Observations and modeling of magnetic reconnection in the solar atmosphere

Hiroaki Isobe (Kyoto University)

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.

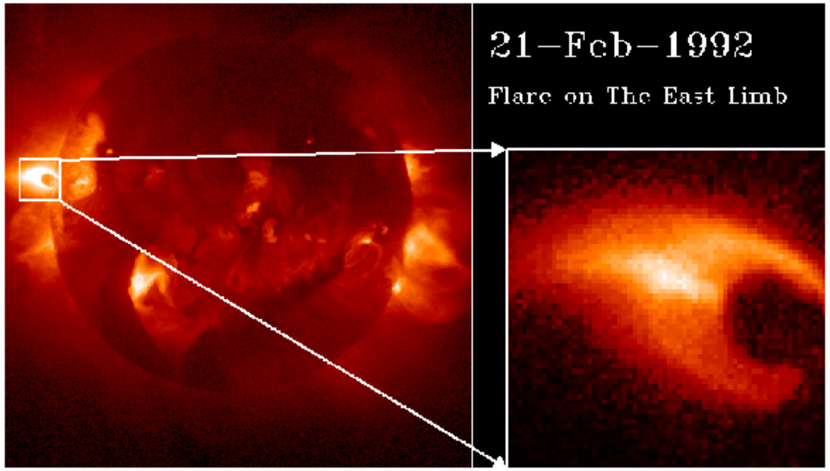
The mechanism works like this: *Well, we know that fast reconnection happens in the Solar corona, and in the Earth magnetosphere. So it should also happen in OUR astrophysical system.*

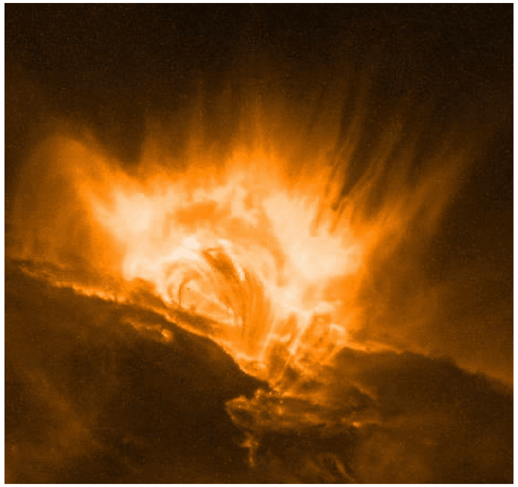
- Reconnection in the corona

- Reconnection in the lower atmosphere

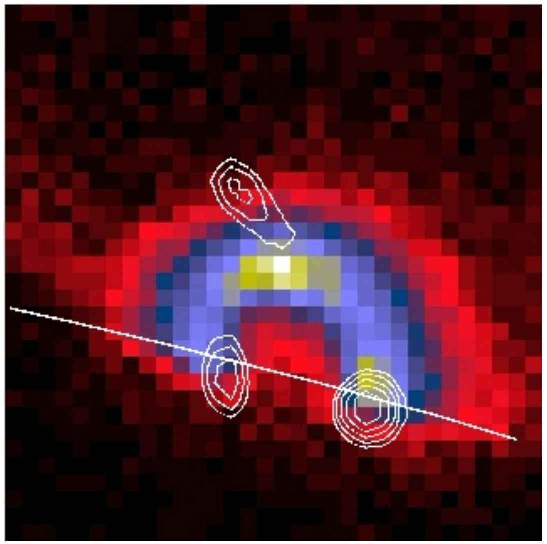
Observational evidence for magnetic reconnection in the corona (before Hinode/SDO)

Cusp (Tsuneta+92)



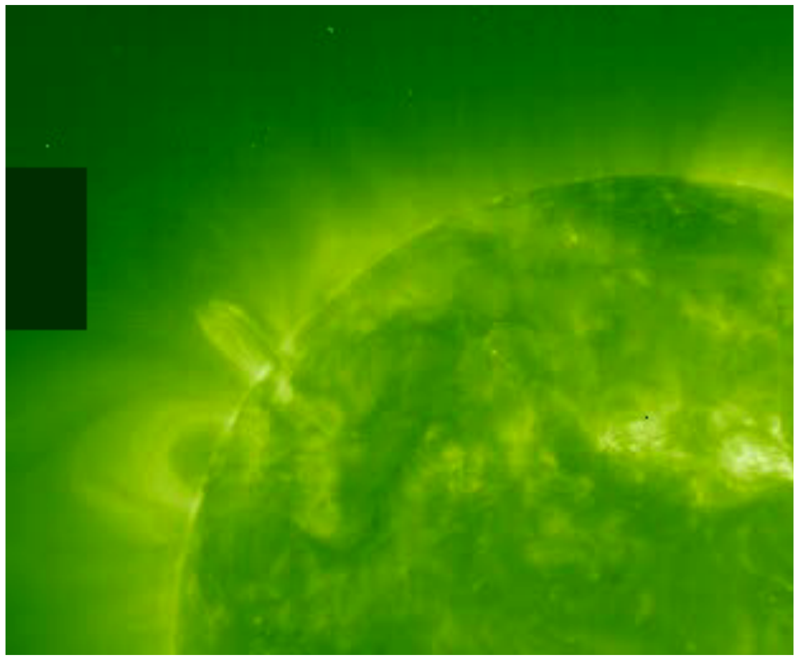


Supra-arcade downflow
(McKenzie Hudson 99)

