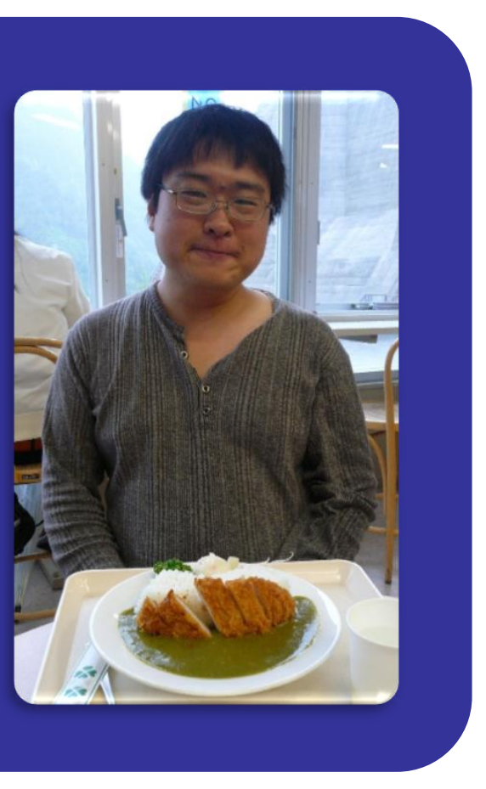
The Role of a Flux Rope Ejection in Three-dimensional Magnetohydrodynamic Simulation of a Solar Flare

Keisuke Nishida[1], Naoto Nishizuka[2], and Kazunari Shibata[1]

[1] Kwasan and Hida Observatories, Kyoto University, Japan, nishida@kwasan.kyoto-u.ac.jp
[2] National Astronomical Observatory of Japan

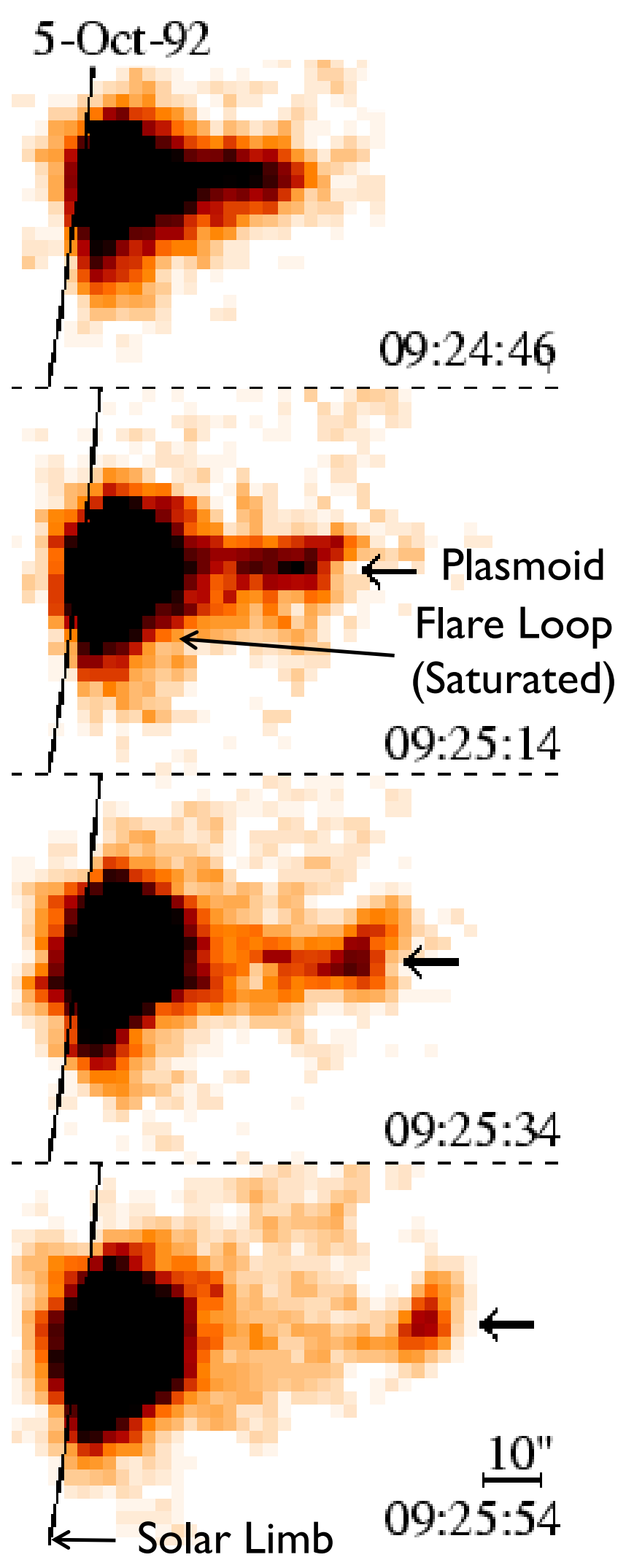


Reconnection Problems

There are some remaining problems in solar magnetic reconnection:

- **What determines the speed of reconnection?**
    - How fast reconnection is realized (M~0.01-0.1)?
    - Petschek type, Sweet-Parker type, others?
- **What is the nature of coupling between micro and macro scales in Petschek-type reconnection?**
    - Microscopic plasma scale (ion Larmor radius / ion inertial length) ~ 10^2 cm
    - The size of a flare ~ 10^9 cm

