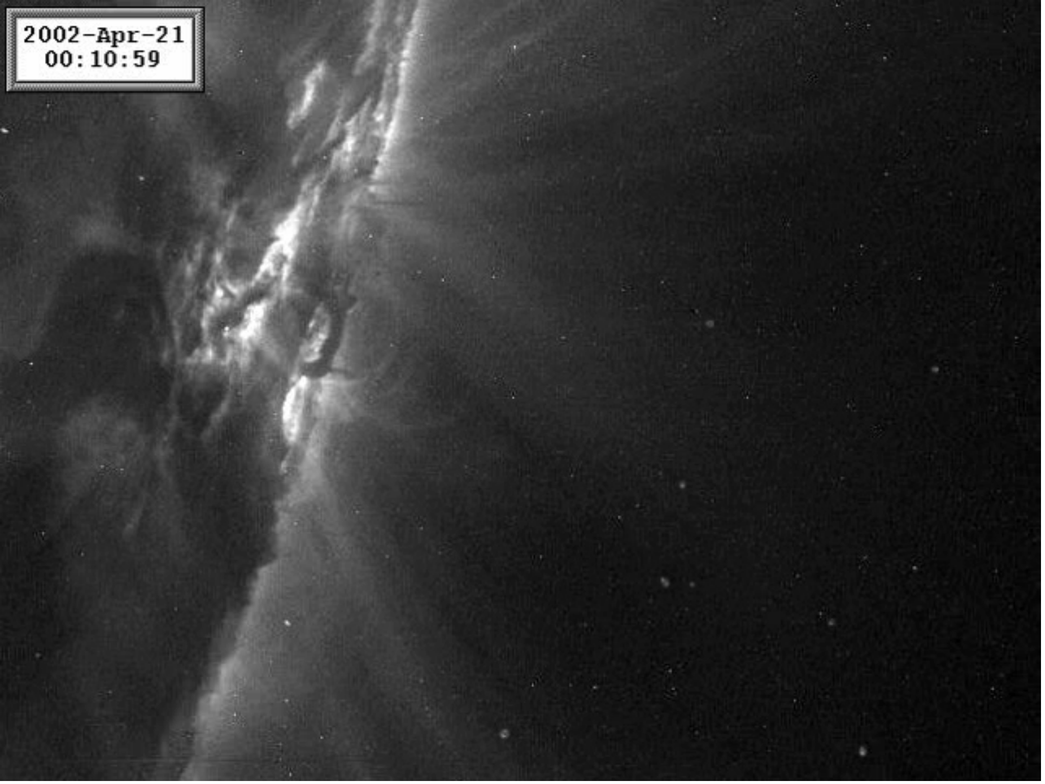
Observational evidence for magnetic reconnection in the corona (before Hinode/SDO)



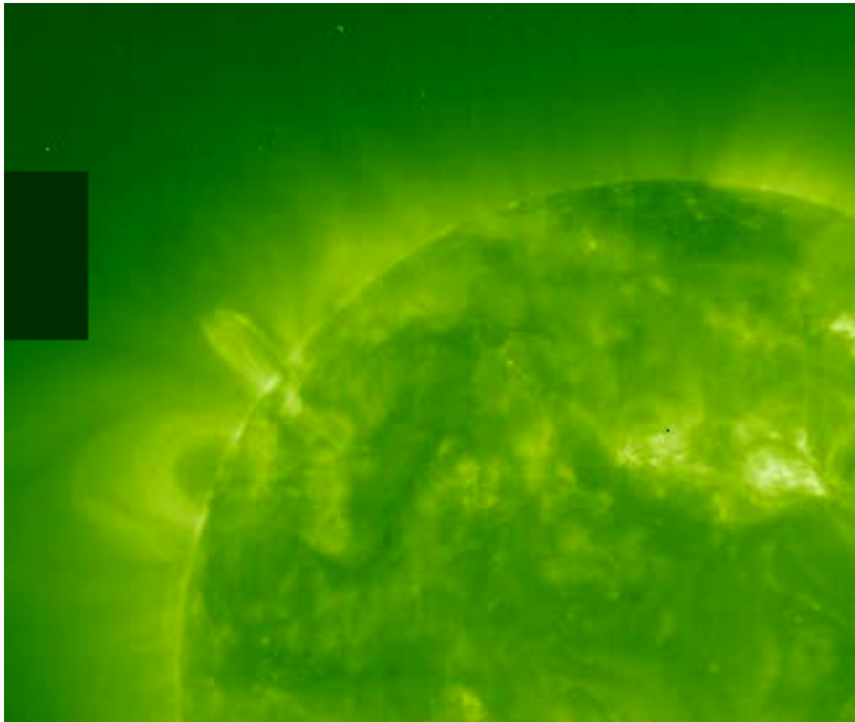
Cusp-shaped loop (Tsuneta+92)



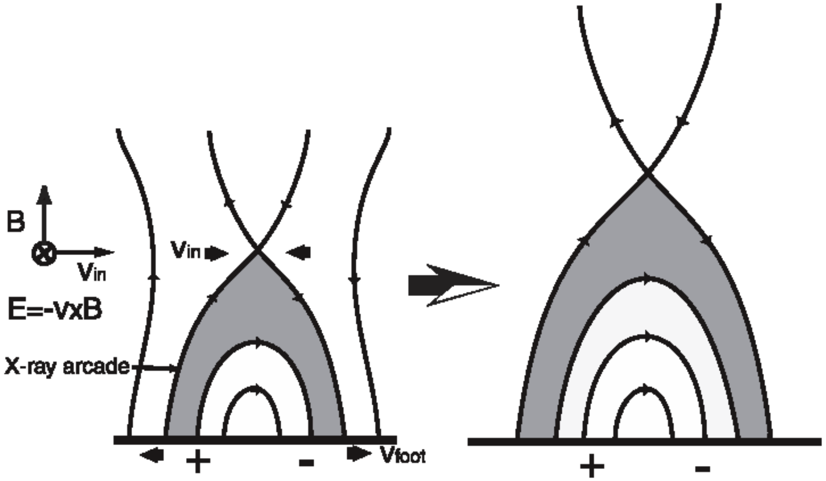
Loop-top Hard X-Ray source (Masuda+94)



Supra-arcade downflow
(McKenzie Hudson99, Innes+03, Asai+04, Savage+12)

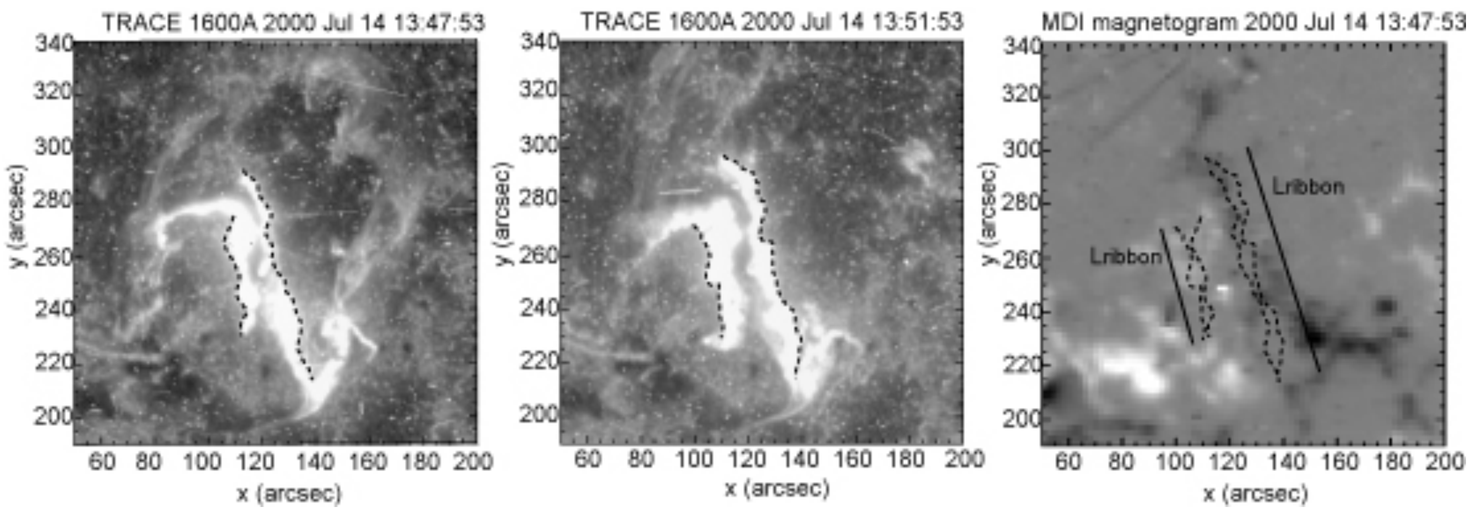


Reconnection inflow
(Yokoyama+01; Narukage & Shibata06 Lin+05, Hara+06)
V_{inflow}~$0.01V_A$



Measurement of reconnection rate

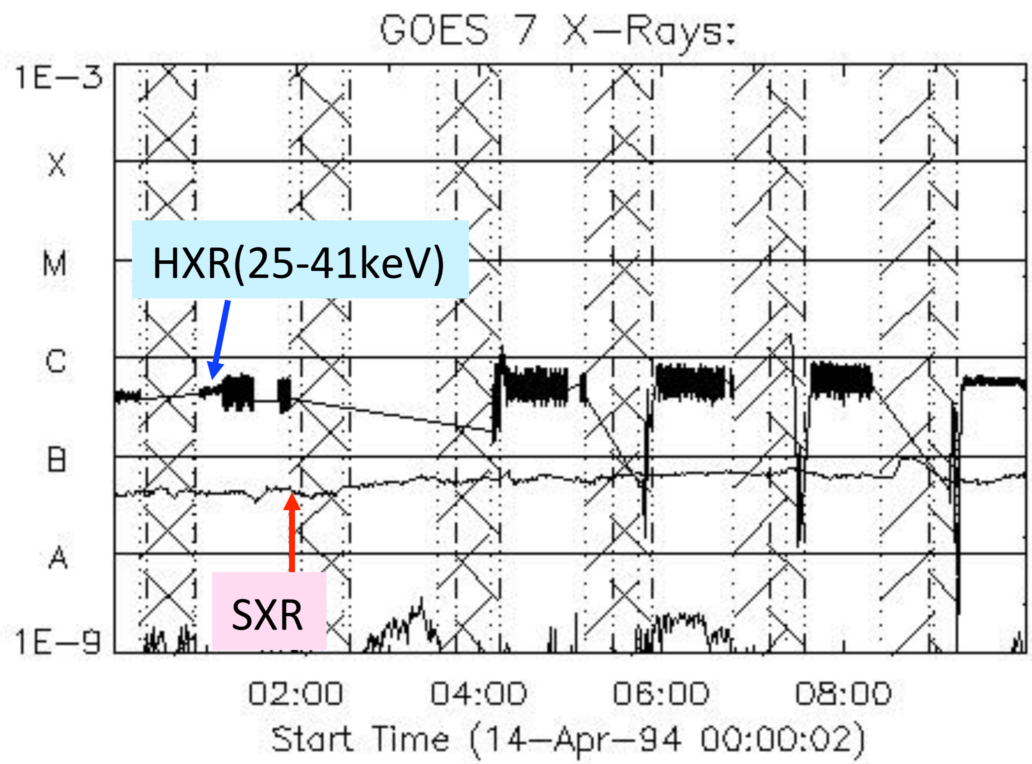
Isobe+02, 05
Qiu+02, 04
Jing+05
Asai+02,04



