

Magnetic reconnection in partially ionized plasmas and its effect in heating of the atmosphere

Hiroaki Isobe (Kyoto University)

Collaborators:

K.A.P. Singh (Centre for Excellence in Basic Sciences Mumbai)

V. Krishan (Indian Institute of Astrophysics)

K. Shibata (Kyoto University)

N. Nakamura (Kyoto University)

CONGRATULATIONS !!!

to

Professor Durgesh Tripathi

on being promoted to

Associate Professor (Scientist-F)

07.11.2014

Ajit Kembhavi

Director

(on behalf of the IUCAA family)

Large amplitude oscillation of a polar crown filament in the pre-eruption phase

H. Isobe^{1,2} and D. Tripathi¹

On the propagation of brightening after filament/prominence eruptions, as seen by SoHO-EIT[★]

D. Tripathi¹, H. Isobe^{1,2}, and H. E. Mason¹

Isobe & Tripathi 2006 A&A

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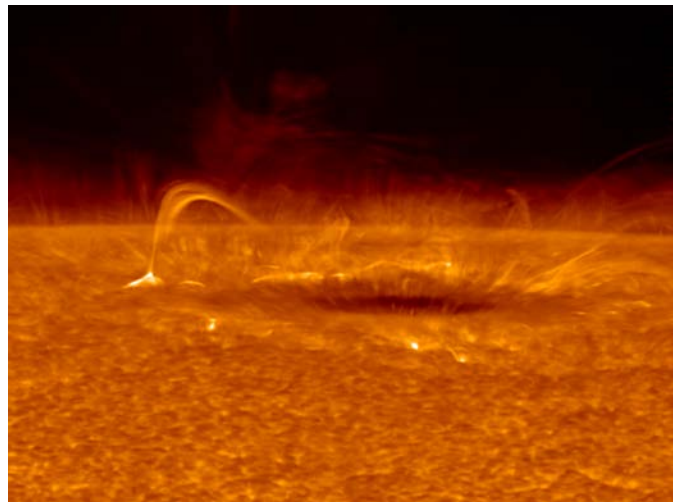
Tripathi, Isobe & Mason 2006 A&A

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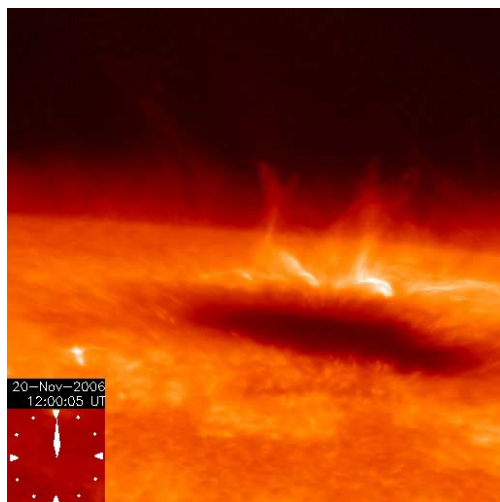
Hopefully a good pub in IUCAA campus in near future...

Reconnection-associated phenomena in lower atmosphere

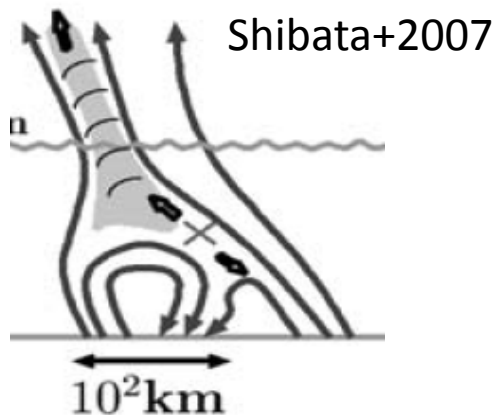
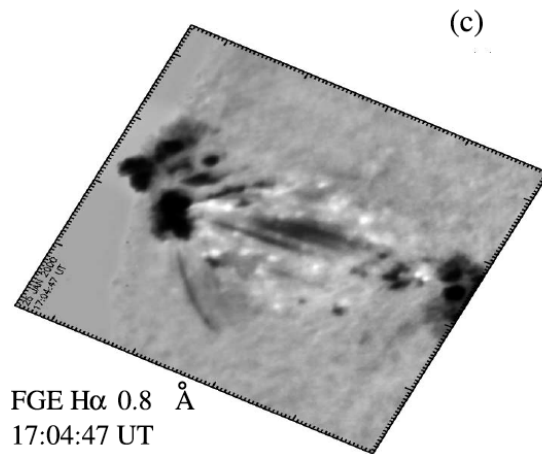
“anemone” or inverse-Y jets



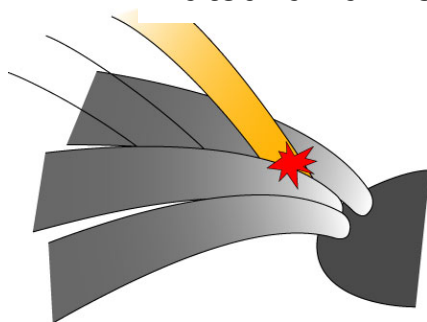
penumbra jets



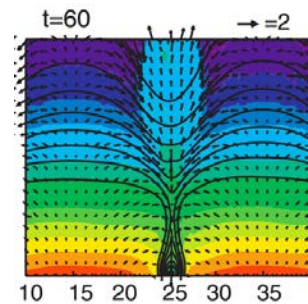
Ellerman bombs



Katsukawa+2007



Georgoulis+2002



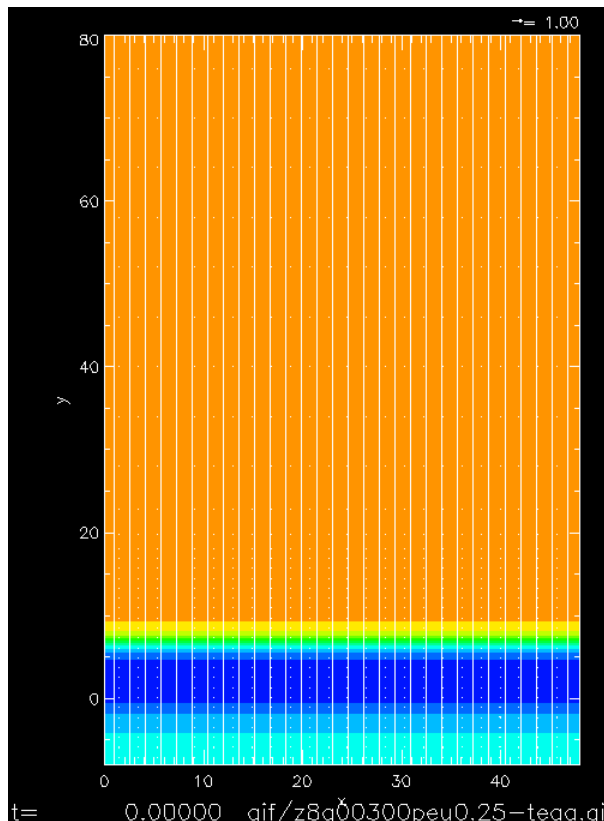
Isobe, Tripathi, Archontis 2007

- And hot (10^5 K) plasma in EB-like events discovered by IRIS (Peter+2014)
- and surges, cancellation, fast spicules...