➡ **Solar flares give us hints!**



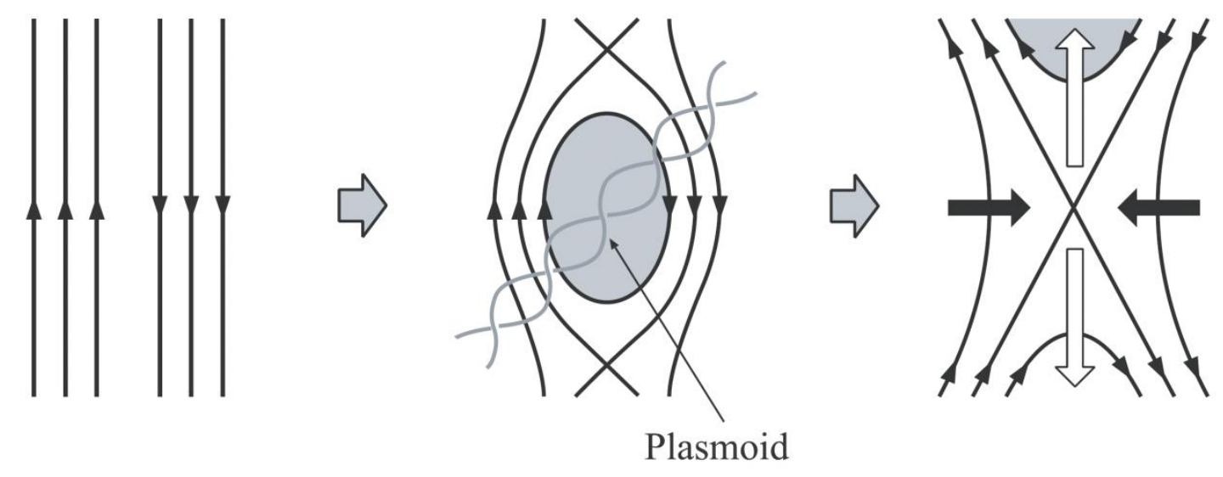
Flux rope (plasmoid) ejections are commonly seen in various plasmatic phenomena with magnetic reconnection. Ohyama & Shibata (1998) found plasmoid ejection in solar flare observed with Yohkoh/Soft X-ray Telescope (right figure).

Observations of solar flares show **positive correlation between the plasmoid velocity and the reconnection speed** (Shibata et al. 1995; Ohyama & Shibata 1997. 1998; Qiu & Yurchyshyn 2005; Shimizu et al. 2008). This relation was also found in laboratory experiments (Ono et al. 2011).

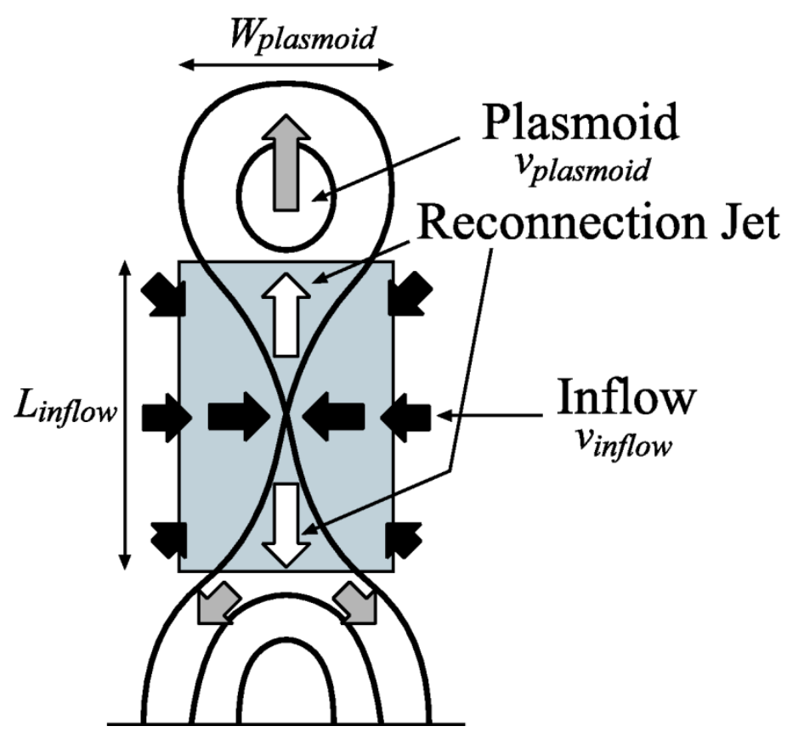
These results suggest that **plasmoid ejections play an important role in magnetic reconnection.**

Role of Ejection in Reconnection

Based on these observations, Shibata (1996, 1997) extended the classical CSHKP model and proposed **the plasmoid-induced reconnection model**.



A plasmoid is created in the anti-parallel magnetic field by the magnetic reconnection. Then the plasmoid inhibits inflows into the sheet, so reconnection is inefficient and **magnetic energy is stored**.