- V_{inflow}: 1 – 100 km/s ~ 0.001-0.1 V_A * spatial/temporal average
- E = V_{inflow} x B ~ 10—1000 V/m
- eEL ~ 1—100 GeV ... comparable to highest energy ions

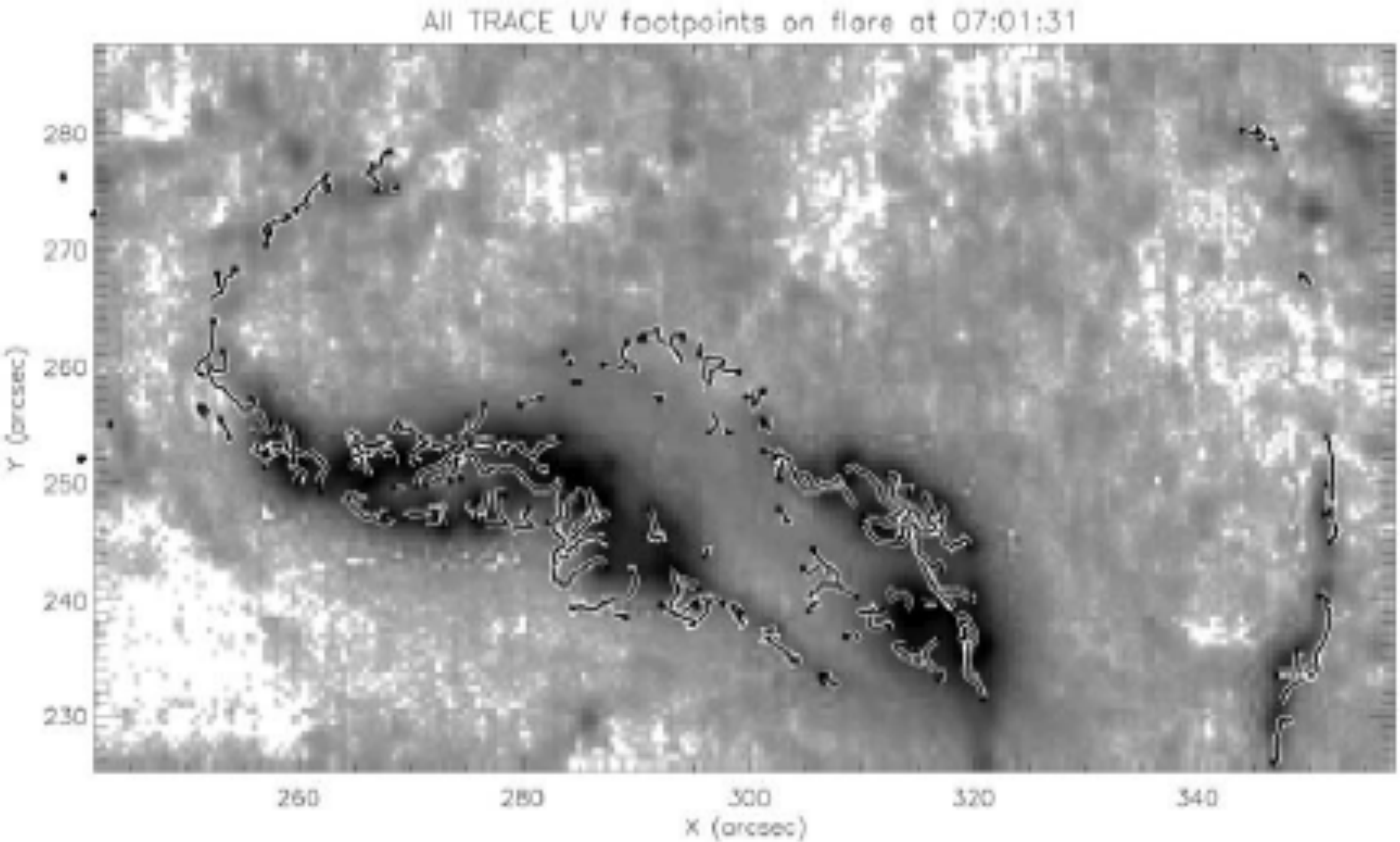
Reconnection in quiet Sun

Yohkoh/SXT

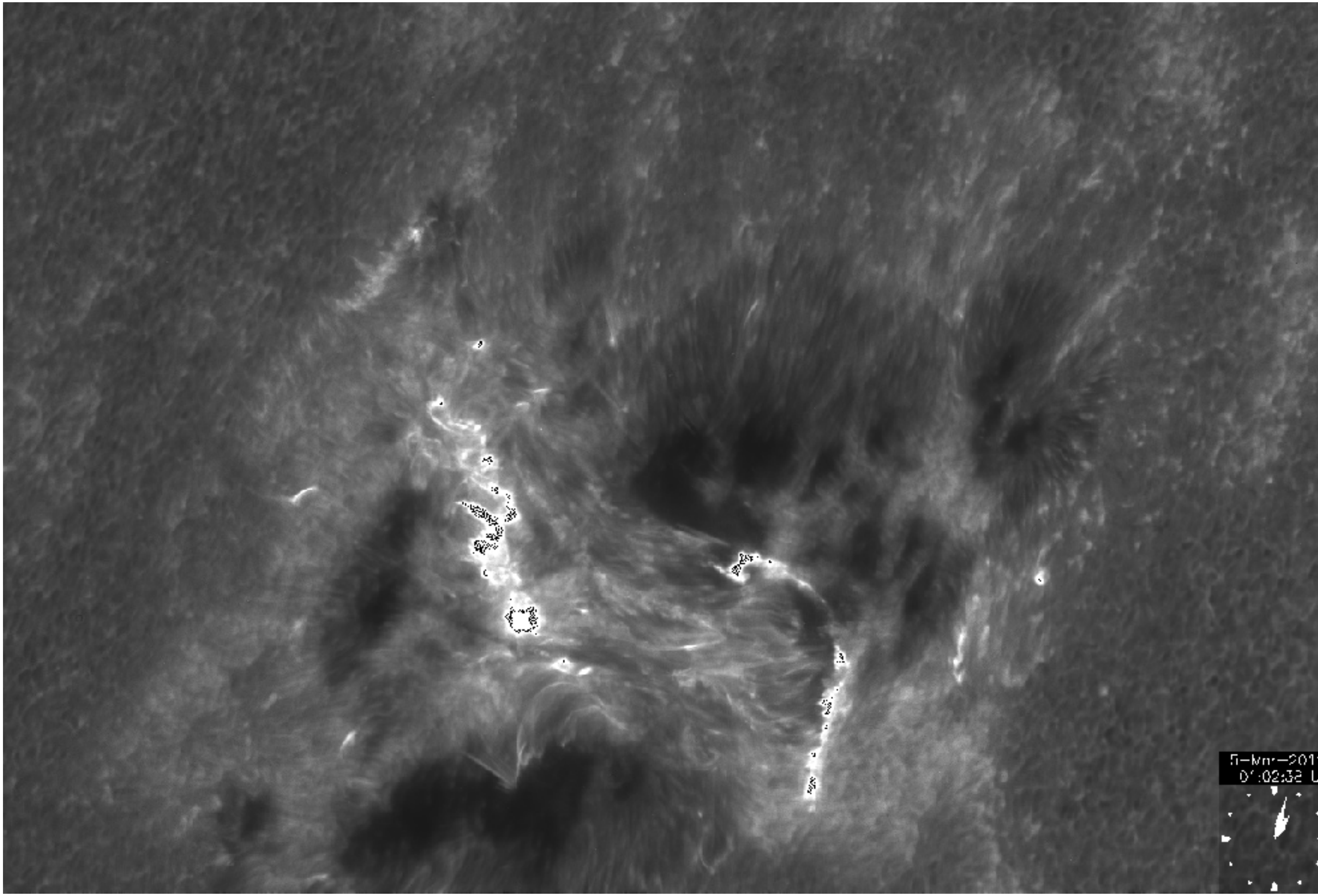


- Associated with prominence eruption.
- Invisible in SXR/HXR light curves
- Can geo-effective (McAllister+94)