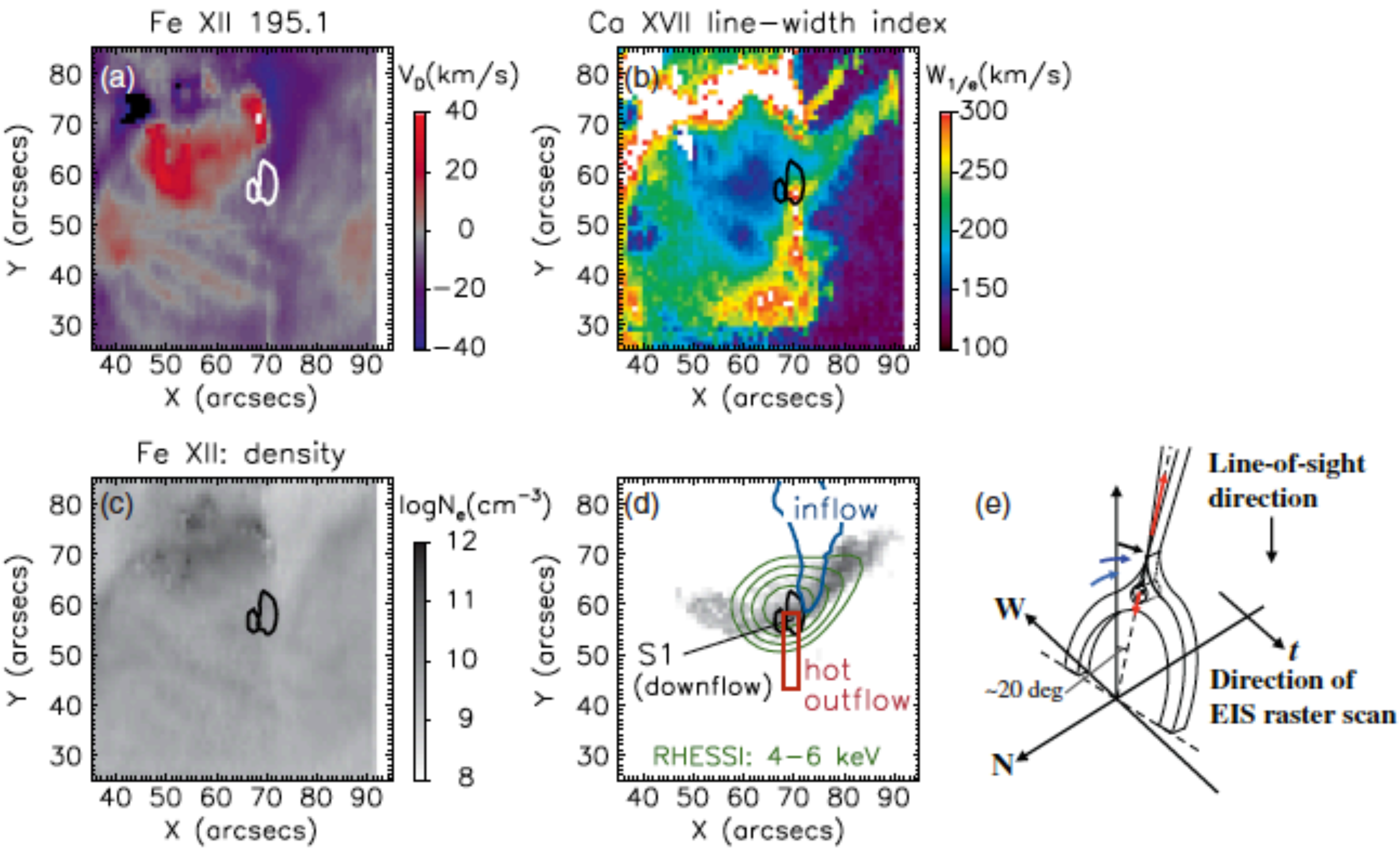


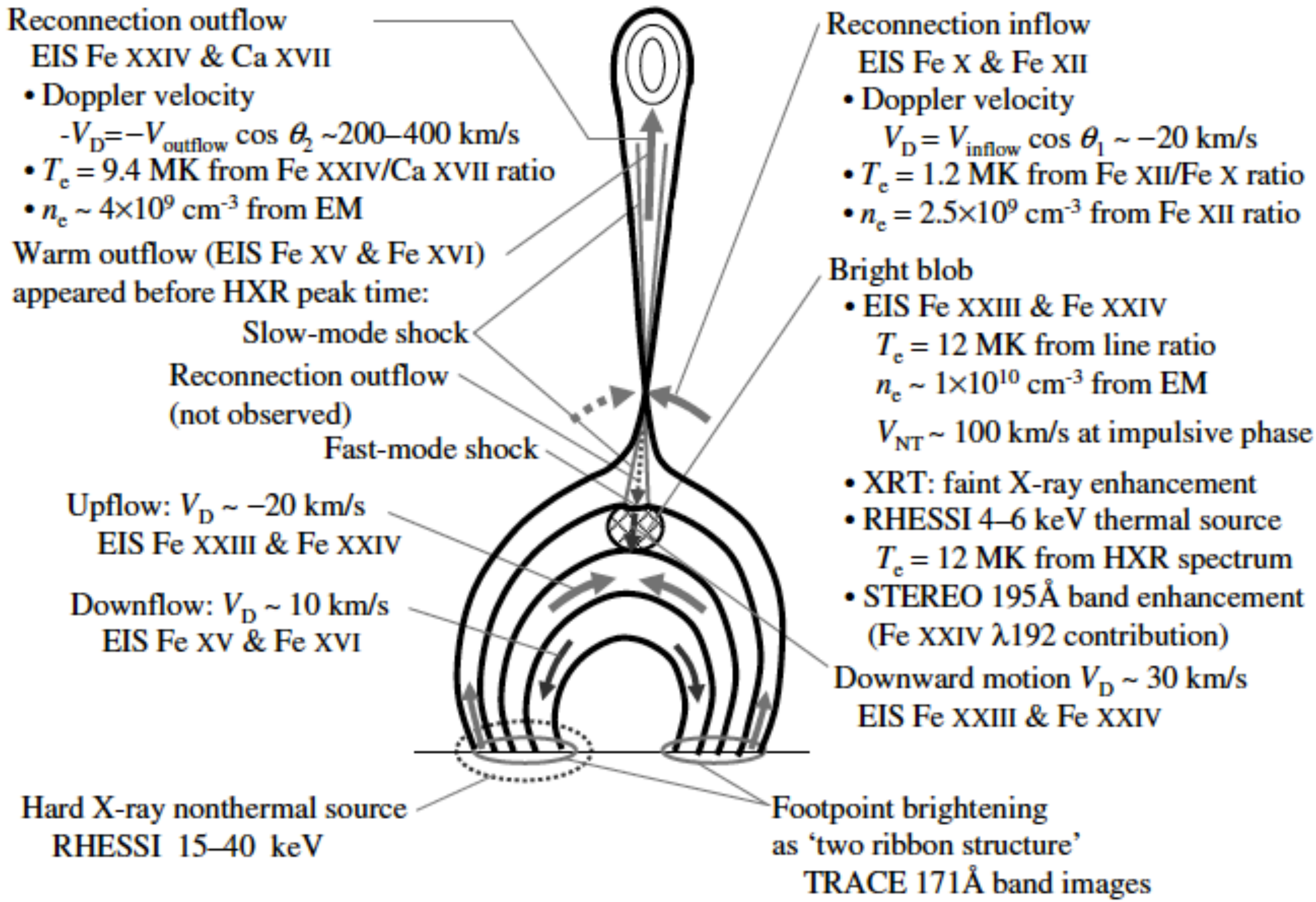
Loop-top HXR source
(Masuda+94)

Inflow
(Yokoyama+01)



Quantification by Hinode/EIS
(Hara et al. 2011, ApJ)





Hara et al. 2011

What's the problem?

- Fast reconnection required for flares

Reconnection rate $M_A = V_{\inf low} / V_A \approx 0.01 - 0.1$

(e.g., Isobe+02,05)

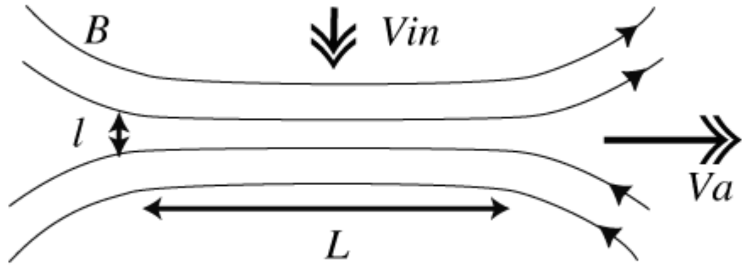
- Extremely small resistivity in corona

Lundquist number $S = \tau_{resistive} / \tau_A = V_A L / \eta \approx 10^{14}$

How to realize fast (independent to S) reconnection?

Classical MHD reconnection models

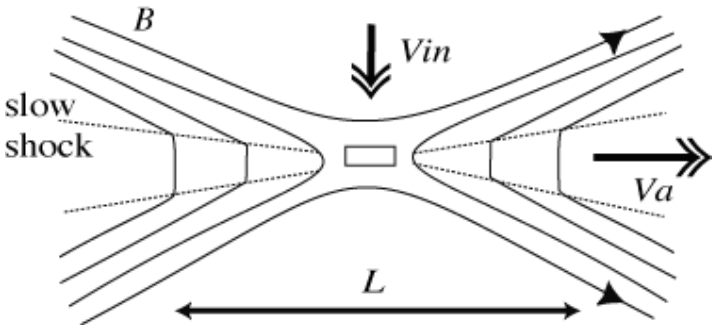
Sweet-Parker reconnection



Uniform resistivity

$M_A = S^{-1/2} \approx 10^{-7}$ ... too slow

Petschek reconnection



Localized resistivity

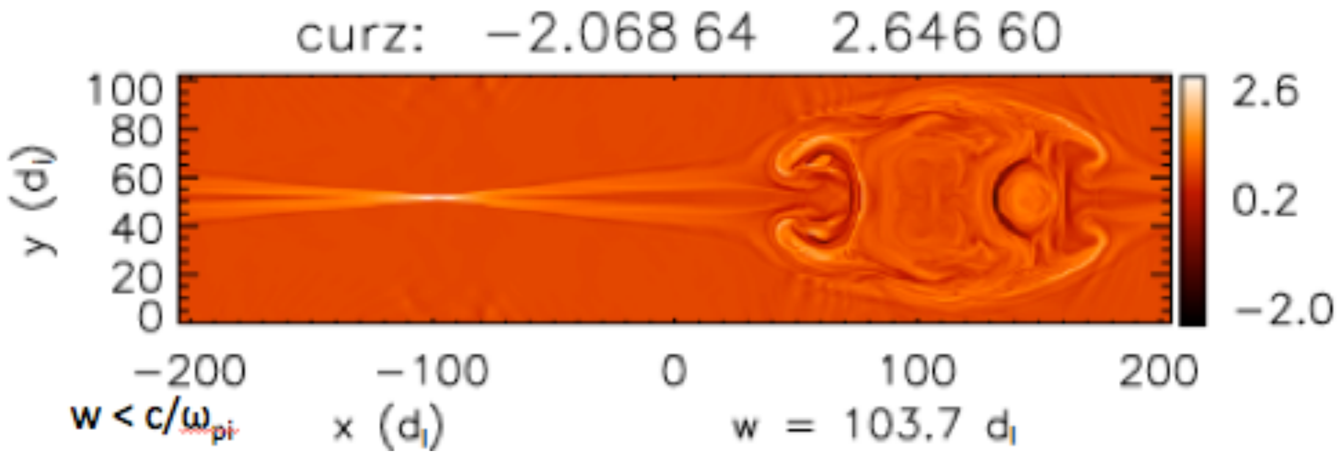
Energy conversion via slow shocks

$M_A = \pi/8\ln S \approx 0.01\text{-}0.1$ ... OK?

How to localize resistivity? Kinetic effects?

Hall reconnection? but...

- When current sheet becomes thinner than ion inertia length $d_i = c/\omega_{pi}$, Hall effect becomes siginificant, and fast reconnection (with Petschek-like configuration) is realized.

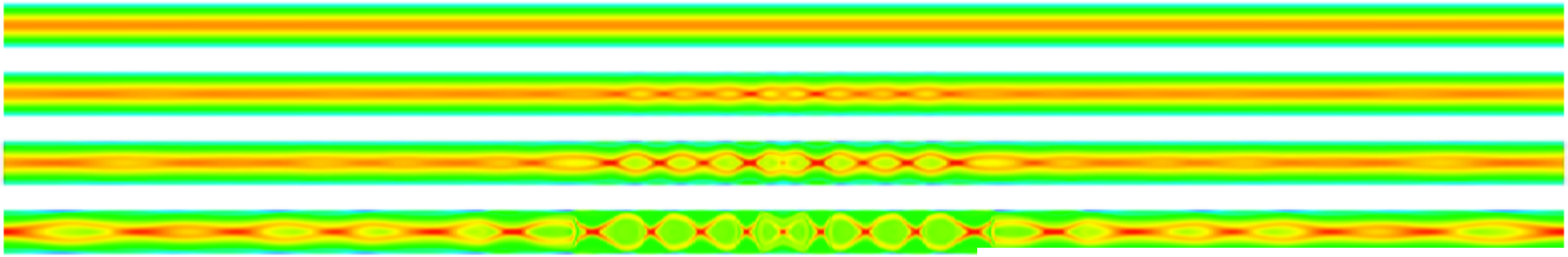


Cassak+05

- Ion scale in corona $d_i \sim 10^2$ cm
- Spatial size of flare $L \sim 10^9$ cm
- How to fill the scale gap?