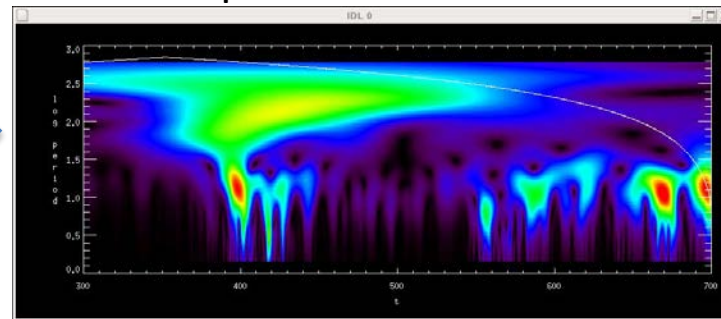
Effects on atmospheric heating (and wind acceleration)

- Local heating in chromosphere (probably not a dominant contribution)
- Emit high-frequency wave to corona
=> easier dissipation by e.g., ion-cyclotron resonance

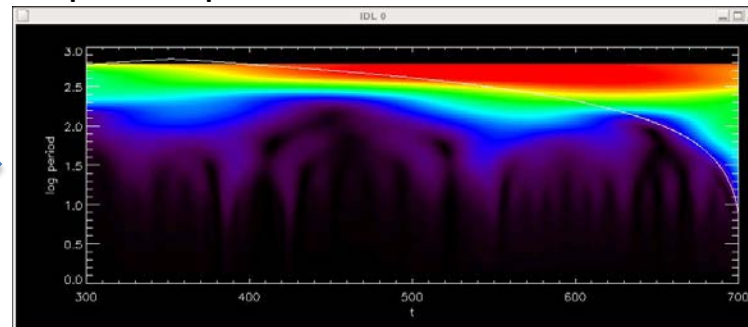
HI, Proctor, Weiss 2008



Wavelet spectrum of V_x in corona

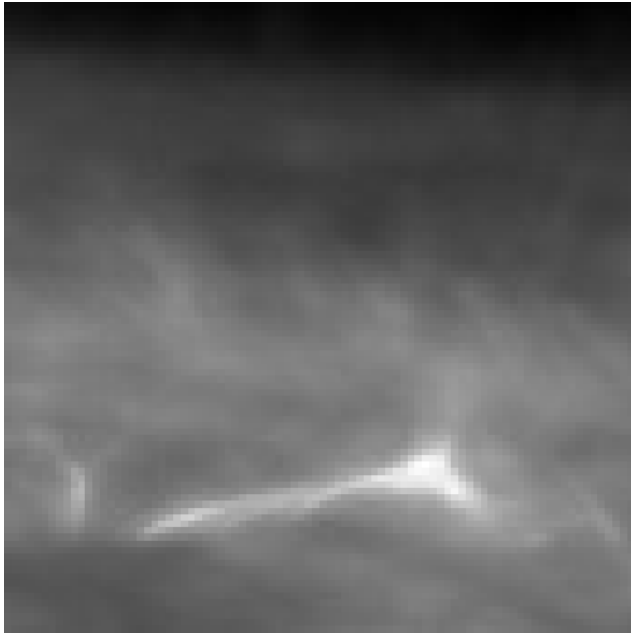


In photosphere

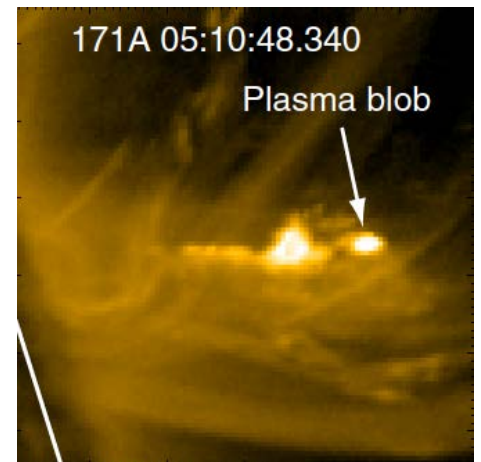
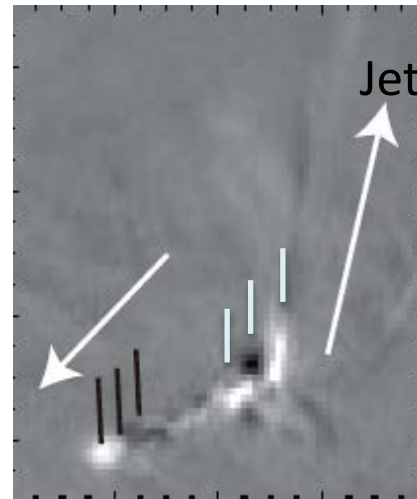
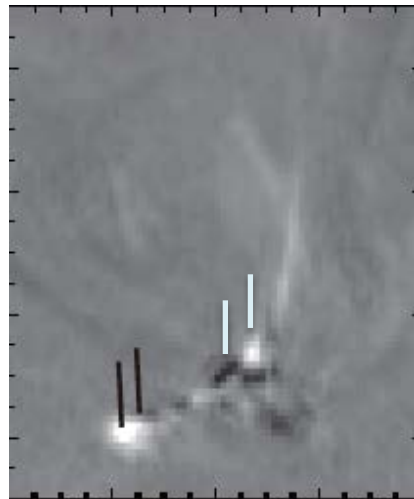
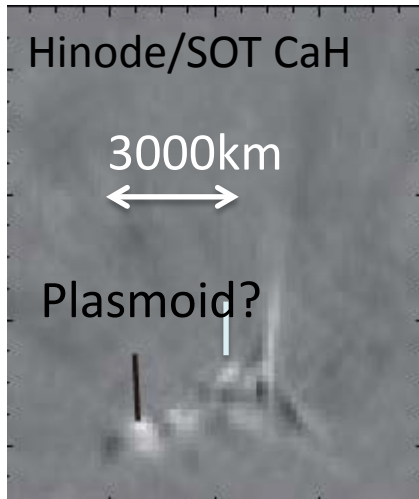


Modes and spectra of emitted waves depend on the detail of reconnection process.

