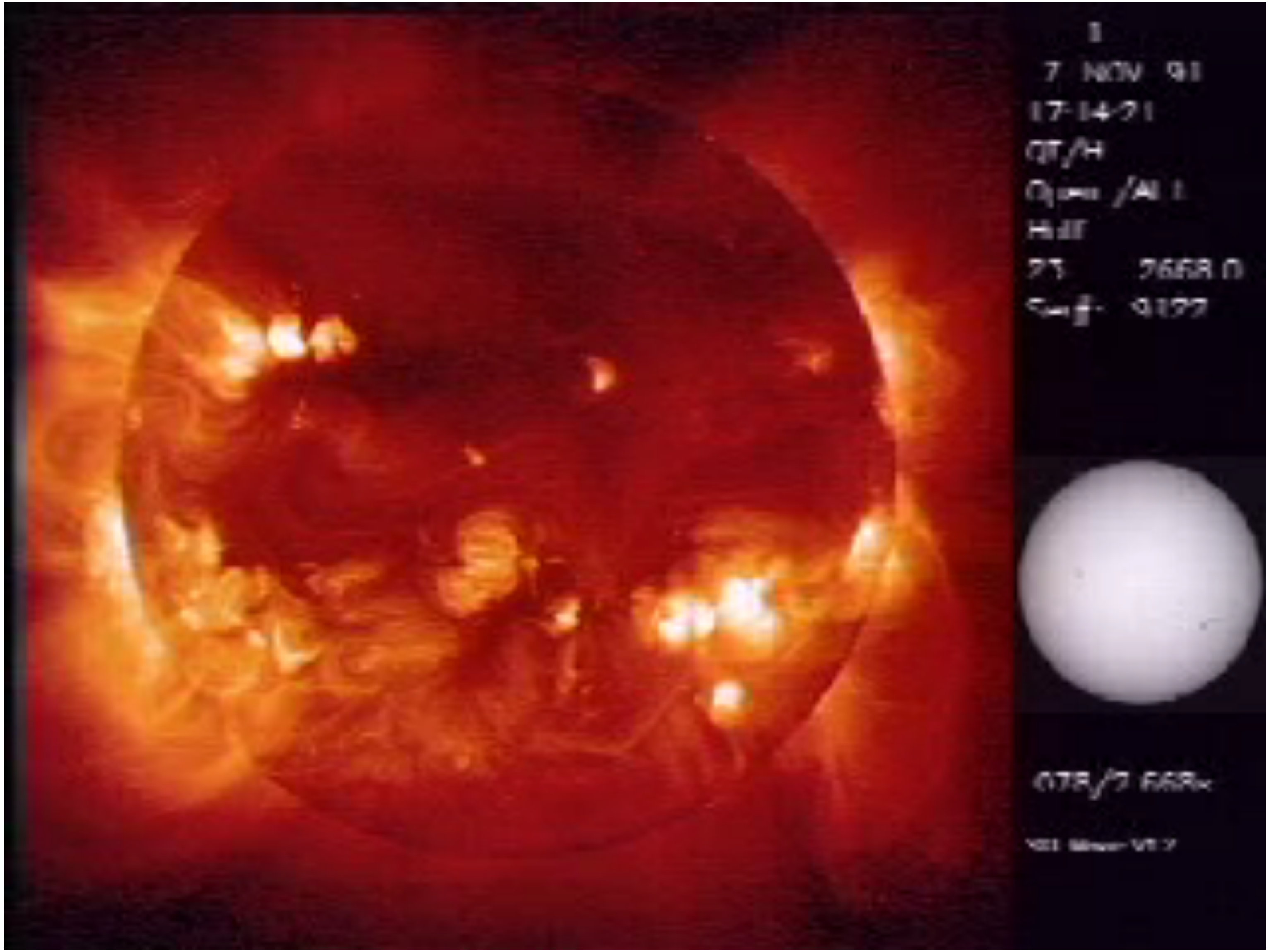
Magnetic reconnection: what are the problems and how we see it in the sun

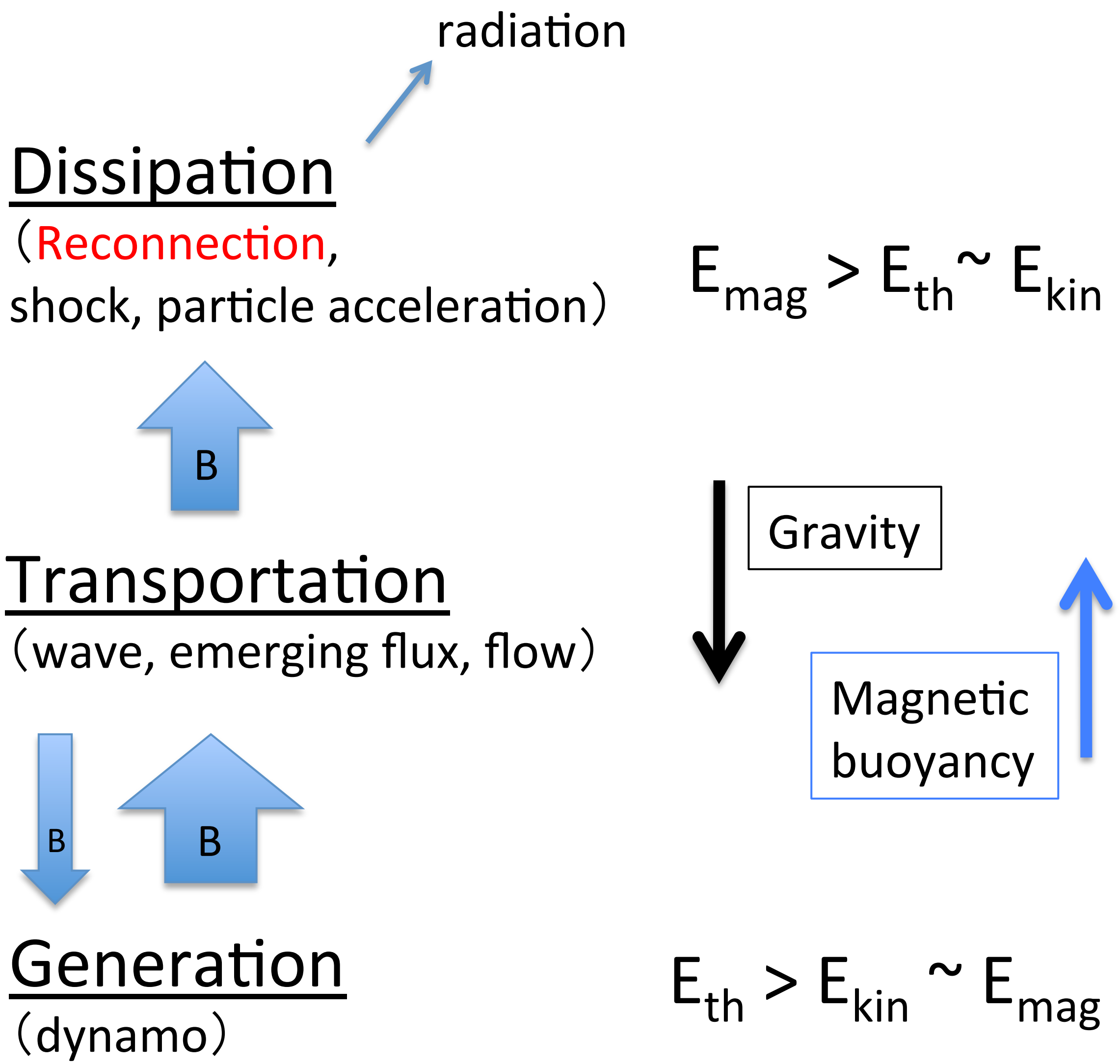
Hiroaki Isobe (Kyoto University)

Magnetic activity in the Sun



Soft X-ray, Yohkoh

Magnetic activity inevitable in gravitationally stratified bodies



Why we need to consider reconnection

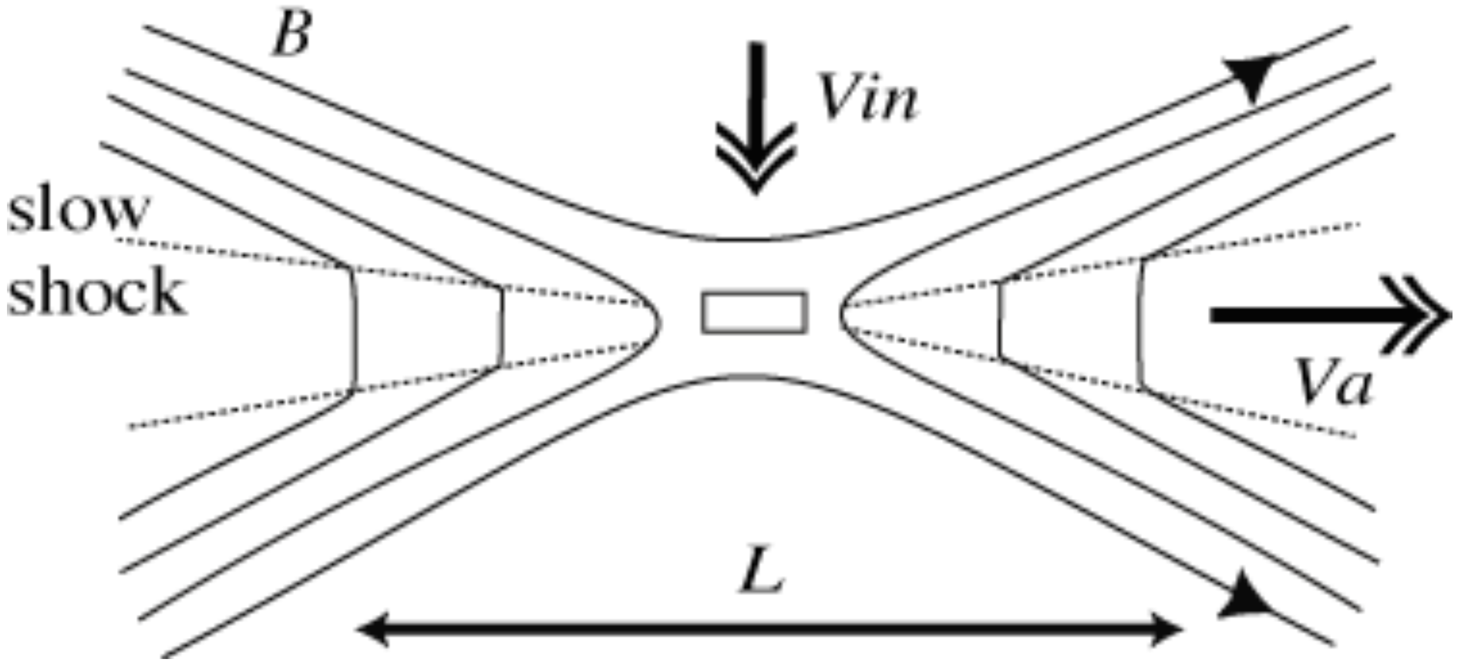
- Magnetic energy converted to thermal and kinetic energies of plasma

- Classical resistivity in space and astrophysics is tiny: resistive time in solar corona $\tau \sim 4\pi L^2/c^2\eta$ ~ 1,000,000 year!