Reconnection with multiple plasmoids/X-lines in High S reconnection

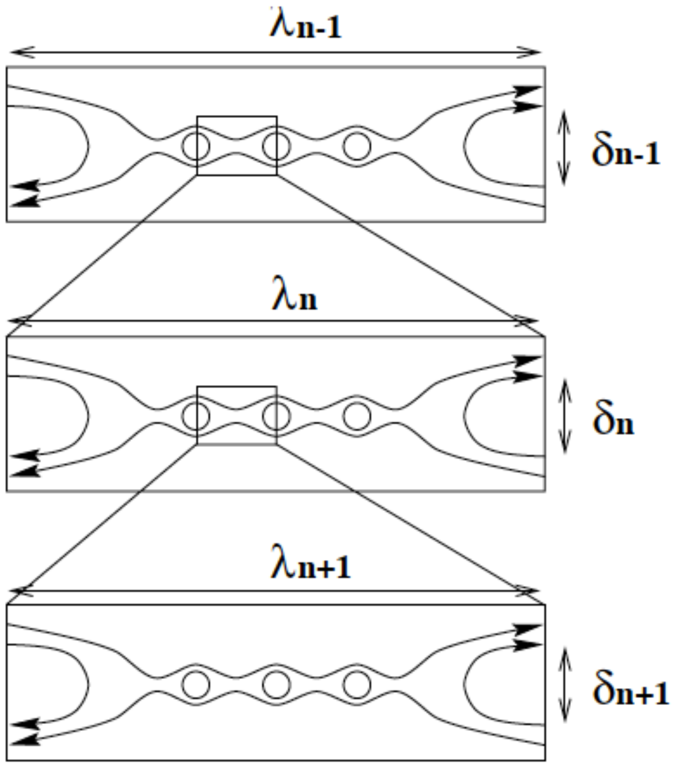
S=10^7 simulation by Samataney+09



- Multiple islands (plasmoids) by tearing
  => effectively reducing L
  => reconnection faster

- Tearing in reconnecting current sheet
  => further thinning
  => connection to kinetic scales?

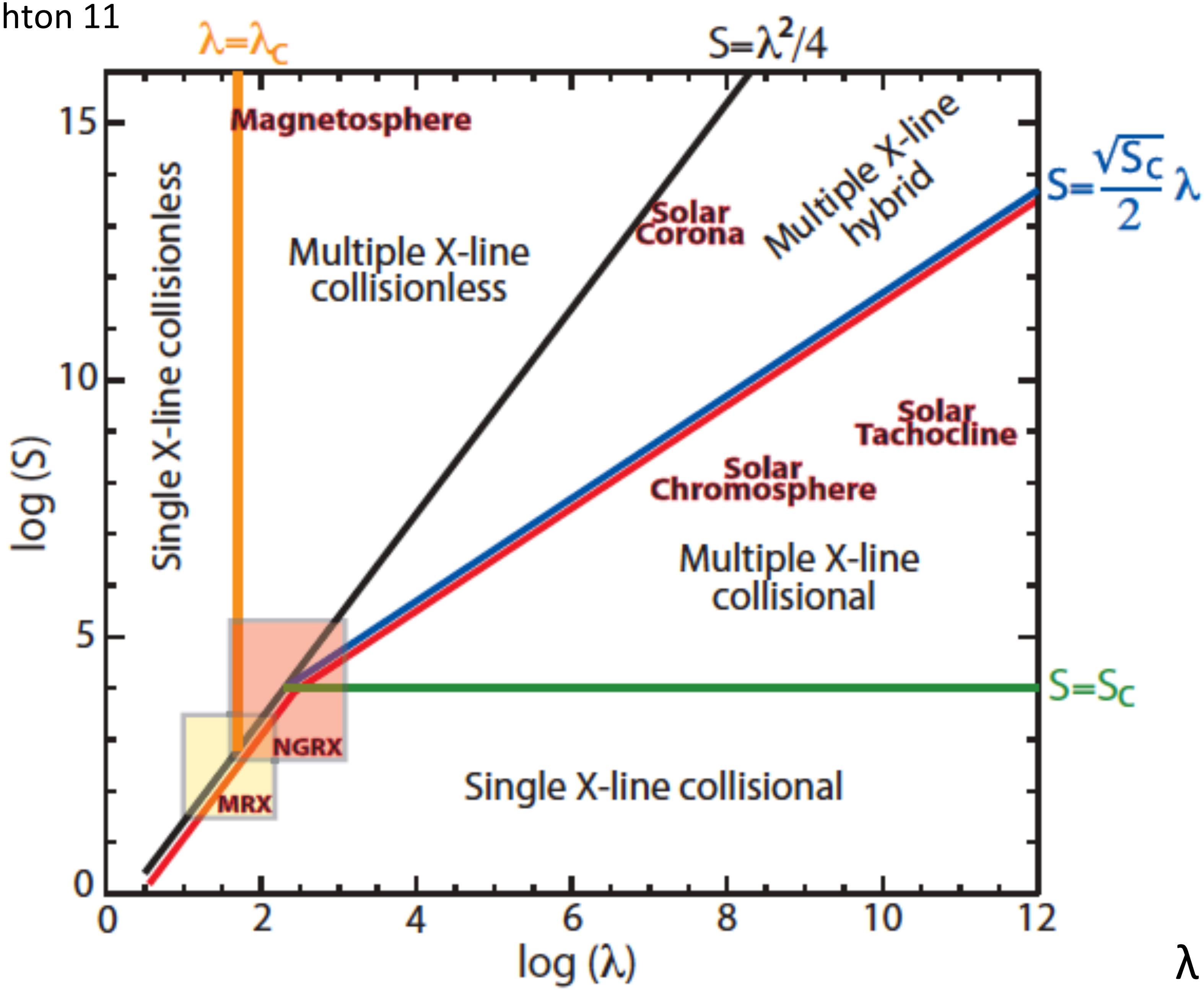
- Enhanced reconnection rate with ejection => inherently intermittent



Shibata & Tanuma 01

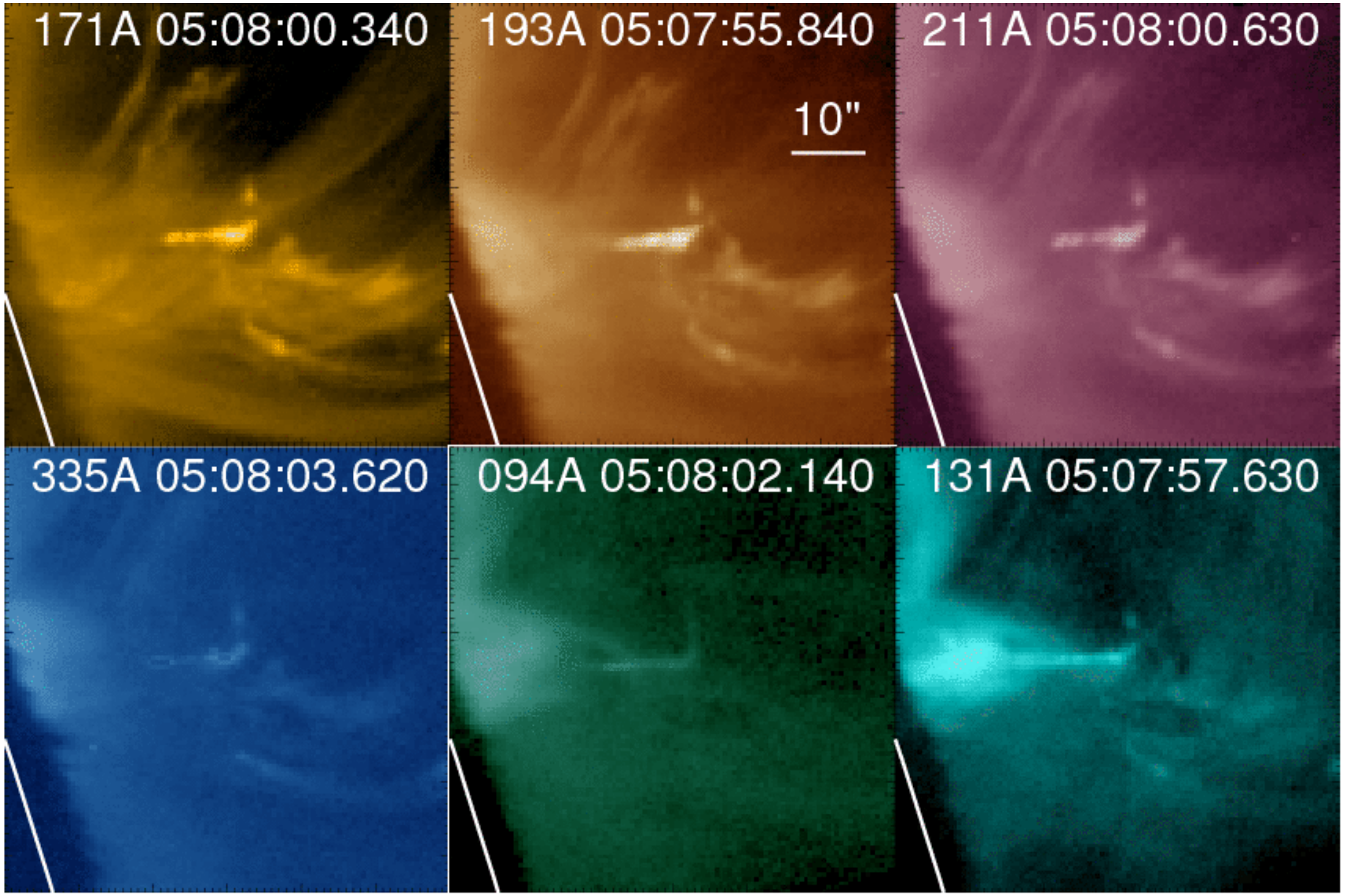
Reconnection type depends on S and system size?