Chromospheric reconnection similar to corona in that:



- Intermittent and bursty
- bright blobs (plasmoids?) ejection
 - ✓ Size 200-1000km
 - ✓ Velocity 10-50 km/s



Singh, HI, Nishizuka et al. 2012

Takasao, Asai, HI, Shibata 2012

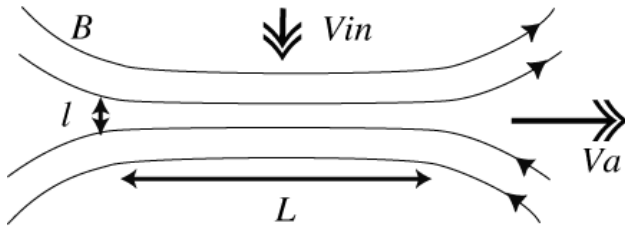
MHD reconnection theory

$S = LV_A/\eta$: Lundquist number

Key: diffusion region structure

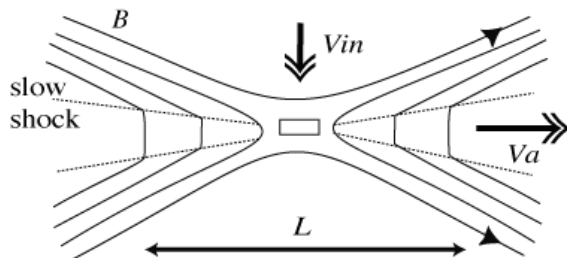
Sweet-Parker type

- Elongated diffusion region
- Slow. $V_{in}/V_A \sim l/L \sim S^{-1/2} \llll 1$
- Uniform resistivity



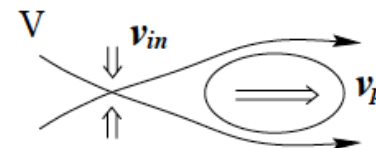
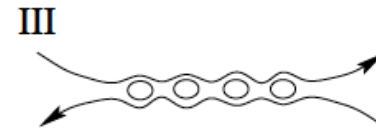
Petschek type

- Localized diffusion region and slow shocks
- Fast. $V_{in}/V_A \sim \pi/8 \ln S \sim 0.01 - 0.1$
- Anomalous resistivity, Hall effect

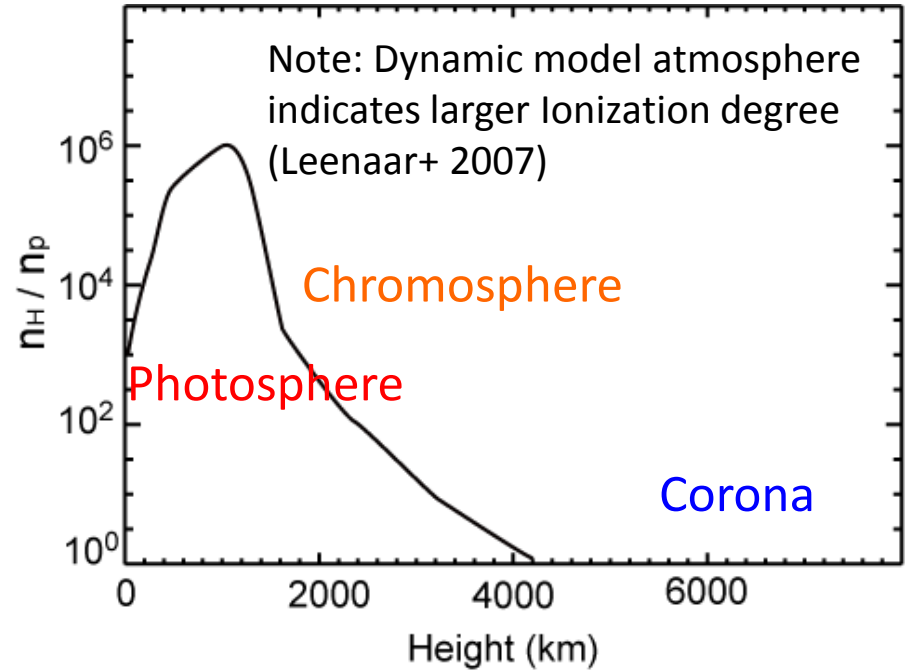
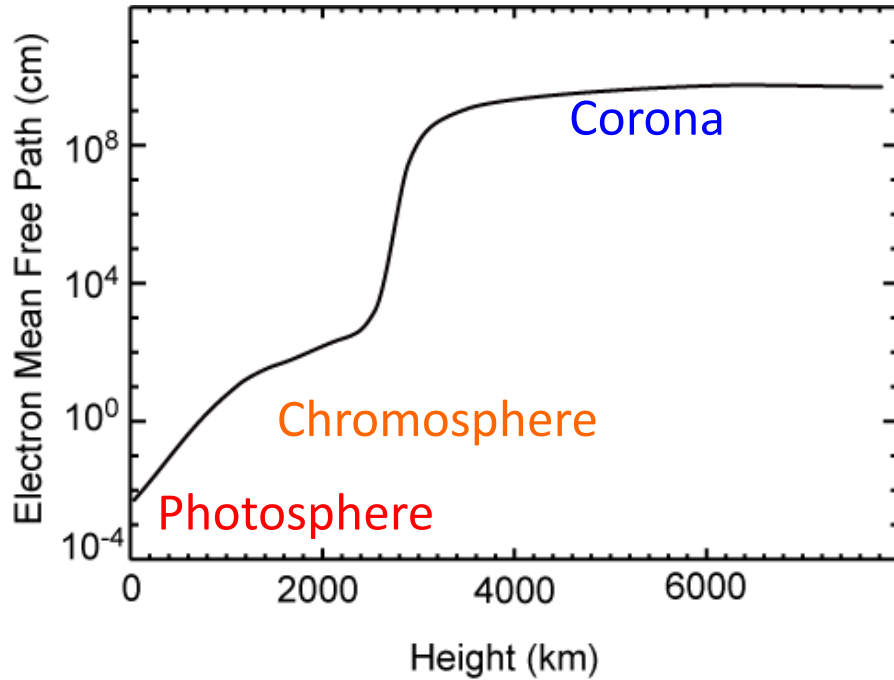


Plasmoid type

- Multiple plasmoids by tearing
- Fast $V_{in}/V_A \sim 0.01 - 0.1$ but **intermittent**
- May occur even with uniform resistivity if $S > 10^4$



BUT plasma parameters are very different



- Lower atmosphere is collisional and partially ionized
- Because of strong collisional coupling, one-fluid MHD is still good approximation for many (not all) problems.