Motion of individual flare kernels

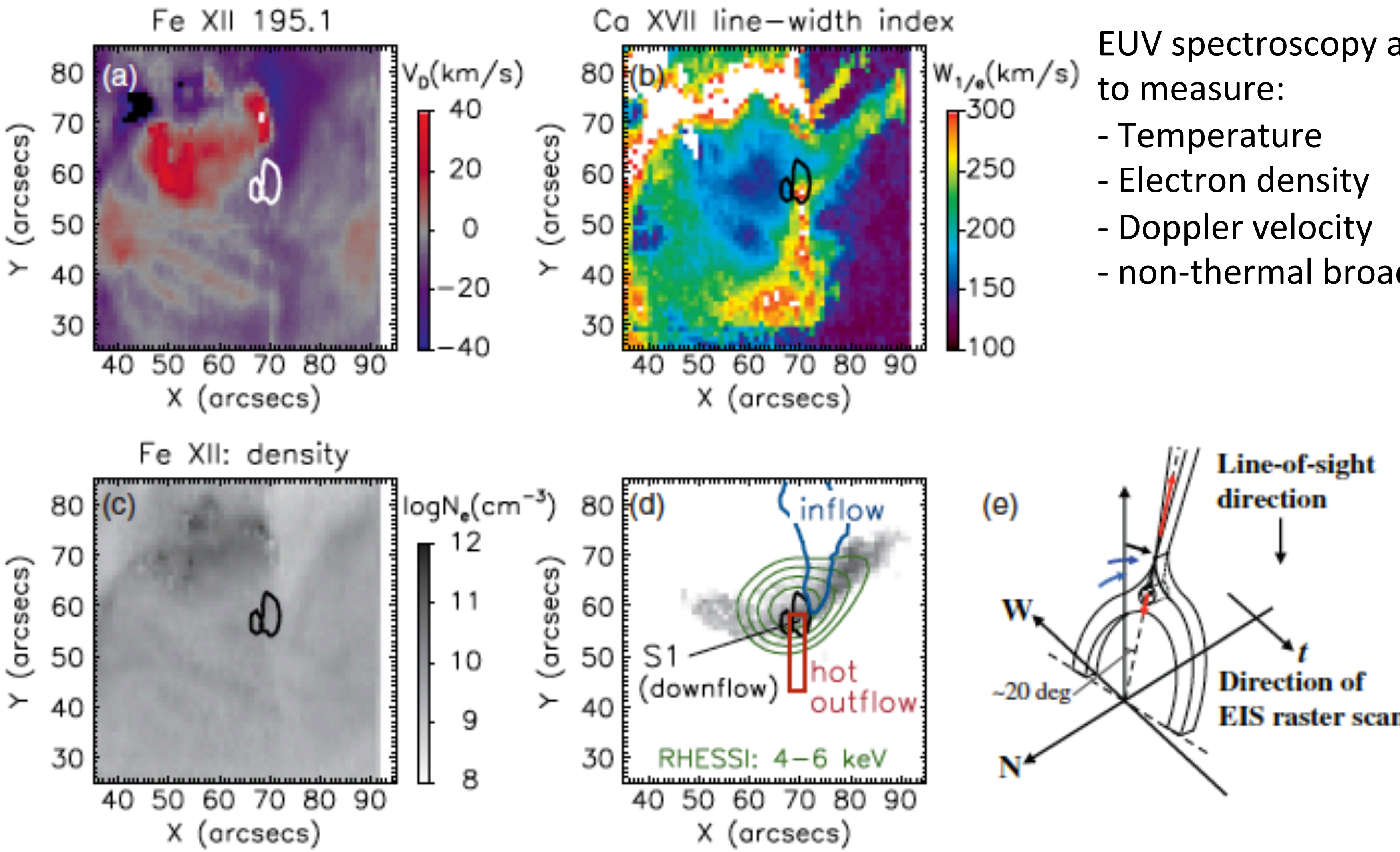


Fletcher+04



Hinode/SOT/CaH 2012 Mar 5

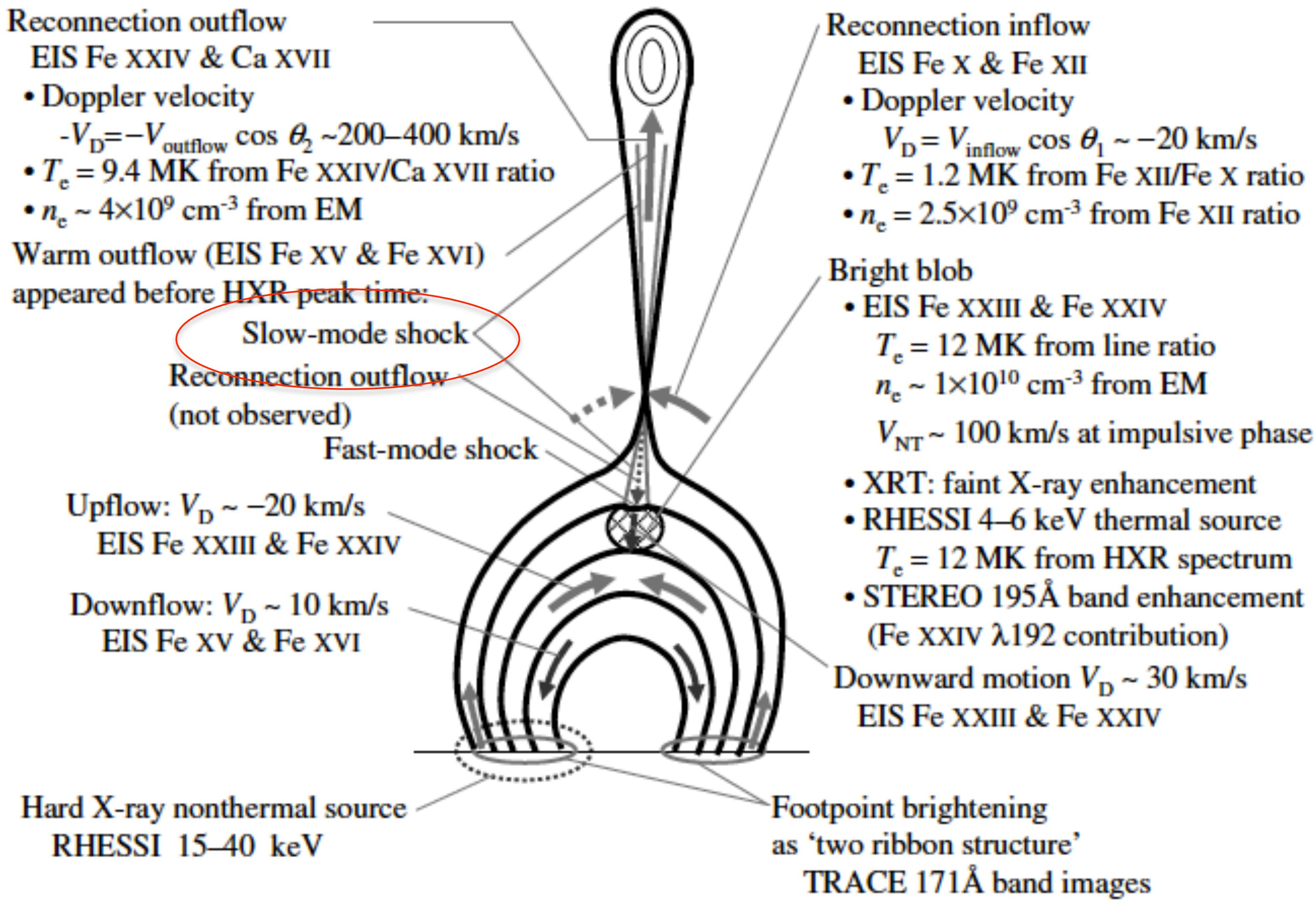
Spectroscopic diagnostics by Hinode/EIS



EUV spectroscopy allows to measure:
- Temperature
- Electron density
- Doppler velocity
- non-thermal broadening

Hara et al. 2011

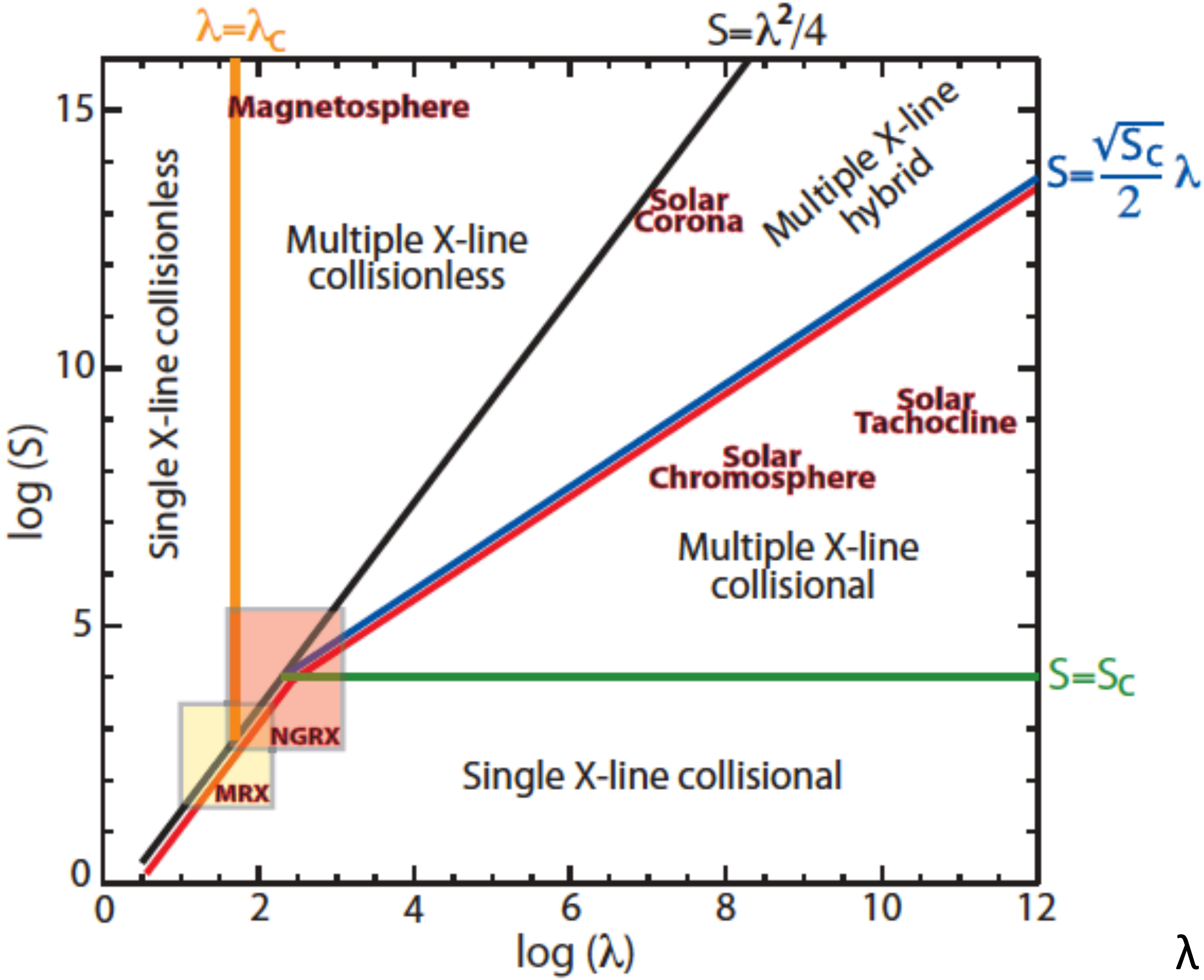
Spectroscopic diagnostics by Hinode/EIS



"Standard model" confirmed qualitatively.
More examples desired to examine the role of shocks.