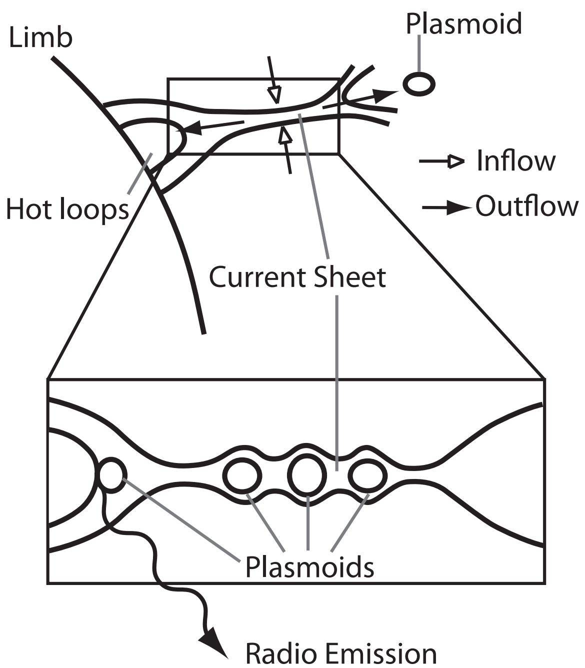
Ji & Daughton 11



$\lambda = L/d_i$

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



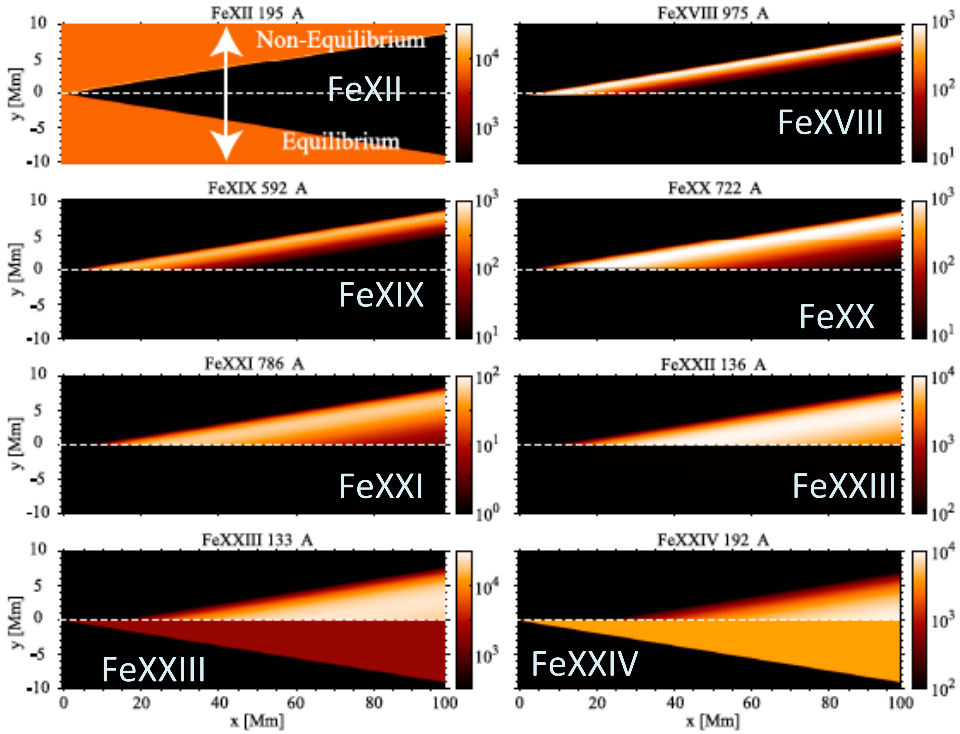


Takasao, Asai, HI, Shibata 2012, ApJ
See Takasao’s (e-)poster

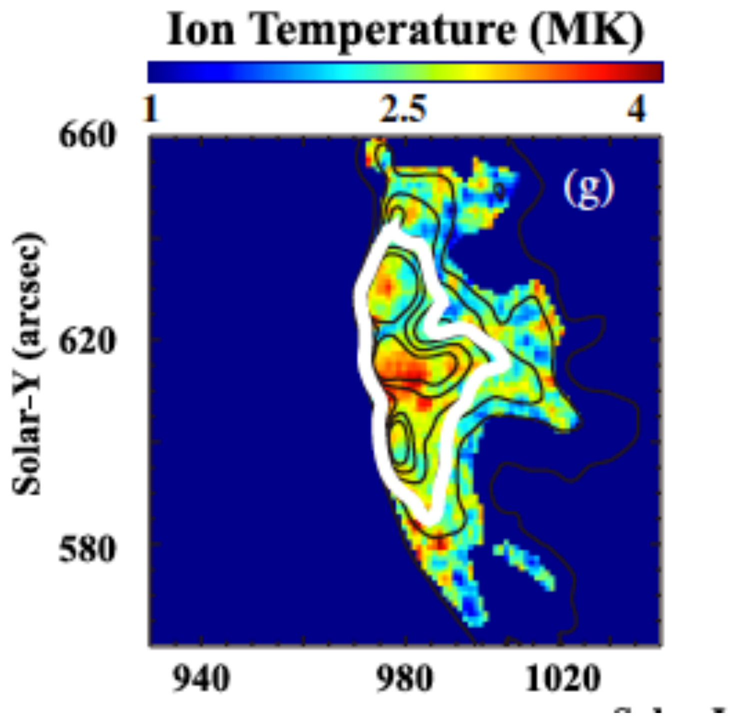
Can we observe non-MHD processes?

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

Time-dependent ionization
(modeling by Imada+ 11)



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



And of course accelerated particles are the consequents of non-MHD processes.

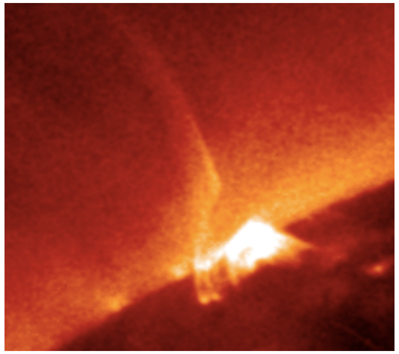
Target of future observations for coronal reconnection

- Role of plasmoids and slow shock

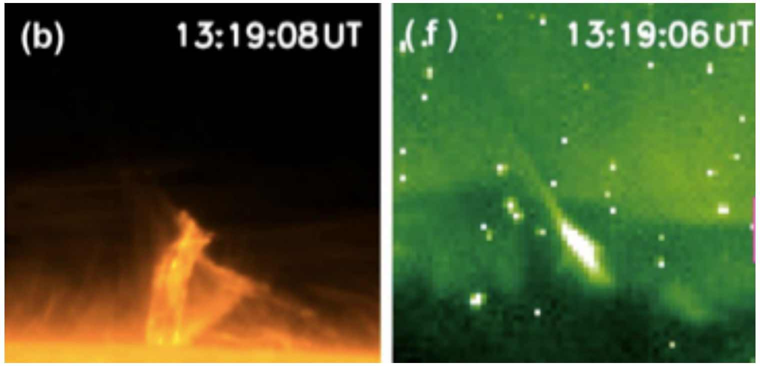
- non-MHD processes
  - non-equil ionization
  - difference of ion and electron temperatures
  - particle acceleration