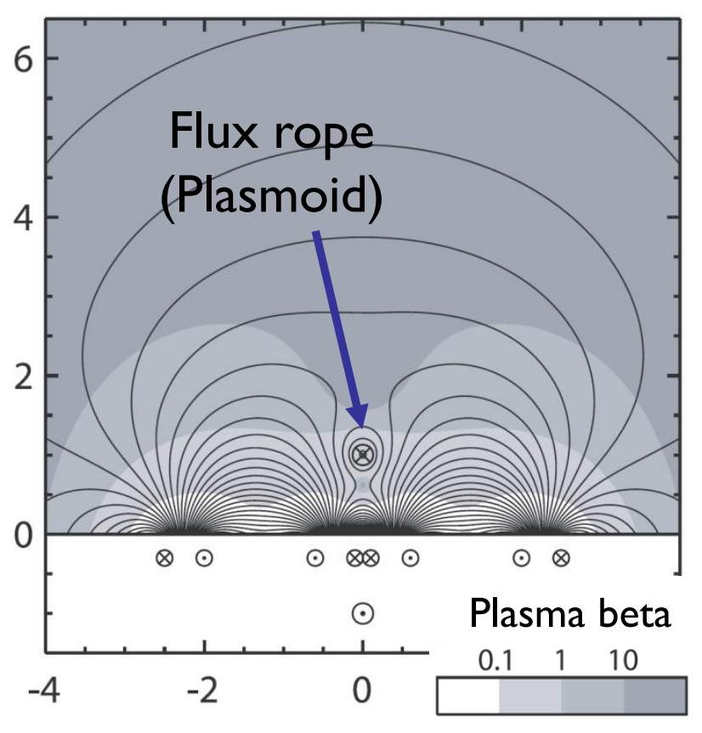
Then the plasmoid starts to move, inflows toward the X-point are induced following mass conservation, and reconnection starts. Since the reconnection rate is determine by the speed of the inflows, **fast reconnection becomes possible when plasmoid ejection is fast**. Moreover the jet from a reconnection point accelerates the plasmoid, so **the fast reconnection further drives fast plasmoid ejection**.

There is **positive feedback**. Reconnection rate, inflow speed, plasmoid ejection velocity are closely related each other, and **it will cause nonlinear instability.**

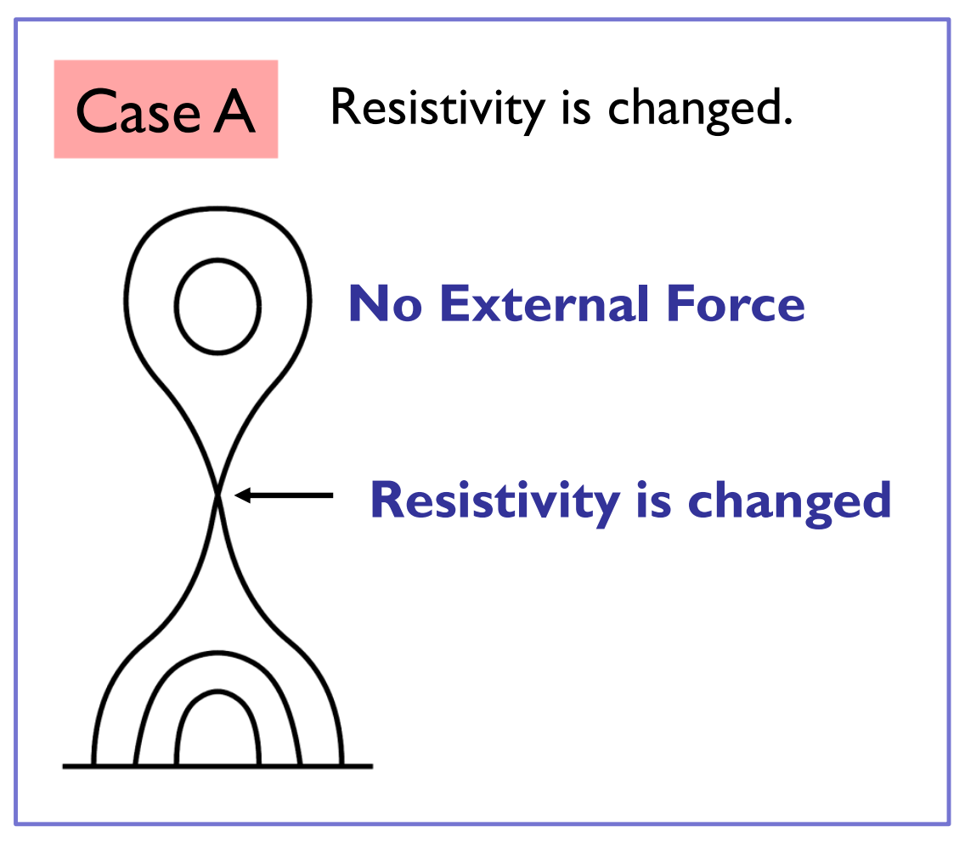

Reconnection
Plasmoid ejection
Positive feedback
Strong inflow

Test by 2D MHD Simulation

The plasmoid induced reconnection model is numerically shown by 2D MHD simulation that a flux rope eruption induces reconnection inflow to the current sheet and enhances both the current density and electric field, finally leading to fast reconnection (Nishida et al. 2009).