- Time scale of solar flares ~ 100 s.

- We need a mechanism to accelerate the dissipation many orders of magnitudes => magnetic reconnection

Magnetic reconnection



- In the presence of finite resistivity, anti-parallel field lines separated by a current sheet are cut and glued so that the connectivity of field lines changes.
- The reconnected field lines accelerate plasma by the tension force like a catapult.

Magnetic reconnection in astrophysics

Uzdensky (2006, astro-ph/0607656)

… the most important reconnection mechanism in Astrophysics invokes waves, a certain type of waves, in fact. Called *handwaves* (See Fig 1).

Fig. 1.— Main Reconnection Mechanism in Astrophysics.

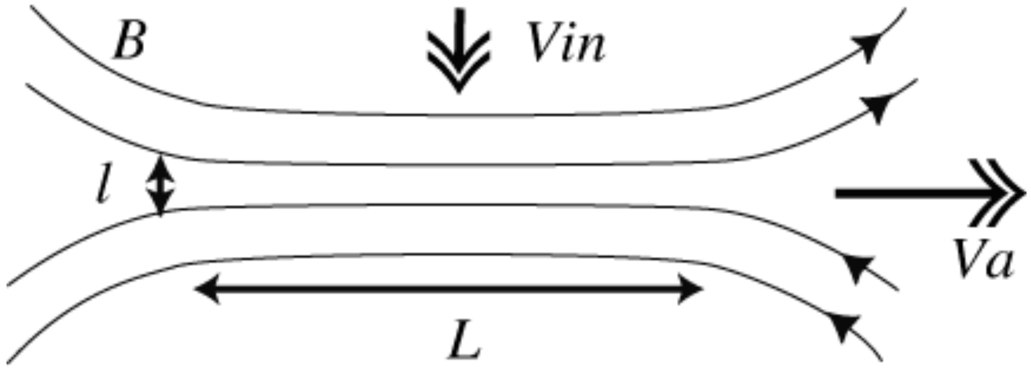
The mechanism works like this: *Well, we know that fast reconnection happens in the Solar corona, and in the Earth magnetosphere. So it should also happen in OUR astrophysical system.*

Classical theories 1. Sweet-Parker reconnection

(Parker 1957, Sweet 1958)

- Assumption: stead state, incompressible.
- Outflow velocity $V_{out} = V_A = B/(4\pi\varrho)^{1/2}$ (Alfven velocity)
- Consider mass conservation: $V_{in}L = V_A l$
- From induction equation: $BV_{in} = \eta J \sim \eta B/l$

- Then we obtain Vin/VA = $(LV_A/\eta)^{0.5}$ ~ 1 year.

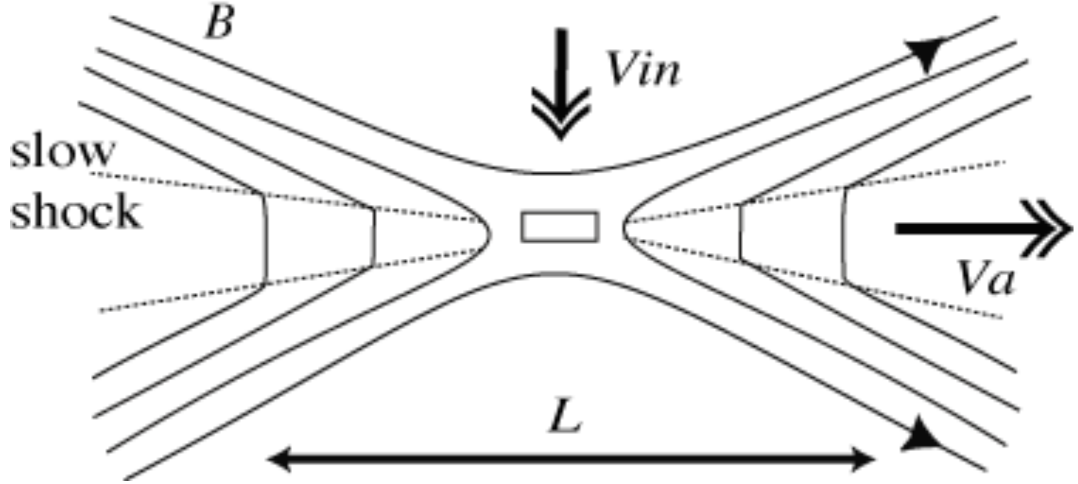


Problem: Still too slow!

Classical theories 1. Petschek reconnection

(Petschek 1964)

- Sweet-Parker reconnection is slow because the outflow width is narrow and hence plasma expelling is ineffective.
- If resistivity is (somehow) localized, standing slow shocks is formed and the magnetic energy is converted via slow shocks.
- The outflow width can become larger and reconnection can be fast $V_{in} \sim 0.1V_A$



Problem: how to localize resistivity?

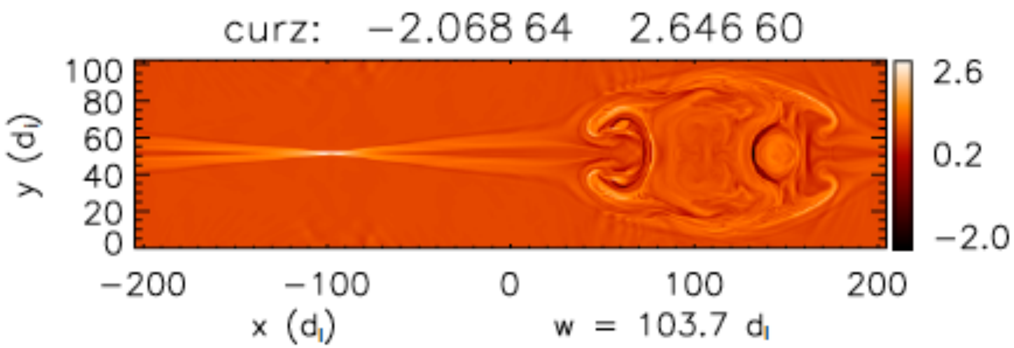
Hall effect

$$\frac{\partial B}{\partial t} = \nabla \times [V_n \times B - \frac{J \times B}{en_e} - \eta J]$$

- Hall-effect (or other kinetic instabilities) becomes important when current sheet width is smaller than ion inertia length c/ω_{pi}
- Hall reconnection produce Petschek-like configuration and fast reconnection

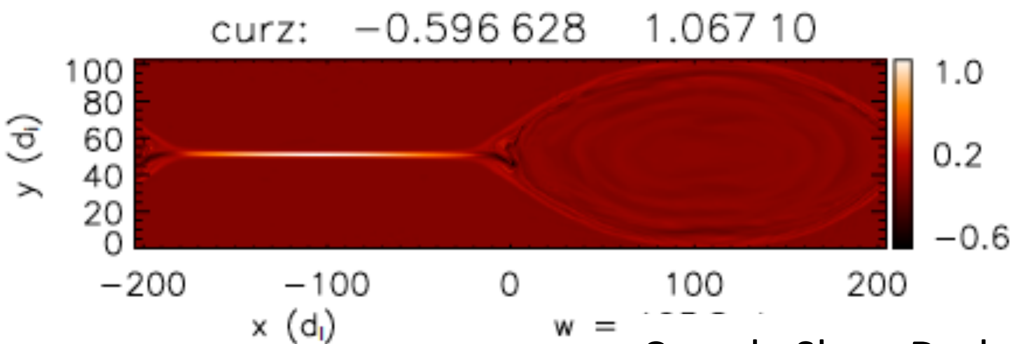
$w < c/\omega_{pi}$

Petschek-type Hall recon.



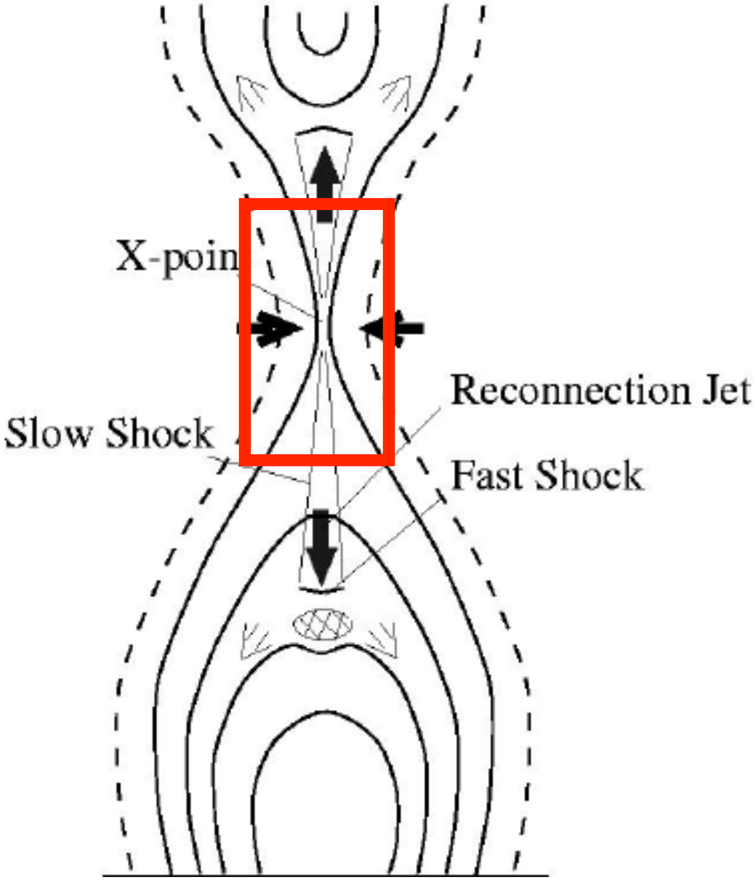
$w > c/\omega_{pi}$

S-P type slow recon.