Reconnection + plasma jets at various heights

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

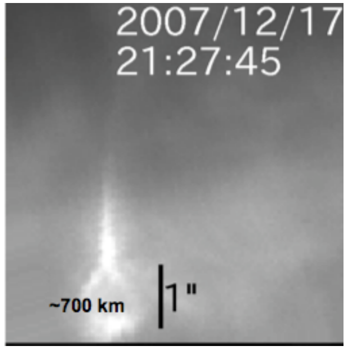


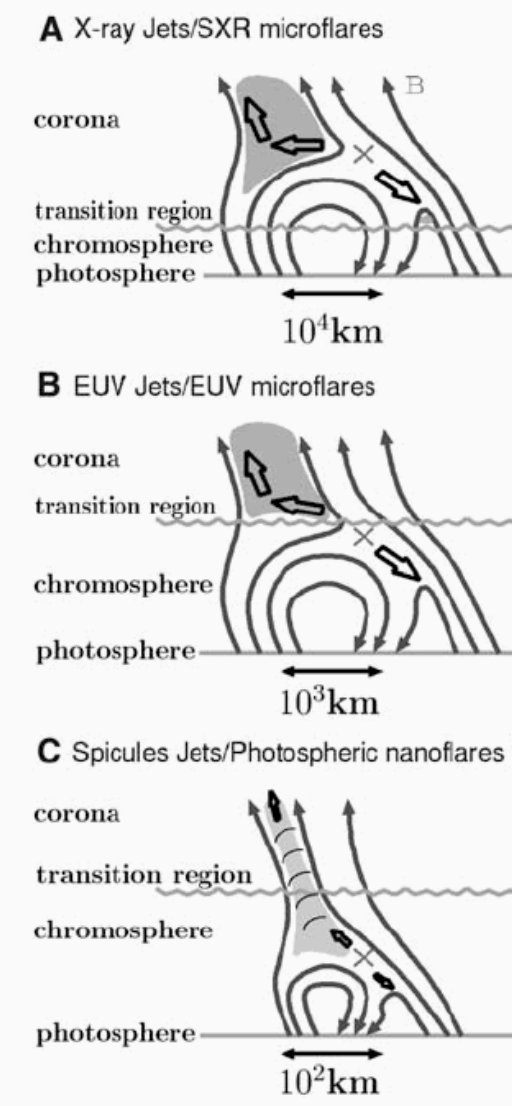
EUV jet ~ 10,000 km
(upper chromo ~
transtion region)



Nishizuka+08

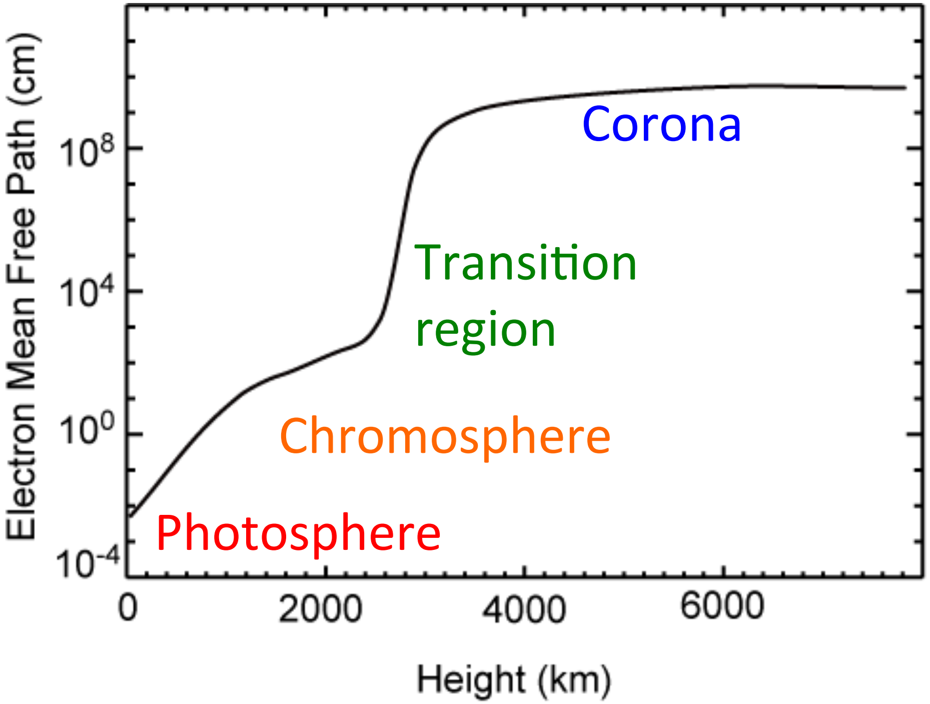
Chromospheric jet
~1000km

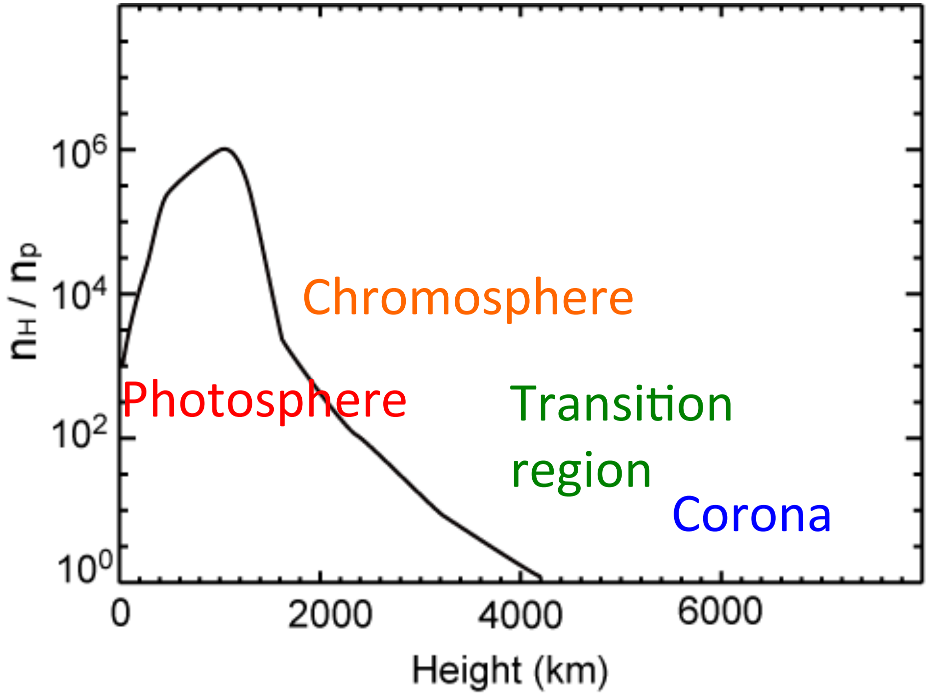




Shibata+07

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

Advection | Hall | Ambipolar | Ohmic

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

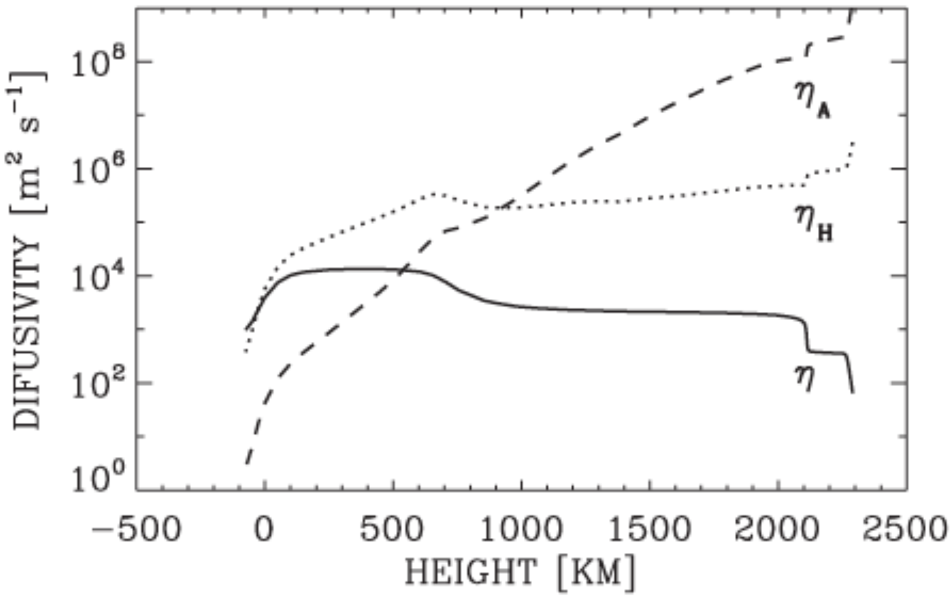
Ambipolar/Hall is important in small scale ... important in reconnection!