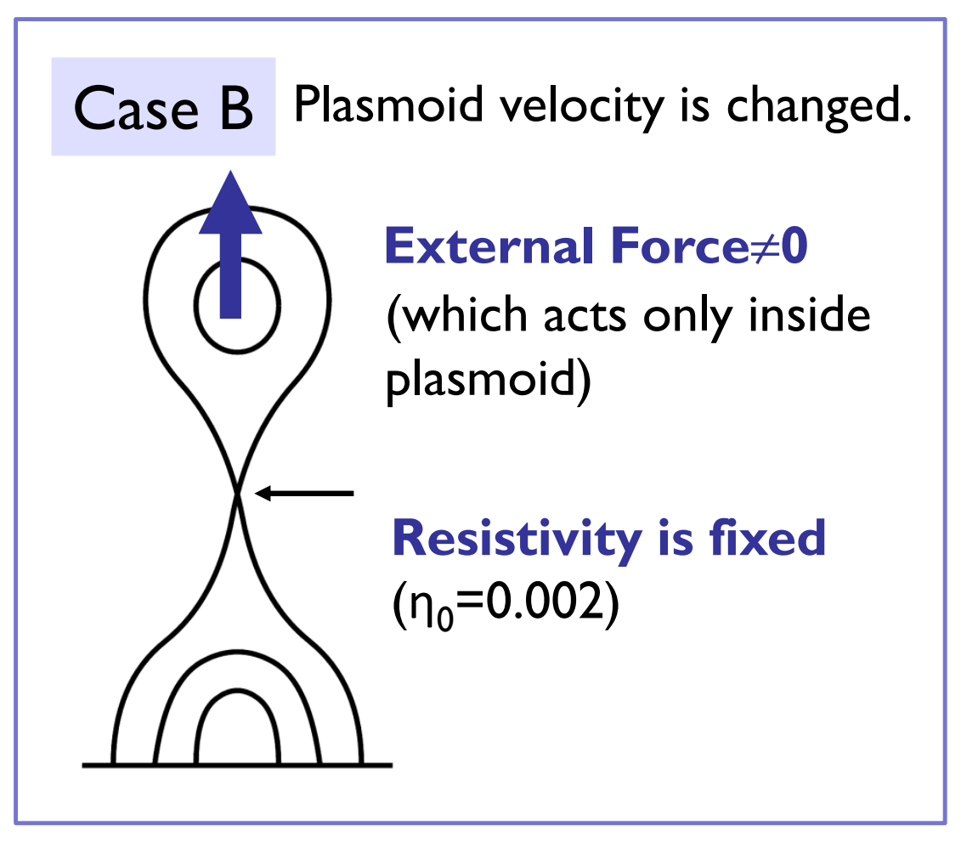


We perform simulations with a multistep implicit scheme (Hu 1989) in order to solve the 2D resistive MHD equations. We perform simulation for the two cases in order to examine the effect of reconnection and rising plasmoid on flare evolution.


Case A Resistivity is changed.

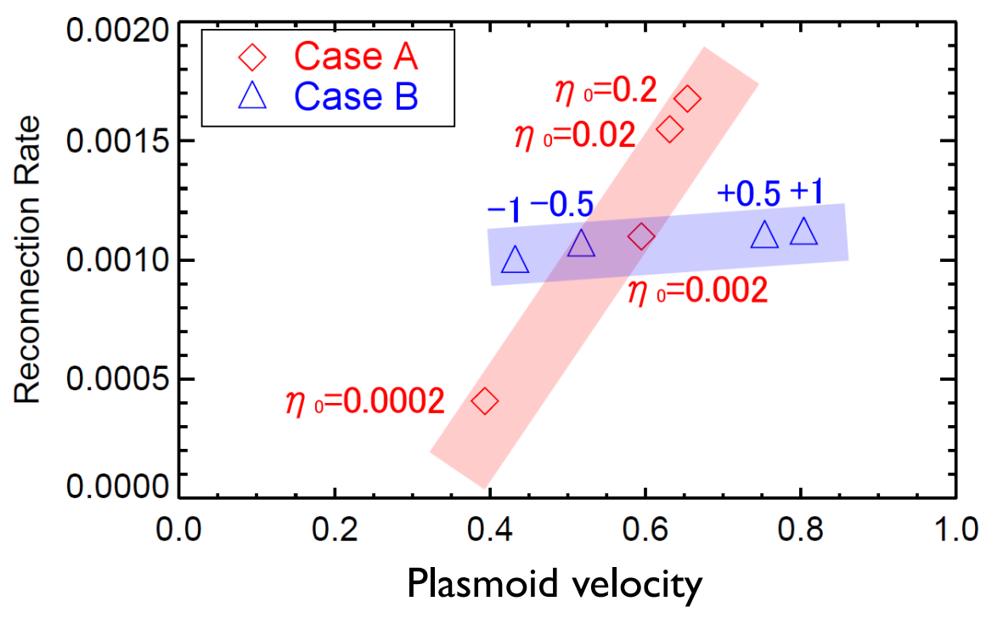
No External Force

Resistivity is changed


Case B Plasmoid velocity is changed.

External Force≠0
(which acts only inside plasmoid)

Resistivity is fixed
(η_0=0.002)