Cassak, Shay, Drake 05

“Scale-gap” problem

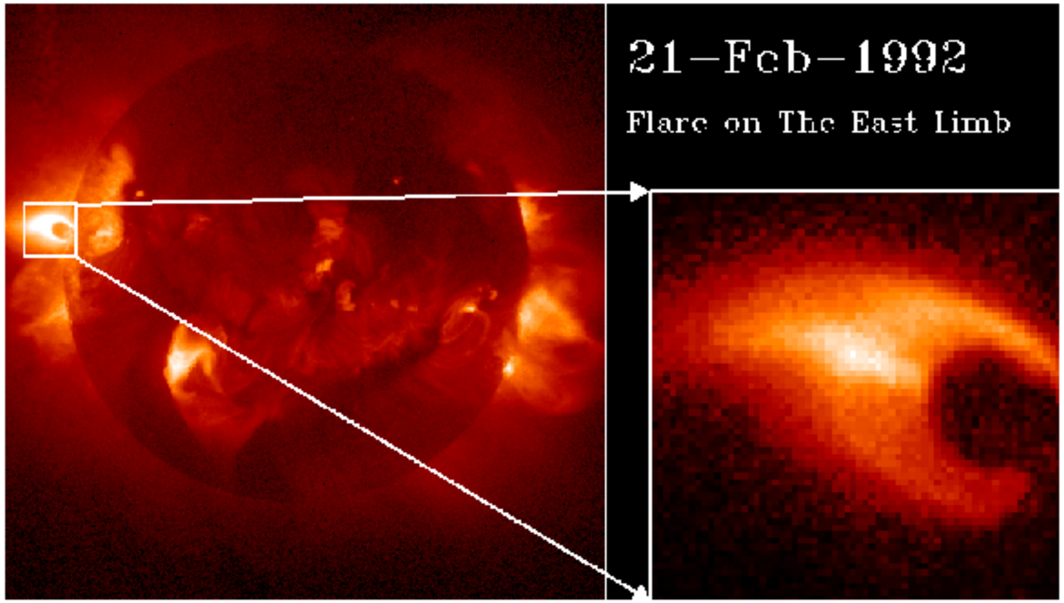


Yokoyama & Shibata 1998

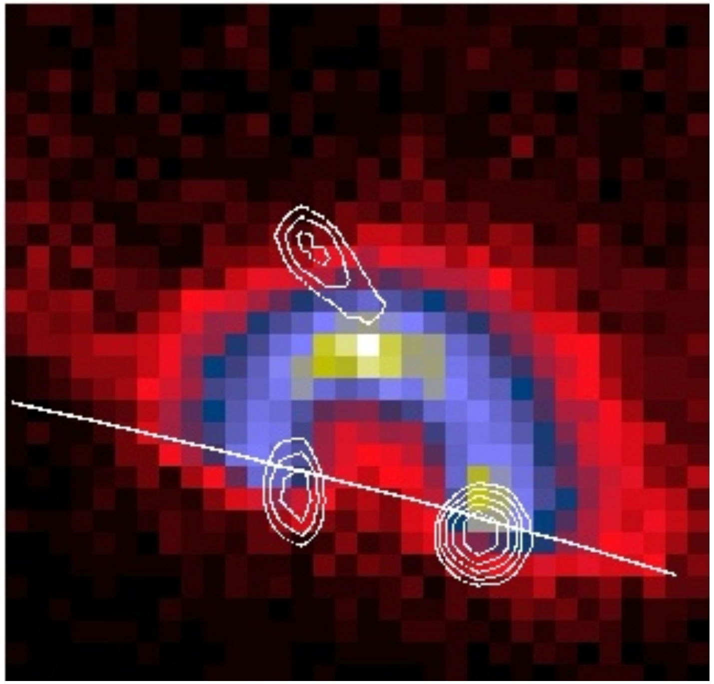
- c/w_{pi} in corona ~ 10^2 cm
- Spatial size of flare ~ 10^9 cm

How can we fill the 7-orders gap?

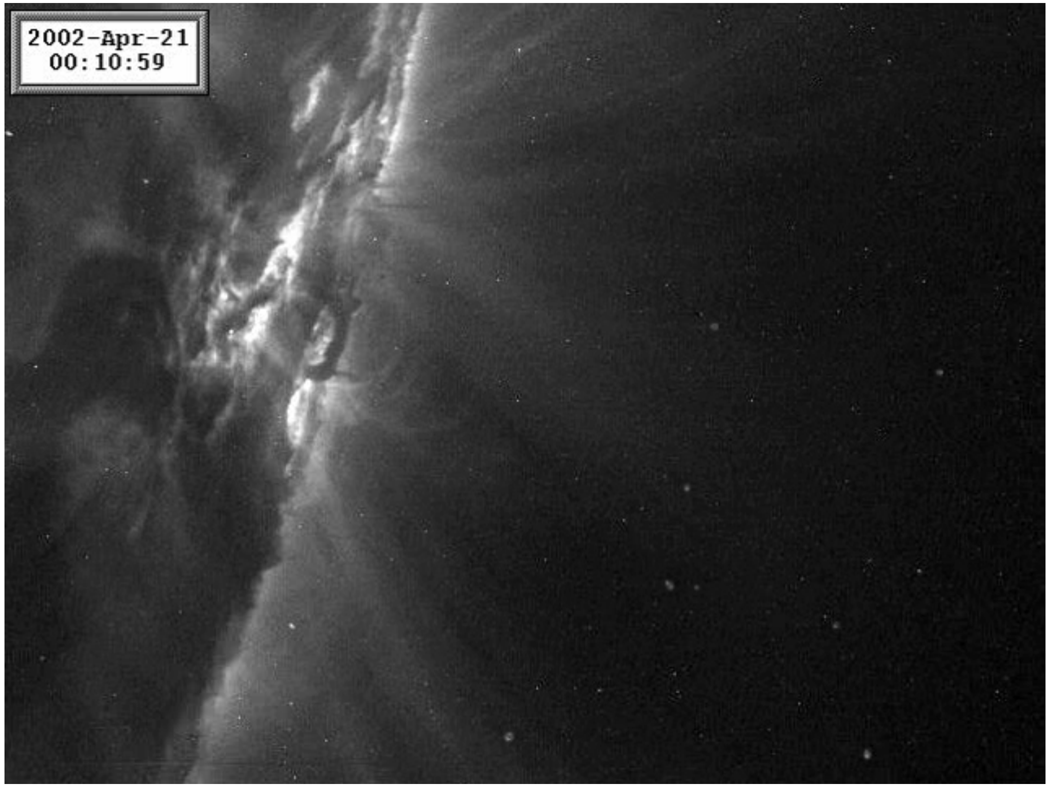
Observational evidence for magnetic reconnection in the corona (before Hinode/SDO)



Cusp-shaped loop
(Tsuneta+92)

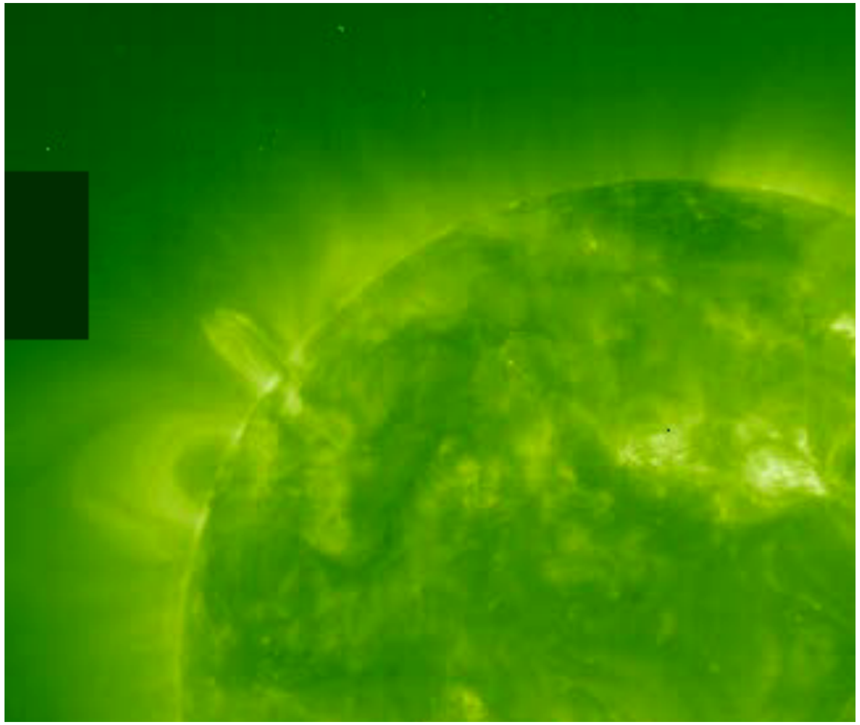


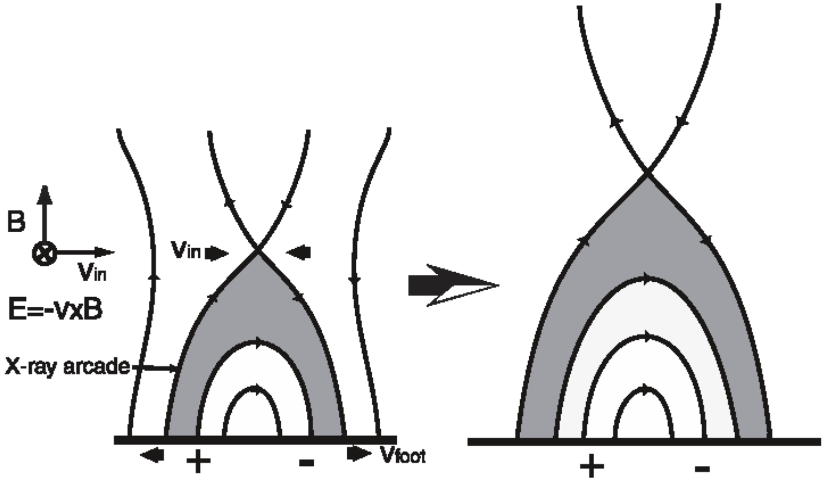
Loop-top Hard X-Ray source
(Masuda+94)



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

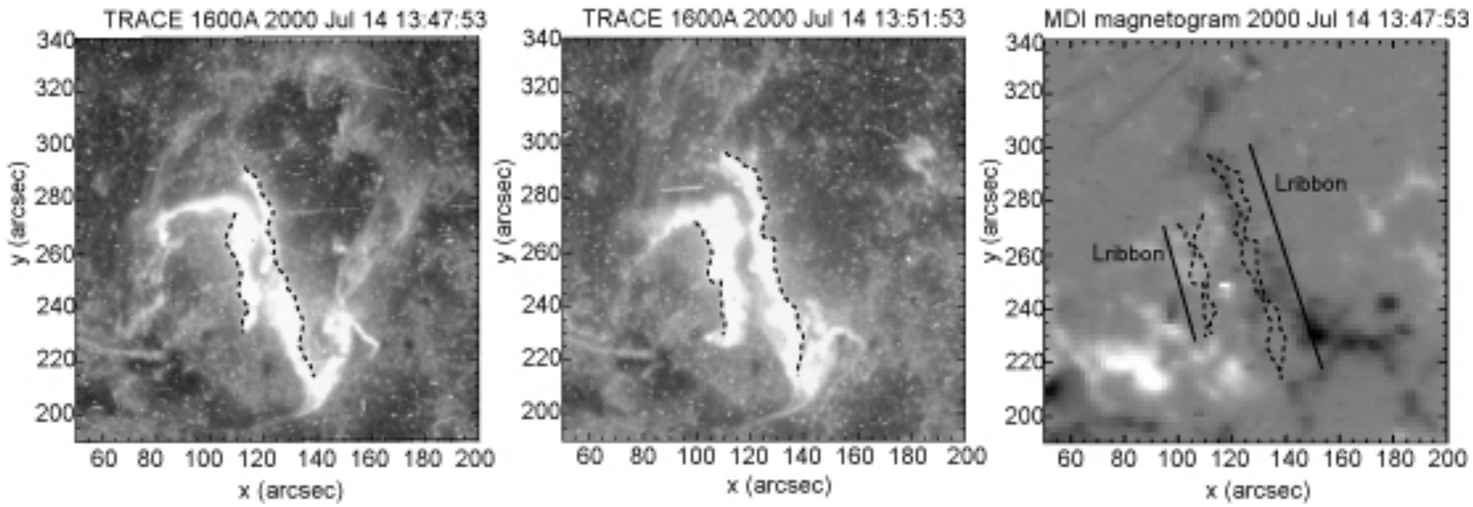
Reconnection inflow
(Yokoyama+01; Narukage & Shibata06
Lin+05, Hara+06)
V_{inflow}~$0.01V_A$





