Magnetic reconnection and associated plasma jets in the solar chromophere

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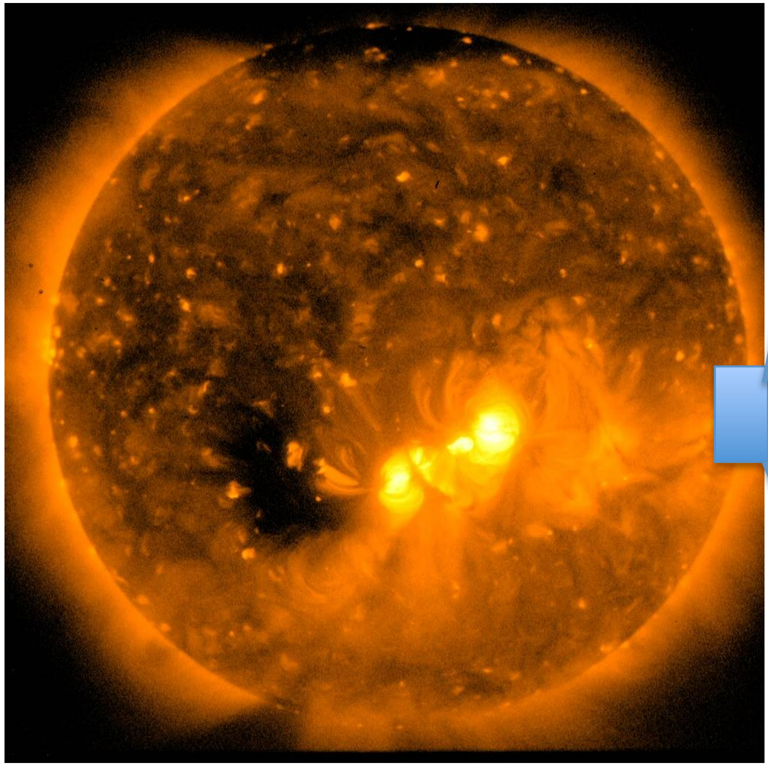
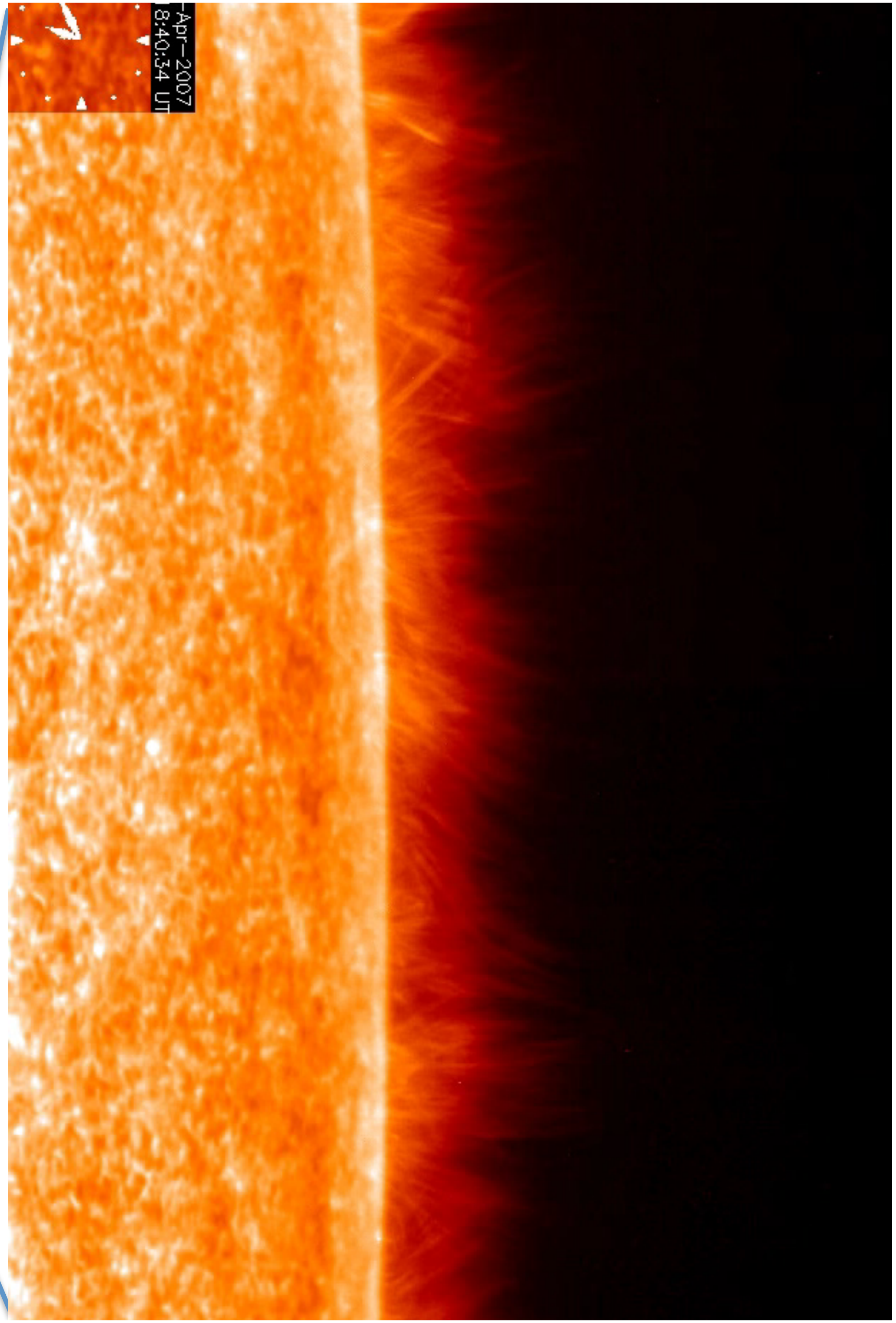
Chromosphere

- Thin (~5000km) layer between the visible surface (photosphere) and the corona
- Why interesting?