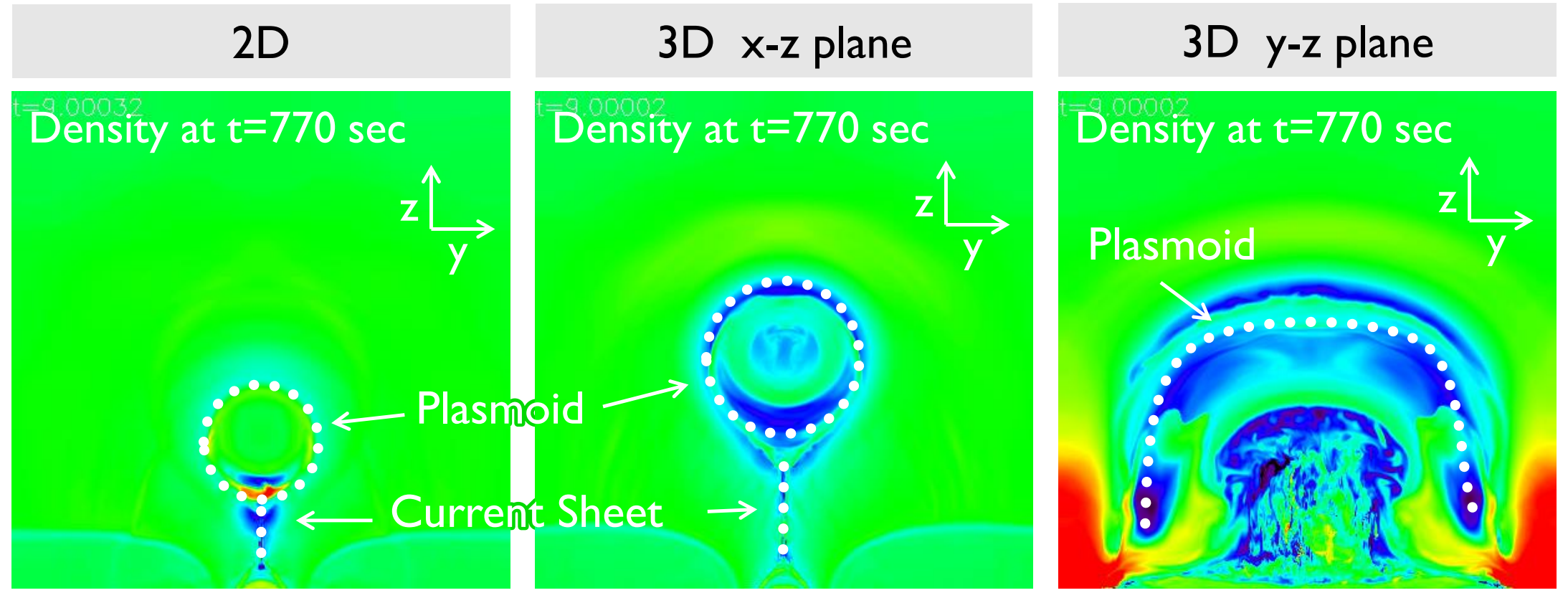
Numerical result shows that **the reconnection rate (i.e., inflow speed) and the plasmoid velocity are closely related to each other.**

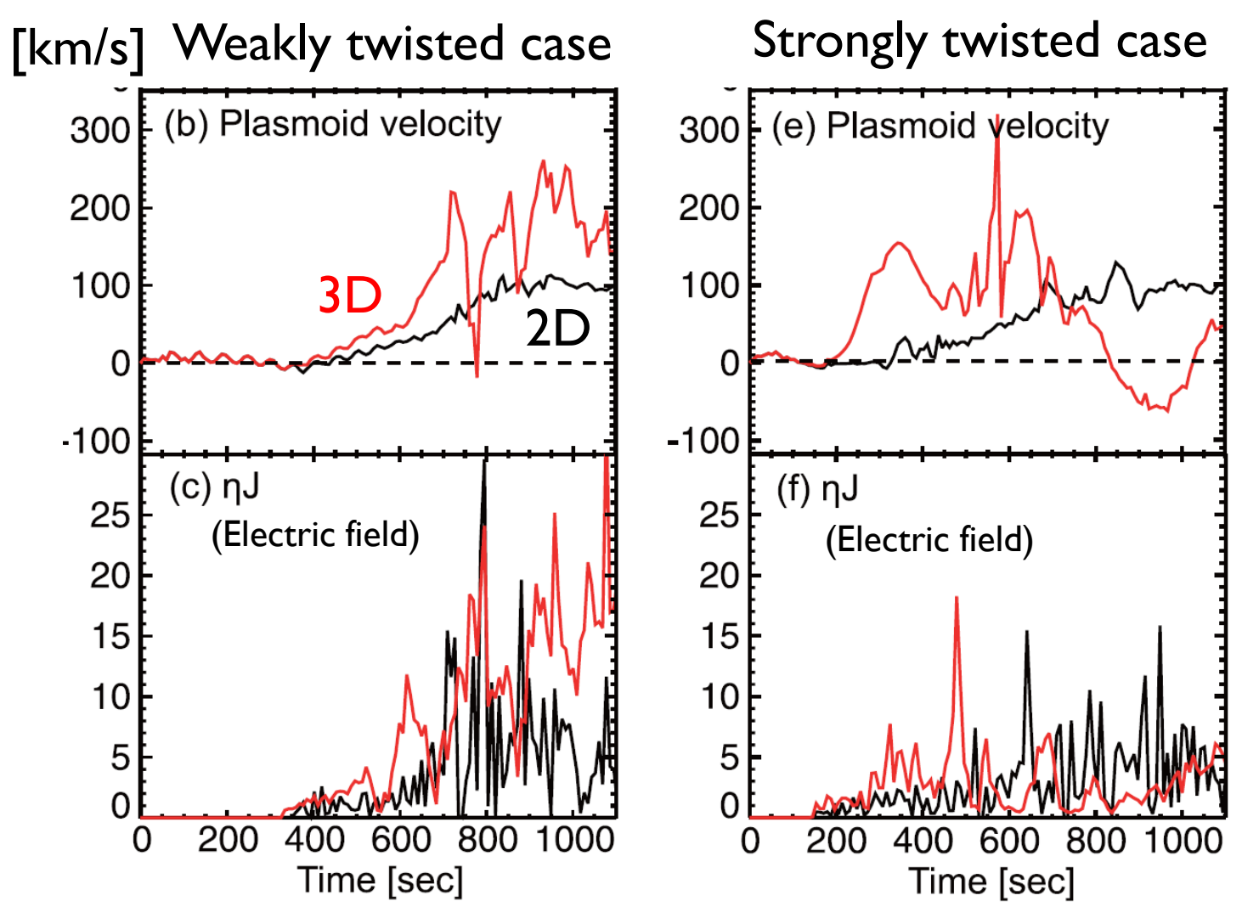
Test in 3D

We **simply uniformly extended the previous 2D MHD model to 3D direction** (see 2D models; Chen & Shibata 2000; Shiota et al. 2005; Nishida et al. 2009). We assumed anomalous resistivity depending on the current density. We used CIP-MOCCT scheme (Kudoh & Shibata 1997). Number of grids are 400^3.