Hara et al. 2011

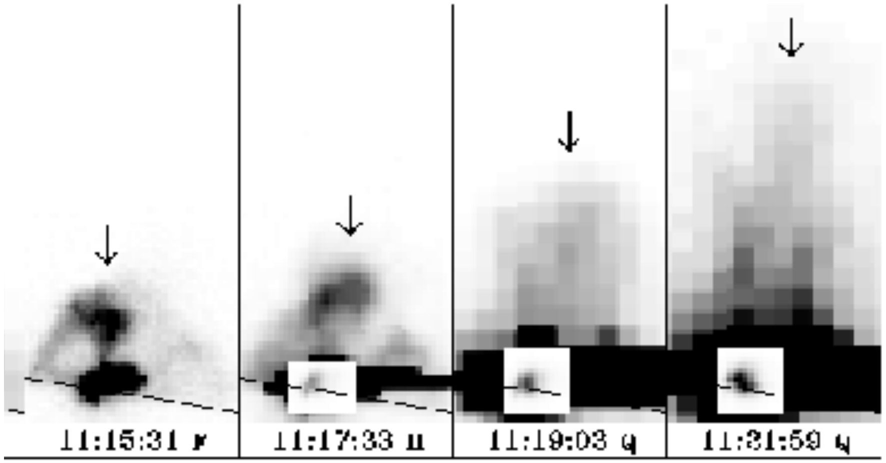
Ji & Daughton 2011

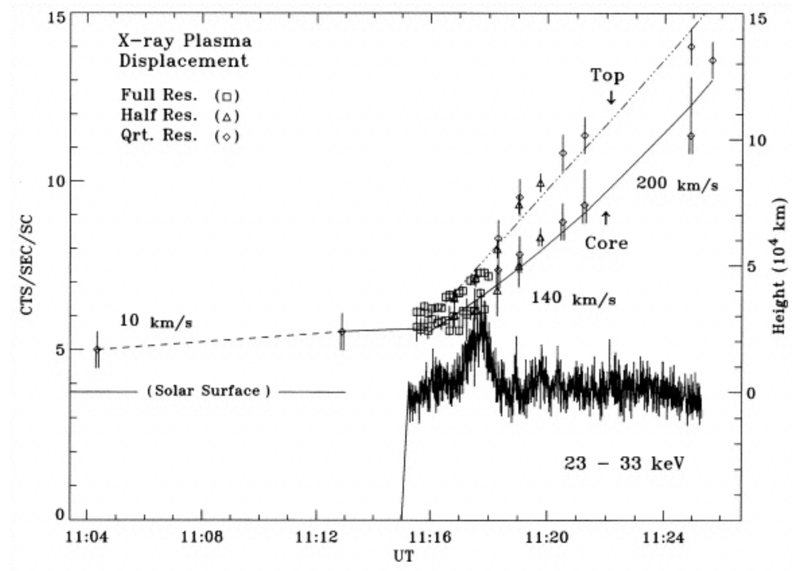


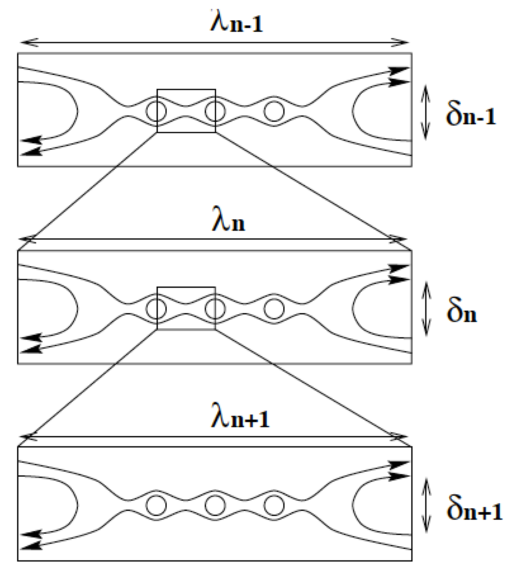
$\lambda = L/d_i$

Plasmoid ejection

Ohyama & Shibata 97



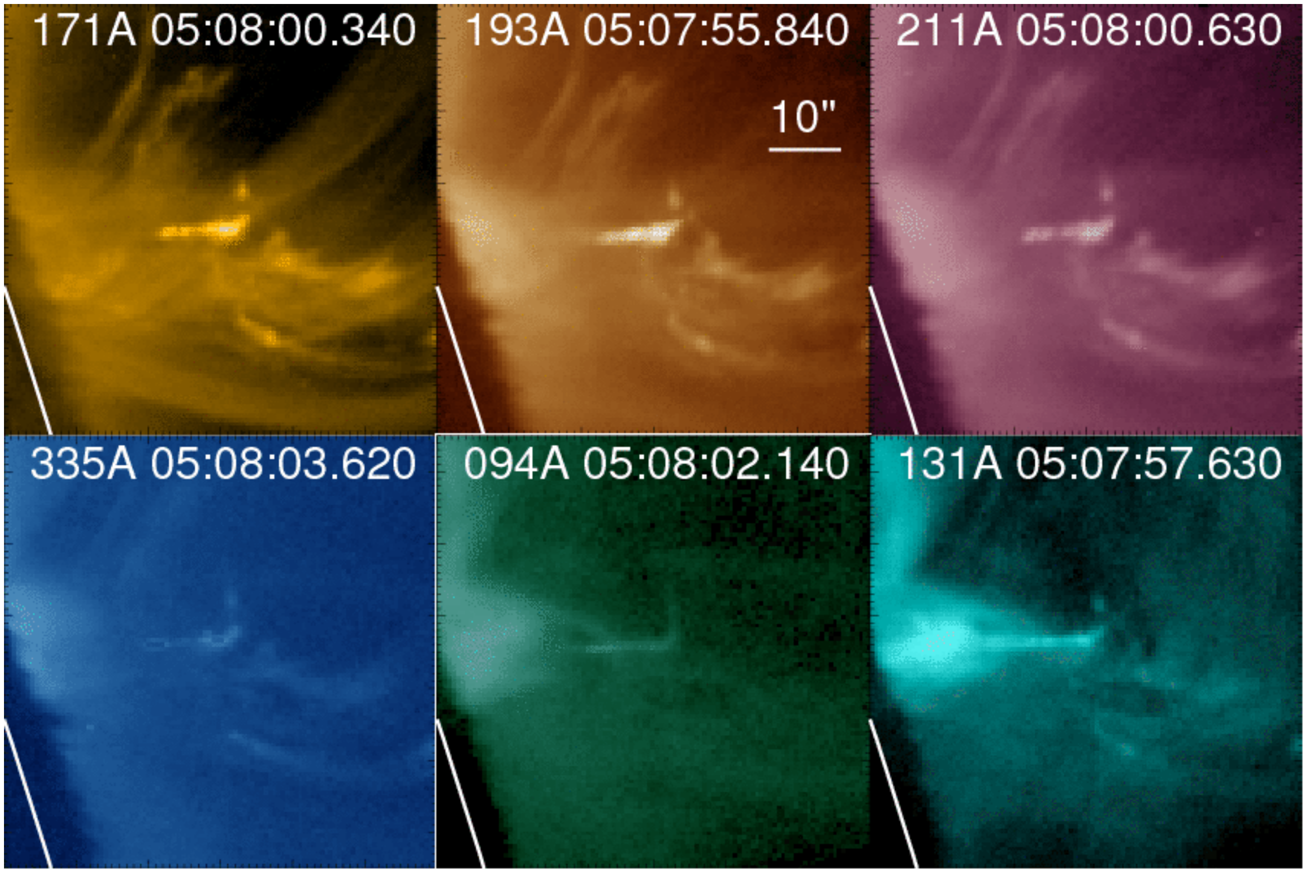


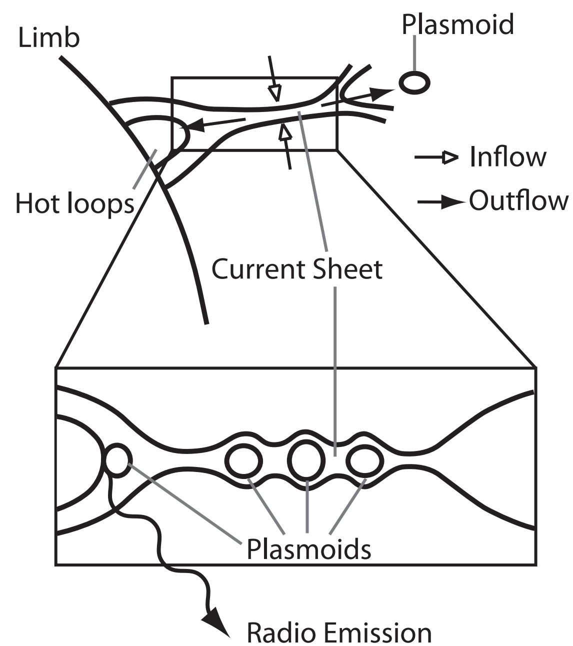


- Plasmoid ejection and hard X-ray emission (electron acceleration) well correlated.

(Asai+04, Nishizuka+10)

- “Lightening”-like reconnection event observed by SDO/AIA
- Formation, coalescence and ejection of multiple plasma blobs



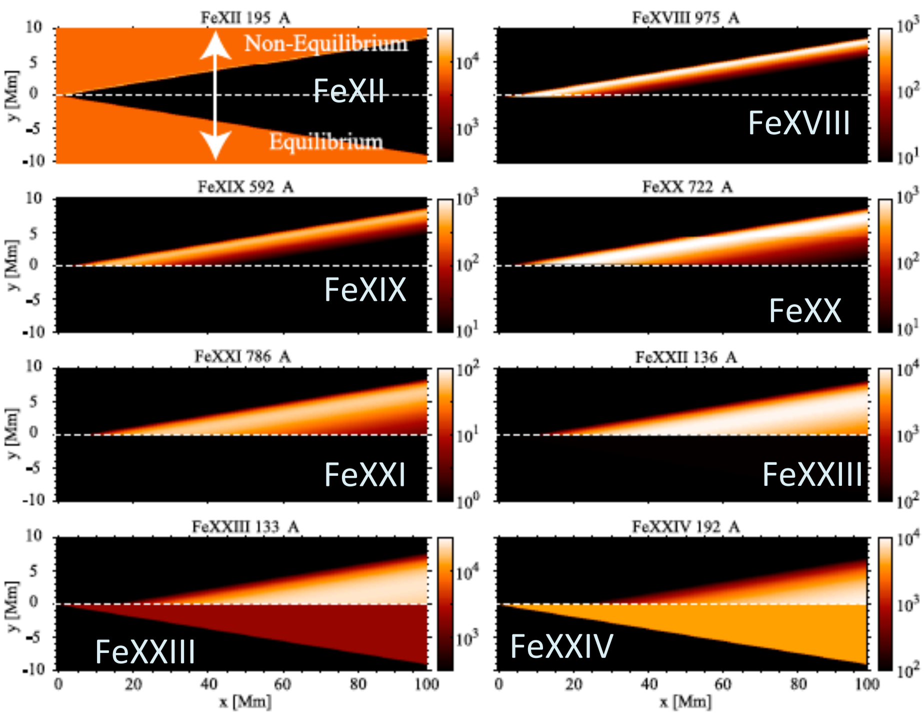


Takasao+12, ApJ

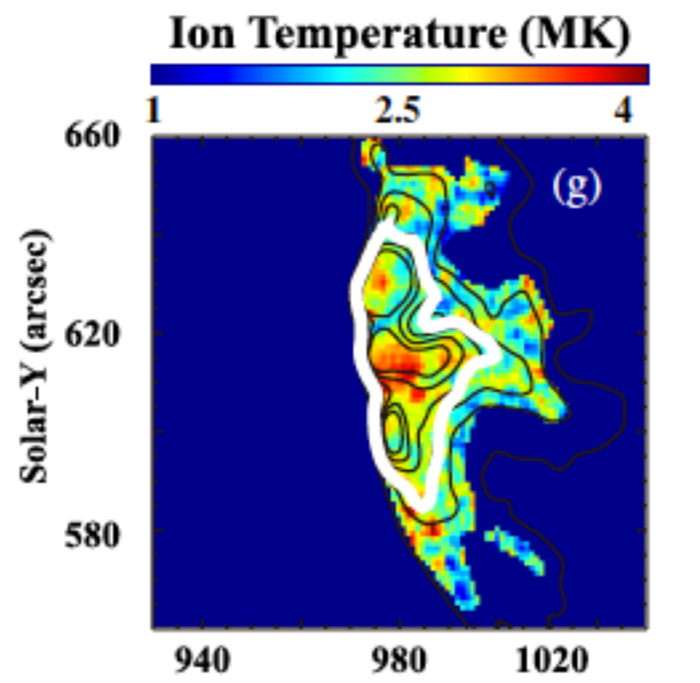
Diagnostics of non-MHD effects

(kinetic scales (< 1m) are too small to resolve, but...)