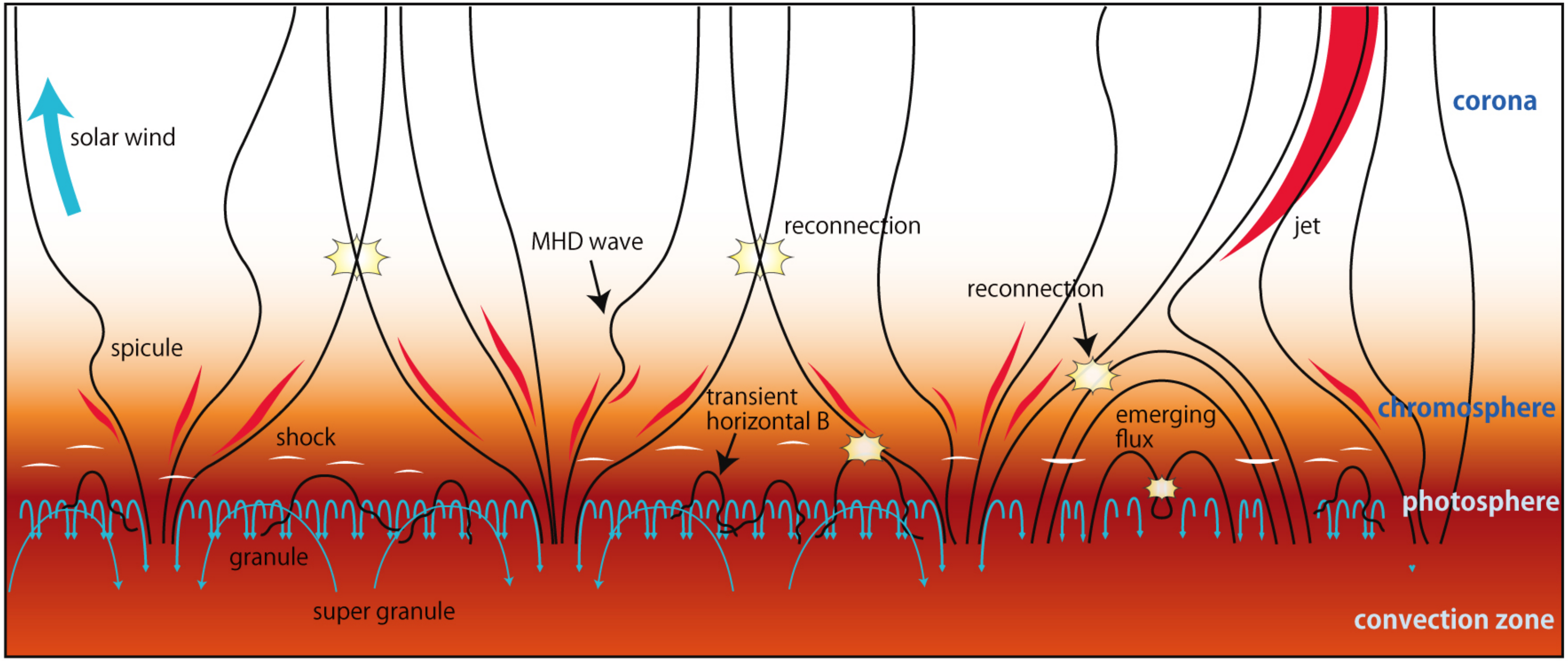


Soft X-ray (Hinode/XRT)



Chromosphere is interesting because:

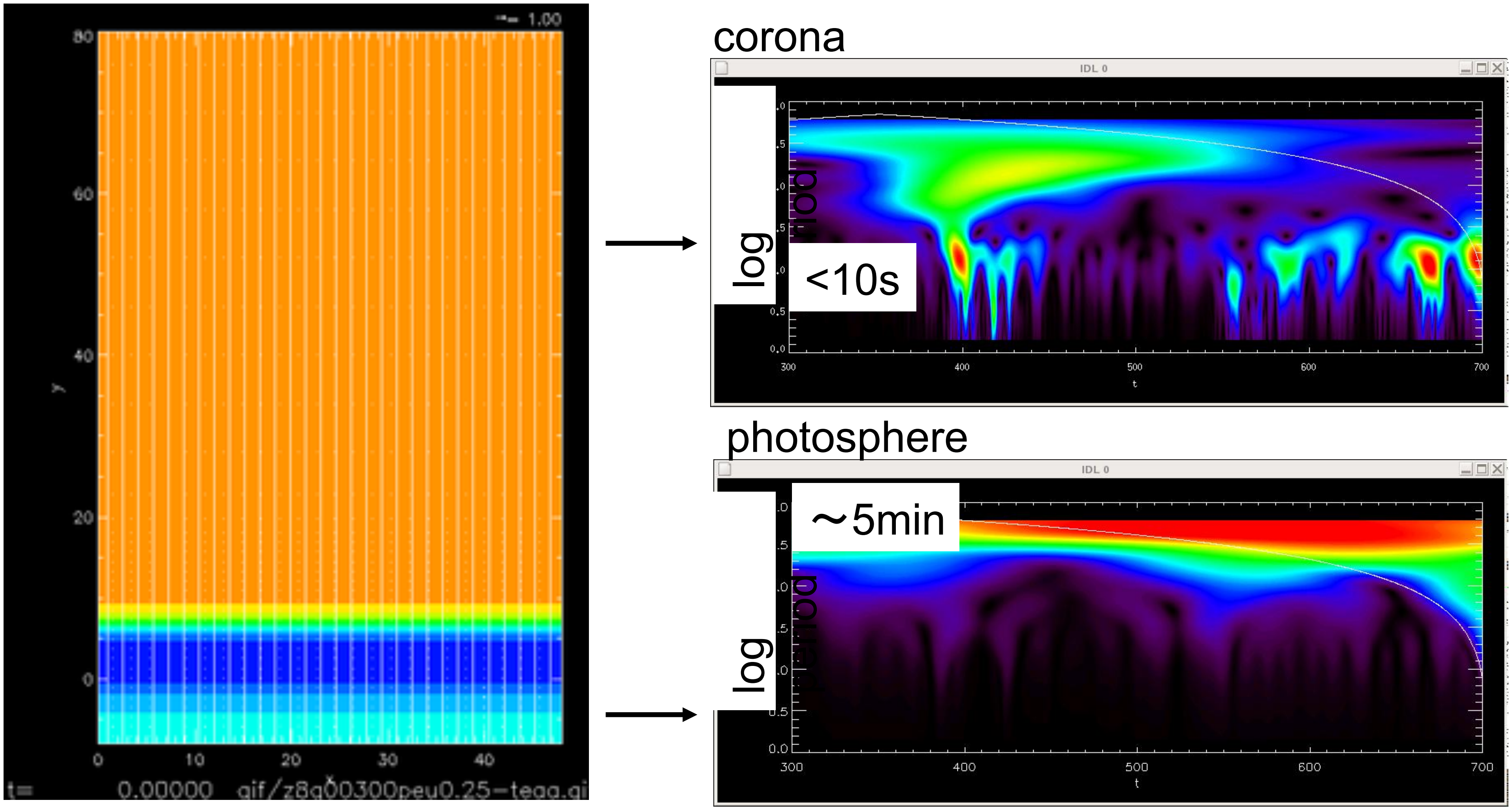
1. Physical parameters change drastically
   - Corona: $T=10^6$K, $n\sim10^9$cm^{-3}, $B\sim1\text{-}10^2$G, $\beta<<1$
   - Photosphere: T=6000K, n~1017cm-3, B~10-103G, $\beta>1$



2. Many things happening
   - reconnection, jets, waves, shocks...

Chromosphere is interesting because:

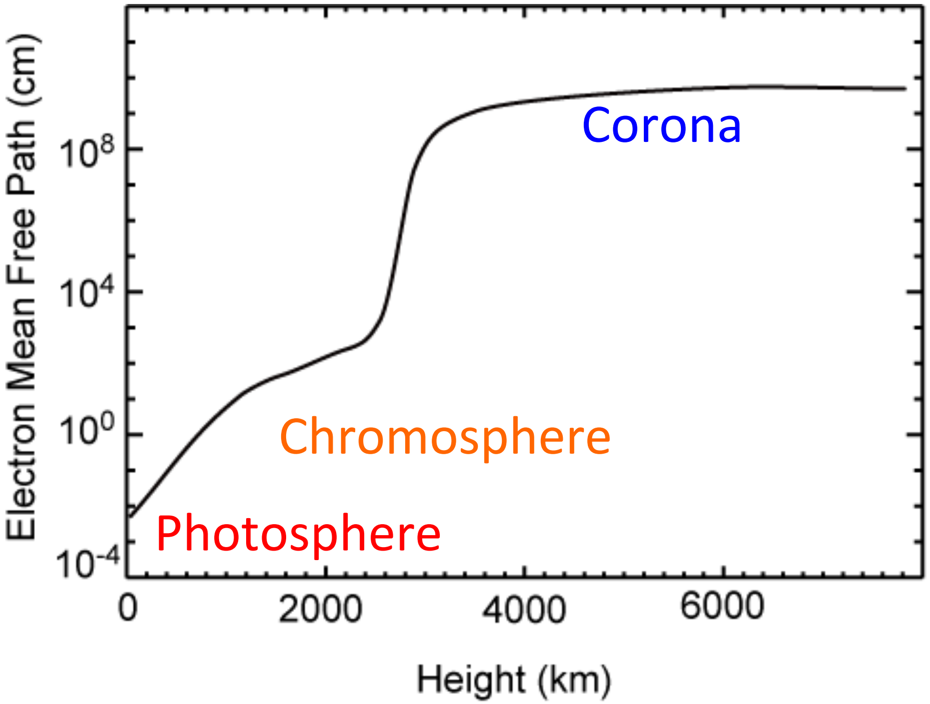
3. It regulates energy and mass flux to the corona
- e.g., high-frequency waves generated by chromospheric reconnection

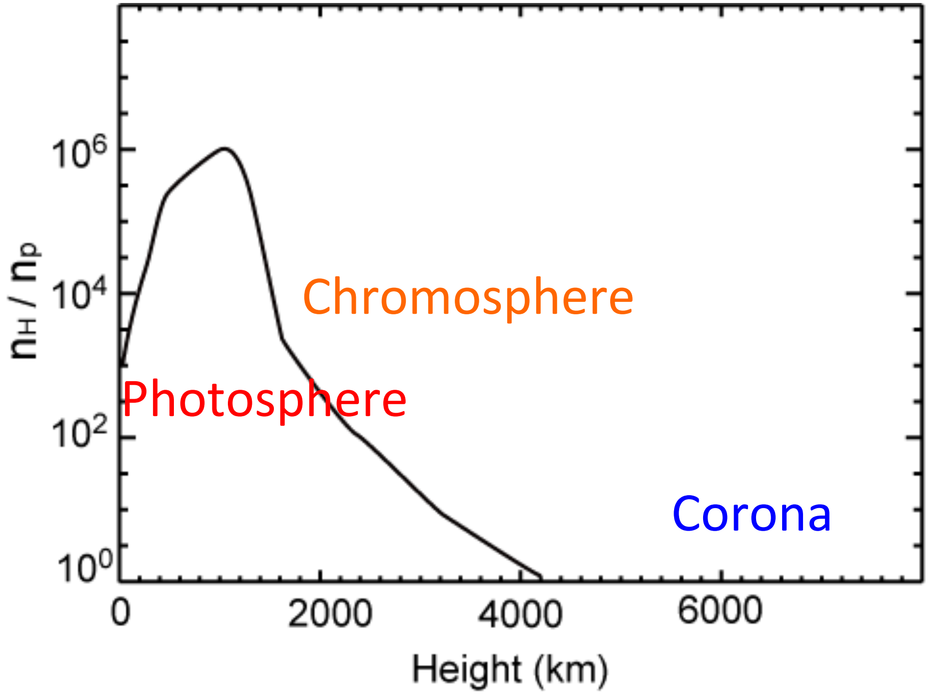


color: log Temperature

Isobe, Proctor, Weiss 2008

Chromosphere is collisional and partially ionized



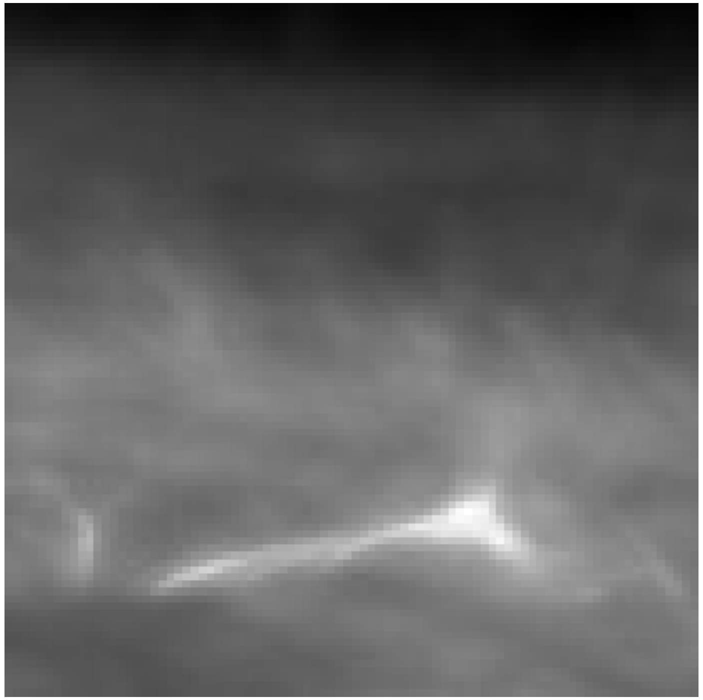


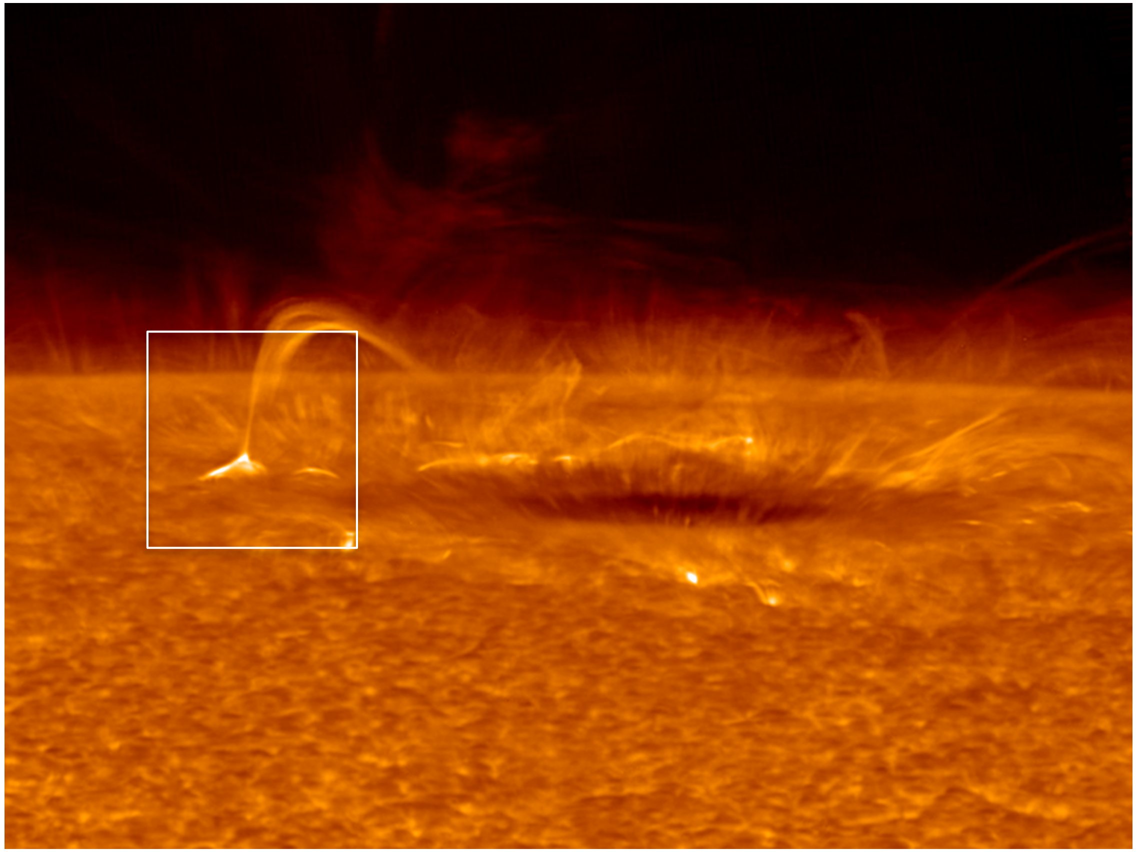
One-fluid MHD is still OK because of strong collisional coupling