2D vs. 3D

Plasmoid in 3D is lifted up by kink instability faster than 2D.



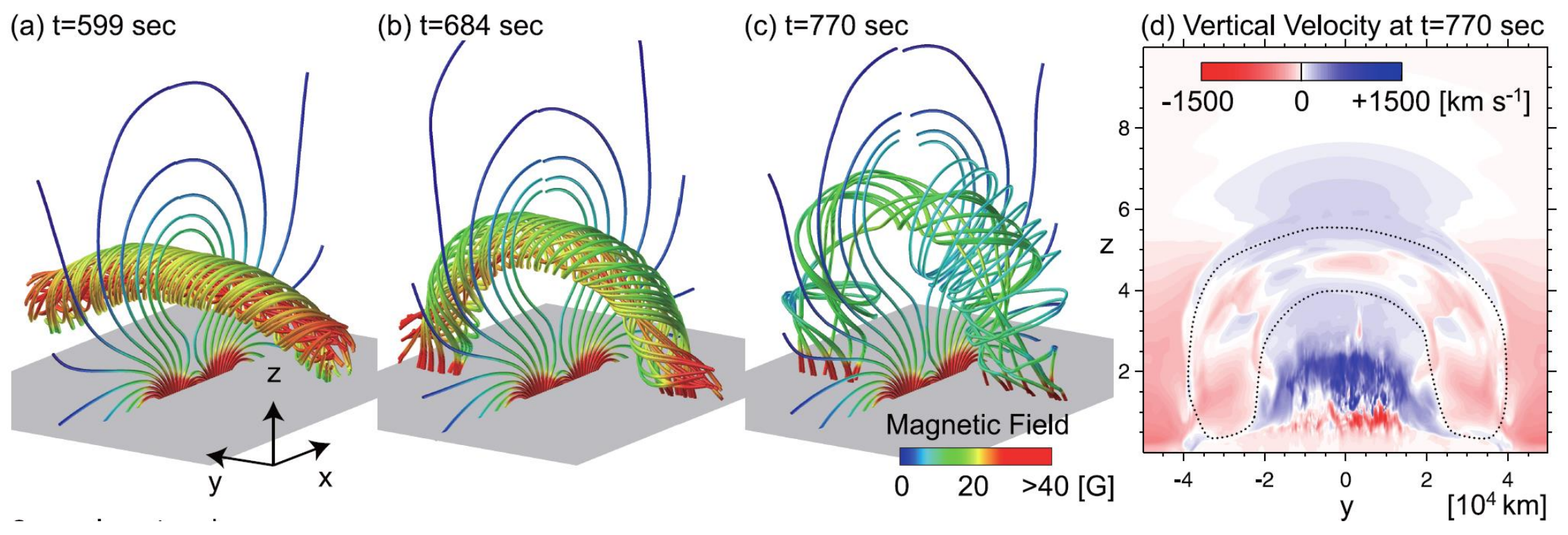


Both the reconnection rate and plasmoid velocity are higher in 3D case.
This result supports plasmoid-induced reconnection model.

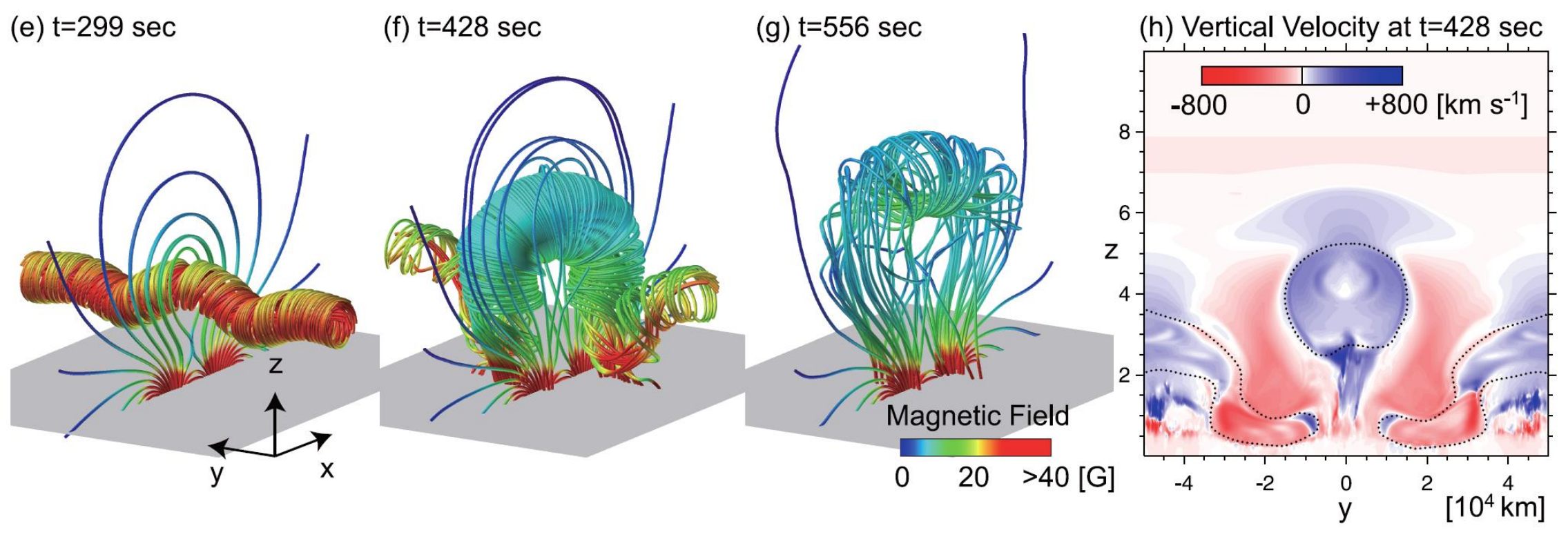
	2D	3D
Kink instability on flux rope	**No**	**Yes**
Plasmoid speed	Slow	Fast Lifted up by kink instability
Inflow speed	Slow	Fast
Electric field (=Reconnection Speed)	Weak	**Strong**