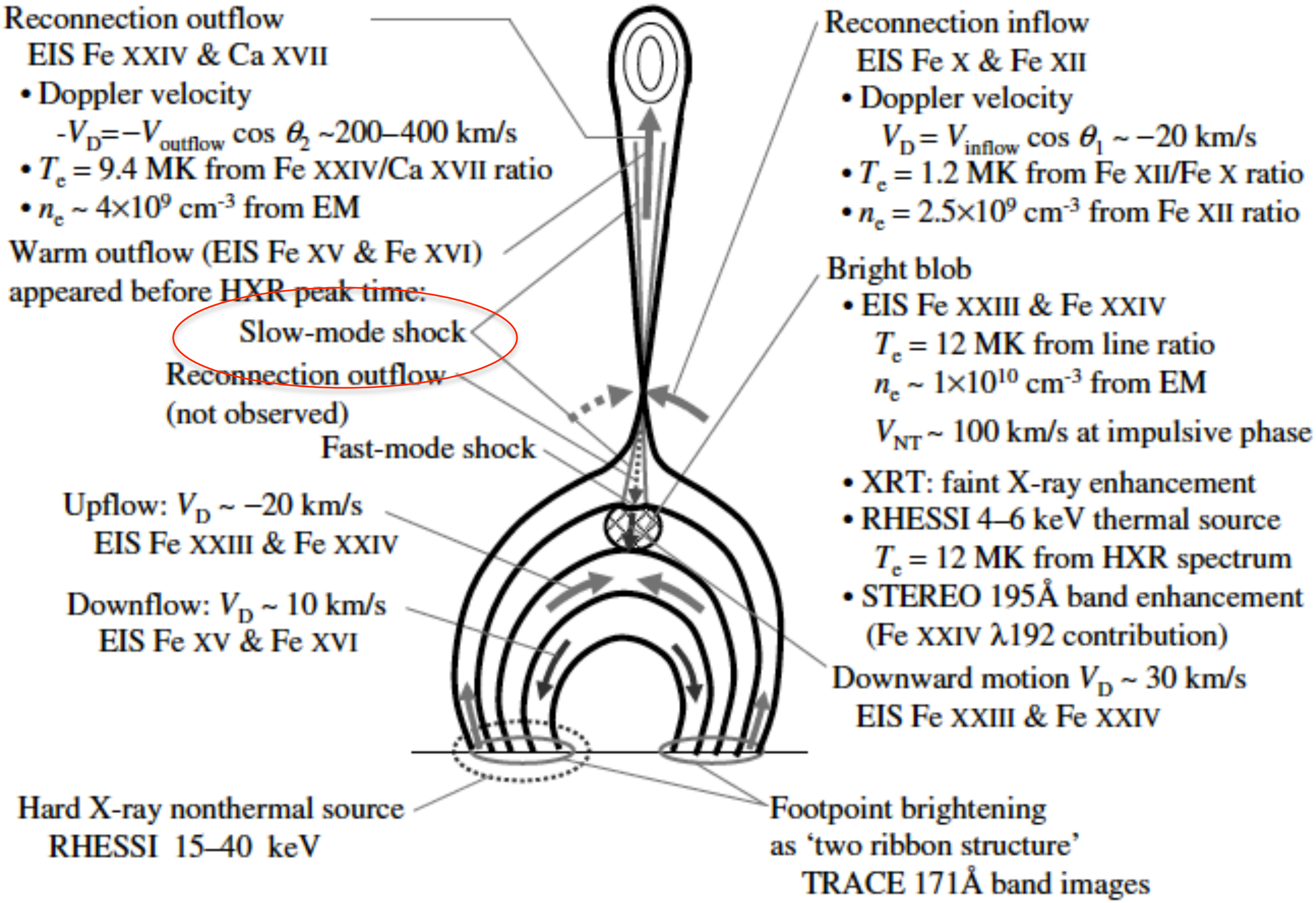
Measurement of reconnection rate

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

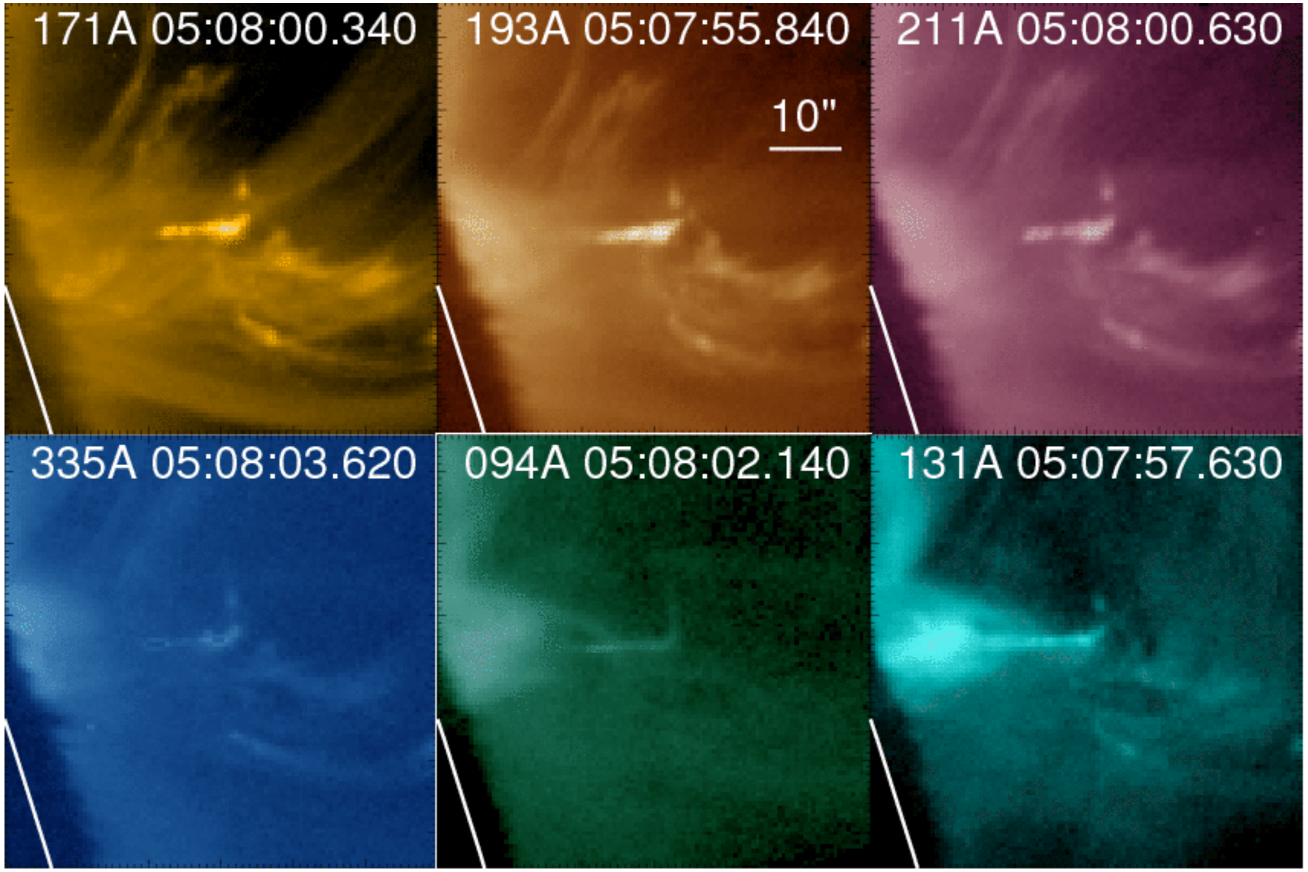
Spectroscopic diagnostics by Hinode/EIS

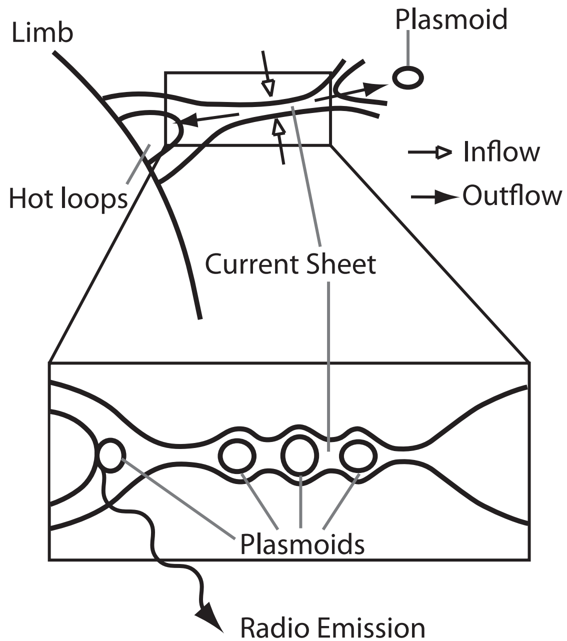


"Standard model" confirmed qualitatively.
More examples desired to examine the role of shocks.