Time-dependent ionization
(modeling by Imada+ 11)



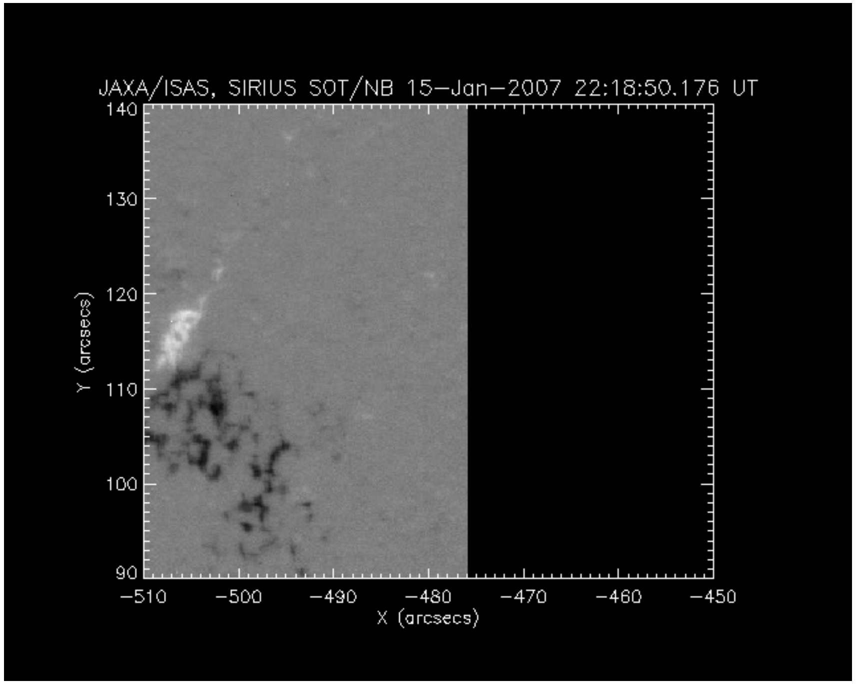
Ion temperature of AR
(EIS obsrevation by Imada+ 09)



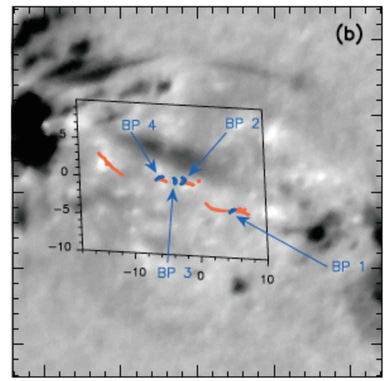
- What remains:
  - Scale coupling: observational resolution (~1" ~ 700km) still far from kinetic scales (~1m)
  - Role of plasmoids and slow shocks in energy conversion
  - particle acceleration

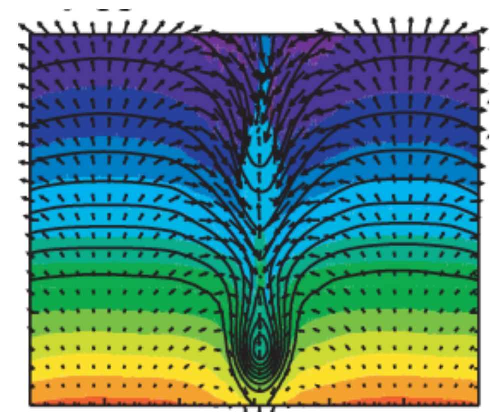
- Hopes in future
  - More date from Hinode and SDO
  - EUV spectrometer on Solar-C with much better capability of plasma diagnostics and spetial/temporal resolution

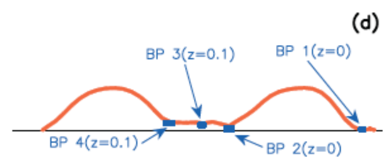
Reconnection in lower chromosphere

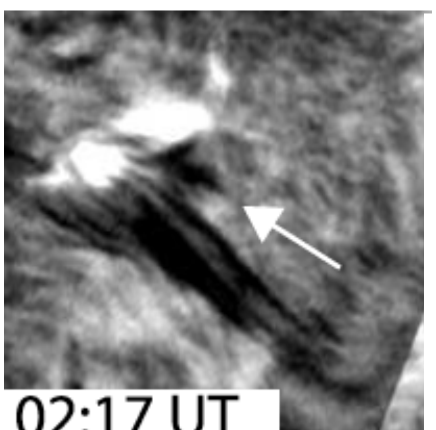


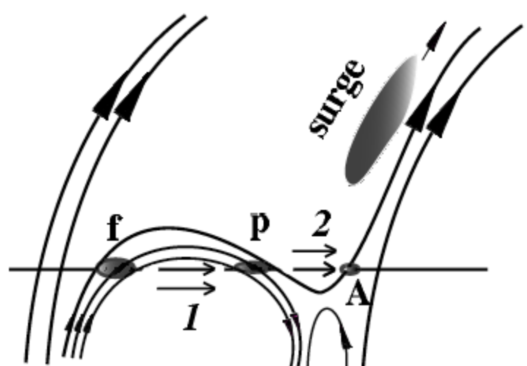
Cancellation of magnetic elements
(e.g. Martin+85, Chifor+08)







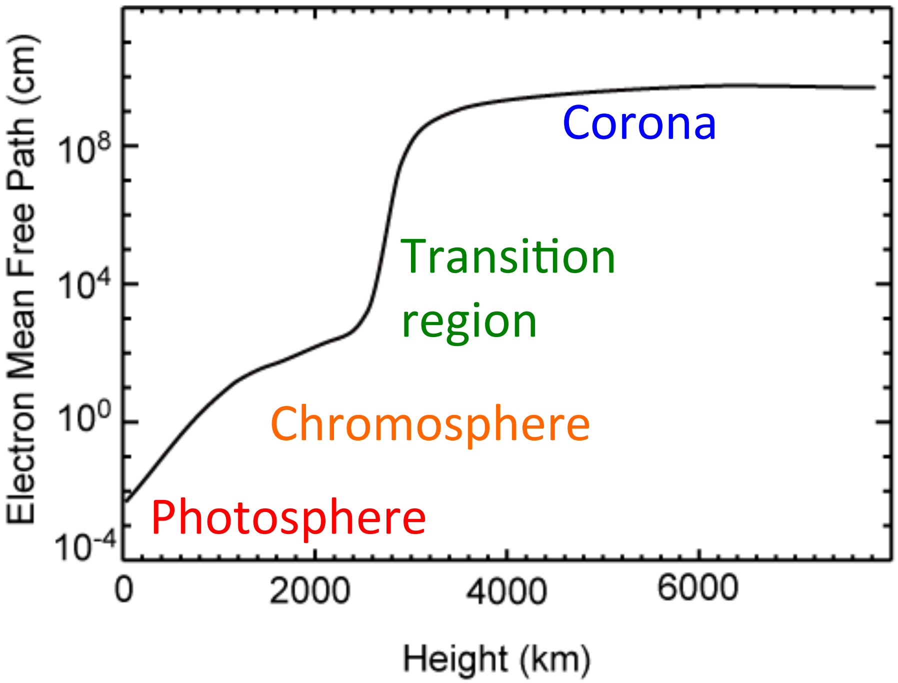


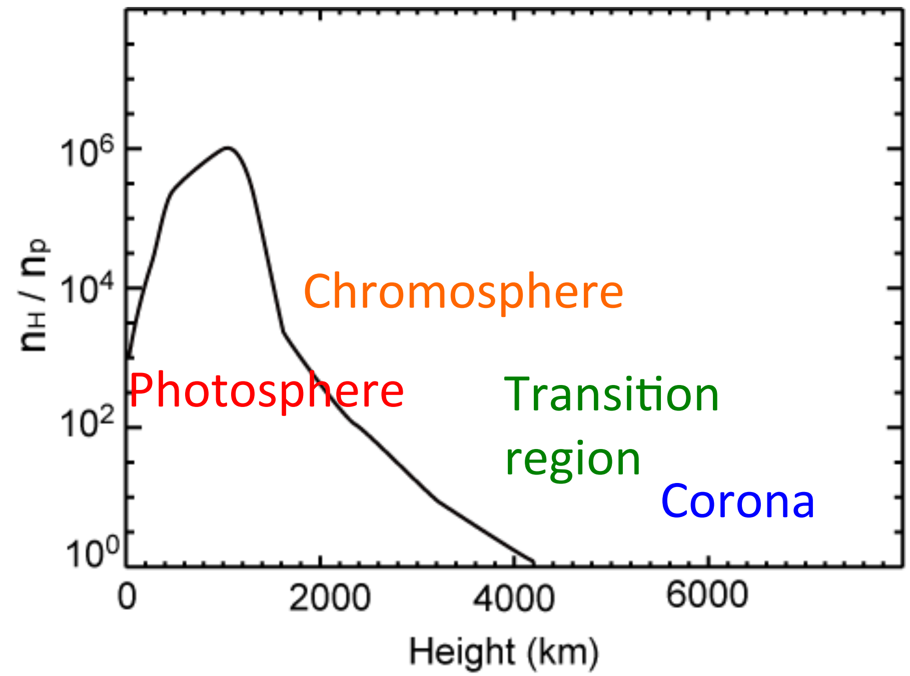


Surges (chromospheric jets) Liu & Kurokawa 05

Ellerman bombs
(reconnection between two neighbouring emerging loops)
Pariat+04, Isobe+07

Chromosphere is collisional and partially ionized





- One-fluid MHD is still good for large scale dynamics

$$\nu_{ni}\rho_n\left(V_n - V_i\right) \approx \frac{J \times B}{c}$$

$$V_n - V_i \approx \frac{B^2}{4\pi L \nu_{ni}\rho_n} \approx 100\left(\frac{V_A}{10\mathrm{km/s}}\right)^2\left(\frac{L}{100\mathrm{km}}\right)^{-1}\left(\frac{\nu_{ni}}{10^3\mathrm{Hz}}\right)^{-1}\mathrm{cm/s}$$

Neutral effects

$$\frac{\partial B}{\partial t} = \nabla \times [\overbrace{V_n \times B}^{\boxed{\text{Advection}}} - \overbrace{\frac{J \times B}{e n_e}}^{\boxed{\text{Hall}}} + \overbrace{\frac{(J \times B) \times B}{c \nu_{ni} \rho_n}}^{\boxed{\text{Ambipolar}}} - \overbrace{\eta J}^{\boxed{\text{Ohmic}}}]$$

Ambipolar/Hall is important in small scale

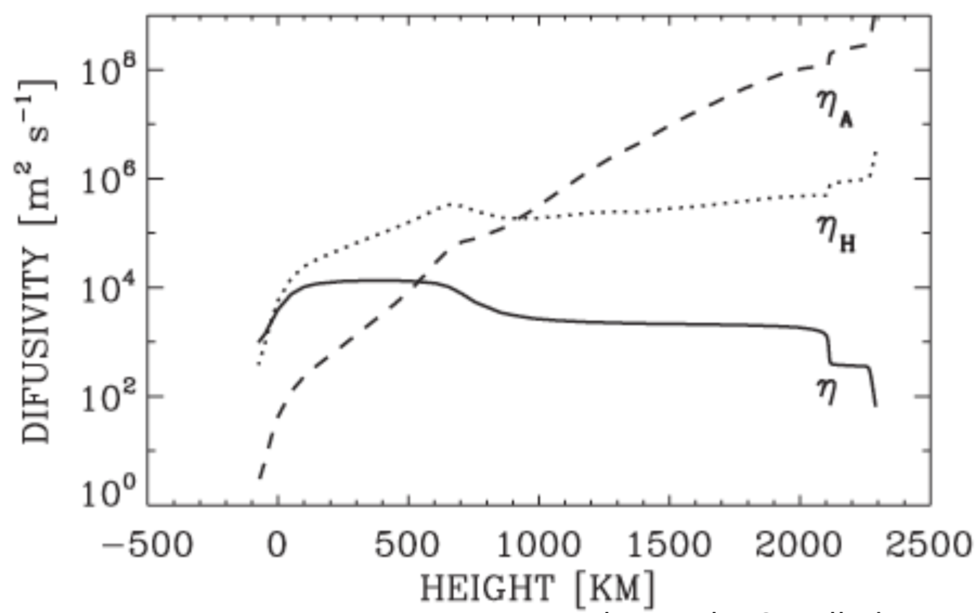
$$V_n \times B < \frac{(J \times B) \times B}{c \nu_{ni} \rho_n} \Rightarrow L < \frac{V_{An} \rho_n}{\nu_{in} \rho_i} \approx 1 - 10 km$$