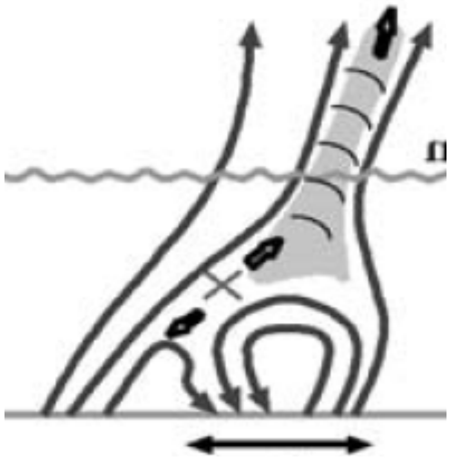
$$\nu_{ni}\rho_n\left(V_n - V_i\right) \approx \frac{J \times B}{c}$$

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

Chromospheric jets



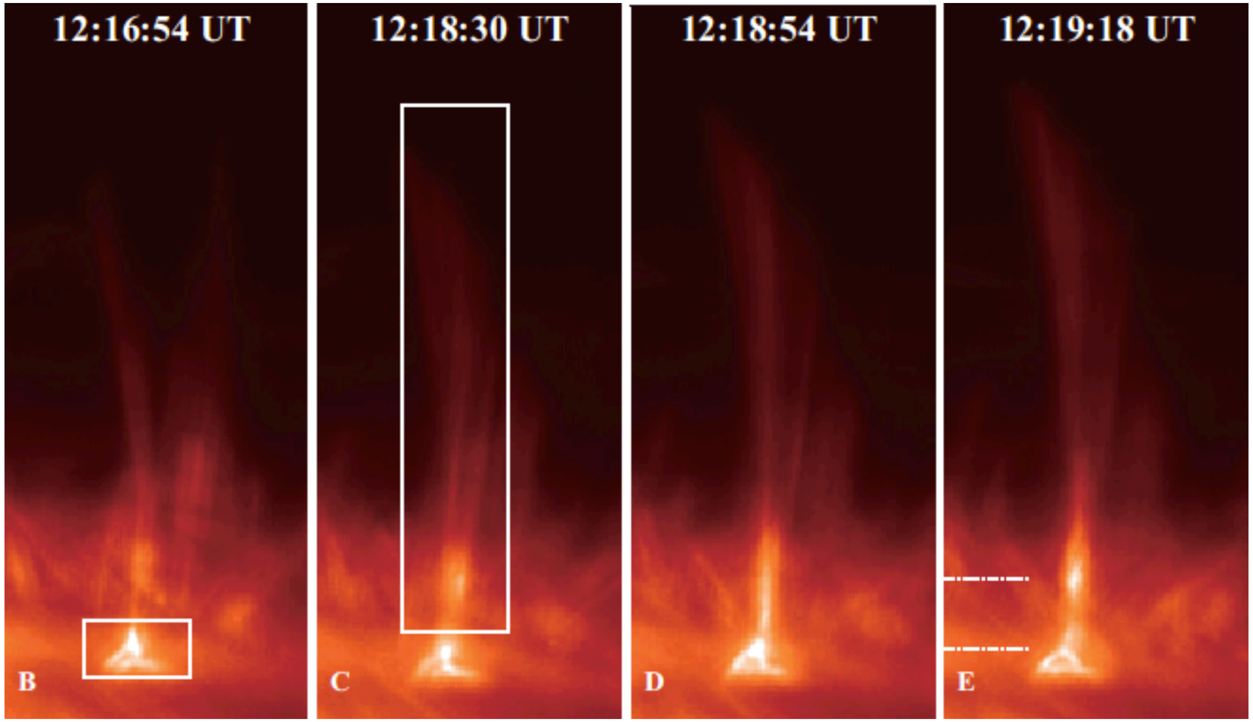




1000km

- Reconnection between small emerging loop and ambient field
- Ubiquitously found in the chromosphere
  (Shibata et al. 2007)

Problems in jets



1. Why that tall?
    - height ~10^4 km >> scale height ~300km
2. Reconnection physics?
    - Collisional
    - Weak ionization
    - $S = V_A L/\eta \sim 10^{5\text{-}6}$

The height problem

Available magnetic energy $B^2/8\pi \approx \varrho g h$ gravitational potentia

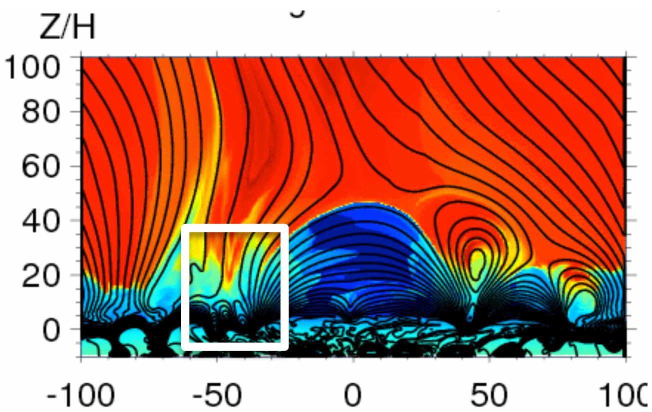
$$\Rightarrow h \approx (B^2/8\pi)/\varrho g$$

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

$$= H/\beta$$ (H: scale hight, β: plasma beta)