Hara et al. 2011

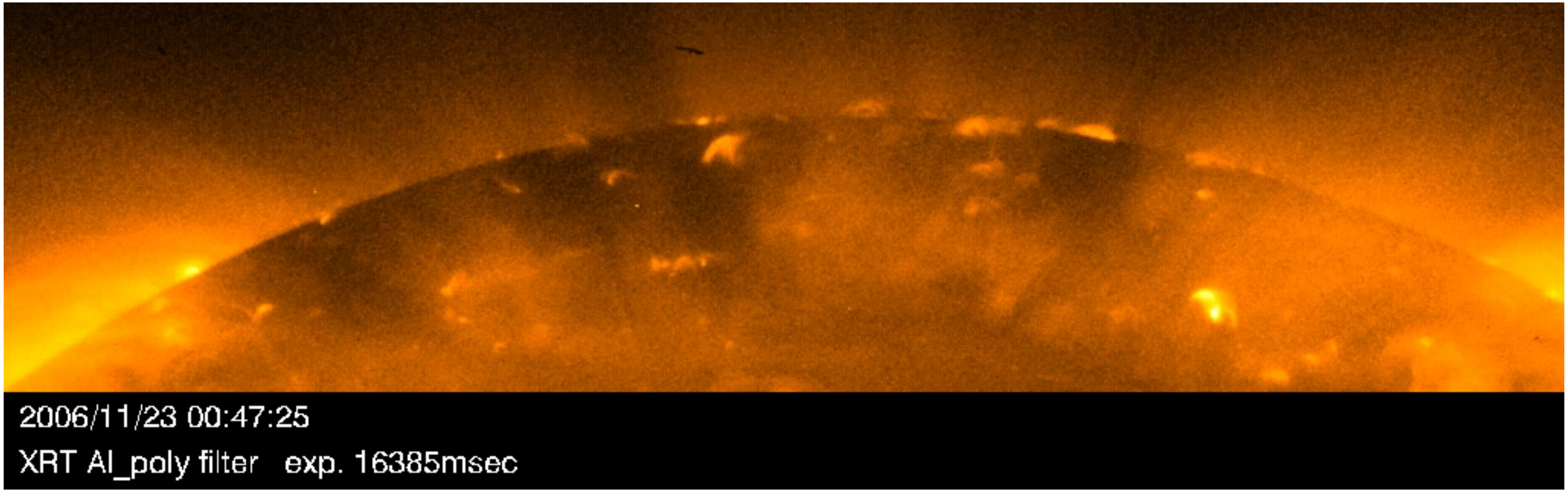
- "Lightening"-like reconnection event observed by SDO/AIA
- Formation, coalescence and ejection of multiple plasma blobs

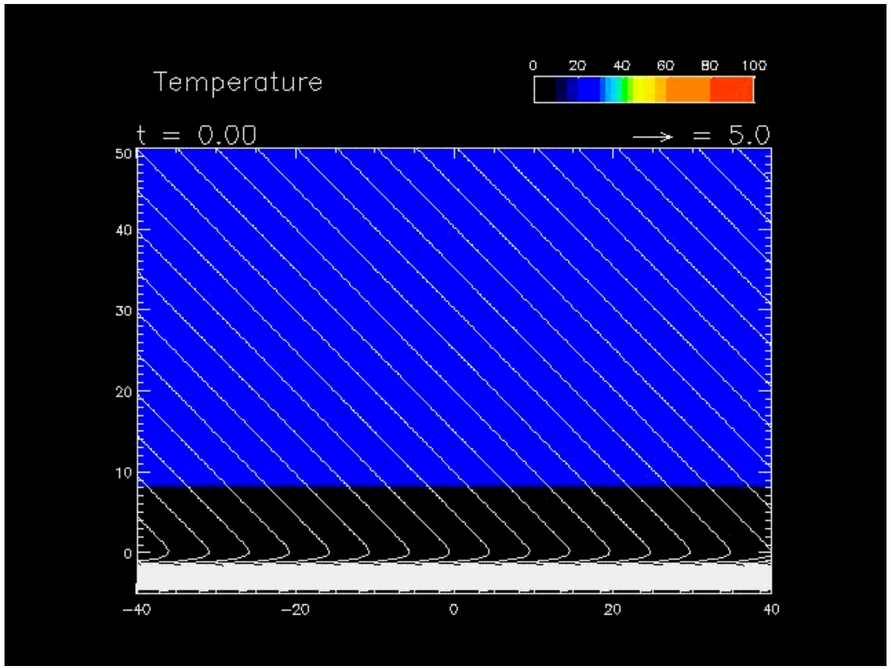




Takasao+12, ApJ

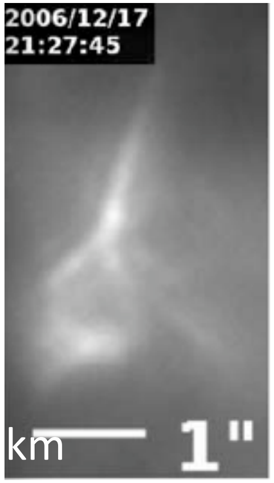
X-ray jet



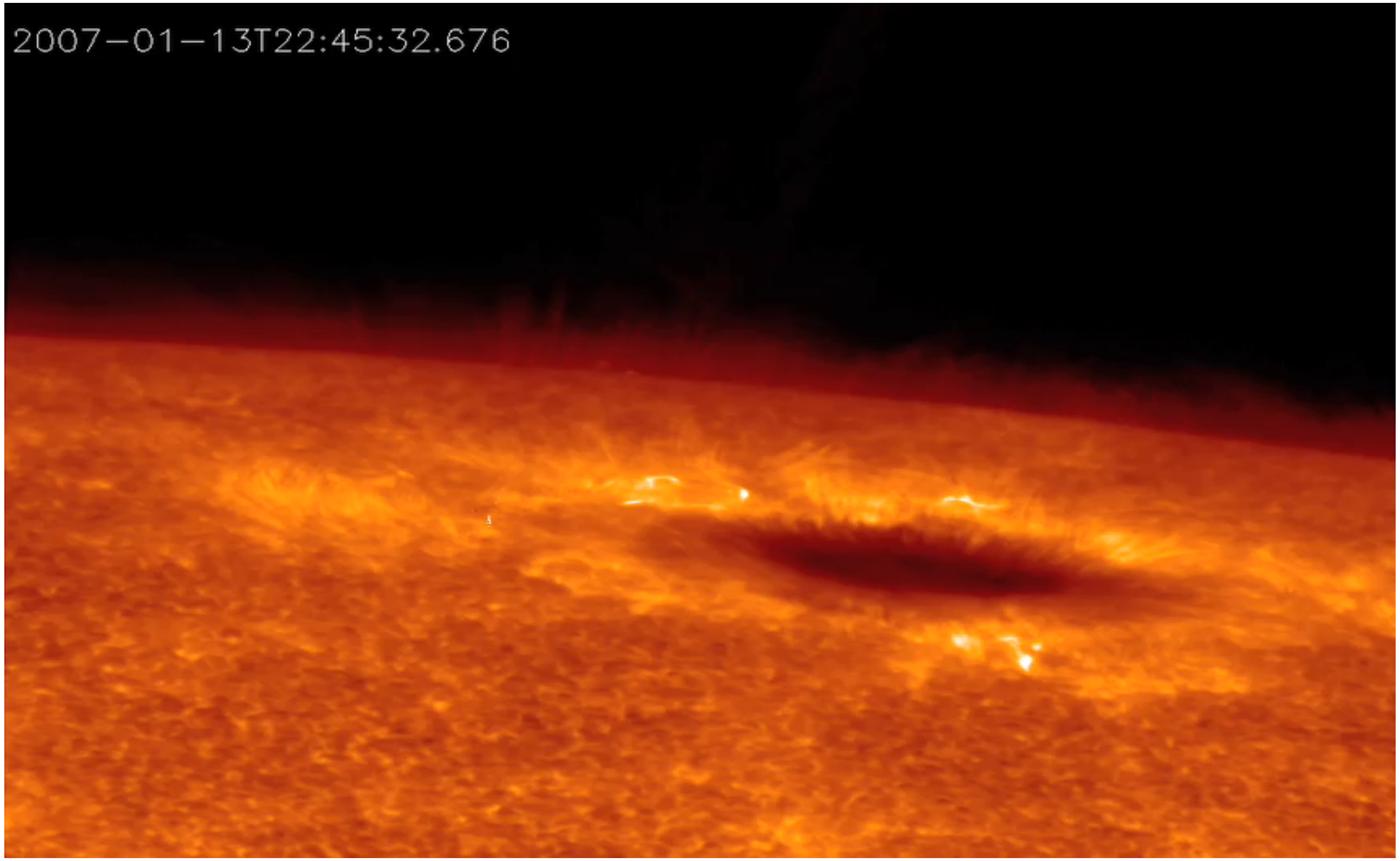


Magnetic reconnection between buoyantly rising loop and open field (Yokoyama & Shibata 1995)

Magnetic reconnection in the chromosphere

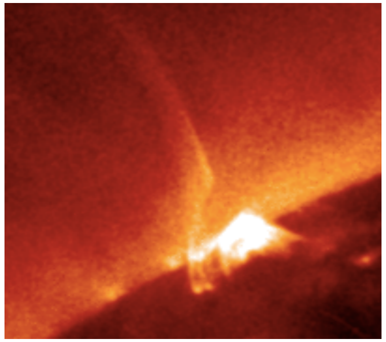


Anemone-jet
Shibata+ 07

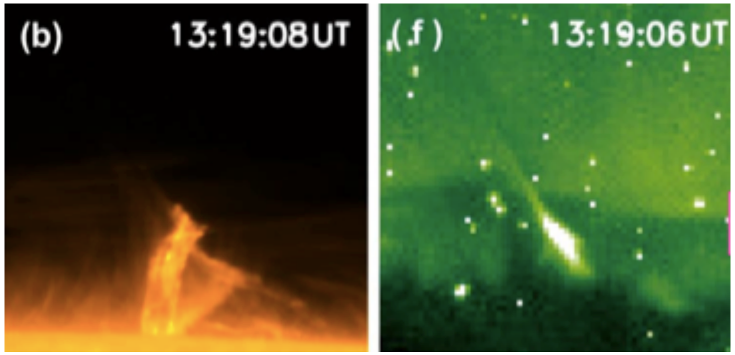


Reconnection + plasma jets at various heights

X-ray jet
~100,000km
(corona)

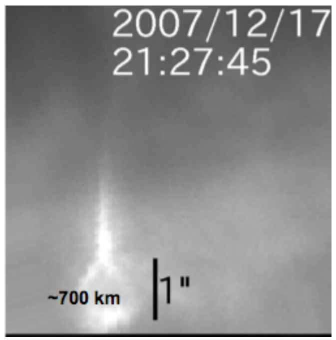


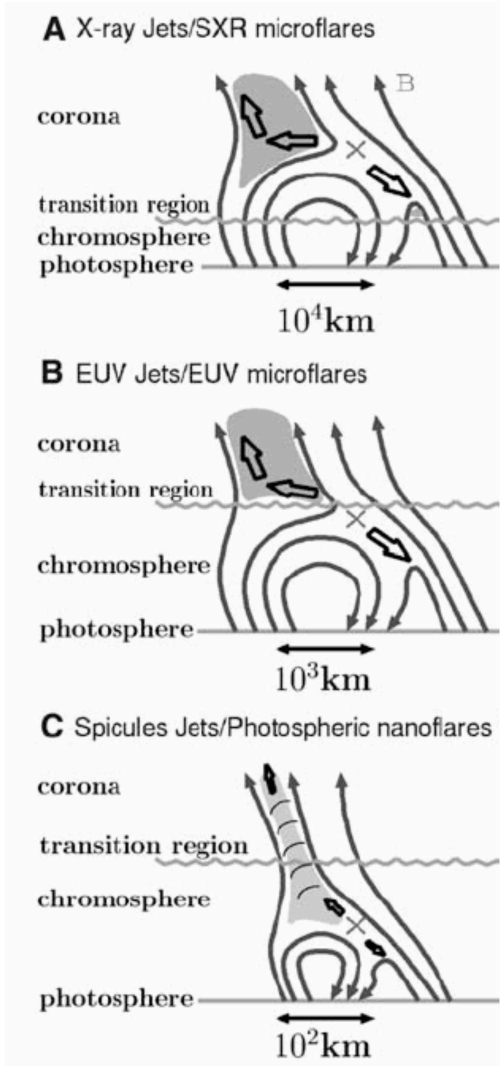
EUV jet ~ 10,000 km
(upper chromo ~
transtion region)