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

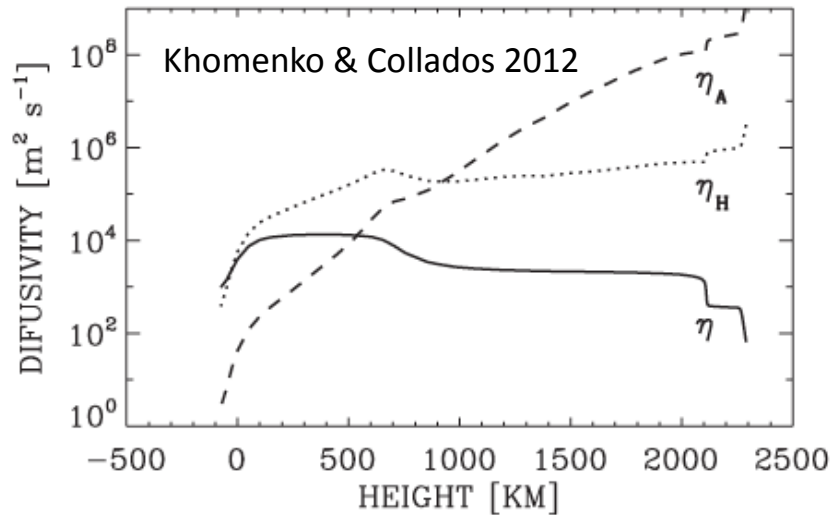
$$V_n - V_i \approx \frac{B^2}{4\pi L \nu_{ni} \rho_n} \approx 100 \left(\frac{V_A}{10 \text{ km/s}} \right)^2 \left(\frac{L}{100 \text{ km}} \right)^{-1} \left(\frac{\nu_{ni}}{10^3 \text{ Hz}} \right)^{-1} \text{ cm/s}$$

Induction equation

*also called Perderson resistivity

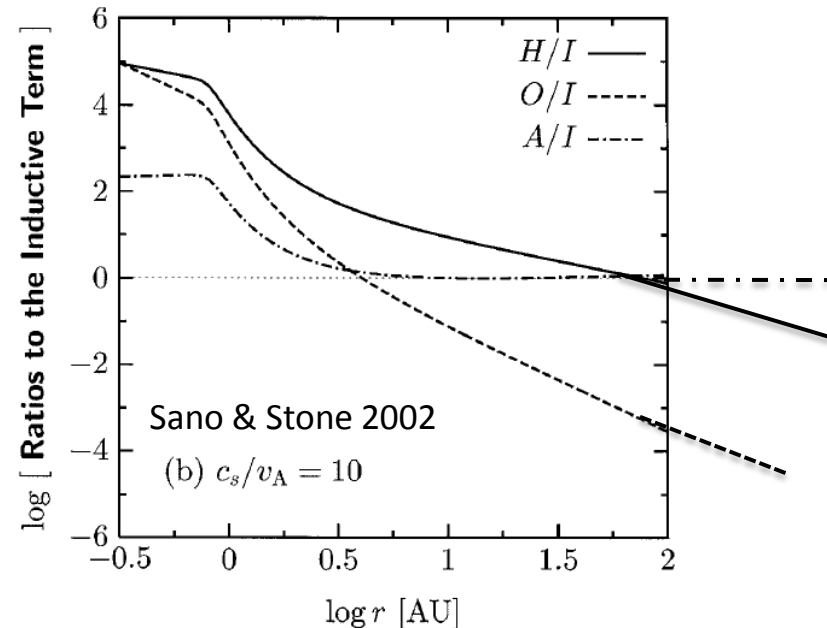
$$\frac{\partial B}{\partial t} = \nabla \times \left[\overset{\text{Advection}}{V_n \times B} - \overset{\text{Hall}}{\frac{J \times B}{en_e}} + \overset{\text{Ambipolar*}}{\frac{(J \times B) \times B}{c\nu_{ni}\rho_n}} - \overset{\text{Ohmic}}{\eta J} \right]$$

Solar atmosphere



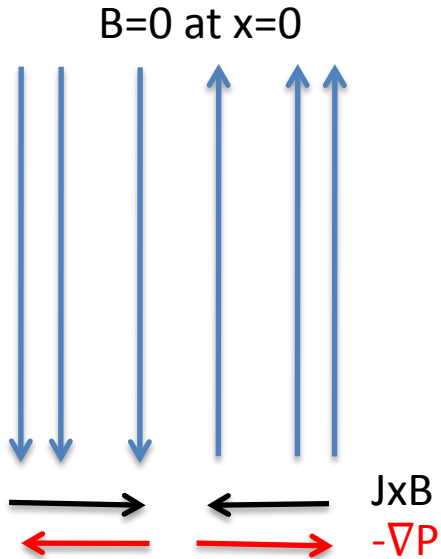
Photosphere-low chromosphere: Hall dominant
 Mid-upper chromosphere: Ambipolar dominant