Ambipolar/Hall = $\omega ci / \nu in$

ωci : Ion-cyclotron freq $\propto B$

νin : Ion-neutral collision freq $\propto n$

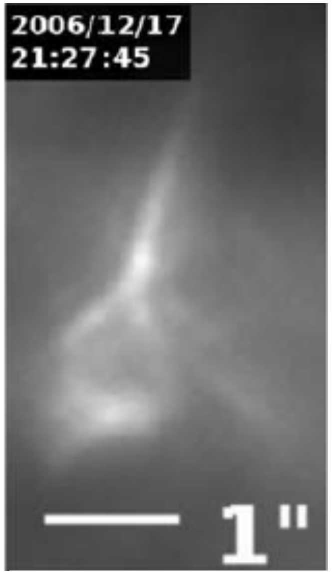
Photosphere: Hall dominant
Chromosphere: Ambipolar dominant

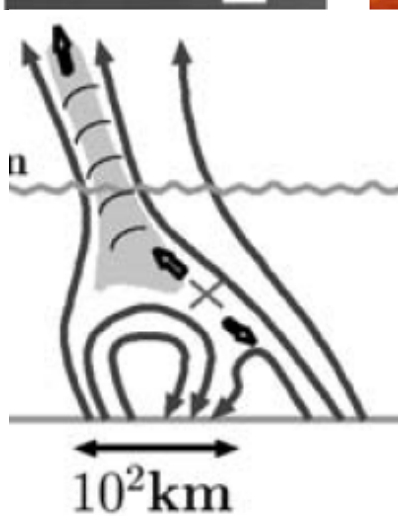


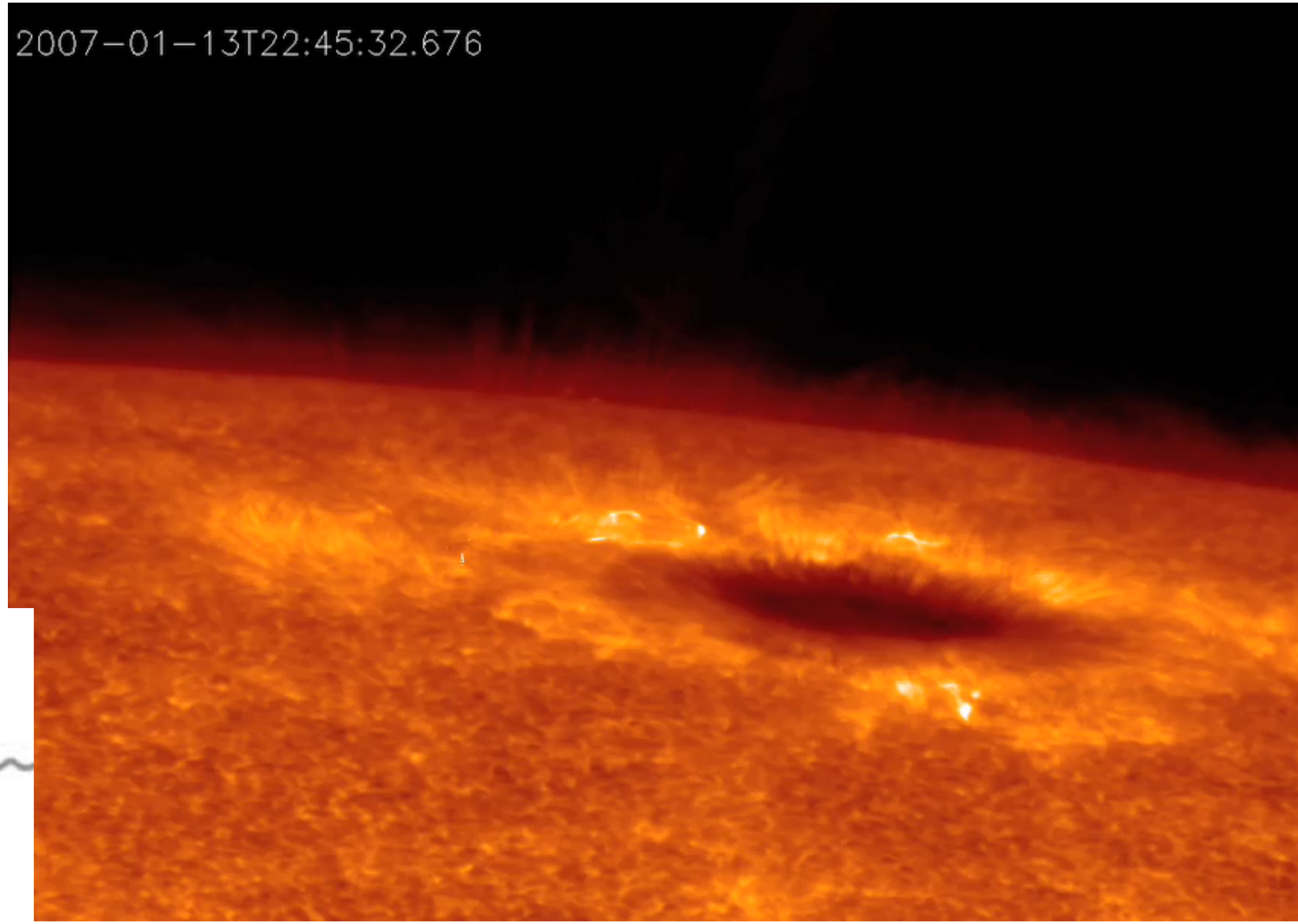
Khomenko & Collados 2012

Ubiquitous chromospheric jets

Hinode/SOT

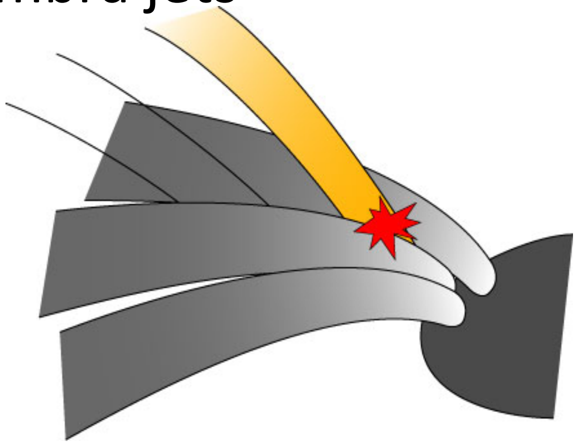




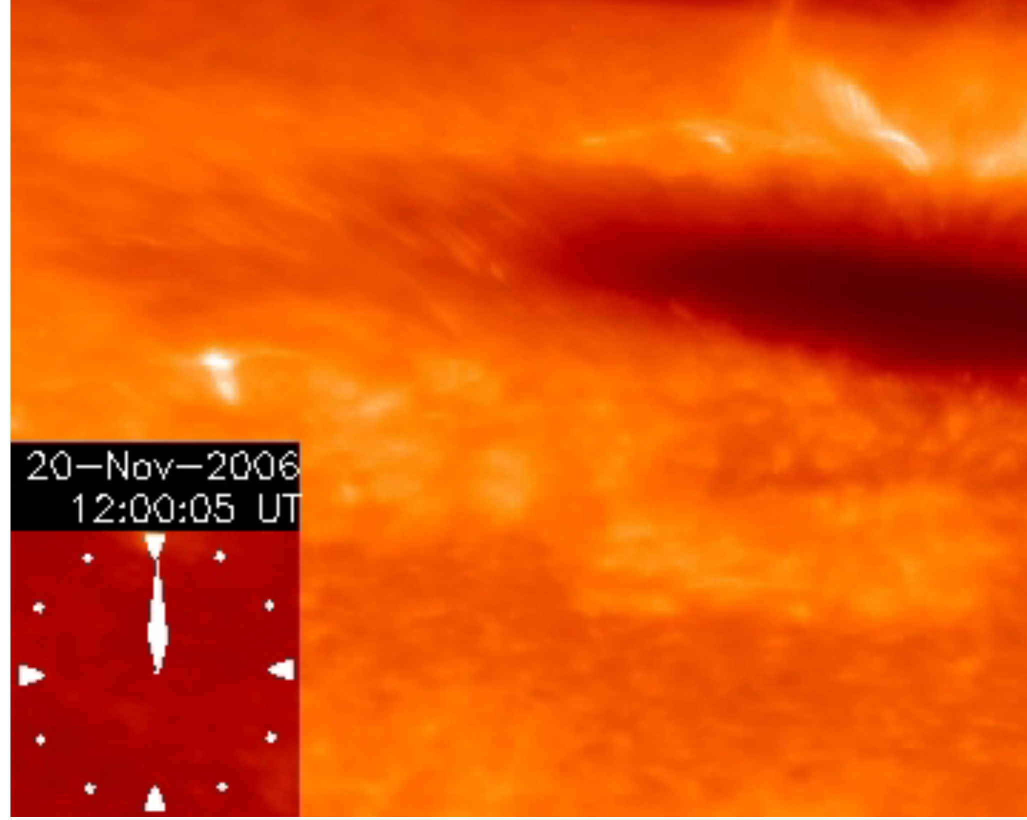


Reconnection between small emerging loop and ambient field (Shibata+07)