Nishizuka+07

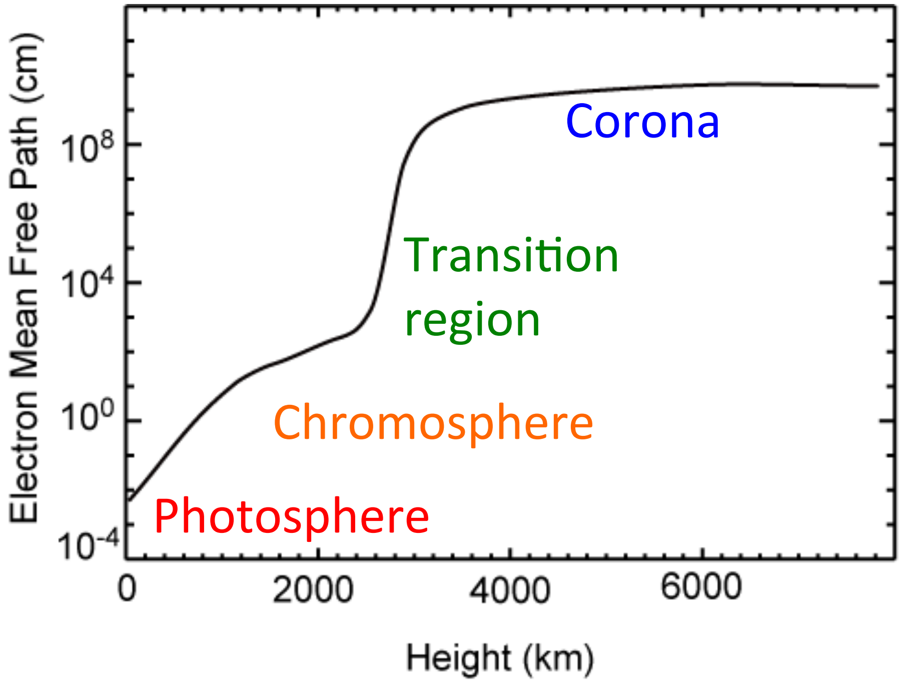
Chromospheric jet
~1000km

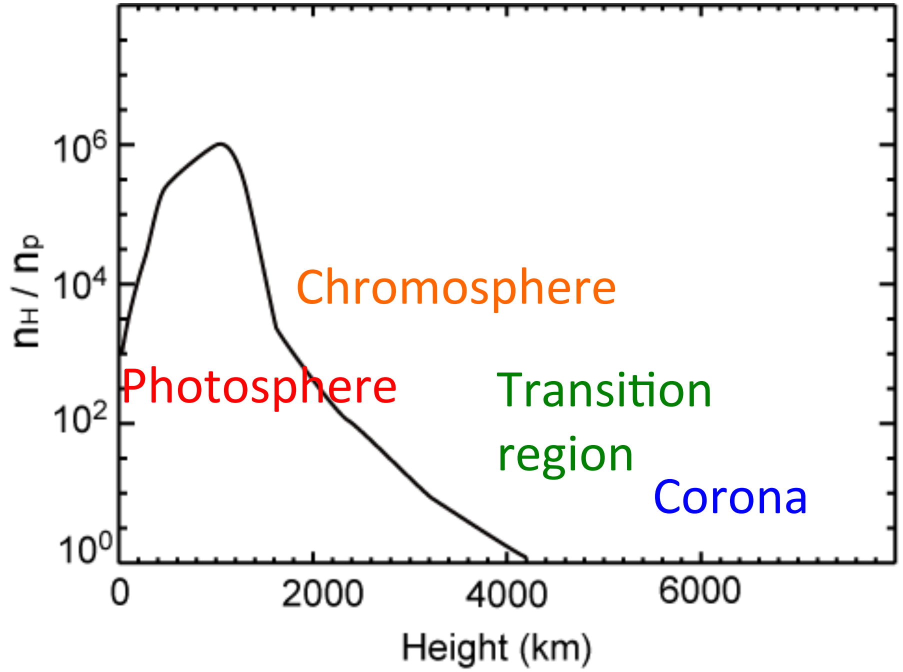




Shibata+07

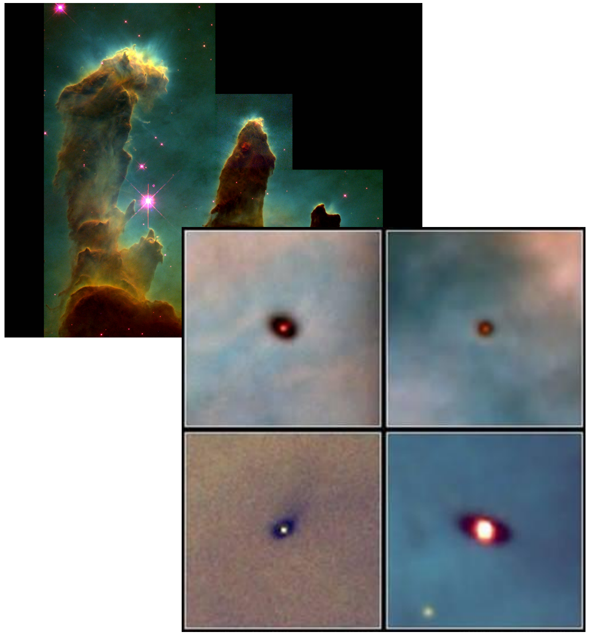
Chromosphere is collisional and partially ionized

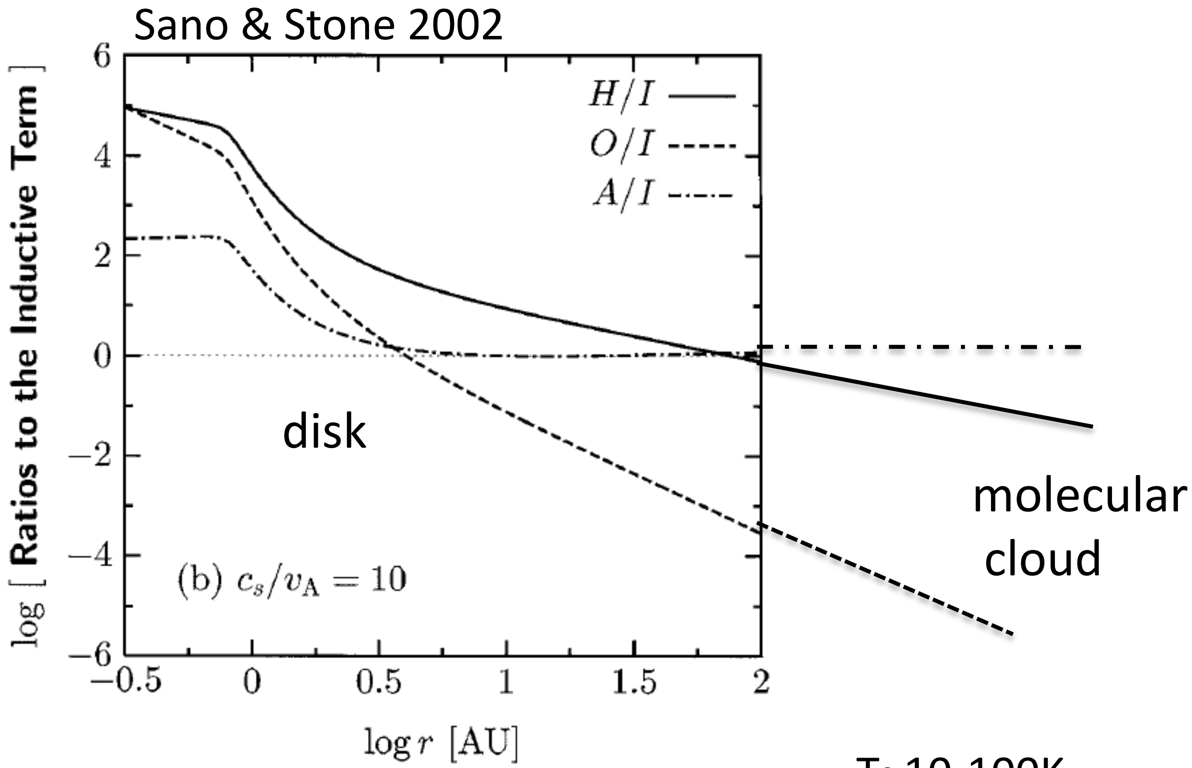




- Plasma parameter very different from (almost) collisionless and fully ionized corona
- Reconnection is chromosphere poorly studied (some pioneering works by Chae, Litvinenko, Sakai, Krishan et al)
- Also important in molecular clouds and protoplanetary disks (Zweibel, Lazarian, Sano et al.)