Protoplanetary disk



Inner disk: photosphere-like
 Outer disk/molecular cloud:
 chromosphere-like

Neutral effects in current sheets



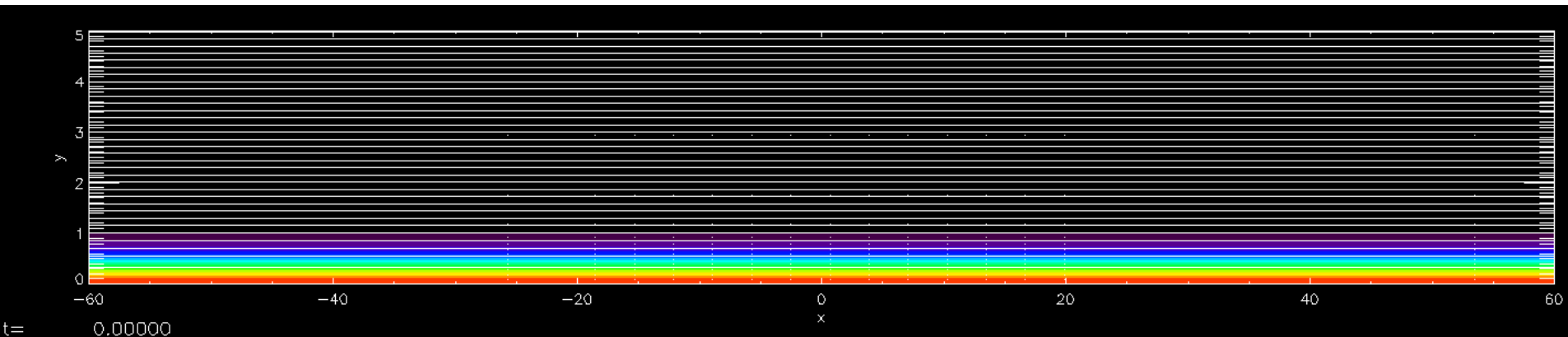
$$\begin{aligned} \frac{\partial B}{\partial t} &= \nabla \times \left[V_n \times B - \frac{J \times B}{en_e} + \frac{(J \times B) \times B}{cv_{ni}\rho_n} - \eta J \right] \\ &= \nabla \times \left[V_n \times B + V_{Hall} \times B + V_{amb} \times B - \eta J \right] \end{aligned}$$

- Hall effect bent B to in the direction of $-\mathbf{J}$
- Ambipolar diffusion transport B to the direction of $\mathbf{J} \times \mathbf{B}$

- In a current sheet, Ambipolar diffusion transports B inward
=> **current sheet thinning** (Brandenburg & Zweibel 1994)
- Physical picture: neutrals diffuse across the magnetic field and escape from the current sheet, thus reducing the gas pressure that support the Harris-type current sheet
- Less effective in the presence of a guide field

Effect of non-uniform ambipolar diffusion

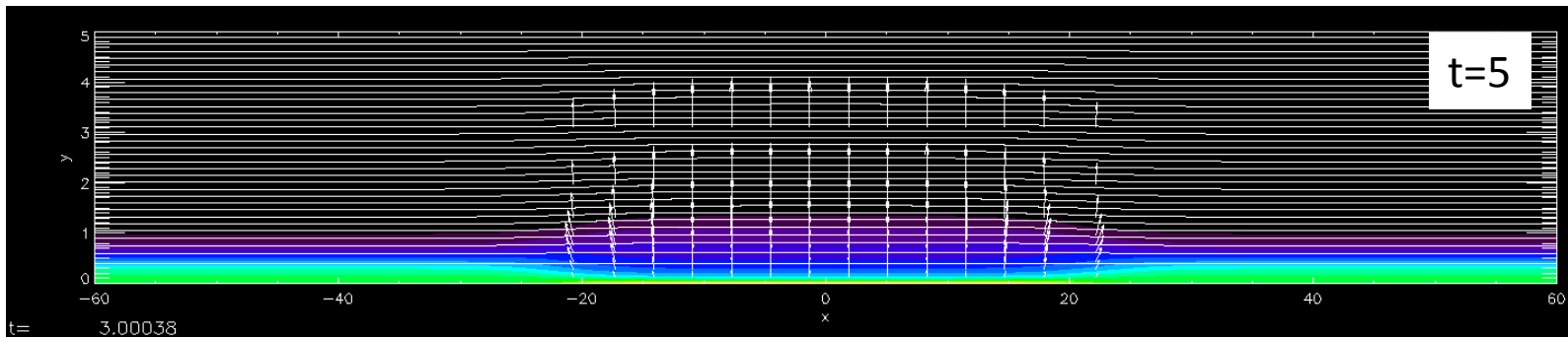
- 2D MHD simulation with uniform resistivity and non-uniform ambipolar diffusion
- No Hall effect, no guide field



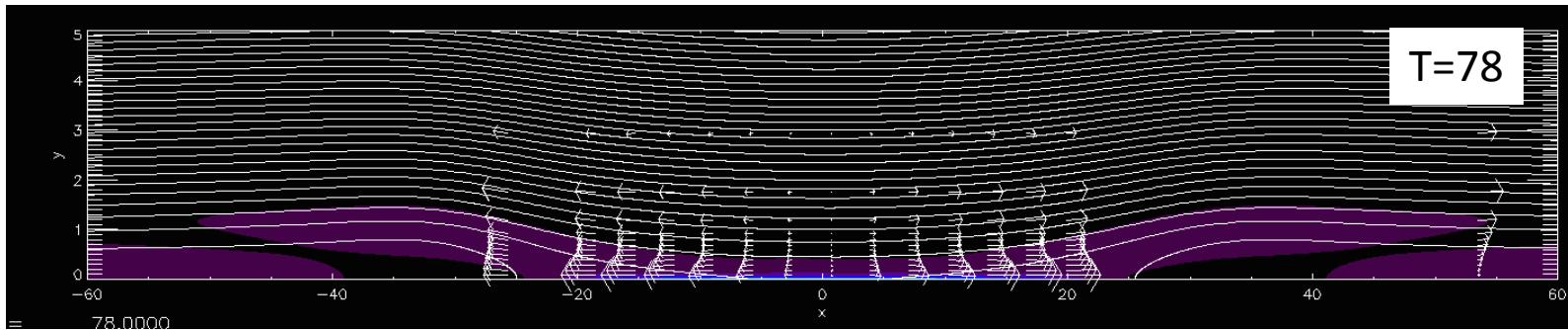
←→
Ambipolar diffusion $\neq 0$

Ambipolar diffusion localized in $x < \pm 20$ (gaussian shape)
Ohmic resistivity is uniform