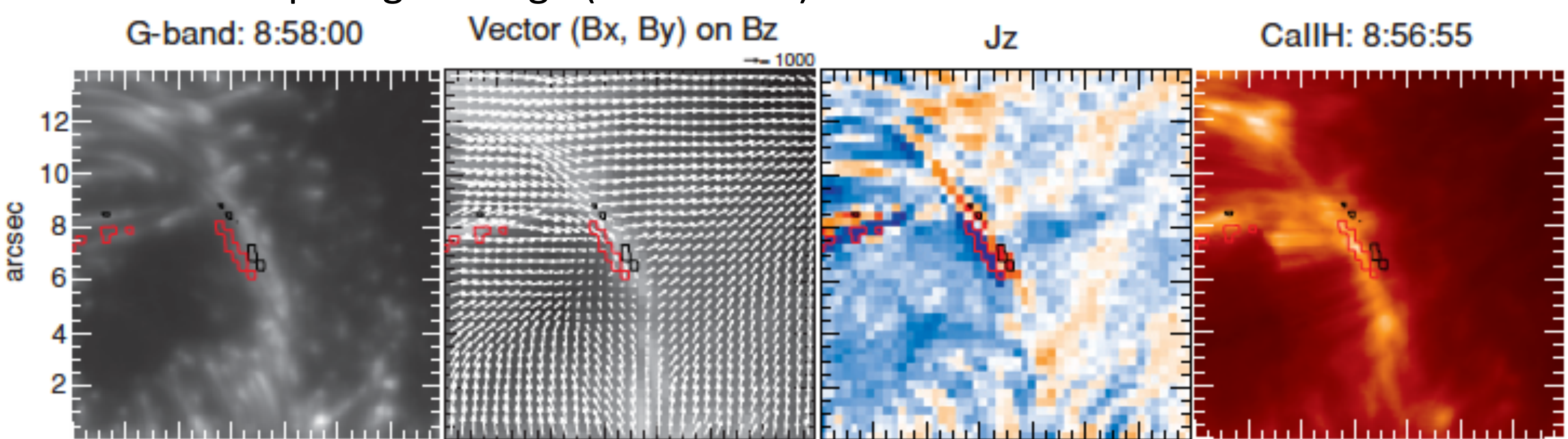
Penumbra jets

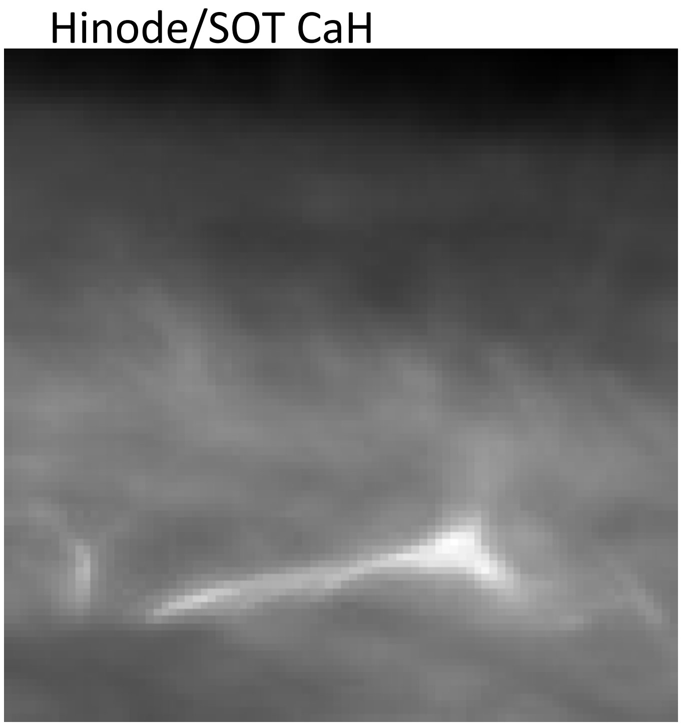


Reconnection of
interlocked-comb structure
= strong guide field
Katsukawa+07



Jets from sunspot light bridge (Shimizu 11)   Nishizuka-san's talk

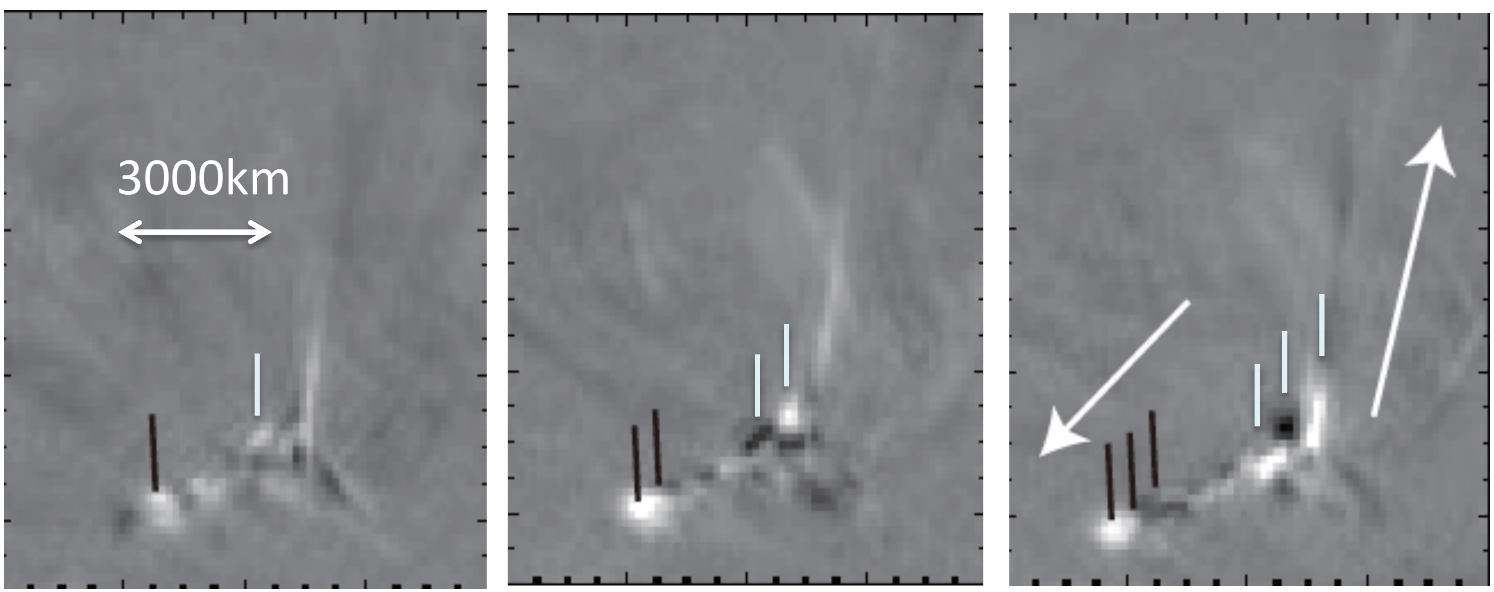


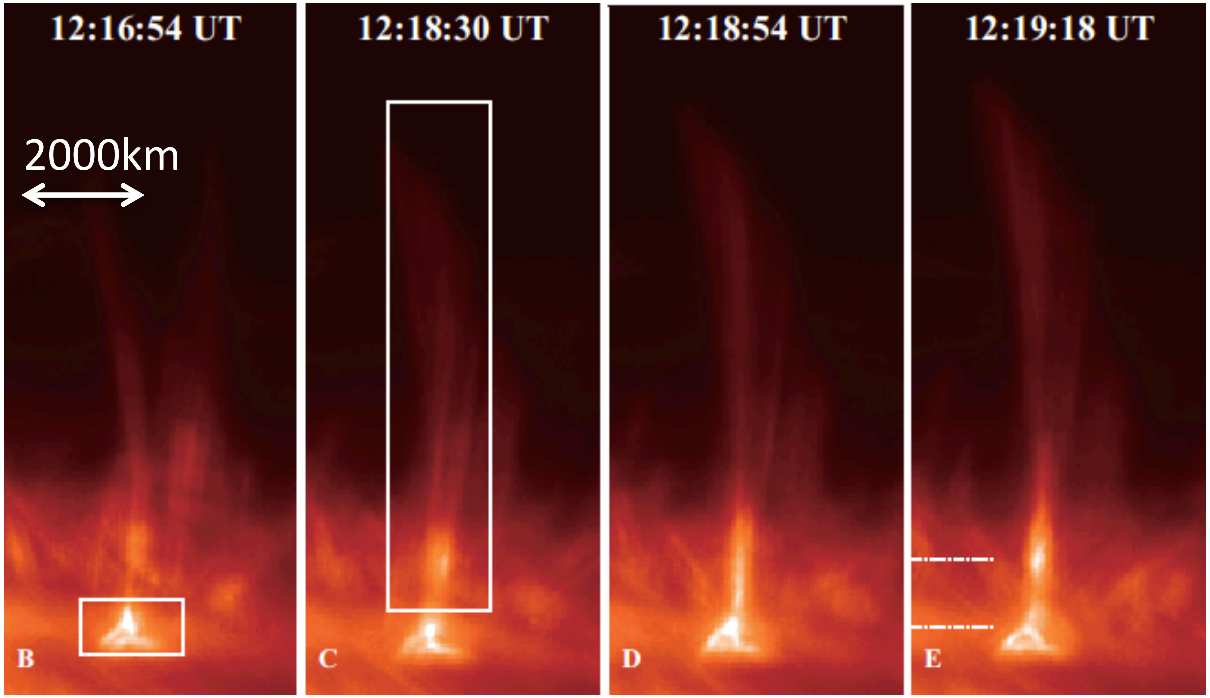


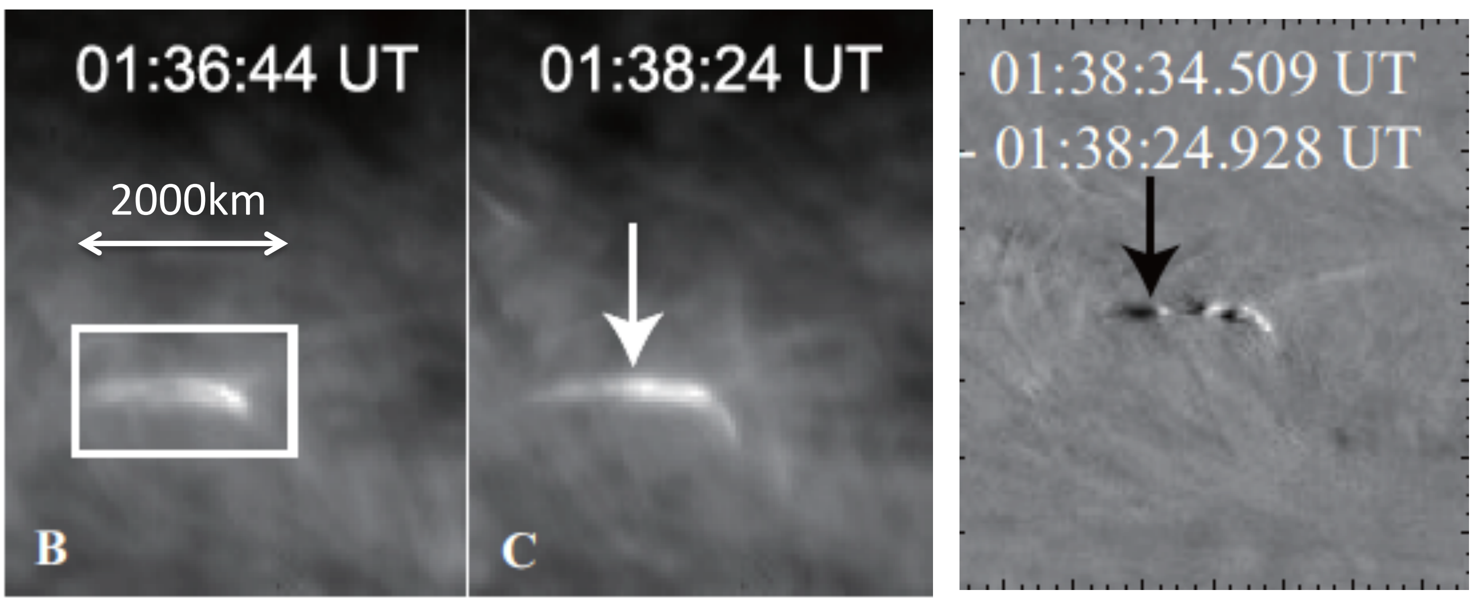
Multiple plasmoids in chromospheric reconnection??

Size ~ a few hundred km
Velocisty ~ 10—50 km/s

Singh et al. submitted.







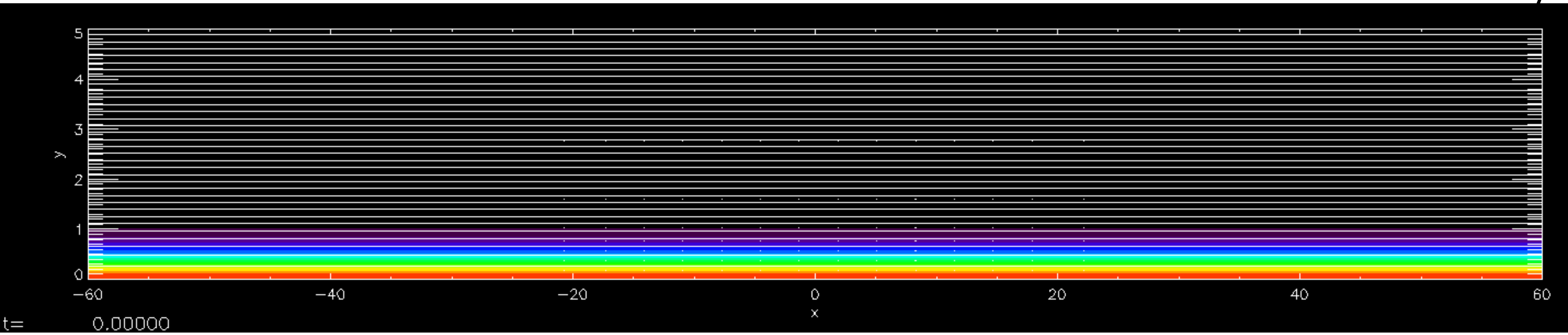
Singh et al. submitted.