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

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

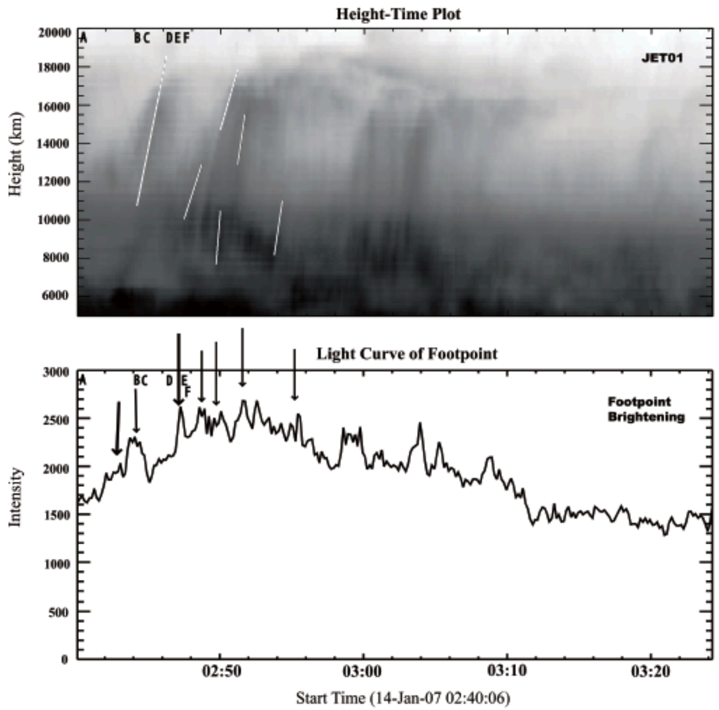
ωci : Ion-cyclotron freq $\propto B$

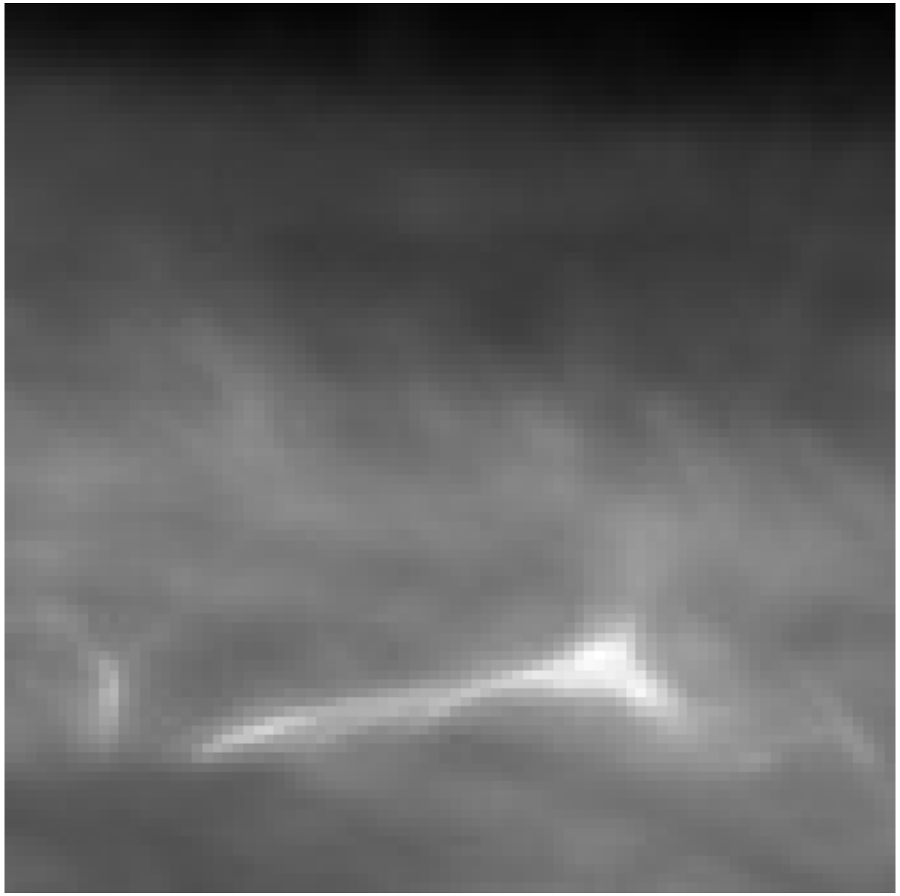
νin : Ion-neutral collision freq $\propto n$



Khomenko & Collados 2012

Chromospheric reconnection intermittent and bursty





Singh et al. submitted to ApJ

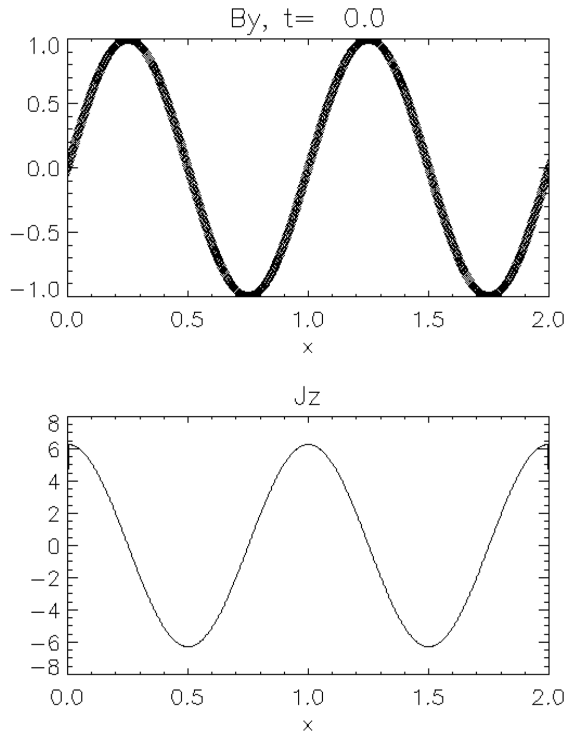
Current sheet thinning by ambipolar diffusion

(Brandenburg & Zweibel 1994)

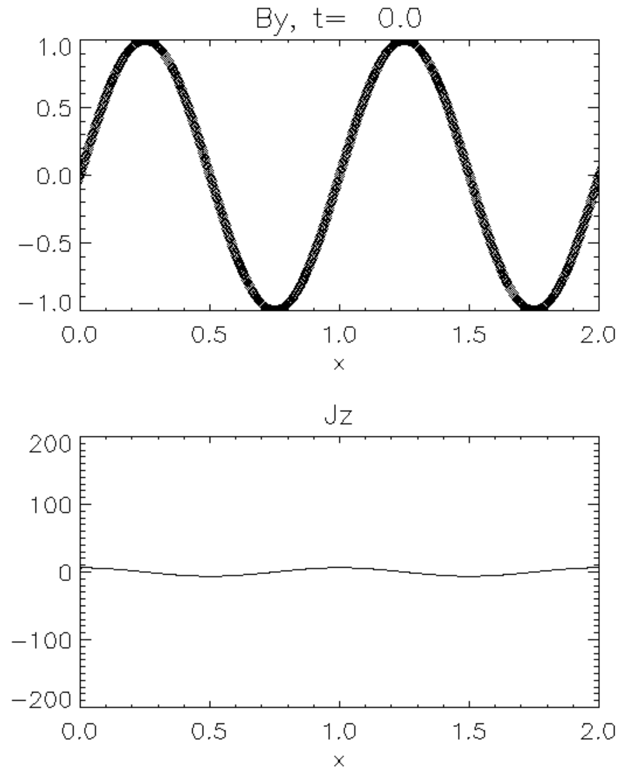
Evolution of sinusoidal field under:

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

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



Only resistive diffusion

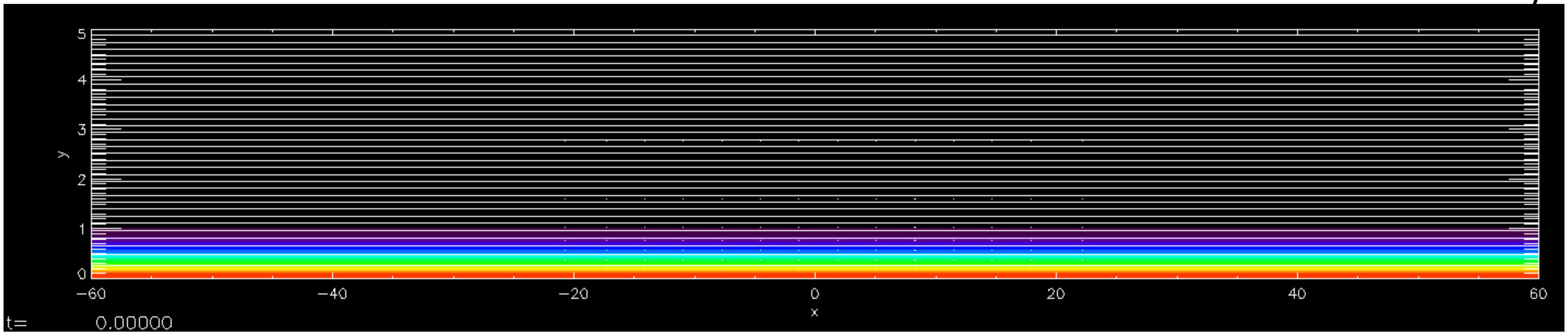


Only ambipolar diffusion

Effect of non-uniform ambipolar diffusion

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

color: current density



Ambipolar diffusion ≠ 0

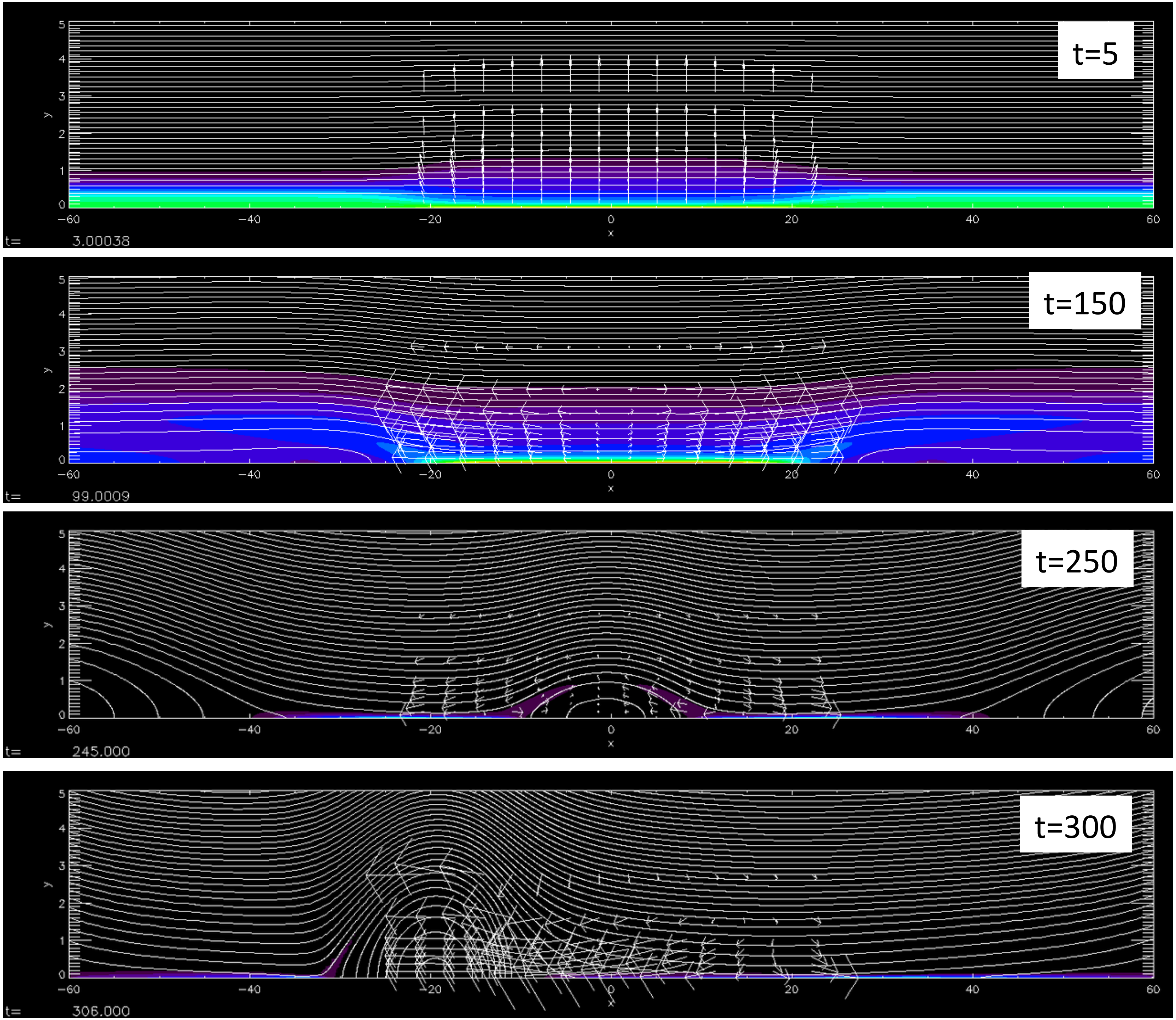
Ambipolar diffusion localized in x < ±20
Ohmic resistivity is uniform

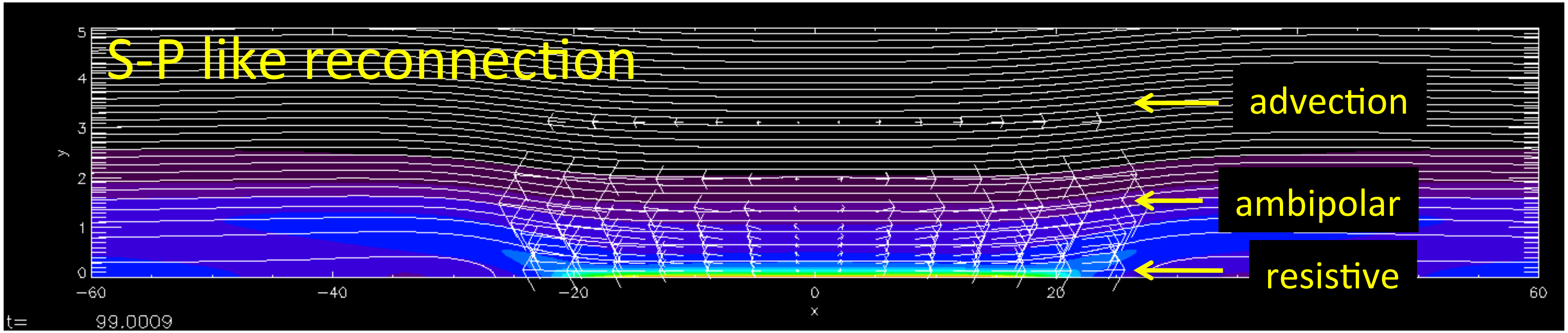
Thinning

Sweet
-Parker
reconnection

Tearing and
island
formation

Island ejection
and time-
dependent fast
reconnection



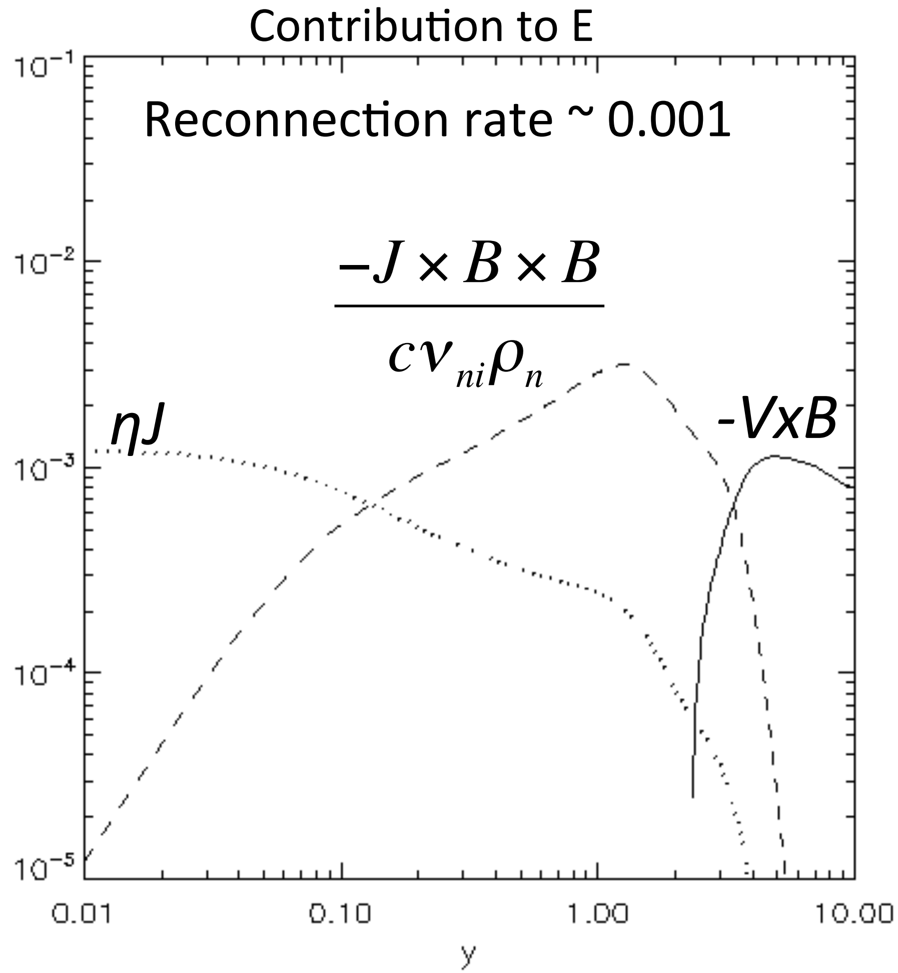


In Sweet-Paker-like stage, the reconnection region consists of 3 layers:

- resistive-dominant inner current sheet
- ambipolar-dominant outer current sheet
- advection-dominant inflow region

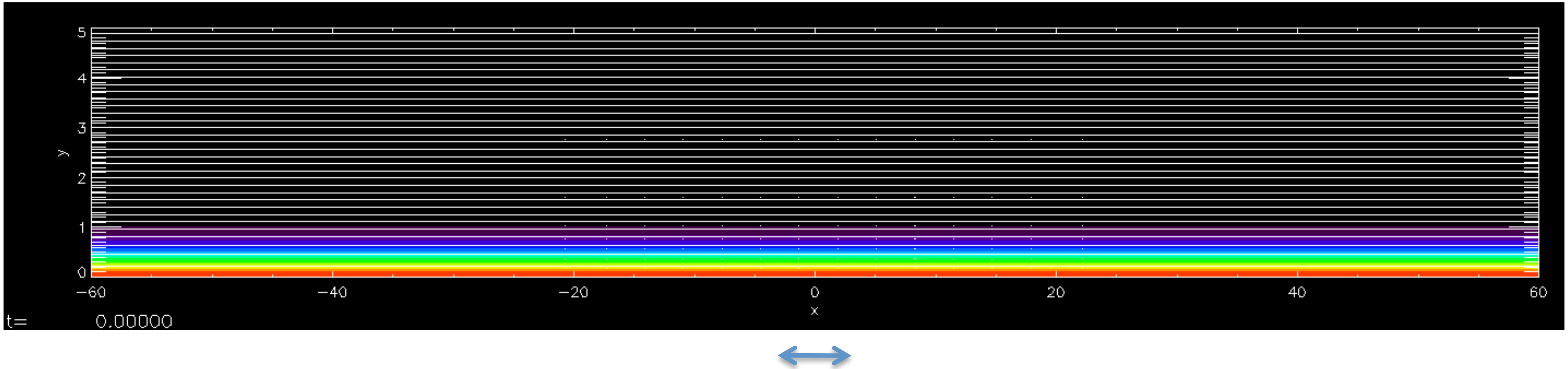
Ambipolar diffusion causes plasma heating ⇒outflow driven by gas-pressure gradient from the ambipolar layer