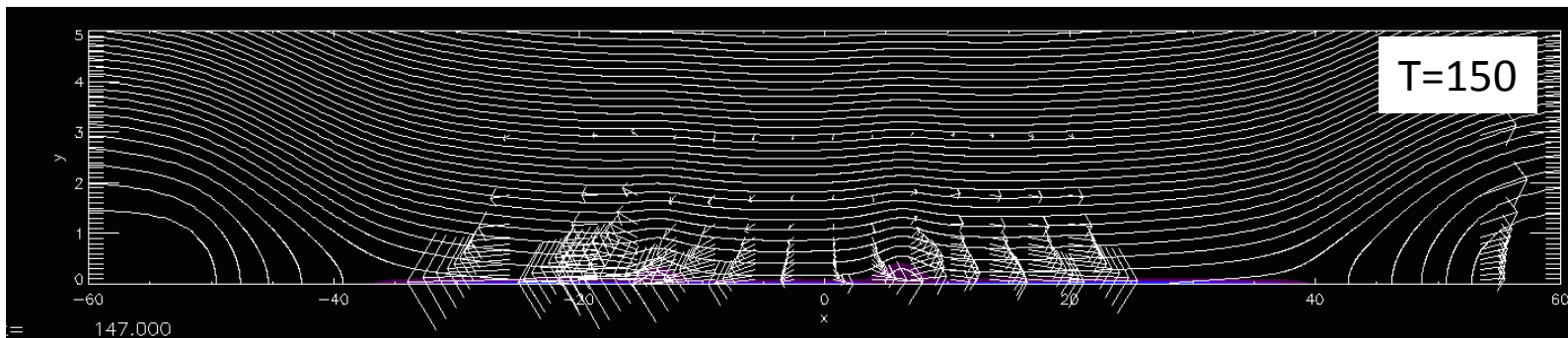
Thinning



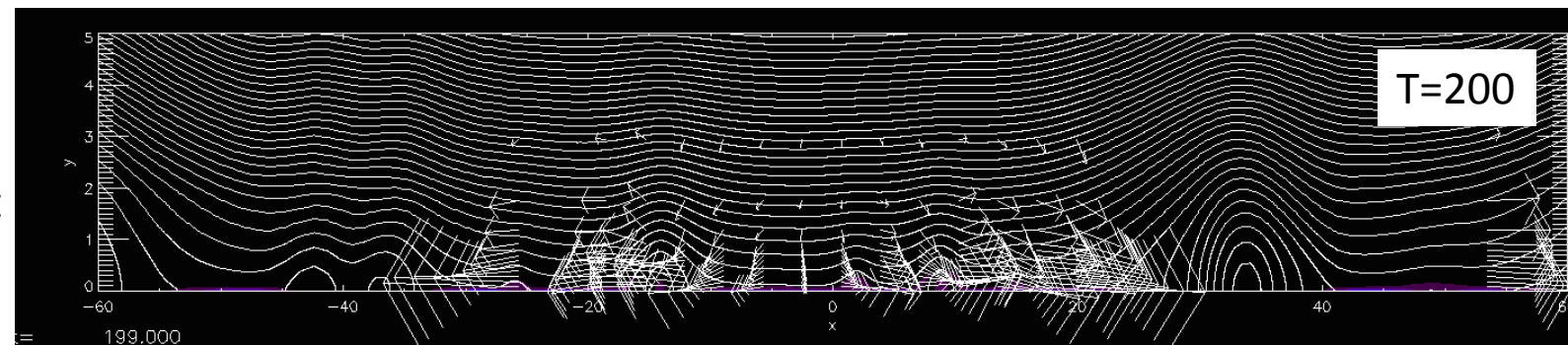
Sweet
-Parker
reconnection



Tearing and
island
formation

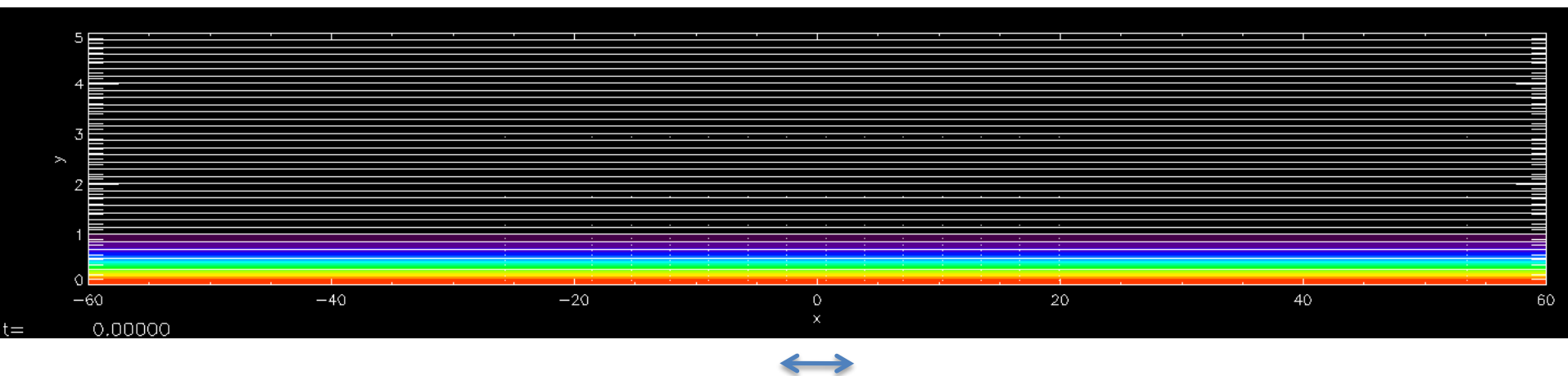


Island ejection
and time-
dependent fast
reconnection

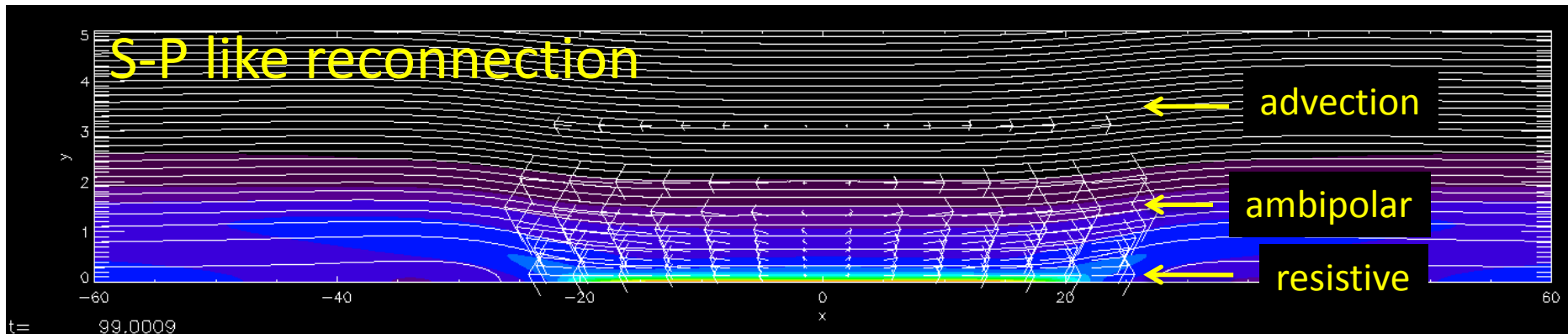


Petschek-like regime

color: current density