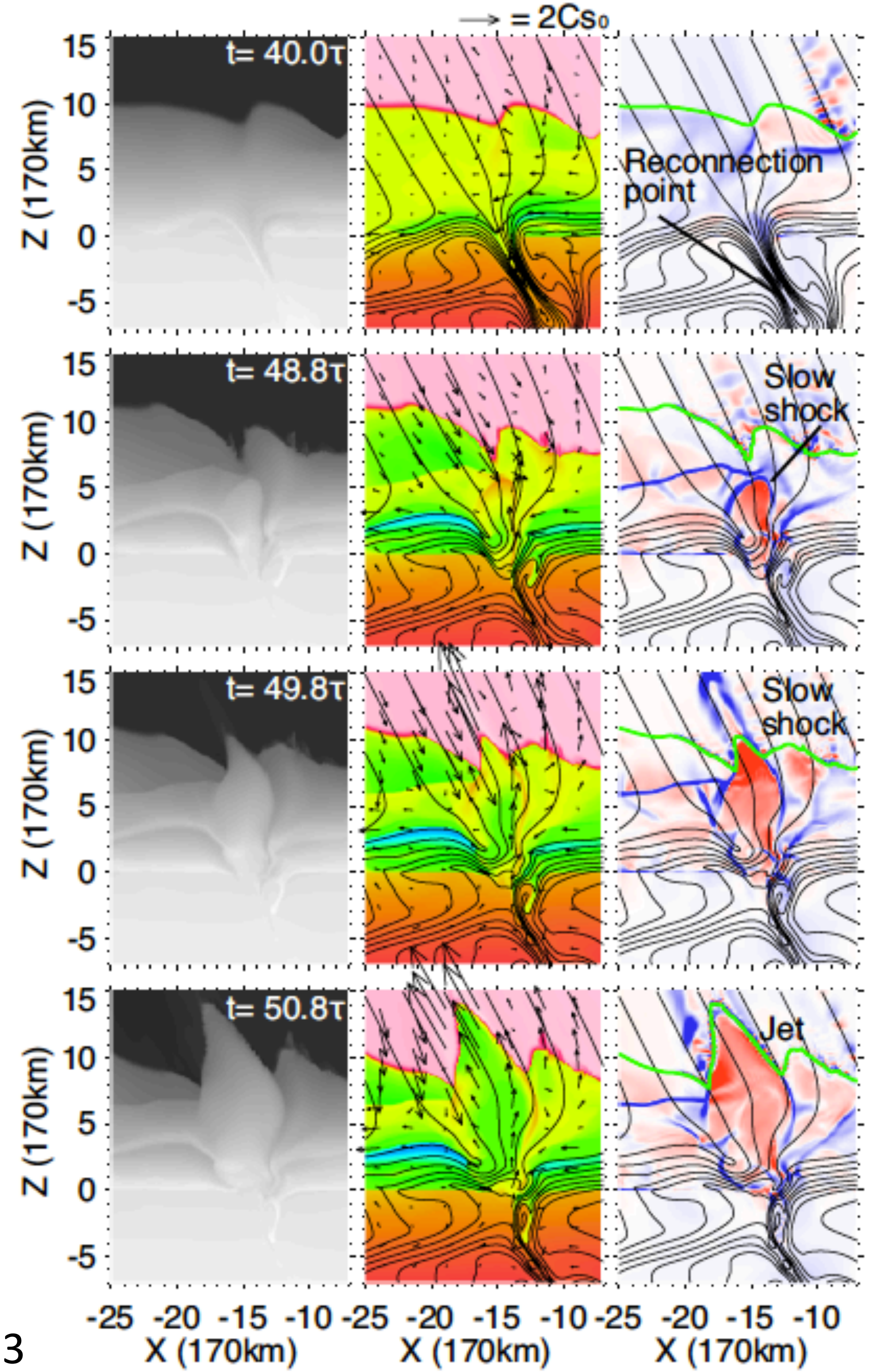
- If $\beta \approx 1$, magnetically driven jet can ascend only $H \approx$ 300 km << observed height (~10^4 km)
- OK if reconnection occur in upper chromosphere where $\beta \ll 1$

Solution: energy transport by MHD slow-mode wave



1. Reconnection in low chromosphere
2. Slow magnetoacoustic wave generated
3. Develop into shock as it propagates upward
4. Transport the energy upward
5. Collides with the transition region (contact discontinuity) and lifts it =>

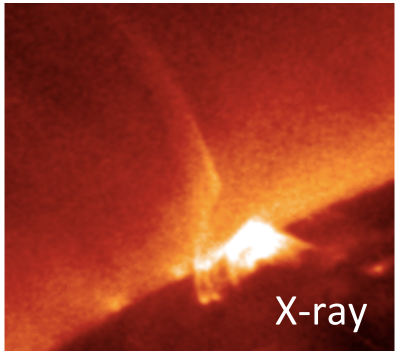
The physics is common to supernovae!



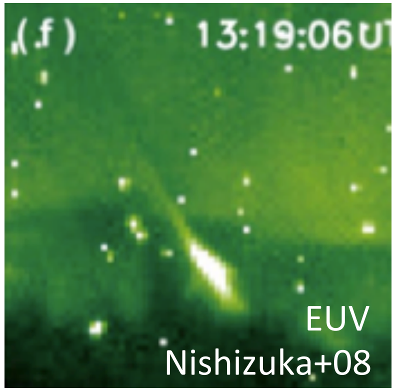
Takasao, Isobe, Shibata 2013

Reconnection and jets with similar morphology but different size and plasma parameters

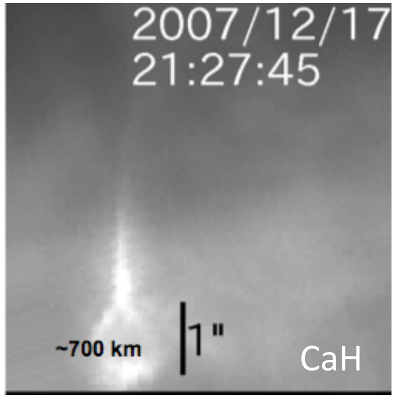
Corona
L ~ 100,000km
Collisionless, fully ionized