Effect of non-uniform ambipolar diffusion

(Isobe+ in prep. See also Leake's talk for multi-fluid approach)

- 2D MHD simulation with uniform resistivity and non-uniform ambipolar diffusion
- No Hall effect, no guide field

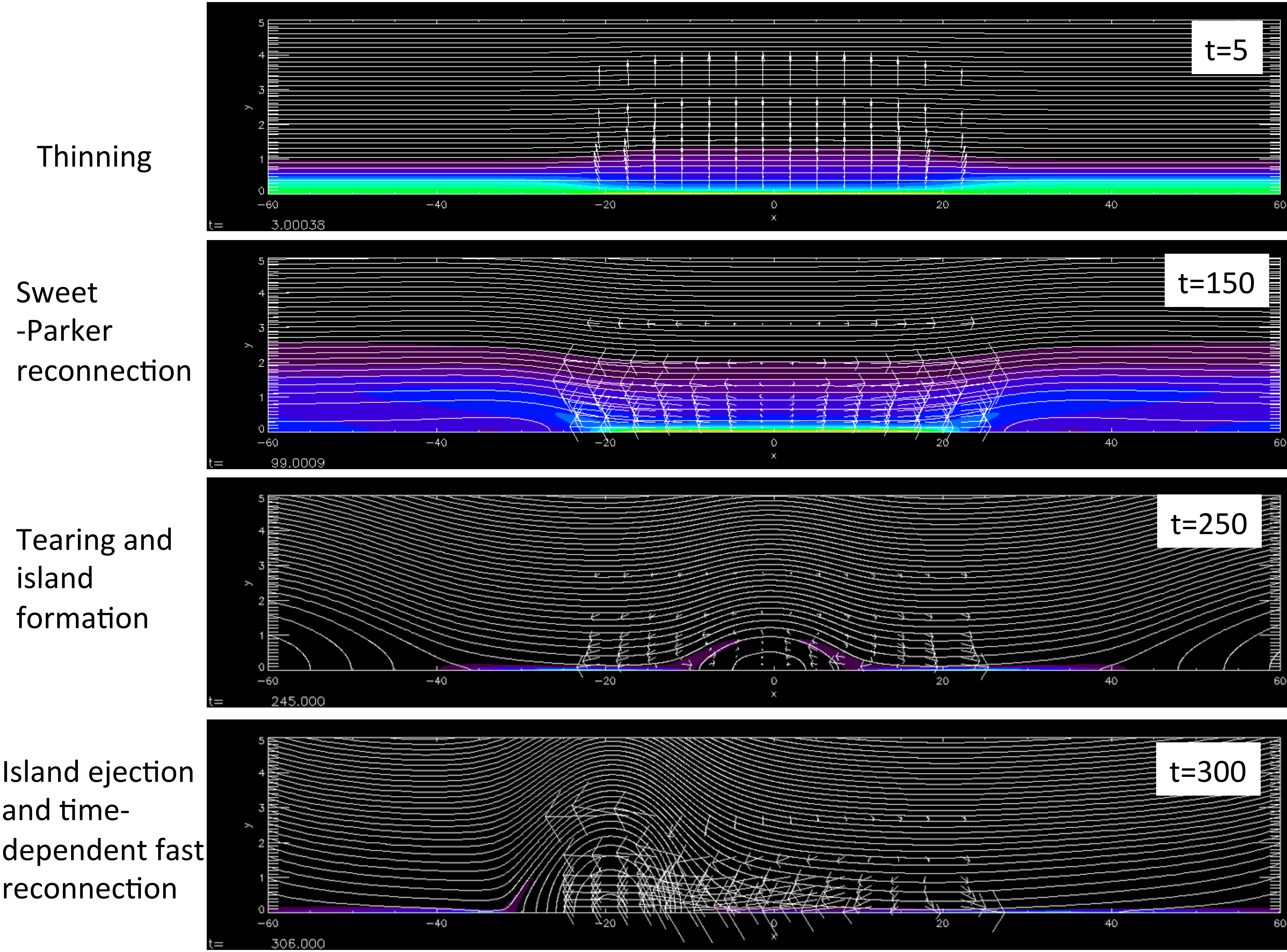
color: current density



Ambipolar diffusion ≠ 0

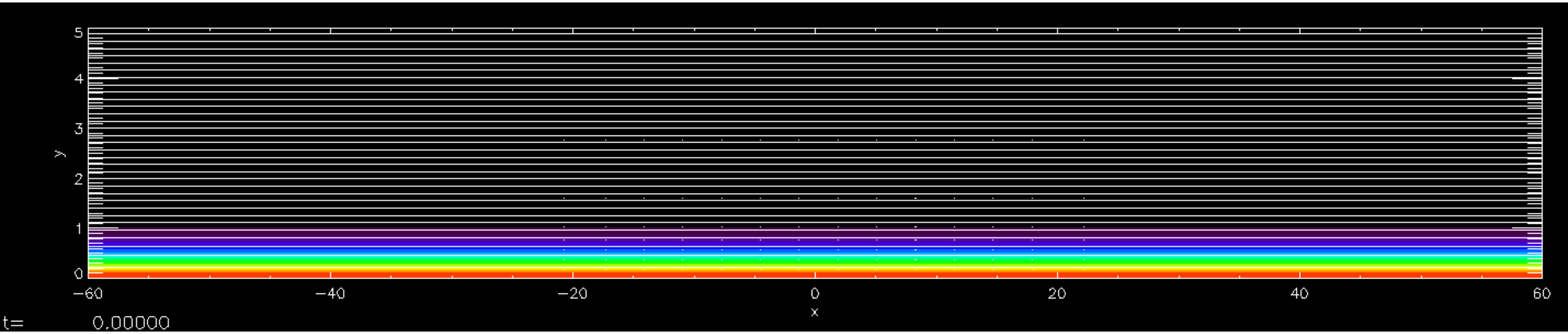
Ambipolar diffusion localized in x < ±20

Ohmic resistivity is uniform

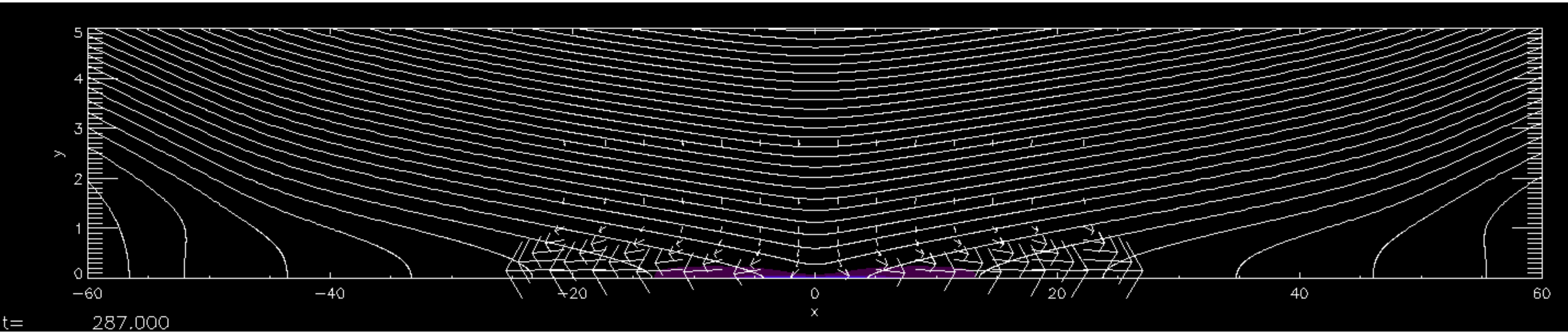

Thinning
t=5
t= 3.00038
Sweet
-Parker
reconnection
t=150
t= 99.0009
Tearing and
island
formation
t=250
t= 245.000
Island ejection
and time-
dependent fast
reconnection
t=300
t= 306.000
y
x
-60
-40
-20
0
20
40
60

Petschek-like regime

color: current density

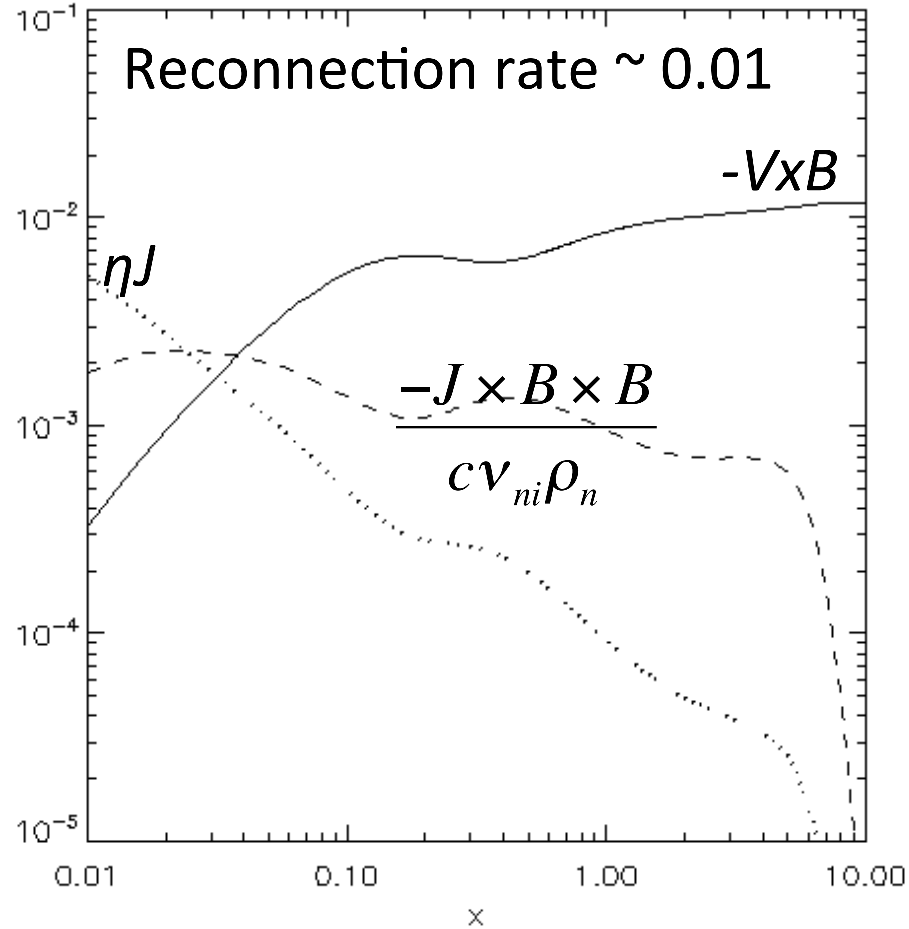


Ambipolar diffusion uniform + enhanced in $x < \pm 2$
Uniform resistivity



Even though the resistivity is uniform, the localization of ambipolar diffusion causes local thinning of the current sheet, leading to Petschek-like fast reconnection

The “ambipolar layer” almost disappears.



Summary

- Reconnection in corona
  - "Standard model" confirmed
  - Many plasmoids, coalescence, ejection
  - Role of slow shocks still unclear (observationally)
  - Kinetic effects being inferred by EUV spectroscopy

- Reconnection in the lower atmosphere
  - partially ionized and collisional
  - Multile-plasmoid ejections found
  - Neutral effects important
  - Observation by ALMA may get close to diffusion scale (~10km) of chromospheric reconnection!