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

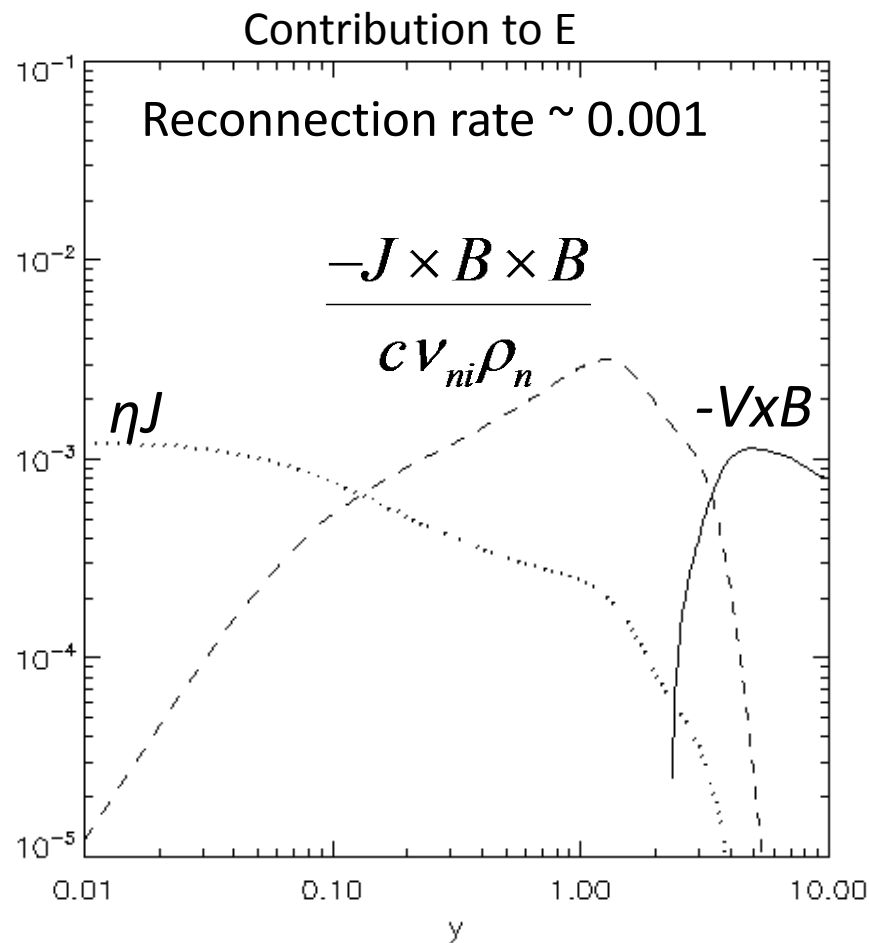


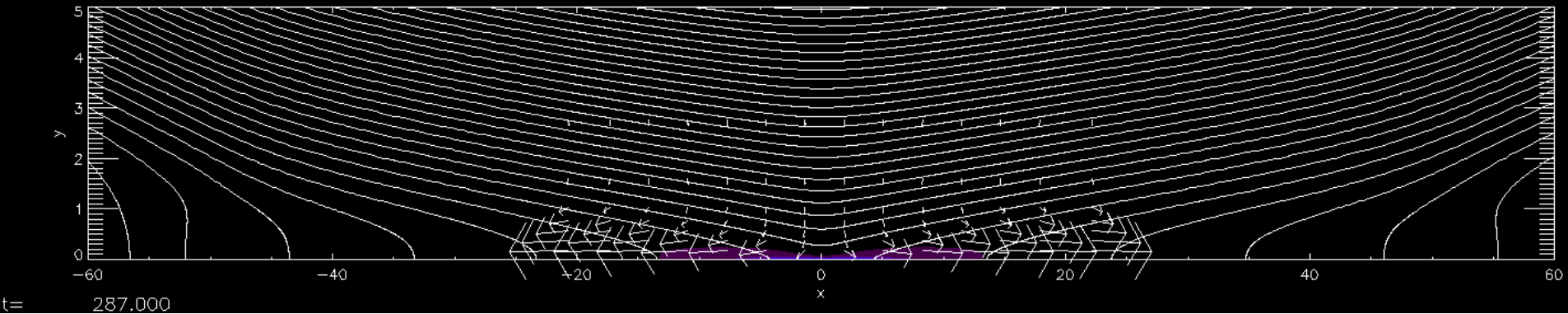
In Sweet-Paker-like stage, the reconnection region consists of **3 layers**:

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

Ambipolar diffusion causes plasma heating
 \Rightarrow 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