Similar astrophysical plasmas: molecular clouds and protoplanetary disk

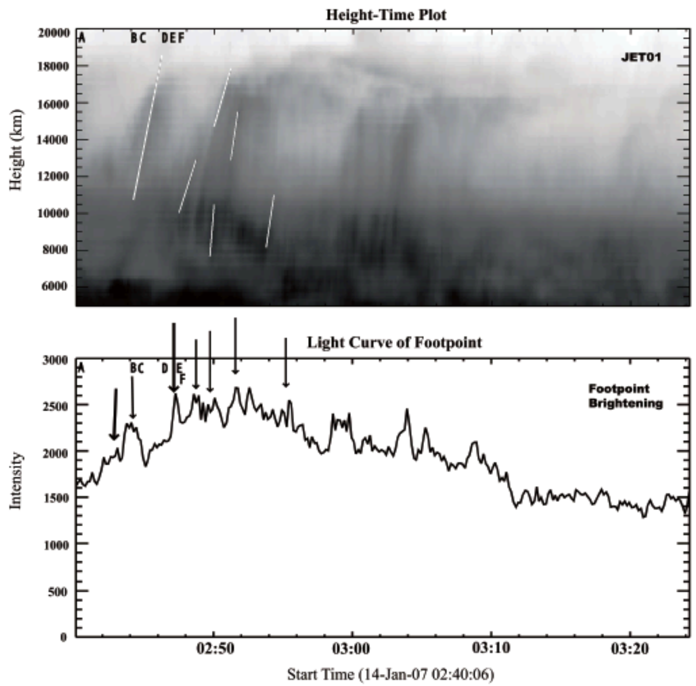


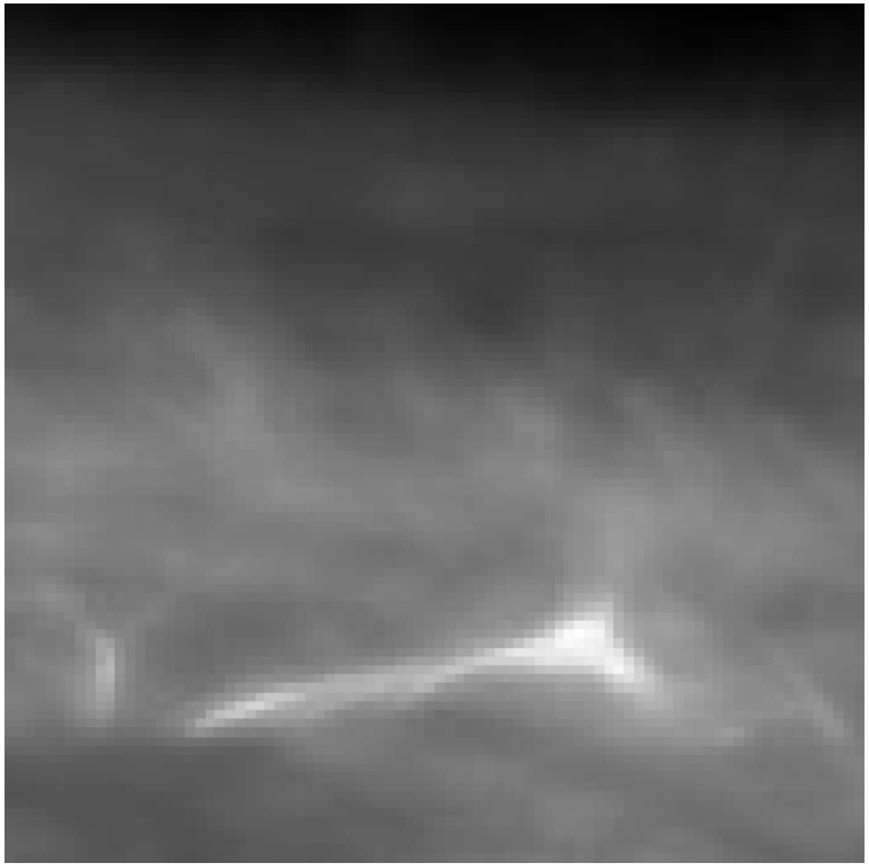


T≈10-100K

- Hall dominates in inner disk ... photosphere - like
- Ambipolar dominates in outer disk and molecular clouds ... chromosphere-like

Chromospheric reconnection intermittent and bursty





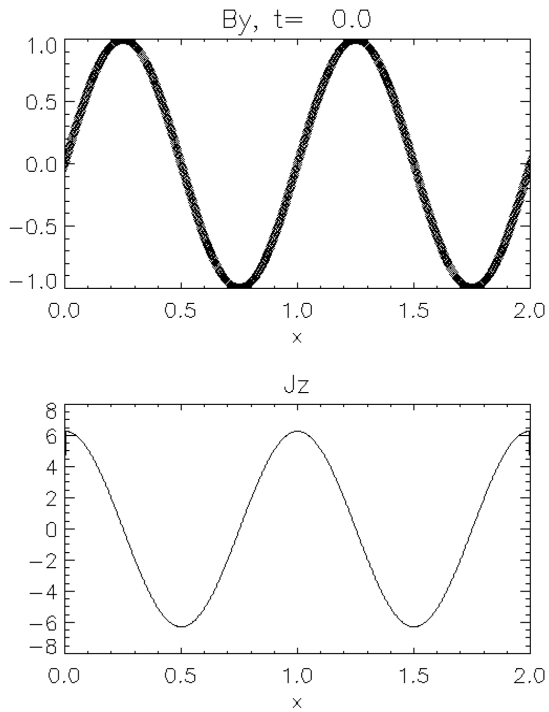
K.A.P. Singh et al. to be submitted soon.

Current sheet thinning by ambipolar diffusion
(Brandenburg & Zweibel 1994)

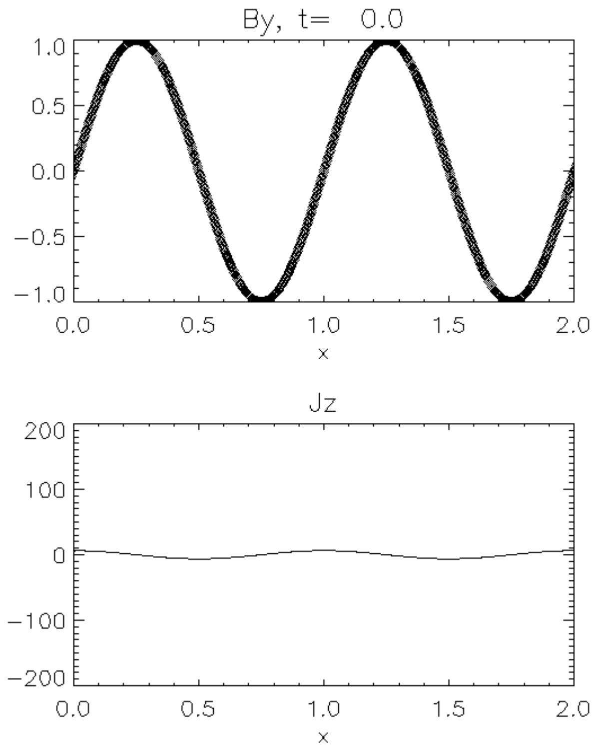
Induction eq. for partially ionized plasma

$$\frac{\partial B}{\partial t} = \nabla \times [V_n \times B - \frac{J \times B}{en_e} + \frac{(J \times B) \times B}{c\nu_{ni}\rho_n} - \eta J]$$

advectio Hall ambipolar resistive



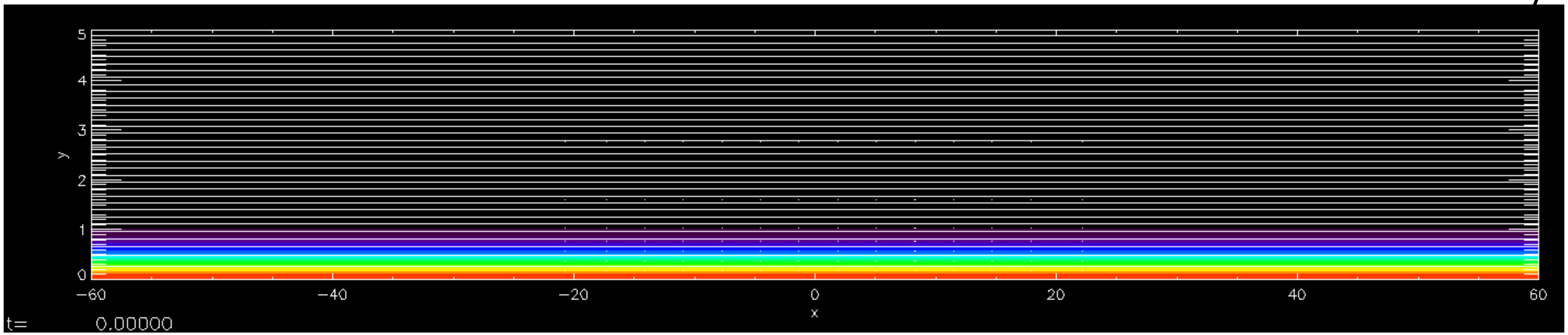
Only resistive diffusion



Only ambipolar diffusion

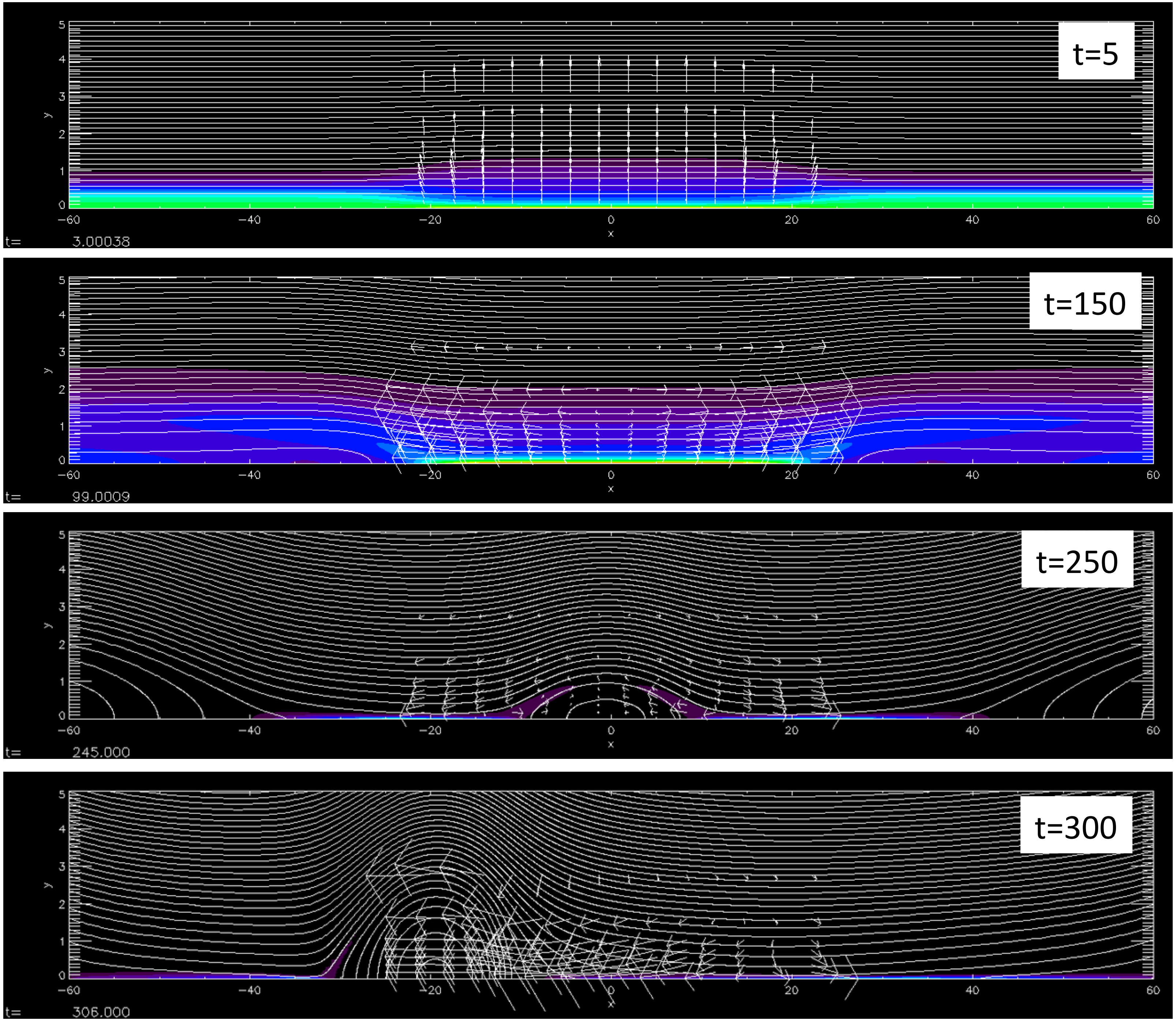
Effect of non-uniform ambipolar diffusion