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

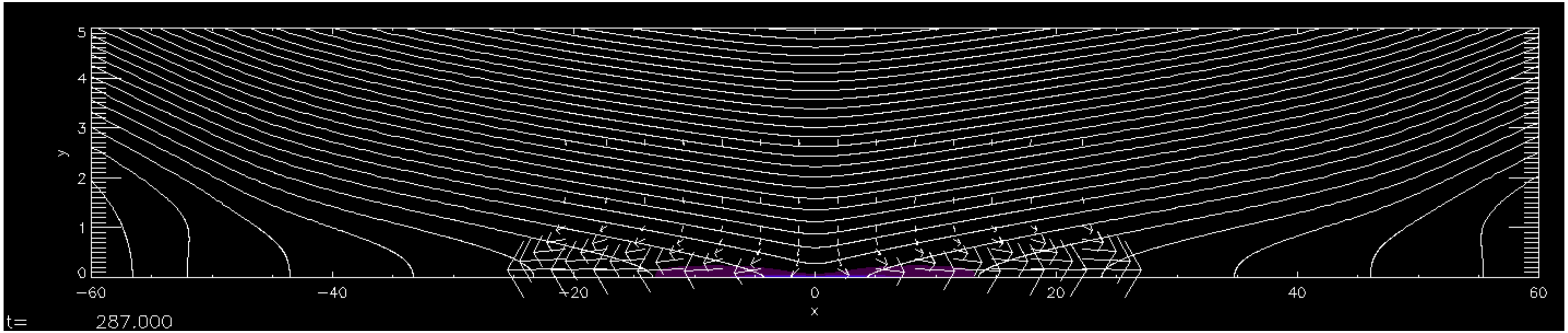


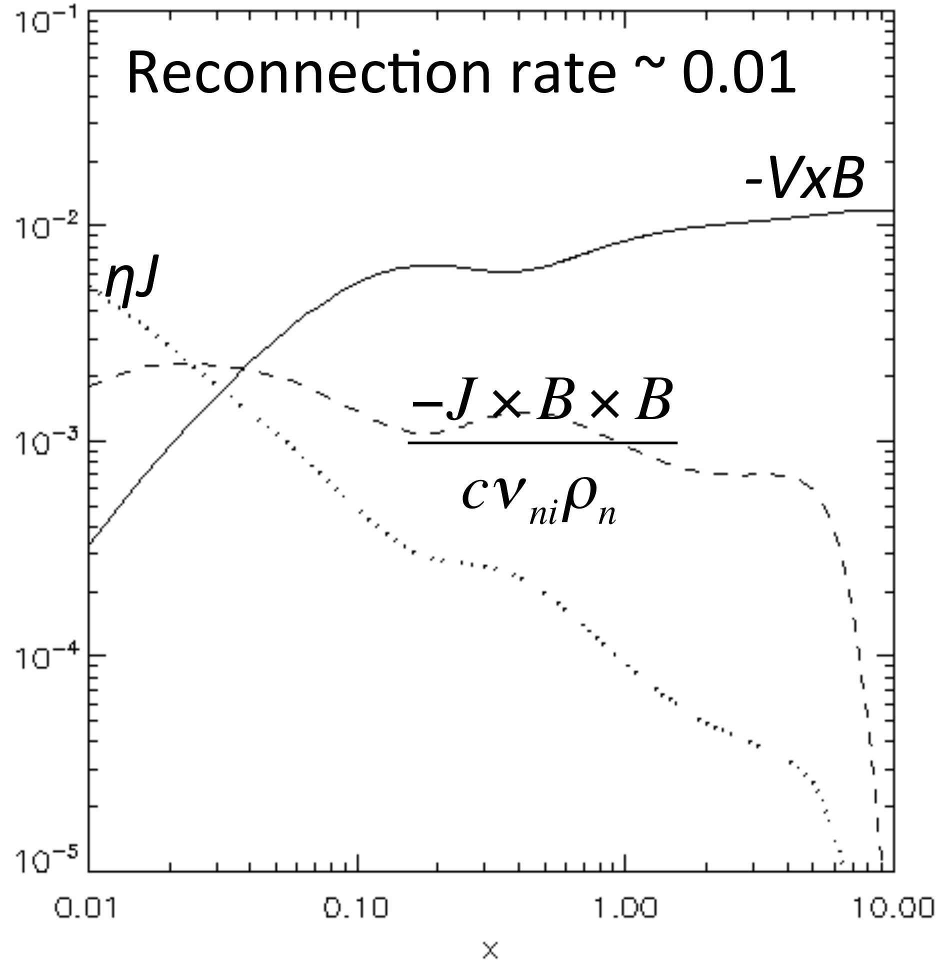
Petschek-like regime

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.

Can low atmospheric reconnection produces tall jets?

Available magnetic energy $B^2/8\pi \approx \varrho g h$ (potential energy)

$$\Rightarrow h \approx (B^2/8\pi)\,/\varrho g$$

$$\approx (B^2/8\pi)/\varrho RT*(RT/g)$$

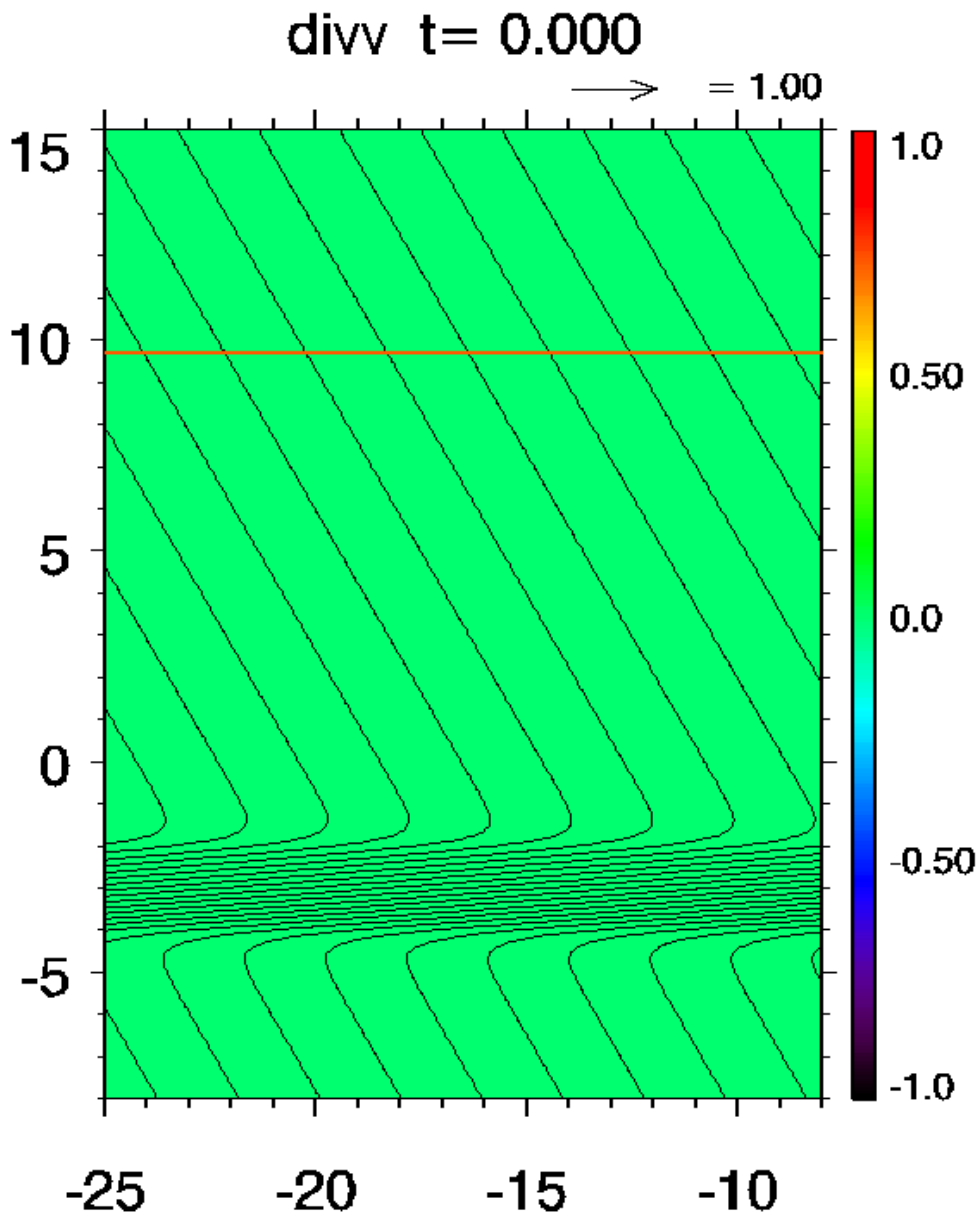
$$= H/\beta$$

(H: scale hight, β: plasma beta)

- If $\beta \approx 1$, reconnection jet (or any magnetic driver) can ascend only $H \approx$ 300 km.

- Needs a clever way to accelerate only a fraction plasma.

- Photospheric reconnection
- Upward slow mode wave
- Develop into shock due to stratification
- Hit transition region => jet



Takasao+ in prep

For Hinode/SDO/IRIS and beyond

- Role of plasmoids and slow shocks

- Diagnostics of non-MHD processes

- Reconnection in partially ionized, collisional plasma
  - also important in molecular clouds and protoplanetary disks
  - ALMA may get close to diffusion scale (~10km) in chromospheric reconnection! (See Shimojo's poster)