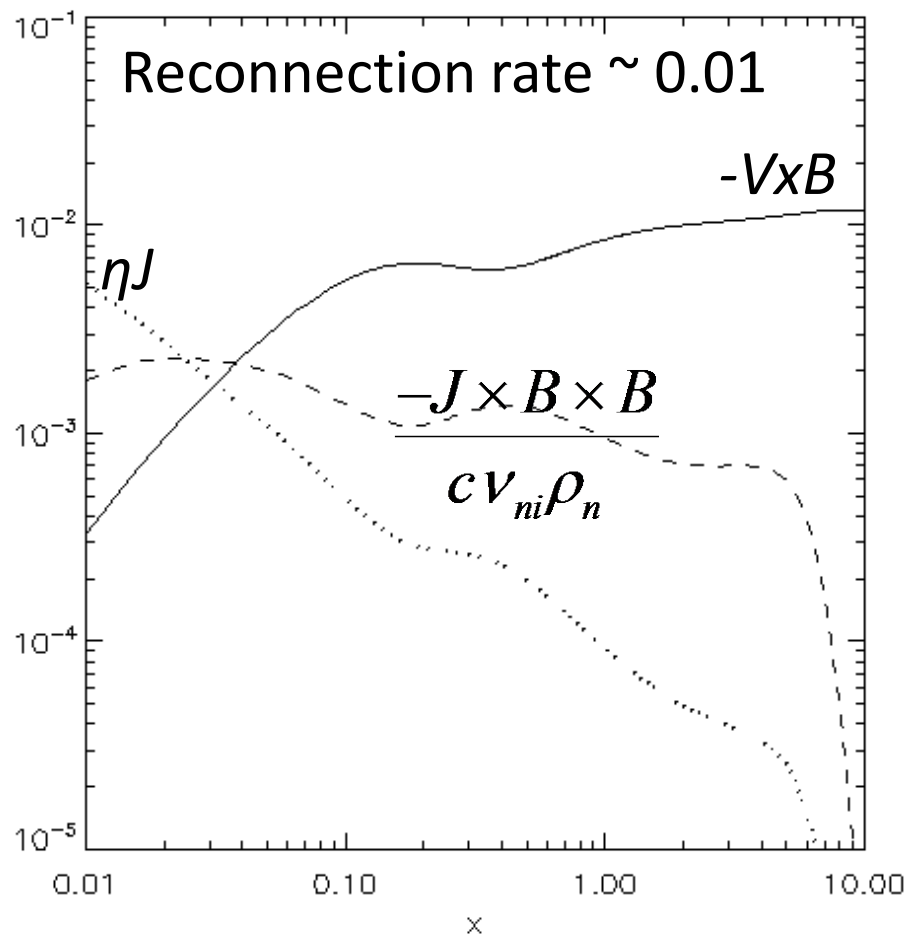




Even though the resistivity is uniform, the localization of ambipolar diffusion causes local thinning of the current sheet, leading to Petschek-like fast reconnection

The “ambipolar layer” almost disappears.

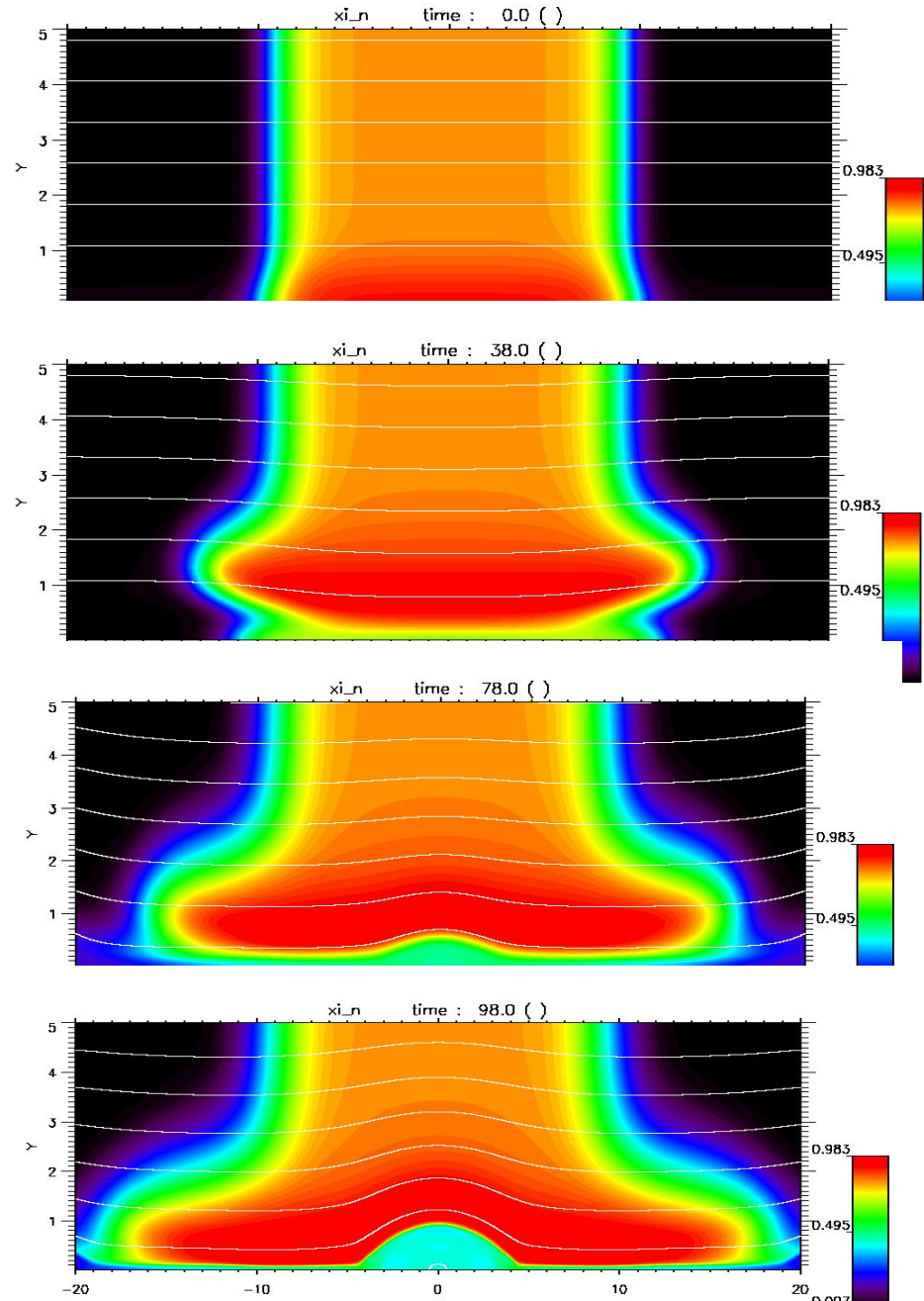
Inhomogeneity of ambipolar diffusion (due to inhomogeneous ionization etc) controls the structure of diffusion region and hence reconnection rate



Two fluid simulation (Nakamura)

- Common with 1-fluid+ambipolar
 - Current sheet thinning due to the escape of neutrals
 - Field-aligned neutral outflow driven by frictional heating
- Two-fluid effect
 - Current sheet and plasmoid becomes ion-dominant
- Recombination can contribute significantly for removing ion from diffusion region (Leake+2012)

Color: Neutral fraction



Probing diffusion region



ALMA looking at the Sun (look at the position of the shadow!)
from M. Shimojo's talk @ ALMA Solar Obs WS

- Ambipolar / Hall scale in chromo / photosphere is $\approx 1\text{km}$
- Highest resolution by ALMA $\sim 0.005'' \sim 3.5\text{km}$ @ 950GHz
- (But due to technical restrictions, highest frequency / longest baseline still not available for solar observation...)
- **Combination of ALMA and other spectropolarimetric obs (Hinode, IRIS, DKIST, Solar-C) may allow us to observe the global and diffusion scales simultaneously.**

Summary

- Inhomogeneity of neutral drift (ambipolar diffusion), due to inhomogeneous density, ionization and possibly the guide field, determines the structure of the reconnection region and hence the reconnection rate
- Outflows are ion-dominant near the diffusion region (not sure in observable scale, though)
- Ionization/recombination in the current sheet suppress/enhance the thinning and hence reconnection rate
- Lower atmosphere of the sun is a perfect lab for partially ionized plasmas