Weak Twist vs. Strong Twist

Time evolution of strongly twisted flux rope case



Time evolution of weakly twisted flux rope case

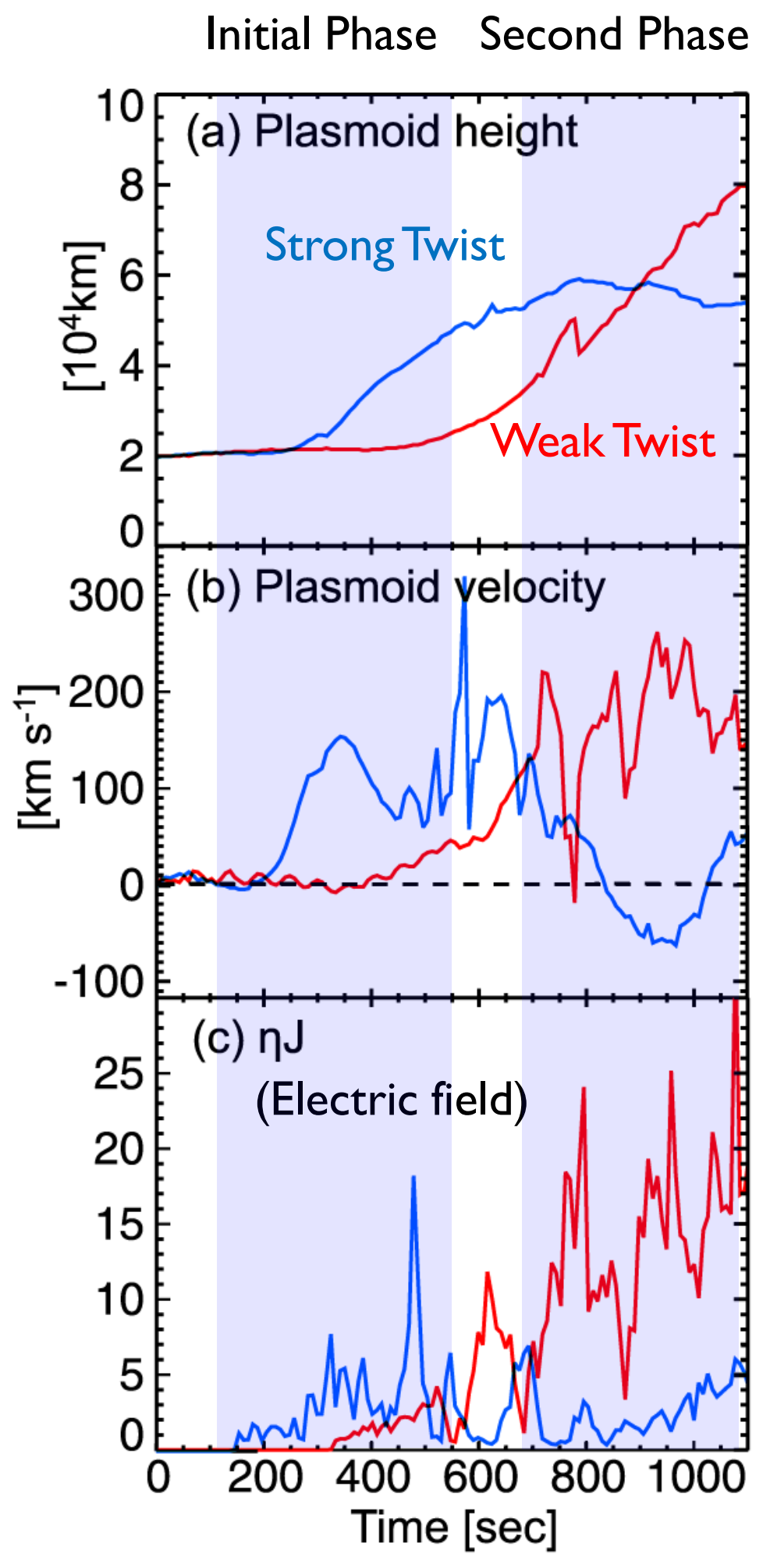


A strongly twisted flux rope initially shows greater upward acceleration than a weakly twisted flux rope and shows a rotation about the z-axis due to the kink instability, the so-called writhe (Kliem et al. 2010), during the nonlinear evolution.

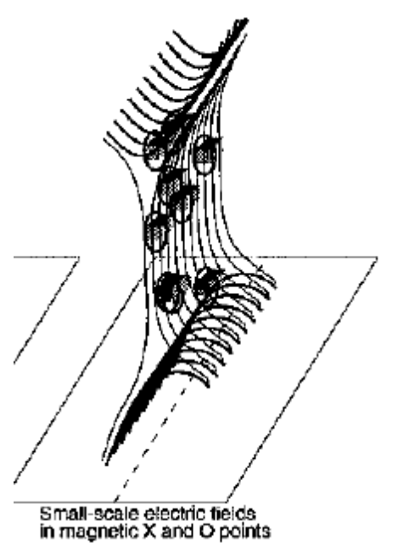
In strongly twisted case,

- **In initial phase, faster kink instability.**
    - Plasmoid is accelerated faster.
    - Then electric field is enhanced.
- **In secondary phase, failed to eject.**
    - Plasmoid stops.
    - Then reconnection stops.