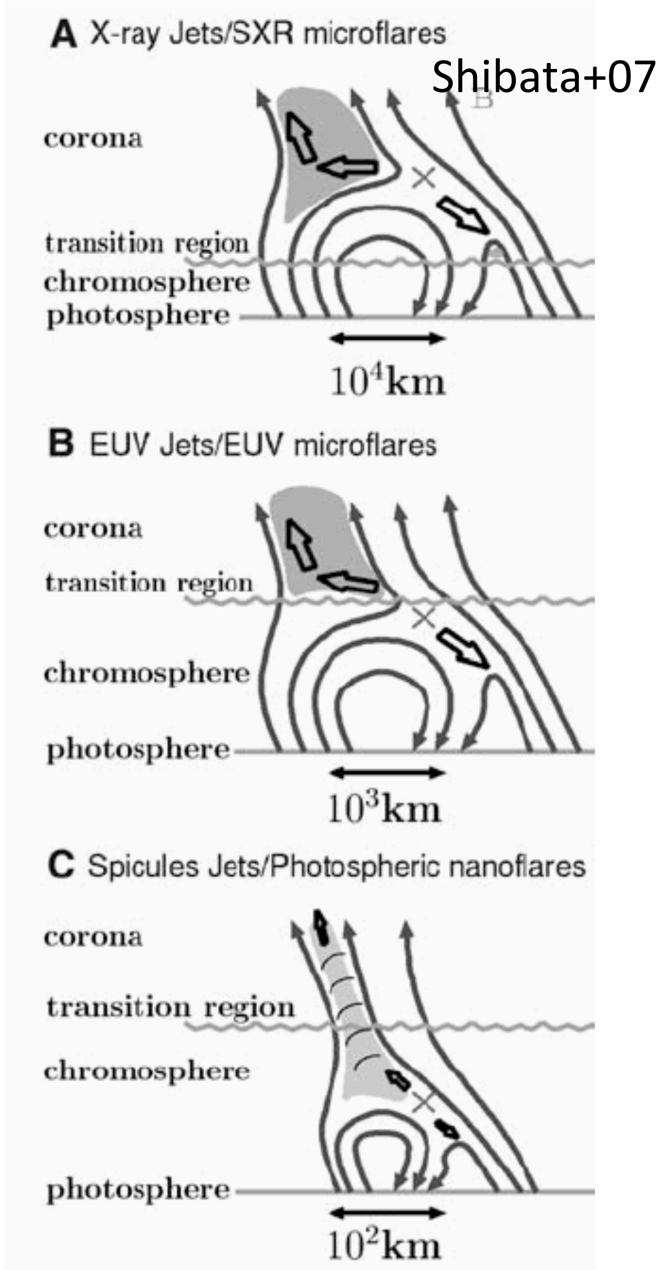


Upper chromosphere
- transition region
L ~ 10,000 km

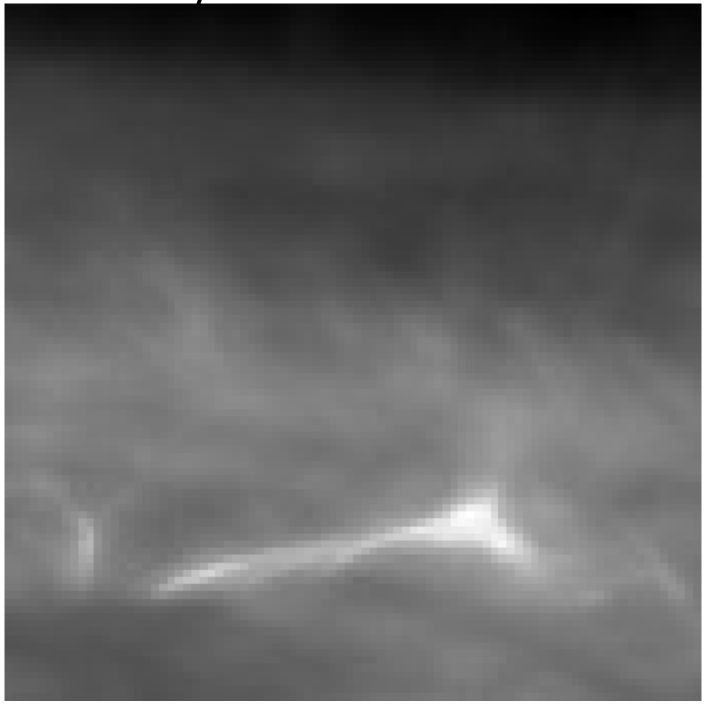


Lower chromosphere
L ~ 10,000 km
Collisional, weakly ionized





Hinode/SOT CaH

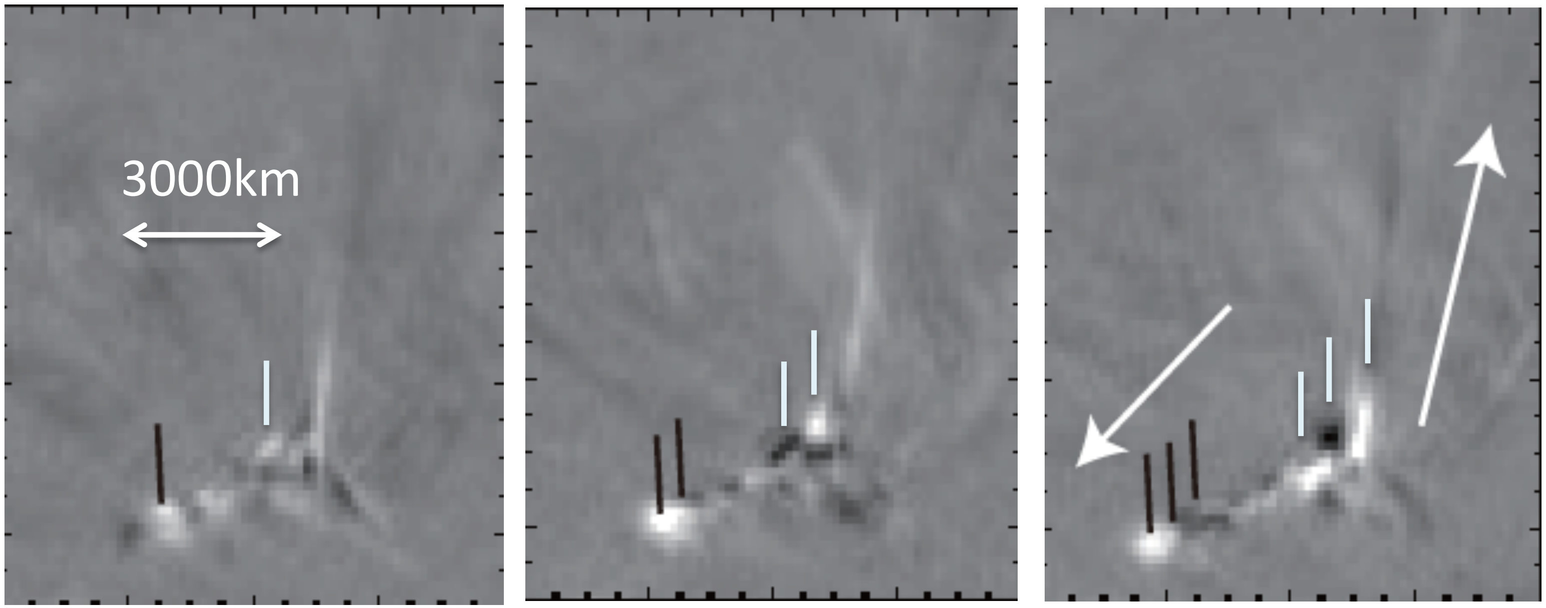


Multiple plasmoids in chromospheric reconnection

Bright blobs (plasmoids?) from reconnection region

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

Reconnection intermittent and bursty



Singh, HI, Nishizuka, Nishida, Shibata 2012 ApJ

Neutral effects

Advection | Hall | Ambipolar* | Ohmic

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

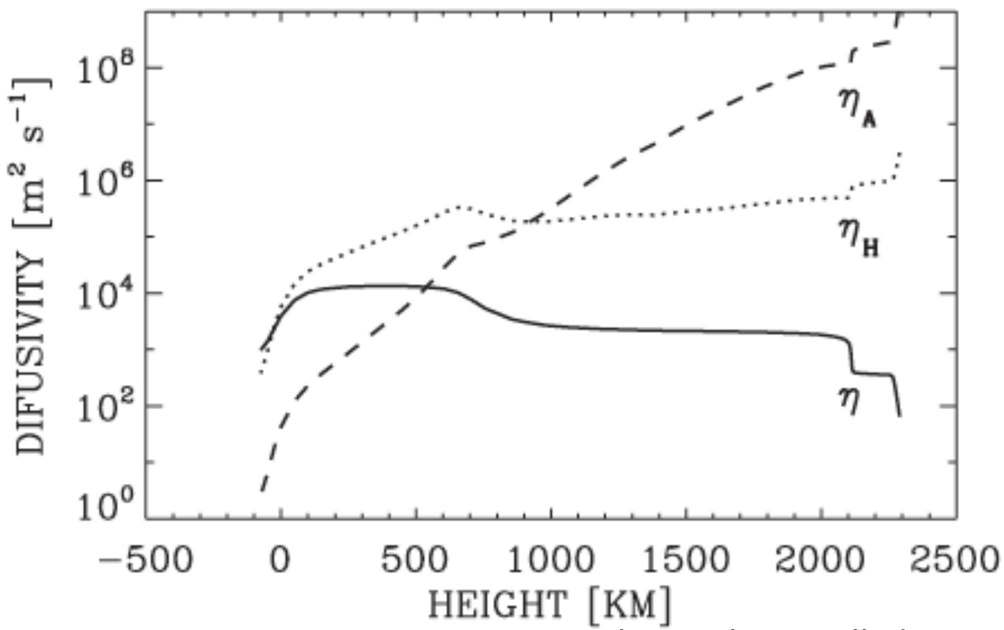
*Essentially same as Cowling/Perderson resistivity