color: current density



Ambipolar diffusion ≠ 0

Ambipolar diffusion localized in x < ±20
Ohmic resistivity is uniform

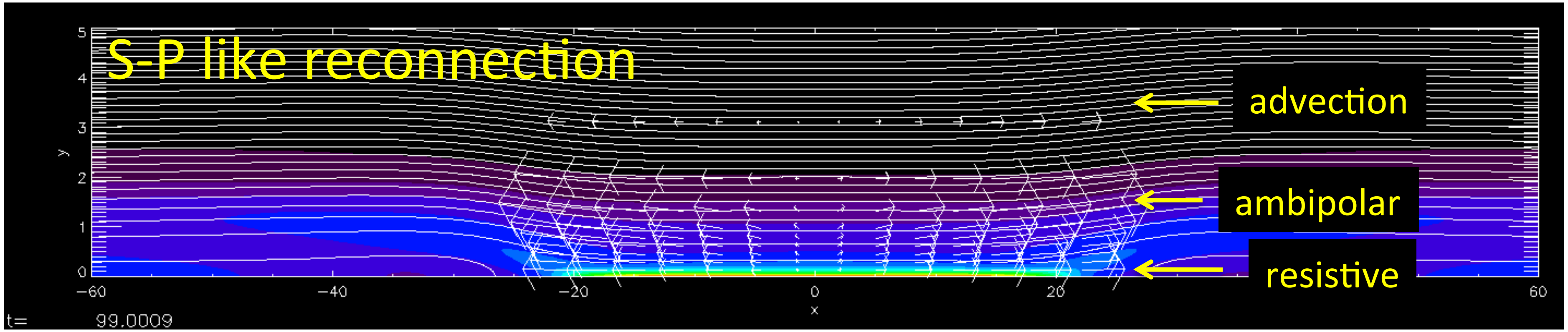


Thinning

Sweet
-Parker
reconnection

Tearing and
island
formation

Island ejection
and time-
dependent fast
reconnection

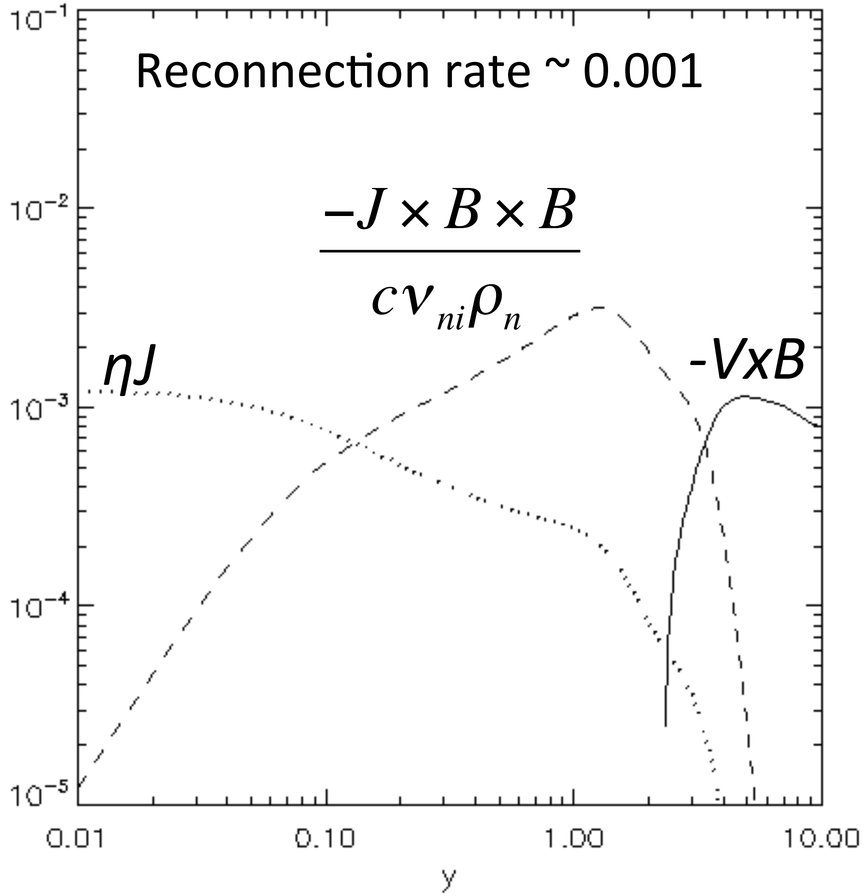


In Sweet-Paker-like stage, the reconnection region consists of 3 layers:
- resistive-dominant inner current sheet
- ambipolar-dominant outer current sheet
- advection-dominant inflow region

Ambipolar diffusion causes plasma heating
⇒outflow driven by gas-pressure gradient from the ambipolar layer

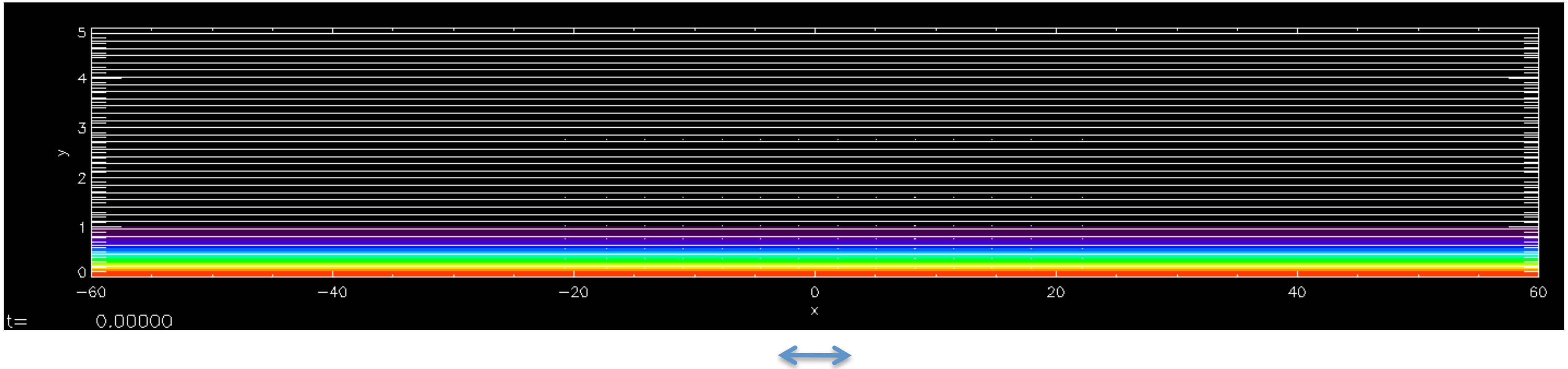
Note: two-fluid treatment is necessary to quantitatively address the (ion-dominant) outflow from resistive layer

Contribution to E

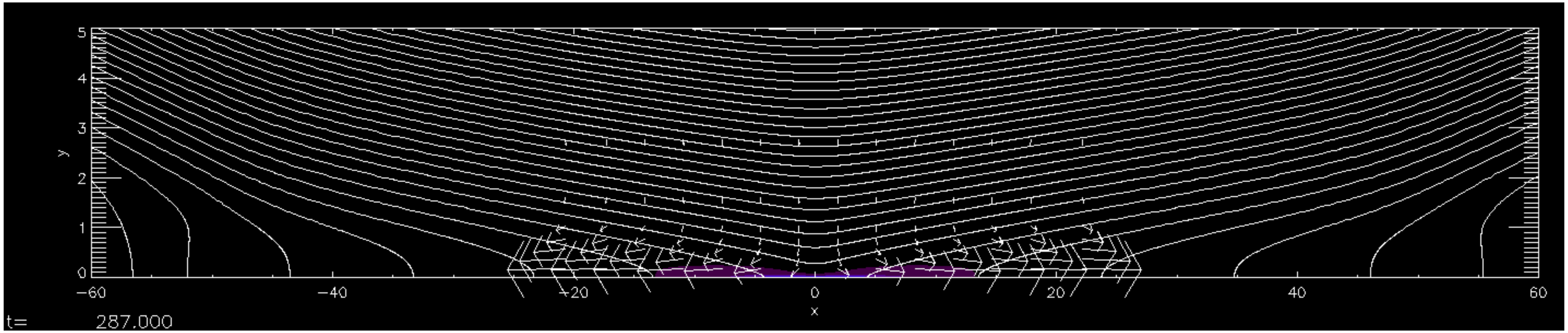


Petschek-like regime

color: current density

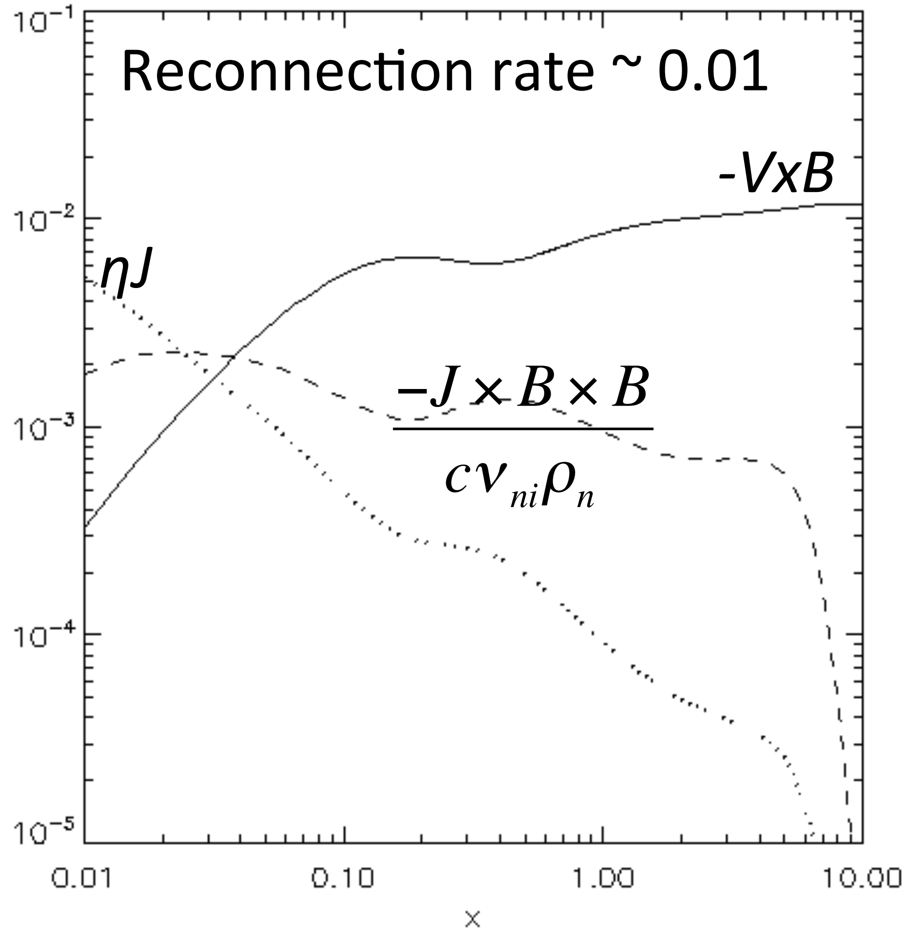


Ambipolar diffusion uniform + enhanced in x < ±2
Uniform resistivity



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.



Conclusions

- Magnetic reconnection is playing important role in physical process in various kinds of space and astrophysical plasmas.

- It still have fundamental unresolved issues:
  - scale coupling
  - multi-fluid effects
  - particle acceleration

- Solar atmosphere is an unique lab to study it, and collaboration with other field is essential