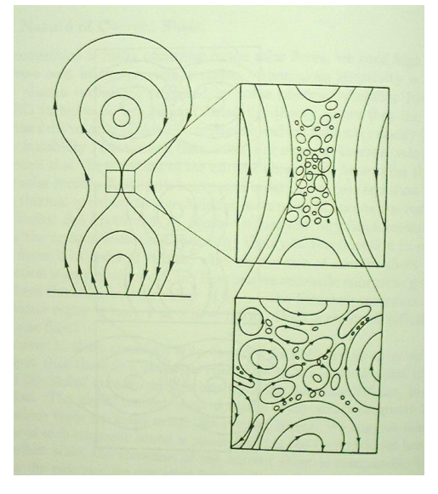
In weakly twisted case, the reconnection rate remains large with bursty time variation even after the upward acceleration of the flux rope levels off.



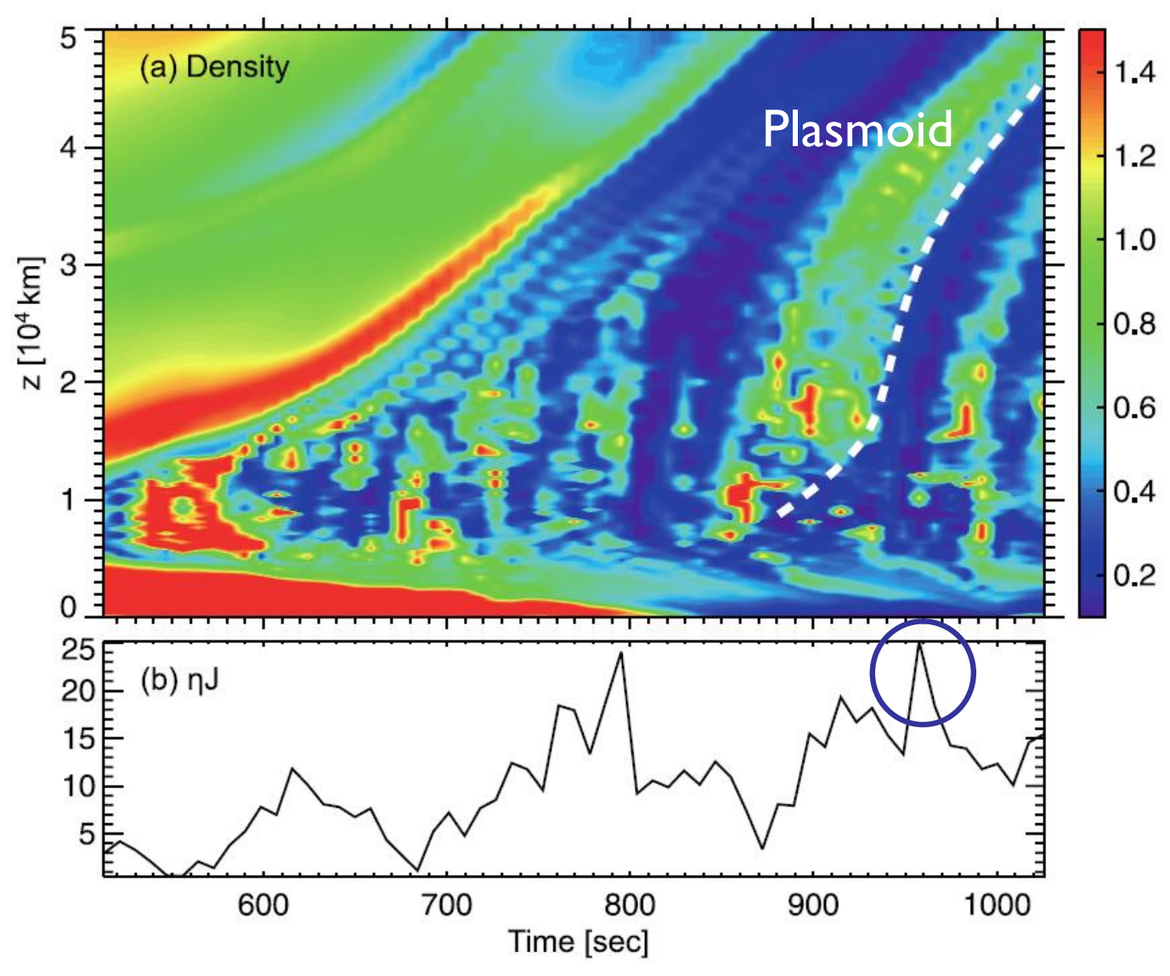
Secondary Plasmoids



Aschwanden (2002)



Tajima & Shibata (1997)



The **enhancement of the electric field around t=900 s corresponds to the small plasmoid ejection** shown as the white dashed line. This result supports plasmoid-induced reconnection model also in small scale.

Summary

- We performed 3D resistive MHD simulations of a plasmoid (flux rope) ejection in a solar flare.
- The larger ejection velocity of the flux rope induced fast magnetic reconnection.
- Many small secondary plasmoid is created in a current sheet.
- The relation between plasmoid and reconnection is also found in this scale. → Fractal reconnection.
- **Results are consistent with plasmoid-induced reconnection model.**

Reference: Nishida et al., ApJL, 775, L39 (2013), Nishida et al., ApJ, 690, 748 (2009).