Ambipolar/Hall is important in small scale

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

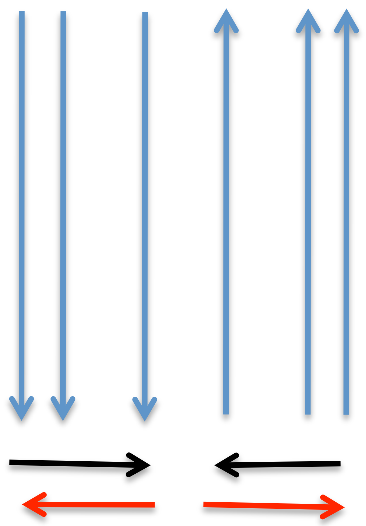
Ambipolar/Hall = $\omega ci/\nu in$

Photosphere: Hall dominant
Chromosphere: Ambipolar dominant



Khomenko & Collados 2012

Neutral effects in current sheets



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

- Hall effect bent B to in the direction of –J
- Ambipolar diffusion transports B inward

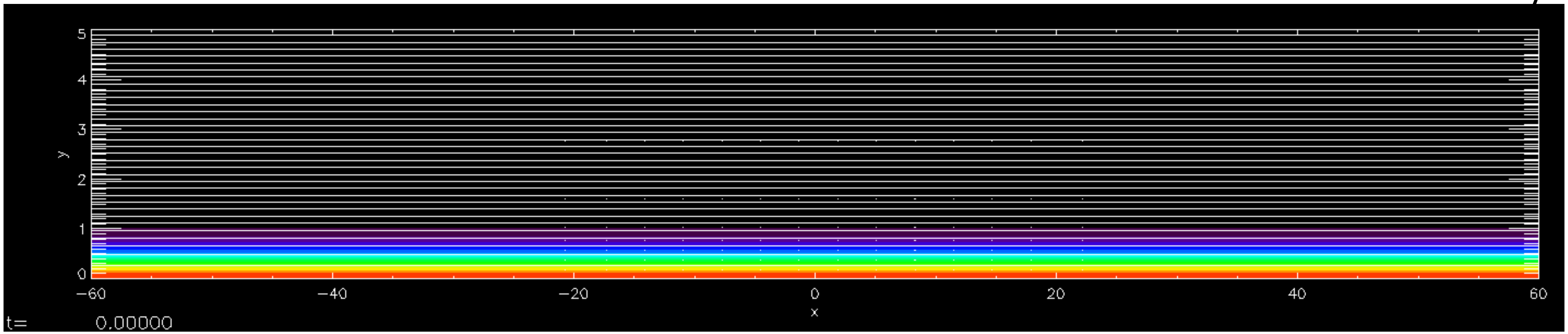
  => current sheet thinning (Brandenburg & Zweibel 1994)

- 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

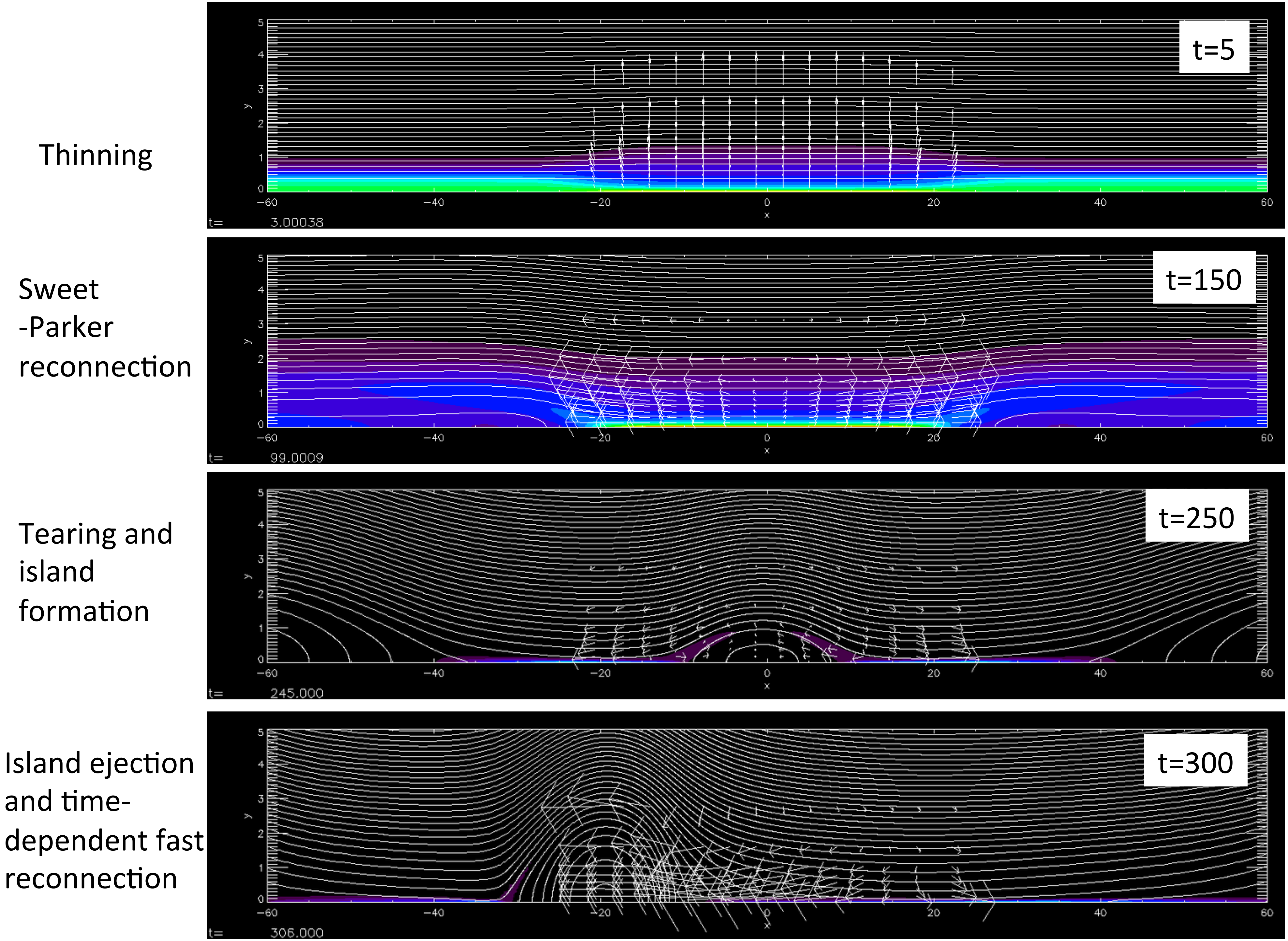
- 2D MHD simulation with uniform resistivity and non-uniform ambipolar diffusion
- No Hall effect, no guide field

color: current density



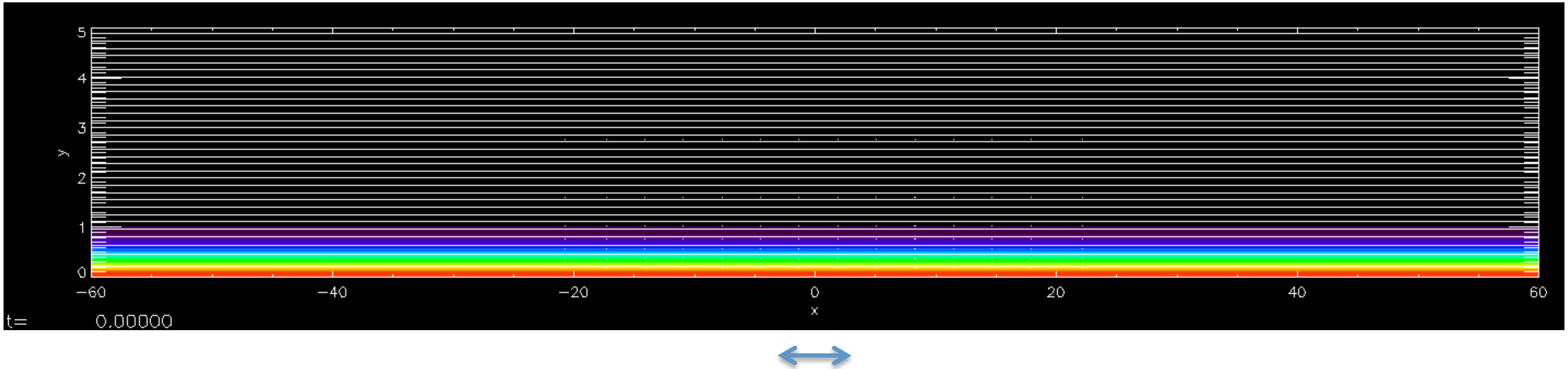
Ambipolar diffusion ≠ 0

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

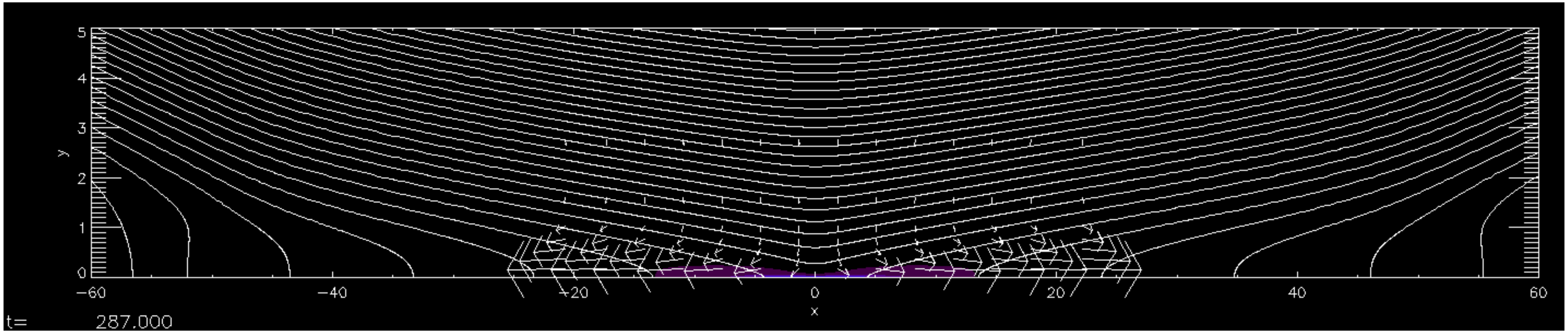

Thinning
t=5
t= 3.00038
Sweet
-Parker
reconnection
t=150
t= 99.0009
Tearing and
island
formation
t=250
t= 245.000
Island ejection
and time-
dependent fast
reconnection
t=300
t= 306.000

Petschek-like regime

color: current density



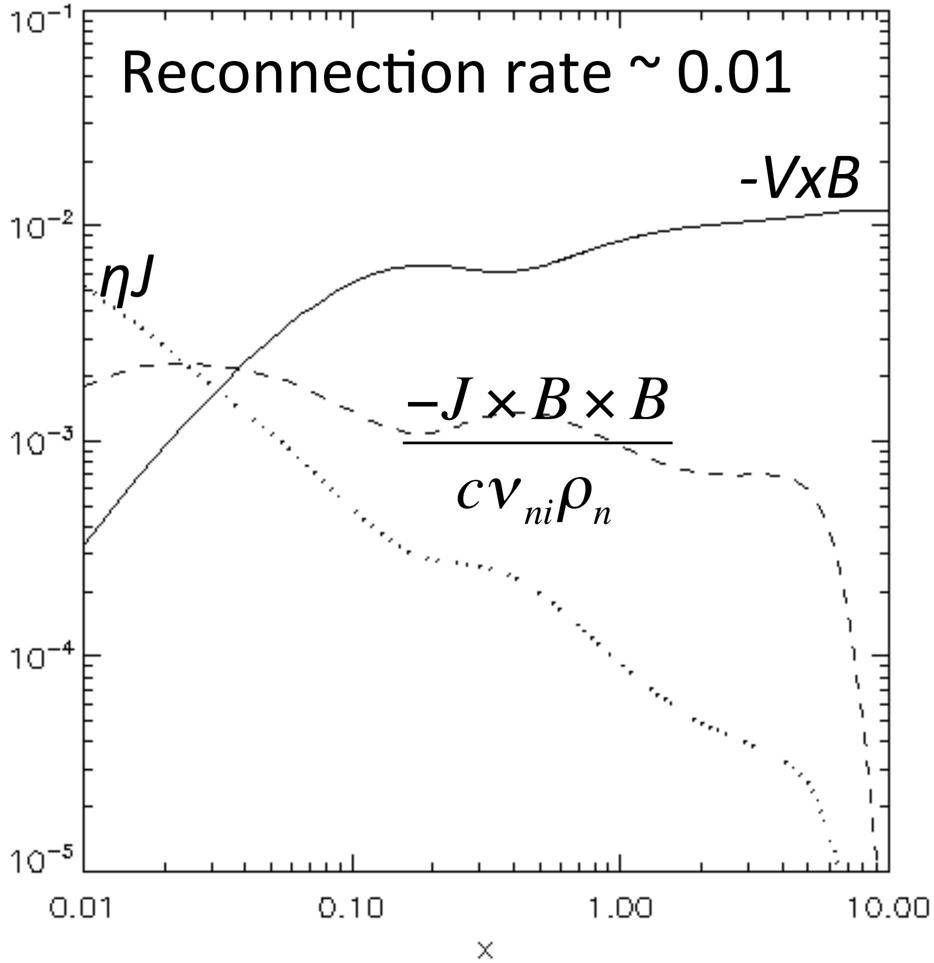
Ambipolar diffusion uniform + enhanced in x < ±2
Uniform resistivity



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.

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



Future: chromospheric reconnection as a target of ALMA

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

- ALMA observes in mm/sub-mm freqency range, corresponding thermal emission from low-middle chromosphere
- Highest resolution by ALMA ~ 0.005" ~3.5km @ 950GHz
- (But due to technical restrictions, currently the longest baseline capable of solar obs is ~2km, corresponding 0.04" ~ 28km resolution...)
- The Hall/ambipolar scales in chromosphere is 1~10km
- Combination of ALMA and other spectropolarimetric obs (Hinode, IRIS, ATST, Solar-C) may allow us to observe the global and diffusion scales simultaneously!